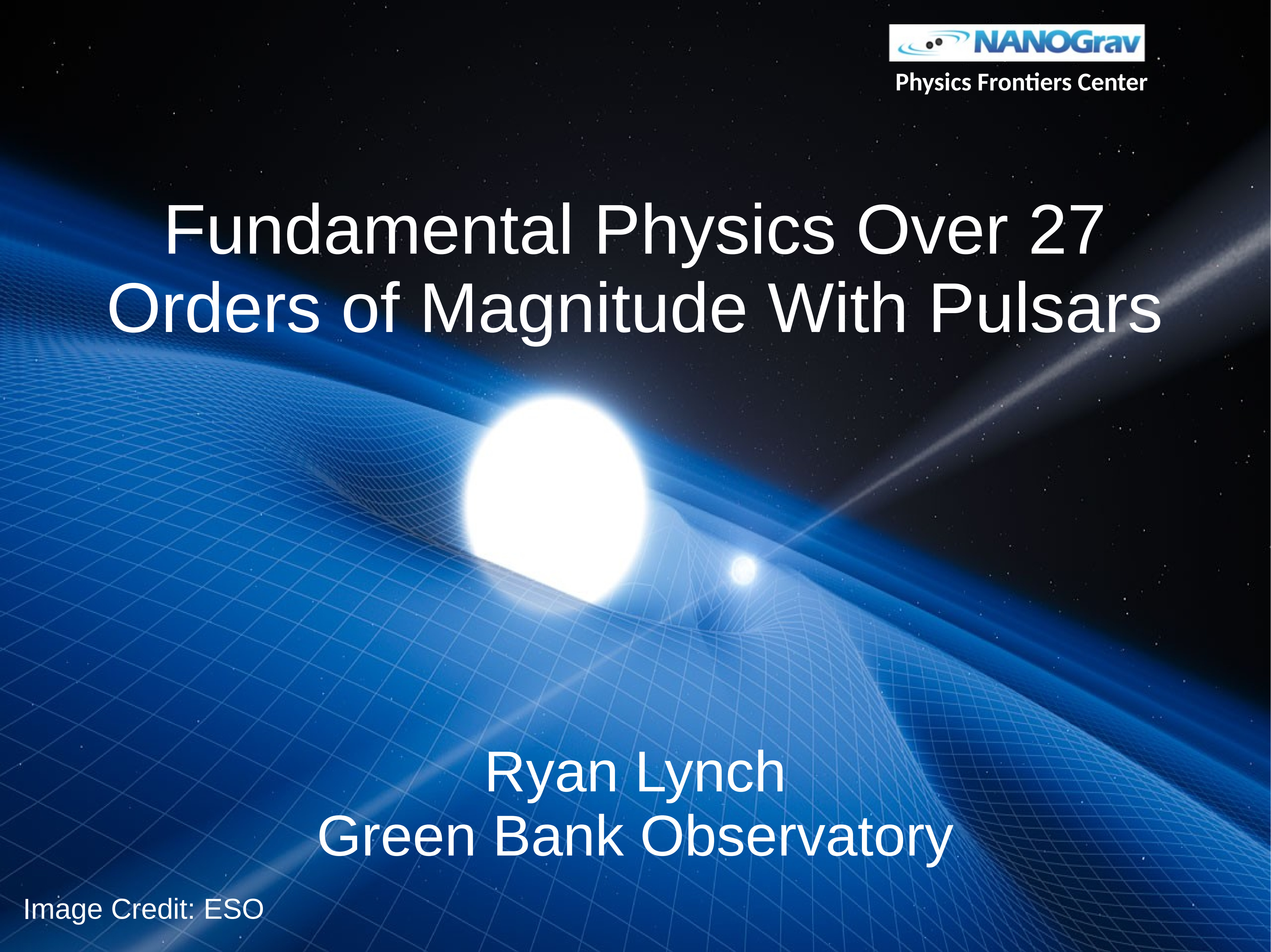
NANOGrav
Physics Frontiers Center

Fundamental Physics Over 27 Orders of Magnitude With Pulsars



Ryan Lynch
Green Bank Observatory

Image Credit: ESO

Pulsars are clocks...

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...that create some of the most extreme environments in the Universe...

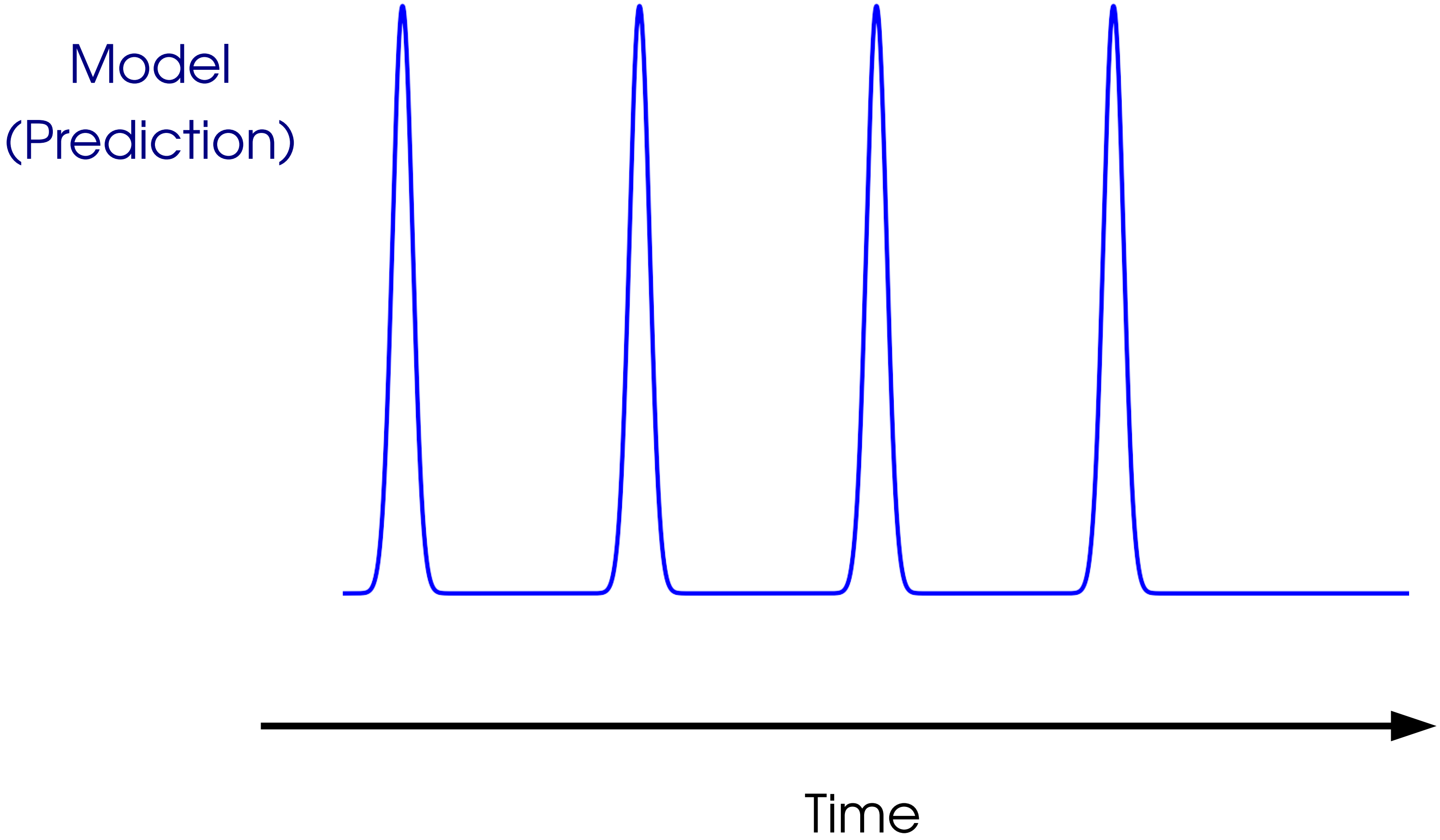
Pulsars are clocks...

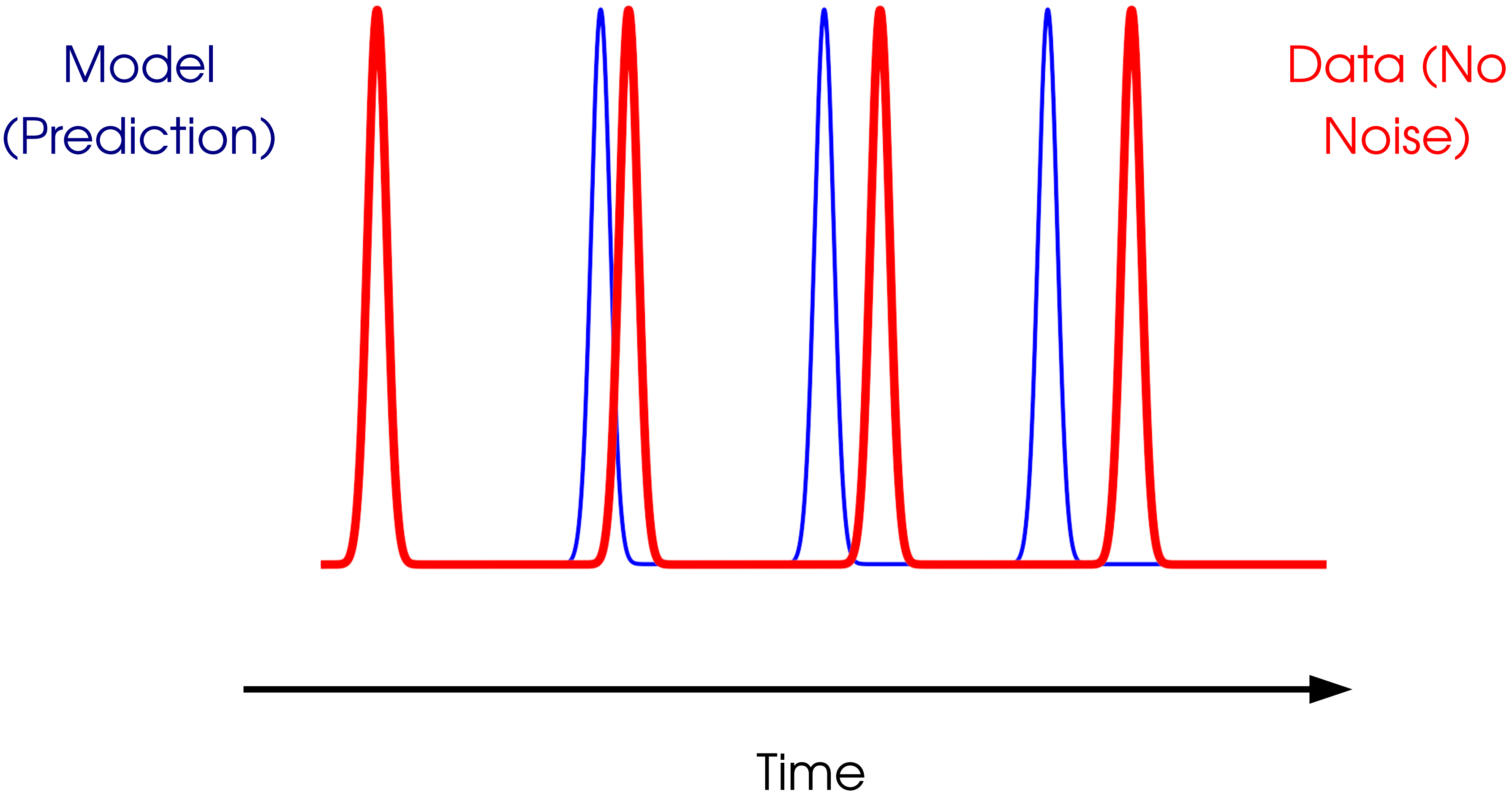
...that create some of the most extreme environments in the Universe...

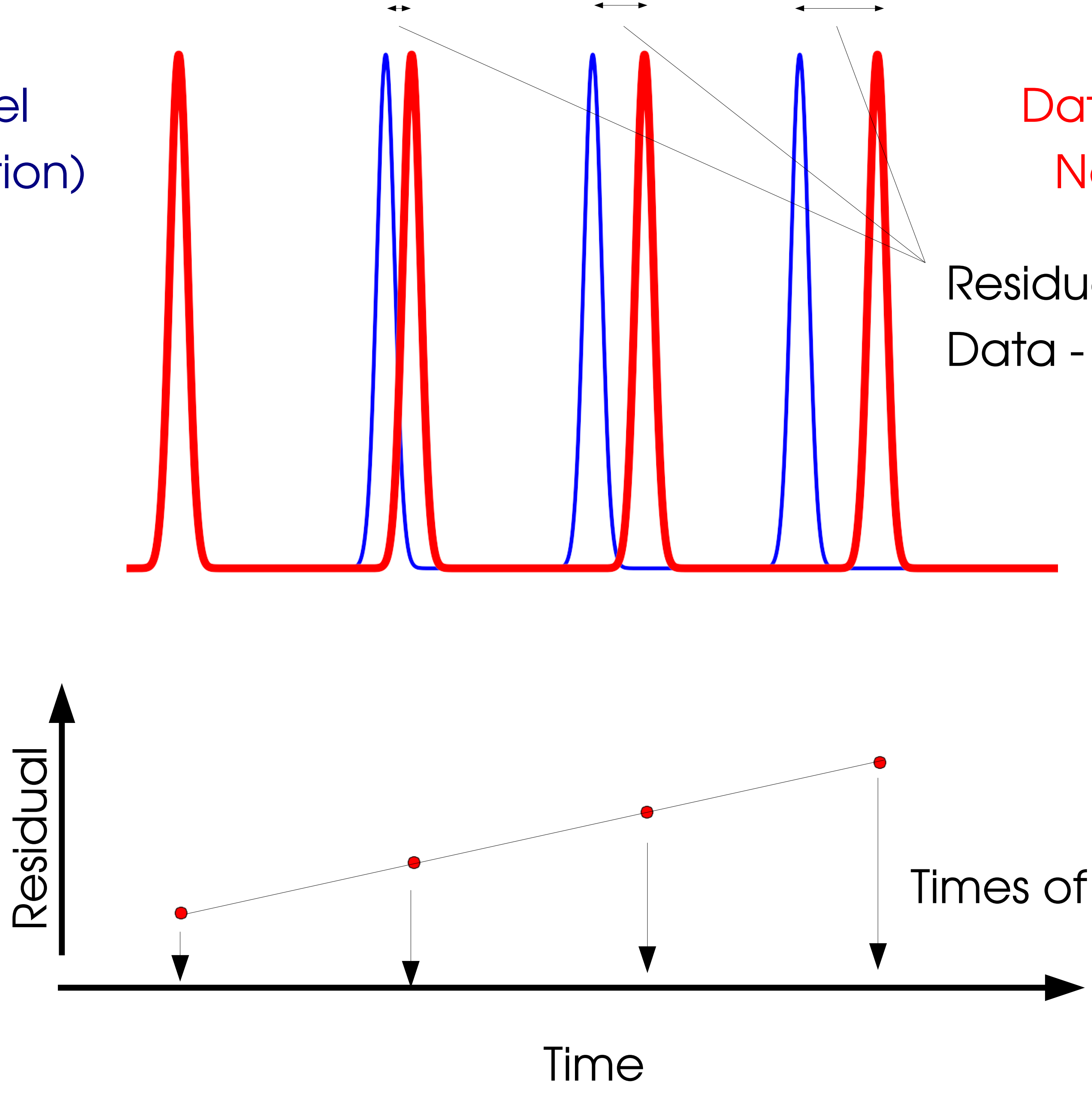
...which makes them natural laboratories for studying fundamental physics

Pulsar Timing

- Track every rotation of a pulsar
- Predict pulse arrival times
  - Deviations from the expected arrival time of a pulse contain useful information


Model
(Prediction)
Time


Model (Prediction)
Data (No Noise)
Time



Model (Prediction)

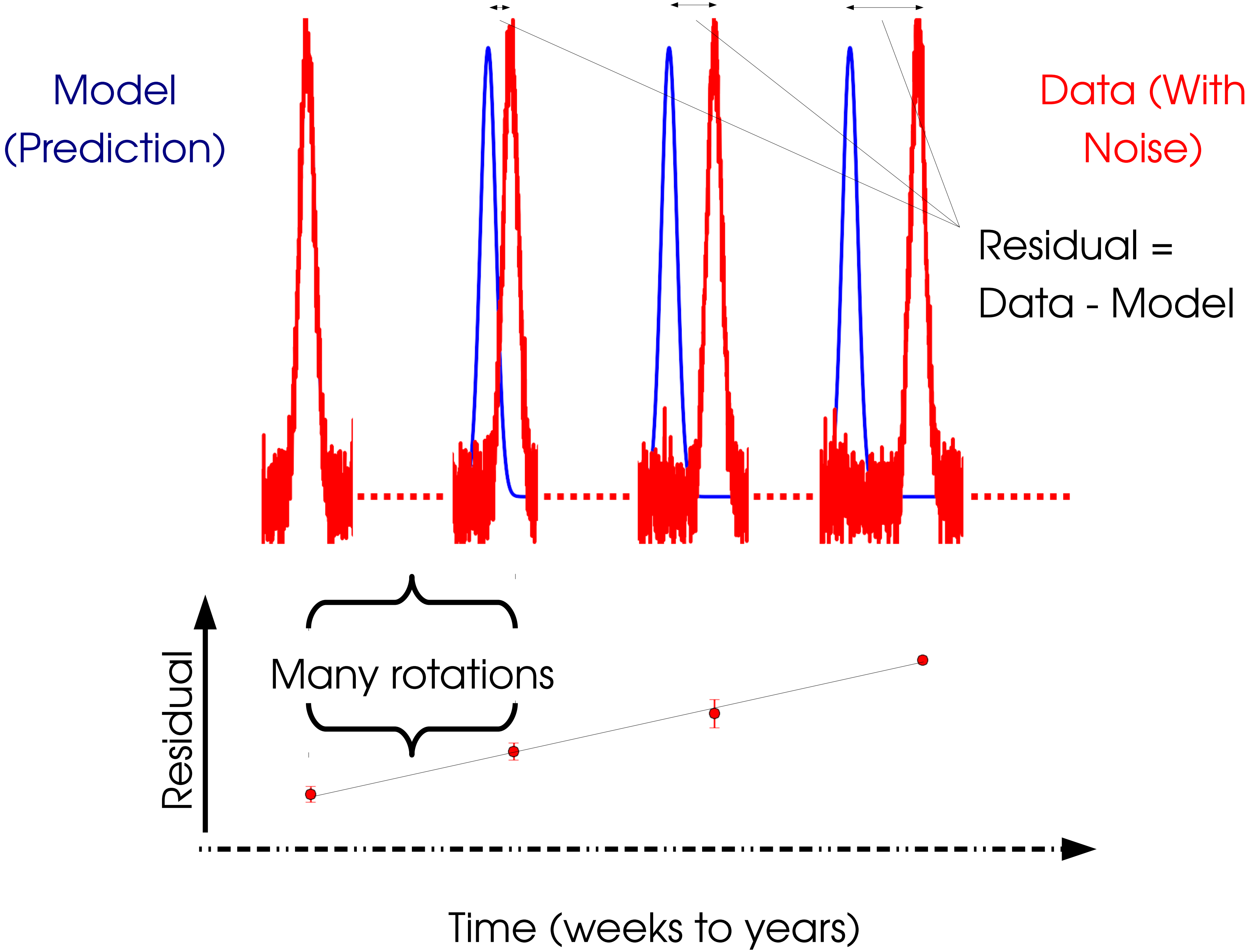
Data (No Noise)

Residual = Data - Model

Residual

Times of Arrival (TOAs)

Time



Model (Prediction)

Data (With Noise)

Residual = Data - Model

Many rotations

Residual

Time (weeks to years)

Power of Pulsar Timing

- Spin period can be measured to $\sim\delta/N_{rot}$
  - For MSPs observed over many years, $N_{rot}\sim10^9$

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- At 2017-10-17 09:10 EDT the frequency of PSR J0437-4715 is/was

`173.701580684374 ±`

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```
173.701580684374 ±
  0.000000000003 Hz
```

Power of Pulsar Timing

a = 10^{11} cm (1.44 R_{sun})

a-b = 18.59 ± 0.01 cm

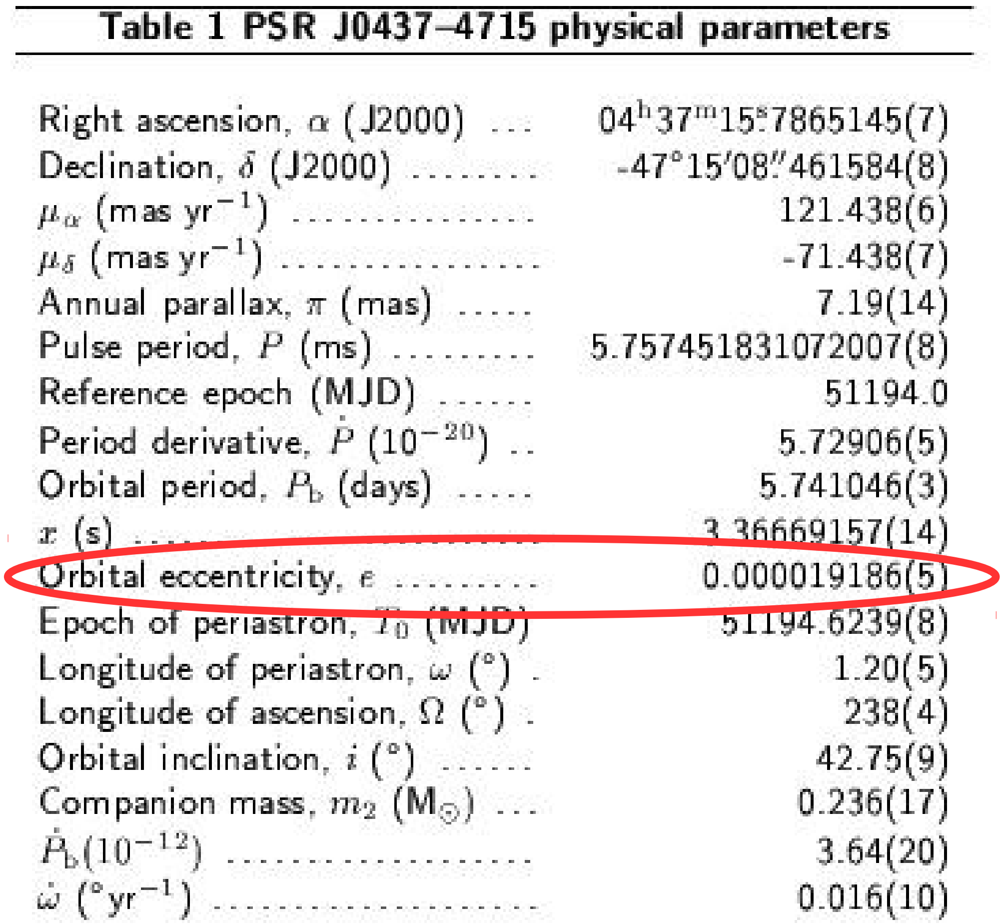


Table 1 PSR J0437–4715 physical parameters

Right ascension, α (J2000)	$04^{h}37^{m}15^{s}.7865145(7)$
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)

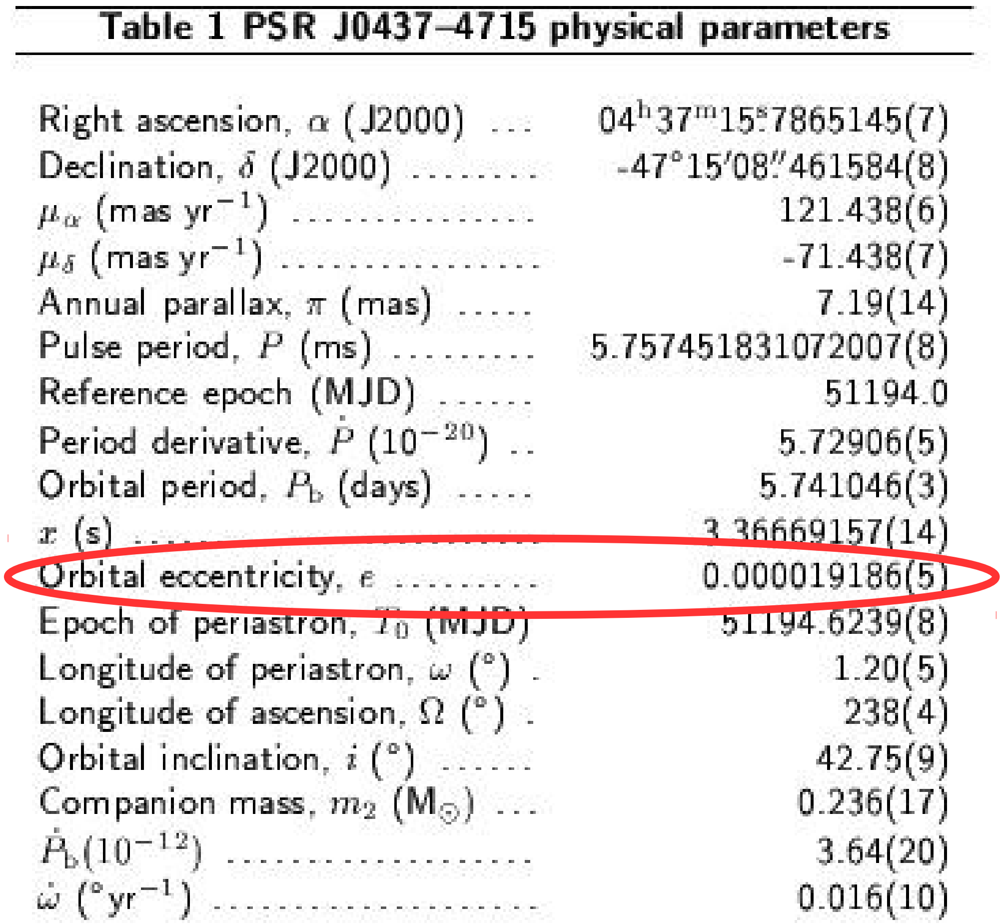
Power of Pulsar Timing

$a = 10^{11}$ cm (1.44 R_{sun})

$a - b = 18.59 \pm 0.01$ cm

Orbit at D = 139 pc

measured to 10^{-13}!!!



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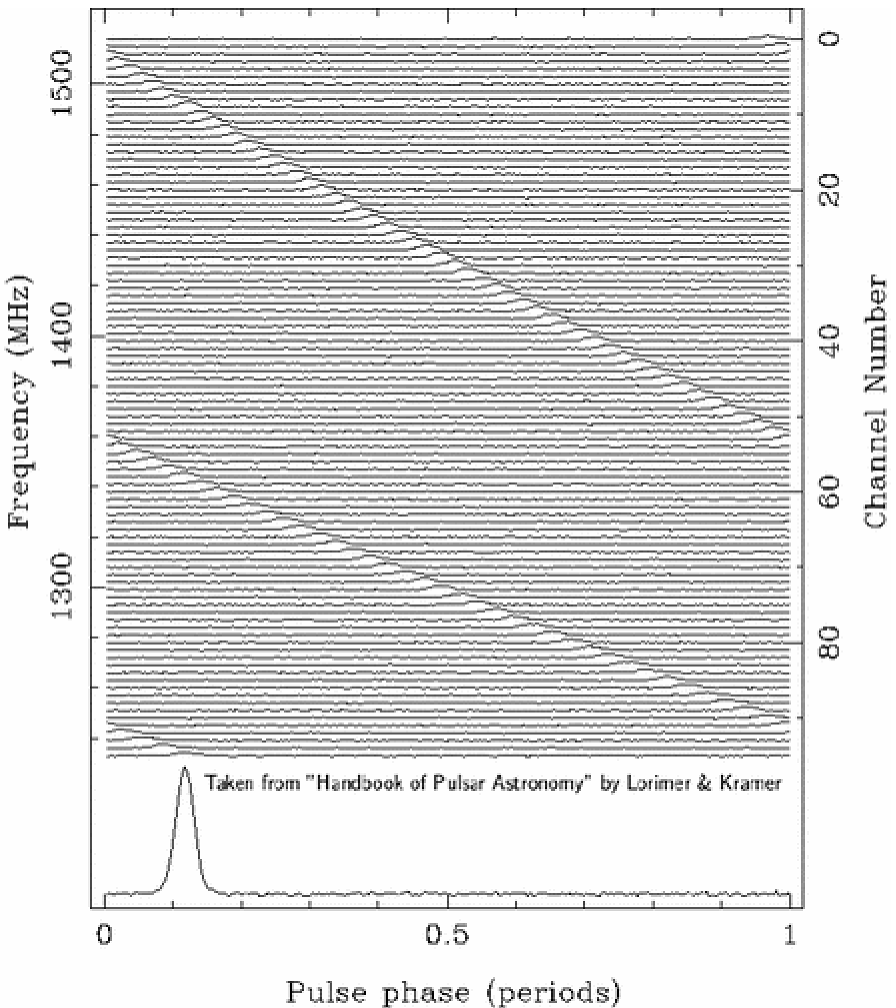
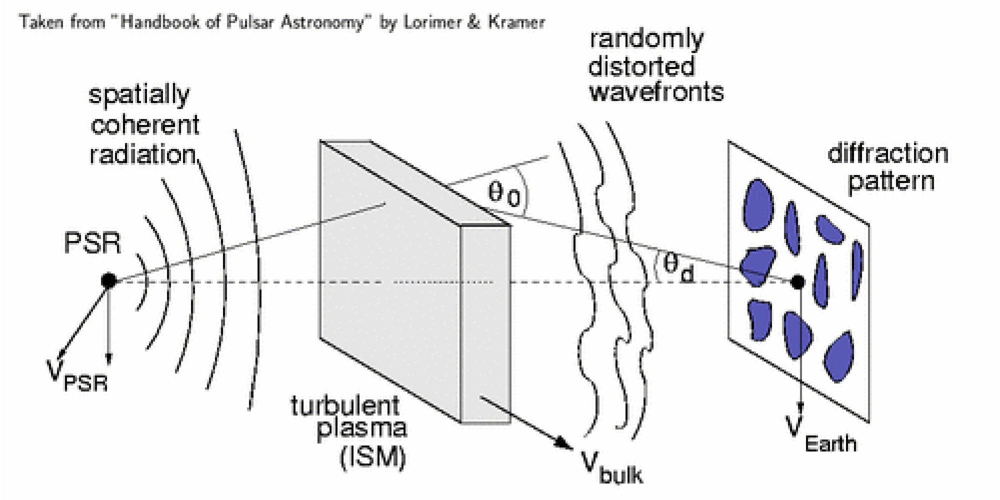
Effects of the Interstellar Medium

- Two frequency-dependent effects: dispersion and scattering



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



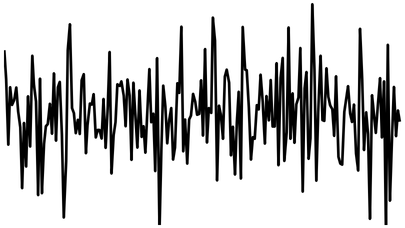
Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

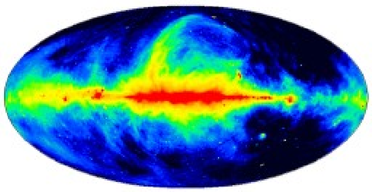
- Both smear out pulses and are worse at low frequencies
- **They are also timing varying!**

White noise residuals

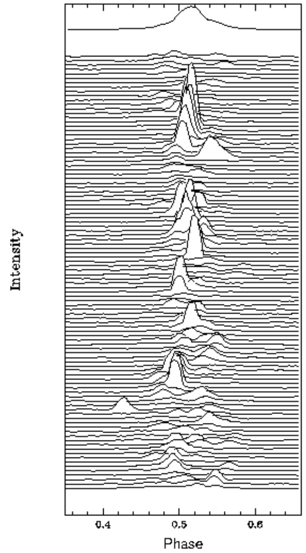
=

Radiometer noise

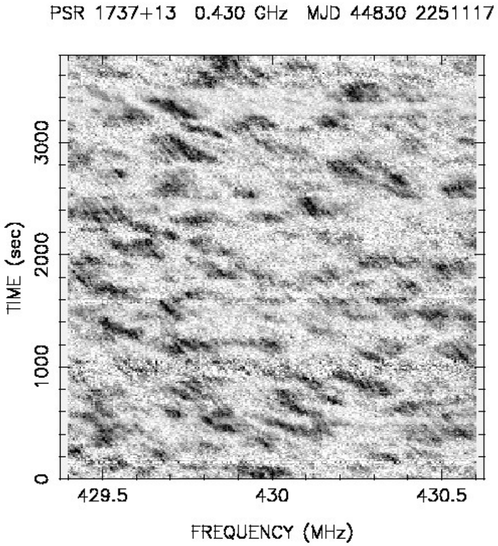




Pulse Jitter

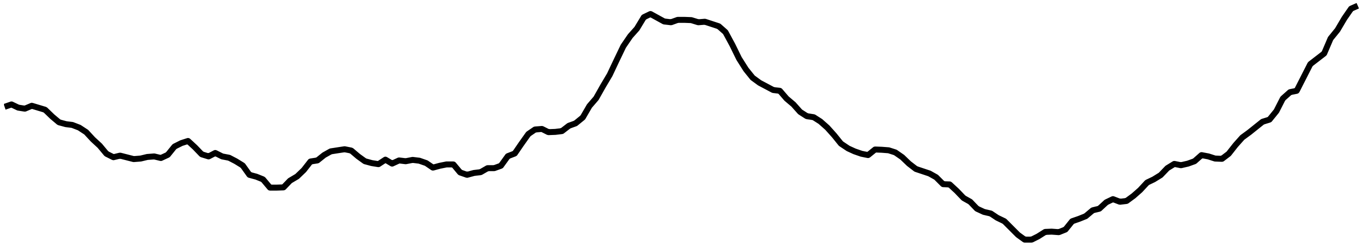


DISS



Slide courtesy of Tim Dolch

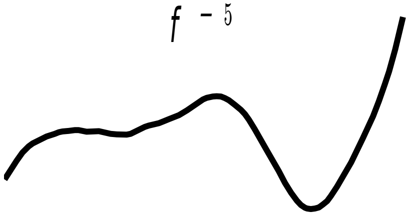
Red noise residuals



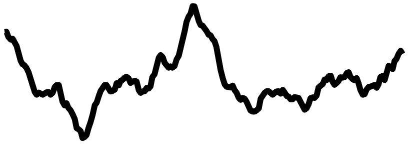
=

Spin noise + DM variations + GWs (stochastic)

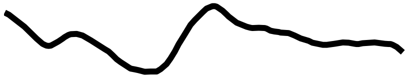
f^{-5}

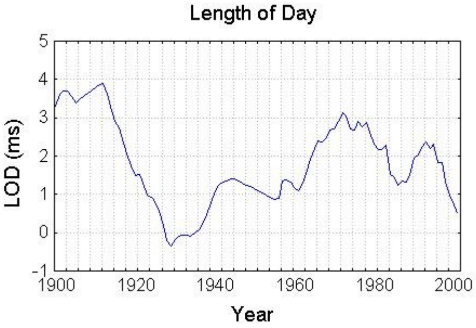


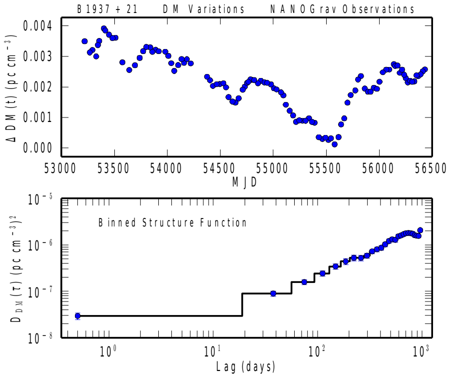
$f^{-8/3}$

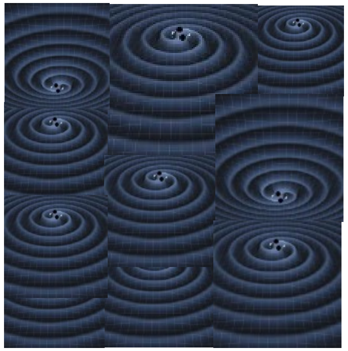


$f^{-13/3}$









Slide courtesy of Tim Dolch

Millisecond Pulsar Timing Arrays

- GWs will cause a quadirpolar angular correlation signature
- Requirements: 10-100s ns residuals, full sky coverage, lots of pulsars, precise ISM measurements

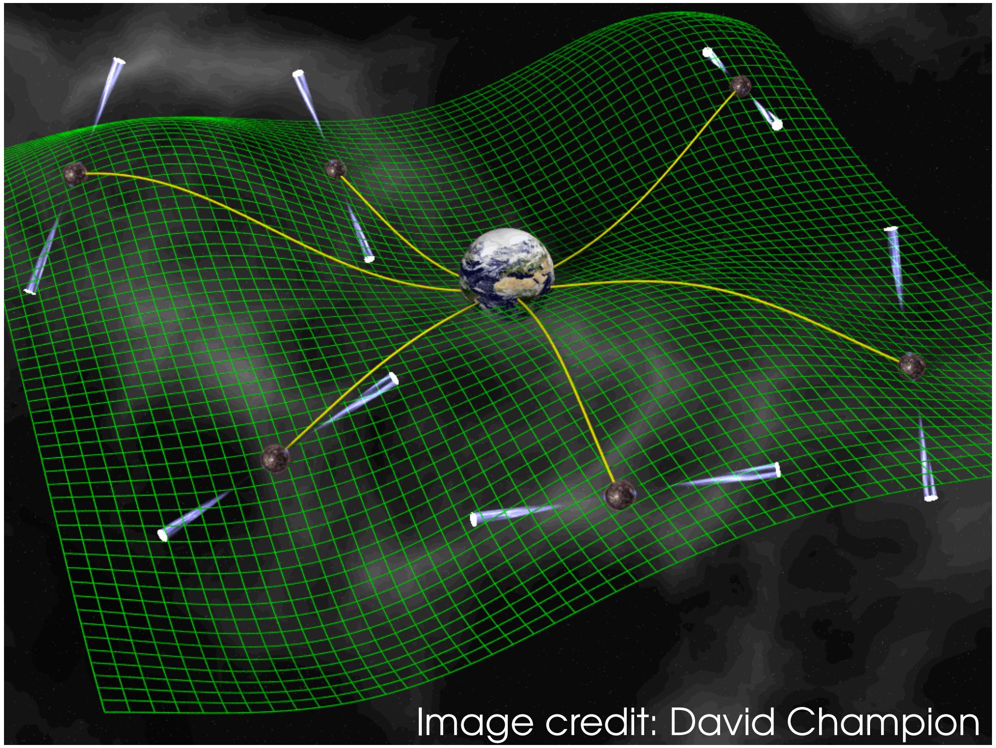


Image credit: David Champion

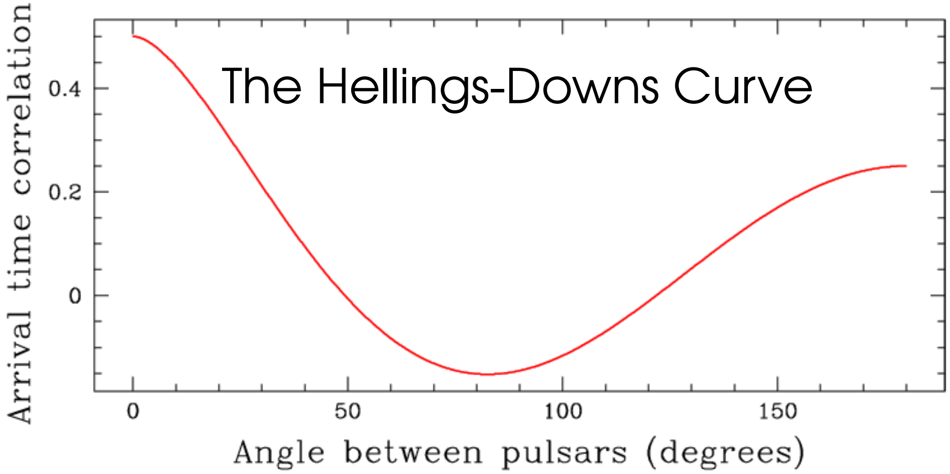
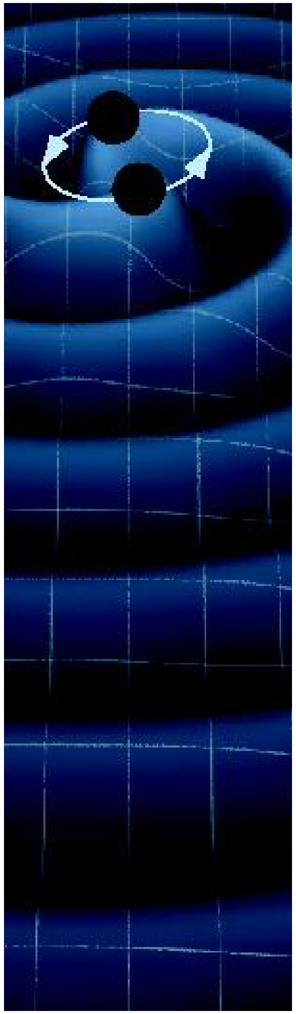


Image credit: NANOGrav

GW Sources

- Coalescing Super-Massive Black Holes
  - Basically all galaxies have them
  - Masses of 106 – 109 M⊙
  - Galaxy mergers lead to BH mergers
  - When BHs within 1pc, GWs are main energy loss
  - For total mass M/(1+z), distance dL, and SMBH orbital freq f, the induced timing residuals are:



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

Slide courtesy S. Ransom

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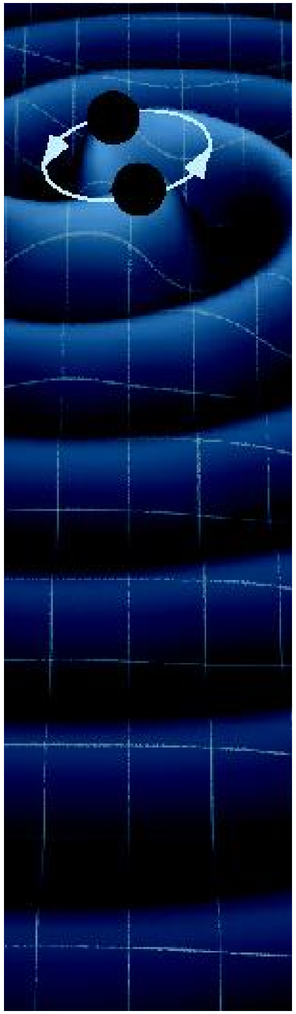

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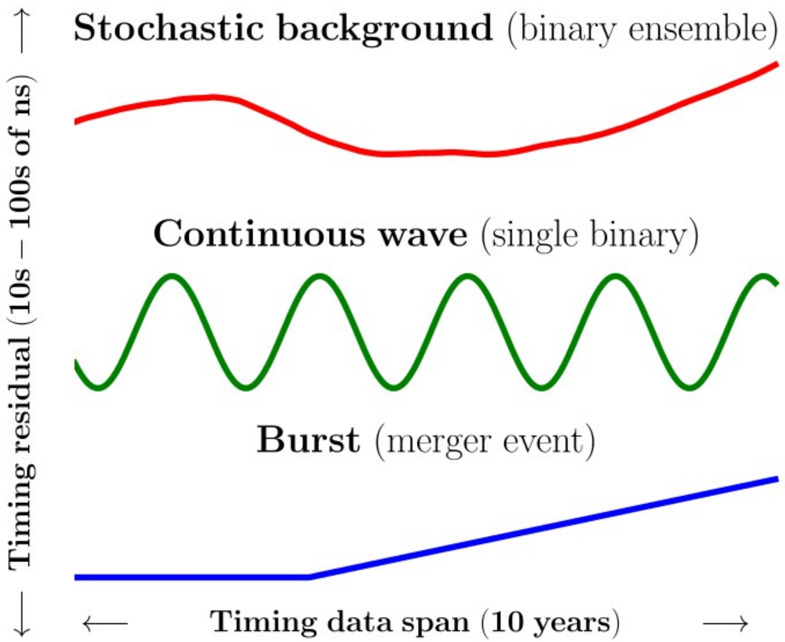
  - Cosmic strings (if they exist) also in this GW frequency range

Slide courtesy S. Ransom

Observational Signatures



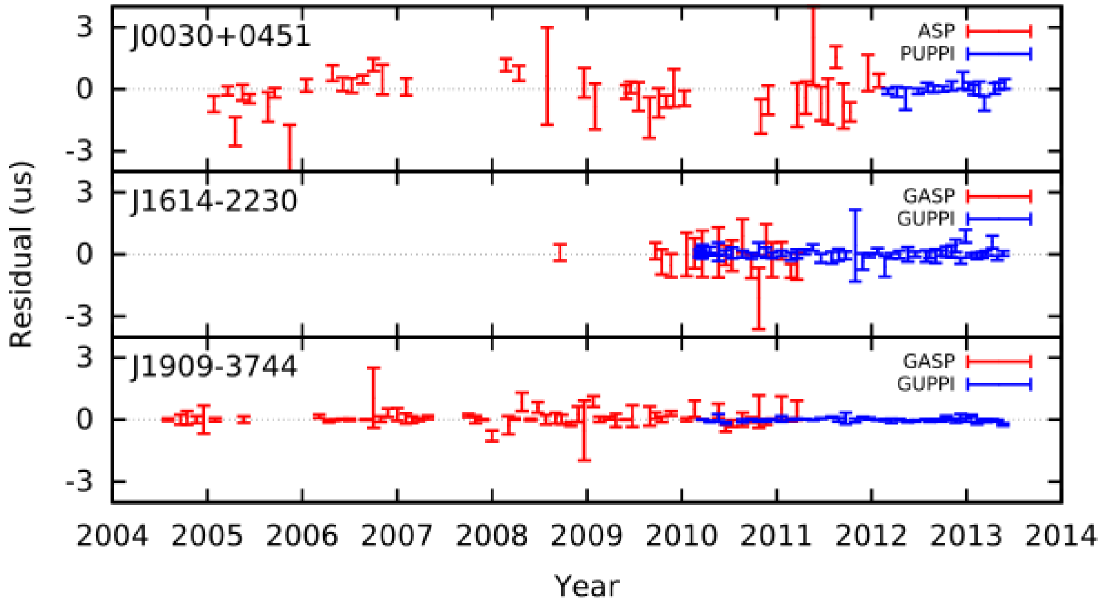
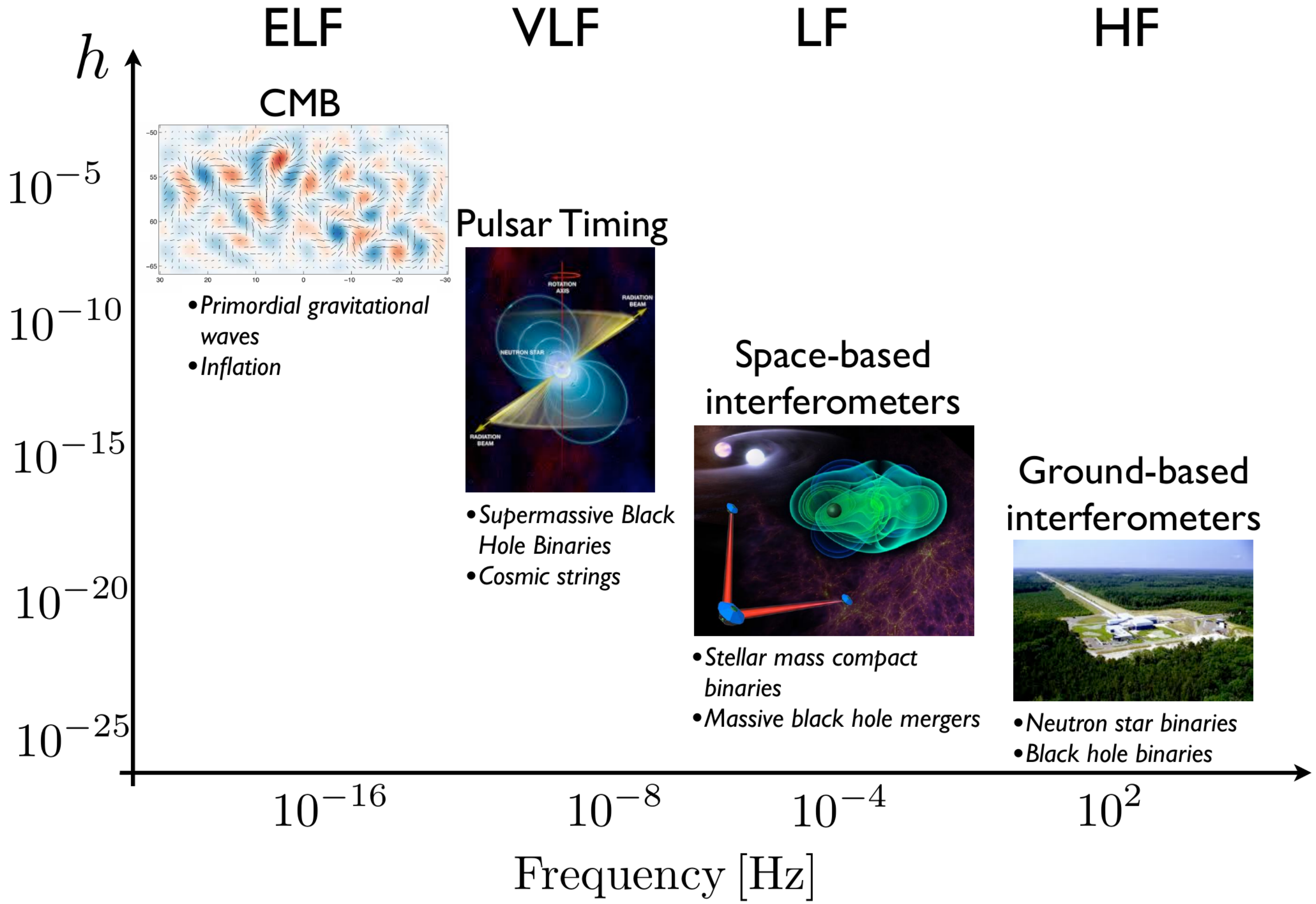


Image credits: NANOGrav

- Different source classes have different structure in residuals
- Sensitive to f_{GW} ~ nHz / $\lambda_{GW} \sim 10^{17}$ m

Complementary Gravitational Wave Detectors

The big picture of gravitational wave astronomy



ELF **VLF** **LF** **HF**

CMB

- *Primordial gravitational waves*
- *Inflation*

Pulsar Timing

- *Supermassive Black Hole Binaries*
- *Cosmic strings*

Space-based interferometers

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

Ground-based interferometers

- *Neutron star binaries*
- *Black hole binaries*

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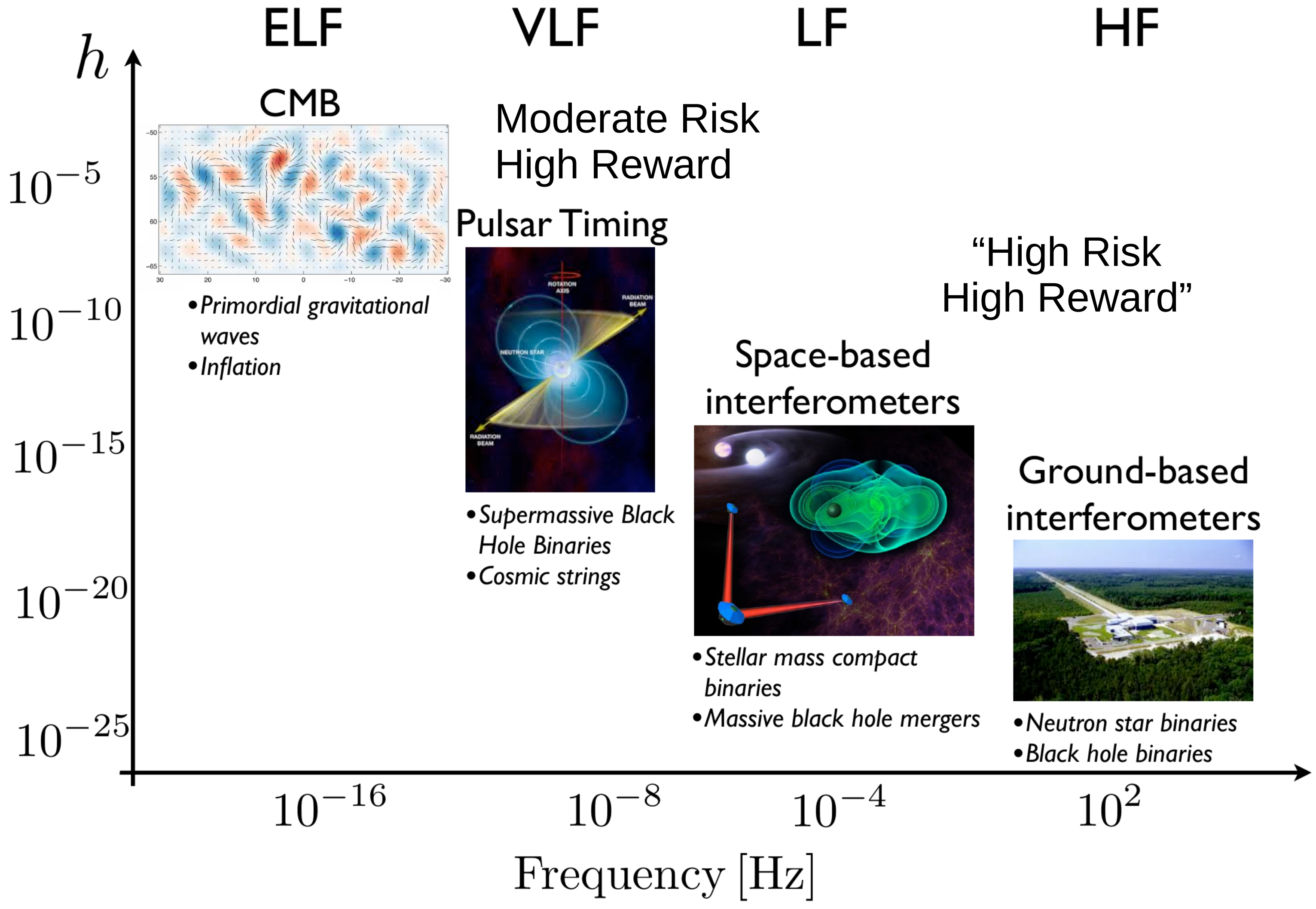

CMB

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Moderate Risk
High Reward

Pulsar Timing

- *Supermassive Black Hole Binaries*
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“High Risk
High Reward”

Space-based interferometers

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Physics Frontiers Center

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- Currently time 45 pulsars at GBT and Arecibo
  - 500 (GBT) + 800 (AO) = 1300 hrs/year
  - Does not include pulsar searches!
  - **Each contributes 50% of overall GW sensitivity**

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- International collaboration through IPTA

NANOGrav Data Releases

5 Year (2013)

- ASP + GASP
- 16 MSPs, 1,095 observations, ~16K TOAs

ASP/GASP
PUPPI/GUPPI

○ ● 327 MHz
○ ● 430 MHz
○ ● 800 MHz
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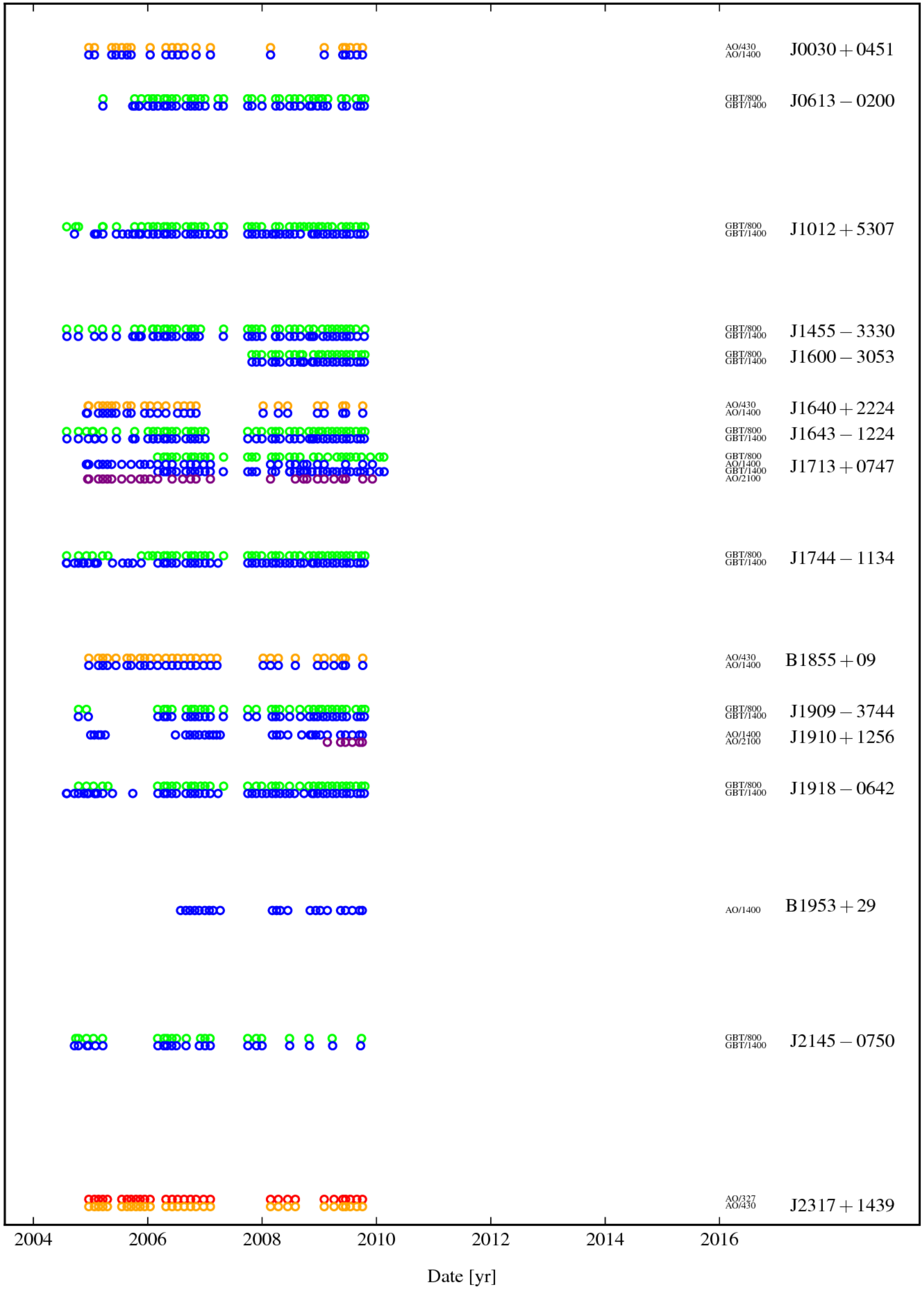
○ ● 2100 MHz



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9 Year (2015)

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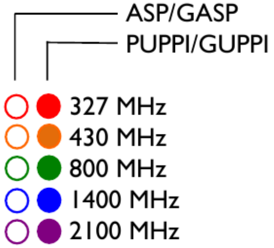

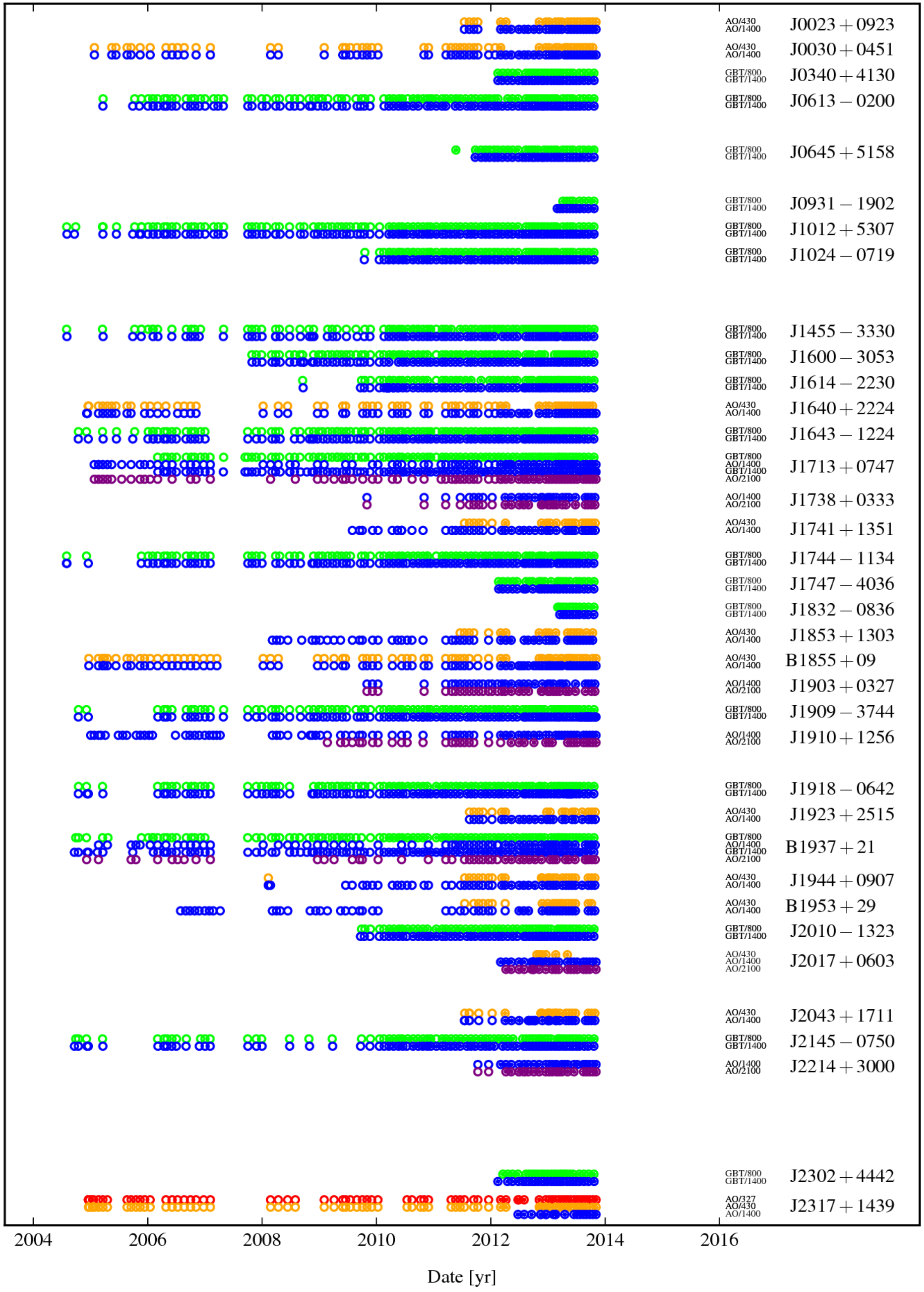

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11 Year (2017)

- 45 MSPs, 6,737 observations, ~310K TOAs

ASP/GASP
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○ ● 327 MHz
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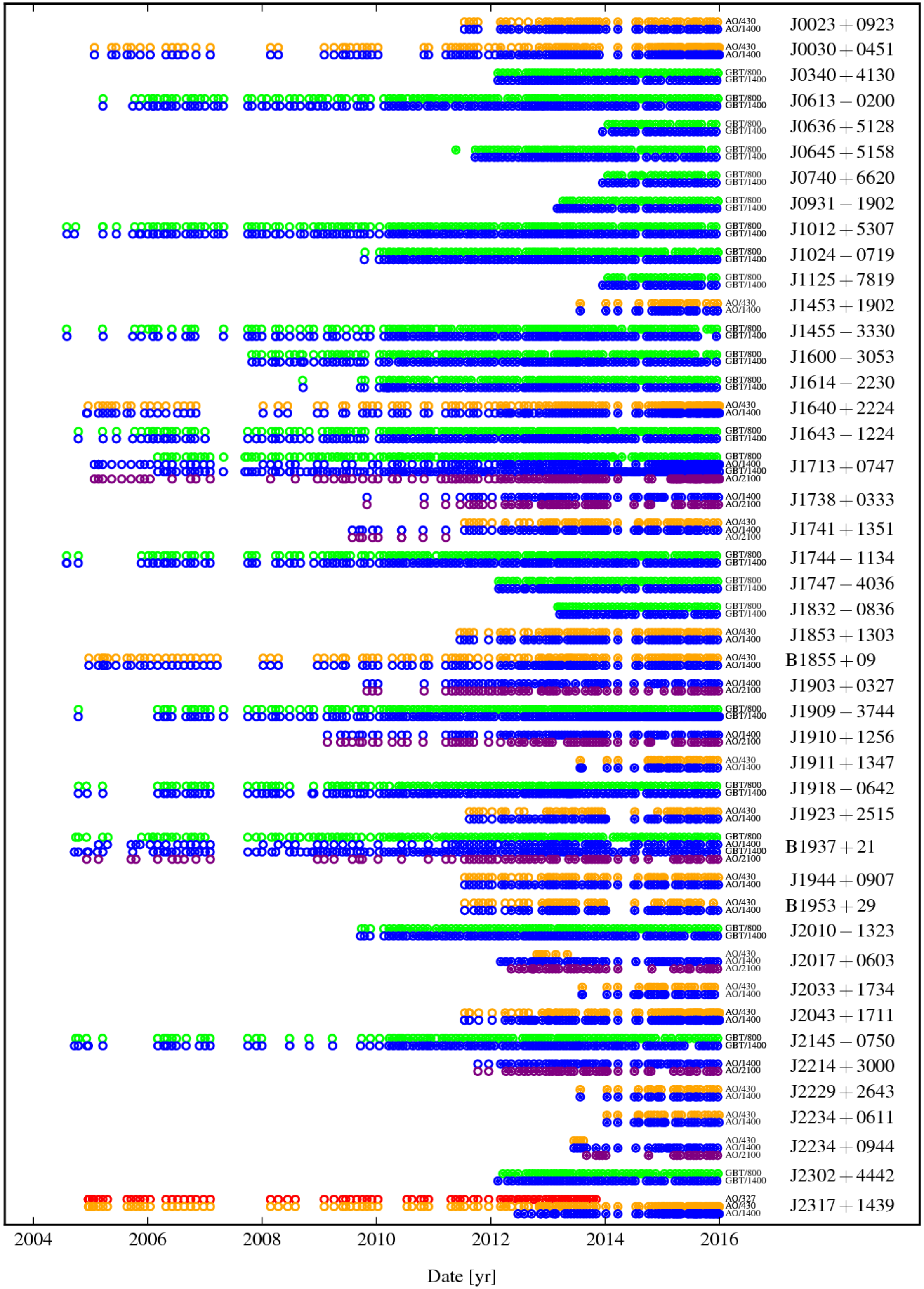
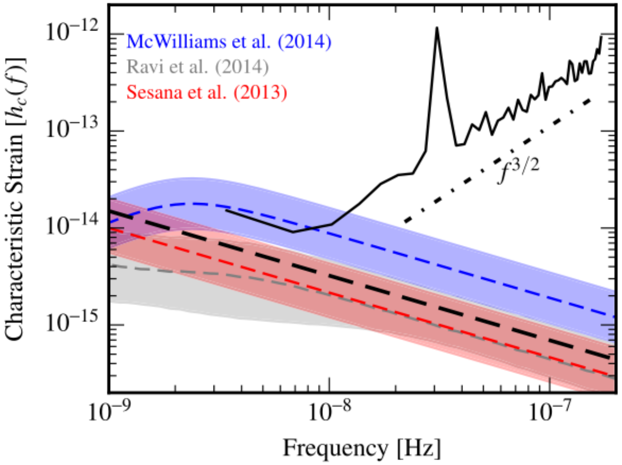
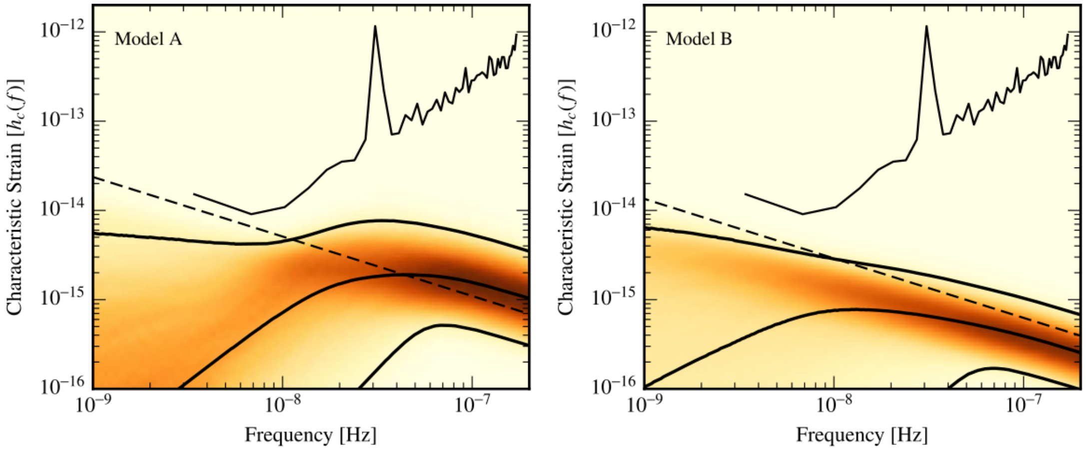
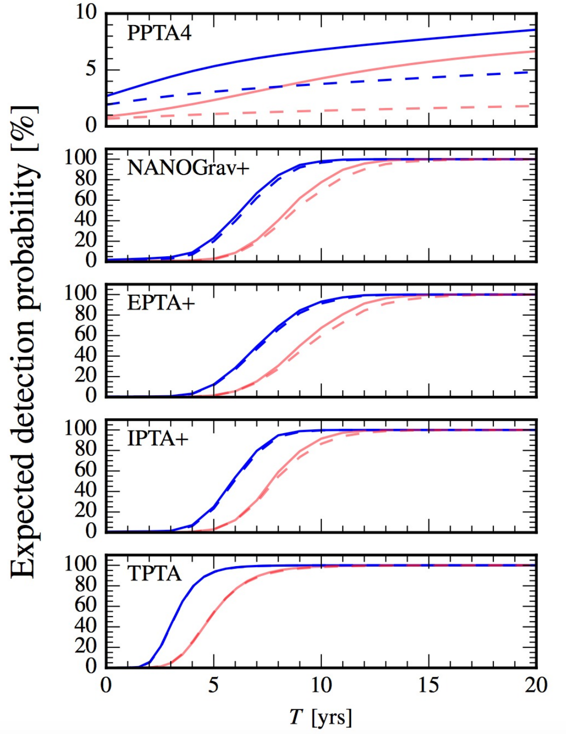


“Current” Results





Arzoumanian et al. (2016)



- Ruling out/tightly constraining early models of BH merger rate
- Constraints on shape of GW spectrum contains information about BH environments

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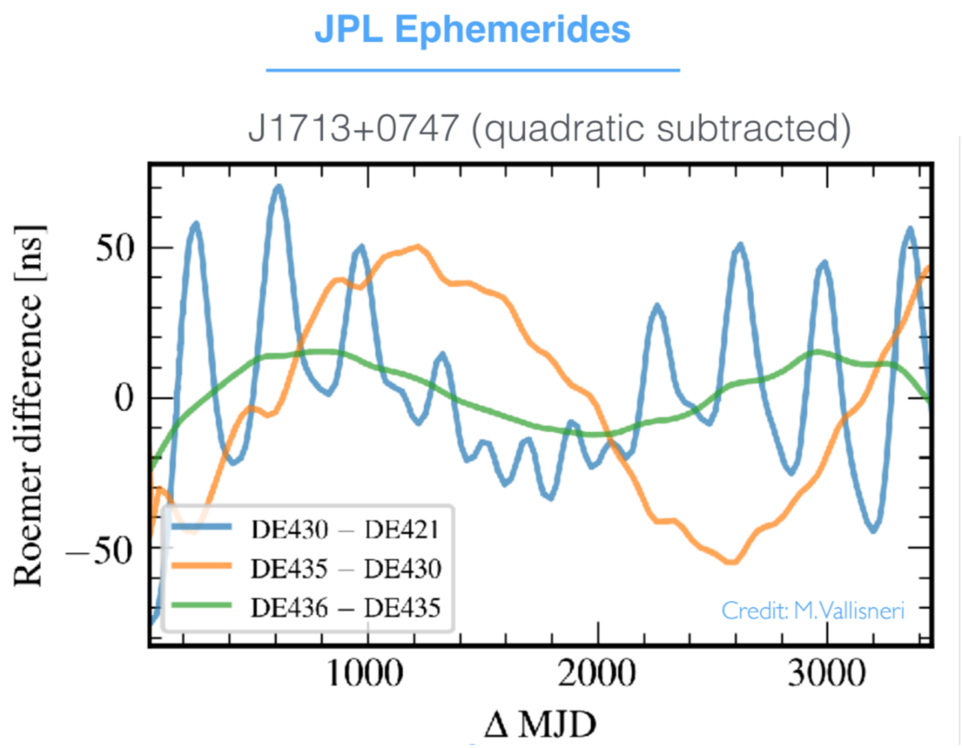
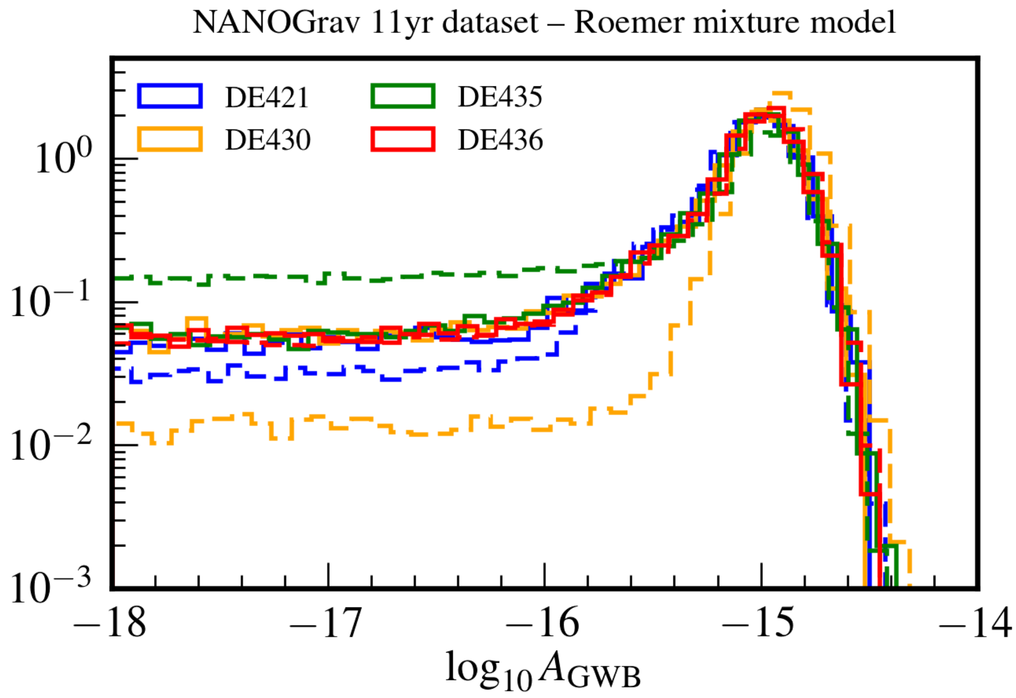
Physics Frontiers Center

11yr Results Soon...

PRELIMINARY!

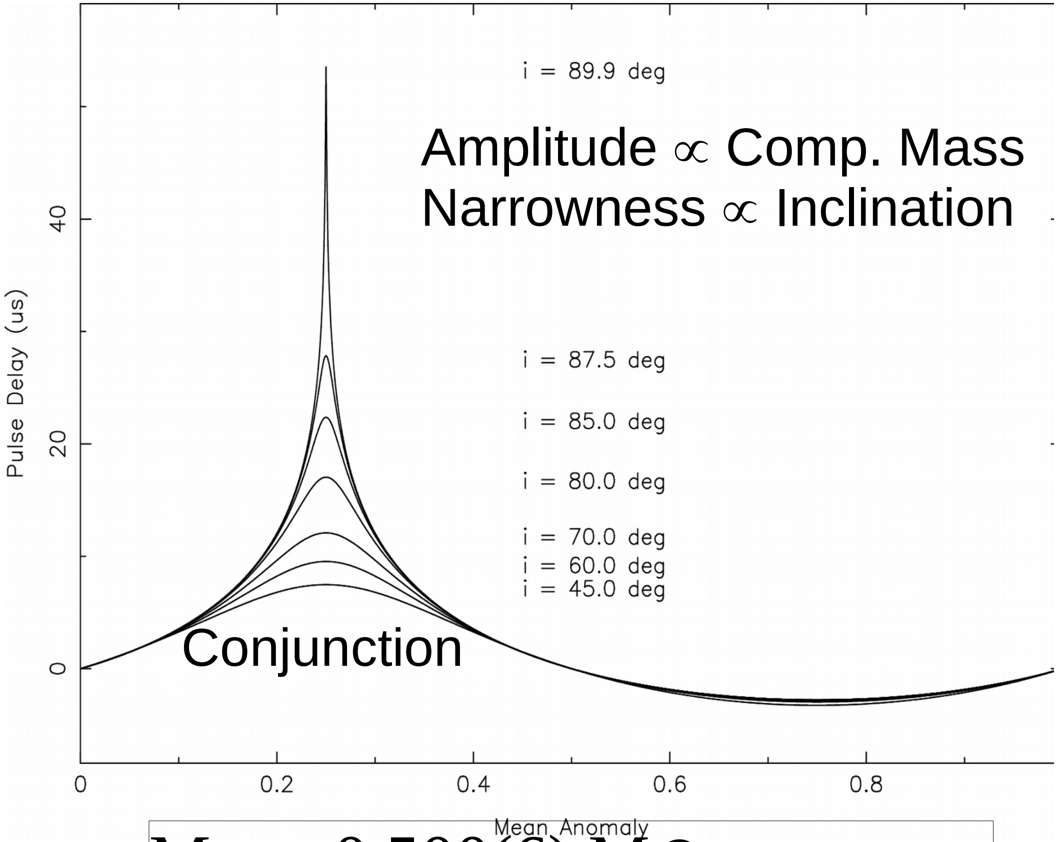
- **11yr stochastic BG limit is ~same as 9yr!**
- Some evidence for correlated GW-like red noise? Or problems with planetary ephemerides? (Or both?)
- Need to know Solar System Barycenter to <100m





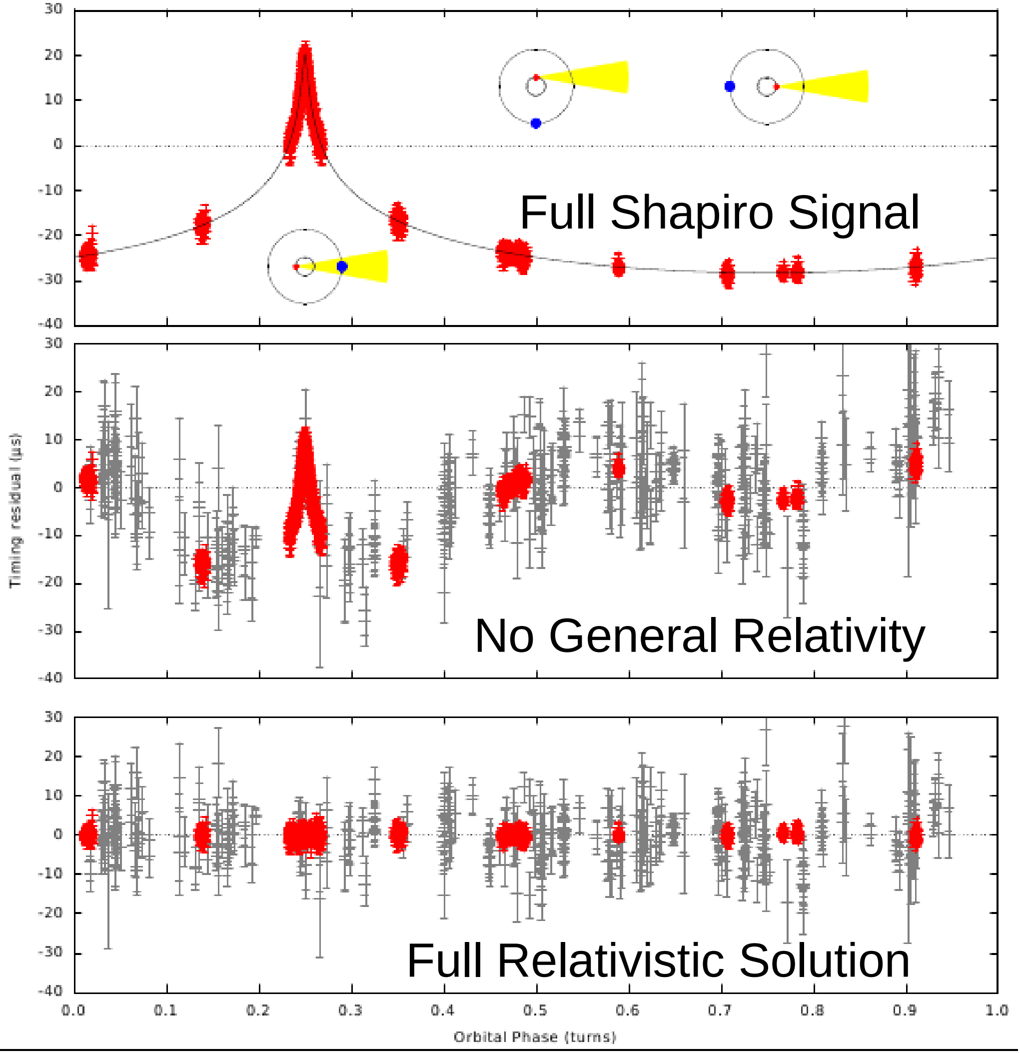
Slide courtesy S. Ransom

Subatomic Physics



Amplitude ∝ Comp. Mass
Narrowness ∝ Inclination

Conjunction



Full Shapiro Signal

No General Relativity

Full Relativistic Solution

$M_{wd} = 0.500(6)\ M_\odot$

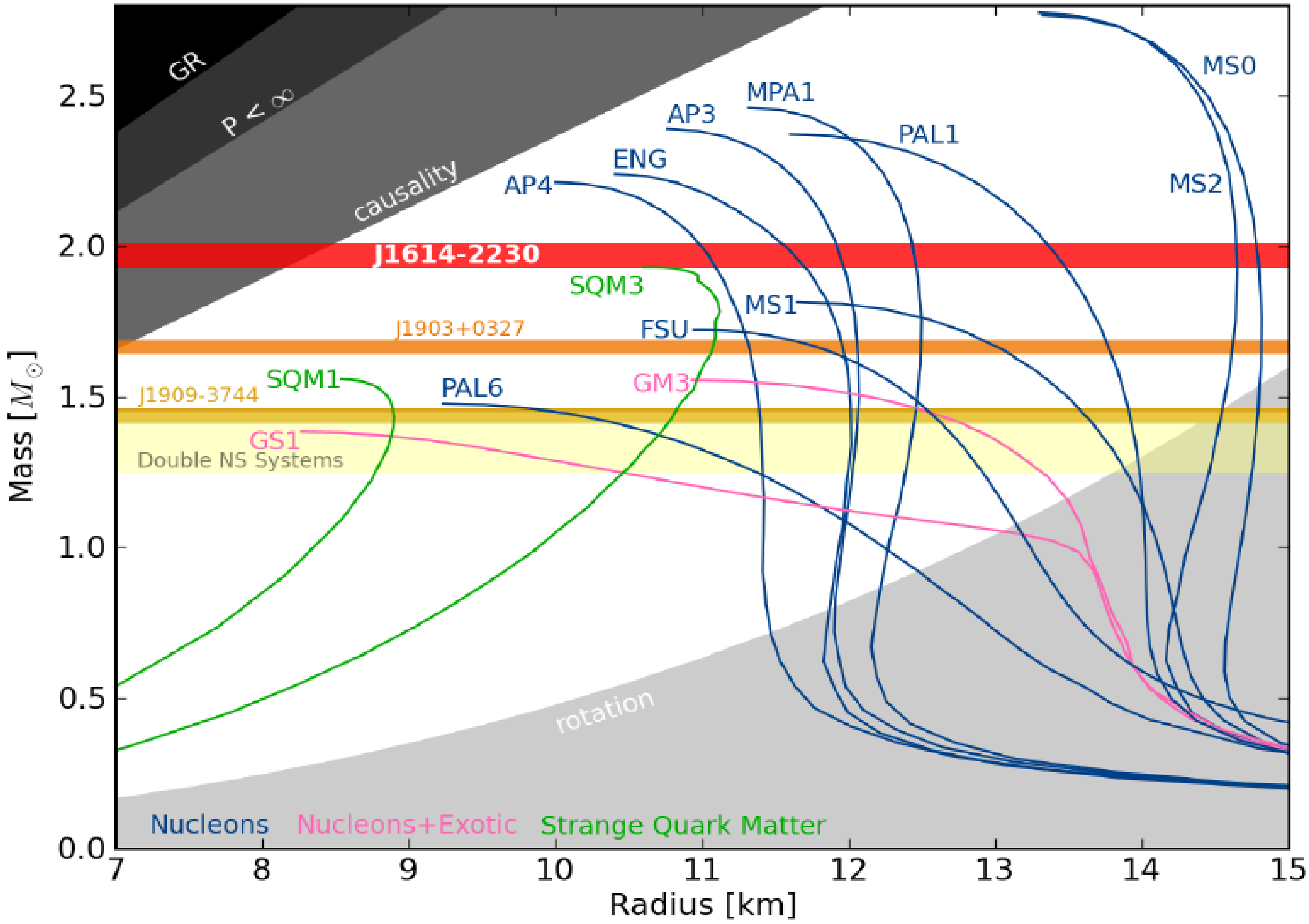
$M_{psr} = 1.97(4)\ M_\odot$!

Inclination = 89.17(2) deg!

Demorest et al. 2010, Nature, 467, 1081D
Most highly cited GBT paper (1,550+)

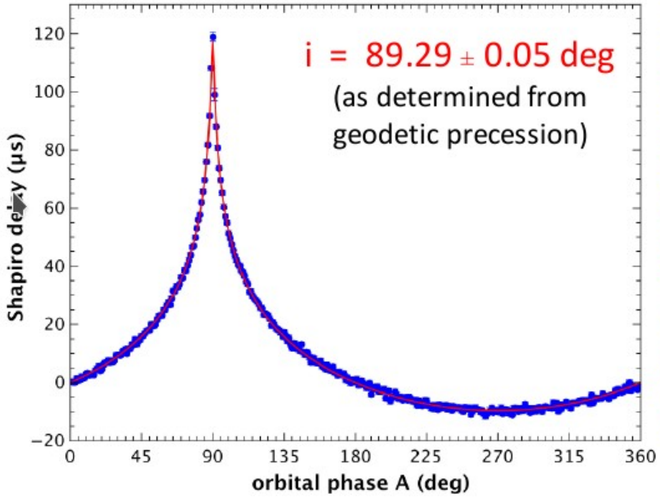
Subatomic Physics

Rules out most or all EOSs
with exotic material in the cores



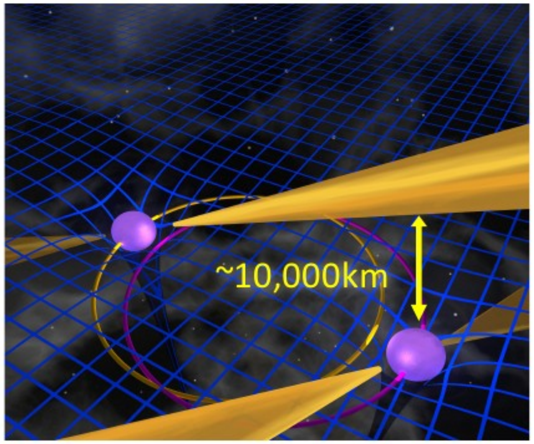
Strong Field GR Tests

- Double Pulsar is the premier system for studying strong-field GR
  - Light from one pulsars passes within 10,000 km of the other
- Seeing 2nd order post-Newtonian effects



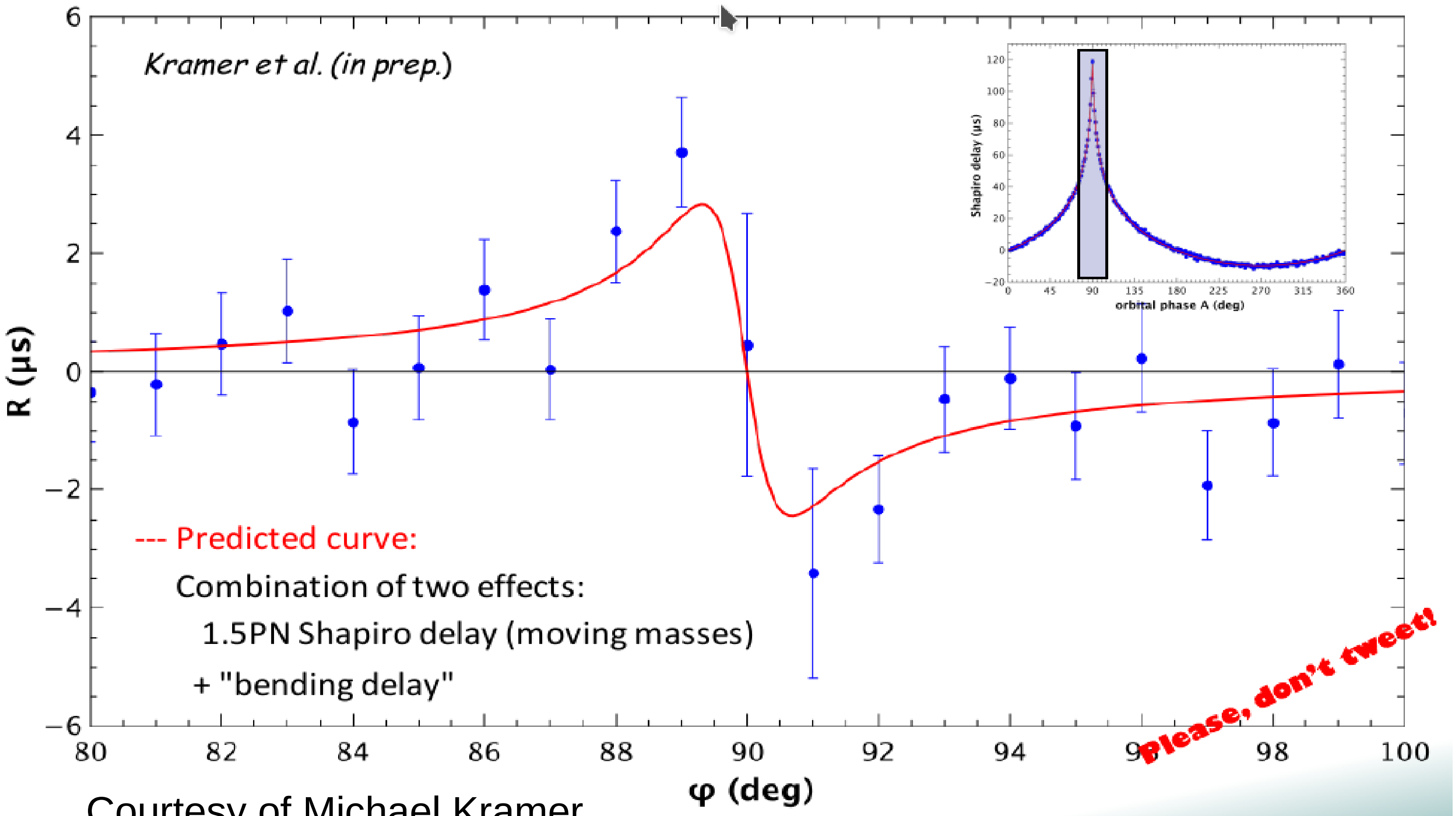
i = 89.29 ± 0.05 deg

(as determined from geodetic precession)



Courtesy of Michael Kramer

- Shapiro delay must take into account moving masses and deviation from point-source masses



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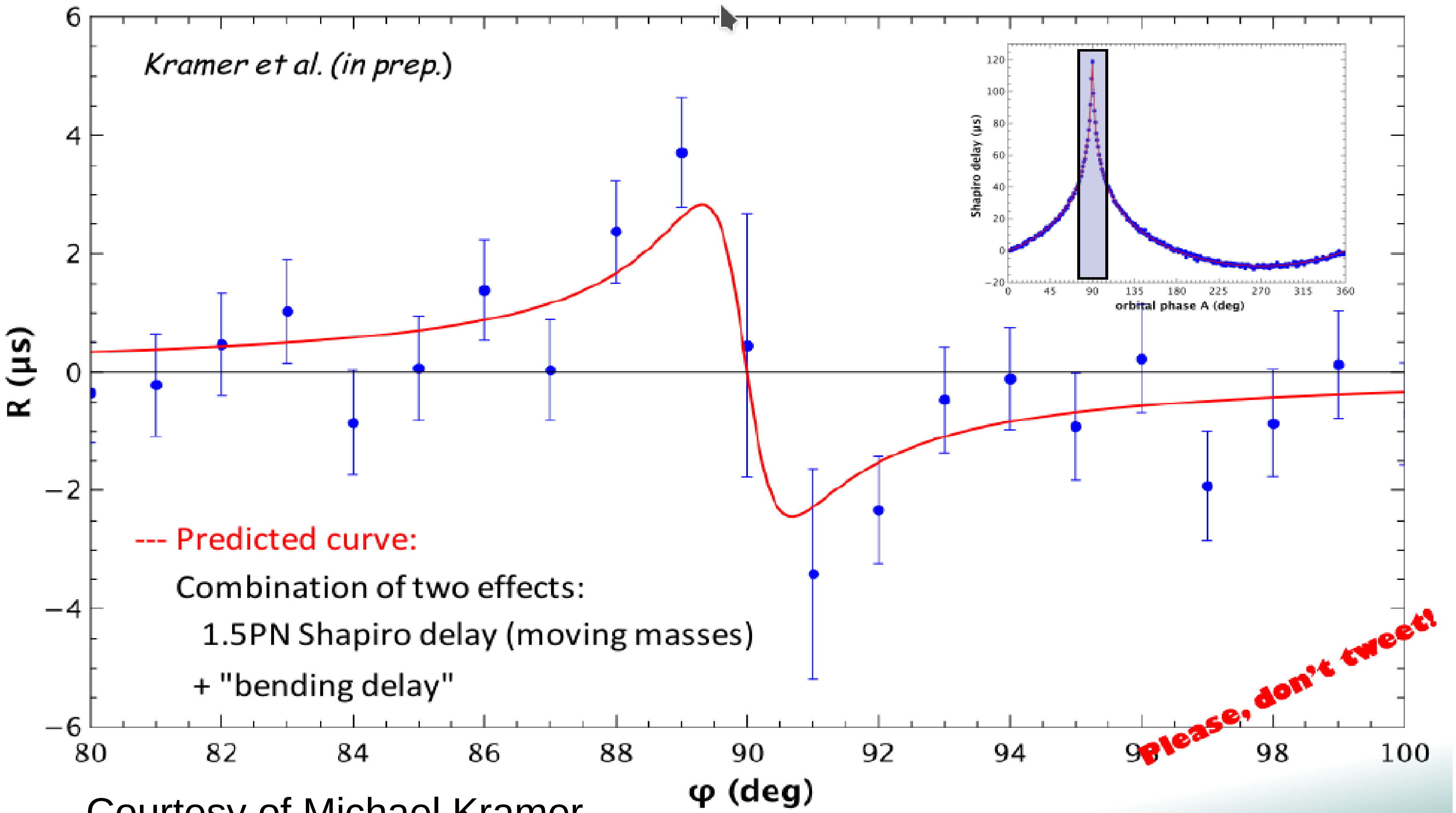
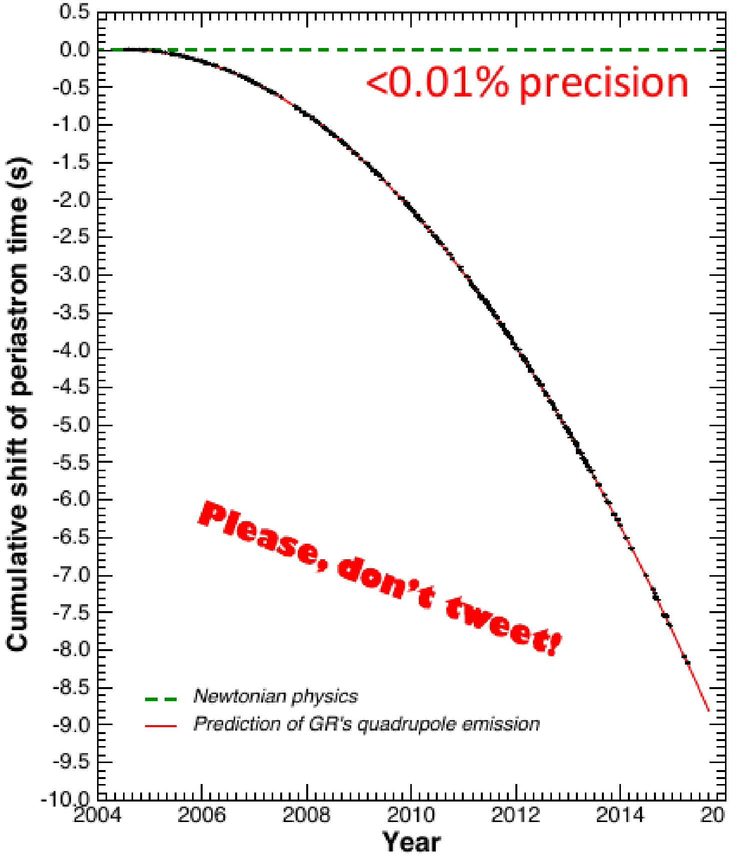


Courtesy of Michael Kramer

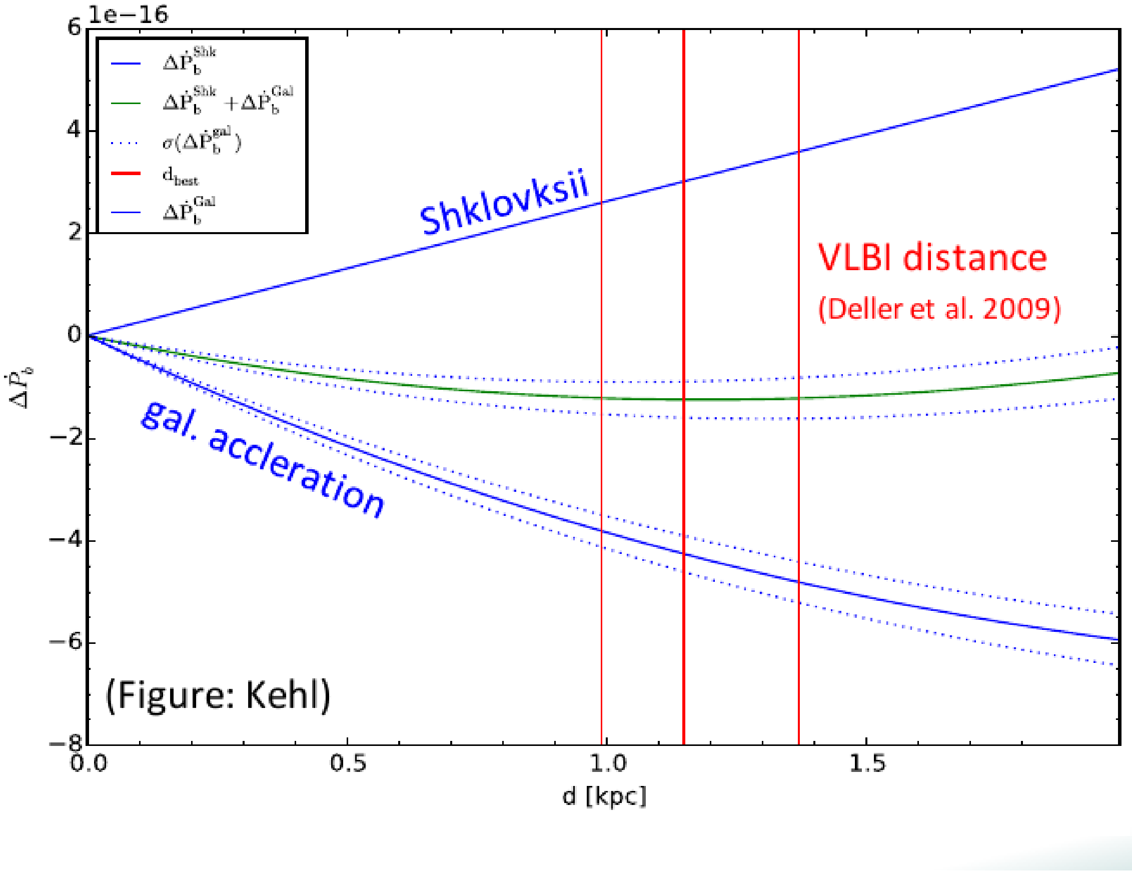
- Can measure spin **direction** of pulsar A (prograde – consistent w/ low-kick supernova)

Shrinkage of orbit due to GW emission: $dP_b/dt = -1.2479(1) \times 10^{-12}$ s/s



<0.01% precision

Please, don't tweet!



VLBI distance

(Deller et al. 2009)

(Figure: Kehl)

- Now limited by uncertainty in kinematic contributions to dP_B/dt
- Close to timing-based parallax measurement

Courtesy of Michael Kramer

Quasi-stationary strong field tests

Precession of periastron (17 deg/yr)

$$\dot{\omega} = 3\frac{G^{2/3}}{c^2}\left(\frac{2\pi}{P_\mathrm{b}}\right)^{5/3}\frac{1}{1-e^2}(m_\mathrm{A}+m_\mathrm{B})^{2/3}$$

Time dilation / Einstein delay (380 μs)

$$\gamma = \frac{G^{2/3}}{c^2}\left(\frac{P_\mathrm{b}}{2\pi}\right)^{1/3} e\,\frac{m_\mathrm{B}(m_\mathrm{A}+2m_\mathrm{B})}{(m_\mathrm{A}+m_\mathrm{B})^{4/3}}$$

Shapiro delay (130 μs)

$$r = \frac{G}{c^3}m_B \qquad s = \frac{c}{G^{1/3}}\left(\frac{2\pi}{P_\mathrm{b}}\right)^{2/3} x_\mathrm{A}\frac{(m_\mathrm{A}+m_\mathrm{B})^{2/3}}{m_\mathrm{B}}$$

Geodetic precession of B (5 deg/yr)

$$\Omega_\mathrm{B} = \frac{G^{2/3}}{c^2}\left(\frac{2\pi}{P_\mathrm{b}}\right)^{5/3}\frac{1}{1-e^2}\frac{m_\mathrm{A}(4m_\mathrm{B}+3m_\mathrm{A})}{2(m_\mathrm{A}+m_\mathrm{B})^{4/3}}$$

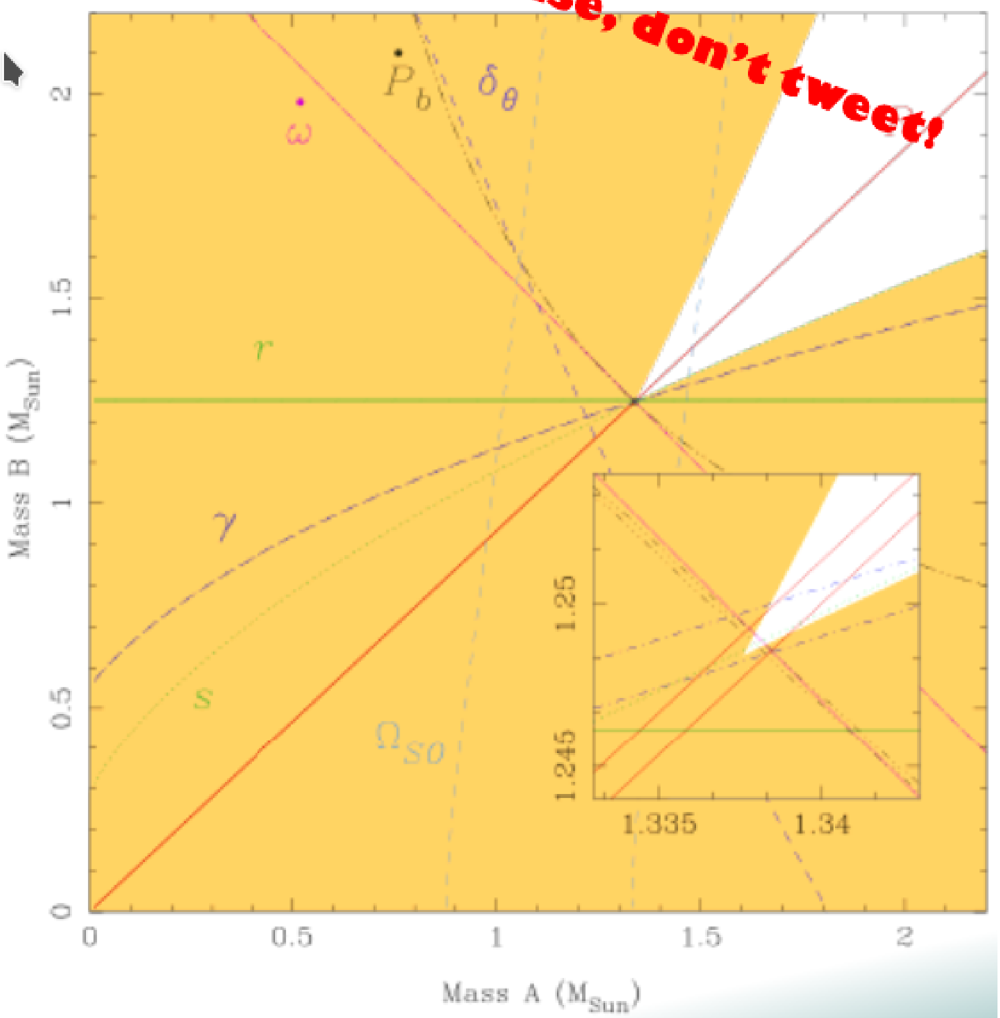
Radiative tests (gravitational wave damping)

Orbital period decay (-39 μs/yr)

$$\dot{P}_\mathrm{b} = -\frac{192\pi}{5}\frac{G^{5/3}}{c^5}\left(\frac{2\pi}{P_\mathrm{b}}\right)^{5/3}\frac{1+\frac{73}{24}e^2+\frac{37}{96}e^4}{(1-e^2)^{7/2}}\frac{m_\mathrm{A}m_\mathrm{B}}{(m_\mathrm{A}+m_\mathrm{B})^{1/3}}$$

Mass ratio (1.07)

$$R = x_\mathrm{B}/x_\mathrm{A} = m_\mathrm{A}/m_\mathrm{B} + \mathcal{O}(v^4/c^4)$$



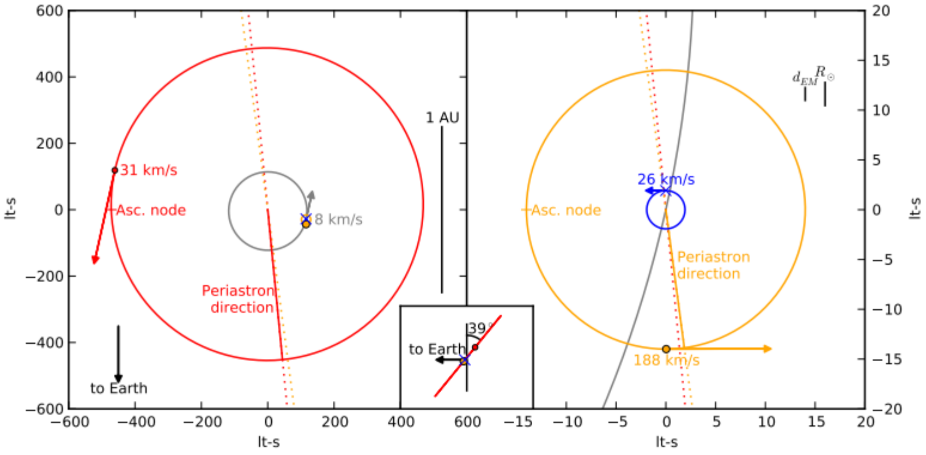
Please, don't tweet!

7 - 2 = 5 tests of GR plus 1 emerging one

Courtesy of Michael Kramer

Testing the Strong Equivalence Principle

- PSR J0337+1717: First MSP in a stellar triple system
  - Discovered in GBT survey
- Three body dynamical effects cause secular changes in orbital parameters
  - Allow us to precisely solve for the **geometry and masses** of all stars and orbits



- All bodies fall at the same rate (?)
- MSP & inner WD falling in gravity of outer WD

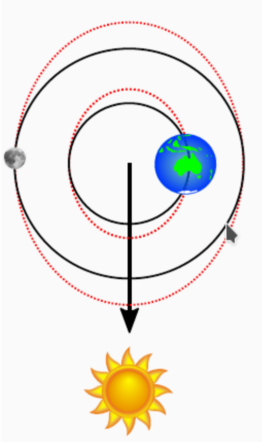
Image credit: Ransom et al. (2014, Nature, 505, 520)

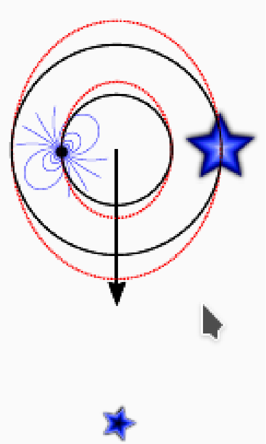
Testing the Strong Equivalence Principle

- Violations parameterized by differential acceleration

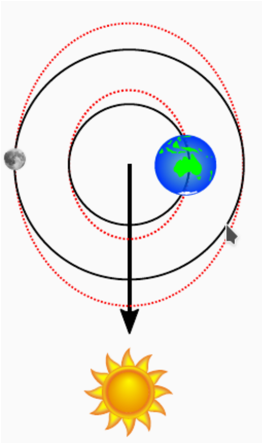
  Currently dominated by systematics

    Sensitive to Solar wind DM variations





Testing the Strong Equivalence Principle



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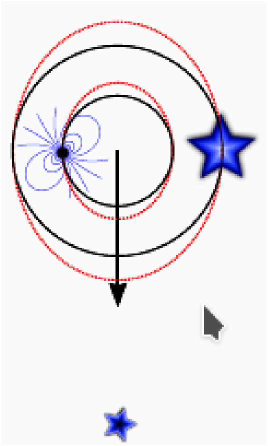

- Current best limit on differential acceleration $\Delta = 10^{-6}$
  - 100x improvement over Lunar ranging tests

Look for Archibald et al. (early 2018)

Testing TeVeS Gravity Theories

- J0348+0432: Relativistic MSP/WD binary
  - Discovered by GBT
- Pulsar + WD spectroscopy → double-line binary
- Get masses + system geometry

Testing TeVeS Gravity Theories

- J0348+0432: Relativistic MSP/WD binary
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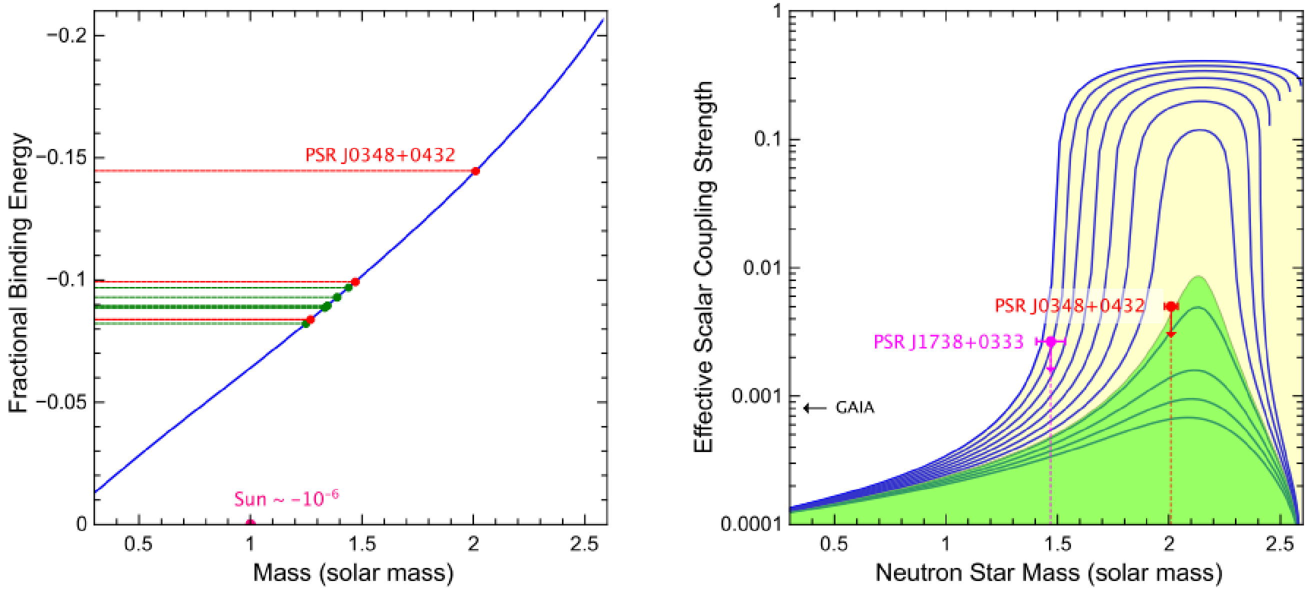
- Get masses + system geometry
- Pulsar is 2 M_{sun} – most massive known (by a hair)
  - Does not significantly improve on EOS constraints
- But…

Antoniadis et al. (2013, Science, 340, 448)

Testing TeVeS Gravity Theories

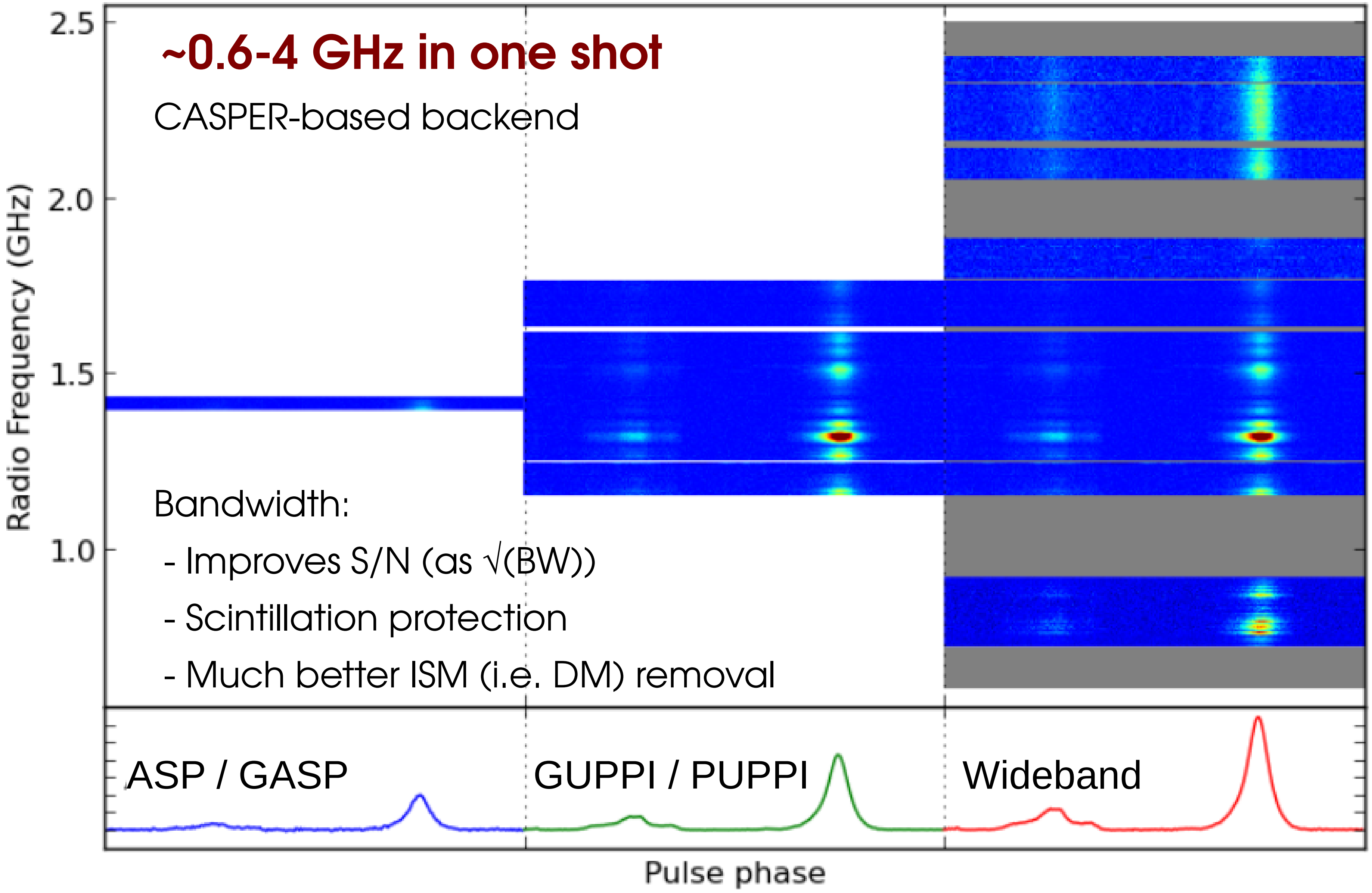
- Relativistic orbit and mass asymmetry provide unique test of tensor-vector-scalar gravity theories
    - Differeing “compactness” would produce dipolar GWs



Antoniadis et al. (2014, Science, 340, 448)

- Significant parameter space for scalar coupling constants ruled out thanks to high binding energy and relativistic orbit

Where Are We Going?



~0.6-4 GHz in one shot

CASPER-based backend

Bandwidth:

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

Fig: Paul Demorest

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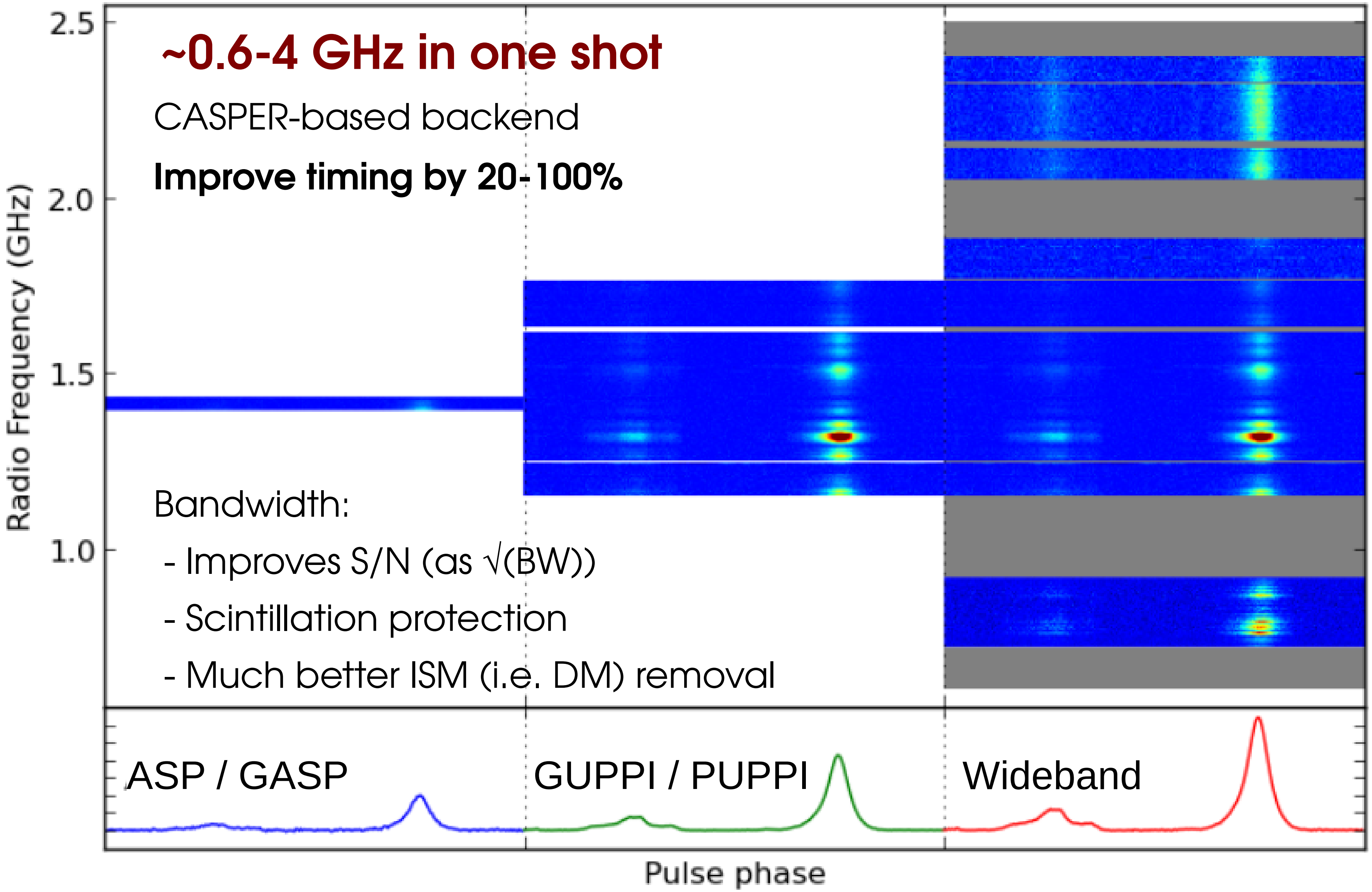

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Improve timing by 20-100%

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Fig: Paul Demorest

Where Are We Going?

- Daily observations of all NANOGrav MSPs w/ **CHIME**
  - All pulsars with ~ few weeks cadence
- Large FOV
- No moving parts – digital telescope
- Relatively inexpensive way to get collecting area

Where Are We Going?

- Stochastic GW background detected by 2022
  - Assumes steady growth in current observing program
- Not just a number!
  - Spectral shape encodes information about supermassive BH environments
  - Find the solution to the last parsec problem

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  - Bursts with memory provide deep test of GR
- Constrain (detect?) cosmic strings
- Eventually measure anisotropies in GW background

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- 3 M_{sun} neutron stars? Sub-millisecond pulsars?
  - Solve the NS EOS?
- Pulsar – BH binary? ("Holy Grail" for gravity tests), Pulsars around Sgr A*
  - Test no-hair theorem
  - Maybe, finally, find breakdown of GR?

Summary

- NANOGrav is on track to detect GWs in the next 5 years
  - Opening the full GW spectrum
- We are on the cusp of a new wave of pulsar discoveries
  - There will undoubtedly be unique and powerful physical laboratories among them
- The GBT (and Arecibo) are the best instruments in the world for precision pulsar timing
  - Wideband systems could make them even better
  - Can leverage new telescopes to maximize scientific return