Pulsar Timing and Gravitational Waves

(SR Taylor, Astrophysics and Space Science, 2005)

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Pulsars as cosmic clocks

- **Pulsars**: Rapidly rotating neutron stars that emit beams of radio waves.
- **Millisecond pulsars**: The “gold standard” for timing. They rotate hundreds of times per second with a stability rivalling atomic clocks.
- **Concept**: If spacetime is flat, pulses arrive with perfect regularity. If the spacetime is warped dynamically – eg. by a gravitional wave – the pulses arrive early or late.

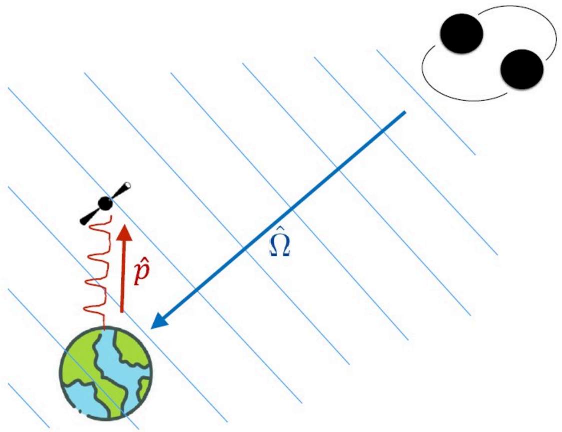
Pulsar Timing Arrays (PTAs)

- **A galactic-scale interferometer**: By monitoring a “mesh” of pulsars across the Milky Way, we can identify large-scale ripples in spacetime.

- **Timing residuals**: The difference between observed and predicted times of arrival:

$$\Delta t = T_{\text{obs}} - T_{\text{pred}}$$

- **Sensitivity**: PTAs are sensitive to nanohertz (nHz) frequencies – waves with periods of years to decades.



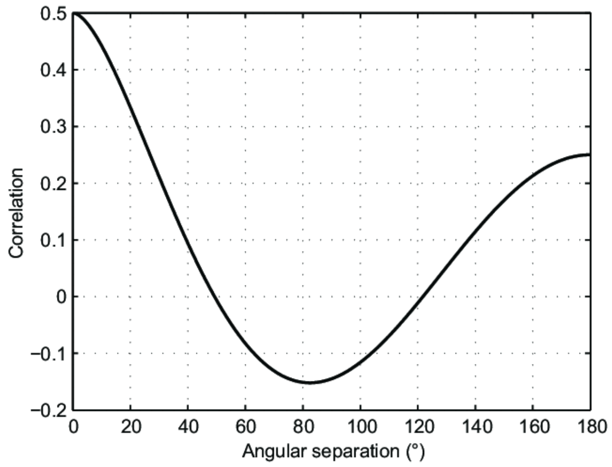
The target - Nanohertz Gravitational Waves

- **Complementary to LIGO/LISA**:
  - **LIGO**: High frequency (Hz to kHz), small sources (stellar mass black holes)
  - **LISA**: Low frequency (mHz) (massive black holes)
  - **PTA**: Ultra-low frequency (nHz), (supermassive black hole binaries, SMBHBs)

-**The Stochastic GW Background**: Instead of one clear signal, PTAs primarily hear the rumble of millions of SMBHBs merging throughout the universe's history

Smoking Gun - The Hellings-Downs Curve

- **Spatial correlation**: To prove timing noise is caused by a GW, we must see a specific correlation between pairs of pulsars
- **The Signature**: The correlation depends on the angle between the pulsars in the sky – This is the **Hellings-Downs curve**.
- **Significance**: Only quadrupolar gravitational radiation produces this exact pattern



The Astrophysical Benchmark (SMBHBs)

The primary target for PTAs is the superposition of waves from supermassive black hole binaries (SMBHBs).

- **Power-law model**: General relativity predicts a characteristic strain spectrum based on circular GW-driven inspirals:

$$h_c(f) = A\left(\frac{f}{f_{\mathrm{yr}}}\right)^{-2/3}$$

- **Chirp mass modeling**: Theoretical distributions of black hole masses (population synthesis) expect a stochastic amplitude of

$$A \approx 2 \times 10^{-15}$$

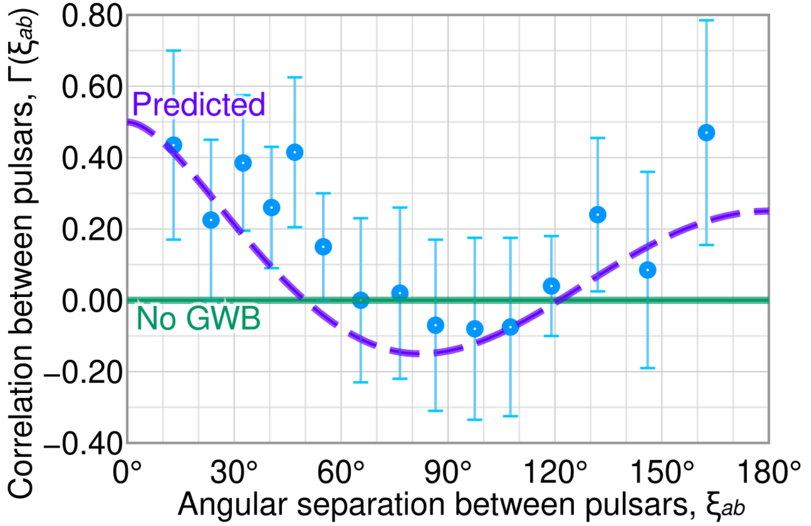
Modeling environmental bottlenecks

- **Gas and stellar interactions**: These harden the binary, causing it to move faster through the nHz band than GW emission alone
- **Spectral turnover**: At very low frequencies, these interactions cause the spectrum to flatten, deviating from the expected $-2/3$ power law
- **Significance**: Identifying this turnover can help understanding galactic merger processes and how BHs overcome the “final parsec problem”

The 2023 Breakthrough

In June 2023, major collaborations (NANOGrav, EPTA, PPTA, CPTA) released data showing the first "compelling evidence" for a stochastic GW background.

- **Key datasets**:
  - **NANOGrav 15-year**: Evidence of a common spectrum process
  - **EPTA Data Release 2**: High-precision analysis of European PTA pulsars
- **Conclusion**: The signal amplitude ($A = 10^{-15}$) is consistent with a background of inspiralling black holes.



- **Noise modelling breakthroughs**: New (2025) EPTA models have mitigated tensions in the data, confirming the spectral index is highly consistent with GR's prediction of $-2/3$.
- **MeerKAT PTA**: The South African telescope has joined the fray, providing the highest cadence timing data ever recorded for southern hemisphere pulsars.
- **Search for Anisotropy**: Scientists are refining techniques to look for "hot spots" in the background to identify individual nearby SMBHBs.
- **Accuracy**: Statistics have increasing significance as more years of data are taken (years $\to$ decades)

Beyond black holes

- **Cosmic strings**: Theoretical “cracks” in spacetime that could emit nHz waves
- **Phase transitions**: Violent events in the early universe (seconds after the Big Bang) that could leave a GW footprint