MONASH University

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Searches for gravitational waves

Xingjiang Zhu

OzGrav-Monash

Outline

- Data analysis techniques
- Recent search results

1) An isotropic stochastic GW background
2) Individual inspiralling supermassive BBHs

- (Burst with memory, cosmic strings, inflationary GWs …)

Pulsar timing arrays

- Foster & Backer 1990

CONSTRUCTING A PULSAR TIMING ARRAY

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ABSTRACT

Arrival time data from a spatial array of millisecond pulsars can be used (1) to provide a time standard for long time scales, (2) to detect perturbations of the Earth's orbit, and (3) to search for a cosmic background of gravitational radiation. In this paper we first develop a polynomial time series representation for these three effects that is appropriate for analysis of the present data with its limited degrees of freedom. We then describe a pulsar timing array program that we have established at the National Radio Astronomy Observatory 43 m telescope with observations of PSR 1620−26, PSR 1821−24, and PSR 1937+21. The results presented in this paper cover a 2 yr period beginning in 1987 July. Individual parameters of these objects are compared to previous measurements. The influence of global parameters—clock, Earth location, and effects of gravitational radiation—on our data is discussed in the context of our polynomial model. Improvements in the data-gathering hardware and the inclusion of data from other observatories will lead to a significant increase in the sensitivity of this effort in the near future.

Subject headings: instruments — pulsars

ASTROPHYSICS

Gravitational waves from binary supermassive black holes missing in pulsar observations

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Gravitational waves are expected to be radiated by supermassive black hole binaries formed during galaxy mergers. A stochastic superposition of gravitational waves from all such binary systems would modulate the arrival times of pulses from radio pulsars. Using observations of millisecond pulsars obtained with the Parkes radio telescope, we constrained the characteristic amplitude of this background, $A_{c,yr}$, to be $<1.0 \times 10^{-15}$ with 95% confidence. This limit excludes predicted ranges for $A_{c,yr}$ from current models with 91 to 99.7% probability. We conclude that binary evolution is either stalled or dramatically accelerated by galactic-center environments and that higher-cadence and shorter-wavelength observations would be more sensitive to gravitational waves.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

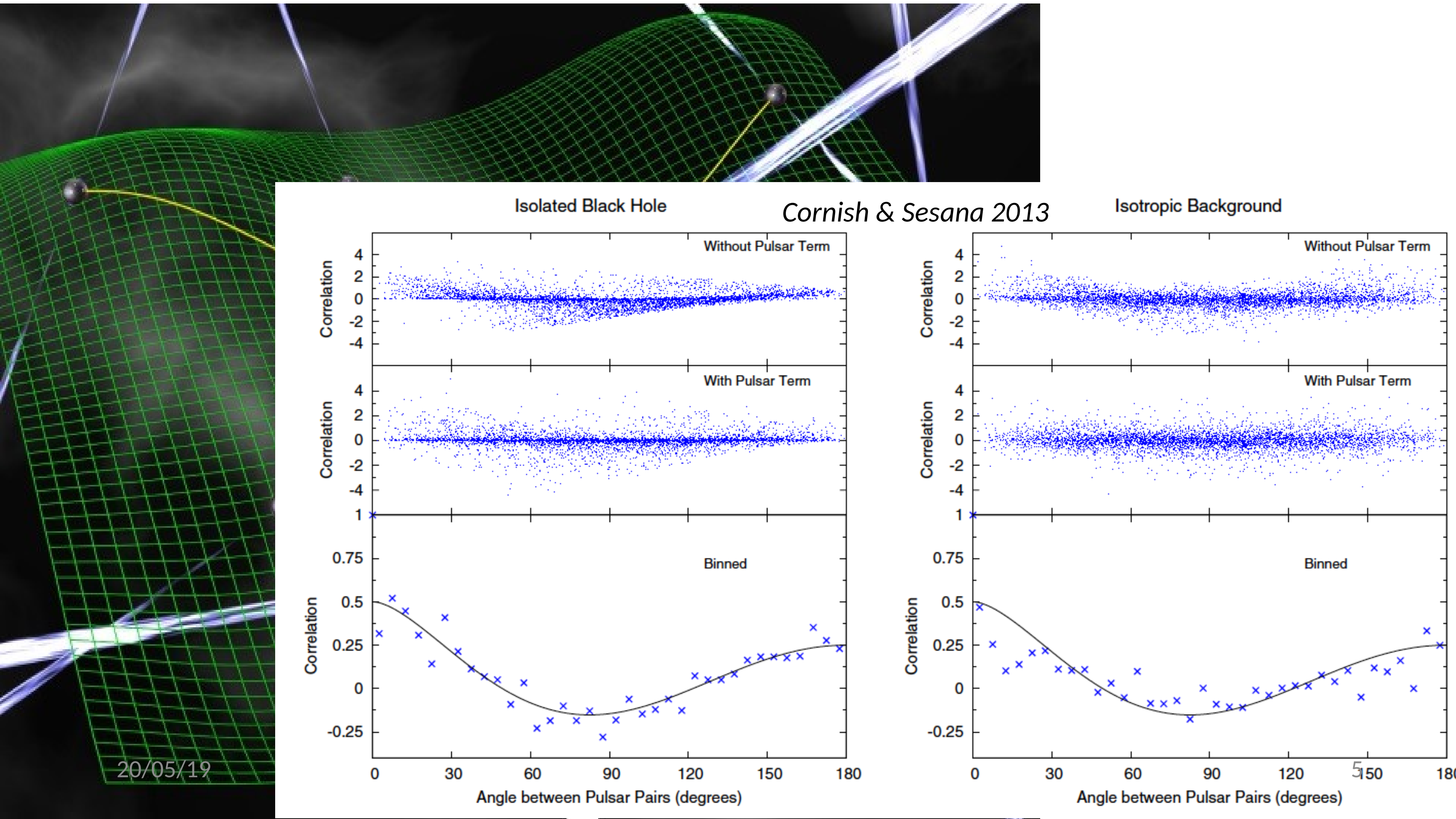
MNRAS **481,** 5501–5516 (2018) doi:10.1093/mnras/sty2632
Advance Access publication 2018 October 1

Studying the Solar system with the International Pulsar Timing Array

MNRAS **000**, 1–17 (2016) Preprint 12 May 2019 Compiled using MNRAS LaTeX style file v3.0

A pulsar-based timescale from the international pulsar timing array

A galactic-scale GW detector: the Pulsar Timing Array



Cornish & Sesana 2013

One realization of an isotropic GWB

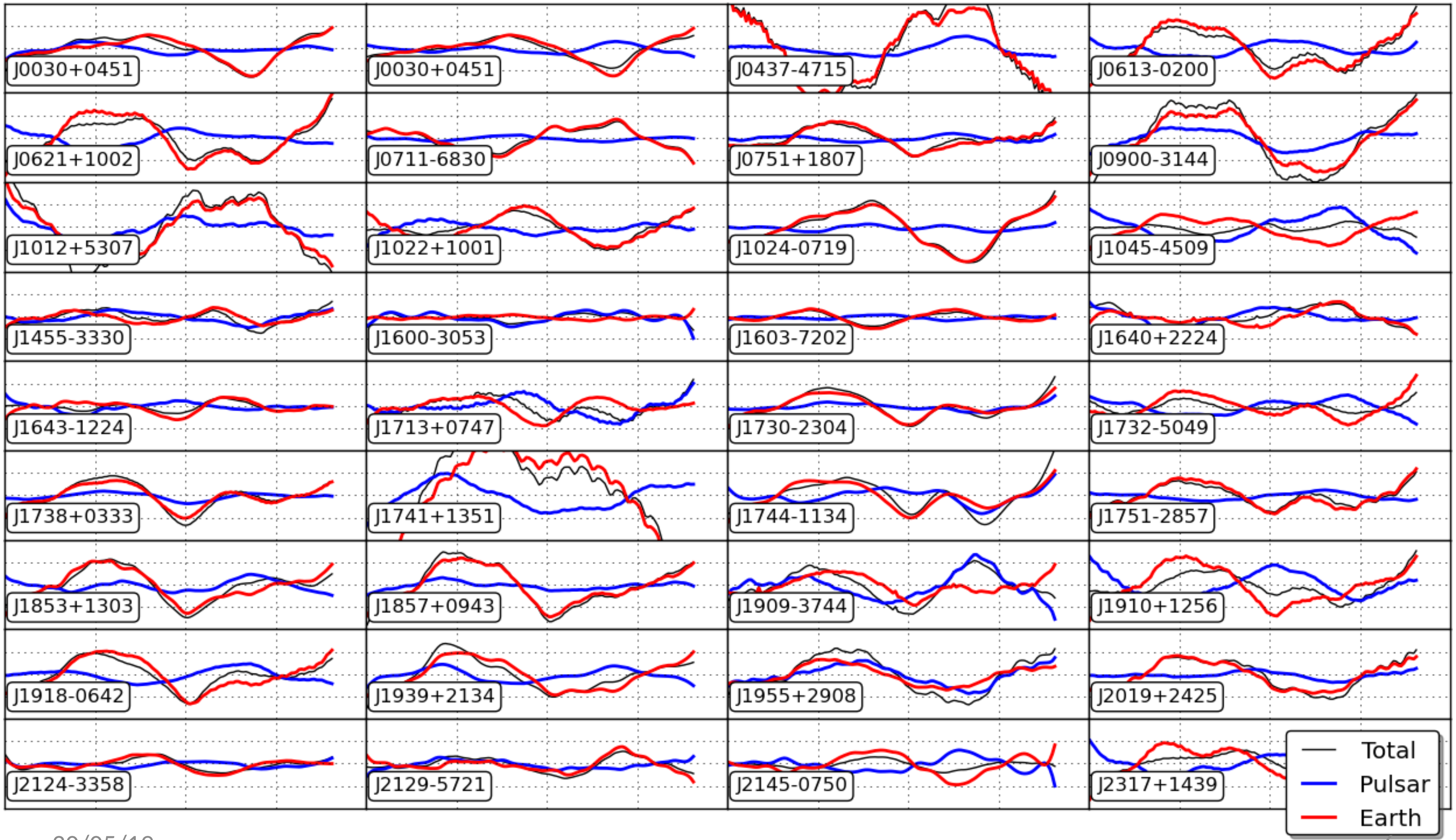


Image credit: Rutger van Haasteren

One realization of a continuous wave

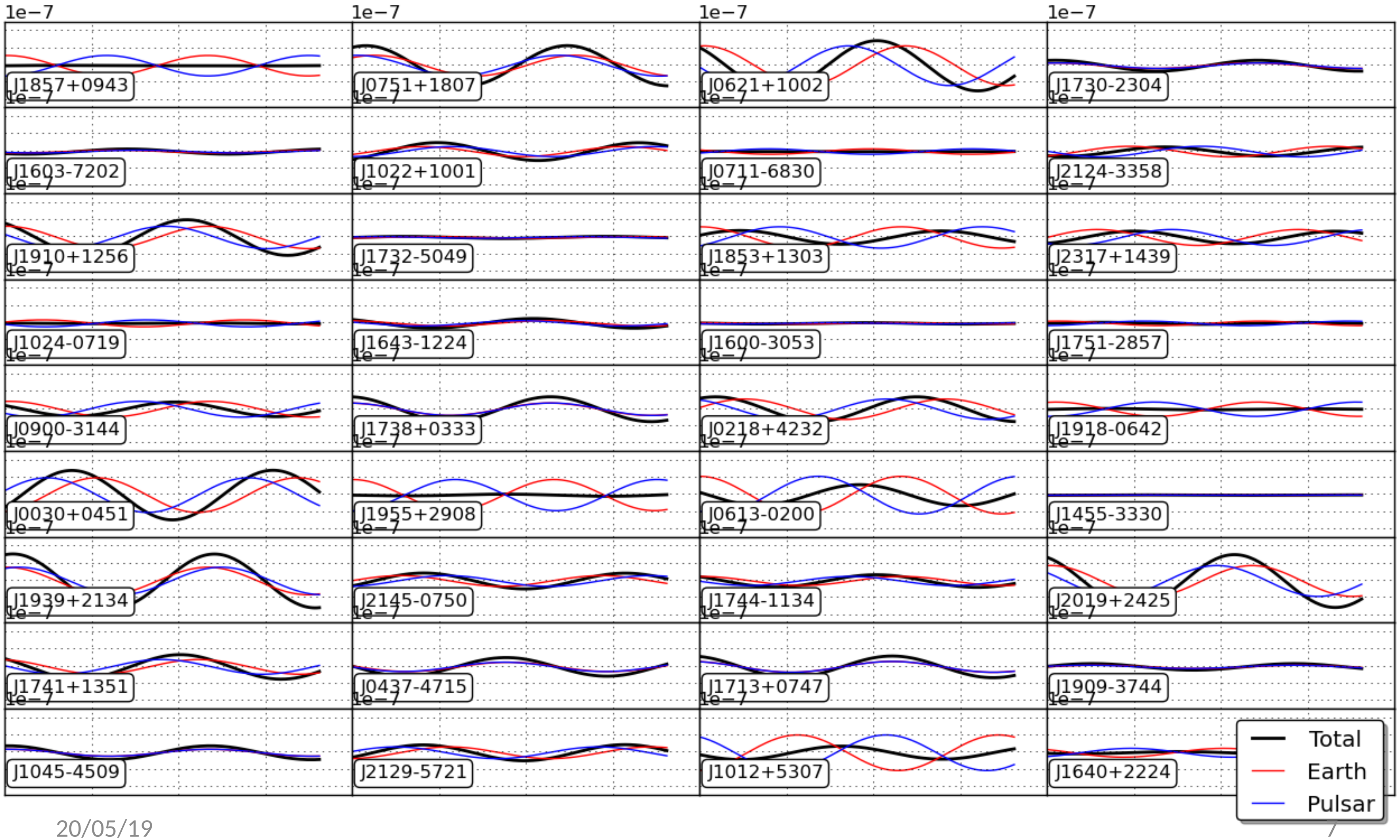


Image credit: Rutger van Haasteren

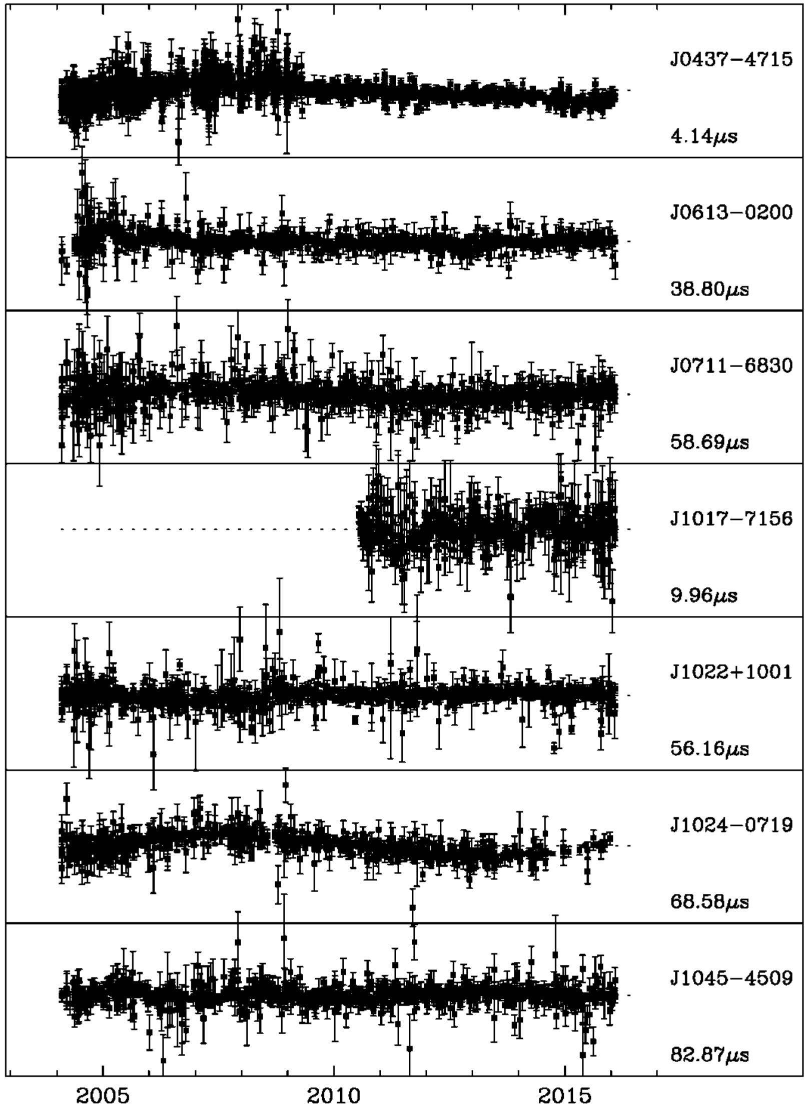
Let us find some GWs

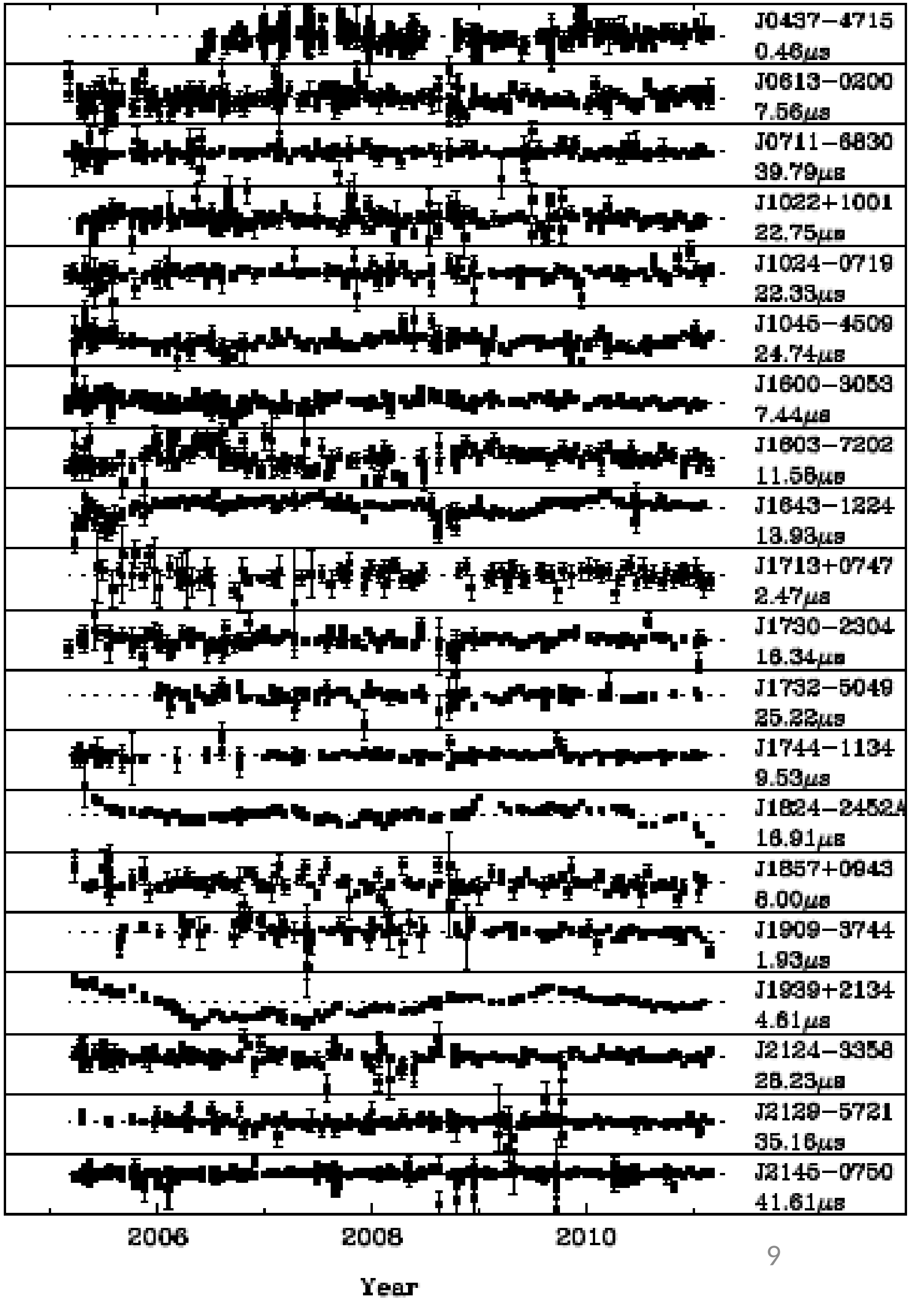
+ Daniel R., George H., Matthew K., Stefan O., Dick M., ...

$$P(\vec{d}|\vec{a},\vec{\theta})=\frac{\exp[-(\vec{d}-f(\vec{a}))C^{-1}(\vec{d}-f(\vec{a}))/2]}{\sqrt{(2\pi)^n \det C}}$$

$$C=C(\tau,\vec{\theta})=\int df \cos(f\tau)P(f)$$

Data look like





Problems

1. Pulsar timing model

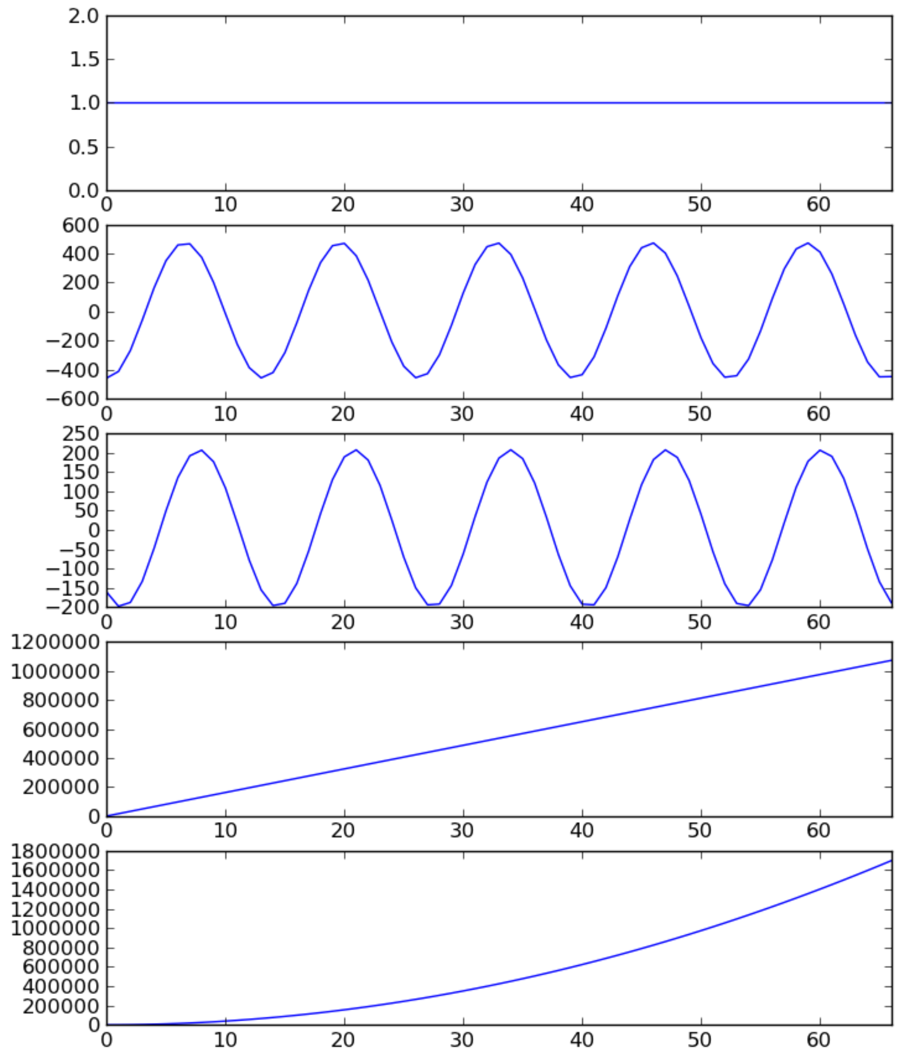
2. Noise model

3. Signal (GW) model

4. Computational challenges

1. Pulsar timing model

PSRJ	
RAJ	237
DECJ	453
F0	98e-13
F1	714e-21
PEPOCH	
POSEPOCH	
DMEPOCH	
DM	117
PMRA	943
PMDEC	012
PX	366
SINI	947
BINARY	
PB	925
A1	381
PBDOT	38e-15
XDOT	365e-17
TASC	505
EPS1	080
EPS2	3714
M2	497



The effect of fitting on a GWB

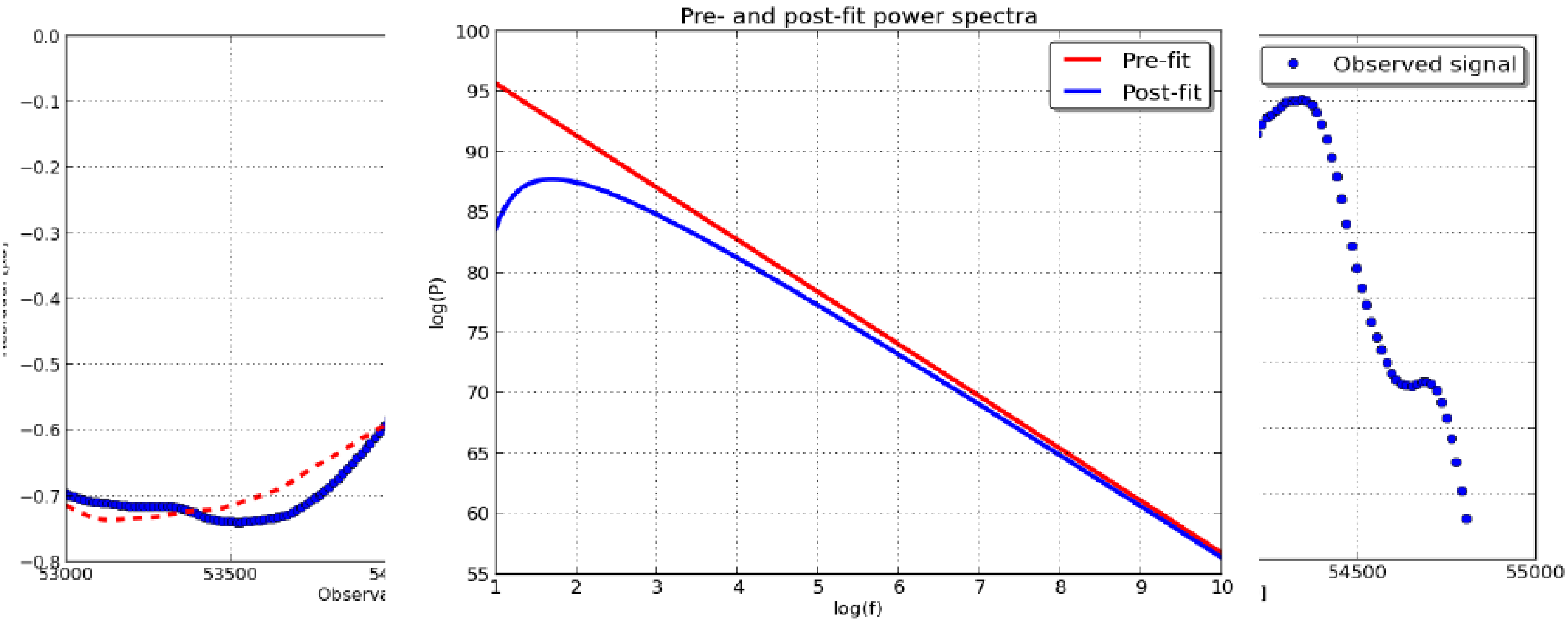


Image credit: Rutger van Haasteren

The effect of fitting on a CW

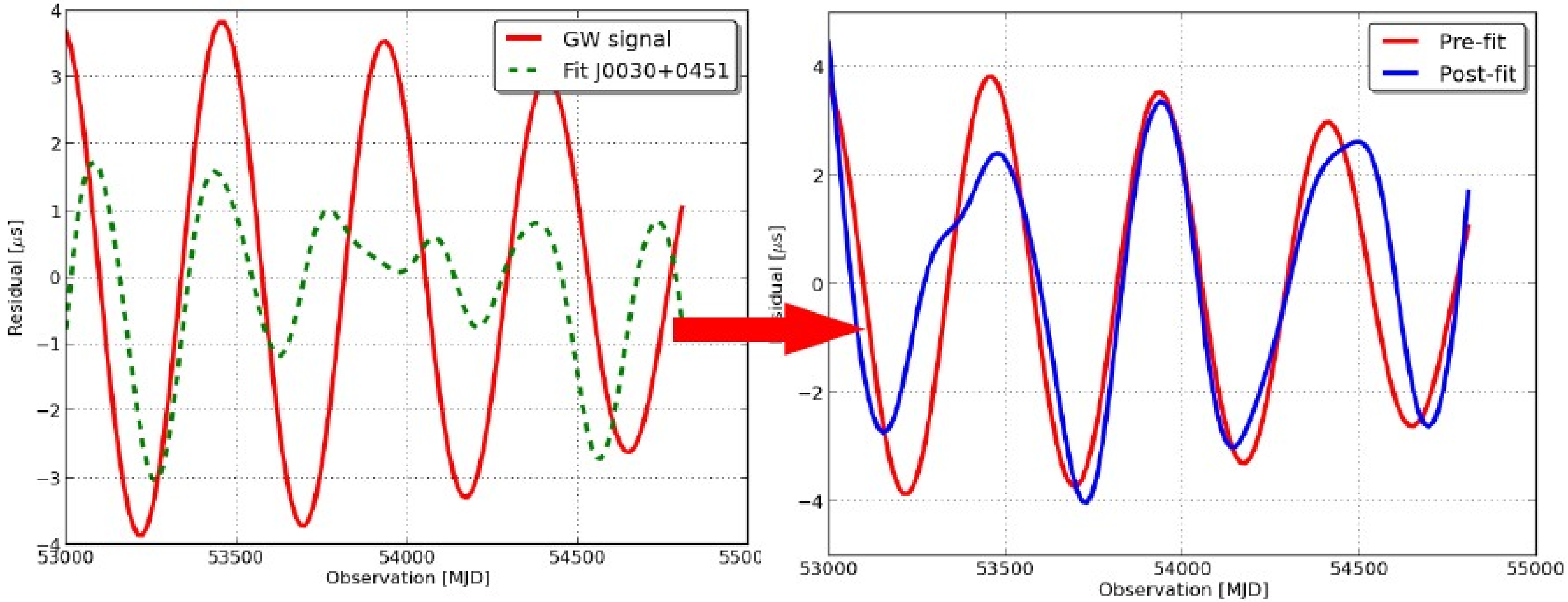


Image credit: Rutger van Haasteren

2. Noise model

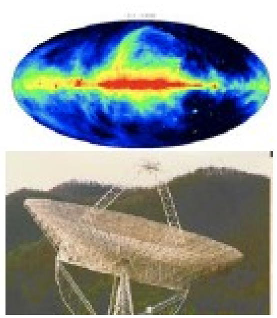
- ✓ TOA errors
- Additional white noise (pulse jitter, scintillation,)
- Red noise (or “timing” noise, spin noise)
- ISM noise
- o Instrumental jumps
- o RFIs, SSE, clocks

White noise

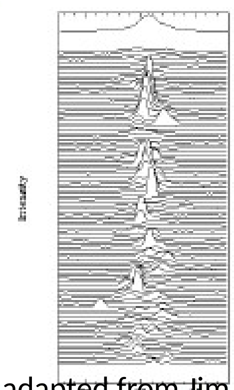
=

radiometer noise + **pulse jitter** + **scintillation noise**

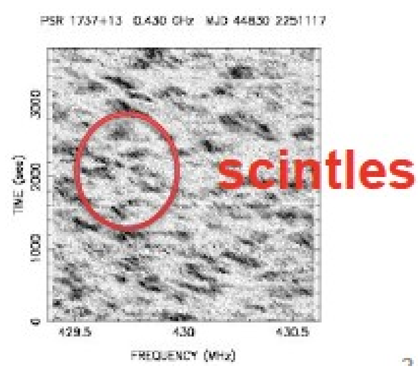
Larger telescope, lower noise receivers, longer integration times, larger bandwidths



Longer integrations (more sensitivity not a help)



Longer integrations, higher bandwidths and frequencies

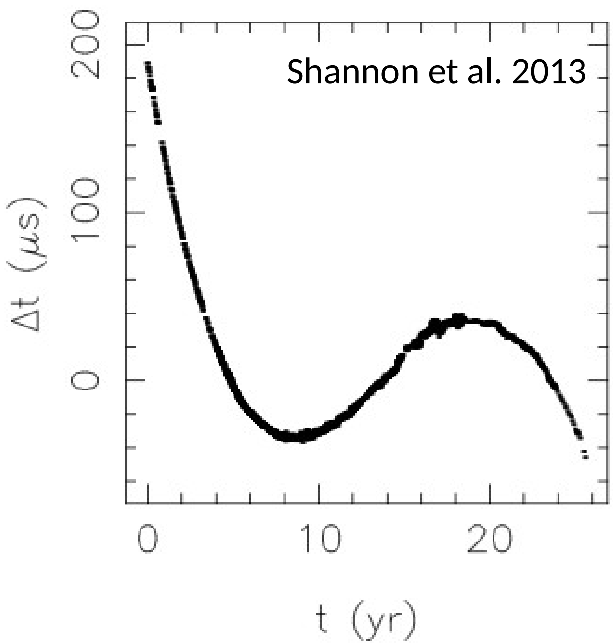


Slide adapted from Jim Cordes

Timing noise:

Spin/torque noise in core and magnetospheres

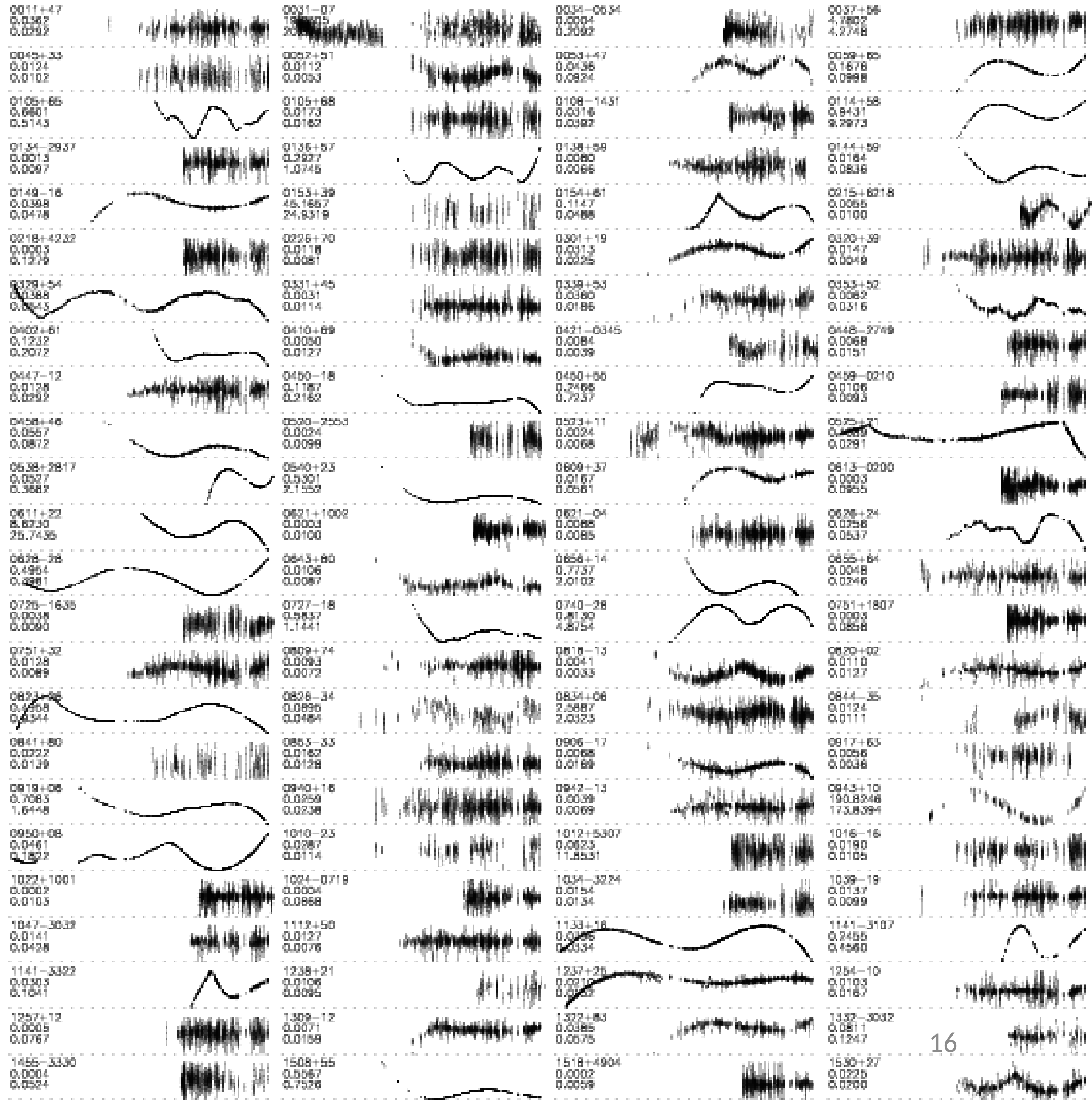
Seen in many young pulsars, some MSPs



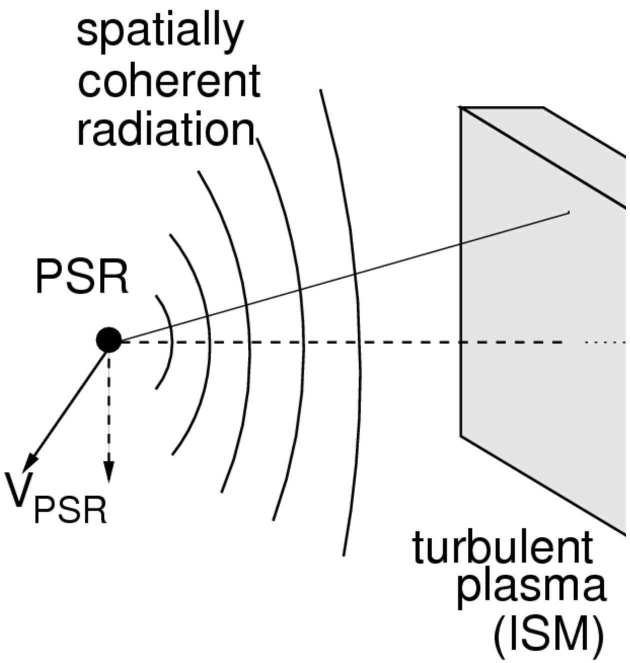
Shannon et al. 2013

- PSR B1937+21

Hobbs et al. 2010



ISM noise



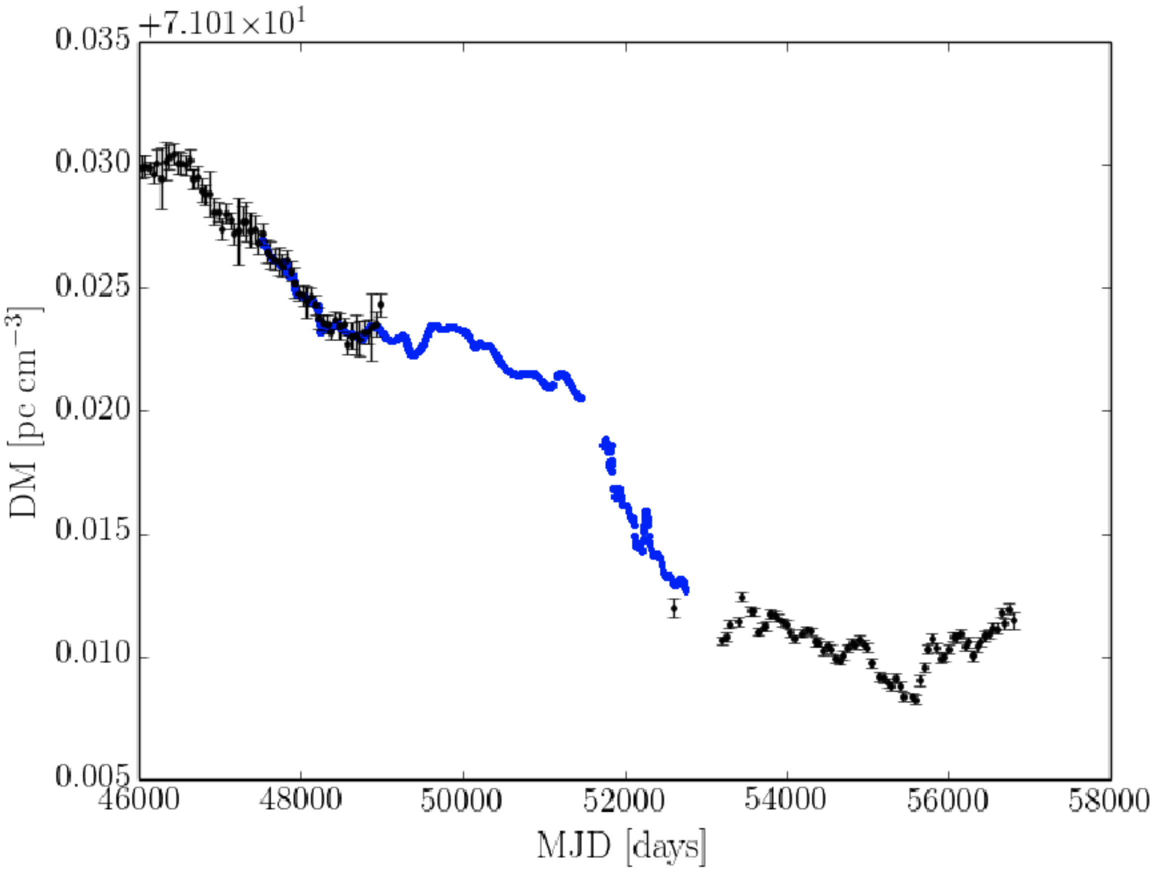


Image credit: Jim Cordes, Ryan Shannon

2. Likelihood & noise model

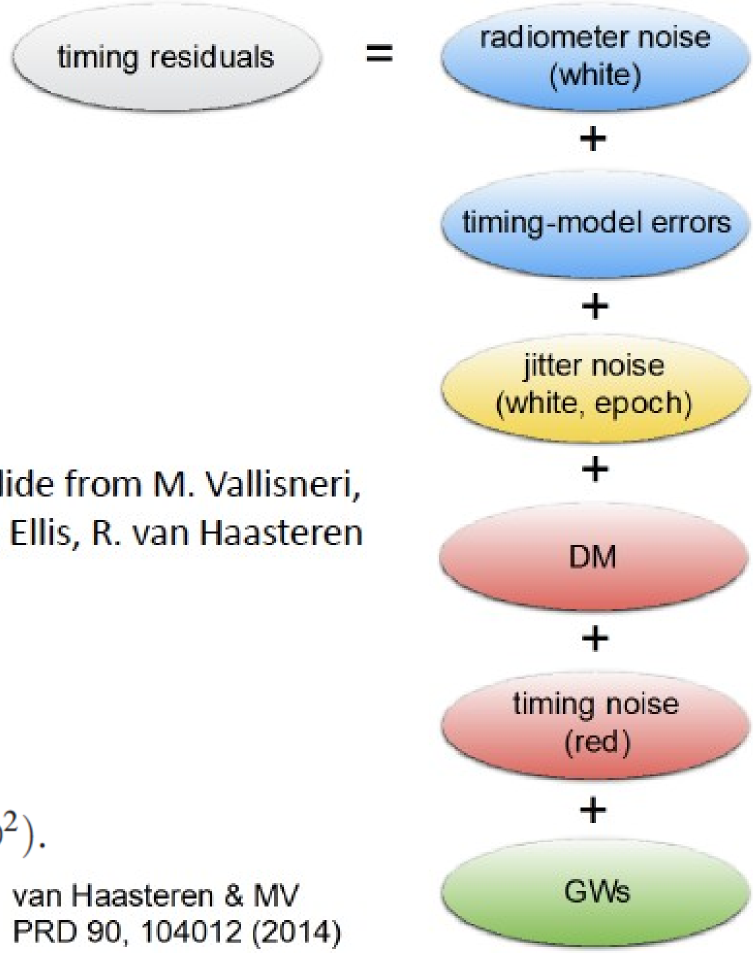
$$\delta \boldsymbol{t} = \delta \boldsymbol{t}^{\mathrm{prf}} + \mathbf{M}\boldsymbol{\xi},$$

$$P(\delta \boldsymbol{t}|\boldsymbol{\xi}, \boldsymbol{\phi}) = \frac{1}{\sqrt{(2\pi)^n \det C}} \times \exp\left(\frac{-1}{2}(\delta \boldsymbol{t} - \mathbf{M}\boldsymbol{\xi})^{\mathrm{T}}\, \mathbf{C}^{-1}\, (\delta \boldsymbol{t} - \mathbf{M}\boldsymbol{\xi})\right).$$

$$\int \mathrm{d}^m \boldsymbol{\xi}\, P(\delta \boldsymbol{t}|\boldsymbol{\xi}, \boldsymbol{\phi}) = \frac{\sqrt{\det\left(\mathbf{M}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{M}\right)^{-1}}}{\sqrt{(2\pi)^{n-m}\det \mathbf{C}}} \times \exp\left(\frac{-1}{2}\delta \boldsymbol{t}^{\mathrm{T}}\mathbf{C}'\delta \boldsymbol{t}\right),$$

with

$$\mathbf{C}' = \mathbf{C}^{-1} - \mathbf{C}^{-1}\mathbf{M}\left(\mathbf{M}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{M}\right)^{-1}\mathbf{M}^{\mathrm{T}}\mathbf{C}^{-1}.$$



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

$$\sigma_s^2 = (\mathrm{EFAC}\,\sigma)^2 + \mathrm{EQUAD}^2.$$

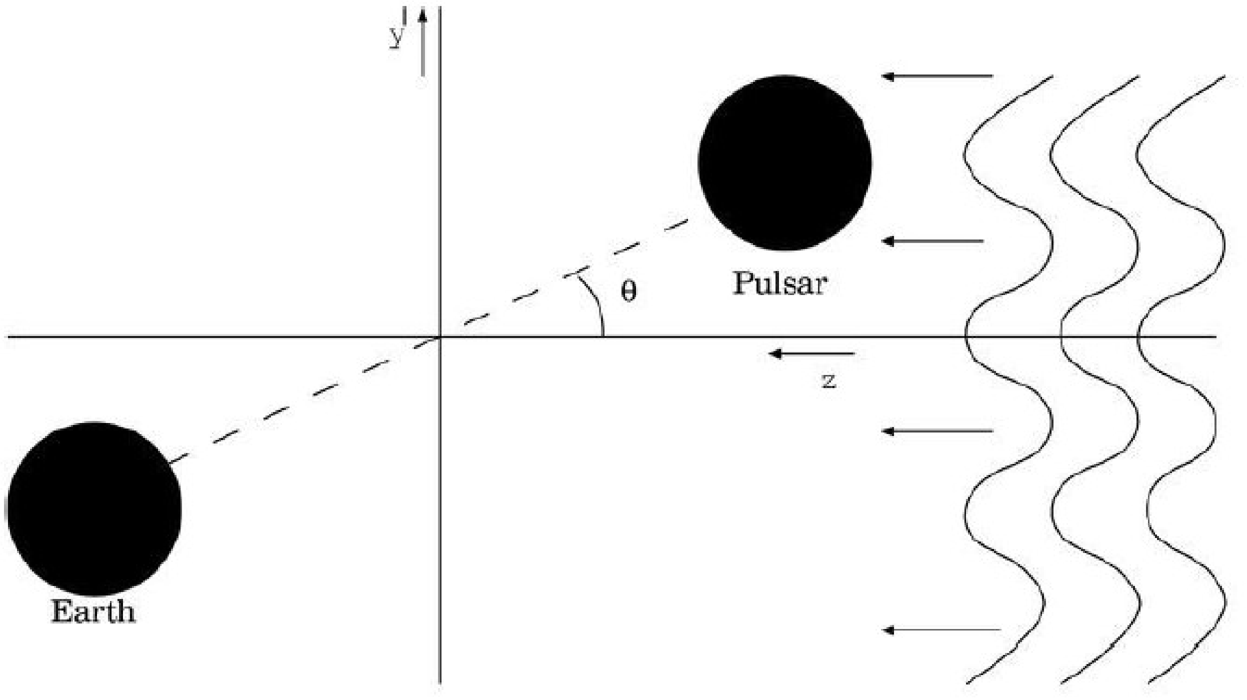
$$\sigma_s^2 = \mathrm{T2EFAC}^2(\sigma^2 + \mathrm{T2EQUAD}^2).$$

$$P(f) = \frac{A^2}{12\pi^2}\,\mathrm{yr}^3\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-\gamma}.$$

$$P(f) = \frac{P_0}{[1 + (\frac{f}{f_c})^2]^{\alpha/2}},$$

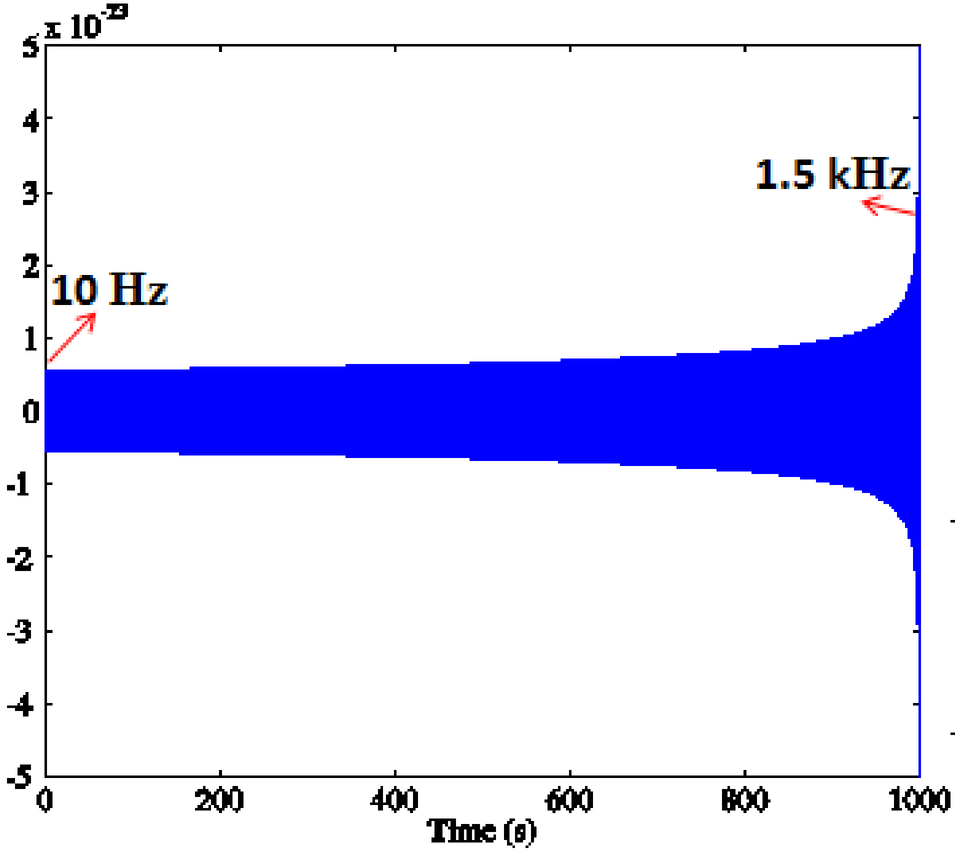
van Haasteren & MV
PRD 90, 104012 (2014)

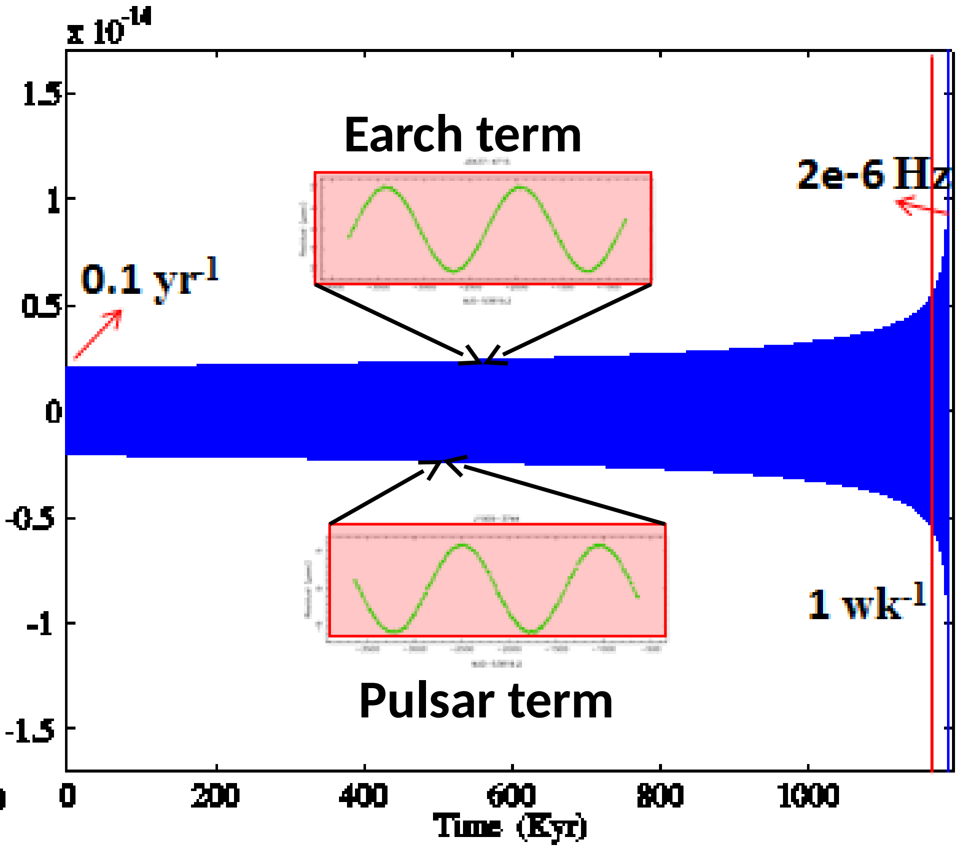
3. Signal model



$$\frac{\Delta \nu}{\nu} = \tfrac{1}{2} \cos 2\phi [1 - \cos\theta]$$
$$\times [h(t) - h(t - l - l\cos\theta)],$$

PTA single-source vs LIGO





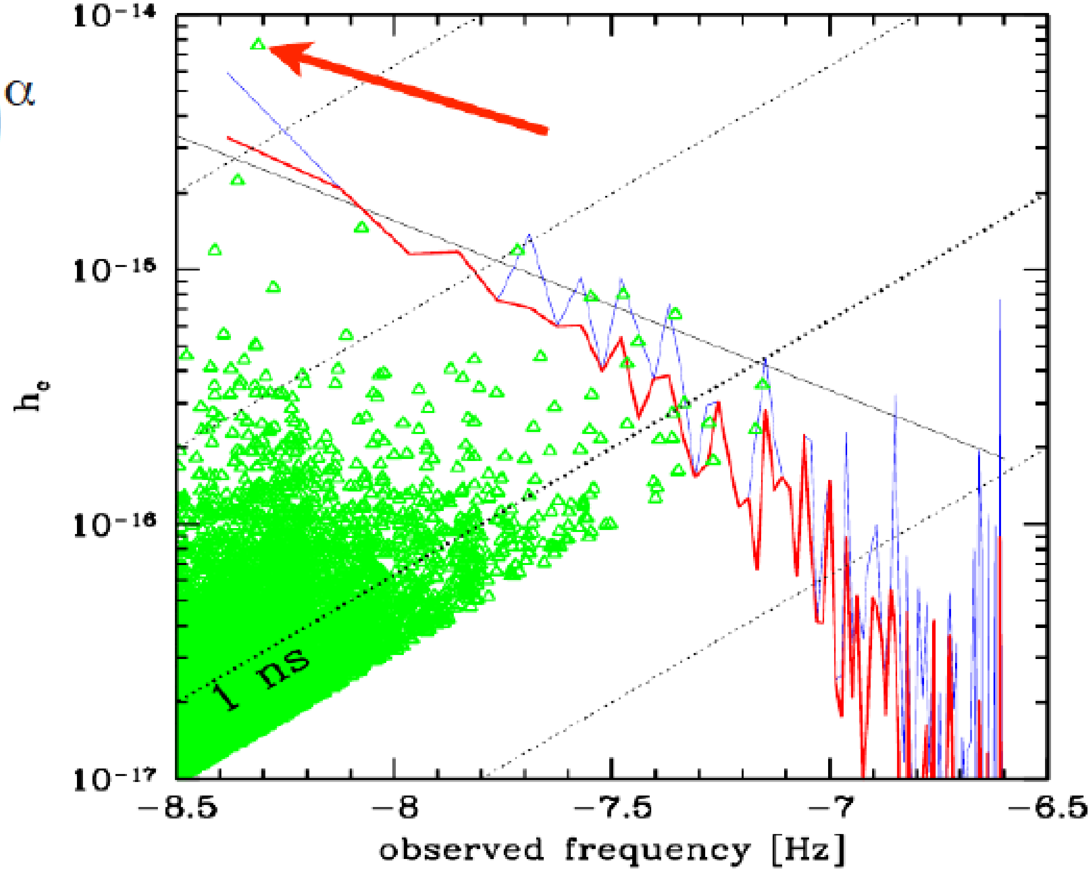
aLIGO: 1.4 -1.4 $M_{\odot}$ BNS, 200 Mpc

PTA: 10^9 -10^9 $M_{\odot}$ BSMBH, 100 Mpc

GWB and single source

$$h_c(f) = h_c \times (f/f_0)^{\alpha}$$
$$\alpha = -2/3$$

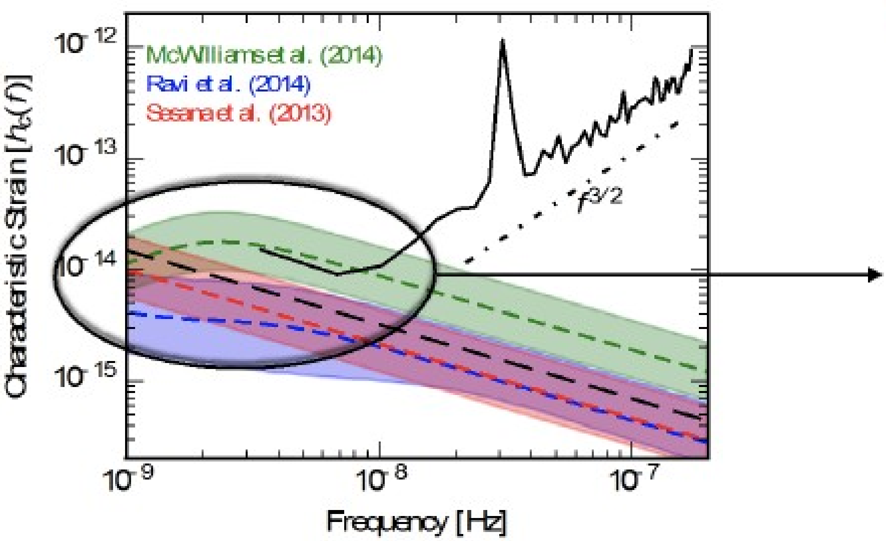
Phinney 01
Jaffe & Backer 03
Wyithe & Loeb 03
Sesana et al. 07, 09



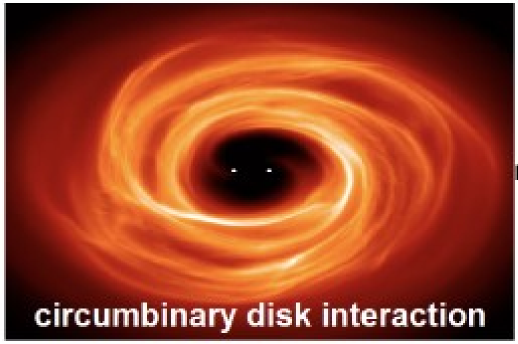
GWB: low-f turn over

$$h_c(f) = A_{\mathrm{GWB}} \frac{(f/\mathrm{yr}^{-1})^{\alpha}}{(1 + (f_{\mathrm{bend}}/f)^{\kappa})^{1/2}},$$

Arzoumanian et al. 2015

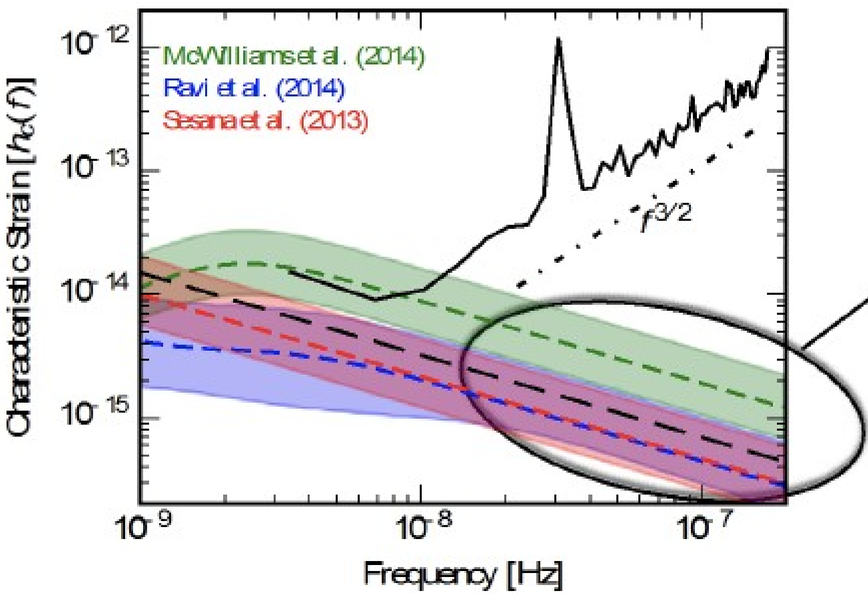


- Low frequency part of spectrum (when black holes are further away) possibly determined by environmental effects (solution to last parsec problem):
  - Stellar Hardening (stellar density in galactic cores)
  - Circumbinary disk interaction (mass accretion rate)
  - Orbital eccentricity (effects of stars/gas)

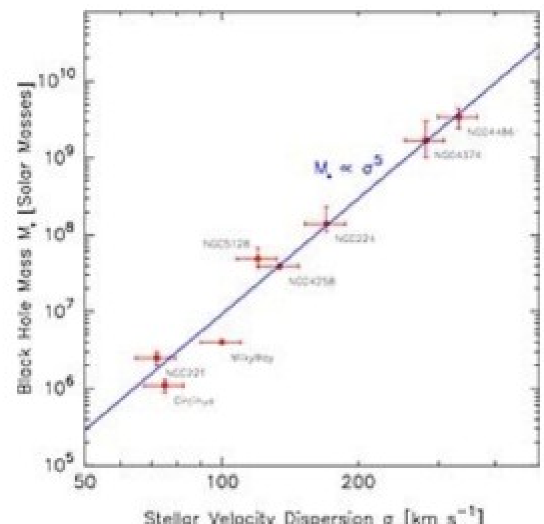


Slide adapted from Jim Cordes

GWB: high-f amplitude



- **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)**



Slide adapted from Jim Cordes

A continuous wave

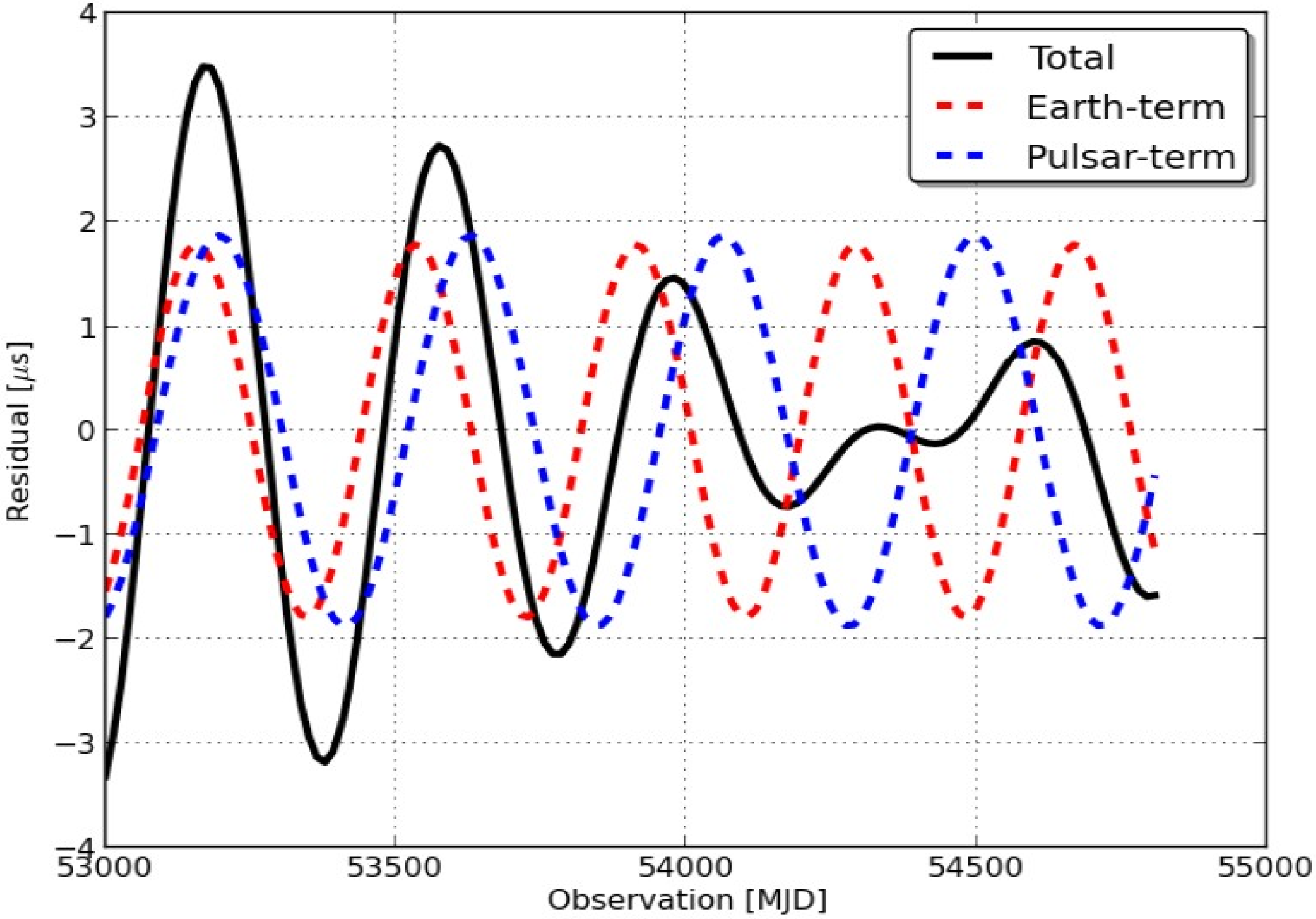


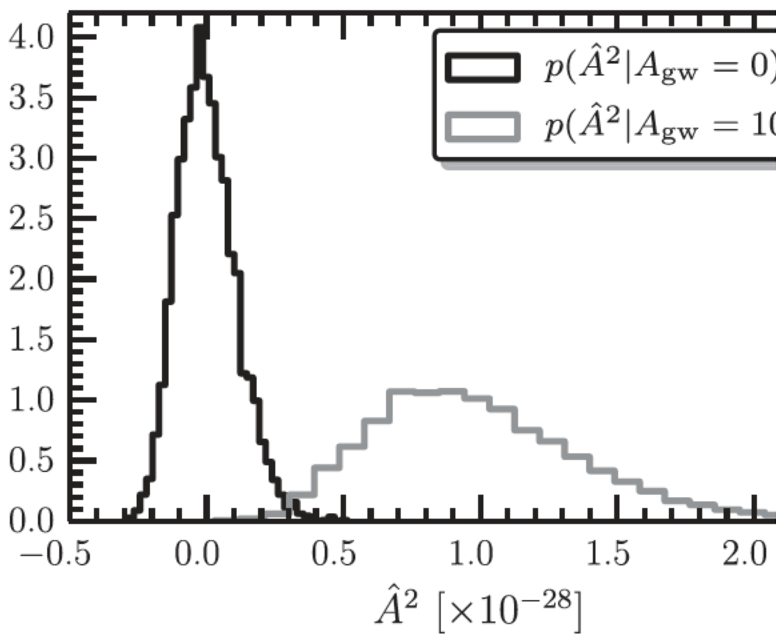
Image credit: Rutger van Haasteren

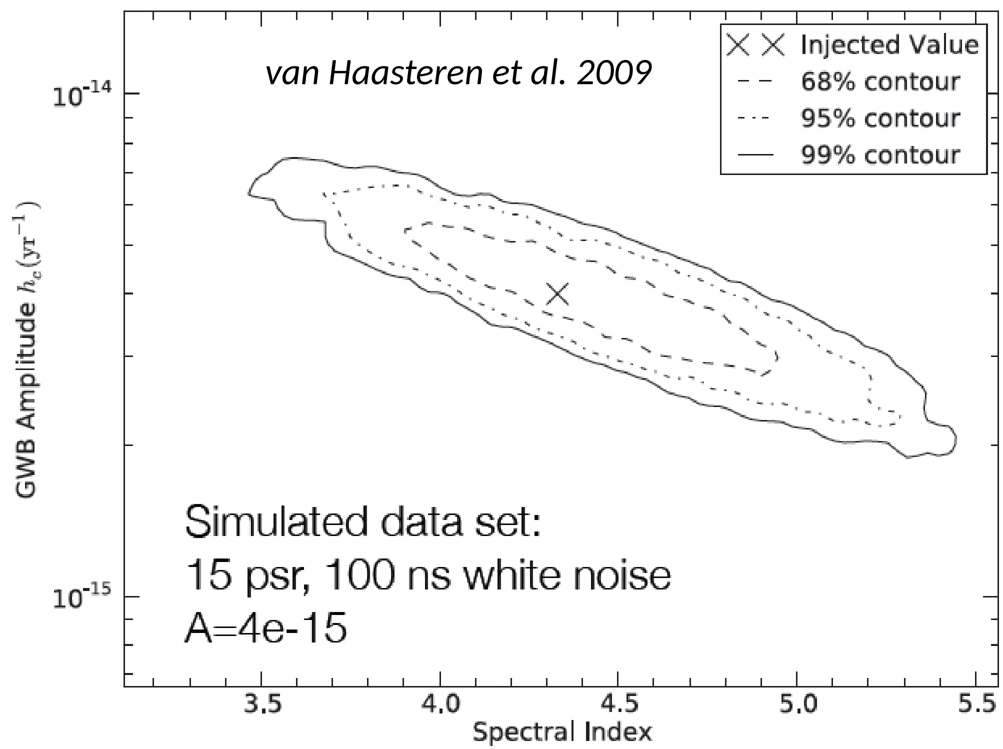
Detecting a GWB

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

$$\Sigma_n = \begin{bmatrix} \mathbf{N}_1 & \mathbf{X}_{12} & \cdots & \mathbf{X}_{1M} \\ \mathbf{X}_{12} & \mathbf{N}_2 & \cdots & \mathbf{X}_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{X}_{M} & & & \end{bmatrix},$$

Chamberlin et al. 2015

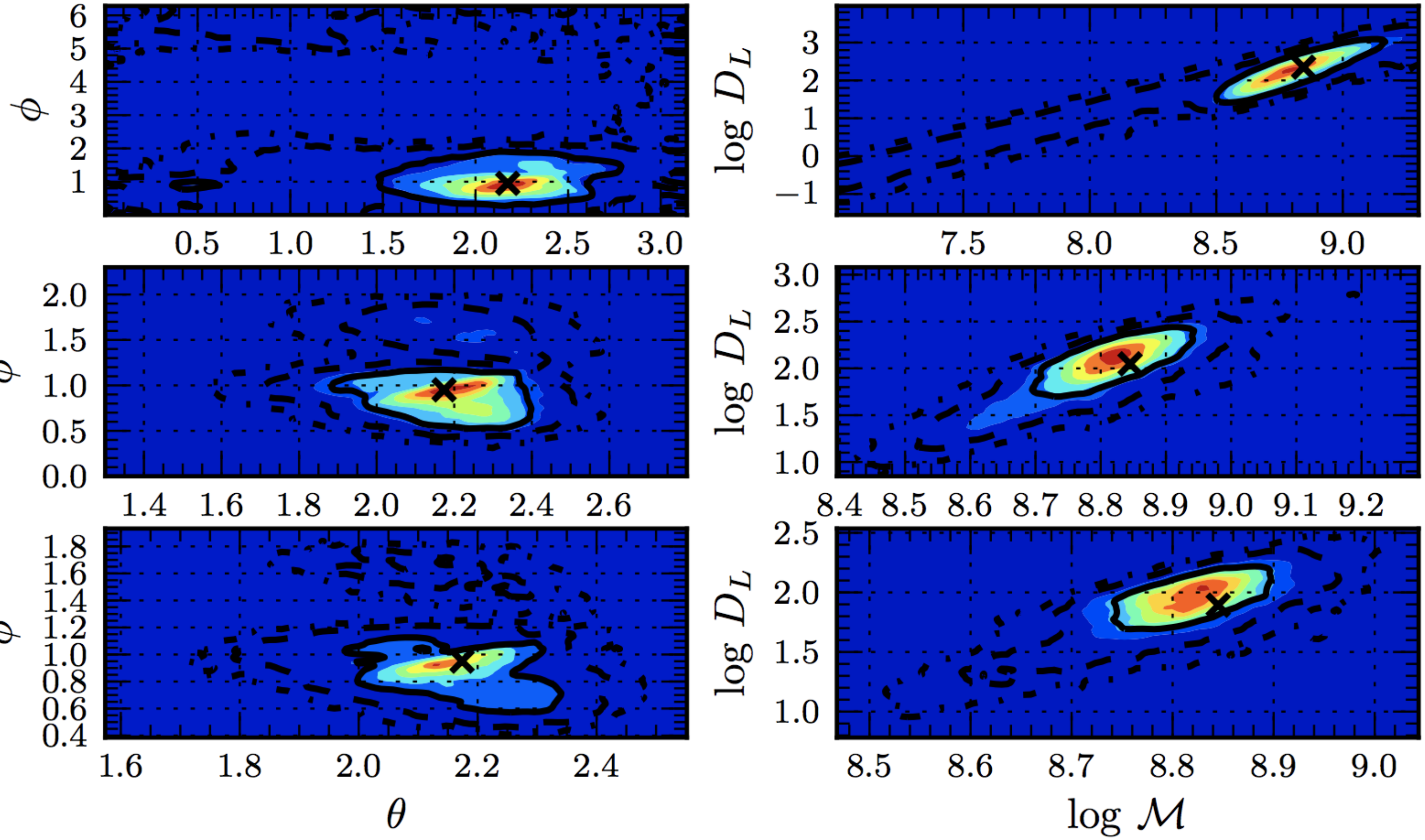




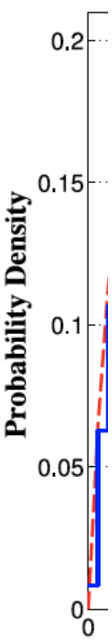
Detecting a single source

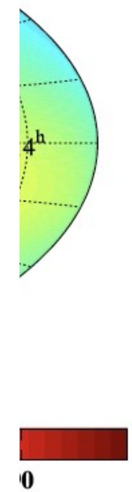
$$r(t, \hat{\Omega}) = F_{+}(\hat{\Omega}) \Delta A_{+}(t) + F_{\times}(\hat{\Omega}) \Delta A_{\times}(t),$$
$$\Delta A_{+,\times}(t) = A_{+,\times}(t) - A_{+,\times}(t_p)$$

Ellis 2013



Zhu (



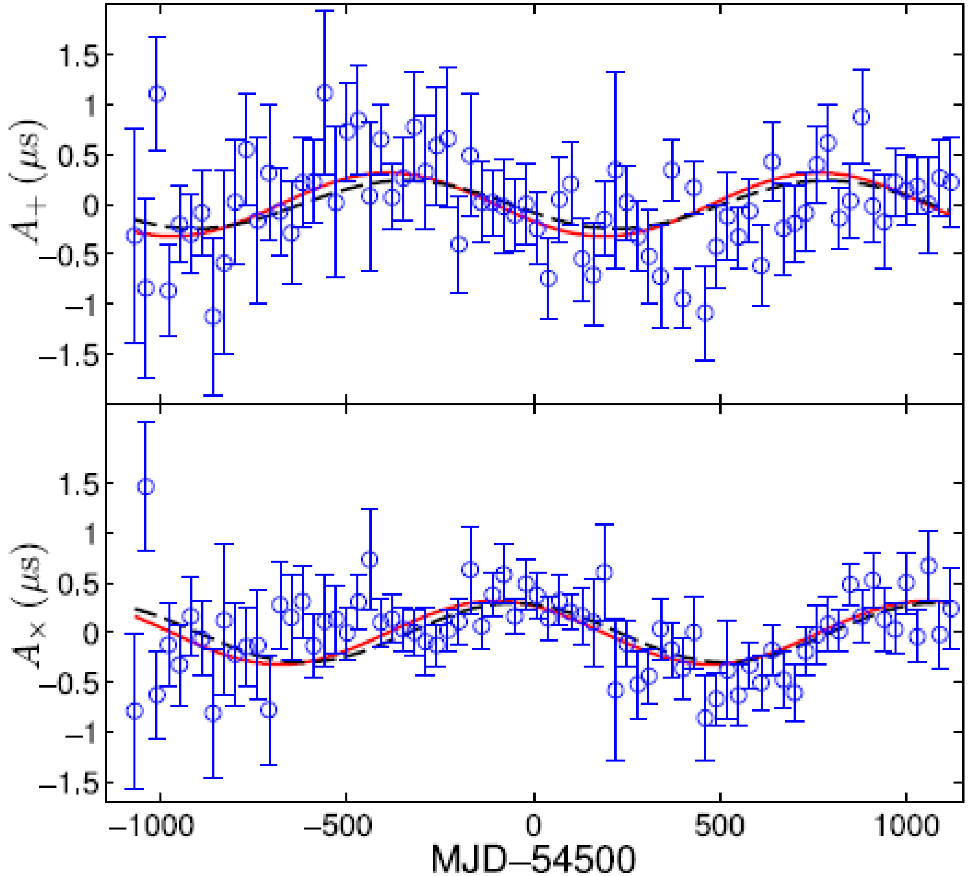


Global fitting for single-source GWs

- In TEMPO2, we can include additionally $r_{GW}(t)$ in pulsar timing models, and fit simultaneously for single-source GW signals and normal timing parameters for individual pulsars

- Search for GW signals of interest in the two output time series

$$r(t,\hat{\Omega}) = F_+(\hat{\Omega})\Delta A_+(t) + F_\times(\hat{\Omega})\Delta A_\times(t),$$



Zhu et al. 2014, Madison et al. 2016

4. Computational challenges

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

$$\Sigma_n = \begin{bmatrix} \mathbf{N}_1 & \mathbf{X}_{12} & \cdots & \mathbf{X}_{1M} \\ \mathbf{X}_{12} & \mathbf{N}_2 & \cdots & \mathbf{X}_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{X}_{M1} & \mathbf{X}_{M2} & \ldots & \mathbf{N}_M \end{bmatrix},$$

High Dimensionality (up to hundreds of parameters), big data sets (10^4 – 10^5 TOAs)

- Low-rank approximations for large stationary covariance matrices (*Lentati+13*, *van Haasteren & Vallisneri 15*)

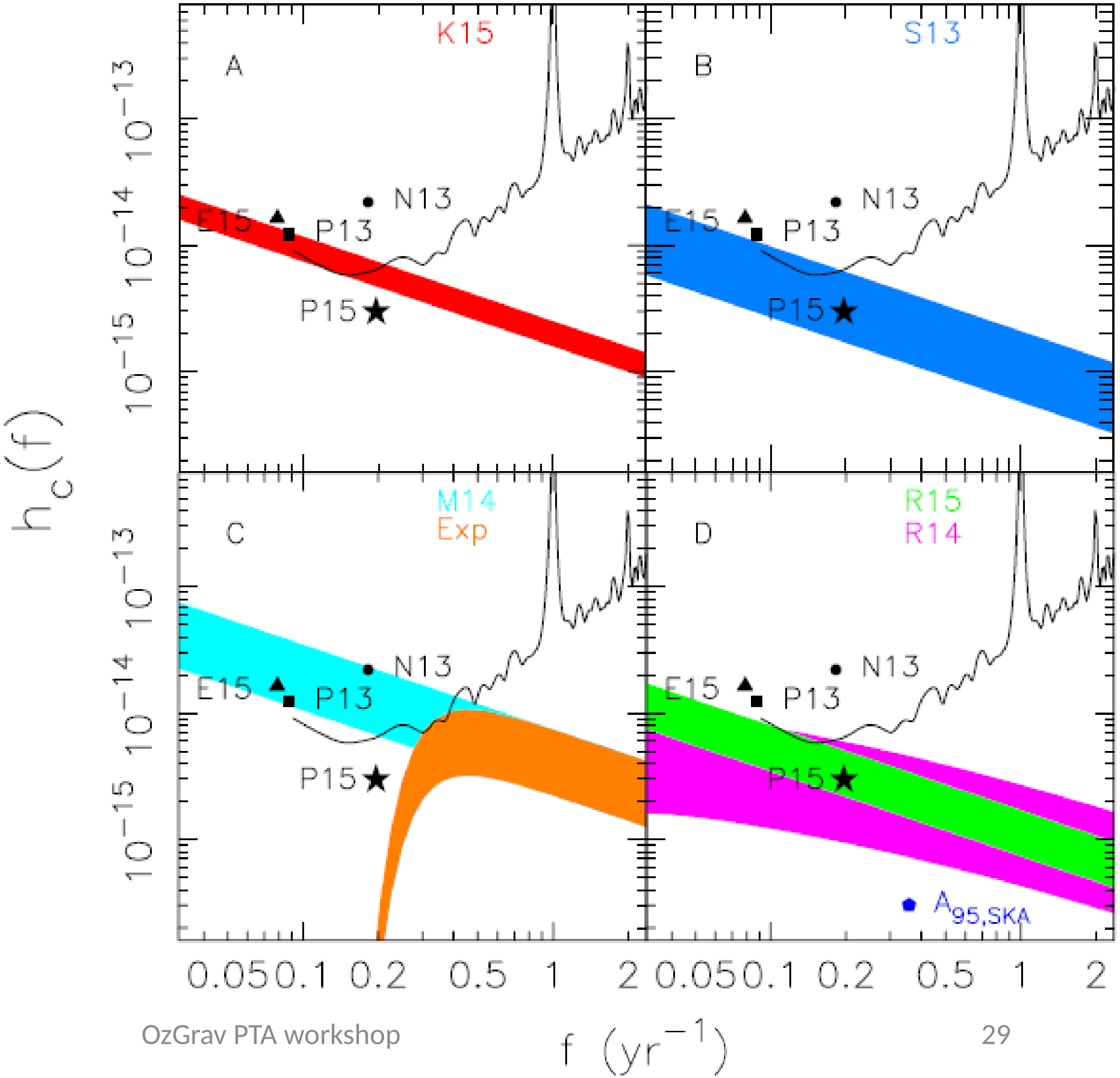
$$C(\tau) = \int_0^\infty \mathrm{d}f\, S(f) \cos(2\pi f \tau).$$
$$= \sum_k \rho_k \cos(2\pi f_k \tau),$$
$$f_k = k/T, \quad \rho_k = S(f_k)\Delta f = S(f_k)/T,$$

$$(\mathbf{N} + \mathbf{K})^{-1} \simeq (\mathbf{N} + \mathbf{F}\Phi\mathbf{F}^{\mathrm{T}})^{-1}$$
$$\simeq \mathbf{N}^{-1} - \mathbf{N}^{-1}\mathbf{F}(\Phi^{-1} + \mathbf{F}^{\mathrm{T}}\mathbf{N}^{-1}\mathbf{F})^{-1}\mathbf{F}^{\mathrm{T}}\mathbf{N}^{-1},$$

$\mathbf{F}$ is $n \times m$ (with $m \ll n$) and $\mathbf{\Phi}$ is diagonal

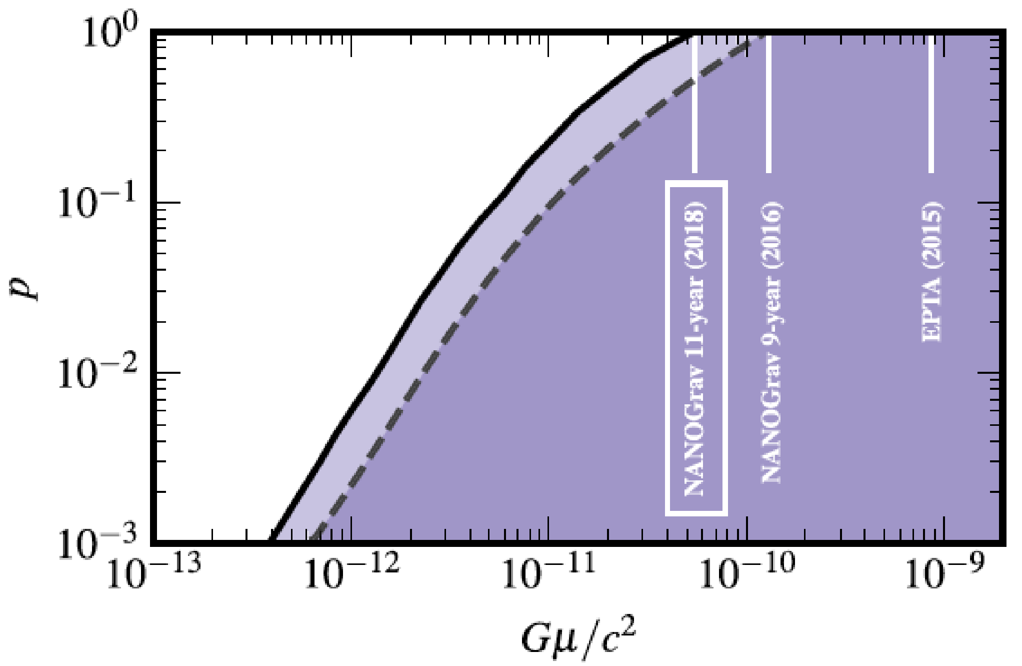
Recent results: SMBBH-GWB limits

- Shannon et al. (2015) ***Science*** 349, 1552
- PPTA 11-yr data, four best pulsars
- Constraints on GWB from SMBBHs



Recent results

Most stringent constraints on cosmic strings

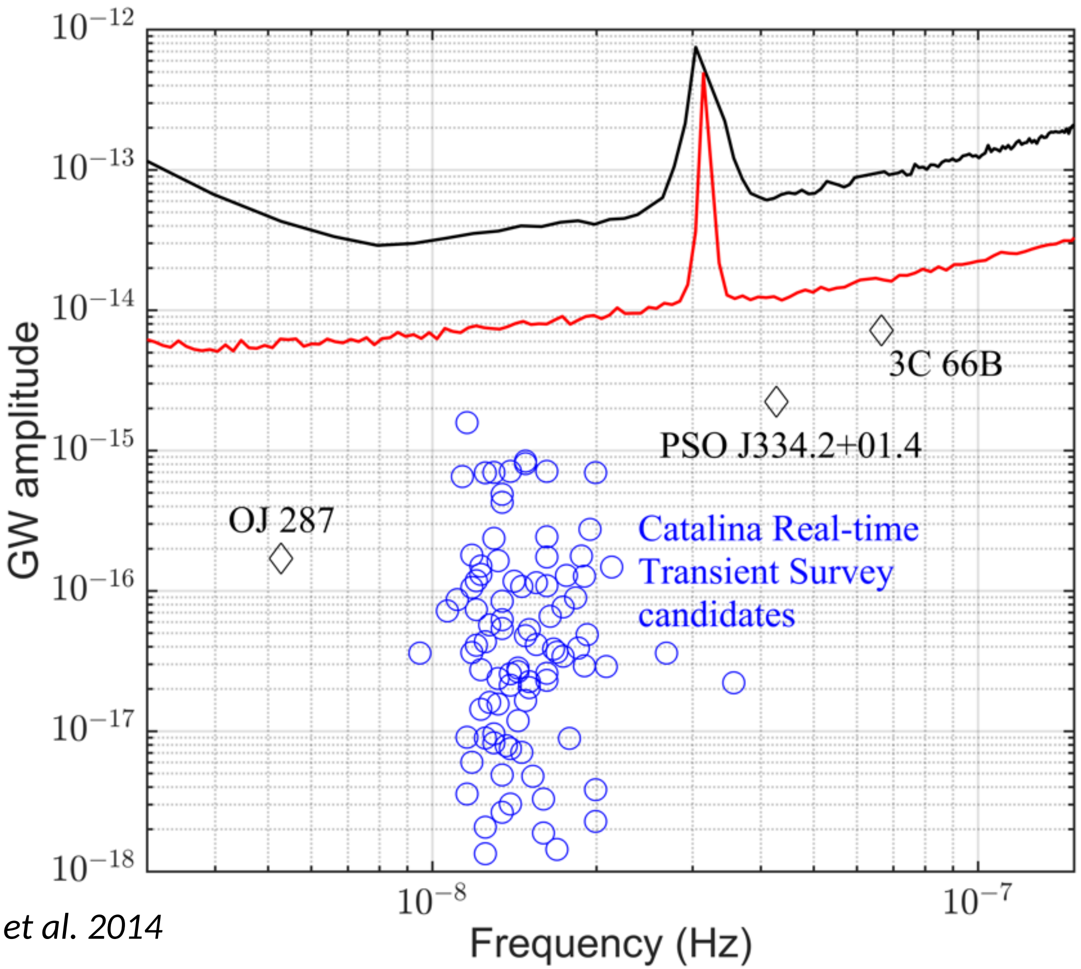


NANOGrav 11-yr
Arzoumanian et al. 2018

Figure 12. Constraints on cosmic-string tension, $G\mu/c^2$, as a function of reconnection probability, p, with the NANOGrav 11 year data set. The excluded region of parameter space is bounded by a solid black line. The corresponding excluded region for the NANOGrav nine-year data set (NG9b) is bounded by a dashed black line, while the EPTA constraints (Lentati et al. 2015) are shown for $p = 1$ only.

Recent results: CW limits

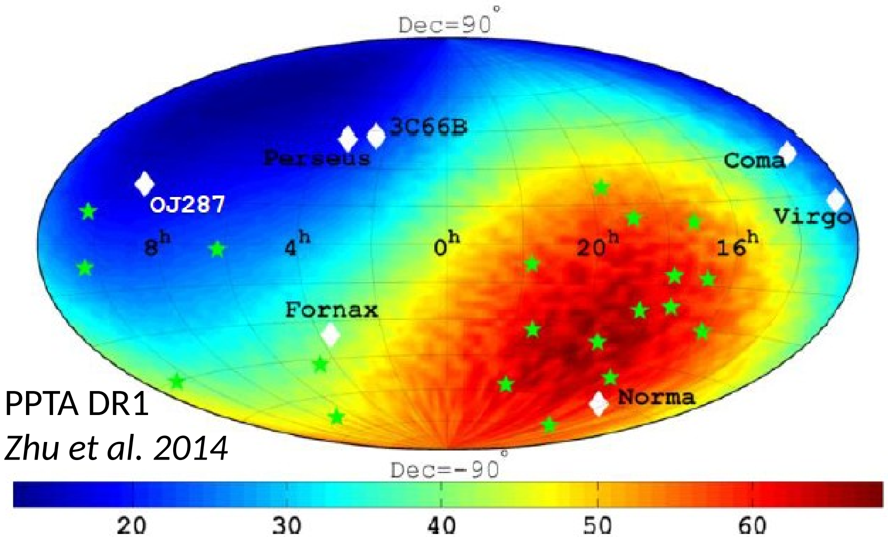
- Black: PPTA DR1
- Red: DR2 expected



PPTA DR1, *Zhu et al. 2014*

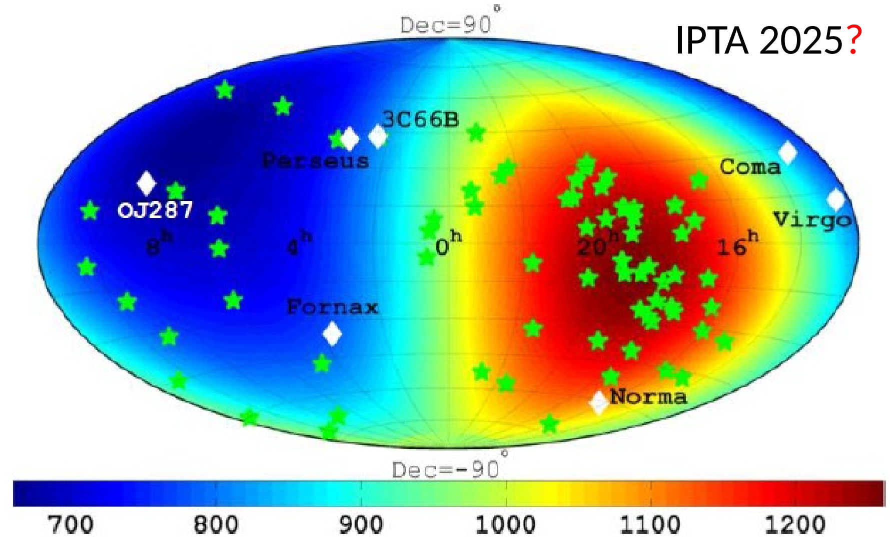
- ❖ 3C 66B is not a binary (Zhu+19)
- ❖ PSOJ334 is probably not a binary (Liu+16)
- ❖ Many CRTS candidates are likely not binaries (Sesana+18)

Recent results: CW sensitivity

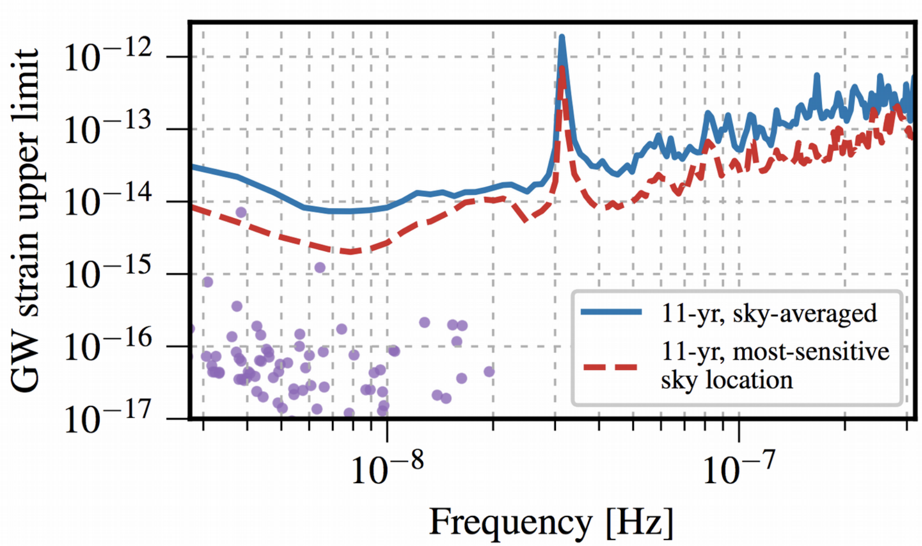


PPTA DR1
Zhu et al. 2014

IPTA 2025?



NANOGrav 11-yr
Aggarwal et al. 2018



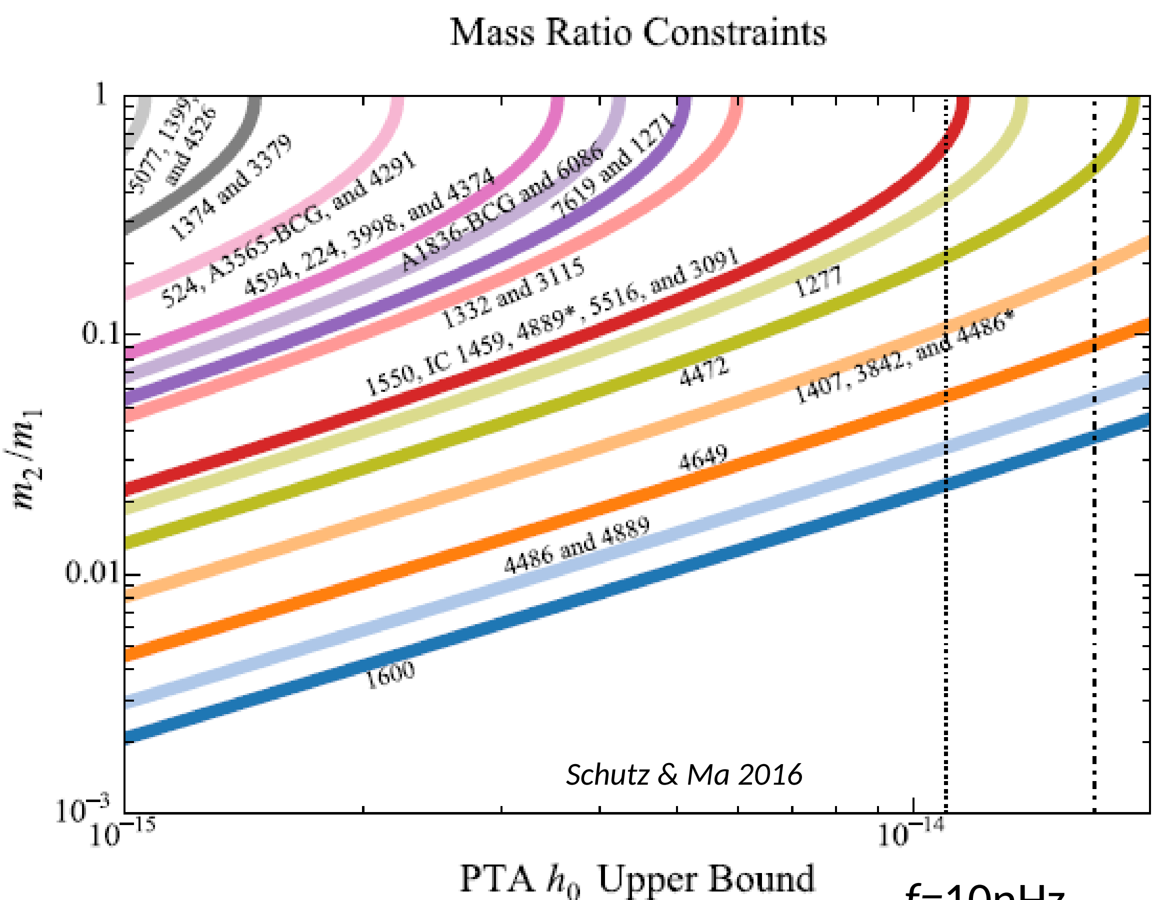
Implications for individual SMBH binaries

Constraints on mass ratios for the hypothetic SMBBHs

1) Direct dynamical measurements of nearby SMBHs

2) 2) the most massive early-type galaxies within 108 Mpc

- For $M_t > 5 \times 10^9 M_\odot$ (e.g., NGC 4889, NGC 4486, NGC 4649, and NGC 1600), mass ratio < a few percent



f=10nHz

$$h_0 = 2\frac{(GM_c)^{5/3}}{c^4}\frac{(\pi f)^{2/3}}{d_L}$$

THE ASTROPHYSICAL JOURNAL, 625:L123–L126, 2005 June 1

DETECTING THE STOCHASTIC GRAVITATIONAL WAVE BACKGROUND USING PULSAR TIMING

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Received 2005 February 13; accepted 2005 April 19; published 2005 May 9

ABSTRACT

The direct detection of gravitational waves is a major goal of current astrophysics. We provide details of a new method for detecting a stochastic background of gravitational waves using pulsar timing data. Our results show that regular timing observations of 40 pulsars each with a timing accuracy of 100 ns will be able to make a direct detection of the predicted stochastic background from coalescing black holes within 5 years. With an improved prewhitening algorithm, or if the background is at the upper end of the predicted range, a significant detection should be possible with only 20 pulsars.

✓Expected sensitivity for a GWB

✓Populations of SMBBHs

✓Direct search for individual SMBBHs out to ~100 Mpc

- Detection could be imminent; *but be patient as signal cycle human lifetime*
- New facilities (UWL, MeerKAT, FAST, … SKA), new pulsars
- Multimessenger search!