Max-Planck-Institut
für Radioastronomie

A Gamma-ray Pulsar Timing Array

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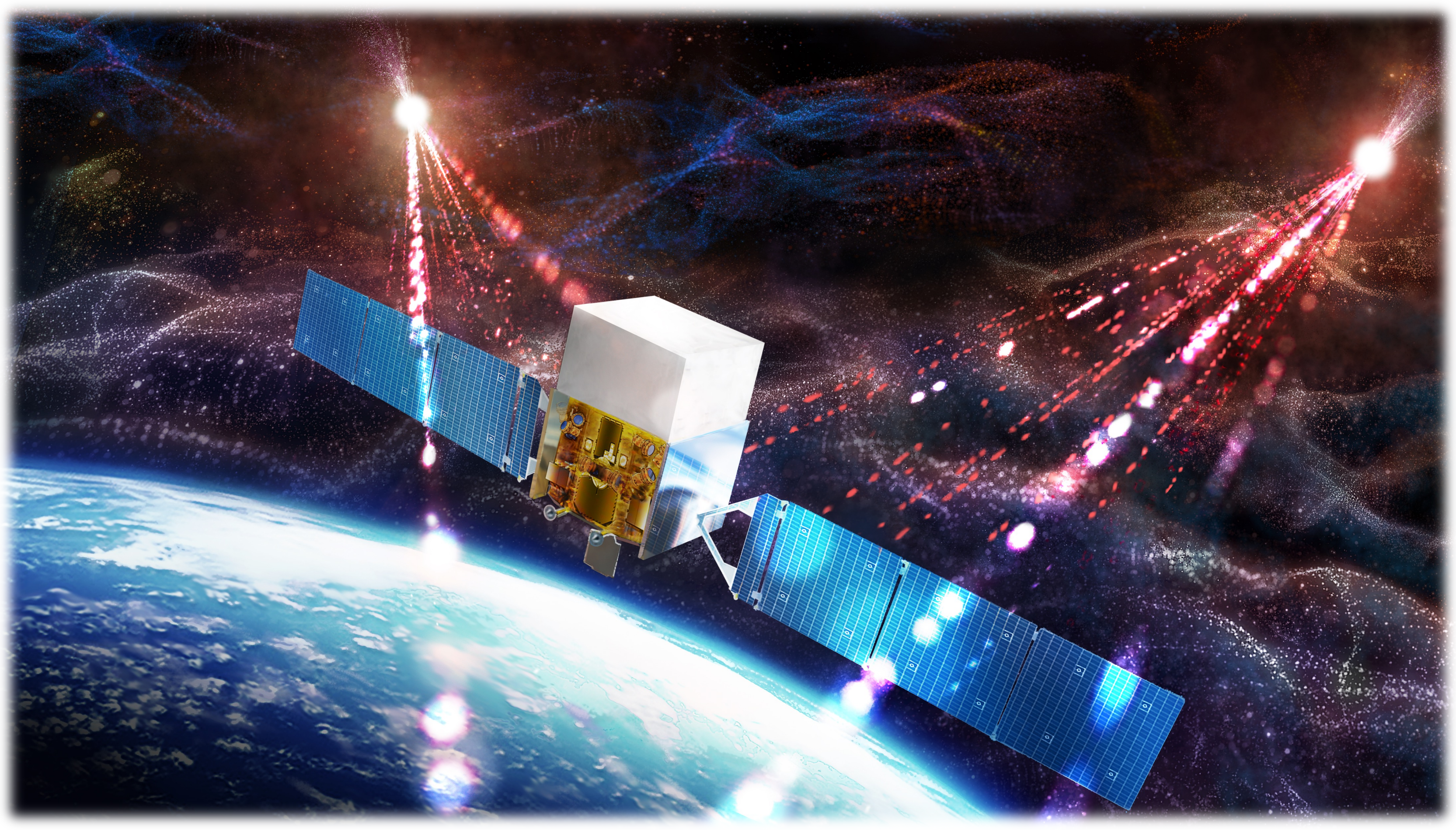
Constraining the nanohertz gravitational wave background using gamma-rays

After large galaxies merge, their central supermassive black holes are expected to form binary systems whose orbital motion generates gravitational waves. The superposition of gravitational waves from many such mergers across cosmic time generates a gravitational wave background (GWB) at nanohertz frequencies. Searches for this background utilize pulsar timing arrays (PTAs), which perform long-term monitoring of millisecond pulsars (MSPs) at radio wavelengths.

Radio PTAs may have recently detected an exciting and long-awaited hint of low-frequency gravitational waves [1]. However, the candidate signal could have other origins, including residual effects from propagation through the ionized interstellar medium (IISM). The candidate also lacks the hallmark quadrupolar pattern [2], indicative of a GWB.

Gamma-ray observations of MSPs offer a complementary approach. They are immune to the effects of the IISM and the solar wind. The long (~12 years), uninterrupted observations of more than 100 MSPs with the Fermi Large Area Telescope (LAT) make it a PTA with unique capabilities. Using results from 35 bright gamma-ray pulsars, we place a 95% credible limit on the GWB characteristic strain (A_{gwb}) of 1×10^{-14} at 1 yr^{-1}, within a factor of a few of the candidate GWB signal.

A gamma-ray pulsar timing array (artistically depicted on the right), not envisioned before the launch of Fermi, represents a powerful new capability in gravitational wave astrophysics.



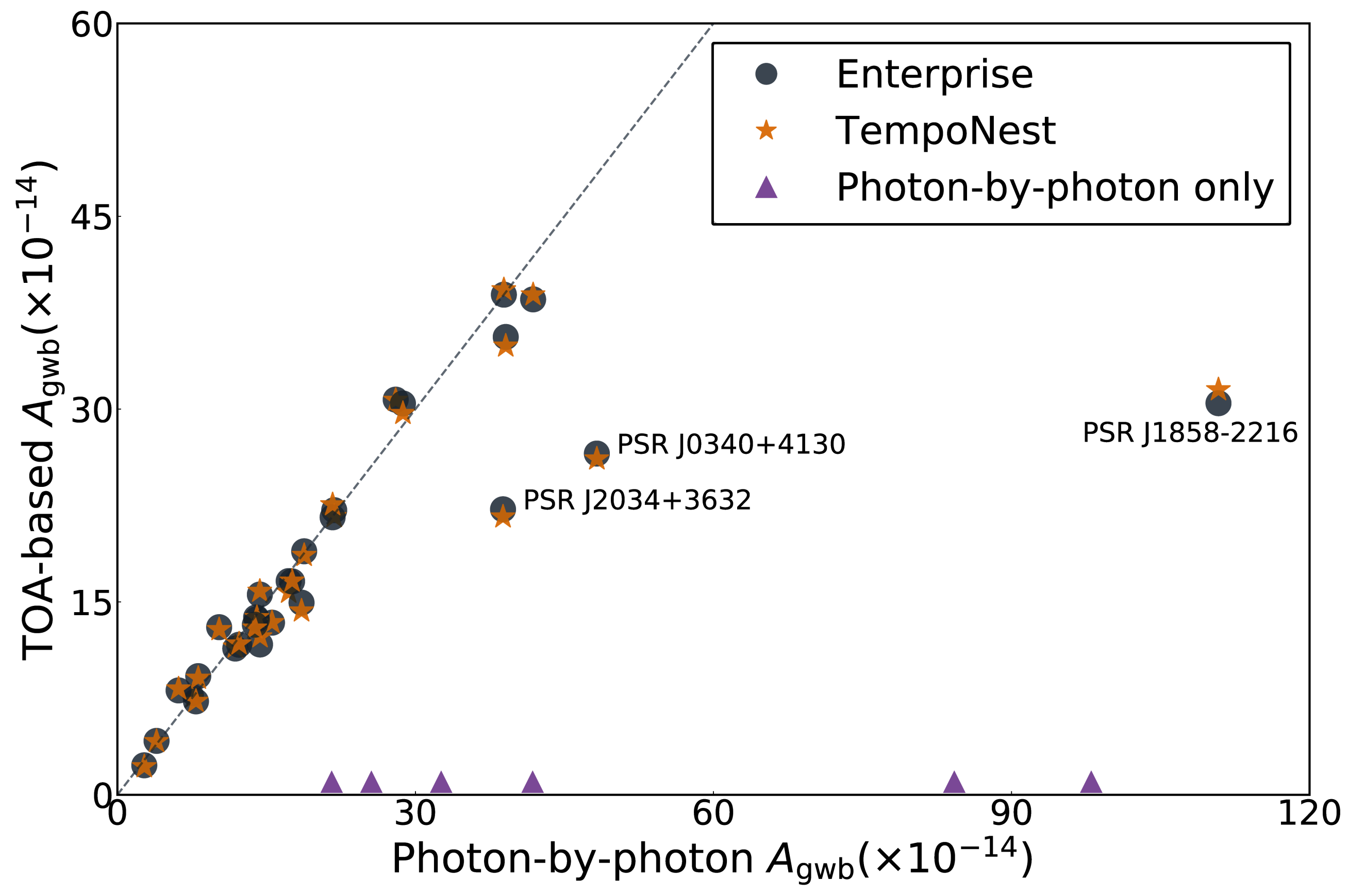
Credit: Daniëlle Futselaar/MPIfR (artsource.nl)

A novel and independent methodology

Subtle signatures like the GWB can be obscured by noise [3], and many noise sources must be accounted for in radio PTA data to reach a typical amplitude in the timing residuals of < 100 ns. To place the Fermi PTA results in context, we provide an overview of the radio PTA noise budget below, drawing distinctions to gamma-ray observations where appropriate.

	Radio		Gamma ray		
Noise Source	Impact	d.o.f.	Impact	d.o.f.	Note
White Noise					
Measurement	moderate	–	major	–	Sensitivity is major limiting factor for gamma rays.
RFI	minor	?	–	–	RFI varies widely between observing systems.
Calibration	minor	?	–	–	Affects certain pulsars/observing systems.
Jitter	moderate	10s	–	–	Jitter affects high signal-to-noise observations.
Red Noise					
DM variation	major	100s	–	–	DM(t) drives radio PTA observing strategies.
Solar wind	moderate	∼10s	–	–	Solar wind mitigation is poorly supported.
Scattering	moderate	100s	–	–	Affects some pulsars/low radio frequencies.
Pulse variability	moderate	0–10s	–	?	No gamma-ray MSP pulse profile changes known.
Discontinuities	moderate	10s	–	–	LAT data are continuous, not a general property.
Spin noise	major	10s–100s	major	10s	Fewer d.o.f. needed for less precise LAT data.

We searched for the GWB in the gamma-ray data using two different techniques [4]. First, we implemented a coherent photon-by-photon analysis which retains < 1 µs resolution. Second, for analysis with the established software used for radio data analysis (*TempoNest* and *Enterprise*), we directly measured arrival times from the LAT data. The three different methods provide consistent results for each pulsar (right), except for three cases which are understood.



The Gamma-ray data set and the methodology to conduct GWB analyses are independent of the established radio PTA experiments. This independence and its immunity to the effects of the IISM make it a more direct and important complementary PTA experiment for the detection of the stochastic GWB signal.

The Fermi space telescope as a gravitational wave detector

Since the expected quadrupolar correlations due to the GWB are only about 10% of the total signal, the GWB is predicted to first appear as a set of independent signals from each pulsar whose power spectra are all consistent with *P(f)* as shown below.

$$P(f) = \frac{A_{\mathrm{gwb}}^2}{12\pi^2} \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-\Gamma} \mathrm{yr}^{-3}$$

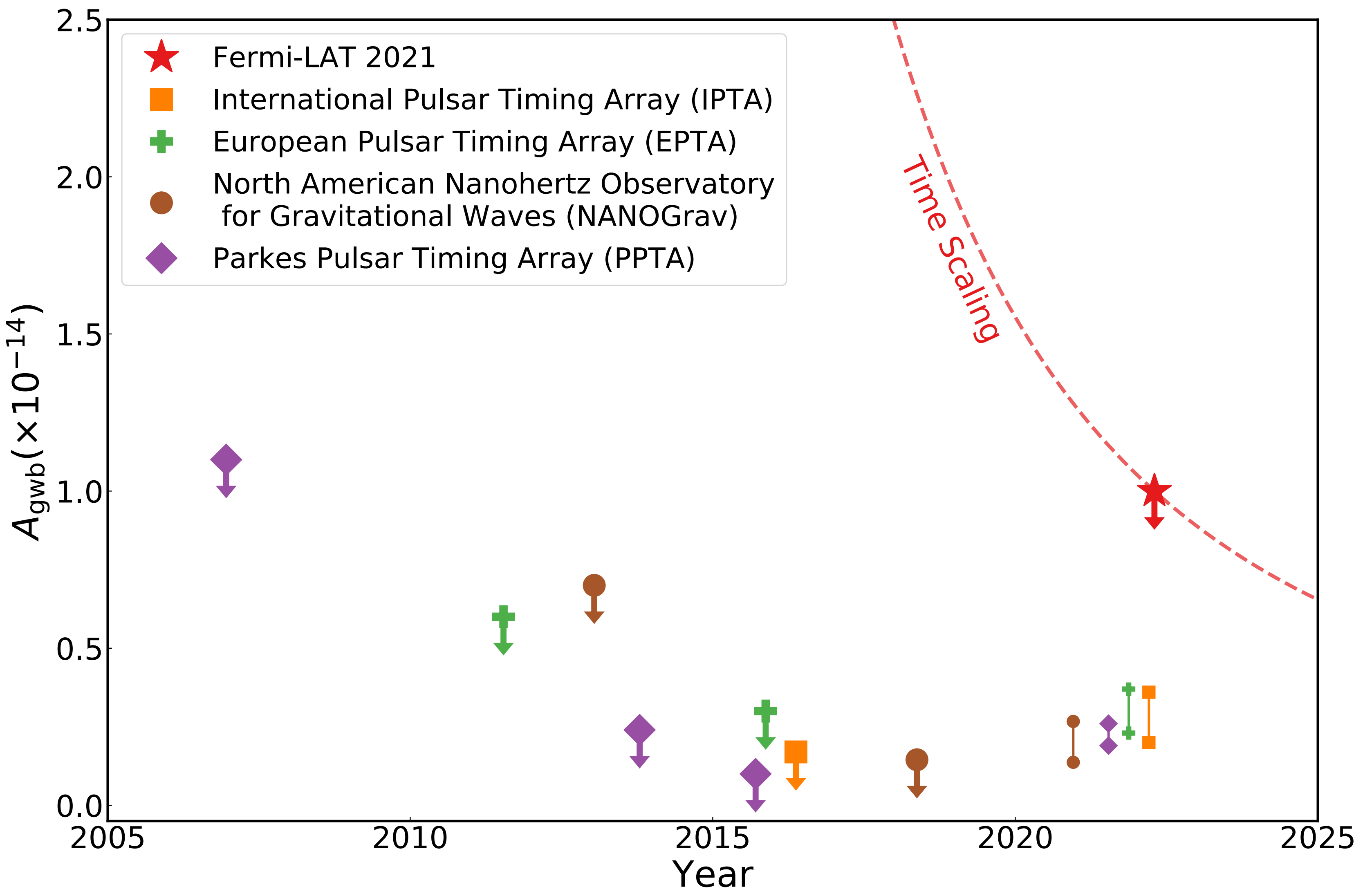
If the candidate signal seen in the radio data is indeed due to a GWB, then the quadrupolar distribution will become evident with longer and more sensitive observations.

However, there could be alternative explanations for this candidate signal, for example, spin noise intrinsic to each pulsar and frequency-dependent effects of radio propagation through plasma.

Combining the 35 gamma-ray MSPs into a pulsar timing array and estimating A_{gwb} limits under a variety of scenarios, the resulting representative 95% confidence limit $A_{\mathrm{gwb}} < 1.0 \times 10^{-14}$, a factor of 3-5 higher than the red spectrum process detected by radio PTAs (right).

For an idealized PTA, when a potential GWB signal is weak compared to other noise sources, the upper limits on A_{gwb} will improve as $t_{\mathrm{obs}}^{-13/6}$. On the other hand, if the signal that terrestrial PTAs are currently detecting does arise from the GWB, then these PTAs are now in the strong signal regime and their sensitivity will improve only slowly as $t_{\mathrm{obs}}^{-1/2}$.

The differing time scaling and noise sources allow the gamma-ray PTA data to distinguish residual IISM variations from a potential GWB signal.

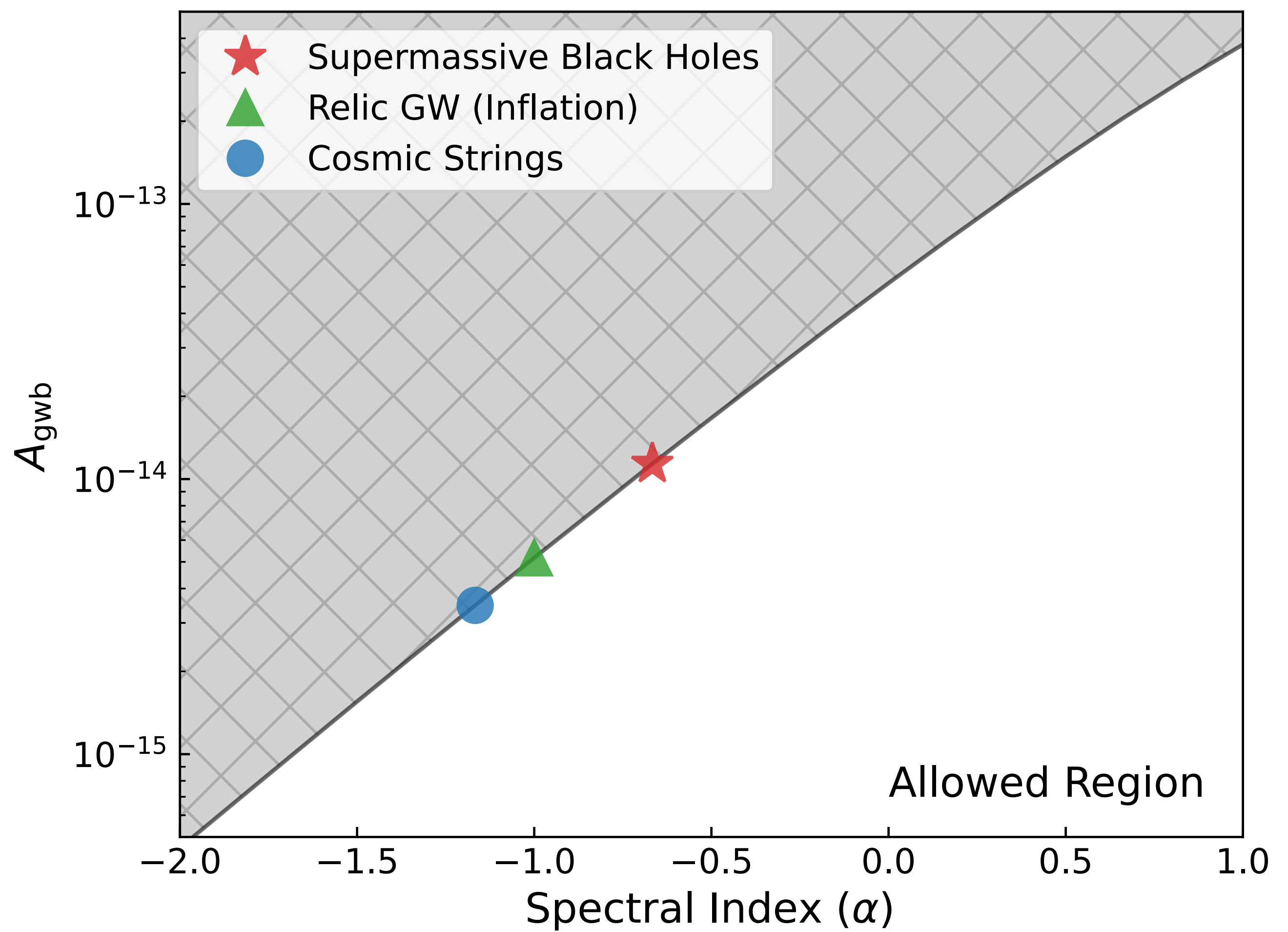


The importance of a gamma-ray pulsar timing array

Mitigating the multitude of noise sources for radio observations requires multi-frequency data, large fractional bandwidths, and homogeneous and regular monitoring, a substantial practical challenge. In contrast, gamma-ray data **only require spin noise and Poisson noise models**. This **eases computational requirements** and reduces systematic uncertainty. Due to continual all-sky monitoring, when a new MSP is discovered, archival LAT **data can provide a full pulse timing history**. The data span for each pulsar is uniform, ensuring that each pulsar is sensitive to the same spectrum of gravitational waves.

Gamma-ray data are also **potentially less subject to astrophysical changes in the radio pulse shape**. This stability is particularly useful for probing GWs with frequencies below 0.1 yr^{-1}, which are predicted to **constrain the spectral shape of the GWB** which contains information about the physical sources – such as relic GWs or decay of (hypothetical) cosmic strings. To constrain such sources, we computed corresponding 95% upper limits on A_{gwb} at different values of the spectral index (α) as shown on the right.

Three of the pulsars in our sample have previous spin noise measurements from radio PTAs. Using the power spectral indices measured from the radio timing data, we calculated 95% upper limits on spin noise amplitudes from the gamma-ray data. Our limits are below the previously measured values, potentially indicating contamination by residual IISM effects on the radio-based spin noise and GWB signal measurements. Similar noise analysis on a larger sample of multi-band data will provide insights into the efficacy of radio noise models for modelling the effects of the IISM – crucial in the detection of the GWB signal.



Summary

We show that a gamma-ray PTA offers sensitivity to the gravitational wave background that is on par with radio PTAs. This surprising result is due to the long, uninterrupted Fermi dataset, its immunity to ISM effects and its many detections of MSPs. **Gamma-ray observations thus provide an independent, direct and simple means of probing the GWB** and refining our understanding of any confounding effects in radio PTA data.

References

[1] S. Chen, et al., Mon. Not. R. Astron. Soc. 508, 4970 (2021)

[2] R. W. Hellings, G. S. Downs, Astrophys. J. 265, L39 (1983)

[3] J. P. W. Verbiest, G. M. Shaifullah, Classical and Quantum Gravity 35, 133001 (2018)

[4] Software for the Fermi PTA: 10.5281/zenodo.6374291

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