The Gravitational-Wave Universe seen by Pulsar Timing Arrays

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Outline

• The gravitational-wave spectrum
• Pulsar Timing Arrays
• Continuous nHz gravitational waves
• The gravitational-wave background
• New results in astrophysics and cosmology
• Future directions: anisotropy
The spectrum of gravitational wave astronomy

LIGO can't see PTA sources

See Brittany Kamai

Holometer

primordial BHs resolvable cosmic strings
Pulsar Timing Array

Animation from John Rowe Animation/Australia Telescope National Facility, CSIRO
Millisecond Pulsars

2300 known pulsars, 230 MSPs
Maybe 30,000 detectable!

courtesy Maura McLaughlin

Figure 20. Timing summary for PSR J1713+0747. Colors are blue: 1.4 GHz, purple: 2.3 GHz, green: 820 MHz, orange: 430 MHz, red: 327 MHz. In the top panel, individual points are semi-transparent; darker regions arise from the overlap of many points.

Figure 21. Timing summary for PSR J1738+0333. Colors are blue: 1.4 GHz, purple: 2.3 GHz, green: 820 MHz, orange: 430 MHz, red: 327 MHz. In the top panel, individual points are semi-transparent; darker regions arise from the overlap of many points.

Figure 22. Timing summary for PSR J1741+1351. Colors are blue: 1.4 GHz, purple: 2.3 GHz, green: 820 MHz, orange: 430 MHz, red: 327 MHz. In the top panel, individual points are semi-transparent; darker regions arise from the overlap of many points.

The Astrophysical Journal, 813:65 (31pp), 2015 November 1
The NANOGrav Collaboration et al.

J1713+0747
43 MSPs

GBT, Effelsberg, Parkes, Nançay, GMRT

adapted Ray et al. (2012)
Gravitational Waves, Pulsar Timing, and the Deep Space Network

courtesy Joe Lazio
Pulsar Timing Array

Galactic GW detector! Each pulsar thousands of light years away. Signal can evolve!
Continuous GW Sources

European Pulsar Timing Array limits on continuous gravitational waves from individual supermassive black hole binaries

Continuous GW Results

- Assume non-spinning SMBHs in circular orbit
- Model contains a single GW signal
- Separate searches: (i) using earth-term only (ii) using full non-evolving signal \((f_p = f_e)\) (iii) using full evolving signal
- Methods: frequentist and Bayesian methods for setting upper limit on the strain of monochromatic GW source
Continuous GW Results

\[6 \times 10^{-15} < \mathcal{A} < 1.5 \times 10^{-14}\]
Continuous GW Results

best 6 pulsars

factor of 4

Bayesian analysis with non-evolving source
Horizon Distance

For $f < 10$ nHz can exclude sub-centiparsec binaries: \textit{with} $M_c > 10^9 \, M$ \textit{out to} 25 Mpc; \textit{with} $M_c > 10^{10} \, M$: \textit{out to} 1 Gpc ($z \approx 0.2$).
the nanoHertz gravitational-wave background
residuals $\propto \int_{S^2} d\hat{\Omega}$ (power distribution x response)

Hellings and Downs, isotropy

Overlap reduction function, $\Gamma_0^0$

Angular separation of pulsars, $\zeta$
Stochastic Background from SMBHBs

Assuming circular SMBH binaries driven by GW emission only, can define a characteristic strain:

\[ h_c^2 \sim f^{-4/3} \int \int dzdM \frac{d^2n}{dzdM} \left( \frac{1}{1 + z} \right)^{1/3} M^{5/3} \]

number of mergers remnants per comoving volume

\[ h_c = A \left( \frac{f}{\text{yr}^{-1}} \right)^{-2/3} \]

\[ \Omega_{\text{gw}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2 \]

Phinney (2001); Sesana (2012)

We know a lot about A, can learn more
Surge in the field in last 10 years, here are the latest results!

New Results: Astrophysics

THE NANOGRAV NINE-YEAR DATA SET: LIMITS ON THE ISOTROPIC STOCHASTIC GRAVITATIONAL WAVE BACKGROUND


(The NANOGrav Collaboration)
Stochastic background from SMBH mergers


Recall Lucio Mayer’s talk

Environmental Coupling
- Stellar hardening
- Gas-driven inspiral
- Eccentricity

Galaxy Population Uncertainties
- Merger timescale
- SMBH - host relations
- Pair fraction
- Redshift evolution

\[
\begin{align*}
\frac{da}{dt} \propto a^2 & \quad \text{stars} \\
\frac{da}{dt} \propto a^{1/2} & \quad \text{gas} \\
\frac{da}{dt} \propto a^{-3} & \quad \text{gw}
\end{align*}
\]

Diminished GW Signal
- BSMBH stalling

Gravitational Wave Frequency, \( f \) (Hz)
Shape of the spectrum

Large uncertainty in signal amplitude at low frequencies due to very poorly understood binary-environment interactions.

\[ \beta = 2.23 \pm 0.15 \]

\[
\left( \frac{da}{dt} \right)_{\text{stars}} \propto a^2
\]

\[
\left( \frac{da}{dt} \right)_{\text{gas}} \propto a^{1/2}
\]

\[
\left( \frac{da}{dt} \right)_{\text{gw}} \propto a^{-3}
\]
Typical densities of massive elliptical galaxies at the MBH influence radius is $10^3 \, M_\odot \, pc^{-3}$.

\begin{itemize}
  \item The figure confirms the equality $\rho > 10^4 \, M_\odot pc^{-3}$ is heavily preferred.
  \item The figure confirms the upper limit $\dot{M} \geq 0.1 \, M_\odot yr^{-1}$ is heavily preferred.
\end{itemize}
Get density of stars in SMBH environment, and accretion rate for an $f_{\text{turn}}$ (Arzoumanian +2016)
Time to detection?

- Given $A < 1 \times 10^{-15}$, how long to detection?
- Large, expanding PTAs, e.g. NANOGrav, will detect in $< 10$ yrs
- **blue line** = no stalling, **red line** = 90% stalling, dashed line = $1/11$yr turnover due to stellar hardening

New Results:

cosmic strings
Cosmic (super)Strings

- Loops decay via GW emission, creating background $10^{-16}$ Hz - $10^9$ Hz, depending on size of loops created
- Create a background which could be detected by PTAs; place limits on string tension

C. Ringeval, F. Bouchet

recall Sotiris Sanidas talk
NANOGrav 9-yr Results

- Both the amplitude and spectral slope information of the GWB limits were used to construct the limits.
- Nambu-Goto (field theory strings) with $p=1$
- 4x better than limit by Planck + Atacama Cosmology Telescope + SouthPole Telescope

In SI units, linear density of string is $10^{20}$ kg/m.
New Results: Primordial Backgrounds

Gravitational-Wave Cosmology across 29 Decades in Frequency

Primordial Background

- Primordial radiation can manifest as a contribution to the present day GW energy density $\Omega_{gw}(f)$
- GWB spectrum directly related to the primordial tensor spectral index $n_t$, tensor-to-scalar ratio “r”
- non-standard evolution of the Universe during inflation or non-standard power in GW modes when exiting horizon can produce blue spectra
- non-inflationary theories e.g. ekpyrosis + string-gas also predict blue spectra

$$\Omega_{gw}(f) = \frac{\Omega_{CMB}^{gw}}{f_{CMB}^{n_t}} \left[ \frac{1}{2} \left( \frac{f_{eq}}{f} \right)^2 + \frac{16}{9} \right]$$

e.g. Turner, White, Lindsey (1993); Smith, Kamionkowski, Cooray (2008)
Primordial background: Better together

Lasky, **CMFM**, Smith, Thrane, Giblin, Caldwell + (2016)
Primordial background: Better together

Lasky, **CMFM**, Smith, Thrane, Giblin, Caldwell + (2016)
Future Directions
Introducing Anisotropy

- residuals $\propto \int_{S^2} d\Omega \ (\text{power distribution} \times \text{response})$
- Nearby and/or loud sources may introduce anisotropy
- CMB anisotropy on very small scales, GWB anisotropy large-scale (?)
Angular separation of pulsars, $\zeta$.

Overlap reduction function, $\Gamma_0$.

Hellings and Downs, isotropy, 1983.

Hellings and Downs, 1983.
Isotropic limit $A < 1.5 \times 10^{-15}$

$\Omega = 180 / \sqrt{\Delta \Omega / \text{deg}^2}$
How much anisotropy?

- Red dashed line shows 95% upper limit on strain amplitude
- 32% GW power contained in higher multipoles, EPTA 40%

Taylor, CMFM + (PRL, 2015)
Detection: Bayes Factors

- To make us credible, we need to show how our signal improves over time
- Preliminary Bayes factor results using the Savage-Dickey ratio
  - ratio of the marginal posterior density and the prior density evaluated in noise regime

<table>
<thead>
<tr>
<th>Description</th>
<th>Bayes Factor</th>
</tr>
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<tbody>
<tr>
<td>anisotropy: (signal + noise) vs noise only</td>
<td>0.6</td>
</tr>
<tr>
<td>anisotropic vs isotropic</td>
<td>0.8</td>
</tr>
<tr>
<td>(isotropic + noise) vs noise only</td>
<td>0.5</td>
</tr>
</tbody>
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CMFM + for NANOGrav, in prep
Summary

• PTA *interdisciplinary* science experiment: radio astronomy, GWB + anisotropy + CW, galaxy evolution, SMBH env, ISM, cosmology

• Rule out sub-centiparsec binaries with \( M_c > 10^9 \, M \) out to 25 Mpc; with \( M_c > 10^{10} \, M \): out to 1 Gpc (\( z \approx 0.2 \)) for \( f < 10 \, \text{nHz} \)

• Already **placing astrophysical constraints** on SMBHB environments

• **Best** cosmic string tension limits, *4x more constraining* that combined CMB + ACT + SPTpol measurements

• **New:** first NANOGrav limit for stochastic background anisotropy, in preparation

• **Detection** expected in 7-10 years, evidence for GWB soon

Thank You!