NANOGrav
Physics Frontiers Center

Fundamental Physics Over 27 Orders of Magnitude With Pulsars

Ryan Lynch
Green Bank Observatory

Image Credit: ESO

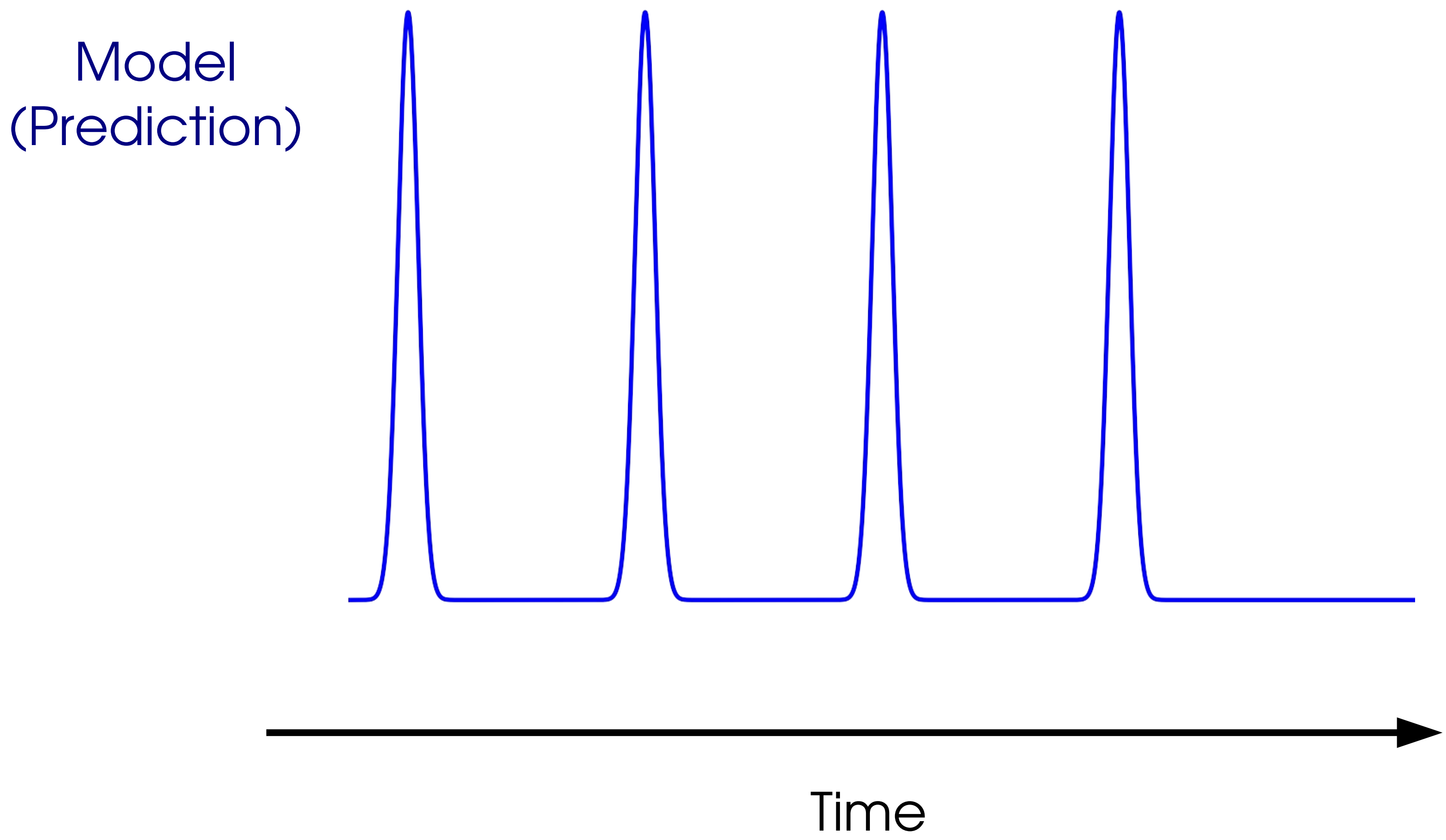
Pulsars are clocks...

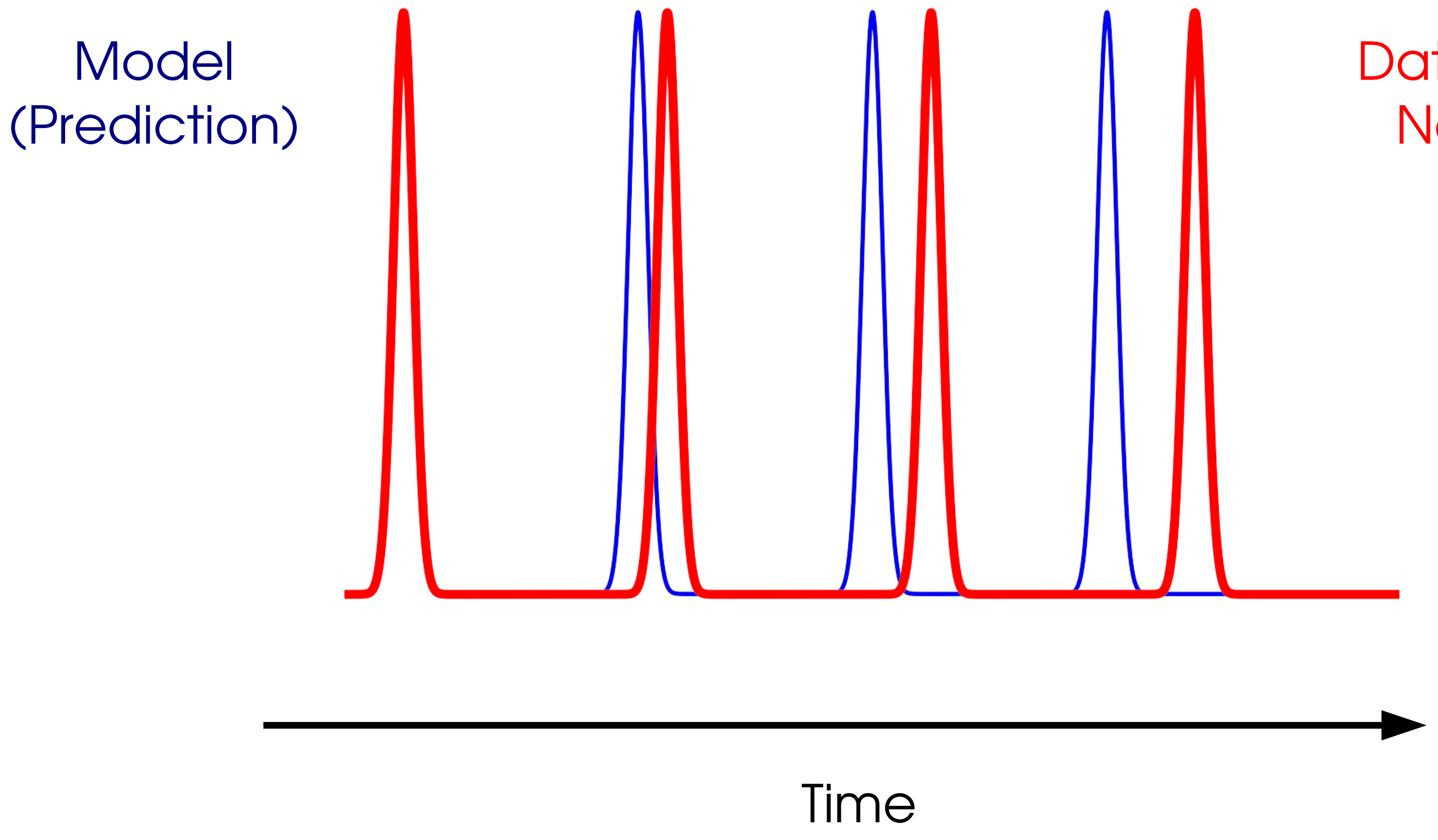
...that create some of the most extreme environments in the Universe...

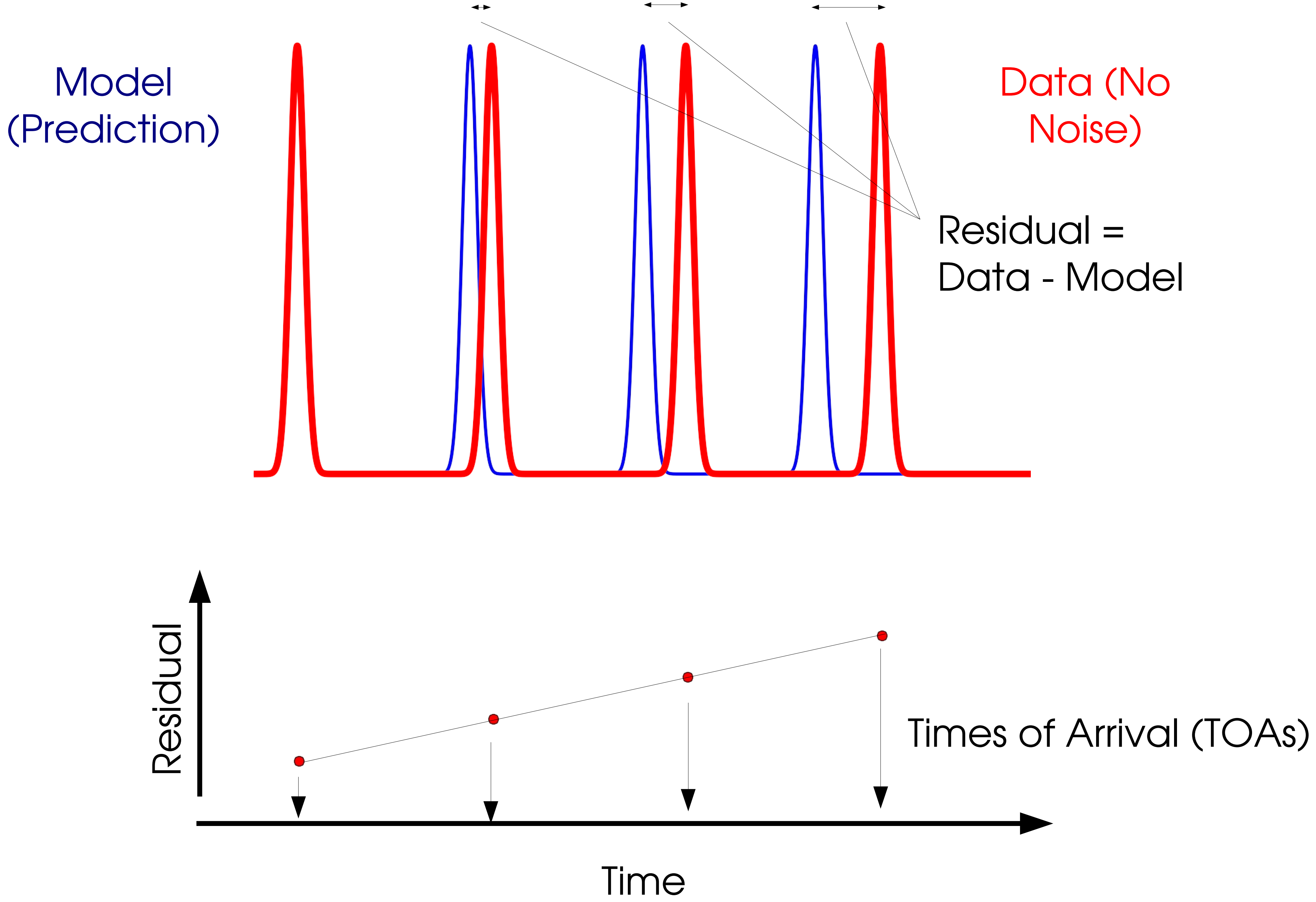
...which makes them natural laboratories for studying fundamental physics

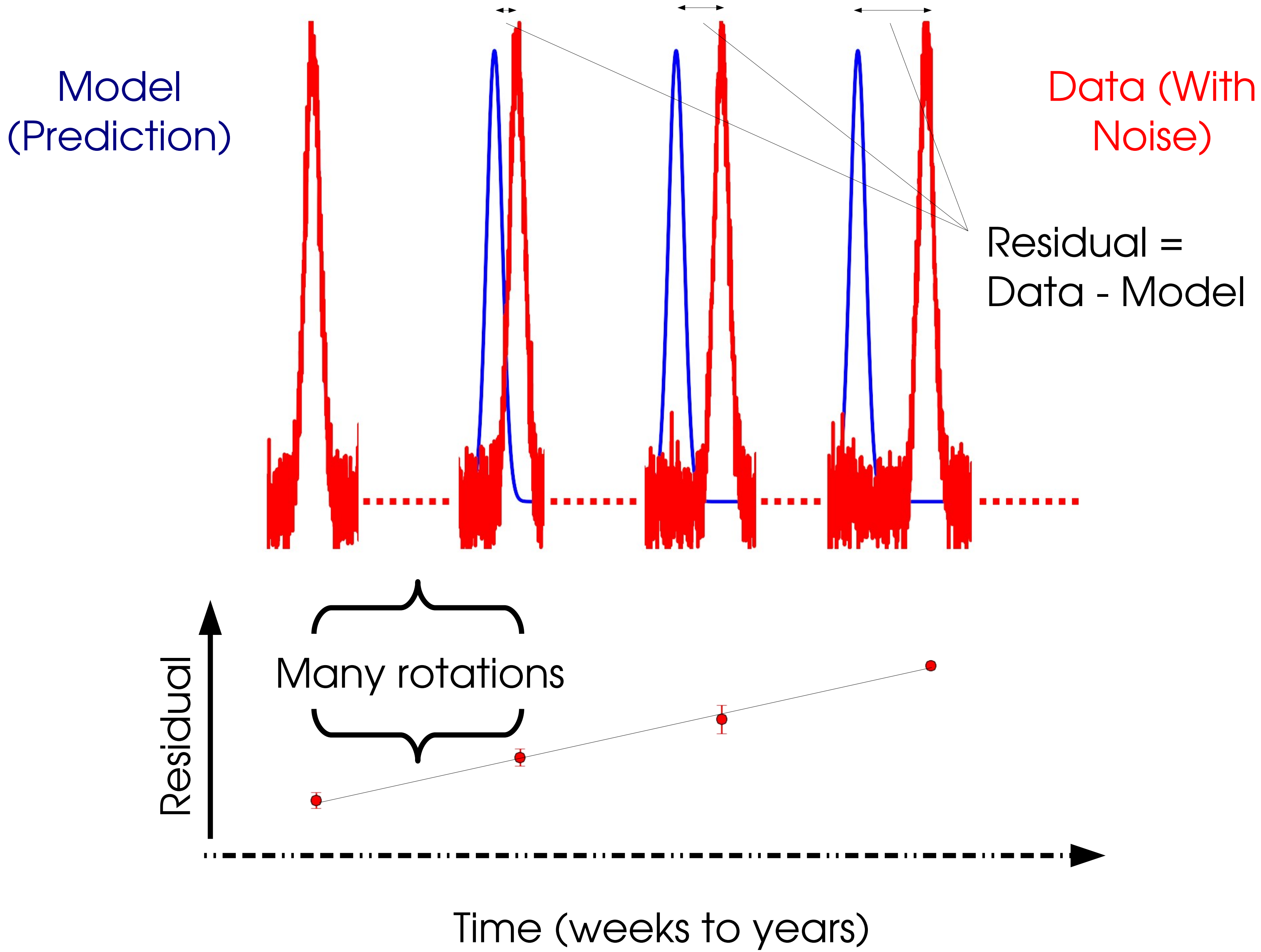
Pulsar Timing

- 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, $N_{rot}\sim10^9$
- At 2017-10-17 09:10 EDT the frequency of PSR J0437-4715 is/was

173.701580684374 ±

0.000000000003 Hz

Power of Pulsar Timing

a = 10^{11} cm (1.44 R_{sun})
a-b = 18.59 ± 0.01 cm

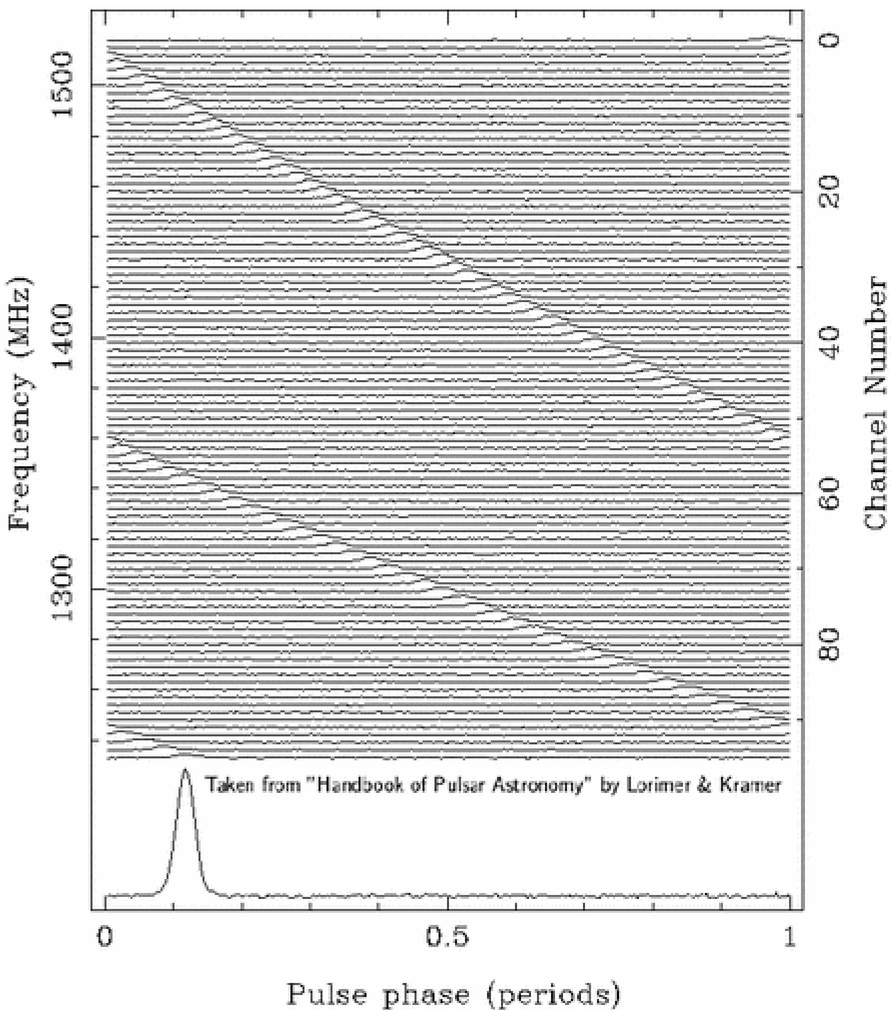
Orbit at D = 139 pc
measured to 10^{-13}!!!

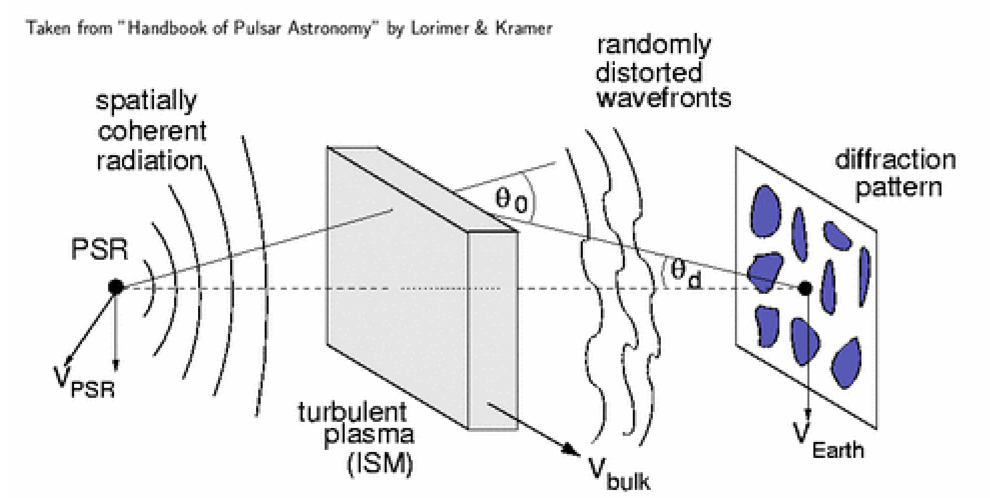
Table 1 PSR J0437–4715 physical parameters

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)

Effects of the Interstellar Medium

- Two frequency-dependent effects: dispersion and scattering



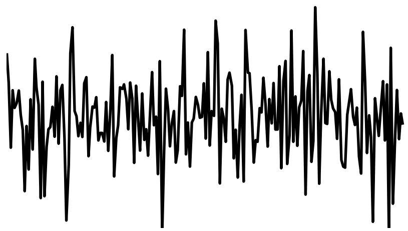


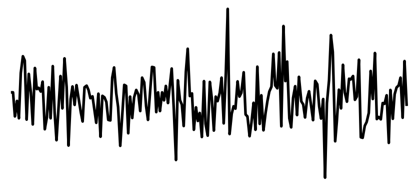
- Both smear out pulses and are worse at low frequencies
- **They are also timing varying!**

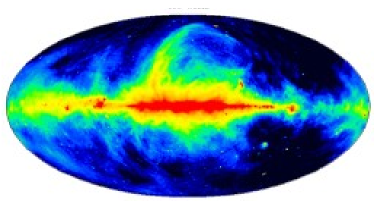
White noise residuals

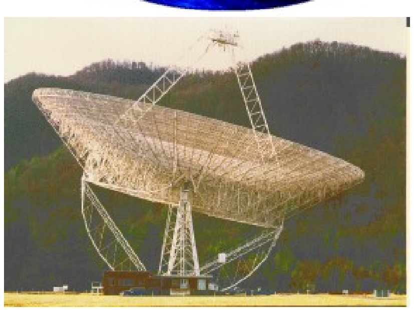
=

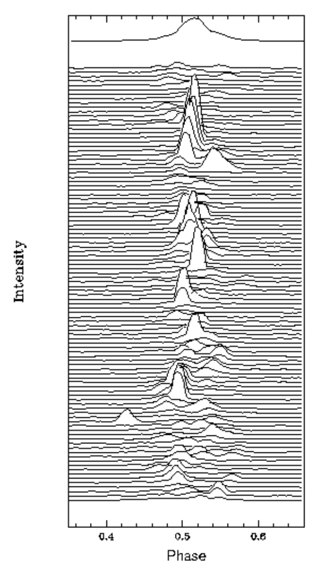
Radiometer noise	Pulse Jitter	DISS

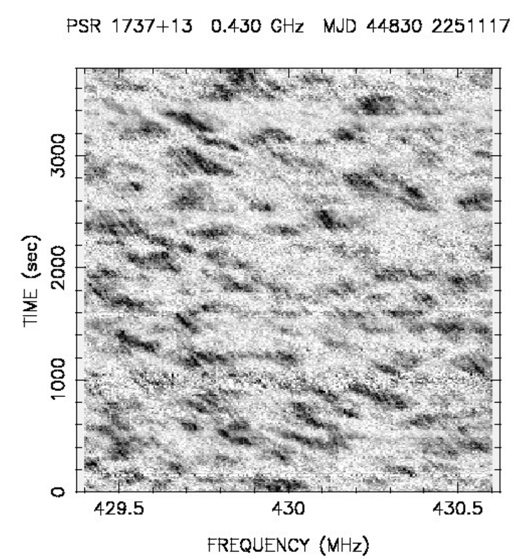






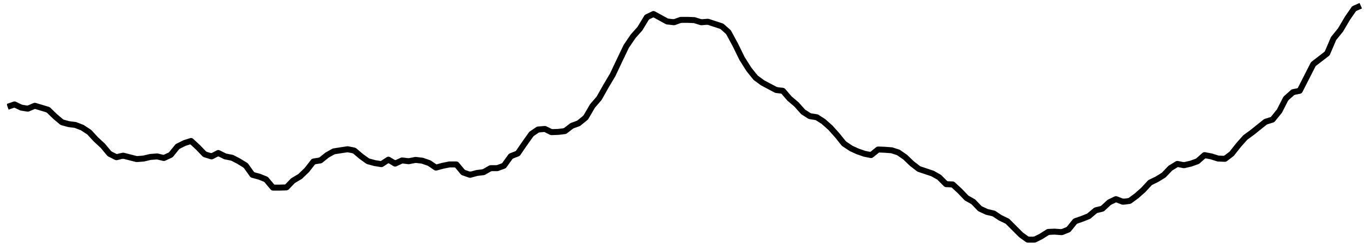






Slide courtesy of Tim Dolch

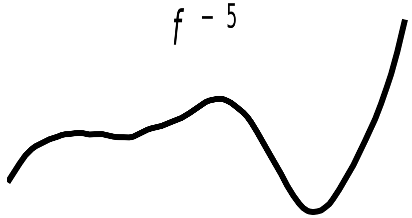
Red noise residuals

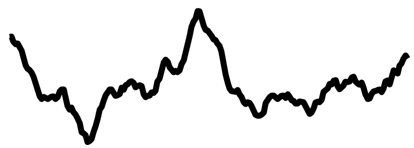


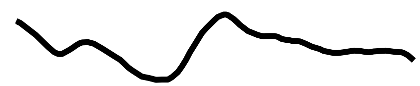
=

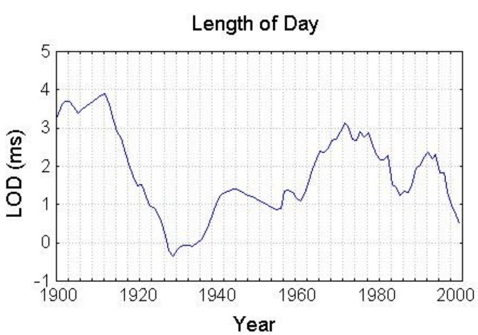
Spin noise + DM variations + GWs (stochastic)

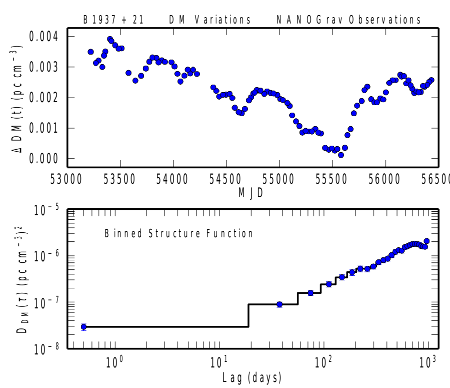
f^{-5} $f^{-8/3}$ $f^{-13/3}$

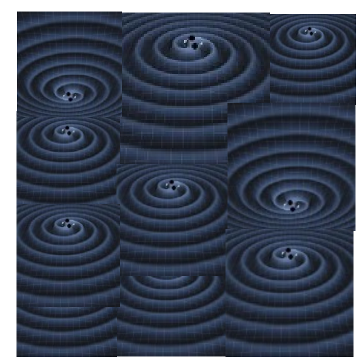












Slide courtesy of Tim Dolch

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

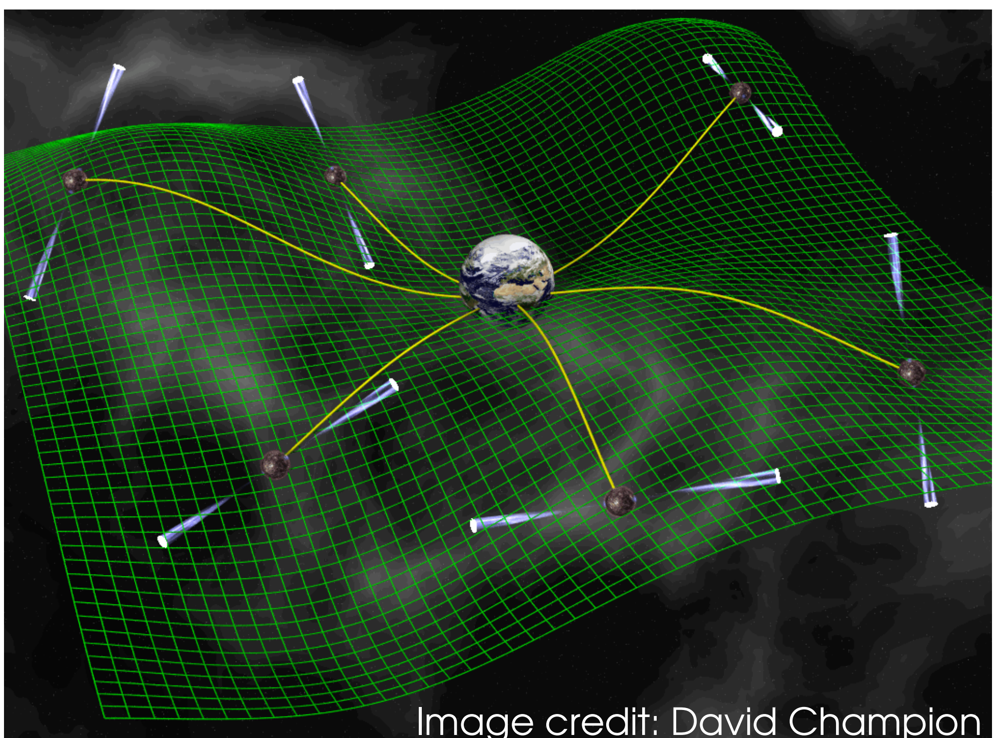


Image credit: David Champion

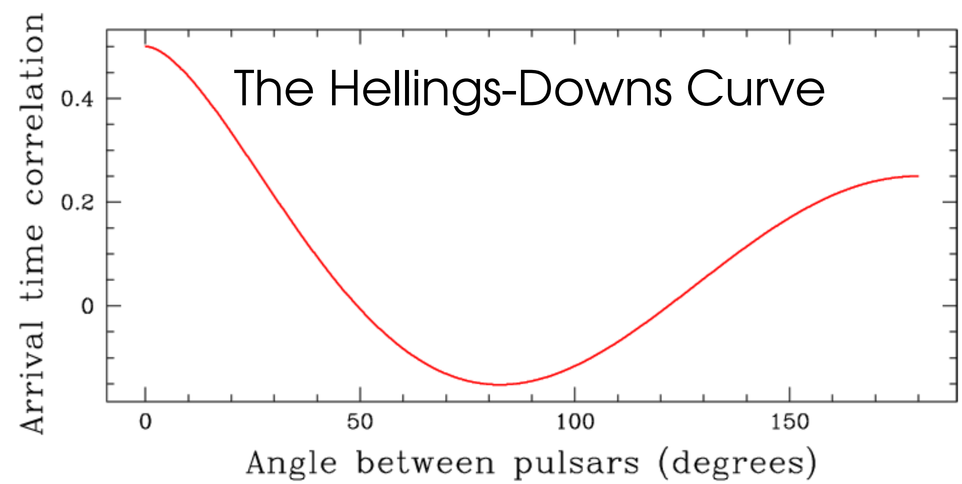
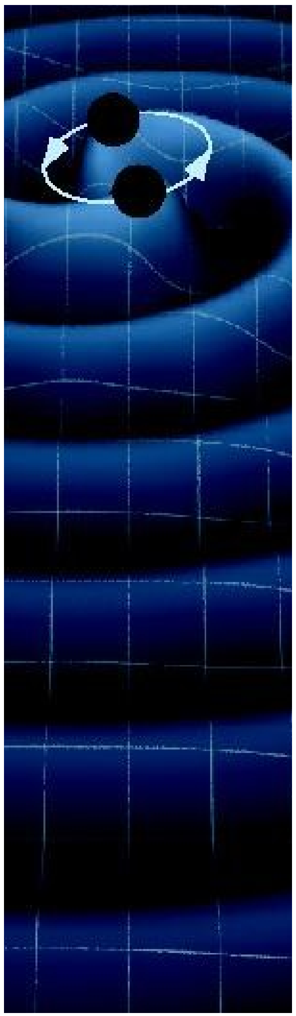


Image credit: NANOGrav

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:

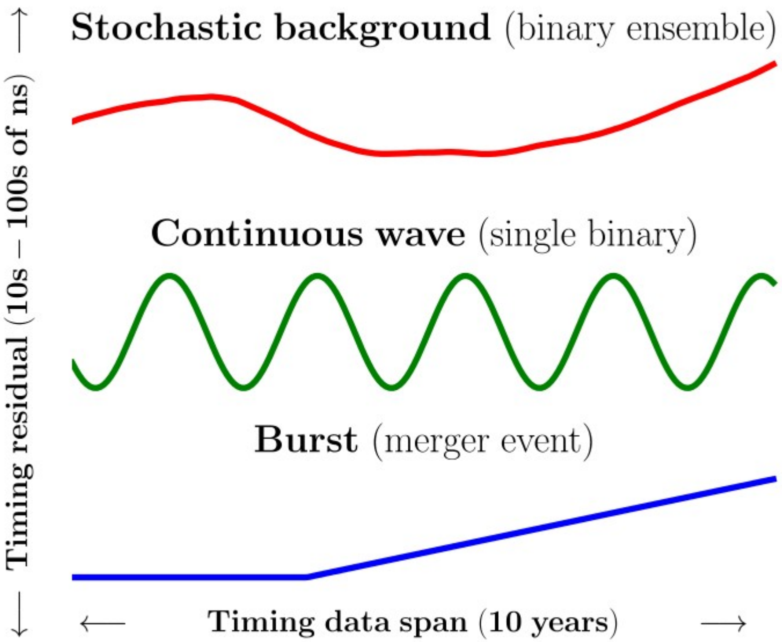


$$\Delta\tau \sim 10\,\mathrm{ns}\left(\frac{1\,\mathrm{Gpc}}{\mathrm{d_L}}\right)\left(\frac{\mathrm{M}}{10^9\,\mathrm{M}_\odot}\right)^{5/3}\left(\frac{10^{-7}\,\mathrm{Hz}}{f}\right)^{1/3}$$

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

Slide courtesy S. Ransom

Observational Signatures



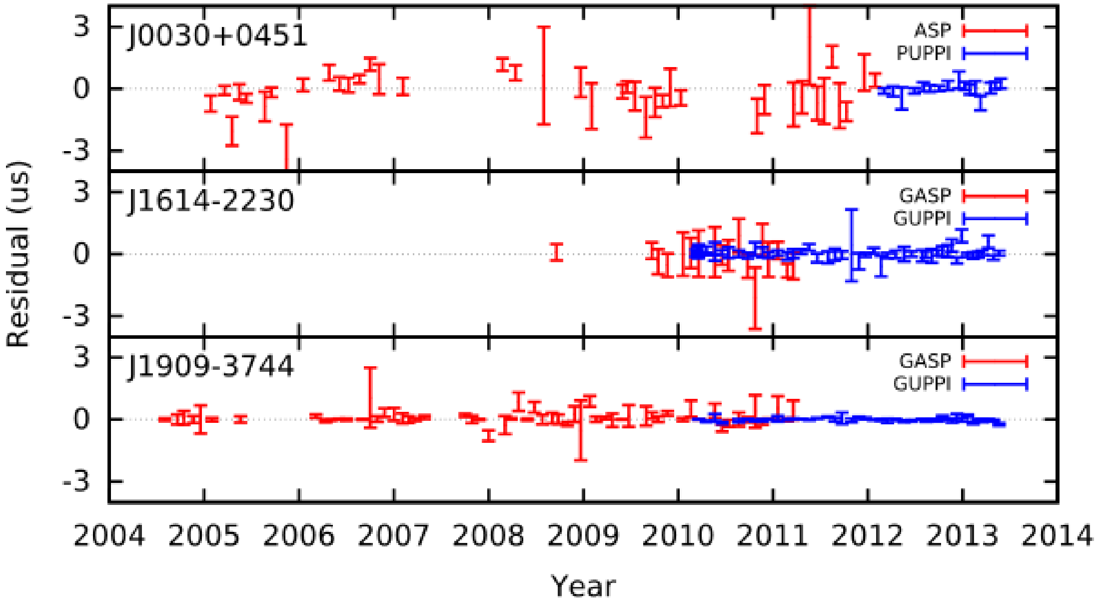
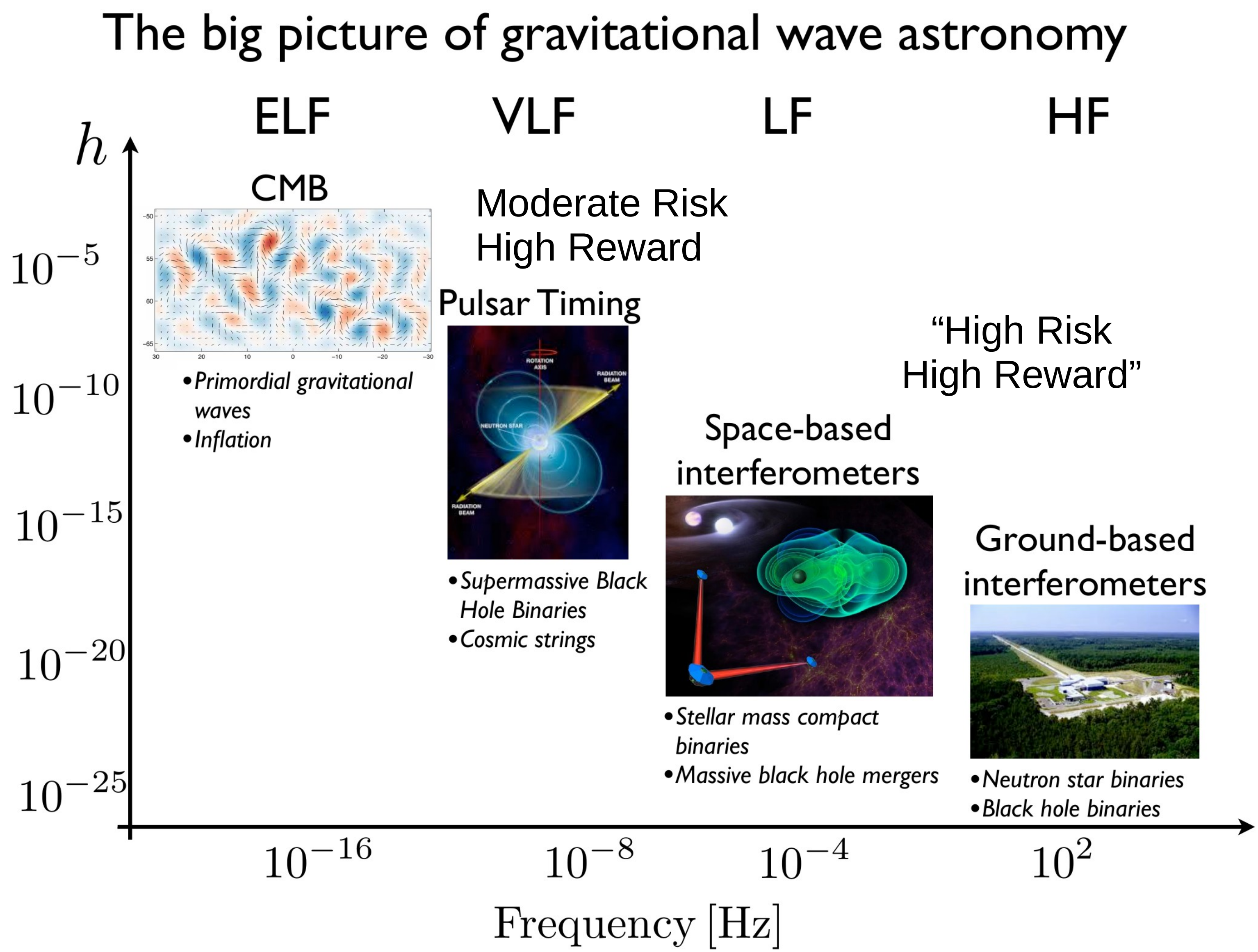


Image credits:
NANOGrav

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

Complementary Gravitational Wave Detectors



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- North American PTA
  - Senior/affiliated researchers at over two dozen institutions (US, Canada, Europe)
- Funded by NSF Physics Frontier Center ($14.5M over 5 years)
  - Portion of funding supports GBT operations
- 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**
- International collaboration through IPTA

NANOGrav Data Releases

5 Year (2013)

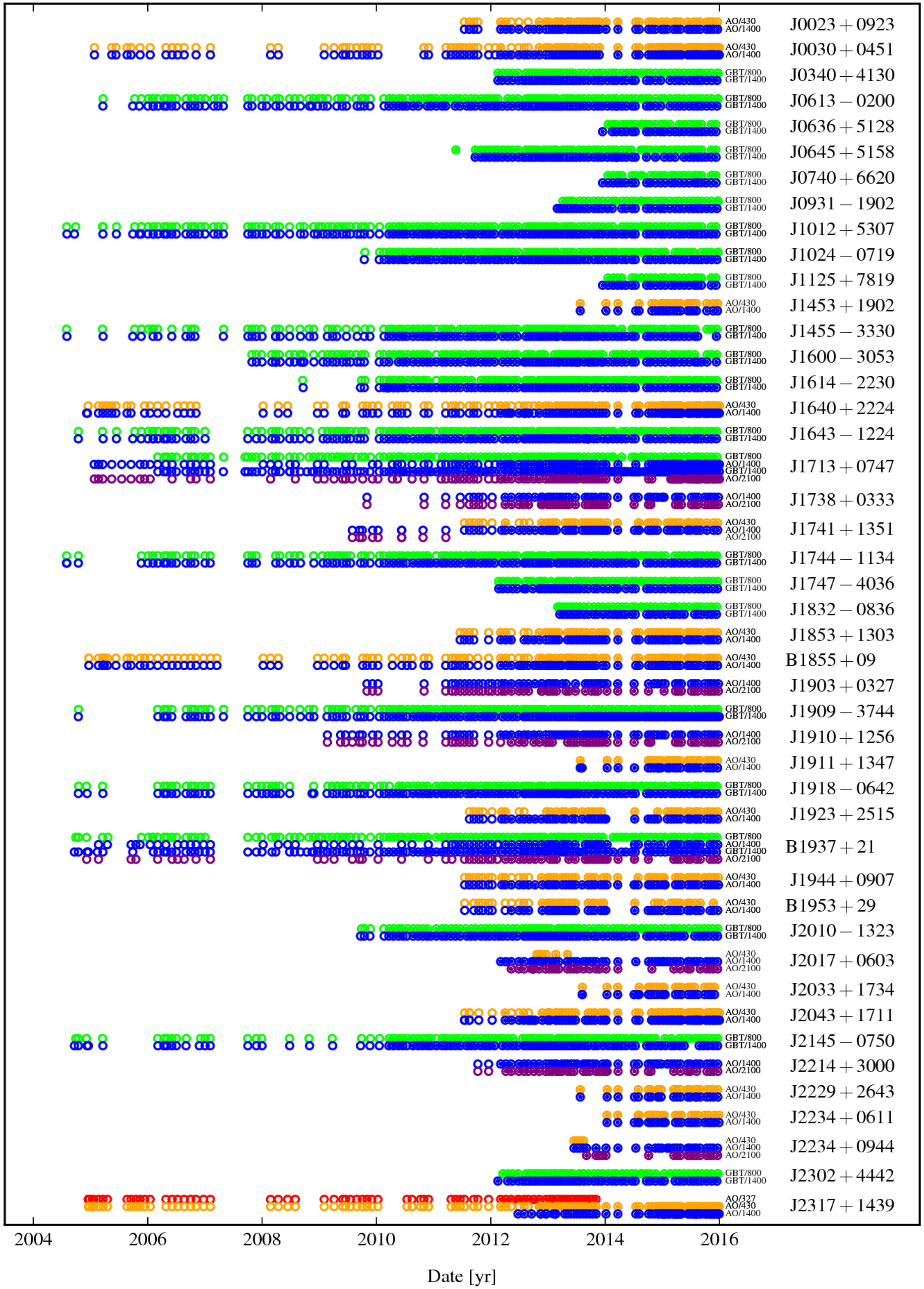
- ASP + GASP
- 16 MSPs, 1,095 observations, ~16K TOAs

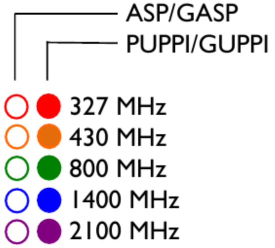
9 Year (2015)

- Transitioned to [GP]UPPI
- 39 MSPs, 4,138 observations, ~170K TOAs

11 Year (2017)

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





“Current” Results

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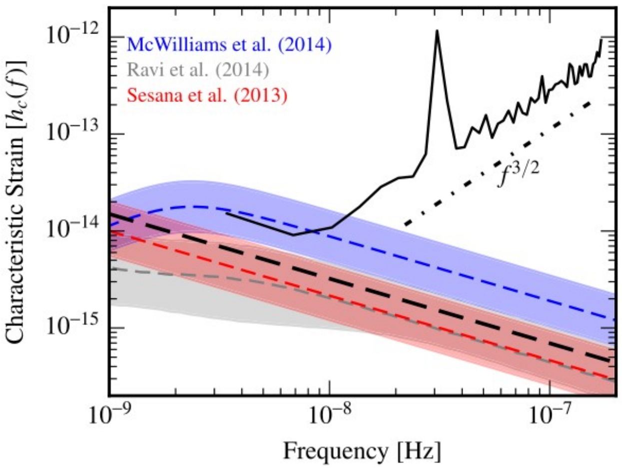
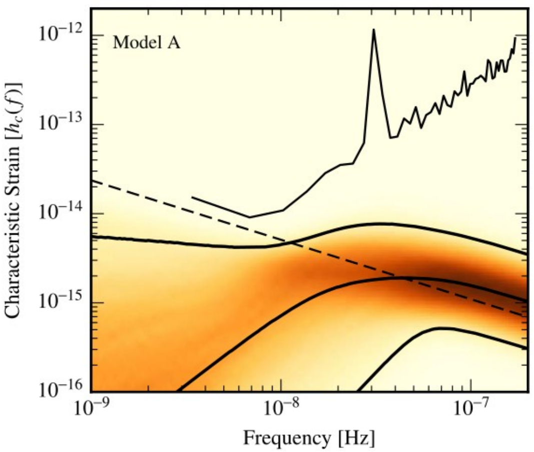
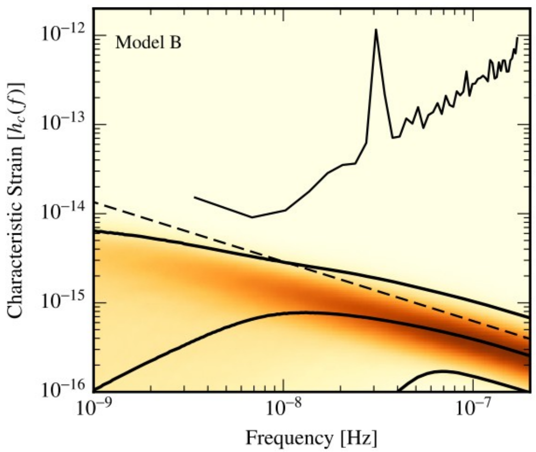
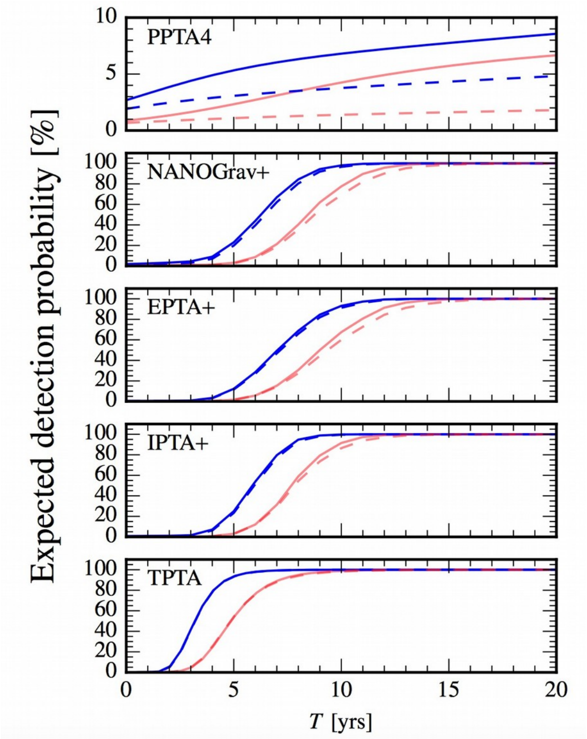




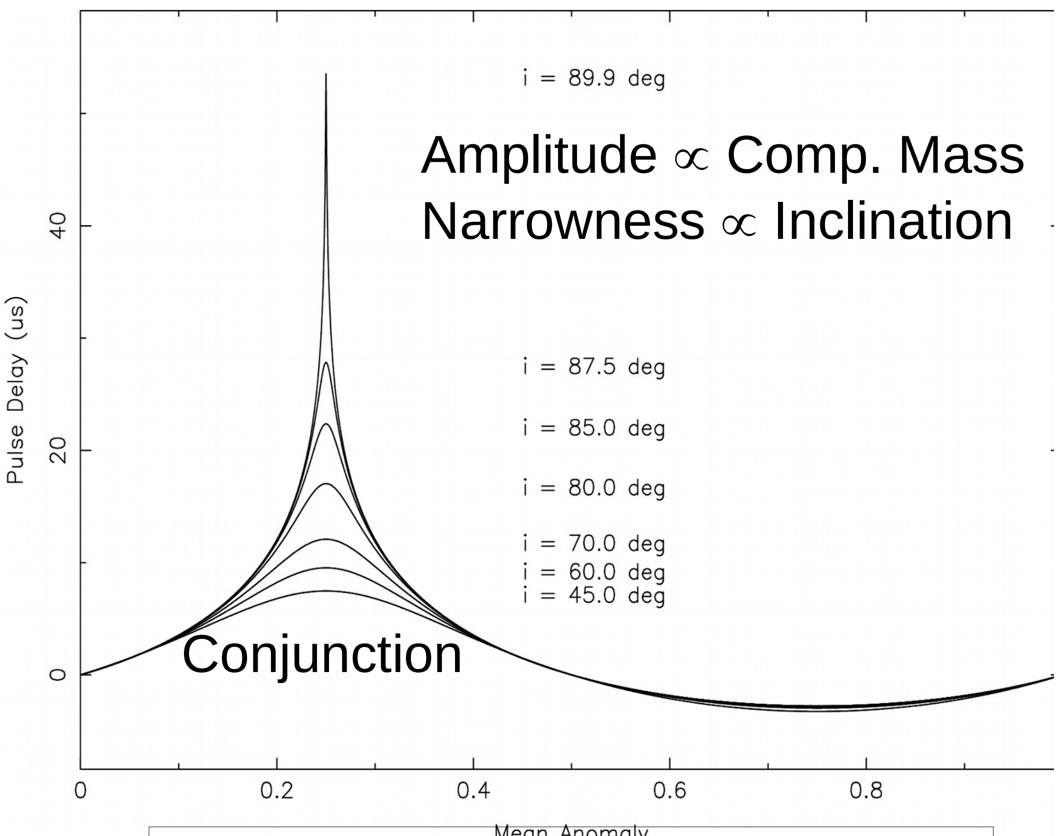


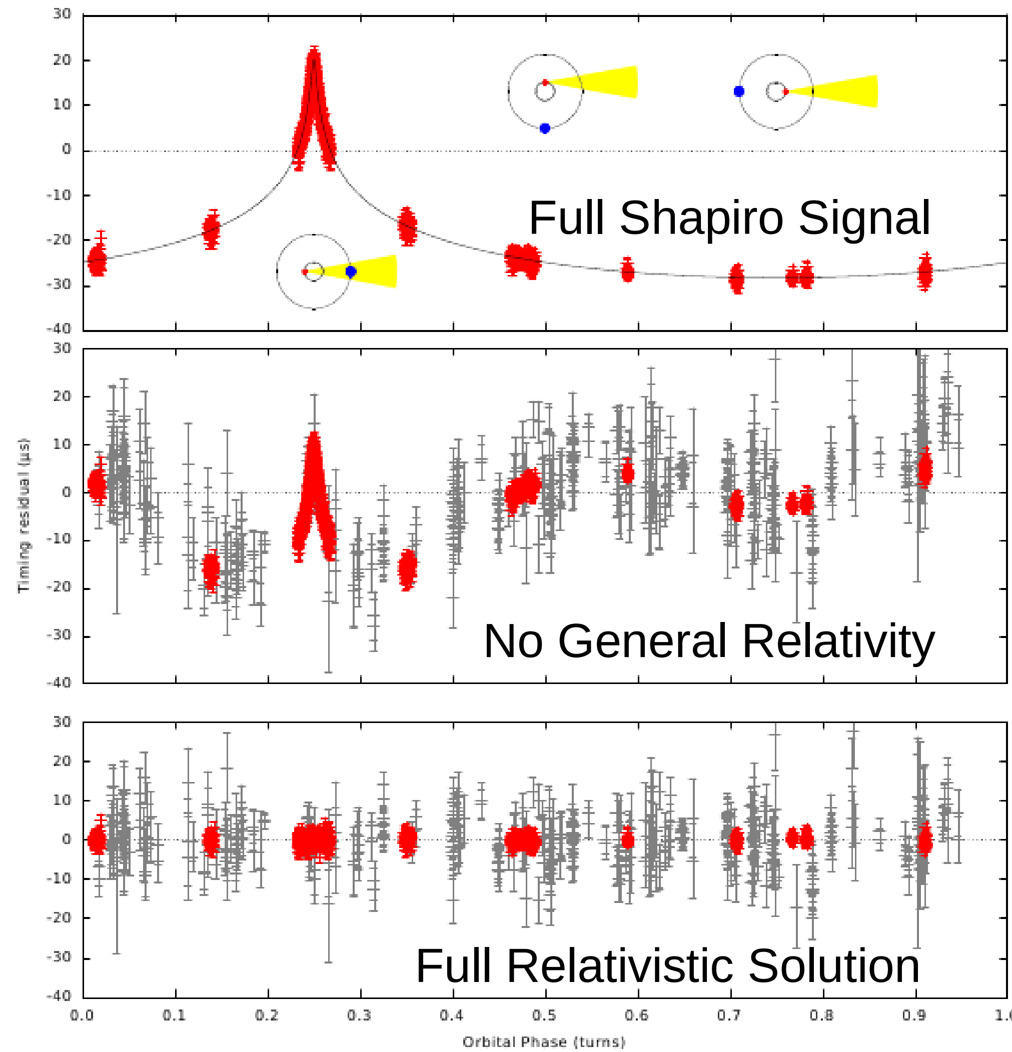
Arzoumanian et al. (2016)



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

Subatomic Physics





M_{wd} = 0.500(6) M⊙

M_{psr} = 1.97(4) M⊙!

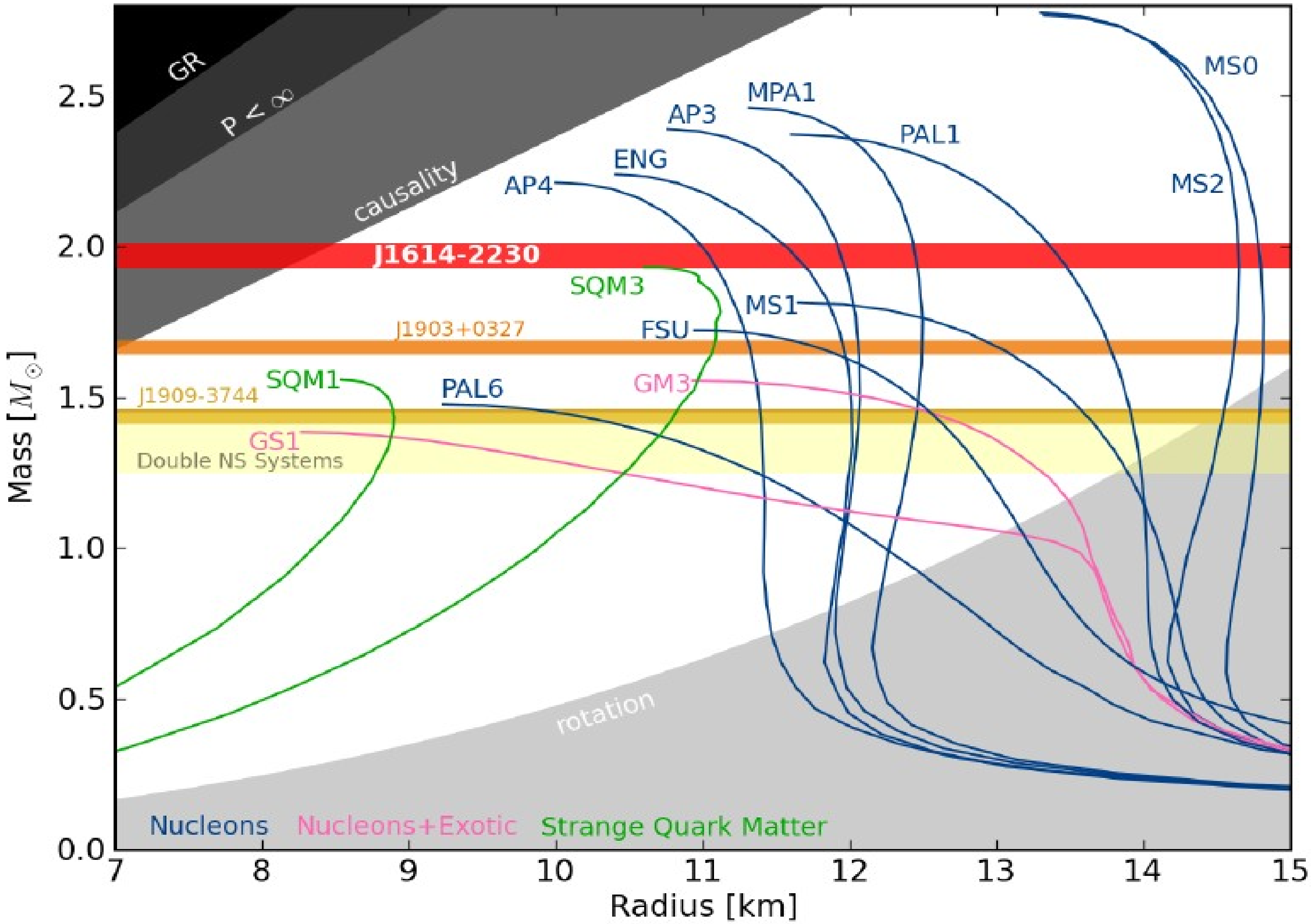
Inclination = 89.17(2) deg!

Demorest et al. 2010, Nature, 467, 1081D

Most highly cited GBT paper (1,550+)

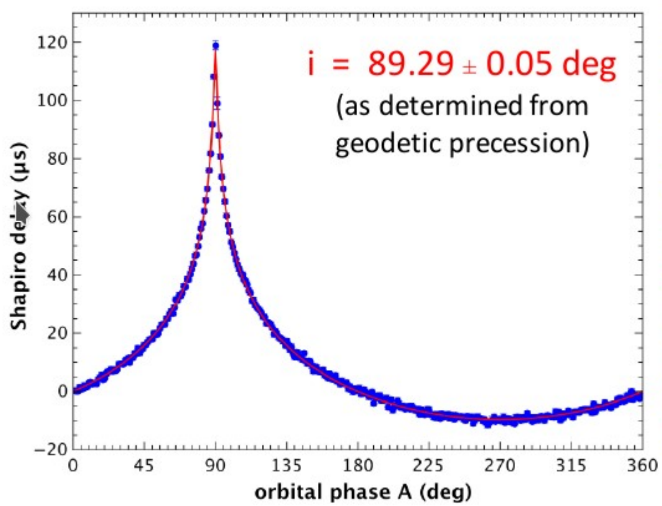
Subatomic Physics

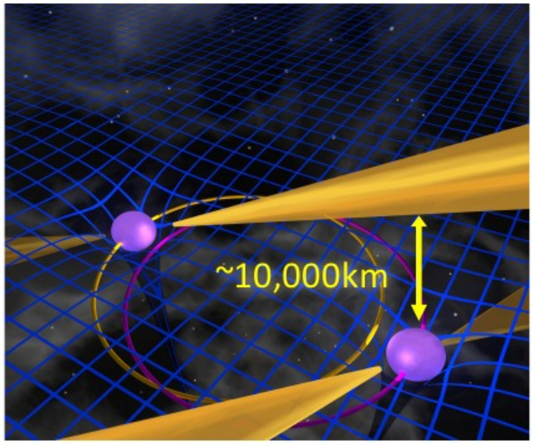
Rules out most or all EOSs
with exotic material in the cores



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

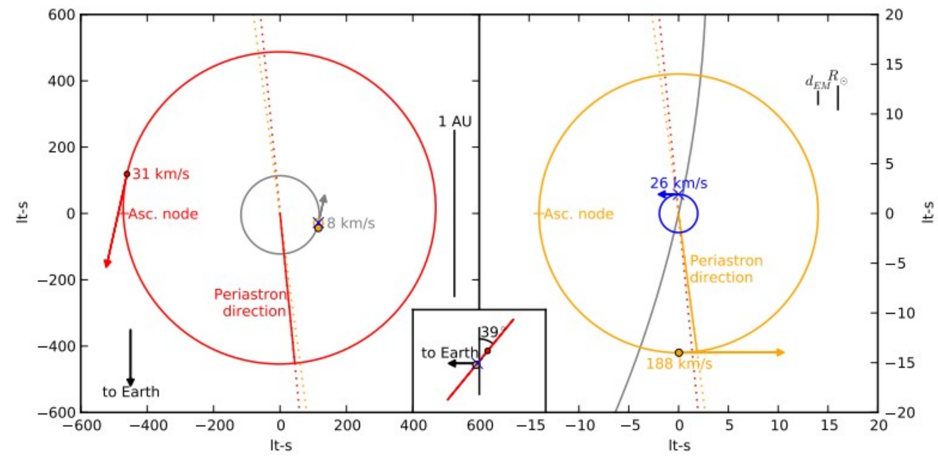




Courtesy of Michael Kramer

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

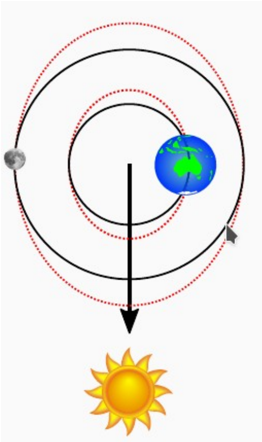
Image credit: Ransom et al. (2014, Nature, 505, 520)

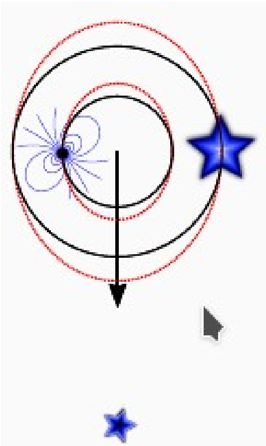
Testing the Strong Equivalence Principle

- Violations parameterized by differential acceleration

  Currently dominated by systematics

    Sensitive to Solar wind DM variations





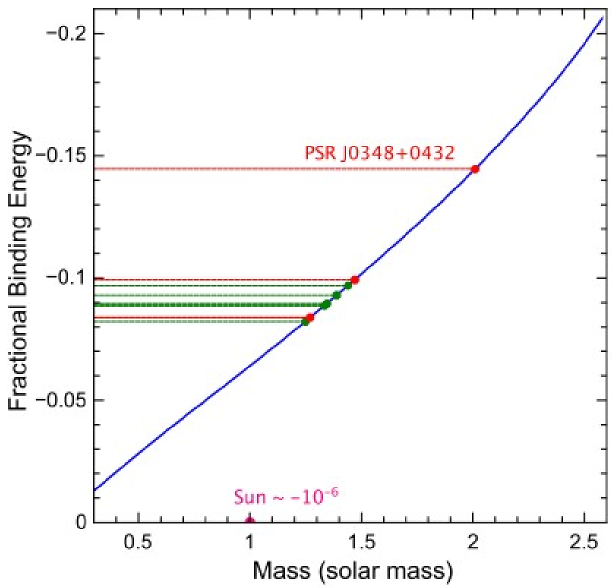
Testing TeVeS Gravity Theories

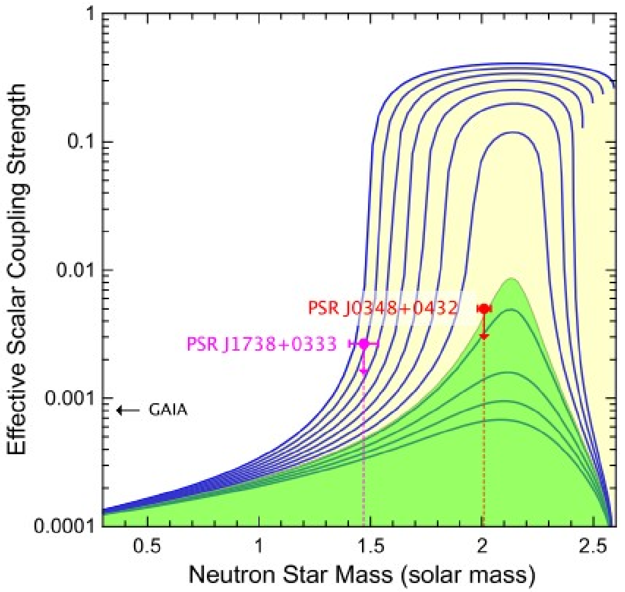
- J0348+0432: Relativistic MSP/WD binary
  - Discovered by GBT
- Pulsar + WD spectroscopy → double-line binary
- Get masses + system geometry
- Pulsar is 2 M_{sun} – most massive known (by a hair)
  - Does not significantly improve on EOS constraints
- But…

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?

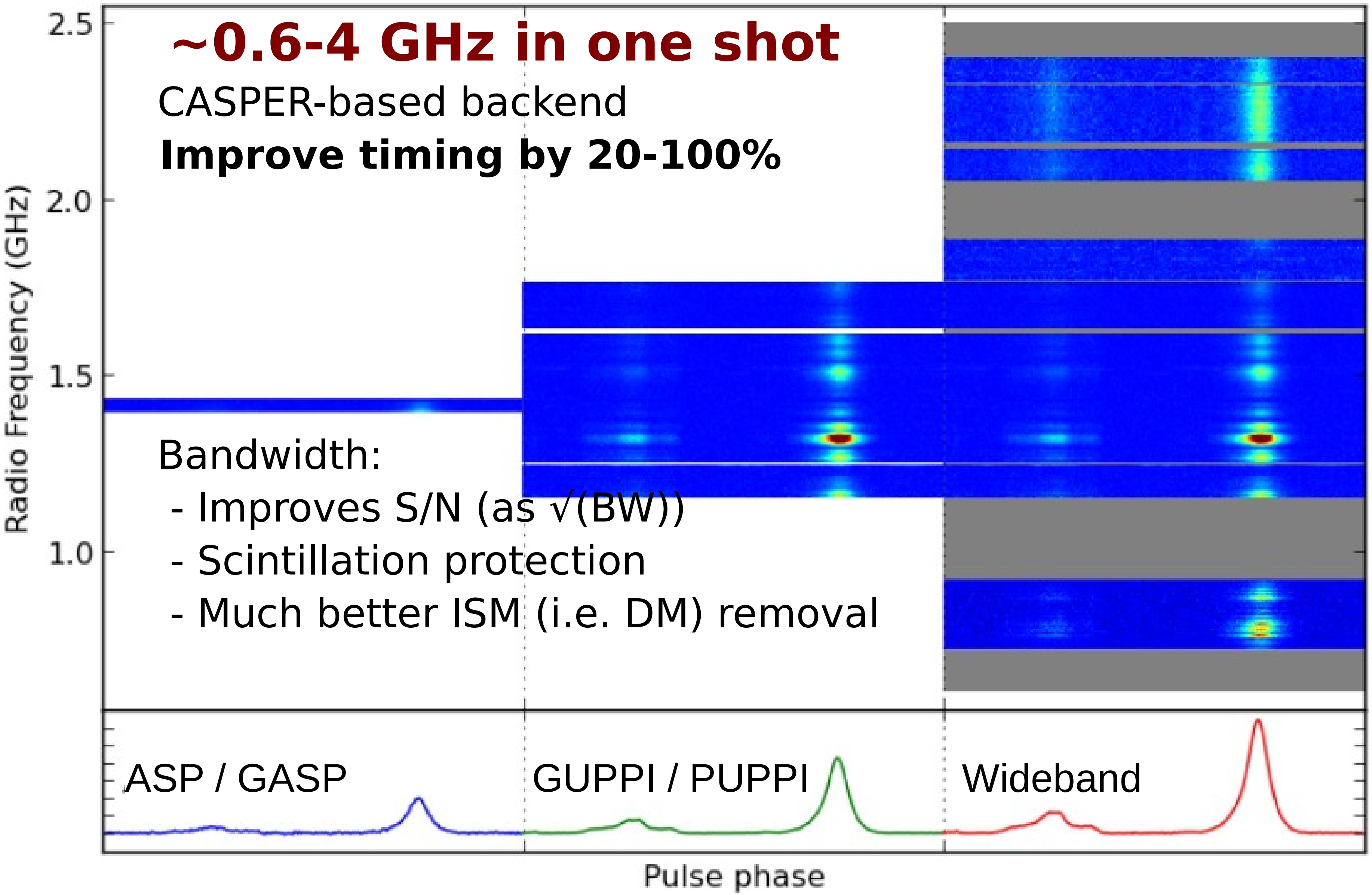


Fig: Paul Demorest

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

Where Are We Going?

- More pulsars! Always more pulsars!
  - **Every time we find new pulsars, we find true gems**
  - Take advantage of new capabilities (PAFs, UWB Rx)
- Next generation surveys (FAST, MeerKAT, SKA) will find many thousands of new pulsars
  - Eventually all the pulsars
- 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