Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Gravitational Wave Detection through Pulsar Timing

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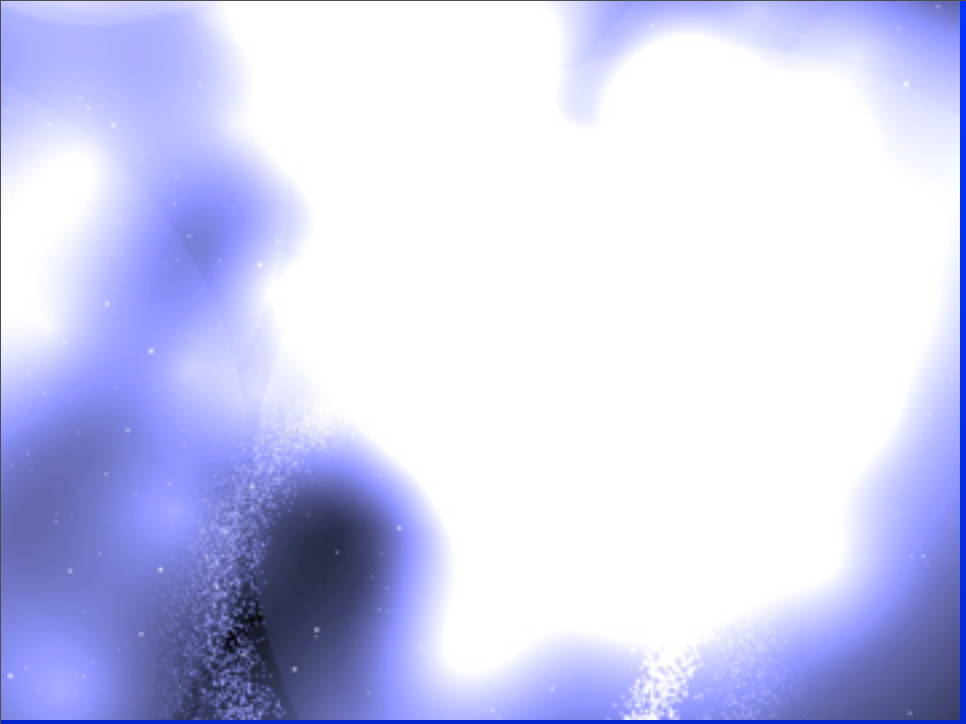
MPIfR, Wednesday 02 March 2011

Outline

- Introduction:
  - Pulsar Timing (Arrays)
  - Gravitational Wave Detection
- Requirements
  - Are our *pulsars* good enough?
  - Are our *systems* good enough?
- What's happening *now*?
- When will we detect Gravitational Waves and *what if we don't*?
- Conclusions

Introduction: Pulsar Timing



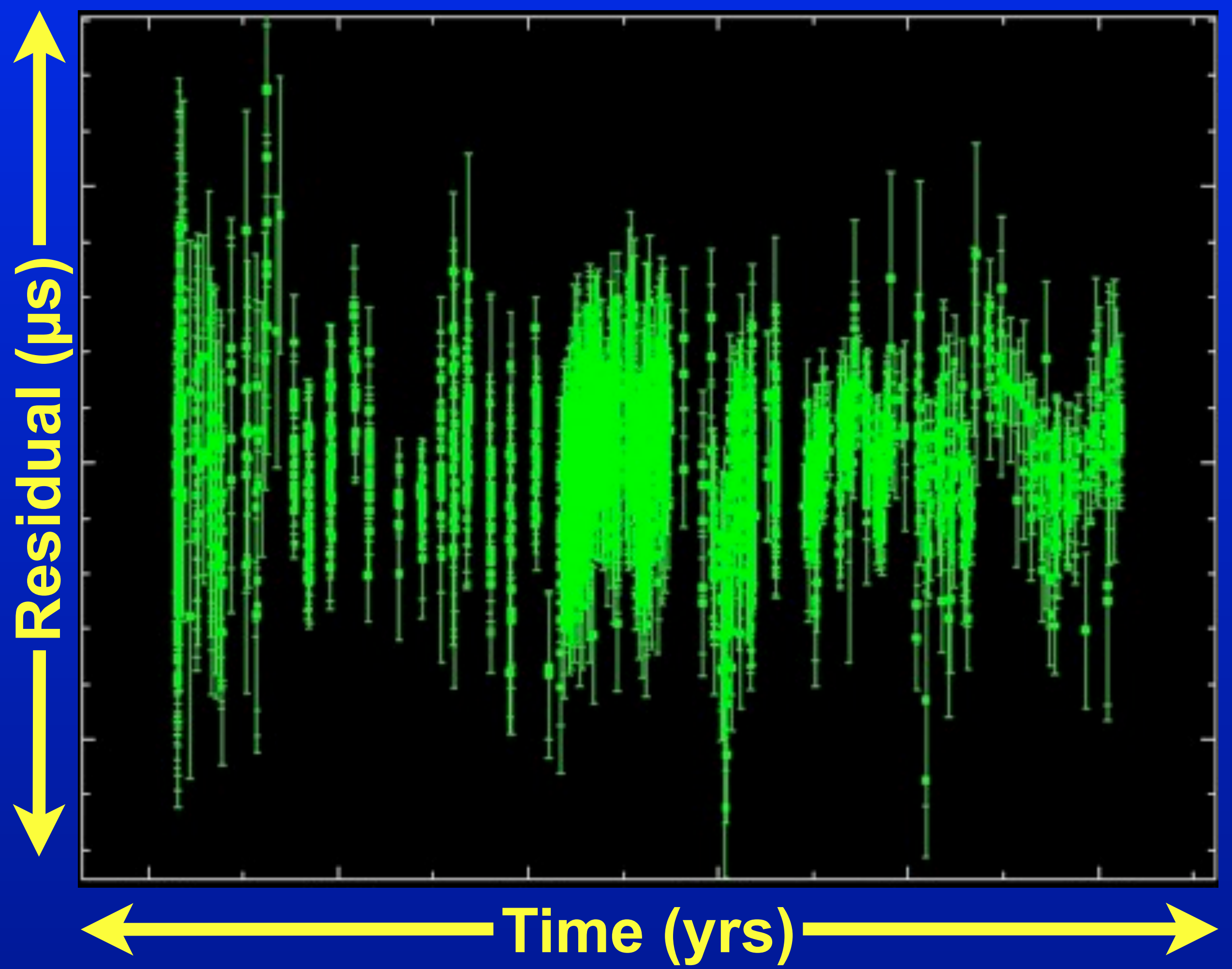
Courtesy Andrew Jameson (Swinburne)

Basic Method:

Actual Pulse Arrival Time

— Theoretical Model

= Timing Residual

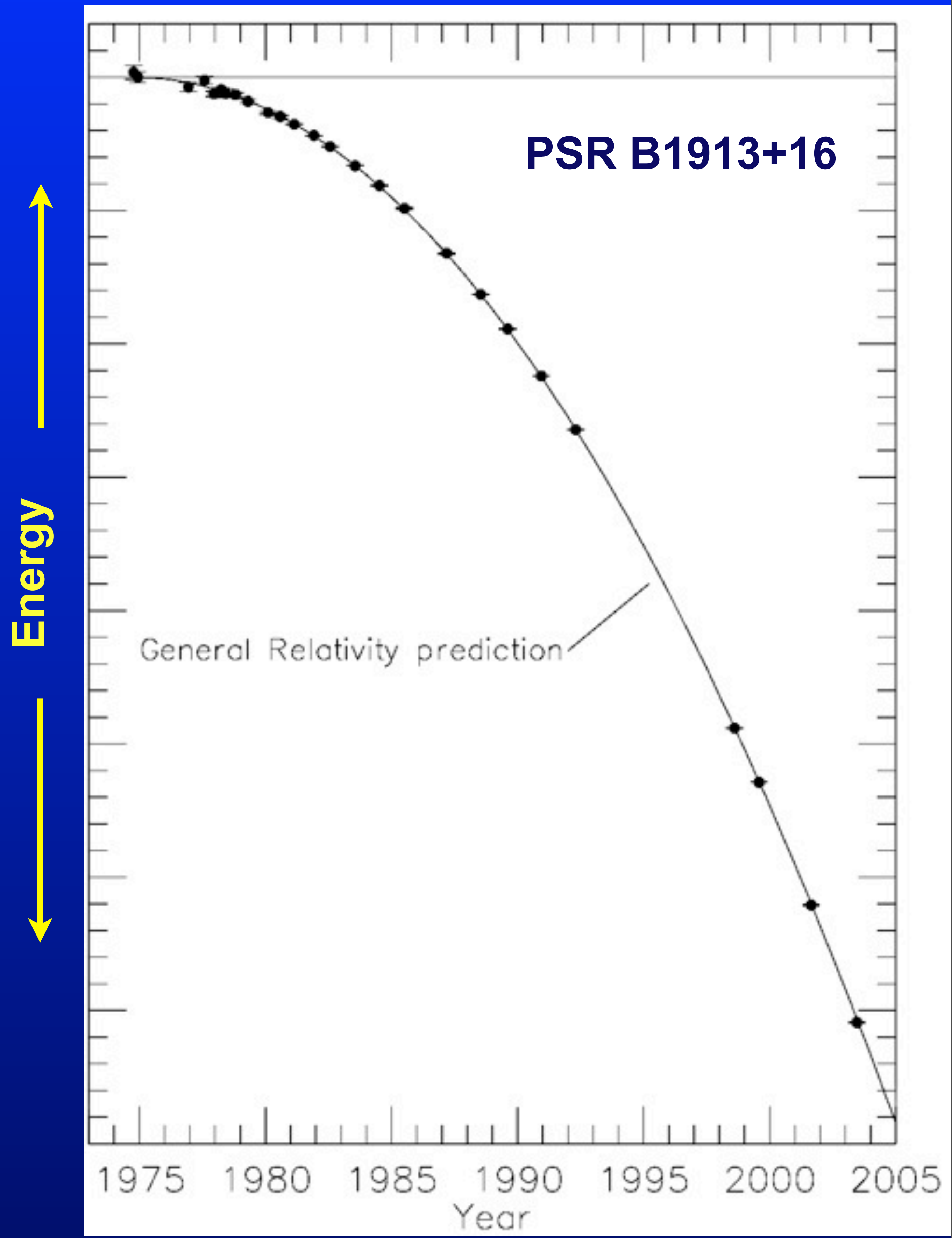


Verbiest et al., 2008

$$T_{\mathrm{th}} = \nu t + \frac{1}{2}\dot{\nu} t^2 + D\frac{\int_0^d n_e dl}{f^2} - \frac{1}{c}\left(\vec{r}\cdot\hat{s}\right) + \frac{V_{\mathrm{T}}^2 t^2}{2cd} - \frac{\left(\vec{r}\times\hat{s}\right)^2}{2cd} + \ldots$$

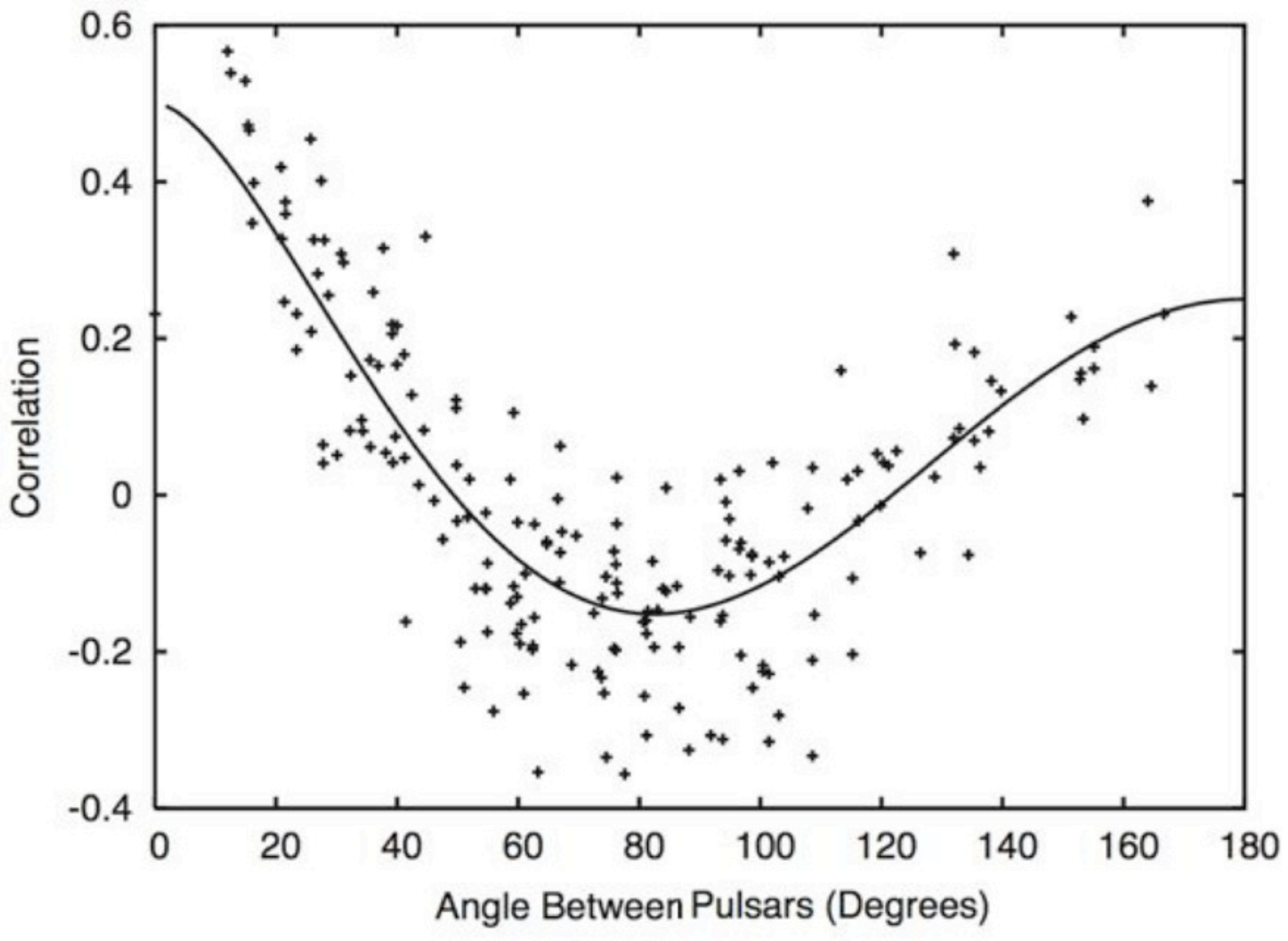
First GW* Detection!

- Binary pulsars: massive objects, continuous acceleration
- GR predicts binary to lose energy due to GW emission
- First shown by Weisberg & Taylor in 1982 (Nobel prize for Taylor in 1993)



*GW = Gravitational Wave

Pulsar Timing Array Concept



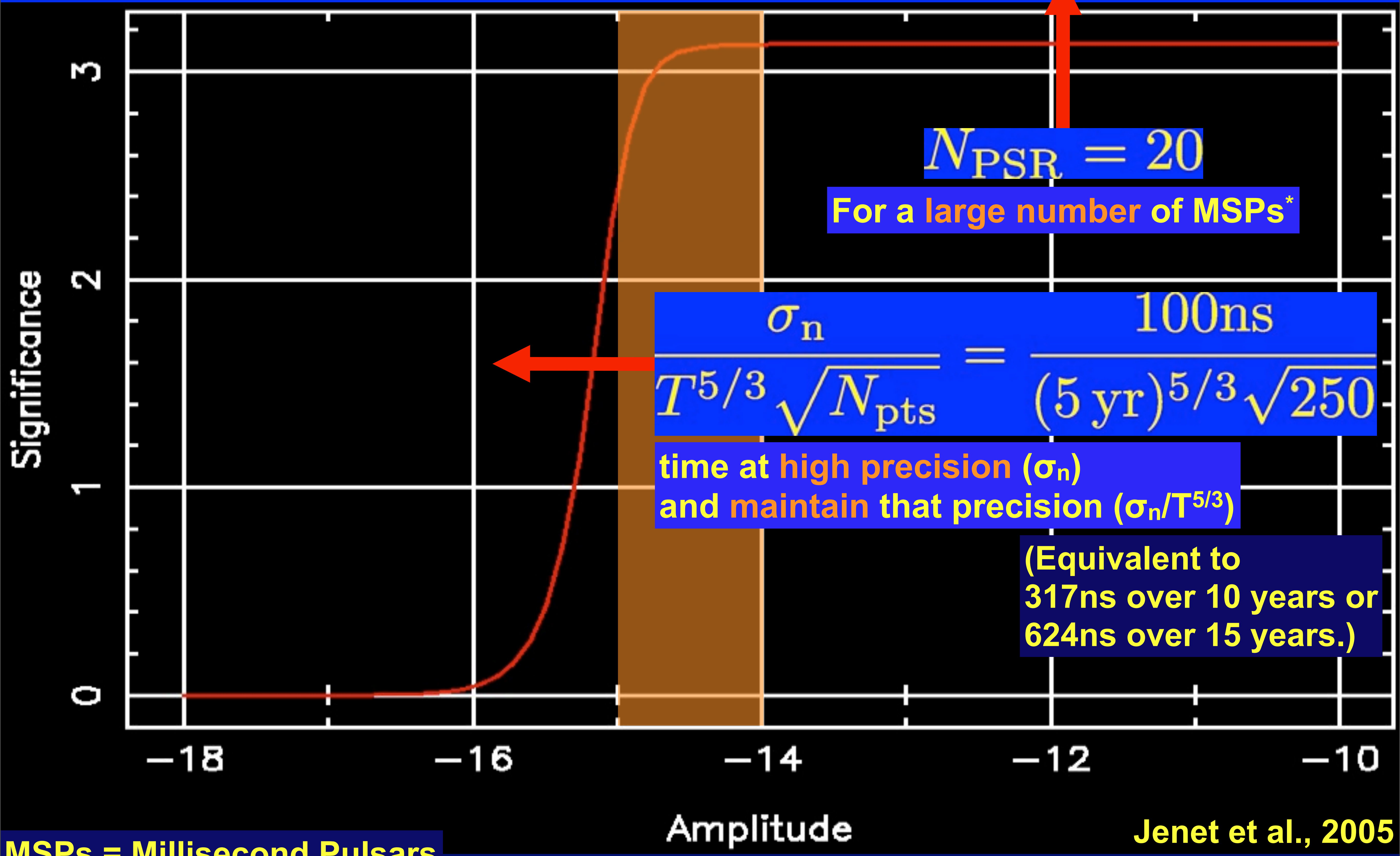
Hellings & Downs, 1983

Graph courtesy of Daniel Yardley (USyd)

Requirements

- Are our **pulsars** good enough?
- Are our **systems** good enough?

Basic PTA* Requirements



$$N_{\mathrm{PSR}} = 20$$

For a large number of MSPs*

$$\frac{\sigma_{\mathrm{n}}}{T^{5/3}\sqrt{N_{\mathrm{pts}}}} = \frac{100\mathrm{ns}}{(5\,\mathrm{yr})^{5/3}\sqrt{250}}$$

time at high precision (σ_n)
and maintain that precision ($\sigma_n/T^{5/3}$)

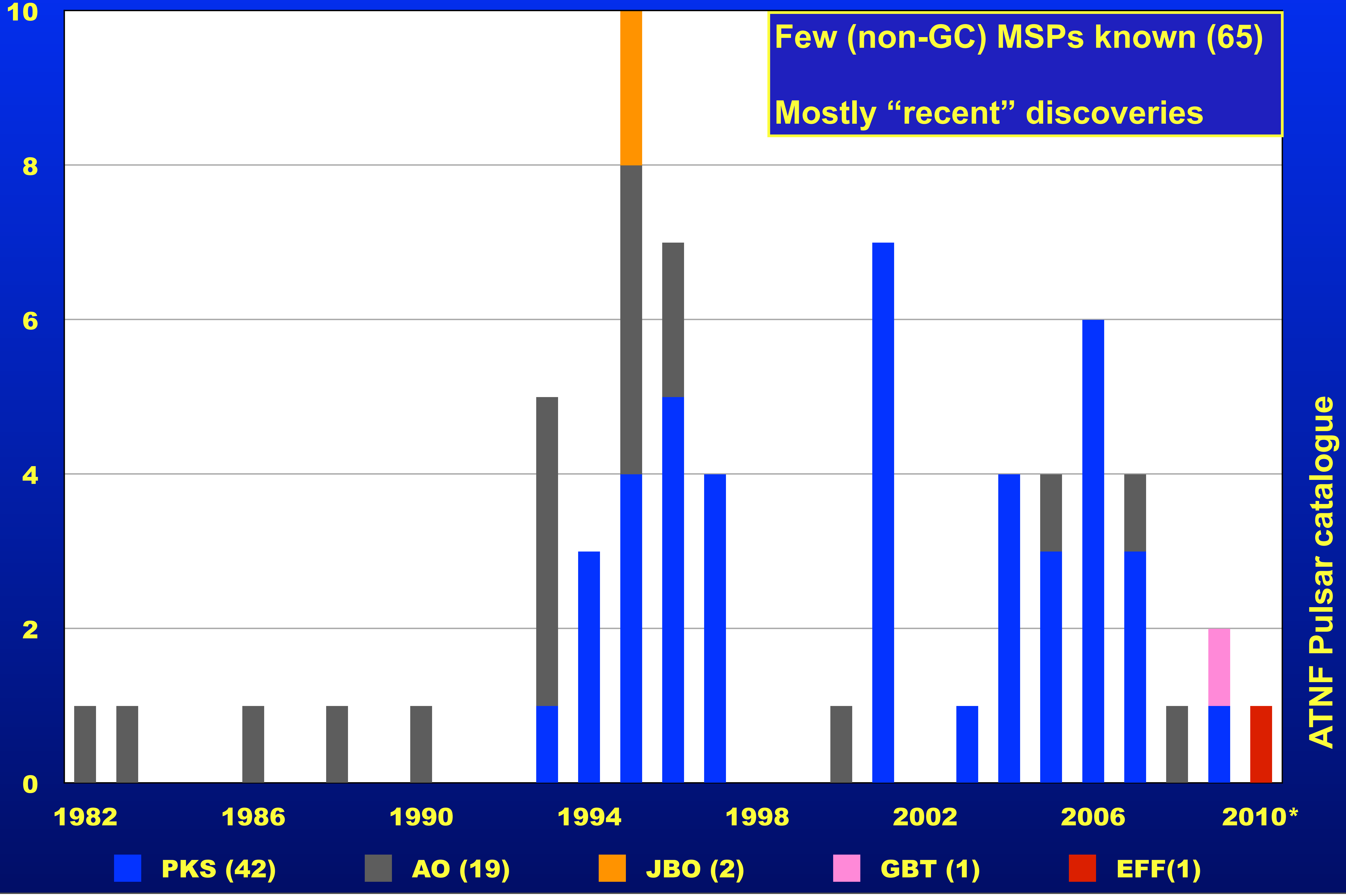
(Equivalent to
317ns over 10 years or
624ns over 15 years.)

Jenet et al., 2005

MSPs = Millisecond Pulsars
PTA = Pulsar Timing Array

$N_{\mathrm{PSR}} = 20$

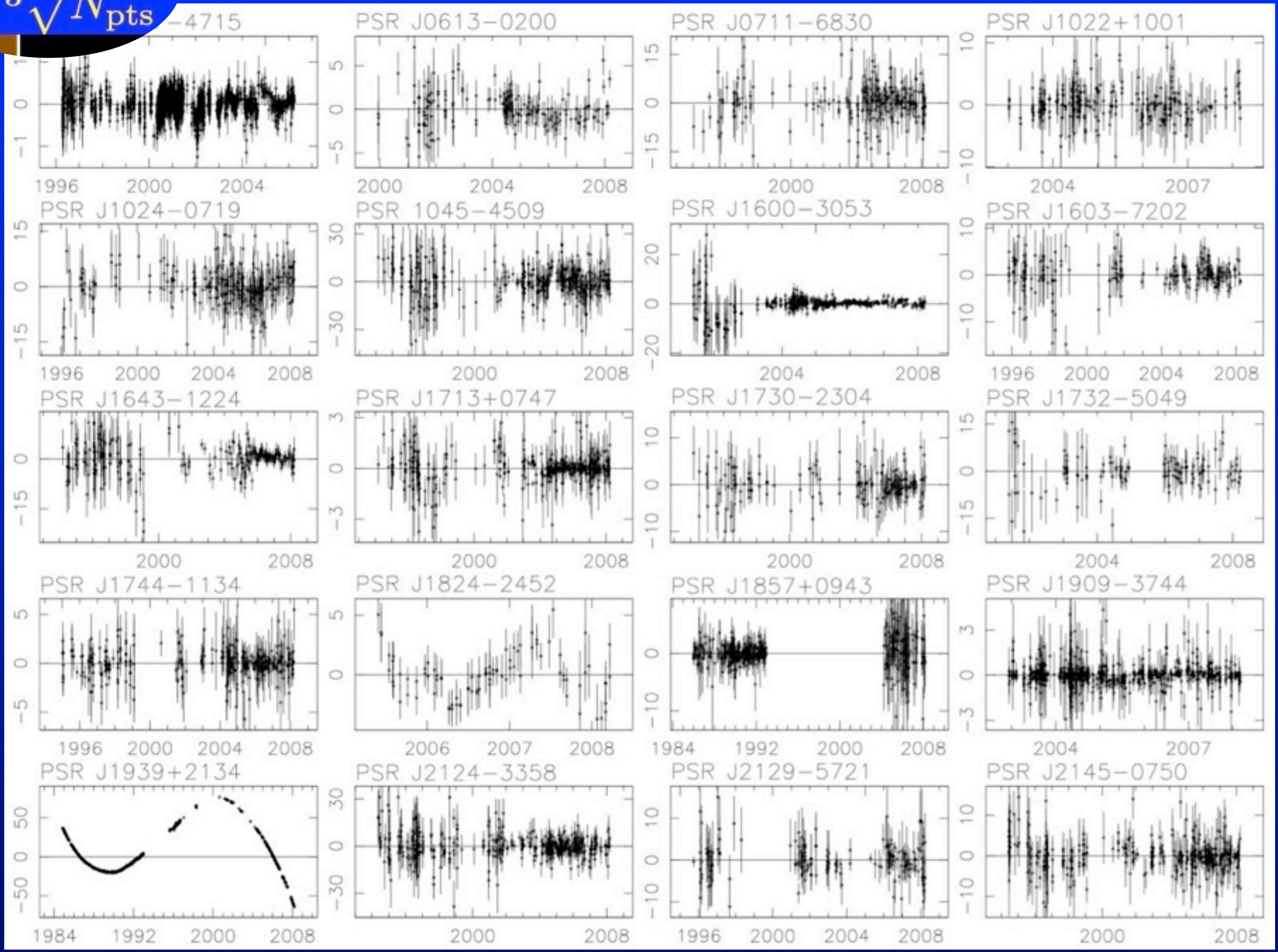
Large Number of Pulsars


Few (non-GC) MSPs known (65)

Mostly “recent” discoveries

MSP Timing Stability

$$\frac{\sigma_n}{T^{5/3}\sqrt{N_{pts}}}$$



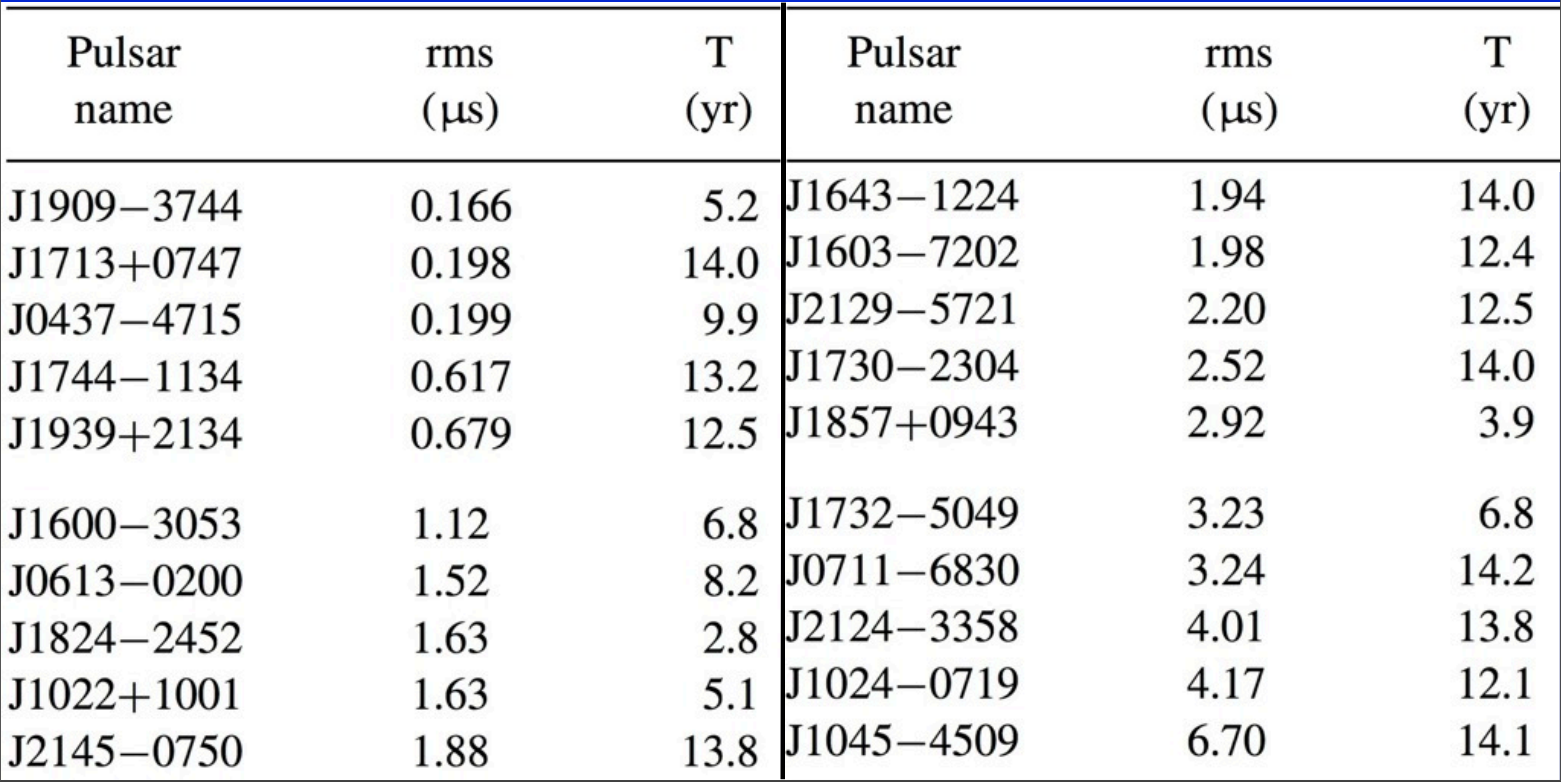
Verbiest et al., 2009

High Timing Precision

σ_n Contributions from:

- White (radiometer) noise
- Frequency-dependent (ISM) noise
- Time-dependent noise (instabilities)

Verbiest et al., 2009
Parkes 64-m dish
1-hr integrations



Pulsar name	rms (μs)	T (yr)	Pulsar name	rms (μs)	T (yr)
J1909−3744	0.166	5.2	J1643−1224	1.94	14.0
J1713+0747	0.198	14.0	J1603−7202	1.98	12.4
J0437−4715	0.199	9.9	J2129−5721	2.20	12.5
J1744−1134	0.617	13.2	J1730−2304	2.52	14.0
J1939+2134	0.679	12.5	J1857+0943	2.92	3.9
J1600−3053	1.12	6.8	J1732−5049	3.23	6.8
J0613−0200	1.52	8.2	J0711−6830	3.24	14.2
J1824−2452	1.63	2.8	J2124−3358	4.01	13.8
J1022+1001	1.63	5.1	J1024−0719	4.17	12.1
J2145−0750	1.88	13.8	J1045−4509	6.70	14.1

What’s happening *now*?

Are Our Systems Good Enough?

$$\frac{\sigma_{\rm n}}{/3\sqrt{N_{\rm pts}}} \rightarrow \sigma_{\rm R} \propto \frac{T_{\rm sys}}{GS\sqrt{N_{\rm p}Bt}} \rightarrow$$

Many observations
Long integrations
Large bandwidth
Large telescopes

$$N_{\rm PSR} = 20 \rightarrow$$

Telescopes in both hemispheres
Surveys

$$+ D\frac{\int_0^d n_e dl}{f^2} - \rightarrow$$

Multi-frequency observations (Lofar!)

International Pulsar Timing Array (IPTA)
LEAP*, LOFAR
Surveys, System Upgrades

LEAP = Large European Array for Pulsars (coherent combination of the 5 major dishes)

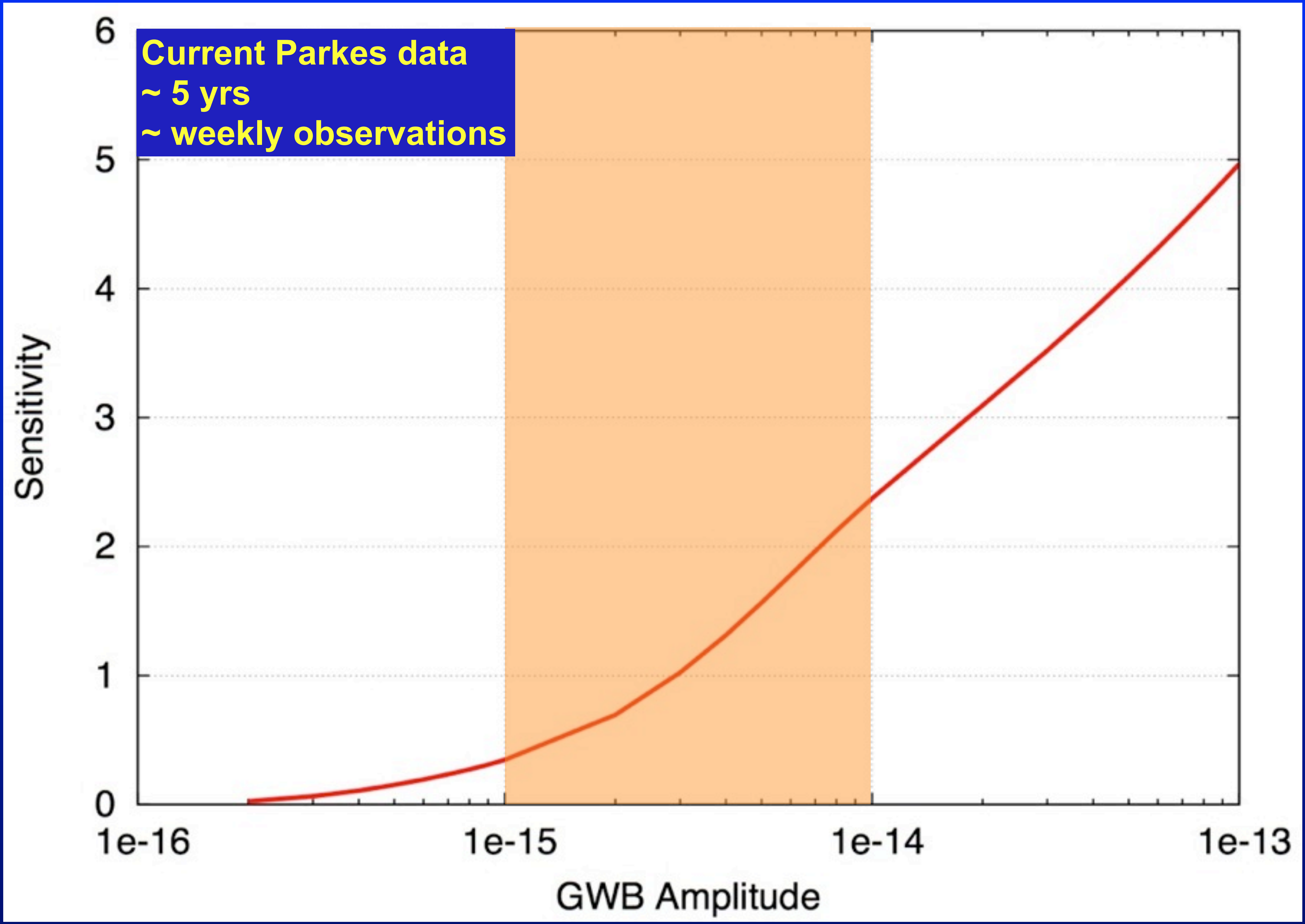
Requirements

- Are our pulsars good enough?
  - ➡ More MSPs would be good (surveys!)
  - ➡ Needs ISM work (LOFAR!)
  - ✓ Most MSPs seem to be stable enough.
  - ✓ 100-300 ns timing precision possible

- Are our systems good enough?
  - ➡ International collaboration (LEAP, IPTA)
  - ➡ System upgrades

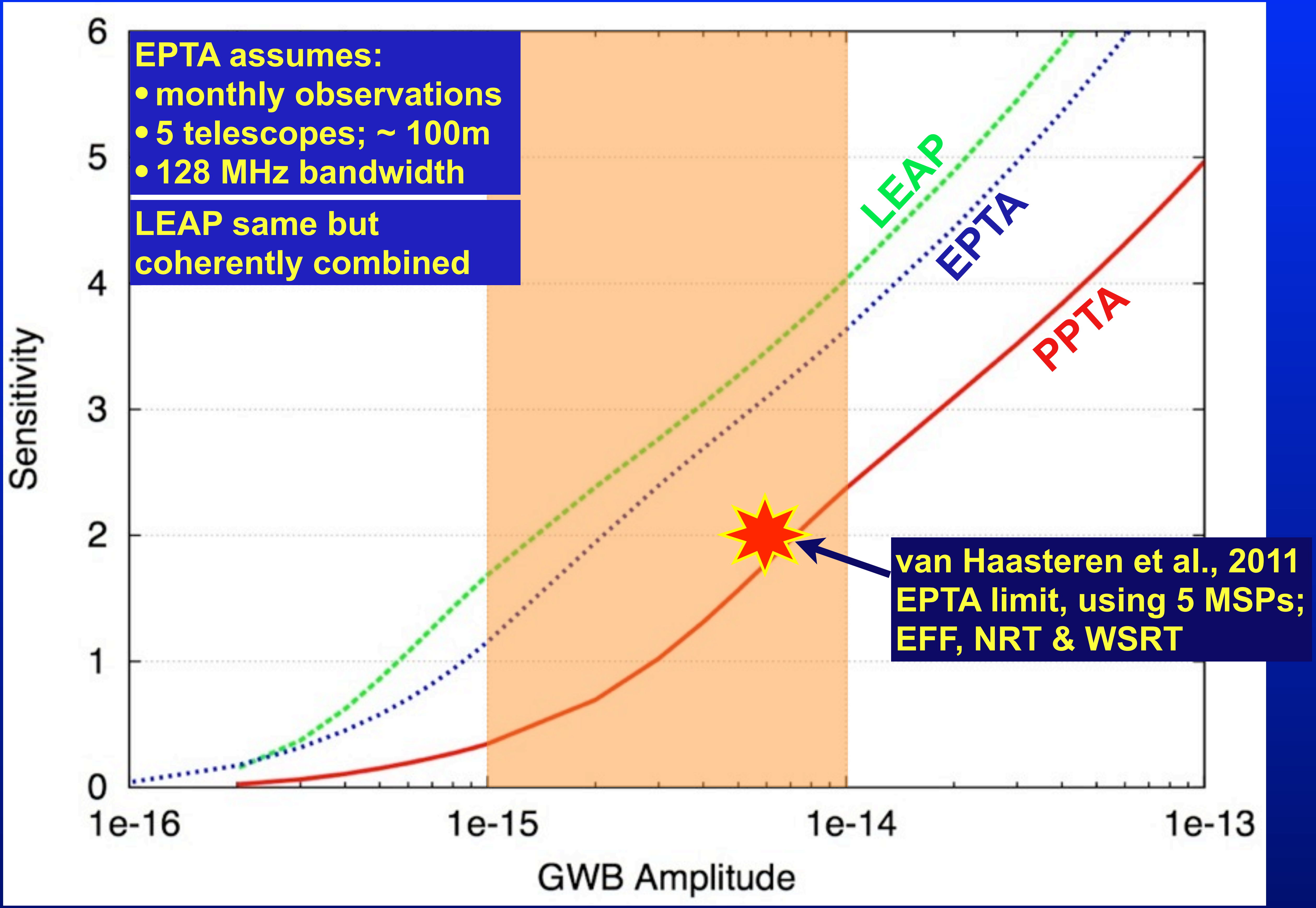
When Will We Detect Them?

Current Sensitivity


Current Parkes data
~ 5 yrs
~ weekly observations

Verbiest et al., 2009

Predicted Sensitivity

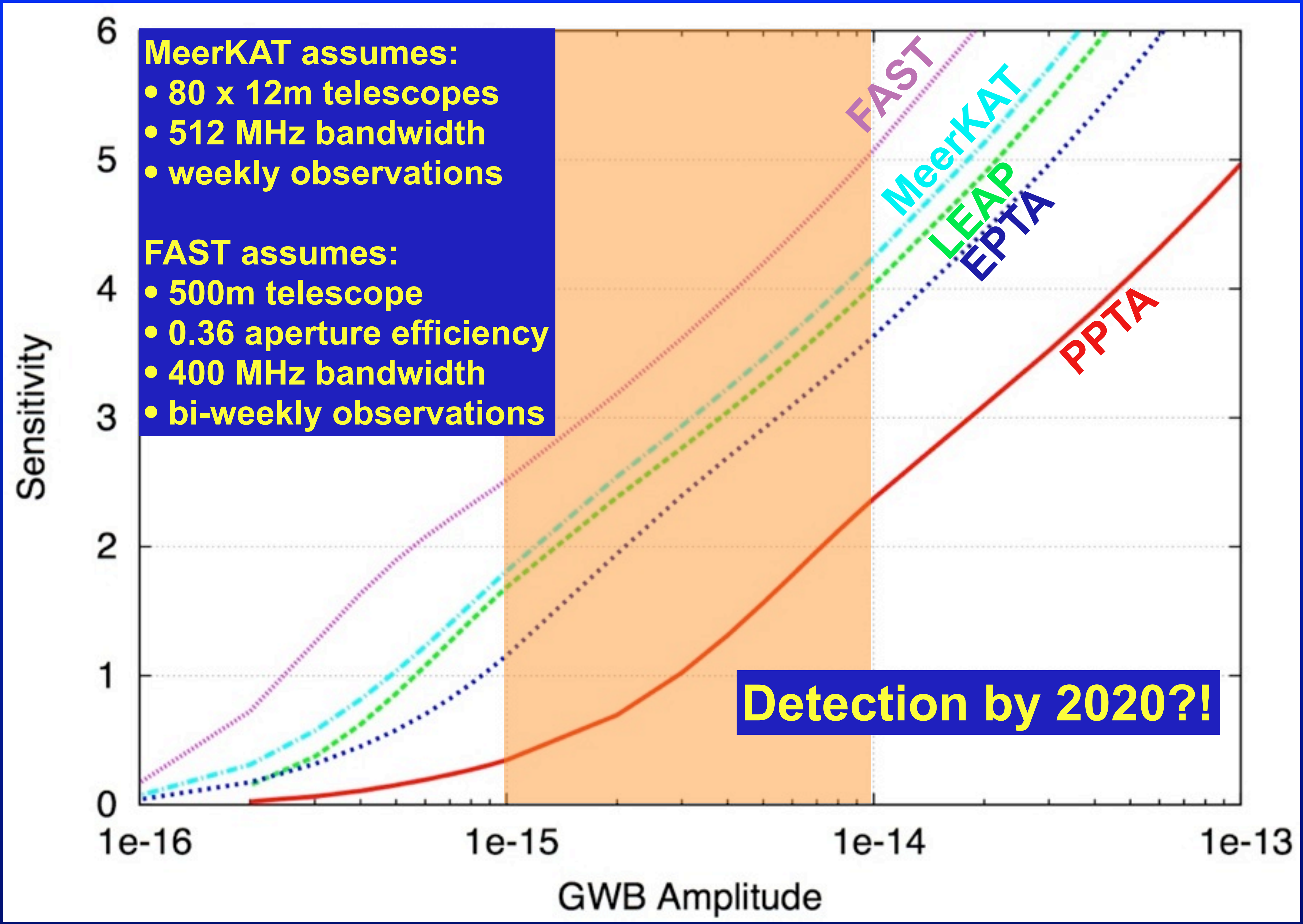


EPTA assumes:
- **monthly observations**
- **5 telescopes; ~ 100m**
- **128 MHz bandwidth**

LEAP same but coherently combined

van Haasteren et al., 2011 EPTA limit, using 5 MSPs; EFF, NRT & WSRT

Future Arrays?



MeerKAT assumes:

- 80 x 12m telescopes
- 512 MHz bandwidth
- weekly observations

FAST assumes:

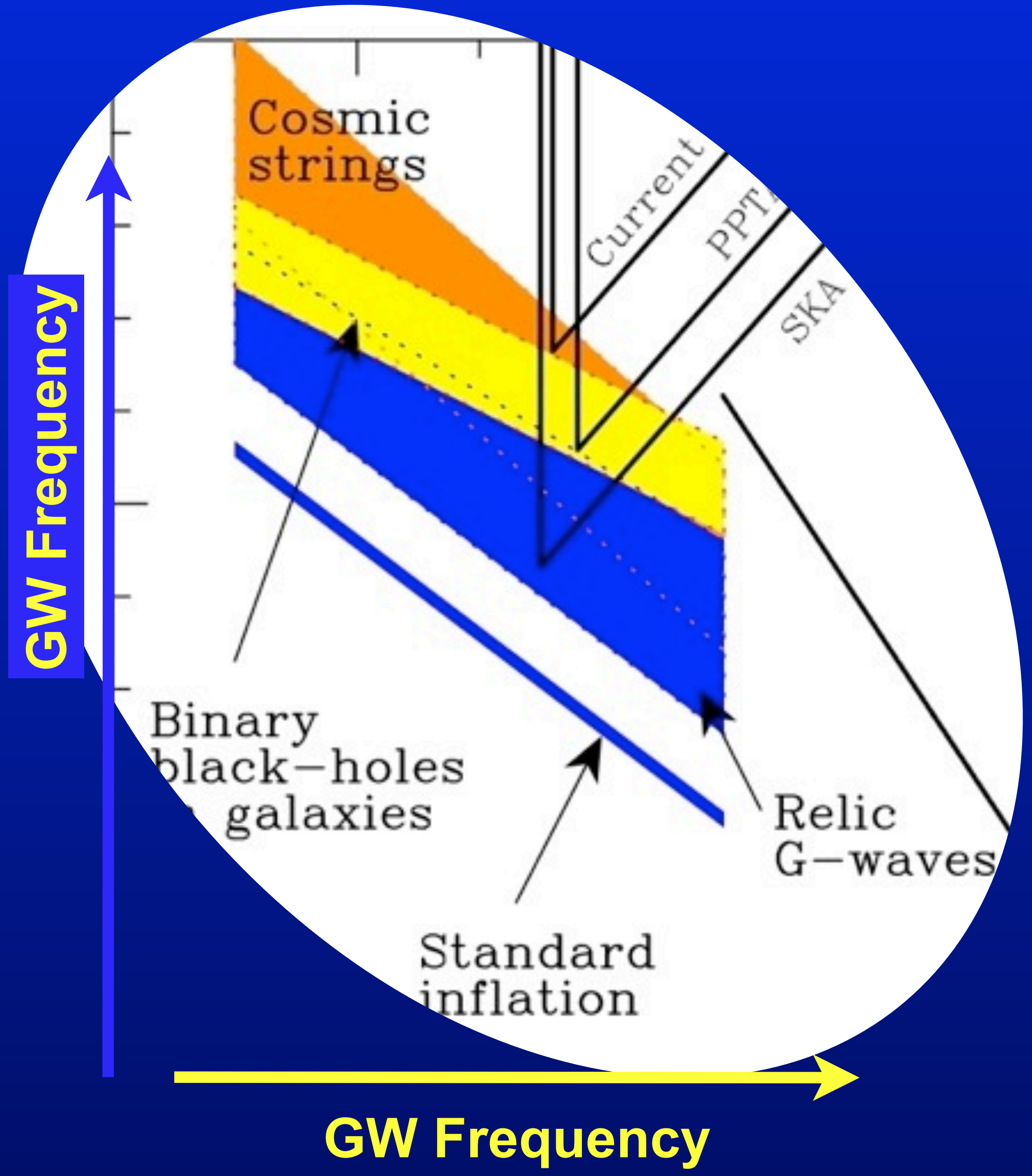
- 500m telescope
- 0.36 aperture efficiency
- 400 MHz bandwidth
- bi-weekly observations

Detection by 2020?!

What if We Don’t?

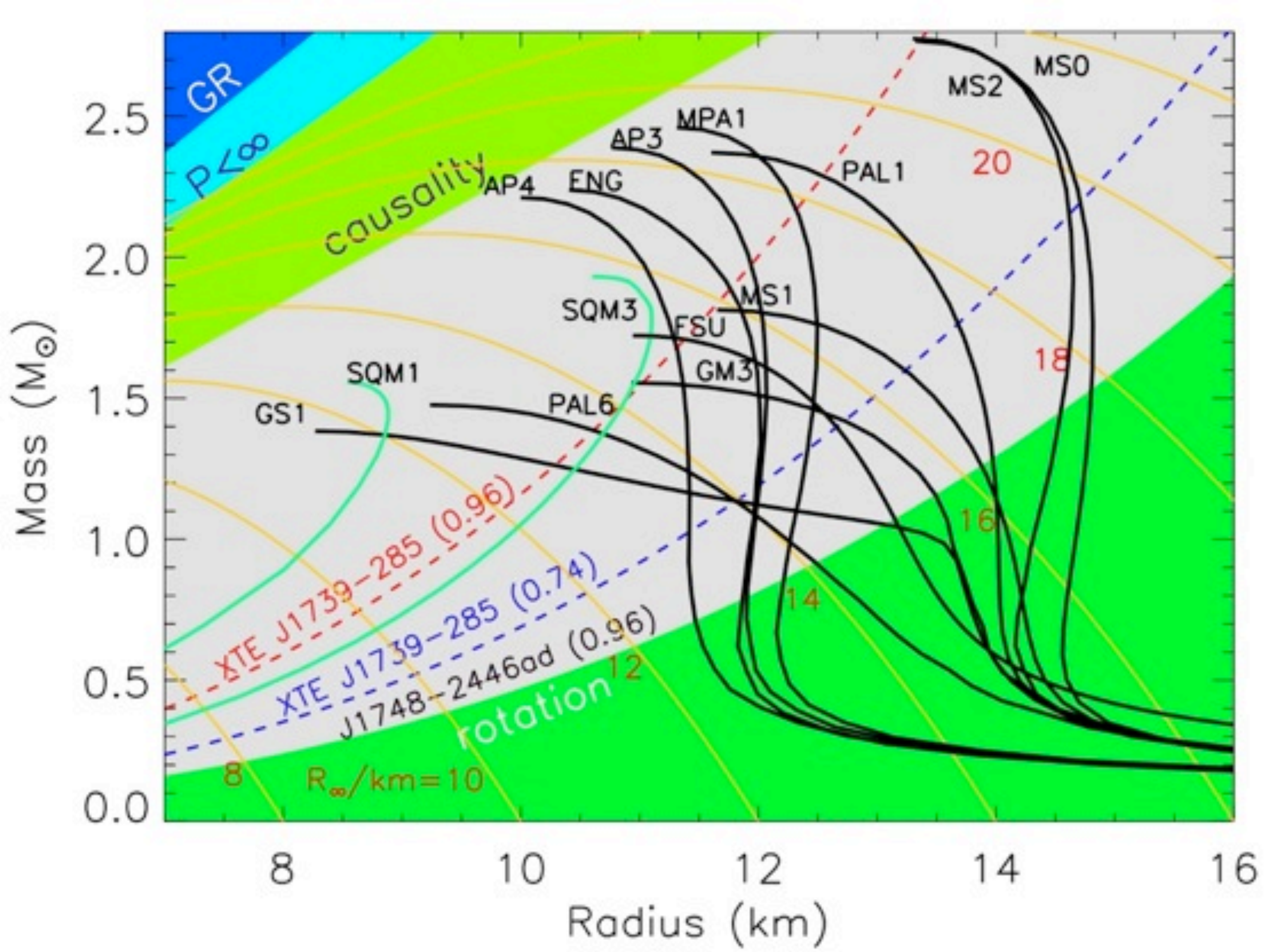
If no detection by 2020...

- Will have:
  - constrained SMBH binary parameters
  - constrained galaxy merger history & evolution
- Continued increase in sensitivity
- Alternative sources
  - Burst sources
  - Single sources
  - Unexpected sources?
- Spin-off science!



Spin-off Science - I

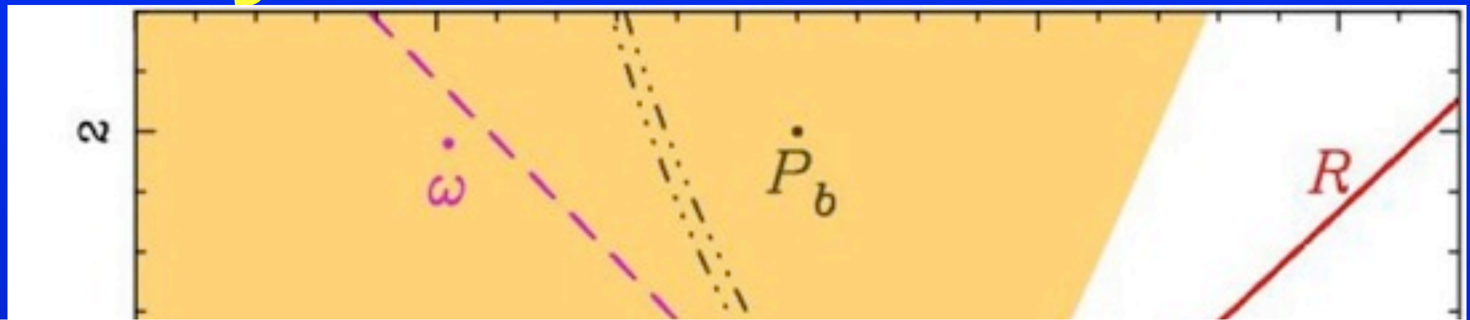
- (Precise) distances
  - Galactic electron distributions
  - Galactic magnetic field
  - Accurate accelerations: limits on $\dot{G}$ and TNOs
- Pulsar masses
  - Equations of State for dense nuclear matter

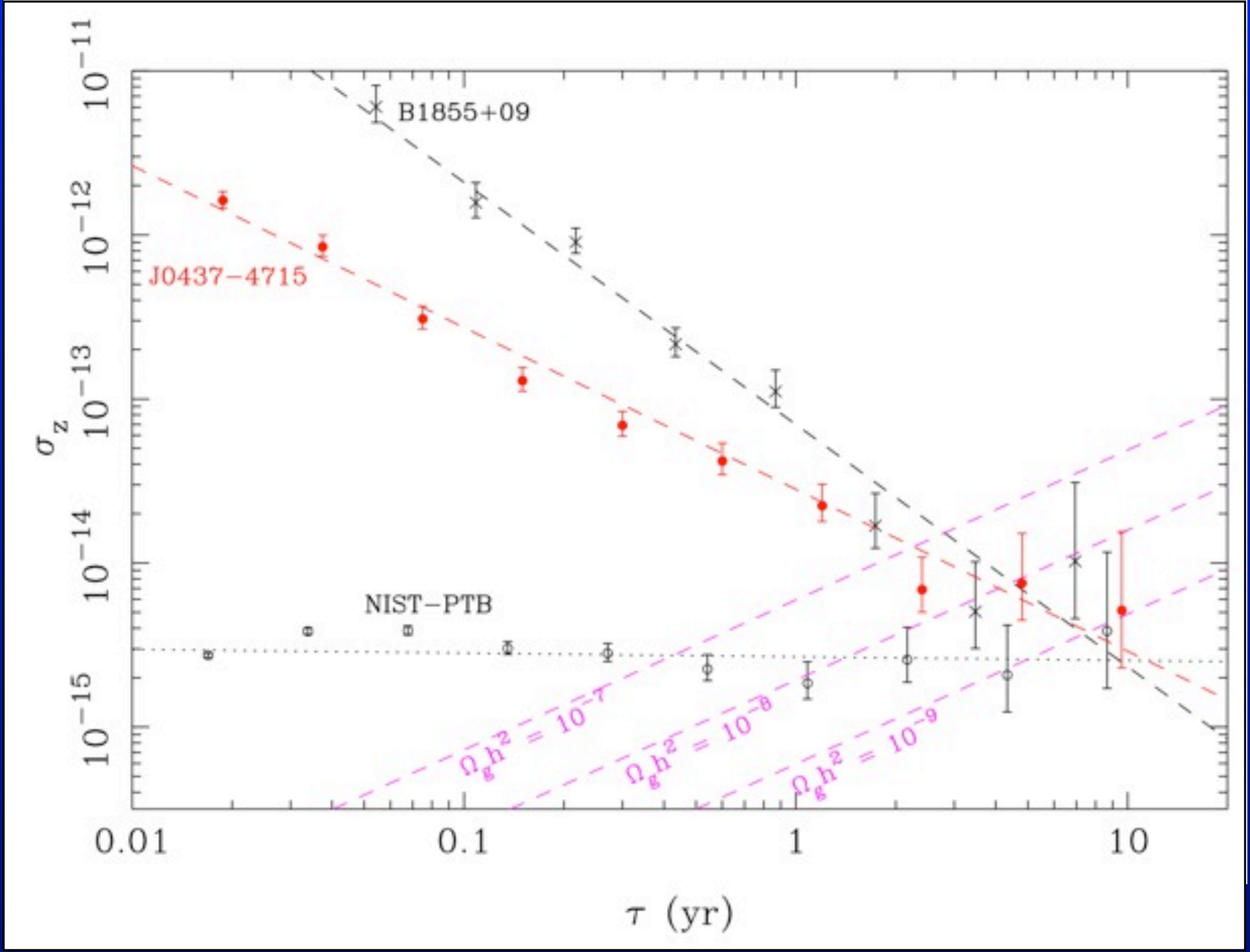


Lattimer & Prakash, 2007

Spin-off Science - II

- Tests of General Relativity
  - Periastron advance
  - Gravitational redshift
  - Shapiro Delay
  - Orbital Decay
- Planetary masses
- Stable clocks





Spin-off Science - III

- New and unexpected discoveries:
  - Relativistic binaries
  - Rotating radio transients (RRATs) and intermittent pulsars
  - Magnetars
  - Eclipsing binaries
  - (Extragalactic?!) bursts

- Population models:
  - Binary evolution
  - Pulsar and MSP populations
  - Galactic distributions

Conclusions

- Aim: To detect GWs from SMBH mergers
- Pulsars are Stable and Precise
- Searches for more MSPs ongoing
- IPTA, LEAP will provide enough telescope time and sensitivity
- Detection by 2020 very likely
- Even without a detection, lots of valuable science will be done.

Extra Slides

Supermassive Black-Hole Mergers

John Rowe Animation/ATNF, CSIRO

The GW Spectrum

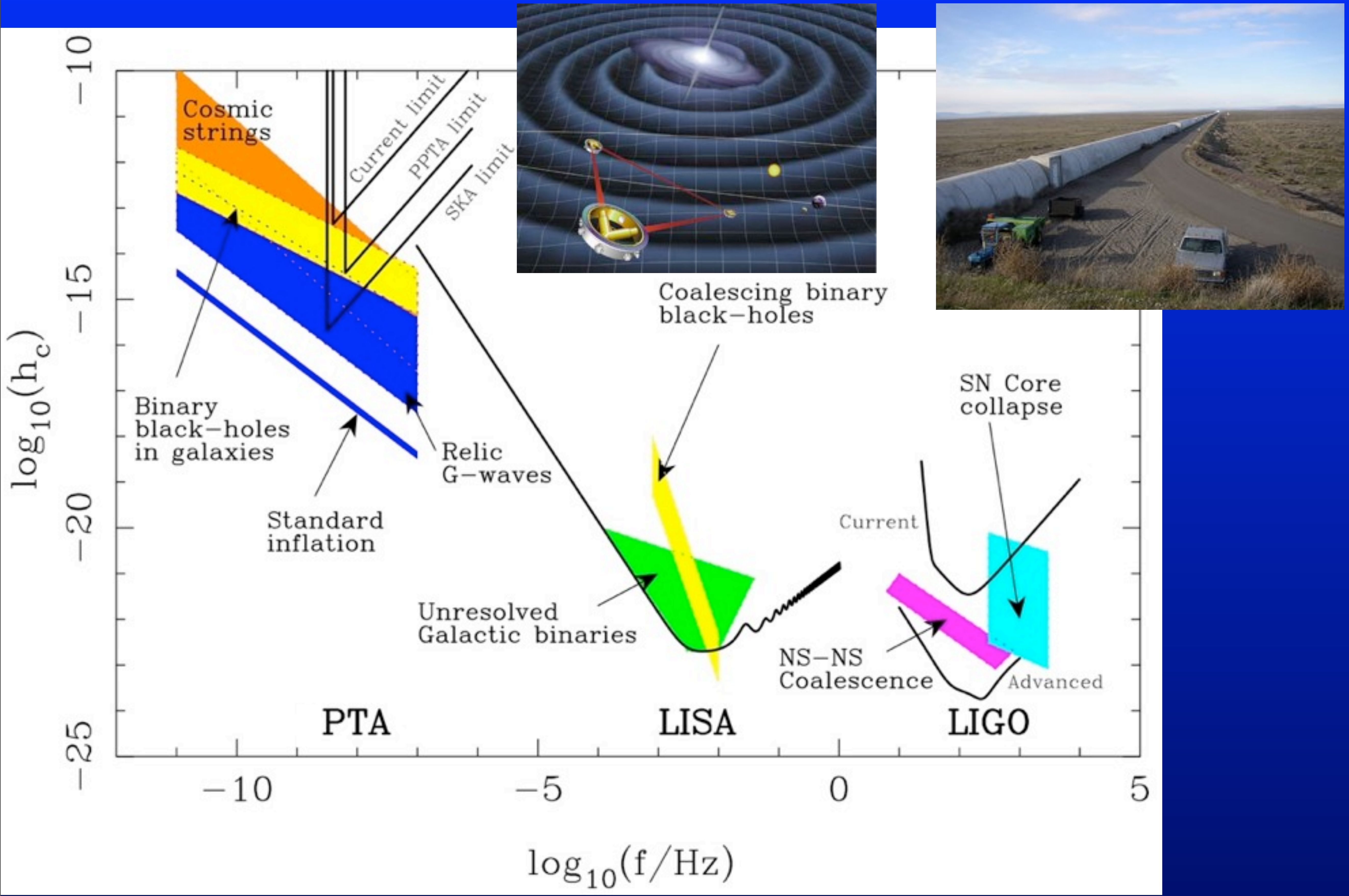


Figure courtesy George Hobbs (ATNF)

Basic GW PTA Theory

Energy density per unit logarithmic frequency interval:

$$\Omega_{\mathrm{gw}}(f) = \frac{2\pi^2}{3H_0^2} A^2 \frac{f^{2\alpha+2}}{f_{\mathrm{ref}}^{2\alpha}} = \frac{2\pi^2}{3H_0^2} h_c^2(f) f^2$$

Characteristic strain:

$$h_c(f) = A\left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha}$$

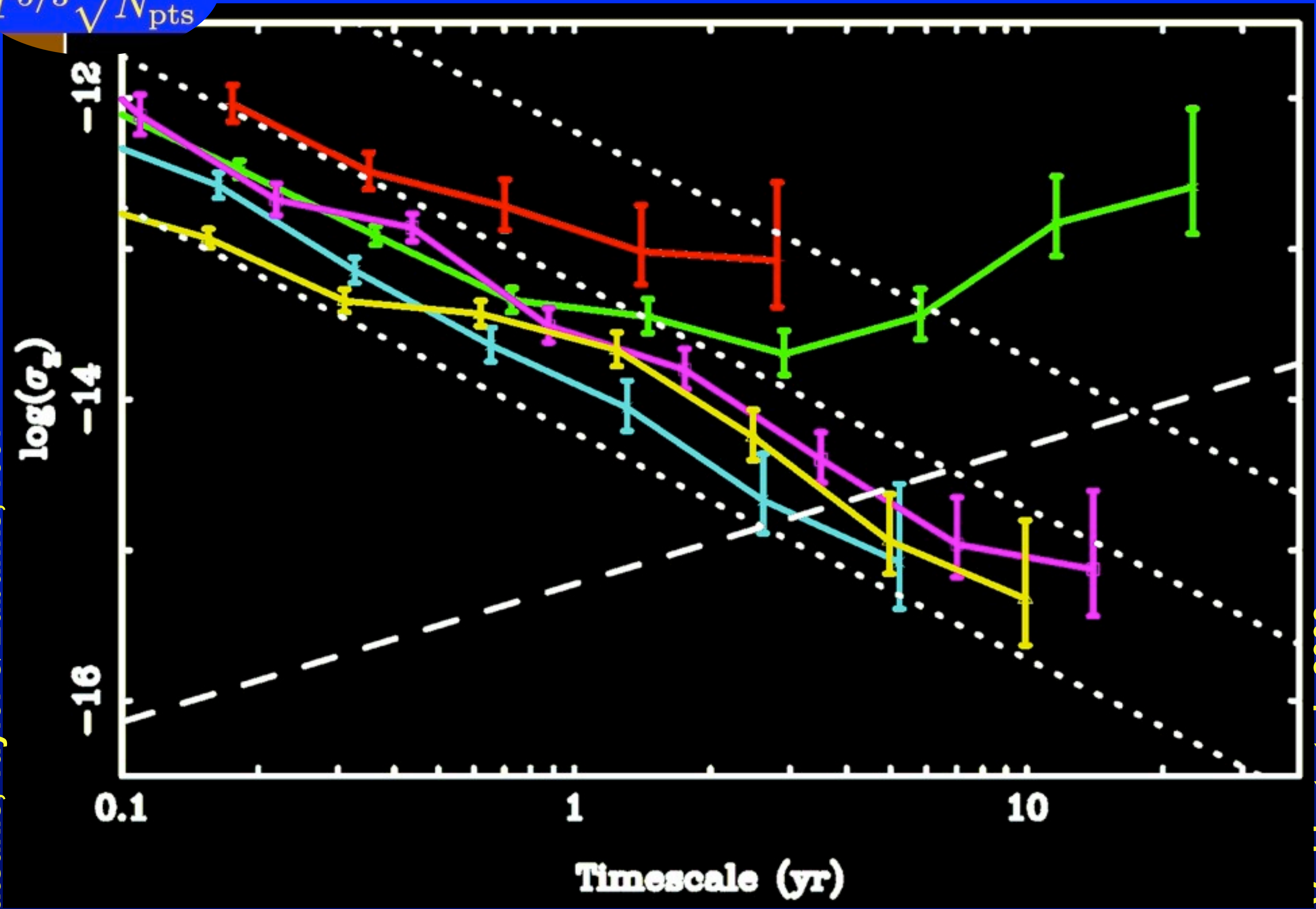
Power in Timing Residuals:

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

See Jenet et al., 2006

MSP Timing Stability

$$\frac{\sigma_\mathrm{n}}{T^{5/3}\sqrt{N_\mathrm{pts}}}$$



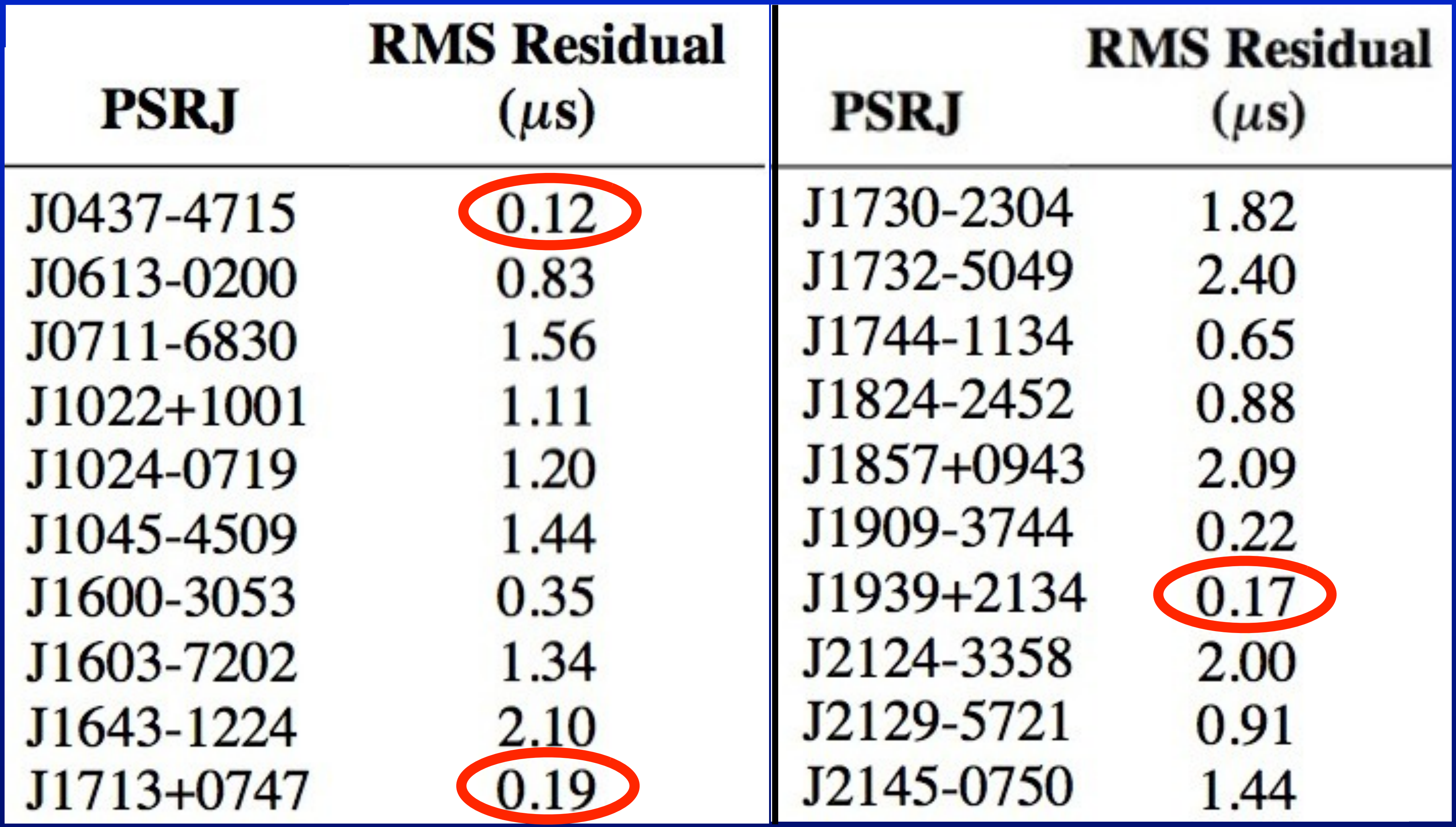
Matsakis, Taylor & Eubanks, 1997

Verbiest et al., 2009

High Timing Precision

Contributions from:

- White (radiometer) noise
- Frequency-dependent (ISM) noise
- Time-dependent noise (instabilities)



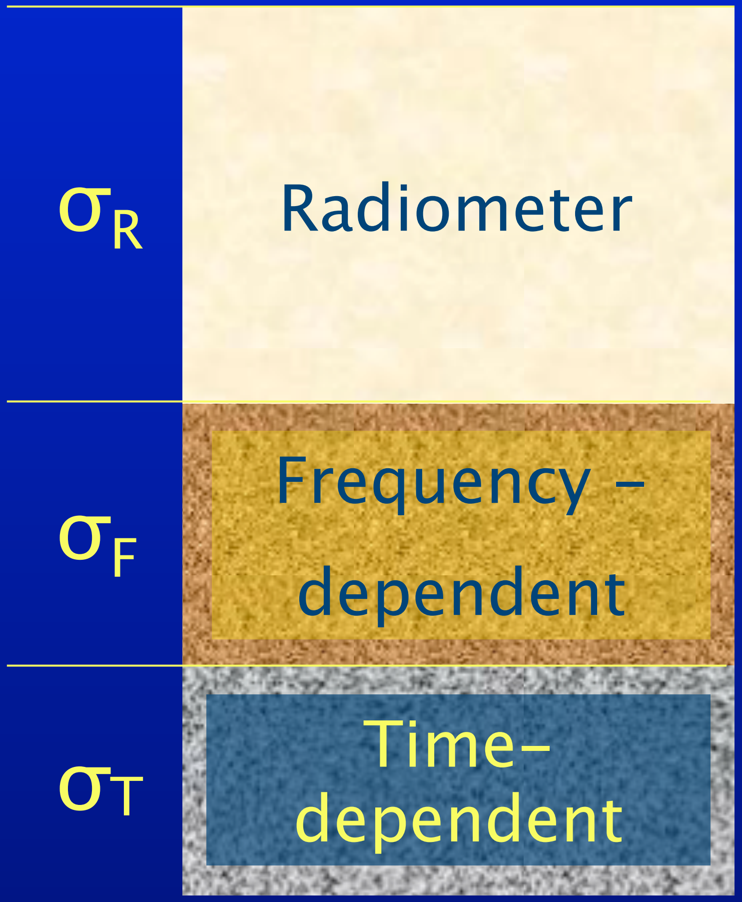
PSRJ	RMS Residual (μs)
J0437-4715	0.12
J0613-0200	0.83
J0711-6830	1.56
J1022+1001	1.11
J1024-0719	1.20
J1045-4509	1.44
J1600-3053	0.35
J1603-7202	1.34
J1643-1224	2.10
J1713+0747	0.19
J1730-2304	1.82
J1732-5049	2.40
J1744-1134	0.65
J1824-2452	0.88
J1857+0943	2.09
J1909-3744	0.22
J1939+2134	0.17
J2124-3358	2.00
J2129-5721	0.91
J2145-0750	1.44

Manchester, 2008
Parkes 64-m dish
1-hr integrations
2 years of data

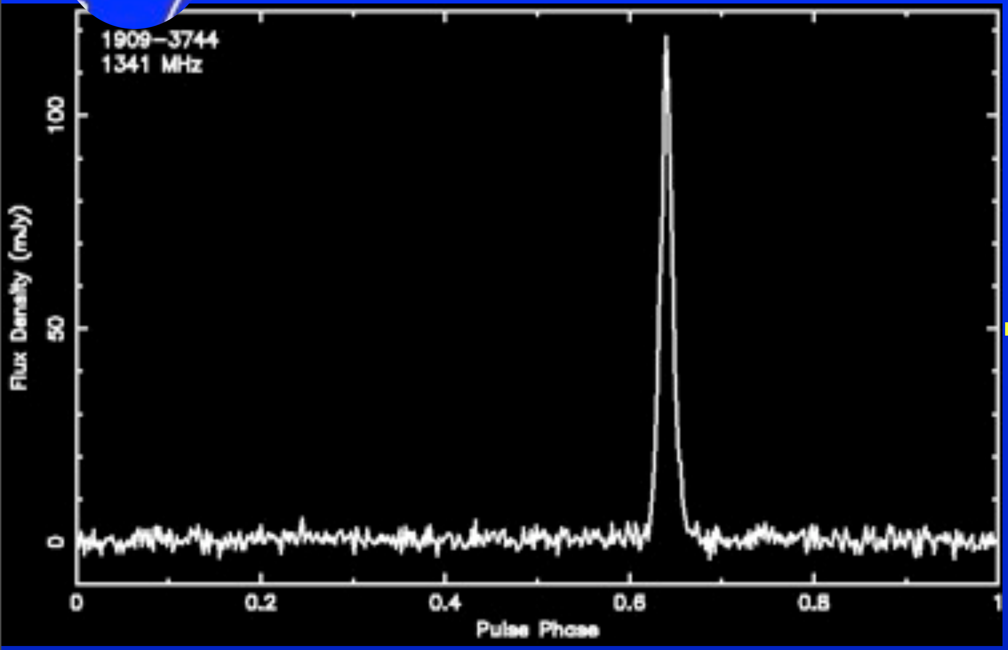
High Timing Precision

Quantify the three contributions to our timing:

- (white) Radiometer noise: σ_R
- Frequency-dependent noise: σ_F
- Time-dependent noise: σ_T



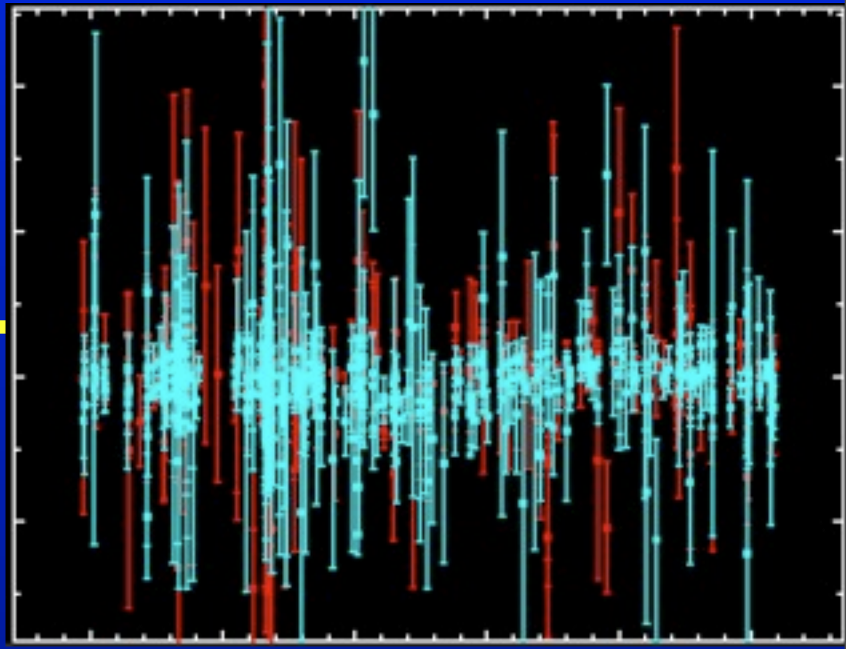
High Timing Precision

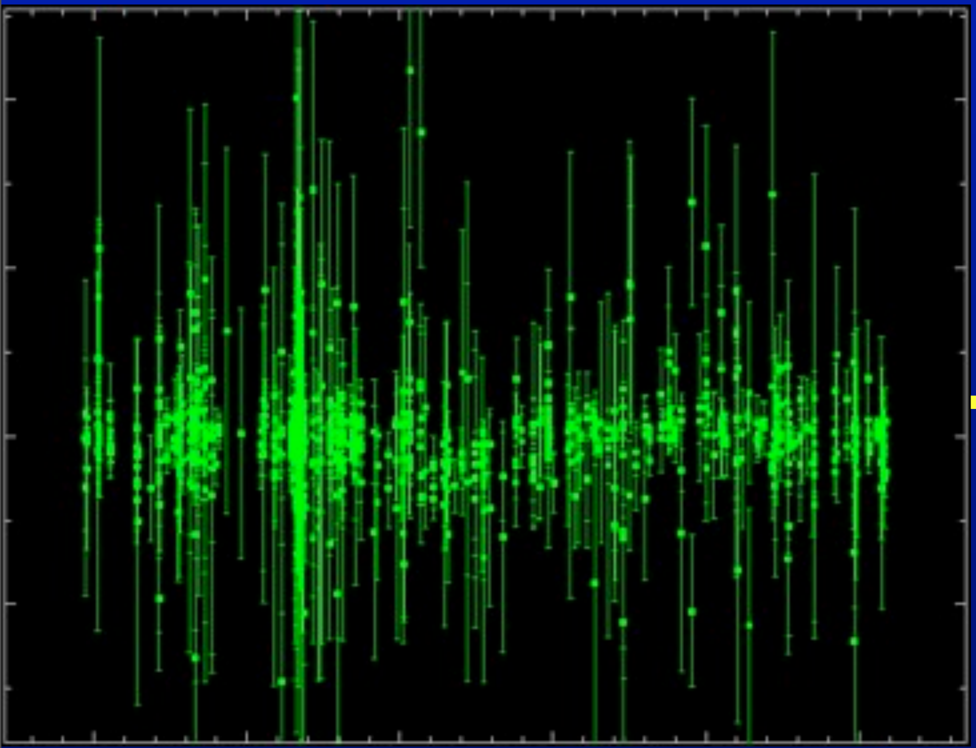


Radiometer noise σ_R

$$\sigma_{\rm SB} = \sqrt{\sigma_{\rm R}^2 + \sigma_{\rm F}^2}$$

Sub-band noise σ_{SB}





Total noise σ

High Timing Precision

Quantify the three contributions to our timing:

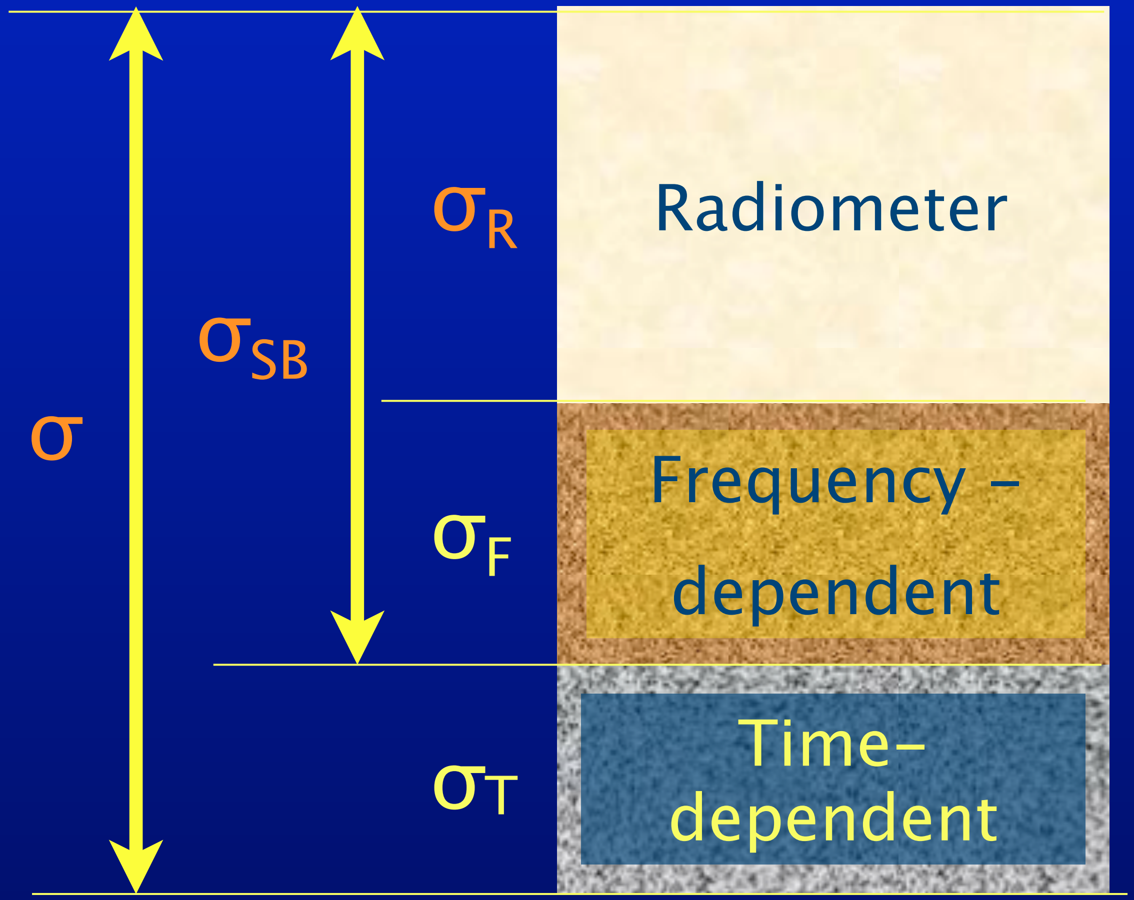
- (white) Radiometer noise: σ_R
- Frequency-dependent noise: $\sigma_{\mathrm{F}} = \sqrt{\sigma_{\mathrm{SB}}^2 - \sigma_{\mathrm{R}}^2}$
- Time-dependent noise: $\sigma_{\mathrm{T}} = \sqrt{\sigma^2 - \sigma_{\mathrm{SB}}^2}$

Results:

- Most Parkes data radiometer dominated
- Brightest 2:

  $\sigma_T \lesssim 80$ ns

  $\sigma_F \lesssim 100$ ns

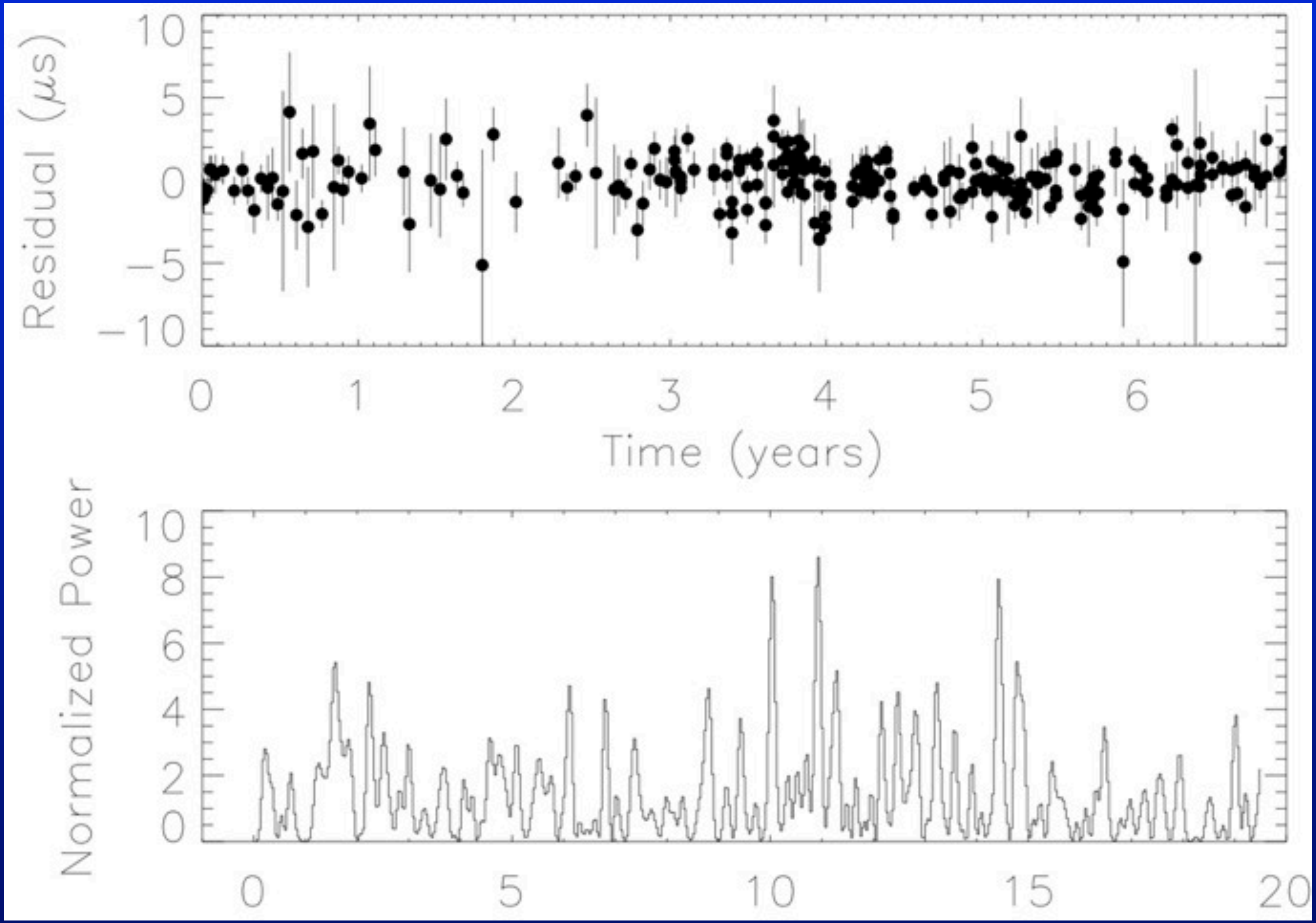


Our Pulsars *Are* Good Enough

Science

AAAS

Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary
Hiroshi Sudou, *et al.*
Science **300**, 1263 (2003);
DOI: 10.1126/science.1082817



Jenet et al., 2003

IPTA

Figure courtesy of Brian Burt, Franklin & Marshall

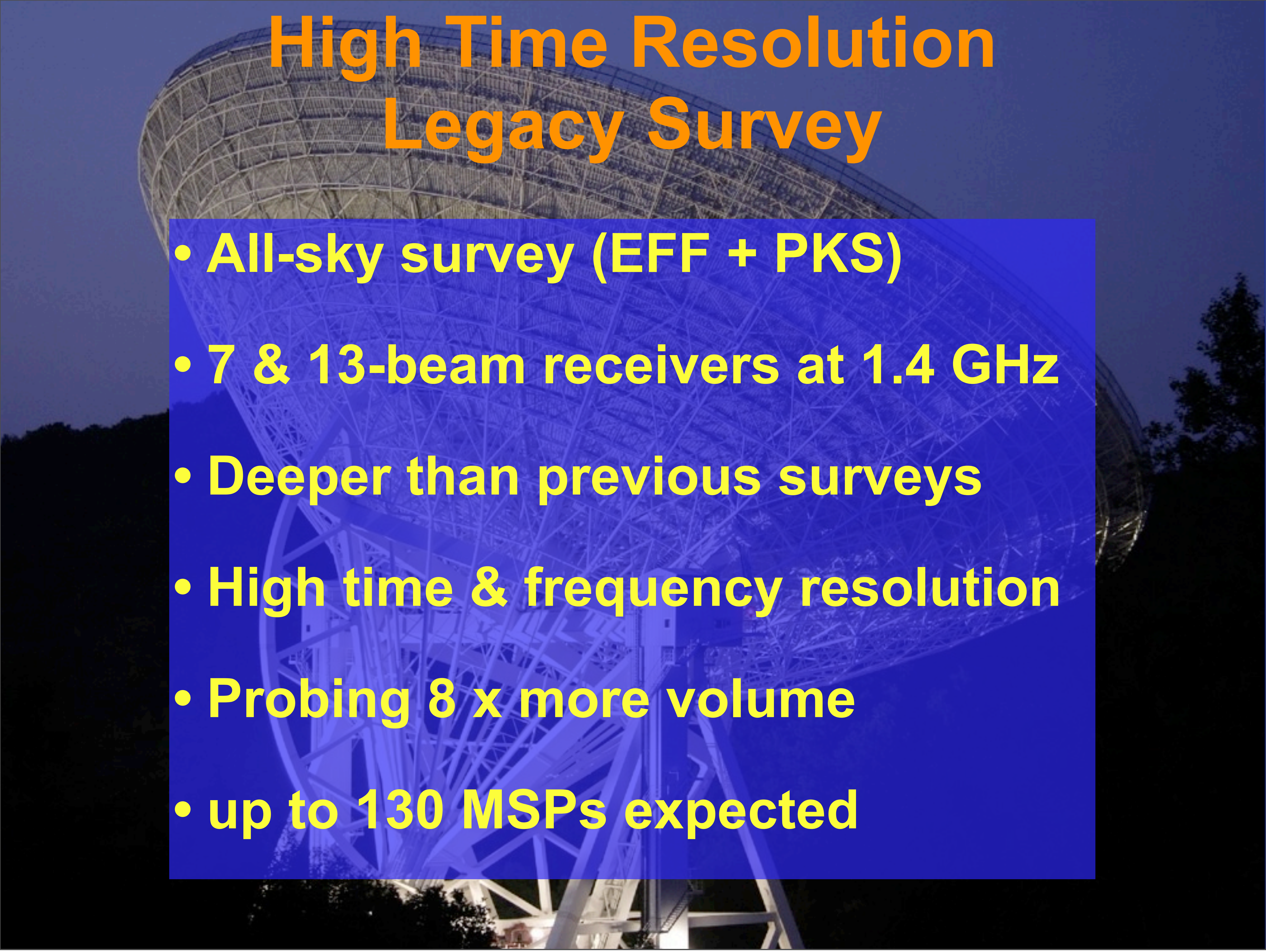
(See also Hobbs et al., 2010)

Large European Array for Pulsars (LEAP)

$$\frac{\sigma_{\mathrm{n}}}{\sqrt[3]{N_{\mathrm{pts}}}}$$

- Add 5 100-m class telescopes coherently:
  - WSRT
  - Effelsberg
  - Jodrell Bank
  - Nançay
  - Sardinia 🚧
- 5-year Advanced ERC grant
- Like AO in Europe

Picture: Thomas Tauris

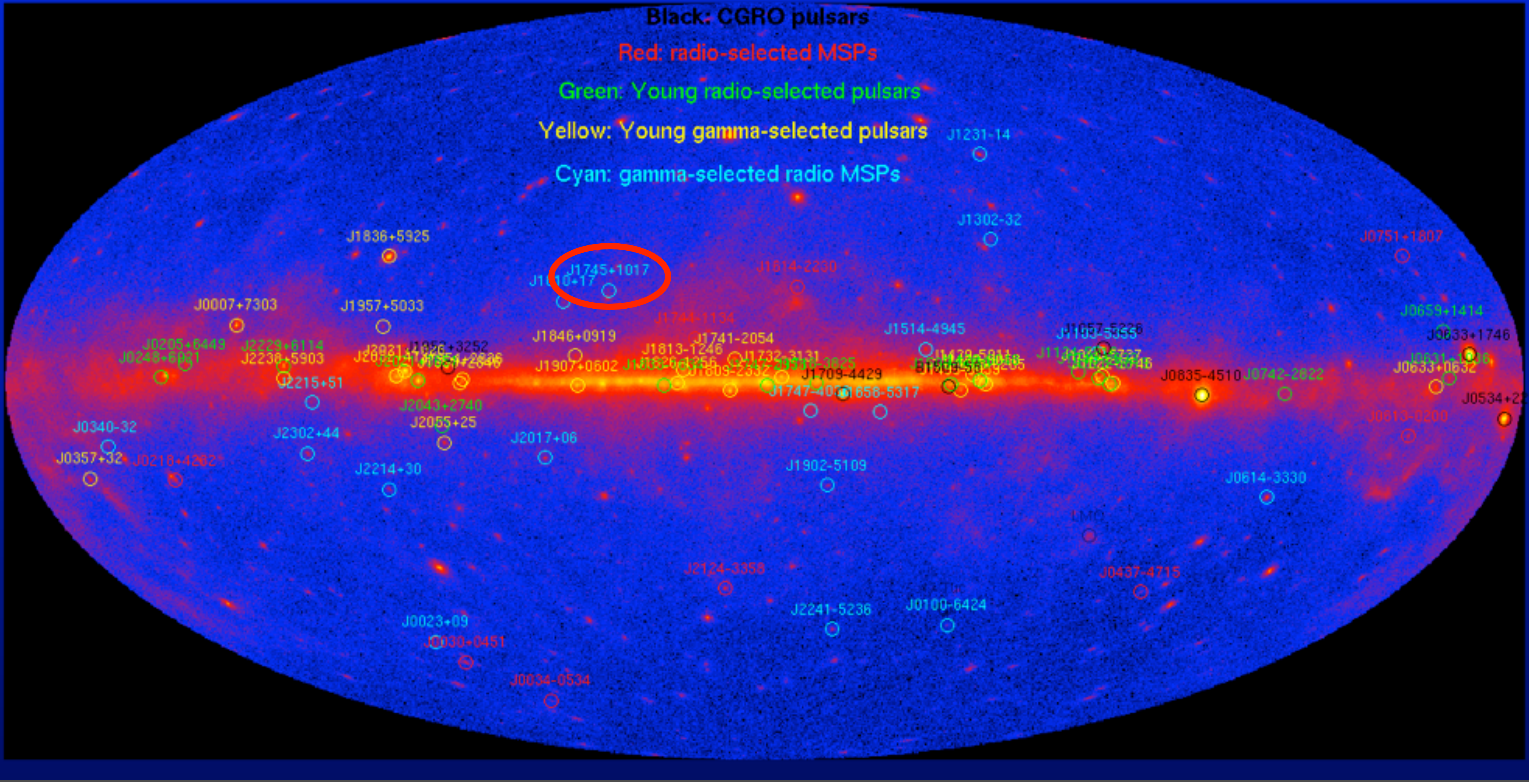


High Time Resolution Legacy Survey

- All-sky survey (EFF + PKS)
- 7 & 13-beam receivers at 1.4 GHz
- Deeper than previous surveys
- High time & frequency resolution
- Probing 8 x more volume
- up to 130 MSPs expected

Fermi Search

- Unidentified Gamma-ray sources
- Many turn out pulsars
- 23 MSPs so far!



When Will We Detect GWs?

- IPTA expects a detection between 2015-2020
- SKA comes online around 2022
- Advanced LIGO operational by 2014
- LISA might be launched by 2018-2020

Predictive Problems

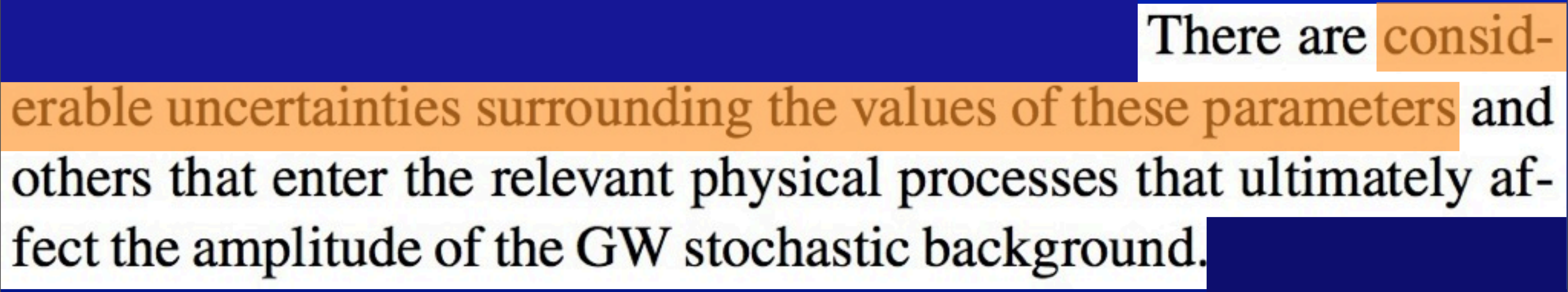
- 3 main GW sources in the PTA band:
  - Cosmic (super)strings
  - Inflation & Big Bang
  - SuperMassive Black Hole Binaries (SMBHBs)

- Problems with these:
  - String models highly tunable
  - Inflationary signal probably too faint (for now)
  - SMBHB population characteristics uncertain

SMBH Uncertainties

GW Amplitude depends on:

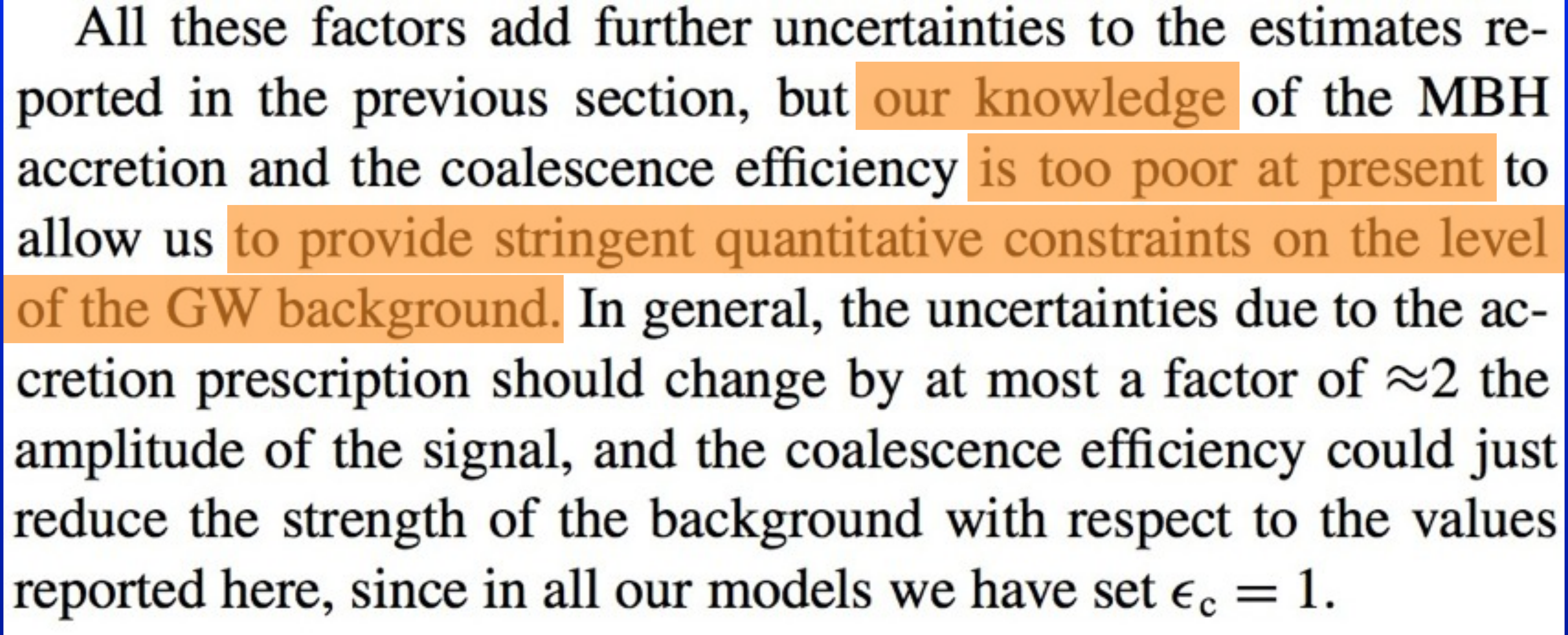
- galactic halo merger rate
- SMBH occupation fraction
- SMBH coalescence efficiency
- SMBH mass function
- SMBHB mass ratio



There are considerable uncertainties surrounding the values of these parameters and others that enter the relevant physical processes that ultimately affect the amplitude of the GW stochastic background.

From Sesana, Vecchio & Colacino, 2008

SMBH Uncertainties

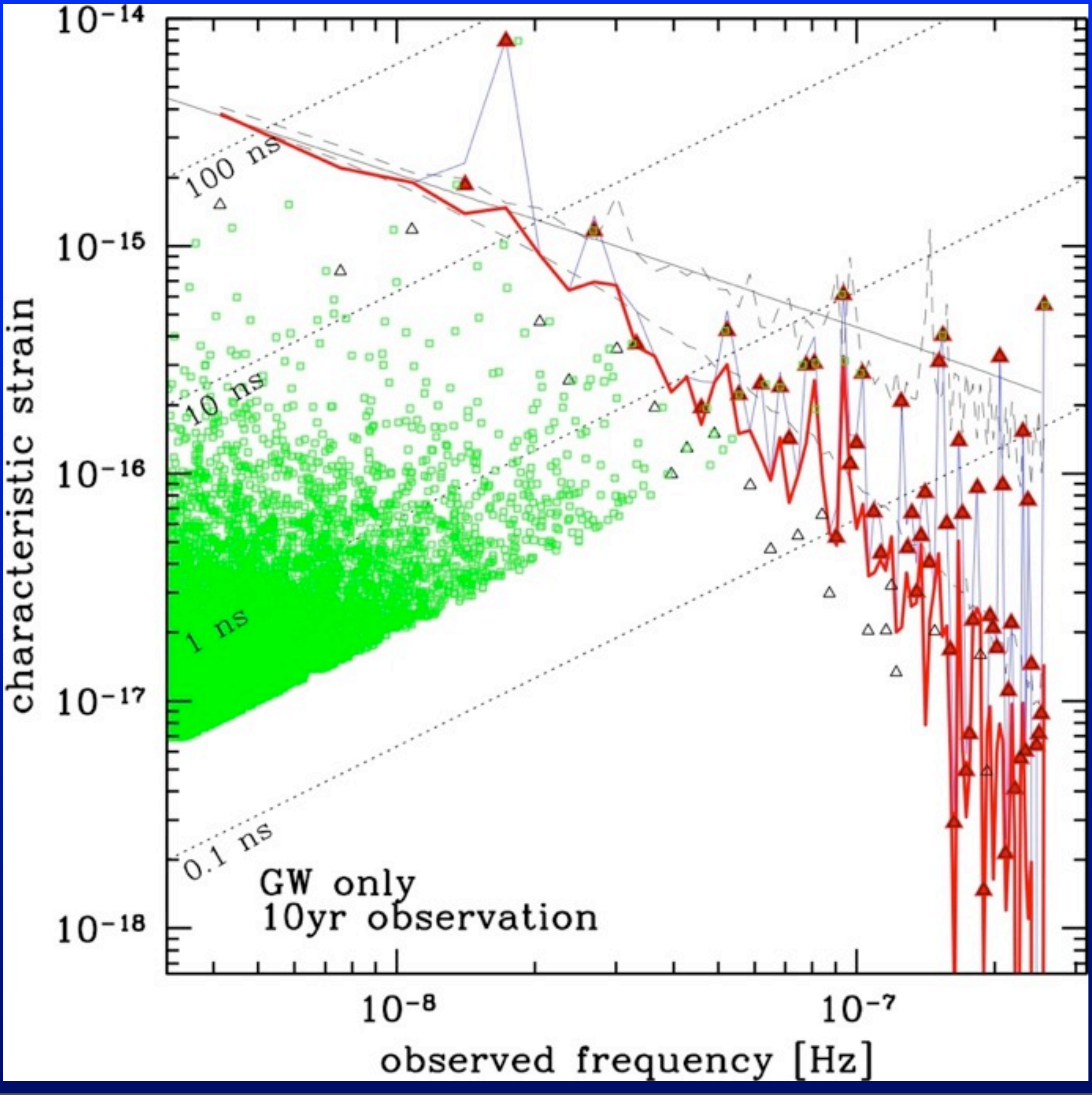


All these factors add further uncertainties to the estimates reported in the previous section, but our knowledge of the MBH accretion and the coalescence efficiency is too poor at present to allow us to provide stringent quantitative constraints on the level of the GW background. In general, the uncertainties due to the accretion prescription should change by at most a factor of ≈2 the amplitude of the signal, and the coalescence efficiency could just reduce the strength of the background with respect to the values reported here, since in all our models we have set $\epsilon_c = 1$.

From Sesana, Vecchio & Colacino, 2008

Ergo: (too?) Many unknowns, but ballpark should be right.

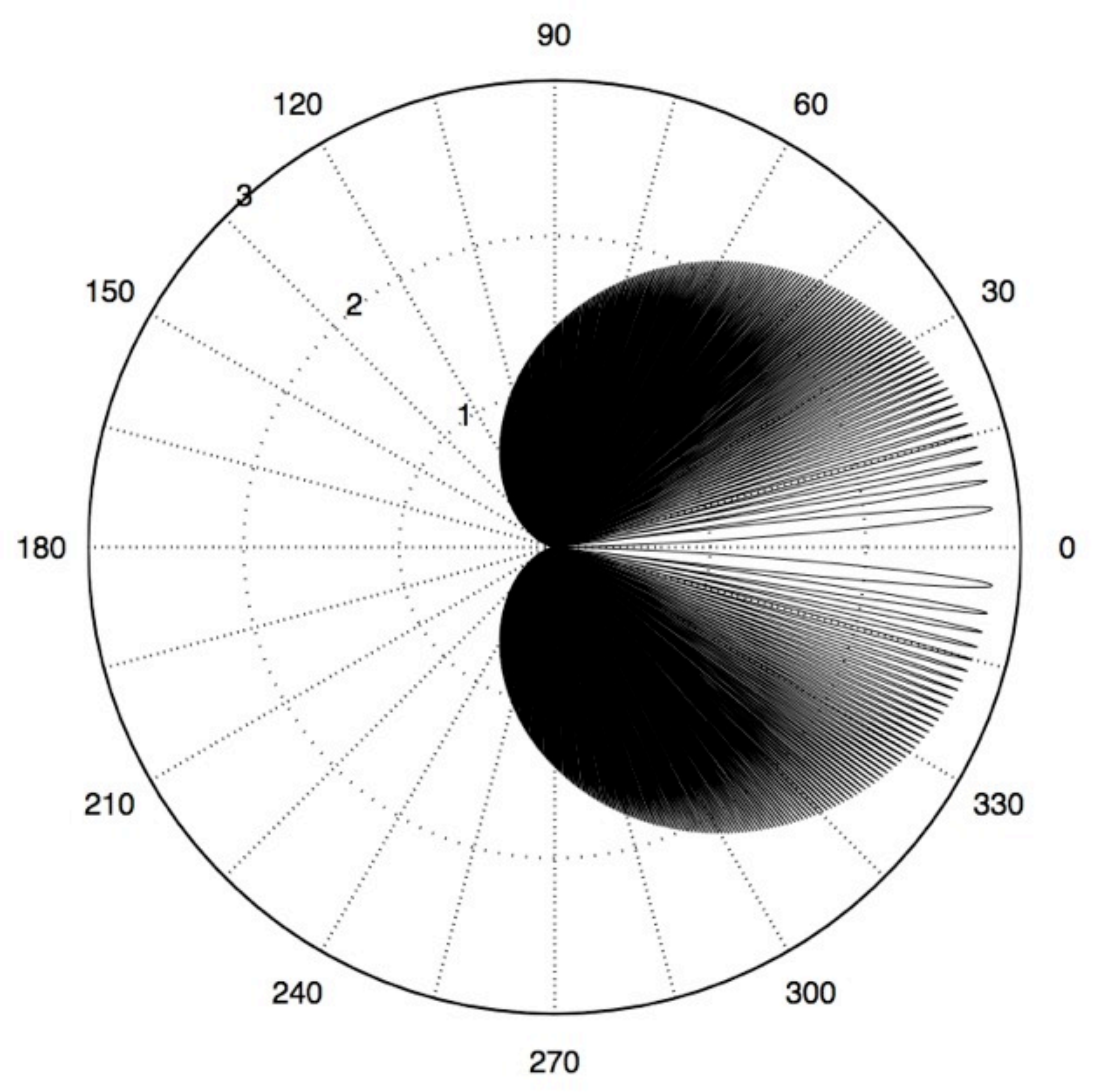
GW sources for PTAs



Kocsis & Sesana, MNRAS, 2010

Single SMBHBs — PSR term

K.J. Lee et al. (MNRAS; 2011)



Single SMBHBs — PSR term

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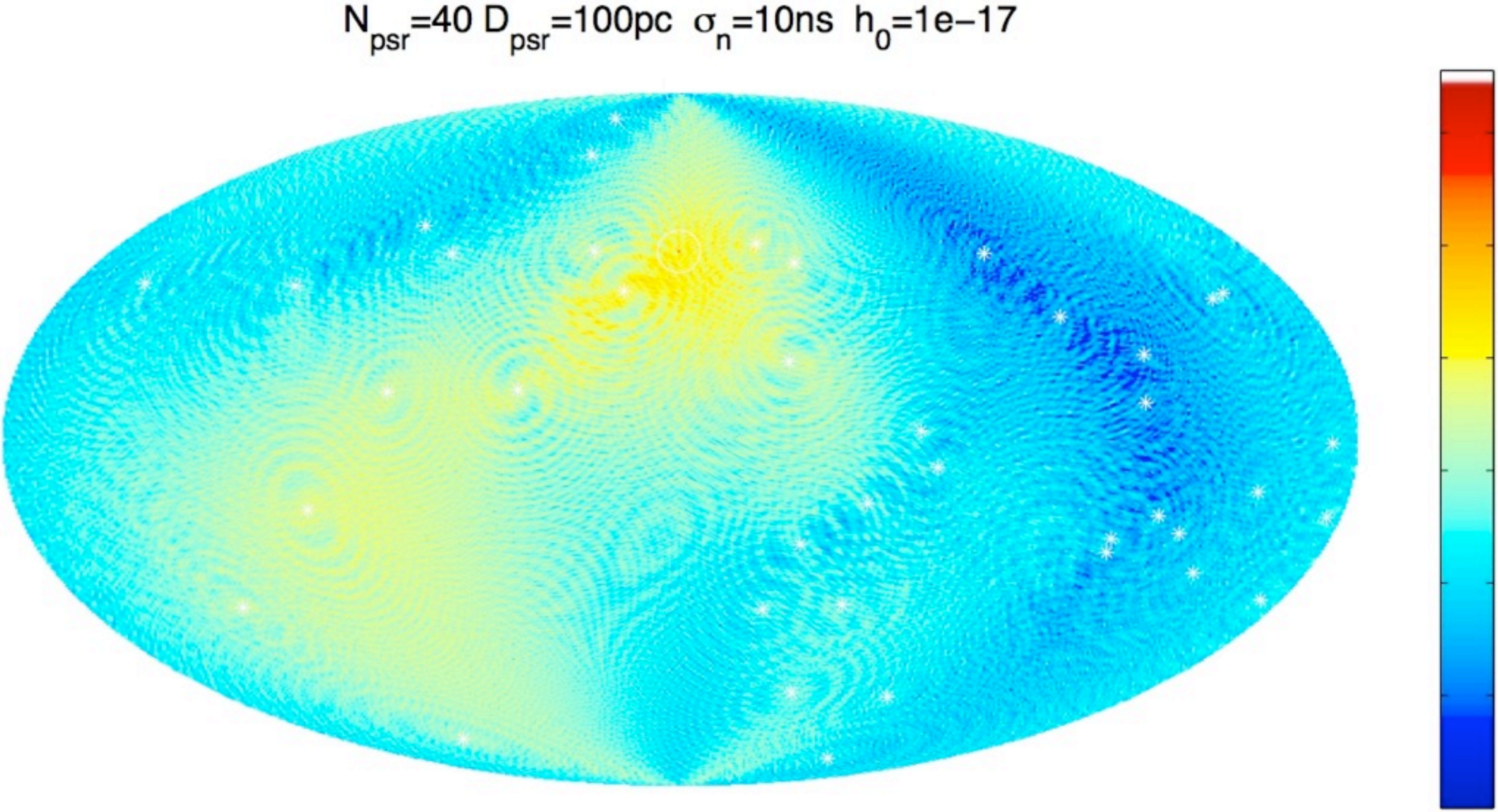

Sigma-z for all 20 MSPs