Title: Extraordinary Physics with Millisecond Pulsars

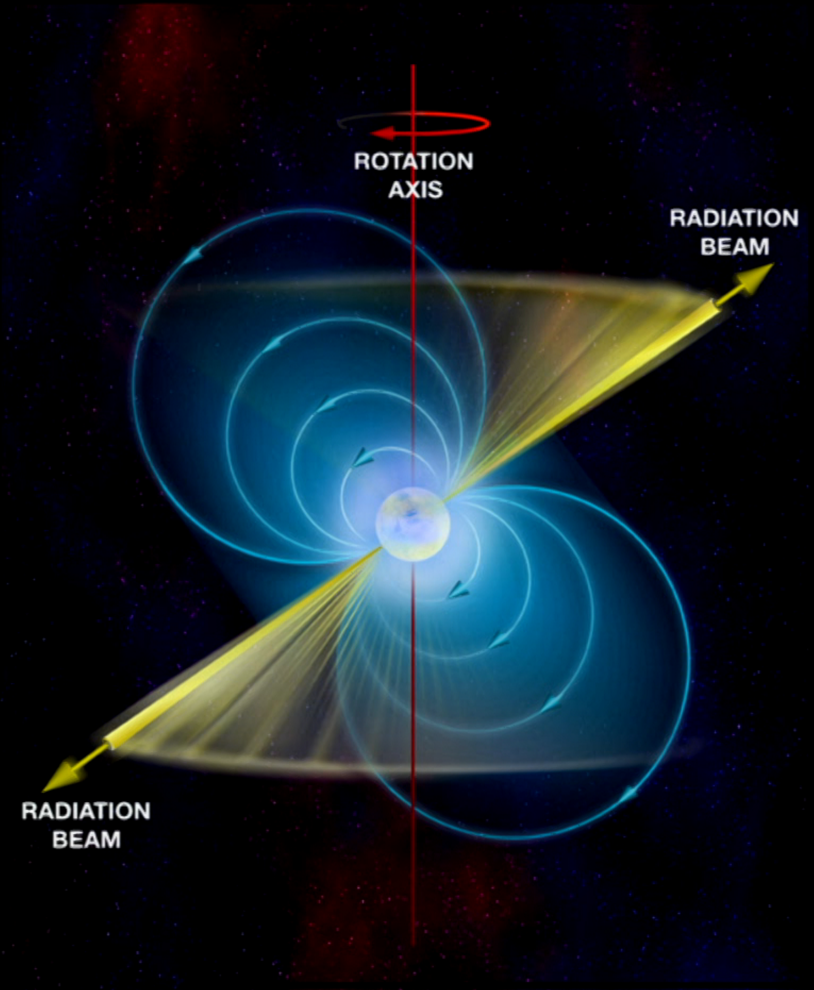
Date: Mar 07, 2017 11:00 AM

URL: http://pirsa.org/17030056

Abstract: <p>Pulsars are some of physics and astrophysicsâ€™ most exotic objects, and they have already earned two Nobel Prizes. We currently know of about 2500 of them in our Galaxy, but a small subset, the millisecond pulsars (MSPs), are truly remarkable. These systems are notoriously hard to detect, yet their numbers have more than doubled in the past 5 years via surveys using the worldâ€™s most sensitive<br />
telescopes, new instrumentation, and huge amounts of computing. Specialized â€œtimingâ€• observations of these systems, accounting for each and every one of the billions of rotations of the stars, are providing fantastic results in basic physics. In this talk Iâ€™ll focus on the efforts to directly detect gravitational waves from super-massive black hole binaries, make strong-field tests of general relativity, and determine the nature of the densest form of matter known in the universe.</p>

# What's a Millisecond Pulsar ?

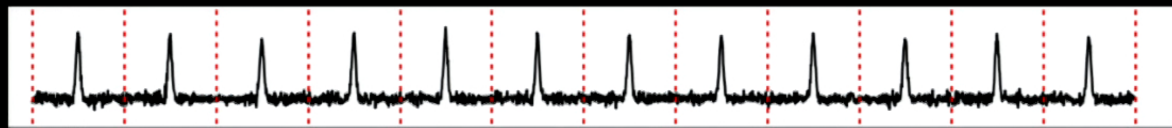
- Rapidly Rotating Neutron Star! (300-700 times/sec!)
- Size of city:
  - R ~ 10-15 km
- Mass greater than Sun:
  - M ~ 1.4-2.0 $M_{sun}$
- Strong Magnetic Fields:
  - B ~ $10^8$-$10^9$ Gauss
- Pulses are from a "**lighthouse**" type effect
- "Spin-down" power up to 1000s times more than the Sun's total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




Credit: Bill Saxton, NRAO/AUI/NSF

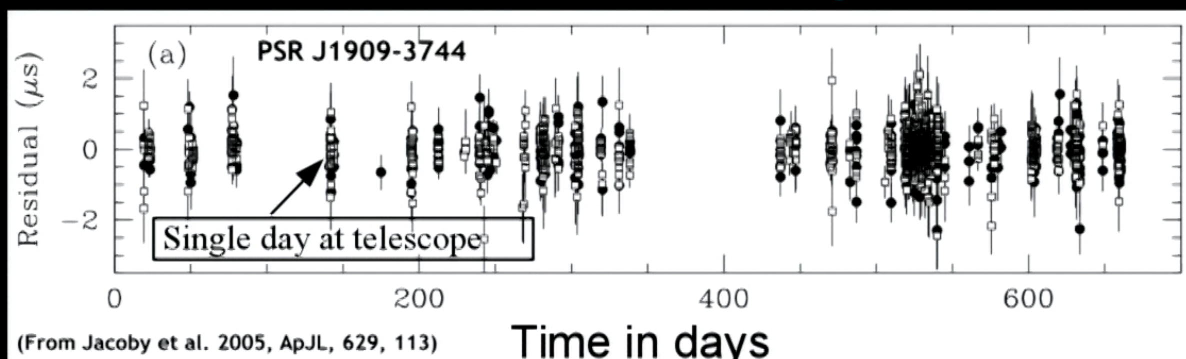
# Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years



Pulse Measurements
(TOAs: Times of Arrival)


Measurement - Model = Timing Residuals




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)° |
| Ecliptic latitude ($\beta$) | −1.256744(2)° |
| Proper motion in $\lambda$ | 9.79(7) mas yr$^{-1}$ |
| Proper motion in $\beta$ | −30(3) mas yr$^{-1}$ |
| Parallax | 0.5(6) mas |
| Pulsar spin period | 3.1508076534271(6) ms |
| Period derivative | 9.6216(9) $\times 10^{-21}$ s s$^{-1}$ |
| Reference epoch (MJD) | 53,600 |
| Dispersion measure* | 34.4865 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° 30′ 31.081(7)″ |
| Orbital eccentricity ($e$) | 1.30(4) $\times 10^{-6}$ |
| Inclination angle | 89.17(2)° |
| 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 | [illegible] |

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?**

| | |
|---|---|
| Orbital period | 8.6866194196(2) d |
| Projected semimajor axis | 11.2911975(2) light s |
| First Laplace parameter (esin $\omega$) | $1.1(3) \times 10^{-7}$ |
| Second Laplace parameter (ecos $\omega$) | $-1.29(3) \times 10^{-6}$ |
| Companion mass | $0.500(6) M_{\odot}$ |
| | 0.999894(5) |
| | 52,331.1701098(3) |
| | 52,469–55,330 |
| | 2,206 (454, 1,752) |
| | 1.1 μs |
| Right ascension (J2000) | 16 h 14 min 36.5051(5) s |
| Declination (J2000) | −22° 30′ 31.081(7)′′ |
| Orbital eccentricity ($e$) | $1.30(4) \times 10^{-6}$ |
| Inclination angle | 89.17(2) |
| 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 | |

## *...get a spectacular answer!*

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

Demorest et al. 2010, *Nature*

# 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

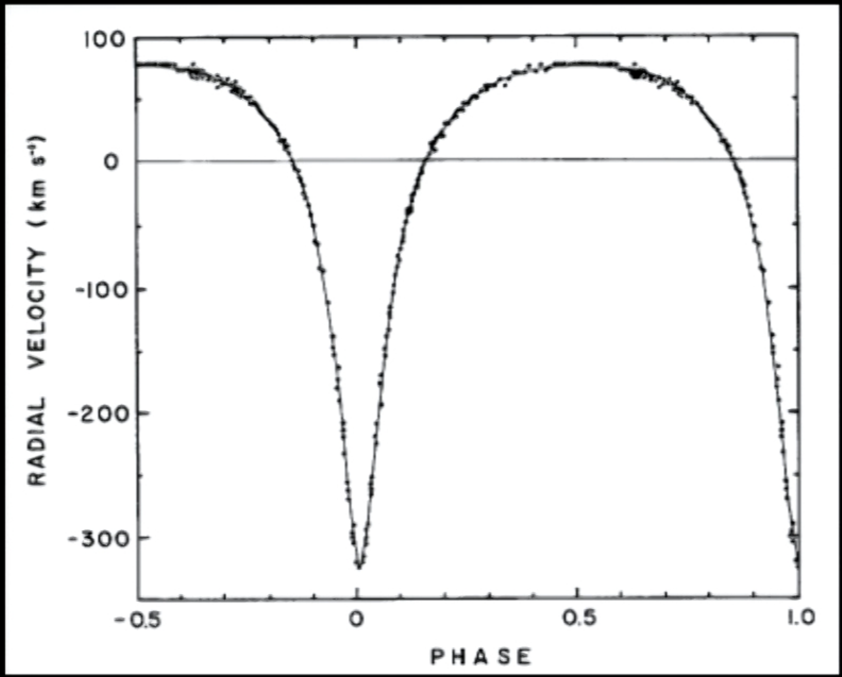
a sin($i$)/c = 2.342 lt-s

e = 0.6171

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

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

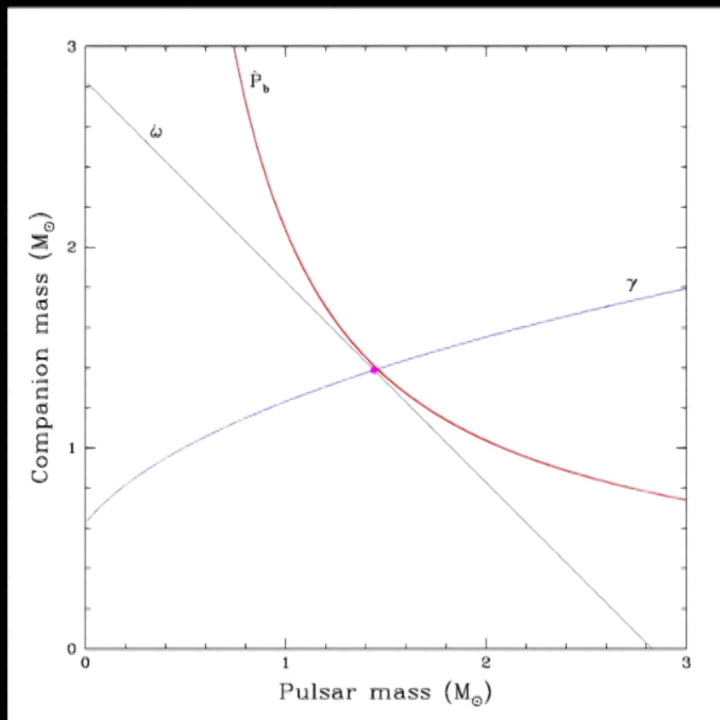
$M_p = 1.4411(7)\ M_\odot$

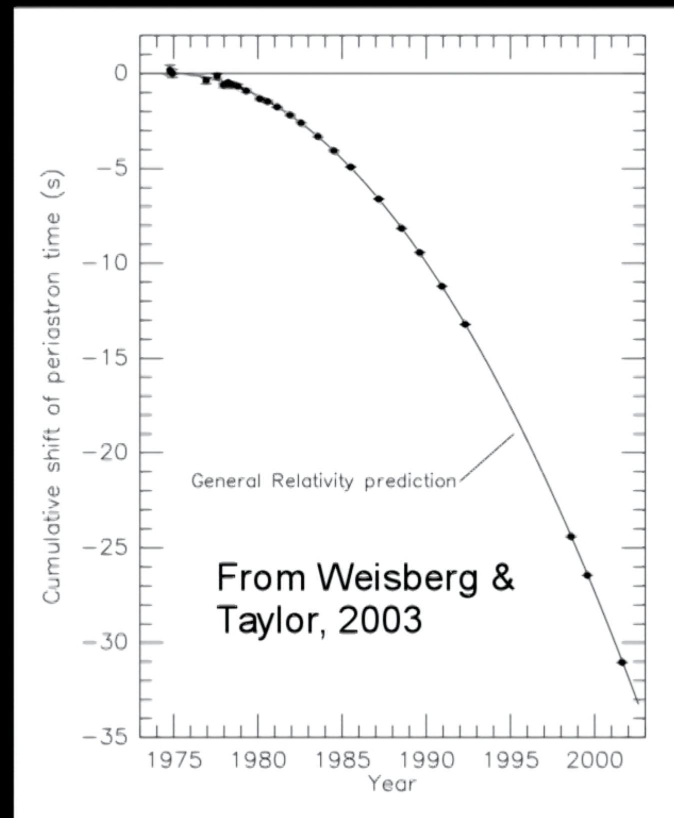


# The Binary Pulsar:  B1913+16

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

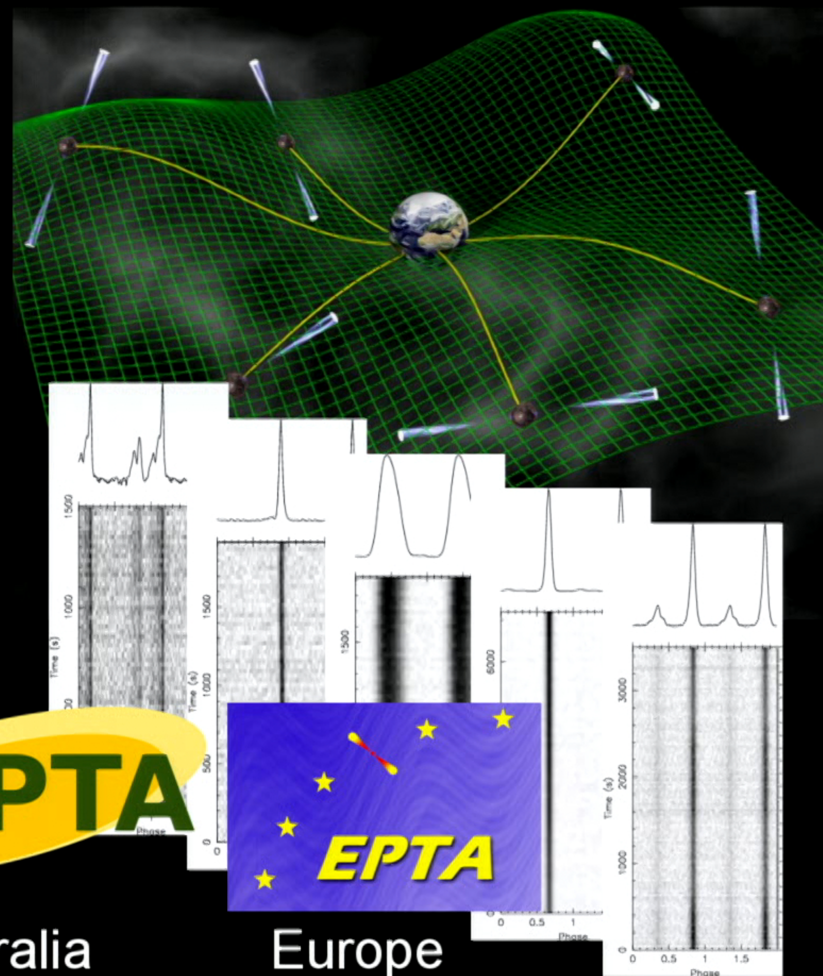
**Indirect detection of Gravitational Radiation!**



# Gravitational Wave Detection with a Pulsar Timing Array

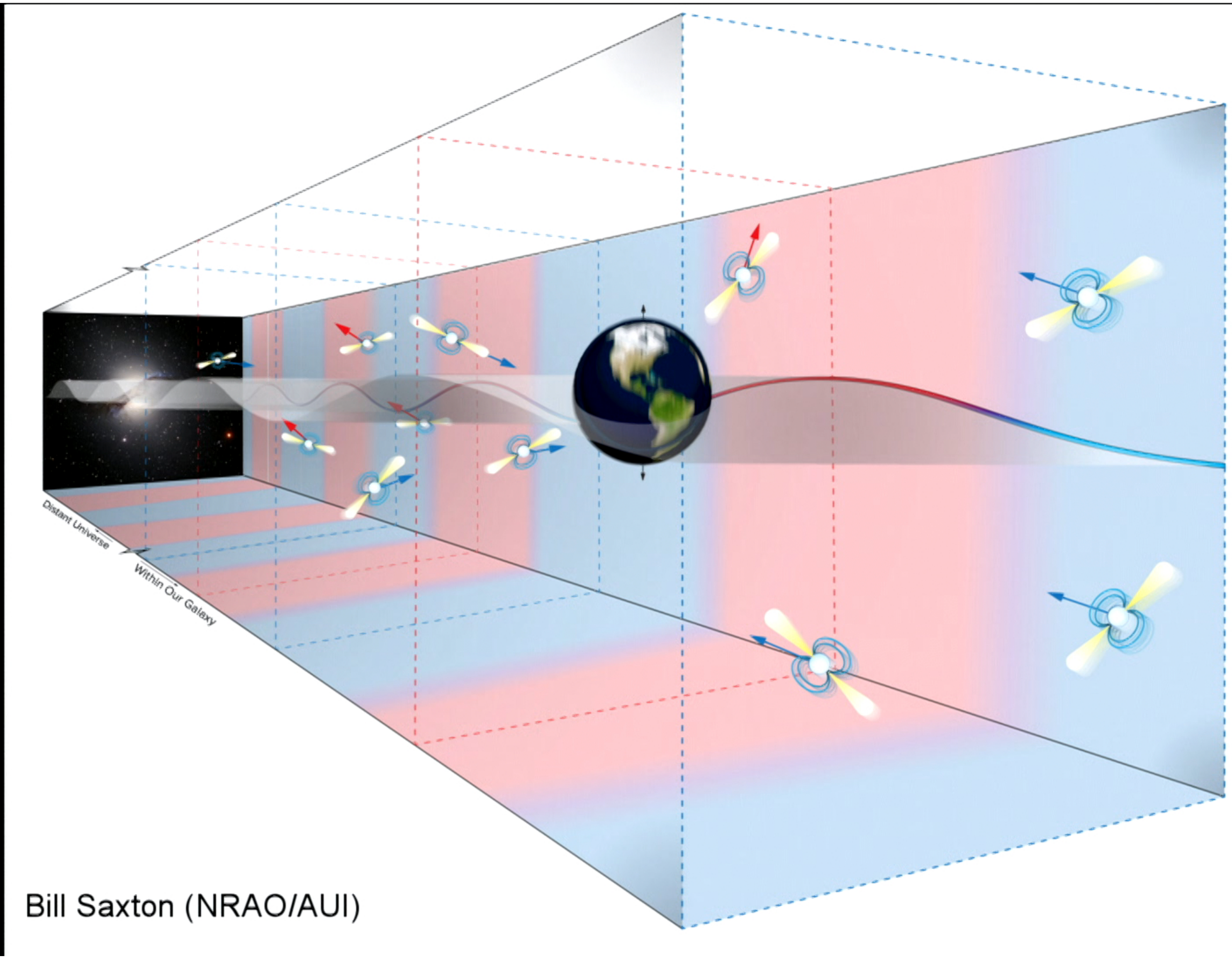
- Need very good MSPs
- Significance scales directly with the number of MSPs being timed. Lack of good MSPs is currently the biggest limitation
- Must time the pulsars for 5-10 years at a precision of ~100 nano-seconds!



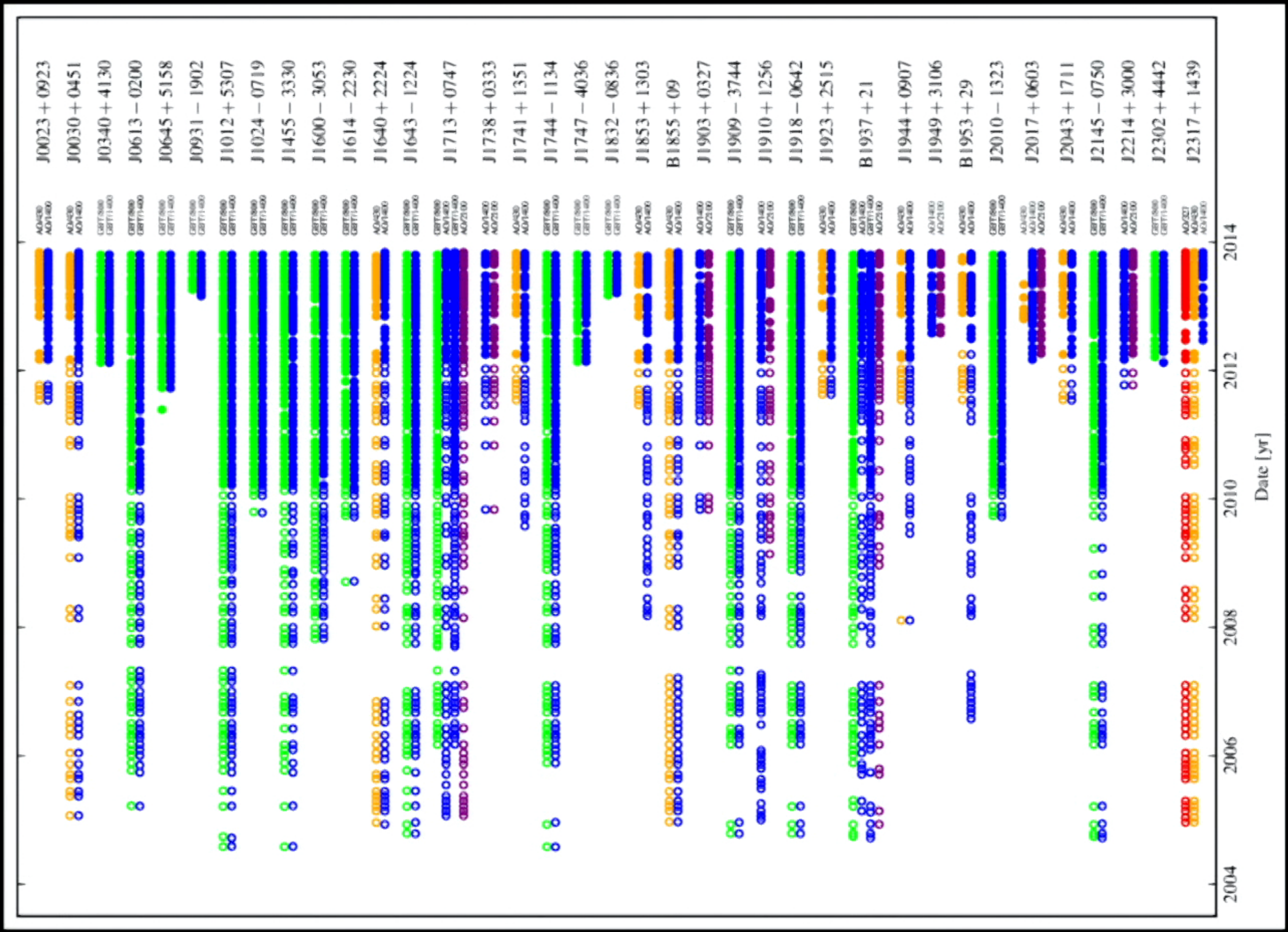
NANOGrav — N. America

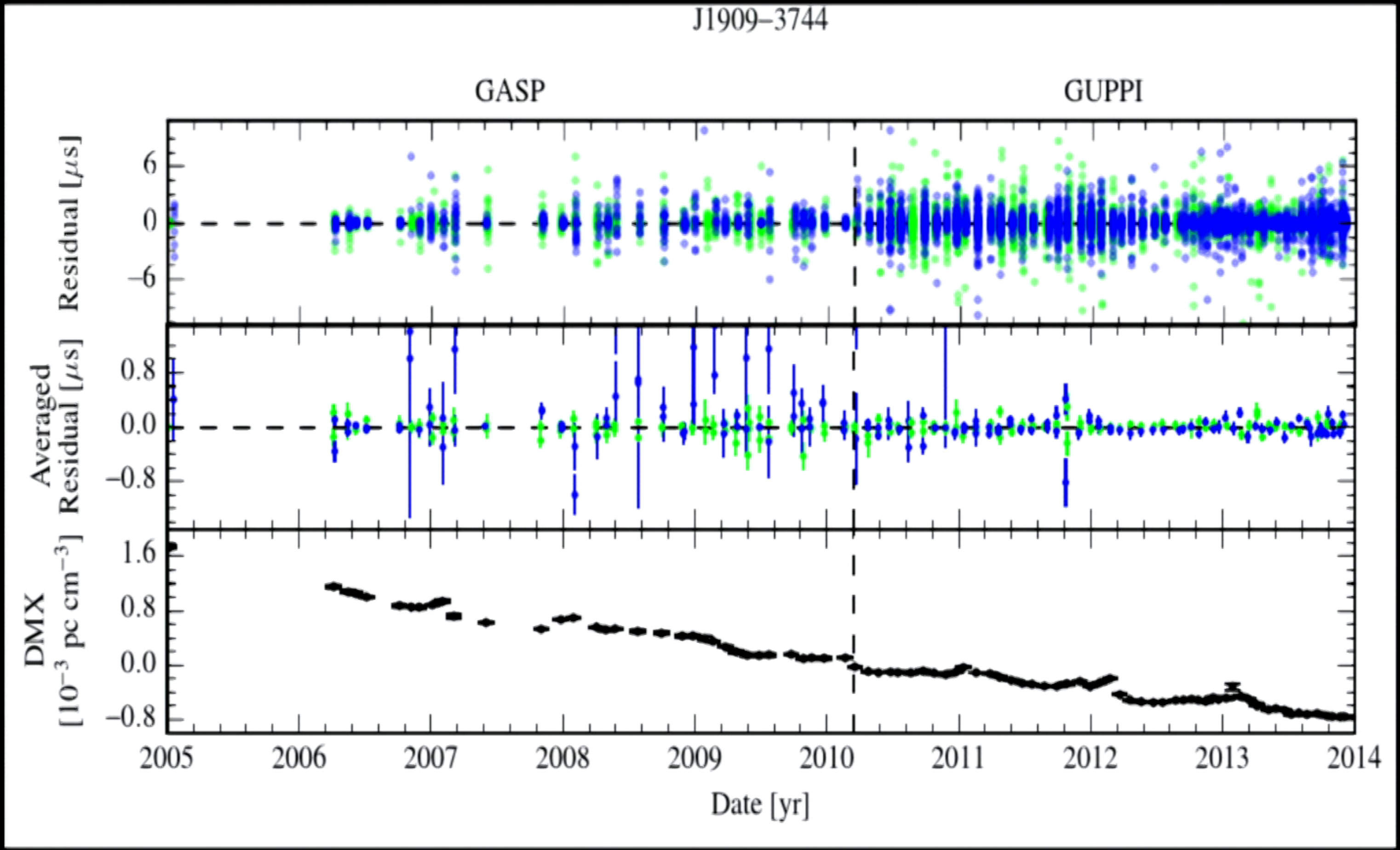
PPTA — Australia

EPTA — Europe


Distant Universe
Within Our Galaxy
Bill Saxton (NRAO/AUI)

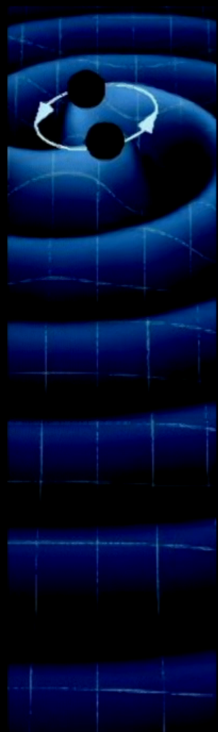
# NANOGrav 9-yr Data




J1909−3744
GASP
GUPPI
Residual [μs]
6
0
−6
Averaged Residual [μs]
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

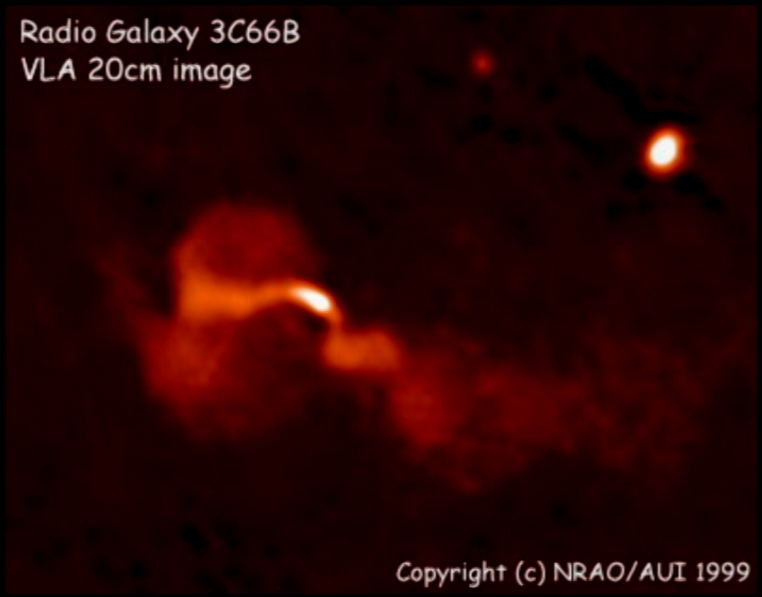


- Basically all galaxies have them
- Masses of $10^6 - 10^9\ M_\odot$
- Galaxy mergers lead to BH mergers
- When BHs within 1pc, GWs are main energy loss
- For total mass $M/(1+z)$, distance $d_L$, and SMBH orbital freq $f$, the induced timing residuals are:

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

Potentially measurable with a single MSP!

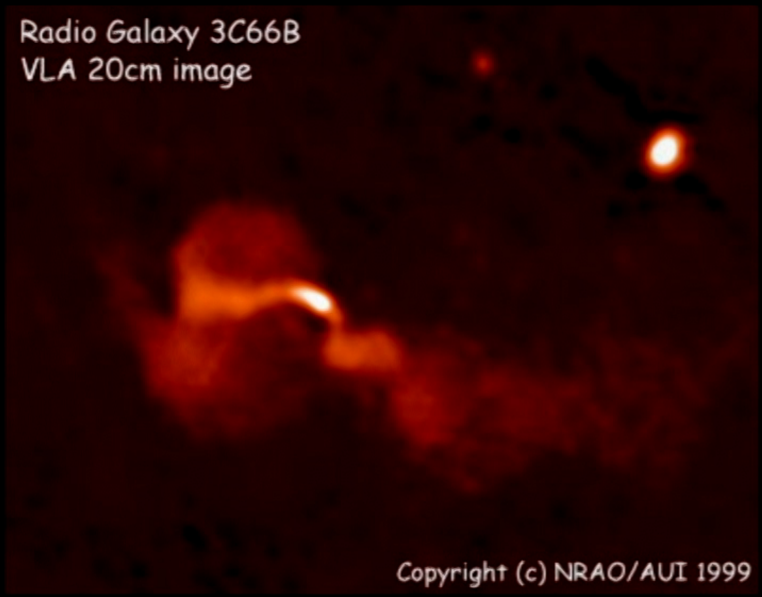
# So where do these GWs come from?




## 3C66B

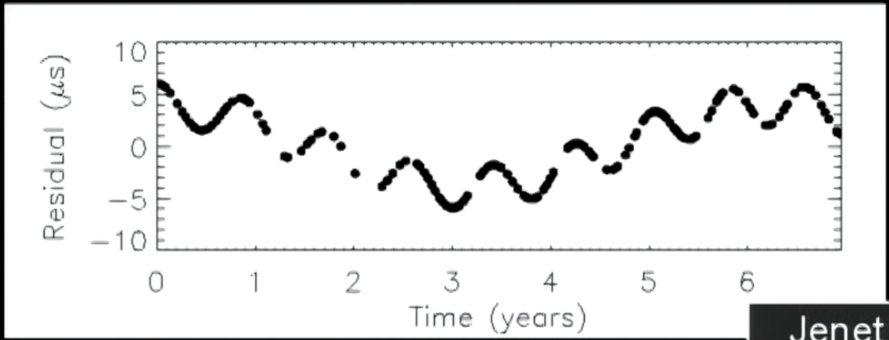
At $z = 0.02$
Orbital period 1.05 yrs
Total mass $5.4\times10^{10} M_{\odot}$
(Sudou et al 2003)

# So where do these GWs come from?




## 3C66B

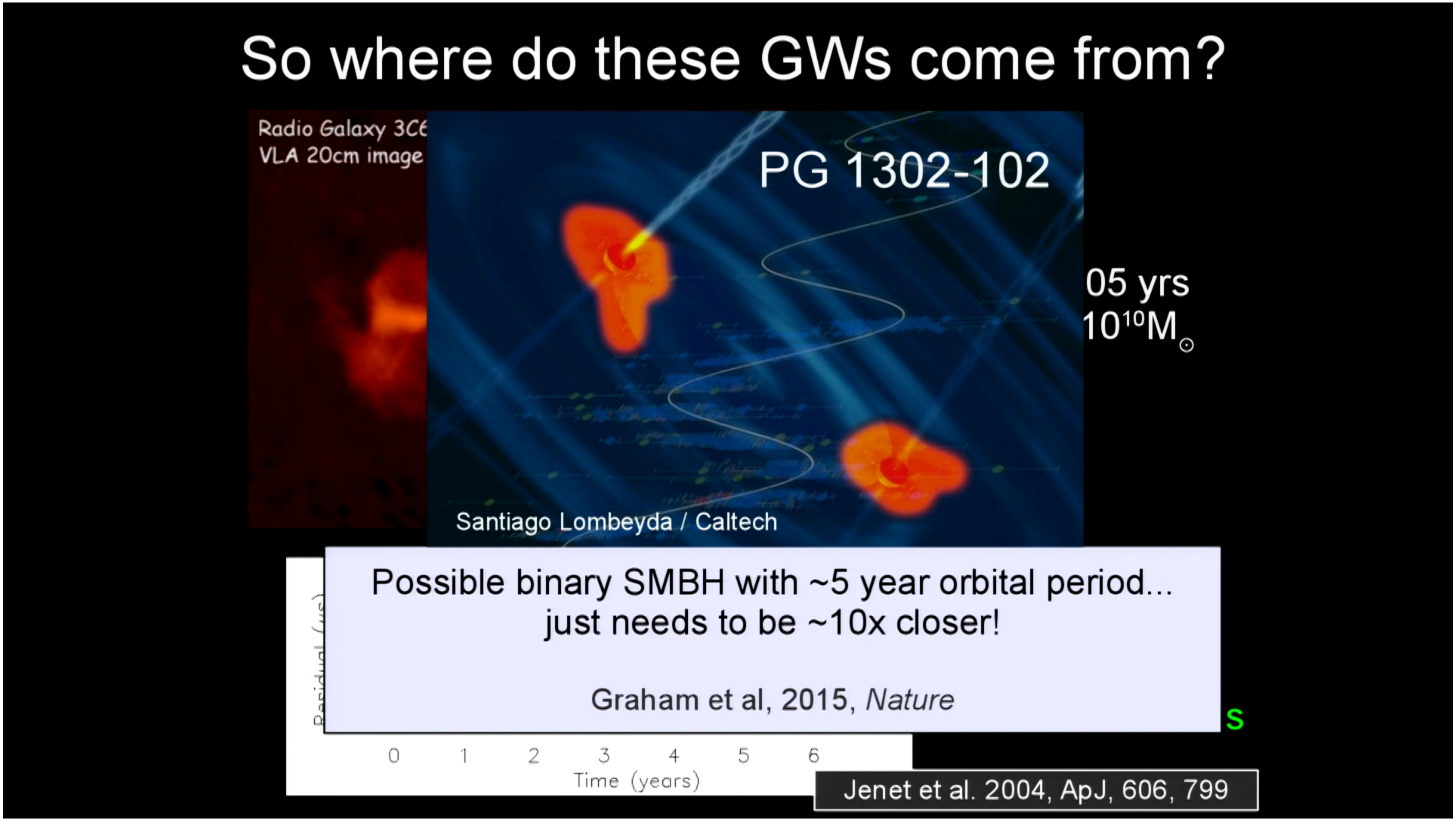
At $z = 0.02$
Orbital period 1.05 yrs
Total mass $5.4 \times 10^{10} M_\odot$
(Sudou et al 2003)




Predicted timing residuals

Ruled out by MSP observations

Jenet et al. 2004, ApJ, 606, 799


So where do these GWs come from?
Radio Galaxy 3C6
VLA 20cm image
PG 1302-102
05 yrs
$10^{10}M_\odot$
Santiago Lombeyda / Caltech
Possible binary SMBH with ~5 year orbital period...
just needs to be ~10x closer!
Graham et al, 2015, *Nature*
s
0 1 2 3 4 5 6
Time (years)
Jenet et al. 2004, ApJ, 606, 799

# 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:

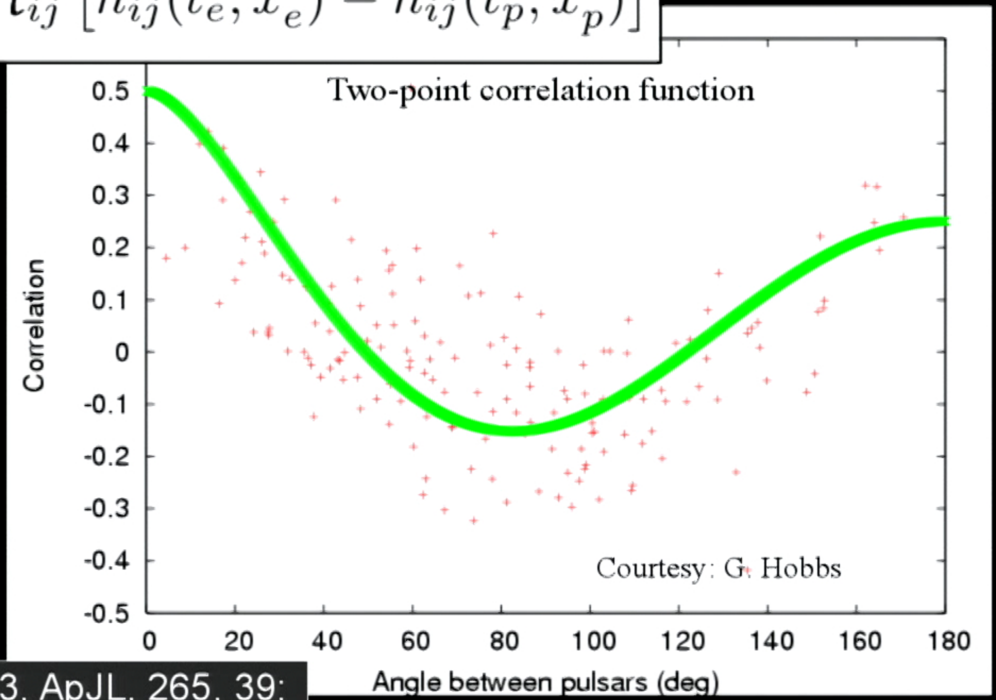
monopole

Ephemeris errors:

dipole

GW signal:

**quadrupole**

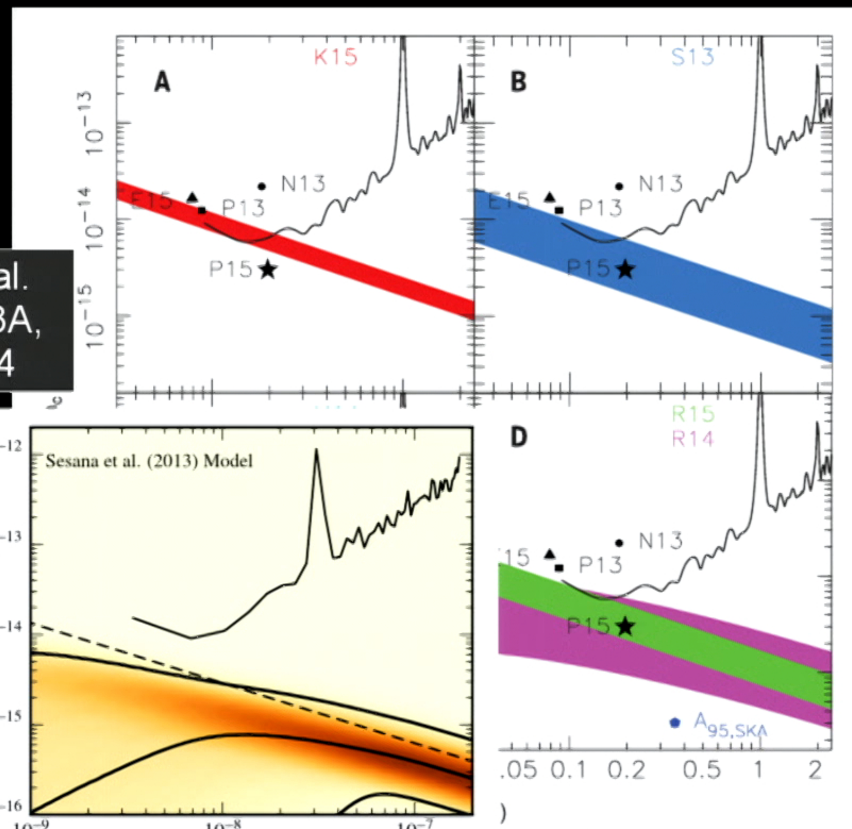



e.g. Hellings & Downs, 1983, ApJL, 265, 39; Jenet et al. 2005, ApJL, 625, 123

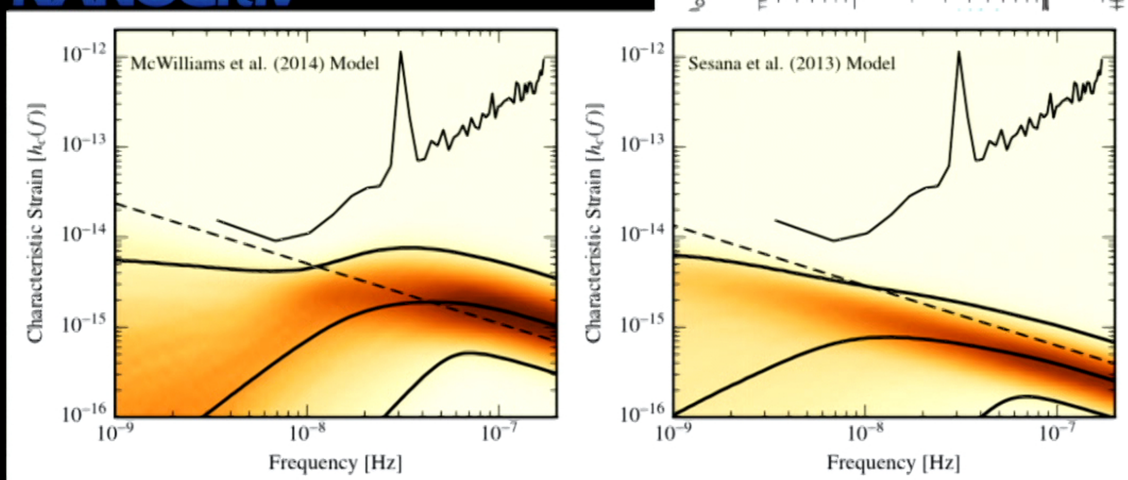
# Where are the GWs?

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

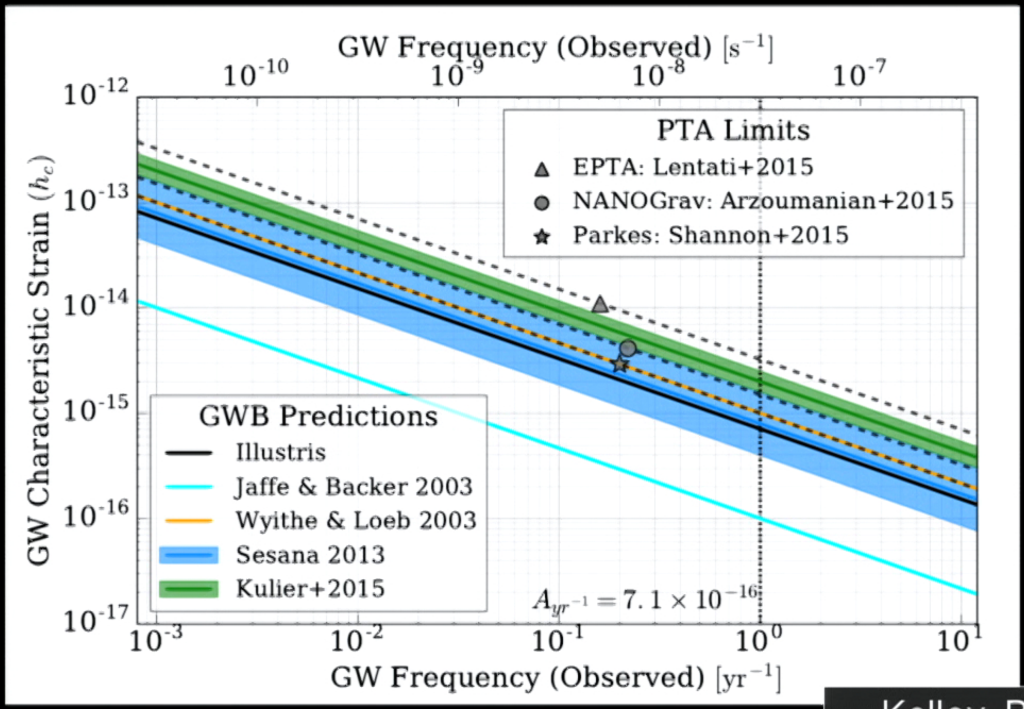
Shannon et al. 2015, Science, 349, 1522 arXiv:1509.07320




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



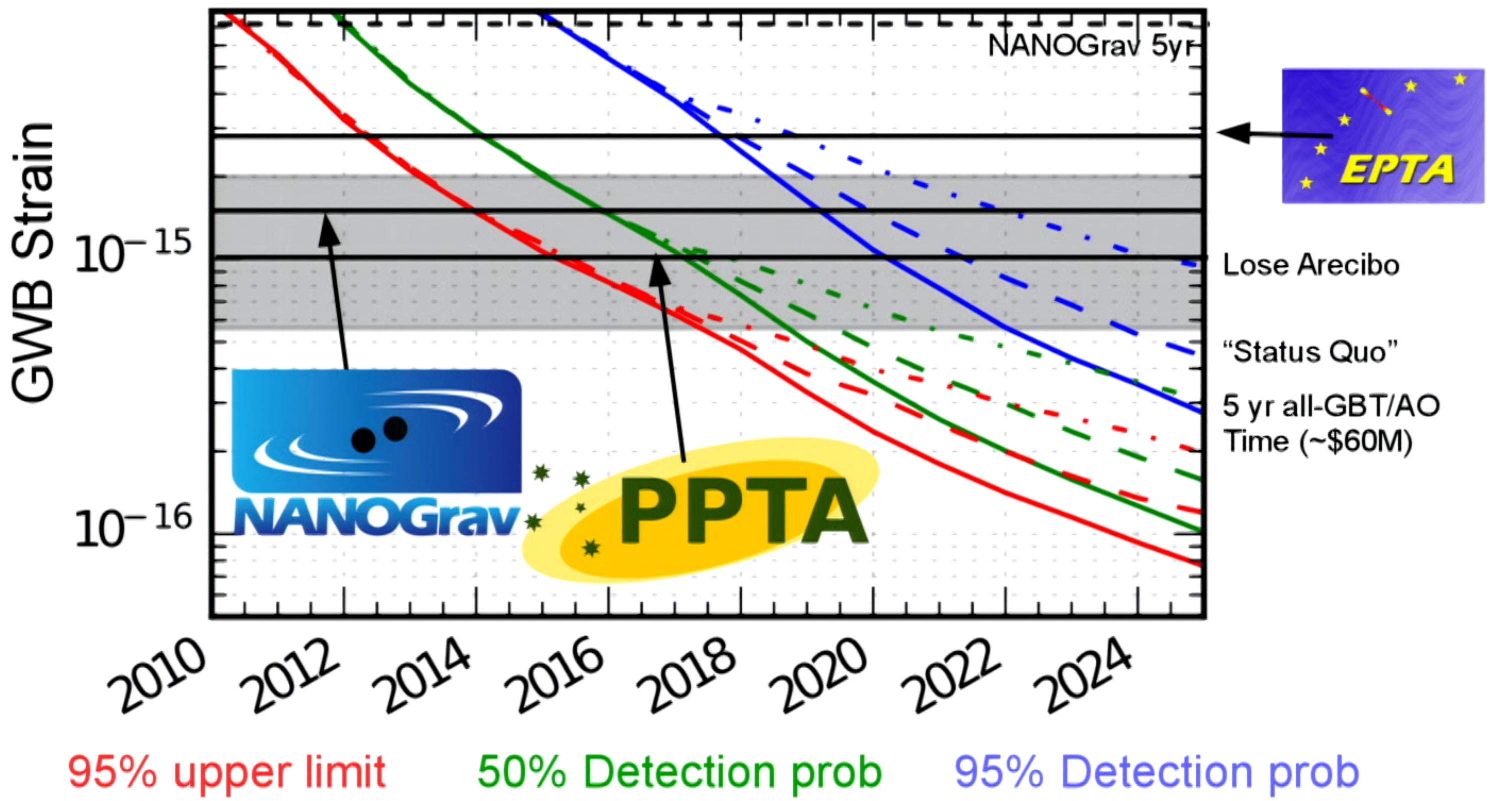
# Latest models don't show a problem...




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

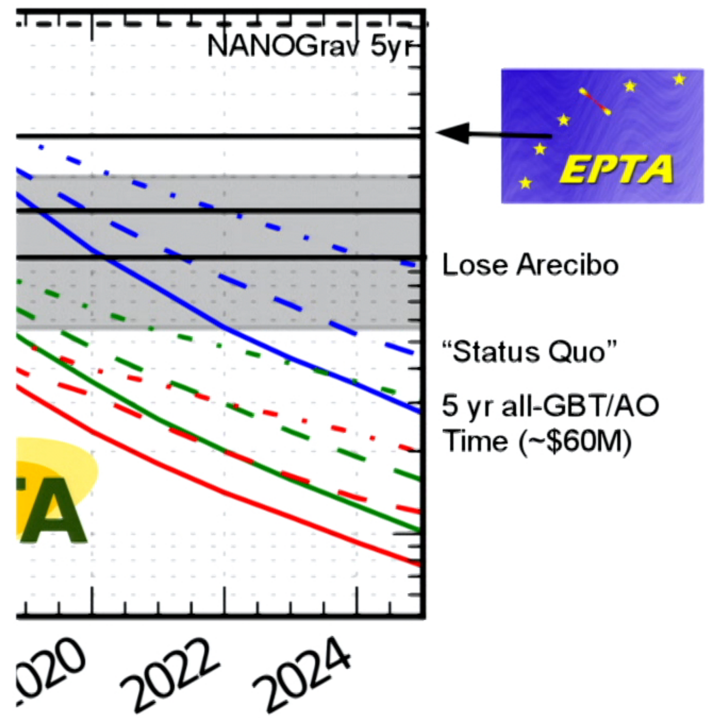
- From Illustris cosmological simulations
- Assuming efficient MBH mergers and power law evolution
- About 30% below the best observational limit

# So what about the future?




Newest models suggest background must be > ~$3x10^{-16}$
(e.g. Kelley, Blecha, & Herrnquist 2016)

# So what about the future?



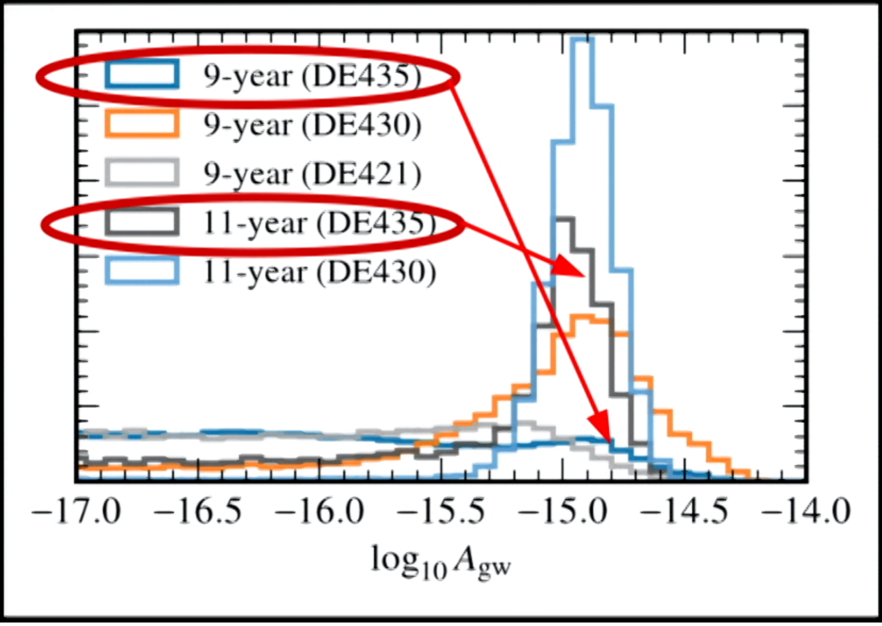

prob     95% Detection prob

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

ound must be > ~3x10$^{-16}$
: Herrnquist 2016)

# 11yr Results Soon…
# PRELIMINARY!

- Twice the # of TOAs than 9yr, 48 vs 38 MSPs
- 11yr stochastic BG limit is ~same as 9yr!
- Some evidence for correlated GW-like red noise? Or problems with planetary ephemerides? (Or both?)



# Ultra-wideband System (planned)

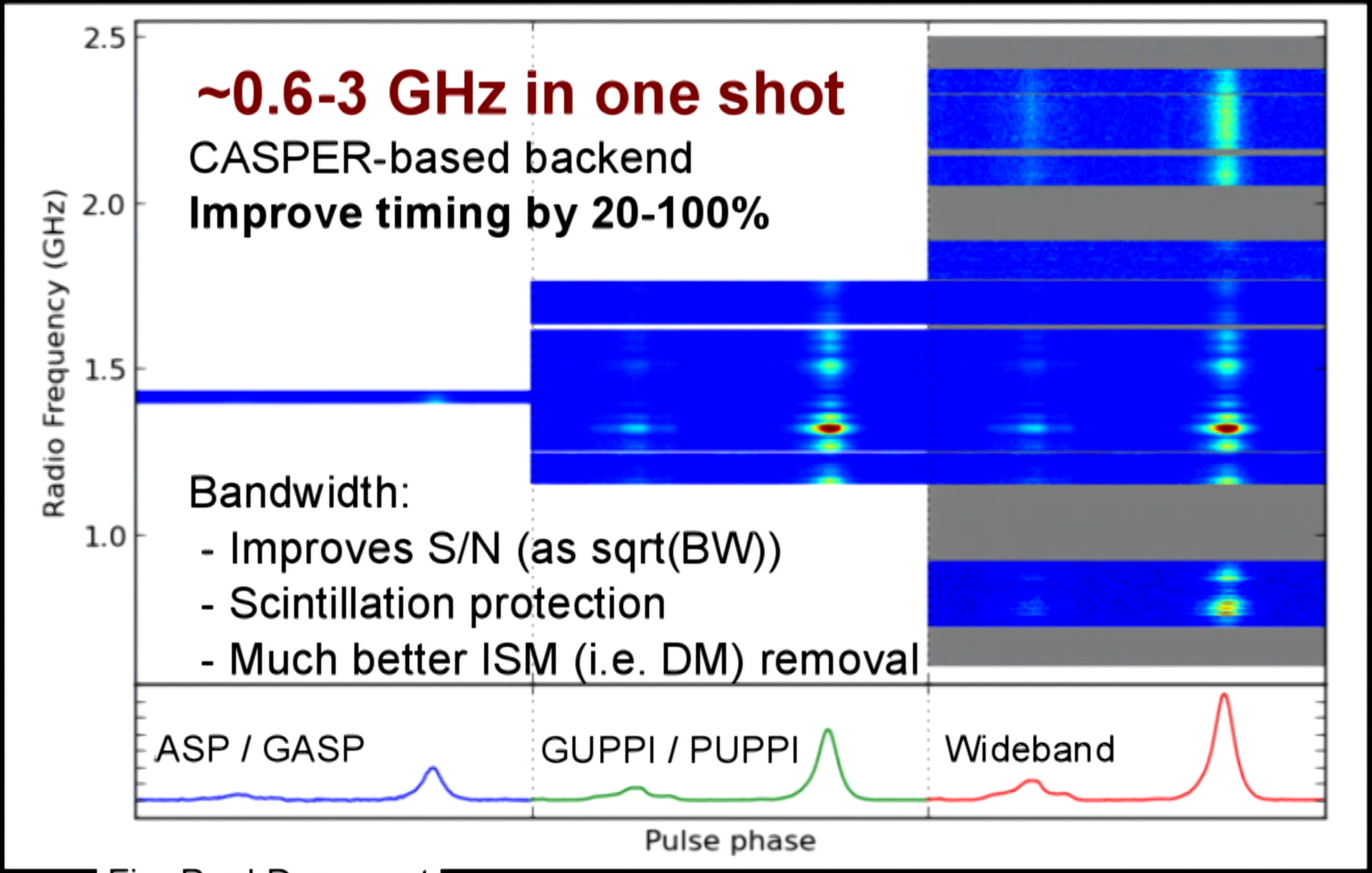
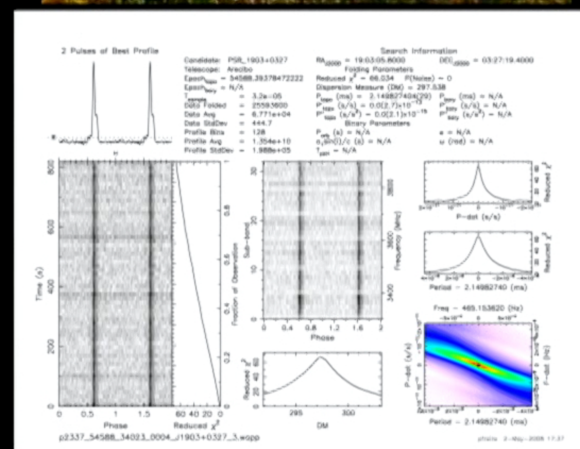



Fig: Paul Demorest

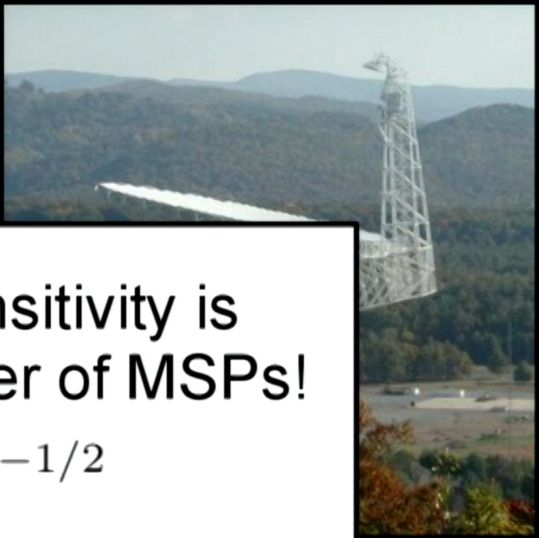
# New All-Sky Pulsar Surveys

- 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

# New All-Sky Pulsar Surveys

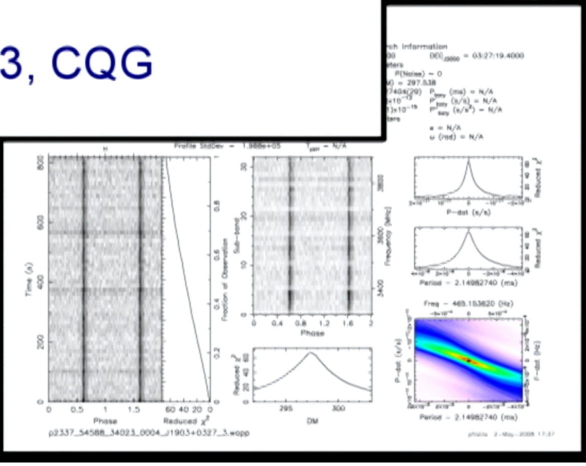
- All major radio telescopes are conducting all-sky pulsar surveys
- We know of only about 5% of the total p
- These
  - 10 ch giv
- Requi performance computing
  - *Many* times real-time and millions of false positives



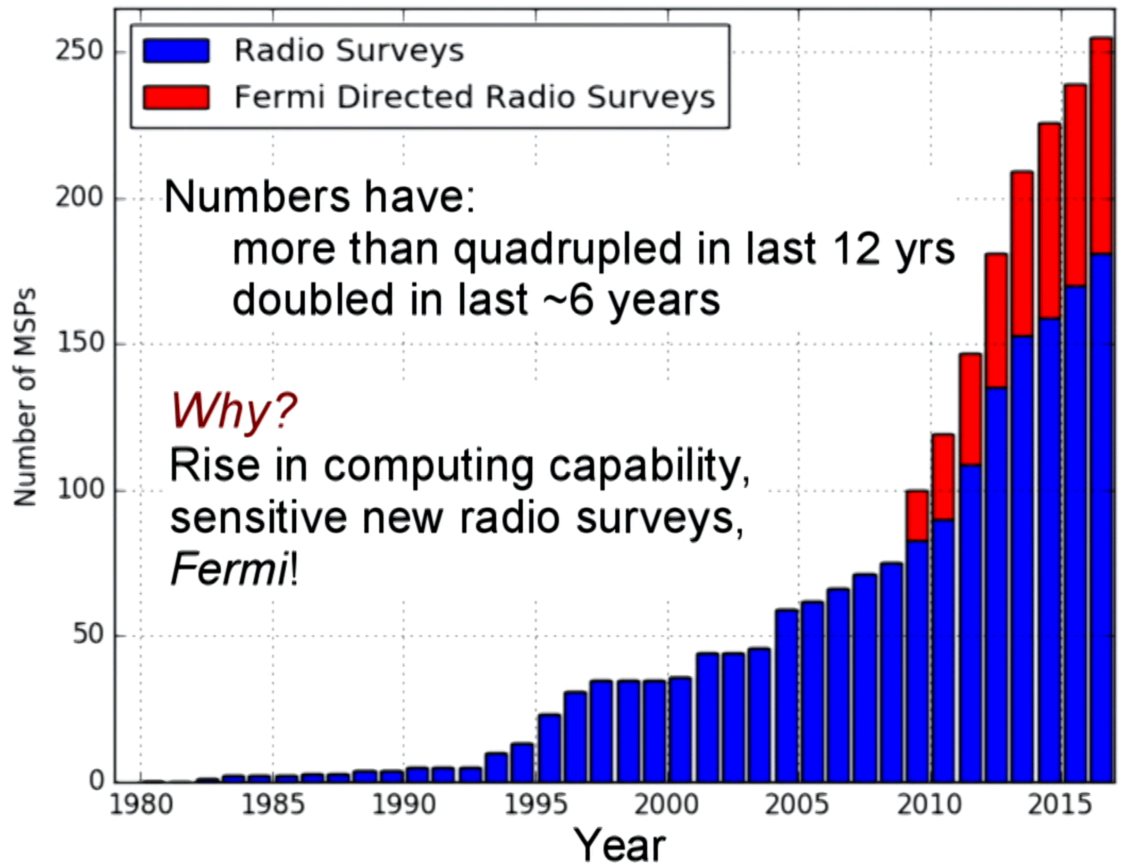
**Gravitational wave sensitivity is proportional to the number of MSPs!**

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

See Siemens et al. 2013, CQG

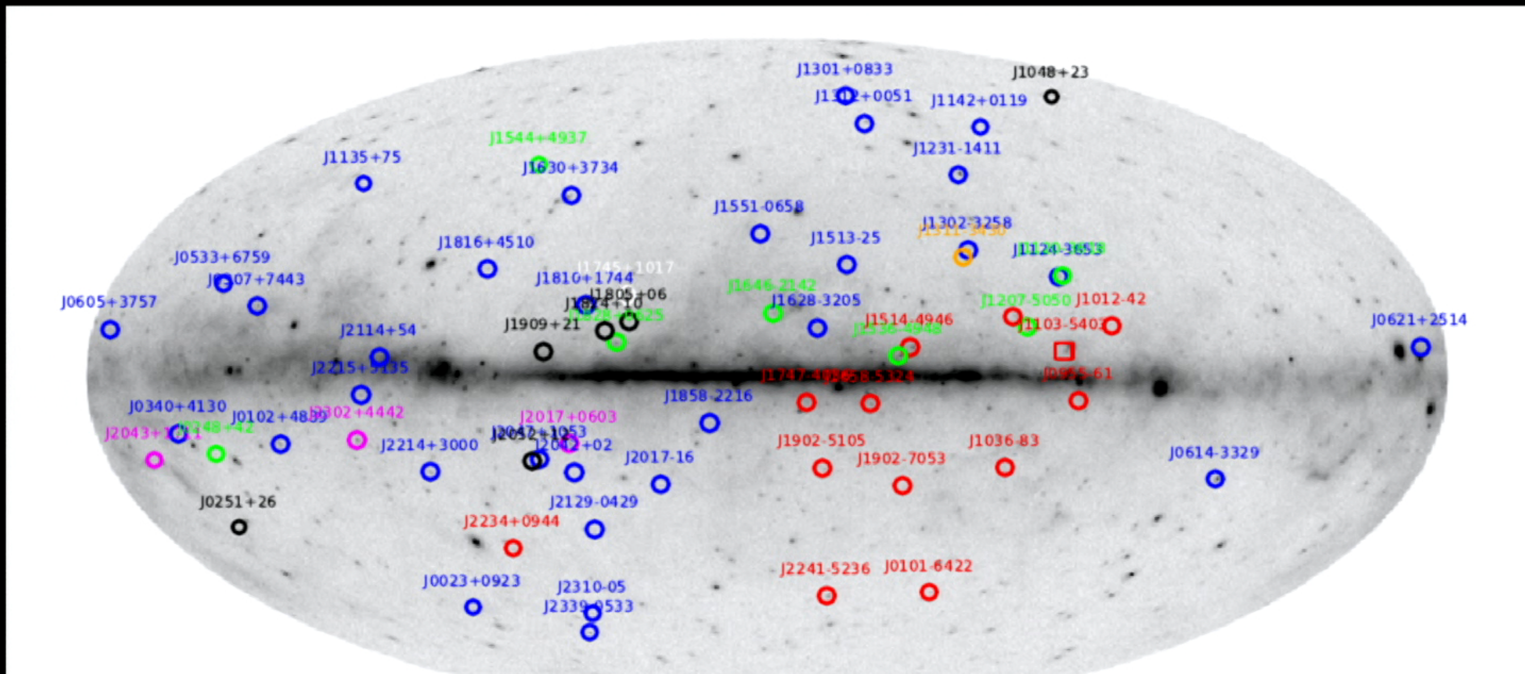


# New Millisecond Pulsars

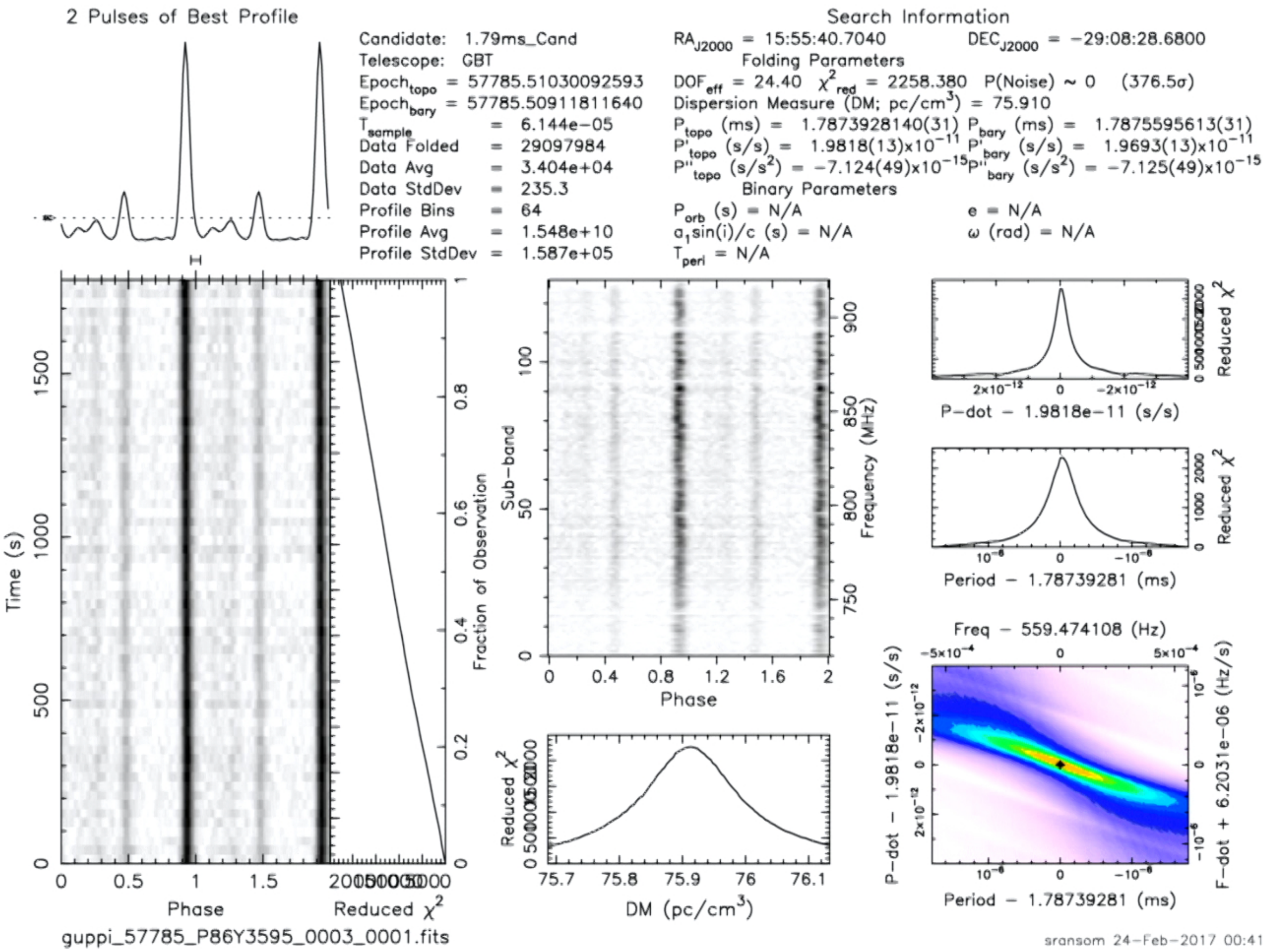


# Currently ~80 new Radio/gamma-ray MSPs because of *Fermi*!

~10-20% of them look like they will be "good timers"
~30% are strange eclipsing systems: "Redbacks" and "Black-Widows"



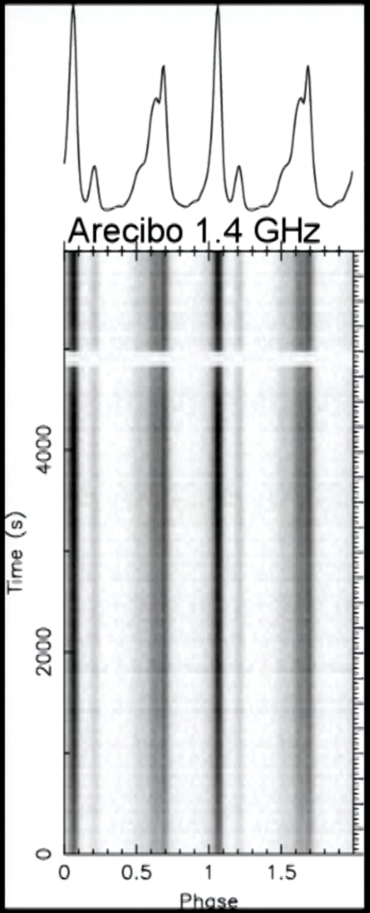

Courtesy: Paul Ray

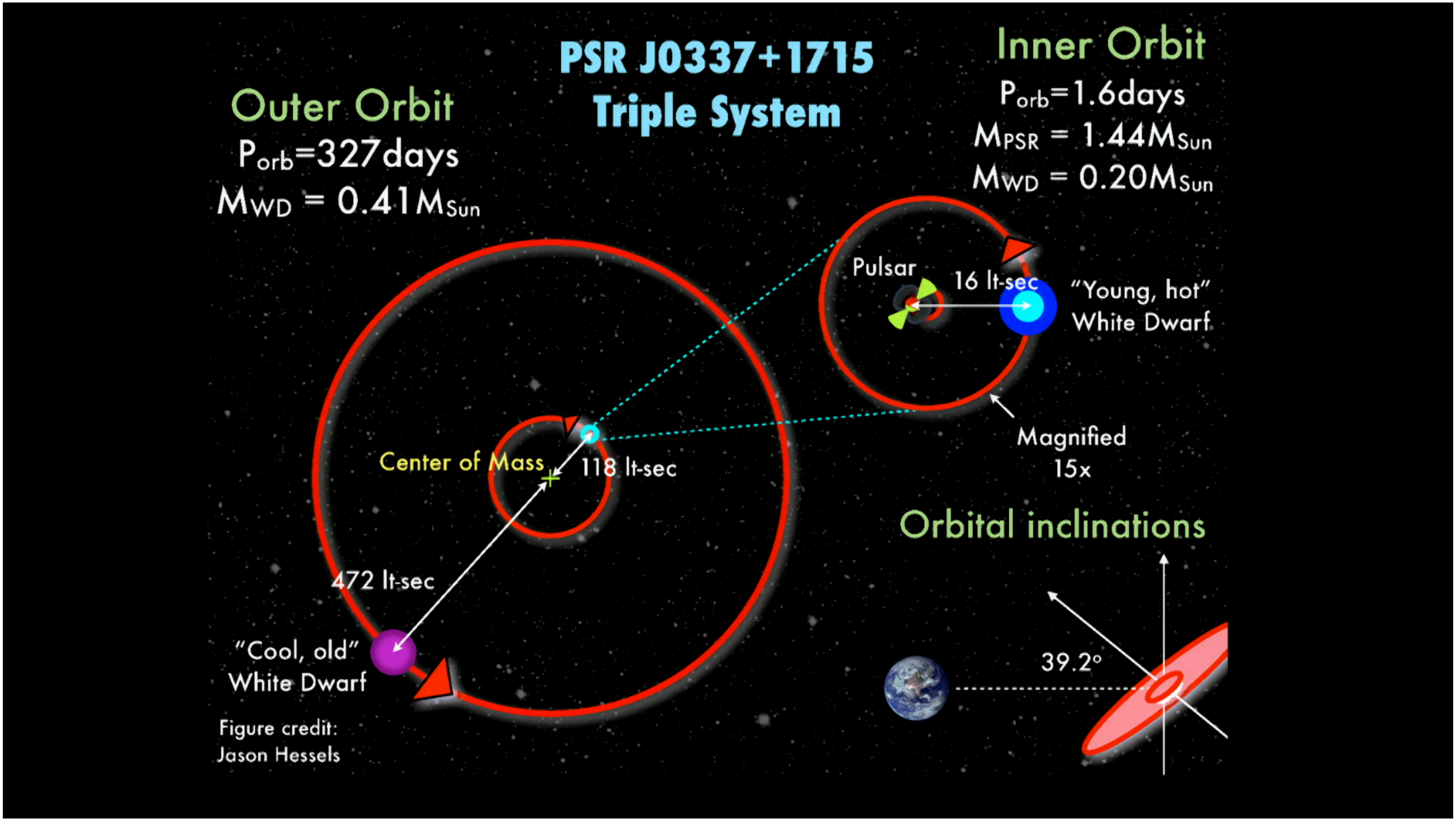

2 Pulses of Best Profile
Search Information
Candidate: 1.79ms_Cand
Telescope: GBT
Epoch_topo = 57785.51030092593
Epoch_bary = 57785.50911811640
T_sample = 6.144e-05
Data Folded = 29097984
Data Avg = 3.404e+04
Data StdDev = 235.3
Profile Bins = 64
Profile Avg = 1.548e+10
Profile StdDev = 1.587e+05
RA_J2000 = 15:55:40.7040
DEC_J2000 = −29:08:28.6800
Folding Parameters
DOF_eff = 24.40 χ²_red = 2258.380 P(Noise) ~ 0 (376.5σ)
Dispersion Measure (DM; pc/cm³) = 75.910
P_topo (ms) = 1.7873928140(31) P_bary (ms) = 1.7875595613(31)
P'_topo (s/s) = 1.9818(13)x10⁻¹¹ P'_bary (s/s) = 1.9693(13)x10⁻¹¹
P''_topo (s/s²) = −7.124(49)x10⁻¹⁵ P''_bary (s/s²) = −7.125(49)x10⁻¹⁵
Binary Parameters
P_orb (s) = N/A
e = N/A
a_1sin(i)/c (s) = N/A
ω (rad) = N/A
T_peri = N/A
Time (s)
Phase
Reduced χ²
Fraction of Observation
Sub-band
Frequency (MHz)
DM (pc/cm³)
P-dot − 1.9818e-11 (s/s)
Period − 1.78739281 (ms)
Freq − 559.474108 (Hz)
F-dot + 6.2031e-06 (Hz/s)
guppi_57785_P86Y3595_0003_0001.fits
sransom 24-Feb-2017 00:41

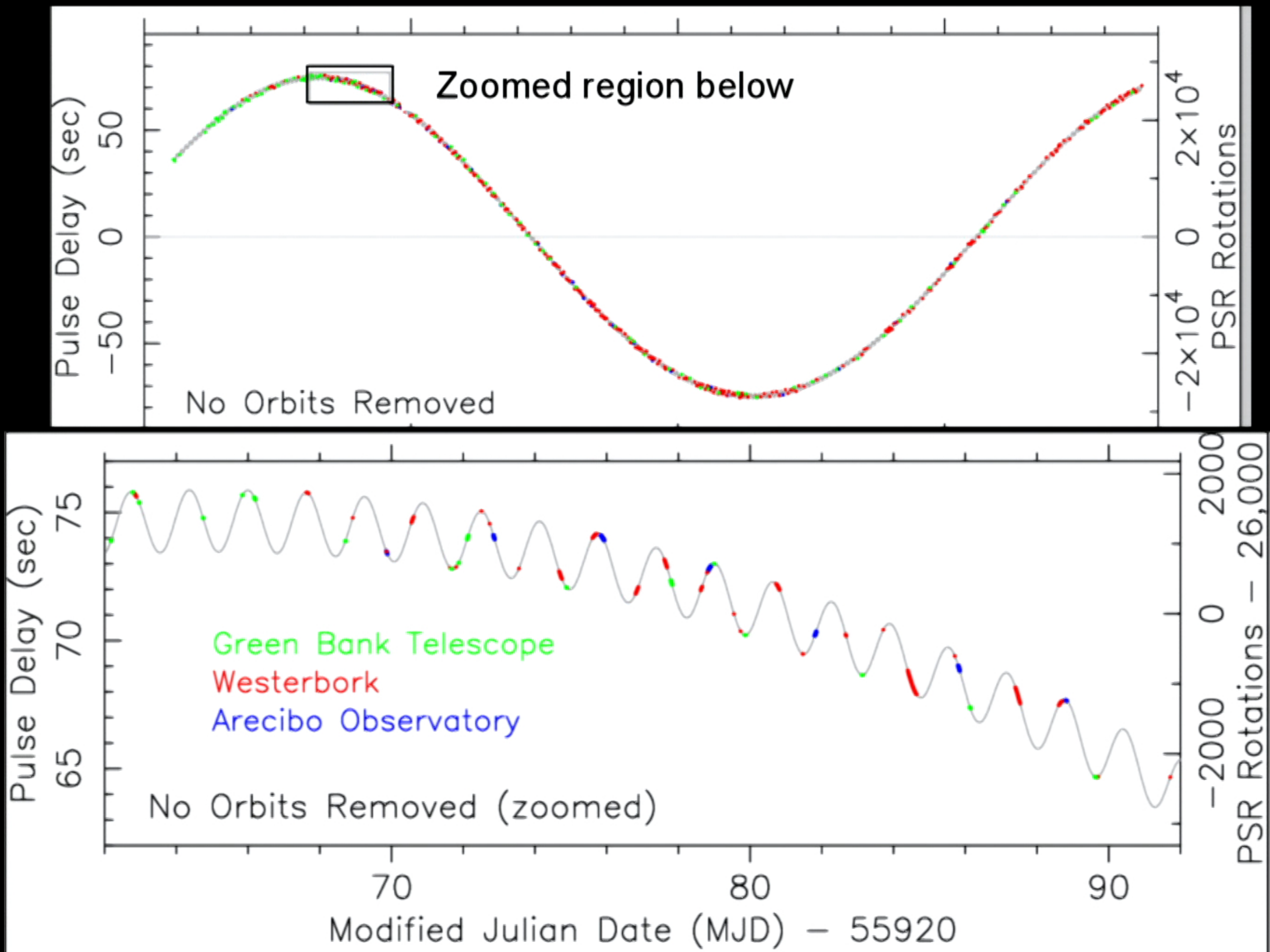
# An MSP in a stellar triple system!

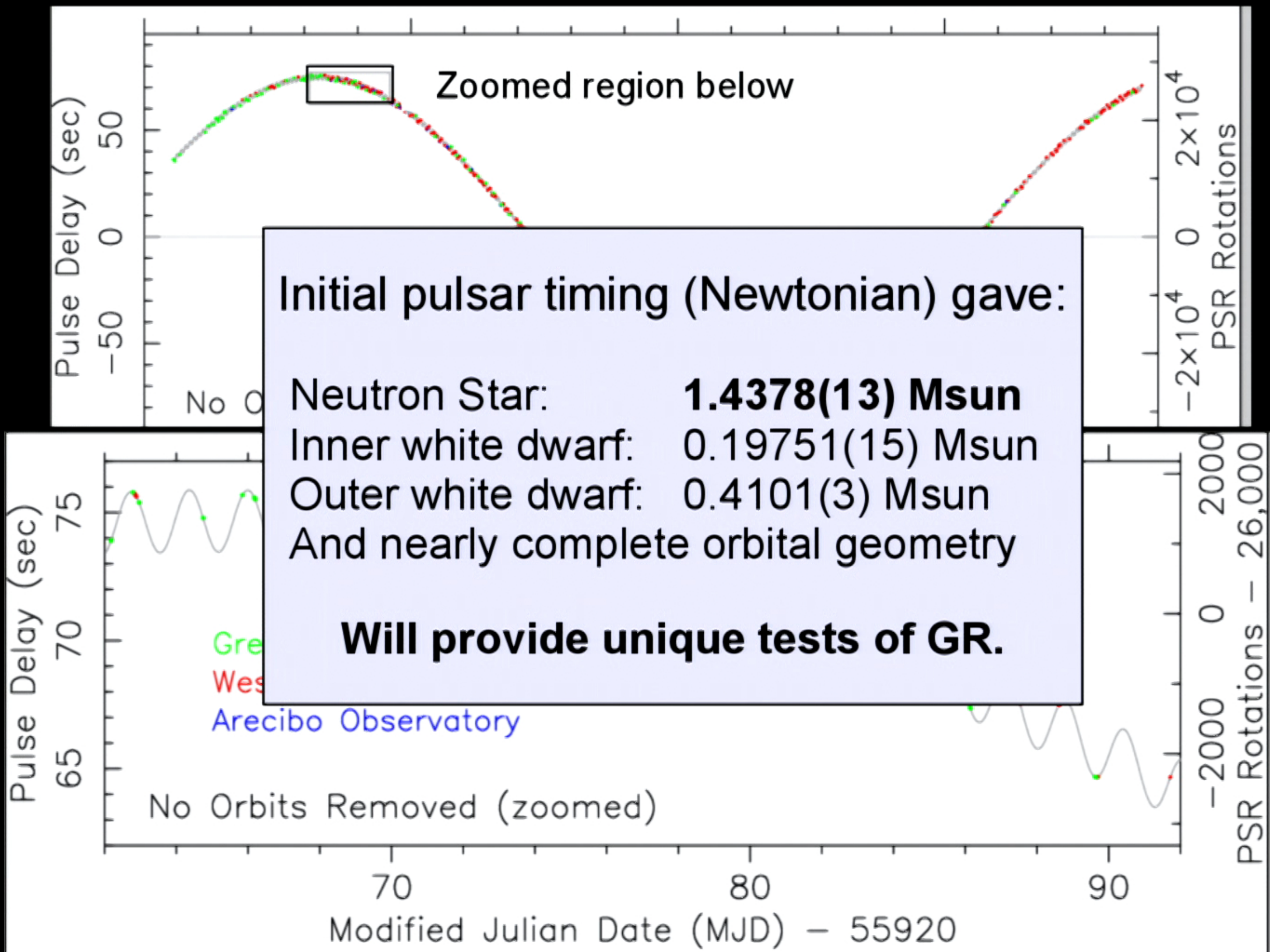
- PSR J0337+1715: In 2012, from the GBT Driftscan survey, a 2.7 ms PSR in a hierarchical triple system!
  - 1.6 day inner binary with hot WD
  - 327 day outer orbit with cool WD
  - Very strong 3-body effects...

Ransom et al. 2014, *Nature*, 505, 520




PSR J0337+1715
Triple System
Outer Orbit
Porb=327days
MWD = 0.41MSun
Inner Orbit
Porb=1.6days
MPSR = 1.44MSun
MWD = 0.20MSun
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
PSR Rotations
2×10^4
0
−2×10^4
No Orbits Removed
Pulse Delay (sec)
75
70
65
PSR Rotations − 26,000
2000
0
−2000
Green Bank Telescope
Westerbork
Arecibo Observatory
No Orbits Removed (zoomed)
70
80
90
Modified Julian Date (MJD) − 55920

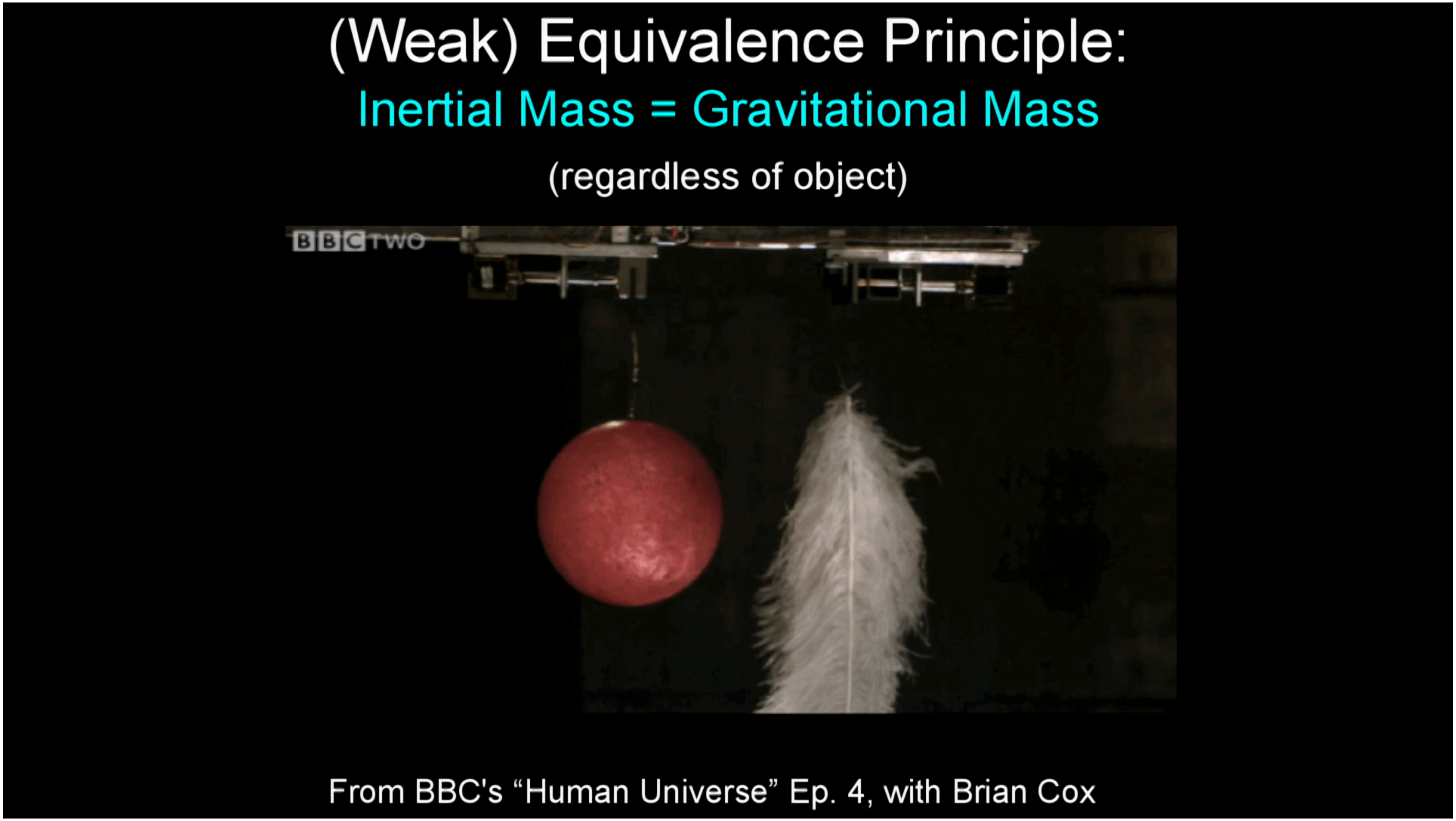



Initial pulsar timing (Newtonian) gave:

| | |
|---|---|
| Neutron Star: | **1.4378(13) Msun** |
| Inner white dwarf: | 0.19751(15) Msun |
| Outer white dwarf: | 0.4101(3) Msun |

And nearly complete orbital geometry

**Will provide unique tests of GR.**


(Weak) Equivalence Principle:
Inertial Mass = Gravitational Mass
(regardless of object)
BBC TWO
From BBC's "Human Universe" Ep. 4, with Brian Cox

# (Weak) Equivalence Principle:

Inertial Mass = Gravitational Mass

(regardless of object)


From BBC's "Human Universe" Ep. 4, with Brian Cox

# Strong Equivalence Principle

- Gravitational and inertial masses are equal
- Composition, shape, mass, location etc doesn't matter
- This applies to objects with strong self-gravity as well:
  - Gravitational binding energy gravitates!
    $\epsilon \sim GM/Rc^2 \sim 0.1$ for NS
  - Only GR embodies this
- Tested via the Nordtvedt parameter, $\eta$:

$$\left(\frac{m_{\rm grav}}{m_{\rm inertial}}\right) = 1 + \Delta = 1 + \eta\epsilon + \mathcal{O}(\epsilon^2).$$

# Strong Equivalence Principle

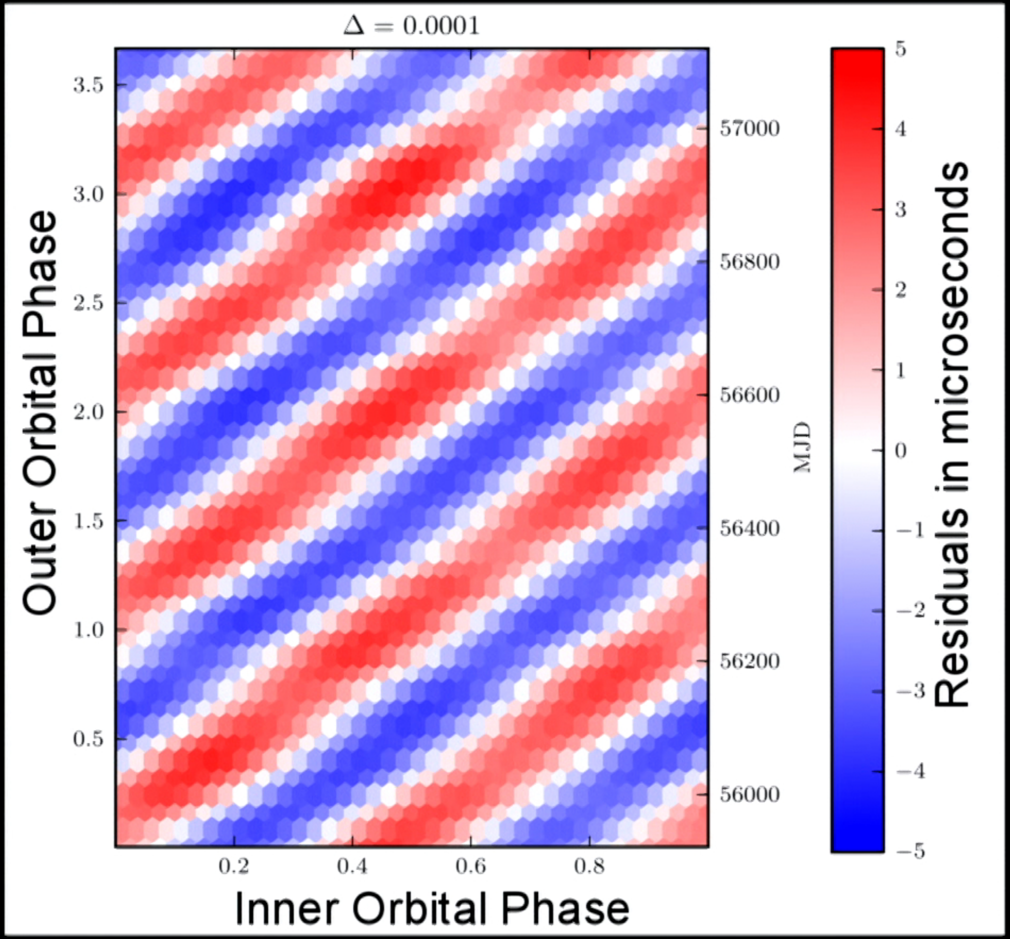
- Gravitational and inertial masses are equal
- Composition, shape, mass, location etc doesn't matter
- This applies to objects with strong self-gravity as well:
  - Gravitational binding energy gravitates!
    $\epsilon \sim GM/Rc^2 \sim 0.1$ for NS
  - Only GR embodies this
- Tested via the Nordtvedt parameter, $\eta$:

$$\left(\frac{m_{\rm grav}}{m_{\rm inertial}}\right) = 1 + \Delta = 1 + \eta\epsilon + \mathcal{O}(\epsilon^2).$$


Lunar Laser Ranging (LLR) has constrained: $|\eta\epsilon| < 2\times10^{-13}$, corresponding to $|\eta| < 4\times10^{-4}$, given weak gravity of Solar System bodies

*Müller, Hofmann, Biskupek, 2012, CQGrav*

# Here is signal we are looking for
## ($\Delta = 10^{-4}$ is ~4x smaller than limit by LLR)



# So where are we now?

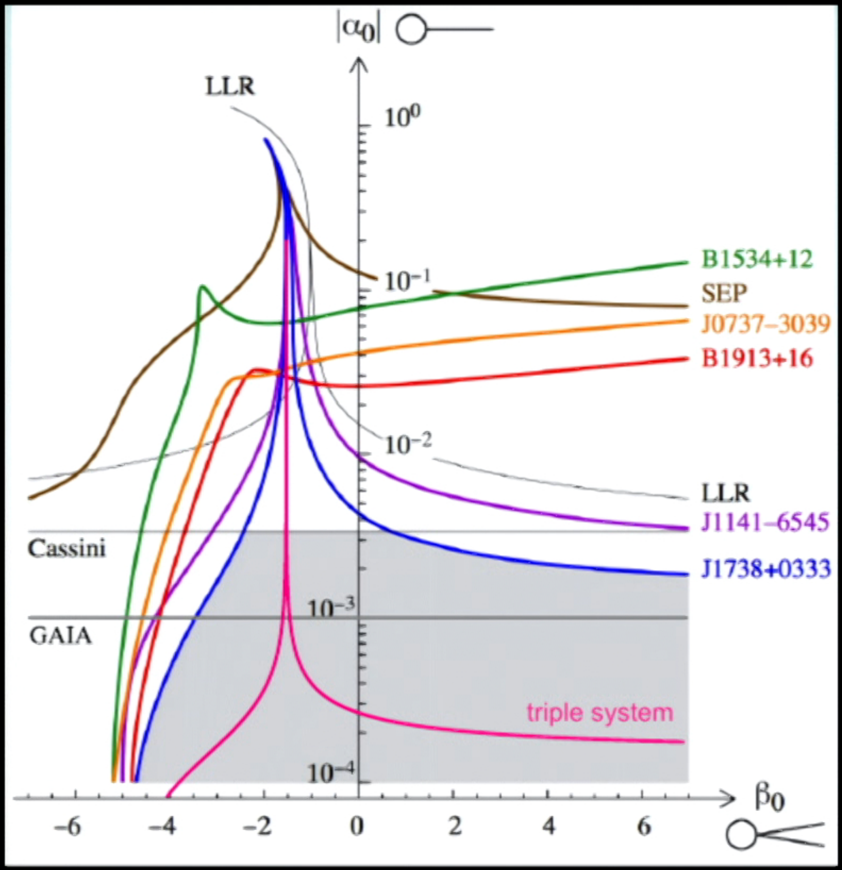
- Using PPN Lagrangian by Nordtvedt (1985) which incorporates potential SEP violations (amazing work by Anne Archibald)
- ~30 params, $\sim 10^4$ TOAs, and no TEMPO(2)!
- Accounting for all known ~us-level effects:
  - WSRT only: $\Delta \sim +3(3)\times10^{-6}$
  - GBT only: $\Delta \sim -2.8(1.4)\times10^{-6}$
  - Arecibo only: $\Delta \sim -3.6(6)\times10^{-6}$
  - GBT+AO: $\Delta \sim -3.0(5)\times10^{-6}$
  - All: $\Delta \sim -3.0(5)\times10^{-6}$

Preliminary!

# J0337+1715 scalar-tensor constraints

- "G" effectively different for NS and WD. They each fall in relatively "strong" grav field of outer WD.

- $T_1(\alpha_0,\beta_0)$ theories
- GR has $\alpha_0=\beta_0=0$
- Jordan–Fierz–Brans– Dicke theory has $\beta_0=0$

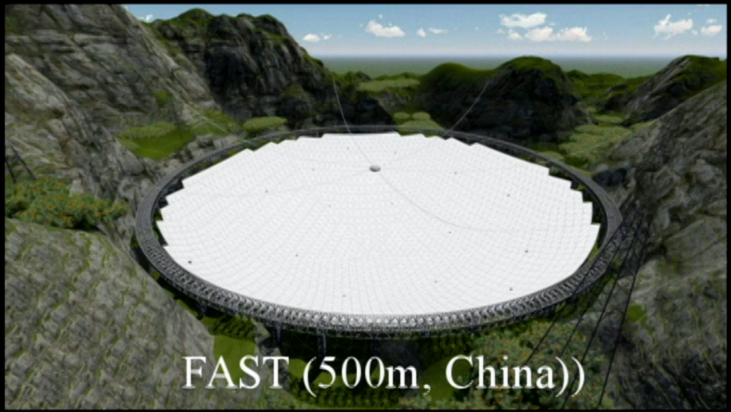


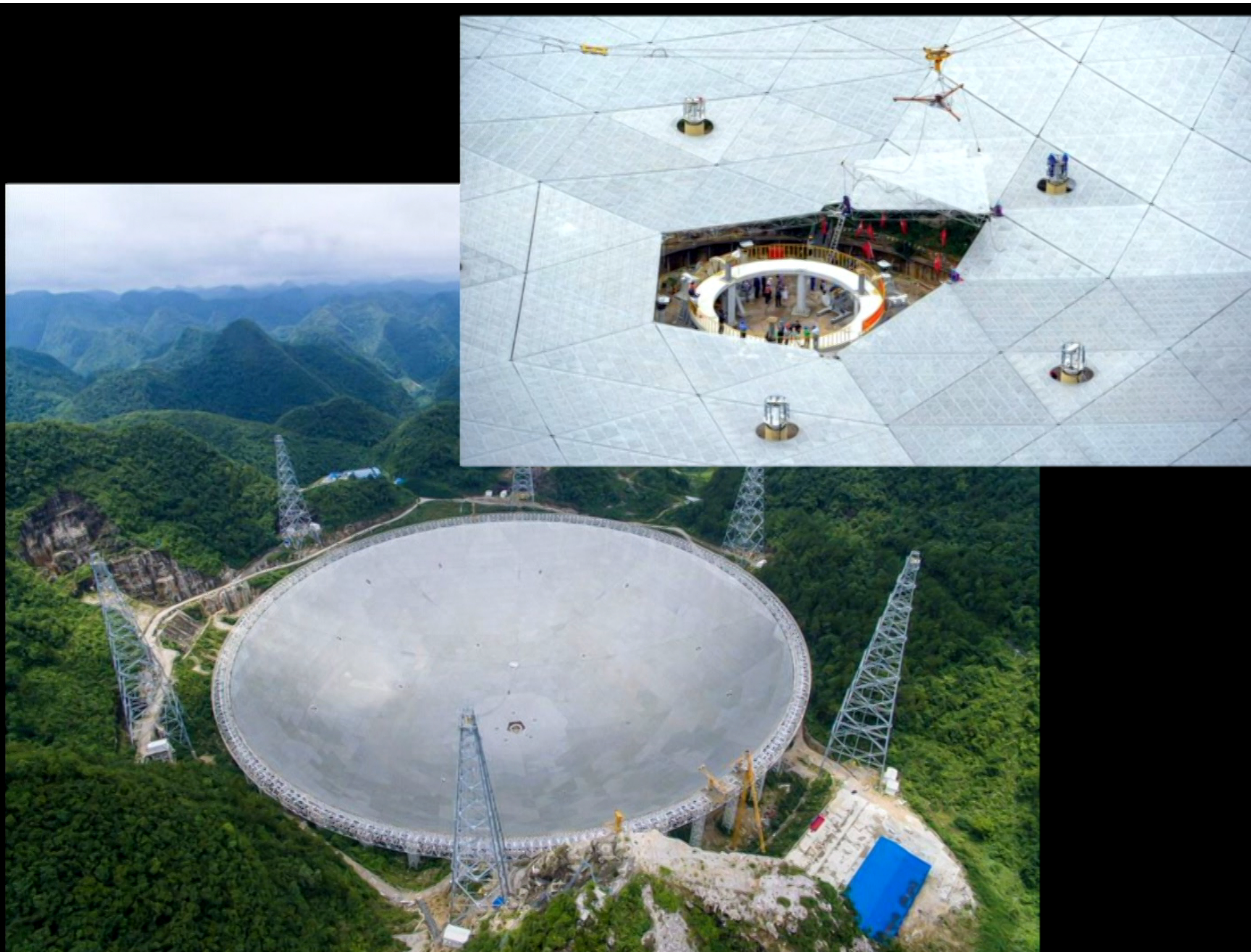

N. Wex, private communication

# 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...

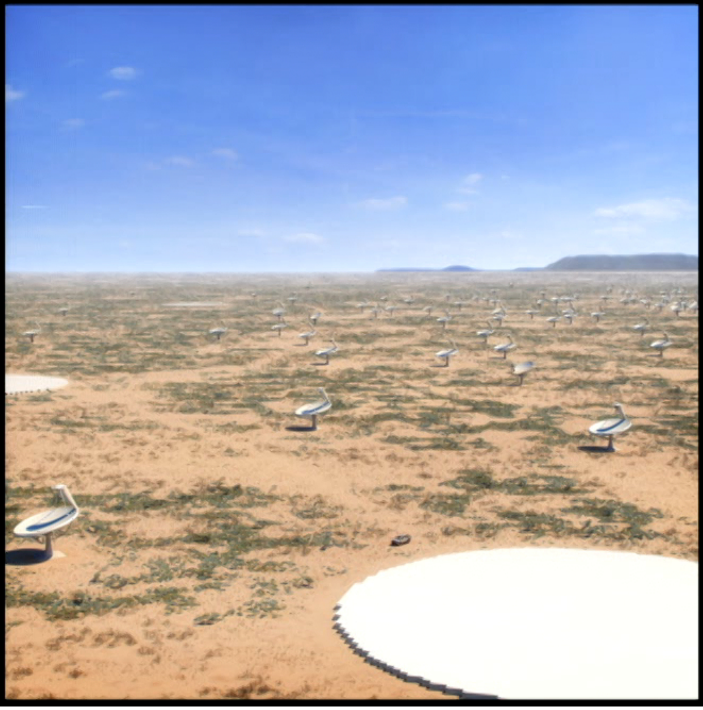
We need them because we are sensitivity limited!



# 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

- Many amazing (and bright!) pulsars to be found in the Galaxy: we know of <10% of total
- Radio pulsars can, do, and will make extremely important contributions to **basic physics**
  - **Direct detection of gravitational radiation**
  - High precision tests of gravitational theories
  - Probes the nature of matter at supra-nuclear densities
  - Study the advanced stages of stellar+binary evolution
- But we are sensitivity limited (Need big scopes!)
  - FAST in China, MeerKAT in S.Africa, eventually SKA?
  - Losing GBT and/or Arecibo would be **bad** for PSRs