



VIRTUAL UNIVERSE

A 3D INTERACTIVE TOOLKIT

Millisecond Pulsar Searching and Timing

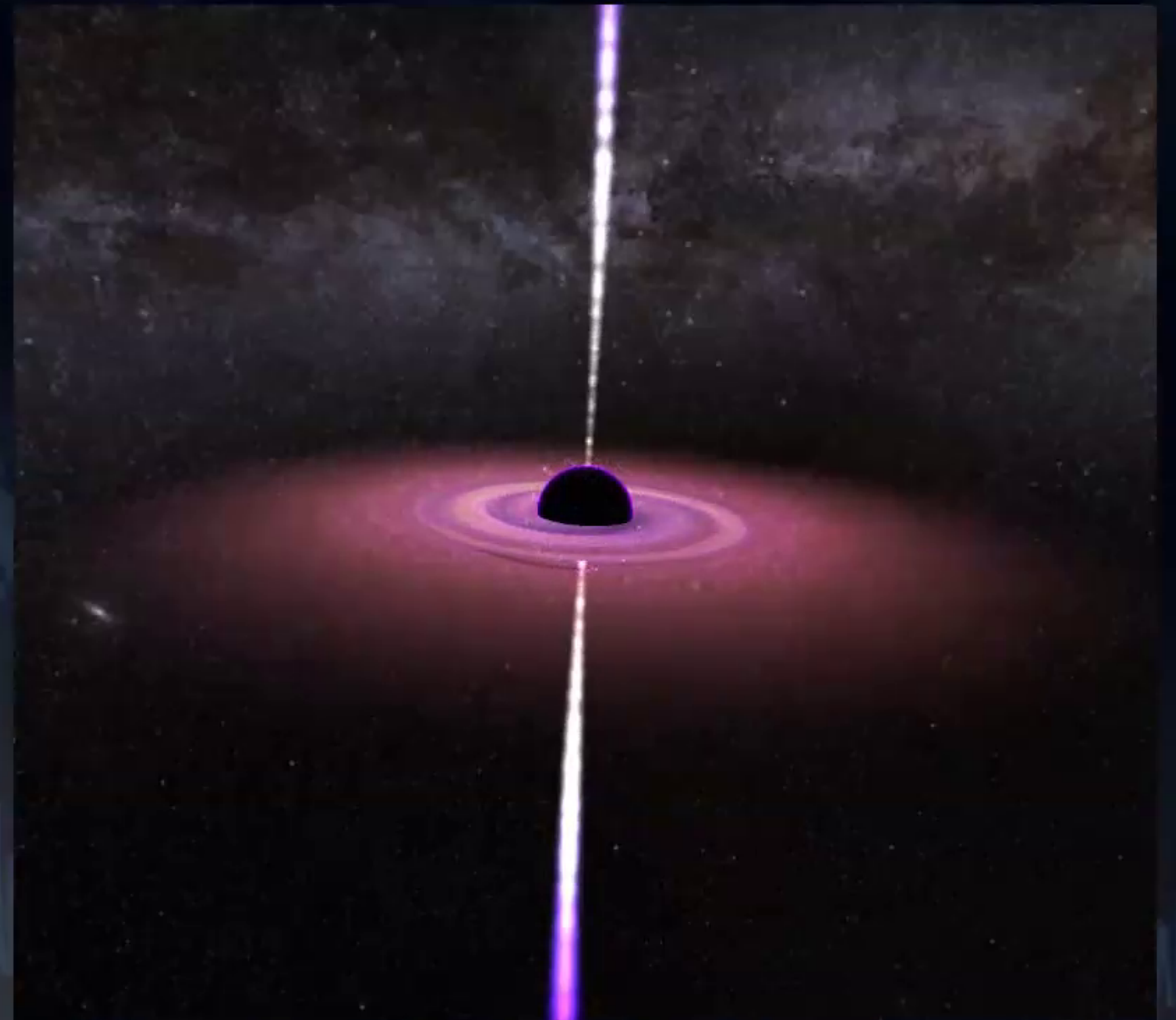
Matthew Bailes
OzGrav (Swinburne)

- Pulsar Discovery
- Millisecond Pulsars
- Applications



THE QUASARS (3C 31)

IMAGE CREDIT: CREDIT: NRAO (LAING ET AL.)

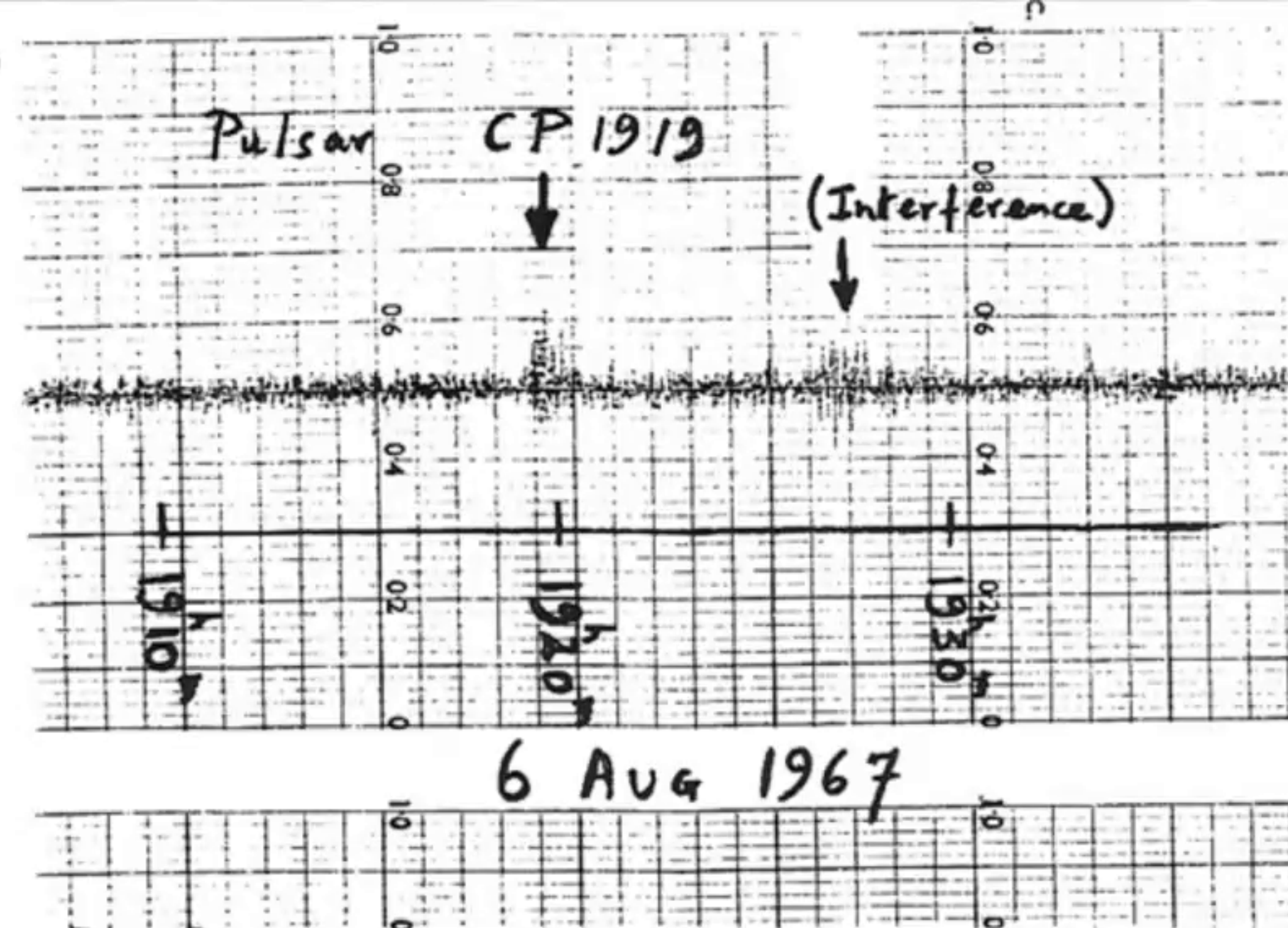




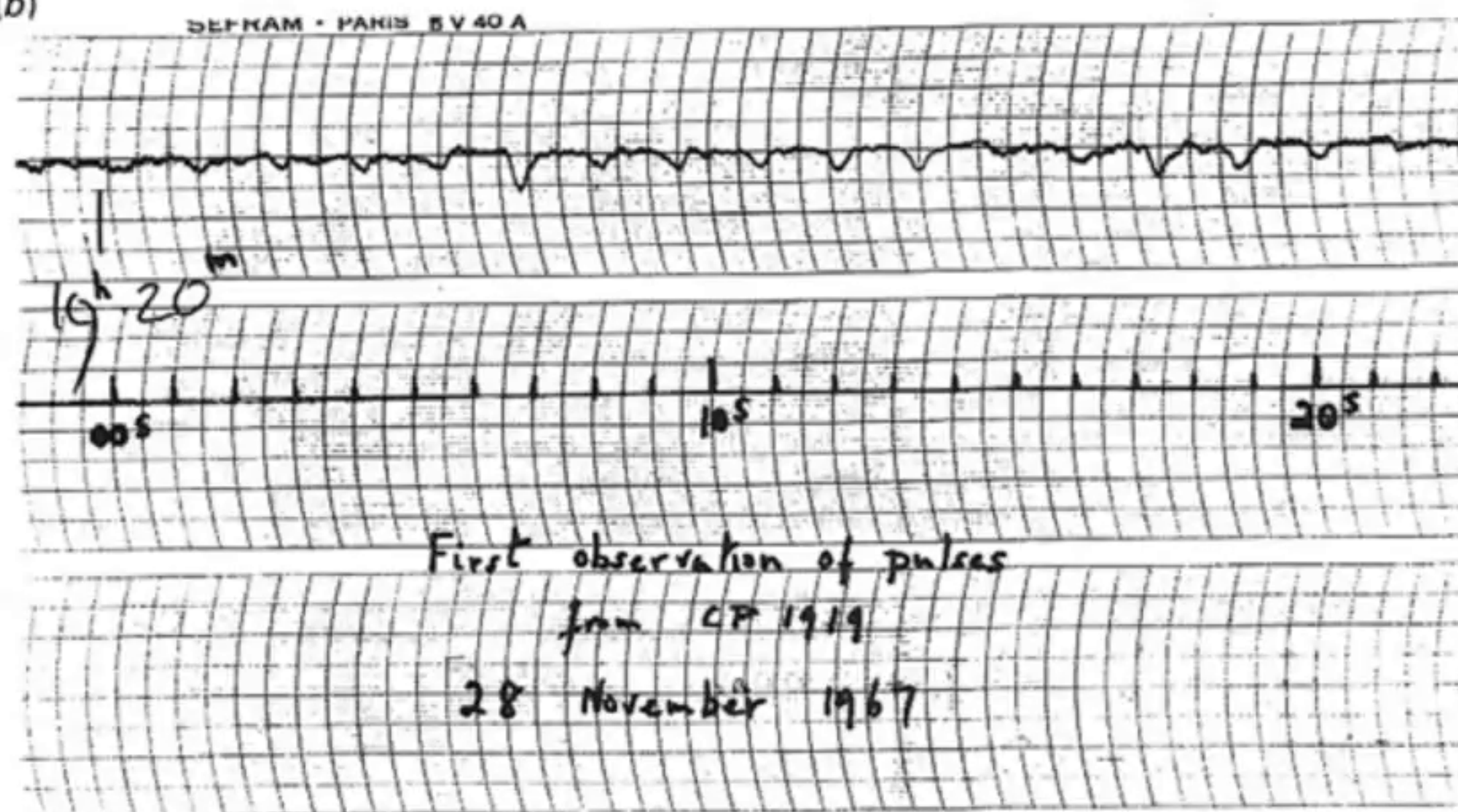
TWINKLING STARS HEWISH AND BELL STUDIED QUASAR SCINTILLATION

IMAGE CREDIT: SARAO

(a)

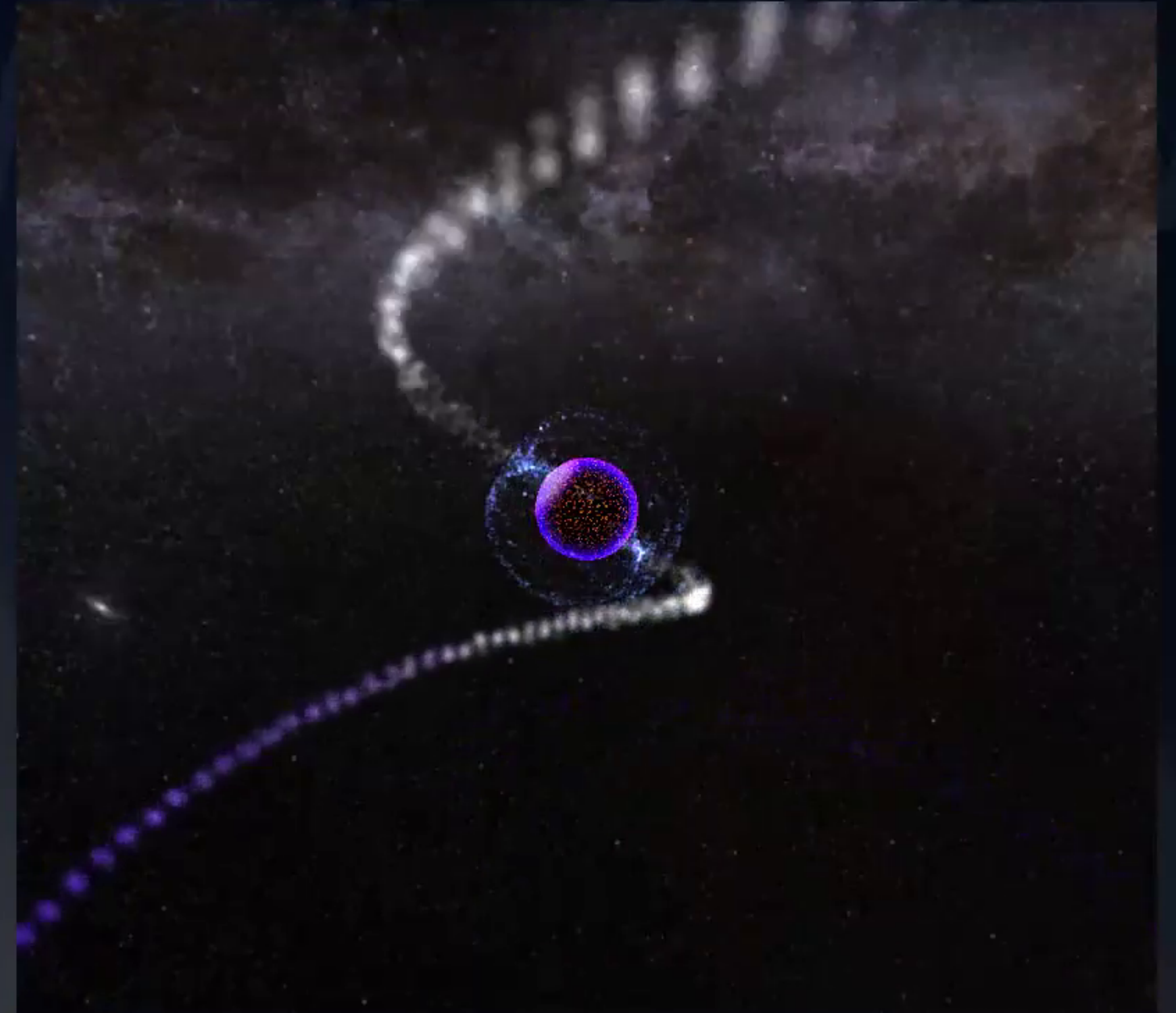


(b)



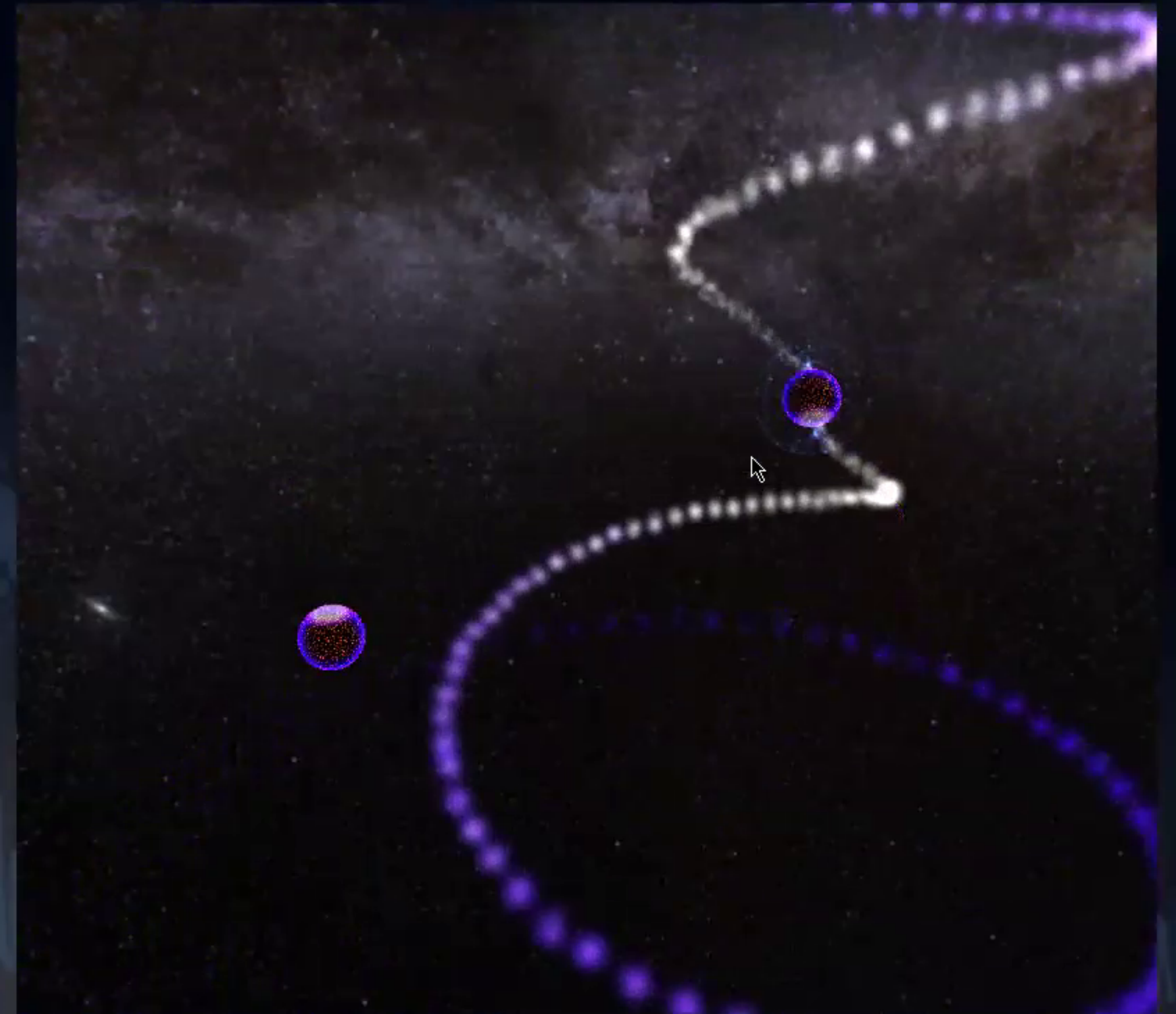
Pulsars! (regular pulse emitters)

- Discovered 1967 by Jocelyn Bell
- Spin 10s of sec to 1.4 ms!
- Magnetic Field $B = 10^8 - 10^{14} \text{ G}$
- $R = 10 \text{ km}$
- $M = 1.4 M_{\odot} = 500,000 M_E$
- 3500 known
- Mainly galactic objects
- 3x bigger than a BH
- Almost perfect clocks!
- You can listen to them...



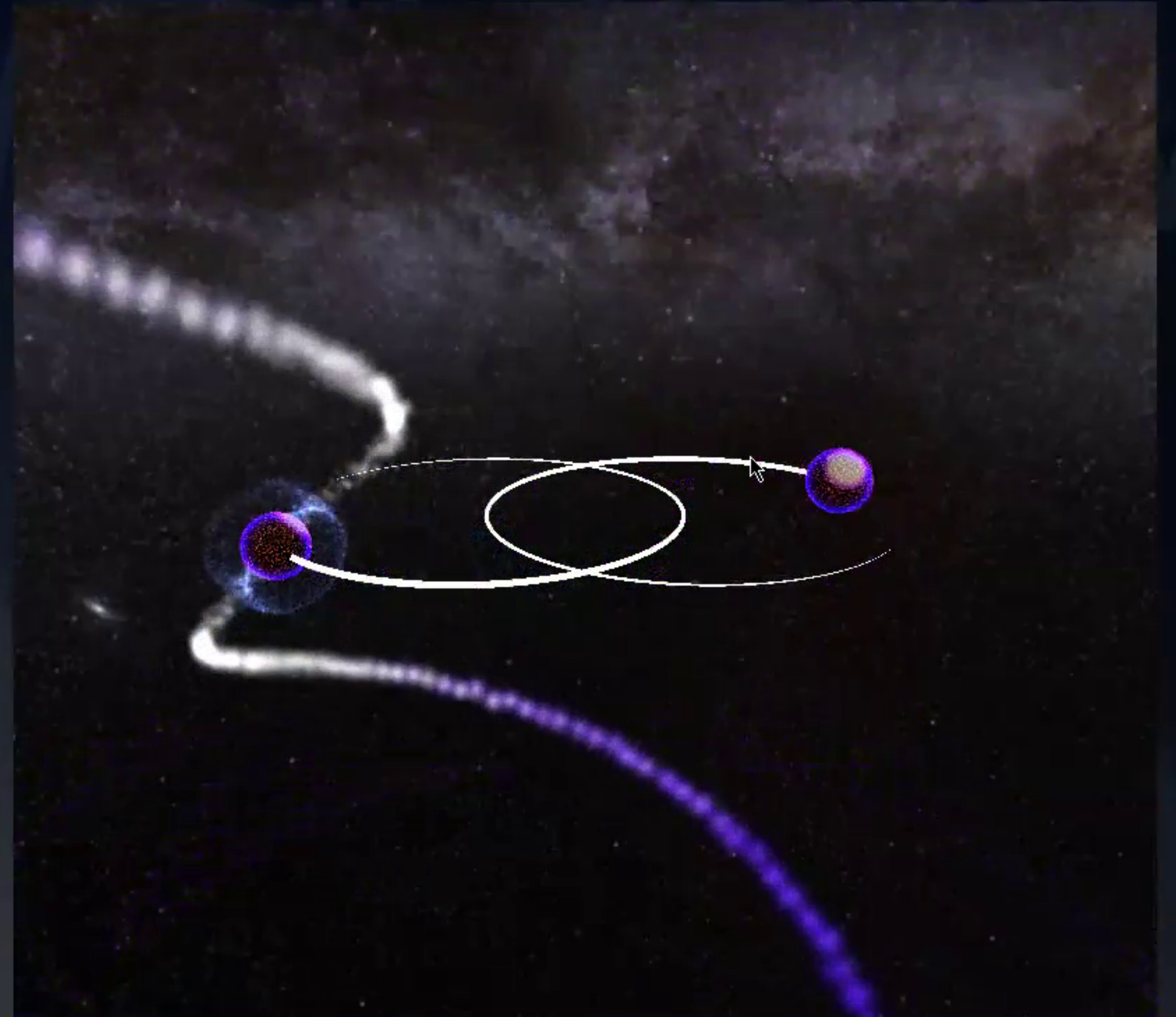
THE 1970S: COMPUTERISED SEARCHES

- LONGER, MORE SENSITIVE SEARCHES
 - HULSE AND TAYLOR (1974) – **40** PULSARS
 - MANCHESTER ET AL. (1978) – **155** PULSARS
- EMPLOYED THE “FOURIER TRANSFORM”
- DISCOVERED A “BINARY PULSAR”
 - 1993 NOBEL PRIZE IN PHYSICS
 - (HULSE & TAYLOR)



The Binary Pulsar Facts

- $P = 59 \text{ ms}$
- $P_b = 7.75 \text{ h}$
- $e = 0.617$
- $\frac{d\omega}{dt} = 4.2^\circ \text{ yr}^{-1}$ ($\sim 40,000 \times$ Mercury)
- Masses:
 - $M_1 = 1.44 M_\odot$
 - $M_2 = 1.38 M_\odot$



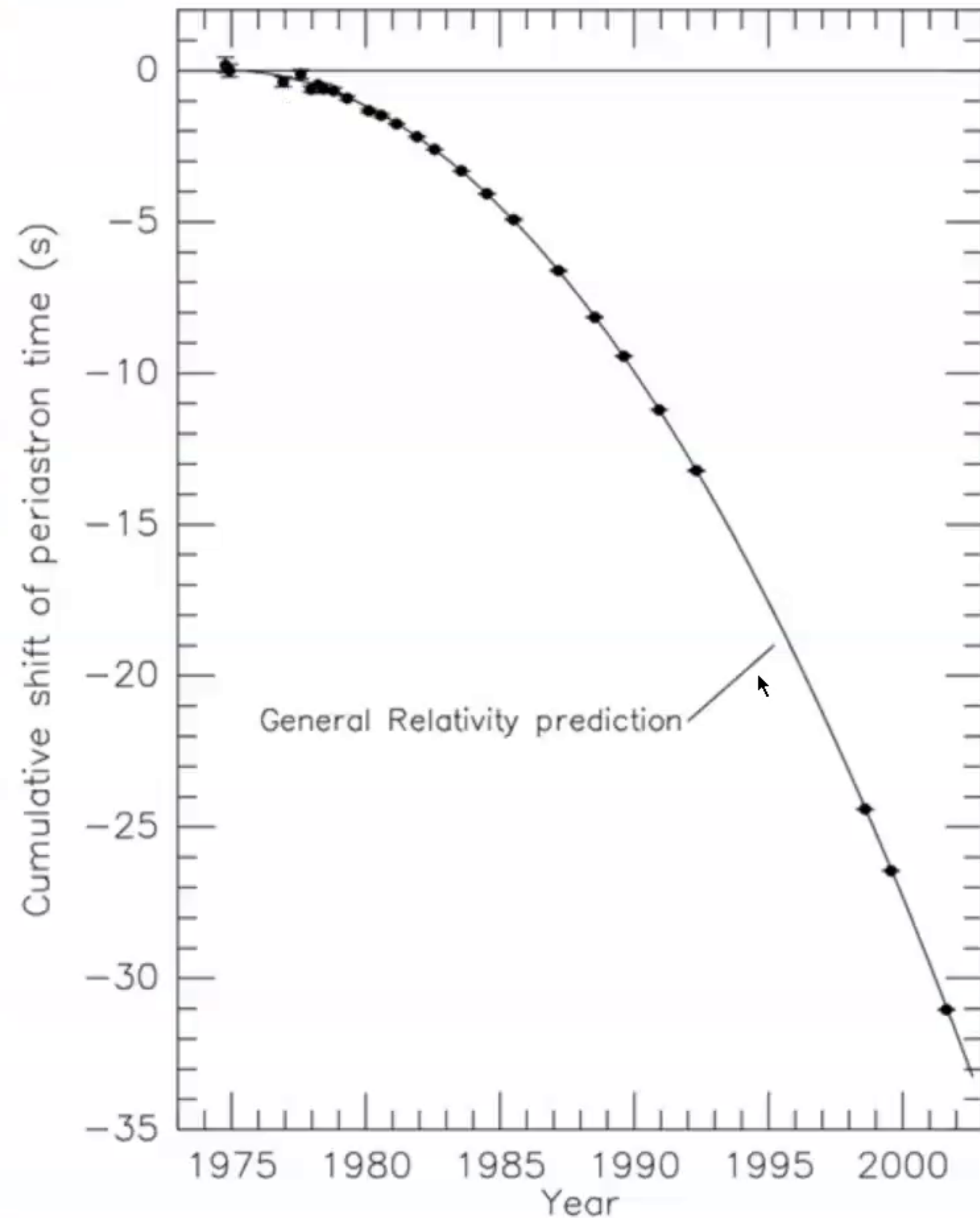
1913+16 Proof of existence of
gravitational waves*

Will merge in ~300 Myr

First guestimate of "merger
rate"

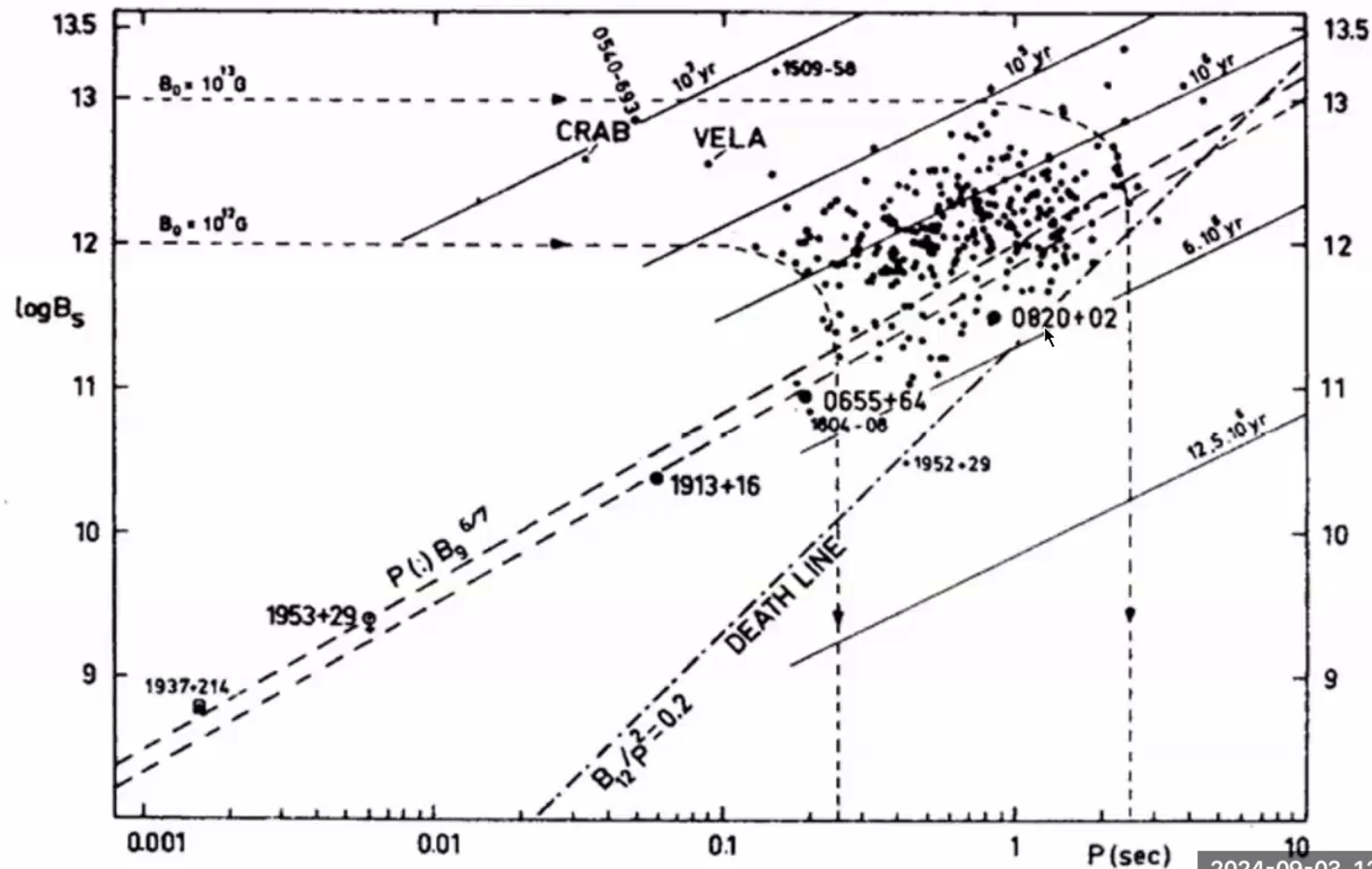
Impetus for LIGO

* 1993 Nobel Prize



Magnetic Field - Period Diagram

Ed van den Heuvel (1984)



Millisecond Pulsar Discovery (1982)

Backer et al. (1982)

Letter | Published: 16 December 1982

A millisecond pulsar

[D. C. Backer](#), [Shrinivas R. Kulkarni](#), [Carl Heiles](#), [M. M. Davis](#) & [W. M. Goss](#)

[Nature](#) **300**, 615–618 (1982) | [Cite this article](#)

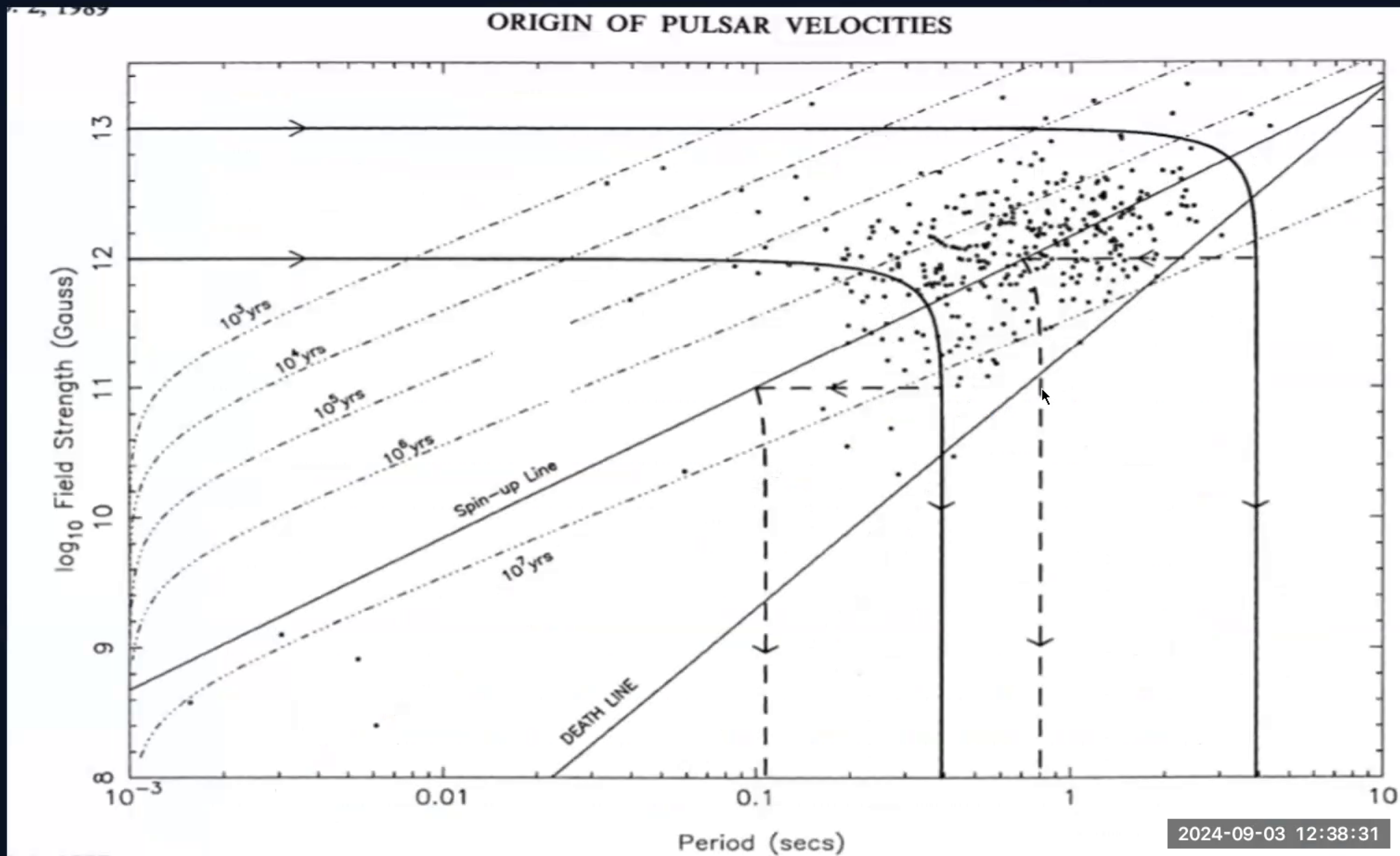
3006 Accesses | **655** Citations | **51** Altmetric | [Metrics](#)

Abstract

The radio properties of 4C21.53 have been an enigma for many years. First, the object displays interplanetary scintillations (IPS) at 81 MHz, indicating structure smaller than 1 arc s, despite its low galactic latitude (-0.3°)¹. IPS modulation is rare at low latitudes because of interstellar angular broadening. Second, the source has an extremely steep ($\sim \nu^{-2}$) spectrum at decametric wavelengths². This combination of properties suggested that 4C21.53 was either an undetected pulsar or a member of some new class of objects. This puzzle may be resolved by the discovery and related observations of a fast pulsar, 1937+214, with a period of 1.558 ms in the constellation Vulpecula only a few degrees from the direction to the original pulsar, 1919+21. The existence of such a fast pulsar with no evidence either of a new formation event or of present energy losses raises new questions about the origin and evolution of pulsars.

Magnetic Field - Period Diagram

Bailes (1989):
No decay
without accretion

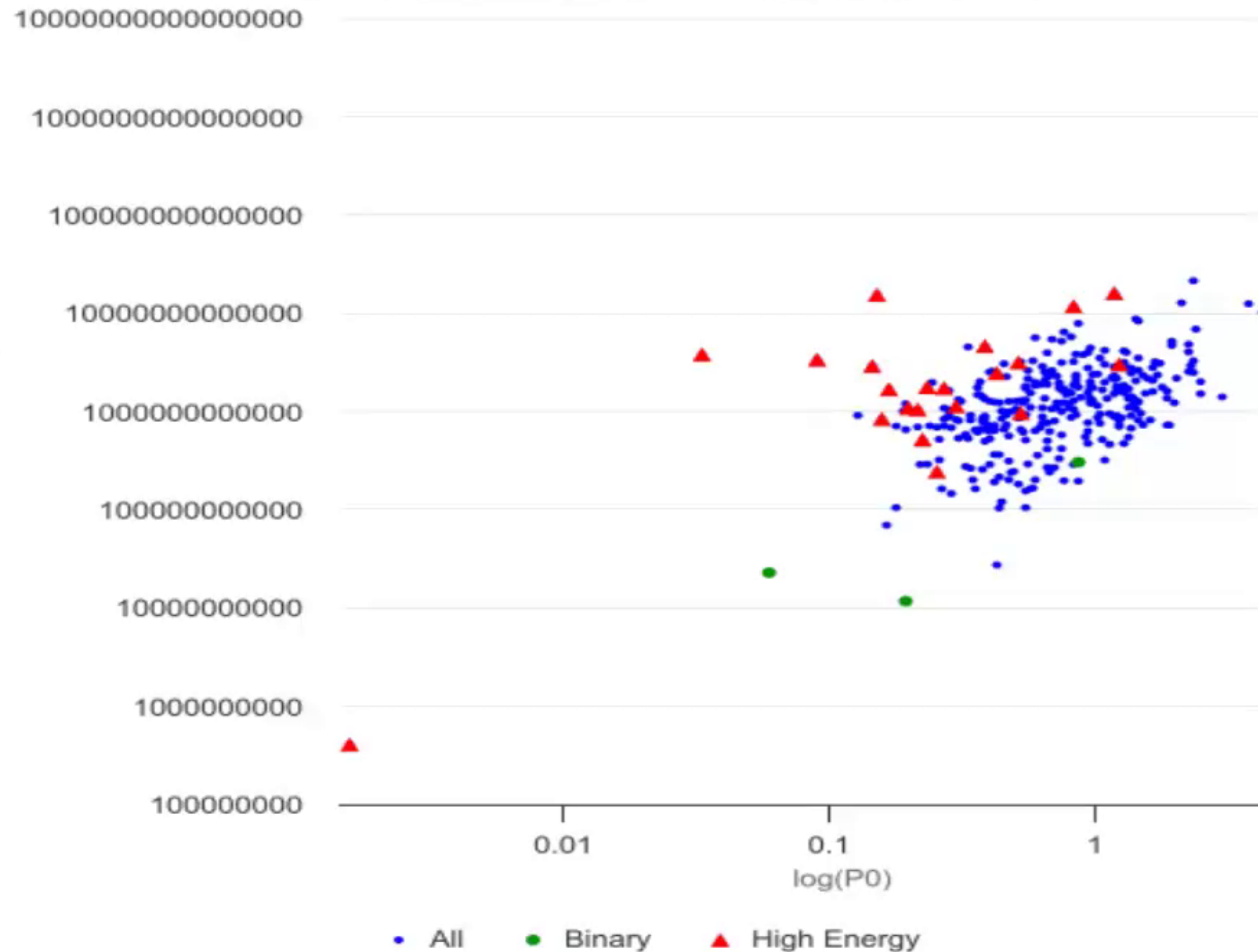


Magnetic Field - Period Diagram

1982 vs 2024

PSRCAT plot (Catalogue v2.4.0)

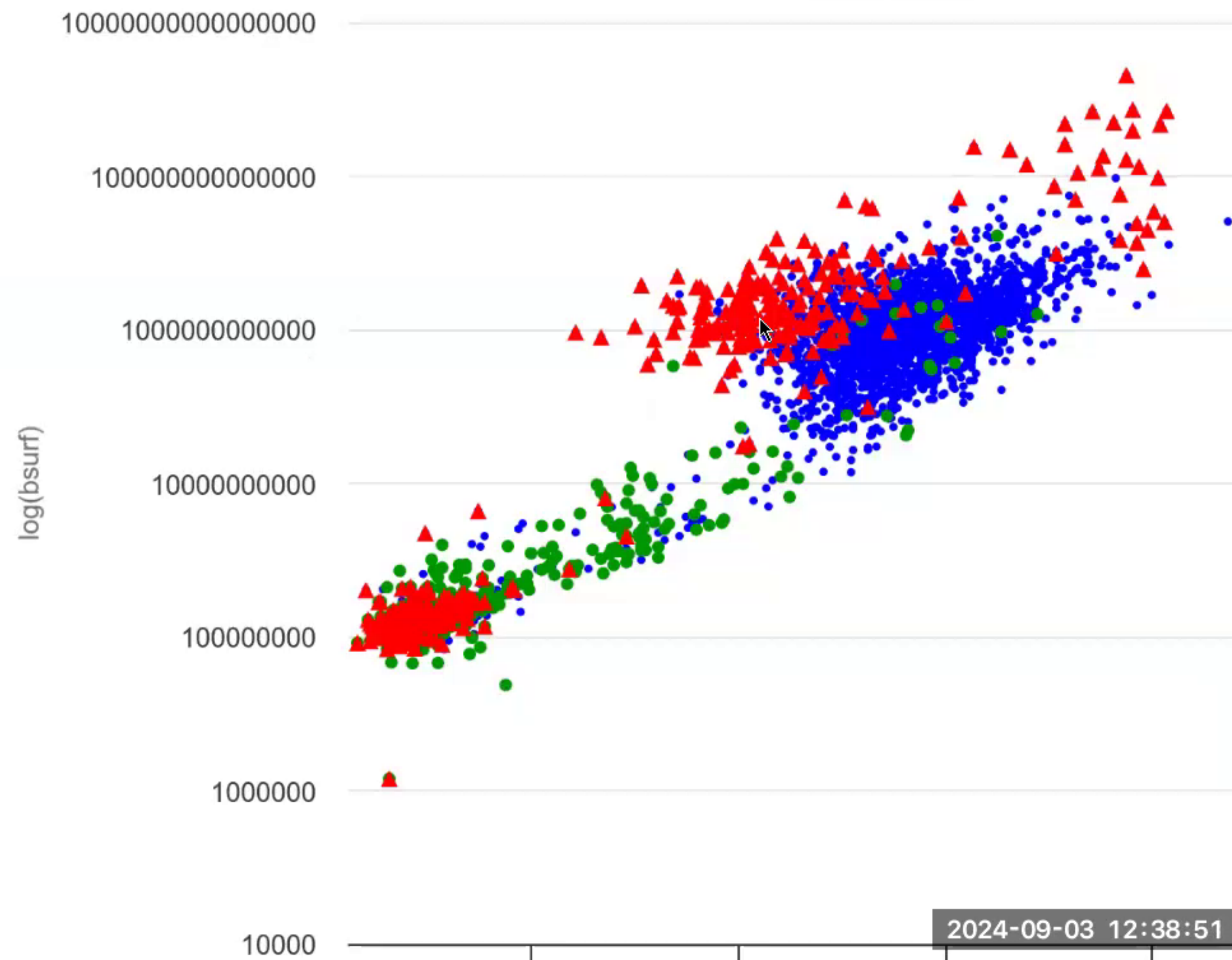
Source: <https://www.atnf.csiro.au/research/pulsar/psrcat>



Highchu

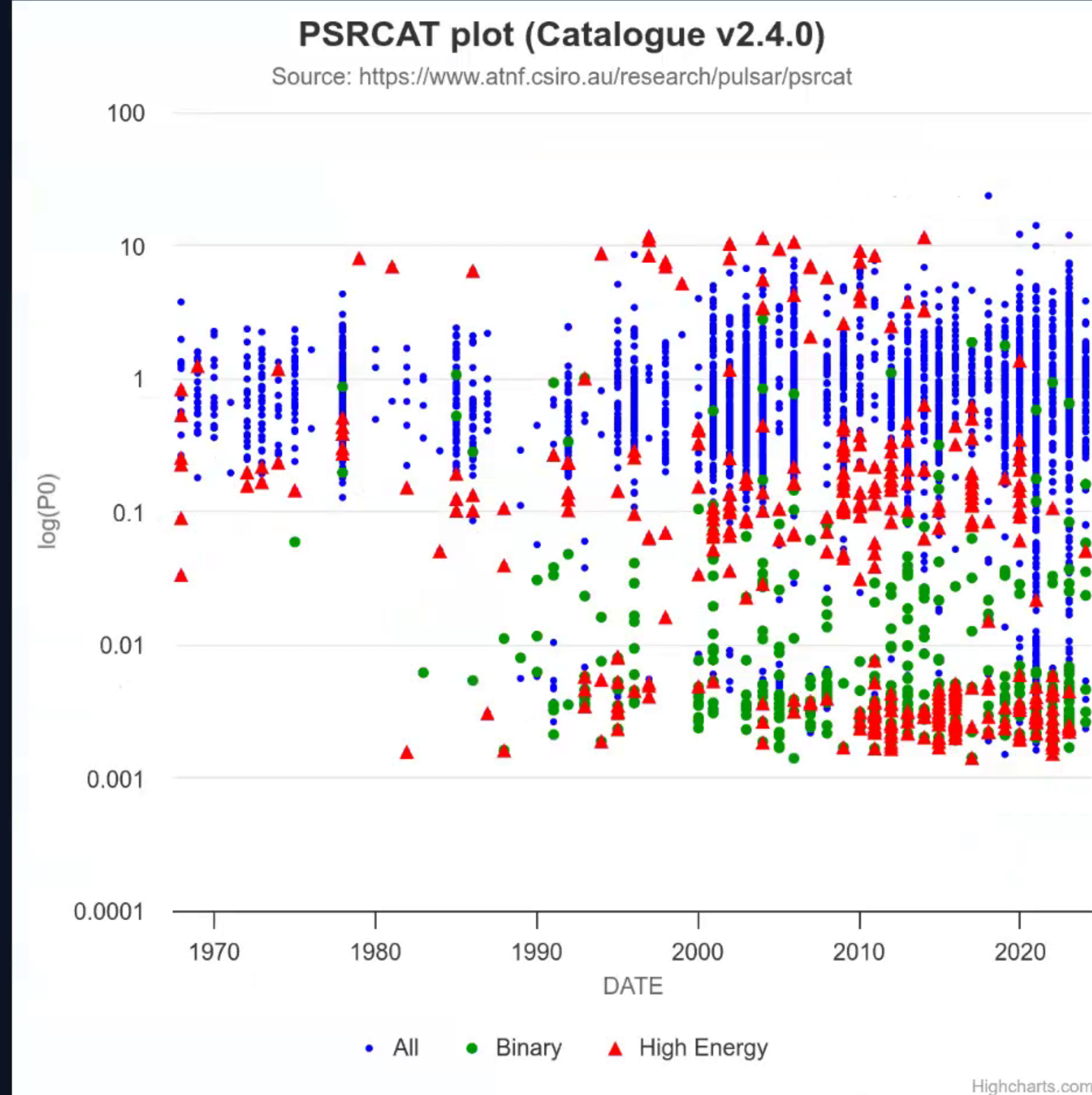
PSRCAT plot (Catalogue v2.4.0)

Source: <https://www.atnf.csiro.au/research/pulsar/psrcat>



2024-09-03 12:38:51

Period vs Discovery Date



RADIO TELESCOPES

1989: Globular Cluster Surveys
1993-1996: PKS 70cm survey
1997: PKS MB surveys
1999: Swinburne surveys
2009: HTRU surveys

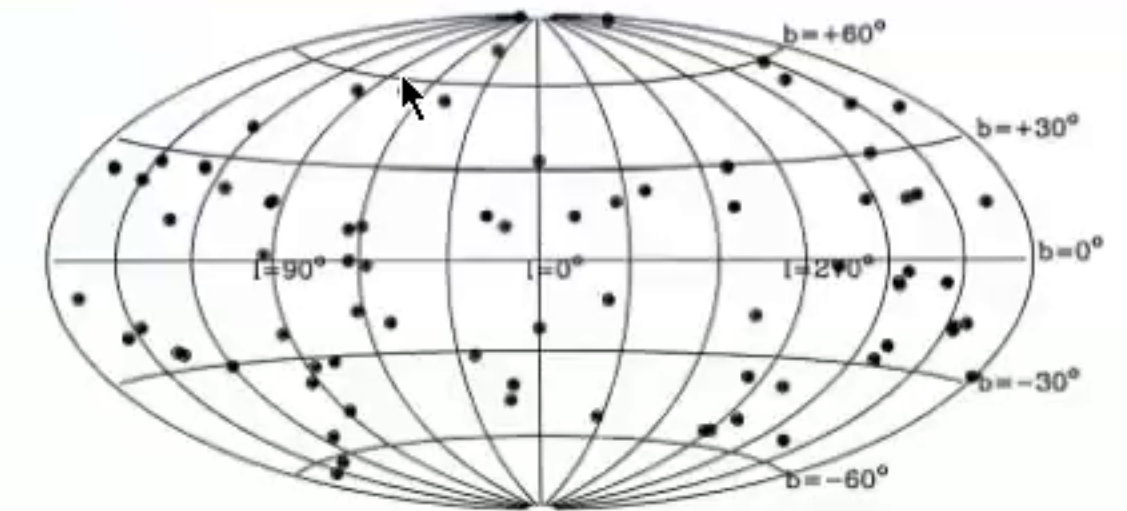


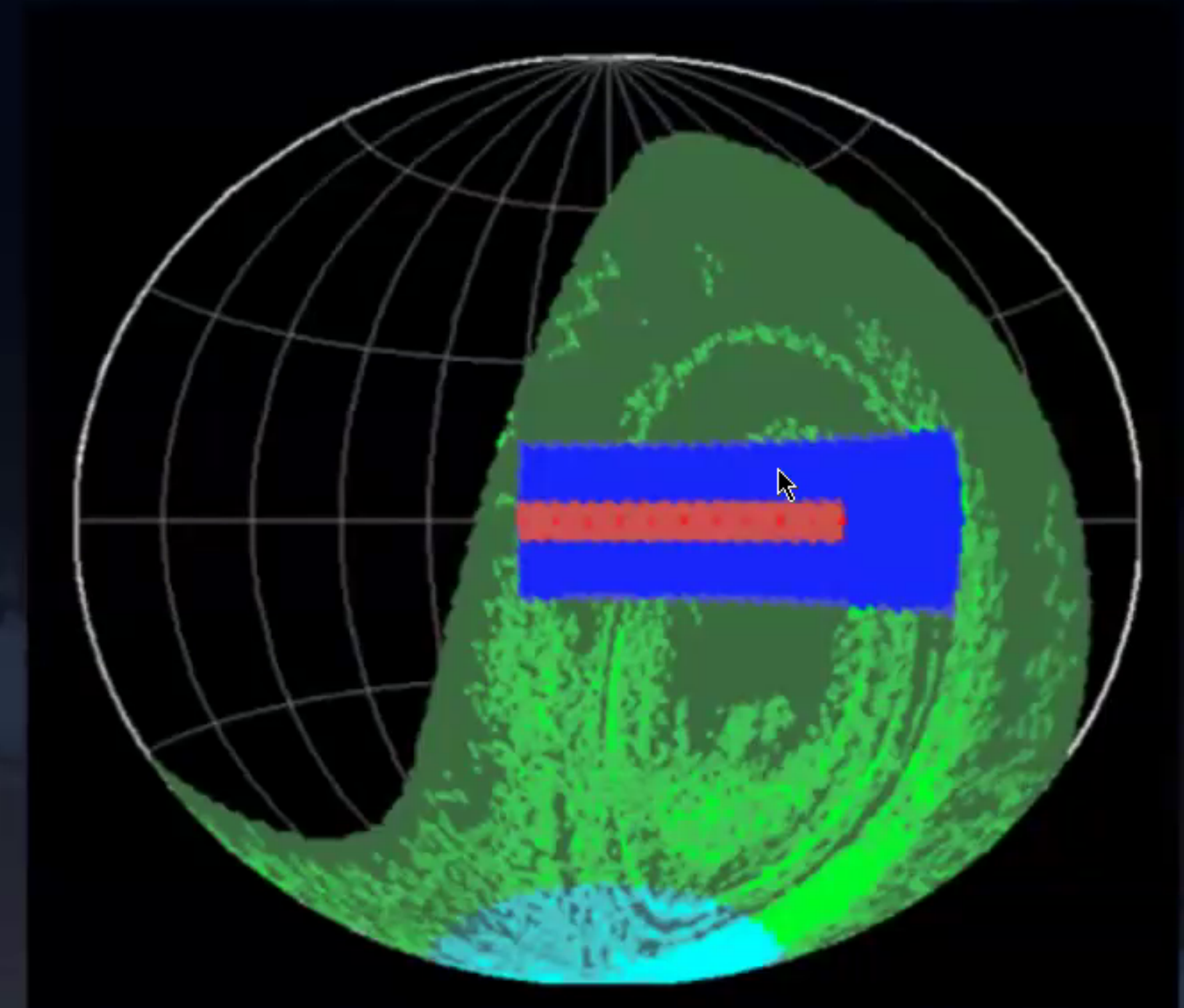
Figure 2. Locations of detected millisecond pulsars in galactic coordinates from a hypothetical all-sky survey in which 2×10^5 pulsars with luminosities and periods similar to that of PSR 1257 + 12 were distributed throughout a model galaxy. Their distribution is largely isotropic, indicating that all-sky surveys are the most appropriate way to find millisecond pulsars.

IMAGE CREDIT: CSIRO

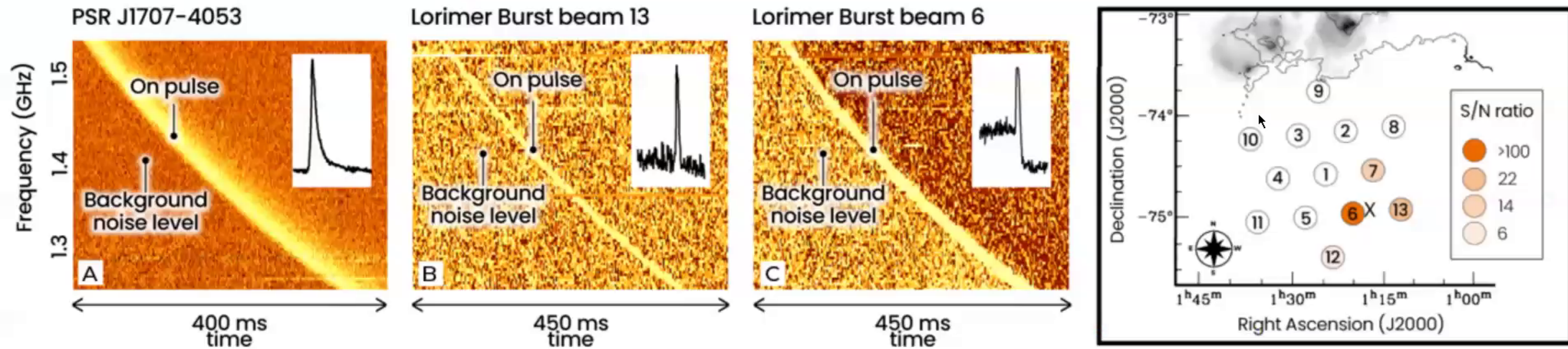
THE HIGH TIME RESOLUTION UNIVERSE SURVEYS

KEITH ET AL. (2012)

- NEW “DIGITAL FILTERBANKS
A LOT LESS SMEARING
- GREATER “SENSITIVITY”
- DAN THORNTON ASSIGNED
THE “LORIMER BURST SEARCH”



THE PARKES MULTIBEAM DETECTIONS



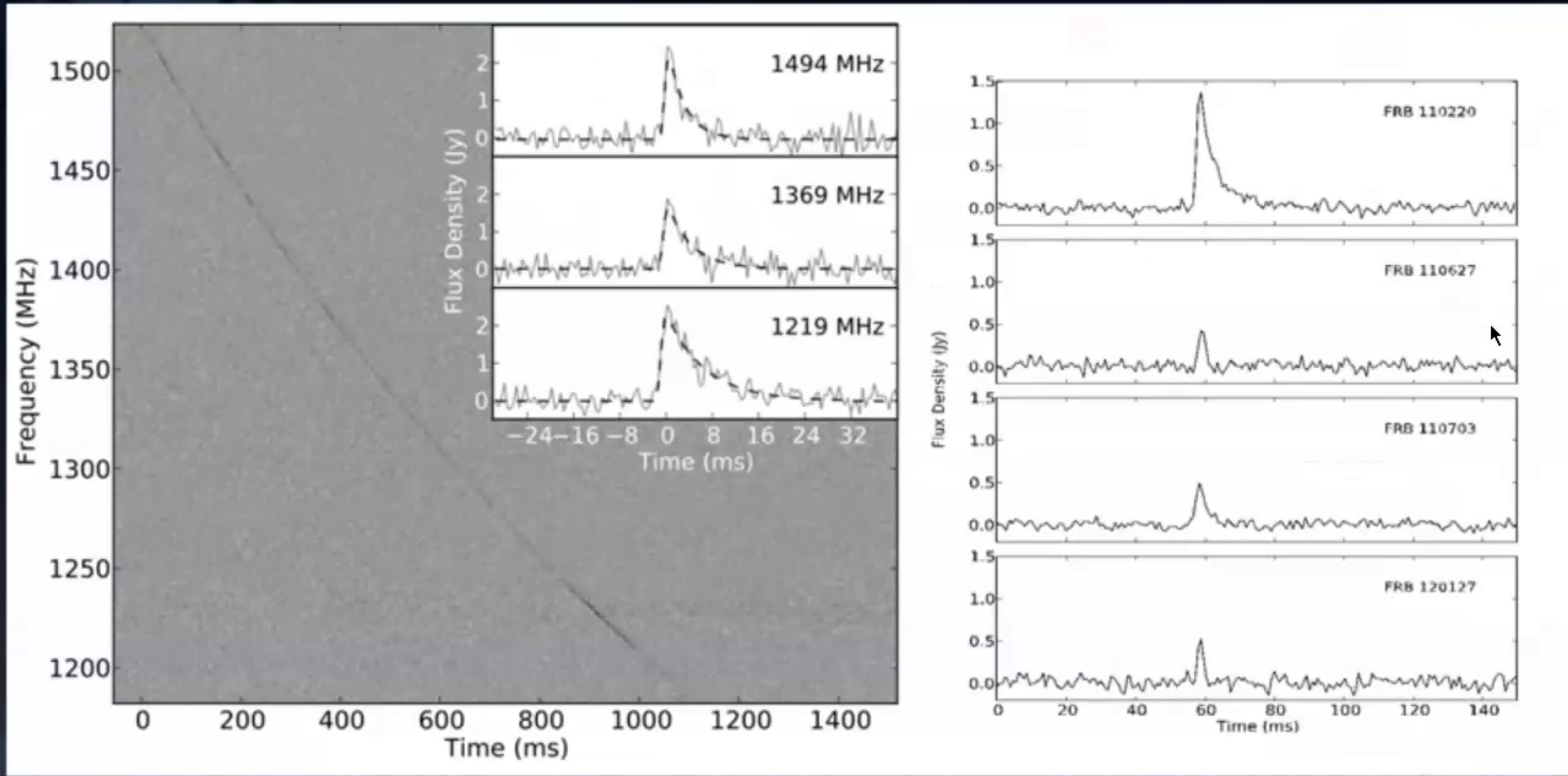
2013: THE THORNTON BURSTS

A Population of Fast Radio Bursts at Cosmological Distances

D. Thornton,^{1,2*} B. Stappers,¹ M. Bailes,^{3,4} B. Barsdell,^{3,4} S. Bates,⁵ N. D. R. Bhat,^{3,4,6} M. Burgay,⁷ S. Burke-Spolaor,⁸ D. Champion,⁹ P. Coster,^{2,3} N. D'Amico,^{7,10} A. Jameson,^{3,4} S. Johnston,² M. Keith,² M. Kramer,^{9,1} L. Levin,⁵ S. Milia,⁷ C. Ng,⁹ A. Possenti,⁷ W. van Straten^{3,4}

Searches for transient astrophysical sources often reveal unexpected classes of objects that are useful physical laboratories. In a recent survey for pulsars and fast transients, we have uncovered four millisecond-duration radio transients all more than 40° from the Galactic plane. The bursts' properties indicate that they are of celestial rather than terrestrial origin. Host galaxy and intergalactic medium models suggest that they have cosmological redshifts of 0.5 to 1 and distances of up to 3 gigaparsecs. No temporally coincident γ - or gamma-ray signature was identified in association with the bursts. Characterization of the source population and identification of host galaxies offers an opportunity to determine the baryonic content of the universe.

FRB 110220: $DM=995 \text{ pc cm}^{-3}$





Binary star after birth



After mass exchange



Eccentric Binary Pulsar (B1259-63, J0045-7319)

47

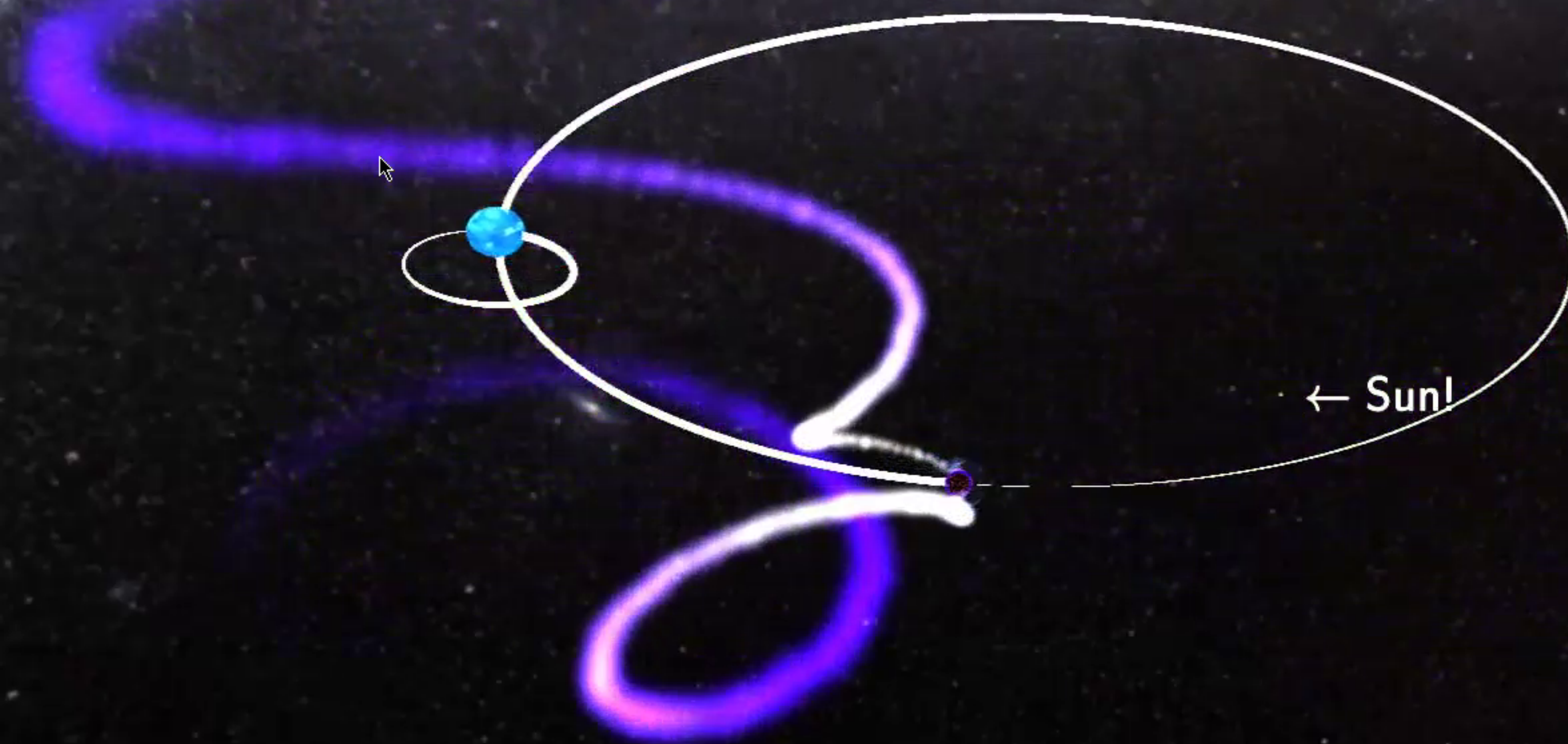
PSR J0045–7319

Companion mass = $8.82 M_{\odot}$

Period = 926.28 ms

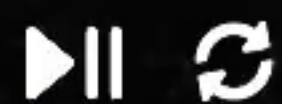
Orbital period = 51.169 days

Eccentricity = 0.80795

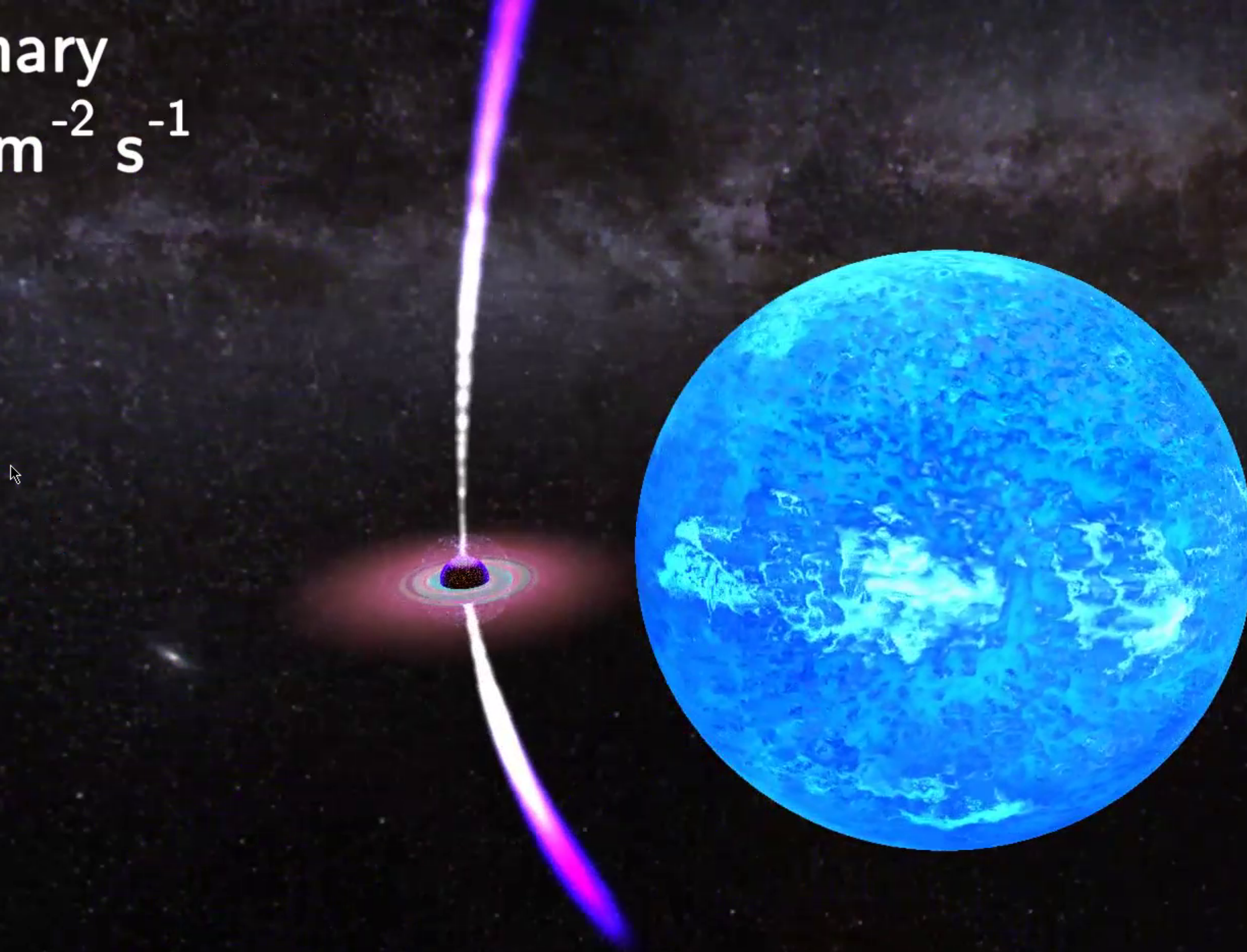


$$\frac{da \sin(i)}{dt} \neq 0$$

(Kaspi et al. 1997)



X-ray Binary
 $10^5 \text{ NW m}^{-2} \text{ s}^{-1}$



MSP+WD
J0437-4715
 $P=5.75\text{ ms}$
 $P_b=5.7d$



PSR J1719–1438 (Diamond Planet)

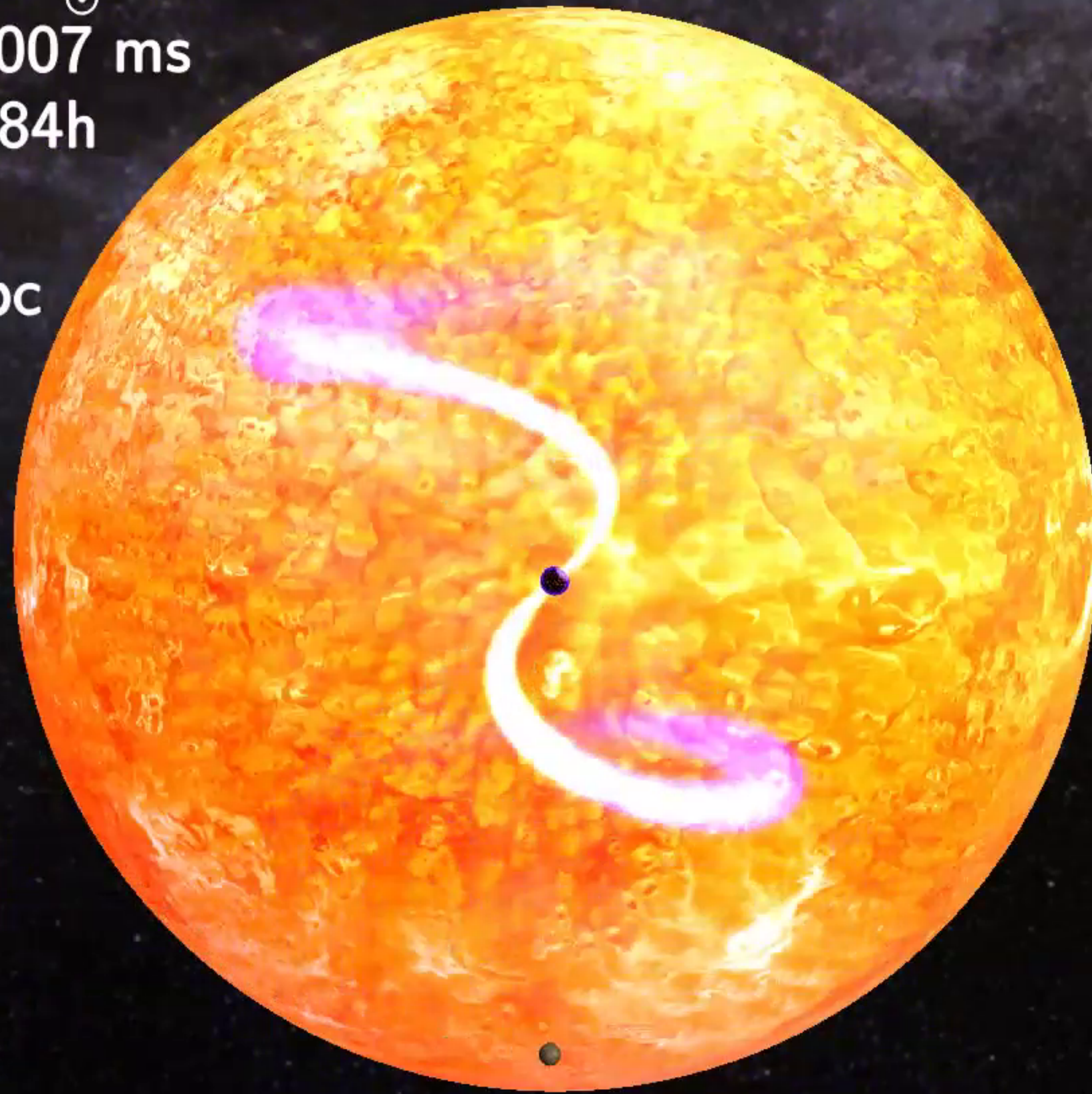
Companion mass = $0.001 M_{\odot}$

Period = 5.790151772889007 ms

Orbital period = 2.17695084h

Velocity = 17.78 km s^{-1}

Distance = $\sim 500\text{-}1000 \text{ kpc}$



PSR J1909–3744

Companion mass $\sim 0.2 M_{\odot}$

Period = 2.94710807505251 ms

Orbital period = 1.533449477490 days

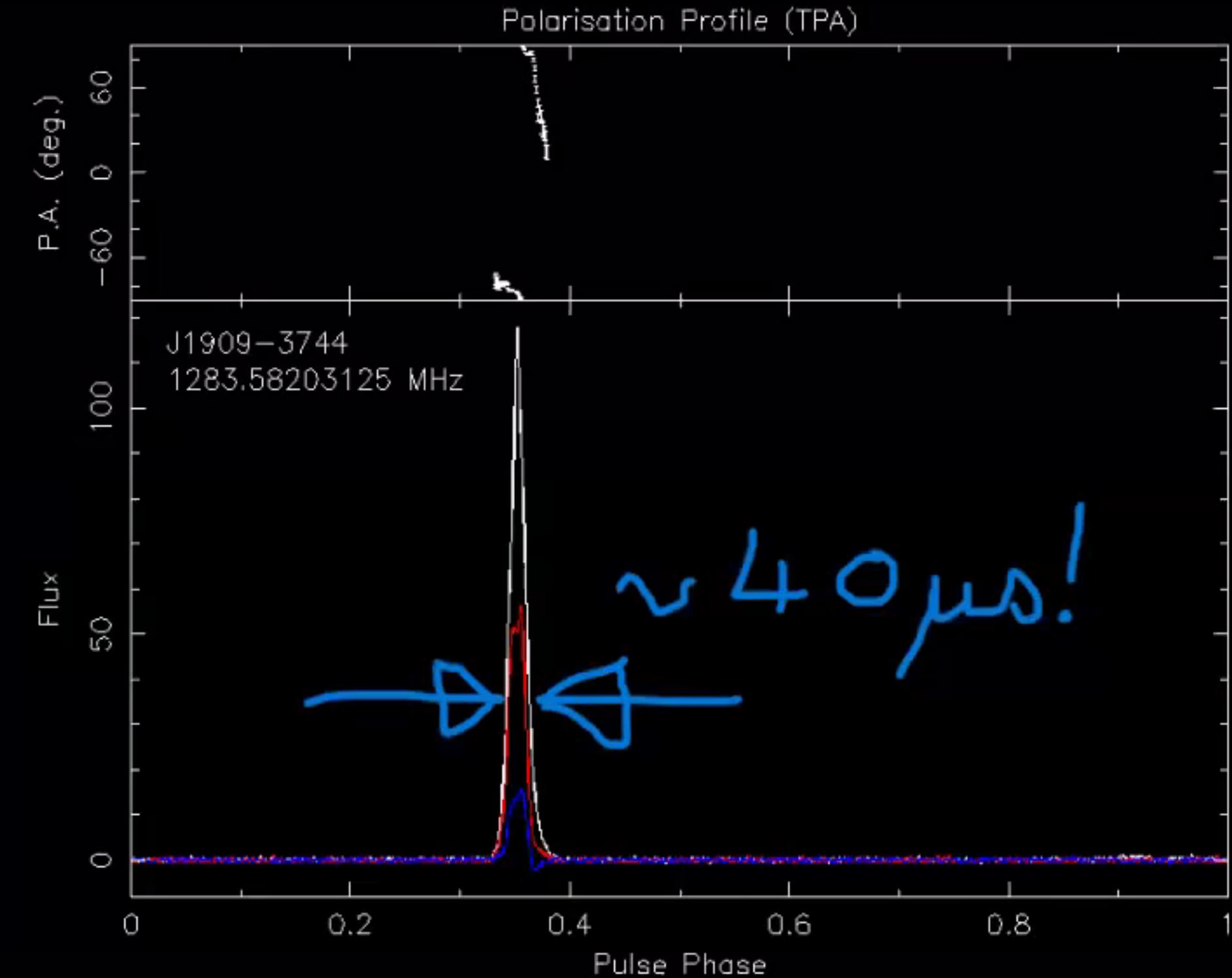
Velocity = 208.08 km s⁻¹

Distance = 1.14 kpc



Pulsar Timing Methodology

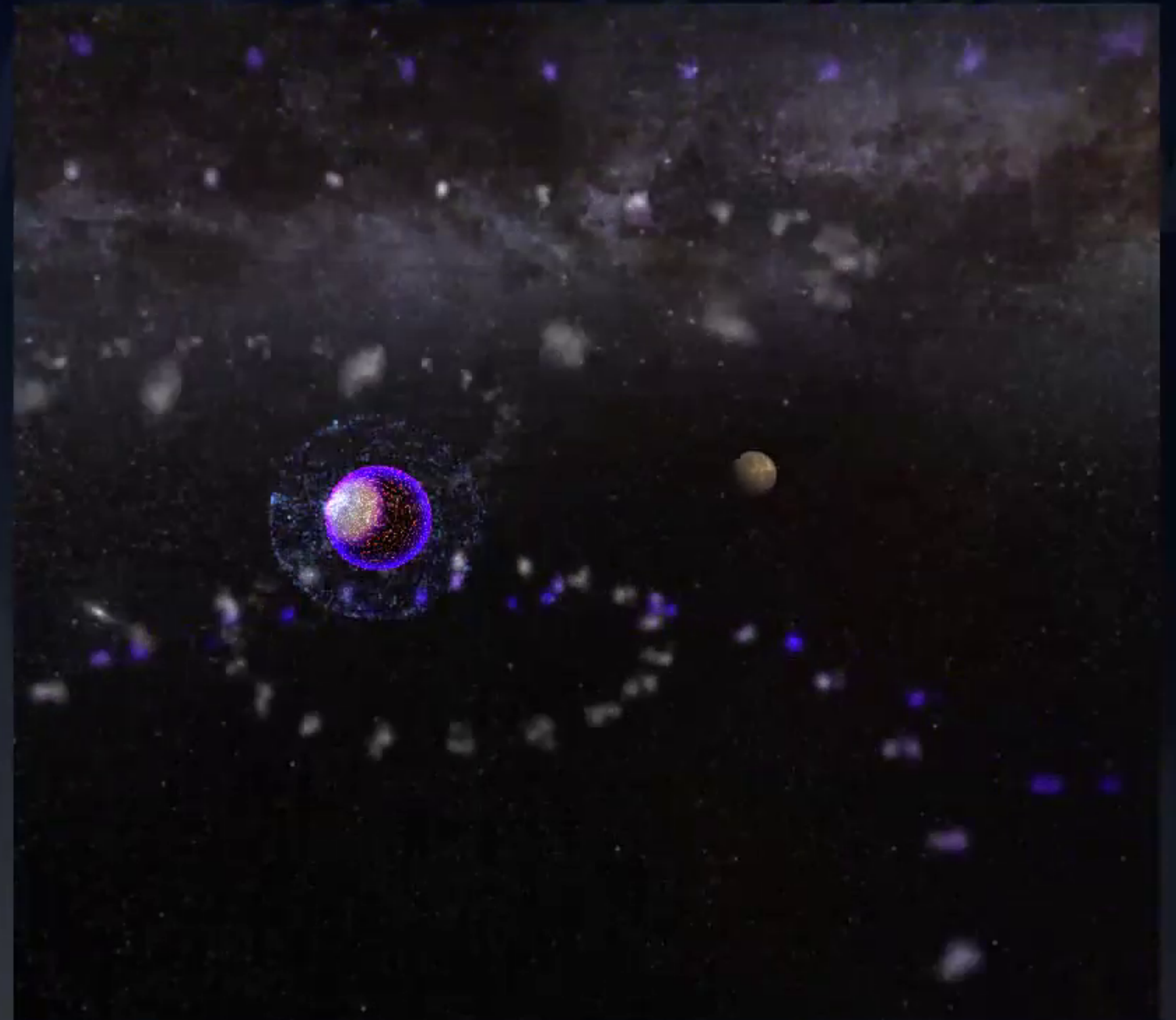
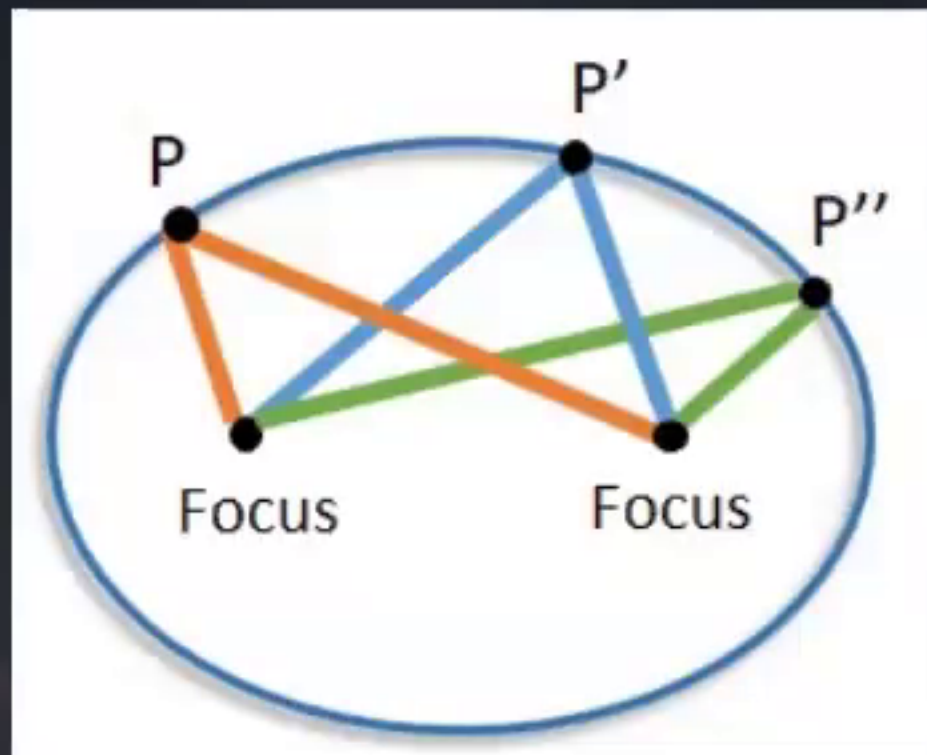
1. Determine the pulse phase.
2. Count the rotations.
3. Correct for the Earth's motion around the Sun
4. Correct for clocks
5. Do physics on the results



PSR J1909-3744

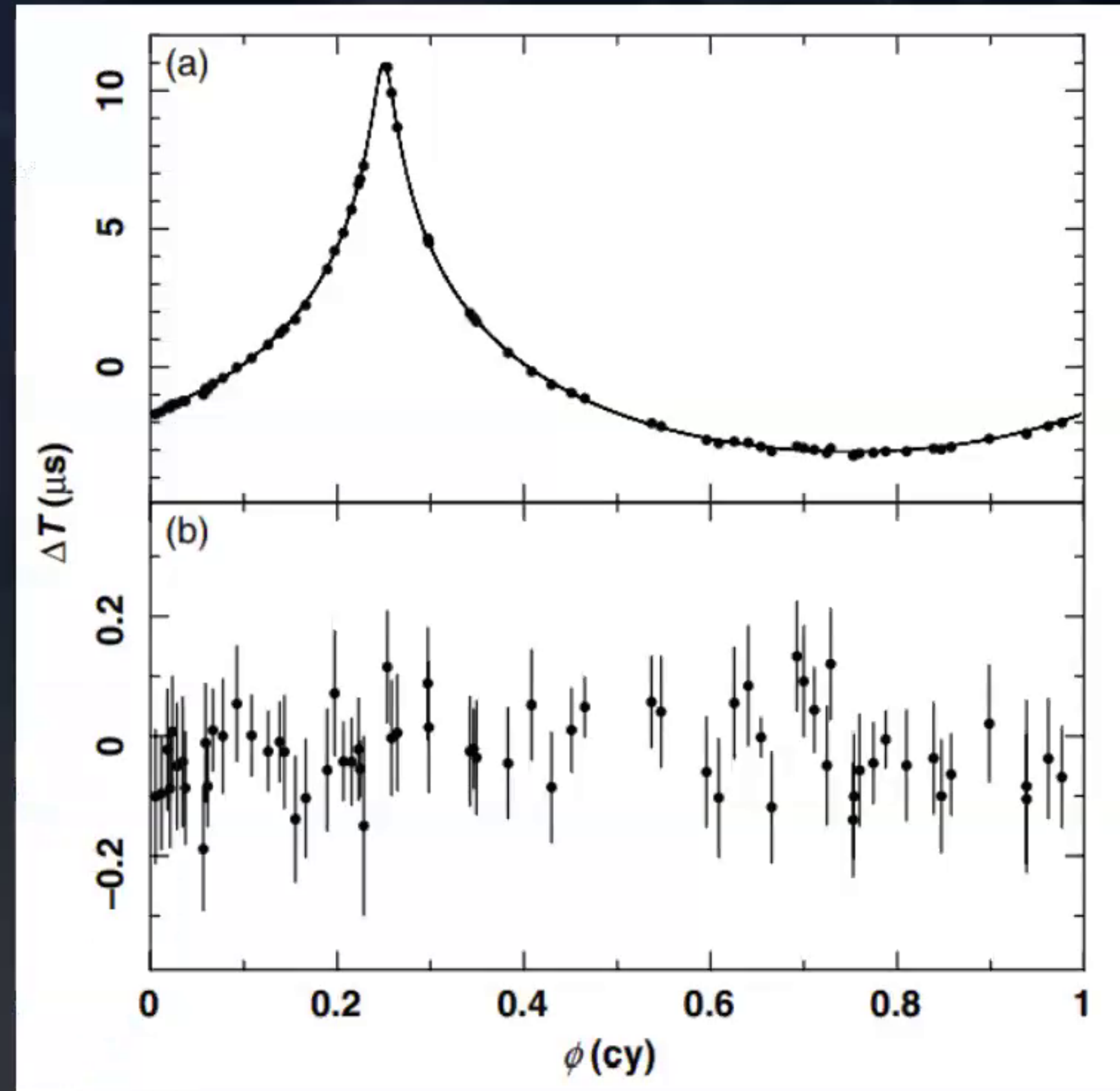
- 2.95 ms pulsar with great timing
- White Dwarf Companion
- $0.2 M_{\odot}$ white dwarf companion
- $P_b = 1.533449474305(5) \text{ d}$
- $a \sim 569,000 \text{ km}$

$$a - b < 4\mu$$



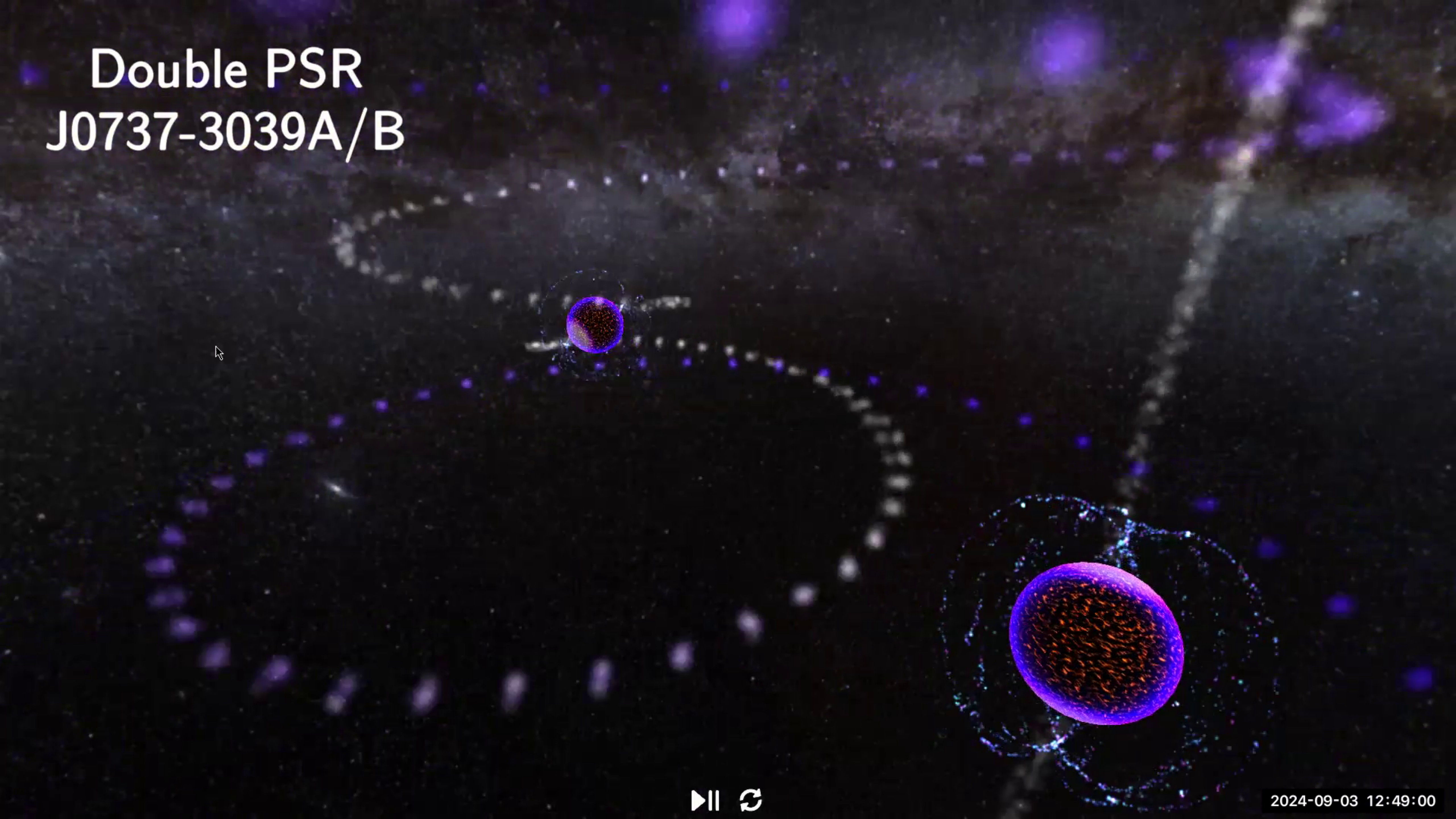
Shrinking of Space-Time

Solid Line = Einstein Prediction
MeerKAT Points = confirmation



Orbital Phase

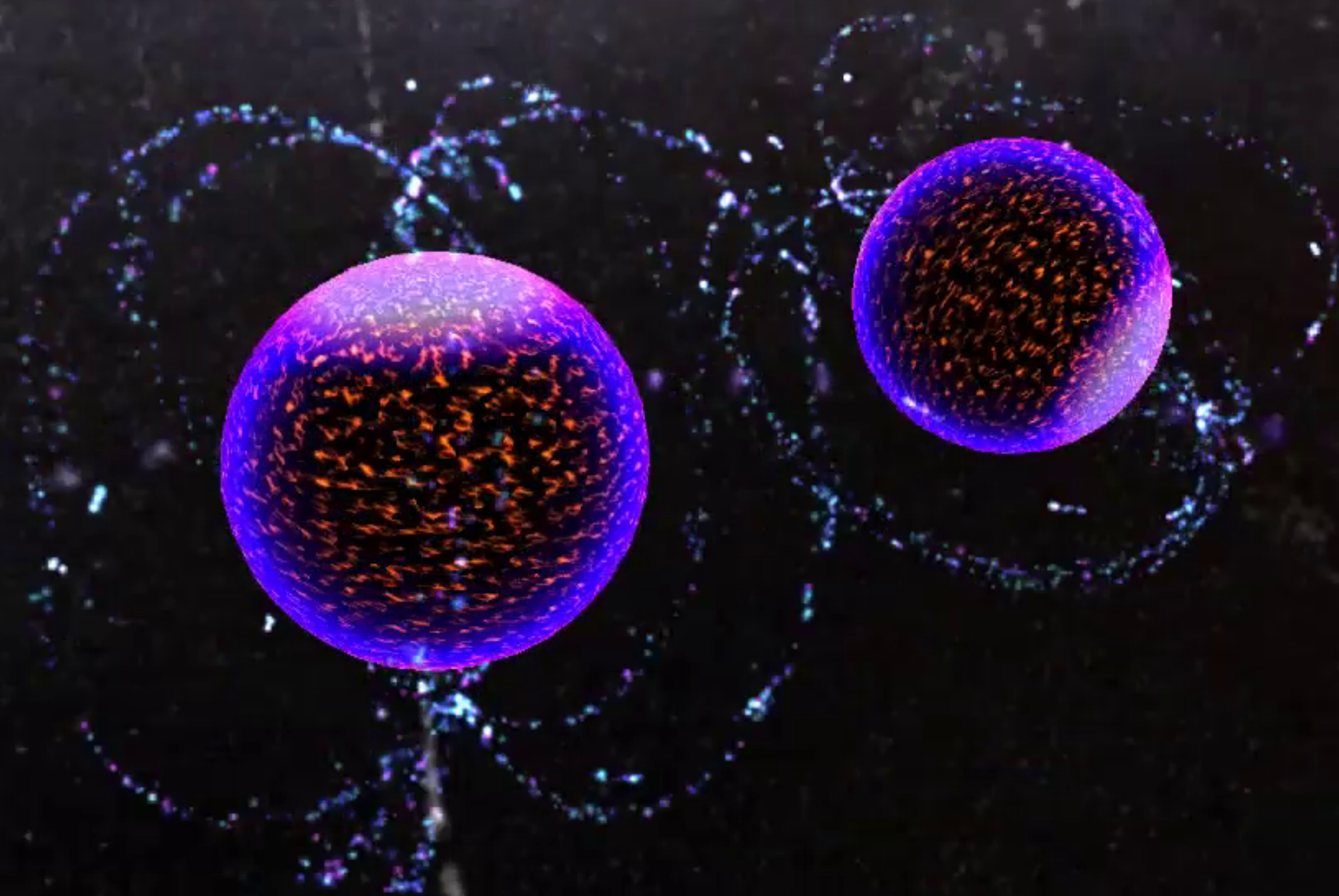
Double PSR J0737-3039A/B



Double PSR J0737-3039A/B



in ~ 300 Myr:
 $P_b = 1$ ms!



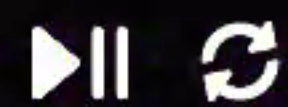
Black Hole?

4

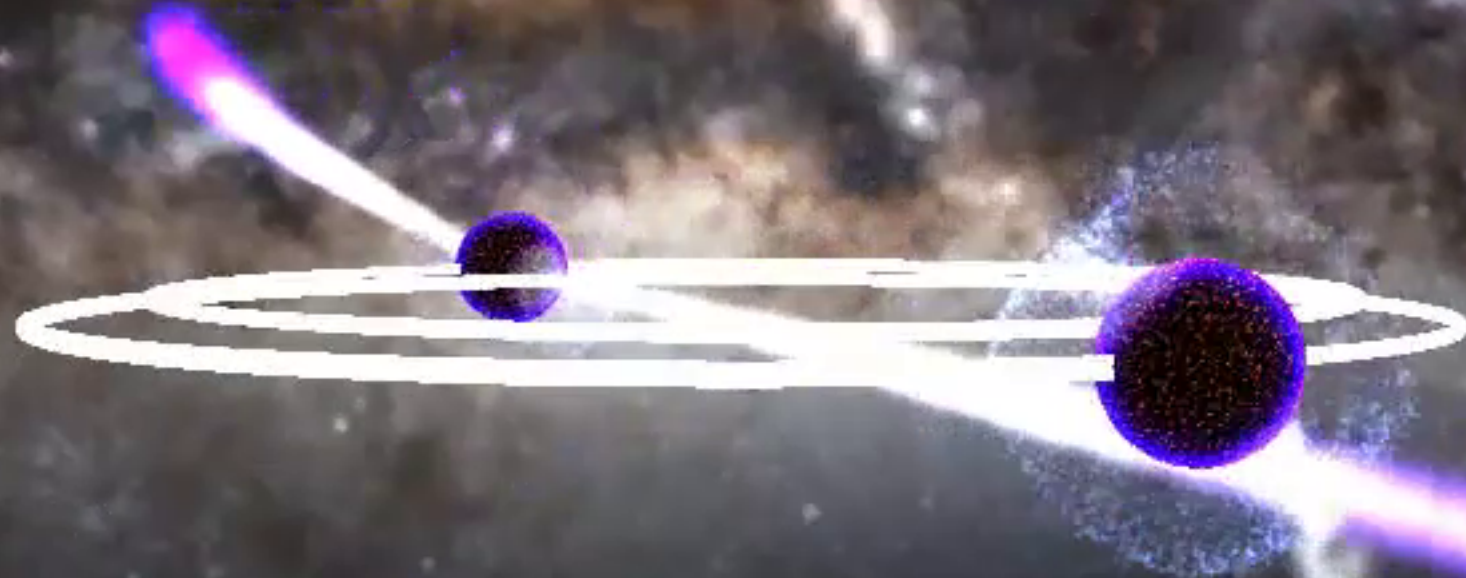
2004: The double pulsar J0737-3039A/B (Hu et al. 2022)

- Two pulsars in orbit around each other!
- Pulsar A = 22.7 ms
- Pulsar B = 2.7 s
 - Mass ratio gives unique tests of GR
- $P_b = 2.4$ hours!
- $e = 0.089$
- witnessed 3,948,400,142 rotations of the pulsar

10 orbits every day!



10 orbits every day!



Postfit Residual (μs)

-40 -20 0 20 40

0

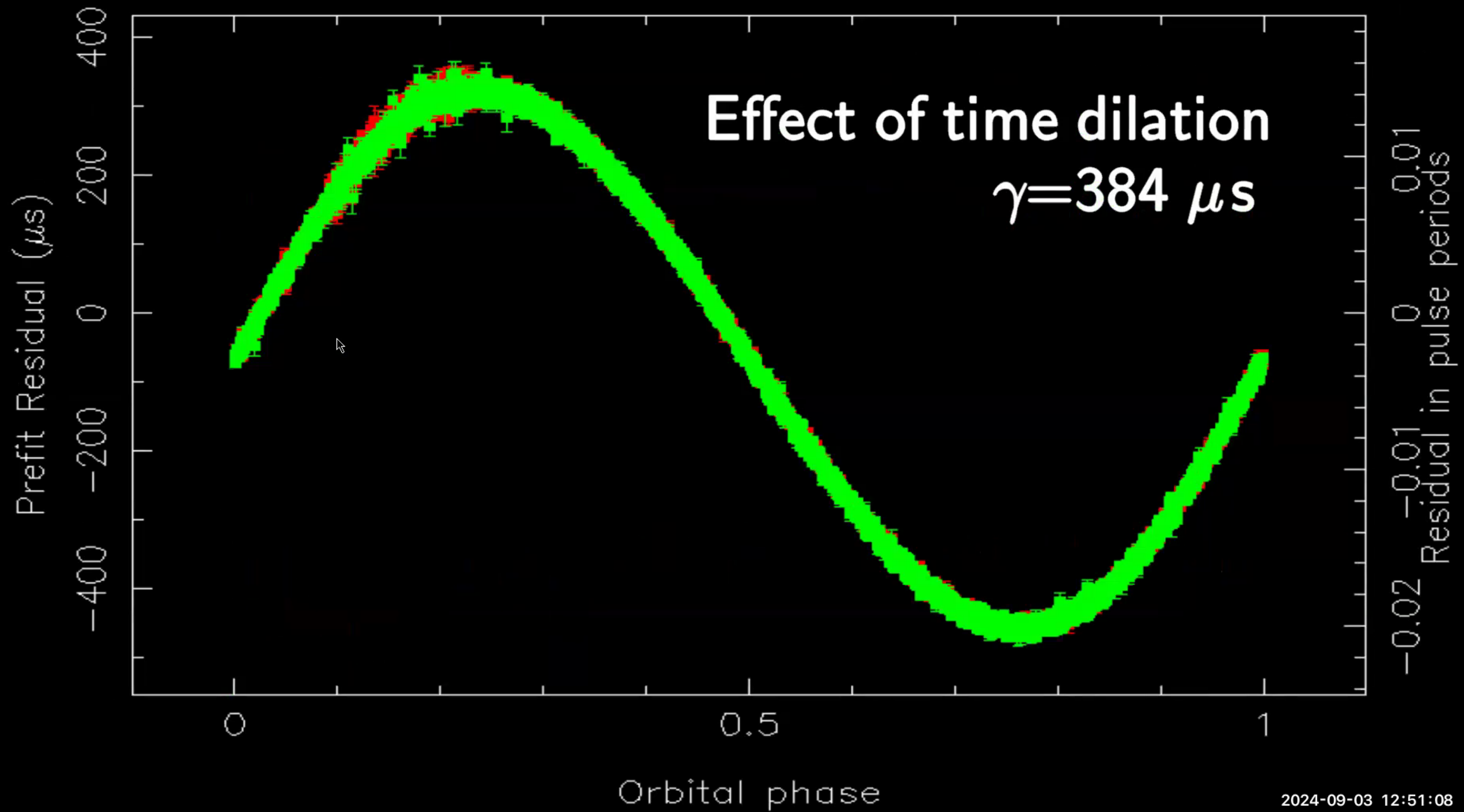
0.5

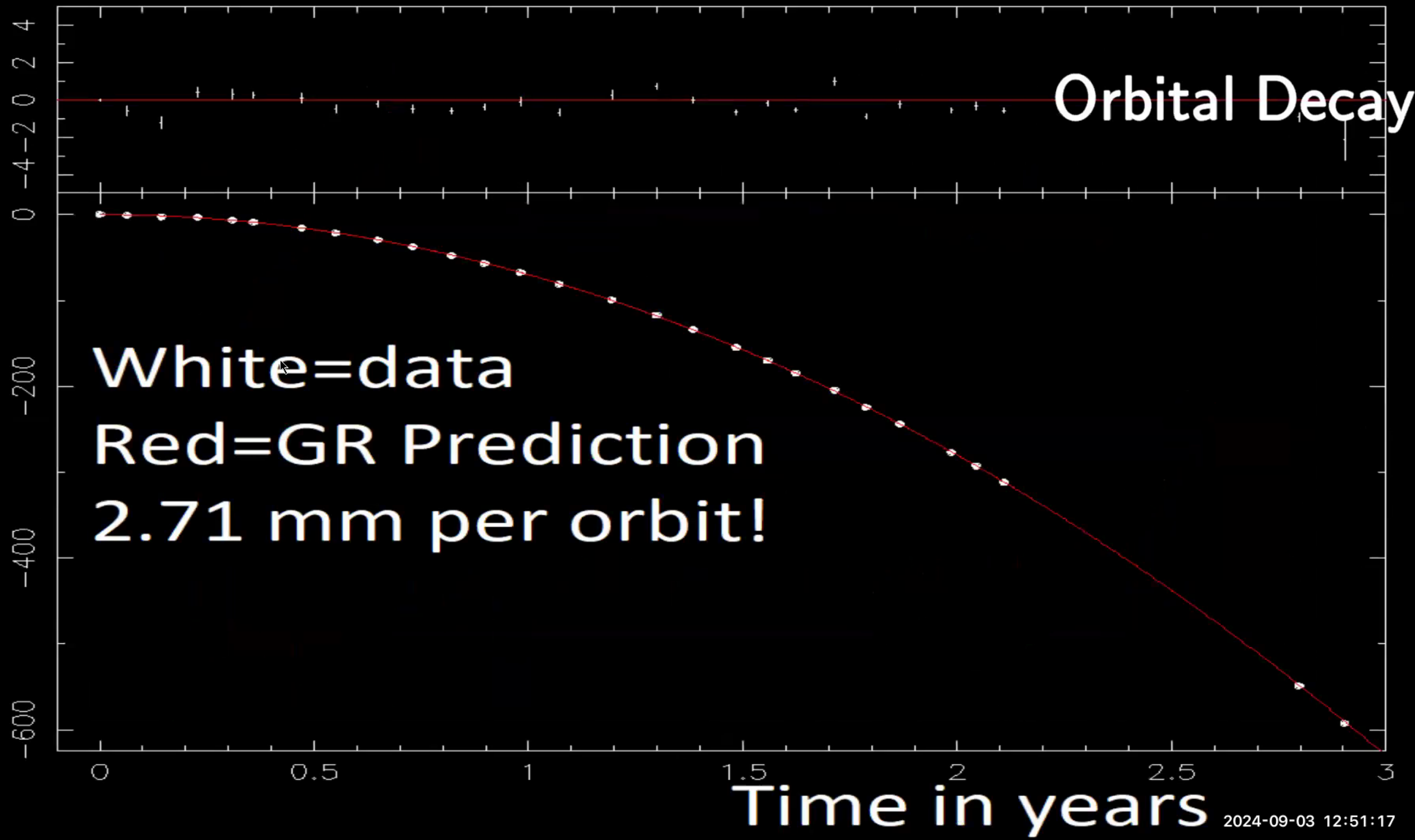
1

Orbital phase

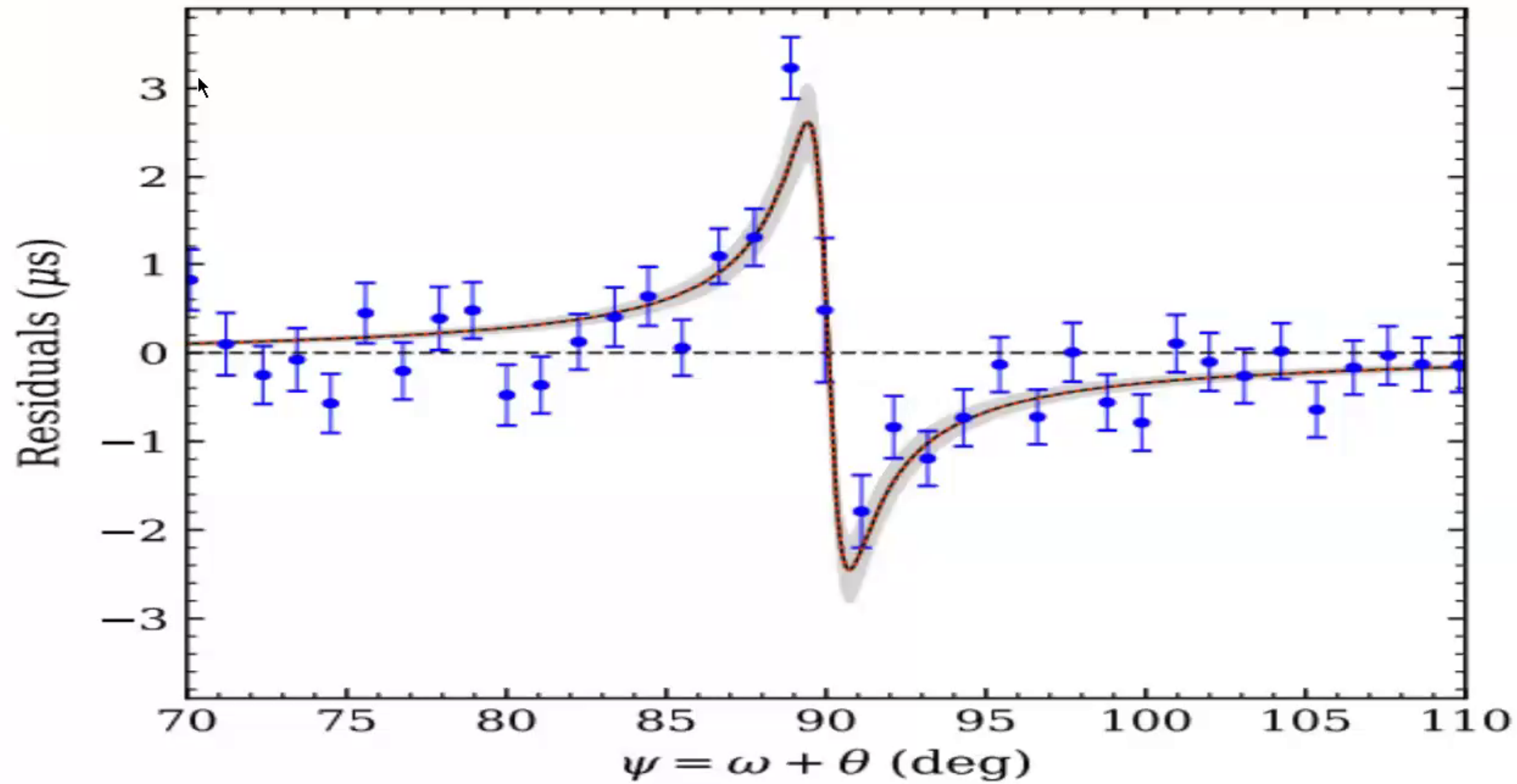
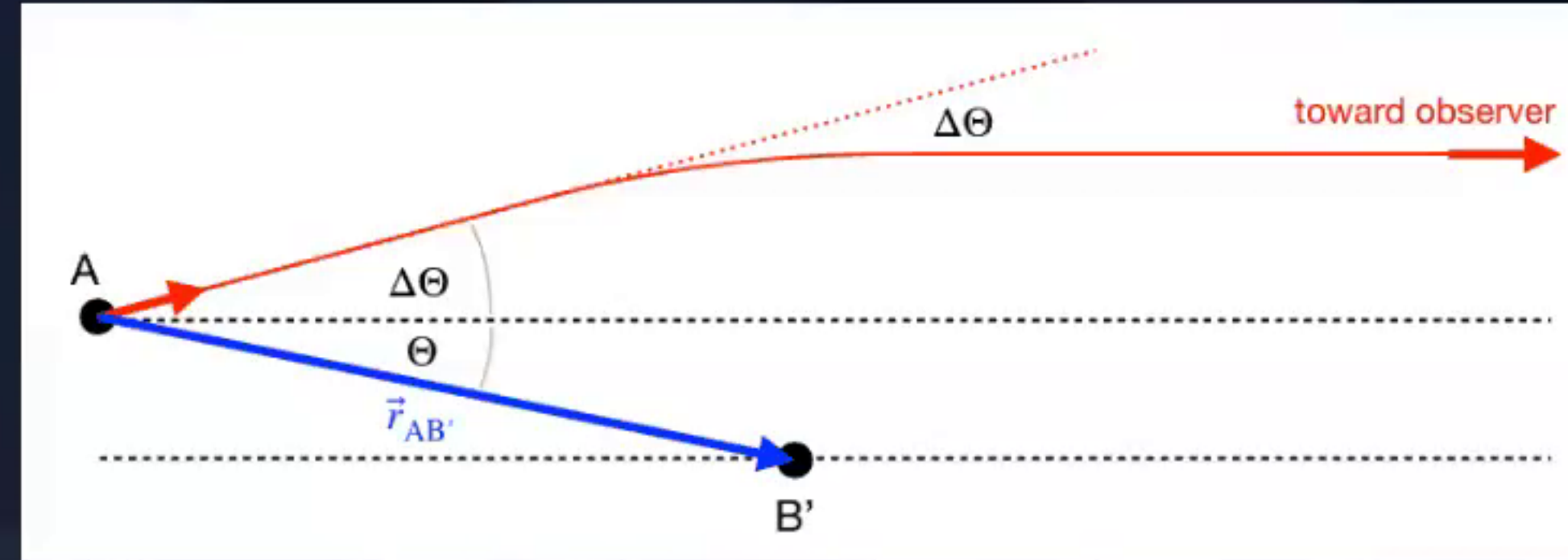
$\sim 30,000$ Timing Residuals

-10^{-3} 0 10^{-3} 2×10^{-3}
Residual in pulse periods





Light bends around the 2nd pulsar!

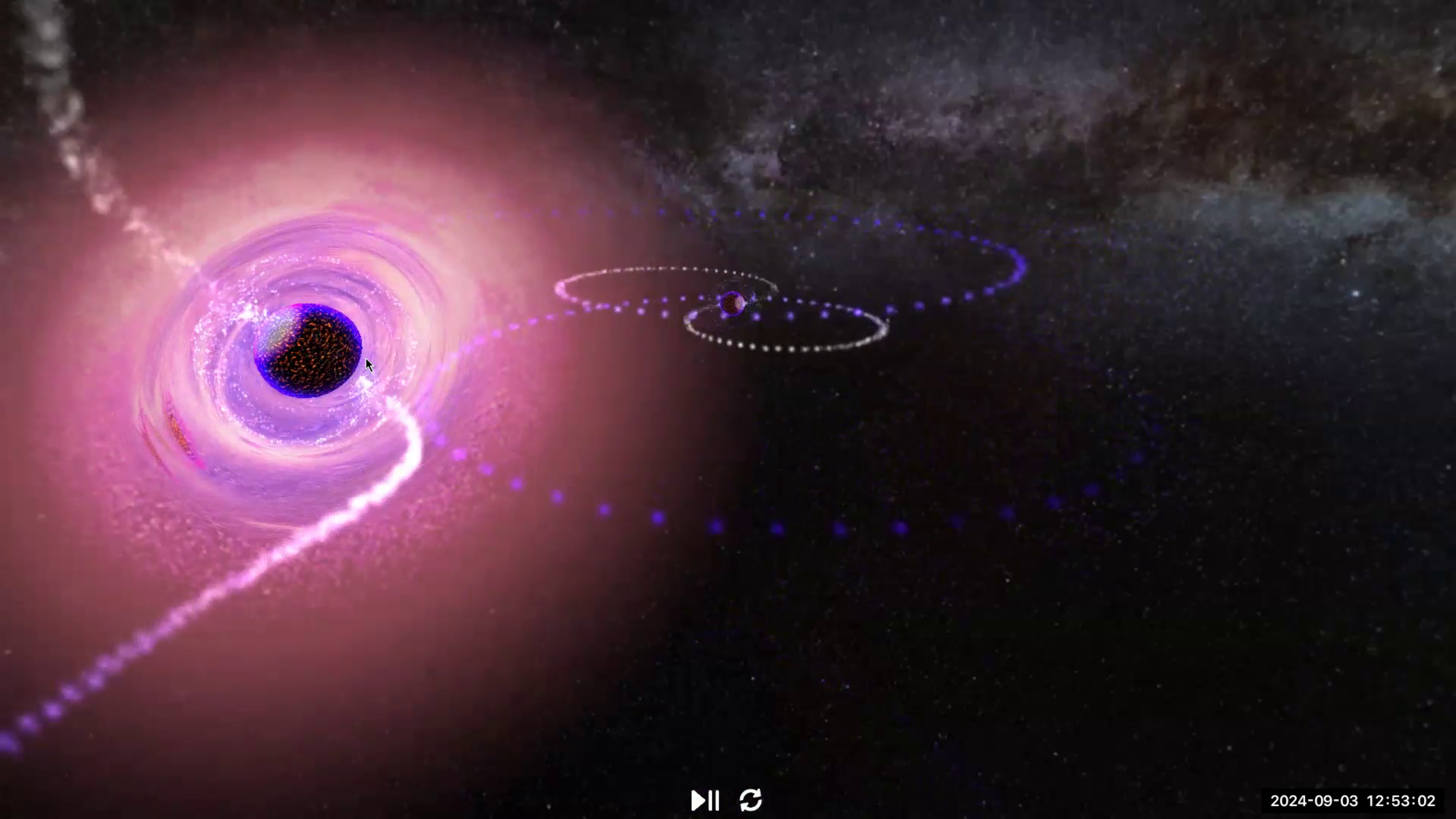


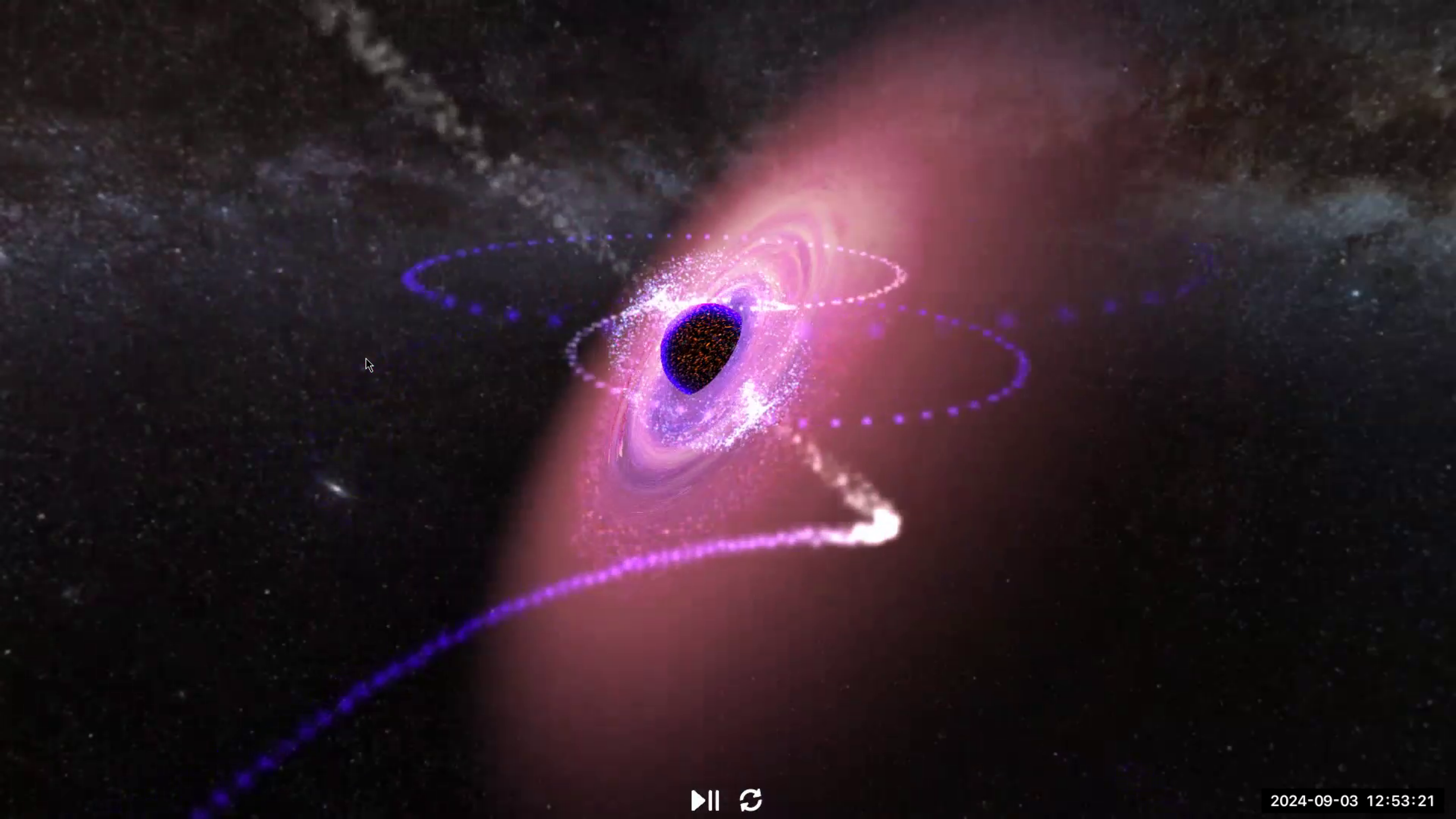
Double Pulsar Masses (Hu et al. 2022)

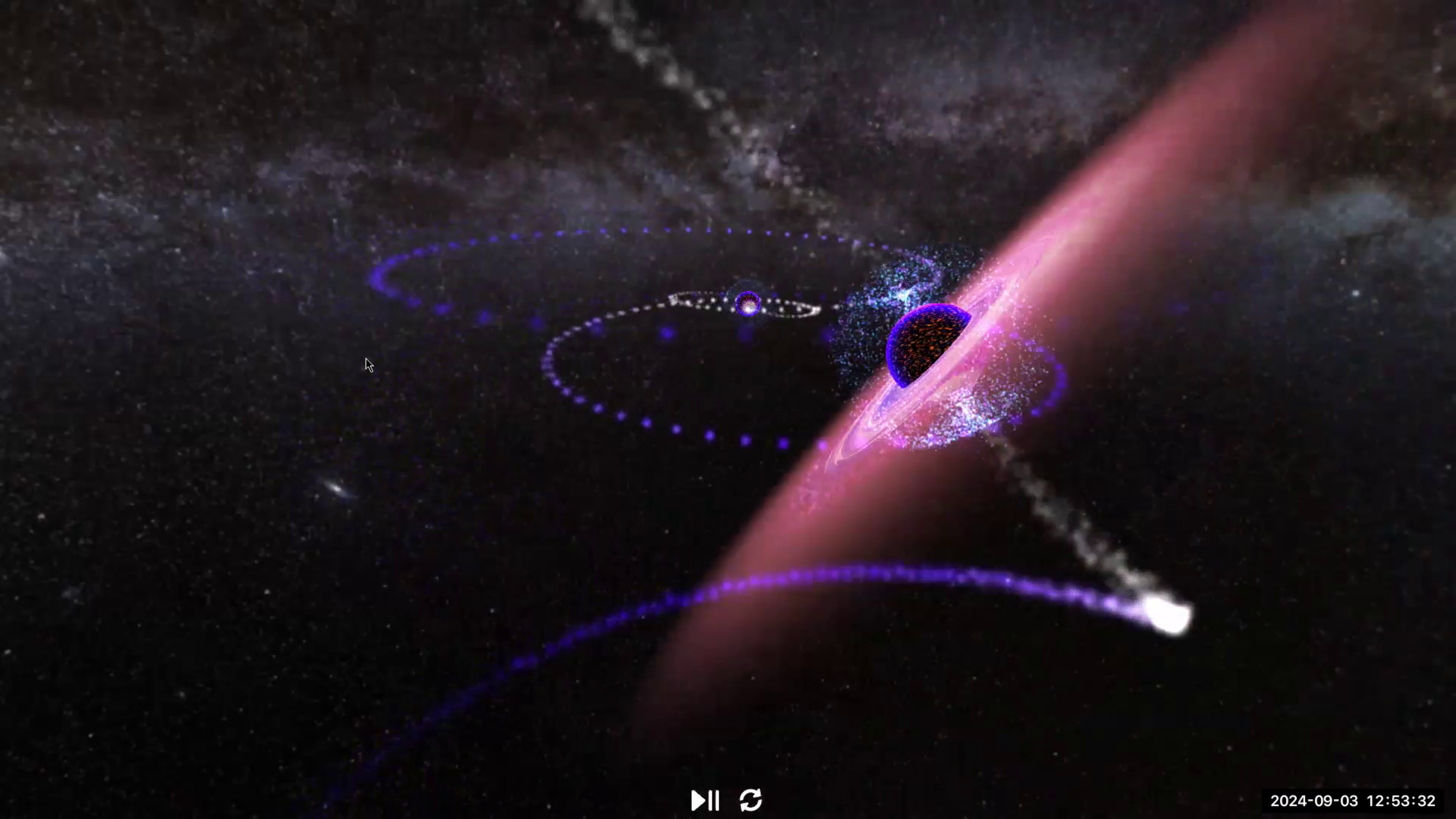
H. Hu et al.: Gravitational signal

Table 3. Mass measurements with a new modified DDGR model which accounts for NLO contributions in the orbital motion and signal propagation in this system. The MOI has been chosen to be $I_A = 1.28 \times 10^{45} \text{ g cm}^2$ in the fit.

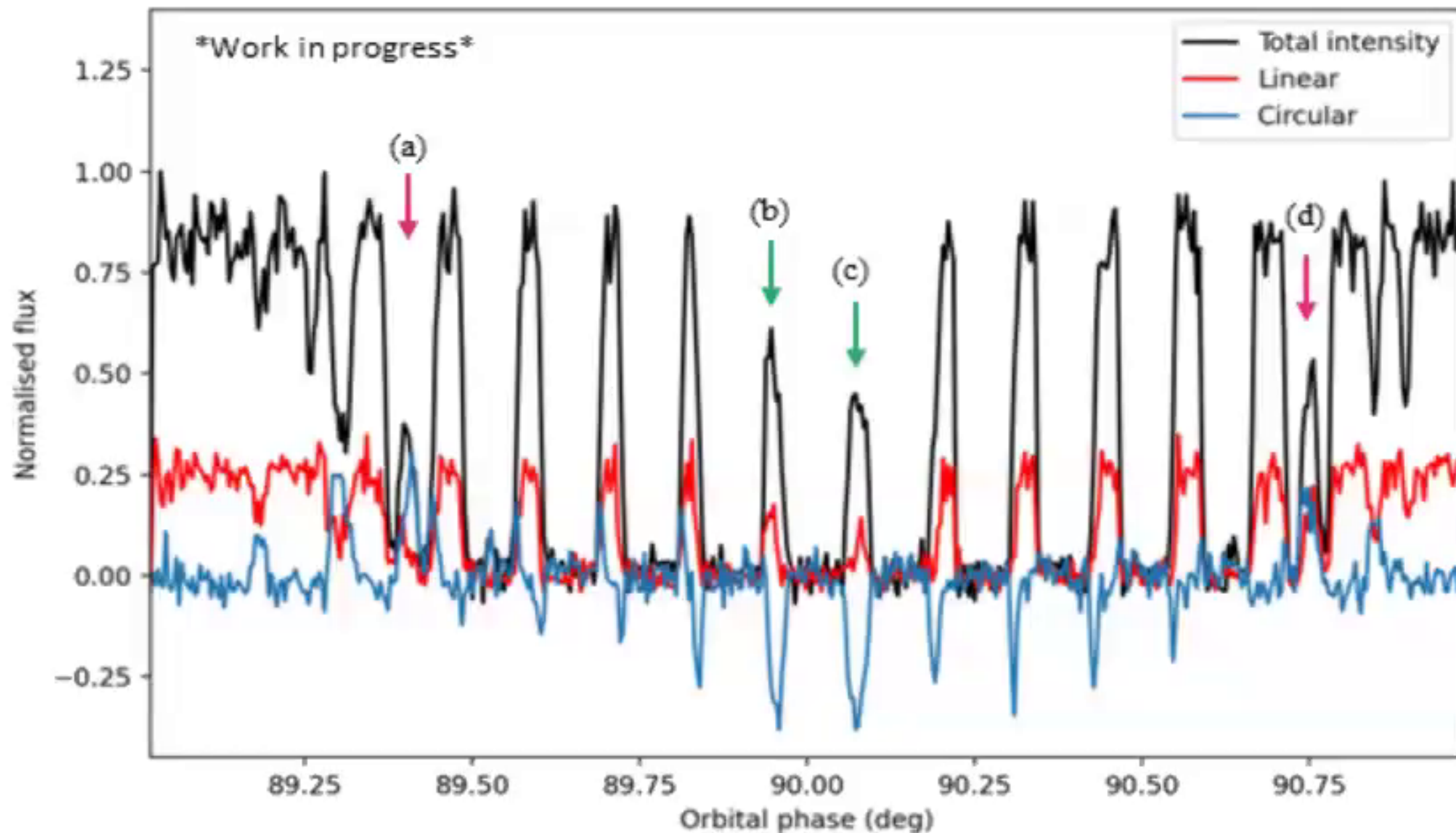
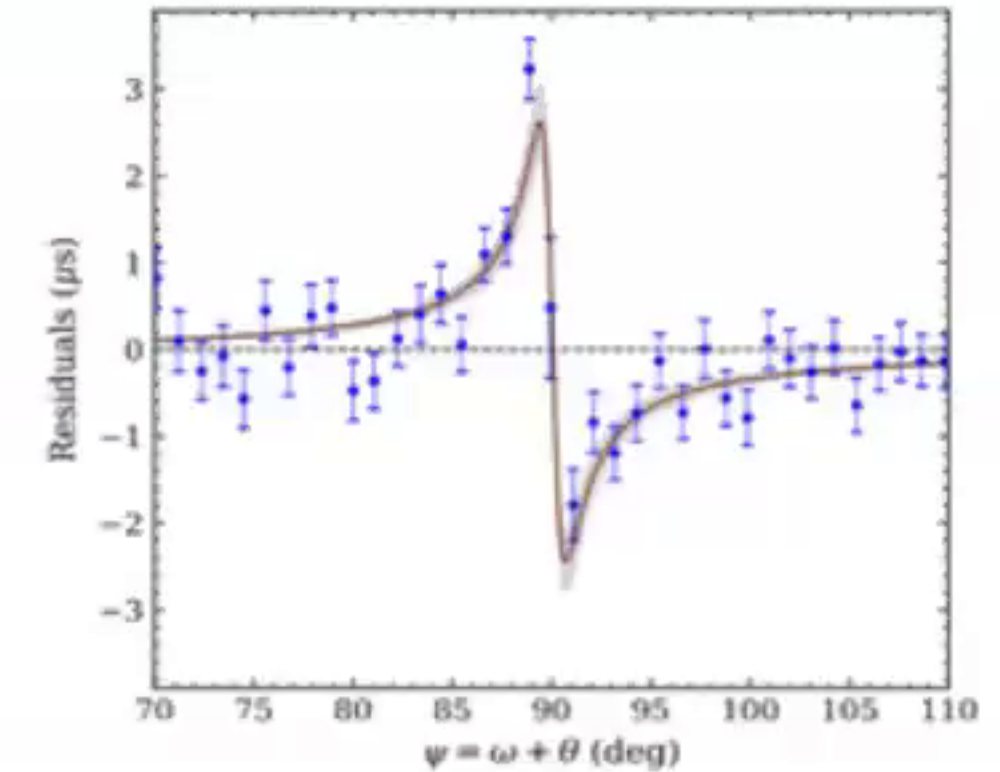
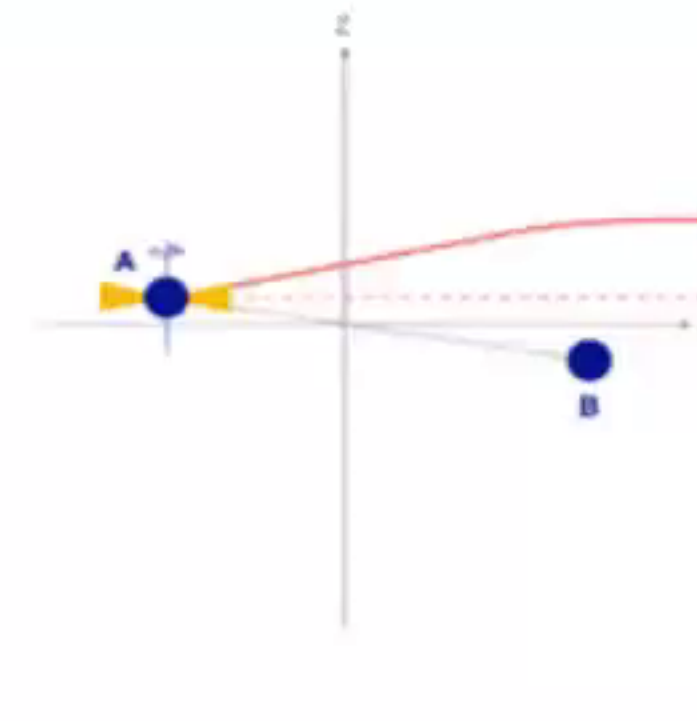
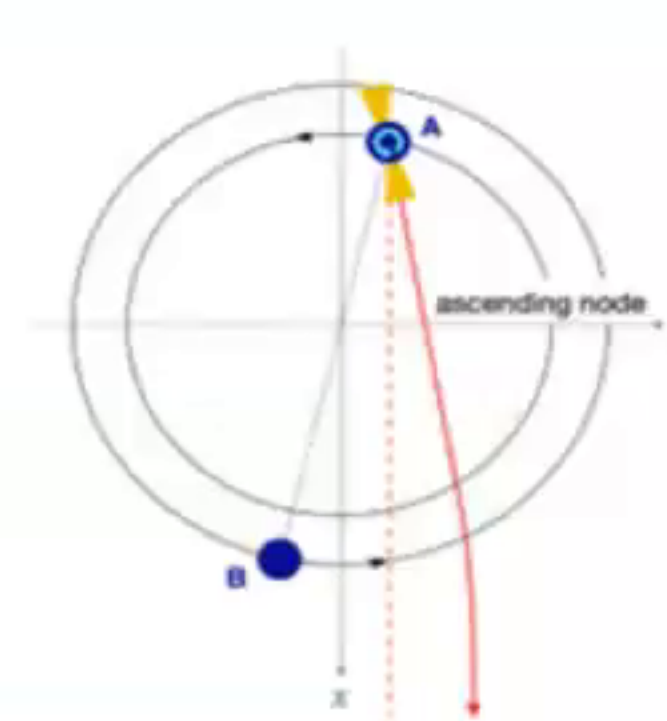
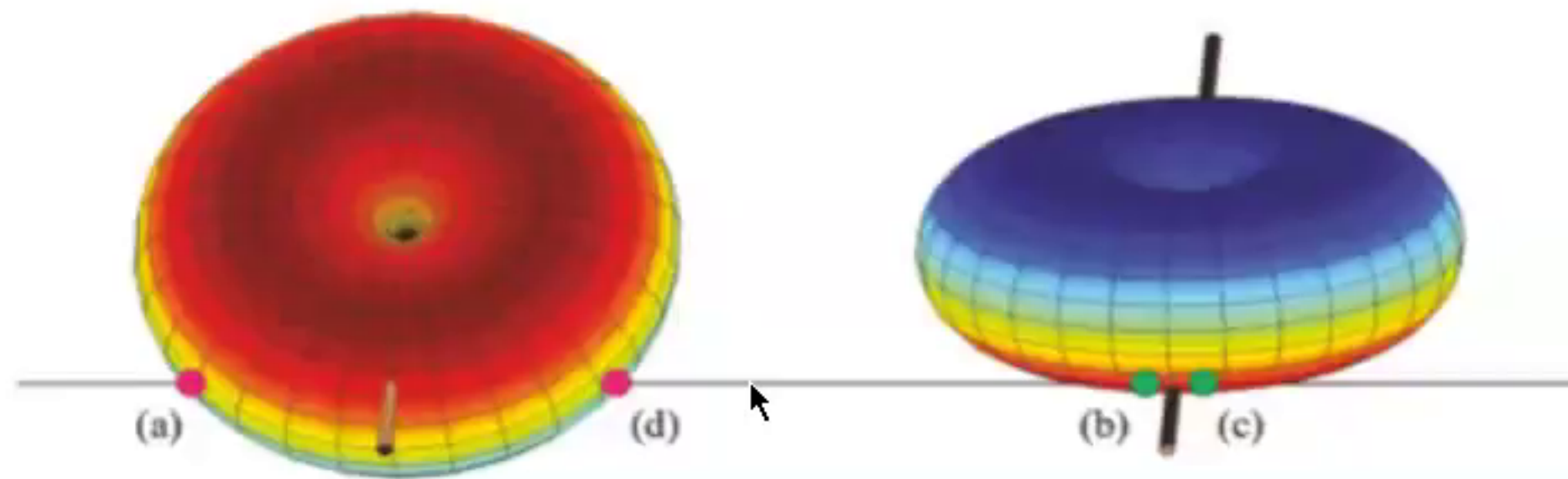
Parameter	Value
Mass of pulsar A, m_A ($M_\odot$)	1.338 186(10)
Mass of pulsar B, m_B ($M_\odot$)	1.248 886(5)
Total mass, M ($M_\odot$)	2.587 050(8)







The double pulsar eclipses

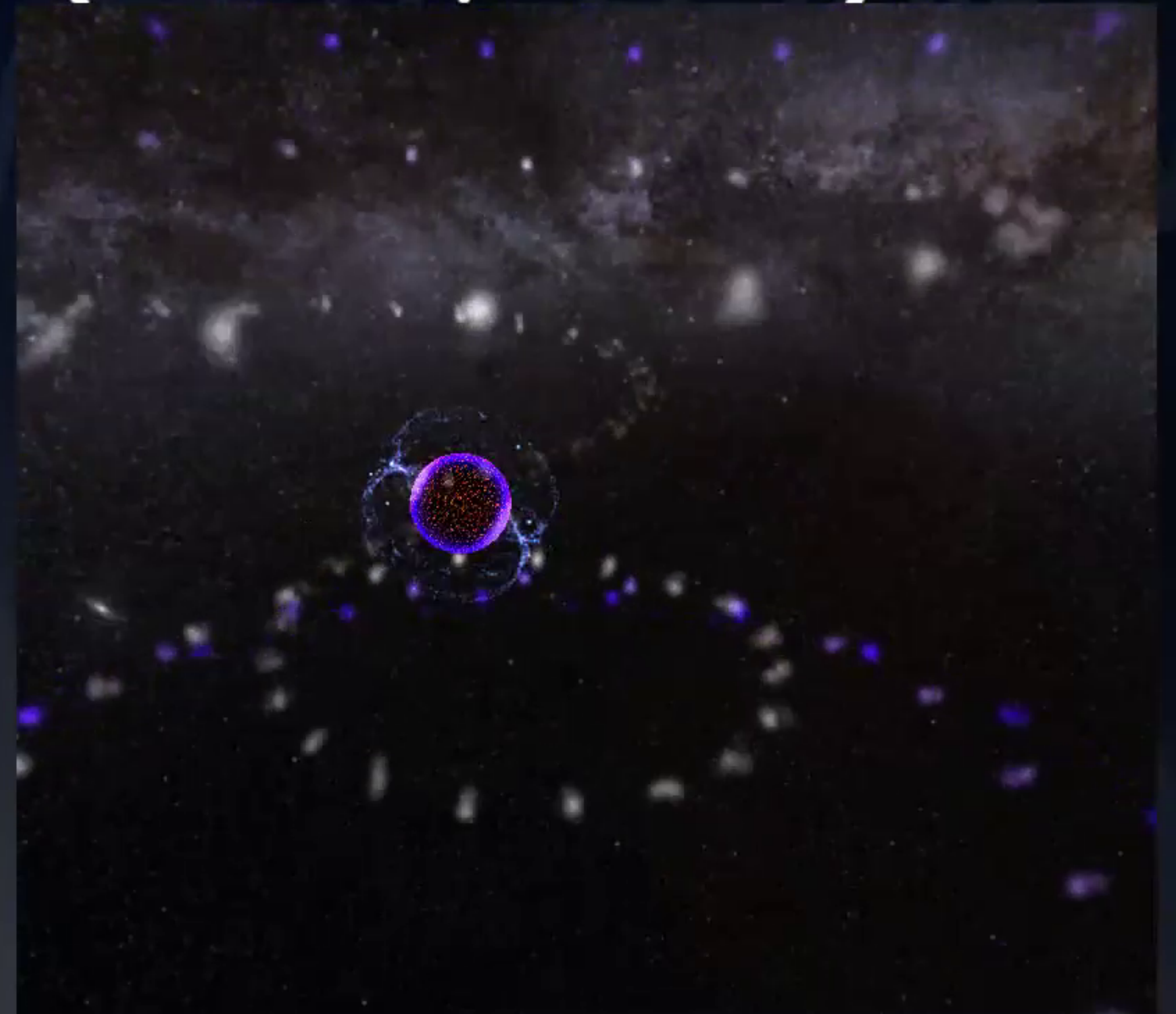


- **PSR J0737-3039A/B:** 22 ms 'pulsar A' and 2.7 s 'pulsar B' bound in a 2.25 hr orbit.
 - Orbital plane is almost perfectly edge on, radio waves from pulsar A undergo ~30 second eclipses by the magnetic field of pulsar B!
- Unusual changes in pulsar A polarisation during 'partial' eclipse periods.
 - Conversion of unpolarised to circularly polarised light???
 - Circular handedness traces B-field direction!
- Excellent laboratory for testing gravity with MeerKAT
 - Measurements of gravitational light bending (Hu et al. 2022) & spin-orbit coupling (Lower et al. submitted).

PSR J0437-4715

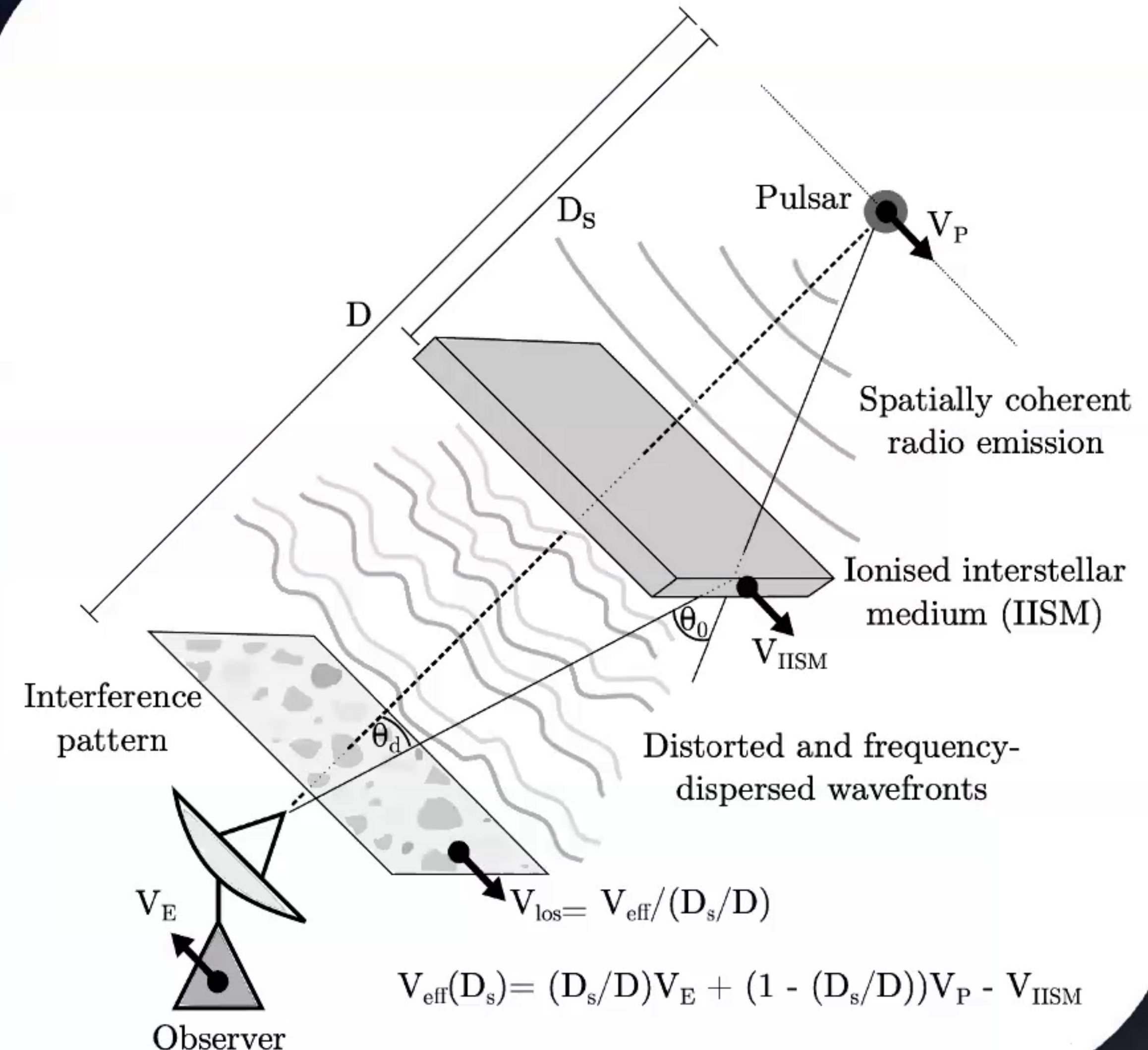
Reardon et al. (2024, 2025)

- Discovered at Parkes in 1992
- Closest Pulsar $d = 156$ pc
- $0.2 M_{\odot}$ white dwarf companion
 - Powering a bow shock



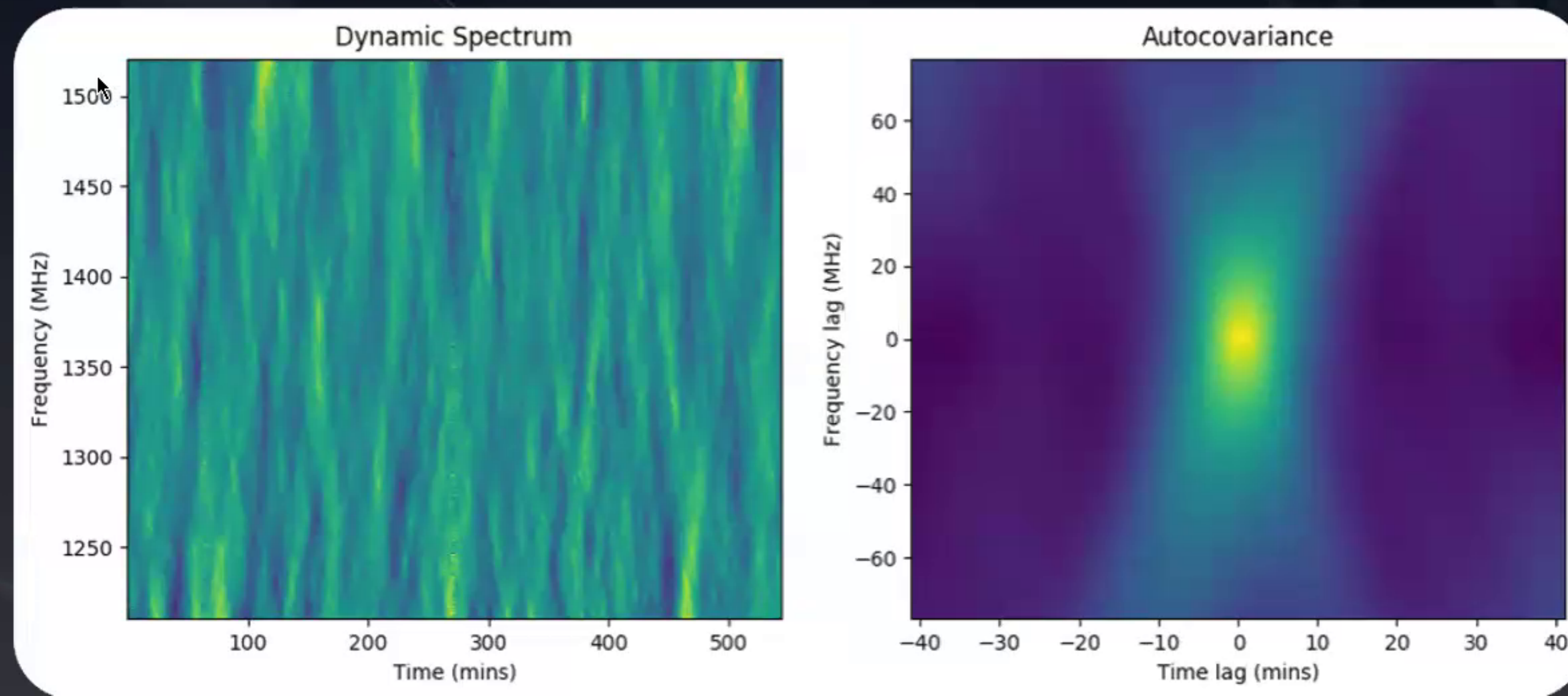
Pulsar scintillation

- Ionised interstellar medium contains **density fluctuations**
- **Scattering** creates a frequency-dependent interference pattern
- Interference pattern changes in time because of the **pulsar, Earth, and plasma motions**



Pulsar scintillation in observations

- **Dynamic spectrum** of intensity variations in frequency and time.
- Often analysed in the 2D autocorrelation or **secondary spectrum** (power spectrum)



- Scintillation arcs appear in the secondary spectrum (right)
- Curvature: **distance** to scattering screen, and the line-of-sight **velocity** through the screen

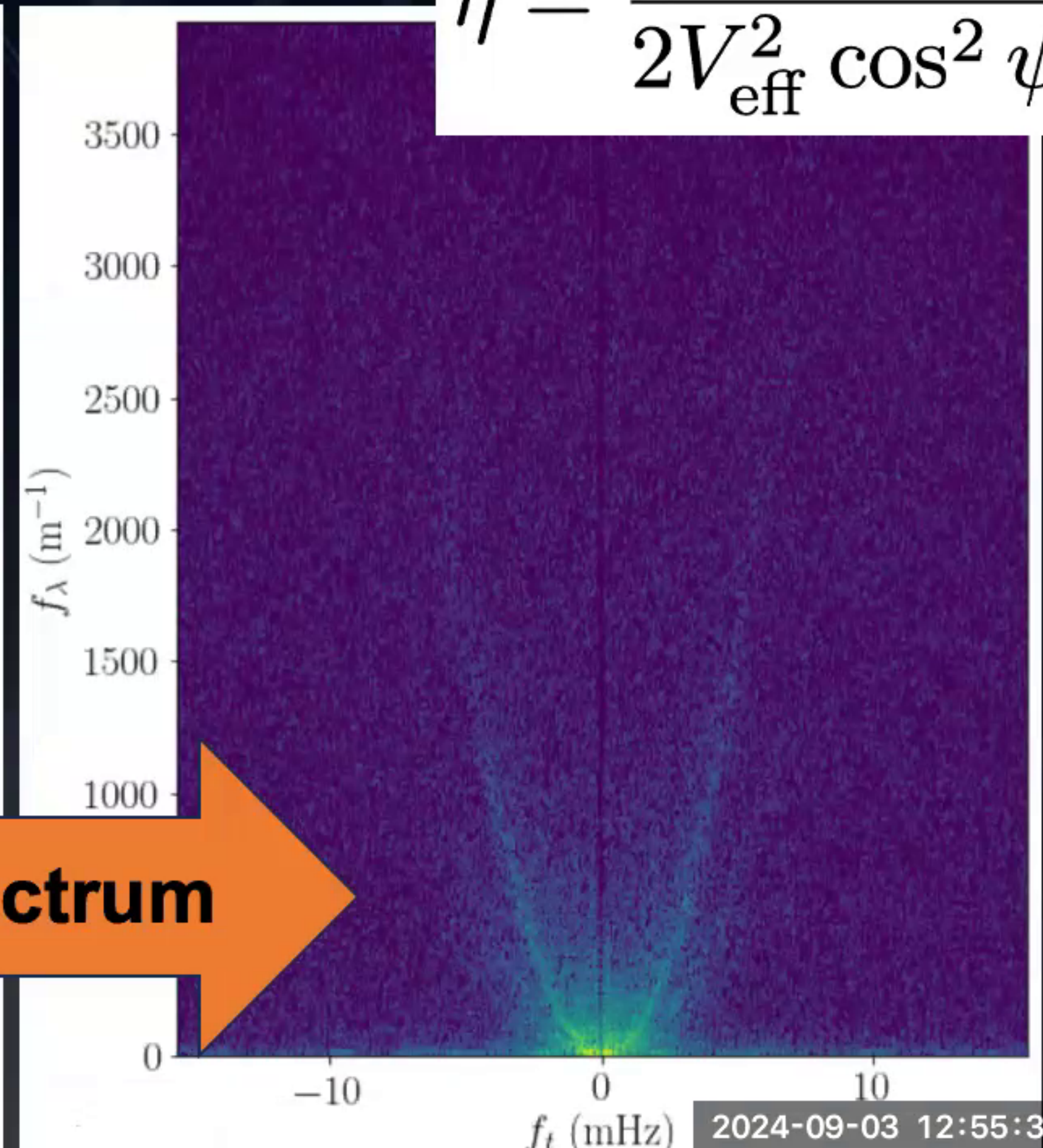
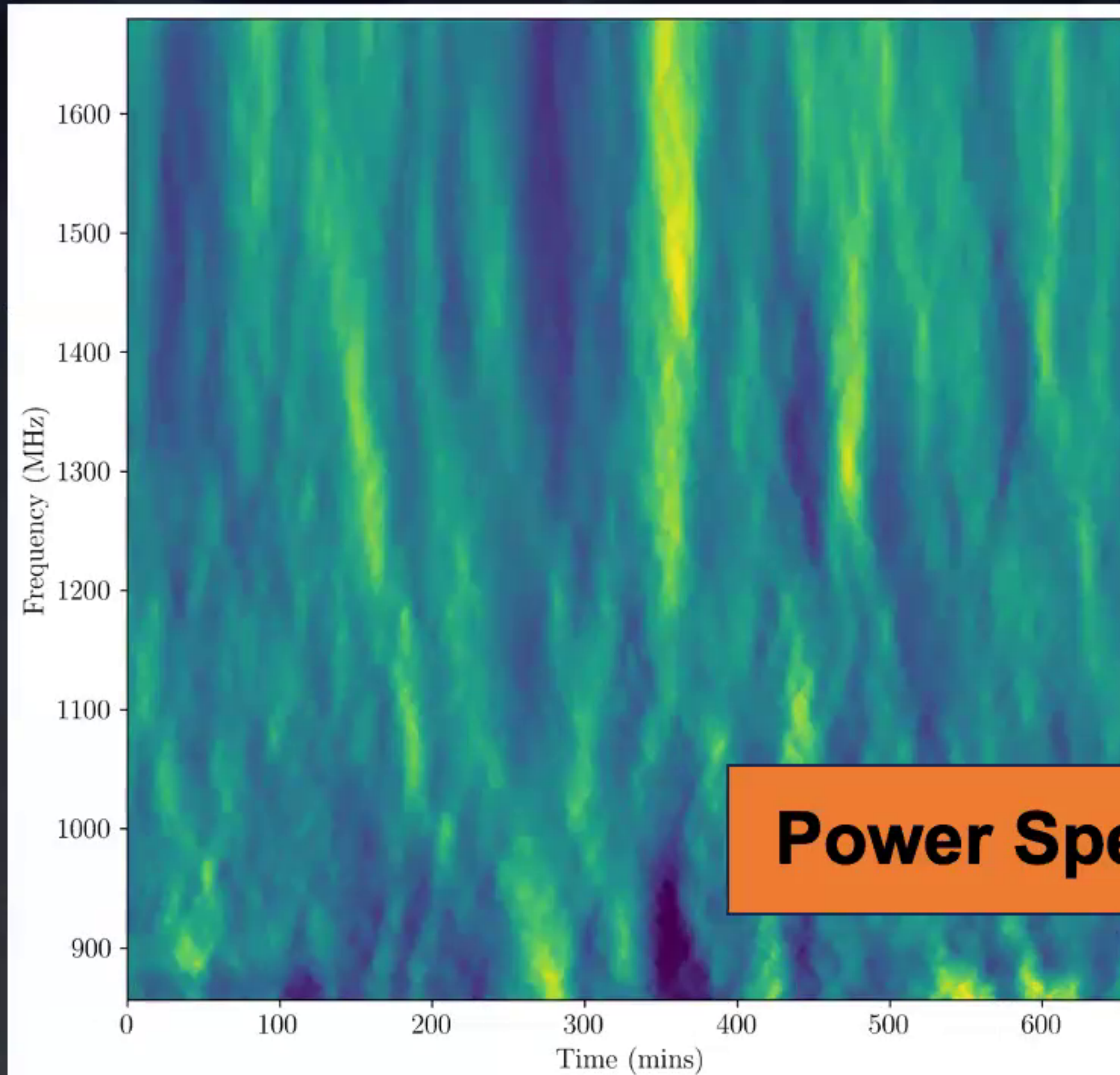
Axes are:

- **Doppler frequency** between pairs of scattered waves

$$f_t = \frac{1}{s\lambda_c} \vec{V}_{\text{eff}} \cdot (\vec{\theta}_2 - \vec{\theta}_1)$$

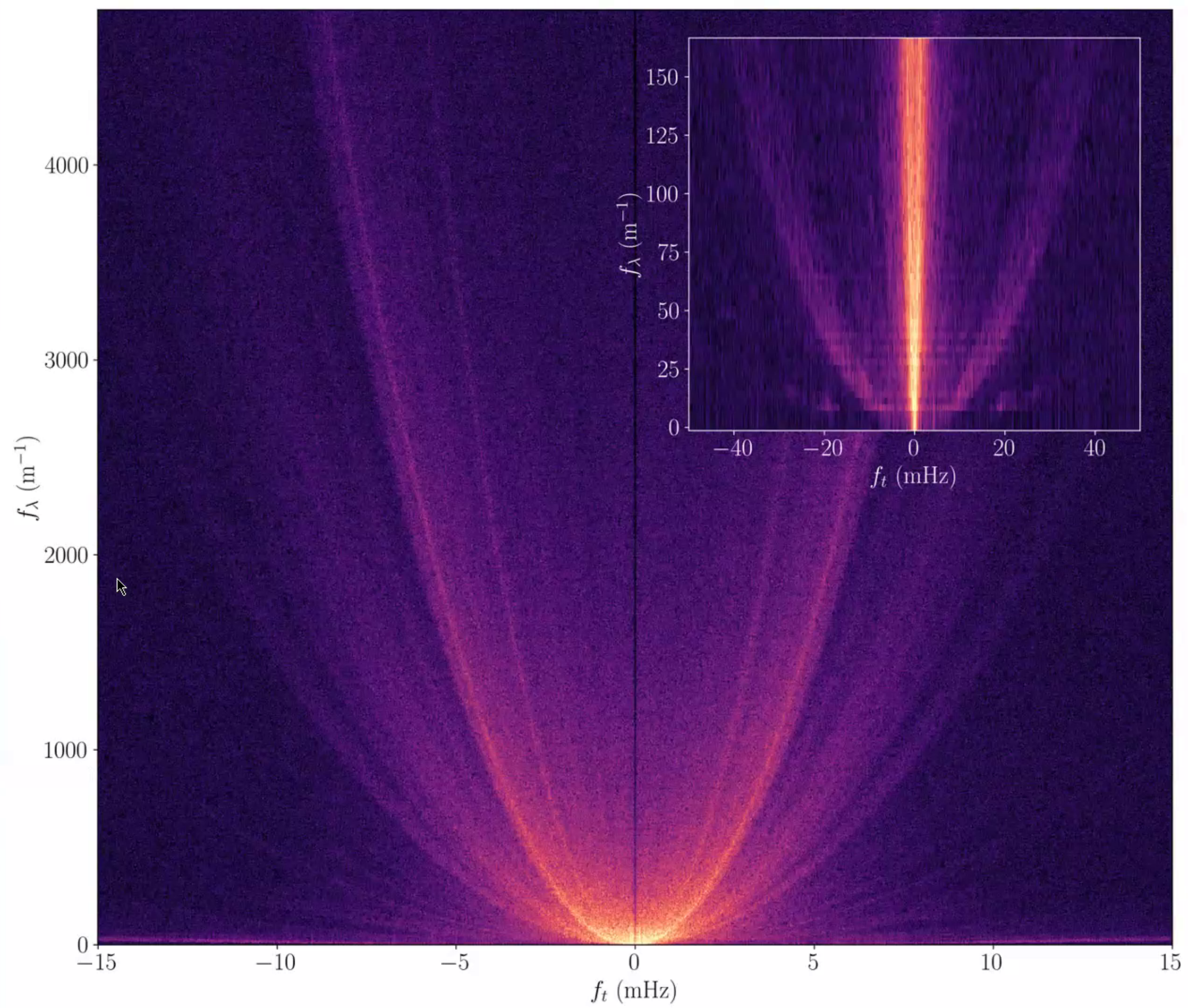
- **Time delay** between pairs of scattered waves

$$f_\lambda = \frac{D(1-s)}{2s\lambda_c^2} (\theta_2^2 - \theta_1^2)$$



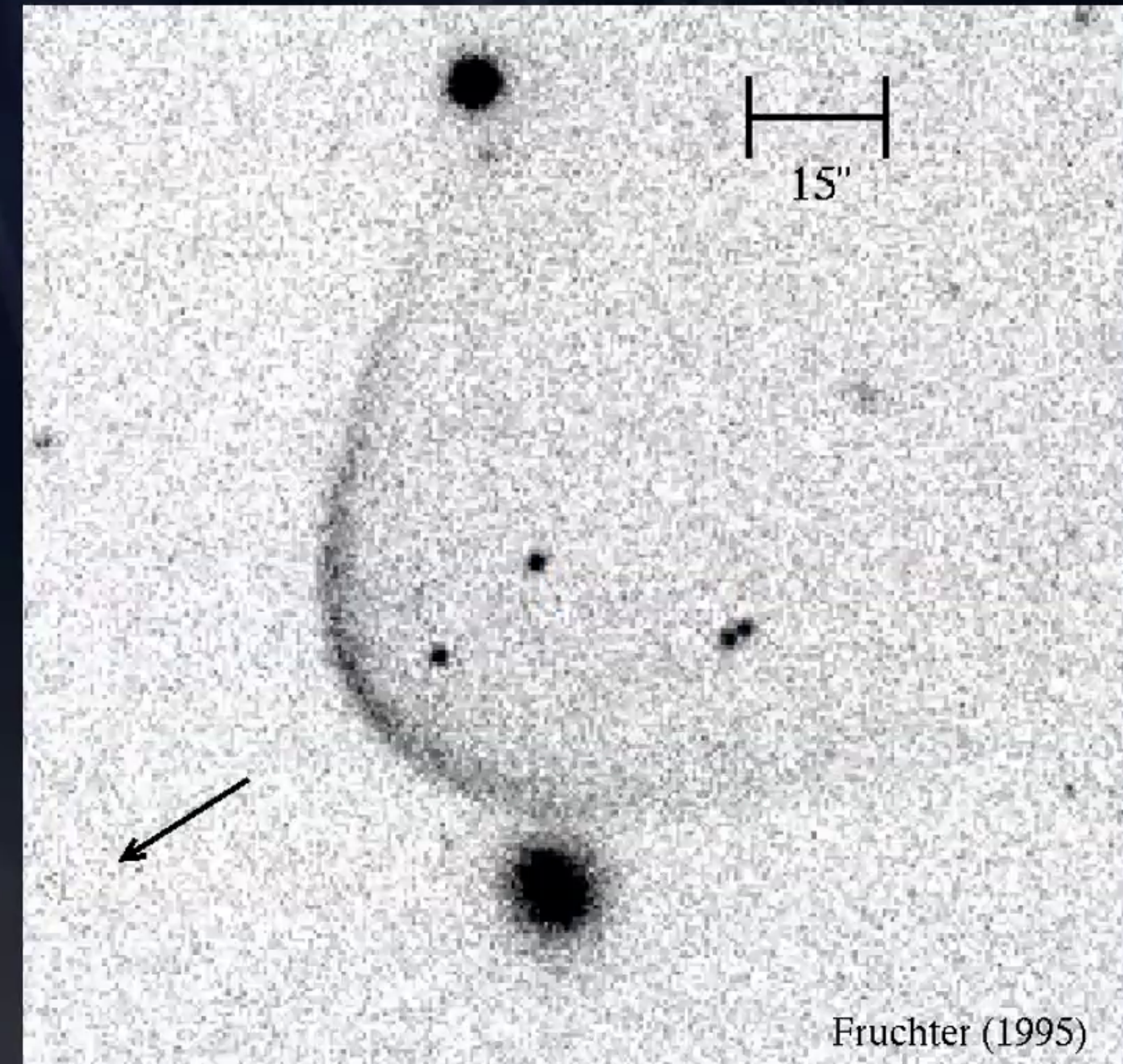
$$\eta = \frac{Ds(1-s)}{2V_{\text{eff}}^2 \cos^2 \psi}$$

Power Spectrum



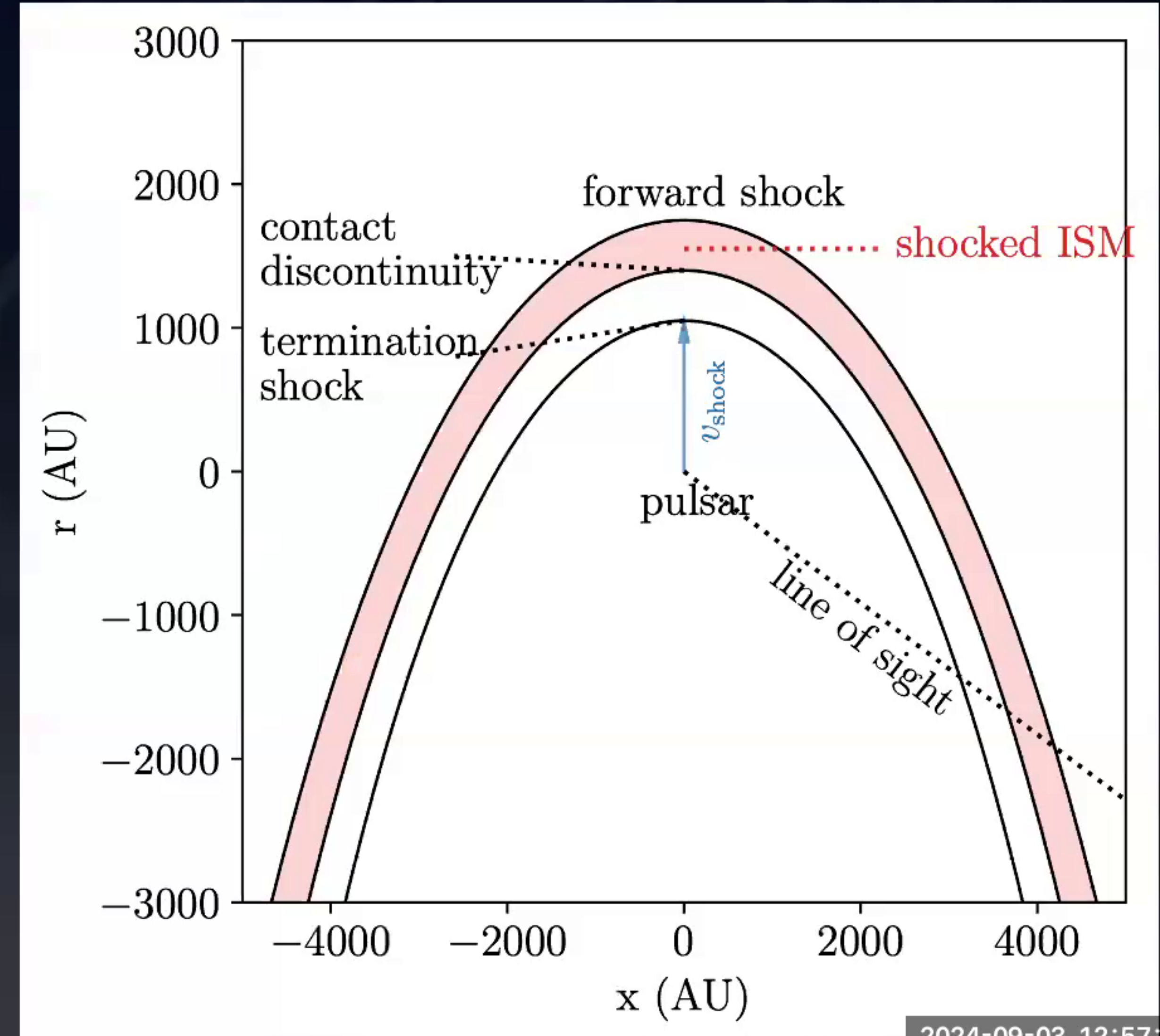
Bow shock arcs

- Three extremely **low curvature** arcs
- Originate from the pulsar **bow shock**
- Arcs probing **~ 1000 au** distances from the pulsar
- Radial distances solves the three-dimensional geometry



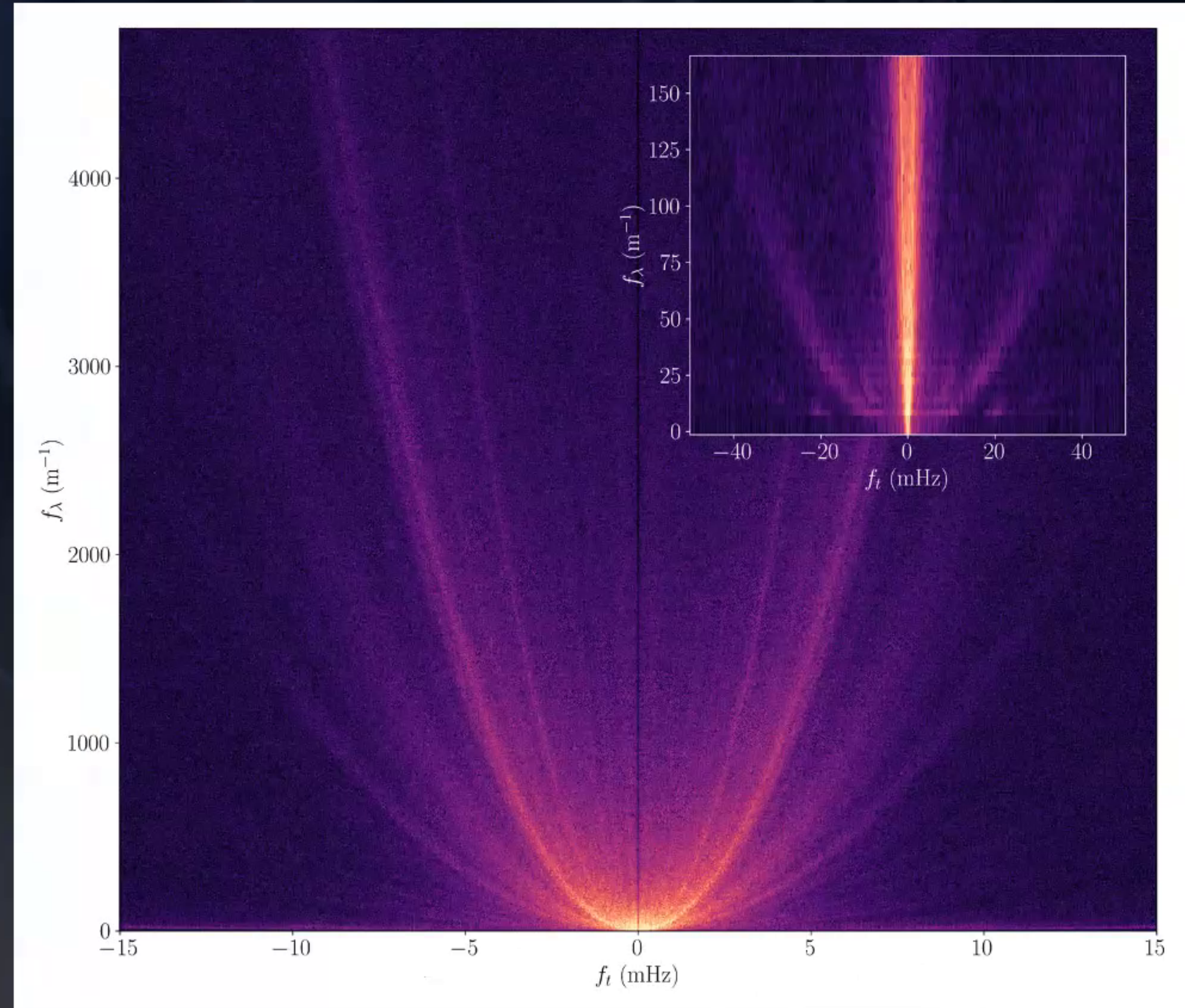
Model of the bow shock

- Three shock arcs
- Forward shock
 - Pronounced arc
 - H-alpha emission
 - Peak originates 4720 ± 190 au from pulsar
 - Radial thickness of ~ 800 au
 - ~ 70 km/s towards tail
- Contact discontinuity
- Termination shock
 - Innermost layer and a plasma inflow at ~ 20 km/s



Summary

- MeerKAT provides unprecedented view of the ionised interstellar medium
- Reveals 20+ structures inside the **Local Bubble**
 - $>1\text{pc}^{-1}$ screen number density
- Enables tomography of a pulsar **bow shock**
 - Discovery of a plasma inflow
 - Measured radial velocity

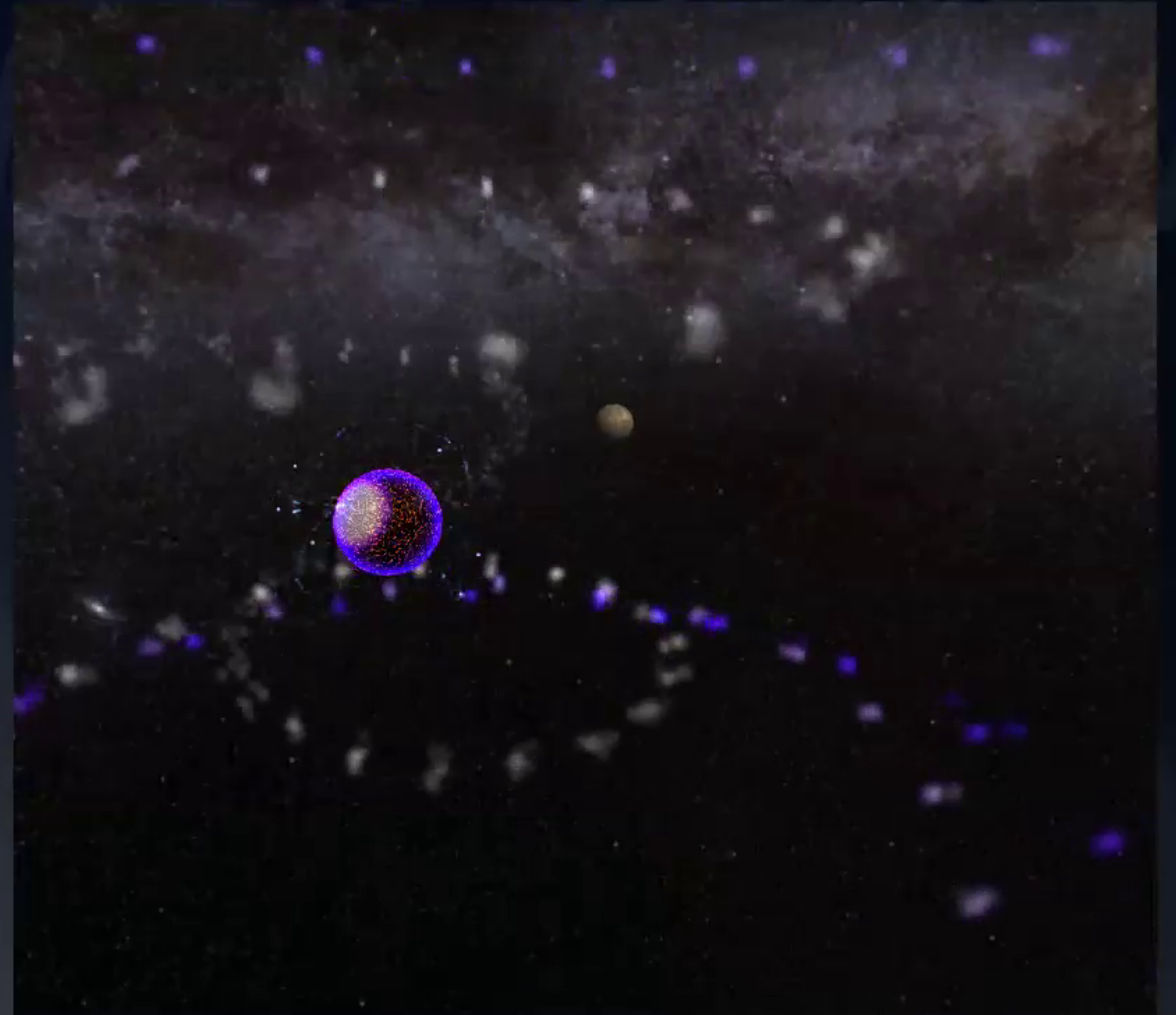


PSR J0437-4715

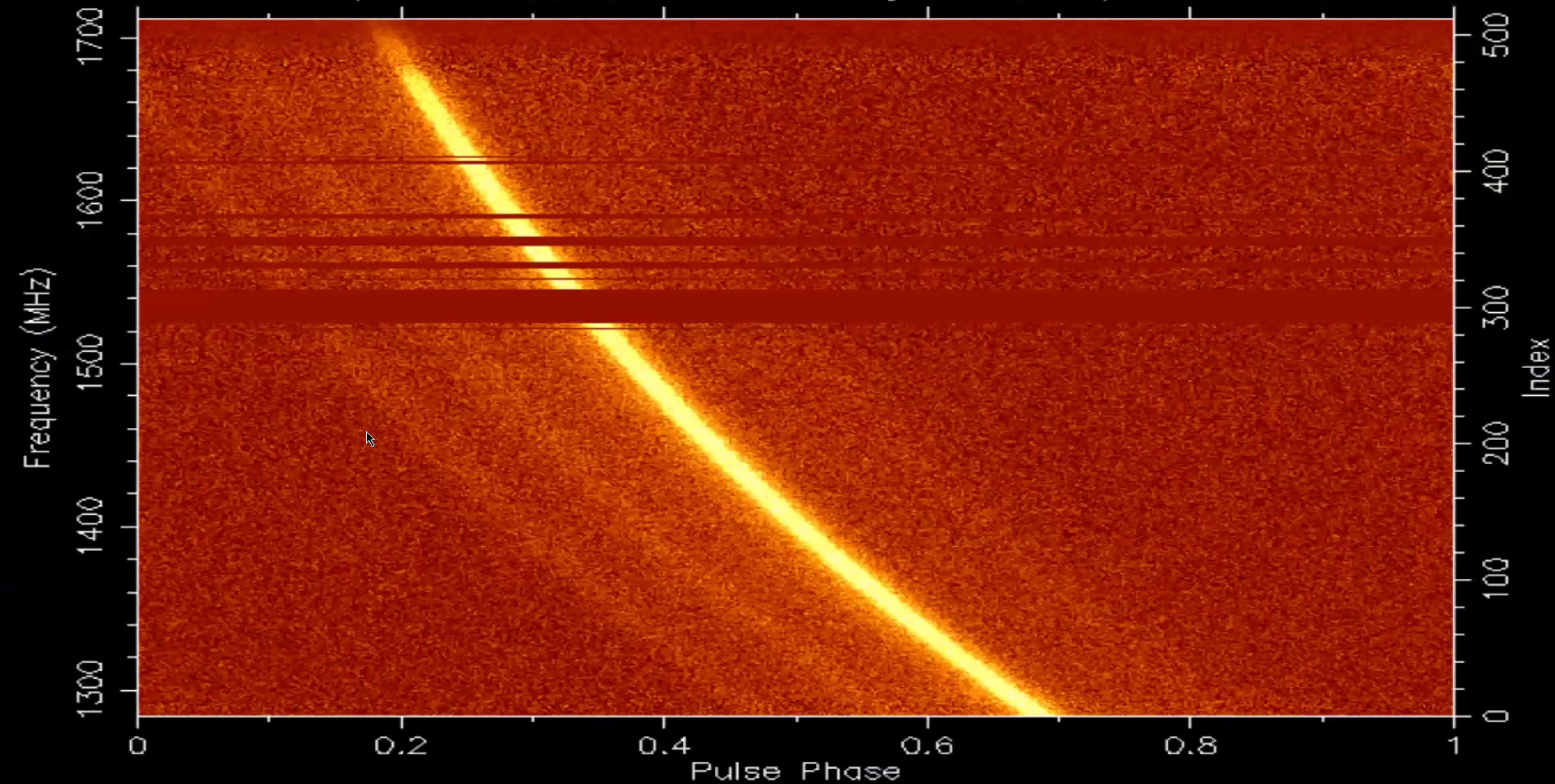
- Discovered at Parkes in 1992
- $P=5.7$ ms
- Closest Pulsar $d = 156$ pc
- $0.2 M_{\odot}$ white dwarf companion
 - Powering a bow shock

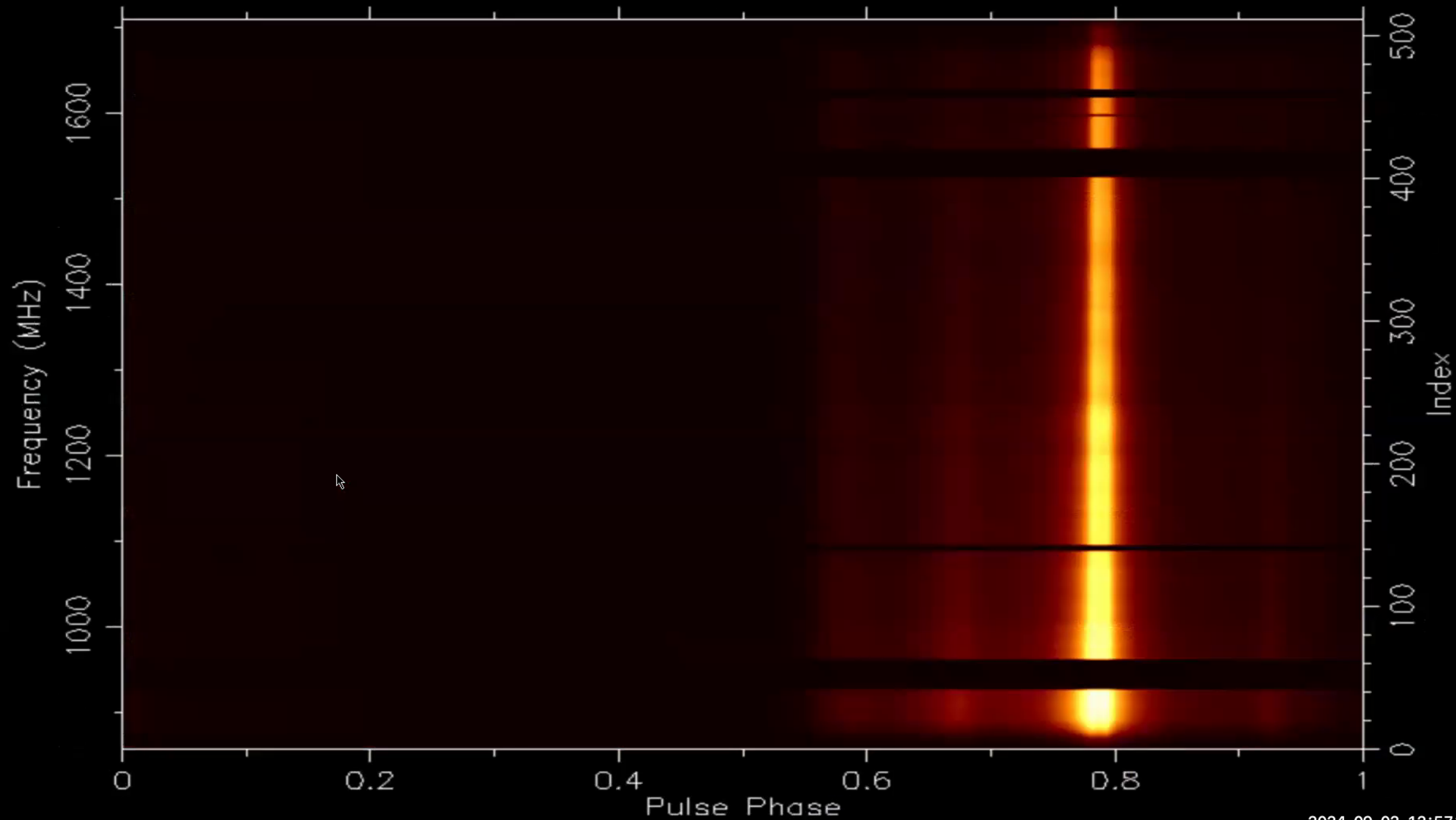
$$a \sin i = 3.36671444(5) \text{ s}$$
$$(1.009 \text{ Mkm})$$

$$a - b = 186 \text{ mm}$$

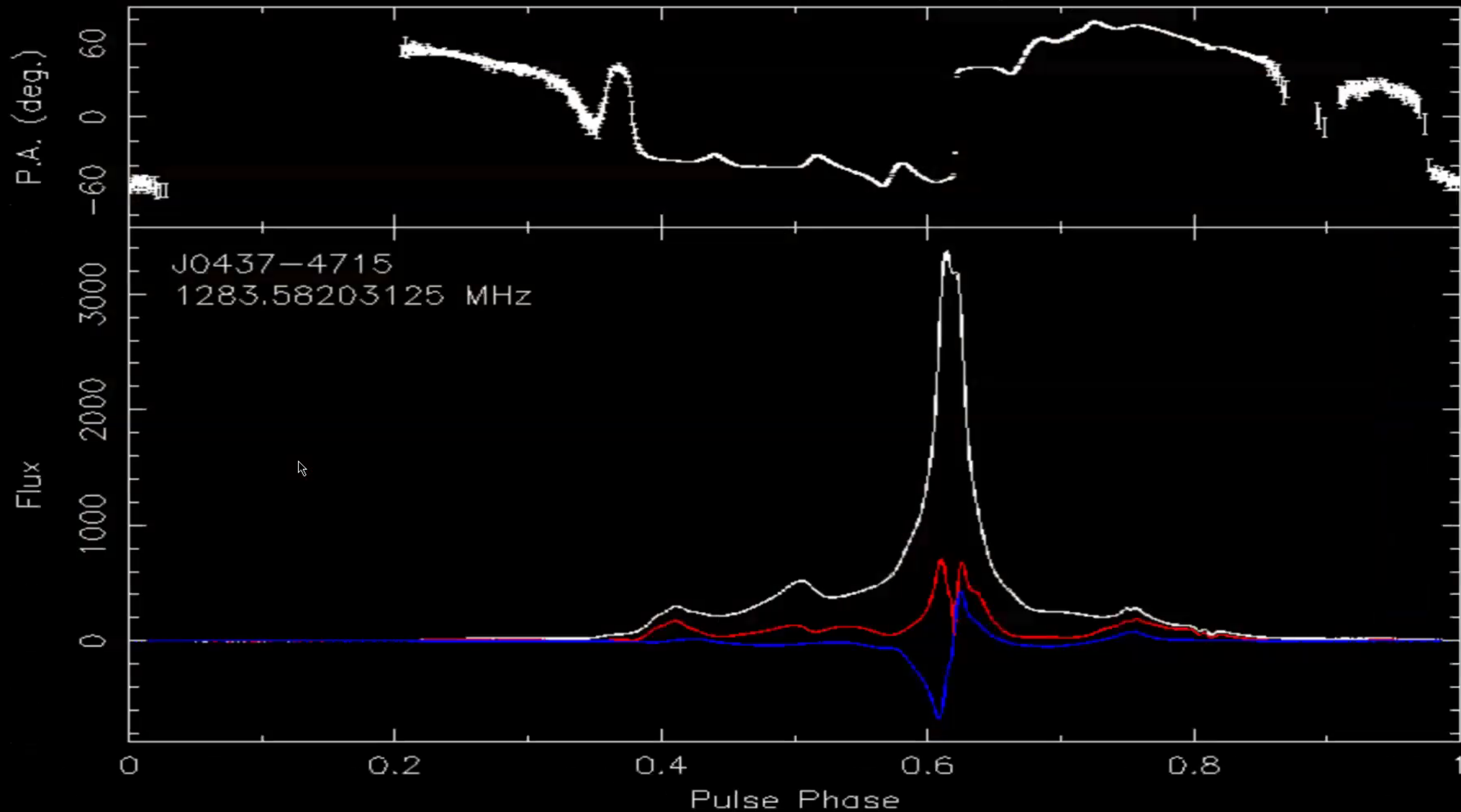


J0437-4715 2022-05-19-15:07:27.ar.pazi
Freq: 1492.298 MHz BW: 428 Length: 0.997 S/N: 732.493





Polarisation Profile (TPA)



MeerKAT Radio Telescope

- A great pulsar telescope!
(Part of the Square Kilometre Array)

$$SNR = \frac{SG \sqrt{BN_p t}}{T_{\text{rec}} + T_{\text{sky}}} \sqrt{\frac{P - w}{w}}$$

$$\sigma_{TOA} = \frac{w}{2SNR}$$



The Parkes 64 m Radio Telescope (Murriyang)

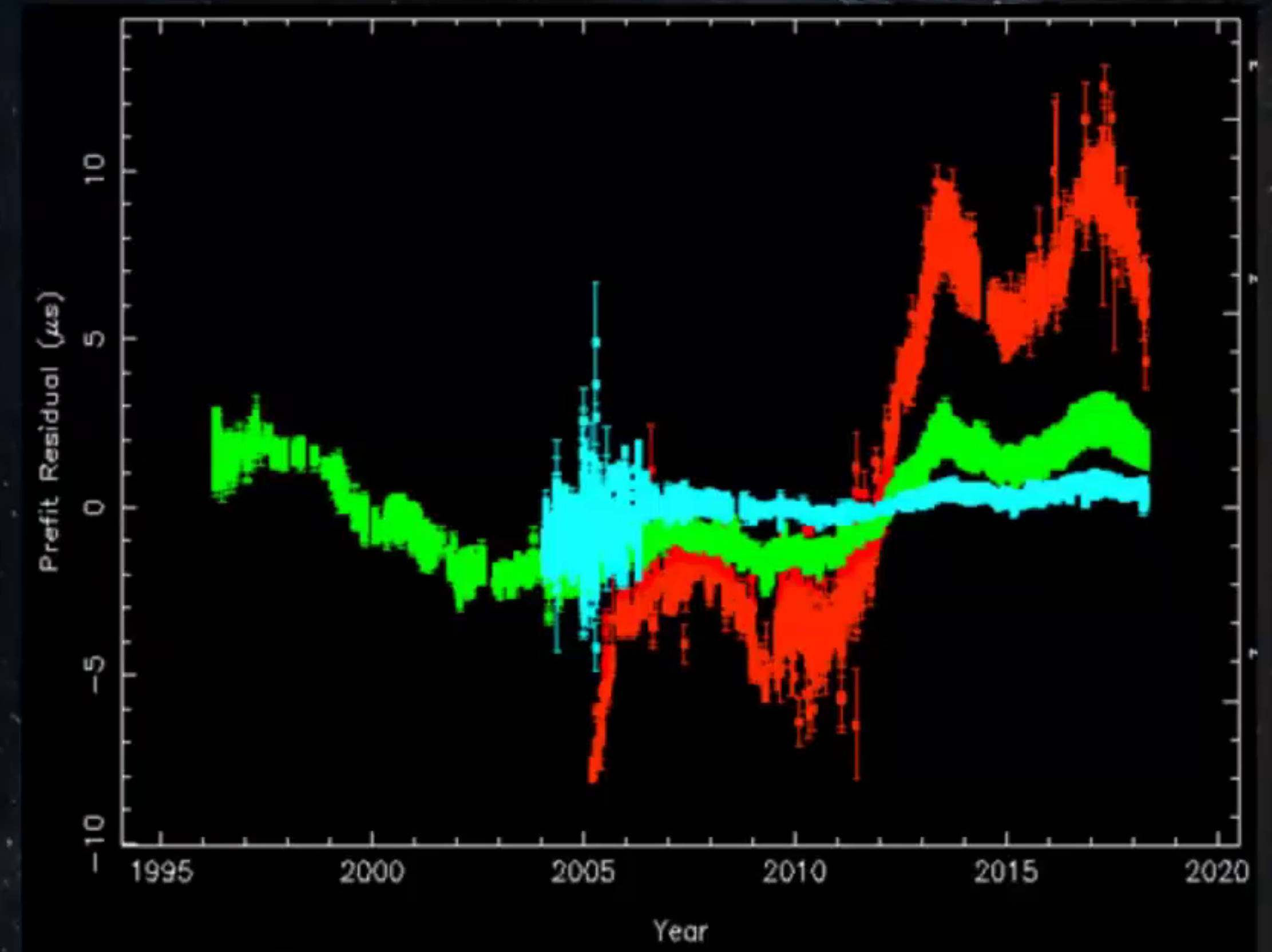


NICER Satellite

- X-rays enable hot-spot modelling
- Pulsar Timing enables masses (Reardon et al)
 - Mass + light curve = radius?

Timing of Millisecond Pulsar, PSR J0437-4715

- **Nearest and brightest** millisecond pulsar
- ~22 years of regular timing observations with Parkes 64m radio telescope
- PPTA second data release
- Noise timescale $\gg$ orbital timescale (5.7 days)



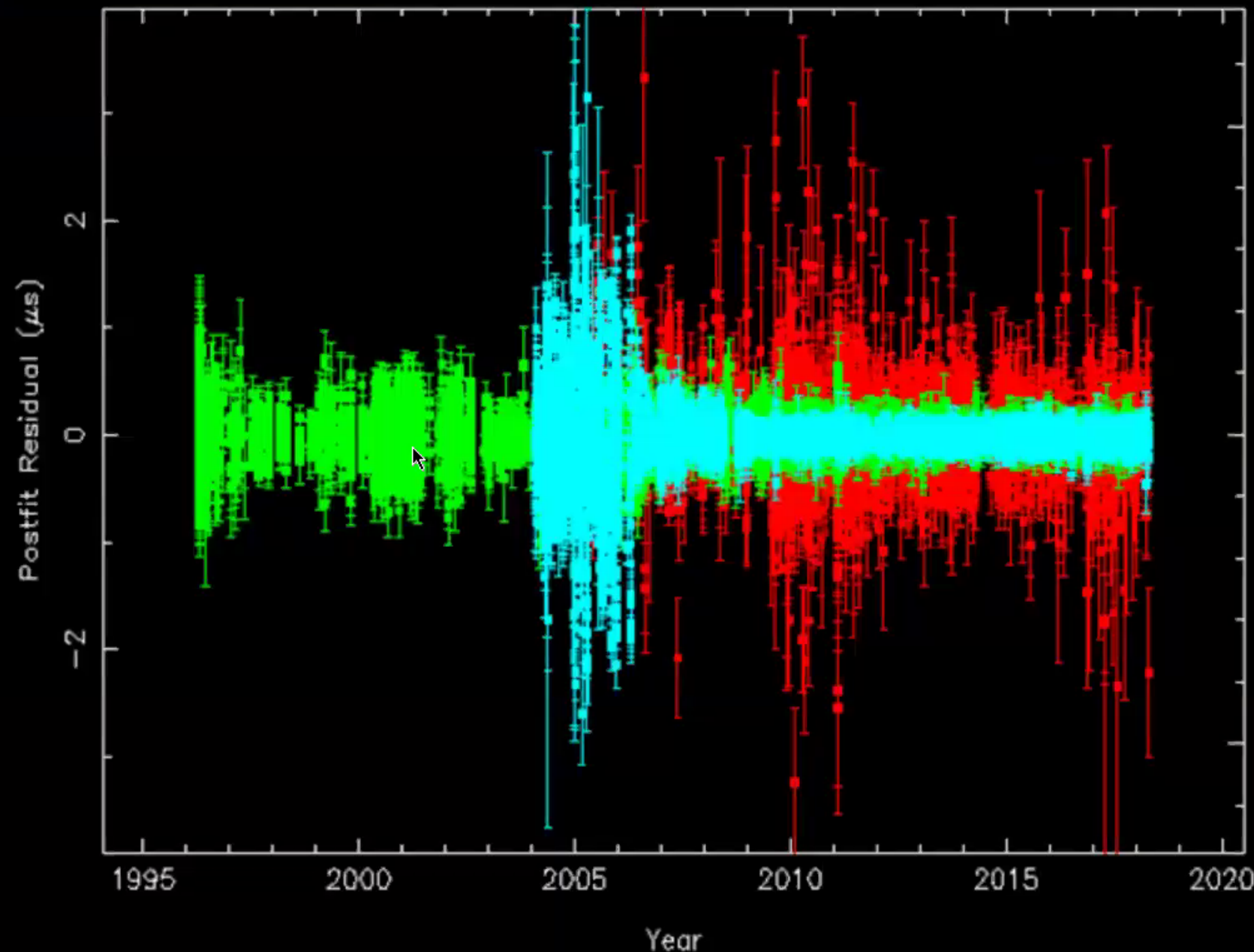
Timing residuals (difference between data and model)

Red: 700 MHz

Green: 1400 MHz

Blue: 3100 MHz

PSR J0437-4715 Timing Precision

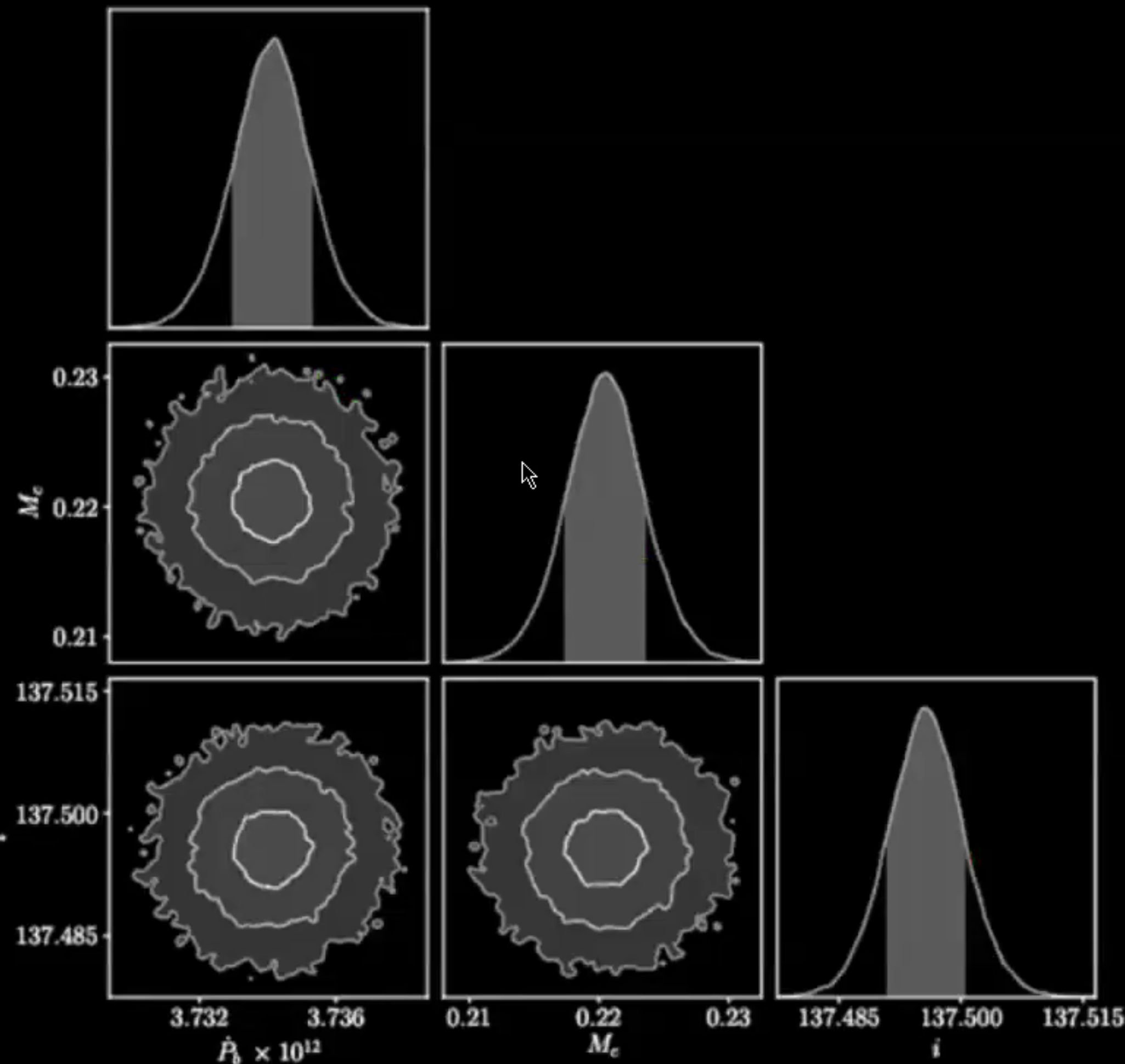


Timing residuals after removing the long-timescale noise.

~100 nanosecond weighted rms residual over ***~22 years***

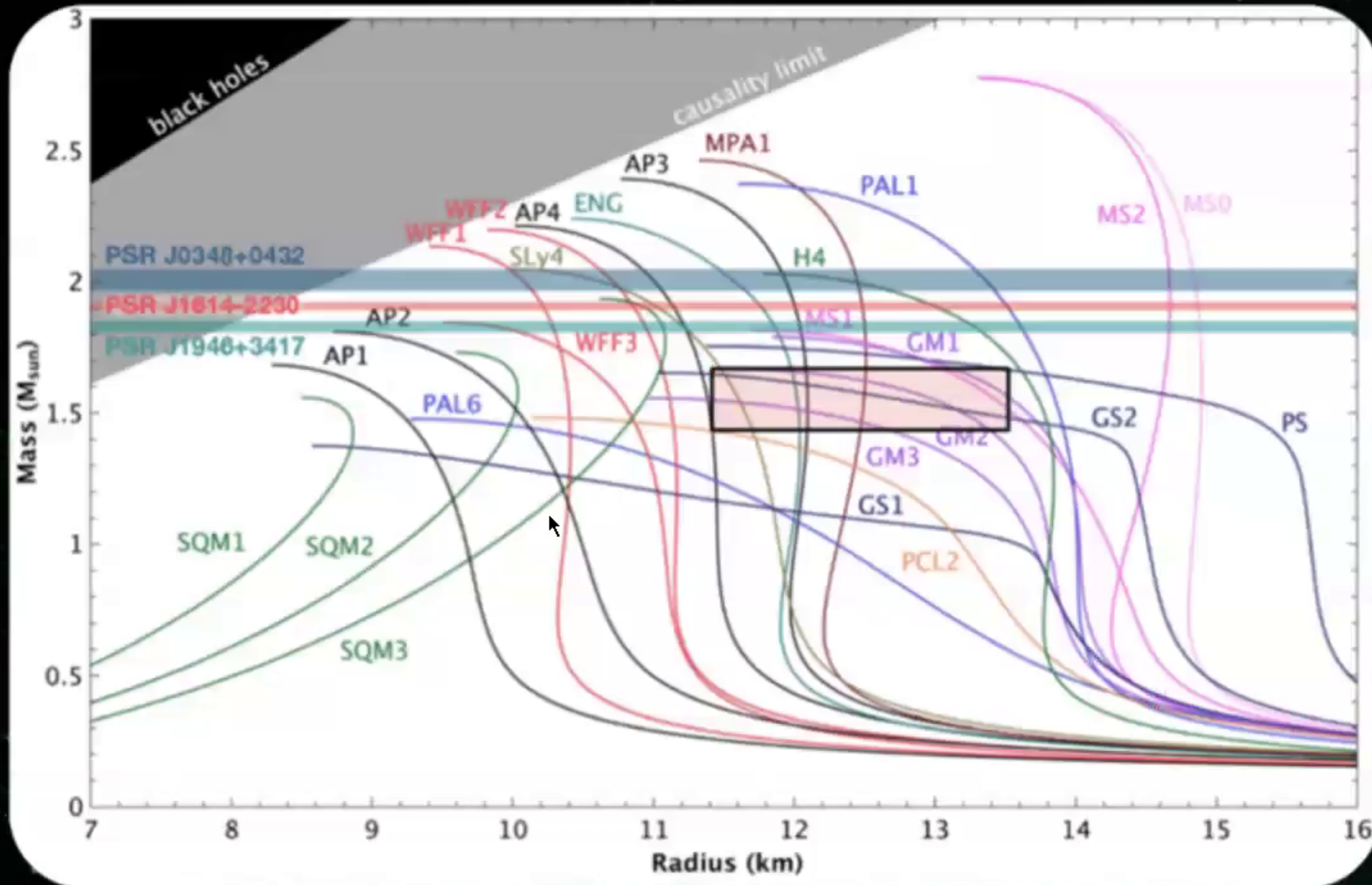
Red: 700 MHz
Green: 1400 MHz
Blue: 3100 MHz

Reardon et al. Timing Results for PSR J0437-4715



- Companion mass measured with **Shapiro delay**
- Inclination angle: 137.496 ± 0.005 degrees
- Companion mass: 0.2205 ± 0.0029 solar mass
- Distance: $157.1(1)$ pc
- Radial velocity: $-75 (15)$ km/s
- **Pulsar mass: 1.411 ± 0.030 solar mass**

Q: Why do we care about this pulsar?



- One of our best opportunities for measuring the neutron star equation of state
- “A two-solar-mass neutron star measured using Shapiro delay” – Demorest et al. (2010)
2500+ citations
- “A Massive Pulsar in a Compact Relativistic Binary” – Antoniadis et al. (2013)
~ 1500 citations
- “GW170817: Measurements of Neutron Star Radii and Equation of State” – Abbott et al. (2018)
~250 citations

From OzGrav telecon presentation by Theo Motta
(University of Adelaide)

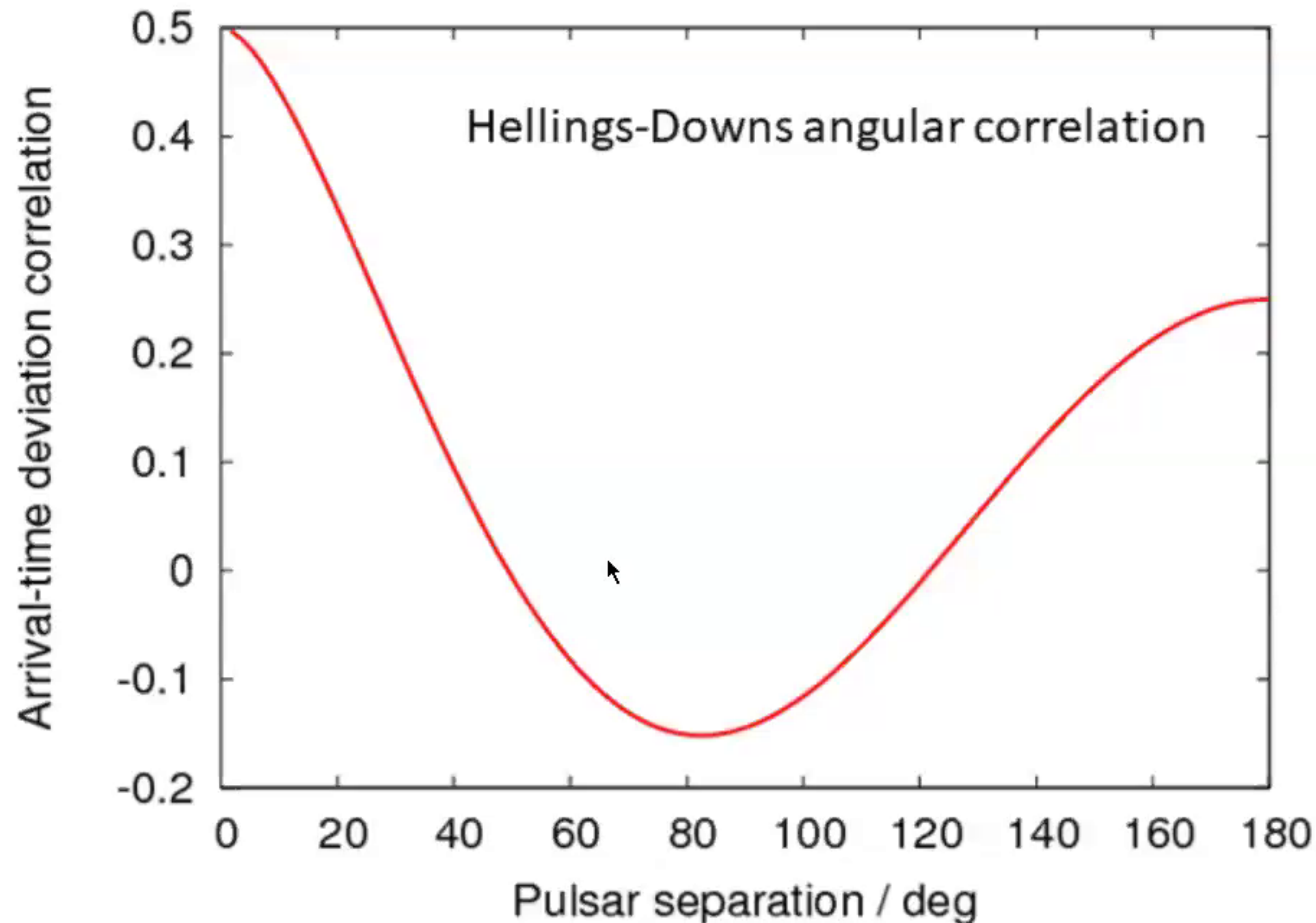
Supermassive Black Hole Hunting

Miles et al. (2024a/b)





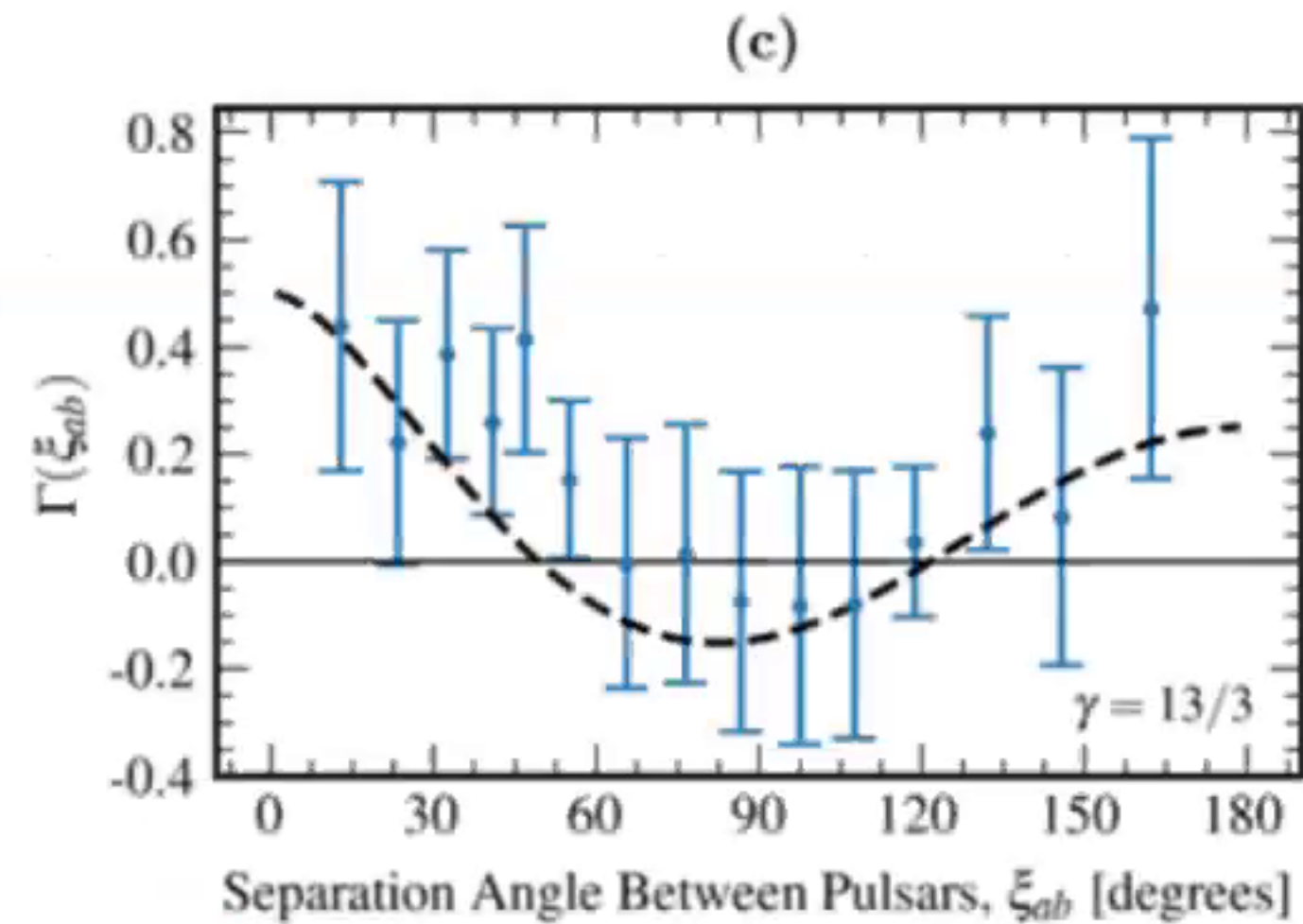
How do we detect a background?



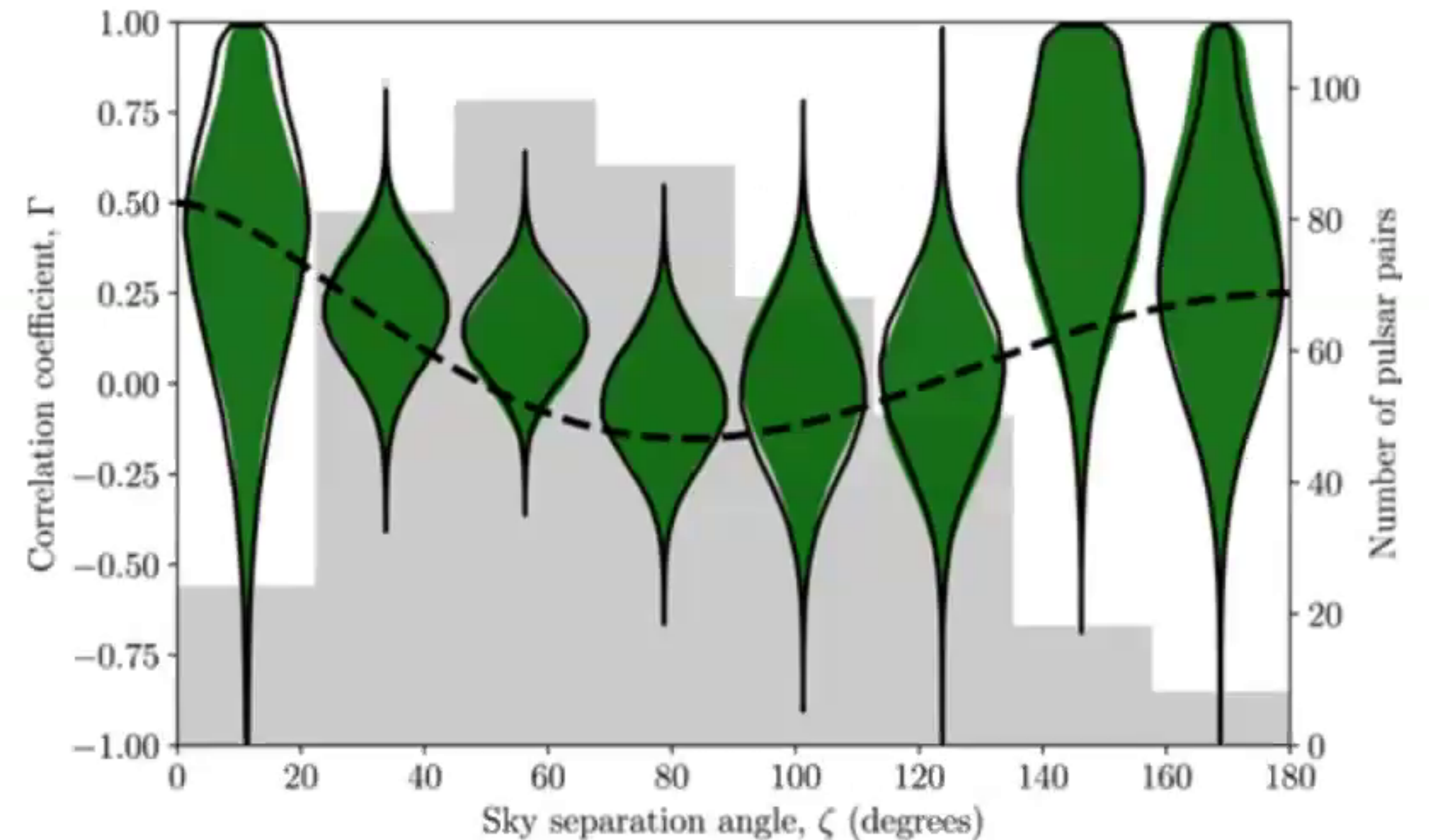
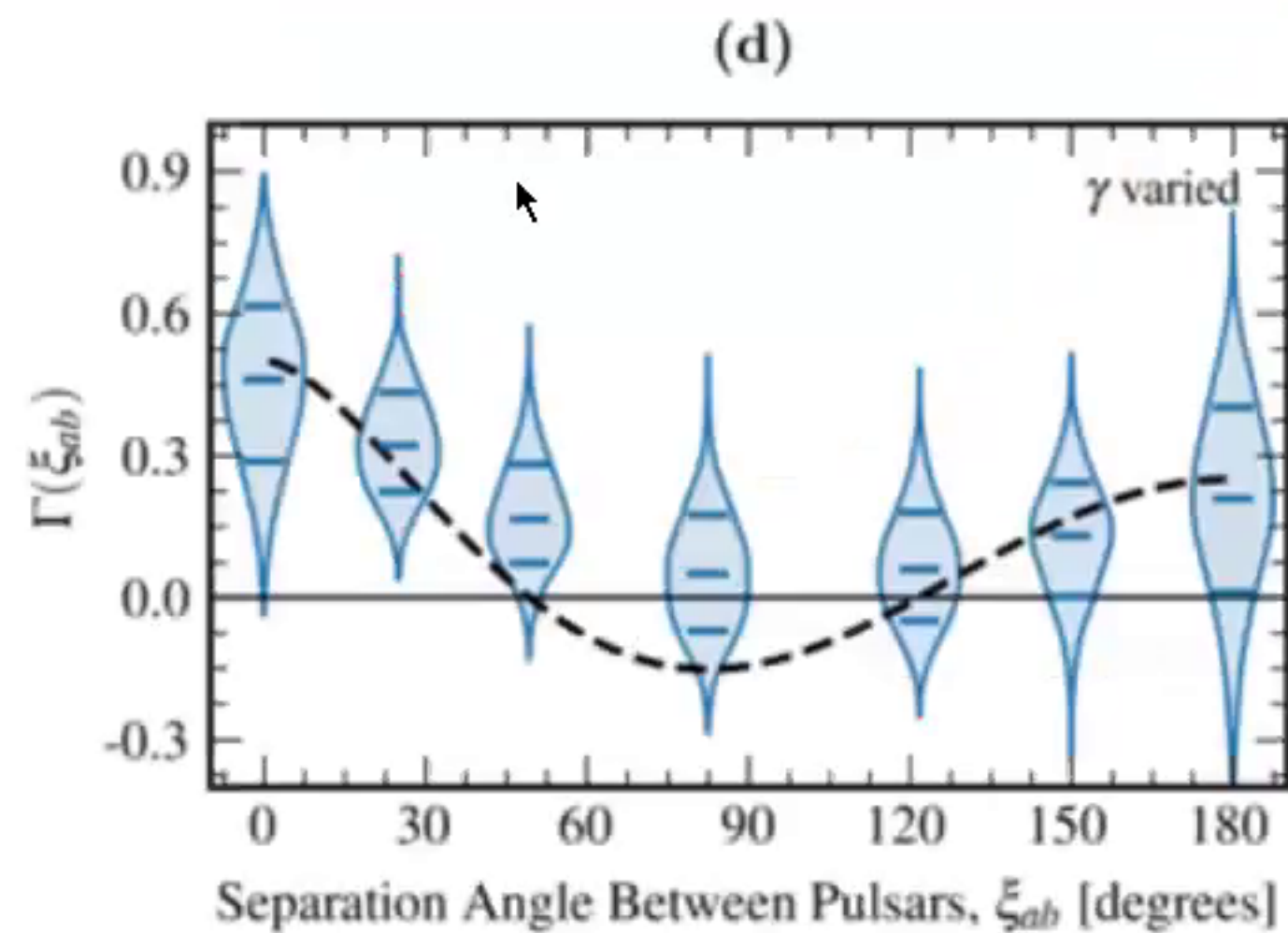
- **Problem:** Other sources of noise can induced similar stochastic variations
- Variations can have similar properties (amplitude/redness) as the GWB
 - Intrinsic rotational irregularities
 - Poorly constrained
- **Solution:** search for angular correlations between pulse arrival times

OzGrav

Latest results: searches for correlations



2-4 sigma evidence for a gravitational wave background

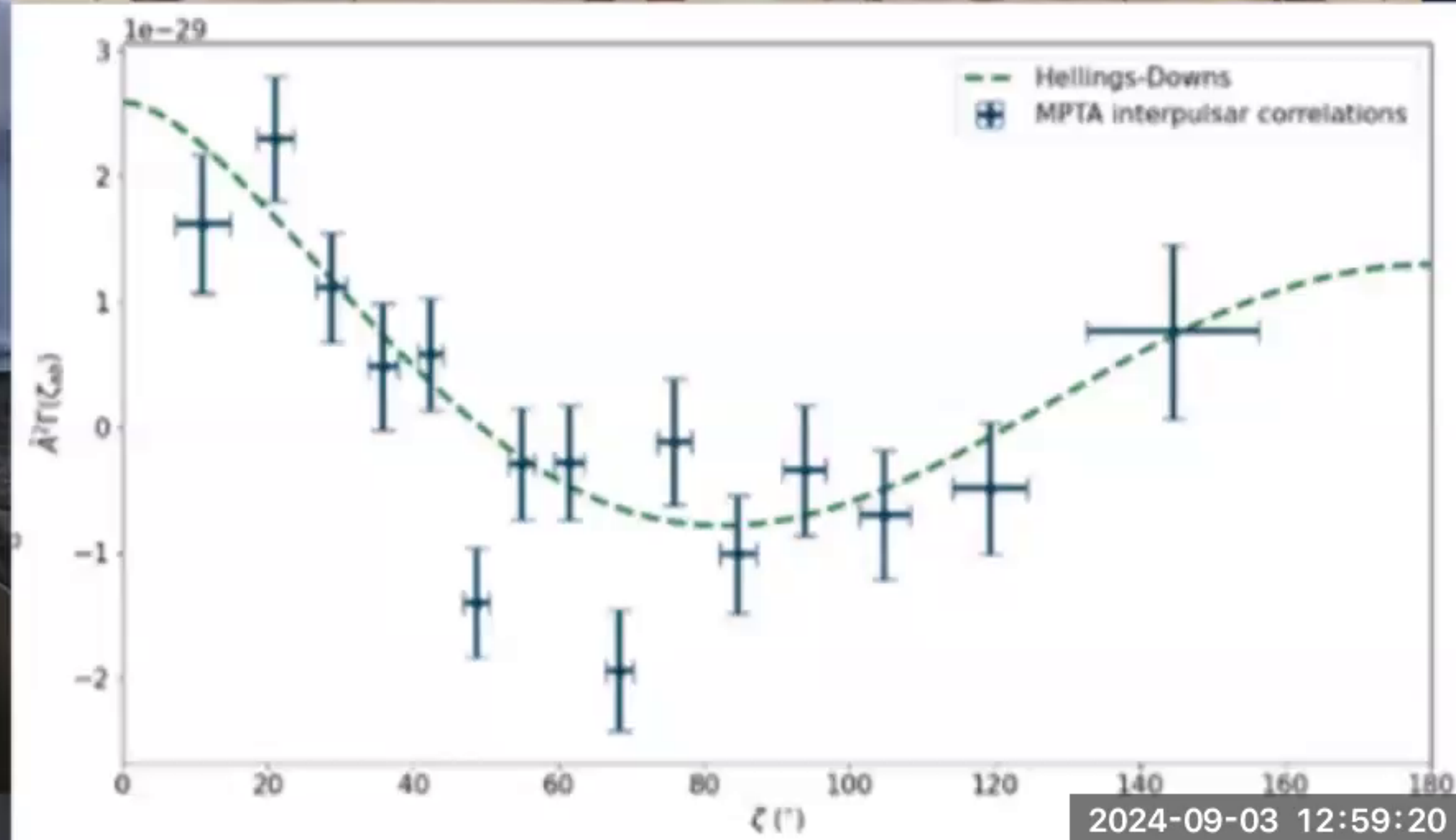


NANOGrav: Agazie et al. (2023)

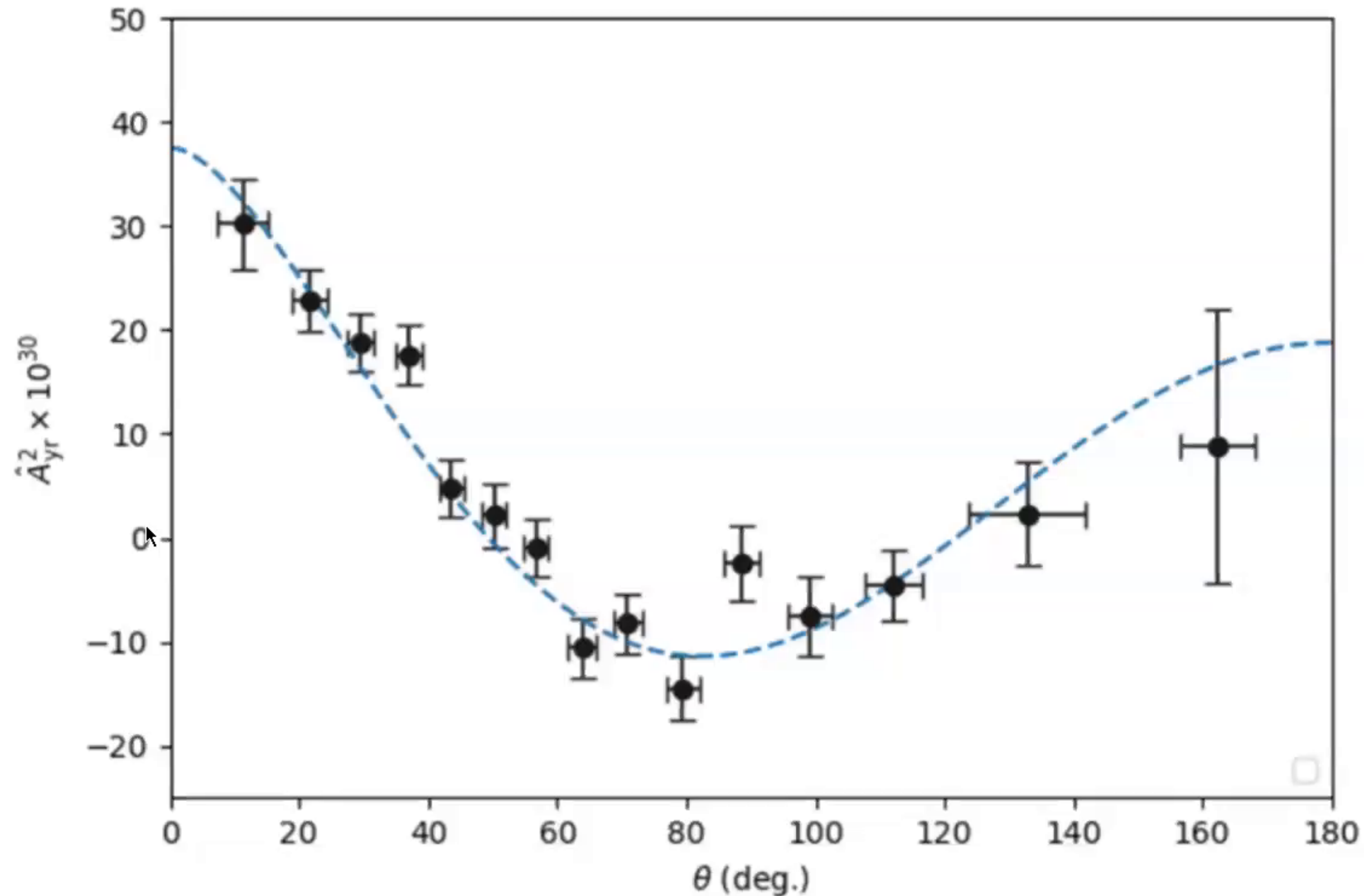
PPTA: Reardon et al. (2023)

OzGrav

Success!

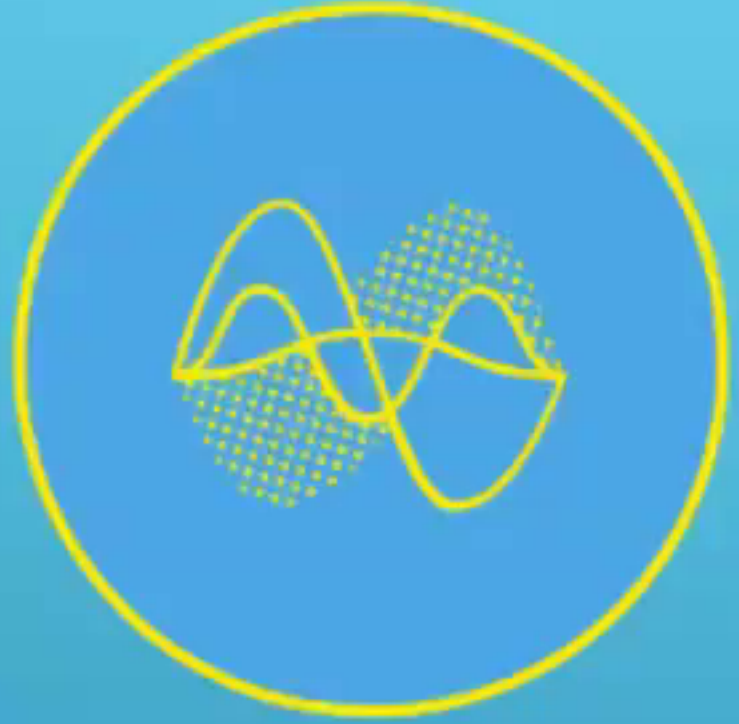


Spatial correlations: MeerKAT



- Strong detection of crosscorrelated power
- Consistent with Hellings-Downs correlations
- Assessment of statistical significance ongoing
- Results sensitive to noise models assumed for pulsars

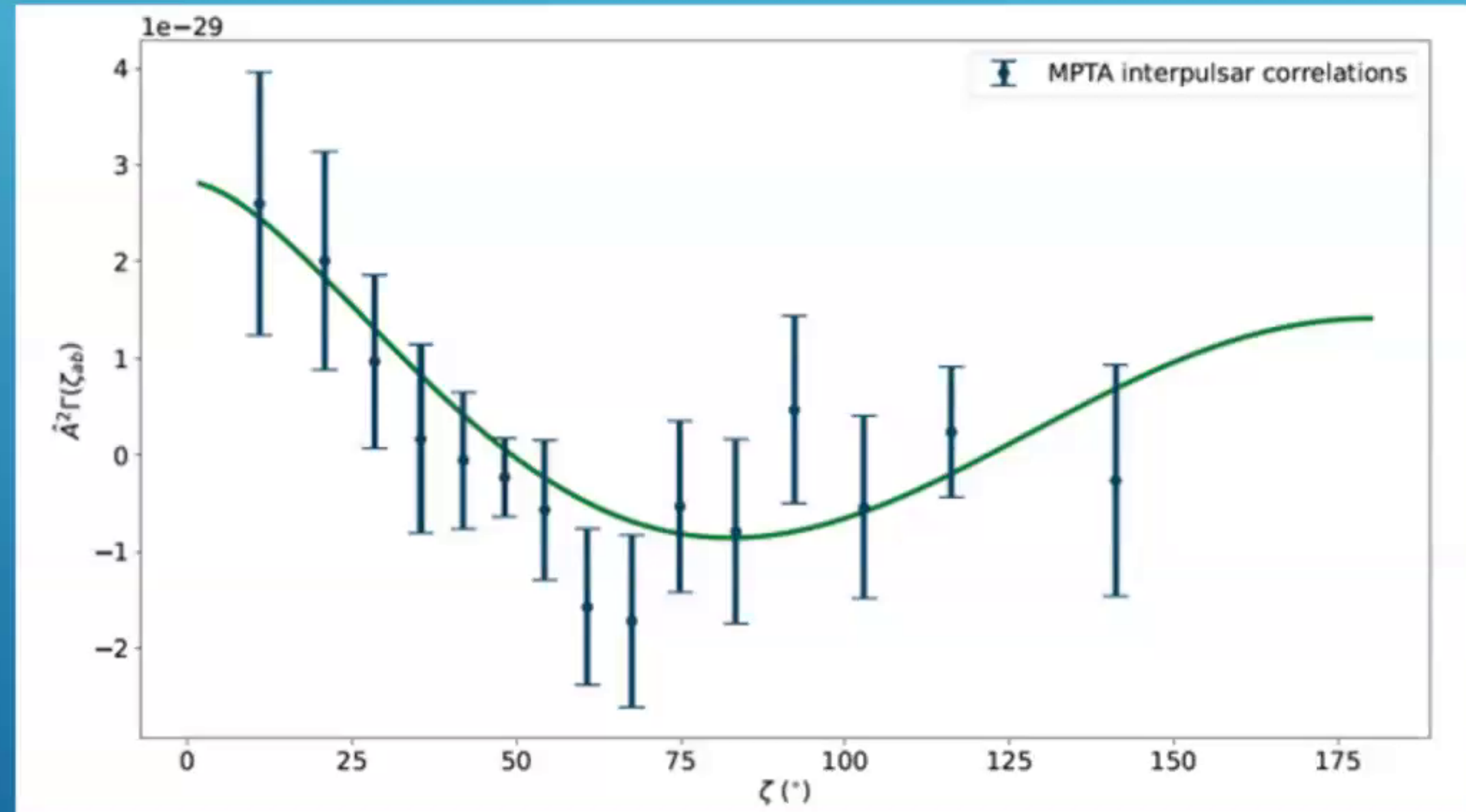


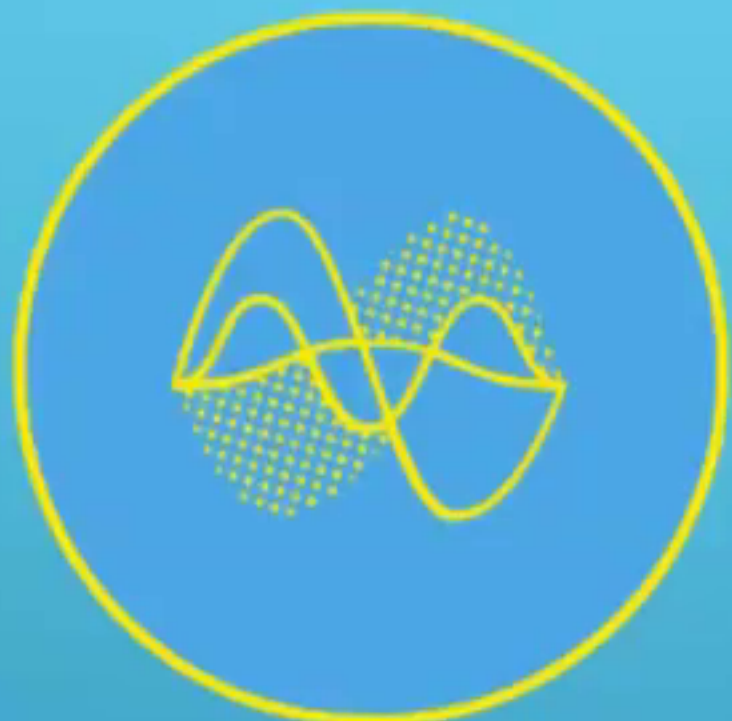


MPTA GW SEARCH

Searches for a correlated signal (DATA model)

- Using MAP values from a Bayesian ensemble run of the data-informed models
 - (The DATA model from paper)
- These correlations are significant at $\sim 3.4\sigma$
- The signal is marginally louder than found in other PTA experiments

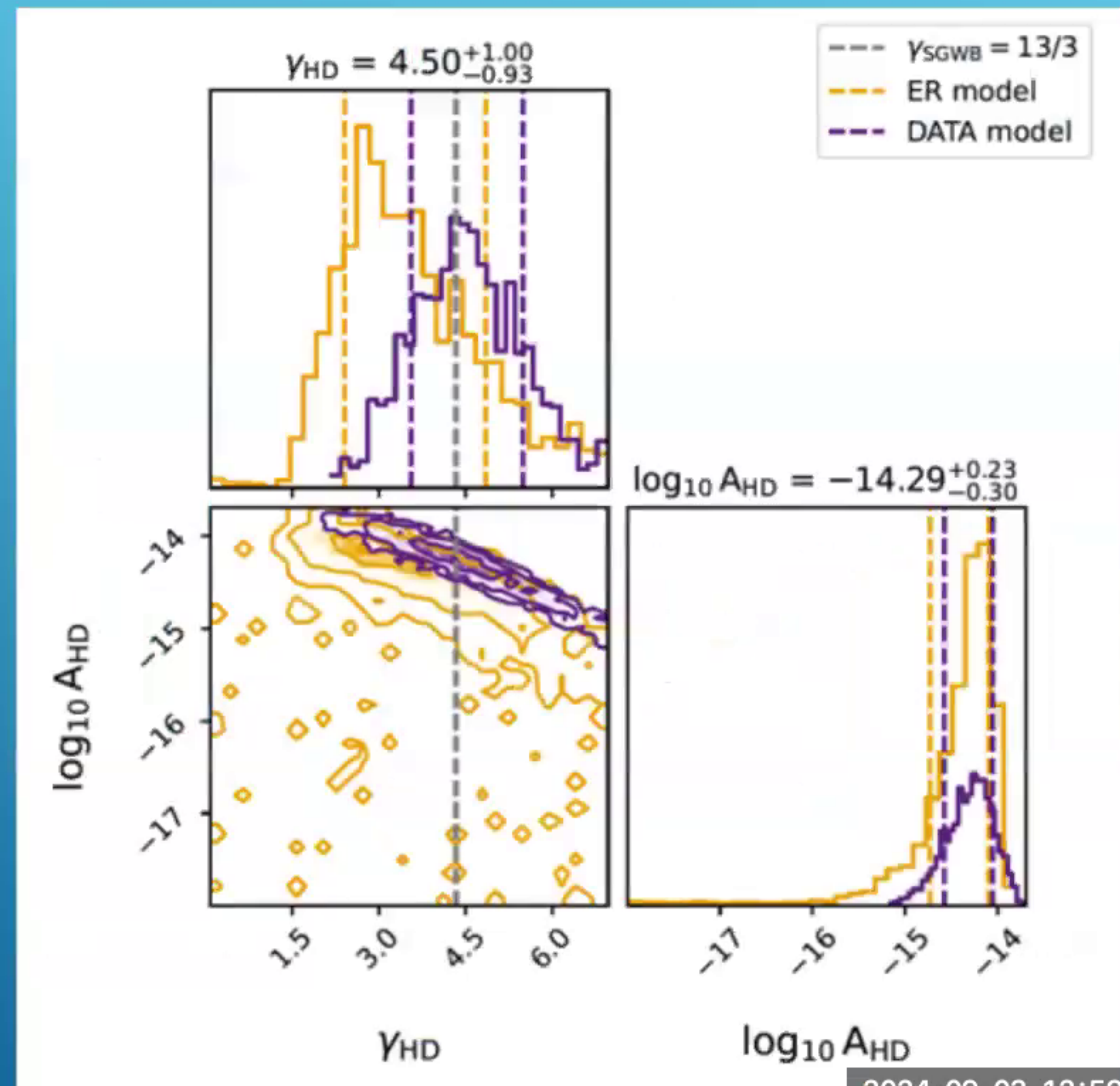


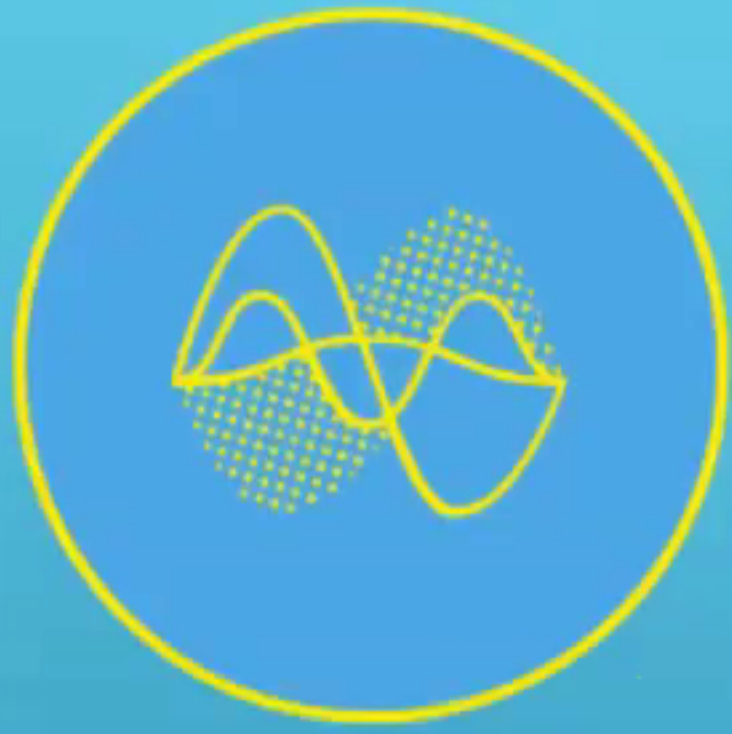


MPTA GW SEARCH

Searches for a correlated signal

- Our Bayesian searches for a common signal possessing HD correlations converge to comparable amplitudes
- This was performed both with the DATA model and the conservative ER model
- The spectral index constraint of the DATA model peaks very near to 13/3

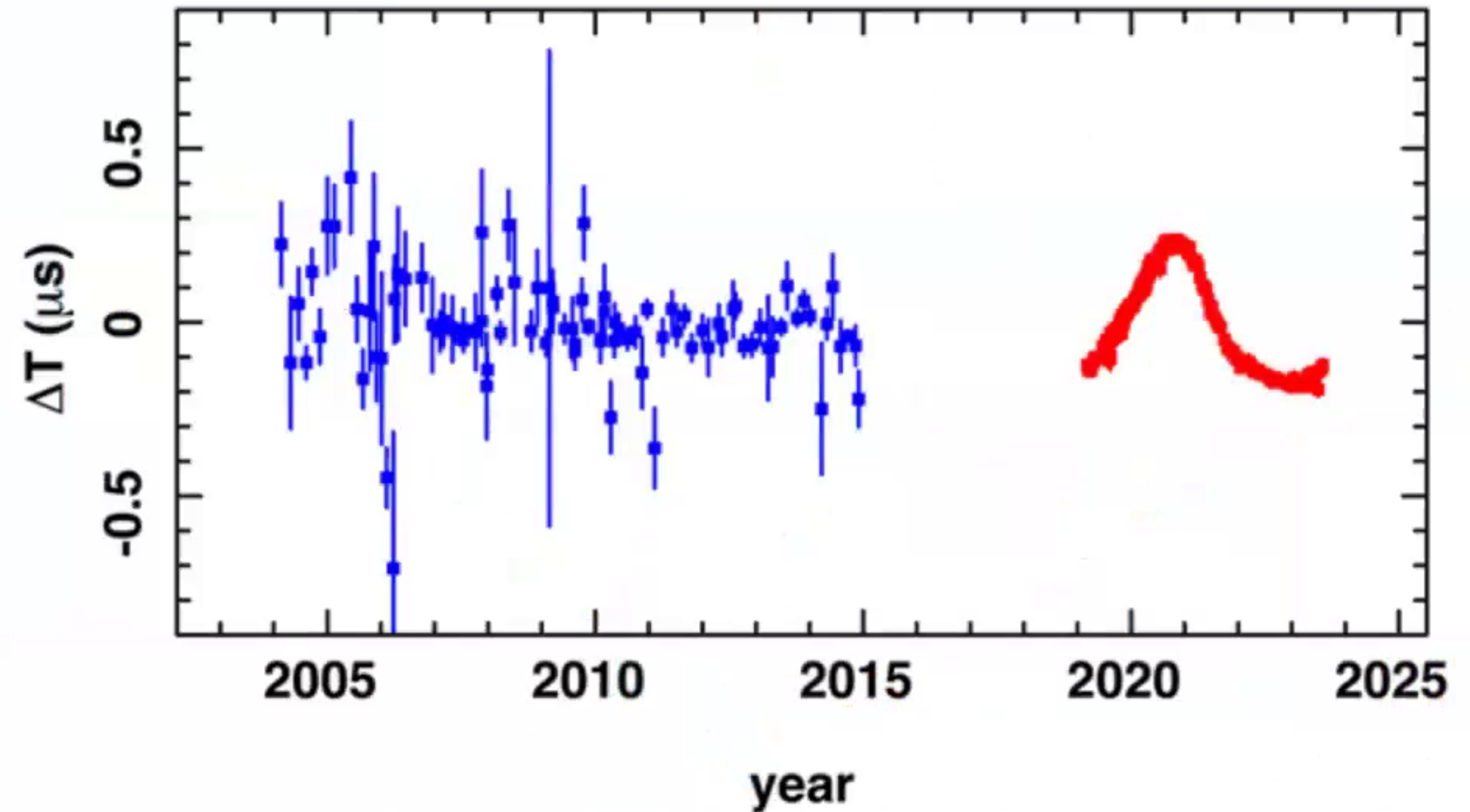




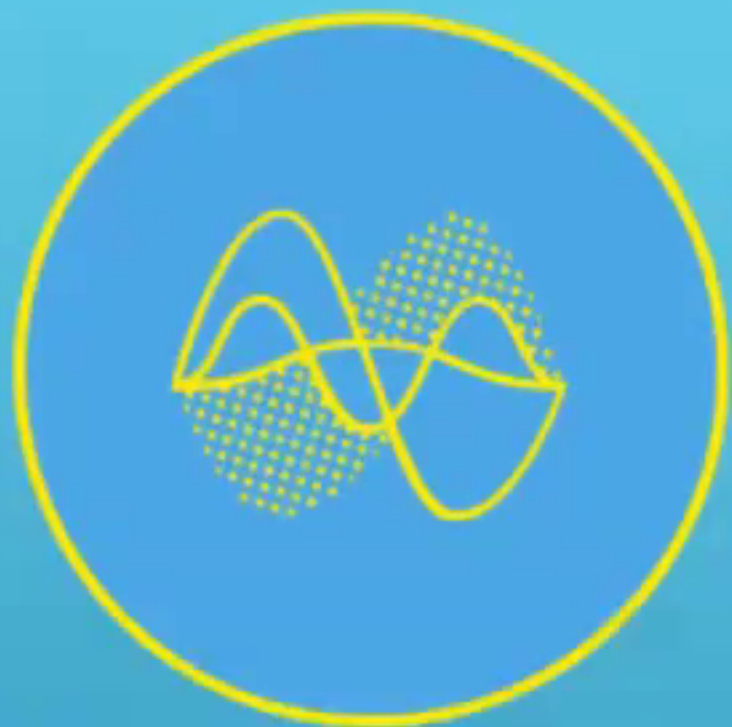
BONUS SLIDES

Red noise comparison between the PPTA and the MPTA

- The red noise in PSR J1909-3744
 - PPTA (blue) vs MPTA (red)
- Disclaimer:
This data hasn't been combined, just plotted together



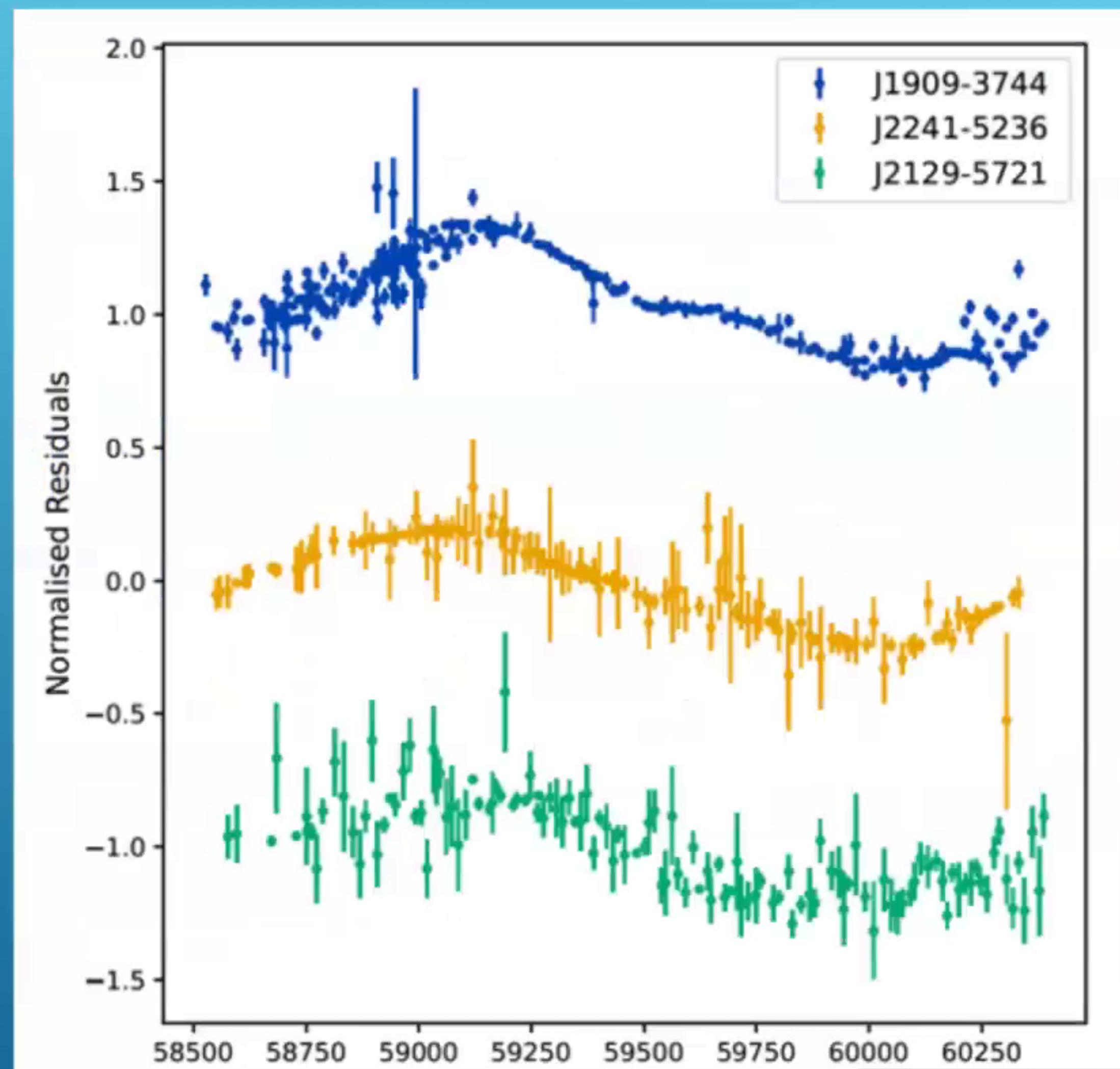
Credit: Ryan Shannon



BONUS SLIDES

PSR J2129-5721

- The pulsar that's removed for the ALT model
- It has incredibly steep red noise that hits the nominal upper prior boundary of 7
 - Extending out to past 10 when expanding the prior range
- Unlike any other noise in the MPTA
- The residuals seem to match the CURN realisations in structure
 - The delay in the J2129's residuals is louder than the others, however



HOME > SCIENCE > VOL. 383, NO. 6680 > A PULSAR IN A BINARY WITH A COMPACT OBJECT IN THE MASS GAP BETWEEN NEUTRON STARS AND BLACK HOLES

RESEARCH ARTICLE | RADIO ASTRONOMY



A pulsar in a binary with a compact object in the mass gap between neutron stars and black holes

EWAN D. BARR , ARUNIMA DUTTA , PAULO C. C. FREIRE , MARIO CADELANO , [...], AND ANDREA POSSENTI 

+20 authors

[Authors Info & Affiliations](#)

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3,762 1



CHECK ACCESS

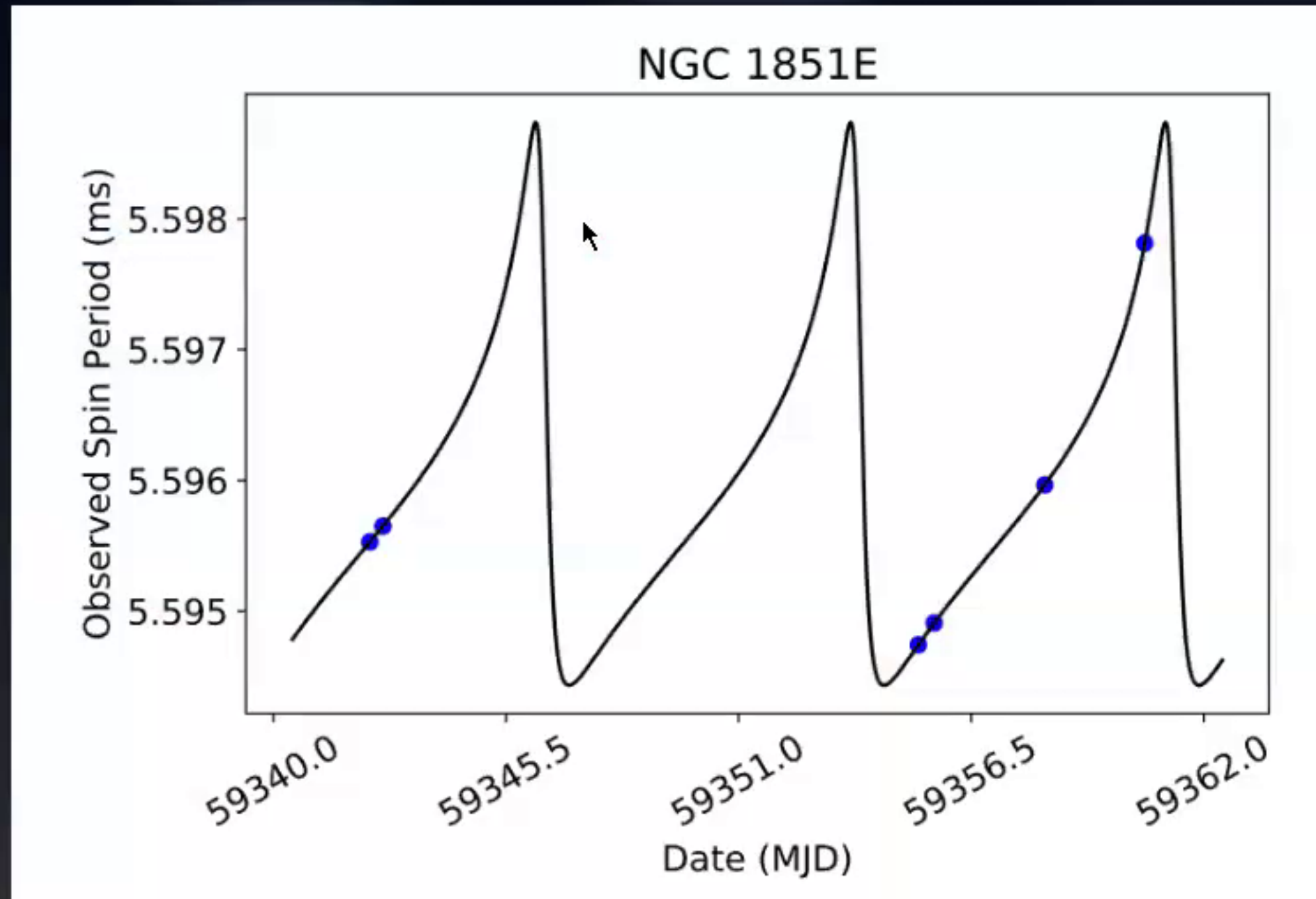
- NGC 1851 (Barr et al. 2024)
- Core Collapse Globular Cluster
- Target for the TRAPUM survey
- 8 kpc distant

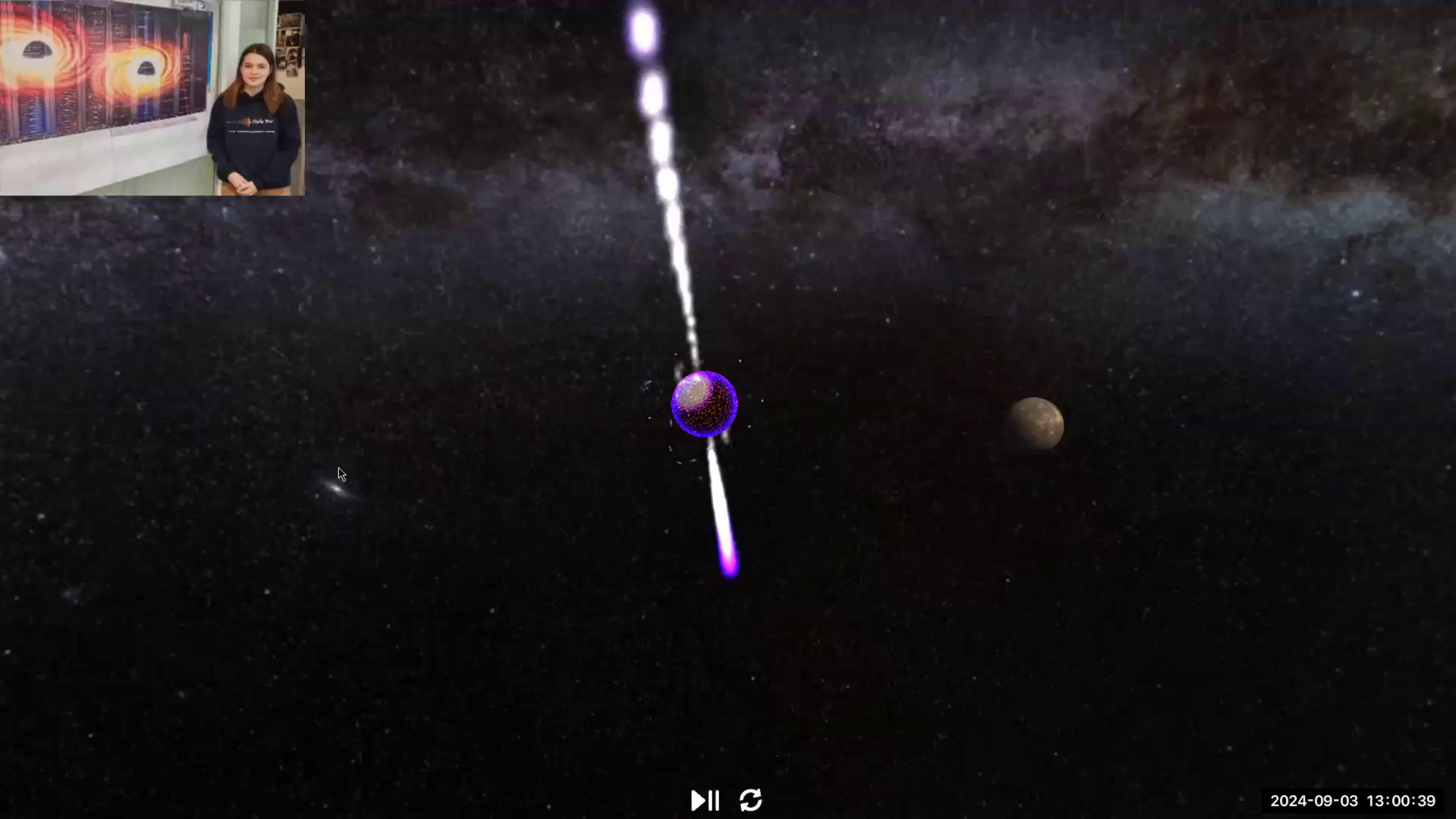
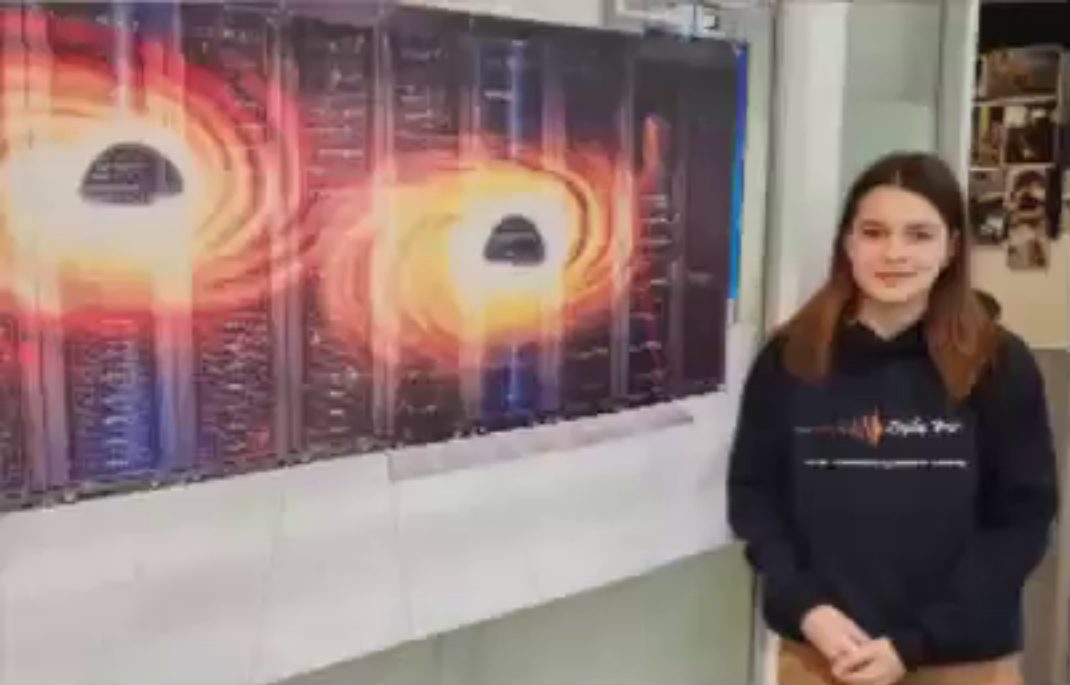


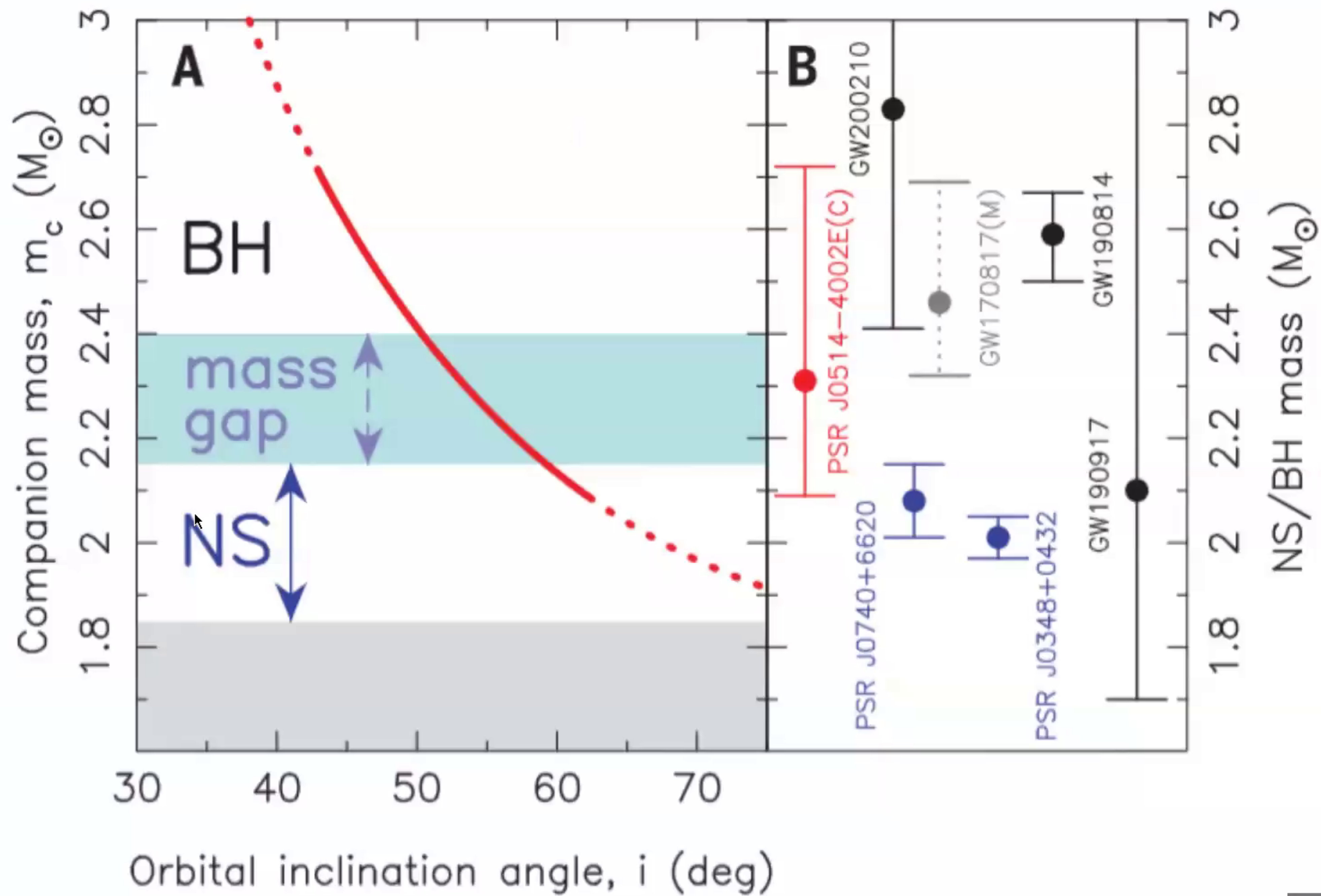
- NGC 1851
- Core Collapse Globular Cluster
- Target for the TRAPUM survey
- 8 kpc distant

TRAPUM discovery of thirteen new pulsars in NGC 1851 using MeerKAT

A. Ridolfi^{1,2*}, P. C. C. Freire^{2**}, T. Gautam², S. M. Ransom³, E. D. Barr², S. Buchner⁴, M. Burgay¹, F. Abbate², V. Venkatraman Krishnan², L. Vleeschower⁵, A. Possenti^{1,6}, B. W. Stappers⁵, M. Kramer^{2,5}, W. Chen², P. V. Padmanabh^{2,7}, D. J. Champion², M. Bailes^{8,9}, L. Levin⁵, E. F. Keane¹⁰, R. P. Breton⁵, M. Bezuidenhout⁵, J.-M. Grießmeier^{11,12}, L. Küinkel¹³, Y. Men², F. Camilo⁴, M. Geyer⁴, B. V. Hugo^{4,14}, A. Jameson^{8,9}, A. Parthasarathy², and M. Serylak^{15,16}







Conclusions

Instrumentation has enabled a spectacular growth in relativistic astrophysics enabled by pulsars.

Thanks to:

- The “Szek”
- Daniel Reardon
- Matt Miles & Ryan Shannon
- Parkes Collaborators
- MeerTime Collaborators

