Galaxies and Cosmology

Report of Working Group 1.1
Australian Astronomy Decadal Plan 2016-2025

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Executive summary

Following substantial progress against many of the goals defined in *New Horizons*, the Australian community is well positioned to capitalise on our unique strengths and resources in our exploration of galaxy evolution and cosmology.

The coming decade will be one of unification. Fields that have been treated as separate are now converging. The study of distant galaxies, probing the early Universe, is being enhanced by detailed dissection of our nearby galactic neighbours and our own Milky Way Galaxy. Searches for gravitational waves from Pulsar Timing Arrays are already ruling out models for galaxy evolution. The study of super-massive black holes has established that they play a role, perhaps significant, in moderating the way their host galaxy evolves. Permeating our understanding of the baryonic Universe is the role played by magnetic fields, that have only recently begun to be explored in detail. And the framework in which all this activity happens is defined by the cosmological measurements that are continuing to be refined as the international community pursues the nature of dark matter and dark energy.

The next decade is likely to see the astronomical community worldwide develop a comprehensive understanding of the history of the Universe. Cosmological developments, spanning the earliest phase of cosmic inflation to the latest stages dominated by accelerating expansion due to dark energy, will be linked directly to the evolving baryonic components that form the first stars and galaxies, triggering the epoch of reionisation, and their own evolution into the galaxies we see in the nearby Universe today. Gravitational wave facilities are anticipating the first astrophysical detections, providing the opportunity to incorporate these into the broader picture of cosmic evolution.

Australia boasts leadership of numerous galaxy survey projects that, linked closely with simulations and theoretical analyses over the decade, will produce a robust description of the evolution of the baryonic Universe, its mass, energy, angular momentum, magnetic field and structure. Australian leadership and involvement in major cosmology projects will refine the framework for the flow of the baryons and potentially give new insights into the standard model of physics. In broad terms, the high impact galaxy and cosmology science in which Australia will have a leadership or key role is summarised by (1) Measuring the characteristics of the epoch of reionisation; (2) Measuring the evolution of the baryonic Universe, its mass, energy, angular momentum, magnetic field and structure, as probed through galaxies and galaxy clusters (3) Measuring cosmological and fundamental parameters, including the properties of dark energy and dark matter.

To achieve these goals requires access to a variety of observational and computational facilities. In addition to our major national telescope facilities and upcoming facilities to which Australia will have access, key additional facilities that will be significant in enabling the highest impact science in these areas include (1) the LSST, (2) 8m telescope access, (3) eROSITA, and (4) positioning our community to play a leadership role in a massively multiplexed spectroscopic survey with a telescope of the 8-12 m class. These observational facilities will need to be supported by a consolidation of expertise in computational physics, and access to large allocations of HPC and storage resources, for managing the theory and simulations work that complements the observational data, as well as the archiving and analysis of both.

A key strength of Australian astronomy arises from the solid links joining the multifaceted observational and theoretical communities. Australia has the opportunity, by capitalising on this strength, to lead international efforts in integrating the progress in formerly separate fields and directing the efforts in unifying our understanding of the Universe.

1 *New Horizons: A Decadal Plan for Australian Astronomy 2006-2015*

The scientific goals identified in the last Decadal Plan, *New Horizons*, were expressed as broad and open-ended questions, "amongst the biggest it is possible to ask". Since the publication of *New Horizons* the Australian community has made substantial progress against each of these ambitious goals. Those relevant to "Galaxies and Cosmology" are highlighted here, along with representative summaries of progress in the past decade. More detail is provided in the appendices.

- ***What is the nature of the dark energy and dark matter?***
  - The 2011 Nobel Prize in Physics was awarded to Brian Schmidt, the Royal Astronomical Society Group Achievement Award in 2008 to the 2dFGRS team, and the Shaw Prize in 2014 to John Peacock and Shaun Cole for 2dFGRS work, recognising earlier successes in measuring the cosmological parameters describing the Universe. Cosmologists established the technique of making simultaneous measurements of the expansion and growth history of the Universe, demonstrated through the 6dFGS and WiggleZ surveys measuring the baryon acoustic oscillation and redshift space distortion signals. The combination of those independent classes of measurement provides a new and non-trivial test of cosmological physics. The technique of HI intensity mapping has also been developed as an independent approach to measuring the baryon acoustic oscillation signal.
- ***How and when did the first stars form in the early Universe?***
  - The SkyMapper telescope began survey operations in 2014. One of its goals is to identify rare populations of low metallicity stars, that may be relics of the earliest star formation epochs. It has already successfully discovered the lowest-metallicity star known. The MWA began operations in 2013, with multiple scientific goals including detection of the epoch of reionisation.
- ***How are galaxies assembled and how do they evolve?***
  - Surveys such as HIPASS, GAMA, SAMI, and ATLAS, among many others, have expanded our understanding of the astrophysics associated with galaxy evolution. This includes the detection of "tendrils" of galaxies extending into the lowest density void environments; evidence for variation between galaxies in the mass distribution with which stars form, and the possibility that this is also different at early epochs; measurement of the heavy element abundance of galaxies over the past 11 Gyr, showing that models predict too high a metallicity in high-mass galaxies. An aspect of galaxy properties that has seen much activity, not anticipated in *New Horizons*, is their internal dynamics. Resolved kinematics of galaxies shows that the high turbulence is driven by star formation and not cosmic accretion as previously thought.
- ***How do the super-massive black holes in the cores of galaxies work?***
  - Feedback from energetic super-massive black holes on their host galaxy has been identified from simulations as a potentially crucial mechanism for regulating the formation of stars in galaxies. We now recognise two primary modes associated with fuelling of the black hole, referred to as "hot-mode" and "cold-mode" accretion, related to the physical properties of the accreting gas, and these have distinct observational signatures. Supermassive black holes seem to grow faster than their host galaxies, reflected in the evolution of the relationship between black hole mass and the velocity dispersion of their host galaxies. There is not yet a clear understanding of the significance of feedback from a central engine in moderating galaxy evolution processes.
- ***What is the origin and evolution of cosmic magnetism?***
  - The strength, properties and distribution of magnetic fields in the local Universe have been extensively explored. The "Faraday rotation measure grid" technique has been established and used to demonstrate that galactic magnetic fields can be generated by rapid dynamo modes. A new technique for directly visualising cosmic turbulence has been developed, providing a new tracer of the impact of magnetic fields. Strong and ordered magnetic fields have been measured in high velocity clouds of neutral hydrogen, providing a physical explanation for their long lifetime and an explanation for how substantial amounts of gas can accrete onto galaxies, to serve as the fuel for star formation.

2 Priorities and recommendations

We have identified three scientific goals most likely to have the highest impact for the Australian community, in the area of "Galaxies and Cosmology". These have been selected with consideration for: (1) Existing or developing strengths in the community; (2) The significance of resolving the scientific question or addressing the goal; (3) The range of facilities to which we have, or are likely to have, access. These goals, listed below, are intertwined in the sense that each informs and is informed by the others. Importantly, Australia is uniquely positioned to capitalise on this linkage across and between fields.

We indicate the facilities needed to achieve these goals. Italics represents facilities not yet available but which Australia will have access to. Bold indicates facilities that the Australian community does not currently, or will not have access to (although individuals or institutions may in some cases). One priority is that Australia should aim to complement its current commitment to SKA and GMT by participating in a massively multiplexed 8-12 m optical/IR spectroscopic survey telescope, such as PFS on Subaru, the Maunakea Spectroscopic Explorer (MSE), or a new Southern Hemisphere facility that Australia might consider leading. Below we refer to such a capability generically as a massively multiplexed spectroscopic survey (MMSS) facility.

- **Measuring the characteristics of the epoch of reionisation.**
  - The EoR will be detected and characterised initially through estimation of 1D and 2D power spectra, followed by tomographic mapping of the neutral hydrogen distribution. This will define the environment, and inform further study, of the physics and astrophysics of the first stars and galaxies. The neutral hydrogen signal from the EoR will be measured over the course of the decade, initially by MWA or LOFAR, and its properties more precisely defined with SKA1-low. Australia has the opportunity to lead much of this science, and to link it directly to the key questions around the formation and early evolution of galaxies through high redshift observations with GMT constrained by the boundary conditions imposed through low-redshift galaxy surveys.
  - Facilities needed: MWA, SkyMapper, *SKA1-low*, **8m Telescopes**, **LSST**, **MMSS**, *GMT*
- **Measuring the evolution of the baryonic Universe.**
  - All sky pan-spectral photometry from radio to ultraviolet wavelengths and massively multiplexed spectroscopic surveys, including integral field surveys, will allow the details of galaxy formation and evolution to be mapped from the epoch of reionisation to today. This comprehensive picture will include a full description of how the mass, energy, angular momentum, magnetic field and structure of baryons in the Universe evolve, producing the galaxies we observe. This will incorporate the formation and evolution of supermassive black holes and their role in regulating galaxy growth. Australia will continue to build on our high international profile in this area through a wealth of existing and planned multiwavelength survey programs.
  - Facilities needed: AAT, UKST, ATCA, LBA, MWA, SkyMapper, *ASKAP*, *4MOST*, *GMT*, *SKA1-survey*, **LSST**, **8m Telescopes**, **eROSITA**, **MMSS**
- **Measuring the properties of dark energy and dark matter.**
  - Understanding the nature of dark energy requires simultaneous measurements of the expansion rate and growth history of the Universe. These require multiple techniques to control systematic errors (BAO at low and high redshift, peculiar velocities at low redshift, redshift space distortion, and more). Importantly, many ongoing and planned Australian survey projects lend themselves either directly or indirectly to these approaches. Advancing our understanding of dark matter requires different techniques, testing simulation and model predictions against galaxy distribution and structure signatures measured in observational surveys, as well as through high energy photon, astro-particle and particle physics approaches. Australia is already establishing close links between the astronomy and particle physics communities through joint Centre of Excellence meetings.
  - Facilities needed: AAT, UKST, SkyMapper, MWA, Parkes, *ASKAP*, *4MOST*, *SKA1-survey*, Auger, IceCube, *HESS-II*, *CTA*, **LSST**, **8m Telescopes**, **eROSITA**, **MMSS**

Each of these goals is enhanced by a close link with theory and simulations. The more sophisticated and complex the observational data become, the more crucial the simulation work is in order to fully develop a physical understanding of the system. Each goal also provides an opportunity to capitalise on the developments in the others. Below we expand on the context leading to the choice of these scientific goals and explore some of the issues in more detail.

2.1 Measuring the characteristics of the epoch of reionisation

This is a field of research that has seen a strong growth in Australian capacity in the past few years. Details are provided in Appendix 2 § 4.3, Appendix 3 § 3.2, Appendix 4 item 4 (and discussion), and Appendix 5 § 1.3, 2.3, 3.3. Australia has the opportunity with MWA to make the initial detection, although international experiments (such as LOFAR) are also working toward this goal. The Australian community in this area is still small, and there will need to be targeted growth in both observational, theoretical and simulations capacity in order to capitalise on the opportunities in this area. The instrumental capability would also be enhanced by expansions of the existing MWA facility, leading toward SKA1-low. The other facilities identified here will be needed to provide complementary optical/IR imaging and spectroscopy to identify the astrophysical sources driving the reionisation, linking the cosmological aspects of the problem to the evolution of the baryonic Universe.

2.2 Measuring the evolution of the baryonic Universe

This is a field which is immensely broad, and encompasses mass growth and assembly in galaxies including gas fuelling, large scale structure, angular momentum and magnetic field evolution, the multiphase IGM and ISM, as well as the formation and evolution of supermassive black holes and establishing their role within their galaxy hosts. Details are provided in Appendix 2 § 4.1, 4.2, 4.3, Appendix 3 § 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, Appendix 4 item 3, Appendix 5 § 2.1, 2.2, 2.3, 3.2, 3.3. The uniquely Australian opportunity here comes from the opportunity to unify the variety of scientific analyses in this field, by unifying the observational datasets and simulations being used, capitalising on our community's close multiwavelength links combined with the links to the theory and simulation community. Anticipated scientific highlights are likely to include understanding galaxy structure and kinematics and their evolution (Appendix 2 § 4.1.8, Appendix 3 § 3.3), identifying the internal and external processes dominating galaxy mass growth and star formation quenching (Appendix 2 § 4.1.1, 4.1.2, Appendix 3 § 3.3), and establishing how supermassive black holes interact with their galaxy hosts (Appendix 3 § 3.5). The facilities required here are necessarily broad ranging, including essentially all facilities Australia already has access to, in order to provide the pan-spectral information needed to construct this comprehensive understanding. Importantly, this also requires 8m telescope access, the highest quality optical photometry available (LSST), high resolution all sky X-ray data (eROSITA), and the next order of magnitude in multiobject spectroscopy (providing tens of millions of galaxy spectra).

2.3 Measuring the properties of dark energy and dark matter

The independent puzzles over the nature of dark energy and dark matter continue to drive substantial international research. Australia has an established community leading many of these efforts, capitalising on uniquely Australian approaches and capabilities to complement the large international programs. Details are given in Appendix 4, and Appendix 5 § 2.5. We emphasise that the observational approaches to understanding dark energy and dark matter are quite different and independent (as detailed in Appendix 4). For dark energy, ever larger spectroscopic surveys are an important component of the strategy. For dark matter approaches needed include gravitational lensing, and the small scale structure around galaxies, also accessible through galaxy spectroscopic surveys (informed by simulations), but with different requirements from those for dark energy. Studies of Local Group galaxies link the evolving baryonic Universe to both dark energy and dark matter investigations. Astro-particle and particle physics approaches to understanding dark matter are significant, and it will be important for our community to ensure we are engaged with these developments as well. Fundamental parameters will be tested as gravitational wave detections become a reality, and this will feed into the cosmological analyses, as well as linking them to the baryonic Universe.

3 Opportunities and goals for Australian astronomy over 2016-2025

The broad scientific drivers behind current and planned Australian astronomical research continue to largely follow the directions laid out in *New Horizons*. There have, however, been many changes in the detail. Some goals have grown and expanded through much activity and attention (e.g., cosmology and galaxy evolution), and others have had less activity due to limited access to necessary resources (e.g., first stars), delays in facility development (e.g., black holes), or scientific developments changing the research direction (e.g., magnetic fields). In addition, opportunities that were not anticipated a decade ago are now driving significant research, facility and instrumentation effort (e.g., MWA, GMT, SAMI, Taipan, Hector, 4MOST).

What has always been clear is that there is a close link between the range of facilities available to the Australian community, the expertise in utilising those within the community, and the areas of research that see high levels of activity and flourish. This is not to say, of course, that other areas may not produce high impact and significant outcomes for both individuals and the community. As the size, cost and scope of major facilities continues to increase, Australia's opportunities to play a leading role in the research programs that will produce the major discoveries of the coming decade must be pursued in a carefully considered and strategic fashion.

The opportunities and goals for the coming decade that will have the highest impact for Australia are most likely to be those that capitalise on our existing and developing areas of strength.

Strengths of the Australian community: Galaxies and Cosmology

Scientific strengths

Over the past two decades, the Australian community has established significant strengths in the areas of cosmology and galaxy evolution, as demonstrated by the results in Section 1 above, and detailed further in the appendices. These results have been achieved through the combination of dramatic advances in observational capacity, strong theoretical expertise, and, increasingly, extensive use of numerical simulations.

The boundaries in the galaxy evolution field are being pushed by improvements in five areas: (1) Sensitivity (fainter and further); (2) Sample size (survey area); (3) Wavelength coverage; (4) Spatial resolution; and (5) Numerical simulations. Largely driven by the capabilities of the facilities we have access to, Australian leadership in this area has to date focussed on large sky surveys at relatively low redshift (such as 2dFGRS, HIPASS and GAMA), and capitalising on new technologies such as SAMI, rather than building a broad capacity to exploit the facilities that are sensitive to the high-redshift universe. There are exceptions, but at present such teams are small compared to those focussing on the low redshift universe. This will need to evolve over the decade in light of Australian access to GMT, in order for the community to have the critical mass to effectively exploit the opportunities provided by this facility, and maximise its scientific return to Australia.

The boundaries in cosmology are being pushed by ever larger, and more tightly focussed, survey experiments (such as BOSS, eBOSS, DES, DESI, Euclid, etc.) paired with equally ambitious simulations. The SKA will be unique in enabling such experiments while also facilitating a broad range of additional science. In order to achieve the next major development in certain areas, the scale of these projects requires large international particle-physics-style collaborations, which no one community can lead. Continued Australian engagement with the international community in at least a selection of these projects over the course of the decade will remain important. Complementing these large international programs are a selection of smaller Australian-led cosmology programs. The WiggleZ, SkyMapper, OzDES and 2dFLenS surveys, along with the planned Taipan and EMU surveys, will enable precise tests of gravitational physics across a range of scales and redshifts. In addition, surveys such as GAMA, Taipan and WAVES, supported through substantial simulation programs by major groups nationally (ANU, ICRAR, Swinburne and Sydney), may enable discrimination between different dark matter candidates. The simulations are now at the stage of making detailed predictions of structure in the non-linear regime (1 kpc - 10 Mpc), that will be directly accessible observationally. These continue to illustrate our community's ability to capitalise on key areas where Australian resources can make a unique and high-impact contribution.

In this broad context, there is both an opportunity and a need to expand the research capacity of our community to encapsulate the full range of cosmic time, linking the epoch of reionisation to the low redshift universe, moderated by an understanding developed through simulations, and within the framework informed through cosmology experiments. We will need to maintain links with, and be mindful of developments in, the gravitational wave and particle physics communities, in order to ensure close collaboration allowing us jointly to take advantage of scientific opportunities as they arise.

Immediate opportunity: Linking simulations with observations

Over the past decade the Australian community has developed a mature and broad ranging theoretical and simulation capability. This has most recently been highlighted through the implementation of the Theoretical Astrophysical Observatory (TAO) node of the All-Sky Virtual Observatory. TAO encapsulates the philosophy that simulations are an integral support for observations and aims to make comparisons between the two as seamless and accurate as possible.

The Australian community now has the capability to enhance observational projects by comparison with simulations on a range of scales and incorporating a variety of physical processes. The current and upcoming spatial resolution of simulations, together with the inclusion of physical processes not earlier possible, allows modelling of both internal galaxy properties along with their local environments. Existing work for the SAMI survey, for example, simulates complete gas, stellar structure and kinematics, metallicity and star formation histories. This kind of detailed comparison between simulations and observations is possible for all the major Australian-led galaxy surveys, providing details on both stellar components, neutral hydrogen and molecular gas. This detailed approach is complemented by large-scale cosmological simulations, such as GiggleZ, and the semi-analytic galaxy models that are generated to populate them. TAO provides a resource to directly link such models with observational survey data.

The simulation work provides the link between the cosmological framework and the flow of baryons over cosmic time. In addition, theoretical modelling of the epoch of reionisation folds in explicitly with the early stages of galaxy formation and evolution, as well as the cosmology. In combination Australia has a clear opportunity to position ourselves as leaders in linking these three key research areas in a unified picture of the history of the dark and visible Universe.

Enabling strategy: Sky surveys

The Australian community has established a world-leading capability over the past two decades in the conduct of large-scale sky surveys. Appendix 2 provides an extensive and detailed overview of the current state, and a potential progression for the coming decade. Galaxy and stellar multiobject spectroscopic surveys have been designed to target scientific questions spanning cosmology, galaxy evolution, and Galactic structure. These are exemplified by the 2dF Galaxy Redshift Survey and the RAdial Velocity Experiment, and now succeeded by 6dFGS, WiggleZ, GAMA, OzDES, GALAH and SAMI. Understanding galaxy evolution, star formation and fuelling, together with the link to supermassive black holes has been driven by highly sensitive and wide area radio continuum and neutral hydrogen surveys. These are exemplified by SUMSS, ATLAS and HIPASS, and succeeded now by low-frequency sky surveys with MWA.

This strength is broadened through the development over the past decade of the now operational SkyMapper telescope. SkyMapper will be the first Australian facility to conduct an optical digital sky survey, and to substantially incorporate the time-domain as part of its strategy.

The community is already planning to build on this legacy through proposed surveys with upcoming instruments. With national facilities, these include the planned ASKAP surveys (EMU, POSSUM, WALLABY, DINGO, VAST and FLASH), and the Taipan galaxy survey and the Funnelweb stellar survey with the TAIPAN spectrograph on an upgraded UK Schmidt telescope. Internationally, elements of the Australian community have positioned themselves to play a significant role in the multiobject fibre survey facility 4MOST on the VISTA telescope, to conduct a survey called WAVES. A survey to be completed by the mid-2020s using an instrument such as Hector, a successor to SAMI for multiobject integral field surveys, would cement Australian leadership in massively multiplexed integral field survey science. Opportunities also exist to partner with the Maunkea Spectroscopic Explorer (MSE) facility, that may be operational toward the end of the decade, or to initiate an Australian-led project to design and build a 12 m class massively multiplexed spectroscopic survey telescope.

Emerging Opportunity: Custodians of the Southern Sky

The Australian community shares extensive experience, ongoing effort and planning for a broad variety of multiwavelength surveys, designed to address high impact scientific goals across a range of galaxy evolution, cosmology and other areas. We have a unique opportunity to unite the wealth of Australian-led existing, ongoing and planned sky surveys with external datasets to provide a multiwavelength spectroscopic and imaging resource that is unparalleled elsewhere in the world. The recently developed All-Sky Virtual Observatory provides a foundation and an infrastructure to house and support such a resource, through modular growth and development. The goal of such a data federation will be to maximise the scientific return to both the contributing surveys and the broader community, by providing quality assured and astrophysically robust panchromatic cross-matching.

Australia is uniquely placed to unite data arising from a variety of optical and radio facilities, to address the scientific goals defined above. The optical and near-infrared data will provide the morphologies and structural analysis (inclination, galaxy components and internal properties and dynamics) while the radio data provides information on the gas reservoirs and angular momenta, along with an unobscured view of central super-massive black hole signatures as well as an independent tracer of star formation. High-resolution follow-up will be provided with the Australian Long Baseline Array (LBA). These capabilities will of course be enhanced through the incorporation of data from other facilities as well. Key resources here, to complement the variety of Australian surveys, will come from the various ESO public surveys (such as the VISTA Hemisphere Survey), GALEX, WISE, eROSITA, as well as major new surveys and facilities such as ALMA, DES and LSST. Perhaps the highest priority of these that will not otherwise be public is LSST.

The Australian community is unique in leading existing and planned optical spectroscopic and radio surveys of the Southern hemisphere. These resources will provide opportunities for Australia to leverage access to other facilities and data, in which Australia would otherwise not have the chance to participate. Australia has an additional advantage, too, in that there is already a theoretical component to ASVO through the Theoretical Astrophysical Observatory (TAO). This provides an additional unique resource, extensible and versatile, to directly link predictions from numerical simulations with pan-spectral photometric and spectroscopic observational data.

4 Available, planned and potential observatory facilities

Here we list existing and new or planned observatory facilities that are of relevance to the Galaxies and Cosmology scientific drivers, and to which Australia or Australian institutions have access. This list indicates those facilities that are important for the Australian community to continue to maintain or operate, or to retain or obtain access to in some form, in order to ensure a broad capability ensuring Australian leadership in these areas.

Bold indicates facilities that are key to delivering the high impact scientific outcomes discussed above, but to which the Australian community does not or will not have access. Italics indicates those to which we have limited, insufficient, or terminating access. Note that we do not require access to all of the various 8 m class facilities, but access to at least one is recommended.

Major facilities currently scientifically operational

Onshore facilities:

- Anglo-Australian Telescope
- Australia Telescope Compact Array
- Murchison Widefield Array
- Parkes Radio Telescope
- Australian Long-Baseline Array
- SkyMapper

Offshore facilities:

- Magellan Telescopes
- *Gemini Telescopes*
- **Keck Telescopes**
- **Subaru Telescope**
- **Very Large Telescopes**
- Karl Janksy Very Large Array
- *Atacama Large Millimetre Array*

New or potential major facilities becoming available during 2016-2025

Onshore facilities:

- Australian Square Kilometre Array Pathfinder
- Refurbished UK Schmidt Telescope
- SKA Phase 1

Offshore facilities:

- 4-metre Multiobject Spectroscopic Telescope
- Giant Magellan Telescope
- **Maunakea Spectroscopic Explorer**
- **Large Synoptic Survey Telescope**
- **eROSITA**
- HESS-II
- *Cerenkov Telescope Array*

5 Capabilities and Facilities

Table 1: The key science questions and the capabilities required to answer them.

	Capability					Wavelength coverage						Theory
	Widefield	High spatial resolution	High redshift sensitivity	High spectral multiplex	Integral field spectroscopy	MHz	GHz (+HI)	THz / FIR	IR	Optical	High-energy	
Measuring the characteristics of the epoch of reionisation	X		X	X		X		X	X	X		X
Measuring the evolution of the baryonic Universe	X	X	X	X	X		X	X	X	X	X	X
Measuring the properties of: (Top) Dark energy; and (Bottom) Dark matter	X	X	X	X			X	X		X		X
	X	X			X		X			X	X	X

Table 2: The required facilities to provide the key capabilities.

Facility	Capability					Wavelength coverage						Theory
	Widefield	High spatial resolution (<1”)	High redshift sensitivity	High spectral multiplex	Integral field spectroscopy / data cube	MHz	GHz (+HI)	THz / FIR	IR	Optical	High-energy	
Imaging facilities												
SkyMapper	X									X		
LSST	X	X	X							X		
LBA		X	X		X	X	X					
Spectroscopic facilities												
AAT	X			X	X				X	X		
UKST	X			X						X		
4MOST	X		X	X						X		
MMSS	X		X	X	?				?	X		
Imaging/spectroscopic facilities												
8m telescopes (Gemini, VLT, Keck, Subaru, Magellan)		X	X		X				X	X		
GMT/E-ELT	X	X	X	X	X				X	X		
eROSITA	X		X		?						X	
Parkes	X				X		X					
ATCA	X	X	X	X	X	X	X					
ALMA		X	X		X		X	X				
ASKAP	X		X	X	X		X					
SKA1-survey	X	X	X	X	X		X					
MWA	X		X	X	X	X						
SKA1-low	X	X	X	X	X	X						
Particle facilities												
HESS-II, Auger, IceCube, CTA	X										X	
Computational facilities												
High-performance computing / TAO		X	X		X	X	X	X	X	X	X	X

6 List of Working Group members

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- Scott Croom, University of Sydney
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- Simon Driver, ICRAR (Co-chair Surveys subWG)
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- Andy Green, AAO
- George Hobbs, CASS
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- Lisa Kewley, ANU (WG Deputy Chair)
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7 Sub-group reports

The five WG1.1 sub-group reports are appended below.

Appendix 1

WG 1.1 Surveys subgroup (Optical/Near-IR) of the Extra-galactic and Cosmology WG

Authors (Optical/near-IR): Simon Driver & Aaron Robotham

Executive Summary

Survey science wish-list:

(1) Direct leadership in a multi-million galaxy wide-area extra-galactic survey (e.g., SUBARU/PFS, **4MOST**, MSE, or DreamMachine)
(2) Construction of a dedicated 12m survey facility with expanded AAOmega/SAMI-like capacity on a high quality seeing site
(3) Access to LSST as the dominant optical imaging facility by 2020.
(4) Involvement in space based imaging (Euclid/ESA and/or WFIRST/NASA)
(5) Access to major 8m survey facilities in particular ESO, Subaru, Magellan and/or Keck
(6) Improved cohesion/linkages between radio and optical survey campaigns (cross-TAC coordination)
(7) Australia to actively take on the role of "Custodian of the Southern Skies".
(8) Expansion of researcher capacity into multi-wavelength astronomy (X-ray, far-IR)

1 Progress against previous Decadal plan

1.1 Optical and near-IR surveys

The previous Decadal plan mentioned the word survey once (page 29) in the context of the AAT moving to sole Australian ownership and the opportunity this presented for large area sky surveys (predominantly spectroscopic). This has very much been realised with the extremely successful culmination of the two-degree field galaxy redshift survey (2dFGRS; Colless et al. 2001) and a variety of more specialist follow-on surveys which include: the Millennium Galaxy Catalogue (MGC; Driver et al. 2005); the six-degree field galaxy survey (6dfGS; conducted on the UK Schmidt Telescope; Jones et al. 2006, 2009); the WiggleZ survey (Drinkwater et al. 2010), the Galaxy And Mass Assembly survey (GAMA; Driver et al. 2011) and the ongoing (recently commenced) Sydney AAO Multi-IFU survey (SAMI) and OzDes surveys. Most of these surveys were aimed at addressing key questions highlighted in the Decadal review related to either refining our cosmological model **or**[1] the formation and evolution processes of galaxies.

Table 1 provides a crude metric of the impact these surveys are having through papers and citations. No attempt has been made to account for either the timescale or the cost of the survey. SDSS for example pre-dates most of the Australian surveys and had a budget in excess of US$100million, many of the other surveys are based on US$billion space-based imaging facilities. However the two-degree field galaxy redshift survey in particular ranks number five on this table and based on innovative Australian built instrument on an existing facility. The 2dFGRS has had this impact for two key reasons: (1) it places a pivotal role in defining the current concordance cosmological model (in conjunction with CMB data), and (2) the survey size constituted an order of magnitude increase over previous surveys (see Fig. 1 right). This should be stressed in the sense that survey astronomy moves the whole front-line forward enabling multiple issues to be address, as opposed to a narrow penetrating focused experiment which has limited legacy value. Both focused and defocused efforts are needed and for the latter the best marker of success is to ask how much new ground is being covered. The 2dFGRS increased the number of known redshifts by an order of magnitude. The SDSS advanced this further and also brought in high quality multi-wavelength imaging data. The lesson to be learnt is that for next generation of surveys to have an equally transformational impact they will need to be equally

[1] An extremely important development is the divergence between cosmology surveys and extra-galactic surveys. At the start of the last decade surveys like 2dFGRS, SDSS and 6dfGS encompassed both, at the current time survey designs for cosmology surveys (all-sky, sparse sampling, tracers) and extra-galactic surveys (all object, small area, dense) have diverged. WiggleZ, BigBOSS, OzDes for example are useless for most extra-galactic science whereas GAMA/SAMI are useless for dark energy studies.

ground-breaking, e.g., a factor of $10\times$ increase in number, wavelength coverage, depth, and/or resolution (preferably all combined).

The achievement of the 2dFGRS Team was internationally recognised through the award of the Royal Astronomical Society's inaugural Team Achievement Award in 2008. The remaining Australian surveys listed in Table 1 are comparable in size to the 2dFGRS and while having a significant and growing impact on the world stage, represent incremental rather then order of magnitude advancements over the 2dFGRS in terms of scope and scale (i.e., target number). Ultimately the GAMA survey will break-ground in terms of wavelength coverage and resolution and SAMI, building on GAMA, will break new ground through spatially resolved spectroscopic studies.

Key science results of the past decade are:

- Publication of the final results from the 2dFGRS constraining the cosmological parameters and confirming concordance cosmology (Cole et al. 2005).
- The WiggleZ survey made refined measurements of the Baryonic Acoustic Oscillations (BAO) constraining both the Dark Energy equation of state as well as the growth of structure (Blake et al. 2011)
- The 6dfGS survey similarly used the BAO feature to constrain the value of the Hubble Constant (Beutler et al. 2011)
- The Millennium Galaxy Catalogue quantified the stellar mass and conventional energy budgets in the local Universe. (Driver et al. 2008; Hill et al. 2010)
- The GAMA survey (see Figs. 1 & 2) has produced the definitive study of structures, i.e., filaments and groups (halos) which will ultimately be used to place constraints on dark matter via the Halo Mass Function (Robotham et al 2010; Alpaslan et al. 2013)
- The SAMI survey, just commencing, constitutes a pioneering study of spatially resolved spectroscopy and therefore acts as both a technology and science demonstrator.
- The OzDes survey, just commencing, looks to maximise the ability of the US-led Dark Energy Survey to constrain the cosmological parameters through SnIa.

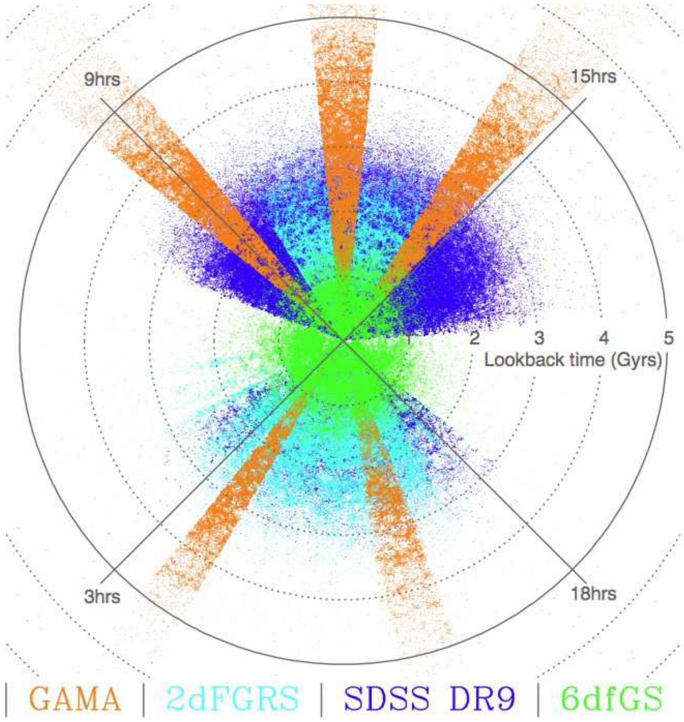
The above Australian Astronomical Observatory (AAO)-enabled surveys (see Fig. 1 left) have or will use between 100-300 nights of telescope time each and together with the 2dFGRS represent approximately 1million distance measurements — approximately one third of the total number of distance measurements known and second only to the US-led Sloan Digital Sky Survey (see Fig. 1 right). Extra-galactic spectroscopic surveys are a clear area in which Australia has positioned itself as a leading force although capacity is also clearly diminishing since the heady days of the 2dFGRS (as seen in the softening of the curve in Fig. 1 right).

In parallel to the spectroscopic surveys has been the development of the SkyMapper telescope, initiated by the Australian National University and not part of the previous Decadal plan. While suffering significant teething problems this facility is now performing close to the originally specified capability (although spatial resolution remains a concern limiting survey depth) and well placed to provide the definitive all-sky optical imaging dataset across the Southern Hemisphere in advance of LSST. While sterling results are emerging on the stellar side (i.e., Nature paper), the main extra-galactic survey has yet to commence in earnest.

2 Key issues for future discussions

2.1 Optical/near-IR imaging surveys

Imaging surveys represent the base from which more detailed observations can follow and therefore the crucial starting point. Hence the underlying imaging survey needs to be competitive from the outset otherwise all that follows is by definition second-rate. There is little point in starting a survey on a 'slow' facility if it will be comprehensively



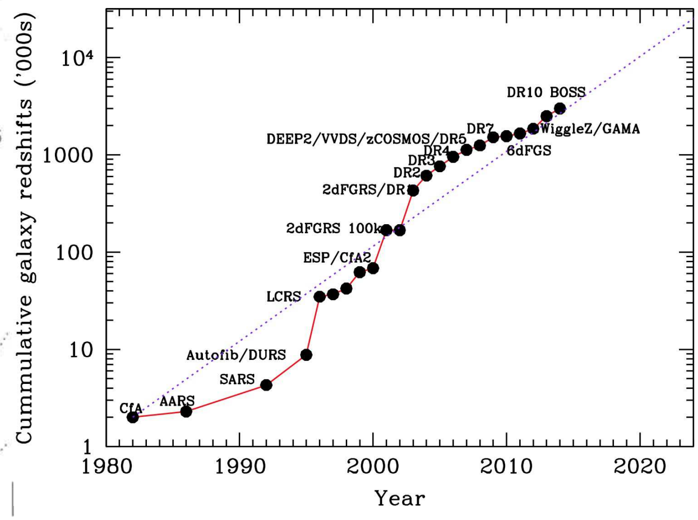
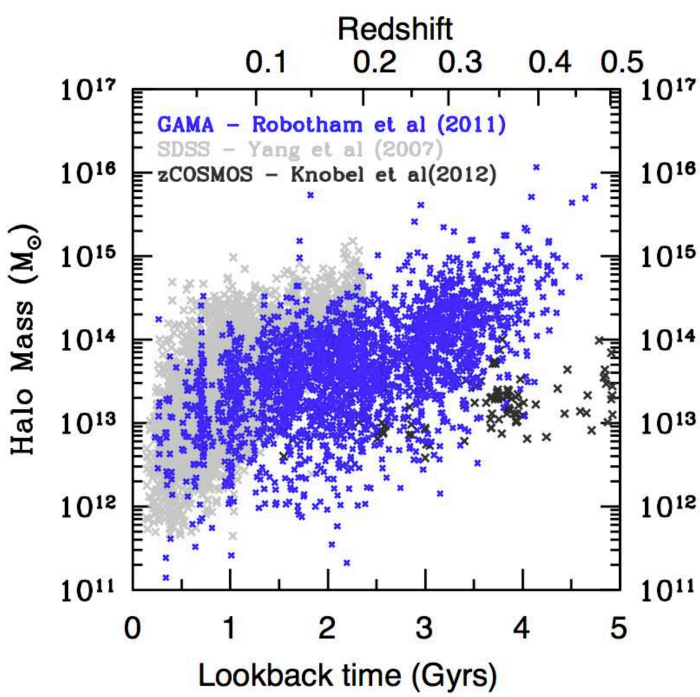


Figure 1: (left) The leading galaxy legacy surveys constructed over the past decade, colours as indicated. Only the SDSS survey is non-Australian led highlighting Australia's prolific activity in wide-area spectroscopic surveys. (right) the increase in number of measured redshifts with time. By the end of the next decade it is estimated that 30 million redshifts will have been measured.



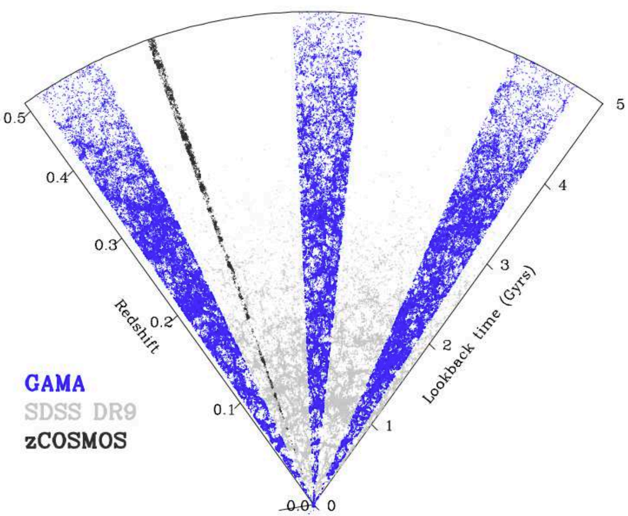


Figure 2: (rightmost figure) The three key survey regions of the GAMA survey are shown in blue with the deep zCOSMOS survey shown in black and the US-led Sloan Digital Sky Survey in grey. The corresponding group (dark matter halo) catalogues are showing in the same colours in the left panels. The AAT GAMA spectroscopic survey and group catalogue is forming a vital connecting bridge between the very near and very far Universe.

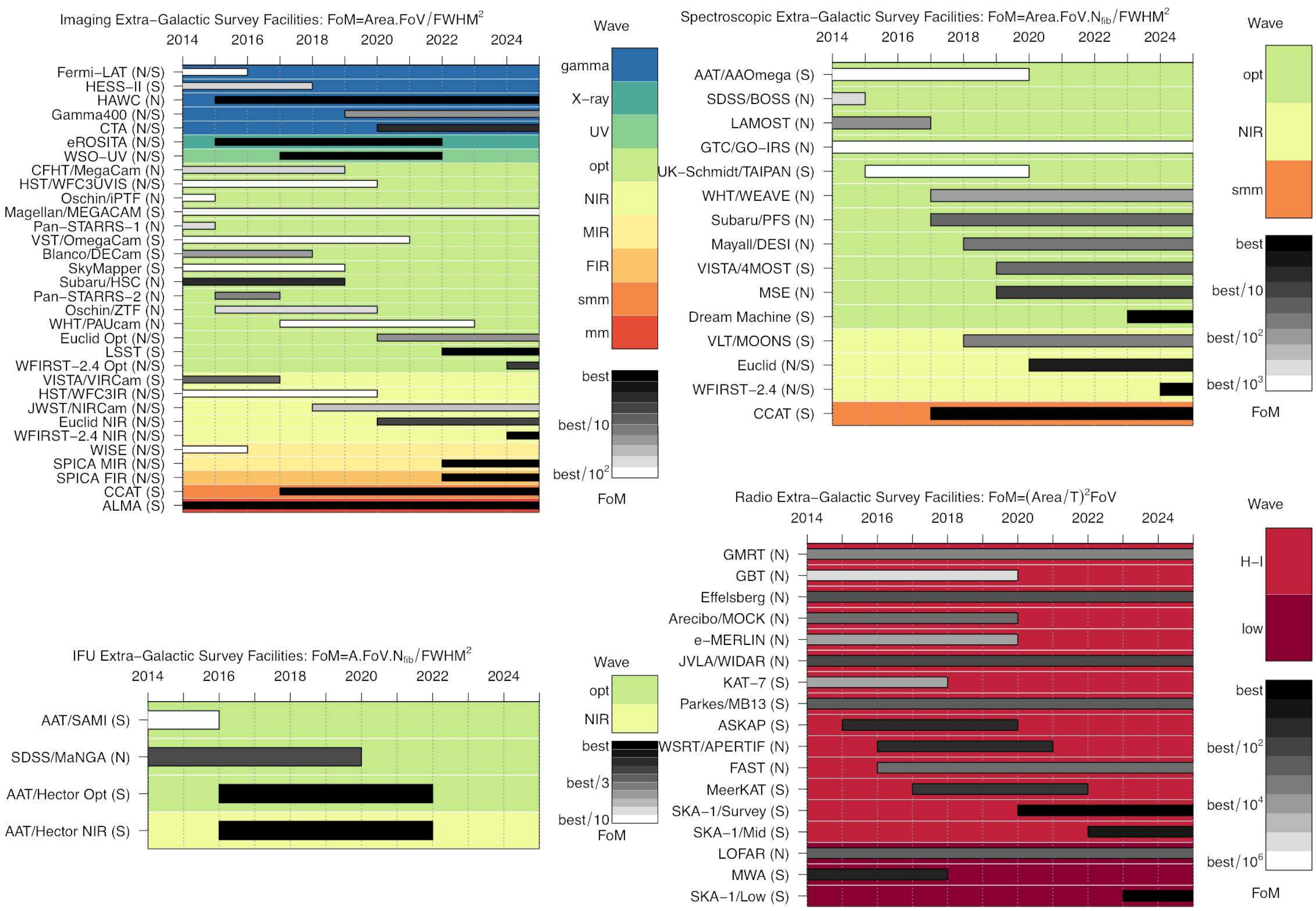


Figure 3: (top left) Gantt-Chart comparing various extra-galactic imaging survey facilities that will operate between now and 2025. Figure of merit (FoM) is calculated using Area.FoV/(FWHM^2). FoM shading is scaled within a wavelength subset. Accompanying data is shown in Table 2. (top-right) Gantt-Chart comparing various extra-galactic spectroscopic survey facilities that will operate between now and 2025. Figure of merit (FoM) is calculated using Area.FoV.N$_{fib}$/(FWHM^2). FoM shading is scaled within a wavelength subset. Accompanying data is shown in Table 3. (bottom-left) Gantt-Chart comparing various extra-galactic IFU survey facilities that will operate between now and 2025. Figure of merit (FoM) is calculated using Area.FoV.N$_{fib}$/(FWHM^2). FoM shading is scaled within a wavelength subset. Accompanying data is shown in Table 4. (bottom-right) Gantt-Chart comparing various extra-galactic radio survey facilities that will operate between now and 2025. Figure of merit (FoM) is calculated using (Area/T)^2.FoV/(FWHM^2). FoM shading is scaled within a wavelength subset. Accompanying data is shown in Table **??**. 'H-I' corresponds to facilities able to observe H-I in the local Universe, i.e. they can observe at frequencies as high as 1.4 GHz.

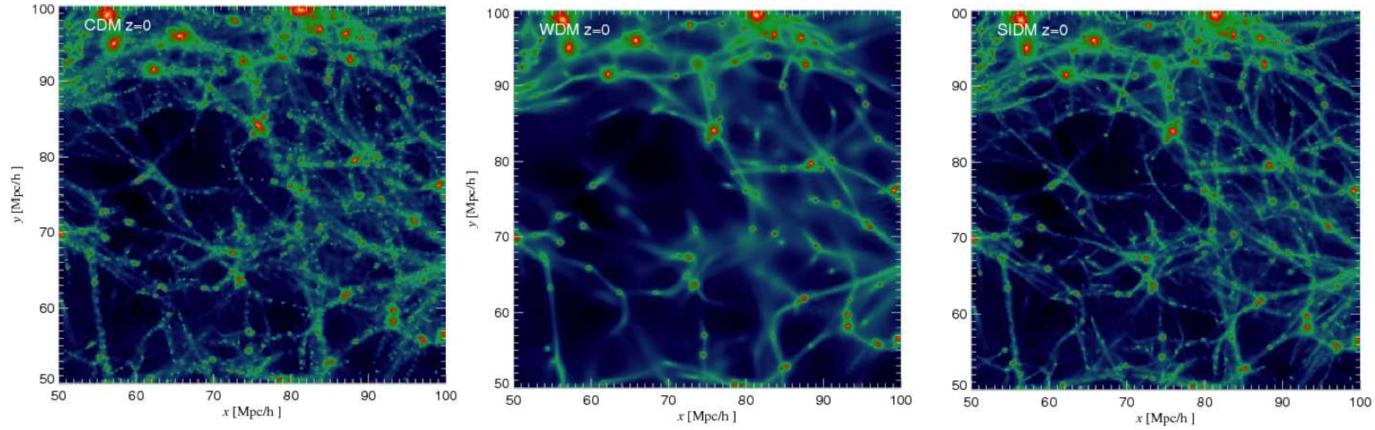


Figure 4: A key focus of the coming decade will be to try to distinguish between the various dark matter models (Cold, Warm and self-interacting). These give distinct predictions for small scale structure and hence very large multiplexed spectroscopic surveys have the possibility of distinguishing between these competing dark-matter flavours.

superseded within a couple of years, given the huge cost and human effort involved in *any* survey. Astronomers typically feel comfortable conducting large surveys on facilities that should be world leading for the next ∼5 years.

There are a significant number of imaging facilities which have recently come online or will come online in the next decade. Figure 3 is a Gantt-Chart representation using data from Table 2, indicating when these facilities might become available, and how 'fast' they are at surveying the extra-galactic sky. The chosen metric provides an insight into depth (telescope area) and sky coverage (FoV) per unit time, and data quality (FWHM image resolution). The majority of facilities will operate in the optical and there are two clear front-runners. Currently Subaru Hyper-SuPrime-Cam, and towards the end of the decade LSST. In the near-IR, arguably the more obvious band for sample selection as it most closely follows stellar mass, the obvious winner is VISTA moving to Euclid towards the end of the decade.

In the Southern hemisphere certain Australian researchers already have some access to VST (European) and DECam (USA) surveys through collaborations. The only facility that is directly Australian controlled is SkyMapper, and has a five year window of opportunity before being outclassed by Euclid and LSST. However it is worth noting that SkyMapper does have the unique niche of being the first all-hemisphere CCD based survey which is likely to lead to a higher impact than indicated by the Gantt-Chart alone. It is a highly dedicated facility which is not captured in the FoM used (Subaru HSC for example while it has an outstanding FoM is a general user rather then dedicated survey facility). Looking much further forward, LSST in the optical and Euclid in the near-IR will be the dominant survey facilities by quite some margin— Australian access to LSST/Euclid data should benefit a large fraction of the extra-galactic community. For LSST an MOU is in place between ICRAR and LSST enabling collaborations during the development phase and the prospect of Australian involvement in the data management side. In the Northern hemisphere Australia has no access to any facilities, having already pulled out of Pan-STARRS-1. Subaru/HSC will be the dominant facility in the North until at least 2025.

2.2 Massively multiplexed spectroscopic surveys

The large Australian-led spectroscopic surveys of the past decade (2dFGRS, MGC, 6dfGS, WiggleZ, GAMA etc) have addressed numerous science questions highlighted in the Decadal plan and future massively multiplexed surveys are likely to be critical in continuing this work. Particular key topics are: continued refinement of our cosmological model (equation of state, growth of structure, alternative gravity models); honing in the dark matter properties and distributions (in particular Cold versus Warm versus Self-interacting dark matter, see Fig. 4); the evolution of the baryon and energy budgets (AGN, stars, gas, and dust, the cosmic star-formation rate, chemical and metallicity evolution); merger rates (galaxy and halo); mass correlations (halo-stellar-gas-dust-baryonic); angular momentum evolution (Tully-Fisher, Faber-Jackson, Fundamental Plane); large scale structure (filaments, tendrils, voids, clusters and groups); and the pathways of galaxy formation and evolution (including the emergence and evolution of internal galaxy structure and comparisons to numerical simulations, semi-analytics and halo occupation distributions). Essentially continuing the themes developed over the previous decade by extending outwards in distance. However the multiplexed surveys of the next decade will be measured in terms of millions rather than thousands of galaxies. Realistically, if the AAT has gathered 1 million redshifts over the past decade an order of magnitude increase will need to come from next generation facilities. Therefore, it becomes impossible to focus overly on the science without first discussing the facilities.

There are a number of multi-object spectroscopic (MOS) facilities available currently, and that are scheduled to come online between 2015–2025. Fig. 3 is a Gantt-Chart representation using data in Table 3 of when these facilities might become available to Australia, and how 'fast' they are at spectroscopically surveying extra-galactic objects.

Australia currently possesses one of the fastest MOS facilities available: the AAT/AAOmega. This has been used to conduct a number of multiple hundred thousand sized extra-galactic surveys: 2dFGRS, WiggleZ and GAMA. Looking forward there are a huge number of next generation MOS facilities scheduled to start operating in the Northern hemisphere before between 2017–2019, however only VISTA/4MOST (European) will be operating in the South. For this reason alone it would be a compelling next generation MOS facility for Australia to become involved in. It is worth noting that these next-generation MOS facilities are all comparably 'fast', and the reality is the faster extra-galactic surveys will be conducted on the most dedicated facilities.

Looking forward, there will be five facilities capable of efficient multi-million galaxy surveys. These are LAMOST, Subaru/PFS, Mayall/BigBOSS, VISTA/4MOST and MSE, all with reasonably comparable survey speeds. Briefly, in expected operational date order:

2.2.1 LAMOST

This Chinese based facility on the outskirts of Beijing is capable of measuring distances to 4000 galaxies in a single observation (i.e., a factor of 10 higher than our current capability with AAOmega). However the site location close to Beijing lights and pollution, teething problems of the facility, along with a complex political situation with LAMOST as a showcase facility suggests that is it unlikely to have the impact it should have. Coupled with the fact that it lies in the northern hemisphere whereas Australia's historical background and radio based surveys are in the Southern Hemisphere, LAMOST appears a non-starter. However an opportunity does exist to pair LAMOST with 6df/TAIPAN to complete an all hemisphere survey, for this specific purpose LAMOST remains of some interest.

2.2.2 Subaru/PFS

This is a Japanese led upgrade to instrumentation on the 8m Subaru telescope located on Mauna Kea. It will be a 2,400 MOS system with a large field-of-view for a current generation 8m, achieved with the addition of massive optical correctors developed for the HSC imager. This is a Northern hemisphere facility, and historically gaining serious access to Japanese facilities has proven difficult to potential international partners, including Australia. Indeed, the current Subaru/HSC survey is prioritising the GAMA survey regions (which is an Australian led extra-galactic survey) but with no involvement or collaboration with any Australian partners. The likelihood of an Australian influenced survey is probably minimal. It is also likely to be the least 'dedicated' of the next generation MOS facilities, since it will need to share survey time with a large number of competing Subaru instruments that will run concurrently.

2.2.3 Mayall/BigBOSS

BigBOSS (now DESI) was selected over DesSpec (a potential spectroscopic instrument for the Blanco telescope) in a recent competition, and it appears likely to be the primary next generation US MOS facility. It will be a 5,000 fibre system mounted on the 4m Mayall telescope in the Northern hemisphere. Its main scientific focus will be a massive BAO experiment, effectively operating as an enhanced version of BOSS which operates on the SDSS telescope.

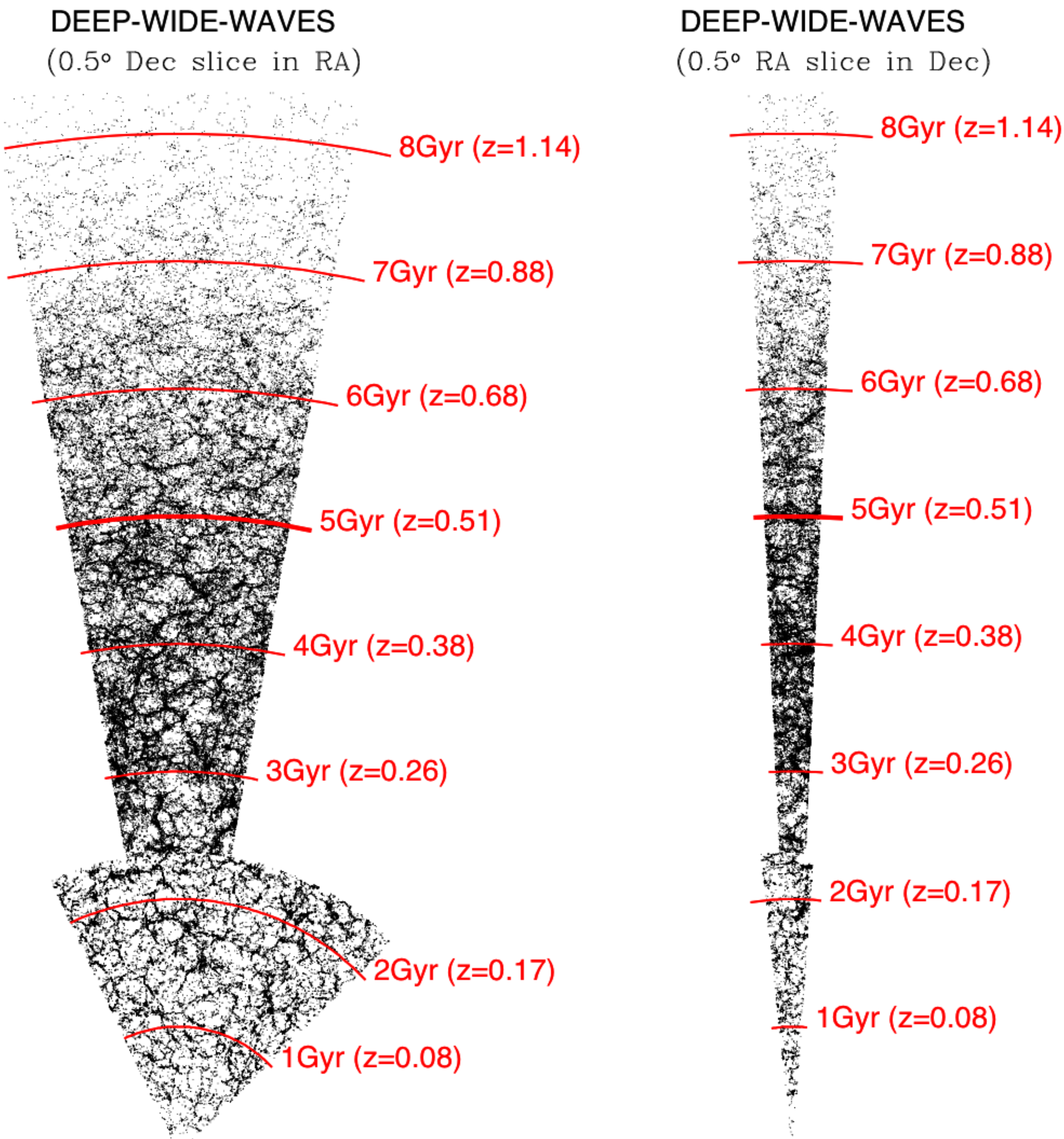


Figure 5: Possible survey concept of a 2million galaxy redshift survey. Extracted from a White Paper submitted to the 4MOST collaboration.

Involvement in BigBOSS is likely to be limited to one or two members of the Australian community with no or little opportunity to increase Australia's engagement in any significant fashion.

2.2.4 VISTA/4MOST

This is a radical rebuild of the European Southern Observatories VISTA top-end (for A$60million), part of which will include a 2,400 fibre-positioning system (AESOP), to be constructed by the AAO. Discussions are currently in progress to form an Australian-Consortium to buy-in to 4MOST by covering either half or the full cost of the AESOP system (total cost A$6million). In return the Australian-Consortium would be allocated 2-3 million fibre-optic hours (or 4-6 million f.o.h.) to design suitable reference survey(s) to satisfy the needs of the Australian community through the coming decade. In addition Australian Consortium members will have access to the other planned surveys which include ESO-GAIA, eROSITA follow-up, and BAO science, all key areas in which the Australian community is engaged. VISTA lies in the Southern Hemisphere and therefore the facility is well aligned for overlap with previous optical and future Australian-led radio surveys (see the proposed Australian-led WAVES survey indicated on Fig. 5 currently under discussions). On a negative note VISTA is a 4m class facility.

2.2.5 MSE (previous ngCFHT)

This is a knock-down and rebuild of the 4m CFHT as a 10m dedicated wide-field 3,200 fibre spectroscopic facility and is currently in the planning and design phase. National membership of this facility is at the A$30million mark and the total facility budget A$180million. The MSE has the capacity to probe deeper and is likely to have a longer lifetime than the other facilities however it will be northern hemisphere based and the opportunities for an Australian-led survey is as yet unclear.

Of the above five facilities 4MOST is currently a clear front-runner for an immediate Australian influenced survey. An additional advantage is the prospect of also using the AESOP positioner as part of an ESO buy-in and hence action towards 4MOST and joining ESO are to some extent aligned.

Finally, although Australian scientists have less involvement in the deep spectroscopic campaigns (with the exception of the Gemini Deep Deep Survey), these are clearly more important as we progress towards the ELT era and as more survey astronomy move onto 8m class facilities allowing for deep surveys. This is already occurring with the Gemini Call for Large Programs now issued, the VLT Call for Large Programs and the ongoing HyperSuprime-Cam survey now underway on Subaru and the planned Prime Focus Spectrograph Survey. Also the MOONS and WEAVE surveys (for which I am not currently aware of any option to join other than ESO membership) and Euclid and WFIRST facilities all of which are capable/optimised to probe the high-redshift Universe to varying degrees. Australia is essentially unable to engage with any of these options at the present time and increasing access on 8m to the level required to lead a major survey of this kind is unlikely (i.e., 100night campaigns). In this area, of deep surveys, we should be aiming for involvement through collaborations best enabled by joining one of the leading 8m facilities as a full partner. The obvious desirable 8m facilities (for deep survey work in particular) are Subaru (HyperSuprimeCam and PFS), Magellan, and ESO (4MOST, MOONS).

2.2.6 Spatial resolved spectroscopic surveys

While massively multiplexed spectroscopic surveys will map out the cosmic web in doing so they will provide legacy datasets suitable for more focused follow-up. An equally important direction for Australia is to continue expanding our capacity for spatially resolved spectroscopy through the development of novel and pioneering instrumentation (e.g., SPIRAL, SAMI, KOALA etc). The science theme of these instruments is the ability to study the spatial distribution of star-formation, metallicity, stellar population ages, angular momenta and stellar dispersions – the spatially resolved

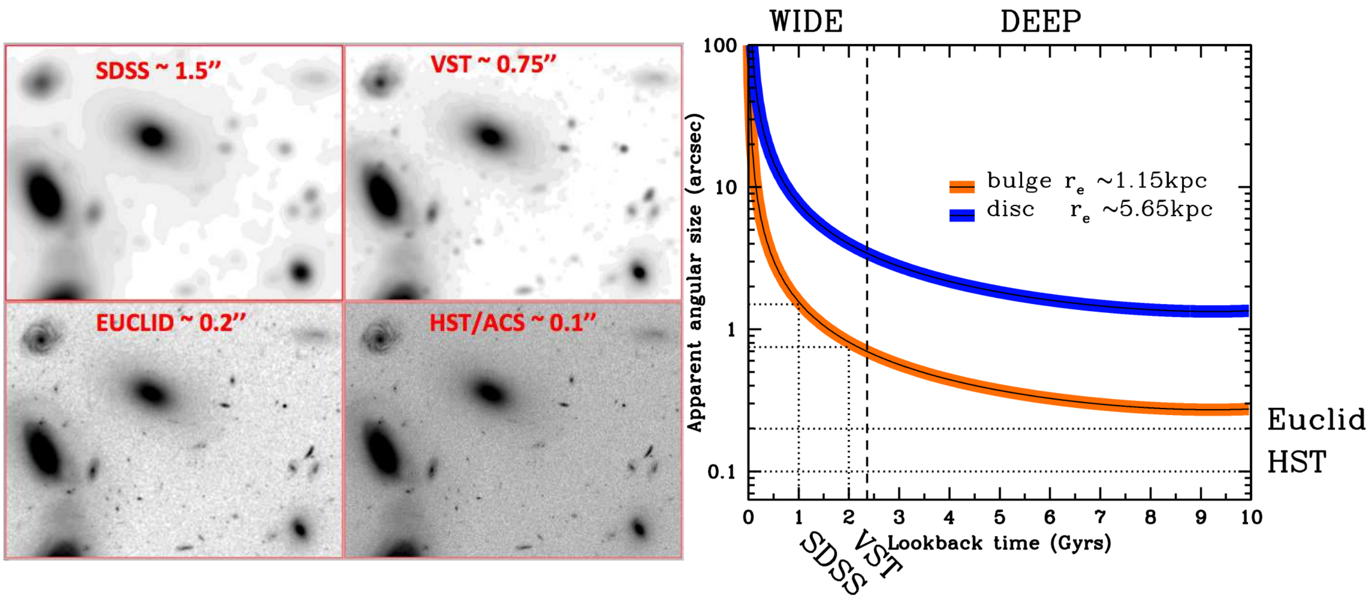


Figure 6: The importance of spatial resolution: (left panel) shows the improvement in image quality as one progress from the Sloan Digital Sky Survey to imaging from an optimal site, to space based imaging. (right panel) shows the effective lookback time one can probe typical bulges and discs to for the four facilities showing in the left panel.

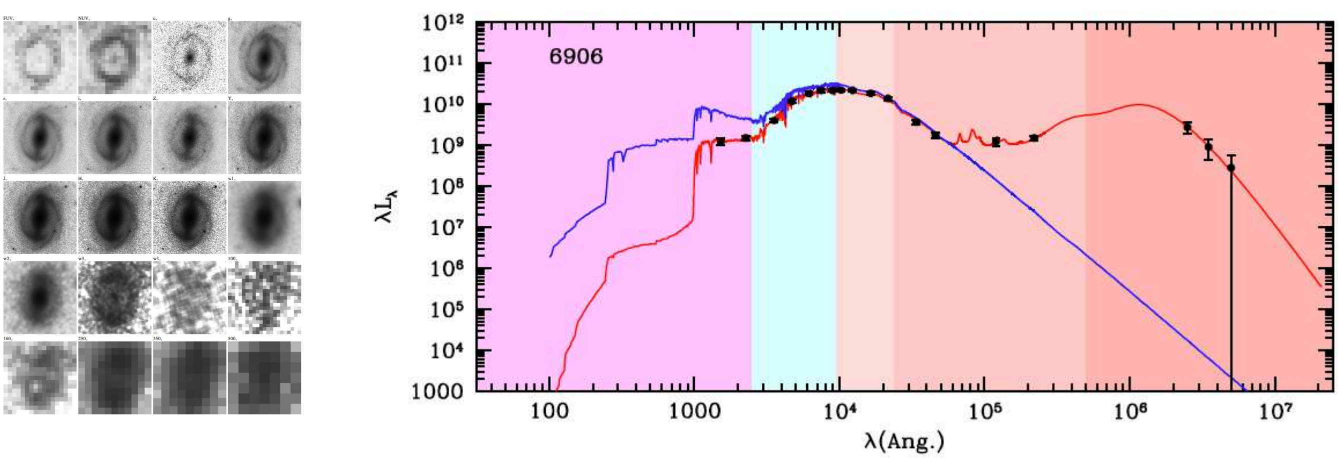


Figure 7: (left) Galaxies look distinctly different at different wavelengths. Show is GAMA galaxy G106638 with observations from GALEX, SDSS, VISTA, WISE and Herschel. At each wavelength different phenomena give rise to the radiation and hence deep insight can only come from pan-chromatic analysis. (right) MAGPHYS analysis of a GAMA galaxy fitting to both the stellar emission and dust emission.

chemistry and dynamics of galaxy stellar populations. Current spatially resolved surveys are at the thousand galaxy mark (the Spain-led CALIFA, the Australian-led SAMI and the US-led MANGA surveys).

The Australian AAT/SAMI facility is the only multi-object IFU facility available currently, but others are scheduled to come online between 2015–2025. Figure 3 is a Gantt-Chart representation using data in Table 4 of when these facilities might become available to Australia, and how 'fast' they are at surveying the extra-galactic objects with IFUs.

Future expansion in this area requires the ability to establish larger IFU samples for greater statistical robustness which requires greater multiplexing capacity, as envisaged with the much discussed HECTOR facility. However care must be taken to match the capacity of the instrument to the quality of the site. Ultimately IFU facilities and surveys will need to move off-shore either in the HECTOR or post-HECTOR era and opportunities should be sought to engage with the instrument programs on facilities at high-quality seeing sites, e.g., Paranal, Pachon or Las Campanas for example, or to look to incorporate extensive IFU capacity into new wide-field spectroscopic facilities in which Australia may become involved in (e.g., MSE, DreamMachine etc).

2.2.7 Multi-wavelength surveys

A key theme of the next decade will be to start unscrambling the messy business of baryon astrophysics which following the typical life-cycle of galaxies (gas -> molecules -> stars -> dust plus AGN) requires sampling a broad wavelength range (radio -> mm/sub-mm -> UV, optical, near-IR -> far-IR plus X-ray), see Fig. 7. At the present time Australia conducts optical and radio astronomy very well but is minimally engaged at the other wavelengths (e.g., X-ray). A key question, given the size of the Australian community, is whether it is possible to sustain communities at all wavelengths or whether a key focus on particular wavelengths, as is the present case, is preferable.

Australia has a very well established tradition of conducting all-sky or rather all-hemisphere surveys. This has been a long tradition in both optical imaging, optical spectroscopy, and radio imaging and to some extent has given rise to both CAASTRO and ICRAR as predominantly survey support organs. In the coming decade datasets will become far larger, more numerous, and cover a broader wavelength range. Certainly far to much for a single individual or small group to collate into a usable form. Ones science is often limited by ones ability to access, manipulate, and visualise the data. While the IVO is the theoretically ideal way to address this it suffers from being an organic entity with minimal direction, accountability or oversight and comes with no quality assurance. Like the Internet it can lead to a lowest common denominator in terms of quality and the good reliable data being lost or swamped in the dross.

An opportunity for Australia might be to embrace the role of "Custodians of the Southern Skies" by establishing a dedicated wide-field unit — this could be something CAASTRO, ICRAR, or the AAO takes on — charged with bringing together the many quality datasets which Australia has produced (SuperCOSMOS, 2dFGRS, 6df, WiggleZ, GAMA, HIPASS I and II, ATLAS etc) and will produce through the next decade (TAIPAN, EMU, WALLABY, SkyMapper) and combine with external datasets (e.g., eROSITA, GALEX, Vista Hemisphere Survey, WISE etc). Such an endeavour represents both a challenge in terms of resources but also an opportunity to maximise the science return to each of the contributing surveys by providing quality assured connections across the wavelength range.

2.2.8 Space based imaging

Crucial to studying galaxy evolution and formation is spatially resolved imaging as best exemplified by the Hubble Space Telescope. From the ground most galaxies become unresolved at redshift 0.2 (see Fig. 6). Potential adaptive optics can continue to resolve normal L^*-systems too high redshifts the cost limits the studies to necessarily small samples. Spatial resolution is critical to determine the growth and assembly of galaxies on kpc scale (the resolution required to identify key astrophysical processes, e.g., clump migration, bar formation, disc growth, bugle formation etc). To reach this resolution requires overcoming the blurring effect of the Earth's atmosphere by observing for space. Currently the HST is due to be decommisioned within the next few years but will be replaced by facilities such as Euclid (wide-area optical/near-IR imaging), JWST (near to mid-IR imaging), and WFIRST (wide area optical imaging). At the present time Australia has no direct access to these facilities other than via collaboration yet they are clearly the future of imaging surveys. To engage Australia needs to consider contributing towards space-agencies

(NASA, ESA) or consider investing in space-based instrumentation capabilities. This is a clear risk area for Australia which could see the next decade relegate Australia to the second-tier. How to solve this requires urgent consideration.

2.2.9 Exploration of time-domain astrophysics

Over the past decade there has been a significant rise in the importance of time-varying phenomena in extragalactic astronomy (it has always been important for other branches) from AGN variability, through distance SN detection, to GRBs.

In particular, Type Ia supernovae were used to establish the existence of the accelerating Universe, and continue to be a key tool in understanding the nature of this acceleration and the properties of the underlying Dark Energy. Over the next decade, we seek to add thousands of Type Ia supernovae to the existing sample, with which we can measure not just the acceleration of the universe, but also the growth of structure within it. Australia can offer two leadership on two fronts: the ability to find large samples of nearby supernovae, and the capacity to obtain redshifts for many distant supernovae and their host galaxies. This large sample over a huge range of redshifts will enable detections of peculiar velocities and gravitational lensing in the motion and brightness of these supernovae, with which we can test competing theories of Dark Energy. Australian capability in these areas will be provided through SkyMapper, the AAT (through the OzDES survey) and LSST.

3 Final comments

So what will future surveys look like in the next decade? To be competitive and capable of addressing critical questions such as the temperature of the dark matter particle surveys will need to probe as far down the halo mass function and stellar mass functions as possible and outwards in distance (backwards in time). This requires an order of magnitude increase in target density (see Fig. 8), i.e., moving from the 1 million galaxy survey mark to the 10 million galaxy survey mark (with an estimated 30 million galaxy redshifts known by 2024, see Fig. 1 right, this would preserve Australia's one third market share). A competitive survey should be Southern Hemisphere based and have supporting high-resolution (space-based) imaging across as much of the electro-magnetic spectrum as possible. The data should feed extensive spatial resolved follow-on studies to understand the chemistry and dynamics of forming galaxies, 8metre and ELT campaigns, and perhaps most critically of all connect with the ongoing radio surveys to be conducted with ASKAP and SKA thereby linking studies of the gas and stars.

It is worthwhile finishing by asking what Australia itself might build, given resources comparable to ESO membership, focusing purely on optical survey science the obvious answer is a suitable wide-field spectroscopic facility which enables follow-up of LSST (6.5m) and feeding of the GMT (24m), i.e., a dedicated 12m wide-field facility which we can call the DreamMachine. Such a facility would need to contain massively multiplexed fibres (i.e., 5000), perhaps operate over a range of resolutions, and contain 100+ inbuilt IFU nodes. Such a facility would enable Australia to essentially replace the functionality of the AAT, restate Australia's pre-eminence in this particular subject area, as well as provide the much needed global facility to bridge the gap between the future planned imaging facilities LSST/Euclid and the future planned ELTs (See Fig. . Such a facility would also support the radio surveys of ASKAP and SKA.

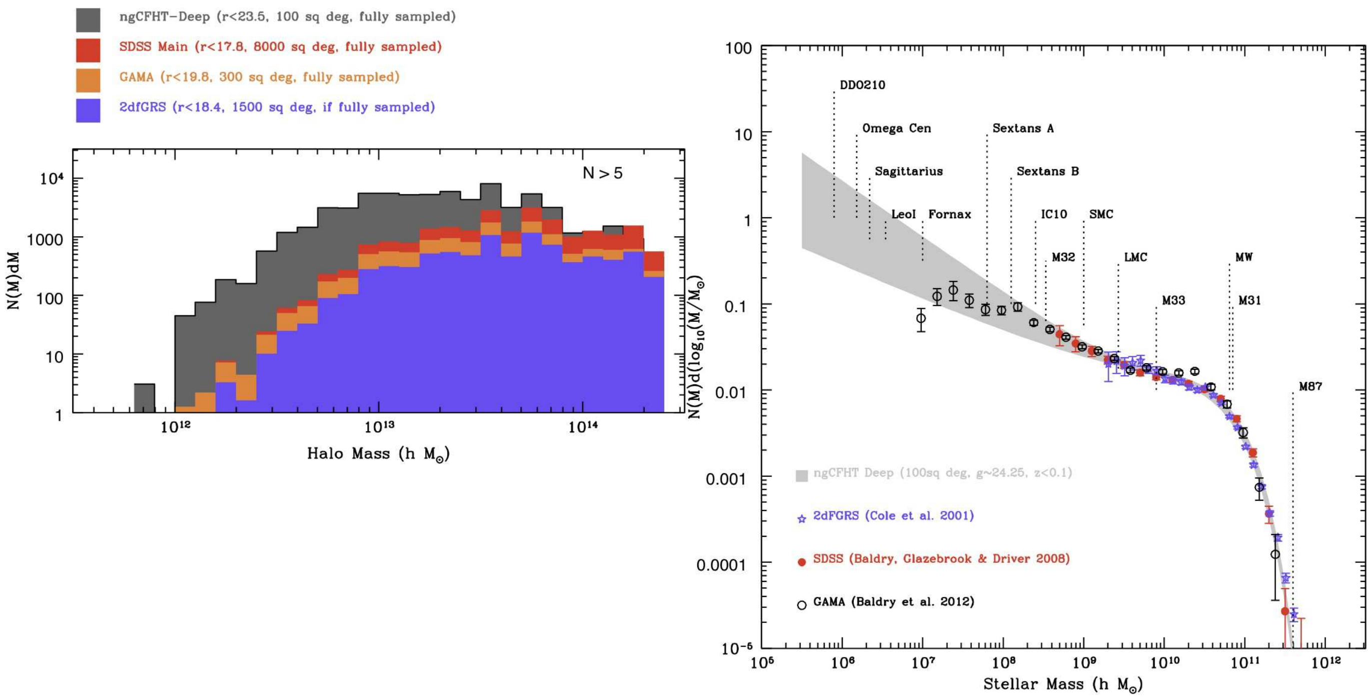


Figure 8: (left) The mass ranges of halos which could be probed with a deep MSE style or 4MOST survey survey and (right) the range of stellar mass which could be probe with a deep MSE or 4MOST style-survey. Extracted from MSE Survey Design Document.

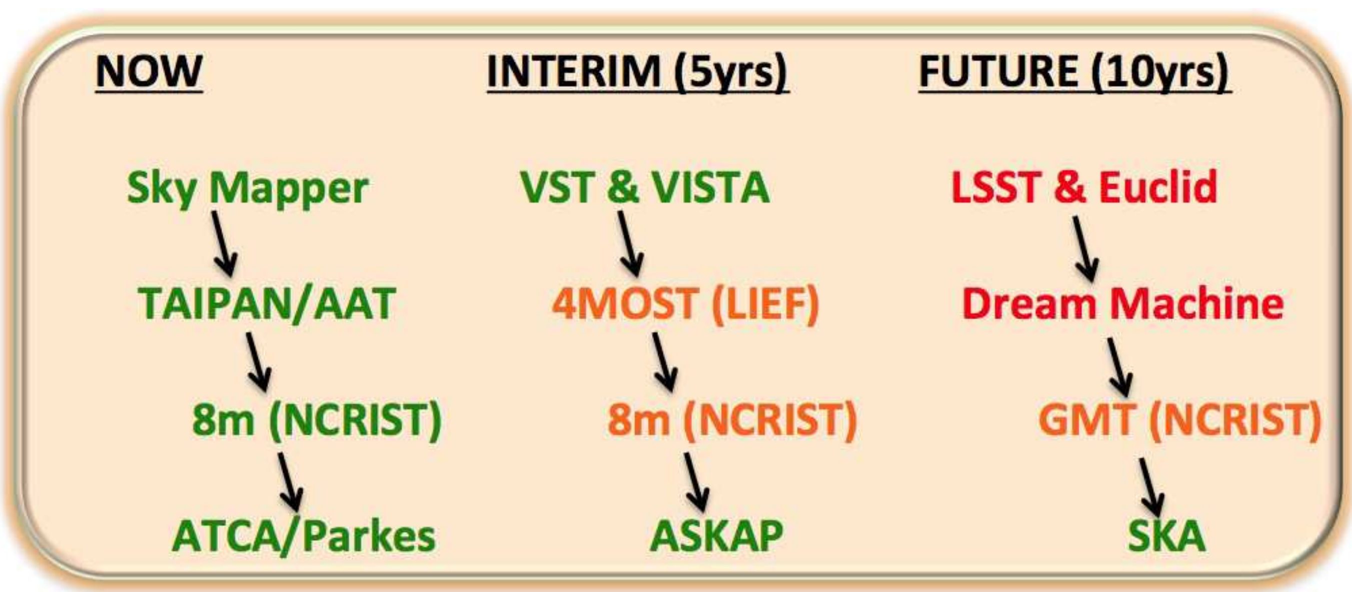


Figure 9: The progression of facilities which would best serve the extra-galactic/cosmology survey contingent of the Australian community. Green text indicates investment secure, orange indicates investment prospects, red indicates no current pathway.

Table 1: Major extragalactic optical/near-IR surveys and their impact in terms of refereed papers and citations

Survey	**Papers**	**Citations**
Sloan Digital Sky Survey (SDSS)	4487	198454
Hubble Deep Field (HDF)	601	52486
Two Micron All Sky Survey (2MASS)	1167	38129
Great Observatories Origins Deep Survey (GOODS)	608	36100
Two degree Field Galaxy Redshift Survey (2dFGRS)	**210**	**27364**
Centre for Astrophysics (CfA)	343	20929
Galaxy Evolution Explorer (GALEX)	631	19599
Cosmic Evolution Survey (COSMOS)	447	16882
Ultra Deep Field (UDF)	231	11067
Deep Evolutionary Exploratory Probe (DEEP/DEEP2)	168	9169
Canada France Redshift Survey (CFRS)	90	9140
Classifying Objects by Medium-Band Observations (COMBO-17/COMBO17)	90	7593
UKIRT Infrared Deep Sky Survey (UKIDSS)	176	6164
VIMOS VLT Deep Survey (VVDS)	89	5441
Canadian Network for Observational Cosmology Field Galaxy Redshift Survey (CNOC/CNOC2)	86	5051
Las Campanas Redshift Survey (LCRS)	97	4506
Southern Sky Redshift Survey (SSRS/SSRS2)	89	4321
APM Galaxy Survey (APMGS)	**57**	**4236**
Point Source Catalogue Survey (PSCz)	101	3832
2dF QSO redshift Survey (2QZ)	**58**	**3606**
CFHT Legacy Survey (CFHTLS)	100	3981
Galaxy Evolution from Morphologies and SEDs (GEMs)	73	3515
NOAO Deep Wide Field Survey (NDFWS)	79	3146
zCOSMOS (ZCOSMOS)	68	3047
Baryonic Acoustic Oscillations Survey (BOSS)	73	2473
Millennium Galaxy Catalogue (MGC)	**37**	**2019**
AGN and Galaxy Evolution Survey (AGES)	36	1978
The 2dF-SDSS LRG And QSO Survey (2SLAQ)	**36**	**1897**
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS)	64	1854
Gemini Deep Deep Survey (GDDS)	22	1627
Stromlo-APM Redshift Survey (SARS)	**19**	**1438**
WiggleZ (WiggleZ)	**40**	**1319**
The 6dF Galaxy Survey (6dFGS)	**33**	**1104**
ESO Slice Project (ESP)	26	1023
Galaxy And Mass Assembly (GAMA)	**57**	**995**
Atlas^{3D} (ATLAS3D)	36	992
2MASS Redshift Survey (2MRS)	24	534
Kilo-Degree Survey (KiDS)	11	440
PRIsm Multi-object Survey (PRIMUS)	11	198
Calar Alto Legacy Integral Field Area Survey (CALIFA)	15	139
VIMOS Public Extragalactic Redshift Survey (VIPERS)	9	86
VISTA Kilo-Degree Infrared Galaxy Survey (VIKING)	6	55
VISTA Deep Extragalactic Observations (VIDEO)	3	15
ZFourGE	1	1

Note these numbers were determined on 16^{th} Jan 2014 using the SOA/NASA ADS Astronomy Query Form by searching for refereed papers which contained abstract keywords based on the following boolean logic: (galaxy or galaxies) and ("<long survey name>" or <short survey name>). The table is purely indicative and not weighted by survey age or effective cost and is updated on an annual basis. My apologies in advance for the many surveys not included.

labels	starts	ends	wave	hemi	area.m2	FoV.deg2	angres.asec	FoM
Fermi-LAT	2008	2016	gamma	N/S	2.5	2,827.4	360.00	0.055
HESS-II	2012	2018	gamma	S	50,000.0	10.2	900.00	0.628
HAWC	2015	2030	gamma	N	10,000.0	24,996.5	2,700.00	34.289
Gamma400	2019	2026	gamma	N/S	0.8	2,827.4	36.00	1.745
CTA	2020	2030	gamma	N/S	500,000.0	19.6	900.00	12.120
eROSITA	2015	2022	X-ray	N/S	0.4	0.8	25.00	0.001
WSO-UV	2017	2022	UV	N/S	2.3	0.2	0.20	11.290
CFHT/MegaCam	2003	2019	opt	N	10.2	1.0	0.70	19.782
HST/WFC3UVIS	2009	2020	opt	N/S	4.5	0.0	0.10	0.239
Oschin/iPTF	2009	2015	opt	N	1.1	7.1	1.50	3.456
Magellan/MEGACAM	2009	2026	opt	S	31.2	0.2	0.70	12.502
Pan-STARRS-1	2010	2015	opt	N	2.5	7.1	1.00	17.671
VST/OmegaCam	2011	2021	opt	S	5.3	0.8	0.70	8.495
Blanco/DECam	2013	2018	opt	S	12.6	3.8	1.00	47.897
SkyMapper	2014	2019	opt	S	1.4	5.7	1.60	3.198
Subaru/HSC	2014	2019	opt	N	52.8	1.8	0.50	373.221
Pan-STARRS-2	2015	2017	opt	N	5.1	13.9	1.00	70.658
Oschin/ZTF	2015	2020	opt	N	1.1	36.3	1.50	17.755
WHT/PAUcam	2017	2023	opt	N	13.9	0.8	1.20	7.581
Euclid Opt	2020	2026	opt	N/S	1.1	0.5	0.20	55.292
LSST	2022	2032	opt	S	55.4	9.6	0.70	1,087.776
WFIRST-2.4 Opt	2024	2030	opt	N/S	2.4	0.3	0.10	271.434
VISTA/VIRCam	2009	2017	NIR	S	13.2	2.1	0.60	78.402
HST/WFC3IR	2009	2020	NIR	N/S	4.5	0.0	0.10	0.597
JWST/NIRCam	2018	2026	NIR	N/S	33.2	0.0	0.04	16.297
Euclid NIR	2020	2026	NIR	N/S	1.1	0.5	0.20	138.230
WFIRST-2.4 NIR	2024	2030	NIR	N/S	2.4	0.3	0.10	678.584
WISE	2010	2016	MIR	N/S	0.1	0.5	5.00	0.002
SPICA MIR	2022	2025	MIR	N/S	9.6	0.2	1.00	1.885
SPICA FIR	2022	2025	FIR	N/S	9.6	0.2	5.00	0.075
CCAT	2017	2026	smm	S	491.0	0.8	2.50	61.701
ALMA	2013	2026	mm	S	6,569.0	0.0	0.01	1,857.341

Table 2: Table comparing various extra-galactic imaging survey facilities that will operate between now and 2025. Figure of merit (FoM) is calculated using Area.FoV/($FWHM^2$). FoM should only be compared within a wavelength subset. Accompanying Gantt-Chart is shown in Figure 3.

labels	starts	ends	wave	hemi	area.m2	FoV.deg2	angres.asec	fibres	FoM
AAT/AAOmega	2006	2020	opt	S	11.9	3.1	1.50	400	6,646
SDSS/BOSS	2009	2015	opt	N	4.9	7.1	1.40	1000	17,671
LAMOST	2012	2017	opt	N	12.6	19.6	3.00	4000	109,956
GTC/GO-IRS	2014	2026	opt	N	84.9	0.0	0.80	1000	6,512
UK-Schmidt/TAIPAN	2015	2020	opt	S	1.1	28.3	1.50	300	4,147
WHT/WEAVE	2017	2026	opt	N	13.9	3.1	0.80	1000	68,231
Subaru/PFS	2017	2026	opt	N	52.8	1.1	0.70	2400	292,484
Mayall/DESI	2018	2026	opt	N	12.6	7.1	1.50	5000	197,920
VISTA/4MOST	2019	2026	opt	S	12.6	4.2	0.70	2400	256,408
MSE	2019	2029	opt	N	78.5	1.8	0.70	3200	905,933
Dream Machine	2023	2040	opt	S	113.1	7.1	0.70	5000	8,157,722
VLT/MOONS	2018	2026	NIR	S	50.3	0.1	0.70	1000	12,900
Euclid	2020	2026	NIR	N/S	1.1	0.5	0.20	1700	234,991
WFIRST-2.4	2024	2030	NIR	N/S	2.4	0.3	0.10	1000	678,584
CCAT	2017	2026	smm	S	491.0	0.8	2.50	100	6,170

Table 3: Table comparing various extra-galactic spectroscopic survey facilities that will operate between now and 2025. Figure of merit (FoM) is calculated using Area.FoV.N_{fib}/FWHM. FoM should only be compared within a wavelength subset. Accompanying Gantt-Chart is shown in Figure 3.

labels	starts	ends	wave	hemi	area.m2	FoV.deg2	angres.asec	fibres	FoM
AAT/SAMI	2013	2016	opt	S	11.9	0.8	1.50	400	1,662
SDSS/MaNGA	2014	2020	opt	N	4.9	7.1	1.50	1423	21,905
AAT/Hector Opt	2016	2022	opt	S	11.9	3.1	1.50	3050	50,677
AAT/Hector NIR	2016	2022	NIR	S	11.9	3.1	1.50	3050	50,677

Table 4: Table comparing various extra-galactic IFU survey facilities that will operate between now and 2025. Figure of merit (FoM) is calculated using Area.FoV.N_{fib}/FWHM. FoM should only be compared within a wavelength subset. Accompanying Gantt-Chart is shown in Figure 3.

Appendix 2

Optical Galaxies Sub-group Report

1 Outline

This Appendix contains three sections that document the work of the Optical Galaxies Sub-group.

- The preliminary report is based on our initial discussions and review of the previous decadal plan. It was the basis of the presentations made at the national Town Hall meetings in March/April 2014.
- The revised list of science priorities was made at the WG1.1 teleconference on April 15, 2014. It incorporated feedback from the Town Hall meetings.
- The final section presents the key science priorities determined by this group. It expands on the previous section by developing short summaries of each topic and its requirements. A suggested priority ranking by the sub group members is also included.

2 Preliminary Report – before Town Hall meetings

2.1 Summary of Report

2.1.1 Progress against previous Decadal Plan

The last decade has seen major progress in optical galaxy science in Australia. We note that it is difficult to measure this directly against the previous Decadal Plan goals as they were only stated in very general terms. There are also some fundamental results that have only small Australian involvement. These are still included, as they will provide strong motivation for future research. We group the results broadly using the same divisions as the previous Decadal Plan WG2.1 report (see below).

<u>Galaxy morphology & kinematics (4.1, 5.1):</u> This area has some of the more surprising developments, notably the new topic of internal kinematics, which has

become very important but was not previously included. In the morphology area, the GAMA survey showed that galaxy morphology changes with the rest-frame filter choice and that field dwarf galaxies form a single sequence. A revolutionary result from resolved (IFU) spectroscopy (mostly outside Australia) of elliptical galaxies is that they form two kinematic populations (fast/slow rotators). Resolved kinematics of distant galaxies has revealed how star formation drives turbulence in disks.

<u>Stars and gas in galaxies (4.2, 4.3):</u> The metallicity of star-forming galaxies has now been measured over cosmic time ($0<z<3$), showing that models predict too high a metallicity in high-mass galaxies. There have been considerable advances in measures of the IMF. Absorption line studies have shown that cool gas accretion is a significant contributor to galaxy formation.

<u>Dark matter and black holes in galaxies (4.4, 4.5):</u> Improved simulations have shown that dark matter halos do not all have the same profiles. This has improved consistency with radio observations. The galaxy NGC300 has been shown to have a declining rotation curve at large radii, giving strong evidence for conventional dark matter, not MOND. The relation between black hole mass and galaxy halo mass is more complex than previously thought; black holes grow faster than their host. Better understanding of the relation improved estimates of BH mass in other galaxies.

<u>Galaxy clusters (5.2, 5.4):</u> Many observations of ultra-compact dwarf galaxies in clusters have contributed to show that these objects are chemically and structurally linked to globular clusters. Deep imaging with the ZFOURGE survey discovered the highest known cluster red sequence at z=2.1. Conversely the massive quiescent red galaxies found at these redshifts are much rarer in the local universe.

<u>The Local Group (5.3):</u> This may have limited Australian involvement, but the Pan-Andromeda Archaeological Survey has many results, such as the strong evidence from stellar streams that many M31 GCs are accreted.

2.1.2 Opportunities

Australia has significant capacity and desire to create and exploit many new and emerging areas of galaxy research in the UV/Optical/IR wavebands.

The main scientific areas in which Australian astronomers see specific new opportunities include: high-z galaxy formation/evolution; Lyman-break-like galaxies; galaxy halo gas, feeding, feedback and the intergalactic medium and their evolution from high to low z; low-z and nearby galaxies/galaxy groups; the role of intermediate-mass black holes; dynamical modelling of galaxies; unknown source populations in nearby galaxies; and transients.

The diversity of interests reflects the many groups at individual universities, most with good links to scientific and instrument-building capabilities at AAO.

Facilities access is a key factor in the community's ability to grasp some of these opportunities. Access to 8–10-m telescopes (primarily VLT, Keck, Subaru) and ELTs (GMT, E-ELT) is fundamental to addressing the scientific areas above. Other facilities, needed to take some specific opportunities include existing/planned facilities, include SkyMapper, Taipan and SAMI, while several other desired capabilities do not exist and are not planned so far, e.g. UV space-based spectroscopy; large-area optical/IR IFUs, wide-field imaging (narrow-band; wide and deep; wide and high-resolution); wide-field optical MOS; automated imaging and spectroscopic transient follow-up.

There are also numerous observational datasets, currently planned or being collected by other facilities, that are also identified as crucial for taking some new opportunities: CANDELS, ZFORGE, 3DHST, PTF, CRTS, DES, 'GAMA++' (deeper spectroscopy and larger area), eBOSS, LSST, Pan-STARRS-1.

Finally, simulations on all scales – individual galaxies and their contents, galaxy groups, galaxy clusters, their gaseous halos and cosmological contexts – are, and will increasingly be, critical in understanding the observational data and comparing them with theories.

2.2 Details: Progress against the previous Decadal plan.

The most relevant material for us is found under WG 2.1 "Cosmology and the high-redshift Universe". (The first few topics in the report from WG 2.2 "The Milky Way Galaxy" and "The Nearby Universe" are also relevant but they are already covered by the WG 2.1 report.) The relevant topics are taken from Section 4 "Understanding the formation and evolution of galaxies" and Section 5 "Other significant and related areas". Two important topics were absent in the previous plan: galaxy kinematics (which we discuss with Section 4.1) and Local Group populations (Section 5.3).

We note that many of the science cases are very general so we can't really evaluate if we have made any progress. The next plan should have specific goals.

2.2.1 The morphological and luminosity distribution of galaxies (4.1)

Only very broad science aims were given here. Our discussion noted that Australia has good survey capacity but will be limited in access to large facilities required for detailed follow-up science.

- Dust attenuation in local disk galaxies is very high; correction of key properties (Driver et al 2007, Graham & Worley 2008, MNRAS, 388, 1708)
- Dwarf galaxies in low-density environments form a single sequence varying in just surface brightness. There is no quantitative justification for the different visual morphological types (Mahajan et al, 2014)
- Work by the GAMA team to automate bulge-disk decomposition showed that apparent galaxy morphology and size transforms with rest-frame filter choice (Kelvin et al 2011)
- New innovations in morphology such as Radio Galaxy Zoo have been brought to Australia (e.g. Wong et al.)

The topic of galaxy kinematics was absent from the previous plan, but there has been major progress in this field.

- The discovery that early-type galaxies have two kinematic populations: fast and slow rotators. Based on resolved (IFU) spectroscopy from SAURON project (but there are few Australian links; e.g. Emsellem et al. 2007, MNRAS, 379, 401) and the ATLAS-3D project (some Australians, e.g. Sarzi et al., 2013, MNRAS, 432, 1845)
- Results are starting to come out from SAMI (Fogarty et al. MNRAS, in prep)

- Resolved kinematics of galaxies shows that the high turbulence is driven by star formation and not cosmic accretion as previously thought (Green et al. 2010, Nature, 467, 684; 2014, MNRAS, 437, 1070)
- There are several works on high-z dynamics and clumps, (e.g. Genzel, R., Tacconi, L. J., Eisenhauer, F., et al. 2006, Nature, 442, 786; Wisnioski, E., et al. 2012, MNRAS, 422, 3339; —. 2011, MNRAS, 417, 2601; Glazebrook K., 2013, PASA, 30, 56)

2.2.2 The stellar populations of galaxies (4.2)

Science: the bimodal distribution of galaxies and the suppression of star formation are not fully understood. The relative importance of gaseous vs. stellar galaxy assembly is also completely open. Surveys such as 6dF will test hierarchical model predictions and define the star formation history of the local universe. Telescope time is a limiting factor: we need a larger field than Gemini/GMOS; wide field MOS on a 20m telescope.

- The cosmic history of star formation is now measured with sufficient precision to put significant constraints on other processes such as core collapse SN and the IMF (Hopkins & Beacom 2006)
- Radial metallicity gradients of early type galaxies change above a mass of 4×10^{10} Msun. This implies lower mass galaxies formed by simple collapse, but the more massive galaxies formed by merging (Spolaor et al., 2009)
- Metallicity history of galaxies (Yuan, Kewley & Richard 2013 ApJ, 763, 9, among others)
- There has been considerable work on the stellar IMF, notably variations at the upper end (Hoversten & Glazebrook 2008; ApJ, 675, 163; Meurer et al. 2009, ApJ 695, 765; Gunawardhana et al., 2011, MNRAS, 415, 1647)

2.2.3 Evolution of gas in galaxies (4.3)

Here the science focus is cool gas, especially accretion. But this is difficult at high z; use Ly-alpha absorption. Our discussion noted this is mostly radio-related (HI, CO).

- Emma Ryan Weber, Jeff Cooke, & Glen Kacprzak are doing good work on high-z absorption line systems and their evolution.

Progress in Australia on quasar absorption-line and simulation-based probes of gas feeding and feedback into/from galaxies, for example:

- Observational evidence of gas feeding through cold accretion at z=2.3 (Bouche et al. 2013, Science, 341, 50).
- Azimuthal dependence of absorption signatures provides evidence for cold accretion and also outflow modes of $0.1<z<1$ galaxies (Kacprzak et al. 2012, ApJ, 760, L7).
- Understanding gaseous halo kinematics and its link to the host galaxy dynamics using quasar observations and simulations (Kacprzak et al. 2010, ApJ, 711, 533).

2.2.4 Dark matter in galaxies (4.4)

Science aims: to observe hierarchical assembly of halos in the early universe; determine how the Tully-Fisher relation evolves. Discussion: need 2D spectroscopy especially in NIR.

- High-resolution computer simulations, established that dark matter halos do not all have the same density profile (Graham et al. 2006, AJ, 132, 2701). This reduces conflict with radio observations (Se-Heon Oh et al. 2011, AJ, 141, 193) and lowers the expected high-energy gamma ray signal at the centres of real dark matter halos (Meade et al. 2010, NuPhB, 831, 178).
- NGC300 has a declining rotation curve at large radius - ruling out MOND (Westmeier et al., 2011, MNRAS, 410, 2217)

2.2.5 Formation and evolution of supermassive black holes (4.5)

Science: how are super-massive BHs, AGN formed and what is physics of accretion process? Discussion: need access to multi-wavelength tools.

- Black holes and their host galaxy do not grow in lockstep, rather, the black hole grows much faster (Graham 2012, ApJ, 746, 113)
- Expanded relations between black hole mass and the host galaxy dynamics and structure aid our understanding of the BH-galaxy connection and better estimate BH masses in other galaxies (Graham & Driver 2007, ApJ, 655, 77; Graham 2008, ApJ, 680, 143; Graham, Onken et al. 2011 MNRAS, 412, 2211).
- The first quantification of the co-existence of massive BHs in dense star clusters at the centres of galaxies (Graham & Spitler 2009, MNRAS, 397, 2148).
- The evolution of the M_{BH} – sigma relation (Wyithe 2006 MNRAS, 365, 1082)

2.2.6 Evolution of the intergalactic medium (5.1)

Science: much work needed on role of radiation and winds on formation of galaxies and the IGM. Discussion: many projects can be described.

- Probing with high-resolution imaging and spectroscopy turbulent primordial star-formation in clumpy galaxies at high-redshift and in nearby-Universe analogues (Wisnioski et al., 2011, MNRAS, 417, 2601)

2.2.7 The intracluster medium of galaxy clusters (5.2)

Science: the IGM can contain up to half the stars of a cluster. Use PN as a tracer of the history of cluster formation. Discussion: use AAOmega to detect PN in nearest clusters.

- The work of Owers & Couch on "Cold Front" clusters is a good way to identify merging clusters.
- Analysis of the intracluster light in several galaxy clusters, showing that the radial concentration of stars is well described by an exponential profile, not $r^{1/4}$ as assumed (Seigar, Graham, Jerjen, 2007, MNRAS, 378, 1575).

2.2.8 Nearby Galaxies and the Local Group (5.3)

Science in this report was limited to HI – radio, but with a cross-reference to W2.2. But the WG2.2 report is mostly Galactic, so optical work on the Local Group was missed out.

- Results of the Pan-Andromeda Archaeological Survey –mapping of Andromeda (Ibata et al 2007, ApJ, 671, 1591, McConnachie et al. 2009, Nature, 461, 66)

- Mackey et al. (2010) of the PAndAS team (now at RSAA) show the correlation between the stellar streams around M31 and globular clusters, arguing strongly that many of the globular clusters are accreted.
- Gary Da Costa (also at RSAA) has also been doing work on stellar pops and globular clusters in nearby galaxies

2.2.9 Evolution of Galaxy Clusters (5.4)

Science: how do cluster galaxies assemble and form stars; what mechanisms drive the evolution? How do clusters form? Discussion: need large telescopes and NIR to extend low-z expertise to higher redshifts.

- Ultra-compact dwarf galaxies are common in galaxy clusters (Jones et al., 2006), but are more like globular clusters than the stripped nuclei of dwarf galaxies (Evstigneeva et al 2007)
- Several groups measured sizes of GCs and UCDs, initially reporting a size-luminosity relation (Evstigneeva et al., 2006, AJ, 132, 1593), but later showing this to be a lower envelope to an extended distribution (Brodie et al. 2011, AJ, 142, 199).
- Deep imaging in the ZFOURGE survey discovering the highest known cluster red sequence at z=2.1, and finding elliptical galaxies at z=3-4.
- The population of compact, massive, and quiescent galaxies at z ~ 2.3 is very rare in the local Universe (Taylor et al, 2010, ApJ, 720, 723)
- Work on HIPASS "Choirs" groups indicates HI + H-alpha selection is a good way to find early-stage merging groups similar to Local group but in a more advanced stage of interaction Sweet et al. (2013, MNRAS, 433, 543)

2.3 Details: New opportunities

Science opportunity	Facilities	Data-sets	People
High-z galaxy formation/evolution			
Understanding evolution of bulge and disc components of massive galaxies, with much-improve dust-correction	SkyMapper	GAMA	Several small groups exist nation-wide
Disk galaxy formation & evolution from z~6 to 0, using metallicity gradients & velocity maps to probe inside-out disk formation models and galactic-scale gas flows.	GMTIFS (+ IFUs on ELTs), supercomputers.	Simulations	Groups in several universities + AAO
High-redshift galaxy formation & evolution	8-m spec. follow-up of new surveys	CANDELS, 3DHST, ZFORGE.	Many ECRs across several universities + AAO.
Role of stellar populations and IMF in high- and low-z galaxy evolution	8-m + GMTIFS (+ IFUs on ELTs)	?	Groups in several universities + AAO
Lyman-Break-like galaxies			
Lyman-alpha escape fraction, UV properties of high-z galaxies, UV background, IGM tomography	UV-responsive ELT with		Groups in a few universities

	low–medium resolution multi-object spectroscopy, Keck Cosmic Web Imager,		
Halo gas			
‘Population III remnant’ damped Lyman-alpha systems	UV-responsive ELT with high-resolution spectroscopy	eBOSS, Simulations	Groups in a few universities
Circumgalactic medium from z~6 to 0	Space- and ground-based UV low–high resolution spectroscopy	eBOSS, simulations	Groups in a few universities
Feeding & feedback at z>2.5	8-m + ELT optical/IR medium–high resolution spectroscopy	eBOSS, simulations	Groups in a few universities
Low-z and nearby galaxies			
Confronting LCDM with high-resolution, panchromatic census of all Local Group members	Multi-telescope approach (i.e. national + international access + collaborations)	Simulations.	Groups in several universities + AAO.
Realistic alternative-cosmology simulations for much more rigorous comparison with observations	Supercomputers.	SAMs with mock-galaxy catalogues.	Groups in several universities.
Detailed gaseous and stellar population studies of nearby (z<0.01) galaxies (metallicity maps, winds, AGN studies, stellar tracers of galaxy/halo dynamics etc.)	Large-area IFUs (‘WIFES++’), IFU photometric studies, wide-field narrow-band imaging, very wide-	LSST, DES, Pan-STARRS-1.	Capacity across many universities + AAO.

	field deep imaging array, 8-m + ELT access (ASKAP/WALLABY synergy), SkyMapper, Taipan, SAMI		
Testing galaxy formation in the group environment. What is role of the (group) halo on galaxy formation? How do mergers drive galaxy assembly in groups?	Wide field 8-m (or larger) optical MOS; high-resolution wide field optical/NIR imaging.	GAMA++, i.e. deeper spectroscopy over larger area, plus group catalogues. Matching simulations	Groups in several universities + AAO.
Intermediate-mass black holes			
Search for intermediate-mass black holes (10^{1-4} solar masses) in small, nearby galaxies	SkyMapper (radio/mm synergy), Advanced LIGO Network, supercomputers	Gravitational wave data, Simulations	Several groups nation-wide
Dynamical modelling of galaxies			
Dynamical and scaling relations as a function of redshift	8-m + ELT optical & IR IFU follow-up of wide-area surveys	Simulations	Several groups nation-wide
Unknown source populations in nearby galaxies			
Serendipitous + planned discovery + follow-up	Deep imaging and spec. follow-up of wide-area + transient surveys, SkyMapper	LSST, PTF, CRTS, HST + other archives (+ASKAP+SKA & other panchromatic data).	Big Data & Data-science expertise
Transients			
Transients in nearby galaxies	Automated imaging + spectroscopic follow-up telescope(s), SkyMapper.	LSST, PTF, CRTS.	AAT + other instrument-building expertise.

3 Revised Priorities – after Town Hall meetings

There was a strong vote from many of the town hall meetings to focus the discussion on the science topics. Here is a revised list of science goals that reflects the topics raised in the meetings. It reflects a preliminary priority ranking (most important first) as discussed at our Working Group 1.1 Teleconference on 15 April 2014.

- Galaxy evolution: explain the origin of the bimodal galaxy population of the Universe today. What is the role of:
  - Feedback & quenching mechanisms
  - Mass growth
  - Minor/major mergers
  - Supermassive black holes
  - Angular momentum
  - Chemical evolution
  - Environment – especially groups
- Galaxy assembly: test lambda-CDM models by comparing:
  - Global properties of galaxies as a function of redshift
  - Observations of dwarf galaxies and galaxy halos
  - Predicted merger rates with resolved galaxy observations
- First galaxies: how do they form?
  - What is their nature?
  - Epoch of reionisation constraints?
- Transient sources: what are the unknown source populations in nearby galaxies?

4 Final List of Science Priorities

4.1 How do galaxies build up over time?

Current galaxy formation theory combines large cosmological simulations with detailed semi-analytic (and/or hydrodynamic) models of the baryonic physics of individual galaxies as they form and evolve. These models have improved dramatically in the last decade, particularly as the role of AGN feedback in damping star formation has been recognised. A key prediction of the models is the growth of the stellar mass of galaxies over cosmic time. The problem with the simulations is that they predict massive galaxies form stars more rapidly than observed. We are reasonably confident about the shape of the observed stellar mass function and the predicted dark matter halo mass function, but the relation between these is not understood. The AGN feedback process is not sufficient to explain this difference.

This discussion divides into internal and external processes that can drive galaxy evolution. We note that most if not all external processes depend on new measures of local environment – listed as the final topic.

4.1.1 Mass Growth and Feedback

Galaxy formation models in the last decade have been dominated by the issue of feedback is several different regimes. Theoretical models of the stellar mass function rely on feedback at both the luminous end (AGN feedback) and the faint end (supernova feedback), but are still unable to predict the growth of massive galaxies as described above. (Feedback that allows the loss of angular momentum in galaxies, is central to the ability of current numerical simulations to form realistic galaxy disks.)

What is the strength and duty cycle of feedback from SF and AGN as a function of stellar mass, star formation rate and AGN accretion? IFU spectroscopy could give a breakthrough in this field, allowing us to discover winds and characterise them (e.g. SAMI/ HECTOR/ MOSFIRE/ KMOS/MANIFEST). At the highest redshift, absorption line studies (including HI 21cm, UV metal lines, Lyman-alpha) can be used to statistically determine outflow properties. GMT will allow Lyman-alpha tomography using Ly-break galaxies enabling us to probe the absorption properties of gas around high redshift galaxies in detail, identifying and characterizing outflows.
An alternative approach to the problem of over-predicted stellar masses is that the stars form, but are stripped from the large galaxies by their environments. We will require sensitive measurement of intra cluster light in rich galaxy clusters – this will require 8m time.

4.1.2 Quenching mechanisms

When, where and how is SF being quenched? It is well known that SF is suppressed in high-density environments, but current measurements of quenching struggle to quantify some of the basic physics (e.g. is quenching fast or slow).

The key to addressing this is having a complete inventory of star formation, which is possible with IFU spectroscopy. Spatially resolved SF maps (SAMI/HECTOR/MOSFIRE/KMOS/MANIFEST) allow a full characterization of star formation. This needs to be compared to detailed measurements of the physical environment of galaxies. This includes dark-mater halo mass, location within large-scale structure, state of the IGM (e.g. measured from X-ray). As well as IFU observations, a key requirement is deep redshift surveys to properly define environment.

4.1.3 Galaxy Mergers – rates

A great uncertainty to galaxy evolution is the exact role of galaxy-galaxy mergers over cosmic time, with LCDM making quite specific predictions about the build up of stellar material from small galaxies into larger ones. As discussed below, this simple picture appears to be in contradiction with the latest high redshift observations, where a large number of galaxies have assembled huge amounts of material in very short amount of time. The merger rates are predicted to vary with time (and mass), but we do not as yet have an accurate value for the local merger rate, even though it provides a major test of galaxy formation.

There are two clear routes to understanding mergers: one is by observing close-pairs of galaxies immediately prior to merging (this data would be provided by the survey above) the other is to observe the disturbed remains of galaxies immediately post-merger. Ideally both observations should be made to ensure consistency. The latter route of observing post-merger galaxies can be achieved somewhat with photometric data alone. A much better option is to use kinematic data from IFU surveys to clean the sample and make more accurate estimates of the likely merger timescales. A combination of deep imaging, highly complete redshift spectroscopy and targeted IFU follow-up in a coherent area of sky is clearly an ideal combination of data to address the many science questions regarding the impact different cosmological models (including LCDM) have on directly observed galaxy evolution.

4.1.4 Galaxy Mergers – internal physics

In the standard picture of galaxy formation and evolution, the mass of galaxies is built up hierarchically through successive mergers. During the merger, the halo and bulge of the galaxy grows. Between mergers, the galaxy disk grows through infall of small gas clumps. Large-scale gas flows combined with central bursts of star formation are critical for transforming merging galaxies into elliptical galaxies (e.g., Springel et al. 2005, Hopkins et al. 2008, 2009a,b). However, we lack a physical understanding of how mergers transform galaxies. How are gas inflows, gas outflows, star formation, and active galactic nuclei (AGN) interrelated? How do these processes combine to transform galaxies from spirals into ellipticals across cosmic time?

Isolating the effects of gas flows from star formation and active galactic nuclei will greatly assist in answering these questions. A large sample of local merging galaxies with spatially resolved spectroscopy is needed (e.g. SAMI and HECTOR on the AAT). To understand how mergers transform galaxies across cosmic time, we require near-infrared integral field spectrographs, assisted by adaptive optics, on 8–10m telescopes for intermediate redshift galaxies (e.g. VLT/SINFONI) and on 20–30m telescopes for the highest redshift galaxies (e.g. GMT/GMTIFS).

4.1.5 How does the gas in galaxies feed star formation?

How does the gas content of galaxies vary with mass and environment, and how does this relate to star formation? Fundamentally star formation is limited by the available gas supply (although this is not the only consideration). We need to understand how galaxies are fed gas from, and feed back energy to, their gaseous halos at all redshifts. The details of these processes are important for understanding the star-formation rates and gas consumption time-scales in galaxies, as well as the mechanisms for polluting the circumgalactic medium and intergalactic medium at all redshifts.

They can be probed by using absorption spectroscopy of background objects (quasars and other galaxies), combined with IFU studies of the intervening galaxies themselves. To cover all redshifts, space- and ground-based low- and high-resolution spectroscopic capabilities are required, and it is better to use a combination of detailed studies from small, targeted samples and also large statistical samples. For example, the future eBOSS survey, plus targeted 8-m and 30-m class observations, will likely yield breakthrough results in this area. However, simulations of the gas clouds responsible for the observed absorption are likely to be indispensable for properly interpreting these detailed observations, especially targeted, smaller surveys. This represents a challenge because of the need to resolve both large-scale (~100 kpc) and small-scale (~10pc) gas cloud sizes.

There is also great potential for progress with new HI surveys. In the first half of the decade ASKAP surveys will do an excellent job of quantifying HI in local and moderate redshift galaxies and it will be vital to connect this with the optical measurements (particularly IFU surveys). ALMA provides a window into the molecular gas content (more directly connected to SF than HI), and the challenge here may be to target sufficient "normal" galaxies with ALMA in a survey mode. In the later parts of the decade SKA phase-1 and IFU instruments on larger telescopes should be married to provide the crucial evolution with redshift.

4.1.6 Chemical Evolution of Galaxies

Chemical elements transform the way new stars are born and evolve, the way planets are formed around young stars, the way stars explode and die, and the way stars assemble into new galaxies. Therefore, tracing chemical elements back to the earliest times in the universe provides one of the most powerful methods of unveiling the birth and growth of galaxies. However, we still do not have a solid observational picture of how the chemical elements are built up in galaxies across cosmic time.

To measure the chemical history of galaxies across 10 billion years of cosmic time requires efficient near-infrared multi-object spectrographs on 8–10m class telescopes (e.g. VLT/KMOS, Keck/MOSFIRE). To probe chemical evolution at earlier times requires infrared spectrographs on 20–30m ELTs. The combination of 8–10m telescopes and ELTs will enable the chemical history of galaxies to be tracked over 13 billion years of cosmic time.

4.1.7 Spiral Galaxy Formation

One of the most compelling science drivers for the next generation of telescopes, such as the GMT and JWST, is to study the formation and evolution of spiral galaxies like our Milky Way. Theory suggests that spiral galaxies form inside out, first assembling halos around compact dense cores, with the outer regions being built up over the subsequent 10 billion years through galaxy mergers or infall of gas from the surrounding medium. Whether this scenario is true, and the effect of galactic-scale gas inflows and outflows for spiral galaxies like our Milky Way, is unknown.

To understand how spiral galaxies formed and evolved requires integral field spectroscopy with adaptive optics on 8–10m and 20–30m telescopes. Large surveys on these instruments will generate a 2 dimensional picture of how galaxy disks formed and evolved.

Can we simulate the observed galaxy disks and galaxy outflows self-consistently? This requires a convergence of hydrodynamic simulations and observations in both the detailed level of feedback and the statistical distribution across galaxies. A key resource is HPC for high-resolution simulations of sufficient number, resolution and in a cosmological context. This needs to be tied to large-scale observational programs that characterise winds and outflows over galaxy mass and environment. At low redshift this can be achieved with SAMI and HECTOR (IFU observations with spectral resolution R~4000-5000). At higher redshift infrared IFUs (KMOS, MOSFIRE etc.) and future instruments such as MANIFEST on GMT will enable feedback to be traced to earlier cosmic time, when gas inflows are expected to be more important.

4.1.8 Angular momentum

Is angular momentum a "second parameter" in determining galaxy properties, and how does the angular momentum content of galaxies evolve with redshift? The role of angular momentum (or ordered versus disordered motion) in dictating a galaxies observed properties has become increasingly apparent both in early-type galaxies (SAURON, Atlas3D) and in late-type galaxies (DYNAMO, Obreschkow & Glazebrook 2014).

A true census of the angular momentum content of nearby galaxies requires spatially resolved spectroscopy of a large sample of galaxies (SAMI, HECTOR). Studies of the angular momentum of galaxies at redshifts >~ 0.3 have been limited to samples of a few tens of objects, and are restricted to star forming galaxies as only emission line measurements have been possible. To quantify the evolution of angular momentum in galaxies as a function of redshift, larger samples representative of typical galaxies at redshifts ~1-2 are required. 8-10m class telescopes (ideally with AO) are required for this. To also determine stellar (as opposed to gas) angular momentum at redshifts ~ 0.5-1.0 ELT-class facilities are absolutely required, and such measurements will still prove demanding.

4.1.9 Intermediate Mass Black holes

Intermediate mass black holes (IMBHs), with masses greater than that of stars and less than the 10^5-10^{10} solar mass monsters at the centres of large galaxies, are a missing population, which astronomers all over the world are actively searching for. A new (black hole)-(host bulge) mass-scaling relation predicts that this missing population should reside in the small bulges of disc galaxies and in dwarf galaxies.

Performing a careful bulge/disc decomposition of small, nearby galaxies in say SkyMapper data will identify the small bulges expected to house these IMBHs. The next generation of large collecting area, radio telescopes should detect the expected faint signal from these black holes when they are active, thereby giving away their presence. Coupling 5GHz radio observations with simultaneous X-ray observations will enable astronomers to estimate the mass of the black hole using the so-called `fundamental plane of black hole activity', confirming or rejecting the existence of this currently missing population of intermediate mass black holes from our Universe. Australia is well placed to lead this exciting research. In particular the initial LIGO detectors were able to conduct searches for the gravitational wave signals from inspiraling systems of IMBHs out to 200 Mpc, resulting in upper limits on the rate density of these sources. The advanced LIGO detectors, for which there is significant Australian involvement, will come online in 2015 with an expected Gpc reach to systems with total masses of 1000 solar masses.

4.1.10 Measurement of local environment

Note that most, if not all measurement of external processes will depend on better measure of local environment than currently available so we list this as a separate item, although it is a method, not an aim in itself.

One additional observational aspect is the definition of environment - halo mass, number density, cluster-centric radius, groups/filaments etc. and how different properties correlate with different definitions of environment. Large redshift surveys (4MOST, others?) are required to accurately define 'environment' and explore different definitions. Theory provides many potential mechanisms for environmental transformation, but detailed cosmological hydro simulations of different environments are required to form accurate predictions for each prospective mechanism to compare to observations.

4.2 How and where do low mass galaxies form?

4.2.1 Observations of dwarf galaxies and galaxy halos

The current greatest-consensus cosmology is undoubtedly Lambda-CDM. However, there are known weaknesses with various aspects of the model on smaller (sub Mpc) scales. Particular issues are current generation LCDM based simulations struggle to assemble massive galaxies at high redshift in sufficient number. Also, the satellite distribution of galaxies in halos is hard to reproduce, with LCDM both over-predicting the number of dwarf satellites and under-predicting the number of massive satellites. LCDM models also tend to over-quench satellite galaxies, aggressively shutting down their star formation compared to recent observations.

A route to address these tensions is to produce highly robust stellar mass functions out to high (z>4) redshifts, forcing strong reconciliation of models throughout the full range of stellar mass, not just at the massive galaxy extreme, which is all we currently observe. To understand the evolution of satellites, specifically the accretion of satellites into halos over a broad range of redshift and the quenching of their star formation, we also require complete sampling of galaxies over a large dynamic range in halo mass. Both these goals will be met with highly complete spectroscopic redshift surveys stretching out to high redshift in carefully selected regions of sky. Such observations will certainly require Australian access to 4m and 8m highly multiplexed multi-object-spectrographs (i.e. 4MOST, DESI, Keck, Magellan, Gemini, VLT and similar). To sample a representative range of environment will require large areas of sky, and such surveys would require many years of data (there is a 12-m spectroscopic survey telescope concept under discussion).

4.2.2 The effect of alternative dark matter models on galaxies

The LCDM model of cosmological structure formation is the archetype of hierarchical models, in which progressively more massive structures are built up over cosmic time via mergers between and with less massive structures. However, it is not unique in this respect – viable alternatives to LCDM are also hierarchical, insofar as galaxies, groups and clusters assemble via merging. Where these alternative models from LCDM will likely differ is in the abundance, clustering and growth rates of lower-mass galaxies over cosmic time. Cosmological N-body simulations of “warm” and “self-interacting” dark matter models indicate that the number of low-mass dark matter halos is suppressed relative to the LCDM model, and that the difference in abundance of lower-mass halos between LCDM and WDM/SIDM alternatives is particularly pronounced in the early Universe.

This has a number of knock-on effects. It will affect the clustering of lower mass satellites around MW-type primaries, as well as the rate of minor mergers, which should reveal itself in measurements of close pairs and morphological disturbances. Arguably these will be the most robust signatures of the presence (or absence) of lower-mass haloes. It will also have implications for galaxy formation, where the predictions are more uncertain. For example, the onset of galaxy assembly occurs earlier in the LCDM model, and so we would expect to see differences in the colours of galaxies as well as in the overall abundance of lower mass galaxies at earlier times. We'd also expect to see differences in, for example, the structure of stellar haloes, assuming that they are built up by mergers in the early Universe, as well as in the structure of galaxies themselves. Studying these effects will require highly complete spectroscopic redshift surveys of targeted areas of the sky, using instruments such as 4MOST.

4.3 How do the first galaxies form?

4.3.1 What is their nature?

The recent observations with the Hubble and Spitzer Space Telescopes started characterizing galaxies in the epoch of reionisation by finding samples at 500-700 Myr after the Big Bang (redshift 7-10), demonstrating that galaxies as luminous as the

Milky Way are already in place at very early times, but also posing several questions: When and how did these objects assemble from smaller building blocks at higher redshift? What are their properties, especially stellar masses, ages, and metal content? Is the IMF different at early times because of the higher temperature floor of the cosmic microwave background? Are galaxies the main agents of reionisation despite the rapid decline with increasing redshift of the luminosity density of sources bright enough to be seen with Hubble?

To answer these questions, deep imaging at infrared wavelengths over large fields of view is needed to find first generation galaxies at redshift z~10-15 (500 to 300 Myr after the Big Bang), critically requiring the James Webb Space Telescope to make progress beyond Hubble's reach at z~7-10. Follow-up observations from current and next generation facilities will characterize the properties of the stellar populations of the galaxies identified by space telescopes, especially ALMA to study molecular gas and dust, and a 30m-class telescope like GMT for rest frame UV/optical spectroscopy. Since current Hubble observations point toward the presence of an abundant population of faint and small dwarf galaxies at early times, complementary probes of star formation such as observations of high-redshift Gamma Ray Bursts and of their host galaxies will shed light on the properties of stars living in galaxies too faint for searches by direct imaging. Combined with theoretical and numerical modelling of radiation transport out of galaxies, all these studies will lead to the characterization of the ionizing flux production and will have a strong synergy with red shifted 21cm observations aimed at measuring the ionization state of the Universe, enabling a comprehensive understanding of one of the most interesting and mysterious epochs in the history of the Universe.

4.4 Ranked Science List

13 members of the sub group who each picked their top 5 topics made this ranking. The highest total scores give the highest rankings.

Item	Description	total
1.1	Mass Growth and Feedback	32
1.5	How does the gas in galaxies feed star formation?	32
1.8	Angular momentum	23
3.1	How do the first galaxies form? What is their nature?	22
1.6	Chemical Evolution of Galaxies	20
2.1	Observations of dwarf galaxies and galaxy halos	20
1.3	Galaxy Mergers - rates	8
2.2	The effect of alternative dark matter models on galaxies	5
1.7	Spiral Galaxy Formation	3
1.2	Quenching mechanisms	2
1.9	Intermediate Mass Black holes	2
1.4	Galaxy Mergers - internal physics	1

Appendix 3

Australian Astronomy Decadal Review: Extragalactic Radio Astronomy (incl. Radio Surveys)

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Executive Summary: Australian extragalactic radio astronomy, including surveys, have a rich and productive history, generating some of the most cited papers in radio-astronomy. Australian radio surveys planned in the early part of the coming decade will not only increase the number of known radio sources by a factor of 30, unravelling expected but still unexplored source populations, but will constitute a significant part of the all international radio surveys, and move radio astronomy from niche science (mainly studying AGNs) to mainstream, where it will take its place alongside optical and infrared as another tool in every astronomer's toolkit, and an indispensable part of every fitted spectral energy distribution or photometric redshift measurement. Here we survey the current state of Australian radio astronomy, and its strengths and weaknesses, and prioritise future developments both to maximise the scientific impact and maximise the benefits to the Australian scientific community.

Priorities for the extragalactic radio astronomy for 2016–2025 are as follows.

Science:

- Constrain the origin, assembly, and evolution of galaxies, including regulation by feedback mechanisms
- Constrain the origin, growth, and evolution of supermassive black holes
- Explore the origin of cosmic magnetism and angular momentum history
- Constrain the composition of intergalactic medium, and to explore large new samples of transient sources, that trace the extreme physics phenomena.

Facilities: In order to pursue the above science goals and to continue supporting both the Australian and international extragalactic astronomy communities, Australia must

- Ensure successful delivery of SKA1-survey and SKA1-low, and continue to play a major role in both the technology and the science of SKA,

- Successfully deliver and commission ASKAP, complete the major surveys for which ASKAP and already operational MWA were constructed, and maintain operations and, if appropriate, continue development and upgrades until SKA construction,
- Ensure stable, long-term access to high-performance computing facilities for both simulation/theoretical work and radio data analysis and storage,
- Continue to support existing national and institutional radio facilities (Parkes, ATCA, LBA) to provide follow-up facilities for ASKAP, MWA, and SKA,
- Ensure VLBI capability of SKA-survey and/or SKA-mid for the beginning of SKA Phase 1,
- Continue maintaining access to overseas facilities such as JVLA and ALMA , and
- Develop collaborations with complementary multi-wavelength international based and run (LSST, eROSITA, JWST, WISE, VHS, 4MOST) and Australian (TAIPAN, AAT, SkyMapper) facilities.

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1 Introduction

1.1 Background

The main science questions currently being addressed by extragalactic radio astronomy include the origin, assembly, and evolution of galaxies, including regulation by feedback mechanisms, the origin, growth, and evolution of supermassive black holes, and the origin of cosmic magnetism and angular momentum history. Current major projects are also exploring the largely unexplored populations of star-burst galaxies and low-power active galactic nuclei (AGN), and surveys of highly redshifted HI.

Australia has the unique capability to lead these through *observational astronomy*, with our traditional strengths including radio survey science, multi-fibre optical spectroscopy, cm-wavelength astronomy, southern hemisphere VLBI, HI surveys and polarisation studies. Australia has also growing expertise in *theory* and *numerical simulations*. Choosing the right science targets for the next decade needs to be driven primarily by the most interesting and productive science questions, but must also take into account achievability and leverage from Australia's strengths, including the realistic availability of existing and future facilities.

1.2 The importance of radio surveys

Surveys will drive progress against many of the key questions for the next decade of astronomy and cosmology. Only through surveys can we acquire a meaningful sample of the highest redshift objects. Surveys will provide the sky coverage and cadence needed to identify and study rare types of transient phenomena. And since dark matter and dark energy are not directly observable, their properties can only be extracted via their statistical signatures on the ensemble properties of very large numbers of galaxies over wide areas. Many of the highest impact and contributions from Australian astronomy have been from surveys (Table 1). Australia continues to develop unique strengths in this area: innovative facilities capable of exploring new regions of phase space with unprecedented survey speeds, world-leading capability in associated supercomputing and advanced processing algorithms, and the theoretical expertise needed to appropriately design such surveys and then to extract discoveries and new physics from these data sets.

For the above reasons, *a strong focus on survey science should be a high priority for the 2016–2025 Decadal Plan*.

1.3 Continuum Surveys

Radio continuum surveys have a rich and productive history, generating some of the most cited papers in

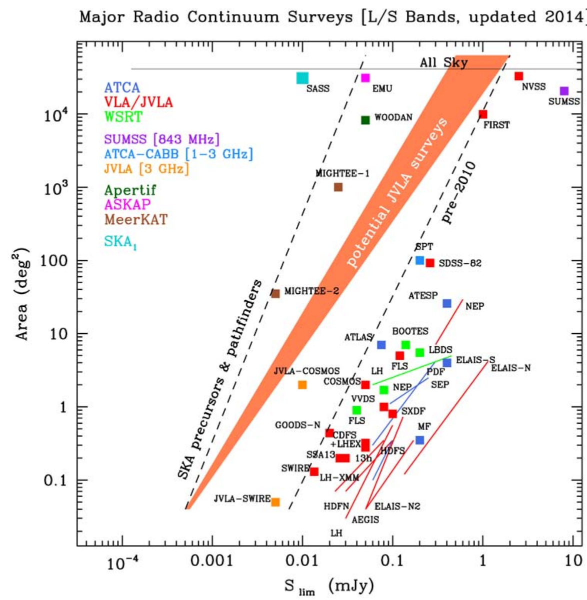

Figure 1 Comparison of existing and planned deep 1.4 GHz (+/- 50%) radio continuum surveys, courtesy of Isabella Prandoni. Surveys not at 1.4 GHz (SUMSS and JVLA) have been shifted to 1.4 GHz assuming a spectral index of -0.7. The horizontal axis shows the 5-σ sensitivity, and the vertical axis shows the sky coverage. The diagonal dashed line shows the approximate envelope of existing surveys, which is largely determined by the availability of telescope time. The squares in the top-left represent the new radio surveys discussed in this chapter. Surveys at frequencies very different from 1.4 GHz are not shown in this diagram, as their relative sensitivity depends on the assumed spectral index of the sources.

radio-astronomy. Radio sources discovered in previous surveys have primarily been AGN (Active Galactic Nuclei) but radio surveys are now crossing a threshold where normal star-forming galaxies dominate the number counts. For example, the EMU (Evolutionary Map of the Universe) survey on the Australian SKA Pathfinder (ASKAP) is expected to detect about 70 million galaxies (compared to $\sim$2.5 million radio sources known at present) which means that a significant number of galaxies studied at optical/IR wavelengths will have had its radio properties measured. Radio-astronomy is, therefore, set to move from niche science (mainly studying AGNs) to mainstream (starting to investigate the unexplored in radio wavelengths the SFG population), where it will take its place alongside optical and infrared as another tool in every astronomer's toolkit, and as an indispensable part of every fitted spectral energy distribution or photometric redshift measurement.

Predicted sensitivities and areas for the main existing and planned surveys at mid radio frequencies (1.4

Table 1 Key extragalactic radio surveys, showing the total number of refereed journal papers based on the survey, and the number of papers that cite the survey. These numbers were measured by searching ADS for refereed papers which contained ('galaxy' or 'galaxies') and ('long survey name' or 'short survey name') in the abstract or title. ATLAS numbers include papers based on the ATLAS survey but using 'CDFS' or 'ELAIS' as a survey name rather than 'ATLAS'. Numbers for 3CR, 4C, and 5C are likely to be overestimates because they include papers which mention a source name starting with 4C etc. Numbers for FIRST are likely to be an underestimate because the short name 'FIRST' was not included in the search, because it produced an unmanageable number of spurious results.

Survey	year	Country	# publications	# citations
4C	1966	UK	458	13831
NVSS	1998	USA	355	11891
3CR	1969	UK	323	15231
HIPASS	2001	Australia	92	3441
PMN	1994	Australia	90	2603
WENSS	1997	Netherlands	64	1580
FIRST	1995	USA	54	2277
5C	1975	UK	46	996
GB6	1996	USA	34	998
SUMSS	1999	Australia	30	838
AT20G	2010	Australia	29	557
ATLAS	2008	Australia	29	412
Phoenix	1999	Australia	15	373
EMU	2015	Australia	13	241
ATESP	2001	Italy/Australia	9	241
ATHDFS	2005	Australia	5	91
ATLBS	2010	India/Australia	5	33

GHz) are shown in Figure 1. The largest existing radio survey, shown in the top right, is the wide but shallow NRAO VLA Sky Survey (NVSS) . The most sensitive existing radio survey is the deep but narrow Lockman Hole observation in the lower left. All current surveys are bounded by a diagonal line that roughly marks the limit of available telescope time of current-generation radio telescopes. The region to the left of this line is currently unexplored, and this area of observational phase space presumably contains as many potential new discoveries as the region to the right. Next-generation surveys such as EMU plan to survey the entire sky to a sensitivity of 10 μJy/beam rms. Only a total of about 10 deg^2 of the sky has been surveyed at 1.4 GHz to this sensitivity, in fields such as the *Hubble*, *Chandra*, ATLAS, COSMOS and Phoenix deep fields.

At low radio frequencies ($<$ 300 MHz) existing radio data, especially of the Southern sky, are sparse compared to 1.4 GHz resources. The recently built and now fully commissioned Murchison Wide-field Array (MWA) and its GaLactic and Extragalactic All-sky MWA (GLEAM) survey, which is underway, is now filling this gap. Low frequency radio astronomy is presently undergoing a boom; we are just starting to explore the largely unknown low frequency radio sky, and characterise the low frequency part of radio spectra of sources at mJy levels and above. MWA has a tremendous brightness temperature capability and is particularly suited to e.g. radio relic and cluster studies as well as studies of evolution of radio galaxies. The first results are already streaming from the MWA commissioning survey and GLEAM data.

Moreover, in the past decade, the development of new wide-band correlators for existing radio facilities, ATCA and JVLA, has dramatically improved the speed and sensitivity of large radio continuum surveys. This has enabled new, large-area continuum surveys, such as COSMOS, ATLAS, and AT20G, which cover areas of sky at a range of radio frequencies rather than a single narrow frequency band. This multi-frequency approach will also be an important feature of future continuum surveys with ASKAP and MWA.

Next-generation radio surveys will measure intensities to unprecedented levels. They will also measure spectral index and polarisation for the strongest 10% of sources, so that about 7 million radio sources will have measured polarisation and spectral index – about 100 times more than at present. In the early part of the decade radio astronomy is likely to be dominated by mid-frequency ASKAP surveys, for which planning, funding, and construction is well advanced, and the low-frequency MWA survey which is underway. In the second half of the decade, radio surveys that are well beyond anything that can be contemplated with current telescopes are planned for SKA. For example, an all-sky survey with SKA1-survey to an rms of 2 μJy will take 2 years with SKA1-survey, but would take 600 years with the JVLA, or 50 years with ASKAP. Such a survey will yield 'radio photometry' for majority of galaxy observed in optical and IR surveys in this decade, and with polarisation and spectral index information for many of them. Similar high-impact HI surveys are also being planned with significant Australian involvement. These surveys, and the follow-up observations from them, are likely to dominate Australian radio-astronomy in the next decade.

These next-generation surveys, however, will also encounter a new set of technical and scientific challenges. For example, to reach the sensitivities predicted by the radiometer equation, surveys such as EMU must have exceptionally high dynamic ranges (e.g., approximately 42 db for EMU) and low systematic errors. This requires very high quality hardware, calibration techniques, and imaging algorithms. In particular, the primary beams must have $< 1\%$ uncertainties in reconstructed position, size, and shape. *Survey astronomers need to work closely with engineers to ensure that amplitude and phase calibration on strong sources in the array field-of-view can be transferred from one primary beam to another.*

The success of a survey depends as much on the survey results being made available to everyone in an easily-accessible fashion (such as through a web portal, or virtual observatory tools, and with useful and intuitive query engines) as on whether the survey actually meets every performance goal, such as sensitivity. For example, EMU differs from earlier surveys in that the survey will cross-identify the detected radio sources with major surveys at other wavelengths, and produce public-domain Virtual Observatory (VO) accessible catalogues as 'value-added' data products. This is facilitated by the growth in the number of major surveys spanning all wavelengths, as discussed in § 6.4.

1.4 HI science

Hydrogen is the most ubiquitous element in the Universe and the fundamental baryonic building block out of which stars and galaxies are made. Large-scale surveys for HI are essential for any true understanding of galactic evolution and remain one of top priorities for the SKA. While a great deal can be learnt by studying the evolution of HI in isolation (HI mass function, cosmic HI density, clustering, galaxy masses and kinematics), a complete picture of HI in galaxy evolution requires the combination of HI data with a comprehensive suite of multi-wavelength observations. These data enable an understanding of how neutral atomic gas has co-evolved with the other major galactic constituents, along with insight into the complex interplay of processes that drive material from one baryonic state and environment to another.

HI is an excellent tracer of dynamics, measured either through global HI profiles or spatially resolved kinematic maps. However, the power of these tracers is significantly increased by combining them with data at other wavelengths. For instance, in the simplest case, optical galaxy inclinations can be used to calculate rotational velocities from global HI profiles, enabling studies of kinematic scaling laws such as the Tully-Fisher relation or the rotational velocity function. Even more can be derived through additional measurements of galaxy size, multi-wavelength emission line diagnostics and IFU data, allowing for studies of angular momentum or comparisons of gas-phase to stellar-phase kinematics.

Australia has played a key role in HI science in the past through surveys such as HIPASS, and observations of individual galaxies and systems with the ATCA, and is now well-positioned to take a key international role with HI observations, both surveys and pointed observations, using ASKAP and SKA.

1.5 Australian radio astronomy in an international context

Australia has a rich history of conducting front-line radio surveys, as shown by Table 1. Although this league table is led by UK and USA, Australia has clearly contributed to this field by a disproportionately large extent, and is set to rise to the top of the league table with the ASKAP and MWA surveys.

Table 1 demonstrates that radio surveys are already an area of strength of Australian astronomy, and Australia will probably dominate this field with the completion of ASKAP, with JVLA, LOFAR, MeerKAT, and AperTIF also occupying significant places. However, these non-Australian radio surveys are not competitors, because none significantly overlap in survey parameters with the ASKAP and MWA surveys.

2 Progress against previous decadal plan

Most of the Dedacal Plan 2006–2015 (with the exception of Australia's top priorities for new infrastructure funding discussed below) tends to not be very specific, and in some places it is difficult to determine what the objectives actually are. The mid-term review (2011) gives a better summary of what these objectives are than the decadal review itself. One lesson to learn from this is that the objectives of a Decadal Plan need to be much clearer.

2.1 Infrastructure

Australia's top priorities for new infrastructure funding in the area of radio astronomy in the previous Decadal

Plan (Decadal Plan 2006–2015: §4.5, Mid-term Review 2011: pp. 9–13) were[1]

- to commence 10% partnership in the SKA and 10%–30% share of SKA Phase 1,
- to develop new radio astronomy infrastructure in Western Australia and protect the site's radio-quiet zone, which would lead to the engagement in the SKA,
- to construct MWA, as a low-frequency precursor to SKA1 and SKA,
- to construct ASKAP, as a wide-field precursor to SKA1 and SKA;
- to continue operations of the existing ATNF telescopes including upgrades (Parkes, Mopra and Compact Array),
- to upgrade the Molonglo telescope (SKAMP), as a university testbed and training facility for Australian participation in SKA and SKA, and
- to engage with ALMA through cost-effective support until ESO membership is secured.

The SKA participation: The participation in the SKA project, at least at 10% level, and possibly hosting the telescope in Western Australia, was set as one of the major priorities of the previous Decadal Plan in the area of radio astronomy. The Australia and New Zealand's bid to host the radio telescope was highly successful; in May 2012 both Australia and South Africa have been chosen as co-hosts for the SKA. Australia secured the SKA1-survey and SKA1-low projects to be constructed in Western Australia. A superbly radio quiet zone land has been acquired to establish the Murchison Radio-astronomy Observatory (MRO), with an initial set of indigenous land use agreements and spectrum management regulations in place. Australia is one of SKA's founding members. The design, specifications and budget for SKA1 have not yet been finalised, and construction is projected to commence in 2017.

New radio astronomy infrastructure (pre-SKA): Significant amount of funding has been allocated for establishing the SKA precursors, and their management, in Western Australia. This includes the construction of ASKAP, MWA, and the Pawsey Centre. In addition, the following research centres have been established: the International Centre for Radio Astronomy Research (ICRAR), the ARC Centre of Excellence for All-Sky Astrophysics (CAASTRO), and the ARC Super Science Fellowships and Initiatives, all of which contribute to the construction, commissioning and management of the SKA precursor facilities.

The MWA, the only precursor of the SKA1-low, is now a fully commissioned, operational and highly productive instrument, delivering science data from the first two semesters of observing (from July 2013). The MWA is part-way through its two-year observing program in which it is searching for the reionization signal, and the associated data processing is underway.

Construction of ASKAP began in 2010, and the six-antenna array (ASKAP-BETA) is currently being commissioned. The first HI auto-correlation spectrum from ASKAP-BETA was detected in Oct 2013, the first continuum image was achieved in Feb 2014, and an image with a dynamic range of 7000 was delivered in early May 2014. Meanwhile, the new phased array feeds (ASKAP Design Enhancements, ADE) are being built for ASKAP-12, and are to be installed in 2014. An international competitive process has led to the formation of 10 ASKAP survey teams (nine of which are led by Australian astronomers), all of which have been pursuing vigorous and detailed design studies. These design studies have driven innovative work on source finding, stacking, line identification, real-time classification and spectro-polarimetry. As a result, there is now substantial Australian leadership in all these areas, and we have correspondingly exerted a profound influence on the wider international community's approach to wide-field surveys.

Finally, the primary aim of the Pawsey Centre is to host new supercomputing facilities and expertise to support the SKA and its data streaming and processing requirements. The operations at the Pawsey Supercomputing Centre began in 2013 and a number of its supercomputing and data-storage systems are already available.

Existing radio facilities: In order to remain competitive and relevant in the field of extragalactic radio astronomy, it was recognised that the existing ATNF facilities need to be maintained (despite the reduction in available funding for them). This goal has been achieved by continuing operations and upgrading the existing ATNF Telescopes. The upgrades include the Compact Array Broadband Backend (CABB) which increased ATCA bandwidth by a factor 16, and allowed higher level data sampling (sensitivity improved by a factor 4); CABB is now in routine use. AT20G, a survey with the ATCA at 20GHz, has also proved surprisingly fruitful, with the discovery of an unexpectedly large number of galaxies with inverted spectra. The exploration of these has triggered a great deal of follow-up. Parkes, LBA, and (to some extent) Mopra have also continued to be supported.

[1] In extracting these priorities from the relevant working group reports from 2005, we have assumed that 'xNTD' refers to ASKAP, that 'LFD' refers to MWA, and that 'SKA pathfinder telescope' is the same as SKA1

Non-ATNF facilities have also been undergoing upgrades in the scope of developing SKA technologies; for instance the University of Sydney's Molonglo telescope has been awarded funding to prototype technologies relevant to the next generation radio telescopes and the Molonglo Prototype (SKAMP) is in progress. The University of Tasmania's Ceduna telescope has successfully been upgraded to support 20cm VLBI observations. Since the last Decadal Plan, the AuScope VLBI array (consisting of antennas in Tasmania, Western Australia and the Northern Territory) has been successfully commissioned by the University of Tasmania and is now fully operational for both astronomy and geodesy.

ALMA engagement: Since 2012 ALMA has provided the community with early science data. The cost-effective support to maintain access to ALMA early science operations until Australia joins ESO as a member (the previous decadal plan goal) has been established through Astronomy Australia Ltd (AAL) that secured modest $20,000 funding from Commonwealth funds (2012). Fellowship programs between CSIRO Astronomy and Space Science and the University of Chile have also been established (e.g. Australis Fellowship). Several Australian-led proposals have been successful in all ALMA Cycles so far (0, 1, and 2) with Australian users achieving a similar success rate to their US and European counterparts.

2.2 Science

The science priorities in the area of extragalactic radio astronomy for the previous Decadal Plan were summarised in WG 2.1 'Cosmology and the High Redshift Universe' document, in §2.3, 4.3–4.5, 5, and WG 2.2 'Nearby Universe'. Although, the science case was presented, there was no clearly listed goals (rather 'requirements' were presented), and hence it is difficult for us to evaluate if any progress has been made. Below we summarise the science topics of the extragalactic radio astronomy that were discussed in the documents 10 and 4 years ago. Here we omit discussions on cosmology (including dark matter, dark energy and cosmological equation of state) as these are all covered separately by the Cosmology sub-group.

Epoch of Reionization: As described in the previous Decadal Plan document, the Low Frequency Demonstrator (LFD) is proposed to have achieved this detection by 2015 using the original 512-tile plan. The MWA is now fully operational (as of July 2013) with 128 tiles. During the first semester, 350 hours of EoR data have been collected towards this goal. By the end of 2014, ~ 1000 hours will have been collected, which would place us within the theoretical expectations of making both a detection, and a ~ 5 sigma estimate of the slope and amplitude of the spherical power spectrum at $z \sim 8$ (150 MHz). Although data have been collected, sufficient processing and analysis will take at least 12 months.

Evolution of gas in galaxies: The last decade has seen much progress in understanding the HI mass function and the HI velocity function observed by the Parkes and Arecibo telescopes. The development of stacking techniques, which have not been anticipated in the previous Decadal Plan, have enabled Australian astronomers to reach the goal of measuring the HI content oat redshift $z = 0.1$ in 21cm-emission detected by the Parkes telescope. ALFALFA and JVLA data allowing an extension of this approach to higher redshift is already being analyzed. At the level of individual galaxies, HI data allowed much progress, including the determination of scaling relations, HI self-absorption, environmental quenching, angular momentum. Enormous progress has been made regarding the detection of molecular material. The ALMA telescope and the upgraded IRAM PdBI both found direct emission from CO at high redshift ($z \sim 2-3$) in tens of normal, star-forming galaxies – contrasting with expectations that only the most massive galaxies would be detectable in CO emission at these distances. The newly installed wide-band CABB correlator and a unique ATCA 7mm system also allowed for high redshift CO emission line observations of Lyα-bright radio galaxies. The new data resulted in an revised picture of the cosmic evolution of cold gas masses, star formation efficiencies, turbulence and disk structures.

Formation and evolution of SMBH: The critical goals in the subject of formation and evolution of supermassive black holes in the previous Decadal Plan were to establish and maintain access to the radio facilities, such as ATCA, xNTD, SKA, ALMA, and supercomputing resources. High sensitivity observations to detect radio-quiet AGN populations were to be provided by the new ATCA broadband correlator (and ultimately by the SKA). It has been also clearly recognised that to facilitate and manage the major survey projects needed for this science goal, a 'matching research time' (i.e. funding for researchers) is crucial. As discussed in §2.1, establishing and maintaining access to crucial radio facilities has been highly successful; the planned surveys of ASKAP and SKA will now allow us to address the science questions posed.

A significant progress has been also made with supercomputing simulations, which presented a convincing evidence for black hole feedback being fundamental for galaxy evolution. The 'matching research time' has been successfully addressed by, for example, the Super Science initiative. It is expected that spectacular scientific advances on the topic of formation and evolution of SMBH will be made in the next decade.

Evolution of radio galaxies: A number of interesting questions were posed on the subject of radio galaxy evolution, but no goals nor requirements were set. The topic of feedback from supermassive black holes, and in particular work relating to AGN triggering and feedback, was absent in the previous Decadal Plan. However, the Decadal Plan was written before we had a real understanding of the triggering and feedback from hot/cold feedback modes. We expect significant growth in the subject of AGN triggering and feedback, and its evolution over cosmic time, over the next decade, especially with the use of facilities such as MWA and ASKAP. MWA operating at frequencies $30-800$ MHz traces the low energy part of the spectra of radio sources and is already proving to be particularly powerful instrument for detection of steep spectrum and low brightness emission radio galaxies (Hurley-Walker et al. *in prep*), and more spectacular results are expected to come from its GLEAM continuum and polarisation survey in the near future.

Origin and evolution of cosmic magnetism: The goals of the previous Decadal Plan were to study the structure and evolution of magnetic fields in galaxies, clusters and the intergalactic medium, using ATCA, MWA and ASKAP. Progress includes: (1) The first successful demonstration of the 'Faraday rotation measure grid' technique. This work, published in *Science*, demonstrated that galactic magnetic fields can be generated by rapid dynamo modes, and also was the proof of concept that has subsequently underpinned the Square Kilometre Array key science project on cosmic magnetism. (2) A new technique has been developed for directly visualising cosmic turbulence via the spatial gradient of the Stokes parameters, as published in *Nature*. (3) Enormous polarised radio lobes associated with the 'Fermi bubbles' were discovered, as reported in *Nature*. These data provide a fossil record of starburst activity in galactic nuclei, and allow us to calibrate the rate at which galaxies magnetise the intergalactic medium in which they are embedded. The progress includes also (4) discovery of strong, ordered, magnetic fields in high velocity clouds (HVCs). This yields a physical explanation for the long lifetime of HVCs, thus providing a mechanism by which substantial levels of gas can accrete onto galactic disks and serve as fuel for star formation, (5) a successful detection of polarisation and Faraday rotation with both the MWA and with the CABB system on the ATCA, as well as (6) tenfold increase in the number of radio galaxies with both Faraday rotation data and redshifts, and a similar tenfold increase in the number of Mg II systems with Faraday rotation data, which has allowed us to probe the evolution of cosmic magnetism out to $z \sim 5$.

Furthermore, MWA started regular observing in 2013 and is already highly productive facility, especially for the studies of clusters of galaxies and magnetic fields (e.g. Hindson et al. *in prep*, Lenc et al. *in prep*). ASKAP is in construction stages and the early science data are expected in 2015; as already demonstrated by the MWA results, we expect significant growth in the subject in the next decade. Australia has now a substantial leadership and participation in the next generation of all-sky radio polarisation surveys, to be performed with ASKAP, WSRT, Arecibo, the JVLA and the SKA.

Important new developments: In addition to the above subjects, there have been several important new developments in the area of extragalactic radio astronomy not anticipated or not seen as a priority when the previous Decadal Plan was written. These developments include: (i) H I intensity mapping, which has been demonstrated through reprocessing of Parkes HIPASS data as a powerful new probe of galaxy evolution, large-scale structure and cosmology, (ii) Fast radio bursts (FRBs), a new population of transient phenomena at cosmological distances discovered with the Parkes telescope, whose dispersion delays can be used to map and weigh the intergalactic medium, (iii) rotation measure synthesis, through which ATCA CABB data have established new modes of feedback in active galaxies and have demonstrated new ways of probing cosmic magnetism – the broadband spectro-polarimetry is now a focus and the priority for MWA, ASKAP and SKA, and (iv) citizen science, in which complex image processing and astro-informatics problems on very large data can be solved by a distributed group of volunteers working over the Internet.

3 Radio astronomy science

3.1 The radio sky at μJy levels

Most extragalactic radio continuum surveys have multiple science goals, but they have one goal in common, which is

- *to understand the formation and evolution of galaxies over cosmic time, and the cosmological parameters and large-scale structures that drive it.*

This will be achieved by making a deep radio continuum survey of a significant fraction of the sky. For example, EMU will cover 75% of the sky at 1.4 GHz to a depth of 10 μJy/beam rms with an angular resolution of 10 arcsec. The largest existing survey is the benchmark NVSS survey, compared to which EMU will be about 35 times more sensitive, with an angular resolution about four times better, and with higher sensitivity to extended structures. EMU is expected to detect and catalogue about 70 million sources, compared to the 2.5 million radio sources currently known.

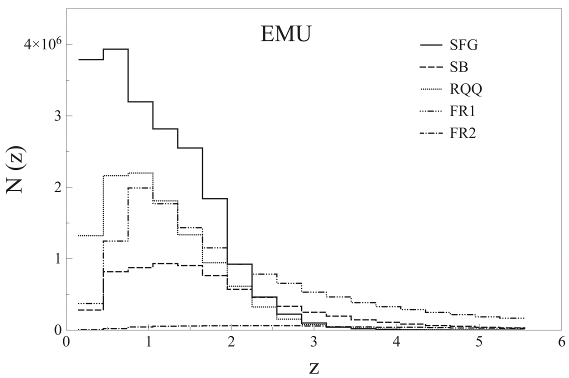

Figure 2 Expected redshift distribution of sources with $S_{1.4} > 50\ \mu$Jy/beam, based on the SKADS simulations. The five lines show the distributions for star-forming galaxies (SFG), star-burst galaxies (SB), radio-quiet quasars (RQQ), and radio-loud galaxies of Fanaroff-Riley types I and II (FRI & FR2). The vertical scale shows the total number of sources expected to be detected.

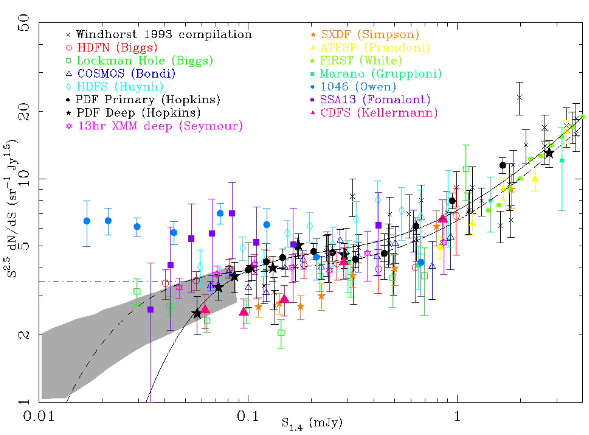

Figure 3 The Euclidean normalised differential radio source counts at 1.4 GHz. The solid and dashed curves are polynomial fits. The horizontal dot-dashed line represents a non-evolving population in a Euclidean universe. The shaded region shows the prediction (a '$P(D)$ analysis') based on fluctuations due to weak confusing sources.

Although the radio sky has already been studied by a number of deep surveys to the sensitivity level of EMU, these surveys cover a total of only a few square degrees. So although we know broadly what types of galaxy we will detect, and their approximate redshift distribution (Figure 2) a number of significant questions remain, discussed below.

At high flux densities, the source counts (Figure 3) are dominated by AGN. Below 1 mJy, the normalised source counts flatten, suggesting an additional population of radio sources, consisting of a mixture of both SF galaxies and AGN, about half of which are radio-quiet. Understanding this breakdown is crucial to understanding feedback processes (both stellar and AGN) that inevitably affect galaxy evolution, and hence all galaxy cosmic history.

It is difficult to distinguish AGN from SF galaxies and techniques include radio morphology, spectral index, polarisation, and variability, radio–infrared ratio, optical and IR colours and SED's, optical line ratios, X-ray power and hardness ratio, and radio source brightness measured by VLBI. None of these techniques is foolproof and universal, and a combination of techniques is necessary to provide unambiguous classification. Furthermore, there is growing recognition that high-luminosity galaxies, particularly at high redshift, are not simply 'star-forming' or 'AGN' but include a significant contribution from both. In extreme cases a galaxy may appear to be 'pure AGN' at one wavelength and 'pure SF' at another. Contribution to the galaxy's luminosity from both AGN and SF activity must be assessed, to measure the relative contributions from underlying physical properties such as black hole and galaxy mass, star-formation rate, environment, etc. However, the relative contribution will vary depending on the observing band, and so comprehensive multi-wavelength data are required.

3.2 Epoch of Reionization

The Epoch of Reionization (EoR) marks the end of the Dark Ages, and the transition of the Universe from a neutral intergalactic medium, to an ionised medium that has been heated by the first ionising radiation sources. Detection of the EoR at $z = 6 - 10$ is one of the remaining pieces in our understanding of the evolution of the early Universe. Within the current Decadal Plan, we discuss the EoR science principally through detection of the 21cm emission from neutral hydrogen prior to, and during, Reionization, using the spin temperature to probe the state of the IGM as a function of redshift. HI is the most reliable tracer of conditions within the IGM through this period, and is observable with low-frequency radio telescopes. Estimation of the angular and temporal distribution of this signal constrains both astrophysical (e.g., radiation mechanisms, properties of the first ionising sources) and cosmological (e.g., source clustering, density distributions) parameters. Detection and estimation of the EoR HI signal are primary science goals for the MWA and SKA-Low. The former is currently undertaking a statistical study of the signal, and the latter will perform deeper statistical studies and direct imaging of HI structures at high redshift.

Beyond the current Decadal Plan, SKA1-Low's primary science goals are

- *detection/confirmation of the EoR signal* (Goal), and
- *estimation of the 1D and 2D power spectra, and direct imaging of HI bubbles in the early Universe.* (Goal)

Australia is exceptionally well-placed to participate substantially in this area, with the current large-scale MWA EoR campaign expected to yield a high-significance detection, and with placement of SKA-Low at the same site as the MWA.

3.3 Gas in galaxies, evolution of galaxies and star formation

Understanding how galaxies form and evolve over cosmic time is one of the main questions of modern cosmology and extragalactic radio astronomy. The past decade has seen major advances in this area. For example, ten years ago, terms such as cold-mode accretion and the galaxy main sequence were unknown. Yet, there are many problems still unsolved, which shape the science goals for the next decade:

- *How does gas in galaxies build up and evolve? What are the physical pathways connecting gas and star formation in galaxies, such as the most important processes governing accretion and outflows? How does this affect the evolution of the IGM?*

Cold gas is a prime component in galaxies as the bridging ingredient between the interstellar medium and stars. In addition to its role as the fuel for star formation, cold gas can also be the product of star formation - both by as the remnant of supernova explosions and the dissociation product of UV radiation from young stars. Cold gas can also be used as a tool to study the kinematics and interactions of individual galaxies, as well as the large scale structure of the universe. With the SKA pathfinders and SKA phase I materializing, the observational study of cold gas, namely atomic hydrogen (HI), has become a central topic in observational astrophysics and cosmology.

Australia is one of the leaders in the new field of intensity mapping. A very wide-area survey of HI, which provided us with formidable data set for statistical studies of neutral Hydrogen in the local Universe, has been performed with the Parkes telescope (HIPASS, Meyer et al. 2004). Similar work is undertaken with Arecibo (ALFALFA, Giovanelli et al. 2005), using the CSIRO-constructed ALFA multibeam feed. However, both of these blind surveys are restricted to the local Universe ($z \sim 0.05$), while the most dramatic epoch in the galaxy evolution is found to peak at redshifts $z \sim 1-3$ when the intense star formation and SMBH activity shaped the galaxy build-up. With the SKA and ASKAP (DINGO, WALLABY, FLASH surveys) Australia has the potential to lead the exploration of the unknown territory of high redshift star formation history, gas assembly and galaxy and large-scale structure evolution through deep HI observations (intensity mapping, absorption, and stacking).

Furthermore, neutral hydrogen observations have revealed HI spiral arm structures in the outer regions of some disks of galaxies, which indicates that significant angular momentum helps to feed the inner disks. This naturally leads to questions:

- *how does the angular momentum build up and evolve across cosmic time? Do some dense cores of galaxies become bulges of spirals, while other become the central regions of giant ellipticals?* (Goals)

Angular momentum measurements across cosmic time will connect connect galaxy formation and cosmology, and will shed more light on angular momentum function, warm dark matter, cold dark matter expanding on the work done with HIPASS and ALFALFA.

Since its beginnings radio astronomy has been focused on AGN studies that dominate radio source counts at mJy flux density levels and above. It is the new-generation radio telescopes that will provide us with wide sky area and frequency range data at μJy levels uncovering the currently inaccessible global view of faint flux densities radio sky.

The cosmic star formation rate declines by an order of magnitude from $z = 1$ to $z = 0$, and is almost flat at higher redshifts, with the suggestion of a decline above a redshift of $z \sim 5$. Evidence from Lyman dropout sources suggest a dramatic decline above $z = 6$, while evidence from gamma-ray bursts suggest a much slower decline. The star formation rate also appears to depend on mass, environment, and history. At high redshifts, when galaxies were evolving rapidly, star formation appears to be dominated by dusty, heavily obscured, star-bursting galaxies. Optical and near-infrared observations are therefore seriously hampered by dust extinction. Since radio is unaffected by dust, deep radio continuum surveys provide an important tool for

- *measuring accurately the cosmic star formation history of the Universe up to high redshifts, as a function of mass, environments and other properties.*

Australian radio astronomy is uniquely positioned to lead this science; the observational way to unravel the full picture of star formation in radio wavelengths is through observations of the main fuel for star formation, the neutral Hydrogen. HI traces star formation and so is able to map evolutionary stages of galaxies. Next generation radio surveys will be able to measure the star formation rate up to high redshifts.

3.4 Evolution of AGN

At flux densities above 1 mJy level radio population is dominated by radio-loud AGN: the large-scale double lobed radio galaxies and luminous compact steep and flat spectrum radio sources. However, models of the sub-mJy radio population unexpectedly seem to include three main components: (a) star-forming galaxies, (b) extrapolation to low flux densities of the classical radio-loud AGN population (radio galaxies and radio-QSO), and (c) weakly radio emitting (radio-quiet) AGN that are unexpectedly common at sub-mJy levels. Detection of statistically significant samples of radio-quiet AGN will allow us to collect evidence and thoroughly examine the long standing problem of radio-loud/radio-quiet bi-modality of the AGN population.

One of the seminal results, with piling evidence, of the last decade is the downsizing of AGN. With such a finding we can conclude that black hole growth must be tightly linked to galaxy (host) growth. However, to be able to thoroughly investigate evolution of AGN in the cosmological and host galaxy evolution context, in the first place we need to create

- *a good understanding of the evolution of AGN as a class of object.*

There are several ways this can be achieved. Observationally, we can construct

- *statistically representative N(z) measures of well-defined classes of AGN* (Goal)

Such number counts need to include all classes of radio-loud AGN, distinguished by radio morphology (FRIs, FRIIs, disturbed morphology radio galaxies, etc) and by luminosity-age criterion (from young GPS/CSS radio sources, through giant, dying and re-started radio galaxies, to those in quiescent stage). We can also combine radio and optical/IR data to derive

- *accurate radio luminosity functions for AGN and star-forming galaxies (including composite objects) over a wide range in redshift* (Goal)

Accurate radio luminosity functions have already been measured for a wide range of radio-source populations in the local universe, and measurements have also been made at higher redshift for bright radio AGN. The next generation of radio continuum surveys will allow this work to be extended to higher redshift and lower radio luminosity, providing direct measurements of the redshift evolution of radio galaxies and their associated feedback processes.

Furthermore, we need to

- *explore in detail the demography of AGN relics,*

since findings in this areas will have crucial implications for our understanding of co-evolution of AGN and their hosts. It is still not clear to us whether all galaxies have an AGN or go through an AGN episode, or whether it is only a sub-set of them. It is also not clear what triggers AGN activity, although mounting evidence suggests galaxy environments play an important role in both the nature of any triggered AGN, and its subsequent evolution.

Finally, an important question is

- *how important the unexpectedly numerous radio-quiet AGN population is in feedback processes and AGN host evolution.* (Goal)

With the oncoming ASKAP and SKA continuum surveys we should be able to address these science questions. This will necessarily require high-resolution (i.e. VLBI) follow-up of unresolved sources, to quantify the birth rate, lifetimes and evolution of radio galaxies across cosmic time, as well as the physical scales of feedback by AGN on their host galaxies and larger-scale environment.

3.5 Co-evolution of AGN and their hosts

Only in the past decade has AGN feedback been recognised as an important ingredient in the evolution of galaxies and large-scale structure. For decades, radio astronomy has been dominated by studies of powerful, but rare radio galaxies. Only recently has the connection between radio galaxies of all luminosities and their hosts been realised, raising even more questions:

- *How do SMBH properties affect host galaxy properties and vice-versa? How does the AGN feedback work and how important is it?*

It is crucial that we understand what processes are responsible for the AGN feedback. The expected prevalence of low power radio galaxies and radio quiet AGN is thought to provide large-scale and continuous feedback, inevitably affecting evolution of their hosts. This feedback can be either kinetic (via radio jets), radiative, or a combination of the two mechanisms. The nature of AGN feedback is related to the mechanisms responsible for triggering AGN activity.

In order to study the relation between the evolution of high-luminosity, low-luminosity and weakly emitting radio-AGN, and the growth of galaxies in which they reside, we need to explore the star formation activity in AGN hosts at high redshifts. Hence, one of the most fundamental issues in understanding the role of AGN in galaxy formation and evolution is the need to

- *measure the cosmic evolution of AGN activity and feedback, and compare this with the build-up of the stellar populations of galaxies.* (Goal)

Combined with a detailed census of AGN energetics, this will enable us to determine the physics driving the evolution of star formation and AGN activity in galaxies.

Another fundamental and unsolved question is on how black holes acquire their mass. Particularly,

- *what processes determine how much gas in distributed as a building block of stars and how much is transported to be accreted onto black hole?* (Goal)

Again, the planned ASKAP and SKA continuum surveys promise a breakthrough in this area. It is fundamental, however, that we investigate these crucial science questions not only observationally, but also theoretically as highlighted and discussed in §3.12.

3.6 The Magnetic Sky

While gravitation sustains the on-going evolution of the Cosmos, it is magnetism that breaks gravity's symmetry and that provides the pathway to the non-thermal Universe. By enabling processes such as anisotropic pressure support, particle acceleration, and jet collimation, magnetism has for billions of years regulated the feedback vital for returning matter to the interstellar and intergalactic medium.

Magnetic fields are crucial to our understanding of astrophysical processes and structures ranging from microscopic processes in the interstellar medium up to the vast scale of cosmic filaments. However, we still have a very limited understanding of the structure, evolution and origin of magnetic fields at all scales.

Radio polarimetry and Faraday rotation are unique probes of magnetic fields on all scales and at all redshifts. Our ability to study and interpret radio polarisation data has greatly matured over the last decade, so that we now have a sophisticated set of tools with which we can probe both thermal and non-thermal magnetised sources, and can begin to disentangle multiple such components both along the line-of-sight and within a telescope's angular resolution.

In contrast, our actual understanding of these processes is still very limited, because of the almost complete absence of spectro-polarimetric radio data, especially over wide fields or with meaningful sensitivity, and even more so in the southern sky. The new generation of survey facilities such as ASKAP, MWA, AperTIF, the JVLA and ultimately the SKA finally provide the capabilities we need to ask even the simplest questions about the magnetised Universe. With such data from these telescopes, we will be able to acquire sensitive broadband polarisation data to very large numbers of polarised extragalactic radio sources, with which we will be able to:

- *determine the 3D magnetic field geometry of the Milky Way* (Goal)
- *establish the typical magnetic properties of galaxies, AGN, clusters and the intergalactic medium* (Goal)
- *establish the extent to which AGN entrain thermal gas in their outflows, and thus pollute the IGM with metals and magnetic fields* (Goal)
- *determine how magnetic fields in individual galaxies and in the overall IGM have evolved over cosmic time* (Goal)

The results of these efforts will not only provide vital physical insight into a whole range of other physical problems, but wide-field polarimetric capabilities are vital for achieving the high dynamic range needed for many other sensitive continuum experiments.

3.7 HI science

HI and Galaxy Evolution Understanding the physical processes that drive the mass assembly of galaxies and their continued evolution is a topic that continues to drive much of extragalactic astronomical research. A central component of this in the coming decade will be to understand evolution in the cold gas content of galaxies and detailed understand the complex interplay of gas content with the other major galactic constituents and their environment. While direct studies of HI emission of previous years have largely been restricted to studies of the local Universe and samples of 100 − 1000s (e.g. HIPASS, ALFALFA), the coming decade offers the opportunity acquire direct measurements of hundreds of thousands of galaxies with the SKA pathfinders. These surveys will enable both the most comprehensive all-sky studies of the nearby Uni- verse ever undertaken (e.g. WALLABY) as well as much deeper studies over smaller areas and billions of years of cosmic time (e.g. DINGO). Phase 1 of the SKA towards the end of the decade will push these boundaries even further, for the first time breaking into the million+ galaxy survey regime and spanning over half the history of the Universe. Direct measurements of the HI content of individual galaxies will be supplemented by studies exploiting statistical methods such as HI stacking and intensity mapping to maximally exploit the sensitivity of HI data sets and further increase the evolutionary baselines over measurements can be made.

The Interstellar Medium in Galaxies In addition to providing large samples of predominantly unresolved sources, the next generation of telescopes will also vastly increase the number of well-resolved objects. Such resolved studies are critical to understanding in detail the processes by which galaxies both gain and lose their cold interstellar medium, and the way this impacts their global evolution. It is on the scale of individual molecular clouds that stars are formed - material in turn cooled from the atomic ISM - and correspondingly it is on these scales galaxies ultimately need to observed to fully understand the global interdependencies between galactic components exhibited by the galaxy population as a whole. A major priority of the next generation of HI survey science facilities will be to deliver large samples of well-resolved galaxies, in the coming decade ultimately extending to surveys with SKA1-mid toward the end of the decade, enabling galaxies to be observed on sub 100pc scales, providing new insight into relations such as the Schmidt-Kennicutt law.

The Intergalactic Medium Despite dominating the baryonic mass content of the Universe and its clear importance in the on-going fuelling of galaxies, the intergalactic medium is one of the most difficult baryonic components to observe. Direct detection of the cosmic web in HI emission are extremely difficult due to the very low column densities at which this material is expected to exist. The SKA will be the first instrument with both the sensitivity and resolution to make significant progress in studies of this material. Detecting the IGM remains a priority, both for understanding the structure and nature of the cosmic web itself, which remains poorly understood, but also how material from the cosmic web continues to fuel and drive the properties of galaxies today through processes such as hot- and cold-mode accretion.

HI Absorbers A technique that avoids the raw redshift-dependant sensitivity limitation of detecting HI in emission is to instead study the properties of HI gas seen in absorption against background continuum emission. The SKA and its pathfinders and ideally suited to these studies, with large survey speeds and instantaneous bandwidths greatly increasing the number of sightlines and redshift ranges that can be examined. Projects such as FLASH and subsequent projects with SKA1 will be at the forefront of this work in the coming decade and remain a priority for the Australian community. Studies of intervening HI absorption will give new insight into the high-redshift HI Universe, while the detection of associated absorption will provide an important probe into the nature of AGN feedback and cold outflows.

HI Cosmology The large redshift samples expected to be delivered by HI surveys with the next generation of telescopes, and the anti-biased nature of this galaxy population, will yield important new constraints in observa- tional cosmology. Particularly important here will be studies of BAOs, through both direct detection and intensity mapping studies, weak lensing, and the measurements of redshift-space distortions to give new insights into the nature of dark energy. New all-sky HI surveys in the coming decade will also give unprecedented peculiar velocity catalogues, giving our best yet measurements of local large scale flows and the distribution of dark matter.

3.8 Exploration of time-domain astrophysics

The Universe is a changing and violent place. These changes are often subtle, brief or difficult to identify, but can provide us with a unique window onto the fundamental physical processes that drive the evolution of the cosmos. For example, supernova explosions and gamma-ray bursts, two related phenomena that were both discovered through their time-varying behaviour, have spawned entire new fields of study on the formation of black holes, the origin of the chemical elements, the generation of cosmic rays, and the acceleration of the Universe's expansion. However at radio wavelengths, tremendous signal-processing overheads have left the time-varying sky still largely unexplored. This will change dramatically in the next decade, with the advent of sensitive wide-field survey facilities that will provide a synoptic, real-time view of the changing sky; these studies are key science drivers for SKA pathfinders, and potentially for the SKA.

When the ASKAP surveys start, initial transient and variability studies through projects such as VAST can be performed commensally via comparison with previous catalogues such as SUMSS and NVSS. Subsequently, surveys such as EMU can be used as a zero-epoch baseline, and compared with dedicated repeat observations.

Compact objects and extreme physics. A host of new, exotic, extragalactic phenomena have emerged over the last decade, all involving some of the most extreme conditions seen in astrophysics. These include long gamma-ray bursts (potentially the collapse of the most massive stars to form black holes), short gamma-ray bursts (possibly the mergers of binary neutron stars), tidal disruption events (accretion events onto supermassive black holes) and fast radio bursts (whose mechanism is as yet unknown). Other phenomena are predicted but not yet observed or confirmed, including black hole mergers and orphan afterglows. Australian astronomers are extremely well-positioned

- *to lead discoveries and new understanding on all these topics, by discovery of large new samples of these events (TDEs, FRBs, orphan afterglows), or by prompt and detailed follow-up of events triggered in other domains (GRBs, gravitational wave triggers).*

The entire suite of Australian observing capabilities will be needed for these activities, but most notably MWA, ASKAP, SKA, SkyMapper, LSST and optical/IR Antarctic facilities.

The composition of the intergalactic medium. The IGM hosts most of the baryonic content of the Universe, but its physical conditions and distribution are still not well constrained. Time-variable phenomena can provide robust new data on the density, magnetic field and ionisation state of the IGM as a function of redshift, through the propagation effects observed toward fast radio bursts (dispersion, Faraday rotation, scattering) and AGN (scintillation). Successful exploitation of these phenomena for studying the IGM will require sensitive radio surveys of the entire observable sky on cadences ranging from milliseconds to years. In the case of FRBs, this will also require immediate arcsecond localisation, followed by deep optical imaging and photometry to obtain redshifts of afterglows and host galaxies. Australian astronomers are extremely well-positioned to lead discoveries and new understanding on all these topics, primarily by discovery of large new samples of these events (TDEs, FRBs, orphan afterglows), and also by participating in prompt and detailed follow-up of events triggered in other domains (GRBs, gravitational-wave triggers). The entire suite of Australian observing capabilities will be needed for these activities, but most notably MWA, ASKAP, SKA, SkyMapper, LSST and optical/IR Antarctic facilities.

3.9 Galaxy clusters, large-scale structure, and cosmology

Clusters of galaxies are not isolated regions, but evolving structures at the intersections of filaments and sheets in the large-scale structure. Tens of thousands of clusters are currently known, but only a few are known at $z > 1$. Radio observations of galaxy clusters not only probe the physics of the intra-cluster-medium (ICM), but also trace the evolution of large-scale structure of the Universe up to very large distances.

Clusters of galaxies have four distinct radio signatures: (a) Tailed galaxies, which are FRI radio sources whose tails are blown by the cluster wind, and which are the most widespread cluster diagnostic, (b) Halos, which are steep-spectrum Mpc-scale diffuse sources in the central regions of X-ray luminous clusters, (c) Relics caused by cluster-cluster shocks in the peripheral regions of merging clusters, (d) Mini-halos in relaxed cool-core clusters, surrounding a powerful central radio galaxy. Radio emission in clusters is therefore likely to become an important tool both for studying clusters themselves, and for detecting large numbers of clusters to study cosmology and trace large-scale structure formation.

Based on ATLAS observations, EMU is expected to detect hundreds of thousands of clusters - similar to the number expected to be detected by eROSITA. MWA, with its extraordinary surface brightness sensitivity, is already producing spectacular results in the subject of galaxy clusters (e.g. Hindson et al. *in prep.*, McKinley et al. *in prep*, Srinivasan et al. *in prep*) and many more are anticipated in the near future.

Continuum surveys will be also able to *constrain cosmological models and parameters* via several probes: (i) the Integrated Sachs-Wolfe effect, (ii) the lensing effect known as cosmic magnification, and (iii) source count correlations. In all three cases, significant constraints may be placed on cosmological (e.g. Dark Energy equation of state) and fundamental physical parameters (e.g. departures from General Relativity, and non-Gaussian inflation), even when redshifts for individual radio sources are unknown. However, the effect of errors in systematic calibration and in the assumed bias and window functions are currently unknown.

3.10 Unexpected discoveries

Experience has shown that the greatest science impact of new telescopes (e.g. HST, JVLA) come not from the science goals listed in the proposal to build the telescope, but from unexpected discoveries. Similarly, about half the great discoveries in astronomy have been made, not by testing a hypothesis, but by observing the sky in an innovative way. There is growing recognition that next-generation surveys should plan for these discoveries, and optimise their survey strategy and data-mining software, to maximise the probability of such discoveries. Surveys can be designed to maximise the volume of virgin observational phase space, and projects are now being assembled, such as the EMU's WTF project, to develop software to mine the data for the unexpected.

- *Searching for the unexpected, and developing software to mine for the unexpected, must be a high priority of the Australian path to the SKA.* (Goal)

A recent example of an unexpected discovery is the fast radio bursts (FRBs) found through developing new processing techniques of existing Parkes pulsar data. FRBs are now an exciting new area of extragalactic astronomy. Australia is perfectly positioned over the next decade with MWA, ASKAP, and ultimately SKA, providing new deep, wide-field surveys which open up new swathes of observational phase space, with a significant likelihood of making significant unexpected discoveries.

3.11 Moving radio astronomy into the mainstream

Because continuum surveys are crossing a sensitivity threshold below which most galaxies detected in radio surveys are normal star-forming galaxies, and because the numbers are so large (70 million galaxies for EMU, about 500 million for SKA1), they will outnumber known optical galaxies, and majority of galaxies found in an optical/IR survey will have radio photometry (and in many cases, polarisation and spectral index information). In 10 years time radio photometry will therefore be as commonplace in galaxy SED and photo-z estimation as IR photometry is now. Australia leads a number of the SKA pathfinders and their key science projects (MWA, ASKAP) which will produce legacy surveys before the arrival of the full SKA facilities. Australia should play a major role in the SKA legacy surveys.

3.12 Theoretical radio astrophysics

Over the past 15 years the cosmological galaxy formation models turned from the intuitive hierarchical evolution towards accepting the downsizing effect – the anti-hierarchical growth of structures where the more massive galaxies formed prior to smaller ones. We need accurate semi-analytical models and hydrodynamical simulations to resolve physics on the sub-pc scales; it is crucial to adequately model star formation and accretion onto supermassive black holes in cosmological simulations if we want to fully understand the physical processes at play. Currently, it is the phenomenology that drives the theoretical modelling of galaxy formation, evolution and co-evolution with SMBHs, especially the star formation aspect. Present observations are limited due to the Malmquist and other selection biases. The sensitivity of the SKA will allow us to overcome bulk of the observational biases, and to target galaxies at all redshifts, luminosities and masses (as much as we can), which will be a powerful test-bed for the theoretical models. *The growing importance of theoretical work in Australian community should be encouraged and further strengthen.* Joint observational and theoretical effort are needed to make significant progress on current key scientific questions. Strong theory groups will guide new ideas as well as will interpret existing and forthcoming data.

4 Extragalactic radio astronomy in the run-up to SKA

4.1 ASKAP

Sensitive large-area surveys, such as ASKAP EMU (continuum), POSSUM (polarisation), FLASH (HI absorption) together with MWA's GLEAM (radio continuum) and Dutch AperTIF WODAN (radio continuum) survey, will be able to track directly the evolution of radio AGN from $z \sim 1$ to $z = 0$ by overcoming the bulk of the Malmquist bias. While the WALLABY (HI) and DINGO (HI) ASKAP surveys will provide us with sought after information on gas reservoirs. ASKAP key science project list also features VLBI project which is to test the long baselines specifications for the SKA.

The Australian SKA Pathfinder (ASKAP) consists of 36 12-metre antennas distributed over a region 6 km in diameter. Each antenna is to be equipped with Phased Array Feeds (PAFs) of 96 dual-polarisation pixels operating in a frequency band of 700–1800 MHz. As a result, ASKAP will have a field of view up to 30 deg^2. To ensure good calibration, the antennas are a novel 3-axis design, with the feed and reflector rotating to mimic the effect of an equatorial mount, ensuring a constant position angle of the PAF and sidelobes on the sky.

ASKAP is now (June 2014) operating in a six-antenna, 15-baseline BETA mode using the first-generation PAFs, and already generating sensitive, high dynamic-range images in both continuum and HI. Even though ASKAP is still in an engineering commissioning phase, it is already the second fastest survey telescope in the world, beating the ATCA and second only to JVLA. Its performance suggests we are well on track to achieve the expected sensitivity and survey speed with the full ASKAP

The new ('ADE') PAFs are working well in prototype, and funding is available to equip 30 of the 36 ASKAP antennas with them. Commissioning observations with 8 ADE PAFs is expected to start in early 2015, with early science expected to start in mid-2015. The remaining antennas will be progressively equipped with ADE PAFS, with full operation tentatively expected for 2016-2017. ASKAP will then be operated as part of the Australia Telescope National Facility (ATNF) by CSIRO.

ASKAP is designed as a survey instrument. From ten ASKAP Survey Science Projects (selected via international open call for proposals in 2009) nine are led or co-led by Australia based scientists. ASKAP's two key projects, which are primarily driving the design, are EMU (the all-sky continuum survey) and WALLABY (the all-sky HI survey). Eight other survey projects are also important drivers for ASKAP. ASKAP is expected to make substantial advances in all key areas of the SKA science. All radio data from the ASKAP surveys will be placed in the public domain as soon as the data quality has been assured.

4.1.1 ASKAP-EMU

In continuum mode, ASKAP will observe a 300 MHz band, split into 1 MHz channels, with full Stokes parameters measured in each channel. As well as producing images and source catalogues, the processing pipeline will also measure spectral index, spectral curvature, and polarisation. All data processing steps, from the output of the correlator to science-quality images, spectra, and catalogues, are performed in automated pipelines running on a highly distributed parallel processing computer.

The Evolutionary Map of the Universe (EMU) will use ASKAP to make a deep (10 μJy/beam rms) radio continuum survey of the entire Southern Sky, extending as far North as $+30°$. EMU will cover roughly the same fraction (75%) of the sky as the benchmark NVSS survey, but will be 45 times more sensitive, and will have an angular resolution (10 arcsec) 4.5 times better. Because of the excellent short-spacing *uv* coverage of ASKAP, EMU will also have higher sensitivity to extended structures. Like most radio surveys, EMU will adopt a 5-σ cutoff, leading to a source detection threshold of 50 μJy/beam. EMU is expected to generate a catalogue of about 70 million galaxies.

4.1.2 ASKAP-POSSUM

POSSUM (POlarisation Sky Survey of the Universe's Magnetism) is an all-sky ASKAP survey of linear polarisation. It is expected that POSSUM will be commensal with EMU (and with WALLABY, the HI survey), and that the two surveys will overlap considerably in their analysis pipelines and source catalogues. POSSUM will provide a catalogue of polarised fluxes and Faraday rotation measures for approximately 3 million compact extragalactic sources. These data will be used to determine the large-scale magnetic field geometry of the Milky Way, to study the turbulent properties of the interstellar medium, and to constrain the evolution of intergalactic magnetic fields as a function of cosmic time. POSSUM will also be a valuable counterpart to EMU, in that it will provide polarisation properties or upper limits to polarisation for all sources detected by EMU.

4.1.3 ASKAP-WALLABY

WALLABY will observe the whole Southern sky and the Northern sky up to δ = +30°, out to a redshift of $z = 0.26$. WALLABY is designed to yield the largest sample of galaxies that is possible to detect in a given observing time with ASKAP, and is expected to detect about half a million galaxies. WALLABY will have a slightly larger sky coverage than HIPASS, but substantially larger frequency coverage, angular resolution, velocity resolution and point source sensitivity. WALLABY will address fundamental science goals relating to galaxy formation, galaxy evolution and cosmology. WALLABY will serve as an accurate zero-redshift anchor for later SKA HI surveys of the distant Universe and will inform SKA HI survey designers of parameters which are presently poorly known.

4.1.4 ASKAP-DINGO

DINGO is a deep, small-area HI survey, consisting of two phases, which differ in area and depth. The deep survey aims to target five fields, 150 sq deg in total, out to z = 0.26. While the redshift range is the same as for WALLABY, the integration time per field is longer providing better sensitivity. The second phase is proposed to consist of two ultra-deep fields, 60 sq deg in total, over the redshift range $z = 0.1$ to 0.43. Whereas WALLABY is designed to provide the largest possible reference data set in the nearby Universe, DINGO is designed to study the HI content of galaxies over the largest possible redshift extent and to understand the factor driving changes in this content and the role it has played in galaxy evolution. DINGO is predicted to detect a total of 10^5 galaxies over the last 4 billion years of cosmic time.

4.1.5 ASKAP-FLASH

ASKAP's large spectral bandwidth, wide field of view and radio-quiet site will open up an exciting new parameter space for large, blind HI absorption-line surveys using background radio continuum sources. The detection limit for such surveys is independent of redshift, and depends only on the brightness of the background continuum source which is used as a probe. 21cm HI absorption–line surveys with ASKAP will therefore provide a new and important measure of the neutral gas content of distant galaxies, particularly in the redshift range $0.5 < z < 1.0$ where the HI emission line is far too weak to be detectable in individual galaxies.

The ASKAP-FLASH survey aims to target over 150,000 sightlines to bright continuum sources, an increase of more than two orders of magnitude over *all* previous HI absorption-line surveys (blind and targeted) with existing radio telescopes. It will detect intervening HI absorbers along the line of sight to background radio galaxies and QSOs (providing an 'HI-selected galaxy sample' in the distant Universe) as well as associated HI absorption within the host galaxies of radio AGN (providing new insights into the gas flow and feeding mechanisms of AGN across a wide span of cosmic time).

4.2 Murchison Wide-field Array

The Murchison Wide-field Array is a low-frequency synthesis telescope located at Boolardy, Western Australia, adjacent to ASKAP. It consists of 2048 dual-polarization dipole antennas, arranged as 128 'tiles', each consisting of a 4×4 array of dipoles designed to operate in the $80-300$ MHz frequency range. Each tile performs an analogue beamforming operation, narrowing the field of view to an electronically steerable ~ 25 degrees at 150 MHz. Real time calibration, using novel position-dependent self-calibration algorithms, is under development.

MWA is focused on four key science projects: (a) the detection and characterization of 3D brightness temperature fluctuations in the 21cm line of neutral hydrogen during the Epoch of Reionization (EoR) at redshifts from 6 to 10, (b) solar imaging and remote sensing of the inner heliosphere via propagation effects on signals from distant background sources, (c) high-sensitivity exploration of the variable radio sky, and (d) detailed galactic and extragalactic science, including cosmic web, galaxy clusters, Galactic magnetic fields, H II regions and SNR among others.

The GLEAM (GaLactic and Extragalactic All-sky MWA) survey is an all-sky (south of $\delta \sim 30°$) radio continuum and polarisation survey. The Southern hemisphere sky is surveyed in five radio frequencies with overall bandwidth extending between 75 and 230 MHz down to ~ 10 mJy/bm rms noise level. The survey is currently ongoing and data release is anticipated in mid- to late-2015, providing the community with both source catalogues and calibrated images. GLEAM will be a tremendous resource on our way to SKA1-low allowing detailed investigations of Southern hemisphere radio sky in spectral (including studies of spectral indices, spectral curvature, and low-energy cut-off) and in polarisation studies, which has not been done at these frequencies before.

MWA is proving to be an exceptional facility of an astounding low surface brightness sensitivity (although low angular resolution, $1.5-4$ arc min) at the largely unexplored radio frequencies (< 250 MHz), which is invaluable particularly (though not only) in the galaxy clusters and radio galaxies studies. Although EoR experiment driven, the MWA instrument has powerful capabilities in the Solar, Galactic and extragalactic science (Bowman et al. 2012). The recent spectacular results include discovery of lenticular, nearby low surface brightness giant radio galaxy (Hurley-Walker et al. *in prep.*), cluster (McKinley et al. *in prep*, Hindson et al *in prep.*) and polarisation studies (Lenc et al. *in prep.*).

We need to maximise exploitation of this unique science over the next 5 years (and do it before LOFAR does if Australia is to be the leader in low frequency radio astronomy). Current MWA funding is secured until the end of 2015;

- *it is therefore of a high priority to ensure further funding is available to maintain, and perhaps extend (~ 6 km baselines), of the MWA.*

Other MWA upgrades include increasing EoR collecting area in the core, moving from analog to digital beamformer, broadening bandwidth and frequency range, etc. Without such funding (2016 – 2020) *Australia will become uncompetitive in the currently booming low frequency radio astronomy until the arrival of the SKA1-low early science data in 2020s, and in such a scenario, the leadership in this scientific area will be handed over to Europe in the second half of the current decade.*

MWA's greatest challenge is currently the lack of long baselines, so that confusion (~ 4 mJy/bm for radio continuum) and angular resolution ($\sim 2'$ at 154 MHz) prevents it from detecting more than 1% of EMU sources. There is a clear upgrade path for MWA involving the addition of additional stations at long baselines, which would then make it even more complementary to ASKAP. By doubling current baseline length (up to 7 km), MWA angular resolution of 60" and rms noise of order of 1 mJy/bm (154 MHz), would additionally complement the existing NVSS and SUMSS legacy surveys.

4.3 VLBI

VLBI is an important follow-up tool to provide high resolution images for sources discovered by ASKAP, MWA, and SKA1. In particular, VLBI provides an unambiguous indicator of the presence of a radio-loud AGN in a galaxy, since all other emission sources, with the exception of the very rare radio supernovae, do not have sufficiently high brightness temperature to be detectable in other galaxies with VLBI.

A specific goal is to do

- *an all-sky VLBI follow-up of EMU, to distinguish AGN from star-forming galaxies.*

This may be achieved with only one baseline, but will require an increase in survey speed of the existing LBA network. Tidbinbilla is likely to be more available in the next few years, making the LBA the most sensitive VLBI array in the world , especially if Westerbork is closed down. The VLBA is also currently under threat, so Australia's LBA network may become the *only* high-sensitivity VLBI array.

A very fast survey speed could be archived by equipping Parkes and Tidbinbilla with PAFs, and by significantly increasing the bandwitdh available to VLBI between antennas. An imaging facility such as an upgraded LBA would enable high-resolution imaging of unresolved high-redshift AGN. As discussed in Section 3.5, this would facilitate detailed studies of the mechanisms driving the triggering of AGN activity and AGN feedback.

VLBI observations of radio-loud AGN are also crucial to all astrometric programs, as these objects are used to define the celestial reference frame. This is particularly relevant with the recent launch of the GAIA satellite, which will provide a new reference frame at optical wavelengths before the end of this decade.

South Africa is also planning to build a VLBI array out of disused telecom dishes. If they are successful, then the two SKA co-host countries both have state-of-art VLBI facilities for SKA follow-up. Joining forces could usher VLBI into a new era.

4.4 International context

Australian-led SKA pathfinders and precursors are at various stages of development: the SKA-Low precursor, MWA, is currently fully operational, the SKA Molonglo Prototype (SKAMP) is being upgraded to the prototype SKA technologies (data collection and processing systems), and ASKAP, which is to be incorporated into SKA-Survey array, is already in construction and early commissioning phases.

Several international new or refurbished radio telescopes are also planning major surveys, and Australia's plans need to be developed in that context. However, none are truly competitors. For example, JVLA and MeerKAT are better suited to surveying small areas to very great depths, and cannot compete with ASKAP for 20cm wide area surveys. LOFAR and Apertif-WODAN will observe a similar frequency range as MWA and EMU, but in the Northern Hemisphere, and Apertif-WODAN will only survey 25% of the sky, compared to EMU's 75%.

Surveys at other wavelengths are also important complements to radio surveys, and the science from our radio surveys will depend on the availability of other multi-wavelength surveys, as shown in Table 2.

4.4.1 JVLA

The Karl G. Jansky Very Large Array represents a major upgrade to the VLA. Despite its high sensitivity, the upgraded VLA is not competitive for all-sky surveys (it would take 10 years of dedicated observing to reproduce EMU, or 600 years for the SKA1-survey all-sky survey). Although the upgraded VLA is not designed to be a survey telescope, its high sensitivity and versatility make it a valuable follow-up instrument to the all-sky continuum surveys. Furthermore, the JVLA is currently unbeatable for making very deep surveys of relatively small fields, such as the proposed JVLA Sky Surveys (VLASS). Even post-SKA it will be the leading high-frequency survey instrument. In all these respects, the JVLA is complementary rather than a competitor to planned Australian surveys.

4.4.2 MeerKAT/MIGHTEE

MeerKAT is the South African SKA pathfinder telescope. It will consist of 64 13.5 m dishes, equipped with cooled single-pixel receivers covering 0.9 to 1.67 GHz, and a longest baseline of 8 km. In this initial configuration, which is optimised for HI and pulsar work, the MeerKAT continuum survey ('MIGHTEE') will be confusion-limited to about 10 μJy rms at 20cm. Potential future extensions include the installation of higher-frequency receivers and extension of the longest baselines to about 20 km, but it is unclear whether these can take place prior to development of SKA1-mid on the same site using the MeerKAT antennas. Here we assume a direct MeerKAT transition from Phase 1 to SKA1-mid, so that MeerKAT is not a competitive continuum survey instrument until the commissioning of SKA1-survey.

4.4.3 LOFAR

LOFAR, the Low Frequency Radio Array, is currently fully operational. 40 stations are distributed over an area of diameter of 100 km in The Netherlands, and a further eight stations are located in Germany, UK, Sweden, and France. Each station includes two antenna types covering 30 – 80 and 110 – 240 MHz, whose signals form many beams on the sky, making LOFAR an extremely efficient survey instrument. LOFAR has already generated images that are the deepest ever at these low frequencies. The LOFAR continuum survey will cover the northern half of the sky (i.e. North of declination 0°). LOFAR will be especially complementary to EMU in surveying the sky at high sensitivity and resolution but at a much lower frequency, and complementary to MWA in surveying the Northern half of the sky. The band from the equator to declination $+30°$ will be surveyed by EMU, LOFAR and MWA, enabling spectral shapes to be measured for 25% of the sky over a broad frequency range.

4.4.4 APERTIF-WODAN

APERTIF is a project to replace the current single front-end feeds on the Westerbork Synthesis Radio Telescope (WSRT) by Phased Array Feeds (PAFs). The WODAN (Westerbork Observations of the Deep APERTIF Northern-Sky) survey will use APERTIF to survey the northern 25% of the sky (i.e. North of declination $+30°$) that is inaccessible to ASKAP, to an rms sensitivity of 10 μJy/beam and a spatial resolution of 15 arcsec. It will also chart about 1000 deg^2 down to 5 μJy/bm. Together, EMU and WODAN will provide (literally!) full-sky 1.3 GHz imaging at $\sim$ 10–15 arcsec resolution to an rms noise level of 10 μJy/beam, providing an unprecedented sensitive all-sky radio survey as a legacy for astronomers at all wavelengths. The WODAN survey will overlap with EMU by a few degrees of declination to provide a comparison and cross-validation, to ensure consistent calibration, and to check on completeness and potential sources of bias between the surveys. Thus WODAN is fully complementary to EMU.

4.4.5 *e*-MERLIN

The *e*-MERLIN array, operated by the University of Manchester, is a significant upgrade to the existing telescopes which form the MERLIN array in the UK. Consisting of seven telescopes, spread across the UK with a maximum baseline of 217 km, *e*-MERLIN provides high angular resolution (10-150 mas) imaging and spectroscopy in three broad cm-wavebands (1.3-1.8 GHz, 4-8 GHz and 22-24 GHz). Although *e*-MERLIN is not a survey telescope, being optimised instead for deep observations of small fields, it is a valuable follow-up for Australian surveys for sources at northern declinations.

4.4.6 Other wavelengths

To maximise the science from radio continuum surveys, complementary multi-wavelngth photometry and spectroscopy are needed. Table 2 shows the multi-wavelength surveys that are of most importance to the SKA pathfinders' surveys. There are two distinct requirements: photometry and spectroscopy.

For much of the science from continuum surveys, spectroscopic redshifts are invaluable, and radio astronomers strongly support projects such as TAIPAN. However, radio surveys (with median z $\sim$ 1.1) are intrinsically much deeper than available spectroscopic surveys, and only a small fraction of EMU's 70 million galaxies will have spectroscopic redshifts in the next decade. The problem becomes even worse for SKA1-survey. However, we note that next generation spectroscopic surveys such as DESI and 4MOST can in principle yield redshifts for a significant fraction of EMU sources, and so the Australian radio-astronomical community strongly supports these initiatives by their optical colleagues.

In the absence of spectroscopic redshifts, photometric redshifts provide an acceptable substitute in many cases, with project such as COSMOS and zFOURGE now producing photometric redshifts which approach spectroscopy in reliability.

Multi-wavelength photometry is essential for extracting the science from radio data to (a) examine the spectral-energy distribution to determine the constitution and evolutionary history of the host galaxy, and (b) to provide photometric redshifts. Table 2 shows that the primary source of imaging for EMU and other next-generation surveys are SkyMapper, WISE, and VHS. WISE data are in the public domain, and radio-astronomers strongly support the SkyMapper project, which is expected to have its data publicly available when the ASKAP surveys start.

5 Extragalactic radio-astronomy in the SKA era

5.1 SKA

The SKA Phase 1 and preparation for Phase 2 remain the ultimate goal for Australian radio astronomy in the next decade. The final design, specifications and available budget for the SKA-phase 1 are to be settled by the end of 2014, and the construction is to start in 2018. The early science data are anticipated by 2022.

Australia will host SKA-low and SKA-survey arrays. The speed and wide-field of view of the SKA1-survey will revolutionise the mid-frequency radio astronomy, and

- *it is Australian priority to ensure undertaking a leadership or a major role in maximum exploitation of the SKA science and building its legacy.*

SKA-low currently suffers most in terms of available funding and design, and it needs to be prioritised and extended (large funding needs, most likely Phase 2) to be truly competitive as compared to the existing low frequency radio facilities, e.g. LOFAR. Statistical indirect measurements of EoR, which is the driving force behind SKA-Low, are expected to be achieved with the reduced sensitivity SKA-low Phase 1, but we need to exploit the full capability of the array to explore the still little known, low frequency radio sky to be competitive to much slower LOFAR (SKA pathfinder).

5.2 SKA1-survey and SKA1-mid

The SKA baseline design locates SKA1-survey in Australia, and SKA1-mid in South Africa. SKA1-survey is optimised for large surveys, while SKA1-mid for deep-pointed observations. The proposed continuum survey for SKA1-survey will survey the entire southern sky to an rms of 2 μJy/beam, yielding a catalogue of about 500 million radio sources.

Not only does SKA1-survey build on the technological expertise developed for ASKAP, but it will also build on the scientific expertise developed for EMU, WALLABY, and the other ASKAP projects. Thus while SKA1-survey is a truly international telescope, with no preferred access to Australian astronomers, it is likely that Australian astronomers will have competitive advantage over their international colleagues in the types of technical and scientific challenges that SKA1-survey is likely to encounter. SKA1-survey therefore represents an invaluable opportunity for Australian radio-astronomy.

SKA1-mid could also, in principle, be used to conduct an all-sky survey. However, as it has a survey speed between $0.2 - 0.3$ of that of SKA1-survey, the planned 2 year SKA1-survey (with rms ~ 2 μJy) would take 6-10 years of continuous observing time on SKA1-mid, and therefore would not be feasible. While a shallower survey (with rms $\sim 5-10$ μJy) might be achievable with SKA1-mid, it offers only a slight improvement over EMU (with rms ~ 10 μJy). The ~ 2 years continuous observing is therefore unlikely to be scheduled in competition with the deep small-area observations for which SKA1-mid is optimised. In short, an all-sky survey is not feasible without SKA1-survey.

5.3 SKA1-low

SKA1-low will consist of $\sim 250,000$ low-frequency aperture array (LFAA) elements. The LFAA elements have no moving parts; they are log-periodic dual-polarised antenna elements and their extraordinary capability is enabled by advanced computing, signal processing and their relevant infrastructure. With the current baseline design for SKA1-low, $\sim 75\%$ of the antennae will be distributed within a compact core of 1 km diameter and the rest of the elements will be arranged into 35 m stations spanning three spiral arms which will create a 90 km diameter array.

The SKA1-low baseline design is optimised for the observations of the highly redshifted 21-cm line of neutral hydrogen in emission and/or absorption, cosmic magnetism and cosmic web; the sensitivity of 1 mK and resolution of 5 arcmin of the compact core of the array are expected to detect the EoR signal. However, the spiral arms of the array will allow for observations at angular resolution of 10 arcsec (150 MHz) and an astounding sensitivity of ~ 20 μJy/beam (250 MHz bandwidth, 1000 hour deep observations, confusion limited). The SKA1-low will hence be also suited for observations of pulsars, Galactic and extragalactic magnetised plasmas, radio recombination lines, populations of star-forming galaxies and radio galaxies of all luminosities up to high redshifts.

The SKA1-low will build on the expertise from the pathfinding work done with MWA and LOFAR. The already established Pawsey centre infrastructure (Perth, WA) will be fundamental for SKA1-low for data processing and storage.

5.4 VLBI

Australia currently leads the VLBI efforts in the Southern Hemisphere. For example, the only African station, Hartebeesthoek, observes as part of the Australian LBA. While Hartebeesthoek also observes regularly with the European VLBI Network (EVN), this combination cannot provide the East-West baselines required for much high-resolution astrometry (e.g. parallax work).

Australia must therefore:

- *take the leading role in the VLBI part of SKA-Mid (South Africa) and/or SKA-Survey (Western Australia),* (Goal)

and

- *ensure that the LBA capability of SKA will be incorporated in the design from the beginning of Phase 1.* (Goal)

6 Challenges and Issues

6.1 High-performance Computing

The High-Performance Computing (HPC) facilities are critical for astronomy in the next decade. Sufficient computer resources are required for simulations, radio data handling and analysis, and data storage. It is crucial that we have *stable, long term* access to HPC facilities. Current and future big telescopes *require* HPC resources to process the data, so HPC is a fundamental part of any new facilities. The next decade is more than ever the decade of 'big data' astronomy and to meet the challenge we will need HPC.

Historically there has been resistance in funding agencies to support software or algorithm development projects. This is not an option in the SKA era and we need to strive to change this culture. In the context of this Decadal Plan, HPC is both 'essential infrastructure' (hence part of a facility) and 'essential research' that is required to make the most of the resources. Current funding for the highly indispensable Pawsey centre finishes within the next few years.

6.2 Data-Intensive Research

The unprecedented area-depth product of the next-generation radio surveys makes them particularly suitable for data-intensive research projects such as stacking, identification of previously unknown types of sources (as discussed in § 3.10), extraction of low surface brightness radio emission to detect the WHIM synchrotron emission from cosmic filaments, cosmological tests involving cross-correlation of large survey samples, and rotation measure synthesis among others.

6.3 Calibration, Imaging, Source Extraction and Measurement

The next-generation radio surveys are entering a domain where traditional approaches may fail. For example, no existing source extractor can successfully find the radio sources in a radio-astronomy image without some manual intervention. No manual intervention will be possible for the 70 million sources from EMU!

At the excellent sensitivities offered by the SKA pathfinder telescopes, imaging and calibration algorithms need to deal simultaneously with issues such as primary beam corrections and polarisation leakage terms changing with frequency, directionally-dependent effects, and the need for high dynamic range and high polarisation purity.

Furthermore, the inherent data volumes are large (typically petabytes) so that computational efficiency and the number of data traversals are important parameters to consider in designing post-processing strategies. At present, a relatively small number of people are tackling these issues. It will become necessary to inject more resources into this area.

6.4 Classification and Cross-Identification

Table 2 lists the current, or planned, large area multi-wavelength surveys that have significant overlap with next generation radio surveys. Approximately 50% of EMU sources are likely to have counterparts in surveys such as SkyMapper, VHS and WISE. LSST will detect most of the radio sources; however, this will not happen until ~2028. SKA surveys reaching 1 μJy will have even fainter counterparts. While these can be detected by the JWST and the Extremely Large Telescopes (ELTs), only a few will be observable in the available time. X-ray surveys are intrinsically much less sensitive than optical/IR surveys, and will detect only a very small fraction of the AGNs detected by radio surveys.

Matching radio sources to optical/IR sources is difficult because of confusion, limited radio positional accuracy, and complex radio structure. EMU and other projects are developing sophisticated cross-matching algorithms, but it is not clear that robust solutions will be developed in time for these surveys.

Any automated algorithm will fail on complex radio sources, which may include those which are scientifically the most interesting. The Australian-led Radio Galaxy Zoo project is being developed to enlist the help of thousands of enthusiastic amateurs, and released its first prototype in late 2013.

6.5 Redshifts

Spectroscopic redshifts are invaluable to extract the science from radio surveys. While projects such as Taipan, OzDES and DES are valuable, they will detect less than 1% of radio sources. Long exposures ($\sim$ 10h) with 8/10 m telescopes can secure redshifts to $m_r \approx 26$, delivering redshifts for the majority of EMU sources, but this is obviously not feasible for 70 million sources. Projects such as 4MOST and DESI will deliver a much greater number, and will be very important in the long term.

In the shorter term, it will be necessary to rely on photometric redshifts. Statistical redshifts, in which the redshift on any individual object is poorly known but the redshift distribution of a population is well estimated, are also likely to be valuable for many of the radio science goals.

About 20% of EMU sources will have photometric data from the six optical bands of the Skymapper survey, two near-infrared bands of the Vista Hemisphere Survey (VHS) and four mid-infrared bands of WISE (see Table 2). With these available datasets, typically an error in redshift of ~ 0.03 can be reached for normal galaxies up to redshift $z \sim 1.5$ using either standard (SED template fitting) or empirical (machine learning) techniques.

About 80% of the EMU sources will have an optical counterpart that is fainter than $r = 22\,\mathrm{mag}_{AB}$ and for these sources the ancillary multi-wavelength data set will be coarse and non homogeneous. Nevertheless, using an approach labelled 'statistical redshifts', it is possible to use these data to constrain redshifts for statistical comparisons of data with models. It is clear that conventional redshift approaches are inadequate for next-generation radio sources, and new statistical approaches need to be developed.

6.6 Access to overseas radio and other wavelengths facilities

At present, a lot of observing with the use of overseas international radio facilities is done via 'open sky' access which does not require financial contribution from Australia, e.g. JVLA, WSRT, eMERLIN, eEVN, LOFAR.

6.7 Human resources & capabilities: the manpower that drives the science

In the run up for to SKA, Australia has focused on the facilities bids and delivery, but more important at this stage is to invest in winning science projects and researchers that will lead them.

- *There is a need for attracting and sustaining enough scientists to be able to make good use of next-generation facilities and science data they will provide; funding for scientists should be the priority in the next decade.*

Extending current grant system ($3-5$ year Discovery Projects) to a longer term 'rolling grant' system ($\sim$ 7 years) would allow larger and more strategic science projects to be undertaken. An example of such system includes the recent and ongoing ARC Centre of Excellence for All-Sky Astrophysics (CAASTRO). CAASTRO is the only centre of excellence within astronomy since The Research Centre for Theoretical Astrophysics (RCfTA) funded between 1991 and 1999. 90% of CAASTRO funding allocated primarily for early and mid career researchers, while the rest of the budgets contributes to activities that are not normally funded by standard grant schemes (e.g. public engagement etc).

Traditionally, Australia has been known through its observational work in both optical and radio wavelengths, though there is a growing expertise and strength of theory groups in the Australian astronomical community (e.g. ICRAR, Swinburne, Melbourne, ANU).

Table 2 Key multi-wavelength surveys with which EMU/WODAN data will be cross-identified (restricted to surveys larger than 1000 deg^2). All magnitudes are in AB. The 'detectable' column is the fraction of 1.4 GHz EMU/WODAN sources that are in principle detectable by the multi-wavelength survey to its $5\,\sigma$ limit. The 'matched' column is the fraction of 1.4 GHz sources which are both detectable and in the area of sky covered by the multi-wavelength survey. The sensitivity shown for the WISE survey is for the $3.5\,\mu$m band.

Survey Name	Area (deg^2)	Wavelength Bands	Limiting Mag. flux^{a}	Detectable (%)	Matched (%)	Data Release Date
WISE[1]	40000	3.4, 4.6, 12, 22 μm	$80\,\mu$Jy	23	23	2012
Pan-Starrs[2]	30000	g, r, i, z, y	$r < 24.0$	54	41	2020
Wallaby[3,b]	30000	20 cm (HI)	1.6 mJy^{c}	1	1	2013
LSST[4]	20000	u, g, r, i, z, y	$r < 27.5$	96	48	2020
Skymapper[5]	20000	u, v, g, r, i, z	$r < 22.6$	31	16	2015
VHS[6]	20000	Y, J, H, K	K< 20.5	49	25	2012
SDSS[7]	12000	u, g, r, i, z	$r < 22.2$	28	8	DR8 2011
DES[8]	5000	g, r, i, z, y	$r < 25$	71	9	2020
VST-ATLAS[9]	4500	u, g, r, i, z	$r < 22.3$	30	4	2012?
Viking[10]	1500	Y, J, H, K	K< 21.5	68	3	2012
Pan-Starrs Deep[2]	1200	$0.5 - 0.8, g, r, i, z, y$	$g < 27.0$	57	2	2020

[a]Denotes $5\,\sigma$ point source detection. However, in many cases, *a priori* positional information will enable $3\,\sigma$ data to be used, resulting in a higher detection rate.
[b]Being an HI survey, WALLABY will measure redshifts for all detected galaxies out to $z = 0.26$.

It should be considered a priority to integrate our theoretical and observational efforts, especially in the next decade with the arrival of large surveys.

We should ensure that scientists get adequate rewards and recognition for outreach activities. Every major project should have an outreach section associated with it, and be supported by appropriate funding. This may be particularly important with reference to developing new techniques for mining large data sets. With the arrival of SKA we will face a new level of big-data science and need of manpower to mine the data for both serendipitous discoveries and planned projects. Australian-led Radio Galaxy Zoo, a global citizen science project launched in December 2013, is currently one of such attempts. Furthermore, equally important is to get political support by building visibility with politicians (e.g. 'Science meets Parliament', and lobbying of individual MPs).

7 Legacy Radio telescopes

7.1 Overview

Australia must take a global leadership role in traditional areas of its international strength (e.g. cm-wavelength astronomy, Southern hemisphere VLBI, Phased Array Feeds, HI surveys, polarization studies), and continue to stay ahead of the rest of the world in these areas. This necessarily involves support of Australian-led instrumentation development, both at radio (PAFs, wide-band receivers) and optical (IFUs) wavelengths. *This should be one of Australia's highest priorities, even if it comes at the expense of buying only a small fraction of time on large international facilities.*

The existing ATNF facilities (LBA, ATCA, Parkes, etc, later also ASKAP) will face funding challenges before the arrival of the SKA. These instruments are delivering high quality science and create the Australia's strength at cm-wavelength astronomy; *they should also gain much higher international visibility*. Most cutting-edge radio astronomy in the next decade will be done from Australia and South Africa, and follow-up of the SKA pathfinder surveys requires

- *continued support for facilities such as ATCA and the Long Baseline Array.*

An important aspect is the role of Australia in improving the Celestial Reference Frame. This is particularly relevant with the recent construction of the AuScope VLBI array; at present there is a real dearth of astrometrically stable radio quasars in the Southern Hemisphere. Following the launch of GAIA we will need a new radio reference frame by $\sim$ 2019 (to align with the future optical reference frame). Furthermore, development and upgrade of the LBA to complement the SKA and ALMA should be also one of the priorities. The upgrade will require wide-band, wide-field receivers, but is necessary for detailed follow-up of ALMA and SKA pathfinder sources, and for astrometric work.

7.2 ATCA

In the next decade, the 20cm band of the ATCA will be rendered almost obsolete by ASKAP and MeerKAT, and the 3mm band by ALMA. However, at frequencies between these, ATCA remains the only cm-wavelength synthesis telescope in the Southern hemisphere. Demand for cm-wavelength follow-up observations are likely to increase as ALMA and ASKAP ramp up, and so it is likely that over-subscription rates for ATCA will reach an all-time maximum in the next decade. Furthermore, the new CABB system and unique 7-mm observing mode has already proved powerful in detecting high redshift CO emission lines. It is clearly essential to continue supporting ATCA.

7.3 Parkes

From the point of view of continuum surveys, the primary role of Parkes will be (a) to provide single-dish data to add short-spacing data to synthesis images, and (b) as a vital element of the Australian VLBI array. While (a) can be satisfied early in the next decade, Parkes role as a VLBI antenna will continue throughout the decade, and can justify upgrades of Parkes to wider bandwidths or PAF feeds.

7.4 VLBI and its constituent antennas

Currently, SKA1 does not have VLBI-scale baselines or angular resolution, and so VLBI will continue to be important throughout the next decade. VLBI will be particularly important for follow-up observations of sources discovered in survey observations with ASKAP, MWA, and SKA1. For example, VLBI is a prime tool for distinguishing AGN from SF galaxies, since SF galaxies (except those with a current radio supernova) do not have sufficient brightness temperature to be detectable with VLBI. For this test, it is not necessary to use an entire imaging array. Instead, one high-sensitivity baseline can be very effective (as was demonstrated in the past by the Parkes-Tidbinbilla Interferometer).

VLBI will also be important for studying the details of feedback processes between AGN and star-formation, the role of binary AGN mergers in galaxy evolution and feedback, and the first supermassive black holes at the highest redshifts.

However, current VLBI systems are limited by their relatively low speed. In traditional VLBI observations, the field of view was severely limited by time- and bandwidth smearing. Since the sub-mJy sky is densely populated with radio sources, VLBI observations are moving from the traditional mode of observing single, bright, widely-separated objects to a mode which allows observations of wide fields, with multiple phase centres directed towards known locations of radio emission. Despite this, VLBI observations are still slow as compared to survey telescopes. To observe more than a tiny fraction of EMU sources will require a major technological upgrade to Australia's VLBI facilities, such as wide-bandwidth feeds, signal transmission, and correlator, or by using phased array feeds.

With the expected increased availability of the Tidbinbilla $\sim$ 80m antenna, Australian VLBI will become the most sensitive VLBI array in the world. If Tidbinbilla and Parkes were both equipped with PAFs, and corresponding wide-bandwidth optical fibres and correlators, it would be the world's first survey VLBI telescope, and would significantly leverage the science output from ASKAP.

Other VLBI antennas (Hobart, Ceduna, Mopra, etc.) will continue to be vital to the imaging VLBI array, and will need to be upgraded using sideband feeds to improve their speed.

8 Australian radio surveys priorities for the next decade

8.1 Radio continuum & polarisation

In the next decade, the priorities for radio continuum and polarisation surveys are:

1. complete ASKAP, and continue supporting and upgrading MWA,
2. support and lead the science programs with SKA pathfinders (MWA, ASKAP, MeerKAT, WSRT-Apertif)
3. ensure the successful deployment of SKA1-survey and SKA1-low,
4. support and lead the science programs with SKA phase 1 (SKA1-low, SKA1-survey, SKA1-mid), in particular leading the all-sky continuum survey planned with SKA1-survey,
5. follow-up the discoveries made with survey telescopes, ensure that complementary radio astronomy facilities in Australia (ATCA, Parkes, Mopra, VLBI) continue to be supported and that we continue to enjoy access to international facilities such as ALMA and JVLA,
6. to ensure and maintain access and support for HPC facilities to simulate, process, analyse, and deliver the survey science outcomes

8.2 HI

In the coming decade, the HI survey science priorities are:

1. support of HI research in core areas, including: HI and galaxy evolution, the interstellar medium, the intergalactic medium, HI absorption systems, cosmology, the Galaxy and Magellanic systems

2. support and leadership of science programs with SKA pathfinders (ASKAP, MeerKAT, WSRT-Apertif, FAST)

3. support and leadership of science programs with SKA phase 1 (SKA1-survey, SKA1-mid)

4. improved coordination and access to multi-wavelength survey programs for HI data sets in the SKA era (deep all-sky imaging, massively-multiplexed spectroscopy, IFU)

5. access and support for HPC facilities to simulate, process, analyse, and deliver HI survey science outcomes

6. continued access, and leadership of, survey science program with the world's leading existing radio facilities (ATNF, NRAO) and the support for advanced instrumentation programs (eg. PAF for Parkes)

The highest priority for HI survey science over the coming decade are the HI surveys to be conducted with ASKAP (WALLABY, DINGO, FLASH) and with SKA. The proposed SKA HI surveys are as follows:

- Wide 30,000 $\deg^2$survey to detect galaxies to z $\sim$ 0.2 (SKA1-survey)
- Mid 3,000 $\deg^2$survey to detect galaxies to z $\sim$ 0.36 (SKA1-survey)
- Deep 300 $\deg^2$survey galaxies to z $\sim$ 0.65 (SKA1-survey)
- Ultra-deep 3 $\deg^2$survey galaxies to z $\sim$ 1 (SKA1-mid)
- Targeted high-resolution survey of nearby galaxies to study the ISM on scales $<$ 500 pc (SKA1-mid)
- HI absorption line survey to study IGM and AGN feedback (SKA1-mid)

9 What radio surveys need from other wavelengths

One of the biggest challenges facing the large radio surveys is the need to cross-identify with optical and infrared surveys. A significant fraction of radio sources found in radio surveys such as EMU will have host galaxies as faint as $m_r = 25$, and it is essential to obtain high quality photometry at a number of optical/infrared bands to enable photometric redshift measurements. Spectroscopic redshifts are even more desirable but are unlikely to be available until late in this decade, making high-quality photometric measurements even more important.

10 Strengths, Weaknesses, Opportunities, Threats

10.1 Strengths

- The founding of Murchison Radio Observatory and its superb radio quiet zone
- A newly-completed world-class low-frequency array (MWA) and a (nearly) fully-funded mid-frequency survey array (ASKAP) which is approaching completion
- Australian participation in, and co-hosting of, the Square Kilometre Array
- A fleet of world-class legacy telescopes (ATCA, Parkes, VLBI array, etc) ideally suited for follow-up observations of sources detected by the survey instruments
- A vibrant and enthusiastic radio-astronomical community at the cutting edge of international radio astronomy
- A large number of word-class postdocs resulting from the recent growth in Australian astronomical funding

10.2 Weaknesses

- Lack of long-term positions to support the large number of word-class postdocs currently in Australia under current funding system
- Lack of facilities for deep optical spectroscopy follow-up of the tens of millions of radio sources

10.3 Opportunities

- Opportunity to capitalise on the growth of Australian expertise in radio survey science, positioning Australia as the world leader in this area
- Greater availability of Tidbinbilla is expected in the next few years, making the Australian VLBI array the most sensitive in the world

10.4 Possible threats

- Lack of further funding for MWA
- Failure of the SKA consortium, or major descoping or delay of SKA
- Loss of access to international multiwavelength telescopes (JVLA, ALMA, LSST, etc)
- Closure of important legacy telescopes (e.g. VLBI) because of funding issues

- Inability to handle the large data volumes from survey telescopes
- Significantly reduced, or lack of, funding for early- to mid-career researchers if CAASTRO centre of excellence is not re-newed
- Budget cuts to astrophysics at CSIRO

11 Conclusions

11.1 Science in the next decade

- Detection of the EoR at $z = 6 - 10$ is one of the remaining pieces in our understanding of the evolution of the early Universe. In the next decade, the EoR signal confirmation and estimation of 1D and 2D power spectra will be one of the main scientific goals of radio astronomical community.
- Only in the past decade has AGN feedback been recognised as an important ingredient in the evolution of galaxies and large-scale structure. One of the most important goals is to measure the cosmic evolution of AGN activity and feedback, and compare this with the build-up of the stellar populations of galaxies. The next-generation facilities will probe deep, μJy levels of source populations, which unexpectedly seem to include a mixture between star-forming galaxies, low flux density equivalents of classical radio-loud AGN population and weakly radio emitting AGN. Exploring the weakly radio emitting AGN, as well as low luminosity density and surface brightness AGN will be enabled with the new-generation radio facilities and is an important goal which will refine our understanding of evolution and activity history of AGN.
- Magnetic fields are crucial to our understanding of astrophysical processes and structures ranging from microscopic processes in the interstellar medium up to the vast scale of cosmic filaments. In the next decade we expect to make significant progress in this area with tools such as radio polarimetry and Faraday rotation measure. Main and exciting goals include determining magnetic field geometry, and establishing the typical magnetic properties of galaxies, AGN, galaxy clusters and the intergalactic medium as function of redshift.
- Understanding how galaxies form and evolve over cosmic time, and what is the cosmic star formation history, are ones of the main questions of modern cosmology and extragalactic radio astronomy in the new radio astronomy era we are entering with SKA and its pathfinders and precursors. A number of dedicated ASKAP surveys are designed with mind of these science goals (DINGO, WALLABY, etc), which will open up the star formation window in historically AGN dominated field of astronomy.
- Studies of cold gas in galaxies with direct detection of HI emission and HI absorption are expected to be domination the HI science in the next decade, which offers the opportunity acquire direct measurements of hundreds of thousands of galaxies with the SKA pathfinders up to high redshifts. Furthermore, a major priority of the next generation of HI survey science facilities will be to deliver large samples of well-resolved galaxies; this is critical to understanding in detail the processes by which galaxies both gain and lose their cold interstellar medium, and the way this impacts their global evolution.
- The time-domain radio astrophysics is largely unexplored due to tremendous signal-processing overheads. This will change dramatically in the next decade, with the advent of sensitive wide-field survey facilities that will provide a synoptic, real-time view of the changing sky, allowing us to explore the most extreme conditions seen in astrophysics (gamma ray bursts, fast radio bursts), as well as study in detail the intergalactic medium as a function of redshift.
- Last but not least, we need to be well prepared for unexpected discoveries; such discoveries had already proved to be the drivers and indispensable tool to our understanding of the Universe.

11.2 Currently funded SKA Pathfinder facilities

- ASKAP and MWA, and their planned continuum surveys, have complementary capabilities which will lead to ground breaking science. Particularly exciting are (a) the ability of EMU to cover the entire sky with high sensitivity and resolution, detecting about 70 million galaxies,(b) the ability of POSSUM to obtain detailed information about the magnetic sky over the same region, (c) deep surveys of HI, and (d) the exceptional ability of MWA to detect low surface brightness radio emission (clusters of galaxies, radio relics, lobes of radio galaxies, SNR). Together, these surveys are likely to make major inroads on some of the pressing questions about the origin and evolution of galaxies, including distinguishing AGN and SF components of galaxies, tracing the evolution of the luminosity function for both, and exploring the causes and signatures of hot-mode/cold-mode accretion and feedback.

- Amongst the sources detected by the surveys will be very high redshift galaxies, possibly the highest discovered. However, identifying them, and measuring their redshift, will be challenging.
- These surveys are likely to detect tens to hundreds of thousands of new clusters, and will also map the extended halo and relic emission from a fraction of these. Comparison with X-ray observations is likely to yield new insights into the physics of clusters and the growth of structure in the Universe.
- The measurement of polarisation and rotation measures is an important part of the surveys, and is likely to yield not only insight into the physics of the radio galaxies, but into the origin of cosmic magnetism. There is a good chance that the intergalactic magnetic field will be detected and traced by these surveys.
- Even without redshifts, several cosmological probes can use survey data from SKA pathfinders and precursors to measure cosmological parameters and test models of gravity, with significantly more precision than current analyses. If photometric redshifts can be obtained for a significant subset of the radio sources, then these cosmological tests become even more powerful.
- Variable and transient sources are currently poorly studied, and VAST is likely to change this field significantly. In addition to constraining models of (e.g.) black hole accretion, these studies are also likely to result in unexpected discoveries.
- Because these surveys are opening up a large area of unexplored parameter space, it is likely that they will make unexpected discoveries. It is important not to leave this process to chance, but to recognise it as a legitimate goal of large surveys, and to plan processes and software accordingly, to mine the deluge of data that these surveys will produce.
- Attractive upgrade paths exist for both ASKAP and MWA, and if the SKA timescale permits, these upgrades could be extremely valuable scientifically and should be supported at a high priority.

11.3 SKA

Apart from the completion of current projects (MWA and ASKAP), supporting SKA, and completing the construction of SKA1-survey and SKA1-low, is the highest priority of the radio-astronomy community.

11.4 Legacy telescopes

To reap the scientific benefits of ASKAP, MWA, and ASKAP, it is essential that instruments such as the Australian LBA network and ATCA continue to be supported and developed for follow-up observations.

11.5 Access to overseas facilities

To reap the scientific benefits of ASKAP, MWA, and ASKAP, it is also essential that Australian continues to have access to overseas instruments such as ALMA, JVLA, and to spectroscopic and photometric projects such as DES, and develop collaborations with complementary multi-wavelength facilities overseas such as LSST and eROSITA.

Appendix 4

New opportunities for the 2016-2025 Decadal Plan in the area of cosmology

Final version (11 April 2014), compiled by Chris Blake

This document reports on new opportunities for the upcoming Decadal Plan in the area of cosmology, and was prepared by the cosmology sub-group (Chris Blake, Krzysztof Bolejko, Matthew Colless, Tamara Davis, Akila Jeeson-Daniel, Geraint Lewis, Chris Lidman, Katie Mack, Michael Murphy, David Parkinson, Greg Poole, Brian Schmidt and Cath Trott) of the Galaxies and Cosmology Working Group 1.1.

Scientific opportunities and priorities

We first list the most important scientific priorities (in our opinion) for the next decade in the area of cosmology.

- (1) We still have no **physical understanding of what dark energy represents,** and this will remain the highest-priority cosmological science question for at least the next decade or two. Answering this question requires *simultaneous measurements of the expansion and growth history of the Universe, using multiple techniques to control systematic errors.* Current datasets have accurately measured the expansion history of the homogeneous Universe, using Type Ia supernovae as standard candles and baryon acoustic oscillations as standard rulers, and future surveys will continue to refine these measurements of the distance-redshift relation. However, an important new challenge is to map the gravitational physics of the clumpy Universe using observable signatures such as galaxy peculiar velocities, gravitational lensing, galaxy voids, the Integrated Sachs-Wolfe effect and Doppler lensing. We break down the scientific opportunities as follows:
  - (a) Map the **expansion history of the Universe** using independent methods. First, we can compare Type Ia supernovae at low and high redshift, using a combination of direct detection (Skymapper) and spectroscopic follow-up of host galaxies (OzDES). The LSST will greatly expand these samples during the course of the decade. Secondly, we can continue to use baryon acoustic oscillations (BAOs) in the galaxy clustering pattern to perform standard-ruler measurements (extending the work of WiggleZ and 6dFGS). In optical wavebands, this can be achieved over the next decade if we can gain access and potential leadership roles in the wide-field spectroscopic surveys of the future performed by DESI, VISTA/4MOST, PFS or ngCFHT. Alternatively in radio wavebands, HI intensity mapping with the SKA phase 1 telescope will enable BAO measurements to high redshifts. Cosmological simulations of these large-scale structure surveys are needed, in order to determine the covariance of the measurements and to test non-linear modelling effects; approximate simulation techniques such as COLA are appropriate here. HI intensity mapping simulations will also need to investigate realistic effects of foreground subtraction. As a longer-term ambitious possibility, gravitational-wave standard sirens may become detectable within the next 10 years.
  - (b) Perform a 1% **measurement of the local expansion rate** (Hubble's constant H_0) by applying the BAO technique to a maximal-sky low-redshift survey with TAIPAN. Such

a measurement would resolve the current discrepancy between *Planck* and local standard candles, and 1% prior information on H_0 significantly enhances measurements of other important cosmological parameters such as dark energy and the total mass and effective number of neutrino species. Simulations are required, as above.

- (c) Measure the **gravitational growth rate of structure on the largest scales** using galaxy peculiar velocities at low redshift. These measurements can discriminate between the best-motivated theories of modified gravity (e.g. $f(R)$ theories or Galileon gravity), which imply a scale-dependent deviation from General Relativity on the largest scales. Possible distance indicators enabling peculiar-velocity measurements are the fundamental plane (TAIPAN), Tully-Fisher relation (ASKAP/WALLABY) and supernovae (Skymapper, OzDES). Full N-body simulations in modified gravity scenarios are required to understand the observable signatures that are expected in these models, and to guide the most promising forms of data analysis. Theory is needed to understand the evolution of perturbations in these different scenarios.
- (d) Refine measurements of the **growth rate of structure on intermediate scales** using redshift-space distortion (RSD) in the galaxy clustering pattern (building on earlier results from 2dFGRS, 6dFGS, GAMA and WiggleZ, which have mapped out the average growth rate with redshift, although not its scale-dependence). Possible datasets that can be used for this purpose will be produced by the TAIPAN, ASKAP/WALLABY, DESI and VISTA/4MOST surveys as well as SKA intensity mapping observations. Simulations are required, as above.
- (e) Perform a **model-independent reconstruction of the metric theory of gravity** by combining velocity datasets (galaxy peculiar velocities or redshift-space distortion) with weak gravitational lensing deep imaging surveys of the southern sky (KiDS, DES, LSST, SKA phase 1). This overlap of spectroscopy and imaging also enables the main systematic errors afflicting those lensing surveys, such as photometric-redshift error, to be addressed. Measurements of cosmic magnification and the Integrated Sachs-Wolfe (ISW) effect by ASKAP/EMU will also test this physics at higher redshift. Cosmological simulations including (ideally fully relativistic) ray-tracing are needed to produce errors in these measurements; full mock catalogues are required for testing the photo-z error reconstruction.
- (f) Investigate the **observable effects of inhomogeneity in the local Universe** on light propagation and interpretations of galaxy velocities, H_0 measurements and differential expansion. Theory should guide the expected observable signatures, with the aim of constructing model-independent tests involving peculiar velocities and galaxy voids, or correlations with the CMB.

- (2) Recent claims by BICEP2 of a higher-than-expected contribution of tensor modes in the CMB B-mode power spectrum have enabled more discriminating **tests of cosmological inflation**. These can be further improved by constraining an independent quantity, large-scale primordial non-Gaussianity, using current and future galaxy redshift surveys. Such measurements can be competitive with the Cosmic Microwave Background through sensitivity to a different set of scales, and through using a greater number of clustering modes (3D vs. 2D). Potential test statistics include the large-scale clustering power spectrum and bispectrum.

- (3) **Can we characterize the nature and distribution of dark matter?** This can be tested via techniques of gravitational lensing, quantifying the sub-structure around galaxies including very small-scale clustering, merger rates, detailed observations of local galaxies and the matter distribution inside cosmic voids. Simulations of different dark matter scenarios are also required. Closer links with particle physics approaches are possible here.

- (4) In low-frequency radio astronomy we will use the MWA to detect the **21cm signal from the EoR and perform basic cosmological parameter estimation.** SKA1-Low will continue this work by estimating 1D and 2D power spectra, and directly imaging HI bubbles in the early Universe.
- (5) We can continue to lead work in **constraining variations in fundamental constants** such as the fine-structure constant using cosmological and Galactic probes, with the next decade promising a further order-of-magnitude improvement in current constraints. These projects require access to new instruments on existing 8-m telescopes (e.g. VLT/ESPRESSO, Keck/SHREK) as well as new facilities (e.g. ALMA, GMT/G-CLEF, E-ELT/HIRES).
- (6) We can continue to detect and characterize the population of **fast radio bursts** including sky localization, host identification and redshifts. This would provide a census of the baryon contribution along these lines-of-sight, as well as potentially constraining cosmology by connecting redshifts with path lengths through the universe (although the application of this latter aspect is currently unproven).

Strategic implications of these scientific priorities

- The topic of **large-scale cosmological galaxy surveys at optical wavelengths** is one requiring crucial consideration in the next Decadal Plan. We list here some relevant comments and concerns.
  - Australian astronomy has a long and successful heritage in cosmological surveys following projects such as 2dFGRS, 6dFGS, GAMA and WiggleZ. The key cosmological motivation of these surveys is to understand the nature of dark energy through interlocking techniques.
  - However, the last decade has seen a transformation in how such projects are performed, toward very large-scale international collaborations where most of the scientists are not directly involved in taking the data. This is now an extremely competitive area and we can expect to see continuing avalanche of data and rapid improvements in the measurements and techniques. Some current and future relevant projects in this category are: BOSS, DES, eBOSS, DESI, 4MOST, PFS, Euclid, LSST, SKA, JWST, WFIRST.
  - The abundance of such projects implies that in most cases it is no longer feasible for Australia to aim to carry out its own smaller-scale projects and expect to be competitive in cosmological surveys (although there are potential exceptions, such as TAIPAN). However, joining such international projects is typically done by individual universities involving a financial contribution of a very awkward magnitude.
  - The issue is not so much to gain access to a facility for general use, but rather to gain access to the collaboration data and be involved in the scientific outcomes. (Although data is often eventually made public, this typically only occurs after the most interesting science has already been performed). This then presents a very great challenge concerning cosmology in Australia: how can we build upon our heritage in this area by identifying funding models to gain access to such datasets?

- The highest-priority datasets we may be interested in accessing include **LSST (for imaging)** and **at least one of the new generation of instruments for wide-field multi-object spectroscopy.** For the latter, **VISTA/4MOST** is a good possibility (because it is southern, and especially if Australia becomes part of ESO), but DESI (at the KPNO) and PFS (on Subaru) are interesting alternatives. There remains an outstanding opportunity in *uniting southern hemisphere imaging from KiDS, DES, LSST, Skymapper and VHS with spectroscopic follow-up from the AAT, TAIPAN, and perhaps new telescopes.* Spectroscopy is urgently required for all sorts of reasons, including cross-correlation of lensing and redshift-space distortion and photometric-redshift calibration.
- There are no easy answers to the funding problem, but one partial possibility is to *leverage access to international cosmological surveys through "in kind" expertise of our national observatories.* The prime example here is how the AAT, and AAO instrumentation capability, has given us opportunities to become involved in DES, DESI and 4MOST – such as the current OzDES survey. A challenge here is that our "buy-in" in this mode can fall short of full membership, which is highly problematic regarding the data access issue. Perhaps a large national collaboration could seek membership of LSST.
- Much will depend on whether Australia joins ESO, the current priority of our optical instrumentation program. An interesting fallback option if this plan is unsuccessful would be to collaborate with some of the other GMT partners who don't have 8m-class access (e.g. Chicago and Korea) to build a third Magellan telescope at Las Campanas. This telescope would be optimised to do things the current Magellan telescopes are not, such as wide-field imaging and spectroscopy, and the intent would be to use this as a "dowry" to join an expanded Magellan consortium, so that all the partners in Magellan and GMT would have access to all three Magellans and GMT - our own "mini-ESO". The funding required for $\sim 1/3$ of an instrumented wide-field Magellan would be up to \$50M. This could potentially provide a uniquely powerful cosmology tool for big surveys in the LSST era.

- The future of large-scale radio projects seems more secure. The **Square Kilometre Array, including its pathfinders** is the foremost opportunity and challenge for many areas of Australian astronomy, including cosmology, where (at high frequencies) it can contribute to peculiar velocity measurements, HI intensity mapping for BAOs/RSD, cosmic magnification and gravitational lensing, and (at low frequencies) it can continue to build understanding of the EoR. It is essential for cosmologists to remain engaged with the SKA program and ensure that its science case not only remains competitive over the long lead-up time, but is also reflected in the engineering design (e.g. the requirements of intensity mapping).
- The **TAIPAN project** and **Skymapper Telescope** are Australian-led projects to contribute new cosmological measurements. They provide secure possibilities of good scientific outcomes, and it will be important to support these projects at a level adequate to achieve these outcomes. Skymapper imaging could also be important for TAIPAN target selection.
- **Continuing 8-m class telescope access** is crucial for a number of cosmological areas, for example work in measuring fundamental constants such as the fine-structure constant.
- In the area of **cosmological simulations** we need to continue to seek access to improved infrastructure to be competitive with international groups, and build long-term expertise. Our

existing facilities have allowed us to build a profile in the field, but are not sufficient for competitive "grand challenge" projects. Larger blocks of time need to be opened up on national facilities for established collaborations to develop large computational programs (in a similar manner to the large survey programs that are supported on our national observational facilities). A natural area to develop is simulations of alternative cosmological models. In this area, we need to build career paths for computational, data or information scientists in an analogous manner to instrument scientists.

- In the area of **cosmological theory** we emphasize that many of the opportunities produced by obtaining large cosmological datasets would be wasted if our community fails to develop, in parallel, the tools for cosmological model fitting and selection (for example, in the field of alternative models of gravity).

- In terms of **dark matter research,** we can further strengthen collaboration with particle physics.

- We can continue to improve on the **international dissemination of our data (observational or theoretical)**. Our databases and project websites (with some notable exceptions) can lag behind international competition.

- The final item we wish to emphasize, which applies across all fields, is that the community should continue to lobby for **improved career paths for early-career and mid-career researchers.** Astronomy has been very successful in recent years in several attractive funding schemes, but those may currently be in decline, and the "follow-through" to longer-term positions seems as hard as ever. Having recruited so many good young researchers to Australia, including in the area of cosmology, there is a big risk of us losing their skills in the next few years.

Appendix 5

The Australian Astronomy Decadal Plan 2016-2025: Cosmology and galaxies (Theoretical Astrophysics)

Theory subworking group members:
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1. Provide report on progress made against objectives of the previous Decadal Plan

1.1 Analytic galaxy formation

There was no explicit focus on theory, including semi-analytic galaxy formation modelling, in the previous Decadal Plan. However, the following key scientific themes were identified by Working Group 2.1 (Cosmology and the high Redshift Universe):

- Gas physics, specifically how gas is accreted, converted into stars and expelled by galaxies and black holes.
- The co-evolution of black holes and galaxies, and feedback effects (both stellar and AGN) on star formation.
- Morphology and luminosity distribution of galaxies, including environmental effects.

To address these, the plan also identified two distinct modes of science: (i) The survey approach, to quantify the classes, components (bulge, disk, halo etc) and constituents (stars, gas, dust, plasma etc.) of galaxies over a wide range in redshift. (ii) detailed dissection of representative case studies, to improve our understanding of the specific physical processes at work.

At the time of writing (2006), semi-analytic models generally were yet to popularise the role of BH feedback in shaping the bright end of the galaxy luminosity function, and the observed bimodality of stellar population ages in the local Universe. In the Australian context, the semi-analytic modelling community was relatively small. Strong observational constraints were available mostly only at $z < 1$, and mostly focused on the stellar properties (luminosities, broadband colours) of galaxies.

Since then, the pivotal role of AGN feedback has been widely recognised (e.g. the Croton et al. 2006 and Bower et al. 2006 papers have > 2600 citations between them), and with it semi-analytic models more broadly. An ADS query for refereed publications with any of ABUNDANCE MATCHING; HOD; SEMI ANALYTIC; SEMI-ANALYTIC in either title or abstract yields 366 publications in the period 2000-2005, and double this number (725) in the period 2006-2012.

Various Australian groups, most notably at ANU (Sutherland & Bicknell 2007, Wagner & Bicknell 2012), have begun considering the effects of a realistic multi-phase ISM on the efficiency of the feedback process. This marks an important point in the evolution of semi-analytic models. The semi-analytic models now also routinely predict gas properties of galaxies in additional to their stellar properties (Power et al. 2010), and data exists to constrain these as far back as the epoch of peak AGN and star formation activity (z$\sim$1-2) and beyond. Finally (and perhaps most importantly), the number of researchers working in semi-analytics in Australia has increased significantly, with new groups established at Swinburne, UWA and Melbourne, and several individual researchers distributed at other locations.

1.2 Computational modeling of galaxy formation and evolution

There were no specific plans on computational modeling of galaxy formation and evolution outlined in the previous Decadal Plane. However, a number of key problems and challenges for theorists were suggested in the previous Decadal Plan for Cosmology and High Redshift Universe. These include (i) modeling the ISM of galaxies (e.g., supernova feedback effects and AGN jets), (ii) galaxy evolution in clusters, (iii) origin of radio galaxies, (iv) stellar populations of galaxies with different types, (v) evolution of neutral and molecular hydrogen in galaxies, and (vi) the formation and evolution of local galaxies. Among these, Australian theorists have contributed to the progress in the following specific areas:

- **Gas outflow through interaction between AGN jets and ISM:** High-resolution 3D computational simulations of interaction between AGN jets and two-phase ISM have been used to understand the physical conditions of gas outflow from ISM in galaxies with AGN jets.

- **Self-consistent modeling of cold gas and dust:** A new simulation code has been developed for predicting neutral and molecular hydrogen, gas-phase metals, and dust contents of galaxies in a fully self-consistent manner. The simulation results have been compared with the latest observations from Spitzer and Herschel.

- **Galaxy transformation in different environments:** New high-resolution collisionless simulations on dynamical evolution of dwarf galaxies in clusters have added new knowledge to the origin of ultra-compact dwarfs, which were discovered by Australian astronomers in the 2dF survey. Also, a major physical mechanism for morphological transformation from spirals into S0s has been proposed based on new chemodynamical simulations of galaxy formation and evolution.
- **Star cluster formation and evolution in a CDM cosmology:** Dynamical evolution of star clusters in a fixed dark matter potential predicted from CDM models was first investigated by using a modified Nbody6 code. The physical connection between physical properties of globular clusters (GCs) and those of galaxies has been simulated by cosmological simulations with GC formation models.
- **Neutral hydrogen in local and distant galaxies:** Very high-resolution cosmological hydrodynamical simulations of galaxy formation have predicted physical properties of neutral hydrogen in galaxies, which will be compared with future Australian ASKAP survey.

1.3 Reionization and first stars

Previously, the theoretical work on reionization in Australia was mainly based on individual theorists. With theoretical projects and simulations becoming larger in scale requiring a broader range of technical expertise and manpower to extract science from large volumes of simulation outputs, there are bigger theoretical groups within universities collectively working towards bigger theoretical and simulation projects. Big groups of technical expertise helps in performing large scale more generic simulations which has more value than the sum of its parts, for example, Wyithe's DRAGONS project and its addons. Some of the research groups working on the theory of reionization and first stars in Australia are - Wyithe's group (reionization), Power's group (supermassive black hole formation), Heger's group (first stars), MWA Reionization theory based different parts of the country.

1.4 Gravitational wave

With respect to the previous decadal plan there have been three major advances and one clear setup in the area of gravitational waves. The first major advance is that Pulsar Timing Arrays (PTAs) are now a major part of gravitational wave detection efforts. The Parkes Pulsar Timing Array (PPTA) project is currently producing World-leading data sets that are already being used to constrain models of galaxy formation. The PPTA project is a member of the International Pulsar Timing Array and a member of the Gravitational Wave International Committee. The second major advance is that, even though there was only a fleeting mention of the possibility of the SKA being useful for GW detection in the previous plan, PTAs are now a large scale international effort and are main science drivers for future telescopes such as MeerKAT, FAST and the SKA. For all this research, the PPTA team has obtained significant recent funding from the ARC and has continued to publish a significant number of science papers. The third major advance has been the development of squeezed light techniques for LIGO, a technique that will allow significant instrumental improvements and in which Australia plays a leading role, mainly at the ANU and in WA.

The setback has been that the previous plan sets the construction of a ground-based interferometer (GW detector) in Western Australia. However, Australia recently declined to invest in setting up one of the LIGO interferometers in WA and the system will now be built in India. Australia's involvement in the LIGO project remains very strong (50+ members making it one of the largest communities in Australia), both through instrumental advances (UWA, ANU, CSIRO and Adelaide) and theoretical work (Wen, Coward, Danilishin and Burman at UWA, Melatos at Melbourne, Scott at ANU, Levin and Galloway at Monash). Efforts are now geared towards instrumentation for next generation instruments, as well as the data analysis pipelines and theoretical modelling that will be required during the era advanced interferometric detectors starting in 2015. In fact the promise of multi-messenger observations has been embraced by a large number of facilities in Australia (e.g. AAT, SKA Pathfinder, MWA, Zadko) as evidenced through MoUs agreed with the LIGO /Virgo Consortium.

1.5 HPC

Theoretical astrophysics research in Australia depends on national high-performance computing (HPC) facilities. The previous Decadal Plan noted that (i) the development of computational infrastructure within universities should be encouraged and (ii) supercomputing centre (e.g. AC3 and VPAC) should be maintained and expanded for productive research. On this regard, Australian theoretical astrophysics community achieved the followings outcomes.

- **New construction of gSTAR:** This GPU-based cluster is a new supercomputer dedicated to astrophysical simulations and astronomy-related research (e.g., 3D visualization). This cluster hosted by Centre for Astrophysics & Supercomputing has been operated as a national facility since 2011. The construction of gSTAR was made possible thanks to funding provided by an an Education Investment Fund (EIF) grant obtained in co-operation with Astronomy Australia Limited (AAL). About 20 referred papers based on the results of gSTAR simulations of galaxy evolution, gravitational lensing, and star cluster evolution have been published in 2011-2013. This is a clear indication that GPU clusters are becoming a fundamental tool for computational studies of galaxies and star clusters.

- **Productive numerical studies based on supercomputers:** A growing number of Australian astrophysicists have started using new supercomputing facilities, such as NCI and iVEC, for their computational studies of large-scale structure formation, evolution of cold gas in galaxies, galactic dynamics, and supernova explosions.

Some of these studies have strong collaborative links with Australian observational projects (e.g., WiggleZ) and thus produced a significant number of papers.

1.6 ANITA

ANITA exists to:

- support development of the theoretical astrophysics community in Australia by facilitating communication and collaboration between theorists, and provide a focus for the community;
- raise the national profile of theoretical astrophysics, and raise the international profile of Australian theoretical astrophysics; and
- promote linkage with the national astronomical community by assisting in the theoretical interpretation of observations, provide motivation for new observational programs, and increase scientific return from national investment in observational infrastructure.

There were no ANITA-specific objectives in the last decadal plan. Rather, the plan focused on theory's role in scientific discovery and education. ANITA has played an active roll in both these areas over the last several years.

ANITA runs an annual workshop where theorists (especially young theorists) showcase their work. It also runs an annual summer school on differing topics. These provide an excellent training opportunity for astronomers to learn new skills, mostly focused on theory and software/HPC. ANITA has additionally begun running a series of online lectures targeted at Masters and early-PhD students to prepare them for their future PhD studies.

2. Provide a stock take of current or future capabilities/resources in the area

2.1 Analytic galaxy formation

Australia now has access to a number of research groups and tenured researchers with expertise in a variety of modelling techniques (e.g. HOD, semi-analytic and semi-empirical). Newly commissioned supercomputing facilities such as Green II and the Pawsey Centre are also now providing the raw computing power needed to fully probe the often complex parameter spaces of these models. Furthermore, the increased availability of graphics processing units (GPUs) brought by these facilities is a resource which future models will be able to harness towards this goal.

Of key importance to future galaxy formation modelling is the proliferation of spatially resolved, multi-wavelength and multi-indicator data made available through instruments such as SAMI, HECTOR, WiFeS, ATCA and ASKAP. This new data will provide an excellent opportunity to parameterize physical processes about which our current knowledge is lacking (e.g. feedback), and to investigate them by comparing to hydrodynamical/MHD simulations. Much of this spatially resolved, multi-wavelength data was unavailable 10 years ago and hence we now have the opportunity for a key paradigm shift in the advancement of galaxy evolution models.

As well as the new availability of spatially resolved data, upcoming and current survey programs such as Taipan, WALLABY & EMU will provide larger, more complete datasets with which to train current models. Furthermore, telescopes such as the ELT, JWST and SKA pathfinders will provide important observations and constraints at high redshifts where our detailed knowledge is most lacking.

These new advances in data volumes, quality and detail will require existing established models to be updated, or in some cases, the creation of entirely new ones. In particular, models which can predict/replicate the properties of high-redshift galaxies and which can provide spatial resolved information will be key.

2.2 Computational modeling of galaxy formation and evolution

Currently Australian theorists have access to CPU- and GPU-based supercomputing facilities such as Raijin at NCI, gSTAR (GPU-based), Epic and Fornax (GPU-based) at iVEC. The results of numerical simulations based on these supercomputers are being compared with those of Australian-led observational projects on galaxy evolution, e.g., SAMI survey. New simulations codes that can be run on the new GPU-based clusters are being developed by a few experts in a number of areas (e.g., star cluster evolution, galactic dynamics, and gravitational lensing).

2.3 Reionization and first stars

Observations - HST observations (first galaxies and stars), JWST (first galaxies and stars), MWA (reionization power spectrum), SKA (topography of reionization, earliest quasars), DEcam (bright galaxies around the epoch of reionization at z=6-7)

Ongoing and future simulations and semi-analytics - Semi-analytic coupling of galaxy properties to Nbody codes and tracking bubble structure through the IGM (DRAGONS, Wyithe, Poole, Mutch), radiative transfer post processing of hydrodynamical simulations for reionization (Duffy), Studying the role of dark matter annihilation on reionization and especially 21 cm signal (Mack), predicting 21 cm from reionization semi-analytic models for MWA and SKA (Kim), modelling properties of early universe galaxies using high resolution hydrodynamical simulations (Tescari, Duffy), high resolution reionization simulations of H and He (Jeeson-Daniel), modelling Lyman Alpha Emitter population around reionization using radiative hydrodynamic simulation (Jeeson-Daniel), PopIII star formation, evolution and spectral properties (Heger), Formation and evolution of the first black holes and in correlation with galaxy properties (Power).

Another potentially useful current/future capabilities would be in the attempts to model the SAMI galaxies using extremely high resolution simulations for individual galaxies to model spatially resolved line emission in galaxies. which would help also in understanding the escape fraction of ionizing photons from galaxies in more detail as the escape fraction is one of the major uncertainties in reionization models at the moment (SAMI theory group).

2.4 Gravitational wave

As mentioned above Australia is playing a leading role in the search for GWs with PTAs at the Parks Pulsar Timing Array. The Australian consortium has, at the moment, the best sensitivity and has managed to place significant constraints on the parameter space, already constraining some of the emission scenarios. They are thus the only at the moment to have produces results of true astrophysical significance. Furthermore they have secured funding from the ARC for personnel and developments. Alongside this significant strength of the Australian community there is a weakness due to the lack of strong ties with the theory community. While the North American NanoGrav consortium is investing on building strong links with the theory and source modelling community (see recent hires at West Virginia) and strong ties already exist in Europe, for example between the Max Planck institutes for Radio Astronomy and that for Gravitational Physics, such a strong connection is missing in Australia. Nevertheless the potential is there and ties are being built. Yuri Levin is now at Monash and is actively involved with the PPTA community, as in Linquin Wen in WA. Melatos' group in Melbourne has grown, with Paul Lasky, Bryn Haskell, and new postdocs there, and ties are starting to be built with the PTA community. There is also a strong involvement in the LIGO project. From a theory point of view the Melbourne group is one of the leading groups for theoretical modelling of neutron stars as gravitational wave sources, is strongly involved in LIGO data analysis and has a solid international reputation. Monash is involved and Duncan Galloway provides a great link between GW source modelling/ radio pulsar observations and X-ray pulsar observations. However also for this kind of work it, given the size and strength of the community, it would be beneficial to build a wider community and more co-ordinated links with the observational and instrumental groups.

2.5 HPC

The ongoing projects based on Australian supercomputers are summarized as follows:

- swinSTAR: High-resolution DM-only cosmological simulations based on CDM models for the WiggleZ dark energy survey and cosmological hydrodynamical simulations of galactic cold gas.
- gSTAR: Dynamical evolution of star clusters, gravitational lensing, and chemodynamical simulations of galaxy evolution in groups, dynamical interaction between the Galaxy and its satellite galaxies.
- Fornax: Formation and evolution of molecular hydrogen and dust in dwarf galaxies at low and high redshifts, formation of globular clusters in galaxies.
- Epic: Structures and abundances of dark matter subhalos in cold and warm dark matter models, interaction of supernova explosions and ISM in the Large Magellanic Cloud,and dynamical evolution of the Galactic satellite galaxies.
- Raijin: Hydrodynamical interaction between AGN jets and ISM in galaxies.

2.6 ANITA

The ANITA community is strong and growing. Each year they undertake new initiatives. We expect this to continue into the next decade. In 2012 ANITA prepared "A Strategic Plan for Theoretical Astrophysics 2012-2015", which took a stock-take of our current state and proposed three priorities for the future. These were:

- Priority 1: The theory community should pursue the development of a named Theory Postdoctoral Fellowship program to attract the best and brightest young international theorists to Australian shores, and retain the best already in Australia.
- Priority 2: The theory community should explore building a National Centre for Theoretical Astrophysics, which could be a virtual institute comprised of numerous distributed theory groups from around the nation, and sharing many common resources and funding.

- Priority 3: The theory community should work to increase active linkages with the observational community on projects of common interest, especially those that enhance theory's influence in priority areas of Australian science.

Clearly these are ambitious goals, and the groundwork to realise the first two in particular will take many years to prepare (if they are at all possible). The plan also laid out a number of secondary priorities, which are the current focus of the ANITA steering committee:

- ANITA should engage in the development of theory related student education to better equip pre and current PhD students for the rigors of research.
- ANITA should consider an early career researcher mentoring program for junior theorists and include this as part of its yearly mission.
- ANITA should encourage interaction between local theory groups through the sharing of colloquium speakers, visitor and student exchanges, and joint organisation of local workshops.
- Where appropriate, Australian theory should explore opportunities to form closer ties with our Asian counterparts given the growing importance of Asia to Australia's broader national interests.
- Australian theory groups should be encouraged to seek out international projects for collaboration, to build linkages and create longterm opportunities.
- ANITA should work to raise awareness of gender and work/life balance issues, and coordinate with the Women in Astronomy Chapter of the ASA in this task.

3. Identify any new national or international opportunities/requirements in the area over the period 2016-25

3.1 Analytic galaxy formation

In order to maximise the impact and usefulness of these new and updated models, it will be necessary to provide their data products to the community in a readily accessible form. As such, an important development for the field of galaxy formation modelling in Australia is the release of the Theoretical Astrophysical Observatory (TAO). This virtual observatory allows for the archiving and distribution of theoretical models. However, most importantly, it also facilitates the direct comparison of model results with observational data, thus reducing the barrier for those with no relevant direct experience to utilise state-of-the-art models.

3.2 Computational modeling of galaxy formation and evolution

The development of faster supercomputers is going very rapidly, and more and more astronomers are getting familiar with necessary skills to run their models on GPU machines these days. Recent observational studies by Spitzer, Herschel, ALMA, and Plank have provided new vital information on the origin of local and distant galaxies, and future very large telescopes, such as ELT and SKA, will also significantly progress our understanding of galaxy formation and evolution. Considering these, the following new opportunities can be identified:

- Usage of Exca-scale supercomputers: Very sophisticated and realistic modeling of ISM, star cluster dynamics, various feedback effects will be done thanks to the new development of Exca-scale supercomputers. A number of new simulations codes will need to be developed by Australian theorists so that their models can be run efficiently on these new ultra-fast supercomputers.
- Extensive comparison between multi-wavelength observations and numerical simulations: Observational studies of galaxies by ELT, ALMA, SKA, and future infrared space-telescopes will provide a comprehensive set of multi-wavelength data that can be compared with the corresponding theoretical predictions for better understanding galaxy formation and evolution. This means that future numerical simulations of galaxy formation and evolution need to include not only the standard stellar and gas dynamics but also the evolution of dust composition and abundances in a self-consistent manner.

3.3 Reionization and first stars

Considering there is going to be a lot of observations of 21 cm lines using MWA, ASKAP and SKA, especially SKA for the coming decade, to truly use these amazing telescope a lot of et needs to go into the detailed modelling of these observations using high resolution large scale reionization simulations. The push needs to be going in the direction of investing in eventually developing large scale high resolution, cosmological, magneto-hydrodynamical radiative transfer simulations which are coupled to each other. There are a large number of codes which do dient parts of this already in Australia. But being a small group, ets must go to strengthening these techniques. Also needed are researchers working on theoretical questions which look into both improving these methods and posing new questions.

3.4 Gravitational wave

Given the stage at which gravitational wave detectors are (both LIGO and PTAs), it is practically inevitable that there will be a first detection during the period covered by the next decadal plan. This will open up a new era of GW astronomy. It will thus be crucial to have both GW source modelling and GW data analysis (GW 'observers') groups. Many North American institutions are making new hires to start GW groups and Europe is investing in compact object modelling and interdisciplinary projects. Furthermore the eLISA mission has been selected by the European Space agency. Australia has a strong involvement in GW projects from an instrumental point of view, but could benefit from a more co-ordinated community with a stronger drive and visibility.

3.5 HPC

The Raijin supercomputer at NCI is the only Peta-Flops machine that Australian theoretics can use at the moment, though the Pawsey centre will host another one soon. Although it is unclear when exactly Exca-Flops supercomputers will be developed for use, it would be no double that Australian theorist will be using one of the supercomputers by 2025. It is currently unclear whether GPU or Xion Phi MIC (Many Integrated Core) cluster will be a major one for computational science in the period 2016-2015. However, Australian theorists will take advantages of these new development of very fast GPU/MIC machines in future. Under these HPC circumstances, the following opportunities and requirements can be identified for the period 2016-2025:

- **Construction of new astronomy-dedicated cluster:** The maximum calculation speed of the present gSTAR is around 500 Tflops, which would be too slow in comparison with future GPU clusters. Therefore, it will be necessary to construct a much faster gSTAR for Australian astronomers in 2016-2019. At this stage, it is unclear whether the future new gSTAR is based on GPU or intel MIC or other new-types of acceleration boards.

- **Access to Exca-scale supercomputers:** It is essential for Australian theorists using high-resolution cosmological simulations to have enough access to Exca-scale supercomputers in Australian and overseas. It is, however, unclear whether and when Australia will have such a Exca-scale machine in future.

3.6 ANITA

Not really relevant for ANITA, other than to say ANITA will continue to support its members through the above primary and secondary priorities.

4. Suggest strategies and the resourcing levels required to maximise these new opportunities

4.1 Analytic galaxy formation

Semi-analytic modelers should continue to work closely with observers. This will yield a new generation of models with less free parameters and more physical insights (e.g. spatially resolved galaxy models). It will also assist observers with interpretation of data, including subtle selection effects. TAO will be a valuable resource in this regard. These collaborations can be additionally strengthened by inclusion of dedicated theoreticians in large survey teams (we note that many groups already do this), and a further increase in the number of Australian theoreticians. Theoretical work must be recognised as a key component at every stage of the observing lifecycle, starting with survey / instrument design and ending with scientific interpretation of results.

Collaborations between Australian theoreticians at different institutions need to continue developing. This is especially important in light of the recent increase in the number of theory groups in Australia. Stronger connections between semi-analytic and hydrodynamical/MHD groups will allow us to go beyond a rudimentary understanding of galaxies to constraining physical mechanisms on a population basis.

4.2 Computational modeling of galaxy formation and evolution

A number of new physical effects that were not included in previous simulations will be able to be included in future simulations of galaxy formation and evolution based on Exca-scale supercomputers and large astronomy-dedicated GPU clusters. Furthermore, such computational power will enable theorists to investigate the formation of stars and star clusters in galaxies in a very realistic way so that the dynamical evolution of small star clusters can be self-consistently modeled in galaxy-scale simulations. Considering these, the following strategies will be required:

- **Collaboration between stellar astrophysicists, galaxy astronomers, and HPC experts:** Conversion from neutral to molecular hydrogen, star formation in giant molecular clouds, time evolution of metals ejected from massive and AGB stars, and dynamical evolution of galaxies can be much more self-consistently included in future Exca-scale simulations. However, the bottleneck of these simulation works is that a large amount of time should be spent on the code development process for massively parallelized simulations. In order to perforce these simulations of galaxy formation and evolution, these experts from the three different areas will need to work closely together. Predicting chemical evolution of galaxies and IGM at different redshifts will require such collaboration between extragalactic, HPC, and stellar astronomers.
- **Incorporation of new physical processes into simulations:** The present sim-

ulations of galaxy formation and evolution are far from realistic in many points, which ends up with less predictive power of simulations. Australian theorists will need to construct a much more sophisticated model of galaxy formation and evolution (e.g., really realist ISM model) by taking advantages of these future supercomputer development and by incorporating missing physical processes in previous works into simulations. It would be interesting to include the role of comic ray in the numerical simulations on the evolution of ISM of galaxies.

- **Performance of multi-scale simulations:** The vast majority of stars are formed as clusters of stars in galaxies and the evolution of star clusters is often investigated by simulation codes that can properly include two-body relaxation effects (e.g., NBODY 6). Future galaxy-scale simulations based on Exca-scale supercomputers will be able to incorporate properly, for the first time, the formation and evolution of star clusters that are fundamental building blocks of galaxies, though this is an extreme challenge in galaxy-scale simulations.

- **Taking an initiative in large observational projects:** Theoretical predictions from these high-resolution simulations will be used to make a strong scientific case in future large observational projects (e.g., SKA). The measurements of 3D motions of local galaxies through high-precession astrometry and the redshift evolution of neutral hydrogen in galaxies will be examples of research areas where theorists will be able to play a leading role in the SKA project.

4.3 Reionization and first stars

There are a lot of computing resources in the country but not enough people to use it. Also, simulation code development is still not a strong hold of Australia. Therefore, along with nurturing current strengths, new skills like new code development should become a part of the strategy for long term scientific opportunities.

4.4 Gravitational wave

Given what is described above, it would be beneficial to build a closer community with a stronger involvement of the theory groups. Clearly more people working on GW theory would be needed, but a closer knit community would help to present a united front and possibly lead to easier access to funds and more constant staffing levels (making it easier, for example, to take responsibility for various tasks in the LIGO community).

4.5 HPC

A large amount of money (an order of ∼\$1M) will be necessary for the new building of astronomy-dedicated supercomputers like gSTAR. Furthermore, it would be very time-consuming for some theorists to develop a new simulation code that can be run on the massively paralleled GPU (or CPU or hybrid) clusters. The following strategies and resourcing levels are required to maximize the new HPC opportunities in the period 2016-2025:

- Financial support for the new astronomy-dedicated clusters: The funding from AAL was an essential part of the building of the present gSTAR and this will be true for the new cluster. The present host institution for gSTAR is Swinburne University, however, the next possible host for the new cluster should be discussed.
- Fostering code-developer: The previous Decadal Plan of Theoretical Astrophysics already noted that code-developer are the theory analogue of instrument-builders and are somewhat underappreciated. Currently some individual astronomers by themselves are updating their original codes for new GPU clusters and teaching how to write a new simulation code for their students. However, these efforts will be possibly made both by ANITA and by individual astronomers.

4.6 ANITA

ANITA has no funding in of itself, but members of the ANITA community are proactive in their involvement in all large current and upcoming national projects, including MWA, ASKAP, SAMI, and TAIPAN. Through their involvement in such projects theorists are looking to increase their scientific, infrastructure, and employment opportunities.