# High-Energy and Multi-messenger Astronomy White Paper for the Mid-Term Review of the 2016-2025 Decadal Plan

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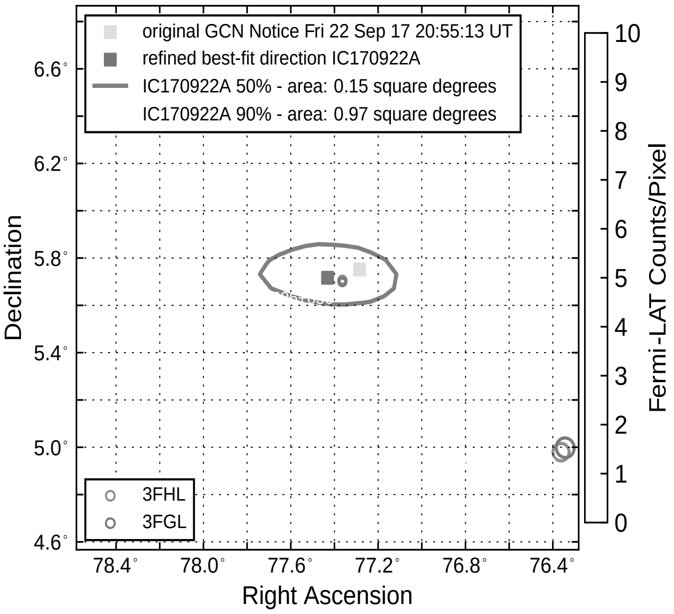
The era of multi-messenger astronomy has begun. Since the writing of the decadal plan, just some of the many high-energy and multi-messenger science breakthroughs are:

- The binary neutron star (BNS) merger GW170817,
- Neutrino emission from blazar TXS 0506+056,
- Detection of TeV gamma rays from several GRBs probing prompt and afterglow phases,
- The first low-frequency radio counterpart to an unidentified TeV gamma-ray source,
- Unequivocal evidence for the extragalactic origin of the highest energy cosmic rays.

These breakthroughs provide new opportunities for Australian Astronomy in the 2020-2025 era. The unique views provided by high-energy and multi-messenger facilities reveal processes hidden from traditional astronomical windows. The 2015-2025 Decadal Plan showed high-energy facilities probing three of six key science questions: in the past 5 years, this number has risen to six. At the same time, radio and optical astronomy have proven invaluable for interpreting these new observations, and Australia's unique geographical location makes it a vitally important site for target-of-opportunity observations. Maintaining a closely linked community of experts spanning all astronomical windows will be invaluable in the multi-messenger era. Therefore, the key recommendations of this white paper are:

- Maintain current levels of access to the Cherenkov Telescope Array (CTA), to ensure Australian participation and leadership in the new TeV gamma-ray science, plus optimise the resulting multi-messenger opportunities for our community [$1M/yr],
- A long-term stable funding mechanism for Australian participation in IceCube, KM3NeT, and the Pierre Auger Observatory to maintain a key presence in the neutrino and cosmic ray windows [$100k/yr total],
- Optimise the science return from already established partnership (MoU) between AAL and the German eROSITA Consortium [$10k/yr],
- Hire and support a critical number of researchers with expertise required to exploit and combine data from existing multi-messenger and high-energy facilities,
- Establishment of a Centre of Excellence to maximise and build upon existing synergies within the extensive high-energy and multi-messenger communities,
- A long-term stable funding mechanism for Stawell Underground Physics Laboratory (SUPL), to enable dark matter searches.

These opportunities are only possible because of key investments prior to the aforementioned breakthroughs. Support for HEMM has proven excellent value for money, leveraging billions in international investment in world-leading instruments, and leading to Australian involvement in the key scientific breakthroughs in this era of Global Astronomy. The HEMM community is united not by individual mega-projects however, but by the high-energy astrophysics it studies. Australia should therefore build upon its many individual successes to form a national body spanning experimentalists and theorists capable of bringing the full range of data to bear on the key scientific questions of the decade.



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## Gamma Rays (Space- and Ground-based: MeV to beyond PeV)

Gamma rays above GeV energies trace accelerated particles and can be used to indirectly probe for dark matter. The fundamental particle physics of gamma-ray production links them to processes producing radio to X-ray photons and neutrinos. Thus, gamma-ray studies of astrophysical particle accelerators like supernova remnants (SNRs), pulsars and their wind nebulae, black hole environments and jets (both AGN and microquasars), and massive star clusters require a multiwavelength and multi-messenger approach. As the highest energy photons, gamma rays can constrain important parameters of particle acceleration such as shock speed, acceleration time scale, magnetic fields and the maximum particle energies attained. Gamma rays often represent a significant fraction of non-thermal energy in extreme objects, and are extremely important in understanding transient and variable sources. Gamma-ray absorption in distant objects probes the extragalactic background light, and allows the study of star formation and galaxy populations.

Gamma rays up to 10’s of GeV energies are detected using space-based methods. In the MeV range, the INTEGRAL mission provides many of the leading results on gamma-ray lines produced from radioactive element decay, and annihilation channels, outbursts from X-ray binaries, and gamma-ray counterparts to GW binary neutron star mergers. From 100 MeV to 10’s of GeV, the Fermi Large Area Telescope (LAT) space mission leads the way. Its data products are publicly available almost immediately after data taking and Fermi-LAT data have been important for Australian transient/variable source studies (e.g. AGN, GWs, FRBs). Fermi's NASA funding runs until the end of 2019 and a review will determine funding for 2020-22.

Detecting gamma rays of energy >100 GeV requires ground-based methods and the current state-of-the-art facilities are HESS (Namibia), MAGIC (La Palma, Spain), VERITAS (Arizona, USA) and HAWC (Mexico). In the Southern Hemisphere, HESS has led the field and has detected the majority of the Galactic TeV sources so far. The University Of Adelaide is involved in HESS and its published results/data are publicly available. HESS operations are funded until 2022 via Uni. Adelaide support ($10k/year/staff). Western Sydney University is an associate member of HESS. HESS will remain the most sensitive TeV facility until CTA (see below) comes online.

Six Australian institutes (over 20 scientists) are involved in the next generation Cherenkov Telescope Array (CTA), a 400MEuro TeV gamma-ray observatory with membership from over 30 countries. CTA will be >10x more sensitive than HESS and is expected to reach an angular resolution or 1 arc-minute or better, enabling high fidelity imaging studies of many sources. CTA’s low threshold <50 GeV will also plug the energy gap with Fermi-LAT, greatly expanding the number of variable and transient sources detectable from the ground with high gamma-ray statistics.

ARC LIEF projects (currently $500k/yr) fund Australia’s CTA construction contribution up to 2021, and NCRIS/AAL funds ($200k/yr) the membership of CTAO (the Observatory organisation operating CTA) and scientific engagement (travel to CTA meetings; CTA-Australia meetings). Eventual CTA operational costs and CTAO membership could be met by a multi-year LIEF of similar scale to that already funded, combined with NCRIS funds (total about $0.8M/yr to $1M/yr). CTA is expected to have a >20 year lifetime with full operations expected from about 2025.

A southern version of the HAWC wide-field TeV gamma-ray observatory complementary to CTA (SGSO), is also being developed and the University of Adelaide is involved in site studies (Peru) for this instrument. We note the Pierre Auger Observatory is also sensitive to >100 PeV gamma rays and has set the most constraining limits so far.

# X-ray Astronomy (space-based missions)

X-ray (0.1 to 500 keV) studies probe a broad range of astrophysics. In particular, accretion onto compact objects (black holes, neutron stars, white dwarfs), constrain general relativity in the strong-field limit, and the neutron star equation of state. X-ray-emitting hot gas reveals the structure of elliptical galaxies and the masses of galaxy clusters. X-rays probe particle acceleration in supernovae and its remnants, the associated outflows and jets, tidal disruption events, GRB afterglows, colliding winds in starburst regions, and stellar flares including their effect on planetary atmospheres. In the multi-messenger era, X-rays have provided evidence for a relativistic jet from GW170817, and the strongest constraints on neutrino production within TXS 0506+056.

The workhorses of X-ray astrophysics for the past two decades have been the *Chandra* and *XMM-Newton* observatories as well as the *Swift*, *INTEGRAL*, and *NuStar* satellites. *Swift* includes UV/optical and gamma-ray detectors for multiband studies and has been the prime facility for the detection and follow-up of transient sources. Australian astronomers have freely benefited from data from all these facilities, which will continue to operate for most of the next decade.

Several new missions provide opportunities for Australian involvement in the 2020-2025 period. eROSITA, onboard the Russian Spektrum-Rötgen-Gamma satellite (launched 2019), will perform an X-ray survey of the entire sky with unprecedented angular resolution and sensitivity. It will:

- Detect the hot intergalactic medium of ~$10^5$ galaxy clusters and groups, and hot gas in filaments between clusters, to map out the large scale structure in the Universe;
- Detect all obscured accreting black holes in nearby galaxies and many (up to 3 million) new, distant active galactic nuclei and
- Study the physics of Galactic X-ray source populations, like pre-main sequence stars, supernova remnants, pulsars and their wind nebulae, and X-ray binaries.
- Provide a new window on large-scale X-ray features in our Galaxy and beyond.

A partnership (MoU) between AAL and the German eROSITA Consortium is expected to be signed on Oct 10th-11th, 2019. The MoU provides major new opportunities for multi-messenger astronomy projects across the southern sky, enabling various synergies with Australian wide-field facilities such as ASKAP, MWA, Mopra, UTMOST, ATCA, SkyMapper, AAT and TAIPAN. Australian astronomers will use eROSITA for studies of extragalactic (e.g. AGN & galaxy clusters) and Galactic objects such as supernova remnants, which are also probed by HESS, CTA, and IceCube/KM3NeT. There are no direct costs to the Australian community, however funding for engagement in eROSITA science would be highly beneficial [~10k/yr].

Other important upcoming missions with data accessible to the Australian community are:

- X-Ray Imaging and Spectroscopy Mission (XRISM: JAXA, 2022) will provide the highest-ever spectral resolution in the soft X-rays; and measure metal abundance in hot plasma in galaxies and clusters, and outflows from accreting compact objects;
- Imaging X-ray Polarimetry Explorer (IXPE: NASA, 2021), with X-ray polarization detectors two orders of magnitude more sensitive than any previous such instruments
- Einstein Probe (EP: Chinese Academy of Sciences, 2023) will scan the whole sky every 6 hours, looking for bright variable and transient sources.
- Advanced Telescope for High Energy Astrophysics (ATHENA, ESA, 2031). Featuring a wide-field imager, and a high-resolution integral field unit, it will study of cosmic feedback, and black hole growth over cosmic time.

## Neutrinos (high-energy: GeV to PeV)

Neutrinos are produced in particle interactions during high-energy astrophysical processes. Neutrino astronomy probes AGN, supernova remnants, GRBs, dark matter, cosmic shocks in the period of reionization, Galactic supernovae, and fundamental particle physics. Energetic hadrons can dominate the energy and momentum budget of astrophysical jets and outflows. Their electromagnetic signature can however be masked or absorbed in the source or during propagation. Unlike other messengers, neutrinos are neither absorbed in dense environments, nor deflected during propagation. Neutrino astronomy provides unique, complementary data to other EM and multi-messenger facilities, opening a new window on the high-energy Universe.

The IceCube Neutrino Observatory, located at the South Pole, has detected many astrophysical neutrinos and characterised their properties, and has now detected the first astronomical source of high-energy (TeV to PeV) neutrinos: the blazar TXS 0506+056. Multiwavelength analysis of this object has benefited from data spanning radio, optical, X-rays, and gamma rays to TeV energies. Blazars alone cannot account for the diffuse high-energy neutrino flux observed by IceCube, it is likely that multi-messenger neutrino astronomy will expand its reach in the coming years.

Uni. Adelaide is strongly involved in the IceCube Observatory, with funding in part from ARC DPs (20k/yr). The TANAMI project (including U. Tas, CSIRO, Curtin U.), using the Australian Long Baseline Array for VLBI studies of blazars were the first to suggest an association between IceCube events and blazars, and have previously used IceCube's public neutrino alerts in their ATCA radio AGN studies, with MWA performing rapid follow-up observations.

Several future projects with Australian involvement will increase the reach of neutrino astronomy. KM3NeT, currently being constructed with a 2024-2025 completion date, is a Northern Hemisphere neutrino telescope with comparable size to IceCube, but improved angular resolution. Its location is complementary to IceCube’s: KM3NeT is optimised to study southern hemisphere, and particularly Galactic, sources. KM3NeT has an MOU with MWA for rapid follow-up observations. Both Western Sydney Uni. and Curtin Uni. are KM3NeT members [~$5k/yr/staff, ~10k/yr/staff from 2020]. Public data will be released after two years. Its predecessor, ANTARES, will prove invaluable for preparing Australian researchers for KM3NeT analysis.

The “IceCube Upgrade” is adding 700 new optical sensors, to be deployed by 2022/23. These new detectors will strongly enhance IceCube’s low-energy capabilities, allowing more precise studies of neutrino oscillations and tests of the neutrino mass hierarchy. Even more significantly, the proposed IceCube Gen2 would extend the detector volume from 1 to 10 km$^3$. The goal will be to probe the highest-energy neutrino flux, presumably dominated by extragalactic sources. The detector would have greatly enhanced sensitivity to point sources, diffuse fluxes, supernovae, and of course continue the already successful neutrino alert and multi-messenger campaigns. The final design is almost complete, and if funded, would begin deployment in the 2025-2030 era.

All neutrino instruments function as probes of fundamental particle physics, with future upgrades to probe the 1-10 GeV range able to resolve the neutrino mass hierarchy, and detect CP violation.

## Cosmic Rays

The University of Adelaide has a long history in the study of the highest energy cosmic rays, and currently holds several leadership positions within the premiere international experiment in this field, the Pierre Auger Observatory. A 400-stong international collaboration, including a group of ten from Adelaide, operates the 3000 km$^2$ detector in western Argentina. Auger's important discoveries include that the highest energy cosmic rays include a significant fraction of heavy nuclei, a surprising result that severely constrains models of astrophysical particle acceleration. In arrival direction studies, Auger has conclusively shown for the first time that the highest energy particles are extragalactic, with a broad-scale anisotropy consistent with the distribution of matter in the local Universe. On smaller angular scales, there is strong evidence for an association of arrival directions with directions of local starburst galaxies, or with gamma-ray-selected active galaxies. Apart from providing information on cosmic ray acceleration sites, both the broad-scale and smaller scale anisotropies set the tightest constraints yet available on magnetic fields in galactic voids. The AugerPrime upgrade, to be completed in 2020, will extend the life of the observatory until 2030, and allow for more-sensitive source searches, and tighter constraints on extragalactic magnetic fields.

The University of Adelaide has been funded for Auger Observatory work through a series of ARC Discovery Projects (most recently 2015-2019) and two ARC LIEF grants (most recently in 2018 for a hardware contribution to AugerPrime). In the next decade, Adelaide will continue to make strong contributions to the analysis of Auger data, with a minimum requirement of $50K p.a. for collaboration subscription fees, plus funding for personnel and travel.

The Adelaide group is contributing to international discussions about the next cosmic ray observatory beyond Auger. The design is likely to be contingent on the discoveries made by AugerPrime in the next 5 years. One attractive possibility is for Australia to join efforts that detect cosmic ray showers in the Earth's atmosphere from space. The EUSO project is currently testing prototypes on balloons and on the International Space Station, and there are international plans for a pair of free-flying satellites known as POEMA. The University of Adelaide and Swinburne University are also collaborating on the CREDO project, to observe cosmic ray coincidences over very large areas using distributed detectors, including smartphones.

Muon and neutron observations allow study of heliospheric modulation, space weather, and provide radiation hazard warning input to airlines and space operators. The Kingston muon telescope (part of the Global Muon Detector Network) and Mawson Cosmic Ray Laboratory (longest global record of such fluxes) will be operated by an international consortium for at least the next decade with the Australian Antarctic Division providing logistic support.

Cosmic rays can also be studied using radio telescope, with this technique providing the highest resolution on cosmic rays in the $10^{17}$-$10^{18}$ eV region. These studies probe the cosmic ray composition where the cosmic ray flux is transitioning from a Galactic to an extragalactic origin, and high-energy particle physics. This method is being developed for the MWA, with ~$100k invested in a partnership between Curtin U., CSIRO, and others; and for the SKA, via the SKA's High Energy Cosmic Particles Focus Group. During 2020-2025, $350,000 is required to complete the MWA project; post-2025, the hardware cost to implement SKA1-low is ~$1M. The highest energy cosmic rays can in theory also be detected via their interactions with the Moon, with Curtin collaborating on a project involving the FAST radio telescope in China.

# Dark Matter

Dark matter is a priority area, worldwide, in particle astrophysics. The decadal plan recognizes dark matter and dark energy as problems of the highest importance.

There is a growing dark matter community in Australia – spanning astrophysics, particle physics and their intersection – with key involvement from ANU, Monash, Swinburne, U.Ade, U.Melb, UNSW, UQ, U.Syd and UWA. A national initiative not anticipated in the decadal plan is the Centre for Dark Matter Particle Physics, www.darkmatter.org.au, and its associated national research infrastructure, the Stawell Underground Physics Laboratory (SUPL).

Dark matter research is deeply embedded in astrophysics in many ways: N-body modelling of the evolution of structure in the Universe; phenomenology such as the bullet cluster, explored using microlensing; dynamics of galaxies and clusters of galaxies; possible indirect detection using Galactic gamma or cosmic ray observations; possible direct detection in underground laboratories; possible involvement in the thermal history of the Universe at the end of the Dark Ages.

It is likely that future advances in modelling structure and galaxy evolution will require some knowledge of the non-gravitational properties of dark matter, a prime motivation for astroparticle physics. There are three conventional ways to probe these properties:

- *Indirect detection* is the search for dark matter annihilation or decay in regions of dark matter density, including the Galactic centre, external galaxies, and the Sun. These signals include x-rays, gamma rays, cosmic rays and neutrinos, offering the possibility of correlated, multi-messenger observations. Australian involvement includes the Fermi-LAT, HESS and CTA gamma-ray telescopes and the IceCube and KM3NeT neutrino observatories.
- *Direct Detection* of ambient dark matter is a rapidly growing field in Australia. The SABRE direct detection experiment, located in SUPL, is the flagship project of the recently announced dark matter Centre of Excellence. R&D for future detector technologies is planned; this includes sub-GeV (cryogenic) direct detection, and involvement in the CYGNUS *directional* detection collaboration, which aims to detect a dark matter flux aligned with the direction of the constellation Cygnus. UWA researchers are involved in the search for very light dark matter, called axions, and have recently joined the flagship international experiment, ADMX. Axion detectors have strong technology spin-offs that make them particularly attractive to advanced physics applications and industry development.
- *Collider production* of dark matter falls within the remit of particle rather than astro physics. However, strong Australian involvement in the dark matter searches at the Large Hadron Collider and the Belle-II experiments provide important synergies with astrophysics.

*Dark Matter theory program:* There is a strong Australian dark matter theory community, whose activities include cosmological simulations, particle and astroparticle phenomenology, and the development of numerical tools for data analysis and parameter estimation. Much of the theory program is computationally intensive, requiring access to high performance computing facilities.

*Planning and resources:* It is timely that the mid-term review coincides with the arrival of SUPL. SUPL is being built as a national research facility with astroparticle, ultra low background biophysics, nuclear astrophysics, astrobiology and geophysics users, and finds a place in the National Research Infrastructure roadmap of 2016 in the category of Advanced Physics & Astronomy. In coming years, the participating universities will guarantee up to $0.5M/year toward SUPL operation expenses, whilst external funding is sought.

## Theoretical Synergies

Theoretical studies are the glue that binds high-energy, multi-messenger and other fields of astrophysics together. These do not require instrumental subscriptions, and often have small computational requirements. Nonetheless, continued support for these theory groups will be critical for exploiting the range of data available in the multi-messenger era.

Example applications of theoretical studies in high-energy/multi-messenger astrophysics include:

- Production of radio to gamma-ray photons, neutrinos and cosmic-rays: These are all linked via a number of fundamental physics processes such as: cosmic-ray/proton collisions, inverse-Compton scattering, bremsstrahlung, matter/anti-matter production and annihilation, photopion production, curvature radiation, synchrotron radiation, radioactive decay, and, beyond-standard model processes. Combinations of these are modeled in numerous astrophysical scenarios that create conditions for particle acceleration and excitation.
- The astrophysical scenarios include: supernova remnants, pulsar environments, accreting objects (AGN, X-ray binaries, microquasars), starburst galaxies, cataclysmic events (supernovae, hypernovae, kilonovae, compact mergers), massive stellar winds and clusters, ISM clouds etc.
- Simulations of jets, which have allowed X-ray and radio data to understand the ejecta from GW170817, probe the physics of microquasars, and limit the neutrino production mechanism in blazars.
- Simulations of Galactic cosmic ray and electron propagation using magnetic fields, infrared photon fields and ISM gas distributions. The aim is to reproduce the cosmic ray spectrum at Earth, the diffuse GeV gamma-ray emission, and predict diffuse Galactic neutrino fluxes. Current applications (e.g. with GALPROP code) include improving the resolution to predict the diffuse TeV gamma-ray emission to be detected by CTA.
- Modeling the propagation of cosmic rays and electrons into specific ISM clouds to accurately predict the TeV gamma-ray morphology seen with HESS, and later, with CTA.
- Modeling of the central Milky Way outflows, driven by either accretion or stellar winds.
- Galaxy formation simulations including cosmic ray pressure find these are an important mechanism for opening magnetic field lines to allow gas to escape and turn off star formation in low-mass galaxies.
- Studies of dark matter provide methods to use high-energy gamma-ray and neutrino observations to search for annihilation products; projects such as GAMBIT limit the parameter space of dark matter; and of course dark matter plays a key role in the formation of cosmic structure, and the first stars and galaxies.
- Gamma-ray observations from GW170817 and AGN flares place strong limits on Lorentz invariance violation (LIV).
- Simulations of shocks from early-universe galaxy formation predict cosmic ray acceleration which can be probed via neutrino fluxes
- The paradigm of the radio-FIR correlation being due to star formation producing cosmic ray electrons is being tested by low Fermi gamma-ray fluxes, and a lack of IceCube and ANTARES neutrino detections, despite Pierre Auger finding star-forming galaxies the best match to the highest energy cosmic rays.
- Additionally, beyond-the-standard-model physics - which the LHC has so-far failed to find - may first be revealed in the high-energy and multi-messenger sector.

## Observational Synergies - Radio to Gamma Rays, Neutrinos, Cosmic Rays, and Gravitational Waves

The many high-energy and multi-messenger facilities are linked to each other, and many astronomical facilities, via their common science goals. The SKA and its pathfinders (MWA, ASKAP, UTMOST, LBA) also target non-thermal physics, transients, and dark matter, while Australia's unique longitude in the Southern hemisphere presents ideal opportunities for Australian radio and optical telescopes to contribute critical multi-wavelength information on transients and variable sources. Involvement in the LSST would aid such monitoring. E.g. GeV/TeV flares in AGN are accompanied by rapid swings in optical polarisation angle as the only contemporaneous multi-wavelength component. Gamma-ray emission could theoretically lead many other multi-wavelength flares, and locating several CTA-type gamma-ray telescopes in Australia for TeV monitoring of southern sources would fill a vital longitude gap in this band.

IceCube, KM3NeT/ANTARES, and in particular HESS are directly linked to Australian-led astronomy facilities, with MoU or ad-hoc agreements established with MWA, Parkes-SUPERB, UTMOST, DeeperWiderFaster, and aLIGO/VIRGO for studies of transients, variable sources, and broad-band continuum. Indirect linkages are via the Astrophysical Multi-messenger Observatory Network (AMON), Gamma-Ray Coordination Network (GCN), and VOEvents and ATELs. In light of neutrino detection from TXS 0506+056, AGN flares are particularly interesting targets, with the recent flaring of the flat-spectrum radio quasar PKS1510-089 seen by HESS (ATel #12965) prompting ATCA radio follow-up, and discussions of the potential for high-frequency (>20 GHz) VLBI in Australia (offering the best resolution and potential to probe rapid outflow development).

More broadly, the above programs aim to explore the full multi-messenger space for time and spatial correlations in order to understand the transient universe. The lack of counterparts to Fast Radio Bursts is one such mystery being targeted. Gravitational wave sources can be targeted within as little as five minutes of a detection now that aLIGO/VIRGO has moved to a public alert system. The A+ upgrade to aLIGO (circa 2025) will increase the detection rate of e.g. binary neutron star mergers 30-fold. OzGrav, the ARC Centre of Excellence for Gravitational Wave Discovery, has cemented Australia's involvement in GW astronomy and its recent breakthroughs, and the ANU has developed a new SkyMapper mode (AlertSDP) for automated optical follow-ups.

Australian-based interstellar medium (ISM) observations with Mopra and soon, ASKAP (eg. GASKAP), provide crucial data in the understanding of Galactic TeV sources (e.g. from HESS) given the ISM's fundamental role in cosmic-ray and electron collisions. The 30 arc-sec resolution of Mopra's molecular and ASKAP's atomic ISM surveys are perfectly matched to the future Galactic plane and Magellanic clouds surveys from CTA. CTA will detect large-scale diffuse TeV emission along the plane and detailed 3D modeling of cosmic-ray and electron interactions with the ISM will be required to build TeV catalogues at >5 times better resolution than GeV source catalogues from *Fermi*-LAT. In combination, IceCube and KM3NeT monitor the entire neutrino sky, and will play a pivotal role in distinguishing between cosmic-ray and electron sources of TeV photons.

The High Energy Cosmic Particles SKA Focus Group aims to use the SKA to directly detect radio emission from cosmic rays. It is collaborating with both MWA and FAST on precursor projects, and shares technical synergies in high-time-resolution radio astronomy with FRB projects. It complements cosmic ray studies with Pierre Auger at both the low- and high-energy regimes.

## Answering the big questions

The 2015-2025 Decadal Plan outlines six key science questions, and the roles that different astronomical observations play in answering them (Table 7.1). In light of recent developments, the role of high-energy and multi-messenger facilities is now:

1) **How did the first stars and galaxies transform the Universe? (supporting)** Neutrinos potentially have the power to probe particle acceleration in the first cosmic shocks; near-future GW observatories will study galaxy formation through supermassive black hole mergers.
2) **What is the nature of dark matter and dark energy? (critical)** Experiments conducted in the Stawell Underground Physics Laboratory (SUPL) aim to directly detect dark matter, while gamma rays and neutrinos look for signatures from DM interaction or decay. GW cosmology promises better constraints on the Hubble constant, and X-rays study the distribution of baryonic mass by directly imaging hot Galactic halos. Hints of beyond-the-standard-model physics are expected to be revealed in the high-energy and multimessenger sector.
3) **How do galaxies form and evolve across cosmic time? (supporting)** Cosmic ray pressure is a critical component in understanding star-formation and feedback in low-mass galaxies. TeV gamma rays probe extragalactic background light and limit the population of low-surface-brightness galaxies. Cosmic rays probe intergalactic and halo magnetic fields. Neutrino, gamma, and X-ray facilities study hadronic and leptonic components of AGN jets, hence their energy/momentum budget, and the effect on their host galaxies. The origin of the far-IR / radio correlation in star-forming galaxies is tested by gamma rays, X-rays, neutrinos, and (in the local universe) cosmic rays.
4) **How do stars and planets form? (supporting)** The population distribution of BH-BH mergers seen in GWs probes the high-mass tail of the initial mass function, while X-ray observations probe exoplanet atmospheres. Gamma-ray studies of cosmic ray interactions in molecular clouds reveal the ionisation distribution and its effects on cloud collapse and cosmic-ray-induced cloud chemistry.
5) **How are elements produced by stars and recycled through galaxies? (supporting)** The binary neutron star merger GW170817 revealed the origin of r-process elements, while cosmic ray elemental and isotope studies reveal the chemical abundance in supernovae ejecta. Cosmic ray interactions with the ISM are probed by gamma rays and neutrinos.
6) **What is the nature of matter and gravity at extreme densities? (critical)** GW detections probe general relativity in the strong-field limit, and together with X-rays, the NS equations of state. Neutrinos provide a direct window to high-energy particle interactions in AGN and GRB jets, while cosmic rays are indisputable evidence of these processes occurring. TeV gamma rays have revealed an unprecedented population of high-energy sources in our own Galaxy - many yet unidentified - while GeV (and recently, TeV) gamma rays study emission processes in pulsars. The interaction physics of cosmic rays probes densities beyond the reach of the LHC, and within one second of the Big Bang.