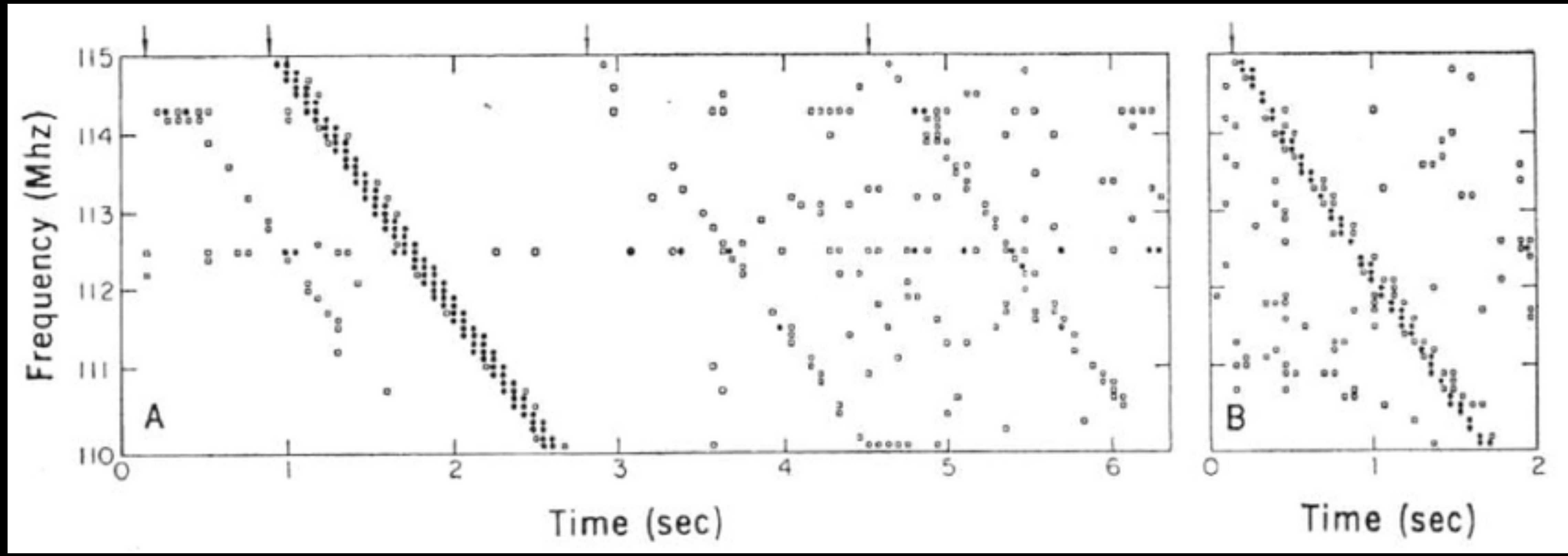
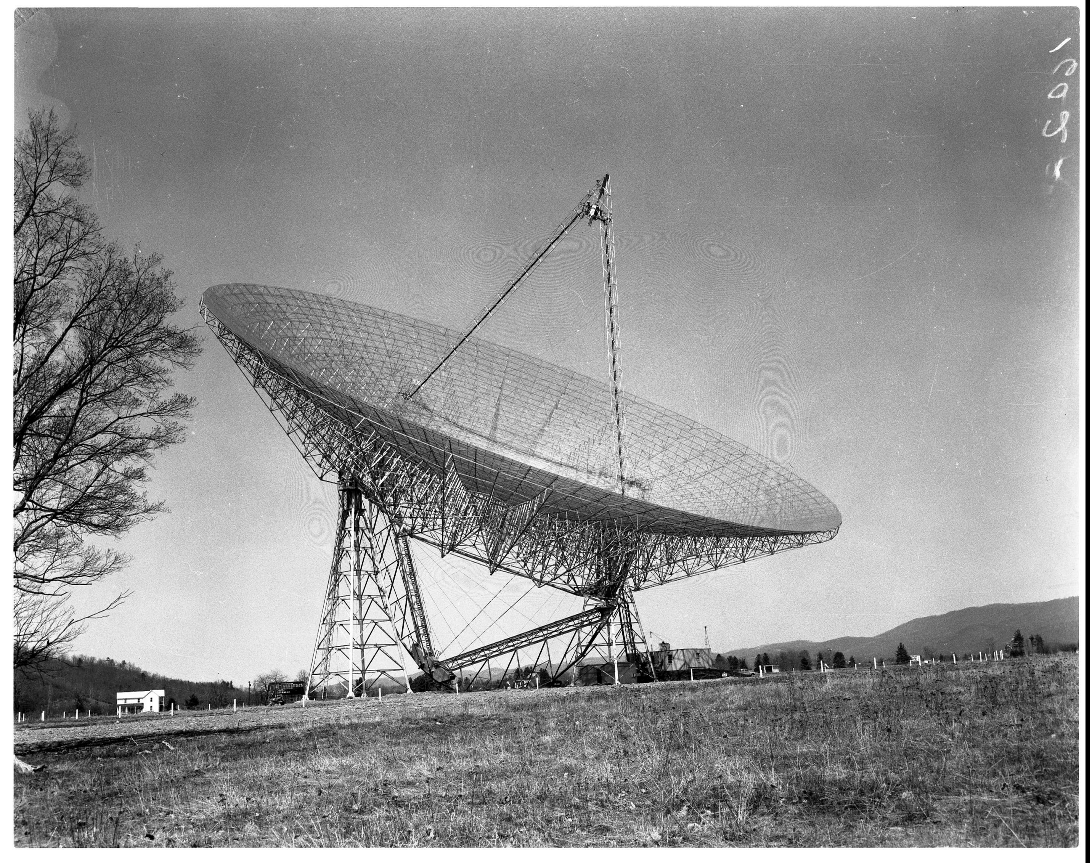
# Giant pulses to nanohertz gravitational waves: the past, present, and future of pulsar research at the Green Bank Observatory

NANOGrav Physics Frontiers Center



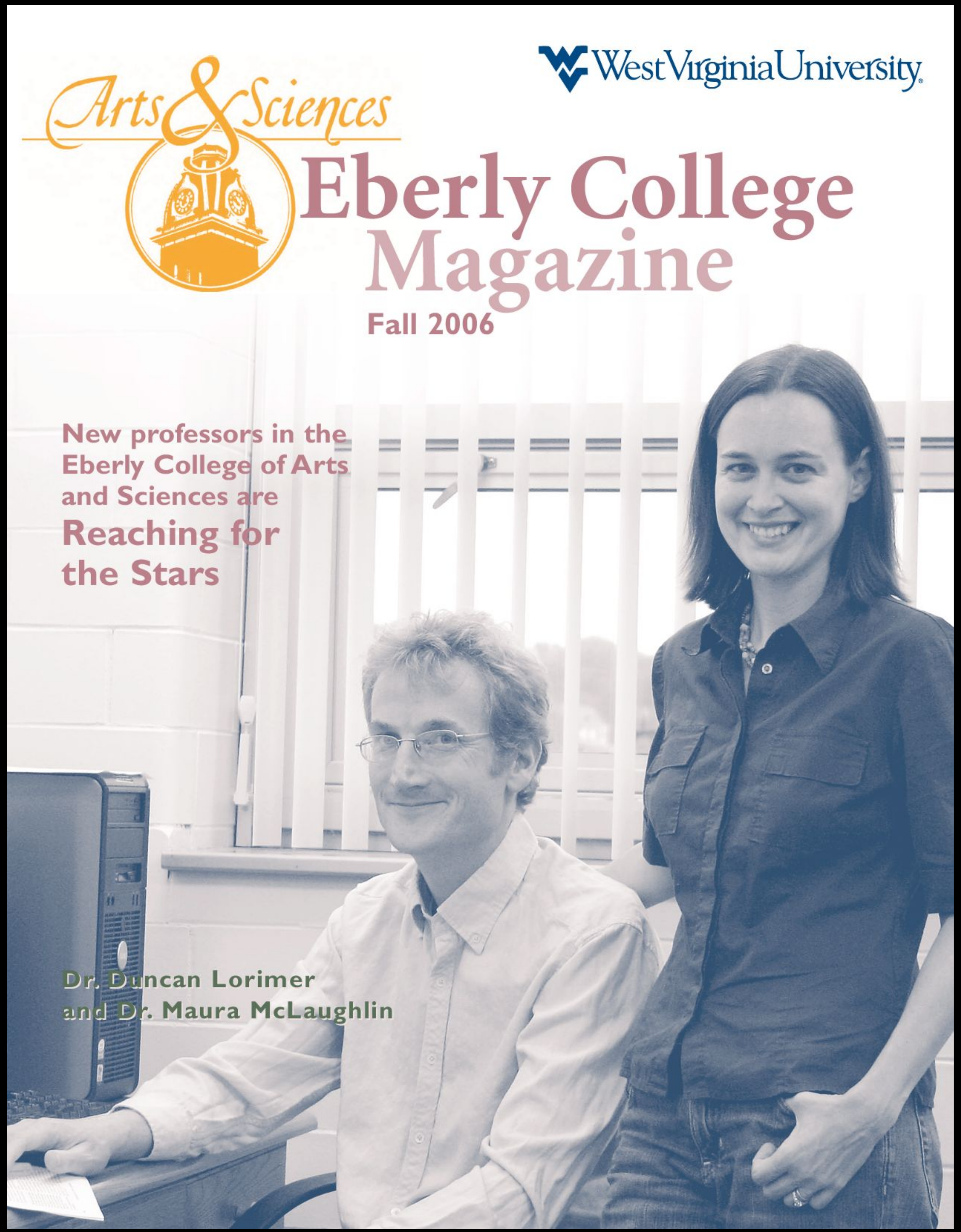

Staelin & Reifenstein, 1968, Science, 162, 3861



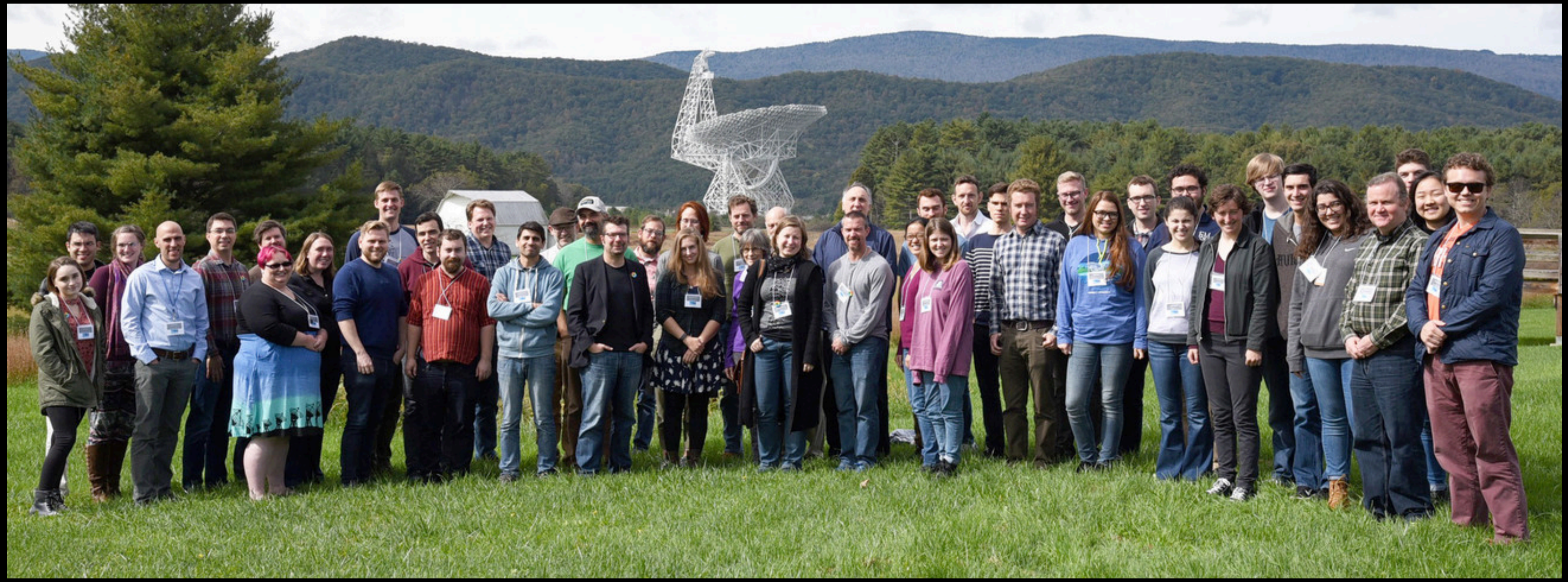

**Maura McLaughlin, West Virginia University (maura.mclauglin at mail.wvu.edu)**

**Co-Director, NANOGrav Physics Frontiers Center**

# Thank you GBO!




*Summer 2012 Pulsar Search Collaboratory Camp*



*Fall 2018 NANOGrav Meeting*

Since my first trip to use the 140-ft in 1996, the GBO has played an incredibly important role in my personal and professional life!

# The GBO Pulsar Greatest Hits

There are ~873 GBO pulsar papers with ~53,922 citations!

2010Natur.467.1081D 2010/10 cited: 2793
**A two-solar-mass neutron star measured using Shapiro delay**
Demorest, P. B.; Pennucci, T.; Ransom, S. M. *and 2 more*

2020NatAs...4...72C 2020/01 cited: 858
**Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar**
Cromartie, H. T.; Fonseca, E.; Ransom, S. M. *and 24 more*

2006Sci...314...97K 2006/10 cited: 664
**Tests of General Relativity from Timing the Double Pulsar**
Kramer, M.; Stairs, I. H.; Manchester, R. N. *and 12 more*

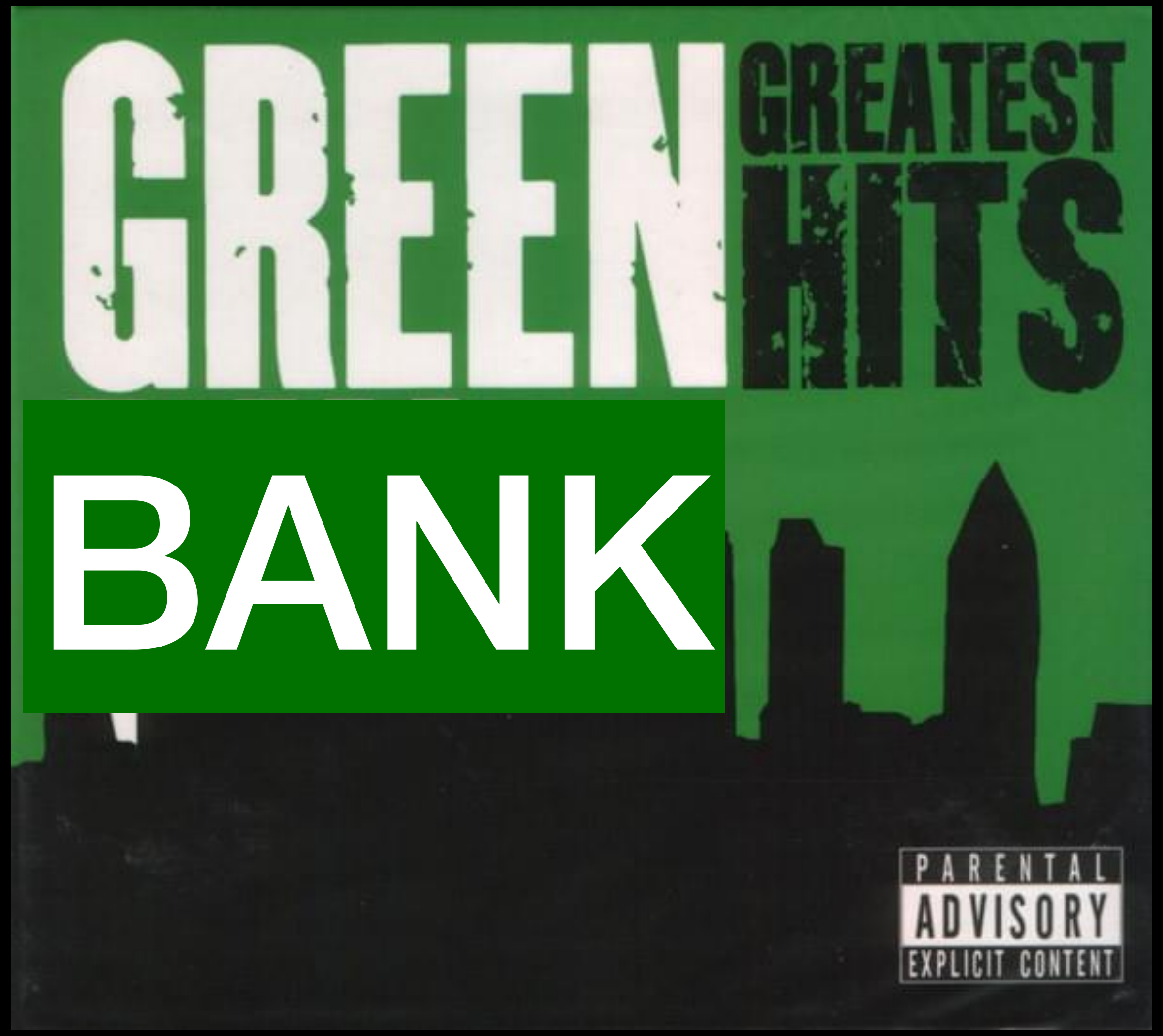
2006Sci...311.1901H 2006/03 cited: 559
**A Radio Pulsar Spinning at 716 Hz**
Hessels, Jason W. T.; Ransom, Scott M.; Stairs, Ingrid H. *and 3 more*

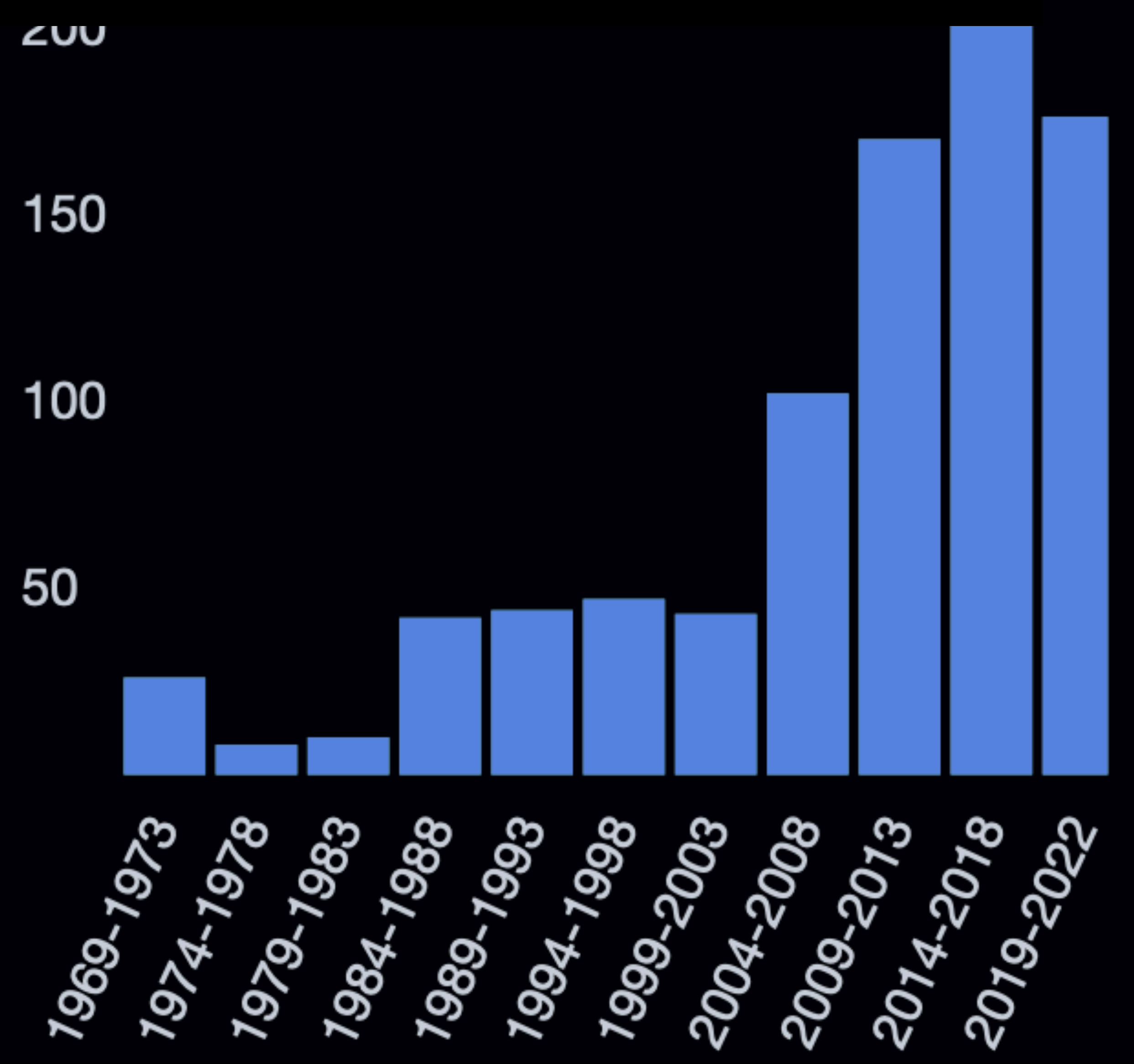
2010CQGra..27h4013H 2010/04 cited: 443
**The International Pulsar Timing Array project: using pulsars as a gravitational wave detector**
Hobbs, G.; Archibald, A.; Arzoumanian, Z. *and 55 more*

2020ApJ...905L..34A 2020/12 cited: 438
**The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background**
Arzoumanian, Zaven; Baker, Paul T.; Blumer, Harsha *and 59 more*

2016ApJ...832..167F 2016/12 cited: 435
**The NANOGrav Nine-year Data Set: Mass and Geometric Measurements of Binary Millisecond Pulsars**
Fonseca, Emmanuel; Pennucci, Timothy T.; Ellis, Justin A. *and 17 more*

2009Sci...324.1411A 2009/06 cited: 423
**A Radio Pulsar/X-ray Binary Link**
Archibald, Anne M.; Stairs, Ingrid H.; Ransom, Scott M. *and 15 more*

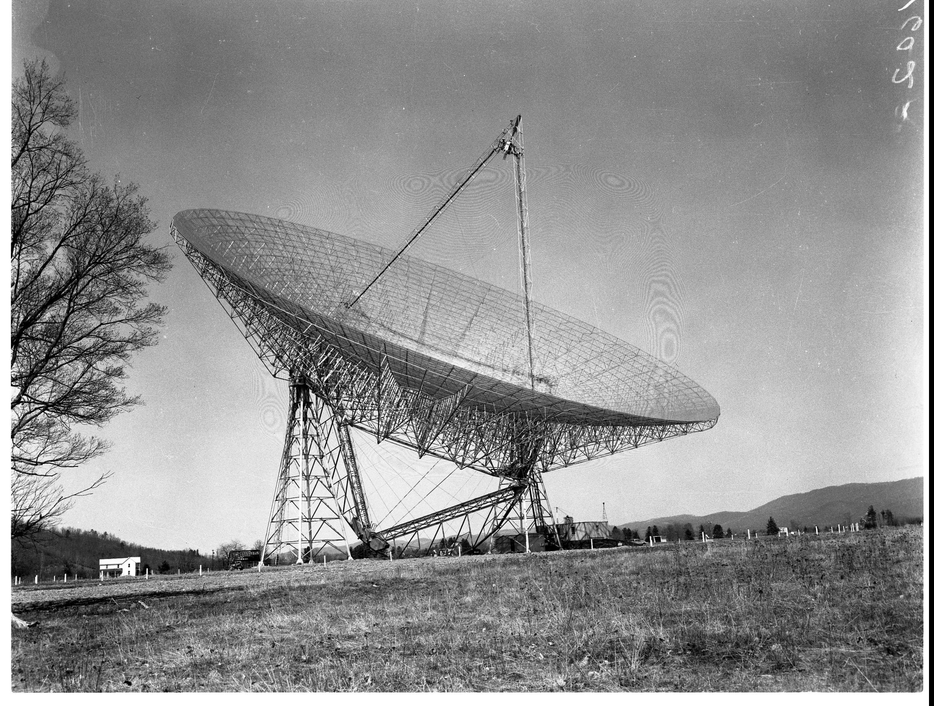



The GBO has made amazing contributions in pulsar searching, tests of GR, neutron star equations of state, searches for nanohertz frequency gravitational waves, neutron star populations and evolution, pulsar emission mechanisms, and more!

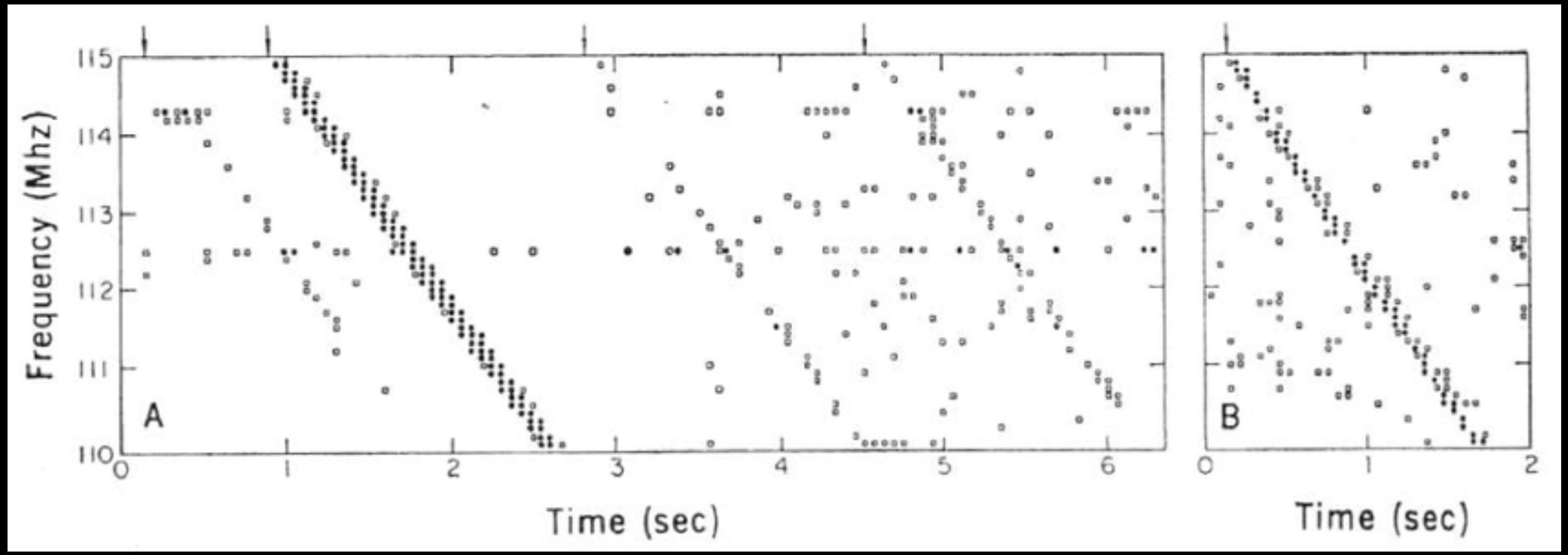
# The Past

# 1968: Pulsating Radio Sources near the Crab Nebula

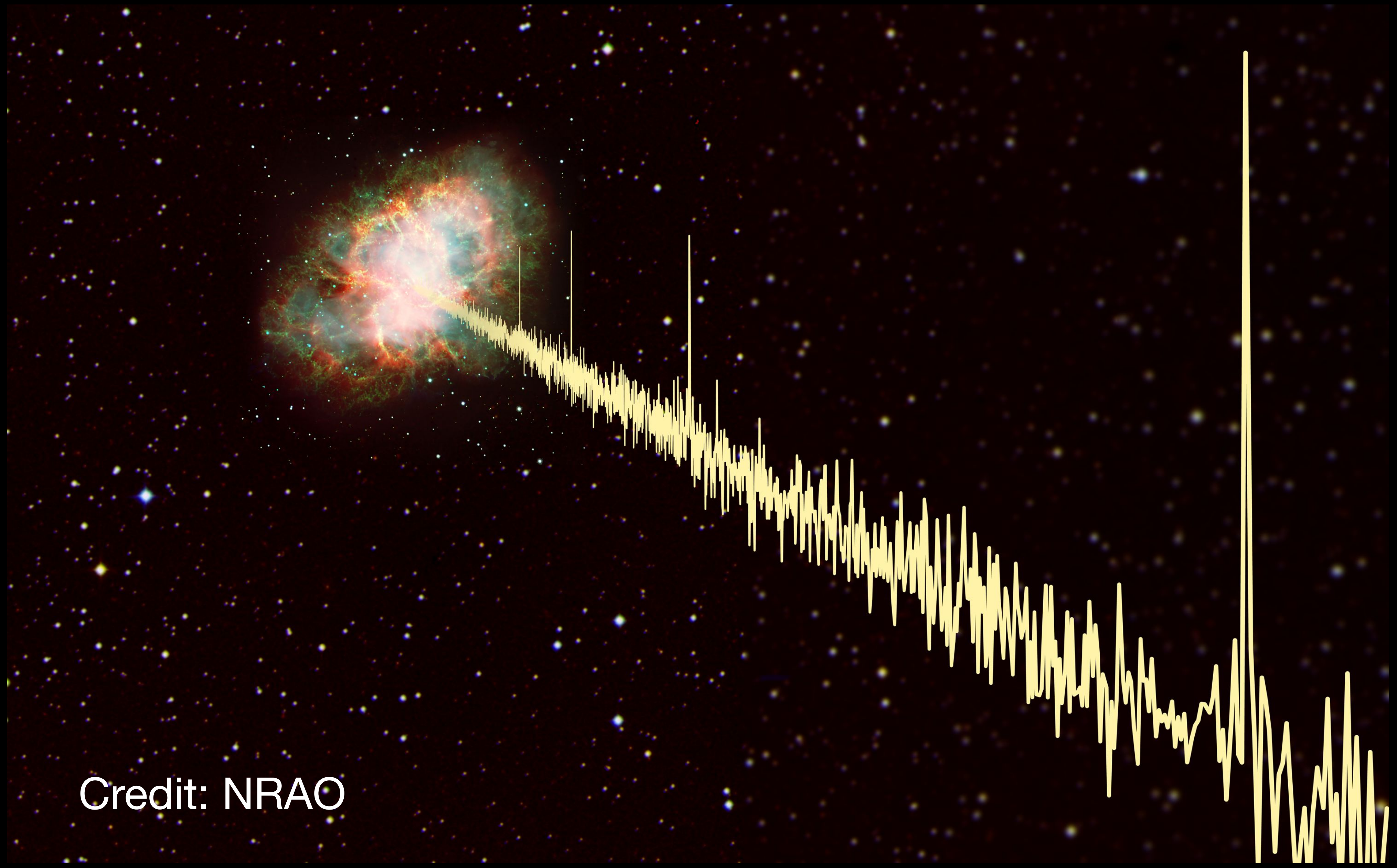


294 Citations

The first observation to show that supernovae cause pulsars!




*Staelin & Reifenstein, 1968, Science, 162, 3861*

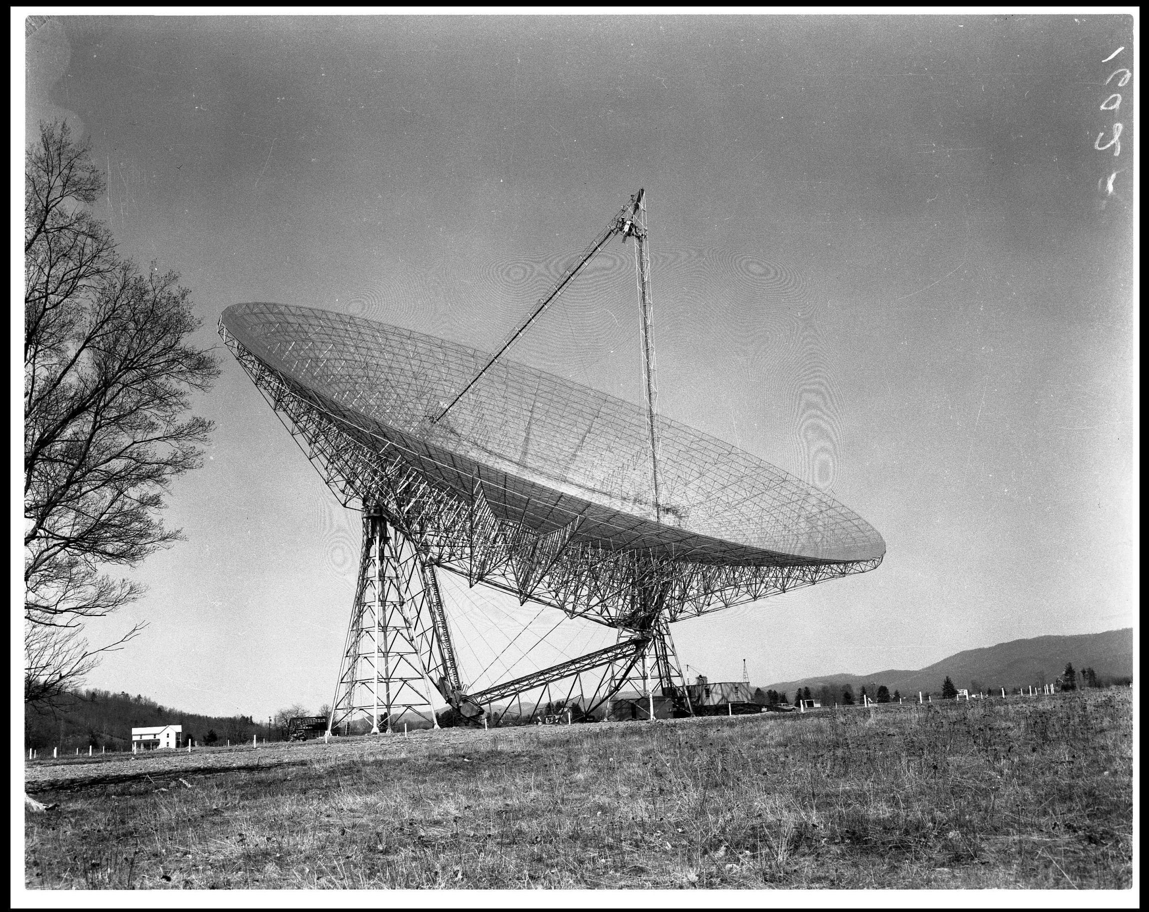




**Abstract**

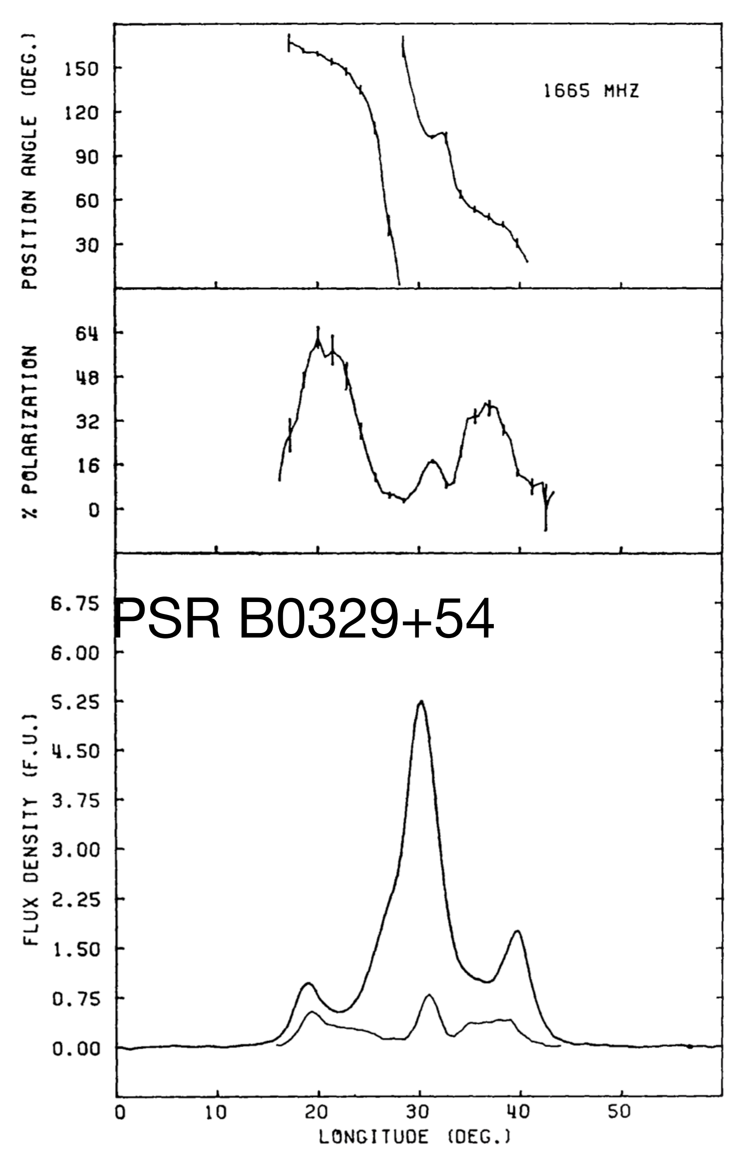
Two new pulsating radio sources, designated NP 0527 and NP 0532, were found near the Crab Nebula and could be coincident with it. Both sources are sporadic, and no periodicities are evident. The pulse dispersions indicate that 1.58 ± 0.03 and 1.74 ± 0.02 × $10^{20}$ electrons per square centimeter lie in the direction of NP 0527 and NP 0532, respectively.

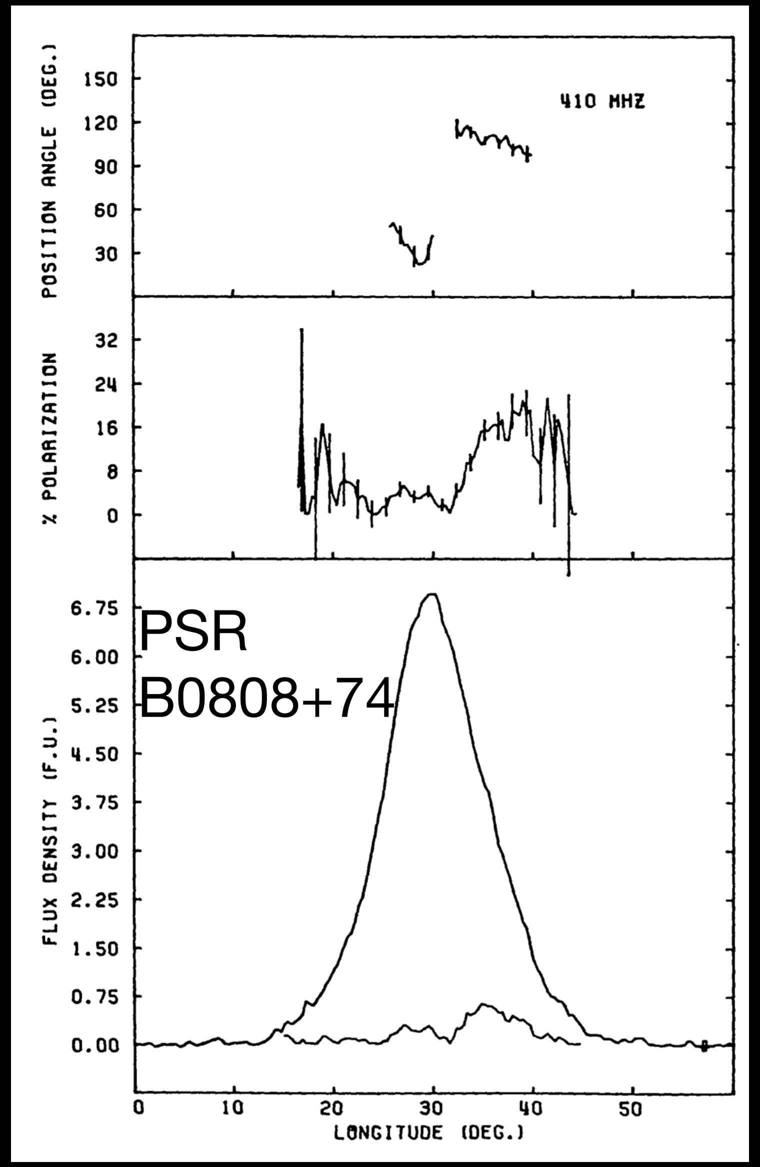
# 1972: Pulsar Rotation and Dispersion Measures and the Galactic Magnetic Field



142 and 108 Citations

$$\langle B_{\parallel} \rangle = \int_{\mathrm{PSR}}^{\oplus} n_e \boldsymbol{B} \cdot ds \Big/ \int_{\mathrm{PSR}}^{\oplus} n_e ds = \mathrm{RM}/(0.81\mathrm{DM}).$$




*Manchester 1971, ApJS, 23, 283*

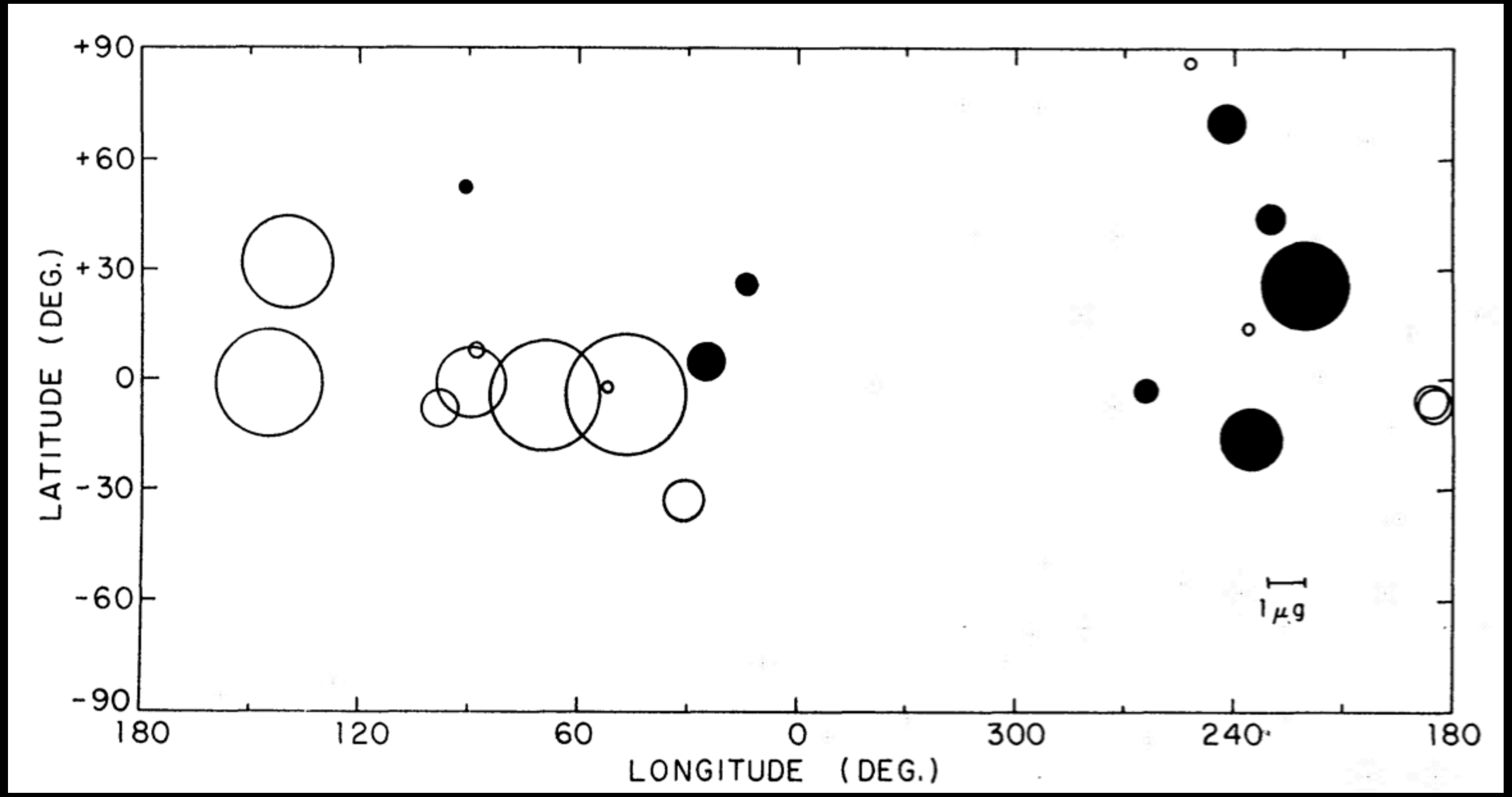



TABLE 1

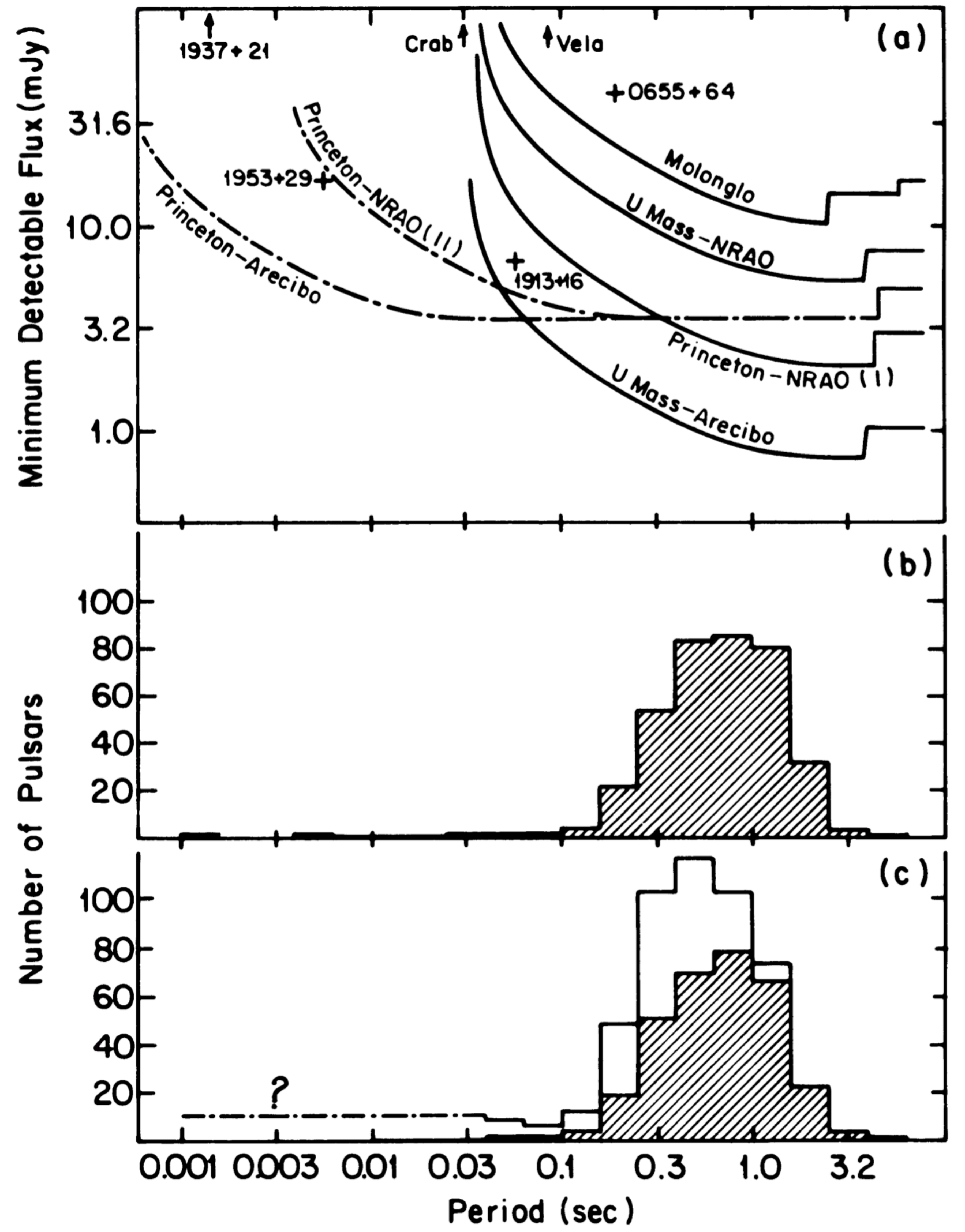
ROTATION AND DISPERSION MEASURES

| PSR | $l$ (deg.) | $b$ (deg.) | Frequency Range (MHz) | DC ($10^{16}$ Hz) | DM (cm$^{-3}$ pc) | RM (rad m$^{-2}$) | $\langle B_{l,e} \rangle$* (microgauss) |
|---|---|---|---|---|---|---|---|
| 0329+54.... | 145 | −1 | 280–485 | 11.110 ±0.002 | 26.776±0.005 | −63.7±0.4 | −2.93 ±0.02 |
| 0525+21.... | 184 | −7 | 281–421 | 21.07 ±0.05† | 50.8 ±0.1† | −39.6±0.2 | −0.960±0.006 |
| 0531+21.... | 185 | −6 | 365–414 | 23.5705‡ | 56.805‡ | −42.3±0.5 | −0.92 ±0.02 |
| 0809+74.... | 140 | +32 | 365–421 | 2.42 ±0.03 | 5.84 ±0.06 | −11.7±1.3 | −2.5 ±0.3 |
| 0818−13.... | 236 | +13 | 365–421 | 16.97 ±0.04 | 40.9 ±0.1 | −2.8±1.7 | −0.08 ±0.05 |
| 0834+06.... | 220 | +26 | 365–414 | 5.35 ±0.02 | 12.90 ±0.04 | +24.5±2.5 | +2.3 ±0.3 |
| 0950+08.... | 229 | +44 | 280–421 | 1.230 ±0.003 | 2.965±0.007 | +1.8±0.5 | +0.7 ±0.3 |
| 1133+16.... | 242 | +69 | 280–421 | 2.006 ±0.003 | 4.834±0.007 | +3.9±0.2 | +0.99 ±0.06 |
| 1237+25.... | 252 | +87 | 365–414 | 3.840 ±0.004 | 9.254±0.008 | −0.6±0.4 | −0.07 ±0.05 |
| 1508+55.... | 91 | +52 | 281–421 | 8.133 ±0.005 | 19.60 ±0.02 | +0.8±0.7 | +0.05 ±0.04 |
| 1604−00.... | 11 | +36 | 365–410 | 4.45 ±0.02 | 10.72 ±0.05 | ... | ... |
| 1642−03.... | 14 | +26 | 365–421 | 14.816 ±0.004 | 35.71 ±0.01 | +16.5±2.5 | +0.58 ±0.09 |
| 1706−16.... | 6 | +14 | 365–421 | 10.37 ±0.03 | 24.99 ±0.08 | ... | ... |
| 1818−04.... | 26 | +5 | 365–421 | 35.06 ±0.04 | 84.48 ±0.08 | +70.5±7.5 | +1.0 ±0.1 |
| 1911−04.... | 31 | −7 | 365–414 | 37.10 ±0.02 | 89.41 ±0.04 | ... | ... |
| 1929+10.... | 47 | −4 | 365–410 | 1.318 ±0.001 | 3.176±0.003 | −8.6±1.8 | −3.3 ±0.7 |
| 1933+16.... | 52 | −2 | 365–421 | 65.78 ±0.02 | 158.53 ±0.05 | −1.9±0.4 | −0.015±0.003 |
| 2016+28.... | 68 | −4 | 365–421 | 5.88 ±0.01 | 14.16 ±0.03 | −34.6±1.4 | −3.0 ±0.2 |
| 2021+51.... | 88 | +8 | 365–414 | 9.369 ±0.002 | 22.580±0.004 | −6.5±0.9 | −0.36 ±0.05 |
| 2045−16.... | 31 | −33 | 281–410 | 4.775 ±0.004 | 11.51 ±0.01 | −10.8±0.4 | −1.15 ±0.04 |
| 2111+46.... | 89 | −1 | 365–414 | 58.6 ±0.2 | 141.4 ±0.4 | −223.7±2.2 | −1.95 ±0.03 |
| 2217+47.... | 98 | −8 | 365–414 | 18.06 ±0.02 | 43.52 ±0.05 | −35.3±1.8 | −1.00 ±0.05 |
| 2303+30.... | 98 | −27 | 365–410 | 20.70 ±0.05 | 49.9 ±0.2 | ... | ... |

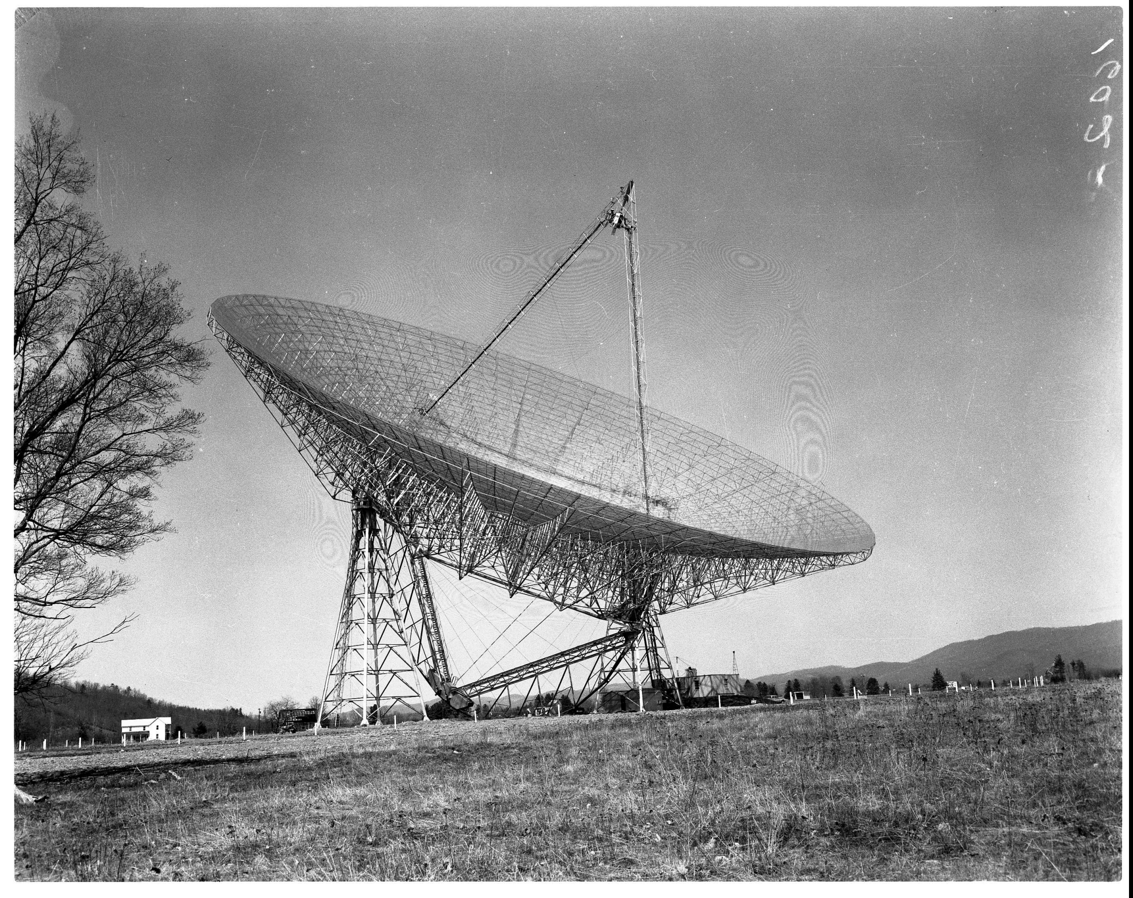
* A positive field component is directed toward the observer.
† Manchester (1971*b*).
‡ Richards *et al.* (1970).

*Manchester 1972, ApJ, 172, 43*

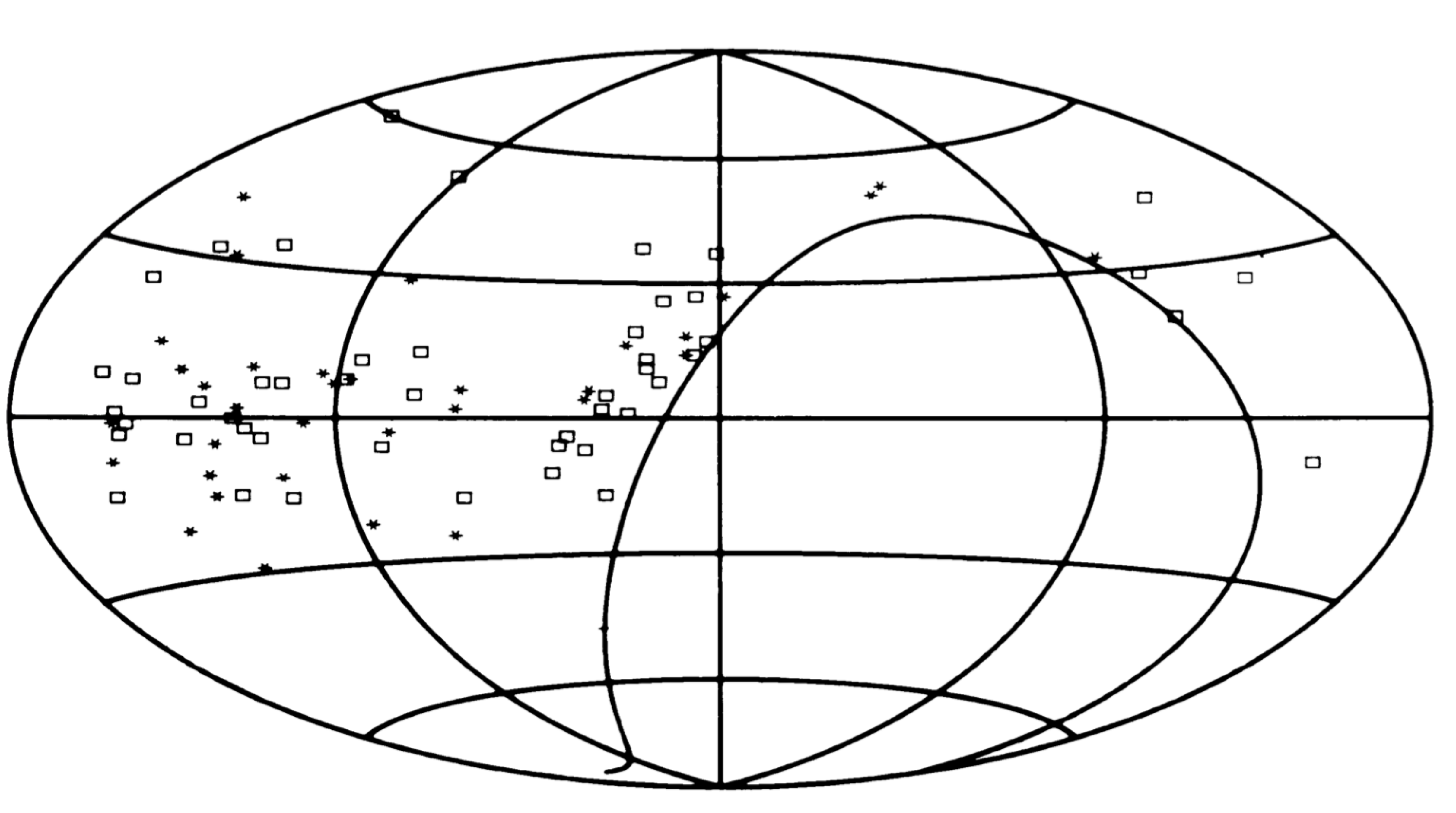
# 1985: A search for low-luminosity pulsars




Dewey et al. 1985, ApJ, 294, L95



169 Citations

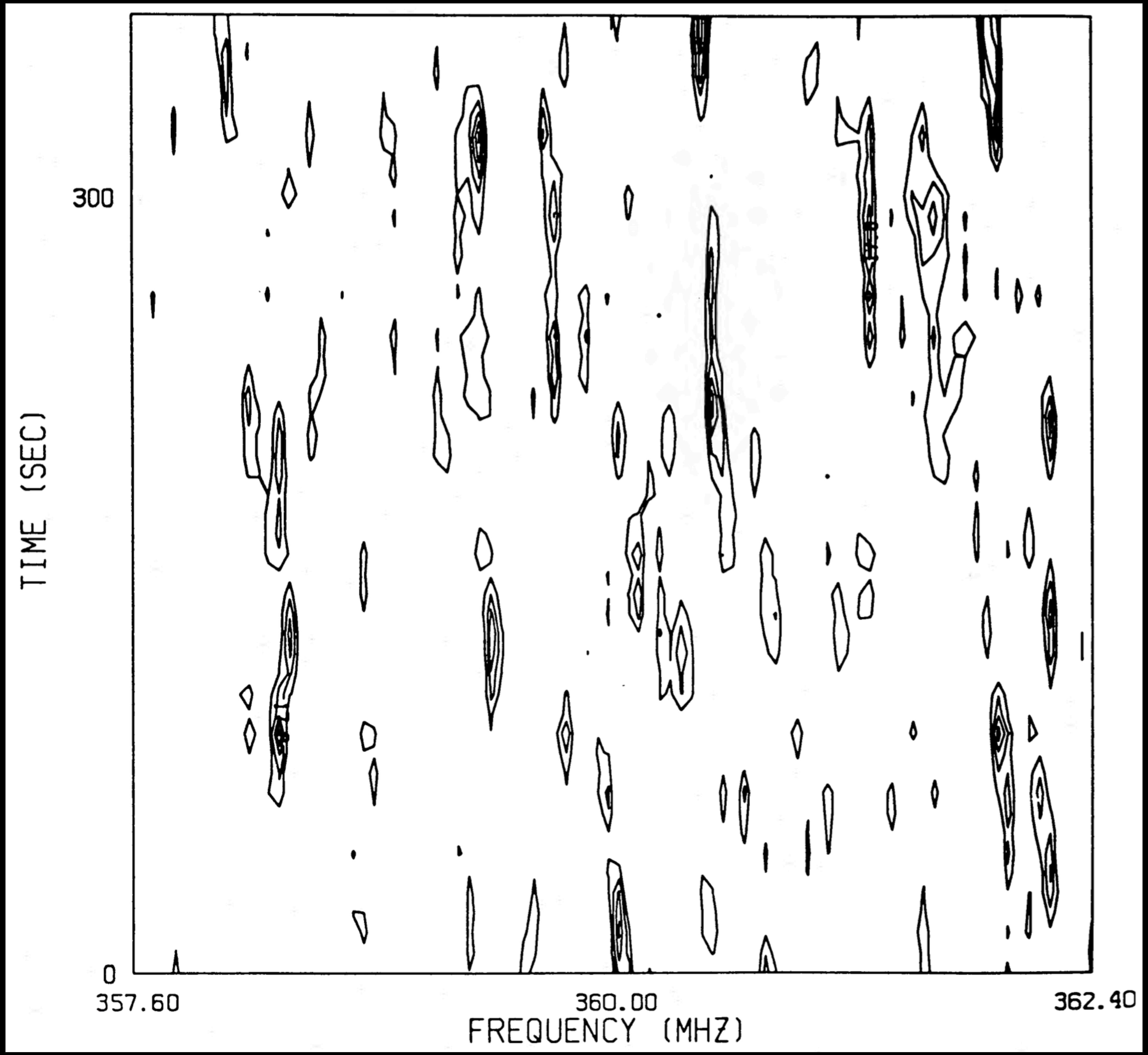


*34 new pulsars and 49 known pulsars*

Found a fall-off at periods below 300 ms, but had little sensitivity to millisecond pulsars

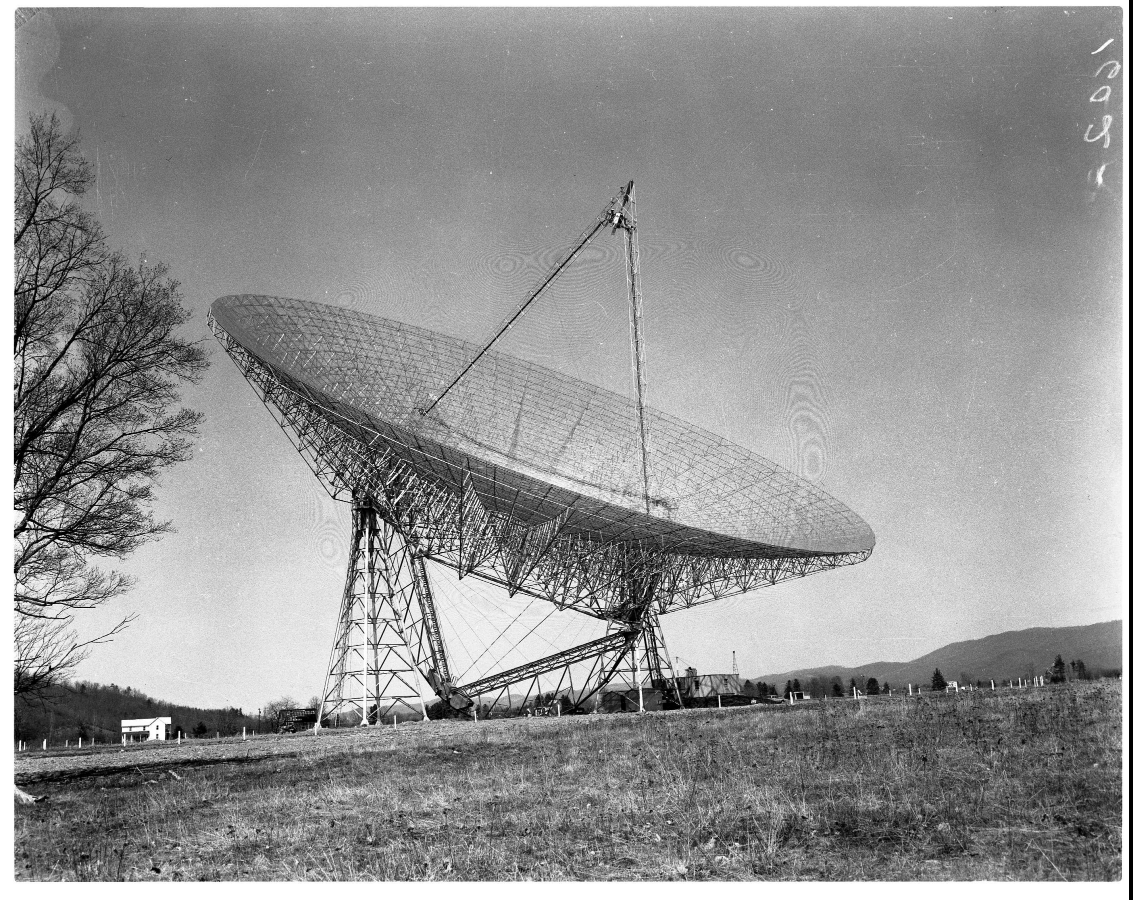
# 1986: Space Velocities from Scintillation

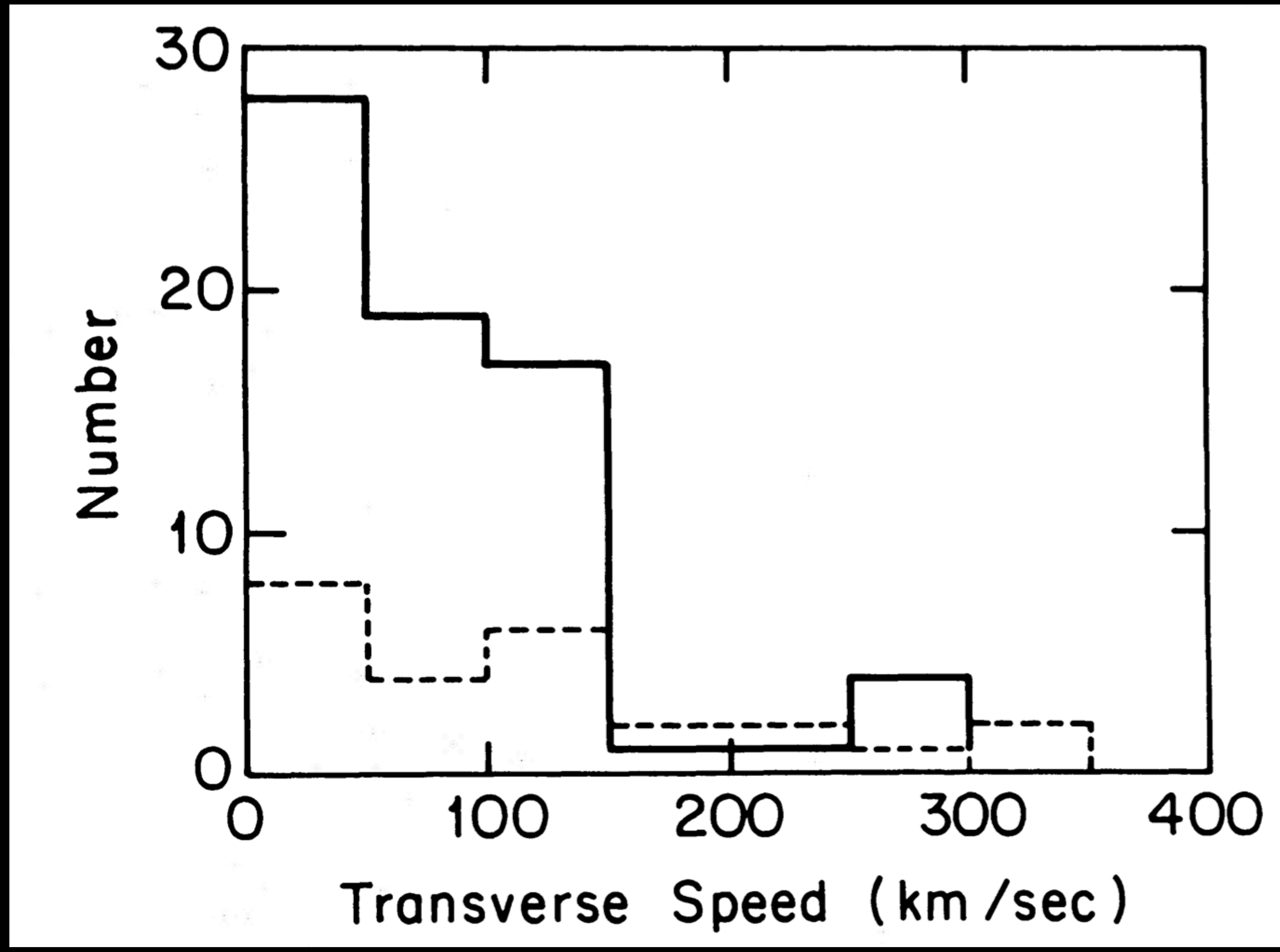
$$V_{ISS} = A_V(\Delta\nu_{ISS} D_{kpc})^{1/2}(\nu_{GHz}\tau_{ISS})^{-1}$$




*Cordes et al. 1986, ApJ, 311, 183*

240 Citations





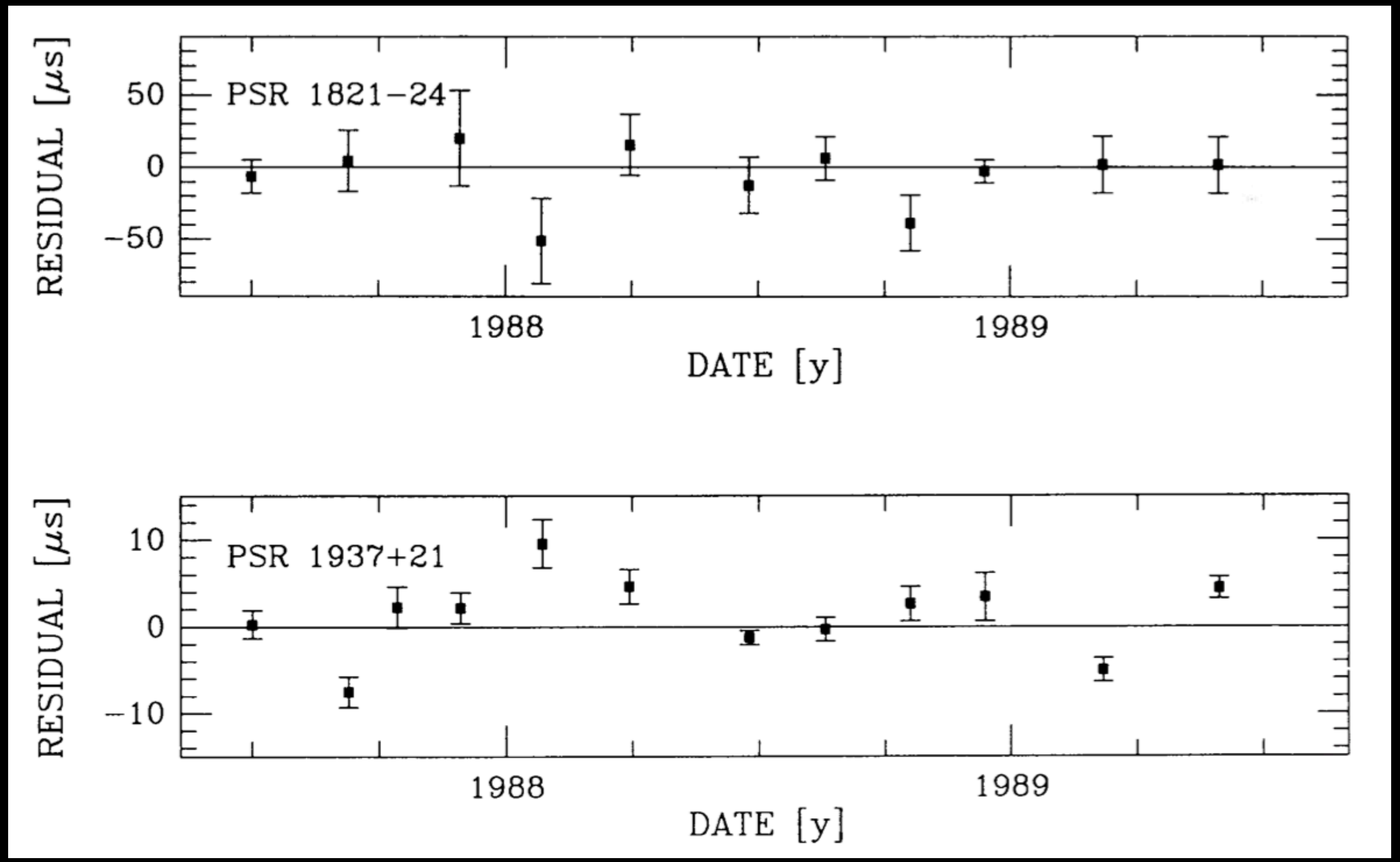

Important implications for supernova physics!

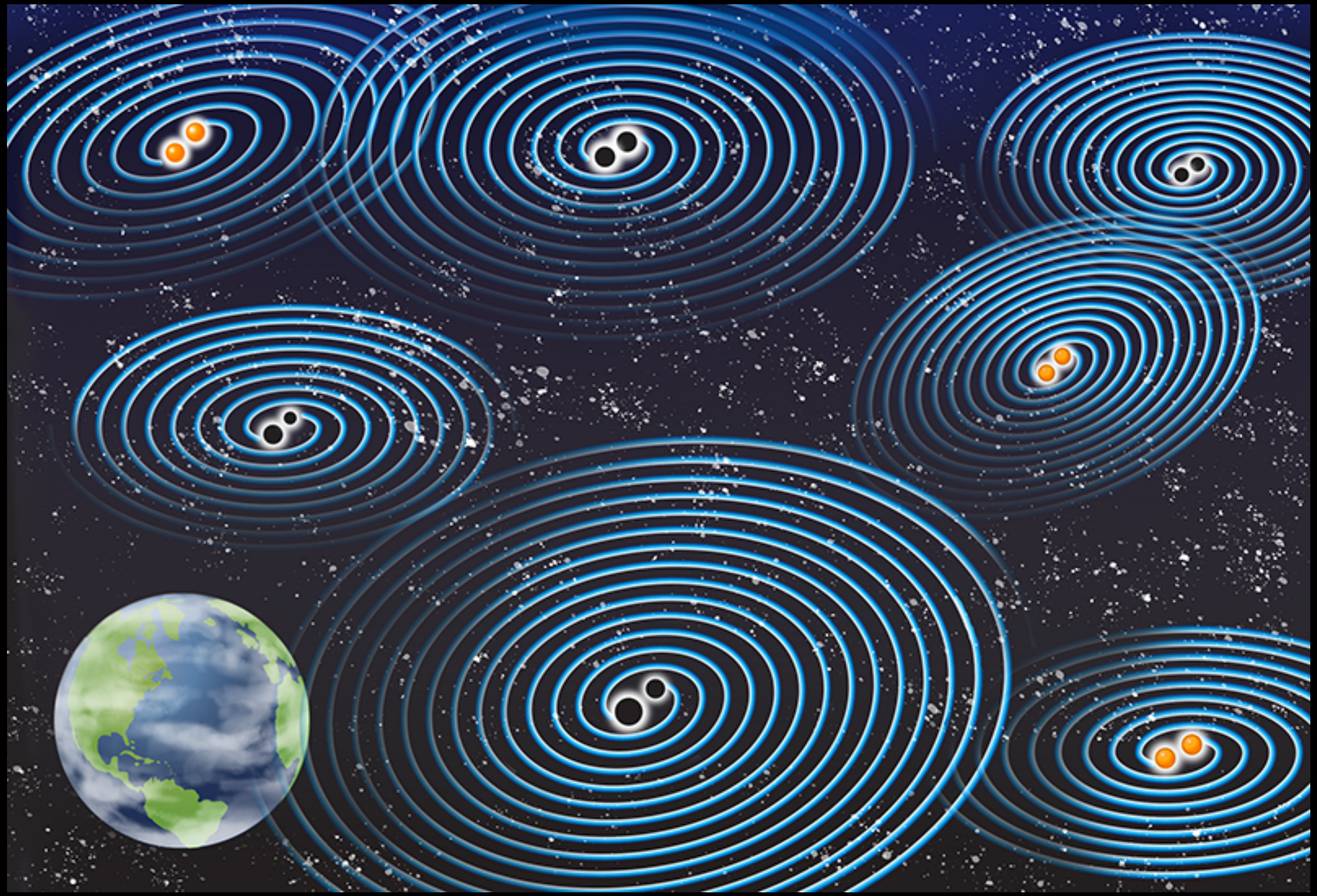
# 1990: Constructing a Pulsar Timing Array

Arrival time data from a spatial array of millisecond pulsars can be used (1) to provide a time standard for long time scales, (2) to detect perturbations of the Earth's orbit, and (3) to search for a cosmic background of gravitational radiation. In this paper we first develop a polynomial time series representation for these three effects that is appropriate for analysis of the present data with its limited degrees of freedom. We then describe a pulsar timing array program that we have established at the National Radio Astronomy Observatory 43 m telescope with observations of PSR 1620−26, PSR 1821−24, and PSR 1937+21.

341 Citations

Analysis of data from several observatories around the globe will provide the best possible solution for these effects.

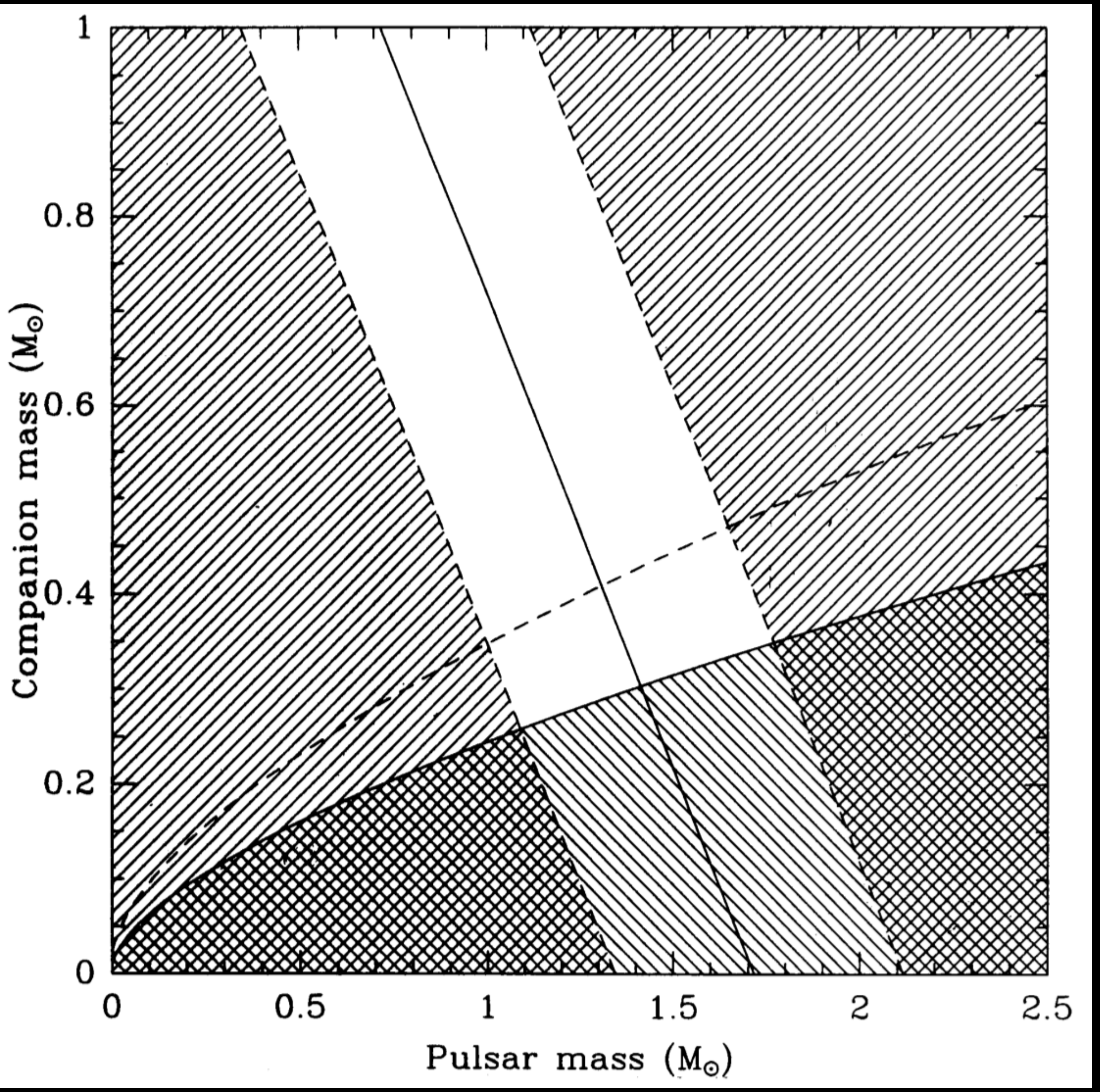


Credit: APS/Carin Cain

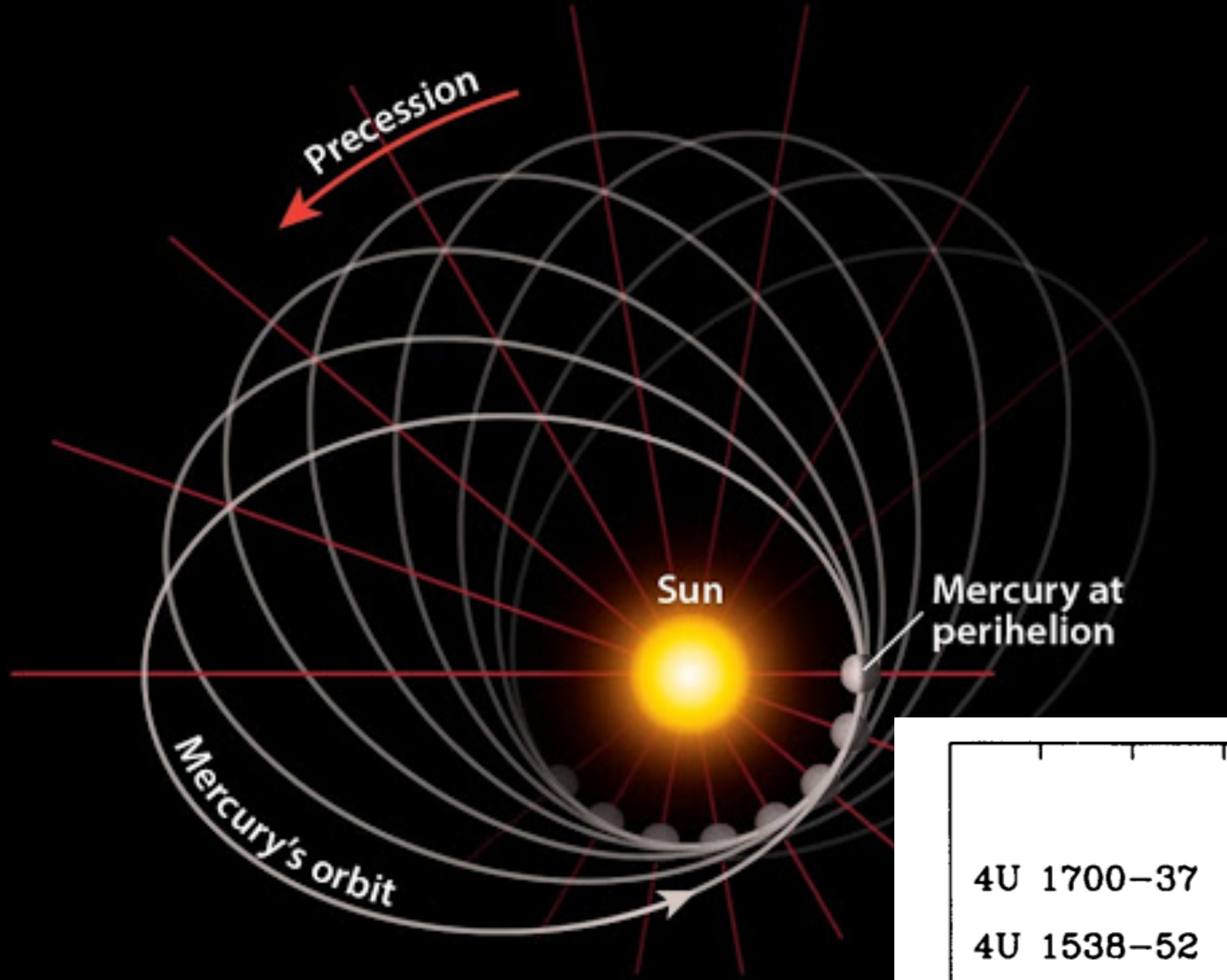
*Foster and Backer 1990, ApJ, 361, 300*

# 1993: The Masses of Two Binary Neutron Star Systems



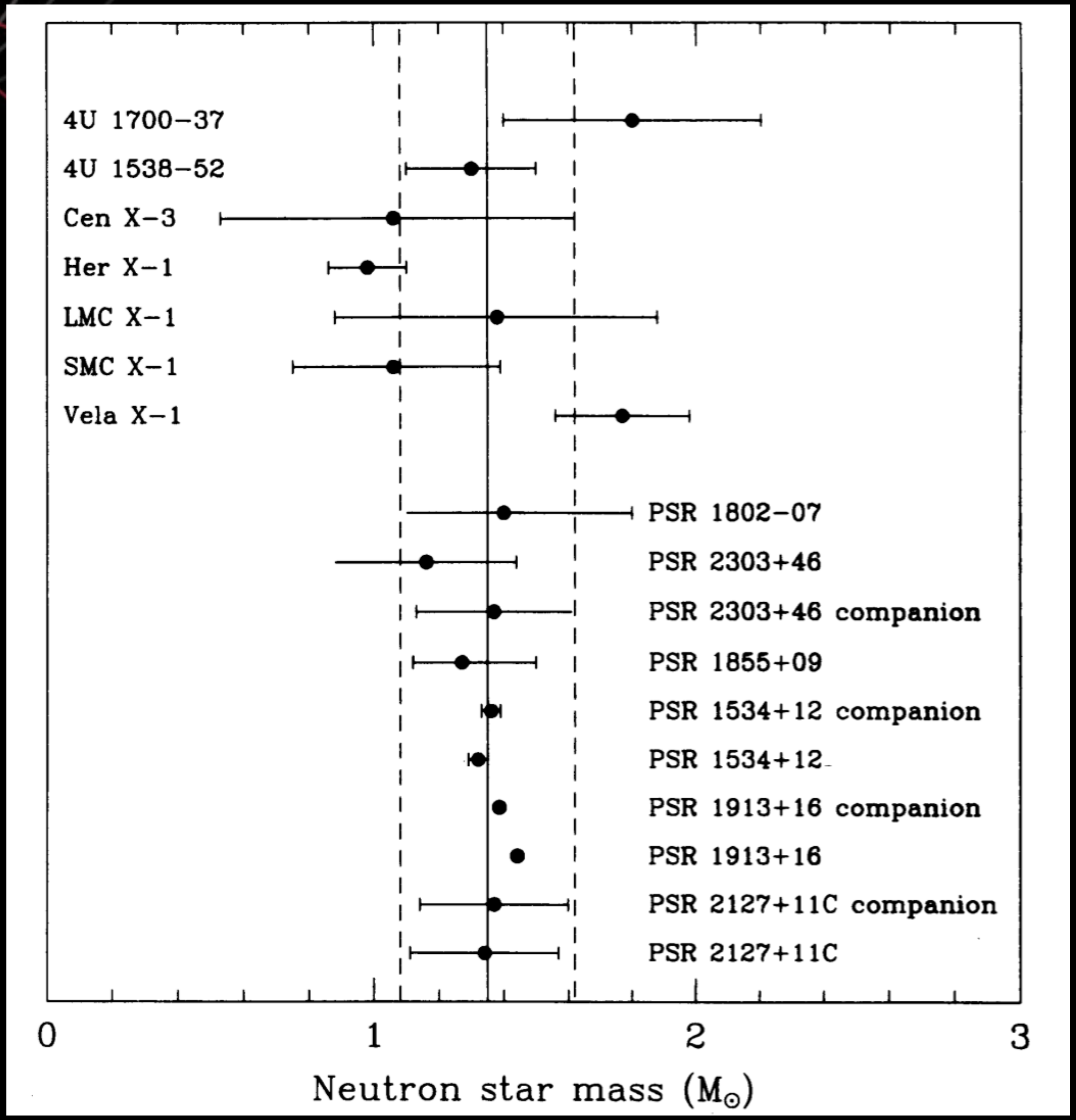

*Thorsett et al. 1993, ApJ, 405, L29*

146
Citations




$$f_1 \equiv \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = \frac{x^3}{(P_b/2\pi)^2}\left(\frac{1}{T_\odot}\right) M_\odot$$

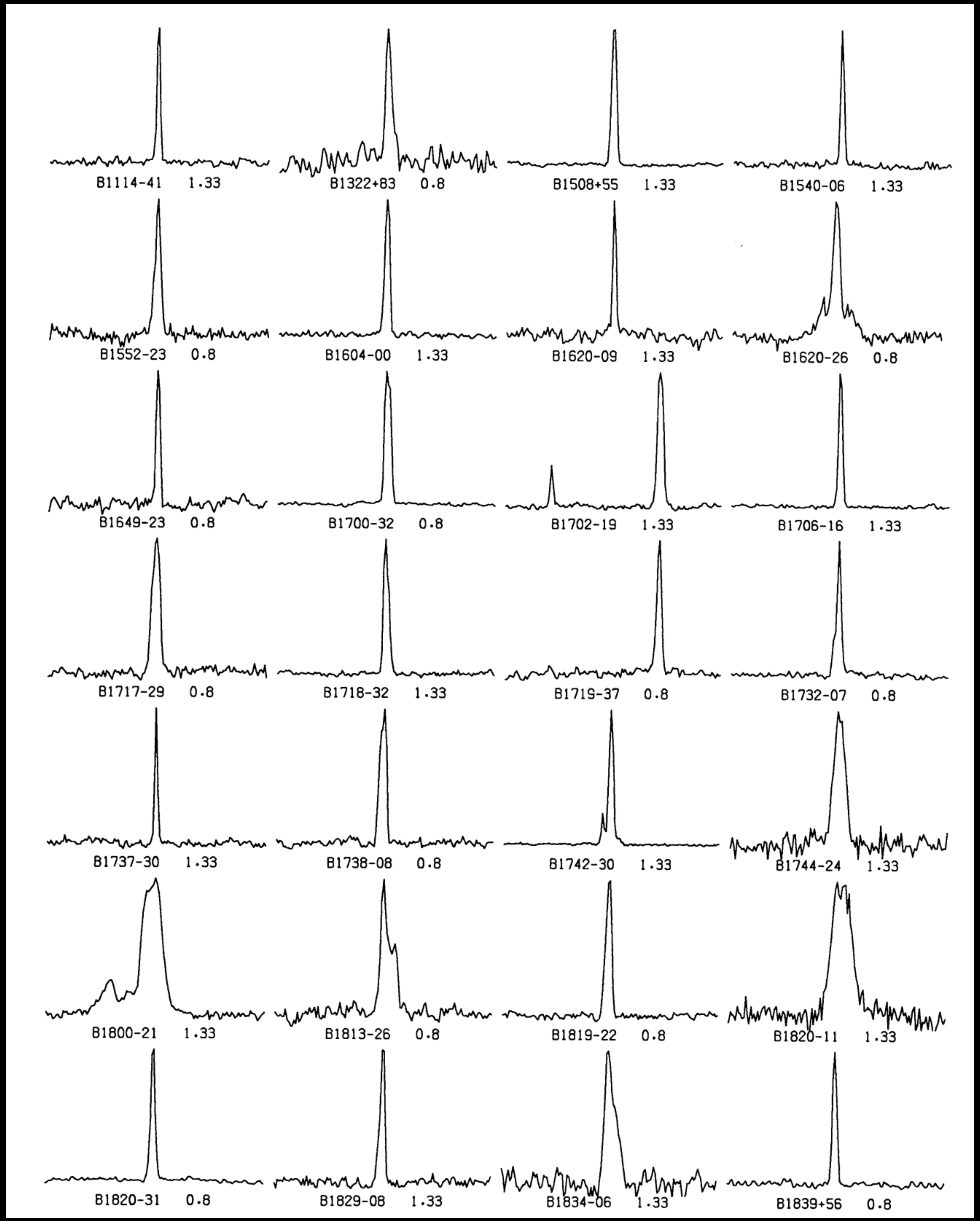
$$M \equiv m_1 + m_2 = \frac{1}{3\sqrt{3}}\left(\frac{P_b}{2\pi}\right)^{5/2}(1 - e^2)^{3/2}\dot{\omega}^{3/2}\left(\frac{1}{T_\odot}\right) M_\odot$$

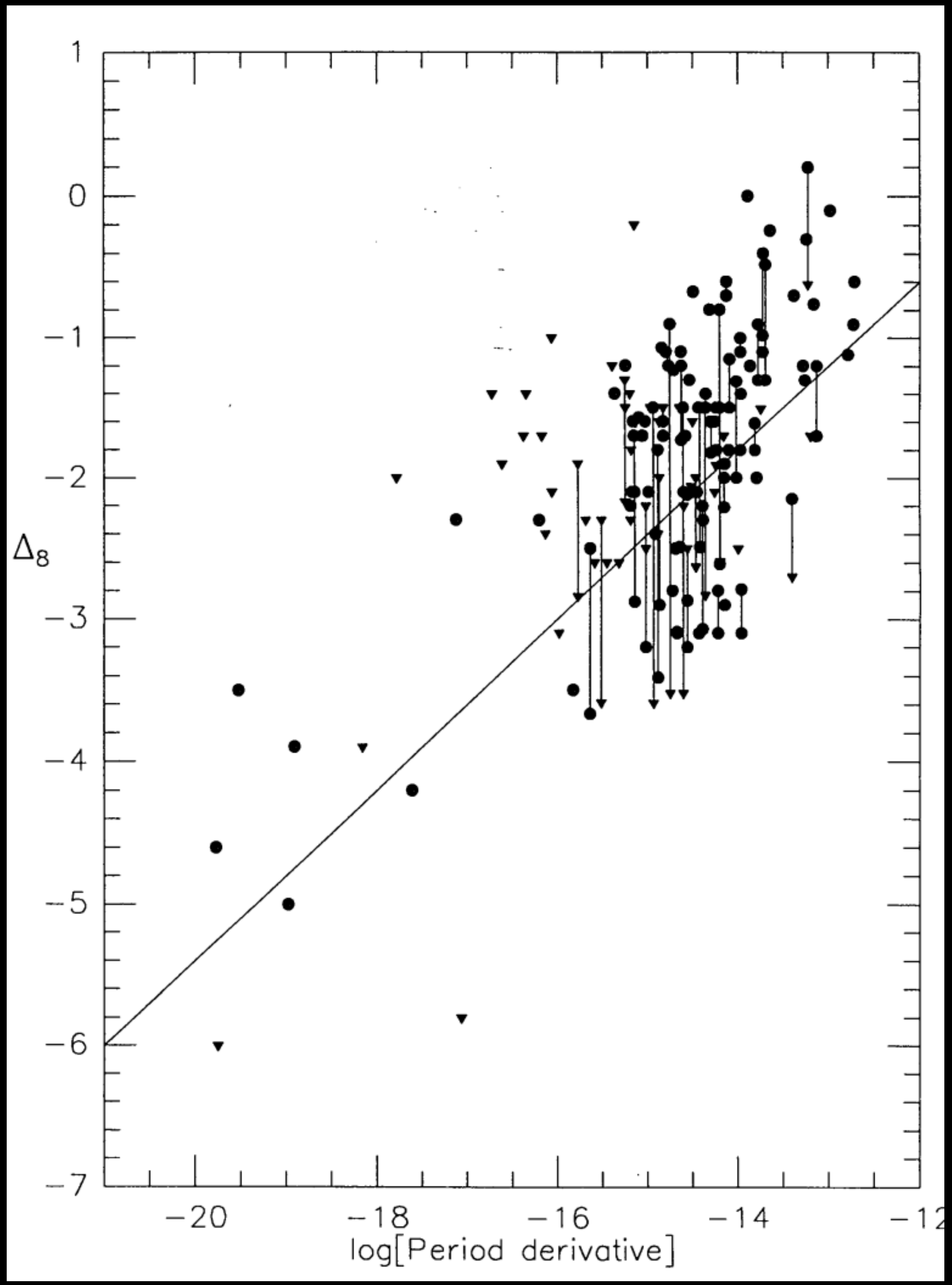



Determined masses for PSRs B1802-07 and B2303+46 through precession of periastron measurements

# 1994: Timing Behavior of 96 Radio Pulsars

205 Citations



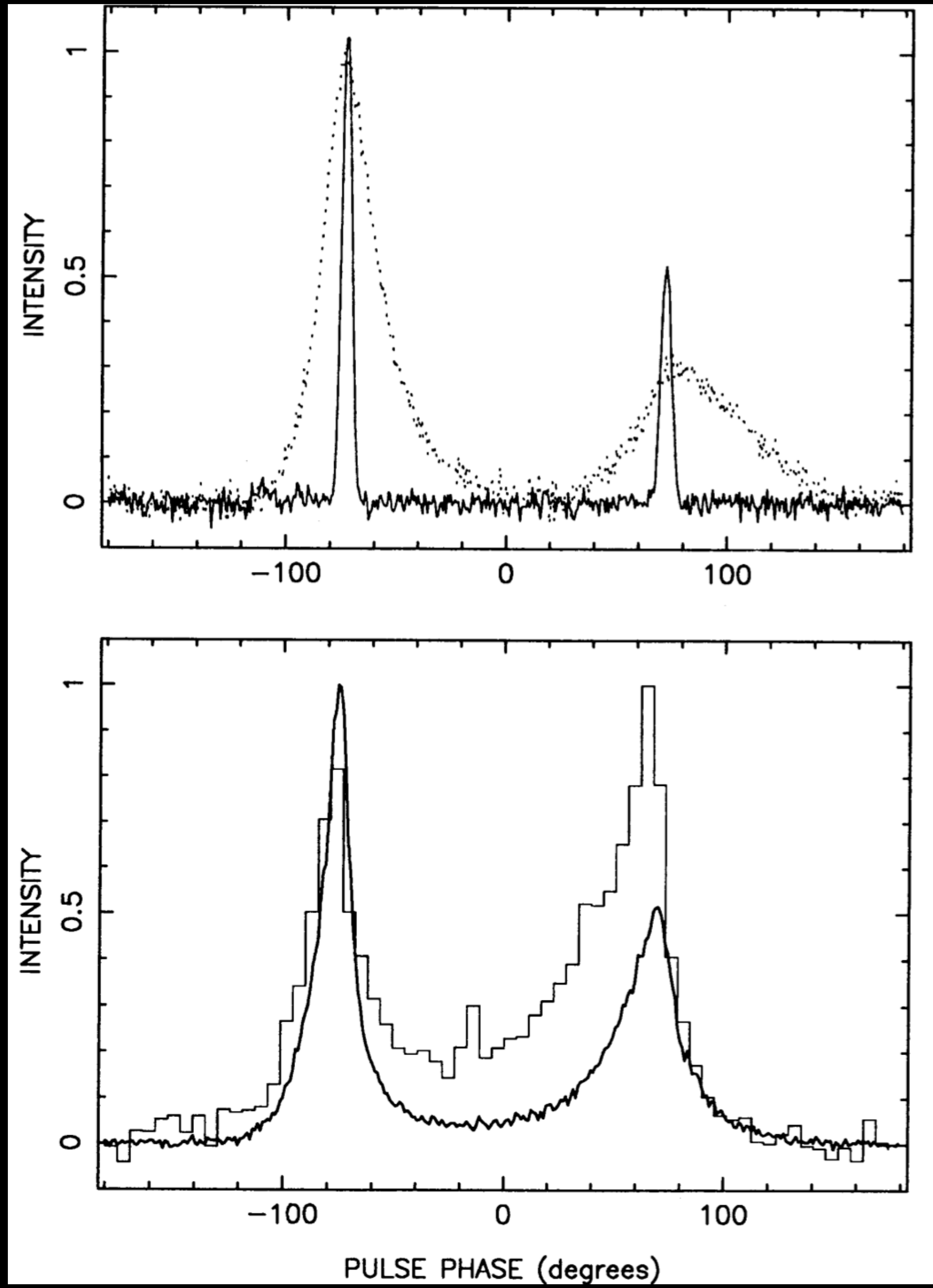

$$\Delta(t) = \log\left(\frac{1}{6\nu}\,|\ddot{\nu}|\,t^3\right)$$

Found strong evidence for correlation of spin-down noise with period derivative

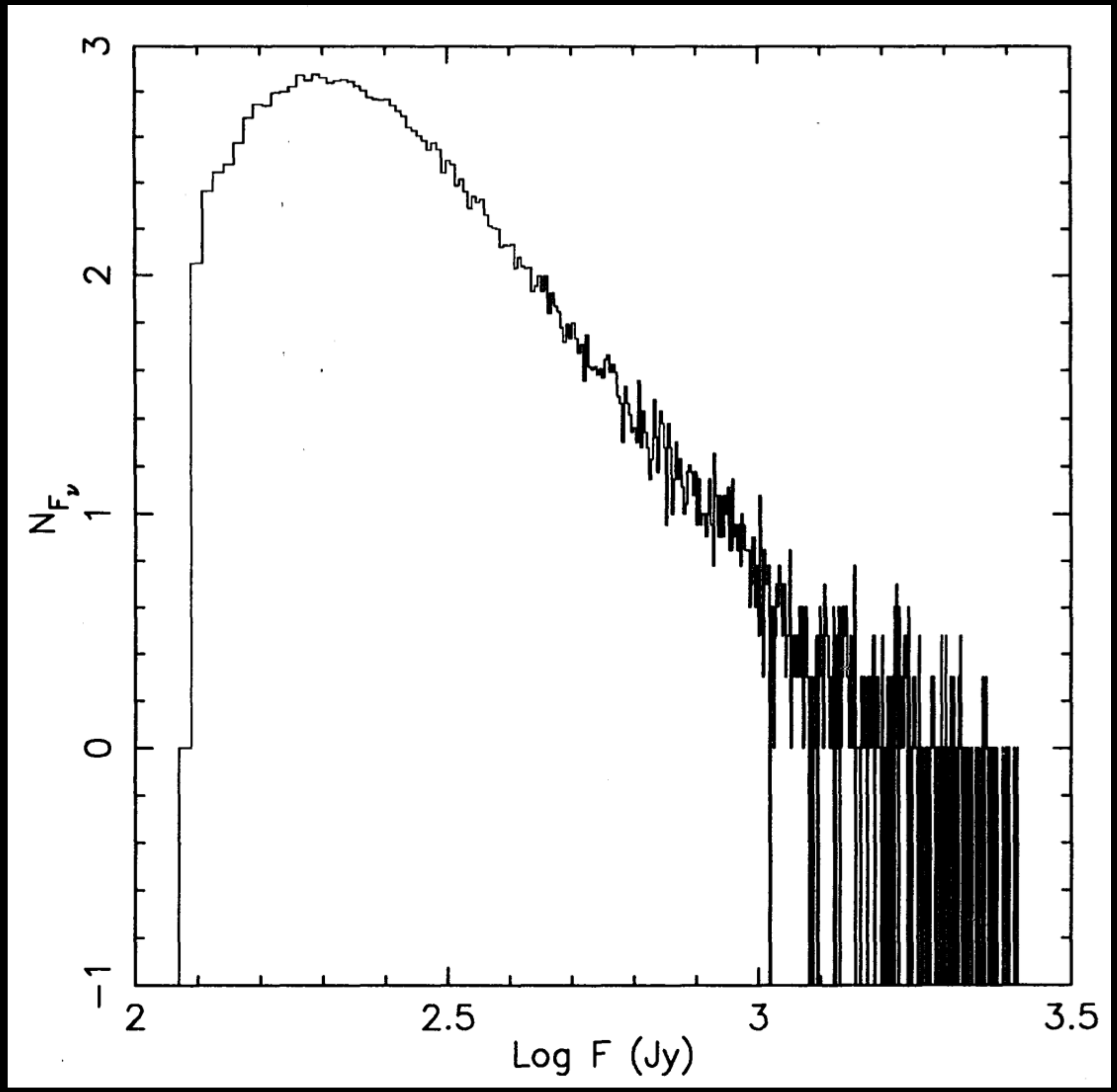
*Arzoumanian et al. 1994, ApJ, 422, 671*

# 1995: Giant Pulsars from the Crab Pulsar: A Joint Radio and Gamma-Ray Study

188 Citations




*Radio and IR (top) and X-ray and Gamma-ray (bottom) pulse profiles*



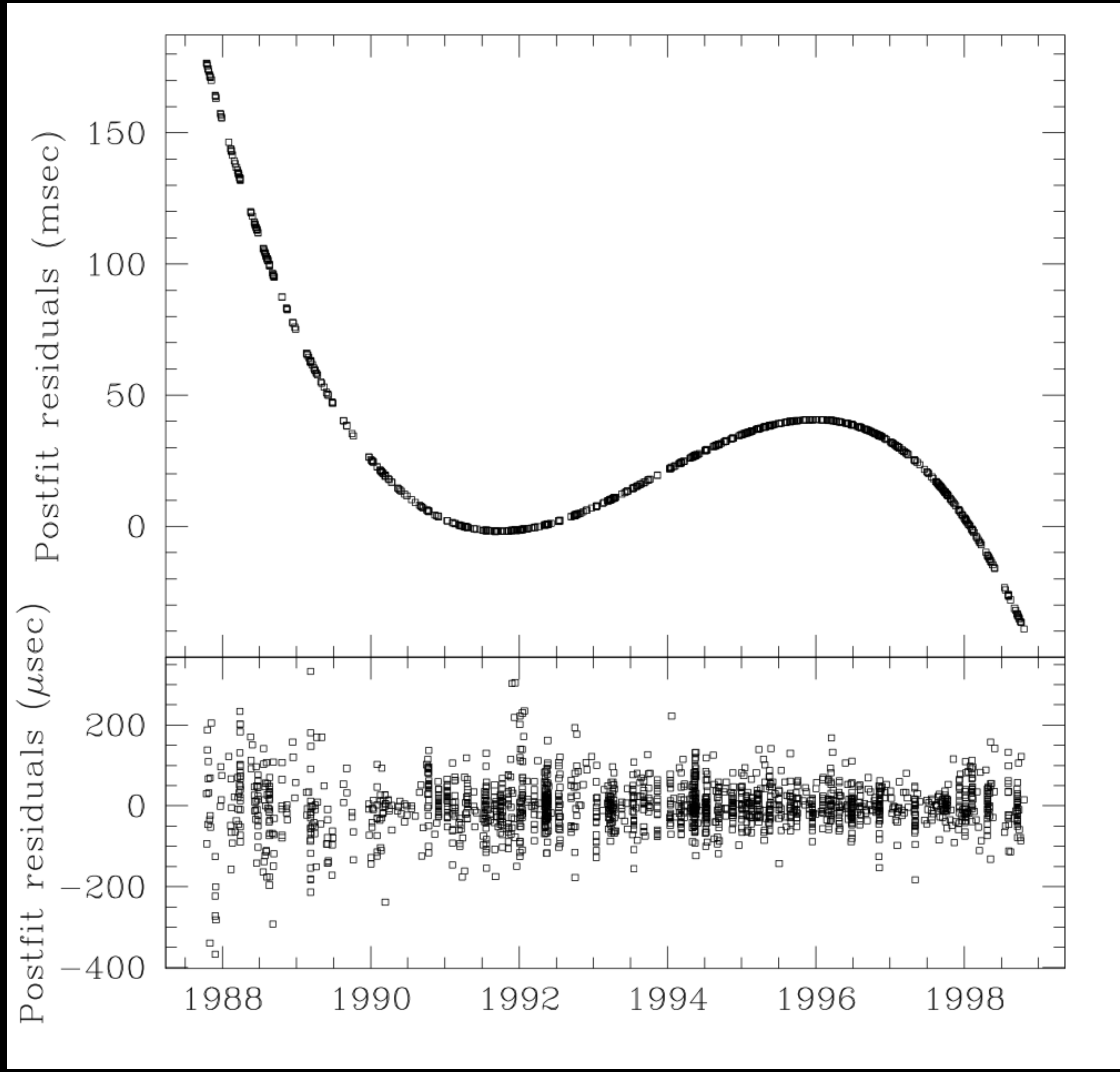

*Flux distribution of Crab giant pulses*

*Lundgren et al. 1995, ApJ, 453, 433*

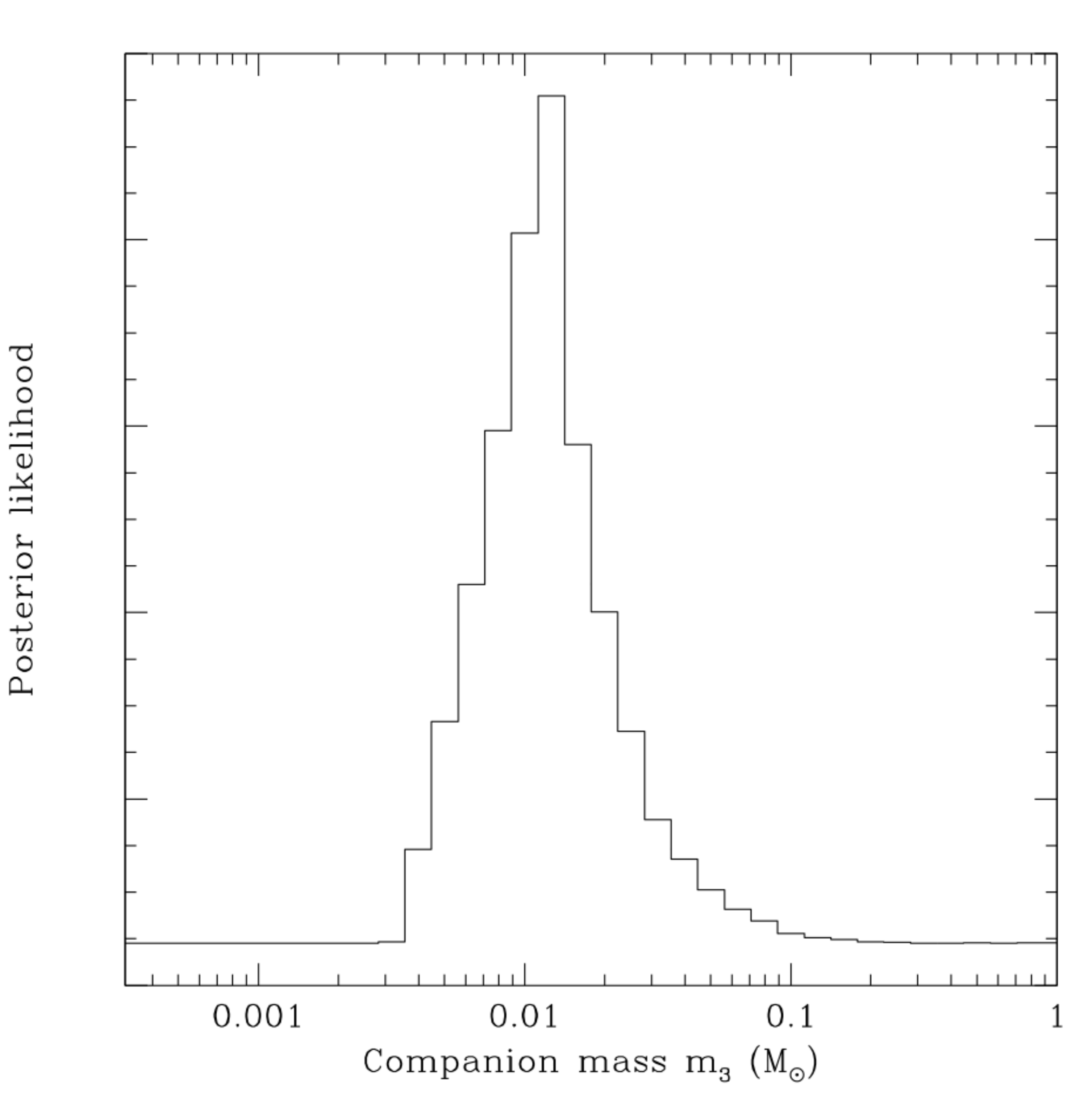
Giant pulses are emitted randomly, with no apparent correlation between gamma-ray and radio flux - implications for radio coherence mechanisms!

# 1999: The Triple Pulsar System PSR B1620-26 in M4

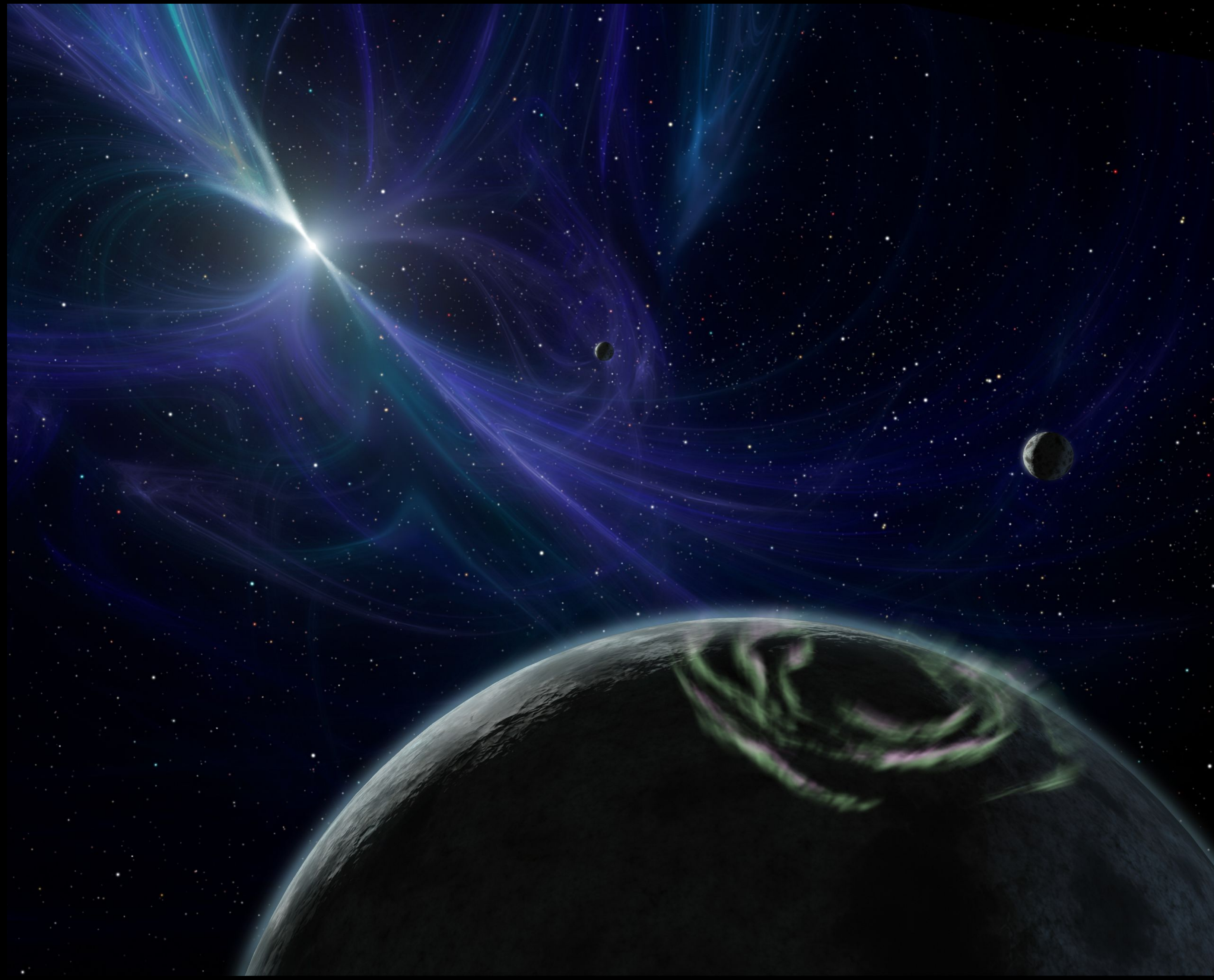
105 Citations




Timing residuals before (top) and after (bottom) accounting for a planet orbiting white dwarf and pulsar

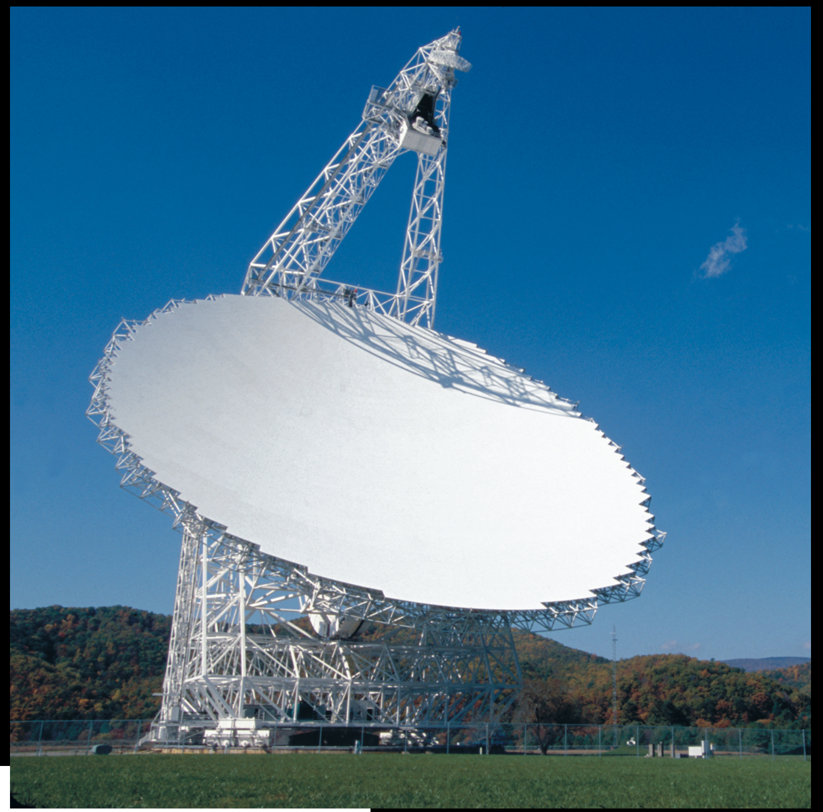


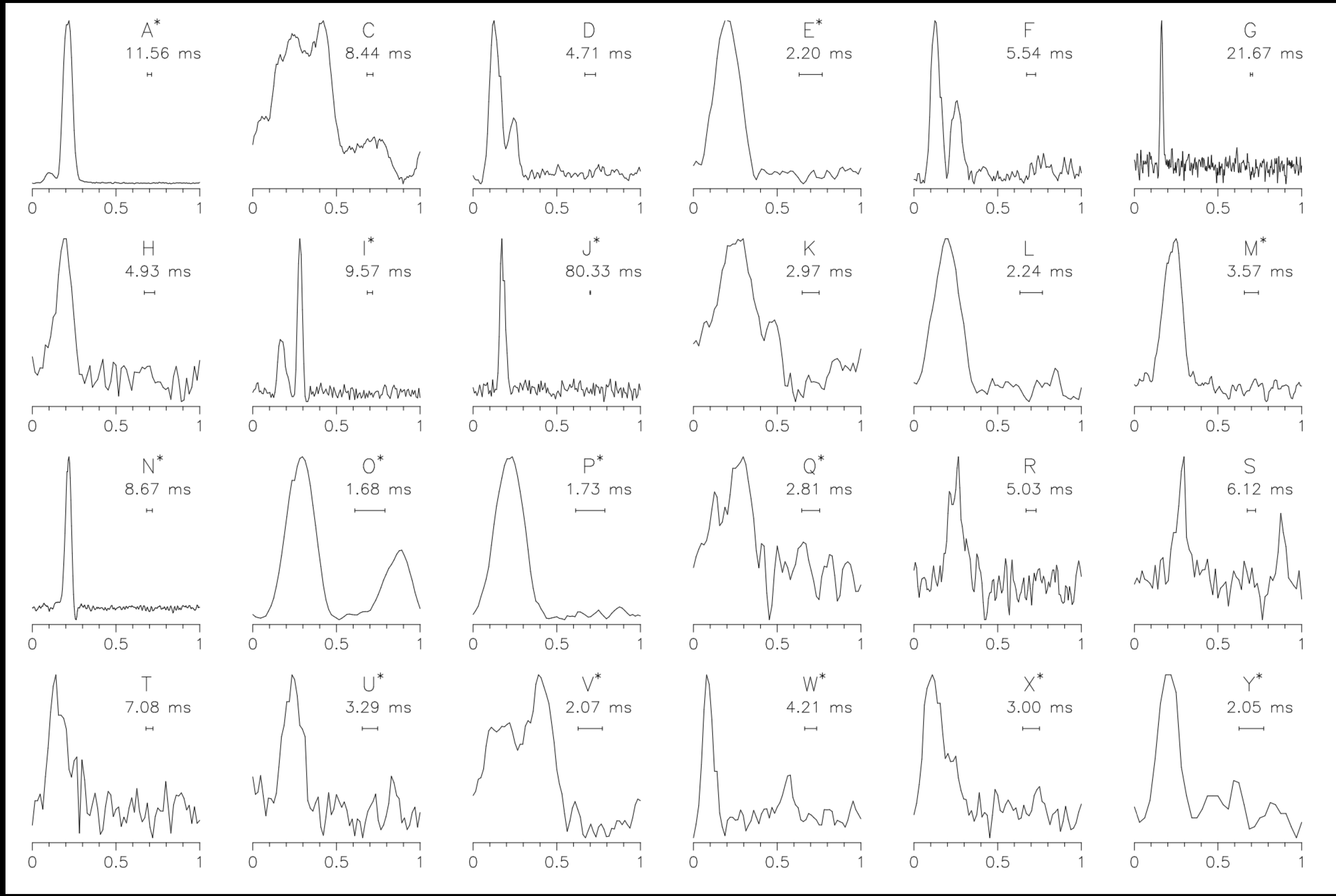

Probability distribution for planet mass



Thorsett et al. 1999, ApJ, 453, 433

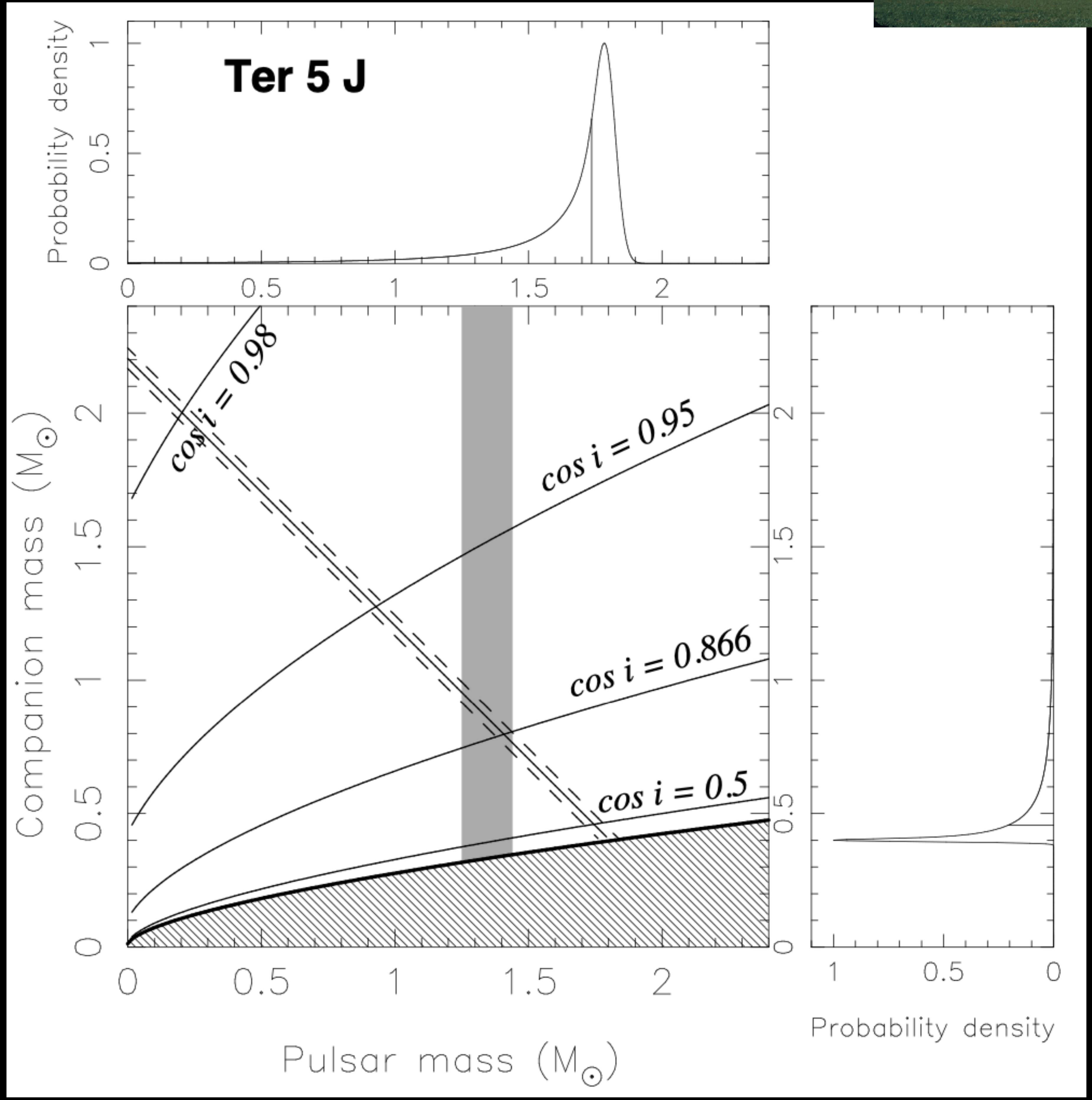
# 2005: Twenty-One Millisecond Pulsars in Terzan 5 Using the Green Bank Telescope






*Ransom et al. 2005, Science, 307, 892*

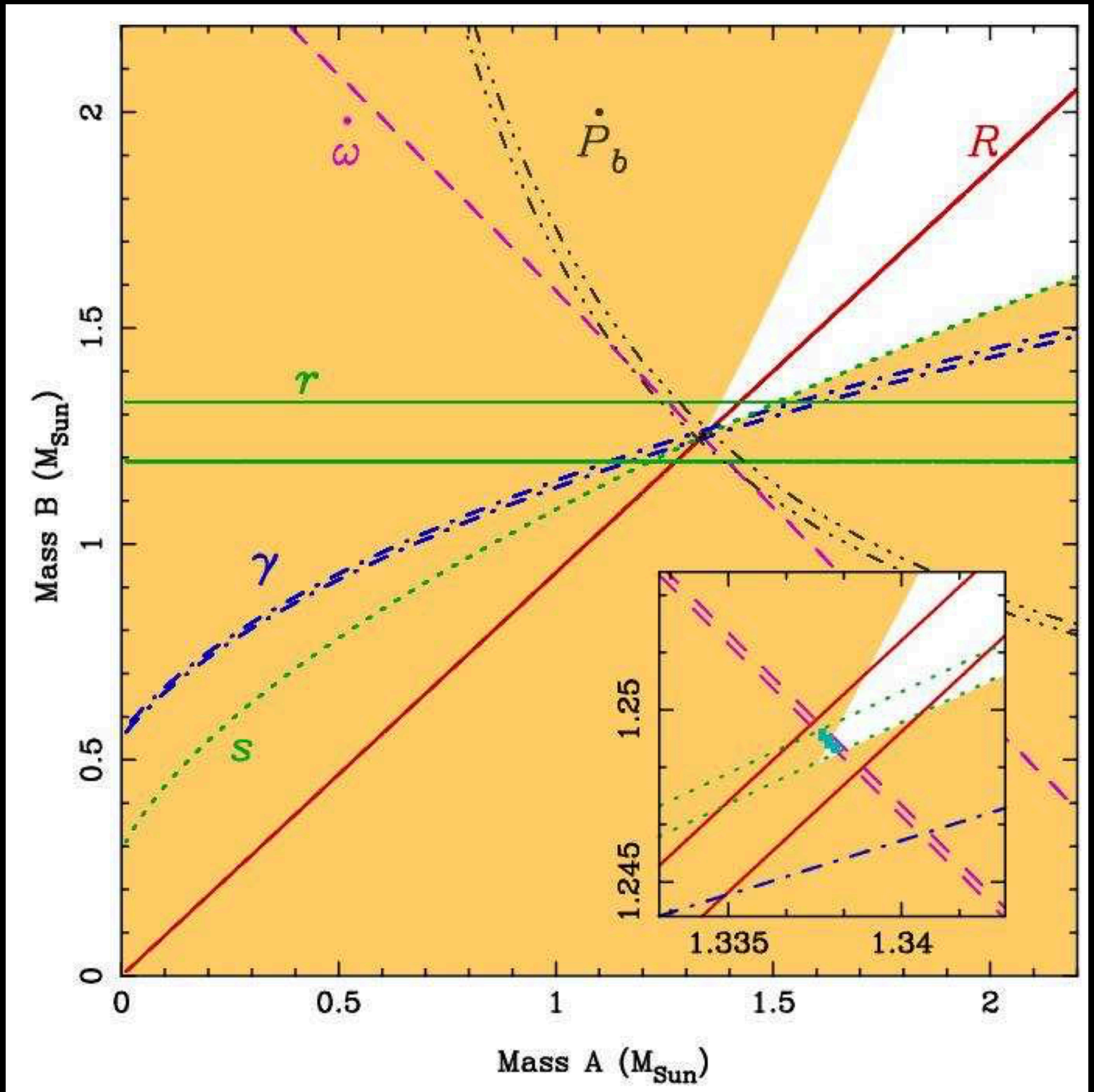
## 267 Citations




*Mass constraints from periastron advance for one binary MSP*

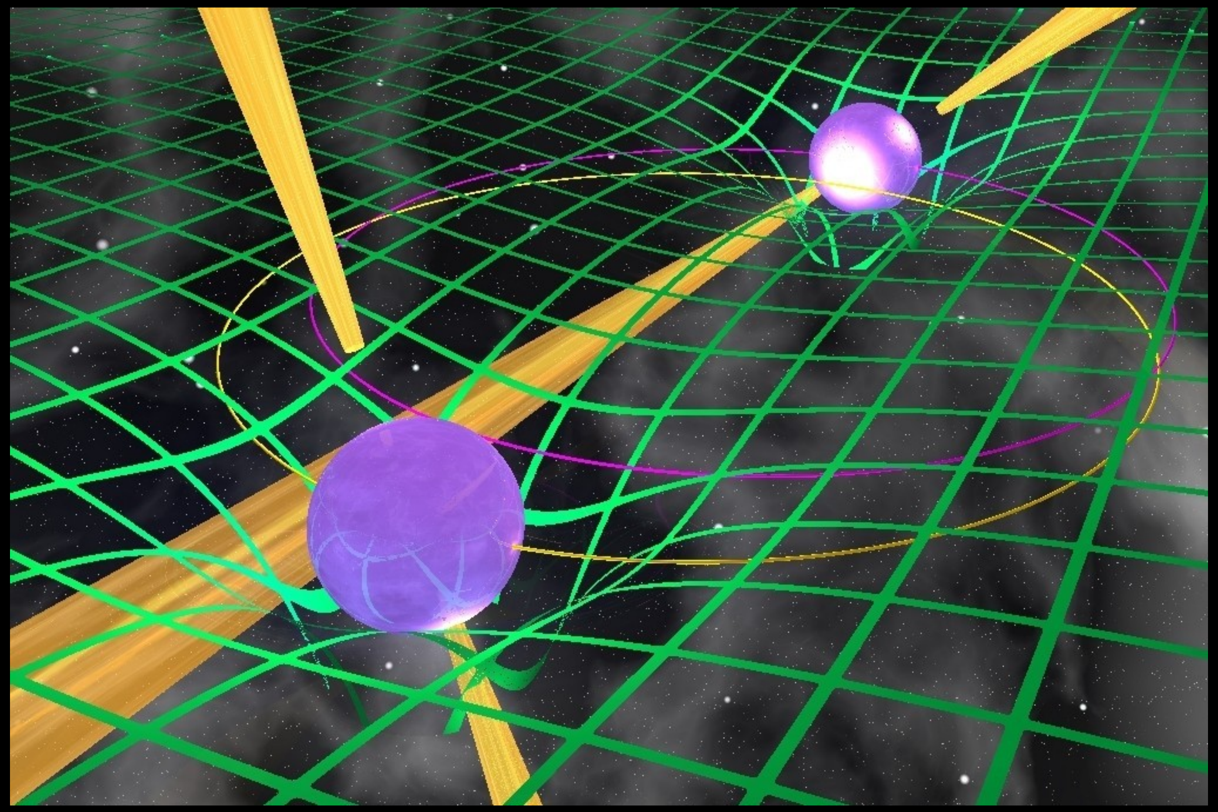
# 2006: Tests of General Relativity from Timing the Double Pulsar

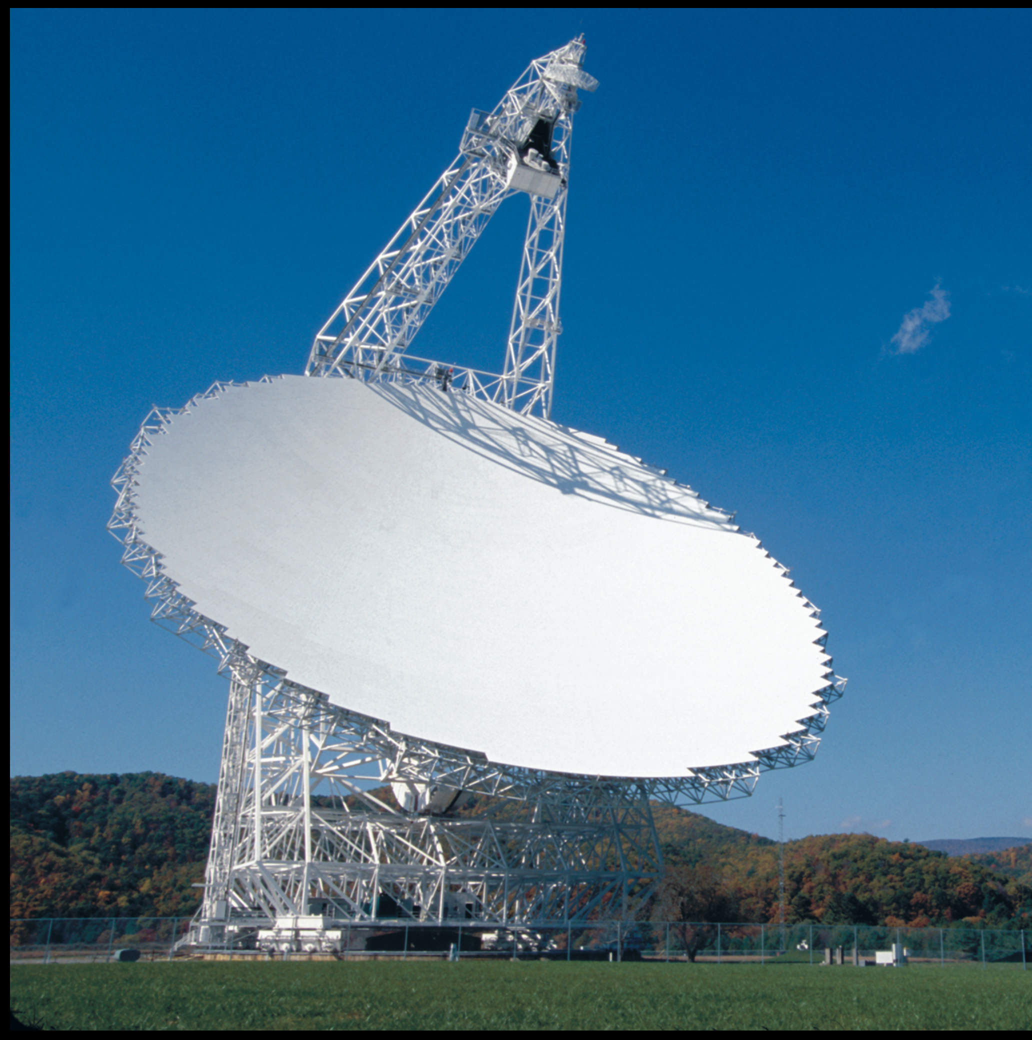
664 Citations

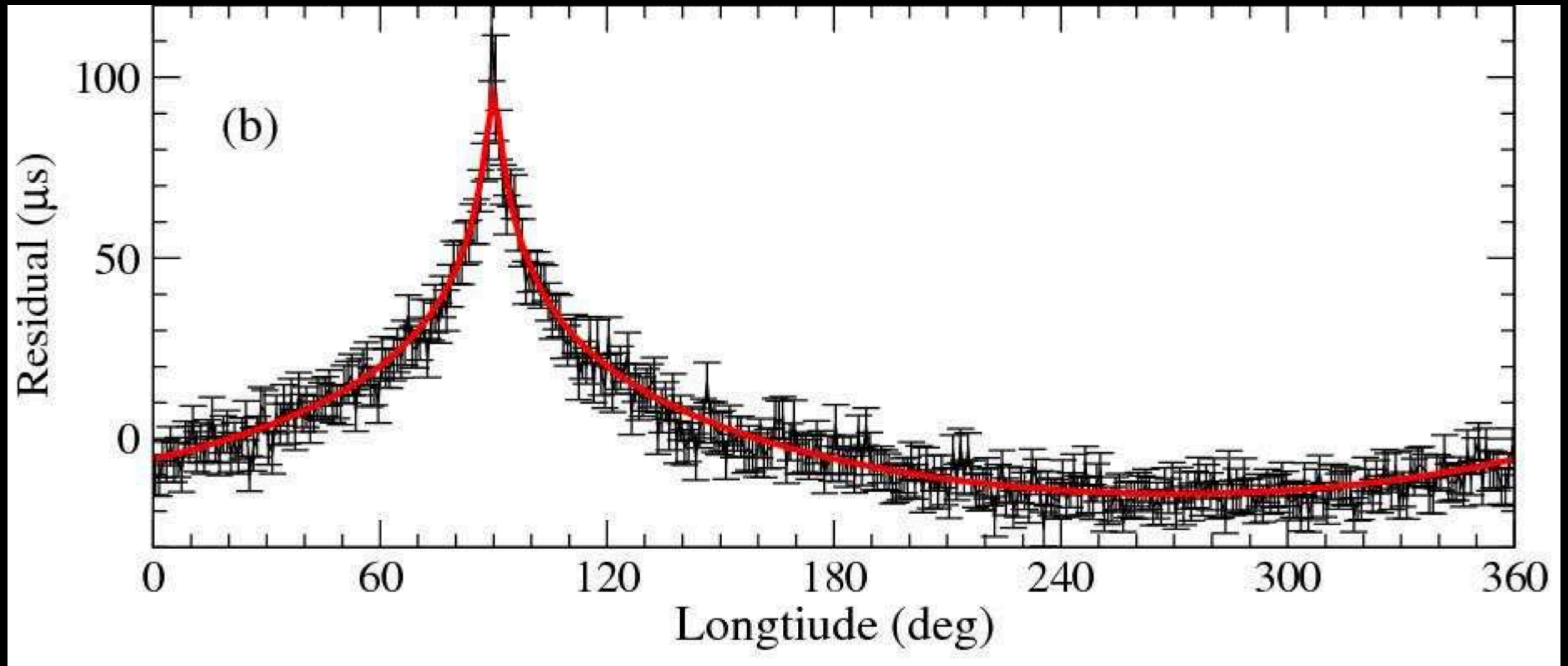



*Mass-Mass Diagram*

*Kramer et al. 2006, Science, 314, 97*

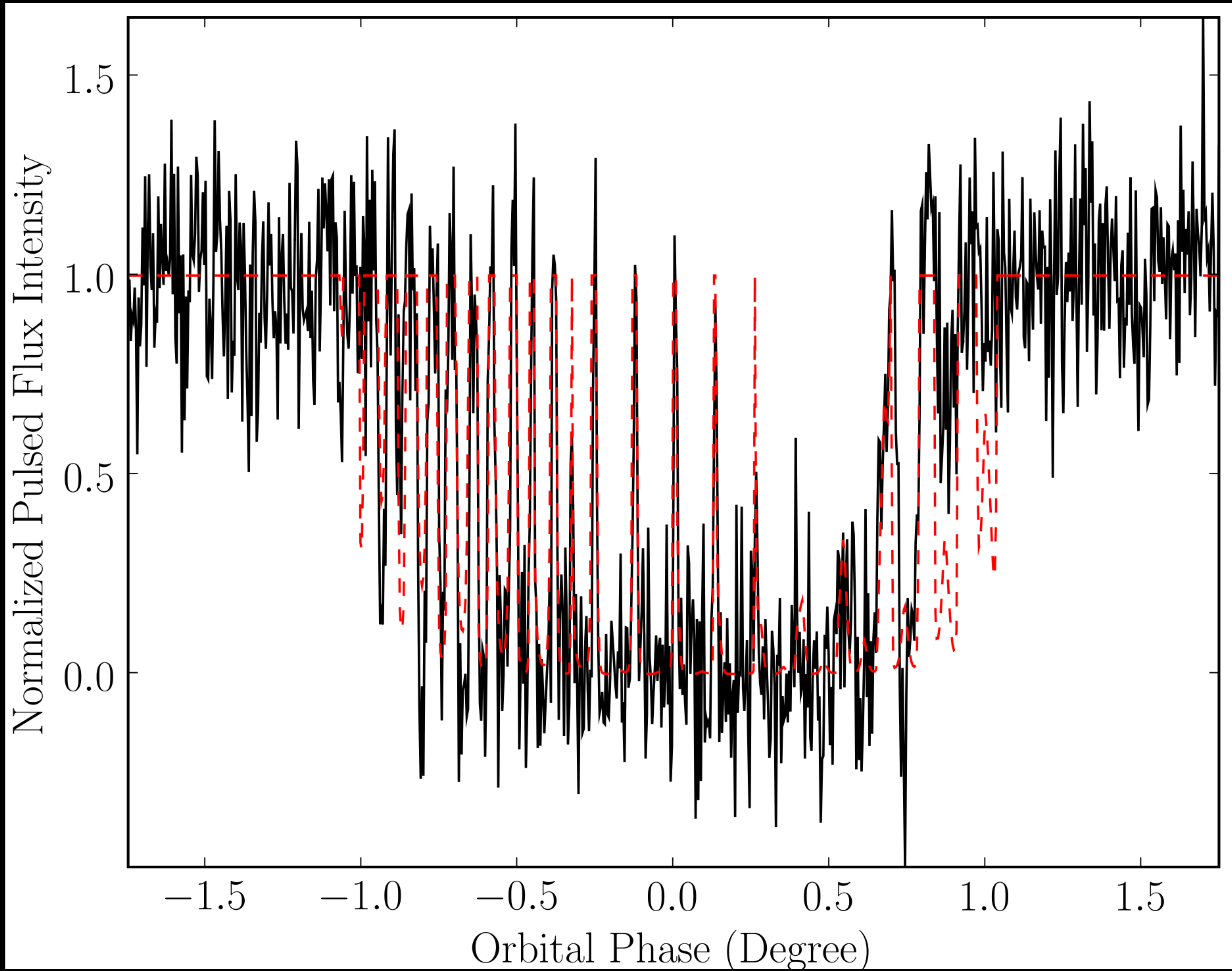






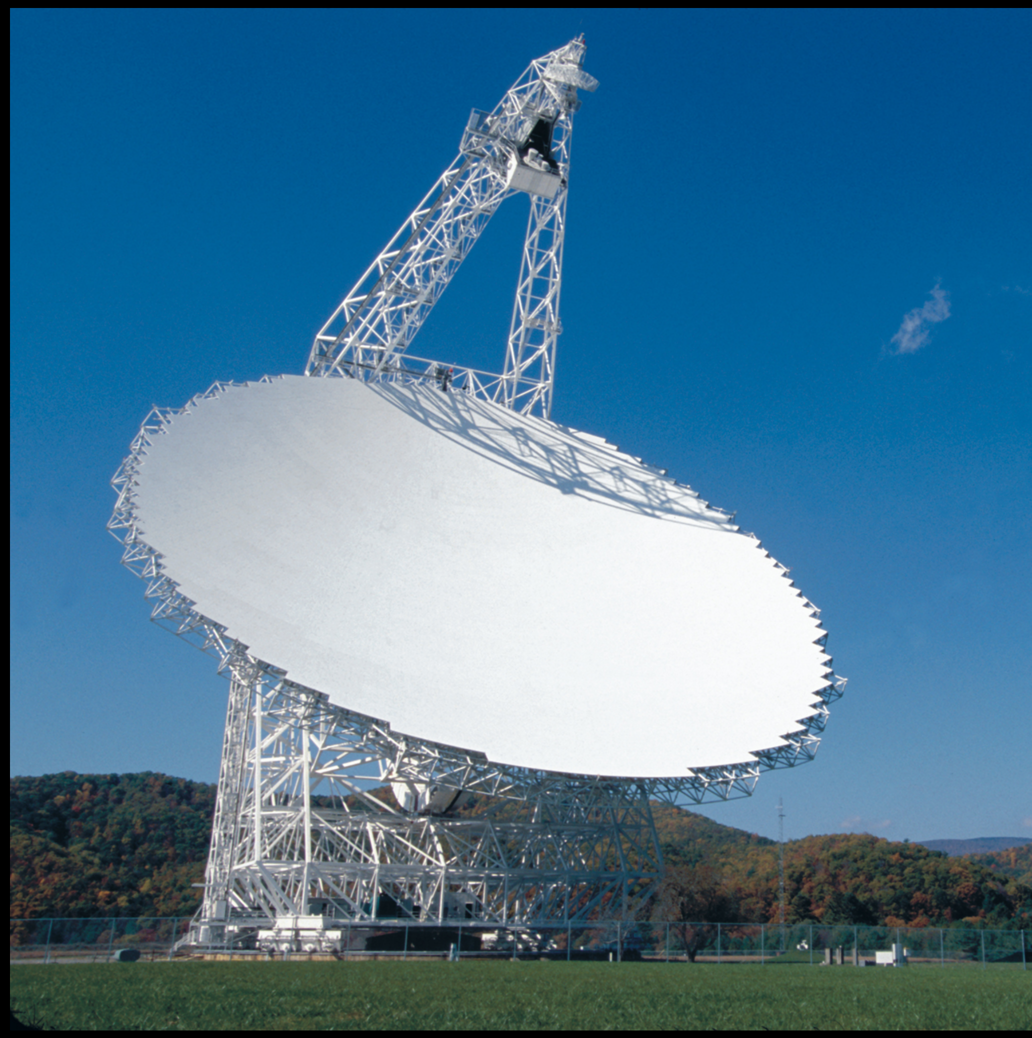

Shapiro delay “shape” parameter is consistent with GR to 0.05%

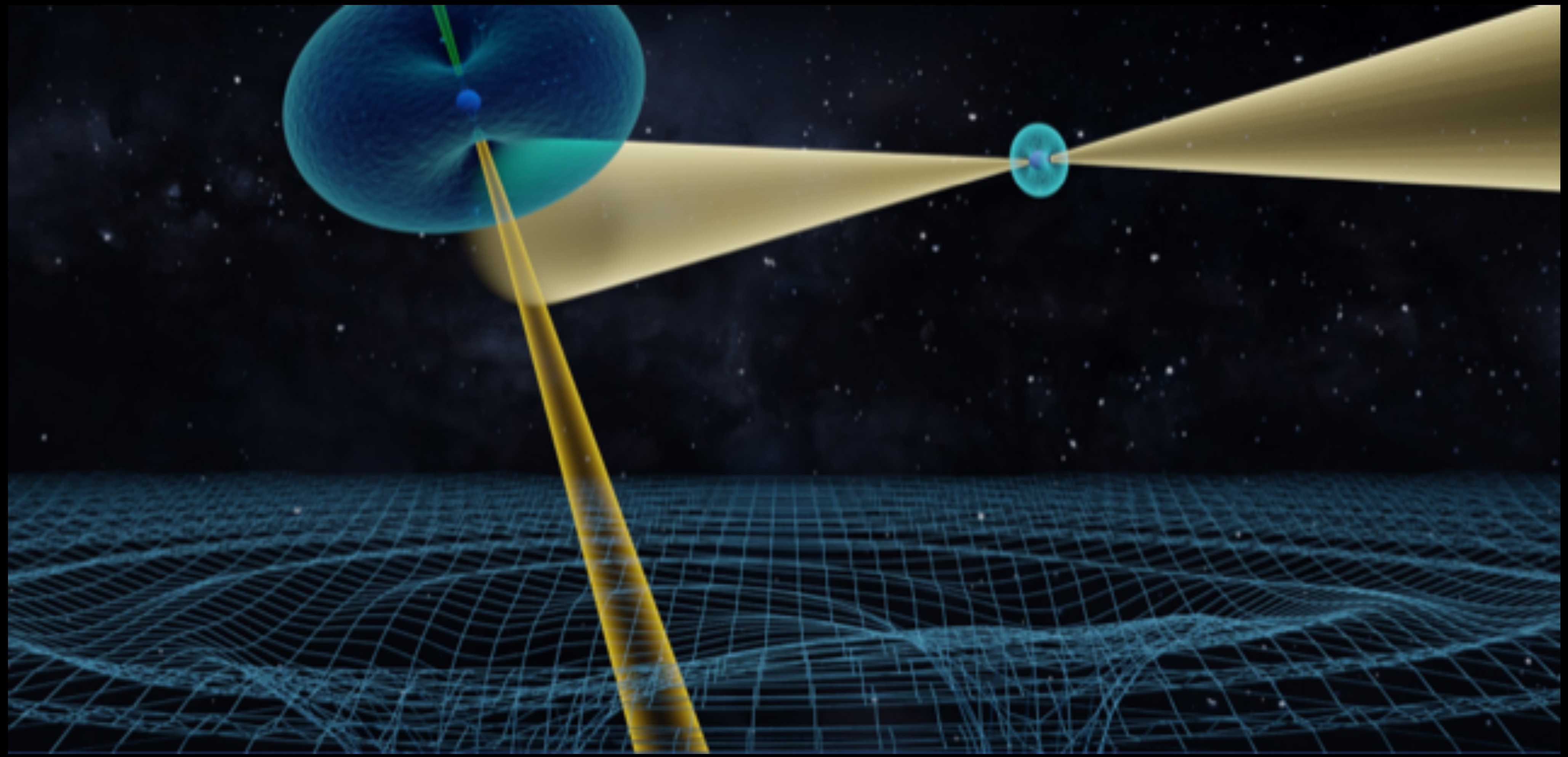
# 2008: Relativistic Spin Precession in the Double Pulsar




*Eclipse of pulsar A fit to pulsar B transparency windows*

135 Citations

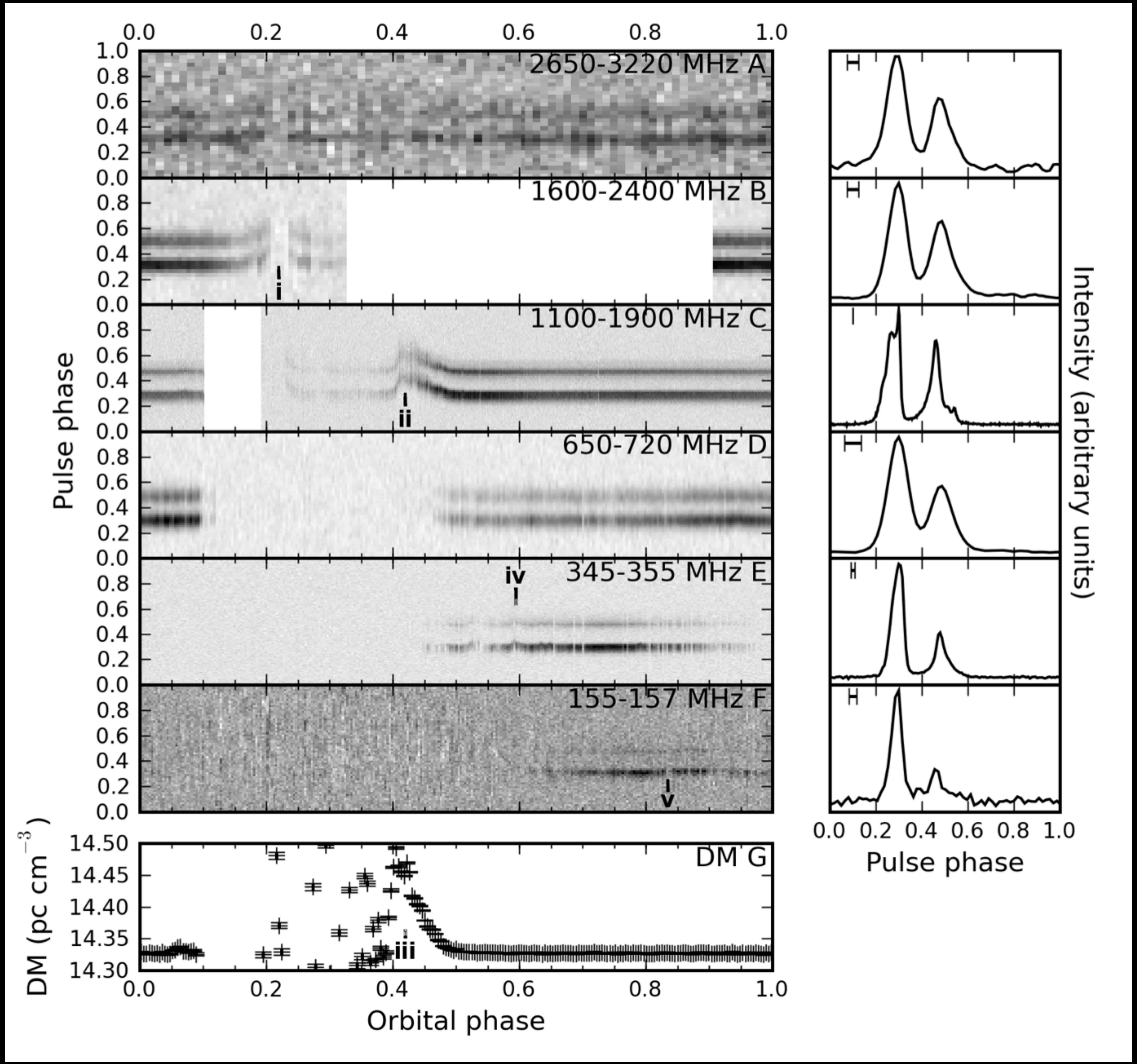




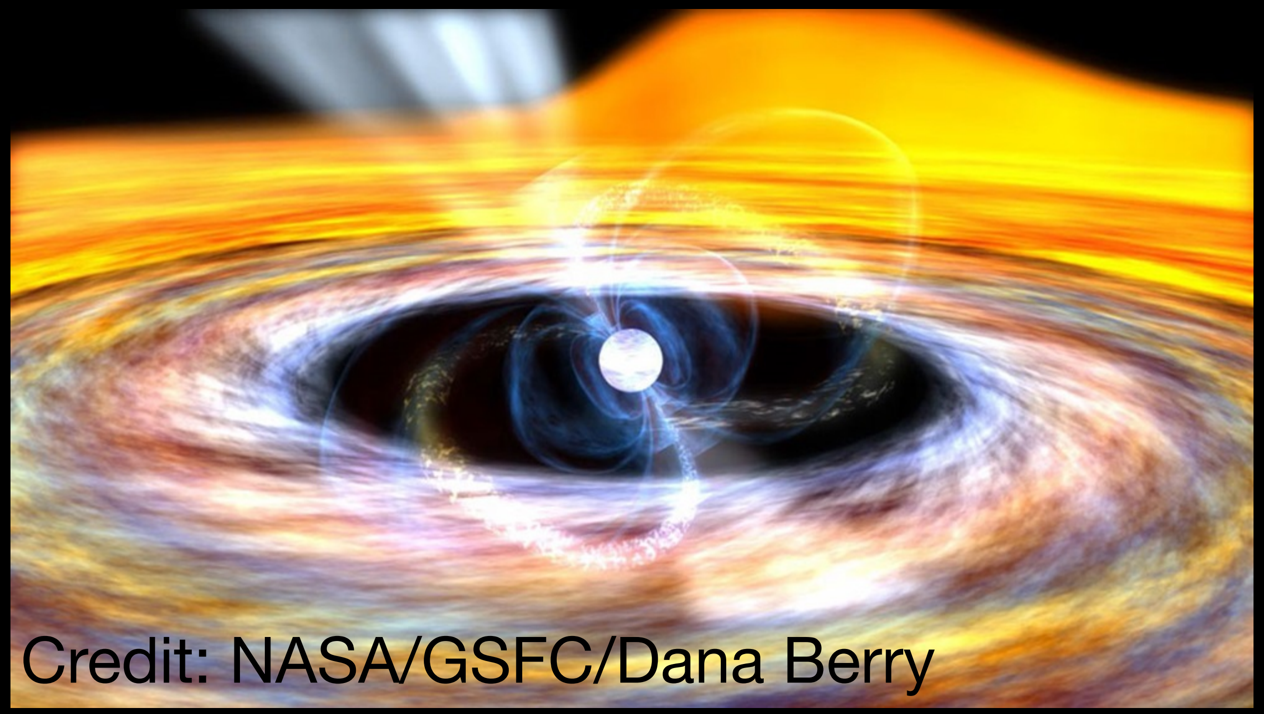
Measured geodetic precession rate consistent with GR to 13%

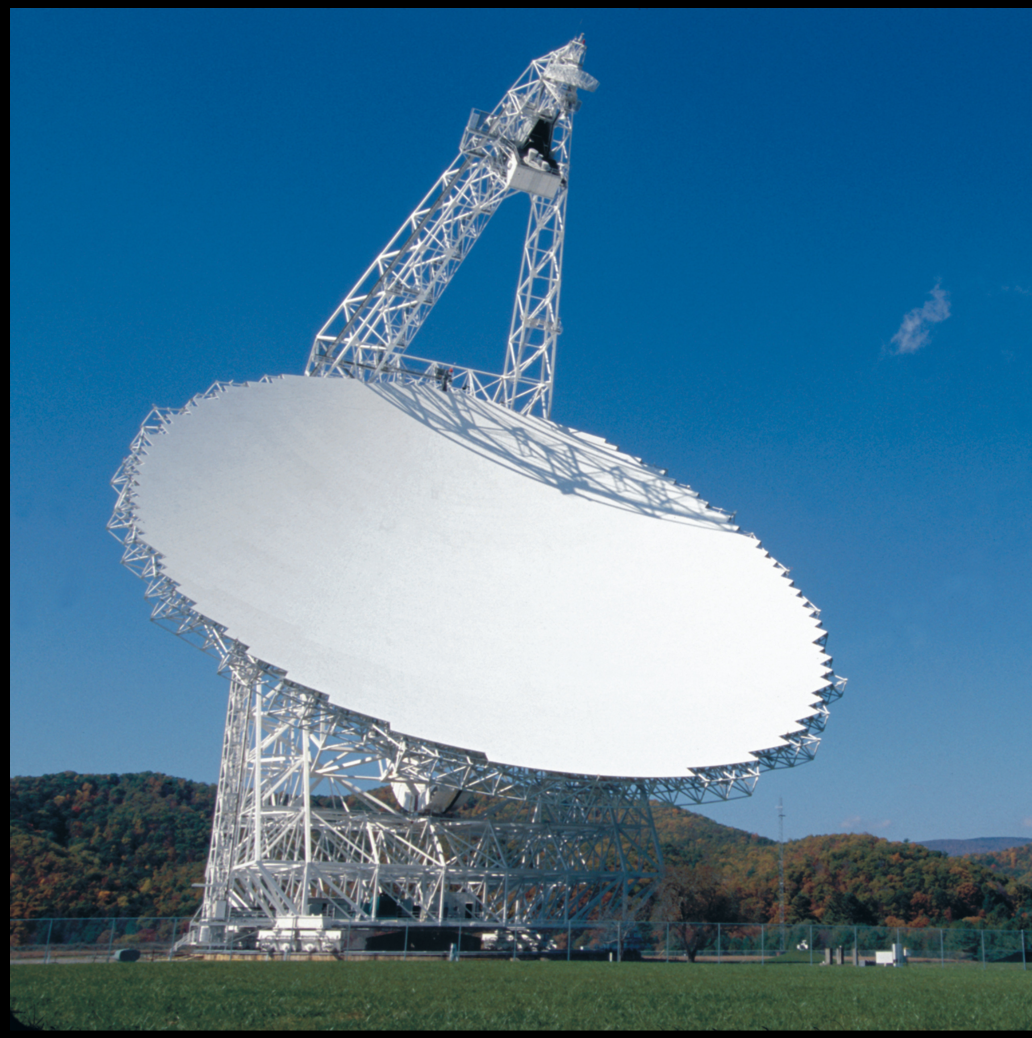
*Breton et al. 2008, Science, 314, 5796*

# 2009: A Radio Pulsar/X-ray Binary Link




*Eclipse profiles, pulse profiles at different frequencies, along with DM measurements*



First millisecond pulsar to show evidence for recent accretion, based on optical observations of companion.

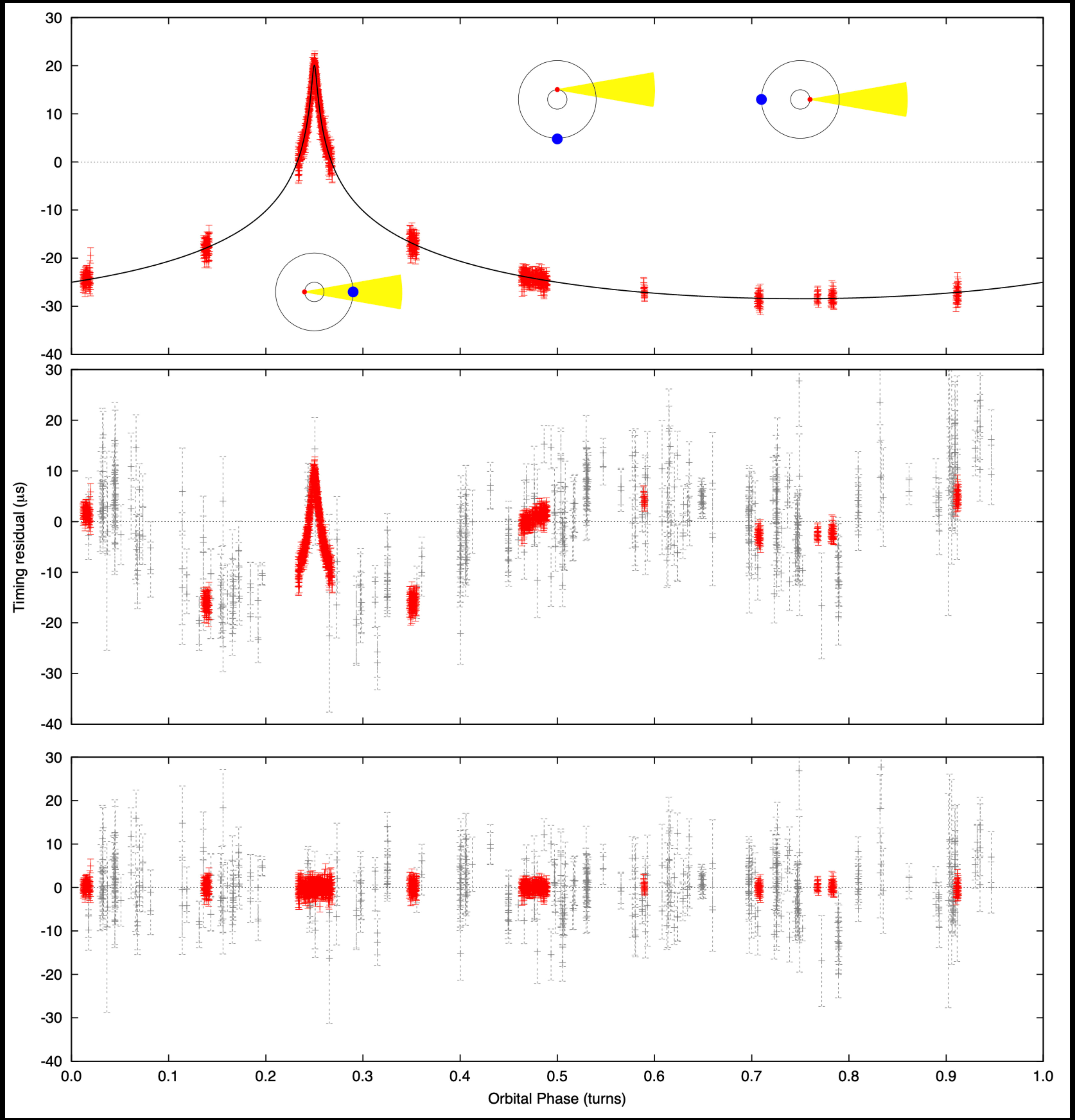
Proof of “recycling” hypothesis for MSP formation.

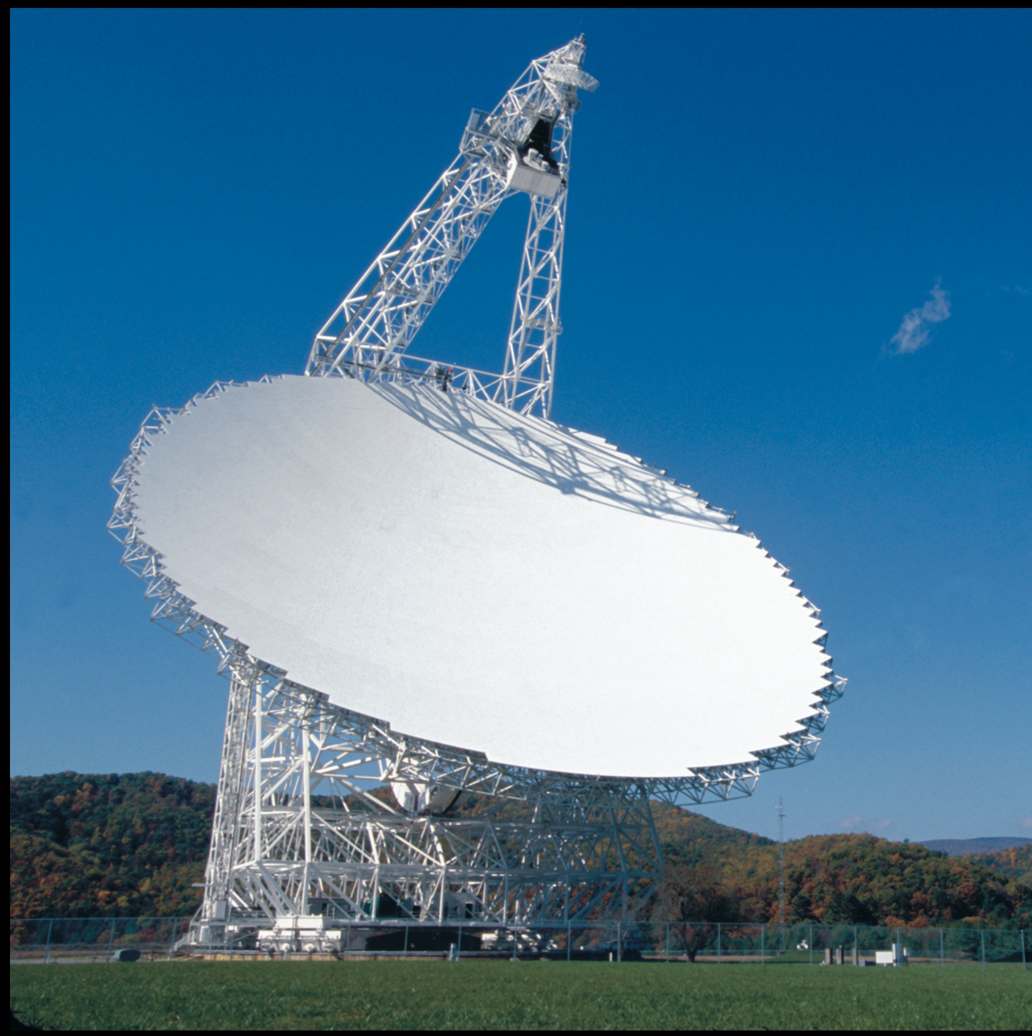
423 Citations

*Archibald et al. 2009, Science, 324, 5933*

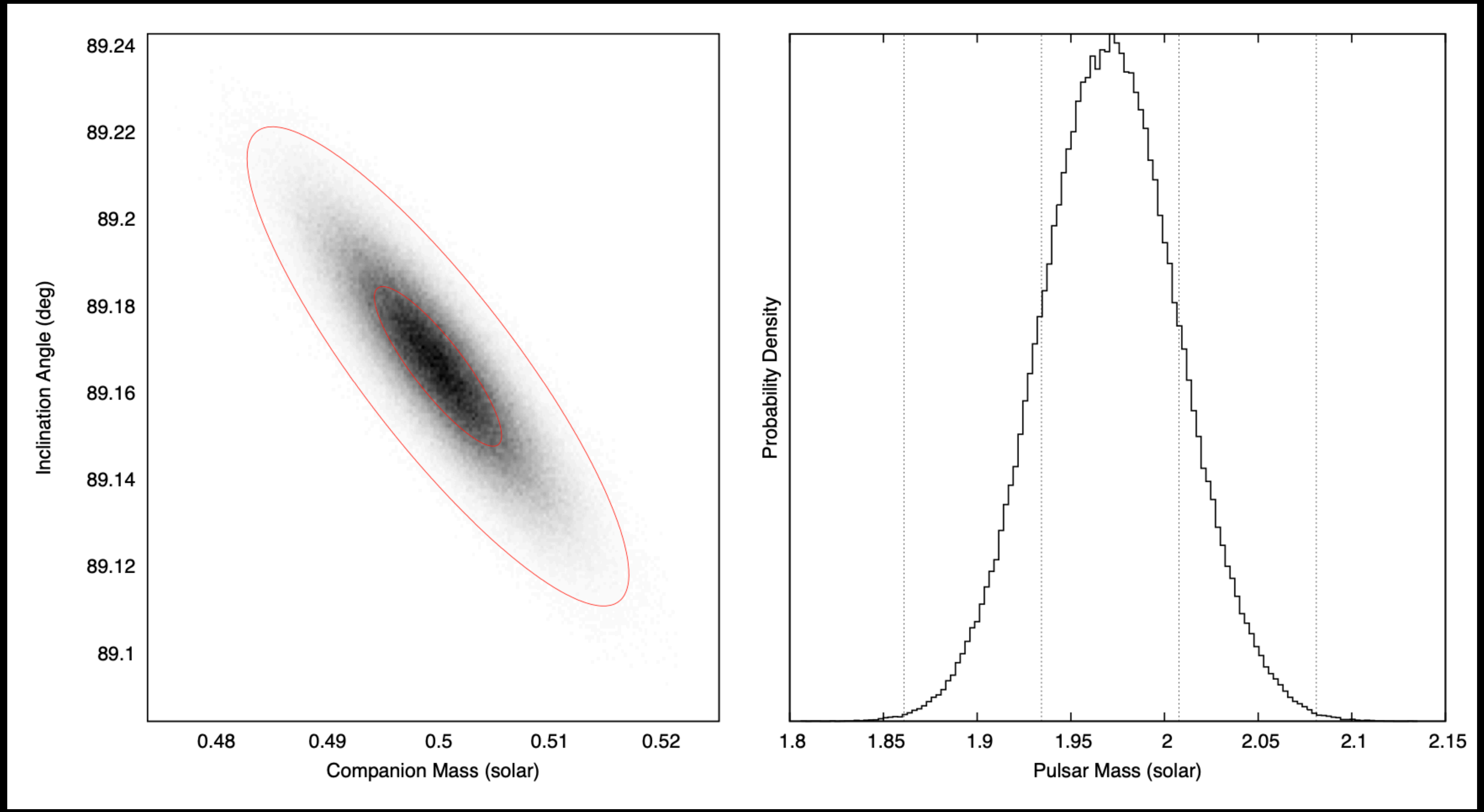
# 2010: A two-solar-mass neutron star measured using Shapiro delay

2793 Citations



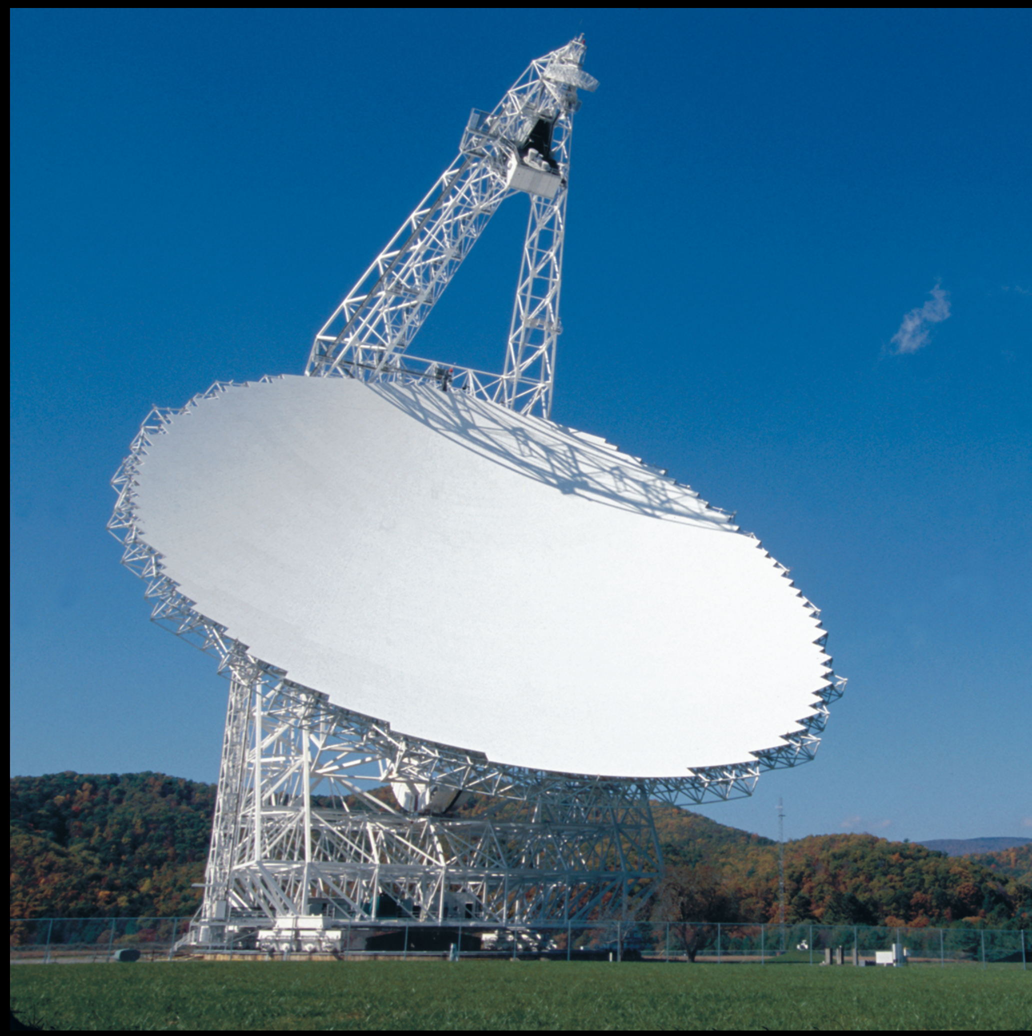
Mass constraints on J1614-2230 rule out most "exotic" equations of state

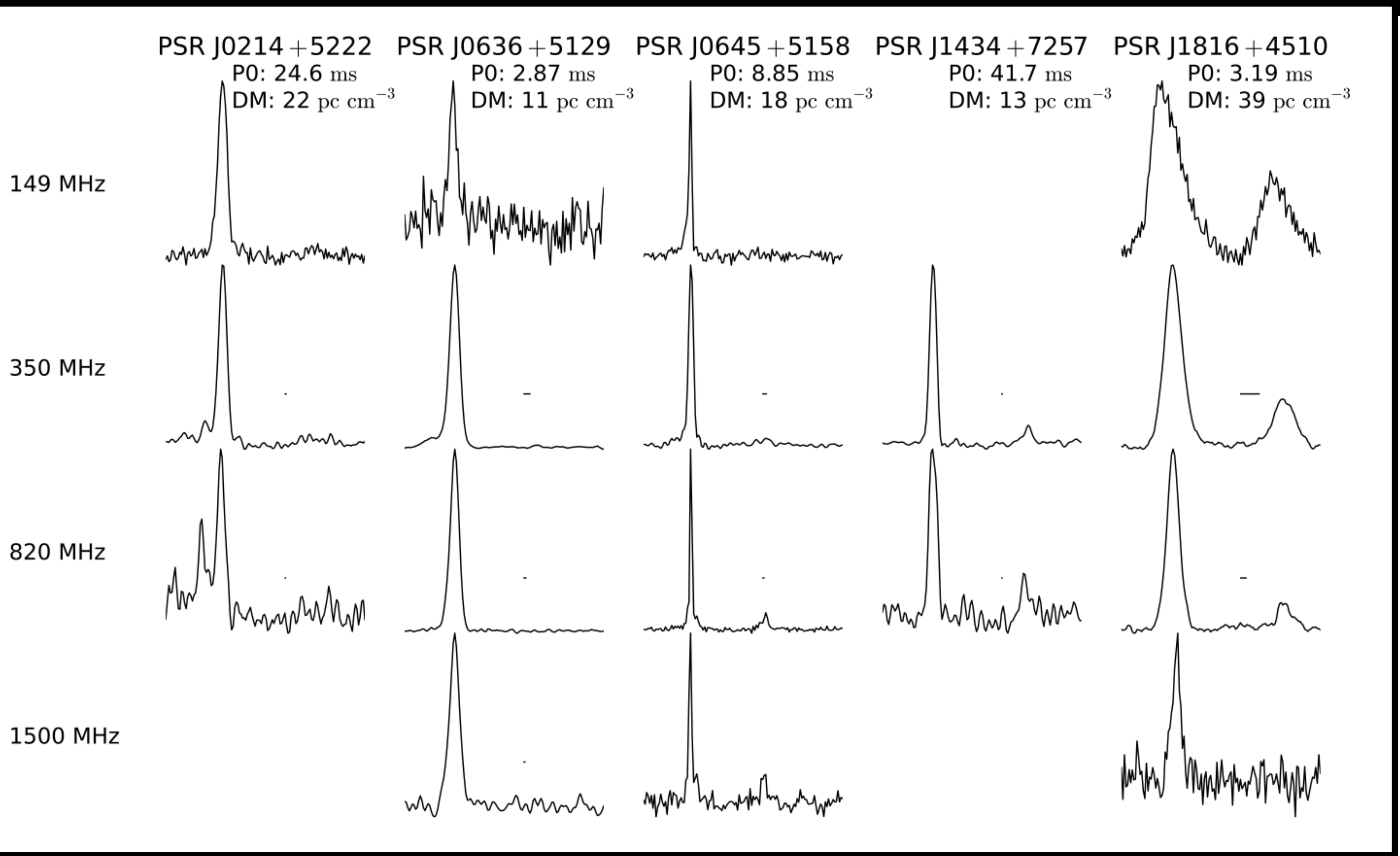


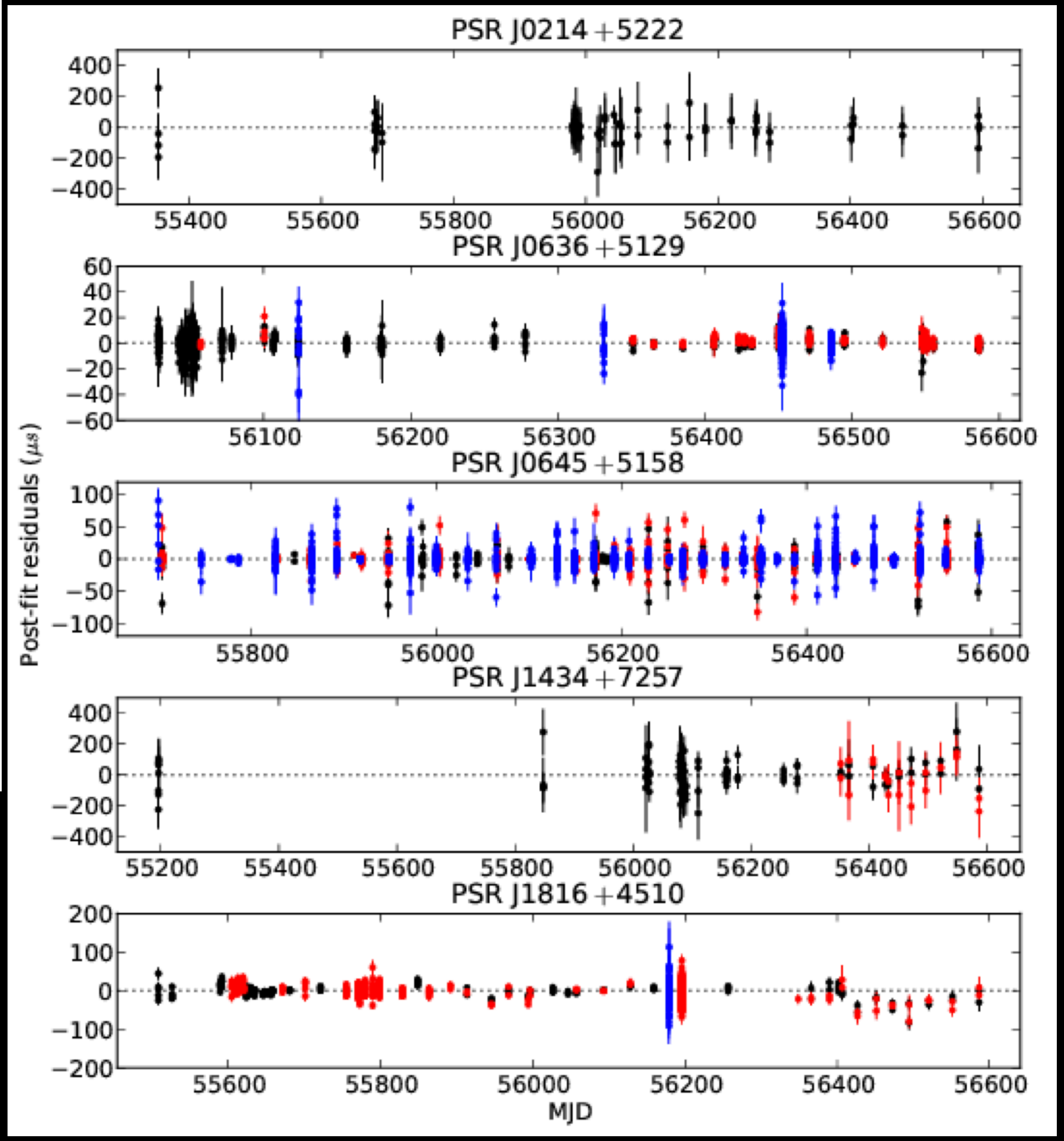

*Demorest et al. 2010, Nature, 467, 1081*

# 2014: The Green Bank Northern Celestial Cap Pulsar Survey

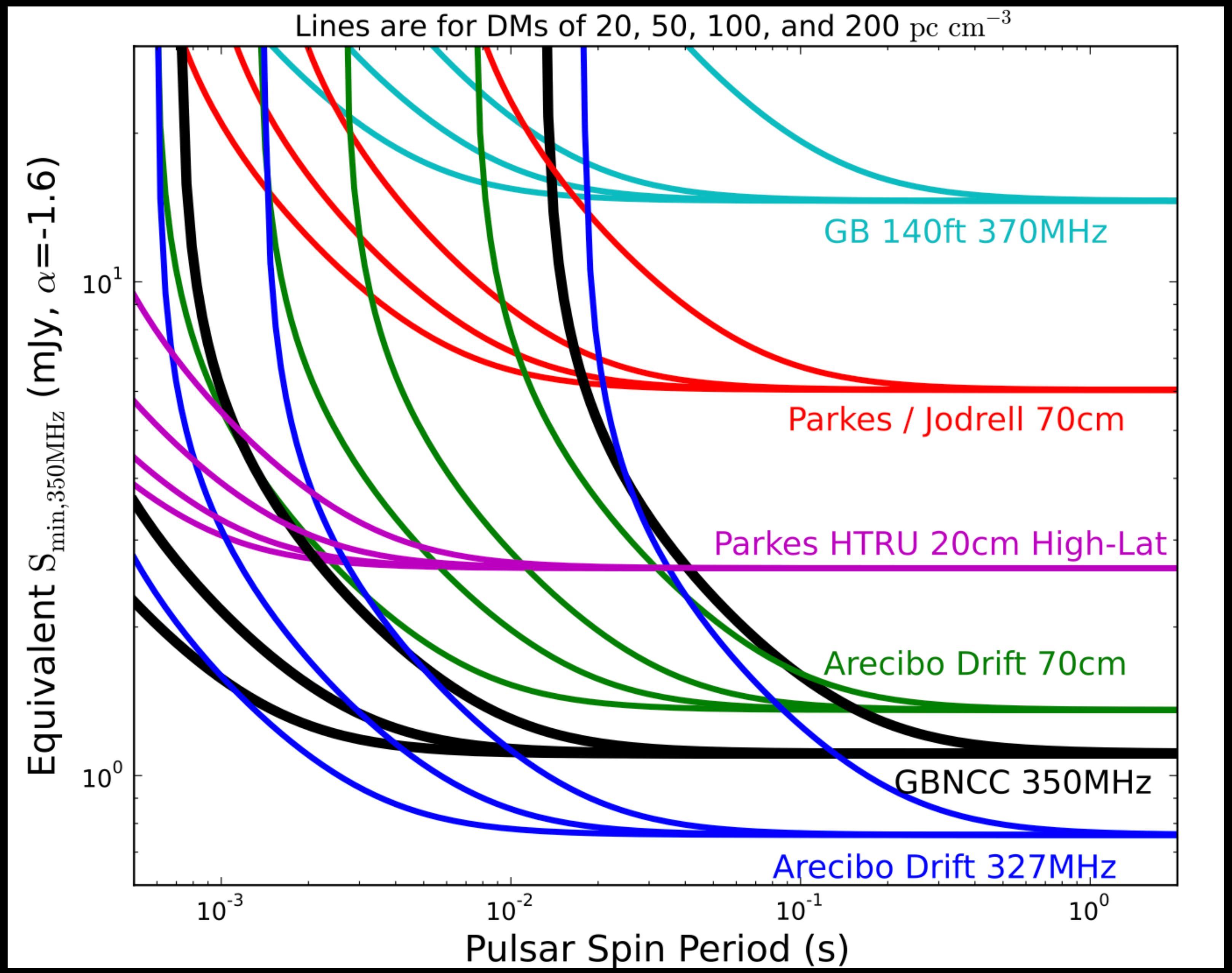
145 Citations






Stovall et al. 2014, ApJ, 791, 1

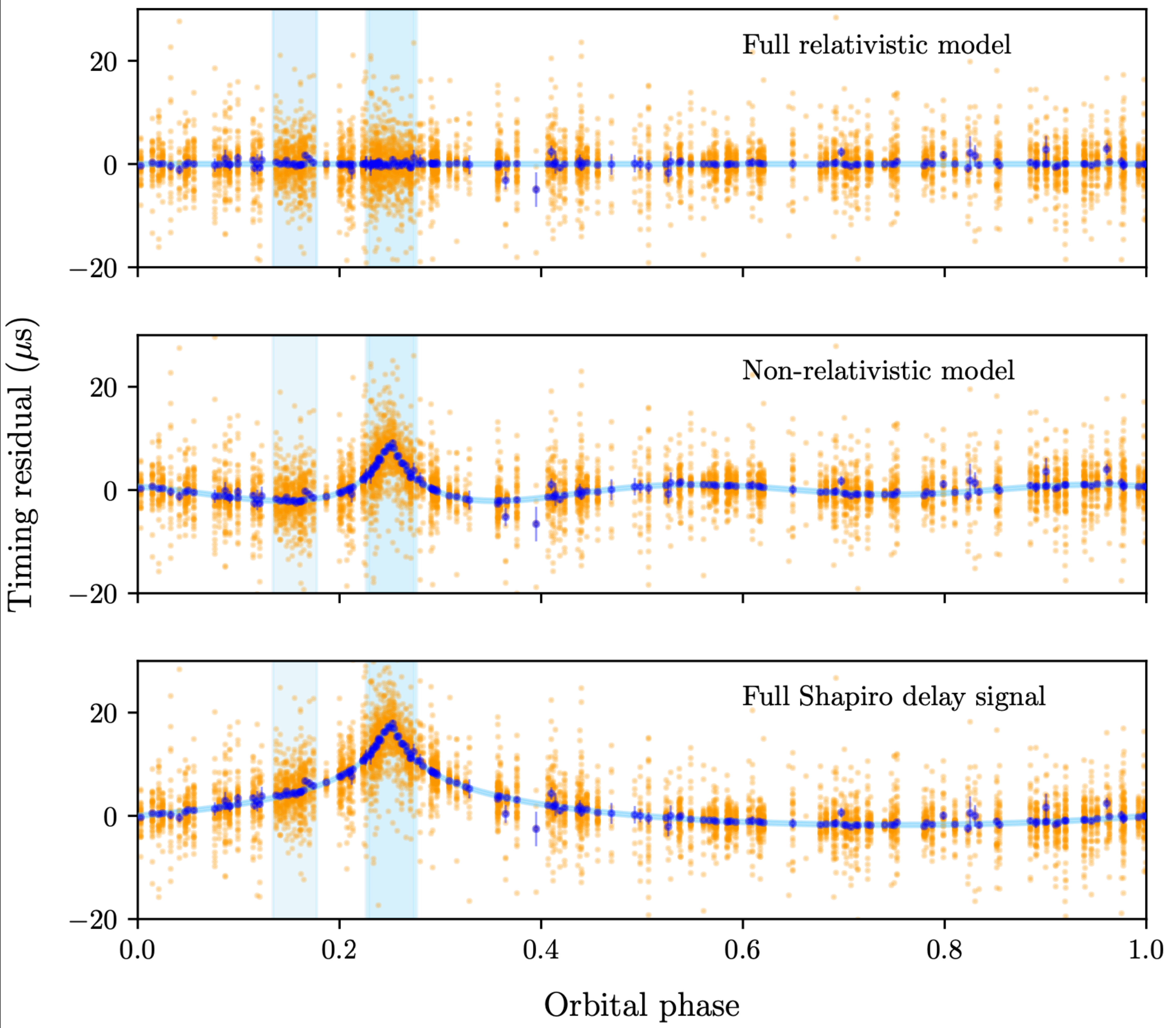



This paper announced discovery of 62 pulsars.

The survey is currently at 195 pulsars, including 33 MSPs.

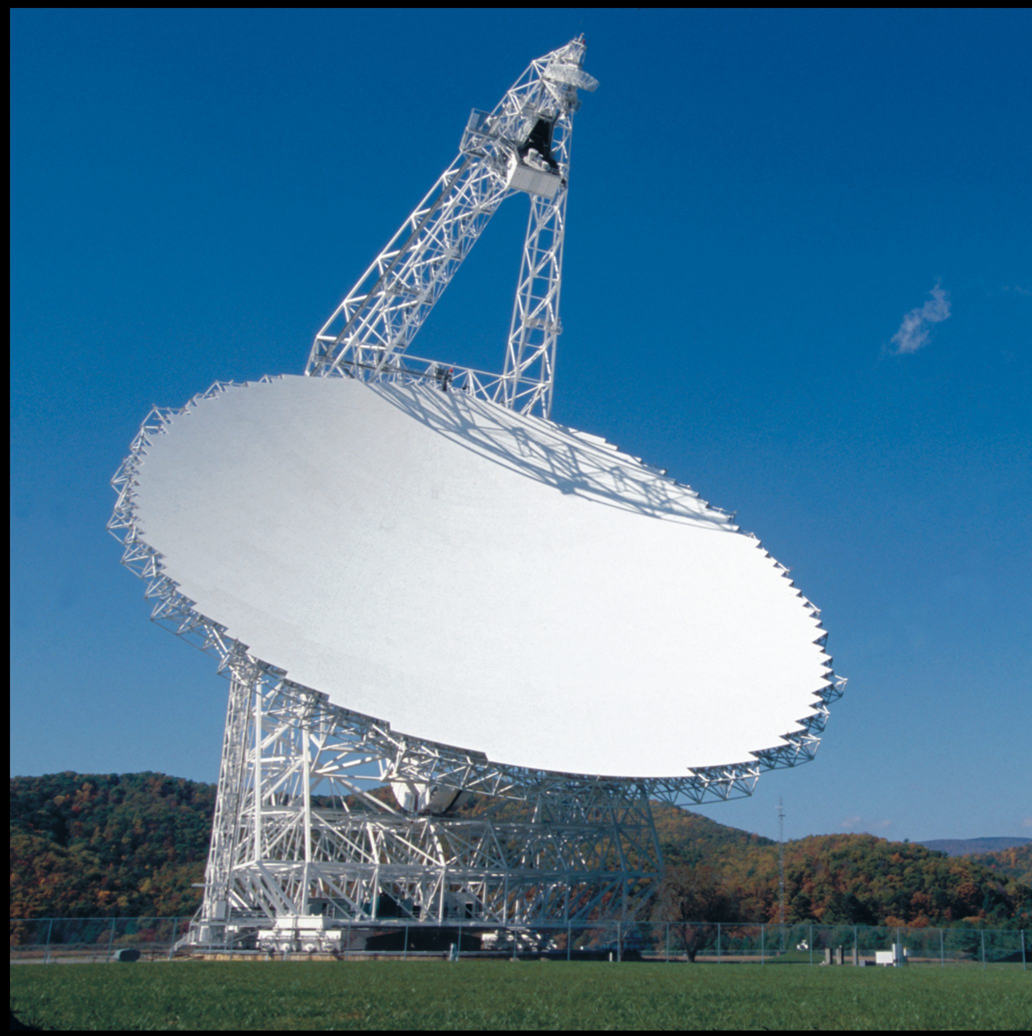
# 2020: Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar

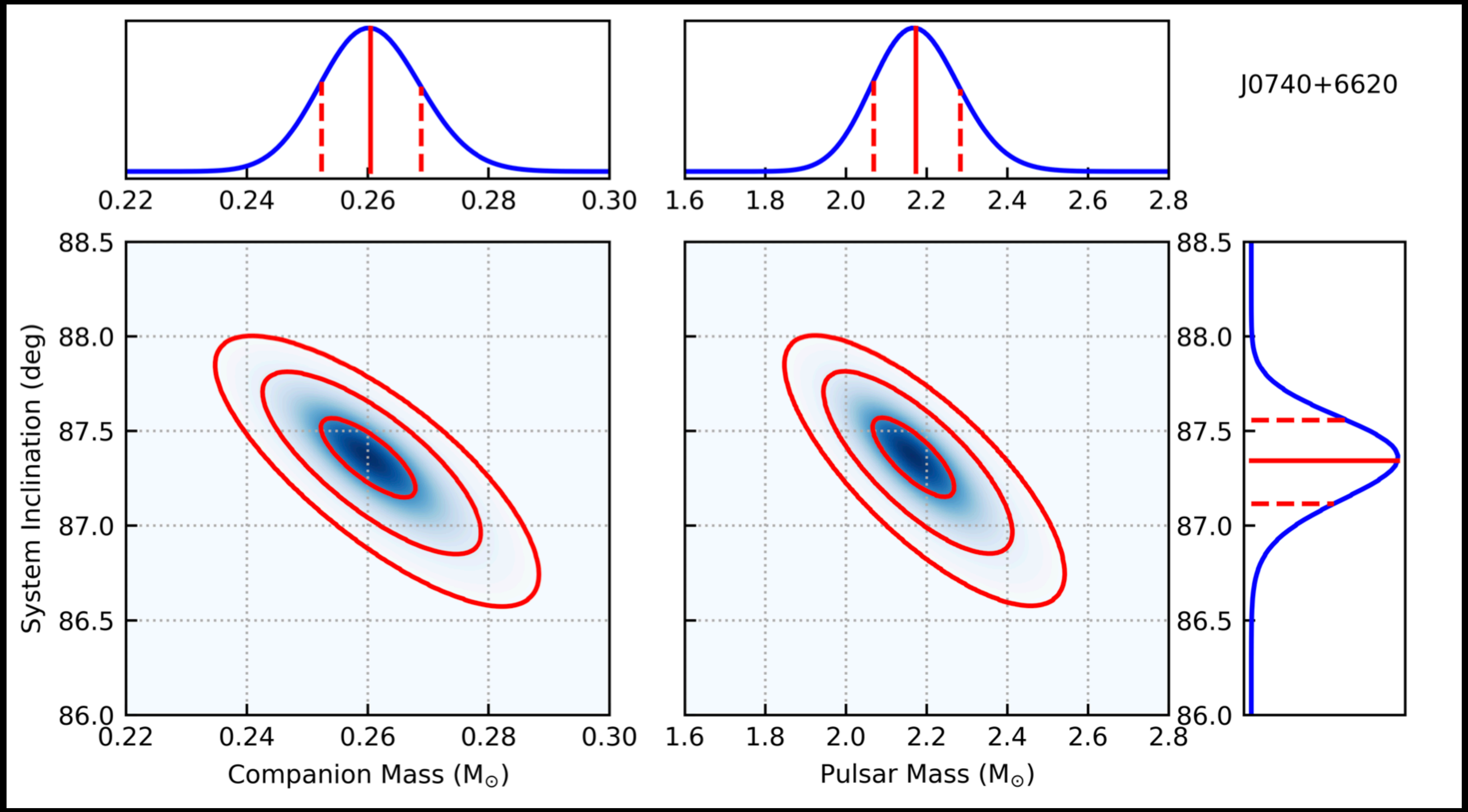
861 Citations




Cromartie et al. 2020, Nature, 4, 72

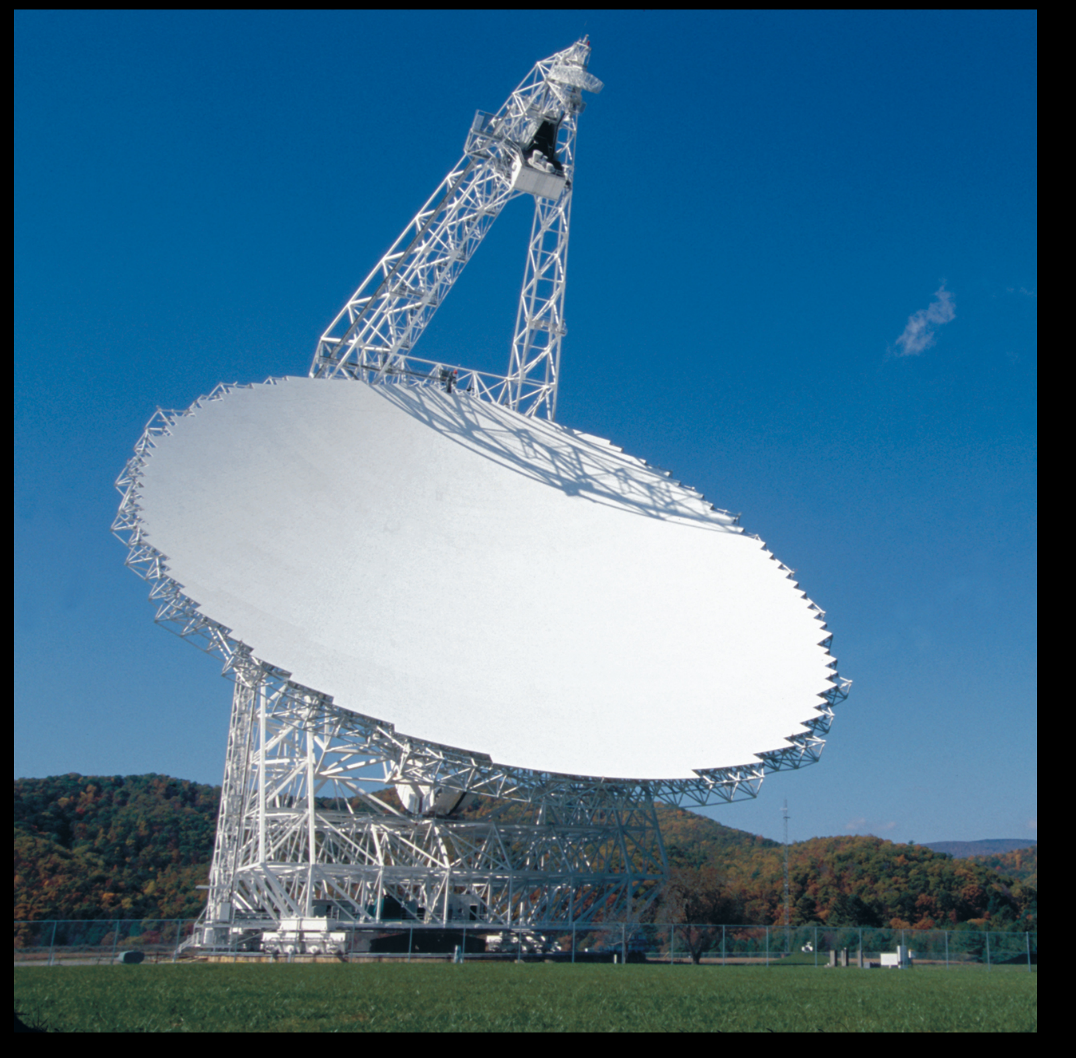
Measured through NANOGrav data and special campaign at superior conjunction



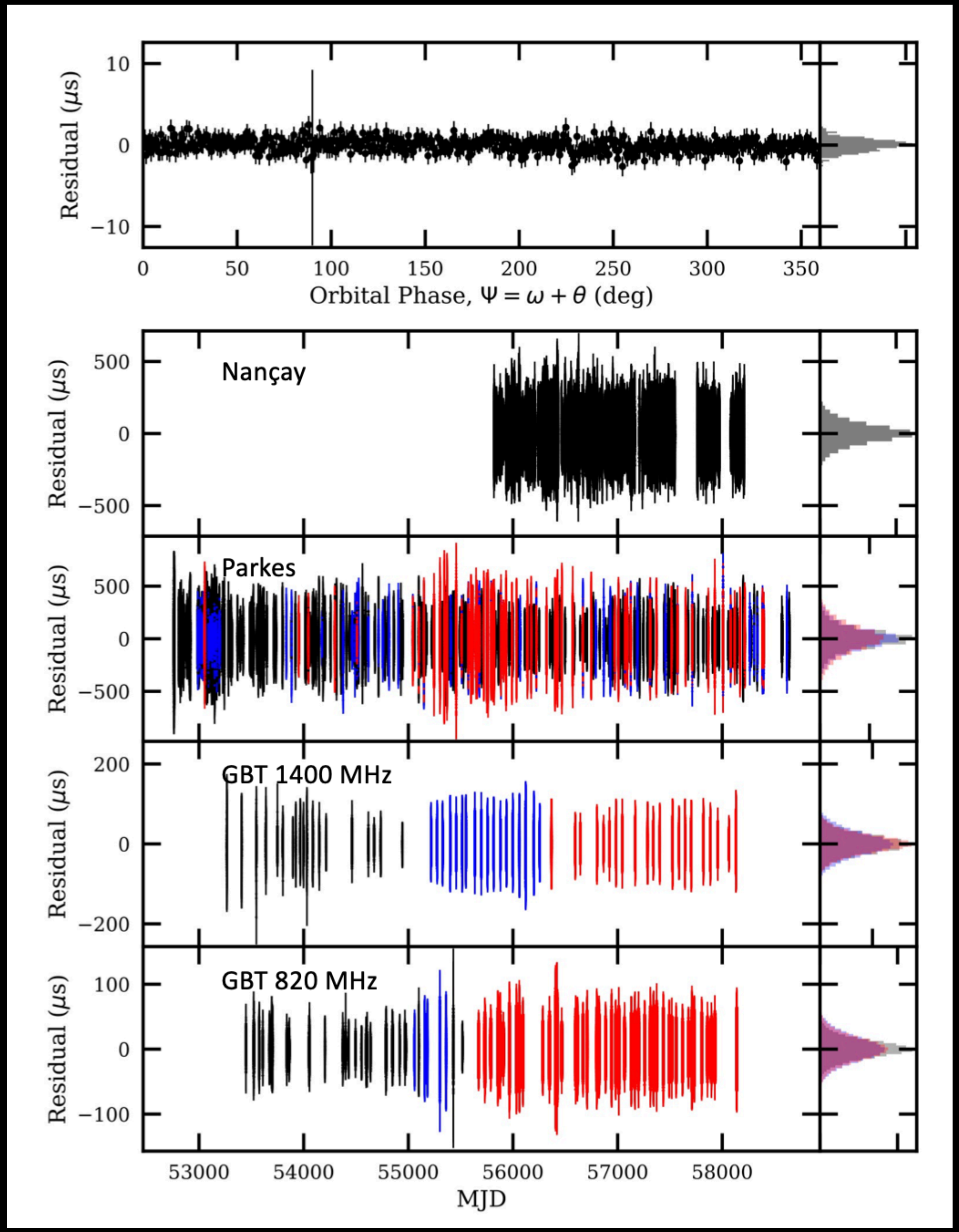


# 2021: Strong-Field Gravity Tests with the Double Pulsar

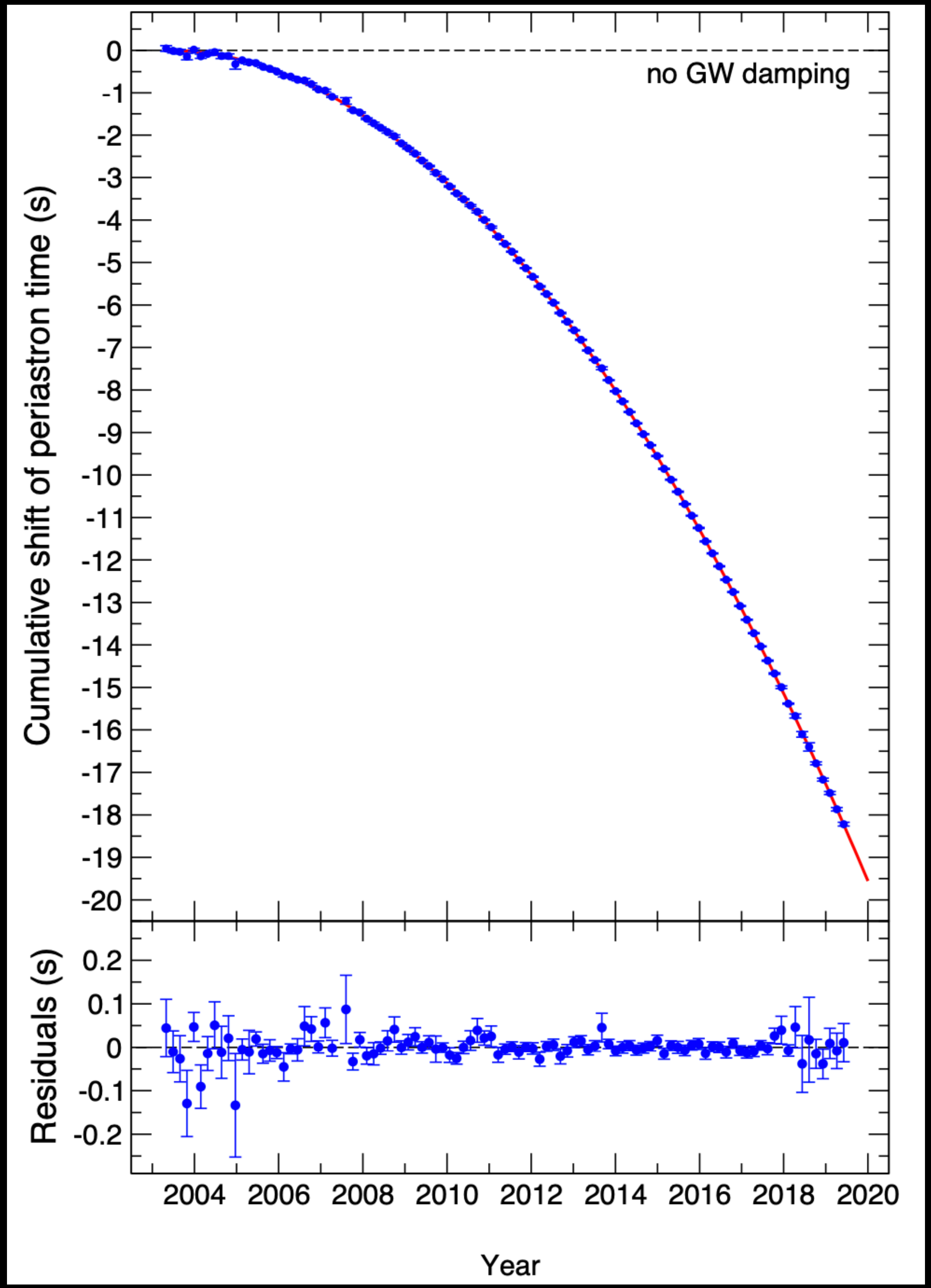
32 Citations (so far)



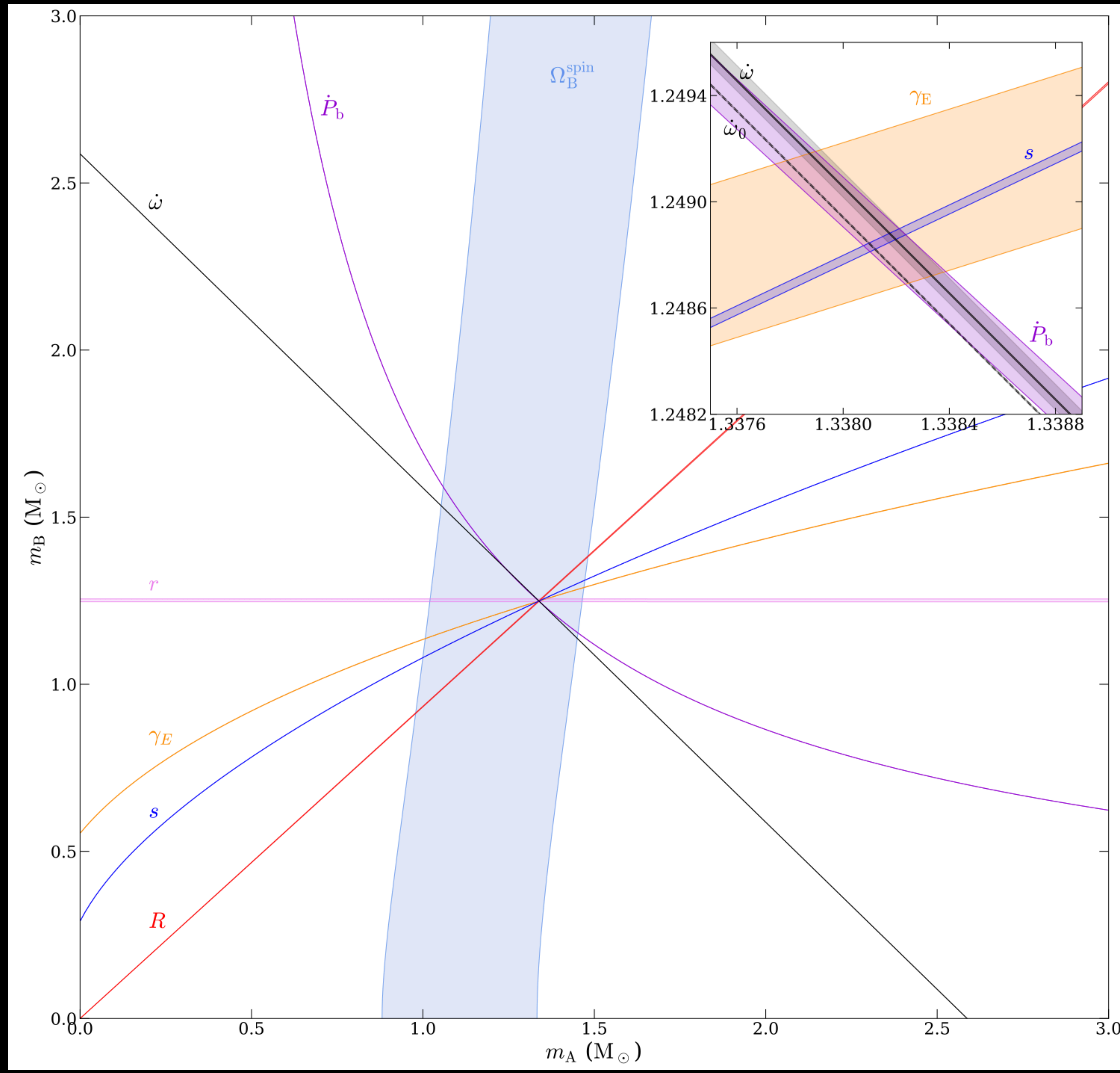
Agrees with GR at less than 0.01%!




*Residuals over 15 years of timing observations*




*Shift of periastron due to GW emission, and GR prediction*




*Updated Mass-Mass Diagram*

Kramer et al. 2021, PRX, 11, 4

# The Present

# North American Nanohertz Observatory for GWs

NANOGrav
Physics Frontiers Center

Includes over 150 students and scientists at over 50 institutions. Formed in 2008, and supported by the NSF PIRE program (2010-2016), as an NSF Physics Frontiers Center (since 2015), and through multiple other NSF AST and PHYS awards.

*NANOGrav meeting at the CCA in NYC, March 2022*

http://nanograv.org

# The International Pulsar Timing Array (IPTA)

NANOGrav Physics Frontiers Center

Includes four regional collaborations in North America, Europe, Australia, and India from institutions in 11 countries. Supported by NSF PIRE (2010-2016), NSF IRES (2017-present), and NSF AccelNet (awarded in 2021).

*IPTA Student Workshop in at NCRA, Pune, India, in June 2019*



http://ipta4gw.org

# How do galaxies evolve through cosmic time?

NANOGrav
Physics Frontiers Center

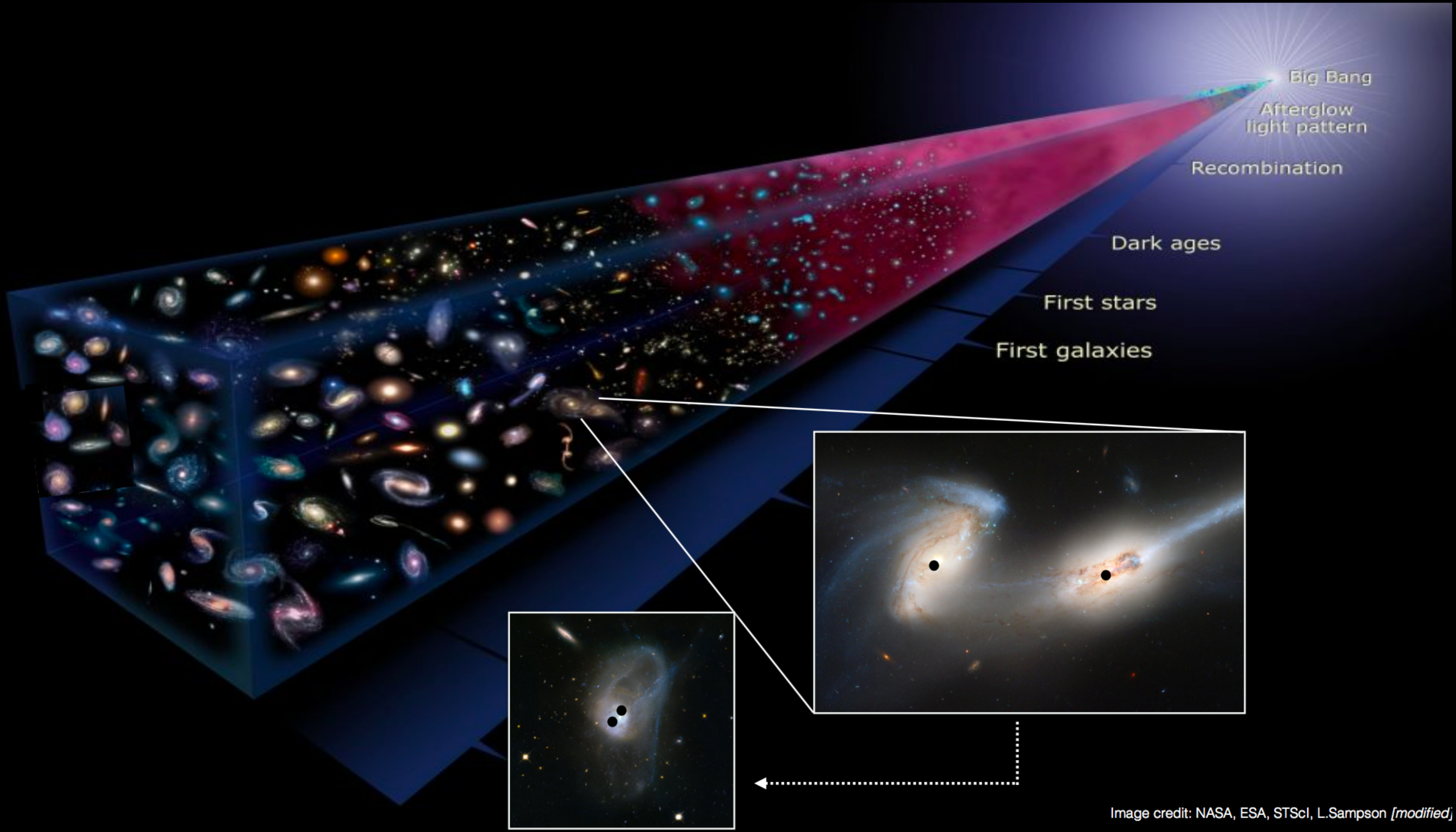



Image credit: NASA, ESA, STScI, L.Sampson *[modified]*

# How do galaxies evolve through cosmic time?

NANOGrav Physics Frontiers Center

They grow through mergers.

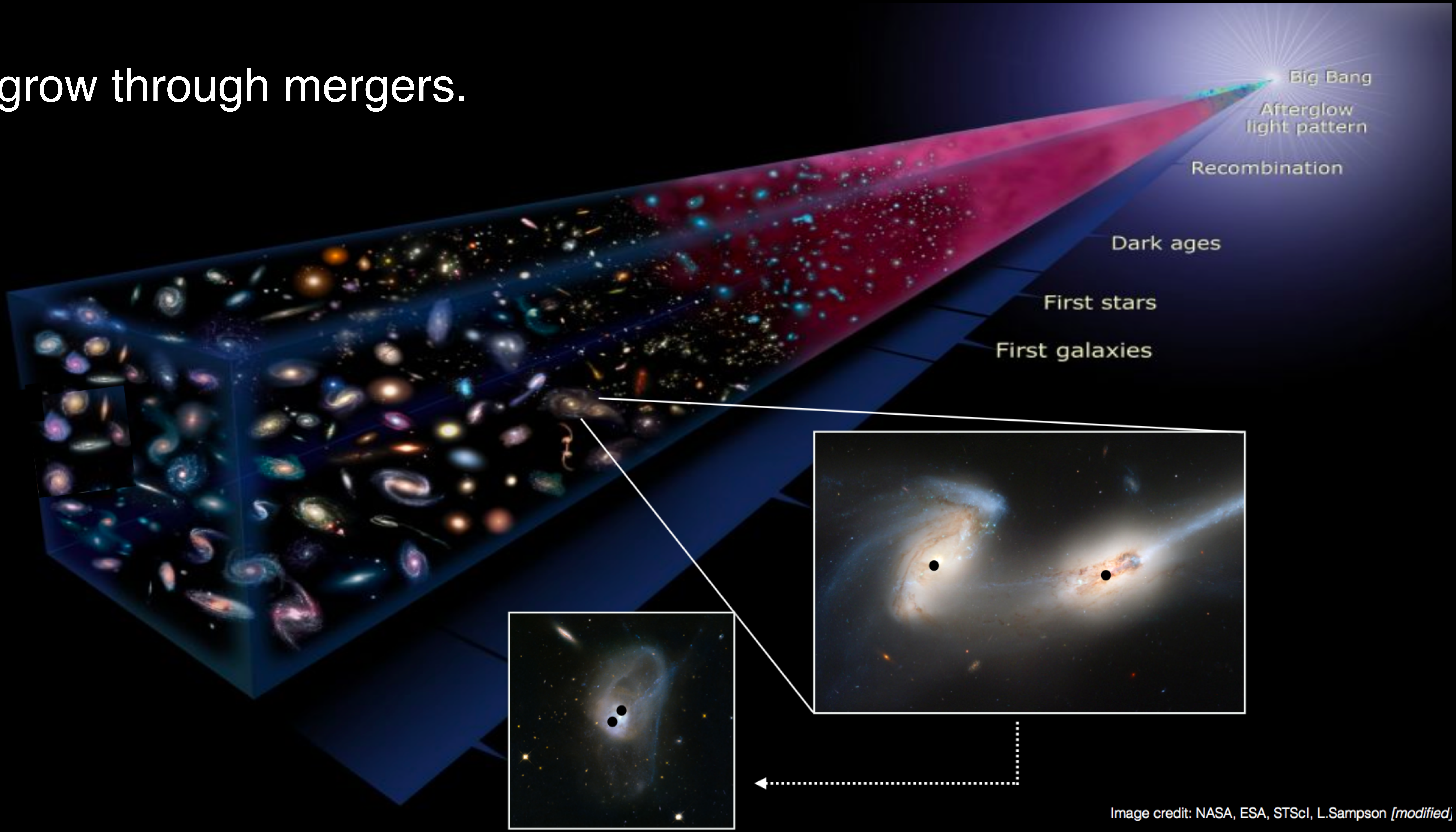



Image credit: NASA, ESA, STScI, L.Sampson *[modified]*

# How do galaxies evolve through cosmic time?

Final parsec problem!
How do galaxies get to these close separations?

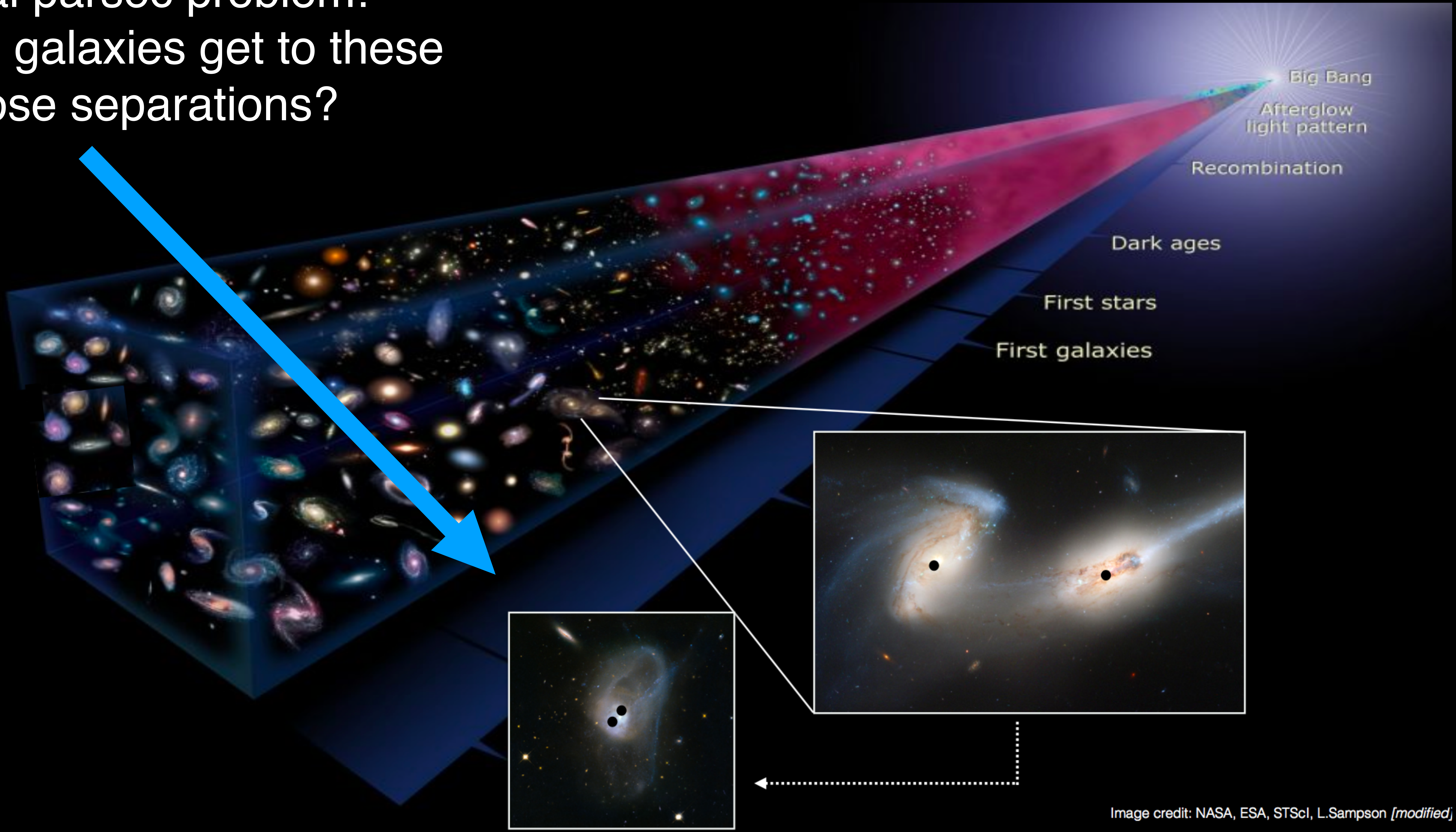



Image credit: NASA, ESA, STScI, L.Sampson *[modified]*

# Pulsar Timing Array

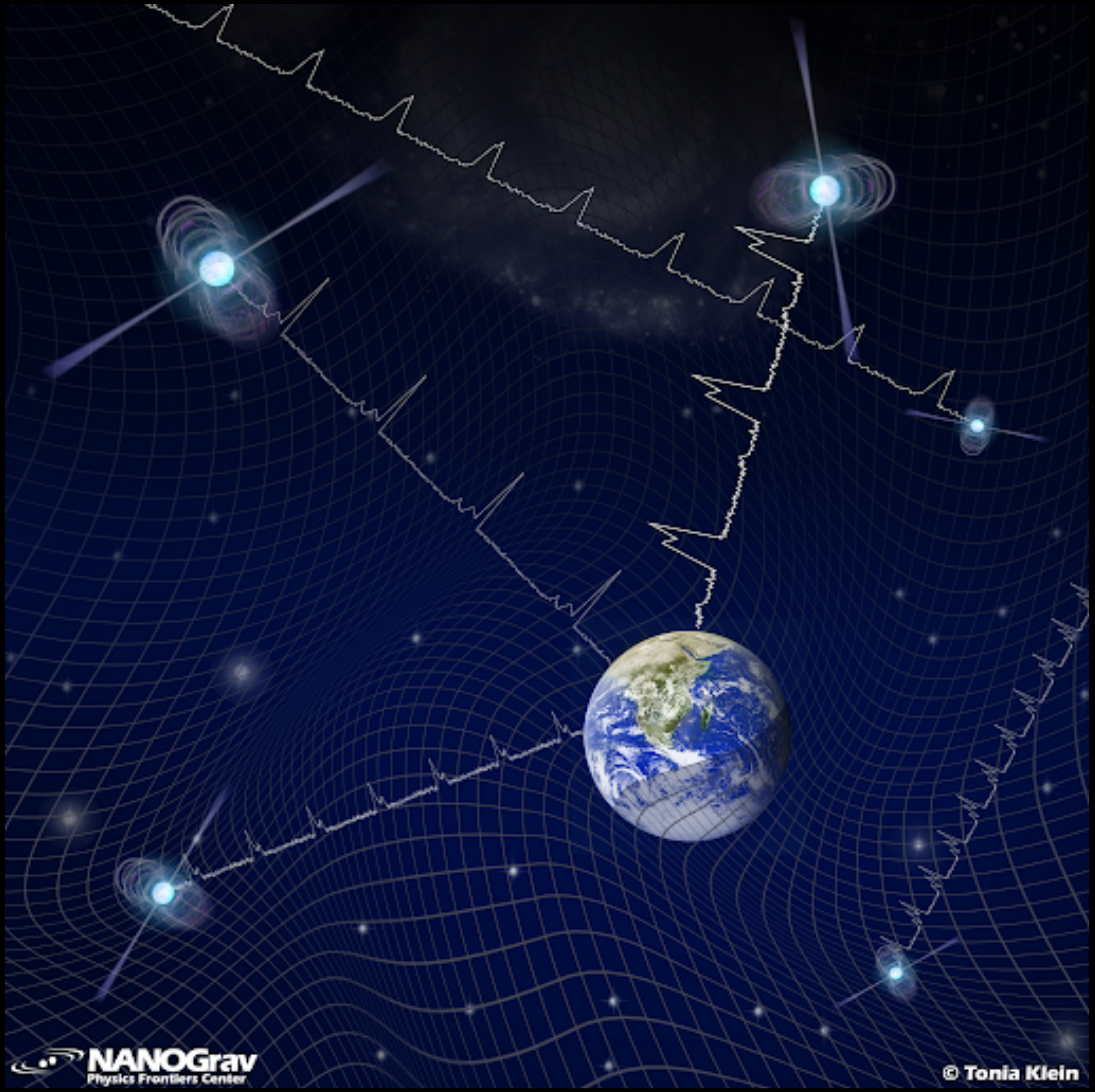
NANOGrav Physics Frontiers Center

Gravitational waves (GWs) produce correlated changes in pulse arrival times.

These changes will have an *earth term* and a *pulsar term*.

We can search for individual sources of gravitational waves and a *stochastic background* of all the sources in the universe.

We do this by searching for specific angular correlations in arrival times.



# NANOGrav's Observing Program

We observe roughly 70 pulsars at frequencies from 400 MHz to 3 GHz using the GBT (funded by Moore and NSF) and CHIME at daily (CHIME) to monthly (GBT) cadence. We also observe about 10 pulsars with the VLA and FAST.

Arecibo Observatory, Puerto Rico
300 m diameter
*(until August 2020)*

Green Bank Telescope, West Virginia
100 m diameter

CHIME Telescope, British Columbia, Canada
100 m effective diameter

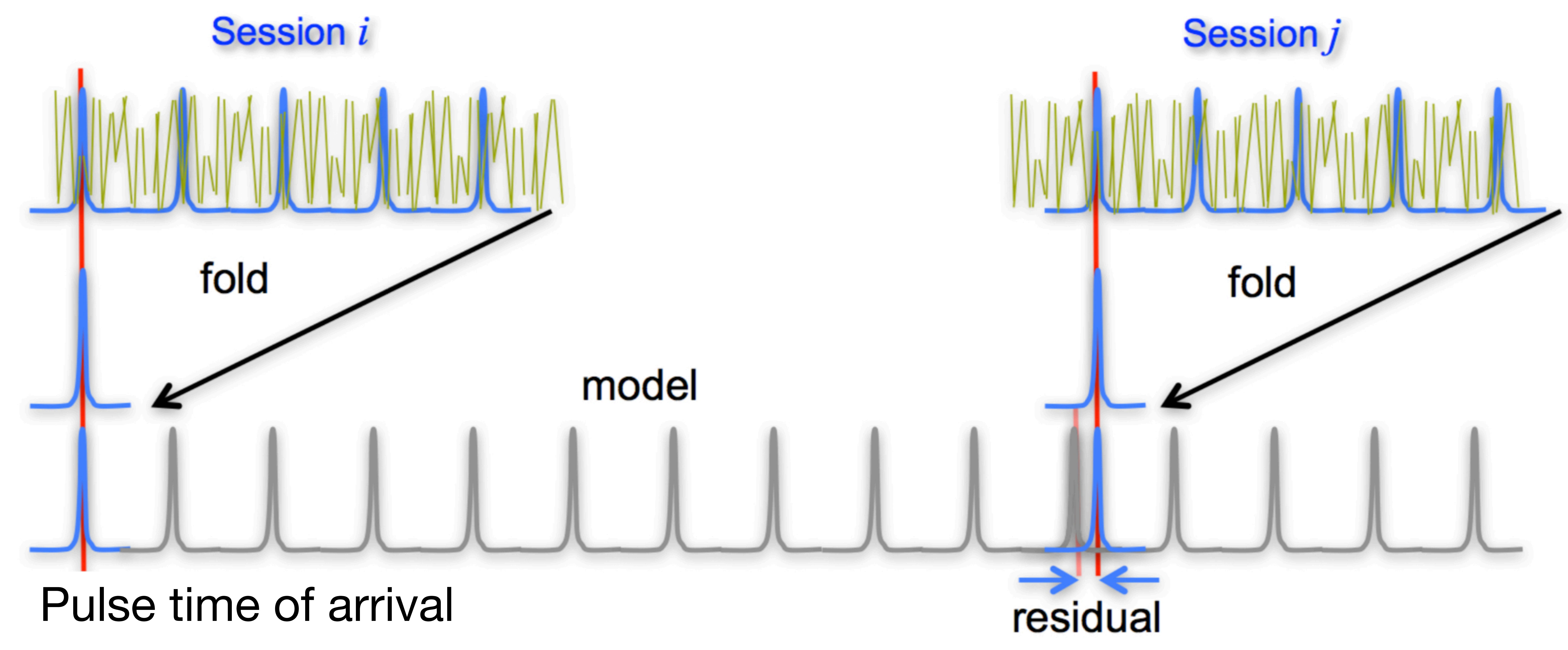
Very Large Array, New Mexico
120 m effective diameter

FAST Telescope, Guizhou, China
500 m diameter

# Pulsar Timing

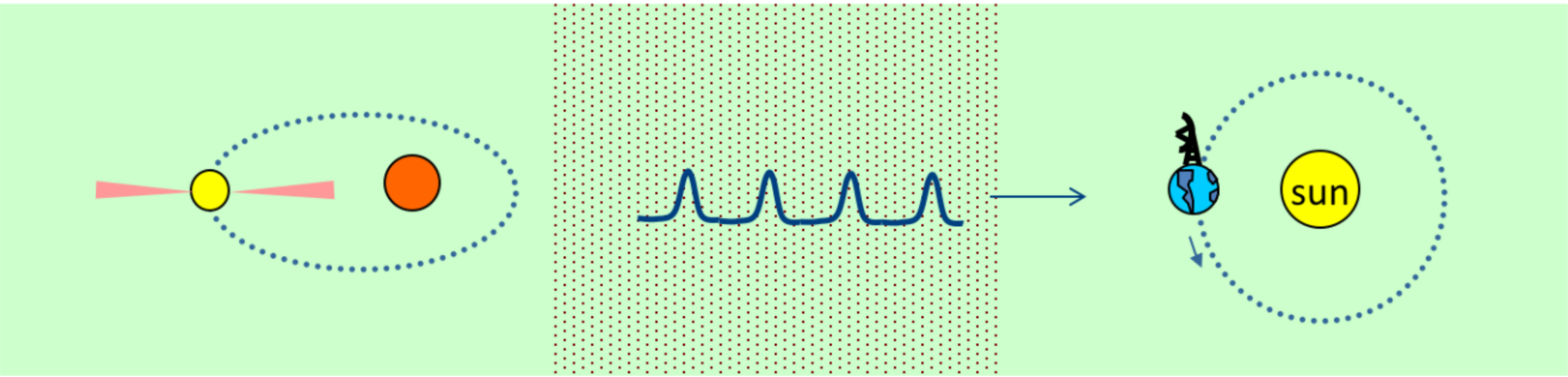
At every epoch, we measure a *time of arrival*.

We subtract this time of arrival from that predicted by a model to calculate a *residual*.




Credit: David Champion

# Fitting for a timing model




| | | |
|---|---|---|
| rotation period<br>rotation period derivative<br>timing noise<br><br>Keplerian orbital elements<br>relativistic orbital elements<br><br>kinematic perturbations of orbital elements (secular and annual phenomena) | dispersion measure<br>dispersion meas. variations | position<br>proper motion<br>parallax<br><br>solar electron density |

Credit: David Nice

| | J1713+0747 |
|---|---|
| MJD range | 48849 – 57053 |
| Number of ToAs | 17487 |
| Weighted rms timing residual ($\mu$s) | 0.24 |
| Reduced $\chi^2$ | 0.99 |
| Reference epoch | 55000 |
| Units | TCB |
| Right ascension, RA (J2000) | 17:13:49.5331960(4) |
| Declination, DEC (J2000) | +07:47:37.49256(1) |
| Proper motion in RA (mas yr$^{-1}$) | 4.924(1) |
| Proper motion in DEC (mas yr$^{-1}$) | −3.913(2) |
| Spin frequency, $f$ (s$^{-1}$) | 218.8118404171579(7) |
| $\dot{f}$ (s$^{-2}$) | $-4.08386(5) \times 10^{-16}$ |
| Parallax, $\pi$ (mas) | 0.83(2) |
| Dispersion measure, DM (cm$^{-3}$ pc) | 15.969(3) |
| $\dot{\mathrm{DM}}$ (cm$^{-3}$ pc yr$^{-1}$) | $-2(3) \times 10^{-5}$ |
| $\ddot{\mathrm{DM}}$ (cm$^{-3}$ pc yr$^{-2}$) | $-3(3) \times 10^{-6}$ |
| Binary model | T2 |
| Orbital period, $P_b$ (d) | 67.825131000(1) |
| Epoch of periastron, $T_0$ (MJD) | 52811.4820(2) |
| Projected semi-major axis, $x$ (lt-s) | 32.34242200(8) |
| Longitude of periastron, $\omega_0$ (deg) | 176.1987(9) |
| Eccentricity, $e$ | $7.49402(4) \times 10^{-5}$ |
| Companion mass, $m_c$ ($M_\odot$) | 0.289(7) |
| Derivative of $P_b$, $\dot{P}_b$ | $5(1) \times 10^{-13}$ |
| Epoch of ascending node, $T_{asc}$ (MJD) | – |
| $\epsilon_1 = e \sin \omega_0$ | – |
| $\epsilon_2 = e \cos \omega_0$ | – |
| Longitude of ascending node, $\Omega$ (deg) | 92(2) |
| Inclination angle, $i$ (deg) | 71.6(4) |

Perera et al, 2019, MNRAS, 490, 4

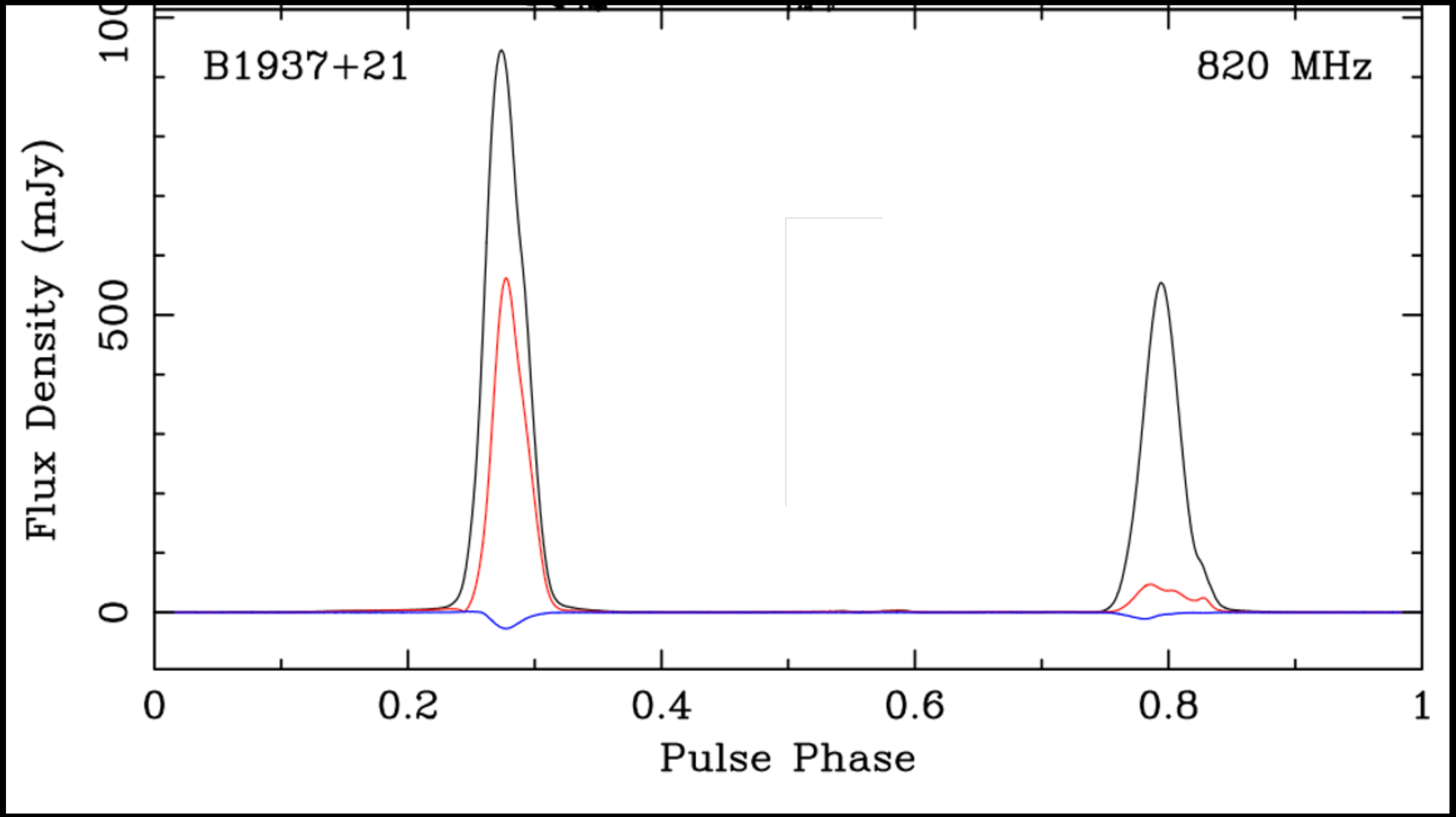
# NANOGrav’s Data Releases

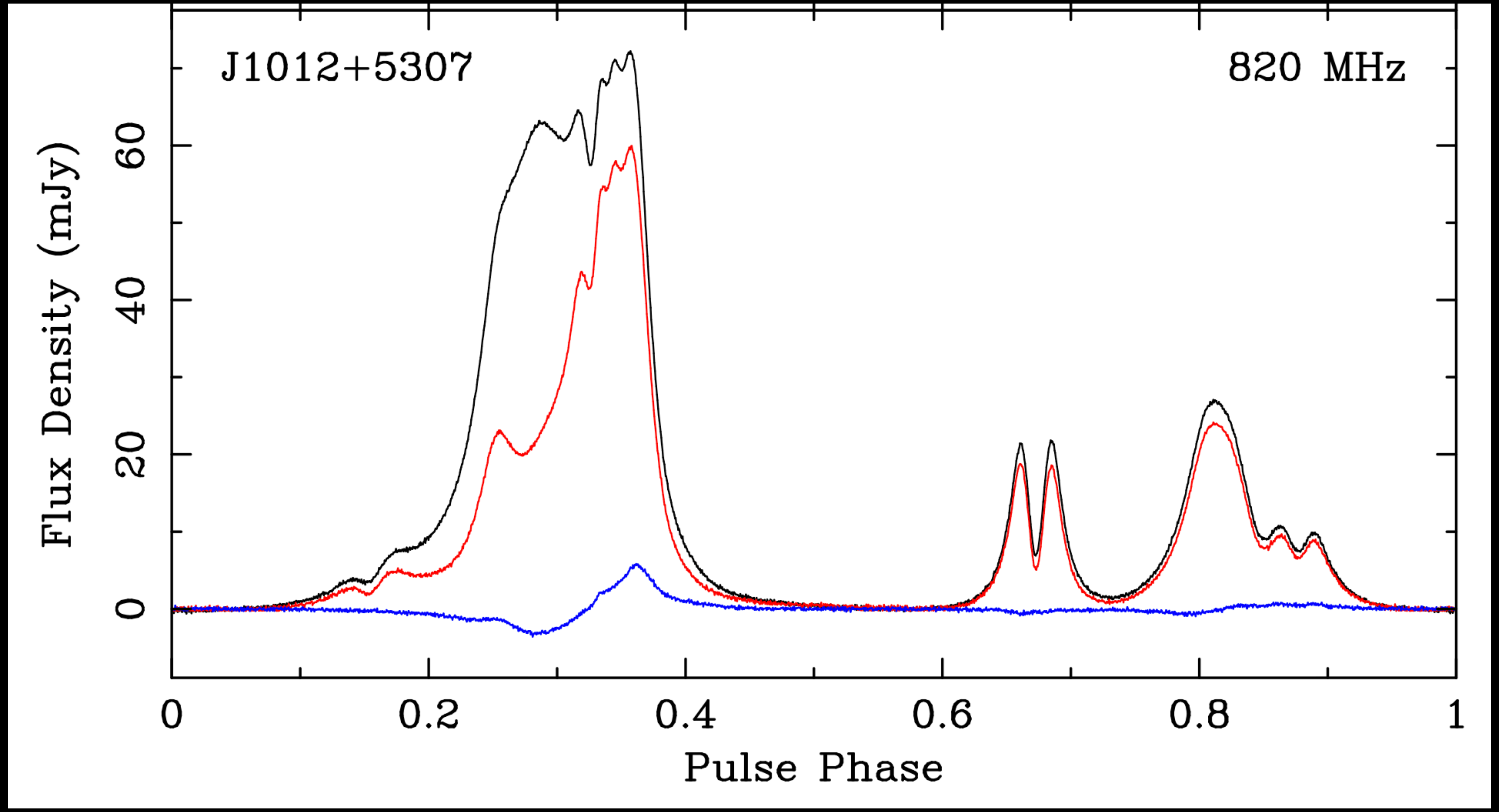
Our data releases include times of arrival measured to *sub-microsecond* precision, timing models, and pulse profiles for each pulsar.

Our 12.5-yr release has 47 pulsars and our 15-yr release will have 67 pulsars.

Publicly available at
[http://data.nanograv.org](http://data.nanograv.org)

*The NANOGrav Collaboration, 2018, ApJS, 235, 37*
*The NANOGrav Collaboration, 2021, ApJS, 252, 48*
*The NANOGrav Collaboration, 2021, ApJS, 252, 53*



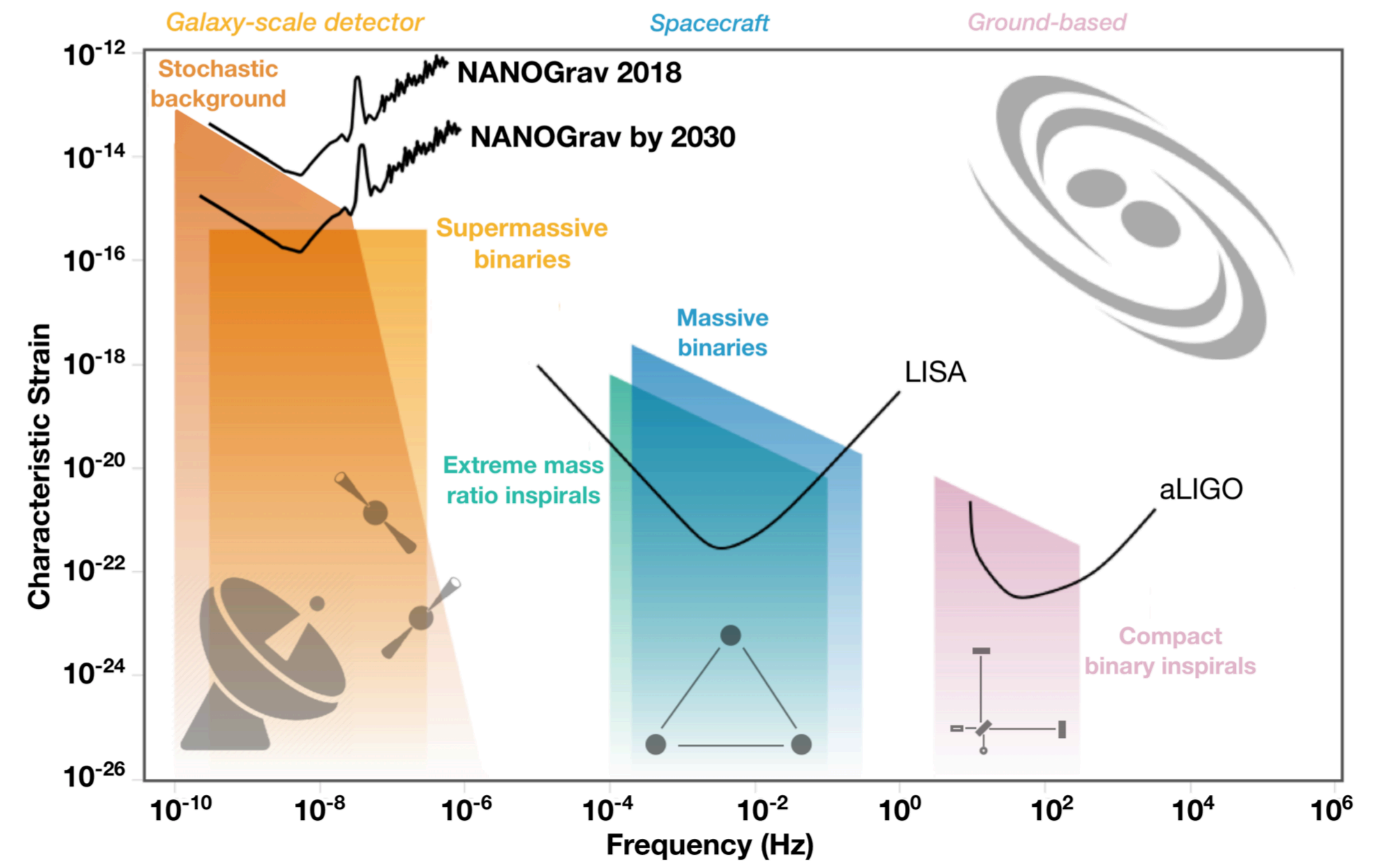

*Wahl et al. 2022, ApJ, 926, 168*

# We are sensitive to *low-frequency* gravitational waves

We are sensitive to *long* GW wavelengths, or *low* GW frequencies.

Our strain sensitivity is roughly

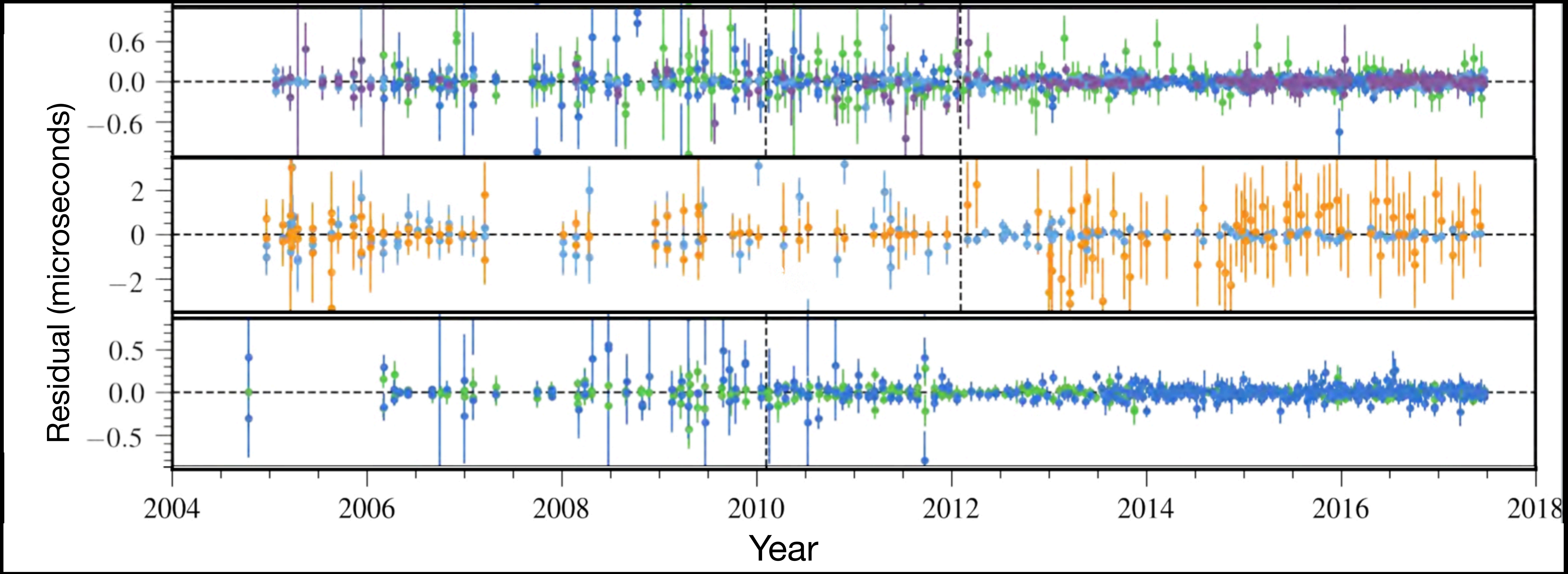
$\Delta t/T \simeq 200$ ns/15yrs $\simeq 10^{-15}$




*Ransom et al., 2019, NANOGrav Decadal Whitepaper, arXiv: 1908.05356*

# We search for GWs by cross-correlating pulsar timing residuals

NANOGrav
Physics Frontiers Center




*The NANOGrav Collaboration, 2021, APSS, 252, 48*

Residual RMS values range from 0.06 to 1.4 microseconds.

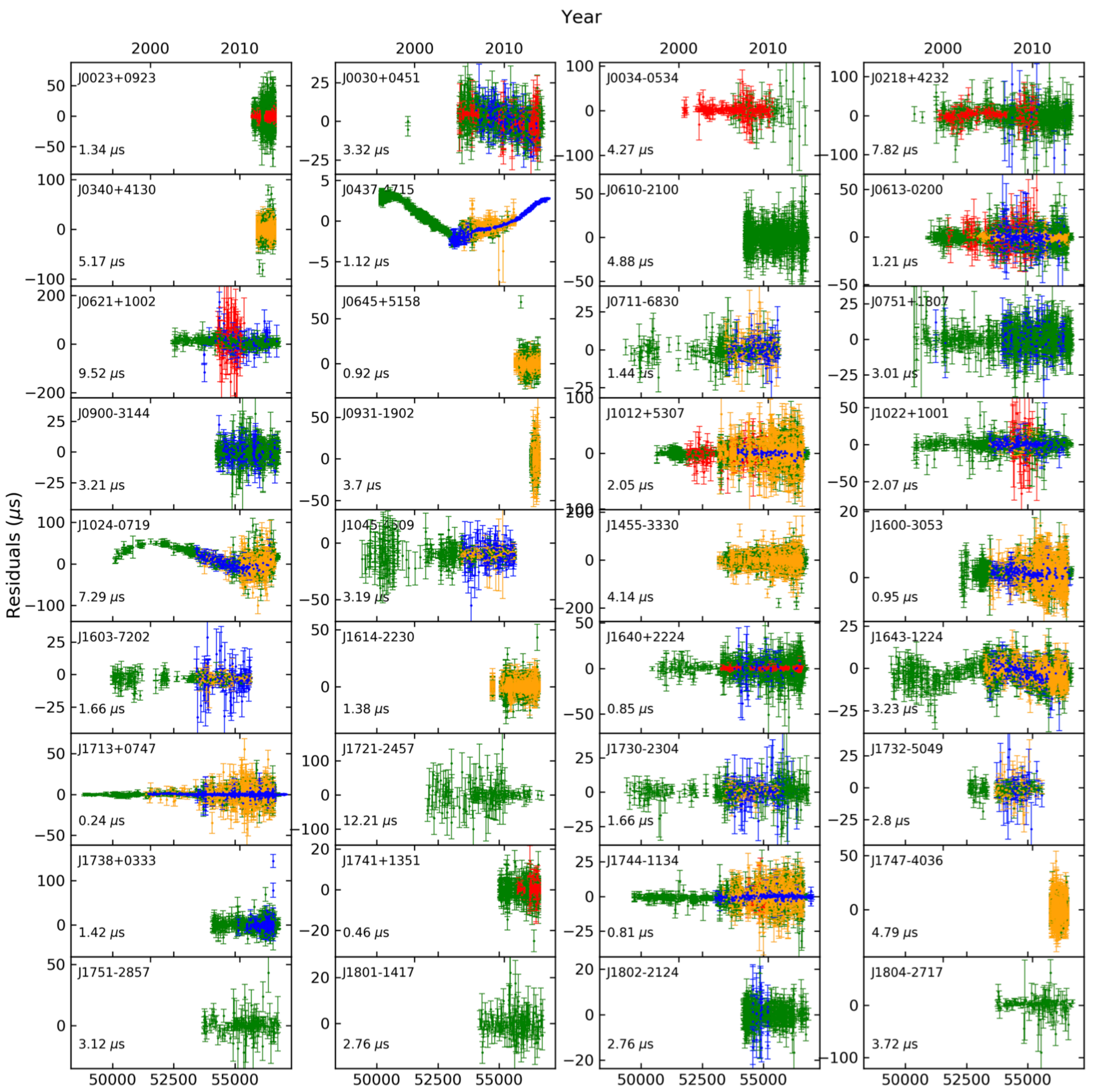
# IPTA Residuals

IPTA Second Data Release includes data for 65 MSPs timed by NANOGrav, European EPTA, and Australian PPTA for timespans of > 30 yrs.

Publicly available at
http://ipta4gw.org/data-release/

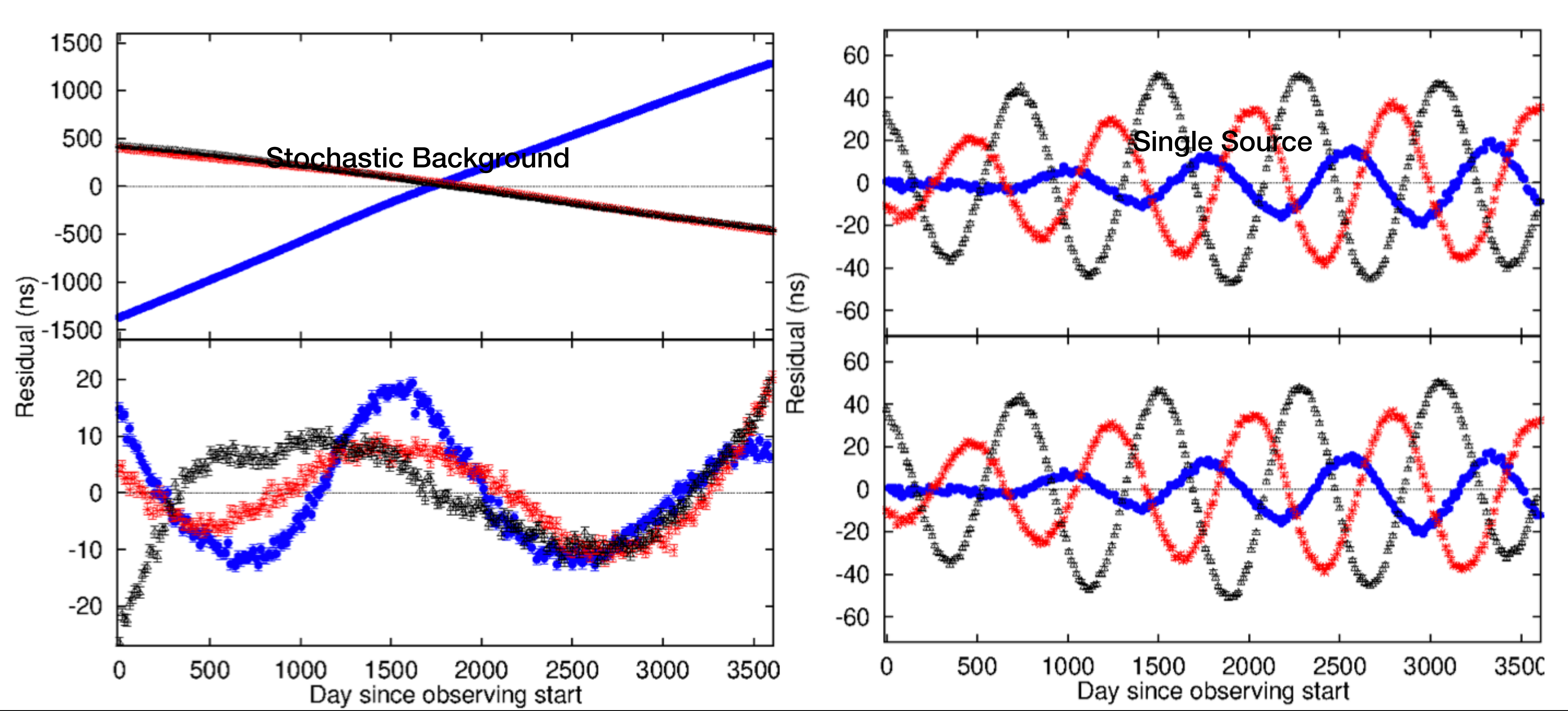
RMS residuals range from 0.2 - 10 microseconds.

*Perera et al., for the IPTA Collaboration, 2019, MNRAS, 490, 4, 48*



# We search for multiple types of GW signatures

NANOGrav Physics Frontiers Center




*Verbiest, Oslowski, & Burke-Spolaor, 2021, arXiv: 2101:10081*

GW signatures pre (top) and post (bottom) timing fit for a stochastic background (left) and single source (right) in the residuals for three different pulsars.

# Sources of Noise

NANOGrav Physics Frontiers Center

| | Noise source | Achromatic? | Correlated in time? | Correlated in space? | Quadrupolar? |
|---|---|---|---|---|---|
| Intrinsic | Pulsar rotational irregularities | ✓ | ✓ | ✗ | ✗ |
| Intrinsic | Pulse jitter | ✓ | ✗ | ✗ | ✗ |
| Extrinsic | Scattering and dispersion measure variations | ✗ | ✓ | ✗ | ✗ |
| Extrinsic | Planetary ephemerides | ✓ | ✓ | ✓ | ✗ |
| Extrinsic | Clock errors/offsets | ✓ | ✓ | ✗ | ✗ |
| | **GW background** | ✓ | ✓ | ✓ | ✓ |

$$P_{\mathrm{RN}}(f) = \frac{{A_{\mathrm{RN}}}^2}{12\pi^2} f_{\mathrm{yr}}^{-3} \left(\frac{f}{f_{\mathrm{yr}}}\right)^{-\gamma_{\mathrm{RN}}}$$

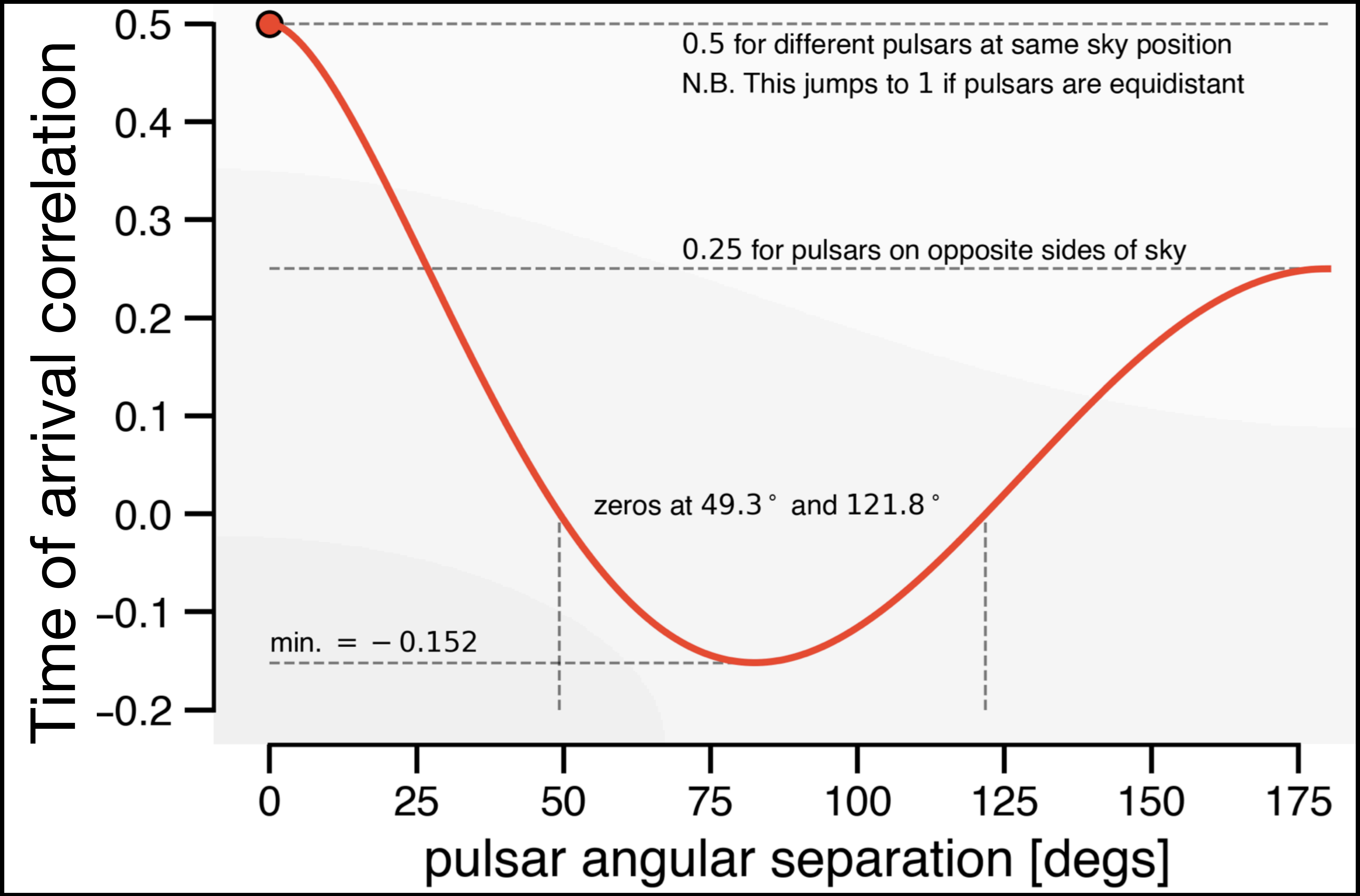
$$P_{\mathrm{DM}}(f,\nu) = \frac{{A_{\mathrm{DM}}}^2}{12\pi^2} f_{\mathrm{yr}}^{-3} \left(\frac{f}{f_{\mathrm{yr}}}\right)^{-\gamma_{\mathrm{DM}}} \left(\frac{1400\mathrm{MHz}}{\nu}\right)^2$$

# The Hellings and Downs Correlation

Prediction for an isotropic, stochastic gravitational wave background assuming general relativity is correct.

Maximum correlation of 0.5 as “pulsar terms” are uncorrelated.

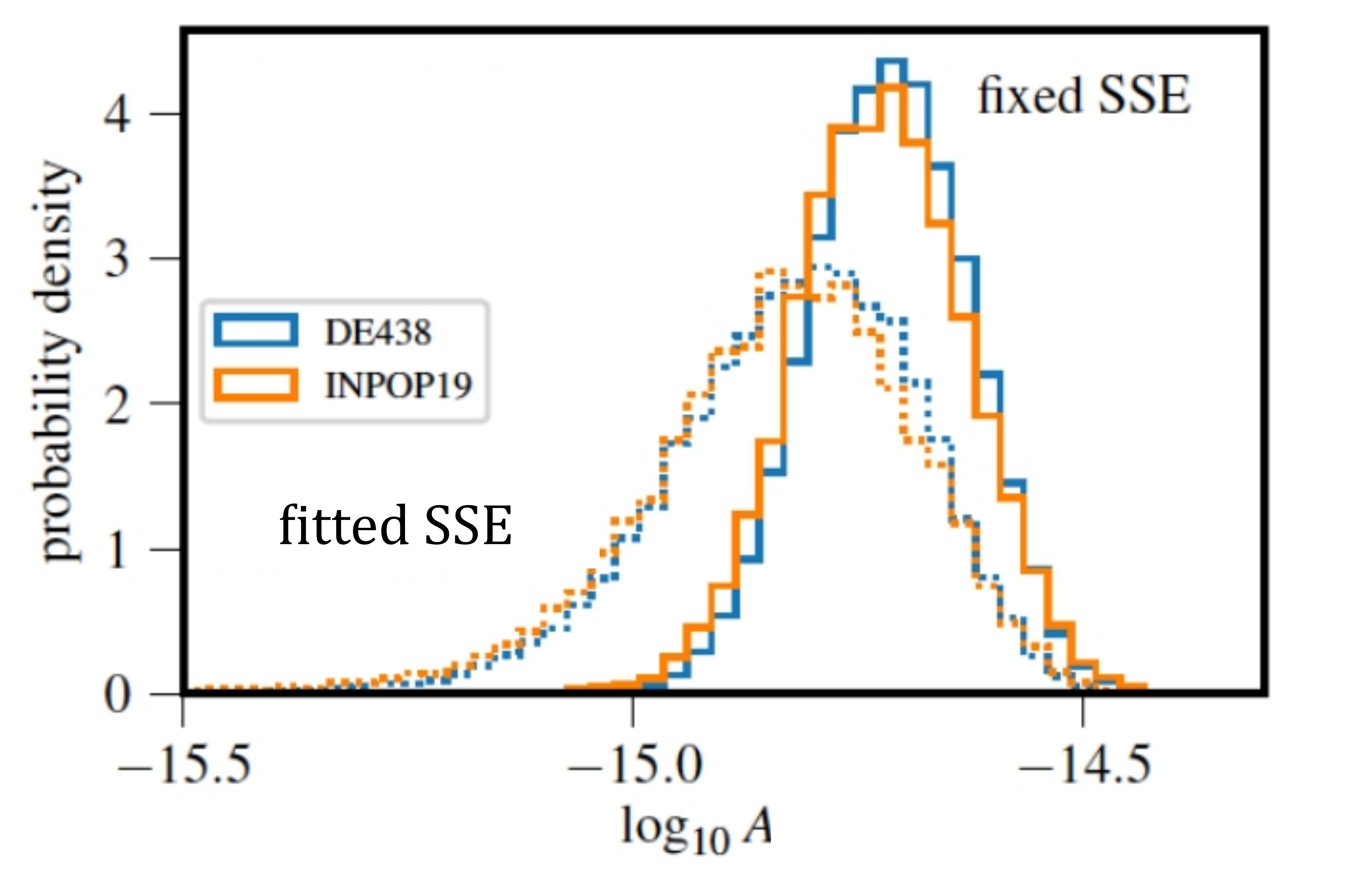
We will detect the effects of GWs on the Earth!

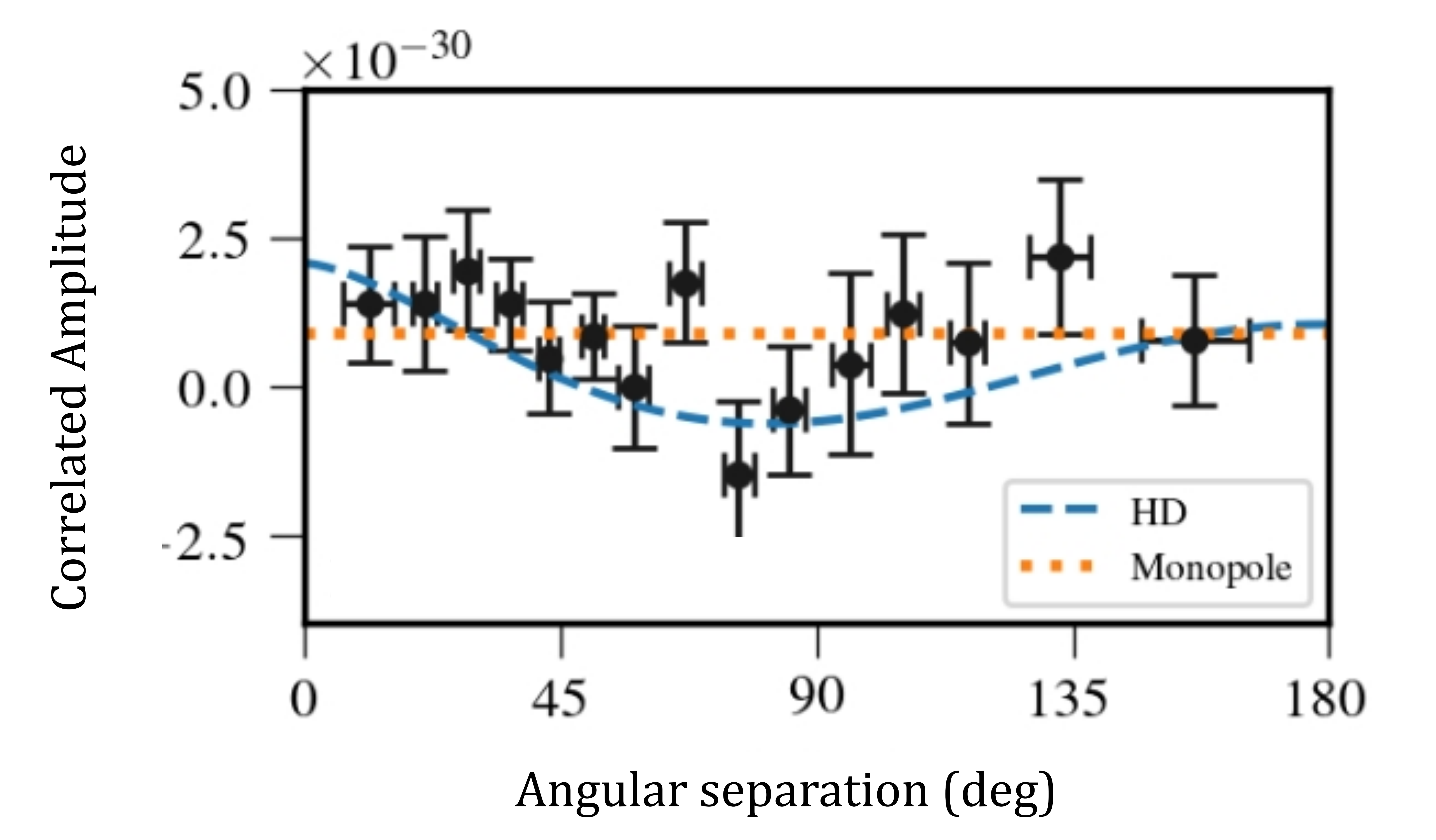



*“The Nanohertz Gravitational Wave Astronomer”, Steve Taylor, arXiv:2105.13270*

*Hellings & Downs, 1983, ApJ, 265, 39*

# In 2020, we made a significant detection… of *something*!




*The NANOGrav Collaboration, 2020, ApJ, 905, 34*

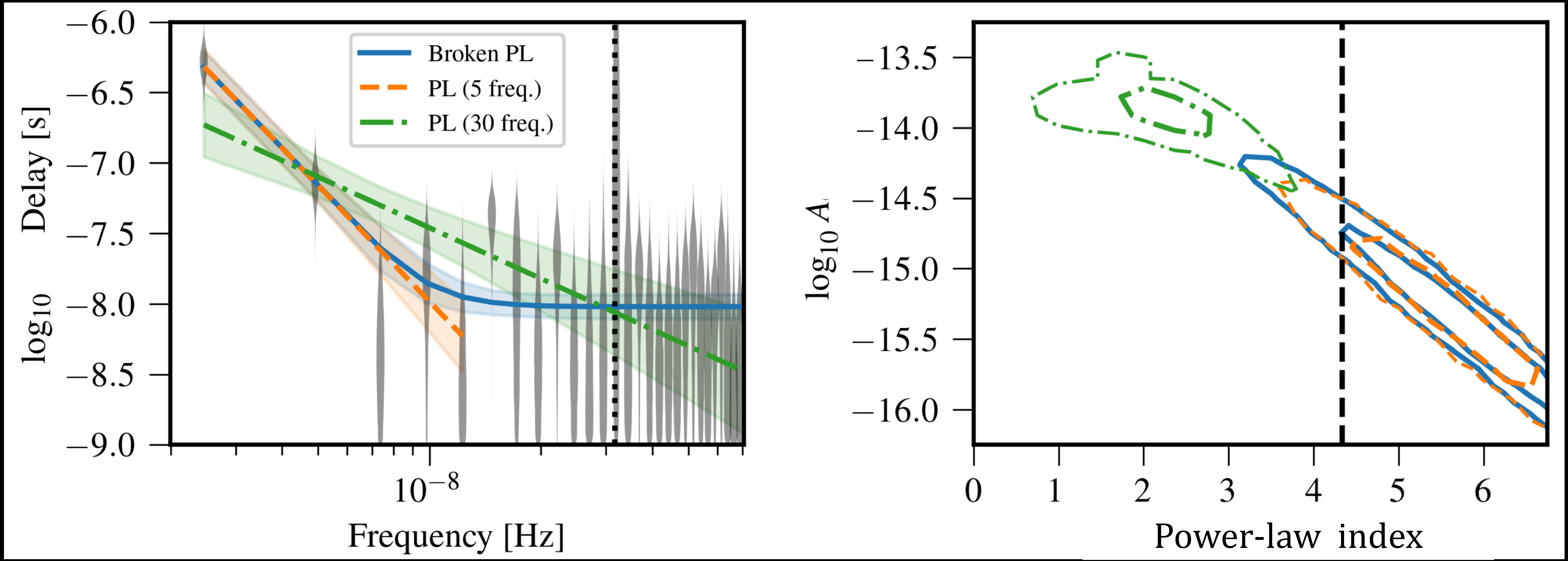
We detect common red noise with high significance. **We cannot make it go away.**

However, we can not yet detect quadrupolar angular correlations.

# It is consistent with a population of supermassive black hole binaries



Under simplest assumptions, we expect a “red” spectrum with a power-law index of 13/3.

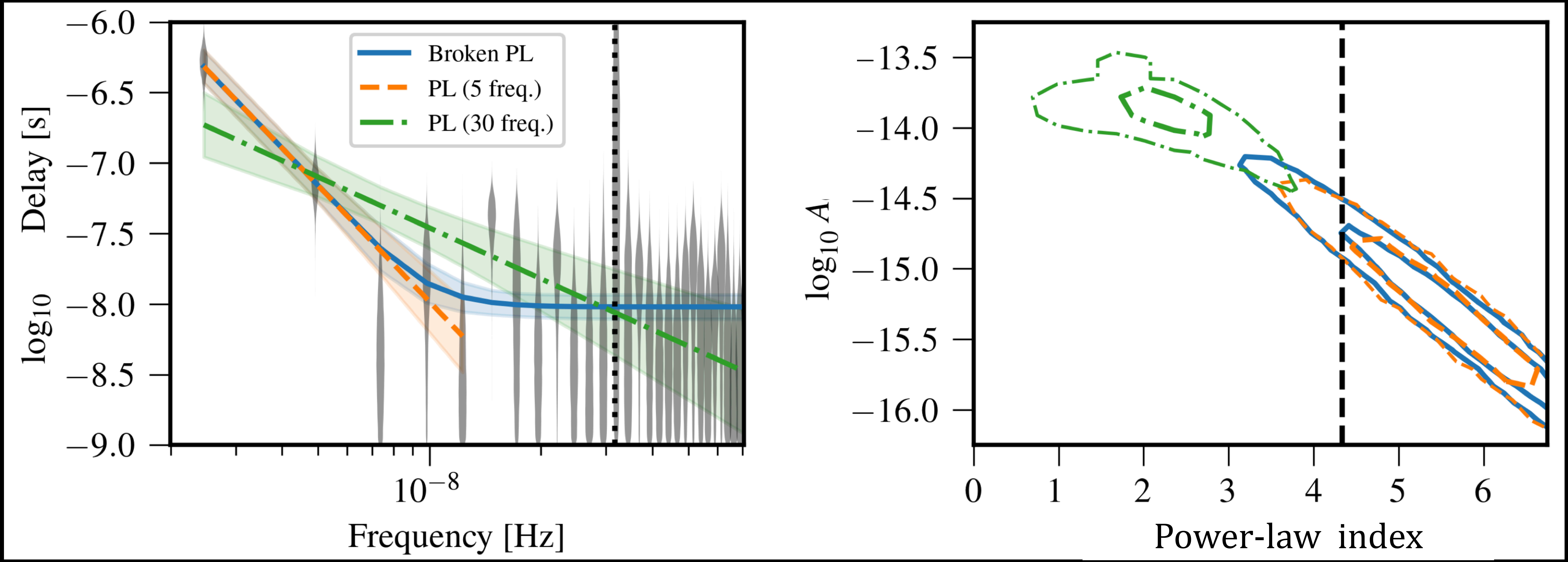



The NANOGrav Collaboration, 2020, ApJ, 905, 34

# It is *also* consistent with primordial gravitational waves or cosmic strings

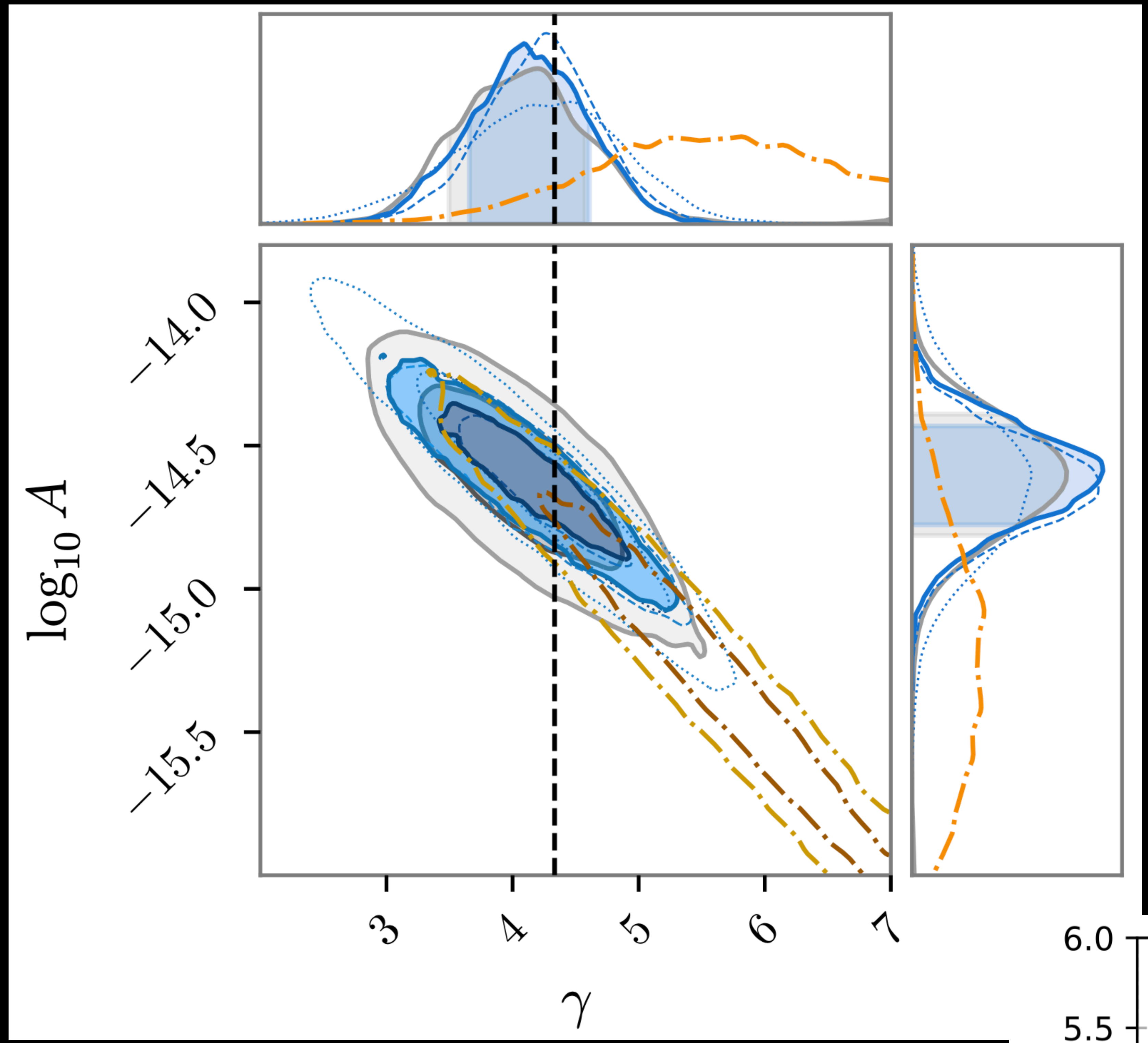
NANOGrav Physics Frontiers Center

We expect “red” spectra with power-law indices of 4-7 (but likely lower amplitudes ...)

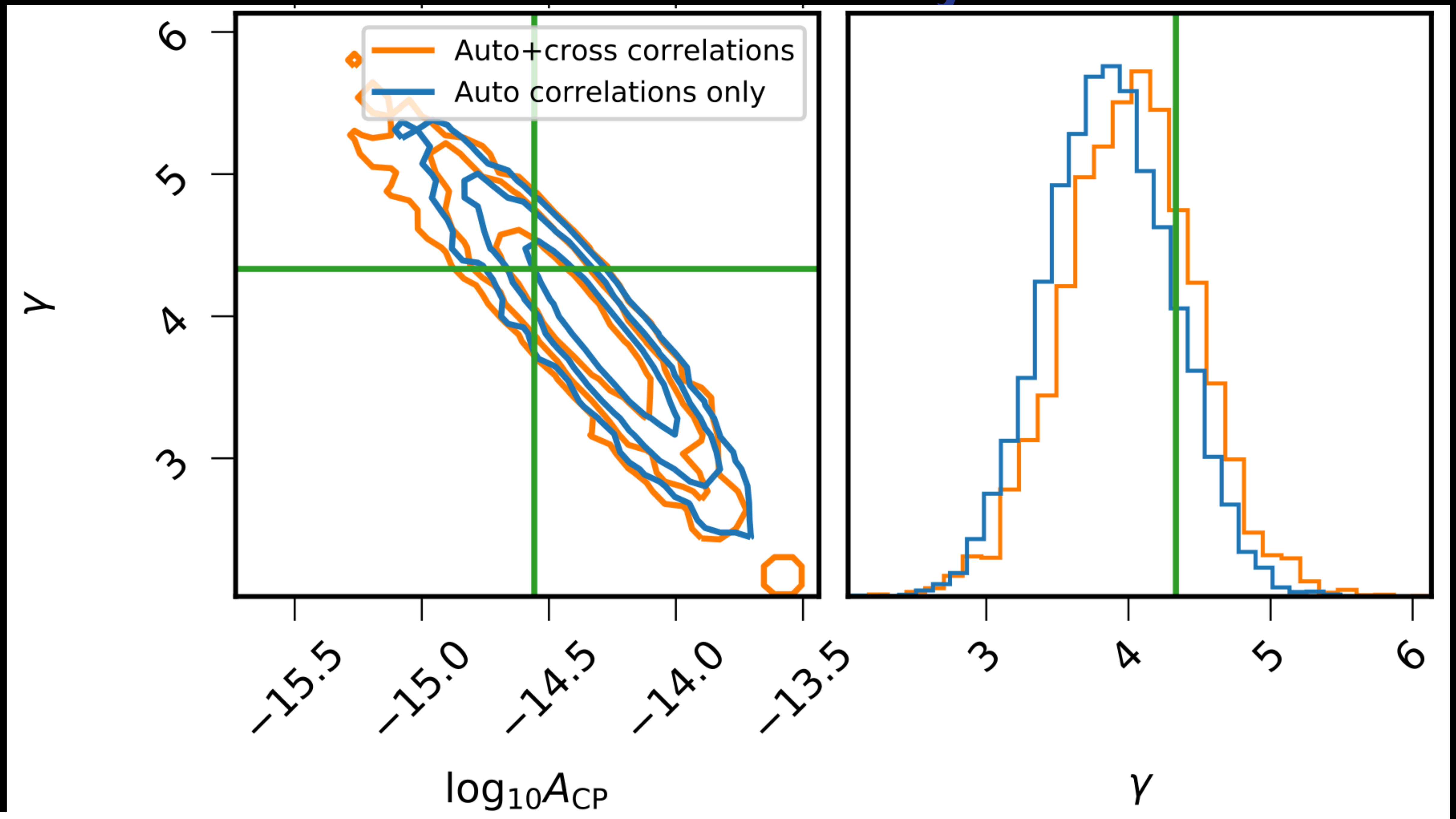



*The NANOGrav Collaboration, 2020, ApJ, 905, 34*

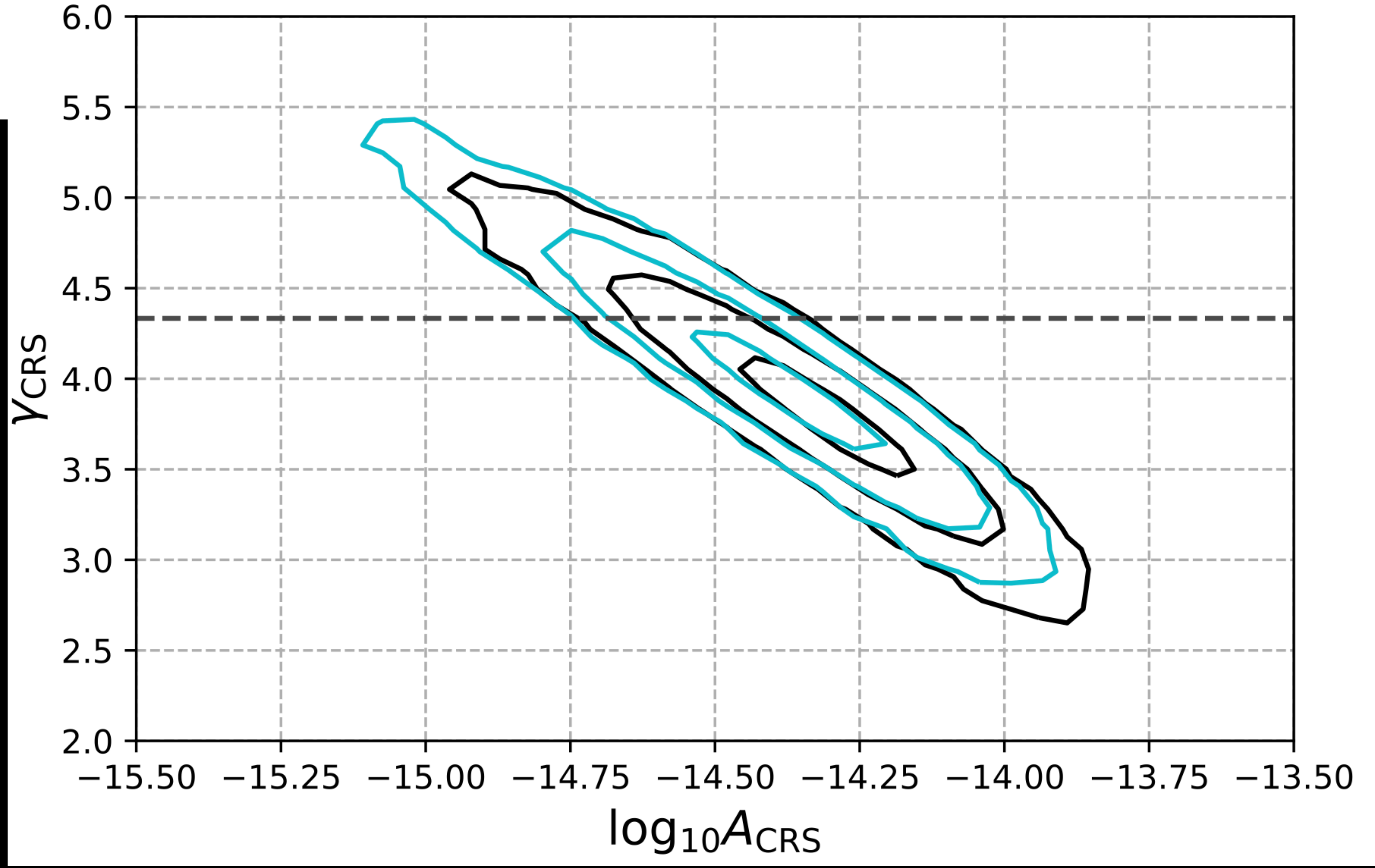
# Seen in EPTA, PPTA, and IPTA data also!




Goncharov et al., for the PPTA Collaboration, 2021, ApJL, 917, 2



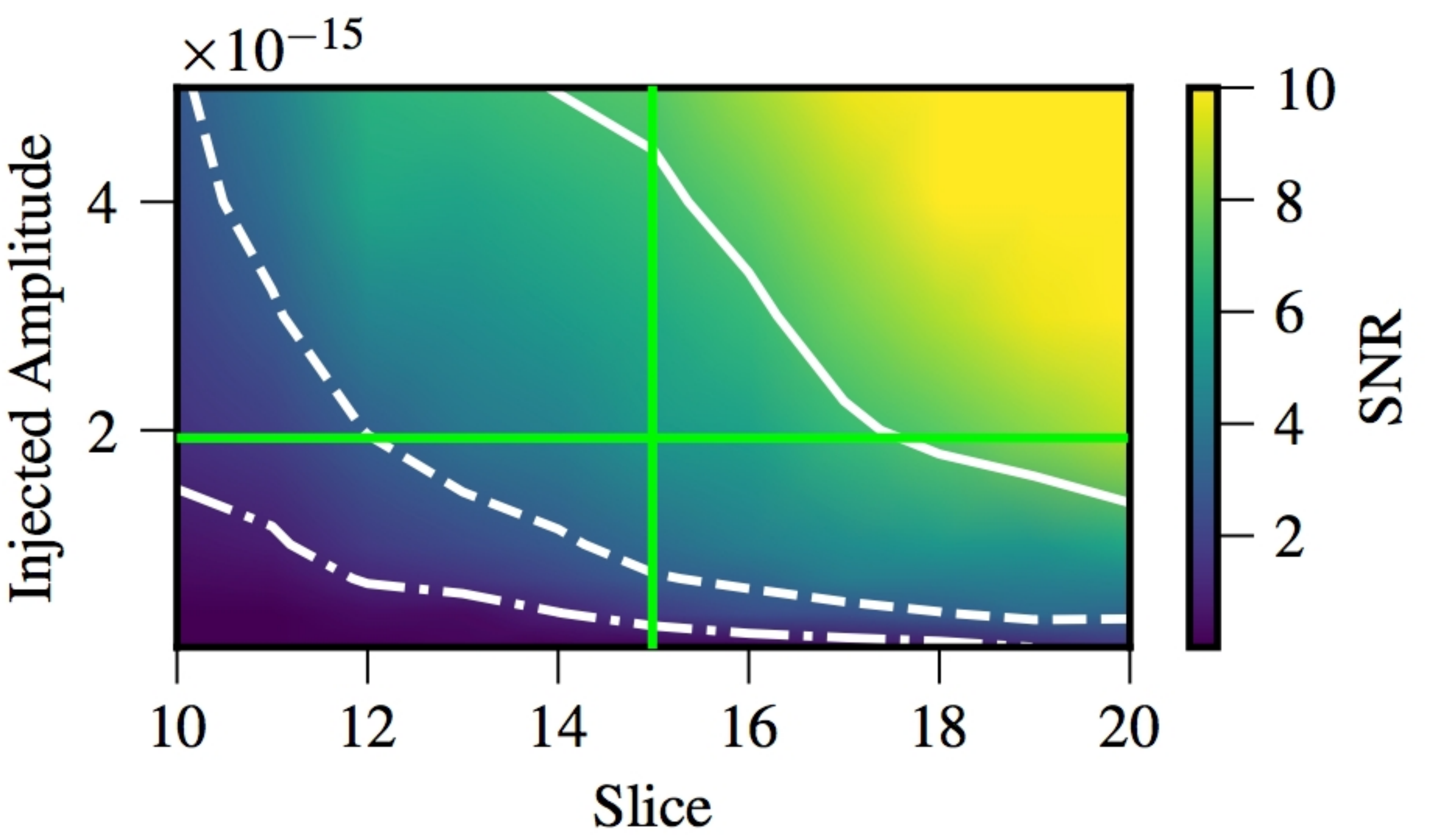

The IPTA Collaboration, 2022, MNRAS, 510, 4

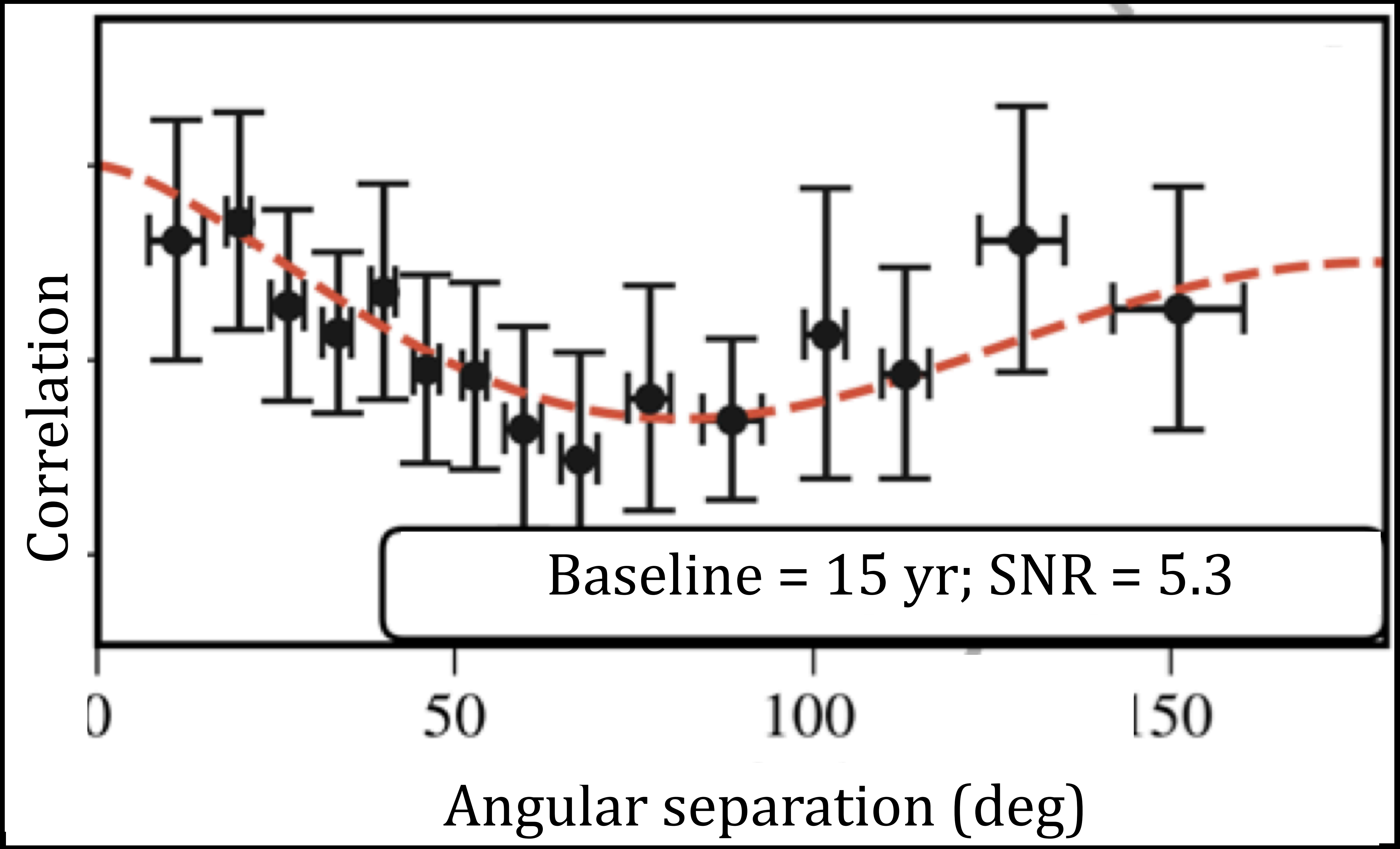



Chen et al., for the EPTA Collaboration, 2021, MNRAS, 508, 4

# When will noise become signal?

NANOGrav Physics Frontiers Center



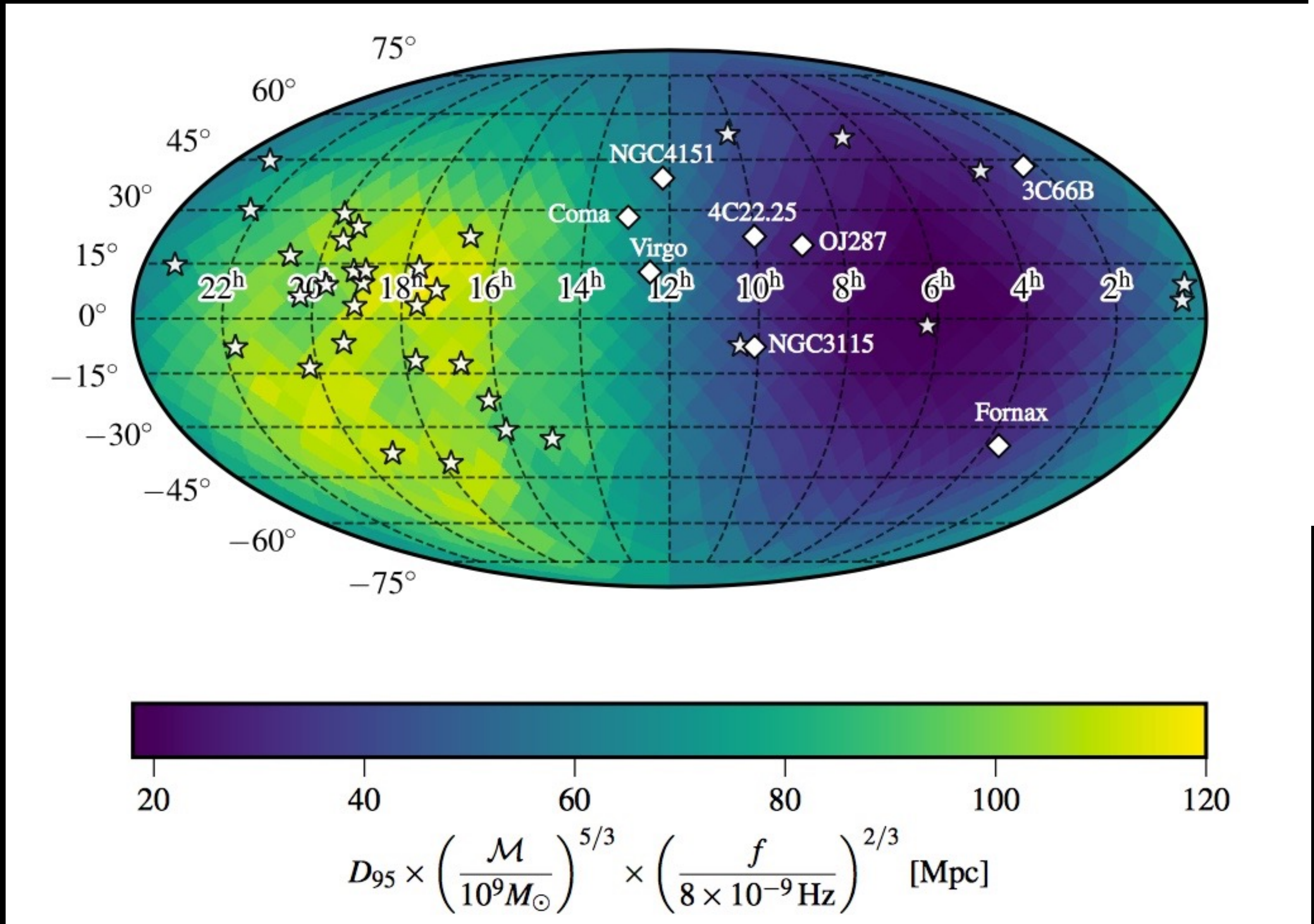

*Pol et al. 2021, ApJ, 911,34*

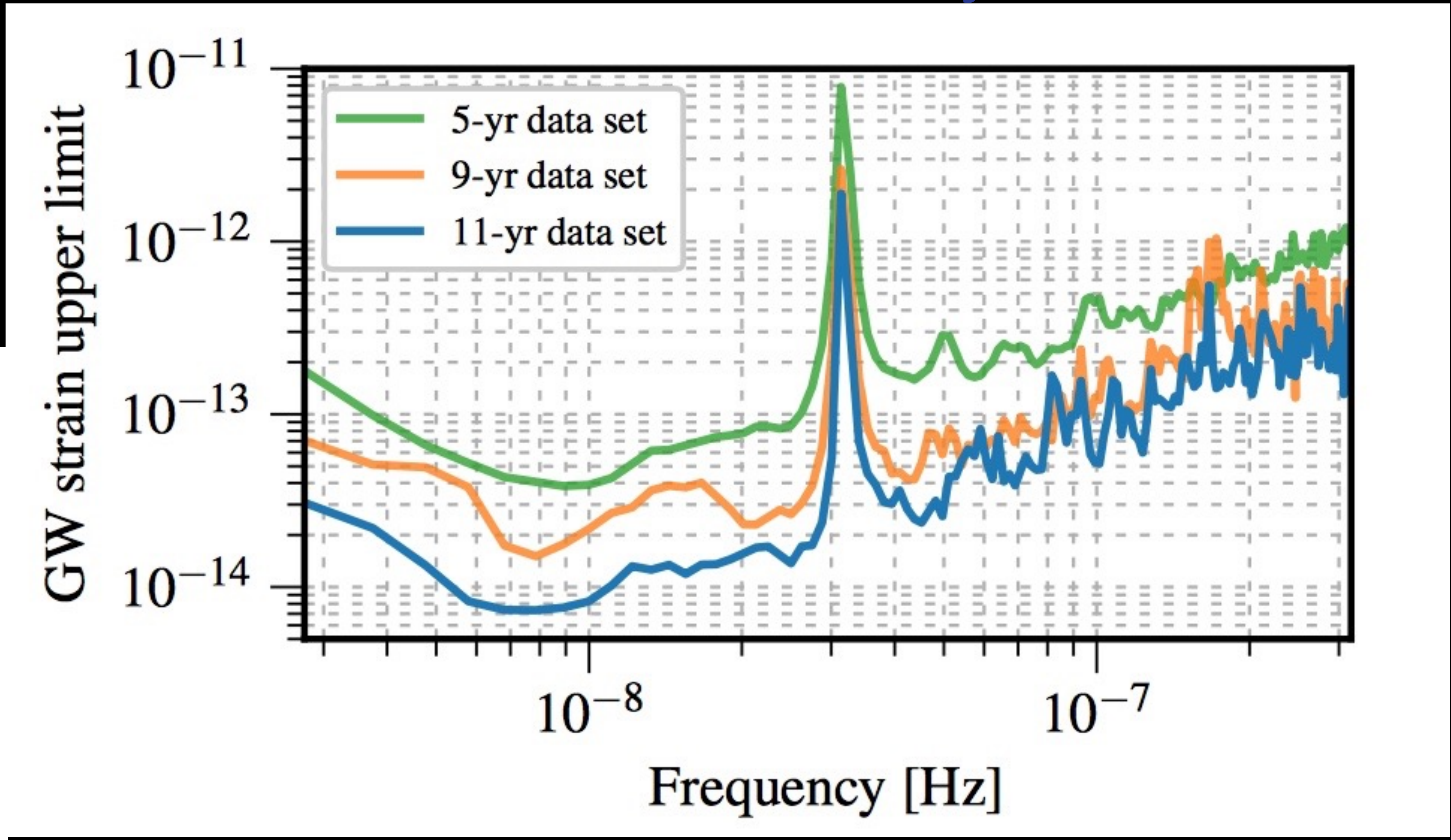
We should detect angular correlations at a S/N of 4-7 in the data set we will publish within the next year. We will likely not be able to identify the source of the background.

S/N will be even higher in combined International Pulsar Timing Array data!

# Eleven-year Single Source Results

Limit is highly direction dependent!




No Virgo SMBHBs with
M > 1.6 x $10^9$ solar masses

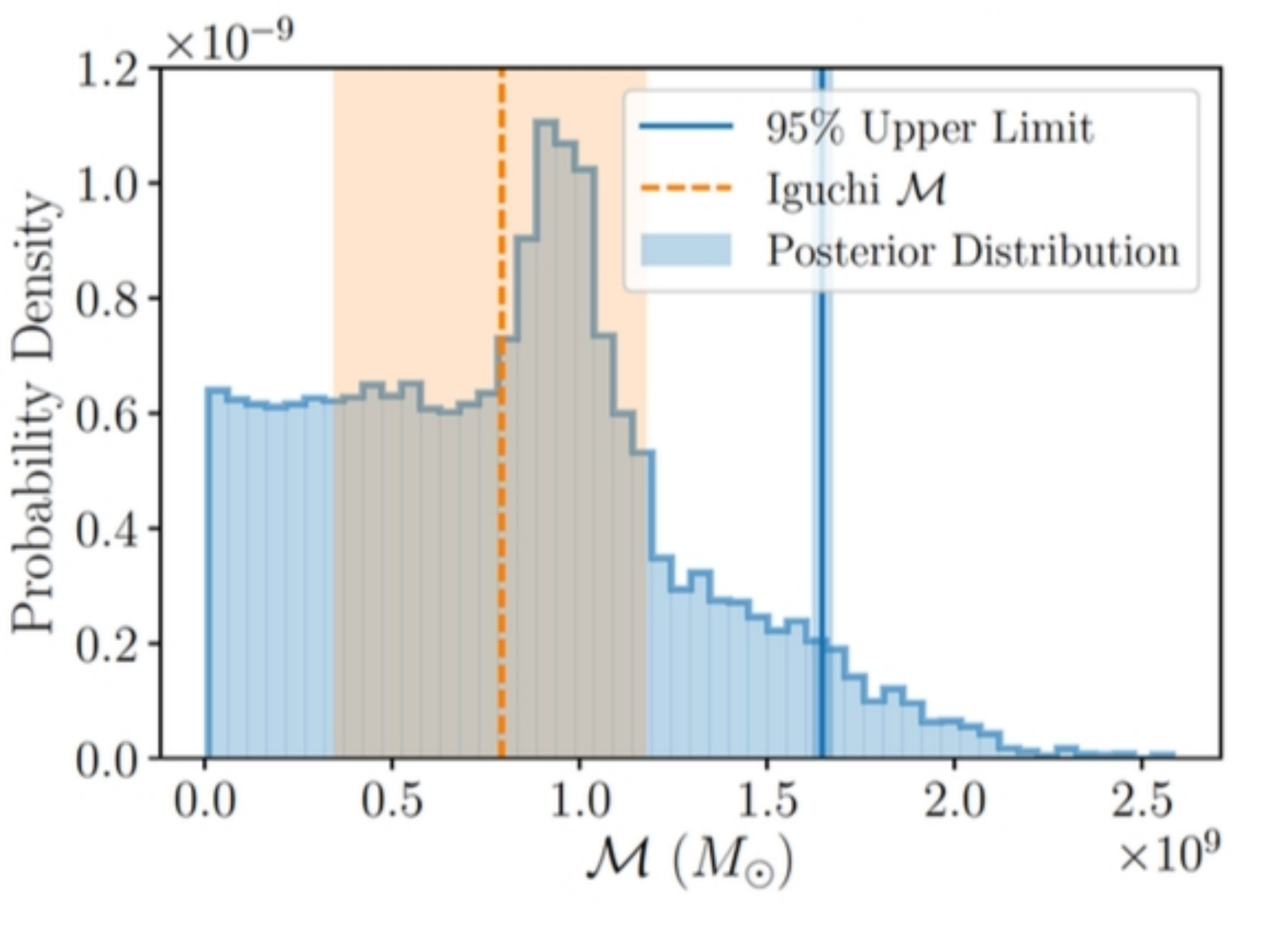
*The NANOGrav Collaboration, 2019, ApJ, 880, 116*

NANOGrav Physics Frontiers Center

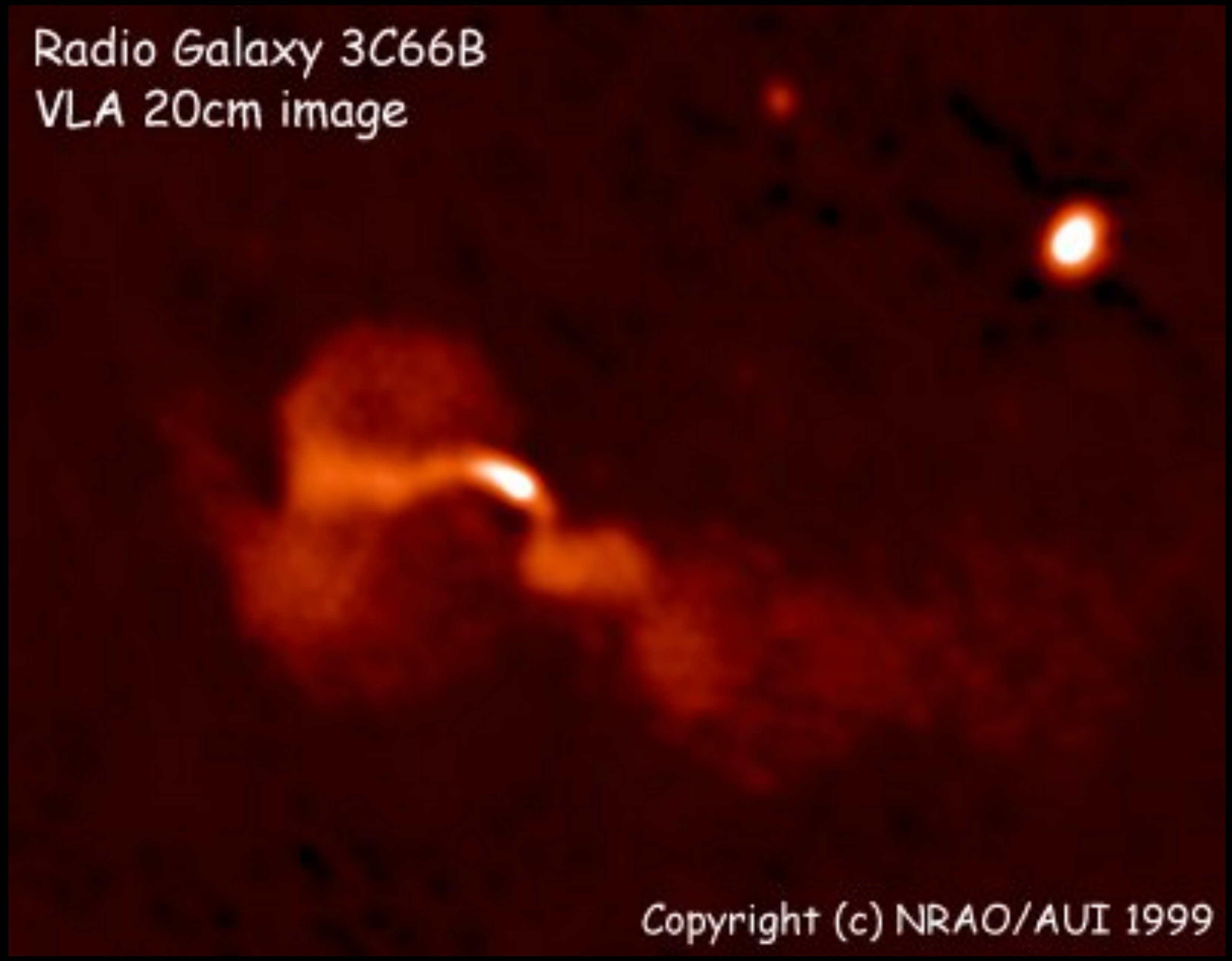
# Multi-Messenger GW Searches

Nearby (85 Mpc) galaxy which shows evidence for binary black hole at core.

Performed GW search with EM priors.

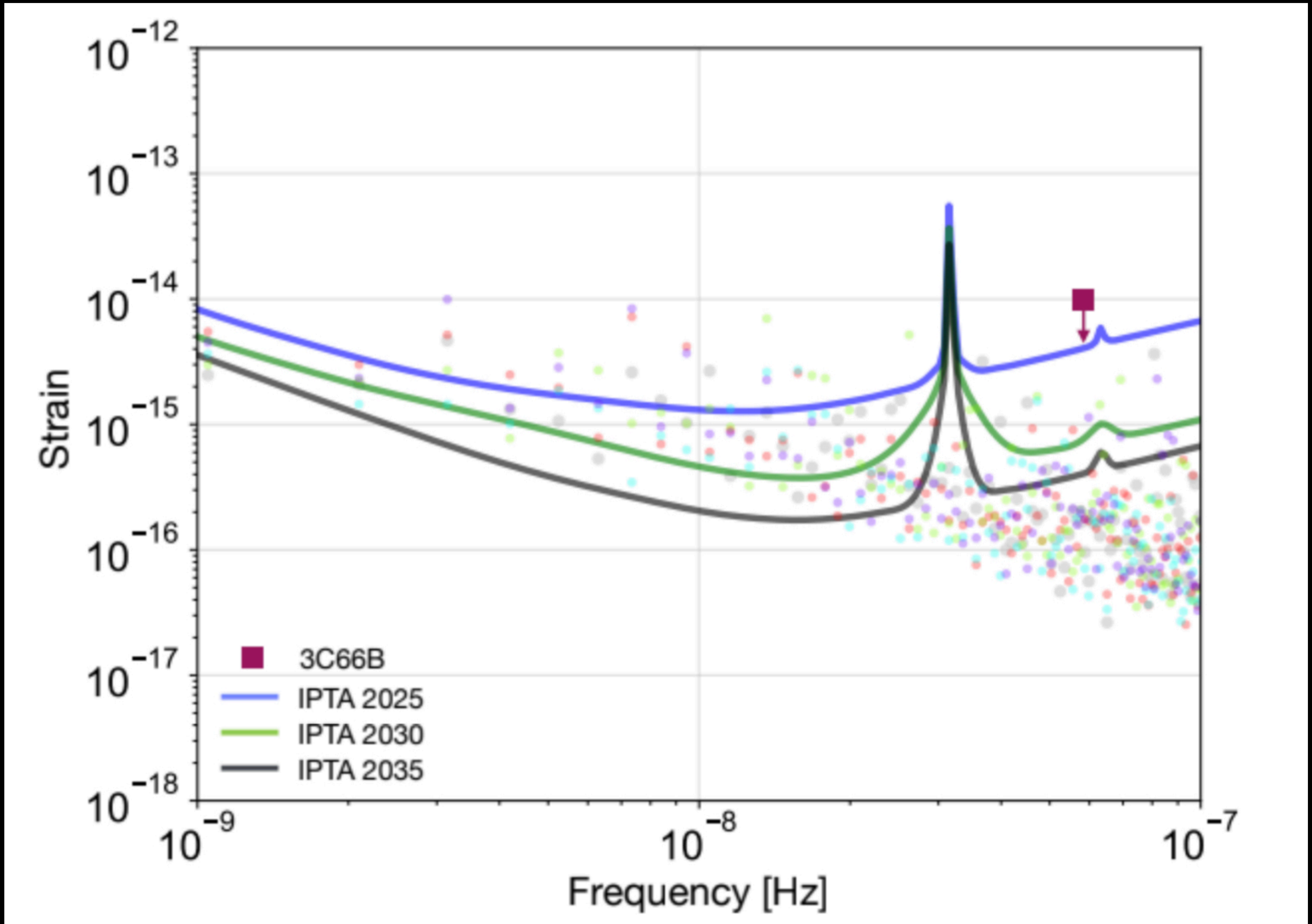



*The NANOGrav Collaboration, 2020, ApJ, 900, 2*




We will rule out the published mass estimate (or make a detection!) a few years.

# We expect single source detections within ~5 years!




The next IPTA data release will also be the most sensitive dataset in the world for single source searches.

**After five years of LSST observations, tens of binary candidates should be identified!**

*Plot based on Kelley et al., 2018, MNRAS, 477, 964 and The NANOGrav Collaboration, 2020, ApJ, 900, 102*

NANOGrav Physics Frontiers Center

# The Future

# Grow to 200 MSPs by 2030

NANOGrav Physics Frontiers Center

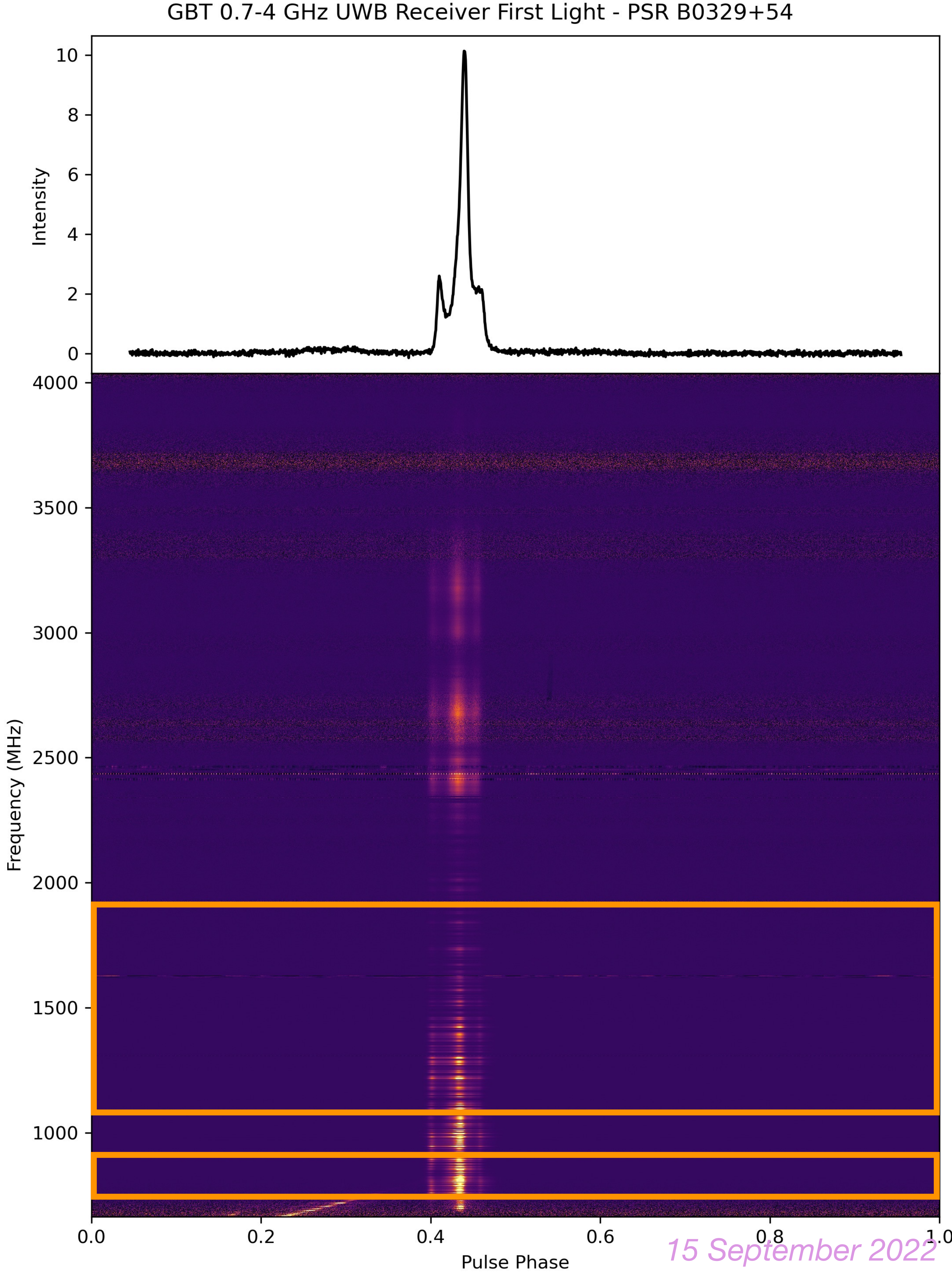
Our GW sensitivity is linearly dependent on the number of pulsars. We also need more uniform sky coverage.

Searches for pulsars are critical! High-school and undergraduate students in the NSF-DRL and NSF-OAI funded Pulsar Search Collaboratory program are contributing towards this important goal!

*PSC Camp at the Green Bank Observatory*

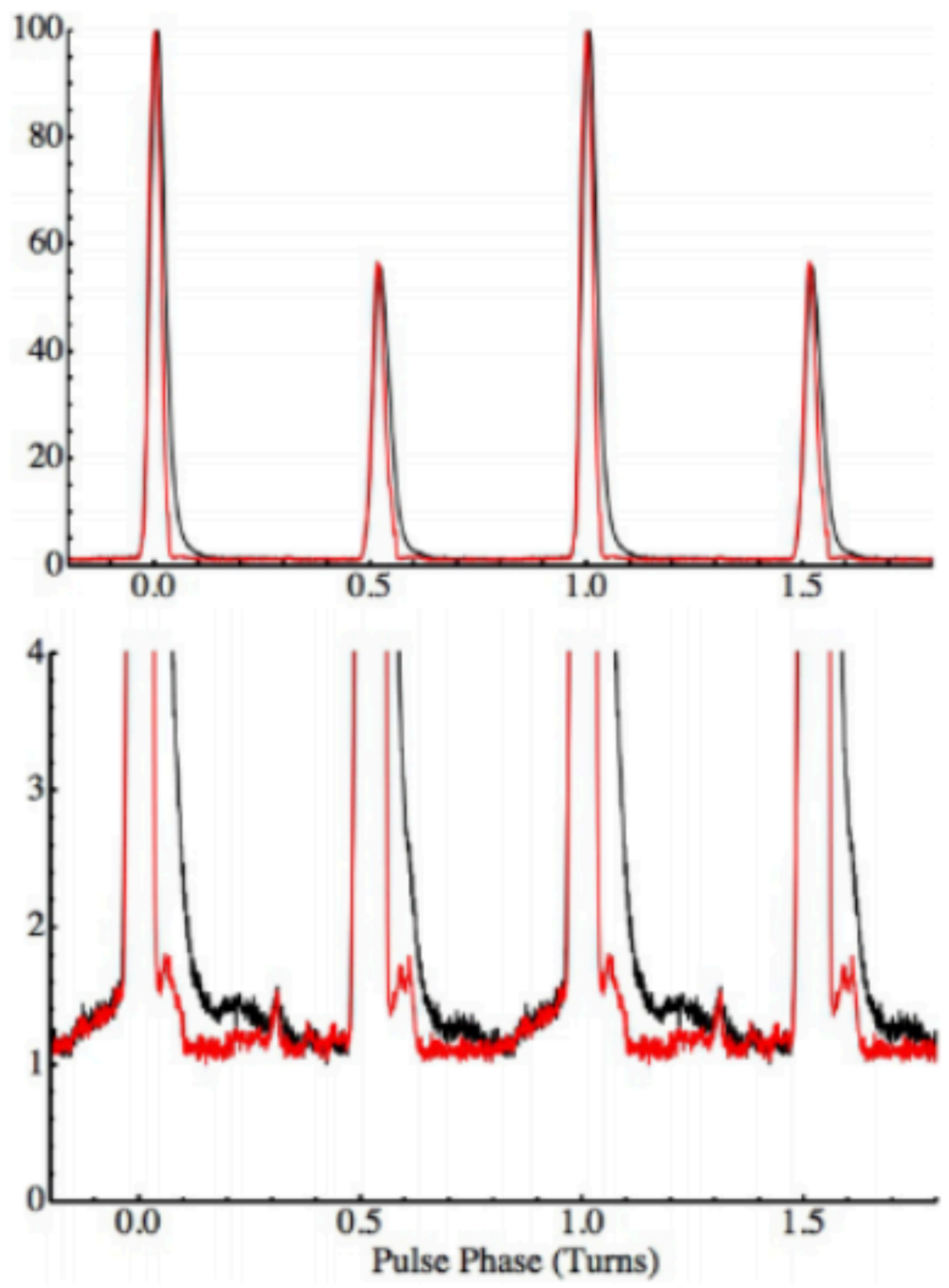
*PSC Capstone at West Virginia University*

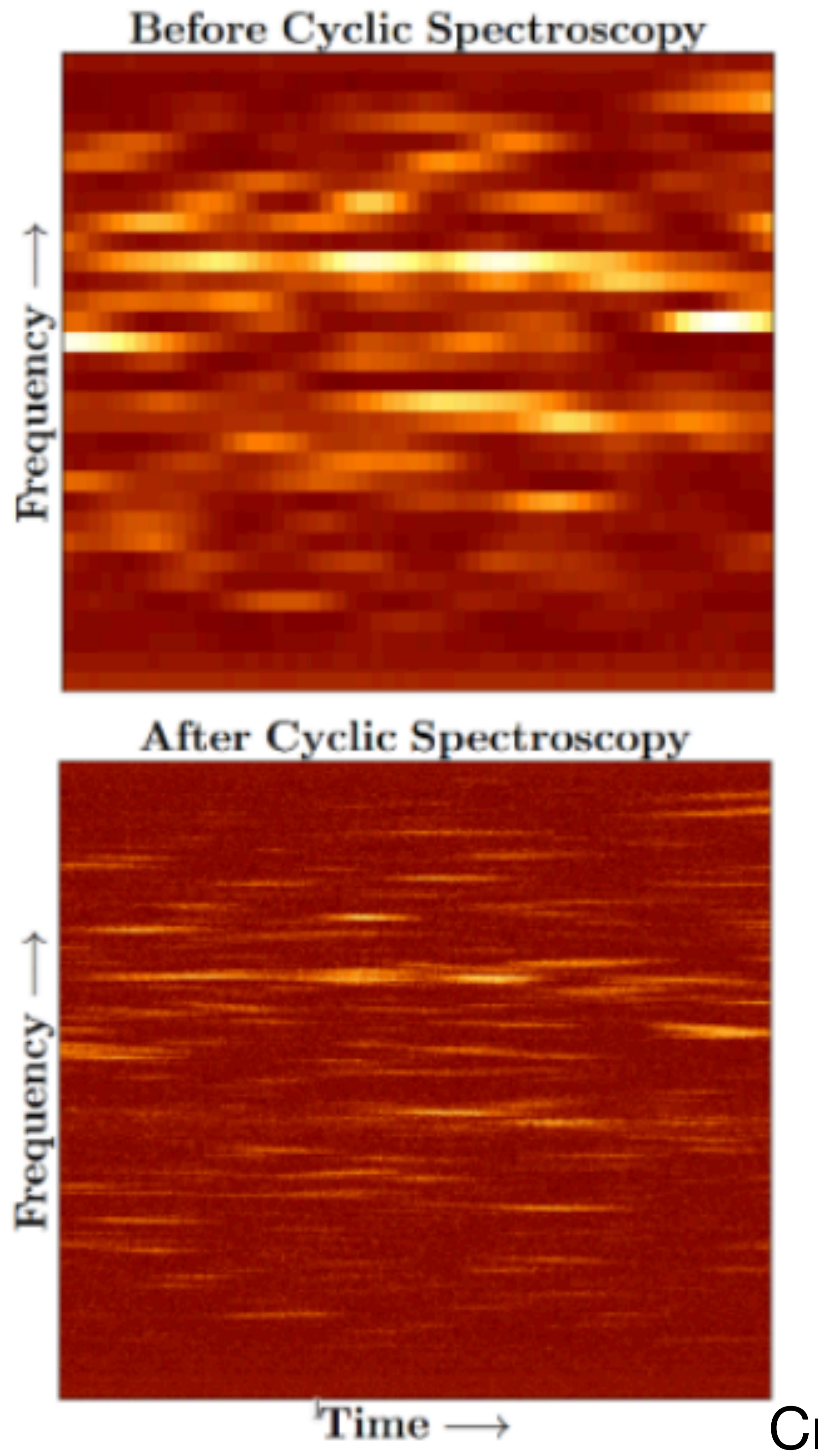
# Commission the GBT’s wideband receiver



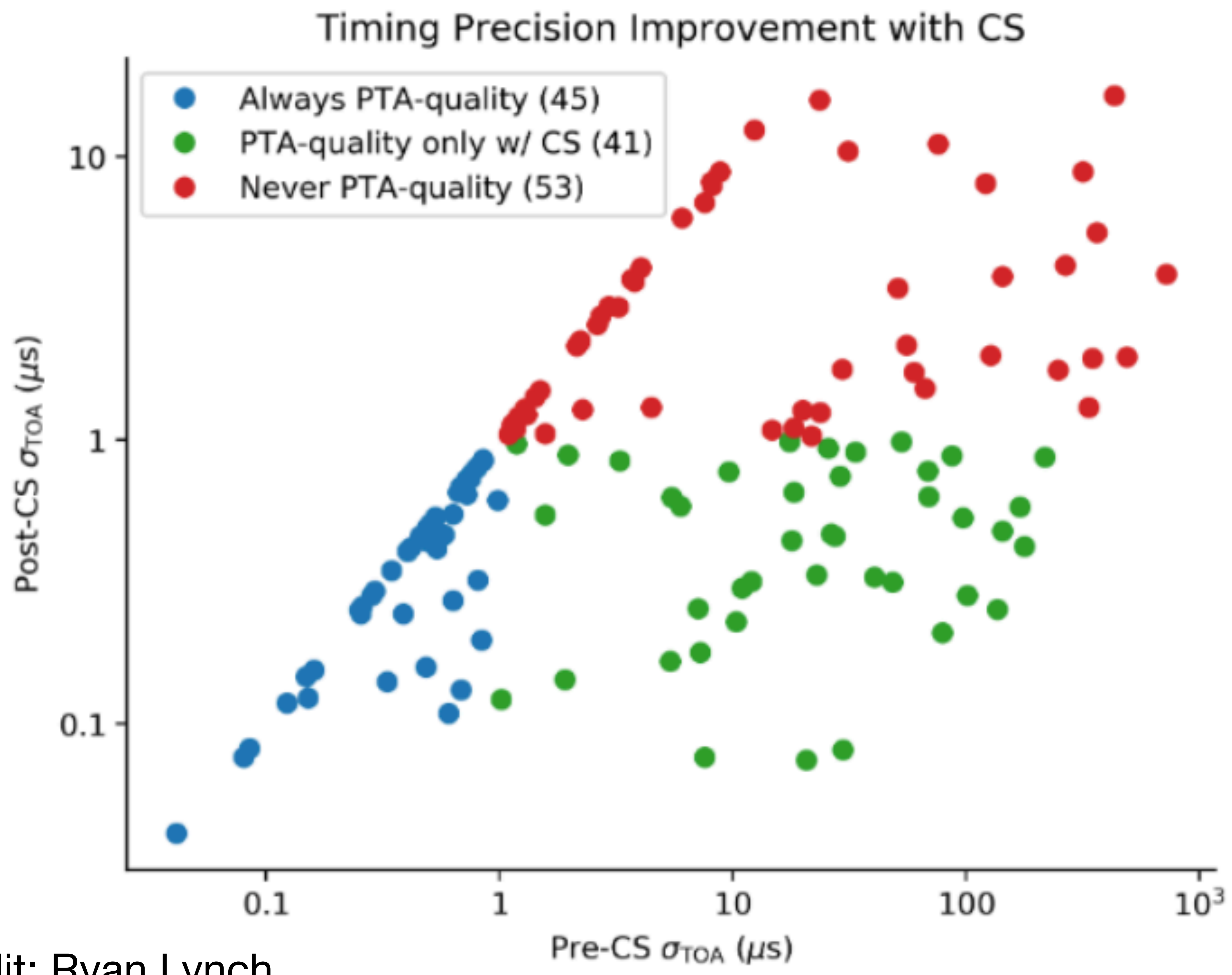
# Improve Our Understanding and Mitigation of Noise Sources

NANOGrav Physics Frontiers Center




Credit: Ryan Lynch

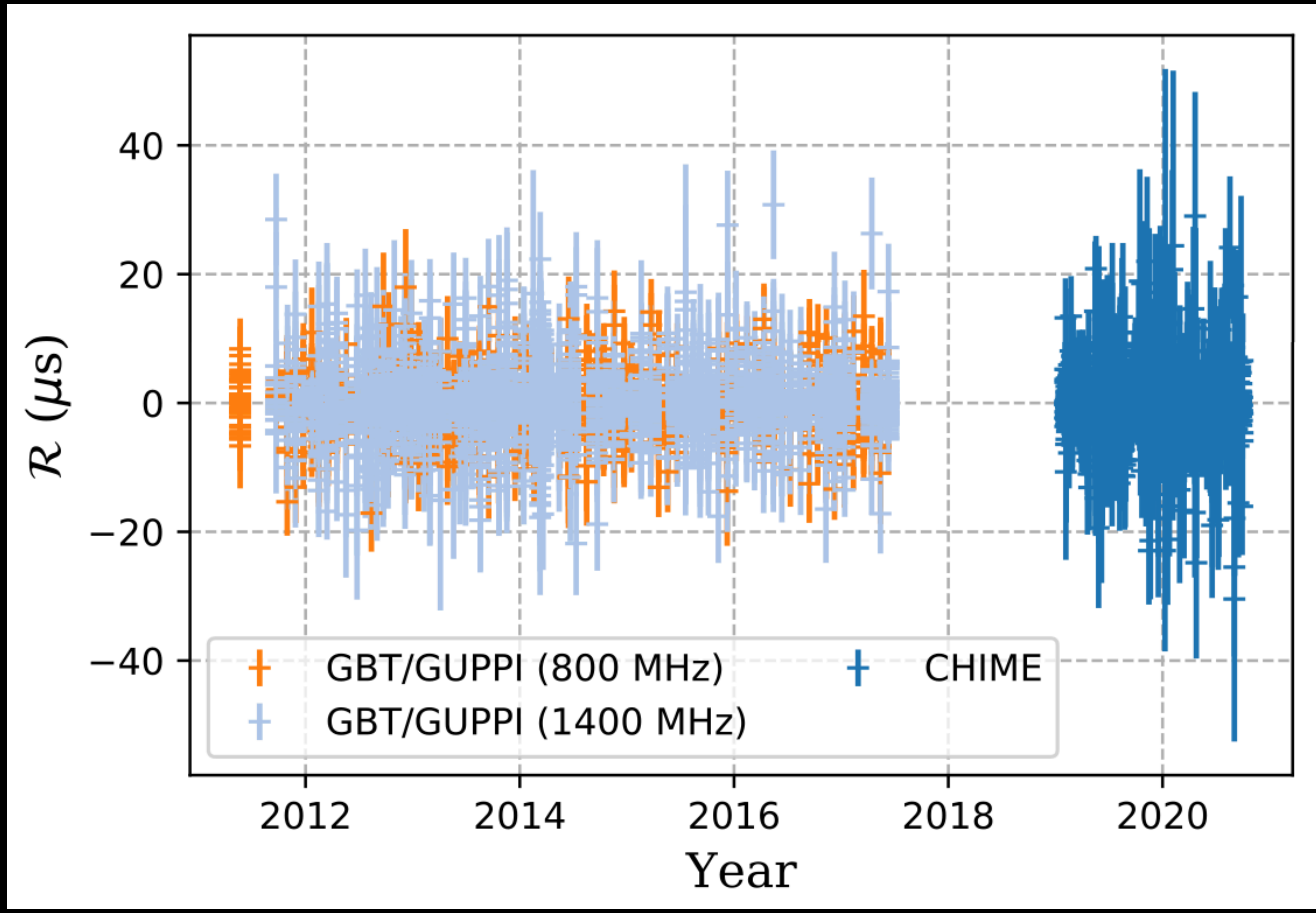



*Left: PSR B1937+21 before and after CS; Middle: Dynamic Spectra before and after CS; Right: Improvement in timing for simulated MSP population*

# Incorporate CHIME data into our datasets

NANOGrav Physics Frontiers Center

Daily cadence complementary to GBT.




CHIME/Pulsar Collaboration, 2021, ApJSS, 255, 1

CHIME Telescope, British Columbia, Canada

Not yet clear how many pulsars we can time well enough with CHIME, and what the improvement will be.

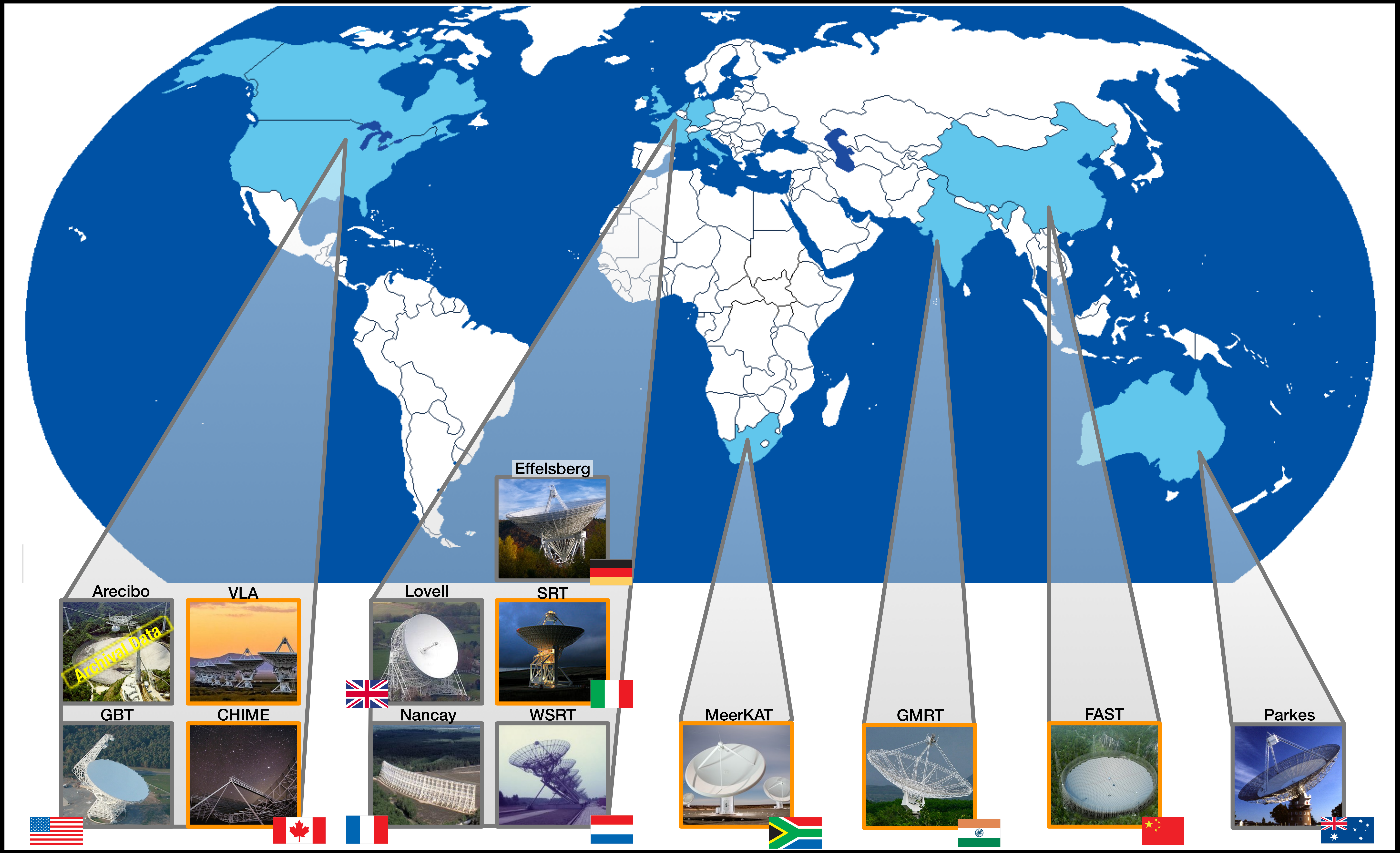
# Grow the IPTA

NANOGrav Physics Frontiers Center

Current dataset includes data from seven telescopes in six countries.

Future datasets may include data from 11 telescopes in 16 countries.

NSF AccelNet funded project manager and cyber-infrastructure specialist will enable this growth!



# Summary

NANOGrav
Physics Frontiers Center

- Tne Green Bank Observatory has played leading and absolutely critical roles in every area of pulsar astronomy since its inception in 1967.
- We are currently timing 70 MSPs with Green Bank, VLA, and CHIME and collaborating internationally to compensate for AO loss.
- Our 12.5-yr dataset - and those of other PTAs and the IPTA - shows strong evidence for a common noise process consistent with gravitational waves. Angular correlations should be detectable in our 15-yr dataset, if signal is indeed due to gravitational waves.
- Measurement of the amplitude and spectrum will provide unique insights into galaxy formation and evolution.
- Sensitivity has increased dramatically due to additional pulsars and improved instrumentation. Will continue to increase with even more pulsars, wider bandwidths, better mitigation of noise, and **continued telescope access.** **Let's bring on another 65 years!**