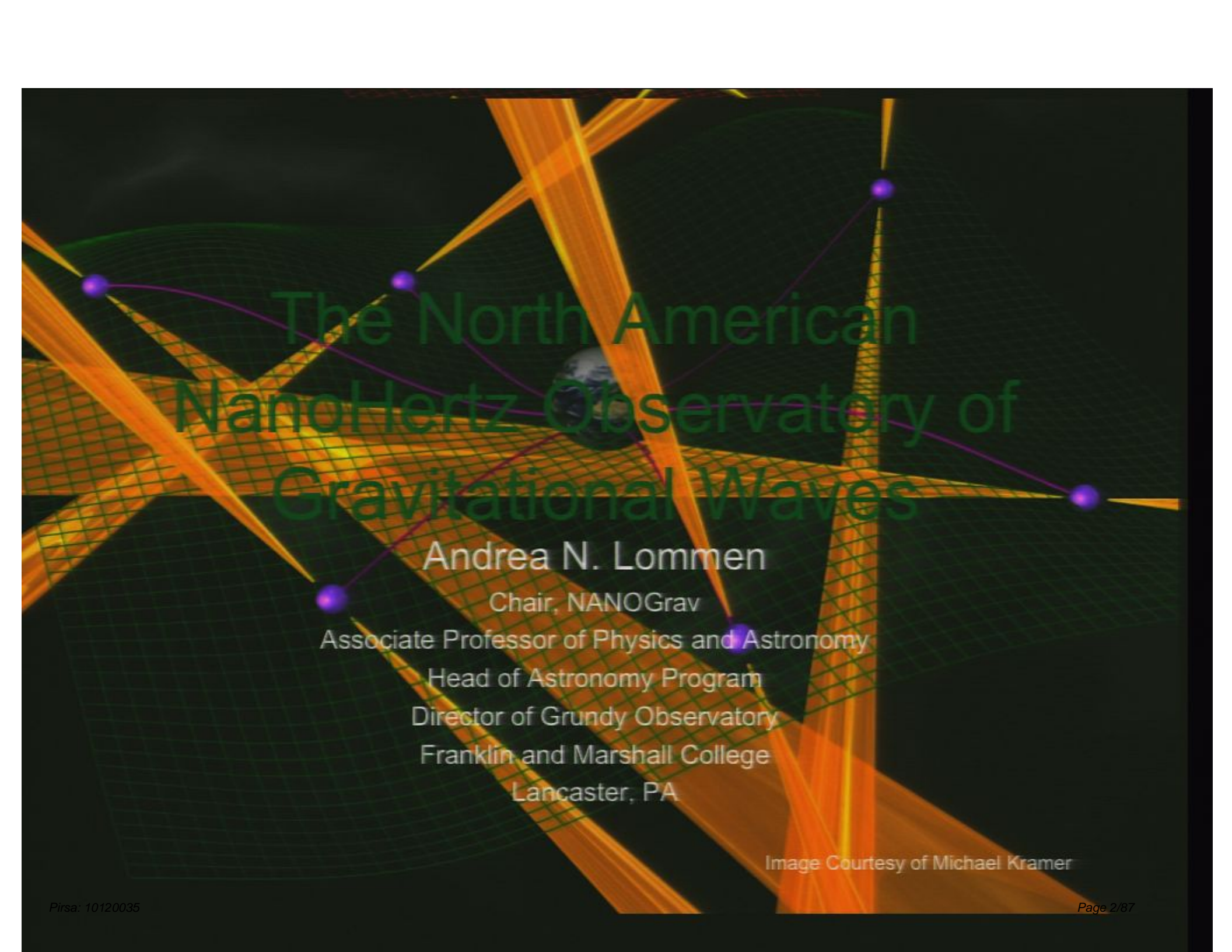


Title: The North American Nanohertz Observatory of Gravitational Waves (NANOGrav)

Date: Dec 16, 2010 03:00 PM

URL: <http://pirsa.org/10120035>

Abstract: NANOGrav is a consortium of radio astronomers and gravitational wave physicists whose goal is to detect gravitational waves using an array of millisecond pulsars as clocks. Whereas interferometric gravitational wave experiments use lasers to create the long arms of the detector, NANOGrav uses earth-pulsar pairs. The limits that pulsar timing places on the energy density of gravitational waves in the universe are on the brink of limiting models of galaxy formation and have already placed limits on the tension of cosmic strings. Pulsar timing has traditionally focused on stochastic sources, but most recently I have been investigating the idea of detecting individual gravitational wave bursts wherein there are some interesting advantages. I will also demonstrate how the array can be used to reconstruct the waveform and obtain its direction.



The North American NanoHertz Observatory of Gravitational Waves

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

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 University
- 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
- Larry Price, University of Wisconsin
- Scott Ransom, National Radio Astronomy Observatory
- Ryan Shannon, Cornell University
- Xavi Siemens, University of Wisconsin
- Ingrid Stairs, University of British Columbia
- Don Stinebring, Oberlin College



The EPTA: partners NANOGrav

University of Manchester, JBO, UK

ASTRON, NL

Max-Planck Insitut fur Radioastronomie, GER

Nancay Observatory, FR

INAF Osservatorio Astonomico di Cagliari, IT



The Parkes Pulsar Timing Array Project

NANOGrav

Collaborators:

- Australia Telescope National Facility, CSIRO, Sydney
Dick Manchester, George Hobbs, David Champion, John Sarkisstan, 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
Keja Lee
- Southwest University, Chongqing
Xiaopeng You
- Curtin University, Perth
Alan Hottel



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The EPTA: partners

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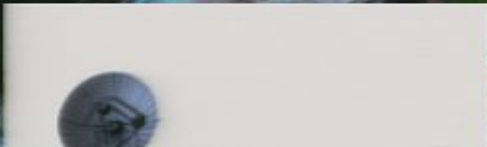
University of Manchester, JBO, UK

ASTRON, NL

Max-Planck Insitut fur Radioastronomie, GER

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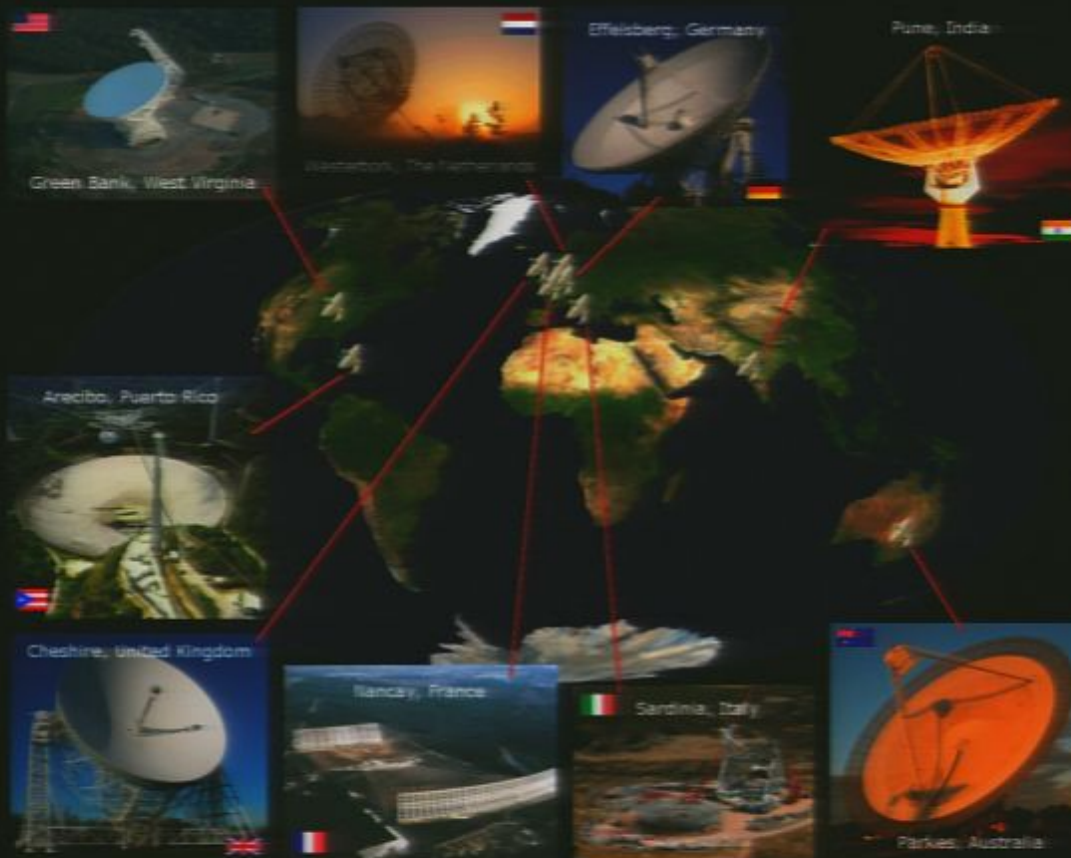
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NANOGrav

The International Pulsar Timing Array





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Talk represents work with:

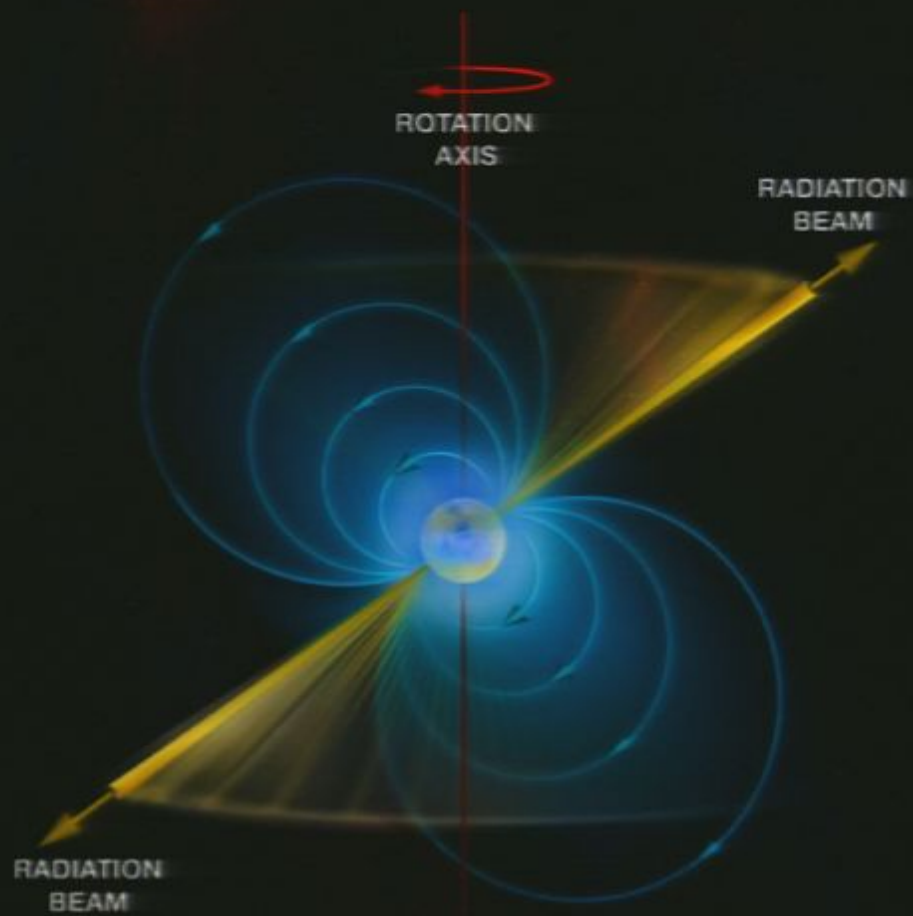
- NANOGrav
- European Pulsar Timing Array
- Parkes Pulsar Timing Array

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

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What is
a
pulsar?





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Millisecond Pulsars are *Very* Precise Clocks

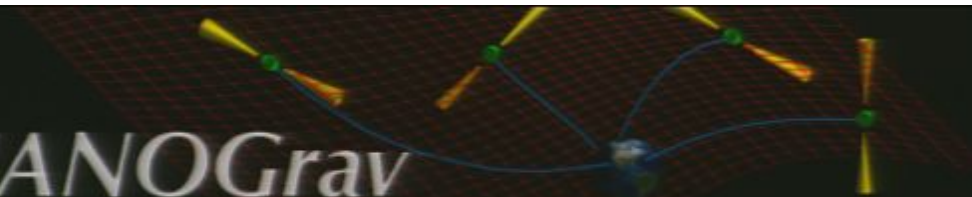
PSR B1937+21

At midnight on 5 Dec, 1998:

$$P = 1.5578064688197945 \text{ ms} \\ \pm 0.000000000000000004 \text{ ms}$$

The last digit changes by about 1 per second!

This extreme precision is what allows us to
use pulsars as tools to do unique physics!



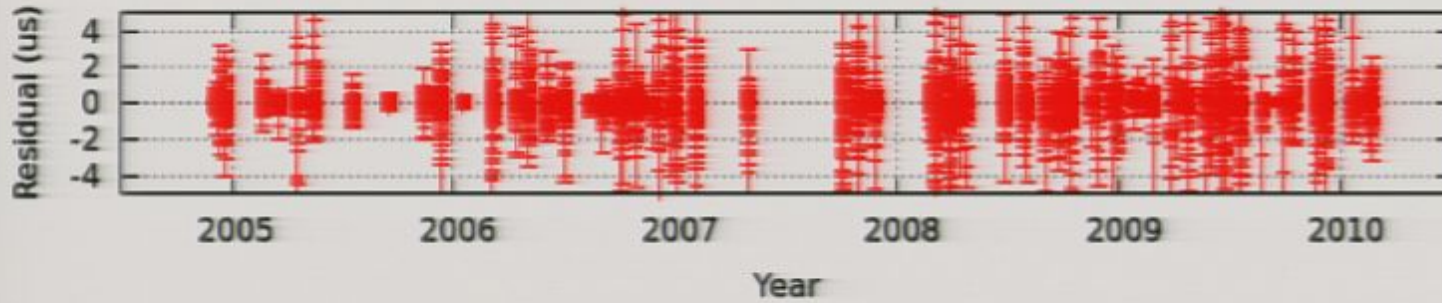
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Typical Pulsar Model

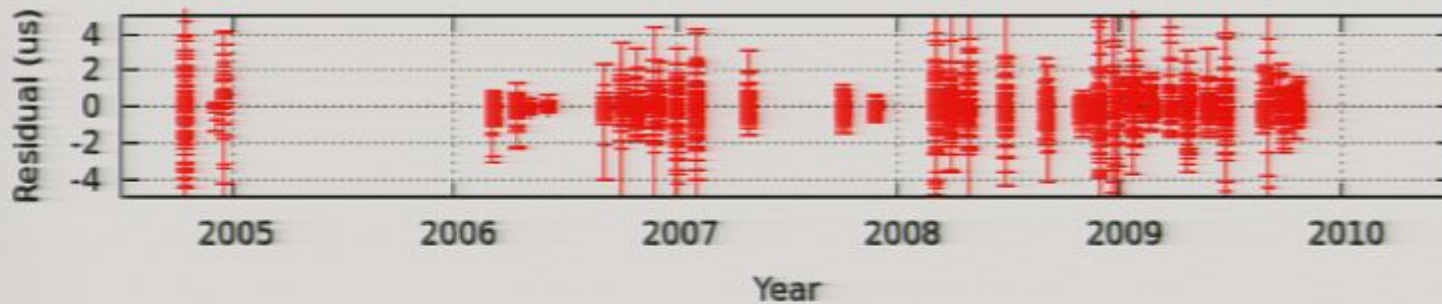
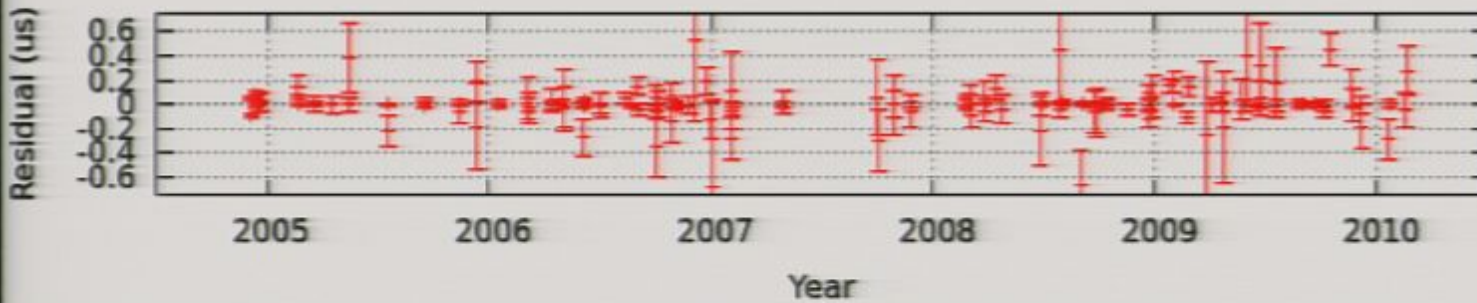
Table 1 PSR J0437–4715 physical parameters

Right ascension, α (J2000) ...	04 ^h 37 ^m 15 ^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)

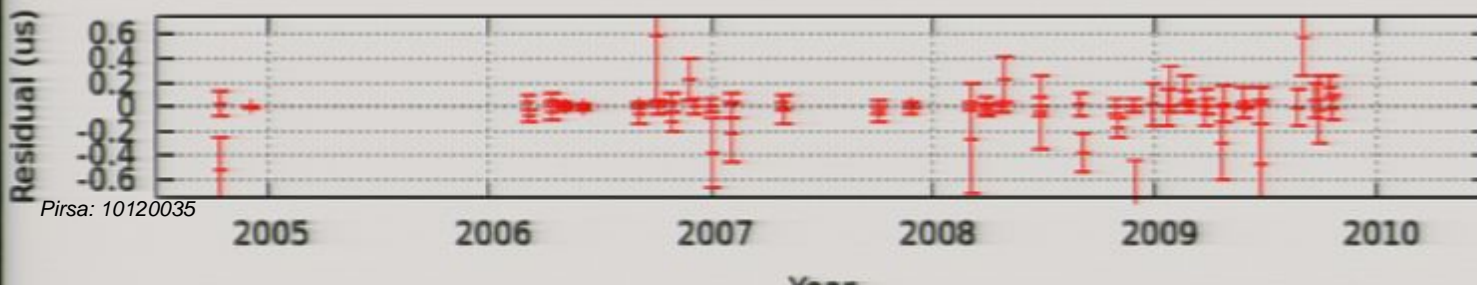
Timing residuals versus time:



J1713+0747



J1909-3744

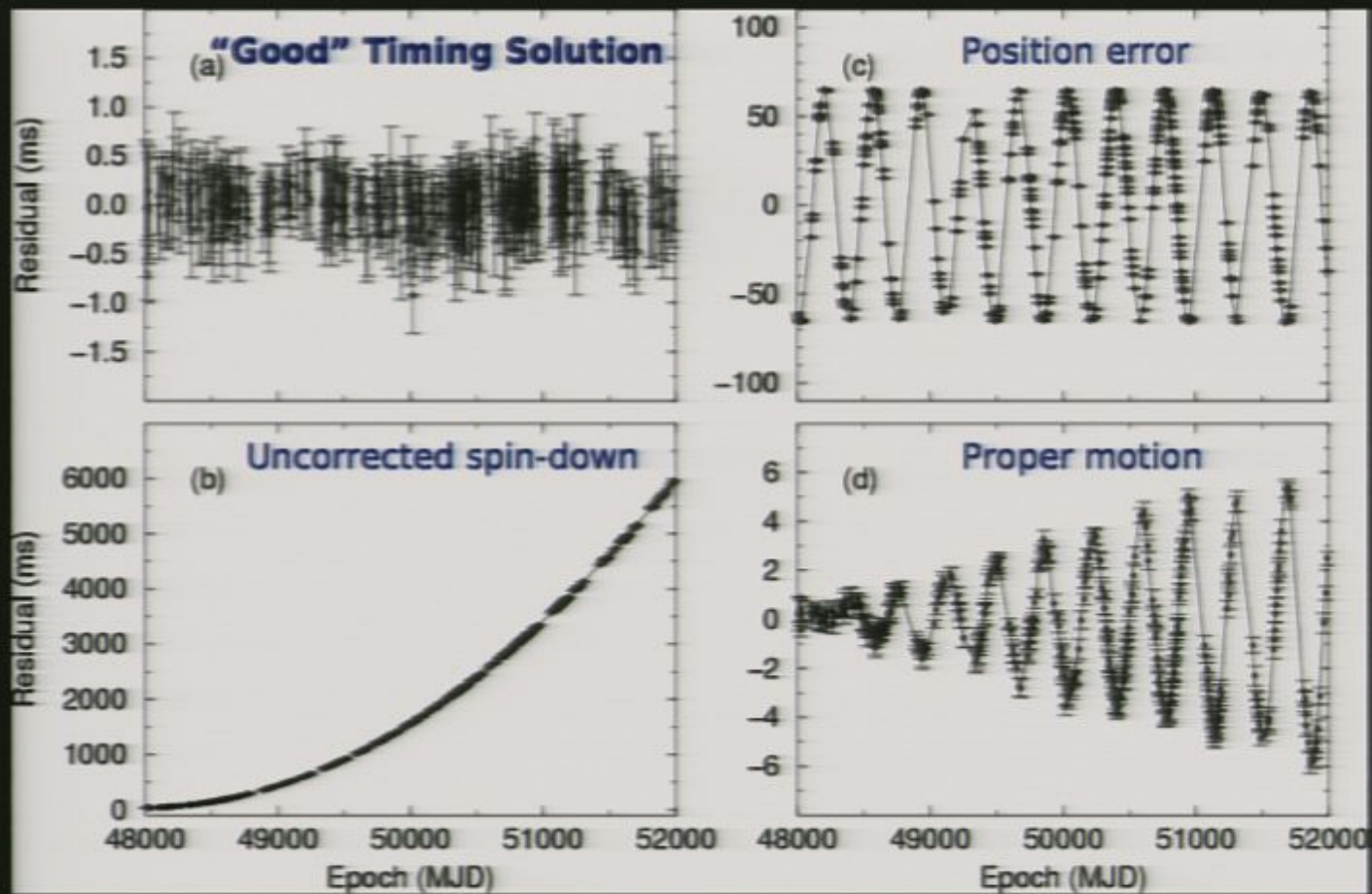


Slide
courtesy of
Paul
Demorest

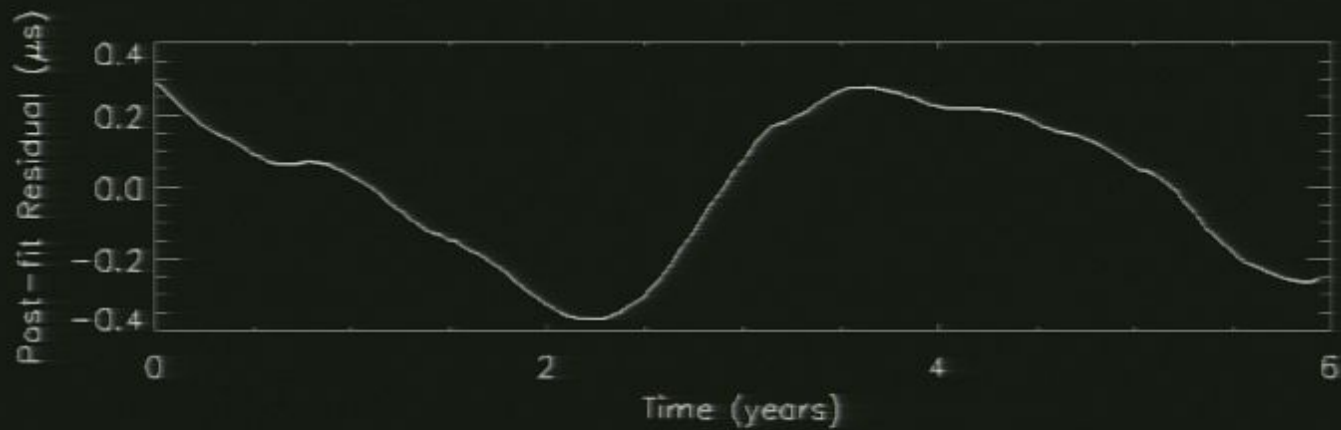
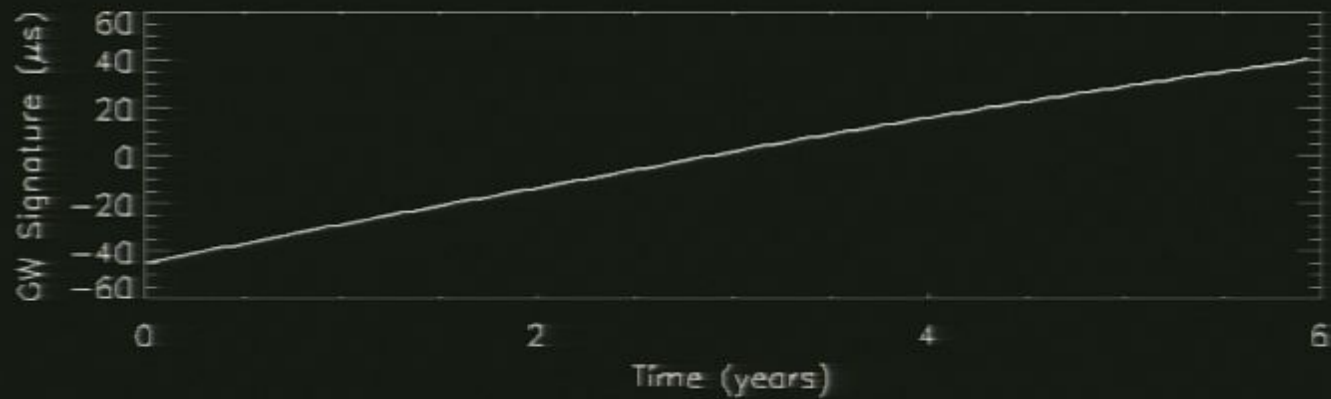
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The science is in the residuals!:

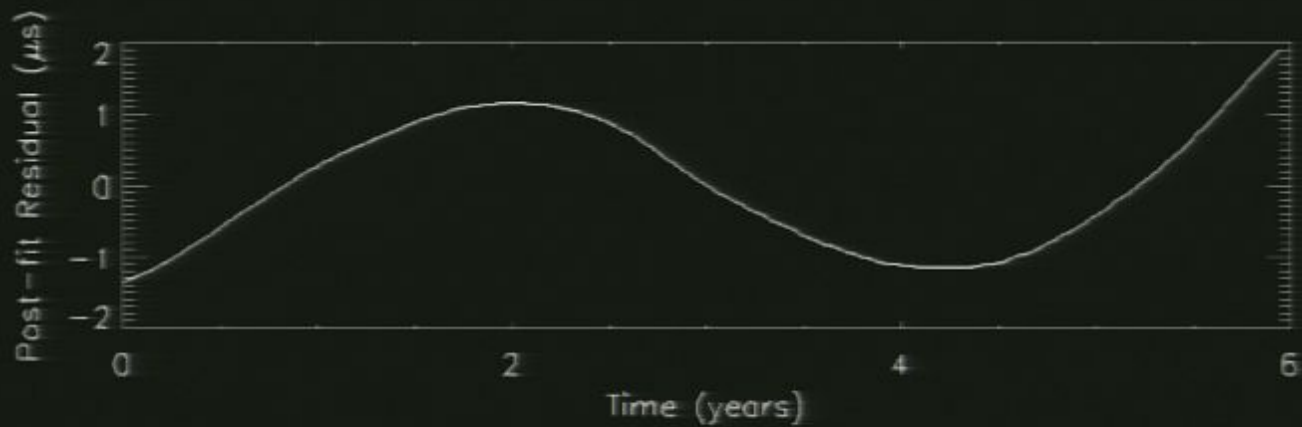
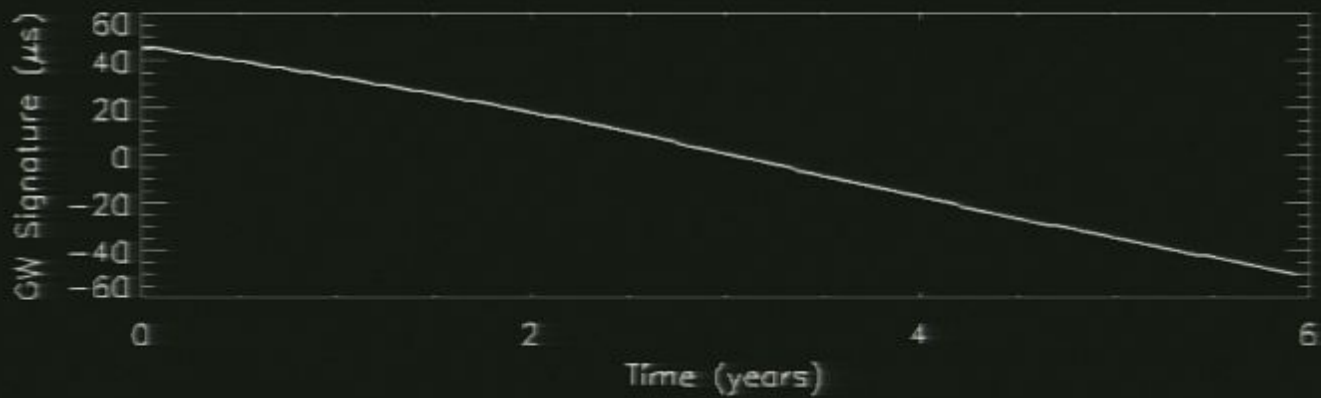
RMS precision $\sim 10^{-5}$ - 10^{-3} P



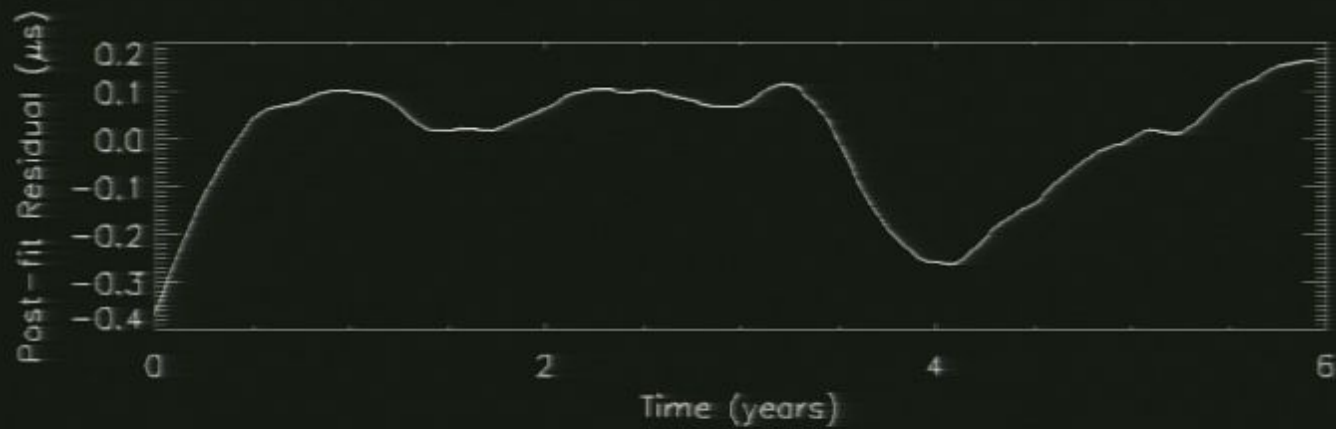
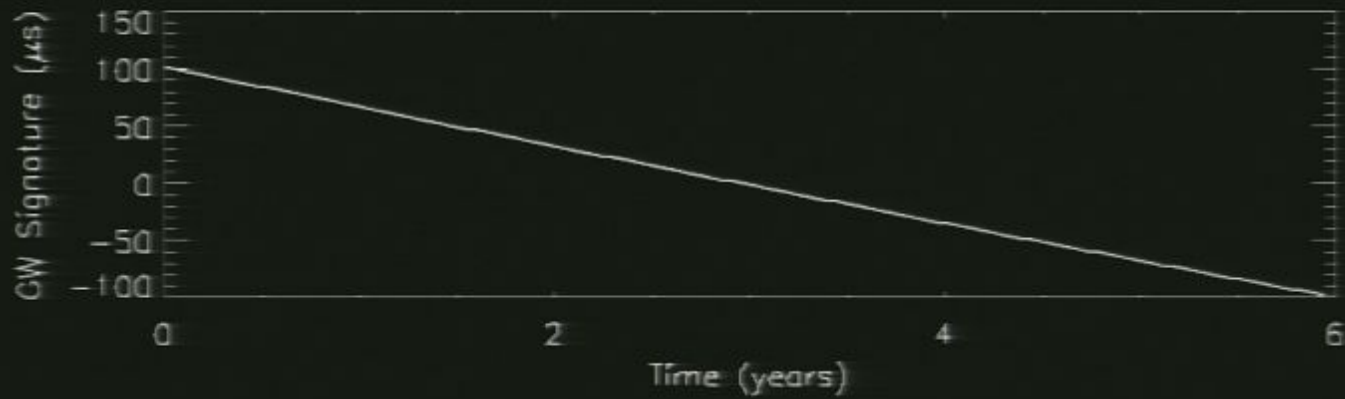
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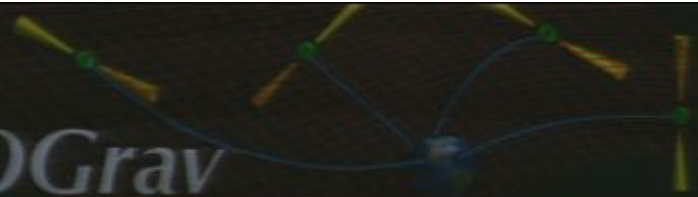
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The image features a large, dark blue background with a series of concentric, glowing white circles that resemble ripples in water or gravitational waves emanating from a central point. In the center of these ripples, there is a small diagram showing two black spheres representing masses, with white arrows indicating their orbital paths around each other. Overlaid on this background is a rectangular inset photograph of the Virgo gravitational wave detector. The photograph shows a vast, flat landscape with a grid of green and brown agricultural fields. Two long, straight, light-colored concrete arms extend from a central station, forming a large 'V' shape. In the distance, a range of blue mountains is visible under a clear sky. The text "Photo Courtesy of Virgo" is printed in white at the top of the inset photograph.

Photo Courtesy of Virgo



The image features a dark blue background with concentric, glowing white circles representing gravitational waves emanating from a central point. In the center, two black spheres are shown in a circular orbit, with white arrows indicating their direction of movement. Overlaid on this background is a rectangular inset showing an aerial photograph of the Virgo gravitational wave detector. The detector consists of two long, V-shaped arms extending from a central station into a rural landscape of green and brown fields. The sky is clear and blue. The text "Photo Courtesy of Virgo" is printed in white over the top portion of the aerial photo.

Photo Courtesy of Virgo



Detectability of a Waveform

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

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

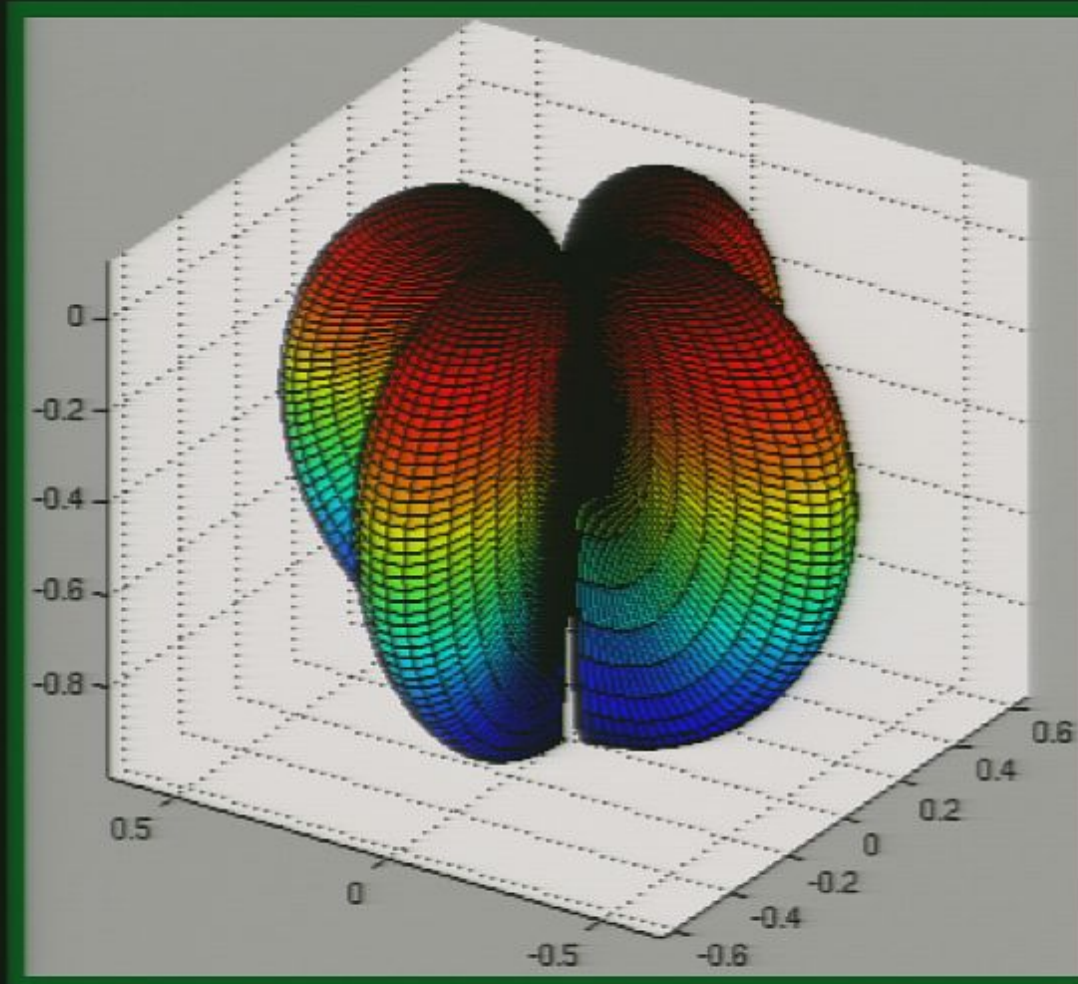
$$\int dt = \int d\lambda - \frac{1 - k_m n^m}{1 + k_m n^m} \int d\lambda n^j n^k h_{jk}(t(\lambda), \vec{x}(\lambda))$$

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

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

NANOGrav

The shape of the GW response





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A sense of what's detectable

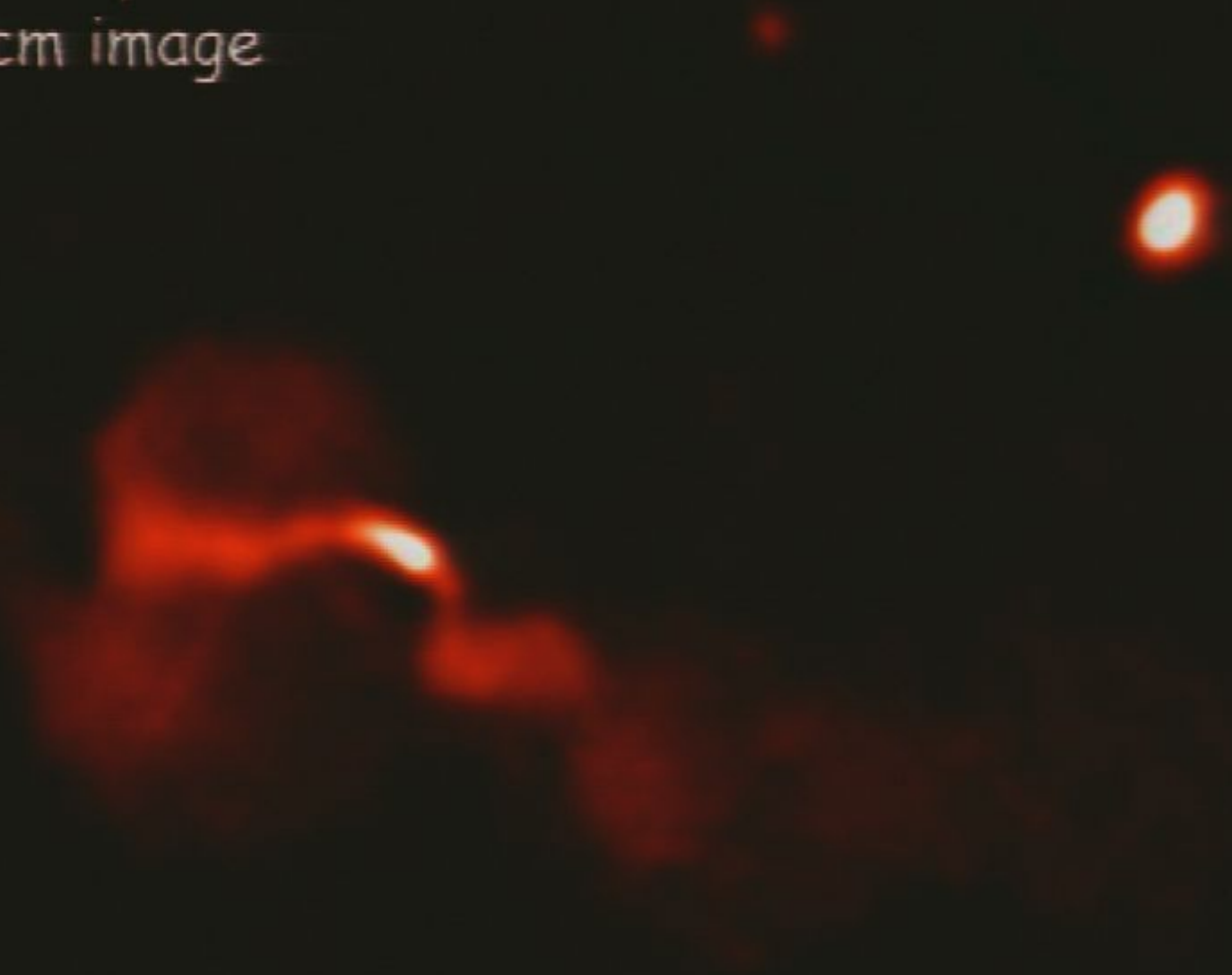
$$h = \frac{M^{5/3}}{P^{2/3} d}$$

$$\tau = hP$$

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

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

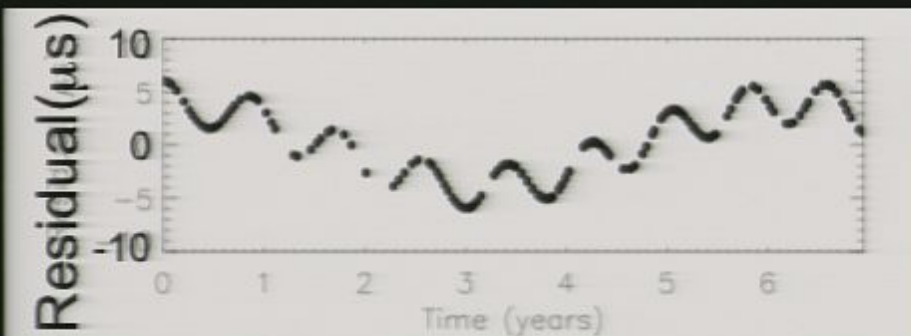
Radio Galaxy 3C66B
VLA 20cm image



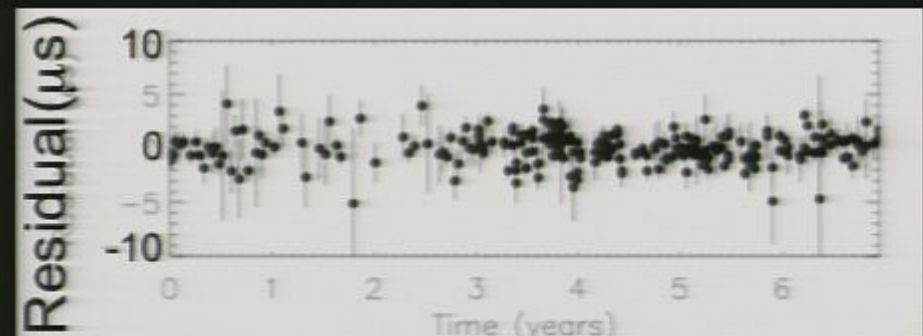
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Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary Sudou, Iguchi, Murata, Taniguchi (2003) Science 300: 1263-1265.

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

NANOGrav 5-year timing results summary

(analysis currently ongoing; PD, M. Gonzalez, D. Nice, I. Stairs, S. Ransom, R. Ferdman)

Source	Per-channel RMS, μs	χ^2	Daily RMS, μs	Hi-freq RMS, μs
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
J1614-1224	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).

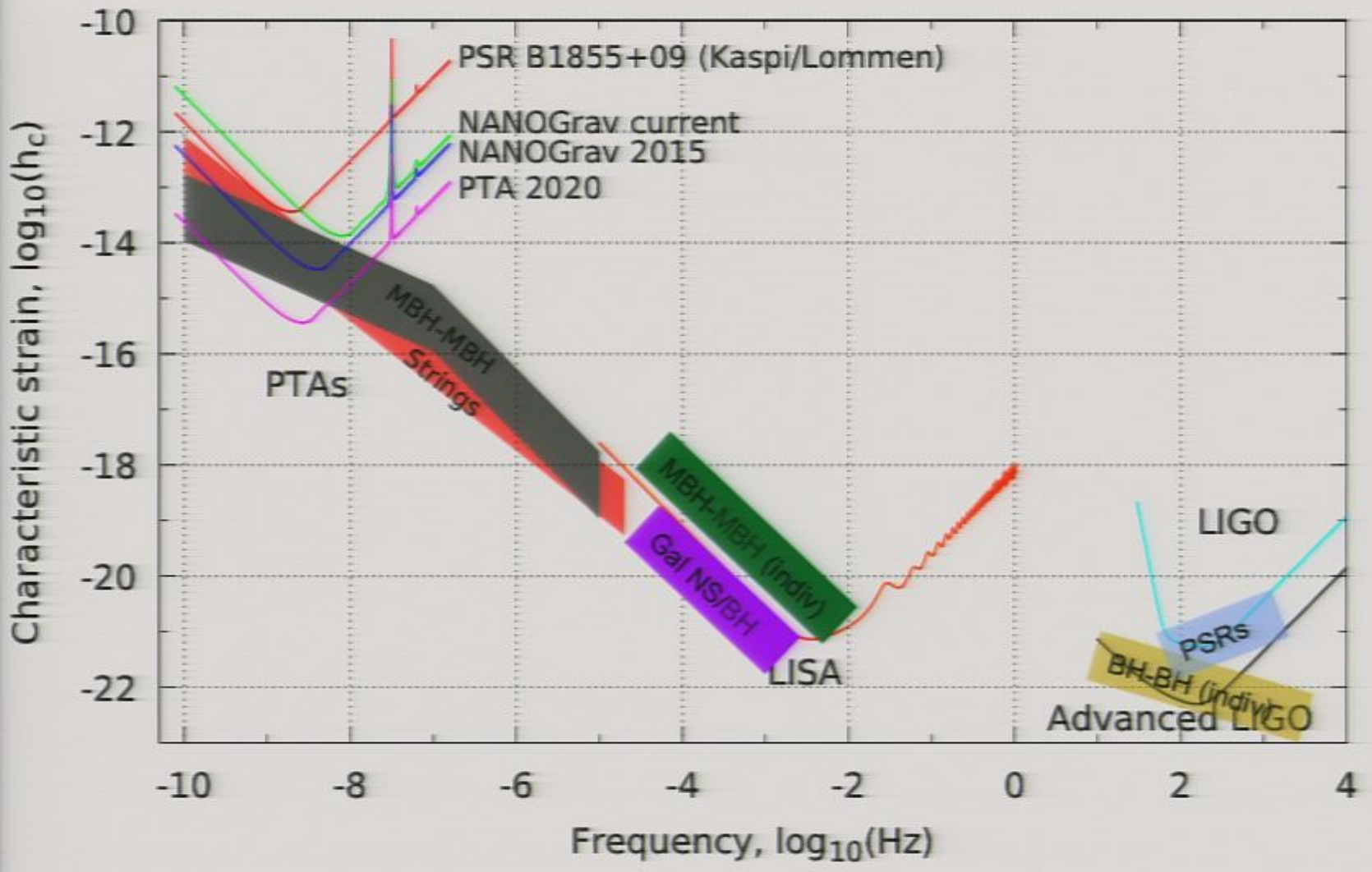
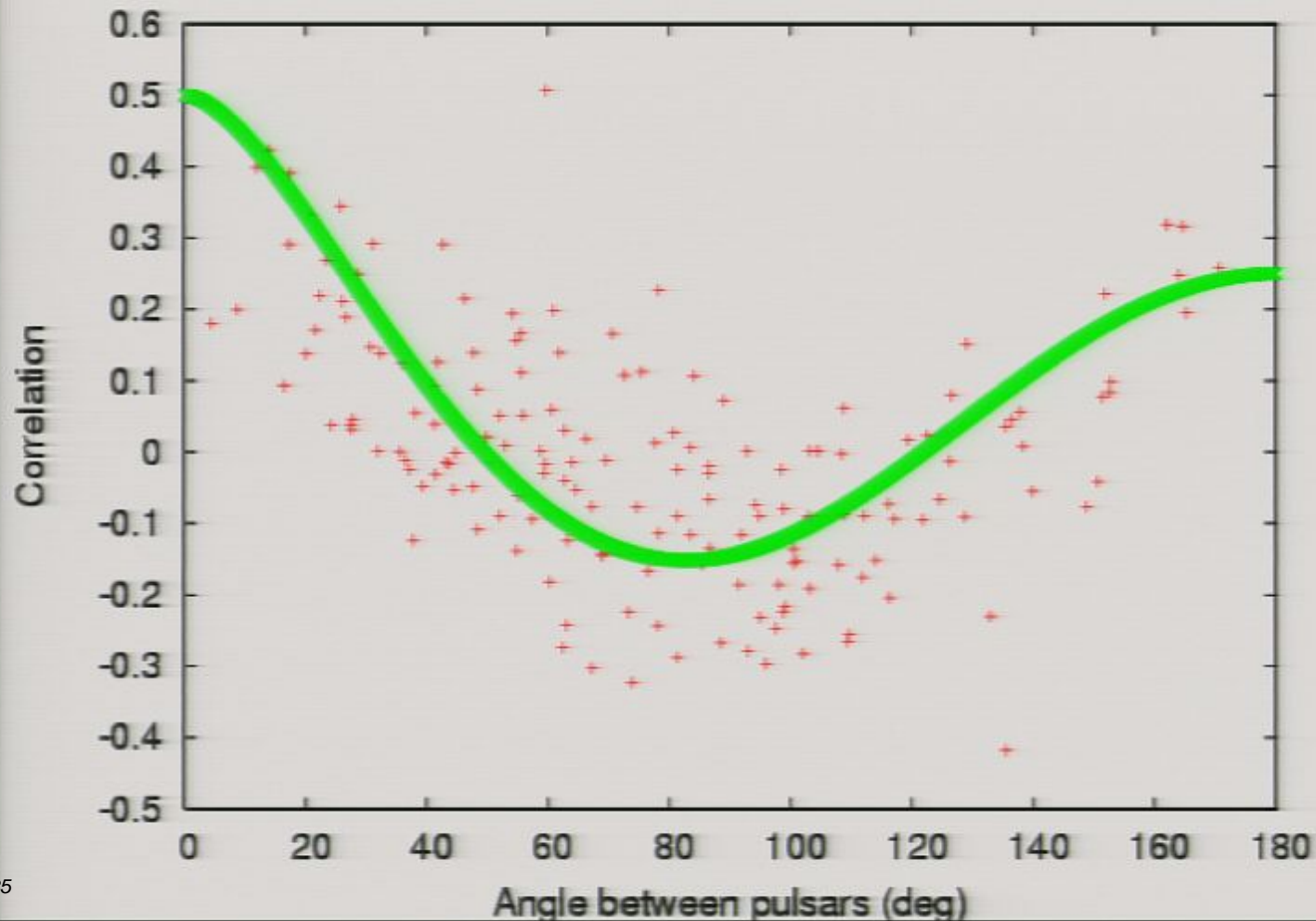


Figure by Paul Demorest (see arXiv:0002.2068)

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Hellings and Downs Curve (Overlap Reduction Function)



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

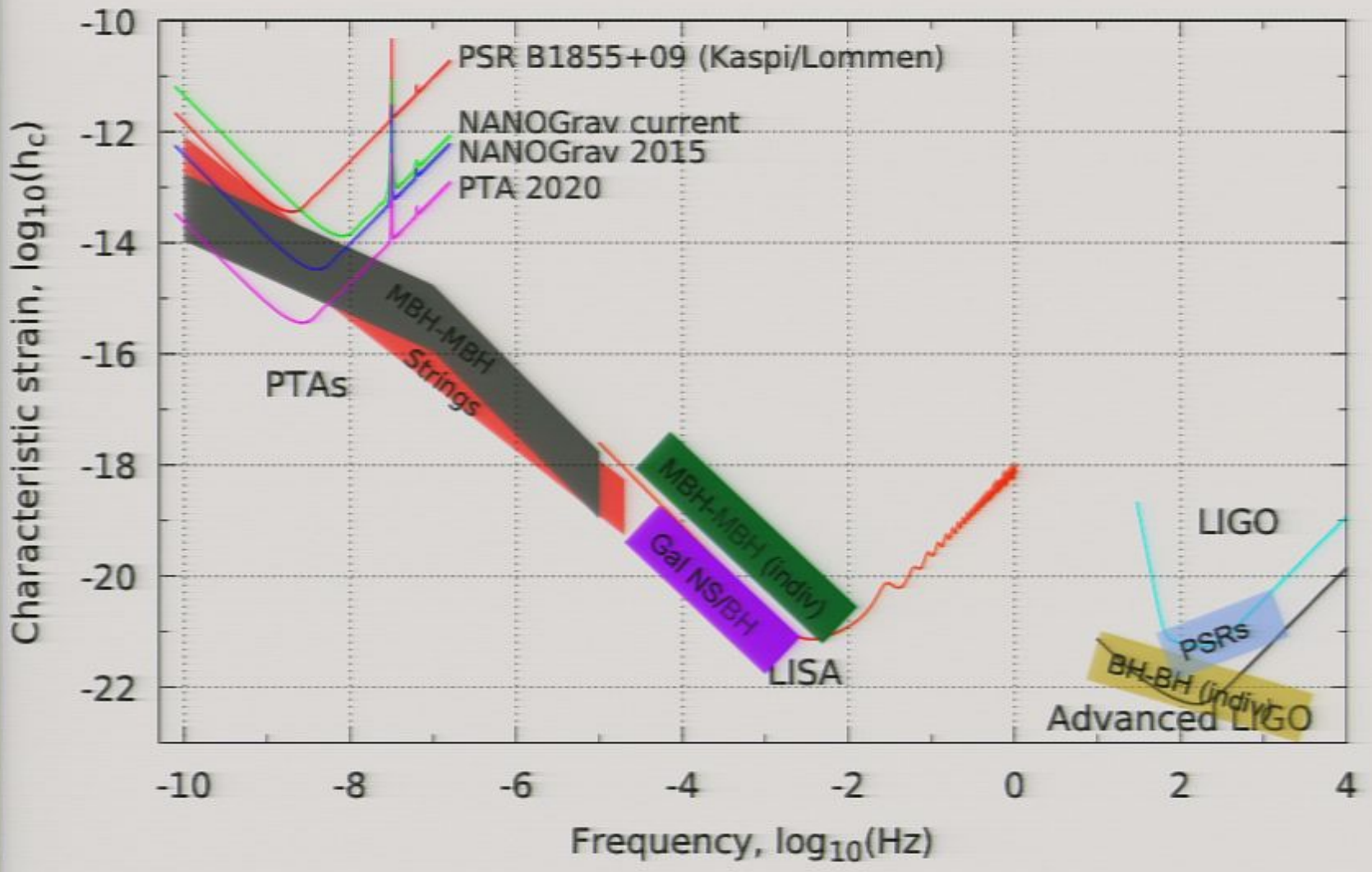
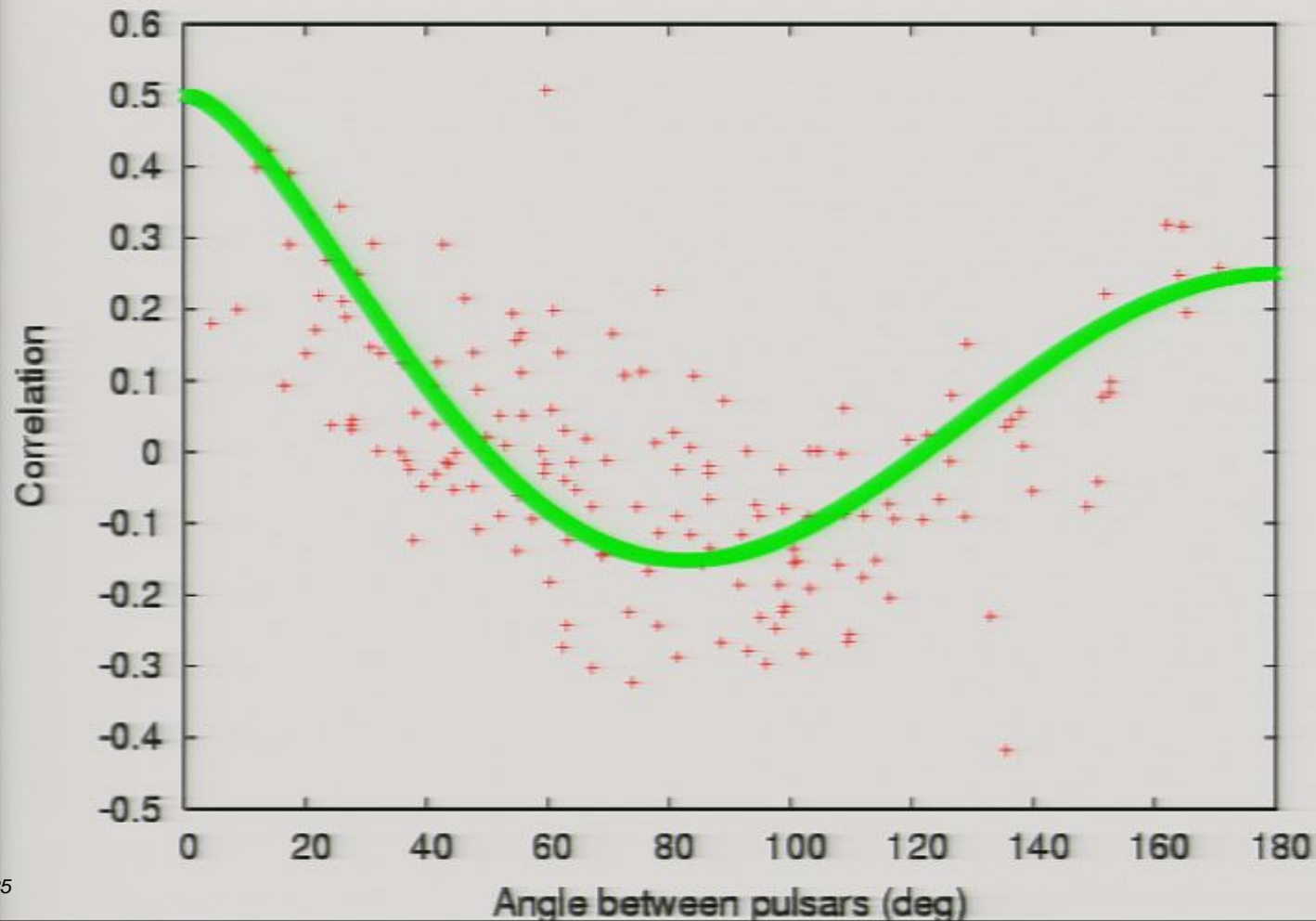


Figure by Paul Demorest (see arXiv:0002.2068)

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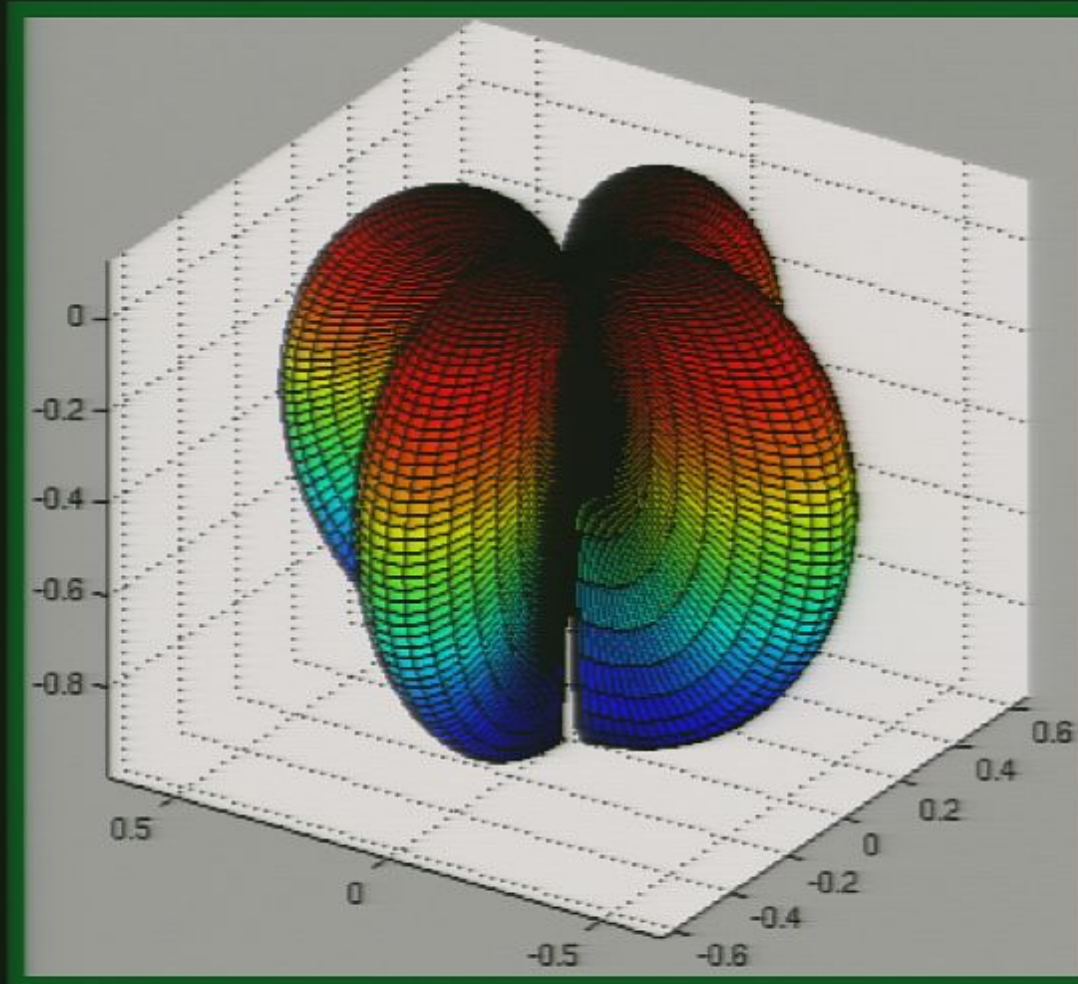
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Original
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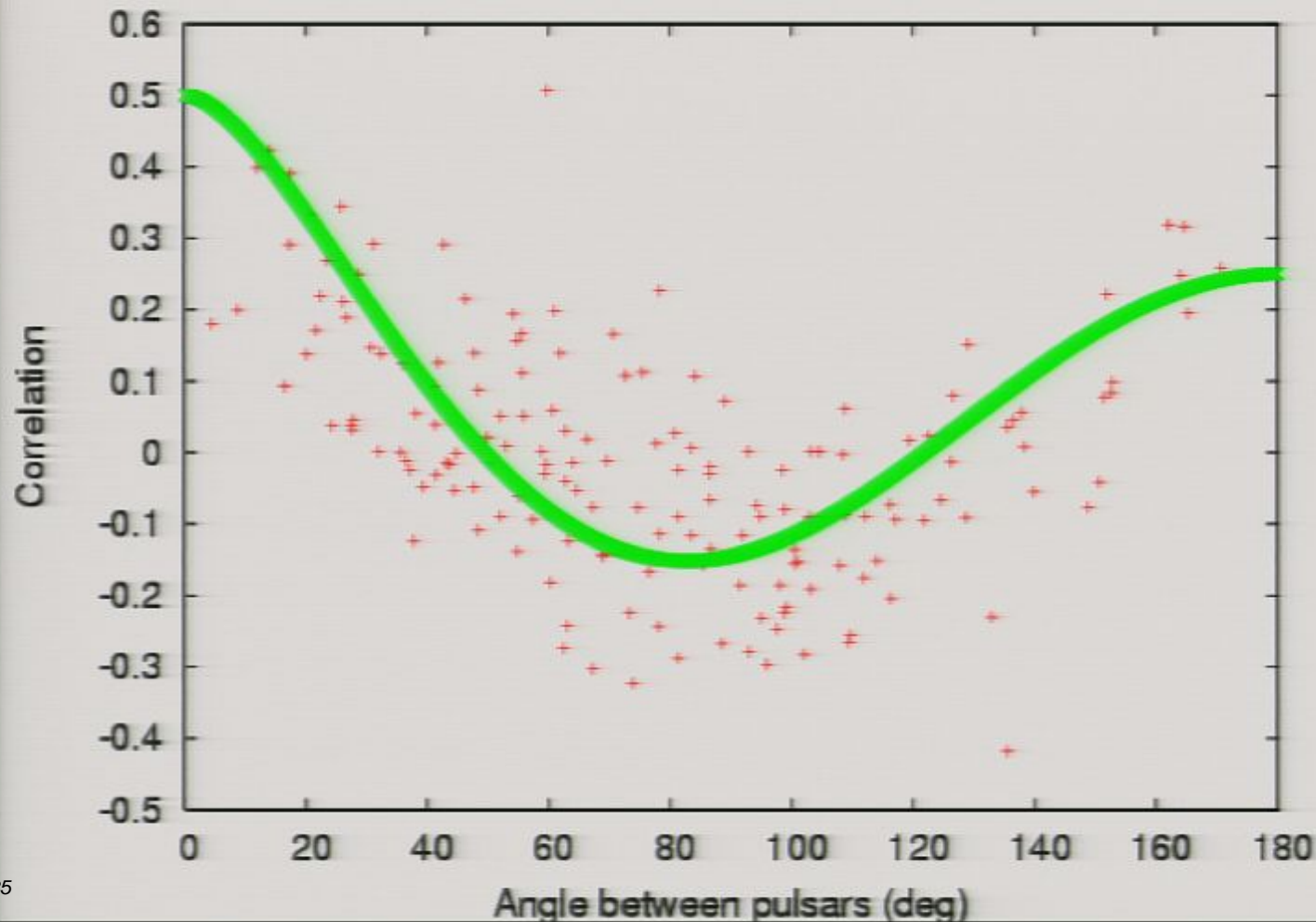
NANOGrav

The shape of the GW response



NANOGrav

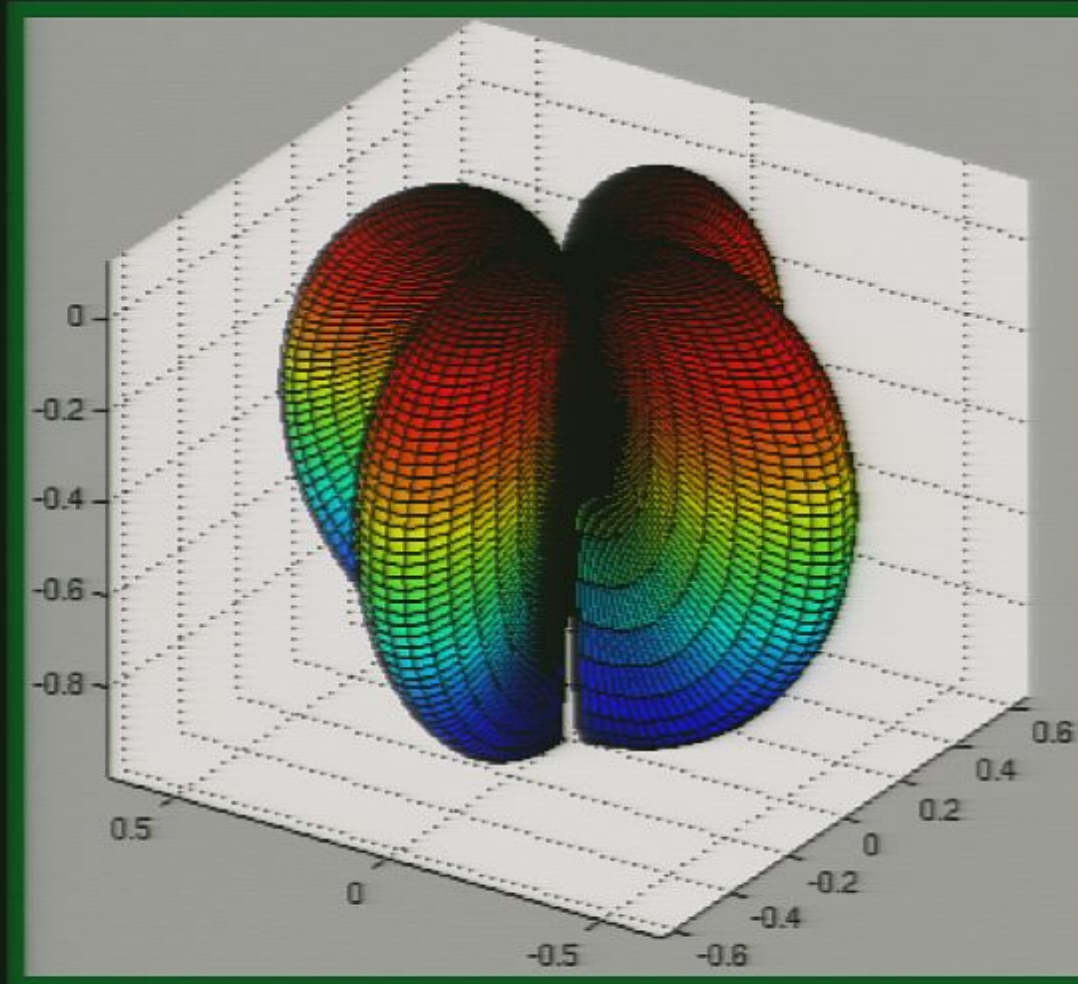
Hellings and Downs Curve (Overlap Reduction Function)



Courtesy
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NANOGrav

The shape of the GW response





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From Rodin, astro-ph:
1012.3038 (14 Dec 2010)

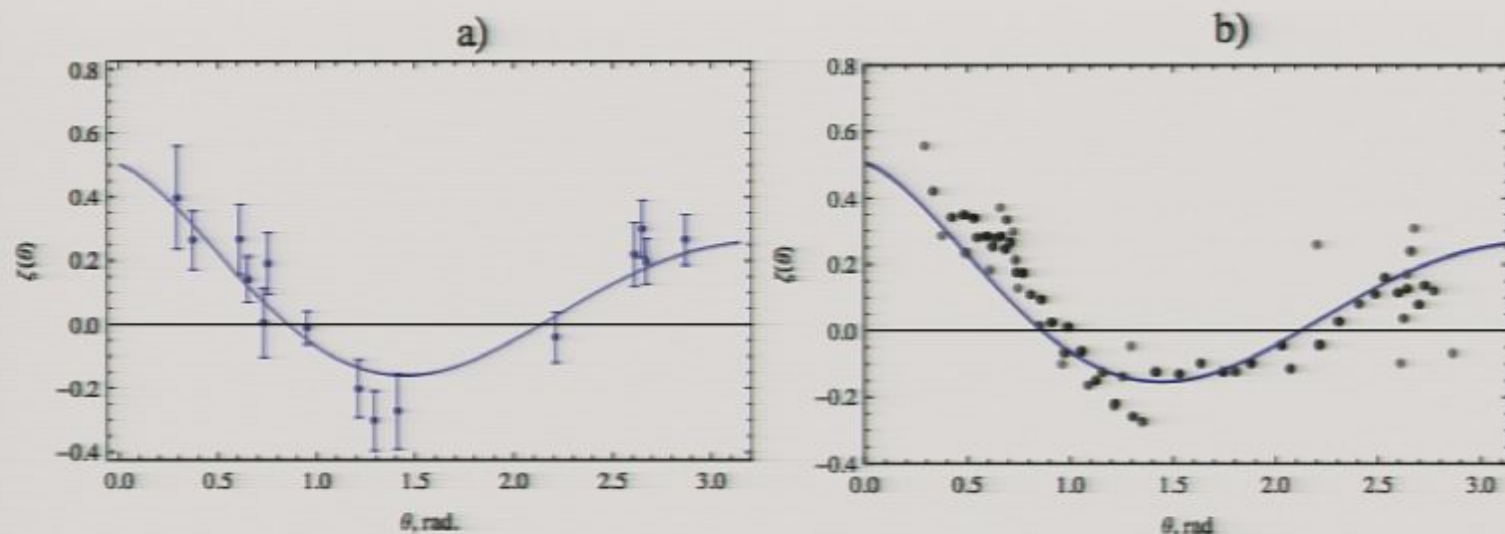
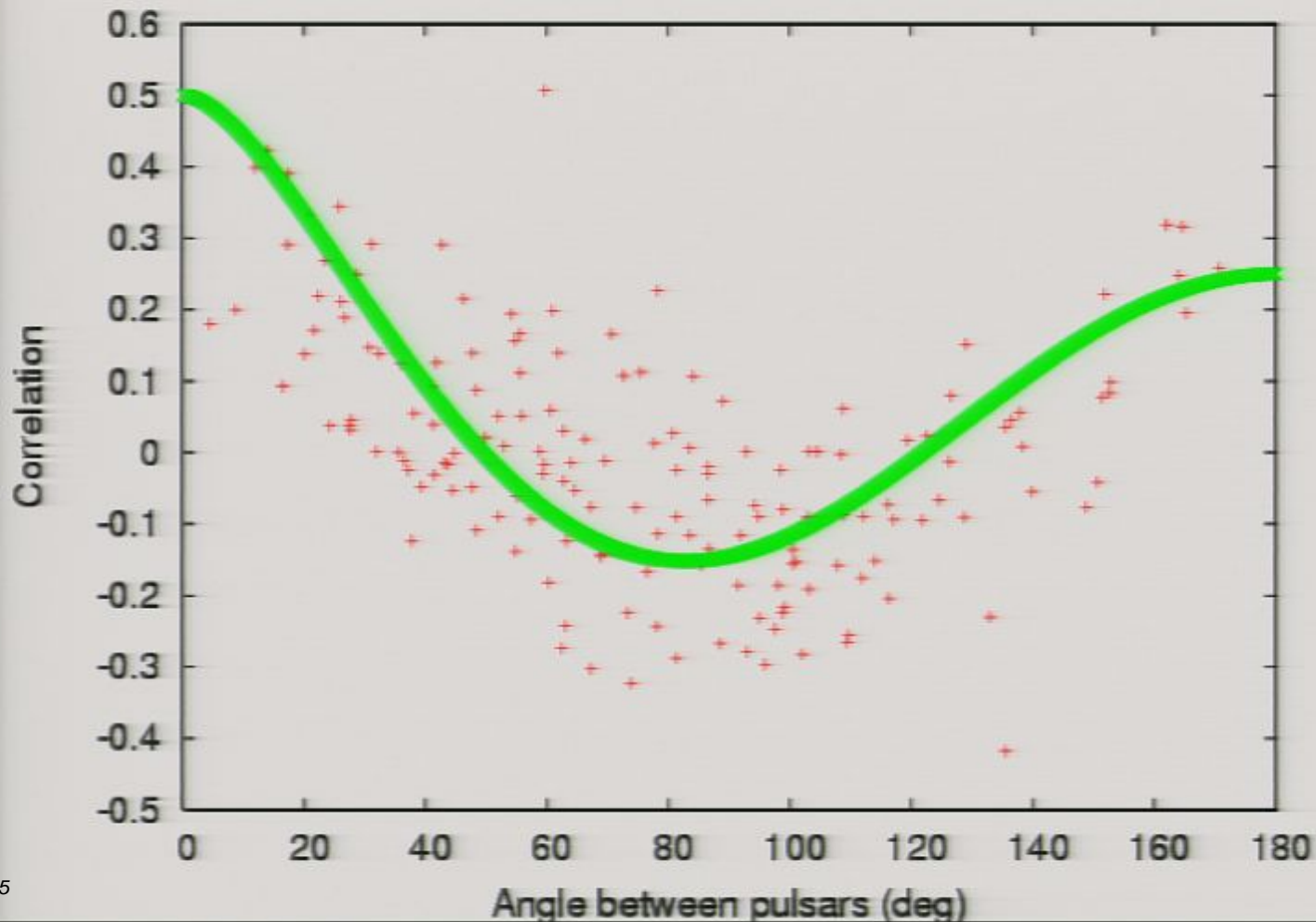


FIGURE 2. a) Results of the numerical simulation of the two-point correlation function for $M = 6$ pulsars and $N = 50$ TOAs. Signal-to-noise ratio $SNR \approx 10$. b) Experimental plot of the two-point correlation function. Moving average by 2-5 points were applied. Correlation coefficient between theoretical curve (solid line) and experimental points $\rho = 0.82 \pm 0.07$

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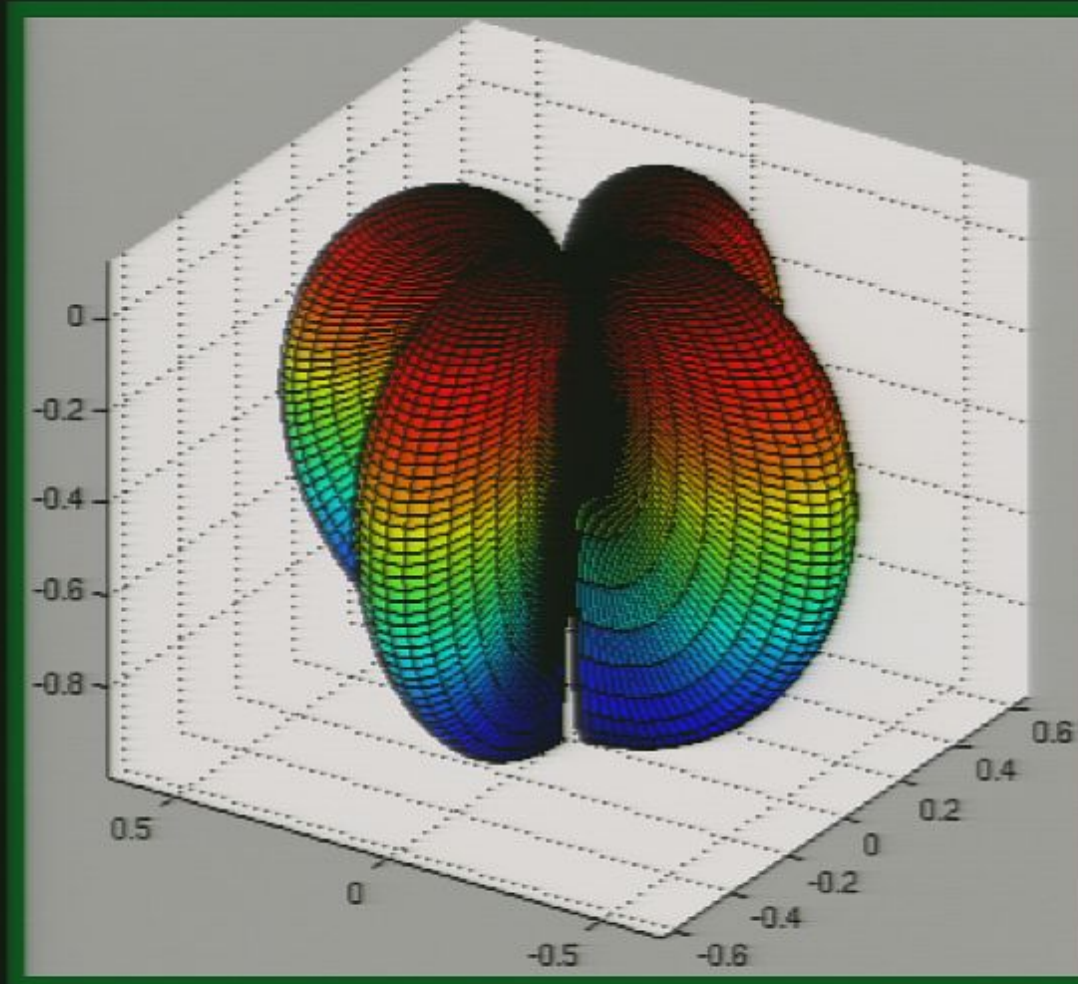
Hellings and Downs Curve (Overlap Reduction Function)



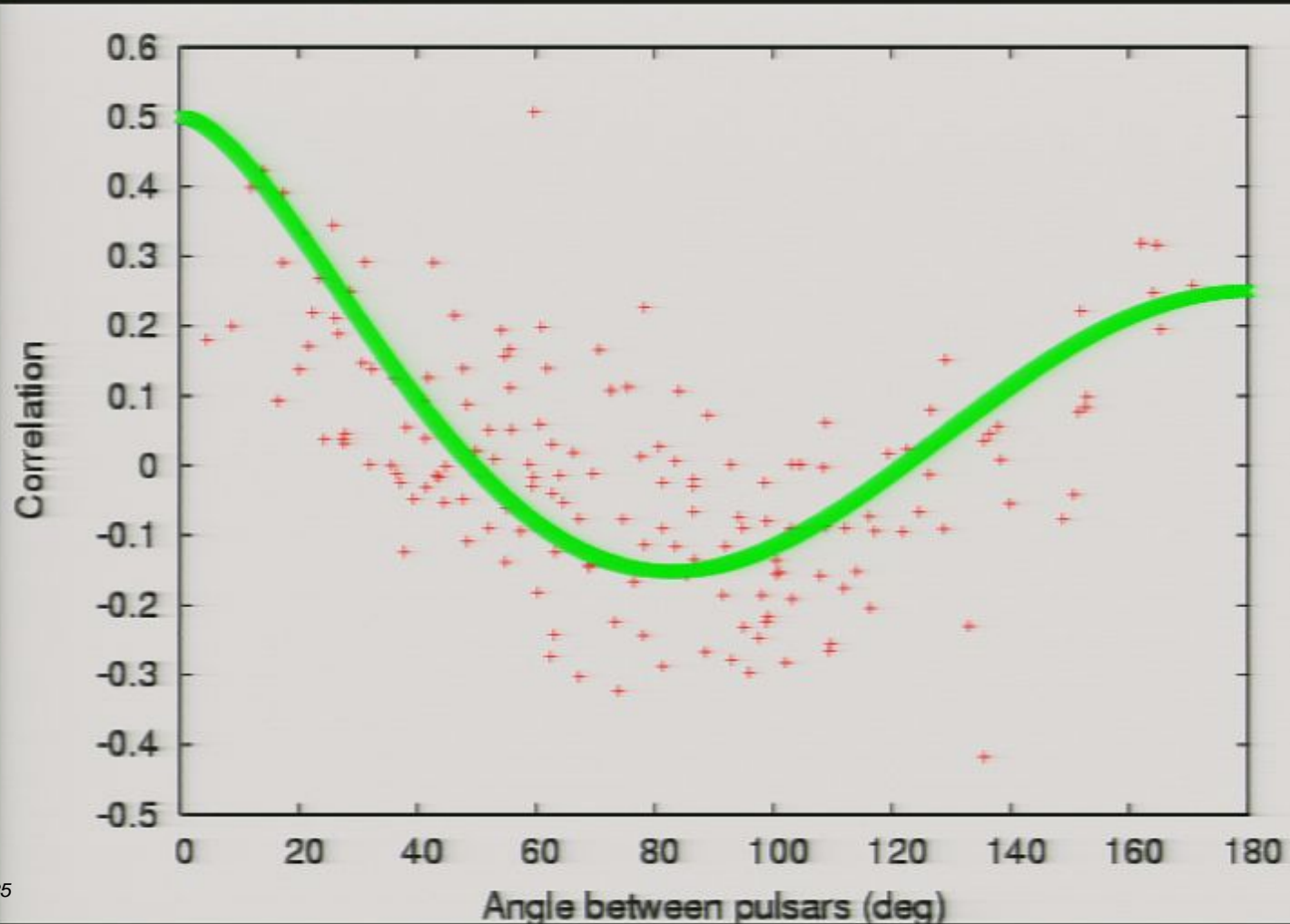
Courtesy of Rick Jenet and George Hobbs. Original figure from Hellings and Downs (1983)

NANOGrav

The shape of the GW response



Hellings and Downs Curve (Overlap Reduction Function)



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

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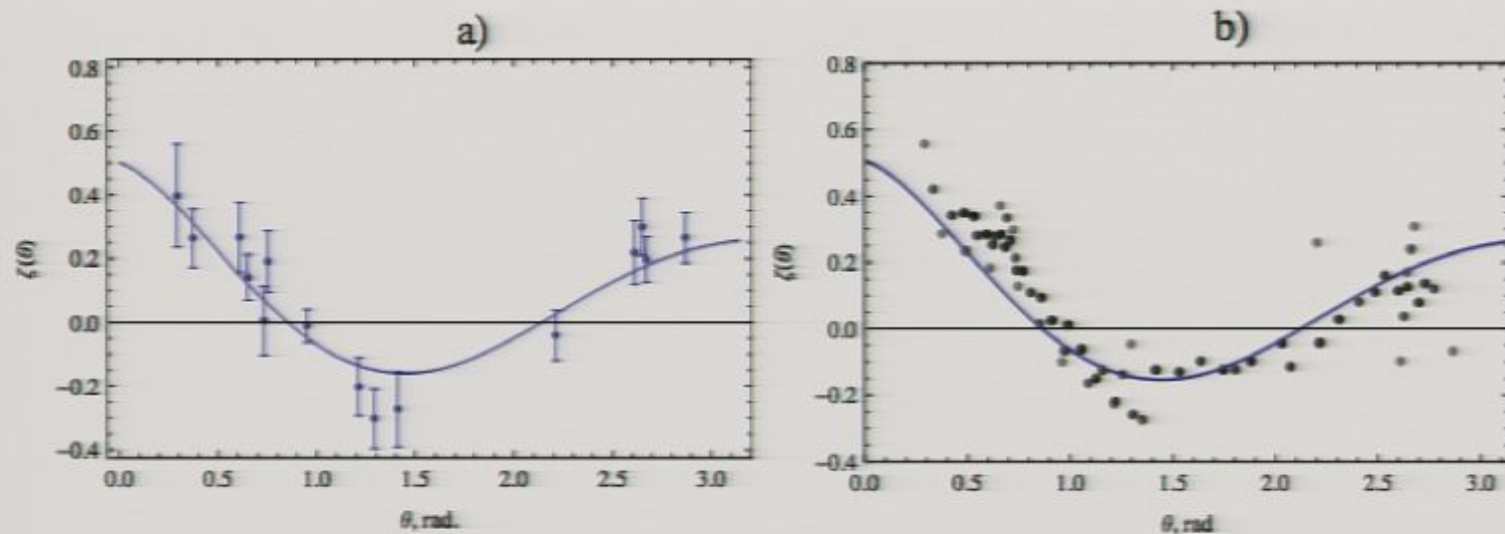
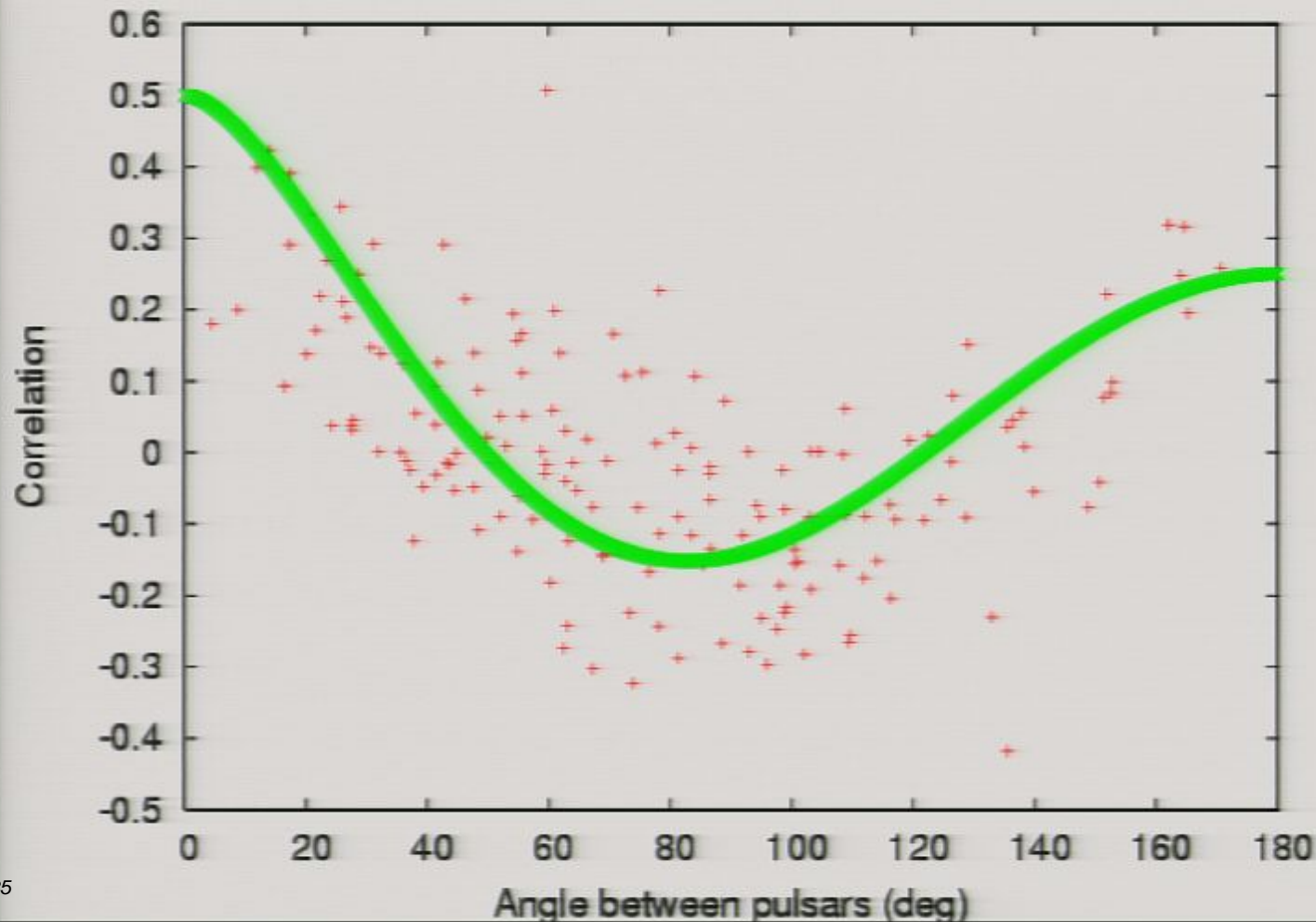


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NANOGrav

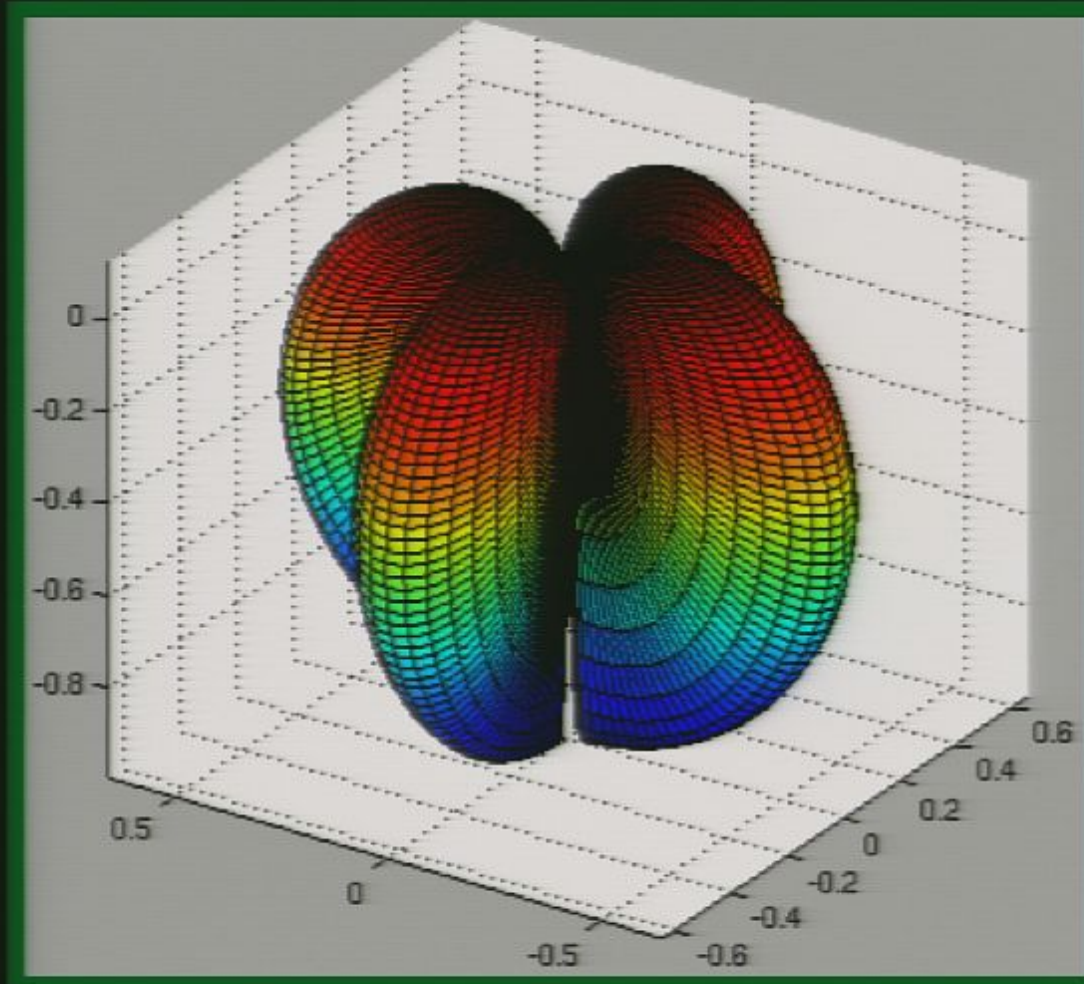
Hellings and Downs Curve (Overlap Reduction Function)



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

NANOGrav

The shape of the GW response



Detectability of a Waveform

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

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

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

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

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

NANOGrav

From Rodin, astroph:
1012.3038 (14 Dec 2010)

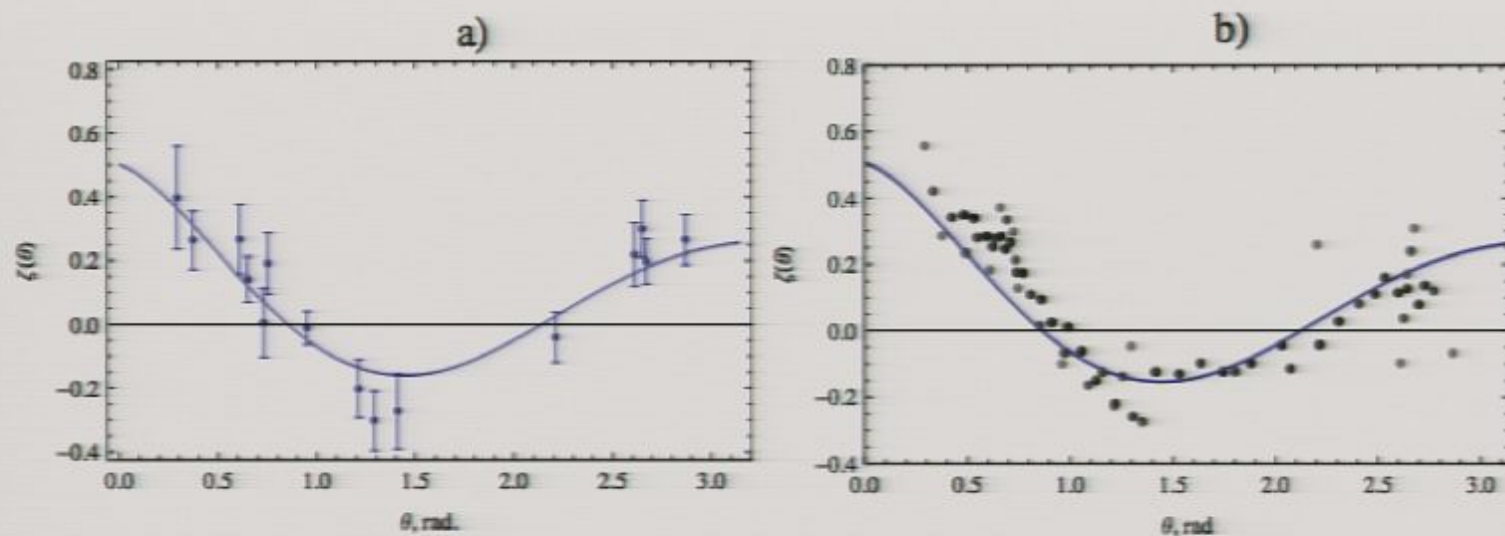


FIGURE 2. a) Results of the numerical simulation of the two-point correlation function for $M = 6$ pulsars and $N = 50$ TOAs. Signal-to-noise ratio $SNR \approx 10$. b) Experimental plot of the two-point correlation function. Moving average by 2-5 points were applied. Correlation coefficient between theoretical curve (solid line) and experimental points $\rho = 0.82 \pm 0.07$

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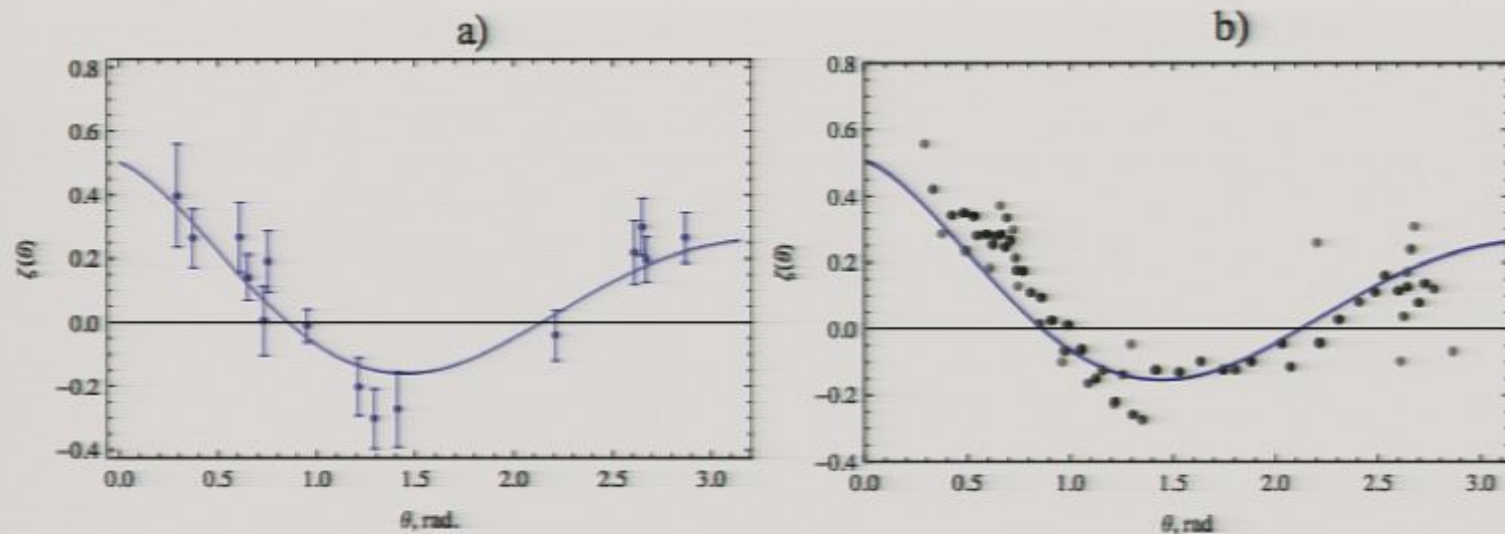
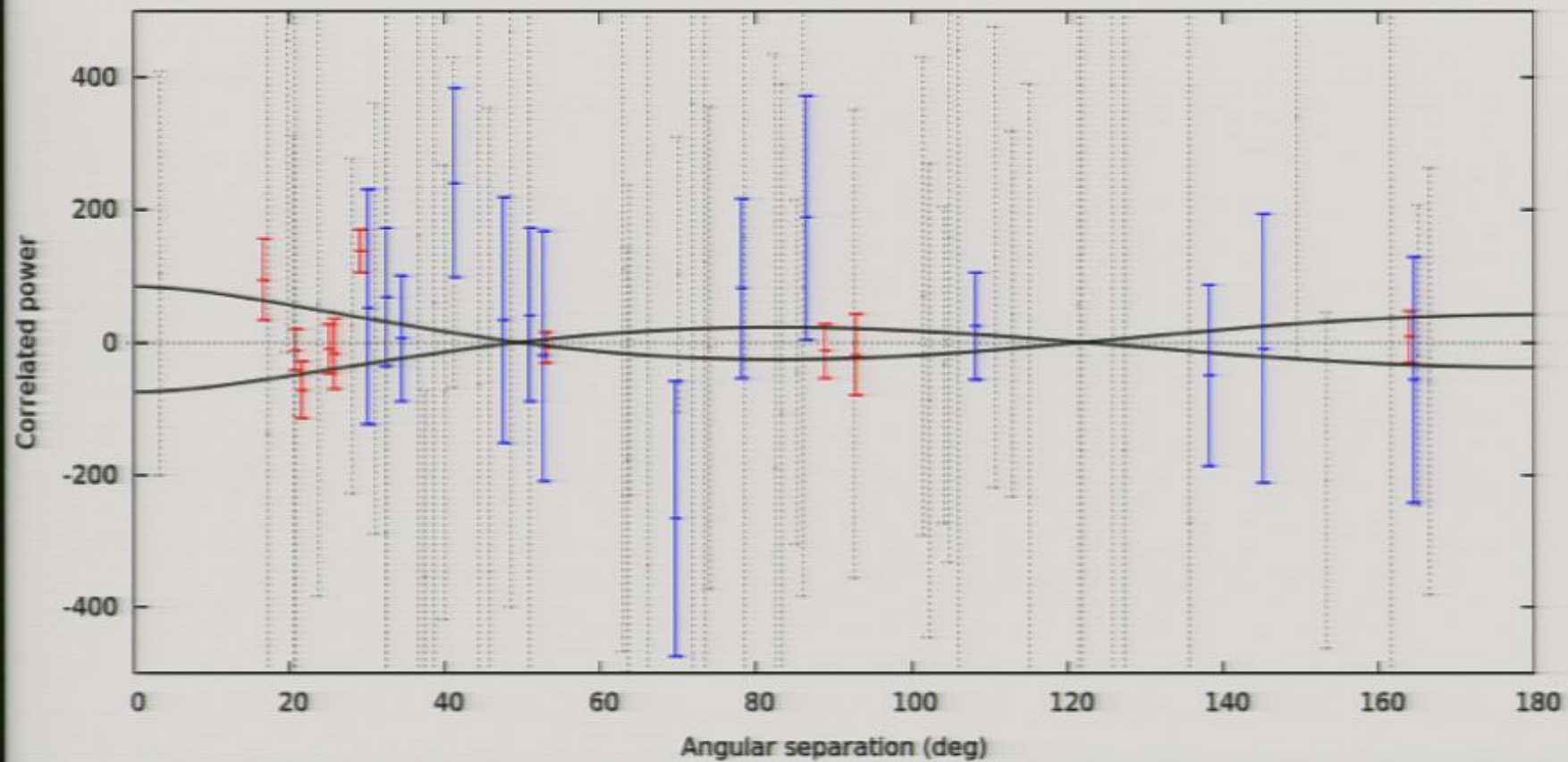



FIGURE 2. a) Results of the numerical simulation of the two-point correlation function for $M = 6$ pulsars and $N = 50$ TOAs. Signal-to-noise ratio $SNR \approx 10$. b) Experimental plot of the two-point correlation function. Moving average by 2-5 points were applied. Correlation coefficient between theoretical curve (solid line) and experimental points $\rho = 0.82 \pm 0.07$

Timing residual GW cross-correlation analysis *NANOGrav*



Computed using methods from Demorest PhD (2007):
Accounts for GW power removed by timing fit.
Assumes/optimized for $-2/3$ power law GW spectrum.



NANOGrav

From Rodin, *astro-ph*:
1012.3038 (14 Dec 2010)

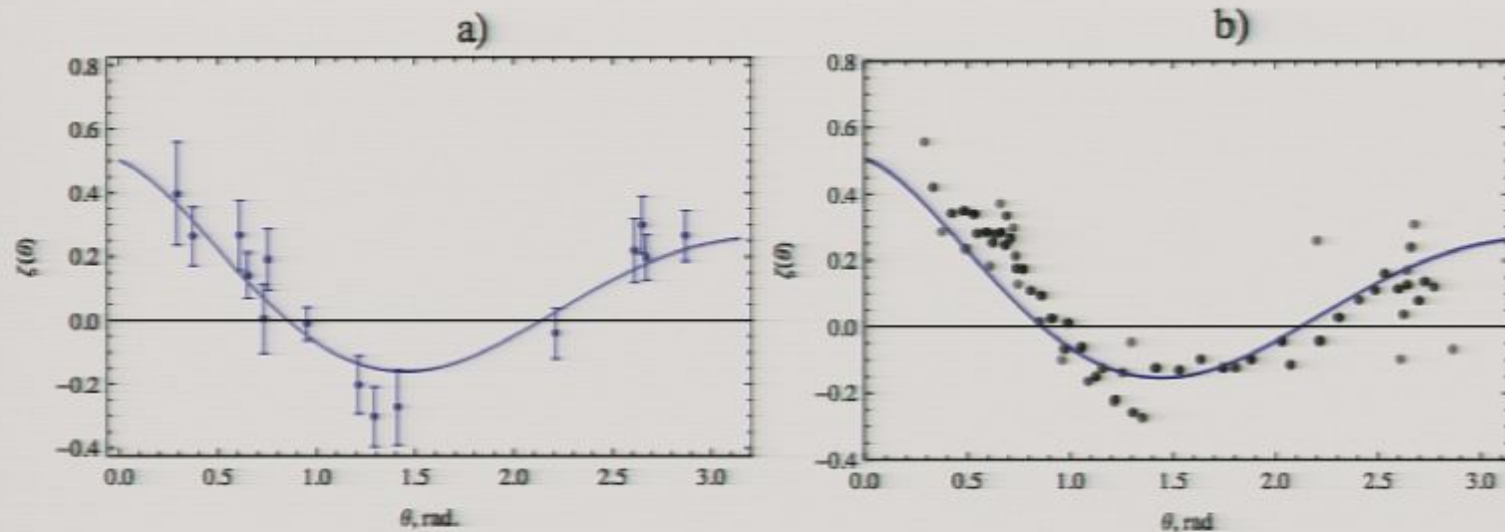
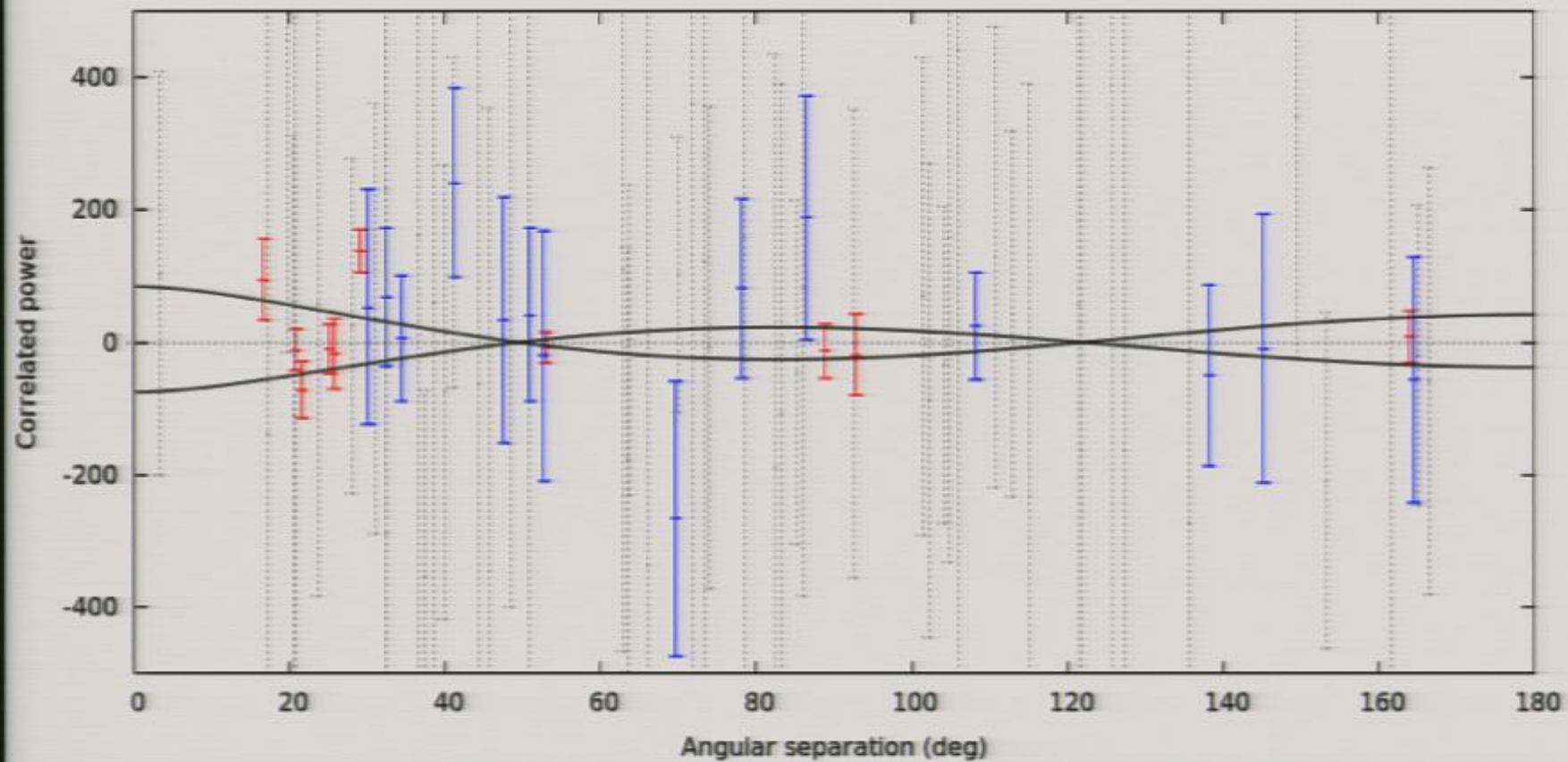


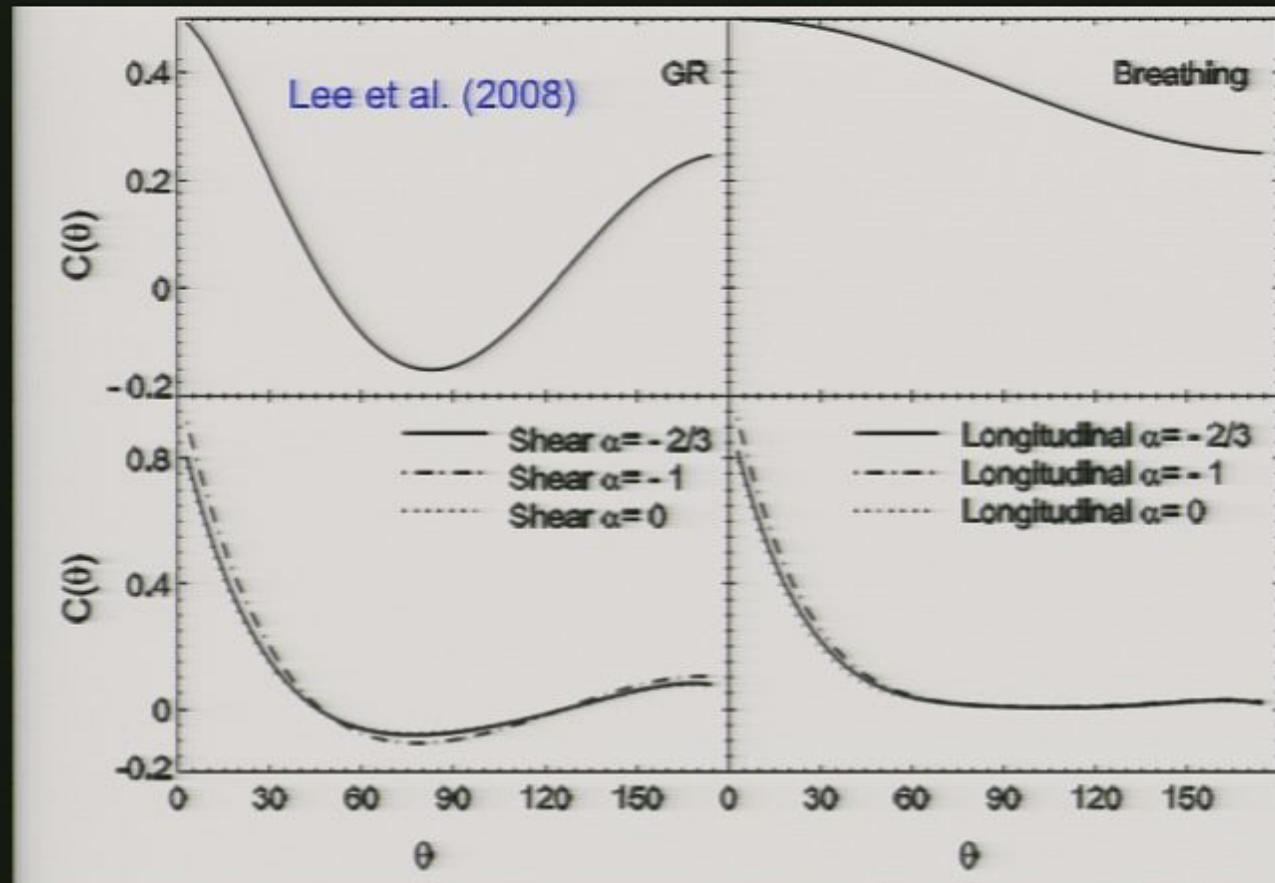
FIGURE 2. a) Results of the numerical simulation of the two-point correlation function for $M = 6$ pulsars and $N = 50$ TOAs. Signal-to-noise ratio $SNR \approx 10$. b) Experimental plot of the two-point correlation function. Moving average by 2-5 points were applied. Correlation coefficient between theoretical curve (solid line) and experimental points $\rho = 0.82 \pm 0.07$

Timing residual GW cross-correlation analysis *NANOGrav*

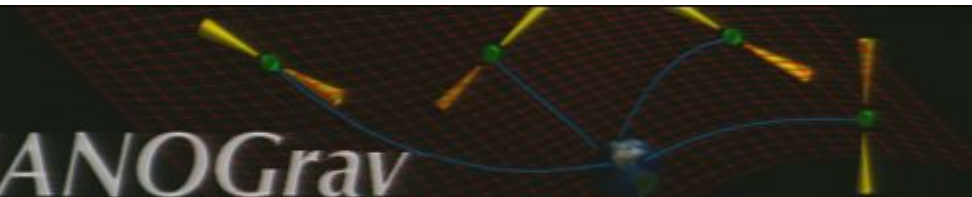


Computed using methods from Demorest PhD (2007):
Accounts for GW power removed by timing fit.
Assumes/optimized for $-2/3$ power law GW spectrum.

NANOGrav

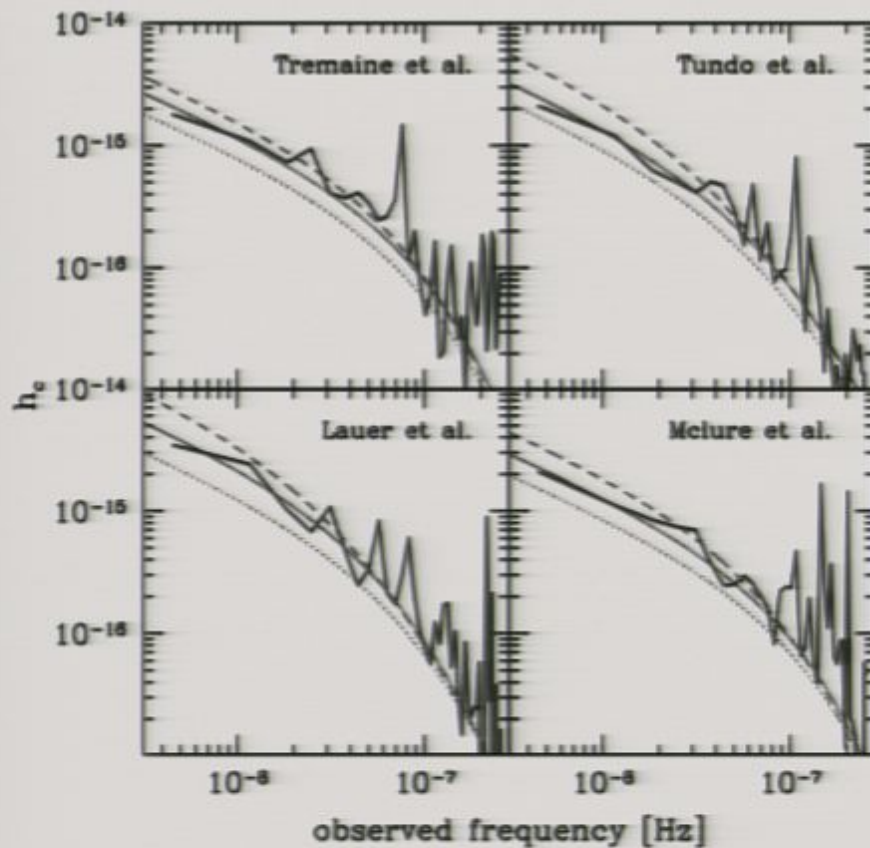


- Measure the polarisation properties of gravitational wave
- Test theories of gravity !



NANOGrav

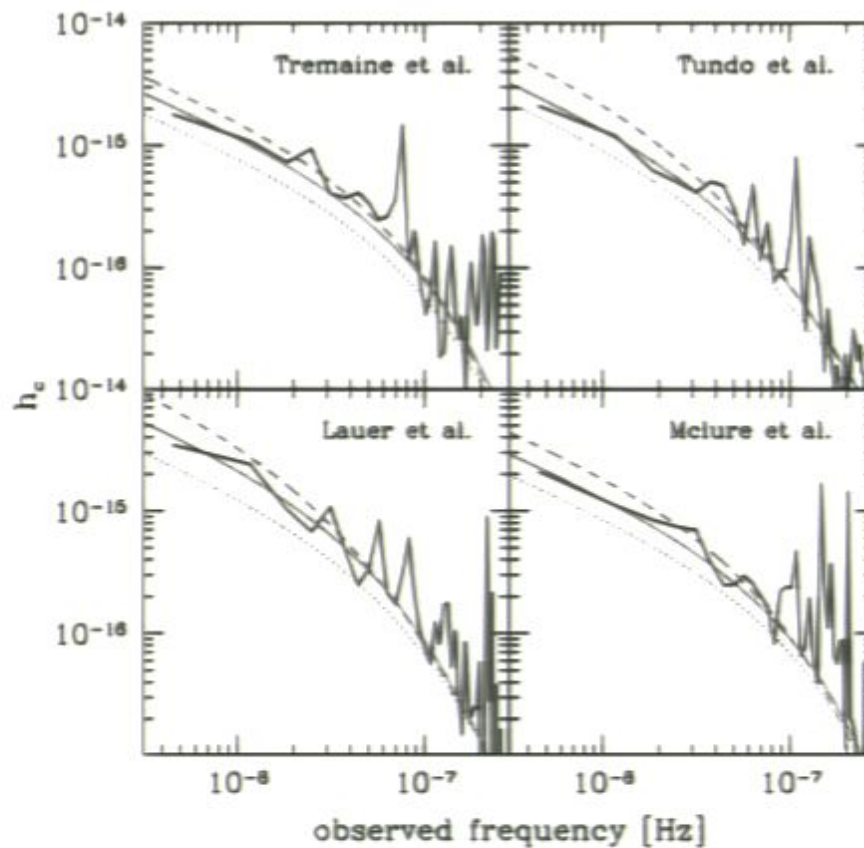
Sesana, Vecchio and Volunteri 2009





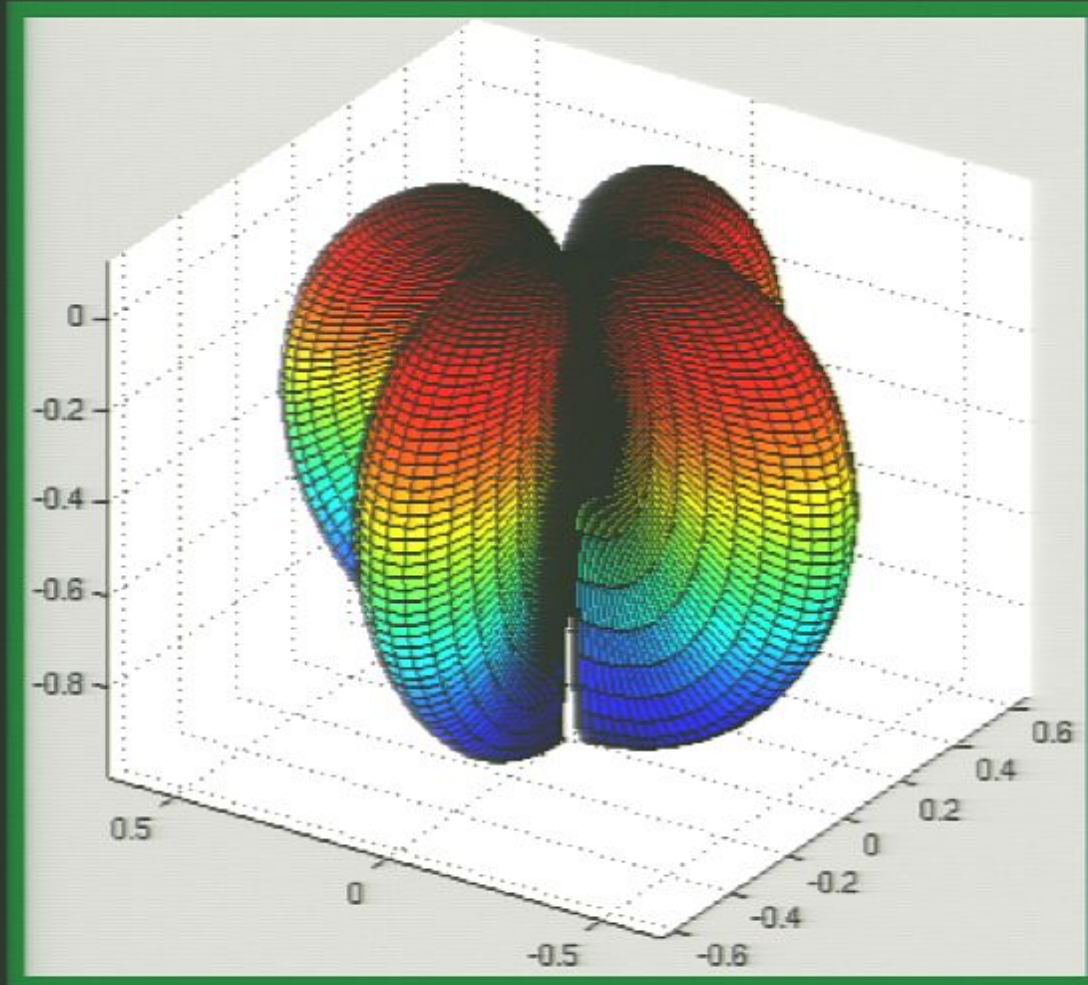
NANOGrav

Sesana, Vecchio and Volunteri 2009

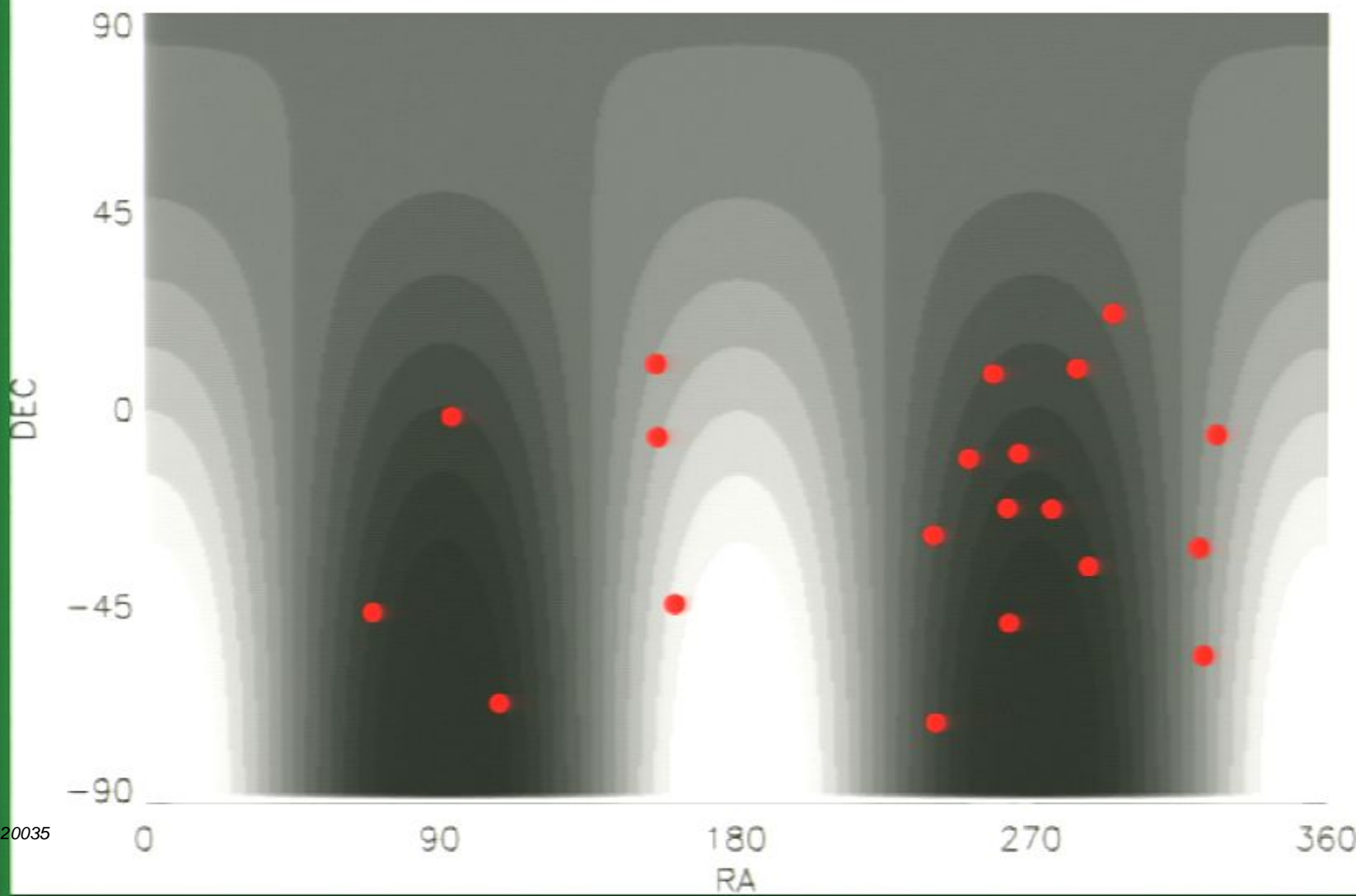


NANOGrav

The shape of the GW response



NANOGrav





NANO Grav

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

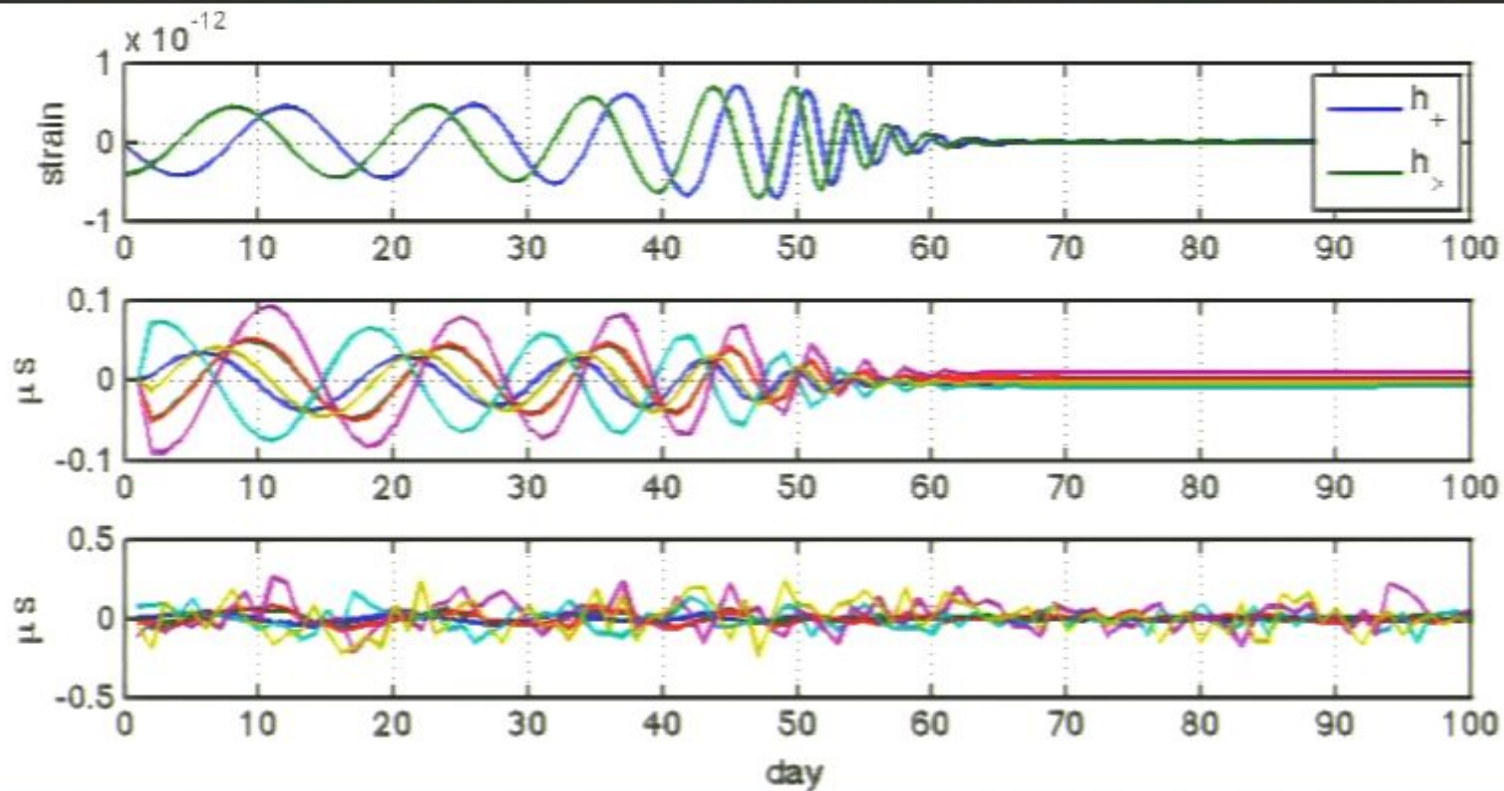
$$x = d - Rh$$

entropy :

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

NANOGrav

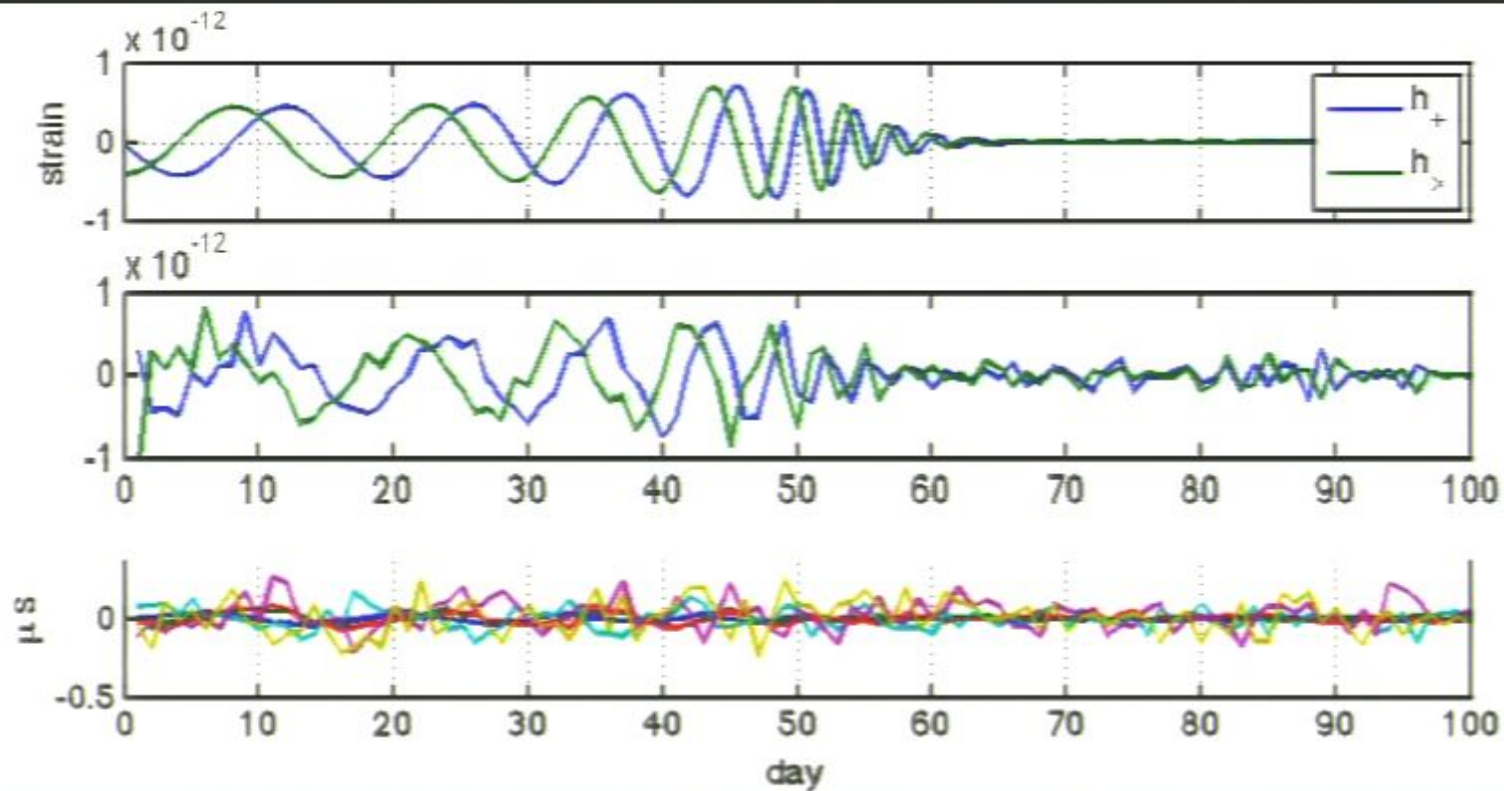
A 5×10^9 solar-mass black hole binary coalescing 100 Mpc away.
30 IPTA pulsars, improved by 10, sampled once a day.



NANOGrav

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

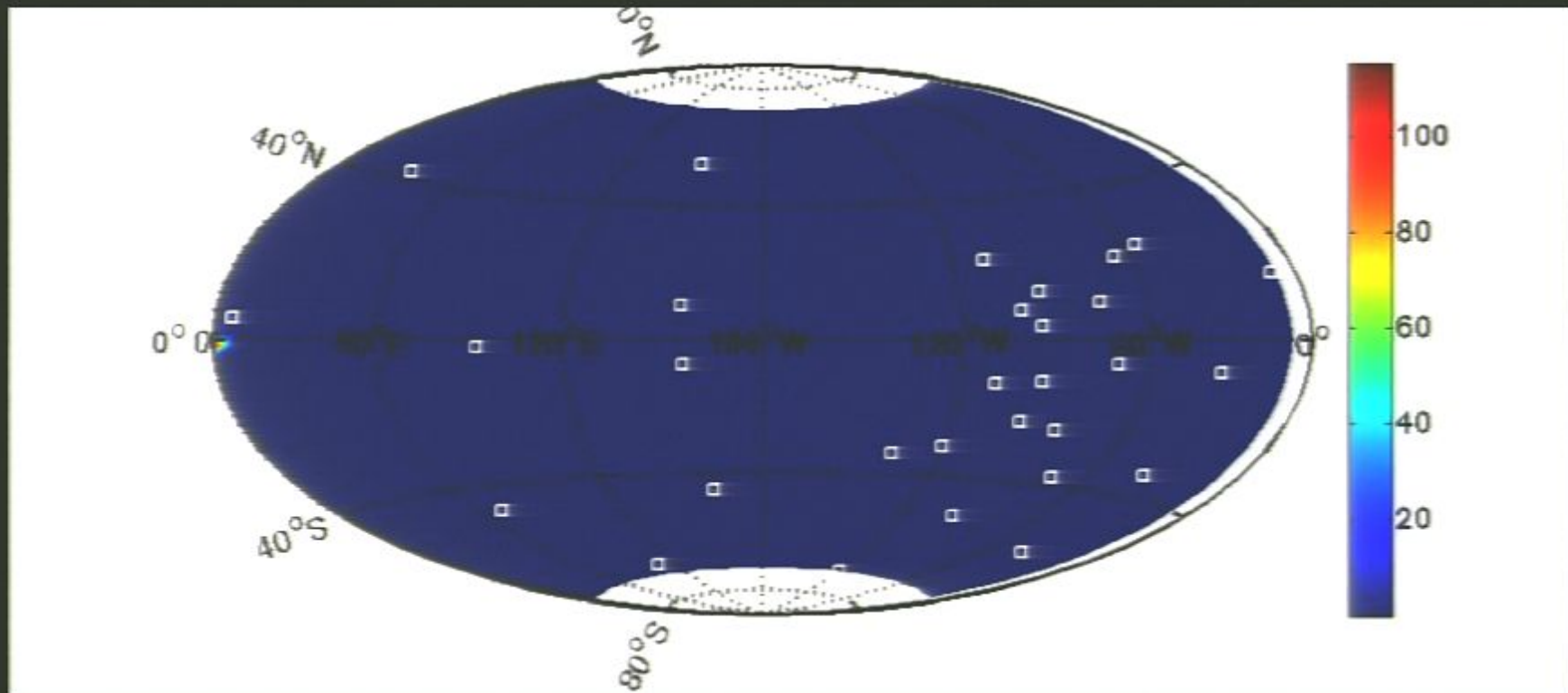
Maximum Entropy based on Summerscales, Burrows, Finn and Ott 2008





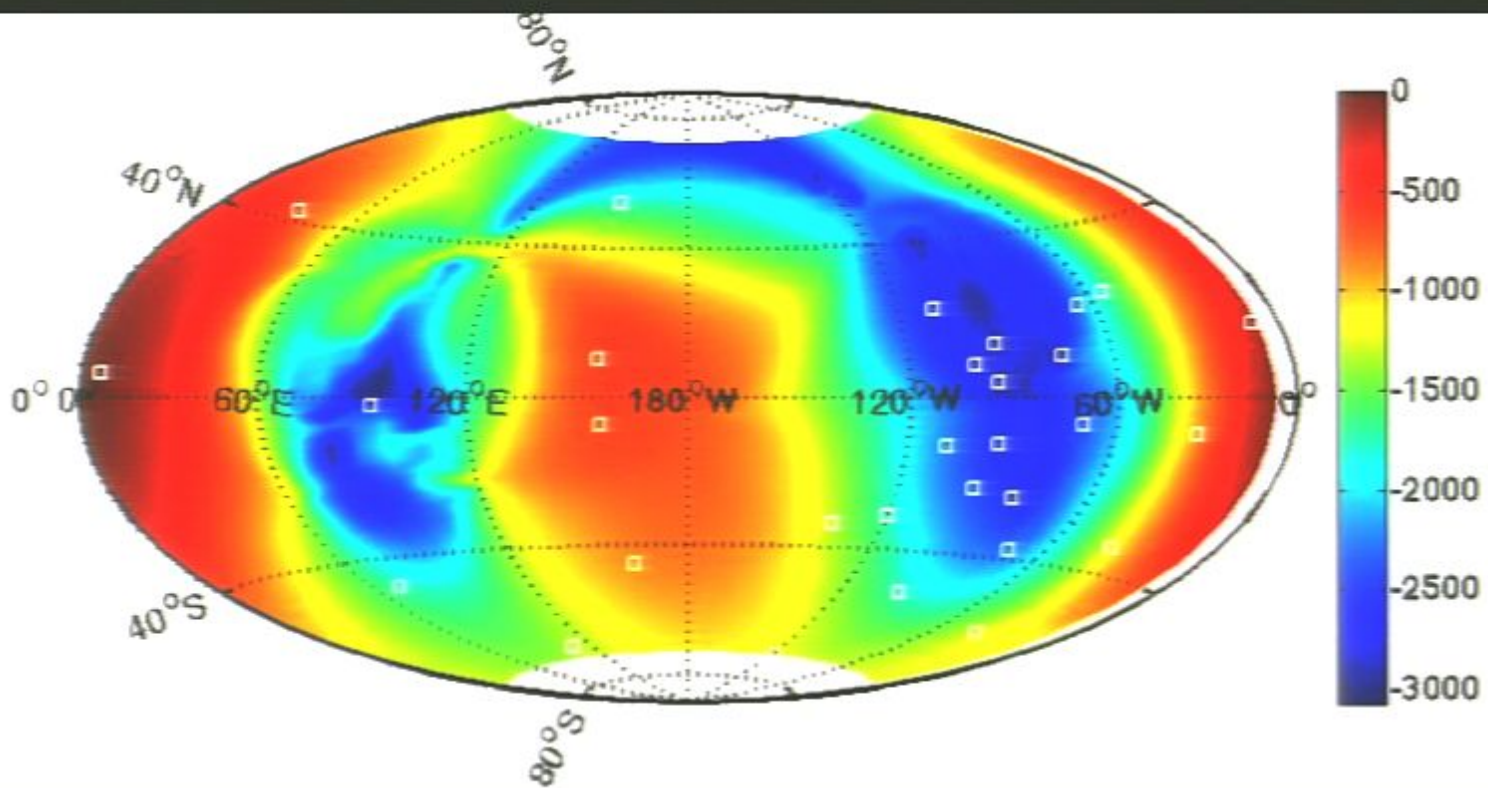
NANOGrav

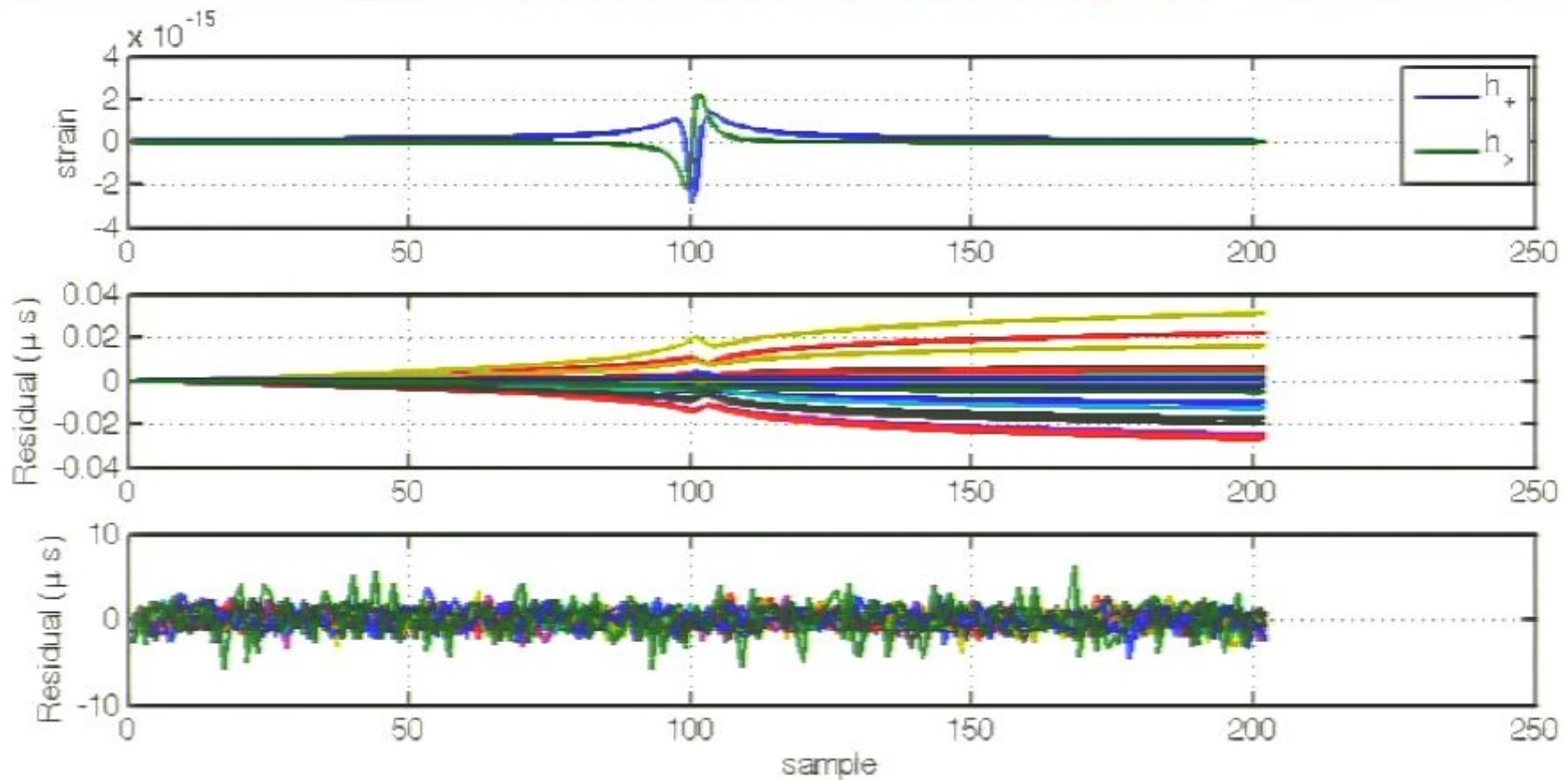
Probability density



NANOGrav

Log of probability density





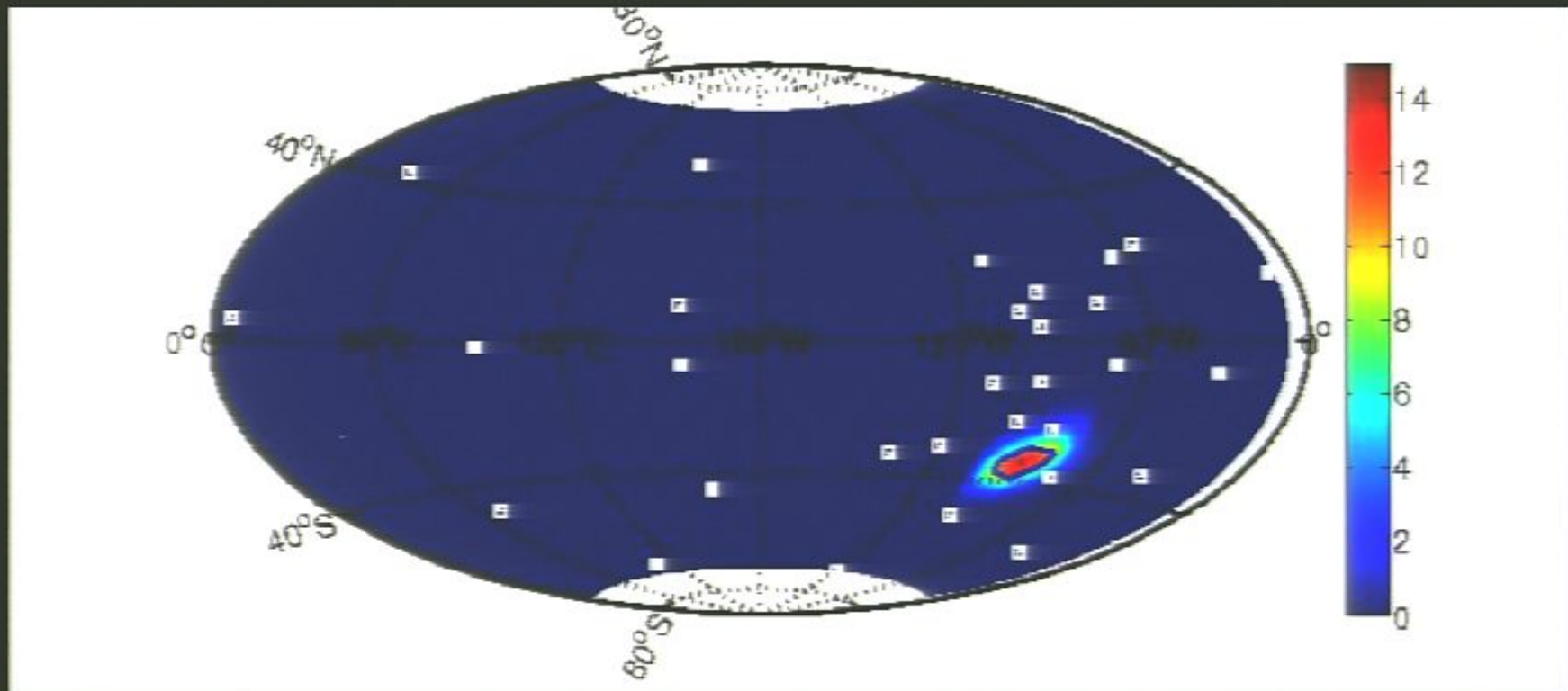
2 10^9 solar mass black holes flying by each other
with a separation of 40 Schwarzschild Radii.

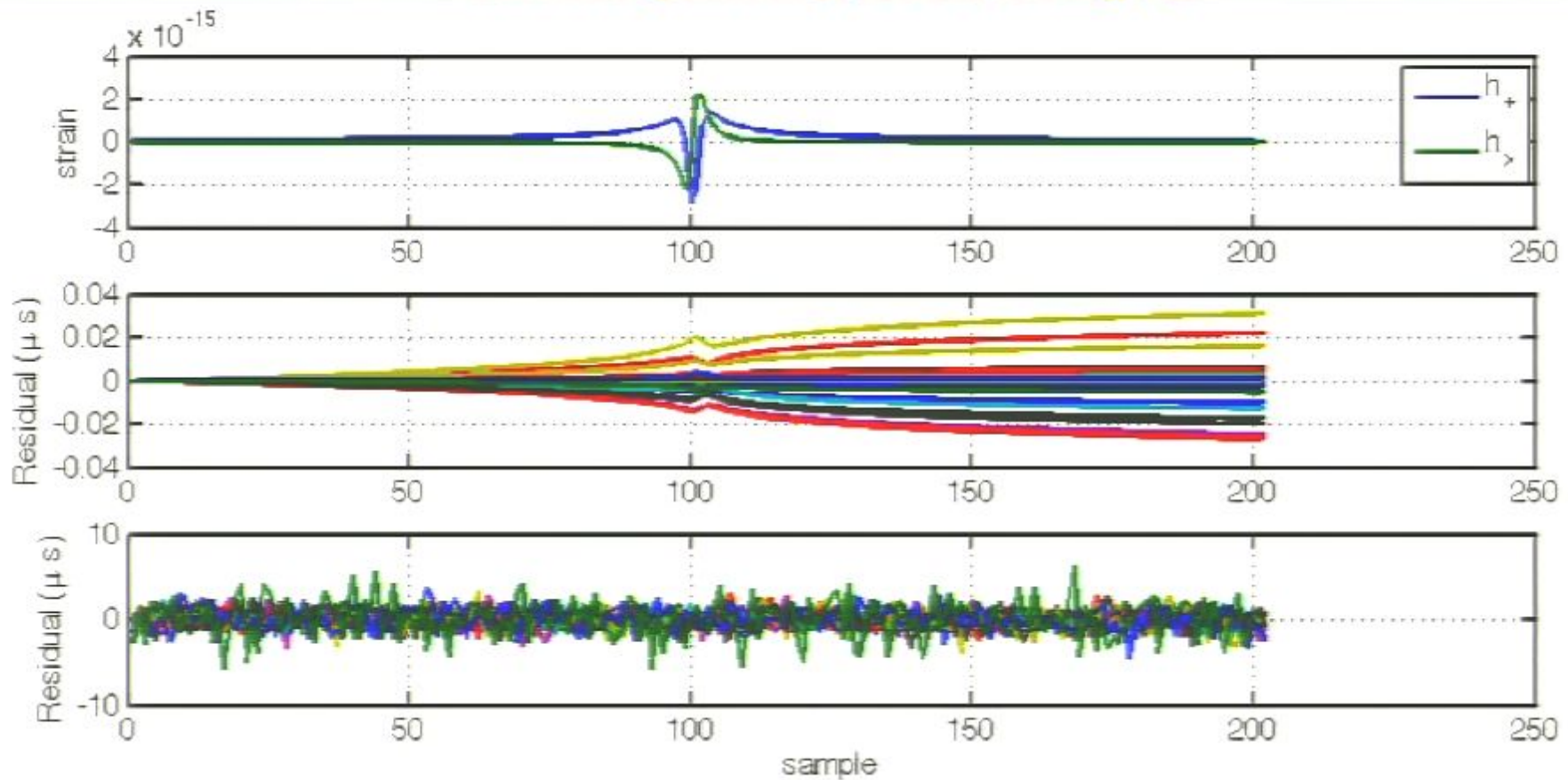
Distance: 100 Mpc

30 IPTA pulsars

NANOGrav

Probability density as a function of sky position





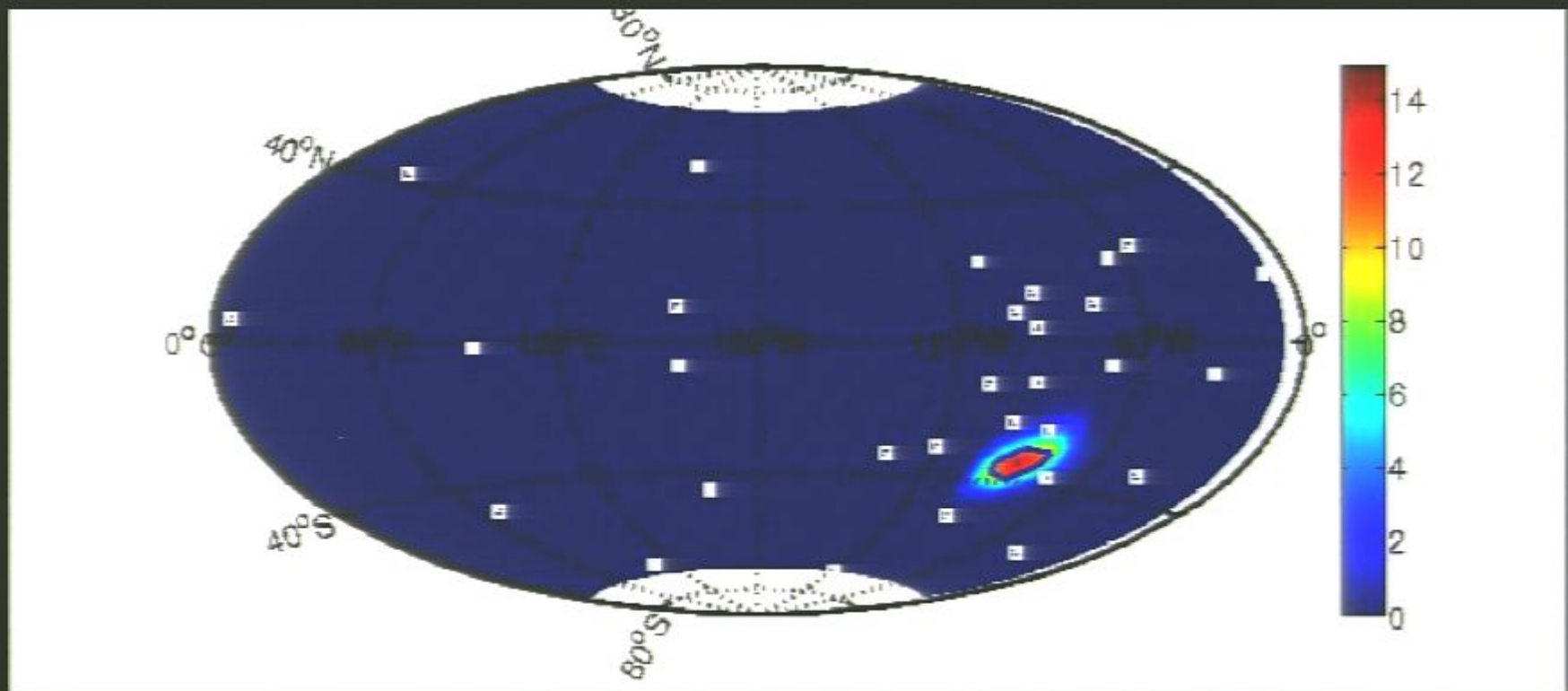
2 10^9 solar mass black holes flying by each other
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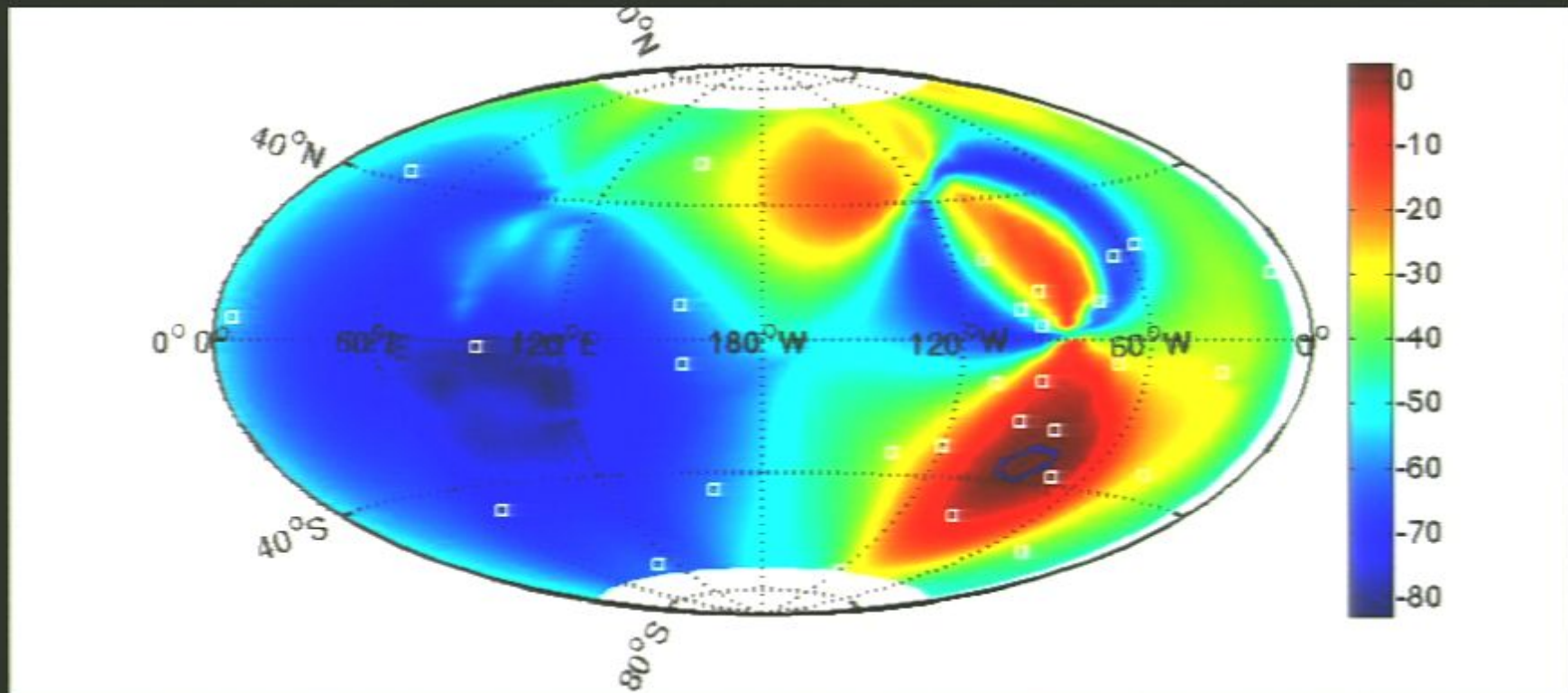
NANOGrav

Probability density as a function of sky position



NANOGrav

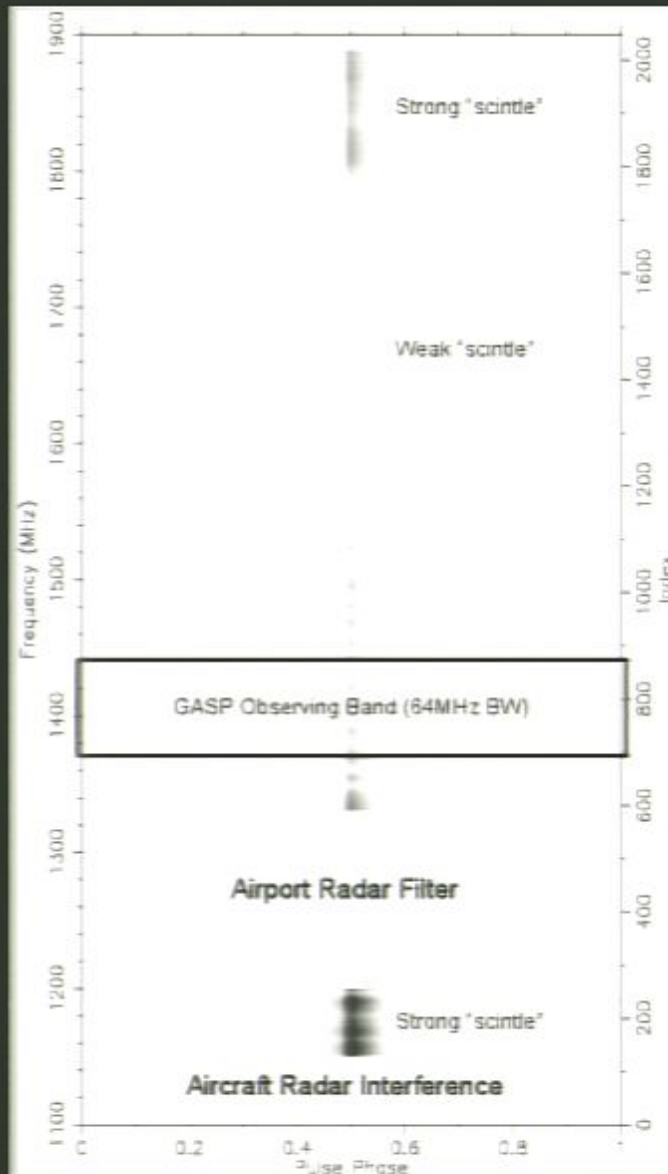
Log(probability density) as a function of sky position



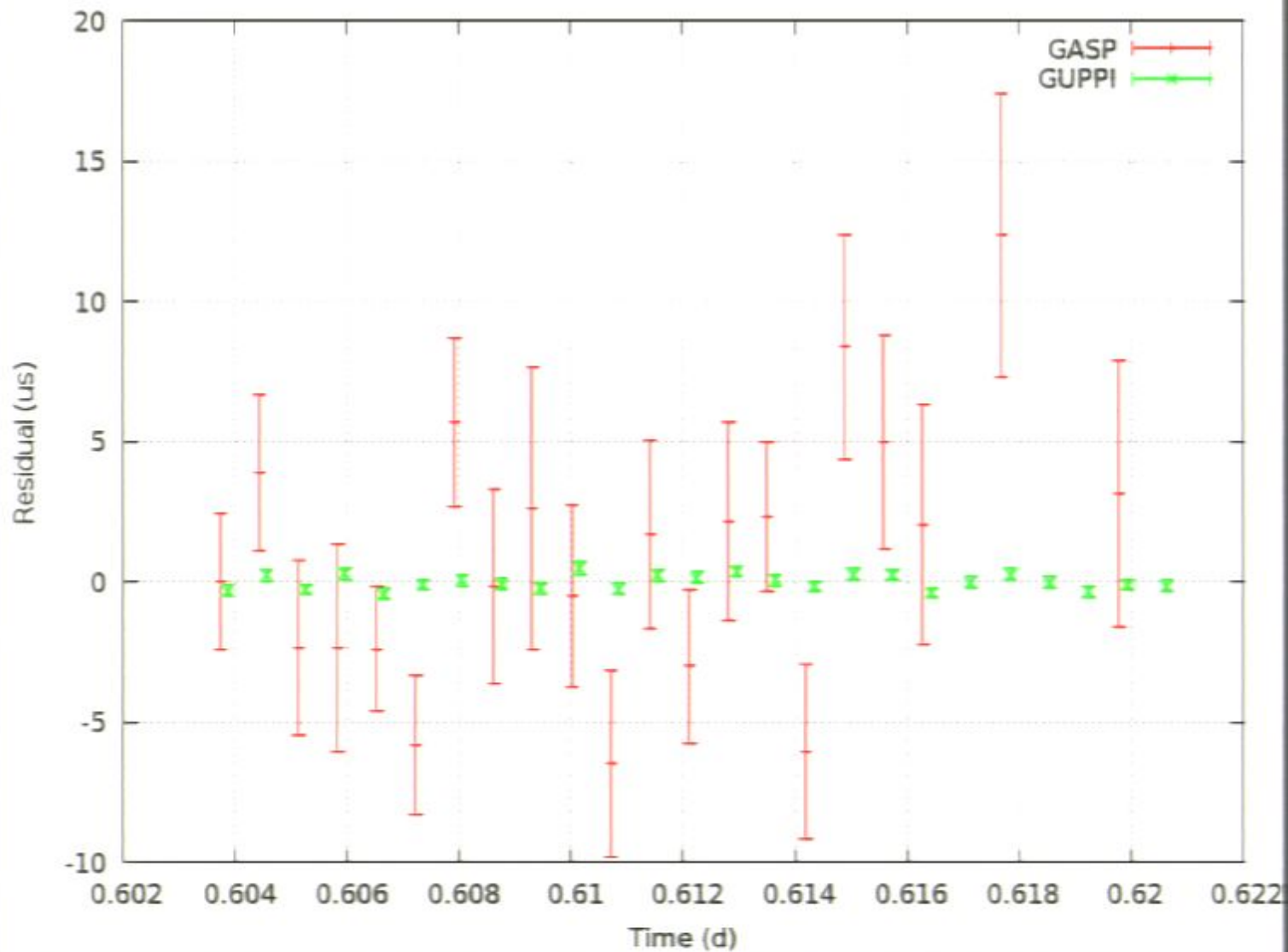
NANOGrav

The

Advantage of
New Wide-
band
Backend
System at
Green Bank
“GUPPI”



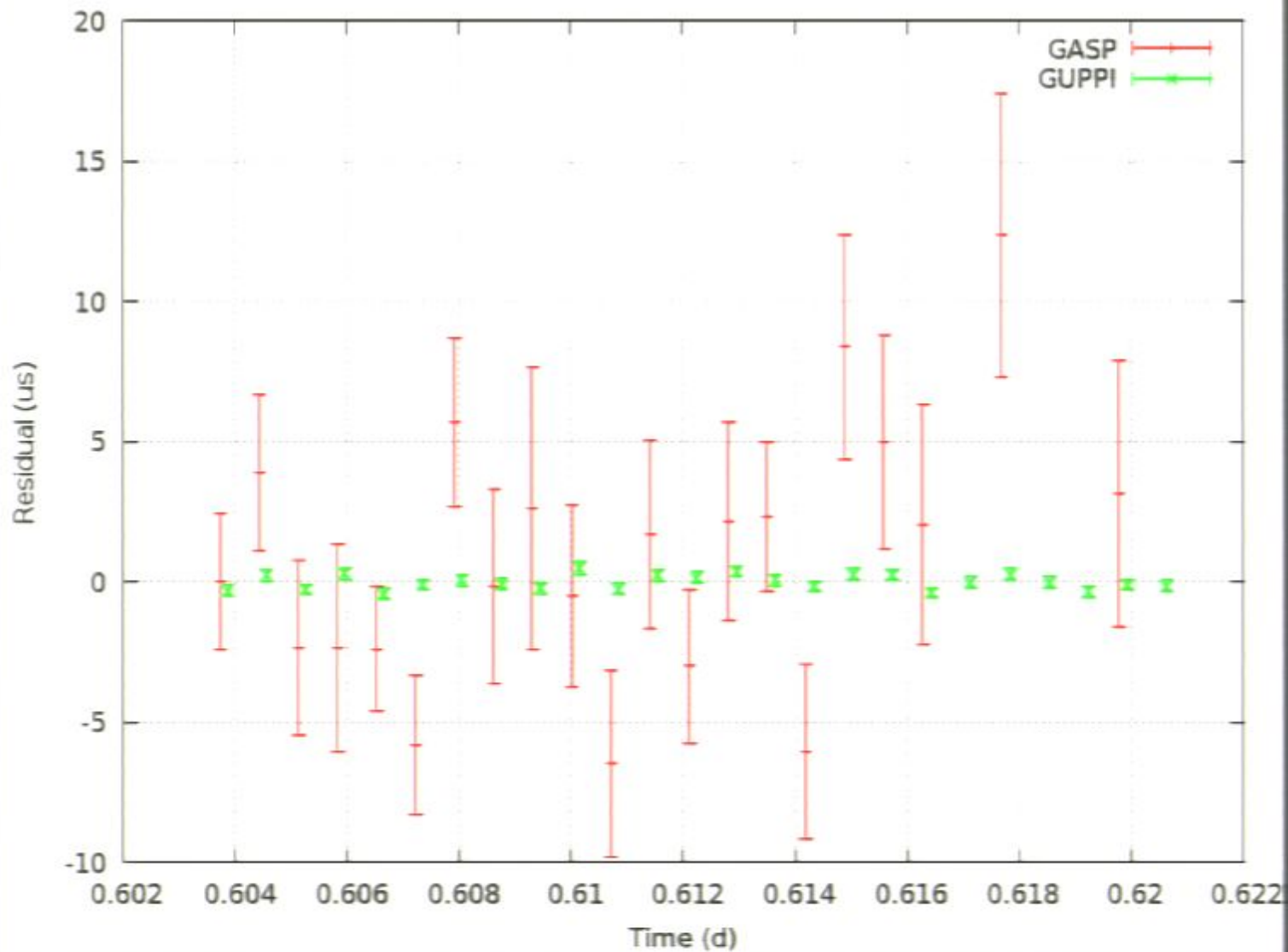
NANOGrav



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 can recover the waveform buried in noise.
- We recover the direction.
- Stay tuned for volume of space covered with current and future sensitivities.
- We expect to be surprised

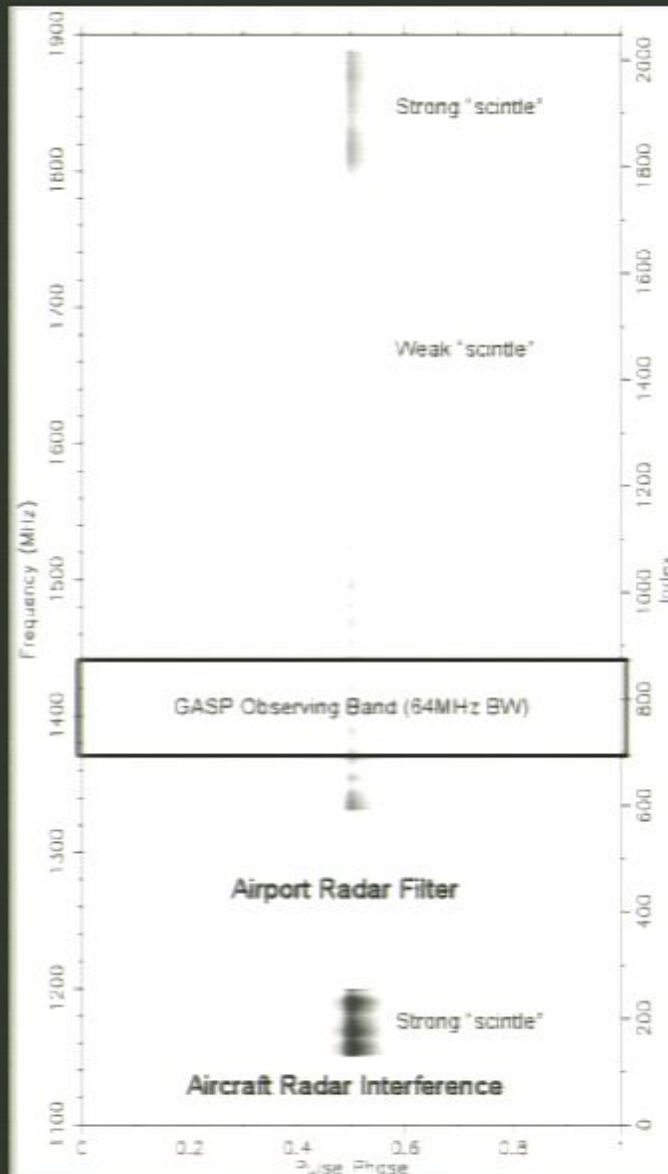
NANOGrav



NANOGrav

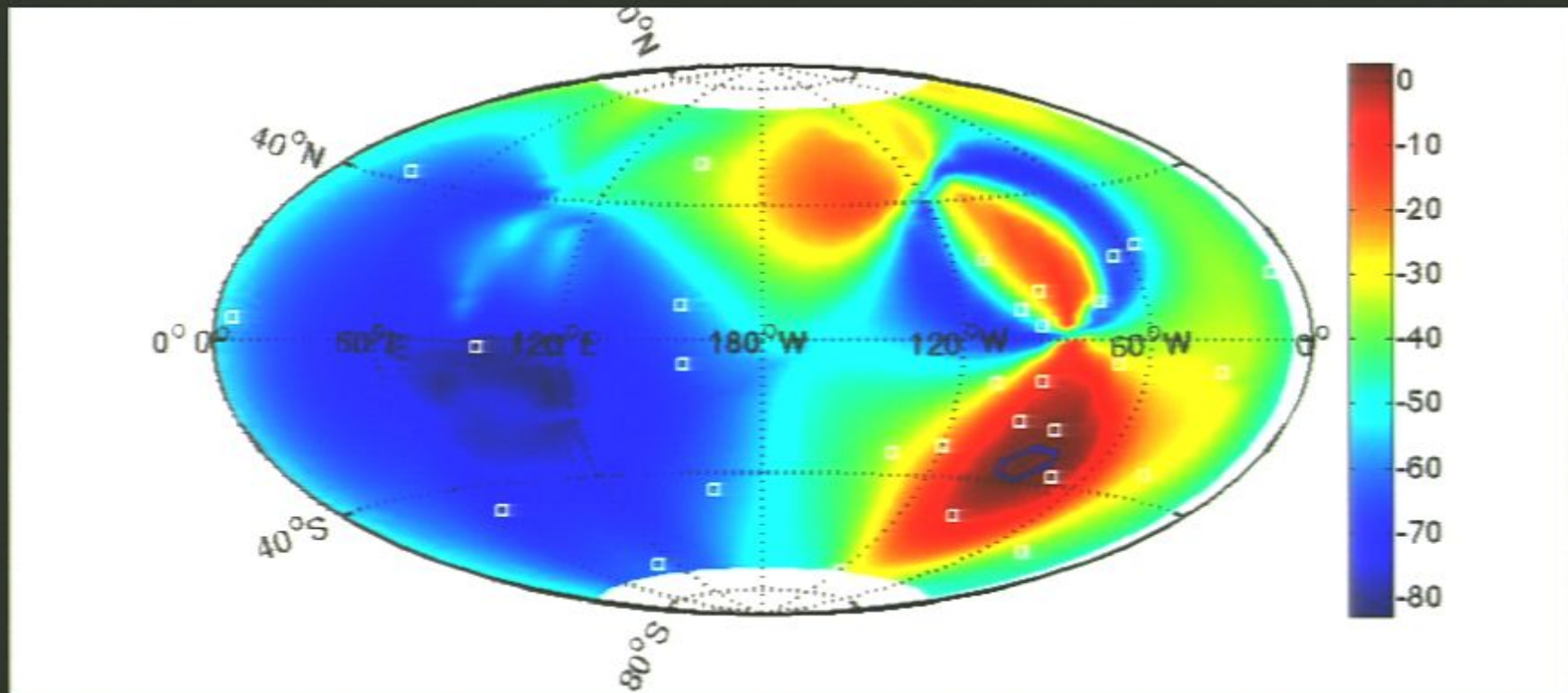
The

Advantage of
New Wide-
band
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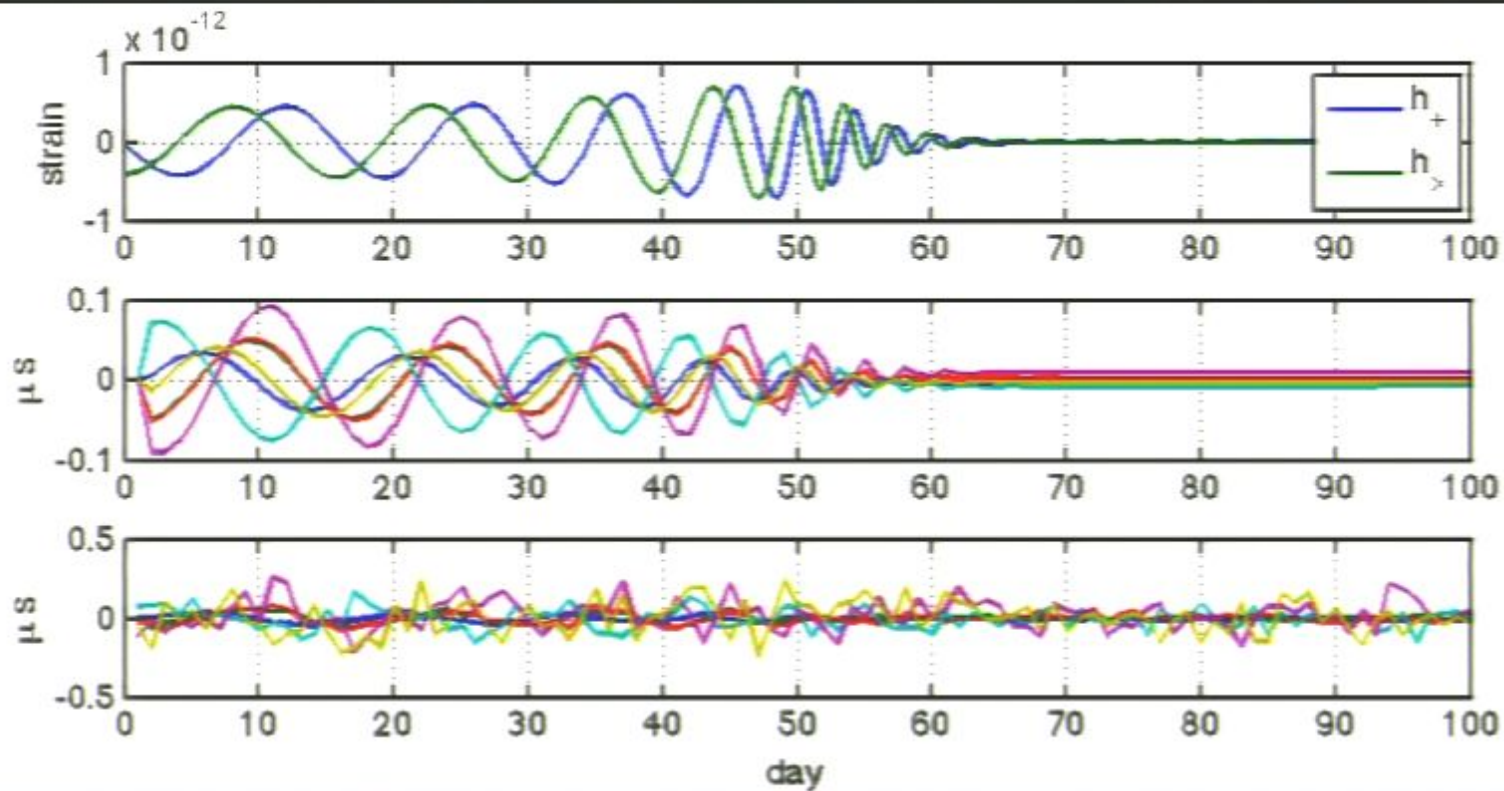
NANOGrav

Log(probability density) as a function of sky position



NANOGrav

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

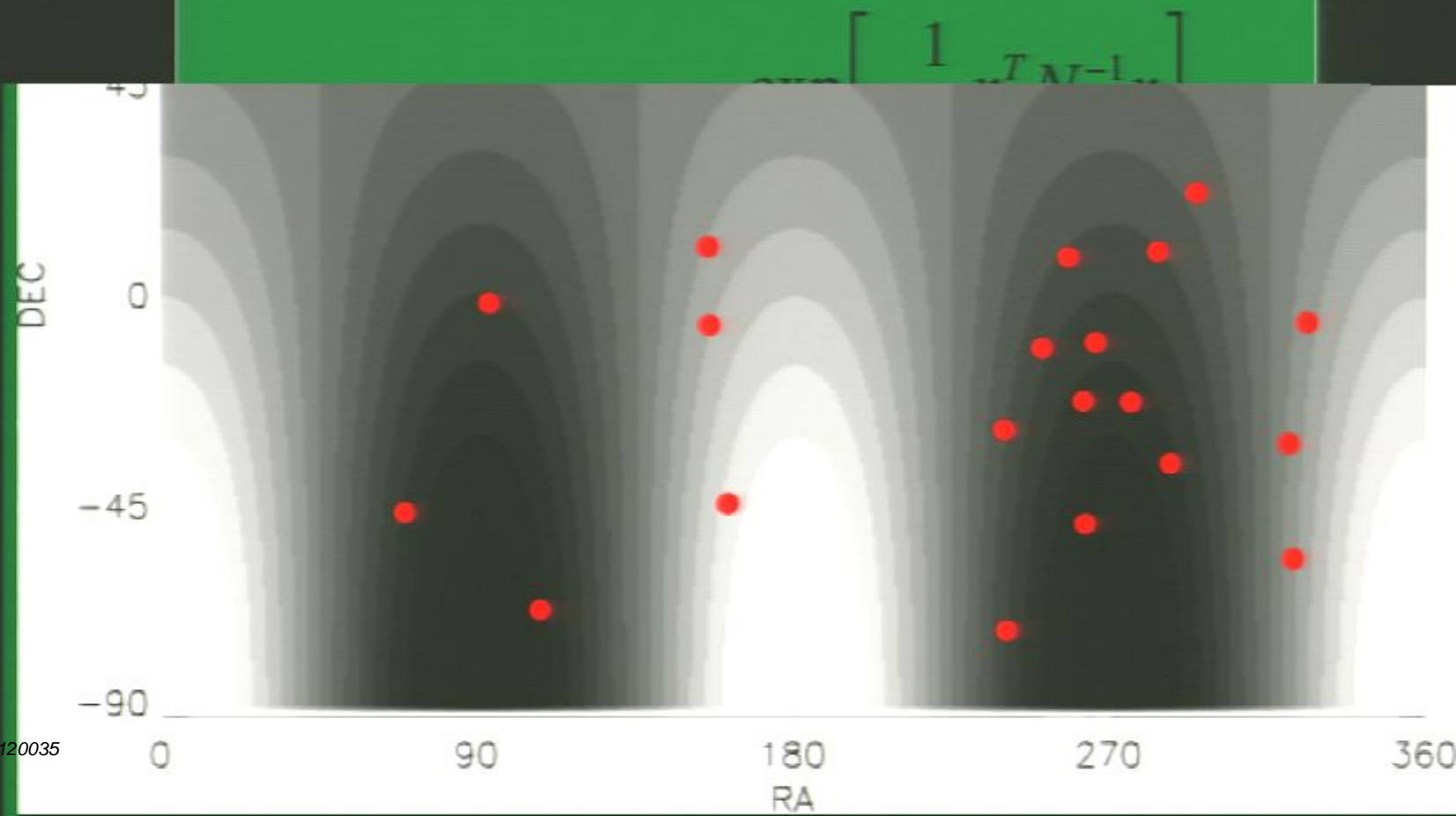




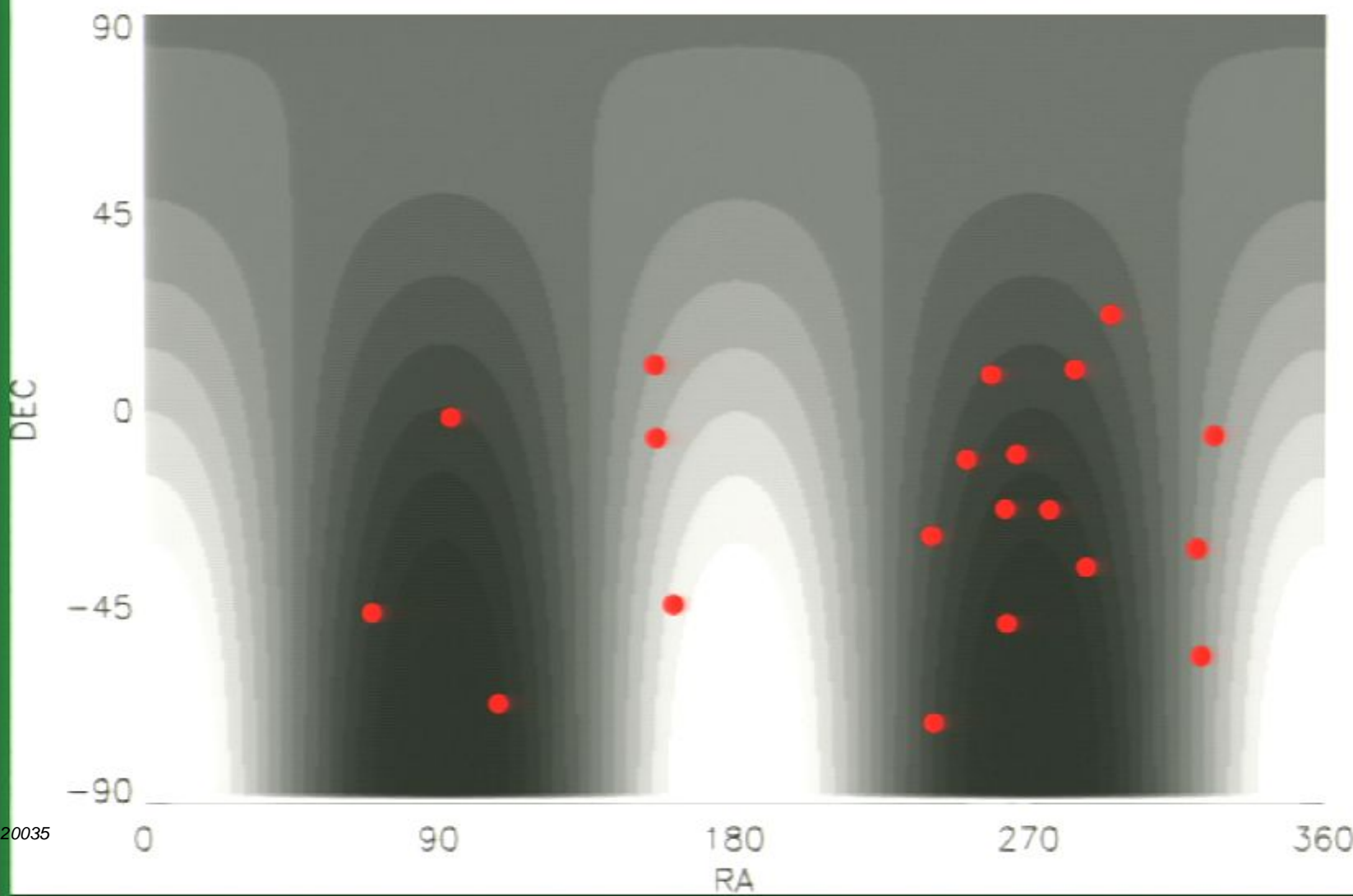
NANOGrav

Maximum Entropy

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



NANOGrav





NANOGrav

From Rodin, astro-ph:
1012.3038 (14 Dec 2010)

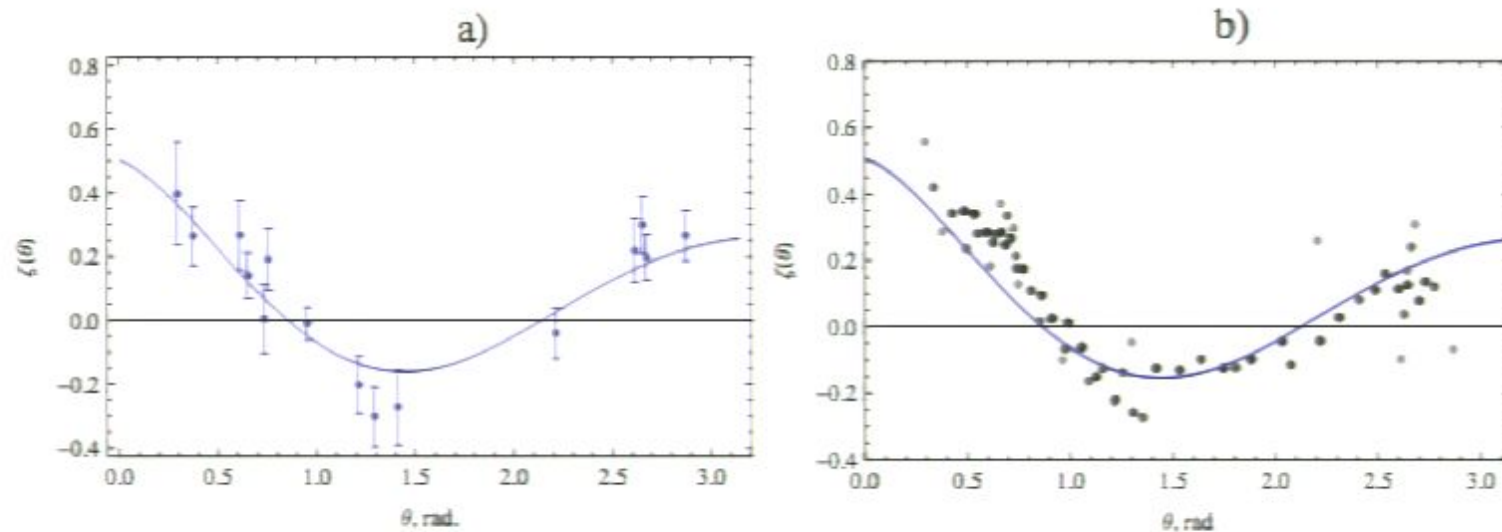


FIGURE 2. a) Results of the numerical simulation of the two-point correlation function for $M = 6$ pulsars and $N = 50$ TOAs. Signal-to-noise ratio $SNR \simeq 10$. b) Experimental plot of the two-point correlation function. Moving average by 2-5 points were applied. Correlation coefficient between theoretical curve (solid line) and experimental points $\rho = 0.82 \pm 0.07$

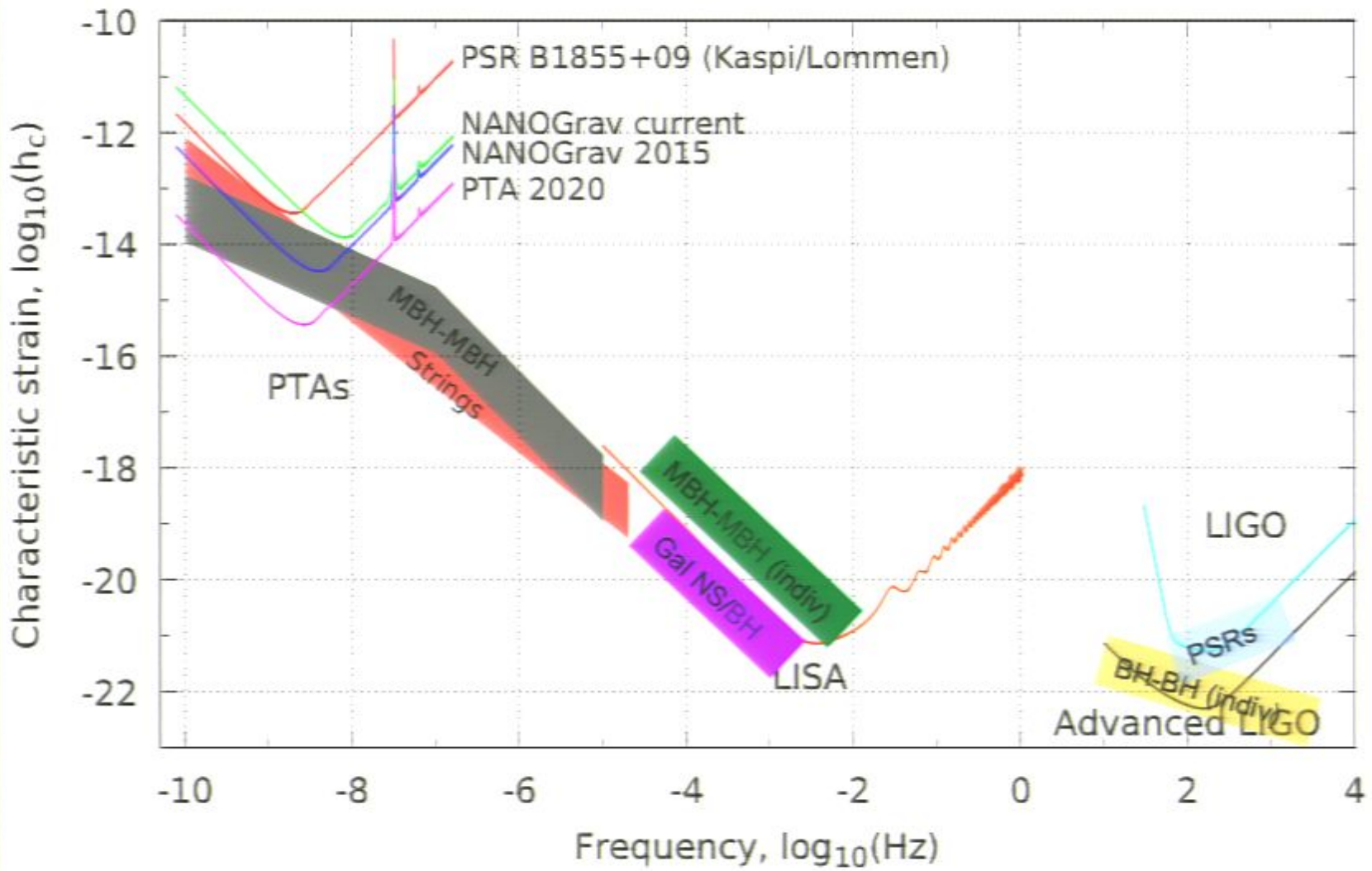


Figure by Paul Demorest (see arXiv:0002.2068)

Detectability of a Waveform

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

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

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

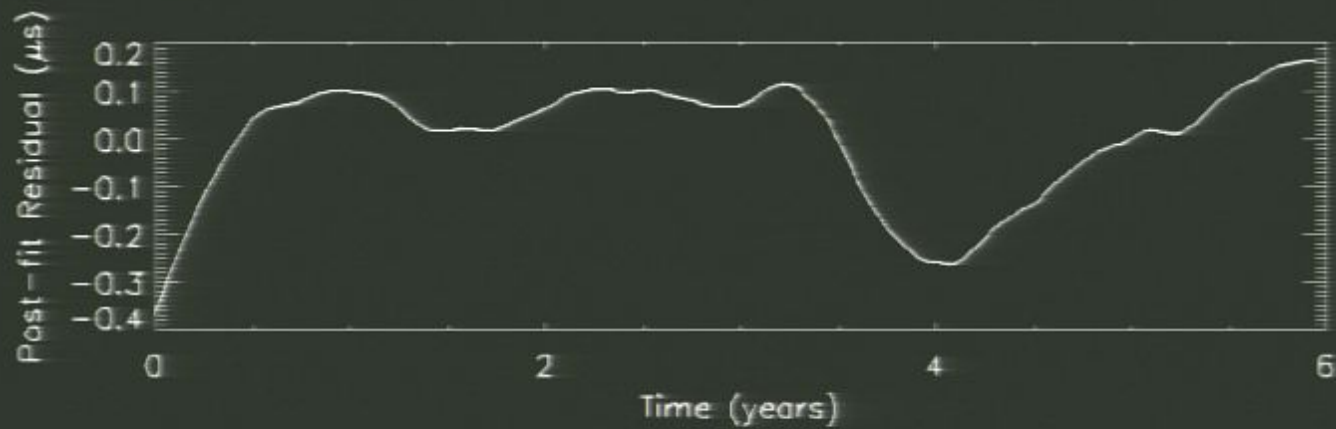
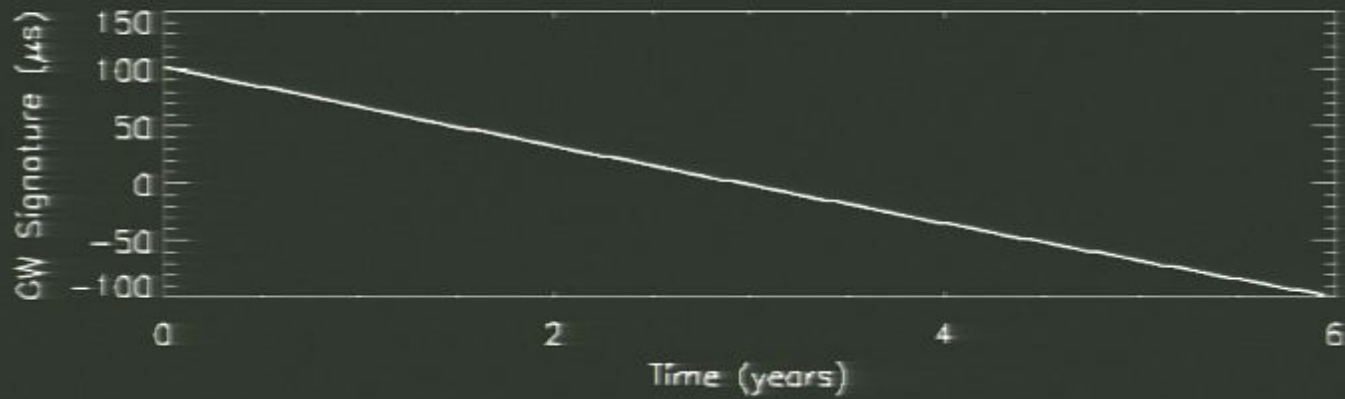
$$\text{Residual} = e_{jk} n^j n^k \frac{h_0}{2} (1 - k_m n^m) \left[f(t_0) - f\left(t_0 - L(1 + k_m n^m)\right) \right]$$

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

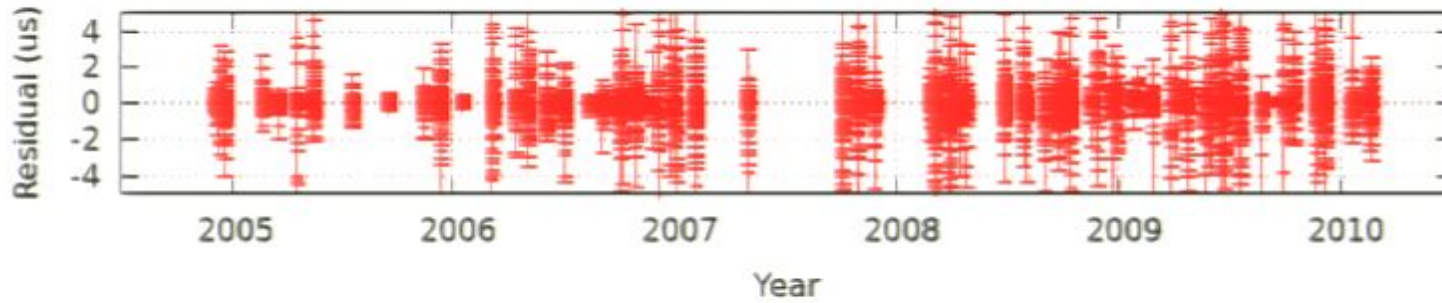


Photo Courtesy of Virgo

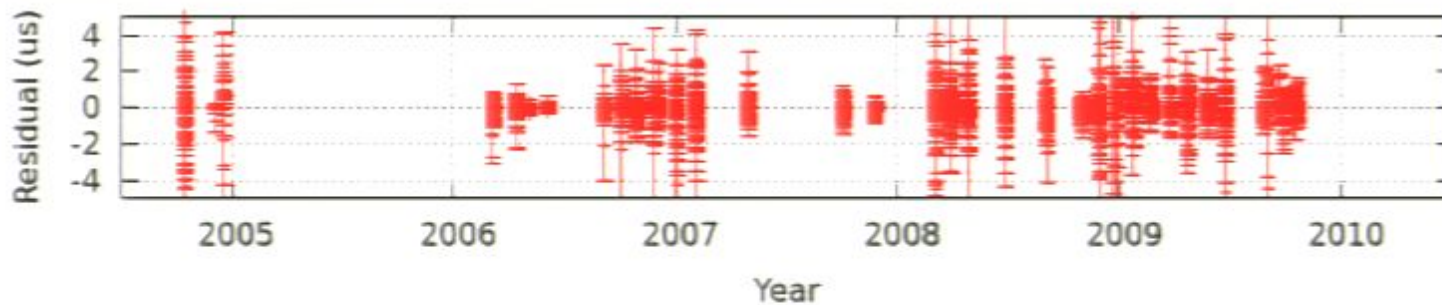
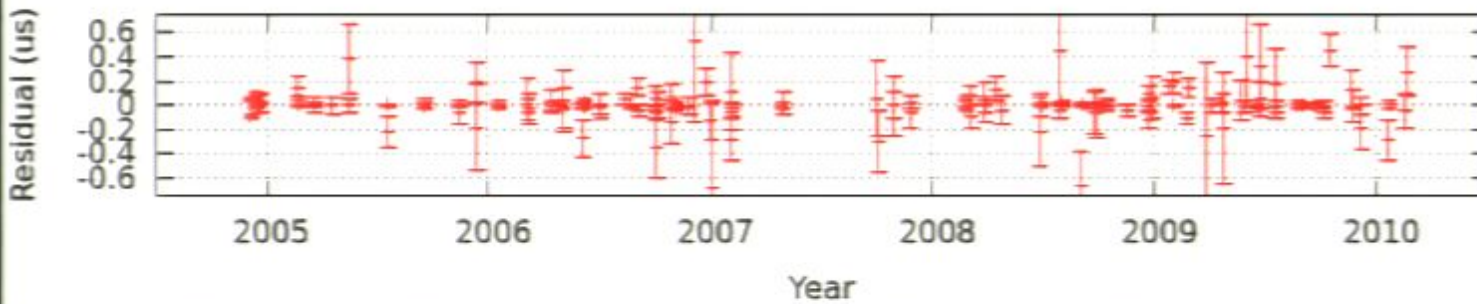
NANOGrav



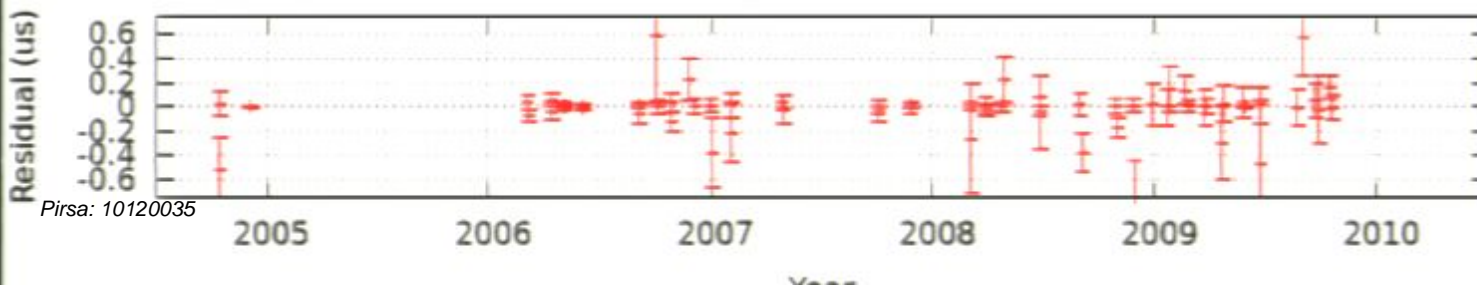
Timing residuals versus time:



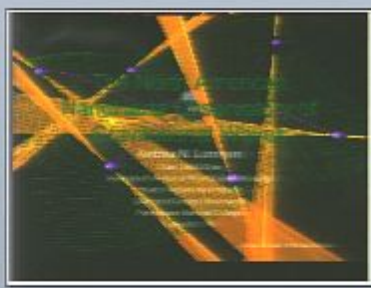
J1713+0747



J1909-3744



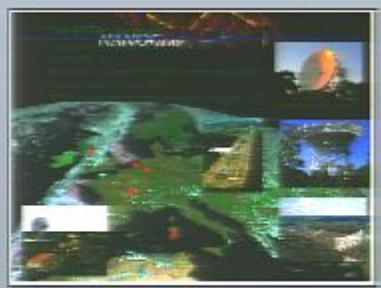
Slide
courtesy of
Paul



1



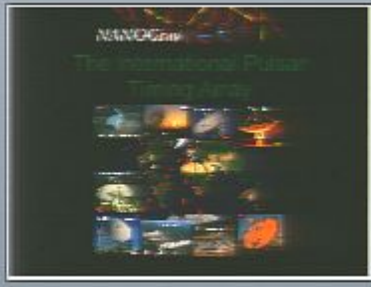
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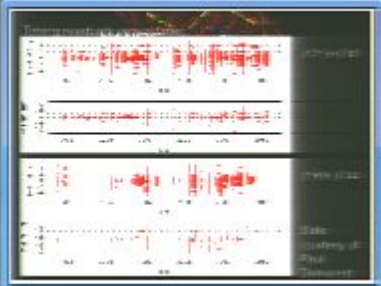
8



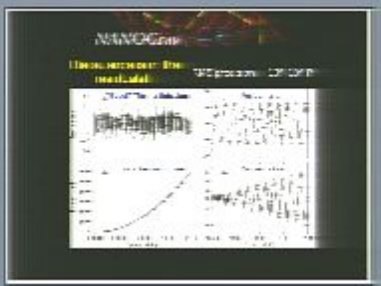
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10



11



12



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14



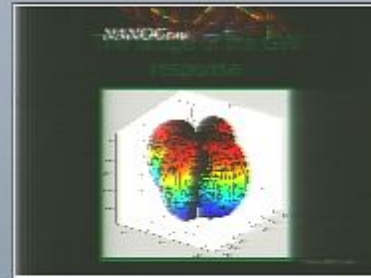
15



16



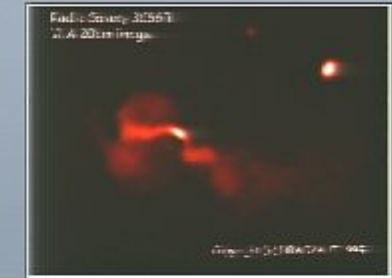
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18



19



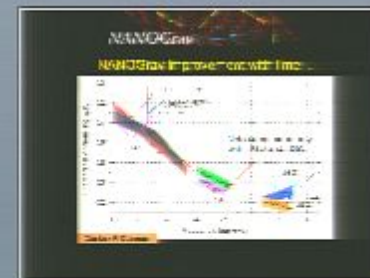
20



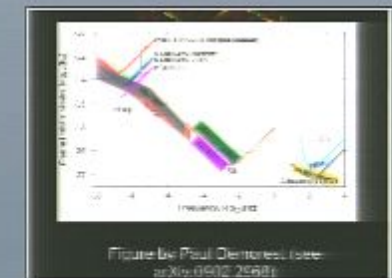
21



22



23



24



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Perimeter Institute 2010.pptx

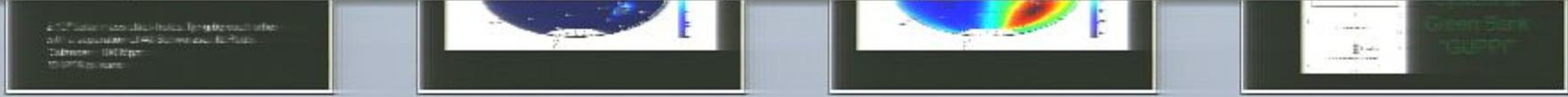
New Open Save Print Undo Redo Format Text Box Picture Shapes Table Media New Slide Slide Show Gallery Toolbox Zoom Help

Slide Themes Slide Layouts Transitions Table Styles Charts SmartArt Graphics WordArt

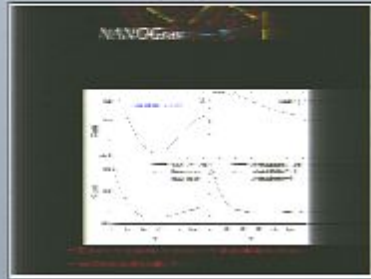
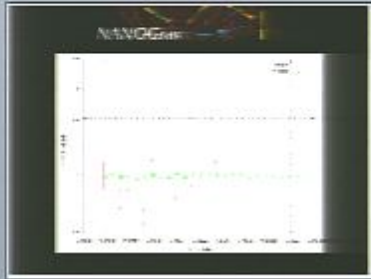
25 26 27 28

29 30 31 32

33 34 35 36



37 38 39 40



- Slide 44: A list of bullet points under the heading 'So how do we improve?'.
- Pulsars...
 - Interferometry...
 - Radio telescope arrays...
 - Pulsar timing arrays...
 - Space-based pulsar timing...
 - Pulsar timing arrays...

41 42 43 44



45 46 47 48

Slide 49: A table with 3 columns: 'RMS response', 'Characteristic strain', and 'Percent observed'.

RMS response (ns)	Characteristic strain (h)	Percent observed
0.7	3.3e-13	93
0.5	2.3e-13	90

- Slide 50: A list of bullet points under the heading 'Scaling that last slide'.
- Strain scales as number of pulsars so e.g. measurable strains have if number of pulsars doubles.
 - Response scales as burst length, so measurable strains have if burst length doubles.
 - If 20 pulsars have 100 ns RMS, divide left two columns by 10.

Slide 51: Mathematical formulas for the strain response.

$$f_{max} = \frac{1}{\Delta t_{pulsar}}$$

$$h(f_{max}) = \frac{rms}{\Delta t_{pulsar}}$$

$$Q_{obs}(f) = \frac{2}{3} \pi^2 f^2 b (f)^2$$

$$Q_{ps}(f) = \frac{rms^2}{\Delta t_{pulsar}^2}$$

Slide 52: Text about the integral of the waveform.

So what matters is the integral of the waveform:

$$\int_{f_{min}}^{f_{max}} h(f) df$$

45

NANOGrav - Pulsar Timing Array

23 pulsars, 1 microsecond RMS. Daily obs. we would detect a 0.771 microsecond maximum response about 4.3% of the time. For a 2 week burst we calculate the corresponding characteristic strain:

Obs response (μs)	Characteristic strain (h)	Event detected
0.7	3.3e-13	93
0.5	2.5e-13	40
0.3	1.4e-13	2

46

NANOGrav - Squaring Pulsar Count Rates

- Statistic scales as number of pulsars (e.g. measurable strains halve if number of pulsars doubles)
- Response scales as burst length, so measurable strains halve if burst length doubles
- if 23 pulsars have 100 ns RMS, divide left two columns by 10

47

NANOGrav - Fourier Transform

$$f_{rms} = \frac{1}{\Delta t \sqrt{2\pi}} \int_{-\infty}^{\infty} h(f) e^{i\pi f t} df$$

$$h(f_{rms}) = \frac{rms}{\Delta t \sqrt{2\pi}}$$

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

$$\Omega_{gw}(f) = \frac{rms^2}{\Delta t^2 \sqrt{2\pi}}$$

From Bond, Hilditch, van Haese, Macquinn, Reardon, Taylor, Edwards, Hellar, Subramanian, 2010, DMR

48

NANOGrav - Fourier Transform

So what matters is the integral of the waveform:

$$h = \int \dot{h} dt$$

Characteristic strain:

$$h = \int_{f_{min}}^{f_{max}} \dot{h} df = \frac{1}{2\pi} \int_{f_{min}}^{f_{max}} \dot{h} df = \frac{1}{2\pi} \int_{f_{min}}^{f_{max}} \dot{h} df$$

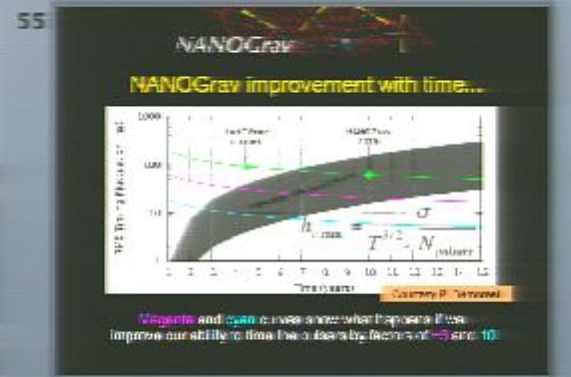
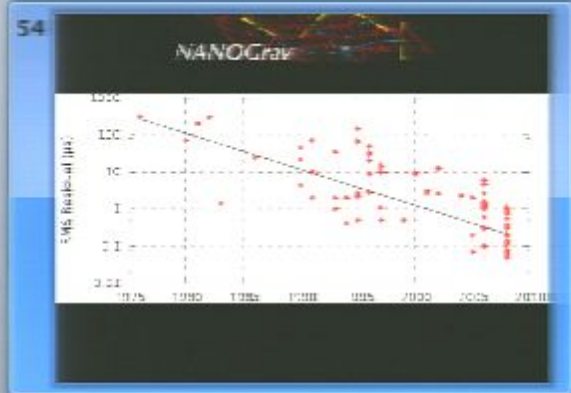
for a Gaussian source:

$$h = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \dot{h} e^{-i\pi f t} dt = \frac{1}{\sqrt{2\pi}}$$

49

NANOGrav - Pulsar Timing Array

Pulsar Name	RA (J2000)	Dec (J2000)	DM (pc cm ⁻³)	Period (ms)	Period Derivative (10 ⁻¹⁵ s/s)
B1509-58	15h 09m 00s	-58d 00m 00s	182	3.76	1.2
B1510-50	15h 10m 00s	-50d 00m 00s	162	3.07	1.1
B1517-50	15h 17m 00s	-50d 00m 00s	162	3.07	1.1
B1534-57	15h 34m 00s	-57d 00m 00s	162	3.07	1.1
B1542-06	15h 42m 00s	-6d 00m 00s	162	3.07	1.1
B1547-04	15h 47m 00s	-4d 00m 00s	162	3.07	1.1
B1553-57	15h 53m 00s	-57d 00m 00s	162	3.07	1.1
B1555-50	15h 55m 00s	-50d 00m 00s	162	3.07	1.1
B1559-50	15h 59m 00s	-50d 00m 00s	162	3.07	1.1
B1613-50	16h 13m 00s	-50d 00m 00s	162	3.07	1.1
B1614-22	16h 14m 00s	-22d 00m 00s	162	3.07	1.1
B1640-22	16h 40m 00s	-22d 00m 00s	162	3.07	1.1
B1641-24	16h 41m 00s	-24d 00m 00s	162	3.07	1.1
B1643-12	16h 43m 00s	-12d 00m 00s	162	3.07	1.1
B1646-00	16h 46m 00s	0d 00m 00s	162	3.07	1.1
B1650-40	16h 50m 00s	-40d 00m 00s	162	3.07	1.1
B1654-50	16h 54m 00s	-50d 00m 00s	162	3.07	1.1
B1656-40	16h 56m 00s	-40d 00m 00s	162	3.07	1.1
B1659-14	16h 59m 00s	-14d 00m 00s	162	3.07	1.1
B1713-03	17h 13m 00s	-3d 00m 00s	162	3.07	1.1
B1719-47	17h 19m 00s	-47d 00m 00s	162	3.07	1.1
B1740-40	17h 40m 00s	-40d 00m 00s	162	3.07	1.1
B1743-30	17h 43m 00s	-30d 00m 00s	162	3.07	1.1
B1749-40	17h 49m 00s	-40d 00m 00s	162	3.07	1.1
B1757-50	17h 57m 00s	-50d 00m 00s	162	3.07	1.1
B1801-03	18h 01m 00s	-3d 00m 00s	162	3.07	1.1
B1802-07	18h 02m 00s	-7d 00m 00s	162	3.07	1.1
B1803-03	18h 03m 00s	-3d 00m 00s	162	3.07	1.1
B1805-01	18h 05m 00s	-1d 00m 00s	162	3.07	1.1
B1806-01	18h 06m 00s	-1d 00m 00s	162	3.07	1.1
B1807-01	18h 07m 00s	-1d 00m 00s	162	3.07	1.1
B1809-01	18h 09m 00s	-1d 00m 00s	162	3.07	1.1
B1814-03	18h 14m 00s	-3d 00m 00s	162	3.07	1.1
B1819-03	18h 19m 00s	-3d 00m 00s	162	3.07	1.1
B1824-03	18h 24m 00s	-3d 00m 00s	162	3.07	1.1
B1828-03	18h 28m 00s	-3d 00m 00s	162	3.07	1.1
B1831-03	18h 31m 00s	-3d 00m 00s	162	3.07	1.1
B1835-03	18h 35m 00s	-3d 00m 00s	162	3.07	1.1
B1843-03	18h 43m 00s	-3d 00m 00s	162	3.07	1.1
B1846-03	18h 46m 00s	-3d 00m 00s	162	3.07	1.1
B1853-03	18h 53m 00s	-3d 00m 00s	162	3.07	1.1
B1855-03	18h 55m 00s	-3d 00m 00s	162	3.07	1.1
B1856-03	18h 56m 00s	-3d 00m 00s	162	3.07	1.1
B1859-03	18h 59m 00s	-3d 00m 00s	162	3.07	1.1
B1900-03	19h 00m 00s	-3d 00m 00s	162	3.07	1.1
B1903-03	19h 03m 00s	-3d 00m 00s	162	3.07	1.1
B1909-03	19h 09m 00s	-3d 00m 00s	162	3.07	1.1
B1910-03	19h 10m 00s	-3d 00m 00s	162	3.07	1.1
B1911-03	19h 11m 00s	-3d 00m 00s	162	3.07	1.1
B1912-03	19h 12m 00s	-3d 00m 00s	162	3.07	1.1
B1913-03	19h 13m 00s	-3d 00m 00s	162	3.07	1.1
B1914-03	19h 14m 00s	-3d 00m 00s	162	3.07	1.1
B1915-03	19h 15m 00s	-3d 00m 00s	162	3.07	1.1
B1916-03	19h 16m 00s	-3d 00m 00s	162	3.07	1.1
B1917-03	19h 17m 00s	-3d 00m 00s	162	3.07	1.1
B1918-03	19h 18m 00s	-3d 00m 00s	162	3.07	1.1
B1919-03	19h 19m 00s	-3d 00m 00s	162	3.07	1.1
B1920-03	19h 20m 00s	-3d 00m 00s	162	3.07	1.1
B1921-03	19h 21m 00s	-3d 00m 00s	162	3.07	1.1
B1922-03	19h 22m 00s	-3d 00m 00s	162	3.07	1.1
B1923-03	19h 23m 00s	-3d 00m 00s	162	3.07	1.1
B1924-03	19h 24m 00s	-3d 00m 00s	162	3.07	1.1
B1925-03	19h 25m 00s	-3d 00m 00s	162	3.07	1.1
B1926-03	19h 26m 00s	-3d 00m 00s	162	3.07	1.1
B1927-03	19h 27m 00s	-3d 00m 00s	162	3.07	1.1
B1928-03	19h 28m 00s	-3d 00m 00s	162	3.07	1.1
B1929-03	19h 29m 00s	-3d 00m 00s	162	3.07	1.1
B1930-03	19h 30m 00s	-3d 00m 00s	162	3.07	1.1
B1931-03	19h 31m 00s	-3d 00m 00s	162	3.07	1.1
B1932-03	19h 32m 00s	-3d 00m 00s	162	3.07	1.1
B1933-03	19h 33m 00s	-3d 00m 00s	162	3.07	1.1
B1934-03	19h 34m 00s	-3d 00m 00s	162	3.07	1.1
B1935-03	19h 35m 00s	-3d 00m 00s	162	3.07	1.1
B1936-03	19h 36m 00s	-3d 00m 00s	162	3.07	1.1
B1937-03	19h 37m 00s	-3d 00m 00s	162	3.07	1.1
B1938-03	19h 38m 00s	-3d 00m 00s	162	3.07	1.1
B1939-03	19h 39m 00s	-3d 00m 00s	162	3.07	1.1
B1940-03	19h 40m 00s	-3d 00m 00s	162	3.07	1.1
B1941-03	19h 41m 00s	-3d 00m 00s	162	3.07	1.1
B1942-03	19h 42m 00s	-3d 00m 00s	162	3.07	1.1
B1943-03	19h 43m 00s	-3d 00m 00s	162	3.07	1.1
B1944-03	19h 44m 00s	-3d 00m 00s	162	3.07	1.1
B1945-03	19h 45m 00s	-3d 00m 00s	162	3.07	1.1
B1946-03	19h 46m 00s	-3d 00m 00s	162	3.07	1.1
B1947-03	19h 47m 00s	-3d 00m 00s	162	3.07	1.1
B1948-03	19h 48m 00s	-3d 00m 00s	162	3.07	1.1
B1949-03	19h 49m 00s	-3d 00m 00s	162	3.07	1.1
B1950-03	19h 50m 00s	-3d 00m 00s	162	3.07	1.1
B1951-03	19h 51m 00s	-3d 00m 00s	162	3.07	1.1
B1952-03	19h 52m 00s	-3d 00m 00s	162	3.07	1.1
B1953-03	19h 53m 00s	-3d 00m 00s	162	3.07	1.1
B1954-03	19h 54m 00s	-3d 00m 00s	162	3.07	1.1
B1955-03	19h 55m 00s	-3d 00m 00s	162	3.07	1.1
B1956-03	19h 56m 00s	-3d 00m 00s	162	3.07	1.1
B1957-03	19h 57m 00s	-3d 00m 00s	162	3.07	1.1
B1958-03	19h 58m 00s	-3d 00m 00s	162	3.07	1.1
B1959-03	19h 59m 00s	-3d 00m 00s	162	3.07	1.1
B2000-03	20h 00m 00s	-3d 00m 00s	162	3.07	1.1
B2001-03	20h 01m 00s	-3d 00m 00s	162	3.07	1.1
B2002-03	20h 02m 00s	-3d 00m 00s	162	3.07	1.1
B2003-03	20h 03m 00s	-3d 00m 00s	162	3.07	1.1
B2004-03	20h 04m 00s	-3d 00m 00s	162	3.07	1.1
B2005-03	20h 05m 00s	-3d 00m 00s	162	3.07	1.1
B2006-03	20h 06m 00s	-3d 00m 00s	162	3.07	1.1
B2007-03	20h 07m 00s	-3d 00m 00s	162	3.07	1.1
B2008-03	20h 08m 00s	-3d 00m 00s	162	3.07	1.1
B2009-03	20h 09m 00s	-3d 00m 00s	162	3.07	1.1
B2010-03	20h 10m 00s	-3d 00m 00s	162	3.07	1.1
B2011-03	20h 11m 00s	-3d 00m 00s	162	3.07	1.1
B2012-03	20h 12m 00s	-3d 00m 00s	162	3.07	1.1
B2013-03	20h 13m 00s	-3d 00m 00s	162	3.07	1.1
B2014-03	20h 14m 00s	-3d 00m 00s	162	3.07	1.1
B2015-03	20h 15m 00s	-3d 00m 00s	162	3.07	1.1
B2016-03	20h 16m 00s	-3d 00m 00s	162	3.07	1.1
B2017-03	20h 17m 00s	-3d 00m 00s	162	3.07	1.1
B2018-03	20h 18m 00s	-3d 00m 00s	162	3.07	1.1
B2019-03	20h 19m 00s	-3d 00m 00s	162	3.07	1.1
B2020-03	20h 20m 00s	-3d 00m 00s	162	3.07	1.1
B2021-03	20h 21m 00s	-3d 00m 00s	162	3.07	1.1
B2022-03	20h 22m 00s	-3d 00m 00s	162	3.07	1.1
B2023-03	20h 23m 00s	-3d 00m 00s	162	3.07	1.1
B2024-03	20h 24m 00s	-3d 00m 00s	162	3.07	1.1
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B2028-03	20h 28m 00s	-3d 00m 00s	162	3.07	1.1
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B2030-03	20h 30m 00s	-3d 00m 00s	162	3.07	1.1
B2031-03	20h 31m 00s	-3d 00m 00s	162	3.07	1.1
B2032-03	20h 32m 00s	-3d 00m 00s	162	3.07	1.1
B2033-03	20h 33m 00s	-3d 00m 00s	162	3.07	1.1
B2034-03	20h 34m 00s	-3d 00m 00s	162	3.07	1.1
B2035-03	20h 35m 00s	-3d 00m 00s	162	3.07	1.1
B2036-03	20h 36m 00s	-3d 00m 00s	162	3.07	1.1
B2037-03	20h 37m 00s	-3d 00m 00s			

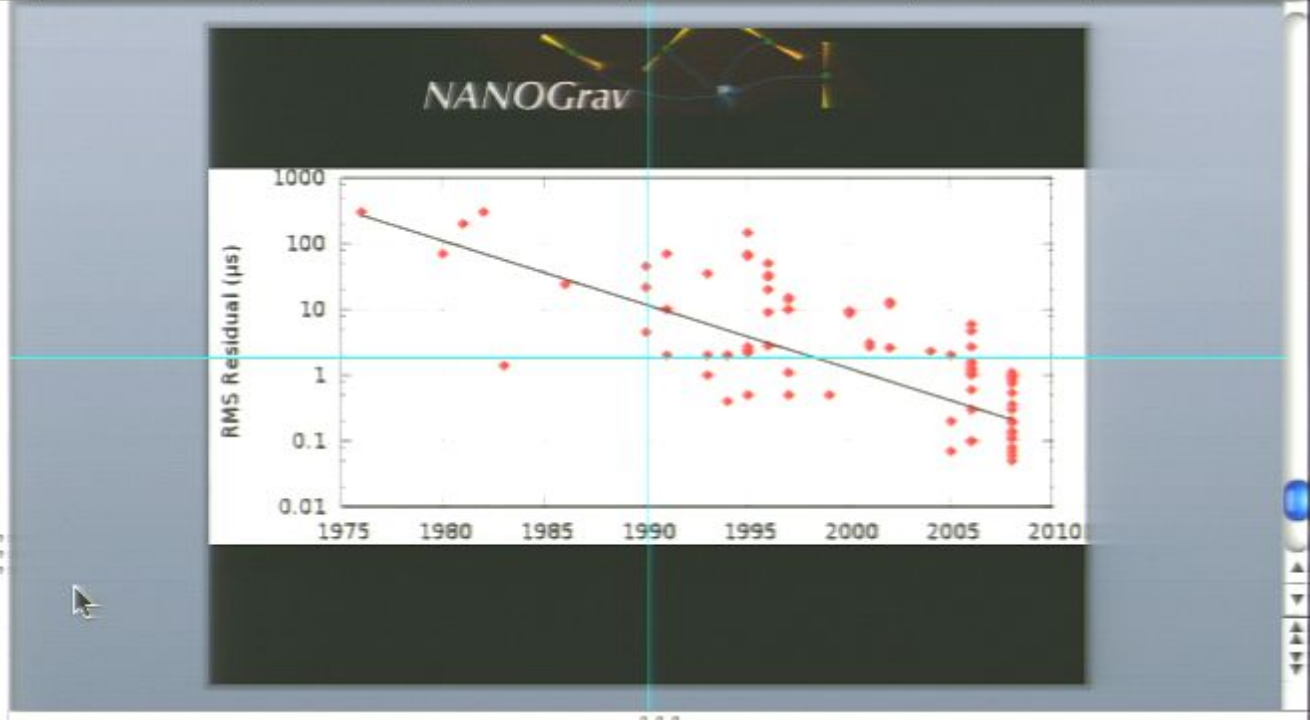


56

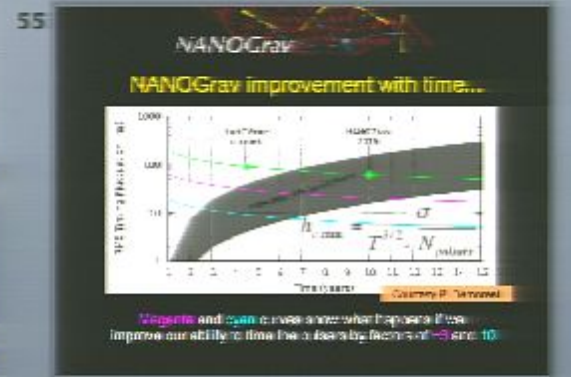
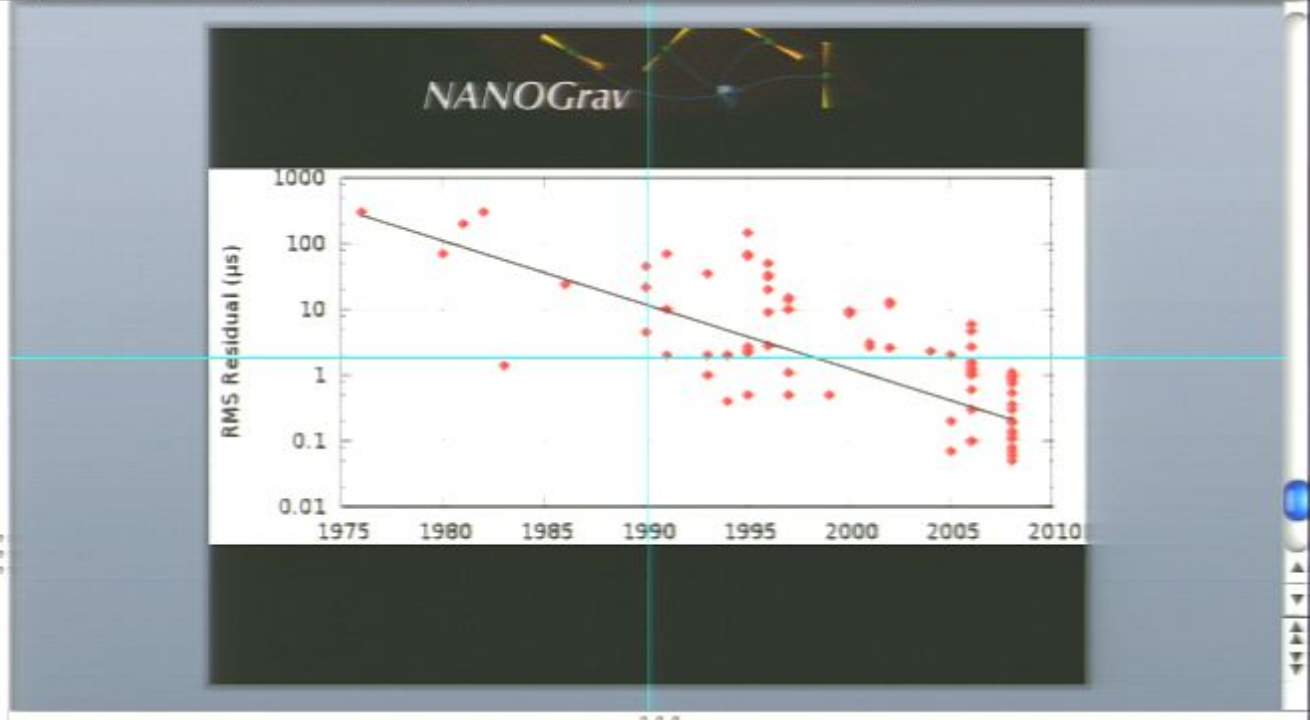
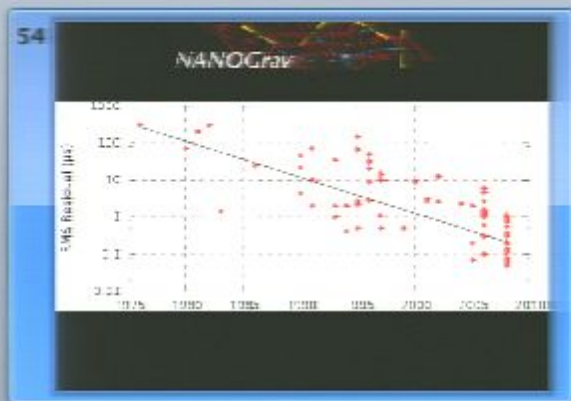
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Physics from Pulsars

- Neutron star and relativistic dynamics (e.g. binary pulsars)
- Gravitational wave physics (e.g. LIGO, MSP timing)
- Binary pulsars (e.g. Hulse and Taylor's discovery)
- Relativistic effects (e.g. Shapiro delay and gravitational redshift)
- Pulsar crystals (e.g. superconducting quanta on the surface)
- Dark matter (e.g. constraints on dark matter)



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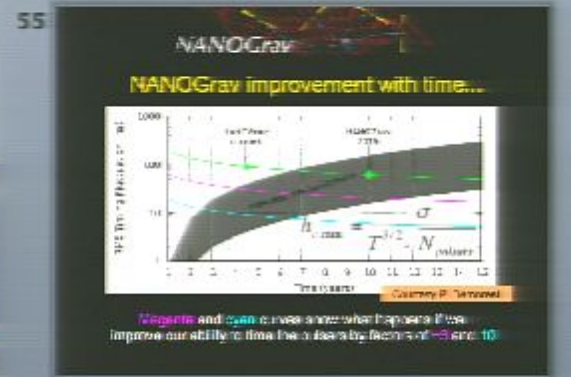
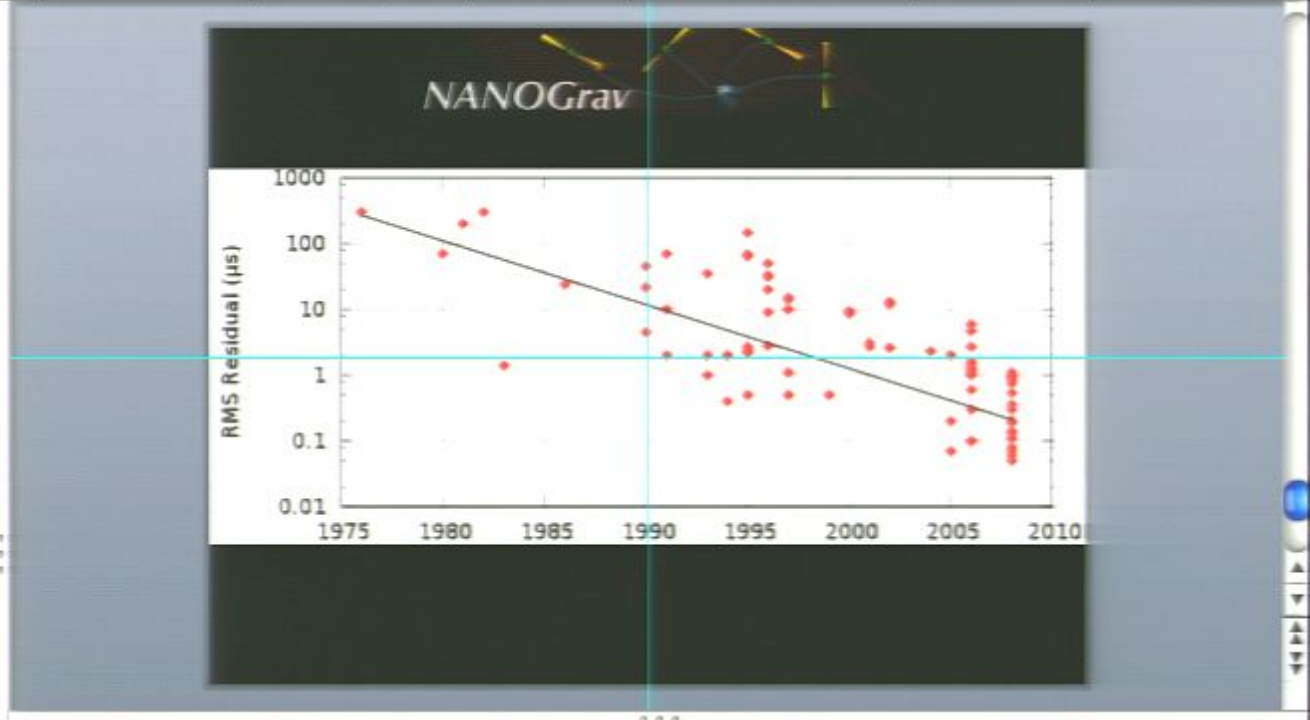
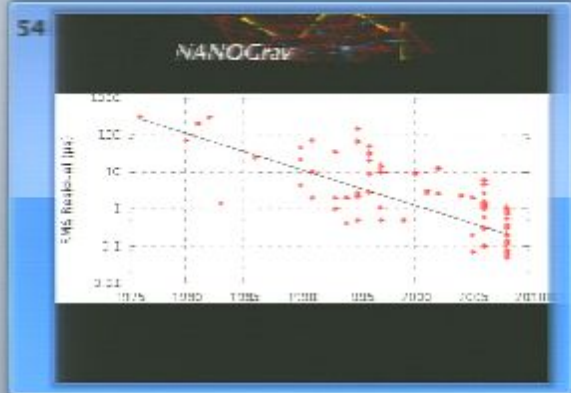
56

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- [Web site on and related data](#) ([http://www.perimeterinstitute.ca/nanograv/](#))
- [Gravitational wave physics](#) (e.g. [LIGO](#), [MSP](#) timing)
- [Binary pulsars](#) (e.g. [PSR 1509-58](#) and [PSR 1534-12](#))
- [Relativistic effects](#) (e.g. [Shapiro delay](#) and [gravitational redshift](#))
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56

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Physics from Pulsars

- Newtonian and relativistic dynamics (see library website)
- Gravitational wave physics (e.g. LIGO, MSP timing)
- Binary pulsars (e.g. Hulse & Taylor's discovery)
- Relativistic effects (e.g. Shapiro delay and gravitational redshift)
- Planck system of units (meters, kilograms, seconds)
- See: [http://www.perimeterinstitute.ca/pulsars](#)

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