Astroparticle Physics in Australia - Discussion Paper

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Astroparticle physics worldwide has grown considerably over the past 20 years with formal recognition in, for example, worldwide (https://iupap.org/commissions/c4-commission-on-astroparticle-physics/), and European (https://www.appec.org/) discussions, several journals using 'Astroparticle Physics' in their title, and, many multi-national facilities attracting several billion Euro in funding. Australia has also experienced a growth in astroparticle physics activities.

This document for the Australian astroparticle physics community outlines a number of discussion points currently under consideration. The key purpose of this paper is to initiate discussion on the topics defining astroparticle physics, and, the future actions on community building and funding plans.

The email list for discussions is here: ozastroparticle.physics@list.adelaide.edu.au

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1. **Astroparticle physics in Australia – Potential Topics and Challenges**
2. **Key projects/involvements for Australian astroparticle physics**
3. **Consider an astroparticle physics chapter of the Astronomical Society of Australia (ASA), or AIP.**
4. **Future funding ideas for Australian astroparticle physics; e.g. ARC Centre of Excellence**
5. **Other discussion points.**

1. Australian Astroparticle Physics - Potential Topics and Challenges

Astroparticle physics is broadly defined here as p*article physics with astronomical observations and related theory.* For the purpose of initiating discussion, we define a number of major themes, loosely based on the science themes driving major facilities with Australian involvement such as the CTA (Cherenkov Telescope Array), IceCube, Pierre Auger Observatory, aLIGO, SABRE

1a. Cosmic particle acceleration and related multi-messengers:

- High energy (> multi-MeV) particles (cosmic rays, neutrinos), particle acceleration, related photon emission (radio to gamma rays)
- How and where are particles accelerated to extreme energies (~10^{20} eV)?

- Particle acceleration sites from the solar system to the largest scales.
- How can we trace these particles?
- How do high energy particles influence the evolution of stars, galaxies, and the Universe?

1b. Extreme environments:

- Neutron star interiors and environments, core collapse, nucleosynthesis, pulsar mechanisms, relativistic flows, accretion, merger environments

- Understanding the structure of neutron stars and extreme astrophysical environments
- How are jets and collimated beams formed?
- Detecting the first signatures of core-collapse.
- How does accretion work and influence galaxy evolution?

1c. Dark matter:

- What is dark matter? (global fits, Australian involvement in GAMBIT)
- Can we detect high-energy particles from dark matter annihilation or decay? (indirect detection, Australian involvement in CTA, HESS, SKA, IceCube, ANTARES, KM3Net)
- Can we directly detect dark matter on Earth? (direct detection and axion experiments, Australian involvement in SABRE, ADMX, ORGAN, BAW)
- Can we produce dark matter in particle colliders? (collider searches, Australian involvement in ATLAS and Belle II)
- How was dark matter created? (cosmological abundance calculations beyond standard thermal production)
- What is the impact of dark matter on stars and compact objects? (stellar structure and evolution)
- How would different types of dark matter impact the large and small-scale structure of the Universe? (N-body sims, minihalos, matter power spectrum measurements)
- How does dark matter fit into ultraviolet complete models of particle physics? (DM model building)

1d. Particle cosmology:

- How do we use 21cm radiation, the distribution of matter on large scales, and the cosmic microwave background to test particle physics? (neutrino masses, N_effective, spectral distortions, energy injection, early DM scattering)
- How does particle physics affect the primordial abundances of the elements? (impacts of neutrinos and new physics on BBN)
- How do phase transitions in the Early Universe work, and what are their implications? (EWPT, cosmic strings, PQ breaking, etc)
- What is the particle physics behind the excess of matter over antimatter in the Universe?
- What is the fundamental theory of inflation, can it be proven, and how? (inflationary model building + testing against observations)
- What is the fundamental theory behind dark energy? (DE model building, including modified gravity + testing against observations)

1e. Standard Model at energies beyond today's colliders:

- Is the Standard Model valid for interactions of cosmic rays with energies over 100 PeV? (corresponding to the LHC centre-of-mass energy)
- Current extrapolations of interaction properties at LHC energies (such as cross sections) are very uncertain at energies 3 orders of magnitude higher.
- What are the best settings in which to probe such energies? Astrophysical settings and/or air showers in the atmosphere?.What type of detectors would be necessary for precision measurement of air showers?

2. Key Projects/Involvements for Australian astroparticle physics

Listed below are activities and facilities with present Australian involvement or facilities in use by Australian astronomers (now), plus key future facilities of high importance (future).

Theoretical and Computational Topics (now/future): Particle acceleration (diffusive, reconnection, other methods..); Magnetohydrodynamics; Particle and photon propagation and interaction (diffusive, ballistic...); Radiative processes (converting particle to photon energy). Standard model and beyond; Supernova and merger simulations; Accretion and jet formation; Particle cosmology simulations, Atmospheric air shower simulations at energies beyond the LHC.

Theoretical and Computational Facilities (now): Desktop PCs, Institutional-scale clusters; National-scale clusters (Pawsey; gSTAR, NeCTAR); Access to international clusters.

Theoretical and Computational Facilities (future): Next generation supercomputers (e.g. Pawsey upgrade);

X-rays (now): NuSTAR, XMM-Newton, Chandra, XRT, Swift

X-rays (future): eROSITA (2020+), ATHENA?

Gamma Rays space MeV to multi-GeV (now): Fermi-LAT, AGILE, INTEGRAL

Gamma Rays space MeV to multi-GeV (future): Fermi-LAT (2020+?),

Gamma Rays ground-based > multi-GeV (now): CTA (2020+), HESS

Gamma Rays ground-based > multi-GeV (future): CTA (2040+), HESS (up to 2022?), SWGO (“HAWC-South”)

Cosmic Rays (now): Pierre Auger Observatory, MWA, IceTop, SKA, Icecube Gen2, Mawson station cosmic-ray monitor (solar and space weather)

Cosmic Rays (future): Pierre Auger Observatory (upgrade; 2030+), updates to neutron monitors, SWGO

Neutrinos (now): IceCube, ANTARES, IceCube Upgrade (2022+), KM3Net

Neutrinos (future): IceCube Gen2 (2030+), KM3Net (2025+?)

Dark Matter and other Particle detectors: SABRE, ADMX, BAW, LHC, ATLAS, Belle-II

Radio, IR, Optical (now & future): Many Australian-based (e.g. ATCA, Parkes, Mopra, VLBI, ASKAP, UTMOST, MWA, SKA, AAT, 1-2m class telescopes) and overseas facilities (e.g. ESO Paranal, LSST, GMT, eELT etc..). Studies of non-thermal sources and transients from extreme environments. Clear implications for the science themes listed above. Key involvements are via multi-wavelength campaigns across all photon energies and particle messenger facilities.

Gravitational waves (now): aLIGO

Gravitational waves (future): aLIGO++, Australian high frequency GW detector OzHF, Einstein telescope, LISA.

All sky virtual observatory (ASVO): Databases linking outputs from many facilities.

Cubesats (future): Role of small-scale satellites are certainly of interest.

3. Consider a new joint chapter/group of the ASA and AIP for Astroparticle Physics?

The ASA's strategic plan (draft circulated Jan. 2019) floats the idea of new ASA chapters devoted to scientific themes, beyond ANITA (for theory).

It is therefore worth looking at such a chapter devoted to astroparticle physics and/or something similar. We would emphasise that astroparticle physics extends beyond just “high energy astrophysics” as the list of topics in items #1 and #2 hopefully illustrate. The chapter would be charged to develop policies on matters of importance to our community and provide input into funding prioritisation for roadmaps such as Decadal Plans. An alternative might be a chapter of the Australian Institute of Physics (AIP).

This new chapter might be compared to the High Energy Astrophysics Division (HEAD) of the American Astronomical Society.

e.g the by-laws of the HEAD https://head.aas.org/bylaws

II. Object
The object of the Division for High Energy Astrophysics (hereinafter called "the Division") shall be to assist and promote the advancement of research and the dissemination of knowledge of high energy events, particles, quanta, of relativistic gravitational fields, and of related phenomena in the astrophysical universe, and to promote the coordination of this research and knowledge with other branches of science.

Following discussion at the Brisbane ASA meeting, a joint group operating under the auspices of the ASA and AIP was considered a useful way forward. A letter of intent addressed to the ASA and AIP Councils will be prepared in order to initiate and explore this process.

4. Future funding ideas for Australian astroparticle physics

This may be based around funding for facility involvements, high performance computing infrastructure, and/or larger-scale funding for personnel and hardware. Facilities and involvements are listed above in item #2.

A major topic no doubt would be an ARC Centre of Excellence (CoE). What topics should a CoE in Astroparticle Physics consider?

It should cover topics not in any CoEs present and planned (Astro3D, OzGrav , Dark Matter/SABRE).

Some example topics and themes:

- The extreme Universe (extreme densities, speeds, temperatures etc), “relativistic universe”
- Origin of energetic cosmic rays (galactic + extragalactic)
- Solar system particle astrophysics (space physics)
- The role of cosmic rays in magnetic field generation, astro-chemistry, life on Earth, star formation and galaxy evolution
- Origin of elements via nucleosynthesis
- What/where is dark matter and what is its role in the Universe? Should be complementary to the dark matter SABRE experiment which is now funded via a CoE.

CoEs should have an effectiveness greater than sum of individual efforts. They require synergies in techniques and applications that are **most** likely to succeed in seven years with available and potential facilities and methods on this time scale.

CoE Personnel should utilise at least several facilities to underpin synergies. Industry linkages are important. Can the CoE lead to new construction in Australia or Australian contributions (hardware/software/in-kind effort) to overseas facilities. One or two key science themes or questions are central to the CoE. There may be scope for more than one CoE addressing the above topics (is this too optimistic?). We should aim for the next CoE round in 2022? Over the 2019-2021 period, there would be a need to identify key themes for new CoE(s) and potential leadership.

5. Other discussion points?

The Australian particle physics community is also discussing its future directions and astroparticle physics is included as one topic. Discussions are being coordinated by Geoff Taylor (U. Melb) and it's suggested to include the outcomes of this discussion paper into this process. A wiki page is being setup to document the various sub groups within the particle physics community and will be listed here.

Please send feedback on this discussion paper to:
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Version 2 feedback via
- Teleconference 11 July 2019 (ASA 2019 Meeting, Brisbane).
- Csaba Balazs, Nicole Bell, Jose Bellido, Bruce Dawson, Clancy James, Jeremy Mould, Pat Scott