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DIVISION D HIGH ENERGY PHENOMENA AND FUNDAMENTAL PHYSICS

DIVISION D COMMISSIONS

Div. D / Commission D1	**Gravitational Wave Astrophysics**
Div. D / Commission X1	**Supermassive Black Holes, Feedback and Galaxy Evolution**

DIVISION D WORKING GROUPS

Div. D / WG	**Supernovae**

TRIENNIAL REPORT 2018-2021

1. Science highlights 2021-2024

As of 2024, division D gathers 2653 members and 262 junior members who explore all high-energy phenomena in the Universe using light observations across the entire electromagnetic spectrum together with cosmic rays, neutrinos, and gravitational waves. They use the wealth of phenomena powered by stellar explosions, neutron stars, black holes, or the merging of those, to study supernovae and the properties and activity of compact objects, as well as their environmental impact and influence on galaxy evolution. They take advantage of these exceptional phenomena to probe gravity, matter, radiation, and particle acceleration under extreme physical conditions. The rapid development of multi-messenger astronomy, polarimetry, and multi-wavelength time-domain observations during this triennium has allowed for great progress. Combining γ-ray and neutrino information can indeed elucidate the dominance of protons or electrons in the observed high-energy radiation; time domain observations unveil the dynamics and time scales that drive extreme phenomena, while polarimetry unravels the magnetic topology channelling matter inflows and outflows. The community of division D has enjoyed exciting highlights since 2021.

On October 9 2022, the "brightest of all time" event ever witnessed in human history blinded most space-based high-energy telescopes. This exceptionally bright γ-ray burst, GRB 221009A, broke many records and offered very detailed light on the launch, development, and deceleration of the relativistic jet that was ejected and that we viewed

almost head-on. Another bright burst a few months later, GRB 230307A, demonstrated the capacity of compact star mergers to produce heavy elements across a broad range in atomic mass.

Supermassive black holes attracted a lot of attention. In 2022, the Event Horizon Telescope (EHT) imaged Sagittarius A*, the Milky Way central black hole, revealing remarkable similarities with the thousand times more massive version resting at the centre of M87. The polarisation images revealed strong inward-spiraling magnetic fields around both black holes, strong enough to impede the accretion flows. This triennium opened the era of multi-scale black-hole mapping: mapping the size and stability of the inner shadow with EHT to confirm general relativity and to test further theories; mapping time-variable structures inside and outside the emission ring with EHT to relate the inner accretion flow and the base of the jet; mapping the gas inflow to sub-parsec scales with Alma to estimate the mass fraction falling to the black hole while the remainder is ejected in jets or in multiphasic winds which provide feedback to the host galaxy (as observed in the Circinus galaxy). In parallel, the detection by H.E.S.S. of TeV radiation from the jets of the Galactic SS 433 microquasar opened the way to studying particle acceleration in reduced-scale, yet much closer relativistic jets than in their AGN counterparts.

Optical-UV variability in accretion discs revealed a characteristic timescale which scales with black-hole mass over the entire range of supermassive black holes. Finding "universal" mass scaling relations and leveraging precise temperature measurements in X rays (combining NuStar and XMM or eROSITA data) open potential ways to use accretion emission as a cosmological candle to provide an independent means to assess the Hubble constant.

The combination of spectroscopy, energy-dependent time lags, and polarisation data was successfully attempted to probe the relative geometry of the accretion disc and hot corona and to investigate the complex matter and radiation interactions between the two regions. But some AGN are very obscured by thick dusty clouds and neutrinos are the sole probes of hidden jet/wind activity. In 2022, the IceCube Neutrino Observatory detected NGC 1068, the second neutrino source found in the sky and one of the most obscured AGN known. The production of TeV neutrinos unveiled the acceleration of TeV-PeV cosmic-ray nuclei and the large neutrino to γ-ray flux ratio showed that even highly penetrating TeV γ rays are severely absorbed in this environment.

Recurrent or quasi-periodic eruptions seen in UV and X rays from quiet galactic nuclei also gained a lot of attention to provide insight into the central black hole properties (e.g. to explore potential reversals of its magnetic field) and to distinguish tidal disruption events where stellar debris fall in from cases where a compact star interacts with a pre-existing weak accretion flow. The tentative association of a neutrino (IceCube-191001A16) with a tidal disruption event (AT2019dsg17) suggests possible acceleration of cosmic rays to PeV energies in such circumstances.

Accreting neutron stars showcased notable highlights. NuSTAR observations confirmed that an ultra-luminous X-ray source (ULX) accreted matter at a rate surpassing the Eddington limit, enabling studies of radiation pressure alteration in the strong magnetic field of a neutron star. INTEGRAL and ATCA jointly witnessed ten thermonuclear bursts from the surface of 4U 1728-34, revealing the robustness of the jet launching process against the explosion as matter was repeatedly injected at a third of the speed of light down the radio jet.

In June 2023, the IceCube team presented the first neutrino image of the Milky Way. This image at energies > 1 TeV is still coarse, but it complements the Fermi LAT γ-ray map to study cosmic-ray propagation and interactions with interstellar gas. It already set constraining upper limits to neutrino emission from multi-TeV γ-ray point sources seen

by LHAASO and HAWC, implying the presence of electron/positron accelerators (e.g. pulsars and their wind nebulae) rather than the long sought after sources of Galactic PeV cosmic-ray nuclei (PeVatrons). The Fermi, MAGIC, VERITAS, HAWC, and Tibet AS-Gamma teams jointly proposed a more promising PeVatron candidate in the G106.3+2.7 supernova remnant.

A new puzzle emerged from comparing the dipole pattern caused by the solar motion in the γ-ray and cosmic microwave backgrounds. The gamma-ray dipole appears to be much more pronounced and oriented differently than the CMB one. It relates more to the spatial distribution of extragalactic ultra-high energy cosmic rays, the second most energetic one, "Amaterasu" at 244 EeV, having been recorded in December 2023 from the apparent direction of empty space known as the "Local Void".

The original LIGO-Virgo consortium, and now the LIGO-Virgo-KAGRA one, detected gravitational waves from 93 inspiraling pairs of compact stars (black-hole couples or neutron-star black-hole pairs), expanding the black-hole mass spectrum to near 100 $M_\odot$ (and the total mass of a pair to $182.3^{+40.2}_{-35.7}$ $M_\odot$!) and challenging models about their progenitors from stellar evolution and binary star evolution. In parallel, five teams in the world (in North America, Europe, India, Australia, and China) found convincing evidence that nanoHerz gravitational waves coherently disturb the regularity of signals received from an array of pulsars, heralding a new era in gravitational-wave astronomy to explore supermassive black-hole mergers in galaxy collisions. Collaborative efforts within the International Pulsar Timing Array and the monitoring of over 100 pulsars are poised to confirm this new window on space-time waves.

2. Developments within the past triennium

2.1. *New IAU Members in division D*

Reflecting these vibrant research activities around high-energy phenomena and multi-messenger studies, the number of active members in division D has steadily increased at a rate of about 80 new members and 40 new junior members per year during the triennium.

2.2. *IAU meetings sponsored by division D*

Division D has regularly approved a number of IAU meetings, including meetings both during and outside the delayed 2021 General Assembly that took place in Busan (South Korea) in 2022, and meetings at the upcoming 2024 assembly at Cape Town (South Africa). The focus during this triennium has evidently been on the burgeoning of multi-messenger astrophysics.

- The IAUS 363 symposium on "Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution" was held at the end of 2021 in Italy. It was a successful meeting despite the virtual mode due to sanitary restrictions. The open-access proceedings are available at `https://www.cambridge.org/core/journals/proceedings-of-the-international-astronomical-union/issue/7318716057687AADE6159B13C0372469`.
- The IAUS 369 symposium focussed on "The dawn of cosmology & multi-messenger studies with fast radio bursts" at the Busan 2022 General Assembly. Lively discussions took place in hybrid mode on the magnetar origin of fast radio bursts, on the heterogeneity of their sample, on their galactic environments, and on their potential use as cosmological candles.
- The IAUS 375 symposium concentrated on "The Multimessenger Chakra of Blazar Jets" in Kathmandu (Nepal) at the end of 2022. It gathered 90 participants from many

countries and a large fraction of young researchers. As the first IAU symposium held in Nepal, it successfully fostered collaborations between Nepal scientists and their colleagues around the world. The open-access proceedings are available at `https://www.cambridge.org/core/journals/proceedings-of-the-international-astronomical-union/issue/7BCAE1A3CA3CD377A3FBB0492033932A`.

- A complementary IAUS 378 symposium reviewed "Black-hole winds at all scales" at Haifa (Israel) in 2023 to discuss observational diagnostics and models of outflows powered by stellar as well as supermassive black holes, to seek their commonalities and differences, and to evaluate their potential for galaxy feedback. The meeting was held in hybrid mode.
- For the 2024 General Assembly, division D will
  - promote discussions in the IAUS 389 "Gravitational wave astrophysics" symposium on the numerous topics served by these observations (from nucleosynthesis to black-hole growth to cosmic evolution and general relativity) and on the organisation of electromagnetic counterpart searches.
  - bring together the transient and massive-star communities in the "Bridging the final stages of massive stars to supernovae and transients" focus meeting, as Rubin and ZTF data are coming on line.
  - contribute to discussions about a better understanding of dark matter, from its nature to its spatial distribution and its impact on baryonic matter in the "Measures of luminous and dark matter in galaxies across time" focus meeting.
  - review in the "High-energy Universe" focus meeting the great recent progress and near-future potential of wide-field ground-based γ-ray telescopes (HAWC, LHAASO, and upcoming SWGO and ALPACA) and discuss their complementarity with other instruments (CTA, Fermi, IceCube, KM3Net, GW detectors) in terms of transient detection and energy reach (PeV).

2.3. *Division D workshops*

The division took advantage of the wide expertise gathered at the General Assemblies to organise two-day workshops on transverse science topics relating to high-energy phenomena.

- "Across the mass spectrum of neutron stars and black holes" at Busan 2022: the wide mass range of stellar black holes revealed in gravitational-wave mergers and the discovery in the early Universe of galactic black holes as massive as the stars in their host galaxy has revived the interest in initial black-hole mass and its further evolution. The finding of neutron stars with masses beyond the Chandrasekhar limit also raised questions about their formation and internal structure. The division has therefore organised a 2-day workshop to review the measurements and discuss theories.
- "Polarimetry of high-energy sources" at Cape Town 2024: the success of recent polarimetric observations, in particular at high energy (IXPE, Polar, AstroSat, POLIX, INTEGRAL), has dramatically expanded our views on the exploitation of polarimetric information and on the physics of supernova remnants, pulsars, accreting compact stars, gamma-ray bursts, and different types of AGN. The goal of this two-day workshop is to familiarise the community with the unique insights into magnetic topology and particle acceleration and radiation enabled by polarimetric data in the radio, visible, X rays, and γ rays. Future prospects for instrumental developments will also be discussed.

2.4. *Division D newsletter*

Thanks to the dedication of Dr. Nanda Rea during this triennium, the division has regularly issued a monthly newsletter to all members to circulate relevant scientific news and meeting announcements.

2.5. *Division D exceptional webinars*

We have launched the" IAU Division D Science Webinar series". These webinars aim at diffusing large-impact scientific results to all the division members (and beyond). They are scheduled at a time that can accommodate the largest world-wide audience and are announced via the division newsletter. We started the series in the summer of 2022 with a presentation of the spectacular EHT images of the M87 and Sgr A* black holes by the EHT project scientist, Geoffrey Bower. Another will take place in 2024 about the BOAT' findings. Others will be organised as important discoveries are made.

2.6. *IAU PhD Prizes in Division D*

At the beginning of each year the division Steering Committee reviews applications for PhD prizes for theses completed the year before. A total of 28, 15, and 17 applications were received in 2022, 2023, and 2024 respectively. Because of the outstanding level of nearly all submitted theses each year, all divisions agreed to confer up to two Honourable Mentions in addition to the PhD Prize. The laureates for division D were:

- 2021 PhD prize to Dr. Riccardo Arcodia for his thesis on "Accretion onto black holes across the mass scale" in Germany: modelling the black-hole spin impact on the luminosities of the accretion disc and corona in AGN and in stellar binaries; discovery with e-ROSITA of quasi-periodic eruptions from tidal disruption events.
    - 2021 honourable mention to Dr. Benjamin Crinquand for his thesis on "Particle acceleration in Kerr black-hole magnetospheres" in France,
    - 2021 honourable mention to Dr. Kishalay De for her thesis on "The Whisper and the Bang: Cosmic fireworks in the lives of compact binaries" in the USA,
- 2022 PhD prize to Dr. Andrew Mummery for his thesis on "Illuminating tidal disruption events with a time-dependent theory of relativistic accretion discs" in England: modelling the time-dependent evolution and radiation output of the transient accretion disc formed from the stellar debris.
    - 2022 honourable mention to Dr. Inés Pastor-Marazuela for her thesis on "Exploring the link between Neutron Stars and Fast Radio Bursts" in the Netherlands,
- 2023 PhD prize to Dr. Yonadav Barry Ginat for his thesis on "Gravitational Waves and Non-Linear Phenomena in Gravitational Astrophysics" in Israel: finding a statistical solution to the 3-body gravitational problem for any dissipative effect, as well as new gravitational-wave signatures in the in-spirals of compact objects and a universal power-law tail in the distribution of gravitational-wave background fluctuations.
    - 2023 honourable mention to Dr. Sylvia Biscoveanu for her thesis on "From Black Holes to the Big Bang: Astrophysics and Cosmology with Gravitational Waves and their Electromagnetic Counterparts" in the USA.

An exceptional inter-division PhD prize has been granted to Dr. David Hosking in 2022 for his thesis on "The decay of MHD turbulence and the primordial origin of magnetic fields in cosmic voids" as his advances in MHD turbulence theory will serve many different research fields in astrophysics (new theory backed by MHD simulations about the decay of MHD turbulence due to magnetic reconnection in small-scale regions of fluctuating helicity).

2.7. *Commissions in Division D*

The two Commissions monitored by Division D (see front page) submitted their reports for 2021-2024 and requested renewal for the next triennium.

3. Conclusion and future plans

Paraphrasing the former division president, Elena Pian, this is a moment of tremendous boost in high-energy and multi-messenger astrophysics. With the development of SKA and LOFAR 2, the overwhelming numbers of radio and visible transient detections, the continuous operation of X-ray and γ-ray space telescopes (XMM, Chandra, AstroSat, NuStar, Swift, NICER, IXPE, Fermi, hopefully e-ROSITA, and the successful start of XRISM this March), with the building of CTA and the continuous monitoring at >TeV energies by HAWC and LHAASO in γ rays and by IceCube and soon Km3NeT in neutrinos, with the start of the O4 run by LIGO-Virgo-KAGRA, the building of the most sensitive pulsar timing dataset within the IPTA, and plans to prepare new generation interferometers (the American Cosmic Explorer, European Einstein Telescope, and the ESA-NASA LISA space antenna), with a new fleet of γ-ray burst detectors to complement Swift and Fermi-GBM to catch electromagnetic counterparts to mergers (the lobster-eyed Einstein Probe launched this January, the tiny BurstCube launched this March, SVOM scheduled for June), the likelihood is high that major breakthroughs will fill gaps in our knowledge and will open up new perspectives on the diversity of high-energy phenomena.

Isabelle Grenier
President of Division D

COMMISSION D1 **GRAVITATIONAL WAVE ASTROPHYSICS**

Astrophysique des Ondes Gravitationnelles

TRIENNIAL REPORT 2021-2024

4. Background

IAU Commission D1 was created in 2015 with the goals of integrating gravitational-wave (GW) observations into mainstream astronomy, expanding the knowledge and science impact of GW astrophysics to the IAU community, and fostering communication among diverse communities. It brings together scientists involved in searching for, detecting, modeling and interpreting GW signals over 12 orders of magnitude in frequency—from nanohertz using Pulsar Timing Arrays, from millihertz to $\lesssim$1 Hz with space-based detectors, and from $\sim$10 Hz to kHz using ground-based detectors—with many connections to high energy phenomena and fundamental physics, the domain of Division D. Observing the Universe across the entire GW bandwidth will provide a quantum leap in our knowledge of the Universe, its constituents and of the laws of Nature.

As of 2024, IAU Commission D1 has approximately 230 members from over 30 countries.

The President of Commission D1 also serves *ex officio* as a member of the Gravitational Wave International Committee (GWIC), a organization dedicated to cooperatively developing the construction and coordinating the operation of current and future GW detection facilities. In this way, the global community of astronomers and astrophysicists embodied in the IAU maintains contact with the expanding GW detection capabilities.

5. Highlights in Gravitational Wave Astrophysics 2021-2024

In June 2023, multiple Pulsar Timing Array (PTA) collaborations from around the globe announced strong evidence for low-frequency GWs in the nanohertz frequency range, detected via careful measurements of the arrival times of pulses from 179 radio pulsars (Reardon *et al.* 2023, Agazie *et al.* 2023, Xu *et al.* 2023, Antoniadis *et al.* 2023). While earlier results had shown correlated variations in the arrival times from pairs of pulsars, the data accumulated over many years finally revealed a systematic dependence on the angular separation between pulsars, consistent with the expectation from a stochastic background of gravitational waves permeating the universe. This long-anticipated finding opened a new front on direct detection of gravitational waves and a new view of the astrophysics of supermassive black hole binaries in galaxies.

This triennium saw the publication of numerous observational results from the O3 observing run of the ground-based LIGO-Virgo-KAGRA (LVK) detector network, which had ended data-taking in early 2020. The release of the GWTC-3 catalog update (Abbott

et al. 2023a) by the LVK collaborations brought the number of detected GW events (and probable candidates) in the catalog to 90. This enabled many studies of the population and astrophysics of compact binary mergers, tests of general relativity, and cosmology measurements by the LVK collaboration and by other researchers. The GW strain data from the full O3 run was released through the Gravitational Wave Open Science Center (GWOSC) (Abbott *et al.* 2023b) which enabled the broader community to identify additional compact binary merger candidates and also to search for continuous-wave and other types of GW signals, complementing the searches for a wide variety of possible GW signals published by the LVK, some in partnership with other astronomers. The first science observations of the KAGRA detector in Japan, in coincidence with GEO 600, were published (Abbott *et al.* 2022). The O4 observing run of LVK detectors commenced in May 2023 and is ongoing.

Among the space-based GW missions under development, the LISA mission completed its conceptual and preliminary design phases and, in January 2024, reached a major milestone with successful reviews and the formal adoption of the mission by the European Space Agency (ESA). LISA is made possible by the collaboration between ESA, its Member State space agencies, NASA and an international consortium of scientists. Following adoption, the mission has now begun an implementation phase which is expected to lead to launching the three-satellite constellation in the mid-2030s. That will open a new observational window for massive black holes and their interactions, Galactic binaries, and other astrophysical sources (Colpi *et al.* 2024).

Planning for the next generation of ground-based GW detectors advanced greatly during this triennium. In Europe, the Einstein Telescope (ET) (Punturo *et al.* 2010, Branchesi *et al.* 2023) project was added to the European Strategy Forum on Research Infrastructures, an important step for recognition and future funding. Technical development and evaluation of candidate sites for the ET interferometers have proceeded with increasing activity, engaging a collaboration with over 1200 members. In the U.S., the Cosmic Explorer (CE) (Evans *et al.* 2021) project completed a "Horizon Study" and received funding from the National Science Foundation for conceptual design studies. Intense activity is ongoing in the formulation and presentation of the science with ET, and synergies with CE and other observatories, by the ET Observational Science Board and its members, with the plan to produce a "blue book" by the end of the year. Once they are built, these new detectors will have superb fidelity for many GW sources and also will make it possible to trace the cosmic star formation history, back to the cosmological dark ages, detecting the gravitational wave signal from millions of merging compact binaries. Joint electromagnetic observations of merging neutron stars will be numerous, and will shed light on the state of matter at supra-nuclear densities, the production of the heaviest elements in the Universe and the deep link of the sources with short GRBs.

6. Commission D1 Activities 2021-2024

IAU Symposium 363, "Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution", had been organized and supported by the Commission D1 Organizing Committee in the previous triennium but was postponed due to the Covid-19 pandemic. It was ultimately held 29 November to 3 December 2021 using a virtual meeting platform, and successfully brought together astrophysicists, computational and nuclear physicists, and gravitational-wave researchers to discuss new findings and prospects in neutron-star astrophysics.

At the 2022 IAU General Assembly in Busan, Republic of Korea, gravitational wave astronomy and astrophysics figured significantly in the Division D meeting, with the

theme "Across the Mass Spectrum of Neutron Stars and Black Holes", and in a Working Group meeting on Global Coordination of Ground and Space Astrophysics. The Korean Gravitational Wave Group, with support from the KAGRA Scientific Collaboration, organized and staffed a GW astronomy exhibit at the General Assembly which featured many aspects of GW and multi-messenger astronomy.

The Commission D1 Organizing Committee (OC) met periodically to share information from different segments of the GW science community, and to discuss issues of international scope. One outcome from those discussions was a decision to create a list of conferences and meetings related to GW Astrophysics on the IAU website, which the OC is actively maintaining as a resource for the community at https://iau.org/science/scientific_bodies/commissions/D1/info/meetings/. The OC also created a "Useful Resources" web page with links to online educational and reference materials for GW astronomy and astrophysics.

The OC offered support and advice to the team proposing an IAU Symposium on Gravitational Wave Astrophysics, and were delighted when the proposal was accepted as one of the Symposia in the 2024 IAU General Assembly in Cape Town, South Africa. It will be a wonderful exploration of all that gravitational waves have to offer to astronomy and astrophysics research.

7. Conclusion and future plans

Building on the first remarkable discoveries, the gravitational wave science community is providing a new view of our Universe that complements the more established observational methods. But the field continues to change rapidly, with improvements to current facilities and data sets, and ambitious, maturing plans for new facilities which will dramatically extend the reach of GW observations. The IAU's Commission D1 will continue to support this growing community and foster the strong international connections which are especially valuable for GW observations. Following the broad IAU Symposium 389 on Gravitational Wave Astrophysics, we can anticipate future meetings focusing on various intersections of GW and traditional astronomy and the astrophysical insights they will enable. With LISA and next-generation terrestrial interferometers coming online near the end of the next decade, Commission D1 will sustain those initiatives focussed on topics related to the joint analysis of the complex incoming data streams.

Peter Shawhan
President of the Commission

References

Abbott, R. *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration) 2022, "First joint observation by the underground gravitational-wave detector KAGRA with GEO 600", *Progress of Theoretical and Experimental Physics* **2022**, 063F01. arXiv:2203.01270. https://doi.org/10.1093/ptep/ptac073

Abbott, R. *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration) 2023a, "GWTC-3: Compact binary coalescences observed by LIGO and Virgo during the second part of the third observing run", *Physical Review X* **13**, 041039. arXiv:2111.03606. https://doi.org/10.1103/PhysRevX.13.041039

Abbott, R. *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration) 2023b, "Open data from the third observing run of LIGO, Virgo, KAGRA, and GEO", *The Astrophysical Journal Supplement Series* **267**, 29. arXiv:2302.03676. https://doi.org/10.3847/1538-4365/acdc9f

Agazie, Gabriella *et al.* 2023, "The NANOGrav 15 yr data set: Evidence for a gravitational-wave background", *The Astrophysical Journal Letters* **951**, L8. https://doi.org/10.3847/2041-8213/acdac6

Antoniadis, J. *et al.* 2023, "The second data release from the European Pulsar Timing Array III. Search for gravitational wave signals", *Astronomy & Astrophysics* **678**, A50. https://doi.org/10.1051/0004-6361/202346844

Branchesi, M. *et al.* 2023, "Science with the Einstein Telescope: a comparison of different designs", *Journal of Cosmology and Astroparticle Physics* **07(2023)**, 068. arXiv:2303.15923. https://doi.org/10.1088/1475-7516/2023/07/068

Colpi, M. *et al.* 2024, "LISA definition study report", *Published by ESA* **2024**, arXiv:2402.07571. https://doi.org/10.48550/arXiv.2402.07571

Evans, M. *et al.* 2021, "A horizon study for Cosmic Explorer: Science, observatories, and communities", *eprint arXiv:2109.09882* **2021**. https://doi.org/10.48550/arXiv.2109.09882

Punturo, M. *et al.* 2010, "The Einstein Telescope: a third-generation gravitational wave observatory", *Classical and Quantum Gravity*, **27**, 194002. https://doi.org/10.1088/0264-9381/27/19/194002

Reardon, Daniel J. *et al.* 2023, "Search for an isotropic gravitational-wave background with the Parkes Pulsar Timing Array", *The Astrophysical Journal Letters* **951**, L6. https://doi.org/10.3847/2041-8213/acdd02

Xu, Heng *et al.* 2023, "Searching for the nano-hertz stochastic gravitational wave background with the Chinese Pulsar Timing Array Data Release I", *Research in Astronomy and Astrophysics* **23**, 075024. https://doi.org/10.1088/1674-4527/acdfa5