NANOGrav

Status of Pulsar Timing Arrays

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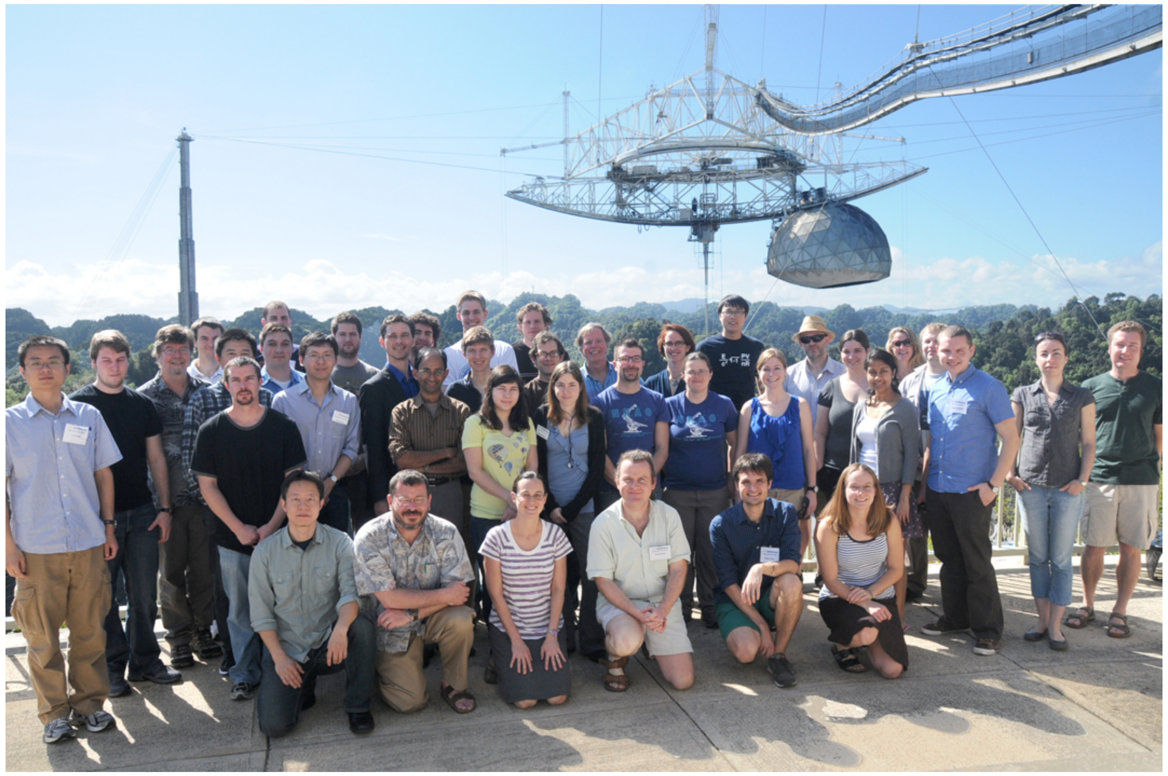
The North American Nanohertz Observatory for Gravitational Waves: about 120 students and scientists in the US and Canada working to characterize the gravitational wave universe at low frequencies using pulsar timing. Part of a world-wide effort including European and Australian partners.



NANOGrav became an NSF Physics Frontiers Center in 2015 (for $14.5M)

The Arecibo Observatory and the Green Bank Telescope

Our measurements are made with the two most sensitive radio telescopes in the world

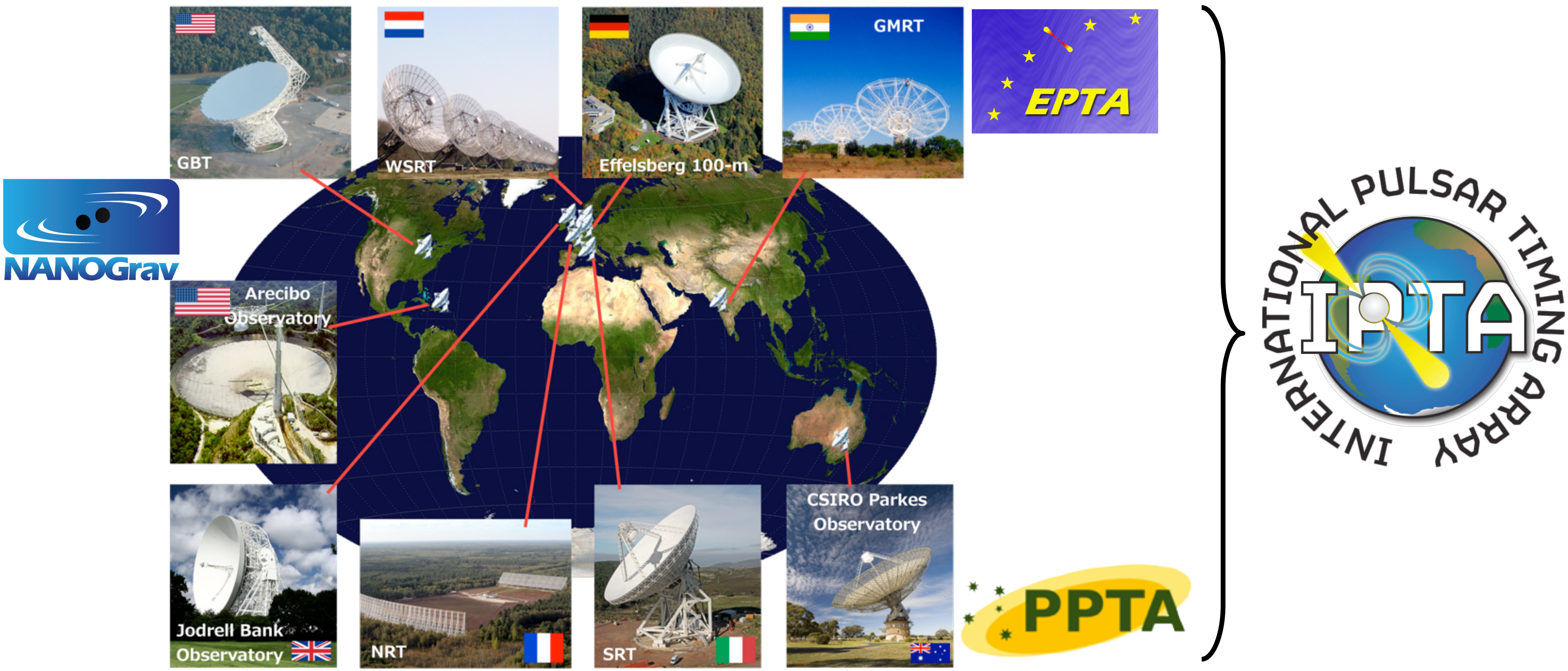
Arecibo Observatory

Green Bank Telescope

Both face budget challenges

The International Pulsar Timing Array (IPTA)

Relationship between PTAs is one of cooperative competition. Data are shared six months after they are taken and analyzed through organized IPTA-wide projects.



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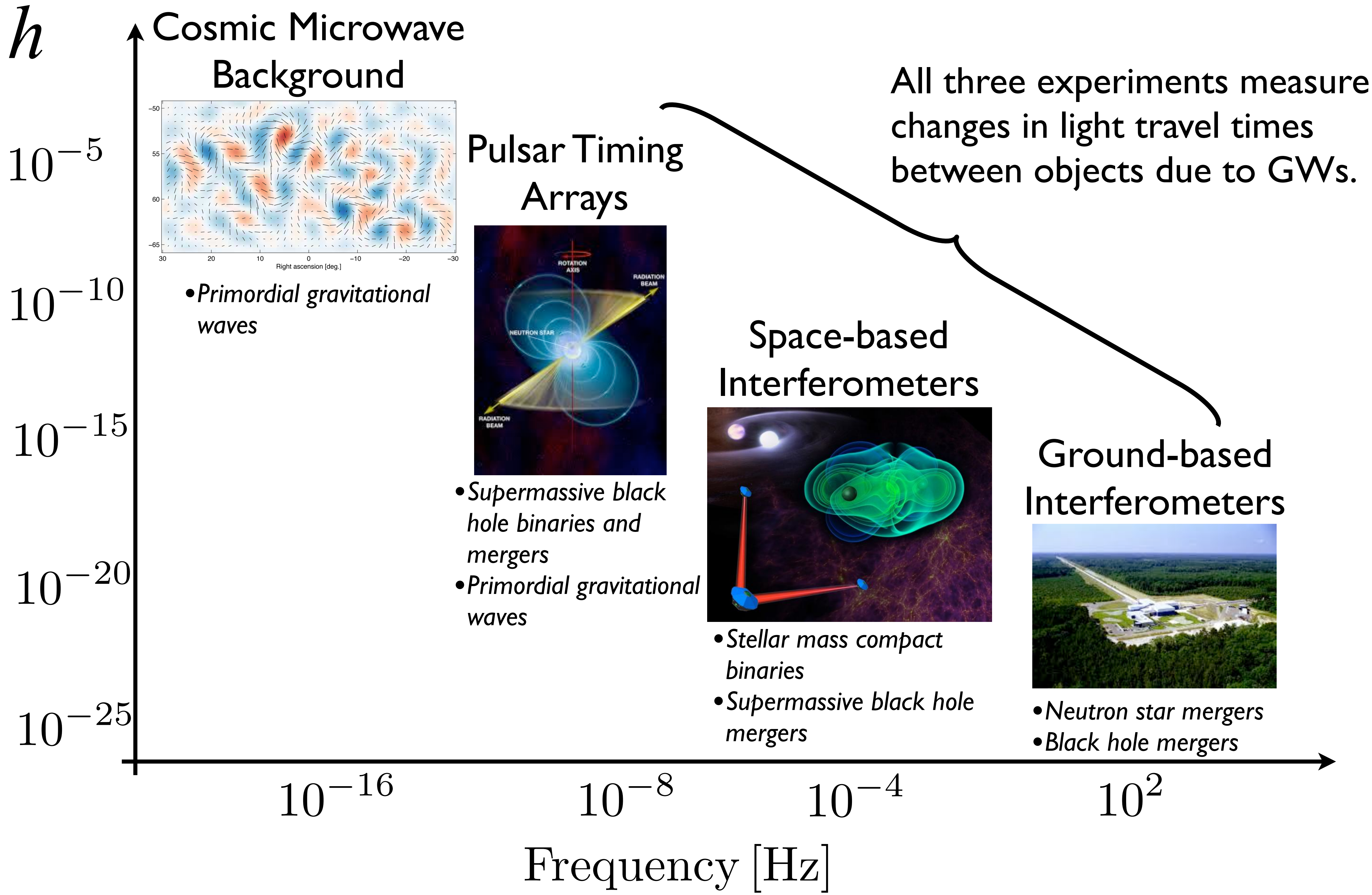
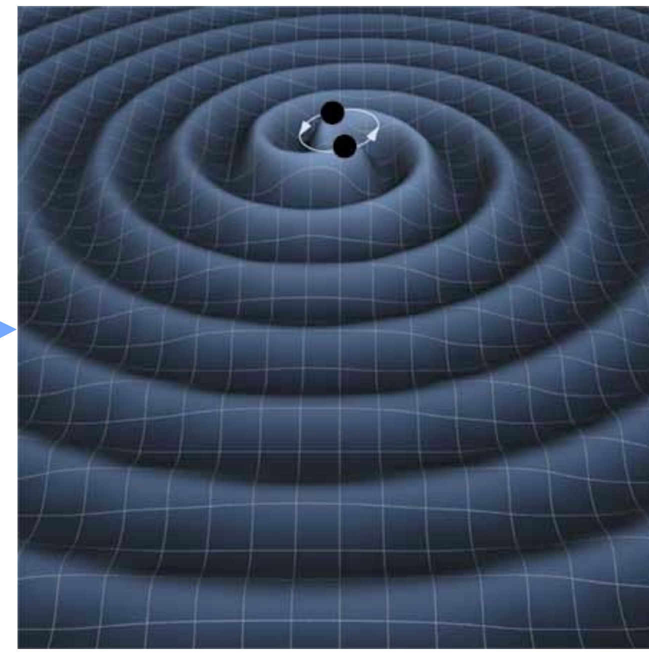
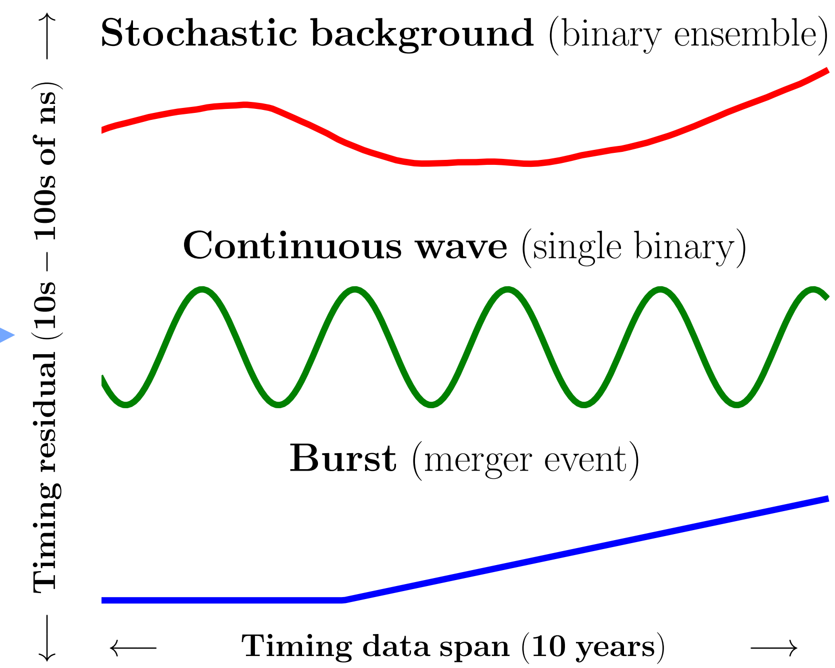
The spectrum of gravitational wave astronomy



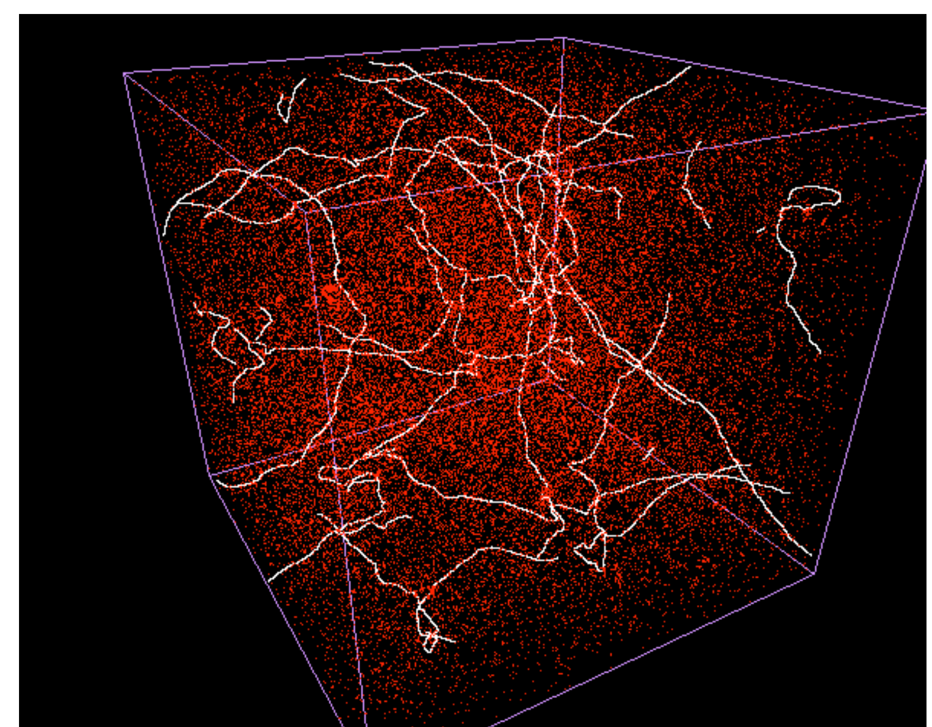
Gravitational wave sources

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

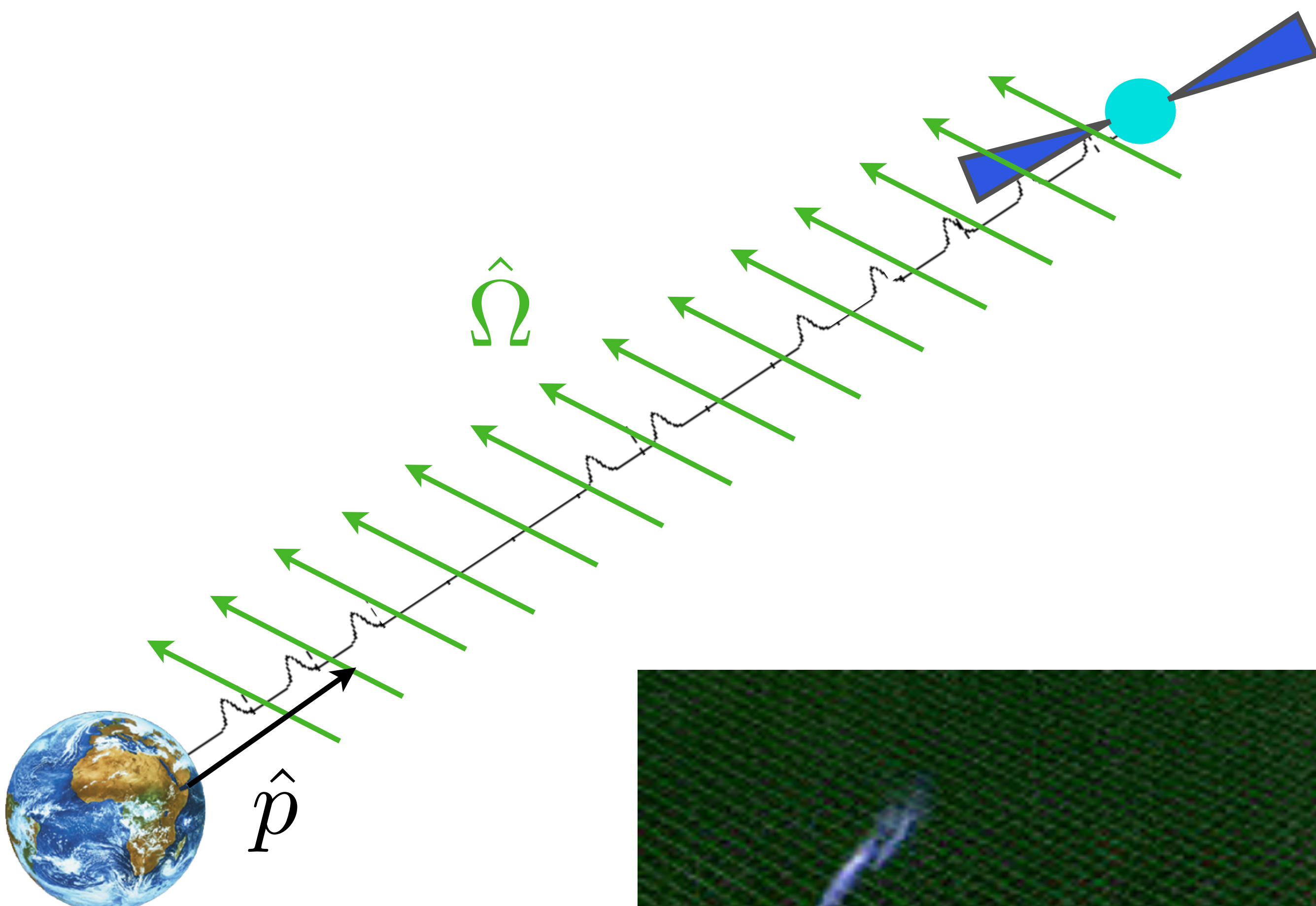




Other sources at nanohertz frequencies include cosmic strings, inflation, and phase transitions in the early universe.



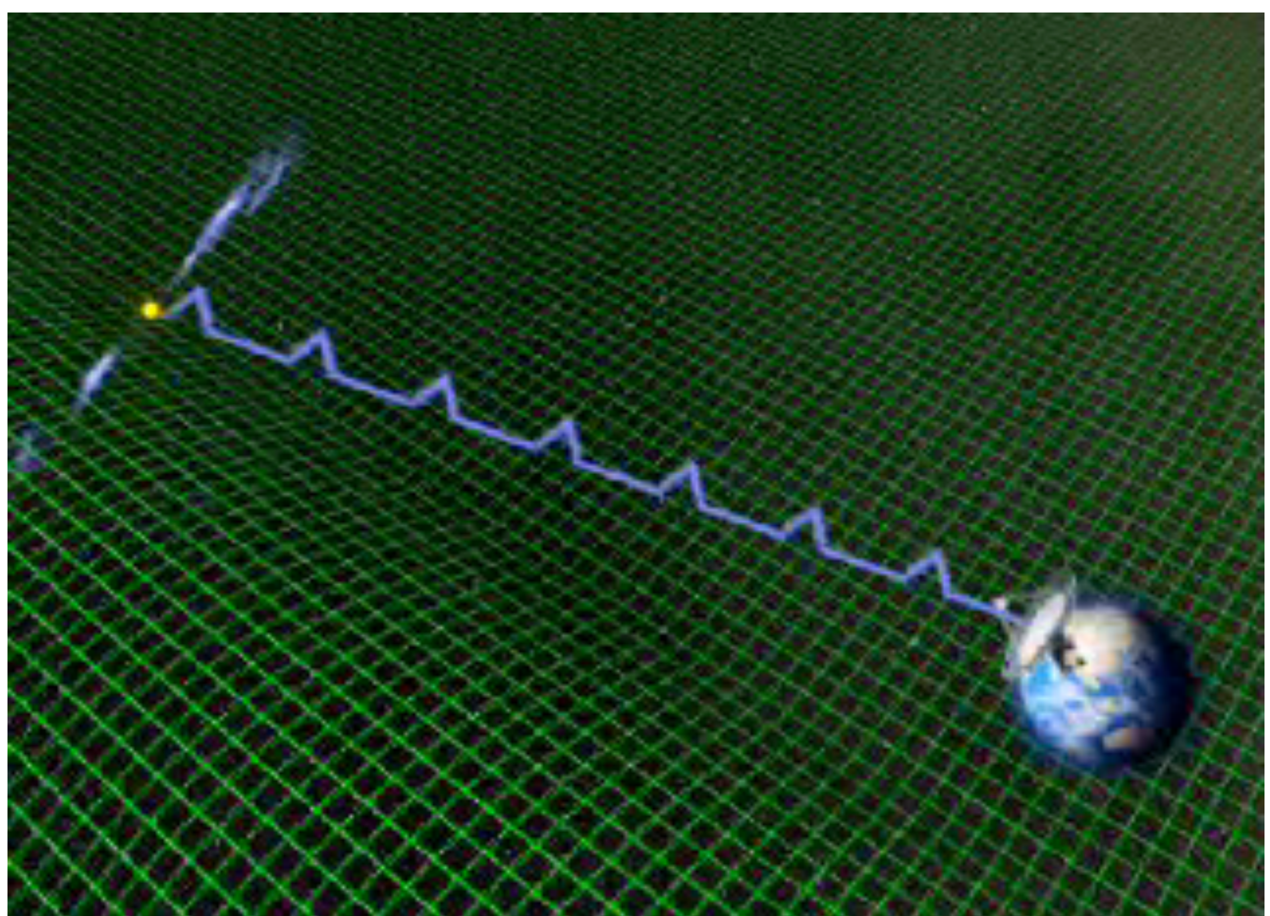
Effect of a gravitational wave on radio pulses



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

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

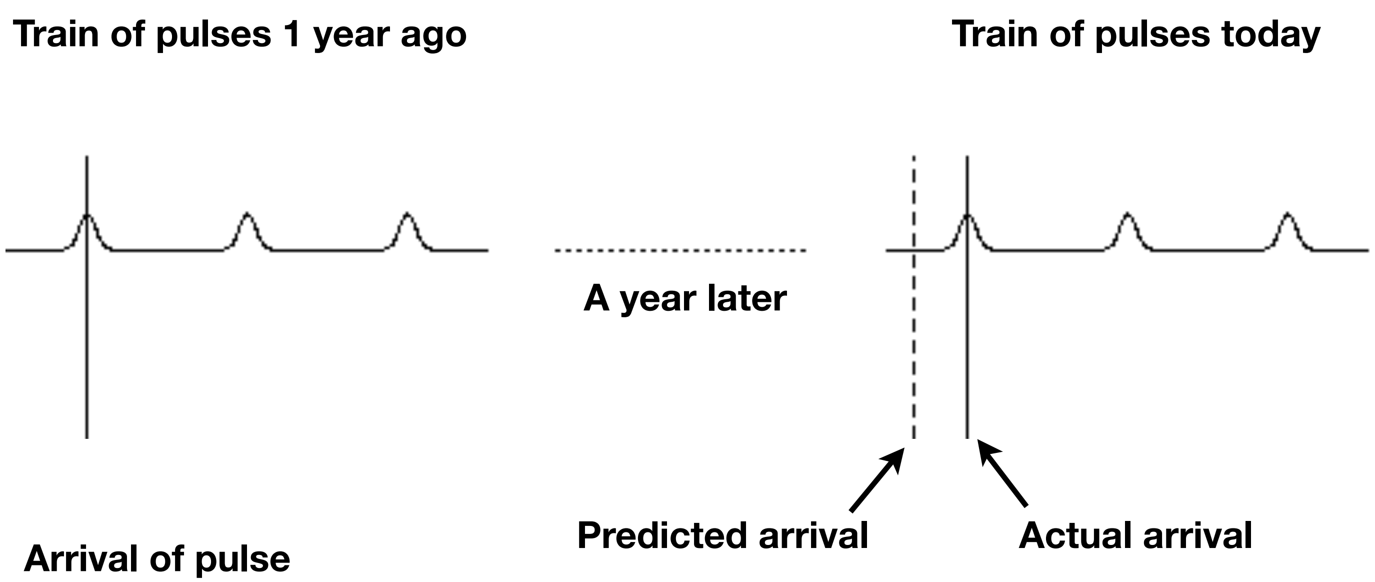
Sazhin (1978)
Detweiler (1979)
Anholm+ (2009)



Credit: John Rowe (Swinbourne)

Effect of a gravitational wave on radio pulses

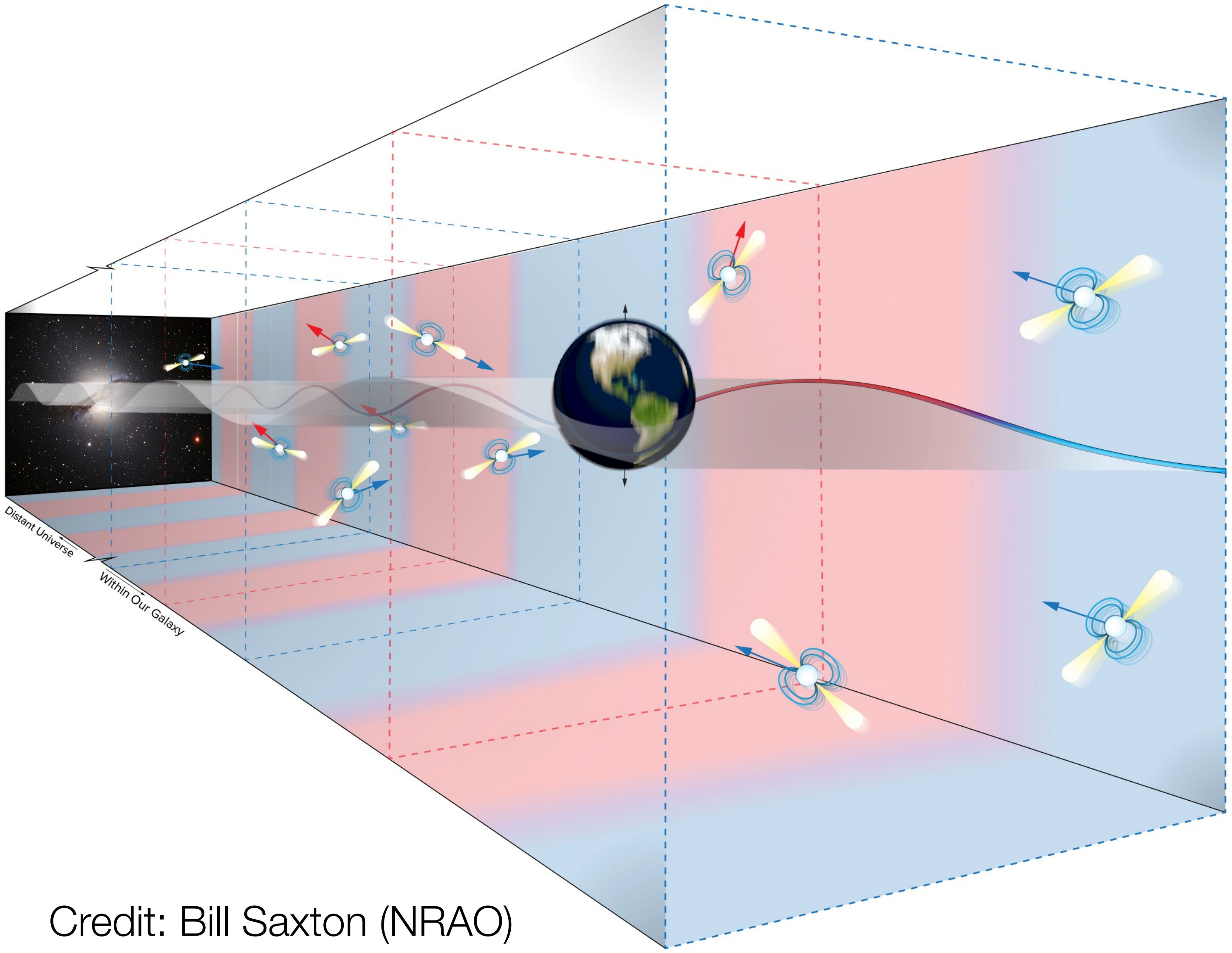
By keeping track of every rotation of the pulsar over the course of years, we can predict when a particular pulse from a pulsar will arrive at our radio telescope. The error in our prediction is called the pulsar timing residual.



Timing residual = Actual arrival - Predicted arrival

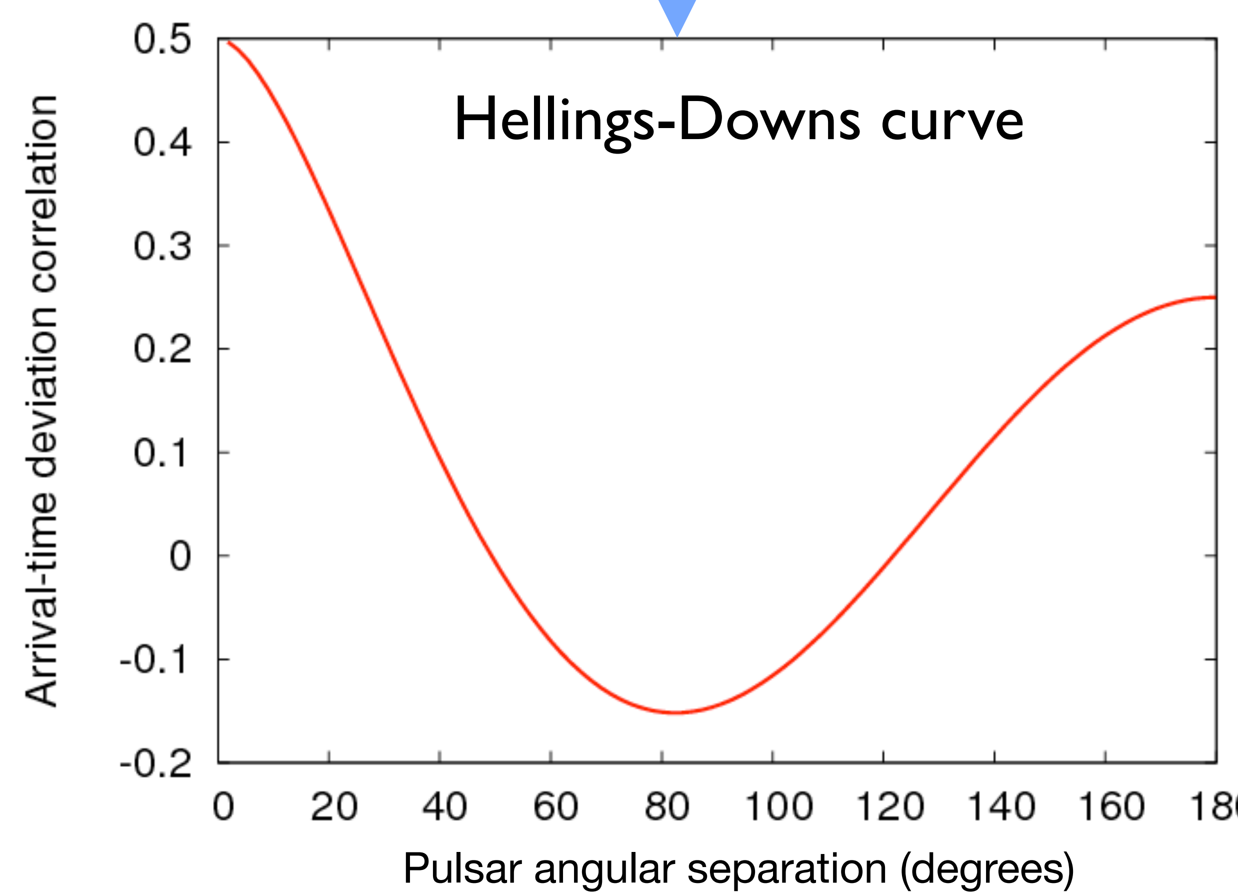
Gravitational waves change the time of arrival of pulses so we can look for gravitational waves in the timing residual data

A galactic-scale GW detector: the Pulsar Timing Array



Credit: Bill Saxton (NRAO)

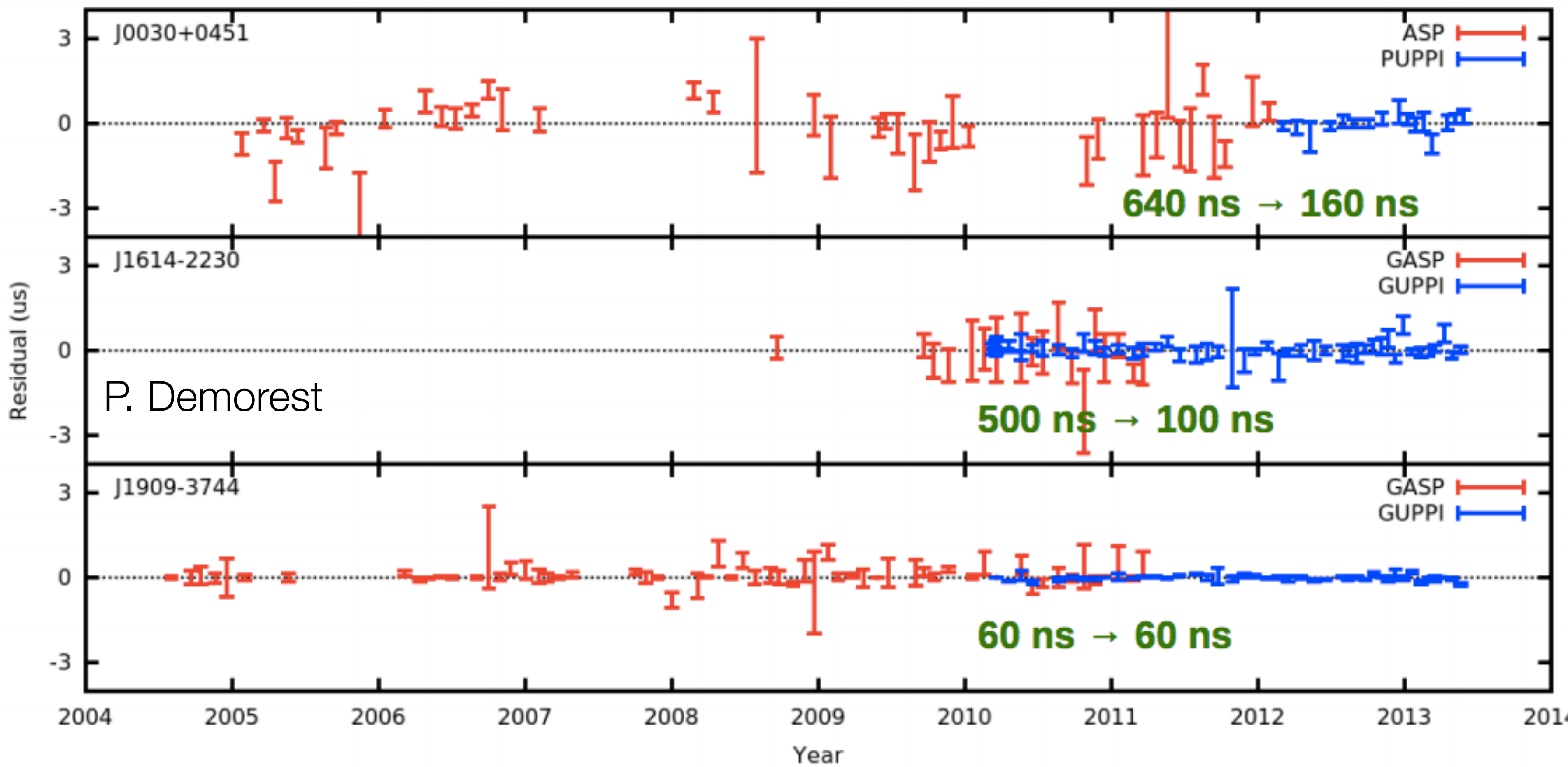
GW perturbations are correlated among different pulsars.



Need to observe an ensemble of MSPs to extract the correlated signal from the noise.

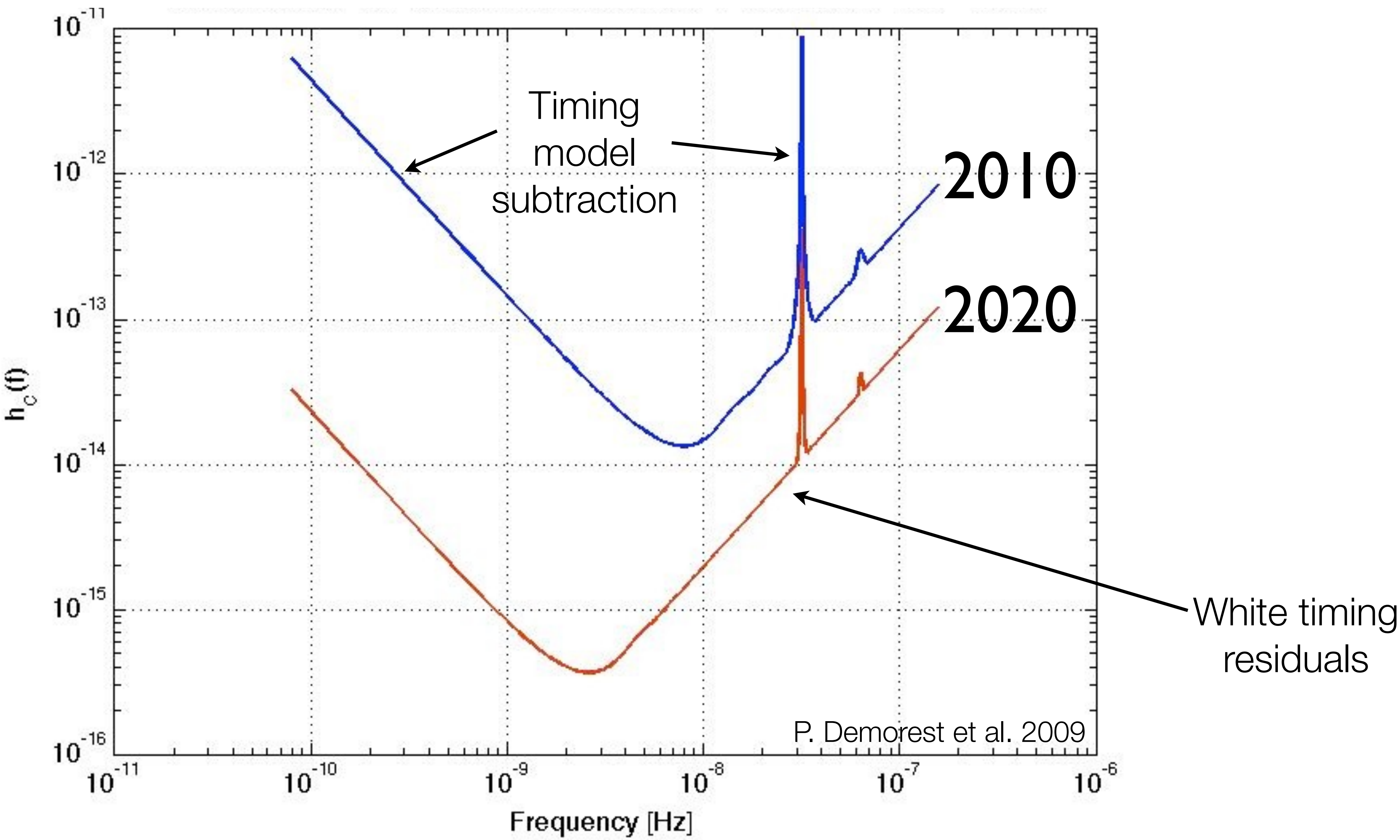
Pular timing experiments

- Can do these measurements very accurately, a few times a month for a few years



- Lowest frequency GW we're sensitive to set by observation length T
- Highest frequency by Nyquist theorem
- Data is irregularly sampled, has different size error bars... time domain methods better suited to analyze this type of data

Sensitivity



$\phi = \phi_0 + 2\pi\nu(t - t_0) + \pi\dot{\nu}(t - t_0)^2 +$ Sky location terms + binary terms (if appropriate) + ...

Where does $h \sim 10^{-15}$ come from?

- Pulsar timing experiments measure residuals not redshifts. Residuals induced by GWs are the integral of the redshift:

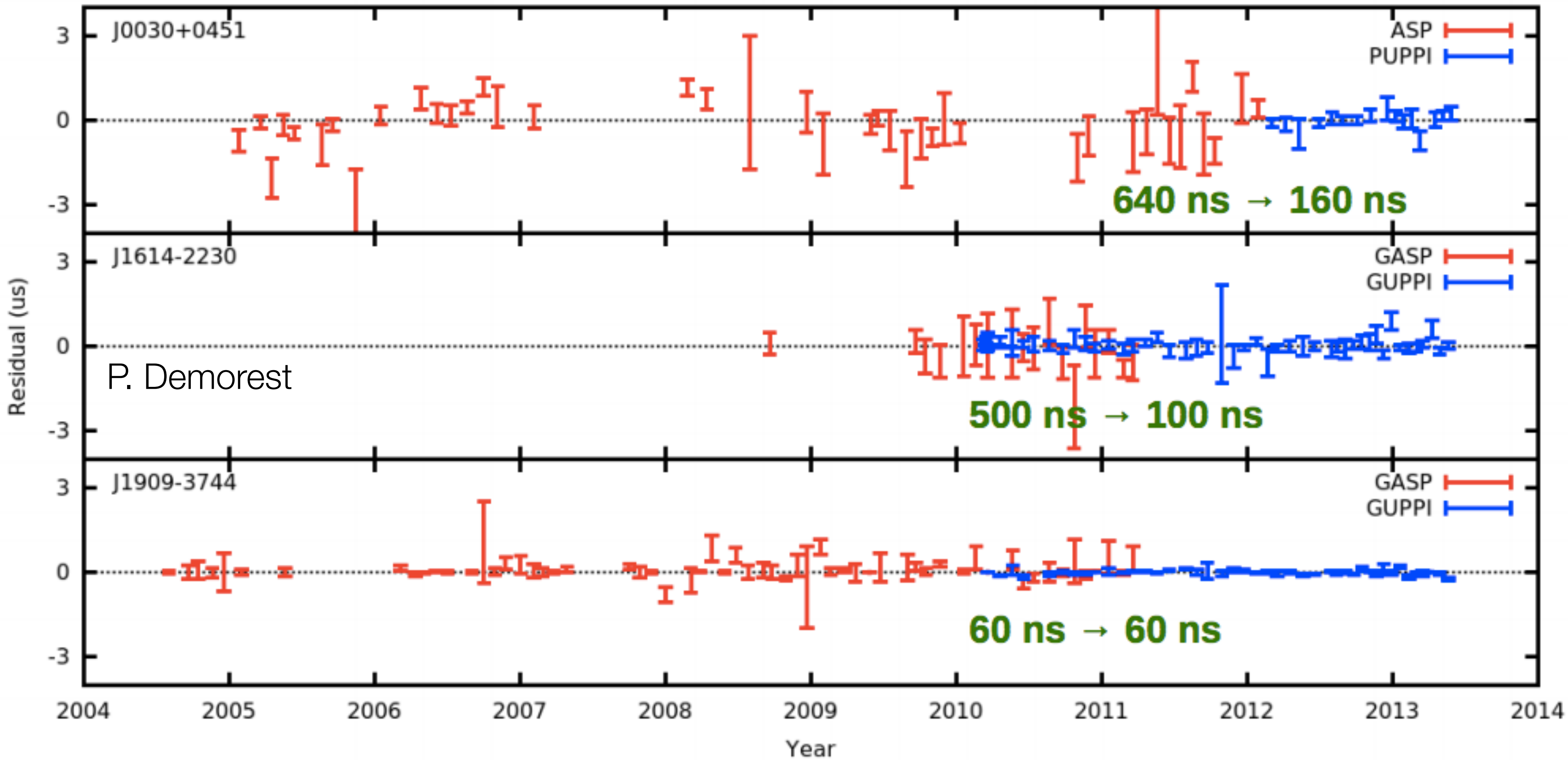
$$R(t) \equiv \int_0^t dt' \, z(t')$$

- In the frequency domain $R \sim \frac{h}{f}$

- Current RMS of timing residuals $R \sim 100 \, \mathrm{ns}$

- At GW frequencies $f \sim 10^{-8} \, \mathrm{Hz} \rightarrow h \sim Rf \sim 10^{-15}$

NANOGrav Observing Strategy

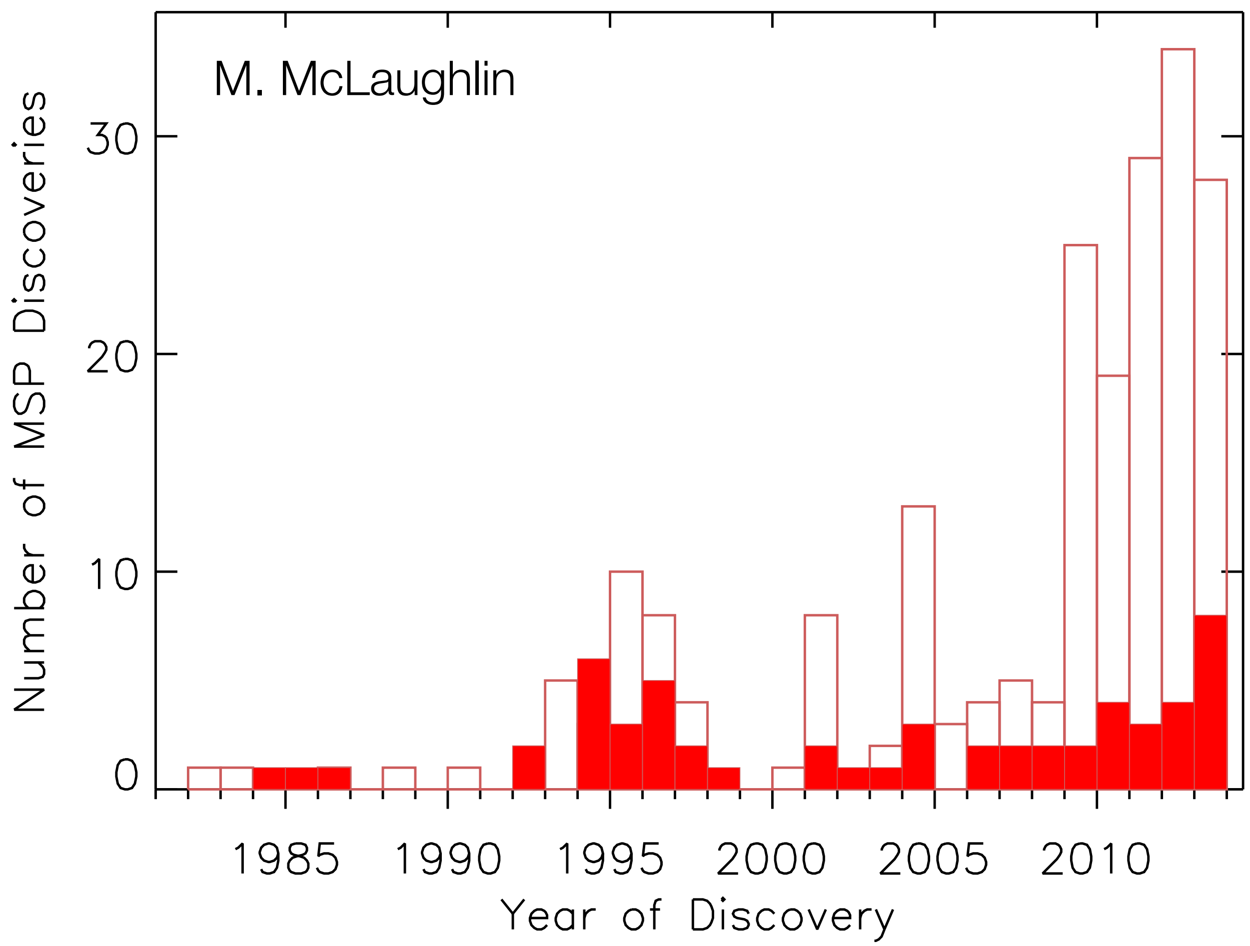


We currently observe 67 MSPs at the GBT and Arecibo, roughly every three weeks, at two radio frequencies. High cadence program for 5-6 MSPs. Add ~4 MSPs per year.

We use roughly 10%-20% of the time on each telescope.

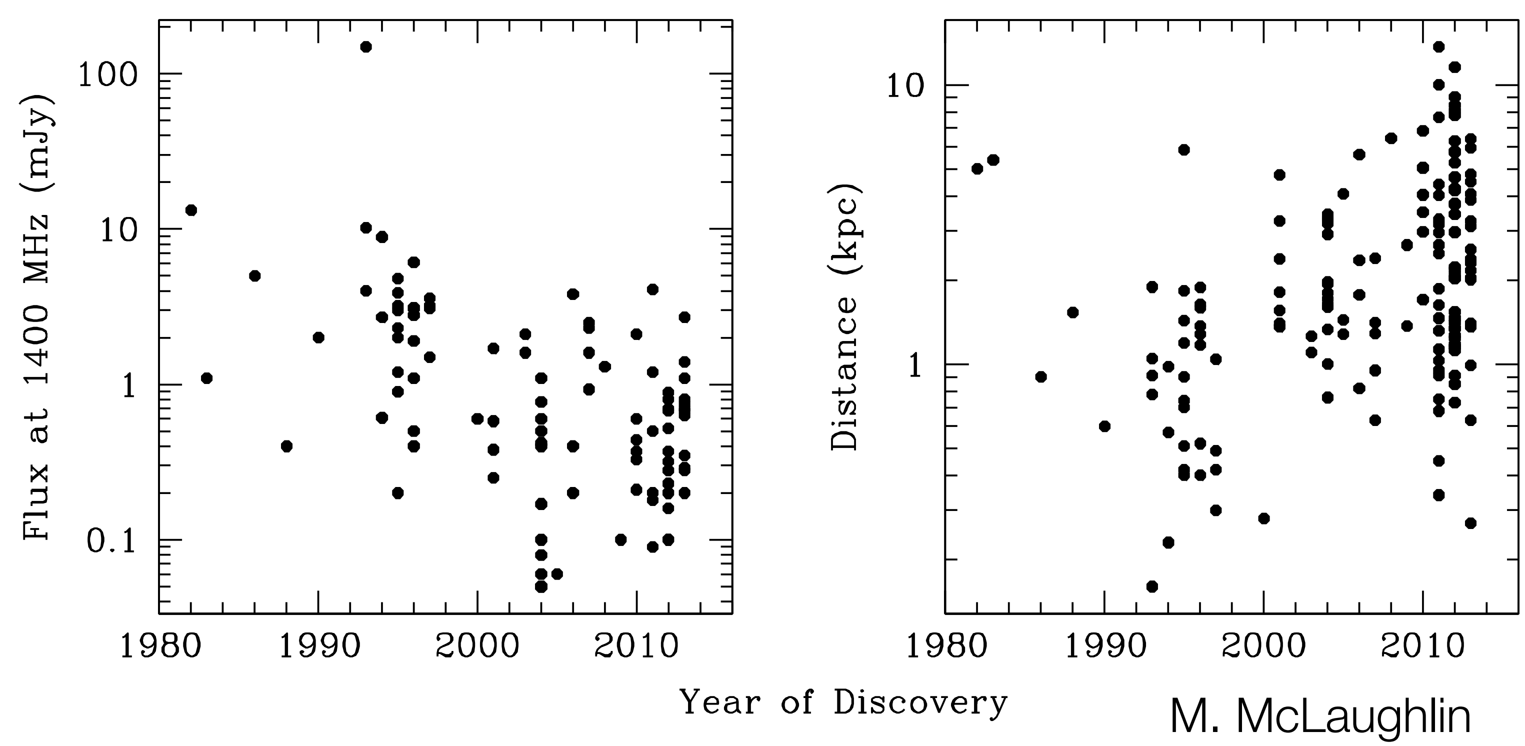
GW data analysis is a challenging astrostatistics problem.

Haven't you found all the pulsars already?



Radio searches (aided by *Fermi* gamma-ray identifications) have ***more than doubled*** the Galactic MSP population since 2010. Ongoing searches with the world's largest telescopes should reveal an additional 100 over the next several years.

Many bright and nearby MSPs remain to be found, meaning increases in our sensitivity are still possible.



NANOGrav Activities/Goals

GW detector construction and characterization

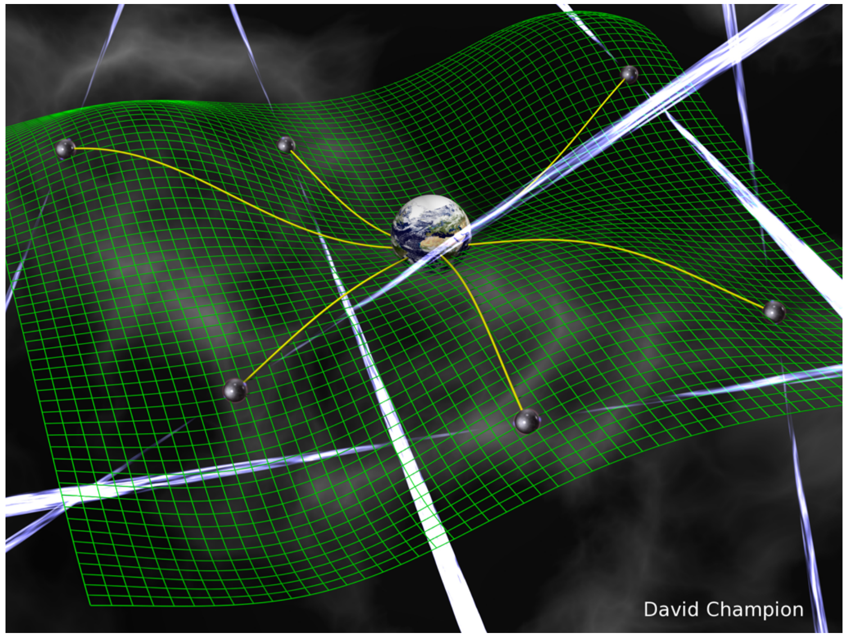
- Find additional MSPs to increase our sensitivity
- More efficient/sensitive pulsar searches
- Fully characterized low-frequency GW detector

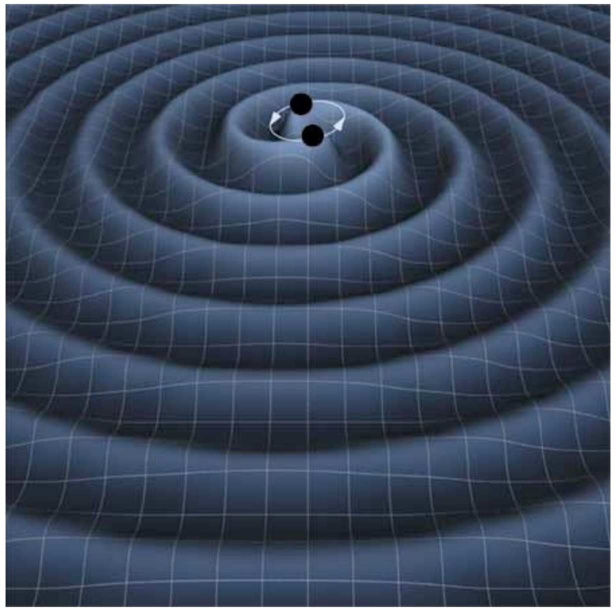
GW data set generation and curation

- 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





About our work

Work is truly interdisciplinary. Requires detailed understanding of:

- GW signals and their sources
- properties of neutron stars, our celestial clocks
- propagation of pulses through the interstellar medium
- characteristics of the radio telescopes
- software designed to make the measurements
- algorithms for GW searches
- searching for additional pulsars
- the long term curation of the data products

work **requires** close collaboration of:

- theorists
- data analysts
- cosmologists
- SMBBH astrophysicists
- NS astrophysicists
- radio astronomers
- cyber-I experts

This makes the work a lot of fun!

Data analysis

For a Gaussian (noise) process y

$$p(y) = \frac{1}{\sqrt{\det(2\pi\Sigma)}} \exp(-\frac{1}{2} y^T \Sigma^{-1} y)$$

$\Sigma = \langle y^T y \rangle$ is the covariance matrix, typically computed from inverse Fourier transform of power spectrum

If we make a measurement $r = s + y$

The probability obtaining r given a signal s is present in our data is

$$p(\mathbf{r}|\mathbf{s}) = \frac{1}{\sqrt{\det 2\pi\mathbf{\Sigma}}} \exp\left(-\frac{1}{2}(\mathbf{r}-\mathbf{s})^T \mathbf{\Sigma}^{-1}(\mathbf{r}-\mathbf{s})\right) \quad (y = r - s)$$

I.e. the probability that there's a signal in the data, is the probability that what you're left with when you've subtracted the signal off is consistent with the noise process y

Data analysis

In pulsar timing experiments we use pulsars as clocks, keeping track of the rotational phase for many years. Residuals are generated by starting with times of arrival TOA (the phase of the pulsar) of pulses and subtracting out a model

$$\phi = \phi_0 + 2\pi\nu(t - t_0) + \pi\dot{\nu}(t - t_0)^2 + \text{Sky location terms + binary terms (if appropriate) + ...}$$

$$\mathrm{TOA} = \mathrm{model} + y$$

Gaussian process: Intrinsic red and white noise + GWs +...

This model subtraction can be performed by projecting out the model piece of the TOA with a linear operator R (see Numerical Recipes -- least squares fitting chapter)

$$r = R\,\mathrm{TOA} = R(\mathrm{model} + y) = Ry$$

Data analysis

The projector is constructed from the basis functions of the model being fitted out:

$$R = I - A(A^T A)^{-1} A^T$$

For example for quadratic subtraction (fitting for initial phase, frequency, and spindown):

$$A = \begin{bmatrix} 1 & t_0 & t_0^2 \\ 1 & t_1 & t_1^2 \\ \vdots & \vdots & \vdots \\ 1 & t_N & t_N^2 \end{bmatrix}$$

Since y is a Gaussian process we can write the standard likelihood for a Gaussian:

$$p(y) = \frac{1}{\sqrt{\det(2\pi\Sigma_y)}} \exp(-\frac{1}{2} y^T \Sigma_y^{-1} y)$$

Can perform the transformation $y \rightarrow r = Ry$

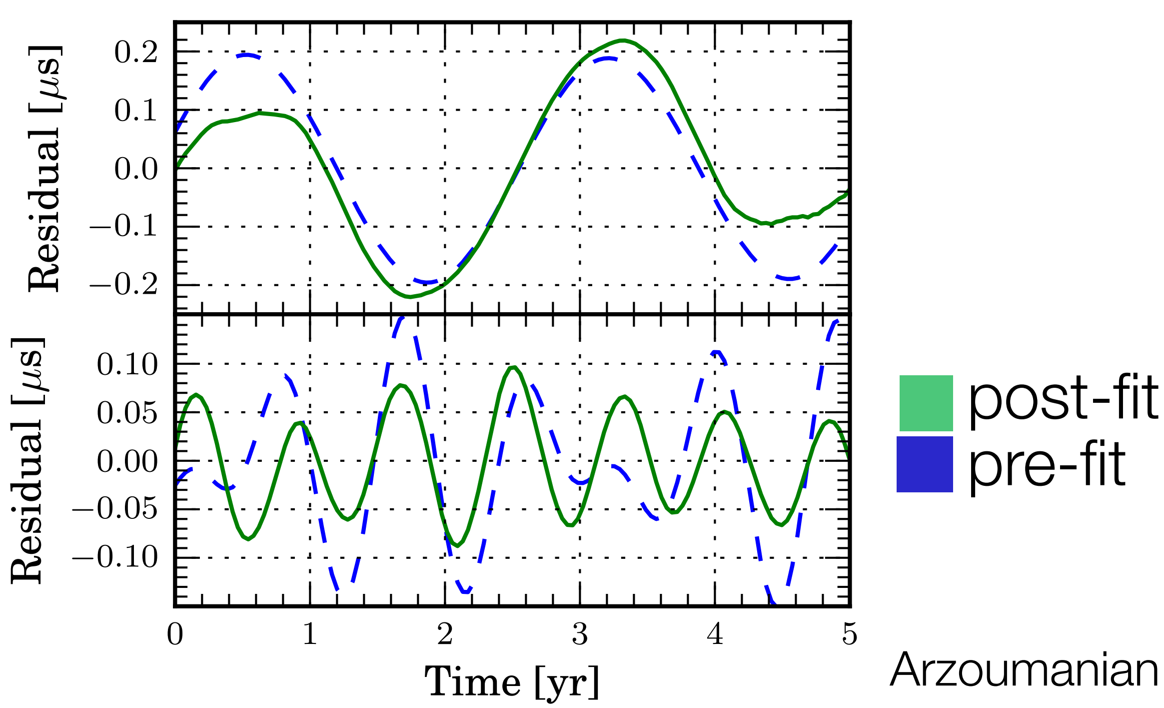
$$p(r) = \frac{1}{\sqrt{\det(2\pi\Sigma_r)}} \exp(-\frac{1}{2} r^T \Sigma_r^{-1} r) \qquad \Sigma_r = R^T \Sigma_y R$$

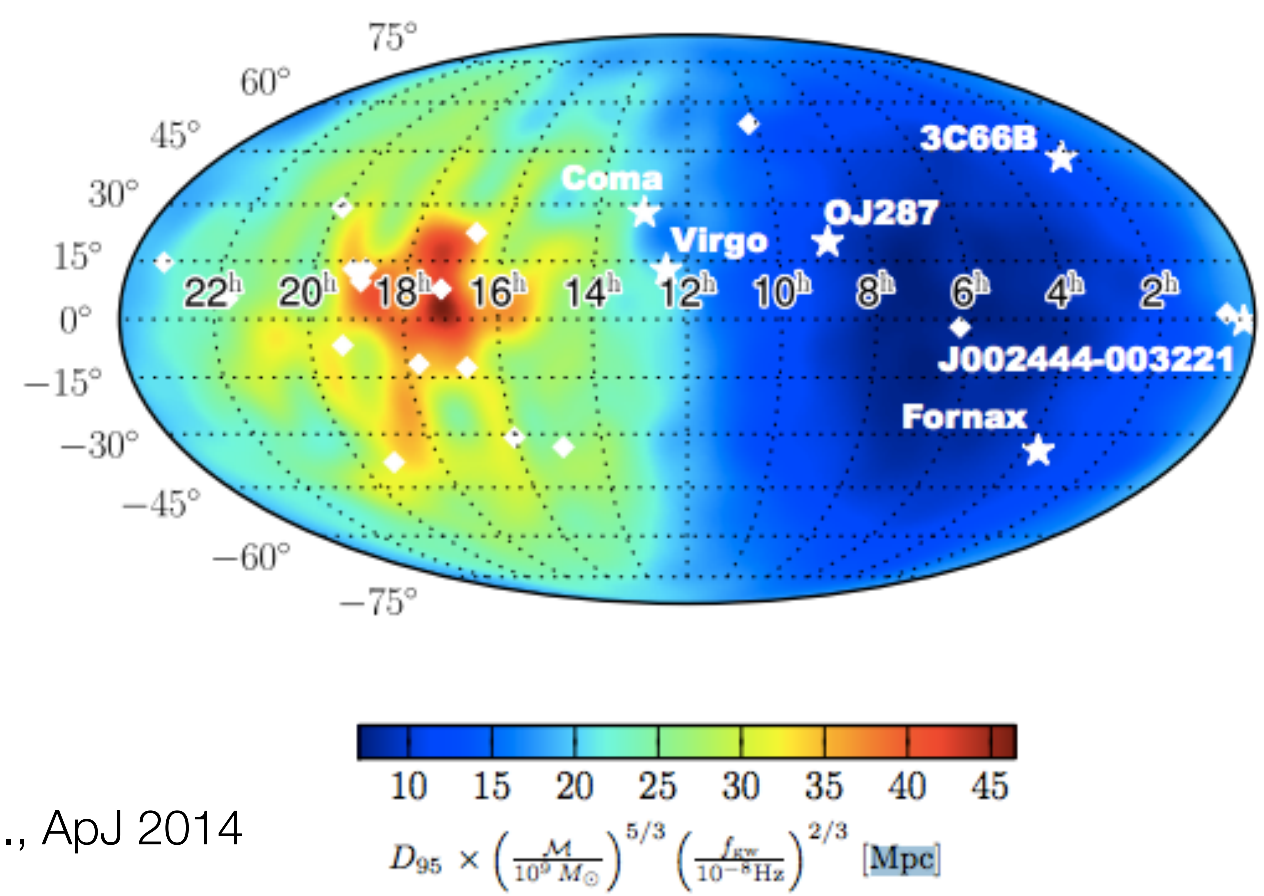
Continuous wave (or other templated) searches

$$p(\mathbf{r}|\mathbf{s}) = \frac{1}{\sqrt{\det 2\pi\mathbf{\Sigma}}} \exp\left(-\frac{1}{2}(\mathbf{r}-\mathbf{s})^T\mathbf{\Sigma}^{-1}(\mathbf{r}-\mathbf{s})\right)$$

Vector of vectors: $\mathbf{r} = \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \\ \vdots \\ \mathbf{r}_l \end{bmatrix}$ Matrix of matrices: $\mathbf{\Sigma} = \begin{bmatrix} \mathbf{P}_1 & 0 & \cdots & 0 \\ 0 & \mathbf{P}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{P}_l \end{bmatrix}$

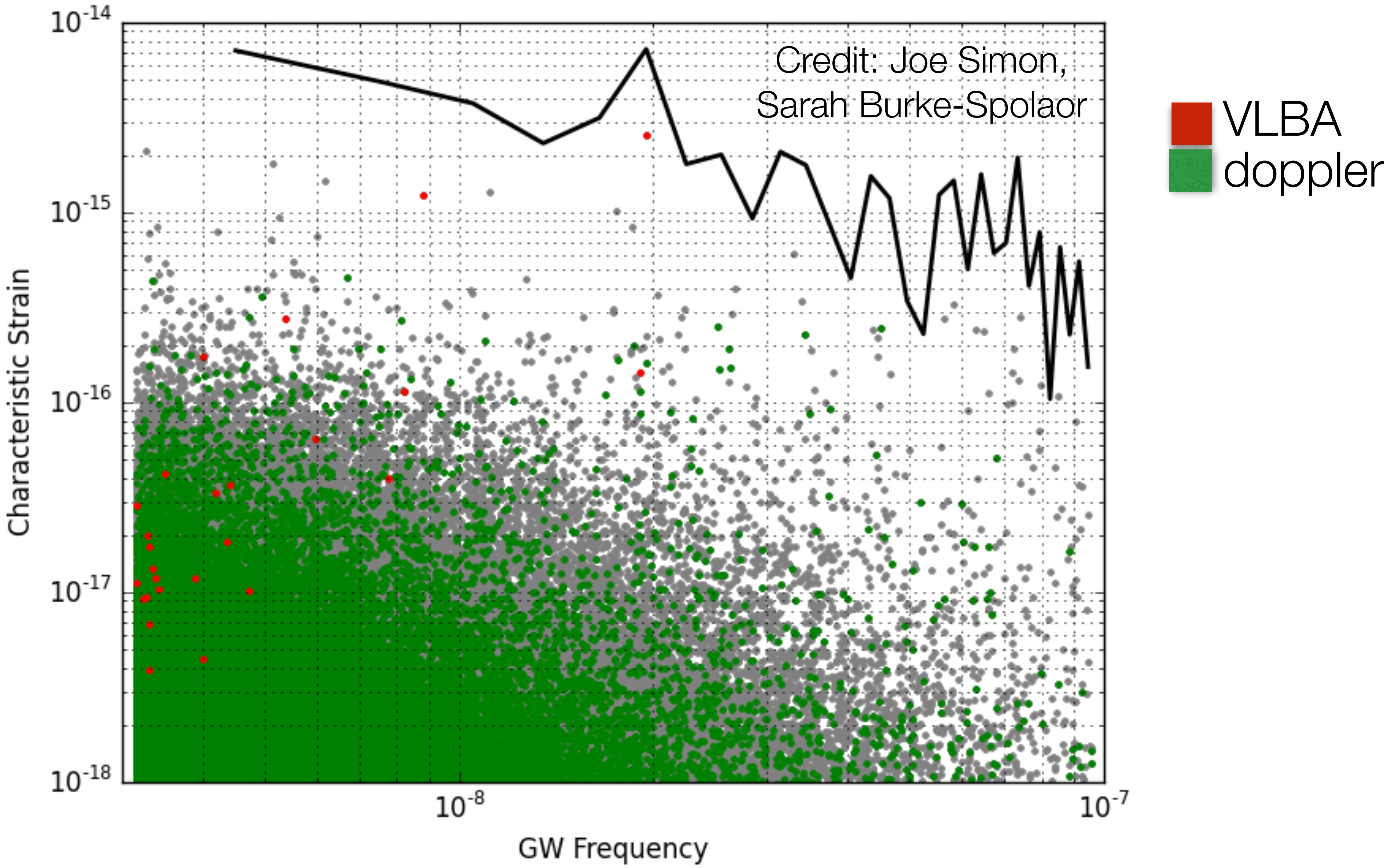
Effects of fitting on the template are important:



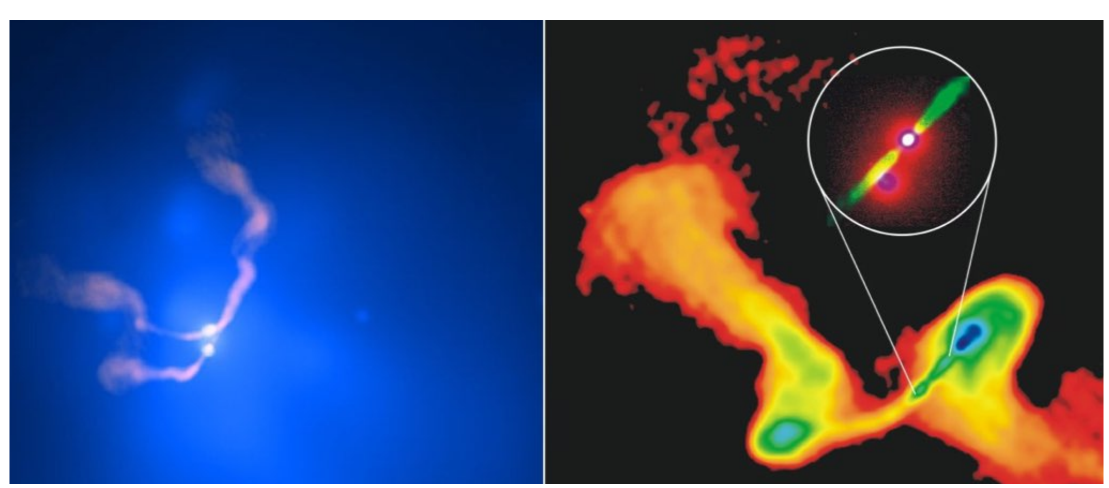


Arzoumanian et al., ApJ 2014

Continuous wave (or other templated) searches



Exciting multi-messenger astronomy potential



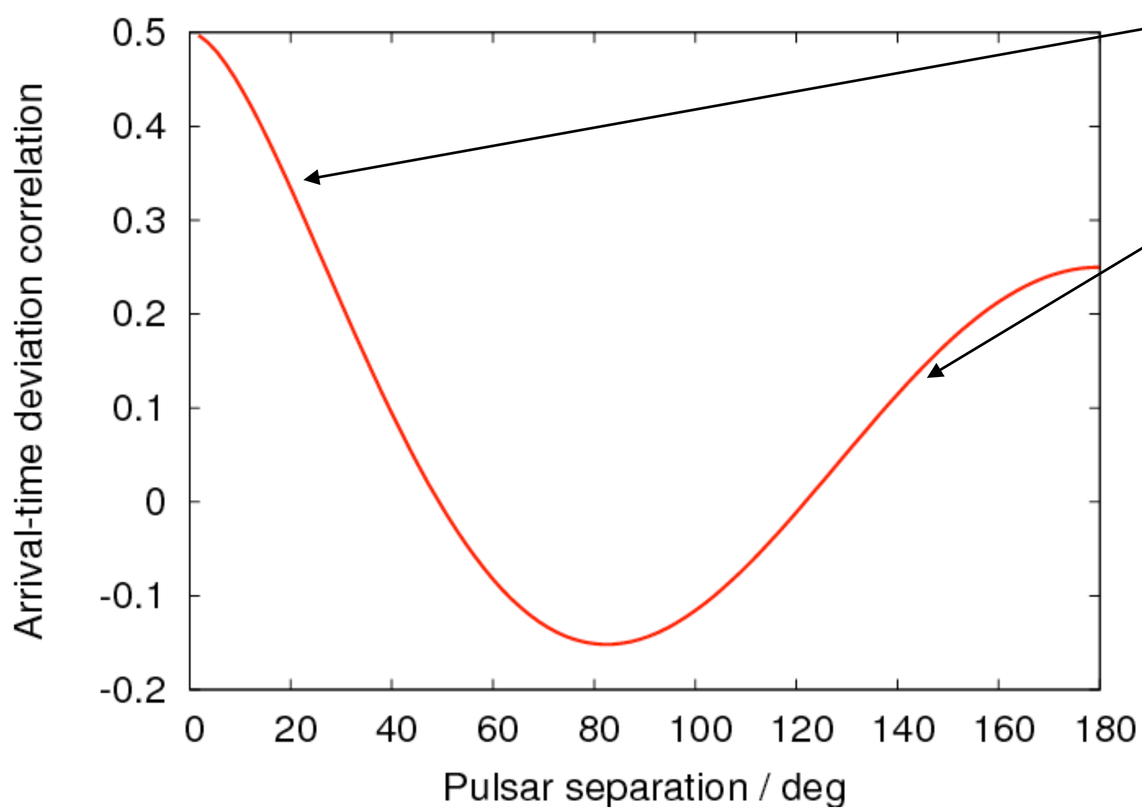
Stochastic backgrounds

$$p(\mathbf{r}|\vec{\theta}) = \frac{1}{\sqrt{\det 2\pi \mathbf{\Sigma}(\vec{\theta})}} \exp\left(-\frac{1}{2}\mathbf{r}^T \mathbf{\Sigma}^{-1}(\vec{\theta})\mathbf{r}\right)$$

Residuals $\mathbf{r} = \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \\ \vdots \\ \mathbf{r}_l \end{bmatrix}$

The signal in this case is in the covariance matrix $\mathbf{\Sigma}(\vec{\theta})$

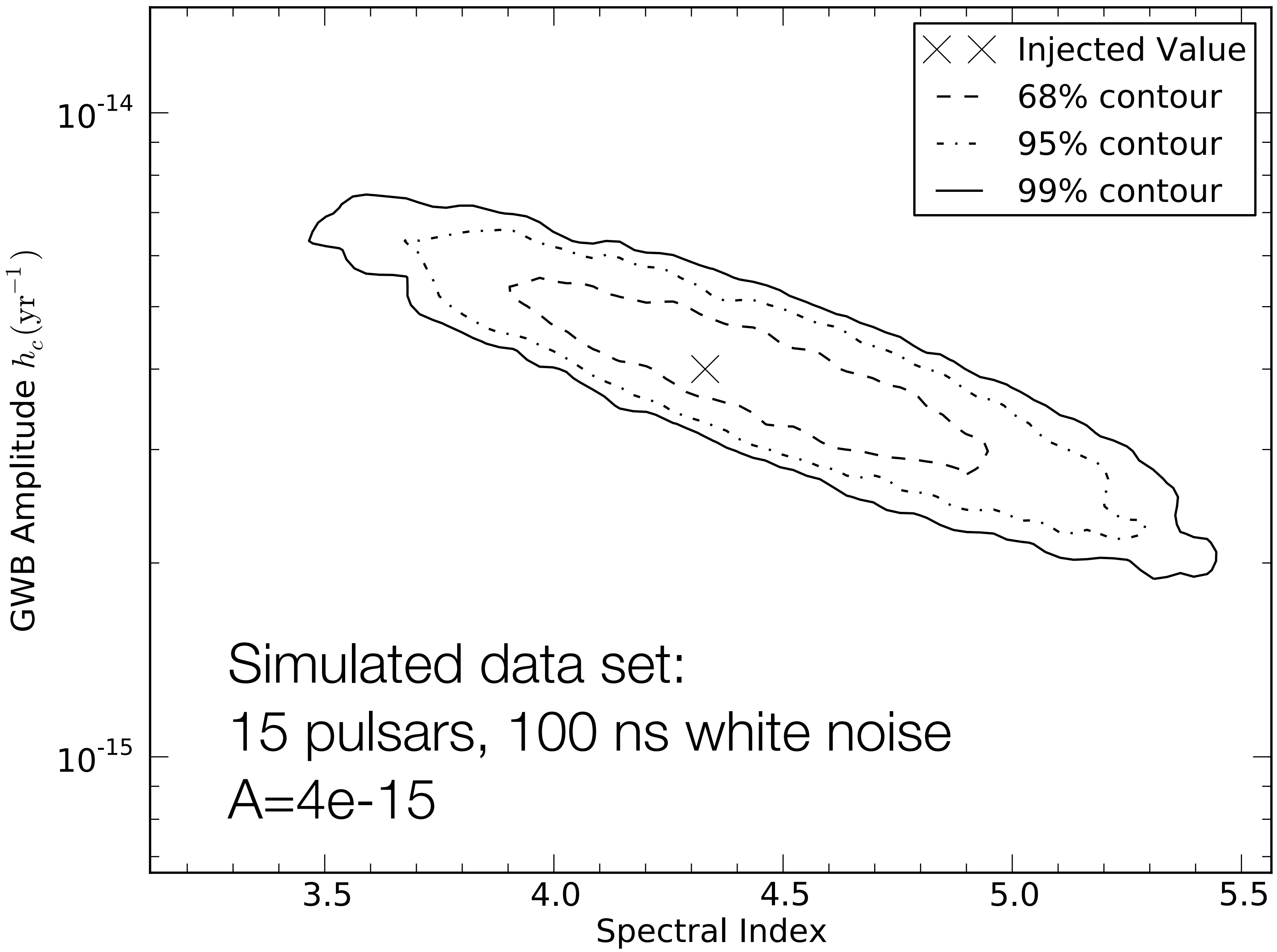
Covariance matrix for residuals $\mathbf{\Sigma}(\vec{\theta}) = \langle \mathbf{r}\mathbf{r}^T \rangle = \begin{bmatrix} \mathbf{P}_1 & \mathbf{S}_{12} & \cdots & \mathbf{S}_{1l} \\ \mathbf{S}_{21} & \mathbf{P}_2 & \cdots & \mathbf{S}_{2l} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{S}_{l1} & \mathbf{S}_{l2} & \cdots & \mathbf{P}_l \end{bmatrix}$



Stochastic backgrounds

$$p(\mathbf{r}|\vec{\theta}) = \frac{1}{\sqrt{\det 2\pi \mathbf{\Sigma}(\vec{\theta})}} \exp\left(-\frac{1}{2}\mathbf{r}^T \mathbf{\Sigma}^{-1}(\vec{\theta})\mathbf{r}\right)$$

$$\vec{\theta} = (\text{GWB Amplitude, Spectral Index})$$



Ellis, van Haasteren, XS, ApJ 2014

Latest observational results

NANOGrav data releases

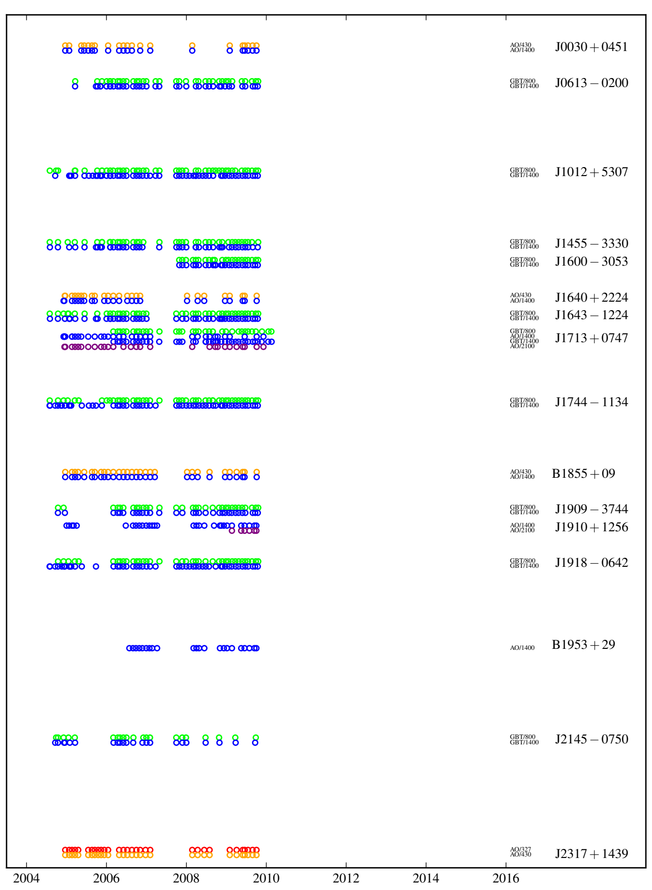
5-yr: 2005-2010

17 pulsars

RMSs between 40 ns and 1 us

No significant GW signal. Set upper limit:

$$h_c < 7 \times 10^{-15}$$



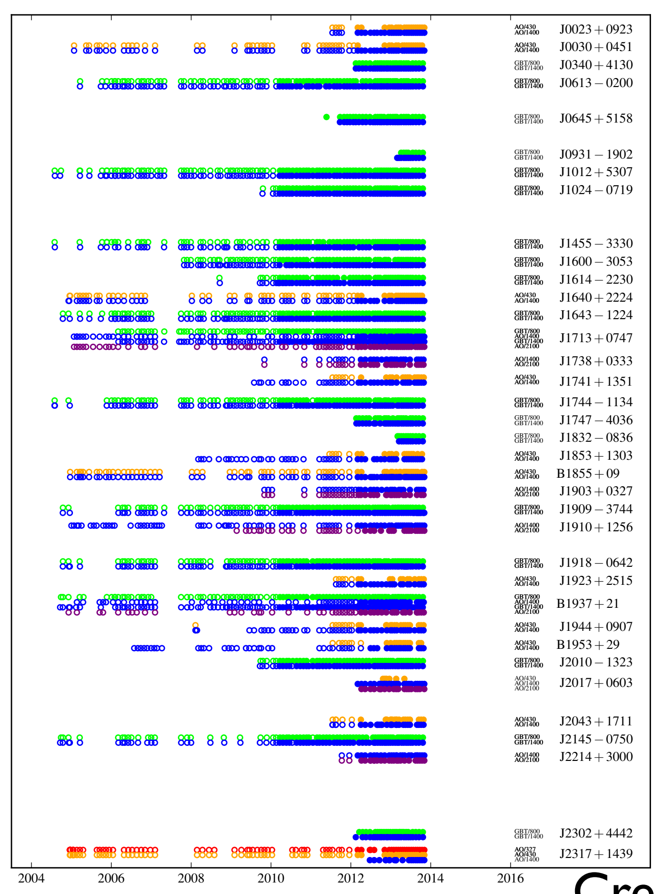
9-yr: 2005-2014

37 pulsars

Improved instrumentation, RMS improvement a factor of 2–3 for most pulsars.

New upper limit:

$$h_c < 1.5 \times 10^{-15}$$



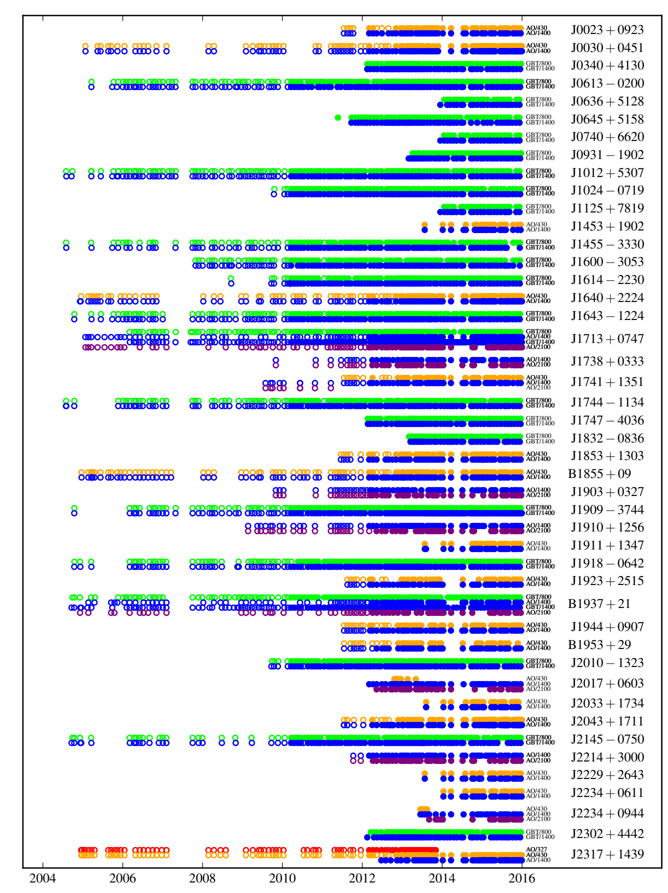
11-yr: 2005-2016

45 pulsars (IN PROGRESS)

Preliminary upper limit shows no improvement over the 9-year data:

$$h_c < 1.5 \times 10^{-15}$$

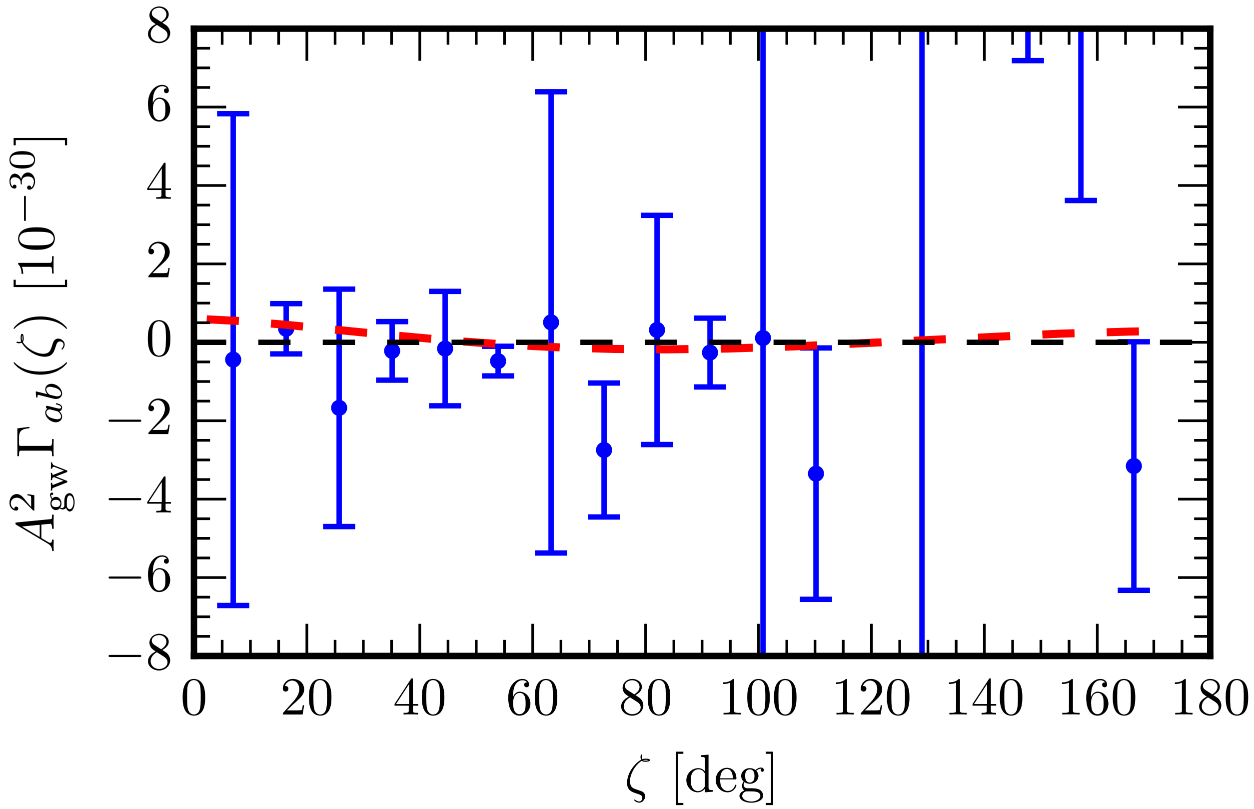
What's going on here???



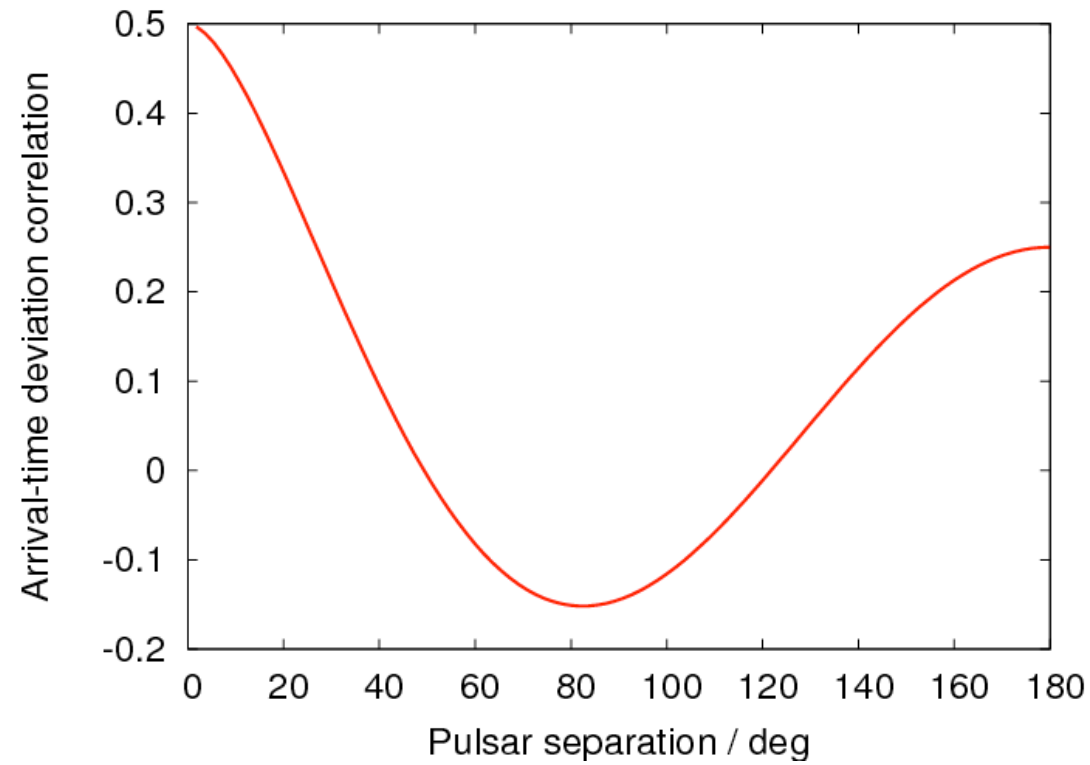
Credit: David Nice

Isotropic stochastic backgrounds (9-yr data set)

Arzoumanian et al. 2015



vs



Cross-correlated power vs. angular separation.

The dashed red curve shows the maximum likelihood amplitude mapped onto the Hellings and Downs coefficients. SNR of cross-correlation is 1.5

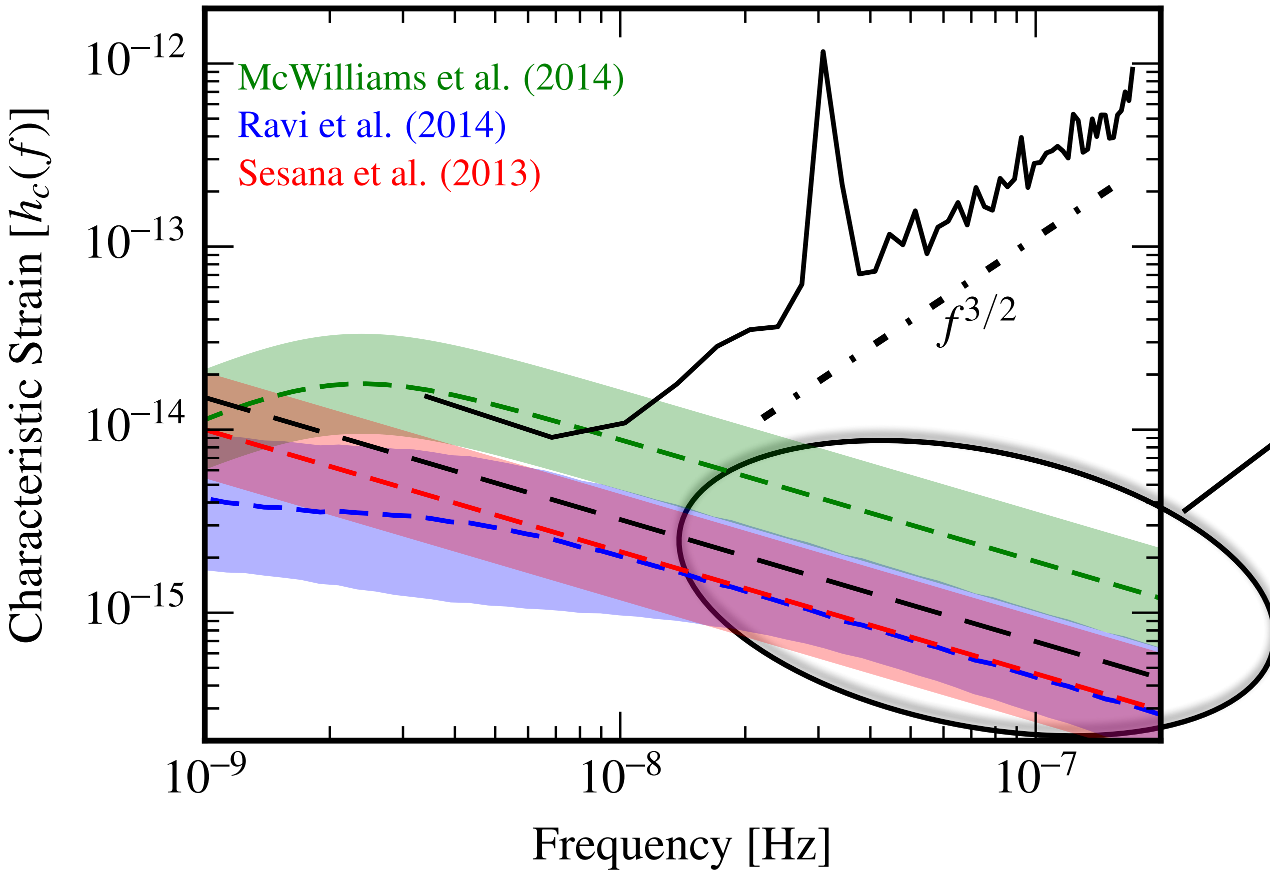
Did not make a significant detection, so we set upper limits.

NANOGrav postdocs and students involved:

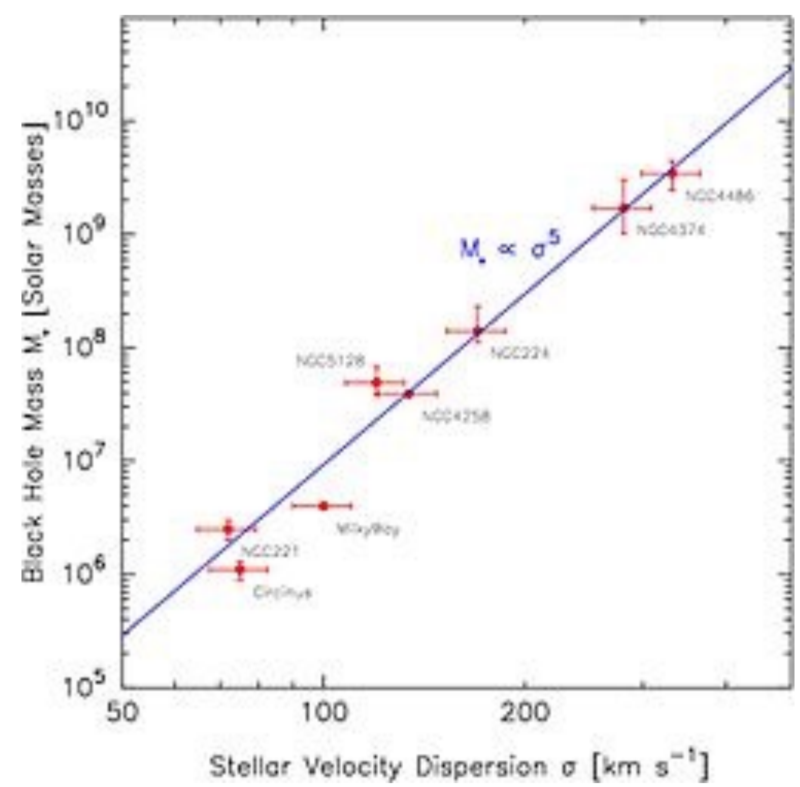
Sarah Burke-Spolaor
Justin Ellis
Chiara Mingarelli
Laura Sampson
Joe Simon
Steve Taylor
Rutger van Haasteren

Stochastic backgrounds—astrophysical inference

Arzoumanian et al. 2015

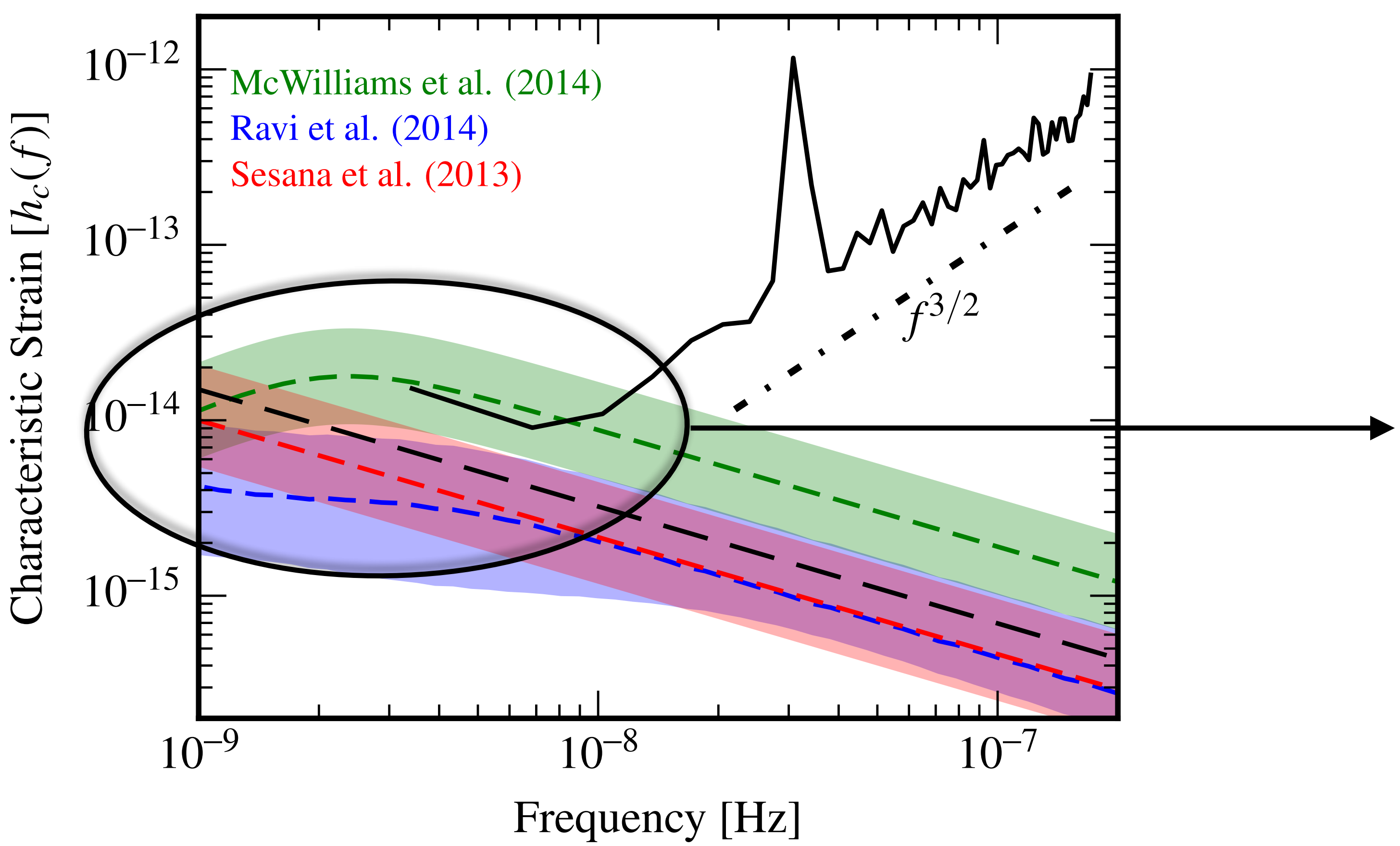


- High frequencies (when black holes are close) dominated by GW emission so spectrum determined by:
  - Galaxy Merger Rates
  - Stalling fraction
  - Black hole-host correlations (i.e., M-sigma, M-M_bulge)

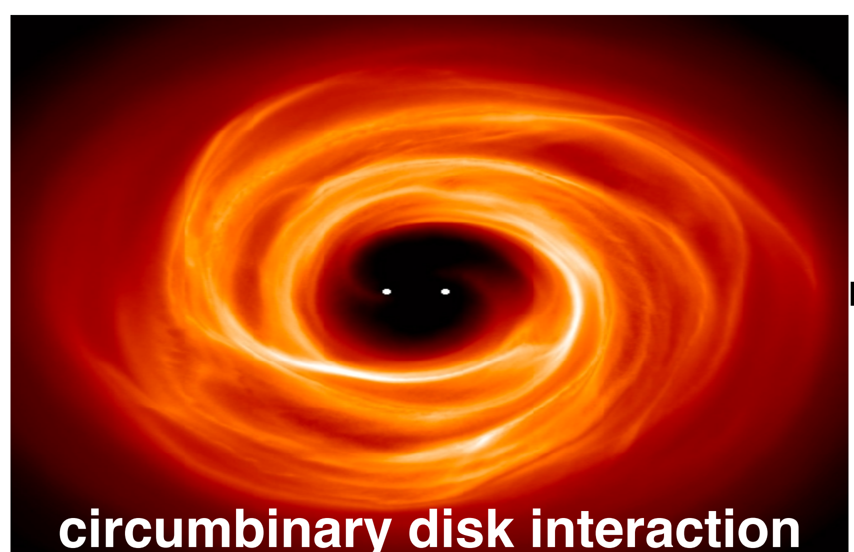


Stochastic backgrounds—astrophysical inference

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!

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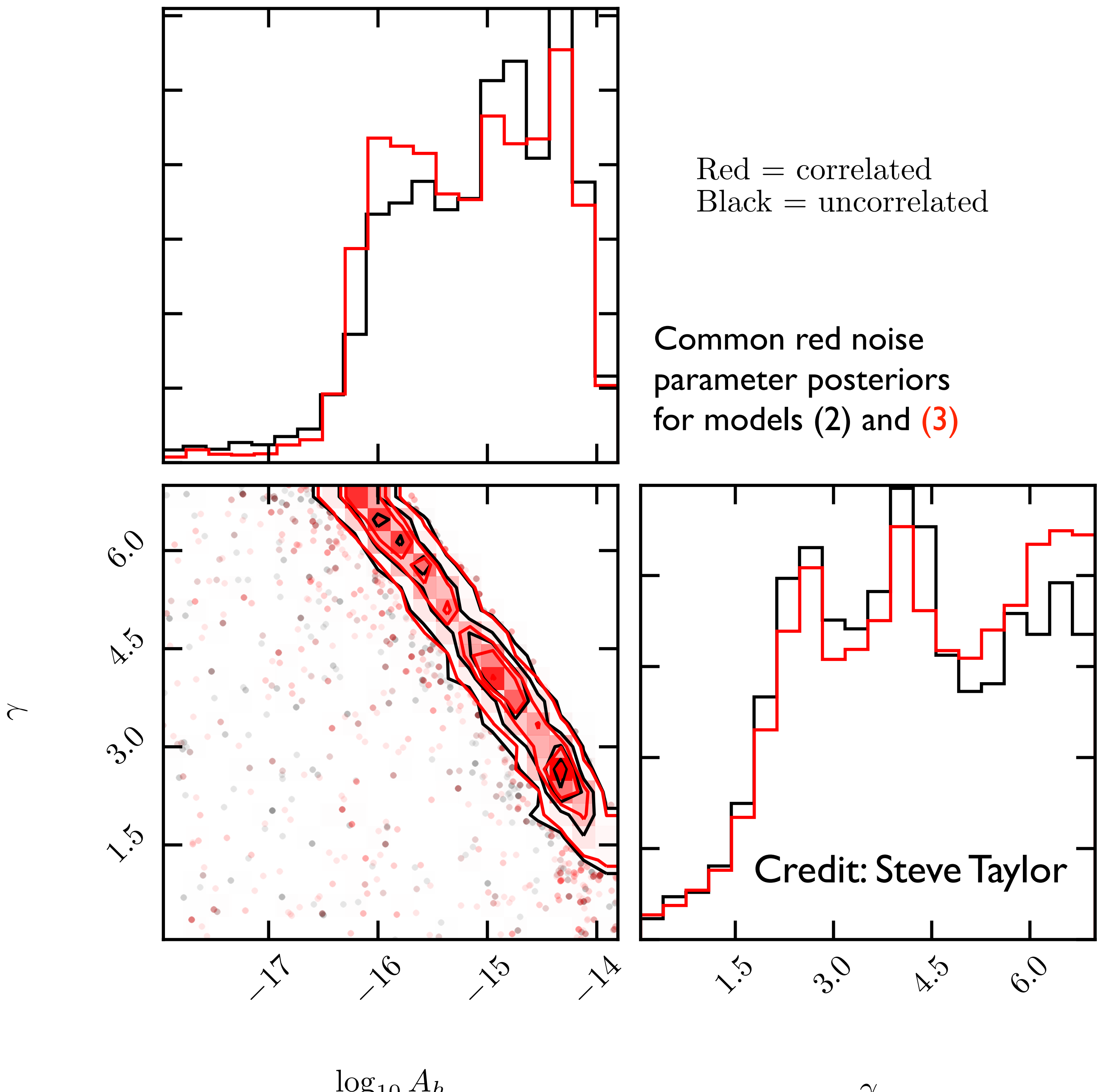
Stochastic background: preliminary 11-yr data release results

$$p(\mathbf{r}|\vec{\theta}) = \frac{1}{\sqrt{\det 2\pi \mathbf{\Sigma}(\vec{\theta})}} \exp\left(-\frac{1}{2}\mathbf{r}^T \mathbf{\Sigma}^{-1}(\vec{\theta})\mathbf{r}\right)$$



Compare three models:

(1) individual red and white noises,

(2) individual red and white noises and **uncorrelated** common red noise,

(3) individual red and white noises and **correlated** common red noise (=GWs)

$$\mathbf{\Sigma}(\vec{\theta}) = \begin{bmatrix} \mathbf{P}_1 & 0 & \cdots & 0 \\ 0 & \mathbf{P}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{P}_l \end{bmatrix}$$

(1)

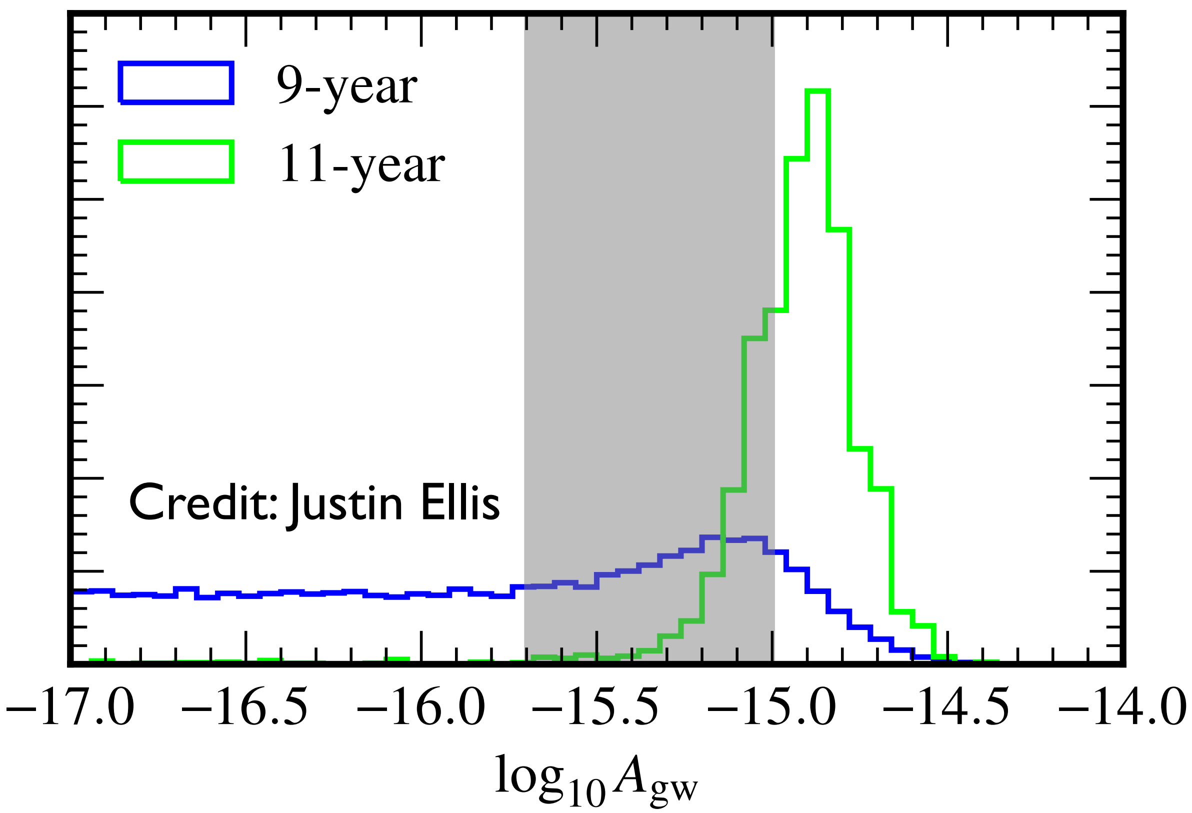
(2)

vs

$$\mathbf{\Sigma}(\vec{\theta}) = \begin{bmatrix} \mathbf{P}_1 & \mathbf{S}_{12} & \cdots & \mathbf{S}_{1l} \\ \mathbf{S}_{21} & \mathbf{P}_2 & \cdots & \mathbf{S}_{2l} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{S}_{l1} & \mathbf{S}_{l2} & \cdots & \mathbf{P}_l \end{bmatrix}$$

(3)

Stochastic background: <u>preliminary</u> 11-yr data release results

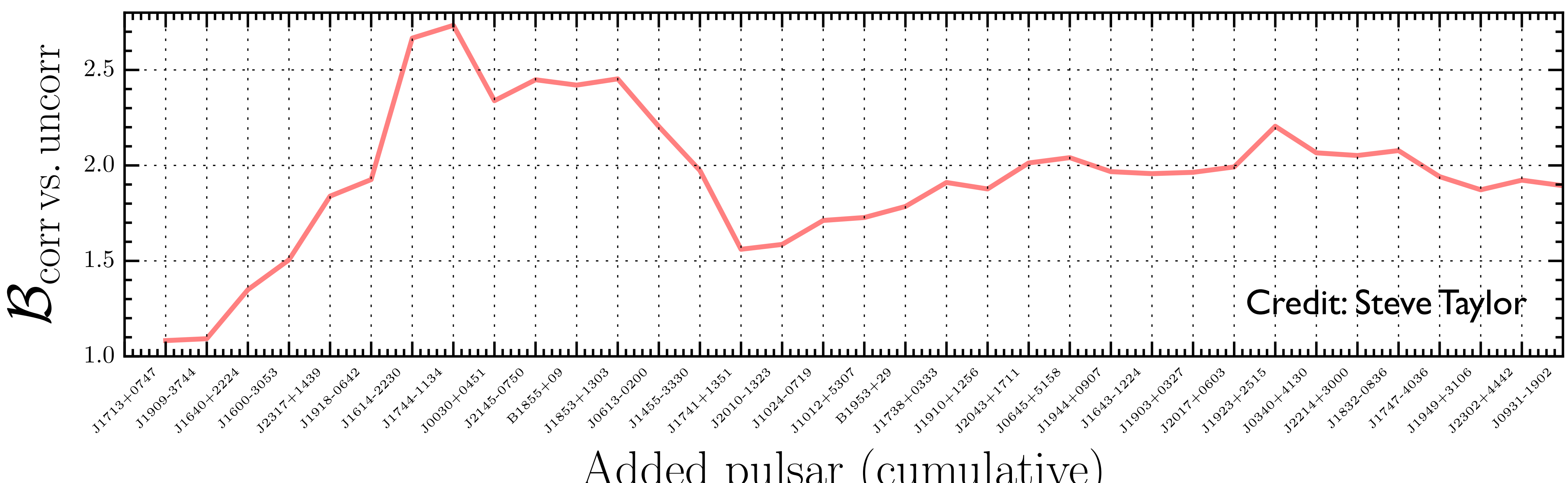


Bayes factor for (2) common uncorrelated vs (1) no common noise ~9

Bayes factor for (3) GWs vs (1) no common noise ~ 18

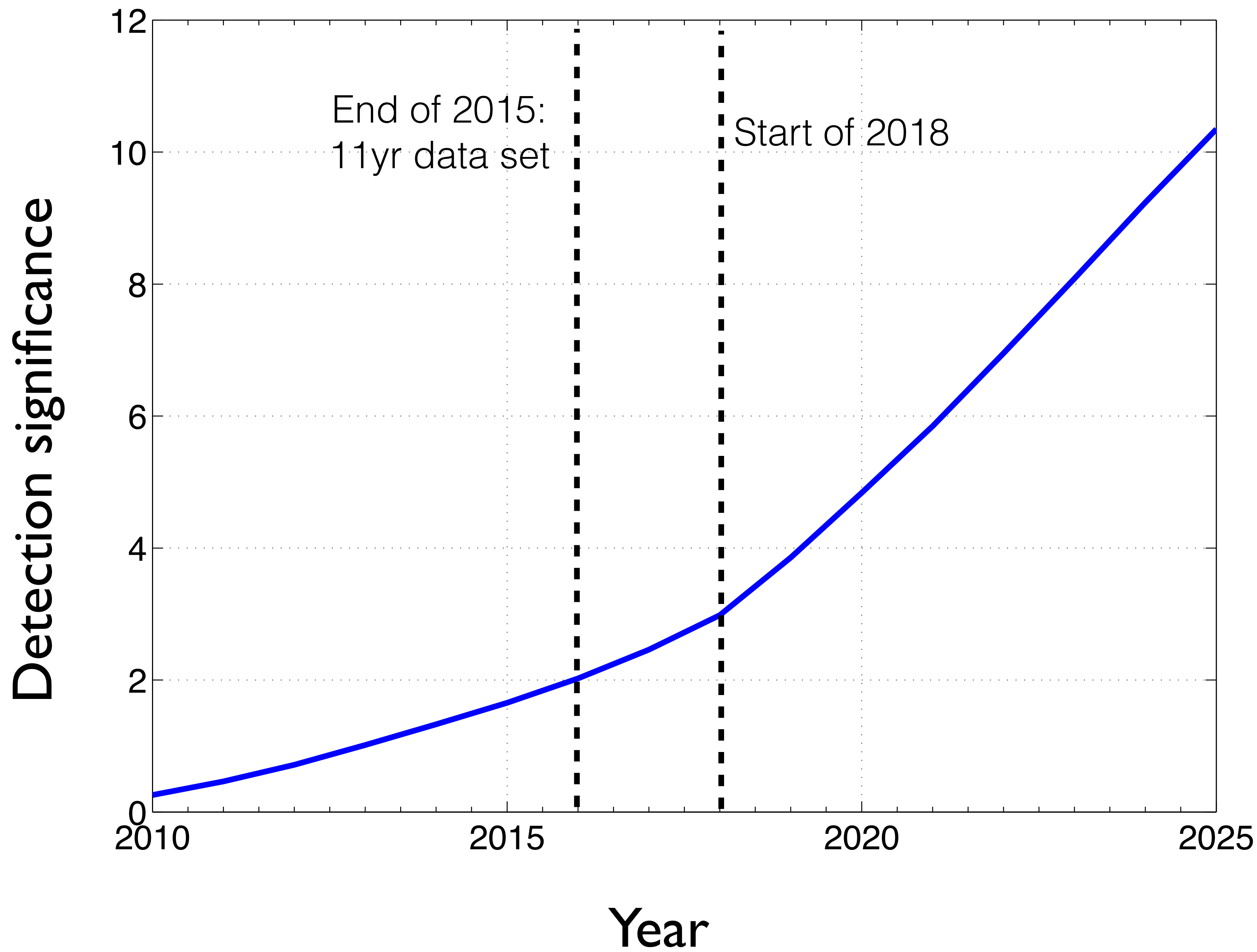
Bayes factor for (3) GWs vs (2) common uncorrelated noise ~ 2

[GWs are also preferred relative to monopolar, and dipolar signals]



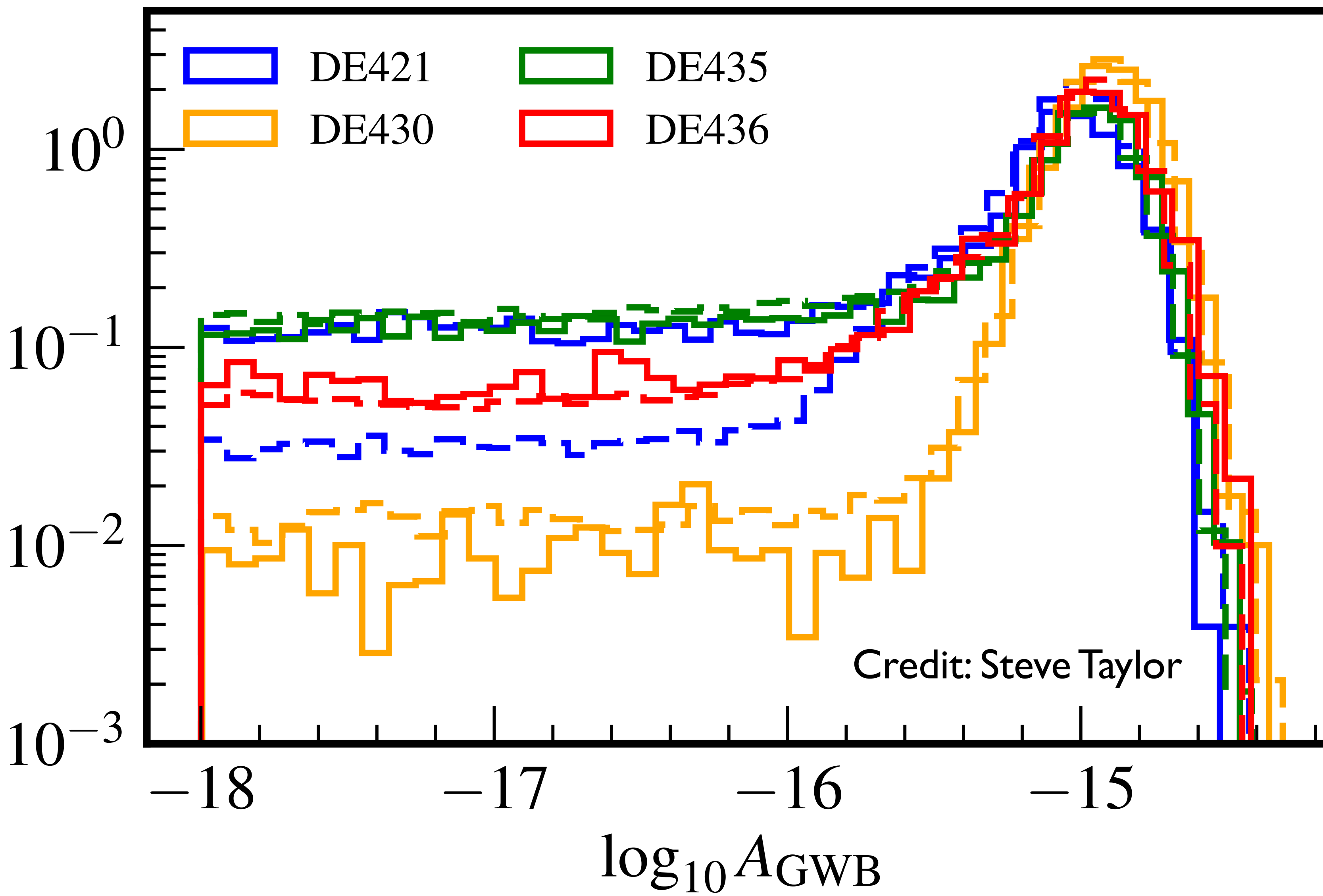
Sensitivity and detection projections

What does the future hold if the signal that we're seeing now is real?



But wait a minute… where are we?

Different ephemerides give us different results for the the significance of the red noise process we are seeing.



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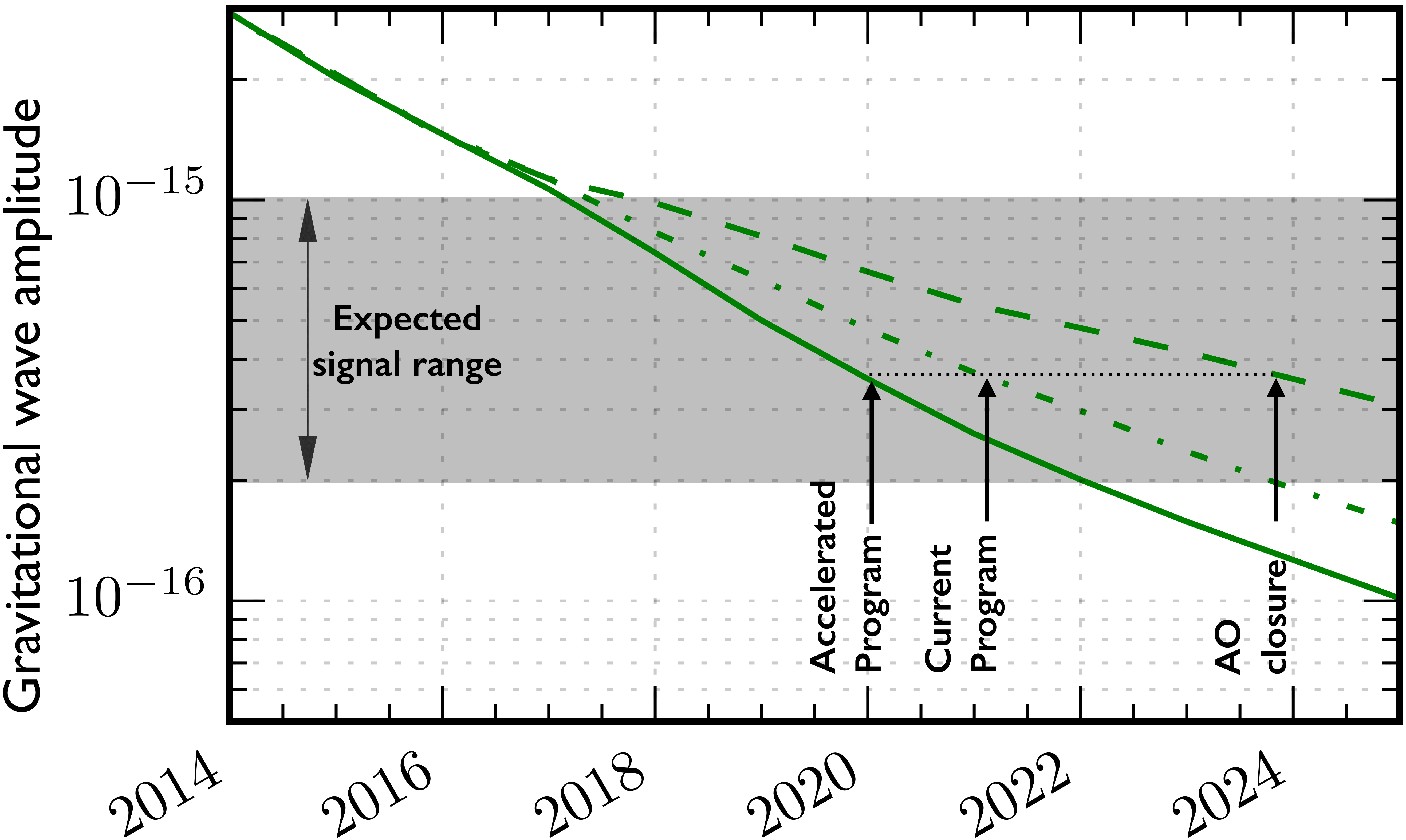
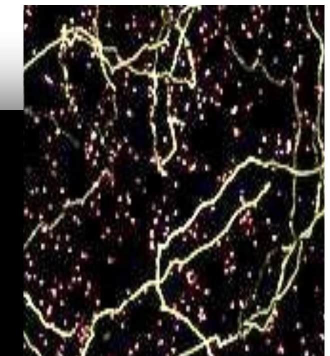
Sensitivity and detection projections



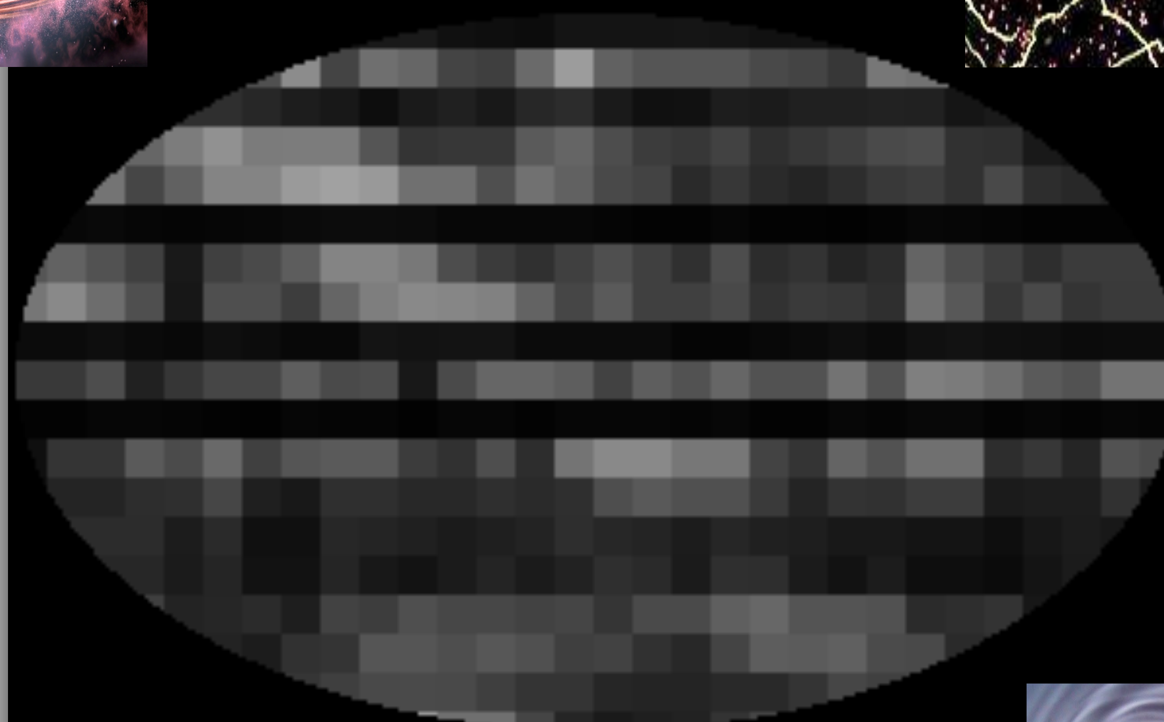
Summary

As the low-frequency GW sky comes into focus, it will offer a **novel view** of **unique and groundbreaking astrophysics.**

Individual supermassive black hole inspirals and their collective “chorus”: physics of accretion, late inspiral dynamics

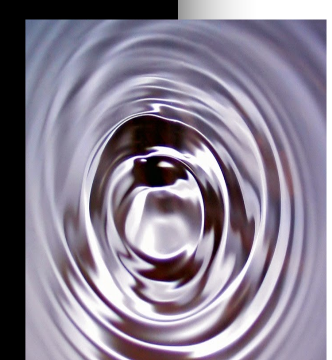


Cosmic strings: early universe physics/high energy physics



New physics: expect to be surprised

?



Black hole merger “memory”: a surprising prediction of strong field general relativity.