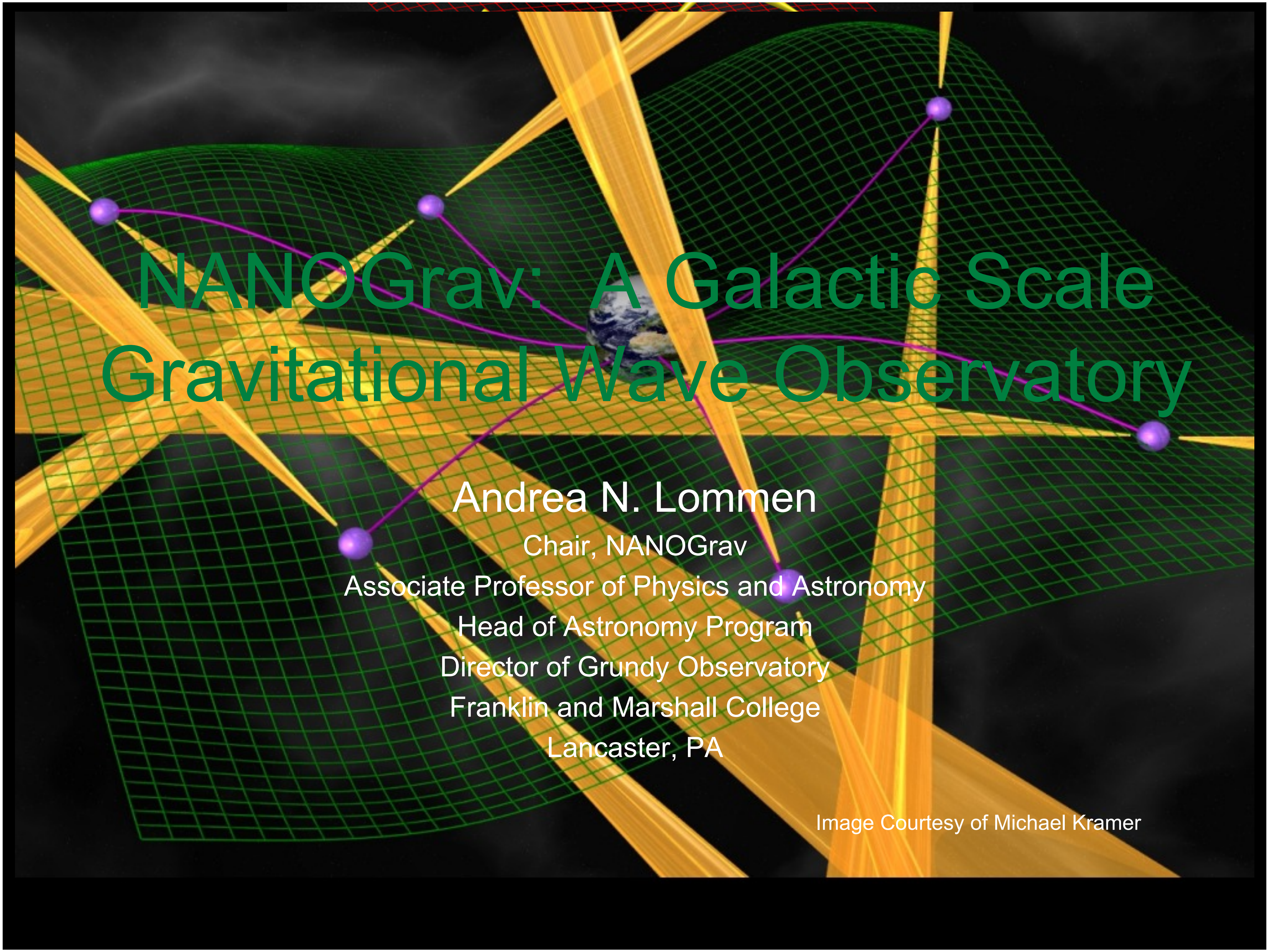


NANOGrav: A Galactic Scale Gravitational Wave Observatory

Andrea N. Lommen

Chair, NANOGrav

Associate Professor of Physics and Astronomy

Head of Astronomy Program

Director of Grundy Observatory

Franklin and Marshall College

Lancaster, PA

Image Courtesy of Michael Kramer

Talk represents work with:

- NANOGrav
- European Pulsar Timing Array
- Parkes Pulsar Timing Array

Thrilled with the work of:

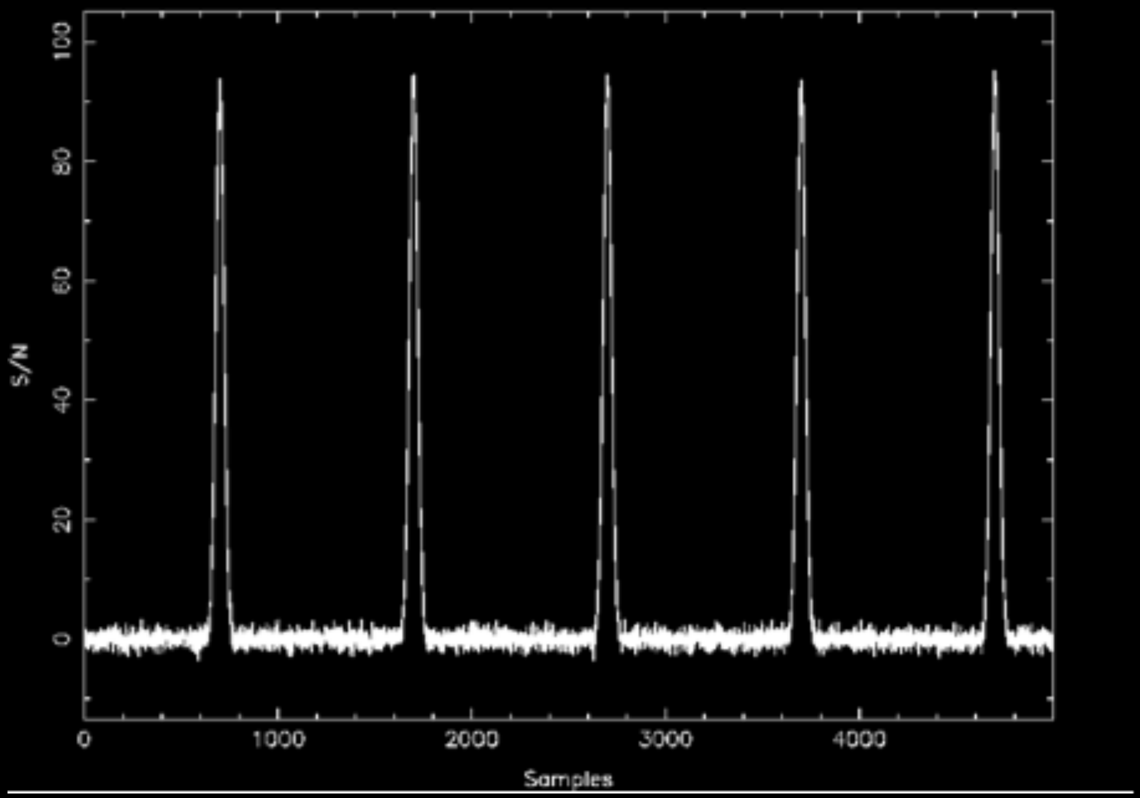
- A. Sesana, A. Vecchio, M. Volunteri, C. N. Colacino
- Melissa Anholm, Xavier Siemens, Larry Price, U. Milwaukee
- Joe Romano, Graham Woan

The International Pulsar Timing Array

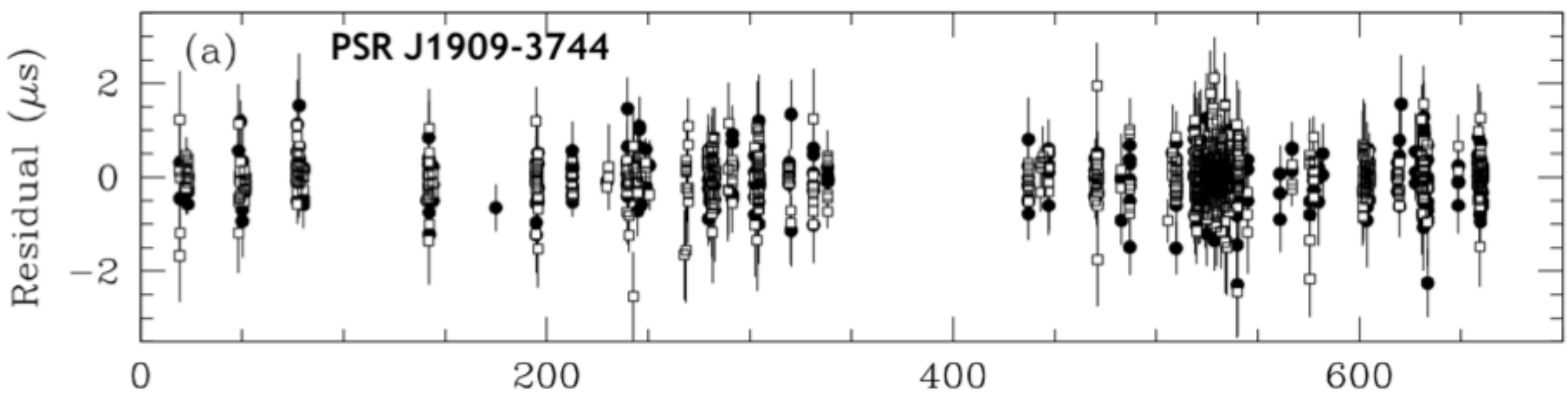
Concept of Using Pulsars to Detect Gravitational Radiation

- Imprint on Pulsar timing residuals
  - Sazhin 1978
- Explicit connection between Doppler data from spacecraft and pulsar timing data
  - Detweiler 1979
- Concept of a Pulsar Timing Array
  - Foster and Backer 1990
- First limit on stochastic GW background
  - Stinebring, Ryba, Taylor, & Romani 1990

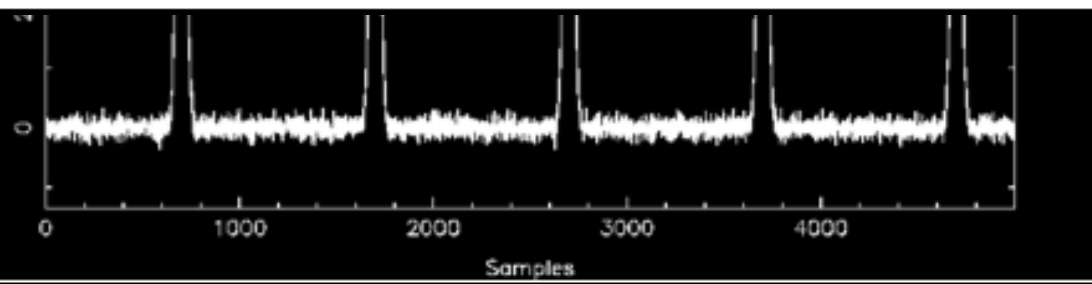
Stability of the clocks



Stability of the clocks



(From Jacoby et al. 2005, ApJL, 629, 113)



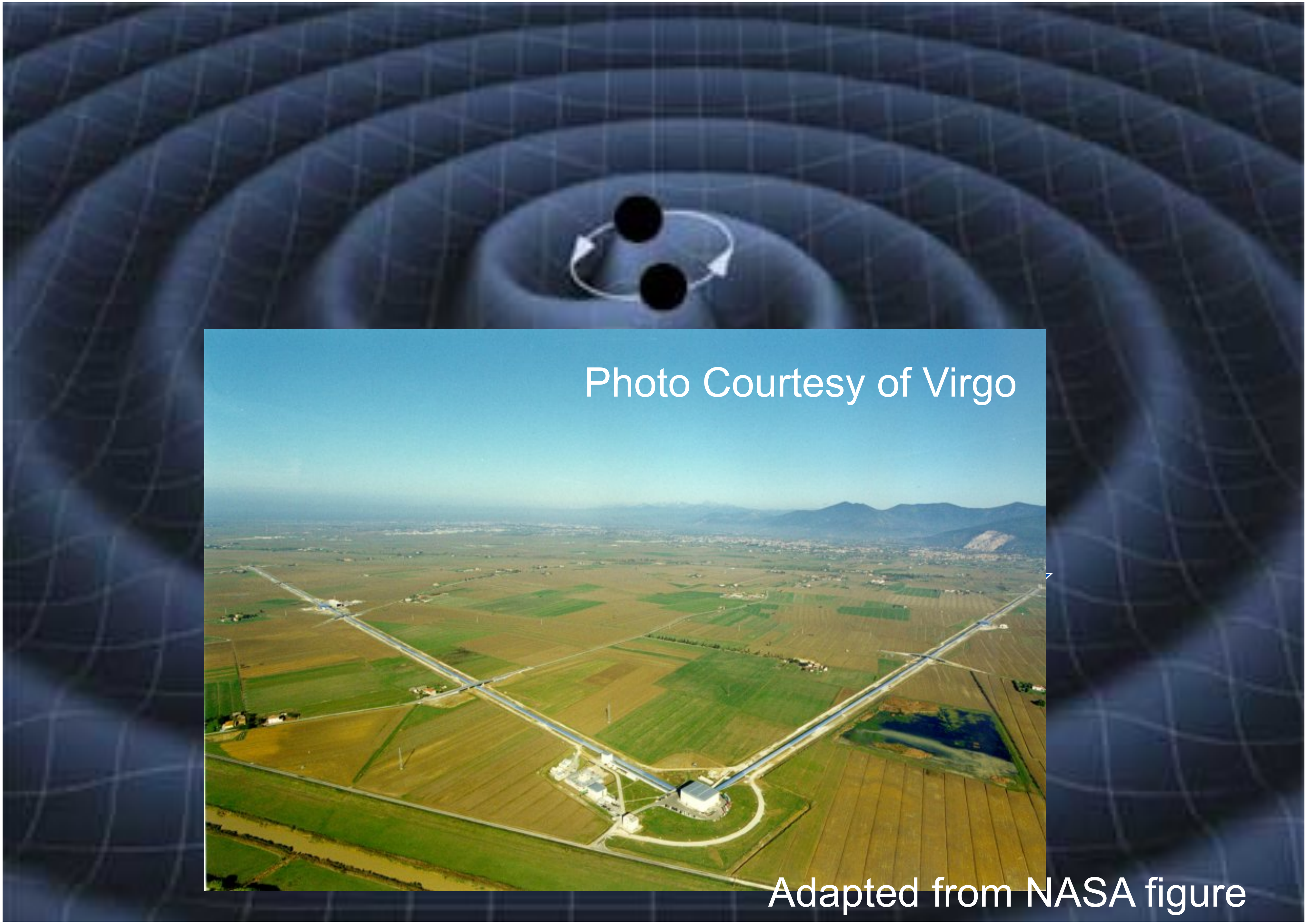
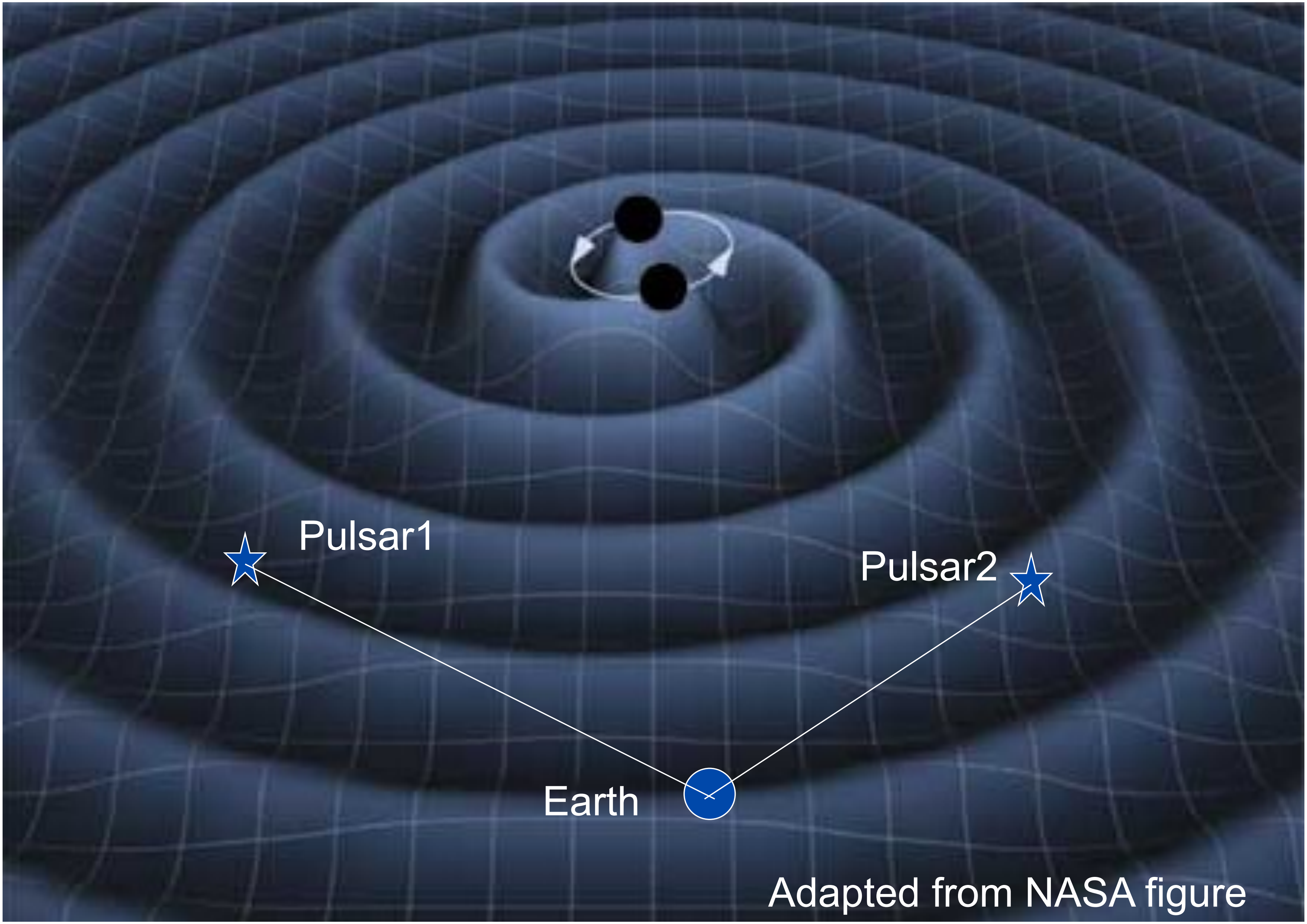


Photo Courtesy of Virgo
Adapted from NASA figure


Pulsar1
Pulsar2
Earth
Adapted from NASA figure

Most obvious GW source: SuperMassive Black Hole Binaries

$$h = \frac{M^{5/3}}{P^{2/3} d}$$

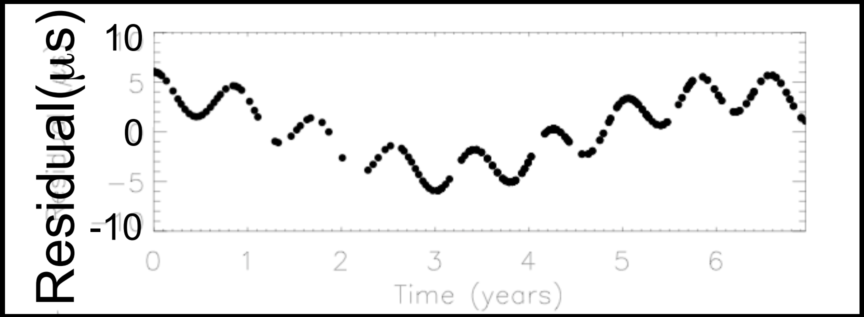
$$\tau = hP$$

$$\tau = \frac{M^{5/3} P^{1/3}}{d}$$

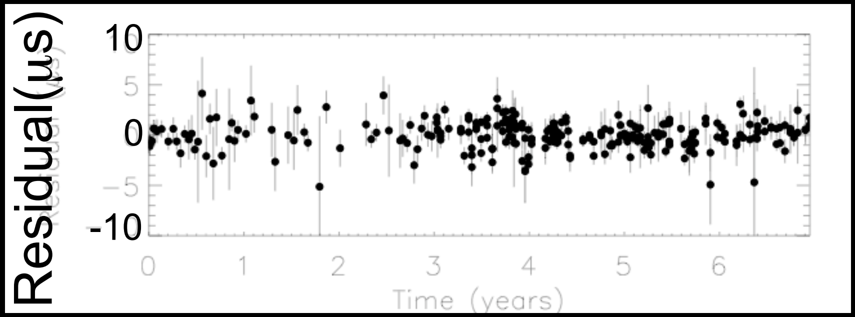
$$\tau = 50ns \frac{\left(\frac{M}{2 \times 10^{9} M_{\Theta}}\right)^{5/3} \left(\frac{P}{1 year}\right)^{1/3}}{\left(\frac{d}{100\, Mpc}\right)}$$

Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary Sudou, Iguchi, Murata, Taniguchi (2003) Science 300: 1263-1265.

Constraining the Properties of Supermassive Black Hole Systems Using Pulsar Timing: Application to 3C 66b, Jenet, Lommen, Larson and Wen (2004) ApJ 606:799-803.



Simulated residuals due to 3c66b



Data from Kaspi, Taylor, Ryba 1994

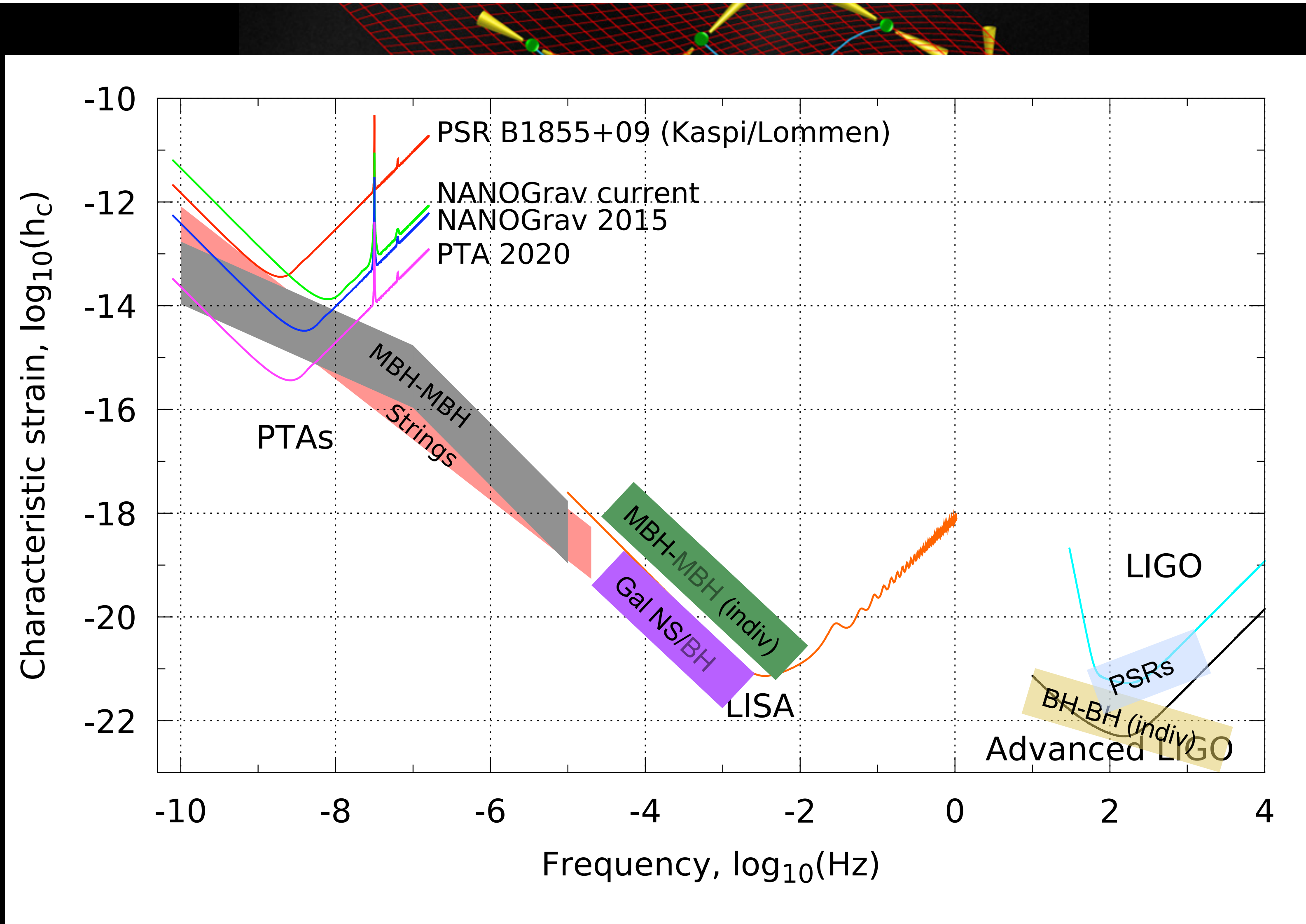
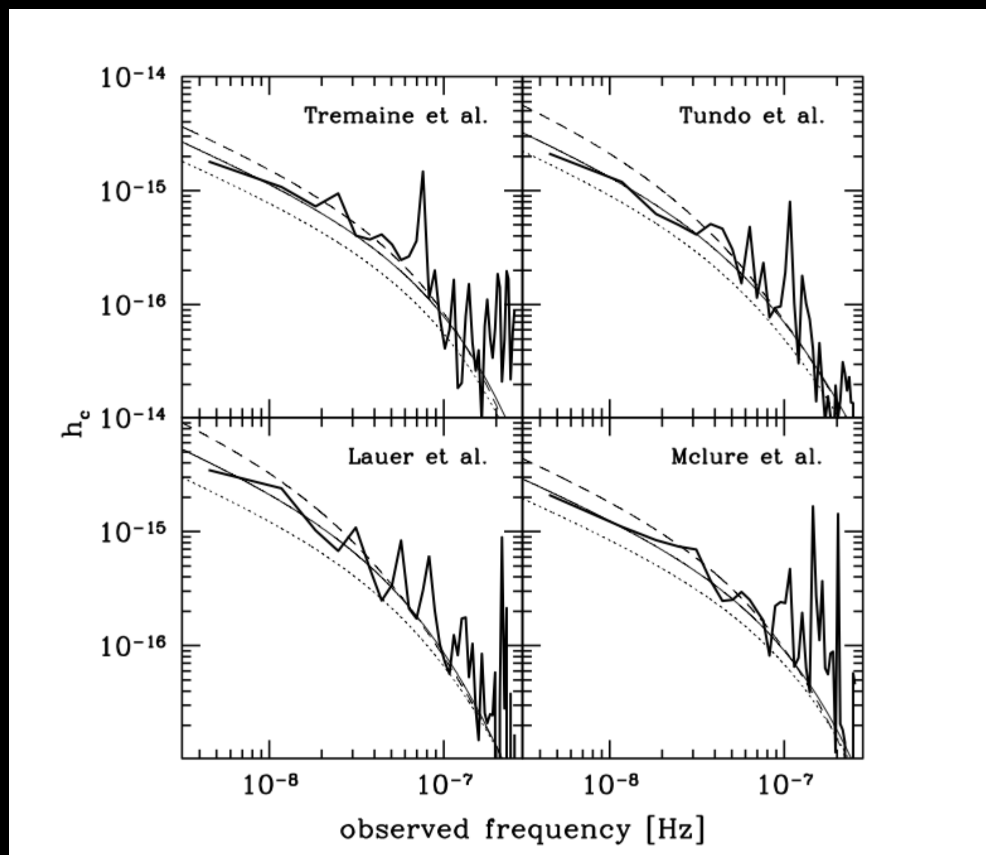
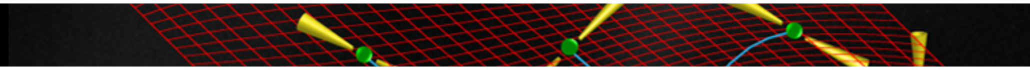
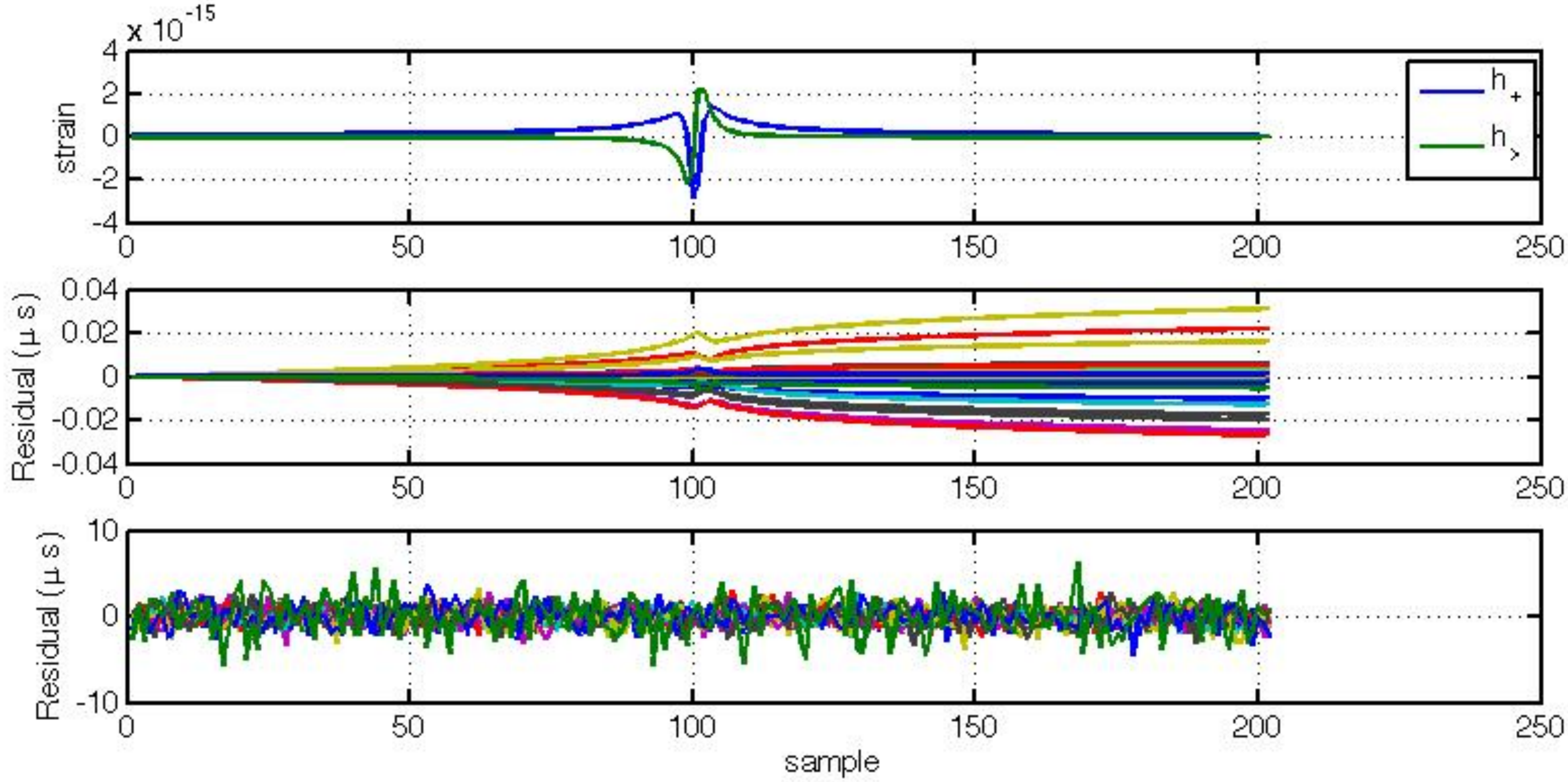


Figure by Paul Demorest (see arXiv:0902.2968)

Sesana, Vecchio and Volunteri 2009





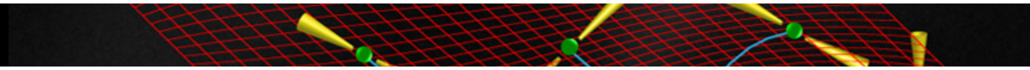


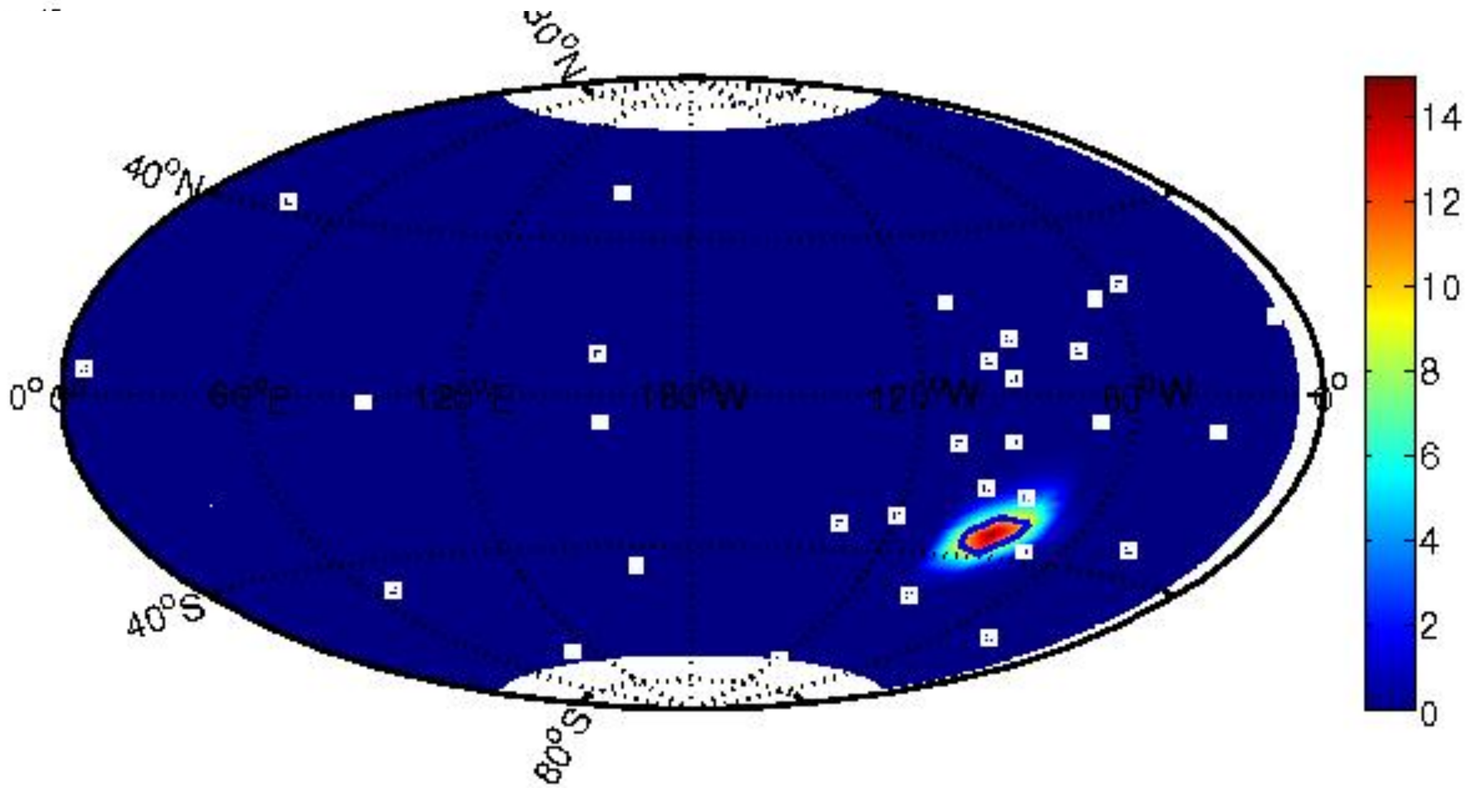
2 10^9 solar mass black holes flying by each other with a separation of 40 Schwarzschild Radii.

Distance: 100 Mpc

30 IPTA pulsars

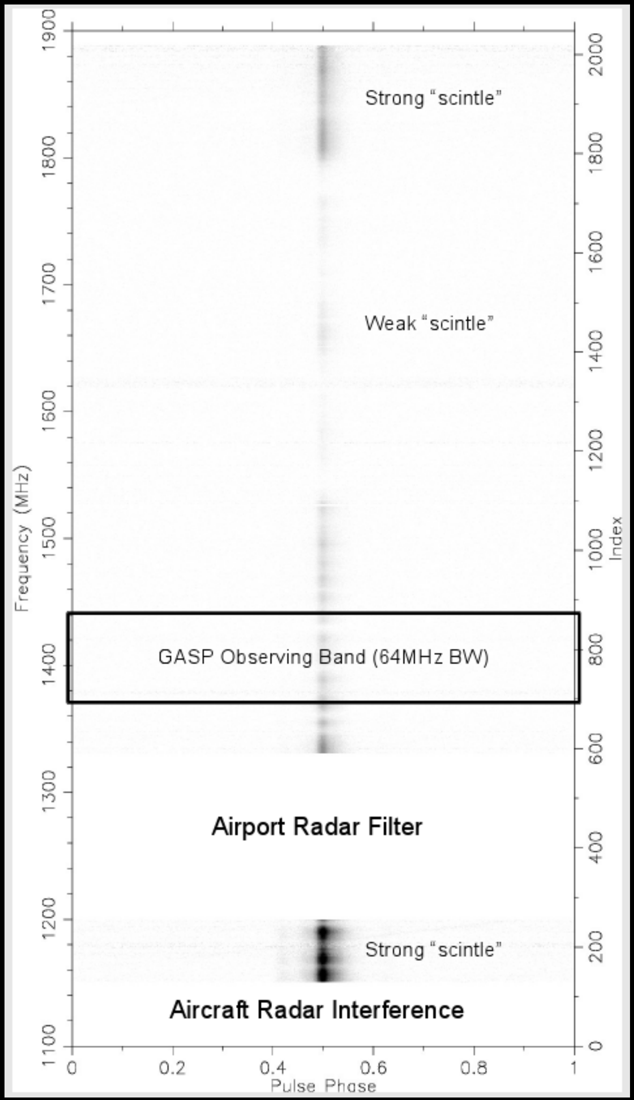
Using Maximum Entropy analysis (Summerscales et al 2008)

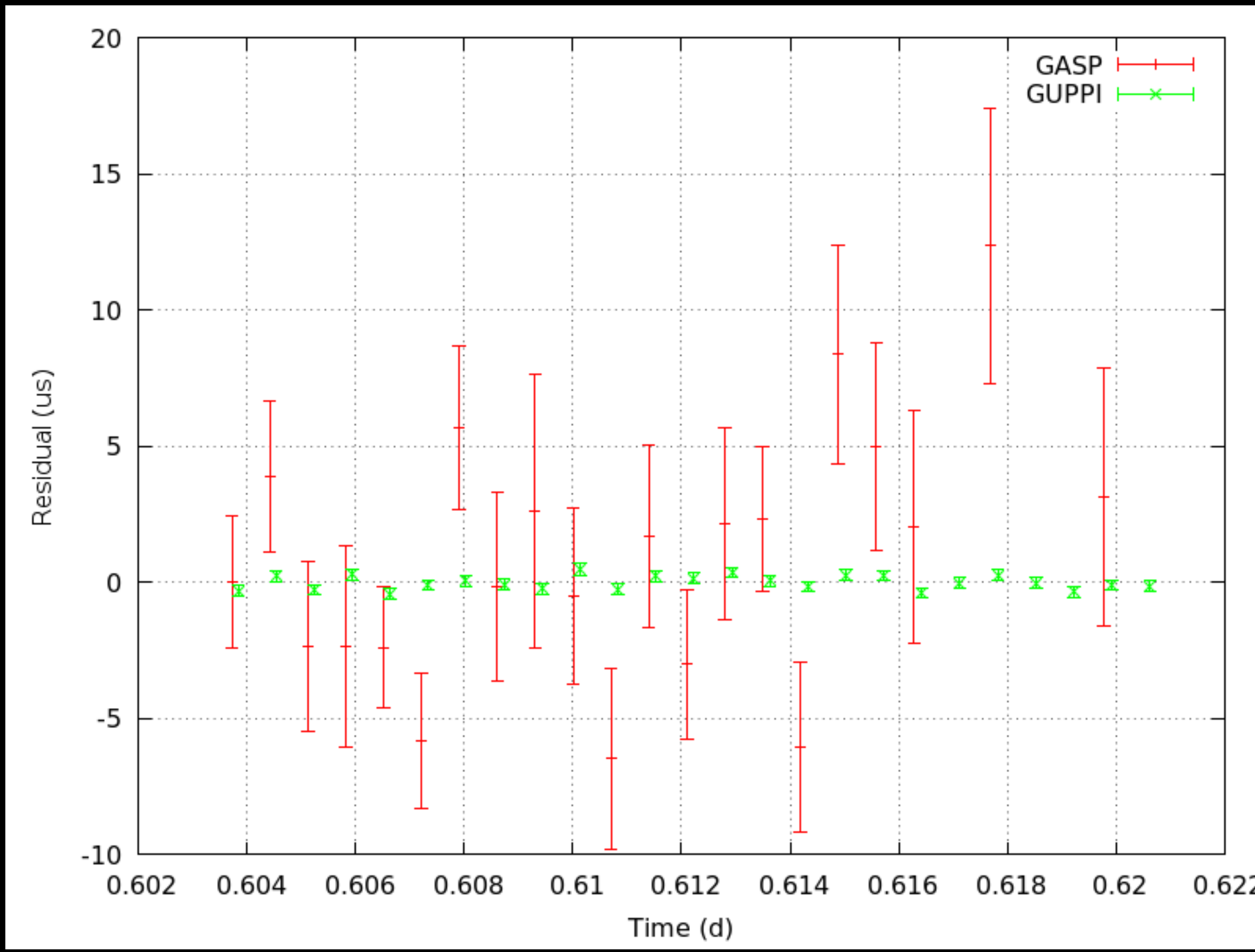


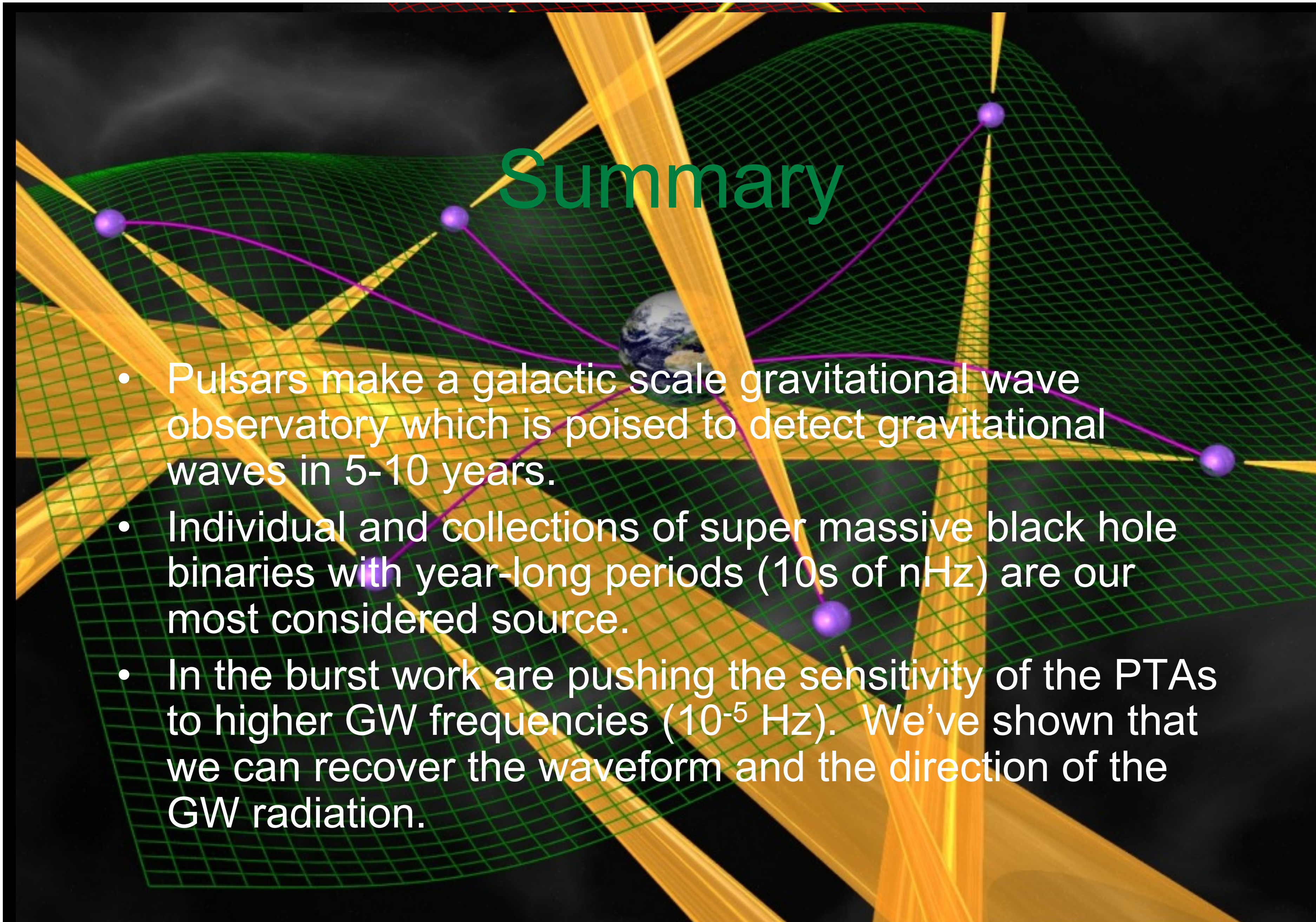


2 10^9 solar mass black holes flying by each other with a separation of 40 Schwarzschild Radii.
Distance: 100 Mpc
30 IPTA pulsars
Using Maximum Entropy analysis (Summerscales et al 2008)

The Advantage of New Wide-band Backend System at Green Bank "GUPPI"



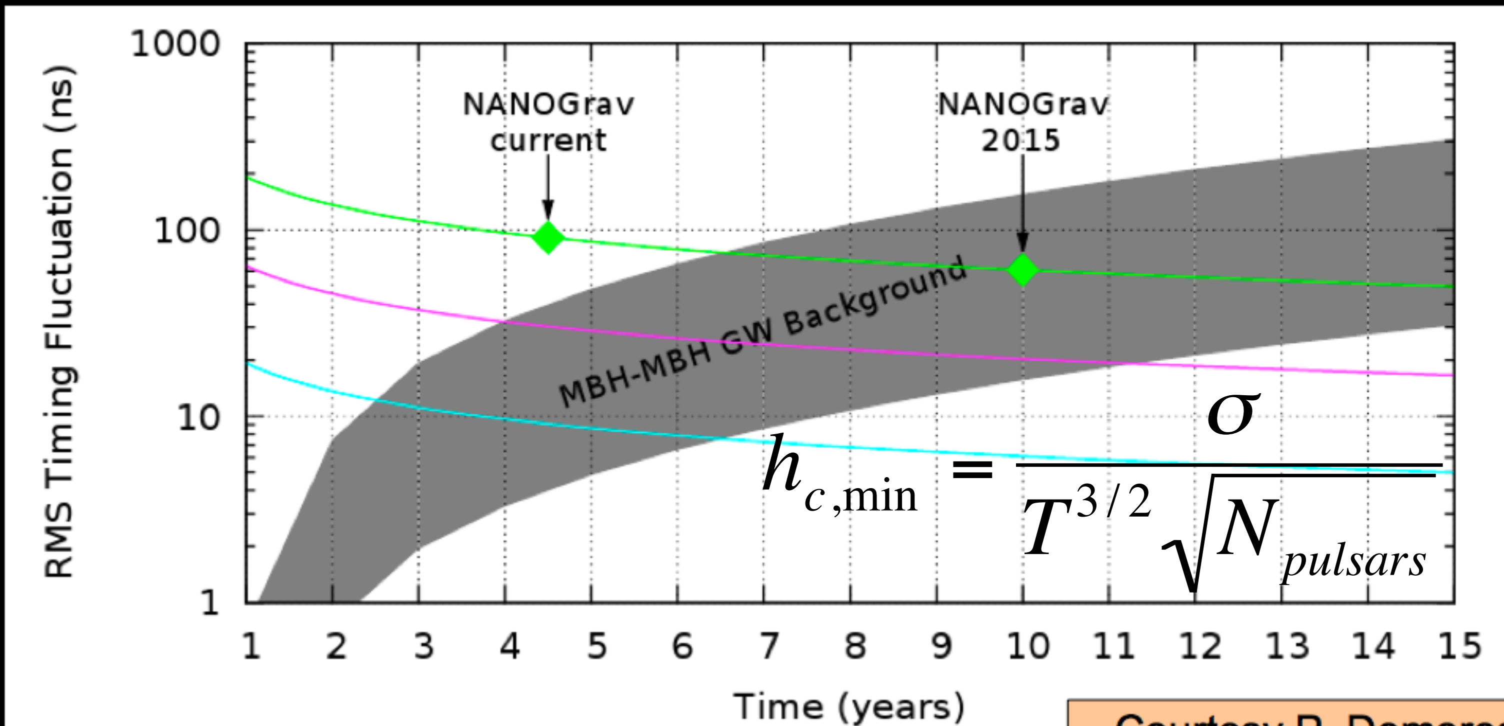

GASP
GUPPI
Residual (us)
Time (d)
20
15
10
5
0
-5
-10
0.602
0.604
0.606
0.608
0.61
0.612
0.614
0.616
0.618
0.62
0.622



Summary

- Pulsars make a galactic scale gravitational wave observatory which is poised to detect gravitational waves in 5-10 years.
- Individual and collections of super massive black hole binaries with year-long periods (10s of nHz) are our most considered source.
- In the burst work are pushing the sensitivity of the PTAs to higher GW frequencies (10^{-5} Hz). We've shown that we can recover the waveform and the direction of the GW radiation.

NANOGrav improvement with time...



Courtesy P. Demorest

Magenta and cyan curves show what happens if we improve our ability to time the pulsars by factors of ~3 and 10

Detectability of a Waveform

$$g_{\mu\upsilon} = \eta_{\mu\upsilon} + h_{\mu\upsilon}$$

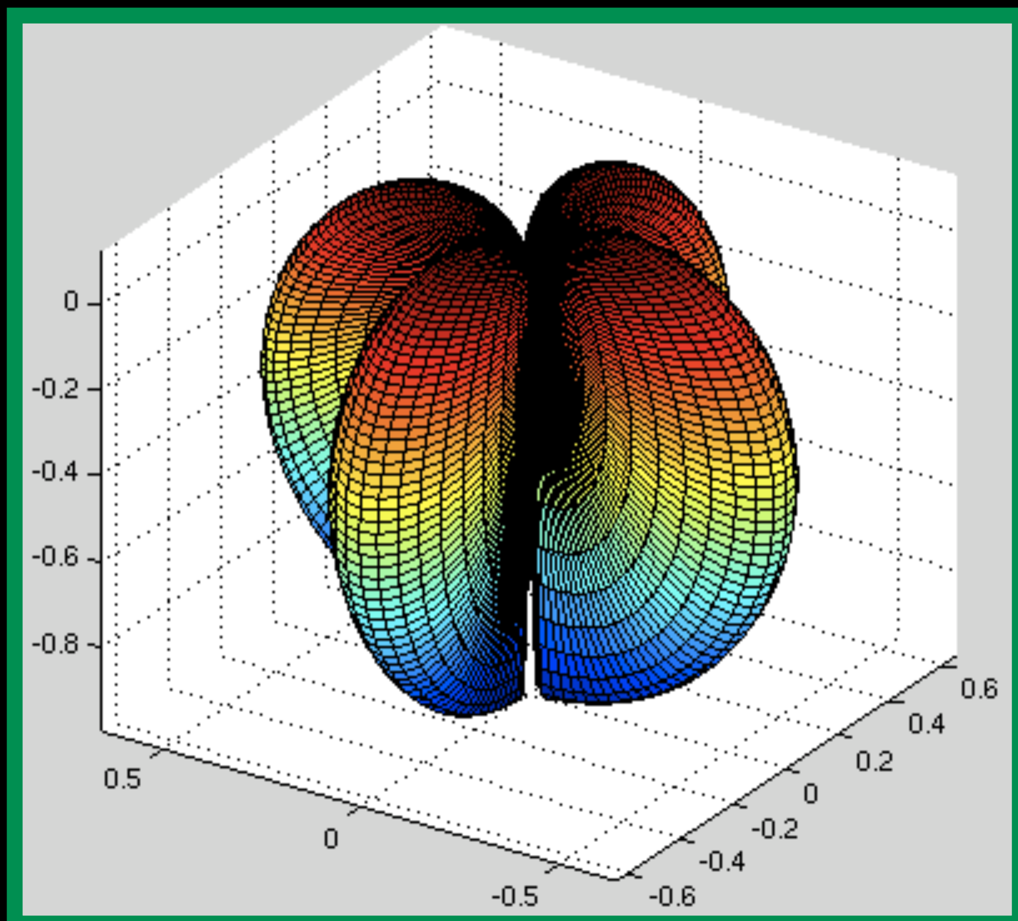
$$\left(\frac{dt}{d\lambda}\right)^2 = \delta_{jk}\frac{dx^j}{d\lambda}\frac{dx^k}{d\lambda} + \frac{dx^j}{d\lambda}\frac{dx^k}{d\lambda}h_{jk}(t,\vec{x})$$

$$\int dt = \int d\lambda - \frac{1-k_m n^m}{1+k_m n^m}\int d\lambda n^j n^k h_{jk}\left(t(\lambda),\vec{x}(\lambda)\right)$$

$$\text{Residual} = e_{jk}n^j n^k \frac{h_0}{2}\left(1-k_m n^m\right)\left[f(t_0) - f\left(t_0 - L\left(1+k_m n^m\right)\right)\right]$$

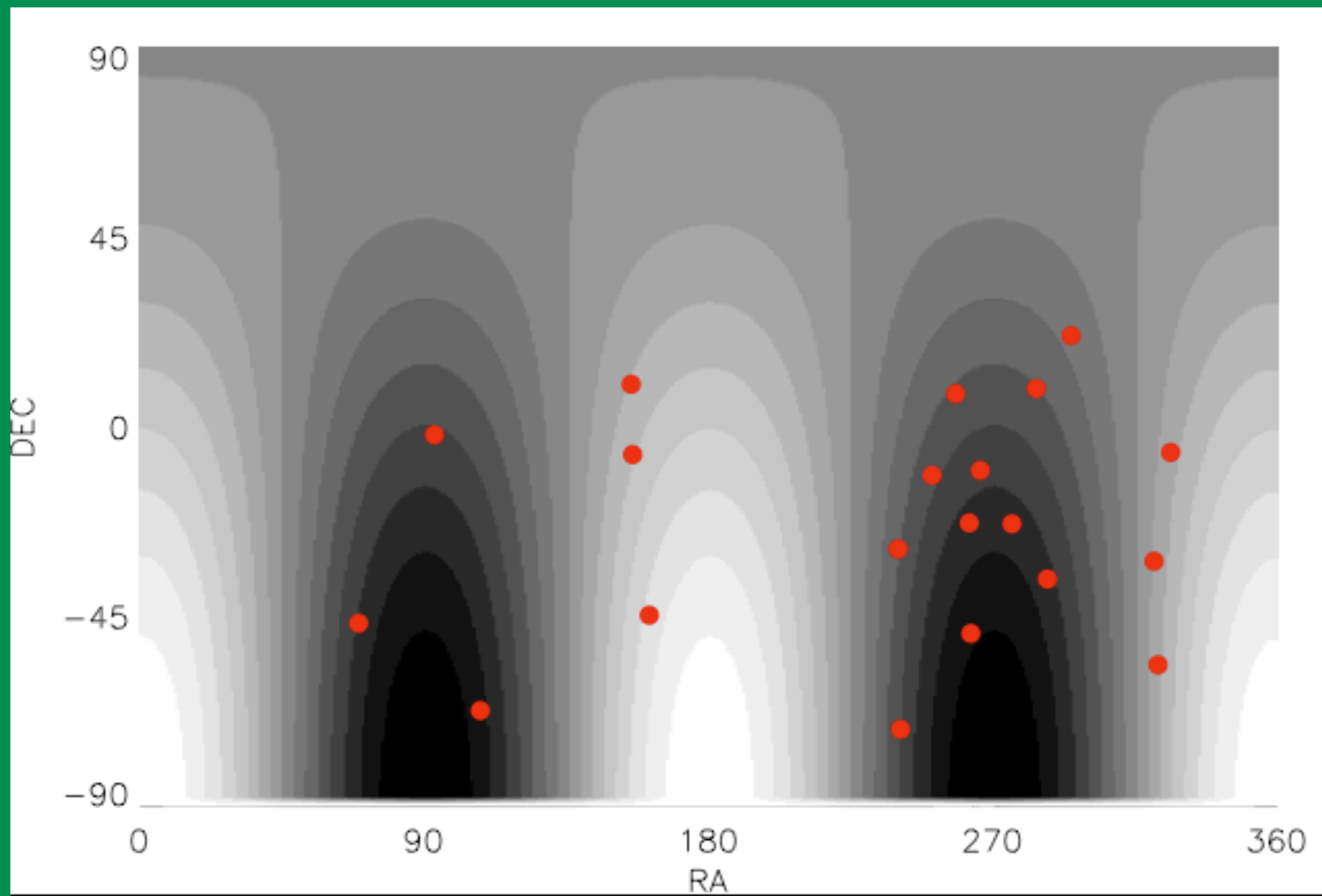
where $h_{jk}(t,\vec{x}) = h_0 f'\left(t - \hat{k}\cdot\vec{x}\right)\mathbf{e}$ and L is the distance to the pulsar

The shape of the GW response

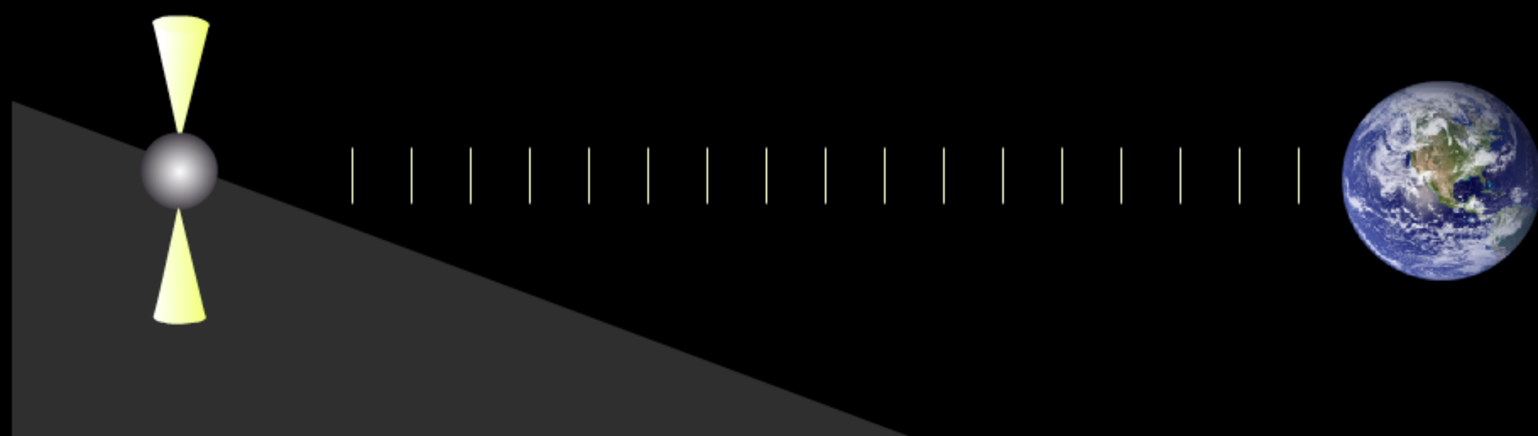


Thanks Bill Coles

NANOGrav



NANOGrav



Graphic: Penn State University

Larger impact parameter is also more detectable

$$a^3 \propto MP^2$$

$$\tau \propto \frac{M^{3/2} a^{1/2}}{d}$$

Maximum Entropy

$$d = n + Rh \Rightarrow n = d - Rh$$

$$p(d \mid h,k,R,N) = \frac{\exp\left[-\frac{1}{2}x^T N^{-1} x\right]}{\sqrt{(2\pi)^{\dim x} \det\|N\|}}$$

$$where$$

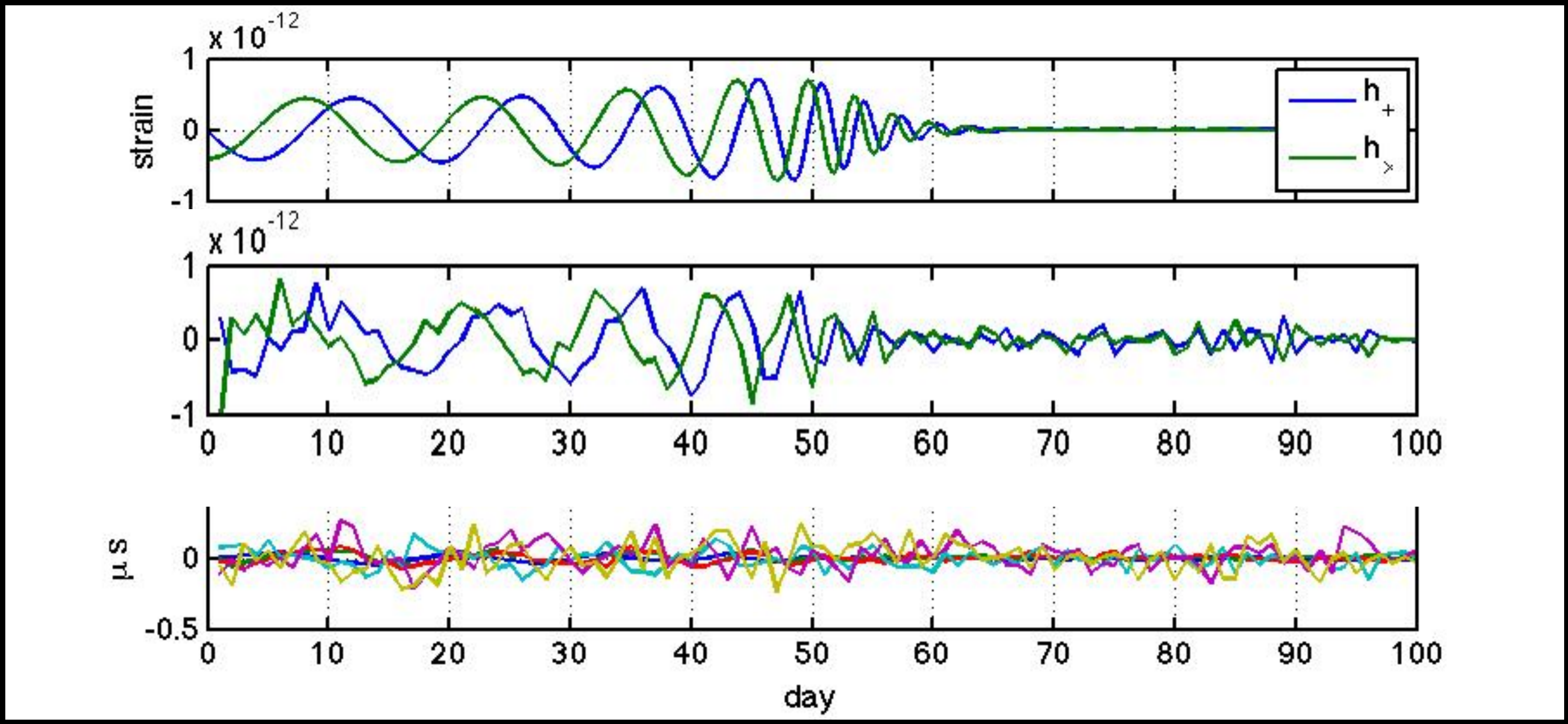
$$x = d - Rh$$

$$entropy:$$

$$H(p) = \int dx^n \, p \ln(p)$$

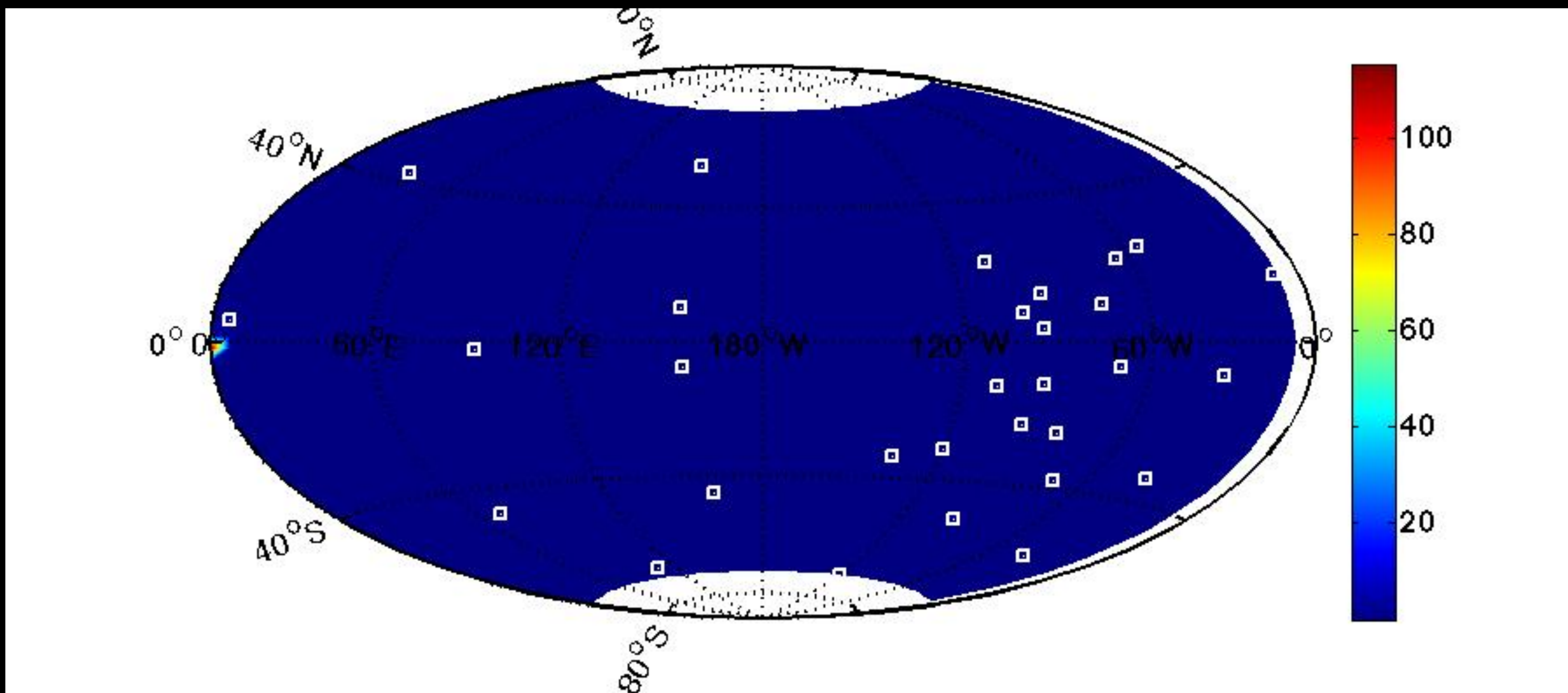
Summerscales, Burrows, Finn and Ott 2008

A 5 x 10^9 solar-mass black hole binary coalescing 100 Mpc away.
30 IPTA pulsars, improved by 10, sampled once a day.



Thank you to Manuela Campanelli, Carlos O. Lousto, Hiroyuki Nakano, and Yosef Zlochower for waveforms. Phys.Rev.D79:084010 (2009). http://ccrg.rit.edu/downloads/waveforms

Probability density



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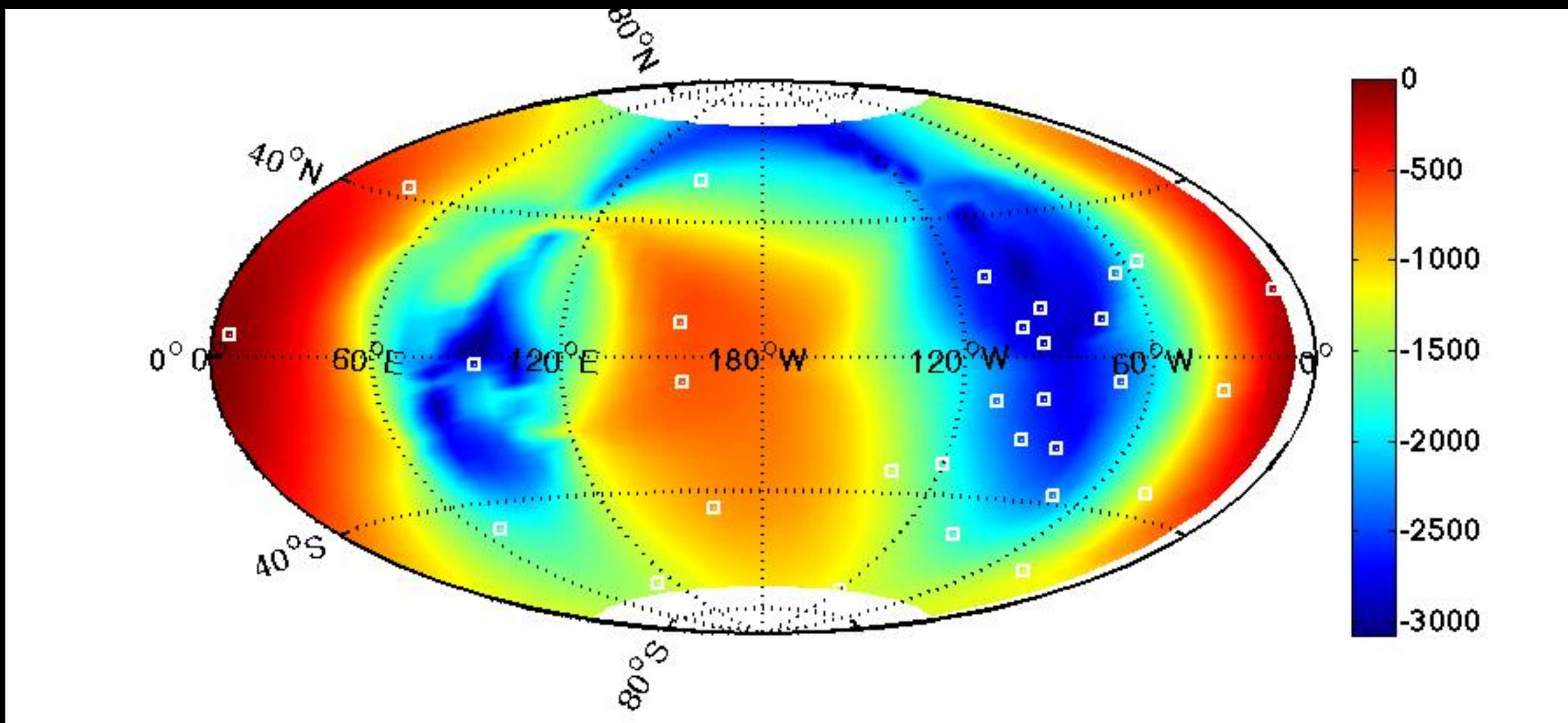
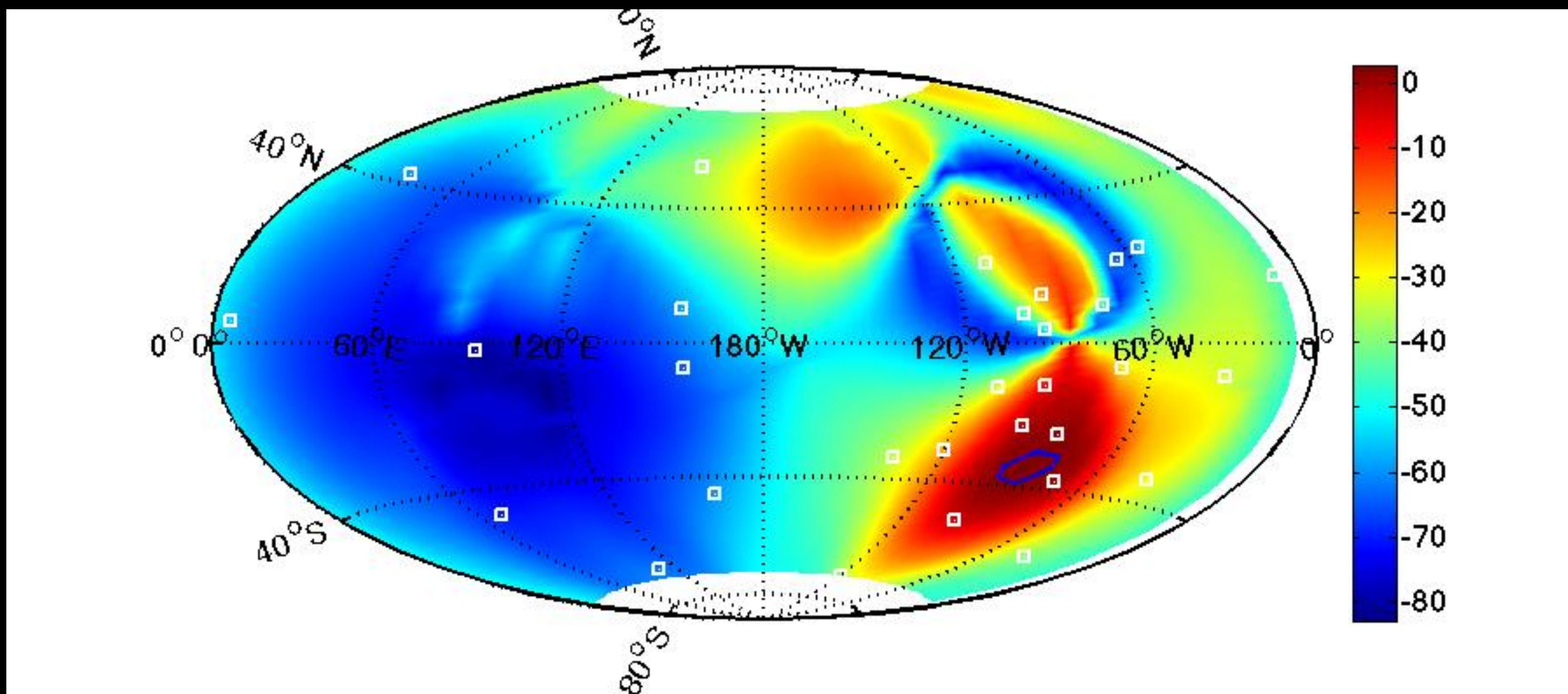
Log of probability density



Log(probability density) as a function of sky position



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So how do we improve?

(in approx order of difficulty)

- Patience...

$$h_{c,\mathrm{min}} \propto \frac{\sigma}{T\sqrt{N_{\mathrm{TOAs}}N_{\mathrm{PSRs}}}} \sim \frac{\sigma}{T^{3/2}\sqrt{N_{\mathrm{PSRs}}}}$$

- International PTA
- New instrumentation (more BW)
- Find more and better MSPs
- Better timing algorithms
- Improved understanding of the systematics. e.g. interstellar medium (ISM) effects
- Bigger telescopes (i.e. *FAST* and *SKA*)

Rms and dataspan are the currency of the field

$$f_{\min} \approx \frac{1}{dataspan}$$

$$h_c(f_{\min}) \approx \frac{rms}{dataspan}$$

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

$$\Omega_{gw}(f) \propto \frac{rms^2}{dataspan^4}$$

From Jenet, Hobbs, van Straten, Manchester, Bailes, Verbiest, Edwards, Hotan, Sarkissian & Ord (2006)

Detectability of a Waveform (continued)

So what matters is the integral of the waveform:

$$R = \int_0^t h(\tau)d\tau$$

Sinusoidal source:

$$R = \int_0^t h_0 \cos(\omega\tau)d\tau = \frac{h_0}{\omega}\sin(\omega t) = h_0 \frac{P}{2\pi}\sin(\omega t)$$

or a Gaussian source:

$$R = \int_0^t h_0 e^{-((\tau - t_c)/\sigma)^2} d\tau = h_0 \sigma\sqrt{\pi}$$

Table from NANOGrav white paper (Demorest, Lazio & Lommen, 2009)

Table 1: International PTA telescope time in terms of a 100-m dish with $T_{sys} = 30$K.

Telescope	Diameter (m)	ϵ[a]	T_{sys} (K)	$\epsilon A / T_{sys}$ (normalized)	Allocated Time/mo (h)	100-m equiv. time (h)
Current Projects						
Arecibo	305	0.5	30	5.0	8	200
Europe	∼100	0.7	30	0.7	125[b]	60
GBT	100	0.7	20	1.1	18	20
Parkes	64	0.6	25	0.3	100	10
Future Projects						
Europe-LEAP	200[c]	0.7	30	3.0	24	220
EVLA	130[c]	0.5	30	0.9	*TBD*	–
ATA-350	110[c]	0.6	40	0.6	*TBD*	–
SKA	750[c]	0.6	35	30	*TBD*	–
Total (Current)						290
Requirements						
GW Detection[d]						500
Advanced GW Study[e]						>1000

[a] Includes the effects of reflector efficiency and partial illumination.
[b] This represents the combined observing time of four European 100-m class dishes.
[c] Equivalent single-dish diameter.
[d] 20 pulsars with $\lesssim$100 ns RMS timing.
[e] >40 pulsars with $\lesssim$100 ns RMS timing.

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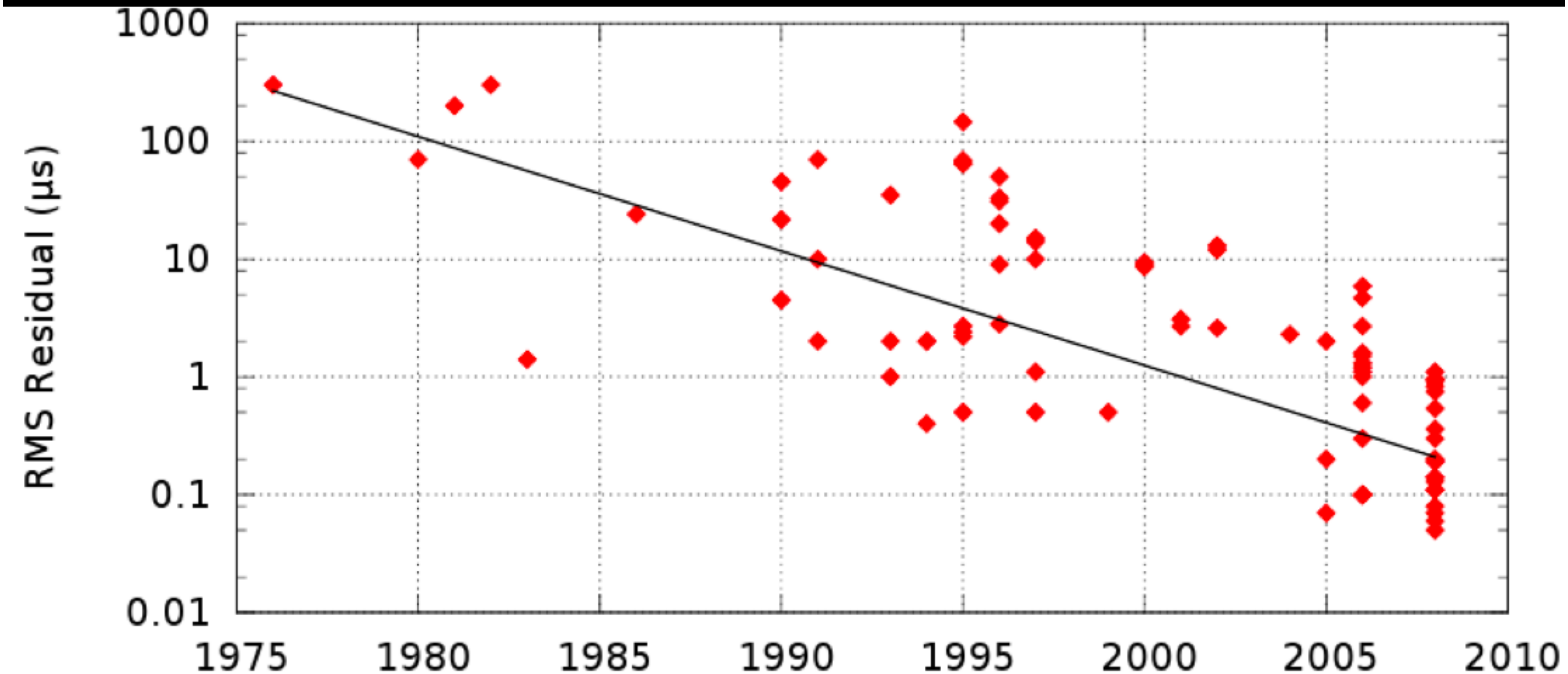
RMS Residual (μs)
1000
100
10
1
0.1
0.01
1975
1980
1985
1990
1995
2000
2005
2010

Precision Timing Example

- Astrometric Params
  - RA, DEC, μ, π
- Spin Params
  - P_{spin}, $\dot{P}_{spin}$
- Keplerian Orbital Params
  - P_{orb}, x, e, ω, T_0
- Post-Keplerian Params
  - $\dot{\omega}$, γ, $\dot{P}_{orb}$, r , s

~100 ns RMS timing residuals!

Table 1 PSR J0437–4715 physical parameters

Right ascension, α (J2000) ...	$04^h37^m15^s.7865145(7)$
Declination, δ (J2000)	$-47°15'08''.461584(8)$
μ_α (mas yr^{-1})	121.438(6)
μ_δ (mas yr^{-1})	-71.438(7)
Annual parallax, π (mas)	7.19(14)
Pulse period, P (ms)	5.757451831072007(8)
Reference epoch (MJD)	51194.0
Period derivative, $\dot{P}$ (10^{-20}) ..	5.72906(5)
Orbital period, P_b (days)	5.741046(3)
x (s)	3.36669157(14)
Orbital eccentricity, e	0.000019186(5)
Epoch of periastron, T_0 (MJD)	51194.6239(8)
Longitude of periastron, ω (°) .	1.20(5)
Longitude of ascension, Ω (°) .	238(4)
Orbital inclination, i (°)	42.75(9)
Companion mass, m_2 ($M_\odot$) ...	0.236(17)
$\dot{P}_b(10^{-12})$	3.64(20)
$\dot{\omega}$ (°yr^{-1})	0.016(10)

van Straten et al., 2001
Nature, 412, 158

Recent work (e.g. Verbiest et al 2009) shows this is sustainable over 5+ yrs for several MSPs