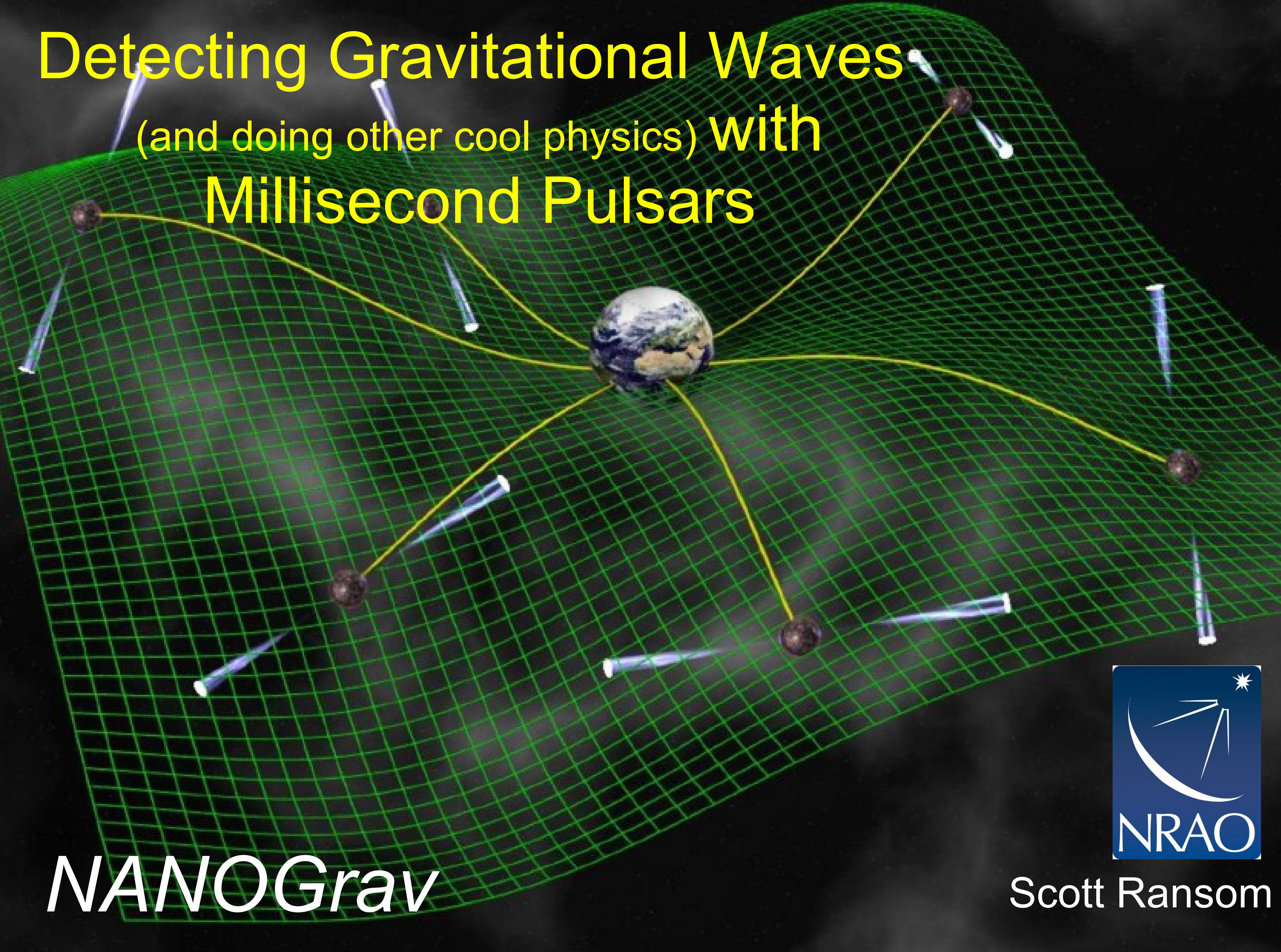
Detecting Gravitational Waves (and doing other cool physics) with Millisecond Pulsars



NANOGrav

NRAO

Scott Ransom

What's a **Pulsar** ?

Rotating Neutron Star!

Size of city:

$R \sim 10\text{-}20$ km

Mass greater than Sun:

$M \sim 1.4\ M_{sun}$

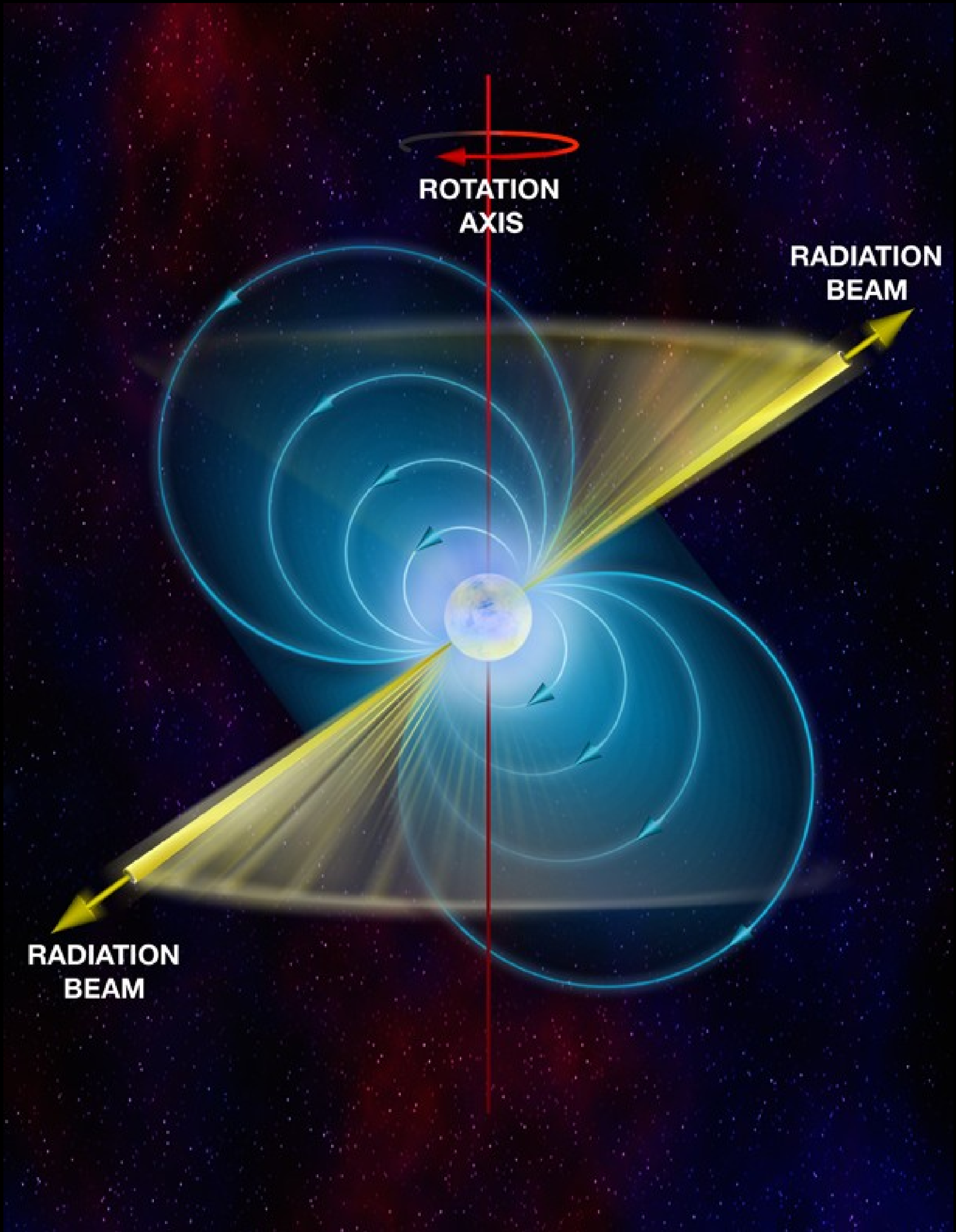
Strong Magnetic Fields:

$B \sim 10^{8}\text{-}10^{14}$ Gauss

Pulses are from a "**lighthouse**" type effect

"Spin-down" power up to 10,000 times more than the Sun's total output!

Weak but broadband radio sources



Pulsar Flavors

Young PSRs

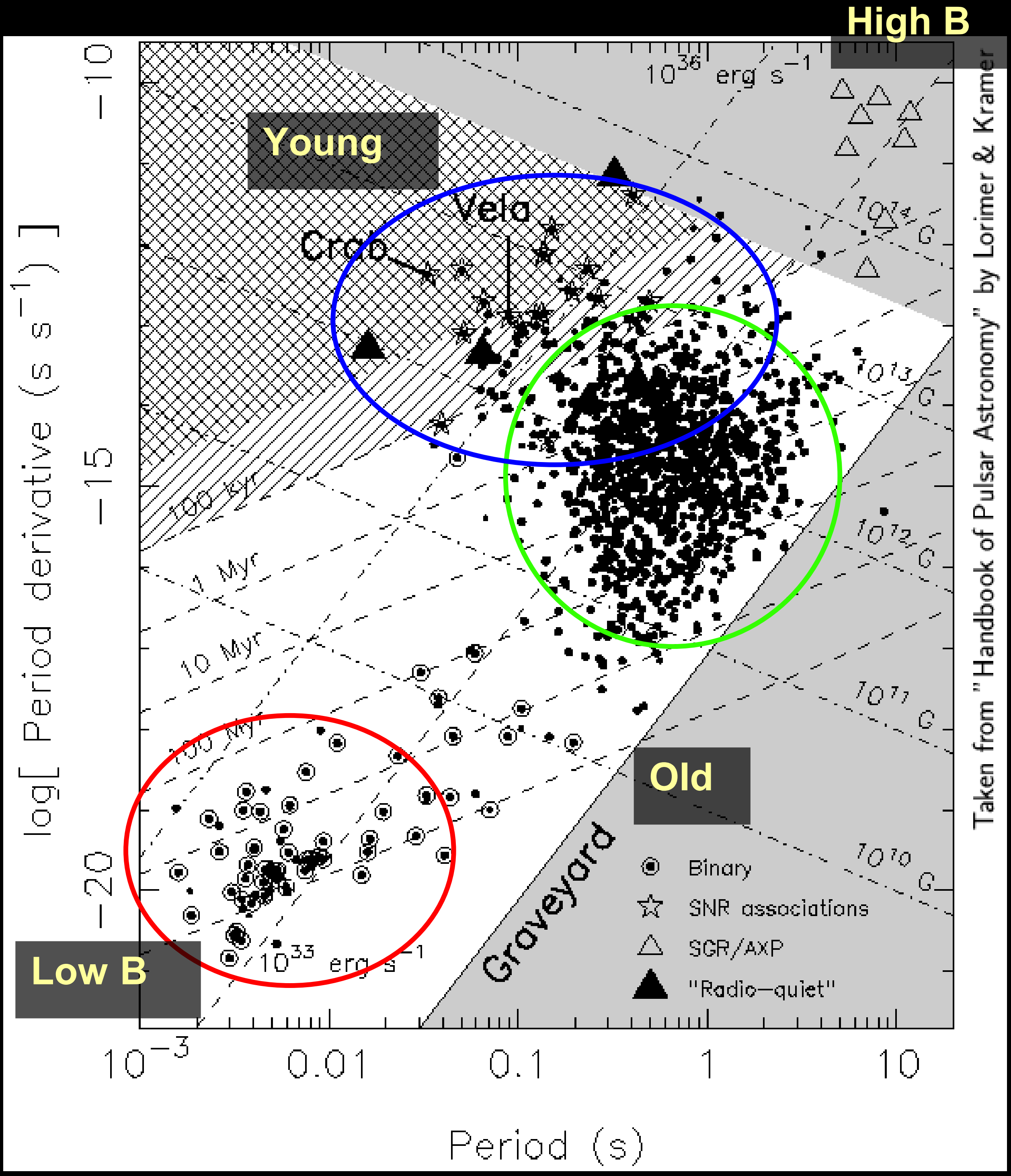
(high B, fast spin, very energetic)

Normal PSRs

(average B, slow spin)

Millisecond PSRs

(low B, very fast, very old, very stable spin, best for basic physics tests)



Millisecond Pulsars are *Very* Precise Clocks

PSR B1937+21

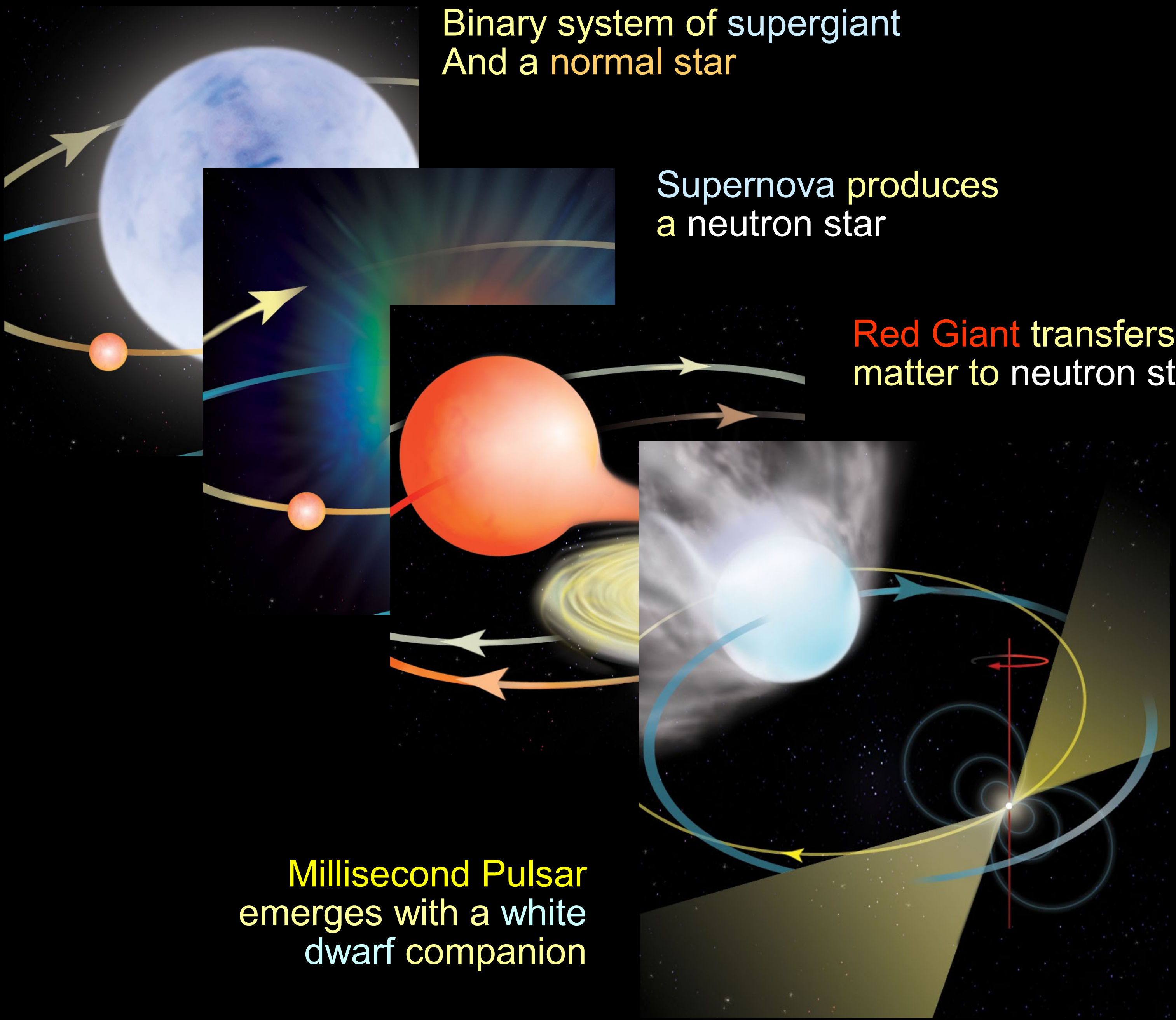
At midnight on 5 Dec, 1998:

P = 1.5578064688197945 ms
+/- 0.0000000000000004 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!

How are millisecond pulsars made?

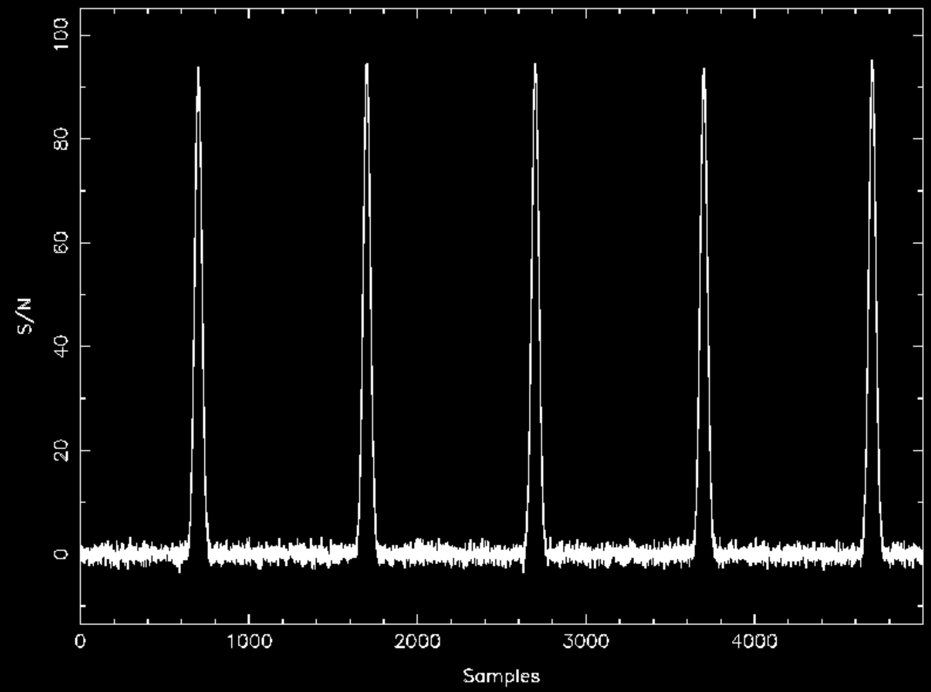


Physics from Pulsars

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

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

Pulsar Timing

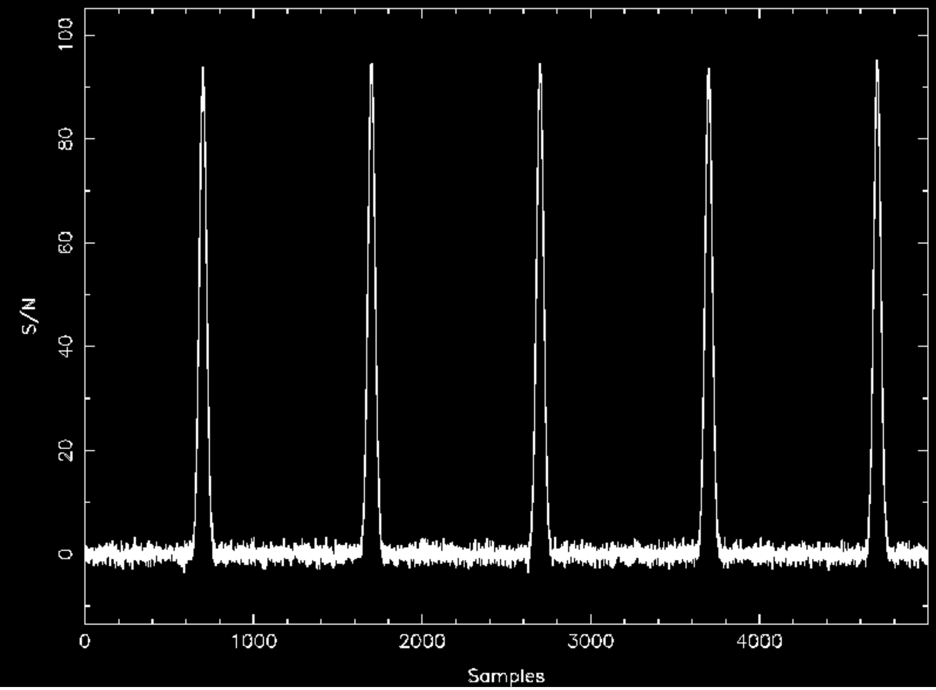


- All of the science is from long-term timing
- Account for every rotation of the pulsar
- Fit the arrival times to a polynomial model after transforming the time:

$$T = t - t_0 + \Delta_C - D/f^2 + \Delta_{R\odot} + \Delta_{E\odot} - \Delta_{S\odot} - \Delta_R - \Delta_E - \Delta_S$$

- Accounts for pulsar spin, orbital, and astrometric parameters and Roemer, Einstein, and Shapiro delays in the Solar System and pulsar system
- Extraordinary precision for MSP timing

Pulsar Timing



- All of the science is from long-term timing
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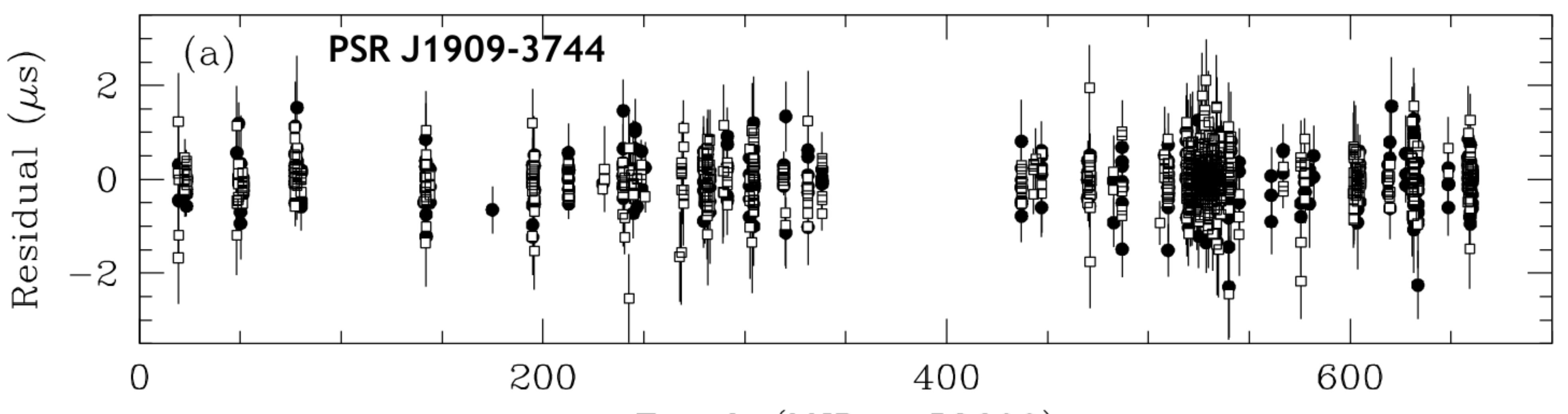


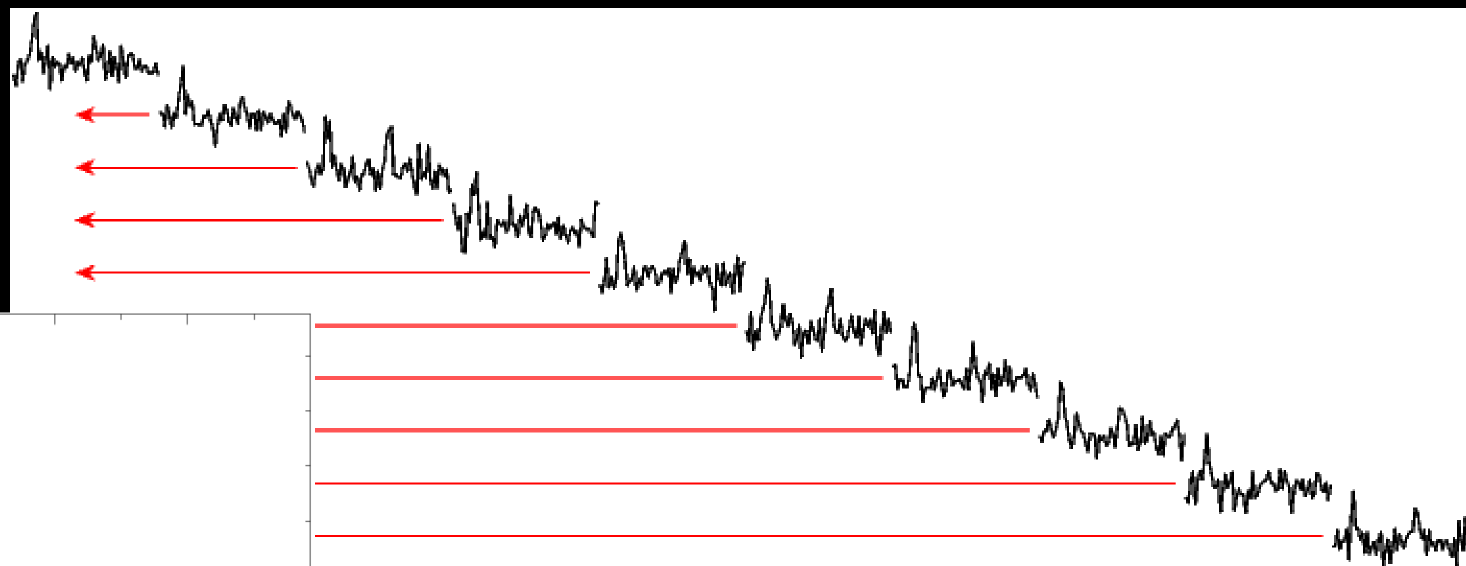
(From Jacoby et al. 2005, ApJL, 629, 113)

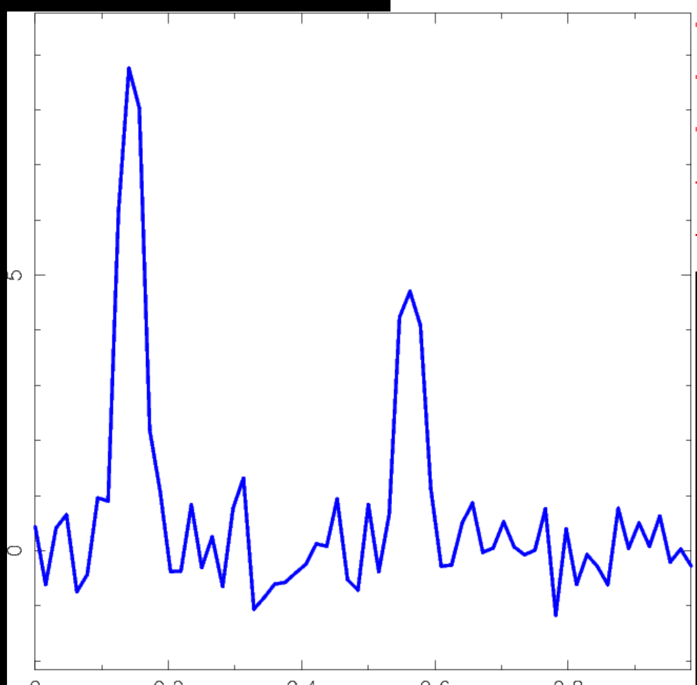
- Extraordinary precision for MSP timing

“Folding” Pulsar Data for Timing

Original time series

Shift and add the pulses

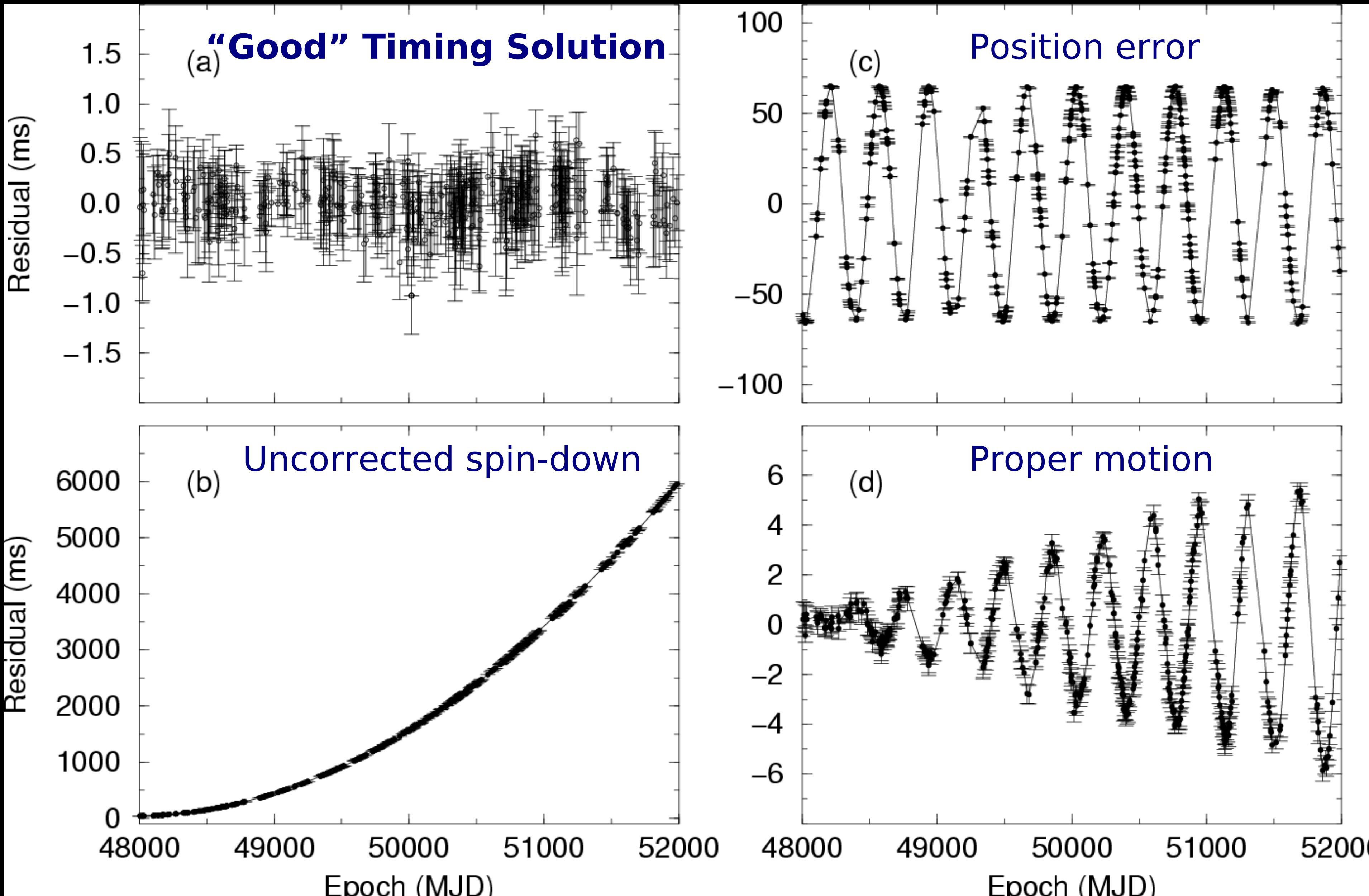




A strong “average” profile that can be cross correlated to get a Time-of-Arrival (TOA)

The science is in the residuals!:

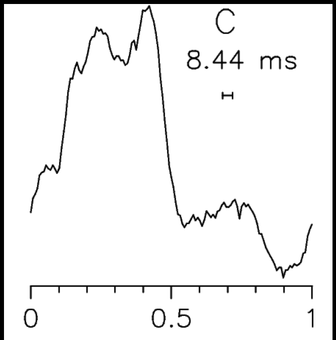
RMS precision ~ 10^{-5}-10^{-3} P

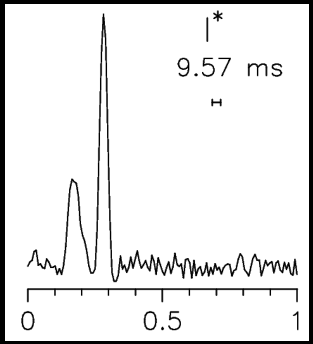


Timing Sensitivity

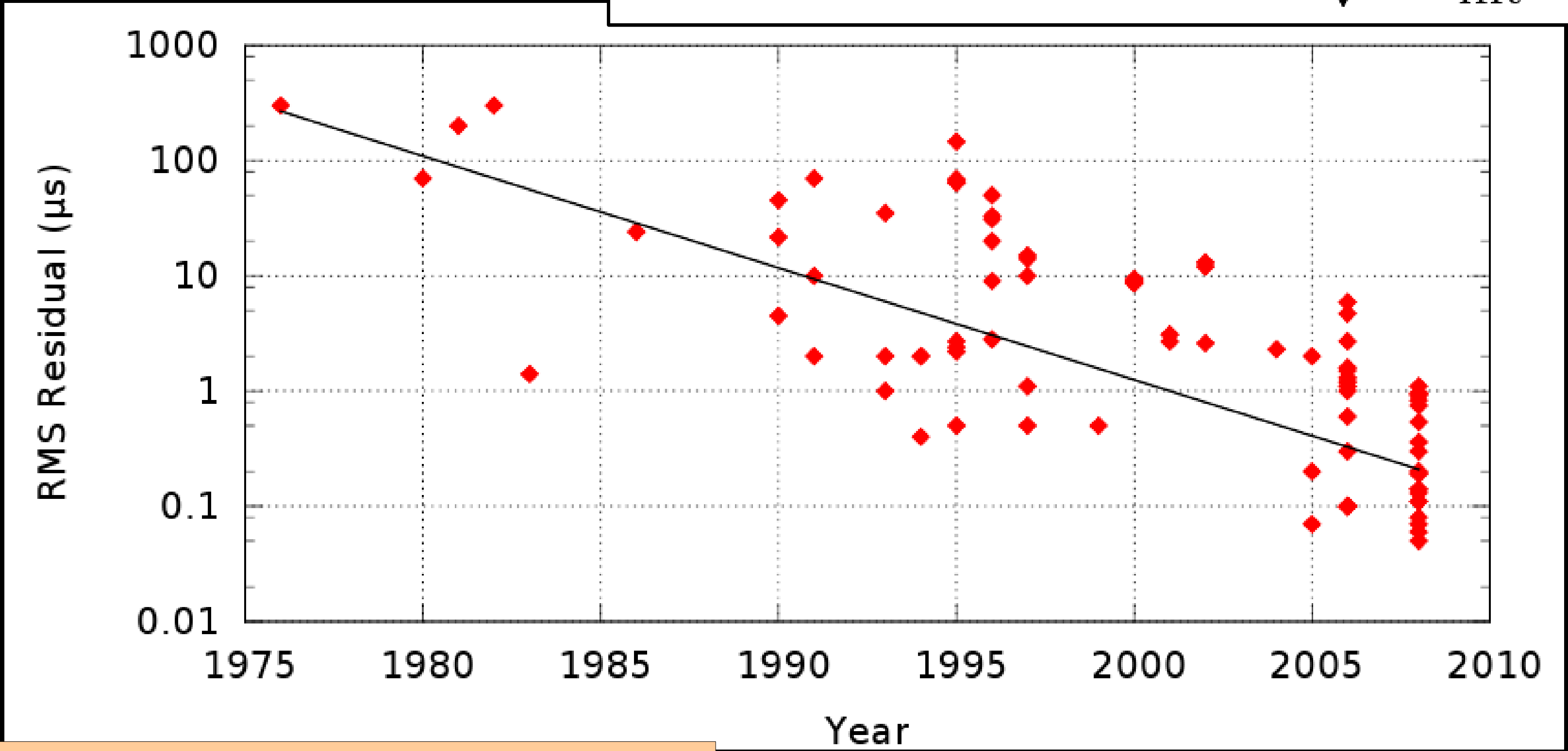
Timing precision depends on:

- Sensitivity (A/Tsys)
- Pulse width (w)
- Pulsar flux density (S)
- Instrumentation





$$\sigma_{\rm TOA} \sim \frac{w}{\rm SNR} \propto \frac{w}{S_{\rm PSR}} \frac{1}{\sqrt{B t_{\rm int}}} \frac{T_{\rm sys}}{A}$$



Jenet & Demorest 2010, in prep.

Precision Timing Example

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

~100 ns RMS timing residuals!

Table 1 PSR J0437−4715 physical parameters

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

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

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

Post-Keplerian Orbital Parameters

General Relativity gives:

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

(Advance of Periastron)

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

(Grav redshift + time dilation)

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

$$r = T_\odot m_2$$

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

(Shapiro delay: “range” and “shape”)

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

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

The Binary Pulsar: B1913+16

- First binary pulsar discovered at Arecibo Observatory by Hulse and Taylor in 1974 (1975, ApJ, 195, L51)

NS-NS Binary

P_{psr} = 59.03 ms

P_{orb} = 7.752 hrs

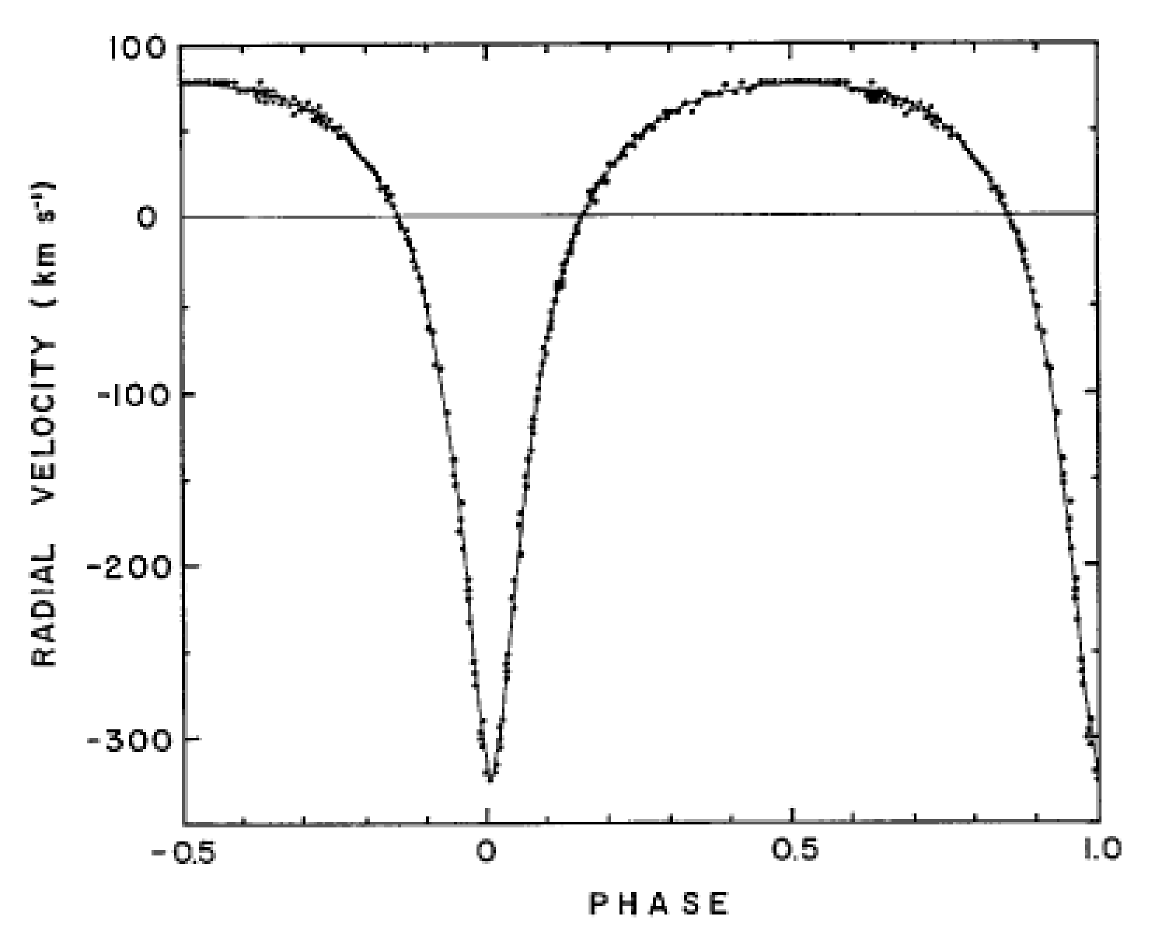
a sin(*i*)/c = 2.342 lt-s

e = 0.6171

$\dot{\omega}$ = 4.2 deg/yr

$M_c = 1.3874(7)\ M_\odot$

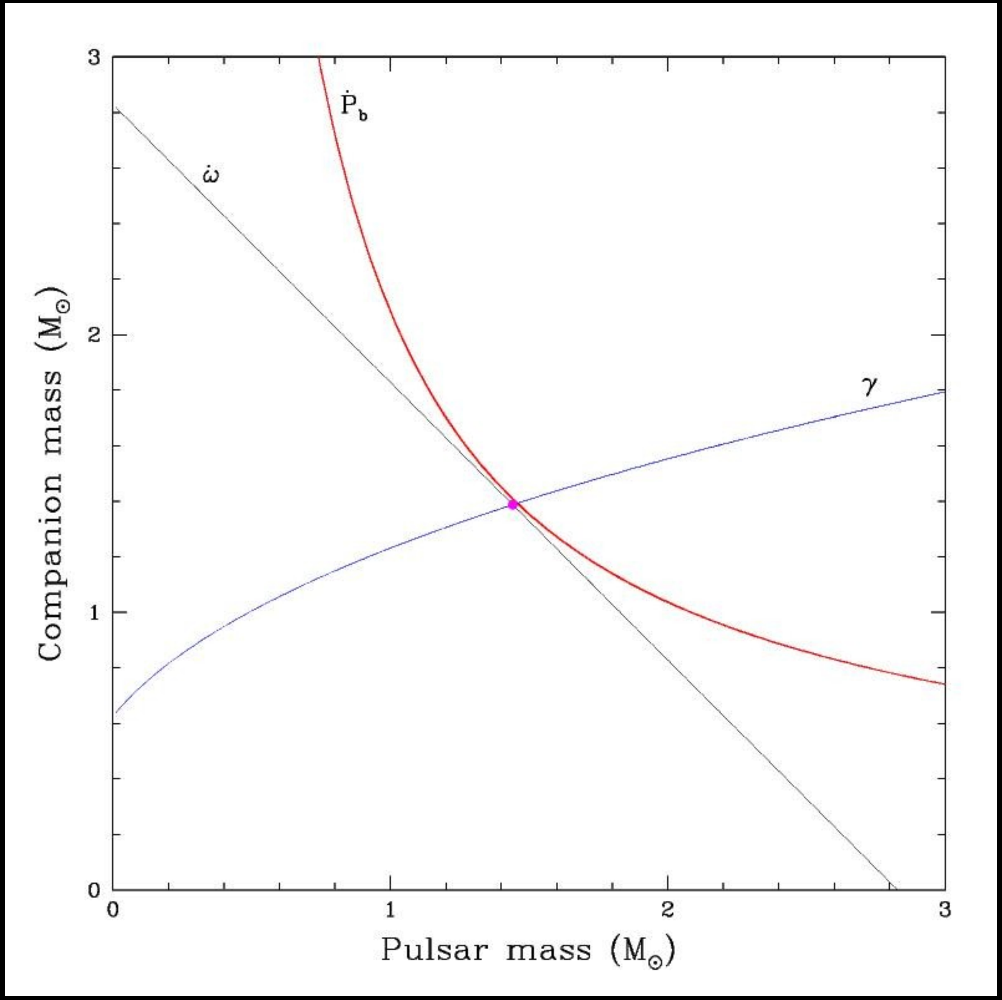
$M_p = 1.4411(7)\ M_\odot$

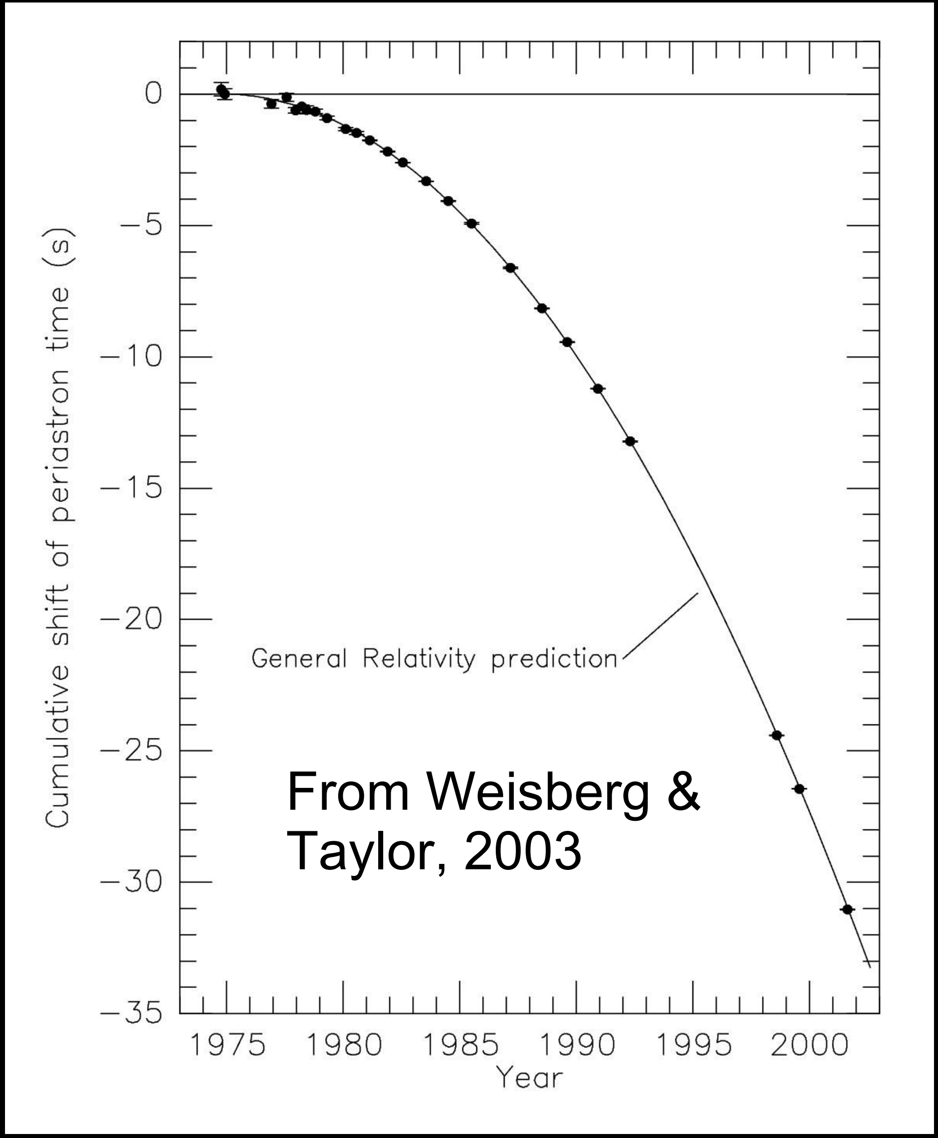


The Binary Pulsar: B1913+16

Three post-Keplerian Observables: $\dot{\omega}$, γ, $\dot{P}_{orb}$

Indirect detection of Gravitational Radiation!

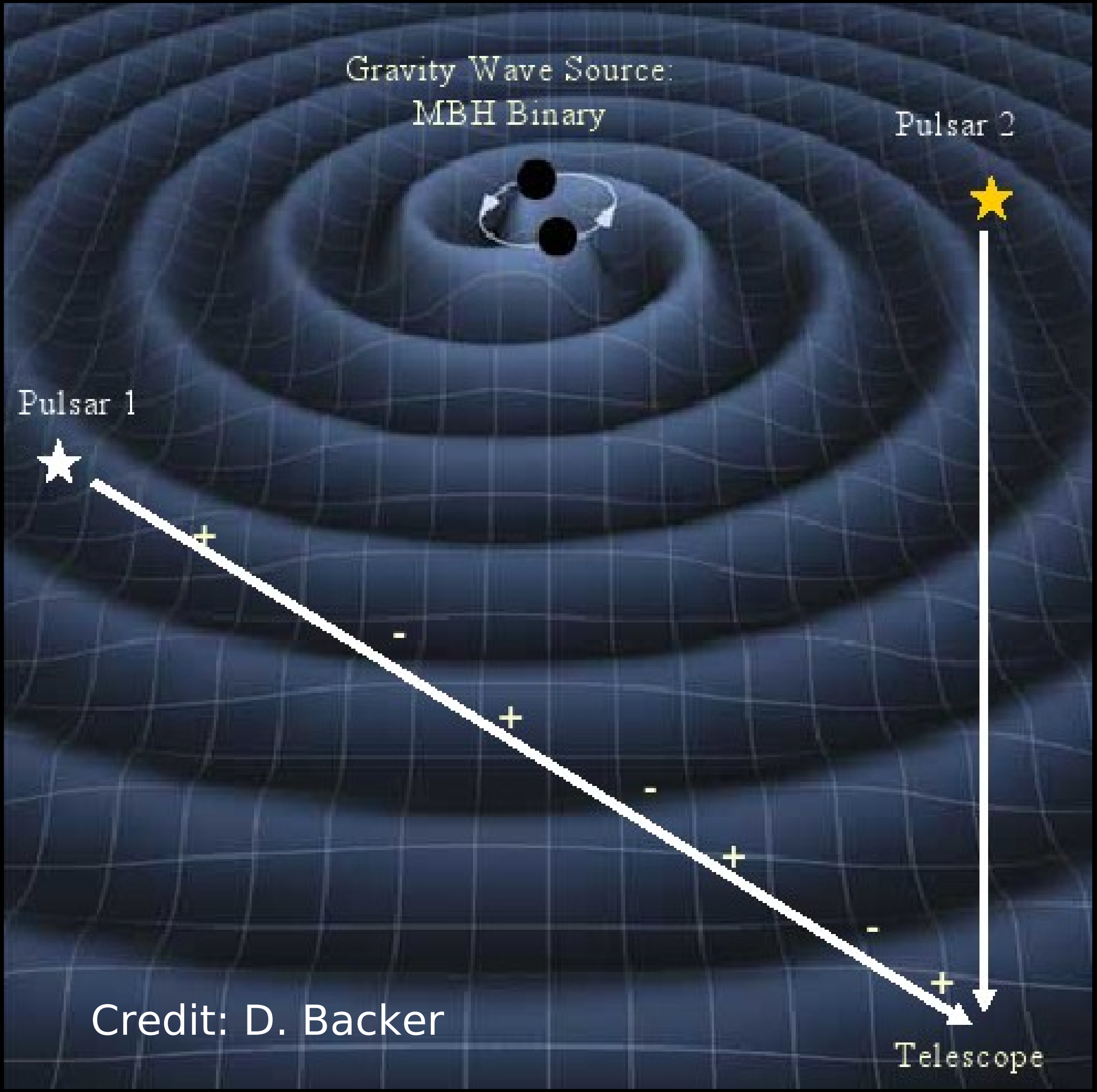




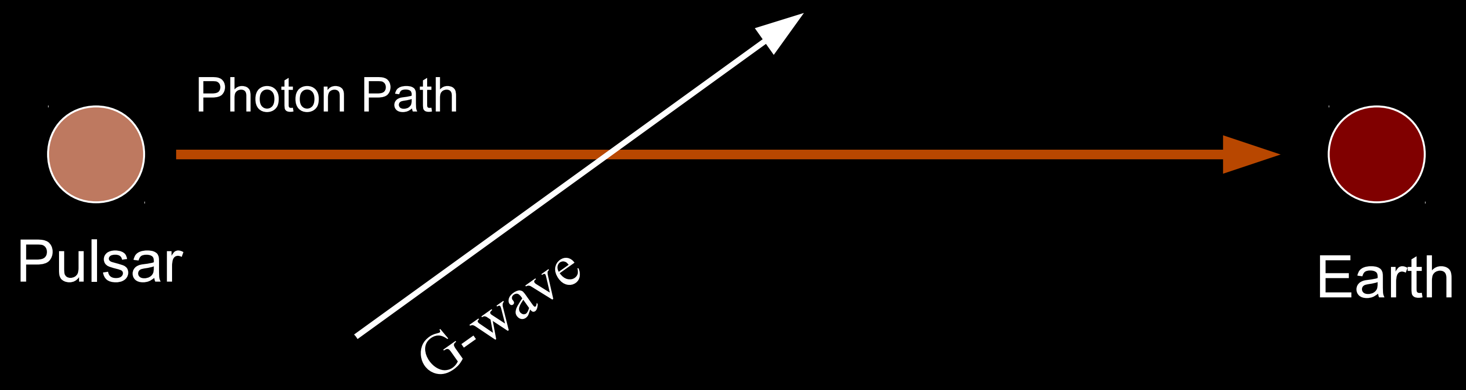
High-precision MSP Timing for Gravitational Wave Detection

e.g. Detweiler, 1979
Hellings & Downs, 1983

- The best MSPs (timing precisions between 50-200 ns RMS) can be used to search for nHz gravitational waves
- ν_{gw} ~1/yrs to 1/weeks
- $h \sim \sigma_{TOA} / T \sim 10^{-15}$
- Sensitivity comparable and complementary to Adv. LIGO and LISA!
- Need best pulsars, instruments, and telescopes!



Pulsars and GW Basics



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

Flat space metric with perturbations

$$\frac{\delta\omega}{\omega} = \frac{1\xi^0 k^0}{2\xi^\mu k_\nu} \hat{k}^i \hat{k}^j \int_{s_0}^{s_1} h_{ij,s}\, ds$$

Frequency shifts occur along the photon path based on the G-wave

$$\frac{\delta\nu}{\nu} = -\mathcal{H}_{ij}\left[h_{ij}(t_e, x_e^i) - h_{ij}(t_p, x_p^i)\right]$$

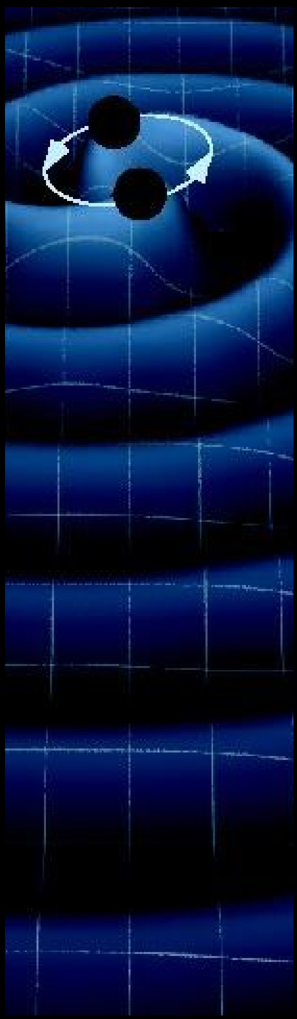
Integral turns out to only be based on the metric at the **Pulsar (then) and Earth (now)**

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

Integrate over the frequency shifts in time to get the timing residuals

So where do these GWs come from?

Coalescing Super-Massive Black Holes

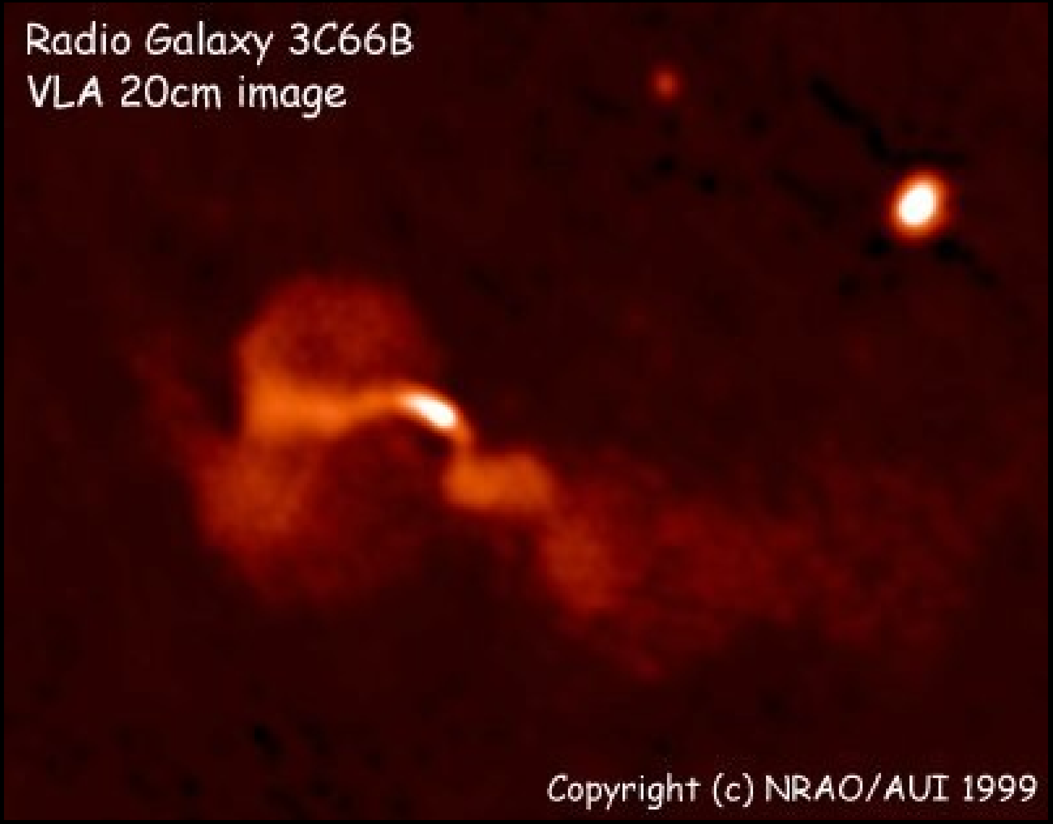


- Basically all galaxies have them
- Masses of $10^6 - 10^9\ M_\odot$
- Galaxy mergers lead to BH mergers
- When BHs within 1pc, GWs are main energy loss
- For total mass *M/(1+z)*, distance d_L, and SMBH orbital freq *f*, the induced timing residuals are:

$$\Delta\tau \sim 10\,\mathrm{ns}\left(\frac{1\,\mathrm{Gpc}}{\mathrm{d_L}}\right)\left(\frac{\mathrm{M}}{10^9\,\mathrm{M}_\odot}\right)^{5/3}\left(\frac{10^{-7}\,\mathrm{Hz}}{f}\right)^{1/3}$$

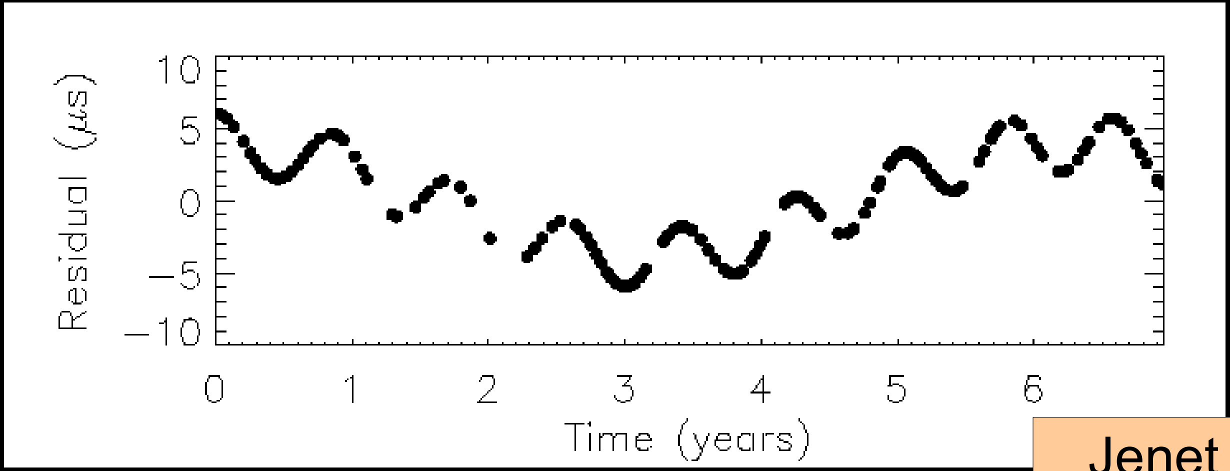
Potentially measurable with a single MSP!

So where do these GWs come from?



3C66B

At $z = 0.02$
Orbital period 1.05 yrs
Total mass $5.4\times10^{10}\,M_\odot$
(Sudou et al 2003)



Predicted timing residuals

Ruled out by MSP observations

Jenet et al. 2004, ApJ, 606, 799

Stochastic GW Backgrounds

An ensemble of many individual GWs, from different directions and at different amplitudes and frequencies

Characteristic strain spectrum is (basically) a power law:

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

But see Sesana et al 2008

Table 1: The expected parameters for predicted stochastic backgrounds

Model	A	α	References
Supermassive black holes	$10^{-15} - 10^{-14}$	$-2/3$	Jaffe & Backer (2003)
			Wyithe & Loeb (2003)
			Enoki et al. (2004)
Relic GWs	$10^{-17} - 10^{-15}$	$-1 - -0.8$	Grishchuk (2005)
Cosmic String	$10^{-16} - 10^{-14}$	$-7/6$	Maggiore (2000)

The amplitude is the only unknown for each model

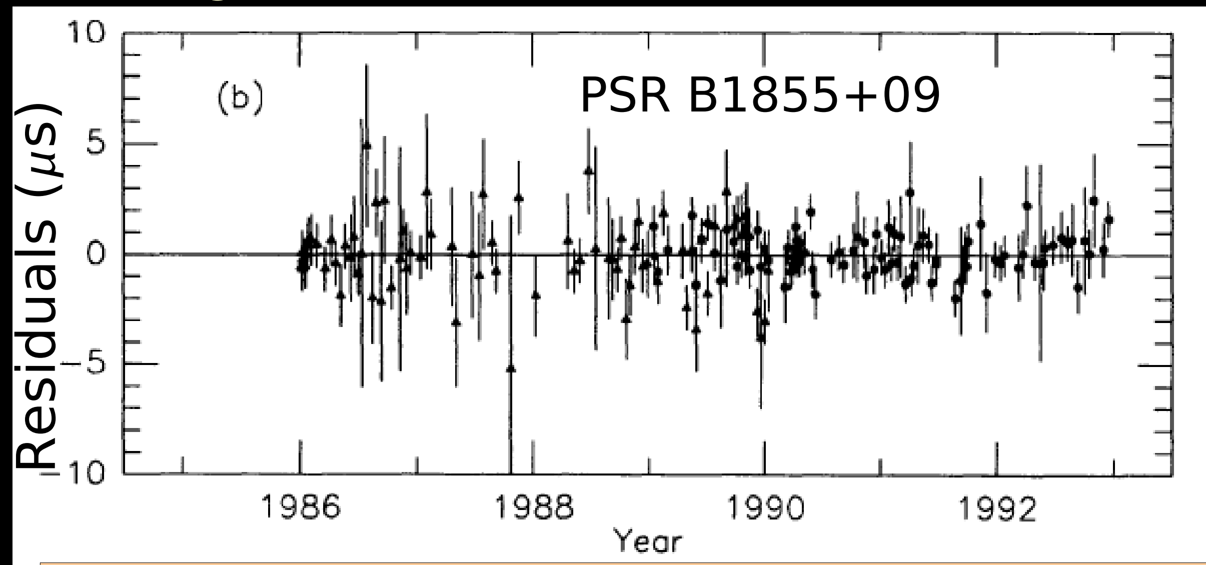
e.g. Jenet et al. 2006, ApJ, 653, 1571

Best Single Pulsar Limits

Power spectrum of induced timing residuals:

$$P(f) = \frac{1}{12\pi^2}\frac{1}{f^3}h_c(f)^2$$

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



Kaspi, Taylor, Ryba. 1994, ApJ, 428, 713

Source(s)	C/I	T (yr)	$\Omega_{GW}(1/T)h^2$	$h_c(1\ \mathrm{yr}^{-1})$	Reference
B1133+16, B1237+25, B1604–00, B2045–16	C	12	$< 1 \times 10^{-4}$	$< 9.1 \times 10^{-13}$	Hellings and Downs (1983)
B1855+09, B1937+21	I	8	$< 6 \times 10^{-8}$	$< 1.9 \times 10^{-14}$	Kaspi et al. (1994)
B1855+09, ...	I	8	$< 2 \times 10^{-8}$	$< 1.1 \times 10^{-14}$	Jenet et al. (2006)
J1713+0747, B1855+09	I	20	$< 2 \times 10^{-9}$	$< 4.9 \times 10^{-15}$	Lommen et al. (2007)

Demorest 2007, PhD Thesis

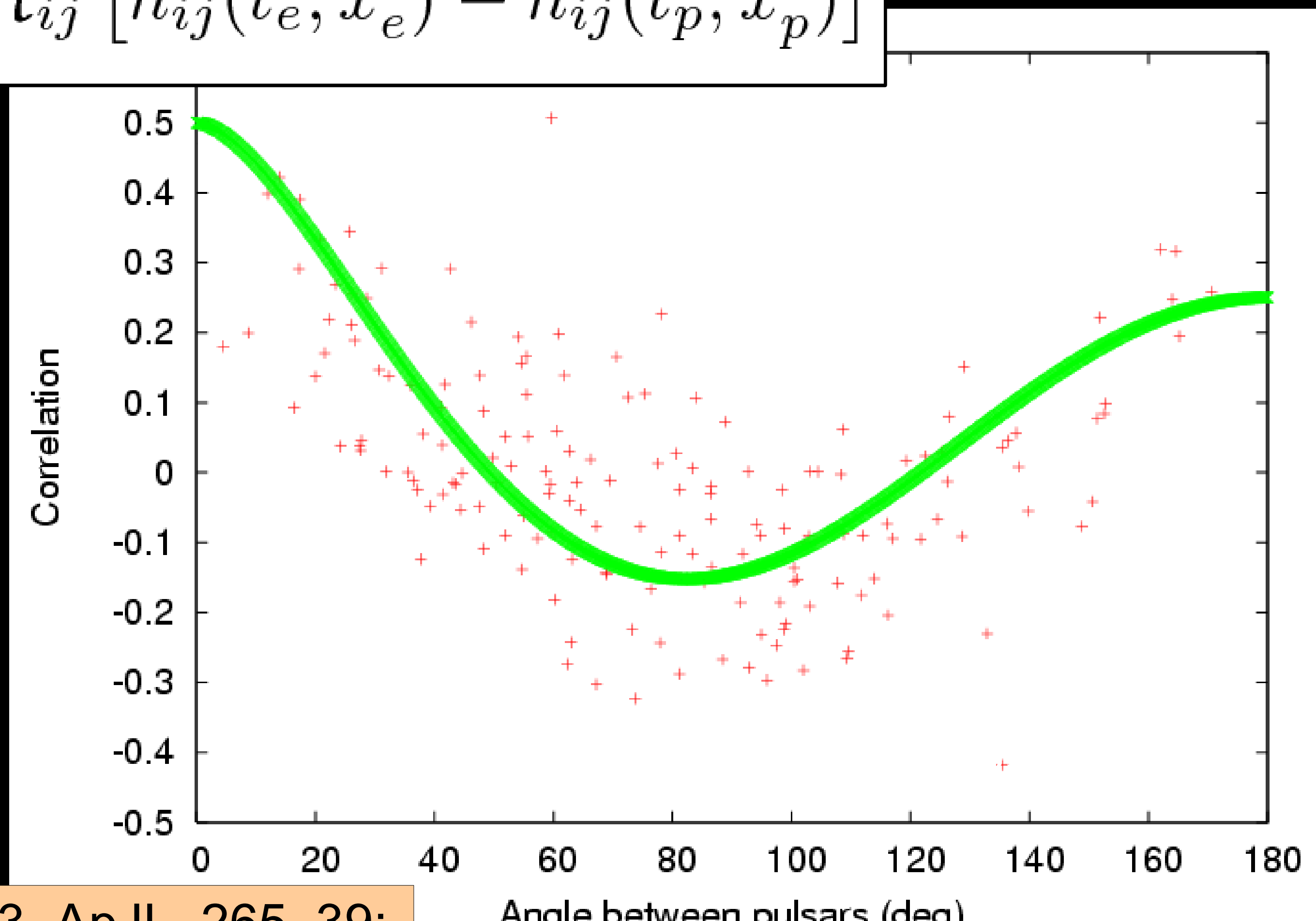
A Pulsar Timing Array (PTA)

Timing residuals due to a GW have two components:

"Pulsar components" are uncorrelated between MSPs

"Earth components" are **correlated** between MSPs

$$\frac{\delta\nu}{\nu} = -\mathcal{H}_{ij}\left[h_{ij}(t_e, x_e^i) - h_{ij}(t_p, x_p^i)\right]$$



Signal in Residuals

Clock errors:
monopole

Ephemeris errors:
dipole

GW signal:
quadrupole

e.g. Hellings & Downs, 1983, ApJL, 265, 39; Jenet et al. 2005, ApJL, 625, 123

GW Detection with a Pulsar Timing Array

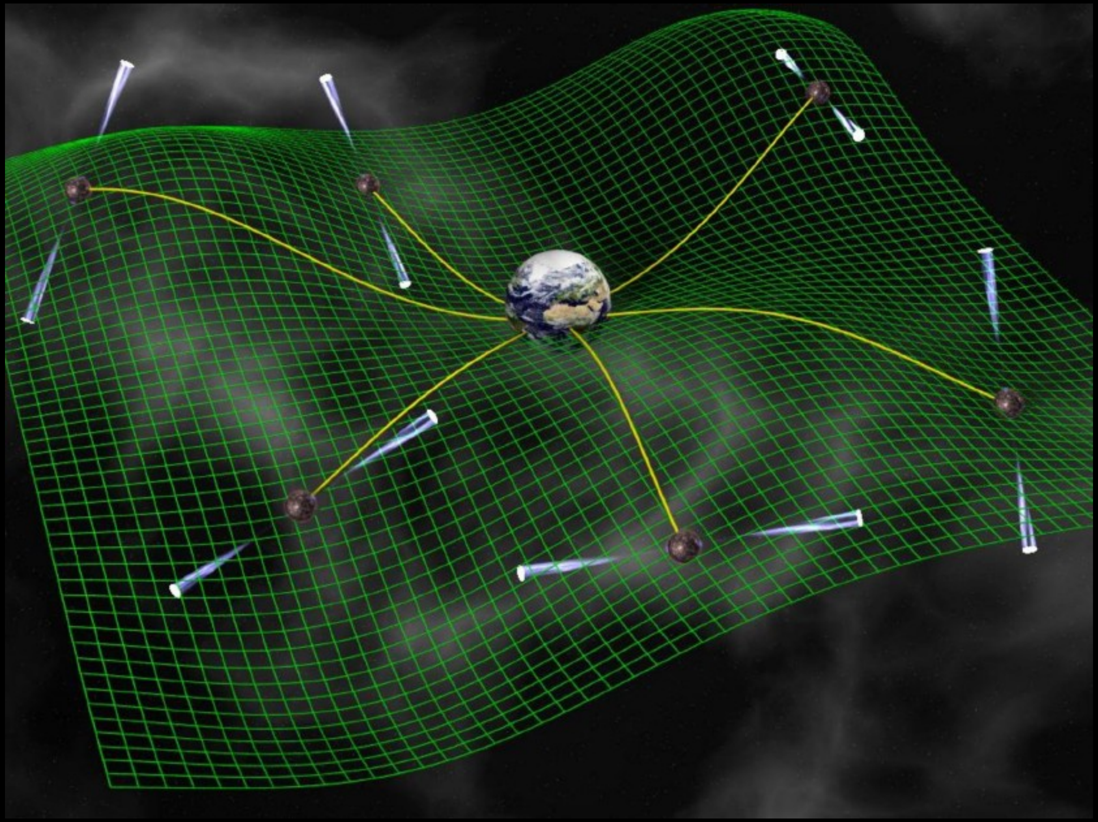
- Need good MSPs and lots of time (patience)
- Significance scales linearly with the number of MSPs

$$\mathrm{SNR} \propto \frac{A^2}{\sigma^2} N_{\mathrm{PSRs}} N_{\mathrm{TOAs}} T^{-2\alpha+2}$$

$$\mathrm{SNR}_{\mathrm{SMBHs}} \propto \frac{A^2}{\sigma^2} N_{\mathrm{PSRs}} N_{\mathrm{TOAs}} T^{10/3}$$

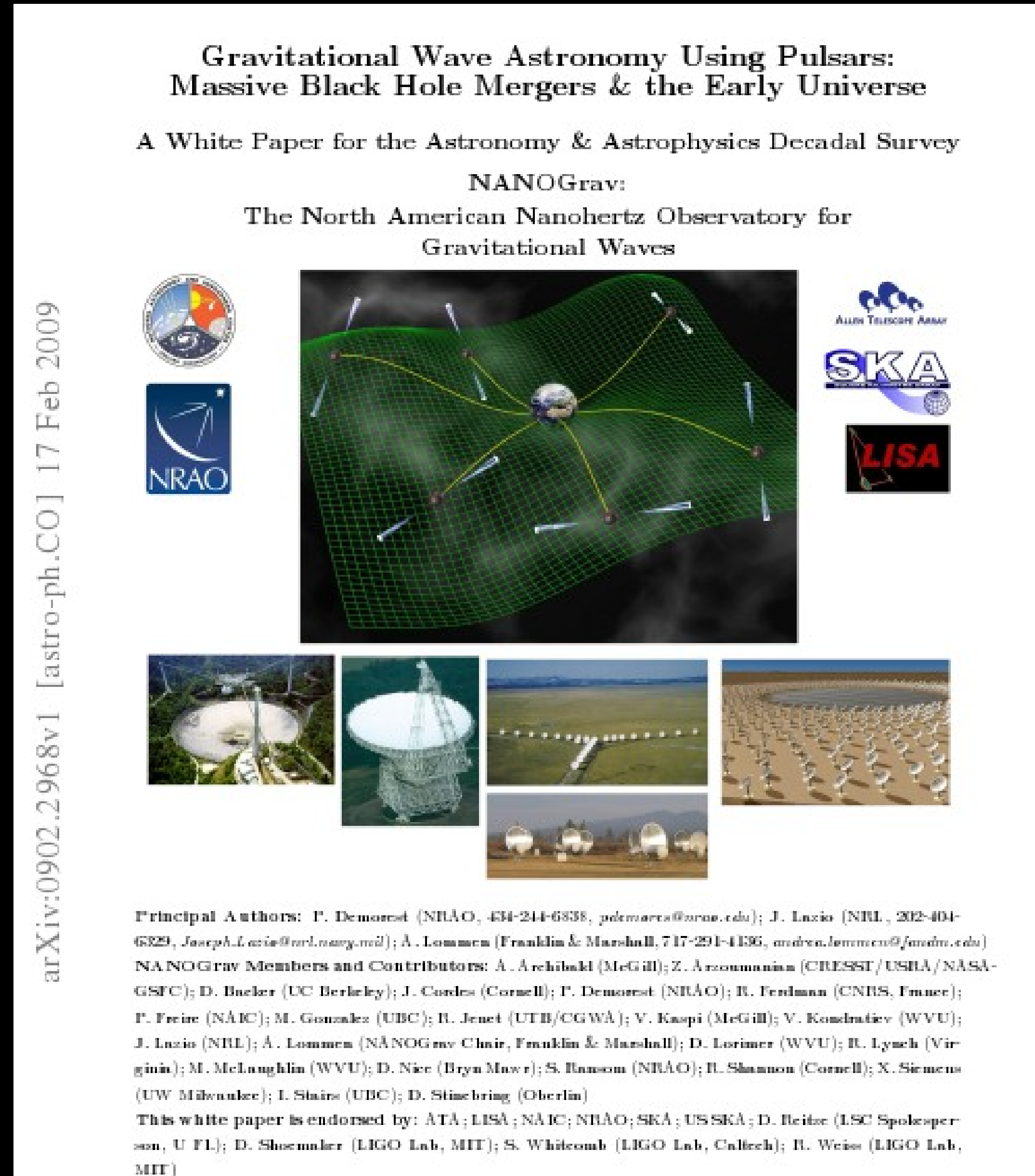
Canonical PTA:

- Bi-weekly, multi-freq obs for 5-10 years
- ~20-40 MSPs with ~100 ns timing RMS
- This is not easy...



NANOGrav

- About 22 members from North America
- Observing ~20 MSPs
- Using Arecibo and the GBT via 2 large projects (PI Paul Demorest)
- 2 obs freqs at GBT, 2-3 at Arecibo per PSR
- RMS residuals from ~100ns to 1.5us
- First 4 years of data limit $h_c(1yr^{-1}) < 7x10^{-15}$ comparable to 20yrs of single MSP



arXiv:0902.2968v1 [astro-ph.CO] 17 Feb 2009

Gravitational Wave Astronomy Using Pulsars: Massive Black Hole Mergers & the Early Universe

A White Paper for the Astronomy & Astrophysics Decadal Survey

NANOGrav:
The North American Nanohertz Observatory for Gravitational Waves

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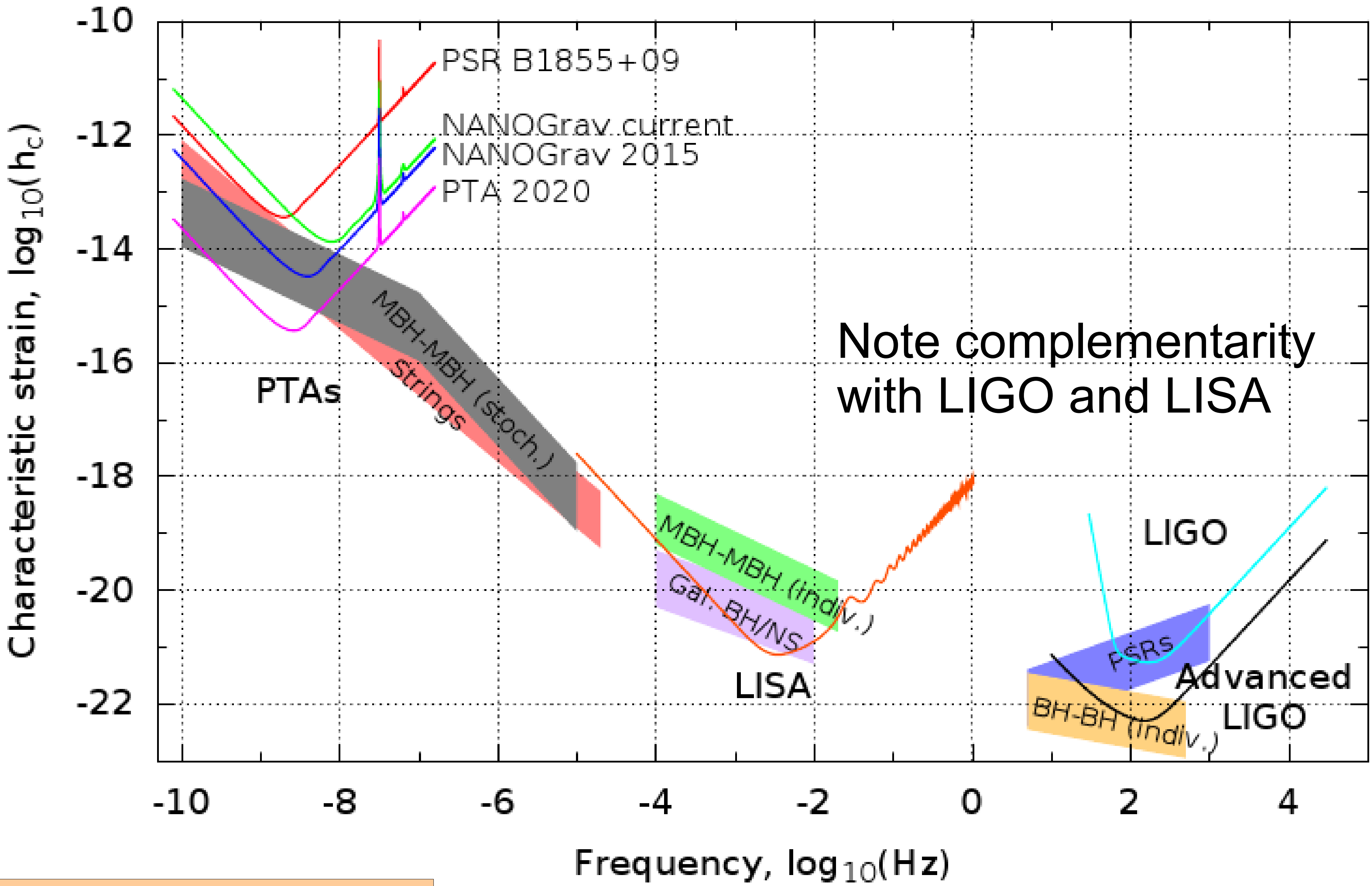
This white paper is endorsed by: ATA; LISA; NAIC; NRAO; SKA; US SKA; D. Reitze (LSC Spokesperson, U FL); D. Shoemaker (LIGO Lab, MIT); S. Whitcomb (LIGO Lab, Caltech); R. Weiss (LIGO Lab, MIT)

arXiv:0902.2968 and arXiv:0909.1058

http://nanograv.org

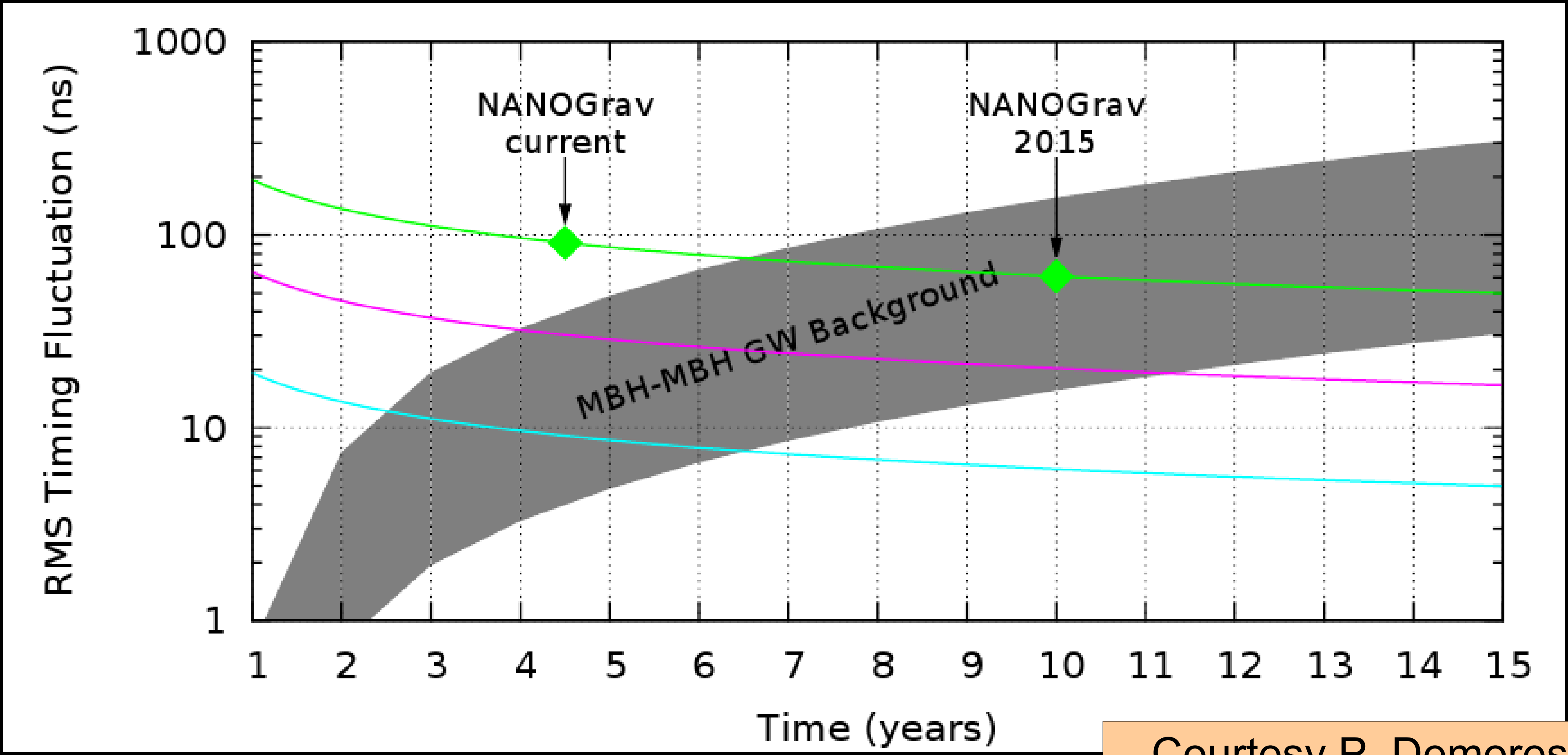
NANOGrav improvement with time...



Note complementarity with LIGO and LISA

Courtesy P. Demorest

NANOGrav improvement with time...



Courtesy P. Demorest

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

So how do we improve?

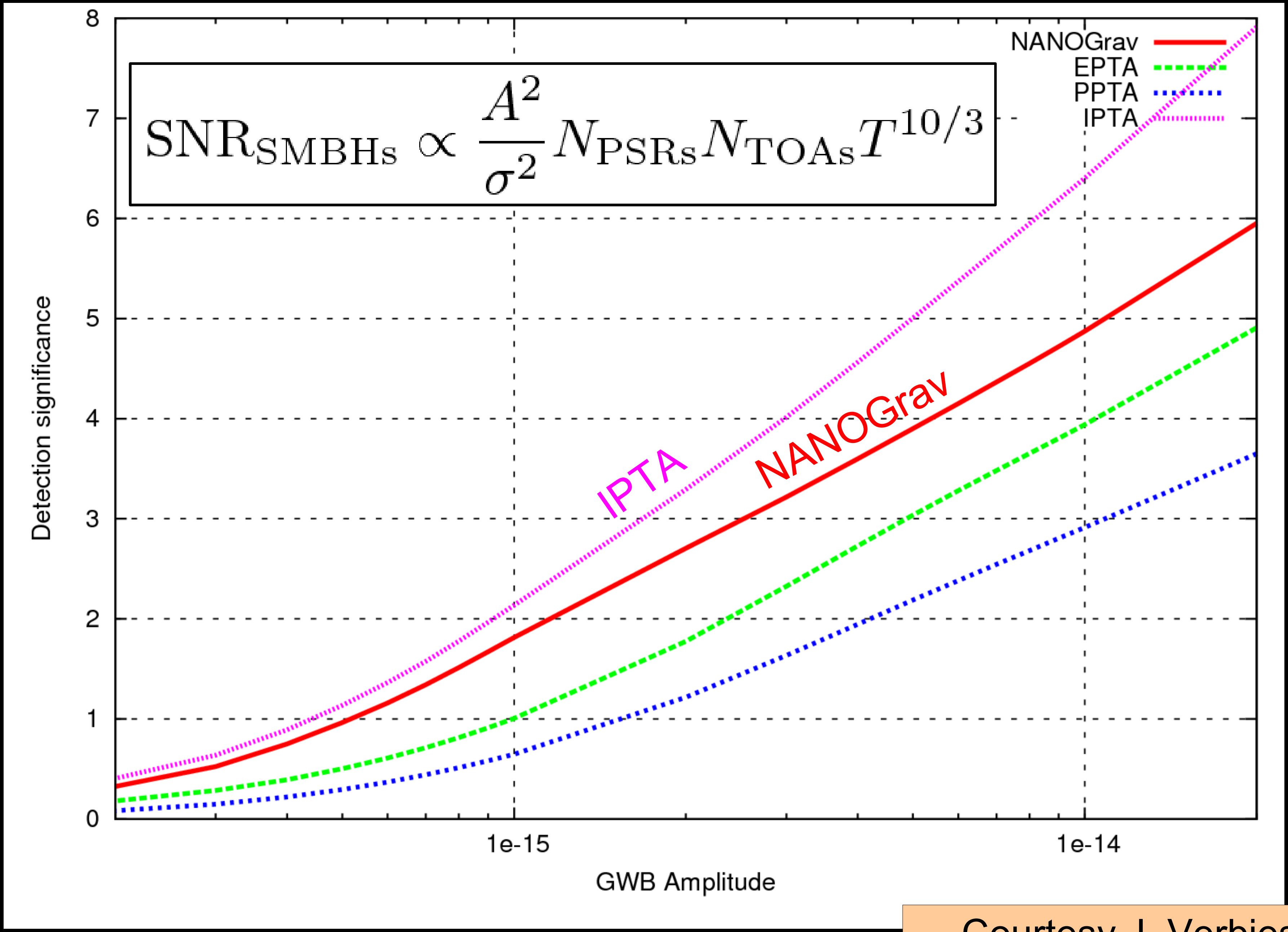
(in approx order of difficulty)

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

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

International PTA

International PTA (5yr campaign)



Courtesy J. Verbiest

GUPPI: A Pulsar "Dream Machine" for the GBT

800 MHz BW coherent de-dispersion backend

9x more BW ~ 3x more sensitive

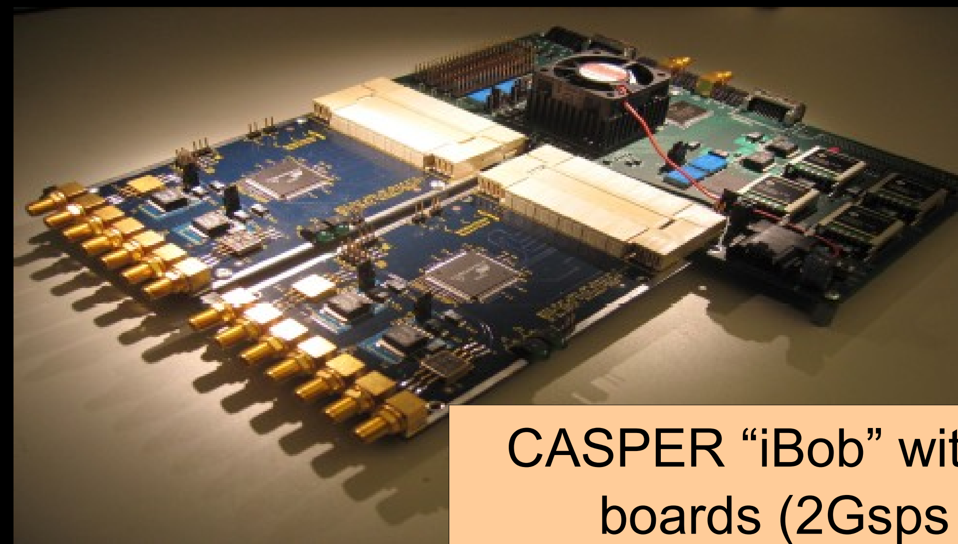
High dynamic range (8-bit sampling) with full polarization

Large improvement in timing precision and "control" of ISM effects

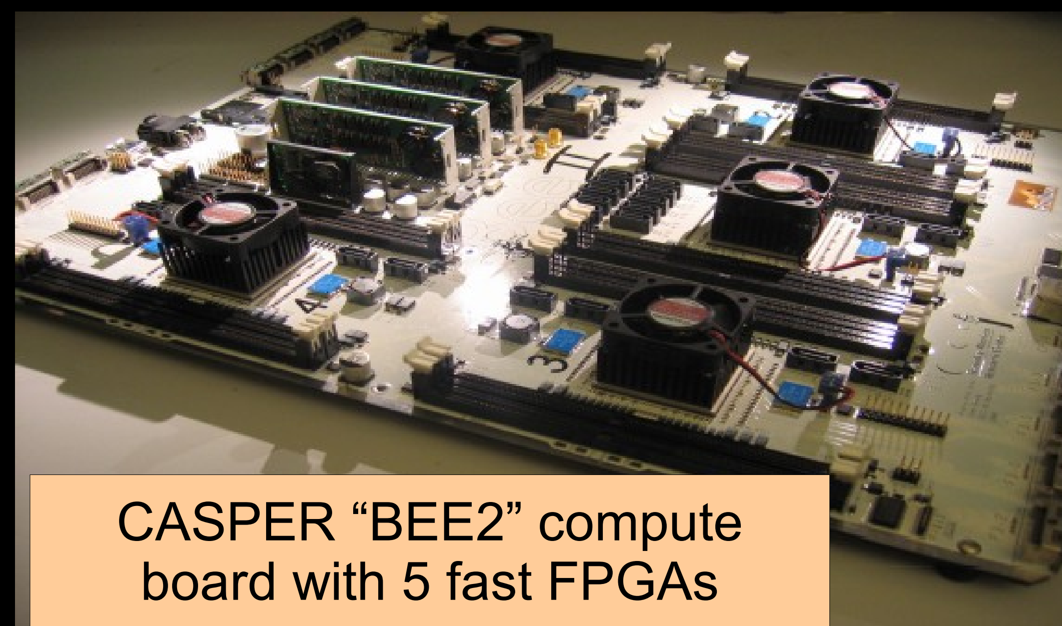
"CASPER" FPGA-based technology from Berkeley

Ready by end of 2009!

e.g. Parsons et al 2006; http://seti.berkeley.edu/casper/



CASPER "iBob" with 2xADC boards (2Gsps each)



CASPER "BEE2" compute board with 5 fast FPGAs

GUPPI: A Pulsar “Drea … GBT

- 800 MHz BW coherent de-dispersion backend
- 9x more BW ~ 3x more sensitive
- High dynamic range (8-bit sampling) with full polarization
- Large improvement in timing precision and “control” of ISM effects
- “CASPER” FPGA-based technology from Berkeley
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e.g. Parsons et al 2006;
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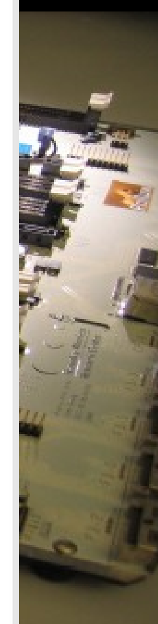
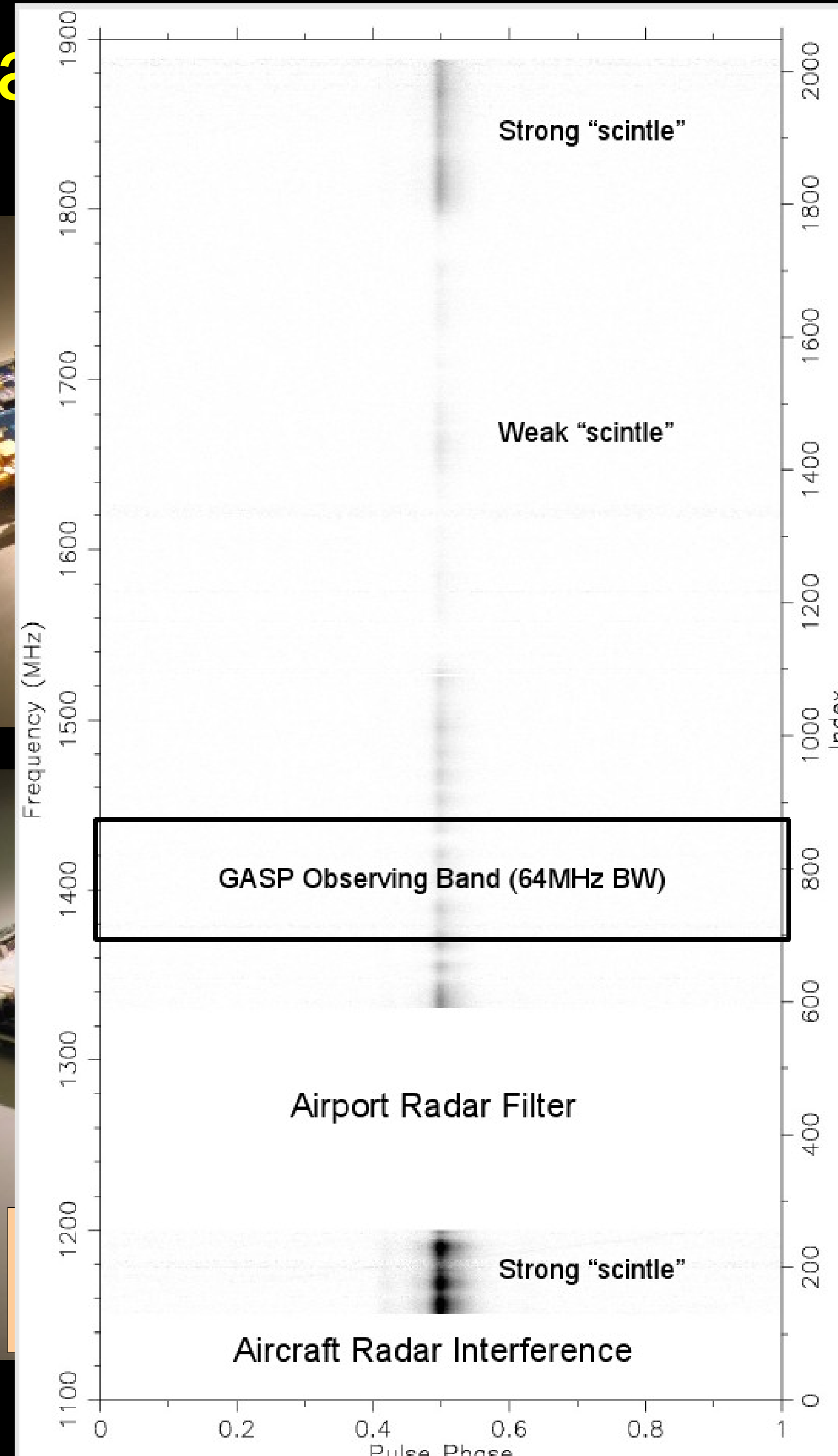
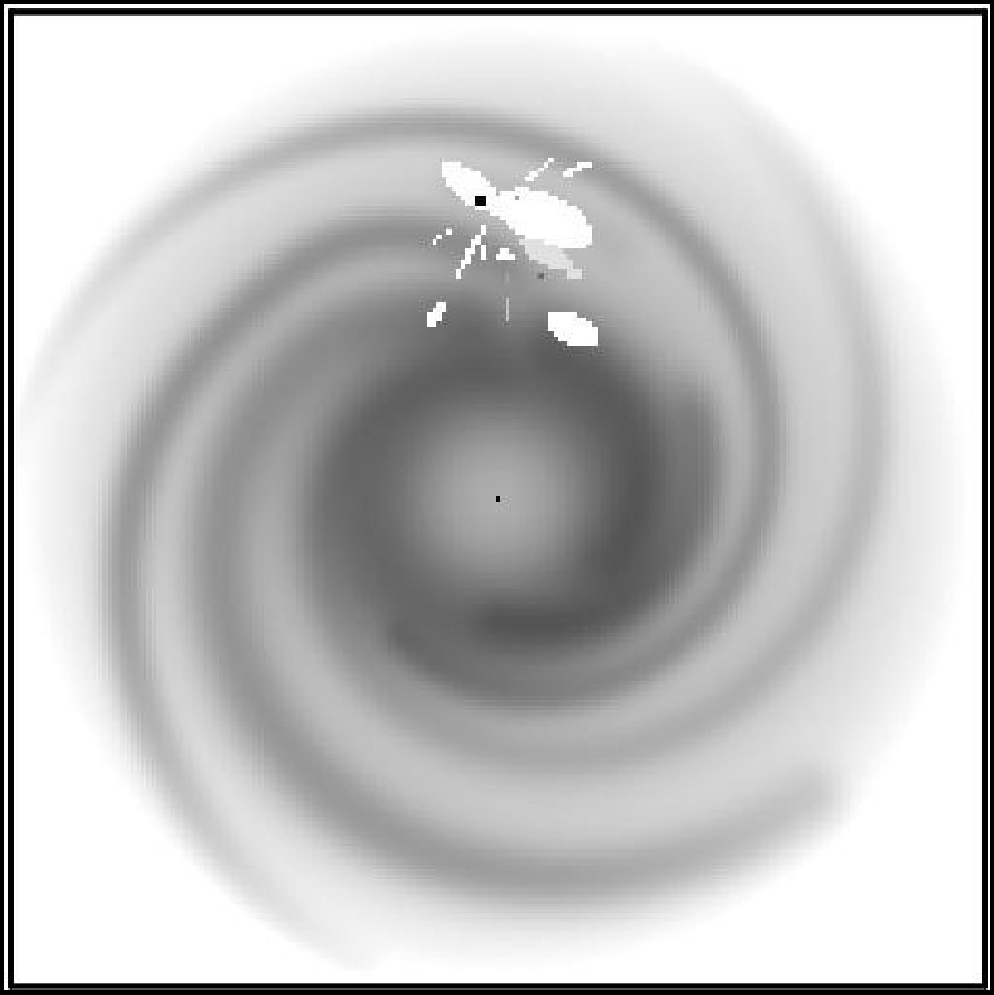


ADC
n)



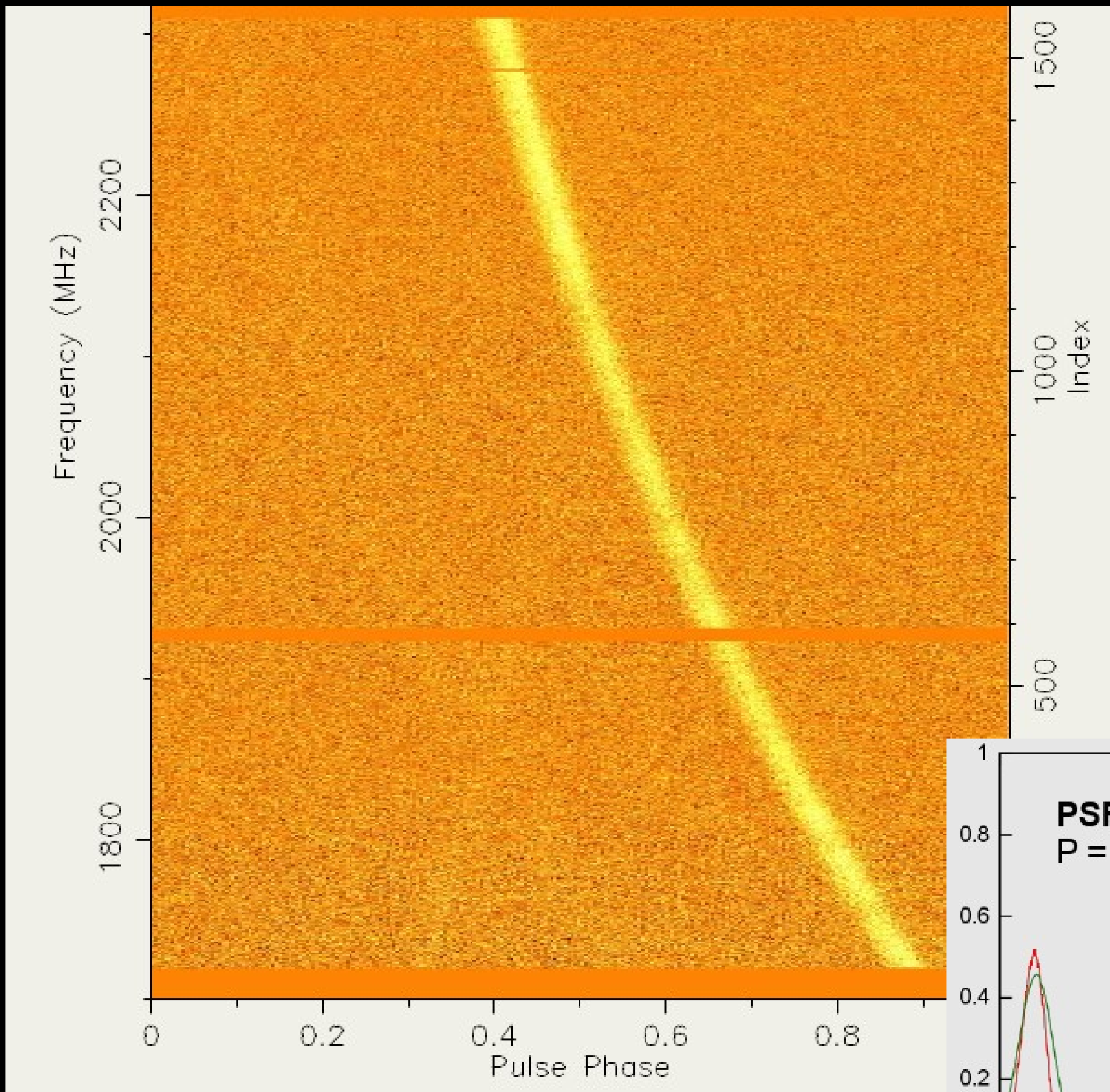
Galactic ISM: electrons and radio waves...

- Turbulent, Ionized ISM causes several time and radio frequency dependent effects:
  - Dispersion
  - Faraday Rotation
  - Multi-path propagation
    - Scintillation
    - Scattering
- Some effects are removable, others aren't (yet?)...
- Much work ongoing in this area (see recent papers by Stinebring, Walker, Demorest, Cordes, Shannon, Rickett etc)



From Cordes and Lazio 2001 (NE2001)

Dispersion

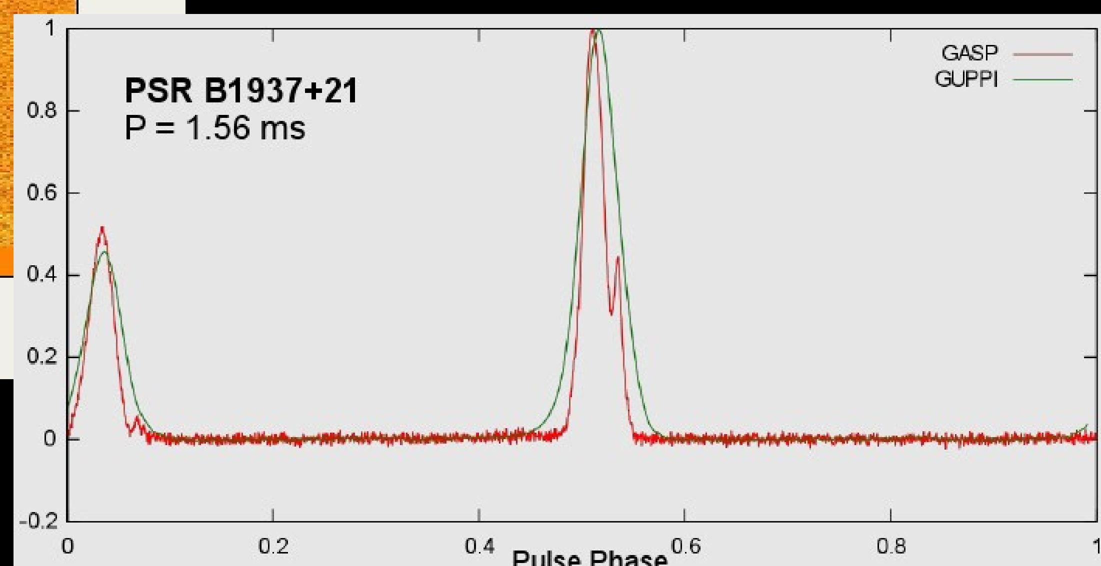


Lower frequency radio waves are delayed with respect to higher frequency radio waves by the ionized interstellar medium

$$\Delta t \propto DM\nu^{-2}$$

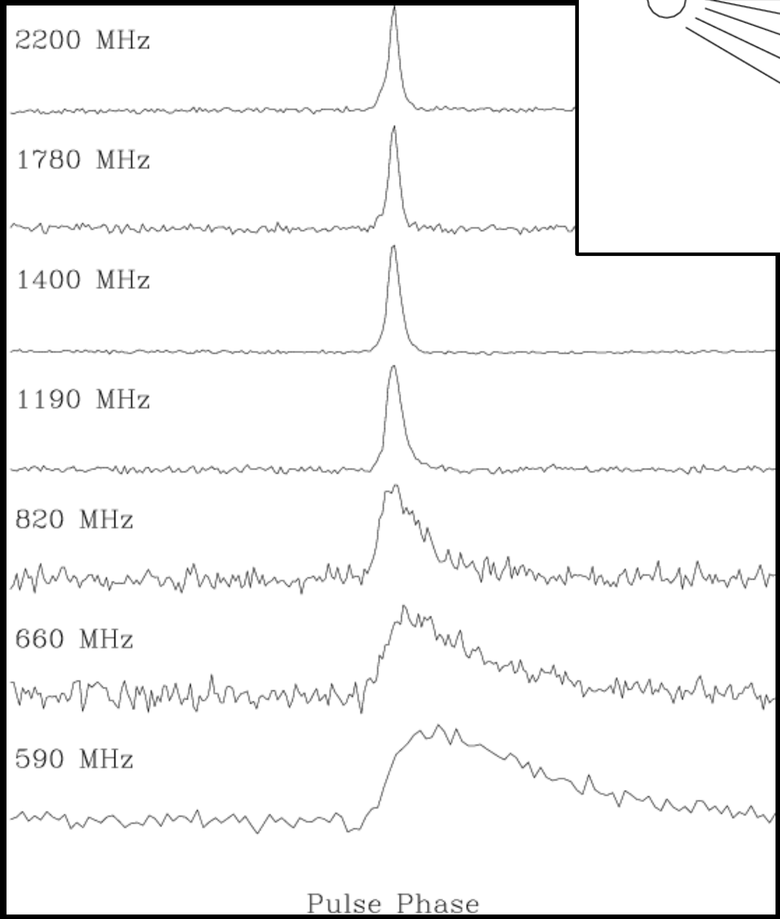
(DM = Dispersion Measure)

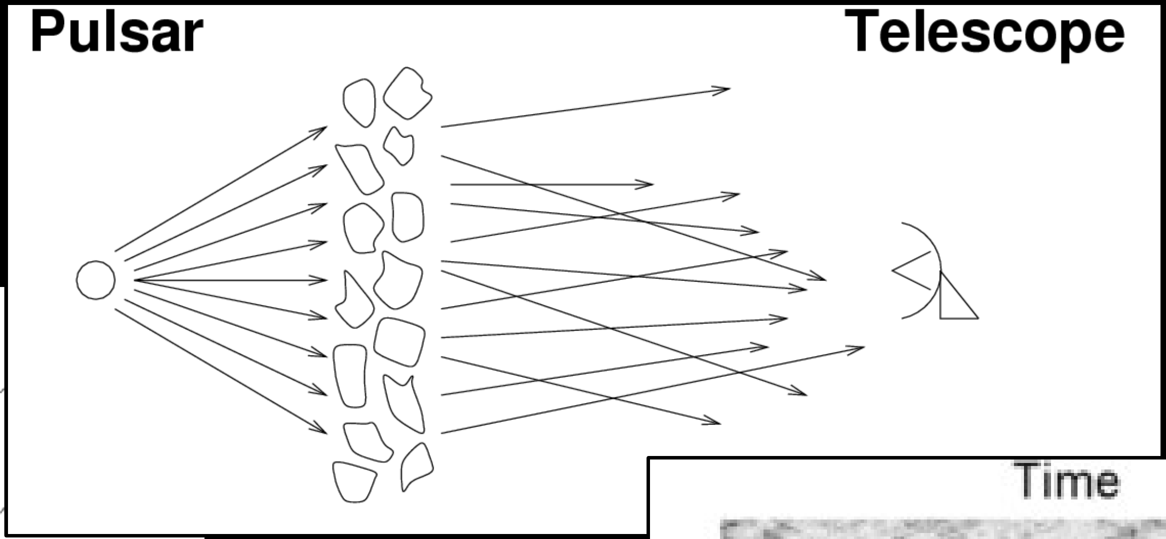
Coherent Dedispersion *exactly* removes this effect

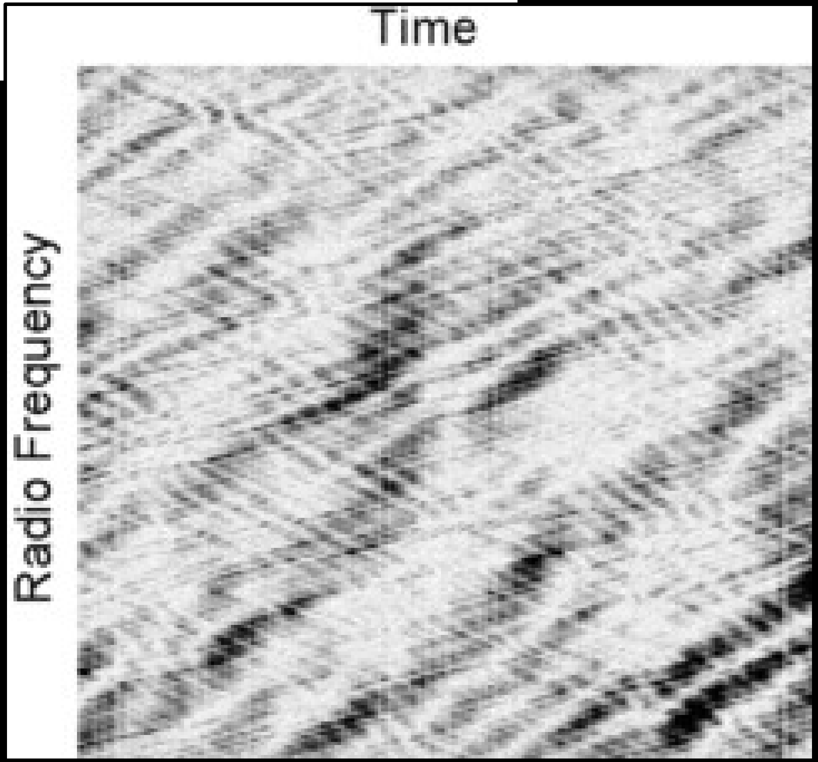


Pulse Broadening and Scintillation

$$\Delta\tau \propto \nu^{4}$$



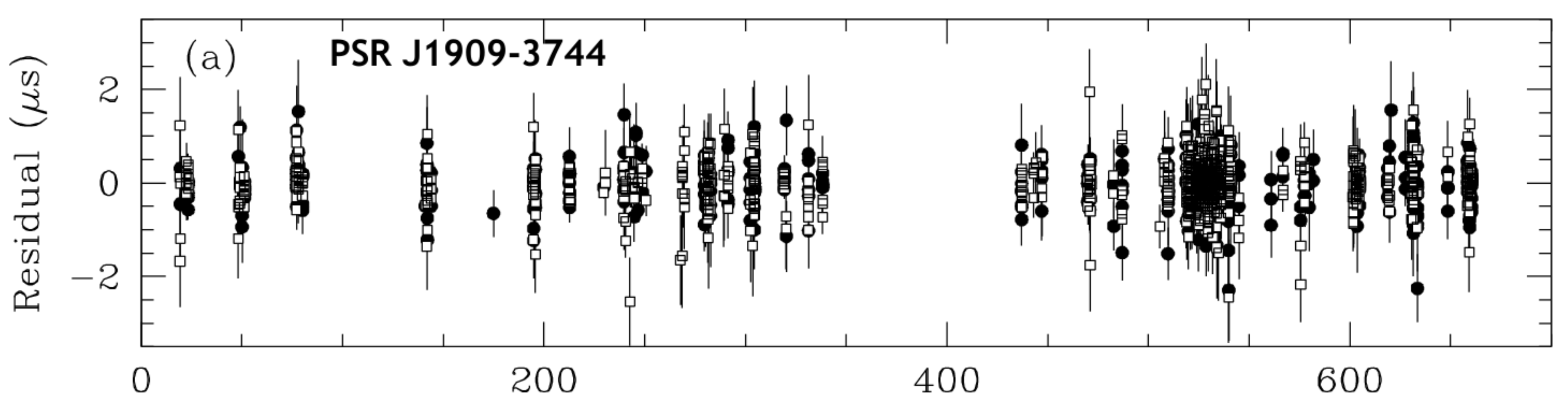




Multipath causes freq dependent pulse broadening and scintillation.

More MSPs

- Several large-scale searches for pulsars ongoing around the world: (GBT, Arecibo, Parkes, Effelsberg)
- MSPs are prime target: know ~1% of total in Galaxy
- Many bright and high-precision MSPs have yet to be discovered – some are very nearby
- Lots of "secondary" science



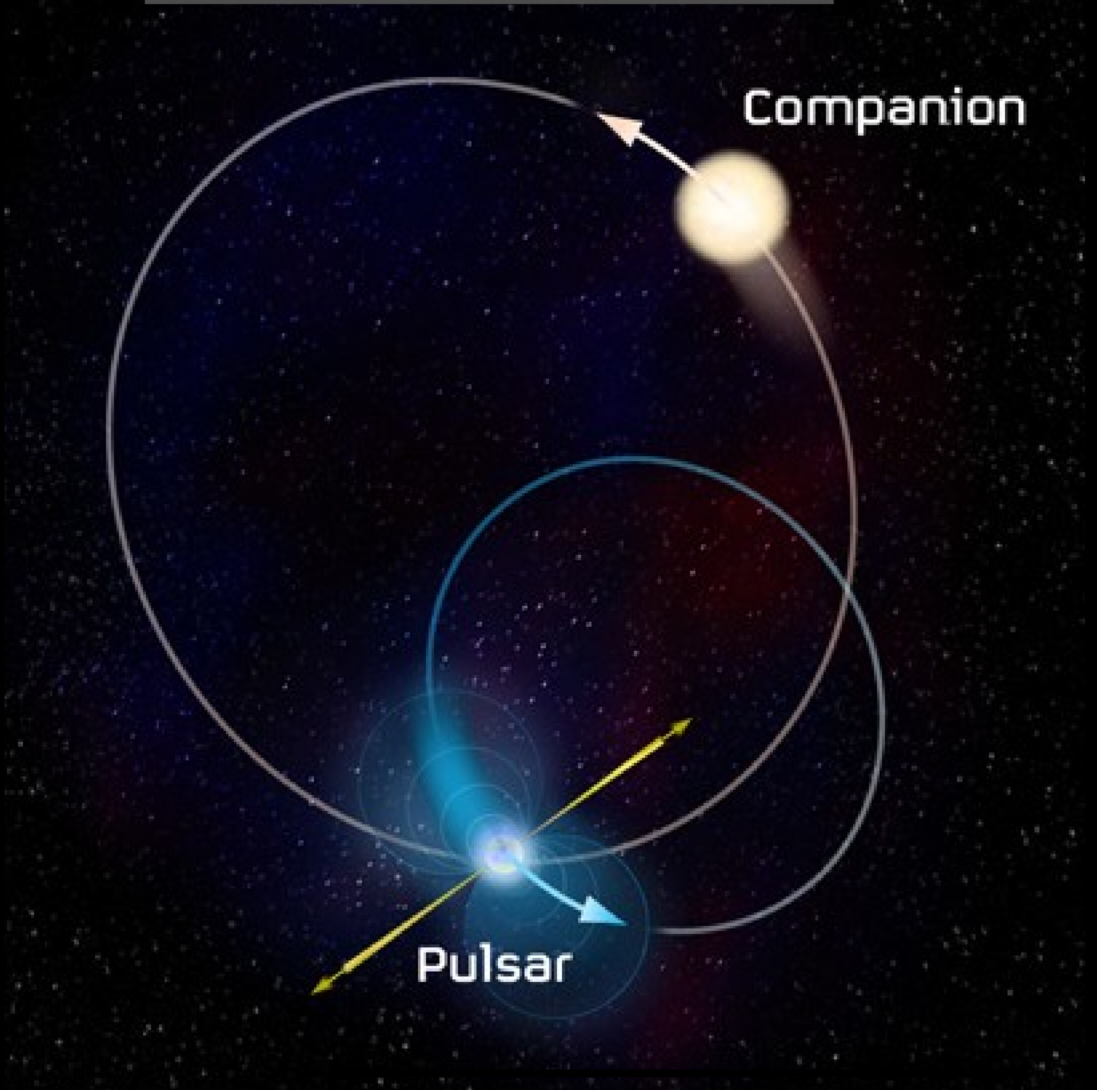
(From Jacoby et al. 2005, ApJL, 629, 113)

PSR J1903+0327 with Arecibo P-ALFA

Champion et al. 2008, *Science*, 320, 1309

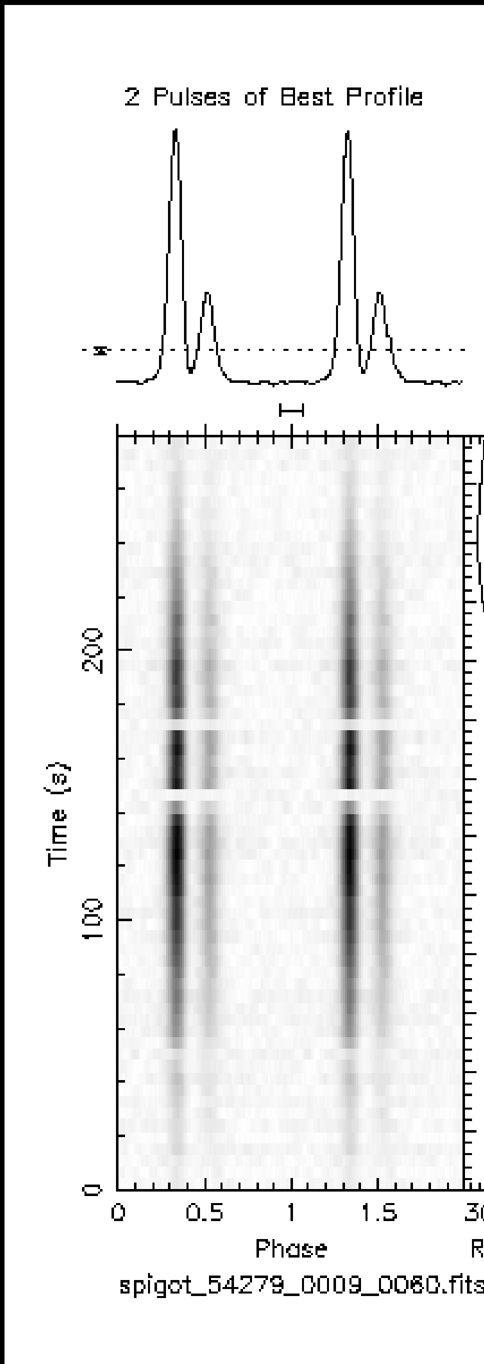
This thing is weird.

- Fully recycled PSR
- Highly eccentric orbit
- Massive likely main-sequence star companion
- Massive NS (1.7 Msun)
- High precision timing despite being distant and in Galactic plane

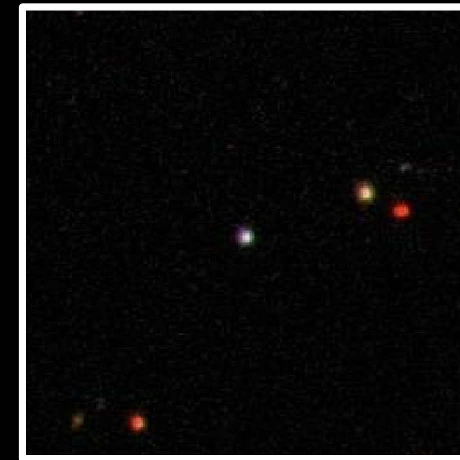


Bill Saxton, NRAO/AUI/NSF

PSR J1023+0038 is a "Missing Link" (w/ GBT)



Previously (over last 10 yrs) detected in FIRST, optical images/spectra, and X-rays and identified as a strange CV or a quiescent LMXB!

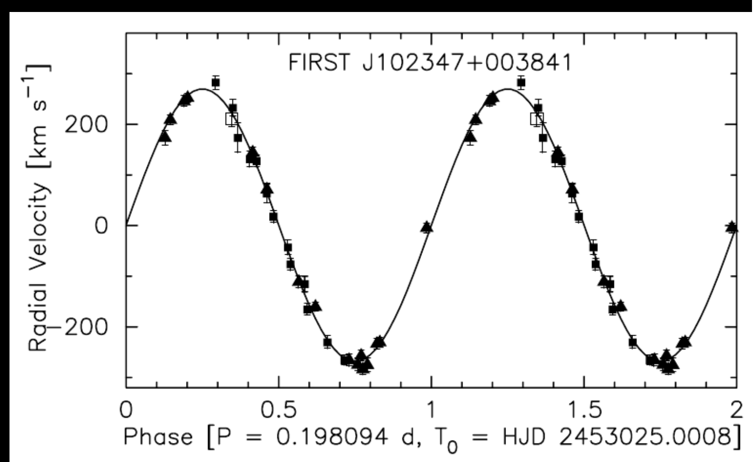


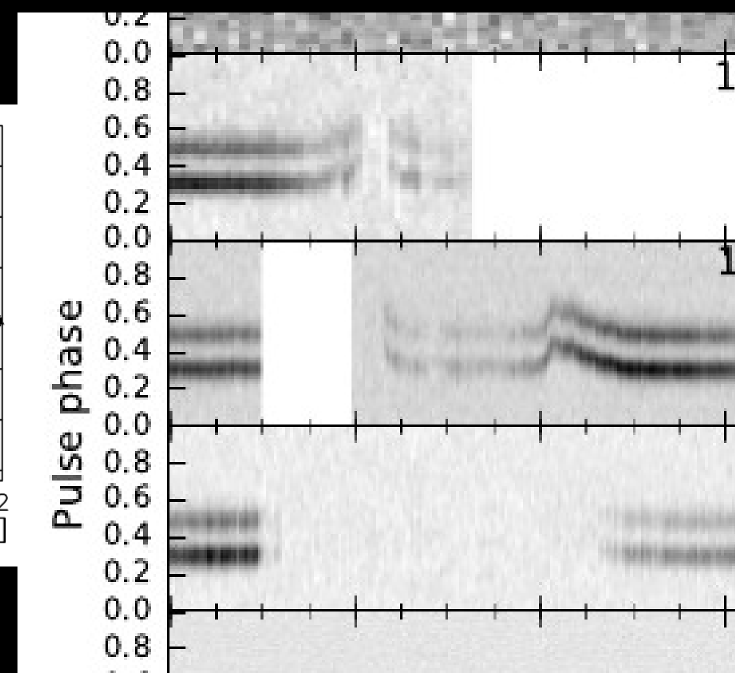
4.75 hr binary!

Evidence for accretion!

"Nasty" eclipses...

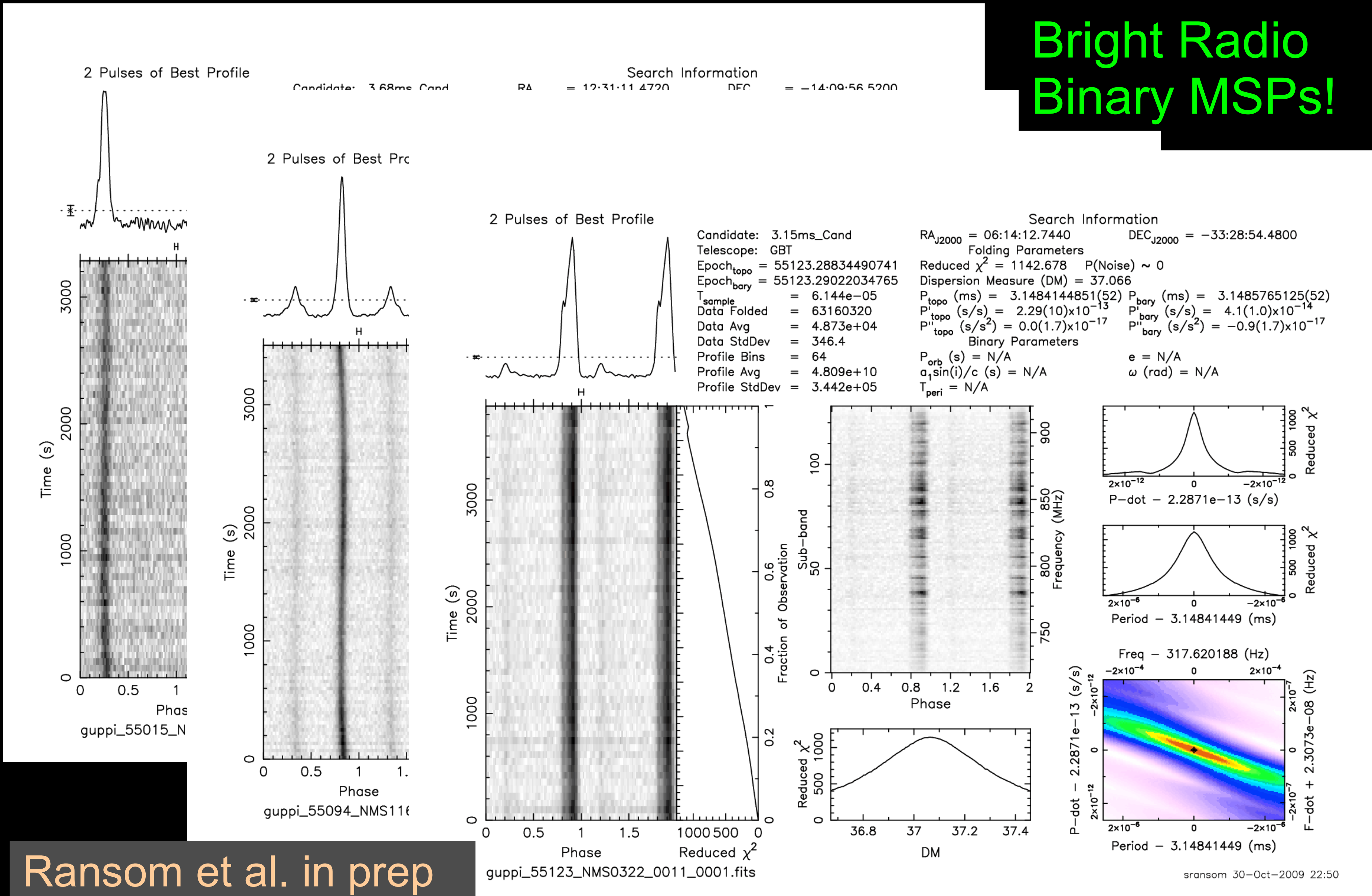
Archibald et al. 2009, *Science*, 324, 1411





Very recently... Bright Fermi UnIDd Sources

Bright Radio Binary MSPs!

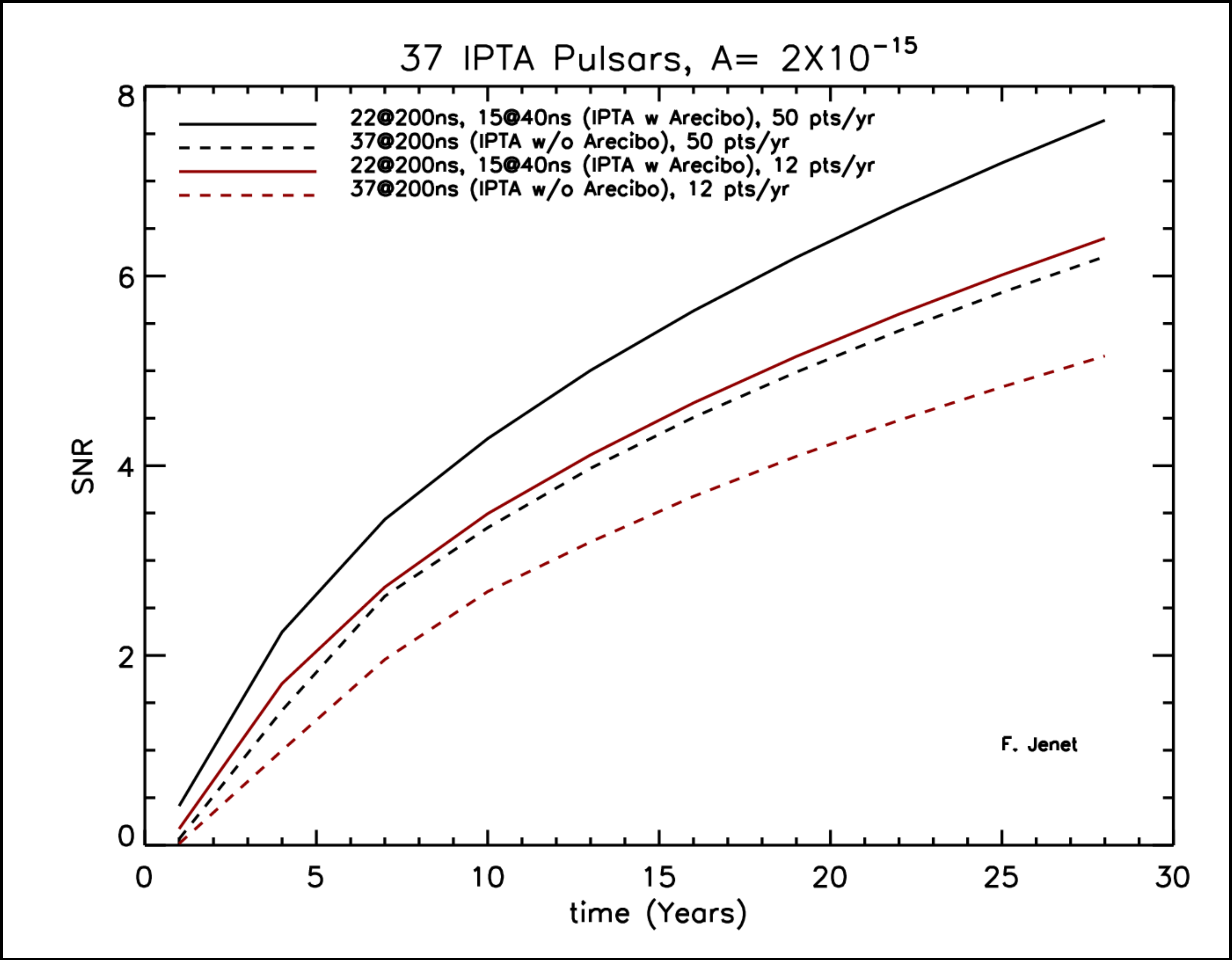


Ransom et al. in prep

MSPs and GWs Summary

- Radio pulsars can potentially directly detect nHz frequency gravitational waves
- A detection with current facilities is possible (maybe even likely) in the next 5-15 years
  - Currently limits from single pulsars and initial PTAs are $A \sim 10^{-14}$ or slightly below (strain amplitude)
  - Arecibo buys us 5 yrs, 3x more obs buys us 3 yrs
- More and better MSPs for quicker detection
- With future very large radio telescopes (e.g. SKA) and many more MSPs, detailed study of nHz GWs is likely ($A \sim 10^{-17}$)
- nanograv.org and white papers for more info

Arecibo and the IPTA



Recycled PSR Distances