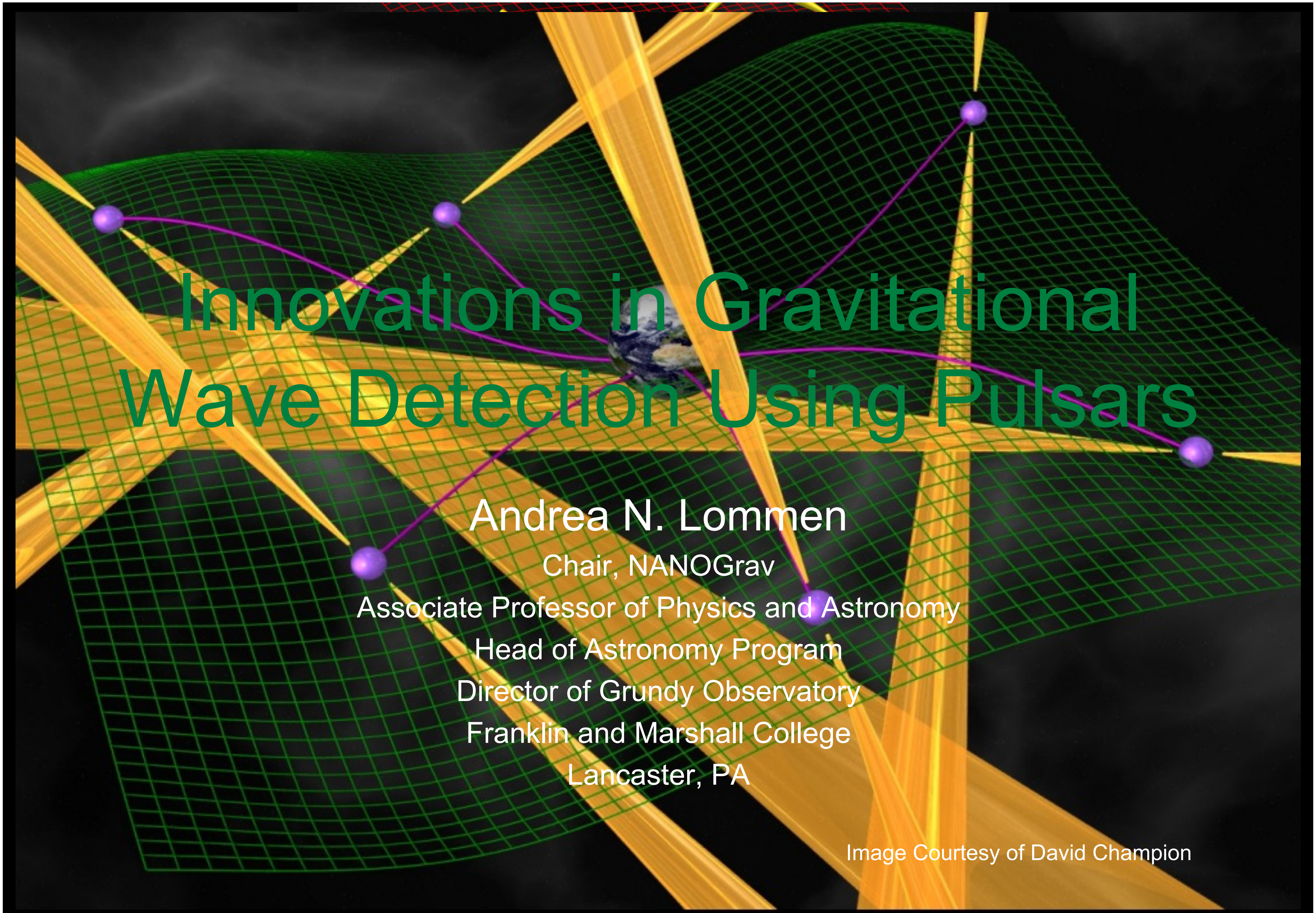


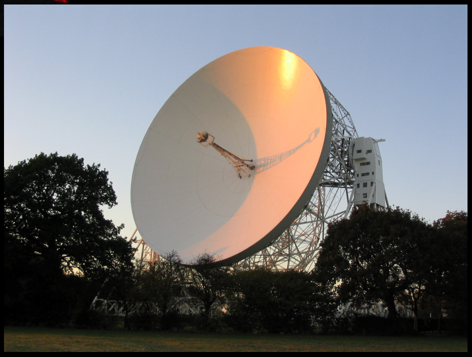
# Innovations in Gravitational Wave Detection Using Pulsars

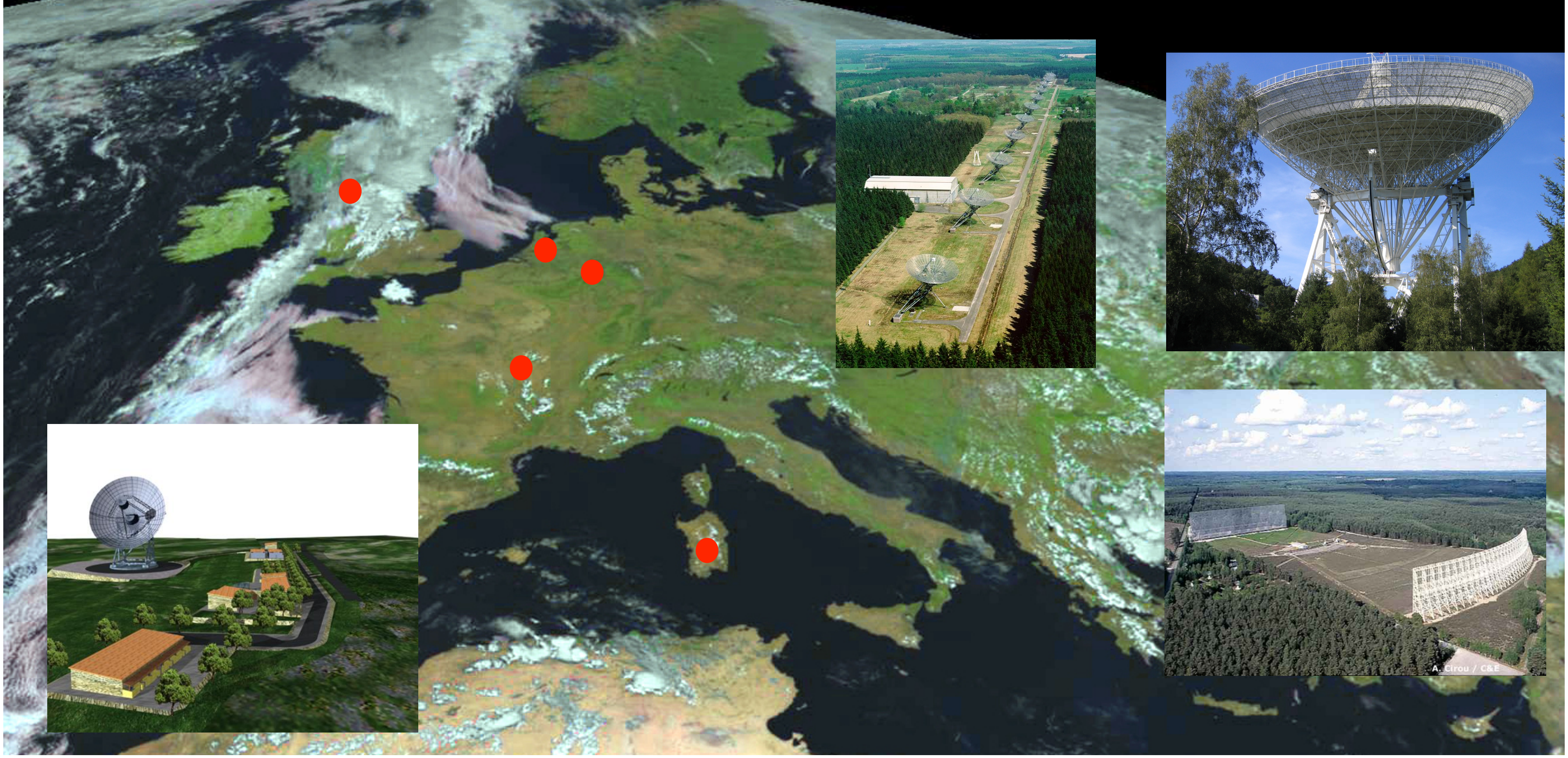
Andrea N. Lommen
Chair, NANOGrav
Associate Professor of Physics and Astronomy
Head of Astronomy Program
Director of Grundy Observatory
Franklin and Marshall College
Lancaster, PA

Image Courtesy of David Champion

# The EPTA: partners

University of Manchester, JBO, UK
ASTRON, NL
Max-Planck Insitut fur Radioastronomie, GER
Nancay Observatory, FR
INAF Osservatorio Astonomico di Cagliari, IT





# The Sardinia radio telescope

64-m fully-steerable: managed by the Cagliari Observatory in Sardinia

Receivers:

- Prime focus: dual L (1.3–1.8 GHz) and P (305–425 MHz) band coaxial
- Gregorian focus: K-band multibeam (18–26 GHz)
- Beam waveguide focus: C-band (5.7–7.7 GHz)

Pulsar observing:

- Digital filterbank on order (from ATNF)
- 2 × 1024 × 0.5 MHz filterbank on site

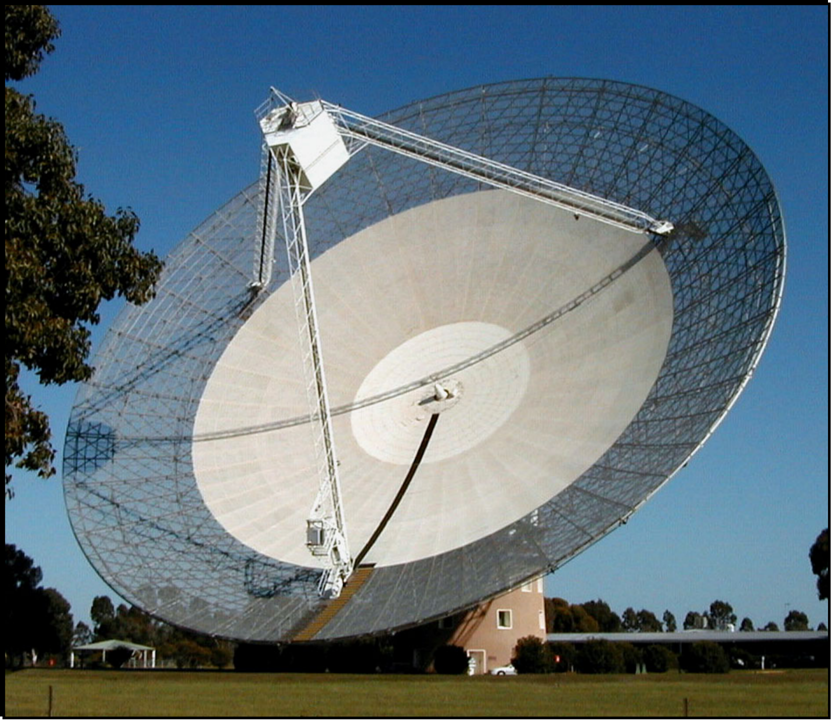
More later...

Slide courtesy of Rob Ferdman

# The Parkes Pulsar Timing Array Project

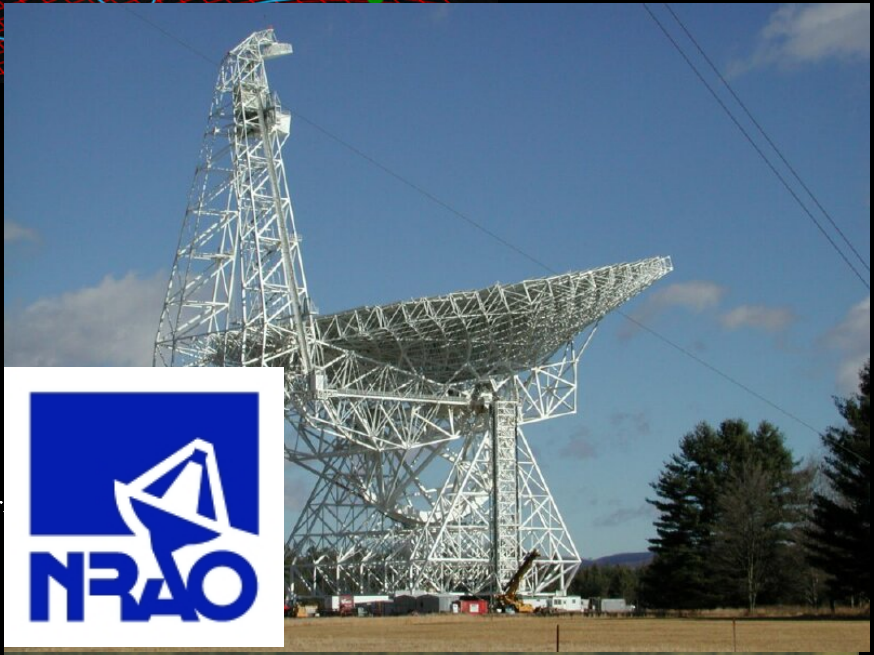
## Collaborators:

- Australia Telescope National Facility, CSIRO, Sydney
  - Dick Manchester, George Hobbs, David Champion, John Sarkissian, John Reynolds, Mike Kesteven, Grant Hampson, Andrew Brown, David Smith, Jonathan Khoo, (Russell Edwards)
- Swinburne University of Technology, Melbourne
  - Matthew Bailes, Ramesh Bhat, Willem van Straten, Joris Verbiest, Sarah Burke, Andrew Jameson
- University of Texas, Brownsville
  - Rick Jenet
- Franklin & Marshall College, Lancaster
  - Andrea Lommen
- University of Sydney, Sydney
  - Daniel Yardley
- National Observatories of China, Beijing
  - Johnny Wen
- Peking University, Beijing
  - Kejia Lee
- Southwest University, Chongqing
  - Xiaopeng You
- Curtin University, Perth
  - Aidan Hotan



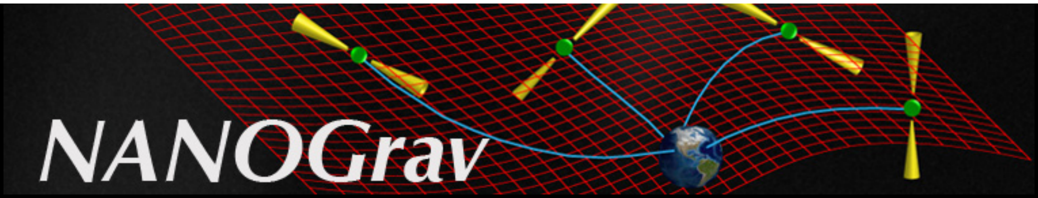
# NANOGrav

- Anne Archibald, McGill University
- Zaven Arzoumanian, Goddard Space Flight Center
- Don Backer, University of California, Berkeley
- Adam Brazier, Cornell University
- Jason Boyles, West Virginia University
- Brian Burt, Franklin and Marshall College
- Jim Cordes, Cornell University
- Paul Demorest, National Radio Astronomy Observatory
- Justin Ellis, West Virginia University
- Rob Ferdman, CNRS, France
- L. Samuel Finn, Center of Gravitational Physics at Penn State Univer
- Paulo Freire, National Astronomy and Ionospheric Center
- Alex Garcia, University of Texas, Brownsville
- Marjorie Gonzalez, University of British Columbia
- Rick Jenet, University of Texas, Brownsville, CGWA
- Victoria Kaspi, McGill University
- Joseph Lazio, Naval Research Laboratories
- Andrea Lommen, Franklin and Marshall College
- Duncan Lorimer, West Virginia University
- Ryan Lynch, University of Virginia
- Maura McLaughlin, West Virginia University
- Jonathan Nelson, Oberlin College
- David Nice, Bryn Mawr College
- Nipuni Palliyaguru, West Virginia University
- Delphine Perrodin, Franklin and Marshall College
- Scott Ransom, National Radio Astronomy Observatory
- Ryan Shannon, Cornell University
- Xavi Siemens, University of Wisconsin
- Ingrid Stairs, University of British Columbia
- Dan Stinebring, Oberlin College
- Kevin Stovall, University of Texas, Brownsville



NANOGrav

# The International Pulsar Timing Array



# 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
- Chris Messenger, AEI -> Cardiff

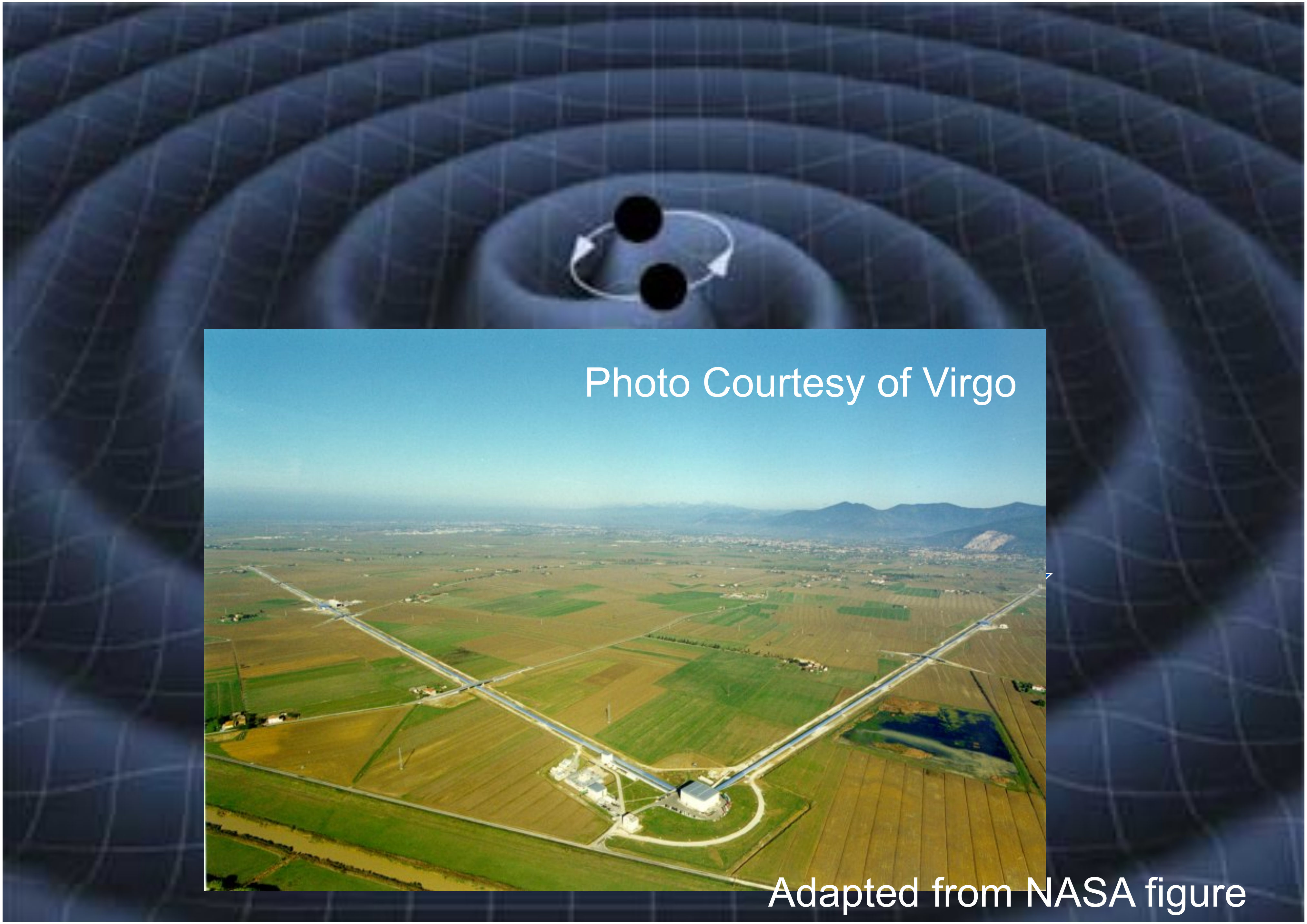
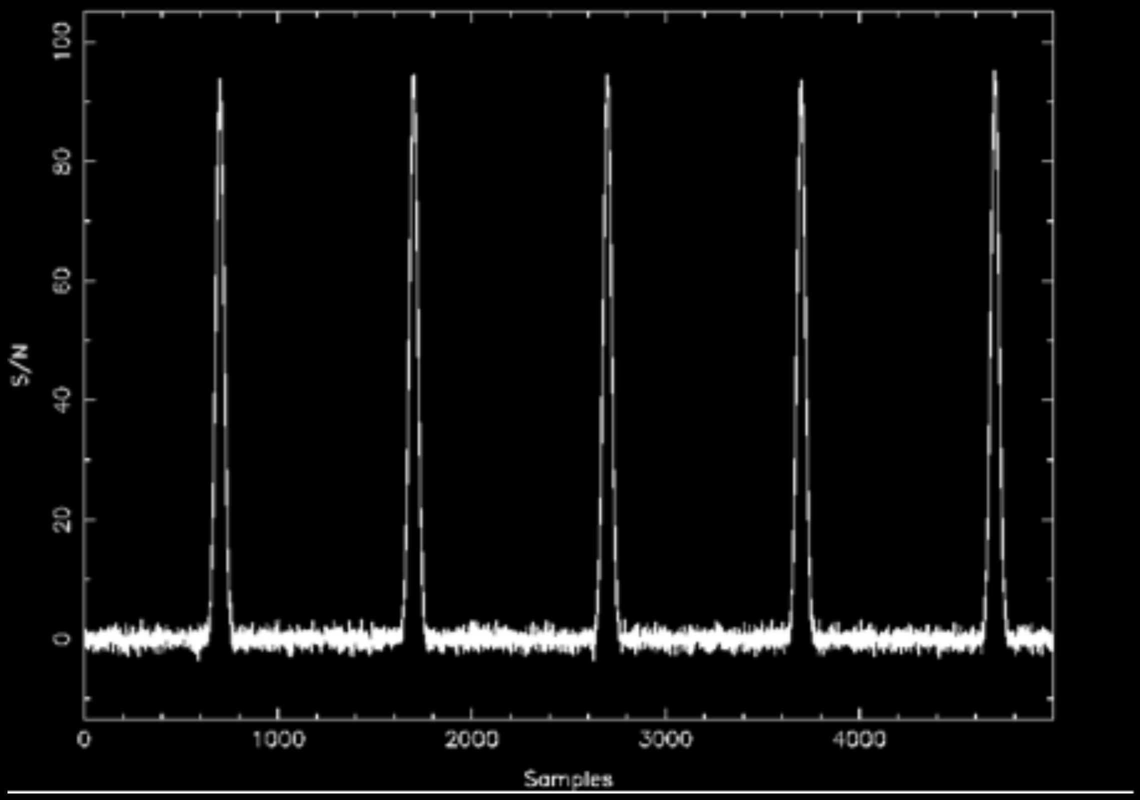
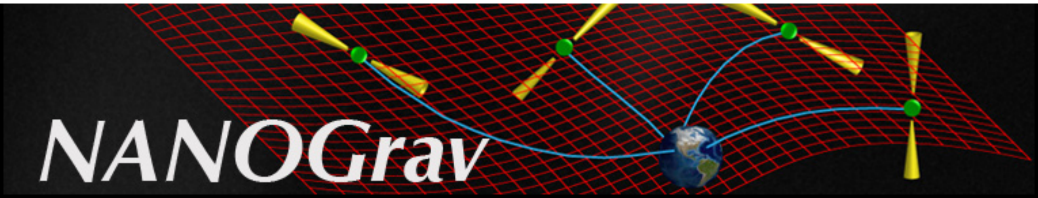


Photo Courtesy of Virgo

Adapted from NASA figure

# Stability of the clocks





# Typical Pulsar Model

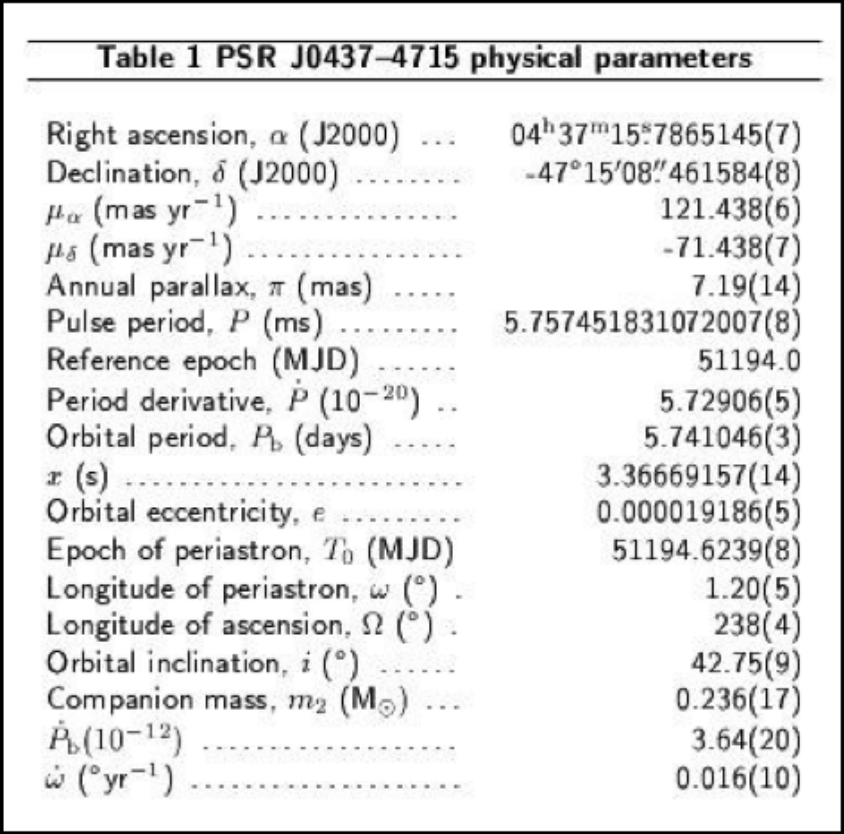
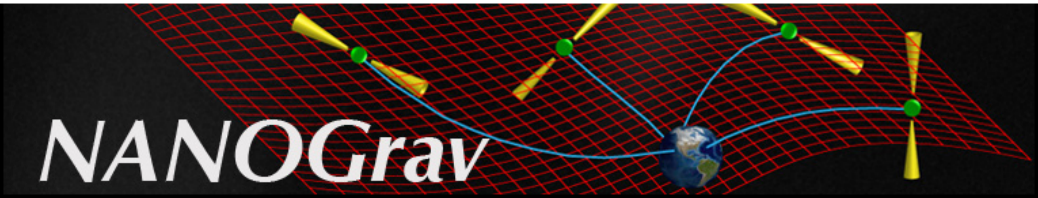


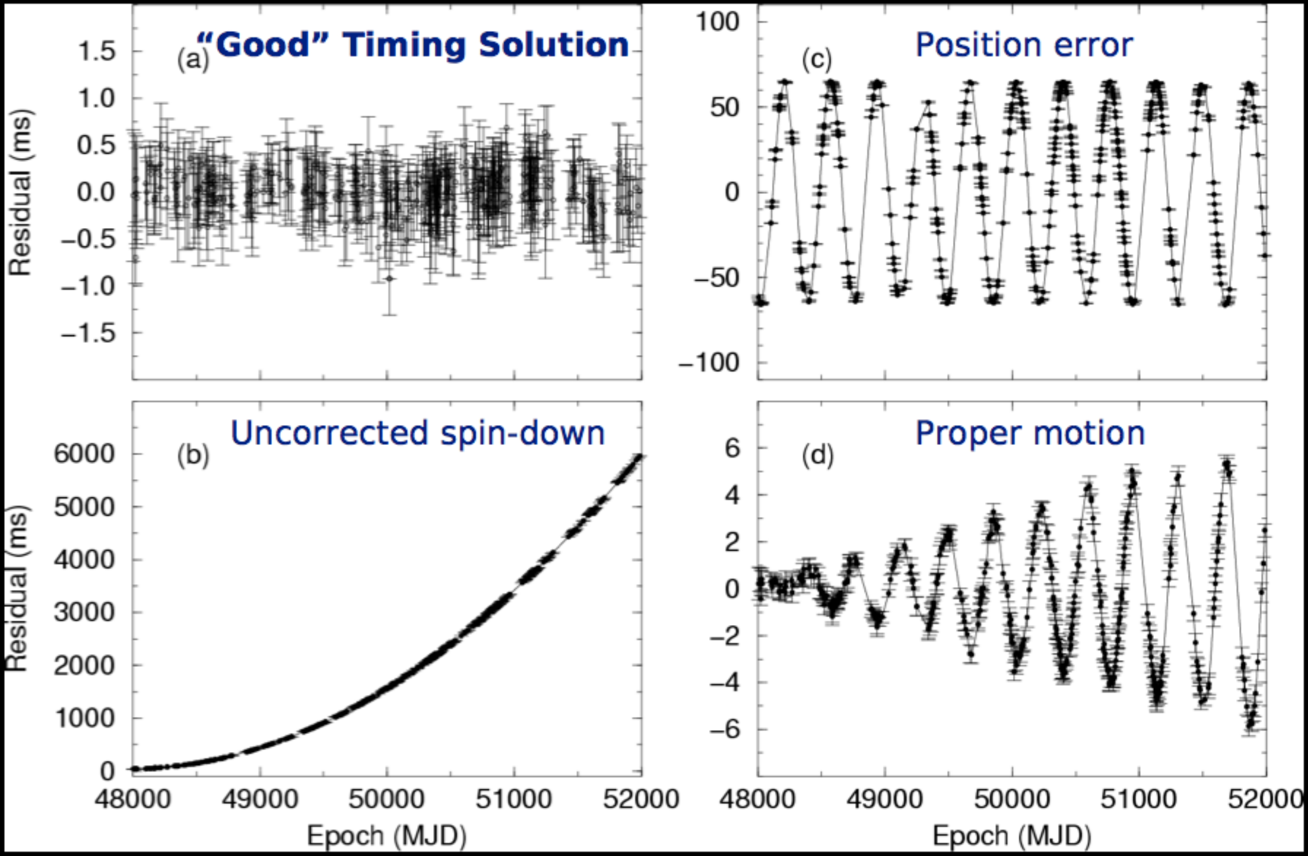
**Table 1 PSR J0437–4715 physical parameters**

| | |
|---|---|
| Right ascension, $\alpha$ (J2000) … | $04^{\rm h}37^{\rm m}15\overset{\rm s}{.}7865145(7)$ |
| Declination, $\delta$ (J2000) ……… | $-47^\circ15'08\overset{''}{.}461584(8)$ |
| $\mu_\alpha$ (mas yr$^{-1}$) ……………… | 121.438(6) |
| $\mu_\delta$ (mas yr$^{-1}$) ……………… | -71.438(7) |
| Annual parallax, $\pi$ (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, $P_{\rm b}$ (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, $\omega$ (°) . | 1.20(5) |
| Longitude of ascension, $\Omega$ (°) . | 238(4) |
| Orbital inclination, $i$ (°) …… | 42.75(9) |
| Companion mass, $m_2$ (M$_\odot$) … | 0.236(17) |
| $\dot{P}_{\rm b}$($10^{-12}$) ………………… | 3.64(20) |
| $\dot{\omega}$ (°yr$^{-1}$) ………………… | 0.016(10) |

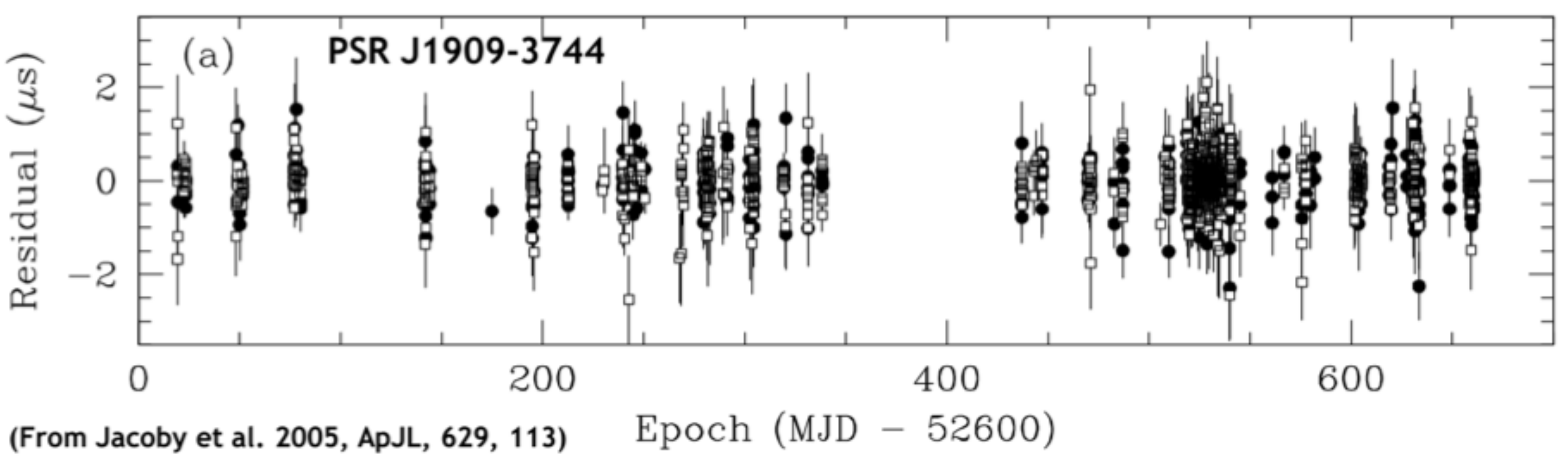


# The science is in the residuals!:

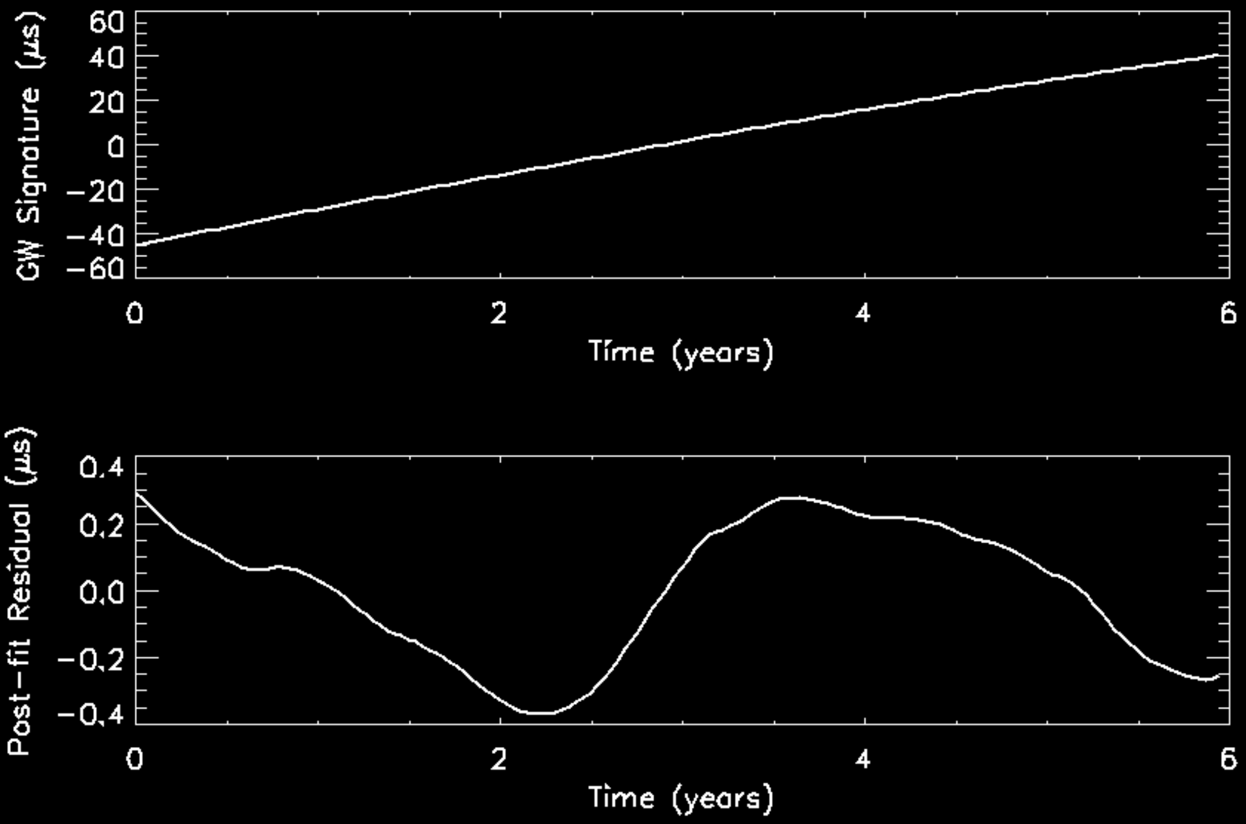
RMS precision ~ $10^{-5}$-$10^{-3}$ P

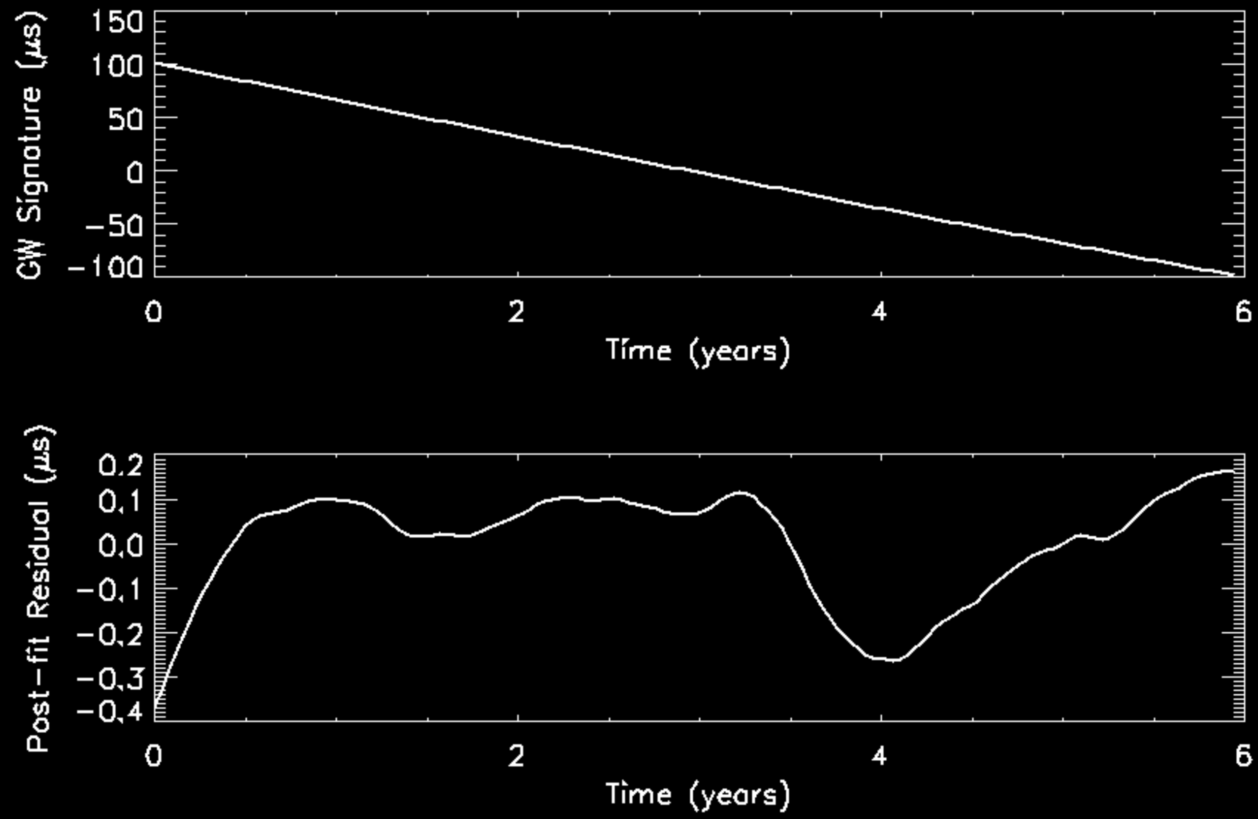


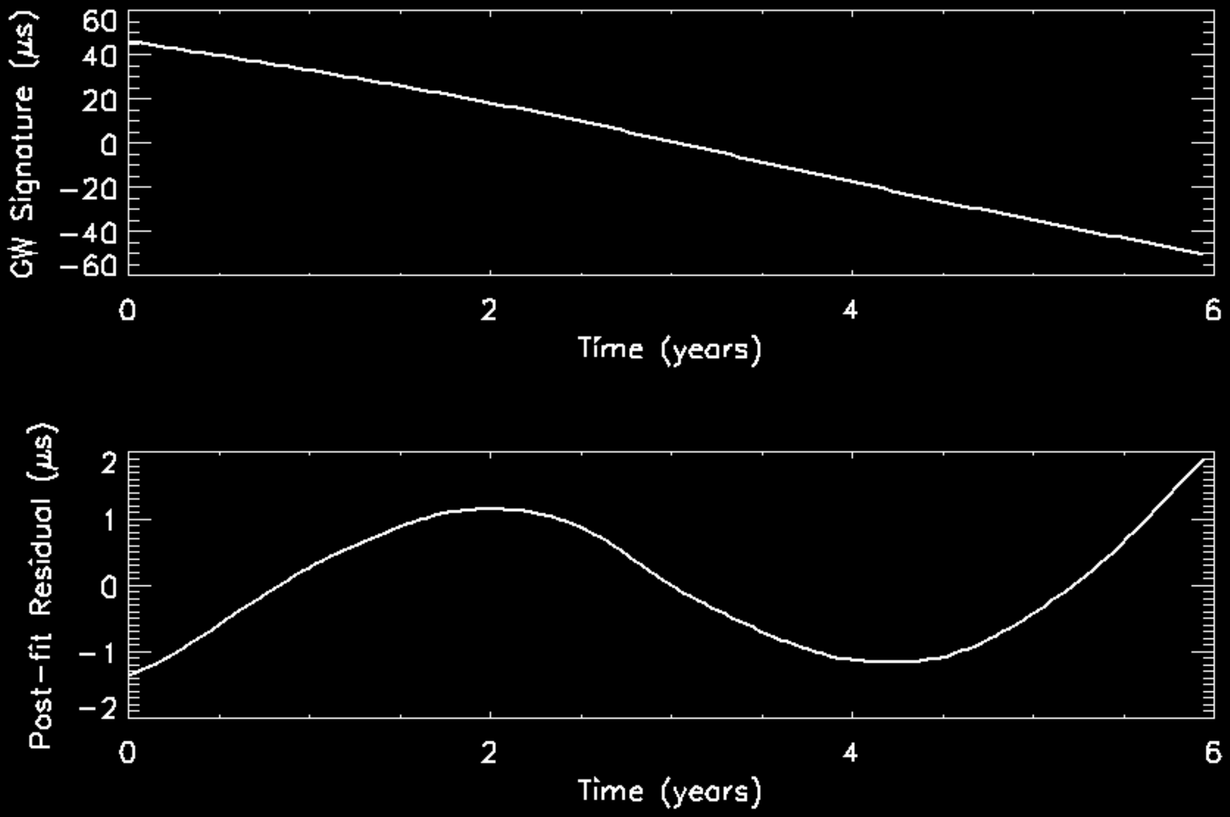
# Stability of the clocks



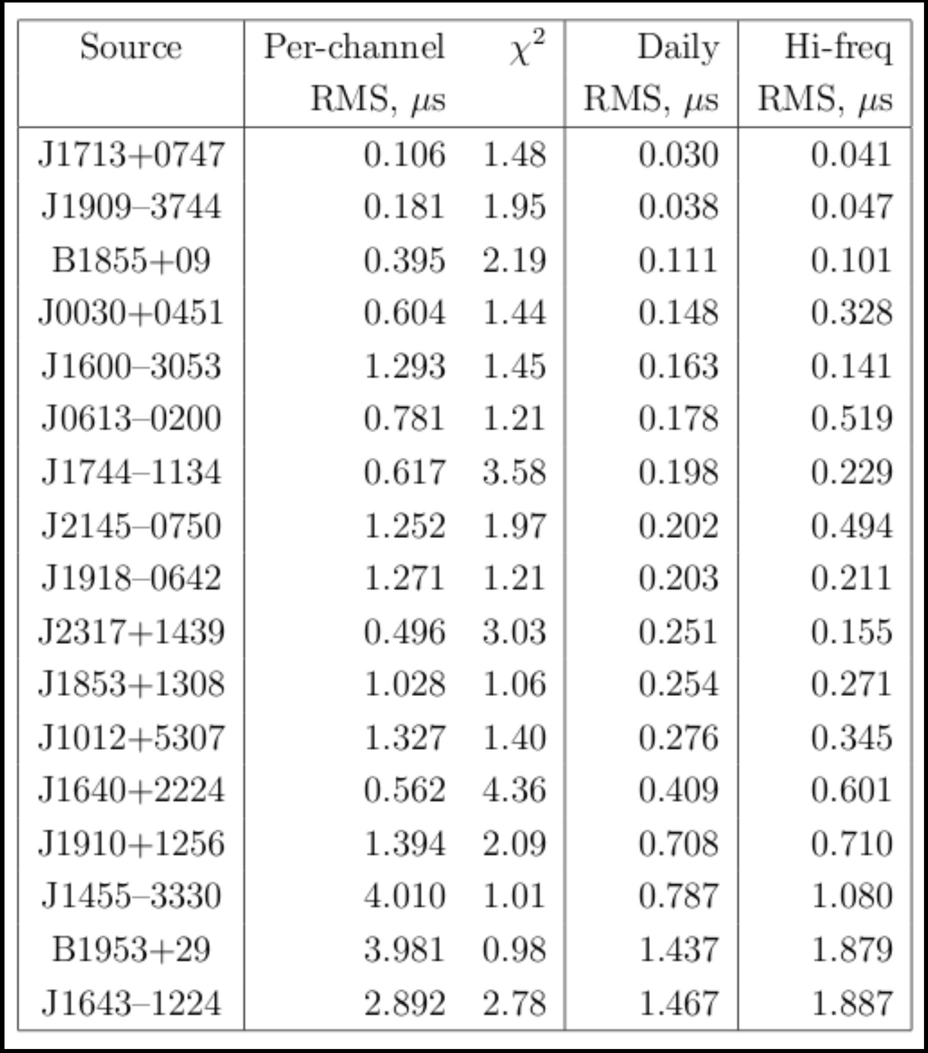
(From Jacoby et al. 2005, ApJL, 629, 113)


GW Signature (μs)
60
40
20
0
−20
−40
−60
0
2
4
6
Time (years)
Post−fit Residual (μs)
0.4
0.2
0.0
−0.2
−0.4
0
2
4
6
Time (years)


GW Signature (μs)
150
100
50
0
−50
−100
0
2
4
6
Time (years)
Post−fit Residual (μs)
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
0
2
4
6
Time (years)


GW Signature (μs)
60
40
20
0
−20
−40
−60
0
2
4
6
Time (years)
Post−fit Residual (μs)
2
1
0
−1
−2
0
2
4
6
Time (years)

# NANOGrav 5-year timing results summary (analysis currently ongoing; PD, M. Gonzalez, D. Nice, I. Stairs, S. Ransom, R. Ferdman)



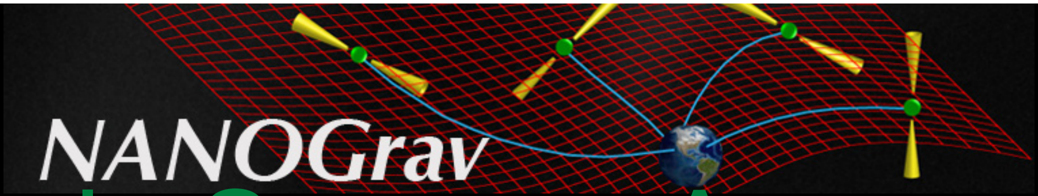
| Source | Per-channel RMS, $\mu$s | $\chi^2$ | Daily RMS, $\mu$s | Hi-freq RMS, $\mu$s |
|---|---|---|---|---|
| J1713+0747 | 0.106 | 1.48 | 0.030 | 0.041 |
| J1909–3744 | 0.181 | 1.95 | 0.038 | 0.047 |
| B1855+09 | 0.395 | 2.19 | 0.111 | 0.101 |
| J0030+0451 | 0.604 | 1.44 | 0.148 | 0.328 |
| J1600–3053 | 1.293 | 1.45 | 0.163 | 0.141 |
| J0613–0200 | 0.781 | 1.21 | 0.178 | 0.519 |
| J1744–1134 | 0.617 | 3.58 | 0.198 | 0.229 |
| J2145–0750 | 1.252 | 1.97 | 0.202 | 0.494 |
| J1918–0642 | 1.271 | 1.21 | 0.203 | 0.211 |
| J2317+1439 | 0.496 | 3.03 | 0.251 | 0.155 |
| J1853+1308 | 1.028 | 1.06 | 0.254 | 0.271 |
| J1012+5307 | 1.327 | 1.40 | 0.276 | 0.345 |
| J1640+2224 | 0.562 | 4.36 | 0.409 | 0.601 |
| J1910+1256 | 1.394 | 2.09 | 0.708 | 0.710 |
| J1455–3330 | 4.010 | 1.01 | 0.787 | 1.080 |
| B1953+29 | 3.981 | 0.98 | 1.437 | 1.879 |
| J1643–1224 | 2.892 | 2.78 | 1.467 | 1.887 |

Analysis features:

Two independent calibration/processing pipelines -- psrchive and ASPfitsreader

DM(t) and timing model in single fit.

Fit includes systematic timing vs freq correction (profile shape evolution).



# Single Source: A sense of what's detectable

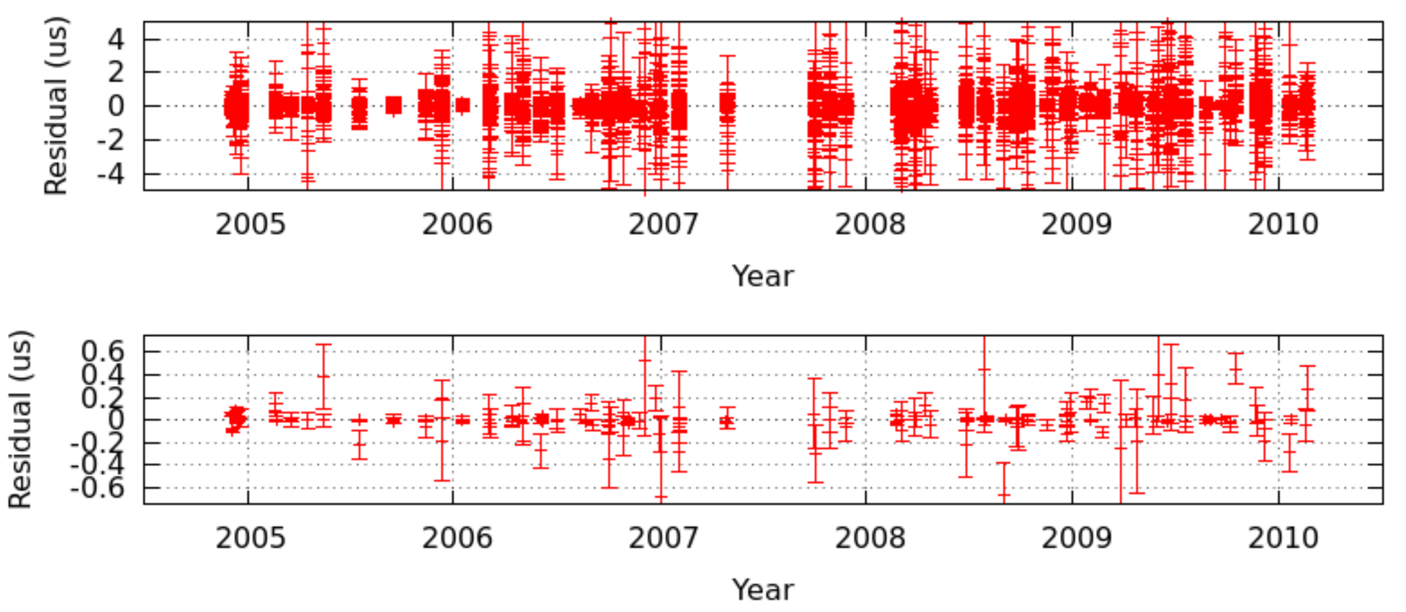
$$h = \frac{M^{5/3}}{P^{2/3} d}$$

$$\tau = hP$$

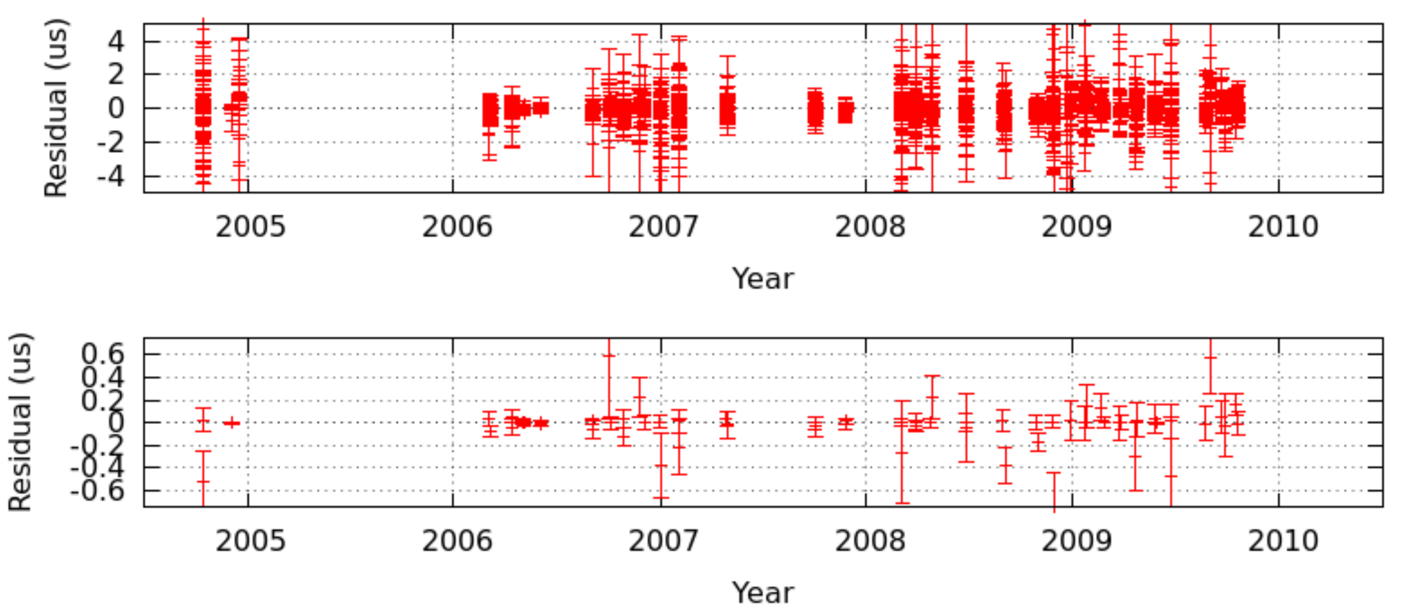
$$\tau = \frac{M^{5/3} P^{1/3}}{d}$$

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

# Timing residuals versus time:



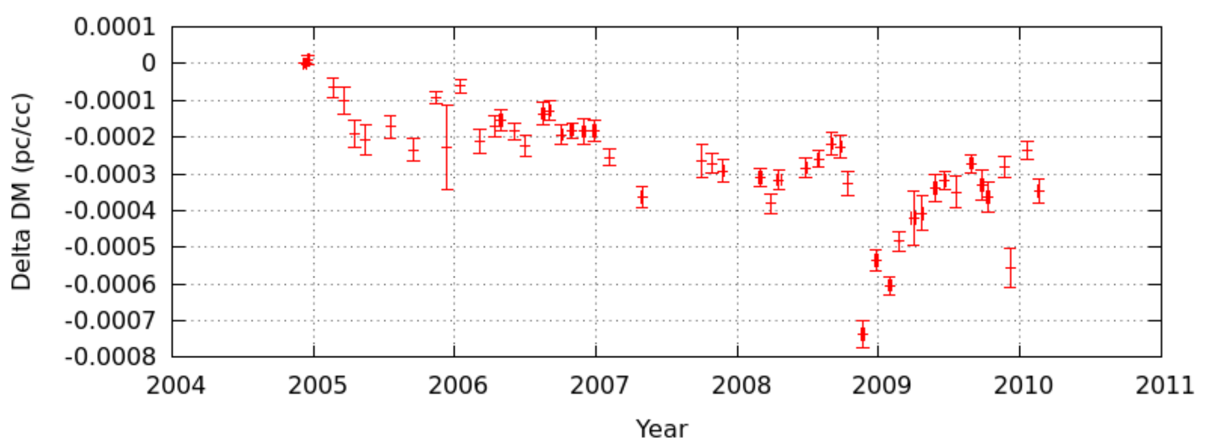
J1713+0747



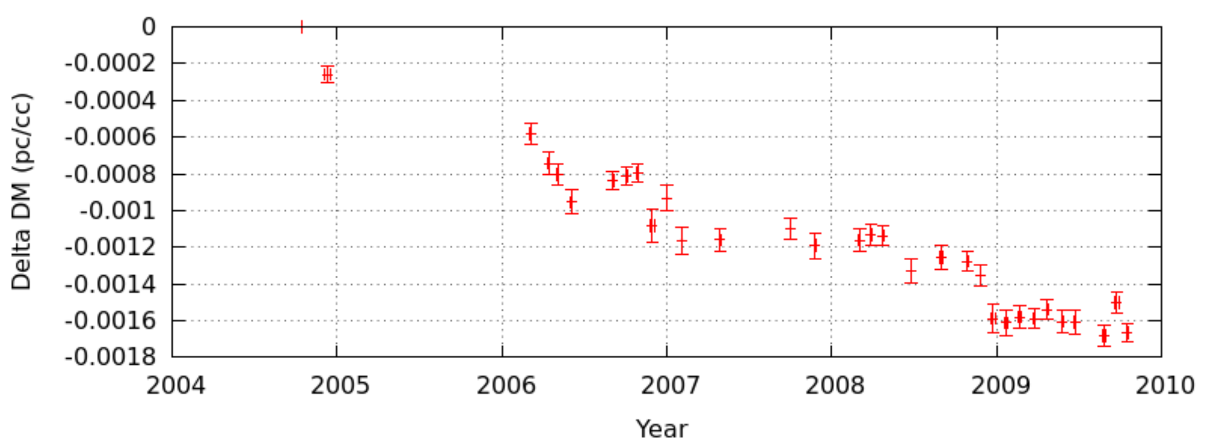
J1909-3744

Slide courtesy of Paul Demorest

# Dispersion measure variation with time



J1713+0747
With DM(t): 30 ns
Without: 90 ns



J1909-3744
With DM(t): 40 ns
Without: 440 ns!

Unfortunately DM(t) fit attenuates GW signal by a factor of ~3...

Slide courtesy of Paul Demorest

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

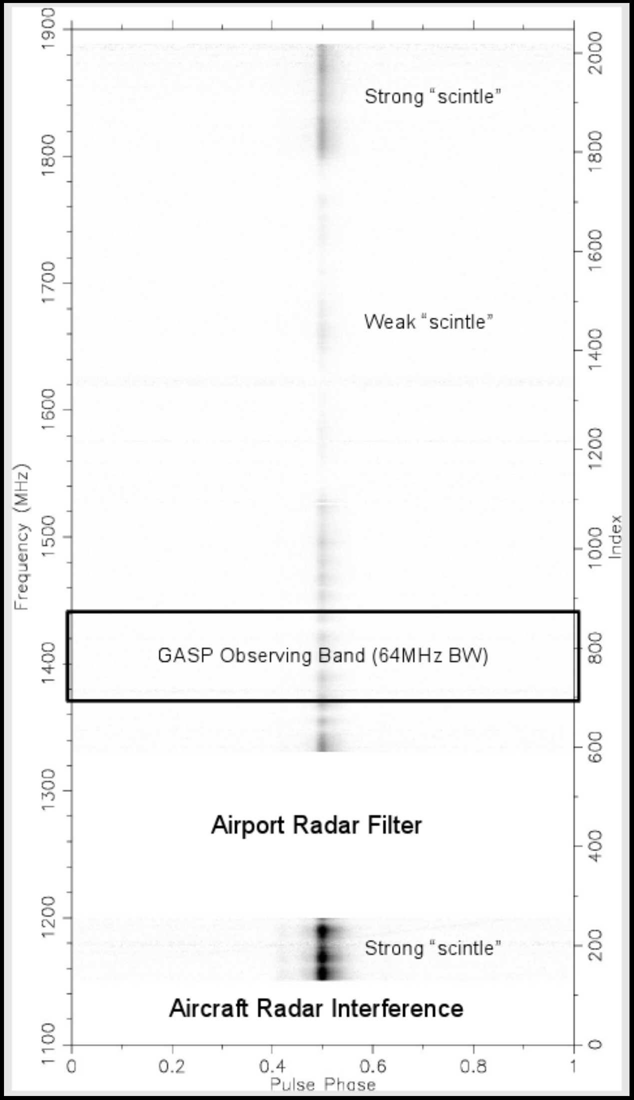


Image courtesy of Scott Ransom

NANOGrav

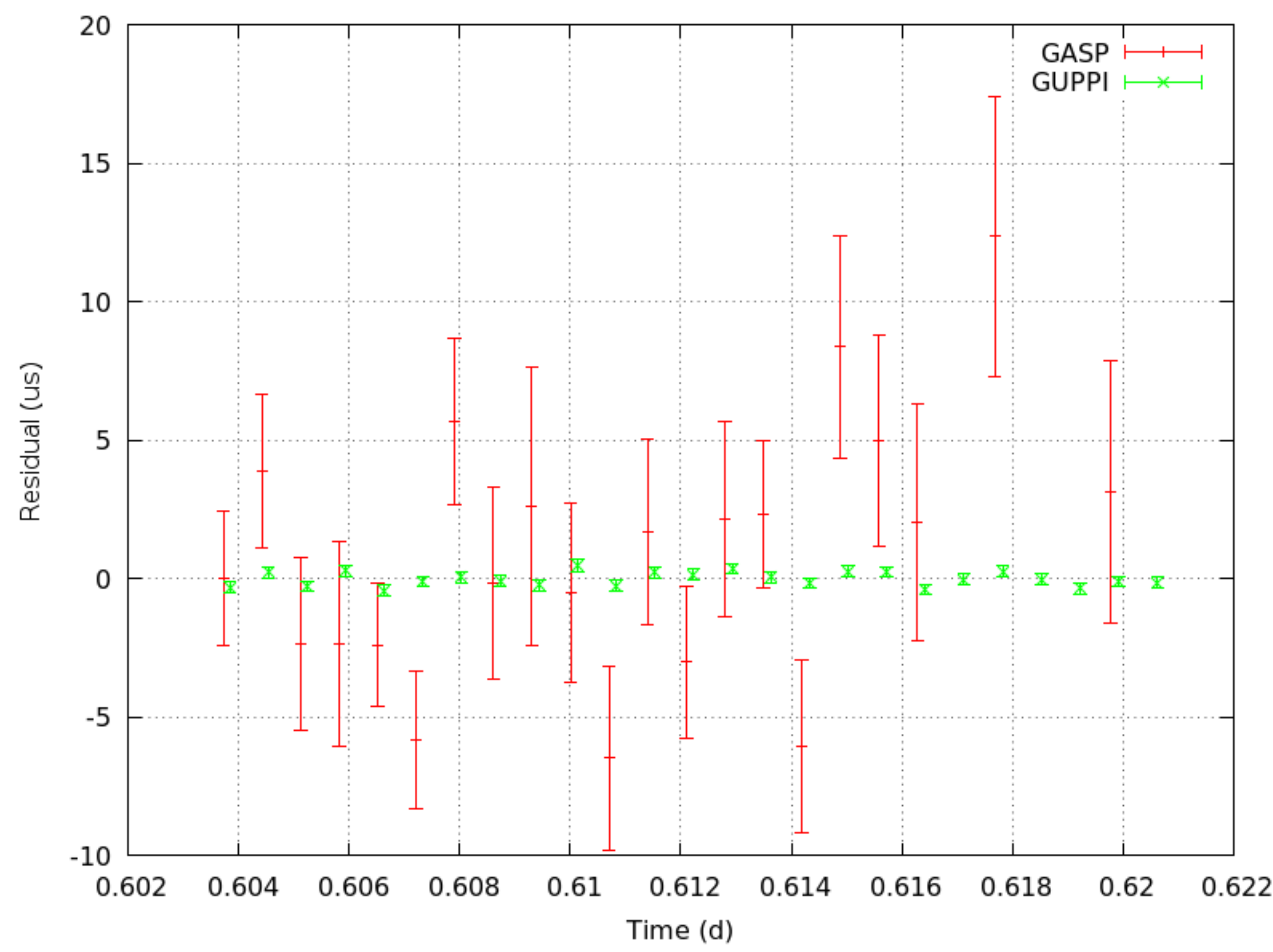
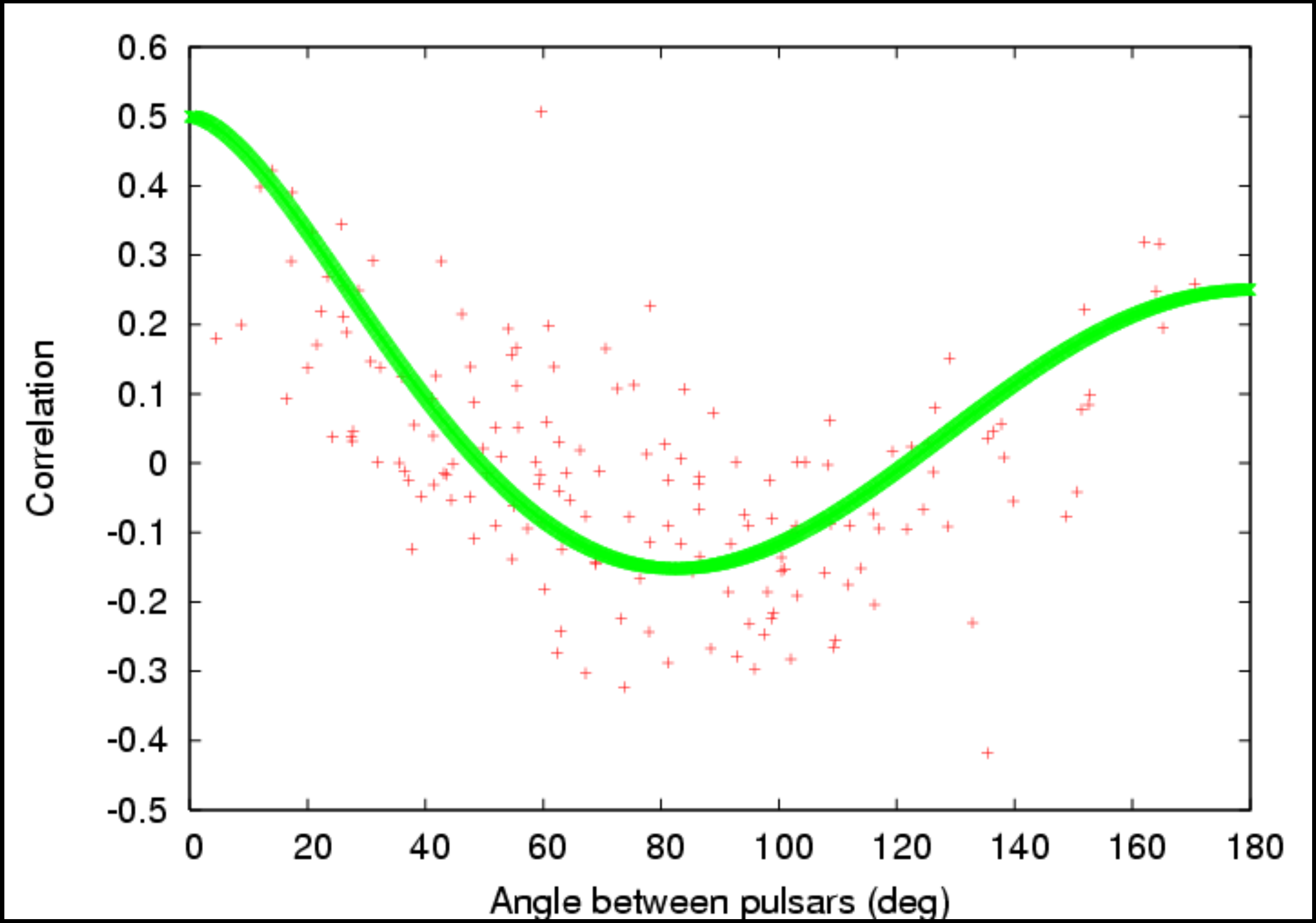


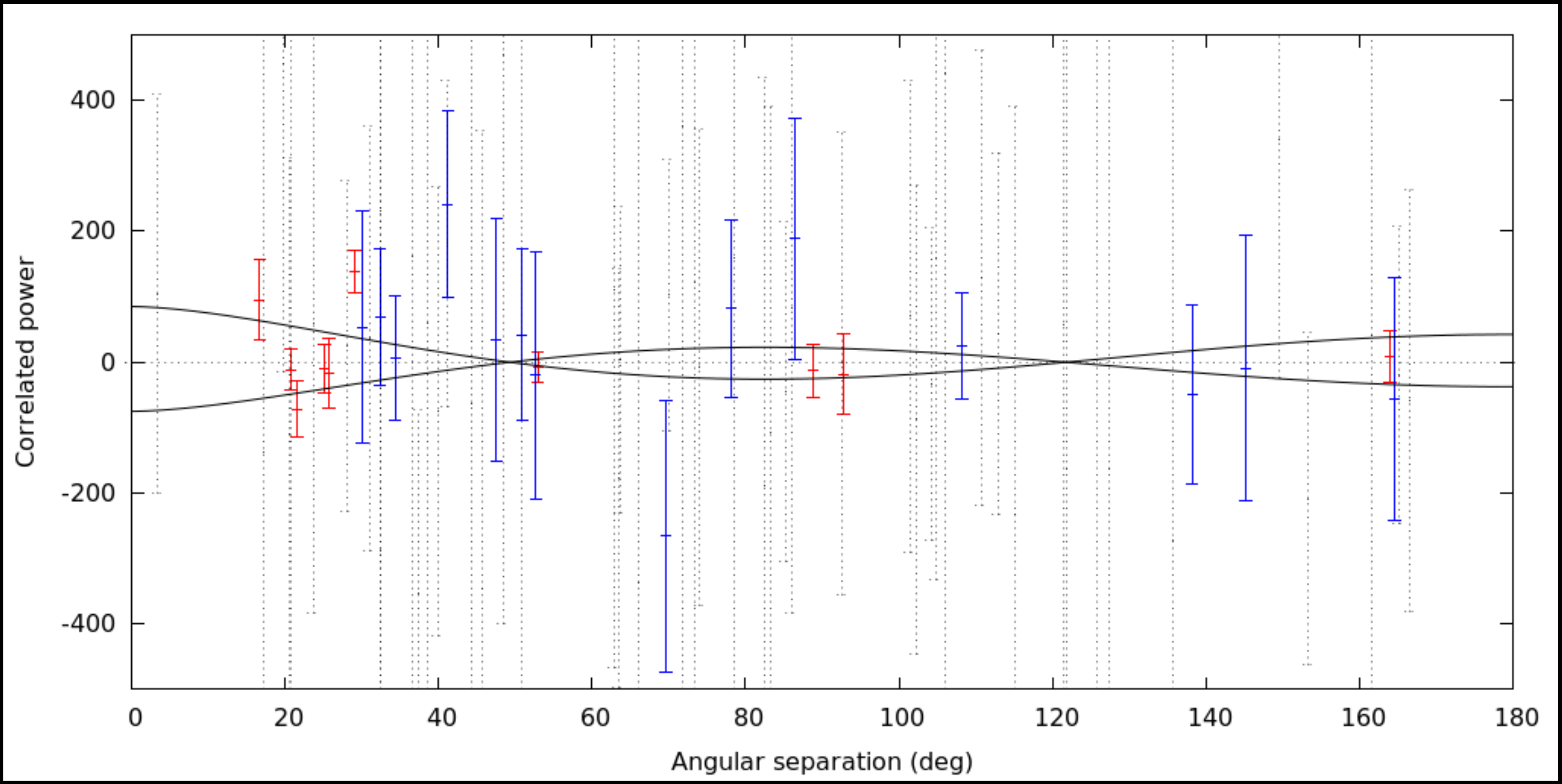
Image courtesy of Scott Ransom

# Hellings and Downs Curve (Overlap Reduction Function)



Courtesy of Rick Jenet and George Hobbs. Original figure from Hellings and Downs (1983).

# Timing residual GW cross-correlation analysis

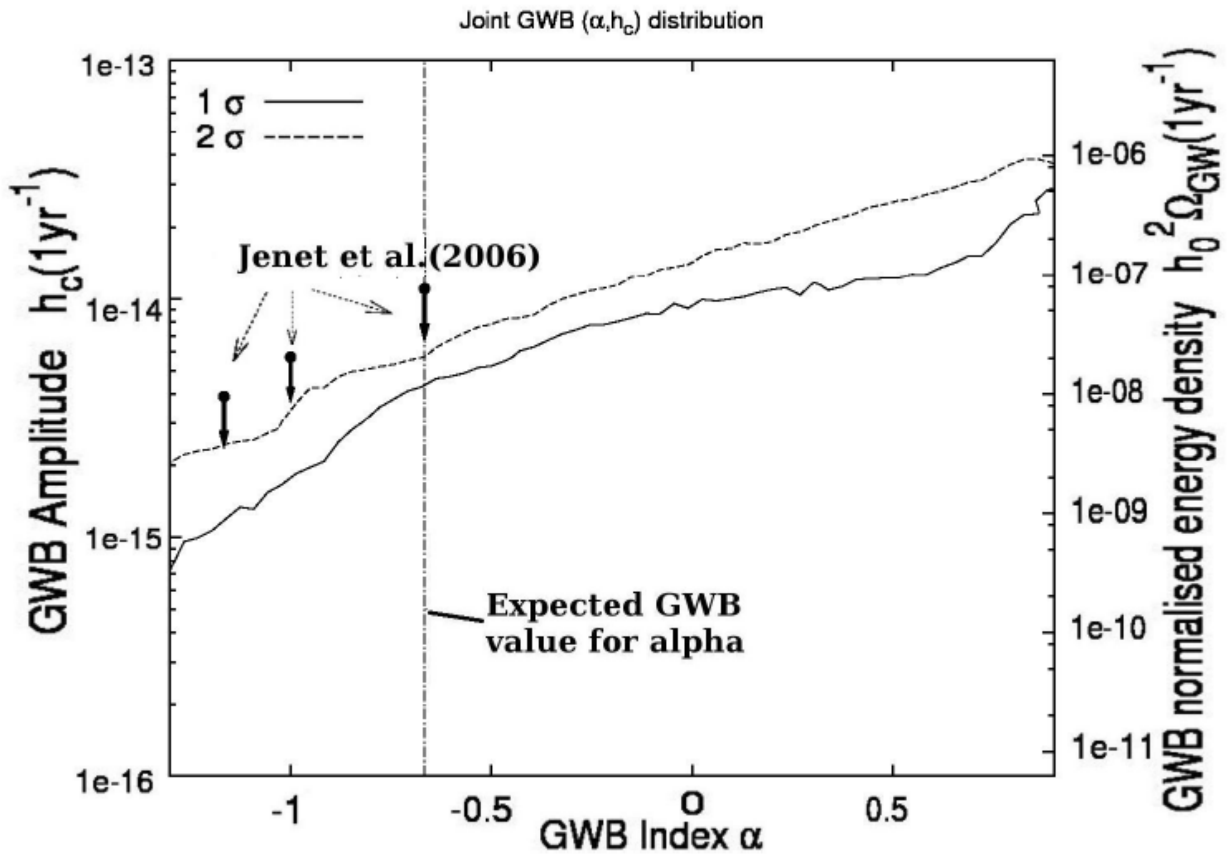


Computed using methods from Demorest PhD (2007):

Accounts for GW power removed by timing fit.

Assumes/optimized for -2/3 power law GW spectrum.

# EPTA GWB Limit: $h_c \leq 6.10^{-15}$



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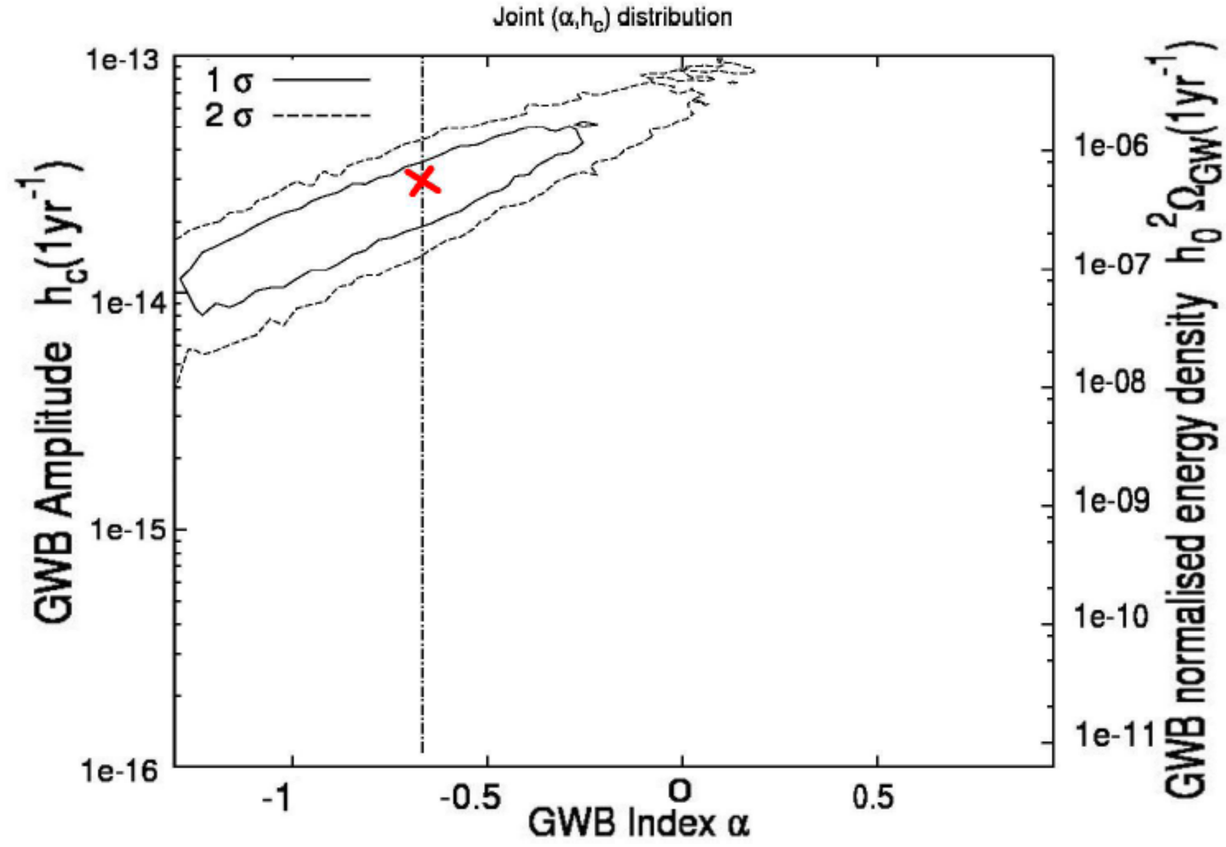
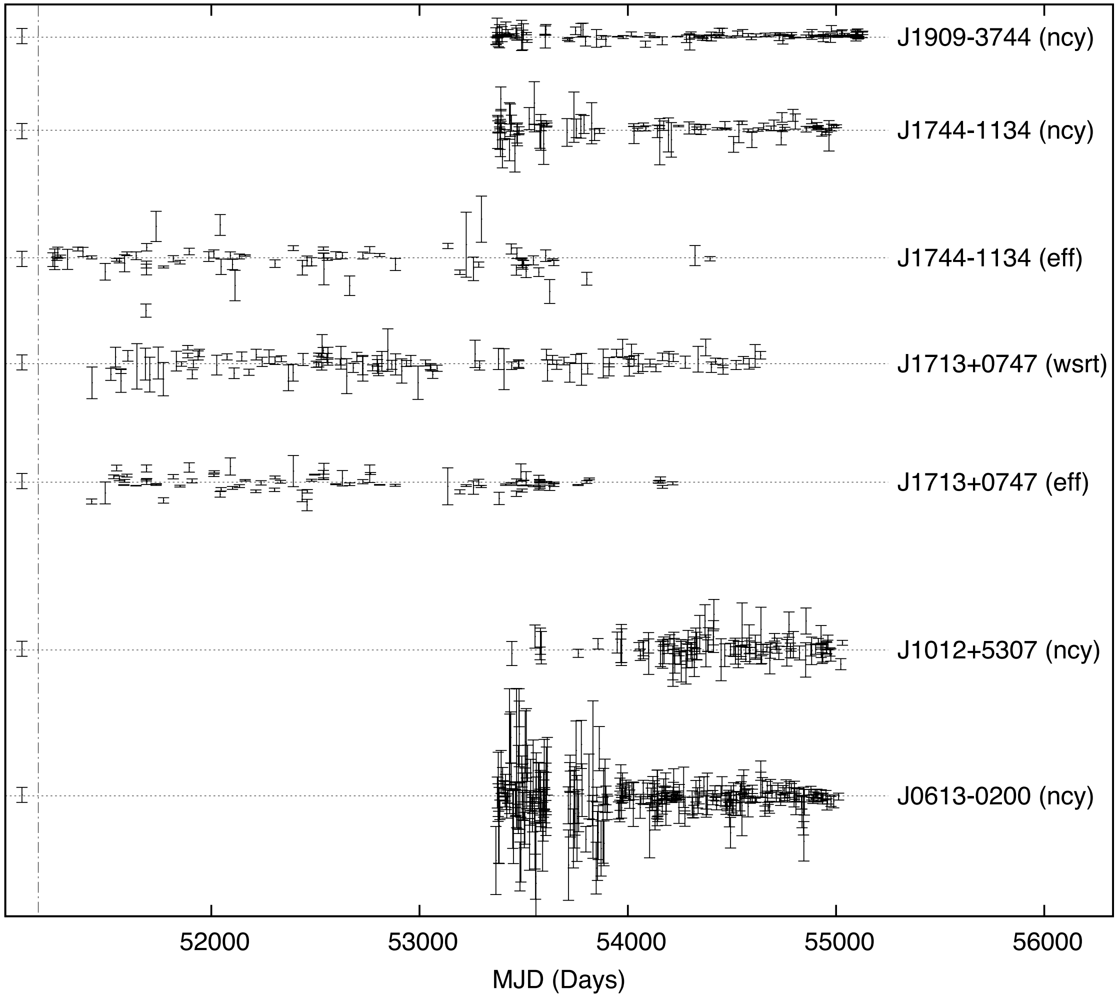
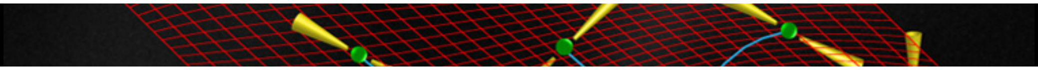
# Same dataset, added $h_c = 3 * 10^{-14}$



# The EPTA residuals that Rutger used (image courtesy of Rutger)





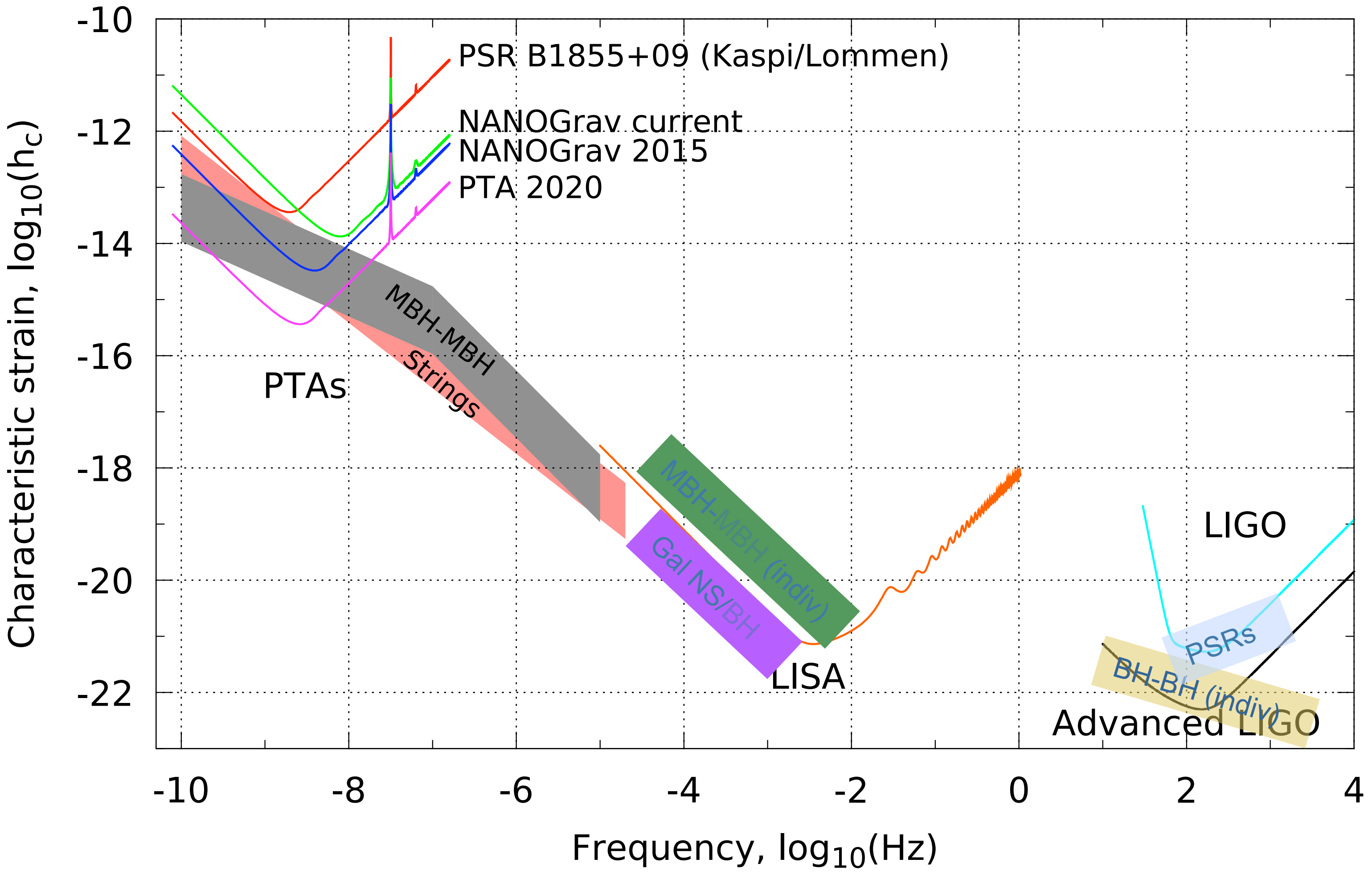
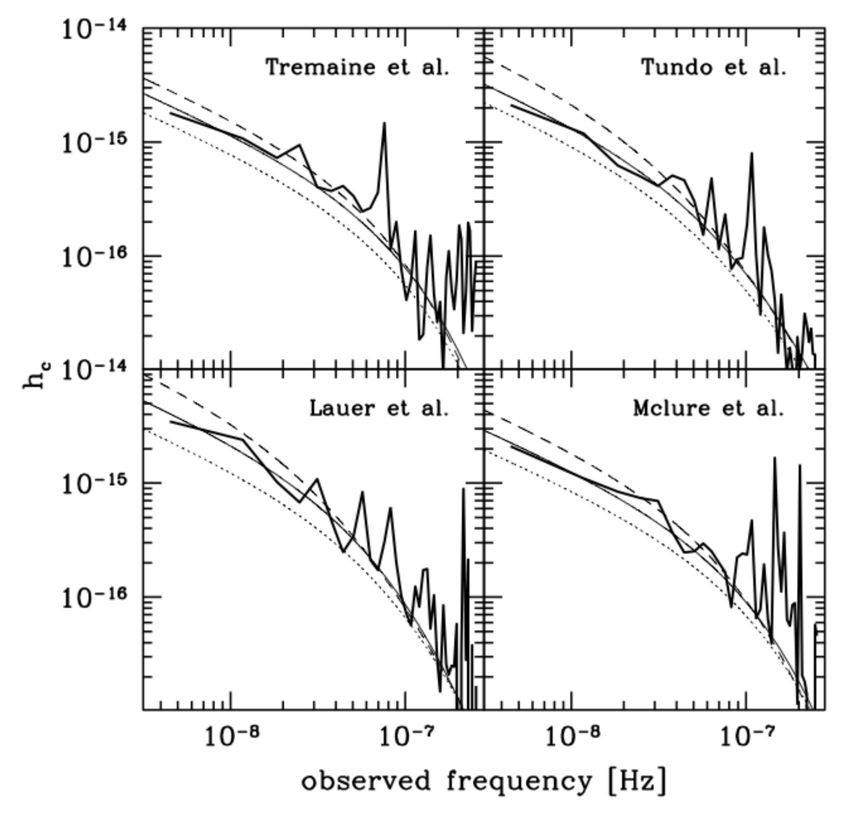


Figure by Paul Demorest (see arXiv:0902.2968)

# Pipelines being developed

- Rutger van Haasteren (also Levin), U Leiden – Bayesian, stochastic
- Xavi Siemens, UWM, Stochastic, Bayesian
- Justin Ellis (also Jenet, McLaughlin), WVU, template bank search for single continuous GWs
- Delphine Perrodin (also Finn, Lommen), F&M, maximum entropy search for bursts

# Sesana, Vecchio and Volunteri 2009



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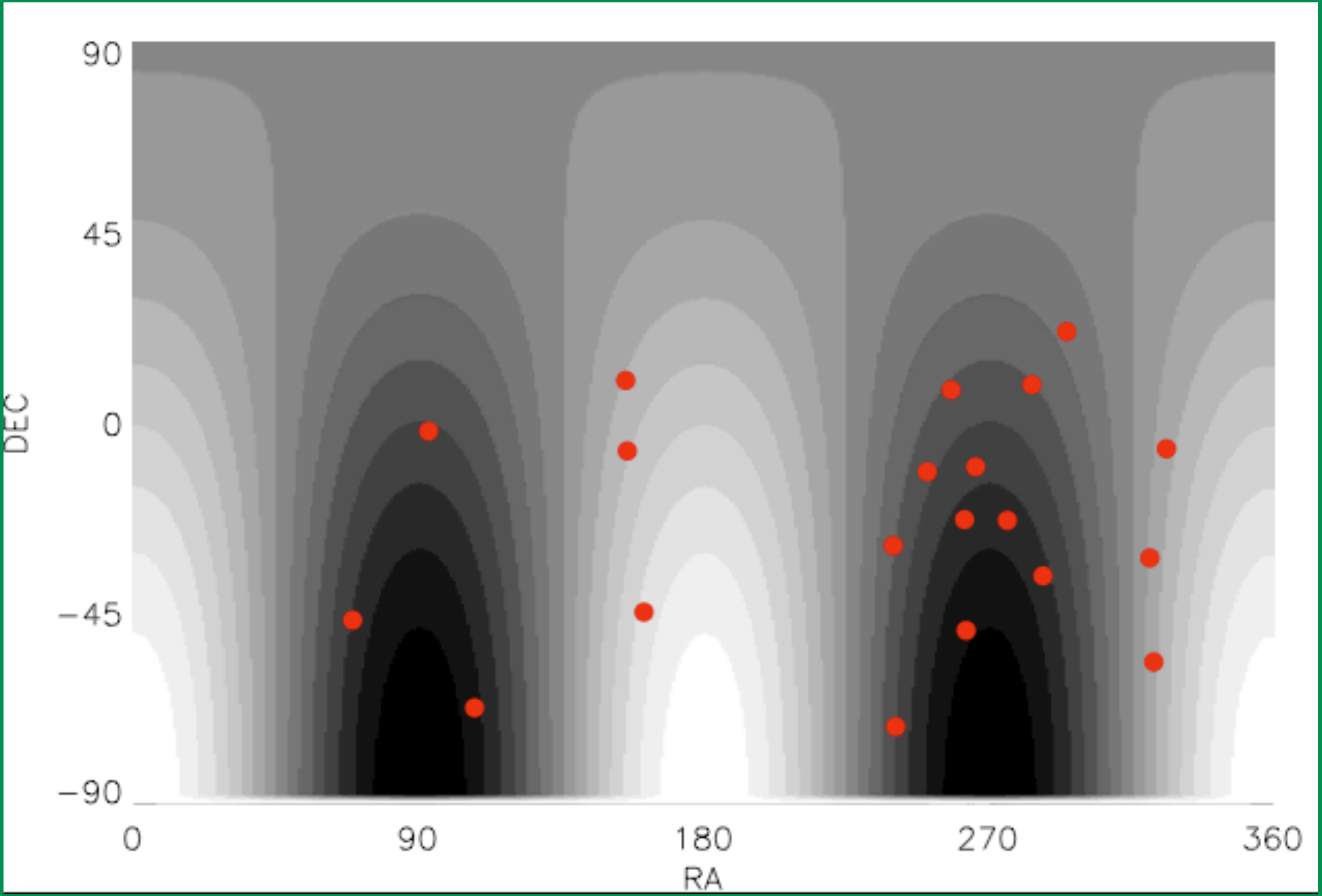
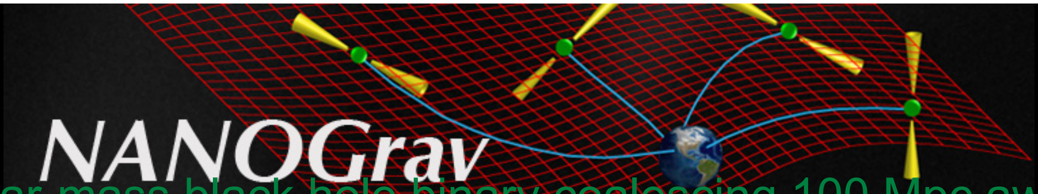
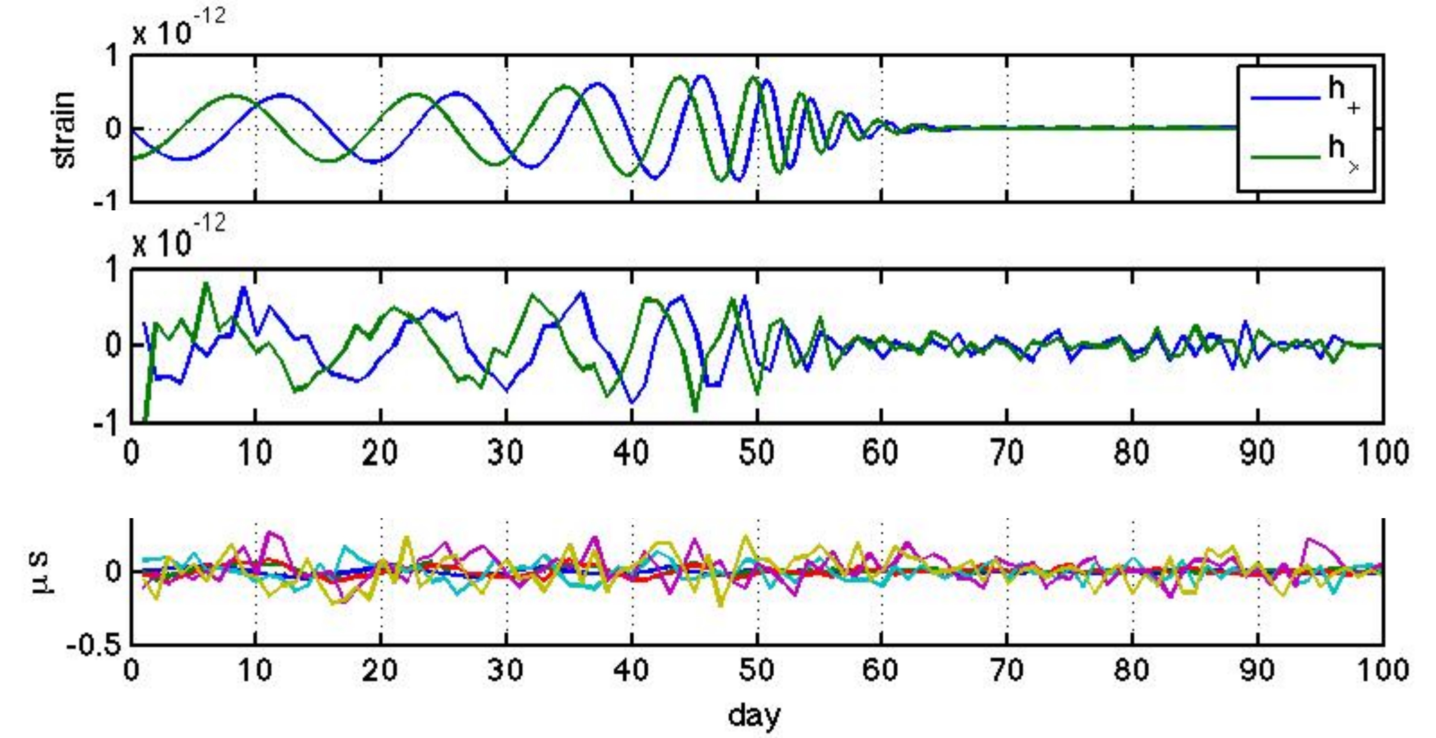




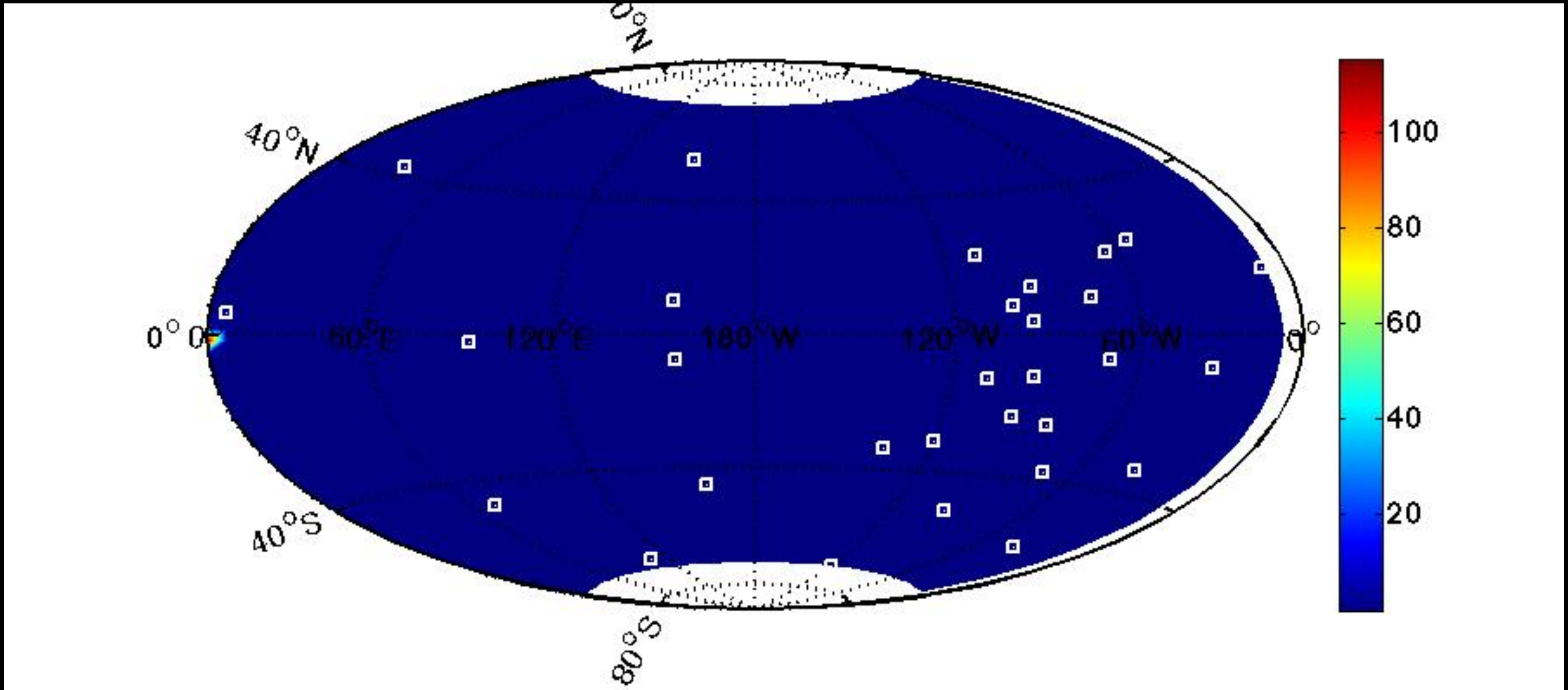
A 5 x $10^9$ solar-mass black hole binary coalescing 100 Mpc away.
30 IPTA pulsars, improved by 10, sampled once a day.

Maximum Entropy based on Summerscales, Burrows, Finn and Ott 2008



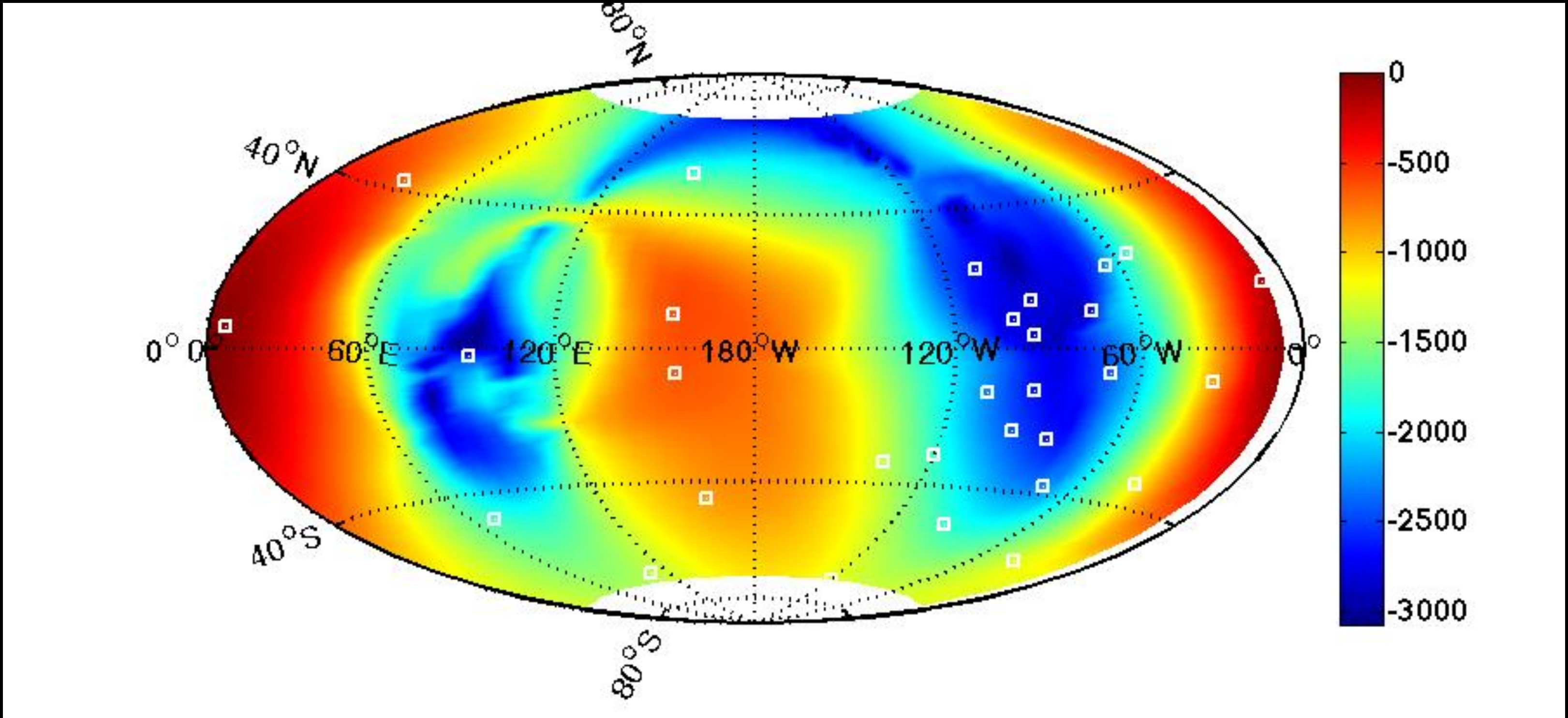
Thank you to Manuela Campanelli, Carlos O. Lousto, Hiroyuki Nakano, and Yosef Zlochower for waveforms. Phys.Rev.D79:084010 (2009). http://ccrg.rit.edu/downloads/waveforms

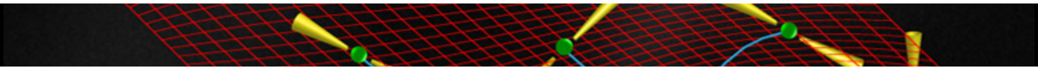
# Probability density

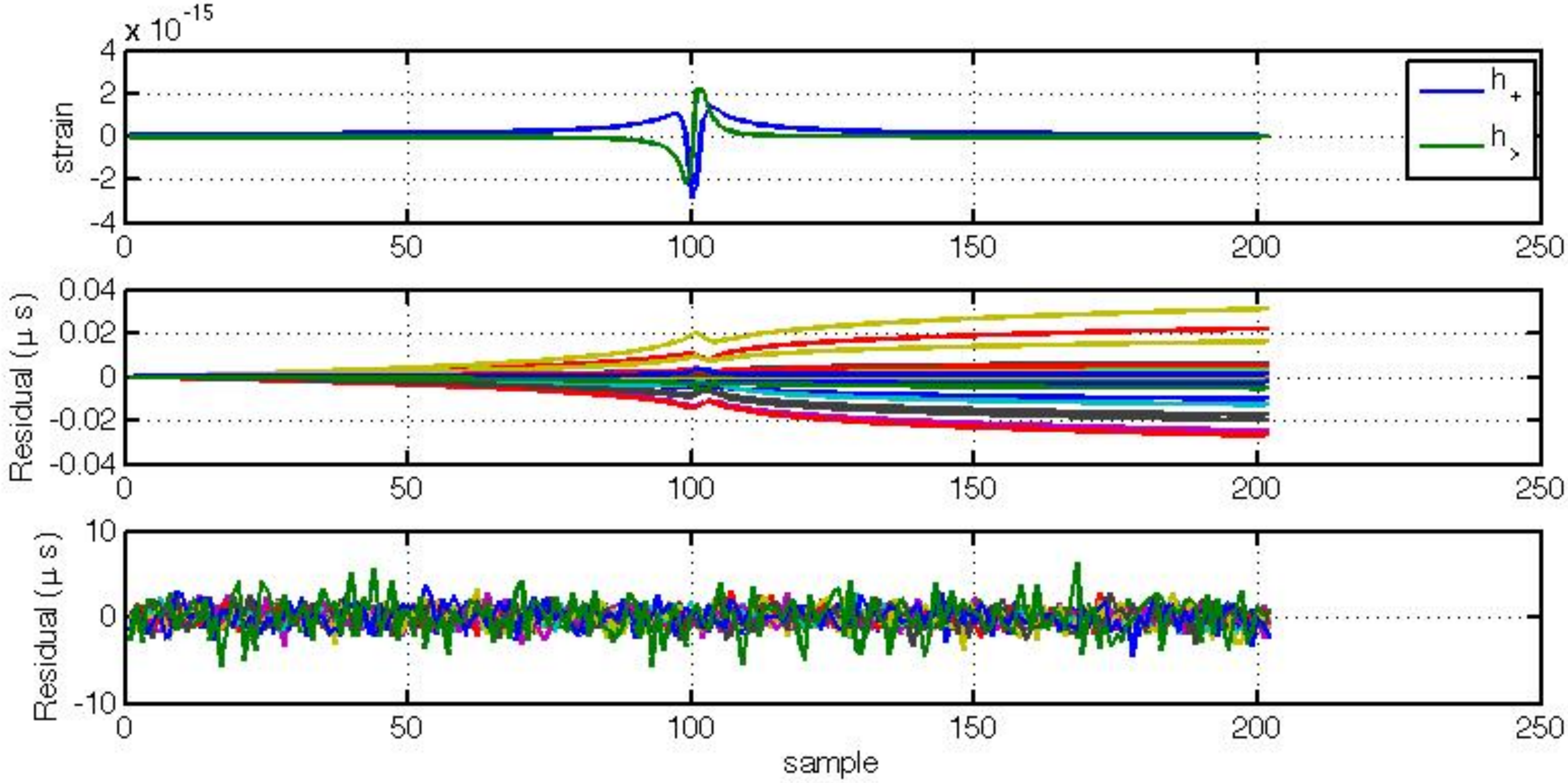


See Finn & Lommen 2010, ApJ

# Log of probability density





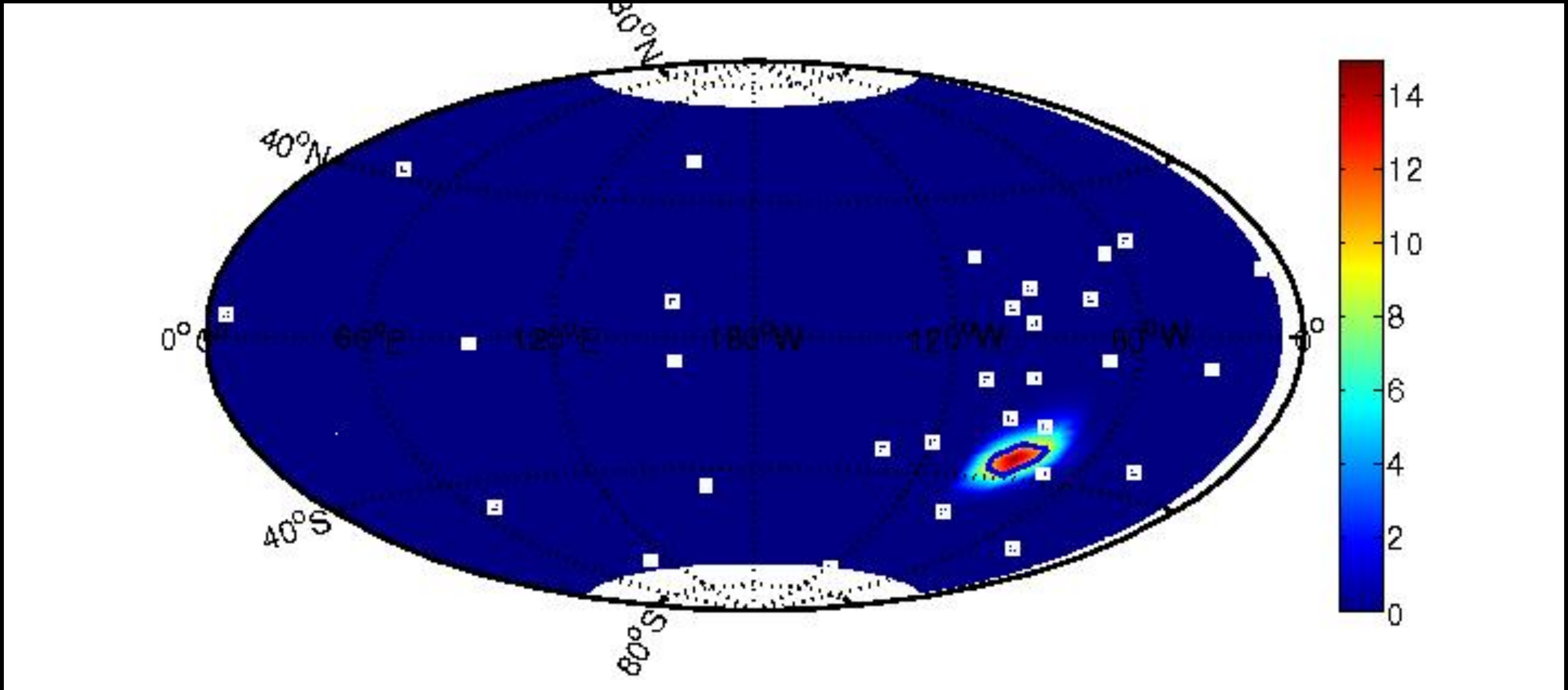


2 $10^9$ solar mass black holes flying by each other with a separation of 40 Schwarzschild Radii.

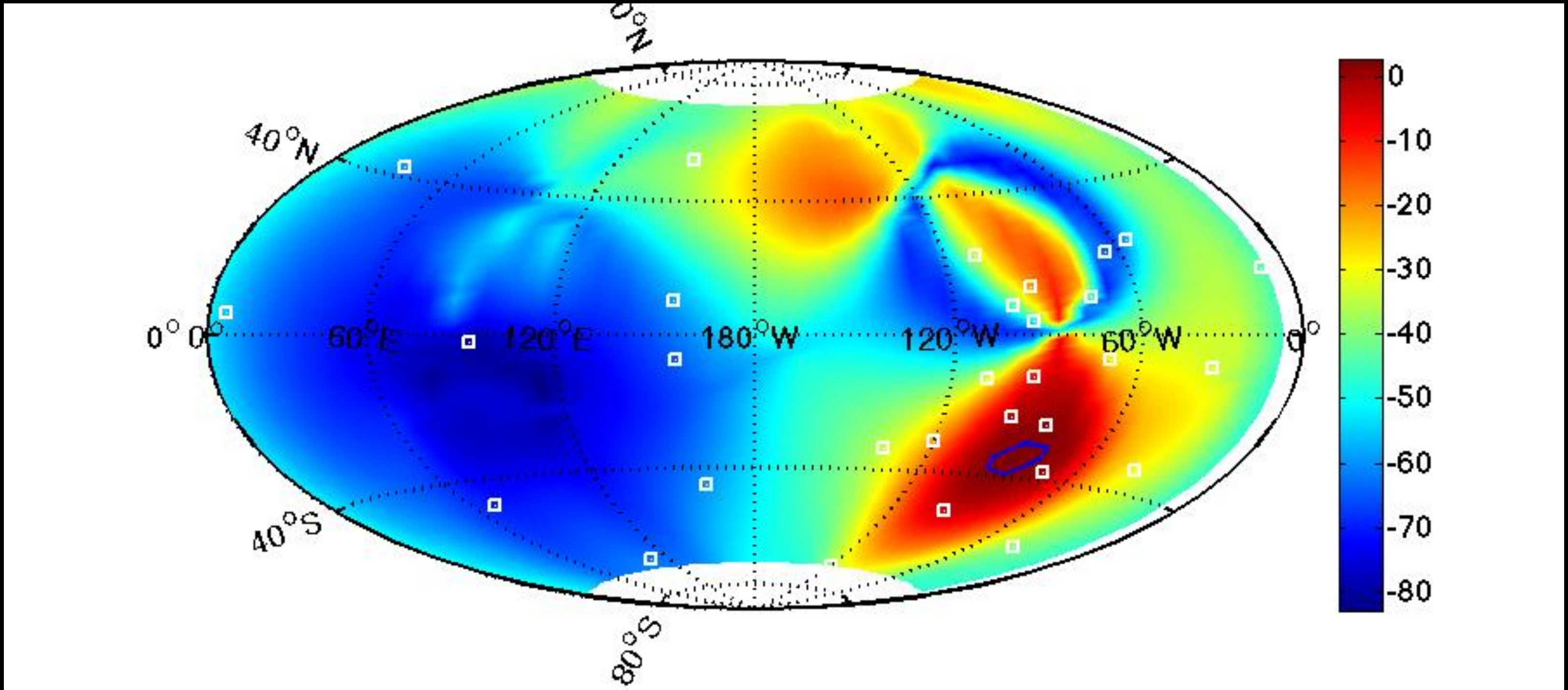
Distance: 100 Mpc

30 IPTA pulsars

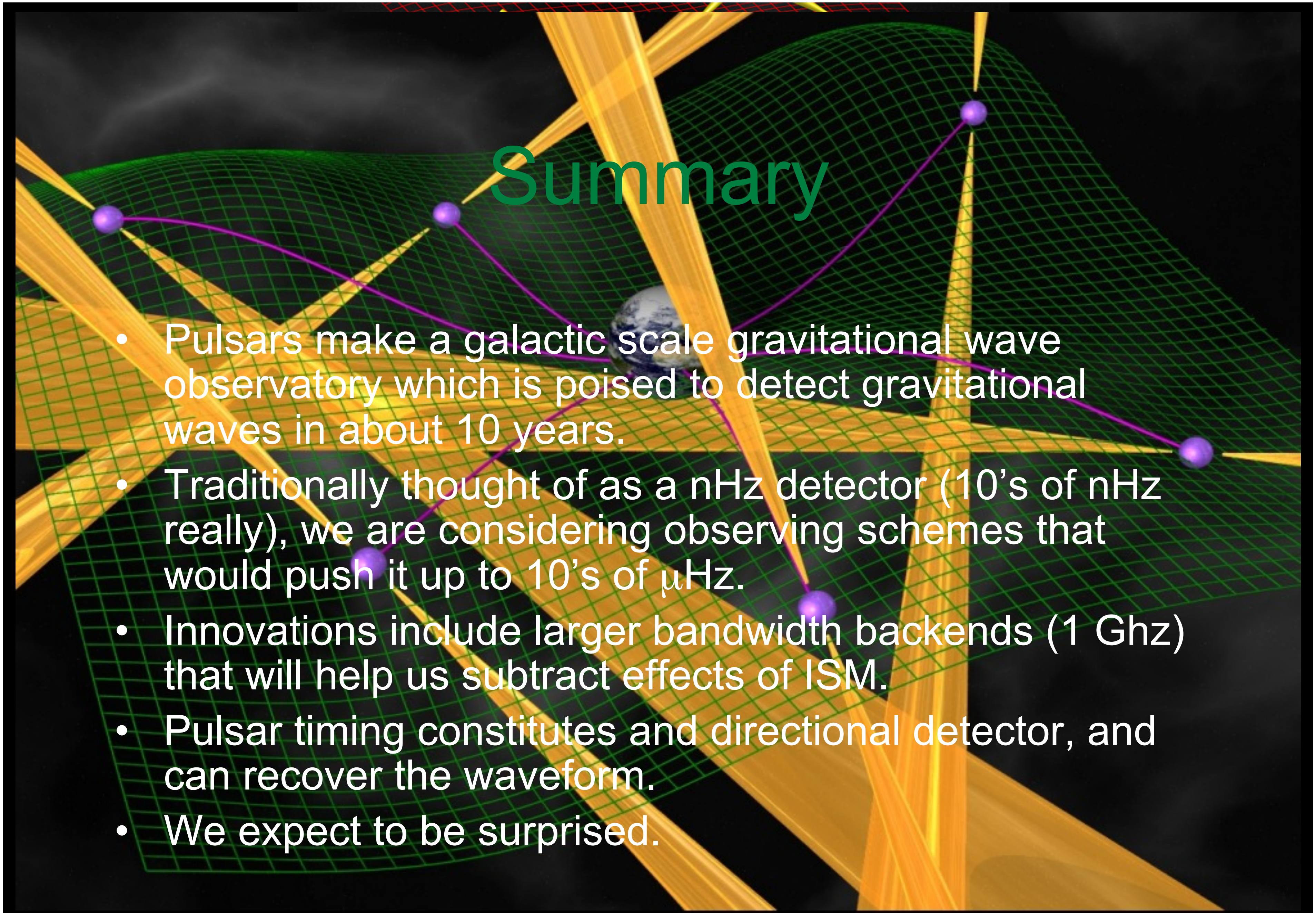
# Probability density as a function of sky position



# Log(probability density) as a function of sky position



# Summary



- Pulsars make a galactic scale gravitational wave observatory which is poised to detect gravitational waves in about 10 years.
- Traditionally thought of as a nHz detector (10’s of nHz really), we are considering observing schemes that would push it up to 10’s of μHz.
- Innovations include larger bandwidth backends (1 Ghz) that will help us subtract effects of ISM.
- Pulsar timing constitutes and directional detector, and can recover the waveform.
- We expect to be surprised.

# 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)

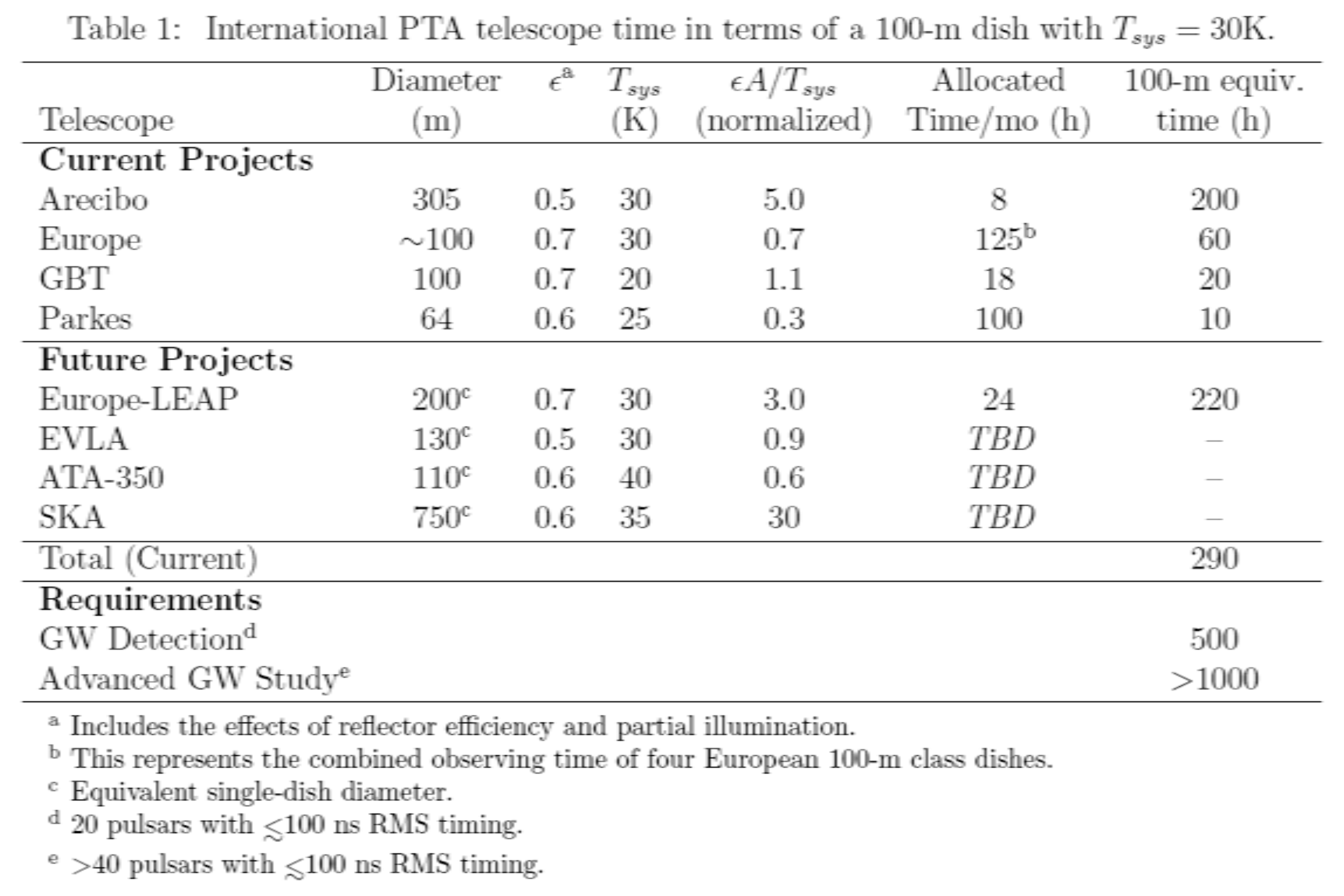


Table 1: International PTA telescope time in terms of a 100-m dish with $T_{sys} = 30$K.

| Telescope | Diameter (m) | $\epsilon$[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.

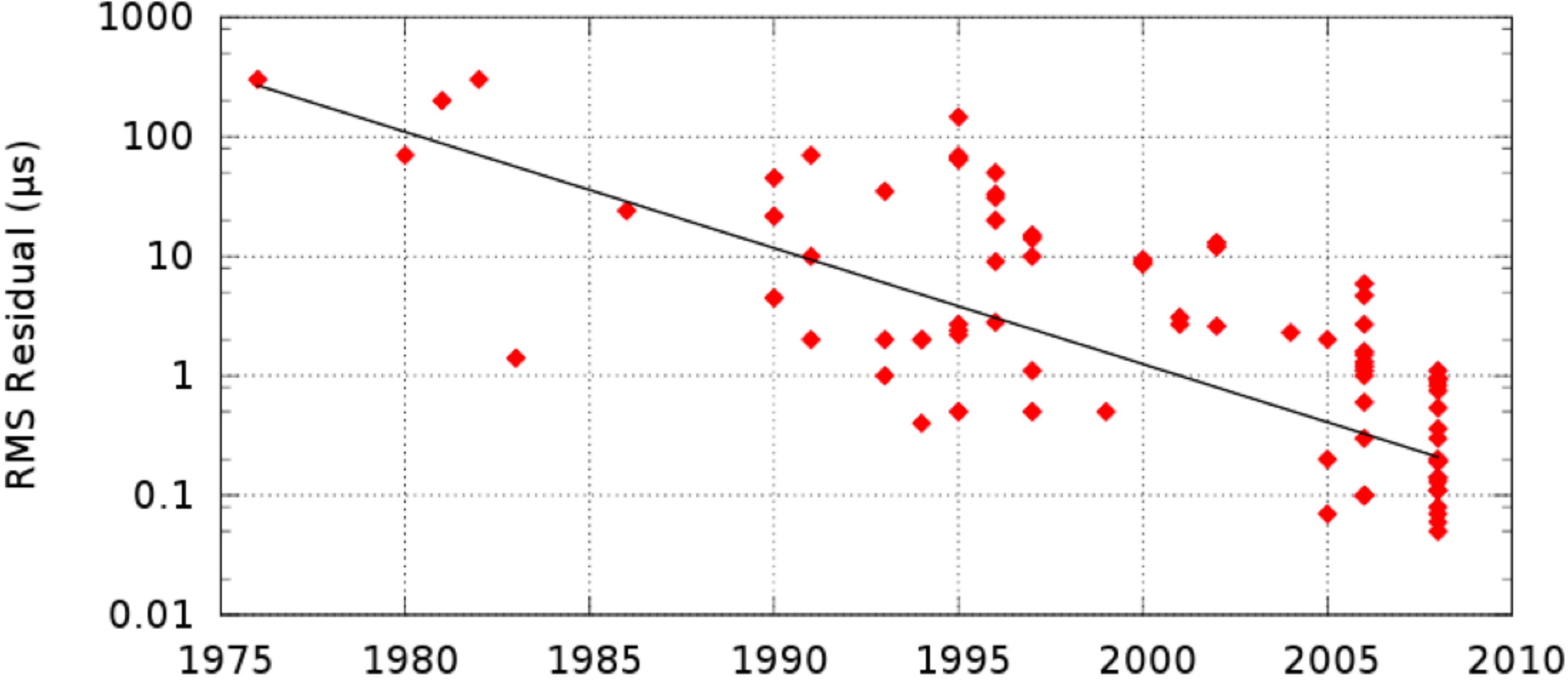
[b] This represents the combined observing time of four European 100-m class dishes.

[c] Equivalent single-dish diameter.

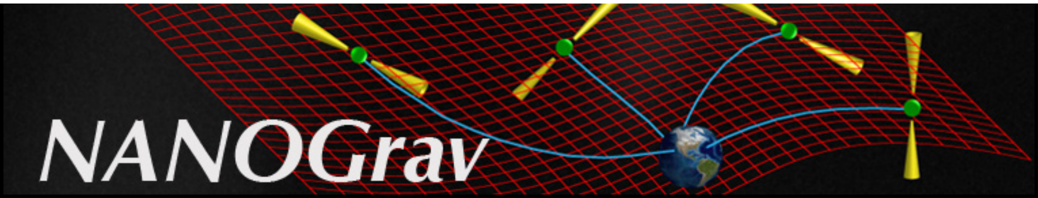
[d] 20 pulsars with $\lesssim$100 ns RMS timing.

[e] >40 pulsars with $\lesssim$100 ns RMS timing.

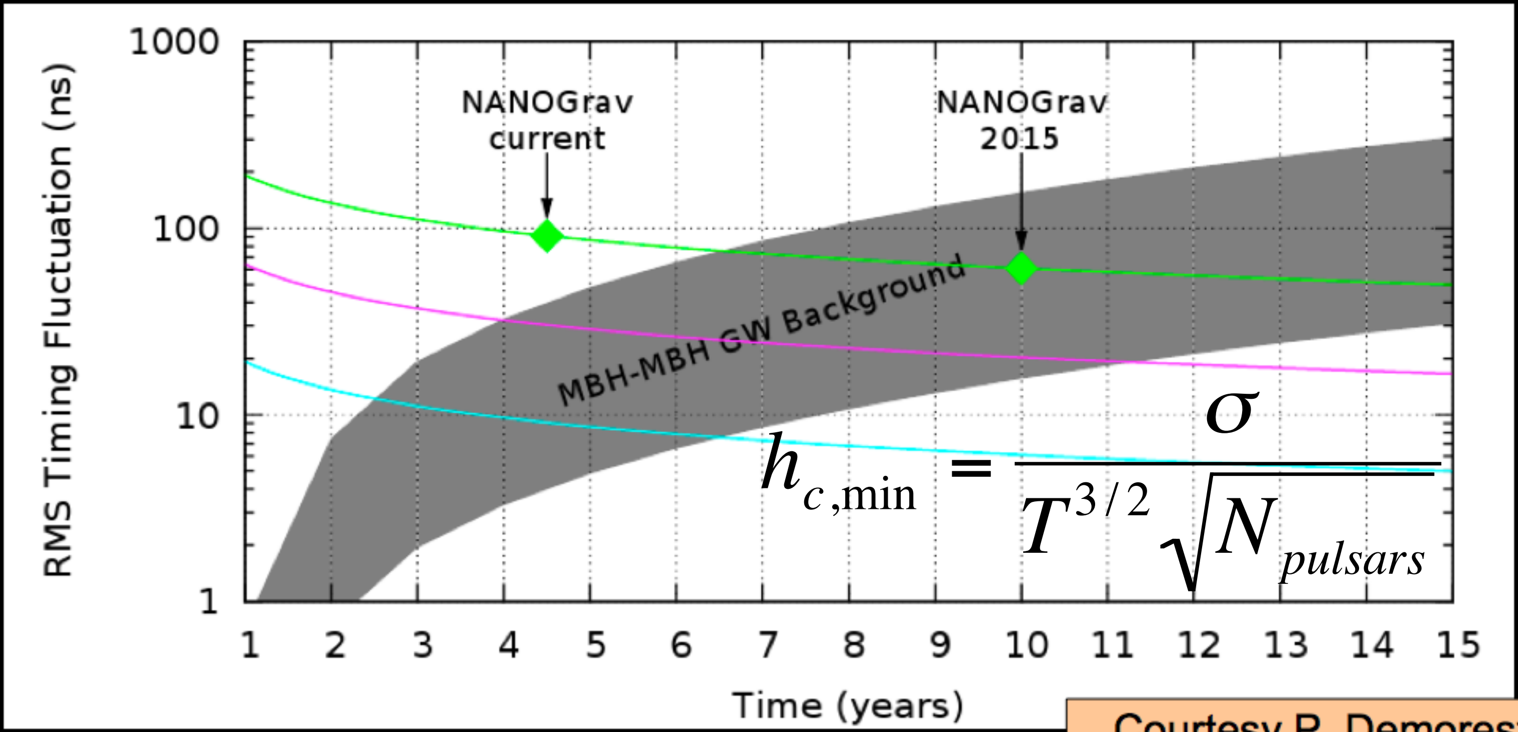
NANOGrav



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



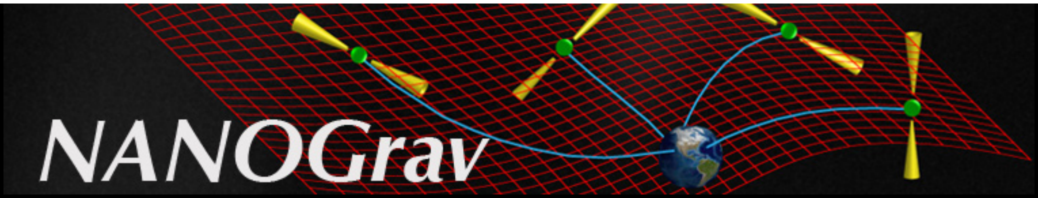
# NANOGrav improvement with time...



$$h_{c,\min} = \frac{\sigma}{T^{3/2}\sqrt{N_{pulsars}}}$$

Courtesy P. Demorest

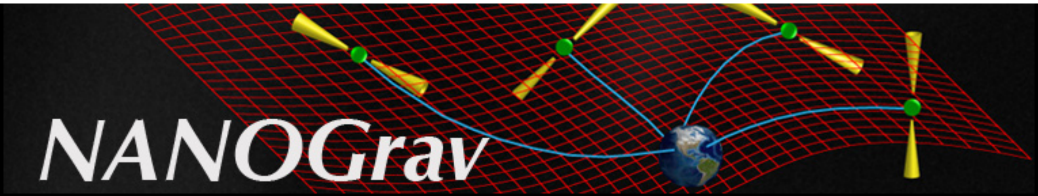
Magenta and cyan curves show what happens if we improve our ability to time the pulsars by factors of ~3 and 10



# Physics from Pulsars

(see Blandford, 1992, PTRSLA, 341, 177 for a review)

- Newtonian and relativistic dynamics (e.g. binary pulsars)
- **Gravitational wave physics (e.g. binaries, MSP timing)**
- Physics at nuclear density (e.g. NS equations of state)
- Astrophysics (e.g. stellar masses and evolution)
- Plasma physics (e.g. magnetospheres, pulsar eclipses)
- Fluid dynamics (e.g. supernovae collapse)
- Magnetohydrodynamics (MHD; e.g. pulsar winds)
- Relativistic electrodynamics (e.g. pulsar magnetospheres)
- Atomic physics (e.g. NS atmospheres)
- Solid state physics (e.g. NS crust properties)



# General Relativity Gives…

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}\,(1-e^2)^{-1}$$

(Advance of Periastron)

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3}\,M^{-4/3}\,m_2\,(m_1+2m_2)$$

(Grav redshift + time dilation)

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2}\,T_\odot^{5/3}\,m_1\,m_2\,M^{-1/3}$$

$$r = T_\odot\,m_2$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3}\,M^{2/3}\,m_2^{-1}$$

(Shapiro delay: “range” and “shape”)

**where:** $T_\odot \equiv GM_\odot/c^3 = 4.925490947\ \mu s$, $M = m_1 + m_2$, and $s \equiv \sin(i)$