Pulsar timing constraints on narrow-band stochastic signals

Quarks-2014

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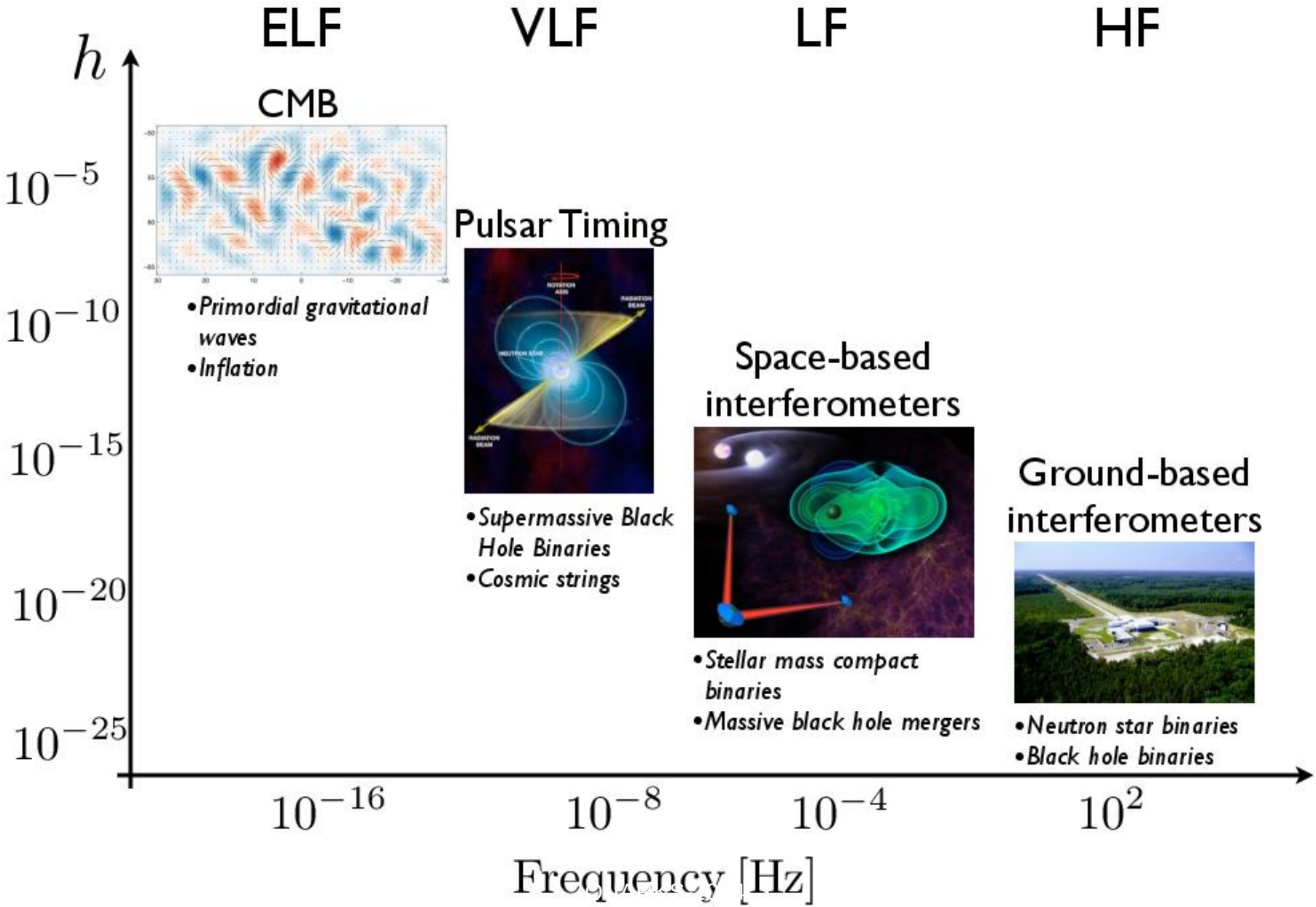
Outline

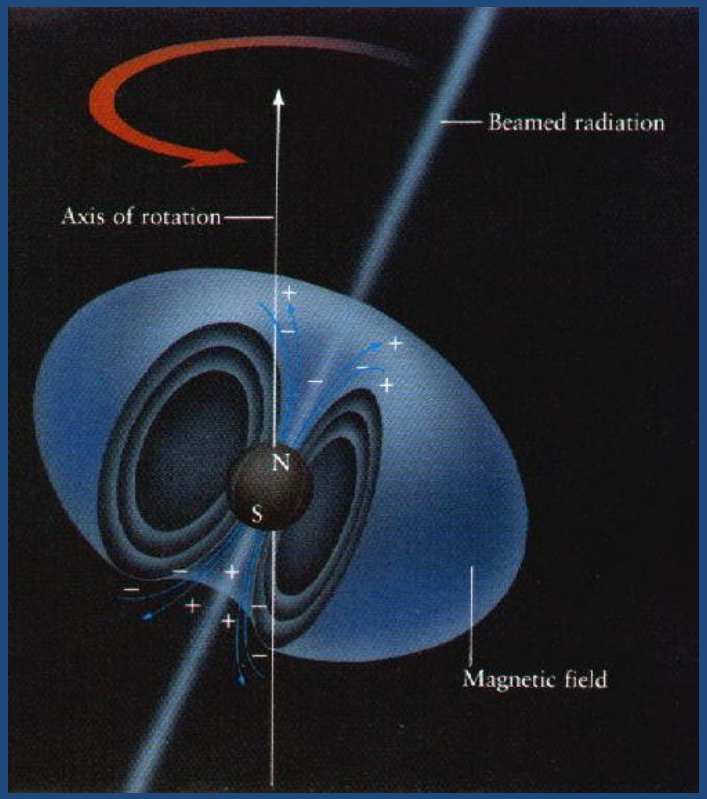
- Introduction: pulsar timing and pulsar timing arrays
- Narrow-band stochastic GW and GW-like signals
- NANOGrav data analysis
- Conclusions

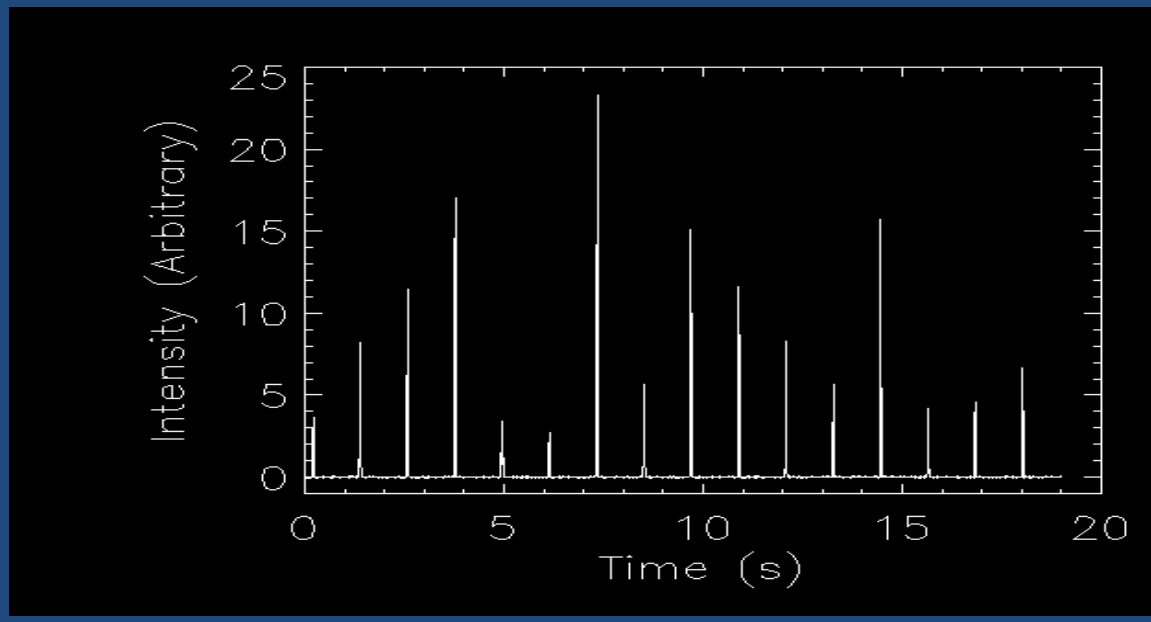
The big picture of gravitational wave astronomy



Radio Pulsars

- Since 1967

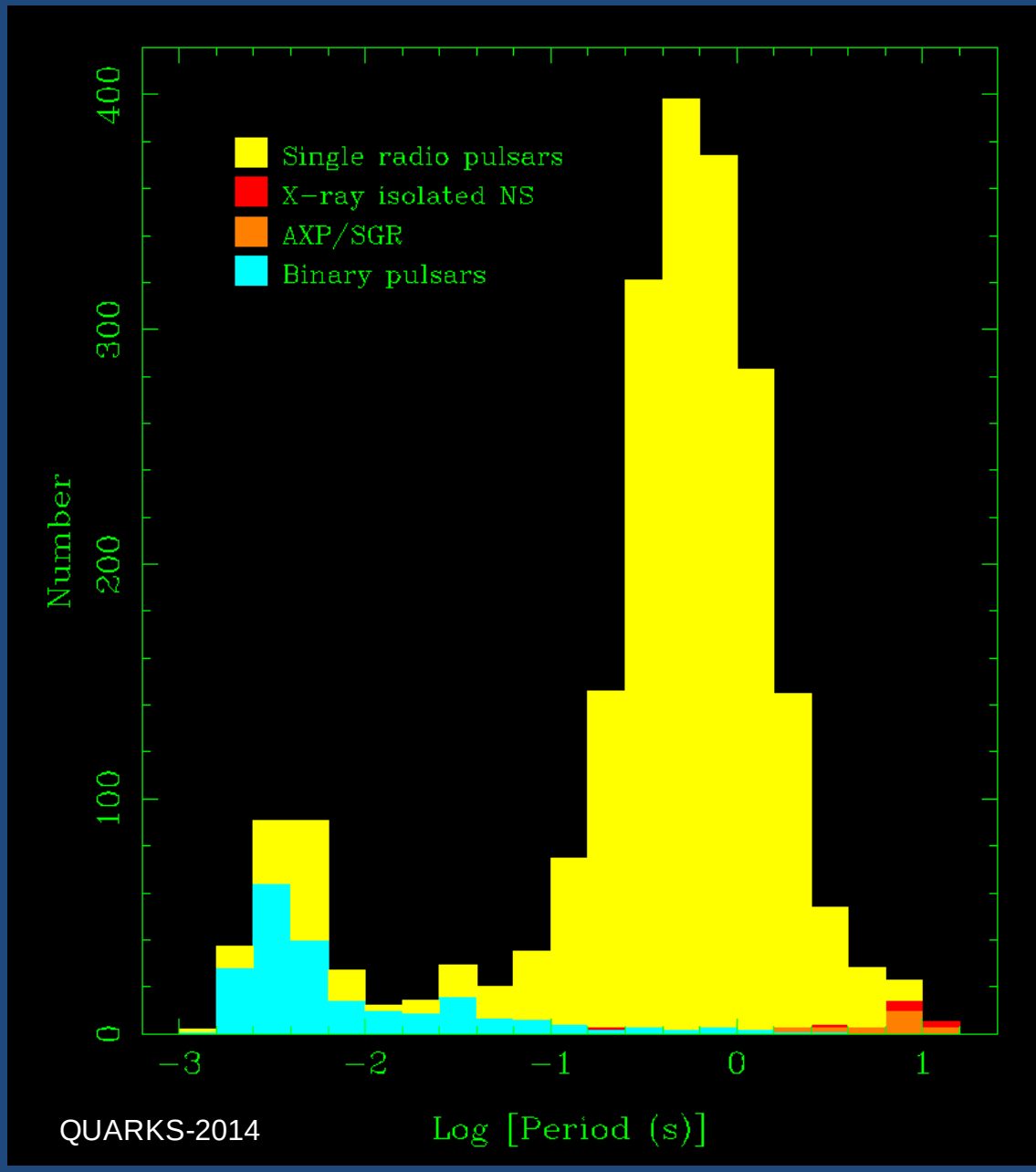




Pulsars: A Census

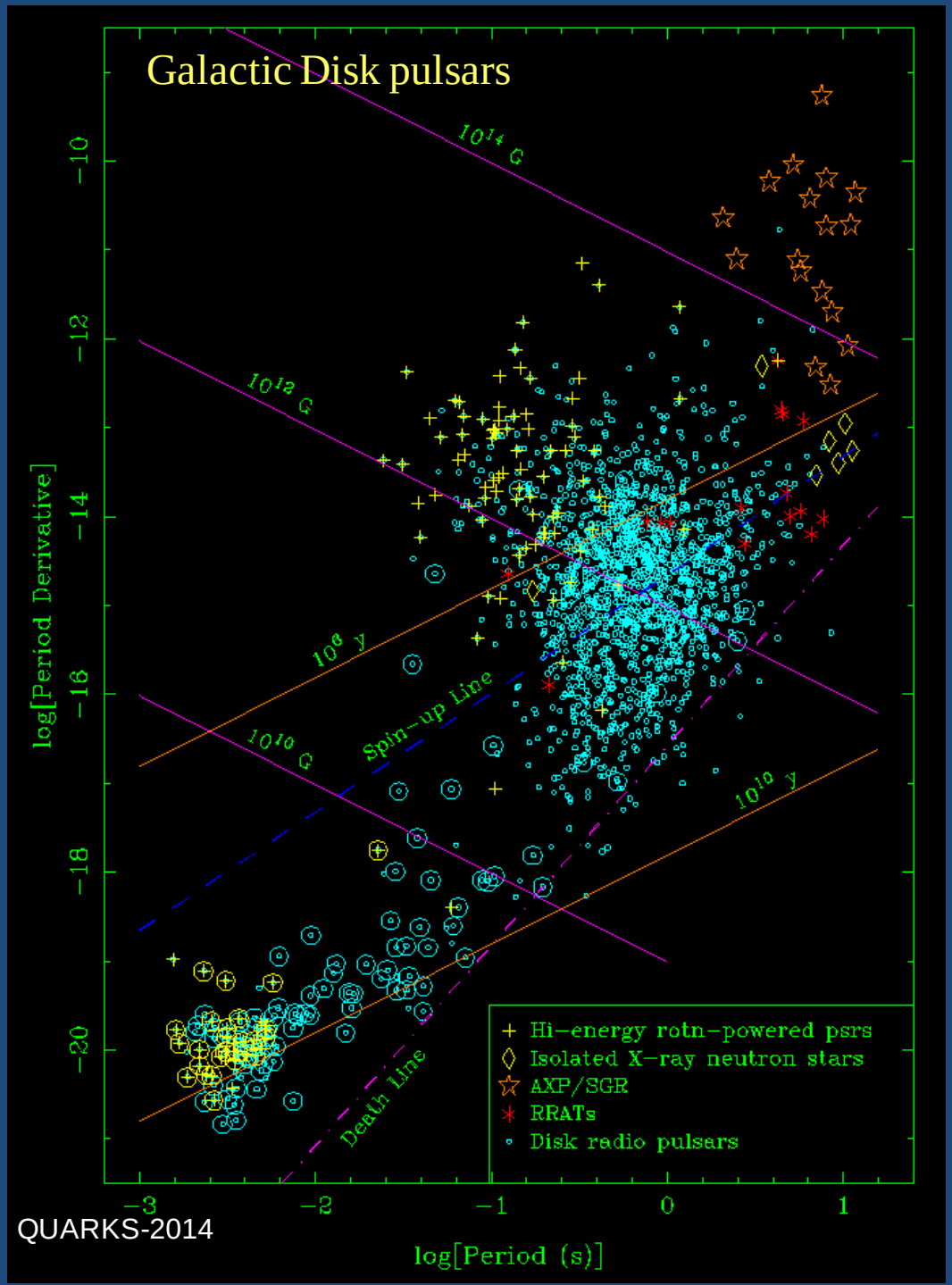
- Currently >2200 known (published) pulsars
- 2050 rotation-powered disk pulsars
- ~210 in binary systems
- ~300 millisecond pulsars
- ~140 in globular clusters
- 8 X-ray isolated neutron stars
- 20 AXP/SGR
- 21 extra-galactic pulsars

ATNF Pulsar Catalogue (www.atnf.csiro.au/research/pulsar/psrcat) (Manchester et al. 2005)



P – dP/dt Diagram

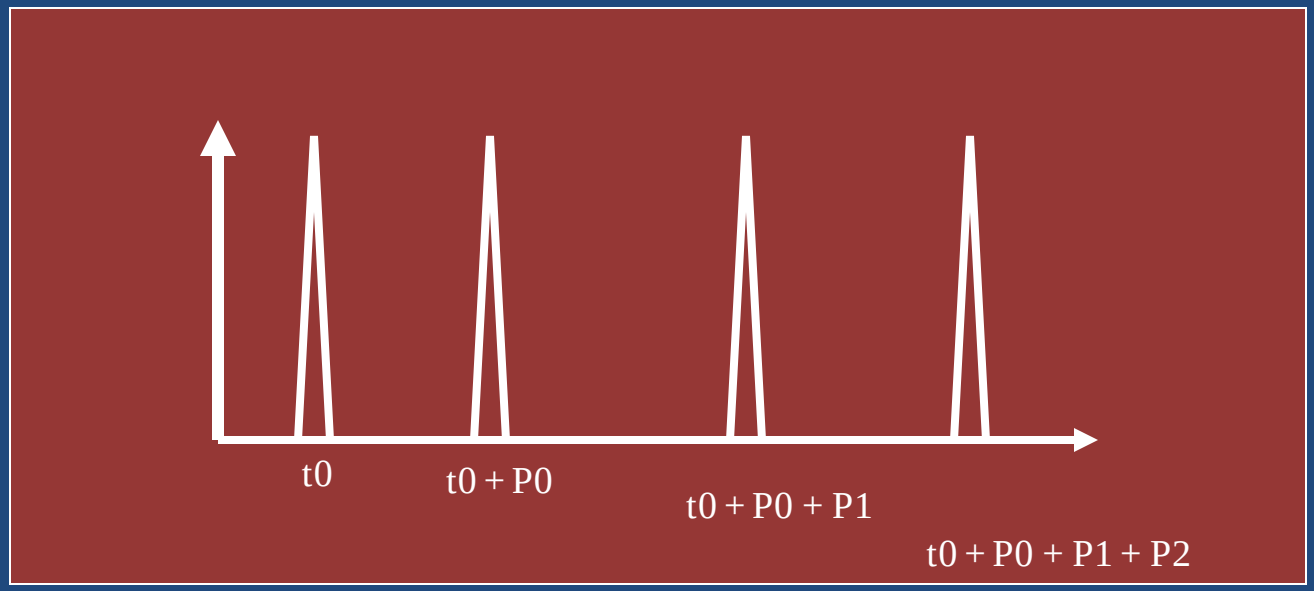
- For most pulsars $\dot{P} \sim 10^{-15}$
- MSPs have $\dot{P}$ smaller by about 5 orders of magnitude
- Most MSPs are binary, but few normal pulsars are
- $\tau_c = P/(2\dot{P})$ is an indicator of pulsar age
- Surface dipole magnetic field $\sim (P\dot{P})^{1/2}$



How does one detect GW using Radio pulsars?

Pulsar timing involves measuring the time-of arrival (TOA) of each individual pulse and then subtracting off the expected time-of-arrival given a physical model of the system.

$$R = TOA - TOA_m$$



$$TOA(N) = \sum_0^{N-1} P_i + t_0$$

$$P_i = P_i^m + \delta P_i$$

$$R(N) = TOA(N) - TOA(N)_m = \sum_0^{N-1} \delta P_i$$

$$P_i = 1/\nu_i = 1/(\nu_i^m + \delta \nu_i)$$

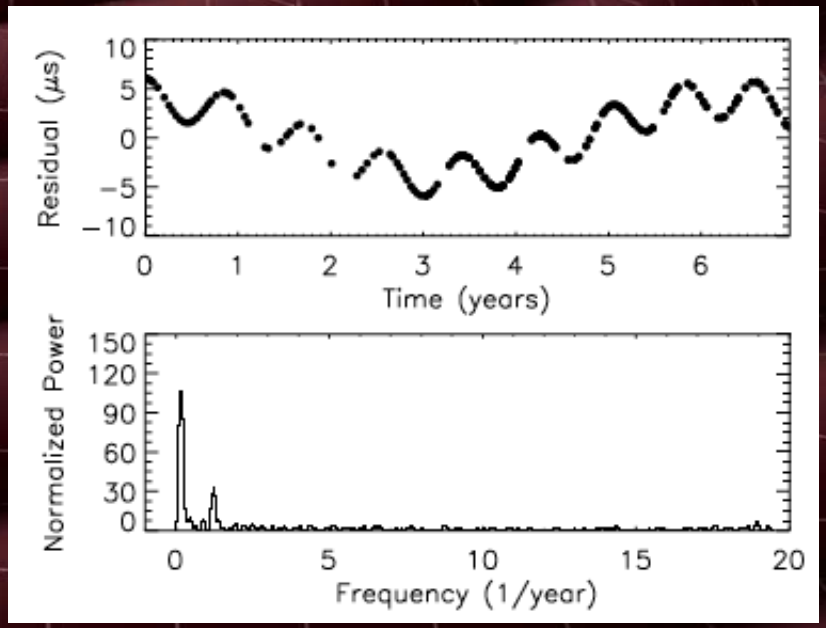
$$R(N) = -\sum_0^{N-1} \delta \nu_i/(\nu_i^m)^2$$

$$R(t) = -\sum_0^{N-1} P_i^m \delta \nu_i / \nu_i^m$$

$$R(t) = -\int_0^t \frac{\delta\nu(t)}{\nu} dt$$

Effect of a GW

Jenet et al. (2004)



Pulsar

Earth

The effect of GW on the Timing residuals

$$\frac{\delta\nu}{\nu} = -\mathcal{H}^{ij}(h_{ij}(t_e, x_e^i) - h_{ij}(t_e - d, x_p^i))$$

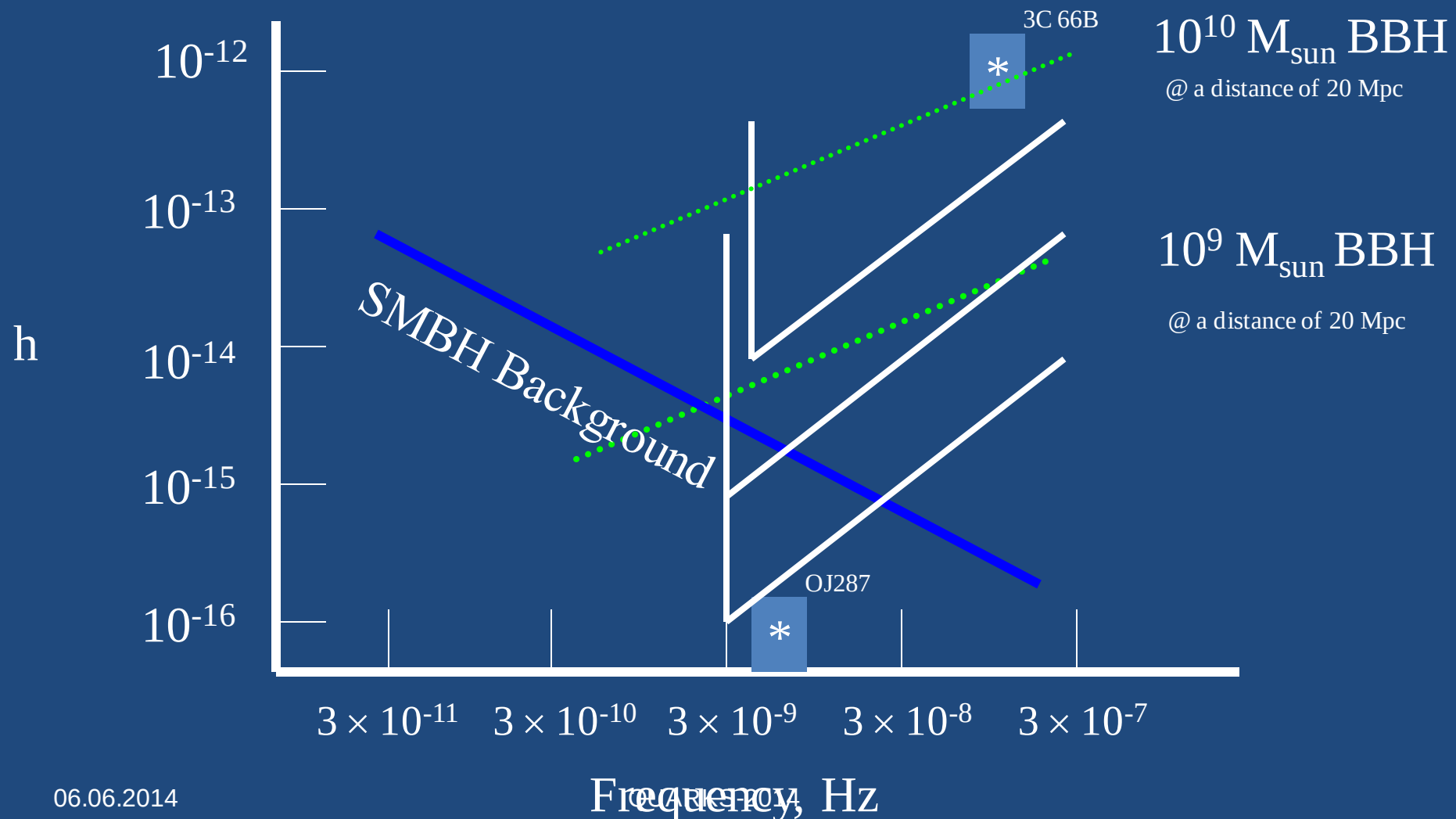
$$R(t) = -\int_0^t \frac{\delta\nu(t)}{\nu} dt$$

$$R \approx \frac{h}{\Omega}$$

Sazhin 1978
Detweiler 1979

Sensitivity of a Pulsar timing to GW

$h = \Omega R$ $\quad R_{rms} \approx 1\ \mu s$ $\quad h >= 1\ \mu s\ \Omega/N^{1/2}$



Pulsar timing: The basics

(e.g. Hobbs, Edwards & Manchester'06)

Model for pulsar spin down

Improve timing model

Obtain pulse arrival times at observatory

Form timing residuals – how good is the timing model at predicting the arrival times

Must average many thousands of pulses together to obtain stable profile

Must convert to conform with terrestrial time standards

Must convert to reference frame suitable for the timing model – e.g. solar system barycentre

Must add extra propagation delays e.g. through the solar system

Must convert to arrival times at infinite frequency

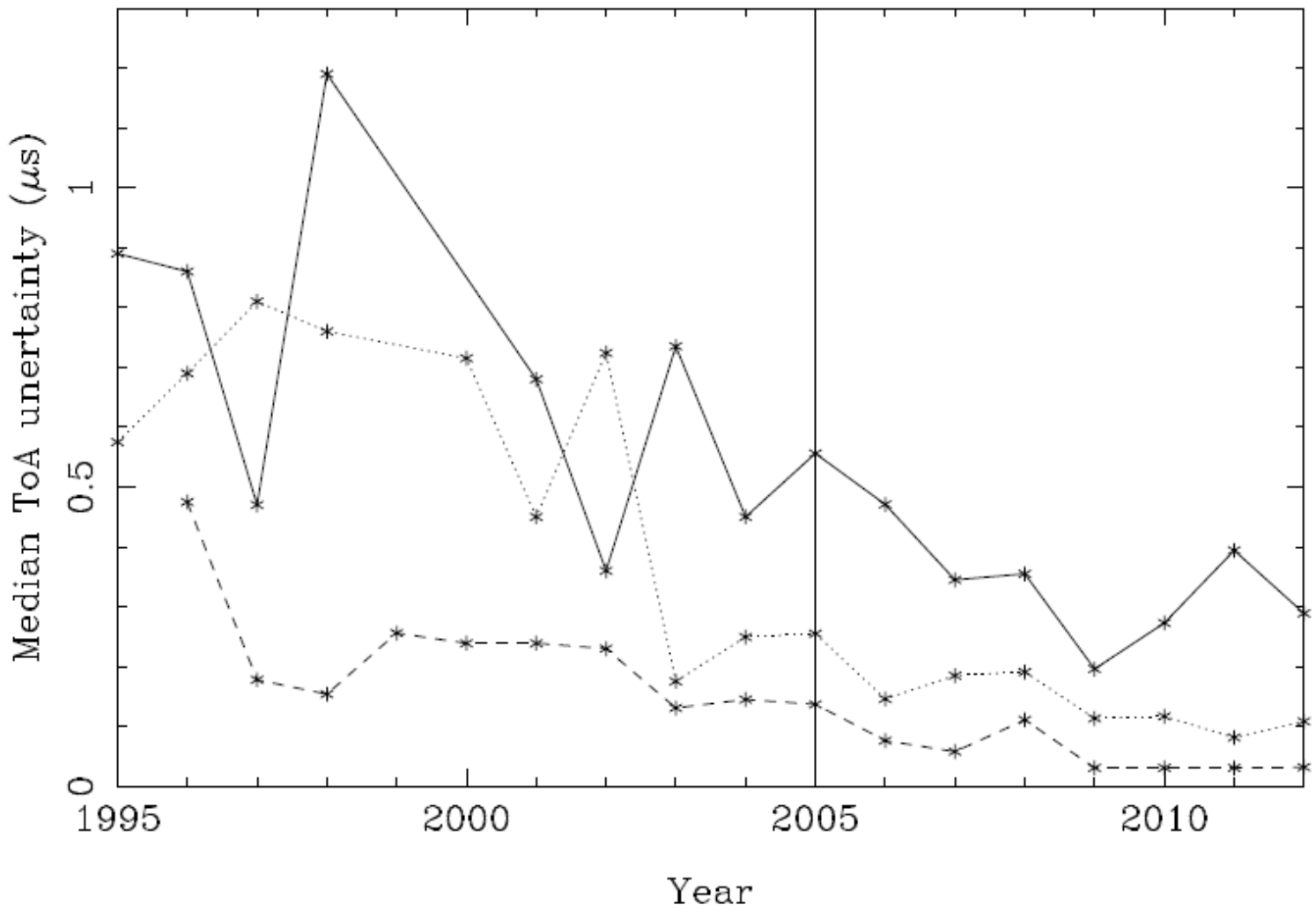
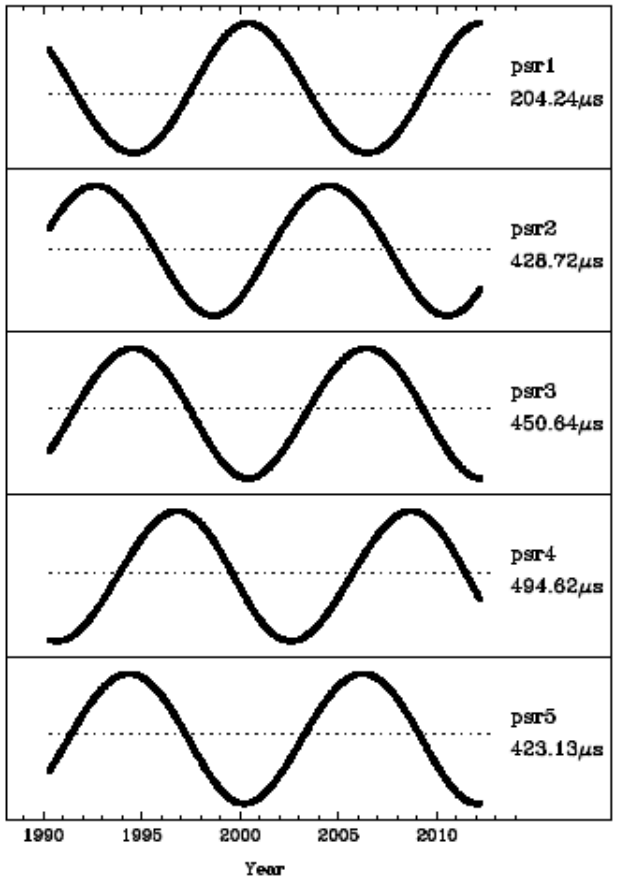


Figure 1. Average median timing residuals per year for PSR J0437−4715 (da
J1713+0747 (dotted) and PSR J1744−1134 (solid)

Hobbs 2013

Sensitivity to Solar system parameters



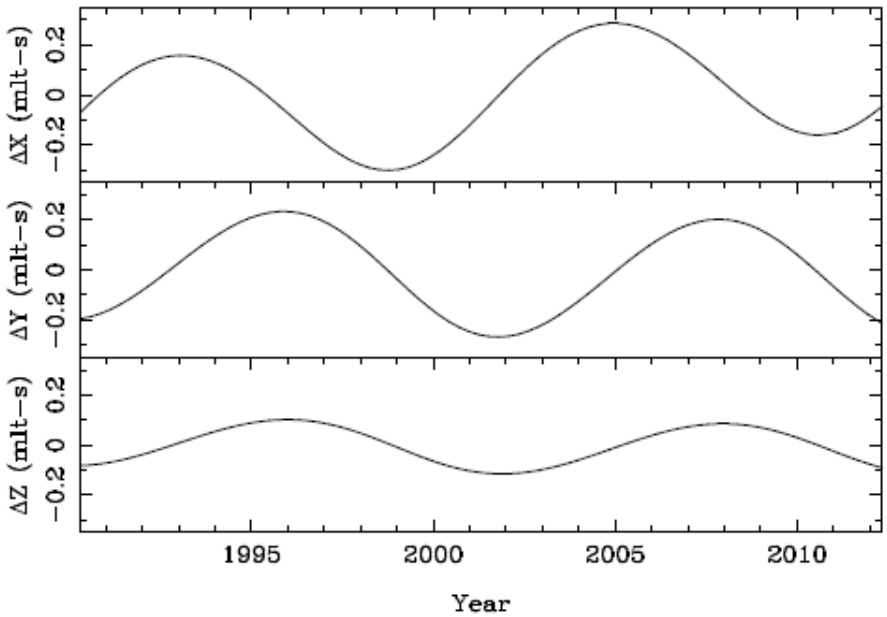
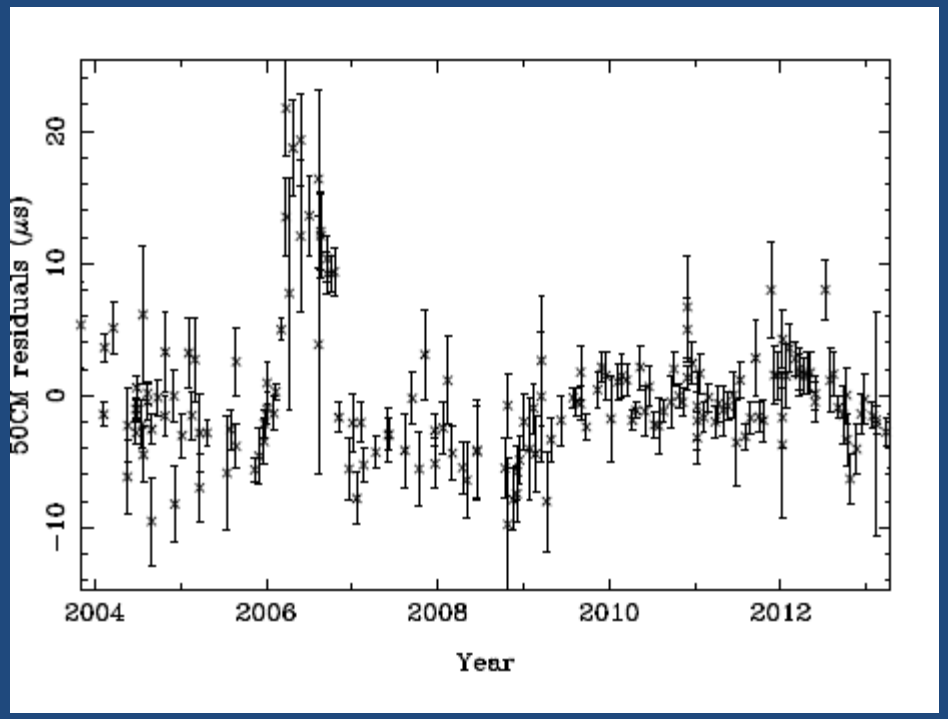


Figure 6. Left-hand panel shows the induced timing residuals due to an incorrect mass of Jupiter of $\Delta M_J = 10^{-7} M_\odot$. The right-hand panel displays the offset in the observatory-SSB position in X, Y and Z as a function of time.

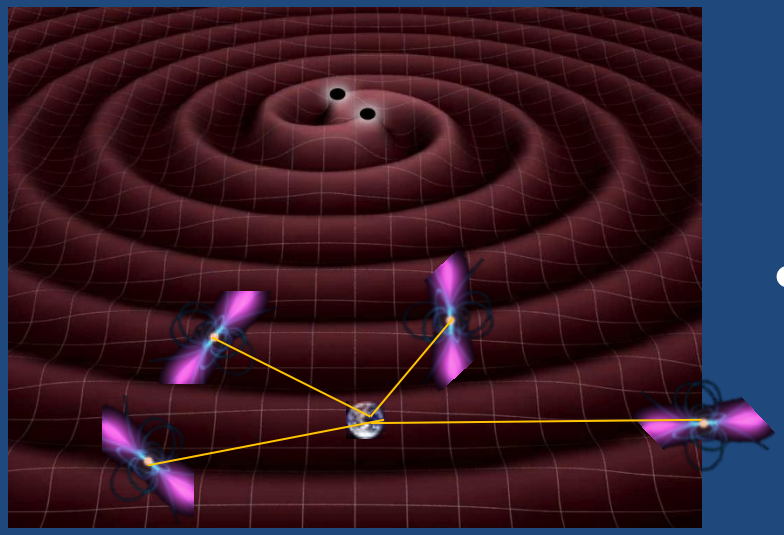
Hobbs 2013

BUT: Low-frequency (red) noise



Example of red noise in PSR J1603-7202 (PPTA, Hobbs'13)

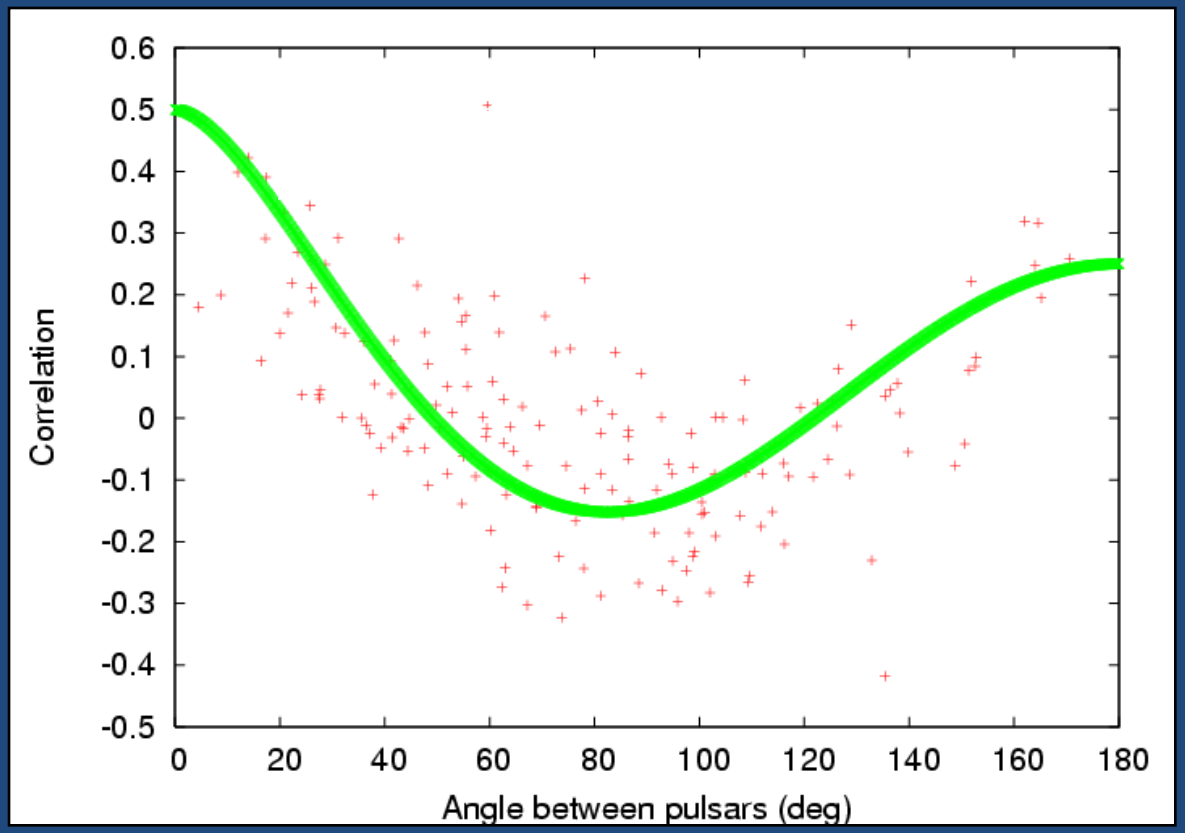
Pulsar Timing *Array*



- Monopolar signature?
  - Atomic time standards (Hobbs+'12)
  - Telescope issues
- Dipolar signature?
  - Planetary ephemeris errors (Champion+'10)
- Quadrupolar signature?
  - Gravitational waves

Detecting a Stochastic GW Background

Simulation of timing-residual correlations among 20 pulsars for a GW background from binary super-massive black holes in the cores of distant galaxies



To detect the expected signal, ~weekly observations of ~20 MSPs over ~10 years with TOA precisions of ~100 ns for ~10 pulsars and < 1 μs for the rest

(Jenet +'05, Hobbs +'09)

PTA Projects

European Pulsar Timing Array (EPTA)

- Radio telescopes at Westerbork, Effelsberg, Nancay, Jodrell Bank, (Cagliar
- 27 millisecond pulsars, 5 with $\sigma_{ToA} < 2\ \mu s$, data spans 5 - 18 years

North American pulsar timing array (NANOGrav)

- Data from Arecibo and Green Bank Telescope
- 17 millisecond pulsars, 16 with $\sigma_{ToA} < 2\ \mu s$, data spans ~ 5 years

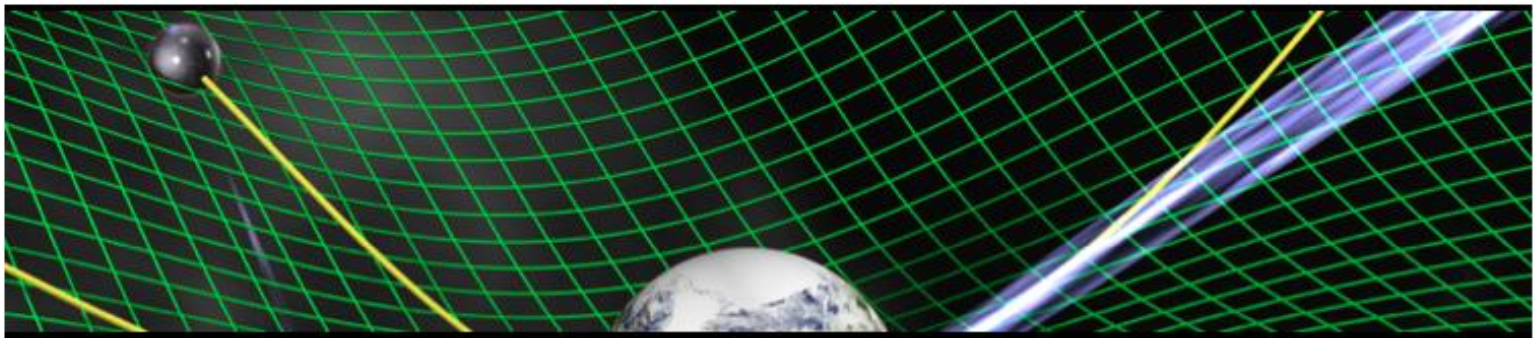
Parkes Pulsar Timing Array (PPTA)

- Data from Parkes 64m radio telescope in Australia
- 22 millisecond pulsars, 16 with $\sigma_{ToA} < 2\ \mu s$, data spans 3 – 19 years

Observations at two or three frequencies required to remove the effects of interstellar dispersion

IPTA Website: www.ipta4gw.org

International Pulsar Timing Array



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Introduction to the IPTA Concept

Posted on May 16, 2011 by admin

The **International Pulsar Timing Array** (IPTA) is a consortium of consortia[1] , comprised of the European Pulsar Timing Array (EPTA), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), and the Parkes Pulsar Timing Array (PPTA). The principal goal of the IPTA is to detect gravitational waves using an array of approximately 30 pulsars. This goal is shared by each of the participating consortia individually, but they have all recognized that their goal will be achieved more quickly in collaboration, and by combining their respective resources. Sharing resources will also help to reach other IPTA goals, for example, establishing a pulsar-based reference timescale.

EPTA

NANOGrav

PPTA

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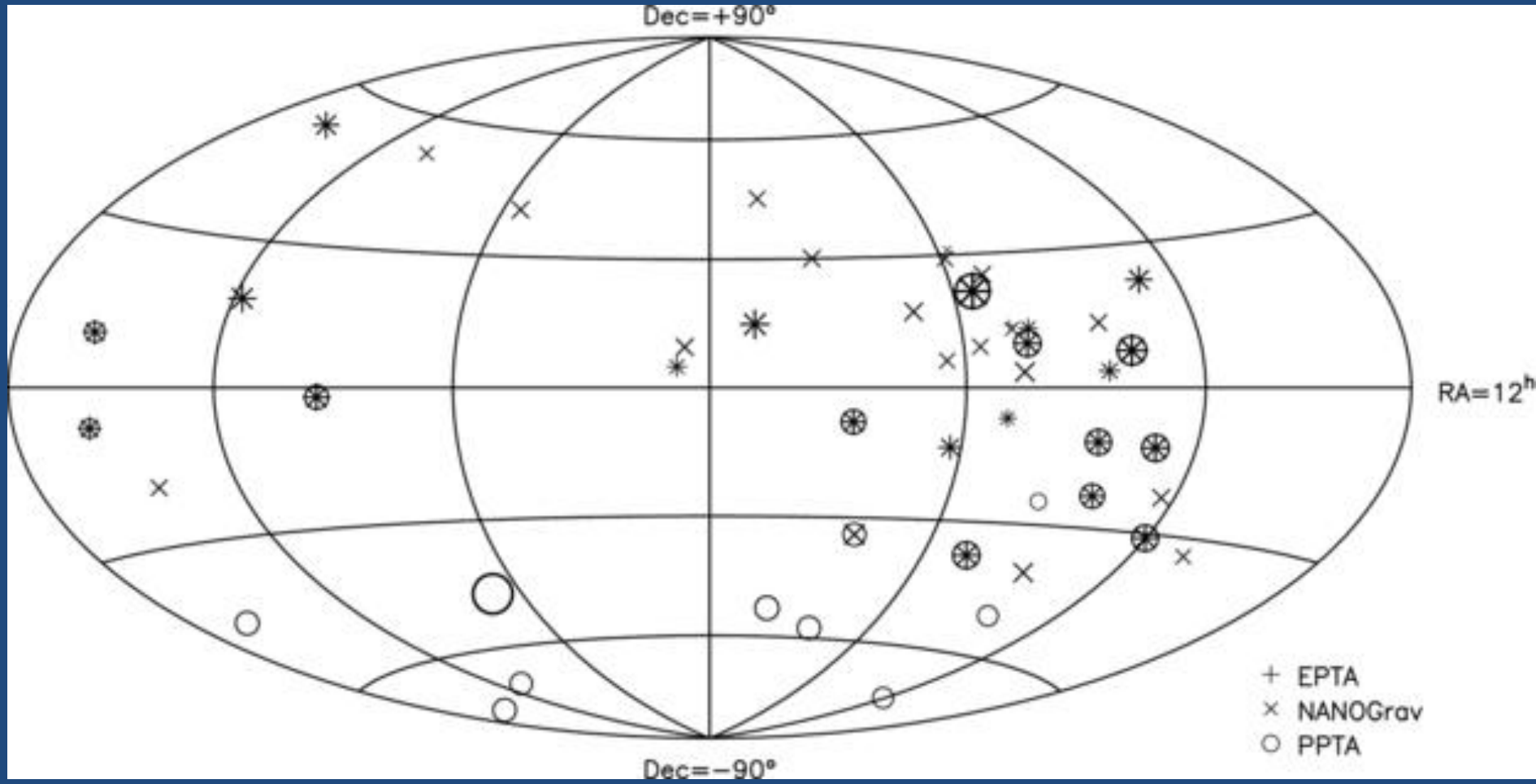
- NANOGrav
- PPTA



Manchester'13

Stochastic GWB

$$\langle h_s(k^i) h^*_{s'}(k'^i)\rangle = \delta_{ss'}\delta^3(k^i - k'^i)\frac{P_h(k)}{16\pi k^3}$$

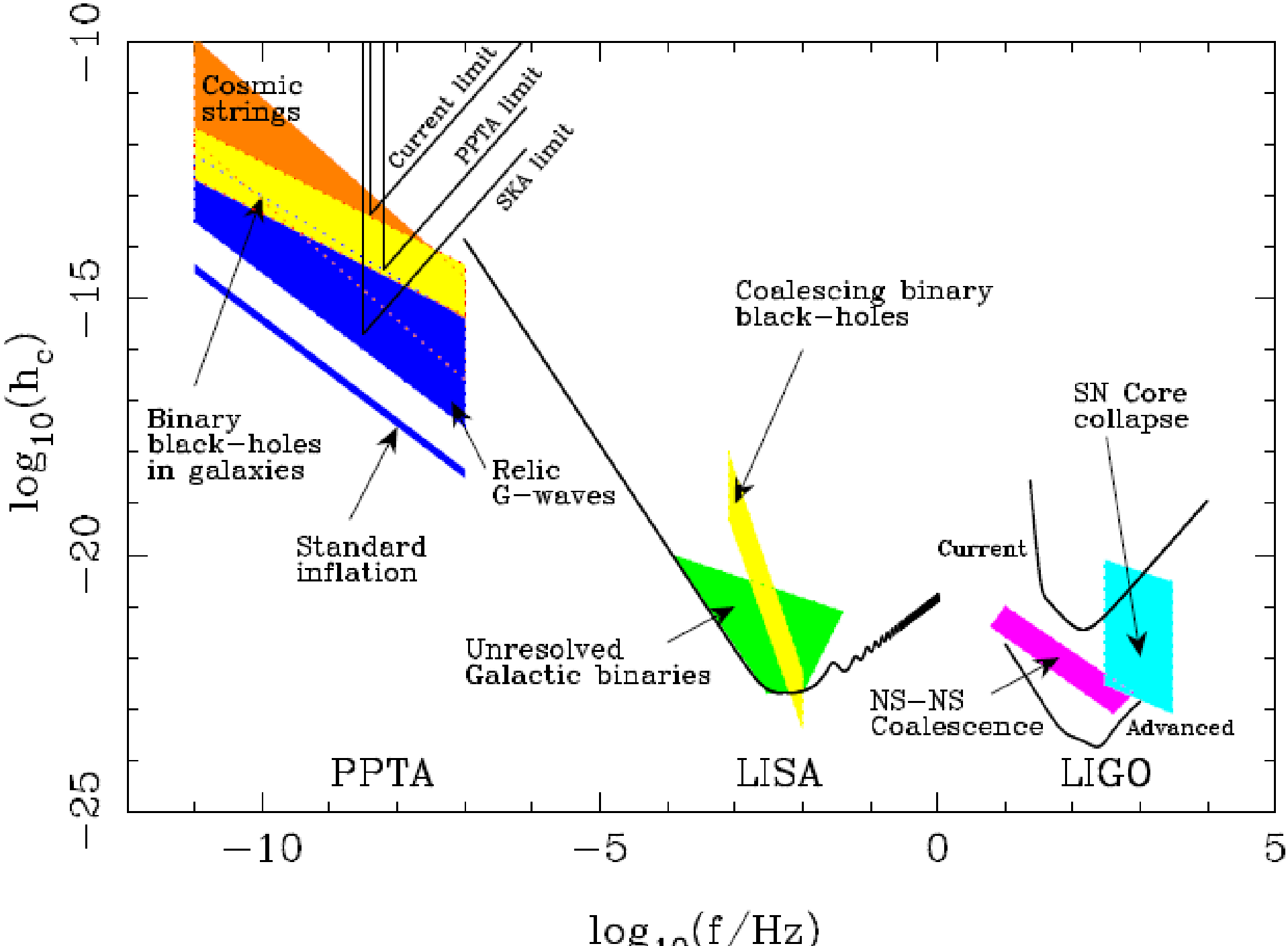
$$h_c(k)^2 = P_h(k)$$

$$\Omega_{GWB} = \frac{\rho_{GWB}}{\rho_{cr}} = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

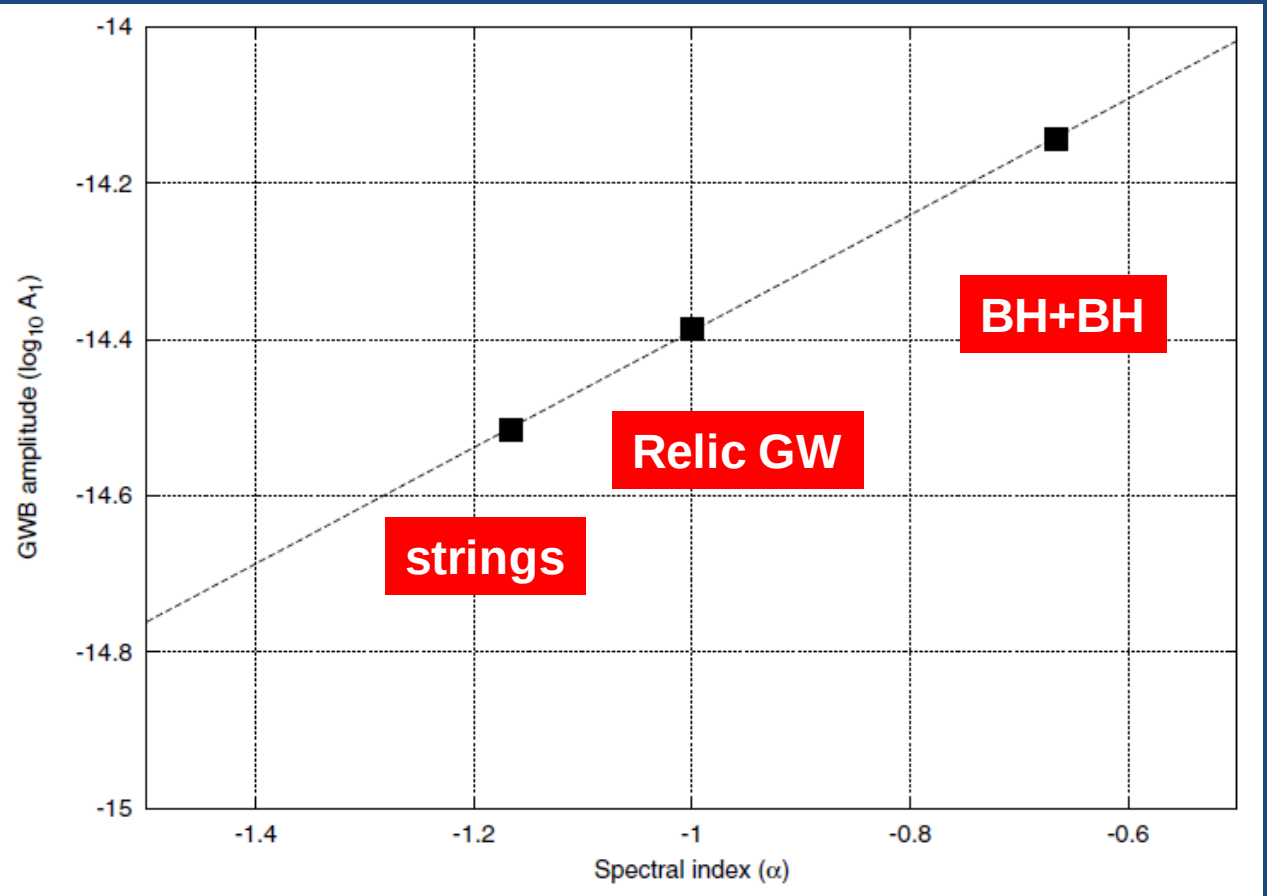
$$< R^2 >= \int \frac{dk}{k} P(k)\tilde{R}^2(k) = \int_0^\infty S(f)df$$

$$\tilde{R}^2_{GWB}(k) = 1/(3k^2c^2)$$

$$S_{GWB}(f) = \frac{h_c^2}{12\pi^2 f^3}$$


Cosmic strings
Current limit
PPTA limit
SKA limit
Coalescing binary black−holes
SN Core collapse
Binary black−holes in galaxies
Relic G−waves
Standard inflation
Current
Unresolved Galactic binaries
NS−NS Coalescence
Advanced
PPTA
LISA
LIGO
−10
−15
−20
−25
−10
−5
0
5
$\log_{10}(h_c)$
$\log_{10}(f/\mathrm{Hz})$

Broadband GWBs: NANOgrav limits (Demorest +'13)



$$h_c(f) = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{\alpha}$$

$$A_1(\alpha) = A_T\left(\frac{T}{1\ \mathrm{year}}\right)^{\alpha}$$

$$A_T = 2.26 \times 10^{-14}$$

Narrow-band signals: motivation

- Ultralight ($m \sim 10^{-23}$eV) massive scalar field as viable warm dark matter candidate (Khmelnitsky & Rubakov'14)
- The field produces gravitational potential oscillations @ twice the mass $f = 5 \cdot 10^{-9}\,\mathrm{Hz}\left(\frac{m}{10^{-23}\,\mathrm{eV}}\right)$
- Oscillation amplitude

$$h_c = 2\sqrt{3}\,\Psi_c = 2 \cdot 10^{-15}\left(\frac{\rho_{DM}}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{10^{-23}\,\mathrm{eV}}{m}\right)^2$$

- Quasi-monochromatic signal $\Delta f / f \sim v^2 \sim 10^{-6}$

Signature of a stochastic variable gravitational potential background

$$\Psi_c = \pi \frac{G\rho_{DM}}{(\pi f)^2} \approx 10^{-16} \left(\frac{f}{10^{-8}\mathrm{Hz}}\right)^{-2} \approx 4.3 \times 10^{-16} \left(\frac{m}{10^{-23}\mathrm{eV}}\right)^{-2}$$

Timing residuals

$$R(t) = \frac{\Psi_c}{2\pi f} \{(\sin(2\pi f t + 2\alpha(\mathbf{x}_e)) - \sin(2\pi f(t - D/c) + 2\alpha(\mathbf{x}_p))\}$$

Earth term **Pulsar term**

Narrow-band approximation

$$P_h(k') = \begin{cases} P_0, k < k' < k + \delta k \\ 0, \text{in other cases,} \end{cases}$$

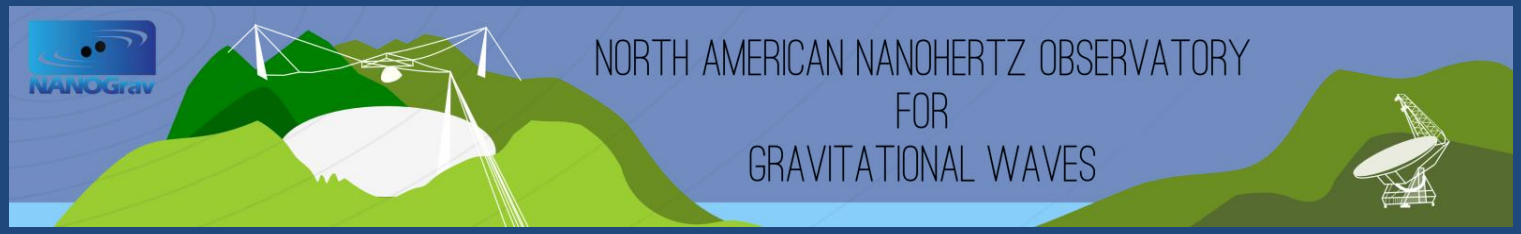
$$h_c^2 = P_0 \delta k / k = P_0 \delta f / f$$

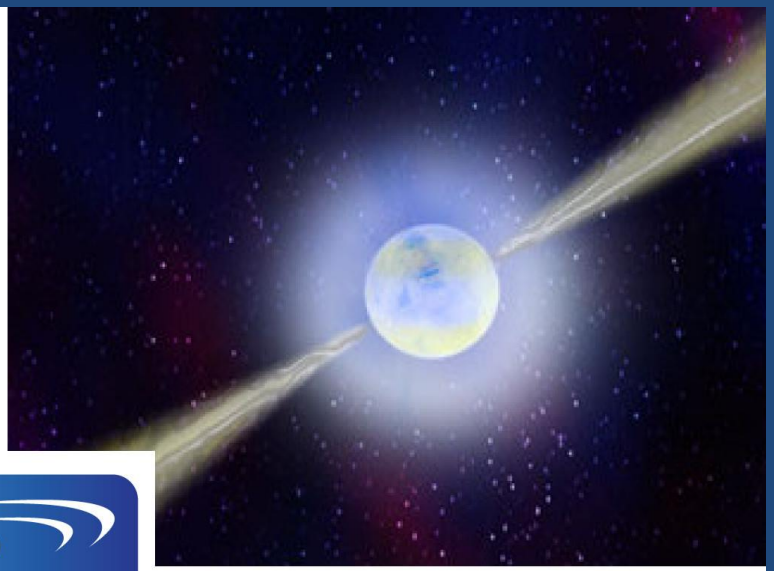
$$S_{GPB}(f) = \frac{\Psi_c^2}{\pi^2 f^3}$$

$$\Omega_{GPB} = \frac{8\pi^2}{H_0^2} f^2 \Psi_c^2$$

$$S_{GWB}(f) = \frac{h_c^2}{12\pi^2 f^3}$$

Pulsar timing is 12 times as sensitive for GPB as for broad-band GWB due to different polarization properties


NANOGrav
NORTH AMERICAN NANOHERTZ OBSERVATORY
FOR
GRAVITATIONAL WAVES



NANOGrav

Pulsar	Freq	Obs	ωRMS (μs)	prob(%)	$C_0(10^{-13}s^2)$	χ^2	Time Factor
J0030+0451	400	AO	0.019	72.3	no fit	0.06	NA
J0030+0451	1400	AO	0.327	5.5	0.2 ± 0.4	0.96	NA
J0613-0200	800	GBT	0.021	59.3	no fit	0.001	NA
J0613-0200	1400	GBT	0.520	46.5	no fit	5.8	5 ± 2
J1012+5307	800	GBT	0.191	75.7	0.01 ± 0.2	0.005	NA
J1012+5307	1400	GBT	0.344	37.4	-0.04 ± 2	1.3	NA
J1455-3330	800	GBT	0.344	58.6	no fit	0.02	NA
J1455-3330	1400	GBT	1.077	34.9	no fit	0.34	NA
J1600-3053	800	GBT	0.208	32.7	no fit	0.05	NA
J1600-3053	1400	GBT	0.135	86.5	no fit	0.07	NA
J1640+2224	400	AO	0.057	23.2	no fit	0.08	NA
J1640+2224	1400	AO	0.601	30.6	3 ± 35	385	79 ± 4
J1643-1224	800	GBT	0.585	17.3	2 ± 52	9.5	3 ± 2
J1643-1224	1400	GBT	1.880	31.7	58 ± 160	762	1.16 ± 0.06
J1713+0747	800	GBT	0.091	21.3	0.02 ± 0.03	1.0	NA
J1713+0747	1400	GBT/AO	0.025	24.3	no fit	15	56 ± 4
J1713+0747	2300	AO	0.039	40.6	no fit	6.7	395 ± 154
J1744-1134	800	GBT	0.140	25.0	no fit	4.0	107 ± 65
J1744-1134	1400	GBT	0.229	91.8	0.1 ± 6	849	179 ± 40
J1853+1308	1400	AO	0.270	6.5	no fit	220	15.8 ± 0.9
B1855+09	400	AO	0.279	26.5	no fit	0.26	NA
B1855+09	1400	AO	0.101	54.4	0.2 ± 2	16.9	21 ± 4
J1909-3744	800	GBT	0.011	69.4	no fit	2.2	NA
J1909-3744	1400	GBT	0.048	78.5	0.2 ± 7	684	14.9 ± 0.4
J1910+1256	1400	AO	0.709	20.4	7 ± 17	294	5.3 ± 0.3
J1918-0642	800	GBT	0.129	92.3	no fit	1.9	NA
J1918-0642	1400	GBT	0.211	28.1	3.2 ± 1.4	950	4.88 ± 0.08
B1953+29	1400	AO	1.863	44.3	no fit	15.5	3.0 ± 0.7
J2145-0750	800	GBT	0.068	63.9	no fit	10	0.33 ± 0.09
J2145-0750	1400	GBT	0.494	1.8	3.2 ± 9	12.4	20 ± 4
J2317+1439	300	AO	0.369	95.2	-0.7 ± 6	57	3.3 ± 0.4
J2317+1439	400	AO	0.153	82.9	no fit	5.5	3.3 ± 0.7

Data: 12 PSRs

Perrodin+'13

Data analysis

Wiener-Khinchin theorem:

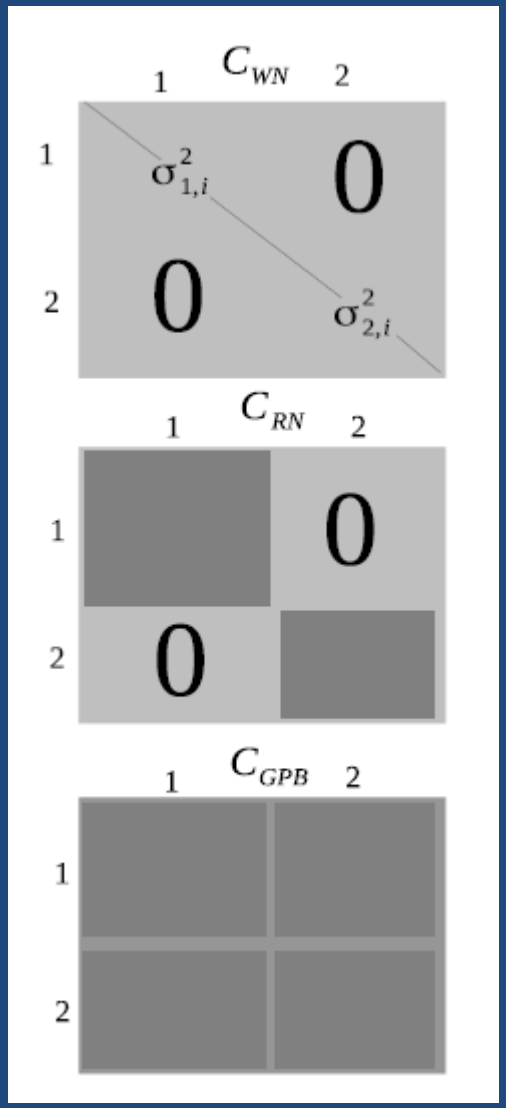
$$C(\tau) = \int_0^\infty S(f)\cos(\tau f)df$$

Correlation between pulsars

$$C_{GPB}(\tau_{ij}) = \zeta_{\alpha\beta}\frac{\Psi_c^2 \delta f}{\pi^2 f^3}\cos(f\tau_{ij}),$$

$$\zeta_{\alpha\beta} = 1/2(1+\delta_{\alpha\beta})$$

Covariation matrices



$$C_{WN} = \sigma^2_{\alpha,i}\delta_{\alpha\beta}\delta_{ij},$$

$$C_{RN} = \delta_{\alpha\beta}A^2_{RN,\alpha}\left(\frac{1}{2\sqrt{3}\pi f_0}\right)^2\left(\frac{f_0}{f_L}\right)^{\gamma^\alpha_{RN}-1}$$

$$[\Gamma(1-\gamma^\alpha_{RN})sin\frac{\pi\gamma^\alpha_{RN}}{2}(f_L\tau_{ij})^{\gamma^\alpha_{RN}-1}-$$

$$-\sum_{n=0}^{\infty}(-1)^n\frac{(f_L\tau_{ij})^{2n}}{(2n)!(2n+1-\gamma^\alpha_{RN})}],$$

$$C_{GPB} = \zeta_{\alpha\beta}\frac{\Psi_c^2\delta f}{\pi^2 f^3}\cos(f\tau_{ij}),$$

Bayesian approach

$$\vec{t}^{\,arr} = \vec{t}^{\,det}(\vec{\beta}) + \vec{\delta t}$$

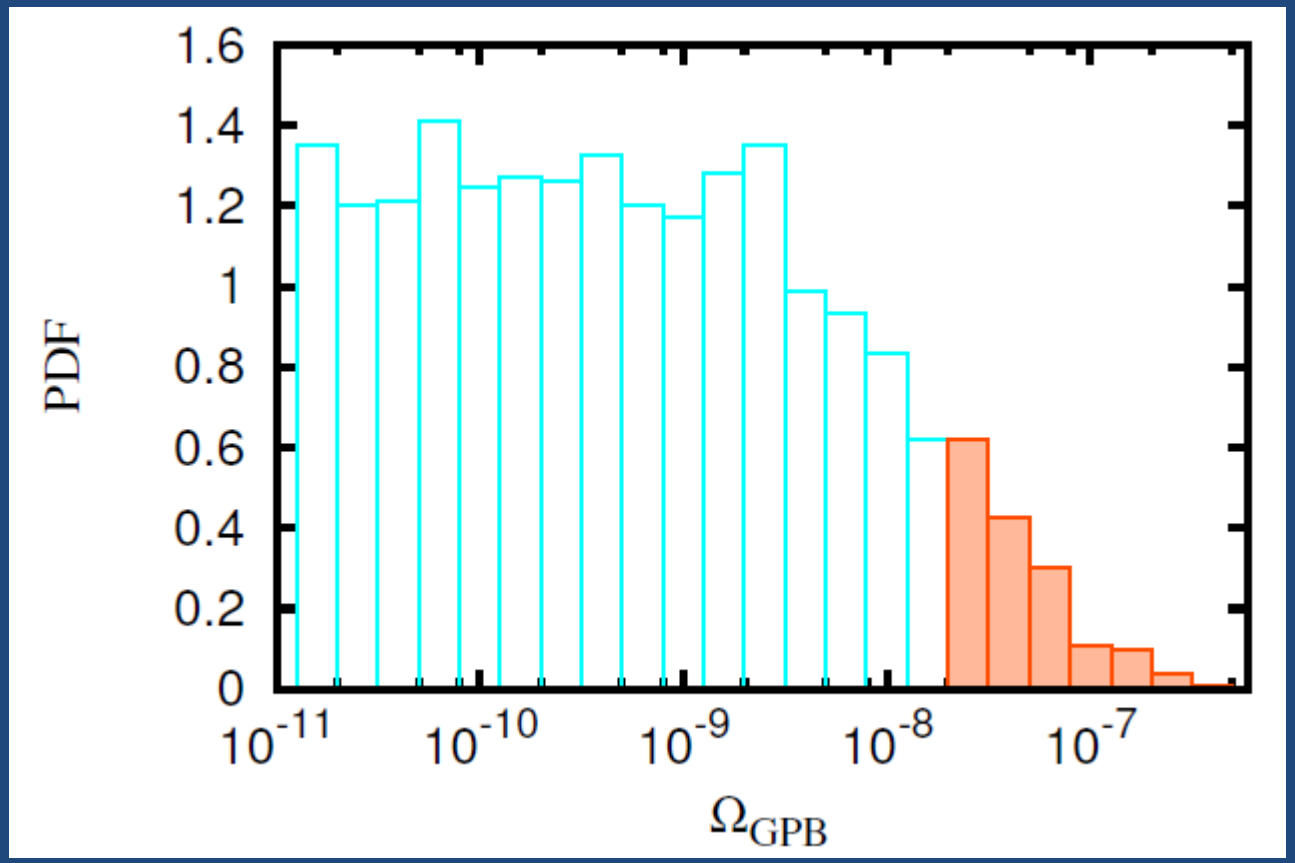
Monochromatic signal s(t):

$$\log\Lambda = \vec{\delta t}^{\,T} G(G^T C G)^{-1} G^T \vec{s} - 1/2\, \vec{s}^{\,T} G(G^T C G)^{-1} G^T \vec{s}$$

Narrow-band stochastic GPB

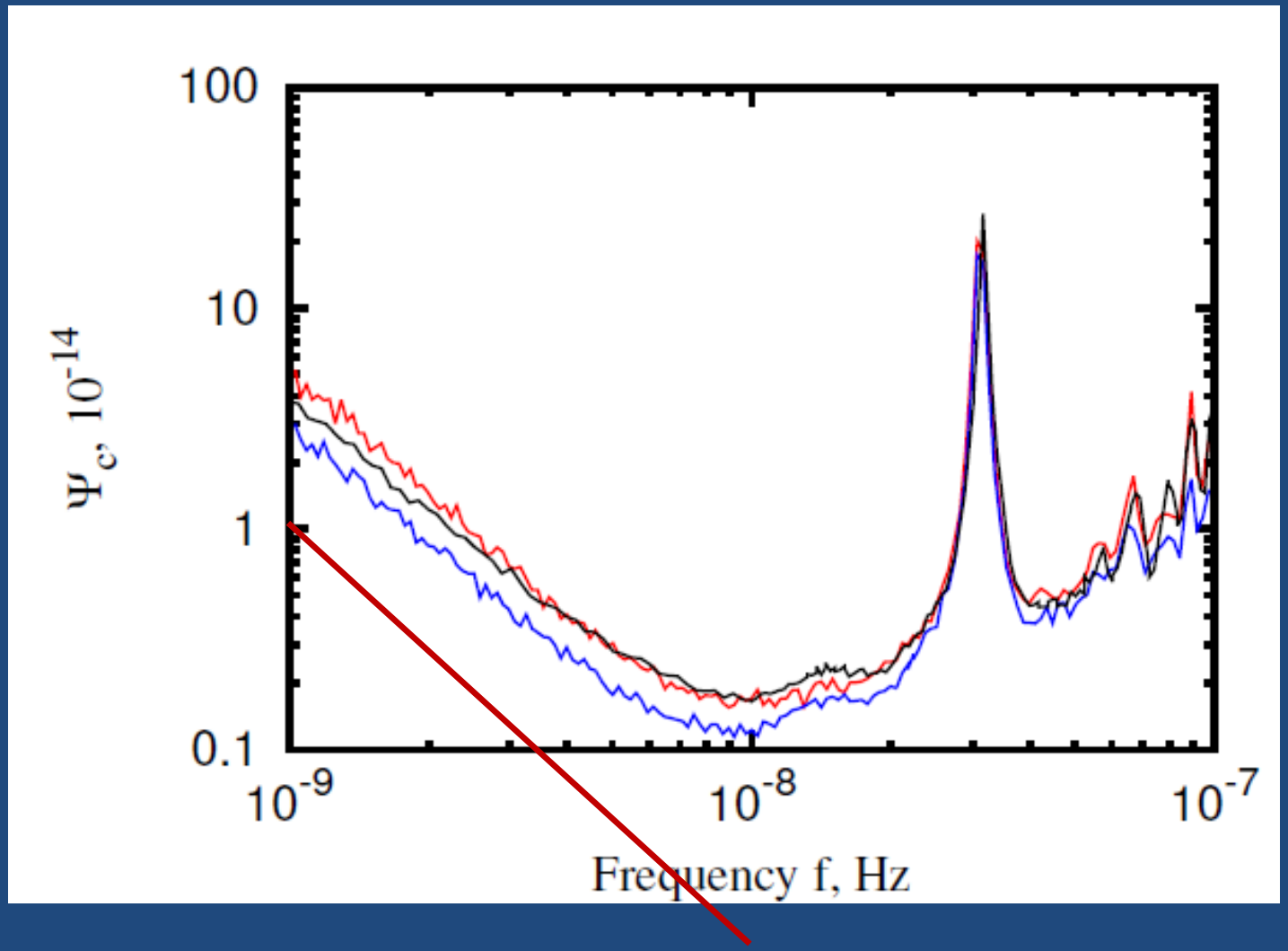
$$P(\vec{\delta t}|\vec{\phi}) = \frac{1}{\sqrt{(2\pi)^{(n-m)} det(G^T C G)}} \exp(-\frac{1}{2}\vec{\delta t}^{\,T} G(G^T C G)^{-1} G^T \vec{\delta t}).$$

Van Haastern+'11



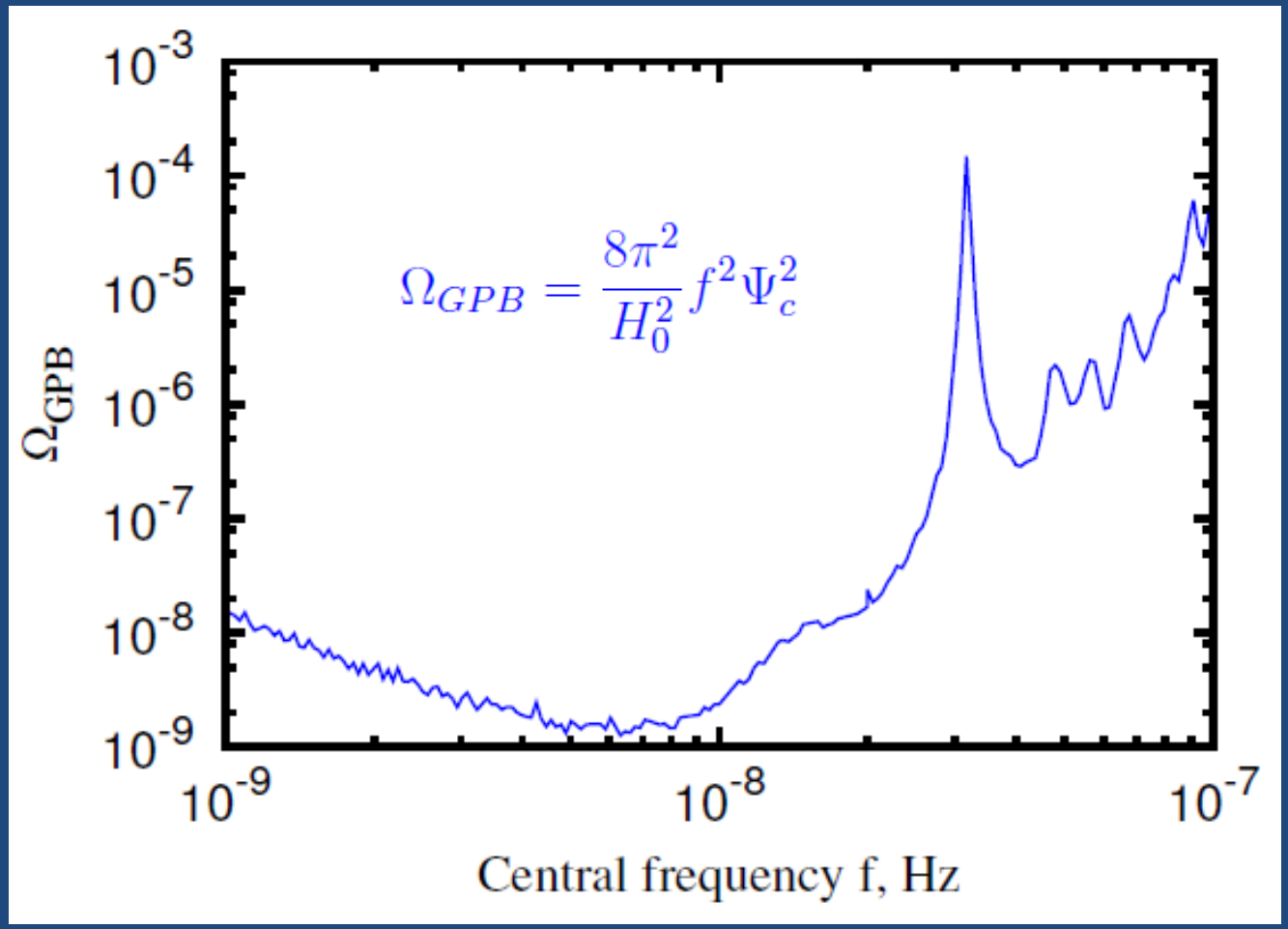
MCMC, ~3000 points per frequency bin

Monochromatic approximation



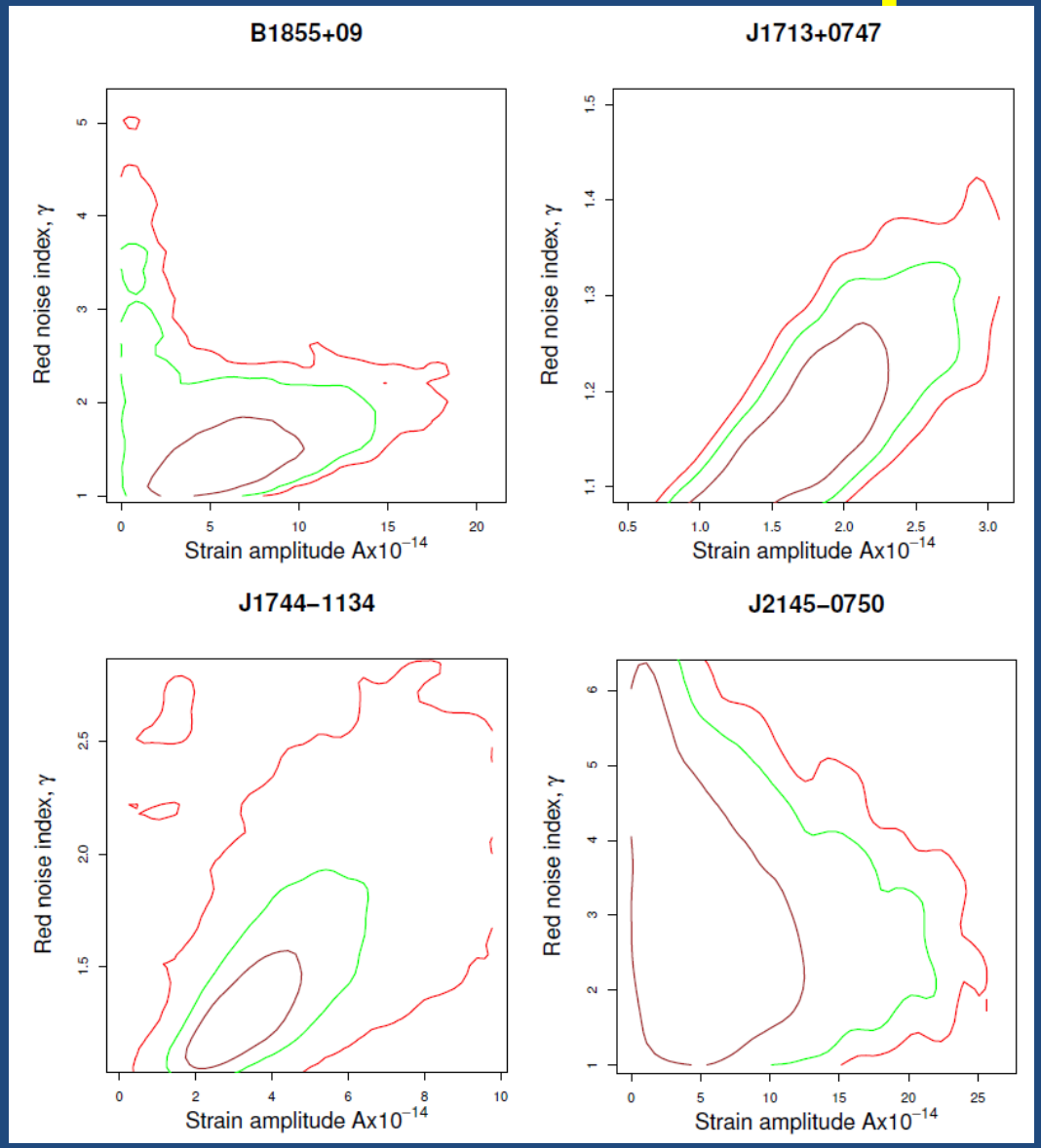
N.Porayko, PK in prep.

Narrow-band GPB



N. Porayko, PK in prep.

Red-noise parameters



$$h_c(f) = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{\alpha}$$

$$S(f) = \frac{A^2}{12\pi^2} f_0^3 \left(\frac{f}{f_0}\right)^{-\gamma}$$

Conclusions

- We searched for narrow-band stochastic signals in 5-year NANOGrav PTA data
- Upper limits for a background produced by variable gravitational potential due to massive scalar field oscillations are (95% c.l.):

$$\Omega_{GPB} < 1.5\times10^{-9} \Leftrightarrow \Psi_c < 10^{-15} \quad @ \quad f \sim (1-8)\times10^{-9}\,Hz$$

- IPTA data analysis of longer range is needed (work in progress)