Pulsar Timing Arrays for Nanohertz Gravitational Wave Astronomy

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- The physics of gravitational wave detection using pulsars
- The astrostatistics of PTAs
- Forecasts and future requirements
The Spectrum of Gravitational Wave Astronomy

- Cosmic strings
- Dimensionless strain $h$
- 20 orders of magnitude in GW frequency corresponds to the 20 orders of magnitude between radio waves and high-energy gamma rays

All three experiments measure changes in light travel times between objects due to GWs.

- Pulsar Timing Arrays
  - Primordial gravitational waves

- Space-based Interferometers
  - Supermassive black hole binaries and mergers
  - Primordial gravitational waves
  - Cosmic strings

- Ground-based Interferometers
  - Stellar mass compact binaries
  - Supermassive black hole mergers
  - Neutron star mergers
  - Black hole mergers

$\Rightarrow$ 20 orders of magnitude in GW frequency corresponds to the 20 orders of magnitude between radio waves and high-energy gamma rays
Glitches
Spin noise
Magnetosphere

Differential rotation, superfluid vortices

Interstellar dispersion and scattering

Emission region: beaming and motion

Uncertainties in planetary ephemerides and propagation in interplanetary medium

GPS time transfer
Additive noise
Instrumental polarization

Using Pulsars as Clocks: Precision Timing of Pulsars

\[ DM = \int_0^d n_e \, dl \]
The GW Spectrum

Schematic PTA sensitivities

Schematic GW stochastic background

Characteristic strain, $\log_{10}(h_c)$ vs Frequency, $\log_{10}(\text{Hz})$
Phases of Supermassive BH binary Mergers

Dusty Madison
Gravitational wave sources

The most promising sources are supermassive binary black holes (SMBBHs):

Other sources at nanohertz frequencies include cosmic strings, inflation, and phase transitions in the early universe.
Basic Picture

- Pulsar pulses = radio-wavelength photons.

- The travel time to reach us is affected by the spacetime metric along the photon path.

- Gravitational waves are ripples in spacetime that alter the distance that a photon travels.

- With sufficient precision, we measure the presence of GWs by monitoring pulsars over long intervals $T = 10$ years and longer

- Detector size = $cT \sim 10^+$ light years (not the pulsar distance)
Effect of a gravitational wave on radio pulses

Gravitational waves red (blue)-shift the train of pulses from a pulsar according to:

\[ z \propto \frac{1}{2} \left( \hat{p}_i \hat{p}_j \right) \left( 1 + \hat{\Omega} \cdot \hat{p} \right) \left[ h_{ij}^P - h_{ij}^E \right] \]

Sazhin (1978)
Detweiler (1979)
Anholm+ (2009)

Credit: John Rowe (Swinbourne)
Basic GW Effect on Pulsar Timing

Pulse width: \( W \geq 40 \, \mu s \)
Want TOA error: \( \sigma_t \leq 100 \, ns \)
\( \rightarrow \) factor of: \( > 400 \)

Consider timing over \( T = 10 \, yr \) and a GW with strain \( h \)

GW induces a frequency shift \( \Delta v/v \sim h \)
\( v = \) pulse frequency = \( 1/P \)
Phase shift \( \Delta \phi = \Delta v T \)
TOA shift \( \Delta t = P \Delta \phi = hT \)

For \( \Delta t = 100 \, ns \) and \( T = 10 \, yr \):

\[
h \sim \frac{\Delta t}{T} \sim 10^{-15.5}
\]
Effect of a gravitational wave on radio pulses

10^{11} cycles

By keeping track of every rotation of the pulsar over the course of years, we can predict when a particular pulse from a pulsar will arrive at our radio telescope. The error in our prediction is called the pulsar timing residual.

Train of pulses 1 year ago

Train of pulses today

A year later

Arrival of pulse

Predicted arrival

Actual arrival

Timing residual = Actual arrival - Predicted arrival

Gravitational waves change the time of arrival of pulses so we can look for gravitational waves in the timing residual data.
RESPONSE OF DOPPLER SPACECRAFT TRACKING TO GRAVITATIONAL RADIATION

FRANK B. ESTABROOK and HUGO D. WAHLQUIST
Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, California 91103
Revised version received 16 January 1975

ABSTRACT

A calculation is made of the effect of gravity waves on the observed Doppler shift of a sinusoidal electromagnetic signal transmitted to, and transponded from, a distant spacecraft. We find that the effect of plane gravity waves on such observations is not intuitively immediate and in fact can have surprisingly different spectral signatures for different spacecraft directions and distances. We suggest the possibility of detecting such plane waves by simultaneous coherent Doppler tracking of several spacecraft.

See Armstrong, Living Reviews in Relativity (Cassini spacecraft, etc.)
1979: the fastest known pulsar was the Crab pulsar
  - $P = 33$ ms … a lousy clock!
    • We measure the spin rate of the crust
    • The internal superfluid spins slightly faster
    • `spin noise’ is from crust-superfluid interactions
1982: Millisecond pulsars discovered
  • B1937+21 = 1.56 ms pulsar; much more spin stable
    (but still not good enough)
Now: about 200 MSPs known with different spin qualities; some are excellent clocks
Difficulties of GW Detection $\Delta L/L \sim h$

### Pulsar Timing Array
- $L \sim cT \sim 3 \text{ pc}$
- $h_{\text{min}} \sim 10^{-16} - 10^{-14}$
- $\Delta L \sim 10^3$ to $10^5 \text{ cm}$

### Ground-based Interferometer
- $L \sim 3 \text{ km}$
- $h_{\text{min}} \sim 10^{-23}$
- $\Delta L \sim 10^{-16} \text{ cm}$

PTA: $\delta t$ includes:
- Translational motion of the NS $\sim 100$ to $1000 \text{ km/s}$
- Orbital motions of the pulsar and observatory: $10 \text{s} - 100 \text{s} \text{ km/s}$
- Interstellar propagation delays: ns to seconds
Definition of Pulsar Timing Array

- **Pulsars** are rotating neutron stars emitting EM pulses by virtue of a rotating beam of radiation (radio to γ rays)

- **Millisecond pulsars** (1.4 to 10 ms spin periods) are the best pulsar clocks (spin stability, narrow pulses)

- **Pulsar timing array** = an array of MSPs monitored with precision time-tagging of pulses to detect GW perturbations
  - Multiple MSPs to measure correlated GW perturbation (quadrupolar)
Pulsar Populations: P - $\dot{P}$ Diagram

**Best timing:**
- Short periods
- Small fields
- Slow spindown

**Worst timing:**
- Long periods
- Large fields
- Fast spindown

**Issues:**
- Differential rotation between crust and superfluid
- Torque variations
- Accretion events?
- Injected asteroids?

**NS-NS binaries:**
A galactic-scale GW detector: the Pulsar Timing Array

GW perturbations are correlated among different pulsars.

Need to observe an ensemble of MSPs to extract the correlated signal from the noise.
The Green Bank Telescope and Arecibo Observatory

Arecibo Observatory (AO), PR
World’s largest radio telescope

Green Bank Telescope (GBT), WV
World’s largest steerable radio telescope
The International Pulsar Timing Array (IPTA)

A Consortium of Consortia: NANOGrav + Parkes PTA (Australia) + European PTA
The PTA Challenge
PTA Challenges

- Time-tag a pulse with $w \geq 40 \, \mu s$ to a precision $\delta t < 100 \, \text{ns}$:
  \[
  \frac{\delta t}{w} < \frac{100 \, \text{ns}}{40 \, \mu s} = \frac{1}{400}
  \]

- Simplest case: localization with matched filtering:
  \[
  \frac{\delta t}{w} \sim \frac{1}{S/N} \implies S/N > 400
  \]

- Need large telescopes, wide bandwidths, long integrations:
  \[
  S/N \propto \frac{S_{pk} \times \text{Area} \times \sqrt{BW} \times \text{Int. Time}}{T_{sys}}
  \]

- Repeat for 10 years with cadence $\Delta < 1 \, \text{month}$

- Done? No!
Departures from matched filtering

Spinning NS = the clock ~ 10 km radius

Relativistic emission regions
- Magnetosphere ~ 100 – 10^5 km
- R_{LC} ~ 50,000 km P_{spin} (sec)

Single pulses show **phase jitter** relative to a fiducial spin phase

**Net effect:**
N pulses averaged ~uncorrelated jitter

\[ \delta t \sim N^{-1/2} \]

**Mitigation:**
N >> 1

< 0.4 ns

Crab pulsar shot pulses (ns)

Hankins & Eilek 2007
Synchronous Averaging

- Stack M pulses ($M = \text{multiples of } 10^5$)
- Time-tag using template fitting
  \[ t_j = \text{TOA} + \delta \text{TOA} \]
  \[ \delta \text{TOA} \sim \frac{W}{S/N} \sim 0.1 \mu s \text{ to } 1 \text{ ms} \]
- Repeat for L epochs spanning $N = T/P$ spin periods ($T = \text{years}$)
- $N \sim 10^8 - 10^{10}$ cycles in one year
- $\Rightarrow P$ determined to
  \[ \delta P \sim \frac{\delta \text{TOA}}{N} \sim 10^{-16} \text{ to } 10^{-14} \text{ s} \]

- B1937+21: $P = 0.0015578064924327 \pm 0.000000000000000004 \text{ s}$
- J1909-3744: eccentricity $< 0.00000013$ (Jacoby et al.)
THE NANOGRAV NINE-YEAR DATA SET: NOISE BUDGET FOR PULSAR ARRIVAL TIMES ON INTRADAY TIMESCALES

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Above S/N > 100 for 2 min averages, RMS residual becomes independent of S/N

Pulse jitter

See also Caballero et al. 2016

Above S/N > 100 for 2 min averages, RMS residual becomes independent of S/N

\[ \sim [S/N]^{-1} \]

J1713+0747
AO: 1400 MHz

ISS Variations

Counts

S\textsubscript{0} = 159.9
n\textsubscript{ISS} = 1.0

\[ \sigma_{R} (\mu s) \]

\[ \sigma_{C} = 180 \pm 4 \text{ ns} \]
Dispersions Delays

Multipath broadening (scattering)

Diffractive Scintillation

\[ t_{DM}(\nu) = \frac{4.15 \times DM}{\nu^2_{GHz}} \]

\[ DM = \int_0^D ds n_e(s) \]

Deterministic, removable with coherent dedispersion

Epoch dependent

Stochastic, not easily removable

\[ t_{scatt} = \frac{D \theta^2_d}{2c} \]

\[ \Delta \nu_{scatt} \approx \frac{1}{2\pi t_{scatt}} \]

100% modulations of flux density

Fig. 1. Integrated pulse profiles and best-fit model profiles for PSR B1833–09 at different frequencies. The profiles at 243, 325 and 610 MHz were observed with the GMRT, whereas the 408 and 1408 MHz profiles were taken from the EPN database (Lovel observations). The alignment of the profiles for different frequencies was done with respect to the peak of the main pulse.
Dispersed Pulse

\[ \Delta t = 8.3 \, \mu s \, \text{DM} \, \nu^{-3} \, \Delta \nu \]

Coherently dedispersed pulse
Coherent Dedispersion
pioneered by Tim Hankins (1971)

Dispersion delays in the time domain represent a phase perturbation of the electric field in the Fourier domain:

\[ E_{\text{measured}}(\omega) = E_{\text{emitted}}(\omega) e^{ik(\omega)z} \]

Coherent dedispersion involves multiplication of Fourier amplitudes by the inverse function:

\[ e^{-ik(\omega)z} \]

For the non-uniform ISM, we have

\[ k(\omega) = -\int dz k(\omega) \propto \omega^2 DM + \text{constant} \]

where DM is known to high precision for known pulsars.

The algorithm consists of

\[ \text{IFFT} \{ \text{FFT} [E_{\text{measured}}] \times e^{-ik(\omega)z} \} \approx E_{\text{emitted}}(t) \]

- Application requires Nyquist sampling of large bandwidths (high data rate)
- Scattering distortion is not removed
- Coherent dedispersion yields the best timing precision and is used routinely in NANOGrav observations at Arecibo and with
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Crab Pulsar
8 – 10.5 GHz
Plasma turbulence in the interstellar medium causes multipath propagation

Coherent waves from compact sources illuminate turbulent plasma in the ISM

- Scattering angle $\sim \lambda^2$
- Solid angle $\sim \lambda^4$

Main effects:
- Dispersive time delays
- Multipath delays
- Pulse distortion
Stochasticity of the PBF

Speckles

$\theta_x$

$\theta_y$

$N_{\text{speckles}} = N_{\text{scintles}}$

$N_{\text{scintles}} = \text{number of bright patches in the t-}ν \text{ plane}$

$N_{\text{scintles}} \approx (1 + \eta B/Δν_d)(1 + \eta T/Δt_d)$

Timing error:

$δt \sim \frac{τ_{\text{PBF}}}{\sqrt{N_{\text{scintles}}}}$

Mitigation: use pulsars with low amount of scattering and high frequencies

PSR 1737+13 0.430 GHz MJD 44830 2251117
Topocentric arrival times $\rightarrow$ solar system barycenter (SSBC)

Pulse phase model is evaluated at the SSBC

Roemer delay 500 s

Solar system barycenter is near the sun's photosphere

$\hat{n}$ is a function of time if pulsar moves and if it is at finite distance. proper motion: milliseconds parallax: $\mu s$ or less

$t_{\text{barycenter}} = t_{\text{observatory}} - c^{-1}\hat{n} \cdot \vec{r}$

Differences in JPL ephemerides: DE 418, 421, 430 @ Saturn's orbital period
Deterministic terms in the clock phase $\phi(t)$

Spin noise due to torque fluctuations (e.g. crust-core interactions)

Simulated results for a millisecond pulsar
Timing Model

TOA = Deterministic terms + Stochastic terms + Systematic Errors

- > 18 terms
  - Spindown polynomial
  - Astrometric
  - Pulsar orbit (post-Keplerian)
  - Variation of pulse shape with RF

- White noise
- Red noise: Spin/torque noise
- ISM noise

- Solar system ephemeris (location of SS barycenter)
- Polarization calibration
- Time transfer (GPS)
- Observatory clock stability

- Stochastic background
  - Continuous waves
  - Bursts (memory)

GW signal increases with data-span length (SBG + bursts with memory)

But so does red spin noise (rms ~ $T^2$)

GWs correlate between pulsars, red noise not

Residuals = data - model
radiometer noise + pulse jitter + scintillation noise

Larger telescope, lower noise receivers, longer integration times, larger bandwidths

Longer integrations (more sensitivity not a help)

Longer integrations, higher bandwidths and frequencies

scintles
Covariance Matrix for Short-term TOA Errors

TOA error:
\[ \epsilon(\nu, t) = \epsilon_{S/N}(\nu, t) + \epsilon_J(\nu, t) + \epsilon_{\text{DISS}}(\nu, t) \]

Covariance matrix:
\[
\langle \epsilon(\nu, t)\epsilon(\nu', t') \rangle = \sigma^2_{S/N} \delta_{\nu\nu'} \delta_{tt'} \\
+ \sigma^2_J \delta_{tt'} \\
+ \sigma^2_{\text{DISS}} \rho(\nu, \nu', t - t')
\]

Many current MSPs: \[ \sigma^2_{S/N} > \sigma^2_J \gg \sigma^2_{\text{DISS}} \]
Red Noise

• The stochastic GW background has a red power spectrum
  – Concentrated at low frequencies
  – Appears to flatten at frequencies lower than about 0.3 cycles yr\(^{-1}\)

• Red noise also contaminates PTA data at similar frequencies:
  – Spin/torque noise in neutron stars and their magnetospheres
  – ISM turbulence
    • DM fluctuations that are imperfectly removed
    • Multipath scattering effects
For these pulsars, the residuals are mostly caused by spin noise in the pulsar:
torque fluctuations crust quakes superfluid-crust interactions
Other pulsars: excess residuals are caused by orbital motion (planets, WD, NS), ISM variations;
Potentially: BH companions, gwaves, etc.

\[
\sigma_{\text{spin,2}} = 5^{+2.5}_{-1.7} \mu s \ \nu^{-1.4 \pm 0.1} \dot{\nu}^{1.1 \pm 0.1} T^{2 \pm 0.2}
\]
\( \nu \) in Hz
\( \dot{\nu} \) in \( 10^{-15} \) Hz s\(^{-1} \)
\( T \) in yr
spread in \( \ln \sigma_{\text{spin,2}} \) is \( 1.6 \pm 0.1 \)
note errors are \( \pm 2\sigma \)
Turbulence in ISM
Discrete plasma lenses
Changing path length to pulsar

DM(t)

$S_{DM}(f) \propto f^{-\gamma}, \gamma = 11/3$

Simulations: Michael Lam

Data courtesy Ryan Shannon
Removing ISM from Timing Data

Simplest case:

– Estimate DM from two-frequency measurements

\[ \Delta t_{12} = a_{DM} DM (\nu_1^{-2} - \nu_2^{-2}) + \Delta t_{C12} + \Delta \epsilon_{n12}. \]

\[ \hat{DM} = \frac{\Delta t_{12}}{a_{DM} (\nu_1^{-2} - \nu_2^{-2})} = DM + \frac{\Delta t_{C12} + \Delta \epsilon_{n12}}{a_{DM} (\nu_1^{-2} - \nu_2^{-2})}. \]

– Correct TOAs to infinite frequency

\[ \hat{t}_\infty = t_\infty + \left[ \frac{\epsilon_{rn2} + \epsilon_{J2} - (\nu_1/\nu_2)^2(\epsilon_{rn1} + \epsilon_{J1})}{1 - (\nu_1/\nu_2)^2} \right]_R + \left[ \frac{t_{C2} - (\nu_1/\nu_2)^2 t_{C1}}{1 - (\nu_1/\nu_2)^2} \right]_S. \]
NANOGrav observations

- Ongoing ~monthly observations of a set of MSPs starting in 2004.
  - Cadence has varied between 20 and 40 days.
  - Now also weekly GBT observations of J1713+0747 and J1909-3744, and five MSPs at Arecibo.
- Source list has grown from ~15 originally to 54 (and counting...) currently, thanks to ongoing PSR seaches!
  - Arecibo used if possible, GBT otherwise.
  - Proportional increase in telescope time commitment: ~5% of GBT, ~10% of Arecibo used for NANOGrav timing.
- Paired dual-frequency sessions at 820 and 1400 MHz (GBT); two of 430, 1400, and 2000 MHz (Arecibo). ~30 min / band / PSR.
Backend instrumentation

2004 – 2012: **GASP** (GBT) and **ASP** (Arecibo)

FPGA-based PFB $\rightarrow$ Real-time coherent dedisp and folding in 20-node CPU cluster.

$\sim 64$ MHz BW (dependent on DM), 8-bit ADCs, full-Stokes, $\sim 1$-minute folds.

2010 – now: **GUPPI** (GBT)
2012 – now: **PUPPI** (Arecibo)

FPGA-based PFB $\rightarrow$ Real-time coherent dedisp and folding in 8-node GPU cluster.

800 MHz BW (all DMs), 8-bit ADCs, full-Stokes, $\sim 1$–10-second folds.

Slide from P. Demorest
NANOGrav Observing Strategy

We currently observe 54 MSPs at the GBT and Arecibo, roughly every three weeks, at two radio frequencies. High cadence program for 5-6 MSPs. Add ~4 MSPs per year.

We use roughly 10% of the time on each telescope.

GW data analysis is a challenging astrostatistics problem.
**Figure 29.** Timing summary for PSR J1909-3744. Colors are: Blue: L-band, Purple: S-band, Green: 800 MHz, Orange: 430 MHz, Red: 327 MHz.
Figure 20. Timing summary for PSR J1713+0747. Colors are: Blue: L-band, Purple: S-band, Green: 800 MHz, Orange: 430 MHz, Red: 327 MHz.
Two Approaches for Noise Modeling

1. TOA time series: decompose `noise’ into empirical terms informed by known processes
e.g. noise modeling in detection pipelines (everything at once)

2. NS $\rightarrow$ Interstellar medium $\rightarrow$ telescope $\rightarrow$ SSB
   - Significant prior info about pulses, ISM, etc.
   - Quantitative error assessments in early stages of pipeline

Short term variations (< 24 hr): ~ understood
Multiple epoch: somewhat $\rightarrow$ un-understood

Some day (soon?) the two approaches will agree

My own opinion: current limits are affected by sensitivity, residual ISM effects, profile evolution, limited number of MSPs and observing systematics (polarization calibration) $\rightarrow$ significant room for improvement
Pre-fit spectrum of timing perturbations: TOA variance = integral of this spectrum

Spectrum of Noise Fluctuations for MSP J1713 +0747

- **Spin Noise**
- **Nyquist frequency**
- **GWs**
- **Jitter**
- **Template fitting error**
- **Scintillation Noise**
- **Kolmogorov δDM(t)**

Fluctuation Frequency (Hz) vs. Frequency (cy yr⁻¹)

- TOA Error from S/N
- Pulse Jitter
- Scintillation Noise
- δDM(t) \( (f^{-8/3} \text{ @low } f) \)
- Red spin noise \( (f^{-5}) \)
- GW SBG \( (f^{-13/3}) \)

8/24/2016

SAMSI  Pulsar Timing GW Arrays
Perturbation Spectrum $\times$ Transmission Function $=$ Residuals’ Spectrum

The 8-parameter fit for the transmission function $H(f)$ includes a quadratic polynomial (3) and astrometric terms (5). For small $f$, the transmission function scales as $f^6$.

* DM variations are assumed to be removed through two-frequency fitting at each epoch, leaving residuals from the frequency-dependent DM effect.
GW Detection Challenges

• Find a signal that is correlated between pulsars in the PTA
  – Not a terrestrial clock error (monopolar signature)
  – Not an error in the location of the solar system barycenter (dipolar)
  – Matches expectation of a quadrupolar signature for GWs

• Stochastic background: measure red signal amid red noise

• Continuous waves from individual SMBH binaries
  Burst with memory: a change in derivative of
Methods: Opportunities for Astrostatistics

• Characterization:
  – White noise: three contributions, well understood
  – Outliers: event identification, PCA on pulse shapes vs epoch & frequency
  – Red spin (or orbital noise): irregularly sampled data
    • Time domain methods: AoV, structure functions (e.g.) Allan variance
    • Frequency domain: MEM, Cholesky decomposition, Bayesian modeling

• Detection:
  – Model (almost) everything in timing model including noise
  – Efficiency an issue given large data sets
    • Hierarchical likelihoods
    • Hamiltonian Monte Carlo
A PTA noise model: everything is a Gaussian process

Slide from M. Vallisneri, J. Ellis, R. van Haasteren

Basis picture
Search over basis coefficients and hyperparameters
\[ y_{gp} = F a \]
\[ p(a) \propto e^{-a^T \Phi(\theta)^{-1} a/2} \]

Kernel picture
Marginalize over basis coefficients, search over hyperparameters
\[ p(y_{gp}) \propto e^{-y_{gp}^T K(\theta)^{-1} y_{gp}/2} \]
\[ K(\theta) = F \Phi(\theta) F^T \]

van Haasteren & MV
PRD 90, 104012 (2014)
Stochastic GWs as correlated Gaussian process

Pulsar #1: Timing residuals = radiometer noise (white) + timing-model errors + jitter noise (white, epoch) + DM + timing noise (red) + GW

Pulsar #2: Timing residuals = radiometer noise (white) + timing-model errors + jitter noise (white, epoch) + DM + timing noise (red) + GW

Pulsar #3: Timing residuals = radiometer noise (white) + timing-model errors + jitter noise (white, epoch) + DM + timing noise (red) + GW

Pulsar #4: Timing residuals = radiometer noise (white) + timing-model errors + jitter noise (white, epoch) + DM + timing noise (red) + GW

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

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

Diminished GW Signal:
- BSMBH stalling

Characteristic strain, $h_c$

Gravitational Wave Frequency, $f$ (Hz)

[Burke-Spolaor 2015]

Expected correlation

Angle between pulsars (degrees)

[Jenet et al. 2015]
Sensitivity projections

NANOGrav 2010 upper limit 5-yr data set (Demorest et al. 2013)

Expected amplitude range for SMBBH background (Sesana 2013)

NANOGrav 2016 estimated upper limit from 11-yr data set (this is my guess!)

NANOGrav 2015 upper limit from 9-yr data set (Arzoumanian et al. 2015)

\[ A \leq 1.5 \times 10^{-15} \]

We are already in astrophysically interesting territory!
Stochastic backgrounds—astrophysical inference

Arzoumanian et al. 2015

- Low frequency part of spectrum (when black holes are further away) possibly determined by environmental effects (solution to last parsec problem):
  - Stellar Hardening (stellar density in galactic cores)
  - Circumbinary disk interaction (mass accretion rate)
  - Orbital eccentricity (effects of stars/gas)

Rich astrophysics!
Stochastic backgrounds—astrophysical inference

Arzoumanian et al. 2015

- High frequencies (when black holes are close) dominated by GW emission so spectrum determined by:
  - Galaxy Merger Rates
  - Stalling fraction
  - Black hole-host correlations (i.e., M-sigma, M-M_bulge)
Continuous waves from individual SMBBH systems


NANOGrav postdocs and students involved:

Justin Ellis

NANOGrav postdocs and students involved:

Sarah Burke-Spolaor
Joe Simon

Exciting multi-messenger astronomy potential
Bursts with memory (BWM)

Maximum luminosity distance of a SMBHB merger causing a BWM detectable with 95% confidence. Diamonds are 12 pulsars in our analysis. Green triangle is the Virgo Cluster (16.5 Mpc away). Virgo Cluster is near the edge of the volume in which we can detect BWMs with these properties.

95% confidence Earth-term upper bound on the rate of BWMs occurring with amplitudes at or above amplitudes $h_B$.

NANOGgrav postdocs and students involved:

Dusty Madison
Most stringent cosmic string constraints to date

Arzoumanian et al. 2015

Slide from X. Siemens

Cannot detect bursts in PTA data: stochastic background too large

\[ G\mu \leq 1.3 \times 10^{-10} \]

10% of loops are formed \( \sim 0.05 \) t

Use the loop distributions of Blanco-Pillado et al. 2014

\[ h^2 < 4.1 \times 10^{-10} \]

Assumes all loops are formed at size given on x-axis
NSF funded NANOGrav Physics Frontier Center

NANOGrav Activities/Goals

**GW detector construction and characterization**

- Find additional MSPs to increase our sensitivity
- More efficient/sensitive pulsar searches
- Fully characterized low-frequency GW detector

**GW data set generation and curation**

- Regular (18 month) open data releases
- New pulsar timing packages
- Cyber-I data curation system

**GW detection and characterization**

- First detection of low-frequency GWs or tightest constraints to date
- Comprehensive open-source GW data analysis suite
Future

• Astrostatistical problems: characterization & detection
• Arecibo, GBT crucial to the PTA/GW program
• Discover more MSPs to reduce pulsar-specific noise (spin, ISM)
  ➔ Pulsar surveys with Arecibo, GBT, LOFAR, FAST, MeerKAT, SKA1, …)
  ➔ Collateral science: fast radio bursts, commensal SETI
• Higher cadence, wider-band observations
  ➔ More telescope time on existing and new telescopes
  ➔ Petascale data sets

MeerKAT (Karoo desert)
• 64 x 13.5m array ~ 1 GBT
• L band (1-1.7 GHz)
• S-band (1.7-3 GHz)
• 6k hr for pulsar timing in first 5 yr
• Full array 2017

SKA1-mid ~ build out of MeerKAT

FAST (Southern China)
• 500m (300m illuminated)
• 0.5 – 3 GHz
• Pulsars high profile but hours TBD
Summary

• A PTA of spin-stable MSPs can detect nanohertz GWs at levels comparable to predictions
• Upper bounds at 0.1 – 1 cycle yr\(^{-1}\) place important constraints on
  – Inspiraling and merging supermassive black hole binaries
  – Cosmic strings
• Improvements in PTA sensitivity will come from
  – Longer data sets and higher timing cadence
  – Discovery and monitoring of additional millisecond pulsars
  – Improvements in the noise model
  – Better algorithms for removing chromatic effects (ISM, profile evolution)
• Detections in the nanohertz band are imminent
• The Green Bank Telescope (GBO) and Arecibo need to be kept in operation
• Need to transition from an ad hoc telescope array to a