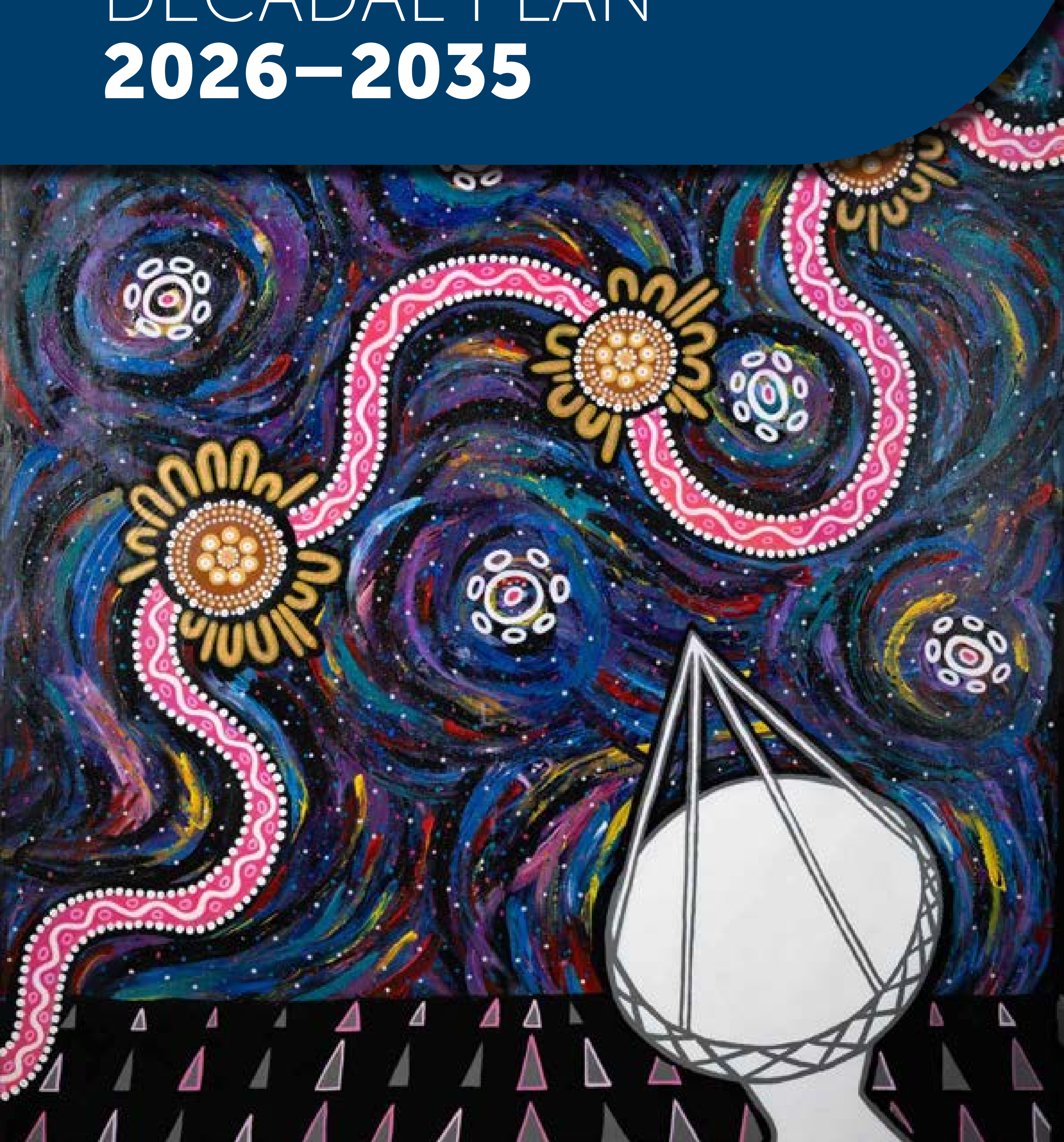
Australian Academy of Science

NATIONAL COMMITTEE FOR
ASTRONOMY

ASTRONOMY DECADAL PLAN **2026–2035**



Cover page artwork:
***Seven Sisters*, 2024**
Noeleen Hamlett, Wajarri Yamaji

"The Seven Sisters in our night sky guiding us in our search with the telescopes and Christmas tree-shaped antennas. Leading us into a better future, as we come together at our meeting places, taking a big step forward."

This artwork is part of the Cosmic Echoes: A Shared Sky Indigenous Art Exhibition, which is an SKAO initiative, in collaboration with South African Radio Astronomy Observatory, CSIRO and the Wajarri Yamaji Aboriginal Corporation. The Wajarri Yamaji are the Traditional Owners and Native Title Holders of Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radioastronomy Observatory, where the SKA-Low telescope is being built. Noeleen's artwork includes representations of antennas from the SKAO's SKA-Low telescope as well as a dish-shaped antenna of CSIRO's ASKAP radio telescope in the foreground.

Noeleen Hamlett bio:
I grew up in the small town of Mullewa on Wajarri Country in Western Australia. As a child I was inspired by my mum and brother who carved emu eggs. I have 8 daughters and 15 grandchildren and currently live in Perth where I studied Visual Arts. As a professional Aboriginal artist, my art and research practice often combine traditional practice with unconventional techniques using other mediums that transform the image to a narrative of 'Memory and Land'. This combination explores how conflicting mediums work together, creating a unique visual language and representing historical stories as part of an ongoing project. A key intention is to invite the viewer to a closer understanding of Wajarri's unique culture through exploring land from topographical views of location. I will always have a passion for my culture and Country.

Image credit: ESO/S. Brunier

ACKNOWLEDGEMENT OF COUNTRY

The Australian Academy of Science acknowledges and pays respects to the Traditional Owners of all the lands on which the Academy operates, and where its Fellows and employees live and work. The Academy recognises Australia's Aboriginal and Torres Strait Islander peoples as the first innovators and scientists of this land and honour their enduring connection to Country, from which we are committed to learn. We pay our respects to, and recognise the cultural authority of, their Elders past and present.

EDITORIAL NOTE

This decadal plan is the culmination of over two year's effort by the Australian astronomical community. The plan is based on the reports of 13 working groups, comprising more than 250 astronomers, and an extensive survey of more than 550 members of the astronomy community including staff and students from more than 30 Australian institutions across all states and the ACT. The working group reports are published electronically as part of the Decadal plan at the following address: **here**. The Decadal Plan was edited for the National Committee for Astronomy by an editorial board that included Professor Virginia Kilborn (Chair), Professor Sarah Brough (Deputy Chair), Professor Tamara Davis AM FAA, Professor Michael Ireland, Professor Chris Power, and Professor Cathryn Trott.

We gratefully acknowledge the financial support provided by CSIRO, Australia's national science agency, and funding from a bequest by the late Professor Michael Dopita AM FAA to the Australian Academy of Science, which supported the development of this Astronomy Decadal Plan.

AUSTRALIAN ACADEMY OF SCIENCE'S NATIONAL COMMITTEE FOR ASTRONOMY

Thank you to the Chair and members of the Astronomy Decadal Plan editorial board, who have worked tirelessly to bring this report to publication. Thanks also extend to members of the Working Groups, who have all contributed significantly to its development, and to the members of the astronomy community who contributed, whether that be by hosting or attending a consultation workshop, providing input or by contributing photos to help this plan truly reflect the breadth of Australian astronomy.

ACKNOWLEDGEMENTS

We would like to acknowledge the work of the Australian Academy of Science's National Committees for Science team. Project management and production of this report was provided by the Australian Academy of Science. Contributing staff members including Swastika Devi, Meaghan Dzundza, Nancy Pritchard, and Chris Anderson are gratefully acknowledged alongside members of the National Committee for Astronomy and members of the astronomical community who provided feedback on the decadal plan.

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ACRONYMS AND ABBREVIATIONS

2dF	Two Degree Field – a robotic positioning instrument used on the AAT.
4MOST	4-metre Multi-Object Spectroscopic Telescope – a spectroscopic instrument on the VISTA telescope for surveying a significant portion of the southern sky.
AAL	Astronomy Australia Ltd – a non-profit company whose members are Australian universities and research organisations with significant astronomical research capability.
AAO	Australian Astronomical Observatory (formerly Anglo-Australian Observatory), operated as Australia's national optical/IR astronomy facility until 2018, through the AAT and instrumentation headquarters in Sydney.
AAT	Anglo-Australian Telescope – a 3.9-metre telescope at Siding Spring Observatory, operated by ANU.
ADACS	Astronomy Data And Computing Services
AIATSIS	Australian Institute of Aboriginal and Torres Strait Islander Studies
AIP	Australian Institute of Physics
ALMA	Atacama Large Millimeter/submillimeter Array – an interferometer of 66 radio telescopes in the Atacama Desert of northern Chile.
ANFF	Australian National Fabrication Facility Ltd – provides access to cutting-edge micro- and nano-fabrication equipment.
ANU	Australian National University
ARC	Australian Research Council
ASA	Astronomical Society of Australia
ASKAP	Australian Square Kilometre Array Pathfinder
ASTRO 3D	Centre for All-Sky Astrophysics in 3 Dimensions – a seven-year $40 million Centre of Excellence project funded by the ARC from 2017 to December 2024.
ASVO	All-Sky Virtual Observatory
ATCA	Australia Telescope Compact Array – a radio telescope operated by CSIRO as part of the ATNF on Gomeroi Country near Narrabri, NSW.
ATNF	Australia Telescope National Facility – collective name for several radio astronomy observatories, telescopes and data archives operated by CSIRO. Includes ASKAP; ATCA; Murriyang, the CSIRO Parkes radio telescope; Inyarrimanha Ilgari Bundara, the CSIRO's Murchison Radio-astronomy Observatory; LBA; Mopra.
ATSE	Australian Academy of Technological Sciences and Engineering
AusSRC	Australian SKA Regional Centre – part of a collaborative network of SKA regional centres that will transfer data from SKA-Low in WA to the global scientific community.
AWLAI	Access to World Leading Astronomy Infrastructure – a program arising from the 2017–18 federal budget that allowed Australia to establish a 10-year strategic partnership with ESO.

BIGCAT	Broadband Integrated GPU Correlator for ATCA – a computational instrumentation project to upgrade the 'electronic brain' of ATCA.
BlueMUSE	An integral field spectrograph instrument for ESO's VLT; extending the capabilities of MUSE.
CAASTRO	ARC Centre of Excellence for All-sky Astrophysics – funded 2011–2018 capitalising on widefield experiments.
CASDA	CSIRO ASKAP Science Data Archive
CoE	ARC Centre of Excellence
CPS	Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference – part of the IAU.
CPU	Central processing unit
CryoPAF	Cryogenic phased array feed – next-generation, wide-field-of-view survey instrument for the Murriyang telescope. It has been designed to discover pulsars, FRBs, redshifted H I, and more.
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTAO	Cherenkov Telescope Array Observatory – a project to build ground-based gamma-ray instruments at two sites: the Spanish island of La Palma and the Atacama Desert in Chile.
DECRA	ARC Discovery Early Career Research Award
DESI	Dark Energy Spectroscopic Instrument – an instrument for conducting surveys of distant galaxies, retrofitted onto the Mayall Telescope in Arizona, US.
ELT	Extremely Large Telescope – an optical/IR 39.3-metre telescope currently under construction by ESO, located in the Atacama Desert of northern Chile.
EoR	Epoch of Reionisation – a crucial era in the early Universe, marked by a switch in the intergalactic medium from neutral hydrogen to ions, triggered by energetic photons emitted by the first stars and galaxies.
ERIS	Enhanced Resolution Imager and Spectrograph – an ESO instrument for VLT, useful for probing distant galaxies, the galactic centre, our solar system and exoplanets.
ESA	European Space Agency
ESO	European Southern Observatory (European Organisation for Astronomical Research in the Southern Hemisphere), an intergovermental organisation
ESPRESSO	Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations – an ESO instrument for VLT, used for searching for Earth-sized rocky exoplanets.
FAIR	Findable, accessible, interoperable, reusable – principles for data.
FAST	Five-hundred-meter Aperture Spherical Telescope – the world's largest single-dish radio telescope located in China.
FORS2	FOcal Reducer/low dispersion Spectrograph 2 – an ESO instrument for VLT, described as the observatory's 'Swiss Army knife'.
FRB	Fast radio burst – extremely bright and brief flashes of radio waves originating from outside the Milky Way, caused by high-energy astrophysical processes.
GALAH	GALactic Archaeology with HERMES – a survey using the HERMES instrument on the AAT to obtain datasets for more than one million stars in the Milky Way, tracing the full history of the galaxy.
G-CLEF	GMT-Consortium Large Earth Finder – a spectrograph for the GMT.

GECKOS	Generalising Edge-on galaxies and their Chemical bimodalities, Kinematics, and Outflows out to Solar environments – a VLT program exploring the evolution of disc galaxies.
GLEAM-X	GaLactic and Extragalactic All-sky MWA survey – completely covering the southern sky, exploring our Universe in high resolution and full 'radio colour'.
GMACS	GMT Multi-object Astronomical and Cosmological Spectrograph – an instrument for the GMT.
GMagAO-X	Extreme adaptive optics for the GMT – a system for the GMT designed to enable high-contrast exoplanet imaging.
GMT	Giant Magellan Telescope – an optical/IR 25.4-metre telescope currently under construction in the Atacama Desert, Chile.
GMTIFS	Giant Magellan Telescope Integral-Field Spectrograph – one of the first instruments expected to be available when the GMT sees 'first light', designed and built by ANU. Will be able to take detailed images of the sky and obtain spectra from across a continuous region of the field of view.
GNSS	Global navigation satellite system
GPU	Graphics processing unit
GWDC	Gravitational Wave Data Centre
HARPS	High Accuracy Radial velocity Planet Searcher – an instrument attached to ESO's 3.6-metre telescope hunting for exoplanets.
HI	'H one' i.e. neutral atomic hydrogen. The H I spectral line is observed in radio astronomy and is particularly important to cosmology because it can be used to study the early Universe.
HPC	High-performance computing
HST	Hubble Space Telescope – a space telescope in low-Earth orbit, with a 2.4-metre mirror.
IAU	International Astronomical Union
ICRAR	International Centre for Radio Astronomy Research – a joint venture between Curtin University and The University of Western Australia with funding support from the Government of WA.
IR	Infrared
ICRF	International Celestial Reference Frame
(ICRF)	A cosmic map used to measure the positions and movements of objects in space
JWST	James Webb Space Telescope – a 6.5-metre telescope in space designed to conduct IR astronomy.
KAGRA	Kamioka Gravitational Wave Detector – located in Japan.
KWFI	Keck Wide-field Imager – an extremely sensitive instrument under development for the Keck telescope in Hawaii.
LAMBDA	Low-frequency Australian Megametre-Baseline Demonstrator Array – a development project by CSIRO to establish low-frequency VLBI capability in the southern hemisphere.
LBA	Long Baseline Array – a large-scale telescope arrangement that combines ATNF telescopes with other instruments around the country using VLBI.
LIEF	Linkage Infrastructure, Equipment and Facilities – an ARC grant.

LIGO	Laser Interferometer Gravitational-Wave Observatory – the two physical observatories are both in the US. Australia supports LIGO and is a member of the LIGO Scientific Collaboration.
LISA	Laser Interferometer Space Antenna – space-based gravitational-wave observatory operated by NASA, ESA, and an international consortium of scientists.
LSST	Legacy Survey of Space and Time – a planned 10-year survey of the southern sky conducted by the Vera C. Rubin Observatory.
MAGPI	Middle Ages Galaxy Properties with Integral Field Spectroscopy – a program on ESO's VLT using MUSE to give an in-depth view of galaxy evolution.
MANIFEST	Many Instrument Fibre System – a robotic positioning system for the GMT, using 'Starbug' technology developed at the AAO.
MAUVE	MUSE and ALMA Unveiling the Virgo Environment – an ESO/VLT program investigating how stars form in galaxies as they fall into the Virgo Cluster.
MAVIS	MCAO Assisted Visible Imager – an instrument being built for the ESO's VLT adaptive optics facility.
MCAO	Multi-conjugate adaptive optics – provides uniform image quality.
MOONS	Multi-Object Optical and Near-infrared Spectrograph – a VLT instrument for studying galaxy formation and evolution.
MRO	Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory, located in WA. Home to the MWA, ASKAP, and under-construction SKA-Low.
MUSE	Multi Unit Spectroscopic Explorer – a VLT instrument operating at visible wavelengths.
MWA	Murchison Widefield Array – located at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory on Wajarri Yamaji Country in WA, a precursor to the SKA telescopes.
NASA	National Aeronautics and Space Administration
NCI	National Computational Infrastructure – one of Australia's two Tier 1 high-performance data, storage and computing organisations.
NCRIS	National Collaborative Research Infrastructure Strategy
NISEP	National Indigenous Science Education Program
PAF	Phased array feed – receivers that extend the field of view of radio telescopes.
PaSD	Power and signal distribution
PLATO	PLAnetary Transits and Oscillation of stars – an ESA-led space mission focused on studying exoplanets.
QuasarSat	Quasar Satellite Technologies – an Australian start-up that provides a new way for satellites in orbit to communicate with ground stations.
SAIL	Sydney Astrophotonic Instrumentation Laboratory
SAMI	Sydney-AAO Multi-Object Integral-Field Spectrograph – an instrument on the AAT used to survey galaxies.
SAURON	Scheduling Autonomously Under Reactive Observational Needs – a tool for automated, autonomous scheduling on ASKAP.
SDA	Space domain awareness – detecting, tracking, identifying, and predicting the behaviour of objects in space including satellites and debris.
SKA	Square Kilometre Array

SKA-Low	SKA Observatory's low frequency telescope array on Wajarri Yamaji Country in Western Australia
SKA-Mid	SKA Observatory's mid frequency telescope array in the Northern Cape of South Africa.
SKAO	The SKA Observatory, a global collaboration of member and participating countries building the world's largest radio telescopes
STA	Science Technology Australia
SWGO	Southern Widefield Gamma-ray Observatory – a planned ground-based gamma-ray detector for the Atacama Desert, Chile.
STEM	Science, technology, engineering, mathematics
TESS	Transiting Exoplanet Survey Satellite – an MIT-led NASA mission discovering transiting exoplanets via an all-sky survey.
UVES	Ultraviolet and Visual Echelle Spectrograph – a high-resolution optical spectrograph for the VLT.
UWL	Ultra-Wideband Low – describes a receiver for Murriyang capable of detecting technosignature observations.
VISTA	Visible and Infrared Survey Telescope for Astronomy – a telescope operated by ESO located in Chile.
VLBI	Very long baseline interferometry – a technique that combines multiple radio telescopes spread across countries or continents to create a virtual telescope with much higher resolution.
VLT	Very Large Telescope – operated by ESO, located in Chile, consisting of four 8-metre main mirrors.
VLTI	Very Large Telescope Interferometer – an instrument that collects the light from the four individual mirrors of the VLT and combines it to create a larger 'virtual' telescope.
WAVES	Wide Area Vista Extragalactic Survey – a survey of 1.7 million galaxies planned for the VISTA telescope, studying the underlying structure of the Universe.

CSIRO's ASKAP radio telescope located at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory on Wajarri Yamaji Country is one of the instruments that makes up the Australia Telescope National Facility. Image credit: CSIRO/A. Cherney.

EXECUTIVE SUMMARY

Australian astronomy is unravelling the deepest mysteries of our cosmos and our place in it – from exoplanets to detecting gravitational waves and accelerating the hunt for dark matter.

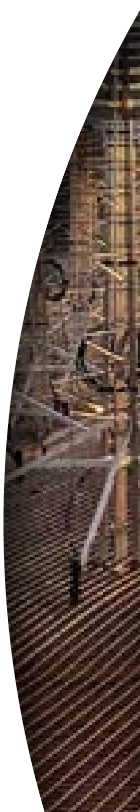
Alongside fundamental scientific discoveries, Australian instrumentation advancements, technology development, data science capabilities, and partnerships with industry are delivering value for the nation.

Astronomy education programs are shaping an in-demand, high-tech workforce contributing to the country's prosperity. Australian astronomy is addressing national priorities, including STEM education, elevating Aboriginal and Torres Strait Islander knowledge systems, and technologies that support new jobs in areas such as manufacturing.

KEY HIGHLIGHTS FROM THE LAST DECADE INCLUDE:

- Construction of the low-frequency SKA telescope (SKA-Low) commenced in 2023, and the first signals were detected in 2024.
- The Access to World Leading Astronomy Infrastructure (AWLAI) program established a strategic partnership with the European Southern Observatory (ESO), including access to the La Silla and Paranal Observatories in Chile for 10 years.
- Construction of the Australian Square Kilometre Array Pathfinder (ASKAP) was completed and science programs commenced.
- The Murchison Widefield Array (MWA) received two upgrades and reached its 10-year anniversary of science operations.
- The 3.9-metre Anglo-Australian Telescope (AAT), the largest optical telescope in Australia, moved to operations led by a consortium of universities and Astronomy Australia Ltd (AAL).
- The Australian astronomy instrumentation program is thriving, and engagement with industry expanded with concepts and methods from astronomy applied in diverse areas such as data science, medicine, satellite imaging, engineering, defence, mining, and position, navigation and timing.
- The international impact of Australian astronomy research is increasing with Australian papers being cited 2.5 times the international average, and astronomers being well represented in awards such as the Prime Minister's Prize for Science.
- The astronomy community's highly collaborative nature enabled the successful bid for two Australian Research Council (ARC) Centres of Excellence (CoE), the CoE for Astronomy in 3 Dimensions (ASTRO3D) and CoE for Gravitational Wave Discovery, (OzGrav).
- The National Indigenous Australians Agency has recognised the partnership between the Australian Government's Department of Industry, Science and Resources, CSIRO, and Wajarri Yamaji Aboriginal Corporation to enable the SKA-Low telescope project under the National Agreement on Closing the Gap.
- Measured over one career step, no gender pipeline leak is apparent from 2014 fixed-term (22% women) to 2024 continuing positions (28% women). Notably, ASTRO 3D achieved gender parity within the lifetime of their centre.

These achievements are made possible by a highly engaged astronomy community, and Australian investment in strategic international partnerships, including ESO and the SKA Observatory (SKAO). Such global collaboration is critical to maintain access to cutting-edge facilities, keep Australia at the forefront of astronomy research, and provide the greatest return to the people of Australia. Upcoming transformational facilities will revolutionise our view of the cosmos, and Australia must have a seat at the table.



This decadal plan outlines the capabilities and facilities that will be key to empowering Australian research that pushes new frontiers across four big questions:

- How is stellar and galaxy evolution interconnected across all scales?
- What is the dark Universe made of?
- How does physics work in extreme environments?
- How do planetary systems form and evolve – and are they habitable?

These complex questions require a cross-disciplinary approach, diverse techniques, high-performance computing capability, industry partnership, and international cooperation.

This plan recommends how the astronomy research community can inspire and connect with all Australians, including engaging with future scientists and boosting diversity in the sector. Building relationships with Aboriginal and Torres Strait Islander peoples is a focus, fostering connections between western science and an ancient body of astronomical observations and knowledge that has been maintained for 65,000 years. This decadal plan is the first time astronomy has focused and incorporated Aboriginal and Torres Strait Islander astronomy. This is not a 10-year process, but the start of a long-term relationship-building effort. Building on previous outreach and education efforts, it emphasises deepening relationships with Indigenous communities and respecting traditional knowledges in astronomy research.

This plan sketches the vision and priorities for Australian astronomy over the next decade (section 1). It traverses the trailblazing discoveries of the last 10 years, and discusses new frontiers waiting to be explored by science (section 2). Section 3 outlines Australia's research impact and excellence in astronomy. Sections 4–8 dive into more future-focused detail on Australia's infrastructure, instrumentation, innovation, and community. We identify nine priorities organised into three overarching themes. Implementing these priority actions will ensure Australia's homegrown research remains a world-class endeavour, where the nation benefits from excellence in fundamental science and the applications that derive from this.

SKA-Low antennas at sunrise, April 2025. Image credit:SKAO

SECURE ACCESS TO LARGE OPTICAL TELESCOPES AND ALMA

- Ensure sustainable, ongoing access to 8-metre-class telescopes, a next-generation 30-metre-class telescope, and the millimetre-wavelength Atacama Large Millimeter/submillimeter Array (ALMA) Observatory.
- Membership of ESO achieves this goal with the best potential for return on investment for Australia.

CAPITALISE ON AUSTRALIA'S ENGAGEMENT WITH THE SKAO

- Continue investment in SKAO to ensure SKA telescopes are constructed successfully and to maintain Australia's influence in international science programs.

STRENGTHEN ACCESS TO HIGH-PERFORMANCE COMPUTING, DATA AND SOFTWARE

- Computing underpins all Australian astronomy. Invest in access, data management and storage, software development and careers.

MAINTAIN AUSTRALIAN INVOLVEMENT IN INTERNATIONAL COLLABORATIONS

- Maintain participation in large international collaborations to connect Australian expertise with world-leading datasets.

CHAMPION INSTRUMENTATION CAPABILITY, TECHNOLOGY AND TRANSLATION

- Establish long-term, sustainable funding to ensure Australian instrumentation programs continue to innovate, lead discoveries, and translate technologies in the era of next-generation telescopes.

HOST ADVANCED ASTRONOMICAL FACILITIES IN AUSTRALIA

- Maintain and develop the domestic ecosystem of national and university advanced astrophysics facilities.
- Fully assess a pathway to host a major gravitational-wave observatory in Australia.
- Strengthen Australian access to space facilities – from payload development to ground stations.

NATIONAL COOPERATION TO AMPLIFY ASTRONOMY'S BENEFIT TO SOCIETY

- Nationally coordinate programs in outreach, industry and translation, education, and space technology.
- Create a pipeline of students skilled in STEM.
- Targeted aims to strive for equity in the astronomy community.

BUILD CONNECTIONS WITH ABORIGINAL AND TORRES STRAIT ISLANDER ASTRONOMY

- Foster respectful relationships with Aboriginal and Torres Strait Islander astronomers and communities through the education of the astronomy community and its institutions, working with Indigenous peoples, knowledge holders and Elders to achieve this.

PROMOTE DARK AND QUIET SKIES AND SUSTAINABLE ASTRONOMY

- Ensure the country's dark and radio-quiet skies are conserved for all Australians.
- Mitigate satellite disruption to observatories.
- Implement sustainable policies, especially in travel and computing practices.

Image Credit: ESO

01 VISION AND PRIORITIES FOR AUSTRALIAN ASTRONOMY

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

In our vision for Australian astronomy, the nation reaps the rewards from excellence in fundamental science, innovative technology, and industry partnership.

We require a diverse community of researchers capitalising on global collaborations to continue to punch above our weight on the world stage. Astronomy has always been an international endeavour, but now more than ever we work as part of a global community. Collaborative research is the norm, and the mega-telescopes of the coming decade are so large that they go beyond any single-nation effort. Within this interlinked research environment, Australia has a major role to play – not only with researchers working on flagship international projects, but also through innovative domestic facilities contributing to worldwide efforts. Small, agile telescopes will complement the mega-facilities with target identification, fast follow-up, and higher cadence observations. Australia's computing infrastructure will play a critical role to store vast quantities of data, analyse it, and run simulations to explain what we detect.

All Australians will feel inspired by and connected to our collective endeavour to answer our deepest questions about the cosmos, empowering a new generation of STEM superstars.

Our nine recommendations for the next decade are grouped into three themes: groundbreaking facilities, building Australian capacity, and a thriving Australian community. The groundbreaking facilities theme is the highest priority for funding. The thriving Australian community theme is to be actioned by the Australian astronomy community and its organisations.

1.1 GROUNDBREAKING FACILITIES

In the past decade, Australia has been involved in two major international astronomy projects: one through the SKA Observatory (SKAO), and one through the European Southern Observatory (ESO) (via the Access to World Leading Astronomy Infrastructure (AWLAI) program).

Involvement in these two intergovernmental organisations has been the highest priority action for every astronomy decadal plan since 1995, recognising that the next big science questions will be answered by international teams with global facilities. Australian astronomers are positioned in leading roles in this new era of discovery, providing not only scientific outcomes but development opportunities for Australian industries.

PRIORITY ACTION 1A: SECURE ACCESS TO LARGE OPTICAL TELESCOPES AND ALMA

To answer the exciting astrophysical questions of the next decade – understanding our origins, explaining the dark universe, exploring black holes, and searching for life on other planets – it is critical that Australia secures access to 8-metre-class telescopes, a next-generation 30-metre-class telescope, and the Atacama Large Millimeter/submillimeter Array (ALMA). This can be achieved with maximum efficiency and return on investment through membership of ESO.

As a suite of facilities, the ESO telescopes provide the best and broadest set of optical, infrared, and millimetre capabilities to deliver Australia's highest impact science. Full access to ESO not only provides the four 8-metre telescopes of the Very Large Telescope (VLT) and the Very Large Telescope Interferometer (VLTI), but also millimetre capabilities through ALMA and access to the Extremely Large Telescope (ELT). In this decade, ELT will provide the highest combination of angular resolution and sensitivity ever built. ESO also maintains a well-developed plan to advance the international dominance of their capabilities through ongoing investment in innovative instrumentation.

Membership of ESO also provides a partnership, where Australia can (and already does) take an active role in the decision-making of the observatory. The role of partner provides additional value by facilitating Australian leadership in instrumentation. This seeds a research and innovation ecosystem that leads to industry translation as well as providing international opportunities for Australian industry.

The alternative to ESO membership would be a distributed portfolio of telescope access to multiple facilities, as described in section 5.1.4. This would include increasing Australia's share in the Giant Magellan Telescope (GMT) to at least 10%. This distributed portfolio option would carry significantly increased management overheads, no access to some key capabilities, less telescope access overall (for example GMT will not start observing until 2035), and fewer opportunities for instrumentation, industry translation, or for Australian industry more broadly. In addition, Australia would weaken its ability to strategically and holistically plan its research direction and instrumentation program. In order for Australia to maintain its world leadership in astronomy in the absence of ESO membership, this option would be critical.

The science capability built in Australia over the past decade – through ARC Centres of Excellence (CoE) and other programs – has interconnected ESO and SKAO observations at their core. Failure to continue a long-term partnership with ESO would require Australian optical astronomers to redirect their research efforts, undoing the community and scientific leadership that has been built over the current 10-year strategic partnership. While the SKAO science goals would still be achieved, Australian leadership of the multi-wavelength observations that will deliver the highest-impact science will be limited.

PRIORITY ACTION 1B: CAPITALISE ON AUSTRALIA'S ENGAGEMENT WITH THE SKAO AND STRENGTHEN RADIO AND OPTICAL SCIENTIFIC CONNECTIONS

Australia must maximise the benefit of our investment in the SKAO, ensuring that the SKA telescopes are constructed successfully, maintaining Australia's influence, and securing a dominant presence in international science programs.

Building on the previous decade of investment and preparation for SKA telescopes, Australia should use this new decade to capitalise on these efforts: leading and driving research programs, developing new technologies, and delivering high-impact science. In the lead-up to full science operations, existing Australian radio facilities should be maintained and used as pathfinders where appropriate. Software development projects will remain a priority for returning value to Australia.

Maximising science with the SKAO can only be achieved with a strong scientific workforce and access to global, large-scale optical and millimetre facilities (such as ESO). The big science questions that Australia will solve demand information across the electromagnetic spectrum, married with theoretical research for interpretation.

1.2 BUILDING AUSTRALIAN CAPACITY

PRIORITY ACTION 2A: STRENGTHEN ACCESS TO HIGH-PERFORMANCE COMPUTING, DATA, AND SOFTWARE

High-performance computing (HPC) is a critical requirement – particularly for simulation and theory work, which is an increasing proportion of Australia's astronomy portfolio. To meet the requirement, 30% of a top-100 machine is recommended, consistent with the previous decadal plan for astronomy.

Computing time at the National Computational Infrastructure (NCI) and the Pawsey Supercomputing Research Centre will be necessary, in addition to investigating commercial providers and overseas facilities. Tier 2 facilities should continue to be funded with regular capital refresh in the coming decade, and the number of such facilities should be increased. These new facilities could be optimised for specific use cases (e.g. data reduction and processing, theoretical simulations), should bring compute to data (rather than moving data), and should aim to use green power.

Australia must secure its key national research data platforms (including Data Central, the CSIRO ASKAP Science Data Archive (CASDA), Gravitational Wave Data Centre, and Australian SKA Regional Centre) to provide high-performance data and ensure long-term availability, via ongoing funding and regular capital refresh. These also need the capability to seamlessly combine data across different platforms. This will require investment in mission-critical software, which should be a condition for the funding of new facilities and instruments. It will also require investment in developing data pipeline capabilities – including scalability and automation – that are sustainable and long term. These platforms will need to have the capacity to host tens to hundreds of petabytes of data.

PRIORITY ACTION 2B: MAINTAIN AUSTRALIAN INVOLVEMENT IN INTERNATIONAL COLLABORATIONS

A large proportion of Australian astronomers focus their work within large international collaborations that are generating world-leading datasets. The investments in these programs are extremely good value for money, as they leverage very substantial international co-investment and allow Australians to take leading roles in the largest astronomy projects worldwide.

Examples include:

- Gravitational-wave detectors such as the Laser Interferometer Gravitational-Wave Observatory (LIGO), which generated some of the highest-impact papers of the last decade
- The Vera C. Rubin Observatory (Rubin), which will run the game-changing Legacy Survey of Space and Time (LSST)
- The Cherenkov Telescope Array Observatory (CTAO), which will unveil the gamma-ray sky like never before.

Australian access to these facilities is historically funded on stochastic and uncertain ARC Linkage Infrastructure, Equipment and Facilities (LIEF) grants, together with in-kind contributions based on Australian expertise in instrumentation and software. Going forward, these must have more stable funding sources (such as the National Collaborative Research Infrastructure Strategy (NCRIS) program) to ensure that Australia can commit to long-term leadership roles, permit industry opportunities, and enable national access.

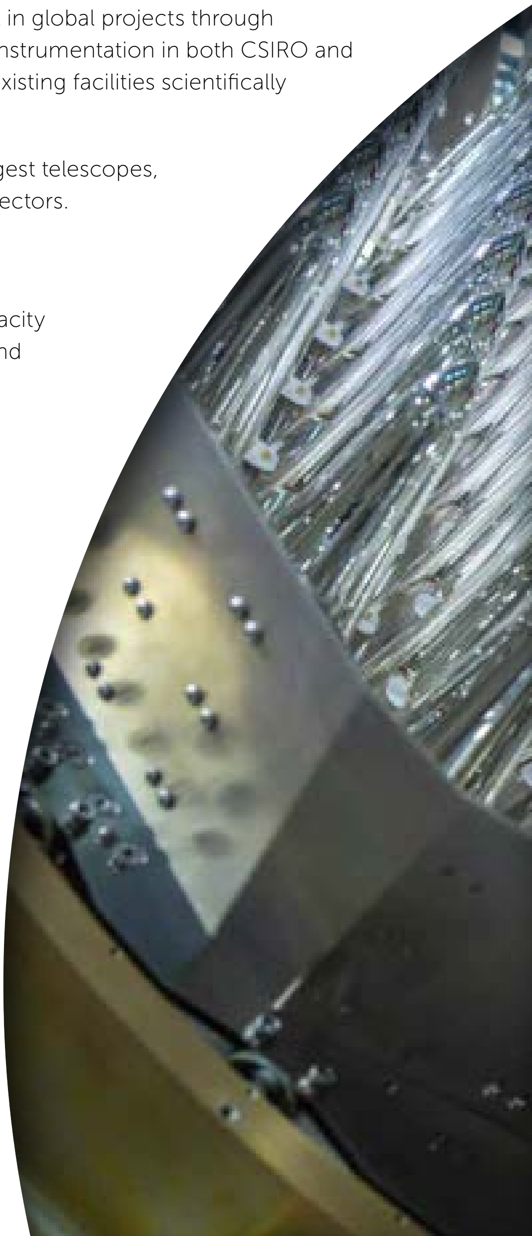
PRIORITY ACTION 2C: CHAMPION INSTRUMENTATION CAPABILITY, TECHNOLOGY AND TRANSLATION

Australia's instrumentation programs are world class. They innovate, lead scientific discoveries, translate technologies, and provide benefits to the astronomical community as well as society at large. The establishment of long-term, stable funding available across the instrumentation landscape – including both ground-based and space technology – will ensure that these programs continue to thrive in the era of next-generation telescopes.

The Astralis Instrumentation Consortium should be maintained through NCRIS or equivalent funding to retain Australia's sovereign capability in optical instrumentation and maximise the country's engagement in global projects through collaborative instrumentation development. Australia's world-class capabilities in radio instrumentation in both CSIRO and university groups will be critical for future upgrades to SKA telescopes and for keeping existing facilities scientifically competitive. These should be considered a high priority in funding decisions.

Instrumentation groups should continue to engage in major projects for the world's largest telescopes, including SKAO, next-generation 30-metre-class telescopes, and gravitational-wave detectors. Many of these instrumentation programs provide guaranteed access for Australian researchers to global facilities.

By the end of the decade, Australian instrumentation teams should have grown the capacity to participate in payload development for major NASA, European Space Agency (ESA) and other agency or independent missions. This should be achieved through the pursuit of new funding pathways that complement our existing ground-based instrumentation programs, in collaboration with adjacent disciplines and with coordination between the national committees for astronomy and space science.



PRIORITY ACTION 2D: HOST ADVANCED ASTRONOMICAL FACILITIES IN AUSTRALIA

Australia's vibrant domestic suite of telescopes and instrumentation facilitates international collaborations. The country's fortuitous longitude is considered valuable (e.g. for transient follow-up from Rubin and LIGO) and can provide in-kind buy-in to international projects. Domestic facilities at the national and university level are also a key training ground for Australian astronomers.

To keep Australian astronomy at the cutting edge, we should host world-leading telescopes and instrumentation. Australia should strengthen its suite of domestic and university radio facilities, building on their niche capabilities in the SKA era. This will provide infrastructure for technology demonstration, capitalise on our unique location on the Earth, and play an essential role in southern hemisphere long baseline interferometry.

Building on the success of the SKAO, Australia should develop the pathway for major new multi-decade efforts to build advanced facilities onshore. This should include hosting a major gravitational-wave observatory in Australia as part of an international partnership.

Australia should strengthen its ability to access space facilities by developing its domestic space capabilities including payload development, construction, ground stations, and perhaps launch. This is aligned with – but does not take the place of – the *Decadal plan for Australian space science 2021–2030*.

CSIRO's expertise in astronomy instrumentation development includes designing and constructing the specialised telescopes and equipment needed to receive and amplify radio waves from space to better understand the Universe. Image credit: CSIRO/K. Schwerdtfeger.

1.3 THRIVING AUSTRALIAN COMMUNITY

A strong, interlinked astronomy community will help to build new connections and opportunities beyond the current reach of astronomy activities.

PRIORITY ACTION 3A: NATIONAL COOPERATION TO AMPLIFY ASTRONOMY'S BENEFIT TO SOCIETY

National collaboration for outreach activities will ensure maximum impact of available resources. We aim to provide the opportunity for all school students to have an astronomy experience in the next decade. This will require engagement with and upskilling of teachers to optimise the student experience. Establishing a central body to promote and facilitate industry engagement will enable maximum engagement with the next generation of global facilities and develop a pipeline for research translation. Moreover, a strategic and coordinated approach should be taken to capitalise on Australia's unique location for space-support operations (i.e. ground-stations, communications, and instrumentation). This approach should aim to leverage greater access and collaboration with space platforms and their science programs, connecting to industry and the Australian and international space agencies.

Astronomy should continue its role in inspiring the next generation of Australia's technological workforce and providing technical training. We should improve opportunities for education and training of TAFE and university students, and, early-career researchers via national and university facilities; expand upon activities that support Aboriginal and Torres Strait Islander students to thrive in STEM fields; and support skills development and training programs to create a pipeline of talent for STEM industries and future industry prosperity.

We will work towards equity across all axes among astronomy staff, so the astronomy community more closely reflects the diversity in the wider Australian community. This includes renewing our focus on turning around the gender gap in PhD completions and expanding efforts to support underrepresented socio-economic and ethnic groups. We propose four targeted aims to improve diversity in the astronomy community:

- At least 40% women participation in astronomy at all levels. This target aligns with the evidence-based findings that 40% is a tipping point for attracting women into research groups.
- Implement focused equity initiatives in STEM across all axes of diversity.
- Expand on activities that support Aboriginal and Torres Strait Islander students to thrive in STEM fields.
- Increase the number of Aboriginal and Torres Strait Islander people with PhDs in astronomy.

PRIORITY ACTION 3B: BUILD CONNECTIONS WITH ABORIGINAL AND TORRES STRAIT ISLANDER ASTRONOMY

Over the next decade, the astronomy community aims to build respectful connections with Aboriginal and Torres Strait Islander astronomers. Education of the astronomy community – including observatories, universities and research centres – will be the fundamental first step. We recommend working with Aboriginal and Torres Strait Islander peoples, knowledge holders, and Elders to incorporate Aboriginal and Torres Strait Islander astronomy into university courses. All introductory undergraduate courses should consider, as a minimum, including components of cultural astronomy. In addition, we should work with professional training bodies such as the Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS) to provide cultural awareness training to all professional astrophysicists specifically focused on Aboriginal and Torres Strait Islander astronomy. These will increase awareness and provide strategies and confidence to incorporate traditional knowledge systems and methods into practice. Alongside education of the existing community, we must increase the number of Aboriginal and Torres Strait Islander PhD students and staff through targeted and supportive schemes.
This should be coupled with specific targets to drive long-term change.

PRIORITY ACTION 3C: PROMOTE DARK AND RADIO-QUIET SKIES AND SUSTAINABLE ASTRONOMY

Dark and radio-quiet skies and sustainable astronomy are crucial to the future success of astronomy as a discipline. Australia has some of the darkest and most radio-quiet skies in the developed world and has always played a major international role in (radio) spectrum management. We recommend that astronomy groups and universities support dark sky conservation and light pollution mitigation tactics and research. Astronomy groups and observatory sites should work with the government and the International Astronomical Union (IAU) Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS) to help mitigate satellite disruption and other impacts on observatories. Additional advantages of light pollution mitigation are to help the conservation of biota adversely affected by abnormal lighting and support astro-tourism that increases awareness of astronomy and engages local communities.

Critically, we must implement sustainable practices in astronomy including considerations around travel and green computing.

Murriyang, CSIRO's Parkes radio telescope, on Wiradjuri Country is one of the instruments that makes up the Australia Telescope National Facility.
Image credit: CSIRO/A. Cherney.

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

1.4 AUSTRALIAN ASTRONOMY PRIORITIES OVER TIME

<table>
<tr><th>Previous decadal plan (2016–2025)</th><th>Mid-term review (2020)</th><th colspan="2">Current decadal plan (2026–2035)</th></tr>
<tr><td>Partnership equating to 30% of an 8-metre-class optical/infrared telescope.</td><td>Achieve full membership of ESO at the earliest opportunity, and well before the current strategic partnership ends in 2027.</td><td rowspan="3">Secure access to large optical telescopes

Ensure sustainable, ongoing access to 8-metre telescopes, the ALMA Observatory, and a next-generation 30-metre telescope.

Membership of ESO achieves this goal with the best potential for return on investment for Australia.</td><td rowspan="3">Maintain Australian involvement in international collaborations

Expand participation in large international collaborations to connect Australian expertise with world-leading datasets.</td></tr>
<tr><td>Partnership equating to 10% of a 30-metre-class optical/infrared ELT, such as the GMT.</td><td>Protect the substantial national investment by supporting the completion of the GMT, including funding of GMT instrumentation built in Australia.</td></tr>
<tr><td></td><td>Pursue data access to the LSST via the exchange of time on Australian national facilities.</td></tr>
<tr><td>Continued development and operations of SKA precursors, ASKAP and MWA at the Murchison Radio-astronomy Observatory (MRO), and membership of the SKA Observatory (SKAO).</td><td>Pursue realisation of the full SKAO, while continuing to exploit its ASKAP and MWA precursors.</td><td colspan="2">Capitalise on Australia's engagement with the SKAO

Continue investment in SKAO to ensure SKA telescopes are constructed successfully and to maintain Australia's influence in international science programs.</td></tr>
<tr><td>Capability within the national observatories (the Australian Astronomical Observatory, AAO; and Australia Telescope National Facility, ATNF) to maximise Australia's engagement in global projects through instrumentation development for these and other facilities.</td><td>Continue supporting world-class national instrument development capabilities that maximise Australia's engagement, influence, and return from global projects.</td><td colspan="2">Champion instrumentation capability, technology, and translation

Establish long-term, sustainable funding to ensure Australian instrumentation programs continue to innovate, lead discoveries, and translate technologies in the era of next-generation telescopes.</td></tr>
<tr><td>World-class HPC and software capability for large theoretical simulations, and resources to enable processing and delivery of large datasets from these facilities.</td><td>Establish a long-term, sustainable, distributed, and interoperable set of HPC and data centre arrangements that span the requirements of gravitational-wave, radio, optical, and theoretical astronomers, and provide funding for commensurate training and education in data science and code development.</td><td colspan="2">Strengthen access to high-performance computing, data, and software

Computing underpins all Australian astronomy. Invest in access, data management and storage, software development, and careers.</td></tr>
</table>

Previous decadal plan (2016–2025)	Mid-term review (2020)	Current decadal plan (2026–2035)
Utilisation of astronomy to improve participation and the standard of science education in schools through teacher-training programs.		**National cooperation to amplify astronomy's benefit to society** Nationally coordinate programs in outreach, industry and translation, education, and space technology. Create a pipeline of students skilled in STEM. Strive for equity in the astronomy community.
Provision of graduate training that includes transferable skills to provide highly skilled graduates for roles in wider society.	Continue investment in training people with strong scientific and translatable skills.	
Adoption of principles and practices that aim for at least 33% female representation at all levels of Australian astronomy by 2025.		
Establishment of a central body to promote and facilitate industry engagement with the next generation of global facilities.		
	Fund the design and development of an Australian gravitational-wave pathfinder to lay the foundations for a future southern hemisphere detector hosted by Australia.	**Host advanced astronomical facilities in Australia** Maintain and develop the domestic ecosystem of national and university advanced astrophysics facilities. Fully assess a pathway to host a major gravitational-wave observatory in Australia. Strengthen Australian access to space facilities – from payload development to ground stations.
	Explore mechanisms to build stronger ties between the Australian astronomy community, the wider Australian space science community, and the Australian Space Agency.	
		Build connections with Aboriginal and Torres Strait Islander astronomy Foster respectful relationships with Aboriginal and Torres Strait Islander astronomers and communities through the education of the astronomy community and its institutions, working with Aboriginal and Torres Strait Islander peoples, knowledge holders, and Elders to achieve this.
		Promote dark and quiet skies and sustainable astronomy Ensure the country's dark and radio-quiet skies are conserved for all Australians. Mitigate satellite disruption to observatories. Implement sustainable policies, especially in travel and computing practices.

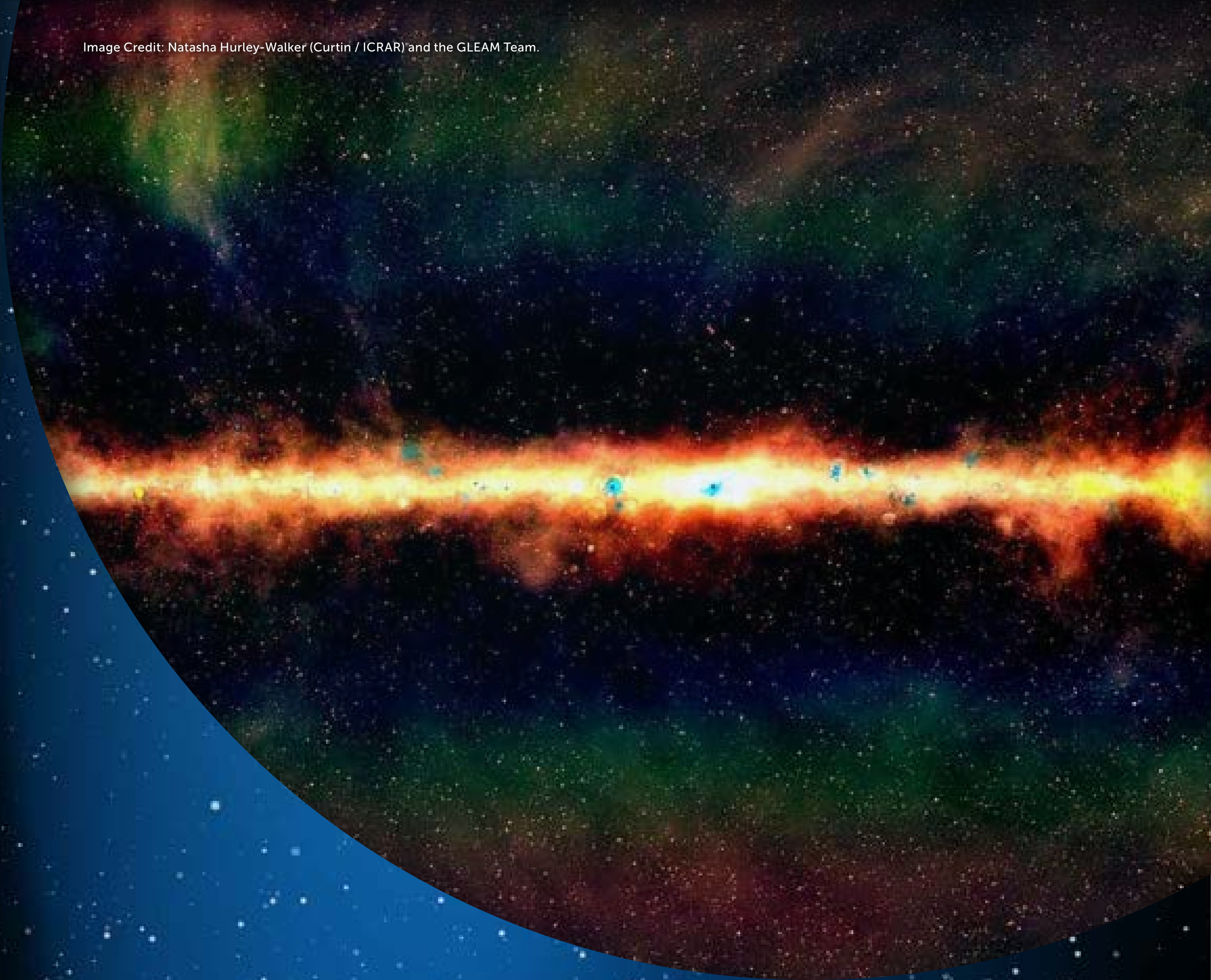


Image Credit: Natasha Hurley-Walker (Curtin / ICRAR) and the GLEAM Team.

02 SCIENTIFIC DISCOVERY: KEY ACHIEVEMENTS AND NEW FRONTIERS

2.1
THE DECADE IN REVIEW

The decade 2016–2025 witnessed major advances in our scientific understanding of the Universe, enabled by spectacular new observational and computational capabilities. Australia has played a central role in driving research excellence on a global stage.

Capitalising on access to some of the world's largest ground- and space-based telescopes, coupled with clever use of agile and specialised domestic facilities, Australian researchers led breakthroughs in our knowledge of the cosmos from the smallest to the largest scales.

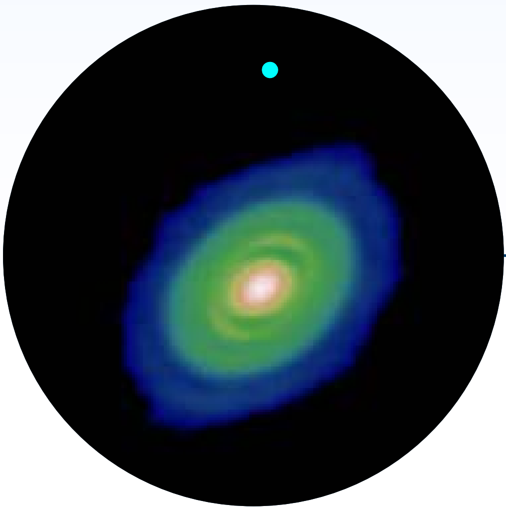


Image credit: Pinte et al.[1]

2.1.1 PLANETS

The number of known exoplanets – planets orbiting stars other than our sun – has exploded over the last decade. Australian astronomers have studied exoplanet properties, characterised their atmospheres and searched for traces of life by taking advantage of the space telescopes TESS (Transiting Exoplanet Survey Satellite), Gaia, and JWST (James Webb Space Telescope).

Using ALMA (a partnership of the ESO with the US National Science Foundation and the National Institutes of Natural Sciences of Japan in cooperation with the Republic of Chile), astronomers have been able to image rings, gaps and spiral arms for the first time in the discs of gas and dust around forming stars, where planets are made. In 2018, an Australian-led team detected an infant planet forming in one of these protoplanetary discs, advancing knowledge of how our own Earth formed. This initial discovery paved the way for Australian leadership in the exoALMA large program hunting for protoplanets with this technique.[1]

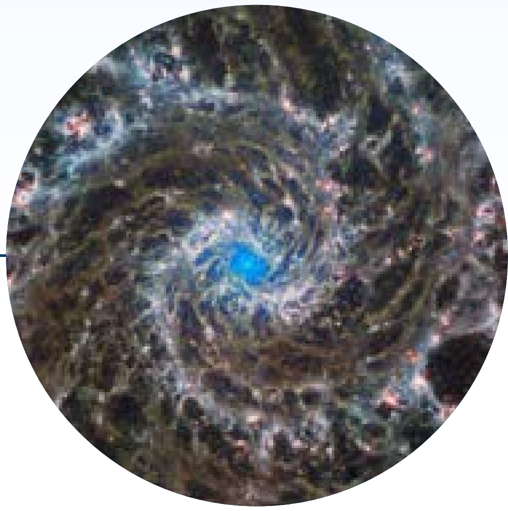


Image Credit: ESA/Webb, NASA & CSA, J. Lee and the PHANGS-JWST Team. Acknowledgement: J. Schmidt

2.1.2 STARS AND THE MILKY WAY

The decade has seen the discovery of ever older and more exotic stars. The ESO VLT enabled Australians to study an extremely old star that was likely formed in the infant Universe.[2] The MWA, located in Western Australia, drove the study of a new class of extreme star located within the Milky Way galaxy.[3] Together these push us closer to understanding the very first stars to have been born in the Universe.

The GALAH (GALactic Archaeology with HERMES) survey used the Anglo-Australian Telescope (AAT) to study the archaeological history of stars in our own galaxy, identifying groups of stars that have been absorbed into the Milky Way from mergers in our distant past, and revealing the story of how the Milky Way came to be as it is today.[4] Australian asteroseismologists continue to lead the world in using stellar pulsations to study the internal structure of stars. Australian theorists computed models of the production of chemical elements in stars through most of the periodic table, delivering an understanding of how most of the elements we see on Earth are forged in stars.[5]

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2.1 THE DECADE IN REVIEW CONT.

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

2.1.3 BLACK HOLES

Australian astronomers discovered the fastest growing supermassive black hole ever found, which is hosted in the centre of a distant galaxy.[6] After discovering it using the Australian National University (ANU) 2.3-metre telescope at Siding Spring Observatory, they undertook precision follow-up to characterise its properties with ESO's VLT. Australians also participated in the discovery of the long-predicted but elusive intermediate mass black holes in globular clusters.[7]

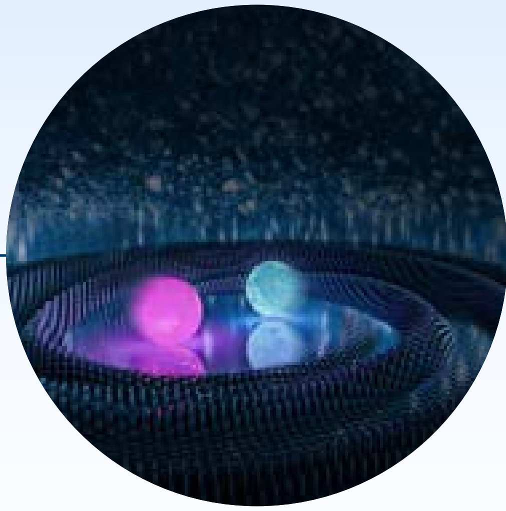

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

2.1.4 GRAVITATIONAL WAVES

The announcement of the discovery of gravitational waves by the LIGO international detectors in 2015 opened a new window on physics, with Australia as partners in the LIGO scientific collaboration. The discovery simultaneously confirmed the existence of gravitational waves and provided the first detection of a binary black hole system, while launching the era of gravitational-wave astronomy. The detection of a coincident gravitational-wave event, gamma-ray burst and kilonova from a coalescing pair of neutron stars in 2017 became one of the most intensely studied astronomical events in history.[8] The Australian gravitational-wave community played a critical role in these discoveries, developing instrumentation for LIGO, developing data analysis pipelines, undertaking follow-up observations by 14 Australian telescopes and partner observatories as part of Australian-based and Australian-led research programs,[9] and leading science results. Emeritus Professor David Blair FAA, Professor David McClelland FAA, Professor Susan Scott FAA and Professor Peter Veitch from the OzGrav CoE won the 2020 Prime Minister's Prize for Science for this discovery. Domestically, using radio telescopes as a gravitational-wave detector, the Australian Parkes Pulsar Timing Array reported a tantalising potential discovery of nanohertz gravitational waves.[10]

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Image credit: ICRAR and CSIRO/A. Cherney.

2.1.5 TIME-VARYING SOURCES

Transient events and variable sources can range from extreme, short-lived astronomical events which can last just fractions of a second, to long-lived variations in a source's brightness over weeks, months, and years. Their study provides a range of information, from the formation and evolution of stars to the shape and structure of the Universe. Australia is a leader in transient and variable science, for example, the CSIRO's ASKAP radio telescope's large instantaneous field of view, enabled by the locally invented phased array feed (PAF) technology, has progressed the exploration of fast radio bursts (FRBs), enigmatic short-lived bursts of radio light from across the Universe. Australian astronomers used ESO's VLT to confirm the bursts' progenitor sources and localised them to distant galaxies.[11] The properties of these bursts were used to measure the amount of normal matter between us and the distant Universe, finding the missing matter (baryons) predicted by our cosmological models, and solving a long-held mystery in cosmology.[12] FRBs were originally detected by the Murriyang telescope, enabled by the innovative multi-beam system. The advances in knowledge provided by FRBs led to the award of the 2023 Shaw Prize and 2024 Prime Minister's Prize for Science to Professor Matthew Bailes FAA from Swinburne University of Technology for his role in their discovery. Australian astronomers were closely involved in discovering very high-energy (TeV) gamma-ray emission from gamma-ray bursts (the most energetic explosions in the universe), the first evidence suggesting extreme particle acceleration in these engines.[13]

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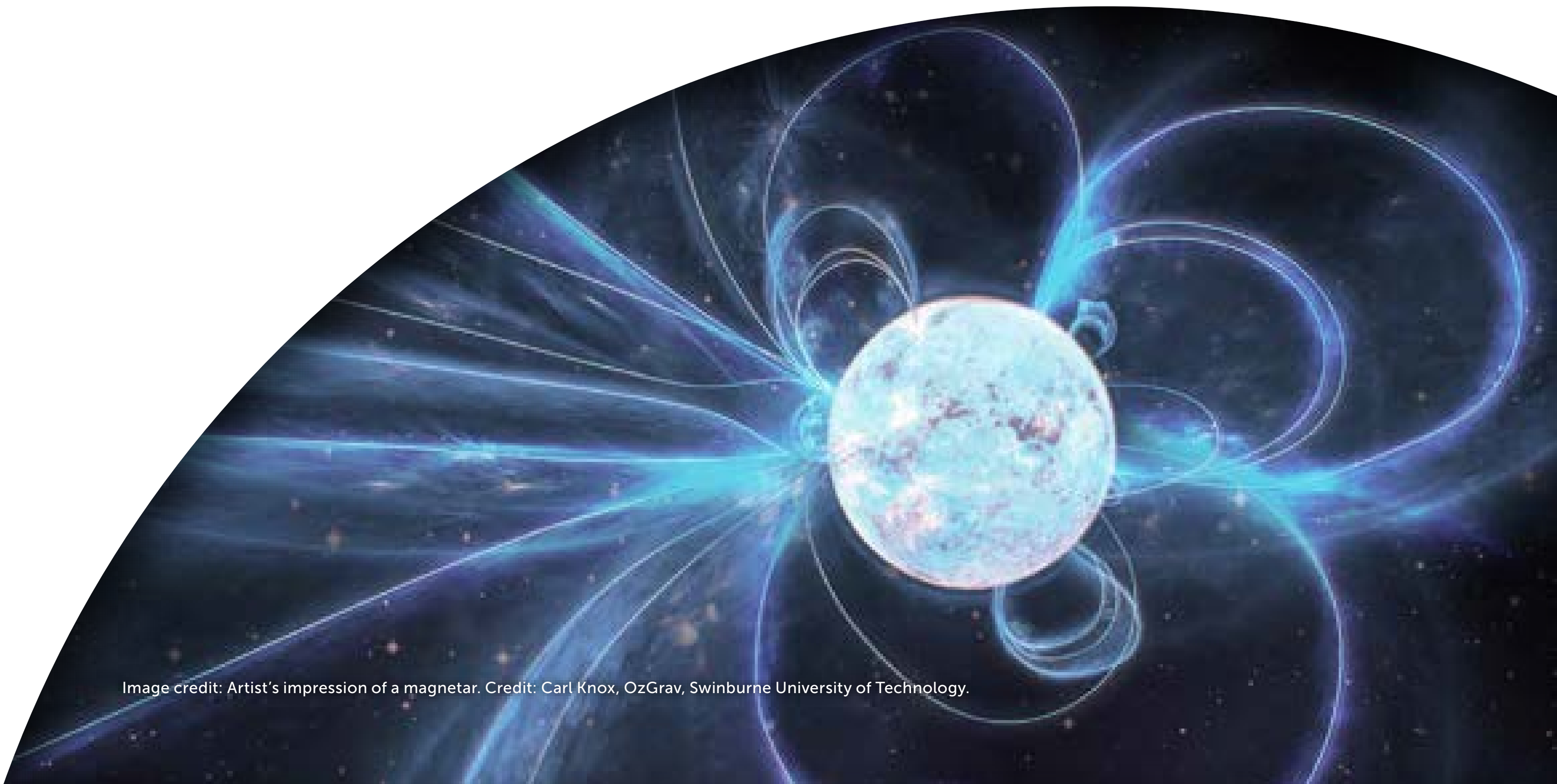


Image credit: Artist's impression of a magnetar. Credit: Carl Knox, OzGrav, Swinburne University of Technology.

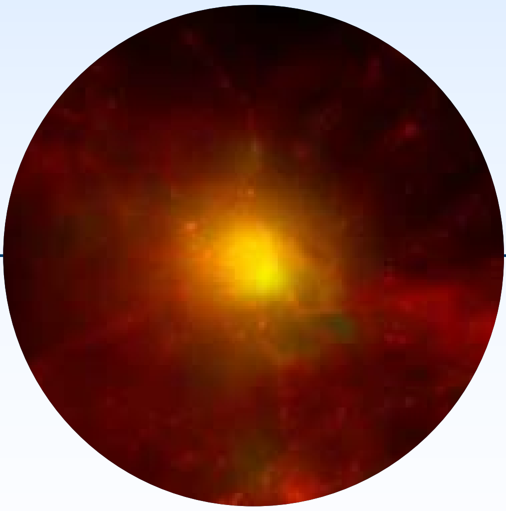
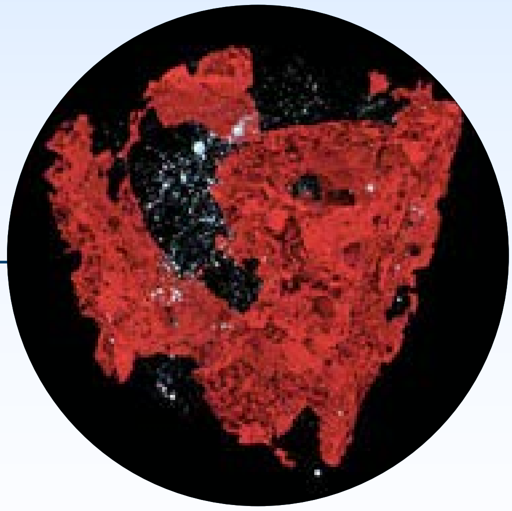


Image credit: ASTRO3D



The Epoch of Reionisation visualisation.
Image credit: Simon Mutch, Dr Paul Geil, The University of Melbourne.

2.1.6 GALAXIES

Astronomers used ESO's VLT to measure the heating of the cosmos in the first billion years, advancing our understanding of the conditions in the Universe at the time of the first stars.[14] The 3.9-metre AAT resolved the star and gas motions in 3,000 nearby galaxies with the SAMI (Sydney-AAO Multi-Object Integral-Field Spectrograph) Galaxy Survey, exploring the relationship of a galaxy's environment to its rotation, shape and type.[15] The SAMI survey led to Australia leading several ESO large programs, using ESO's exceptional instruments to study aspects of these relationships in significantly more detail (the MAGPI,[16] GECKOS,[17] and MAUVE[18] surveys). Australian researchers took advantage of JWST's capabilities to lead important observing campaigns, making groundbreaking discoveries, such as a massive galaxy existing only 500 million years after the Big Bang, challenging our models for the growth of galaxies in the earliest times.[19] ASKAP's combination of excellent resolution and sensitivity to faint diffuse gas led to the discovery of odd radio circles, providing clues to the explosive history of a galaxy.[20] Australian astronomers were closely involved in the first clear detections of extreme-energy neutrino sources, both from an external galaxy and from our Milky Way.

2.1.7 COSMOLOGY

The last decade has seen a rise in 'tensions' in cosmology, in which different measurements disagree on important cosmological values – such as the expansion rate of the Universe (Hubble's constant). There is much speculation as to whether new beyond-standard physics is needed to explain these tensions. Leveraging AAT optical multi-object spectroscopy and instrumentation contributions to partners internationally, Australian cosmologists played critical roles in the international collaborations that made the most precise measurements of dark energy's impact on the acceleration of the Universe. By measuring thousands of distant supernovae[21] and mapping the precise positions of tens of millions of galaxies[22] they revealed early hints that dark energy might be time varying. There has also been extensive work in Australia using the MWA to pursue a detection of redshifted H I (neutral atomic hydrogen) radio emission from the Epoch of Reionisation (EoR) which marks the transition from the 'cosmic dark ages' to the era of galaxies we see today.[23]

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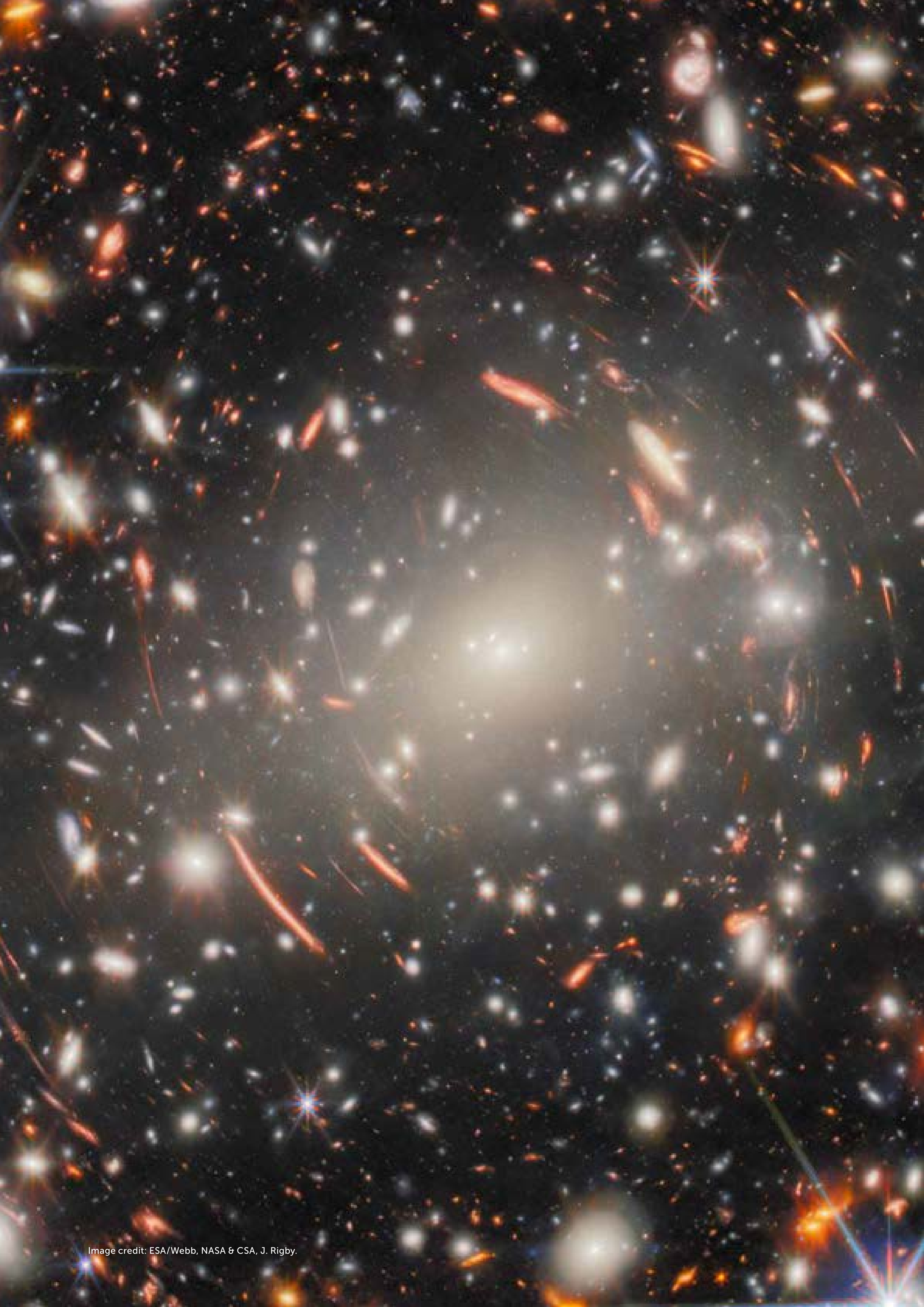


Image credit: ESA/Webb, NASA & CSA, J. Rigby.

CASE STUDY

AUSTRALIAN ESO SCHOLARSHIP WINNER PROBING DISTANT GAS AND GALAXIES

ESO student scholarship recipient Simon Weng is investigating an intergalactic tug-of-war over gas that fuels star formation.

Combining ASKAP and ESO's MUSE instrument on the VLT, Weng is detecting potentially outflowing or extragalactic clouds of gas formed by interactions between neighbouring galaxies. The combination of radio and optical data through ASKAP and MUSE allows him to probe the intricacies of gas behaviour at a much higher redshift than previously possible.

Studying gas behaviour is important for unravelling an astronomical conundrum: the timescales over which star-forming galaxies use their gas are calculated to be too short relative to the age of the Universe so, astronomers conclude that galaxies must have a way to replenish their gas reservoirs for stars to continue to form over time. In theory, cosmological simulations reveal cold gas being channeled along dark matter filaments, but at the same time, galaxies lose a significant amount of their gas through feedback processes caused by starbursts, supernova explosions, or active galactic nuclei. This indicates a tug-of-war on galactic scales, with cosmic consequences, as inflowing gas competes with consumption for star-formation and galactic winds. The behaviour of gas in galaxy groups becomes even harder to track as interactions between galaxies result in tidal stripping and extragalactic clouds – the game of tug-of-war has now moved to extragalactic scales.

ASKAP has opened a new window for the detection and study of neutral hydrogen, a key ingredient for star formation, in distant galaxies through absorption-line measurements of the redshifted 21-cm H I line. The First Large Absorption Survey in H I (FLASH) takes advantage of ASKAP to search for the 21-cm H I line in absorption at redshifts between $0.4 < z < 1.0$. During the commissioning stages of the telescope, an H I absorption line around four billion light years from Earth was detected towards a background quasar. Earlier imaging of the quasar and surroundings revealed four galaxies, but it remained unclear which of these galaxies was responsible for the H I absorption without further imaging and spectroscopy.

In a map of the gas kinematics, Simon and the team find that the velocity kinematics of the detected gas suggests it is not tracing a rotating disk, but potentially outflowing or extragalactic clouds of gas formed by interactions between galaxies A and B which are located only 17 kiloparsecs apart. The combination of ASKAP and MUSE data allows us to probe the intricacies of gas behaviour at a largely unexplored redshift (time in cosmic history). With hundreds of cold gas detections expected in the full FLASH survey, many of these fascinating systems are waiting to be explored.

Photo caption: Simon Weng is a University of Sydney PhD student currently undertaking work in Garching, Germany with an ESO scholarship.


LINDAU
NOBEL LAUREATE
MEETINGS
EDUCATE. INSPIRE. CONNECT.
SINCE 1951


SYDNEY
ASTRO 3D
Simon Weng

Image credit: ICRAR

2.2 QUESTIONS FOR THE NEXT DECADE

The next decade is beginning with a sense of excitement over the prospects of new discoveries. It is a special moment in human history as our telescopes are probing to the edge of the observable Universe, and our computations strive to explain the evolution of the Universe from its birth to the present day, and beyond.

Here we detail some of the most exciting questions that Australia can help answer in the next decade.

2.2.1. QUESTION 1 – FORMATION AND EVOLUTION: HOW IS STELLAR AND GALAXY EVOLUTION INTERCONNECTED ACROSS ALL SCALES?

Understanding the origin of galaxies like our home galaxy, the Milky Way, requires knowing about the interlinked processes that govern galaxy formation and evolution. Unlike previous studies in which stars and galaxy formation were considered in isolation, the coming decade will increasingly bring these together into a holistic evolutionary picture. Astronomers will reveal how structures form and evolve, from stellar scales to the intergalactic environment. We will better understand how black holes shape the environment of galaxies through feedback, regulating star formation, redistributing gas, and affecting galaxy structure and size.

We will probe how elements form in stars and supernovae, including using spectra to reveal elemental and isotopic fingerprints. Studying the effects of stellar mergers and binary stars will help us interpret the life cycles of galaxies.

The Milky Way is our closest laboratory for understanding the key physical galaxy evolution processes we observe throughout the Universe. It is a site of star formation, gas outflow and infall, and a way to investigate the role of magnetism, plasma, and high-energy processes in a galaxy's structure and star formation cycle. The horizon for galactic archaeology is expanding to include the entire Local Group and these new research directions present a major opportunity for the galactic and extragalactic research communities to collaborate across the methodological divide.

Observations of intergalactic hydrogen gas and stars forming in the earliest galaxies at cosmic dawn together will reveal the conditions of the early Universe, its composition and temperature, and the nature of the first stars.

Multi-wavelength observations of phenomena spanning all sizes and timescales will be combined with theory and multi-scale simulations to answer:

a. How do galaxies form and evolve through multi-scale processes and what role does environment play?

b. Where are the different elements forged? How are they transported to new environments to form new generations of stars?

c. What can the composition of the Milky Way's stars tell us about our home galaxy's history?

d. What were the properties of galaxies and the intergalactic medium during the EoR and cosmic dawn?

Image credit: Visualisation of the gas shroud of starburst galaxy IRAS 08339+6517 based on observations by Dr Nikki Nielsen (Swinburne). Image credit: Cristy Roberts, ASTRO 3D.

CSIRO's ASKAP radio telescope and South Africa's MeerKAT telescope have been used to detect 'odd radio circles'. This artist's impression shows odd radio circles exploding from a central galaxy. Credit: CSIRO/S. Moorfield.

2.2.2. QUESTION 2 – COMPOSITION AND COSMOLOGY: WHAT IS THE DARK UNIVERSE MADE OF?

The last decade revealed some cracks in the standard model of cosmology. Different measurements of the expansion rate of the Universe show a 'tension' where cosmic microwave background measurements disagree with local direct measurements; dark matter continues to elude direct detection; and we have seen hints of potential time variation of the properties of dark energy. The telescopes of the new decade will open up new windows on the Universe that will allow us to delve into these mysteries and potentially make fundamental discoveries.

Using gravitational waves, we will investigate how black holes grow with time. With radio observations, we will map the intergalactic gas in the early Universe and study supermassive black holes at the centres of galaxies. FRBs will reveal the hidden matter between the galaxies. Surveys of large-scale structure, supernovae, and gravitational waves will quantify the expansion rate and acceleration of the Universe to measure the properties of dark energy and dark matter in fine detail. Particle physicists and astronomers will work together to elucidate the nature of dark matter and dark energy, taking advantage of a new generation of experiments, observations of high-energy particles, theoretical advances including the use of artificial intelligence (AI), and the new generation of immersive cosmological surveys.

Together these will answer:

a. What are the properties of the black hole population across the Universe?

b. What is the expansion rate of the Universe, and how is it changing with time?

c. Can we identify new particles or new physics that explain dark matter and dark energy?

2.2.3. QUESTION 3 – EXTREME PHYSICS: HOW DOES PHYSICS WORK IN EXTREME ENVIRONMENTS?

Astrophysics gives us the opportunity to test physics in environments more extreme than can be created here on Earth. Advances in supercomputing are improving the resolution of simulations and their ability to take into account the combined effects of small- and large-scale physical processes. Observations will also be crucial to advancing our understanding of physics in extreme environments, including across the electromagnetic spectrum and using other messengers such as gravitational waves, cosmic rays, neutrinos and gamma rays. Such observations will further reveal the multi-scale, multi-physics processes in cataclysmic events such as neutron star mergers and stellar eruptions.

Over the coming decade, black holes will increasingly be the tool of choice for precision tests of general relativity in the ultra-relativistic regime (i.e. moving close to the speed of light). From very long baseline interferometry imaging of the black hole event horizon to tests of the no-hair theorem with gravitational waves, black holes arguably provide our best chance of finding new gravitational physics. Pulsar observations will continue probing fundamental physics and gravitational waves. Asteroseismology reveals the internal structure and properties of stars, using machine learning together with traditional time-domain data analysis methods. Stellar rotational and magnetic evolution is a major research area for solar and low-mass stars, including the effect these phenomena have on planets and their atmospheres.

Some of these research areas overlap with Australian expertise in solar physics, space weather, and asteroid detection and characterisation. These have important implications for safeguarding Earth and its environment.

Key aims for the next decade include:

a. What are the best models to explain the complex interiors of stars?

b. How does matter behave at extreme densities, such as in merging neutron stars?

c. What are the progenitors of gravitational waves, fast radio bursts, and other explosive events?

2.2.4. QUESTION 4 – LIFE AND OUR PLACE IN THE UNIVERSE: HOW DO PLANETARY SYSTEMS FORM AND EVOLVE – AND ARE THEY HABITABLE?

We may be on the verge of discovering evidence of life outside of our own solar system. Surveys in the coming decade will discover thousands of new exoplanets and take spectra of their atmospheres, which may have the power to reveal the signatures of life. ALMA will continue to reveal how these planets sculpt their nascent discs and planetary system. New high-angular-resolution ground-based facilities will significantly augment data from JWST to reveal the composition of planetary atmospheres. Interpreting these data will only be possible in combination with theoretical models, especially those using HPC. Only by understanding how planets at all ages around other solar systems form and evolve will we understand what makes our solar system special.

Together, these new data, opportunities and advanced theory will answer:

a. How can we improve our ability to detect planets of all sizes around different types of stars?

b. How do solar and stellar activity influence planetary atmospheres and their habitability?

c. How can we best detect signatures of other life in the Universe?

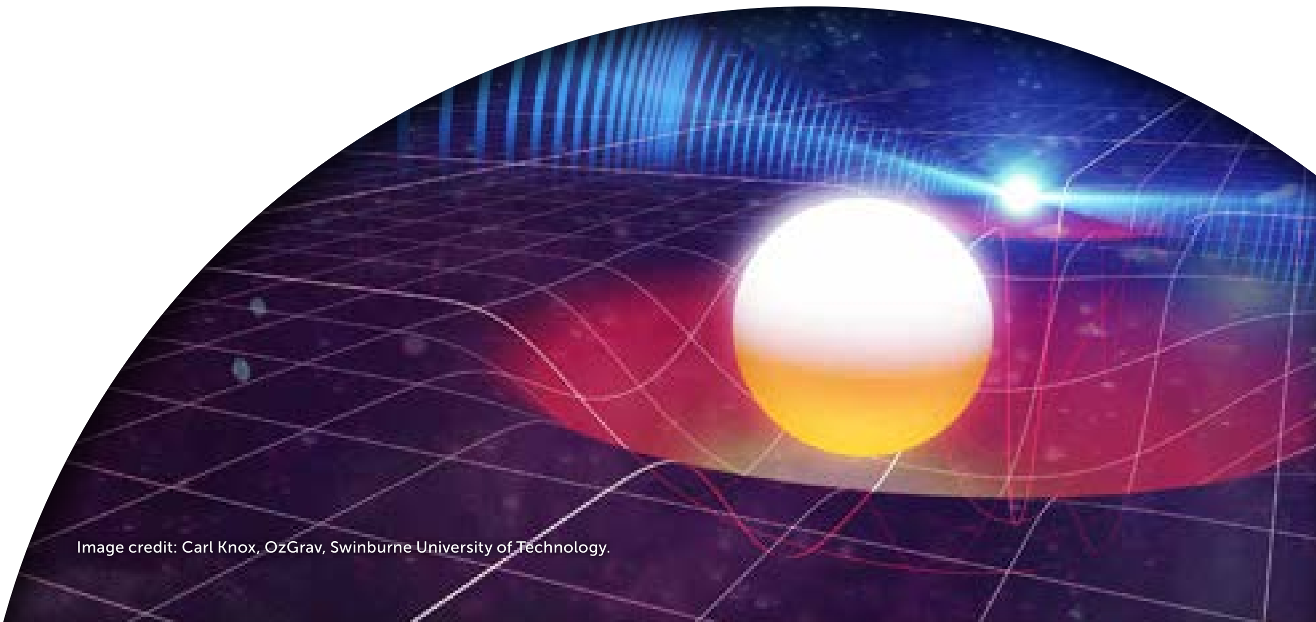
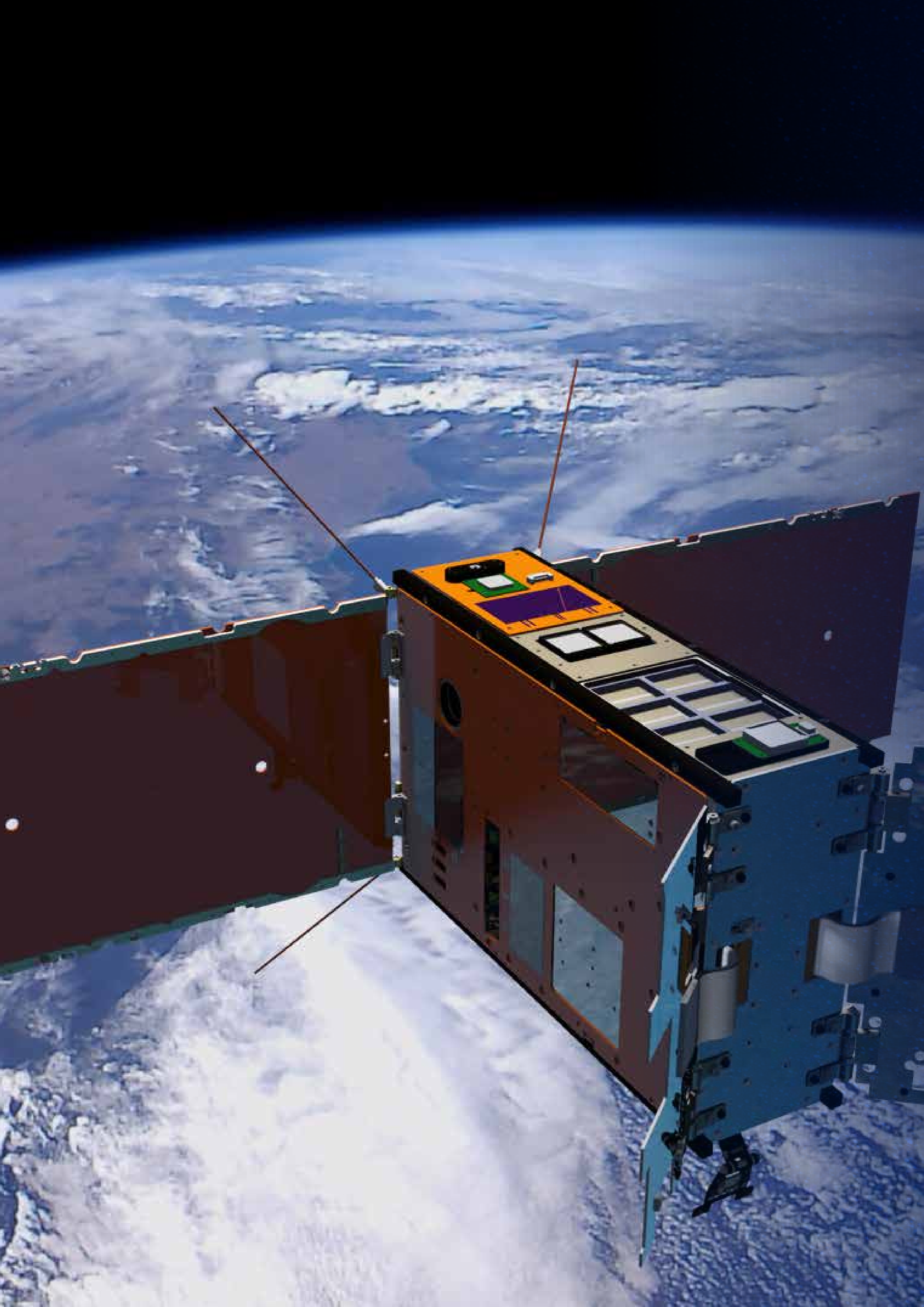


Image credit: Carl Knox, OzGrav, Swinburne University of Technology.



CASE STUDY

SpIRIT SATELLITE TELESCOPE: UNLOCKING INNOVATION, INDUSTRY AND SPACE CAPABILITY

Currently, gamma-ray monitors dedicated to the search of high-energy transients are mostly monolithic instruments hosted on large, complex and ageing satellites (e.g. NASA Swift and Fermi, ESA Integral). Yet a new paradigm for the field is emerging, based on distributed-aperture space telescopes equipped with state-of-the-art sensor technology and hosted on nanosatellites developed for a fraction of the cost of a traditional spacecraft.

The Australia-Italy SpIRIT satellite is at the forefront of this revolution. Led by the University of Melbourne, it successfully launched in December 2023 thanks to more than $6.5 million in funding from the Australian Space Agency and international cooperation with the Italian Space Agency. The SpIRIT satellite was built in Australia through a university-industry consortium including about 40 partners and contractors ranging from start-ups to medium and large enterprises. This endeavour has supported approximately 35 jobs and 10 student internships, and is estimated to support around 25 jobs in the future, as part of opportunities that are unlocked as a result of SpIRIT work. It represents how science-driven innovation can nurture the growth of the industry ecosystem.

The SpIRIT mission is also promoting international scientific cooperation as it carries as main payload an innovative space telescope for precision detection of gamma and x-ray photons developed by the Italian National Institute of Astrophysics. Six other satellites carrying the same instrument have been launched in March 2025 by the Italian Space Agency, establishing the SpIRIT-HERMES scientific pathfinder constellation. The project has grown Australia capabilities to carry out all phases of a space telescope mission project, from initial concept formulation to in-orbit operations.

Render of the Australia-Italy SpIRIT space telescope satellite (launched in December 2023 to monitor the skies for gamma ray bursts) with background image of Victoria's coastline captured by the satellite. Image credit: The University of Melbourne & SpIRIT team.

03
RESEARCH EXCELLENCE AND FUNDING

Professor Emma Ryan-Weber (Swinburne) speaks with Nate Byrne on ABC TV *News Breakfast* about gener equity in ASTRO 3D. Image credit: Niall Byrne, Science in Public.

3.1. IMPACT OF AUSTRALIAN-LED RESEARCH

The scientific impact of Australian astronomical research is not dominated by any one field, method or data type. Of the 16,299 refereed publications in astronomy including Australian authors from the past decade, 6,099 were Australian led.

Australian-led refereed papers that make major use of optical and infrared data (approximately 2,300, 38%) were almost twice as numerous as those using radio data (approximately 1,200, 20%), representing similar fractions to the preceding decade. Compared to internationally led papers, Australia has a higher fraction of papers that use radio data.

The past decade has seen a significant growth in gravitational-wave publications since the first detection in 2015 (1,100 papers including Australian authors), and theoretical and computational astrophysics have maintained their strength at about one-third of research outputs.

The overall impact of Australian papers is proportionally larger than that of the international community, with Australian papers cited 2.5 times the international average (23 cites per paper over the decade compared to an international average of 9 cites per paper). This is an improvement in quality on the previous decade, where Australian papers were cited 2.0 times the international average.

Over the past decade, the number of Australian-led papers using data from ESO telescopes has increased substantially, with a 65% increase in papers using ESO data for 2023 (the last complete year) compared to 2015. Papers using ESO data have an average of 56 cites per paper, which is 2.4 times the average of non-ESO papers.

In terms of astrophysical research area, outputs of Australian researchers are slightly biased towards larger-scale structures in the Universe. Australian-led papers about galaxies are 1.45 times as numerous as those about stars (compared with 1.2 internationally), and papers about stars are 4 times as numerous as those about planets (compared with 2.1 internationally). All areas are roughly equally cited.

Recognising new and expanding research areas, two new chapters of the Astronomical Society of Australia were created in the last decade. The Time Domain Astronomy chapter encompasses this burgeoning field and, while only created in 2023, it already has more than 100 members. The Group for Astroparticle Physics is the first joint chapter between the Astronomical Society of Australia and the Australian Institute of Physics, bringing these two groups formally together for the first time, and bridging the 'gap' between astrophysics and particle physics.

3.2. FUNDING

The broad aims for astronomy research funding set out in the previous decadal plan have largely been met. The combined operations cost of core Australian astronomy infrastructure was approximately $45 million per annum over the last decade, compared with the projection of $46 million.

The total funding for astronomy research has increased over the past decade, although the total funding per astronomer in real terms may have declined slightly. The approximate ratio of funding international:national:university has shifted to approximately 4:3:12 as foreseen in the 2016–2025 decadal plan, to support Australian participation in international-scale astronomy infrastructure, while maintaining the operation of national-scale facilities.

The majority of funding for research in Australia continues to be sourced from the federal government. The Australian Research Council (ARC), which sits within the Department of Education, is the most prominent funder of astronomy research for the higher education sector. Other federal government departments support a range of more targeted research programs and astronomy lies within the scope of some of these, but they are typically much more limited in the total funding available and data for these is incomplete.

Australian universities are a major supporter of astronomical activities, through providing salaries of academics, research and technical staff in universities, co-funding in grant schemes, access to university facilities and higher degree research stipends. Also noteworthy is the contribution of the Government of Western Australia which has provided an average of $4–5 million per year to the International Centre for Radio Astronomy Research (ICRAR) equal joint venture between Curtin University and The University of Western Australia since 2009. To a lesser extent, funding has come from industry, other state governments, and philanthropy.

3.2.1. ARC FUNDING

Figure 1 shows that since the last decadal plan there has been an approximately 30% increase in competitive grant funding from the ARC comparing the average of 2021–2022 with 2014. This exceeds the previous decadal plan target of a 20% increase. However, over the same period, the Consumer Price Index has increased by 23%, so in real terms the increase in astronomy research funding from national competitive grants is modest (around 5%). Furthermore, over the same period of time, continuing positions within the Australian astronomical community have increased by 64%, as highlighted in section 8.

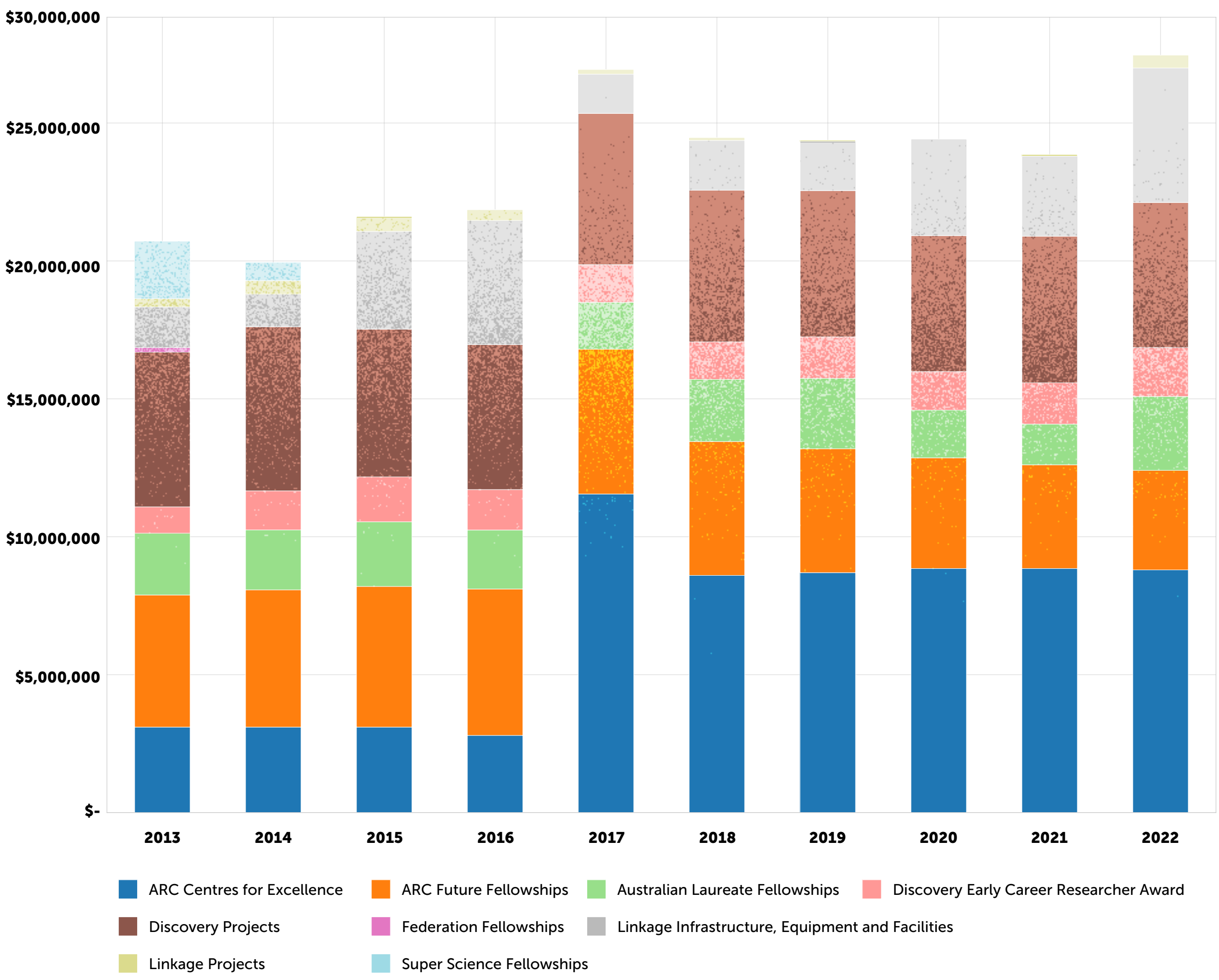


Figure 1: ARC funding awarded to astronomy (grants for which the primary four-digit fields of research code is 0201) by scheme over the period 2013–2022. Note for the Centres of Excellence program, the funding has been allocated equally over a seven-year period, while for all other schemes the funding is the sum of the grants awarded in that year for the duration of the project.

Examining Figure 1 in more detail, the astronomy community's funding substantially increased in 2017 when both the OzGRAV and ASTRO 3D CoE bids were successful. To note the importance of these centres to the Australian astronomy landscape, the last decadal plan also found that all of astronomy's competitive grant increase in that decade was due to the formation of the ARC CoE for All-Sky Astrophysics (CAASTRO). Among ARC fellowships, Discovery Early Career Researcher Award (DECRA) Fellowships have remained stable while Future Fellowships have reduced and Laureates are quite stochastic, although seven were successful over the 2015–2024 timeframe. ARC LIEF grants have increased over this decade, supporting a number of Australia's mid-scale capabilities and instrumentation programs. Linkage grants, however, have not been a substantial source of funding and this could be a potential area of growth for our community. One major challenge for our fundamental science is that the proportion of Discovery Grants per researcher has substantially diminished.

Dr Angel Lopez-Sanchez in the top-end of the Anglo-Australian Telescope with the SAMI instrument. Image credit Cristy Roberts, ASTRO 3D

ASKAP view of Corkscrew and Wide Angle Tail Galaxies. Image credit: Stefan Duchesne

3.2.2. OTHER GOVERNMENT FACILITIES FUNDING

The last decadal plan outlined a reduction in funding to national-scale facilities in order to enable investment in international-scale facilities and infrastructure. Some of the significant funding allocations to astronomy supporting this move from Australian Government-related programs beyond the ARC include the following.

- Astronomy Australia Limited (AAL) has distributed approximately $12 million annually between 2019 and 2023 (inclusive of the $5 million per year Astralis funding) as part of NCRIS/infrastructure funding.
- The 10-year ESO strategic partnership arrangement represents approximately $13 million annually from the Department of Industry, Science and Resources.
- Australian Government support for SKA telescope construction (including the Australian SKA Regional Centre, AusSRC) represents $643 million in funding over a 10-year period. The membership of the SKA Observatory (SKAO) will generate an estimated $1.8 billion in foreign income flows to Australia over the next 30 years.
- An additional funding injection through SKA-Low telescope construction and operations, as well as other purchases of telescope time, such as Breakthrough Listen with Murriyang, and contracts using AAT.
- CSIRO continues to operate all facilities of the ATNF and supports their instrumentation program. Significant and vital investment into astronomy, facilities, and instrumentation programs is supported through CSIRO, averaging $20.2 million per annum over the last decade (excluding capital investments/upgrades).

3.2.3. FUTURE FUNDING REQUIREMENTS

The current funding landscape in Australia presents a range of challenges which the astronomy community acknowledges. It will be necessary to find ways to further broaden sources of astronomy research funding to achieve modest growth in real terms and so that Australia can maintain its international position in astronomy research. A detailed funding plan will be developed by the community, but in broad terms the funding requirements to support this decadal plan are as follows.

- Support Groundbreaking Facilities (section 1.1) – This is the highest-priority infrastructure funding item for the nest decade as this is where the greatest potential for return lies – both from a scientific perspective, and for Australian instrumentation and industry.
- Sustain and modestly grow core funding – Maintain current real-term funding levels for astronomy, with a target of 10–20% growth to preserve Australia's international standing and scientific output. Focus on diverse avenues for funding growth such as industry partnerships, international observatories, the space sector, and defence.
- Balance investment across research scales – Preserve the current funding ratio (4:3:12) across university, national, and international facilities, ensuring foundational research at smaller scales supports major international projects.
- Coordinate national infrastructure and industry engagement – A unified federal approach to applied research funding and establishing a central portfolio of astronomy infrastructure and services will attract industry collaboration and streamline cross-institutional efforts. The shift from the AAO to the Astralis Consortium has diversified capabilities and enhanced collaboration with industry and the space sector but has also introduced funding instability due to reliance on university budgets. Direct federal funding for astronomical instrumentation would ensure sustainability, reduce fragmentation, and support strategic national and international objectives.
- Secure pathways for mid-scale facility renewal – Develop a clear strategy for sustaining and renewing national-scale (mid-tier) infrastructure, which is critical for enabling future participation in next-generation international observatories.

3.3. MAJOR AWARDS AND RECOGNITION

Numerous Australian astronomers have won national and international awards, demonstrating the outstanding quality and impact of their research and innovation.

Over the last 10 years, astronomers have won three Australian Academy of Science Pawsey medals, two Prime Minister's Prizes for Science, and a Shaw Prize. Astronomers have also been recognised for their work and leadership through election to peak national scientific bodies, including the Australian Academy of Science and Australian Academy of Technological Sciences and Engineering (ATSE).

3.3.1. AWARDS

PRIME MINISTER'S PRIZES FOR SCIENCE

PRIME MINISTER'S PRIZE FOR SCIENCE

- Emeritus Professor David Blair FAA, Professor David McClelland FAA, Professor Susan Scott FAA, Professor Peter Veitch – 2020
- Professor Matthew Bailes FAA – 2024

MALCOLM MCINTOSH PRIZE FOR PHYSICAL SCIENTIST OF THE YEAR

- Dr Keith Bannister – 2021

INTERNATIONAL AWARDS

SHAW PRIZE

- Professor Matthew Bailes FAA – 2023

NEWCOMB CLEVELAND AWARD (AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE)

- Dr Keith Bannister, Professor Jean-Pierre Macquart, and co-authors – 2020

S. CHANDRASEKHAR AWARD OF PLASMA PHYSICS (DIVISION OF PLASMA PHYSICS, ASSOCIATION OF ASIA PACIFIC PHYSICAL SOCIETIES)

- Professor Donald Melrose FAA – 2016

JACKSON-GWILT AWARD (ROYAL ASTRONOMICAL SOCIETY)

- Dr Keith Bannister and Professor Ryan Shannon – 2024

AUSTRALIAN ACADEMY OF SCIENCE HONORIFIC AWARDS

PAWSEY MEDAL

- Professor Paul Lasky – 2018
- Professor Adam Deller – 2020
- Dr Keith Bannister – 2022
- Associate Professor Claudia Lagos – 2025

NANCY MILLIS MEDAL

- Professor Cathryn Trott – 2021
- Associate Professor Natasha Hurley-Walker – 2025

THOMAS RANKEN LYLE PRIZE

- Professor Joss Bland-Hawthorn FAA – 2017
- Professor David McLelland FAA – 2021
- Professor Susan Scott FAA – 2023

FREDERICK WHITE MEDAL

- Professor Michael Ireland – 2016

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

AUSTRALIAN INSTITUTE OF PHYSICS (AIP) AWARDS

AIP AWARD FOR OUTSTANDING SERVICE TO PHYSICS IN AUSTRALIA

- Dr Marc Duldig – 2021

RUBY PAYNE-SCOTT AWARD FOR EXCELLENCE IN EARLY-CAREER RESEARCH

- Dr Cullan Howlett – 2024

WOMEN IN PHYSICS LECTURER

- Dr Katie Mack – 2017

WOMEN IN LEADERSHIP MEDAL

- Professor Celine Boehm – 2022

WALTER BOAS MEDAL FOR EXCELLENCE IN RESEARCH

- Professor Susan Scott FAA – 2022
- Professor Joss Bland-Hawthorn FAA – 2020
- Professor David McClelland FAA – 2017
- Professor Geraint Lewis – 2016

EUREKA PRIZE FOR PROMOTING UNDERSTANDING OF AUSTRALIAN SCIENCE RESEARCH

- Dr Lisa Harvey-Smith – 2016

3.3.2. RECOGNITION

AUSTRALIAN ACADEMY OF SCIENCE FELLOWS

- Professor Susan Scott FAA – 2016
- Professor Karl Glazebrook FAA – 2017
- Emeritus Professor David Blair FAA – 2018
- Professor Rachel Webster AO FAA – 2018
- Professor David McLelland FAA – 2019
- Professor Tim Bedding FAA – 2020
- Professor Matthew Bailes FAA – 2022
- Professor Naomi McClure-Griffths FAA – 2022
- Professor Mark Krumholz FAA – 2024
- Professor Tamara Davis AM FAA – 2025
- Professor Trevor Ireland FAA – 2025

AUSTRALIAN ACADEMY OF TECHNOLOGICAL SCIENCES AND ENGINEERING FELLOWS

- Dr Douglas Bock FTSE – 2019
- Dr Sarah Pearce FTSE – 2020
- Distinguished Professor Brian Schmidt AC FAA FTSE FRS Nobel Laureate – 2023
- Professor Anna Moore FTSE – 2023

US NATIONAL ACADEMY OF SCIENCES INTERNATIONAL MEMBERS

- Professor Ken Freeman AC FAA FRS – 2017
- Professor Ron Ekers AO FAA FRS – 2018
- Professor Lisa Kewley FAA – 2021

AMERICAN ACADEMY OF ARTS AND SCIENCES INTERNATIONAL HONORARY MEMBERS

- Professor Lisa Kewley FAA – 2022
- Professor Joss Bland-Hawthorn FAA – 2023

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

ASTRO 3D Science Legacy Meeting in Sydney. Image credit: Cristy Roberts, ASTRO 3D.

AUSTRALIAN HONOURS SYSTEM

- John Sarkissian OAM – 2016
- Professor Ken Freeman AC FAA FRS – 2017
- Dr Bruce Slee AM – 2017
- Professor Elaine Sadler AO FAA – 2019
- David Malin AM – 2019
- Professor Ron Ekers AO FAA FRS – 2019
- Professor Rachel Webster AO FAA – 2020
- Professor Tamara Davis AM – 2020
- Emeritus Professor Lawrence Cram AM – 2021
- Professor Anne Green AC – 2022
- David Luchetti PSM – 2022
- Professor Matthew Colless AO FAA – 2023
- Mark Stickells AM – 2024

INTERNATIONAL ASTRONOMICAL UNION HONORARY MEMBERSHIP

- David Luchetti – 2021
- Ghillar Michael Anderson – 2024

AUSTRALIA'S WOMEN IN STEM AMBASSADOR

- Professor Lisa Harvey-Smith – 2018–2024

NATIONAL HERITAGE LIST

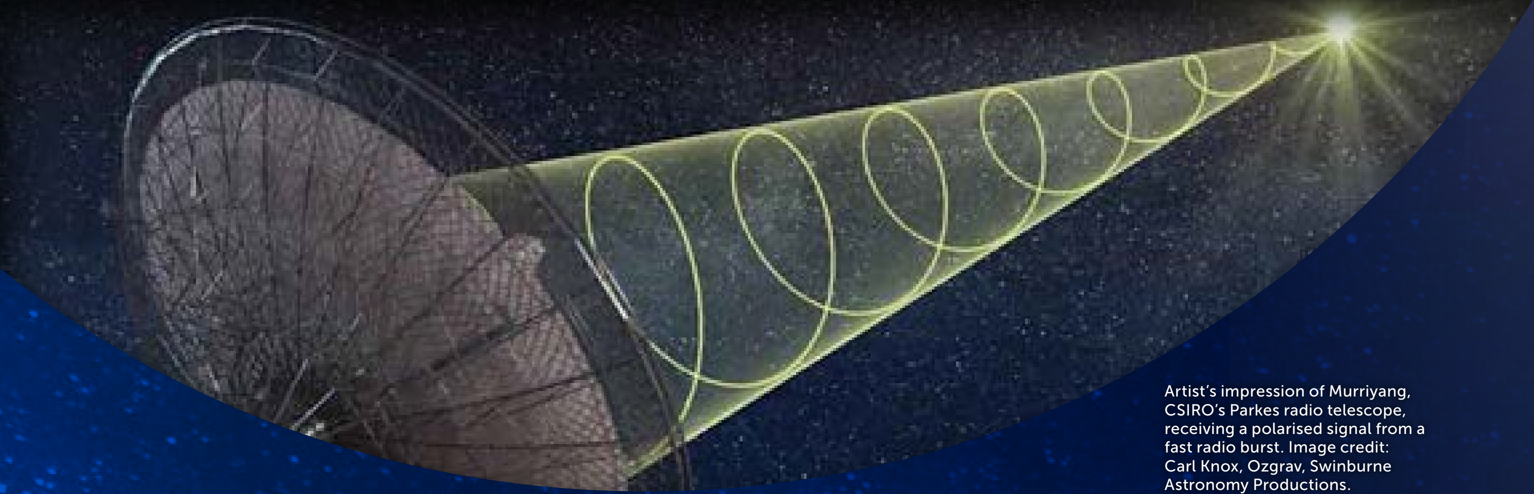
- Murriyang Parkes Radio Observatory – 2020

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE) SPECIAL CITATION

- Commonwealth Solar Observatory (now Mount Stromlo Observatory) – 2024

CLOSING THE GAP PARTNERSHIP

The National Indigenous Australians Agency has recognised the partnership between the Australian Government Department's of Industry, Science and Resources. CSIRO and Wajarri Yamaji Aboriginal Corporation to enable the SKA-Low telescope under the National Agreement on Closing the Gap.



Artist's impression of Murriyang, CSIRO's Parkes radio telescope, receiving a polarised signal from a fast radio burst. Image credit: Carl Knox, Ozgrav, Swinburne Astronomy Productions.

CASE STUDY

PROFESSOR MATTHEW BAILES: WINNER OF THE 2023 SHAW PRIZE

Professor Matthew Bailes FAA has been a pioneering force in Australian astrophysics, leading groundbreaking research into fast radio bursts (FRBs), pulsars and the nature of gravity. His team's discovery of the first FRB – a powerful flash of radiation from a distant galaxy – marked a major milestone in cosmology. In a landmark 2007 Science paper, Professor Bailes and colleagues detailed the FRB's immense energy, compact size, and vast distance, proposing their use as cosmological probes. Through his leadership, Australia has become a global hub for FRB research, thanks to modernisation of the Parkes/Murriyang and Molonglo radio telescopes. The new digital receiver systems at the radio telescopes have propelled Australia into a leading position in early FRB discovery. In recognition of his transformative contributions, Professor Bailes was awarded the prestigious US$1.2 million Shaw Prize in Astronomy in 2023, along with his US colleagues Professor Duncan Lorimer FRS and Professor Maura McLaughlan. Professor Bailes is only the second Australian to receive the honour after Professor Brian Schmidt AC FAA FTSE FRS Nobel Laureate.

Professor Bailes founded Swinburne's Centre for Astrophysics and Supercomputing, which now hosts more than 100 staff and PhD students, as well as one of Australia's largest supercomputers. His accolades include an ARC Laureate Fellowship in 2015, election to the Australian Academy of Science in 2022, and appointment as Chair of the Gravitational Wave International Committee in 2023. In 2024, Professor Bailes was awarded the Prime Minister's Prize for Science for leading Australia's role in the discovery of FRBs and his broader contributions to research and public outreach. He is currently the Director of the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav).

Matthew Bailes receiving his Shaw Prize from Nobel Laureate Professor Dr. Reinhard Genzel.
Image Credit: Shaw Prize Foundation

The SKAO's SKA-Low telescope at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory, on Wajarri Yamaji Country under the Milky Way. Image credit: CSIRO / A Cherney

04 CURRENT FACILITIES AND CAPABILITIES

The last decadal plan for Australian astronomy, for the decade 2016–2025, identified five top-level science infrastructure priorities:

- partnership equating to 30% of an 8-metre-class optical/infrared telescope
- continued development and operations of SKA precursors and membership of the SKAO
- partnership equating to 10% of a 30-metre-class optical/infrared extremely large telescope
- capability within the national observatories to maximise Australia's engagement in global projects through instrumentation development
- world-class HPC and software capability and resources to enable processing and delivery of large datasets.

As a result of these clearly identified priorities, this decade has been one of Australia's most stable for optical and radio astronomy. Australian observational researchers have been well-placed to lead the global science advances highlighted in section 2, thanks to:

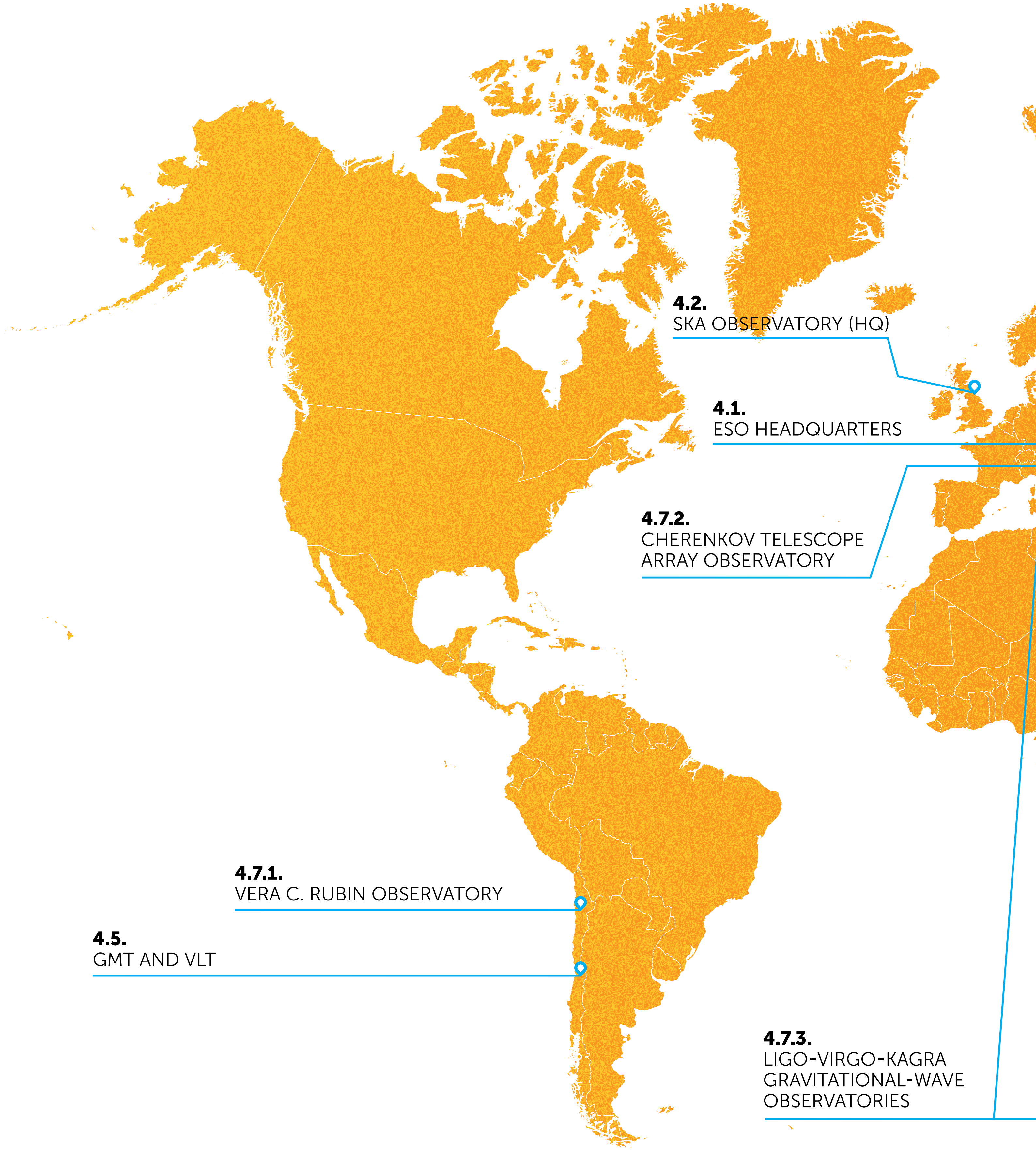
- diverse scientific and technical contributions from domestic facilities
- access to large world-class international optical facilities
- the start of construction of the SKA telescopes
- strong instrumentation capability (section 7)
- significant developments in data and computing (section 6)
- mid-scale access to international multi-wavelength and multi-messenger facilities.

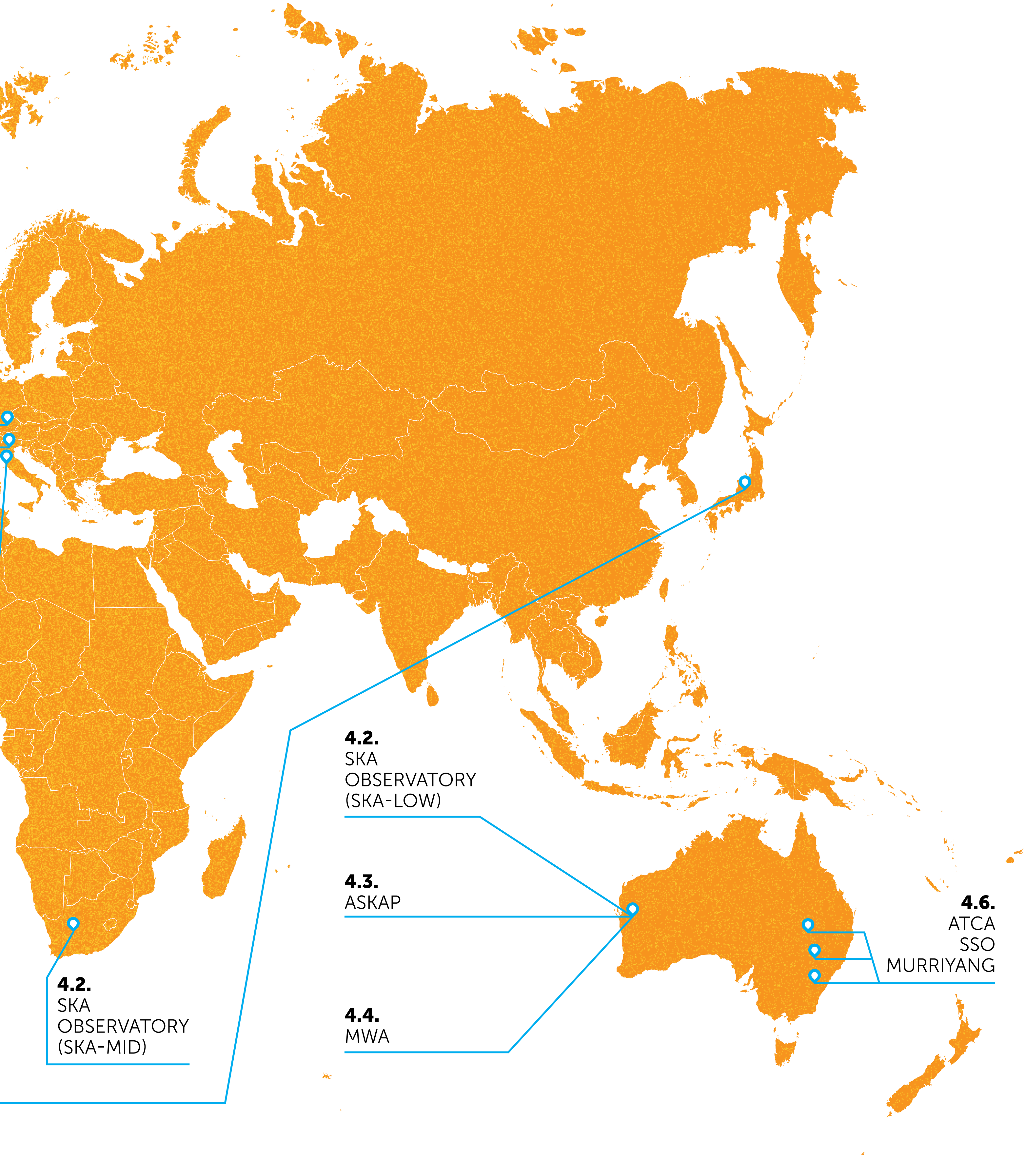
Effective short-term access to Rubin, CTAO, and LIGO has been achieved through community-driven funding pathways augmenting some NCRIS support. Given the substantial scale of these international facilities, Australia gets an excellent return on investment. However, access to a 30-metre-class optical telescope, world-class HPC, and stable funding for mid-scale facilities did not meet the level envisaged in the previous decadal plan.

This section outlines Australia's current facility access and infrastructure capabilities. Section 5 describes the facilities that will be needed in the coming decade. Section 6 covers advanced scientific computing and data, and section 7 considers instrumentation.

Image credit: Karl Glazebrook

4. CURRENT FACILITIES AND CAPABILITIES




4.2.
SKA
OBSERVATORY
(SKA-LOW)
4.3.
ASKAP
4.4.
MWA
4.2.
SKA
OBSERVATORY
(SKA-MID)
4.6.
ATCA
SSO
MURRIYANG

4.1. EUROPEAN SOUTHERN OBSERVATORY

As part of the Australian Government's investment in optical astronomy, the 2017–18 budget included funding for the Access to World Leading Astronomy Infrastructure (AWLAI) program. AWLAI enabled Australia to establish the ESO strategic partnership, including access to the La Silla and Paranal Observatories in Chile, for 10 years to 1 January 2028.

This access currently encompasses the four 8-metre telescopes of the VLT, the Very Large Telescope Interferometer (VLTI), and the 4-metre VISTA (Visible and Infrared Survey Telescope for Astronomy) telescope at Paranal Observatory. At La Silla Observatory, this includes the ESO 3.6-metre telescope and 3.6-metre New Technology Telescope.

Access to these world-class large-scale optical telescopes opened new opportunities for discovery. The strategic partnership enabled an increase of large Australian-led projects on ESO telescopes, with 88% of Australia's observing time on the ESO/VLT in recent semesters coming from collaborative large programs. This far exceeds the average of other ESO member states. Australia's average time allocation over the 6.5 years of the partnership to the end of 2024 has been around 6% – equivalent to 24% of a single 8-metre class telescope and almost meeting the criteria recommended in the last decadal plan.

In 2023, the Department of Industry, Science and Resources commissioned ACIL Allen to evaluate the AWLAI program, and found the ESO strategic partnership has:

- increased Australia's access to ESO facilities, creating workforce and training opportunities including for students and postdoctoral fellows
- increased collaboration between Australian and international researchers, Australia's international competitiveness, and the quality and quantity of scientific output
- enabled access to and awards of commercial tenders, enhanced industry collaboration, and the commercialisation of astronomy technical expertise.[24]

The report found that Australia's return on investment is neutral but that this 'likely underestimates the full benefit of … including broader socio-economic impacts, knowledge advances and innovations arising from astronomy research.'[25]

24. ACIL Allen. 2024. Evaluation of the Access to World Leading Astronomy Infrastructure (AWLAI) program: Final report. https://www.industry.gov.au/publications/mid-term-evaluation-access-world-leading-astronomy-infrastructure-program
25. ACIL Allen. 2024. Evaluation of the Access to World Leading Astronomy Infrastructure (AWLAI) program: Final report.

The MWA at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory, on Wajarri Yamaji Country. Image credit: Marianne Annereau, 2015

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

4.2.
SKA OBSERVATORY

The SKA Observatory (SKAO) intergovernmental organisation was established by treaty in 2019, with Australia as a founding member. The SKAO will be the world's largest radio astronomy observatory, poised to unravel some of the most profound mysteries in astrophysics.

The SKA-Mid telescope is located in the northern cape of South Africa, while Australia hosts the SKA-Low telescope at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory. The Wajarri Yamaji, as Traditional Owners and Native Title Holders of the observatory site, have negotiated an Indigenous Land Use Agreement (ILUA) with the Australian and Western Australian governments and CSIRO. Signed in 2022, the ILUA ensures the preservation of cultural heritage on site and that the Wajarri Yamaji People will benefit through community development, infrastructure, training and education opportunities.

In a major milestone, construction of the SKA-Low telescope commenced in 2023, and the first signals were detected in 2024. With SKA-Low construction already started, and the first science verification data to be taken in 2027, we have achieved our aims of the last decade in the radio domain. This sets us up for the next decade of SKA science in which construction will be ongoing and operations will start.

The SKA telescopes, however, have been partially descoped from the facilities that were used originally to motivate the first SKA science book in 2015. The constraints induced by the increased costs associated with a global mega-science project have affected observatory development programs, and refocused efforts to a phased build and operation of a preliminary array, known as AA*, by 2029.

4.3.
ASKAP

The mid-frequency SKA pathfinder ASKAP is a wide-field radio survey telescope.

It is observing a program of nine large community-led surveys spanning continuum and neutral hydrogen observations, and fast radio transients (flashes). In the past decade, construction of ASKAP was completed and science programs commenced. ASKAP has made discoveries about the nature of neutral hydrogen, localised FRBs and detected thousands of radio galaxies.

4.4.
MURCHISON WIDEFIELD ARRAY

The low-frequency SKA precursor, the Murchison Widefield Array (MWA) is an international partnership with six partners (Australia, Canada, China, Japan, Switzerland, and the United States).

In the past decade, the MWA received two upgrades and reached its 10-year anniversary of science operations. MWA has made discoveries in radio transients, detection and characterisation of new pulsars, mapped the polarised radio sky, and achieved some of the deepest observations of hydrogen gas in the EoR, probing the state of the Universe 13 billion years ago.

Image credit: Giant Magellan Telescope - GMTO Corporation.

4.5. GIANT MAGELLAN TELESCOPE

Australia became a founding member of the Giant Magellan Telescope (GMT) partnership in 2009 and has invested in the design and construction of this 25.4-metre telescope located in Chile's Atacama Desert.

Australia has remained engaged in the development of GMT and is responsible for construction of three major instrumental components of the facility (the GMTIFS near-infrared imager and integral-field spectrograph, the MANIFEST facility multi-object fibre system, and crucial components of the adaptive optics systems). Site construction commenced in 2014, and completion of the telescope and its first instruments is expected in 2035. At this time, Australia's share of GMT will be around 5%, which will not meet the 10% of a 30-metre-class telescope target of the last decadal plan. Although GMT is smaller than the other 30-metre-class telescopes, some of GMT's capabilities will be truly unique in the next generation of extremely large telescopes. This makes it a valuable complement to other potential 30-metre-class telescope investments.

4.6. DOMESTIC NATIONAL FACILITIES

The last decadal plan noted that domestic national facilities, including the AAT and CSIRO's ATNF that operates Murriyang, ASKAP, Long Baseline Array (LBA), and CSIRO's Australia Telescope Compact Array (ATCA), provided critical capability that should be maintained during the development of the next generation of telescopes.

However, the plan also noted that resources would increasingly need to be redirected to those next-generation facilities in order to answer the scientific questions posed by the Australian community. This has happened for the AAO under AWLAI with the 3.9-metre AAT, the largest optical telescope in Australia, now operated by a consortium of universities and AAL. Consortium members are able to conduct major survey programs with four facility-class instruments. The past decade saw several instrumentation upgrades including integral-field spectrographs. Funding for the AAT is secured until mid-2027.

CSIRO seeks additional external funding to support the operations and development of new technologies for the telescopes of the ATNF, such as through the sale of telescope time on Murriyang and ATCA, as well as leading new technology developments, and operating them in unique frequency and temporal parameter spaces.

Murriyang is the only large single dish radio telescope (64 m) dedicated to science observations in the southern hemisphere. Murriyang is still used for high-cadence monitoring campaigns of large numbers of sources such as pulsars, studying atomic hydrogen, and carrying out continuum and polarisation surveys. It also remains an integral component of the LBA. With new survey capability from the wide field of view available following the CryoPAF (cryogenic phased array feed) upgrade in 2024, Murriyang will survey large sky areas with both high time resolution and high spectral resolution.

ATCA is a radio interferometer of six 22-metre antennas. It can rapidly respond to automatic triggers of astronomical events, and has wide frequency coverage, including millimetre receivers, and flexible array configurations. The backend system is currently being upgraded to increase the available bandwidth (BIGCAT). ATCA is an essential element of the LBA and international very long baseline interferometry (VLBI) networks. The Australian LBA uses radio telescopes all over Australia to enable high-resolution imaging and spectroscopy, utilising VLBI. This nationwide facility is managed by CSIRO and collaborators at participating institutions. The LBA utilises the ATNF telescopes (Murriyang, ATCA, and Mopra), and the Hobart, Ceduna, Yarragadee, and Katherine antennas operated by the University of Tasmania, plus telescopes in New Zealand and South Africa to observe in VLBI mode.

4.7.
MID-SCALE INTERNATIONAL FACILITIES

4.7.1. VERA C. RUBIN OBSERVATORY

The 2016–2025 decadal plan also indicated the need for complementary investments for mid-scale facilities including wide-field optical imaging. This provides synergies with the next generation of radio facilities and builds on Australia's leadership in all-sky surveys. The Vera C. Rubin Observatory (Rubin) is currently under construction in Chile and will operate the Legacy Survey of Space and Time (LSST) 2025–2035, creating the largest and most sensitive optical image of the southern hemisphere ever created. In 2024, Australia signed a data rights agreement with Rubin to allow Australian astronomers prompt access to LSST data and enable joining-LSST science collaborations. This access is funded to mid-2027 from an ARC LIEF grant and NCRIS support.

4.7.2. CHERENKOV TELESCOPE ARRAY OBSERVATORY

Approximately 30 of Australia's high-energy, gamma-ray, and other astronomers from seven institutions, led by the University of Adelaide, are engaged with the Cherenkov Telescope Array Observatory (CTAO). CTAO's construction phase is well underway with its first telescope at CTAO-North producing scientific data, and the CTAO-South site being prepared. As a member of CTAO, Australia has access to the CTAO key science projects which account for about half of CTAO's observing time in its first 10 years of operation, as well as guest-observer time for small-scale proposals. Australia's engagement with CTAO has been funded through several ARC LIEF grants supporting construction as well as NCRIS support for membership.

4.7.3. LIGO-VIRGO-KAGRA GRAVITATIONAL-WAVE OBSERVATORIES

The field of gravitational-wave astronomy has undergone a major transition since the previous decadal plan. Since the first gravitational wave detection in 2015, the LIGO-Virgo-KAGRA gravitational-wave observatories have detected almost 200 merging black hole and neutron star systems. Australia is a major stakeholder in LIGO with 119 active members covering instrumentation, data, astrophysics, and fundamental physics. LIGO is now part of a global network of gravitational-wave observatories including Virgo in Italy, KAGRA in Japan, and LIGO-India (under construction). Pulsar timing arrays, including Australia's Parkes Pulsar Timing Array, have published tantalising evidence for the discovery of nanohertz gravitational waves from the superposition of signals coming from coalescing supermassive binary black holes throughout the Universe. Membership in LIGO, and support for commissioning, has historically been underwritten through LIEF grants. The funding of the OzGrav ARC Centre of Excellence (funded 2017–2031) provides the personnel grant support and research fabric to support gravitational-wave astronomy.

4.8.
INTERNATIONAL SPACE-BASED FACILITIES

JWST, launched in 2021, has opened a new space window on the earliest galaxies in the Universe and probed planetary atmospheres in distant solar systems.

Australian researchers have leveraged the JWST and other international space-based facilities, including the Hubble Space Telescope (HST) and Spitzer Space Telescope, and have been preparing for the launch of several more facilities that span the electromagnetic spectrum. A growing proportion of the Australian community now uses datafrom these facilities through open access or via a suite of access paths.

Humanity's final look at the James Webb Space Telescope as it heads into deep space to answer our biggest questions. Alone in the vastness of space. This image was captured by the cameras on board the rocket's upper stage as the telescope separated from it. The Earth hovers in the upper right.
Image credit: Arianespace, ESA, NASA, CSA, CNES.

CASE STUDY

AUSCOPE VERY LONG BASELINE INTERFEROMETRY (VLBI): A CRITICAL COMPONENT OF GLOBAL GEODESY

The continent-wide AuScope Very Long Baseline Interferometry (VLBI) array of radio telescopes, operated by the University of Tasmania through a research collaboration with Geoscience Australia, is a critical component of the global geodesy supply chain.

This research instrument provides Australia's only contributions to the International Celestial Reference Frame (ICRF), a cosmic map used to measure the positions and movements of objects in space. This map uses black hole jets – known as radio-loud quasars – as reference points. These quasars are so distant and bright that from our perspective on Earth, they don't appear to move, making them useful reference points in the sky. The ICRF underpins the accurate positioning of objects in space, and is critical for deep space navigation, planetary ephemeris (record of planetary movements over time), and satellite services. It's also important for the precise positioning on Earth required to study global-scale processes such as sea level rise.

In 2015, the United Nations adopted a resolution on the importance of a global geodetic reference frame for sustainable development.[1] International activities towards achieving this are coordinated by the United Nations Global Geodetic Centre of Excellence headquartered in Bonn, Germany.

The accuracy of the global reference frame has historically been limited by the lack of infrastructure and quality observations in the southern hemisphere.[2] The AuScope VLBI telescopes contribute more than half of all geodetic observations in the southern hemisphere, and are among the busiest observatories globally. The *Hidden risk* report,[3] published by the United Nations in 2024, outlines how weaknesses in the global geodesy supply chain, including a deterioration of the ICRF, can have catastrophic impacts on critical infrastructure such as telecommunications and financial systems, and consequently national economies. Thanks to innovative broadband technology, the AuScope VLBI array is the only southern hemisphere instrument capable of matching the measurement accuracy achieved by the best telescopes in the northern hemisphere, and hence together with international partners of producing the highest-quality global reference frame.

1. United Nations General Assembly. 2015. Resolution 69/266: Establishment of the Committee of Experts on Global Geospatial Information Management (A/RES/69/266). Retrieved from https://ggim.un.org/documents/a_res_69_266_e.pdf
2. Jacobs, C. S., Arias, F. F., Boboltz, D. A., Böhm, J., Bolotin, S. V., Bourda, G., de Witt, A., Fey, A. L., Gaume, R. A., et al. 2014. ICRF-3: *Roadmap to the next generation ICRF* [Conference paper]. In N. Capitaine (Ed.), *Proceedings of the Journées "Systèmes de référence spatio-temporels"* (pp. 51–56). http://hdl.handle.net/20.500.12708/43389
3. United Nations Global Geodetic Centre of Excellence. 2024. *Hidden risk: Critical weaknesses in the global geodesy supply chain* (Policy Brief No. 001). https://ggim.un.org/UNGGCE/documents/20240620-Hidden_Risk_Report.pdf

‘These [AuScope VLBI] stations form some of the most crucial geodetic infrastructure in the world, given the sparsity of VLBI infrastructure in the southern hemisphere.’

Dr Nicholas Brown, Head of Office, UN Global Geodetic Centre of Excellence.

CSIRO’s Australia Telescope Compact Array on Gomeroi Country is one of the instruments that makes up the Australia Telescope National Facility. Image credit: CSIRO/A. Cherney.

The Milky Way hangs over the Very Large Telescope (VLT) in this spellbinding panorama taken at ESO's Paranal Observatory in the Atacama desert, Chile. Image credit: F. Char/ ESO.

05 KEY FACILITIES FOR THE NEXT DECADE

Answers to the astrophysics questions of the coming decade (section 2.2) will rely on access to world-leading facilities with spectroscopy and imaging capability across the electromagnetic spectrum, as well as gravitational-wave and high-energy particle detection.

In this section we describe the observational capabilities needed. We begin with optical and near-infrared wavelengths followed by radio wavelengths. We then leave the electromagnetic spectrum to explore multi-messenger capabilities with gravitational waves and high-energy particle detection. Finally, we outline the theoretical astrophysics capabilities we need to support the science questions. The order of topics does not imply priority, as answering the complex science questions will require all modes of scientific exploration.

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

5.1. ELECTROMAGNETIC SPECTRUM

5.1.1. HIGH-ANGULAR-RESOLUTION IMAGING

The capability to see and detect the finest detail in the Universe relies on angular resolution. Resolution is improved by increasing the diameter of telescope mirrors (optical/infrared (IR)) or dishes (radio/millimetre (mm)) or increasing the baseline between telescopes in optical or radio interferometers.

5.1.1.1. OPTICAL/IR ADAPTIVE OPTICS AND INTERFEROMETRY

Going beyond JWST's resolution needs the most powerful adaptive optics system combined with a significantly larger telescope, or interferometry at visible and infrared wavelengths.

This resolution is critical for many key questions of the coming decade, including the following.

- The nature of galaxies at cosmic dawn (Q1d). Only the angular resolution of the largest ground-based optical telescopes will see what these galaxies are made of.
- Resolving individual stars in nearby galaxies. This will extend our knowledge of the types of stars that make up different types of galaxies (Q1a, 1c).
- Resolving individual planets at the scale of most solar systems (Q4a), including the habitable zone. This is only possible for an optical interferometer.
- Imaging of galaxies in the epoch of cosmic change 3–8 billion years ago. This lets us observe as galaxies first start to take on their current-day shapes (Q1a, 1b).
- Directly imaging jets from the earliest stages of star formation. This will reveal how angular momentum is gained through discs and lost in jets in forming stellar systems (Q1b, 3a, 4a, 4b).

At infrared wavelengths, ESO's VLTI and Extremely Large Telescope (ELT; 39-metre diameter) offer the highest current and planned combination of angular resolution and sensitivity. This combination of large aperture and high angular resolution (using either adaptive optics or interferometry) drives key science outcomes. Currently ESO's VLTI facilities are world leaders in angular resolution, while sensitivity at high angular resolution is led by ESO's 4 Laser Guide Star Facility with adaptive optics at the VLT. The latter feeds the ERIS and MUSE instruments and represents an internationally unique $150 million upgrade to an 8-metre telescope.

The next leap in technology is the Australian-led MAVIS instrument (a total investment of $40 million), which will be more sensitive and have significantly higher angular resolution than the HST. Australia is guaranteed some access to MAVIS in its first three years of operation but has no access to VLTI after 2027 and no access to the ELT. After 2035, Australia will have access on GMT to the only extreme adaptive optics system on any 30-metre-class telescope (GMagAO-X) and the unique exoplanet science this will enable, in addition to high-resolution imaging capabilities through GMTIFS.

5.1.1.2. VERY LONG BASELINE INTERFEROMETRY

The SKA VLBI science case is strong, both for SKA-Mid (where the LBA would play a role) and SKA-Low (including the LAMBDA (Low-frequency Australian Megametre-Baseline Demonstrator Array) demonstrator being developed by CSIRO). Over the next decade, the LBA is likely to remain the leading high-resolution radio instrument at centimetre wavelengths and needs to be supported as an essential complement to SKA-Mid, for science and celestial reference frame determination.[26]

SKA-Low VLBI on Australian baselines gives matched resolution to high-angular-resolution optical/IR observations allowing:

- galactic processes to be studied in great detail (Q1a, 1d)
- the exploration of supermassive black holes and their life cycles (Q1b, 2a).

26. Charlot, P., Jacobs, C. S., Gordon, D., Lambert, S., de Witt A., Böhm J., Fey A. L., Heinkelmann R., Skurikhina E. *et al.* 2020. *The third realization of the International Celestial Reference Frame by very long baseline interferometry Astronomy and Astrophysics.* no. 644, A159. https://doi.org/10.1051/0004-6361/202038368

5.1.2. WIDE-FIELD IMAGING – OPTICAL/IR

Australia has undertaken many of its premier galaxy surveys based on wide-field optical imaging from the Sloan Digital Sky Survey, which focused primarily on the northern hemisphere. Since then, the Dark Energy Survey has added even more sensitive imaging for some of the southern hemisphere. Upcoming surveys will provide us with exquisite detail, both more sensitive and higher-resolution images with much-needed time resolution, on astronomical objects across the whole of the southern hemisphere. Imaging is the primary method for:

- mapping the Universe, including its most distant galaxies, which can also be used to measure dark matter and dark energy (Q1a, 1b, 1c, 2a, 2b, 2c)
- measuring violent cosmic explosions, as a probe of the objects themselves and the expansion of the Universe as a whole (Q1a, 2a, 2b, 2c, 3a, 3c)
- probing objects with variable flux, such as starquakes using asteroseismology or detecting the shadow of an exoplanet (Q1a, 2c, 3a, 4a, 4b).

5.1.2.1. VERA C. RUBIN OBSERVATORY'S LEGACY SURVEY OF SPACE AND TIME

Rubin's LSST will observe the whole southern hemisphere sky in six optical wavebands to unprecedented sensitivity with multiple visits over its 10-year survey.

These unique capabilities will enable:

- the selection of stars in the Milky Way, galaxies, and quasars for the study of stellar and galaxy evolution (Q1a, 1c, 2a)
- studies of galaxy shapes via lensing to explore the nature of dark matter (Q2c)
- a new window to time-domain astronomy (Q2a, 2b, 2c, 3a, 3b, 3c, 4b) and the most explosive phenomena in the Universe.

LSST will detect 10 million transients per night, such as supernovae, kilonovae, and other explosions. This is orders of magnitude more than previously discovered. Australia's unique location enables critical follow-up observations just hours after Rubin detections – which is important to understand the physical nature of these transients – and before many events fade away forever. Continued secure funding past mid-2027 is critical, otherwise access to the LSST annual data releases will be restricted for a two-year period, putting Australia at a significant disadvantage in terms of time-critical competitive science.

Aerial view of the Rubin Observatory enclosure and support building at top, with the Auxiliary Telescope for atmospheric monitoring in the foreground.
Image credit: Rubin Observatory/NSF/AURA.

5.1.2.2. WIDE-FIELD SPACE TELESCOPES

Most space telescopes have focused on very high-resolution imaging, sacrificing wide field for detail. In contrast, the Euclid space telescope, an ESA mission that launched in 2023, plans to image more than one-third of sky over the next five years in the infrared and visible wavelengths and will be a key facility for the Australian community. Australia has limited access to Euclid through legacy science projects. Separate to this proprietary access, Euclid data will be released publicly after a two-year delay.

PLAnetary Transits and Oscillations of stars (PLATO) is an ESA space telescope being developed for launch in 2026, with data publicly available. PLATO will use 26 cameras to characterise planets' host stars, measure the sizes of exoplanets, and discover exomoons and rings around them.

The Nancy Grace Roman mission (Roman) is NASA's next flagship mission scheduled for launch in 2027. It will undertake three community-defined surveys including a wide area survey (up to 4,000 deg^2), and two time-domain surveys. All Roman data will be immediately publicly available.

The data volumes of these major imaging surveys are immense, with petabytes of data being made available, and individual frames being tens of gigabytes. This is fundamentally changing how we approach astronomy, since downloading the data to a local machine and analysing it there is no longer feasible (see section 6.2).

5.1.3. SPECTROSCOPY – OPTICAL

5.1.3.1. MULTI-OBJECT SPECTROSCOPY

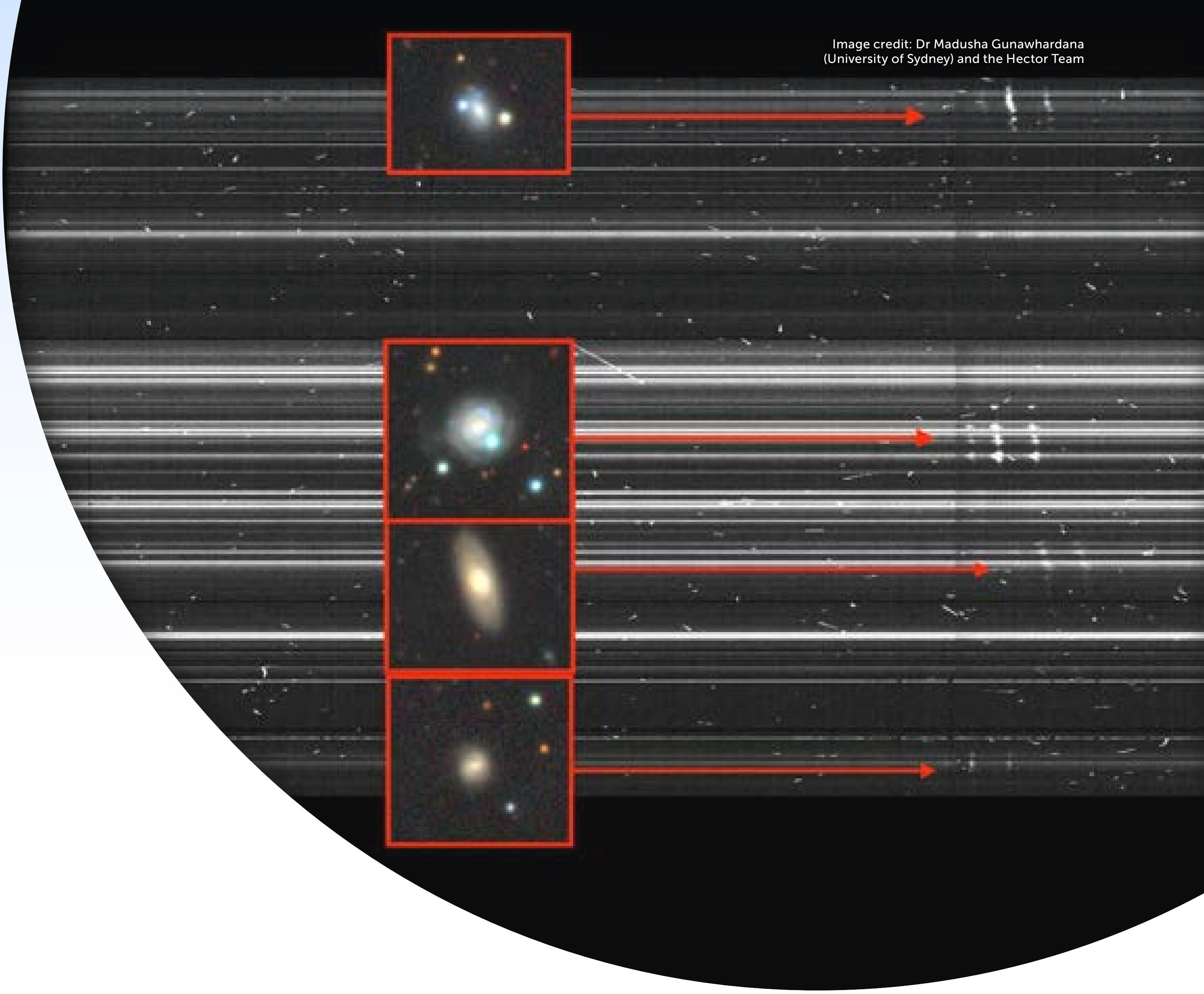
Since Australia's pioneering 2dF robotic fibre positioning system on the AAT, we have been among the world leaders in multi-object spectroscopy, which enables the line-of-sight velocities and elemental make-up of stars and galaxies to be probed.

Key science drivers include:

- mapping the distribution of galaxies using redshift surveys, in order to measure the expansion of the Universe and reveal the nature of dark energy (Q2b, 2c)
- mapping the motion of galaxies using peculiar velocity surveys, in order to map the presence of dark matter and determine its properties (Q2c)
- galactic archaeology – piecing together the building blocks of the Milky Way through their elemental fingerprints (Q1a, 1b, 1c)
- exploring the structure of the cosmic web and galaxy environment (Q1a, 1c).

To observe fainter stars and galaxies, key instrumentation is moving to sites of excellent atmospheric quality like Chile. Most importantly, this includes 4MOST (4-metre Multi-Object Spectroscopic Telescope) on ESO's VISTA telescope, where Australian astronomers already have access over the 2025–2029 period, and the Dark Energy Spectroscopic Instrument (DESI) in the north and its extensions from 2026–2030. For 8-metre-class telescopes, the ESO/MOONS multi-object spectrograph, to be commissioned in 2026, will be substantially more capable than any other southern hemisphere capability. Australian astronomers from six universities are also part of the proposing team for the 10–12-metre Wide-field Spectroscopic Telescope, a potential major new ESO facility for the 2030s. GMT is also the only 30-metre-class telescope planned with ground layer adaptive optics over a full field of view. This unmatched wide field of view and the Australian MANIFEST facility multi-object fibre system planned for the late 2030s will enable simultaneous spectroscopic observations of stars and distant galaxies. At first light at the end of this decadal plan, GMT will also extend multi-object spectroscopy to fainter stars beyond the Milky Way with the seeing-limited GMACS instrument.

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.



5.1.3.2. INTEGRAL FIELD SPECTROSCOPY

Australia built some of the earliest multiplex integral field spectroscopic units (GIRAFFE for the VLT and more recently the SAMI and Hector instruments for the AAT). Today the AAT/Hector instrument is the only multi-object integral field spectrograph that has a spectral resolution high enough to determine the stellar kinematic properties of low-mass galaxies and the outer regions of disc galaxies. The Hector Galaxy Survey is currently underway and plans to observe 15,000 galaxies. This survey will be completed in the first half of the decade, establishing the current-day properties of galaxies.

To extend this understanding to the redshift range where galaxies first start to take on their current-day shapes (Q1a), access to integral field spectroscopic units on 8-metre telescopes like MUSE on ESO's VLT and much larger telescopes will be crucial if Australia is to maintain its leadership in this area.

5.1.3.3. HIGH-RESOLUTION SPECTROSCOPY

Many telescopes have high-resolution spectroscopy capability, with Australian astronomers currently having access to Veloce on the AAT, as well as the world's best high-resolution spectrographs HARPS, ESPRESSO and UVES through ESO. At the end of the decade, G-CLEF on GMT will extend precision stellar astrophysics and exoplanetary science to significantly fainter stars.

High-resolution spectroscopy of stars enables two primary scientific themes:

- the measurement of elemental fingerprints of populations of stars and even the first supernovae that exploded in the Universe (Q1a, 1c, 2c, 2d, 3c)
- the measurement of very precise radial velocities, enabling the gravitational pull of planets orbiting their host stars to be seen and exoplanetary masses and orbits measured (Q4a, 4c).

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

5.1.3.4. TRANSIENT FOLLOW-UP SPECTROSCOPY

As new fast imaging facilities come online, we are expecting millions of new transient discoveries nightly. These transient detections come from a wide variety of sources, but they all are temporary flashes in the sky. They often come from explosive events and can last from fractions of a second to months in duration. The ability to follow up interesting transients opens a new world of time-domain astronomy. Interesting transient objects found with imaging facilities need spectroscopy at low or medium spectral resolution in order to identify the properties of the transient source and put them in a cosmic context (Q1c, 2a, 2b, 2c, 3a, 3b, 3c, 4b).

Australian astronomers currently use the AAT and the now robotic ANU 2.3-metre telescope for this follow-up (accessible nationally), as well as key ESO facilities such as X-Shooter and FORS2. With Australian sunset following Chile's by approximately eight hours, our domestic facilities are perfectly placed to be competitive for time-critical follow-up of transients discovered by facilities such as Rubin.

5.1.4. THE NEXT DECADE: OPTICAL, INFRARED AND MILLIMETRE ASTRONOMY

To answer the science questions outlined in section 2.2, it is clear that ESO membership meets every required capability in the optical, infrared and millimetre wavelengths in one single organisation.

In the optical and infrared, ESO provides:

- the highest available angular resolution imaging via the VLTI, the Laser Guide Star facility with adaptive optics at the VLT and the ELT (to be completed in 2028)
- multi-object spectroscopy via 4MOST on ESO's VISTA telescope and MOONS (to be commissioned on the VLT in 2026)
- integral-field spectroscopy via MUSE on the VLT
- high-resolution spectroscopy via ESO's HARPS, ESPRESSO and UVES instruments
- transient follow-up spectroscopy via X-Shooter and FORS2 on the VLT.

In the millimetre, ESO also provides access to ALMA, a unique facility at these wavelengths (described in section 5.1.5.2).

In addition, ESO membership also offers a broader return on investment to Australia as a whole. The 2024 review of AWLAI noted that Australia's strategic partnership has:

- created workforce and training opportunities
- increased collaboration between Australian and international researchers
- increased Australia's international competitiveness
- enabled access to and awards of commercial tenders
- enhanced industry collaboration and the commercialisation of astronomy technical expertise.[27]

The report also noted that full membership of ESO would further enhance the contracting opportunities for Australian industry.

Without ESO, a distributed approach can provide some of the capabilities required to answer the science questions. It is not possible to assemble an ESO-equivalent suite of optical/infrared facilities, as the critical, highest-angular-resolution

27. ACIL Allen. 2024. Evaluation of the Access to World Leading Astronomy Infrastructure (AWLAI) program: Final report. https://www.industry.gov.au/publications/mid-term-evaluation-access-world-leading-astronomy-infrastructure-program

capabilities are unique to ESO. The high-angular-resolution capability could be partially achieved by GMT's GMagAO-X and with the Australian-led GMTIFS instrument. GMT will also have unique strengths in wide-field astronomy compared to other 30-metre-class telescopes, as well as substantial optical capabilities. Therefore, ensuring the completion of GMT to protect Australia's early investment is critical. Nonetheless, these capabilities will not become available until after 2035, and would require a significant additional investment (around $300 million at current prices) to expand Australia's share in the GMT from 5% to the 10% envisioned in the 2016–2025 decadal plan, should ESO membership not go ahead.

Without ESO membership, other options exist for optical/infrared multi-object, high-resolution, and integral field spectroscopy with 8-metre-class telescopes. Multi-object spectroscopy may be possible through the Subaru telescope. As of 2019, there are two categories of Subaru partnership, with Subaru still actively looking for partners in 2024. Either option would provide less than half of the access to 8-metre-class facilities compared to the current ESO partnership, but could also partly achieve visible-light high-angular-resolution needs with the adaptive optics capability planned for Ultimate-Subaru.

High-resolution spectroscopy may be possible through the Gemini, Keck, and/or Magellan telescopes. Gemini includes two 8-metre optical/IR telescopes, one in each hemisphere. Australia let their previous time access agreement with Gemini lapse in 2016 as the outcomes had been suboptimal as a relatively minor partner in the observatory. There is currently little opportunity to join Gemini as a member state and any future opportunities would likely be at a <10% level. Keck has the most comparable instrumentation suite to ESO's optical instruments and has an existing partnership with Swinburne University of Technology. Any national agreement would need to provide the same number of 8-metre nights currently being used by the community in the ESO partnership (~60 nights per year) which may be deemed infeasible by the other Keck partners. Magellan includes two 6.5-metre optical/IR telescopes in the southern hemisphere. Australia let their previous limited time access agreement with Magellan lapse in 2017. Magellan has a range of instrumentation capabilities including multiple spectroscopic facilities, but it lacks a large-format integral field spectrograph. Purchasing time may be available for Magellan. Transient follow-up spectroscopy is enabled at some level at most 8-metre-class telescopes.

A piecemeal approach also lacks access to the millimetre science enabled by ALMA. ALMA access may be possible through its East Asian or North American nodes, but that option has not yet been explored.

Building the relationships required to establish these agreements with other telescopes would take a significant amount of time and, should they be successful, would require managing multiple significant foreign partnerships with different contractual requirements, expectations, and delivery models.

Furthermore, we estimate that the combined annual cost of the portfolio approach is comparable to the annual fee for ESO membership, yet it lacks key capabilities that are important to Australian research.

In contrast, the benefits of ESO membership extend beyond their excellent optical, infrared, and millimetre capabilities. A partnership with ESO brings return on investment through enabling Australian contribution to the Observatory's strategic decision-making. ESO's long-term stability is essential in leveraging Australian astronomy's ability to attract, retain, and develop a highly skilled workforce and ESO enables access for Australian industry to their construction and instrumentation programs.

Image credit: ESO/B. Tafreshi (twanight.org).

5.1.5. WIDE-FIELD IMAGING AND SPECTROMETRY – RADIO

With a major step-change in radio astronomy coming with the SKA telescopes, large radio astronomy surveys will for the first time have comparable angular resolution to optical astronomy surveys, enabling more opportunity for radio and optical data to synergistically examine the same physical processes.

5.1.5.1. WIDE-FIELD IMAGING AT LOW FREQUENCIES

MWA

The MWA will remain a key technology and science precursor at low frequencies until SKA-Low completes construction and becomes available to astronomers during the coming decade.

Until that time, MWA will continue to:

- study low-frequency radio transients (Q2a, 3c)
- map the radio sky including galaxies and their active galactic nuclei (Q1a, 1c)
- search for primordial hydrogen in the Epoch of Reionisation (EoR) and cosmic dawn (Q1d).

Along with ASKAP, MWA will play a key role in the development of the AusSRC toward full SKAO science operations.

SKA-LOW

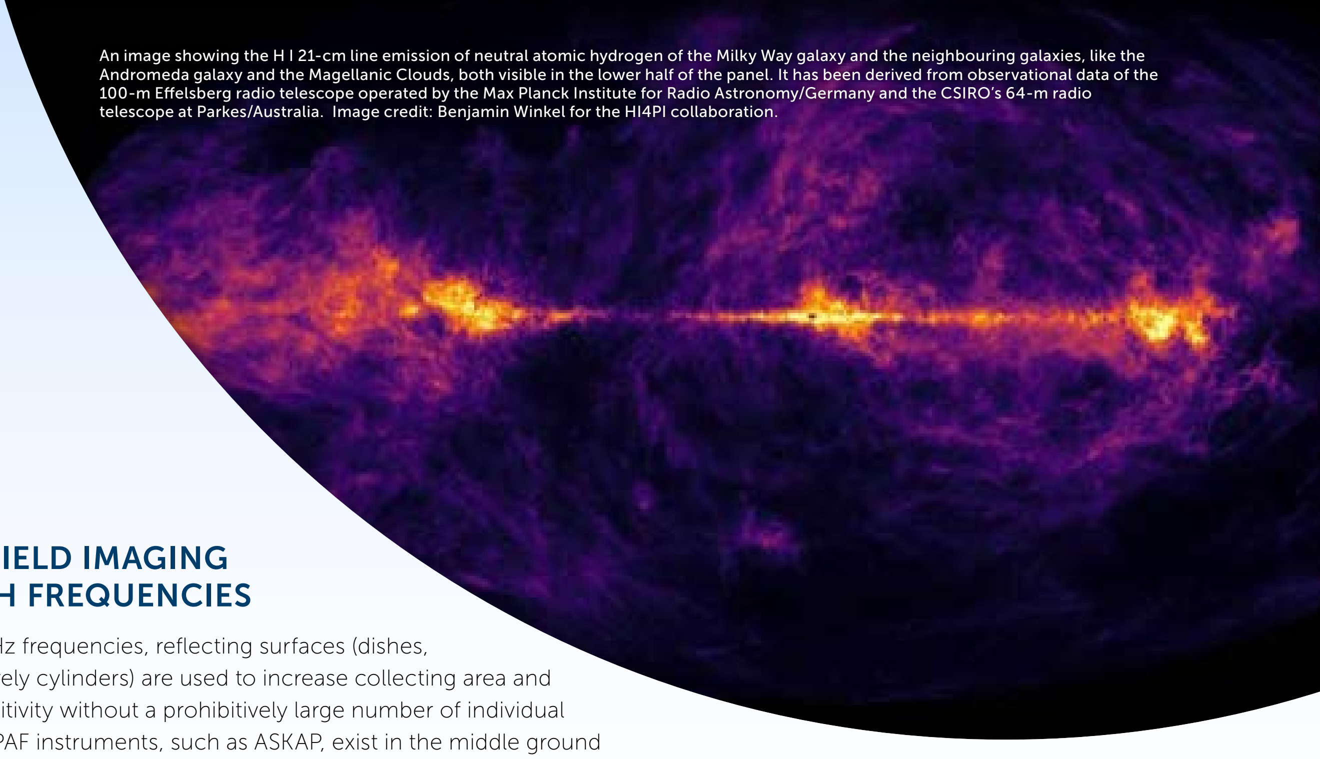
SKA-Low, hosted on Wajarri Yamaji Country in the Western Australian outback, will revolutionise our understanding of the Universe. It will become the most sensitive low-frequency telescope in the next decade, allowing detailed studies of galaxies across the electromagnetic spectrum.

It will be the key facility for direct detection and imaging of the EoR and cosmic dawn (Q1a, 2a). Its higher angular resolution and excellent surface brightness sensitivity will provide the best chance to overcome the systematic limits that currently inhibit detection of the EoR in 21 cm emission from neutral atomic hydrogen (H I). It is the only telescope capable of directly mapping the primordial gas. This will open up the first billion years of cosmic time, revealing how the first galaxies shaped the Universe that we see today.

SKA-Low will open new parameter space in detecting, characterising and monitoring extreme stars, such as pulsars, magnetars and other radio transients (Q3b, 3c), complemented by follow-up with 8-metre-class optical telescopes and coordinated observations with the existing radio facilities in Australia such as ASKAP.

Australian researchers will be at the forefront of programs exploring the cosmic dawn era and observing low-frequency pulsars (Q3b).

SKA-Low antennas at the S8 station on the southern spiral arm of the SKA-Low telescope.
Image credit: SKAO/Max Alexander



An image showing the H I 21-cm line emission of neutral atomic hydrogen of the Milky Way galaxy and the neighbouring galaxies, like the Andromeda galaxy and the Magellanic Clouds, both visible in the lower half of the panel. It has been derived from observational data of the 100-m Effelsberg radio telescope operated by the Max Planck Institute for Radio Astronomy/Germany and the CSIRO's 64-m radio telescope at Parkes/Australia. Image credit: Benjamin Winkel for the HI4PI collaboration.

5.1.5.2. WIDE-FIELD IMAGING AT HIGH FREQUENCIES

At >350 MHz frequencies, reflecting surfaces (dishes, or more rarely cylinders) are used to increase collecting area and hence sensitivity without a prohibitively large number of individual elements. PAF instruments, such as ASKAP, exist in the middle ground between reflector-less aperture arrays and traditional 'single-pixel' dish arrays. These combine a reflecting surface with an array of feeds on each telescope to provide a survey speed dozens of times greater than the equivalent single-pixel instrument.

Using this technique, neutral hydrogen can be studied from two billion years after the Big Bang until the present day, and hydrogen structure can be resolved on much finer scales (Q1a, 1d, 2b, 2c).

MURRIYANG

Murriyang, the CSIRO Parkes radio telescope, in Australia. With its CryoPAF upgrade, large 64-metre dish diameter, and new ultra-wide feeds, is a flexible, high-sensitivity, and fast-survey-speed facility. The CryoPAF upgrade to reduce the system temperature and increase its wide-field capability will deliver game-changing discovery-space opportunities.

Sharing a common sky with Western Australian facilities including SKA-Low, Murriyang can provide the wide-field information to complement interferometers, particularly for:

- neutral hydrogen studies in the local Universe (Q1a, 1b)
- studies of technosignatures (i.e. potential signs of life from technology) from distant stellar systems (Q4b)
- detection, timing and characterisation of pulsars (Q3b).

With a continued technology development and upgrade path, Murriyang will continue to be attractive to external paid users while developing technology for future pathways for SKA telescopes and others.

ASKAP

ASKAP is co-located with MWA and SKA-Low at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory, with frequency coverage that targets hydrogen in the most recent few billion years of the Universe.

Its fast survey speed, large instantaneous field of view, excellent polarisation characteristics, and high sensitivity are delivering key five-year science programs, including:

- mapping the Universe (Q1a, 2b, 2c) and studying local hydrogen (Q1a, 1b) (positioning Australian researchers for future studies with SKA-Mid)
- world-leading FRB research (Q2b, 3c) and polarisation studies (Q1a)
- discovery of odd radio circles (very large unexplained astronomical objects)
- finding supermassive black holes in the centres of galaxies (Q2a).

ASKAP's future contributions as part of the national facility suite beyond the existing survey science programs will depend on potential upgrade possibilities, complementary alignment with the international radio telescope landscape, and extending its unique scientific and technical capabilities.

ATCA

ATCA operates to much higher frequencies than ASKAP and extended observing programs with the flexibility for array reconfiguration. With the BIGCAT upgrade close to completion, studies of astrophysical objects can be achieved over a wider frequency range simultaneously, increasing its science impact.

Moving toward the era of SKA-Mid full operations, ATCA will provide leadership in unique capabilities such as its rapid-response modes and millimetre-wavelength receivers. ATCA will move to a new phase of operations and funding pathways to support its role in student training, transient follow-up, technology demonstration, and as an essential part of the LBA. It will take advantage of its unique geographic location for global monitoring, playing a role in international programs that require continuous longitude coverage, such as LSST.

ATCA will remain scientifically valuable for projects that require large amounts of observing time, and for rapid transient follow-up from SKA-Low or ASKAP events when SKA-Mid is not able to see the shared sky (Q3b, 3c).

ATCA will play a unique role in the southern hemisphere in providing capabilities at mid frequencies (2–5 GHz), with these bands being delayed on SKA-Mid beyond 2030. It will play a unique role in the 15–35 GHz bands that are key to the detection of atoms and molecules in our galaxy that are responsible for star formation and evolution, filling the frequency gap between SKA-Mid and ALMA (Q1b).

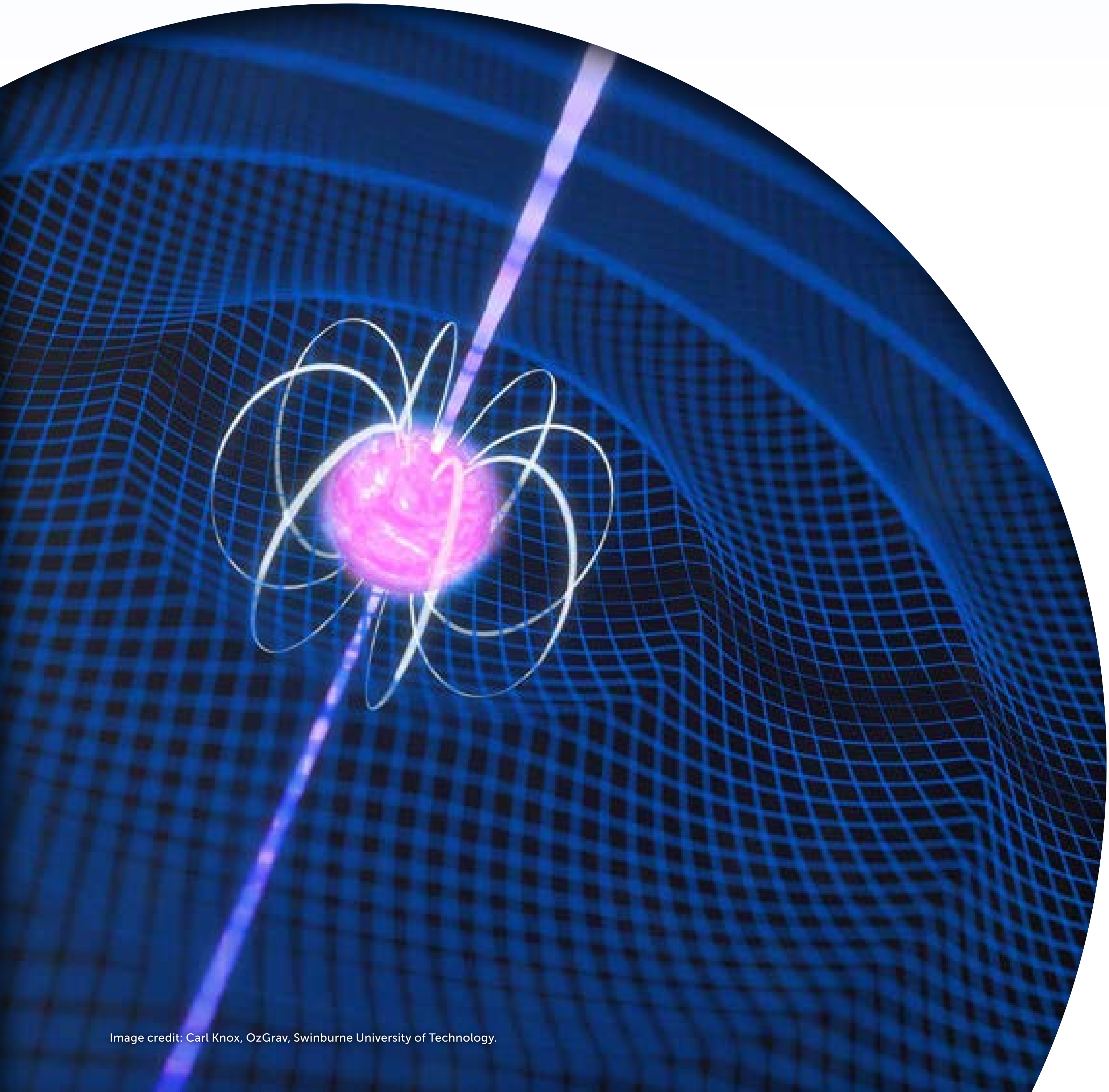


Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

An antenna at the SKAO's mid frequency telescope array (SKA-Mid) in South Africa. Image credit: SKAO / Max Alexander

SKA-MID

SKA-Mid, a high-angular-resolution, high-sensitivity array hosted in the Karoo region of South Africa, will be a key facility for the study of:

- FRBs and pulsars (Q3b, 3c)
- cold gas in galaxies (Q1a, 1b, 1c)
- galaxy evolution across cosmic time and extreme stellar environments (Q1a, 3c)
- high-precision timing of pulsars – complementing multi-messenger programs to detect the background of nanohertz gravitational waves from coalescing neutron stars (Q2a).

With high sensitivity and resolution, SKA-Mid will survey the sky tens of times more rapidly than its precursors. Australia will lead the detection of tens of thousands of FRBs localised with exceptional precision.

SKA-Mid's sensitivity means that it could:

- observe FRBs out to redshift z=10, providing a complementary measure of helium reionisation at z=3
- observe pulsar timing, which provides an astrophysical probe of gravitational waves
- reveal the cosmic web of diffuse emission illuminated by magnetic fields
- map star formation and kinematics of cold gas in galaxies, in tandem with ALMA.

ALMA

ALMA's large frequency range covers 35 GHz to 950 GHz. There are no comparable facilities to ALMA with respect to its sensitivity and frequency range. Australian astronomers currently only have access to ALMA through a very limited amount of open time as access is not included in the strategic partnership with ESO. As a result, Australians are not able to lead large programs despite it being one of the most popular facilities among astronomers according to a survey conducted for this decadal plan. As an extremely versatile facility, in addition to surveying the sky one square arcminute at a time, it can see detail that is comparable to MAVIS on the VLT or the ELT.

This enables:

- observing star formation tracers such as CO and CII in individual galaxies in the first billion years of the Universe, and in individual star-forming regions at cosmic noon (Q1a, 1b)
- providing direct measures that complement 21 cm EoR studies with MWA and SKA-Low, and future optical observations with 30-metre-class telescopes (Q1d)
- resolving clear signatures of newly formed exoplanets sculpting their protoplanetary discs, right down to solar system scales in nearby star-forming regions (Q4a, 4b).

Although completed, ALMA is not static – an upgrade of the most popular Band 6 (1 mm wavelength; 300 GHz frequency) is already funded and underway, increasing the speed of observations two to four times by mid-decade.

CASE STUDY

ASTRONOMY MEETS DEFENCE: DETECTING SATELLITES AND SPACE DEBRIS

Swinburne University of Technology PhD student Tallulah Waterson was awarded a Defence Science Institute Research Higher Degree Student Grant of $15,000 for her work connecting astronomy with both industry and defence. She uses the Vera C. Rubin Observatory and the Fink alert broker to detect satellites and space debris.

To maintain the viability and safety of space, it is critically important to enhance capability for space domain awareness (SDA). Most SDA activities are conducted by defence-aligned organisations or commercial entities that perform SDA as a service. Australian astronomers have a unique opportunity to contribute by providing an additional source of information for global SDA efforts. Waterson's work focuses on the role that astronomical facilities can play in SDA by repurposing data, with the goal of sustaining space for all.

Tallulah Waterson's work has provided work experience students with the opportunity to work at the intersection of astronomy and SDA. Image credit: Christopher Fluke (Swinburne University of Technology), CC BY-NC-ND 4.0.

5.1.6.
THE NEXT DECADE: RADIO AND MILLIMETRE

Prior to full SKAO science operations, MWA, ASKAP, Murriyang and ATCA provide science capabilities and enable technological developments. ATCA will also play a role in rapid transient follow-up and some millimetre science while Australia does not have full access to ESO/ALMA and will retain unique millimetre capabilities in the ALMA era.

Once SKAO is fully operational in the middle of this decadal plan period, SKA-Low and SKA-Mid provide the majority of the capability needed in the 50 MHz–15 GHz frequency range. Radio instrumentation and technology development programs will continue to support future SKAO and domestic technology priorities. SKA-Low's excellent sensitivity can provide the anchor for a new low-frequency VLBI capability, to complement the mid-frequency capability of the LBA.

Access to ATCA and ALMA will deliver the science needs of the community in the millimetre bands. ATCA is likely to remain an essential instrument at least until SKA band 5 becomes operational towards the end of this decade. Australia has an opportunity to lead the development of higher field-of-view capabilities for higher frequency telescopes through PAF technologies.

We should aim to secure strong Australian representation in the leadership teams of SKA's key science projects, leverage the AusSRC and the SKA Regional Centre Network to maximise the scientific return on the data taken with SKA-Low and SKA-Mid, and be ready to take and process data for the highest-impact science.

5.1.7.
ROLE OF DOMESTIC FACILITIES IN THE INTERNATIONAL CONTEXT

Although international-scale facilities such as ESO and SKAO provide unprecedented opportunities, they cannot deliver everything required to advance our understanding. National and university facilities provide valuable complementary and additive capabilities, enabling rapid and experimental innovation. These facilities increase Australia's impact and multiply our benefit from participating in international projects. In particular, for rapid-response time-domain explorations or joint multi-wavelength campaigns, having facilities located in Australia is a critical component (Q1a, 1b, 1c, 1d, 2a, 2b, 3b, 3c, 4a).

Examples of such capabilities include:

- world-leading surveys being completed by the AAT, ASKAP and MWA
- the frequency range and rapid response of ATCA
- Murriyang for technology development and demonstration, in addition to single-dish support for future radio interferometric surveys
- the LBA southern hemisphere VLBI capability
- the fully automated ANU 2.3-metre telescope
- the University of Tasmania geodetic VLBI network.

Within the coming decade, the AAT will reach the natural end of its life as a professional multi-use observatory, following completion of high-priority science surveys like the Hector Galaxy Survey and the shift to better sites than Siding Spring for optical astronomy. Subsequently, the AAT will need a new operational model. The future of Siding Spring Observatory includes consideration of a growing base of external users, including for space domain awareness.

University-scale facilities currently play a key role in national VLBI, and sustained funding is needed to keep these operating in a national facility capacity.

With a continued technology development and upgrade path, Murriyang and ASKAP can demonstrate technology for future pathways for SKAO and other telescopes. ATCA will move to a new operational and funding model, focusing on the scientific value of sharing a common sky with SKA-Low and ASKAP, unique frequency bands, rapid-response capabilities, and extended observing campaigns. Upgraded capabilities of the MWA will continue to support Australia's low-radio-frequency research community in preparation for SKA-Low.

Murriyang, CSIRO's Parkes radio telescope, on Wiradjuri Country. Image credit: CSIRO/Red Empire Media.

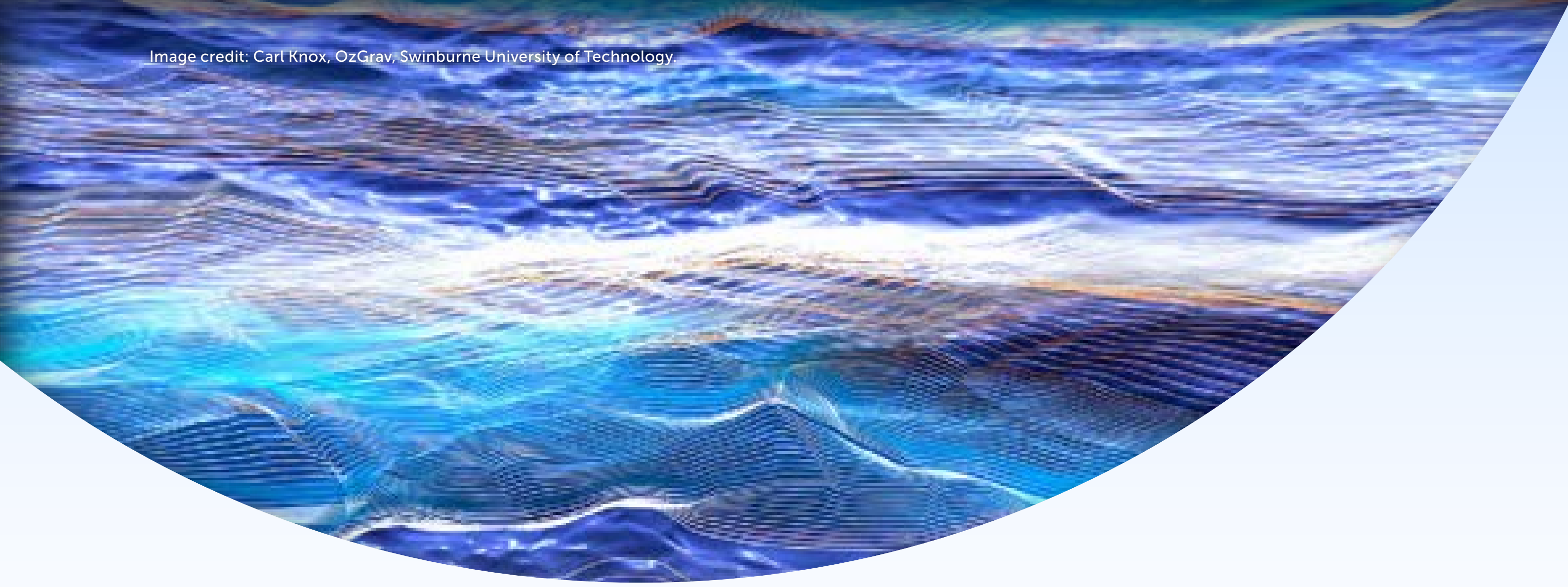


Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

5.1.8. INTERCONNECTION

Very few of the science questions posed in section 2.2 can be answered by a single facility, instrument, or wavelength alone.

Answering these questions takes capabilities across the electromagnetic spectrum, together with detection of gravitational waves and high-energy particles. For each of the science question groups in section 2.2, we give examples of the synergies in capability that are required to answer them.

5.1.8.1. FORMATION AND EVOLUTION

Galaxies are made up of stars, gas, dust, and dark matter. Gas flowing into, out of, and around galaxies plays a key role in shaping how their properties evolve over cosmic time. To understand this process in detail we need to bring together facilities in the optical/IR (stars), millimetre (dust), radio (gas), as well as theoretical expertise.

5.1.8.2. DARK UNIVERSE

Galaxy redshift, cosmic microwave background and Type Ia supernova surveys are the mainstay of dark matter and dark energy studies. In addition, gravitational-wave events caused by the merger of compact objects (black holes or neutron stars) can act as 'standard sirens', allowing an estimate of distance and hence expansion rate that is independent of the cosmic distance ladder. Key to this will be follow-up of the next generation of gravitational-wave sources to characterise them and measure redshifts, which will require wide-field imaging telescopes and spectroscopy. Alternative routes include cross-correlation with galaxy catalogues. This means that complete and deep optical and radio spectroscopic galaxy redshift surveys will be a valuable resource both in their own right and for cosmology with gravitational waves.

5.1.8.3. EXTREME ENVIRONMENTS

Studies of explosive and transient astronomical events are implicitly multi-wavelength. For example, as their name suggests, FRBs are found in radio data, which pinpoint the location of the burst on the sky. With the locations in hand, optical/IR spectroscopy with 8-metre-class telescopes (such as the ESO/VLT) is necessary to identify and characterise the host galaxies of these objects and measure how far away the galaxies are. This brings us closer to understanding what astronomical phenomena cause these bursts.

5.1.8.4. EXOPLANETS

Understanding the planet-forming regions around stars requires observations at different angular resolutions across the electromagnetic scale. Some of the most exciting research will come from combining high-angular-resolution observations of binary stars, thermal emission from the dust ring in which the planets form, the scattered light from the disc surface, and the dust emission from the planet-forming region.

Investigation of the full spectrum of electromagnetic radiation is going to improve in a dramatic way in the next decade, creating synergies that progress multi-wavelength and multi-messenger astrophysics.

5.2. LASER INTERFEROMETER GRAVITATIONAL-WAVE DETECTORS

Gravitational-wave observatories, including VIRGO, KAGRA and Australia-supported LIGO have ushered in a new era of gravitational-wave astronomy.

The newly discovered families of merging black holes (Q2a, 3c) and ultra-compact objects (Q3b, 3c) will continue to grow, as each observing campaign pushes to deeper limits, uncovering more merging objects of more types. This is especially true with the inclusion of new Australian technology in LIGO's upgrade for their fifth observing run and the addition of the recently approved LIGO-India. At the end of the coming decade, new facilities such as the Einstein Telescope (Europe), Cosmic Explorer (US), or the Laser Interferometer Space Antenna (LISA) may be about to come online.

Given Australia's geological stability and beneficial location on Earth, there is a strong argument for hosting a gravitational-wave detector here. Long baselines (large separation between detectors) allow for the best localisation of gravitational-wave sources, and a detector located in Australia would allow for the longest baselines in the Earth-based gravitational-wave detector network. The feasibility, design, and development of an Australian detector is currently being explored. The project would need to engage international partners, generating significant investment for construction of a world-class facility on Australian soil. Such a detector could potentially focus on kHz frequencies. This would make it sensitive to neutron star mergers, which offer some of the best potential for exciting scientific discoveries such as understanding the physics of matter at extreme densities (Q3b) and measuring the expansion rate of the Universe (Q2b).

5.3. HIGH-ENERGY GAMMA-RAY AND PARTICLE DETECTION

Observing some of the highest energy phenomena in the Universe (0.05 to 300 TeV energies) will become possible over the next decade using the CTAO, which has more than a factor of 10 gain over previous gamma-ray observatories.

Australia's growing community of approximately 30 scientists working in this field currently have access to CTAO through LIEF and NCRIS funds. Supporting longer-term ongoing access is a key priority.

Australia also has access to the IceCube Neutrino Observatory, a neutrino observatory constructed at the South Pole Station in Antarctica, and the Pierre Auger Observatory, an international cosmic-ray observatory in Argentina.

Investigating these highest energies grows our understanding of ultra-compact objects and cosmic explosions as well as galaxy evolution (Q1a, 2b, 2c, 3b, 3c).

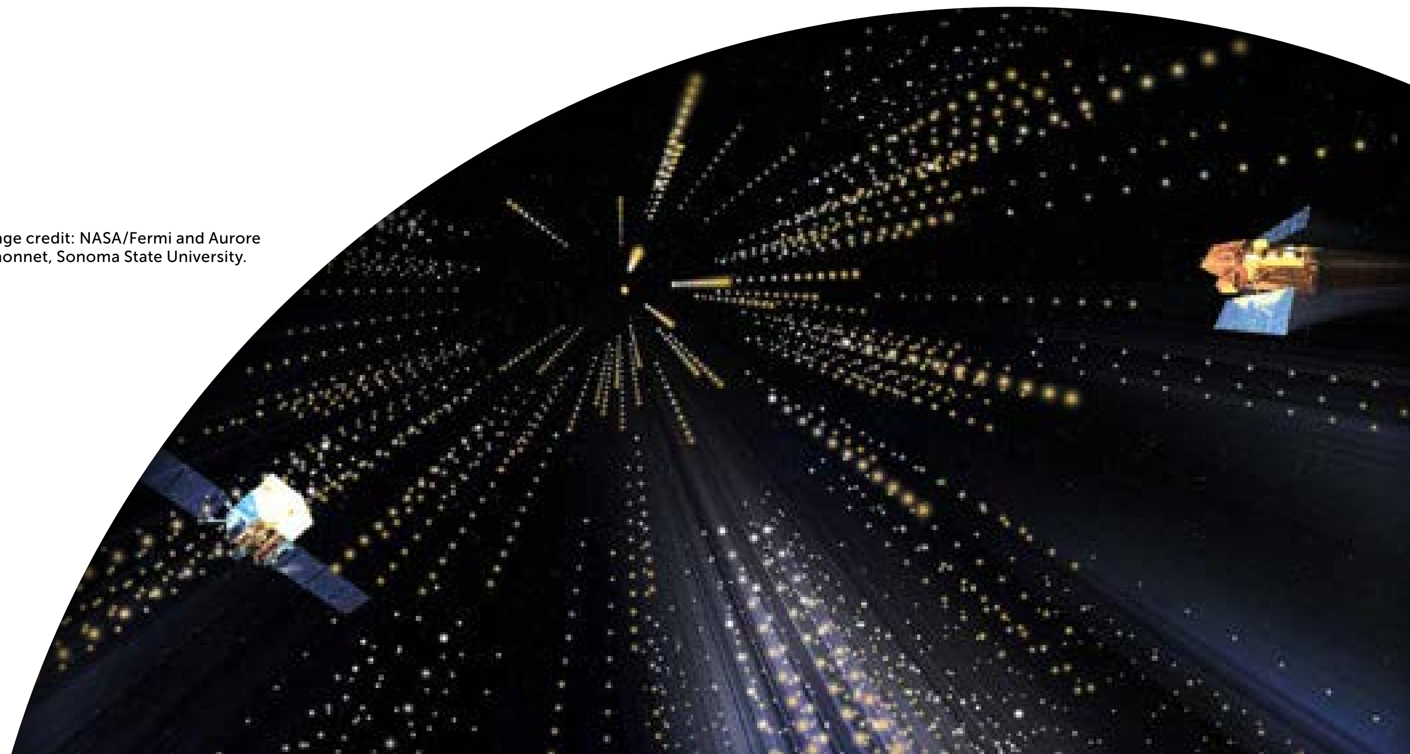


Image credit: NASA/Fermi and Aurore Simonnet, Sonoma State University.

Image credit: Carl Knox, OzGrav, Swinburne University of Technology..

5.4. THEORETICAL ASTROPHYSICS

Unravelling the key science questions of the next decade requires more than just observations. Theoretical astrophysics is thus an integral element in our quest to understand the Universe. Australia's theoretical astrophysics community is of a similar size to the radio and optical communities and is working on problems at the forefront of science.

5.4.1. GALAXIES, STAR FORMATION AND INTERGALACTIC MEDIUM

Theoretical astrophysicists are building bridges between the large and small scales in simulations by developing models for unresolvable processes (e.g. pressure from cosmic rays and dynamo-amplified magnetic fields, and energy and momentum injection by supermassive black holes, Q1a, 1c, 2a). They are building models for the structure and evolution of the interstellar medium on small scales – for example, the origin of turbulence and magnetic fields, and the distribution of metals (Q1b, 1c, 4b).

5.4.2. COSMOLOGY AND ASTROPARTICLE PHYSICS

Theoretical astrophysicists are developing alternative dark matter models, which can then be compared to the data alongside the standard cold dark matter model (Q1a, 1d, 2c). Analysing the standard cosmological model in large galaxy surveys (Q2b, 2c) requires detailed theoretical modelling. This requires close collaboration between the cosmological simulation, astroparticle physics, observational, and statistical inference communities. Theoretical astrophysicists are modelling how to exploit SKA telescope capabilities and similar wide-area, low-frequency radio facilities. This requires collaborations between galaxy formation theorists and simulators, survey designers, and machine learning specialists. Theorists are also furthering our understanding of FRBs, and their use for measurements of the state of the gas in the intergalactic and circumgalactic medium (Q1b, 3c).

5.4.3. HIGH-ENERGY ASTROPHYSICS: JETS, COMPACT OBJECTS, COSMIC RAYS

Theoretical astrophysicists are understanding how black hole jets launch and how they interact with their surroundings (Q1b, 2a, 4b). This theory is refining our understanding of source populations that will emerge from gravitational-wave observations with LIGO and Advanced LIGO and large transient surveys such as LSST (Q2a, 3b, 3c). It is also furthering our understanding of the population of gamma ray sources revealed by CTAO (Q1a, 2b, 2c, 3b, 3c).

5.4.4. STARS, PLANETS AND SUPERNOVAE

Theoretical astrophysicists are characterising habitable exoplanets and their atmospheres (Q4a, 4c), studying the nature and demographics of the first stars and second-generation stars (Q2, 4), and finding any signs of pair instability supernovae (Q3c). They are also understanding the internal mixing and angular momentum transport processes in stars and planets (Q4a, 4b, 4c). Theoretical astrophysicists are understanding how the magnetic field of the Sun and stars is generated and how it provides a conduit for energy transport through stellar systems (Q4b). They are revealing the origins and properties of globular clusters and their connection to reionisation (Q1c, 1d).

5.4.5. THE NEXT DECADE

The theory community is spread across the nation and lacks the coordination and focus that comes as a natural consequence of a physical telescope facility. The potential success of the community in answering the big theoretical science questions would be increased by improving the representation at senior leadership levels and building critical mass.

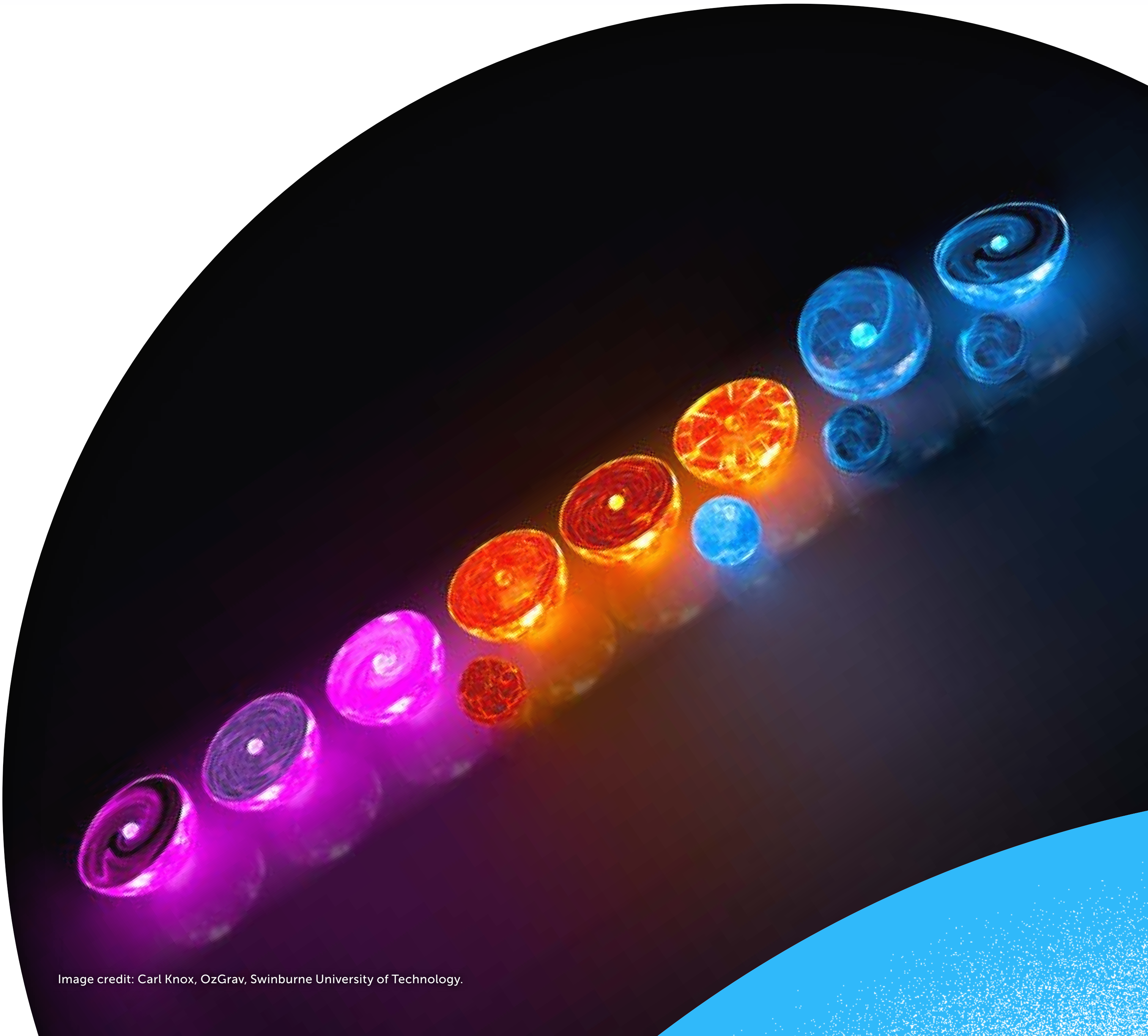


Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

06
ADVANCED SCIENTIFIC COMPUTING AND DATA INFRASTRUCTURE

Image credit:

Image credit:
Carl Knox, OzGrav,
Swinburne University
of Technology.

6.1. THE DECADE IN REVIEW

High-performance computing (HPC) is a critical capability for astronomy – both for theoretical simulations and for data processing in the age of next-generation telescopes. The 2016–2025 decadal plan called for 'world-class HPC and software capability', estimating that 30% of a top-100 supercomputer would fulfil this goal.

This decade has seen the significant increase of HPC capabilities, both supporting the deluge of data from telescopes, and also placing the Universe in a virtual laboratory for simulations of physical processes. Data-science expertise has developed in tandem with the increasing size and complexity of astronomical datasets. Long-term career paths and ongoing training is required to ensure the astronomy community retains HPC and data specialists. AI and machine learning will become increasingly important in astrophysical data analysis. A focus on sustainable computing is vital as we head towards net-zero carbon emissions.

6.1.1. ADVANCED SCIENTIFIC COMPUTING

The total resource available to the Australian astronomy HPC community is approximately 15% of a top-100 supercomputer, substantially less than the need estimated in the last decadal plan.

Australia's peak (Tier 1) HPC facilities at the National Computational Infrastructure (NCI) and the Pawsey Supercomputing Research Centre contribute to the HPC requirements of the astronomy community's largest users – primarily for theoretical astrophysical simulations and radio astronomy data processing.

The institution-scale (Tier 2) HPC facilities of OzStar and Ngarrgu Tindebeek at Swinburne University of Technology are open to all astronomers in Australia upon request and provide vital computing infrastructure for the majority of the community.

The total amount of computing capability in Australia normalised to GDP is significantly smaller than some peers – such as Germany and the US – but is comparable to or larger than others such as Canada and the UK. Despite this, the amount of time accessible to researchers is several times smaller in Australia than in peer countries. This is largely a result of the access model used in Australia, which places only a very small (<10%) fraction of computing resources in an open pool that is allocated by merit. This strongly inhibits the growth of the Australian theoretical simulation community, which is one the largest users of HPC in astronomy, and limits its ability to perform internationally competitive flagship simulations.
The dependence of the radio astronomy community on the Pawsey Supercomputing Research Centre for its processing could represent a concentration risk.

6.1.2. DATA

Australia has transformed its approach to astronomical data over the last decade with the development of an extensive and coordinated data infrastructure. This includes Astronomy Data And Computing Services (ADACS), which is widely regarded by the community as a valued success. ADACS was established in 2017 by AAL to provide training and software development support to astronomers via its merit allocation program. ADACS-supported projects have enabled both new software to be built from the ground up or existing software and data pipelines to be modernised, especially benefitting research teams working with ESO, MWA, and the AAT.

Data platforms have emerged as a critical component of how Australian astronomers engage with their data and are now regarded as essential by the observational community for interacting with modern observatories. These platforms have created new opportunities for discovery by enabling multi-wavelength, multi-messenger, and theoretical data to be worked with in a common framework.

The All-Sky Virtual Observatory (ASVO) comprises five nodes, including the AAO Data Central science platform, the CSIRO ASKAP Science Data Archive (CASDA), the MWA ASVO, SkyMapper, and the Theoretical Astrophysics Observatory. It is regarded as an outstanding investment by the community. AAO Data Central in particular brings together an array of heterogeneous astronomical data in one accessible data portal, maximising the scientific return on Australian optical datasets of national significance, providing access and support for novice astronomers, expert survey team members, and members of the public alike.

The Gravitational Wave Data Centre (GWDC) enables processing of data from the international gravitational-wave detectors and pulsar timing array information from the SKA precursors and pathfinders. The AusSRC will process and disseminate data from SKAO and SKA precursors to Australian researchers.

6.2. THE NEXT DECADE

6.2.1. ADVANCED SCIENTIFIC COMPUTING

Advanced scientific computing is a critical capability for astronomical research in the coming decade. This includes both large-scale HPC and smaller-scale dedicated computing resources outside of traditional HPC environments. More than 50% of the Australian astronomical community make use of data and advanced computing infrastructure and services as part of their research, according to a survey conducted to inform this decadal plan. Theoretical simulations and radio astronomy processing have been the biggest historical users of HPC, but access is now considered crucial in other areas of astronomy, such as optical and infrared astronomy, where technological advances have led to an enormous increase in data volumes and an increasing complexity in processing pipelines.

To enable world-class theoretical research, astronomers require comparable access to those in peer nations – that is, enough HPC time to carry out large theoretical and simulation programs. To meet these needs, a target of 30% of a top-100 machine is recommended – echoing the last decadal plan's recommendation. Australia must move more of its computing resources into an open, merit-based allocation scheme, with the goal of reaching approximately 30% open access, in line with peer countries.

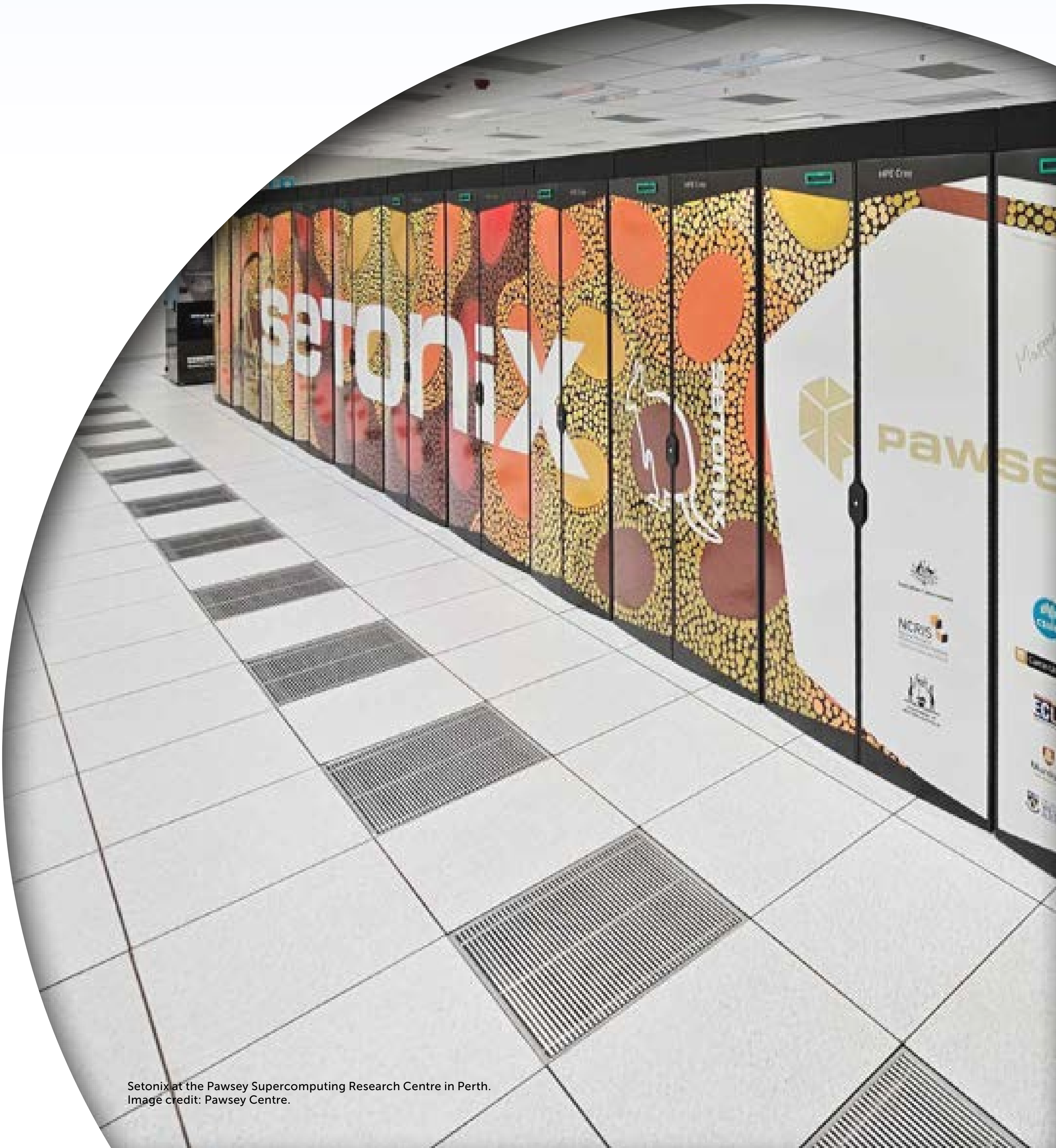
In addition to HPC, sustained investment in mid-tier computing infrastructure is needed to support a broad range of astronomical workflows. These include continuous data processing pipelines for telescope observations, long-running data analyses, and real-time monitoring, which do not fit well within batch-queue HPC environments. Expanding institutional computing resources will help meet these critical needs and ensure efficient access for the astronomy community.

Tier 2 facilities remain important and should continue to be funded with regular capital refresh in the coming decade, and the number of such facilities should be increased. These new facilities should ensure computing power can be co-located with data storage and access. They could be optimised for specific use cases (e.g. data reduction and processing, theoretical simulations).

It is expected that the flagship machines at both NCI (Gadi) and the Pawsey Supercomputing Research Centre (Setonix) will have capital refreshes during the first half of the coming decade. These will be heterogeneous CPU/GPU architectures, which dominate the top end of HPC hardware, and which will impact the ability and performance of software and workflows.

The astronomy community should provide strong support to a wider research community investment in an Australian exascale Tier 0 international facility. With resources comparable to large programmes overseas, the theory community will be able to tackle more ambitious problems, undertake flagship projects that are internationally leading, and grow Australia's expertise in this area.

The continued support of ASKAP and MWA by high-availability HPC systems is critical for the real-time, high-throughput compute required to support surveys in the coming decade. Any refresh of operations-critical compute platforms for high-data-rate telescopes needs to take account of the unique requirements around sustained data throughput and the emphasis these requirements place on storage, file systems, and isolation from general users to ensure reliability.



Setonix at the Pawsey Supercomputing Research Centre in Perth.
Image credit: Pawsey Centre.

6.2.2. DATA

Astronomical datasets are crucial for research. They are generated, handled, and stored; they may be reduced and processed; they require analysis and interpretation; and they need to be findable and accessible. This requires the expertise of data engineers and data scientists, as well as coordination between data centres, data and software engineering teams, funding agencies, and industry.

'Bringing compute to the data' is an approach shaping data management. In this paradigm, data are stored in the same location as the computing facility required to process and analyse them. It is a direct response to the size – often, tens of petabytes – and heterogeneity of datasets and the growing complexity of the pipelines required to process and analyse them. Growing volume and complexity also drive the need for universal standards and protocols (for example, those of the International Virtual Observatory Alliance) and to FAIR principles (findable, accessible, interoperable, and reusable).

The emergence of science platforms – which allow researchers to perform science analysis interactively via their web browser on a secure computing facility co-located with the data – is a transformational development. A science platform is not merely an archive or data storage system, but rather an ecosystem of services and tools that support research. Science platforms will enhance scientific productivity and outcomes but require significant planning and ongoing investment.

The Data Central science platform already plays a vital role in processing, reduction, and analysis for the ESO/MUSE MAGPI, GECKOS, and MAUVE surveys. It runs services that support the MWA/GLEAM-X and AAT/GALAH, Hector and SAMI surveys, as well as their data. Key simulation services are deployed within the platform. The upcoming 4MOST/WAVES and 4MOST Hemisphere Surveys also rely on Data Central to help run and manage their surveys.

The NCI hosts the Australian Research Environment, a science platform that serves the range of numerate disciplines in Australia, including astronomy, oceanography, climate modelling, and other data-intense disciplines. AusSRC will provide users with a science platform as part of the global network of SKA Regional Centres.

Australia should continue to invest in astronomy-focused science platforms that are linked to one another and to international counterparts. This will open up new discovery spaces and support high-impact research into the future, ensuring Australia's continued leadership in this space.

Data, software, and platform specialists are critical to managing the scale of the data and computing requirements in the coming decade. At present, researchers who have developed expertise in these areas and who wish to specialise in them face a precarious career if they remain in astronomy research, given the limited opportunities for career progression. However, retaining astronomers with software skills is not enough: we must also attract trained software engineers and data specialists from outside the field, since the challenges ahead will surpass what many astronomers can manage alone. It is imperative that there are credible pathways for these specialists to build stable and long-term careers in astronomy. Without this expertise, our goals for the coming decade will be hampered, and Australia could lag behind the forefront of global astronomy.

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

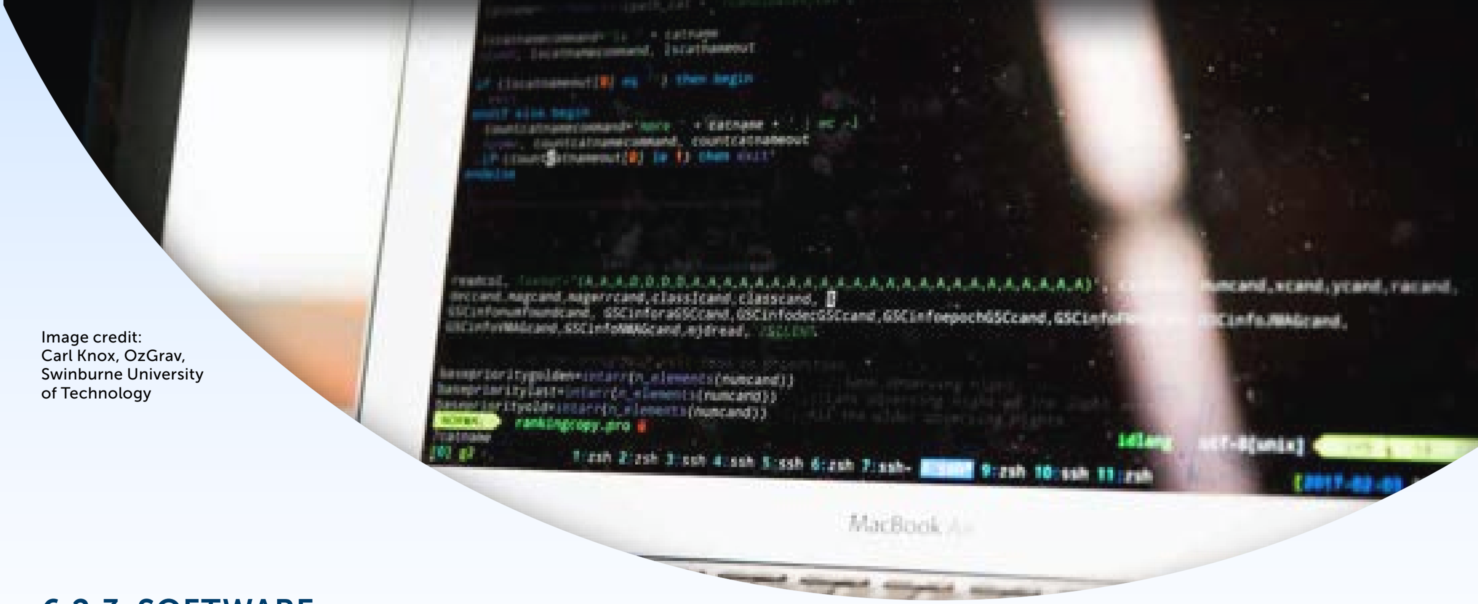


Image credit:
Carl Knox, OzGrav,
Swinburne University
of Technology

6.2.3. SOFTWARE

Software is increasingly important for Australian astronomy – from how it is developed and maintained, to its ability to maximise the hardware on which it is deployed. There is a need for general community-wide training in the essentials of software, computing, and data best practice. However, it is also essential that the community supports software specialists with domain expertise. Australia must expand its investment in software and in the specialists that will develop portable, scalable software and workflows that can make best use of the increasingly heterogeneous systems underpinning future HPC and data facilities.

ADACS represents such an investment, and its continued support is essential in the coming decade. Investment in mission-critical software and data support should be a condition for funding of new telescopes and instruments. Similarly, highly optimised, high-accuracy software is essential for flagship theoretical simulations. Investment will ensure software is robust, sustainable, reproducible, open source, and adheres to FAIR principles.

6.2.4. ARTIFICIAL INTELLIGENCE, MACHINE LEARNING AND STATISTICS

Artificial intelligence (AI) and machine learning (ML) have emerged as significant research techniques in Australian astronomy over the last 10 years and will continue to grow in importance in the coming decade. The recent emergence of large language models may also affect research, but exactly how remains to be seen.

More broadly, astrostatistics and data analytics are tools used commonly on datasets of all sizes, with modern astronomy demanding a robust and deep understanding of our data. Much of the value of AI/ML and statistics in astronomy is about dealing accurately and precisely with modest (MB/GB) scale data, and focusing on elements such as robust uncertainty quantification, and teasing small signals out of difficult noise. With substantial data rates and volumes from the SKAO and other leading optical observatories, ML will power source classification and anomaly detection. AI will allow for compression of exceptionally large datasets without losing information. For example, Rubin will use the Fink broker, a software system that ingests, processes, and serves astronomical alerts to the broader scientific community. Fink leverages ML techniques to classify transients and detect anomalies.

AI and ML will transform telescope operations by improving efficiency via optimised scheduling and predictive maintenance. Next-generation adaptive optics systems will benefit from the computational efficiencies of AI and ML methods for real-time control. The ASKAP telescope's SAURON scheduler is an excellent example of this being used in an operational environment. AI and ML research tools benefit from science platforms with fast data access and good workflow management, emphasising the importance of software, data, and platform specialists. Astronomy software has the potential for translation into start-ups and other industries.

6.2.5. SUSTAINABLE COMPUTING

The carbon footprint, water usage, and power-intensive nature of HPC and AI have come under scrutiny as this technology becomes ubiquitous in modern society. Australian astronomers' total greenhouse gas emissions from supercomputer usage are estimated to exceed 15 kilotons of CO_2 per year – a significant fraction of the total astronomy CO_2 budget.

HPC facilities are moving towards greener power and more efficient computing. Pawsey's Setonix is a green supercomputer, ranked number four in the world in 2022. This is made possible by a mixture of GPUs, innovative direct liquid cooling of all system components, geothermal cooling, and solar cells. A move to GPU-enabled codes – which can accelerate computationally intensive tasks – will further ensure HPC is as efficient as possible. Taking advantage of these architectures will require support and investment in new workflows and software.

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

07 INSTRUMENTATION, INDUSTRY AND TRANSLATION

Image credit: AAL/Julia Bryant.

Instrumentation programs have developed significantly in the past decade, involving national and international optical and radio astronomy projects (including SKAO, ESO, and GMT contracts) as well as gravitational-wave detection, high-energy particle detection, and space technology.

As part of the AWLAI, the optical astronomy instrumentation that was managed by the government in the AAO moved to Macquarie University. The Astralis Instrumentation Consortium (Astralis) was formed to link a combined team of instrumentation experts across three major Australian universities. An increasing number of Australian companies are growing and benefitting from astronomical projects, including start-ups and small-medium enterprises. Astronomy-trained professionals are developing innovative industry solutions.

7.1. INSTRUMENTATION AND SOFTWARE DEVELOPMENT

Australia has an established history of designing and building innovative astronomical instrumentation, spanning astronomy domains from radio to optical to gravitational waves.

By enabling new capabilities, Australian instrumentation forms the backbone of many discoveries. Instrumentation programs also provide key strategic benefits to the astronomical community:

- enabling access to state-of-the-art telescopes
- keeping existing facilities globally competitive
- providing diversified training and career paths
- seeding industry engagement, technology translation, and spin-off companies.

This work is enabled through a skilled workforce, forming a sovereign capability in which Australia excels relative to the size of its community.

7.1.1. ASTRALIS INSTRUMENTATION CONSORTIUM

The introduction of AWLAI saw the transfer of Australia's existing research and instrumentation capabilities in the AAO from the Government to the research sector. This resulted in the splitting of the AAO into the AAT, operated by a consortium of universities through Astronomy Australia Limited (AAL), and the Astralis Instrumentation Consortium (with nodes at Macquarie University, The University of Sydney, and the Australian National University). Instrumentation activity is now concentrated within CSIRO (predominantly radio instrumentation), Astralis, and a small number of university groups, each with different expertise across various areas of instrument science.

Astralis currently supports a range of instrumentation-related activities, from the decade-scale multinational MAVIS facility instrument for the ESO VLT, to seeding industry engagement activities and translational technology development. It was successfully awarded a contract over five years to develop and maintain ESO data reduction software.

Research and development not directly associated with instrumentation projects is generally funded through competitive research grants, such as ARC Discovery Projects and Fellowships. Without such grants, novel and innovative R&D will be very difficult to maintain. This is especially true in optical/infrared instrumentation, as we no longer have a national observatory to support such research. Astralis is generally dedicated to project activities and other national priorities like industry engagement. It does not fund basic research. Yet without R&D at this level, Australia risks losing its competitive reputation as a leader in innovative instrumentation.

7.2. AUSTRALIAN INSTRUMENTATION ON THE WORLD STAGE

Instrumentation projects for the world's best telescopes, including ESO, SKAO, the next-generation GMT and gravitational-wave detectors, are now significant time and funding investments.

Australian instrumentation groups are engaged in a number of such major projects and the sector has invested more than $100 million across astronomy instrumentation portfolios over the past five years via universities alone (mostly salary costs). Development of non-astronomy activities is a growing feature of Australian instrumentation groups, driven by a need to generate diversified income streams.

Examples of Australian instrumentation capabilities enabling access to state-of-the-art telescopes and keeping existing facilities globally competitive include those described below.

7.2.1. AESOP AND 4MOST

The construction of the Australian ESO Positioner (AESOP) facilitated Australian membership of the 4MOST Consortium team. 4MOST, a multi-object fibre-fed spectroscopic telescope, will be installed on the 4-metre ESO/VISTA telescope in 2025. Using AESOP, 4MOST will observe the southern sky, undertaking 25 consortium and community-led surveys over the next five years, obtaining spectra for millions of targets. AESOP guaranteed time observations led to the Australian-led WAVES survey to study the underlying structure of the Universe. In addition, 4MOST access has led to the Australian-led 4MOST Hemispheric Survey, a direct result of the ESO strategic partnership.

7.2.2. MAVIS

The $40 million MCAO (multi-conjugate adaptive optics) Assisted Visible Imager and Spectrograph (MAVIS) instrument for ESO/VLT is being designed and constructed by a consortium of Australian, Italian and French institutions together with ESO. Australia's contribution to building MAVIS provides Australian astronomers guaranteed time observations with the instrument when it comes online in 2030. MAVIS will push the frontier of new astronomical instrument technologies to provide angular resolution two to three times better than the HST. This will make MAVIS a powerful complement at visible wavelengths to the JWST and the next-generation 30-metre-class telescopes under construction, which are optimised for science at infrared wavelengths. Australia's involvement in MAVIS is funded primarily through NCRIS with additional funding supported through an ARC LIEF grant.

7.2.3. GMT INTEGRAL FIELD SPECTROGRAPH

The GMT Integral-Field Spectrograph (GMTIFS) instrument for the GMT is one of the first three instruments that will be available on the telescope when it is completed. GMTIFS is a near-infrared imager and integral field spectrograph, meaning that it will not only have the ability to take detailed images of the sky, but also obtain spectra from across a continuous region of the field of view. GMTIFS will combine with the GMT adaptive optics system to deliver 3D spectroscopic data with angular resolutions 10 times sharper than the HST. Astralis-ANU is leading the GMTIFS instrument design and construction.

7.2.4. BLUEMUSE

BlueMUSE is an optical, blue-optimised integral field spectrograph with medium spectral resolution being developed for ESO/VLT. It is currently in the conceptual design phase by a consortium of nine institutes that is led by the University of Lyon, France, and includes Astralis. The expected first light for BlueMUSE is 2031. The science goals include studying ionised nebulae, starburst and low-surface-brightness galaxies, and detecting the intergalactic medium in emission for the first time. It will also study the evolution of the circumgalactic medium properties near the peak of the cosmic star formation history.

7.2.5. KECK WIDE-FIELD IMAGER

The Keck Wide-Field Imager (KWFI) is a major (US$25 million) Australian-led instrument involving Astralis and Swinburne University of Technology in collaboration with Caltech and the University of California. It is expected to see first light as early as 2030. Since 2019, more than AU$1 million has been invested in the project, which has progressed through feasibility and conceptual design studies to a mature final design, with several components built by Swinburne and tested on site, and under fabrication by Astralis-ANU. KWFI will provide additional deep ultraviolet-wavelength sensitivity beyond LSST, rapid-response capability, deep narrow-band imaging, and the freedom to target specific sources of interest for individual projects.

7.2.6. SYDNEY ASTROPHOTONIC INSTRUMENTATION LABS

Many instruments are under development at the Sydney Astrophotonic Instrumentation Labs (SAIL) at the University of Sydney. These depend on several sovereign capabilities: the Australian National Fabrication Facility (ANFF) Advanced Fibre Bragg Grating factory, fibre fuse and splice technology like the photonic lantern factory, and the hexabundle technology developed for the AAT.

7.2.7. RADIO MULTI-BEAM TECHNOLOGY

Radio telescopes traditionally used single-pixel feeds. This meant that large-scale surveys were inefficient, and observations often concentrated on radio data for previously known sources. CSIRO pioneered multi-beam technology more than 20 years ago, improving survey speed, and allowing Murriyang to survey the whole southern sky in around four years.

This technology was then used at major radio telescopes around the world, including the Lovell telescope in the UK. CSIRO engineers delivered a 19-beam multibeam system for the Five-hundred-meter Aperture Spherical Telescope (FAST), the biggest and most sensitive single dish in the world, and have also contributed to the design of the US-led next-generation Very Large Array currently under development.

7.2.8. RADIO PHASED ARRAY FEED SYSTEM

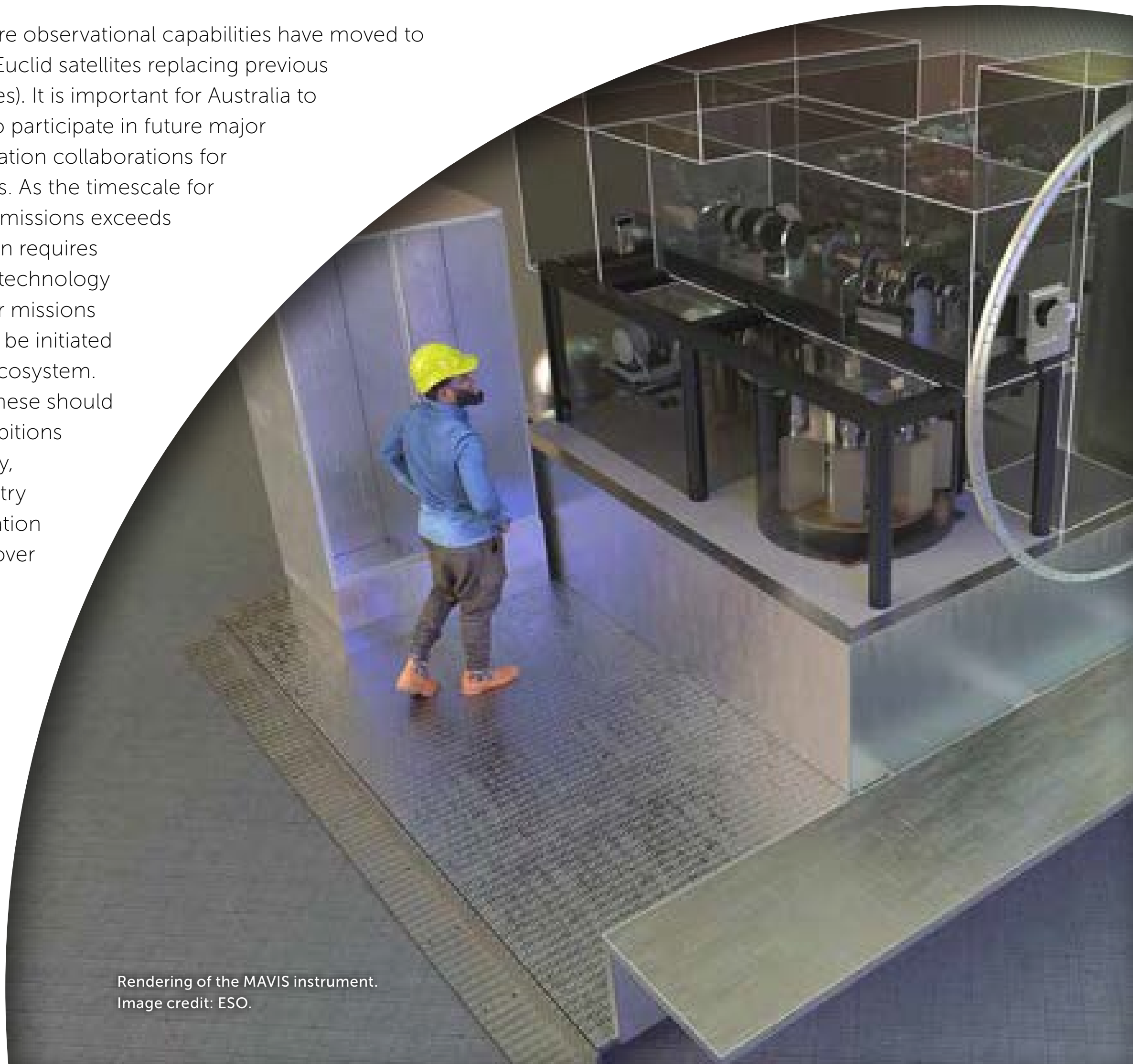
CSIRO's technology developments over the past decade have completely revolutionised the surveying capabilities of radio telescopes. They have designed and deployed the cryogenically cooled phased array feed cryoPAF system to increase the sensitivity and speed of Murriyang. CryoPAF has also been adapted for satellite tracking via spinoff company QuasarSat and the integrated circuit technology developed has been deployed for the SKA-Low correlator.

7.2.9. RADIO ULTRA-WIDEBAND LOW RECEIVER

The CSIRO-designed and -built ultra-wideband low (UWL) receiver was installed on Murriyang in 2018. This receiver provides wide instantaneous frequency coverage from 704–4032 MHz. The receiver is used for a range of observations, including pulsar timing and searching, and follow-up of repeating FRBs and spectral lines.

7.2.10. SPACE INSTRUMENTATION

Internationally, some core observational capabilities have moved to space (e.g. JWST, Gaia, Euclid satellites replacing previous ground-based capabilities). It is important for Australia to develop the expertise to participate in future major international instrumentation collaborations for space-based endeavours. As the timescale for flagship scientific space missions exceeds 10 years and participation requires experienced teams and technology development, pathfinder missions and partnerships should be initiated now to build a mature ecosystem. Over the next decade, these should scale up in scientific ambitions and technical complexity, capitalising on the industry linkages the instrumentation community has forged over the past decade.



Rendering of the MAVIS instrument.
Image credit: ESO.

7.3. INDUSTRY

7.3.1. THE DECADE IN REVIEW

Engagement with Australian industry over the last decade has opened up exciting new opportunities for commercialisation, resulting in economic benefits and enhancing the impact of research. Concepts and methods from astronomy have been applied in diverse areas such as data science, medicine, satellite imaging, engineering, defence, mining, and position, navigation and timing.

Australia's international leadership as an innovator in astronomical instrumentation has opened opportunities for Australian industry to engage with international organisations, such as the SKAO and ESO. By far the largest industry benefit in the last decade has been through Australian SKAO contracts – worth more than $200 million for SKA-Low infrastructure alone.

Astronomy's engagement with industry can be classified into three broad categories. First, collaboration with existing industry, where companies are contracted as part of the development of instrumentation or an observatory capability. Second, where a technology or technique is translated for commercialisation, or leads to the creation of a new company or industry. Third, where academia and industry work in partnership.

Examples of such industry collaborations are listed below.

- Nicholas Hacko Watchmaker – high-precision parts for the AAT's Hector instrument were delivered in a partnership with industry. This has led to the company taking on contracts from other industries (such as the biomedical industry), and the creation of a new business arm.
- Aquamate worked with the Southern Widefield Gamma Ray observatory to develop a prototype tank for this transformative instrument. If Aquamate wins the supply contract, this will involve an order of around 4,000 tanks.
- Engineers from ICRAR at Curtin University designed the Power and Signal Distribution (PaSD) System, an essential component of the SKA-Low frequency telescope. ICRAR handed over the design to SKAO, under a pre-construction contract, and SKAO has contracted a Perth company, AVI, to manufacture thousands of SMART boxes based on this design. AVI is a privately-owned wholly Australian company, who won the contract to build the PaSD system in a competitive tender process. The work was fundamentally enabled by access to the MWA site.
- ICRAR-Curtin and Nova Systems have each contributed 50% shares of intellectual and financial capital to develop a dedicated commercial space domain awareness (SDA) system, spun out of radio astronomy technologies and techniques.[28]
- Pentalym, a company that catalogues and tracks medical devices, grew out of the work of CSIRO project engineer Matt Shields on the parts-tracking system for ASKAP.
- Quasar Satellite Technologies (QuasarSat) is an Australian start-up company that pioneers the 'space data as a service' concept and provides a new way for satellites in orbit to communicate with ground stations, based on ASKAP PAF technology.
- mDetect is a new technology company that has developed a device that allows for the density and composition of structures and substances to be identified using subatomic particles known as muons. The technology was developed from the instruments being designed to attempt to detect dark matter.

28. Beasley, V. 27 October 2022. Nova Systems and ICRAR Curtin partner on new Space Domain Awareness technology. *Curtin University*. https://www.curtin.edu.au/news/media-release/nova-systems-and-icrar-curtin-partner-on-new-space-domain-awareness-technology/

Image credit: Kim Steele (2017).

An SKA-Low antenna array station under construction at the SKA-Low telescope on Wajarri Yamaji Country.
Image credit: SKAO

CASE STUDY

SKAO CREATES TRAINING AND EMPLOYMENT OPPORTUNITIES

The collaboration between SKAO, CSIRO, and the Wajarri Yamaji People has created exciting local training and employment opportunities. The initial SKA-Low field technician team comprised 70% Wajarri Yamaji, including entry-level roles where no experience is necessary.

All training is provided for those who have a willingness to learn and enjoy being on Country. SKA-Low has partnered with Central Regional TAFE to develop a tailored training program that is delivered both on site and at the Geraldton campus with supportive and encouraging staff. The nationally recognised qualifications include Certificate II in Resources and Infrastructure Work Preparation, and Basic Open Cabler Registration. The field technician training supports the construction and maintenance of the SKA-Low telescope and may potentially generate pathways for further education and career progression.

7.3.2. THE NEXT DECADE

Consistent funding for collaborations with industry to research cutting-edge instrumentation is lacking. For astronomers wishing to secure funding via government, applied and industry-focused research schemes are often highly focused with relatively small funding pools. They impose complex eligibility requirements and assessment criteria. This is a barrier to astronomers wishing to engage with industry-focused and applied research.

The skills and capabilities required to properly address industry-focused and applied research problems are spread across groups in different institutions. This is a challenge that has been exacerbated over the past decade. The nature of industry and defence calls for tender – which are highly competitive and often require non-disclosure agreements – together with university engagement with external stakeholders, is often not conducive to cross-institutional collaboration with industry.

To overcome this and create opportunities in the coming decade, the astronomy community should create a central portfolio of infrastructure and services that may be of interest to industry. Support is also needed to bring researchers across institutions and industry partners together.

7.4. TECHNOLOGY TRANSLATION AND SKILLS TRANSFER

Enhanced collaboration between industry and astronomy research can offer significant opportunities to both sectors, fostering innovation, accelerating technological advancement, and driving economic and scientific progress.

This has been a focus in the astronomy community, with many university and national research organisations supporting these efforts.

Astronomical instrumentation and engineering methods are often at the forefront of technological design. For industry, collaboration with the astronomy community provides direct access to cutting-edge scientific research, advanced technologies, and specialised expertise.

This can lead to the development of new products, services, and technologies. Examples include:

- Liquid Instruments, a scientific test equipment company that arose from gravitational-wave researchers and was described by the *Australian Financial Review* as potentially the ANU's first billion-dollar spin-out
- Quasar Satellite Technologies, a satellite communications company partly derived from the ASKAP and Murriyang telescope PAF developments
- Redback Systems, an industrial and scientific spectrograph company based on astronomical spectrograph technology
- NH Micro, a precision manufacturing company created from collaboration with Astralis through work on AAT/Hector that has now expanded to service other fields, including biomedical companies
- VAI Photonics and Forge Photonics, who provide sensing capabilities that can be used for Global Navigation Satellite System (GNSS)-denied navigation.

Working with industry often requires astronomers to collaborate across disciplines. This cross-disciplinary exchange can lead to breakthroughs that advance both scientific knowledge and commercial technologies. For example, Fourier Space Pty Ltd takes software technology that was originally designed to make the most sensitive radio telescopes in the world and licences it to suppliers of satellite-tracking telecommunication systems. Astrophysicists have used their knowledge of machine learning and highly parallel computing to interpret satellite images for early detection of bushfires and vegetation growth infringing on remote rail networks, as well as using hyperspectral imaging to detect algae blooms in Australia's waterways. Many technologies and techniques are directly translatable from astronomy to the space sector (e.g. SDA).

A central body should be established to promote and facilitate industry engagement and technology translation with the next generation of global facilities. It will be vital to foster a culture of innovation and entrepreneurship, and encourage innovative, collaborative solutions addressing challenges in both astronomy and industry. This must be supported by skills development and training programs to create a pipeline of industry-ready researchers.

Precision machining from NH Micro/Nicholas Hacko Watchmaker. Image credit: NH Micro.

CASE STUDY

NICHOLAS HACKO WATCHMAKER AND THE AAT'S HECTOR INSTRUMENT

Hector is a new multi-integral field unit spectrograph built for the AAT by Professor Julia Bryant and her team from the Astralis Instrumentation Consortium at the University of Sydney. The construction of Hector demanded a precision in the machining of small parts that could not be provided by Astralis's conventional machining suppliers. This led to Astralis forging a new partnership with Nicholas Hacko Watchmaker, an Australian company that specialises in very high-precision machining of miniature parts for their range of exclusive watches.

A team from Nicholas Hacko Watchmaker visited the project laboratory several times and worked through different prototypes, eventually manufacturing parts for Hector worth tens of thousands of dollars. Throughout the course of the project, the watchmakers were also brought up to speed on the instrumentation industry and its specialised requirements, leading to Nicholas Hacko Watchmaker expanding the application of their work – using existing equipment – into the science and medical fields. Through their connection with Astralis, Nicholas Hacko Watchmaker have new work packages from other groups – including biomedical companies – and have a new arm of their business called NH Micro.

From the perspective of the Hector team, the partnership with Nicholas Hacko Watchmaker resulted in a more flexible and efficient design for the instrument, attributable to the much higher levels of precision achieved by the watchmakers. In turn, this collaboration has opened up a new and profitable line of business for Nicholas Hacko Watchmaker – a most successful collaboration on both fronts.

Working with Professor Bryant and her team has been an extremely rewarding experience – not only has it taught us how to interface with university clients and address their direct needs, it's been extremely exciting to see the projects we've worked on succeed! Many of the parts we made for Hector were very challenging and helped push the boundaries of what we can achieve here in our workshop, and also within Australia.
– Josh Hacko, technical director, NH Micro, Nicholas Hacko Watchmaker

CSIRO's ASKAP radio telescope at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory on Wajarri Yamaji Country. Image credit: CSIRO/Dragonfly Media.

CASE STUDY

SAURON

National facilities as testbeds for innovation and experimentation, leading to international collaboration contracts

The ASKAP radio telescope is an SKA precursor, owned and operated by CSIRO, and an innovative instrument across research science and operations.

One of these innovations was to implement a new, autonomous operations model that leveraged new technologies to improve efficiencies. This included a scheduling system, SAURON (Scheduling Autonomously Under Reactive Observational Needs). The SAURON system combines knowledge of astronomy targets in the sky at any time, current observing priorities and constraints, and real-time environmental and system conditions, to select the best targets and observing modes without manual input, while still enabling flexible and agile operations management in conjunction with human experts.

Other large-scale telescopes around the world require new and innovative approaches to build into their systems and processes, such as the Deep Synoptic Array, funded by Schmidt Sciences and under development by Caltech. A next-generation telescope, the Deep Synoptic Array will employ 1,650 antennas and novel radio camera technology when it is complete.

The global relevance of technology innovation developed within Australia was highlighted when CSIRO's work led to a collaboration with Caltech to develop a similar autonomous system for the Deep Synoptic Array. This ongoing collaboration continues to strengthen Australia's ability to facilitate long-term knowledge-sharing and co-development of new technologies with world-leading international institutions.

CASE STUDY

ATNF
TELESCOPES HELP INDUSTRY REACH FOR THE MOON

While astronomers from all over the world can access CSIRO's ATNF telescopes for free, based on the scientific merit of their observing proposal, telescope time can also be purchased.

The large collecting area and advanced data acquisition systems of the ATNF radio telescopes make them particularly valuable for tracking robotic and crewed spacecraft exploring our Solar System.

Murriyang, CSIRO's Parkes radio telescope, began supporting space missions in 1962, when it tracked the first interplanetary space mission, Mariner 2, as it flew by the planet Venus. Since then, the telescope has been called on regularly to support NASA missions including Apollo 11's lunar landing.

In 2024, Murriyang and CSIRO's experienced operations team provided ground station support to Houston-based aerospace company Intuitive Machines' IM-1 mission, the first commercial lander to reach the Moon under NASA's Commercial Lunar Payload Services initiative.

Operating as a ground station for space missions complements the astronomy research conducted with the ATNF telescopes, and great care is taken to provide for both researchers and industry partners to ensure great outcomes.

'Murriyang, CSIRO's Parkes radio telescope, adds significant capability to Intuitive Machines' Lunar Data Network. The network utilises multiple large ground station antennas, like Parkes, strategically located around the Earth to provide continuous communications with our spacecraft.' – Intuitive Machines

Murriyang, CSIRO's Parkes radio telescope, on Wiradjuri Country. Image credit: CSIRO/A. Cherney.

Wajarri Yamaji artist Margaret Whitehurst's work celebrates the completion of the first Rapid ASKAP Continuum Survey with CSIRO's ASKAP radio telescope, which detected 3 million galaxies. Image credit: Margaret Whitehurst, RACS, 2019.

08 ASTRONOMY FOR AUSTRALIA: COMMUNITY, DIVERSITY AND OUTREACH

Astronomy is a science for all of Australia. Its influence is felt well beyond discoveries and research. The number of people working in astronomy has grown by a third in the past decade, with more than 40% undertaking some form of outreach and education activities outside of university programs.

Astronomy inspires students to enter STEM fields, and many astronomy graduates move into Australian industry, contributing to data science and the high-tech Australian workforce. Industry further benefits through commercialisation of astronomy technologies and expertise in the instrumentation and space sectors.

Aboriginal and Torres Strait Islander astronomy is becoming more widely and deeply appreciated, accompanied by increased training of Aboriginal and Torres Strait Islander students. To build on this, engagement with Indigenous communities is a priority for the coming decade. A strong focus on sustainability is also important in the next 10 years, including maintaining dark and quiet skies for the good of all Australians.

The last decadal plan identified four priorities for the Australian astronomy community to increase its engagement, diversity, and broader societal impact:

- aiming for at least 33% women representation at all levels by 2025
- using astronomy to improve science education in schools
- providing highly skilled graduates
- establishing a central body to facilitate industry engagement.

To assess changes in the astronomy community, a census surveyed anyone who 'works in astronomy, including support and technical staff'. This wording was more inclusive than the previous 2014 census, which focused on research astronomers. Within that uncertainty, the numbers indicate that there are now 627 positions (including 184 (29%) continuing), an increase of 62% from the 2014 total of 387 positions (139 (36%) continuing) in Australian astronomy. Measured against the 2014 census – including all support and technical staff, a substantial number of whom are employed at CSIRO – the full-time equivalence in astronomy increased 35% over the last decade. This is the most accurate measure of growth. There is a slightly lower proportion of people with a PhD working in astronomy (80% compared to 85% in the last decadal plan). This may indicate changing roles or might reflect the more inclusive design of this survey. However, the number of astronomy PhD students has doubled from a decade ago.

8.1. DIVERSITY IN ASTRONOMY

Gender equity has been a key focus for Australian astronomy for more than a decade. While gender equity has not yet been achieved, significant improvements have been made through a targeted focus from the astronomy community. Now more urgent is the under-representation of Aboriginal and Torres Strait Islander astronomers and people from low socio-economic backgrounds. Consistent, long-term effort is required to address these imbalances.[29]

29. Kewley, L.J., J.S.B. Wyithe, K.-V. Tran and I. McCarthy. 2023. The achievement of gender parity in a large astrophysics research centre. *Nat Astron* 7: 1525–1531 https://doi.org/10.1038/s41550-023-02079-6

Image credit: ASTRO3D

8.1.1. GENDER DIVERSITY

The last decadal plan set a priority to grow women's participation at all levels to at least 33% by 2025 – a goal aligned with the PhD student cohort at the start of that decade. There has been a significant increase in the overall fraction of women employees in Australian astronomy over the past decade. The percentage of women in fixed-term positions has increased from 22% to 34%, and in continuing positions, women have increased from 19% to 28%. The numbers represent a significant change from the two previous decades, which remained stubbornly low at ~20% across the non-student astronomy research community in 2005 and again in 2015. The instrumentation workforce has similar gender proportions to the wider astronomy community, with 56 (33%) of survey respondents identifying as women – although this declines at more senior levels.

Measured over one career step, no gender pipeline leak is apparent from 2014 fixed-term (22% women) to 2024 continuing positions (28% women). This is evidence that gender equity initiatives are working, and this is an opportunity to expand efforts to other diversity axes while being careful to ensure that the hard-won gains on gender equity are not lost.

However, the percentage of women PhD graduates in the past five years (2019–2023) continues to decline and is now 27% – continuing a downward trend from 37% (2000–2004 graduates) to 33% (2010–2014). Thus, there is a substantial risk that the achievement of 28% women in continuing positions cannot be maintained or grown into the future. While the percentage of women PhD graduates has declined over this decade, the actual number of women PhD graduates has increased. Proportionally, the number of women PhD graduates has not kept up with the growth in male graduates. Further, systemic barriers may prevent career progression and retention in astronomy. For example, 60% of alumni reported that their partner's job was a significant factor for leaving astronomy while 20% cited parental responsibilities.

Gains in gender equity achieved over the last decade have been driven by dedicated programs within the astronomy Centres of Excellence, such as CAASTRO's gender action toolkit and ASTRO 3D's hiring guidelines and guide for inclusive meetings.

Notably, ASTRO 3D achieved gender parity within the lifetime of their centre. Many universities have also implemented targeted women-only hires to help redress the imbalance. The evidence-based methodology of ASTRO 3D showed that 40% women was a tipping point for women students and postdocs joining research teams.[30]

The Pleiades award, instigated by the Astronomical Society of Australia in 2014, has helped push astronomy departments (and physics faculties more generally) to institute more gender equitable policies. By striving to achieve high levels in the Pleiades awards, faculties have implemented many initiatives such as running annual culture surveys and compiling gender statistics, improving hiring and retention policies, and education efforts to improve workplace climates.

The pipeline of women students entering STEM fields remains somewhat weak, with gendered stereotypes beginning in early childhood, and students dropping out of STEM fields at the high-school level. This emphasises the importance of astronomers – and particularly women astronomers – taking leadership in outreach and role modelling efforts to high schools. A 2023 study[31] revealed a major imbalance of men over women role models being presented to high school students in STEM classes. Astronomer Dr Kat Ross led the #IncludeHer movement, a program to increase the representation of women and diverse scientists and researchers in the high school curriculum.

30. Ibid.
31. Ross, K., S. Galaudage, T. Clark, N. Lowson, A. Battisti, H. Adam, A.K. Ross, N. Sweaney. 2023. Invisible women: Gender representation in high school science courses across Australia. Australian Journal of Education 67, no. 3: 231–252. https://doi.org/10.1177/00049441231197245

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

PhD students Manasvee Saraf (UWA) and Tamsyn O'Beirne (Swinburne) draw their ASKAP science.
Image credit: Cristy Roberts, ASTRO 3D.

The First Astronomers, 2024
Leeann Kelly-Pedersen and Dawn Hamlett, Wajarri Yamaji

'Our ancestors travelled this land for many years in Australia, living off the land and following the seasons in search of food and water in their tribal family groups. All men carried out cultural ceremonies from their tribal grounds. They would attend meetings on a special ground where they would gather with other tribes. Travelling across our Country was always at night. Our ancestors found a way to travel to their destination by studying the night sky and using the stars as a compass to guide their way, with the full Moon for light. This painting represents our ancestors' travel method, including the Milky Way which was also important to them. It guided the way and they also followed the movement of the emu, which can be seen in the Milky Way, to know when it was the egg-laying season. The Nyarluwarri (Seven Sisters, Pleiades) can be seen on the right. The Morning Star can be seen at the bottom, to the left is the Southern Cross and the large circle at the top is the full Moon with the Evening Star next to it. The pink dots represent the wildflower seasons and also the aurora in the sky. The Southern Cross, Morning and Evening stars are the main features used as a compass.'

This artwork is part of the *Cosmic echoes: a shared sky Indigenous art exhibition*, which is an SKAO initiative, in collaboration with South African Radio Astronomy Observatory, CSIRO and the Wajarri Yamaji Aboriginal Corporation. The Wajarri Yamaji are the Traditional Owners and Native Title Holders of Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory, where the SKA-Low telescope is being built.

Dawn Hamlett bio:
I am a proud Wajarri Woman with connections to the Byro area. I love painting all things connected to my wonderful Country. Painting is one of my passions.

Leeann Kelly-Pedersen bio:
I was born in Carnarvon, Western Australia and lived for most of my childhood between Carnarvon and Mullewa. I had an early interest in art, it was always my favourite subject at school, and I studied visual art. I am inspired by my mother, Dawn Hamlett, and also by places and things I have experienced or seen on my life journey. I have illustrated a book and created and designed topical themed posters for the Wajarri, Badimaya and Nhanda languages for the Bundiyarra Irra Wangga Language Centre. As a Wajarri Language Teacher, I've also created children's storybooks and other resources in the Wajarri language to teach children.

8.1.2. ABORIGINAL AND TORRES STRAIT ISLANDER ASTRONOMY

For more than 65,000 years, Aboriginal and Torres Strait Islander peoples have maintained the world's most ancient and continuous astronomical knowledge and observations. The past decade has seen an increased awareness of this rich tradition of Aboriginal and Torres Strait Islander astronomy. There is growing recognition of how Aboriginal and Torres Strait Islander research methods – such as yarning and Country as method – prioritise relationships and respect for the land.

However, to date, only two Aboriginal and Torres Strait Islander people in Australia have obtained doctorates in astronomy. The growth in appreciation for Aboriginal and Torres Strait Islander astronomy has been accompanied by acknowledgement of the relative lack of Aboriginal and Torres Strait Islander voices in the professional community. Efforts have sought to grow and cement relationships between astronomers and Aboriginal and Torres Strait Islander peoples.

One example of acknowledgement was the renaming of the Parkes Radio telescope to Murriyang in 2020 by local Wiradjuri Elders. In the Wiradjuri Dreaming, Biyaami (Baiame) is a prominent creator spirit. The stars that portray the Orion constellation also represent this spirit. Murriyang represents the 'Skyworld' where Biyaami lives.[32]

Educational programs to support Aboriginal and Torres Strait Islander peoples are varied, and include formal university education and self-education of the community. ASTRO 3D and ANU have developed an Aboriginal and Torres Strait Islander work experience program that is designed to cater to the specific needs of Aboriginal and Torres Strait Islander students interested in astronomy. Since 2022, ASTRO 3D has conducted pre- and post-program evaluations to better understand student motivations and outcomes. The post-program feedback was overwhelmingly positive, with students expressing continued interest in Aboriginal and Torres Strait Islander astronomy, STEM careers, and engagement with scientists.

OzGrav has developed long-term engagement with all-girls schools and regional schools, particularly those with a high percentage of Aboriginal and Torres Strait Islander students. Similarly, ICRAR offers summer internships and work experience programs that prioritise Aboriginal and Torres Strait Islander students, providing them with practical research opportunities. These programs are complemented by events such as Aboriginal and Torres Strait Islander art exhibitions, astrophotography workshops, and the 'Star Dreaming Full Dome Show', which combines Aboriginal and Torres Strait Islander sky stories with modern astronomical science.

The National Indigenous Science Education Program (NISEP) was designed in consultation with Indigenous Elders and takes a holistic approach to supporting Indigenous students through high school and into tertiary education. With a focus on inclusion and equity, NISEP's initiatives include science demonstrations in local schools, Indigenous student leaders as demonstrators, and university campus tours.

32. CSIRO. 9 November 2020. Murriyang: Parkes radio telescope receives Indigenous name. https://www.csiro.au/en/news/all/articles/2020/november/parkes-telescope-indigenous-name

Image credit: ESO/S. Brunier

CASE STUDY

INDIGENOUS WORK EXPERIENCE PROGRAM: ENGAGING STUDENTS WITH ASTRONOMY

Aboriginal and Torres Strait Islander knowledge of astronomy holds a unique place in Australia's cultural heritage, yet there are precious few Indigenous astronomers in our academic community. Currently only 8% of Aboriginal and Torres Straight Islanders aged 25–34 have a bachelor's degree.

The Indigenous Work Experience Program aims to provide a cohort of Aboriginal and Torres Strait Islander students insight into the daily life of a research astrophysicist, while showcasing and acknowledging the legacy of Indigenous Australians as the world's first astronomers.

During the first week of July 2024, eight students in years 10–12 from around Australia attended Swinburne University of Technology in Melbourne and engaged in activities to inspire them to pursue a career in astronomy or STEM. Organised and lead by Gomeroi astronomer and ASTRO 3D education and outreach affiliate Krystal De Napoli, the students took part in week-long astrophysics research tasks.

They were warmly welcomed onto campus by Joel Boojers of the Moondani Toombadool Centre, the Indigenous support centre at Swinburne, who provided insight on pathways and programs related to tertiary study. They connected with Aboriginal and Torres Strait Islander academics to hear firsthand journeys into science and university generally, including Dja Dja Wurrung woman and machine learning expert Kiowa Scott-Hurley. The students participated in tours of the supercomputer, Discovery Wall, and virtual reality applications, while exploring the brilliant science that exists in Aboriginal and Torres Strait Islander oral traditions.

Over the week, the students independently researched an area of astronomy that had captured their interests to understand it further, with the goal of teaching their program peers. They stepped up to the challenge of communicating these new ideas or concepts in an oral format – encoding science into stories of their own making in honour of the role story plays in encoding Aboriginal and Torres Strait Islander scientific knowledge. These stories were the highlight of the week and best way to wrap up the program. Students explained concepts such as stellar birth from the remnants of previous generations, the mechanics of Hawking radiation, and the relationship between religion and the skies.

The program was run in partnership with ASTRO 3D, OzGrav and the Dark Matter CoE, which will ensure the program will be carried forward in future years.

Indigenous astrophysics work experience participants pictured with mentors and ANU PhD students Karlie Noon and Pete Swanton at Mt Stromlo. Image credit: Cristy Roberts, ASTRO 3D.

8.1.3. DIVERSITY IN THE NEXT DECADE

We propose four targeted aims to improve diversity in the astronomy community in the next decade, building on the previous decades of work.

- **A goal of 40% women participation in astronomy at all levels.** This target aligns with the evidence-based findings that 40% women is a tipping point for attracting women into research groups.
- **Implement focused equity initiatives across all axes of diversity.** The previous decade's work focused on gender initiatives, but in the coming decade this should be expanded to a much broader definition of diversity and inclusion.
- **Expand on activities that support Aboriginal and Torres Strait Islander students to thrive in STEM fields.** The successful programs illustrated above should be continued and expanded in reach.
- **Increase the numbers of Aboriginal and Torres Strait Islander people with PhDs in astronomy.** The representation of Aboriginal and Torres Strait Islander people in the professional astronomy community is lower than would be expected from population statistics. In the next decade, it is important to provide support and career paths for Aboriginal and Torres Strait Islander astronomers to obtain PhDs and positions in universities and observatories. Universities should consider schemes such as the one started at ANU that pay and treat Aboriginal and Torres Strait Islander students as postdocs while allowing them to complete their PhD over five years, providing a competitive option for prospective students that can and will drive change.

8.2. ASTRONOMY OUTREACH

Astronomy captures the attention of the nation – rarely a week goes by where there is not an astronomer on television or in the media.

The purpose of astronomy outreach is not only to educate, but to build public trust in science and enhance critical thinking, which are especially important in today's world of misinformation. This supports Australia's national science priorities and inspires the next generation of the STEM workforce. Understanding how precious our Earth is in the vastness of space strongly motivates transitioning to a net-zero future and protecting and restoring Australia's environment, and astronomy has a role to play in elevating Aboriginal and Torres Strait Islander knowledge systems.

Outreach efforts by the Australian astronomy community are broad and increasingly coordinated, reaching across a range of demographics. Among census survey respondents, 41% reported engaging in outreach activities below undergraduate level. School-based and public-facing talks were the most popular activities, with 20% of survey respondents involved. Almost 10% reported engaging in media and social media, such as TV interviews, radio, podcasts, and social media sites such as Facebook, X/Twitter, Instagram, and TikTok.

One of the most effective ways astronomers have communicated their new results is through articles in *The Conversation*, which are syndicated and often picked up by the international media. More than 410 astronomy articles were published by Australian authors in *The Conversation* in the last decade. Observatories such as Siding Spring, Murriyang, and ATCA host engaging visitor centres. Many astronomers participate in outreach events in addition to their normal workloads. For this to be a sustainable activity, recognition of the value of this work in home organisations is essential.

The past decade has been a rise in astronomy 'super communicators' – researchers who have made a deliberate decision to communicate science beyond their own research. They are having a wide impact outside normal academic routes, including via TikTok which helps to reach younger generations.

Examples include:

- Dr Kirsten Banks who is an Indigenous astronomer with more than 430,000 followers and 11 million likes on TikTok
- AstroKobi with more than 2 million subscribers on YouTube
- Dr Sara Webb with more than 35,000 followers on social media and 17 million video views
- Professor Tamara Davis AM, who hosted ABC TV Catalyst episodes reaching more than 4 million viewers.

SUPERSTARS OF STEM

The Science Technology Australia (STA) Superstars of STEM program is an initiative for women and non-binary researchers, aiming to break down gender-based stereotypes around people working in science and technology, engineering, and maths. This competitive program sees 'superstars' undertake a two-year program, equipping them with communication skills and outreach opportunities in the media and in schools. Astronomers have been involved in each iteration of the program, making an impact in outreach and providing visible role models.

- Dr Rebecca Davies – 2024
- Krystal de Napoli – 2024
- Dr Adelle Goodwin – 2023
- Dr Laura Driessen – 2023
- Dr Sara Webb – 2023
- Dr Vanessa Moss – 2023
- Karlie Noon – 2021
- Dr Clare Kenyon – 2021
- Dr Sabine Bellstedt – 2021
- Dr Devika Kamath – 2019
- Associate Professor Natasha Hurley-Walker – 2019
- Dr Sarah Pearce FTSE – 2019

Ongoing outreach programs are largely limited to (successful) major institutional outreach, such as CSIRO's PULSE@Parkes, which has recently been working alongside the Young Indigenous Women's STEM Academy and targeting more regional and remote schools. Funding of outreach programs within universities is somewhat ad hoc, with dedicated programs from ARC Centres of Excellence such as OzGrav's award-winning Einstein-First Project[33] and the ASTRO 3D Scientists Taking Astronomy to Regional Schools (STARS) program.[34] Through programs such as these, more than 135,000 school kids in the last decade have attended or otherwise been exposed to astronomy outreach or education from an astronomy professional.

8.2.1. OUTREACH IN THE NEXT DECADE

A new nationally coordinated and funded program of education and outreach focused on inspirational science from SKAO and ESO could target a specific age demographic (there are around 330,000 students in each school year level across Australia) to offer astronomy to schools across the nation. We envisage this will involve national coordination of current and new programs and greater engagement with education communities (e.g. teachers and education officials at the state and federal levels). A longitudinal study evaluating the program, led by science communication experts and supported by software developers, could lead to the development of a generalisable evaluation tool for governments to improve STEM outcomes for young Australians.

33. OzGrav. 20 August 2024. Einstein-First wins Western Australia Premier's Science Awards 2024: Science Engagement Initiative of the Year. https://www.ozgrav.org/news/einstein-first-wins-wa-premiers-science-awards-2024-science-engagement-initiative-of-the-year/
34. Chapman, V. 20 May 2021. Regional kids seeing stars. *Space Australia.* https://spaceaustralia.com/news/regional-kids-seeing-stars

Image credit: Carl Knox, OzGrav, Swinburne University of Technology.

8.3. ASTRONOMY EDUCATION AND TRAINING

In the five-year period 2019–2023, 304 students graduated with a PhD in astronomy or astrophysics – almost double that of 10 years ago, and continuing a doubling trend from 2005 (83 graduates).

More than a quarter of these graduates move directly into Australian industry – an increase of 19% on the previous decade. There is high demand in industry for the technical skills and quantitative analysis expertise that astrophysicists possess.

Over the last decade, the growth in postgraduate student commencements has been driven by domestic students. By contrast, international student enrolments in MSc and PhD degrees in astronomy and astrophysics declined by 30% to 26 per year. International commencements averaged 40 per year and appeared to be maintained at that level in 2019. Figure 3 breaks down the current numbers into a year-by-year comparison. The COVID-19 pandemic caused a significant drop in international enrolments in 2020, recovering to pre-pandemic levels by 2023.

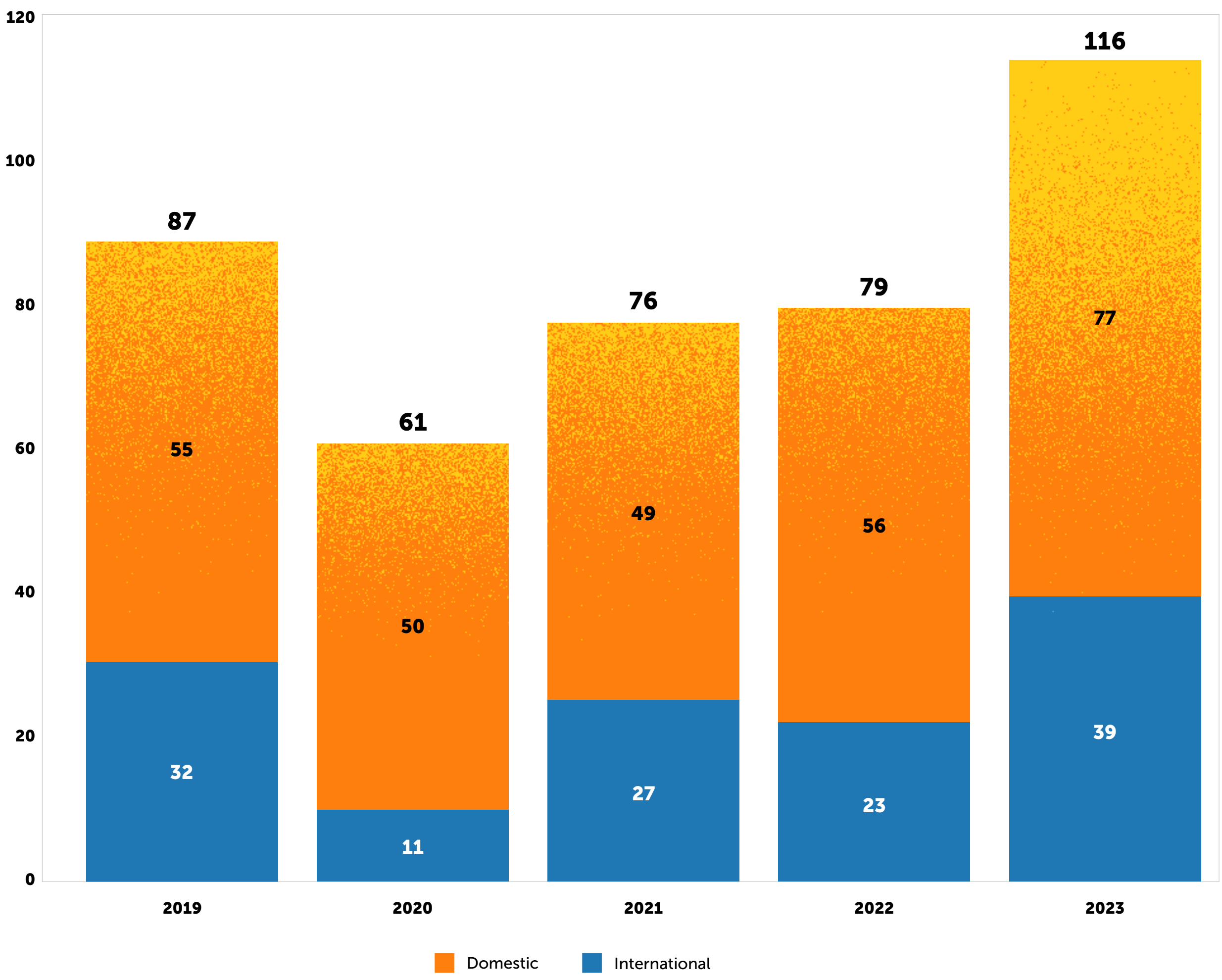


Figure 3: The number of domestic and international postgraduate (MSc and PhD) student commencements over the previous five years for 12 and 13 reporting universities, respectively.

In terms of hands-on student training, 66% of survey respondents identifying as PhD candidates use national or university facilities (such as ATCA, Murriyang, and AAT) for their research, slightly higher than the proportion for the non-PhD cohort (53%). This supports anecdotal evidence that access to these resources is critical for training and research development, and must be maintained into the future.

8.4. SKILLS DEVELOPMENT

Data and computing are key pillars of astronomical research. A growing proportion of the Australian astronomical and industrial community requires HPC and data infrastructure to carry out their work.

Training opportunities, especially for PhD students and early-career researchers, equip emerging astronomers with the necessary skills to work with this infrastructure. However, many astronomers do not receive formal training in modern software engineering and development practices. While the subset of astronomy researchers with these skills has been growing over time, we need general community-wide training in the essentials of software, computing, and data best practice.

Collaboration between industry and academic institutions plays a vital role in driving skills development and creating a pipeline of industry-ready workers equipped to tackle new technological challenges. This synergy benefits both industry and academia. Such partnerships foster long-term innovation, shared resources, and the co-creation of solutions that address both commercial and scientific needs. By engaging closely with industry, academic institutions enhance their graduates' employability and contribute to building a skilled workforce capable of advancing technological innovation and addressing future challenges – essential for industries aiming to remain competitive and push the boundaries of possibility.

8.4.1. SKILLS DEVELOPMENT IN THE NEXT DECADE

We recommend the creation of a nationally coordinated training and accreditation scheme for data and computing competency, incorporated into PhDs but accessible to early-career researchers and the community as a whole. We also recognise the importance of communities of practice – groups of researchers within specific sub-disciplines (e.g. AI and ML) that collectively manage their shared software and data needs, working with teams of dedicated infrastructure specialists.

Image credit: Carl Knox, OzGrav, Swinburne University of Technology

Dr Caroline Foster (UNSW) with PhD students Alma Sebastian (Swinburne) and Aishwarya Selvaraj (Curtin) deep in problem-solving mode at an ASTRO 3D retreat. Image credit: Cristy Roberts, ASTRO 3D.

8.5. CAREER PATHS

After graduating from PhDs in astronomy and astrophysics, 60% of men and 71% of women were working in academia one year after graduation, with 32% of men and 24% of women working in industry, and 8% of men and 5% of women in government employment or teaching.

This represents a shift away from academic employment compared to a decade earlier. Among graduates with reported outcomes in the 2016–2025 survey, 77% were in academia, 19% in industry and 3% in teaching. Those employed in academia were overwhelmingly in astronomy research positions, while those in industry were primarily working in data science. Astronomy PhD graduates also work in finance, natural resources, digital technology, not-for-profit, and other industry sectors. Domestic and international students appear to have similar overall employment outcomes, but 65% of domestic students remain in Australia one year post-PhD, while only 35% of international students do. Astronomy PhD programs are producing highly skilled workers, who are increasingly moving into data science and other roles in Australia and overseas.

A consistent picture has emerged from community feedback of the critical role of data, software, and platform specialists in providing the foundations for the Australian astronomical community's research programme. At present researchers who have developed expertise in these areas and who wish to specialise in them face a precarious career if they remain in astronomy research, given the limited opportunities for career progression. There is a strong community desire for there to be credible pathways for these specialists to build stable and long-term careers in astronomy.

There are examples of universities that offer opportunities for researchers who focus on research software development to pursue a career within the university environment but distinct from the traditional academic and professional staff roles (see, for example, the Melbourne Data Analytics Platform). Similarly, there are dedicated astronomy specialists attached to the likes of ASVO, ADACS, Data Central, Pawsey Supercomputing Research Centre, and AusSRC. However, the scale of the data and computing requirements in the coming decade mean that the Australian astronomy research community will need more specialists. Therefore, these careers need to offer the stability and opportunity for progression that top-level data scientists find appealing. The importance of this is recognised in the *National digital research infrastructure strategy*, and there is an opportunity for astronomy to address this need in the coming decade.

Programs, such as Teach for Australia, have already prepared PhDs in astronomy to enter school teaching as a career. Facilitating such a transition would help address the shortage of science and mathematics teachers in the Australian school system, and have the added benefit of igniting young people's interest in astronomy and other branches of STEM.

8.5.1. CAREER PATHS IN THE NEXT DECADE

Astronomy-trained workers are increasingly finding employment in industry, often in the area of data science. To undertake the ambitious scientific and technological plans of this decadal plan, it is important to also retain some of the data science talent and develop stable career pathways for astronomical data science specialists.

8.6. SUSTAINABLE ASTRONOMY AND DARK AND RADIO-QUIET SKIES

Astronomy is increasingly threatened by environmental factors such as light pollution, atmospheric interference, and wavelength congestion.

The preservation of dark skies is vital not only for scientific discovery but also for ecological health and public enjoyment of the night sky. Despite efforts like the designation of Dark Sky Parks – such as the Warrumbungle National Park near Siding Spring Observatory – light pollution from distant urban centres continues to degrade sky quality. While local councils have implemented effective mitigation strategies, broader national adoption is needed to protect Australia's unique southern skies and support both biodiversity and cultural engagement with the cosmos. Australia is well positioned to lead in dark sky conservation and advocate for global standards that protect this shared resource.

8.6.1. SATELLITE INTERFERENCE

The rapid expansion of satellite megaconstellations poses a growing challenge to both optical and radio astronomy. With tens of thousands of satellites planned for launch, their reflective surfaces and radio emissions are already contaminating astronomical data, increasing skyglow, and interfering with sensitive instruments – even in remote observatories. Although some satellite operators have begun collaborating with astronomers to reduce their impact, these efforts remain limited and inconsistent. Stronger regulatory frameworks and sustained mitigation strategies are urgently needed to safeguard astronomical research and preserve the night sky for future generations.

We recommend that:

- astronomy groups and universities support dark sky conservation and light pollution mitigation tactics and research
- astronomy groups and observatory sites should work with the government and the International Astronomical Union (IAU) Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS) to help mitigate satellite disruption and other impacts on observatories.

8.6.2. SUSTAINABLE ASTRONOMY

Climate change is already having a measurable impact on astronomy, with extreme weather events damaging major observatories and environmental shifts affecting daily operations. Facilities like Siding Spring and Mount Stromlo have experienced fires, while others globally have suffered from storms and atmospheric instability. These changes reduce data quality and increase operational challenges, making it essential for Australia's astronomical institutions to build resilience into their infrastructure. Preparing for more turbulent conditions – through better monitoring, site adaptation, and robust design – will be critical to sustaining observational capabilities in the coming decades.

At the same time, the astronomy community is increasingly aware of its own environmental footprint. Supercomputing and travel, particularly by senior researchers, are major contributors to the sector's carbon emissions. While Australia has made strides in adopting renewable-powered computing infrastructure, the carbon cost of travel – especially for international conferences – remains high and disproportionately tied to wealthier nations. This not only raises sustainability concerns but also highlights issues of equity and access. The shift toward hybrid and online collaboration since 2020 has improved inclusivity and reduced emissions, offering a model for more sustainable scientific engagement.

Looking ahead, observatories must not only withstand climate impacts but also operate more sustainably.
This includes reducing emissions from construction and operations, and planning for environmentally responsible decommissioning. Meanwhile, the broader astronomy community must continue refining how it collaborates – balancing the benefits of in-person interaction with the need to minimise carbon costs. This includes considerations around travel and green computing.

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