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ATNF of the Future Working Group 2 Report
Future developments and opportunities in broad-EM and multi-messenger astronomy

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1. OVERVIEW

With construction of the Square Kilometer Array (SKA) – consisting of SKA-Low in Australia and SKA-Mid in South Africa and neighbouring countries – now under way and projected to finish around 2030, we contemplate the future role of the Australia Telescope National Facility (ATNF) in the upcoming decade and how to prepare for the wide range of challenges and opportunities. This will likely mean an evolving ATNF to focus on a new vision and re-position its role in Australia as a long-term international partner.

Initially founded in 1988 to support and champion science with the Australia Telescope Compact Array (ATCA), the 64-m Parkes radio telescope (also known as "The Dish" and "Murriyang"), the 22-m Mopra radio telescope, and the Long Baseline Array (LBA), ATNF has aimed and mostly succeeded to stay at the cutting edge of radio astronomy technology, computing and science. Preparations for the international SKA have long been under way, including the design, construction and commissioning of the 6 km diameter Australian SKA Pathfinder (ASKAP) consisting of 36×12-m dishes with innovative wide-field Phased Array Feeds, participation in the growing low-frequency Murchison Wide-Field Array (MWA) and the Pawsey Supercomputing Centre, as well as enormous strides in custom software, algorithm and pipeline developments. There are exciting times ahead, working together to explore and expand this new discovery space.

ATNF and the Australian community are strongly engaged in SKA Science Working Groups, SKA Pathfinder survey science, and multi-wavelength follow-up of exciting discoveries, transient sources, and multi-messenger events. CSIRO is a partner organisation in the growing Australian SKA Regional Centre (AusSRC, aussrc.org) whose major task it will be to transfer data from SKA-Low to the global scientific community. While the AusSRC currently supports ASKAP and MWA science projects, its focus is strongly on creating new frameworks, tools and methodologies to work and interact with large SKA data sets. The role of the "ATNF of the Future", if well funded, can be broader, supporting SKA via expert teams, complementary observatory projects as well as multi-wavelength follow-up studies. A bold vision could see the establishment of a vibrant National Astronomy Centre, formed in consultation with the Australian astronomy community.

Here we list major telescope and science projects relevant for ATNF's future and strategic planning in the SKA era (expanded in the Appendix), each providing new challenges, collaboration opportunities and discovery potential:

- the European Southern Observatory (ESO): ALMA and optical/infrared telescopes
- the optical Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST)
- the Laser Interferometer Gravitational-Wave Observatory (LIGO) and 3G Detectors
- the Five-hundred-meter Aperture Spherical radio Telescope (FAST)
- the Meer Karoo Array Telescope (MeerKAT)
- the expanded Giant Metrewave Radio Telescope (eGMRT)
- the Deep Synoptic Array (DSA)
- high energy facilities (e.g., CTA, ATHENA, KM3NET)

2. LONG-TERM DIRECTION OF AUSTRALIAN ASTRONOMY

Traditionally, Australia's Astronomy Decadal Plan sets the scene for the next 10+ years and aims to prioritise science goals and key projects. It serves as a strong, united multi-institutional voice to propose future government funding. ATNF's participation and leadership in this process is essential in ensuring its future role as a key partner in exciting Australian and international projects.

Strong engagement with the broad-EM and multi-messenger community in Australia and overseas is critical for ATNF's future. Long-term leadership in radio astronomy requires upgrading ASKAP, maintaining other ATNF facilities (e.g., for legacy projects, training / testing, dedicated follow-up, discovery potential), and expanding into new areas. It also requires investing in our people through more funding, making sure the traditionally strong and creative interactions between top engineers, scientists, software developers and data analysts are allowed to flourish. A strong presence at international meetings, collaboration hubs, facility headquarters, exchange visits, etc. is essential while providing ample opportunities, incentives and expert hubs (e.g., a National Astronomy Centre) to attract a wide range of people from around the world to Australia for collaborations, workshops, brainstorming, joint ventures and education/training.

Centimeter and millimeter radio follow-up observations of transient events and other discoveries made by partner observatories require agile and fast response to alerts by dedicated support teams aided by automated response pipelines. Strengthening our linkages to those Australian Universities involved in major projects through joint engineering, computing and science projects with dedicated personnel (e.g., students, postdocs, and joint leadership). A Lorentz Centre-like workshop/meeting facility would encourage interdisciplinary interactions between observers and "analysers" (AI, statisticians, data processors, etc.), as well as theorists and computational astrophysicists. Other examples are Hackathons and Gordon-like Conferences (grc.org).

While raw data from ATNF were initially made public through the Australia Telescope On-line Archive (ATOA), our new, user-friendly approach delivers science-ready, fully calibrated data products and valuation reports through the dedicated CSIRO ASKAP Science Archive (CASDA) together with growing linkages to other sky surveys via the CASDA SkyMap, and, for example, DataCentral (datacentral.org.au). Dedicated resources would allow expansion of the archive, cross-matching with optical/radio images and catalogues, and enhanced 2D and 3D visualisation tools as well as making radio surveys (incl. ATNF surveys) and catalogs publicly available in key multi-wavelength databases (e.g. SkyView, ESAsky, legacyserver.org, CADC) for easy access to all astronomers. ATNF could be a vibrant and green hub of expertise with an interactive 3D-visualisation centre to attract people for collaborations, discovery space and data exploration (incl. AI/ML applications). At the same time, a continuing strong focus to train students at ATNF facilities (hands-on telescope experience and radio schools), is essential for the future of astronomy as new large telescopes will be more automated and less accessible.

3. SPECIFIC TOPICS

Opportunities for Australian astronomy from multi-messenger (EM radiation, gravitational waves, neutrinos, cosmic rays, dark matter particles, etc.) and optical/infrared observations are many-fold.

- What are the likely developments in these fields over the next decade?

  The growing volume of astronomical data delivered by many new, cutting-edge telescopes together with their complexity, reliability and reproducibility pose challenges (e.g., new algorithms to store, ingest, search data in spatial, spectral and time domains; data analysis, validation and security) and opportunities (e.g., making discoveries, cross-identification). Data science and artificial intelligence (AI) are rapidly growing areas that will underpin most astronomical research.

  For example, in the high-energy domain, CTA will dramatically expand the opportunities to study γ-ray transients for energies >30 GeV. It is estimated over 1000 hr/year of radio cm and mm coverage will be needed to support CTA's Key Science Projects (mainly transients/variable sources) in the southern hemisphere over the coming decade. Furthermore, many expansions and improvements have been proposed to gravitational wave observatories, some of which will come online on this timescale. New observatories will likely have improved detection rates and localisation regions, which will make very wide field instruments less important. LSST alerts, issued publicly in real time, provide a discovery space for multi-wavelength radio follow-up.

- Are there opportunities to combine data with radio astronomy in ways to make new discoveries more likely?

  The detection of gravitational waves by LIGO (Abbott et al.) opened a new field of astronomy, allowing us to investigate what happens when neutron stars or black holes collide. Thanks to ASKAP's wide-field Phased Array Feeds, quick follow-up radio continuum observations allow to pinpoint candidate sources within the large LIGO event areas (typically 30 – 100's deg^2). This is likely a growing domain. ASKAP has already demonstrated the benefits of wide-field imaging at high angular resolution for the localisation of fast radio bursts (FRBs). The detection of millions of radio sources in large sky surveys provides an enormous discovery space, but their full potential can only be realised through detailed multi-wavelength follow-up observations and partnerships (e.g., eROSITA, LSST) together with numerical simulations for our understanding of the physical processes over time. Combined data visualization together with advanced analysis tools play a key role in enabling discoveries.

- What are the implications of possible decisions made around ESO in 2027? What are the possible scenarios for the ATNF-ESO relationship?

  The decision for Australia to become a full member of ESO in 2027 (or not) will impact collaborations, industry involvement, and the ability of Australian-based astronomers to lead projects, e.g., linked to ATCA, ASKAP, and SKA-low. It will attract (or drain) astronomers and staff in related areas. Full access to ALMA, provided through full membership of ESO, would likely increase demand for complementary ATCA 4 – 25 GHz observations. The recent SKAO – ESO workshop on *"Coordinated Surveys of the Southern Sky"* (held in Mar 2023; www.eso.org/sci/meetings/2023/CSSS.html) highlighted exciting examples of transformative projects that require both observatories. Strong synergies for ATNF – ESO ALMA in data science (archive, exploration, people).

- Are there natural niches for Australian astronomy in the fields of multi-messenger and broad-EM astronomy?

  ASKAP sky surveys have opened a massive discovery space that has just started to be exploited. An upgraded ASKAP (expanded into SKA-survey ?) would drive the science into new domains, complementing SKA-mid and DSA-2000 in the radio, while partnering with ESO, LSST, eROSITA/ATHENA, CTA, LIGO science teams.

  Furthermore, with ALMA Bands 1 and 2 soon operational (30 – 50 GHz and 67 – 116 GHz) and MeerKAT receivers extending to 3.5 GHz, the ATCA 4 – 25 GHz receivers gain in importance for wide-band imaging, high-resolution spectroscopy, and polarimetry as well as transient monitoring (possibly complemented by Mopra, Parkes UWH, and Tidbinbilla). Fast and flexible radio follow-up observations would benefit many fields, supported by a dedicated alert team, procedures and data processing pipelines to optimise time-critical science.

- How does increased or decreased funding vary the ability for ATNF to help the broader field of astronomy flourish ?

  Increased funding would allow the ATNF to upgrade its facilities and operations as well as expand into new, exciting areas, able to deliver cutting-edge engineering and science to remain a vibrant centre of dedicated people with expertise in engineering, computing and science, attracting a regular stream of visitors, hosting workshops, think-tanks, training students and providing career opportunities.

  Decreased funding would likely mean the closure of facilities and losing key people / groups, resulting in long-term loss of knowledge, experience and expertise built up over decades. While other countries' national radio facilities are expanding (e.g., ngVLA, DSA-2000, eGMRT, FAST, ALMA, and MeerKAT+ in the US, India, China, Chile, and South Africa, respectively) Australia could be left behind, with a loss of relevance and leadership in international collaborations.

- What is the optimal positioning and resourcing for ATNF to best support Australian astronomy ?

  Increased resourcing would allow ATNF to maintain a competitive position into the future and best serve the Australian astronomy community, provide an umbrella or hub for multi-institution (incl. Australian universities), multi-wavelength projects, and engage in key international partnerships. ATNF can be more flexible than SKA in supporting the community and its diverse endeavours.

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APPENDIX

Major telescope and science projects relevant for ATNF's strategic planning in the SKA era are listed below in some detail. This includes key international astronomy projects and facilities currently supported by Australia Astronomy Limited (AAL) via NCRIS funding (e.g., eROSITA, ESO, CTA, GMT and the Rubin Observatory). We envision the ATNF of the Future to strongly support their key science projects through close collaborations, instrument development, student training and as a hub of radio astronomy science, technology, visualization and computing expertise.

- The Square Kilometer Array (SKA)
  - **SKA-Low** (50 – 350 MHz, maximum distance between antennas is 74 km), located on the Murchison Radio Observatory (MRO) site in Australia: construction is under way, projected to finish **around 2030** (includes some science commissioning). Compared to its predecessors (LOFAR and MWA) it will provide higher resolution, better sensitivity and higher survey speed. Strong linkage to MWA (infrastructure, calibration, expertise, personnel, science goals, user base, etc.). One of its key science goals is the study of the red-shifted 21-cm hydrogen line from the earliest phases of star and galaxy formation in the Universe (e.g., Mellema et al. 2013). — SKA-low will be supported by a range of AusSRC activities.
  - **SKA-mid** (350 MHz – 14 GHz, maximum distance between antennas is 150 km), located in the Karoo region of South Africa: construction is under way, projected to finish **around 2030** (includes some science commissioning). Will incorporate the existing 64 MeerKAT dishes. ASKAP sky surveys at 0.9 – 1.7 GHz will inform some of the key science and highlight data challenges as well as provide experience, expertise, personnel, user base, software, databases, etc. SKA-mid will largely make the 20cm mapping and continuum projects on the ATCA obsolete, and greatly reduce Parkes' Southern hemisphere dominance as a pulsar facility.

- Australian radio facilities
  - With **ASKAP** fully operational and ATNF's custom-designed data processing pipelines currently delivering high-quality outputs to all eight dedicated science teams and the public via CASDA[1], the full survey science projects – expected to continue for five years – are now under way. The CRAFT Coherent (CRACO) upgrade project is progressing well. Calls for ASKAP Guest science proposals will be issued from the 2023OCTS semester onwards. Planning of future **ASKAP upgrades** has started and will likely include replacing the low-noise amplifiers (LNAs) to improve the sensitivity of the PAFs by a factor of 2 in Tsys. A call for new ASKAP Survey Science Projects (SSPs) is also planned.

    Adding more antennas and increasing the observing bandwidth by a factor 2–3 could be considered. Notable ASKAP science outputs include: the localisation of many fast radio bursts (FRBs, e.g., Bannister et al. 2017, 2019), and the Rapid ASKAP Continuum Survey (RACS, McConnell et al. 2020; Hale et al. 2021).

    Could a massive extension of the current ASKAP telescope realise the more ambitious SKA-survey goals initially envisaged as one of three SKA components ?
  - ATNF facilities like **ATCA** with BIGCAT, **Parkes** with a cryogenically cooled PAF ('CryoPAF') and an Ultra-Wide bandwidth High frequency receiver ('UWH') , and the **LBA** provide a wide range of options to support key multi-messenger science projects through flexible and fast follow-up of discoveries, transients

[1] Lifetime of CASDA ?

and other alerts. Custom data processing pipelines and a user-friendly data archive for the output products would much enhance their productivity as well as high-impact observatory and guest science projects. They are also ideal instruments for hands-on student training. — It is essential for ATNF to transition all facilities to green energy asap, ideally through cutting-edge solar power and sustainable battery storage on-site.

  - **Expanded MWA:** deemed essential for future SKA-low data calibration and validation. MWA is poised to continue cutting-edge science until its capabilities are overtaken by SKA-Low. Notable MWA science outputs include the GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) survey (Hurley-Walker et al. 2017) and limits on the Epoch of Reionisation (EoR, Trott et al. 2020).

- Optical and mm-wavelength facilities:
  - The **European Southern Observatory** (ESO): In July 2017 Australia entered into a 10-year strategic partnership with ESO at the cost of EUR 7.8M per year. Discussions are under way to consider the benefits of full ESO membership from 2027, which would include access to the Extremely Large Telescope (ELT) and Atacama Large Millimeter Array (ALMA). The usage of ESO telescopes has allowed detailed multi-wavelength studies of discoveries made with Australian facilities by scientists in Australia. Noteworthy is also the ESO studentship programme. — ALMA science opportunities and collaborations are particularly valuable to ATNF and will go much beyond the capabilities of the ATCA high-frequency receivers. New ALMA Band 1 (30 – 50 GHz) receivers will be offered in Cycle 10 on the 12-m array. Band 2 (67 – 116 GHz) receivers are expected from around 2026. **ALMA in the 2030s** (Carpenter et al. 2020) — near to mid-term goals: (1) wideband sensitivity upgrade (broaden receiver IF bandwidth by up to $4\times$, and upgrade of associated electronics and correlator for gains in speed), and (2) Archive: increase usability/impact. Longer term goals include the addition of longer baselines, wide field mapping speed and additional antennas.
  - The 10-year **"Legacy Survey of Space and Time"** (LSST, lsst.org) of the southern sky, conducted by the Vera C. Rubin Observatory, is set to commence in 2024. Using a 8.36-m aperture telescope (FOV 9.6 deg^2) it will gather wide-field optical images in the *ugirzy*-bands. LSST alerts of transient sources will be issued publicly in real time. Its core science goals are probing dark energy and dark matter, cataloging the solar system, exploring the transient optical sky, and mapping the Milky Way. — Through a successful ARC LIEF grant (PI: Sarah Brough), starting on 22 Feb 2023 – 21 Feb 2026, significant Australian participation (from ATNF: E Mahony, OI Wong, and BS Koribalski) and data rights have been negotiated. ASKAP science surveys will hugely benefit from the variable source alerts, optical images, stellar masses, photometric redshifts and stellar properties provided by this survey (see, Brough et al. 2020).
  - The **4-metre Multi-Object Spectroscopic Telescope** (4MOST, 4most.eu) will provide the ESO community with a fibre-fed spectroscopic survey facility on the VISTA telescope with a large enough field-of-view to survey a large fraction of the southern sky in a few years. Operations are expected to start in Q1 2024. — 4MOST enables many science goals, but its design in particular complements a number of key large-area, space-based observatories of prime European interest: Gaia, eROSITA, Euclid, and PLATO, and future ground-based, wide-area survey facilities like the Vera C. Rubin Observatory and SKA. The 4MOST consortium consists of 15 institutes in Germany, Australia, France, the Netherlands, Sweden, Switzerland, and the UK, under leadership of the Leibniz-Institut für Astrophysik Potsdam (AIP).
  - The **Giant Magellan Telescope** (GMT; giantmagellan.org) is a next generation optical/infrared telescope, currently under construction in Chile. When completed in the late-2020s, the GMT will be 25 metres in diameter and will have over six-times the collecting area of the largest telescopes currently in existence. Australia holds a 5% share in GMT through the Australian National University (ANU) and AAL.
  - The **Gran Telescopio Canarias** (GTC; gtc.iac.es) is a 10.4m telescope with a segmented primary mirror. Instrument developments and collaborations with AAO.
  - The new **James Webb Space Telescope** (JWST; webb.nasa.gov) is already delivering amazing science. Some discoveries will require follow-up radio observations and vice versa.
  - **High-frequency (or mm) VLBI** ($>$ few 10's of GHz) can probe the daily variability of transient and flaring sources, in particular those associated with relativistic jets. At present only the Mopra telescope is (being) setup to contribute to such VLBI observations with recent investment from KASI (Korean Astronomy

and Space Science Institute) to join the East-Asia VLBI Network (https://radio.kasi.re.kr/eavn/main.php). However, longer term, ATCA may be the ideal facility to contribute to mm-VLBI in further efforts, for example the Global mm-VLBI array (GMVA – https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/).

- Gravitational Waves
  - The **Laser Interferometer Gravitational-Wave Observatory** (LIGO, ligo.caltech.edu) plans further upgrades and observing periods beyond 2028 into the next decade, contingent upon availability of LIGO Operations funding. Their 4th observing run (O4) starts in May and will probably quadruple the number of known events during its 18 month duration as the range of the facility exceeds 150 Mpc for neutron star mergers (and may reach 170 Mpc). Feasible upgrade paths exist that could double O4's range (and hence 8$\times$ the event rates) up until 2030. LIGO/Virgo is expected to identify $\sim$1 binary neutron star merger/month with a median error region of 120 – 150 square degrees. For events without a confirmed optical counterpart ASKAP is an ideal instrument to conduct blind searches for radio afterglows that will then be followed-up at all wavelengths. For ASKAP follow-up observations of LIGO events (AS111) see, e.g., Dobie et al. (2019, 2022); Wang et al. (2020). — The ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav, ozgrav.org, PI: Matthew Bailes) brings together advanced data processing techniques, a global network of telescopes for follow-up observations, and astrophysical modelling to help interpret the data. It is also pursuing novel instrumentation research, see Bailes et al. (2021). In Nov 2022, the ARC awarded AUSD 35M to support a further seven years of funding of OzGrav, with an expanded, diverse leadership team and an ambitious new science program.

    Globally, there is considerable momentum behind next generation (3G) detectors aiming to increase the range by a further factor of 10 and be sensitive to black hole (BH) mergers throughout the entire Universe. The US is championing a 40 km long detector (Cosmic Explorer; cosmicexplorer.org) whilst Europe favours a triangular underground system with 10 km arms (the Einstein Telescope; et-gw.eu). A third detector in the Southern hemisphere would greatly improve almost all of the science cases as it permits triangulation of the source positions and breaks the degeneracy between source location, orientation and polarisation. OzGrav is strongly in favour of participation in 3G detector R&D and deployment. 3G detectors need to overcome the issues faced by high laser powers and a pathfinder built in Australia operated by ATNF would have many synergies with its strengths in engineering, vacuum systems, data transport and operating a National Facility. A 3–6 km high laser power "3G pathfinder" system could be built in Narrabri where existing infrastructure is present at reduced cost, although site studies are essential. A design concept is presented in Ackley et al. (2020).

- Radio Telescopes (cm-wavelength)
  - The **Five-hundred-meter Aperture Spherical radio Telescope** (FAST; fast.bao.ac.cn) is currently the biggest radio dish, focusing on studies of pulsar and FRBs. A FAST++ array consisting of multiple 500m dishes is being considered in China with baselines up to 1000? km.
  - The **Meer Karoo Array Telescope** (MeerKAT; sarao.ac.za) is a recently completed 8 km diameter radio interferometer consisting of 64 $\times$ 13.5-m dishes (0.5 – 1.7 GHz). Discoveries made in ASKAP wide-field surveys are often followed-up with MeerKAT to improve both sensitivity and resolution. — As part of the MeerKAT Extension Project (MeerKAT+), a new receiver system (1.6 – 3.5 GHz) from the Max Planck Institute for Radio Astronomy in Bonn will be installed in the next few years (e.g., Padmanabh et al. 2023). Furthermore, SARAO and the Max Planck Society are providing EUR 20 million each for the construction of 20 additional antennas, increasing the array size to 84 dishes, which will increase the telescope sensitivity by 50% and extend the antenna baselines to 17 km. INAF recently joined the MeerKAT+ project with EUR 6M. In future, MeerKAT will be integrated into SKA-Mid (197 dishes in total in Phase 1, baselines to 150 km, construction is expected to be completed by 2028). MeerKAT and SKA-Mid are also supported by D-MeerKAT (glowconsortium.de).

- The **Next Generation Very Large Array** (ngVLA; ngvla.nrao.edu), currently in the design phase, includes: 10× the sensitivity of the Jansky VLA & ALMA, science operations from 1.2 – 116 GHz, 30× longer baselines (1000 km) that yield mas-resolution, with extended baselines to continental scales (8860 km), and a dense antenna core on km-scales for low surface brightness imaging.
- The **Giant Metrewave Radio Telescope** (GMRT; gmrt.ncra.tifr.res.in) currently operates at <100 to 1450 MHz with max 50 km baselines. Patra et al. (2019) consider an expanded GMRT (**eGMRT**) with 30 new antennas at short distances (<2.5 km) and 26 new antennas at long distances (∼5–25 km0 from the array centre, in addition to the existing 30 GMRT antennas, much increasing the telescope sensitivity and survey speed.
- **The Canadian Hydrogen Intensity Mapping Experiment** (CHIME, 400 – 800 MHz; chime-frb.ca) is a radio telescope designed to answer major questions in astrophysics and cosmology. Currently the world-leading FRB detection telescope and soon to be equipped with outriggers to enable it to accurately localise FRBs. It's proposed replacement, the **Canadian Hydrogen Observatory and Radio-transient Detector** (CHORD; 300 – 1500 MHz; 3000 km baselines, incl. outriggers, van der Linde et al. 2019) - likely to increase the FRB detection rate by a factor of 10.
- The **Deep Synoptic Array 2000-antenna concept** (DSA-2000; 0.7 – 2 GHz; 19 km baselines; Hallinan et al. 2019) is a cm-wave survey telescope due to begin operations in 2026. With 2000 × 5-m dishes, it will have an equivalent point-source sensitivity to SKA1-mid, but with ten times the survey speed. DSA-2000 aims to survey 30,000 deg^2 (DEC > –30°) down to 500 nJy beam^{-1} and detect one billion radio sources, find >30 million H I galaxies, and localise $\sim 10^4$ FRBs. It is a direct competitor to an ASKAP upgrade. – Important to evaluate the concept, science goals and the possibility of collaboration / partnership.
- Further non-Australian radio astronomy facilities are listed in a related document by Ivy Wong et al. (2023).

• High-energy facilities

- the **Cherenkov Telescope Array** (CTA; cta-observatory.org) is a new TeV γ-ray astronomy facility, currently under construction (330M EUR). With more than 70 telescopes located in the northern and southern hemispheres, CTA will be the world's largest and most sensitive high-energy γ-ray observatory, building on the technology of current generation ground-based γ-ray detectors (H.E.S.S., MAGIC and VERITAS) with an expected tenfold increase in the number of known γ-ray-emitting celestial objects, detecting more than 1,000 new objects (CTA-Consortium 2019). — Australia is a founding member[2] and our principal contribution will be multi-messenger follow-up observations and interstellar medium surveys (via Mopra, Parkes, ATCA, ASKAP, MWA and SKA). CTA's Key Science Projects will require >1000 hours per year of supporting cm and mm radio studies, mainly for variable and transient sources like AGN, GRBs, Novae, XRBs, etc. Already, ATCA is used in several projects monitoring or following up TeV γ-ray-active AGN and GRBs based on results from H.E.S.S. The AGN monitoring programme (within the ATCA 'Calibrator' monitoring program) expands on the long-term TANAMI project set up to monitor AGN active in the GeV band as seen by **Fermi**-LAT. Fermi will continue to provide MeV–GeV γ-ray data including alerts from GRBs etc. for at least the next few years. ATCA follow-up of TeV-active GRBs (PI: G. Anderson) is enabled by a private alert from H.E.S.S. online results. The CTA era will trigger a natural extension of these programmes.

  The CTA-Australia consortium comprises seven institutions, led by the University of Adelaide. NCRIS funds complement the ARC LIEF funding for CTA which is used for constructing and commissioning the CTA telescopes, site infrastructure and the software used to process the data. A key area for Australian involvement and leadership will be the development of an SKA-CTA science synergies white paper, underpinned by an MoU between the SKAO and CTAO.

  All-sky coverage of the southern TeV γ-ray sky is expected to come from the **Southern Widefield Gamma-ray Observatory** (SWGO; swgo.org) (Albert et al. 2019). If funded, it will provide full southern-sky TeV γ-ray monitoring with 24-hour coverage from about 2026–7. SWGO will build on the experience

[2] See Gavin Rowell's talk on CTA and ATNF linkages, ATUC Science Day, 8 Nov 2022.

from HAWC (hawc-observatory.org) and LHAASO (english.ihep.cas.cn/lhaaso/) in the Northern Hemisphere which have both provided exciting new discoveries of diffuse, large-scale and transient sources in the past few years. LHAASO's recent detection of γ-rays up to 18 TeV from GRB221009A points to exciting opportunities for extreme transient studies. Real-time information on multi-messenger transients is available from the Astro-COLIBRI (astro-colibri.science) and AMON (amon.psu.edu) projects and can be used to trigger radio observations.

– X-ray sky surveys: the **extended ROentgen Survey with an Imaging Telescope Array** (eROSITA; erosita.mpe.mpg.de) is expected to observe the sky eight times. The eROSITA design driving science is the detection of large samples of galaxy clusters up to redshifts $z > 1$ in order to study the large-scale structure of the Universe and test cosmological models including Dark Energy (Predehl et al. 2021). The first release of the German eRASS data is scheduled for Sep 2023. — The **Advanced Telescope for High ENergy Astrophysics** (ATHENA; the-athena-x-ray-observatory.eu) is the X-ray observatory mission selected by the European Space Agency (ESA), within its Cosmic Vision programme, to address the Hot and Energetic Universe scientific theme. It is due for launch in the second half of the 2030s.

– **KM3NET** (km3net.org) refers to the next generation of neutrino telescopes. Science goals include searching for neutrinos from distant supernovae, γ-ray bursts and colliding stars. — Western Sydney University and Curtin University are the two Australian members. KM3NET will go well beyond the capabilities of the IceCUBE Neutrino Observatory (icecube.wisc.edu) at the South Pole. Upgrades to IceCube are under way aiming to increase the detector volume to beyond several km^2 in what is termed IceCube-GenII. If funded, construction for GenII would commence towards the end of this decade.

- Dark matter particle detection experiments

  – While instruments like the SKA and CTA provide indirect searches for Dark Matter (DM), there are also direct detection experiments. In Australia, the **SABRE South** experiment, located in a gold mine in Victoria, is searching for WIMPS as a likely DM candidate, while the **ORGAN** experiment in Western Australia is searching for axions. Both are part of the ARC Centre of Excellence for Dark Matter Particle Physics (centredarkmatter.org).

  From the radio perspective, it is the indirect DM detection method that is perhaps most relevant. Here, the radio continuum is an important constraint on the astrophysical backgrounds that severely complicate DM searches. WIMP DM decay models predict a secondary synchrotron component extending to the radio domain that can complement the γ-ray signal CTA and others will search for. The direct detectors like SABRE look for local DM the Earth is passing through. For completeness though, the CYGNUS project (potentially also located at the SUPL lab in Victoria) will have directionality and so hopefully will tell us from where (broadly) in the sky the DM flow is coming from.

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