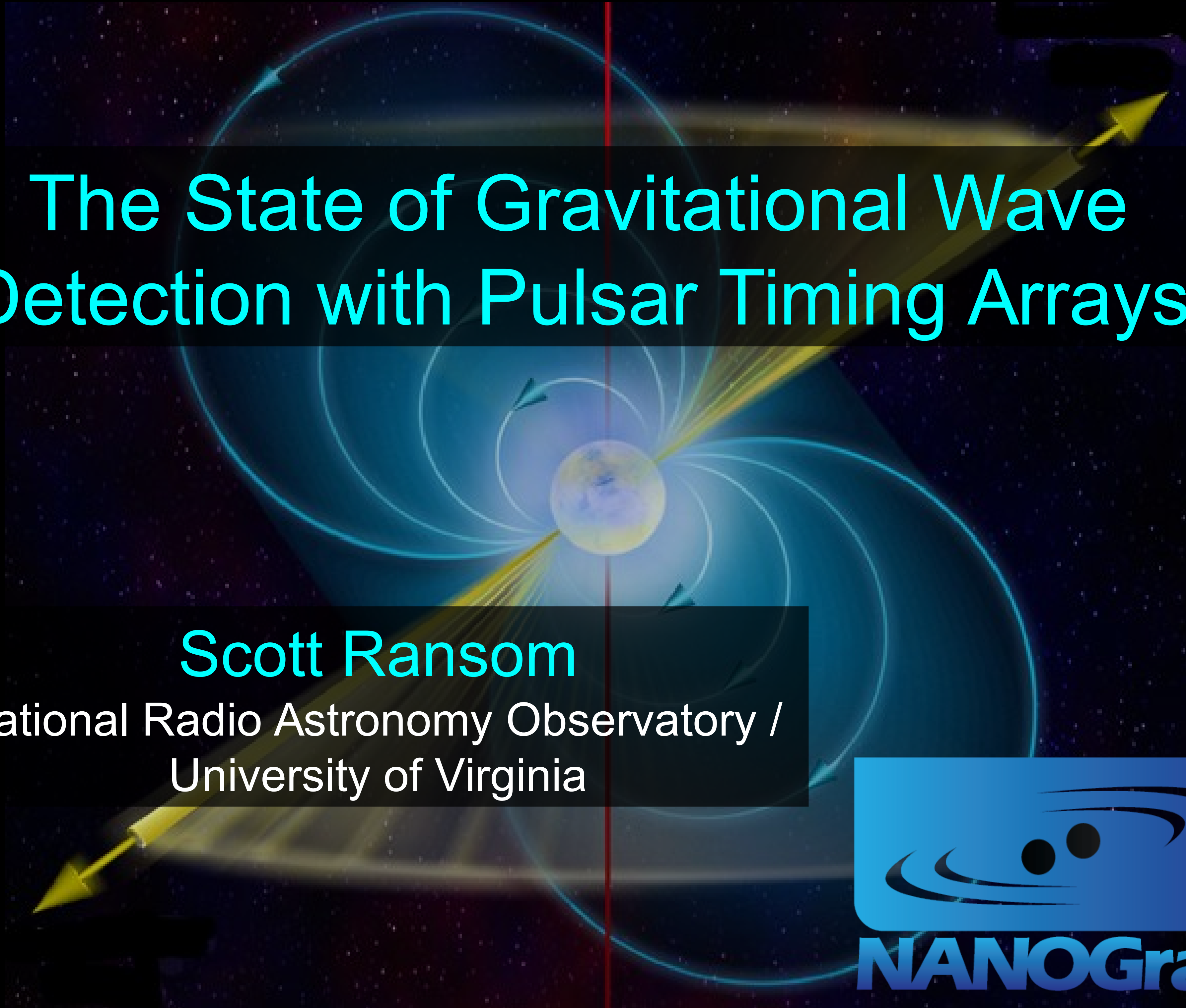
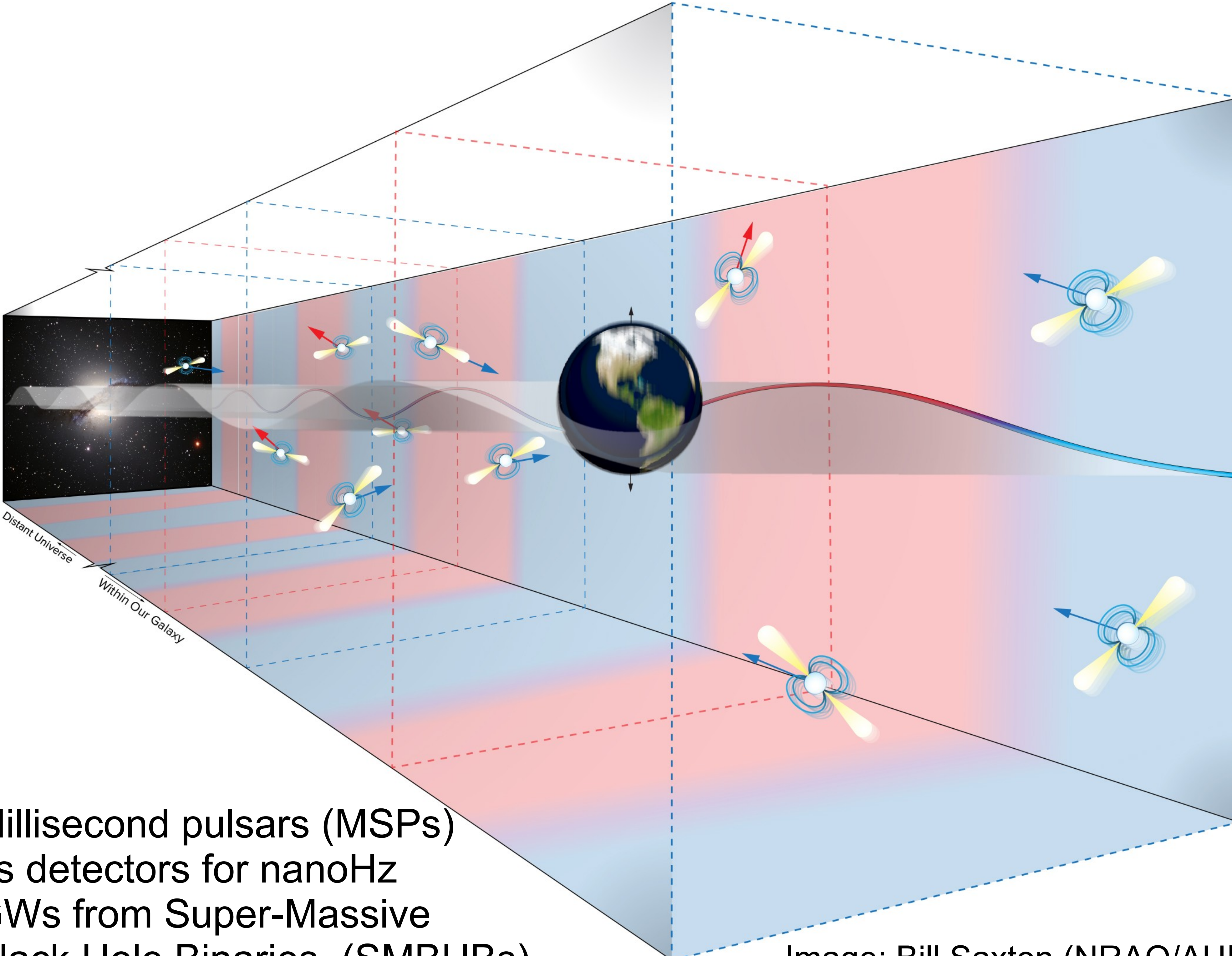


# The State of Gravitational Wave Detection with Pulsar Timing Arrays


Scott Ransom

National Radio Astronomy Observatory / University of Virginia


NANOGrav




Millisecond pulsars (MSPs) as detectors for nanoHz GWs from Super-Massive Black Hole Binaries (SMBHBs)

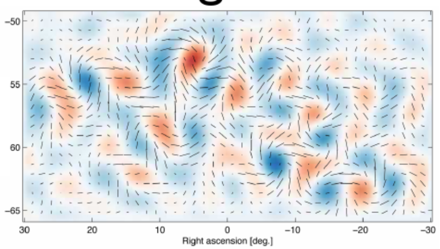
Image: Bill Saxton (NRAO/AUI)

# Gravitational wave physics experiments

Strain $h$

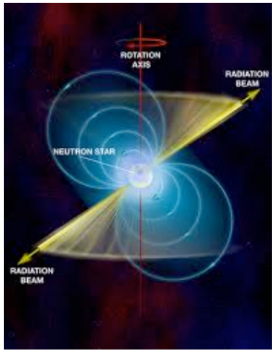
$10^{-5}$, $10^{-10}$, $10^{-15}$, $10^{-20}$, $10^{-25}$

**Cosmic Microwave Background**



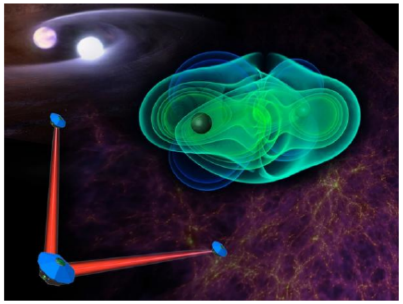

- *Primordial gravitational waves*

**Pulsar Timing Arrays**




- *Supermassive black hole binaries and mergers*
- *Primordial gravitational waves*

**Space-based Interferometers**



- *Stellar mass compact binaries*
- *Supermassive black hole mergers*

**Ground-based Interferometers**

- *Neutron star mergers*
- *Black hole mergers*

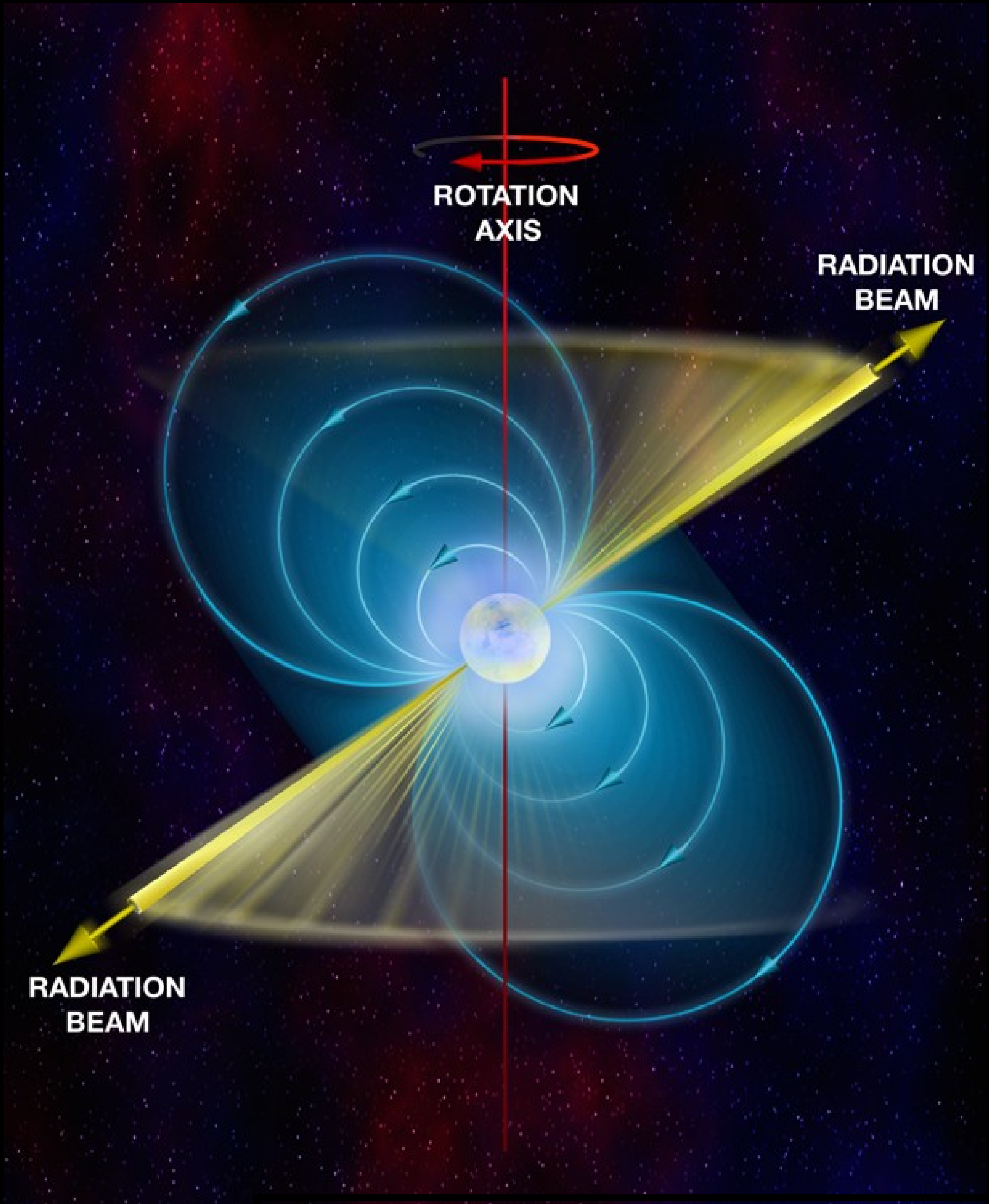
All three experiments measure changes in light travel times between objects due to GWs.

$10^{-16}$, $10^{-8}$, $10^{-4}$, $10^{2}$

Frequency [Hz]

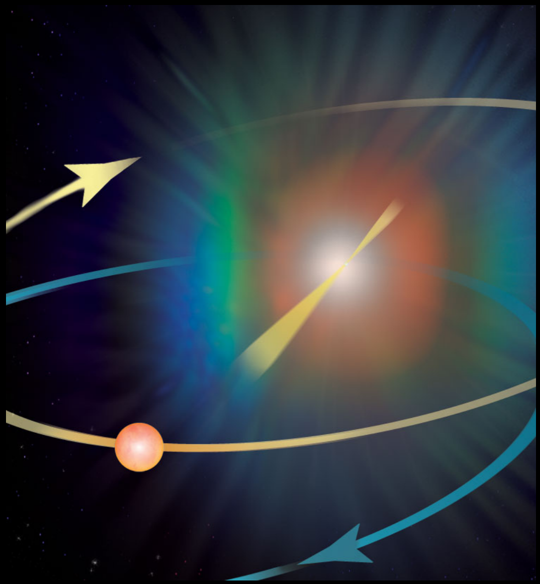
# What's a Millisecond Pulsar ?

- Rapidly Rotating Neutron Star! (300-700 times/sec!)
- Size of city:
  - R ~ 10-15 km
- Mass greater than Sun:
  - M ~ 1.4-2.0 $M_{sun}$
- Strong Magnetic Fields:
  - B ~ $10^8$-$10^9$ Gauss
- Pulses are from a "**lighthouse**" type effect
- "Spin-down" power up to 1000s times more than the Sun's total output!




Credit: Bill Saxton, NRAO/AUI/NSF

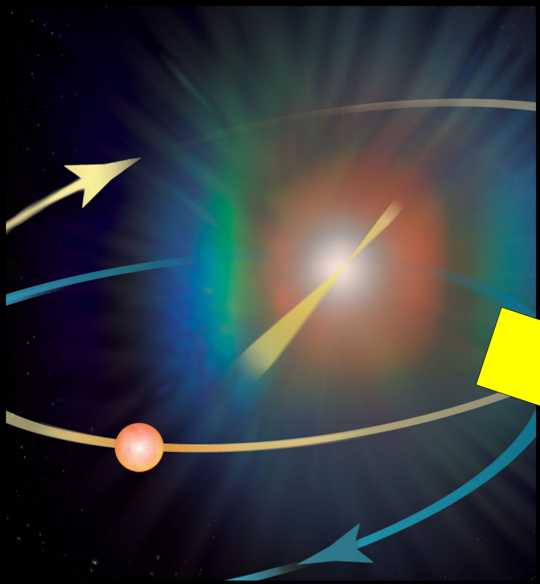
# Millisecond Pulsars: via “Recycling”



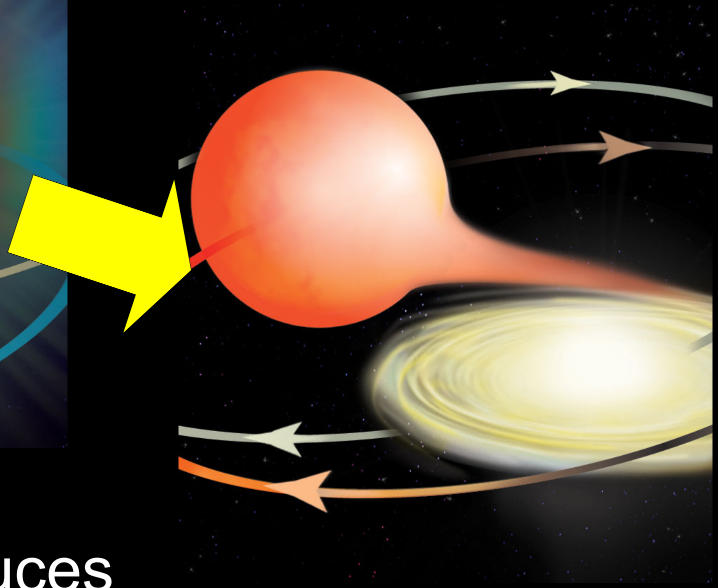
Supernova produces
a neutron star

Picture credits:  Bill Saxton, NRAO/AUI/NSF

# Millisecond Pulsars: via “Recycling”



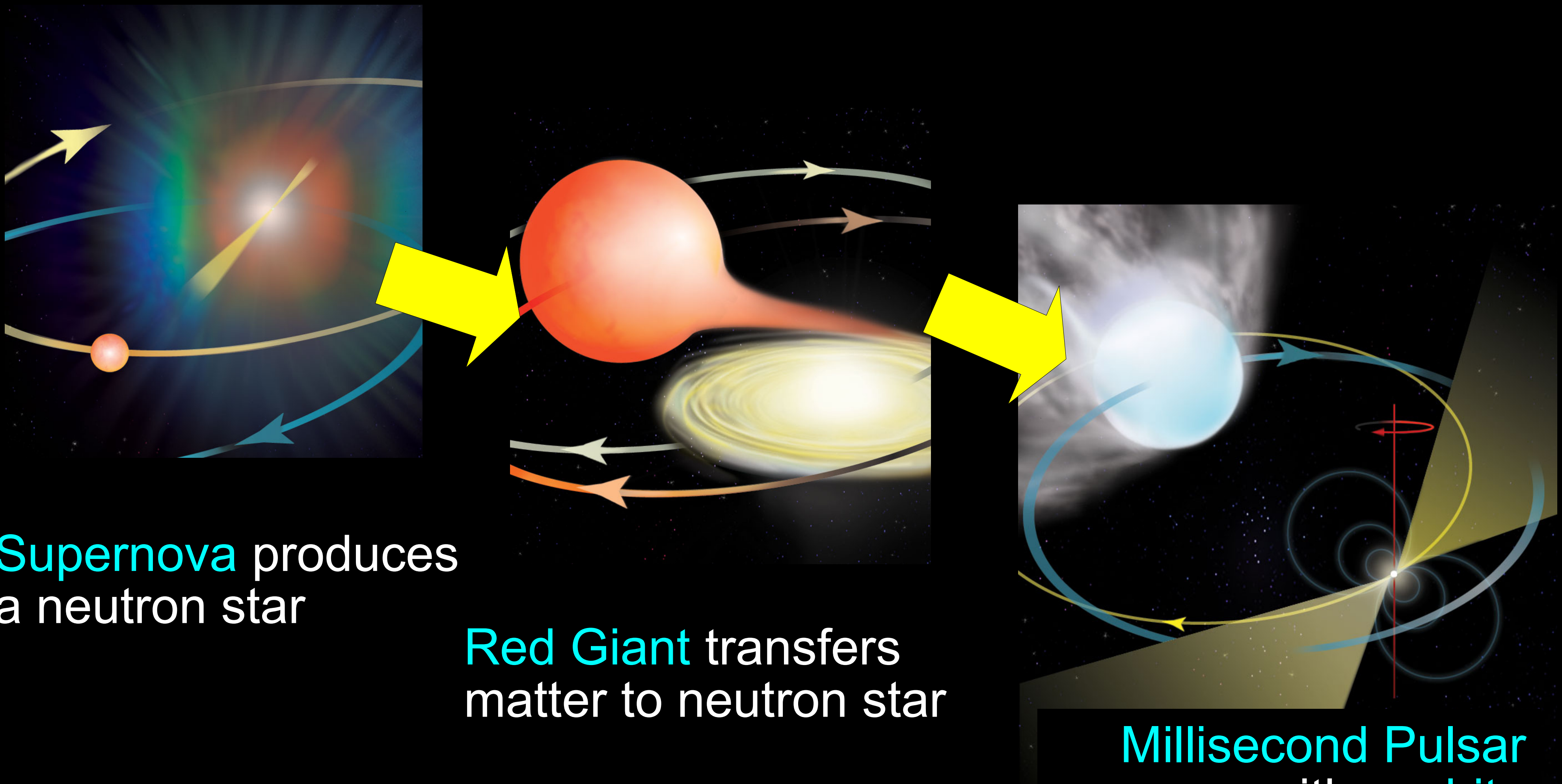
Supernova produces
a neutron star



Red Giant transfers
matter to neutron star

Picture credits:  Bill Saxton, NRAO/AUI/NSF

# Millisecond Pulsars: via “Recycling”



Supernova produces a neutron star

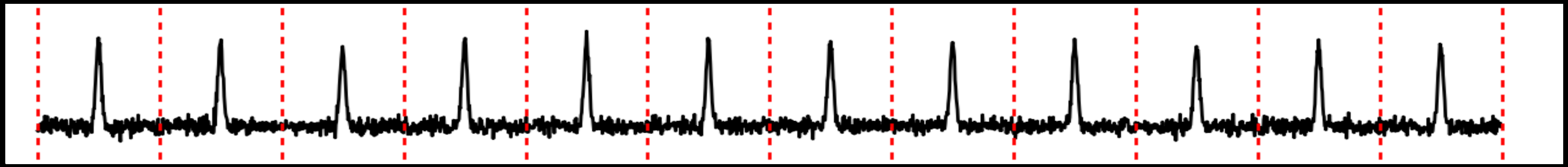
Red Giant transfers matter to neutron star

Millisecond Pulsar emerges with a white dwarf companion

Picture credits: Bill Saxton, NRAO/AUI/NSF

# Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years



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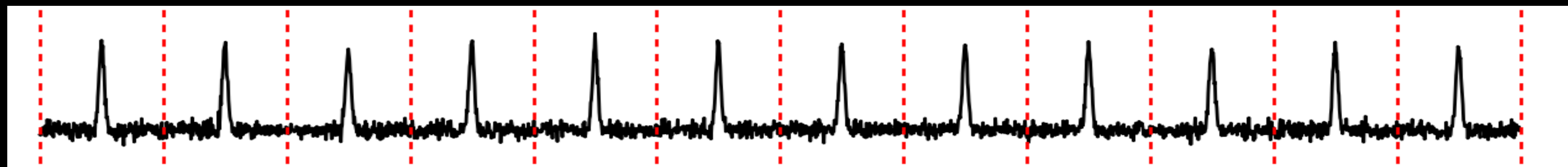
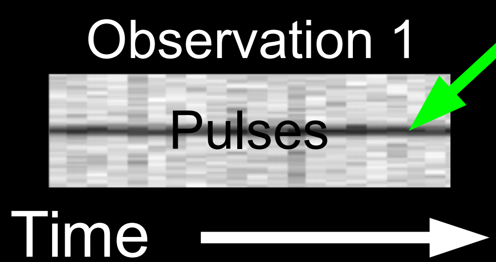


Pulse Measurements
(TOAs: Times of Arrival)



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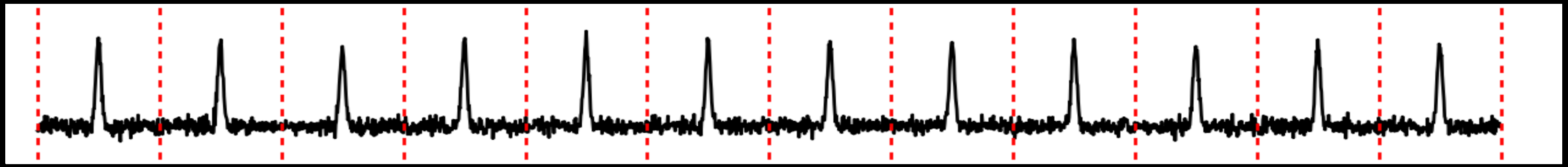

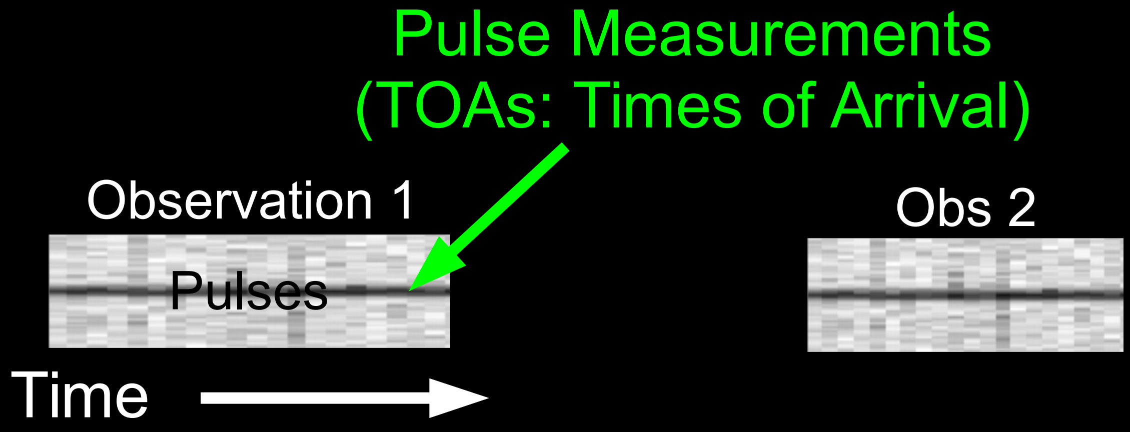

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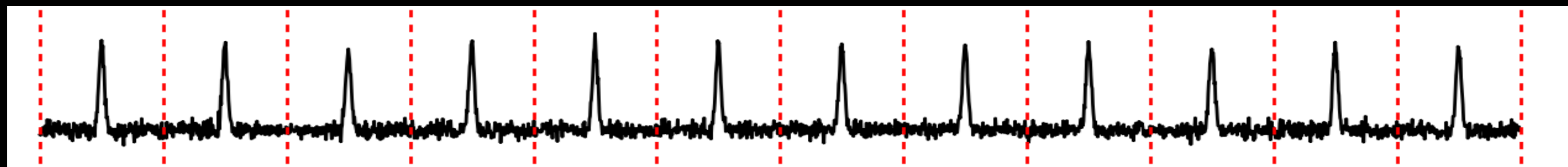

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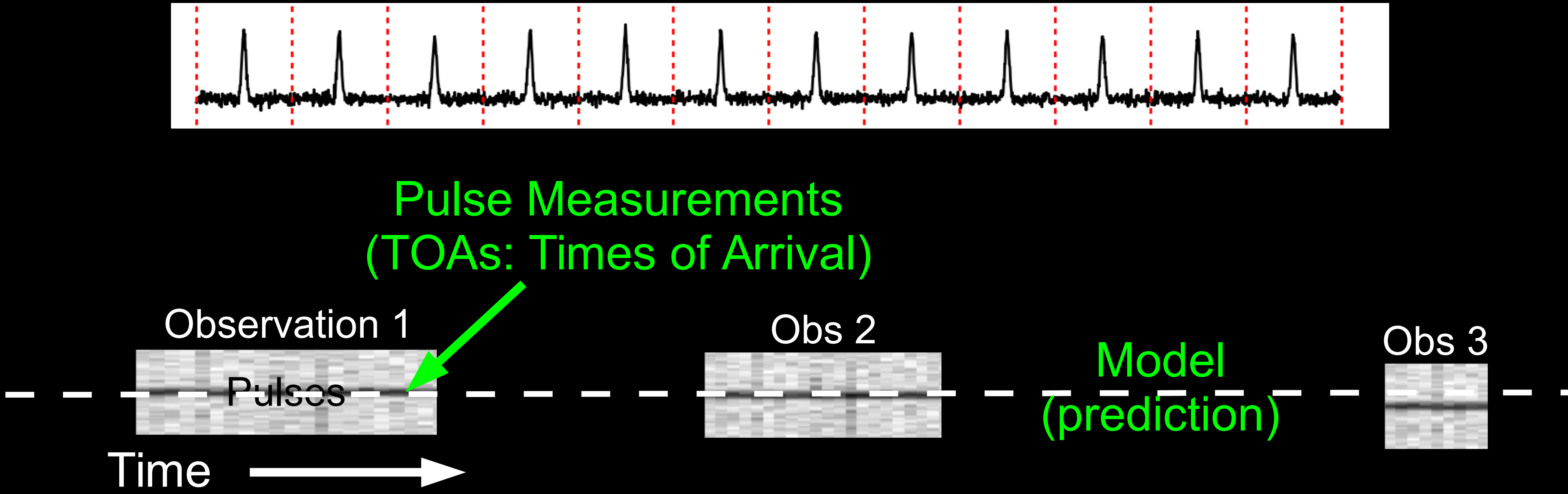

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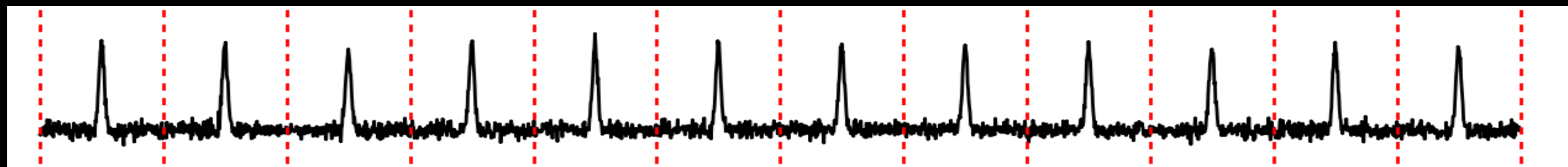
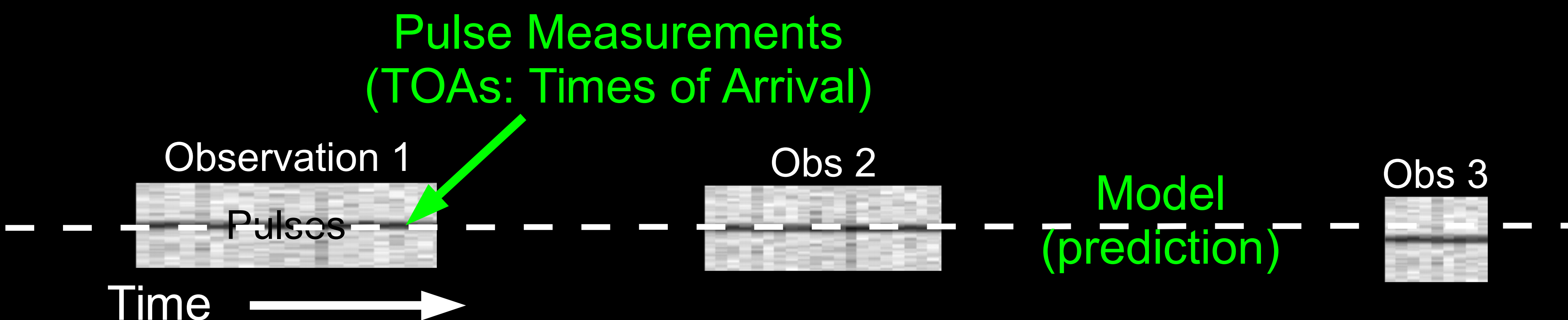
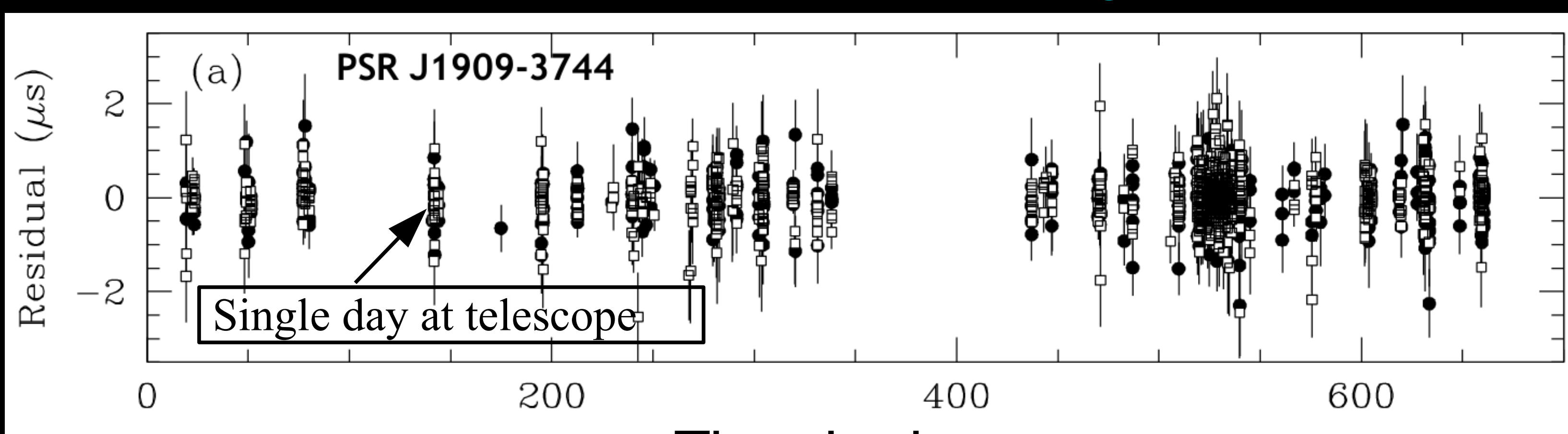





Measurement - Model = Timing Residuals




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

Predict each pulse to ~200 ns over 2 yrs!

**Table 1 | Physical parameters for PSR J1614-2230**

| Parameter | Value |
|---|---|
| Ecliptic longitude ($\lambda$) | $245.78827556(5)^{\circ}$ |
| Ecliptic latitude ($\beta$) | $-1.256744(2)^{\circ}$ |
| Proper motion in $\lambda$ | $9.79(7)\ \mathrm{mas\ yr^{-1}}$ |
| Proper motion in $\beta$ | $-30(3)\ \mathrm{mas\ yr^{-1}}$ |
| Parallax | 0.5(6) mas |
| Pulsar spin period | 3.1508076534271(6) ms |
| Period derivative | $9.6216(9) \times 10^{-21}\ \mathrm{s\ s^{-1}}$ |
| Reference epoch (MJD) | 53,600 |
| Dispersion measure* | $34.4865\ \mathrm{pc\ cm^{-3}}$ |
| Orbital period | 8.6866194196(2) d |
| Projected semimajor axis | 11.2911975(2) light s |
| First Laplace parameter ($e\sin\omega$) | $1.1(3) \times 10^{-7}$ |
| Second Laplace parameter ($e\cos\omega$) | $-1.29(3) \times 10^{-6}$ |
| Companion mass | $0.500(6) M_{\odot}$ |
| Sine of inclination angle | 0.999894(5) |
| Epoch of ascending node (MJD) | 52,331.1701098(3) |
| Span of timing data (MJD) | 52,469–55,330 |
| Number of TOAs† | 2,206 (454, 1,752) |
| Root mean squared TOA residual | 1.1 μs |
| Right ascension (J2000) | 16 h 14 min 36.5051(5) s |
| Declination (J2000) | $-22^{\circ}\ 30'\ 31.081(7)''$ |
| Orbital eccentricity ($e$) | $1.30(4) \times 10^{-6}$ |
| Inclination angle | $89.17(2)^{\circ}$ |
| Pulsar mass | $1.97(4) M_{\odot}$ |
| Dispersion-derived distance‡ | 1.2 kpc |
| Parallax distance | >0.9 kpc |
| Surface magnetic field | $1.8 \times 10^{8}$ G |
| Characteristic age | 5.2 Gyr |
| Spin-down luminosity | |

Demorest et al. 2010, *Nature*

**Table 1 | Physical parameters for PSR J1614-2230**

# *Ask the right question...*

Highly circular orbit has a radius of ***~3.4 million km***
(~5 x Solar radius or ~9 x Earth-Moon distance)

**What is the difference in length between the semi-major and semi-minor axes?**

| | |
|---|---|
| | 6(5)° |
| | (2)° |
| | $yr^{-1}$ |
| | $yr^{-1}$ |
| | s |
| | 71(6) ms |
| | $^{-21}$ s $s^{-1}$ |
| | $m^{-3}$ |
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| Characteristic age | 5.2 Gyr |
| Spin-down luminosity | |

# *...get a spectacular answer!*

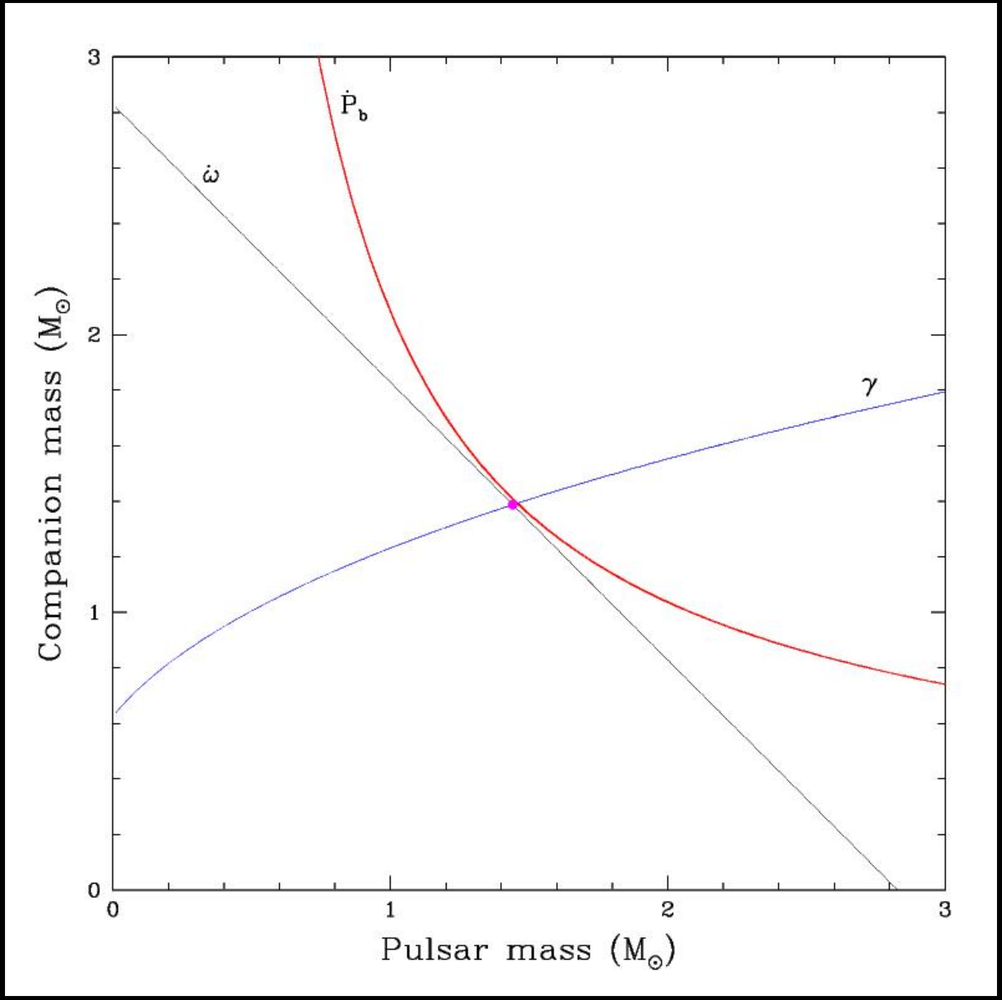
# ***2.8 +/- 0.2 mm!***

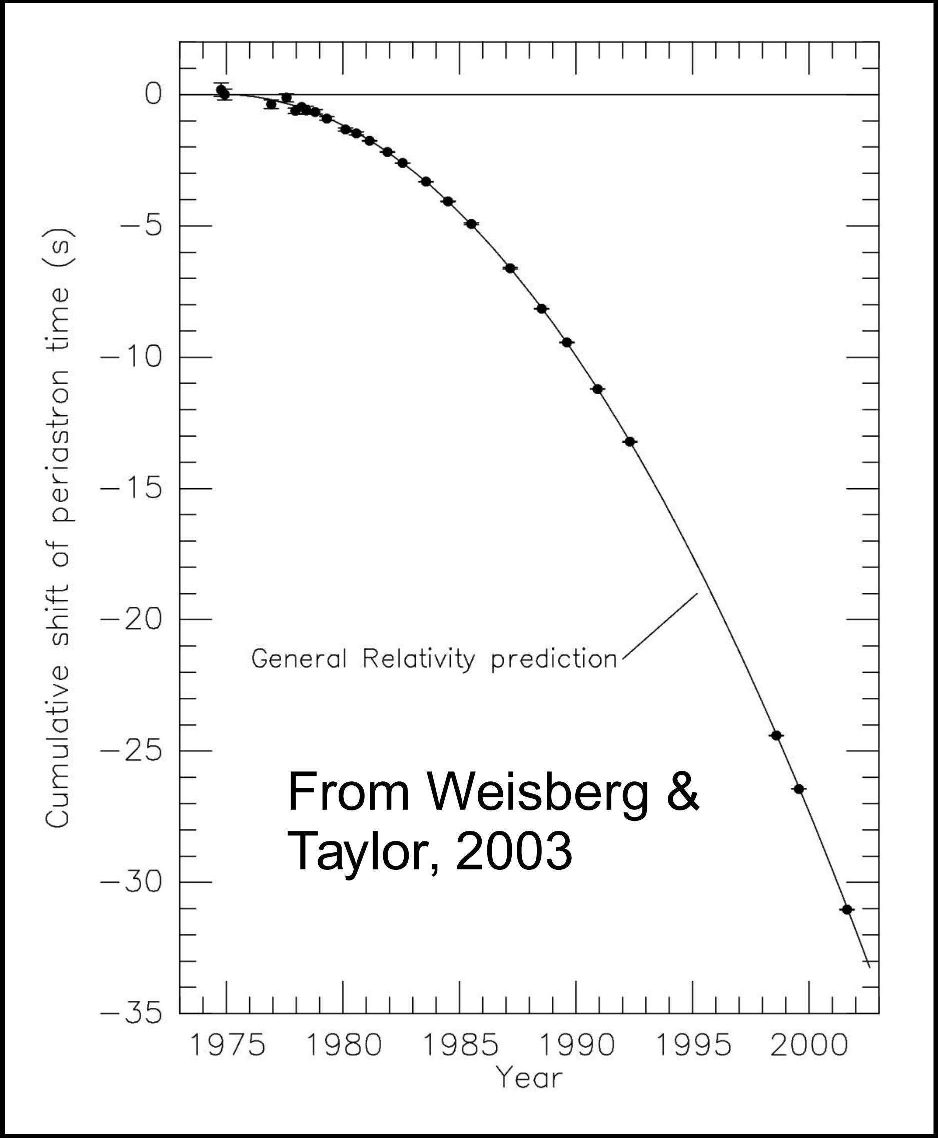
Demorest et al. 2010, *Nature*

# The Binary Pulsar: B1913+16

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

**Indirect detection of Gravitational Radiation!**

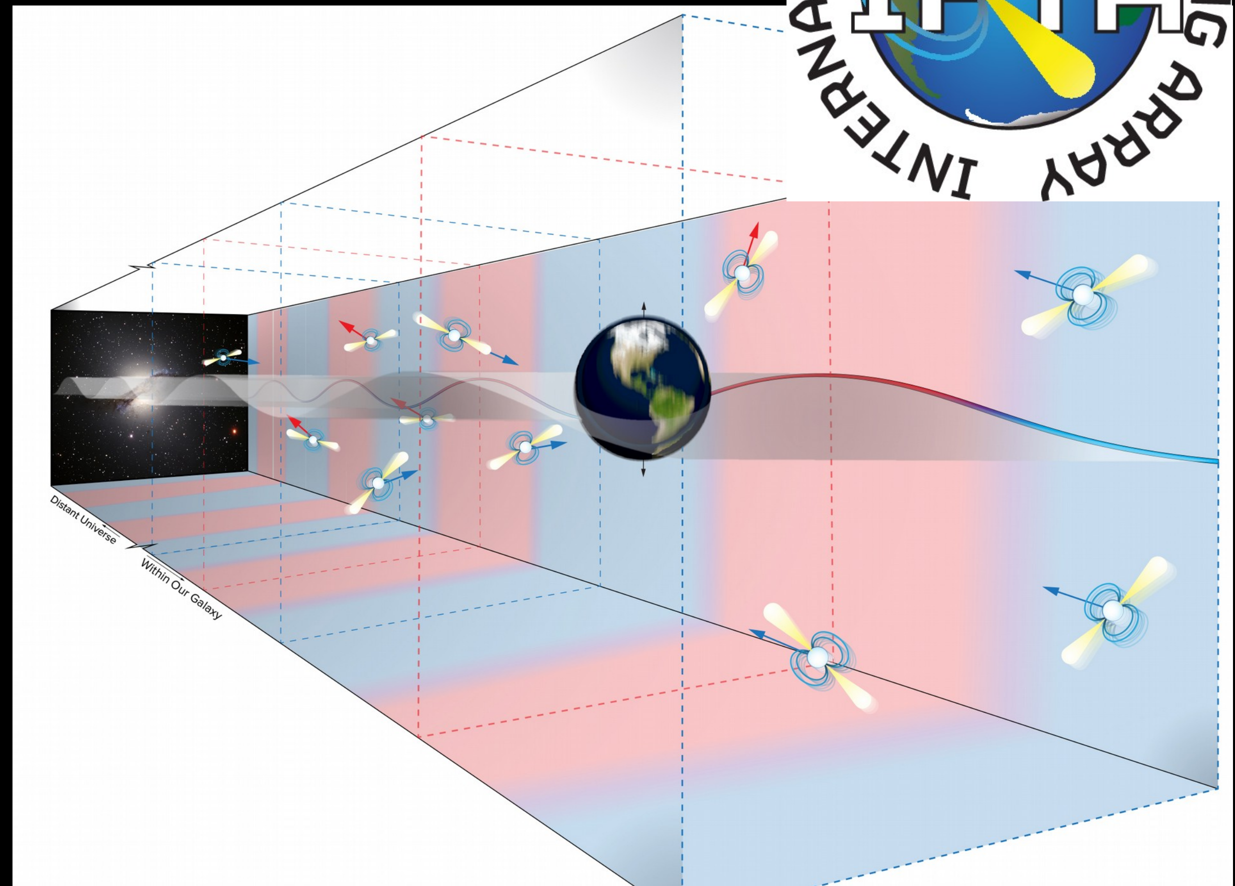



From Weisberg & Taylor, 2003

# Direct Gravitational Wave Detection (Pulsar Timing Array)

- Looking for nHz freq gravitational waves from super massive black hole binaries
- Need good MSPs:
  - Significance scales with the number of MSPs being timed
- Must time 20+ pulsars for 10+ years at precision of ~100 nanosec!



Bill Saxton (NRAO/AUI)

PPTA
Australia

EPTA
Europe

NANOGrav
North America

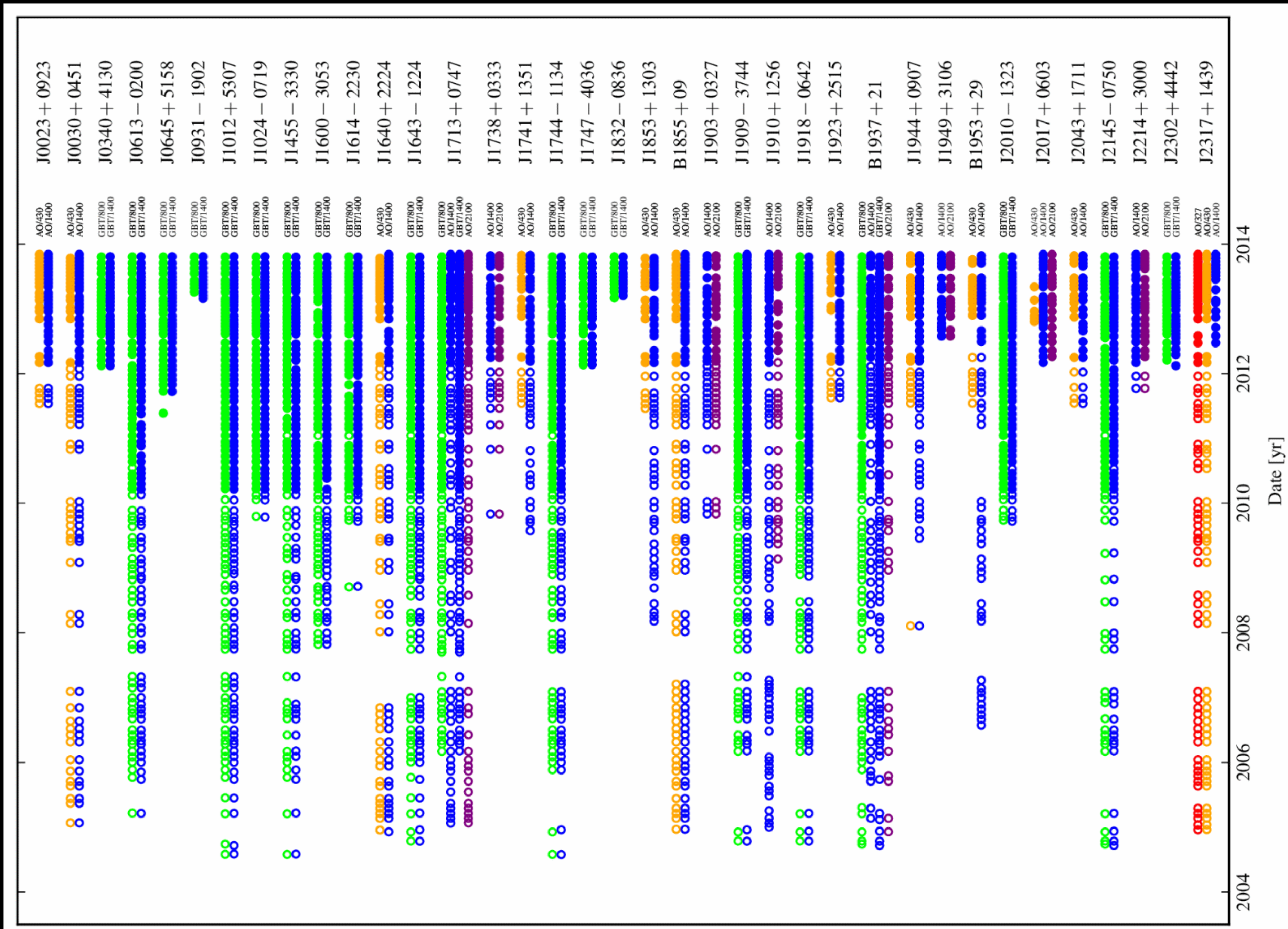
For more information, see *nanograv.org*

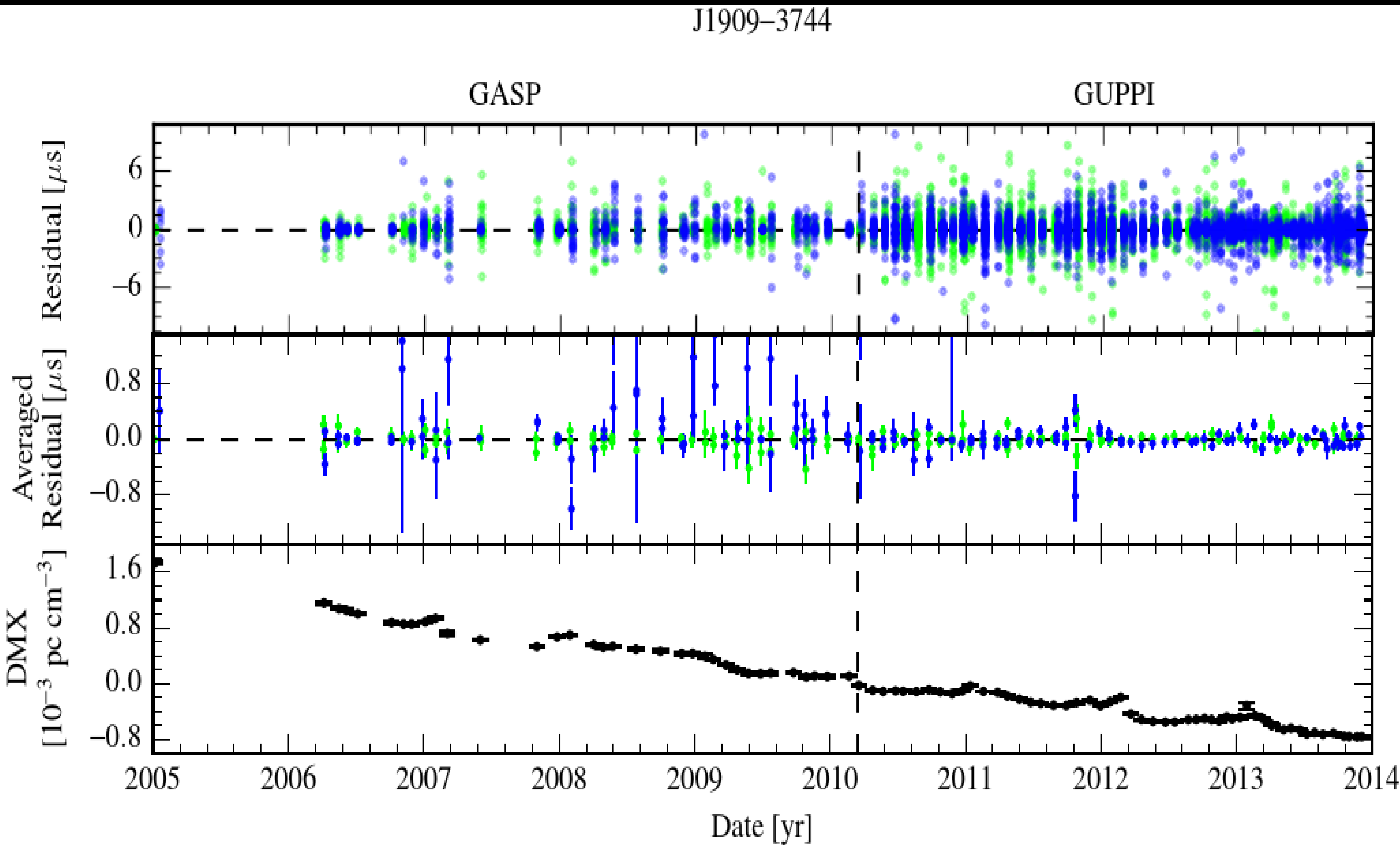
| | NANOGrav | EPTA | PPTA |
|---|---|---|---|
| Telescopes | Arecibo<br>GBT | Nancay<br>Effelsberg<br>Westerbork<br>Jodrell Bank<br>Sardinia RT | Parkes |
| Observing Time | 1x | ~5x+ | ~3x |
| Advantages | Sensitivity | Cadence<br>Phased Array<br>(LEAP) | Cadence<br>Unique Pulsars<br>Single telescope |
| Disadvantages | Sky coverage<br>Oversubscription<br>Telescope threats | Systematics | Sensitivity<br>Telescope threat |

| | | | |
|---|---|---|---|
| Telescopes | Arecibo<br>GBT | Nancay<br>Effelsberg<br>We | rkes |
| Observing Time | | | ~3x |
| Advant | | adence<br>Phased Array<br>(LEAP) | Cadence<br>Unique Pulsars<br>Single telescope |
| Disadvanta | ky coverage<br>Oversubscription<br>Telescope threats | Systematics | Sensitivity<br>Telescope threat |

Major releases / limits from each PTA have just come out!

# NANOGrav 9-yr Data

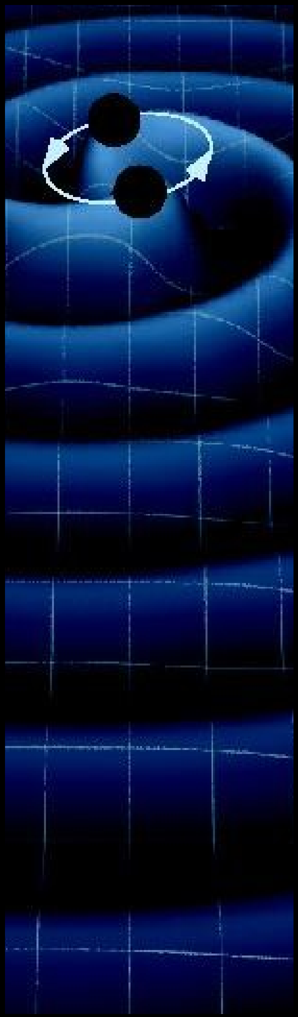




J1909−3744
GASP
GUPPI
Residual [$\mu$s]
6
0
−6
Averaged Residual [$\mu$s]
0.8
0.0
−0.8
DMX [$10^{-3}$ pc cm$^{-3}$]
1.6
0.8
0.0
−0.8
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Date [yr]

# 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?

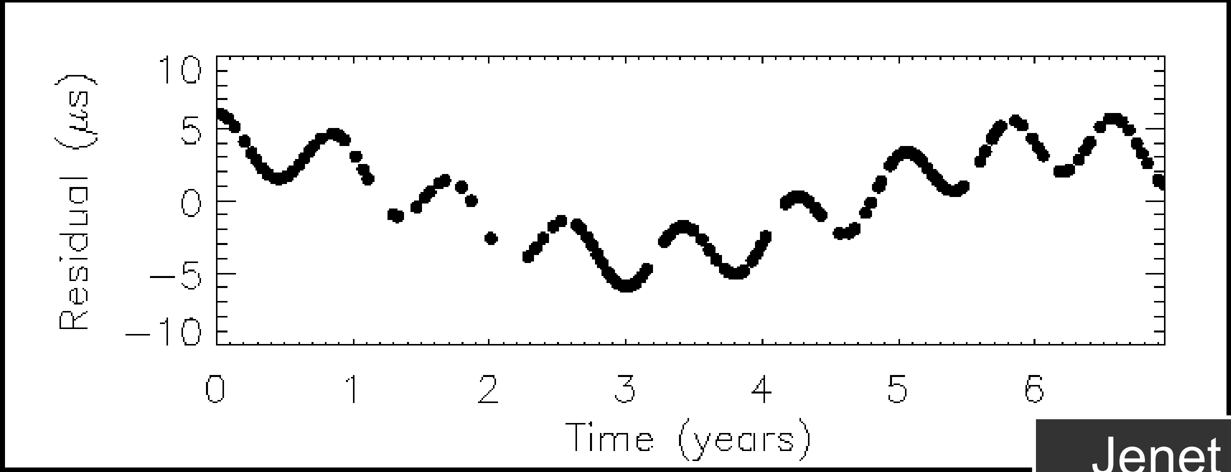

## 3C66B

At $z = 0.02$

Orbital period 1.05 yrs

Total mass $5.4\times10^{10}M_{\odot}$

(Sudou et al 2003)

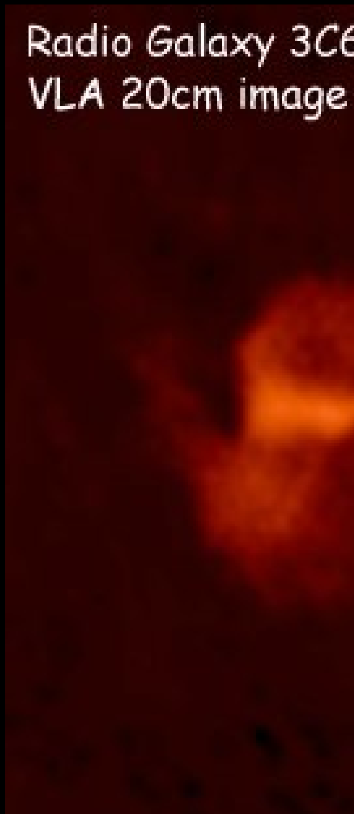


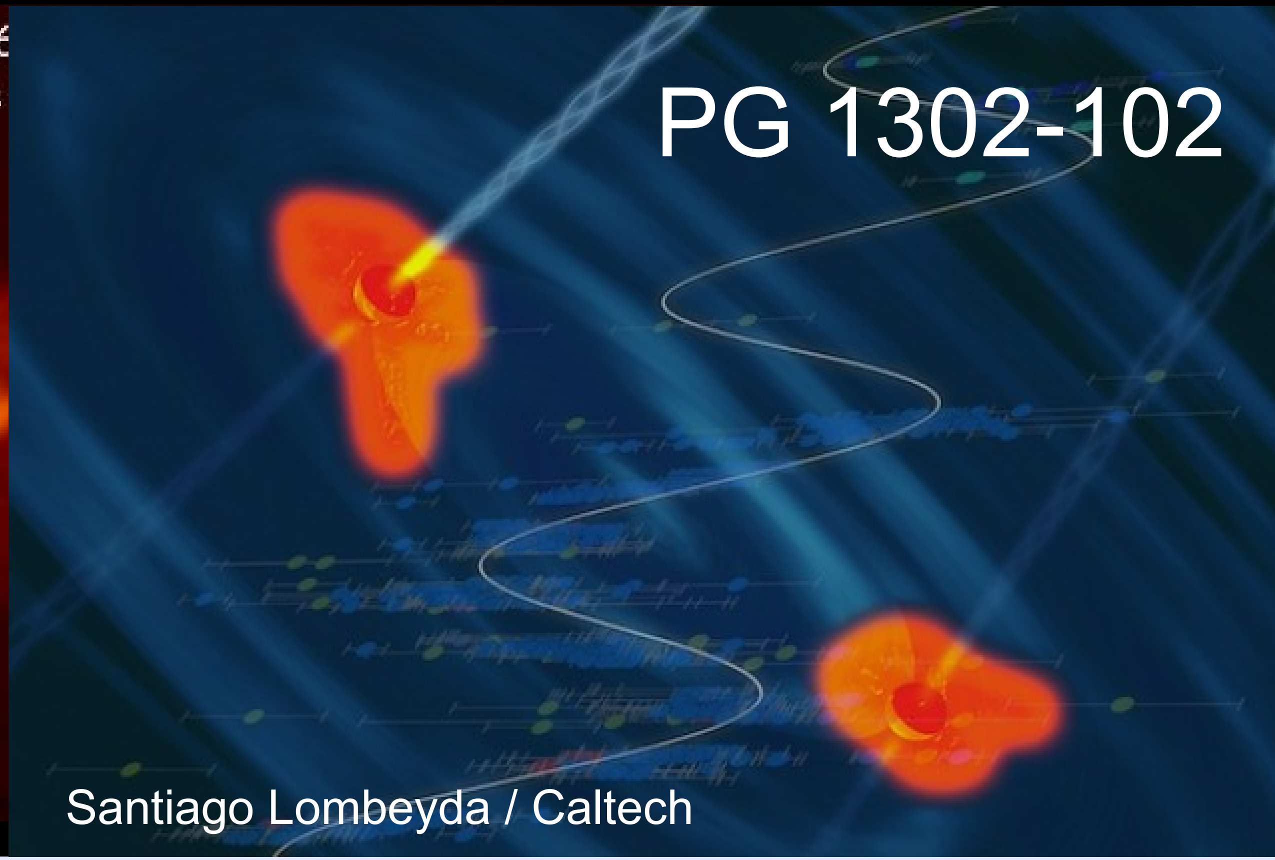

Predicted timing residuals

Ruled out by MSP observations

Jenet et al. 2004, ApJ, 606, 799

# So where do these GWs come from?

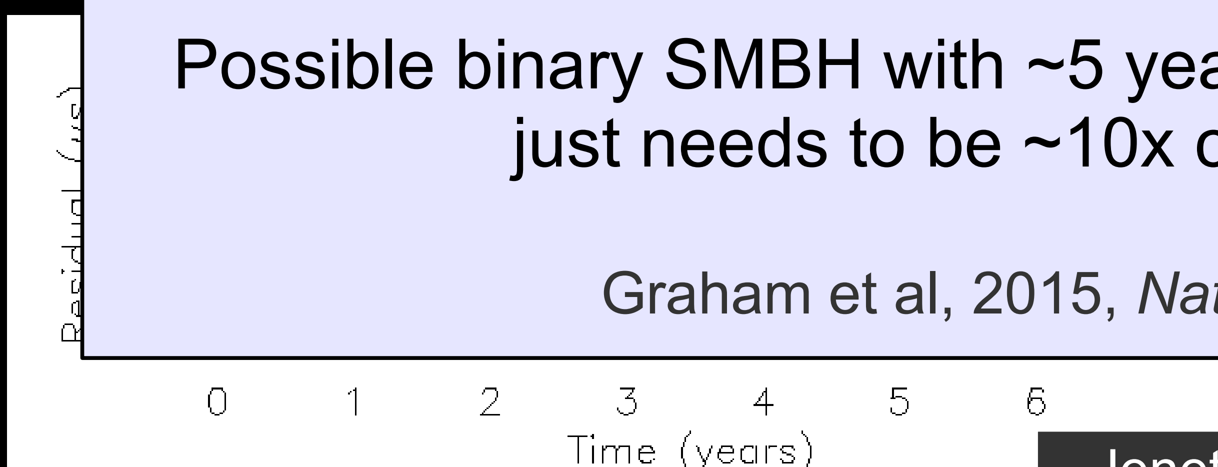



05 yrs
$10^{10} M_\odot$

Possible binary SMBH with ~5 year orbital period...
just needs to be ~10x closer!

Graham et al, 2015, *Nature*




S

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, 2010, ...

Table 1: The expected parameters for predicted stochastic backgrounds

| Model | A | $\alpha$ | 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

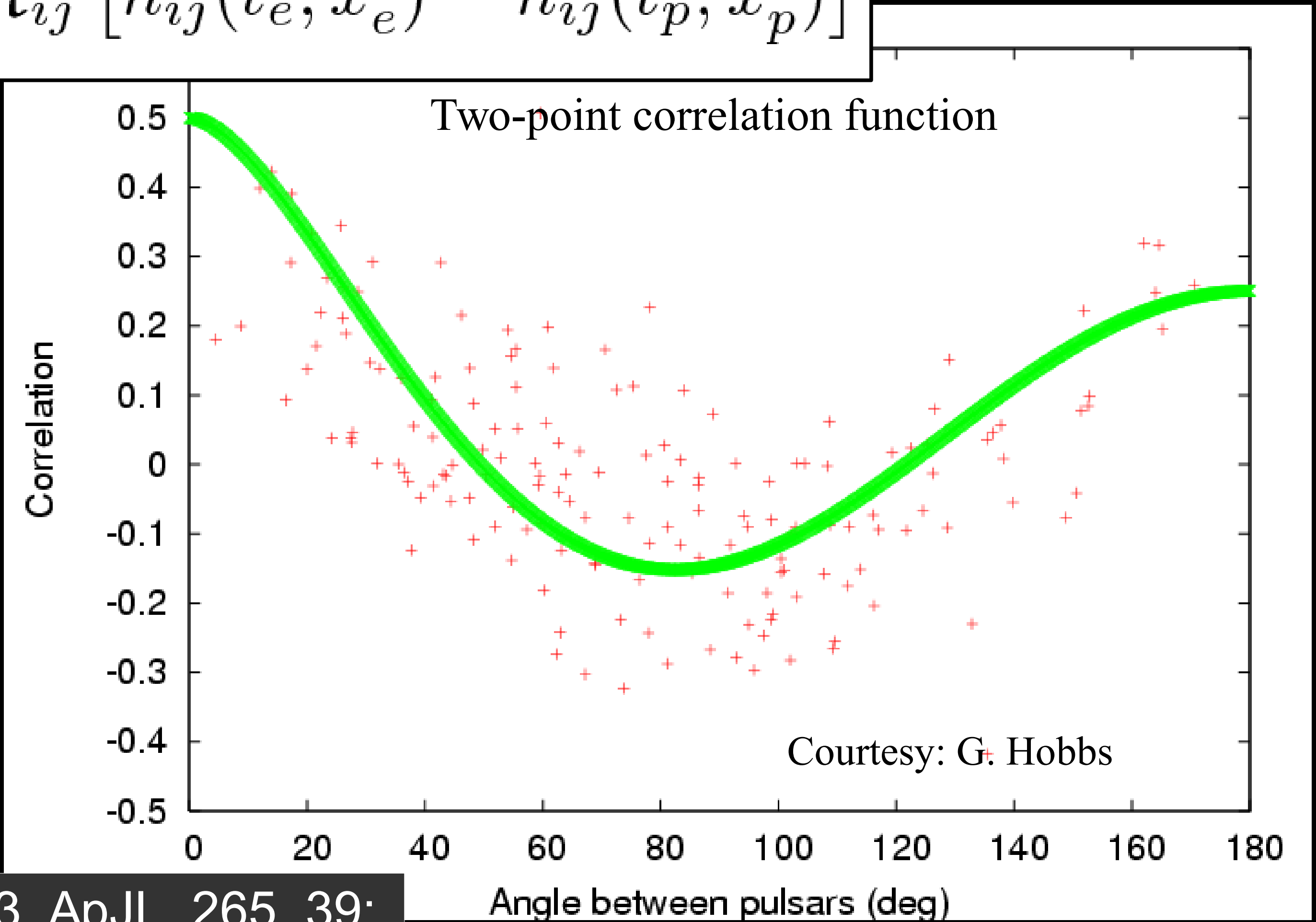
# A Pulsar Timing Array (PTA)

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

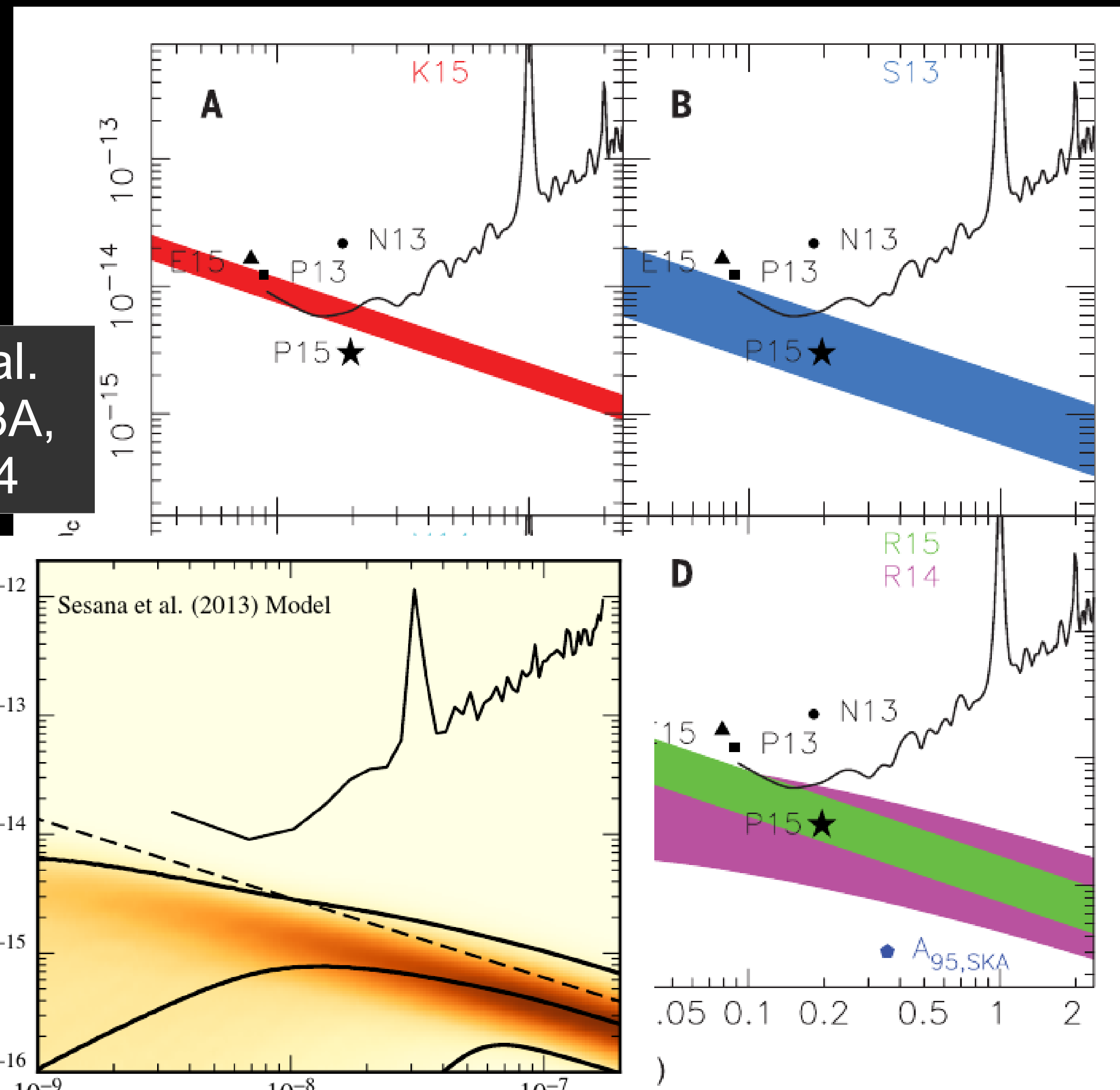
GW signal:
**quadrupole**

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

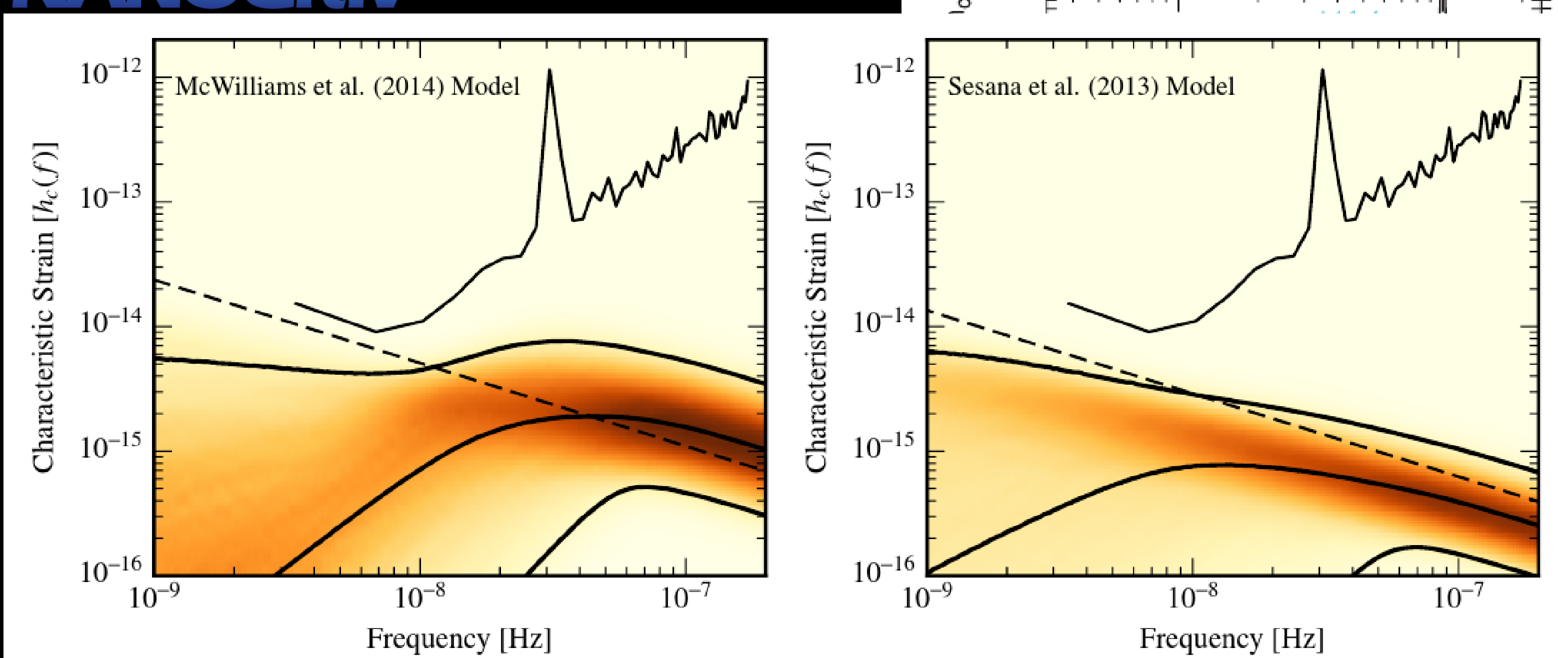
# Where are the GWs?

Current power-law models in tension. Maybe environmental effects? (stars, gas, eccentricity, ...)

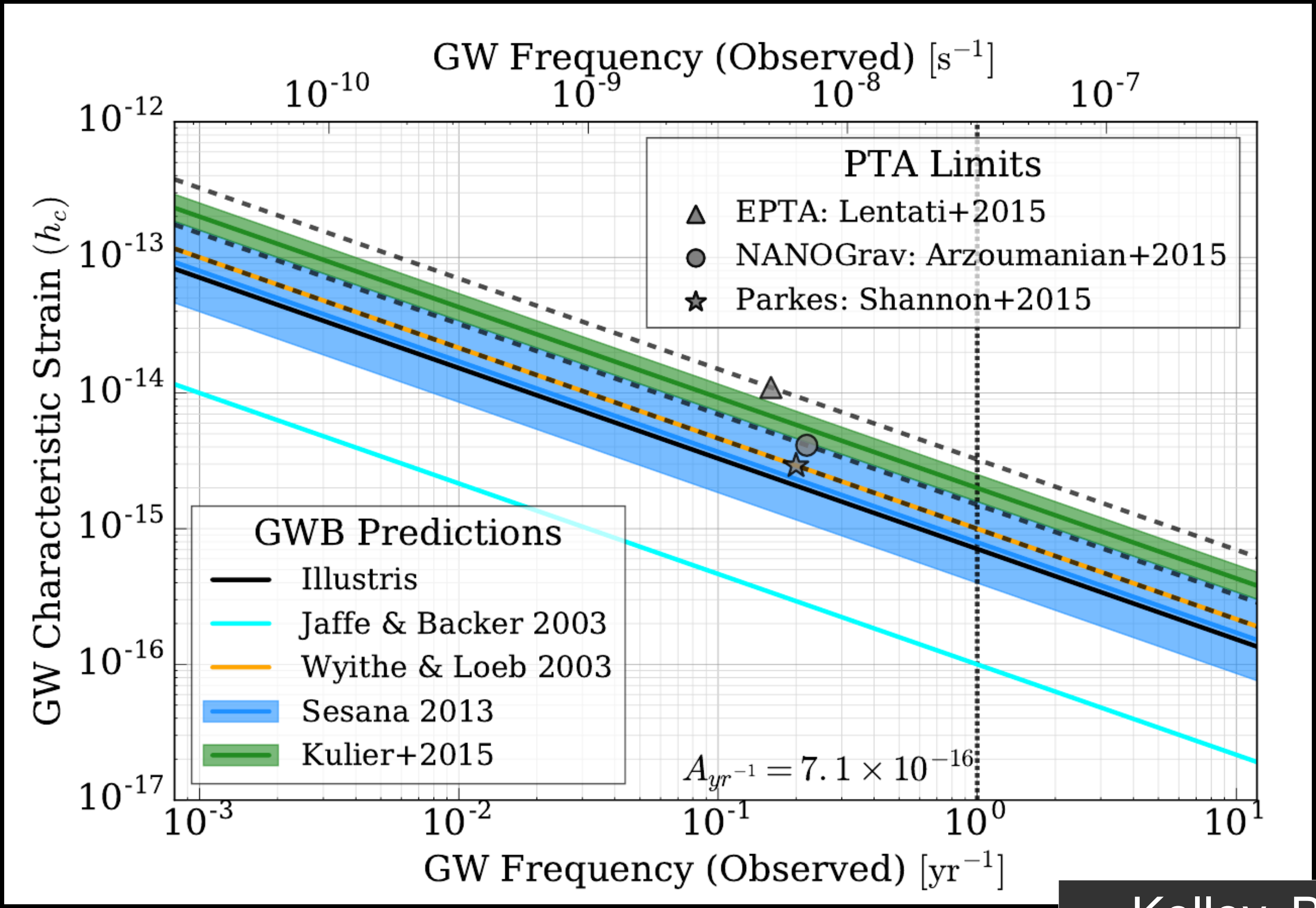
Shannon et al. 2015, Science, 349, 1522 arXiv:1509.07320




Arzoumanian et al. 2016, ApJ, 821, 13A, arXiv:1508.03024



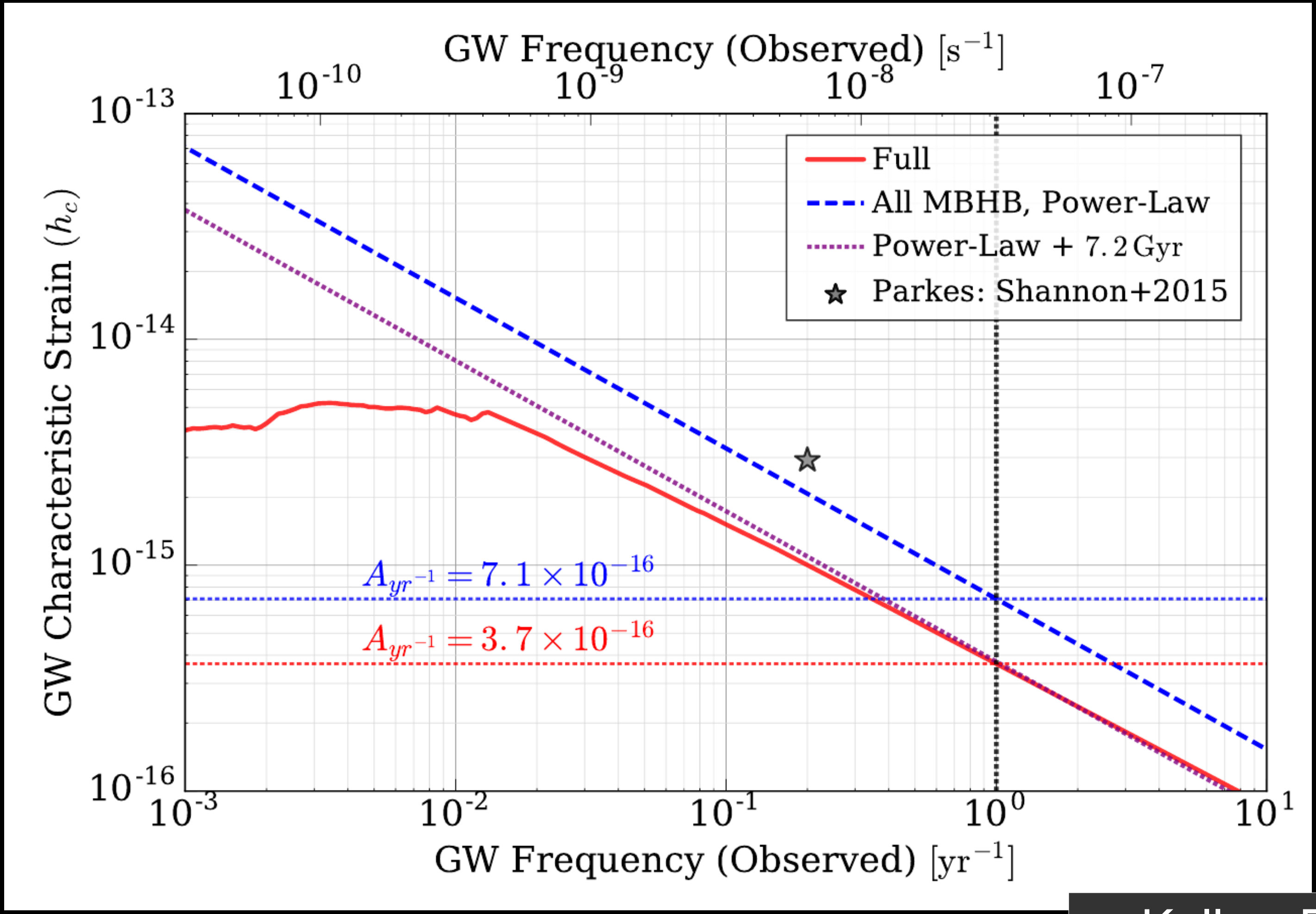
# Latest models don't show a problem...




Kelley, Blecha, & Herrnquist 2016, sub., arXiv:1606.01900

- From Illustris cosmological simulations
- Assuming efficient MBH mergers and power law evolution
- About 30% below the best observational limit

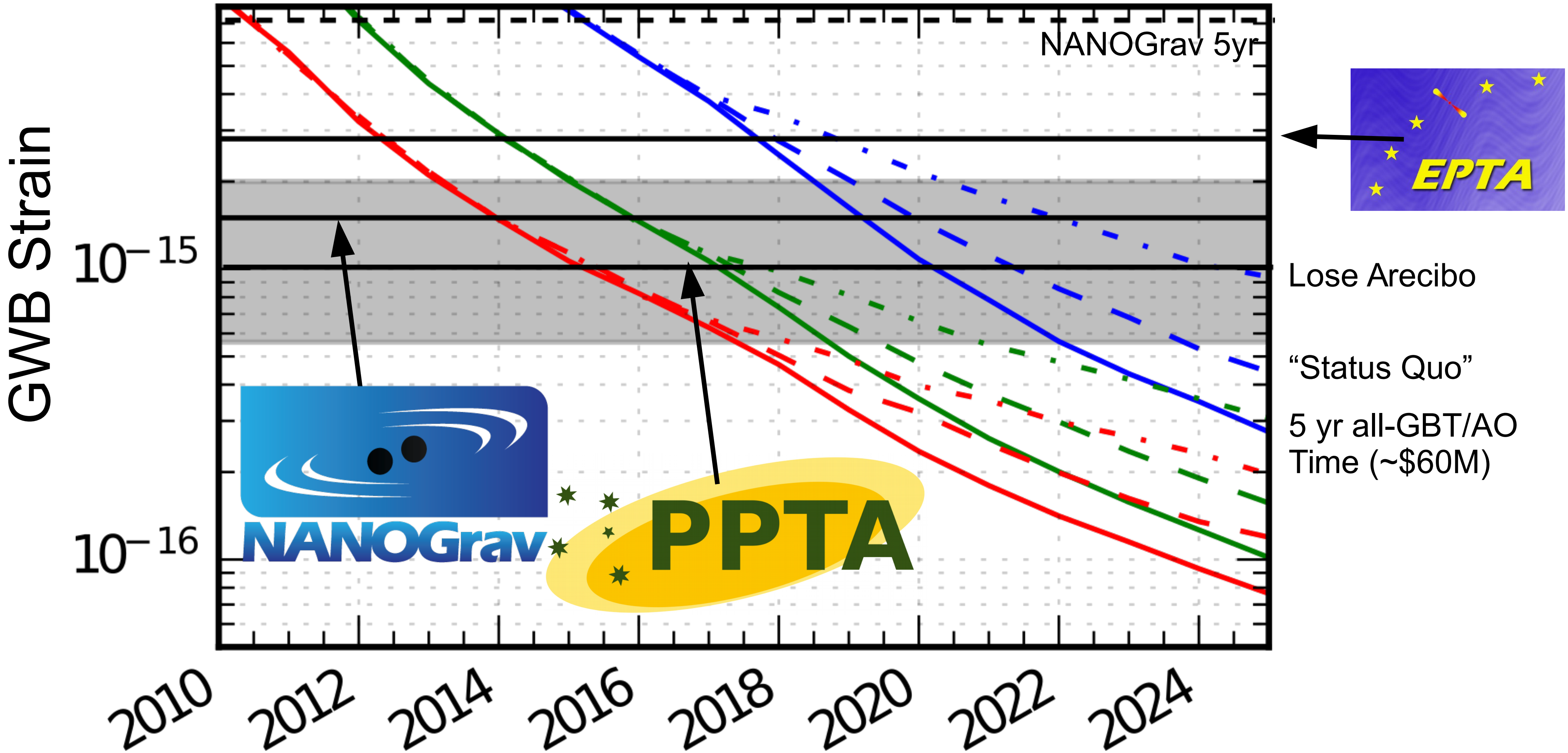
# Latest models don't show a problem...




Kelley, Blecha, & Herrnquist 2016, sub., arXiv:1606.01900

- From Illustris cosmological simulations
- Including environmental effects (dynamical friction, stellar scattering, viscous circumbinary disk), but no eccen (yet)

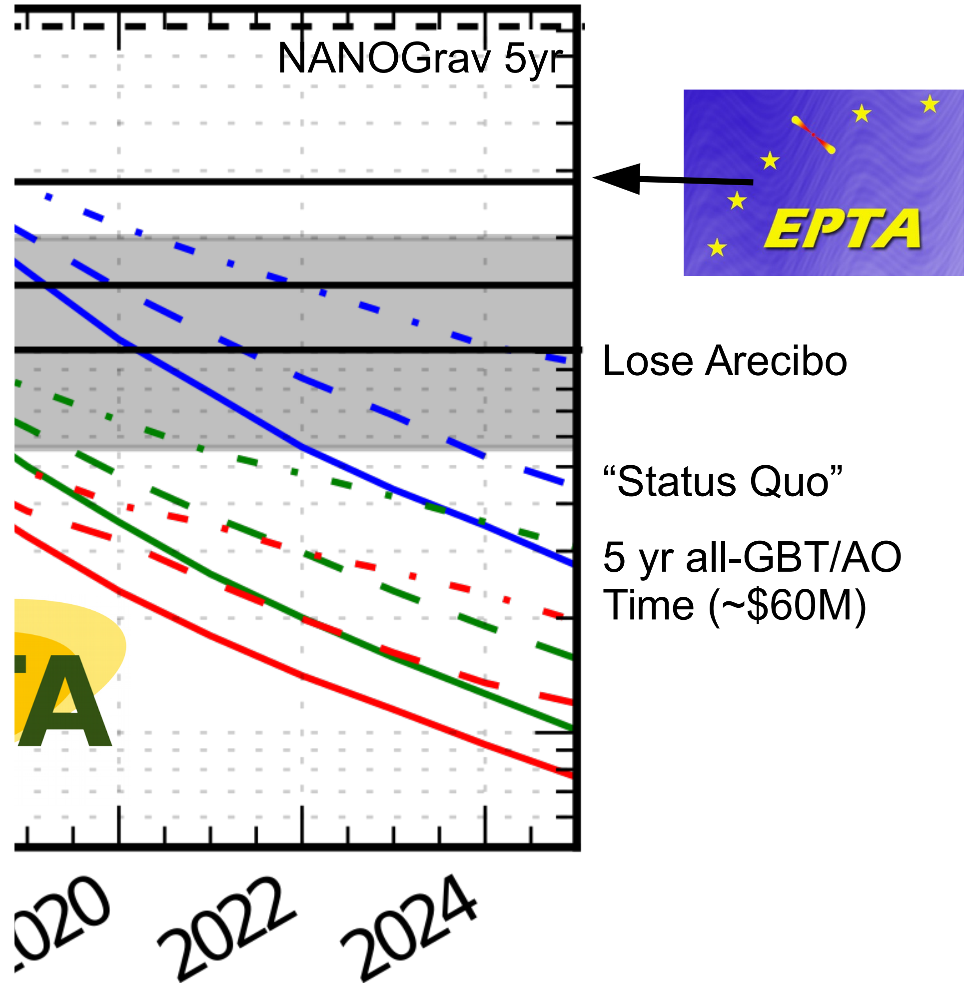
# So what about the future?




95% upper limit 50% Detection prob 95% Detection prob

Newest models suggest background must be > ~$3\times10^{-15}$
(e.g. Kelley, Blecha, & Herrnquist 2016)

# So what about the future?




prob 95% Detection prob

Combined as IPTA, likely factor of ~2 improvement in GW sensitivity

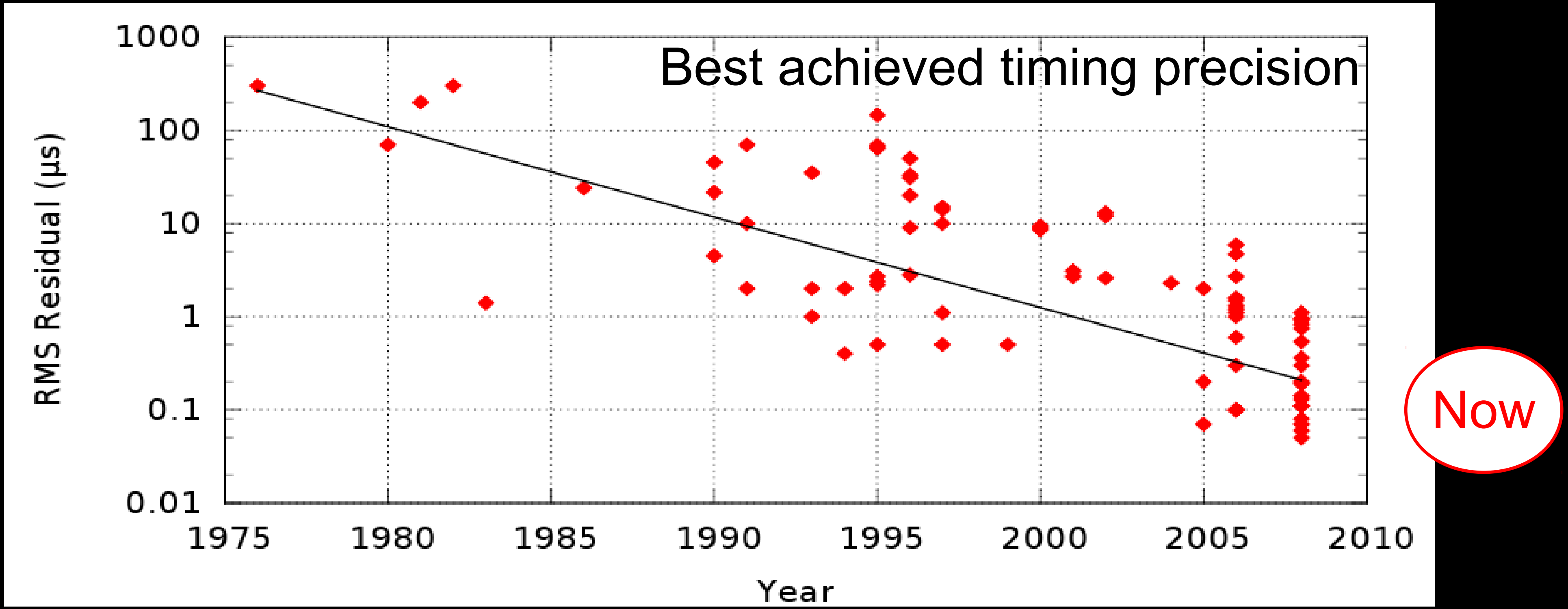
ound must be > ~$3 \times 10^{-15}$

, Herrnquist 2016)

# How to do better?

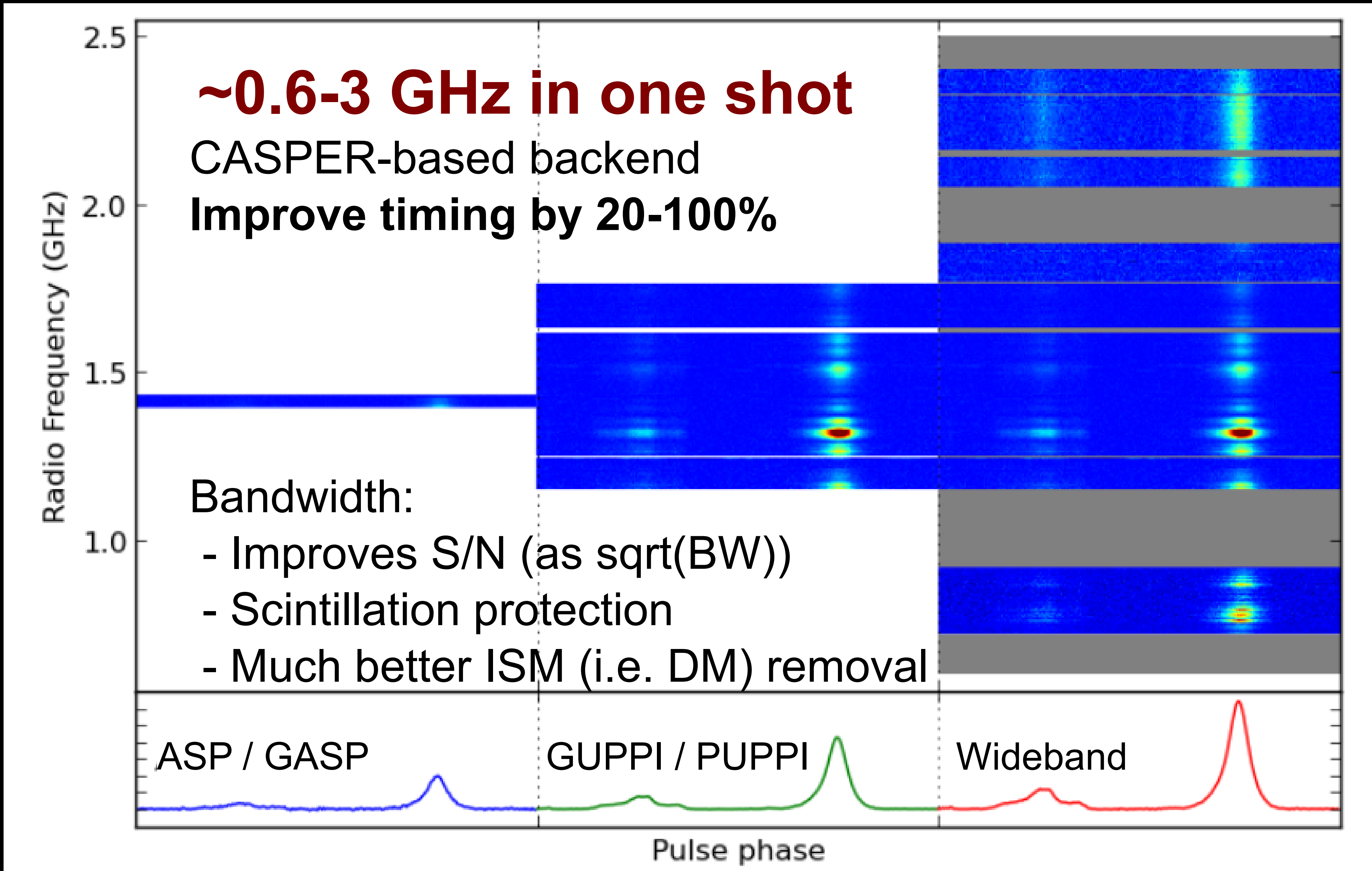
- Improved fidelity and systematics – instrumentation
- Better pulsars (right ones are rare) – searches
- PSRs are faint (sensitivity limited) – bigger telescopes

**These improvements dramatically help all pulsar science!**




R. Jenet & P. Demorest

# Ultra-wideband System (planned)




**~0.6-3 GHz in one shot**

CASPER-based backend

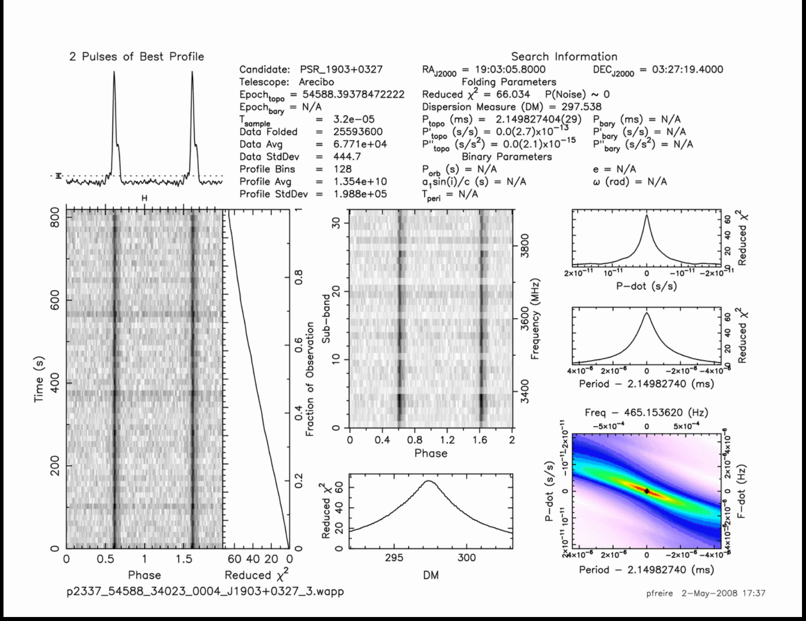
**Improve timing by 20-100%**

Bandwidth:
- Improves S/N (as sqrt(BW))
- Scintillation protection
- Much better ISM (i.e. DM) removal

Fig: Paul Demorest

# New All-Sky Pulsar Surveys

- All major radio telescopes are conducting all-sky pulsar surveys
- We know of only about 5% of the total pulsars in the Galaxy!
- These generate lots of data:
  - 1000s of hrs, 1000s of channels, 15000kHz sampling: gives more than a Petabyte!
- Requires huge amounts of high performance computing
  - *Many* times real-time and millions of false positives

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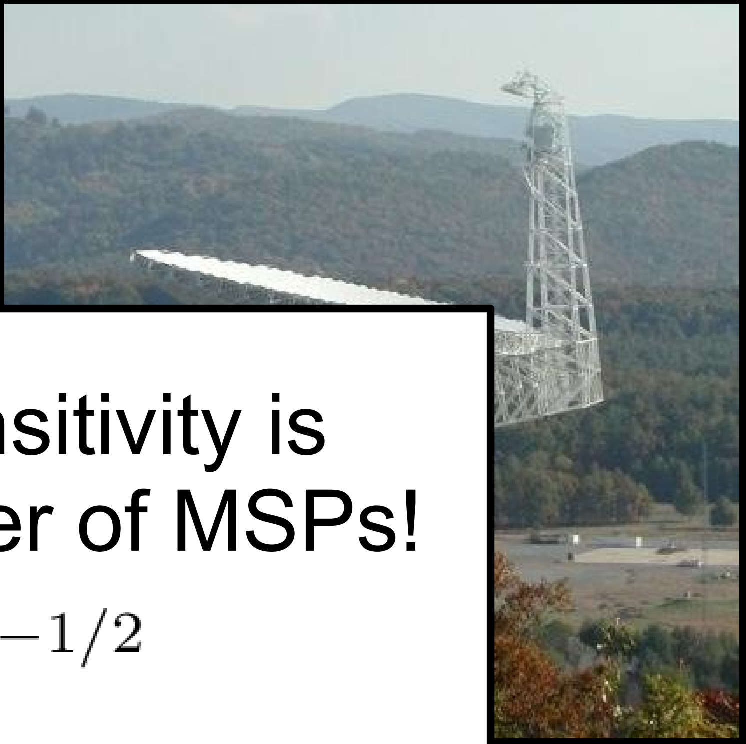
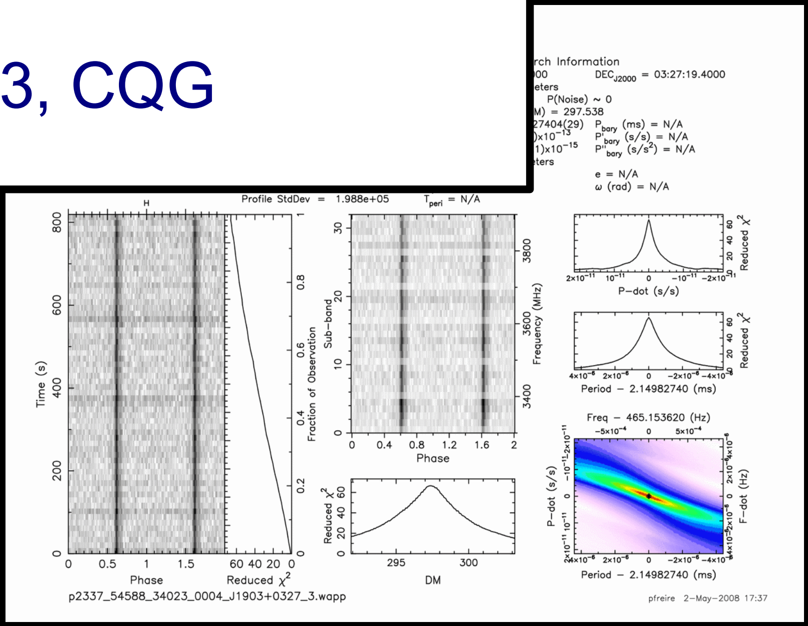


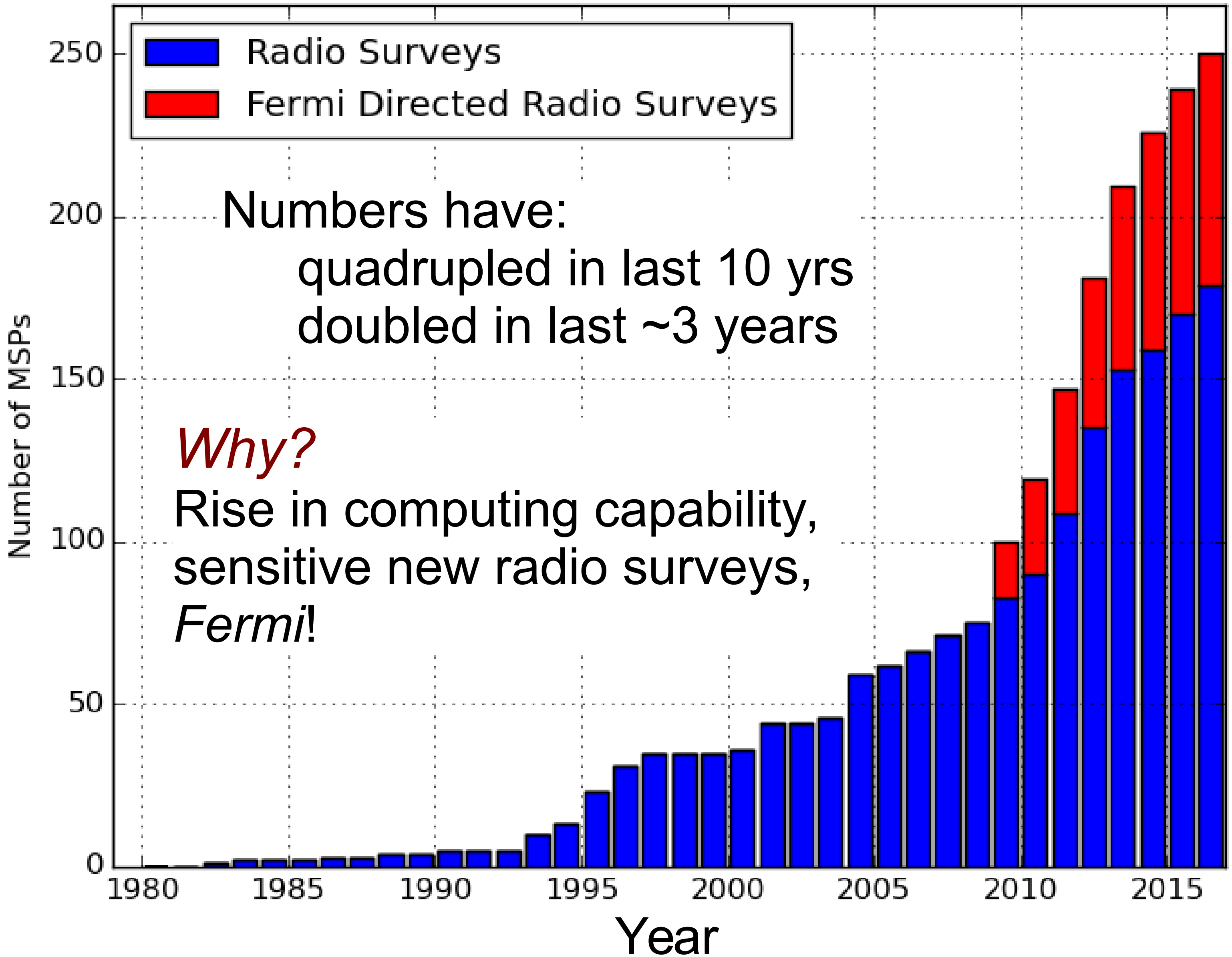



Gravitational wave sensitivity is proportional to the number of MSPs!

$$h_{c,\min} \propto \sigma N_{\rm PSRs}^{-1} T^{-1/2}$$

See Siemens et al. 2013, CQG

# New Millisecond Pulsars

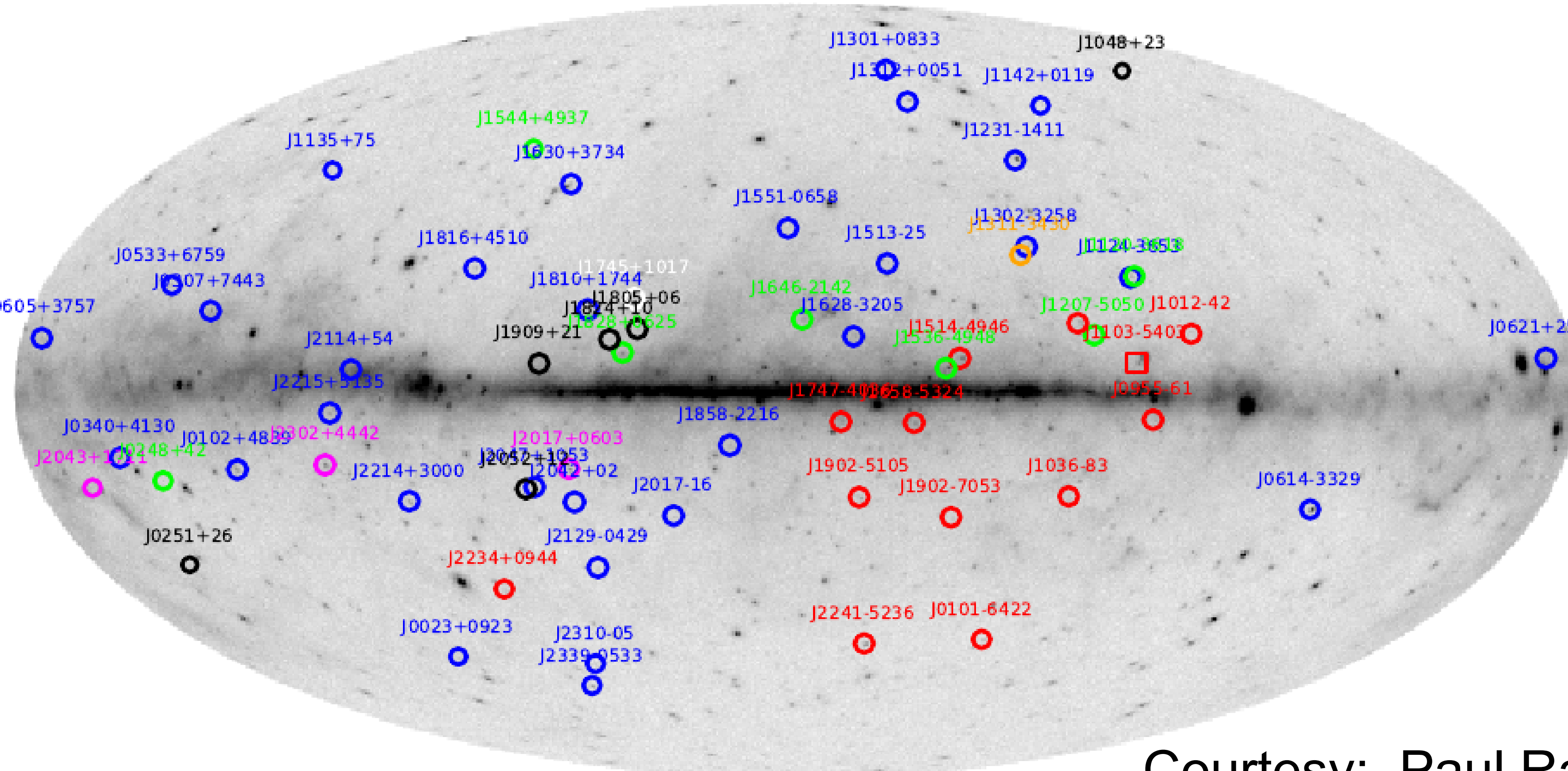



Numbers have:
quadrupled in last 10 yrs
doubled in last ~3 years

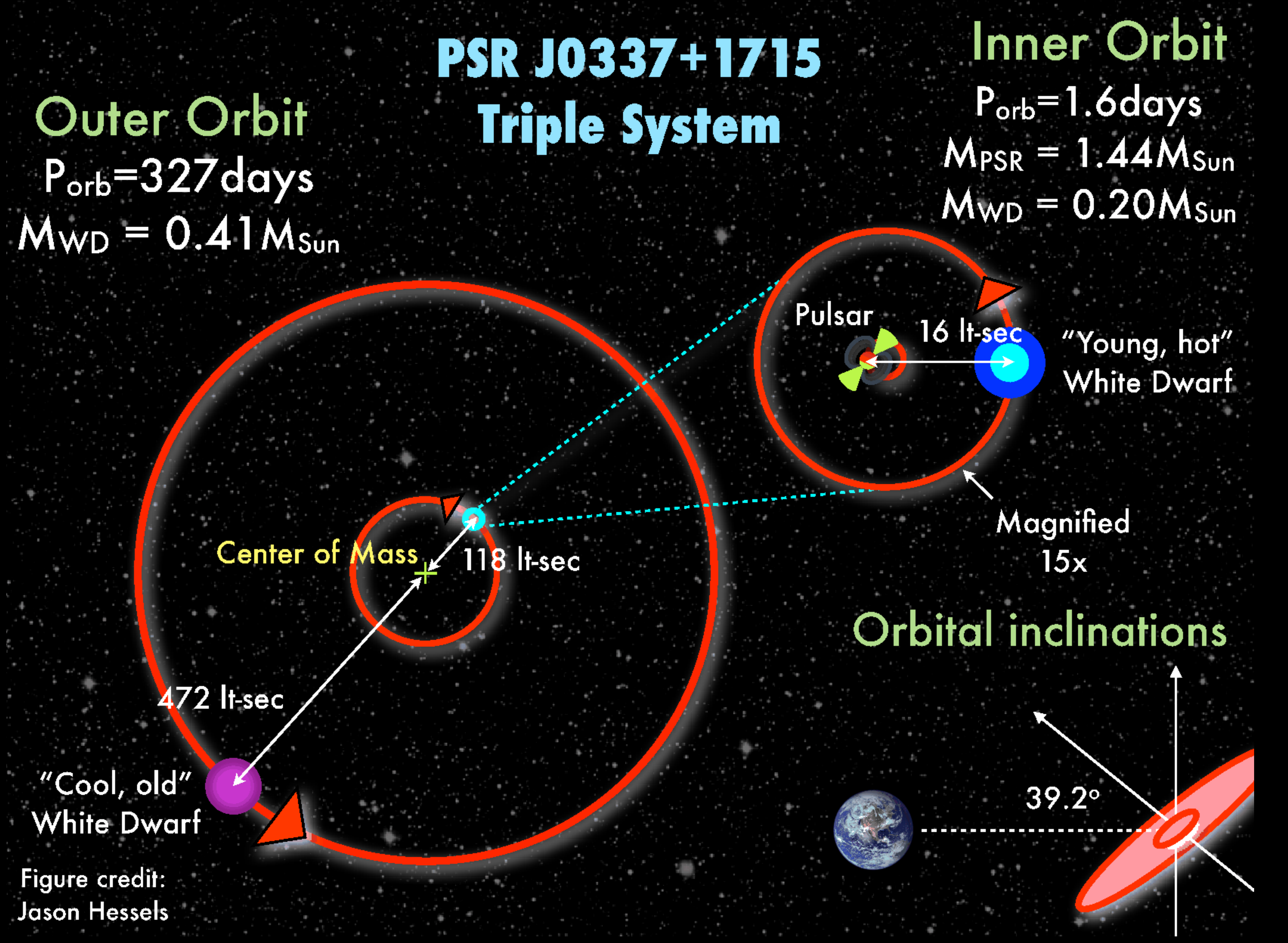
*Why?*
Rise in computing capability,
sensitive new radio surveys,
*Fermi*!

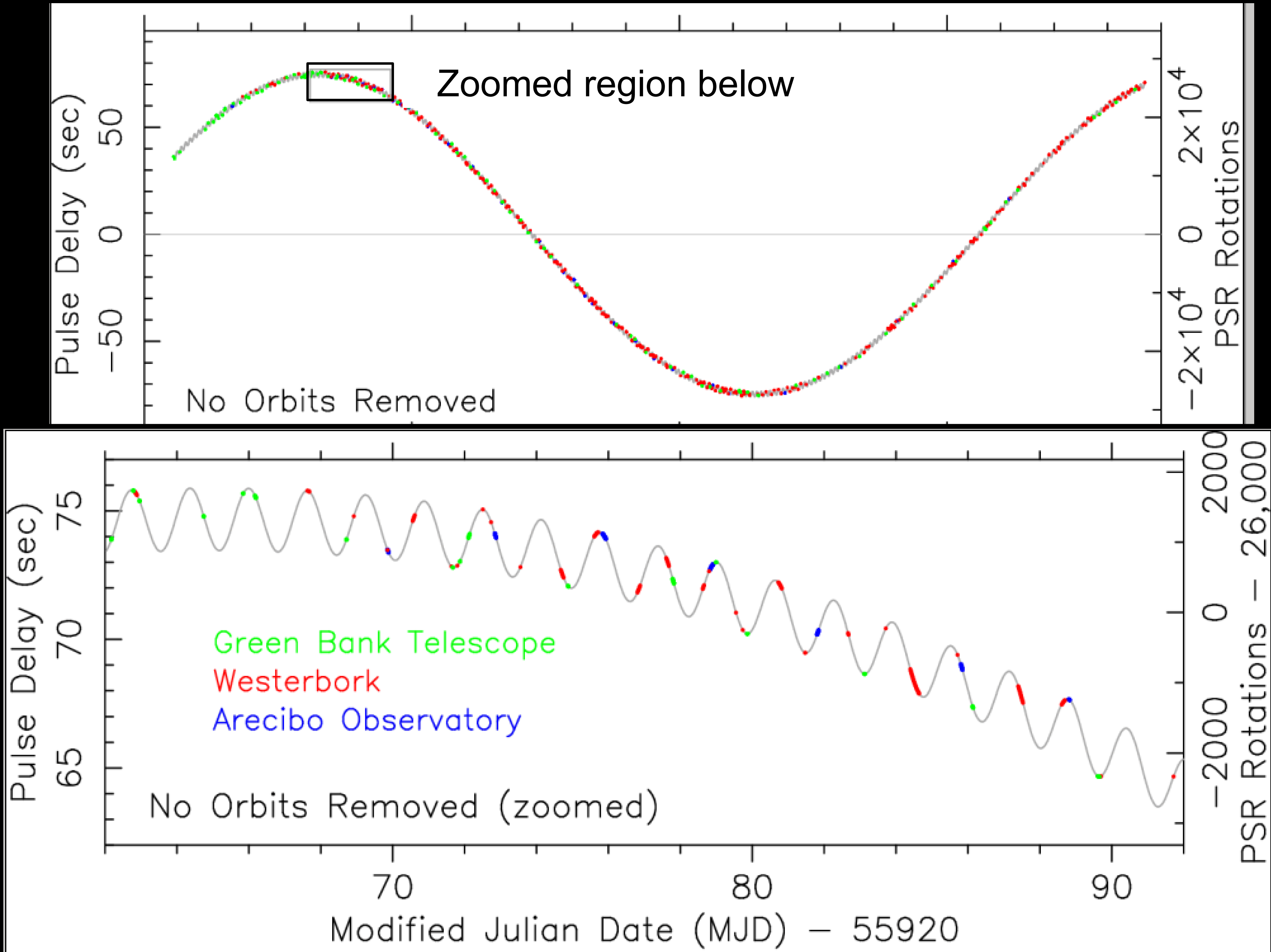
# Currently ~70 new Radio/gamma-ray MSPs because of *Fermi*!

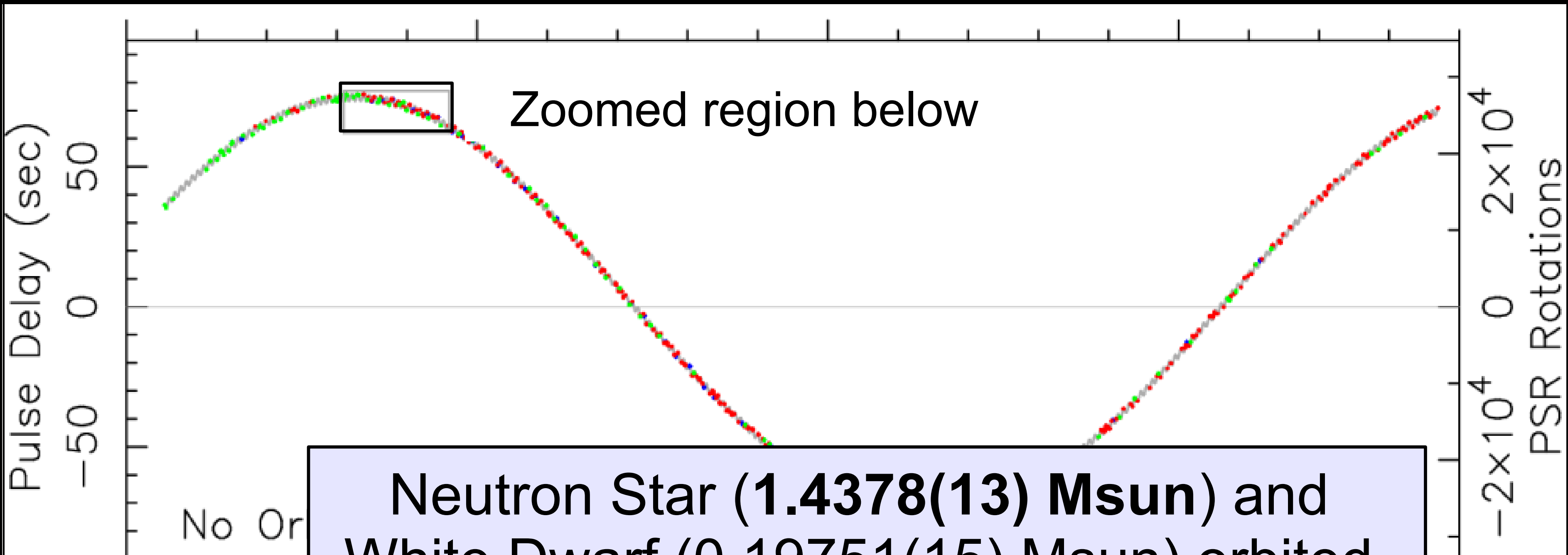
~10% of them look like they will be “good timers”




Courtesy: Paul Ray


PSR J0337+1715
Triple System
Outer Orbit
$P_{orb}$=327days
$M_{WD}$ = 0.41$M_{Sun}$
Inner Orbit
$P_{orb}$=1.6days
$M_{PSR}$ = 1.44$M_{Sun}$
$M_{WD}$ = 0.20$M_{Sun}$
Pulsar
16 lt-sec
"Young, hot"
White Dwarf
Magnified
15x
Center of Mass
118 lt-sec
472 lt-sec
"Cool, old"
White Dwarf
Orbital inclinations
39.2°
Figure credit:
Jason Hessels

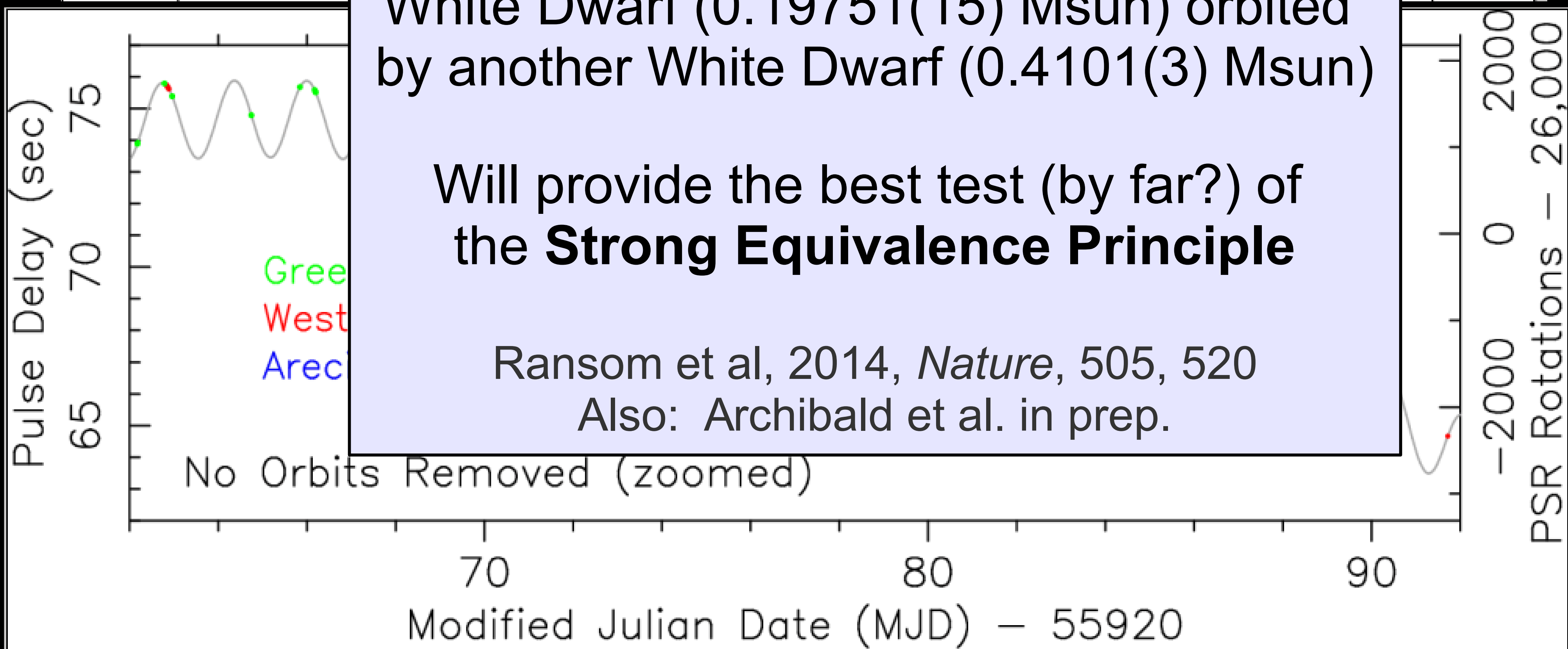

Zoomed region below
Pulse Delay (sec)
50
0
−50
2×10^4
0
−2×10^4
PSR Rotations
No Orbits Removed
Pulse Delay (sec)
75
70
65
Green Bank Telescope
Westerbork
Arecibo Observatory
No Orbits Removed (zoomed)
2000
0
−2000
PSR Rotations − 26,000
70
80
90
Modified Julian Date (MJD) − 55920




Neutron Star (**1.4378(13) Msun**) and White Dwarf (0.19751(15) Msun) orbited by another White Dwarf (0.4101(3) Msun)

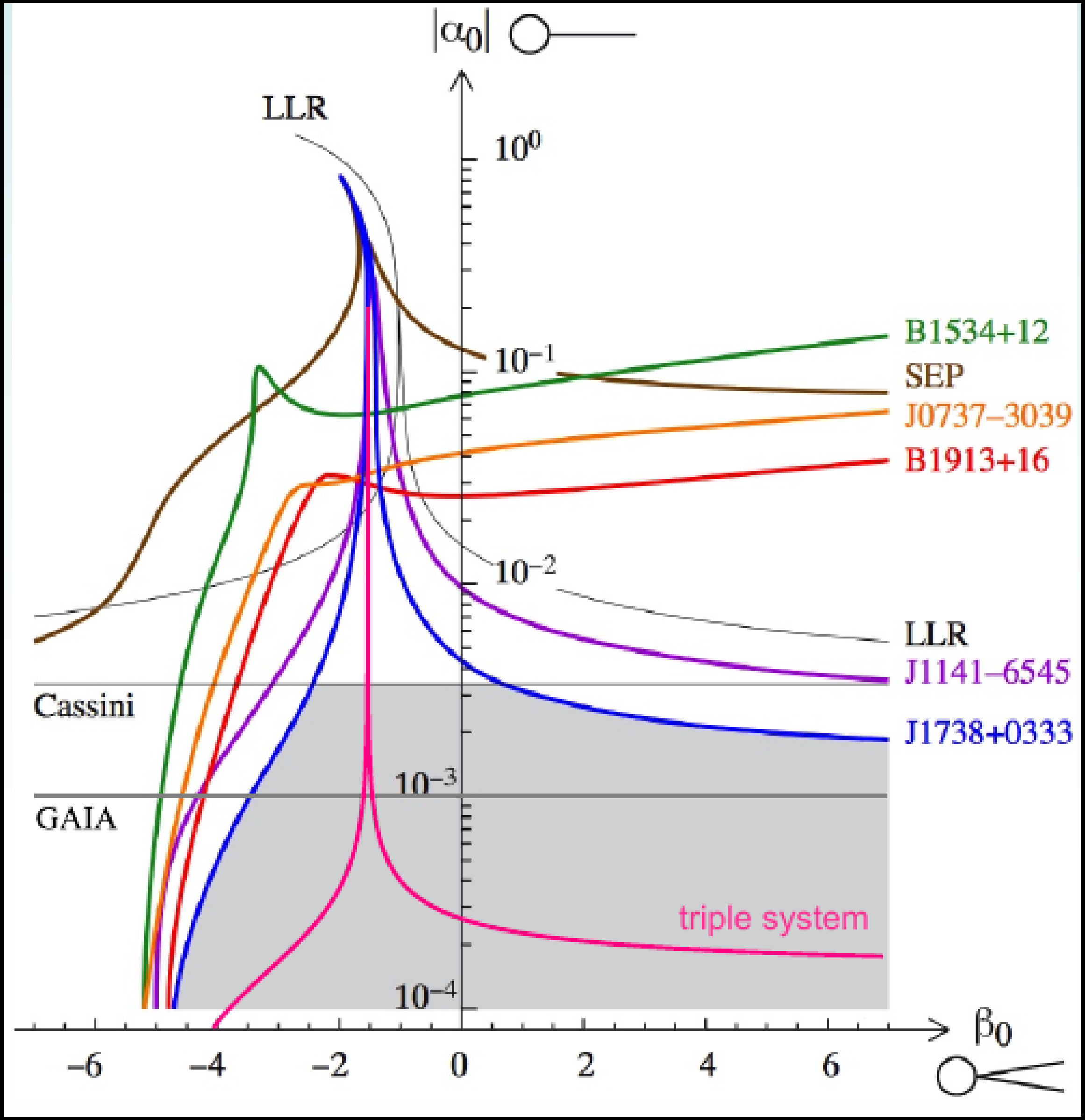
Will provide the best test (by far?) of the **Strong Equivalence Principle**

Ransom et al, 2014, *Nature*, 505, 520
Also: Archibald et al. in prep.



# J0337+1715 scalar-tensor constraints

- “G” effectively different for NS and WD. They fall in relatively “strong” grav field of outer WD.
- Prediction is ~1-2 orders of mag better than other current or future tests (including Lunar Laser Ranging!), and soon! (Archibald et al in prep).
- $T_1(\alpha_0,\beta_0)$ theories
- GR has $\alpha_0=\beta_0=0$
- Jordan–Fierz–Brans– Dicke theory has $\beta_0=0$

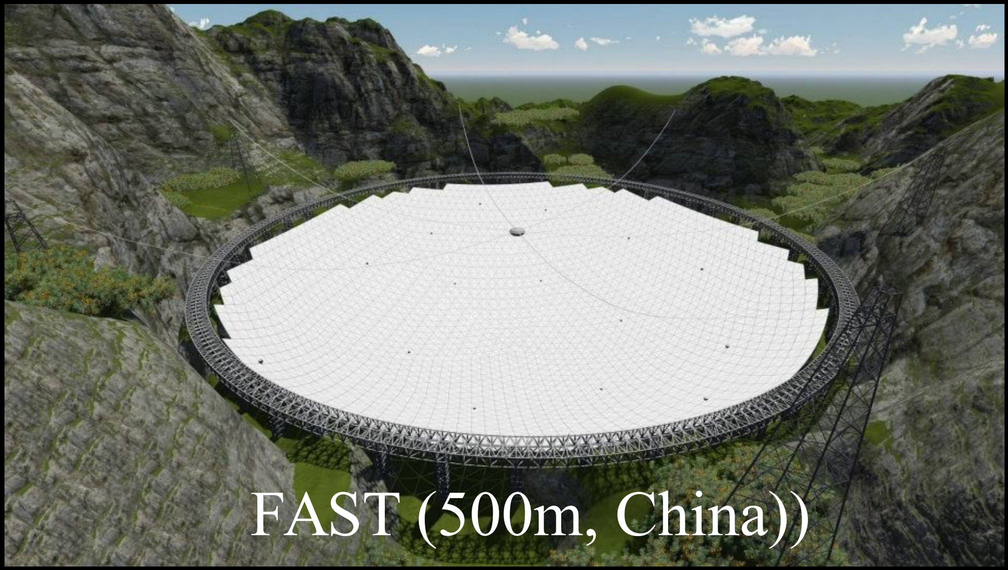



N. Wex, private communication

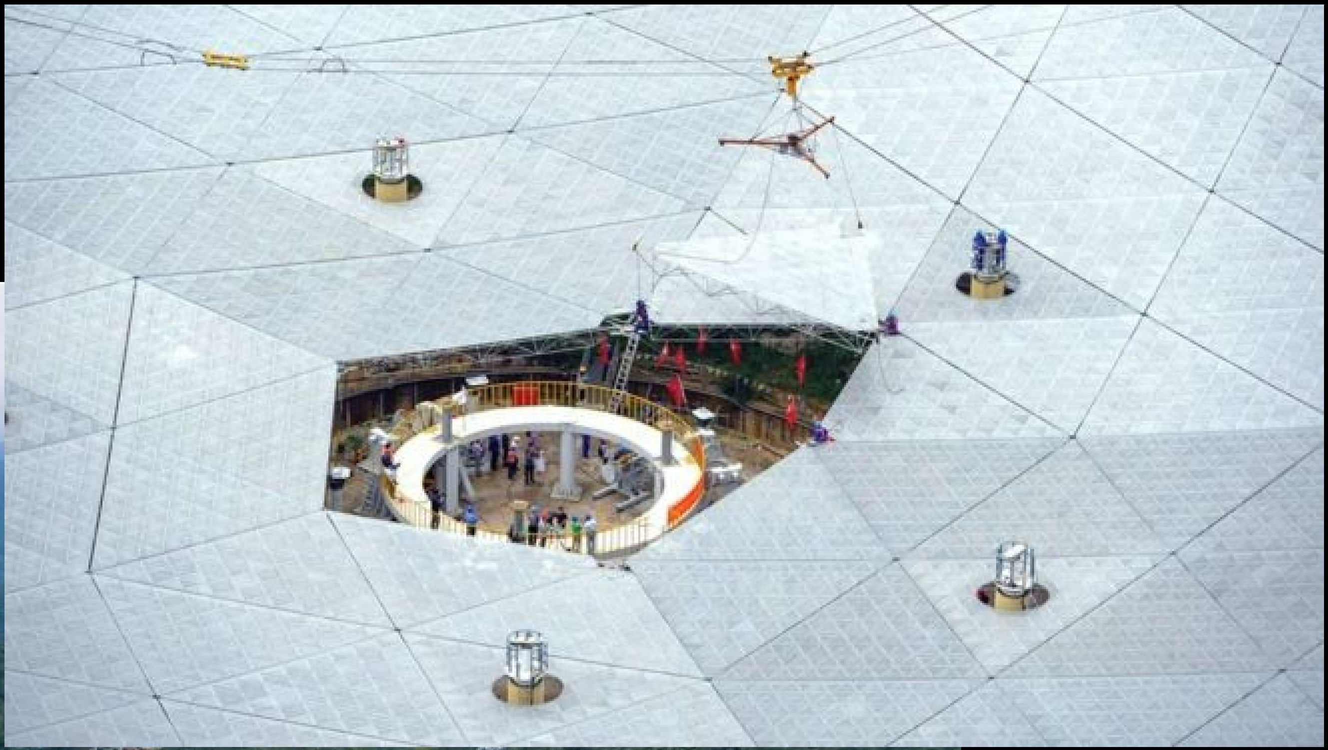
# What about the future?

- We only know of about 2,500 out of ~50,000+ pulsars in the Galaxy!
  - Many of them will be "Holy Grails"
    - Sub-MSP, PSR-Black Hole systems, MSP-MSP binary
- Several new huge telescopes...

We need them because we are sensitivity limited!

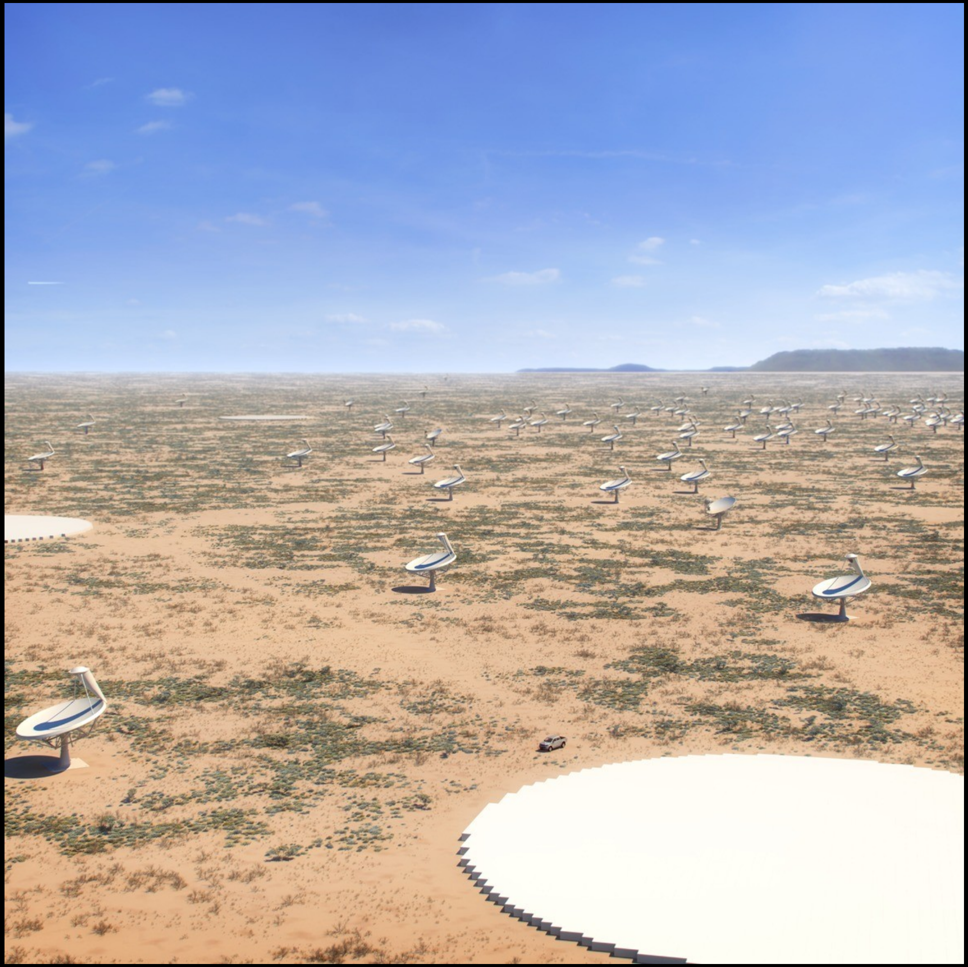




WWW.NEWS.CN

# Square Kilometer Array

- SKA-1 (650 M€) 2020+,  SKA-2 (3-5G€) 2025+
- 2 (or 3) arrays in S. Africa and W. Australia
- Should find most of the pulsars in the Galaxy
  - But will be incredibly difficult – can't record the data!



# Summary

- The pulsars are behaving very well
- GW detection at nHz freqs is likely within 10 yrs
- Many amazing (and bright!) pulsars to be found in the Galaxy: we know of ~5% of total
  - Will provide a huge amount of secondary science
- But we are sensitivity limited (Need big scopes!)
  - FAST in China, MeerKAT in S.Africa, eventually SKA?
  - Will be hard to get the time we need on those
  - Losing GBT and/or Arecibo would be **bad** for PSRs