Title: Detecting Gravitational Waves with Millisecond Pulsars

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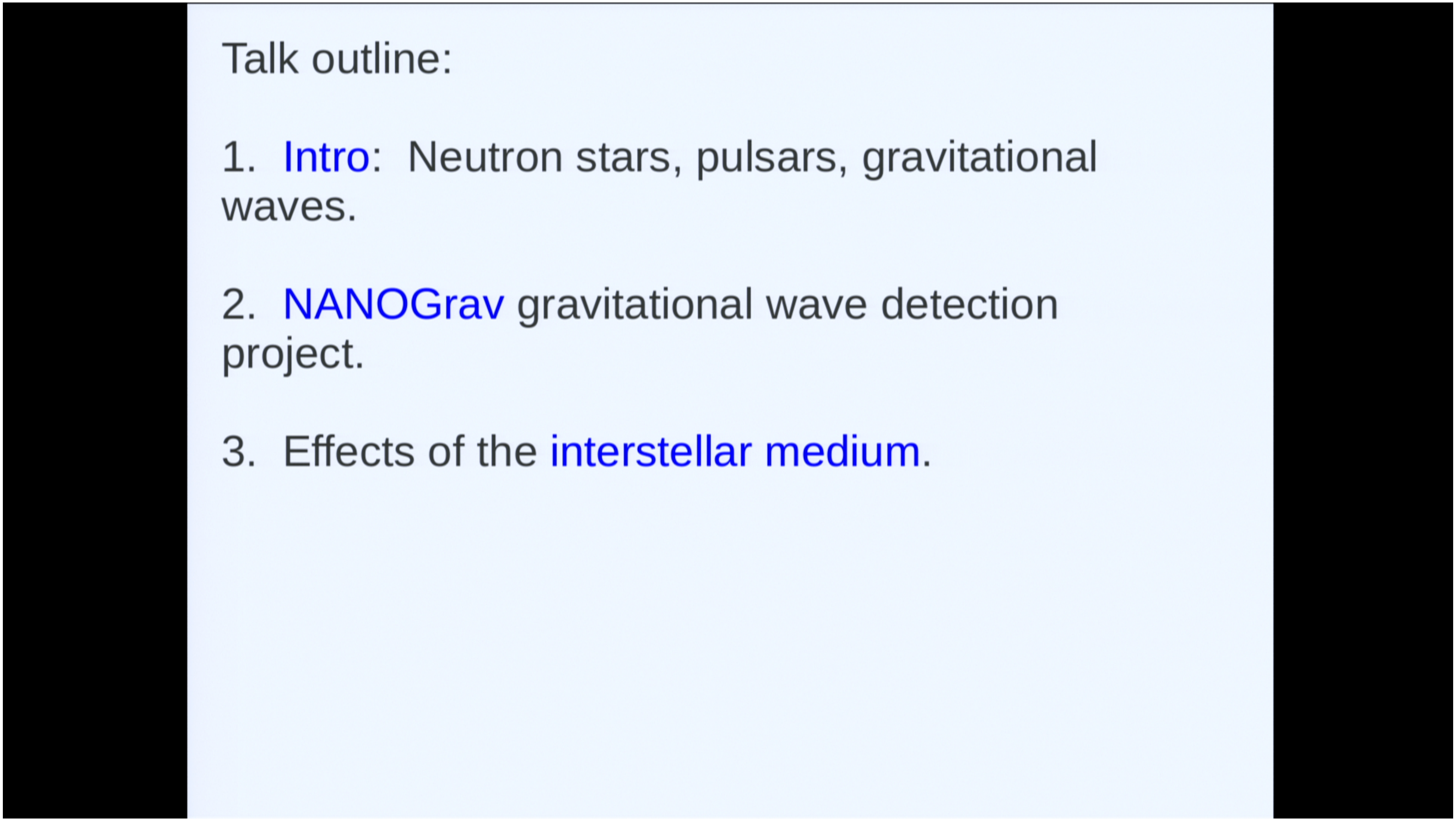
Abstract: Millisecond spin-period radio pulsars provide us with unique astronomical "laboratories" for exploring fundamental physics in a variety of ways -- from the physics of matter at super-nuclear density, to experimental tests of gravity. They have also provided the only experimental evidence so far for the existence of gravitational waves (GW). A set of millisecond pulsars acting as precise astronomical clocks may also be used as a direct GW detector, sensitive to the nanohertz-frequency GW expected to be emitted by supermassive black hole binary systems or other more exotic sources. In this talk I will present the project status and recent GW upper limits from the NANOGrav project. I will also discuss expected near-future improvements in the measurement, including recent work aimed at better characterizing and mitigating the effect of multi-path propagation effects in the interstellar medium.

Detecting gravitational waves with millisecond pulsars

Paul Demorest, NRAO

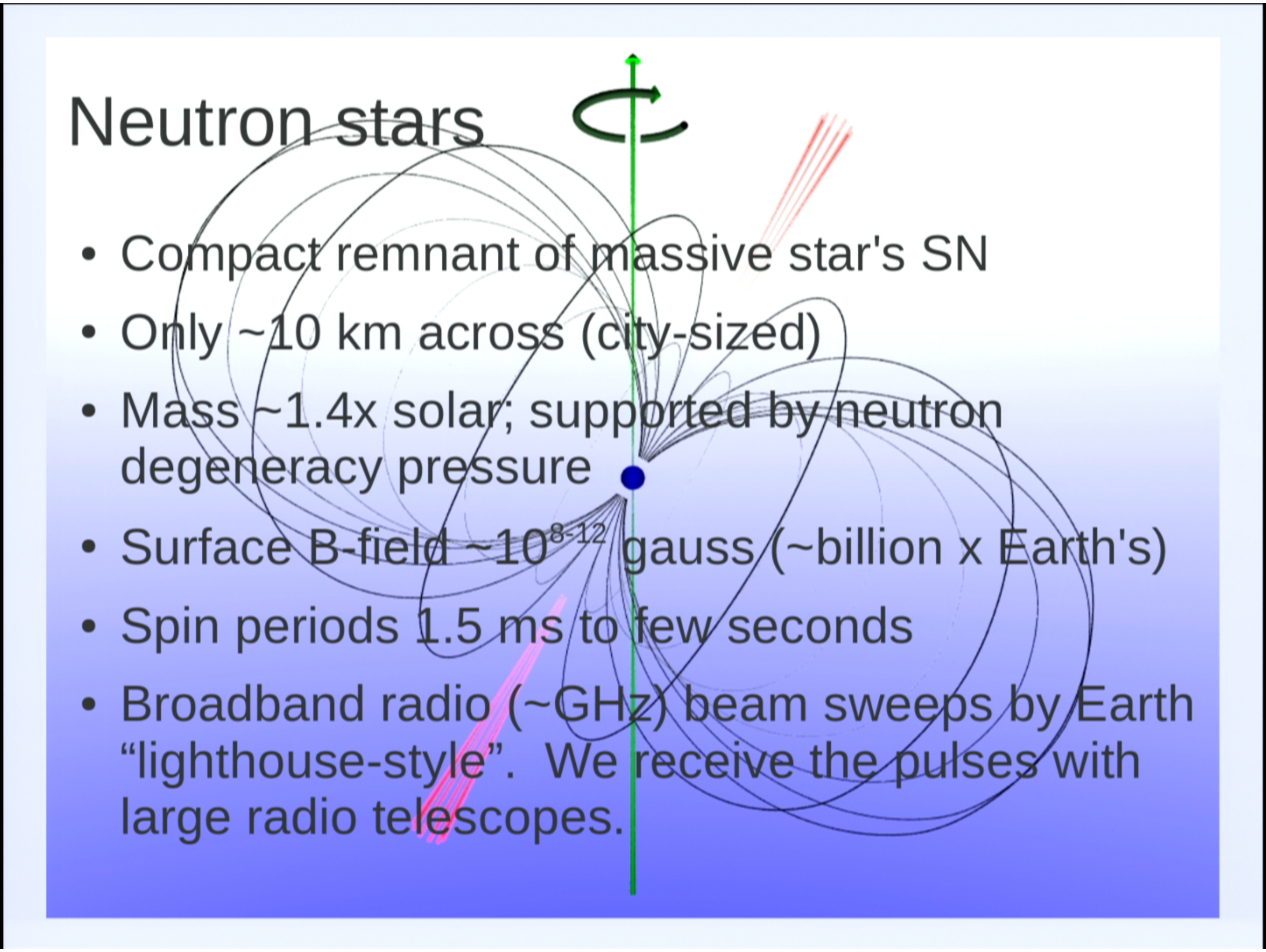


Talk outline:

1. Intro: Neutron stars, pulsars, gravitational waves.

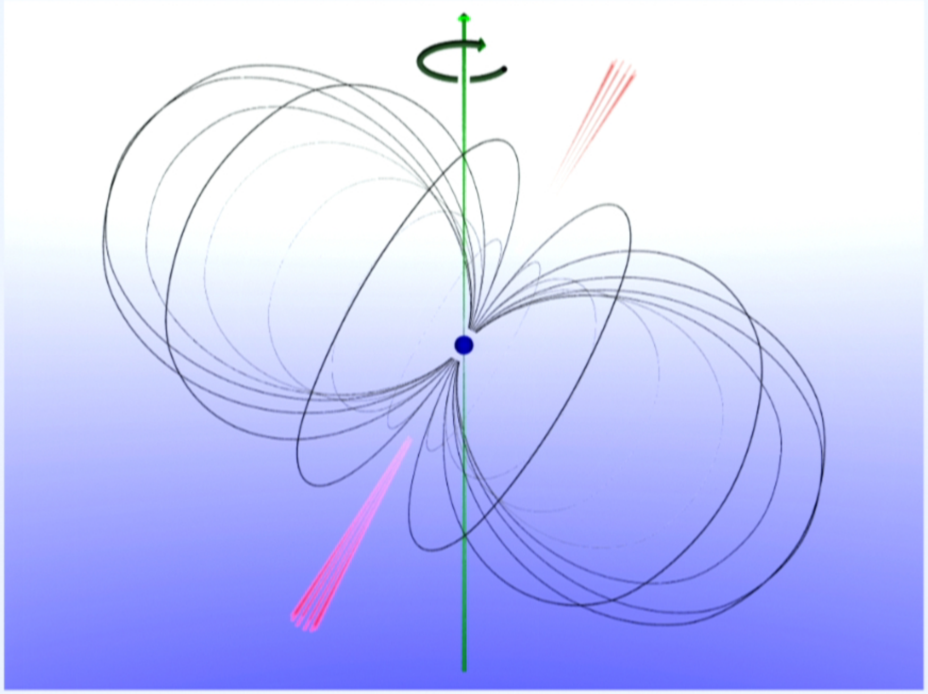
2. NANOGrav gravitational wave detection project.

3. Effects of the interstellar medium.



Neutron stars

- Compact remnant of massive star's SN
- Only ~10 km across (city-sized)
- Mass ~1.4x solar; supported by neutron degeneracy pressure
- Surface B-field ~$10^{8\text{-}12}$ gauss (~billion x Earth's)
- Spin periods 1.5 ms to few seconds
- Broadband radio (~GHz) beam sweeps by Earth “lighthouse-style”. We receive the pulses with large radio telescopes.

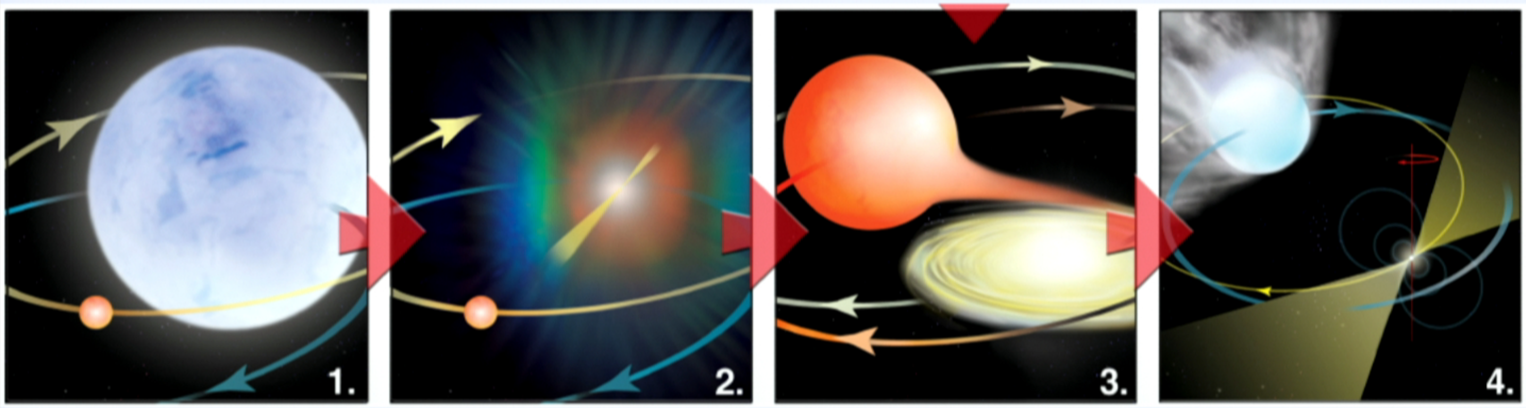


Beamed radio emission is generated by plasma interactions in the star's magnetosphere.

Understanding how this works is still an active research topic.

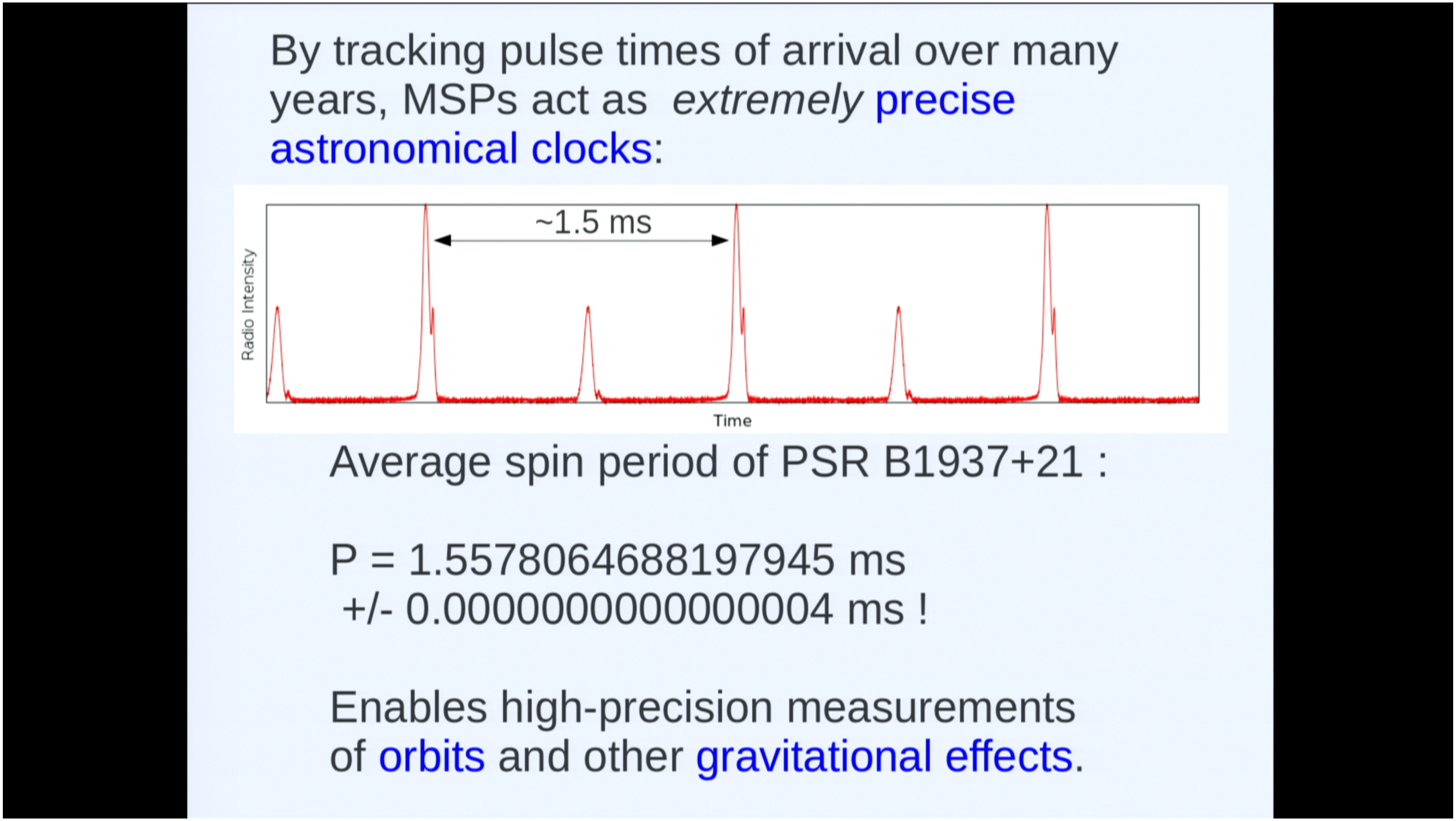
We take advantage of this naturally-occurring pulsed signal source as a unique tool for making precise astrophysical measurements!

About 10% of known radio pulsars are "recycled" millisecond pulsars (MSPs). These are spun up by accreting matter from a companion star:



(Image: B. Saxton, NRAO)

This produces very "clean" compact binary systems (NS-WD or NS-NS).



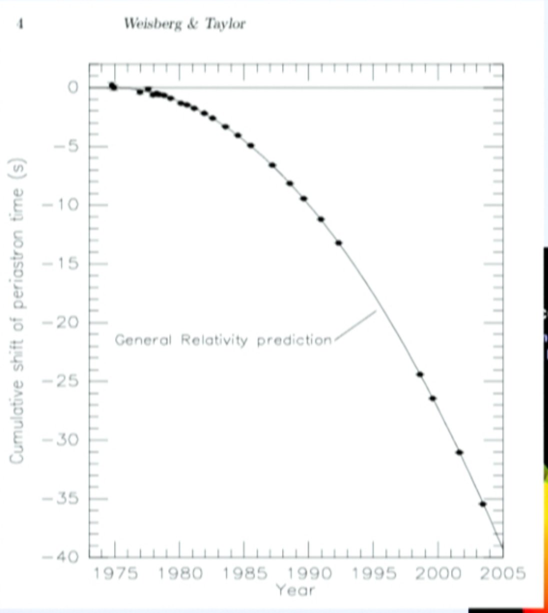
By tracking pulse times of arrival over many years, MSPs act as *extremely* precise astronomical clocks:

Average spin period of PSR B1937+21 :

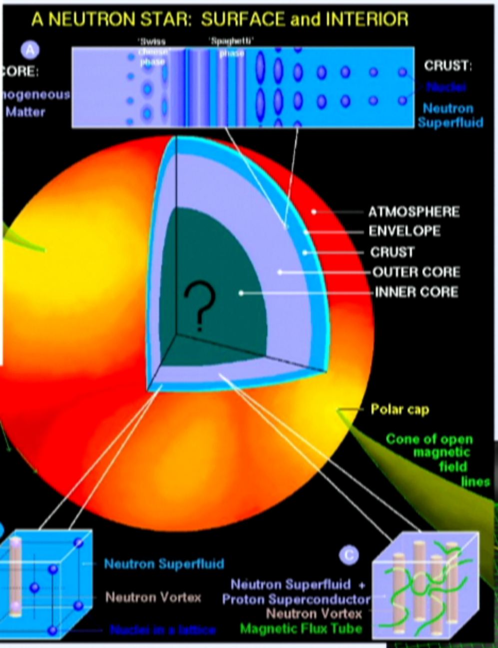
P = 1.5578064688197945 ms
+/- 0.0000000000000004 ms !

Enables high-precision measurements of orbits and other gravitational effects.

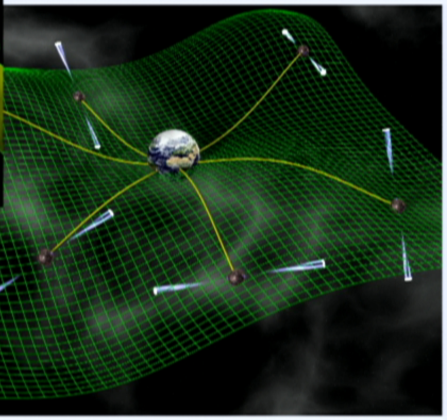
Testing gravity / GR



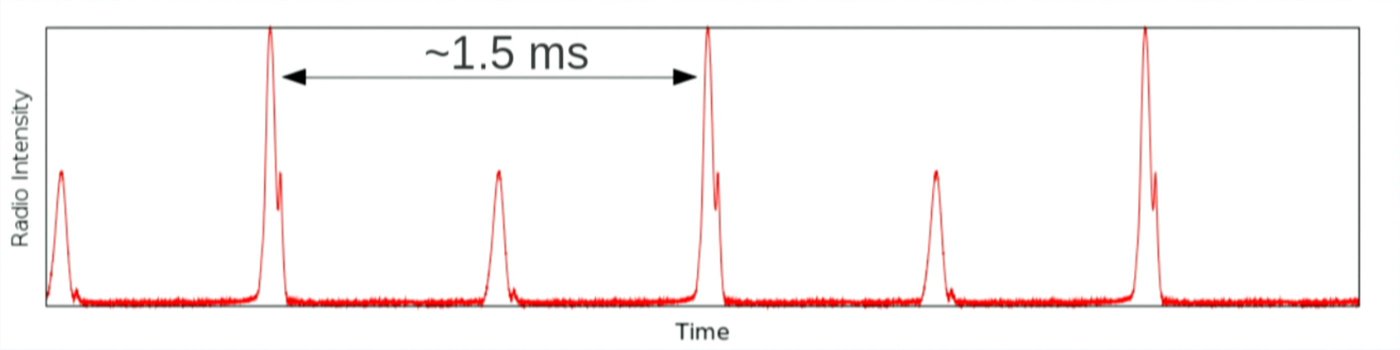
Properties of nuclear matter



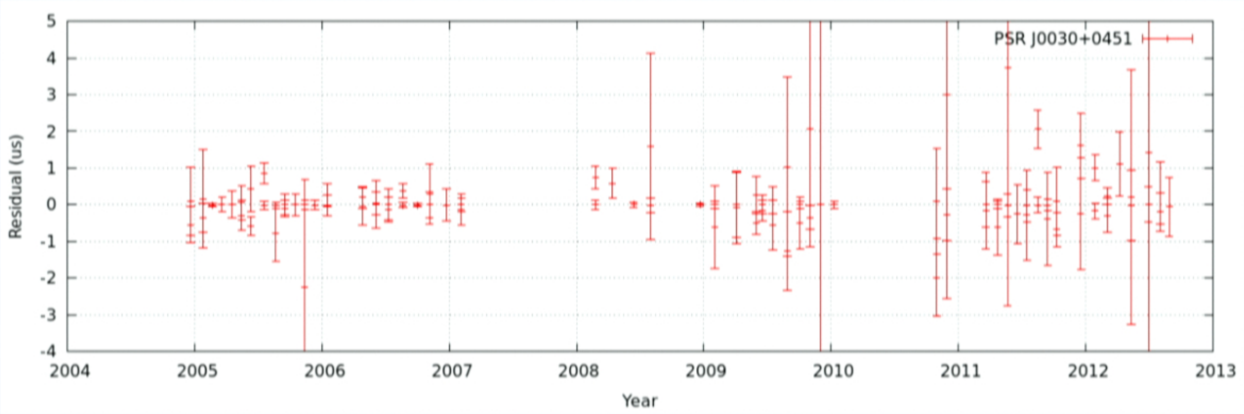
Detecting GW?



Done via a “phase-connected timing model”

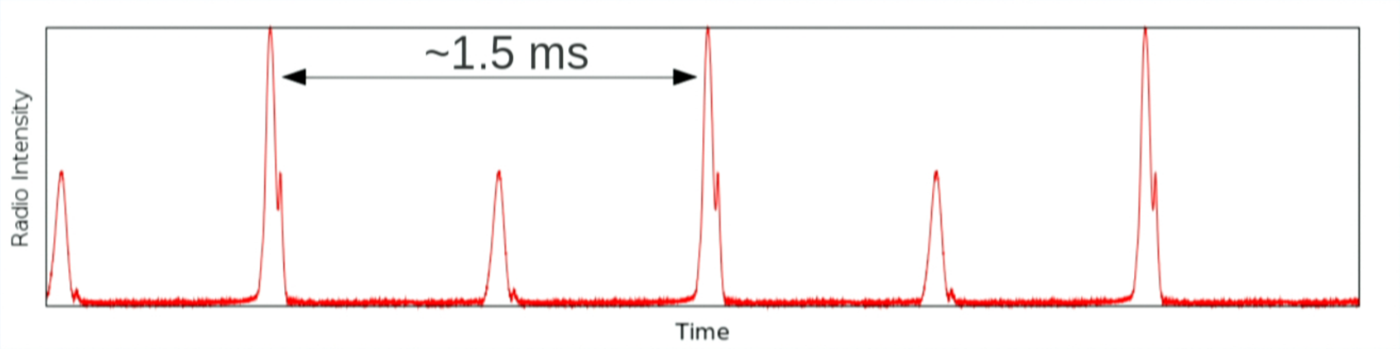


Model counts every rotation of the star over years or even decades:



Parameters: Spin/spin-down rate, astrometry, binary orbit.

Done via a “phase-connected timing model”



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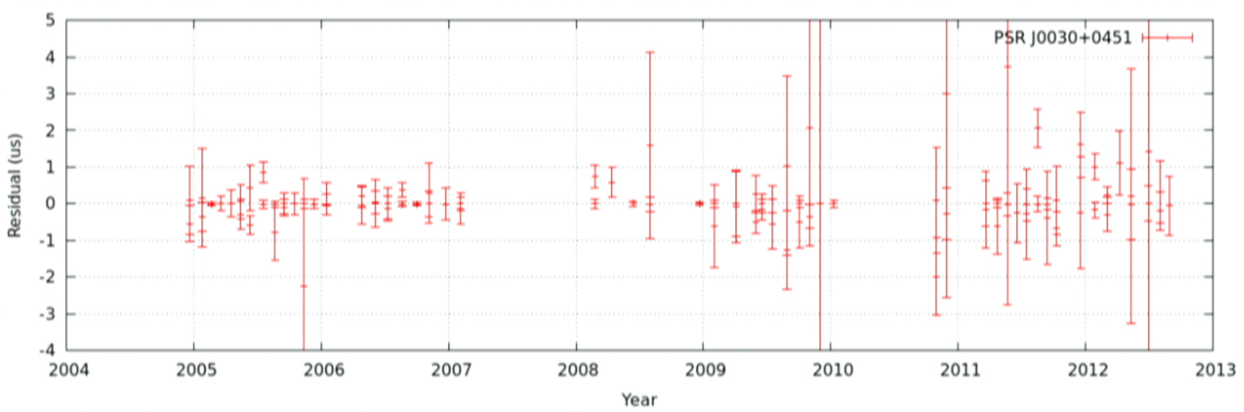


Parameters: Spin/spin-down rate, astrometry, binary orbit.

Relativistic binary orbits

Besides the normal 5 “Keplerian” orbital parameters (P_{orb}, e, *a*sin(*i*)/c, T_0, ω), General Relativity gives:

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

(Orbital Precession)

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

(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 μs, $M = m_1 + m_2$, and $s \equiv \sin(i)$

These are only functions of:

- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2

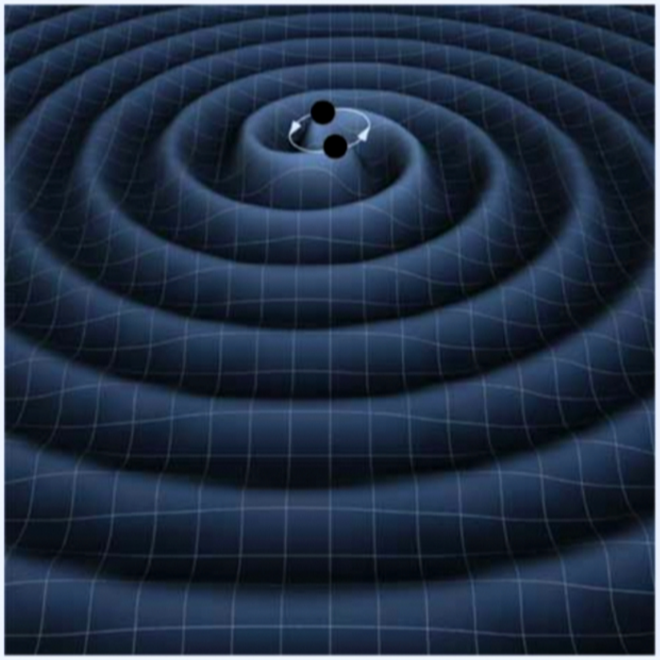
Gravitational waves:

Freely-propagating "space-time ripples" predicted by GR.

Generated by almost any moving mass (binaries, etc).

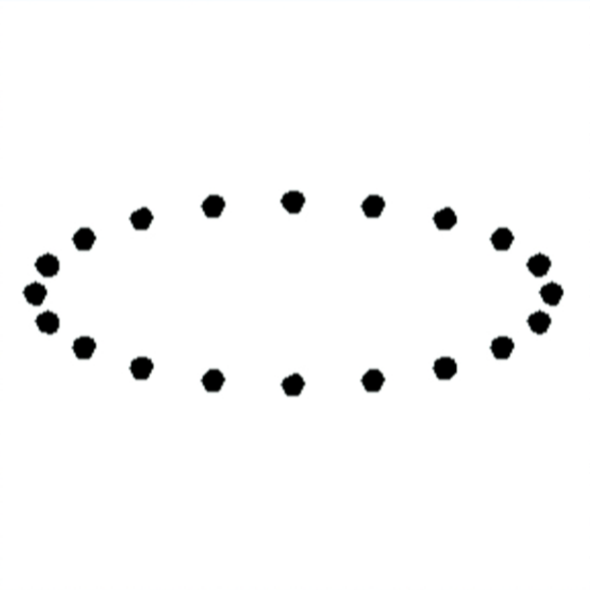
Are *very* weak and not yet directly detected.

Detection will be another confirmation of GR. And will enable gravitational wave astronomy.

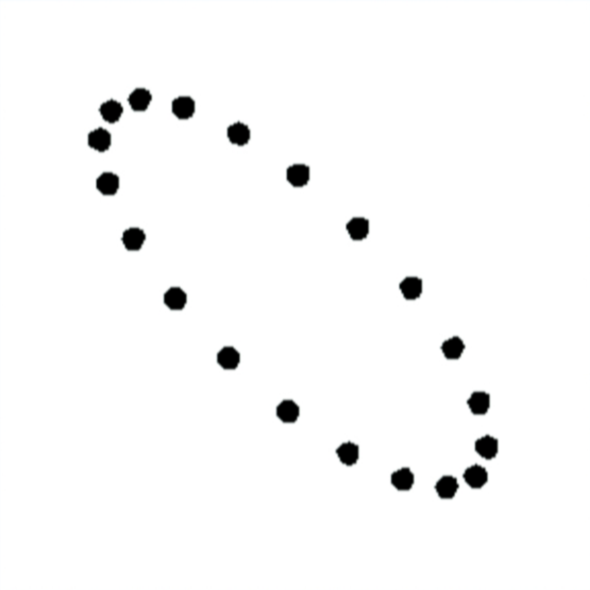


GW are two-polarization, quadrupolar waves:

“Plus” polarization



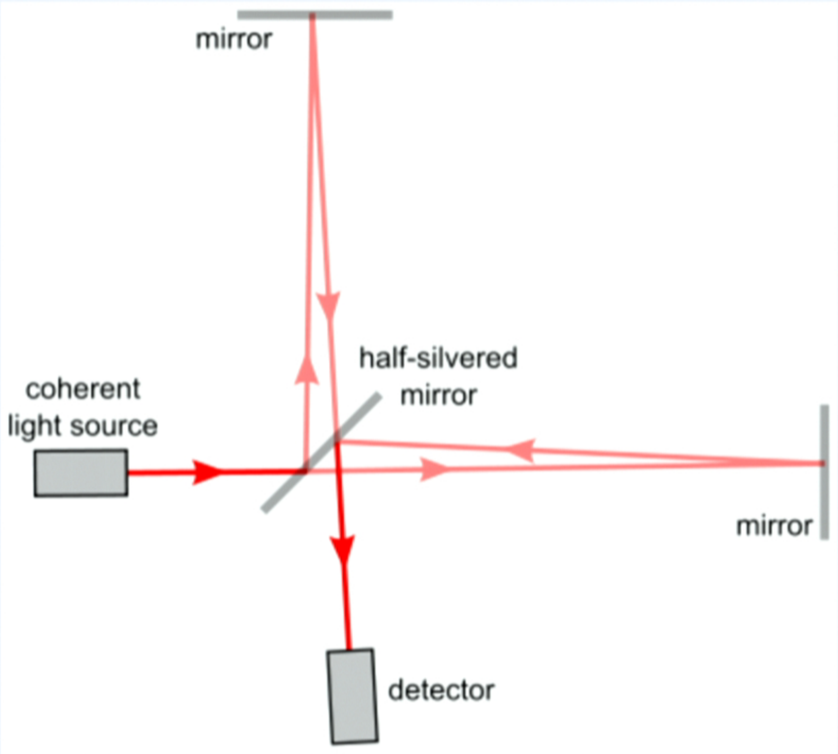
“Cross” polarization



Quantified by dimensionless strain aka metric tensor h_{ij} from GR. Gives fractional change in length: Typical values for astronomical sources 10^{-20} to 10^{-15}!

All modern GW detection experiments use light as a probe of the gravitational field:

For example, a laser interferometer is sensitive to GW-induced path length changes:



GW sensitivity: h ~ dL / L

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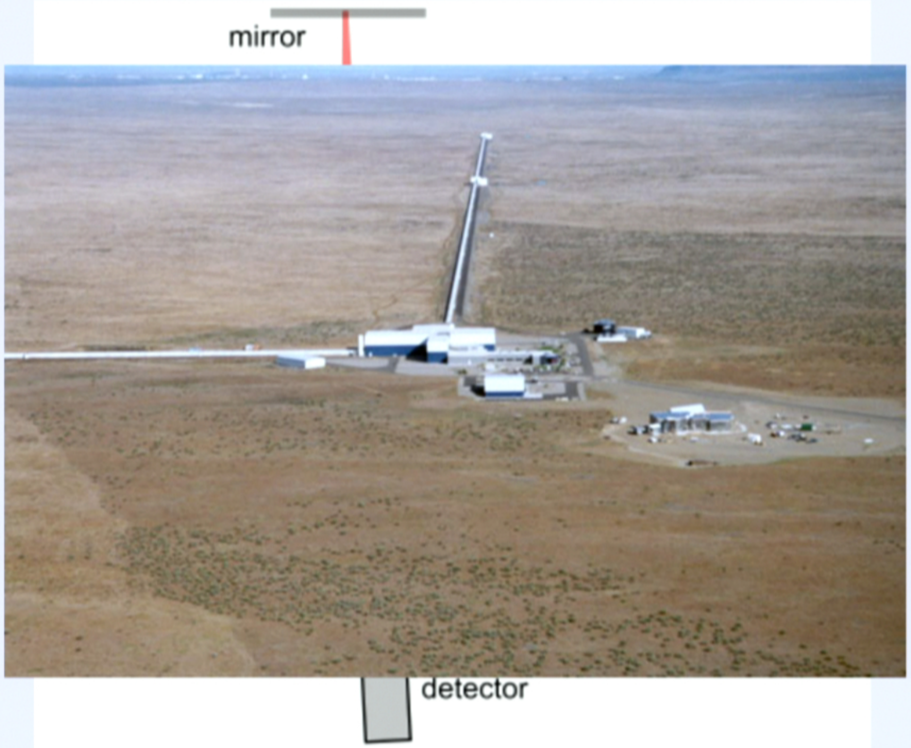
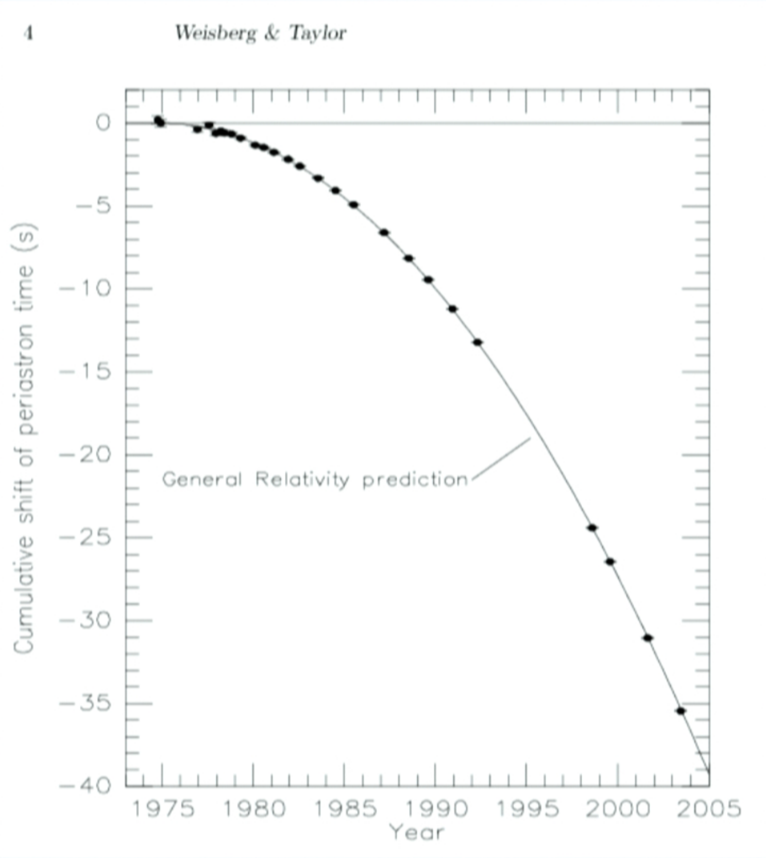


GW sensitivity: $h \sim dL / L$

(Photo: LIGO Labs)

But so far no direct GW detection has been made.

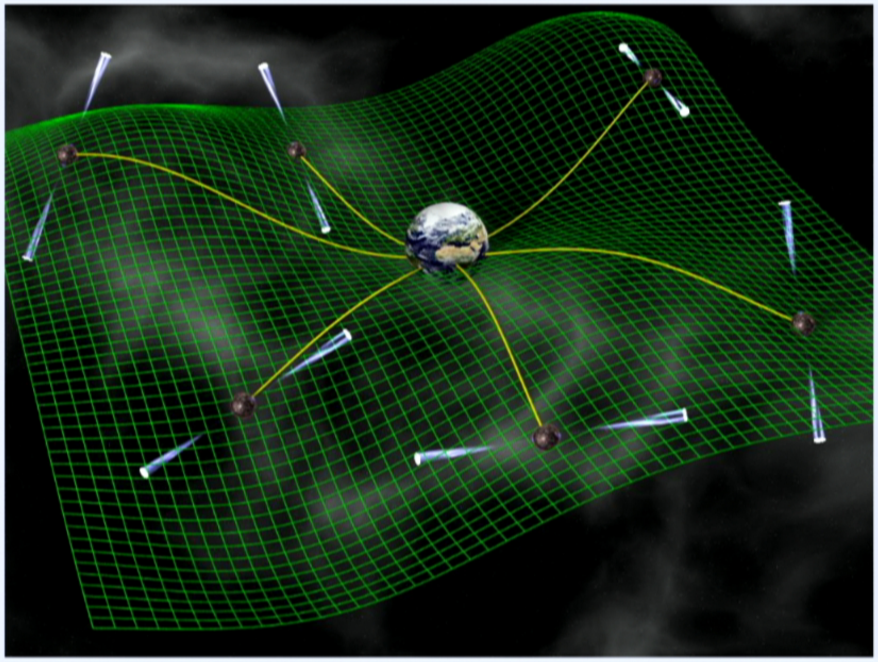


Only experimental evidence for GW comes from pulsars!

Orbital decay of PSR B1913+16 measured by radio timing *exactly* matches expected energy loss to GW emission.

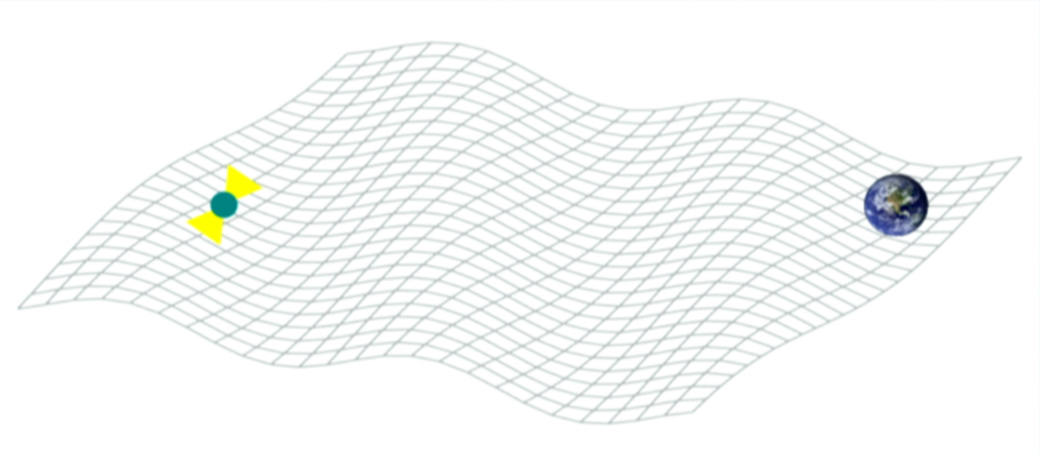
(Physics Nobel prize for Hulse & Taylor in 1993)

Pulsar Timing Array: a galactic-scale gravitational wave detector.



Sensitive to very low frequency (~nHz) GW.

How does this work?



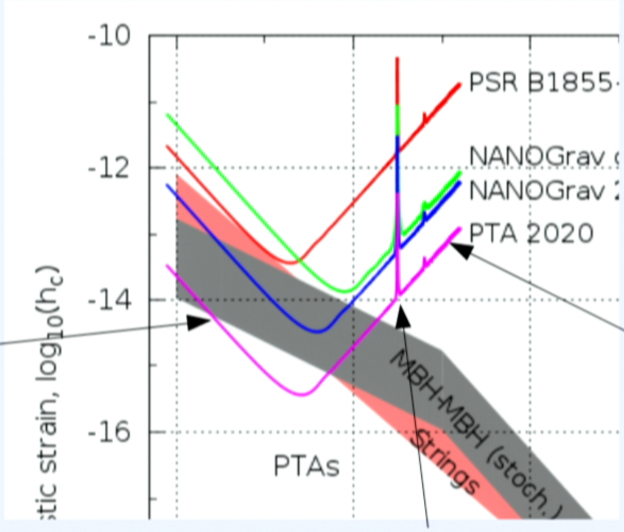
Radio pulses traveling from PSR to Earth through GW experience a time delay:

$$\Delta T = -\frac{1}{2} n_i n_j \int_0^d h_{ij}(x,t) dr$$

Delta-T is time-variable (at the GW freq) and therefore detectable by pulsar timing!

PTAs work on the same principle as laser experiments. Some differences in the details:

1. Obs time (T) much less than light travel time
   --> h ~ dt/T (not dL/L).
2. T sets freq scale --> very short wavelength limit.
3. Pulsar parameters not known a priori.

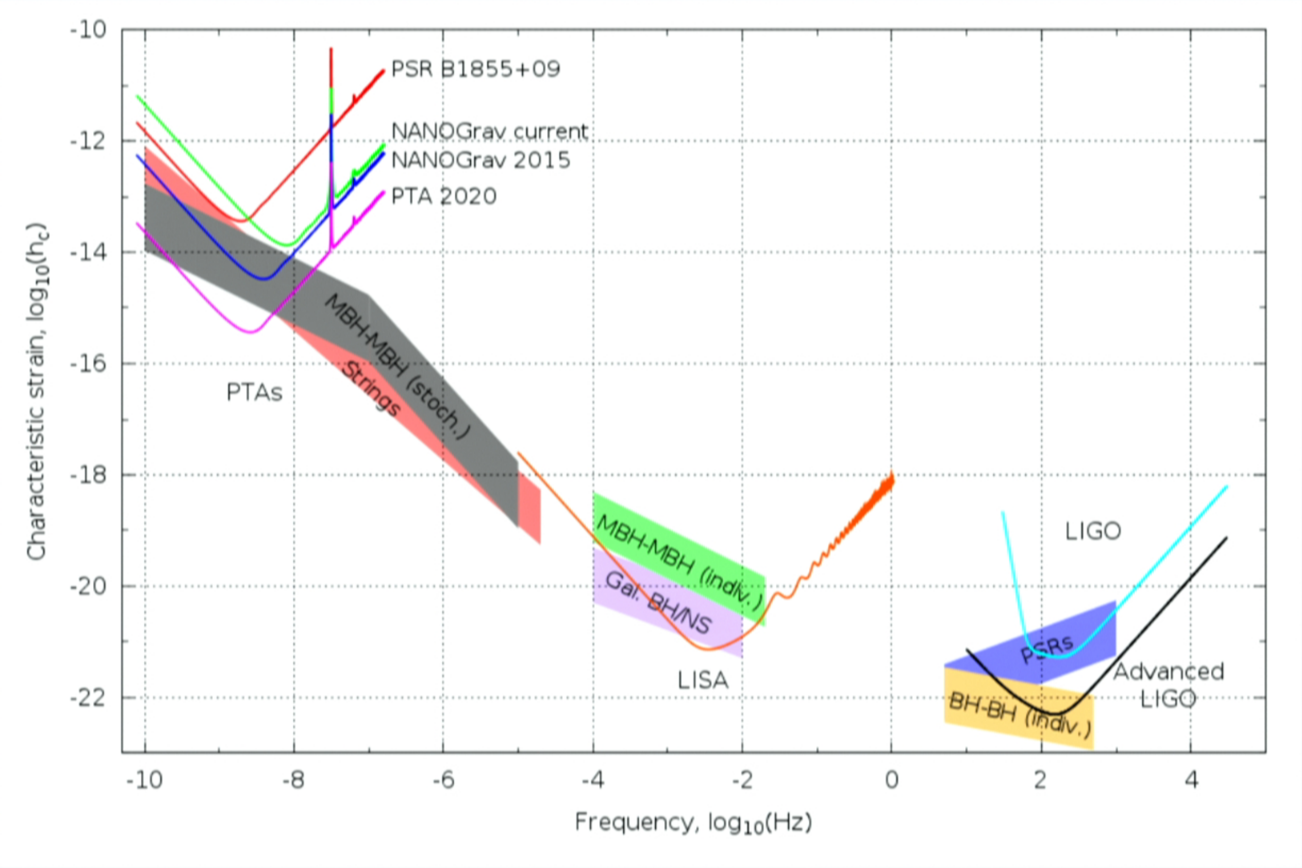


Fit for P, spindown

$$\text{“}\; dt = \int h\, ds \;\text{“}$$

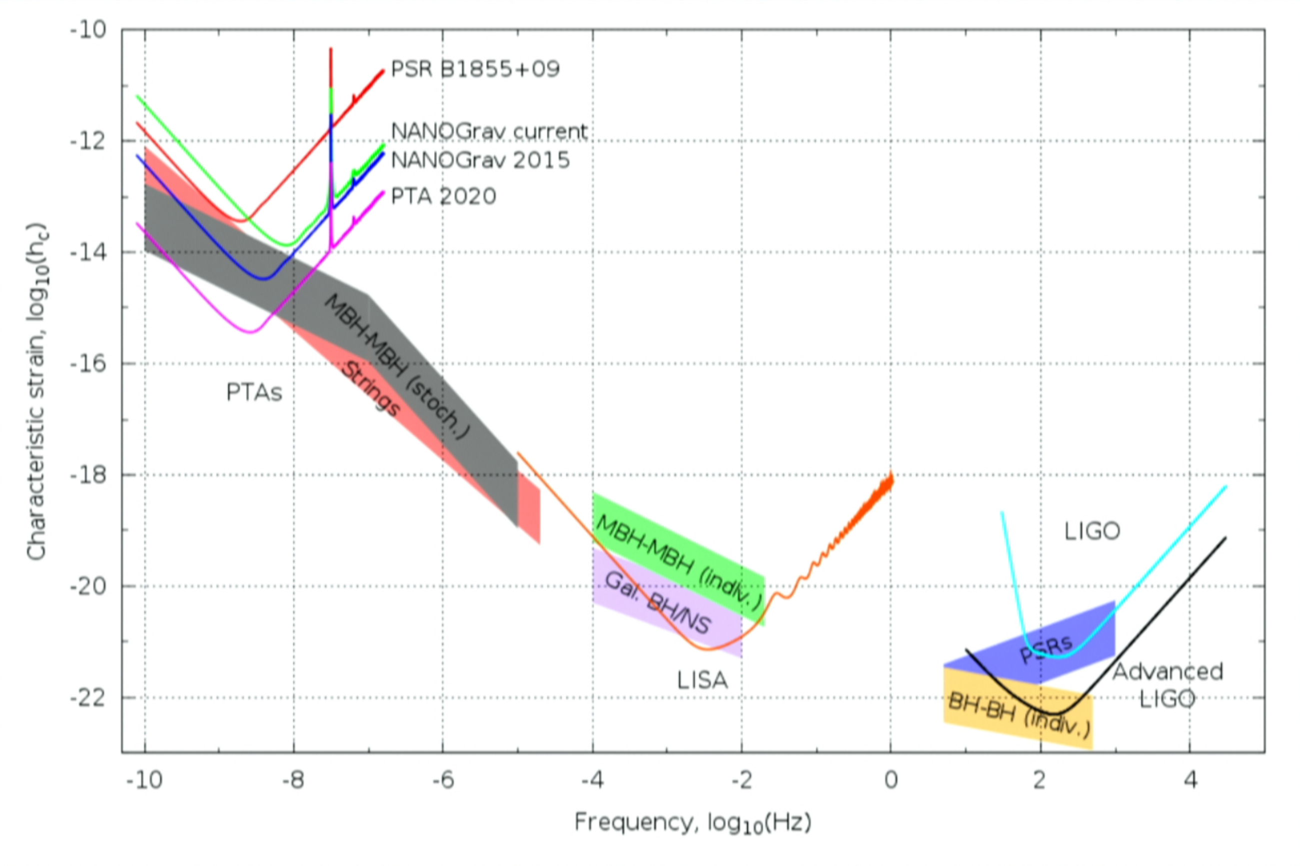
Fit for position, parallax

GW detector complementarity:



For PTAs, sensitivity h ~ dt / T --> requires 10s of ns over years!

GW detector complementarity:



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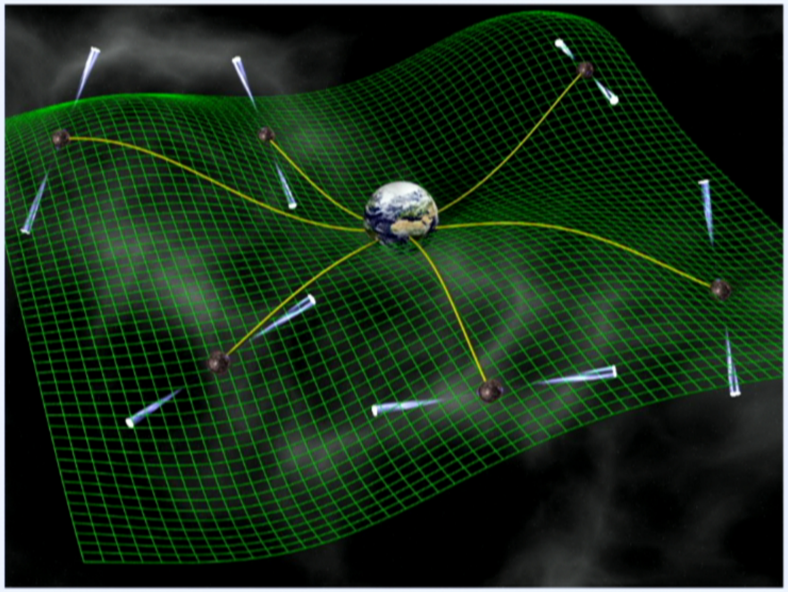
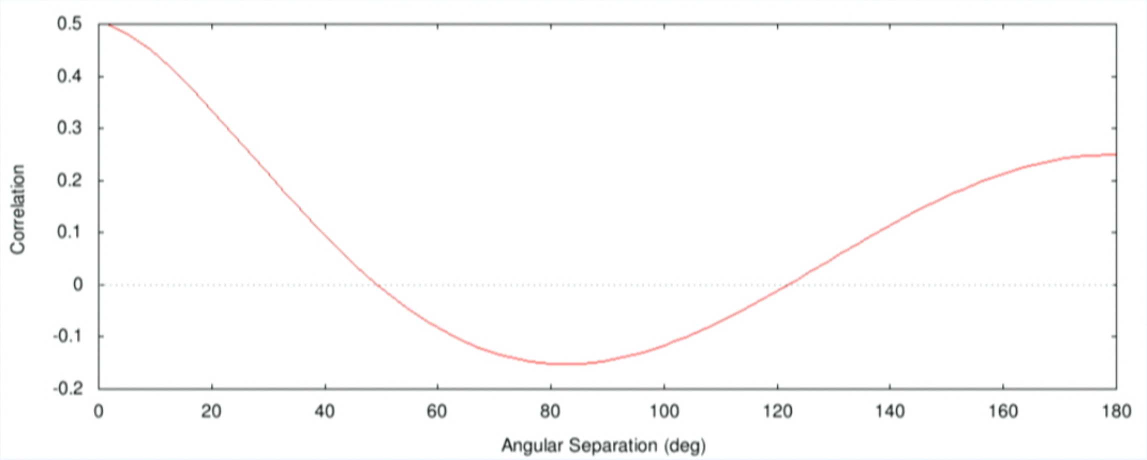


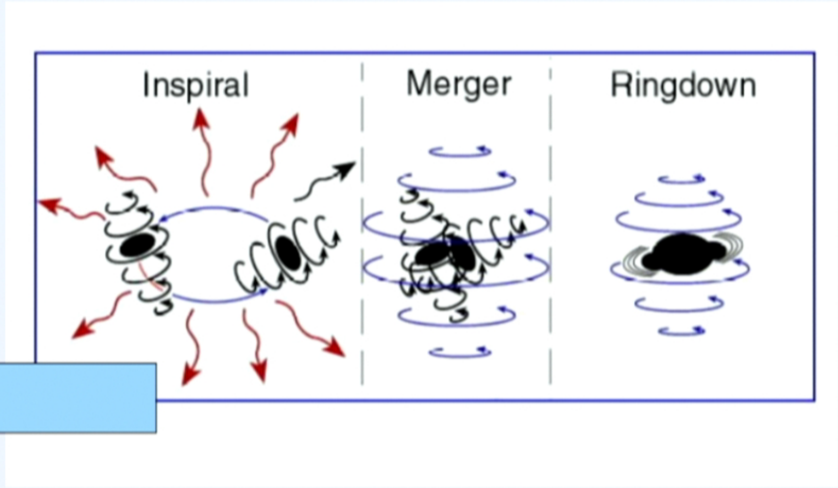
GW induce correlated timing signal in pulsar pairs.

Characteristic signature vs pairwise angular separation for an isotropic GWB (Hellings & Downs 1982).



Nanohertz GW sources:

"Monochromatic"
MBH-MBH
binaries of >10^7
solar mass.



PTA Sources

- Stochastic MBH background (e.g., Jaffe & Backer 2003, Sesana et al 2008, ...)
- Resolved CW MBH sources (Sesana et al 2009, Boyle & Pen 2010, …); GW bursts (e.g. Jenet & Cordes 2012).
- Also cosmic strings, other exotica / the unknown!

Pulsar Timing Arrays around the world:

Parkes Pulsar Timing Array (PPTA)

European Pulsar Timing Array (EPTA)

North American Nanohertz Observatory for Gravitational Waves (NANOGrav; www.nanograv.org)

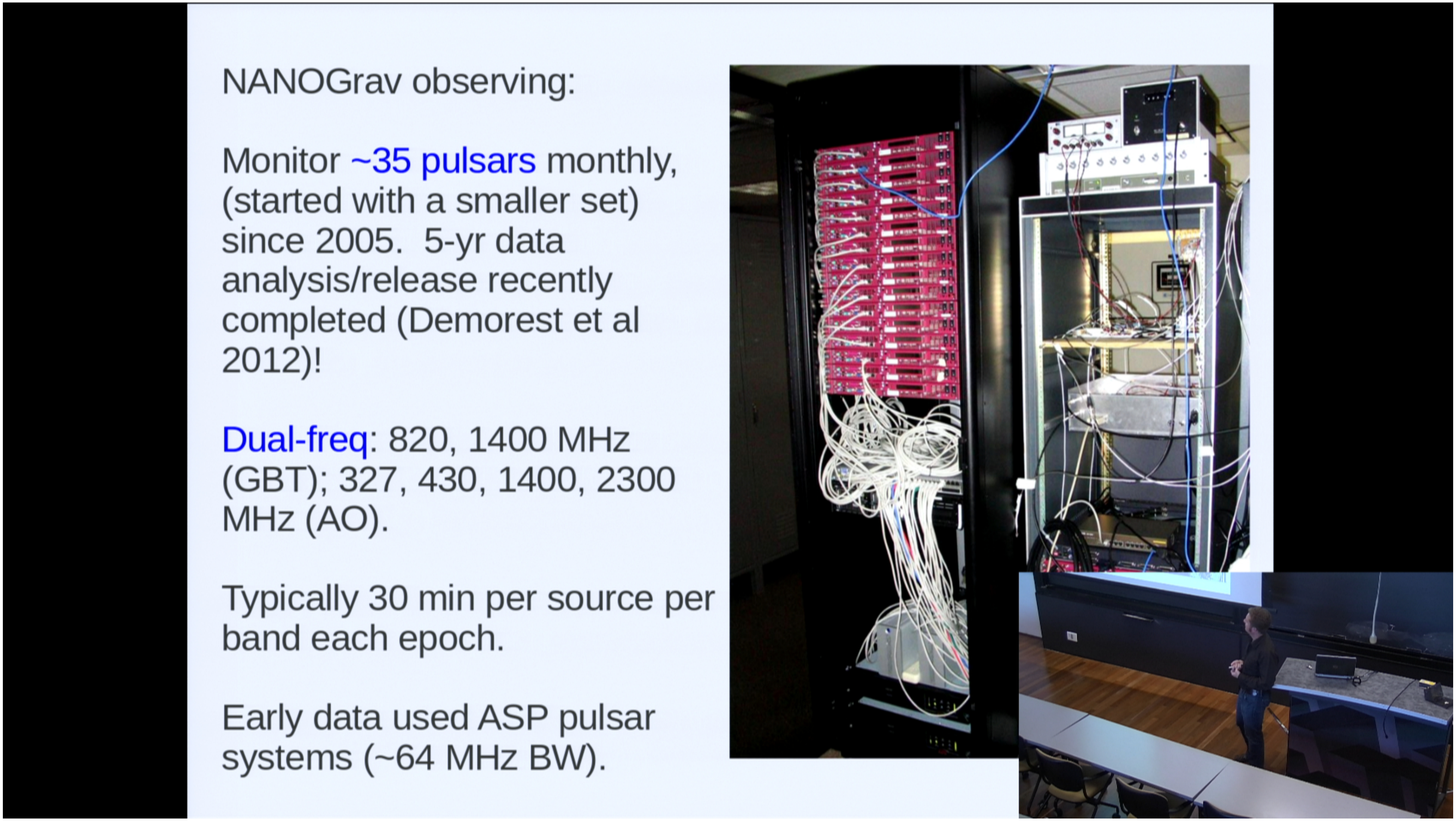
In combination, International Pulsar Timing Array (IPTA; www.ipta4gw.org)!

NANOGrav at Arecibo, 2012:

15 senior researchers, 6 postdocs, 15 grad students, 14 undergrads at 14 US/Canadian institutions. See www.nanograv.org for more details!

Arecibo observatory: 305-m fixed reflector

Green Bank Telescope: 100-m, fully steerable



NANOGrav observing:

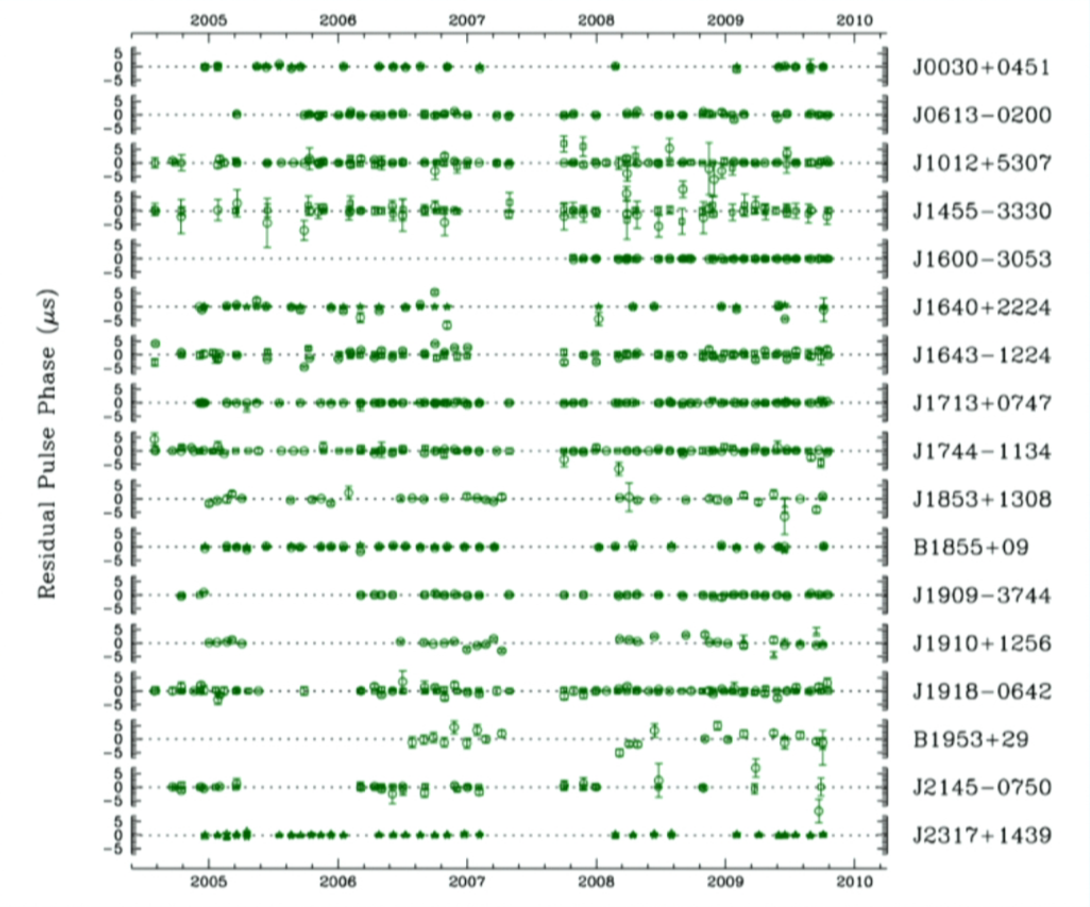
Monitor ~35 pulsars monthly, (started with a smaller set) since 2005. 5-yr data analysis/release recently completed (Demorest et al 2012)!

Dual-freq: 820, 1400 MHz (GBT); 327, 430, 1400, 2300 MHz (AO).

Typically 30 min per source per band each epoch.

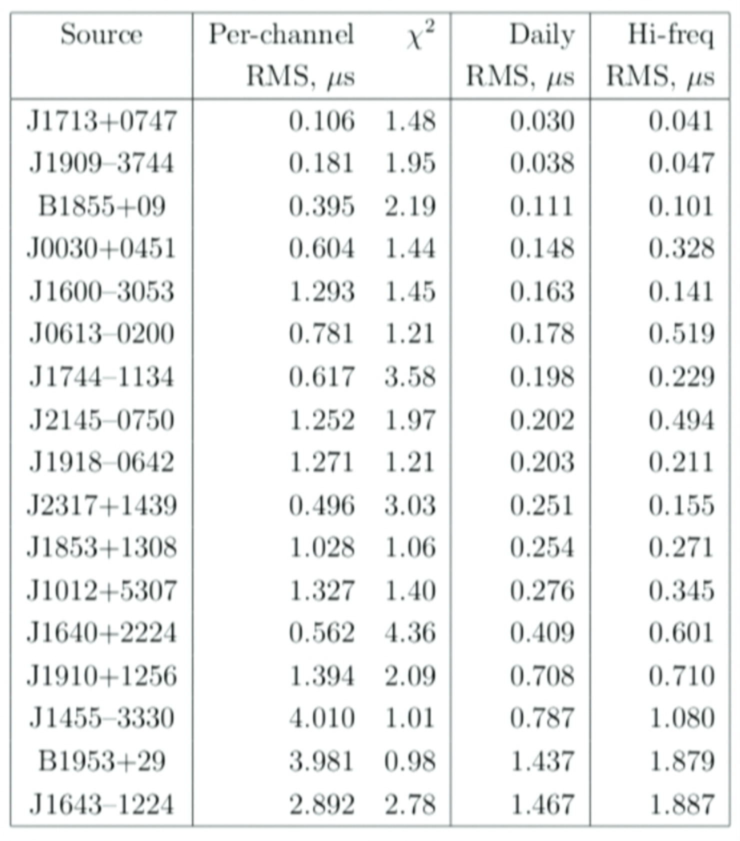
Early data used ASP pulsar systems (~64 MHz BW).

NANOGrav 5-year timing results overview:



(plot: D. Nice)

NANOGrav 5-year timing results summary
(Demorest et al. 2012, arXiv:1201.6641)



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
J1643–1224	2.892	2.78	1.467	1.887

Analysis features:

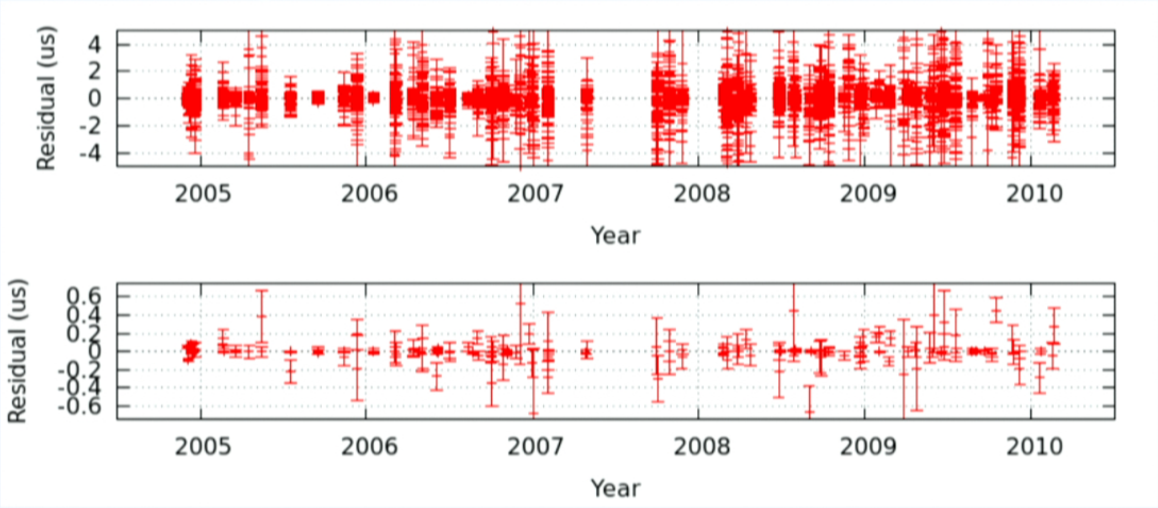
2 PSRs at ~40 ns!

Two independent calibration/processing pipelines -- psrchive and ASPfitsreader

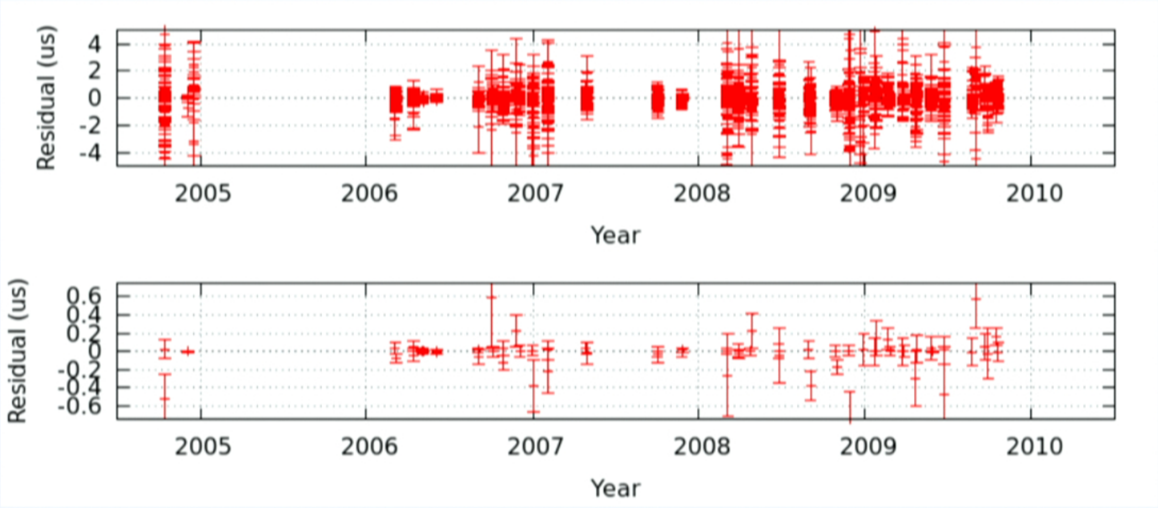
DM(t) and timing model in single fit.

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

Best timing residuals versus time:



J1713+0747



J1909-3744

Accounting for the timing model fit

Weighted least-squares fit, solved via the normal equations:

$$\mathbf{A}^T\mathbf{W}\mathbf{A}\mathbf{a} = \mathbf{A}^T\mathbf{W}\mathbf{y}$$

Residuals (data – model) are calculated via application of the “R-matrix”:

$$\mathbf{r} = \mathbf{y} - \mathbf{A}\mathbf{a} = \mathbf{R}\mathbf{y}$$

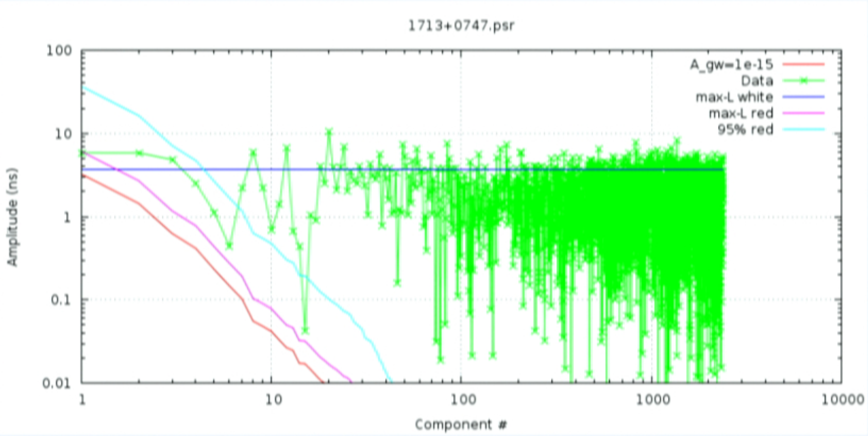
$$\mathbf{R} = \mathbf{I} - \mathbf{A}\left(\mathbf{A}^T\mathbf{W}\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{W}$$

The R-matrix can be used to calculate cov matrix of the residuals, given cov matrix of the pre-fit data:

$$\mathbf{C}_\mathbf{r} = E\left\{\mathbf{r}\mathbf{r}^T\right\} = \mathbf{R}E\left\{\mathbf{y}\mathbf{y}^T\right\}\mathbf{R}^T = \mathbf{R}\mathbf{C}_\mathbf{y}\mathbf{R}^T$$

Note, R accounts for everything that was fit (including DM, etc). This approach also works for cross-cov matrices.

Eigenvalue spectra and noise likelihood



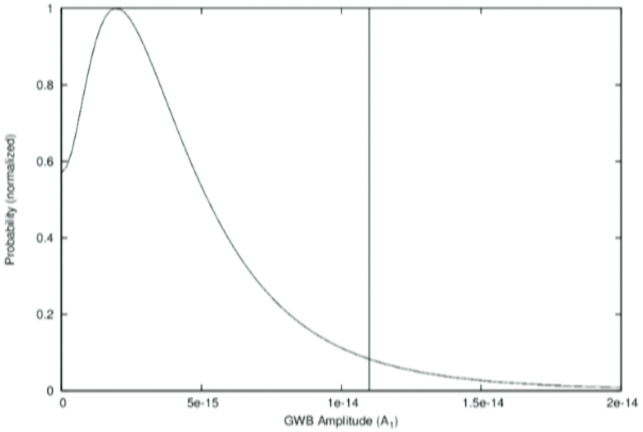


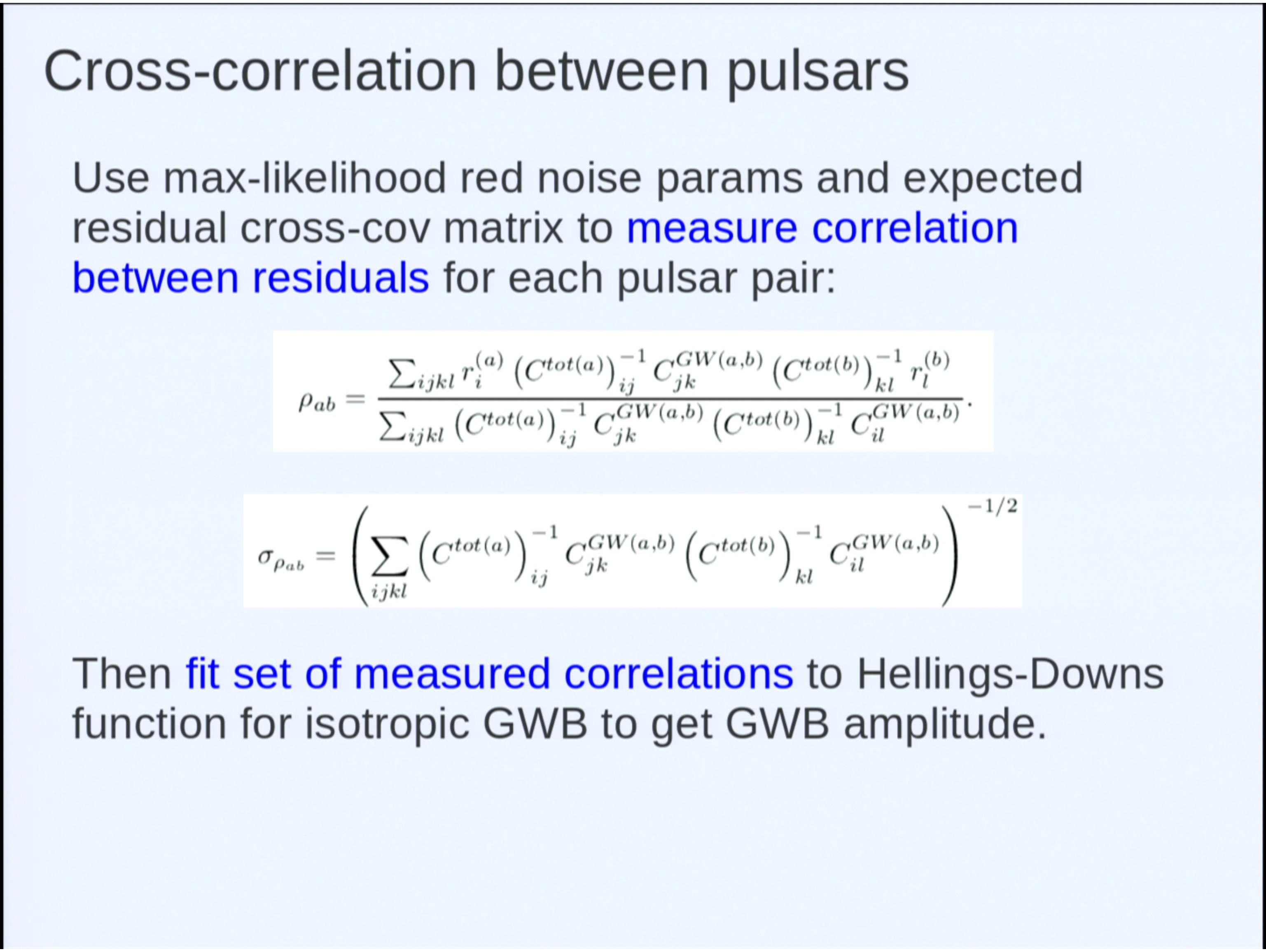
FIG. 5.— Probability distribution for the GWB amplitude A_1 based on J1713+0747 timing, and assuming $\alpha = -2/3$. 95% of the distribution is contained in $A_1 < 1.1 \times 10^{-14}$ (vertical line), the maximum-likelihood value $\hat{A}_1 = 1.9 \times 10^{-15}$, and the likelihood ratio between this point and $A_1 = 0$ is $R = 0.6$. In this case, a non-zero value of A_1 provides the best fit to the data, but without much statstical significance over a white noise only model. These statistics for all sources, considering several different values of α, are presented in Table 3.

Diagonalize C_r^{GW} –

In the diagonal basis, the likelihood function for GW amplitude is easy to evaluate.

Based on likelihood ratios, probable "non-white" results are seen in:

J1643-1224
J1910+1256
J1640+2224
B1953+29



Cross-correlation between pulsars

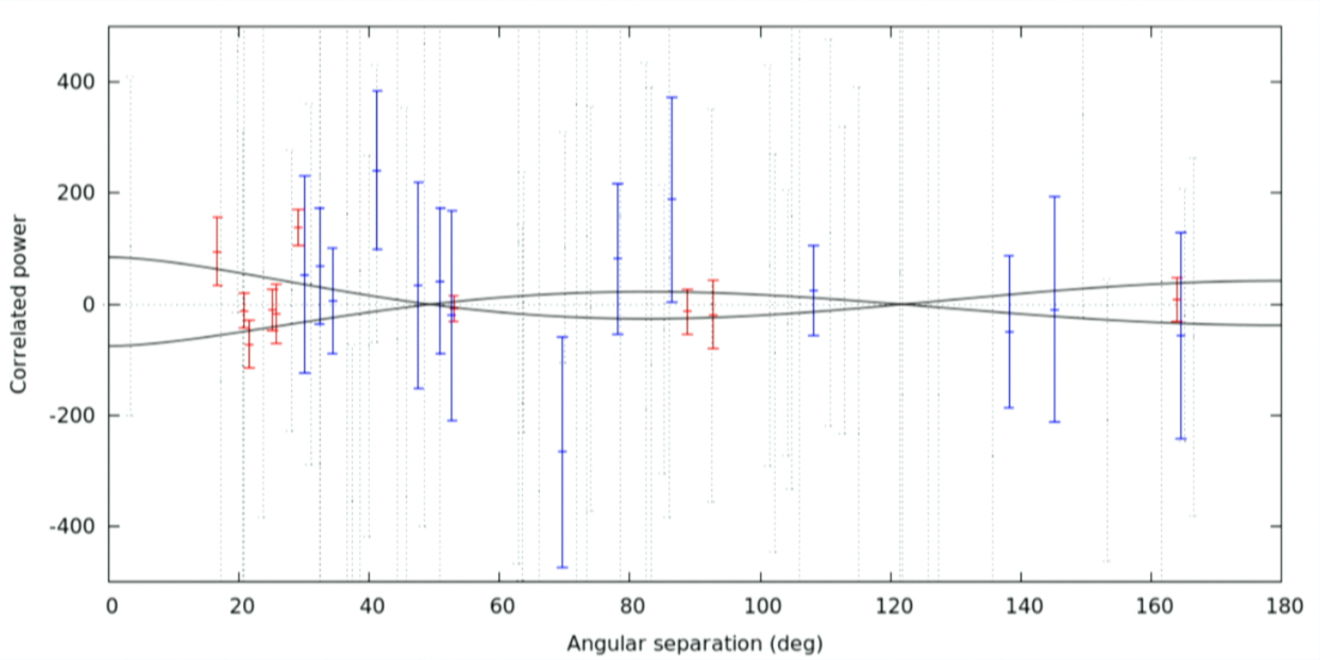
Use max-likelihood red noise params and expected residual cross-cov matrix to measure correlation between residuals for each pulsar pair:

$$\rho_{ab} = \frac{\sum_{ijkl} r_i^{(a)} \left(C^{tot(a)}\right)^{-1}_{ij} C^{GW(a,b)}_{jk} \left(C^{tot(b)}\right)^{-1}_{kl} r_l^{(b)}}{\sum_{ijkl} \left(C^{tot(a)}\right)^{-1}_{ij} C^{GW(a,b)}_{jk} \left(C^{tot(b)}\right)^{-1}_{kl} C^{GW(a,b)}_{il}}.$$

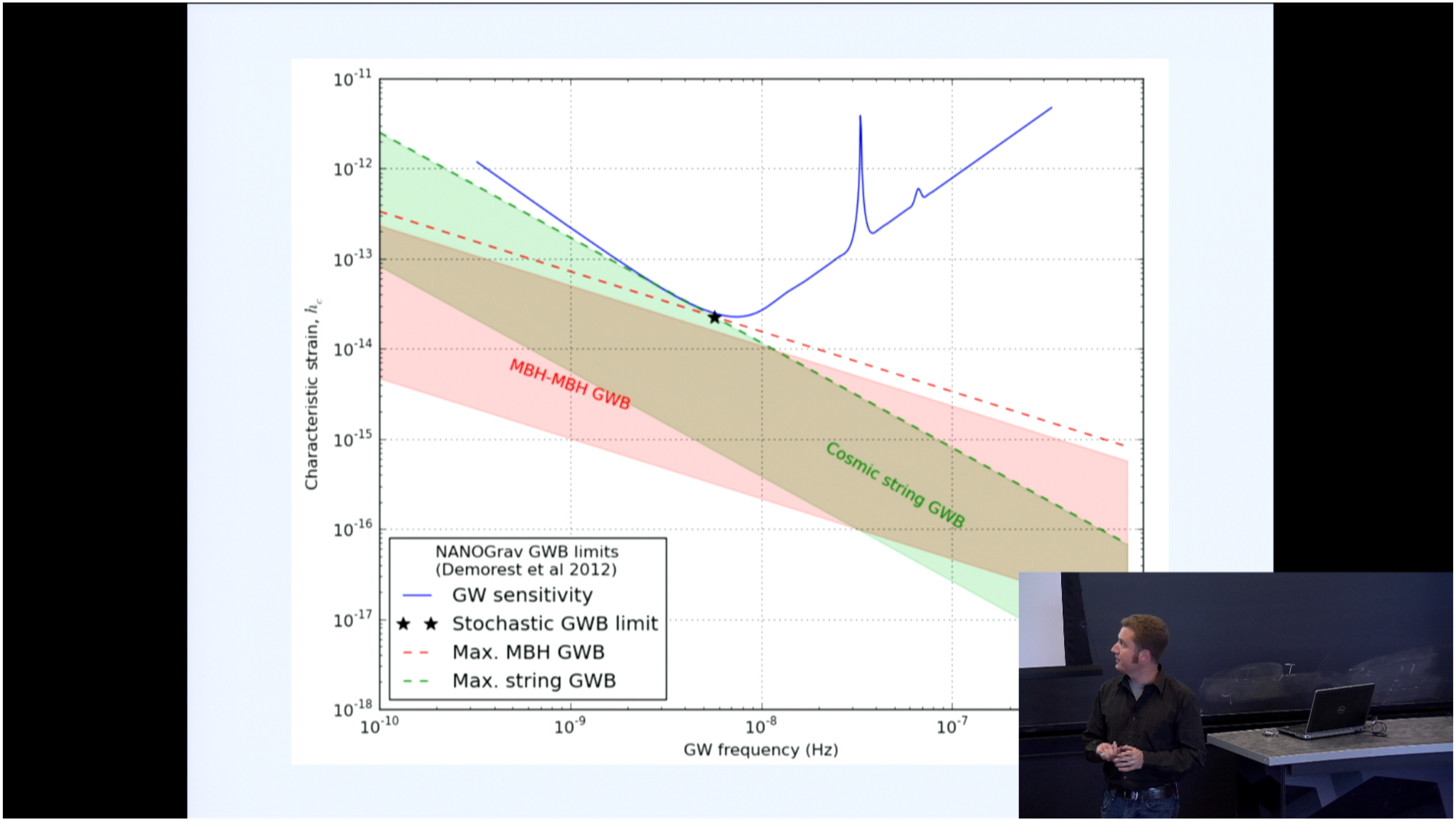
$$\sigma_{\rho_{ab}} = \left(\sum_{ijkl} \left(C^{tot(a)}\right)^{-1}_{ij} C^{GW(a,b)}_{jk} \left(C^{tot(b)}\right)^{-1}_{kl} C^{GW(a,b)}_{il}\right)^{-1/2}$$

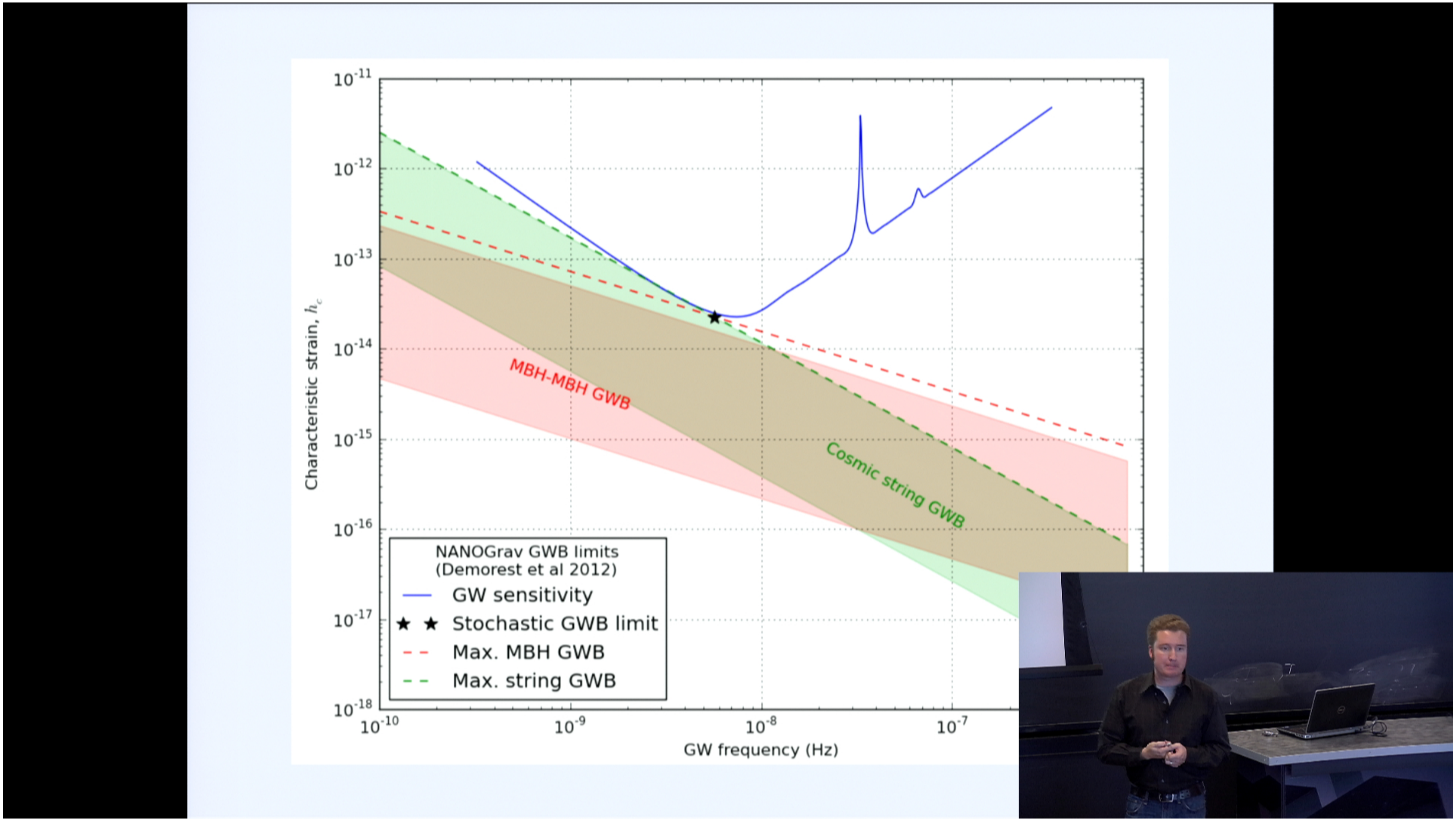
Then fit set of measured correlations to Hellings-Downs function for isotropic GWB to get GWB amplitude.

5-year NANOGrav GW cross-correlation analysis

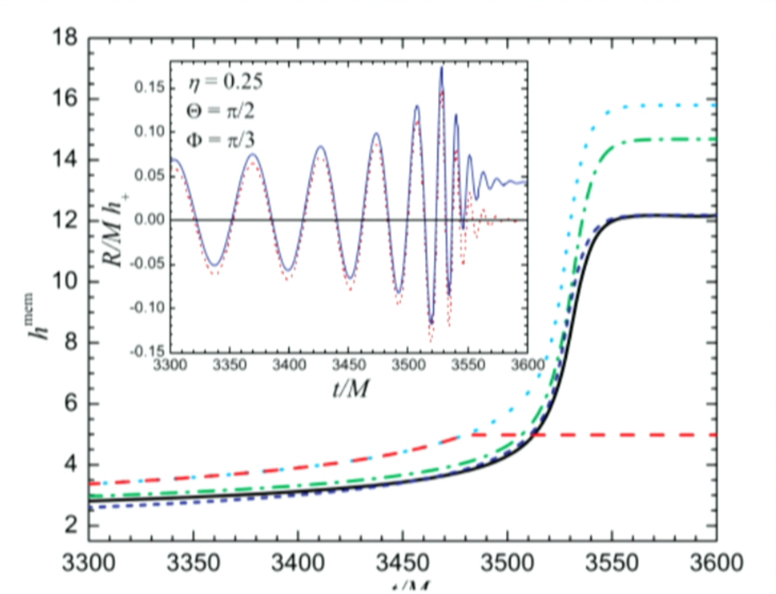


No (isotropic, stochastic BW) GW detection at h_c(1 year) < 7×10^{-15} level (95%).


NANOGrav GWB limits
(Demorest et al 2012)
GW sensitivity
Stochastic GWB limit
Max. MBH GWB
Max. string GWB
MBH-MBH GWB
Cosmic string GWB
Characteristic strain, h_c
GW frequency (Hz)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-10}
10^{-9}
10^{-8}
10^{-7}


10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
Characteristic strain, h_c
10^-10
10^-9
10^-8
10^-7
GW frequency (Hz)
MBH-MBH GWB
Cosmic string GWB
NANOGrav GWB limits
(Demorest et al 2012)
GW sensitivity
★ ★ Stochastic GWB limit
Max. MBH GWB
Max. string GWB

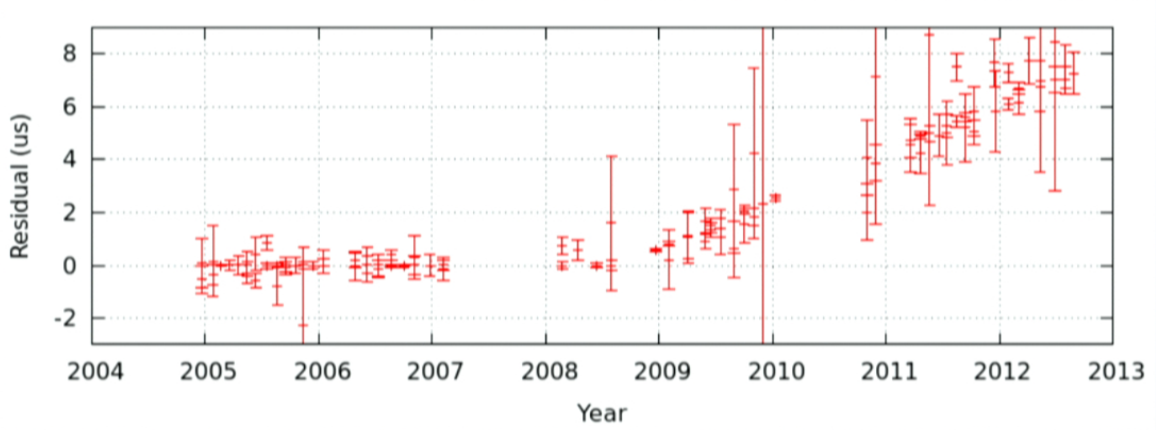
GW “bursts with memory”:



(Favata 2009)

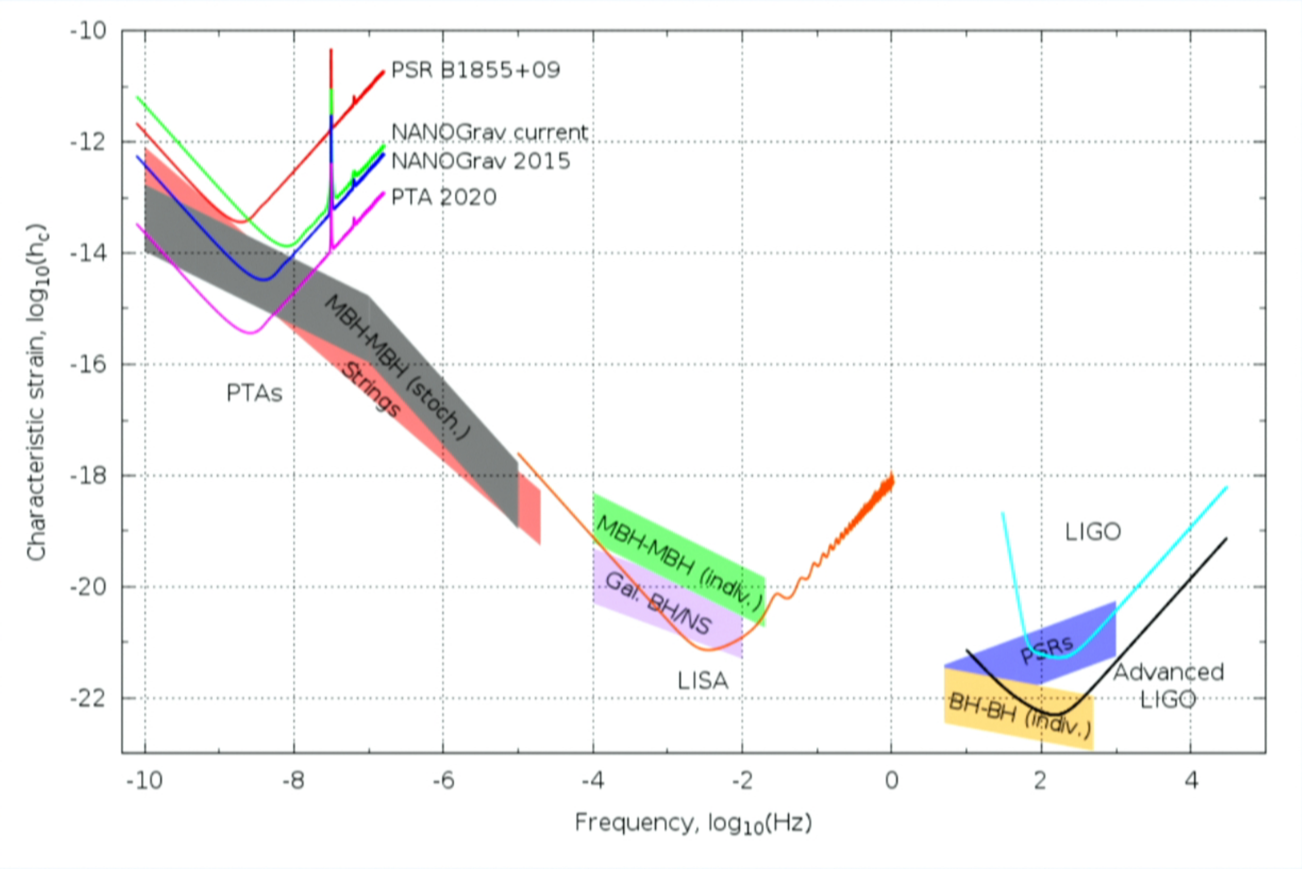
May produce a glitch-like signal in all PSRs (e.g. Cordes & Jenet 2012).

(Huge fake signal added!)



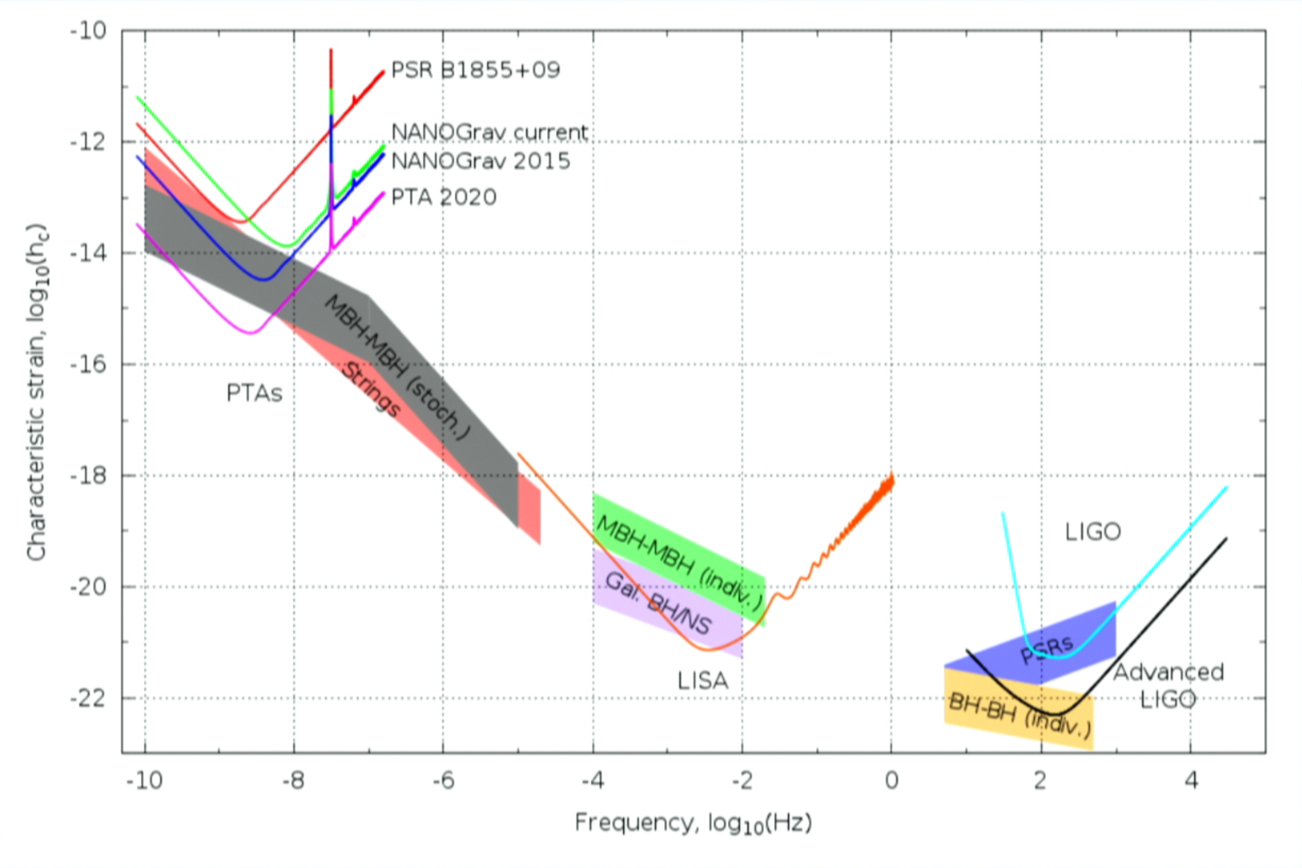
How to improve the measurement?

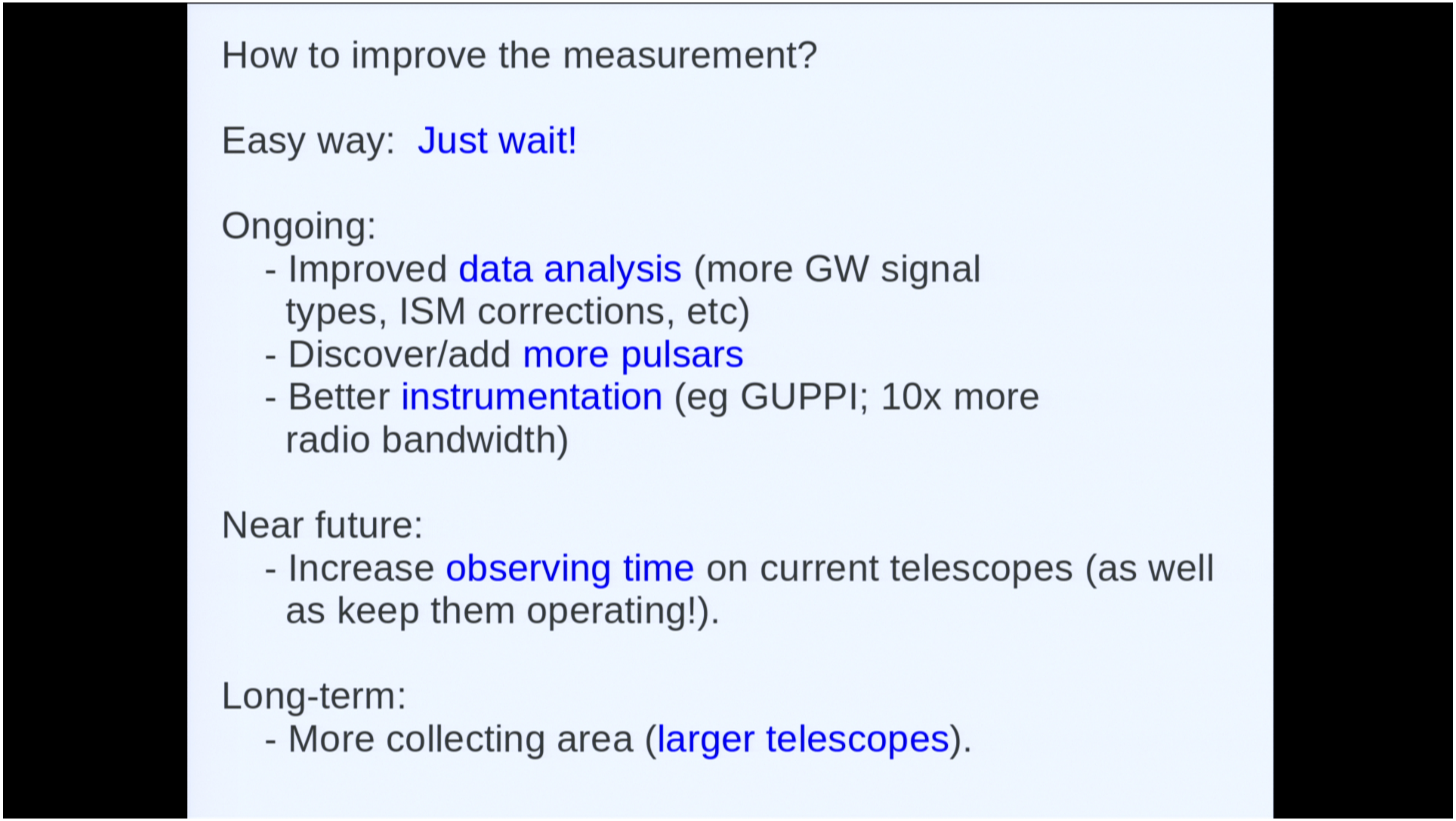
Easy way: Just wait!



How to improve the measurement?

Easy way: Just wait!





How to improve the measurement?

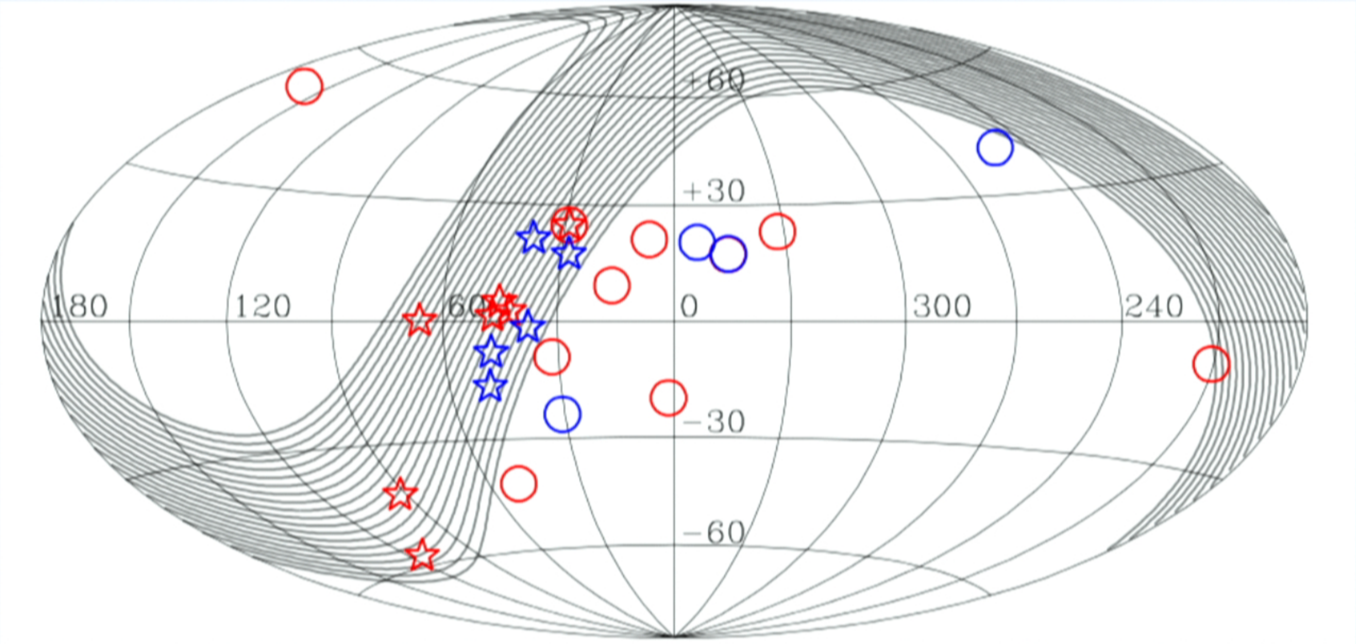
Easy way: Just wait!

Ongoing:
- Improved data analysis (more GW signal types, ISM corrections, etc)
- Discover/add more pulsars
- Better instrumentation (eg GUPPI; 10x more radio bandwidth)

Near future:
- Increase observing time on current telescopes (as well as keep them operating!).

Long-term:
- More collecting area (larger telescopes).

Rapidly increasing number of known MSPs:



NANOGrav pulsars (in galactic coords):
red="classic", blue=recently added (past ~year)
From 17 orig sources -> 35 currently

Driven by Fermi MSP discoveries; also GBNCC (GBT), PALFA (Arecibo), HTRU (Parkes) ongoing pulsar surveys.

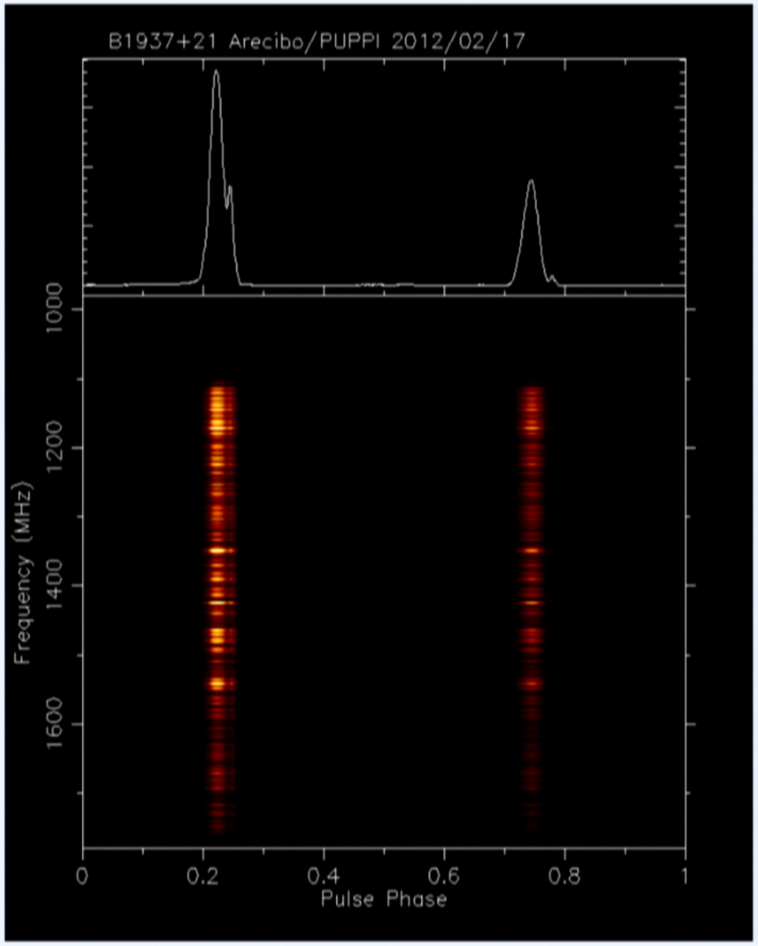
Improving/maintaining existing telescope resources:

Current usage ~3-5% total time at GBT/ Arecibo.

Wideband receiver upgrades (~0.5-3 GHz)

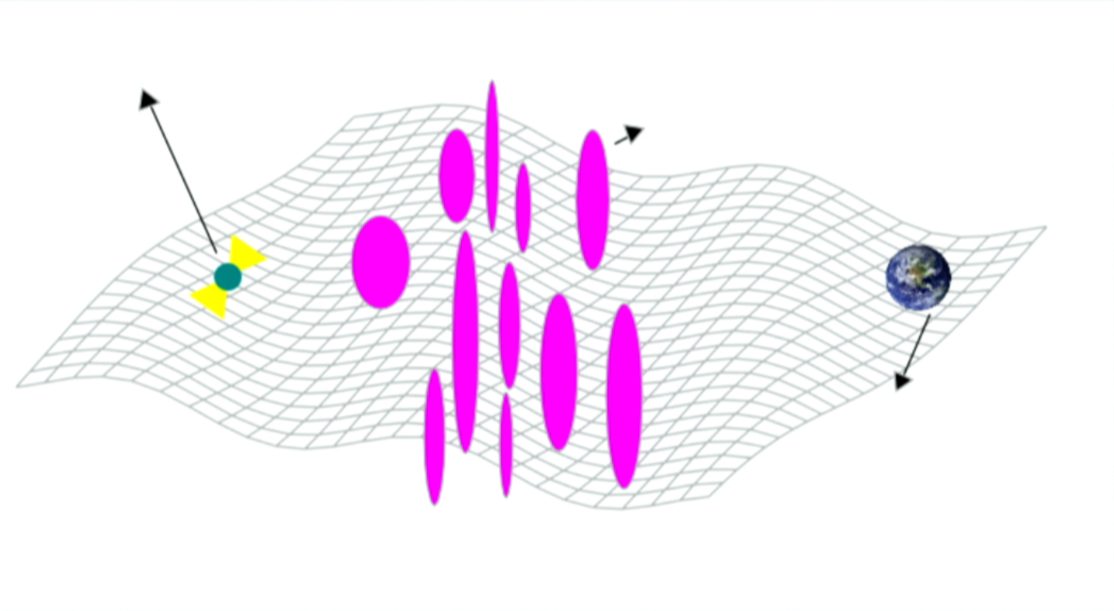
“PUPPI” for Arecibo is now available!

Long-term project: keeping our current best telescopes operating is crucial!



PUPPI first light plot, Feb 2012

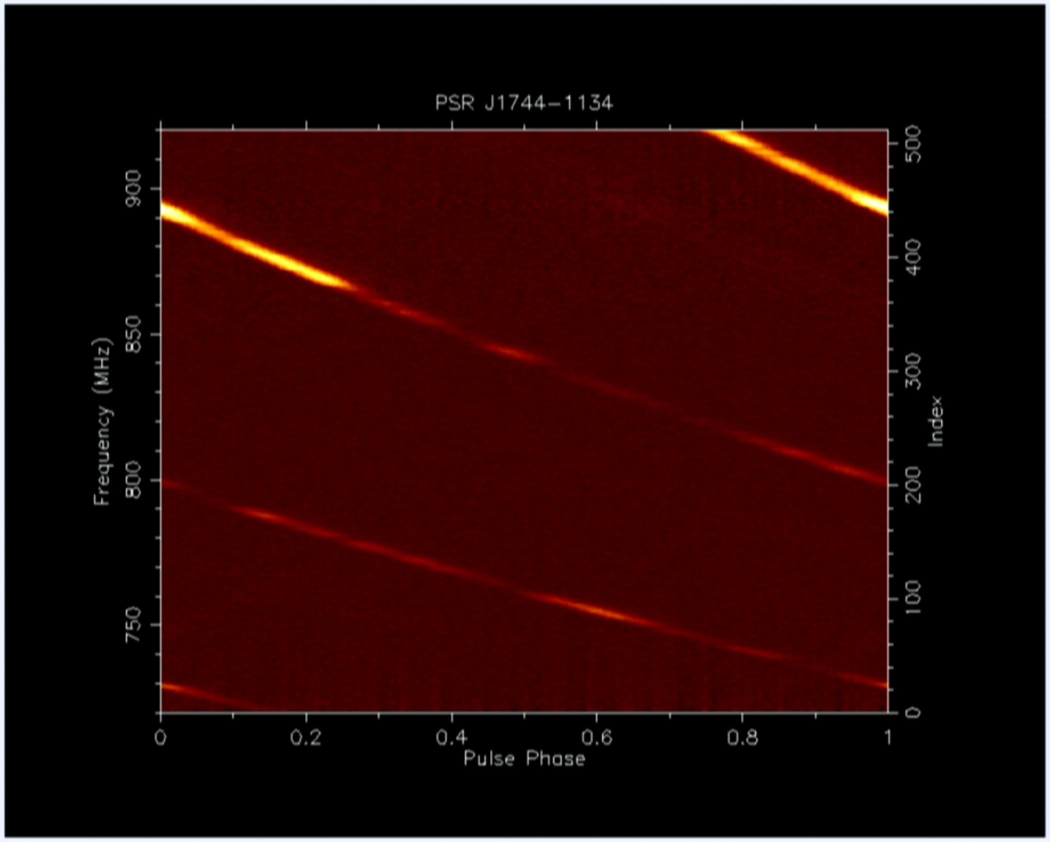
The interstellar medium:



Propagation through the ionized ISM affects the pulsar radio signal and pulsar timing in various ways...

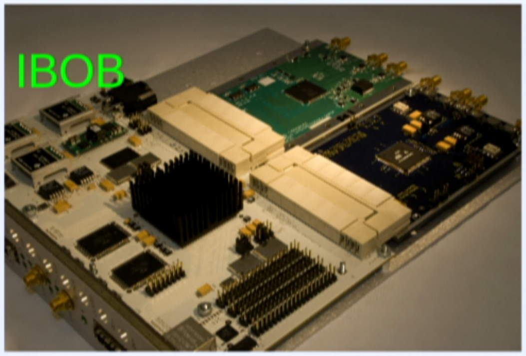
Interstellar dispersion

Due to travel of pulsar signal through ionized ISM.

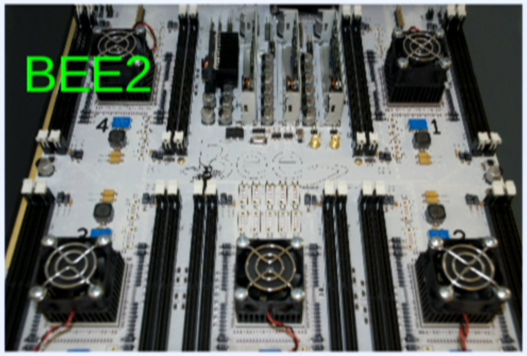


Dispersion measure (slope of signal in plot) proportional to total electron column density.

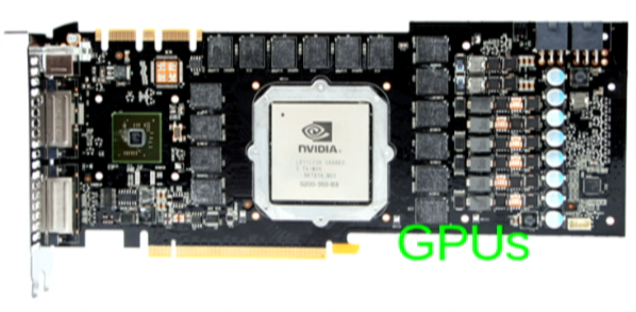
GUPPI architecture:
~1 MHz PFB in FPGAs
Coherent dedisp in GPUs



XAUI

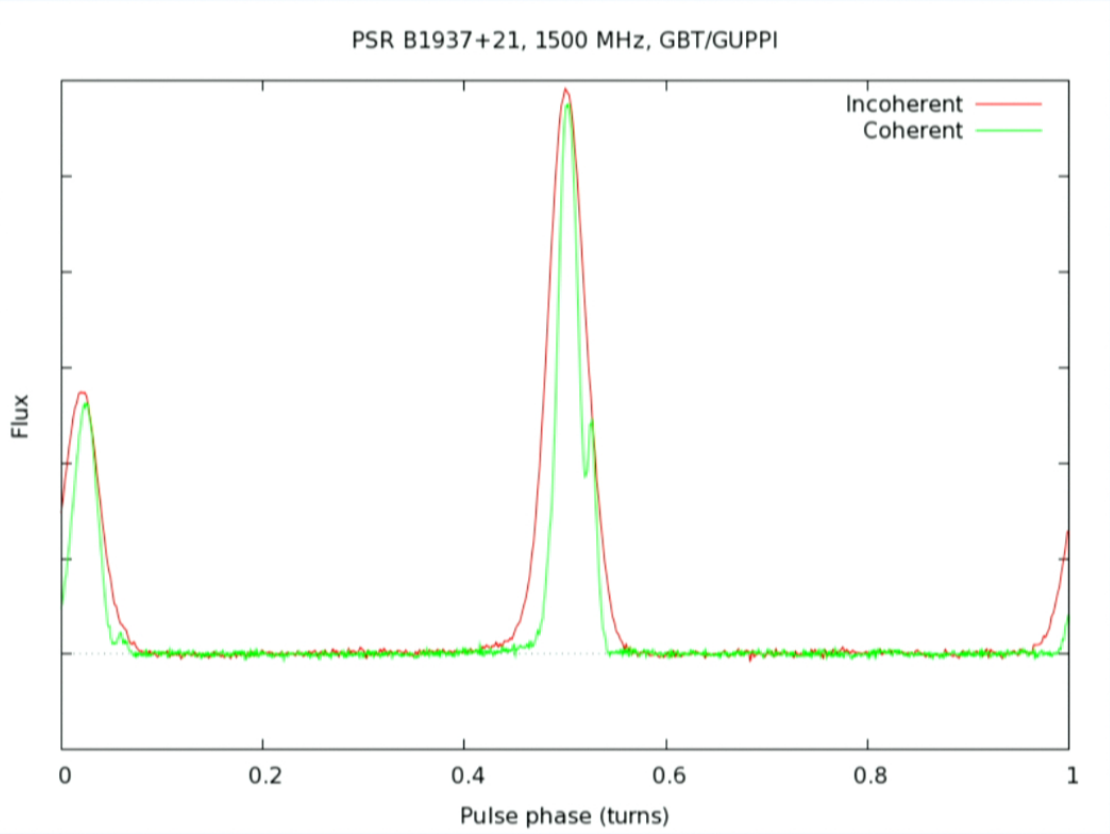


10 Ge
switch;
24 Gb/s

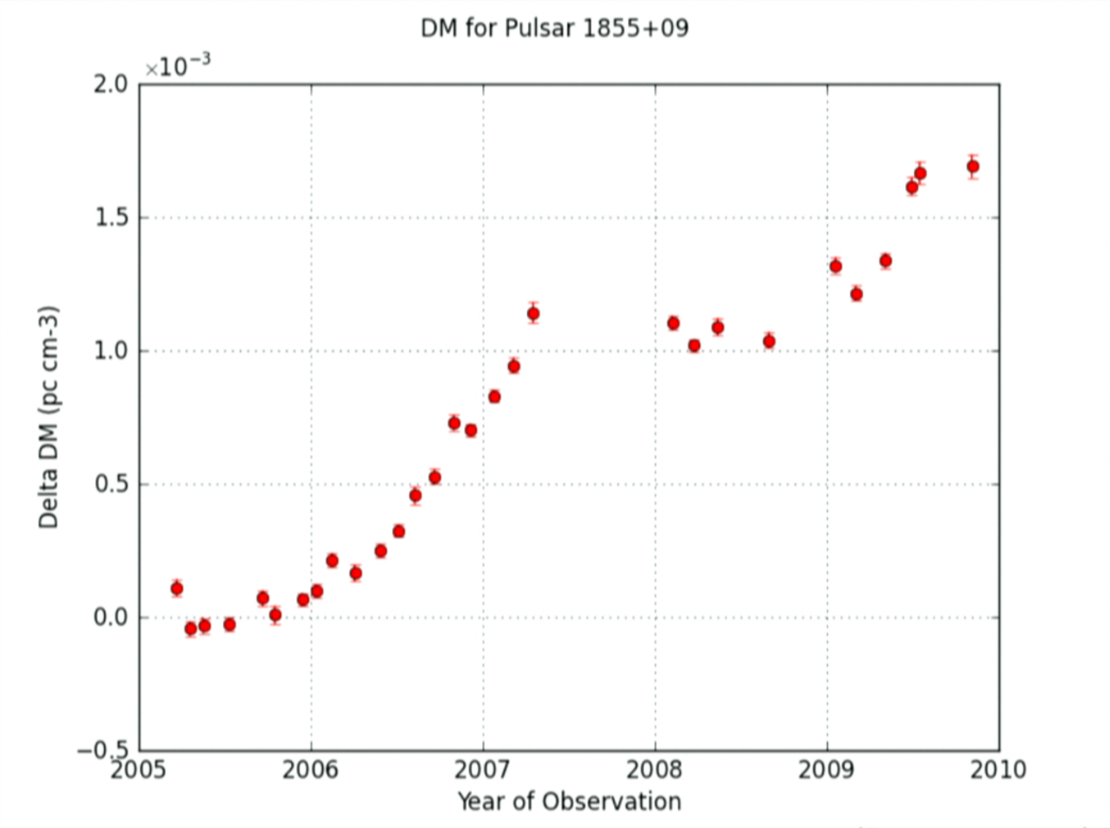


Coherent dedispersion

DM-specific pre-detection filter sharpens pulses, leading to better TOA measurements:



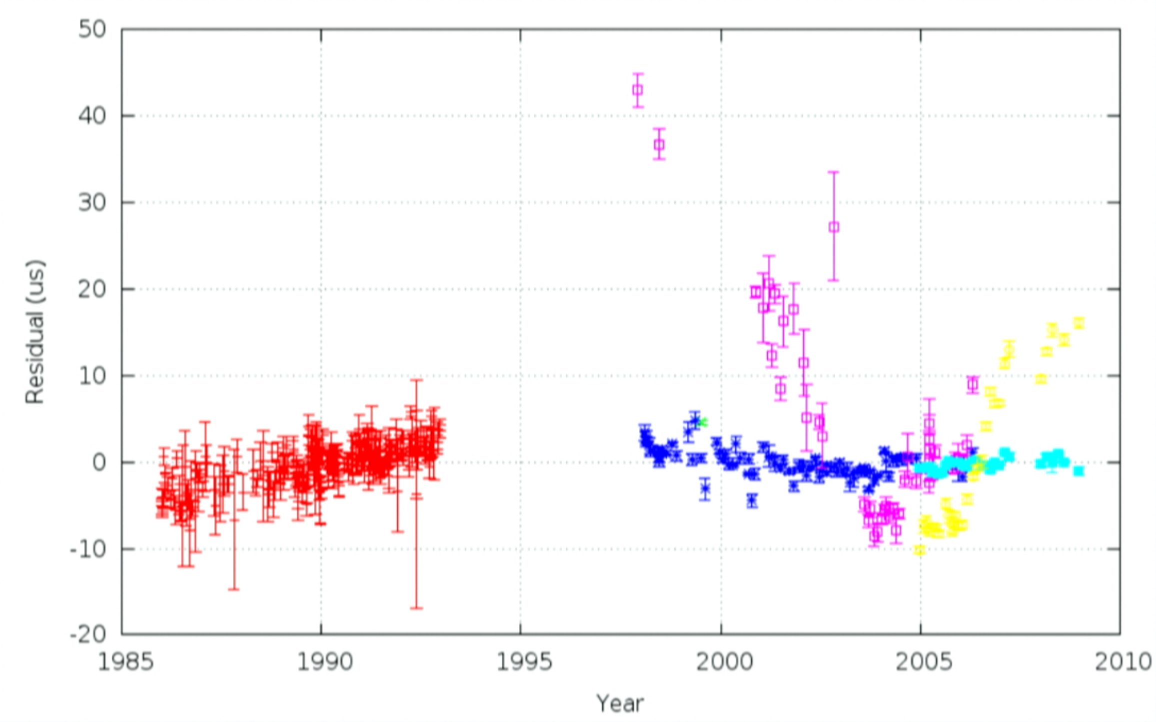
DM varies with time:



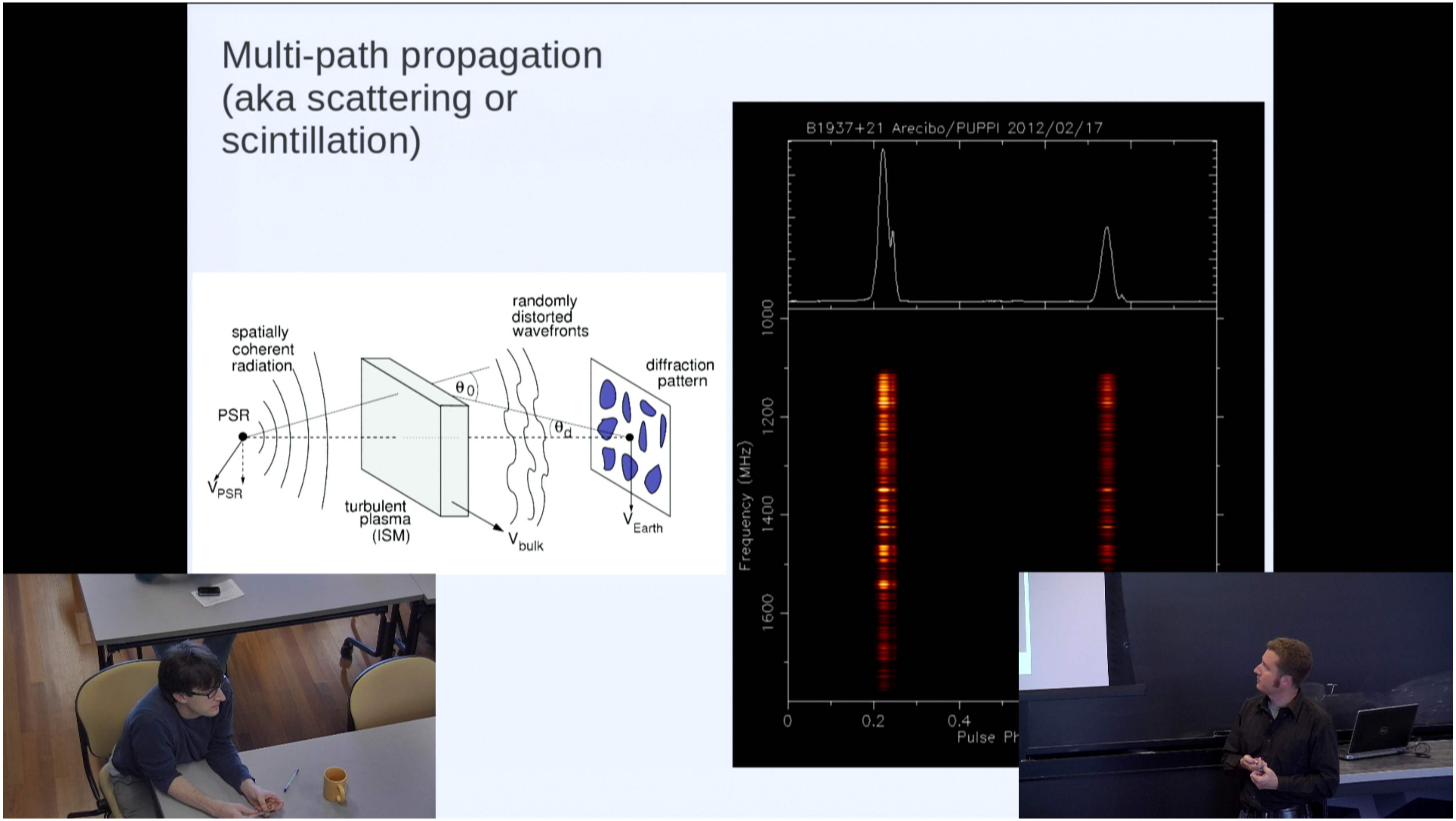
(Demorest et al 2012)

Due to LOS motion with respect to ISM

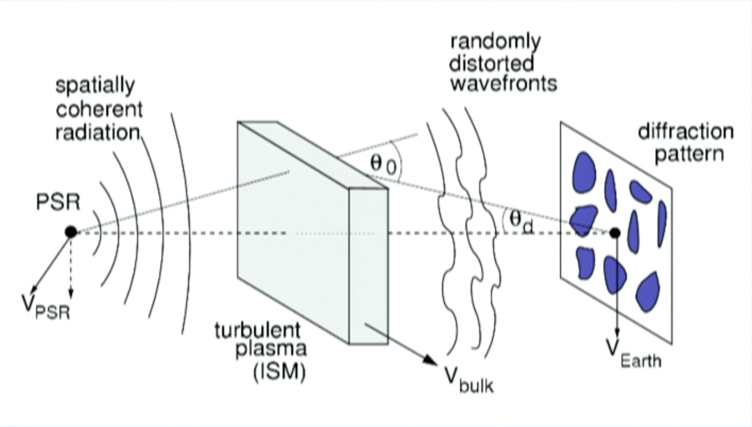
If not measured/corrected, this causes big timing problems:

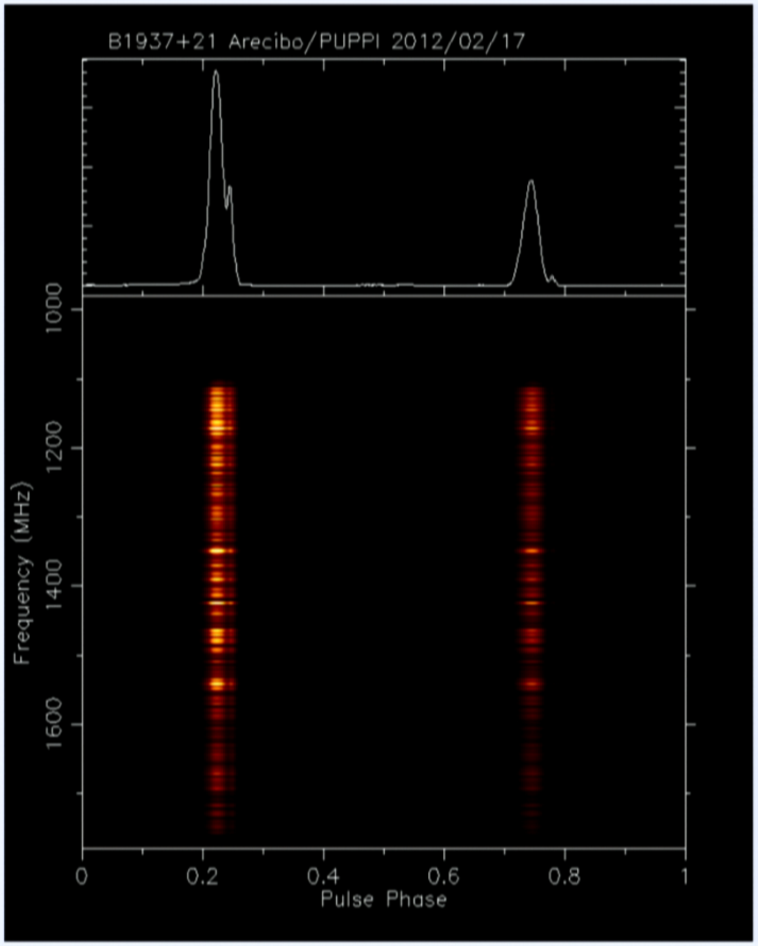


Multi-path propagation (aka scattering or scintillation)



Multi-path propagation (aka scattering or scintillation)





Dynamic spectra

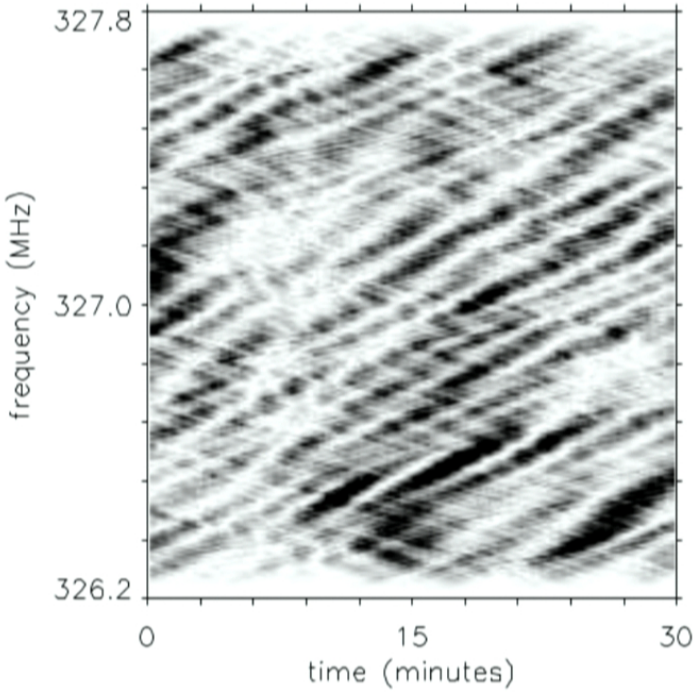


FIG. 1.— The dynamic spectrum of PSR B0834+06 observed on 2003 Dec 31. The flux density as a function of frequency and time is shown using a grayscale that is linear in power, with dark regions indicating high power. The crisscross pattern is due to radio waves reaching the observer from a variety of angles ($\sim$ 10 mas away from the pulsar position), as detailed in the text.

(Hill et al 2004)

Dynamic spectra

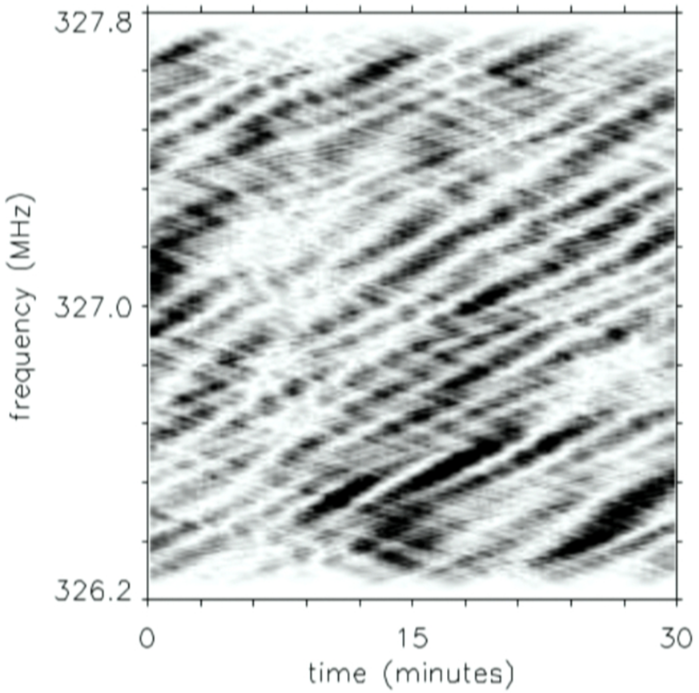
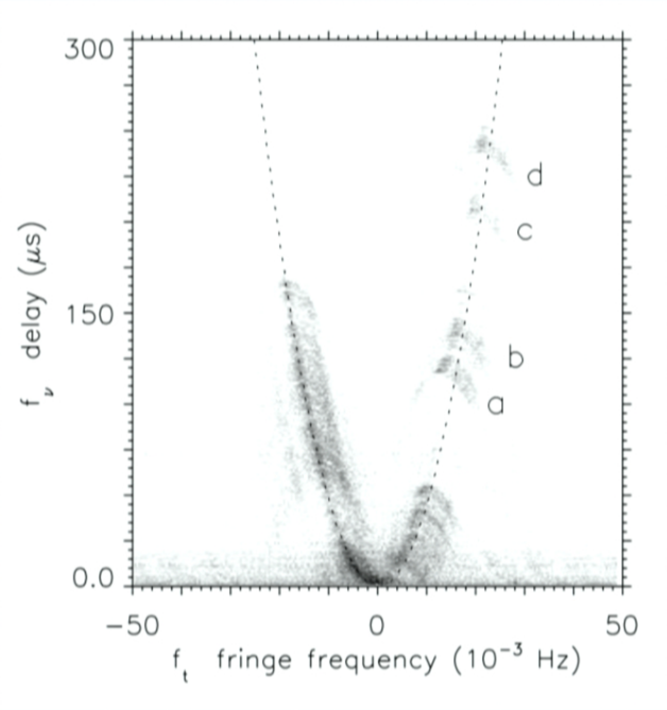


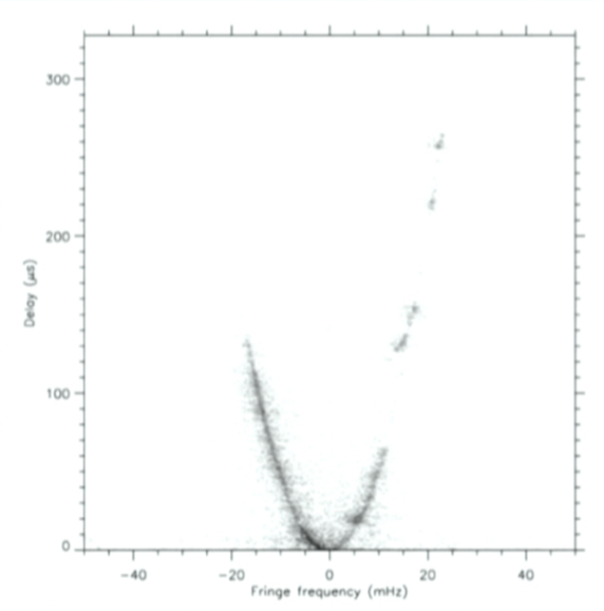
FIG. 1.— The dynamic spectrum of PSR B0834+06 observed on 2003 Dec 31. The flux density as a function of frequency and time is shown using a grayscale that is linear in power, with dark regions indicating high power. The crisscross pattern is due to radio waves reaching the observer from a variety of angles (∼ 10 mas away from the pulsar position), as detailed in the text.

(Hill et al 2004)

“Secondary spectra”



Raw SS (Hill et al 2004)

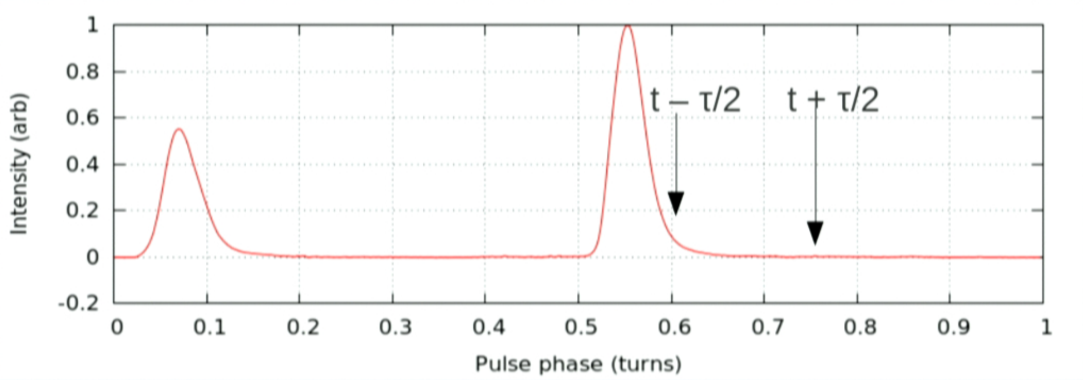


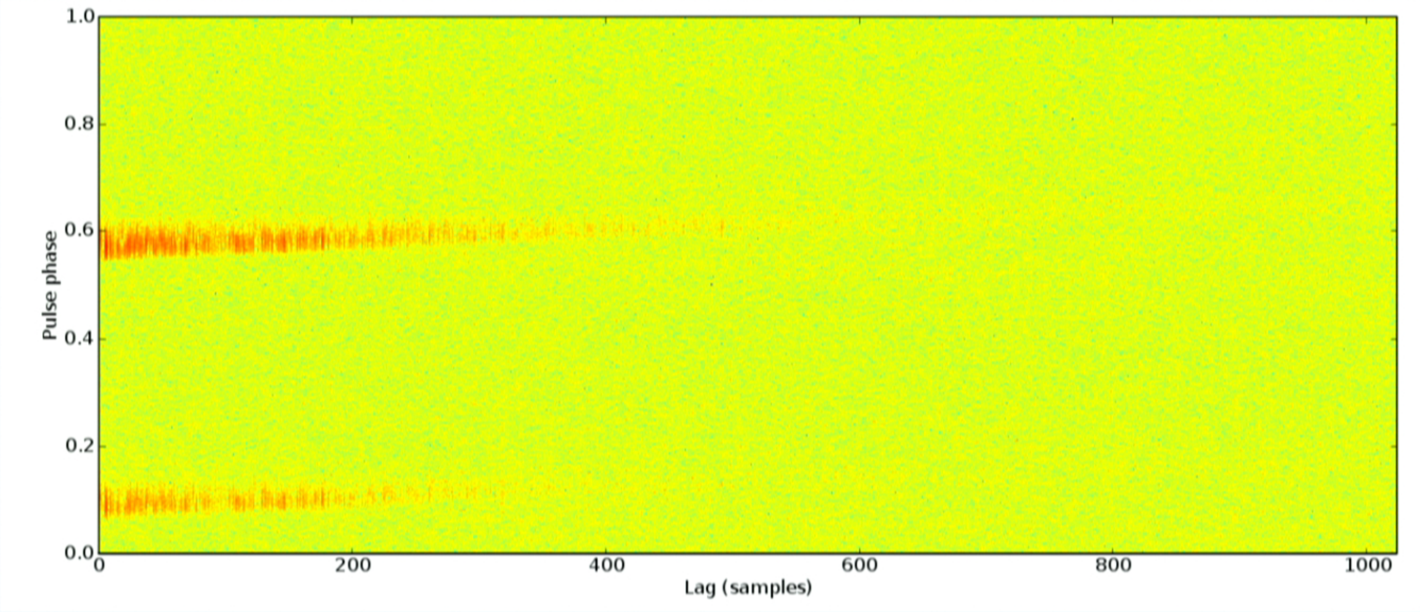
Deconvolved SS (Walker et al 2008)

However, we can also make use of the pulsar's intrinsic time variability to retrieve more ISM information!

Pulse phase-resolved correlations:

$$C_x(t,\tau) = E\left\{x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})\right\}$$



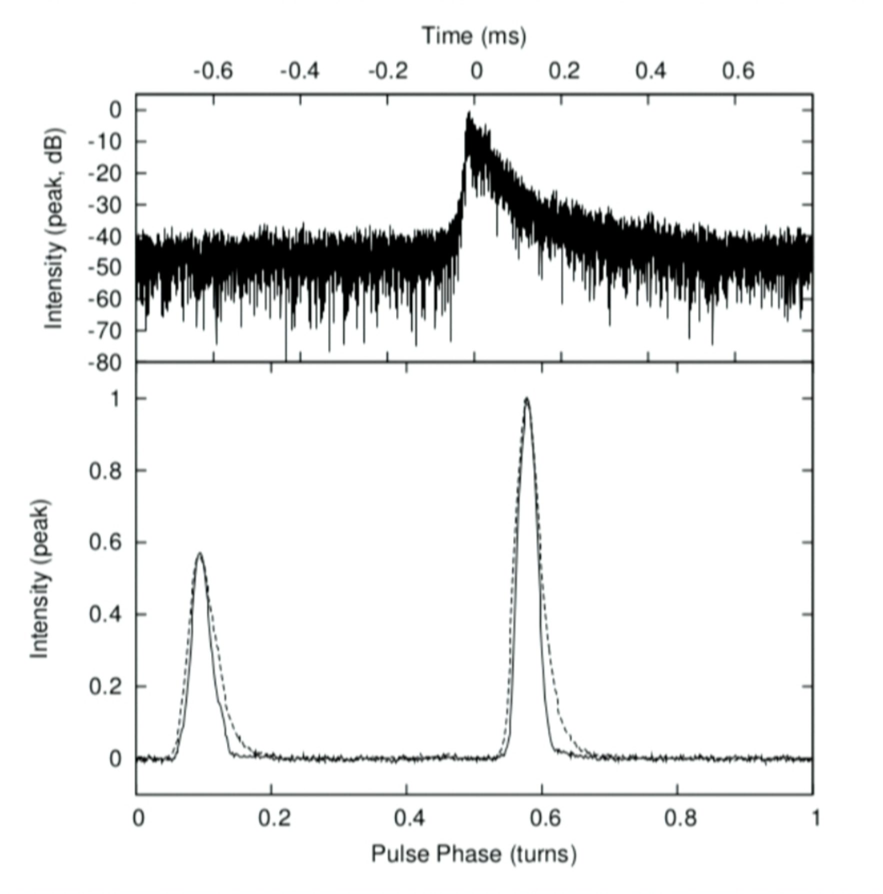


Cyclic spectrum

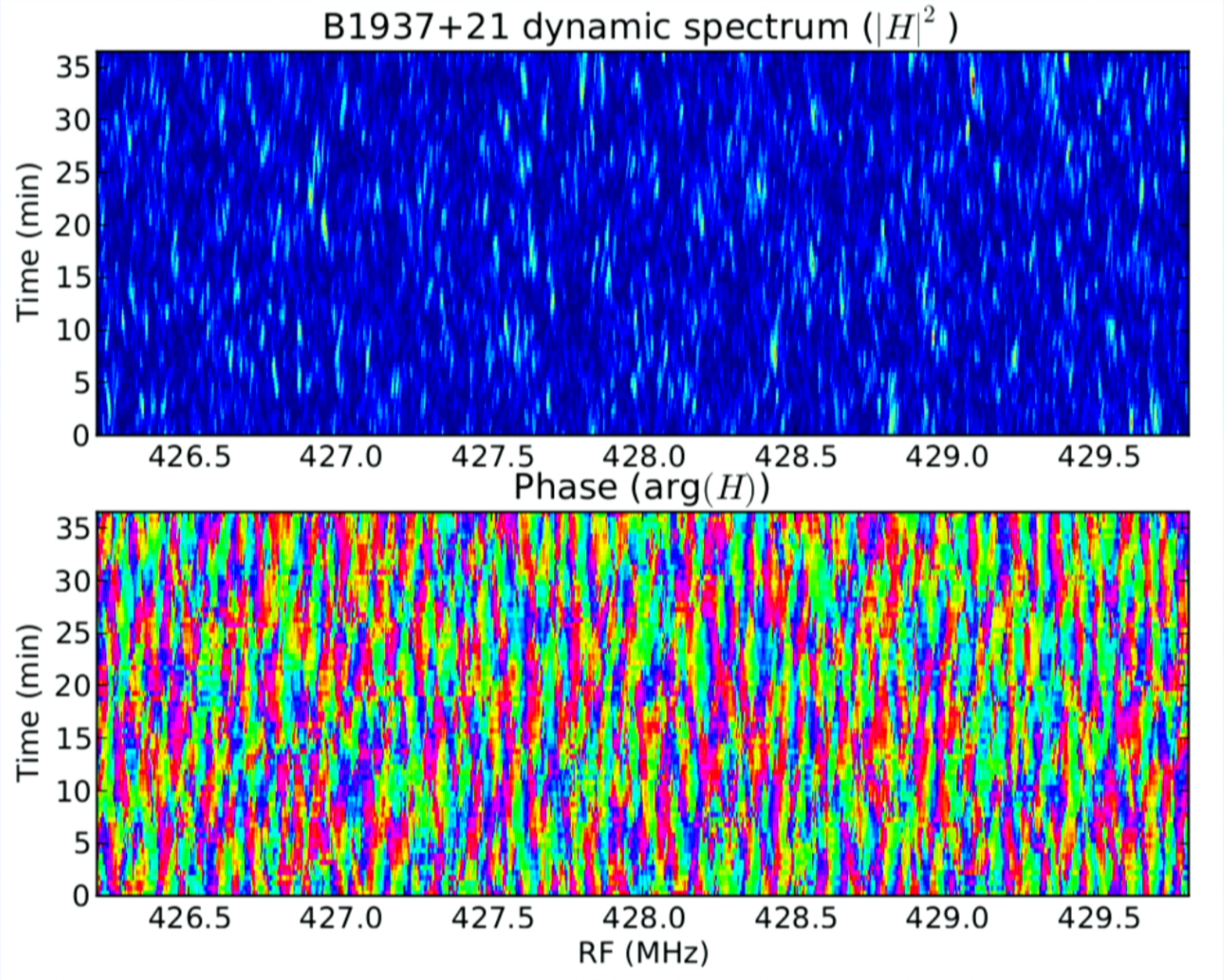
$$S_{post}(\nu,\alpha) = H(\nu + \frac{\alpha}{2})H^*(\nu - \frac{\alpha}{2})S_{pre}(\alpha)$$

2-D Fourier transform of C(t,τ).

Can be used to deconvolve ISM transfer function from “pre-ISM” intrinsic pulse profile.

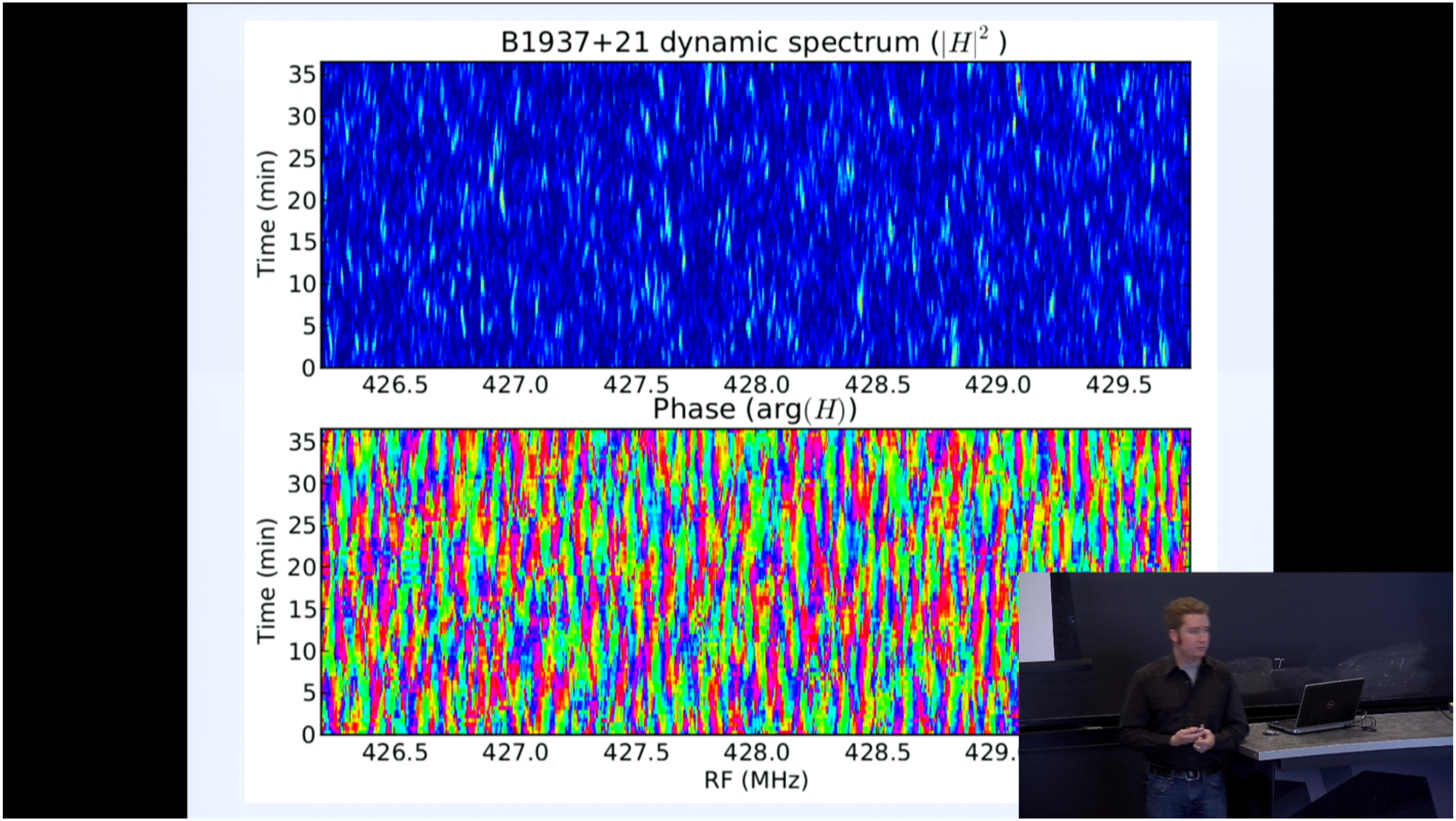


(Demorest 2011)


B1937+21 dynamic spectrum ($|H|^2$)
Time (min)
0
5
10
15
20
25
30
35
426.5
427.0
427.5
428.0
428.5
429.0
429.5
Phase (arg(H))
Time (min)
0
5
10
15
20
25
30
35
426.5
427.0
427.5
428.0
428.5
429.0
429.5
RF (MHz)

Some cyclic spectrum limitations:

1. Works best for scattering delays comparable/larger than the (intrinsic) pulse width.
2. Need enough S/N per scintillation timescale to deconvolve ISM filter.
3. Not currently clear how this will translate to timing improvement for GW (and other timing) projects – but this is a work in progress!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Phase ($\arg(H)$)
Time (min)
0
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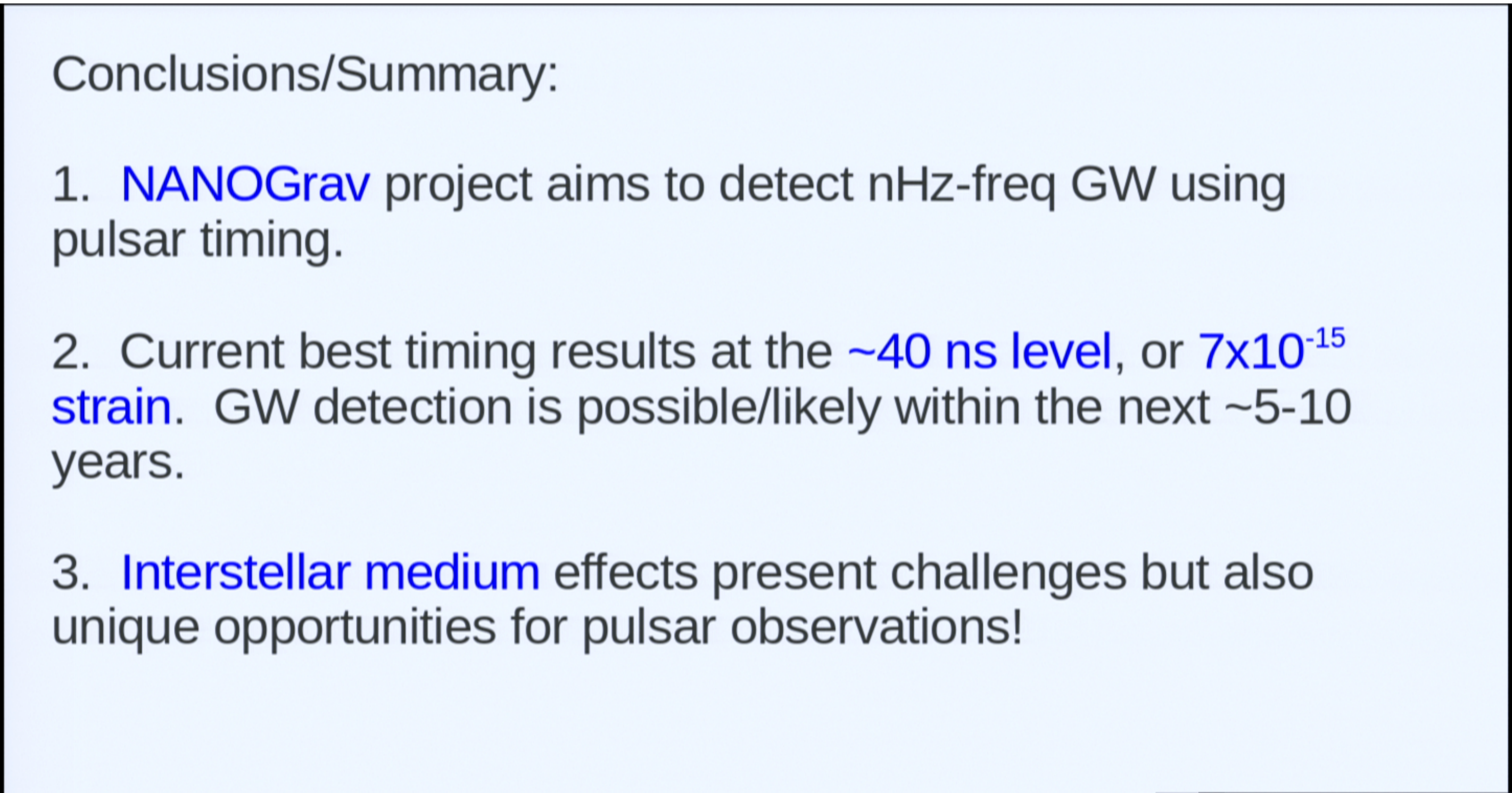
15
20
25
30
35
426.5
427.0
427.5
428.0
428.5
RF (MHz)



Conclusions/Summary:

1. NANOGrav project aims to detect nHz-freq GW using pulsar timing.

2. Current best timing results at the ~40 ns level, or 7×10^{-15} strain. GW detection is possible/likely within the next ~5-10 years.

3. Interstellar medium effects present challenges but also unique opportunities for pulsar observations!