

WEST VIRGINIA UNIVERSITY

Center for Gravitational Waves and Cosmology Symposium 2026

📅 Wednesday, June 3, 2026 | Morgantown, WV

Full Program Timetable

Time	Morning Sessions (I & II)	Time	Afternoon Sessions (I & II)
09:00 - 09:15	☕ Welcome Coffee & Check-in	12:00 - 13:00	🍽️ Lunch Break (Provided on-site)
09:15 - 09:30	Shawaiz Tabassum	13:00 - 13:15	Duncan Lorimer
09:30 - 09:45	Tim Olszanski	13:15 - 13:30	Vladimir Strokov
09:45 - 10:00	Sean McWilliams	13:30 - 13:45	Maura McLaughlin
10:00 - 10:15	Sid Mahesh	13:45 - 14:00	Emmanuel Fonseca
10:15 - 10:30	Jackson Taylor	14:00 - 14:30	☕ Afternoon Coffee Break
10:30 - 10:40	📷 Symposium Group Photo Session	14:30 - 14:45	Graham Daskoch
10:40 - 11:00	☕ Morning Coffee Break	14:45 - 15:00	Randy Loberger
11:00 - 11:15	Yechan Kweon	15:00 - 15:15	Ross Jennings
11:15 - 11:30	Tyler Thomas	15:15 - 15:30	Anuj Kankani
11:30 - 11:45	Maria C. Babiuc Hamilton	15:30 - 15:40	👏 Closing Remarks & Discussion
11:45 - 12:00	Suchindram Dasgupta	---	---

Morning I | 09:15 AM - 09:30 AM

Shawaiz Tabassum

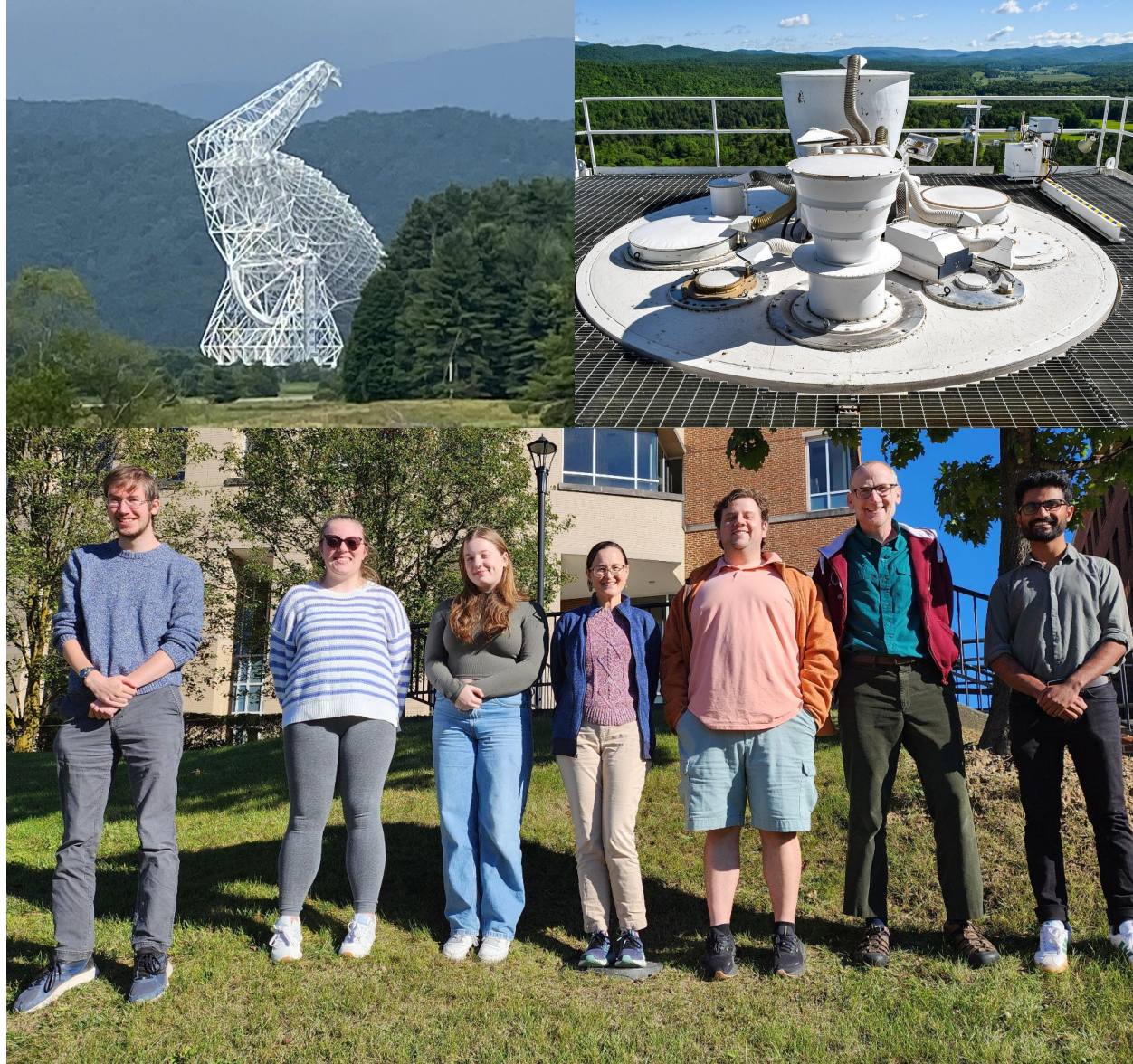
*"GREENBURST View of Millisecond Pulsar Single
Pulse Emission"*

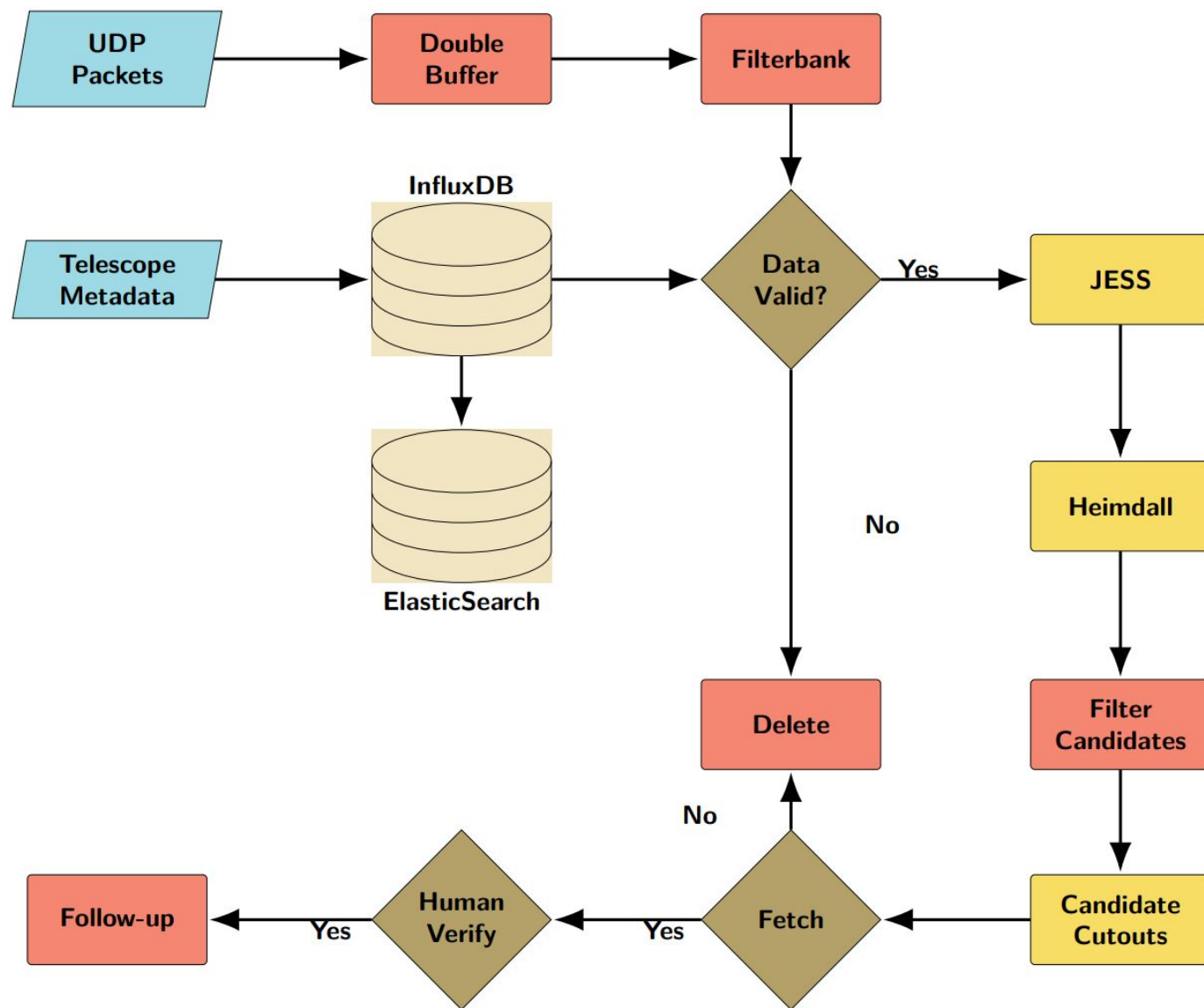
Outline

- Introduction to GREENBURST
- Millisecond Pulsars
- Single Pulse Emission & Giant Pulses
- GREENBURST View
- Perspective from the View

GREENBURST

greenburstwvu.github.io





GREENBURST

Science Goals:

1. Search for Fast Radio Bursts (FRBs)
2. Study repeating FRBs
3. Discover and measure the distributions of pulsar single pulse emission
4. Search for and constrain the populations of ultra-long period sources

GREENBURST

Science Goals:

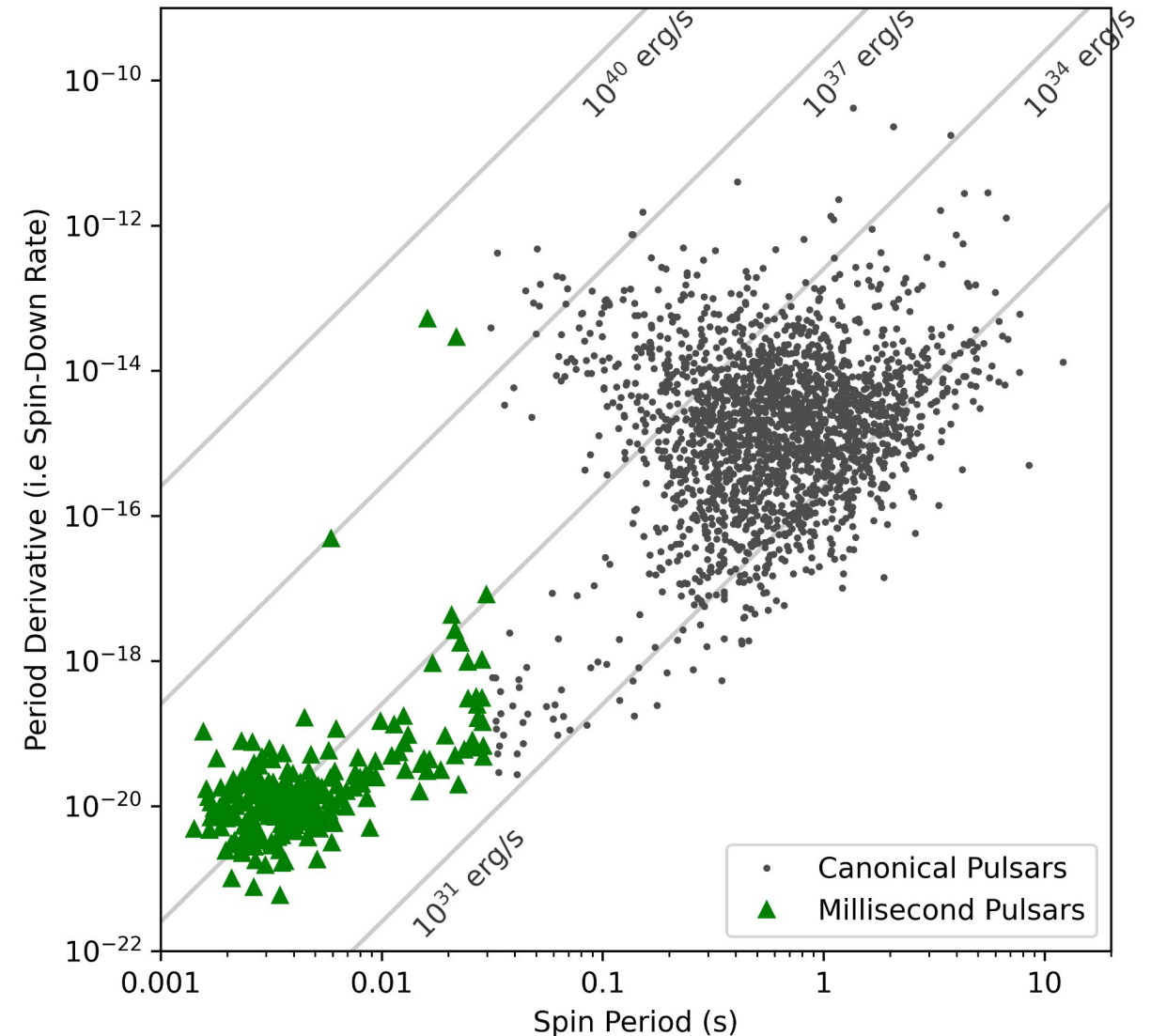
1. Search for Fast Radio Bursts (FRBs)
2. Study repeating FRBs

3. Discover and measure the distributions of ~~pulsar~~ millisecond pulsar single pulse emission

4. Search for and constrain the populations of ultra-long period sources

Millisecond Pulsars (MSPs)

- Neutron stars spun-up due to accretion from a companion in a binary, resulting in $P < 30$ ms.
- Highly Stable $\rightarrow$ Timing Arrays
- Massive $\rightarrow$ EoS of dense matter
- Pulsed periodic emission $\rightarrow$ How?



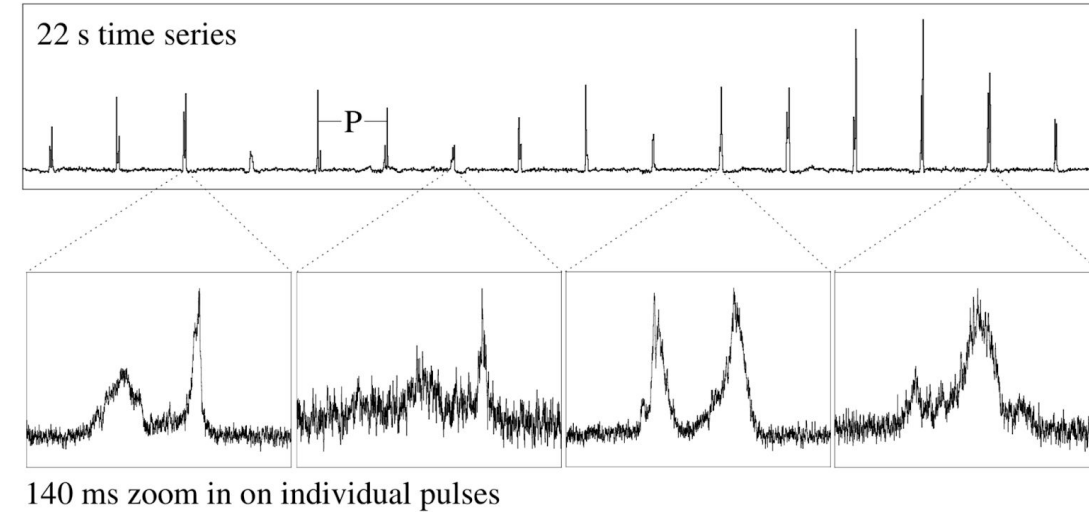
Single Pulse Emission

Observed Variability

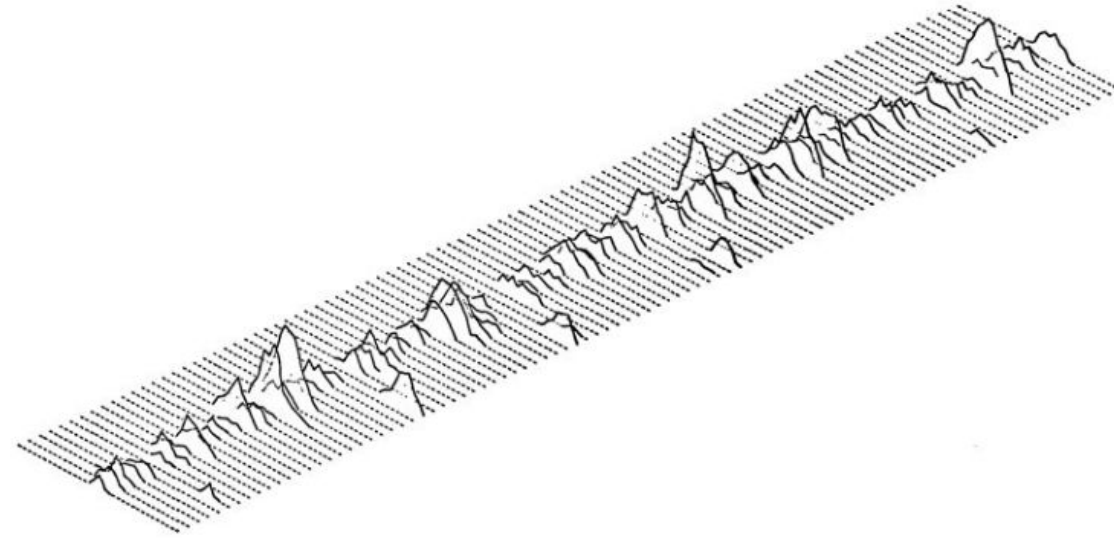
- Giant Pulses (GPs)
- Nulling
- Mode Changing
- Drifting
- Microstructure & periodicities

Importance of GPs:

- Emission physics
 - What, How and Where?
- Timing precision improvement
- Scintillometry & ISM studies
- Connection with high energy emission (X-ray, Gamma-ray)



Lorimer & Kramer (2004)

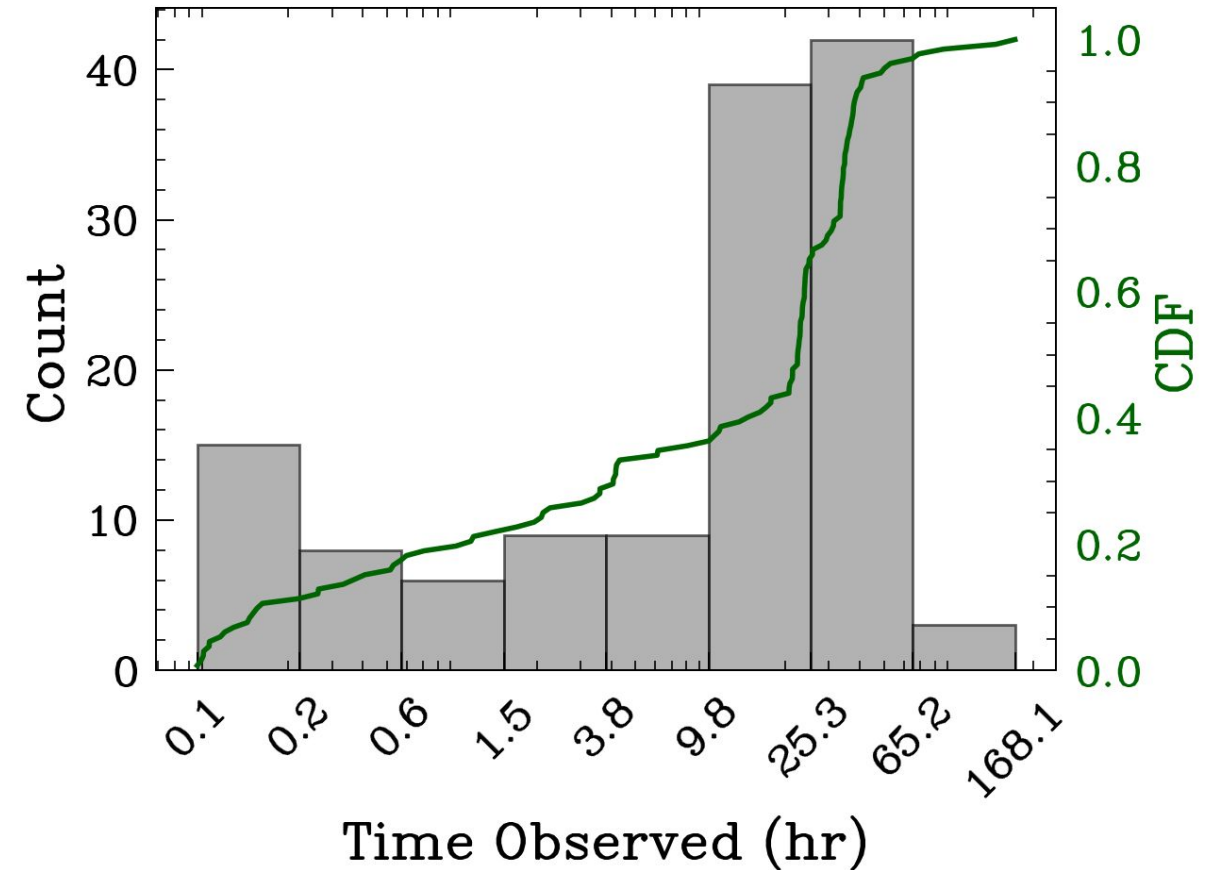


Grower & Argyle (1971)

The Current View

Single Pulses detected from 5 Galactic MSPs out of 132 Observed:

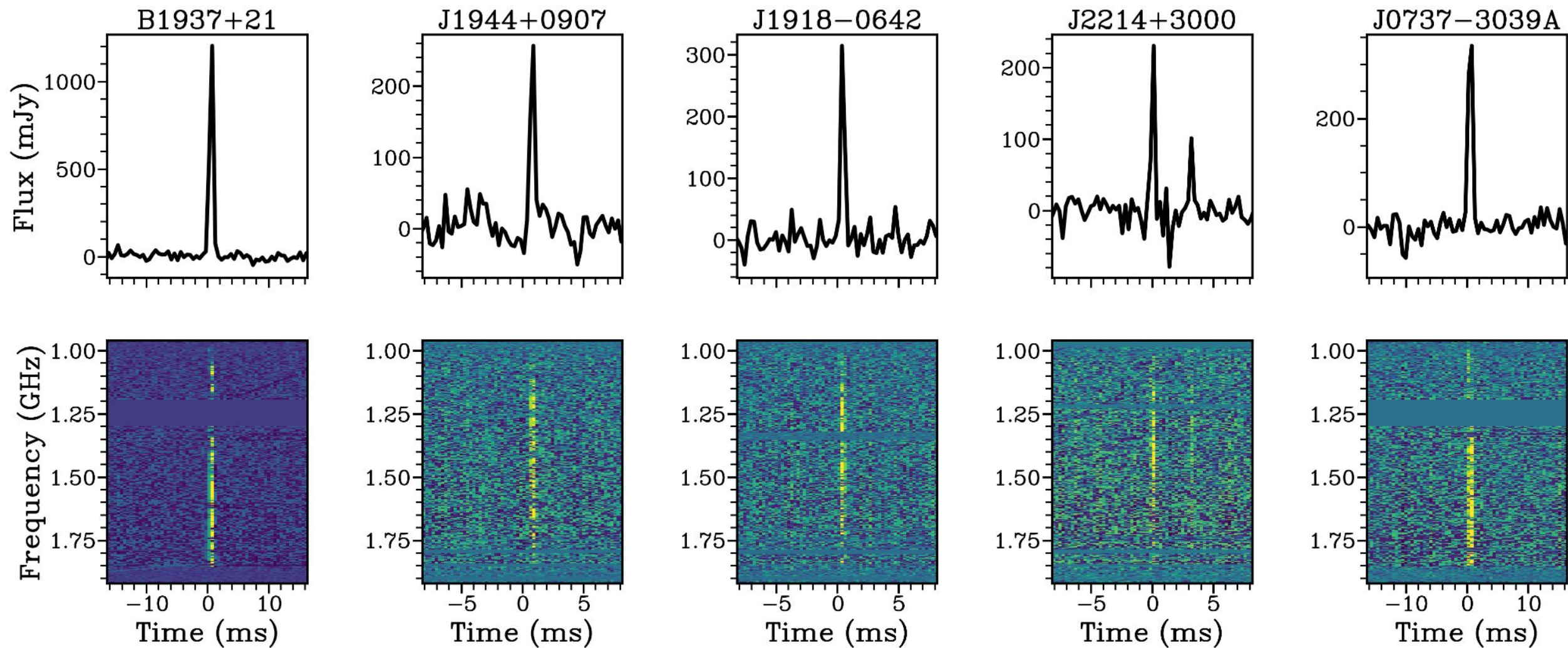
1. B1937+21
2. J1944+0907
3. J2214+3000
4. J1918-0642
5. J0737-3039A



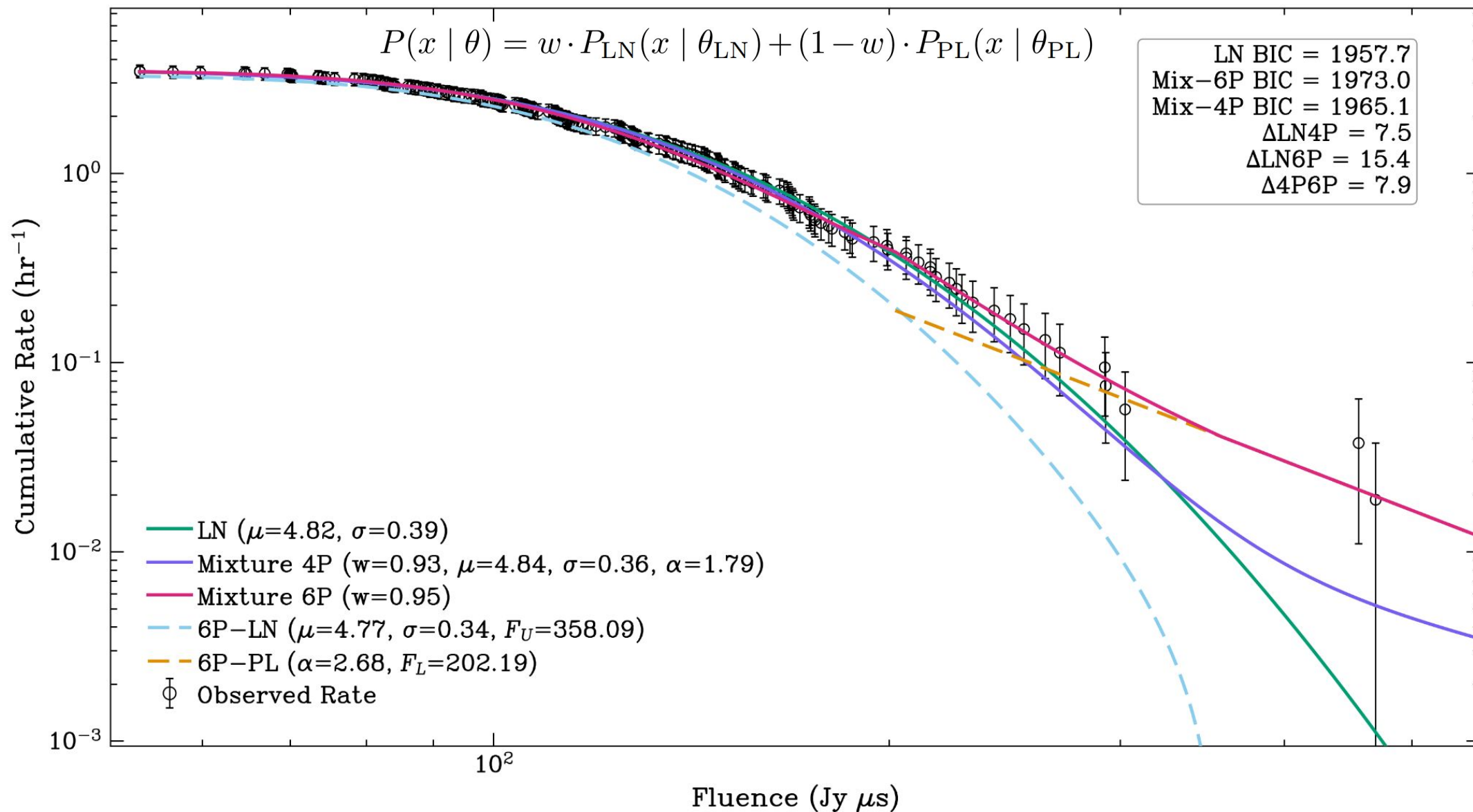
Pulse Statistics

Pulsar	Number of Pulses	Time Obs. (hr)	Pulse Rate (hr^{-1})	Flux Extremum (mJy)
B1937+21	191	53.1	3.6	(55, 1200)
J1944+0907	23	25.7	0.9	(69, 257)
J1918−0642	5	33.3	0.15	(114, 314)
J2214+3000	2	21.4	0.09	(101, 231)
J0737−3039A	16	86.9	0.18	(141, 334)

Examples of Pulses



PSR B1937+21 (P=1.56 ms)



Perspectives from the GREENBURST View

- ❖ Why do we see single pulses only from 5 MSPs out of 132 that were observed over the past 7 years?
- ❖ What makes GP emitting MSPs unique?
- ❖ Are GPs truly the result of a different physical mechanism?
- ❖ Can we separate the impact of the ISM and the local environment from intrinsic emission?

What's your perspective?

Morning I | 09:30 AM - 09:45 AM

Tim Olszanski

"On the Amplitude Modulation in PSR B0540+23"

ON THE AMPLITUDE
MODULATION OF PSR B0540+23

GWAC SYMPOSIUM 6/3/2026

MAIN TAKEAWAYS

1. PSR B0540+23 has an unusual amplitude modulation
2. The nature of this modulation hides a 5 component profile
3. PSR B0540+23 appears to have two position angle tracks, suggesting emission is produced at two distinct heights.
4. Conclusion and Future Work

WHY DO WE CARE
ABOUT
COMPONENT
STRUCTURE?

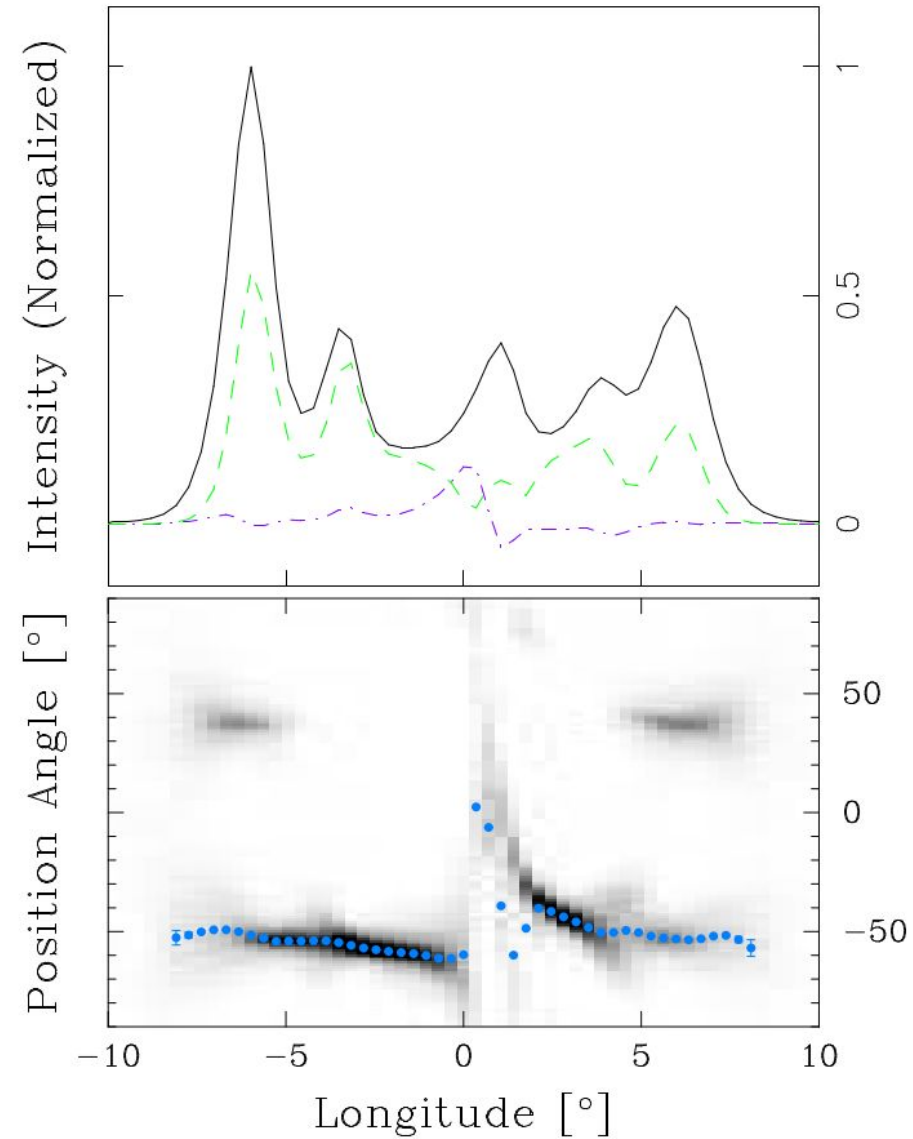
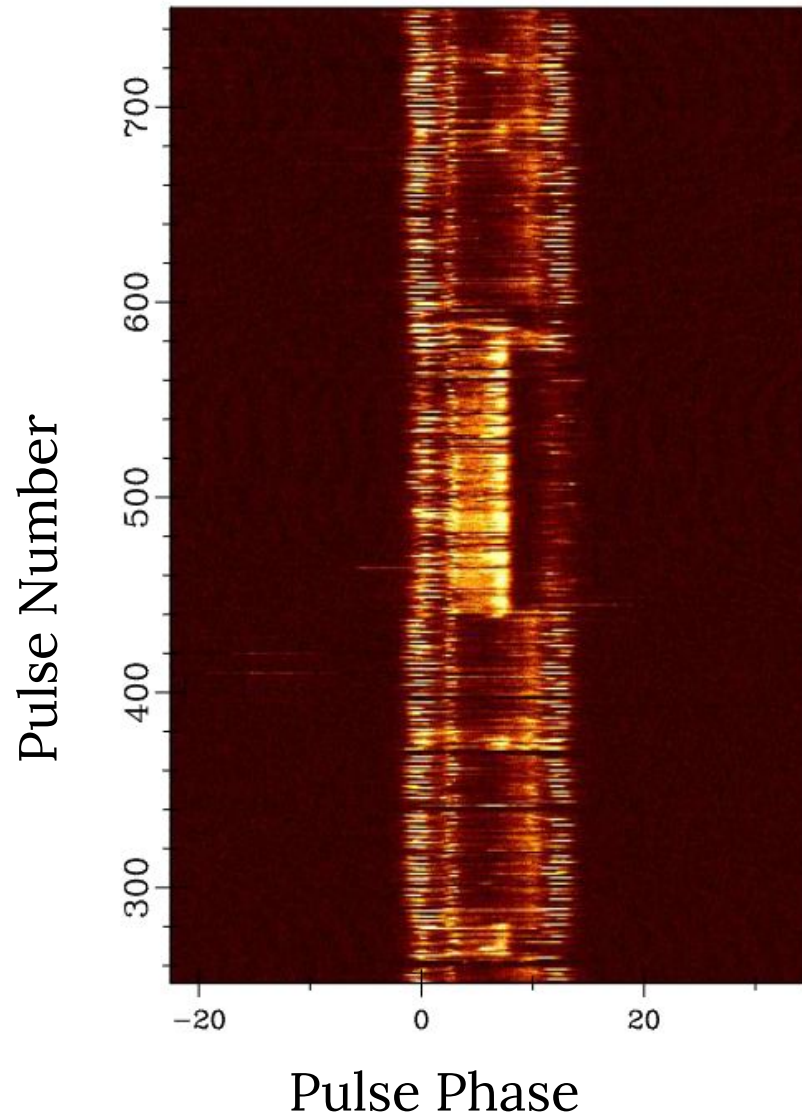
WHY DO WE CARE ABOUT COMPONENT STRUCTURE?

WHAT IS EVEN COMPONENT STRUCTURE?

SINGLE-PULSES AND PROFILES

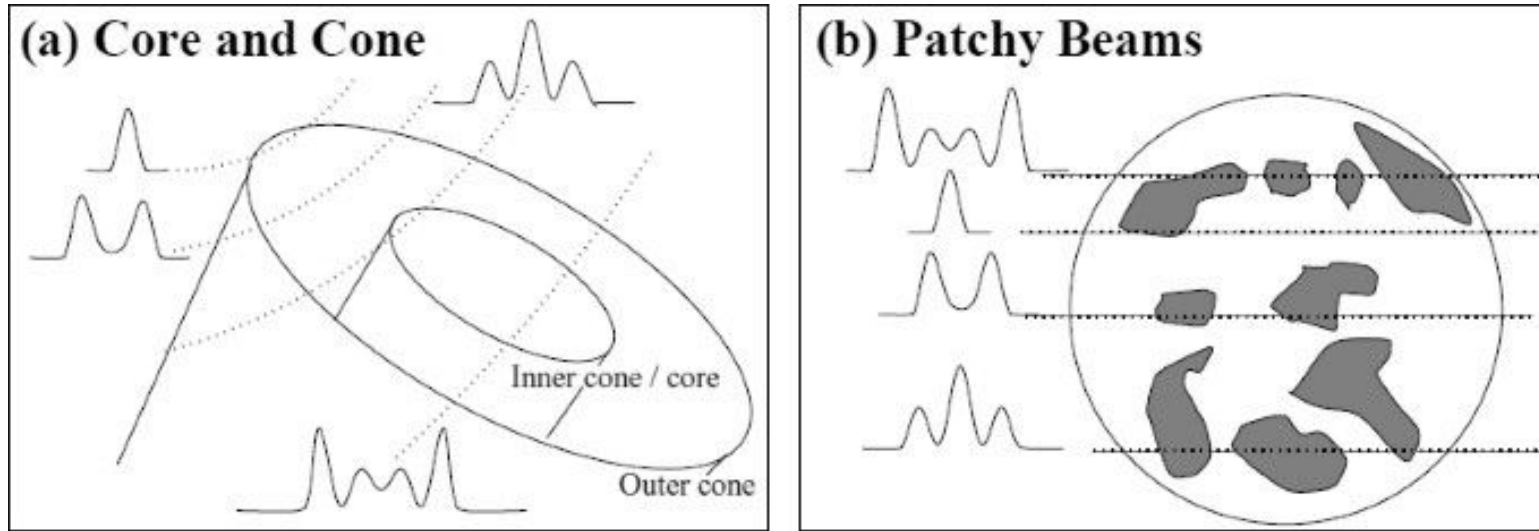
PSR B1237+25 | MJD 53378 | ν : 327. MHz

PSR B1237+25

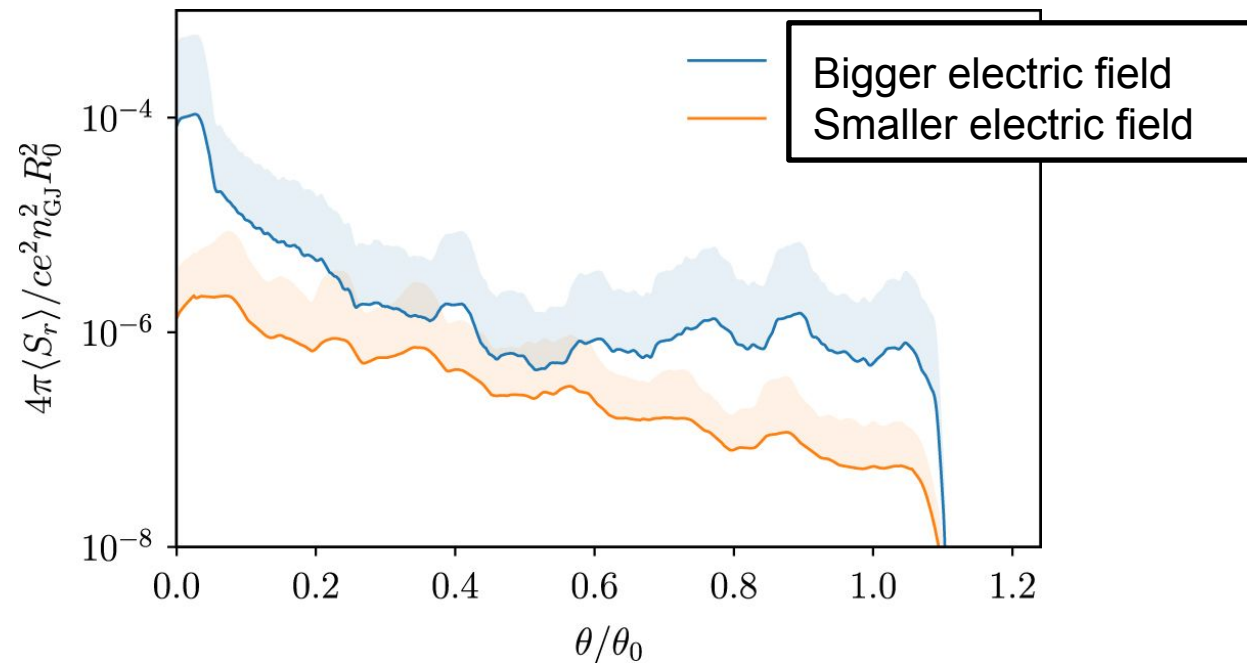


Polar cap emission in canonical (slow) pulsars show at most 5 components – S-shaped tracks relate to viewing geometry

CORE-CONE STRUCTURE



Model A is consistent with pulsar cap emission in canonical (slow) pulsars



PIC Simulations show hints of core-cone emission structure! (Cruz et al 2023, ApJ, Coherent Emission from QED Cascades in Pulsar Polar Caps)

OK, WE NOW KNOW
WHAT CORE-CONE
STRUCTURE IS.

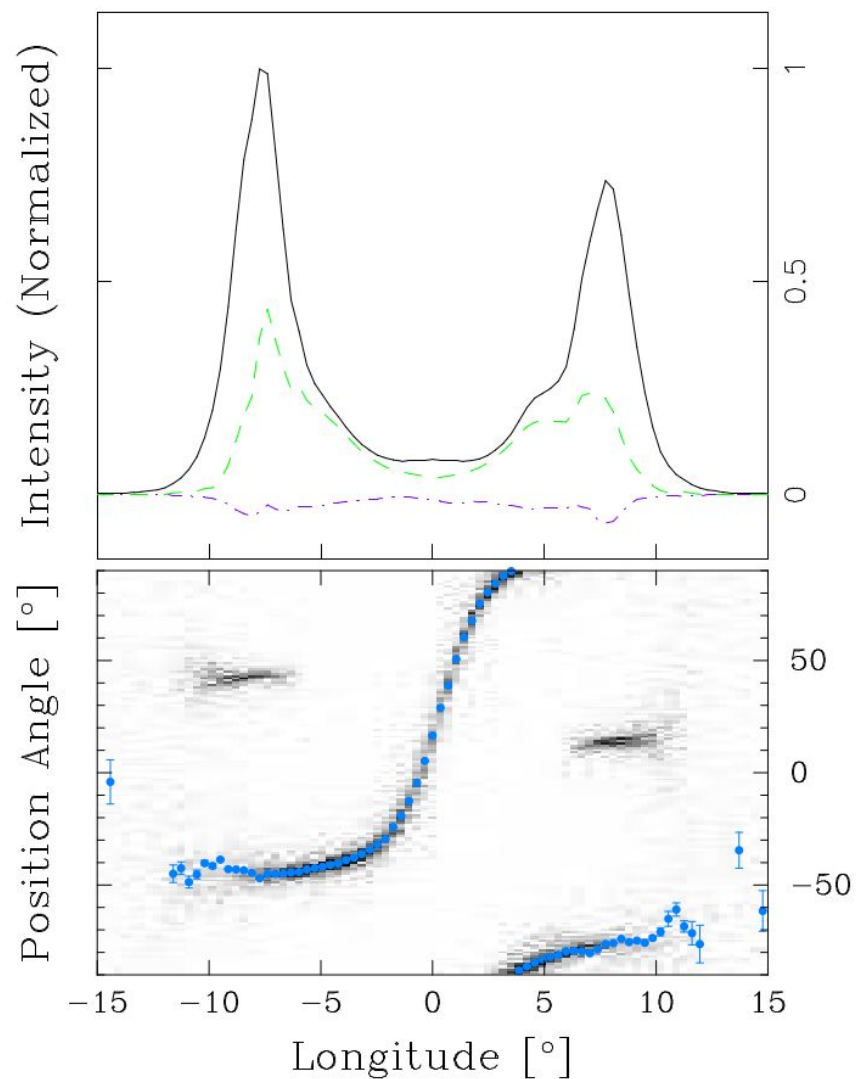
OK, WE NOW KNOW
WHAT CORE-CONE
STRUCTURE IS.

SO WHAT ARE THE
EXCEPTIONS?

ANSWER: PARTIAL CONES

WHAT IS A PARTIAL CONE?

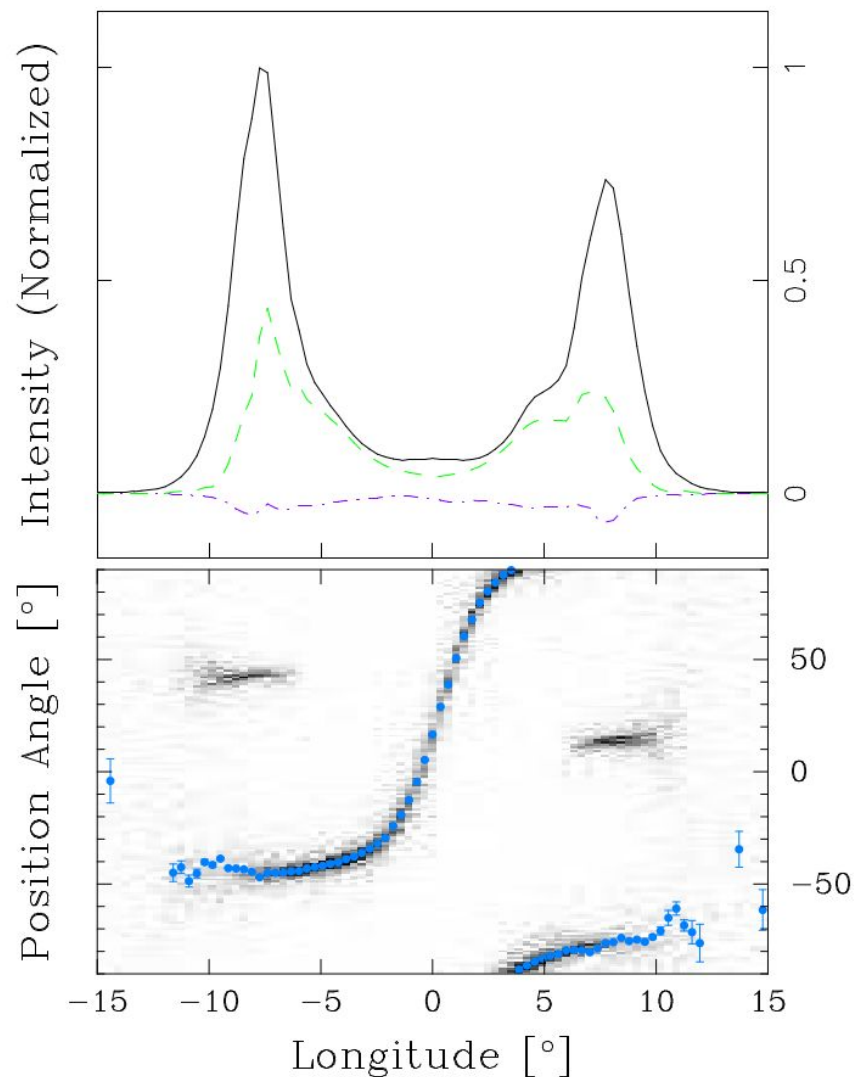
PSR B0525+21 |MJD 56164| ν : 326. MHz



Conal Double

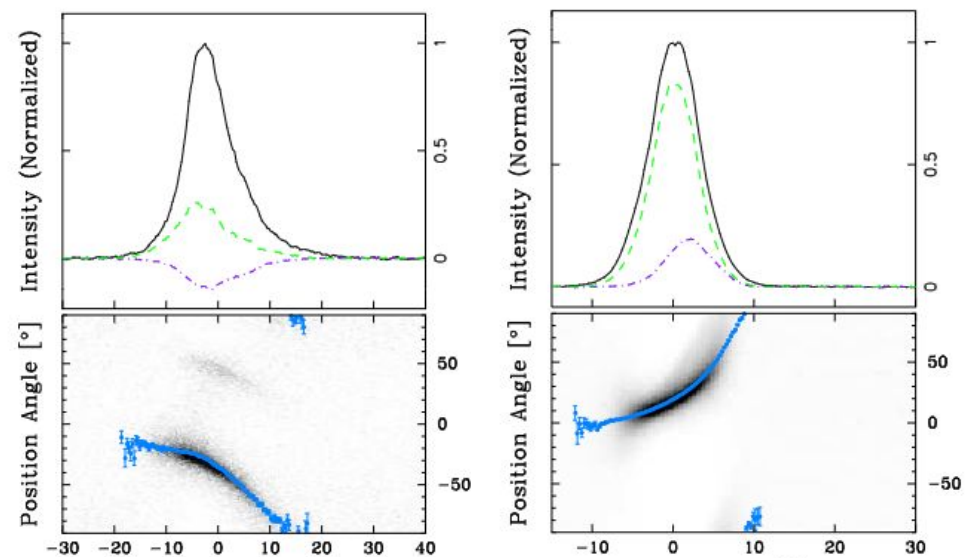
WHAT IS A PARTIAL CONE?

PSR B0525+21 | MJD 56164 | ν : 326. MHz

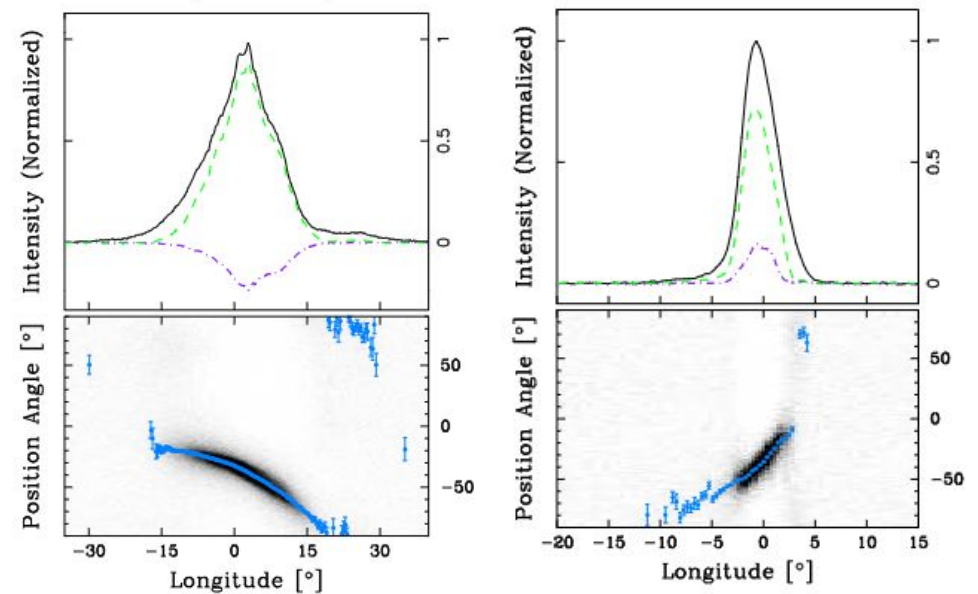


Conal Double

PSR B0540+23 | MJD 57271 | ν : 4555. MHz PSR B0611+22 | MJD 57867 | ν : 1392. MHz



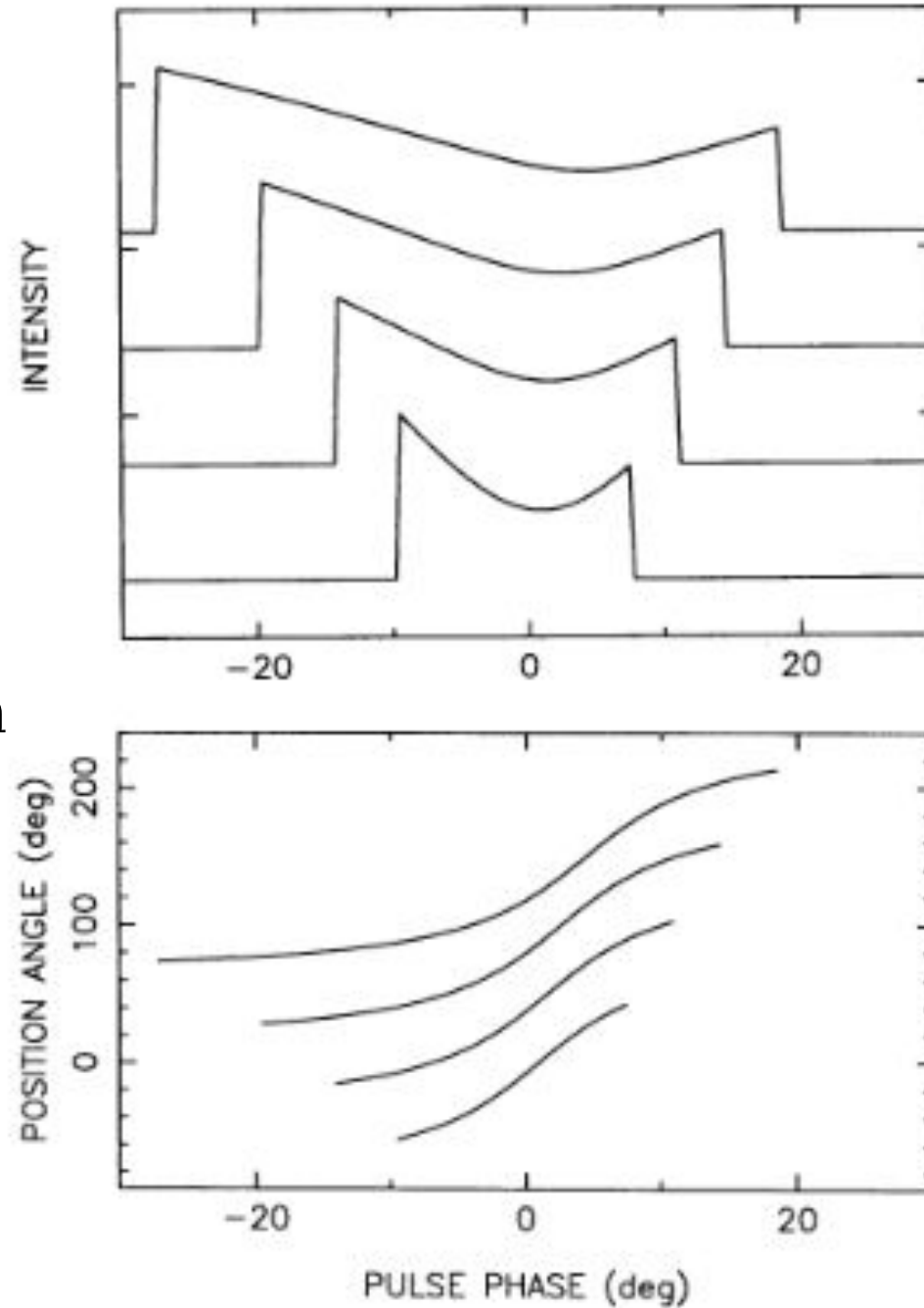
PSR B0656+14 | MJD 56423 | ν : 1492. MHz PSR B0919+06 | MJD 57292 | ν : 4555. MHz



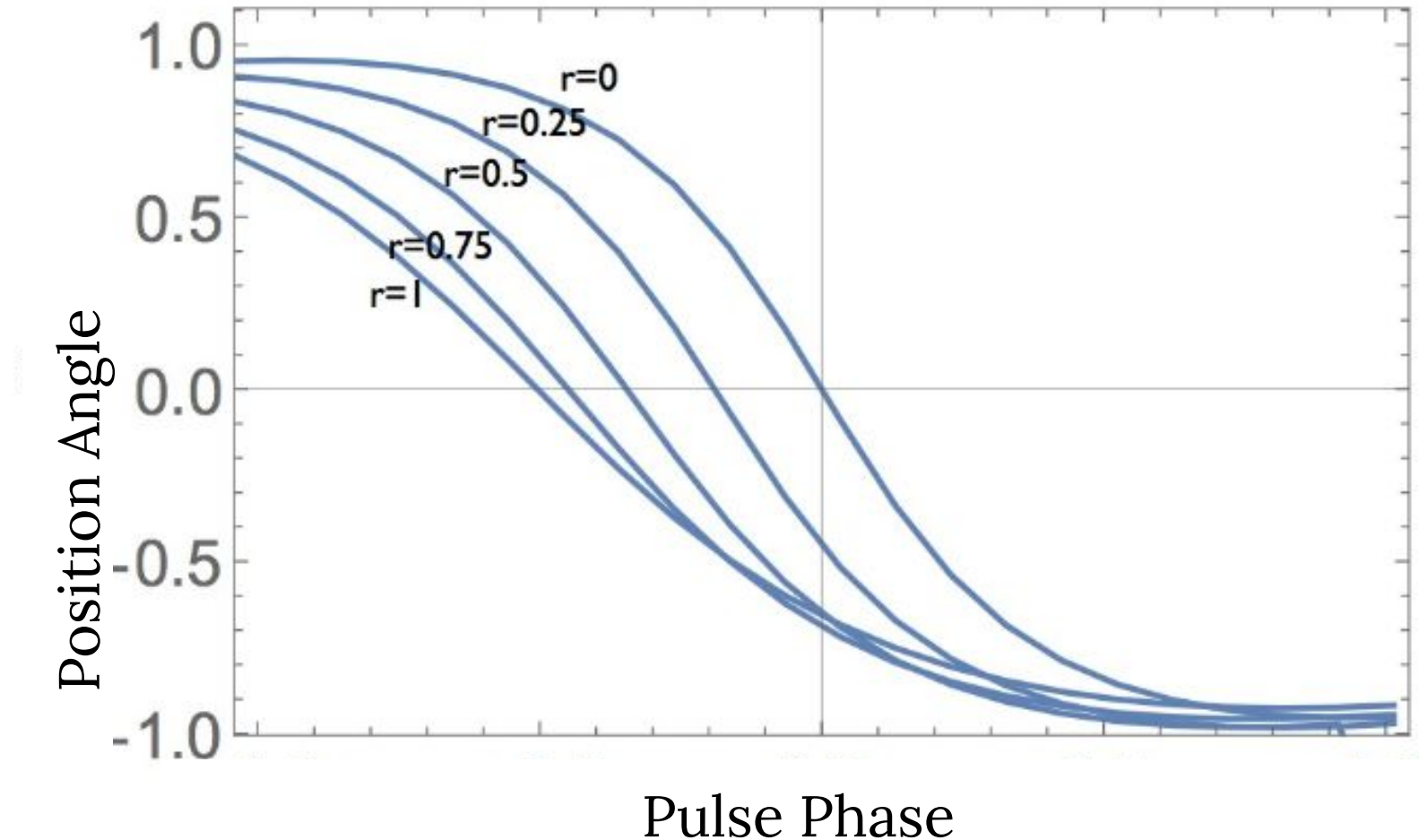
Partial cone *pastiche*

ABERRATION RETARDATION

Relativistic effects distort
Polarized position angle
(PPA) track, delay inflection
point

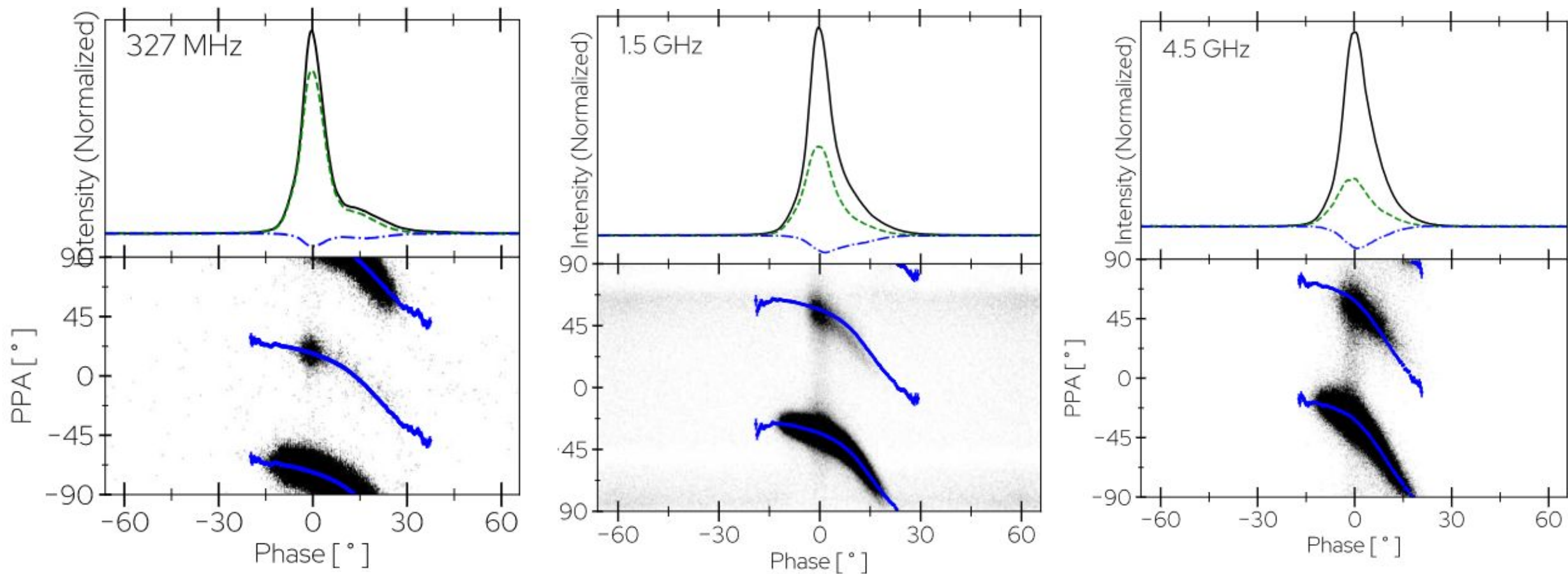


Blaskiewicz,
Cordes,
Wasserman 1991



Relativistic effects distort Polarized position angle (PPA) track, delay inflection point

B0540+23's EMISSION

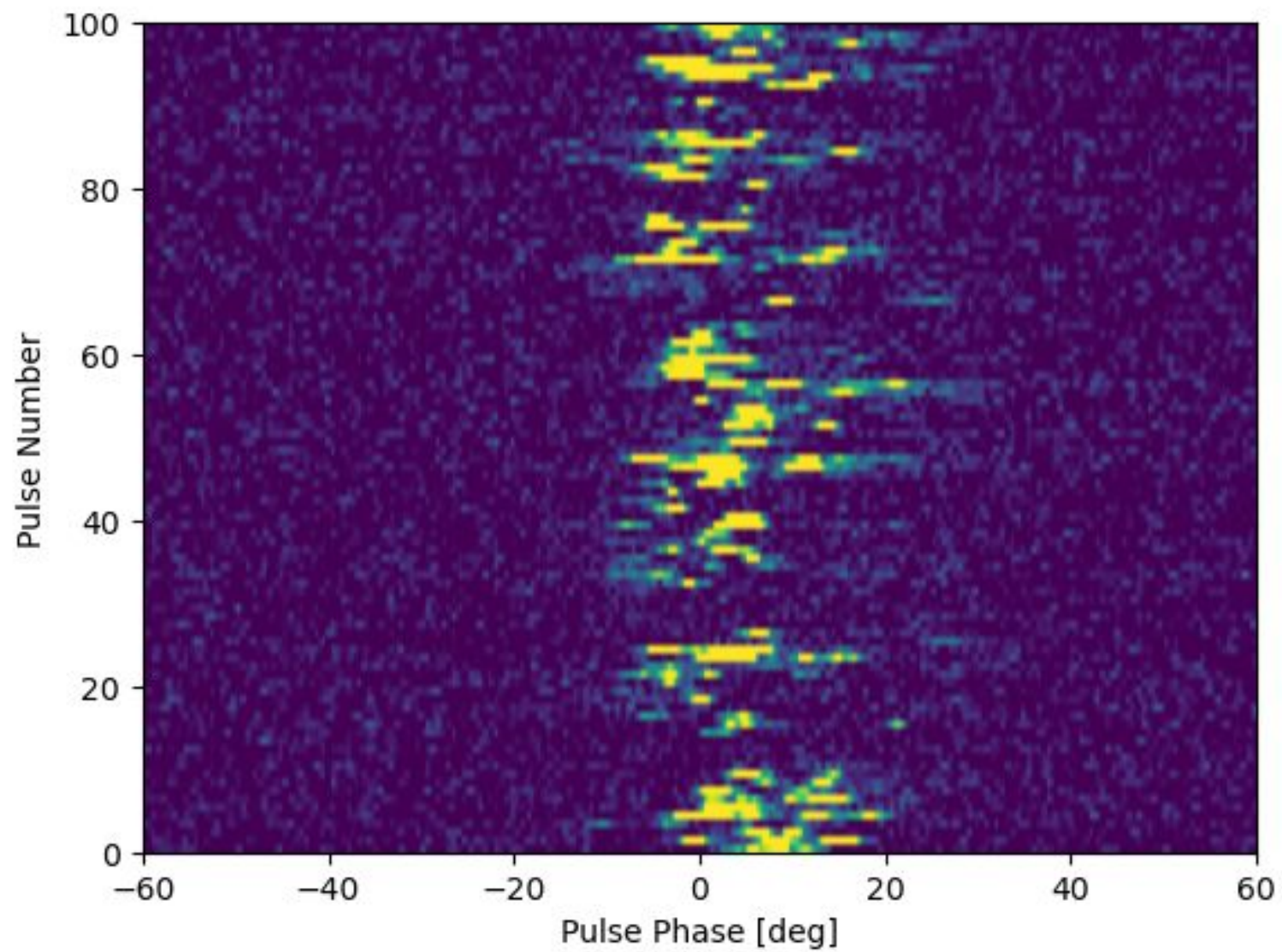


Observations of $\sim 35,000$ pulses at 327 MHz, 1.5 GHz, and 4.5 GHz
Classic partial cone!

SO, LET'S GET MORE INTO THIS
PULSAR

WHAT DOES THE PULSE SEQUENCE
LOOK LIKE?

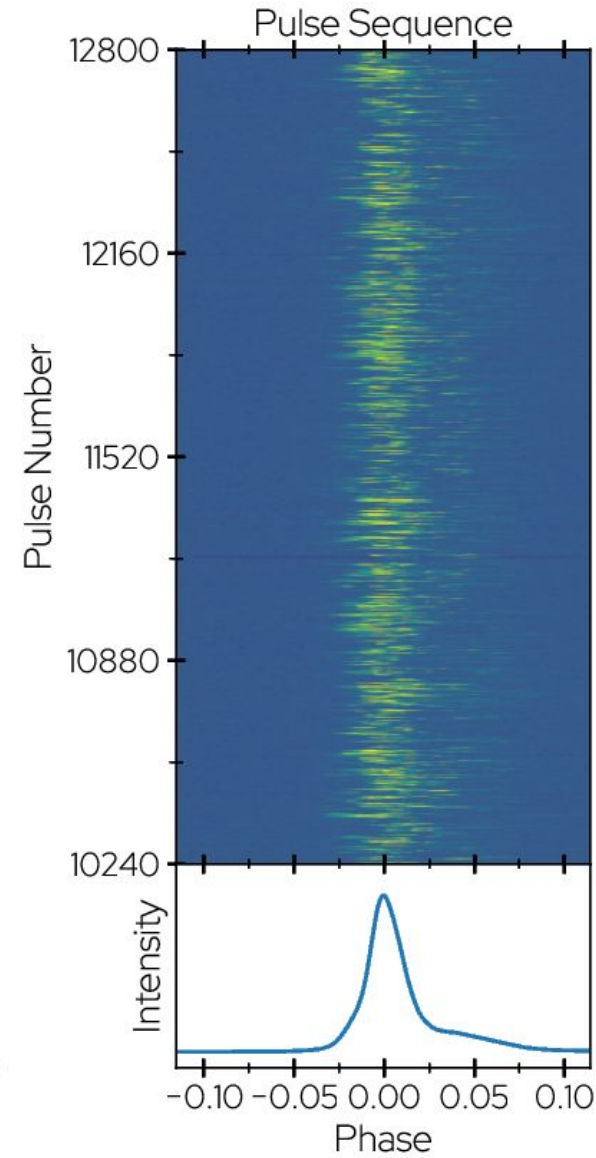
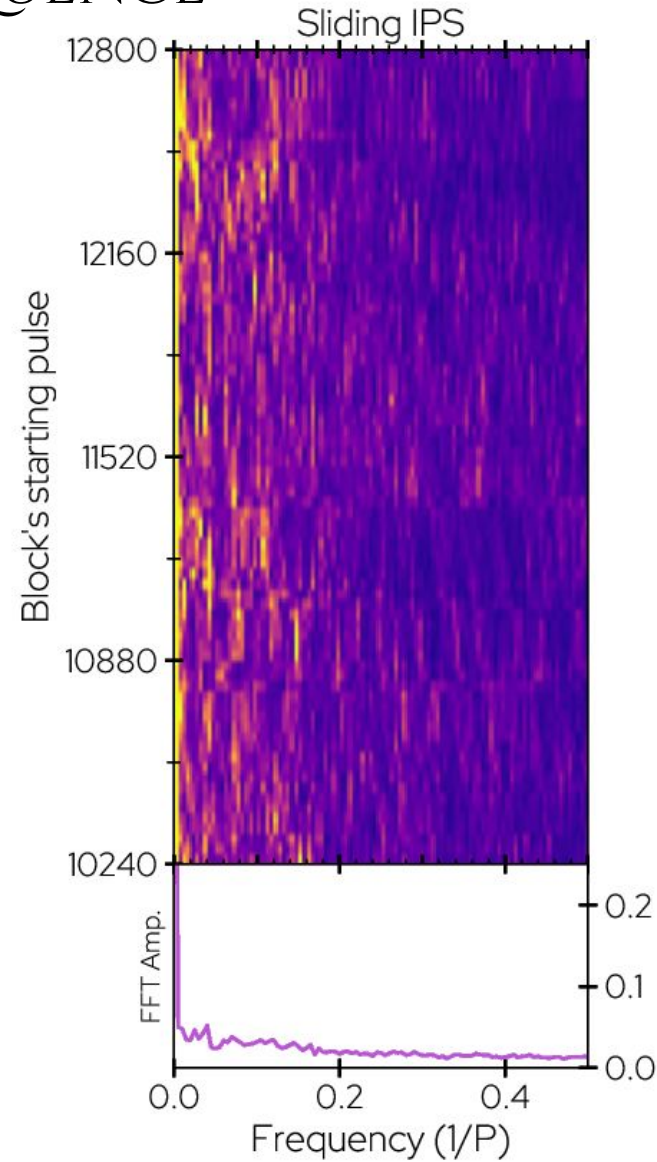
SHORT EXAMPLE PULSE SEQUENCE



EXAMPLE PULSE SEQUENCE

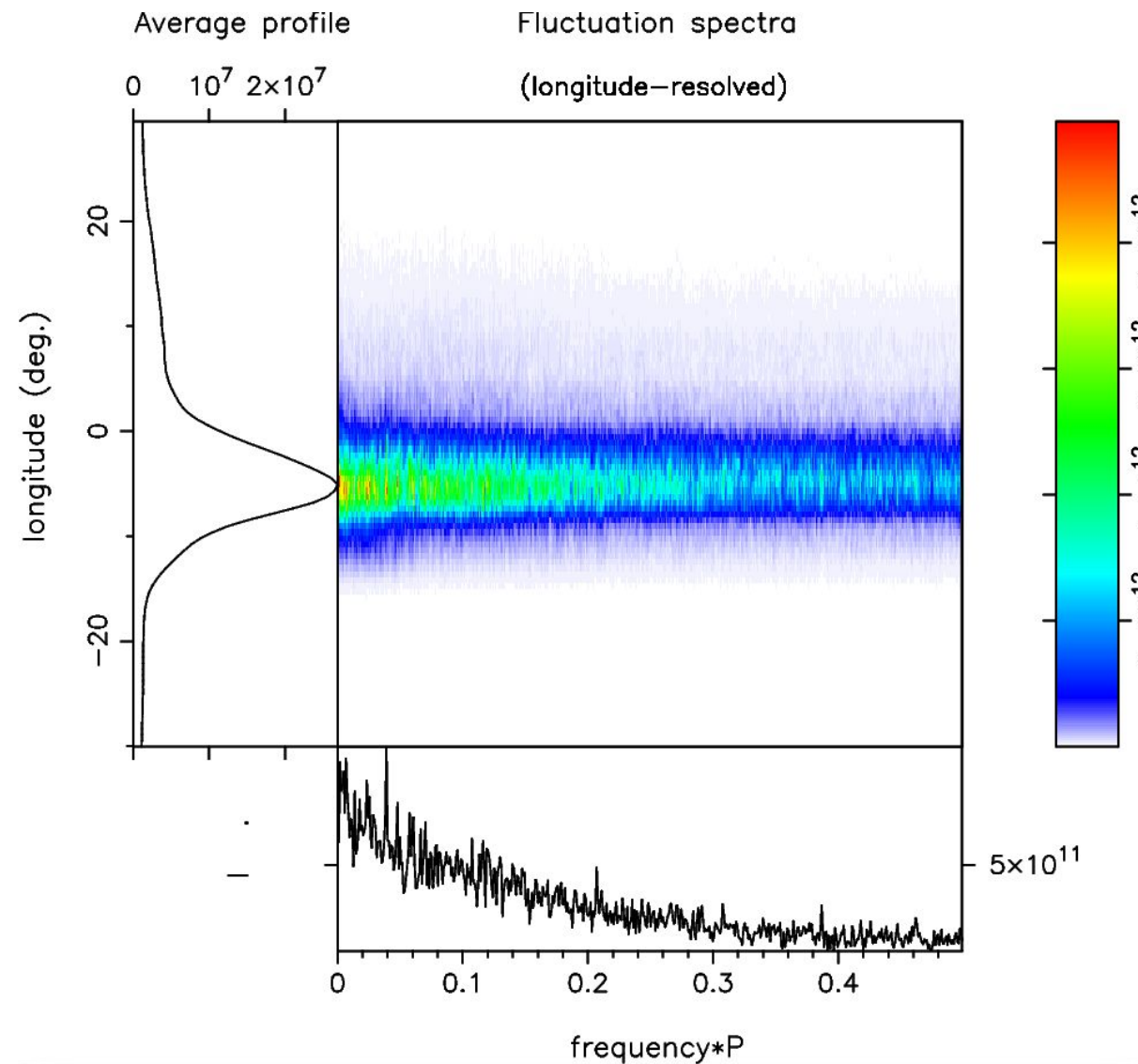
B0540+23 | MJD 57845

Key point
Periodicity
changes



Left: Sliding Integrated Power spectrum
Right: Pulse sequence

LRFS



Longitude Resolved fluctuation spectra at 327 MHz

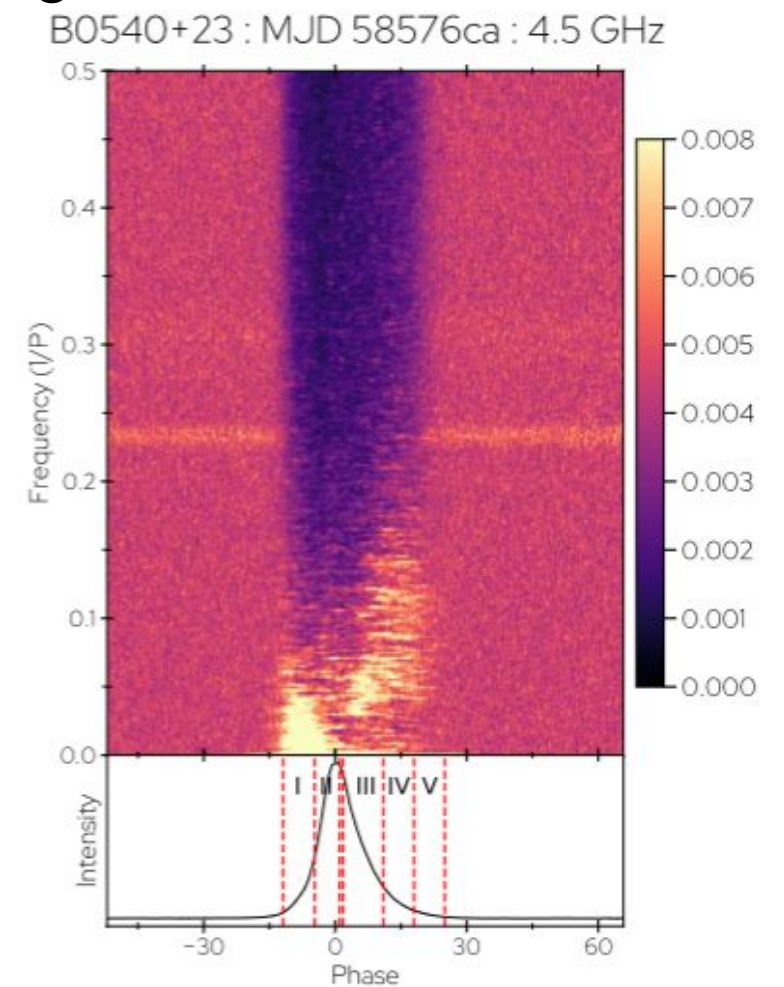
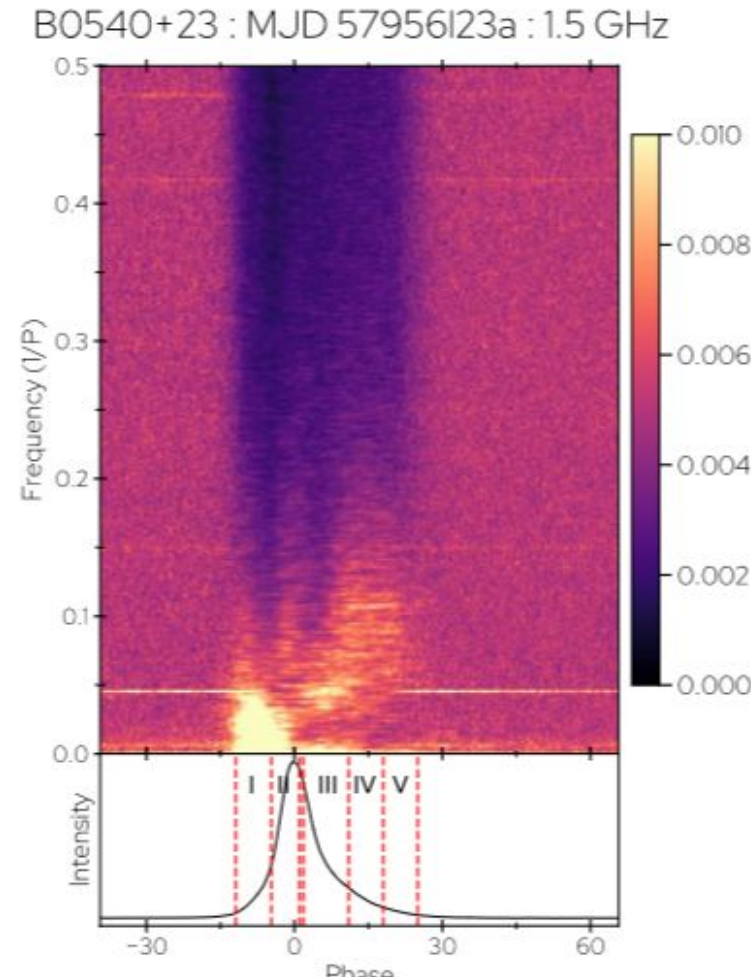
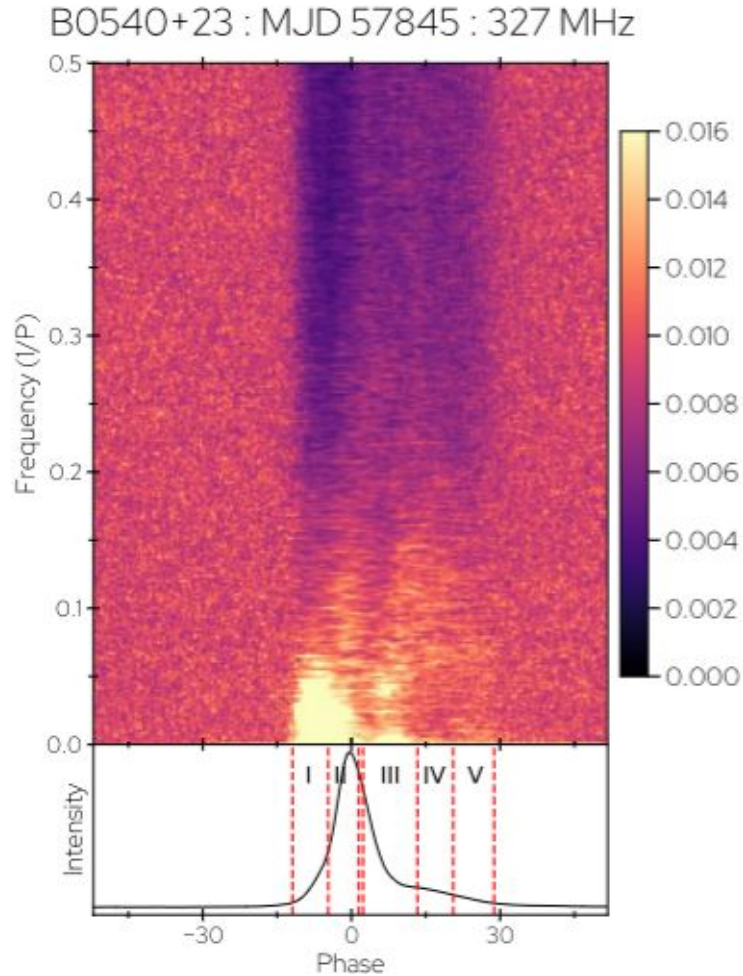
SO, AMPLITUDE MODULATION IS
THERE, BUT NOT REALLY OVER THE
PROFILE?

WRONG – SOME SUBTLETIES

NORMALIZED LRFS

Key point

Looks like 5 distinct modulation regions



Normalized Longitude Resolved Fluctuation Spectra

- Normalized means each spectra (at each phase bin) normalized by total power in spectra

CAN WE RESOLVE COMPONENT
STRUCTURE?

YES!

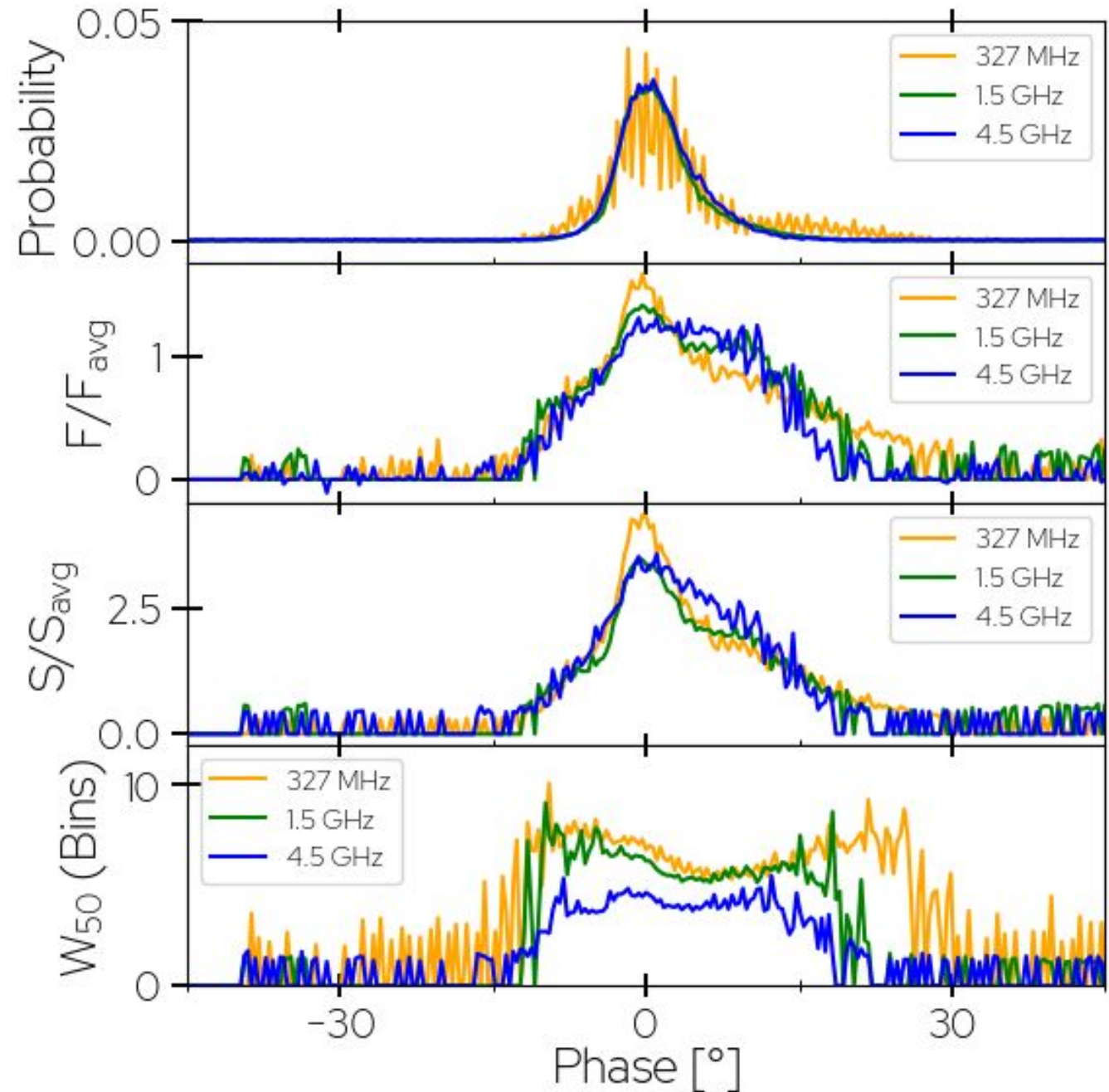
PEAK CHARACTERISTICS

Normalized Histograms
of where peaks fall on
each pulse

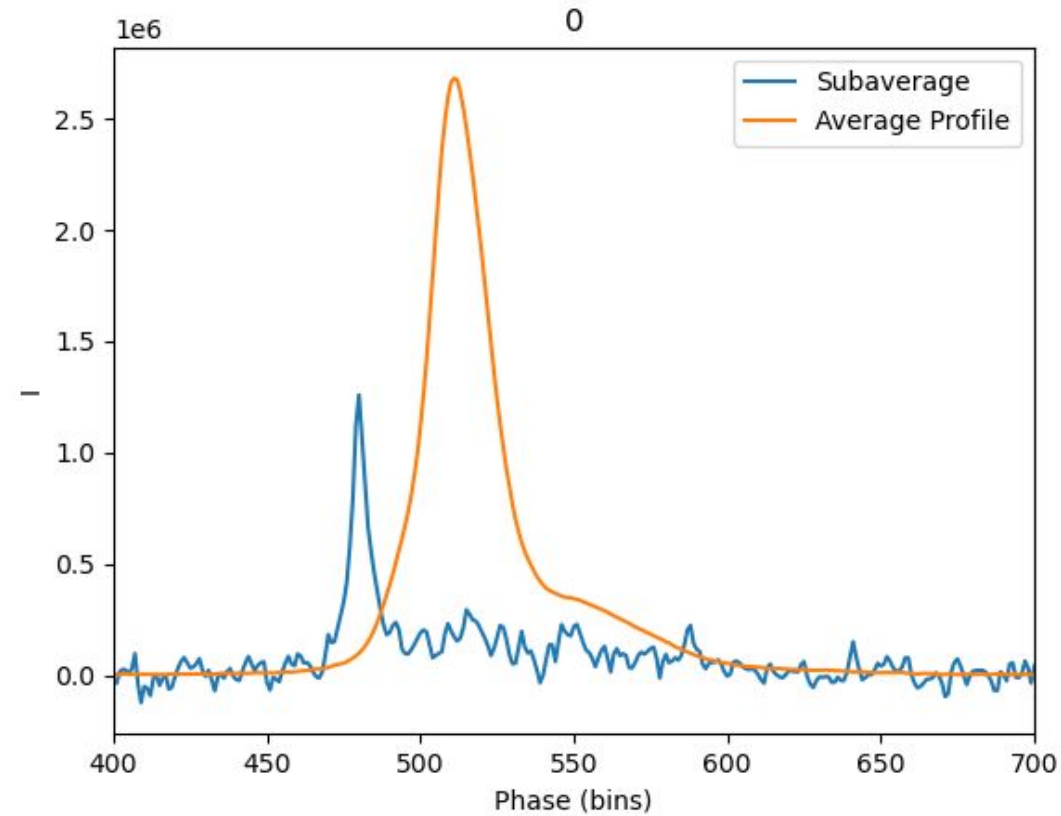
Integrated Flux

Peak Flux Density

Peak Half-width



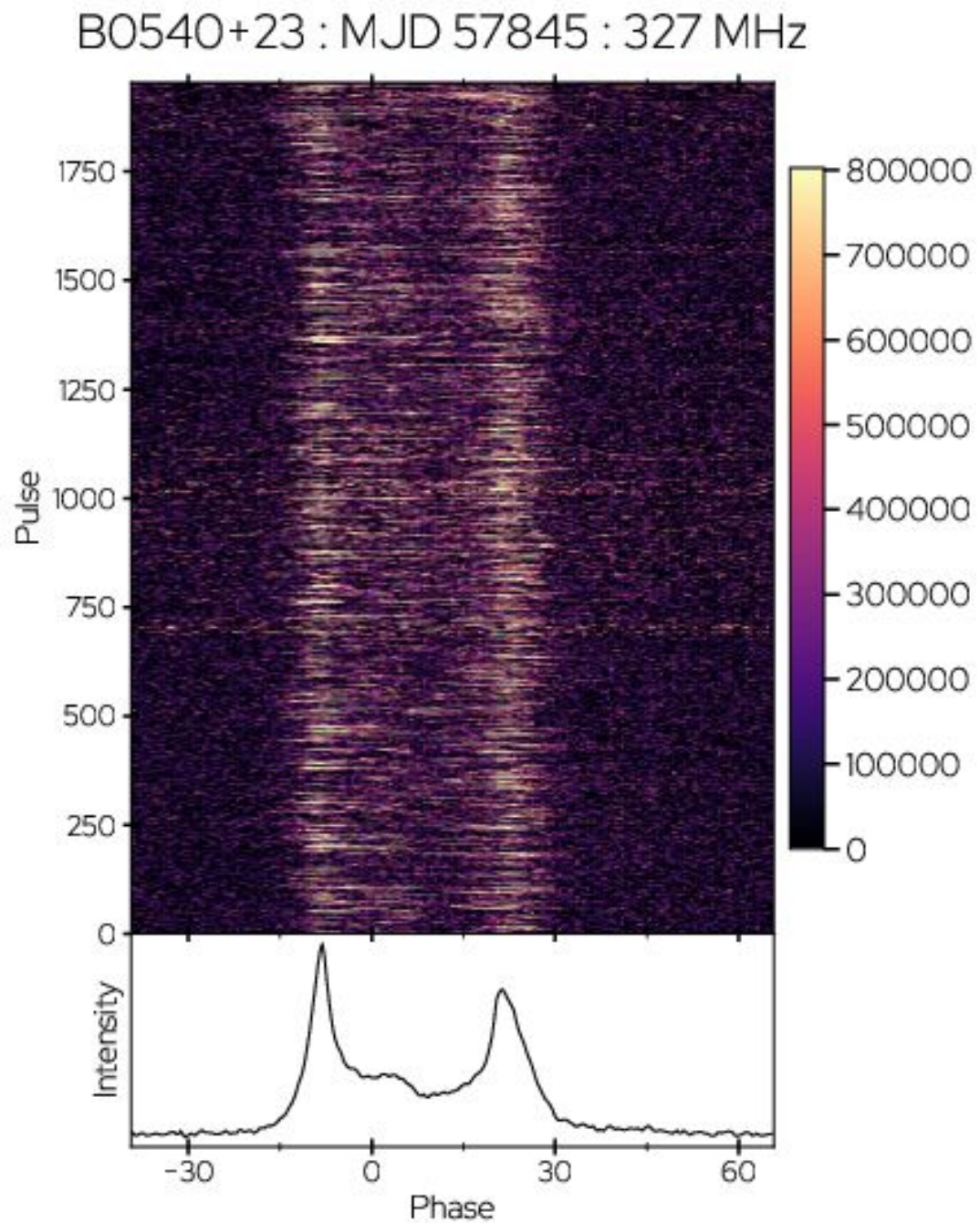
PEAK SUBAVERAGES – ANIMATIONS – 327 MHz



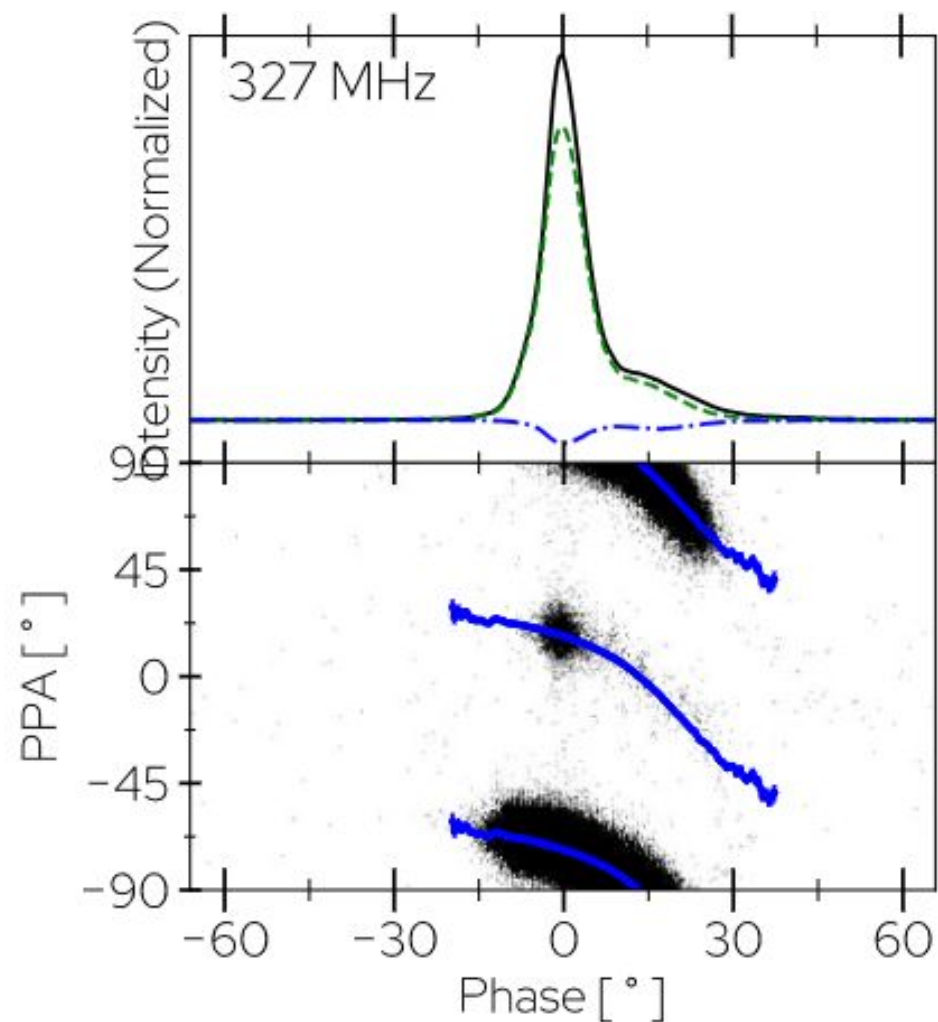
Subaverages of all pulses with peak at fixed longitude – sliding over the window to show profile changes

PEAKS *LIVIN'* ON THE EDGE

Pulses that peak on the edge
resolve 5 components!

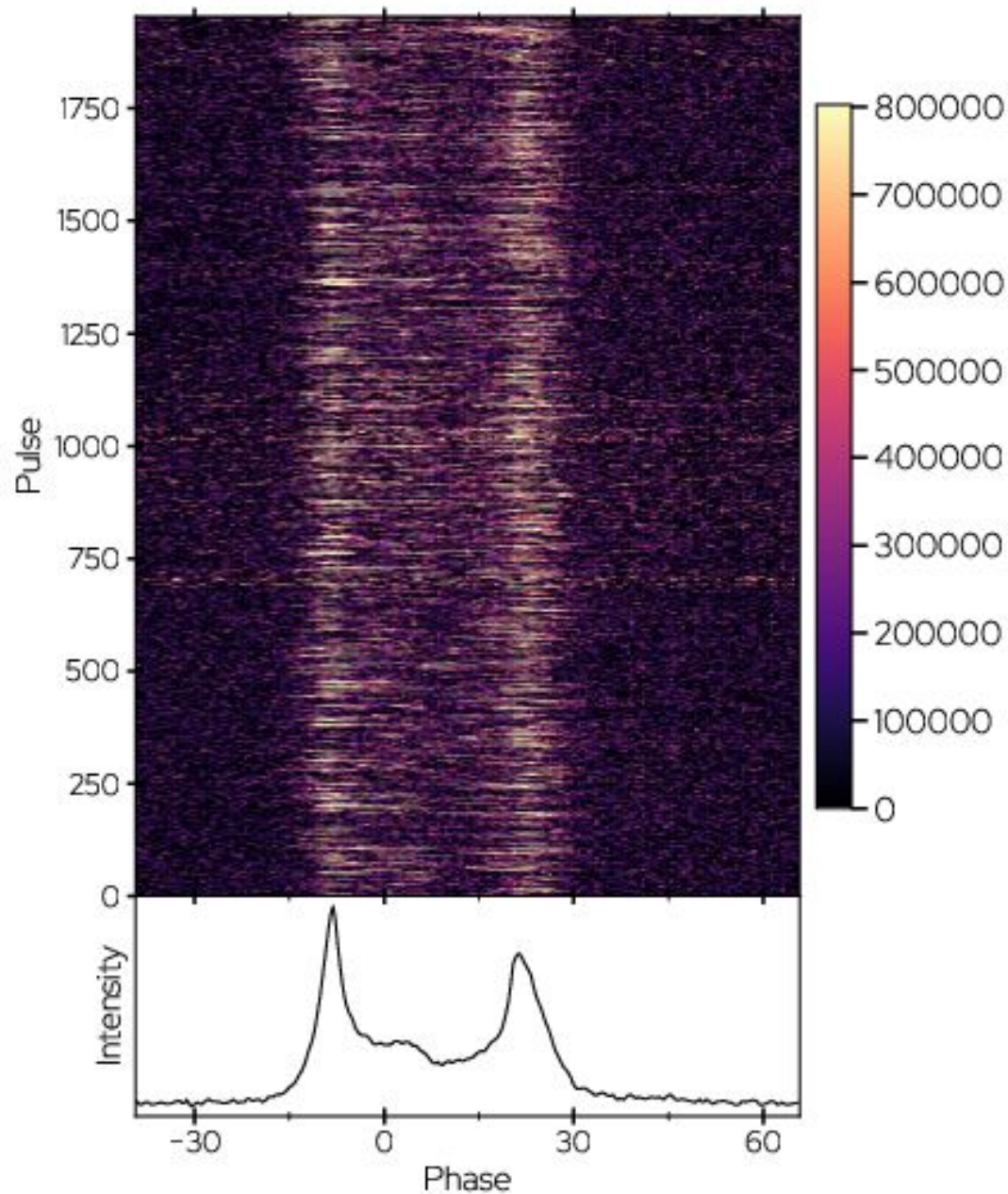


PEAKS *LIVIN'* ON THE EDGE

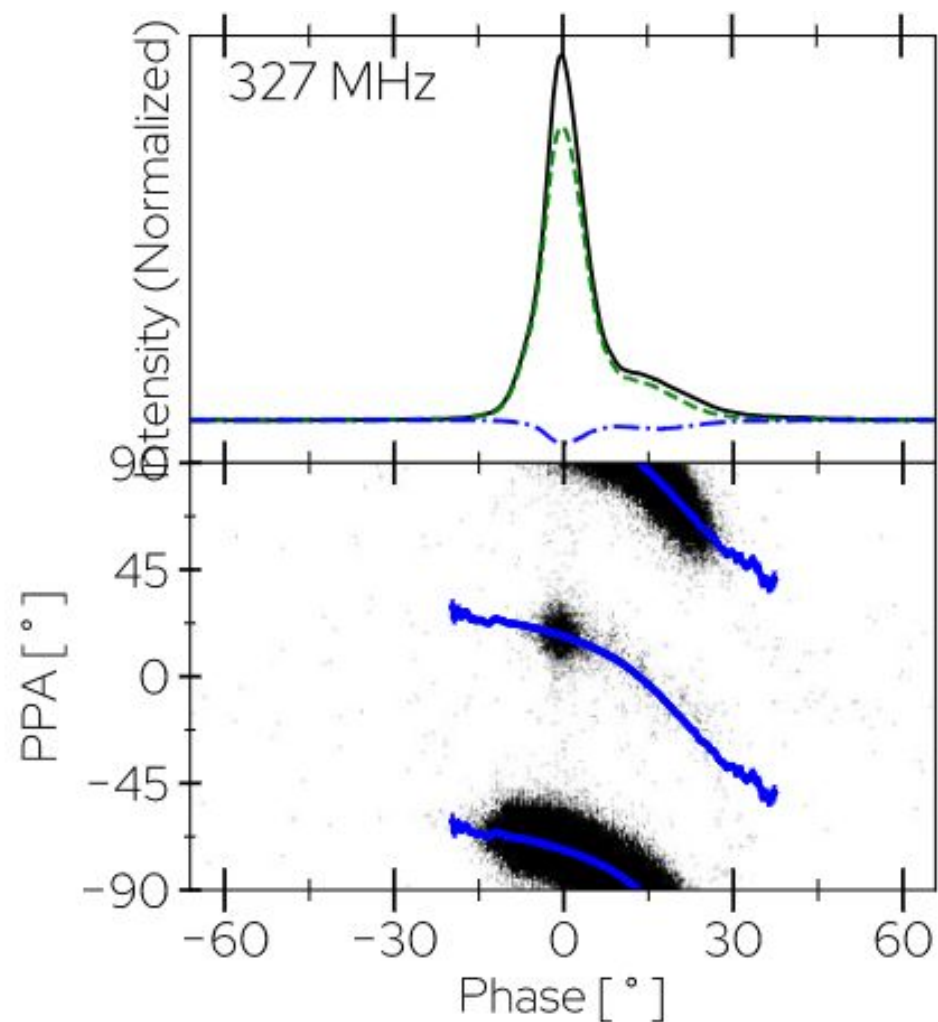


Pulses that peak on the edge
resolve 5 components!

B0540+23 : MJD 57845 : 327 MHz

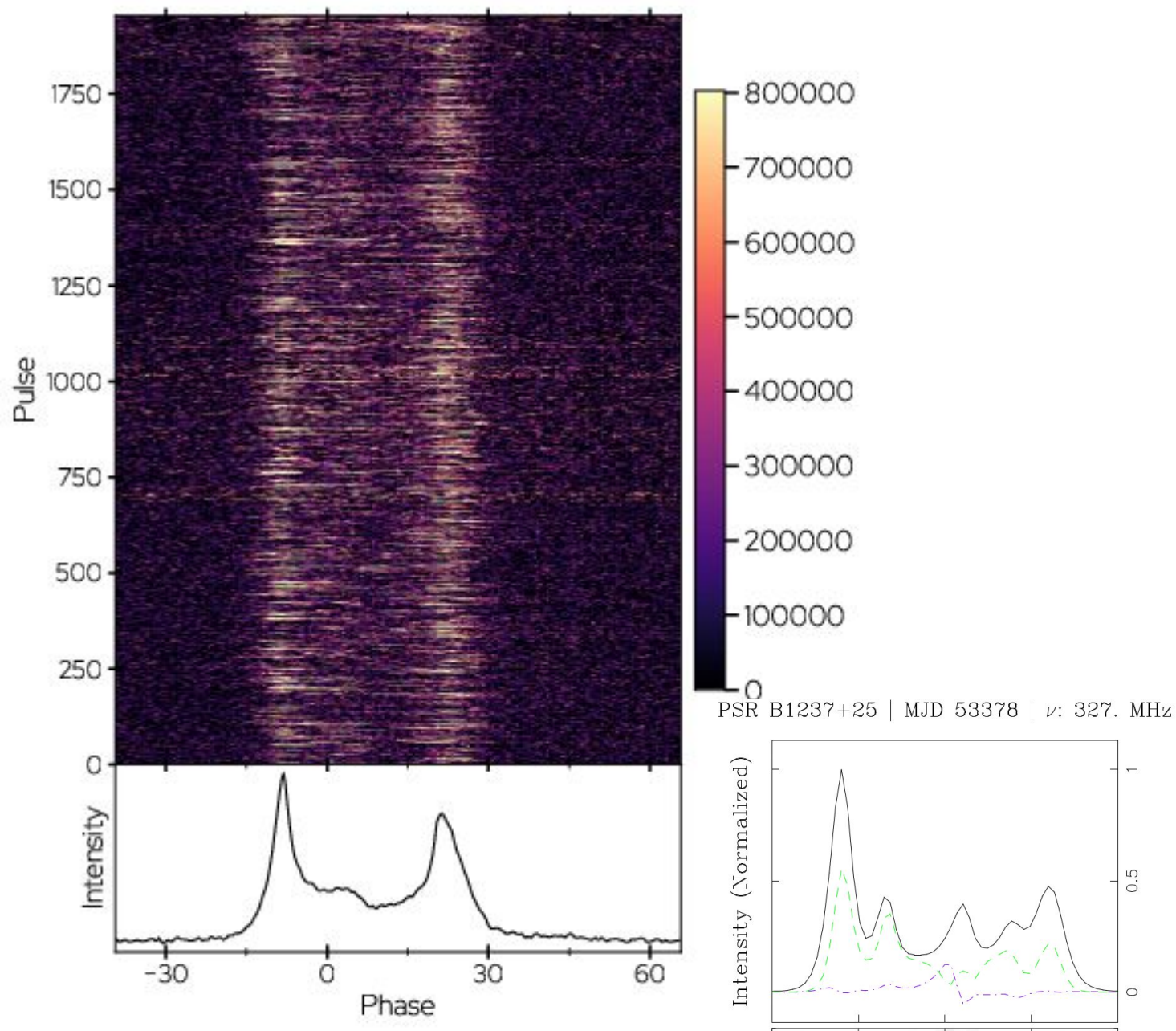


PEAKS *LIVIN'* ON THE EDGE

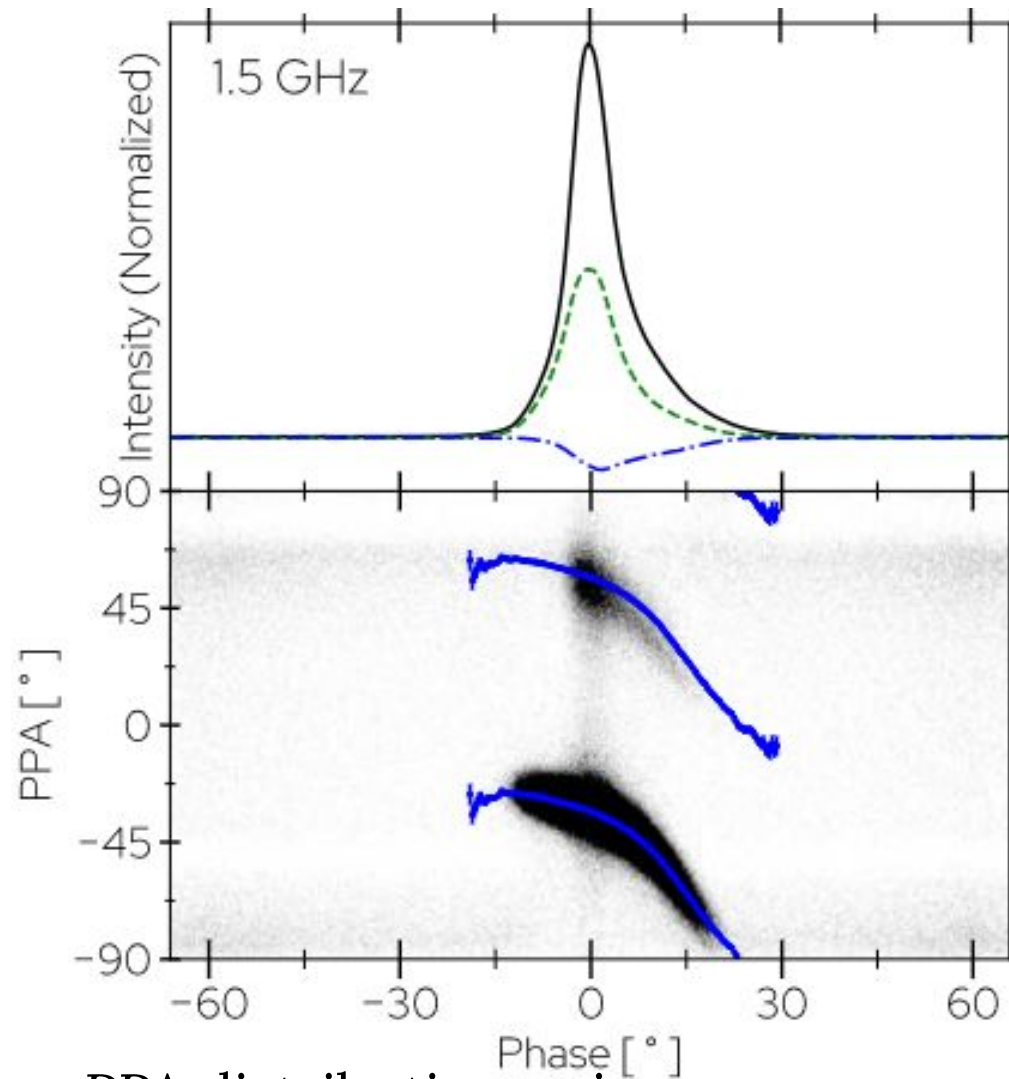


Pulses that peak on the edge
resolve 5 components!

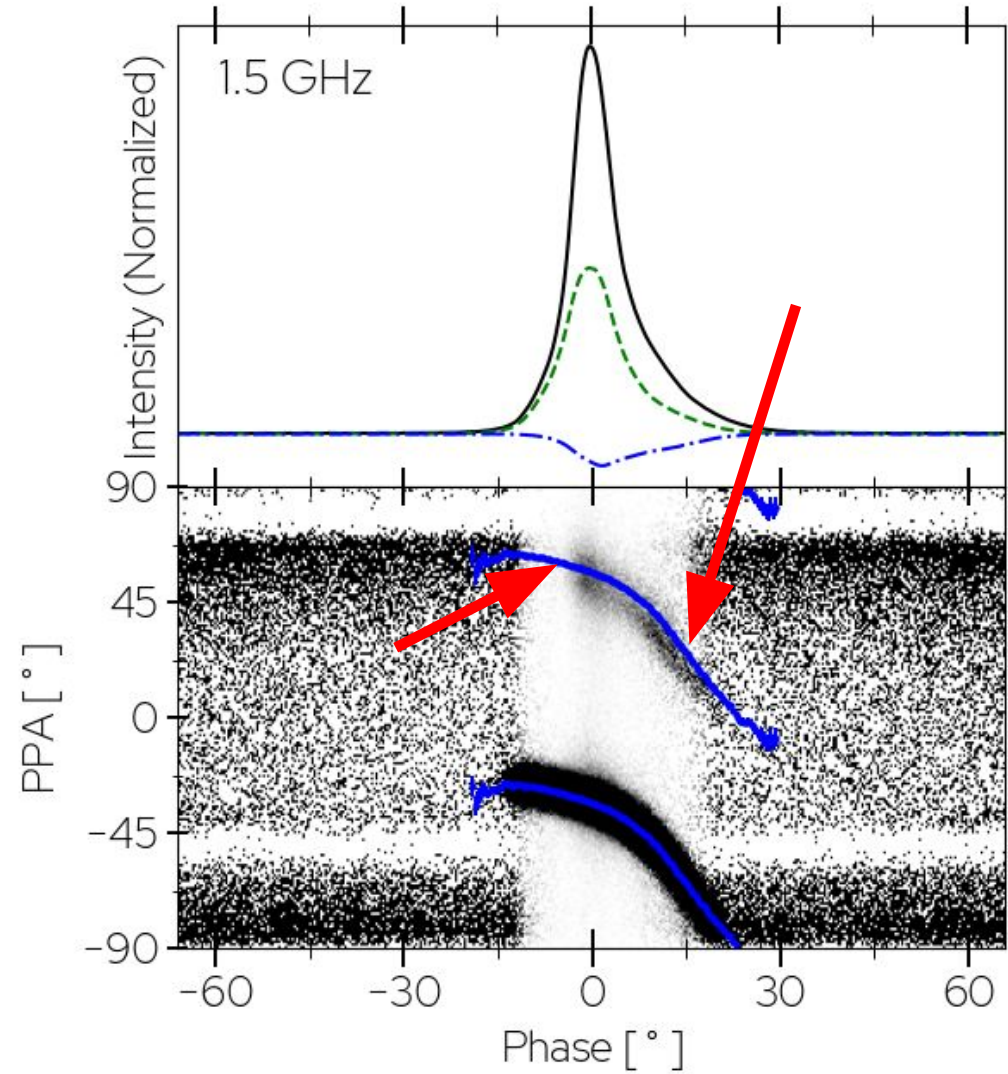
B0540+23 : MJD 57845 : 327 MHz



A CLOSER LOOK AT THE PPA TRACKS

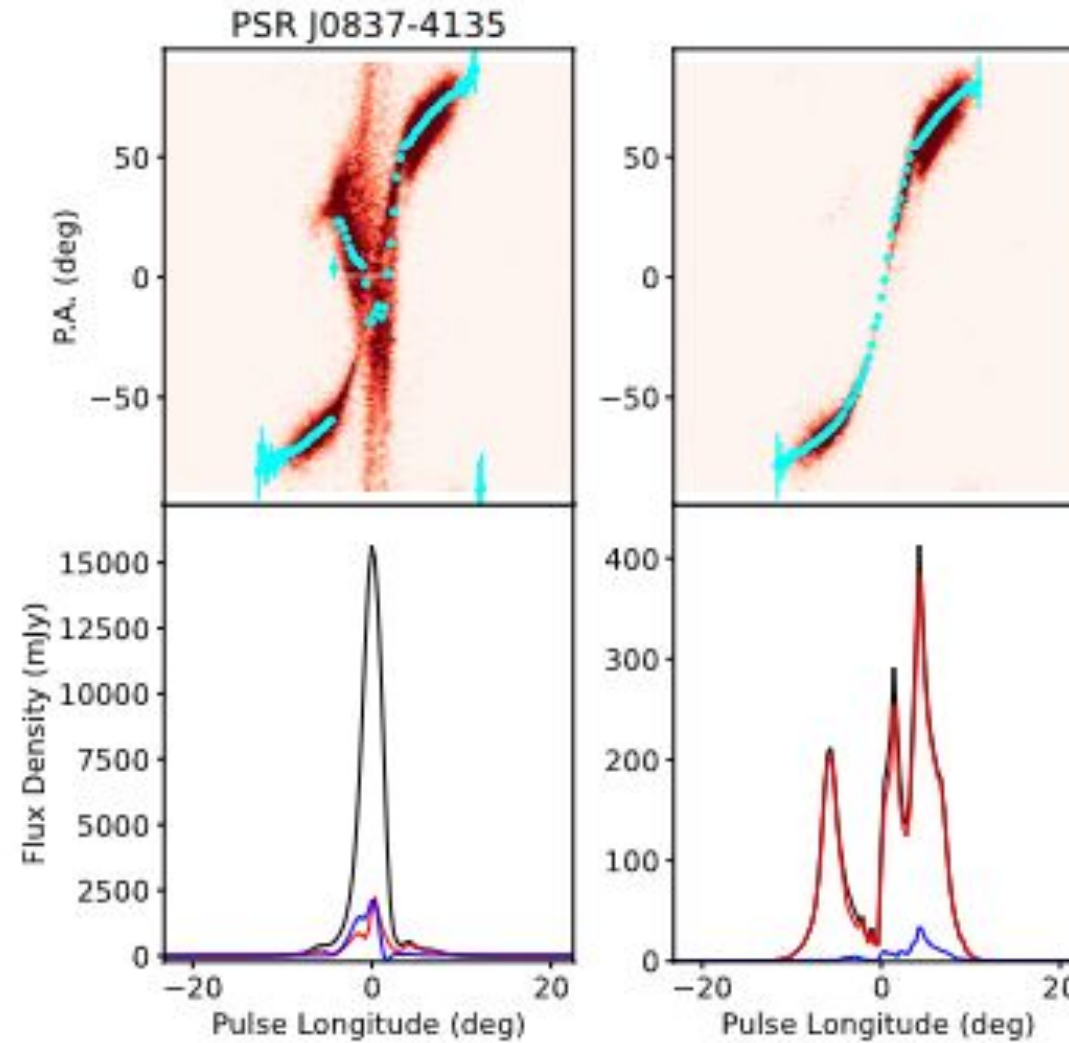


PPA distribution as is



Longitudinally Normalized PPA distribution

SAMPLES, *SM*AMPLES

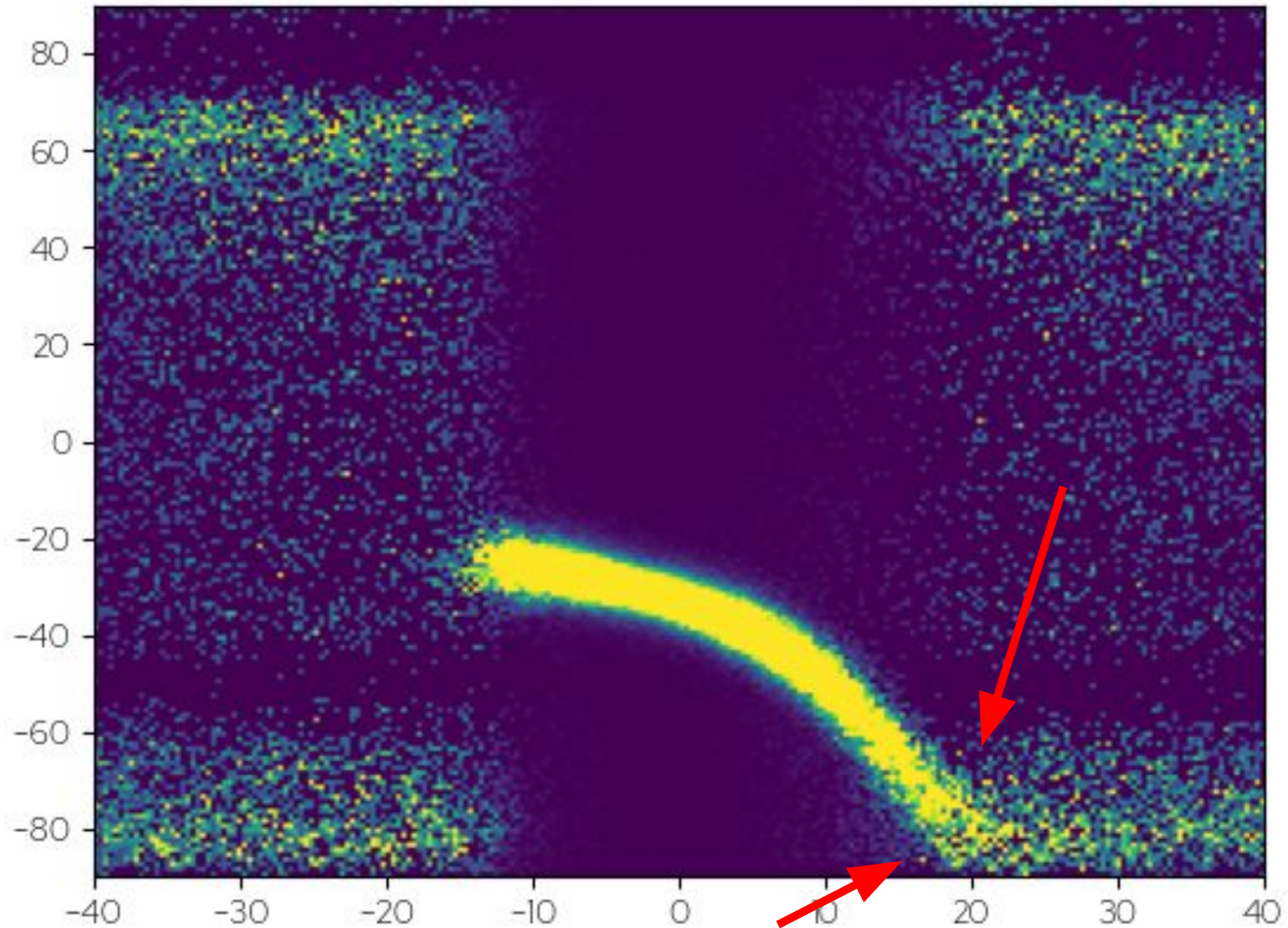


Johnson, Mitra
et al, 2024

Highly polarized samples reveal PPA tracks

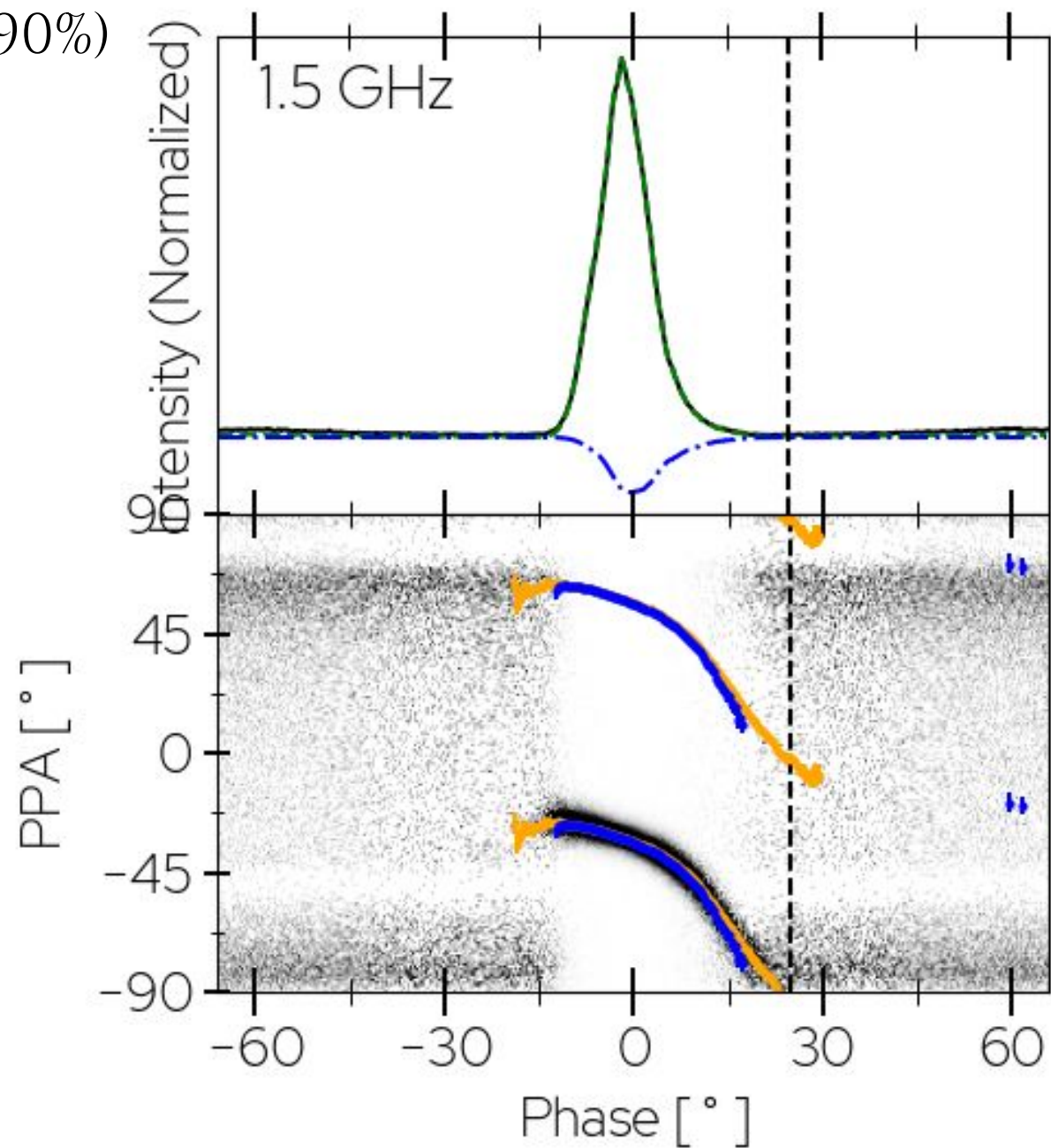
SAMPLES, *SMAMPLES* ($L/I > 90\%$)

BIFURCATION
IN THE TAIL!



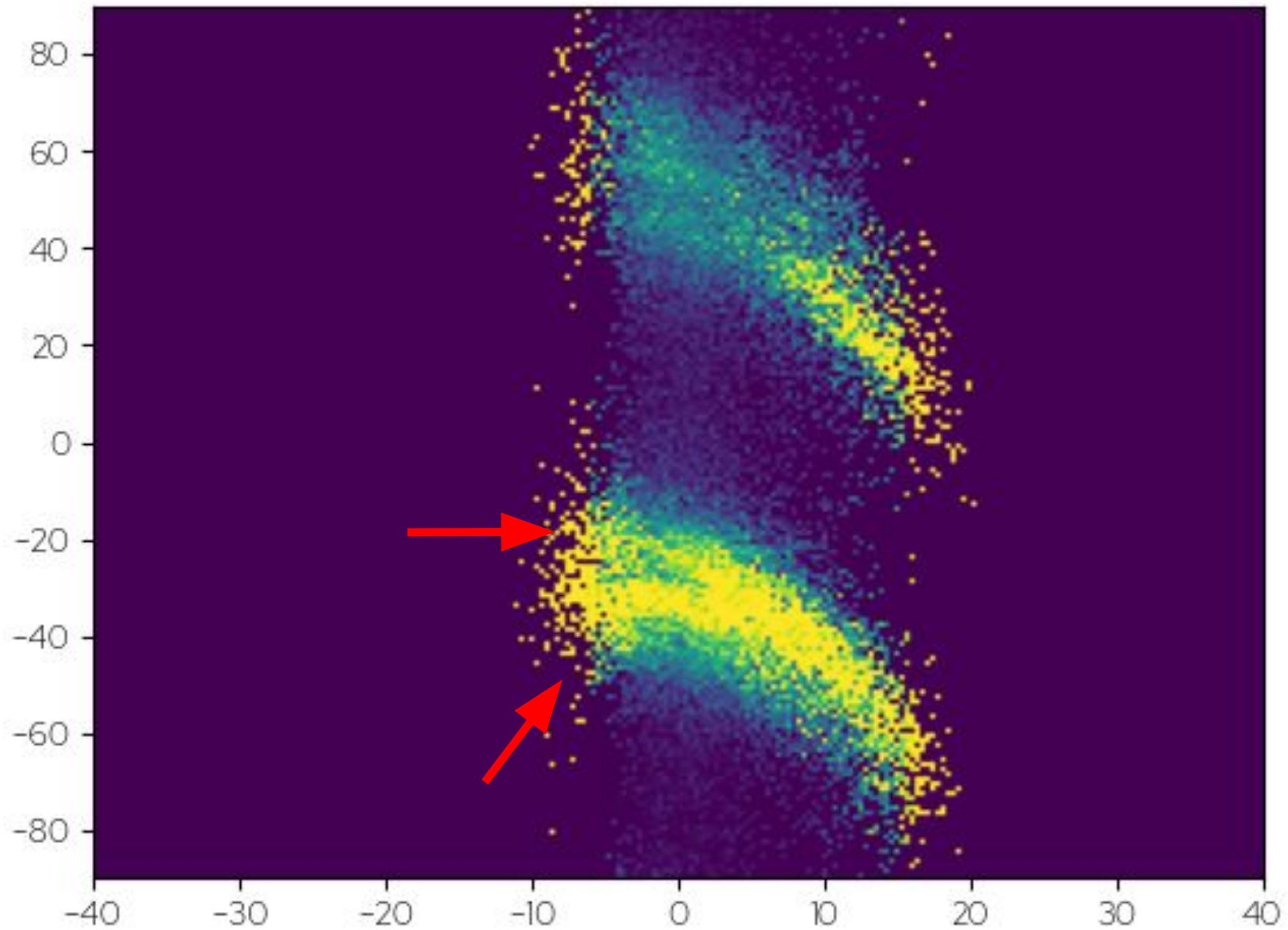
SAMPLES, *SMAMPLES* ($L/I > 90\%$)

POWER IS STRONGLY
ASSOCIATED WITH STEEPER
TRACK

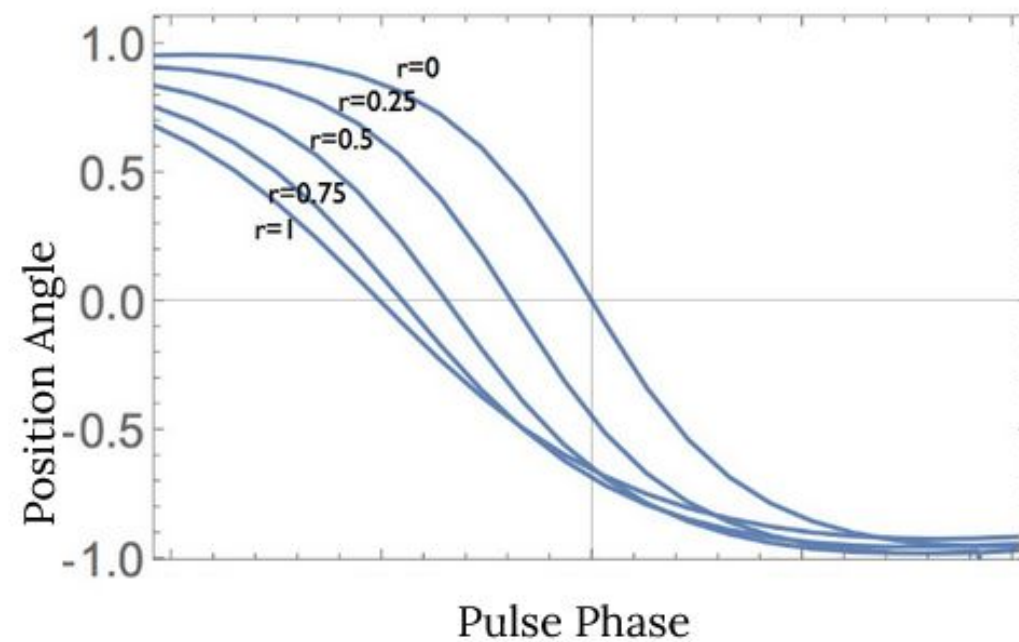
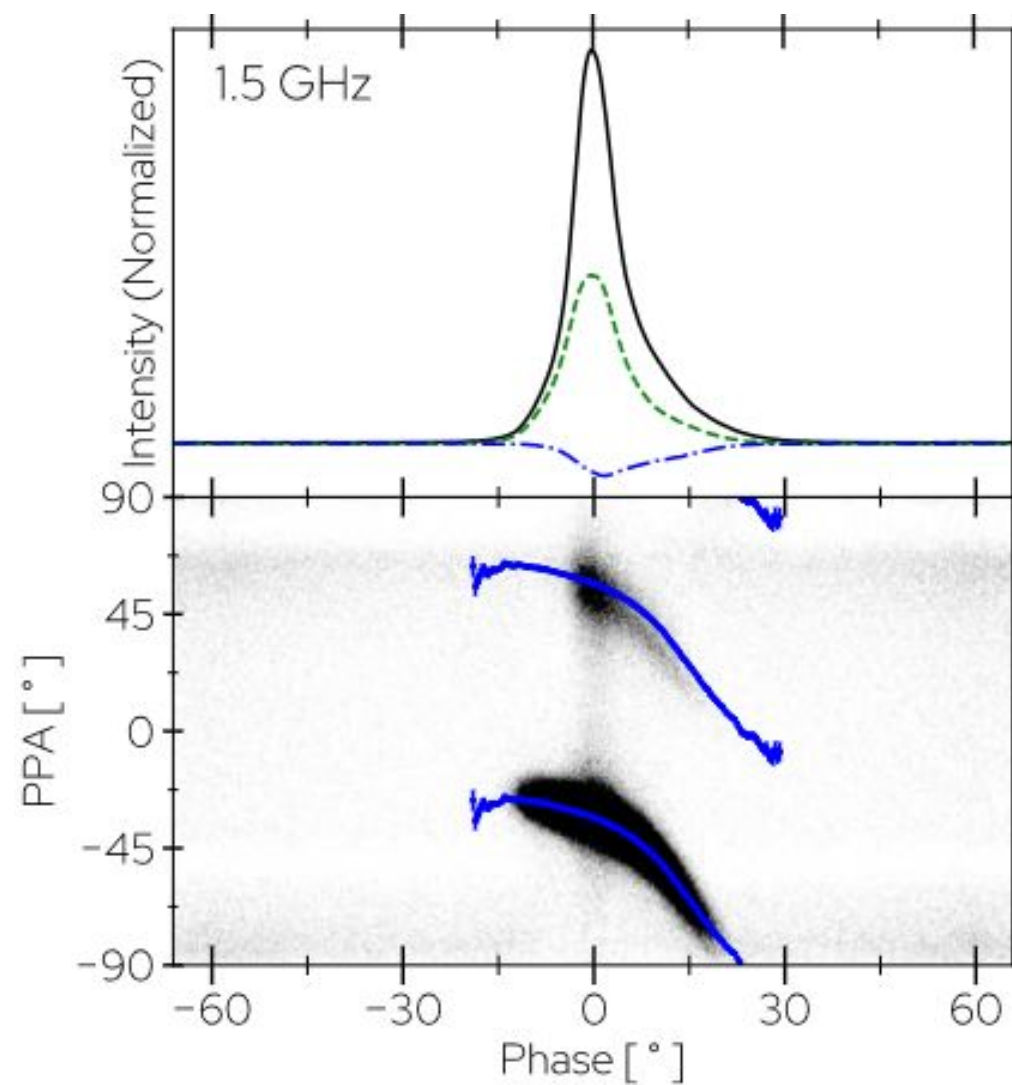


SAMPLES, *SMAMPLES* ($L/I < 25\%$)

TWO
TRACKS!



COMPARING PPA TRACKS TO A/R

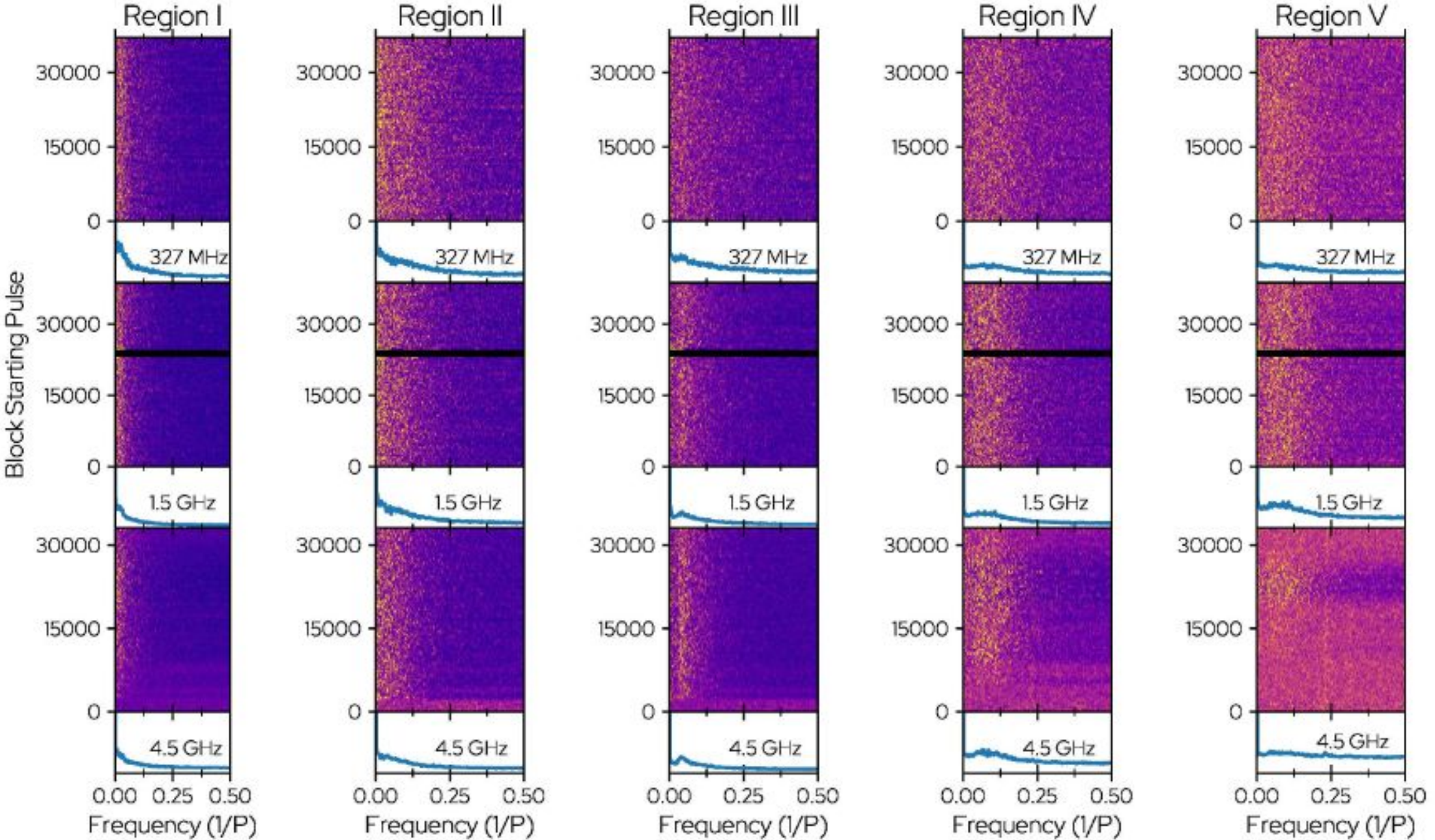


CONCLUSIONS AND FUTURE WORK

- PSR B0540+23 has an unusual amplitude modulation
- The nature of this modulation hides a 5 component profile
- PSR B0540+23 appears to have two position angle tracks, suggesting emission is produced at two distinct heights.
- Likely that the modulation corresponds to one of the two tracks
- How to disentangle the two?

BACKUP SLIDES

STABILITY ANALYSIS



Morning I | 09:45 AM - 10:00 AM

Sean McWilliams

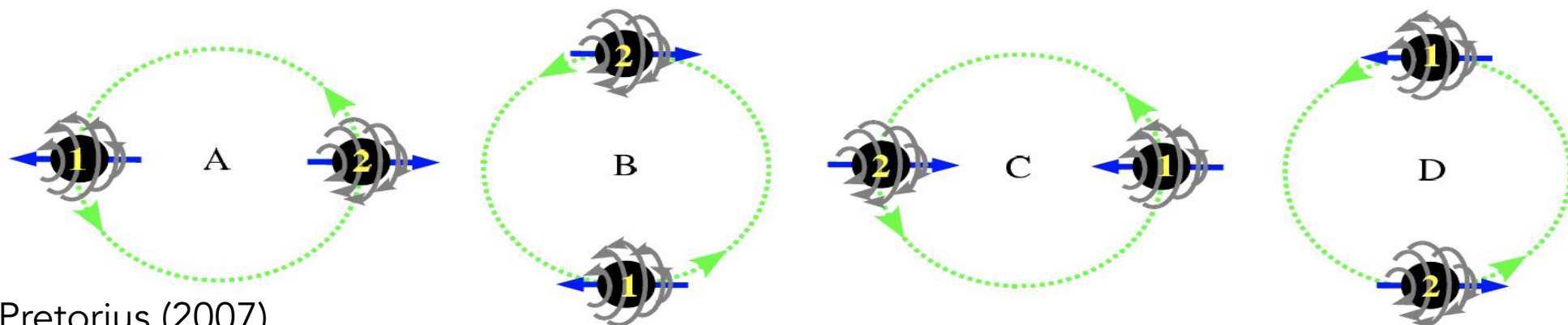
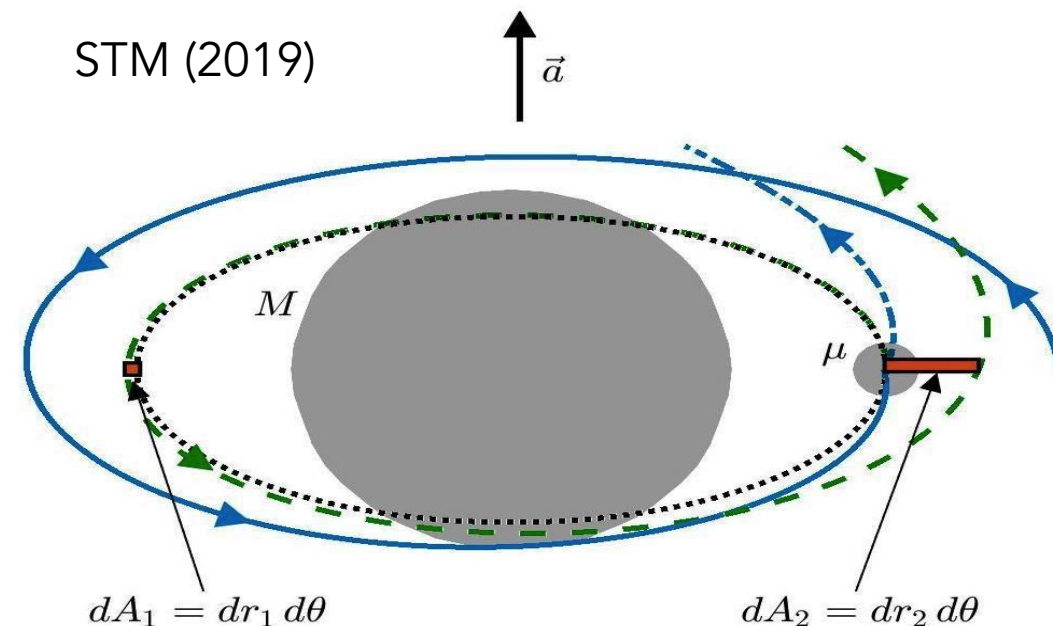
"How black holes get their superkicks: spins and the radiation rocket"

Backwards One Body (BOB)

- BOB is a first-principles model for the late inspiral and merger-ringdown of coalescing black holes – see STM, Phys. Rev. Lett. 122, 191102 (2019)
- As accurate as the state-of-the-art alternatives with far fewer parameters
- BOB amplitude evolution can be recovered from the ringdown's quasi-normal mode (QNM) pole contributions, and BOB models the “direct wave” non-QNM content really well – see Kankani and STM, arXiv:2603.15474
- Also models charged mergers (Matt Cerep), memory (Suchindram Dasgupta), superkicks, beyond GR, and probably more!
- Available open-source as a stand-alone model or combined with SEOBNRv5's inspiral to make SEBOB – see Mahesh, STM, and Etienne, Phys. Rev. D 112, 124065 (2025)

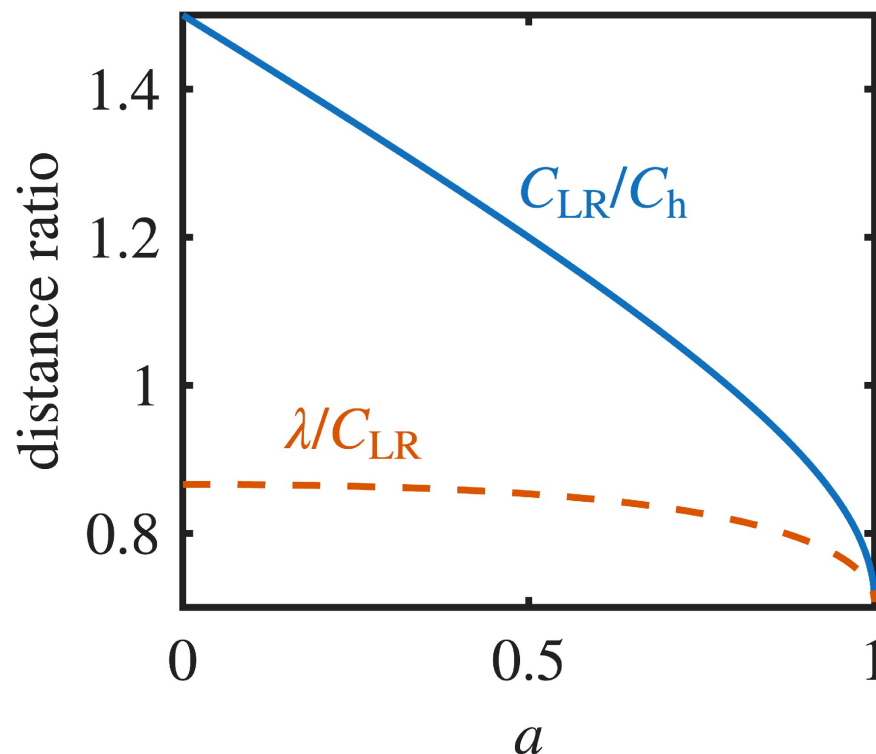
Explaining “superkicks”

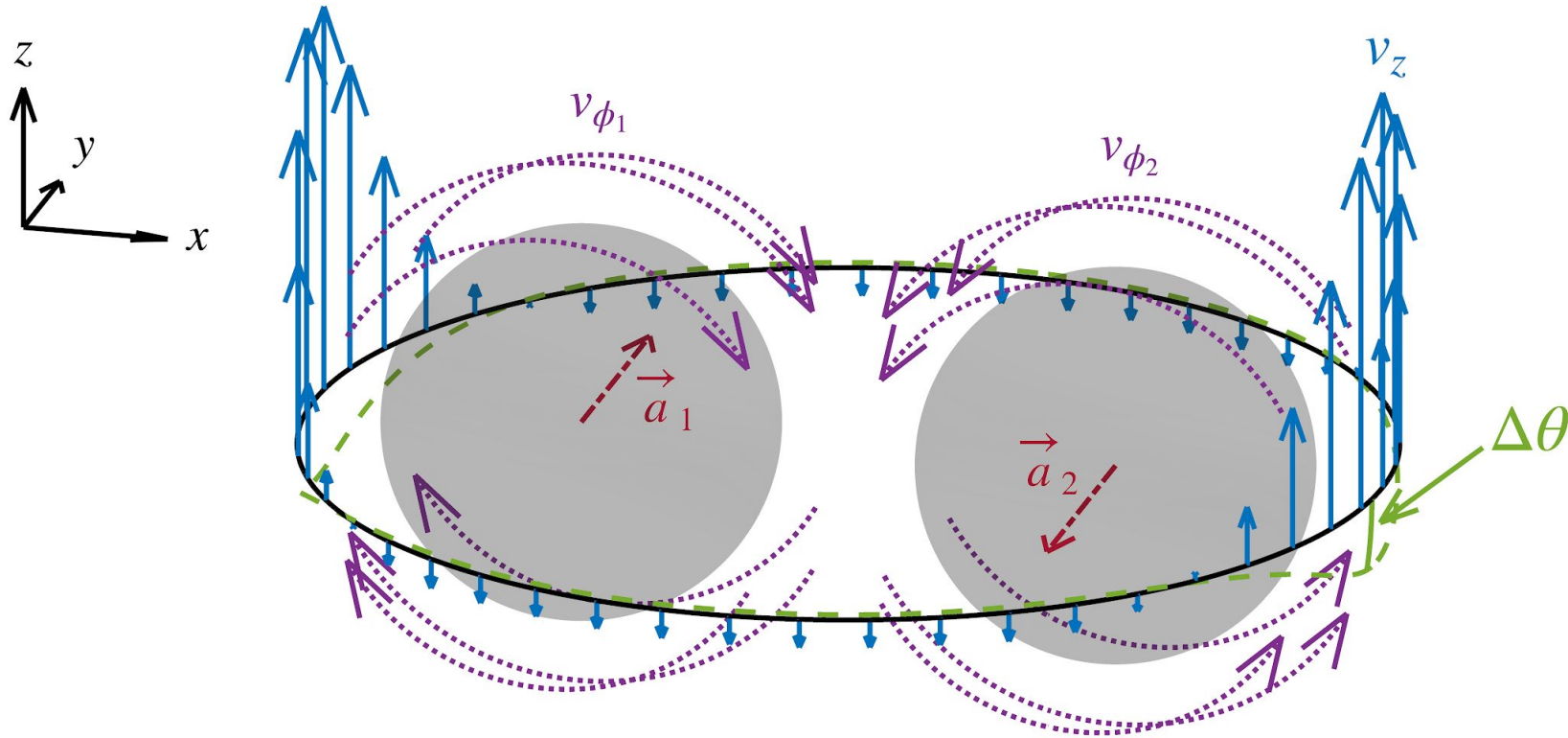
- Kicks, or gravitational radiation recoils, occur mostly during the merger, so we can try to understand them with BOB
- Spin-orbit/spin coupling, mutual frame-dragging of each black hole, momentum stored in the field were all used to explain spin kicks
- Near merger, GWs are affected by frame-dragging, explains spin-induced kicks



Pretorius (2007)

- At merger, the gravitational wavelength λ is less than the proper circumference of the light ring C_{LR} .
- PN assumes $C_h \ll C_{LR} \ll \lambda$.
- For superkick configurations, in-plane spins cancel in the remnant, so BHPT won't help.



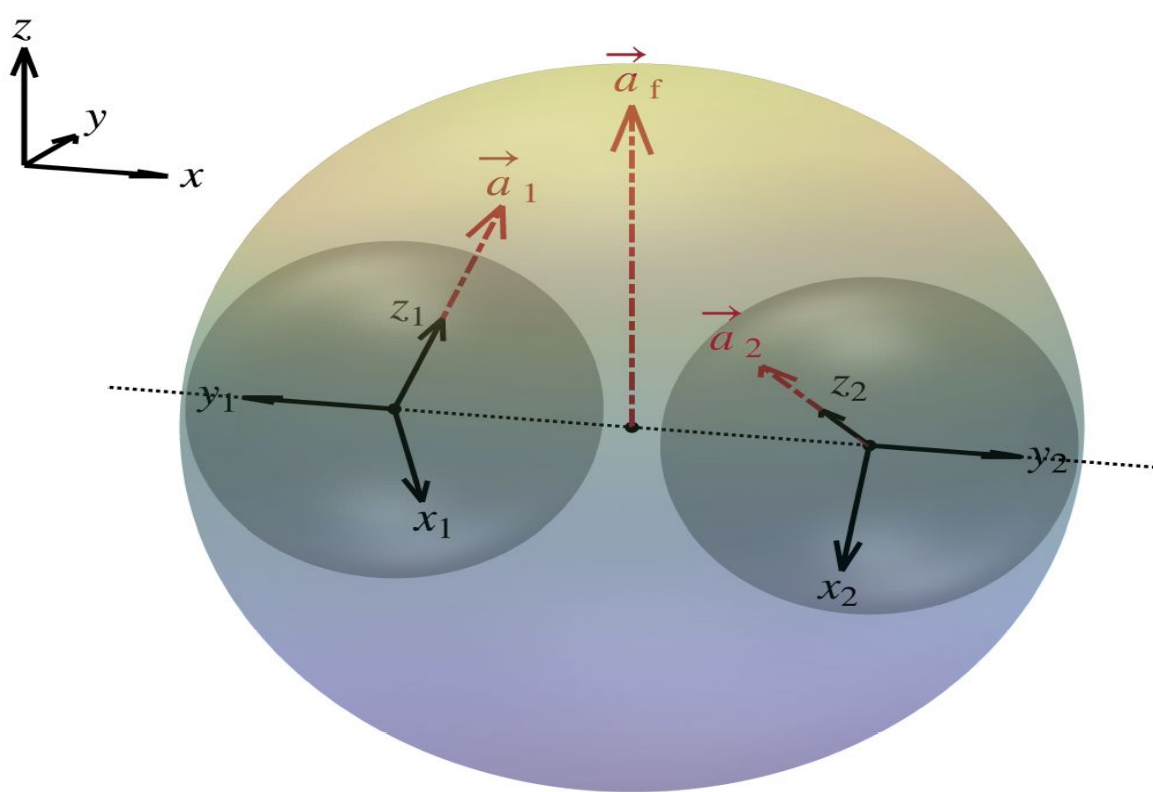


$$\Delta\theta \equiv \theta' - \theta$$

$$\theta' = \cos^{-1} \left(\frac{-v_z/c + \cos \theta}{1 - (v_z/c) \cos \theta} \right) \Big|_{\theta=\pi/2} = \cos^{-1}(-v_z/c)$$

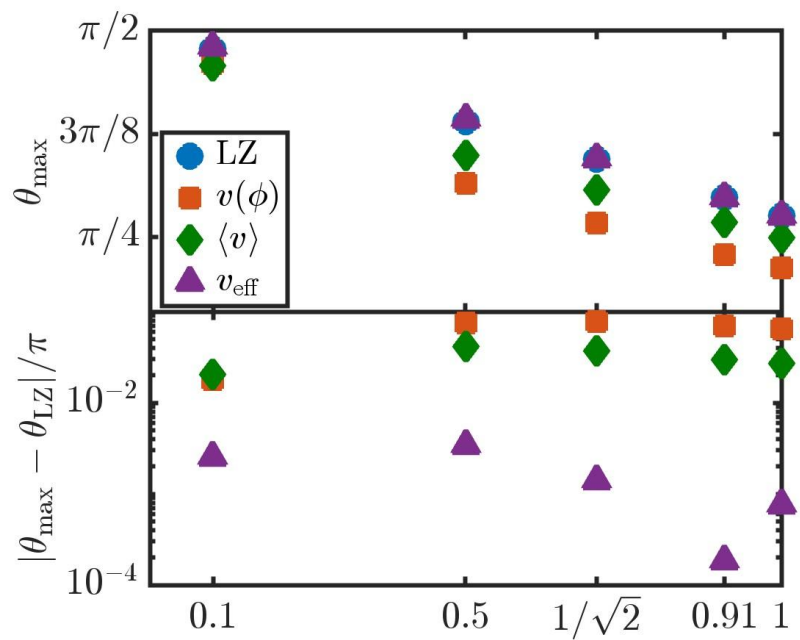
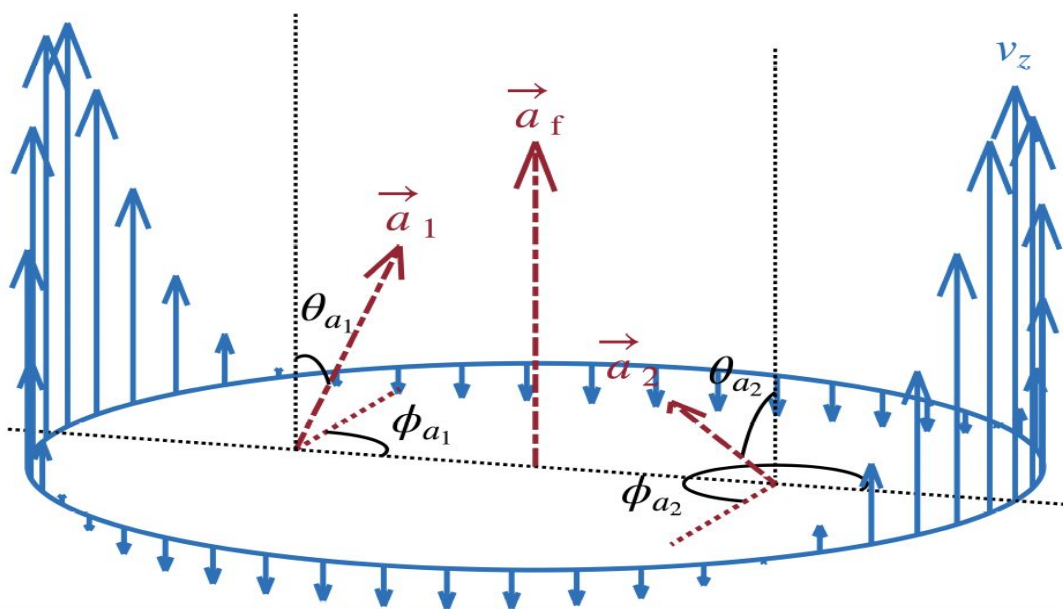
$$\Delta E = E_{\text{rad}} \int_0^{2\pi} d\phi \left(\int_0^{\theta'} d\theta Y^* Y \sin \theta - \int_{\theta'}^{\pi} d\theta Y^* Y \sin \theta \right)$$

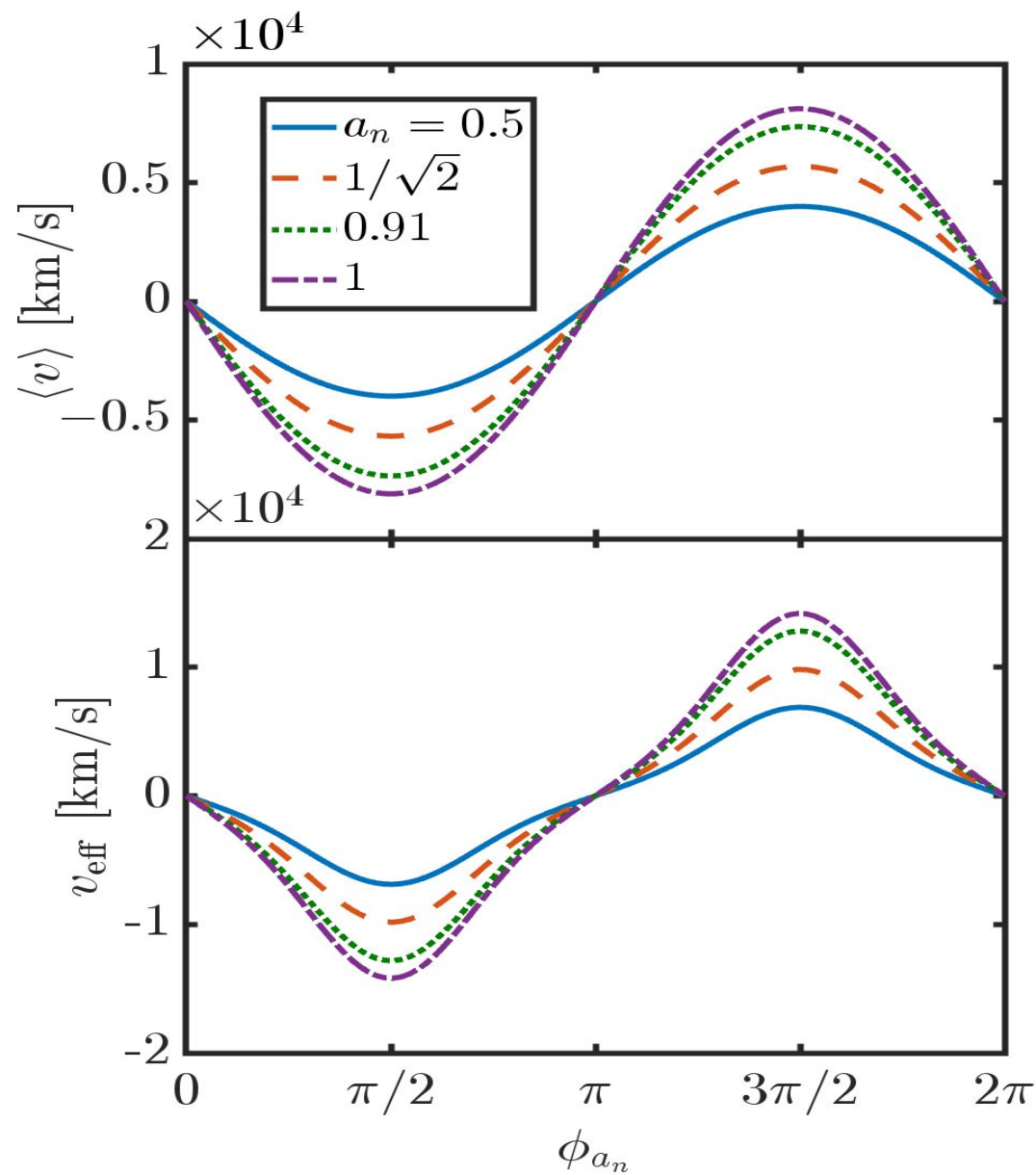
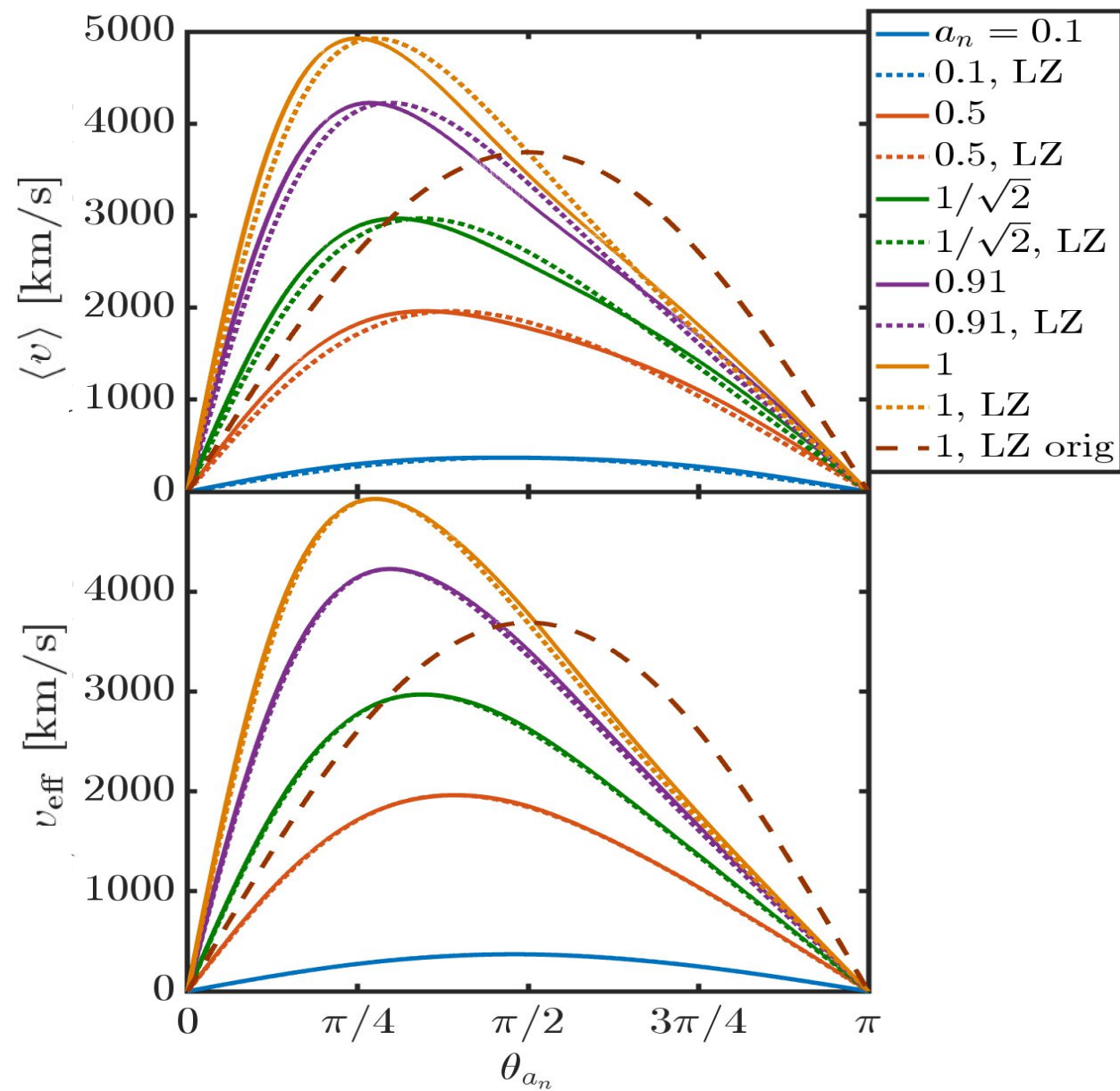
$$Y = Y(\theta, \phi) \equiv {}^{-2} Y_2^2(\theta, \phi) + {}^{-2} Y_2^{-2}(\theta, \phi).$$



$$\langle v \rangle \equiv \frac{1}{2\pi} \int_0^{2\pi} d\phi v(\phi)$$

$$\frac{v_{\text{eff}}}{8c} (5 + 10v_{\text{eff}}^2 + v_{\text{eff}}^4) = \frac{\Delta E}{M_f c^2}$$





Morning I | 10:00 AM - 10:15 AM

Sid Mahesh

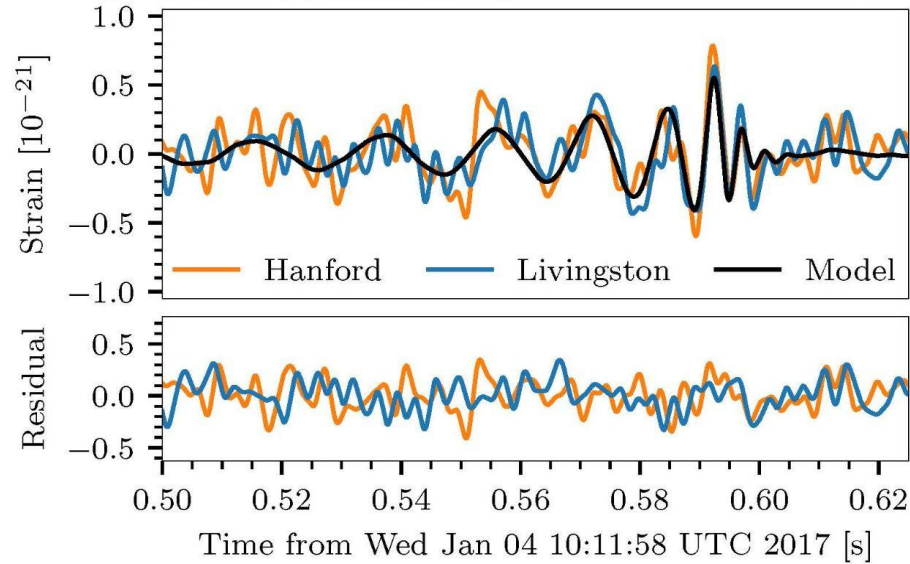
*"Adventures in Black Hole Binary Waveform
Modeling"*

Adventures in Black Hole Binary Waveform Modeling

Sid Mahesh,
Ph.D., West Virginia University

In Collaboration with: Sean McWilliams, Zach Etienne, Michal Pirog, Shay Reddy, Suchindram Dasgupta, Anuj Kankani, Matthew Cerep, ... and many more!

Gravitational Wave Parameter Estimation



Masses, spins estimated using likelihood maximization

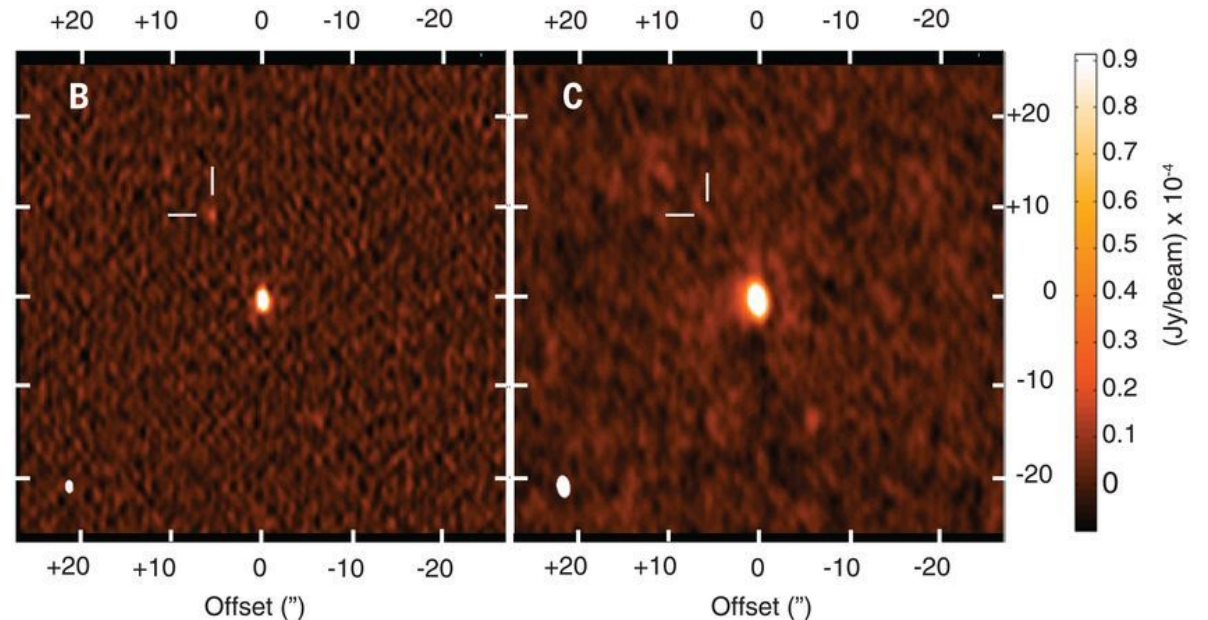
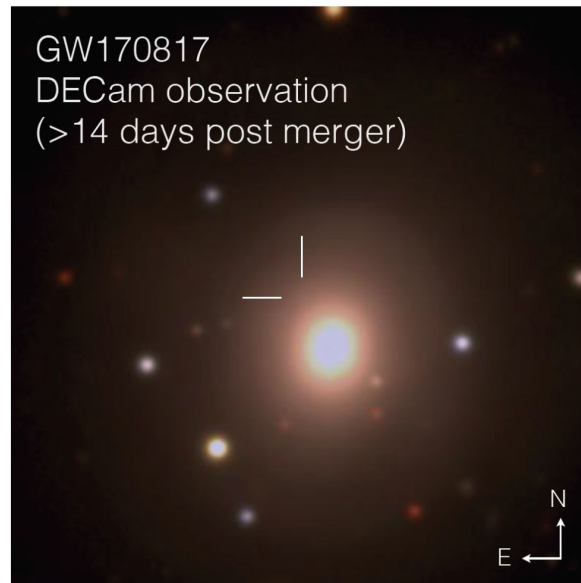
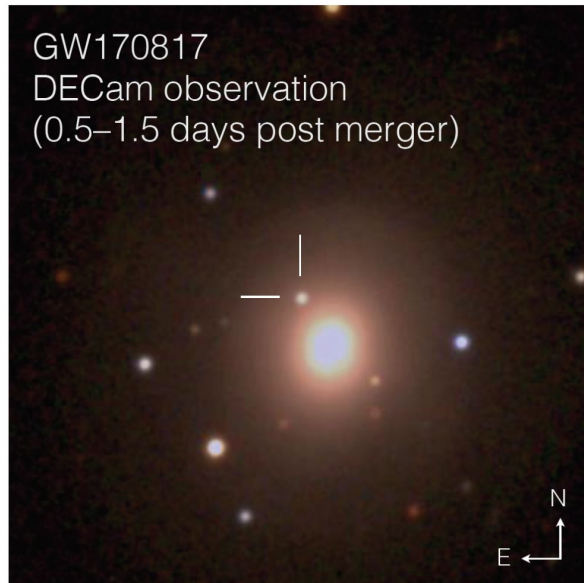
$$\log \Lambda(\theta) \propto 2\langle s, h_T(\theta) \rangle - \langle h_T(\theta), h_T(\theta) \rangle$$

$$\langle a, b \rangle = \int_{-\infty}^{\infty} \frac{\hat{a}(f)\hat{b}^*(f)}{S_n(|f|)} df$$

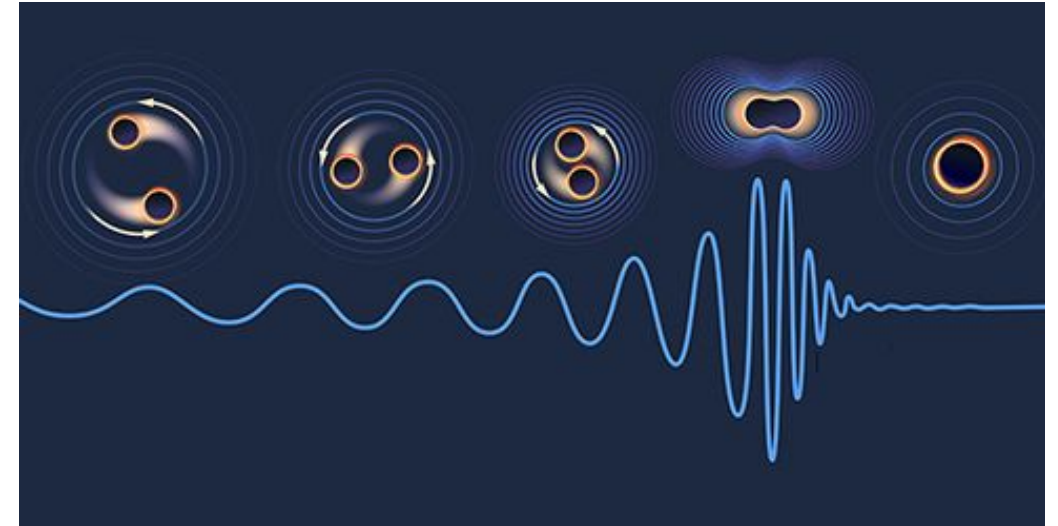
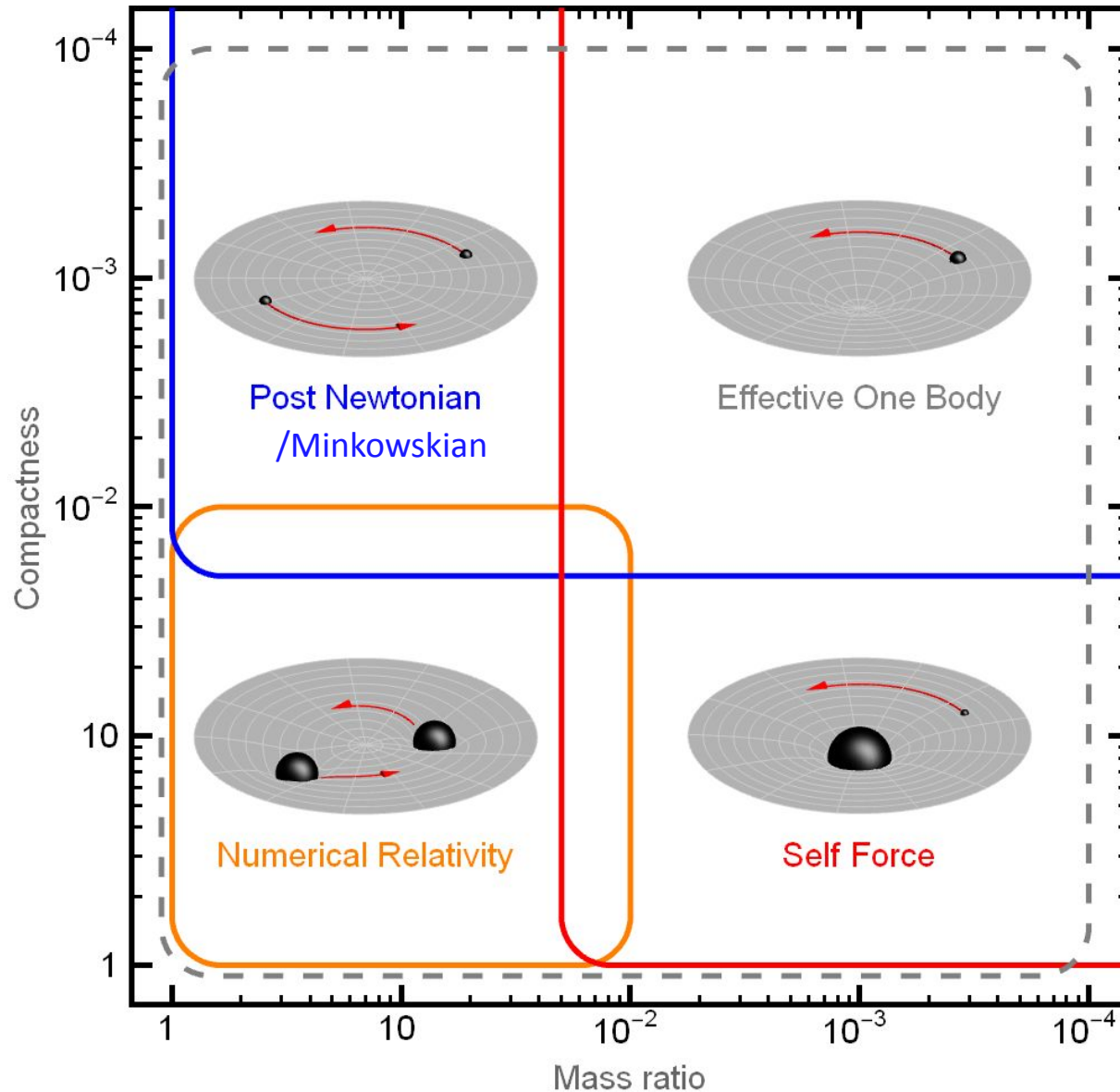
GW models translate GR to template signals.

Accuracy + Computational Speed

Speed is ESSENTIAL for Multi-messenger prospects!



Theory space for BHB mergers



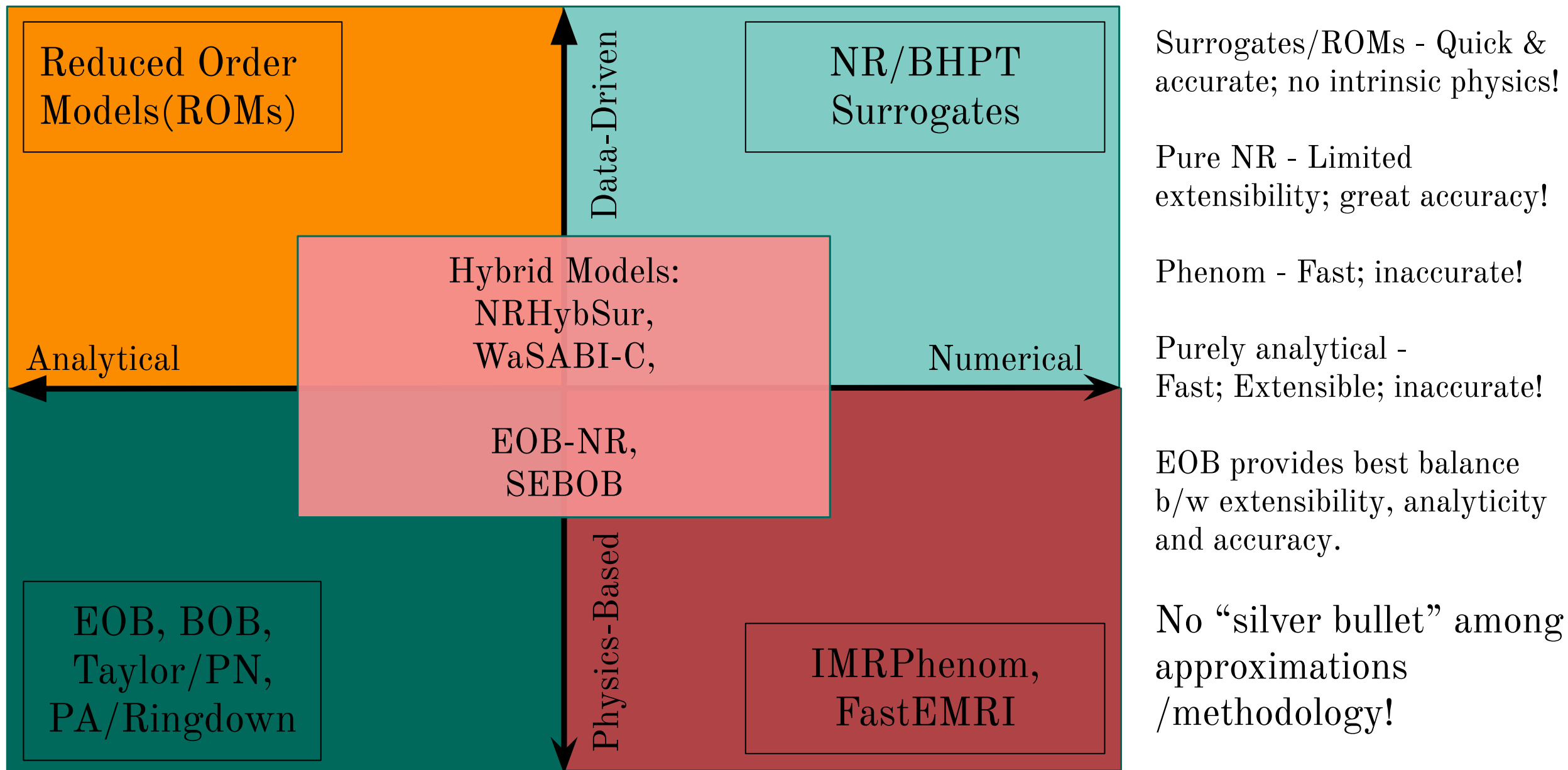
^ Typical signal from BHB coalescence.

Methods (No self-contained solution in GR):

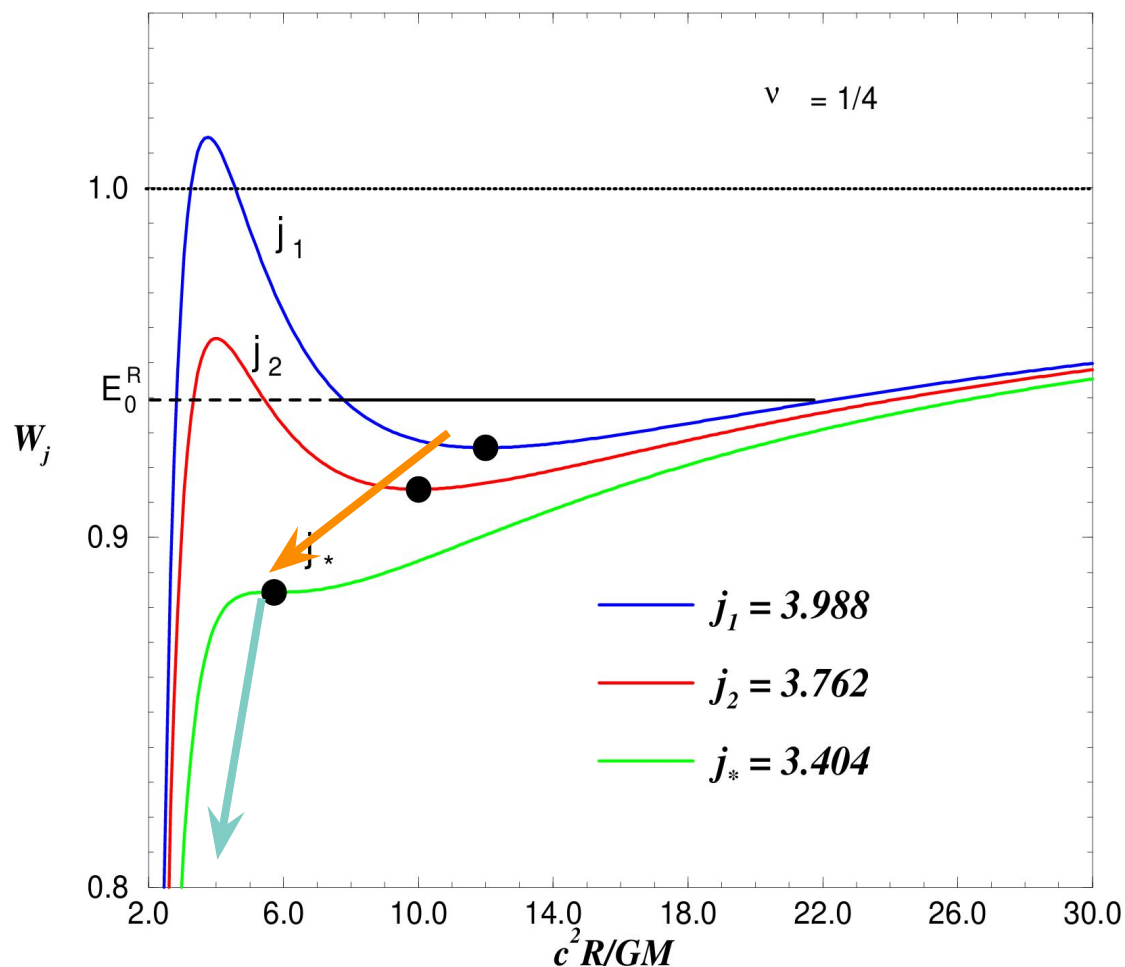
- PN/PM - Purely Analytical
- Self Force - Analytical(PA/Ringdown) or numerical(BHPT)
- NR - Numerical Simulations

Strategies: Improve solutions in one domain
AND
Improve attachment between domains.

The BHB model political compass



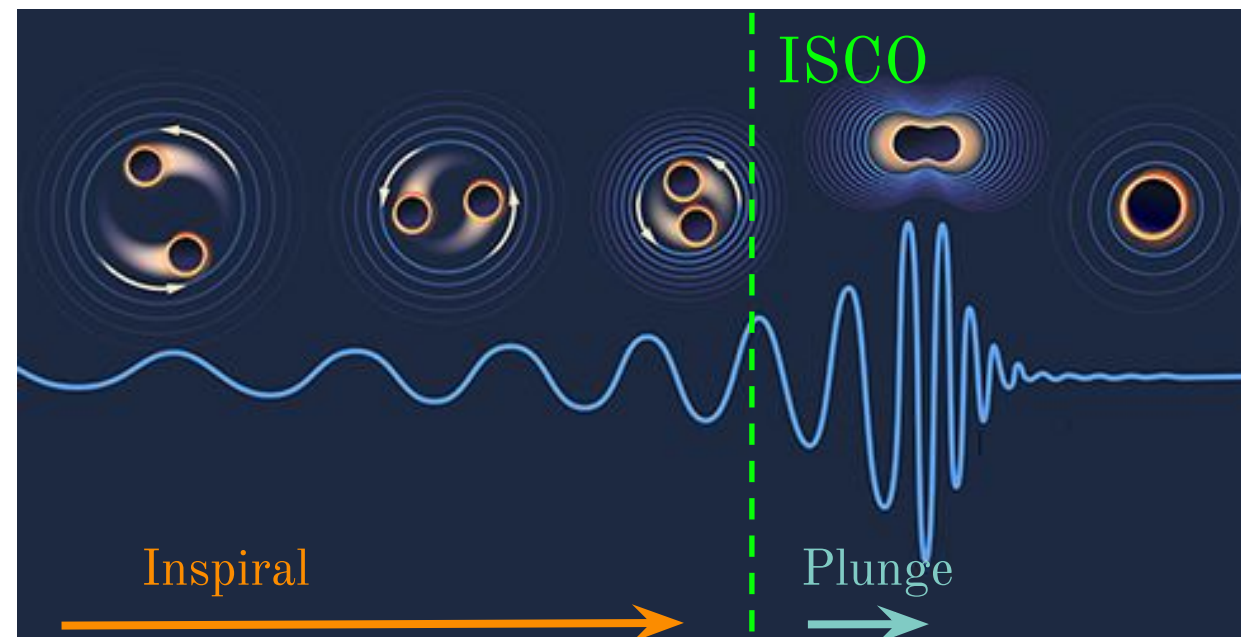
The 2PN Effective One Body Problem



2PN orbits can be mapped to “effective” black hole orbits!

At test particle limit ($v \rightarrow 0$), it is identical to the Schwarzschild black hole!

Motion is mapped to the GW signal!

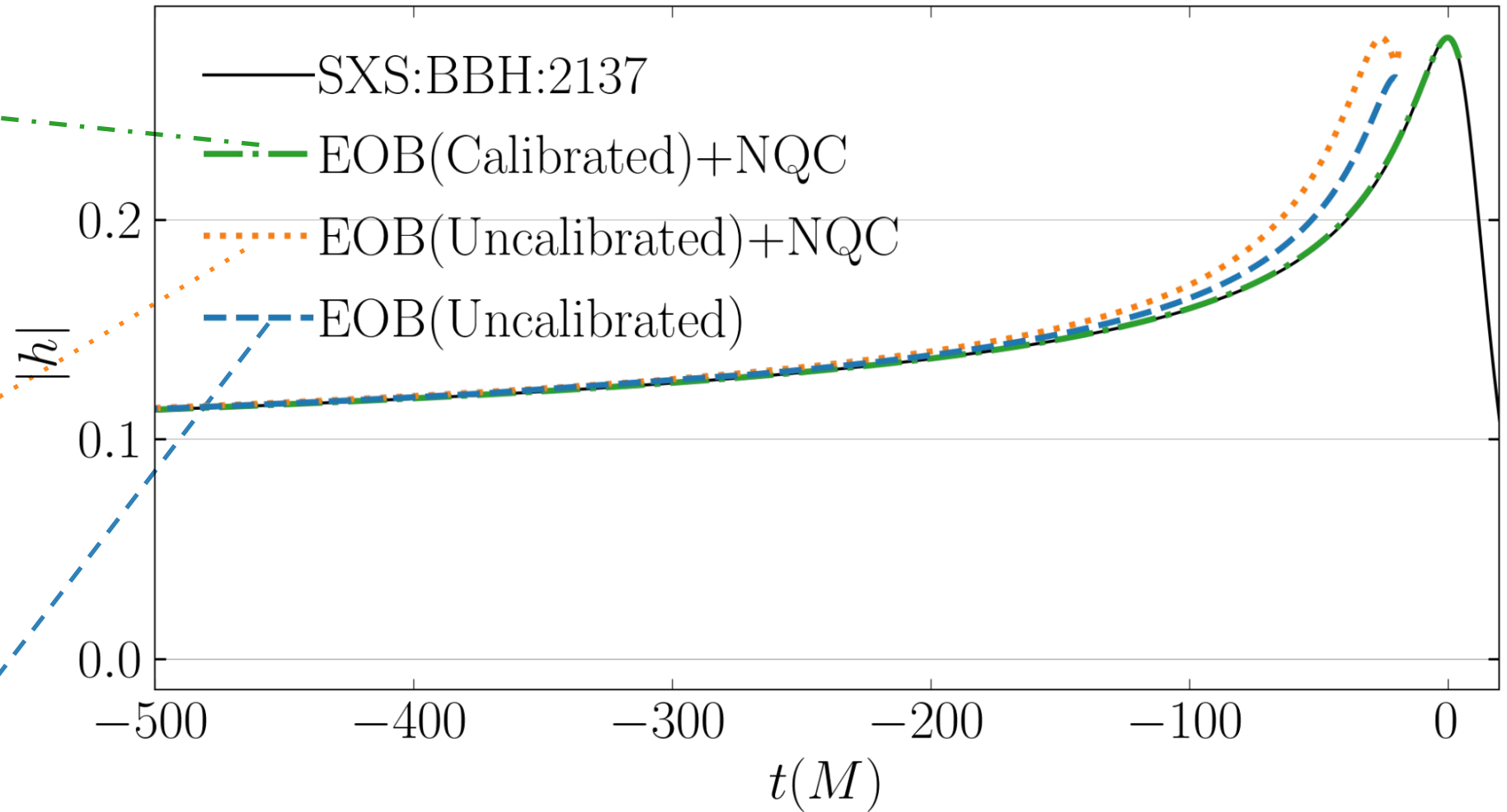


Impact of NR calibration

Non-circular
strain,
Correct
Evolution

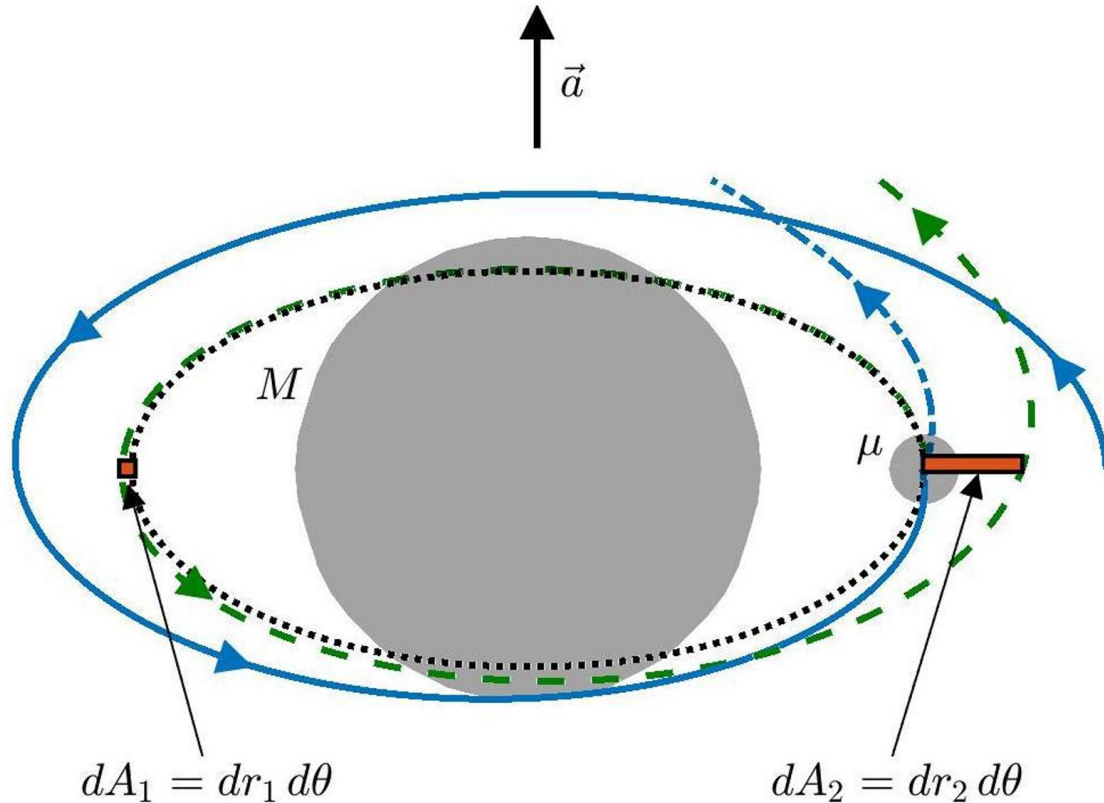
Non-circular
strain,
Incorrect
Evolution

Only circular
strain,
PN diverges
near merger



Two-fold corrections: NQC corrections (strain) and calibrations (Hamiltonian). Address lack of PN information in the late-inspiral/plunge regime

Merger-Ringdown: Backwards One Body (BOB)



MR analog to EOB:

- Final BH spacetime (2 NR fits)
- Radiation $\Rightarrow$ Null Congruences

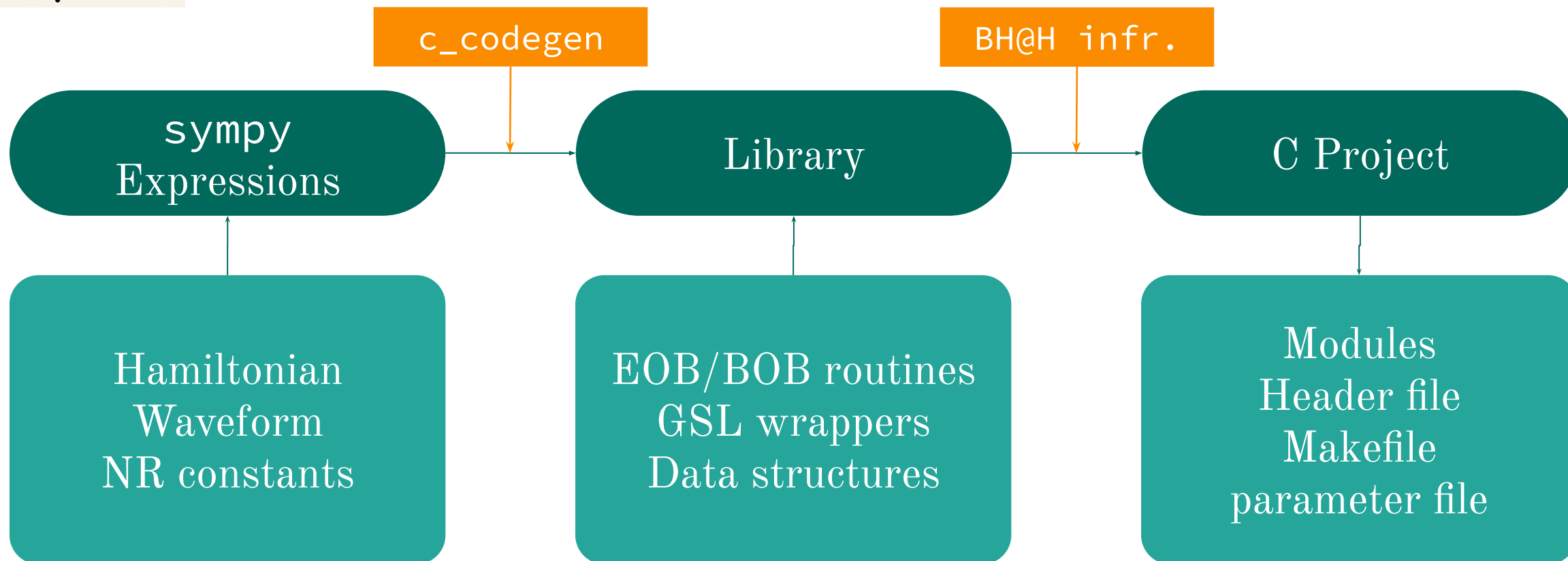
$$|\psi_4| = A_p \text{sech}(\gamma(t - t_p))$$

$$|\mathcal{N}|^2 \sim d(\omega^2)/dt$$

- Can be attached to EOB at merger (SEBOB):
 - EOB NQCs $\rightarrow$ Match to BOB
 - Significantly reduces degree of NR fitting



Computational Speed: NRPy Interface

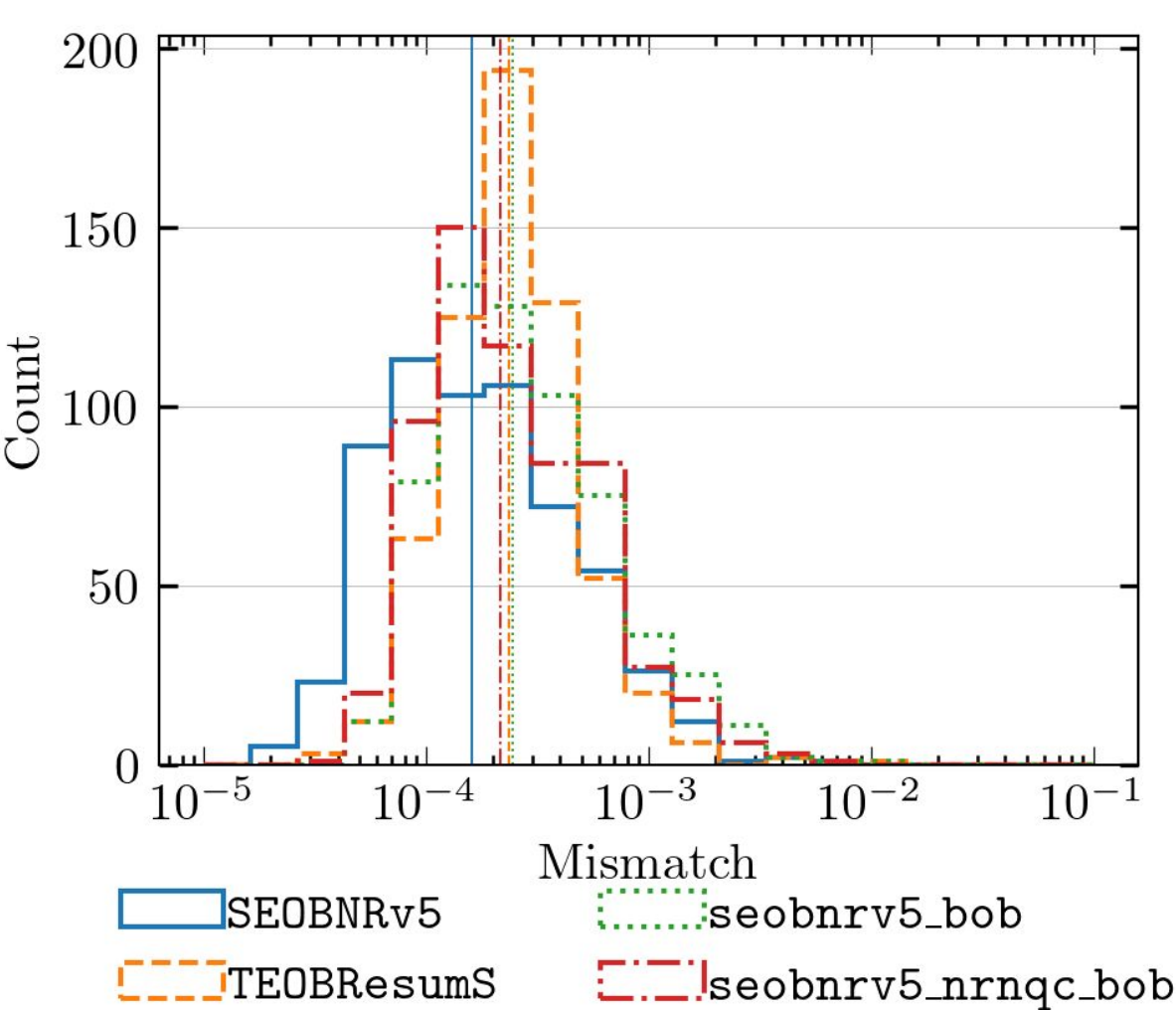


<https://github.com/nrpy/nrpy/>

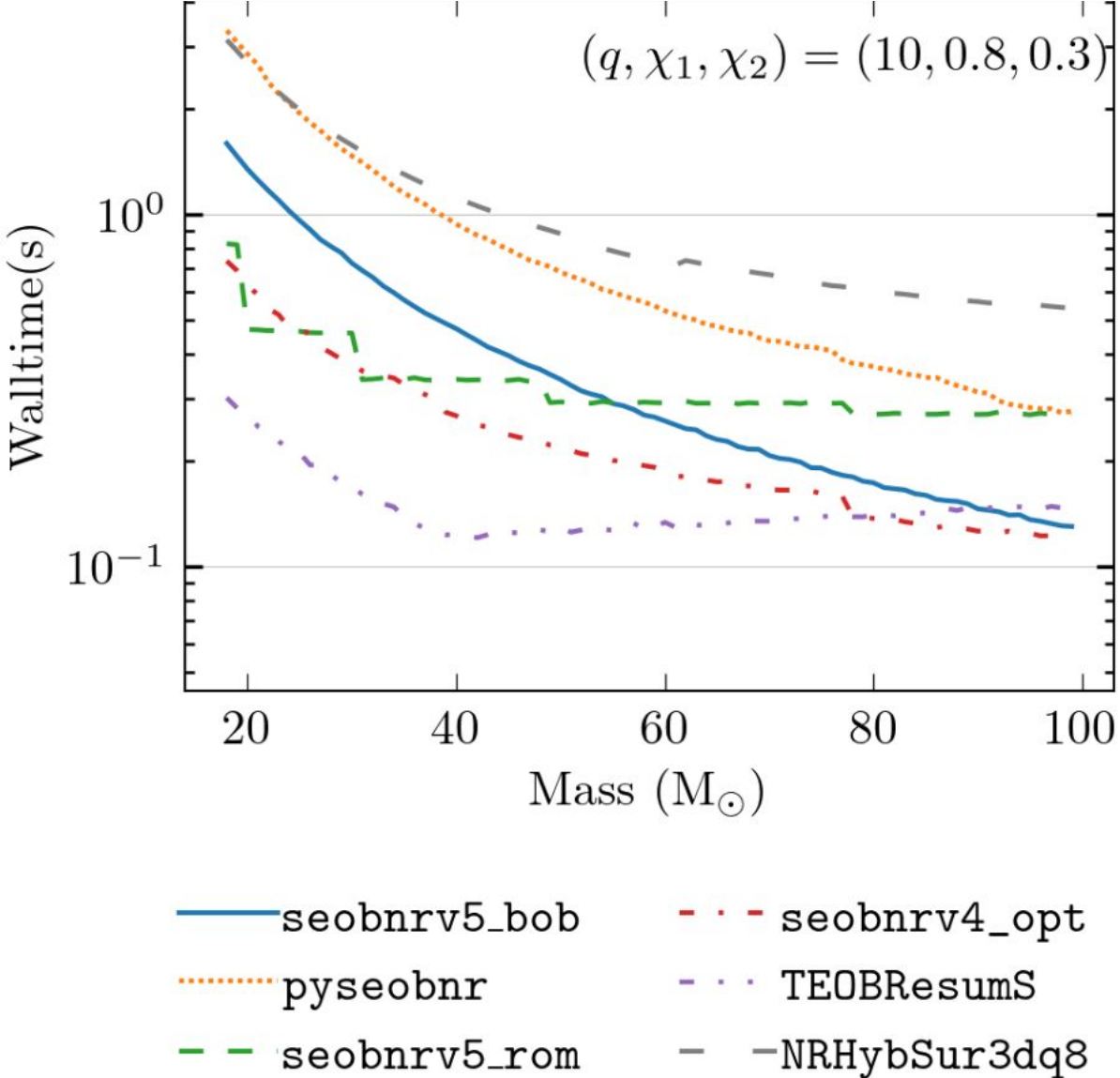
```
pip install nrpy
```

```
python -m nrpy.examples.seobnr5_aligned_spin_inspiral
```

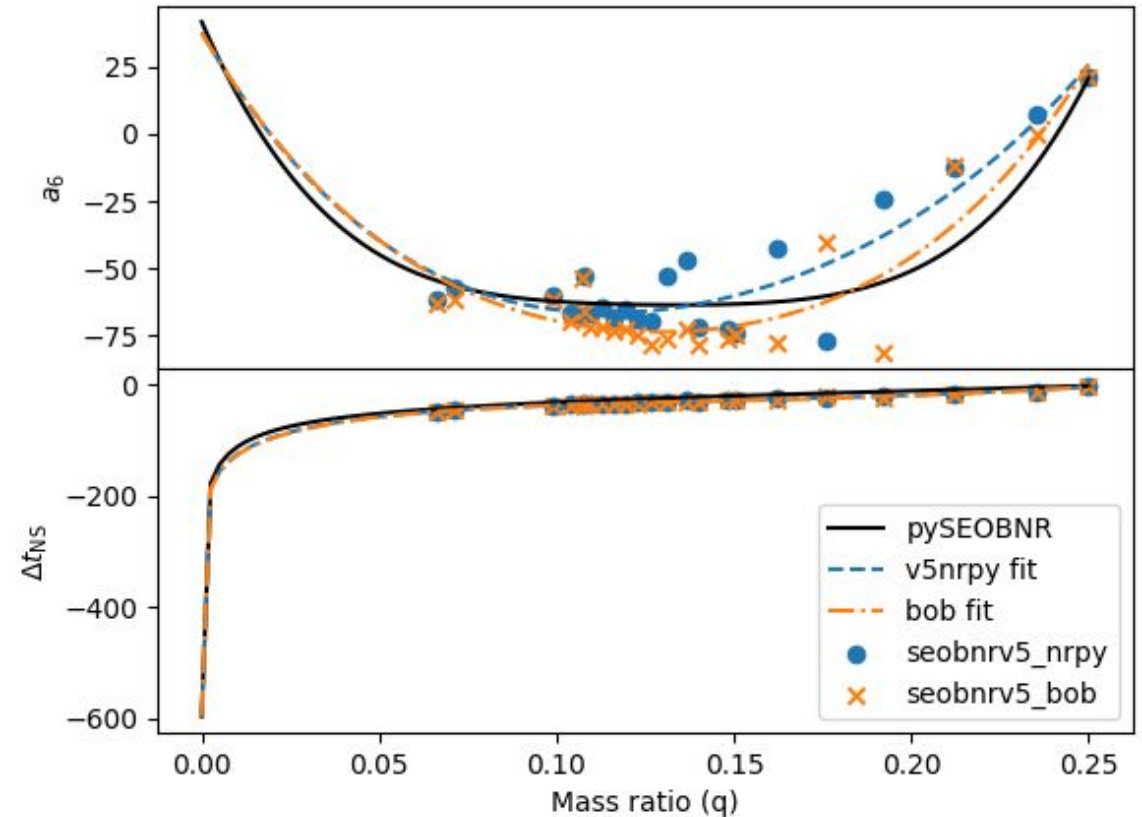
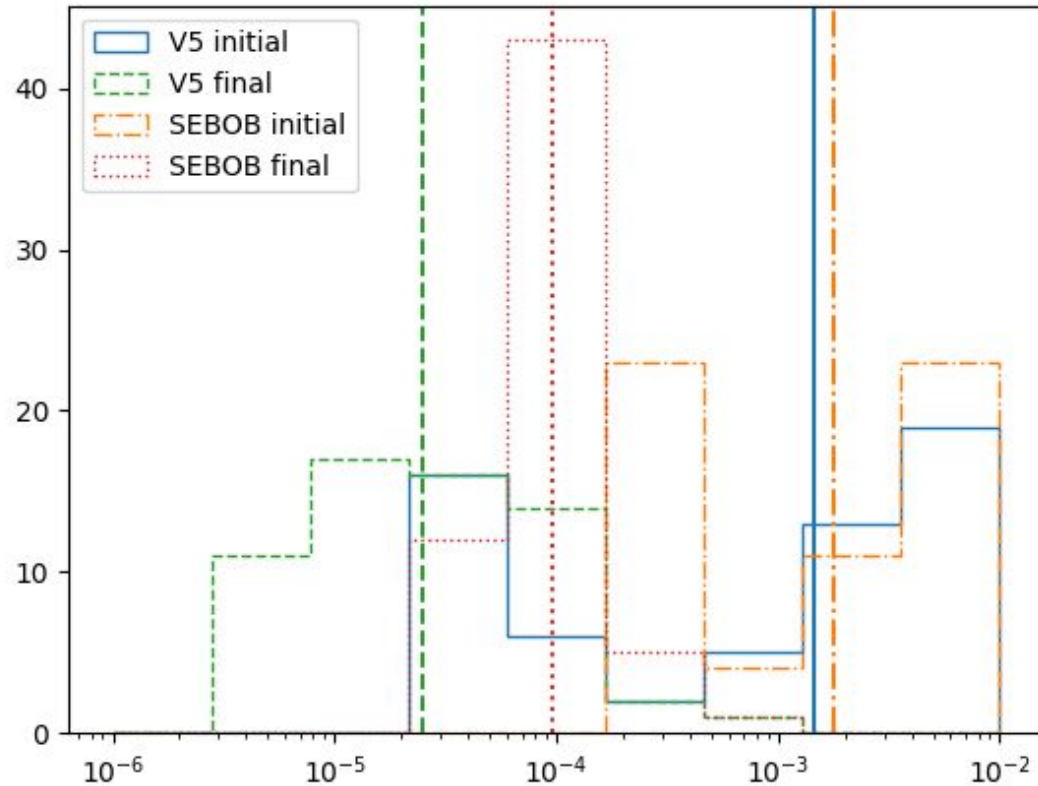
Result: First Principles Model - Accurate & Fast!



$$\mathcal{M} = 1 - \frac{\langle h_1 | h_2 \rangle}{\sqrt{\langle h_1 | h_1 \rangle \langle h_2 | h_2 \rangle}}$$



Next Steps: Calibration routines & Systematic Biases



Re-examine EOB calibration parameters with new NR simulations and new optimization techniques.

Evaluate systematic errors in calibration datasets, estimated parameters.

Extrapolation outside of calibration parameter space.

Next Steps: Neural Calibration of SEOBNRv5

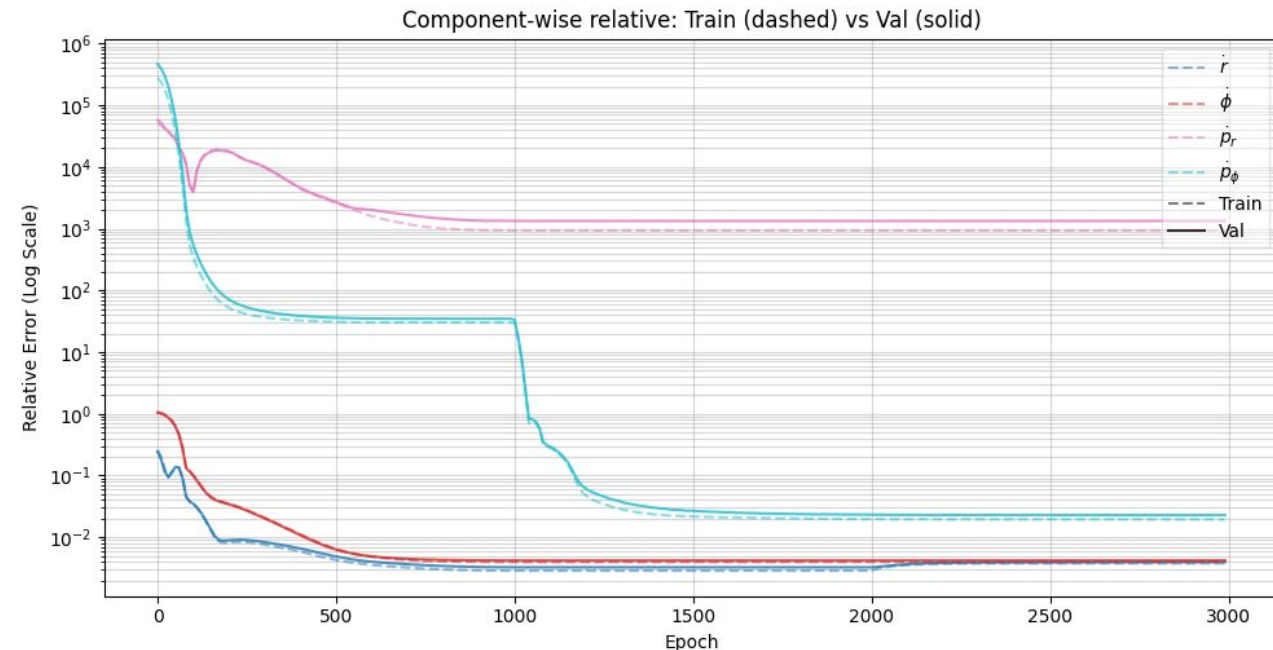
- **Architecture:**
 - Linear: 32 hidden dimensions.
 - Rational Polynomial: (1,5).
- **Training against RHS:**
 - Optimizer: Adam w/ cosine LR
 - 3 stage training on different channels
- **Results:**
 - Can train an NN to mimic v5, but not produce PN connections.
 - Require eccentric corrections to break “gauge” ambiguities.

$$\mathcal{L}(t) = \lambda_0(t) (\mathcal{L}_{\dot{r}} + \mathcal{L}_{\Omega}) + \lambda_1(t) \mathcal{L}_{\mathcal{F}} + \lambda_2(t) \mathcal{L}_{\mathcal{Q}}$$

$$\mathcal{L}_{\dot{r}} = \text{MSE} \left(\frac{\dot{r}_N - \dot{r}}{\dot{r}} \right) \quad \mathcal{L}_{\Omega} = \text{MSE} \left(\frac{\Omega_N - \Omega}{\Omega} \right)$$

$$\mathcal{L}_{\mathcal{F}} = \text{MSE} \left(\frac{\mathcal{F}_{N,\phi} - \mathcal{F}_{\phi}}{\mathcal{F}_{\phi}} \right)$$

$$\mathcal{L}_{\mathcal{Q}} = \text{MSE} \left(\frac{\left(\dot{p}_{N,r_*} - \frac{p_{r_*}}{p_{\phi}} \mathcal{F}_{N,\phi} \right) - \left(\dot{p}_{r_*} - \frac{p_{r_*}}{p_{\phi}} \mathcal{F}_{\phi} \right)}{\left(\dot{p}_{r_*} - \frac{p_{r_*}}{p_{\phi}} \mathcal{F}_{\phi} \right)} \right)$$



Morning I | 10:15 AM - 10:30 AM

Jackson Taylor

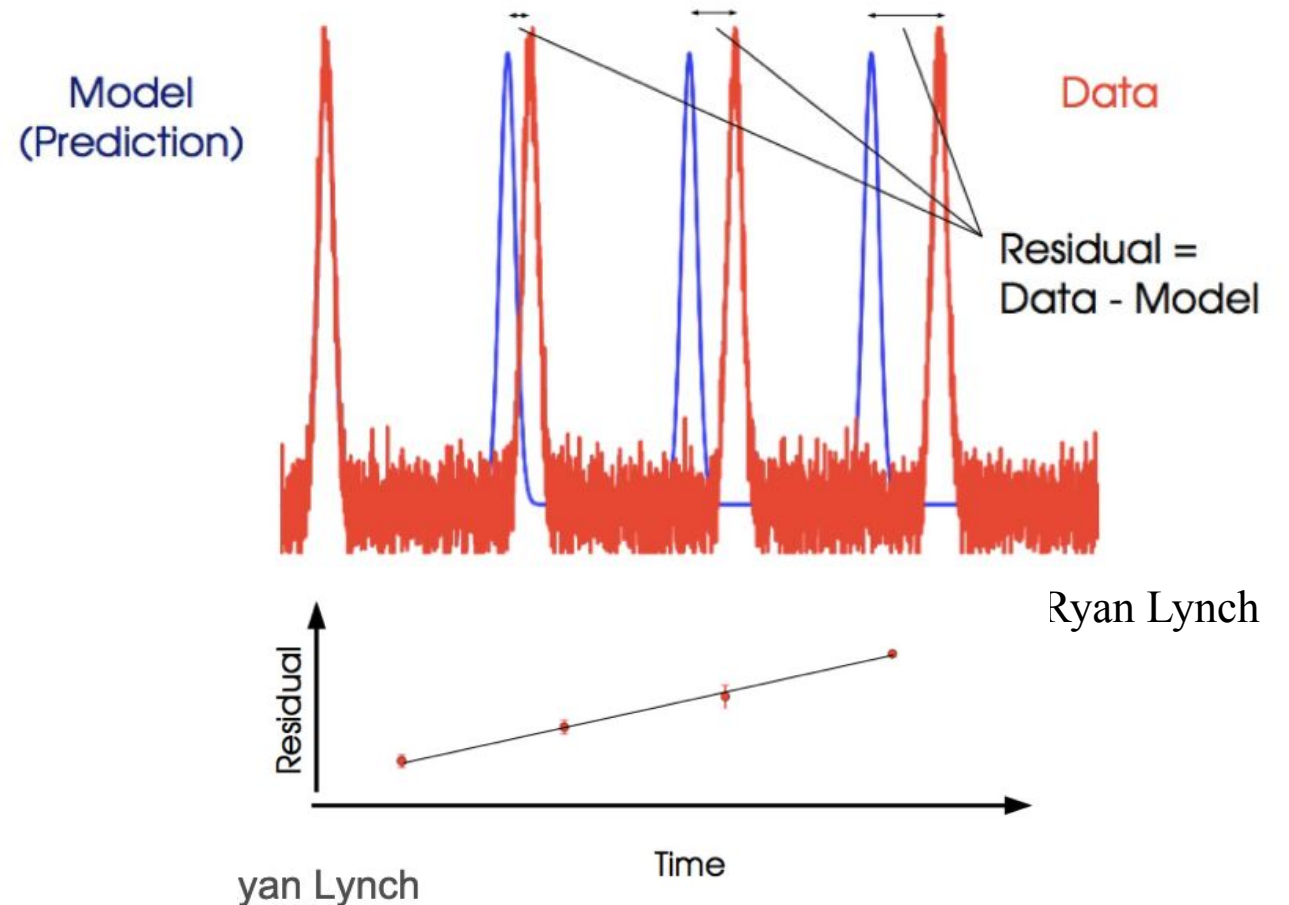
*"Pulsars as
Accelerometers"*



Pulsar Timing

- Pulses will arrive at different times than expected
- $\text{Residual} = \text{Data} - \text{Model}$

Here, the spin frequency is wrongly modeled:



Pulsar Timing – Light Travel Time Delays (Roemer)

$$R_{\text{Roemer}}(t) = \frac{\mathbf{r}(t) \cdot \hat{\mathbf{n}}}{c} = \frac{r_{\text{los}}(t)}{c}$$

$$r_{\text{los}} = r_0 + v_0 t + \frac{1}{2!} a_0 t^2 + \frac{1}{3!} j_0 t^3 + \dots$$

$$\Delta\phi = \Delta f_{\text{spin}} t + \Delta \dot{f}_{\text{spin}} \frac{t^2}{2!} + \Delta \ddot{f}_{\text{spin}} \frac{t^3}{3!}$$

- Need a changing acceleration, or confident knowledge known kinematic/intrinsic terms

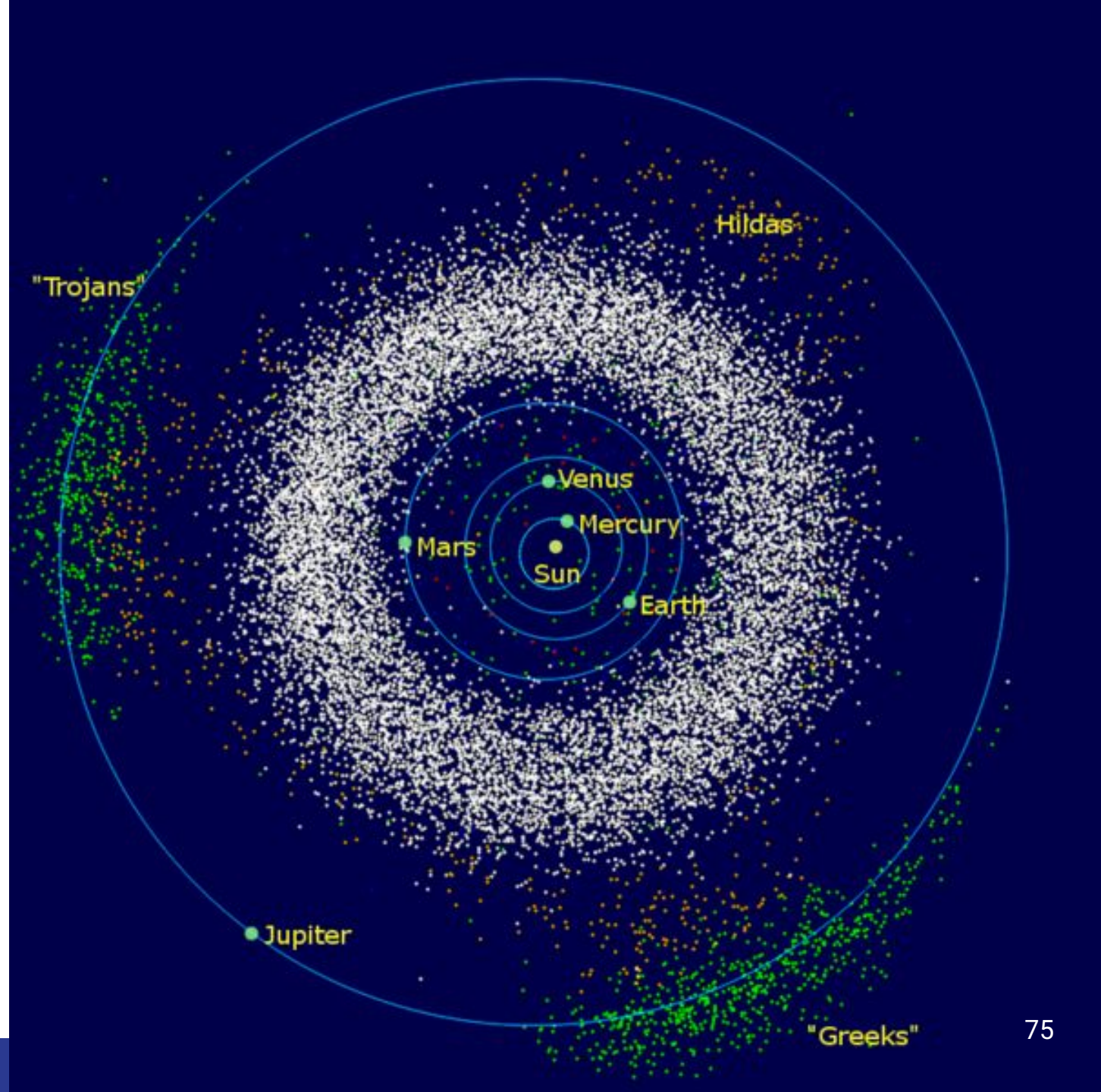
What Accelerations Can We See?

- A pulsar orbiting a companion
- A pulsar undergoing rapid acceleration (or jerk too) in a globular cluster
- A pulsar accelerating under the Galactic potential
- **A pulsar binary hosting a co-orbital Trojan**
- **A Planet Nine in our solar system causing a dipolar acceleration and jerk pattern on the sky**

Trojans in General

- L4/L5 Lagrange Points
- Stable over billions of years
- Predicted to form from disk-based planet formation

$$m_c/m_p < 1/27 \approx 0.037$$



Should binary pulsar systems bear Trojans?

- 8 NANOGrav 15-year binary pulsars satisfy stability

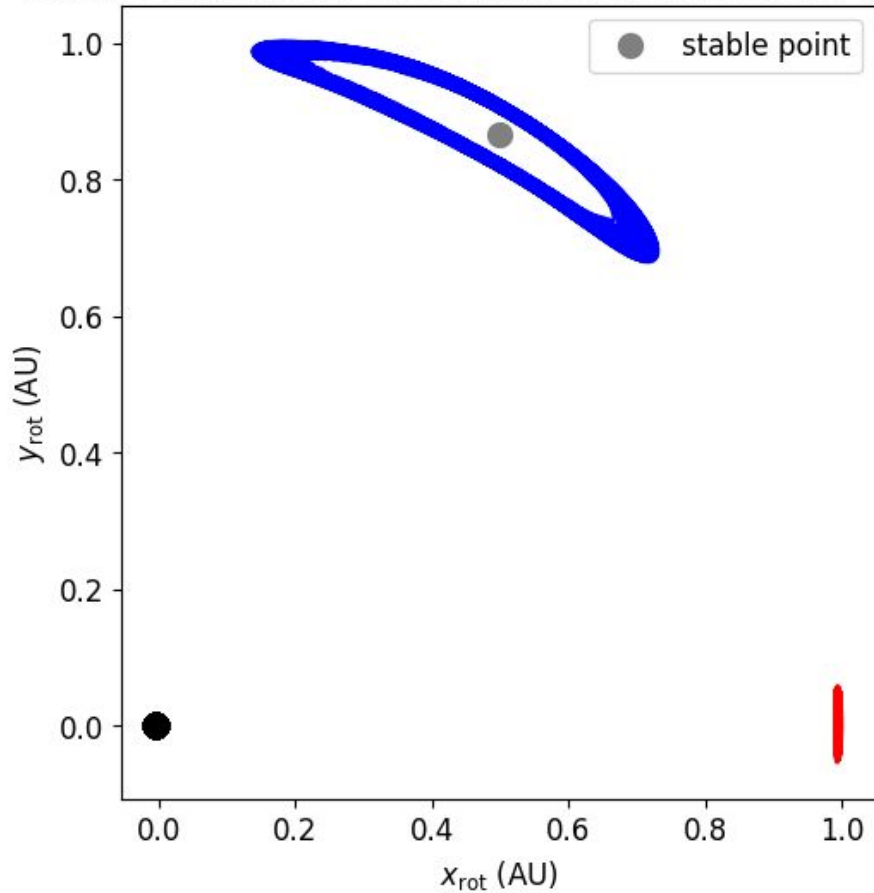
$$m_c/m_p < 1/27 \approx 0.037$$

- Pulsar planets likely formed from a post-supernova disk
- Stripped matter from the companion may accumulate in the stable Lagrange points

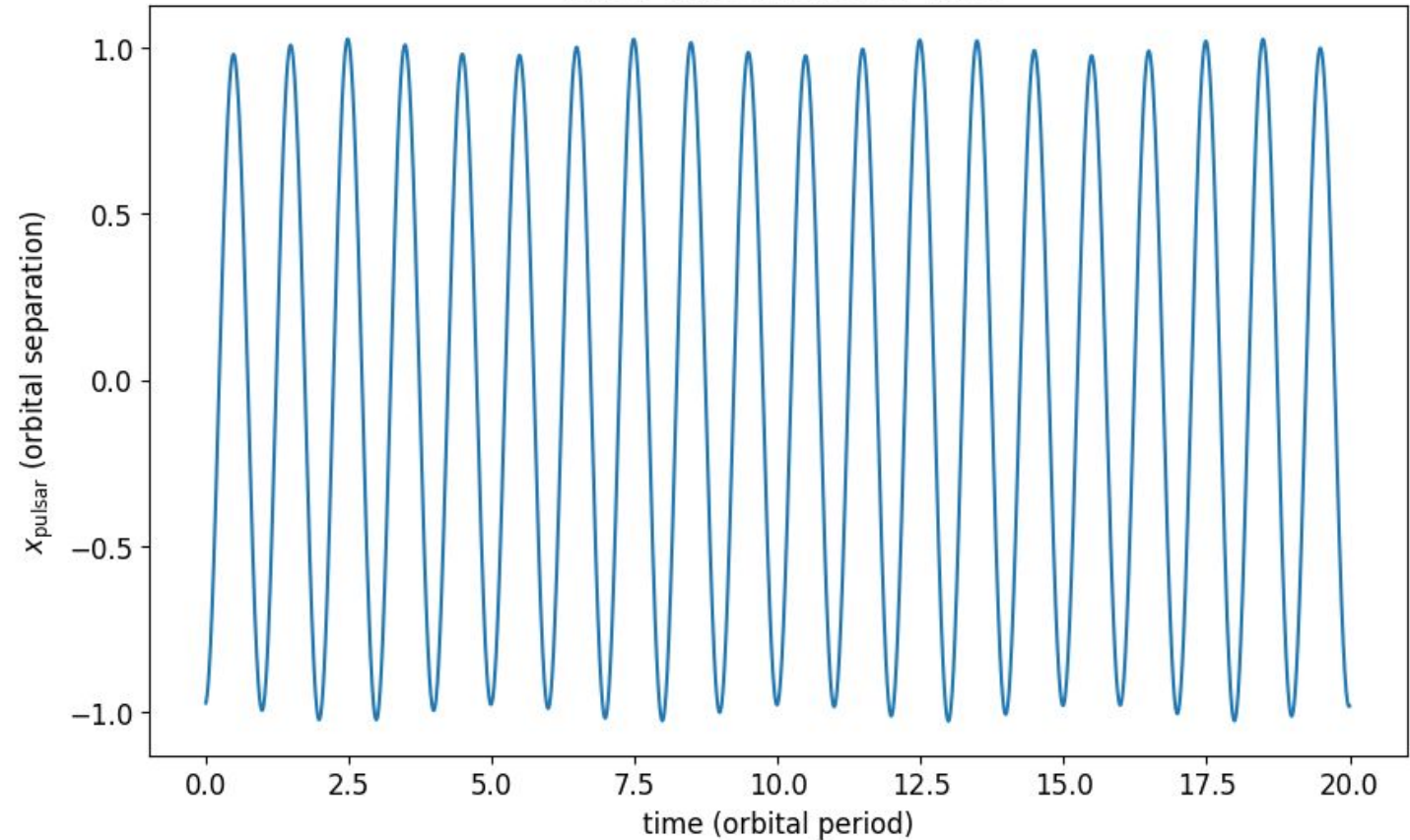
Pulsar	$m_{c,\min}/m_p$
J0023+0923	0.012
J0610−2100	0.016
J0636+5128	0.005
J1630+3550	0.007
J1705−1903	0.030
J1719−1438	0.001
J1745+1017	0.010
J2214+3000	0.010
J2234+0944	0.011

TOA-Only Method that Measures Librations

Pulsar, companion, and trojan position (rotating frame)



Pulsar x-position over time

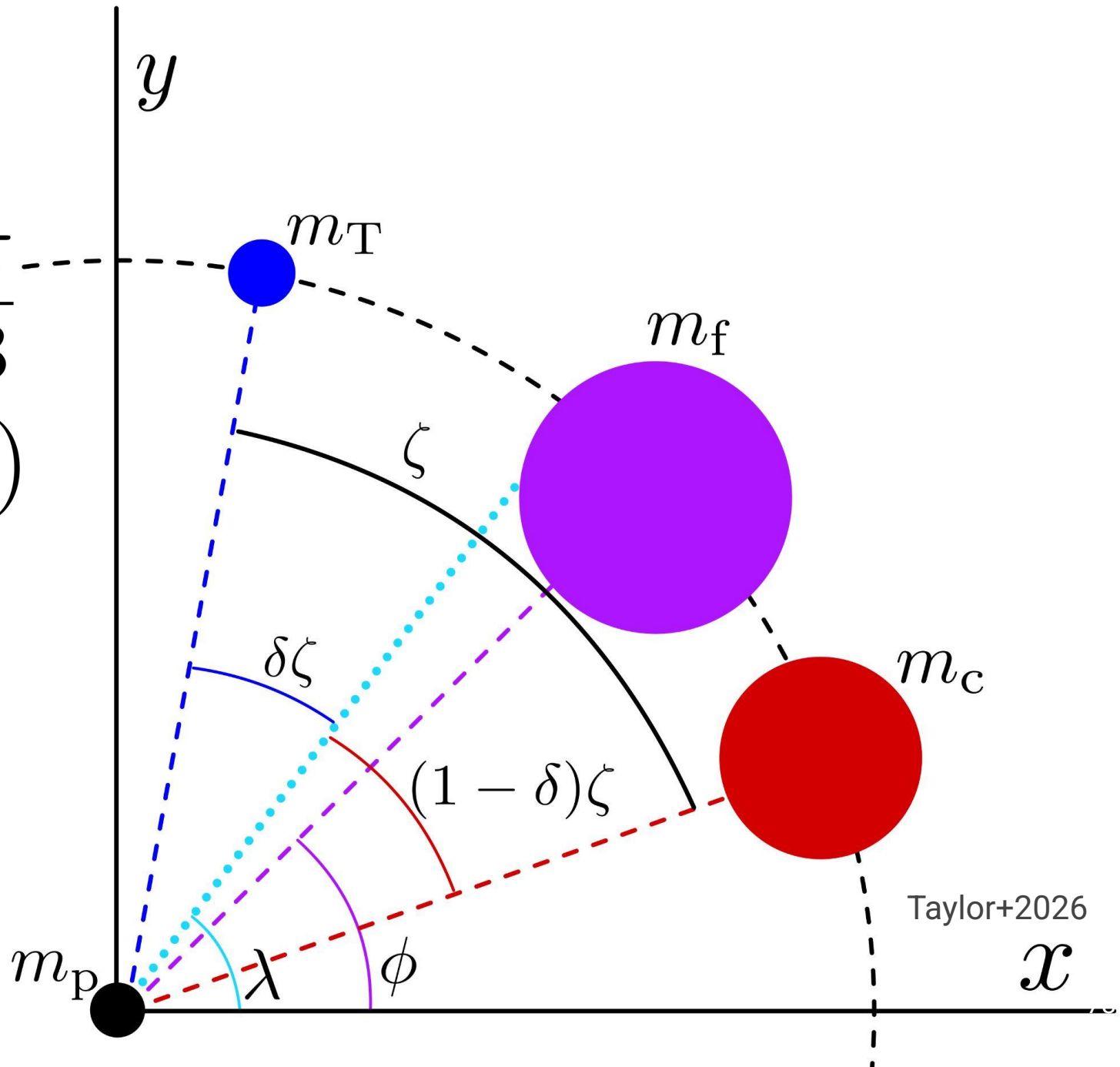


Libration Model

$$\zeta = z \cos (\nu t + \varphi) + \frac{\pi}{3} \dots$$

$$\delta = m_{\mathrm{c}}/(m_{\mathrm{c}} + m_{\mathrm{T}})$$

$$\lambda = n_{\text{b}} \tilde{t} + \lambda_0$$

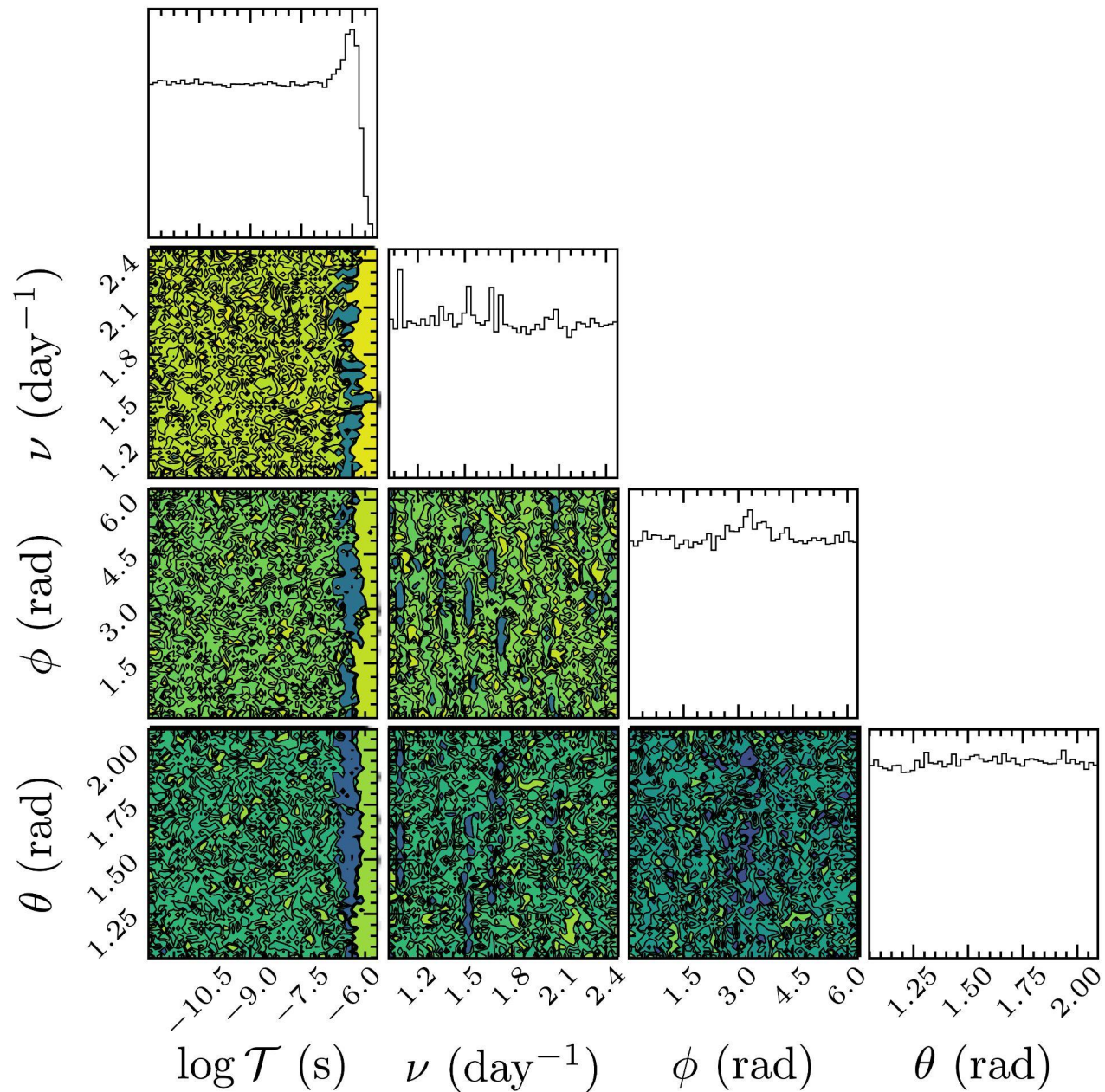


Taylor+2026

Pulsar Trojan Timing Delay Model

$$\Delta\tau = \mathcal{T} \left[\cos(\nu\tilde{t} + \varphi) \cos(n_b\tilde{t} + \theta) + \frac{2}{3} \frac{\nu}{n_b} \sin(\nu\tilde{t} + \varphi) \sin(n_b\tilde{t} + \theta) \right]$$

- **Deterministic and closed form** (no 3-body integration required)
- n_b = binary orbital frequency
- ν = librational frequency
- $\tilde{t} \equiv t - T_{\text{asc}}$
- θ = a direct measure of the fractional Trojan mass. Physically between $\pi/3$ and $2\pi/3$. See bonus slides for more detail.
- $\mathcal{T}$ = “libration strength” (units of time)
- φ = arbitrary phase

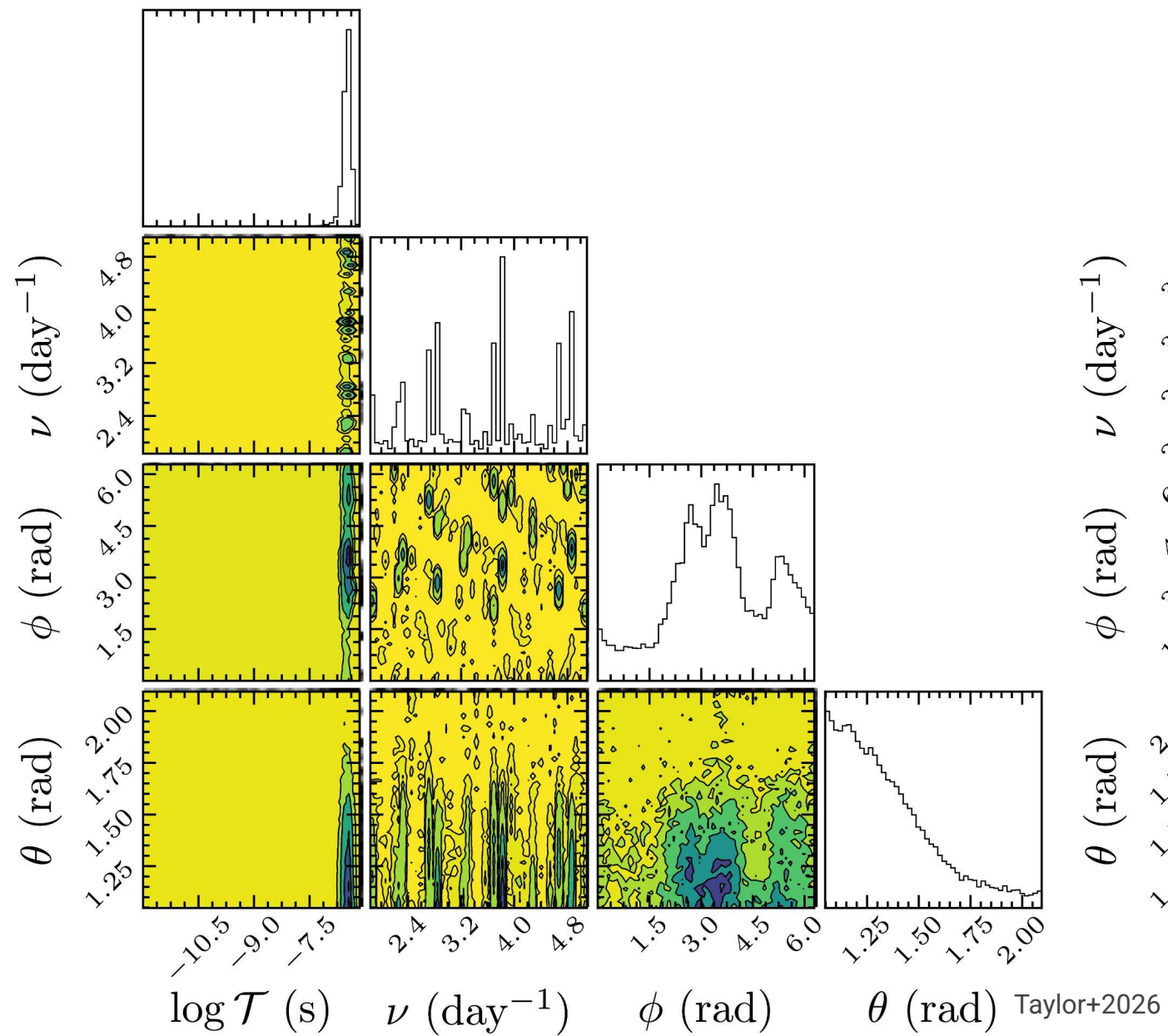


Enterprise and PTMCMC Results

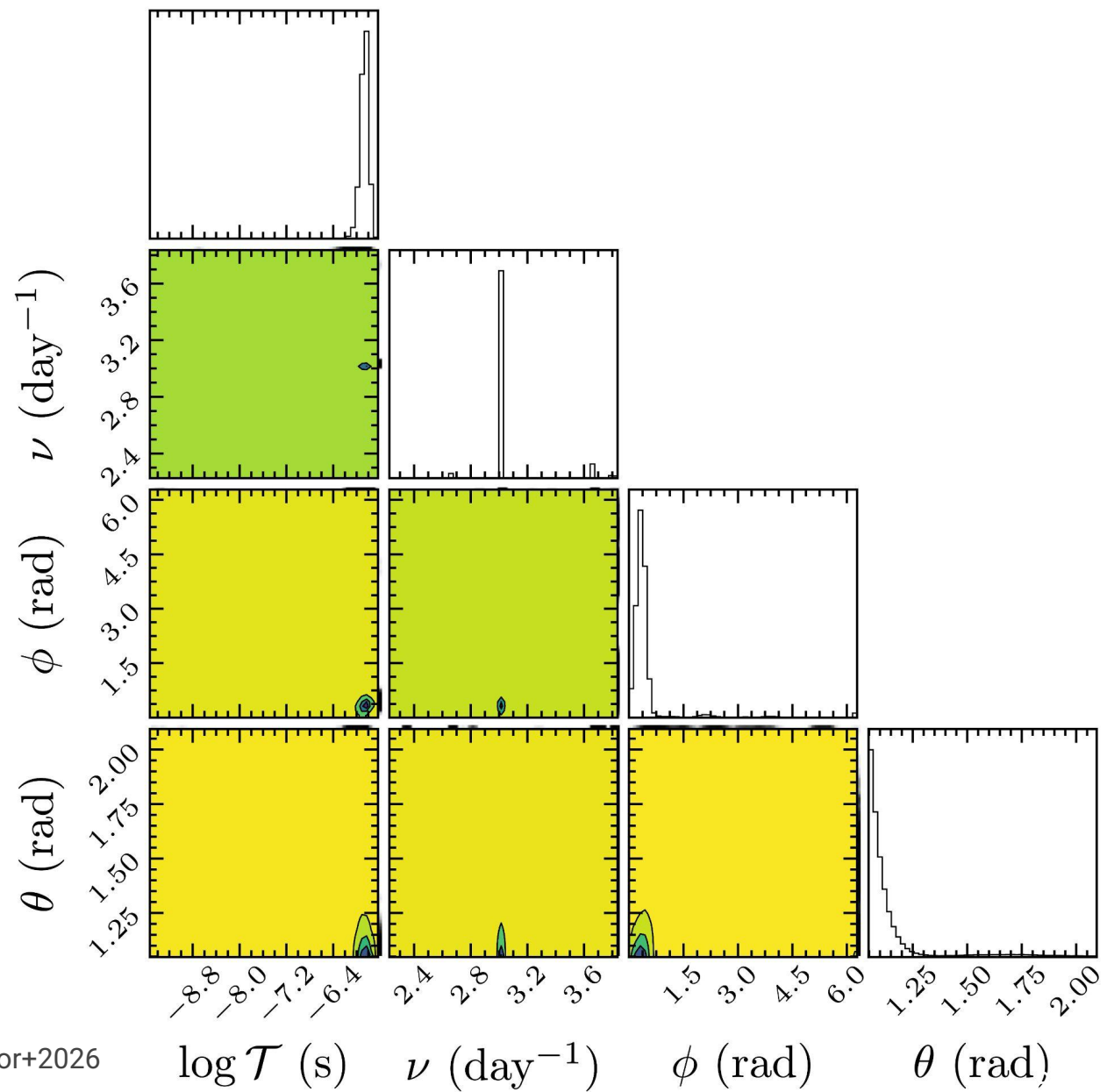
PSR	$\mathcal{B}_{\mathcal{T}}$	$\mathcal{T}_{\text{UL}}$ (μs)	$m_{\text{T,UL}}$ ($M_{\oplus}$)	$\mathcal{B}_{\xi}$
J0023+0923	11.5(2)	0.47	0.79	0.95(7)
J0610–2100	0.824(7)	2.8	1.8	-
J0636+5128	0.801(8)	0.37	0.81	-
J1705–1903	5700(300)	1.7	2.7	0.83(5)
J1719–1438	0.73(1)	1.4	2.0	-
J1745+1017	0.792(8)	4.2	1.5	-
J2214+3000	0.90(1)	1.8	1.1	-
J2234+0944	0.96(2)	1.0	0.66	-

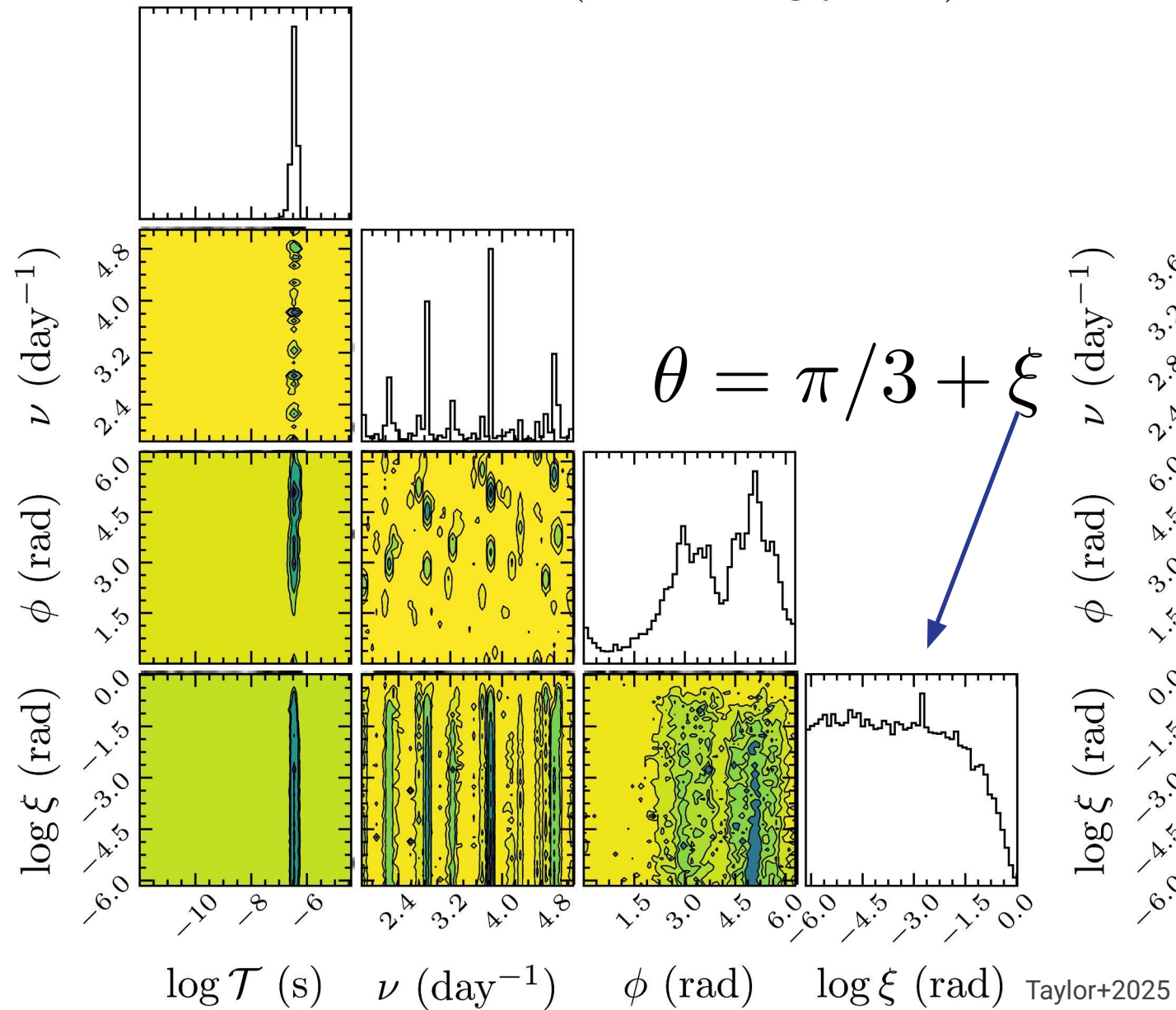
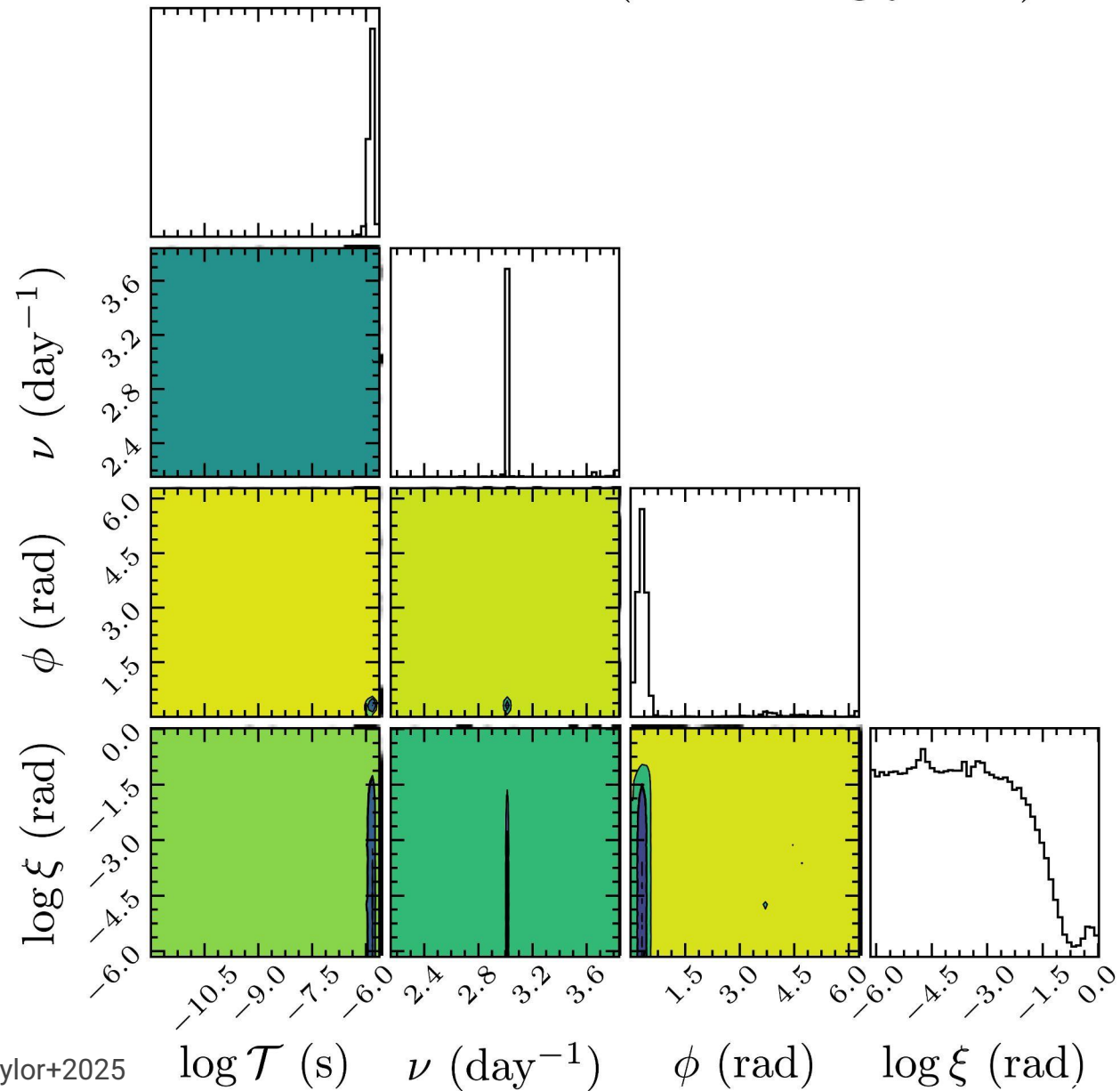
Savage-Dickey: $\mathcal{B}_{\mathcal{T}} = \frac{\text{prior}(\mathcal{T} = 0)}{\text{post}(\mathcal{T} = 0)}$

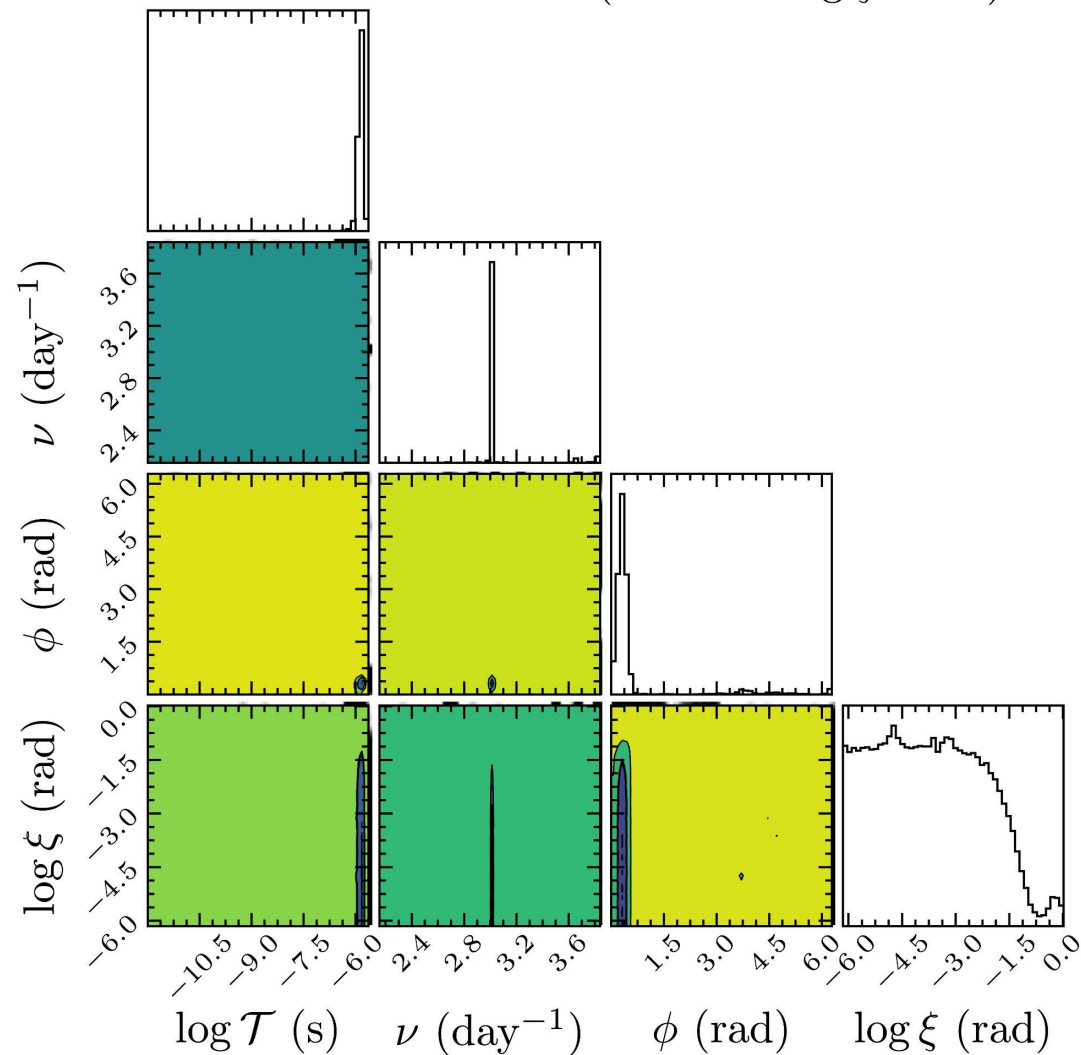
J0023+0923 Posteriors



J1705–1903 Posteriors



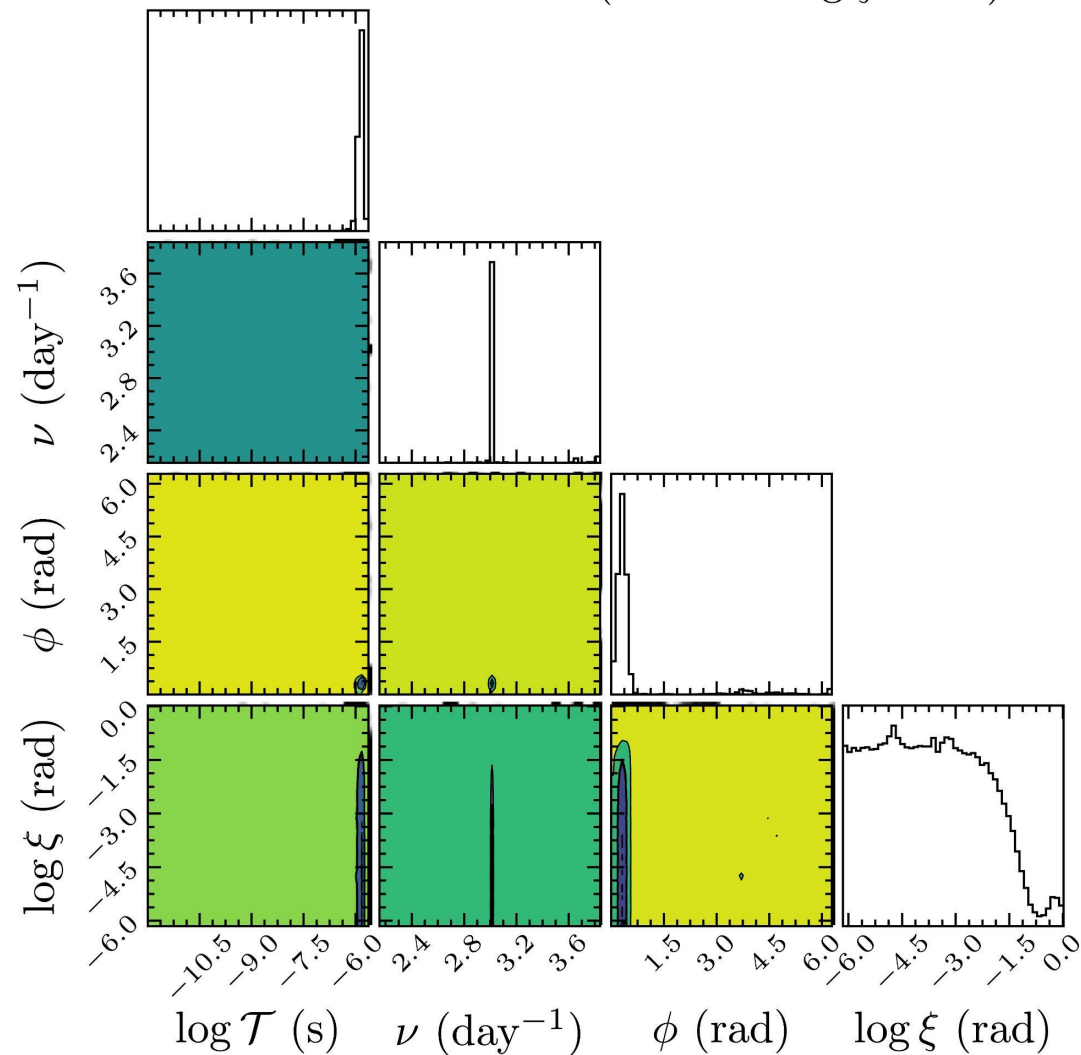
J0023+0923 Posteriors (Uniform $\log \xi$ Prior)J1705–1903 Posteriors (Uniform $\log \xi$ Prior)

J1705–1903 Posteriors (Uniform $\log \xi$ Prior)

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J2214+3000	0.90(1)	1.8	1.1	-
J2234+0944	0.96(2)	1.0	0.66	-

$$\mathcal{B}_{\xi} = \frac{\text{prior}(\theta = \pi/3)}{\text{post}(\theta = \pi/3)}$$

PSR	δ	$q \equiv m_{\text{p}}/m_{\text{c}}$	z ($^{\circ}$)	m_{T} (M_{J})	m_{c} ($\text{M}_{\odot}$)	I ($^{\circ}$)
J0023+0923	$0.064^{+0.082}_{-0.049}$	$31.3940^{+0.0004}_{-0.0006}$	$0.0095^{+0.0335}_{-0.0054}$	$3.5^{+5.6}_{-2.7}$	$0.0458^{+0.014}_{-0.002}$	13^{+1}_{-5}
J1705–1903	$0.042^{+0.061}_{-0.031}$	29.6472 ± 0.0005	$0.019^{+0.052}_{-0.011}$	$2.4^{+4.0}_{-1.8}$	$0.048^{+0.014}_{-0.002}$	32^{+3}_{-12}

J1705–1903 Posteriors (Uniform $\log \xi$ Prior)

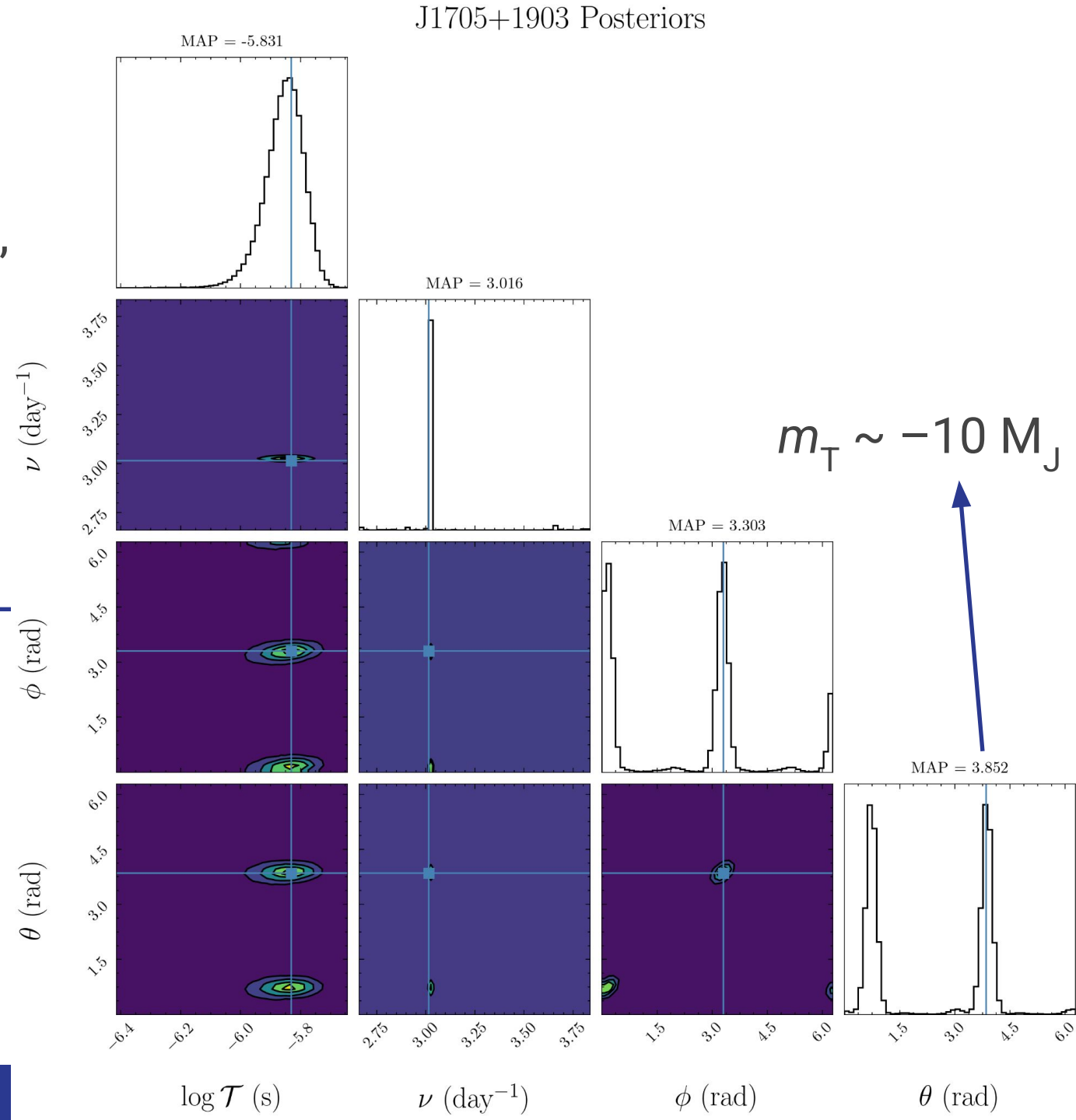
PSR	$\mathcal{B}_{\mathcal{T}}$	$\mathcal{T}_{\text{UL}}$ (μs)	$m_{\text{T,UL}}$ ($\text{M}_{\oplus}$)	$\mathcal{B}_{\xi}$
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Causes and Implications

- No extrojans, but strong ($B \sim 10$ and $B \sim 6000$) false-positive “noise” is present.
 - Black widow systems. Chaotic mass transfers.
-
- Pulsar Trojans are likely rare. Prevalence upper limit of 28%
 - **Should these pulsars remain in the array?**



Summary

- No pulsar trojans detected. $\sim 1 M_{\oplus}$ constraints for the NG systems. (Published)

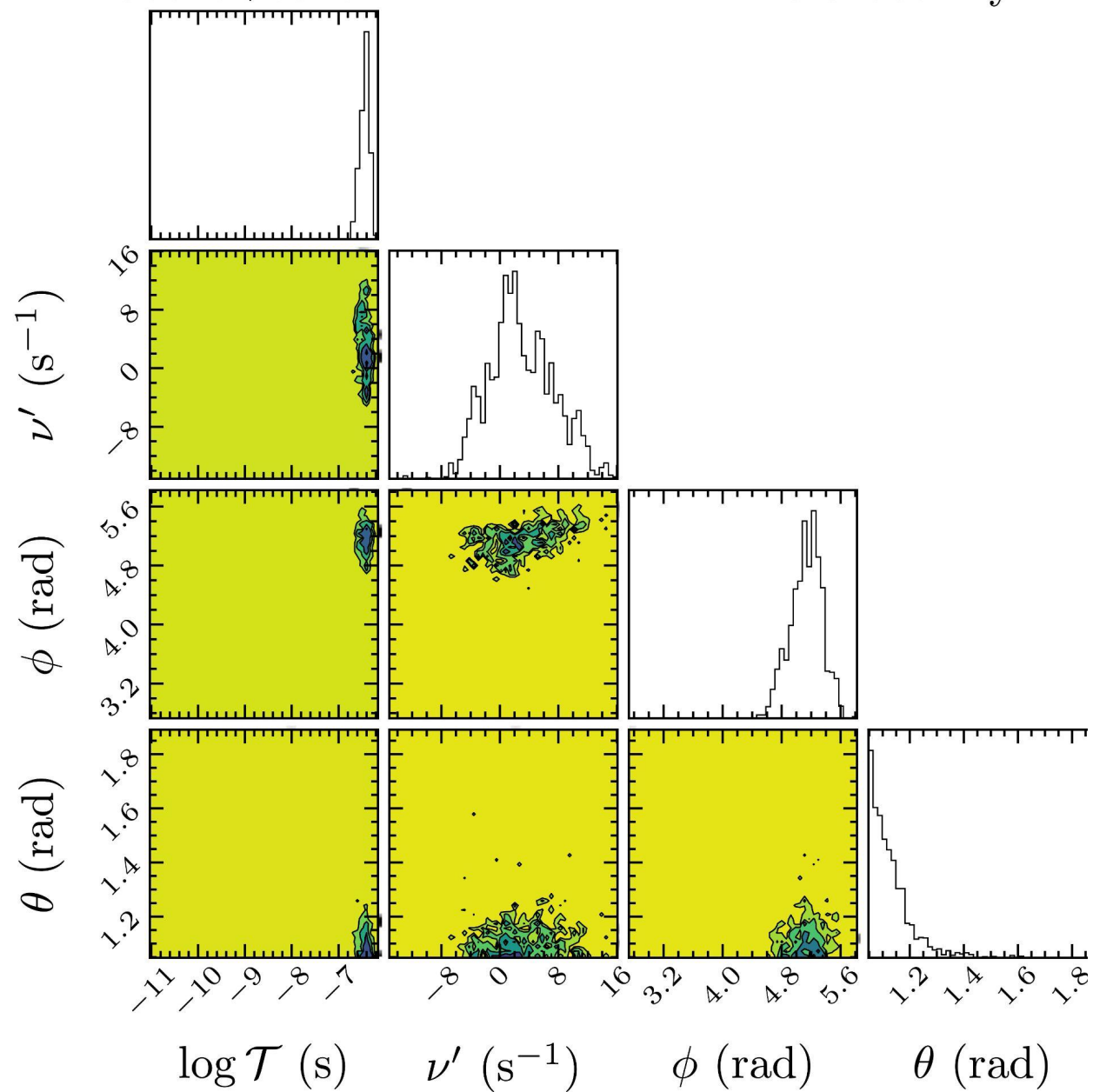
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Pulsar
Trojans
Paper in Ap

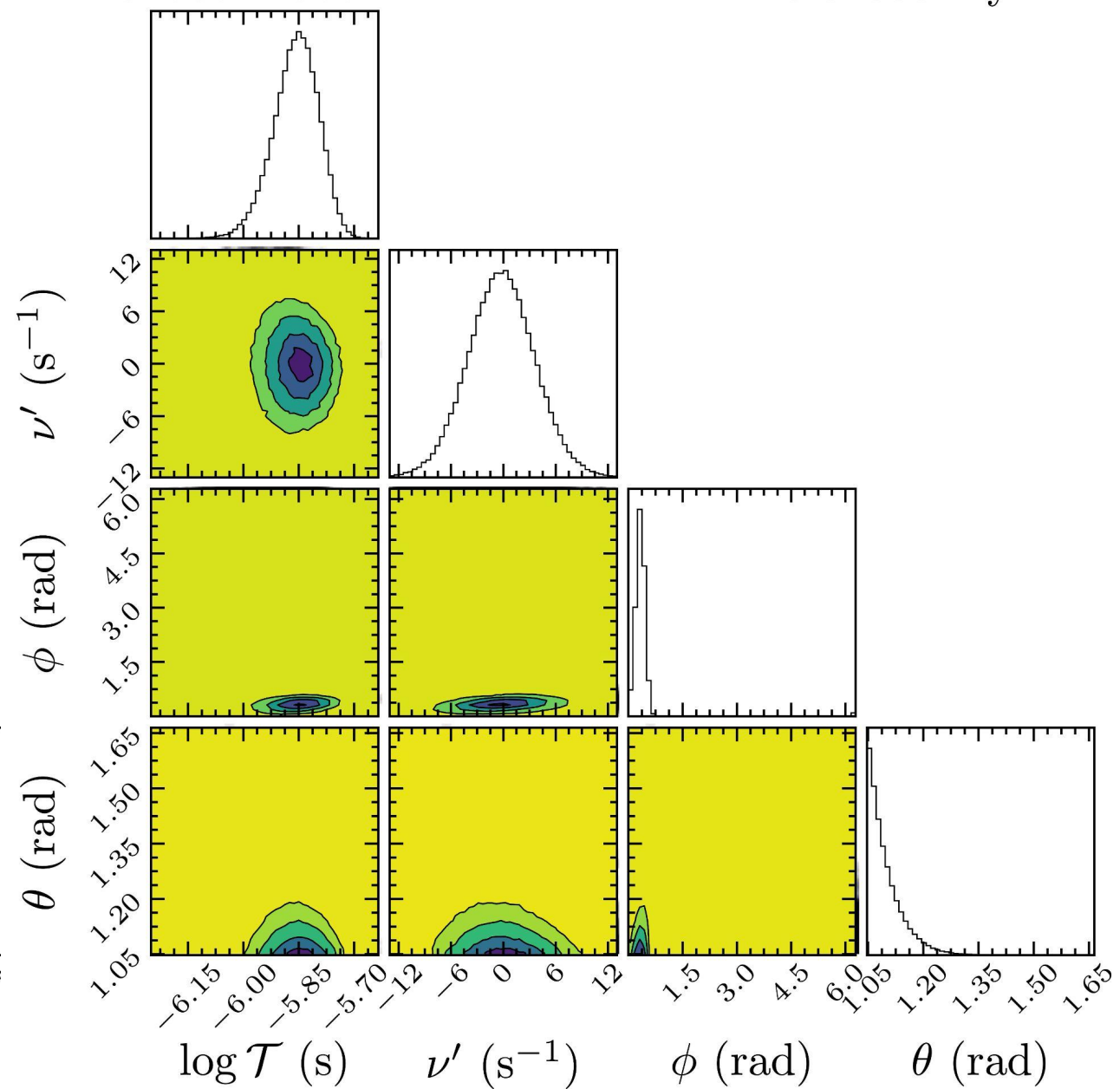


Bonus slides

J0023+0923 Posteriors Near $\nu = 3.81759 \text{ day}^{-1}$



J1705-1903 Posteriors Near $\nu = 3.01600 \text{ day}^{-1}$

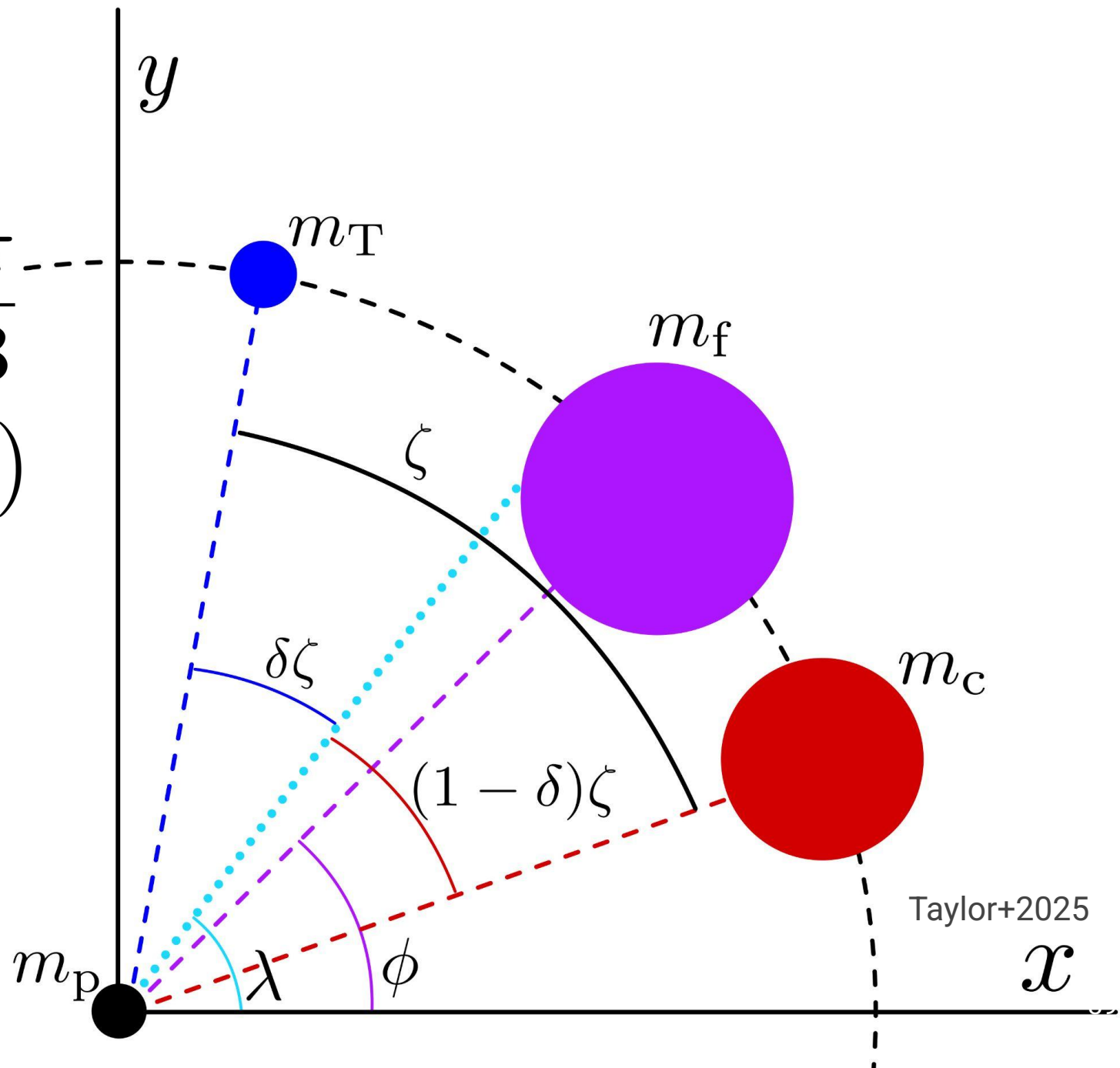


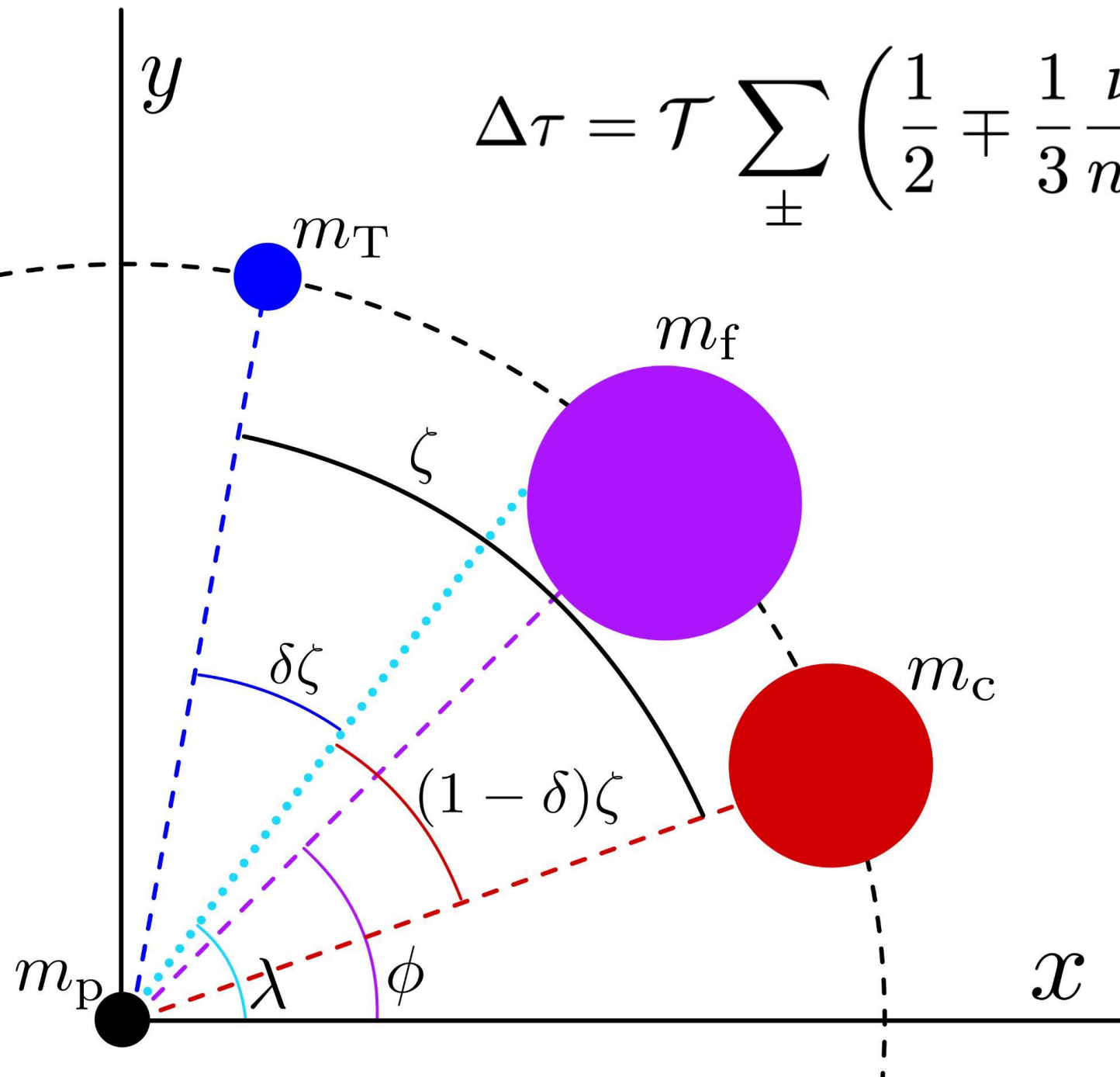
Libration Model

$$\zeta = z \cos(\nu t + \varphi) + \frac{\pi}{3}$$

$$\delta = m_c / (m_c + m_T)$$

$$\lambda = n_b \tilde{t} + \lambda_0$$





$$\Delta\tau = \mathcal{T} \sum_{\pm} \left(\frac{1}{2} \mp \frac{1}{3} \frac{\nu}{n_b} \right) \cos \left[(n_b \pm \nu) \tilde{t} + (\theta \pm \varphi) \right]$$

Trojan TOA Model

$$\nu = n_b \sqrt{\frac{27\mu}{4}}$$

$$\mathcal{T} = \alpha z \delta (1 - \delta),$$

$$K = \alpha \sqrt{1 - \delta(1 - \delta)},$$

$$\theta = \arctan \left(\frac{\delta \sqrt{3}}{2 - \delta} \right) + \frac{\pi}{3}$$

$$\alpha = \mu a \sin(I) / c$$

Stability as a function of eccentricity

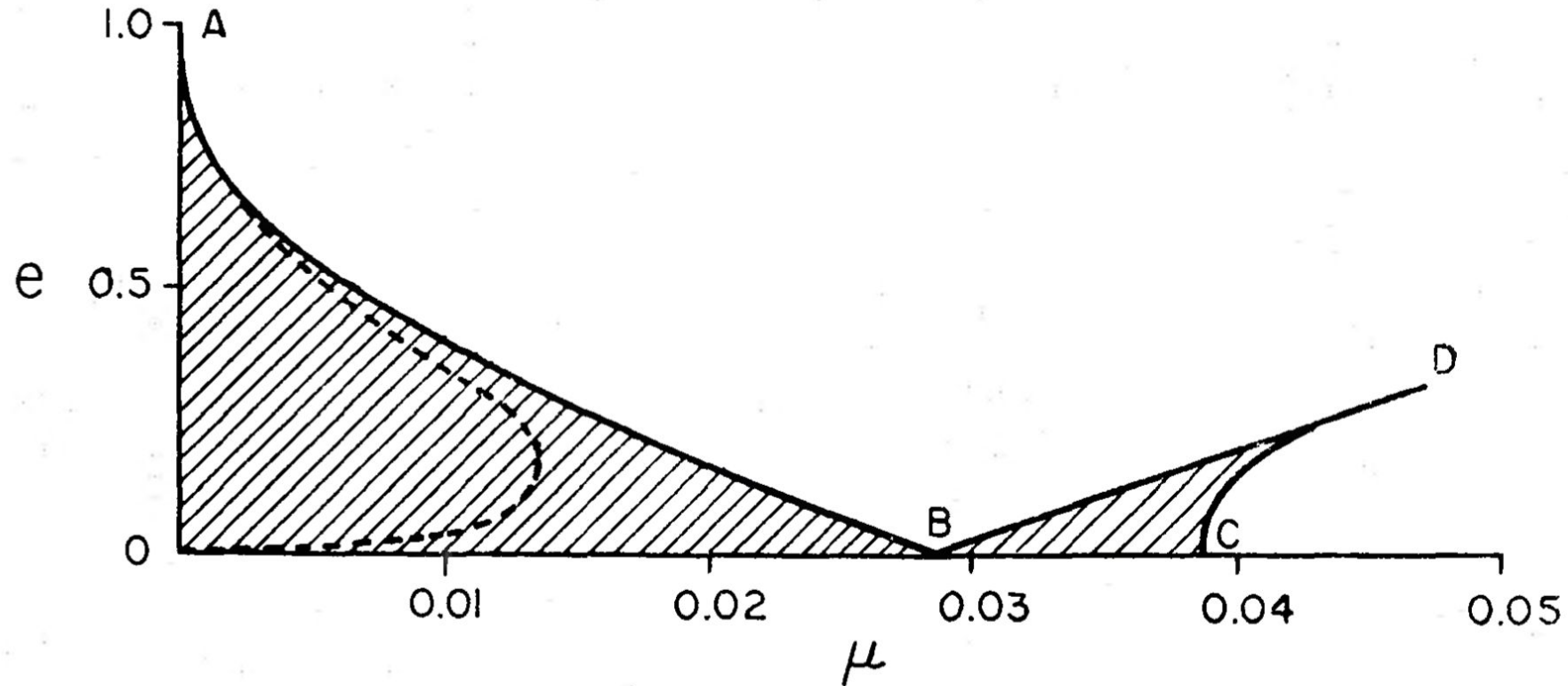


FIG. 1. For values of μ and e within the shaded area the triangular points are positions of stable equilibrium. Danby 1964

Additional Equations

$$\Re(\mathbf{r}_f) \frac{\sin I}{c} = \frac{\mu a \sin I}{c} \sqrt{1 - \delta(1 - \delta)} \cos \left[n\tilde{t} + \lambda_0 + \delta \frac{\pi}{3} - \arctan \left(\frac{\delta \sqrt{3}}{2 - \delta} \right) \right]$$

$$\phi - \lambda = \frac{\delta \pi}{3} - \arctan \left(\frac{\delta \sqrt{3}}{2 - \delta} \right) \in \sim [-0.02, 0.02]$$

$$m_f = \frac{m_p(m_T + m_c) \sqrt{1 - \delta(1 - \delta)}}{m_p + (m_T + m_c)(1 - \sqrt{1 - \delta(1 - \delta)})} = (m_c + m_T) \sqrt{1 - \delta(1 - \delta)} + \mathcal{O} \left(\frac{m_T}{m_p}, \frac{m_c}{m_p} \right)$$

$$\Delta\tau = \mathcal{T} \sum_{\pm} \left(\frac{1}{2} \mp \frac{1}{3} \frac{\nu}{n_b} \right) \cos [(n_b \pm \nu)\tilde{t} + (\theta \pm \varphi)]$$

$$\delta = \frac{2\beta}{\sqrt{3} + \beta} \text{ where } \beta = \tan(\theta - \pi/3)$$

$$\delta = m_c / (m_c + m_T)$$

Morning II | 11:00 AM - 11:15 AM

Yechan Kweon

*"A Computer Vision Approach to Radio-Frequency Interference Analysis in
Radio Astronomy Data"*

Setup & Goal

The Data

- Complex valued, channelized voltages
- L-Band GBT
 - Dual polarization
 - 8files of 5 GB each
 - 5 Chunks of 65024 samples
 - 800 MHz bandwidth (1.1-1.9 GHz)

Target: PSR J1713+0747

- Known and unknown underlying interference

The Goal

Develop **transform-domain** RFI detection under constraints:

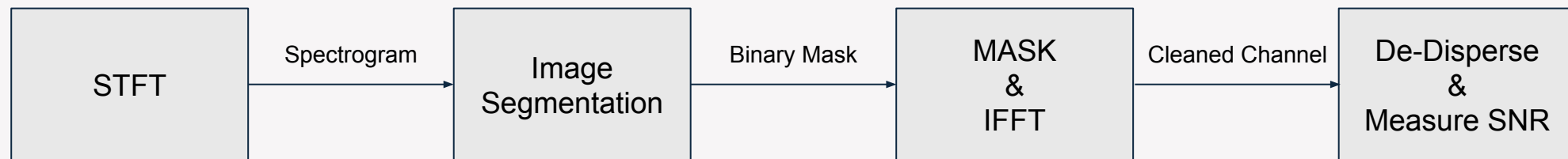
- **No prior knowledge** of RFI morphology
- **No cross-channel** information exchange required by FPGA implementation



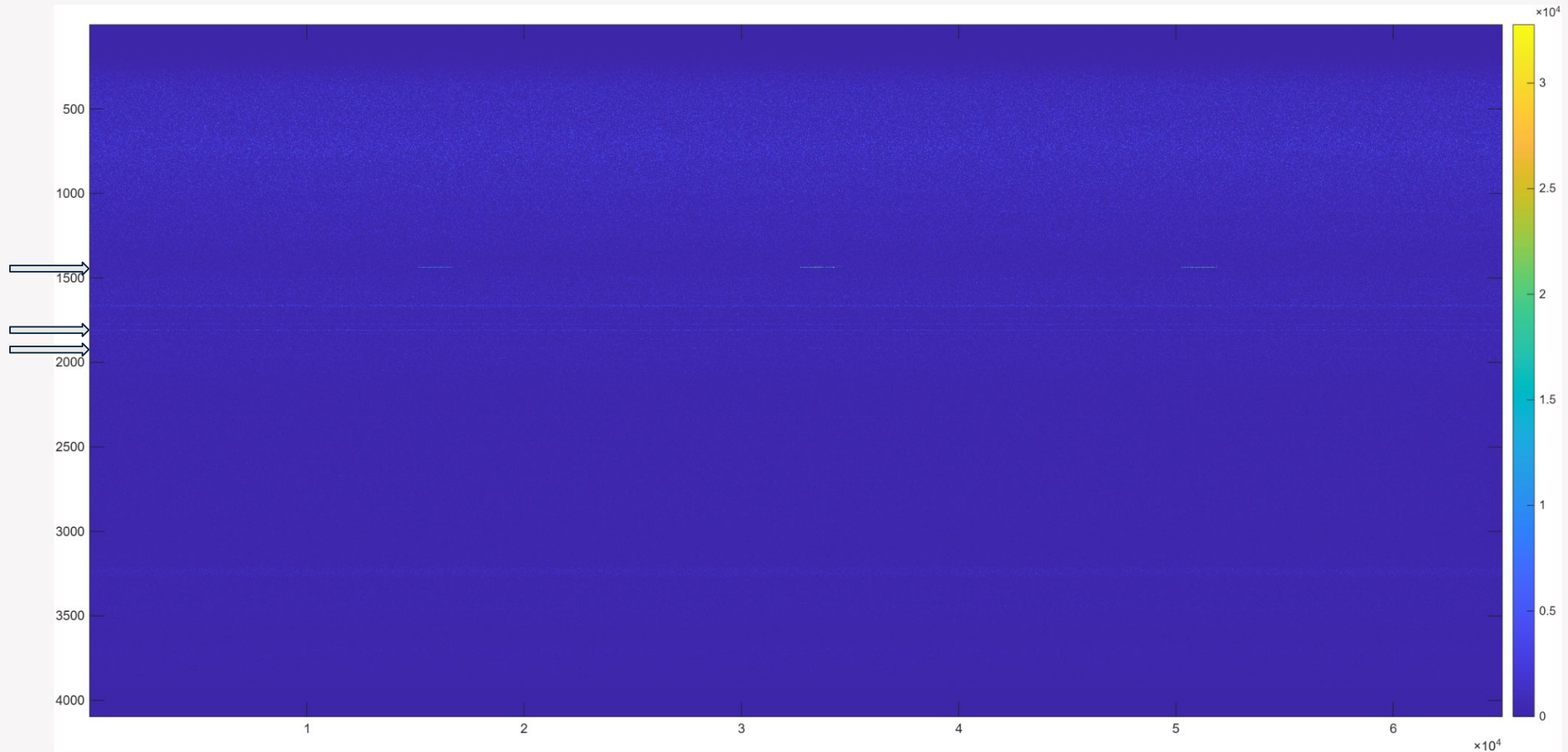
Processing Pipeline

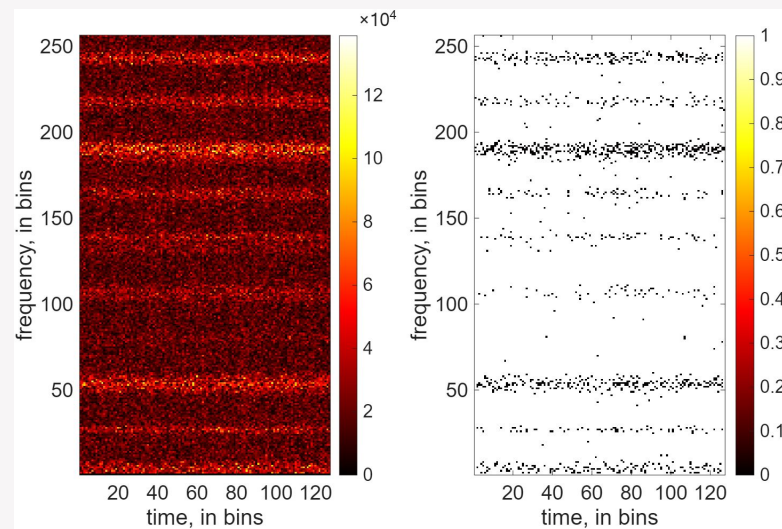
Assumptions

- RFI concentrates energy into dominate frequencies
- Image segmentation isolates RFI from background noise

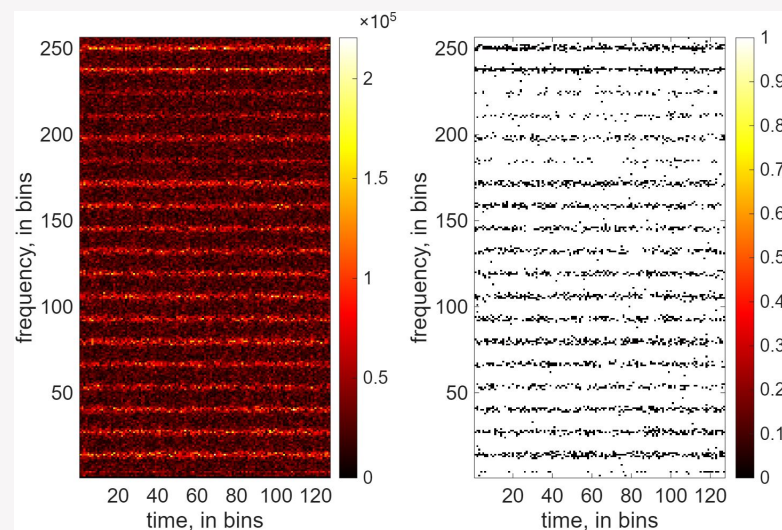


Raw Data

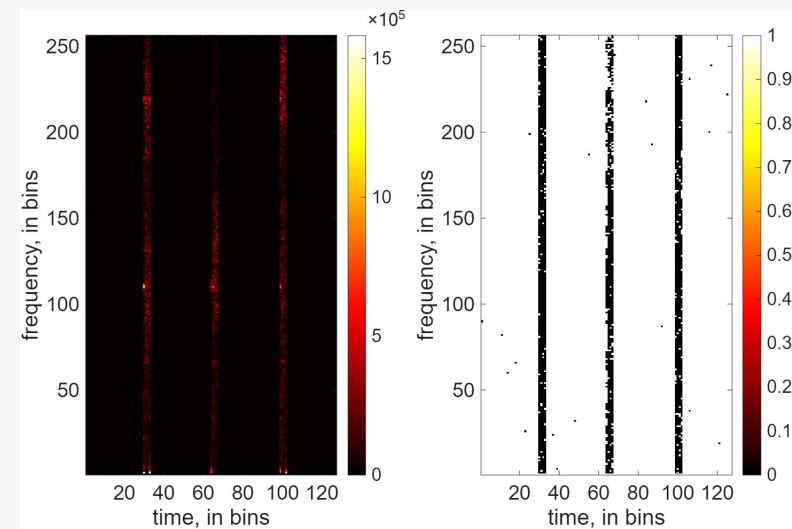




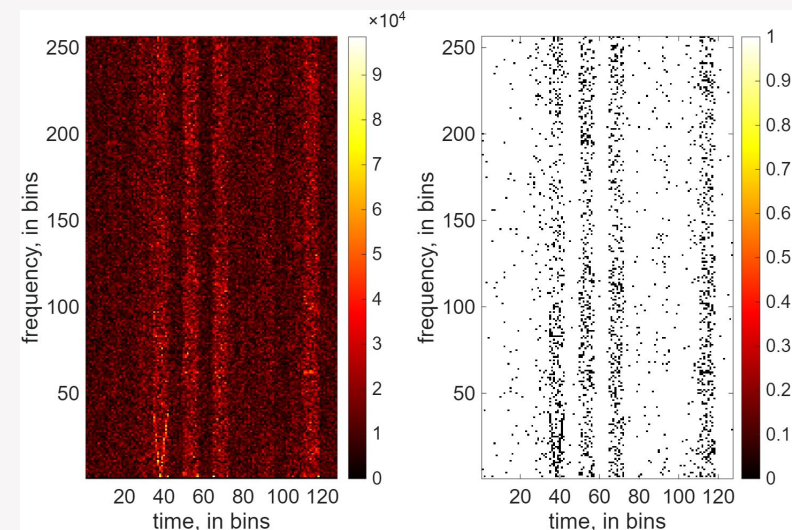
1814



1818



1436



1913



Masking Methods

Median Average Deviation

- Robust estimator of standard deviation

$$|x_k(i, j) - \text{med}(X_k)| > 1.4828 \cdot \text{med}(|X_k - \text{med}(X_k)|) \cdot \gamma$$

Gaussian Mixture Model

- Data-clustering approach
- Expectation Maximization

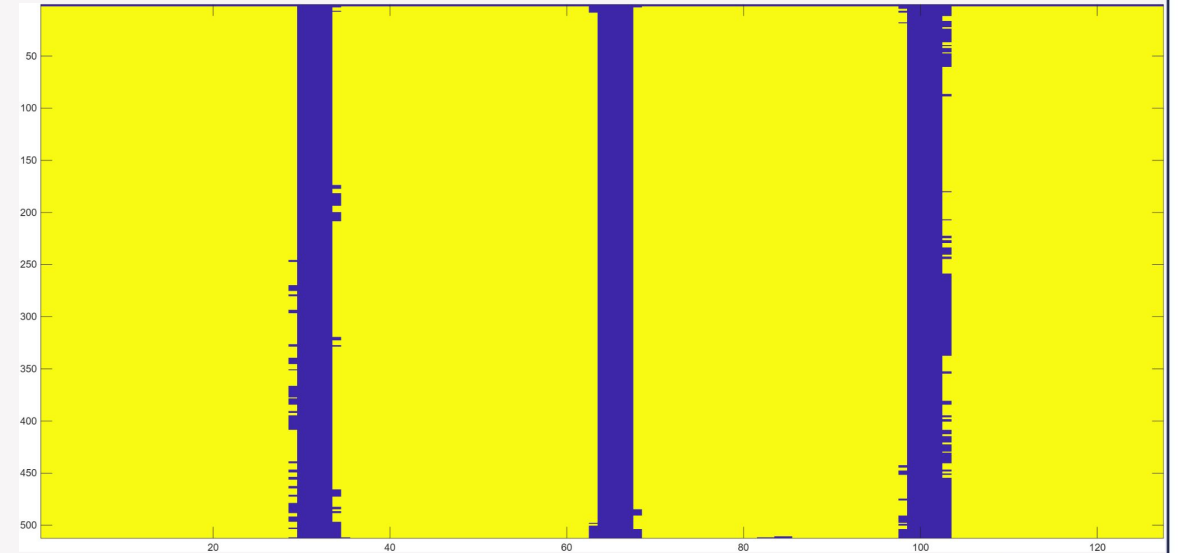
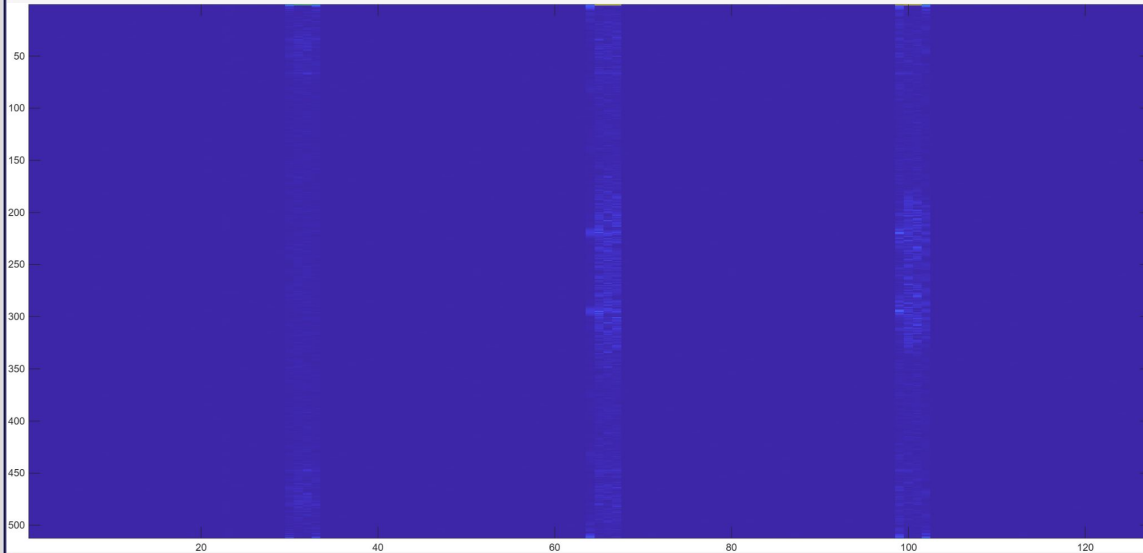
$$\pi_0 \mathcal{N}(\mu_0, \sigma_0^2) + (1 - \pi_0) \mathcal{N}(\mu_1, \sigma_1^2)$$



Baseline Methods

Segment Anything Model

- ViT based segmenter with strong zero-shot capabilities



Baseline Methods

Spectral Kurtosis

- Estimator of deviation from Gaussian noise

$$S_1 = \sum_{m=1}^M P(m), \quad S_2 = \sum_{m=1}^M P^2(m)$$

$$\text{SK} = \frac{M+1}{M-1} \left(\frac{MS_2}{S_1^2} - 1 \right)$$



Baseline Methods

SumThreshold

- Iterative flagging with adapting thresholds

$$\frac{1}{M} \sum_{i=1}^M \chi_i > \Lambda_M$$

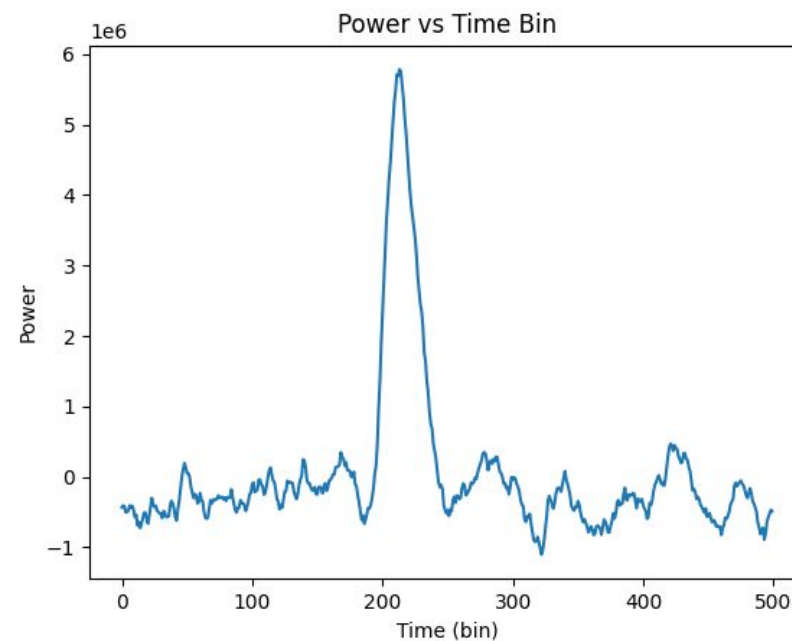
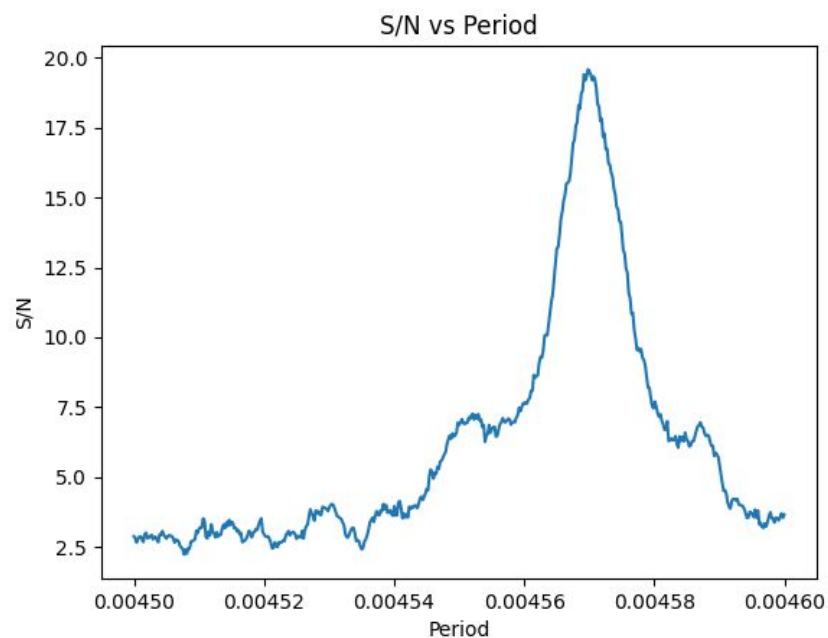
$$\Lambda_M = \frac{\Lambda_1}{\eta^{\log_2 M}}$$



Riptide-FFA

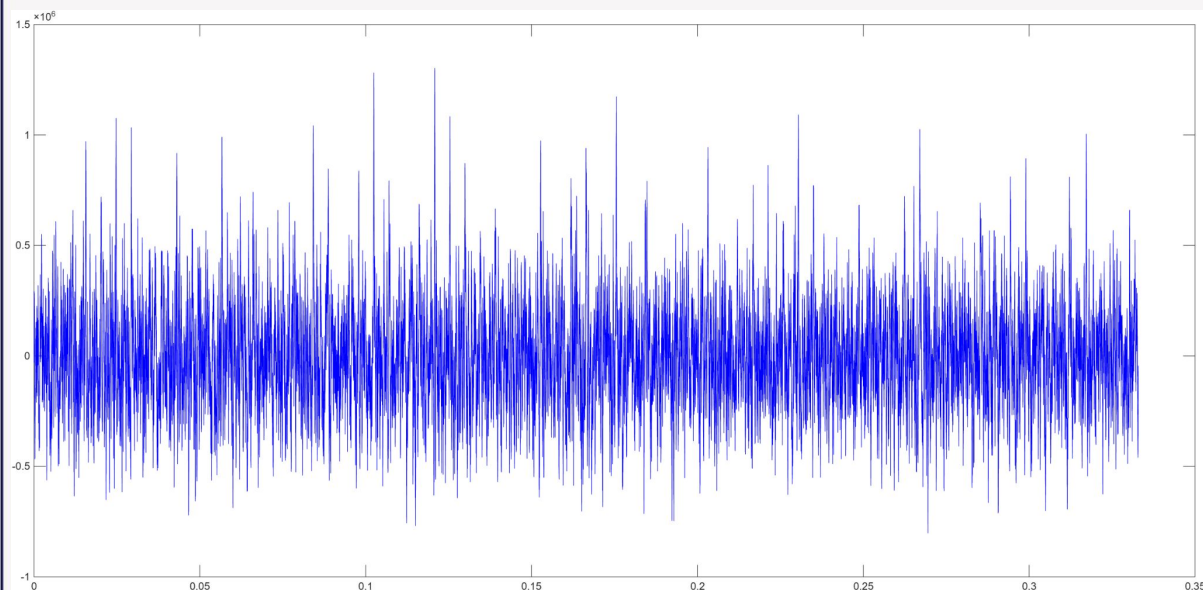
Riptide Fast Folding Algorithm

- Folds and calculates S/N
- Open source python

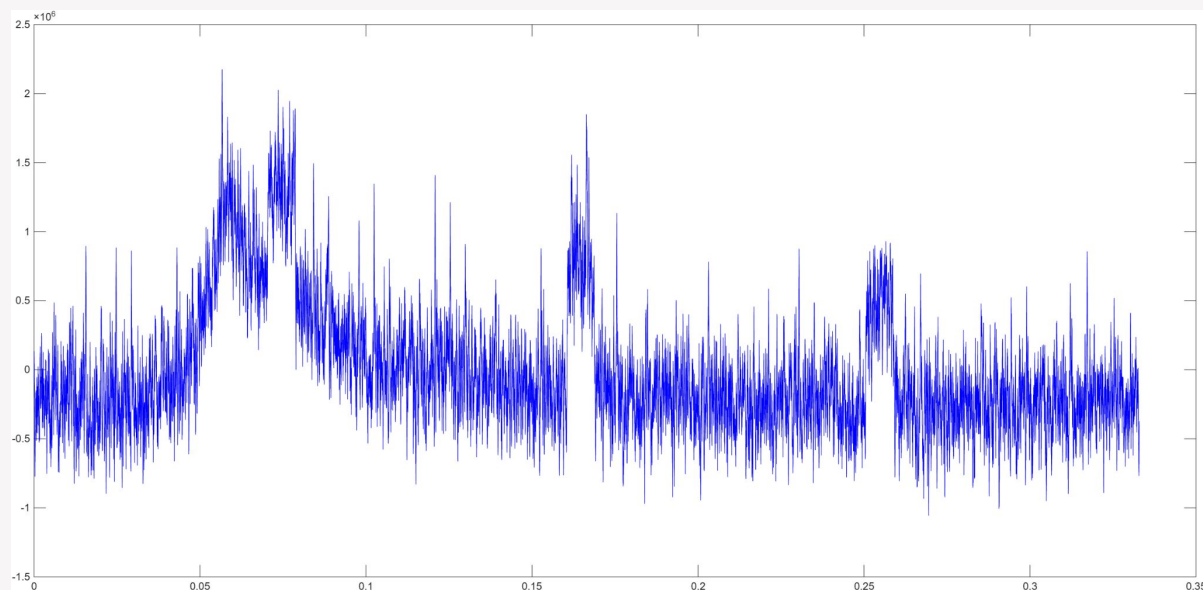


Results

Mat 0 Chunk 0



MAD | GMM



Raw



Performance

S/N values based on Riptide-FFA

Method	SK	SumThreshold	SAM	MAD GMM	Raw
S/N	22.849	24.267	24.068	30.578	19.585

Mat 0 Chunk 0

Method	SK	SumThreshold	SAM	MAD GMM	Raw
S/N	29.260	32.826	13.153	32.115	10.811

Mat 2 Chunk 2



Future Work

Data

- GREENBURST

Methods

- 2D SumThreshold
- Wavelet Segmentation
- CNN Based Segmentors
- HQ-SAM



Questions



Morning II | 11:15 AM - 11:30 AM

Tyler Thomas

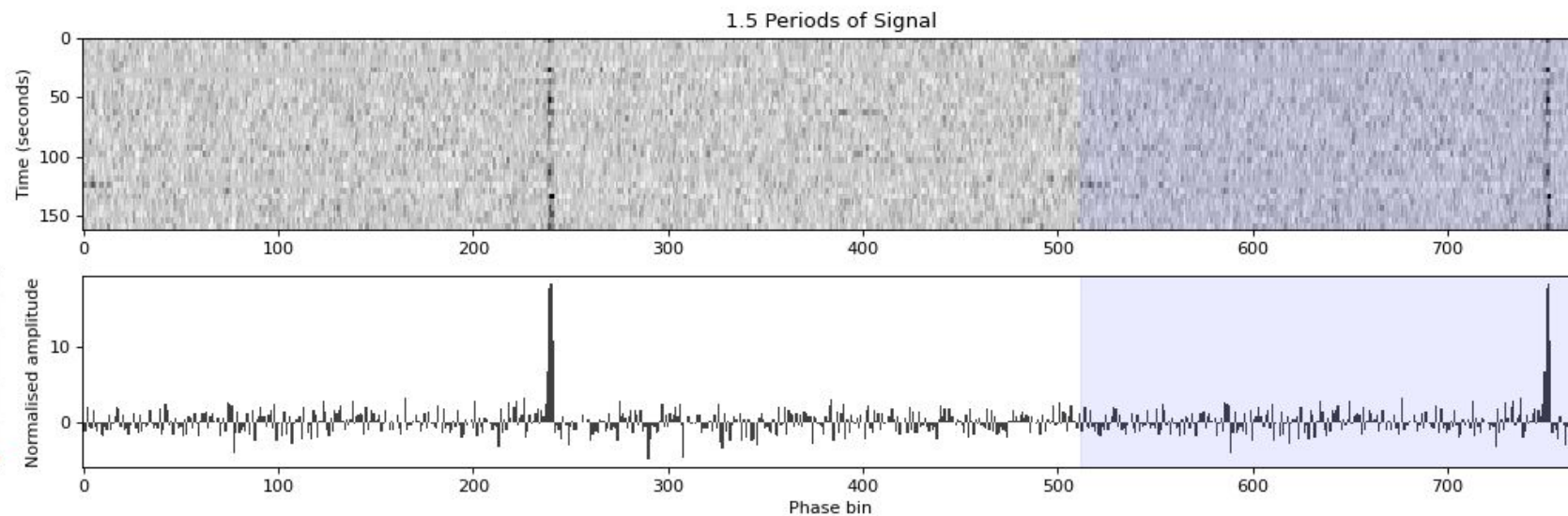
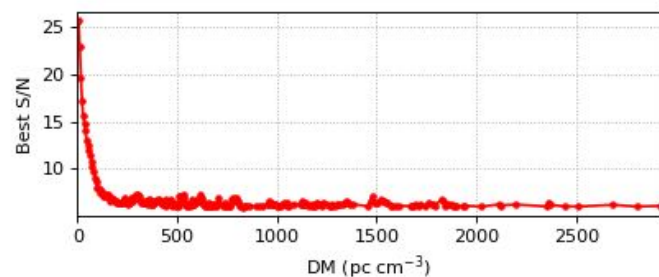
"Revisiting the Parkes 70 cm Survey with Machine Learning"

Parkes 70 cm Survey Overview



Period 4254.727475 ms
DM 5.80 pc cm⁻³
Width 3 bins
Duty cycle 0.71 %
S/N 25.6

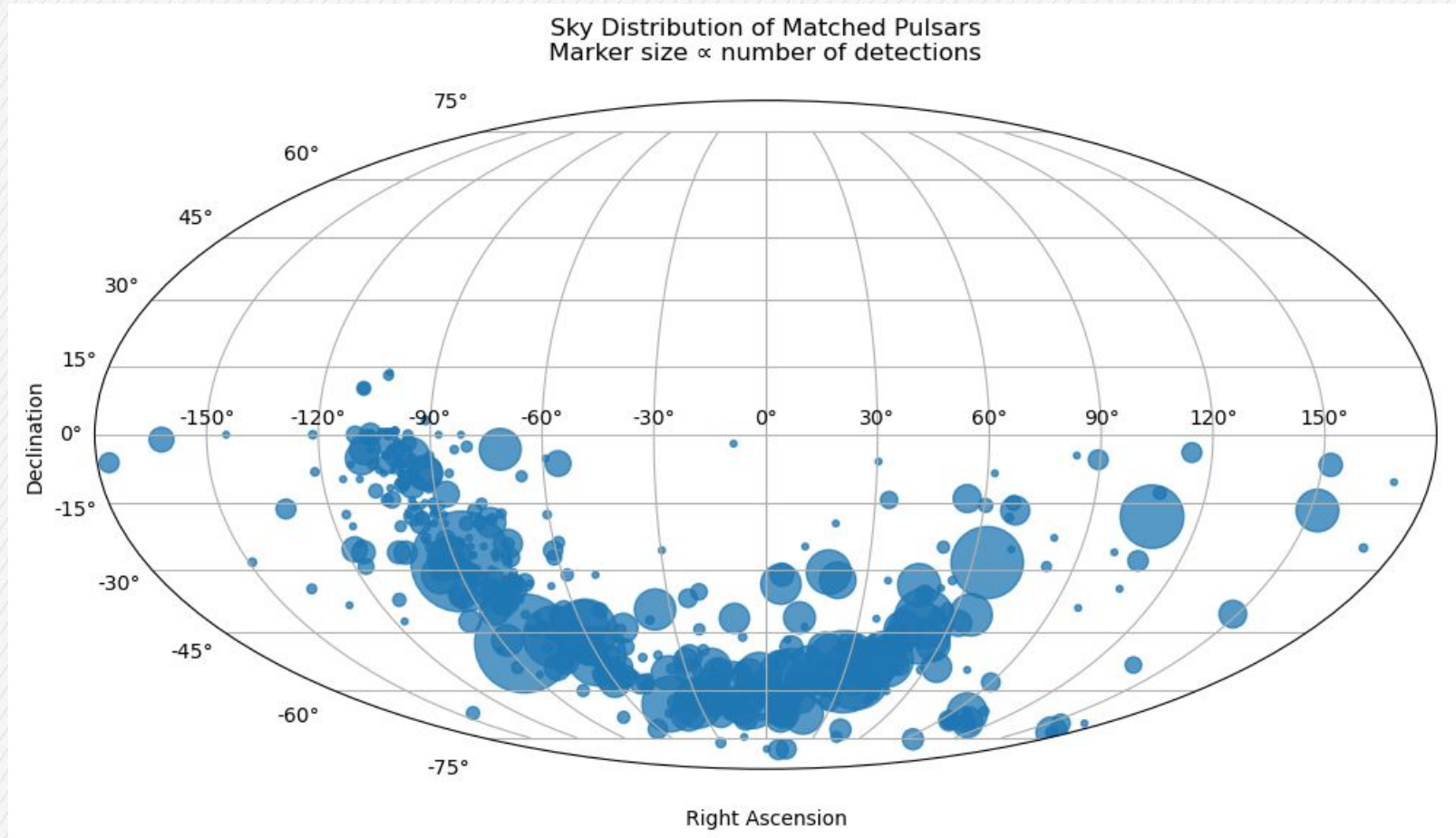
Source Unknown
RA 21:42:39.38
Dec -39:39:00.00
MJD 48474.565361
UTC 1991-08-06 13:34:07



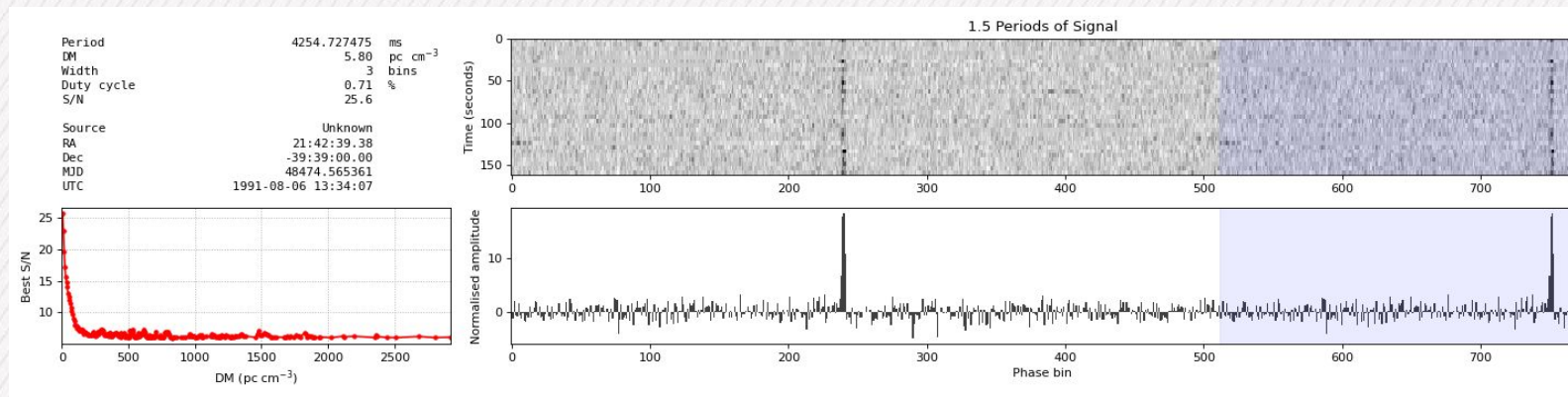
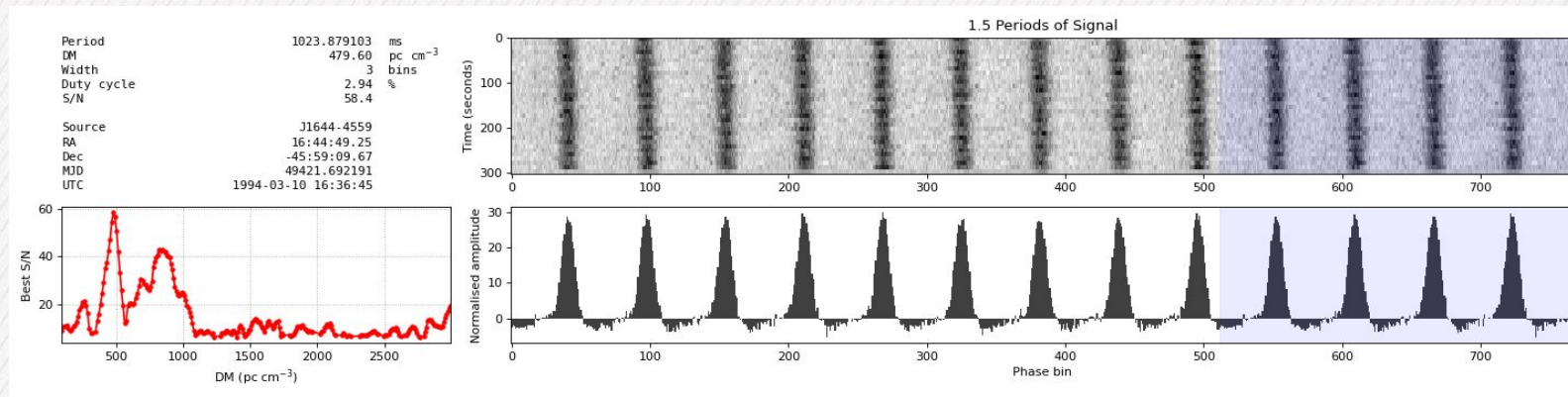
Diagnostic plot for 8.4 second pulsar

*How can we find these
single-peaked
candidates?*

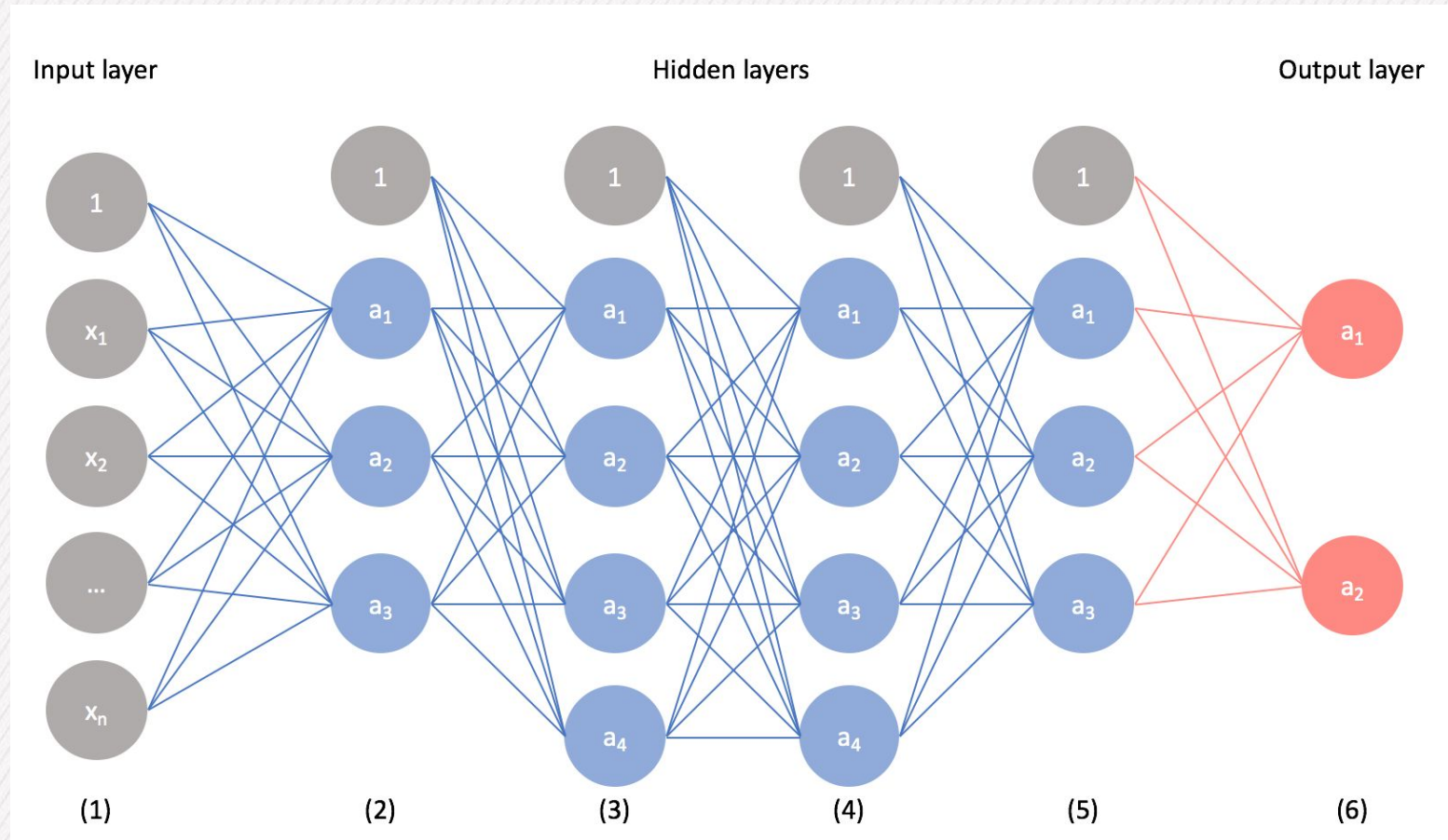
Training set built through ATNF cross-matching...



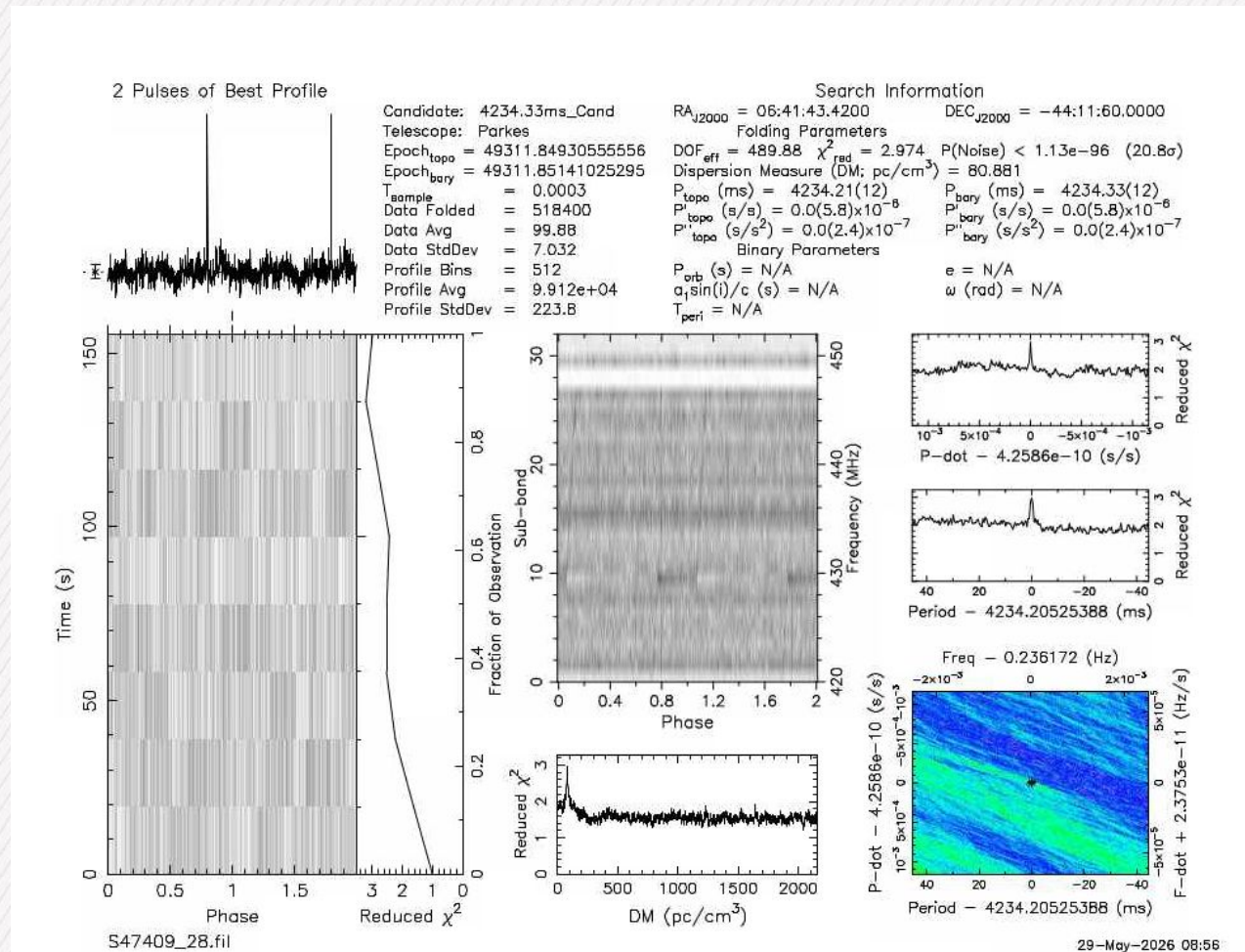
... then culled through visual inspection



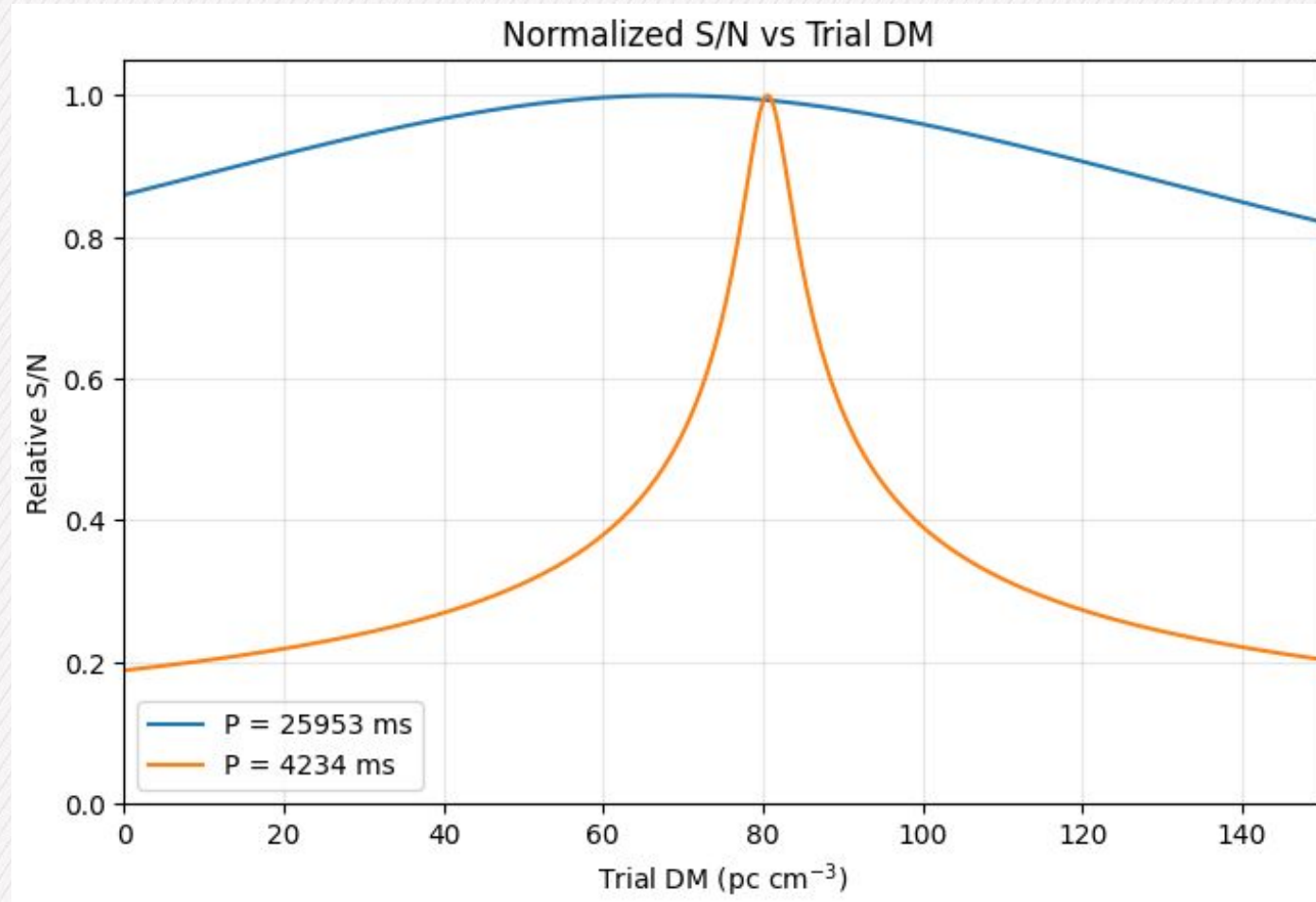
Candidates classified using a 4 layer CNN



Promising 4.2 second candidate



S/N vs DM curves broaden with longer periods



Next steps: observe 4.2 second candidate



Morning II | 11:30 AM - 11:45 AM

Maria C. Babiuc Hamilton

*"From Raw Numerical Gravitational Wave Data to Maximum Neutron Star
Mass Constraints"*

Binary Neutron Star Simulations

From Raw NR Data to Maximum NS Mass Constraints

Maria Babiuc Hamilton

Marshall University, Huntington, WV

Center for Gravitational Waves and Cosmology Internal Symposium

West Virginia University, Morgantown, WV — June 3, 2026

The Science Motivation

Next-generation detectors (ET, CE) will observe post-merger GW from BNS remnants.

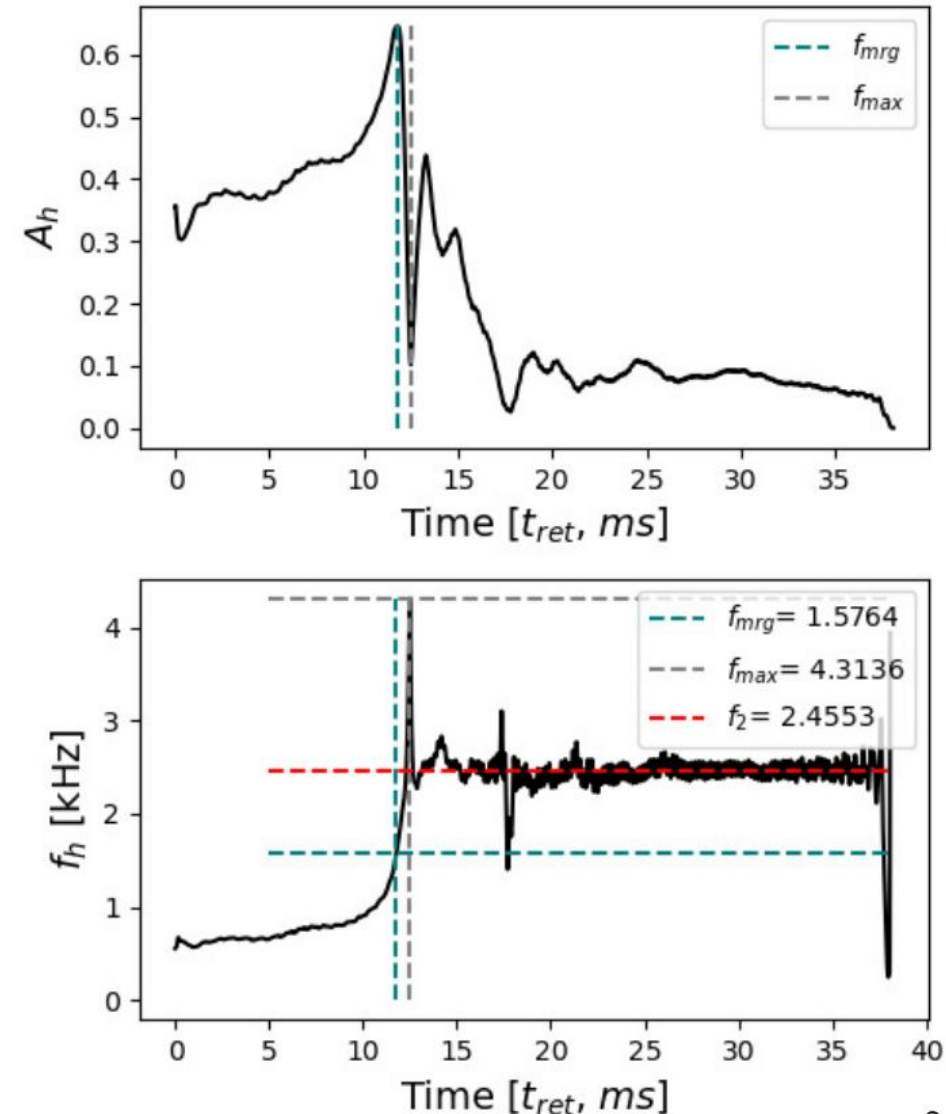
Key observable:

- Maximum frequency ($f_{\max}$)
- Dominant frequency & chirp ($f_2, \dot{f}_2$)
- Higher & lower harmonics (f_1, f_3)
- Collapse time (t_{coll})

Key physics: these observables encode EOS information and constrain **maximum TOV mass**

This work: builds and validate the NR pipeline needed to make that constraint rigorous.

e-Print: 2411.10552 (MBH & W. Messman)



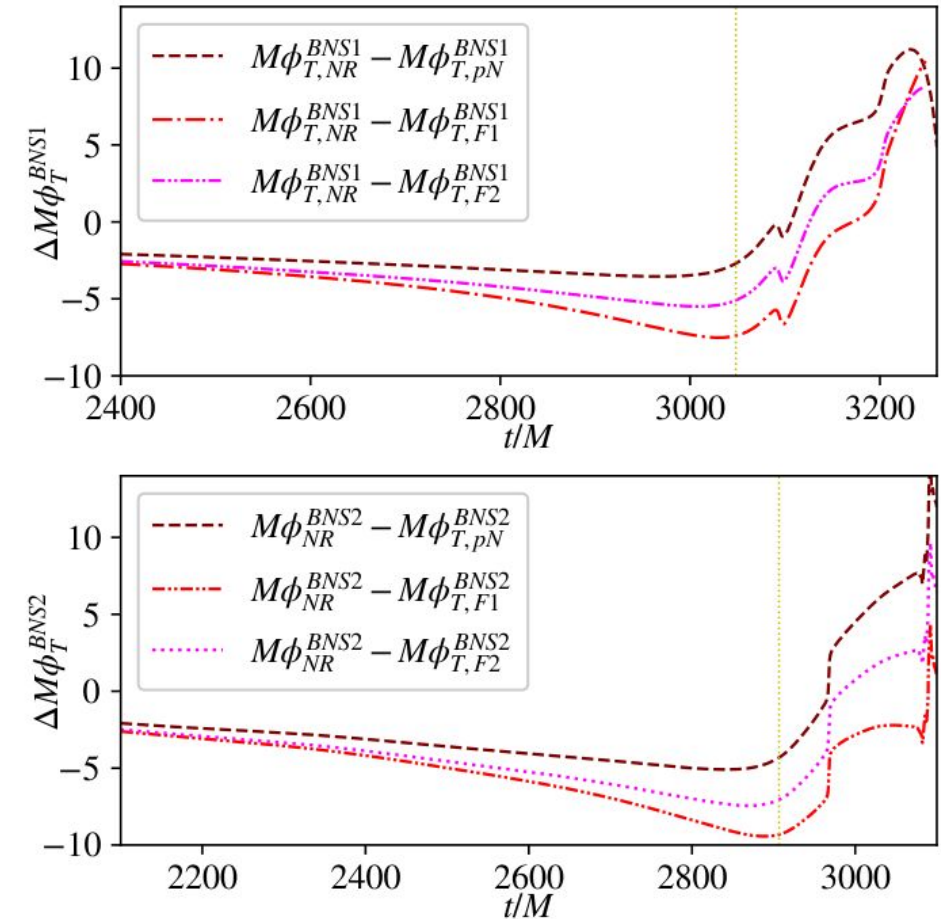
Why Not Post-Newtonian?

PN is good and well-tested *during inspiral*,
but it **diverges** at and beyond merger.

Post-merger physics is nonlinear:

- Strong field & black hole formation
- Nonlinear dynamics & fluid oscillations
- Shock formation & heating
- Differential rotation & turbulence
- Magnetic fields & neutrino cooling

e-Print: 2307.16022 (A O'Dell & MBH)



Numerical Relativity solves the full coupled Einstein+(magneto)hydrodynamics+
microphysics system numerically, thus is essential for interpreting post-merger GW.

The NR Challenge: Systematics

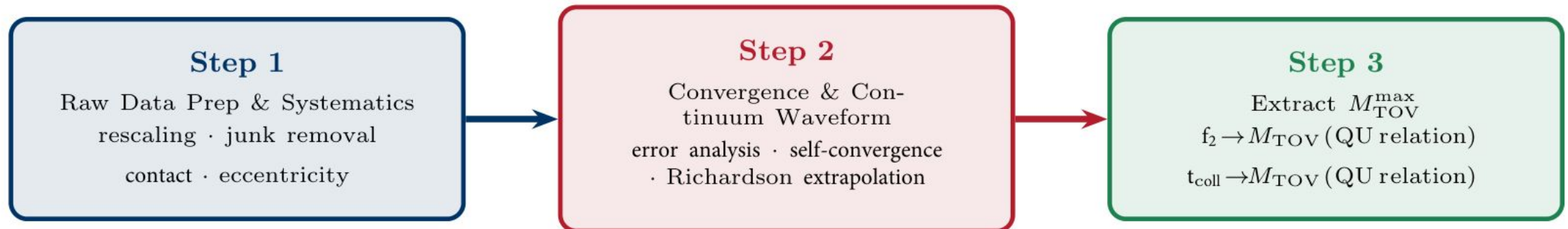
NR is *not* free of errors. Before extracting physics we must quantify and remove them.

Sources of systematic error:

- Finite numerical resolution
- Junk radiation (spurious initial data)
- Residual orbital eccentricity
- Finite extraction radius
- Gauge and interpolation artifacts

Our pipeline addresses each:

- Rescaling and unit conversion
- Stability-based junk cutoff
- Residual eccentricity analysis
- Error analysis and self-convergence
- Richardson extrapolation



Sample Dataset

SHFo equation of state, equal-mass, equal-radius. Two independent NR codes:

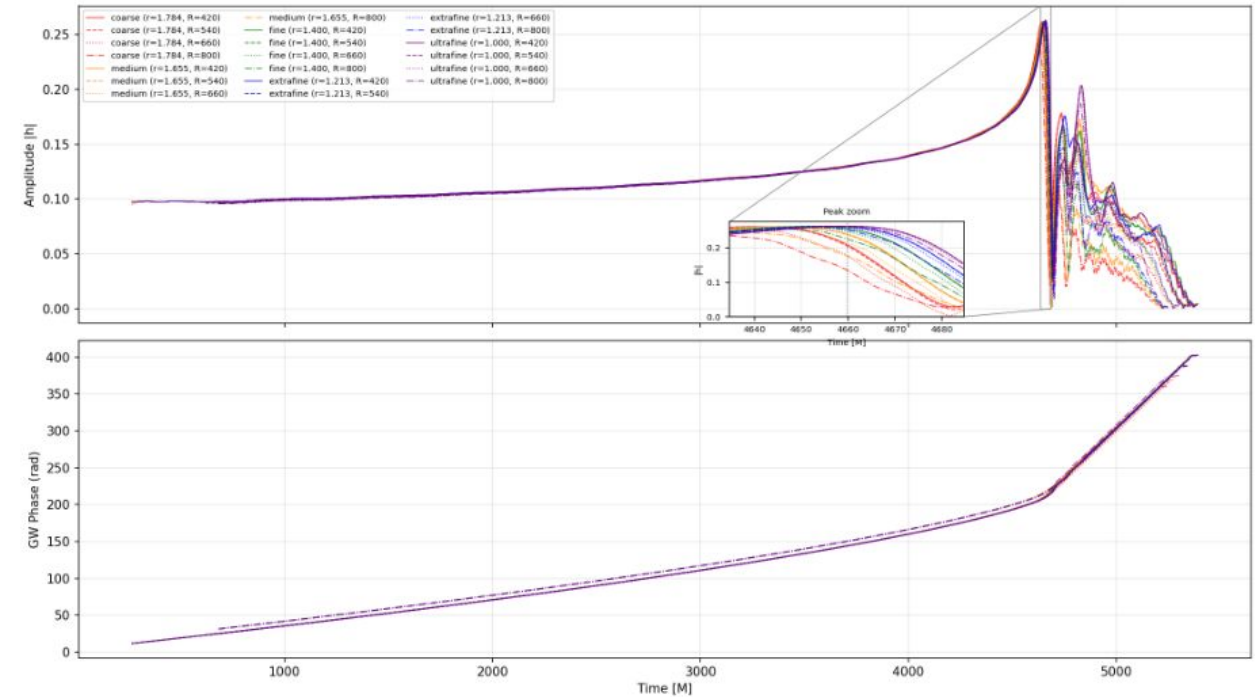
- **SACRA**
- **WhiskyTHC**

Multiple resolution levels per code — essential for convergence analysis.

Raw Data:

1. Time in *geometric units*
2. Strain: $h_{22}(t) = h_+ - i h_\times$
3. Weyl scalar: $\psi_4(t)$, $\ddot{h} = -\psi_4$

Raw data, all resolutions & extraction radii, SACRA



Why two codes? Cross-validation of numerical systematics.

Raw Data Preparation

Junk radiation: spurious GW burst from imperfect initial data, excised before analysis.

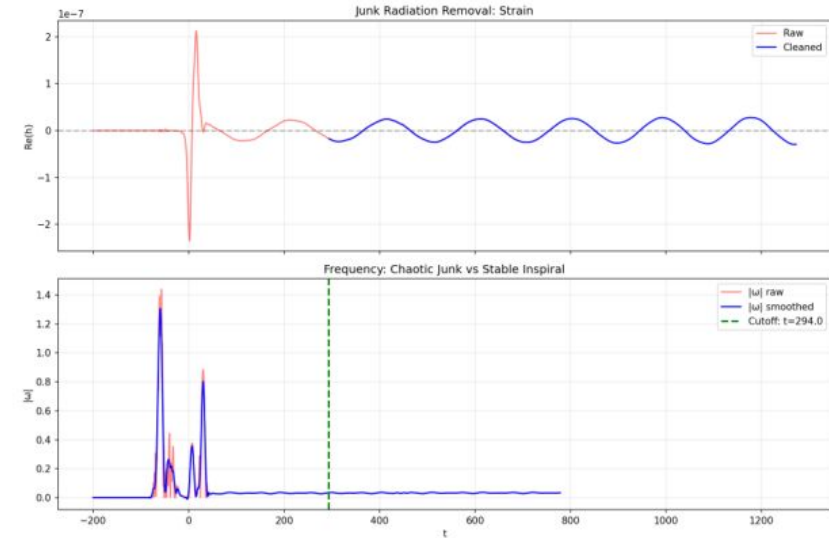
Stability-based cutoff:

1. Amplitude-based preliminary cut
2. Followed by frequency-stability search
3. Safety buffer add n_{cut} orbital period
4. Most conservative cutoff across resolutions

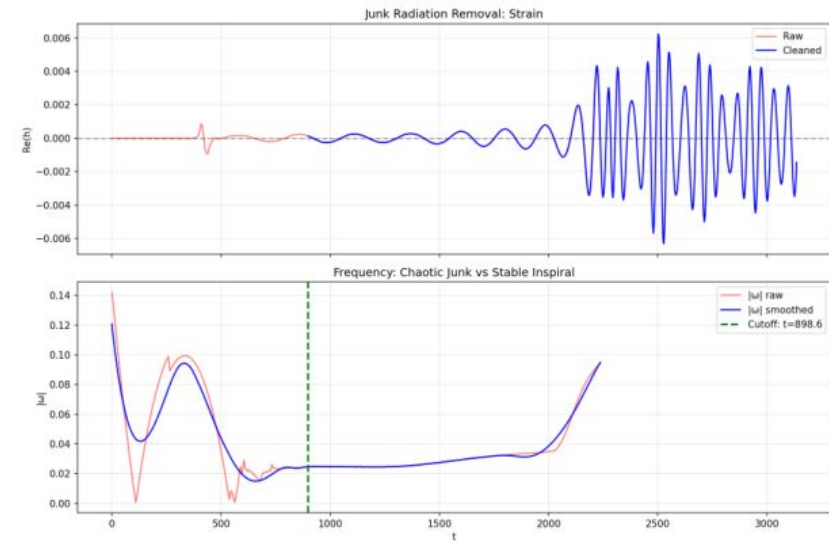
Resampling to a common time grid $\Rightarrow 5^{\text{th}}$ order interpolation to highest resolution.

Result: consistent, physically normalized waveforms ready for systematic analysis.

Junk radiation removal SACRA



Junk radiation removal THC



Convergence — Errors Analysis

The Convergence Problem starts with numerical resolution-dependent error:

$$\varepsilon_{i,i+1}(t) = \varphi_{r_i}(t) - \varphi_{r_{i+1}}(t)$$

Convergence requires hierarchy condition:

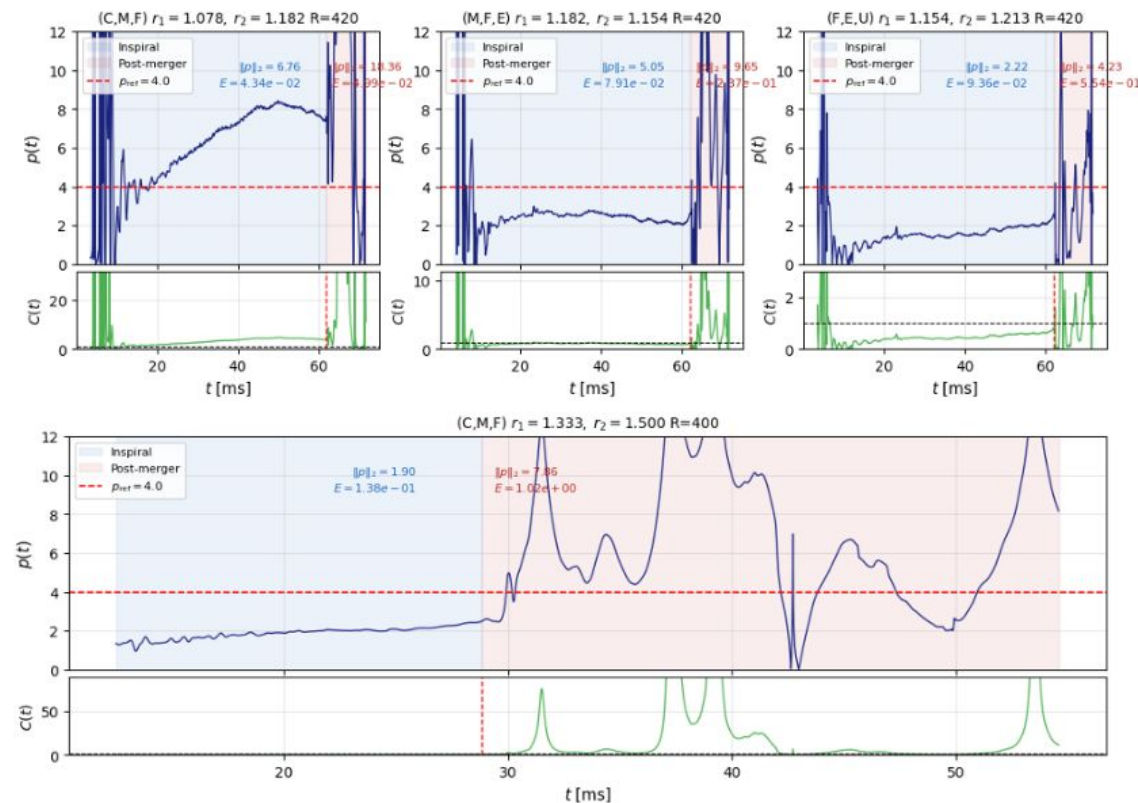
$$|\varepsilon_{C-M}| \gg |\varepsilon_{M-F}| \gg |\varepsilon_{F-EF}| \gg |\varepsilon_{EF-UF}|$$

Classifying the convergence regime:

$R(t) = \varepsilon_{ij}(t)/\varepsilon_{jk}(t)$ diagnostic:

1. $0 < R < 1$ Monotonic convergent
2. $-1 \leq R < 0$ Oscillatory convergent
3. $R < -1$ Oscillatory divergent
4. $R > 1$ Monotonic divergent

Phase self-convergence order, SACRA & THC



Correction factor: $C(t) = \frac{r_{jk}^{p(t)} - 1}{r_{jk}^{p_0} - 1} \approx 1$

$$q = \ln \left[\frac{(r_{ij}/r_{jk})^p - s}{r_{jk}^p - s} \right], \quad p = \frac{1}{\ln r_{jk}} |\ln(sR) - q|$$

Convergence — Richardson Extrapolation

Estimates continuum solution by fitting the truncation error model per resolution:

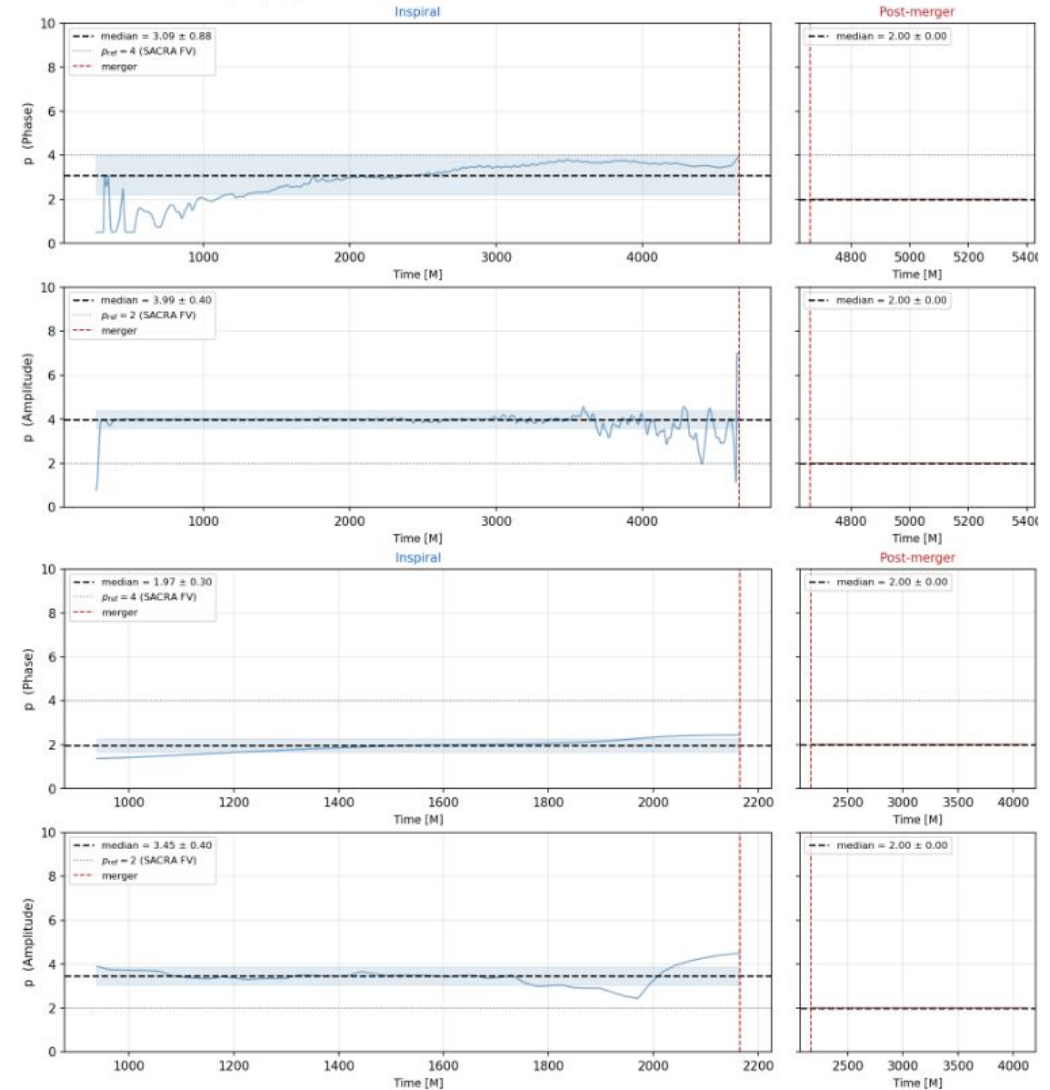
$$S_i(t) = S_0(t) + c(t) \cdot r_i^p + \mathcal{O}(r_i^{p+1})$$

Convergence order for SACRA

$R [M]$	p_φ	p_A
420	3.085 ± 0.880	3.988 ± 0.402
540	3.234 ± 0.720	3.988 ± 0.375
660	3.243 ± 0.688	3.995 ± 0.400
800	3.248 ± 0.667	3.988 ± 0.438

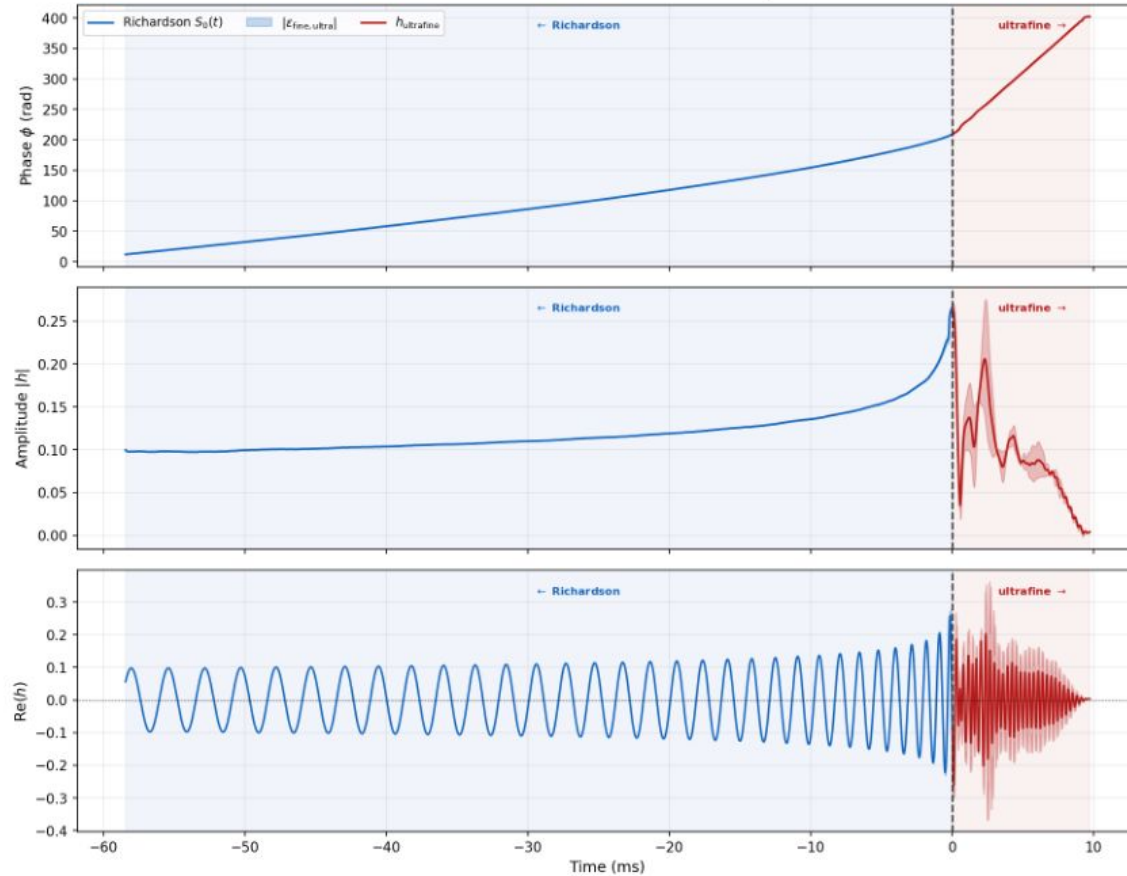
Post-merger (turbulence-limited) p fixed at 2

Measured $p(t)$ from the Richardson fit, SACRA & THC

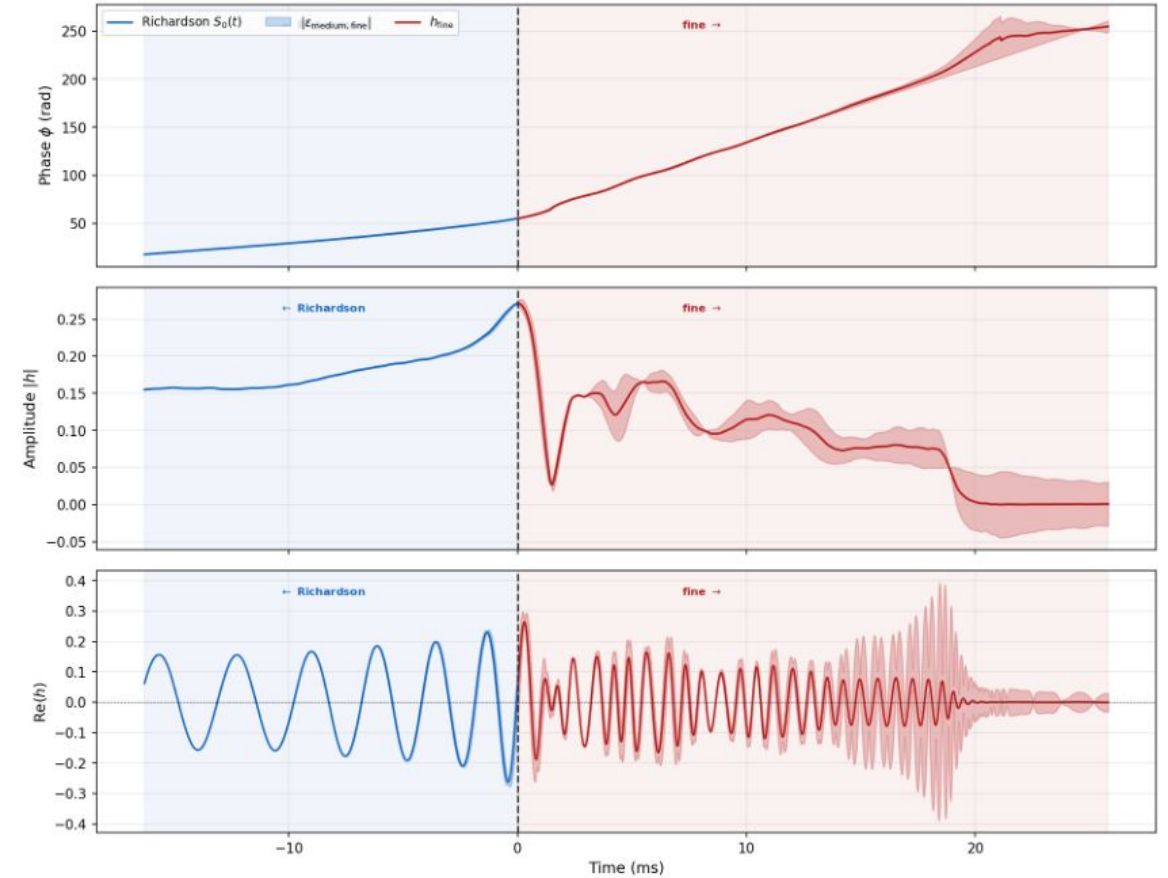


The Continuum Waveform

Continuum Waveform Reconstruction, SACRA



Continuum Waveform Reconstruction, THC



Result: systematic errors are quantified and minimized $\Rightarrow$ improved NR waveform.

Inspiral region: Richardson continuum eliminates leading-order truncation error

Merger region: trust only the robust features, not every detail (stable vs unstable)

The Post-Merger Challenge

Post-merger requires separate treatment:

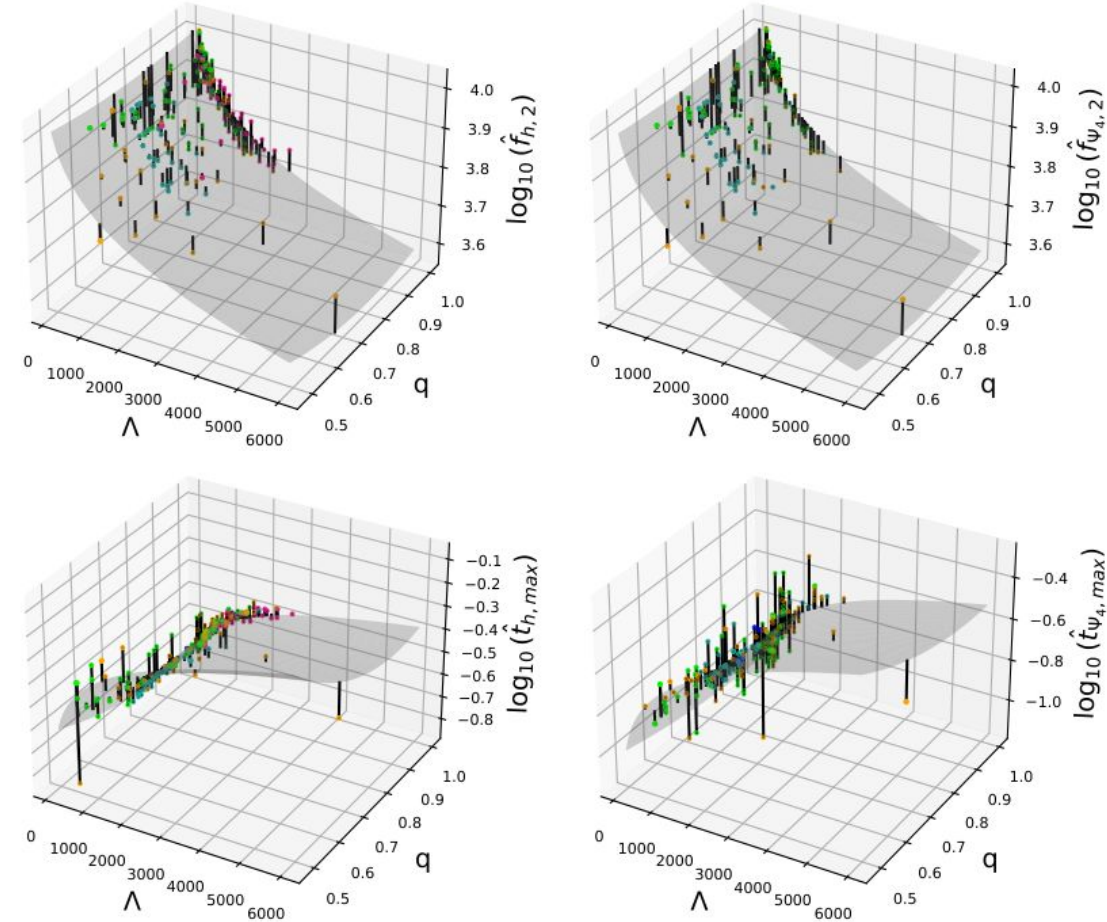
- Asymptotic convergence breaks down.
- Solutions have genuinely diverged.
- Richardson extrapolation is invalid.
- Finest resolution must be used directly.

Quasi-universal relations to the rescue

- We verified and extended fits for:
$$\log_{10} \left(\hat{f}_{\text{mrg}}, \hat{f}_{\text{max}}, \hat{f}_2 \right) = a + \tilde{\Lambda}^{1/5} \sum_{i=0}^2 b_i q^i$$
- We found a new QUR as early EOS probe:

$$t_{\text{bounce}} = t_{f_{\text{max}}} - t_{f_{\text{mrg}}}$$

e-Print: 2411.10552 (MBH & W. Messman)



Post-merger Reliability

Post-merger simulations can only be used to calibrate **robust trends and bounds**, and not for precise waveform predictions. Switch from raw waveform to **observables**.

What to trust:

- Observables stability under changes in resolution (e.g. $\leq 5\%$ for f_2)
- Observables consistency across at least two independent codes
- Approximate observables trends with EOS and total mass
- A broad dominant spectral frequency
- Prompt vs delayed collapse trends

What not to trust:

- Error analysis and self-convergence
- Observables changing with resolution
- Small differences in f_2 or dependence on the FFT window
- Narrow secondary peaks
- Fit coefficients that change a lot
- Threshold mass bracketing outside a physically sensible range

Toward Constraining Maximum Neutron Star Mass

TOV limit: cutoff between stable neutron star and black hole, depends on the nuclear EOS.

The initial guess: (Bauswein et al. fit)

1. Extrapolate low mass $f_2(M)$ to f_2^{thres}
2. Map: $f_2^{\text{thres}} \rightarrow M_{\text{thres}} \rightarrow M_{\text{TOV}}^{\text{max}}$

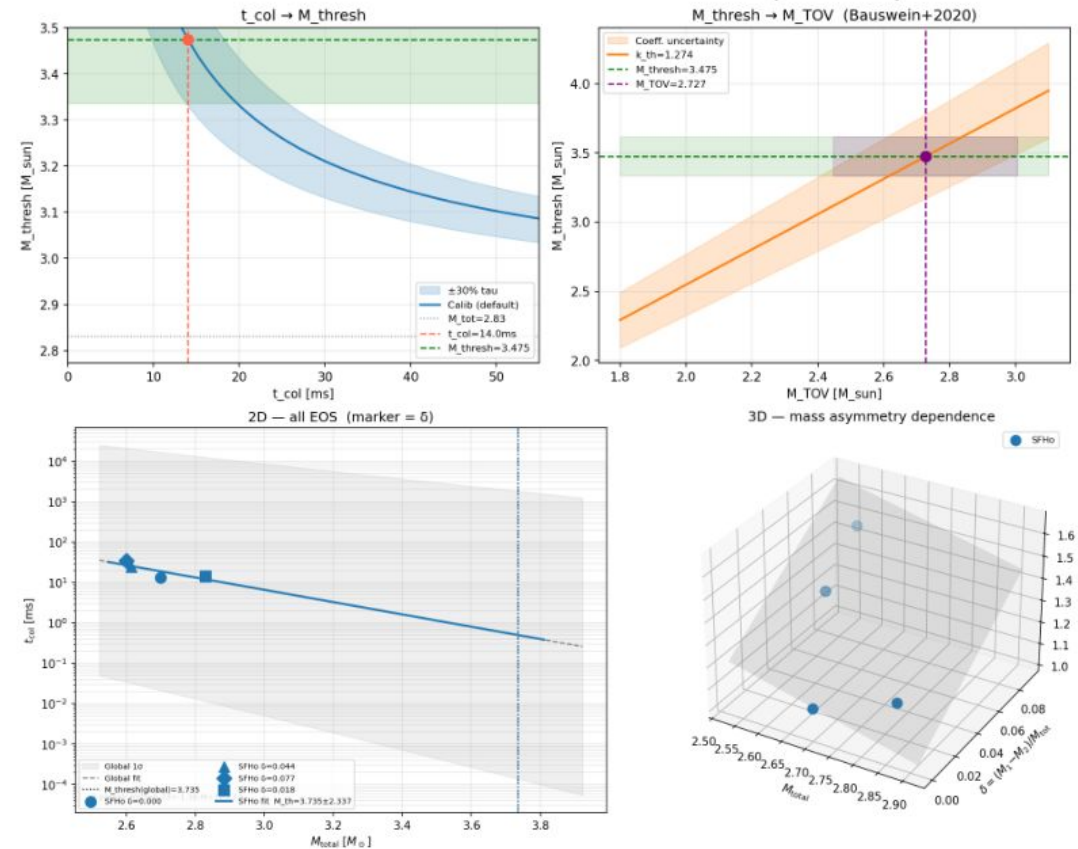
The refinement:

1. Fit collapse time $t_{\text{coll}}(M)$ (if available)
2. Map $t_{\text{coll}} \rightarrow M_{\text{thres}} \rightarrow M_{\text{TOV}}$.

Combine the two estimates:

$$(t_{\text{coll}}, f_2, M_{\text{rem}}) \rightarrow M_{\text{thres}} \rightarrow (M_{\text{TOV}}, R_{\text{TOV}})$$

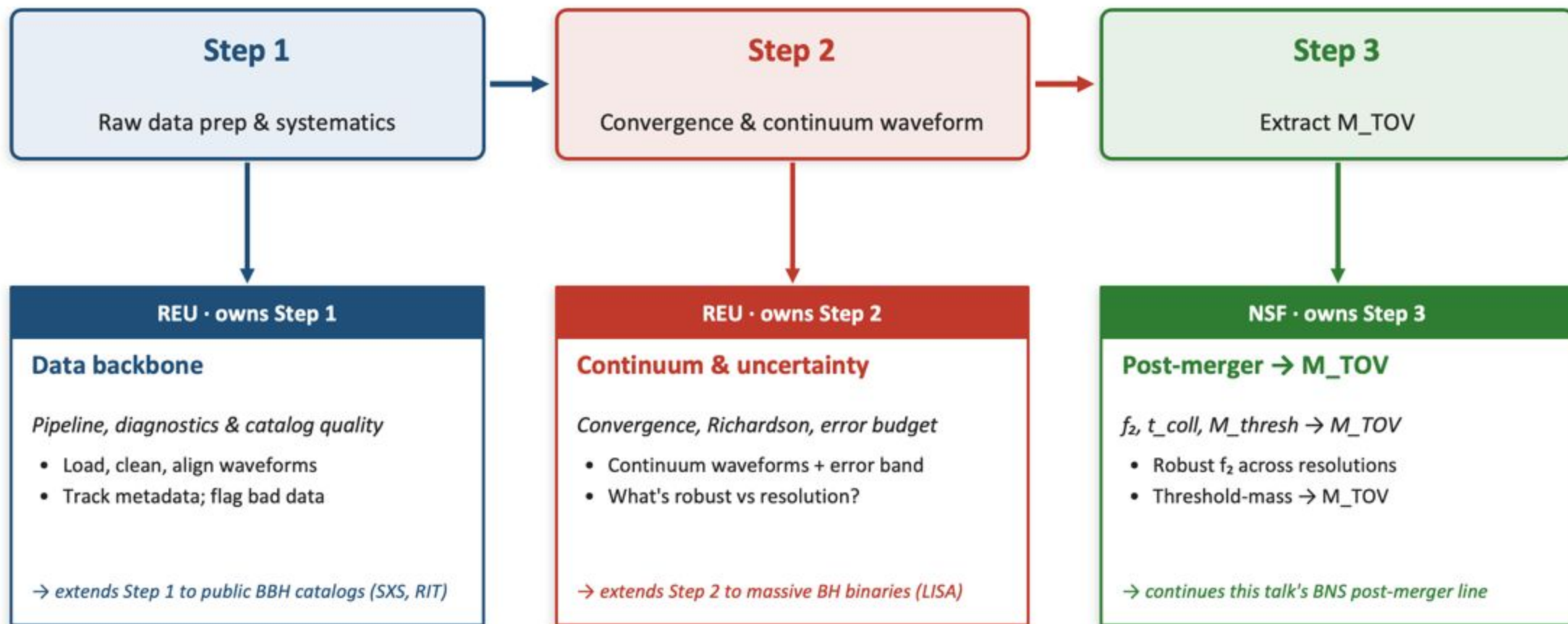
Threshold mass inference from THC (SFHo)



The threshold mass inferred for the SFHo EOS lies above the known value.

This Summer: Four Students Extend the Pipeline

The Step 1–2–3 pipeline from this talk, carried forward in four directions.



+ NSF · new branch: BNS inspiral tidal signal — isolate $\Delta\phi(f)$ vs tidal deformability Λ from the clean continuum inspiral (Step 2 output minus a TaylorF2 baseline).

Four Projects, Four Deliverables

Each student owns one clean, checkable result by the end of the summer — and a reproducible pipeline behind it.

Data backbone

REU · BBH/MBHB

A documented, reusable pipeline: cleaned, aligned waveforms + a searchable catalog-quality audit across SXS and RIT.

Continuum & uncertainty

REU · BBH/MBHB

Continuum (infinite-resolution) waveforms with a numerical error budget — which observables are trustworthy for LISA-band black holes.

Inspiral tidal signal

NSF · BNS

The tidal residual $\Delta\phi(f)$ extracted from NR, and a first $\Delta\phi$ - Λ relation tying the inspiral phase to the equation of state.

Post-merger → M_TOV

NSF · BNS

Stable f_2 and threshold-mass estimates across EOS, and a first M_TOV constraint with an honest error bar — extending this talk.

The thread: *same systematics methodology — from this BNS pipeline outward to LISA-band black holes, and forward to a maximum-mass constraint.*

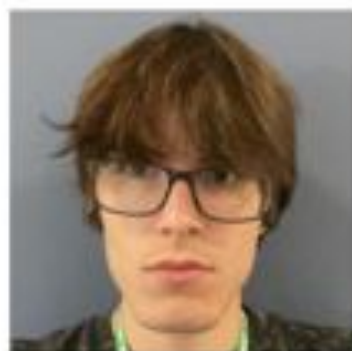
Summary

1. **We built and validated a full analysis pipeline** covering junk removal, eccentricity, error bounds, convergence and Richardson extrapolation, for **SFHo** EOS with two independent codes (SACRA, THC)
2. PN cannot reach the post-merger regime; NR can, but convergence is lost.
3. **Quasi-universal relations** become the benchmark for code performance.
4. **Post-merger NR constrain $M_{\text{TOV}}^{\text{max}}$ if systematics are rigorously controlled.**
5. With better numerical modeling and improved gravitational-wave observations, a new path toward precision studies of matter at extreme density is opening.

Thank You



Niko Faulcon



Diesel Bryant



David Graham



Willam Messman



Acknowledgements: NSF grants No.2513544, No.2349289 and Marshall University.

Thank you — [babiuc@marshall.edu]

Morning II | 11:45 AM - 12:00 PM

Suchindram Dasgupta

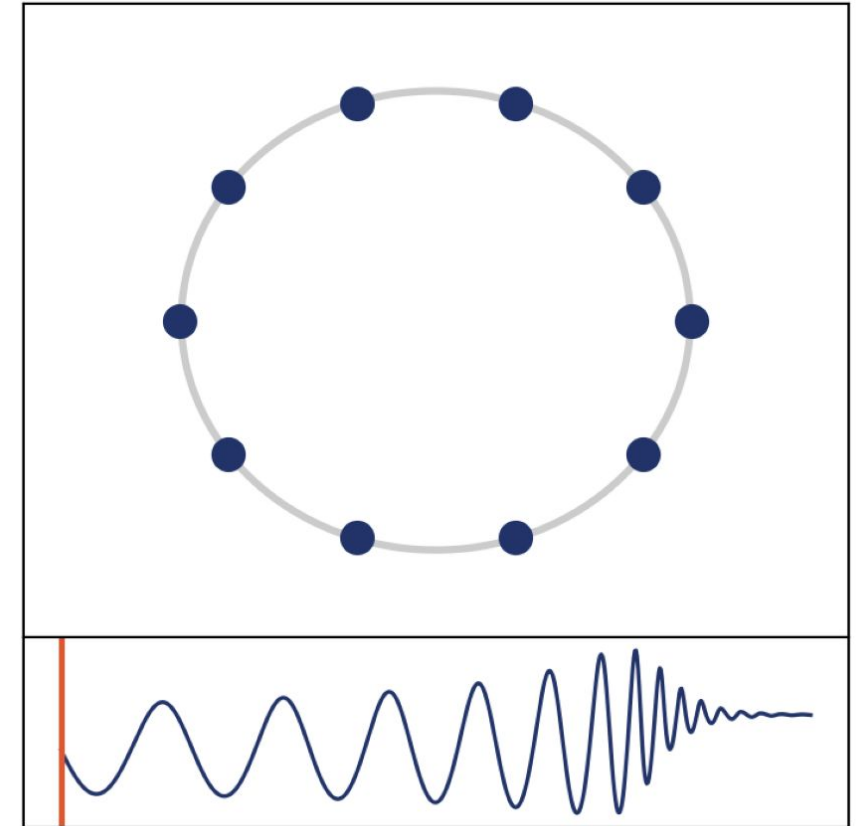
*"Modelling Gravitational Wave Memory with
SEBOB"*

What is Memory?

- Gravitational wave displacement memory refers to **the permanent displacement of test masses following the passage of a gravitational wave**
- There are various kinds
 - Linear
 - Non-linear (Christodoulou memory)
- Gravitational wave strain can be decomposed as a sum of (l, m) modes over a basis of spin-weighted spherical harmonics

$$h_+ - ih_\times = \sum_{l=2}^{\infty} \sum_{m=-l}^l h^{lm}_{-2} Y^{lm}(\Theta, \Phi)$$

- Non-linear memory is a zero-frequency effect that is dominant in the (2,0) mode

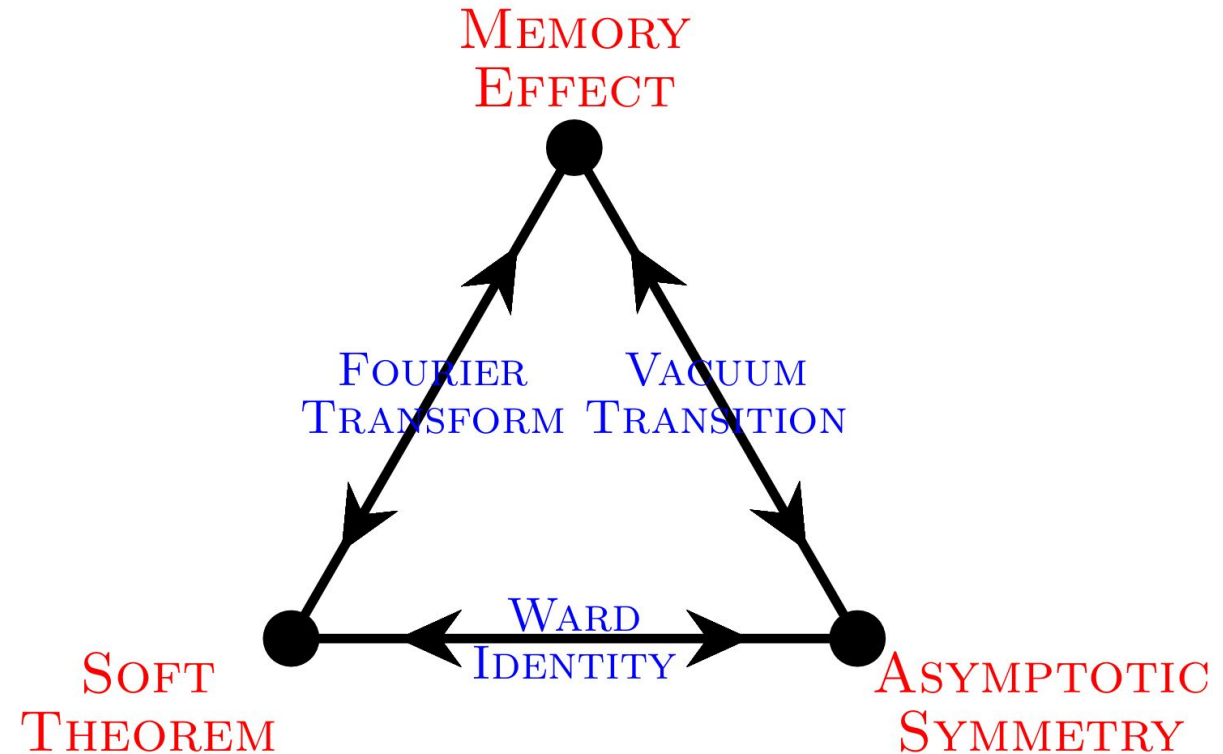


A ring of test masses being permanently displaced by a passing gravitational wave.

Credit: Keefe Mitman, SXS

Why Memory?

- A Test of GR
- Probes the asymptotic structure of spacetime, i.e., Bondi-Metzner-Sachs (BMS) symmetries
- It is a bridge between quantum field theory (soft theorems) and classical GR

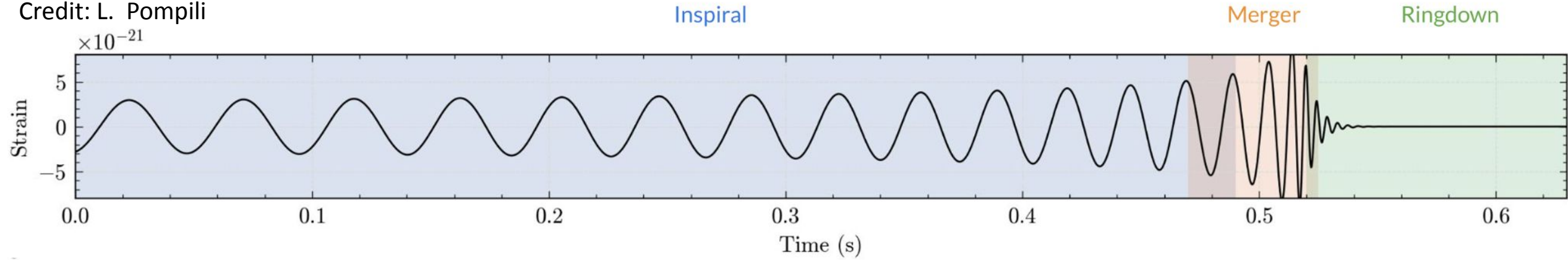


Credit: Andrew Strominger, arXiv:1703.05448v2

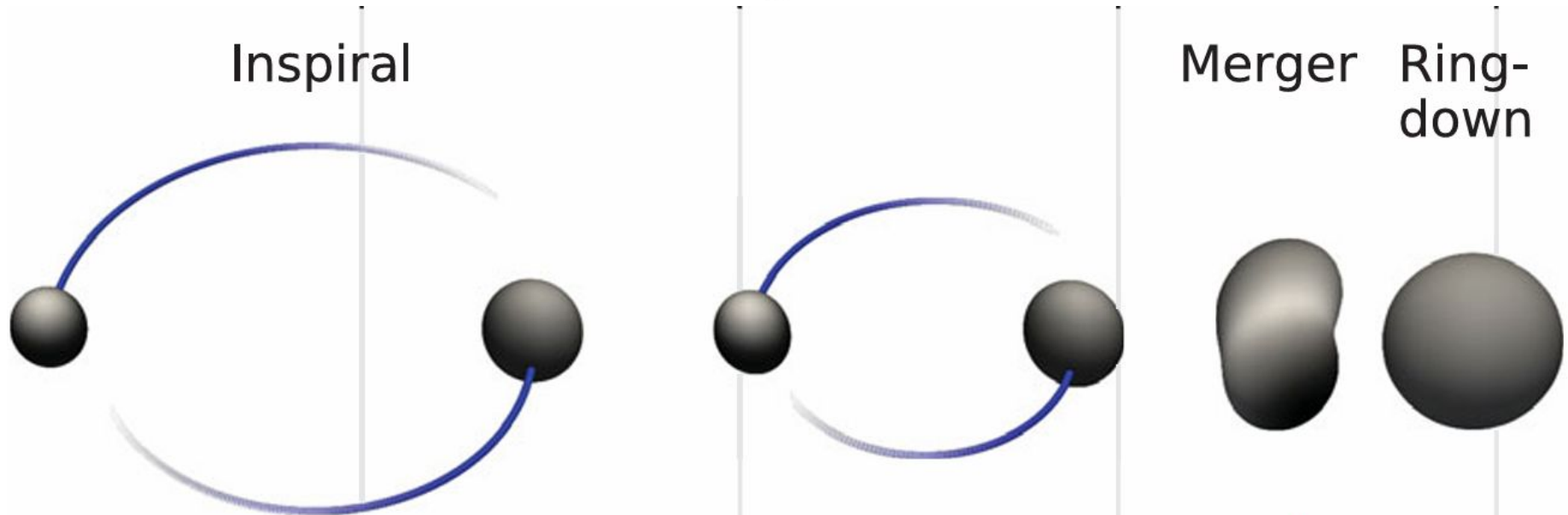
How do we model
gravitational waves and
memory?

Anatomy of a gravitational waveform

Credit: L. Pompili

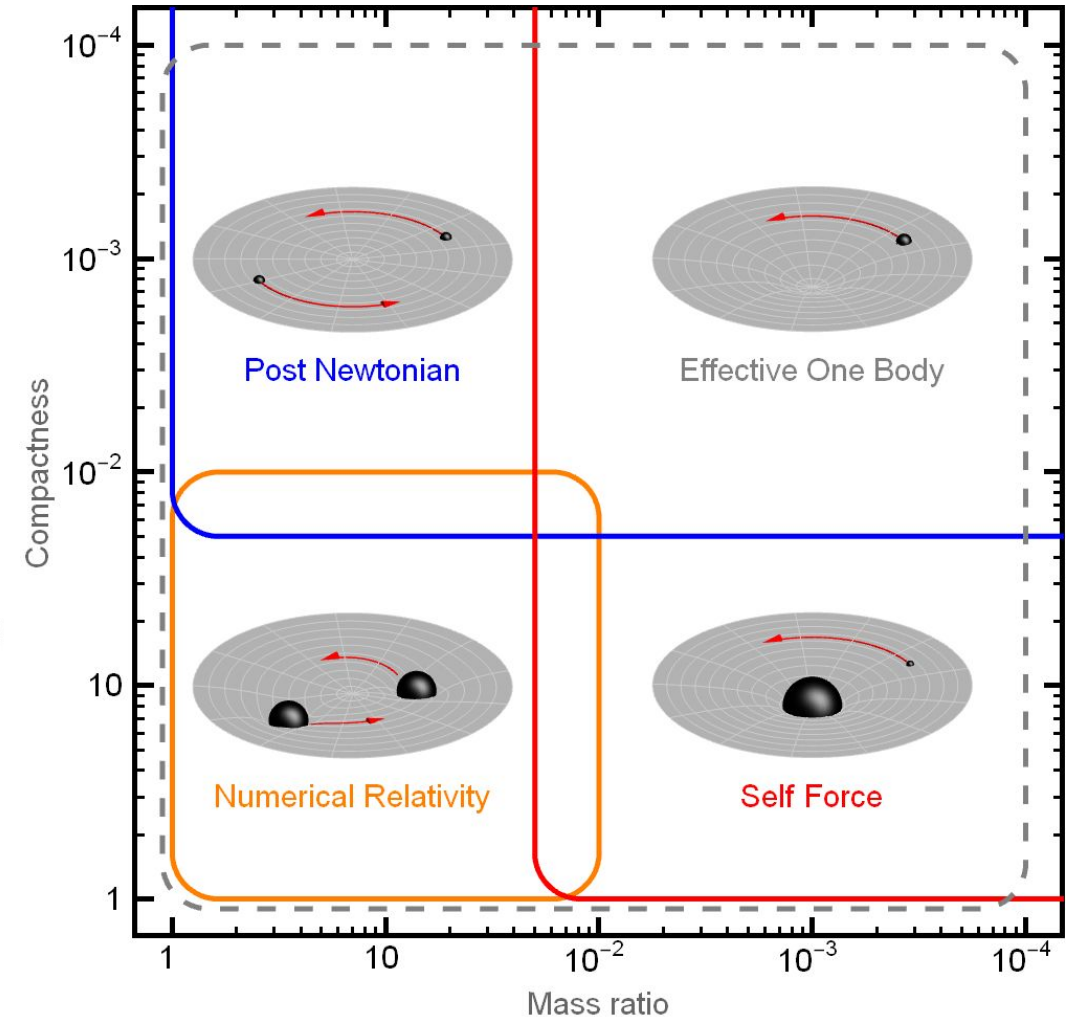
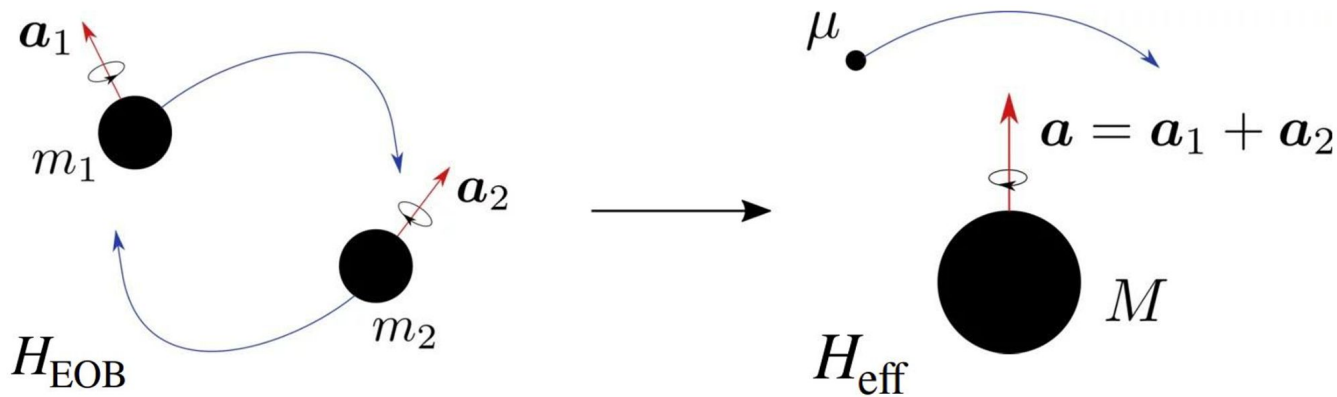


Credit: Phys. Rev. Lett.
116, 061102 (2016)



Effective One Body (EOB) Inspiral Model

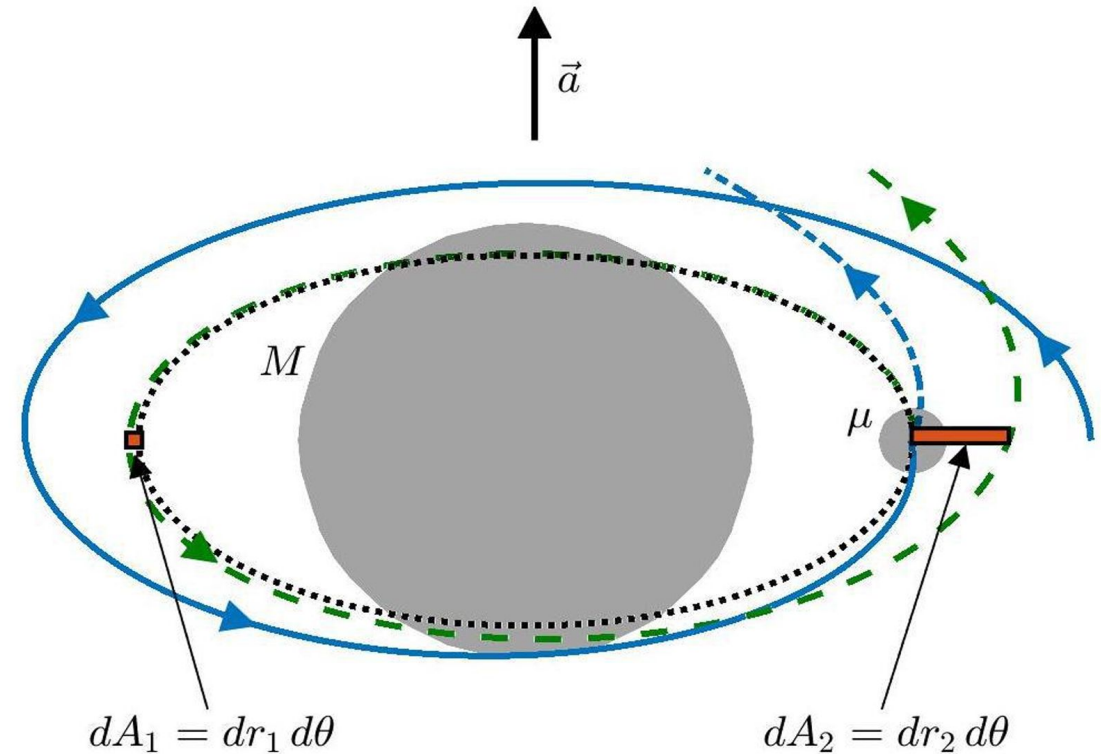
- Two-body dynamics are mapped to that of an “effective one body” in curved spacetime
 - Inspiral coalescence governed by the EOB Hamiltonian and Radiation Reaction (RR) force



Credit: Maarten van de Meent, CC BY-SA 4.0

Backwards One Body (BOB) Merger-Ringdown Model

- ▶ An analytical merger-ringdown model (MR analog to EOB)
- ▶ Models late inspiral, merger and ringdown as a perturbation of the final remnant black hole
- ▶ Radiation governed by divergence of the null congruence near the remnant light ring.

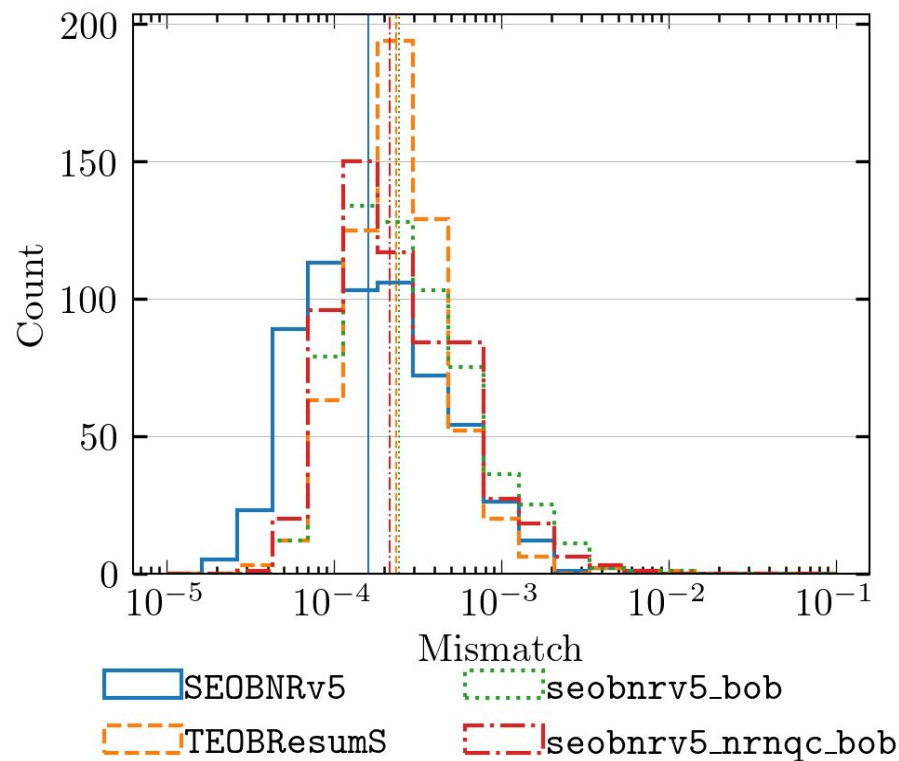


$$|\mathcal{N}| = A_p \operatorname{sech}(\gamma(t - t_p))$$

S. T. McWilliams, Phys. Rev. Lett. 122, 191102 (2019)

Spinning Effective-to-Backwards One Body (SEBOB)

- SEBOB is a semi-analytical gravitational waveform model which combine the inspiral model of SEOBNRv5 with BOB merger ringdown model
- SEBOB removes 6 out of 13 NR parameters, is fast to compute and is highly accurate!
- Computed using NRPY 2.0
 - A Python-based, numerical relativity infrastructure for generating highly-optimized C code from Sympy expressions

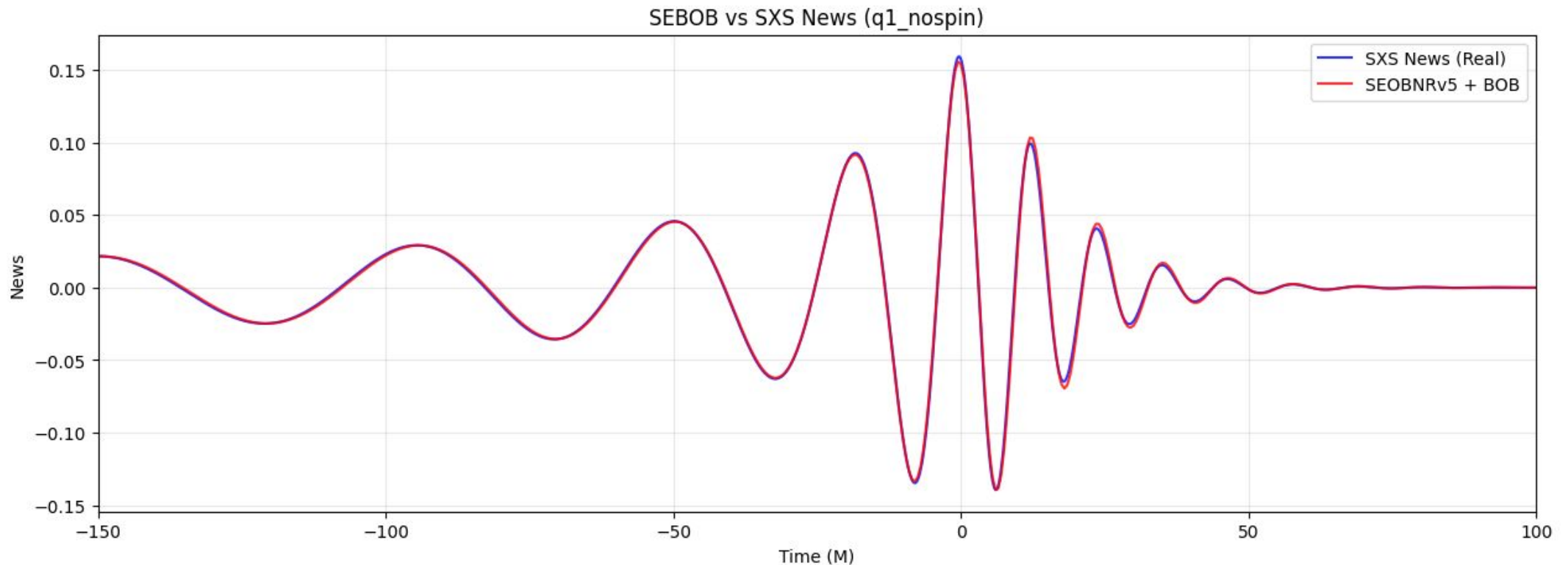


Noise-free strain mismatch against SXS catalog
S. Mahesh, [Phys. Rev. D 112, 124065](#)



MODELLING MEMORY WITH SEBOB

1. First, we compute the SEBOB Strain waveform using NRPY and then differentiate to get the News
 - a. We force alignment of the time and phase of the waveform at the peak News



Approaches to Memory

1. Favata Memory Formula (arXiv:1003.3486v1)

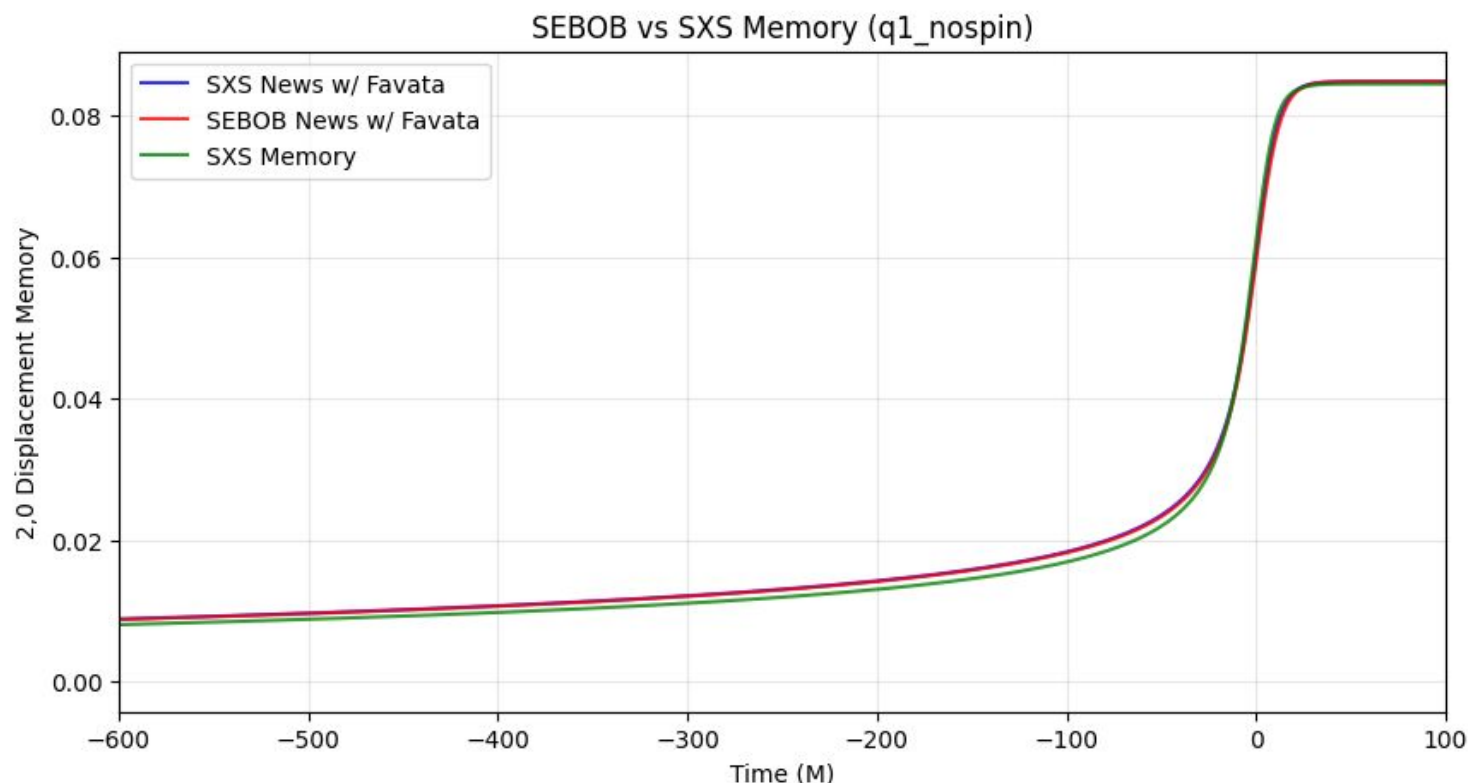
$$h_+^{(\text{mem})} \approx \frac{R}{192\pi} s_\Theta^2 (17 + c_\Theta^2) \int_{-\infty}^{T_R} |\dot{h}_{22}|^2 dt.$$

Pros:

- Simple
- Captures the shape of the memory in NR simulations extremely well

Cons:

- Requires phenomenological scaling parameter α for optimal agreement
- Does not include higher-order modes

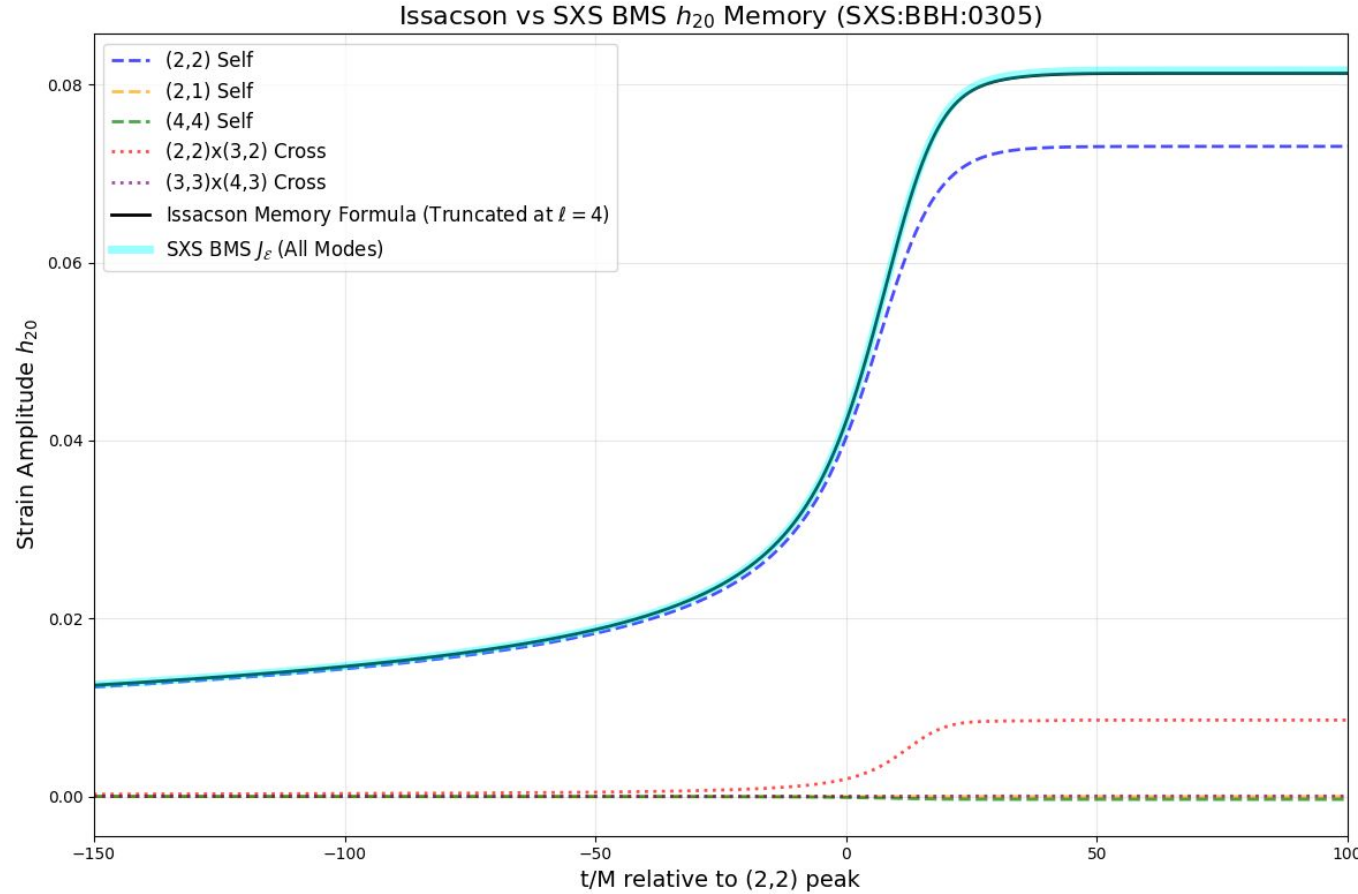


Approaches to Memory

2. Isaacson Memory Formula (arXiv:2601.23019v1)

$$h_{20}^L = \frac{1}{r} \int_{-\infty}^u du' r'^2 \left[\frac{1}{7} \sqrt{\frac{5}{6\pi}} |\dot{h}_{22}^H|^2 - \frac{1}{14} \sqrt{\frac{5}{6\pi}} |\dot{h}_{21}^H|^2 + \frac{5}{4\sqrt{42\pi}} \left(\dot{h}_{22}^H \dot{h}_{32}^H + \dot{h}_{22}^H \dot{h}_{32}^H \right) \right. \\ \left. + \frac{1}{2\sqrt{10\pi}} \left(\dot{h}_{33}^H \dot{h}_{43}^H + \dot{h}_{33}^H \dot{h}_{43}^H \right) - \frac{2}{11} \sqrt{\frac{2}{15\pi}} |\dot{h}_{44}^H|^2 \right].$$

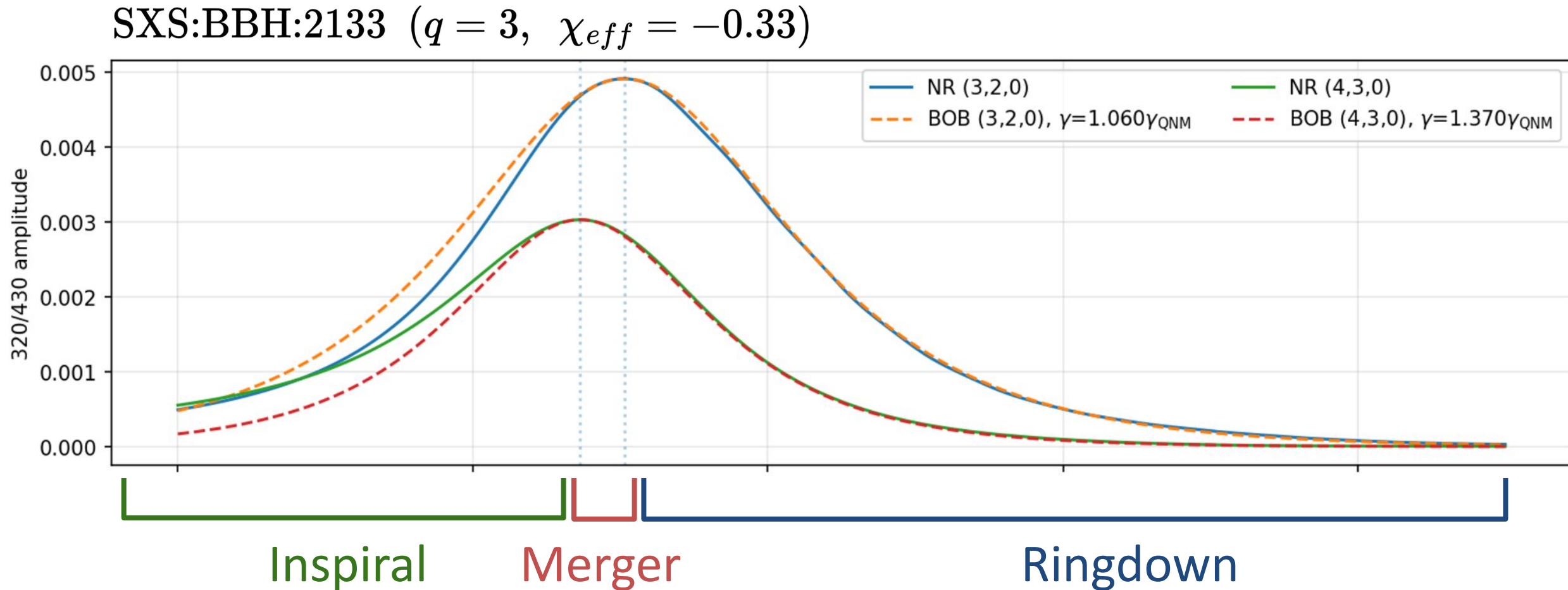
- A more robust approximation for (2, 0) mode memory including several mode contributions
- No phenomenological parameter required and it is highly accurate



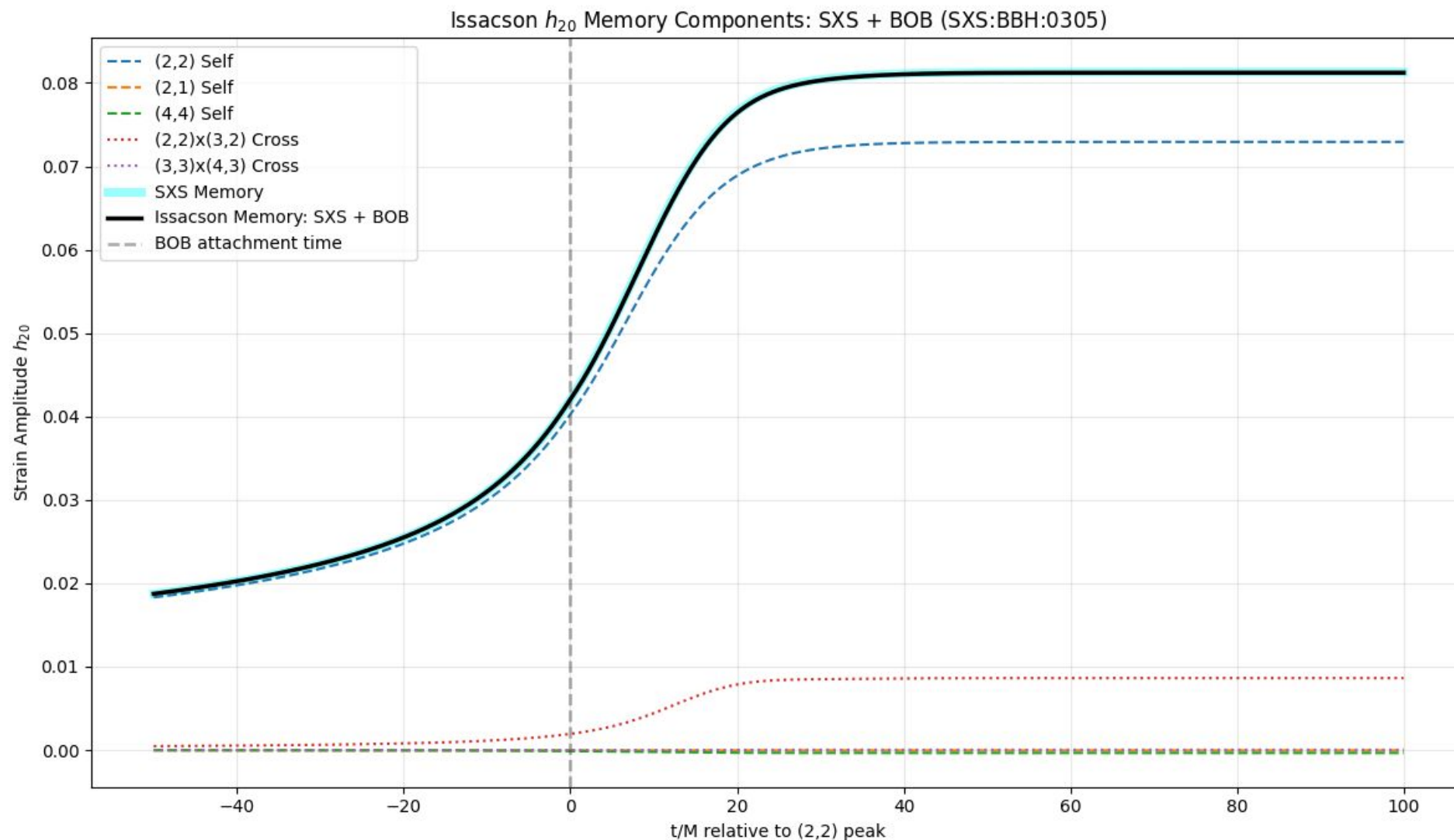
Improving BOB to Model Higher Order Modes

- Isaacson Memory **requires (4,3) and (3,2) modes** in addition to (2, 2), (3,3), and (4,4) modes
- BOB has been tested and proven against NR for the dominant (2,2) mode emission and in general (l, m) modes for $l = m$
- **Extending BOB to $l \neq m$ modes** is the focus of my current work

BOB for (4,3,0) and (3,2,0) spheroidal modes

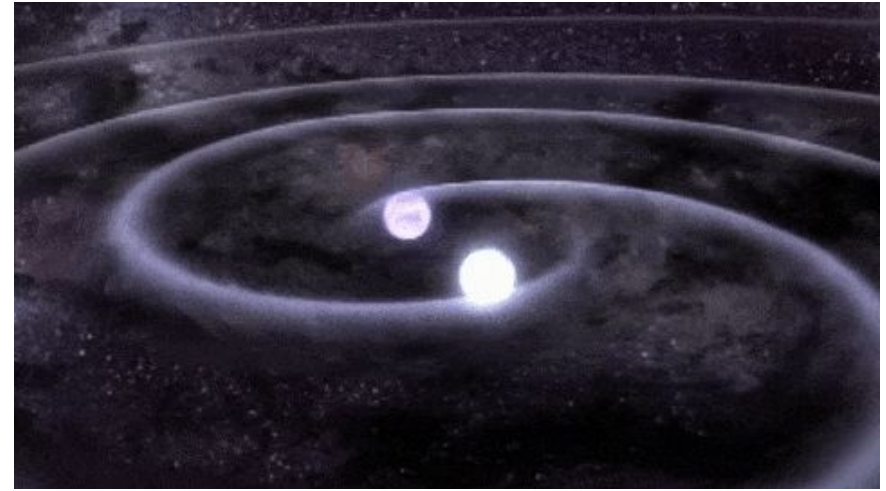


BOB + SXS Isaacson Memory vs. SXS Memory



Future/Ongoing Work

- ▶ Improve BOB (3,2,0) and (4,3,0) models and test them against a large set of SXS simulations
- ▶ Attach BOB to SEOBNRv5 inspiral for the $l \neq m$ modes to produce next generation SEBOB
- ▶ Use next-generation SEBOB to capture memory effects



Credit: NASA

Afternoon I | 01:00 PM - 01:15 PM

Duncan Lorimer & Hannah Lawson

"Gamma-ray and radio models of millisecond pulsars in globular clusters"

Gamma-ray and radio models of millisecond pulsars in globular clusters

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Abstract

The populations of millisecond pulsars across the Milky Way's globular cluster system serve as powerful diagnostics of neutron star evolution in a variety of dense stellar environments. Using properties of 118 Galactic globular clusters, we performed Monte Carlo simulations to explain the gamma-ray flux observed by *Fermi*. We compared two distinct luminosity models: a 3D fundamental plane (model A) and a log-normal distribution (model B). Both models successfully reproduce the observed gamma-ray fluxes and mirror the underlying scaling law with the globular cluster stellar encounter rate established for low-mass X-ray binaries and radio millisecond pulsars, suggesting a universal production mechanism. Due to its lower average gamma-ray luminosities, model B predicts a 6–7 times larger millisecond pulsar population (5140^{+760}_{-810}) than model A (770 ± 70). Invoking a radio-to-gamma-ray luminosity scaling ($L_\gamma \sim 3 \times 10^{-7} L_r$), we find that model B predicts a mean radio pseudoluminosity ($\log L_{\text{pseudo}} \sim -1.7$) that is fainter than canonical pulsars. This result is consistent with recent observational evidence found by Karastergiou et al. which attributes the apparent faintness of Galactic millisecond pulsars to geometric effects. In contrast, model A implies an intrinsically brighter population ($\log L_{\text{pseudo}} \sim -0.3$) that lacks a clear physical basis and is inconsistent with the results found for Galactic pulsars. The larger underlying population of faint millisecond pulsars predicted by model B could be probed by sensitive surveys with emerging radio facilities to further constrain the evolutionary pathways of recycled pulsars.

Keywords: Gamma-ray astronomy, Globular clusters, Millisecond pulsars, Low-Mass X-ray Binaries

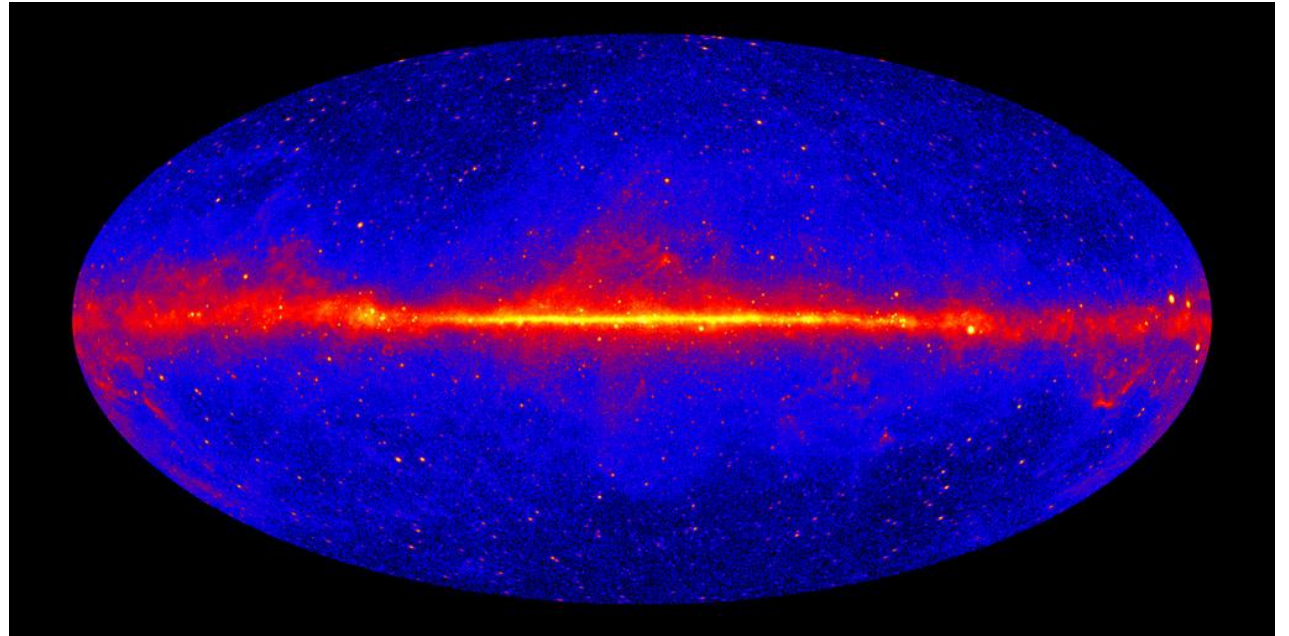
HANNAH LAWSON



2025 REU STUDENT



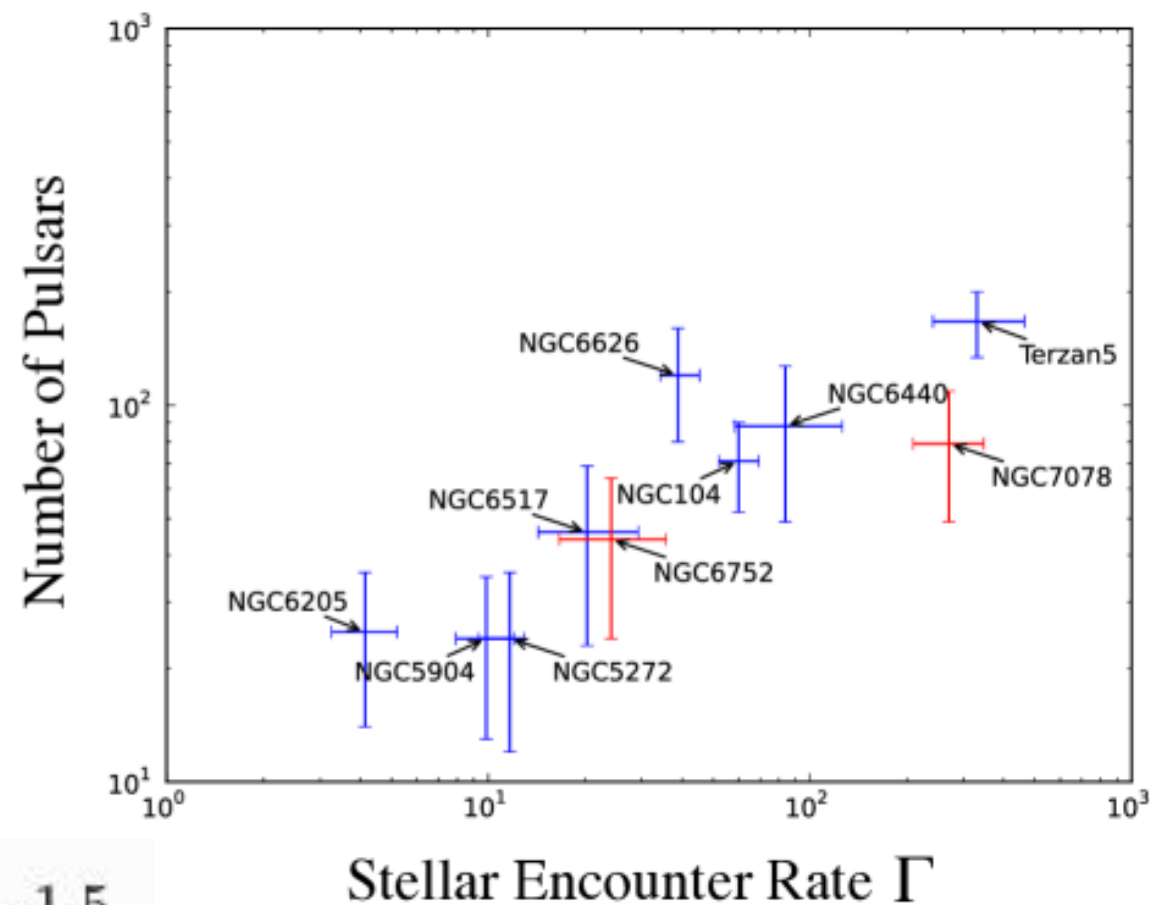
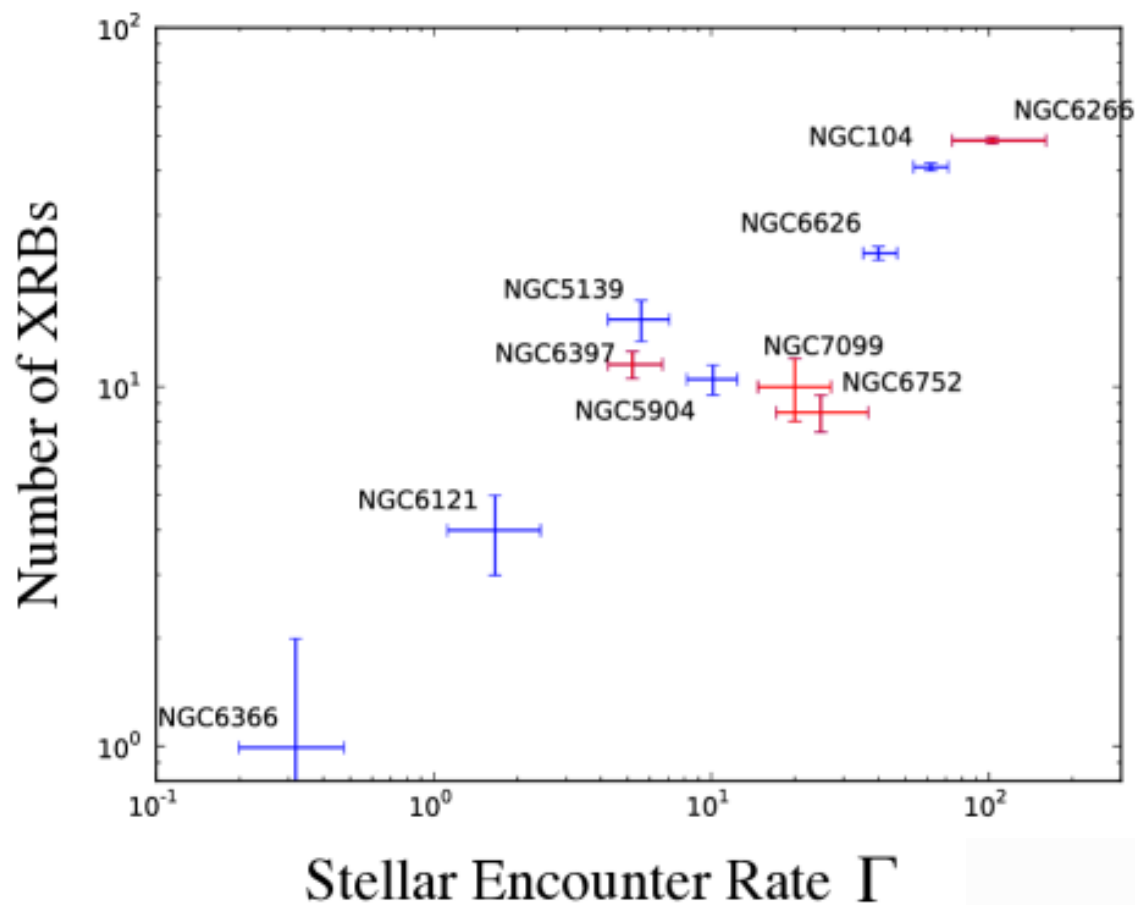
CREDIT: NASA



Credit: NASA/DOE/Fermi



GLOBULAR CLUSTER POPULATIONS INVOLVING NEUTRON STARS

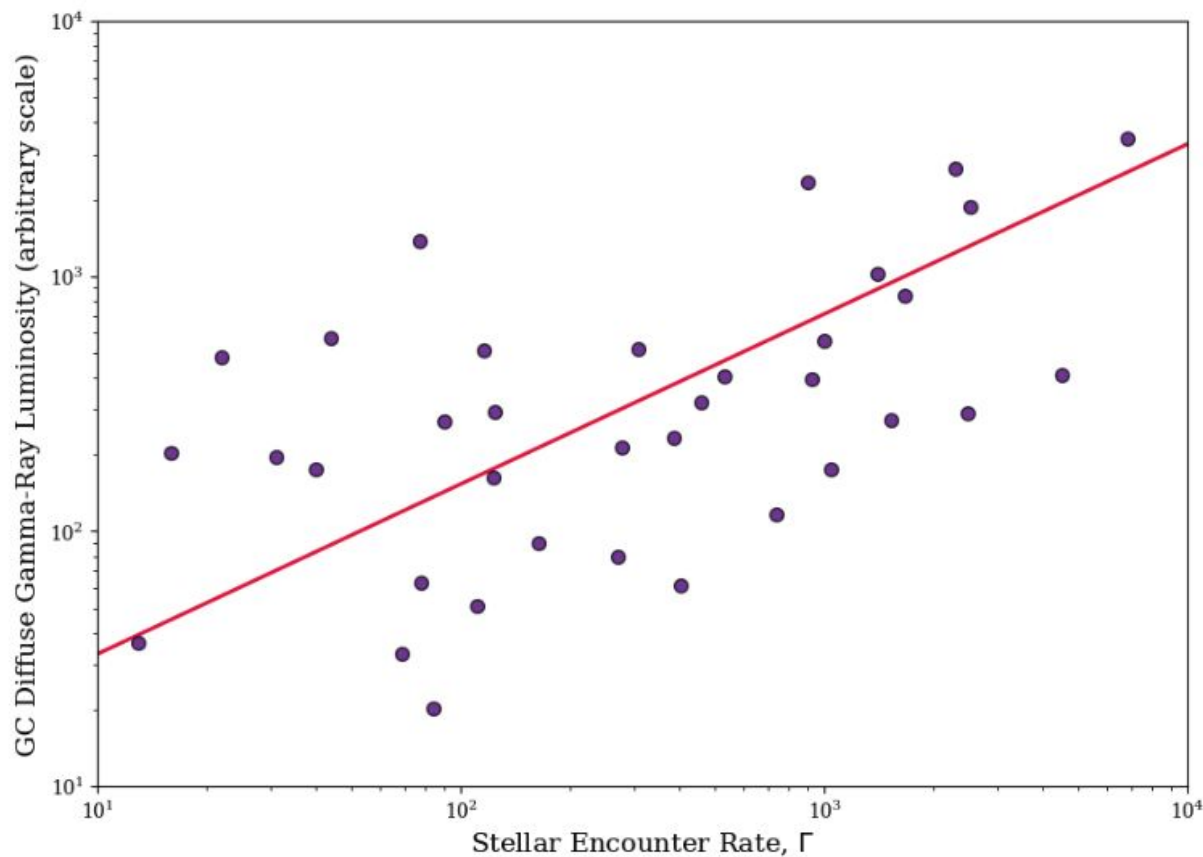


Credit: Kremer 2023, Pooley et al. 2005, Hui et al. 2010

$$\Gamma \propto \frac{\rho_0^{1.5}}{r_c}$$

Central density^{3/2} / Core radius

DO WE SEE THE SAME THING IN THE GAMMA-RAY SKY?



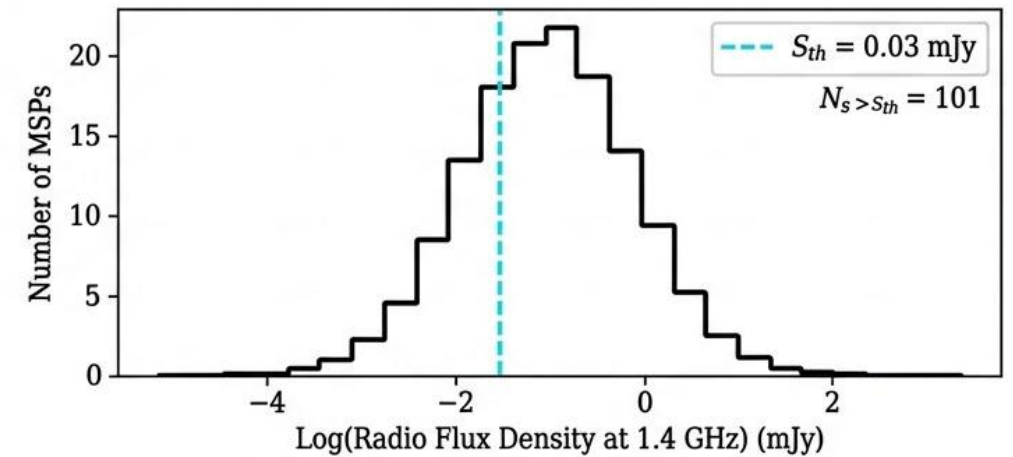
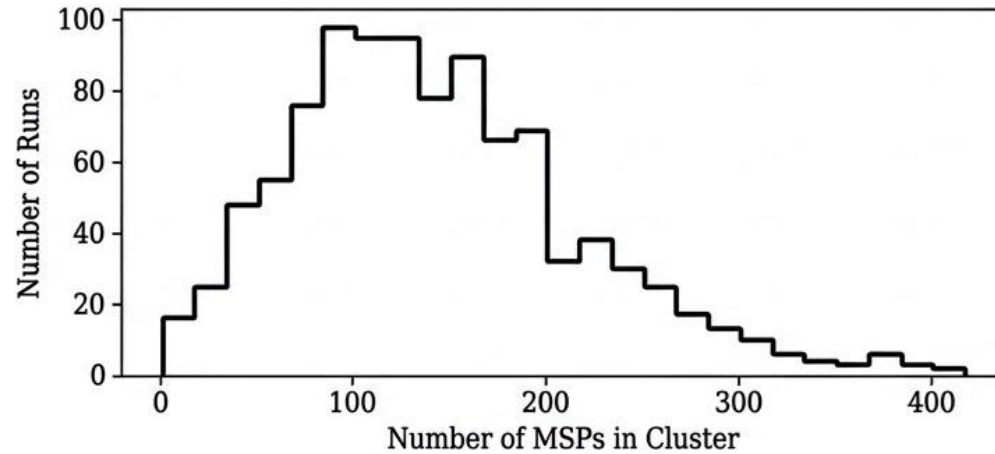
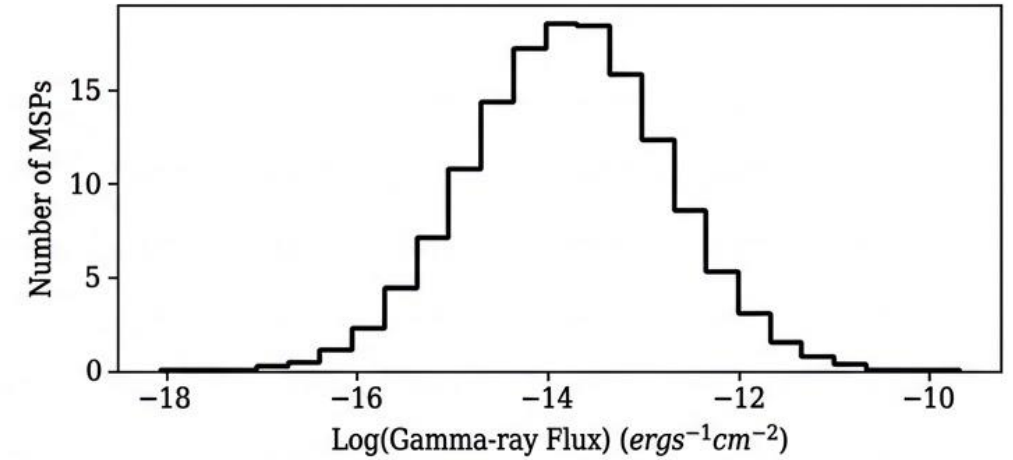
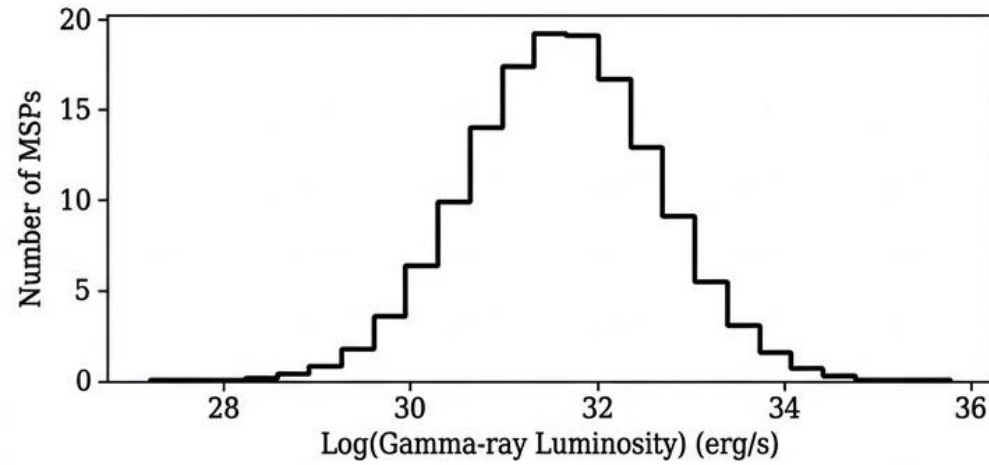
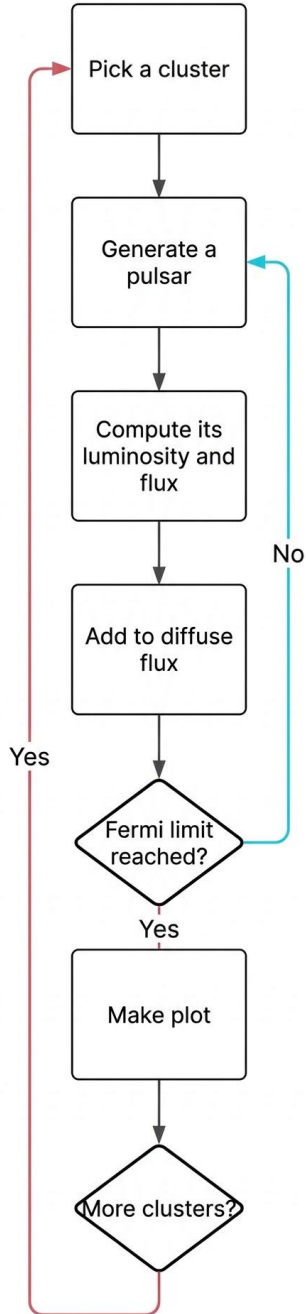
MODEL A

$$L_{\gamma} = 2.2 \times 10^{37} \text{ erg s}^{-1} \left(\frac{B}{10^8 \text{ G}} \right)^{0.12} \left(\frac{\dot{E}}{10^{31} \text{ erg s}^{-1}} \right)^{0.39} \left(\frac{\epsilon_{\text{cut}}}{\text{MeV}} \right)^{1.39}$$

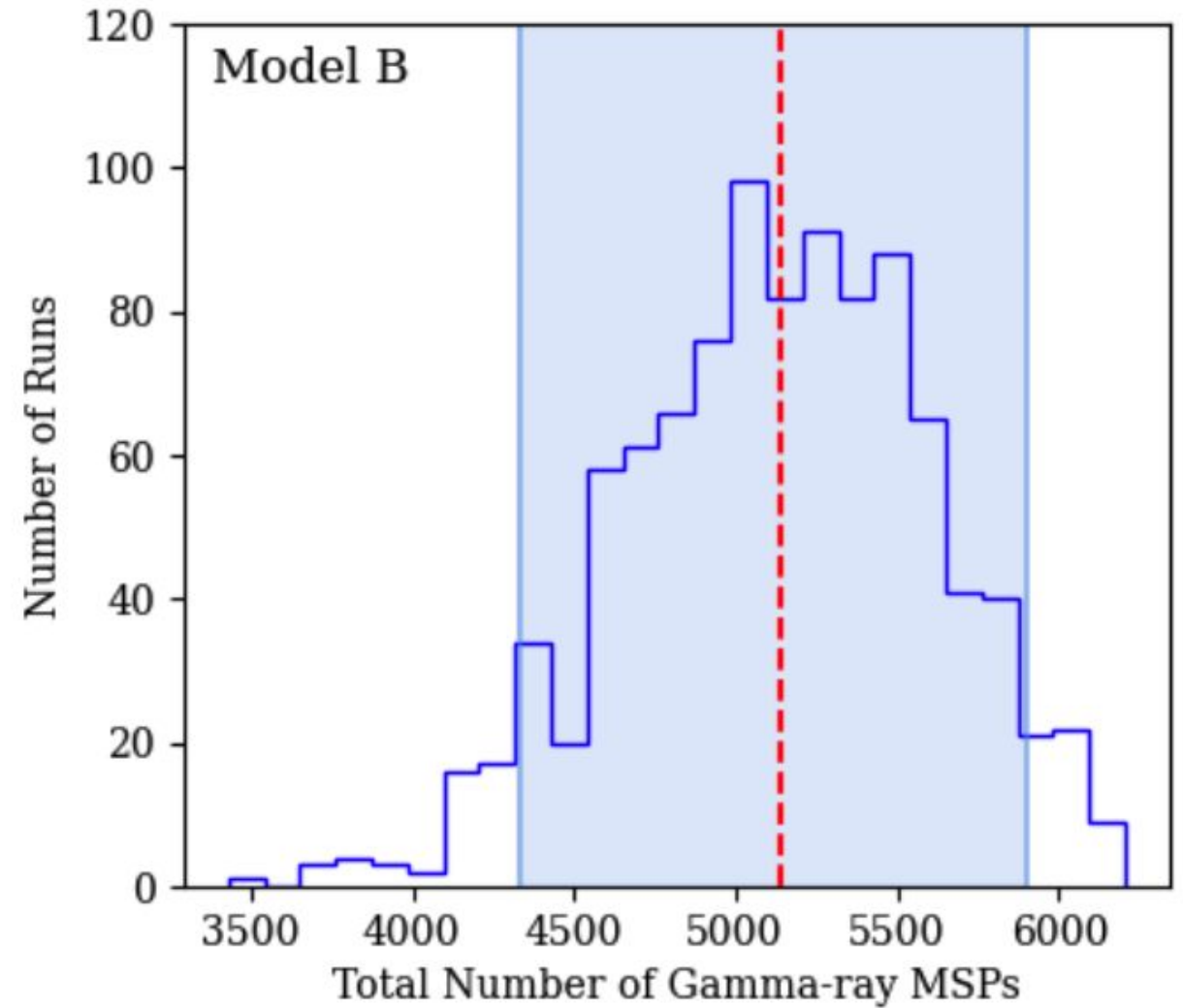
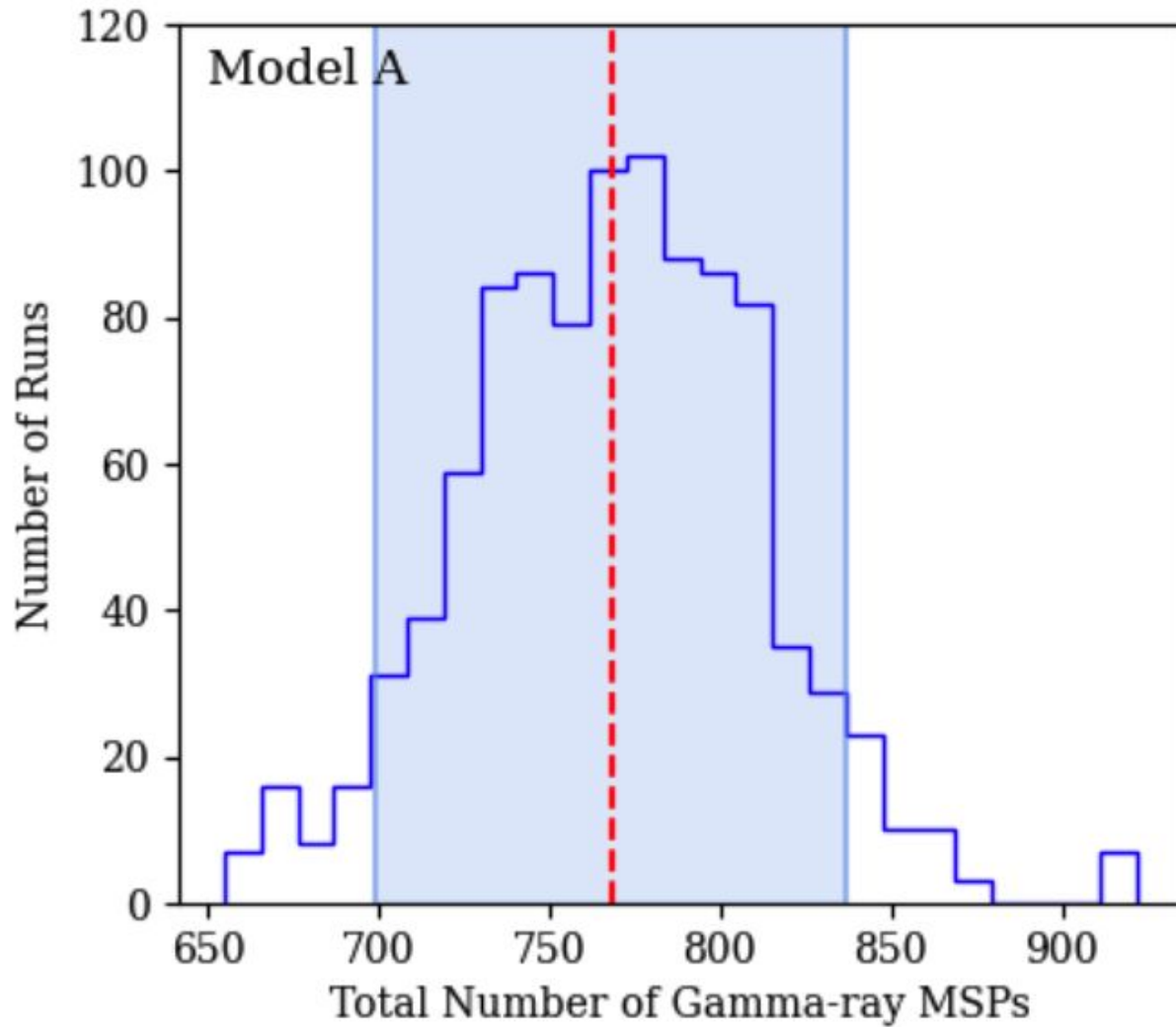
MODEL B

$$dN \propto \frac{1}{L_{\gamma}} \exp \left(-\frac{(\ln L_{\gamma} - \ln L_0)^2}{2\sigma_L^2} \right) dL_{\gamma}$$

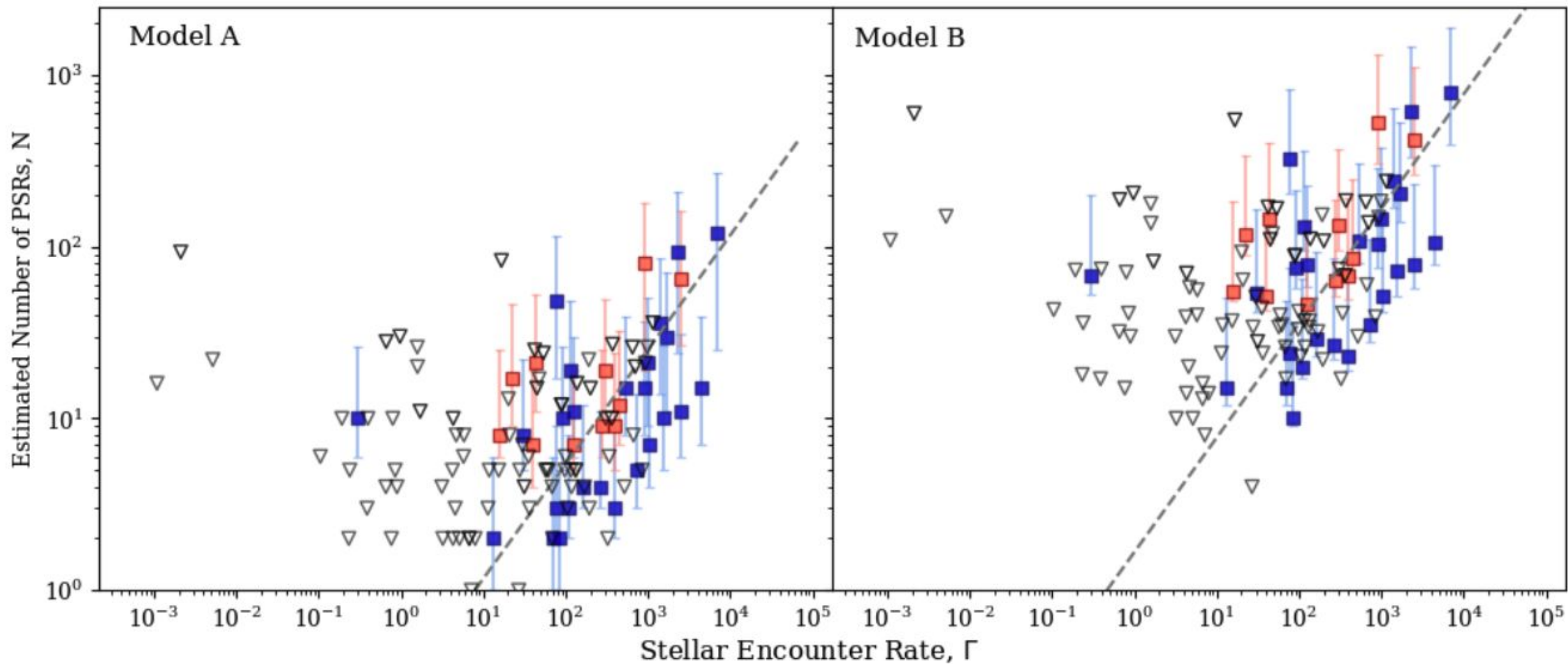
GENERATING GLOBULAR CLUSTER PULSARS



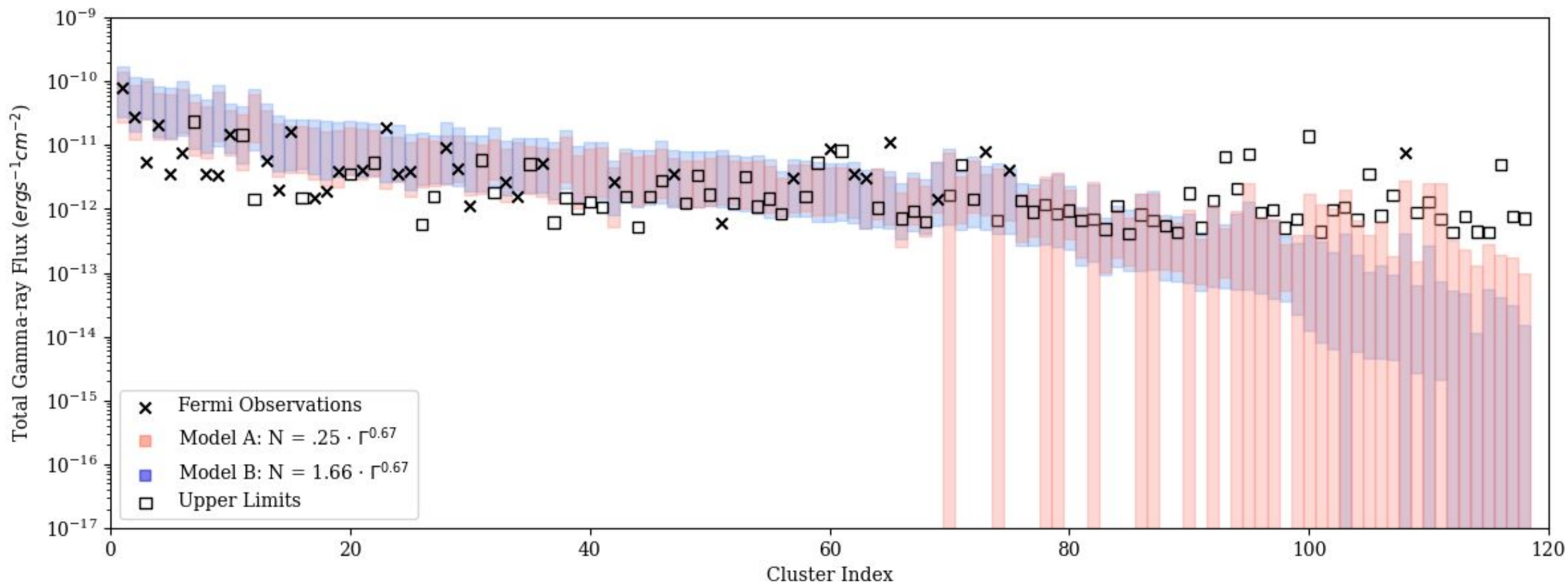
RESULTS FOR TWO MODELS FOR 118 GLOBULAR CLUSTERS



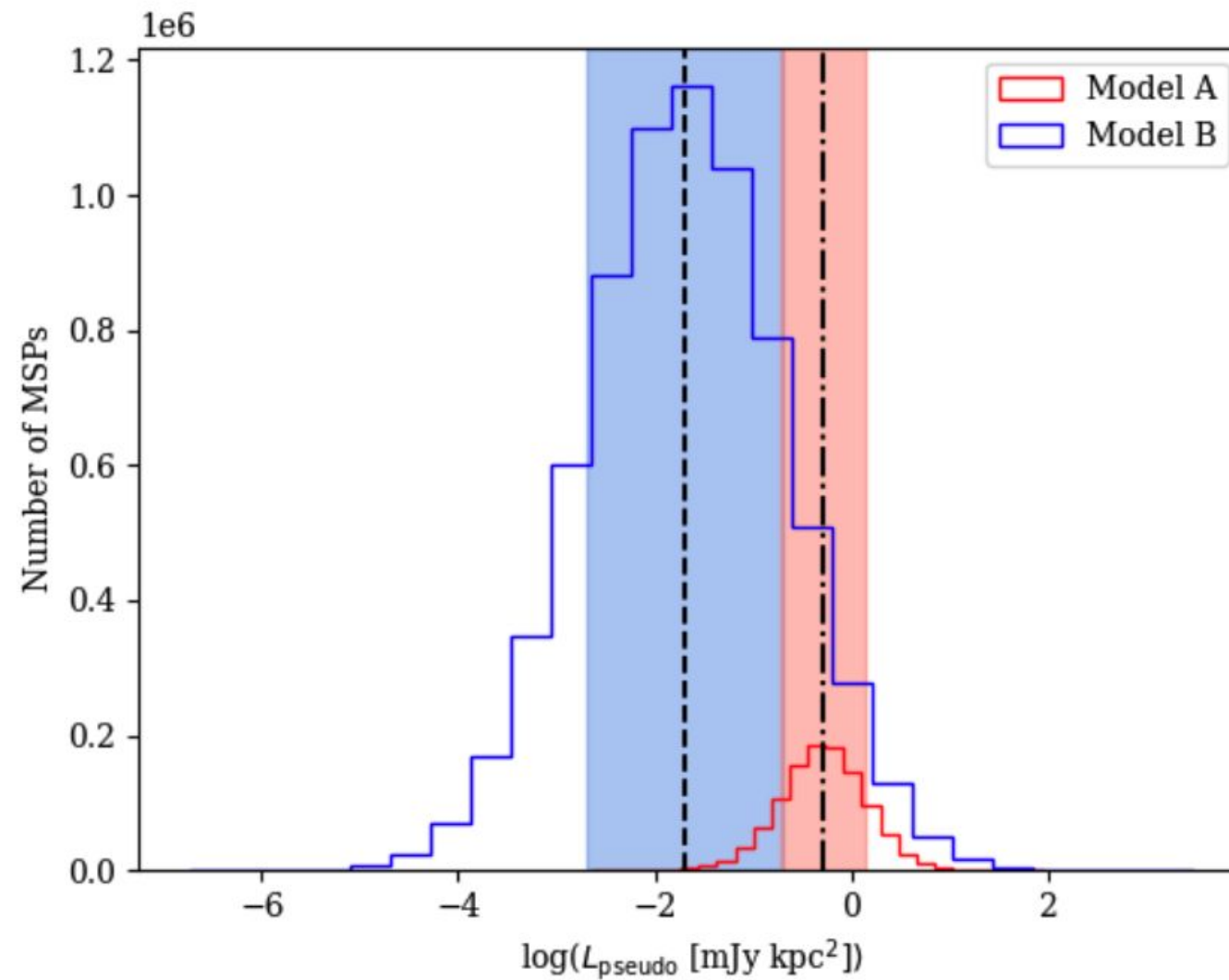
RESULTS FOR TWO MODELS FOR 118 GLOBULAR CLUSTERS



RESULTS FOR TWO MODELS FOR 118 GLOBULAR CLUSTERS



IMPLICATIONS FOR RADIO PULSARS



CONCLUSIONS

1. Gamma-ray emission correlated with stellar encounter rate
 - Model A - fundamental plane -> 770 MSPs
 - Model B - log normal -> 5140 MSPs
 - Seems to better explain radio population?
2. Not enough pulsars in model A?
 - Only a few MSPs dominate each cluster?
 - Radio and gamma-ray populations uncorrelated?

Afternoon I | 01:15 PM - 01:30 PM

Vladimir Strokov

"Gravitational-wave source mixing in LISA"

Afternoon I | 01:30 PM - 01:45 PM



WOOLY MCLAUGHLIN (1980-1985)

Maura McLaughlin

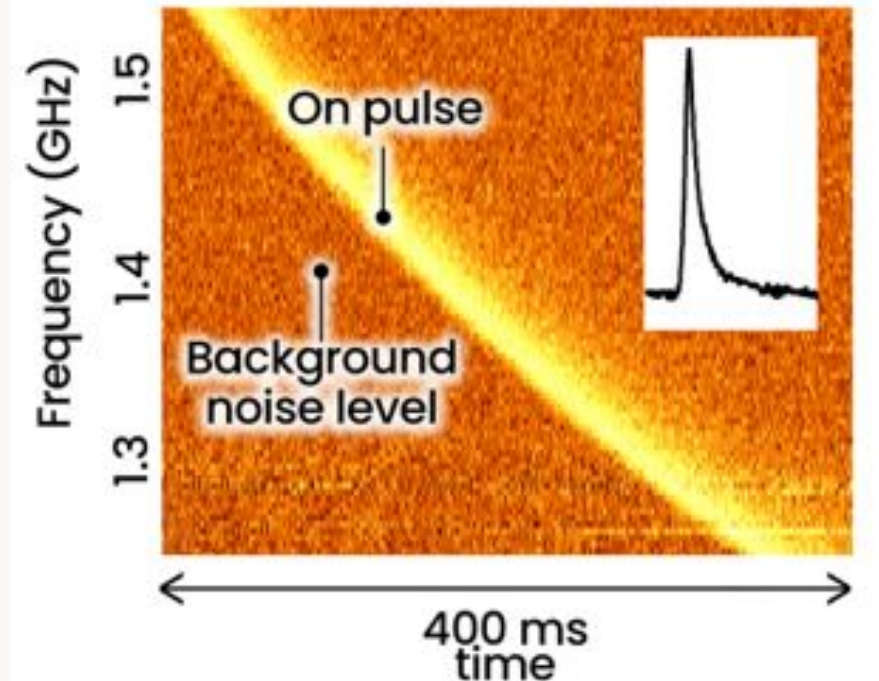
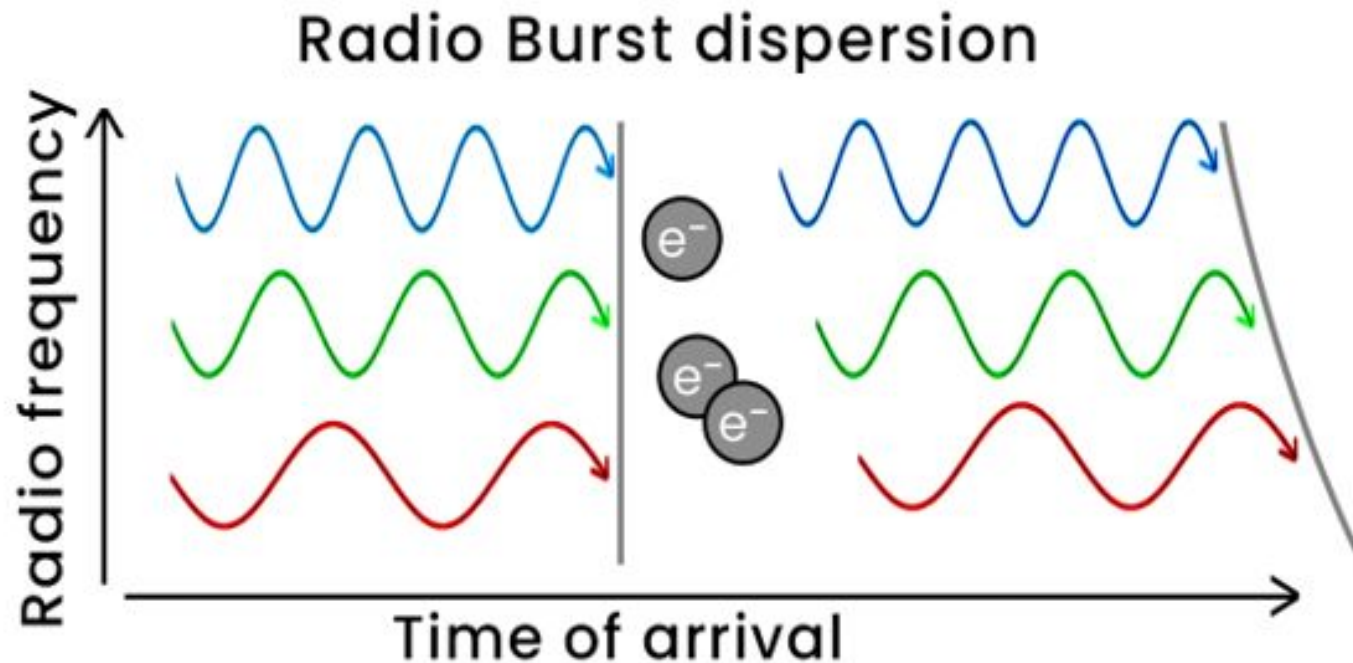
"The RRATALOG: Towards a classification and understanding of rotating radio transients"

Dispersion

$$t_d = \frac{e^2}{2\pi m_e c} \frac{DM}{\nu^2}$$
$$= 4140. \left(\frac{DM}{\text{cm}^{-3} \text{ pc}} \right) \left(\frac{\nu}{1 \text{ MHz}} \right)^{-2} \text{ sec.}$$

Dispersion measure (DM) is the integrated electron column density along the line of sight to a source.

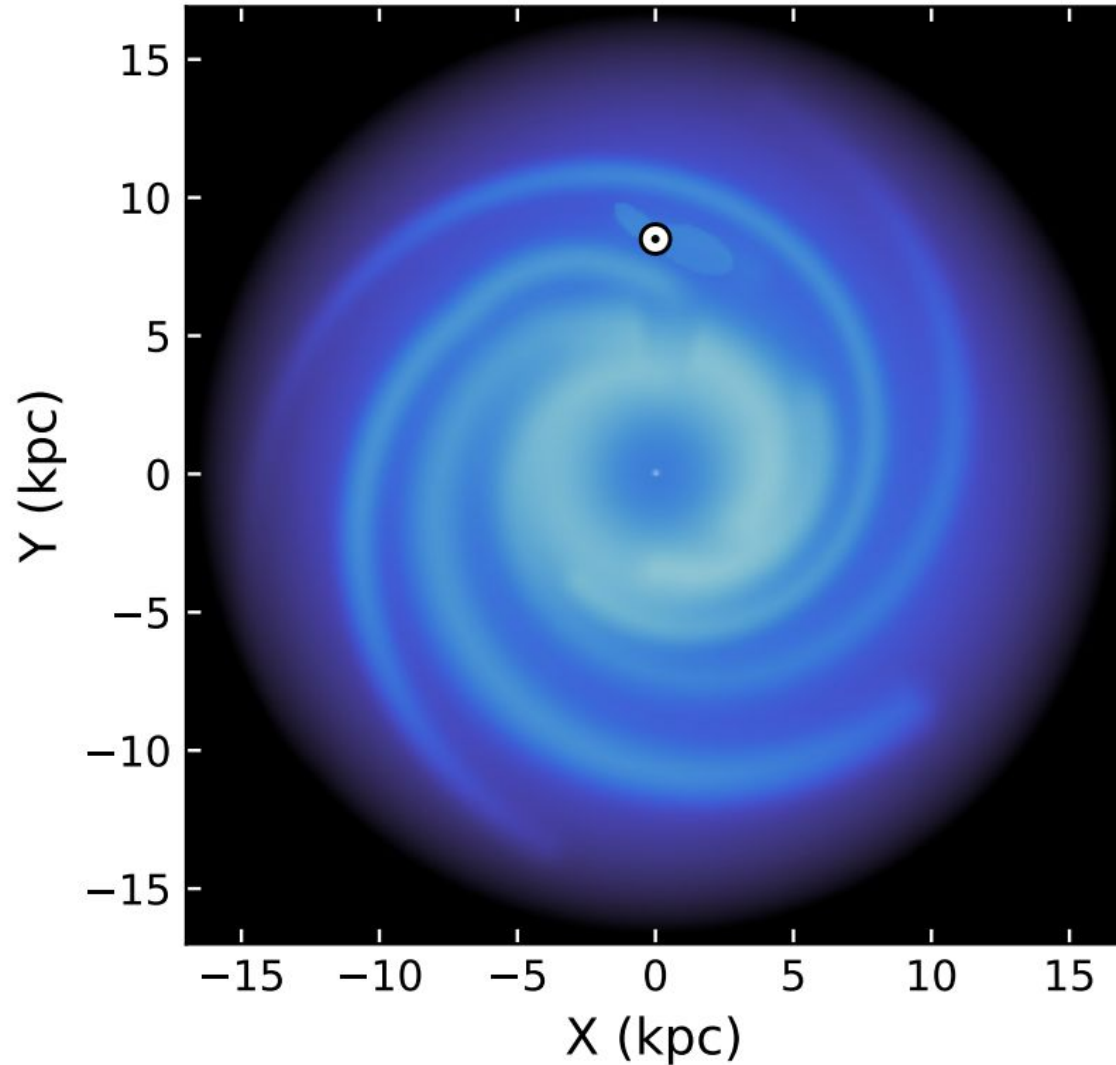
$$DM = \int_0^d n_e(l) dl$$



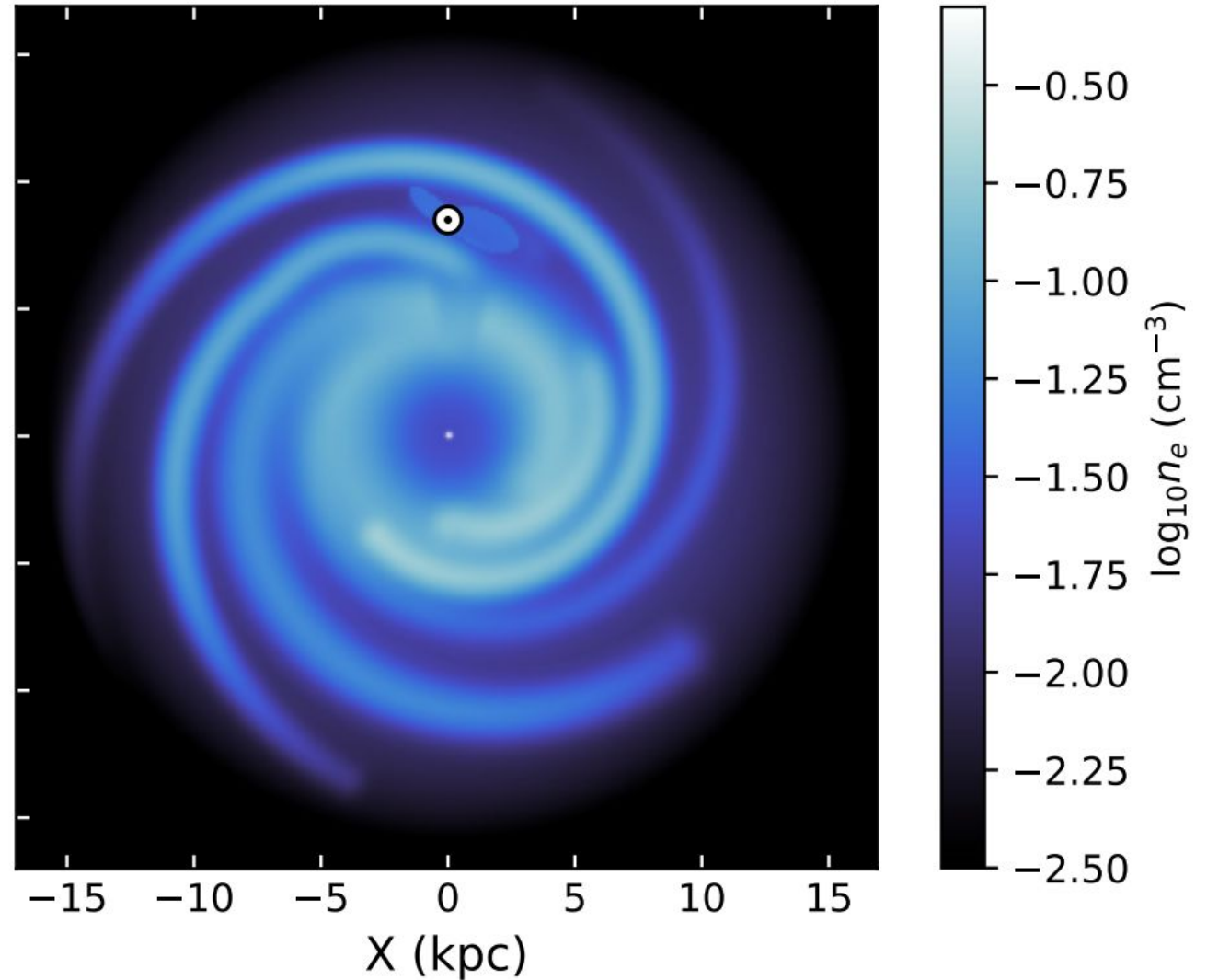
Dispersion Measure (DM)

DMs give us an idea of how far away a source is!

NE2001

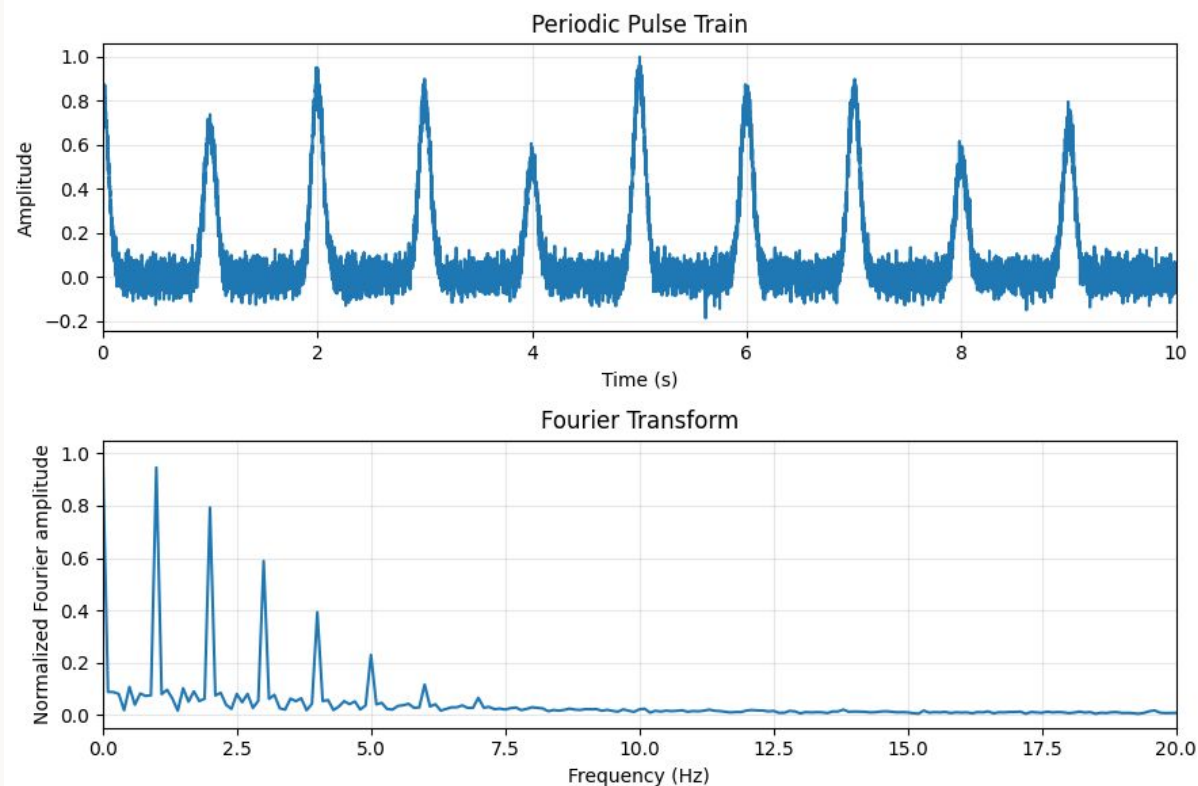
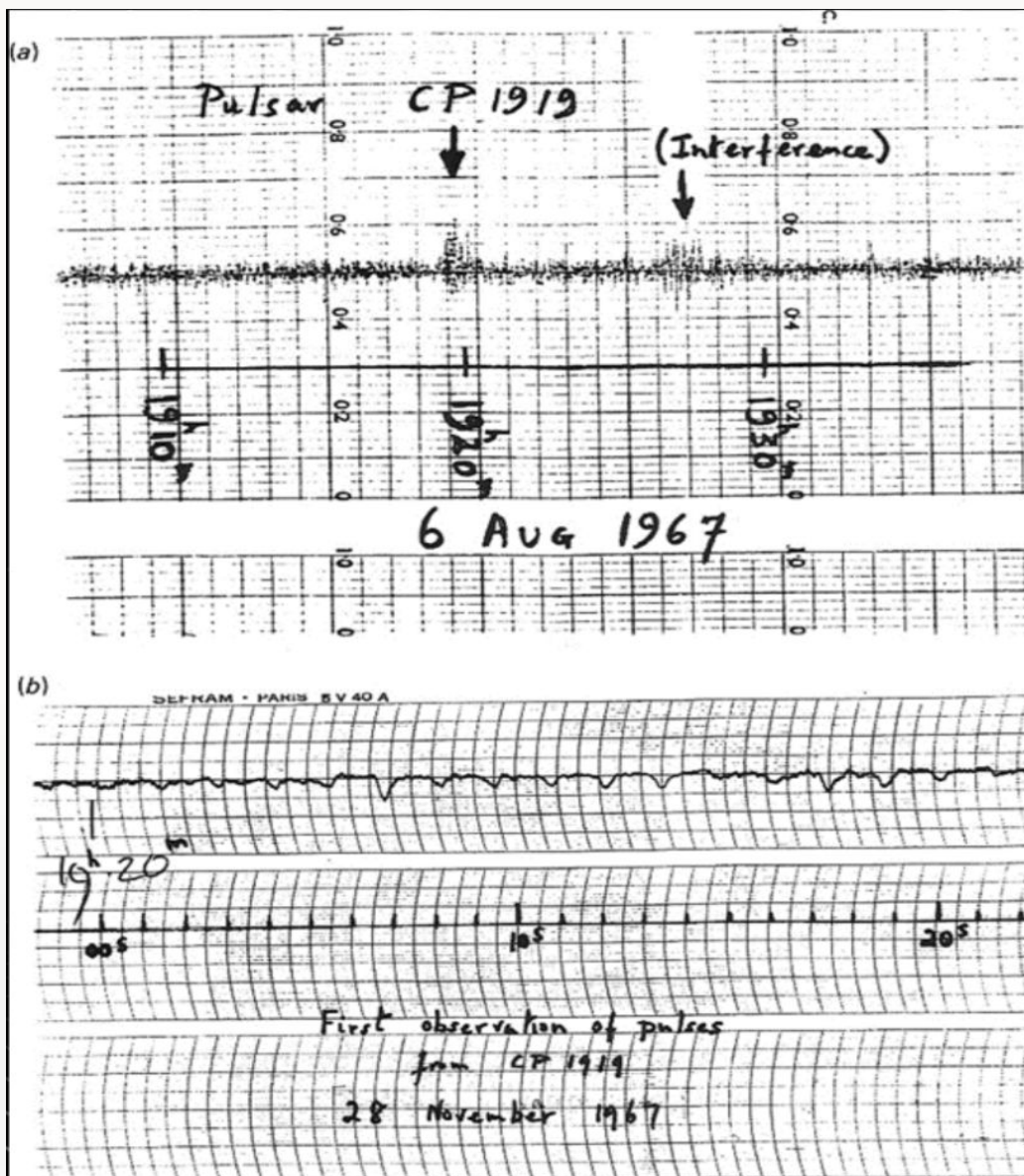


NE2025



Pulsar Searching

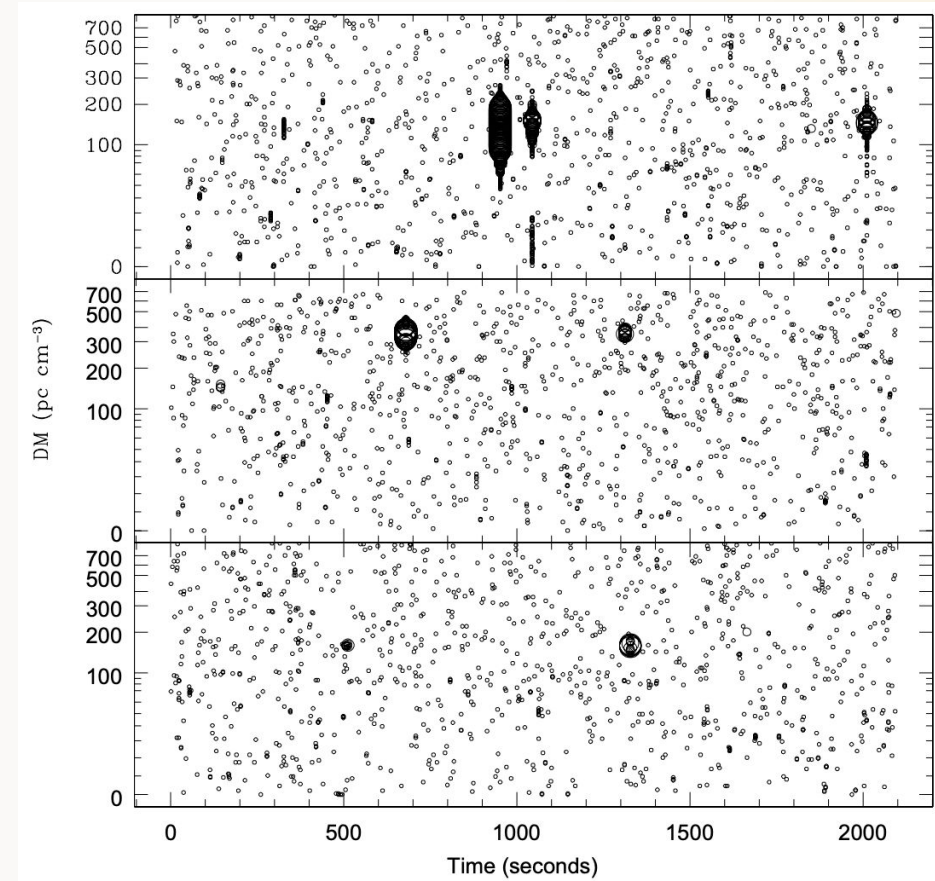
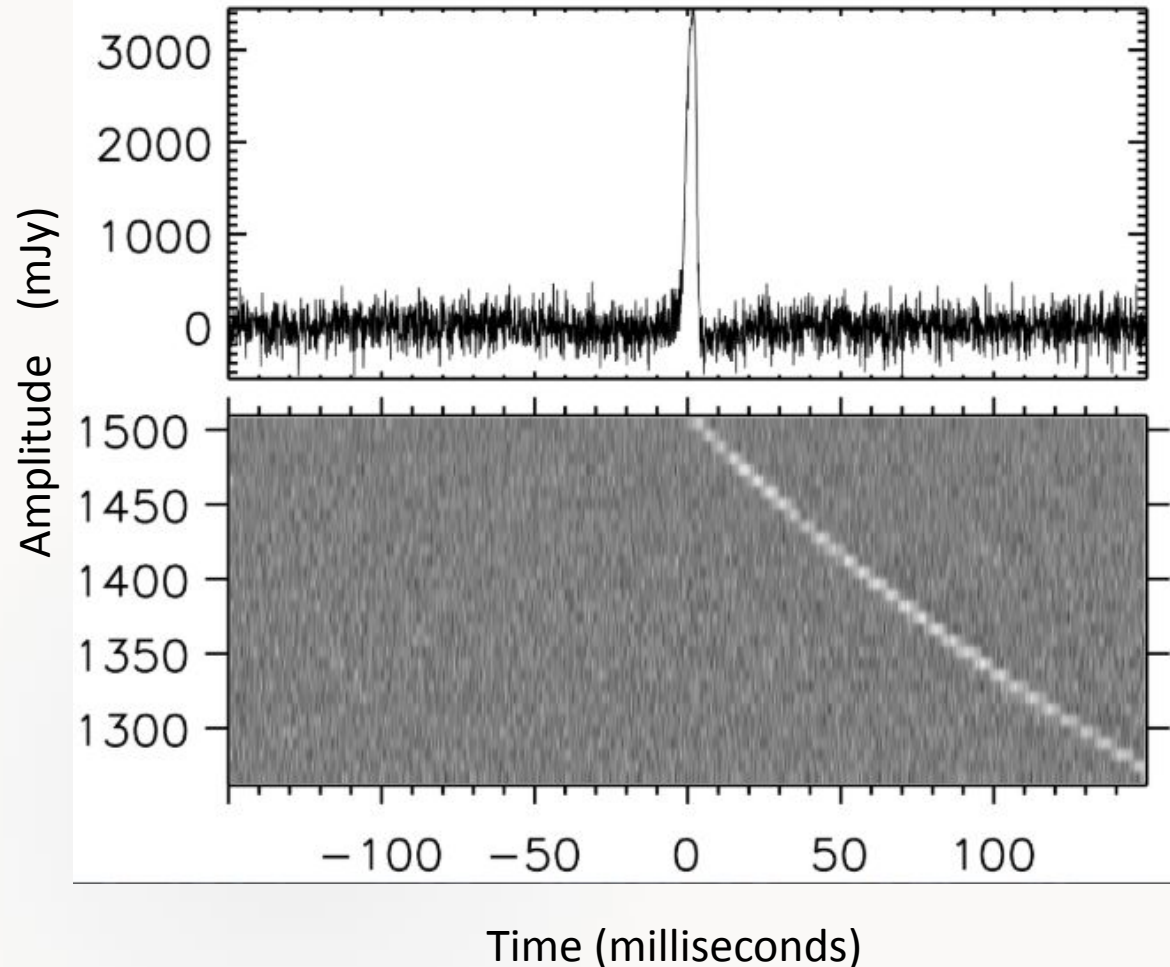
While the first pulsars were found through their single pulses, nearly all pulsars since that time have been found through periodicity searches.



Rotating Radio Transients (RRATs)

Transient radio bursts from rotating neutron stars

M. A. McLaughlin¹, A. G. Lyne¹, D. R. Lorimer¹, M. Kramer¹, A. J. Faulkner¹, R. N. Manchester², J. M. Cordes³, F. Camilo⁴, A. Possenti⁵, I. H. Stairs⁶, G. Hobbs², N. D'Amico^{5,7}, M. Burgay⁵ & J. T. O'Brien¹



“DESPITE THE SMALL NUMBER OF SOURCES PRESENTLY DETECTED, THEIR EPHEMERAL NATURE IMPLIES A TOTAL GALACTIC POPULATION WHICH SIGNIFICANTLY EXCEEDS THAT OF THE REGULARLY PULSING RADIO PULSARS.”

What is a RRAT?

We have defined a RRAT as a pulsar originally detectable only through its single pulses.

Perhaps they are part of the normal pulsar intermittency spectrum.

Perhaps they are a different class of object!

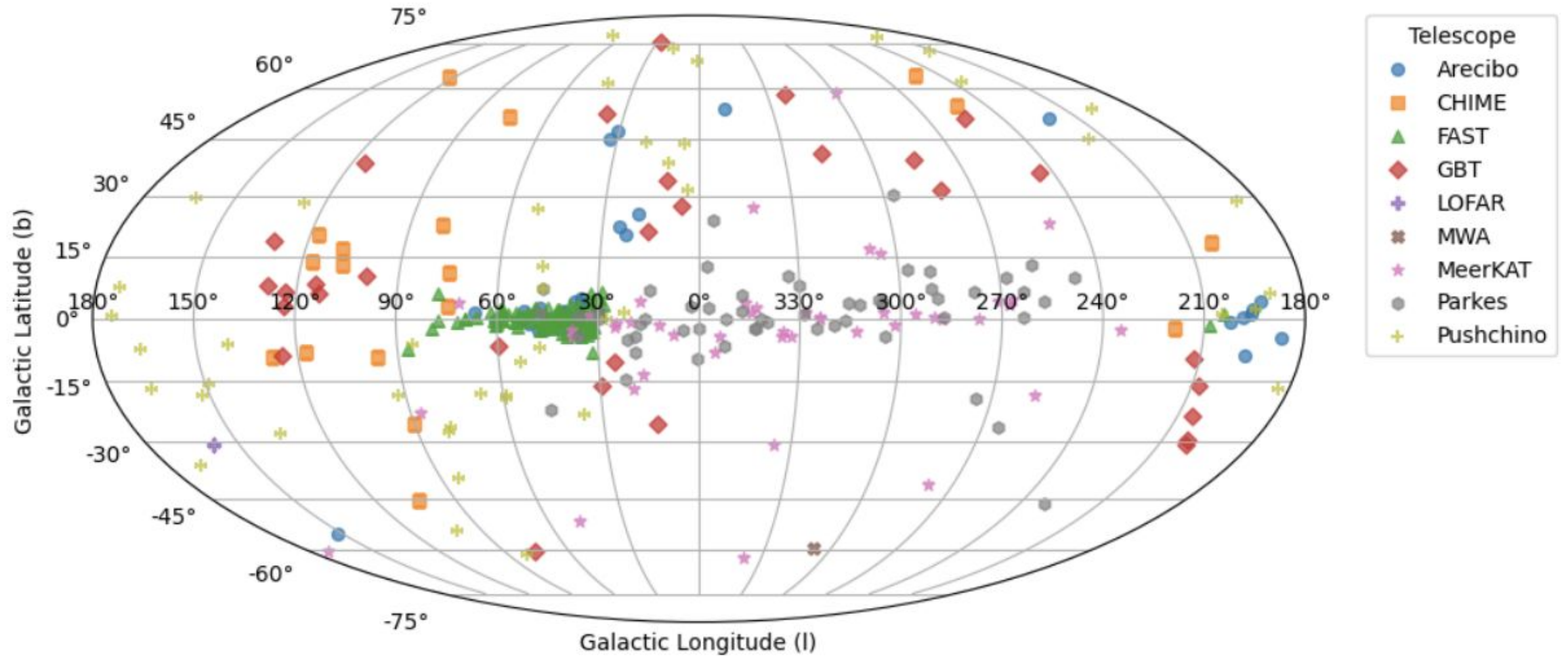
<https://rratalog.github.io/rratalog/>

The RRATALOG

Name	RA (hh:mm:ss.ss)	Dec (dd:mm:ss.ss)	DM (pc cm ⁻³)	Period (s)	$\dot{P}$ (10 ⁻¹⁵ s/s)	P _{epoch}	Frequency (Hz)	$\dot{F}$ (10 ⁻¹⁵ Hz/s)
J0012+5431	00:12:23.3(1)	+54:31:40(9)	131.3(7)	3.0253007099(2)	---	59128.0	0.33054565344(2)	---
J0031-5726	00:31:31.8(13)	-57:26:37(2)	6.75(3)	1.570328(1)	---	---	0.6368096(4)	---
J0054+6650	00:54:55.412(14)	+66:50:23.81(8)	14.560(2)	1.390218110074(8)	5.5532(8)	59478	0.719311590572(4)	-2.8733(4)
J0054+69	00:54:30(20)	+69:26(2)	90.3(2)	---	---	---	---	---
J0102+5356	01:02:57.786(12)	+53:56:11.86(15)	55.6200(8)	0.354299198996(4)	0.5203(5)	59545	2.82247321708(3)	-4.145(4)
J0121+53	01:21(11)	+53:29(16)	91.38(3)	2.7247846(4)	---	---	0.36700149(5)	---
J0139+3336	01:39:57.23(4)	+33:36:59.7(9)	21.23(1)	1.2479609557(1)	2.064(8)	57901	0.80130712057(6)	-1.325(5)
J0156+04	01:56:01(01:54)	+04:02(8)	27.5	1.359077	---	---	0.735793	---
J0201+7005	02:01:41.344(7)	+70:05:18.11(6)	21.029(2)	1.349184471847(9)	5.514(1)	56777	0.741188488948(5)	-3.0292(5)
J0219-06	02:19:00	-06:10:00	8.46(7)	1.87868(4)	---	59330.517875	0.53229(1)	---
J0249+52	02:49:00(90)	+52:46(15)	28(2)	---	---	---	---	---
J0302+2252	03:02:31.990(4)	+22:52:12.1(2)	18.9922(6)	1.207164839778(2)	0.0825(1)	57811	0.828387281545(1)	-0.05661(7)
J0305+40	03:05:30(30)	+40:01(15)	24(2)	---	---	---	---	---
J0313+36	03:13:10(90)	+36:15(15)	21(2)	---	---	---	---	---
J0317+1328	03:17:50(10)	+13:29(3)	12.745(1)	1.9743	---	---	0.5065	---
J0332+79	03:32:40(20)	+79:10(5)	16.67(2)	2.05621(6)	---	---	0.48633(1)	---

<https://rratalog.github.io/rratalog/>

Observed RRAT Population

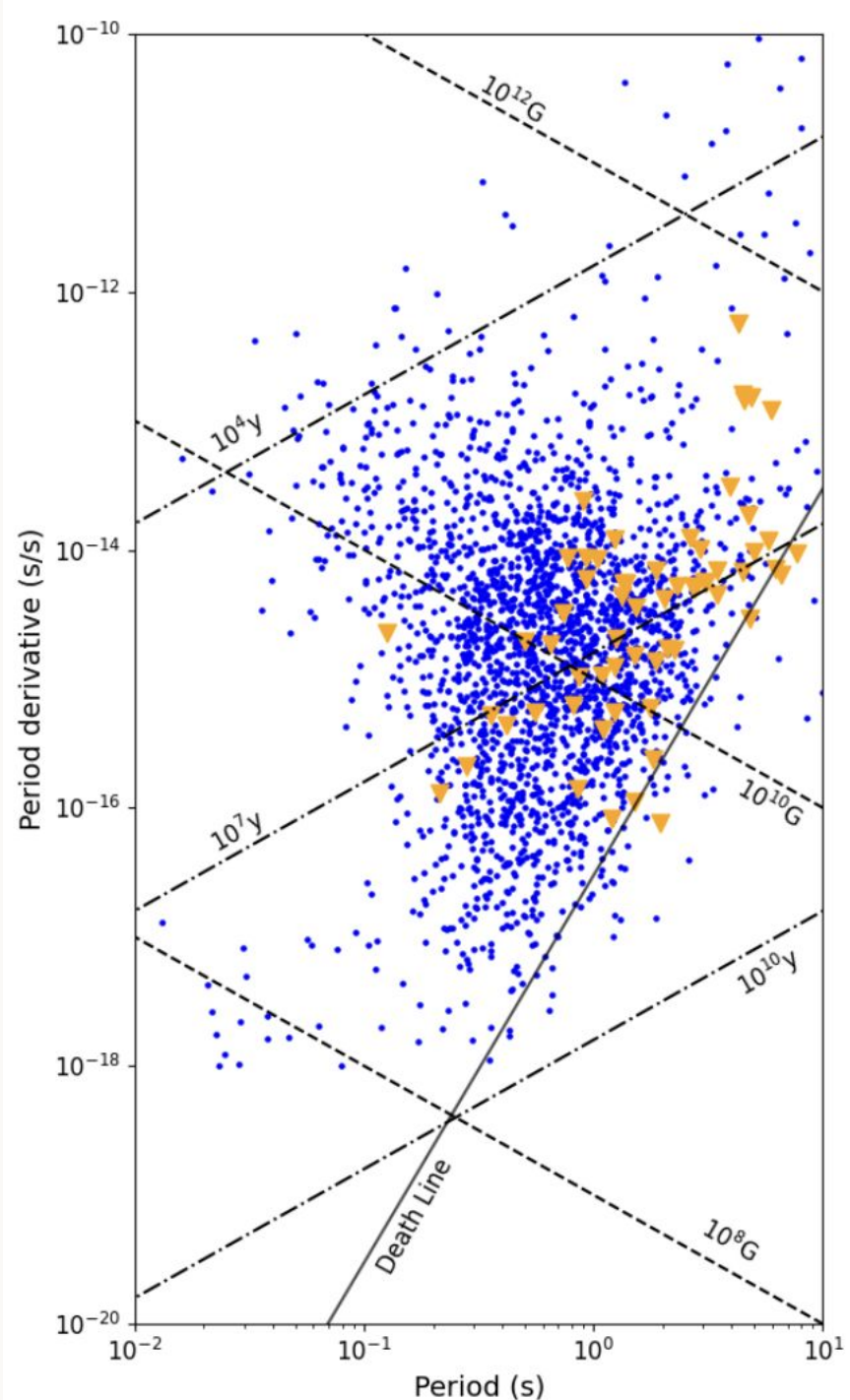


335 sources, all in our galaxy

Observed RRAT Population

The 335 sources include 230 with measured spin periods and 61 with measured period derivatives.

They are generally older and slower!

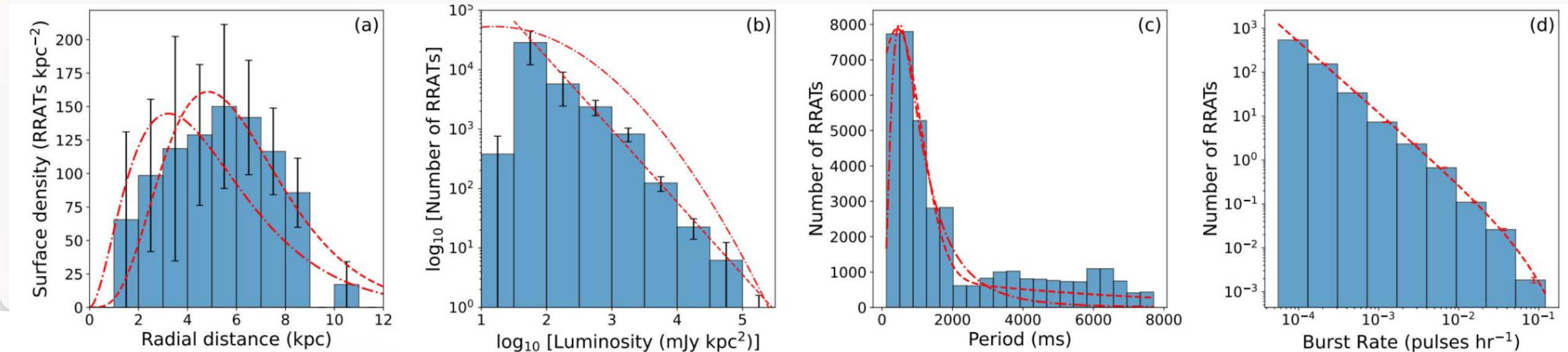
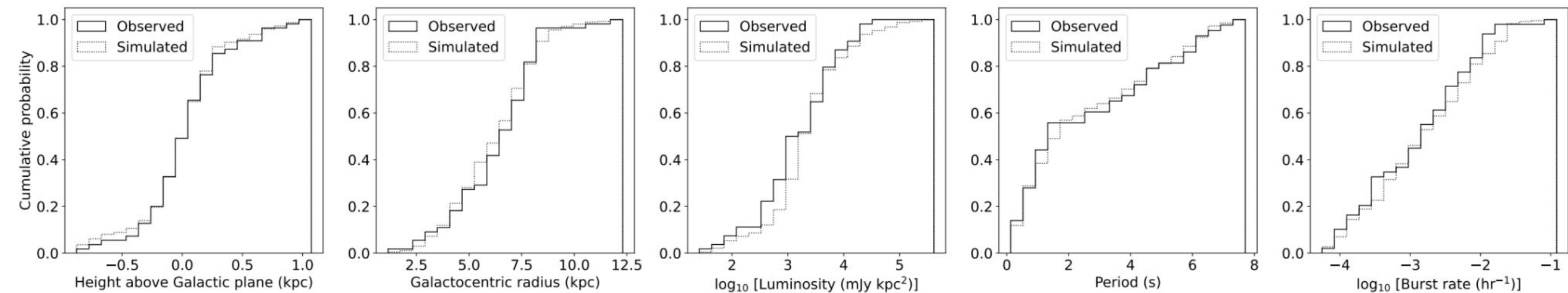


What is the True RRAT Population?

Simulate a population and then “detect” that population given the observational parameters of radio surveys.

Compare the two and find the true population that best matches the detected population.

The True RRAT Population



What are they?

Their single pulses, spectra, and Galactic distribution look similar to most pulsars.

They are generally older and more evolved than most pulsars.

We expect 34000(1600) potentially observable RRATs in the Galaxy, out of a total population of $< 400,000$.

There are many more RRATs than pulsars at high peak luminosities.

This requires a birth rate of $< 1.4/\text{century}$ - consistent with the Galactic supernova rate.

We do not require any separate formation mechanism or neutron star population.

Afternoon I | 01:45 PM - 02:00 PM

Emmanuel Fonseca

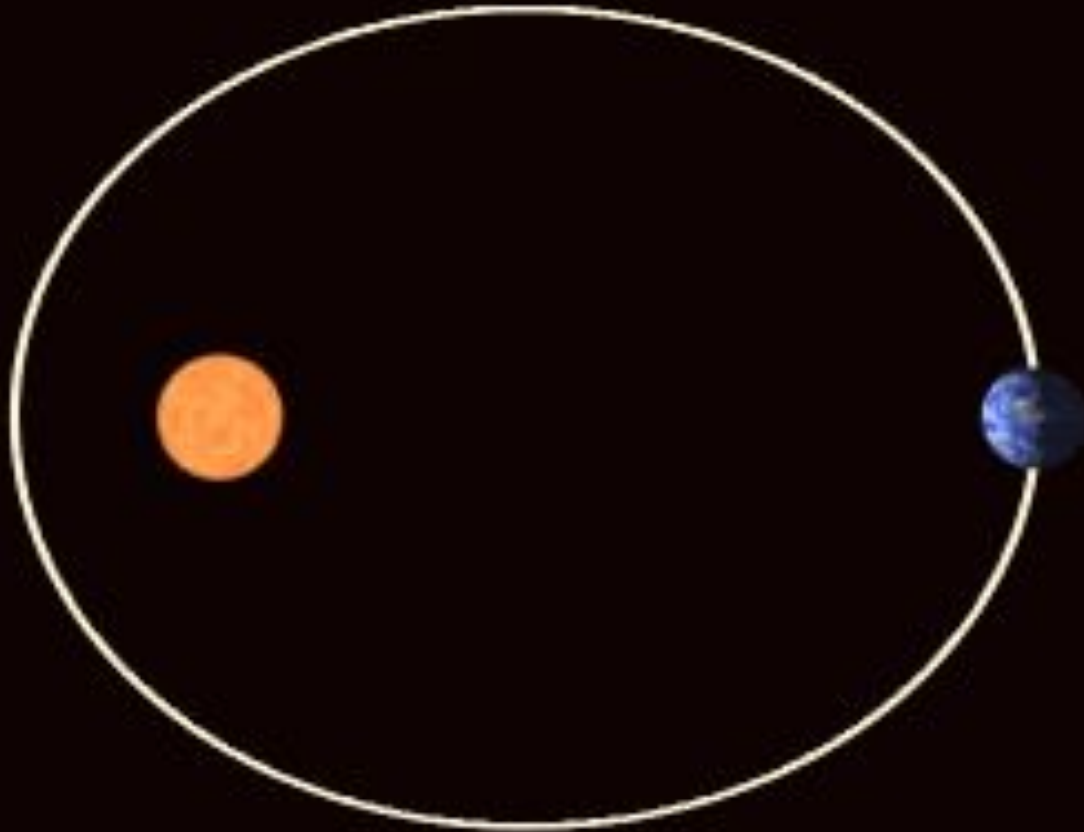
"Measuring Frame Dragging and the Moment of Inertia in Binary Radio Pulsars"



Among many other things, I like to study **binary pulsars** to probe fundamental aspects of gravity!

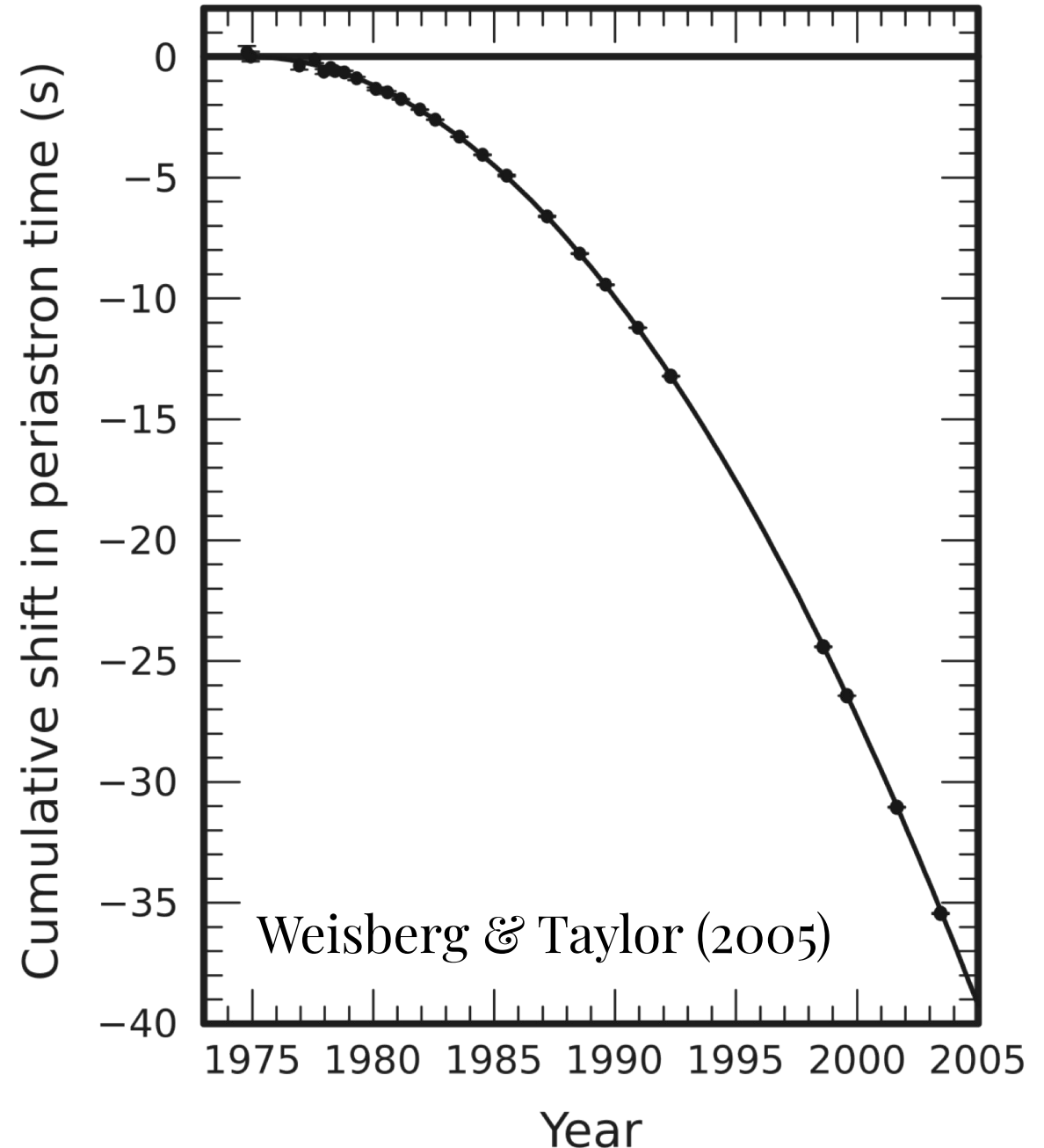
Credit: M. Kramer (MPIfR)

Historically, the orbit of Mercury was known to precess over time — a prediction **A. Einstein's general relativity (GR)**.



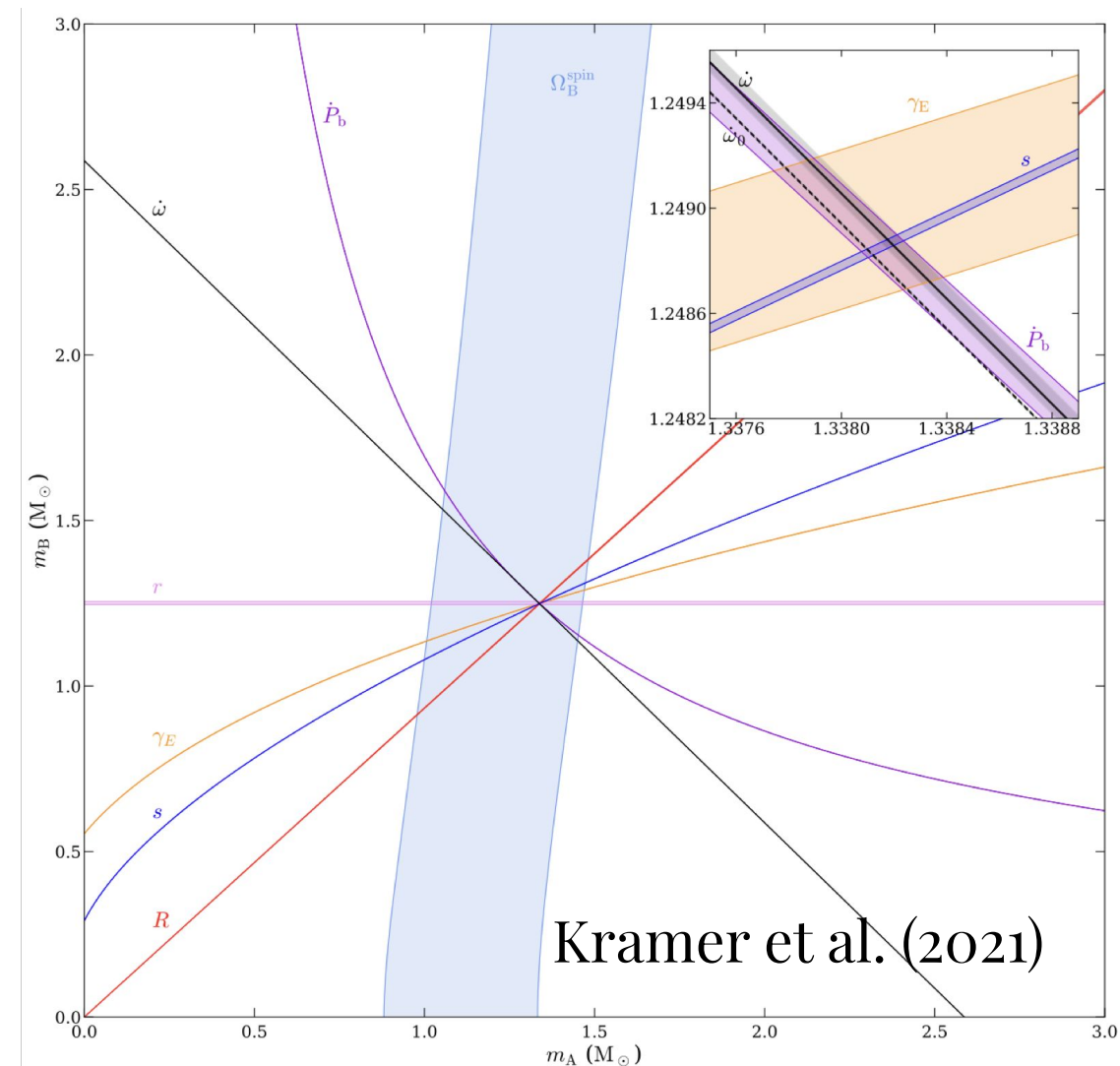
GR in Binary Pulsars, I

- Binary pulsars also exhibit GR effects, but larger in magnitude and number!
- The “Hulse–Taylor” pulsar exhibit precession, time dilation, and orbital decay due to emission of gravitational waves (GWs) from the system (see right).
- First evidence of GWs!



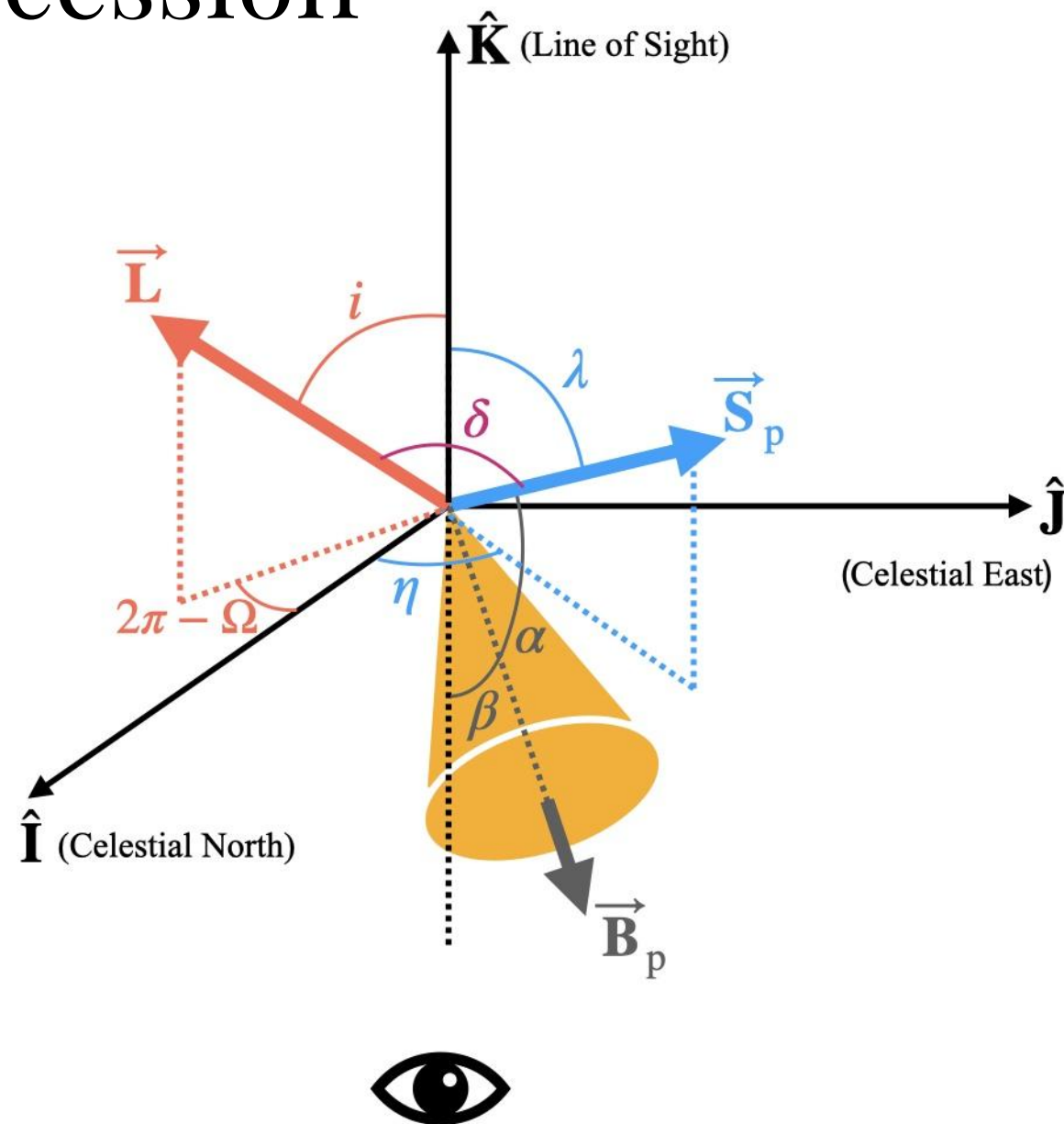
GR in Binary Pulsars, II

- GR effects are best seen in “double-neutron-star” (DNS) systems.
- According to GR, these effects depend on the orbital elements (already known from timing) and the masses of the system (a priori unknown)
- Can measure masses and test GR! This is best done with the “double-pulsar” DNS system as shown on the right.



Lense–Thirring (LT) Precession

- DNS pulsars are also known to exhibit changes in their orientation due to GR.
- Two forms of “spin precession”:
 - “de Sitter” (or “geodetic”) – due to motion in curved spacetime;
 - **LT** (or “**frame dragging**”) – due to spin of the pulsar.



Gravity Probe-B Satellite: relativistic precessions

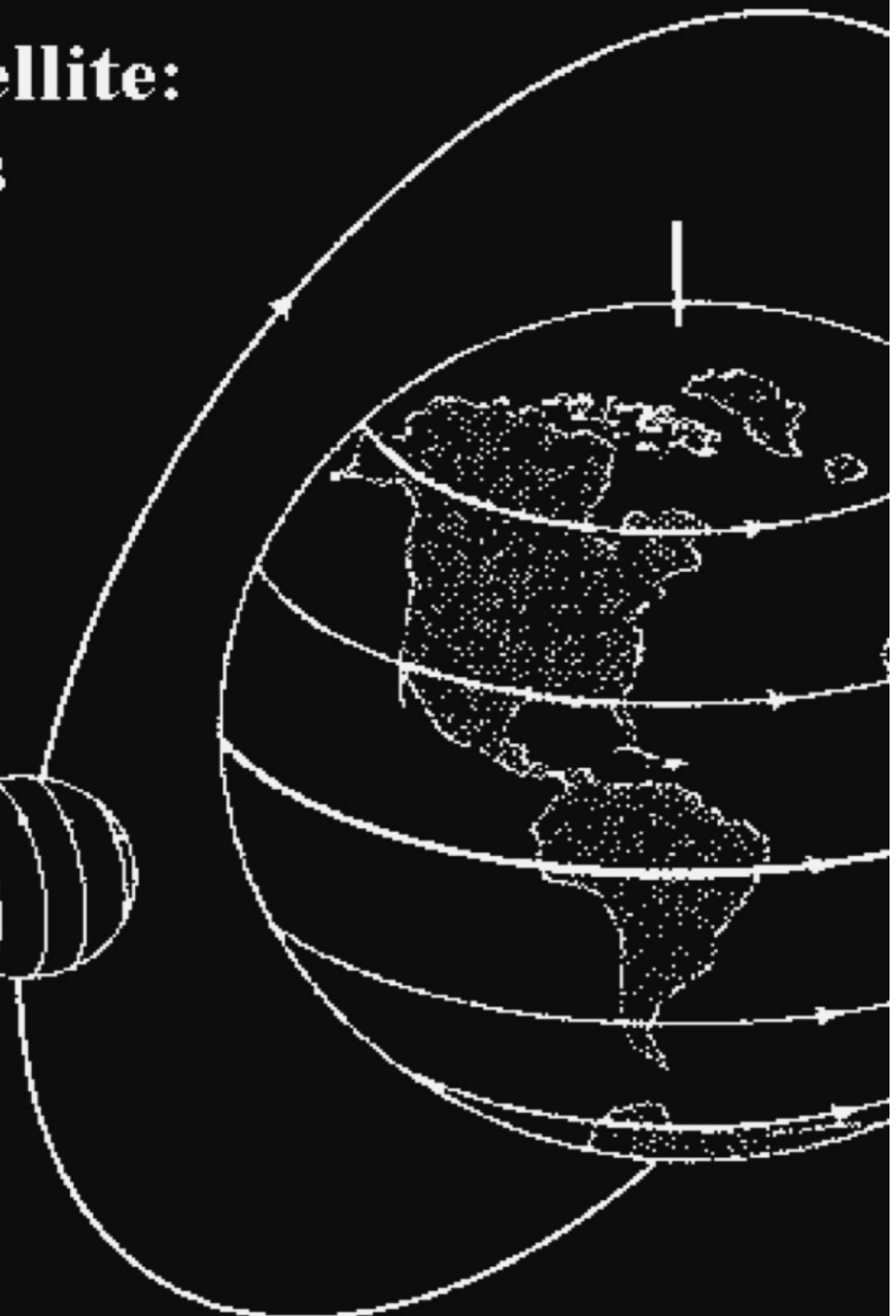
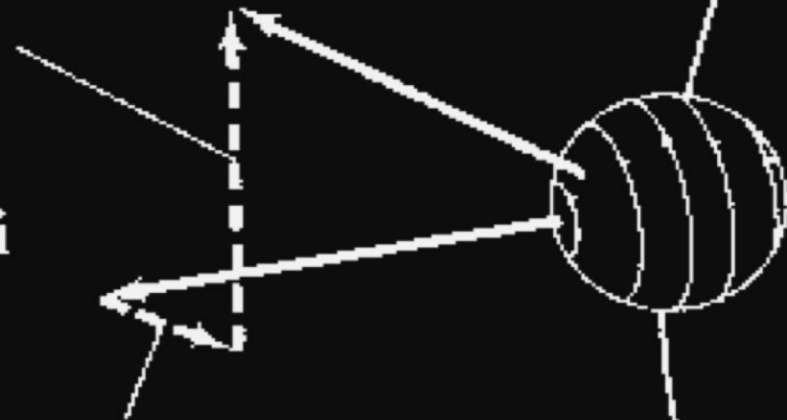
Credit: Sigismondi (2006)

$\Delta\theta=6.6$ arcsec/year
Geodetic precession

IM Pegasi

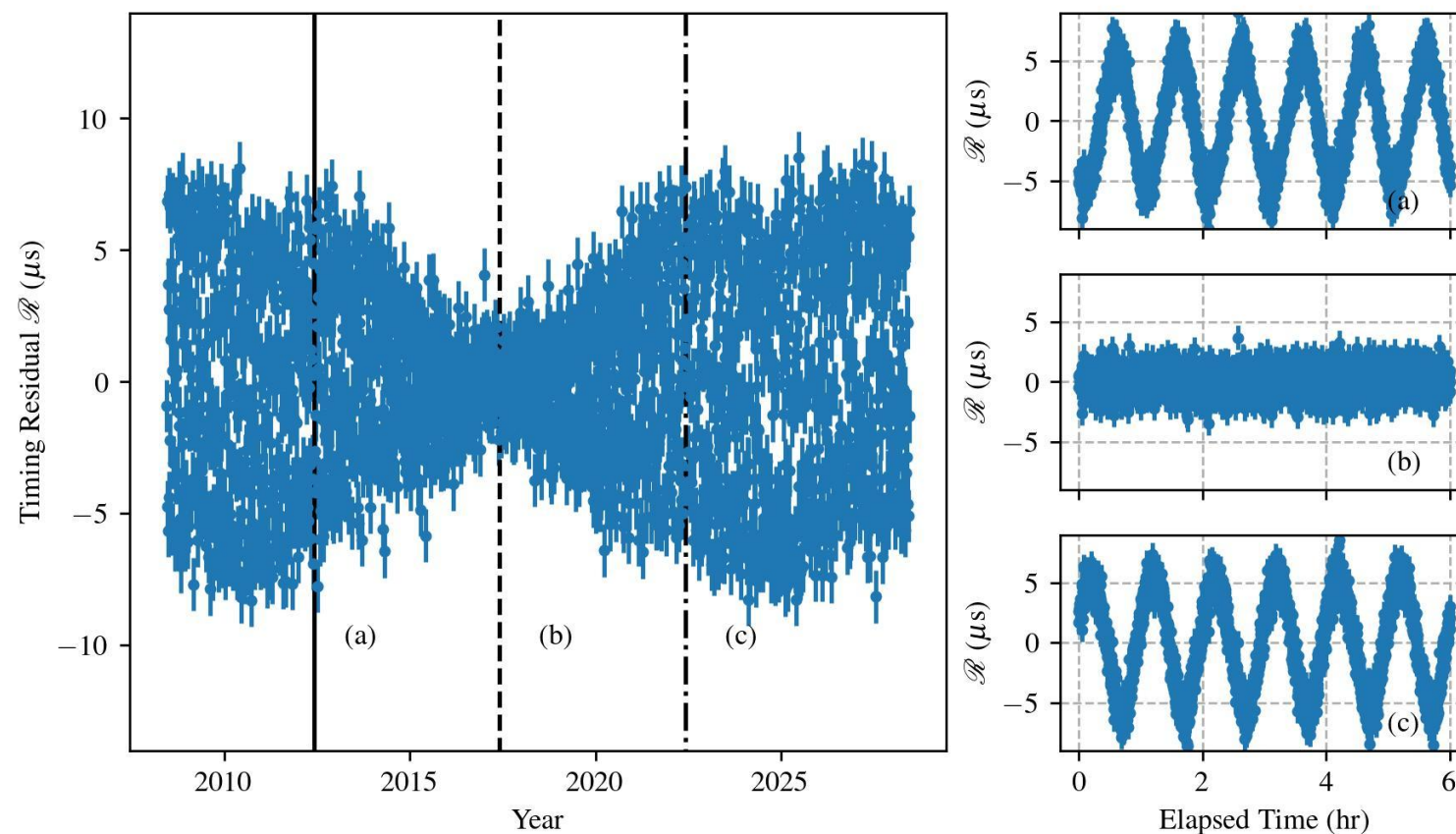


$\Delta\theta=0.042$ arcsec/year
Lense-Thirring precession



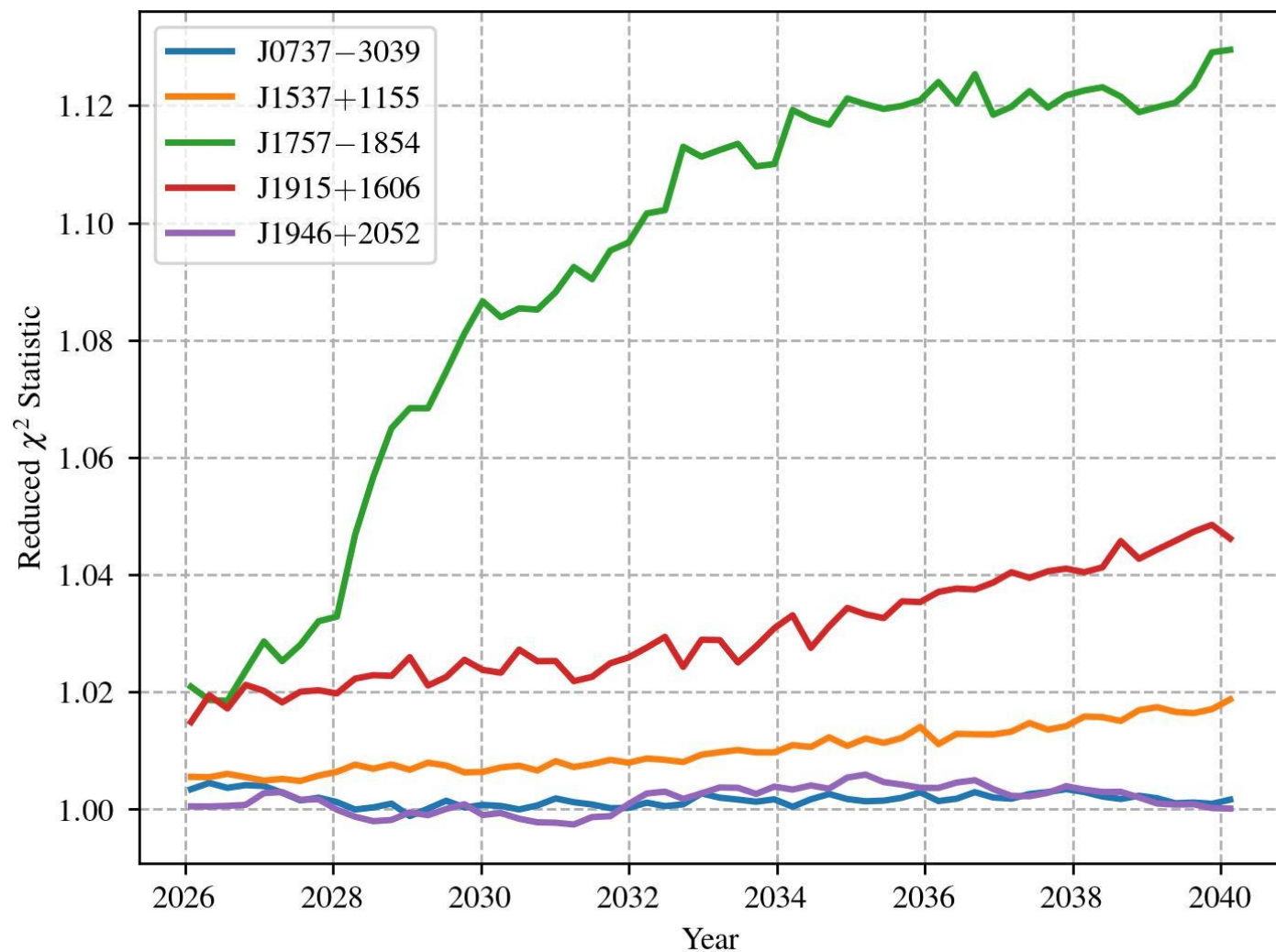
Expected Frame Dragging in Pulsar Timing

- I recently developed a timing model in the PINT pulsar-timing framework, to include timing perturbations from LT precession.
- Right: PINT timing residuals showing **nonlinear variations due to LT precession**.



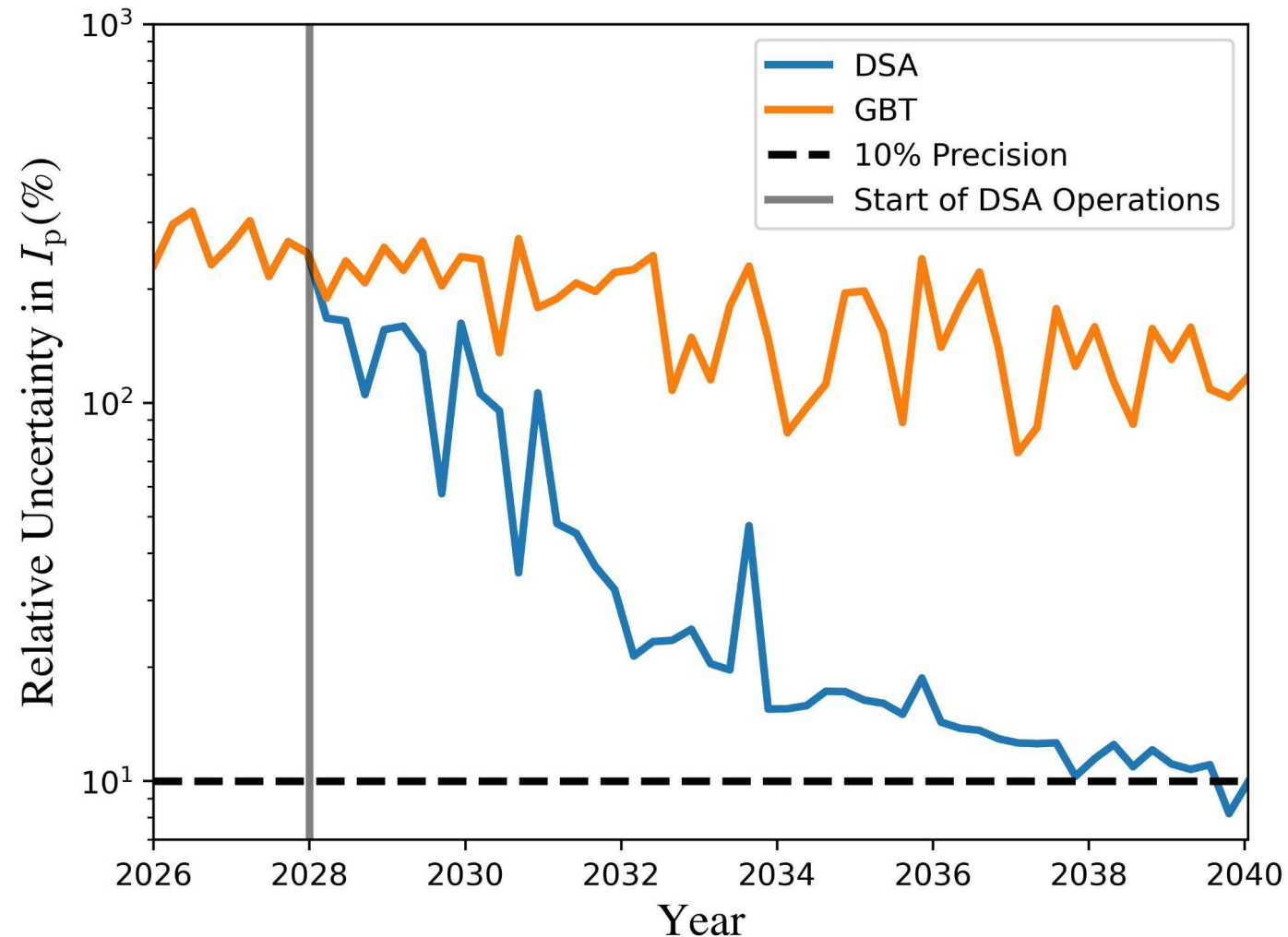
(Non)linear LT Variations in Known DNS Pulsars

- I simulated the presence and detectability of LT precession in five known DNS pulsars:
 - timing data generated with my “DDGRI” model;
 - then fitted a “linear” binary (DD) timing model.
- Right: goodness of fit over the next ~15 years. **LT precession should be detectable in 2-3 pulsars soon!**



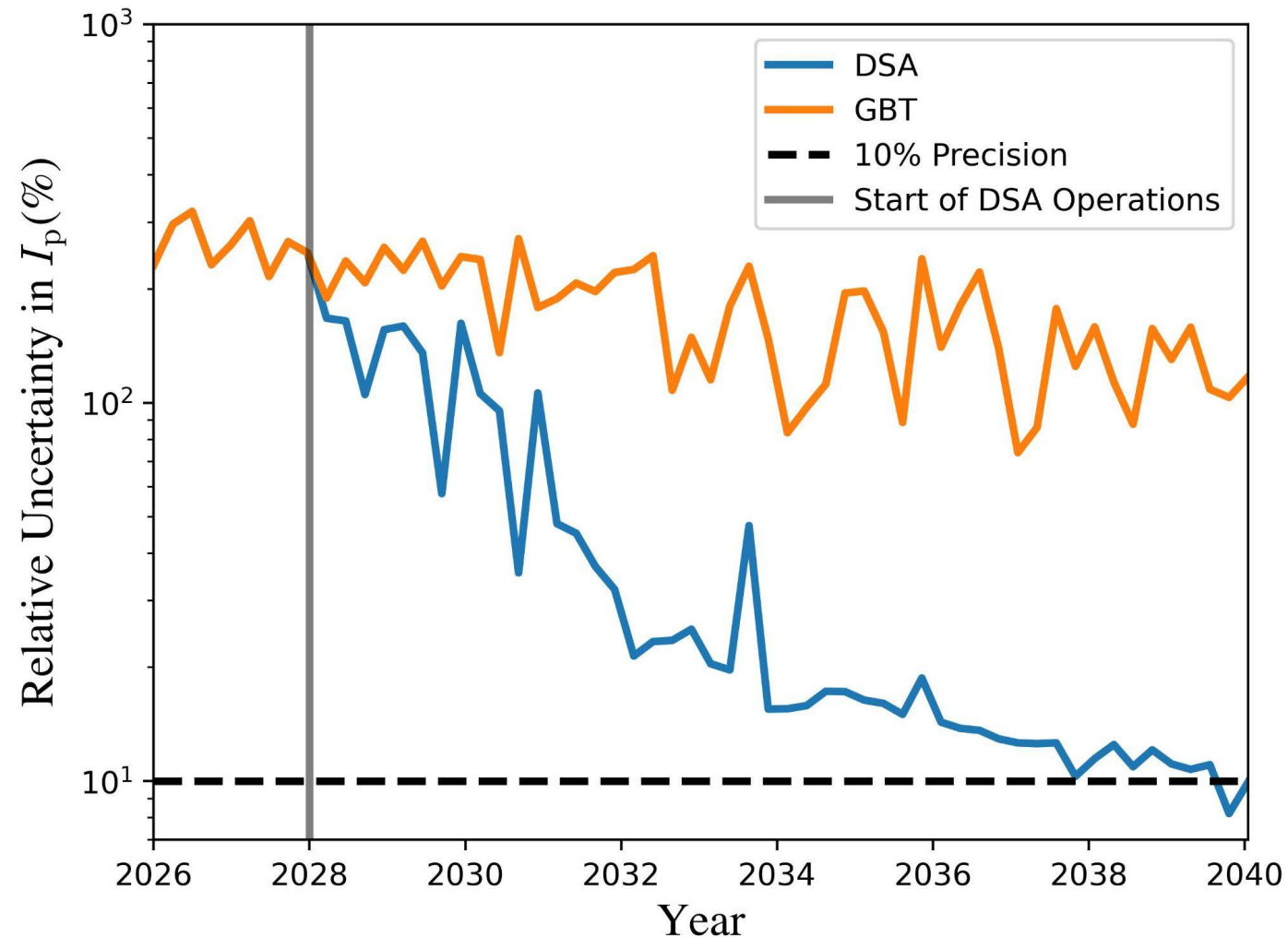
(Non)linear LT Variations in Known DNS Pulsars

- **PSR J1757-1854** apparently shows the most promise in detecting LT precession through timing.
- Since LT precession reflects spin, a measurement will yield the **moment of inertia of the pulsar**.
- Right: simulations that show a measurement of the MoI will reach O(10%) precision by ~2040!



Summary

- LT precession should be detectable in pulsar timing within the next decade.
- A key advantage of nonlinear LT is that measuring the MoI doesn't depend on extraordinary info (e.g., distance).
- Moreover, measuring the MoI through pulsar timing will be fairly “**model independent!**”





Thank You!

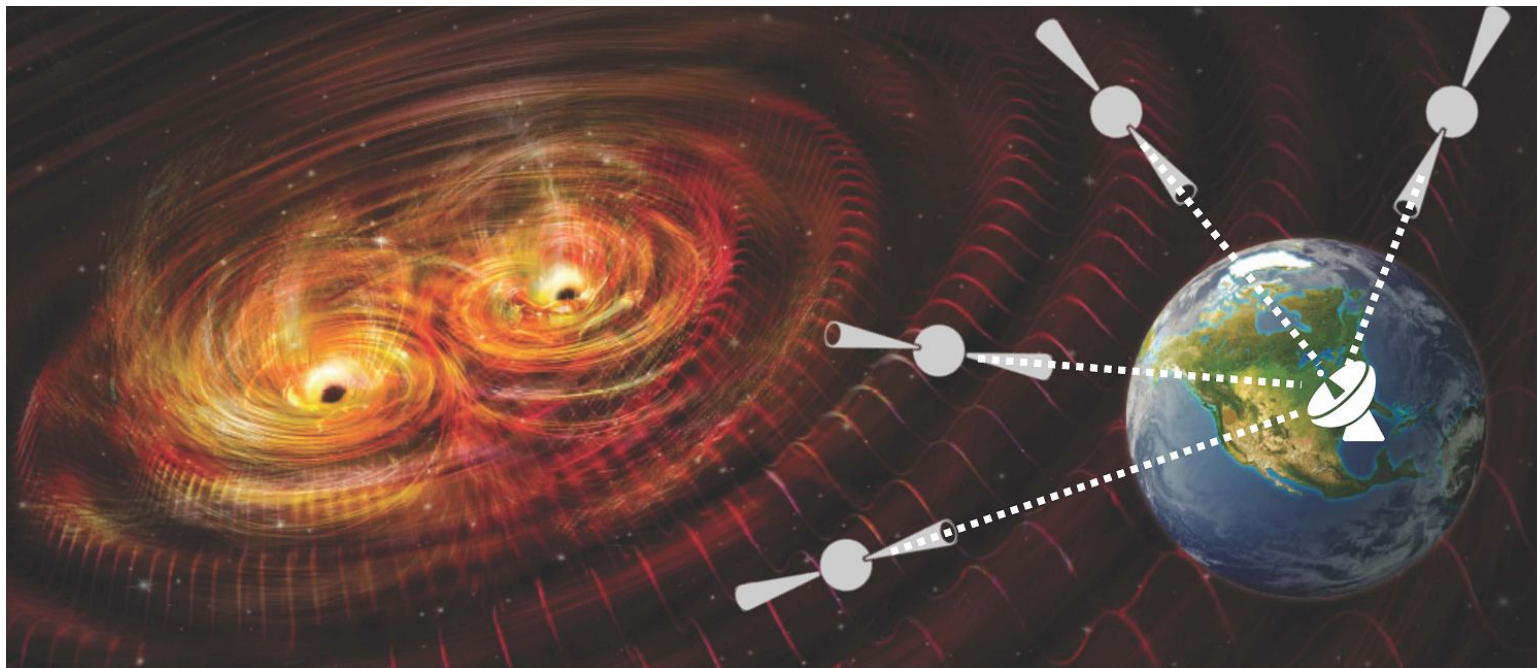
Credit: M. Kramer (MPIfR)

Afternoon II | 02:30 PM - 02:45 PM

Graham Doskoch

*"A Search for Chromatic Transient Events in IPTA
DR3"*

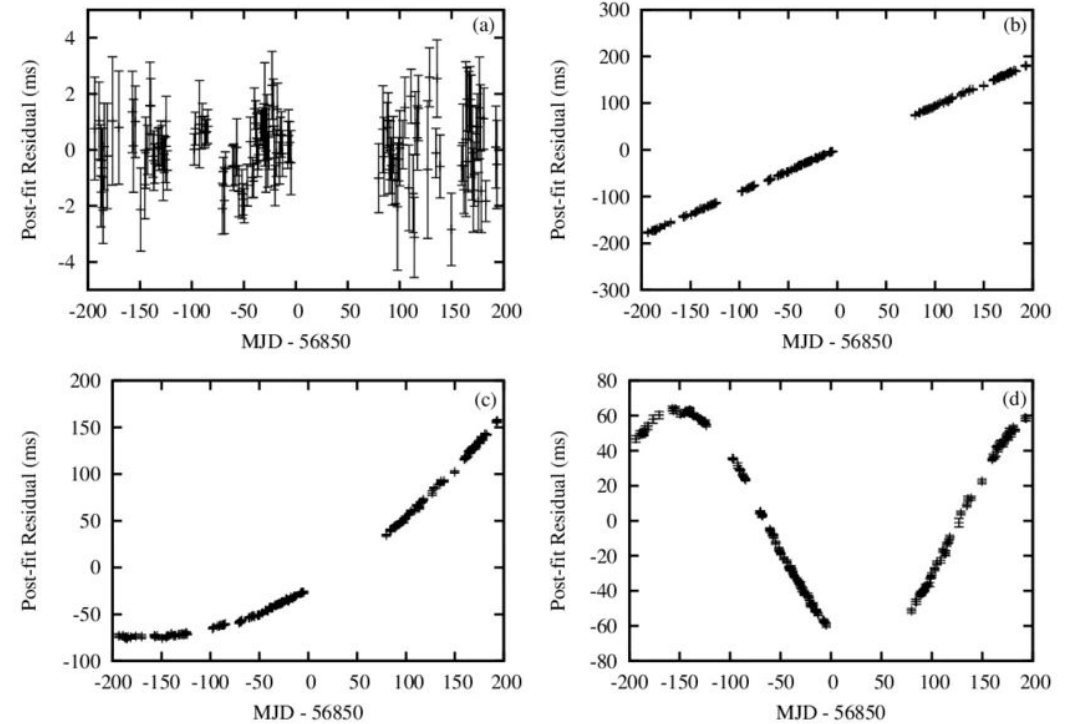
Pulsar timing arrays



N. R. Fuller/Science

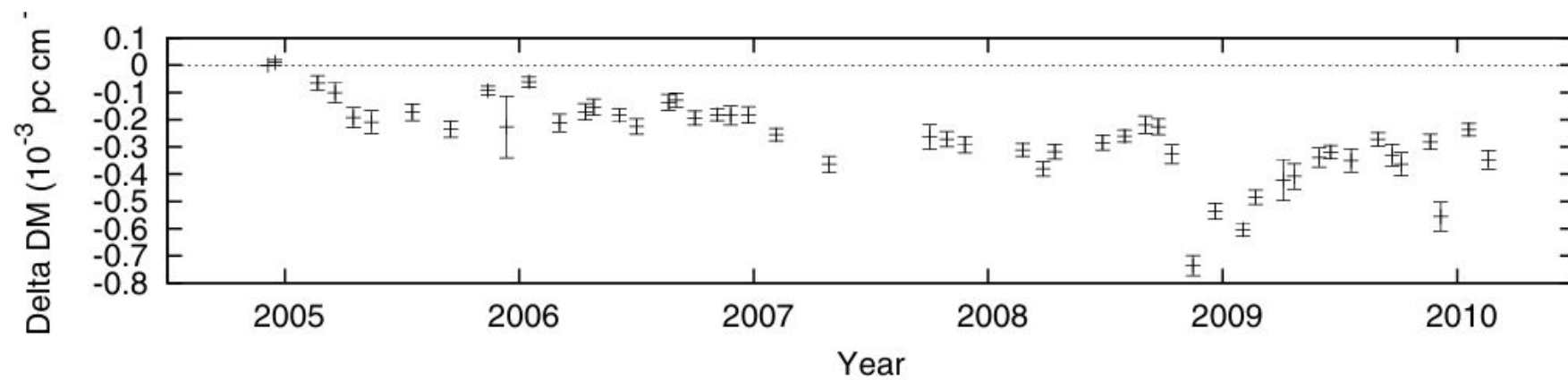
Timing models

- Celestial coordinates
- Spin period + period derivatives
- Proper motion
- Parallax
- Binary parameters
- Solar wind
- Interstellar medium
- Instrumental effects
- Additional time-correlated noise



Mayuresh Surnis

J1713+0747

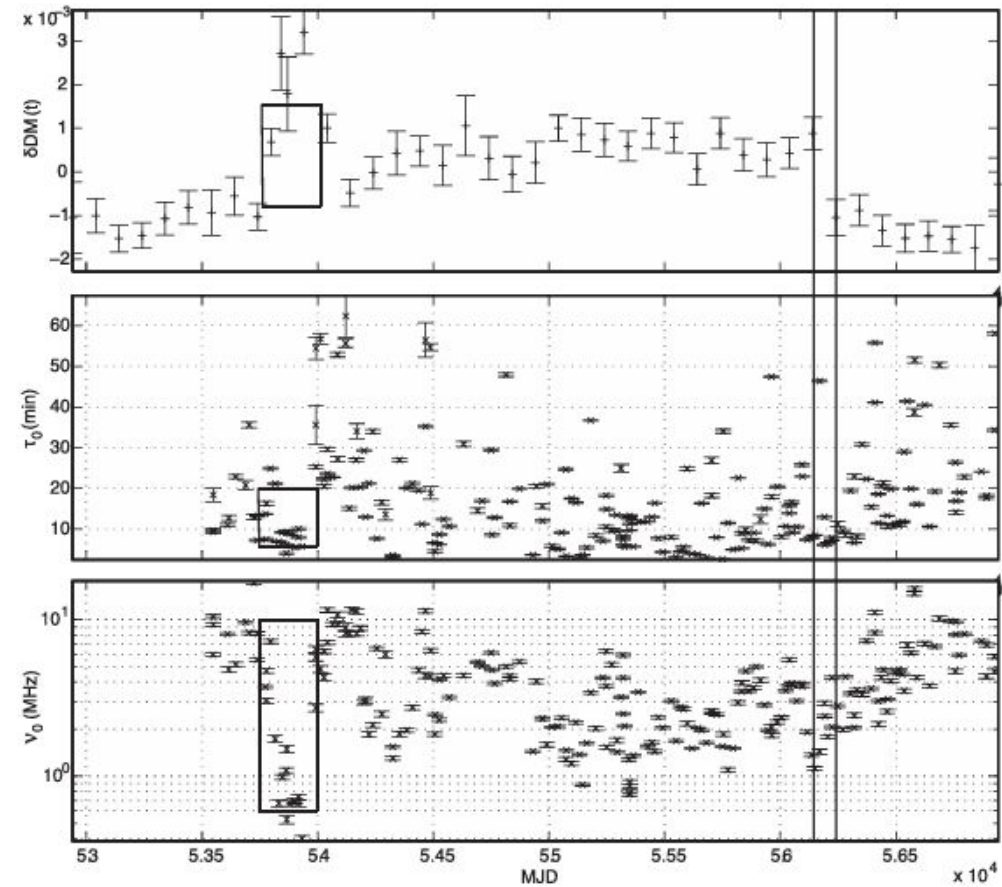


Demorest+2013

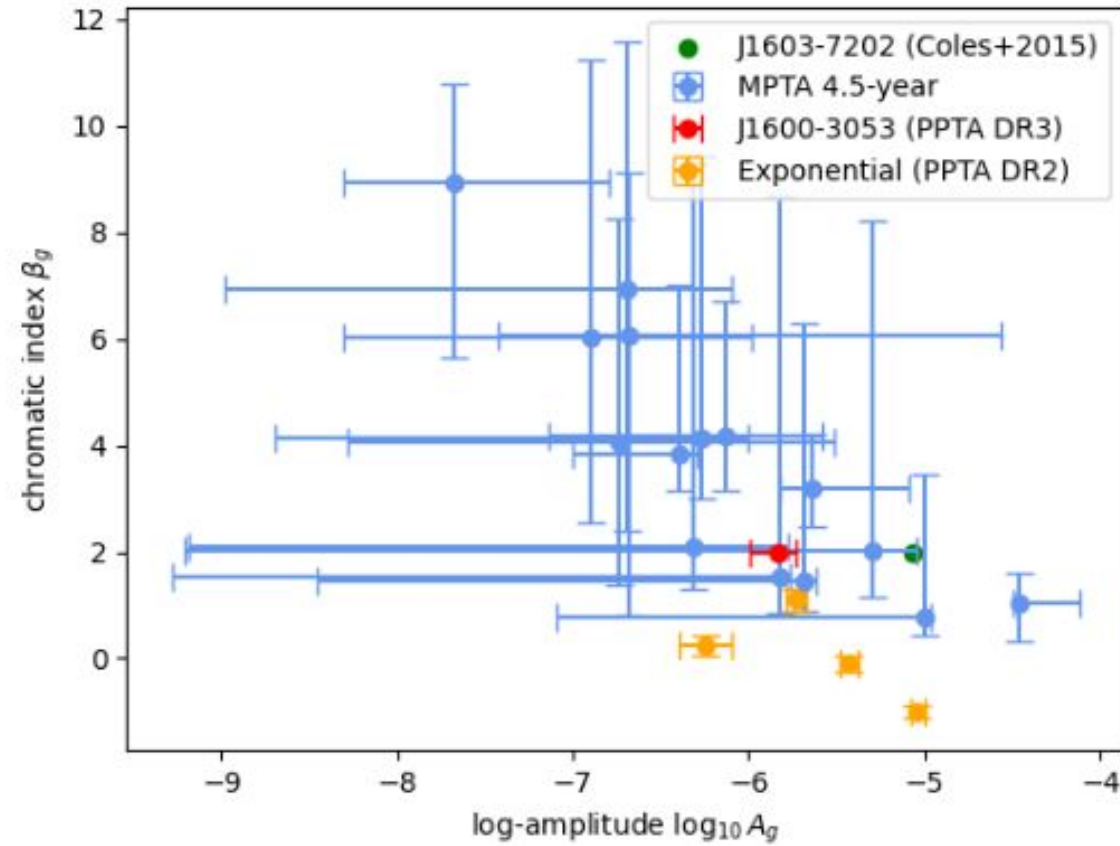
Chromatic transient mischief

Known troublemakers:

- J0437-4715
- J1600-3053
- J1603-7202
- J1643-1224
- J1713+0747 (x3!)
- J2145-0750



Chromatic transient mischief



Some questions. . .

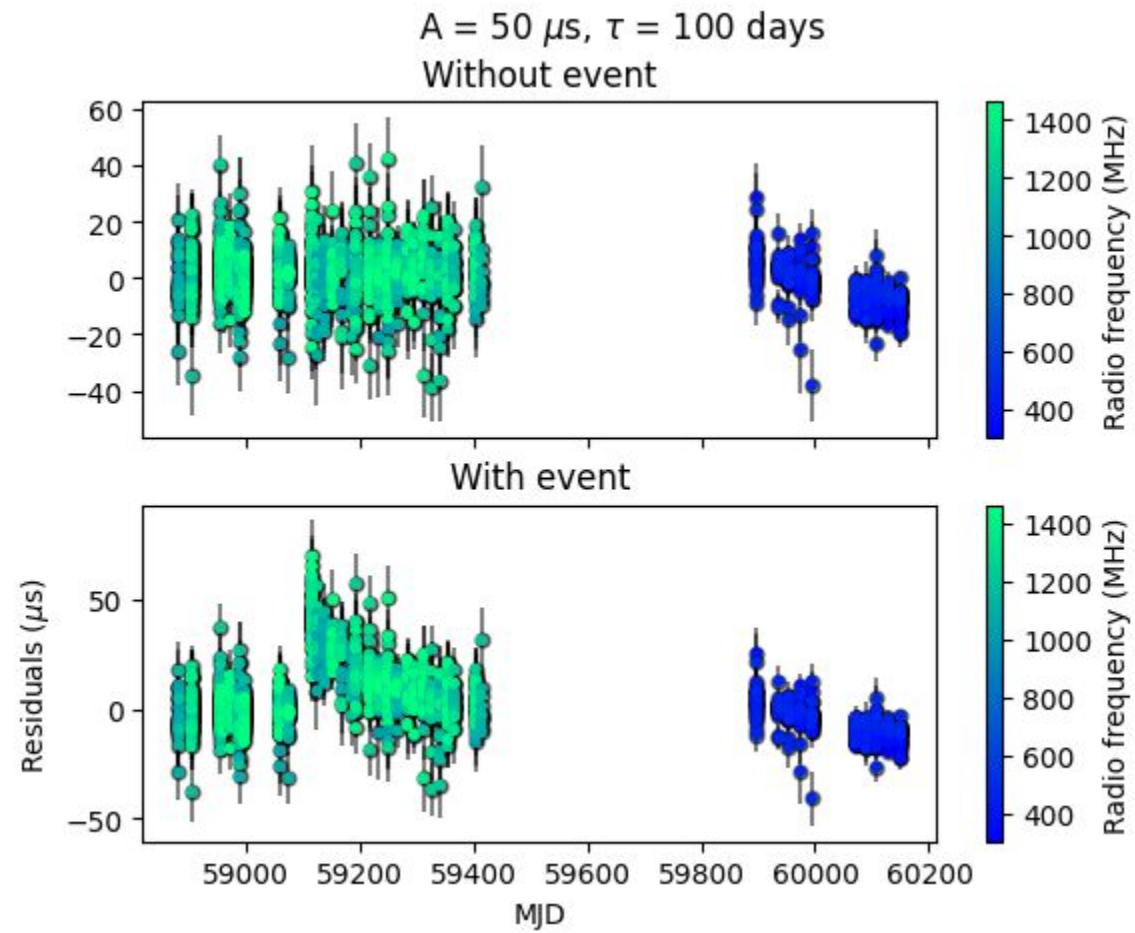
- These are the strong events. Which ones are we **missing**?
- Are small-scale events biasing our noise modeling?
- What causes them? Are current explanations sufficient?
- Can we extract any physics from them?

IPTA + IPTA DR3

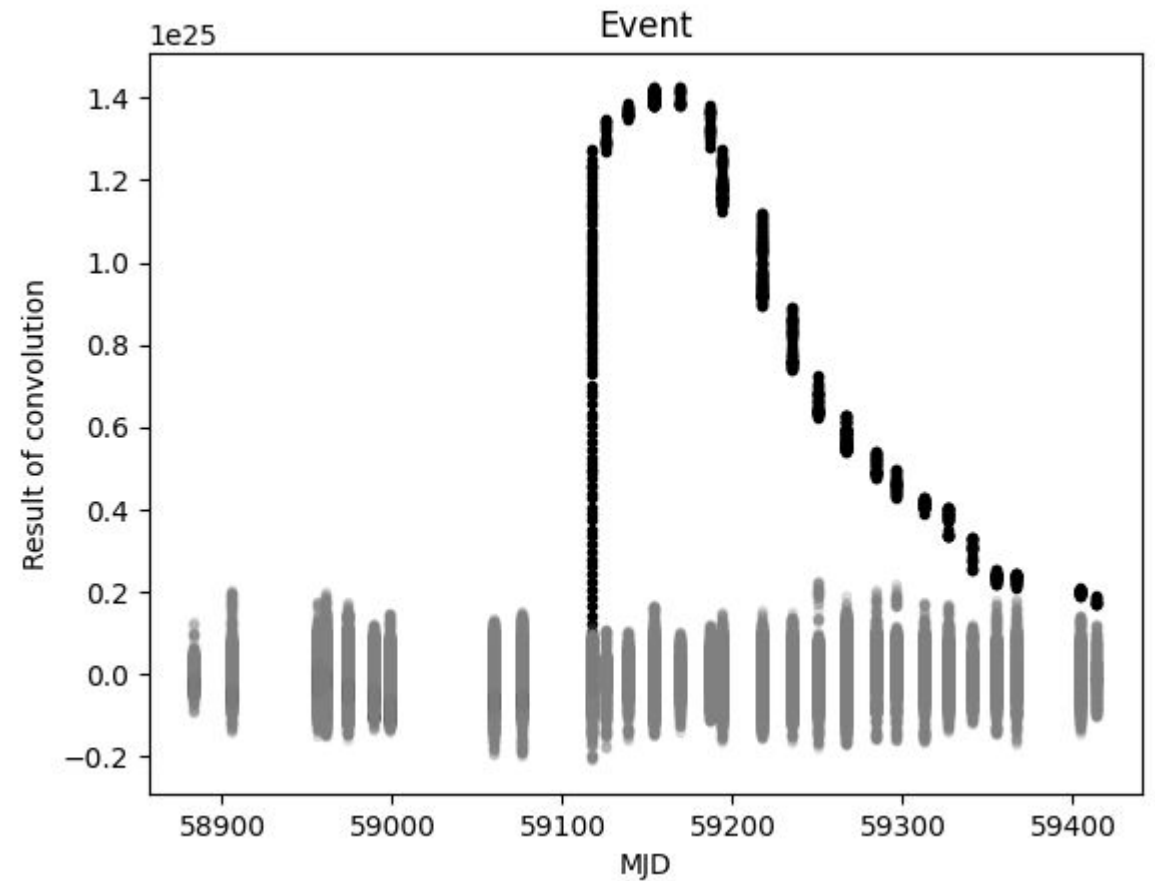
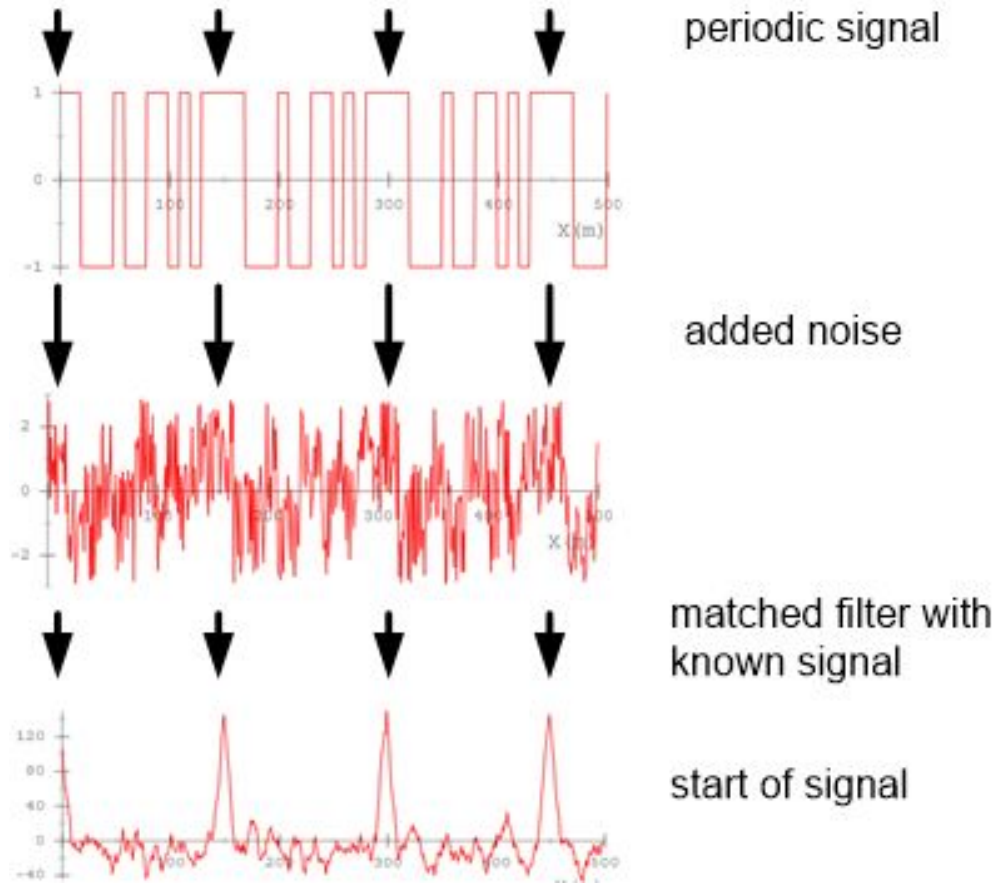


Thankful Cromartie/Deborah Good

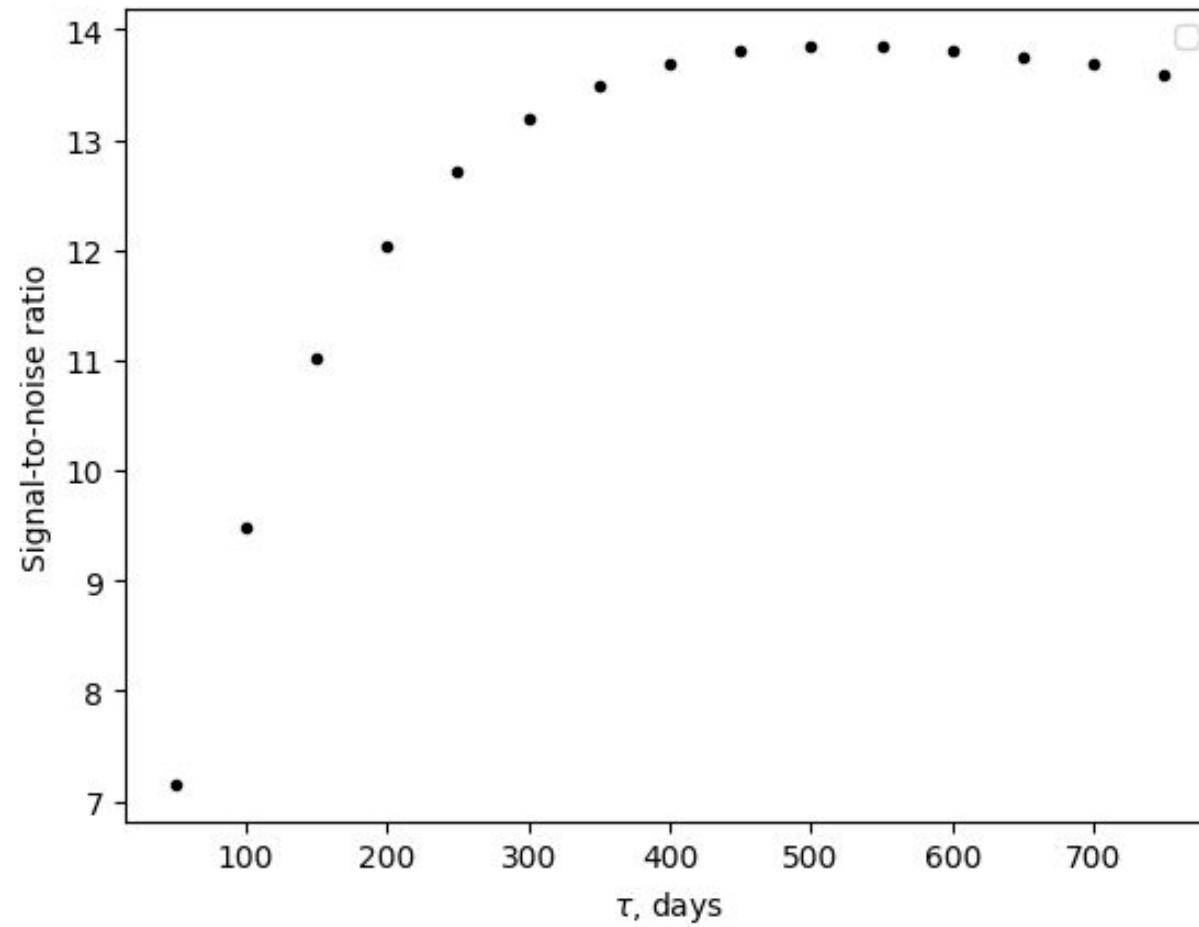
Simulations: J0034-0534



Method #1: Matched filtering



Method #1: Matched filtering



Method #2: Bayesian analysis

- Apply our normal noise modeling pipeline
- Two models:
 - Ordinary noise model (“vanilla”)
 - Noise model + event
- Compute Bayes factors and find which is favored

Current + future work

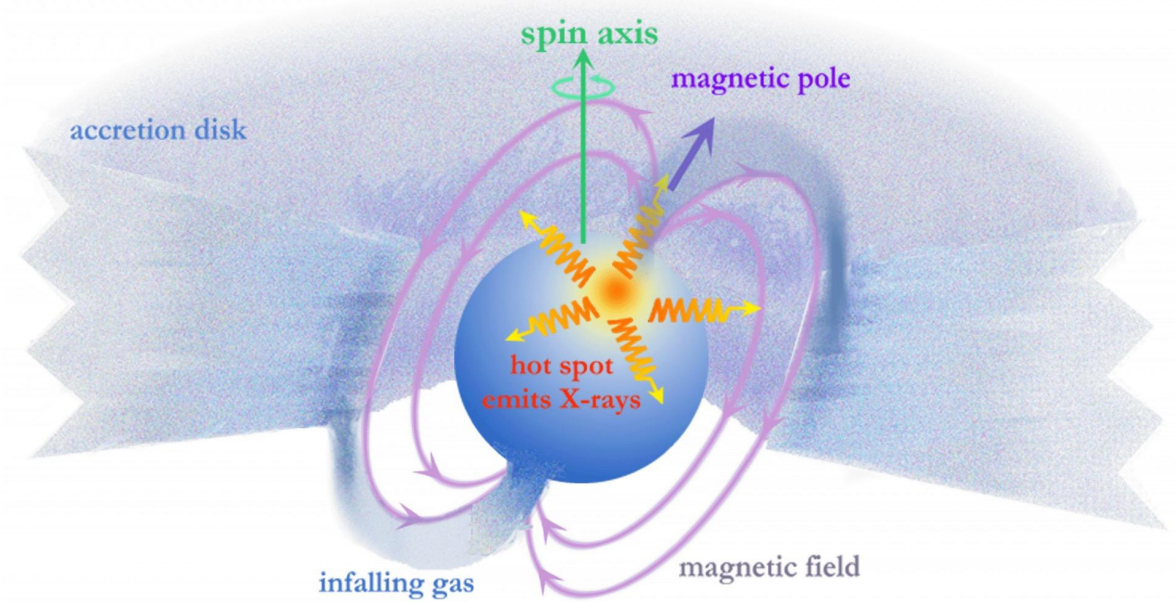
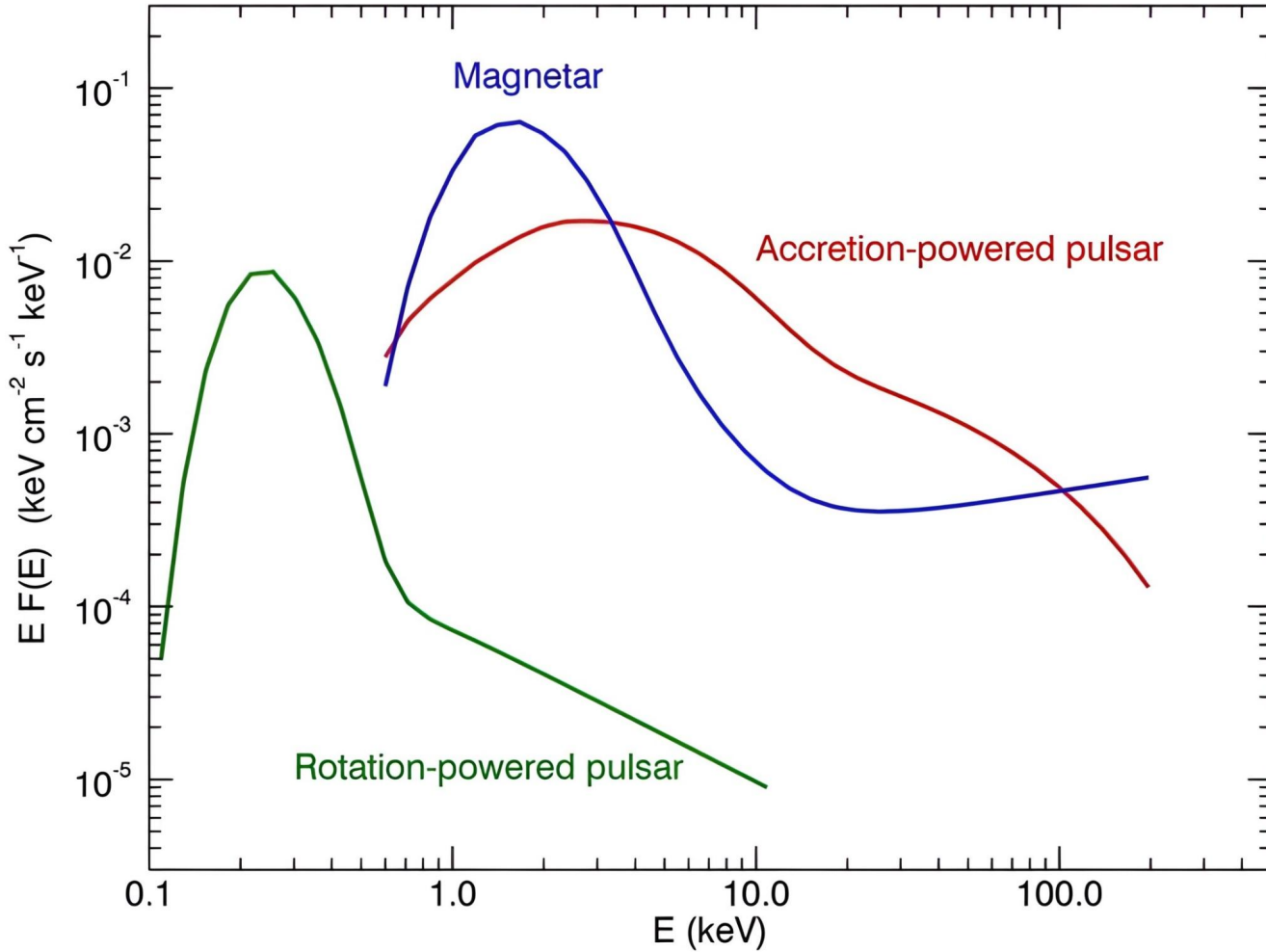
- Rigorously check how events can bias noise runs
- Matched filtering:
 - Include chromaticity in templates
 - Test Gaussians in addition to exponentials
 - Compute p-values or SNRs for candidates
- Bayesian analysis
 - Speed up individual noise runs
 - Computes Bayes factors
 - Integrate with other advanced noise modeling techniques

Afternoon II | 02:45 PM - 03:00 PM

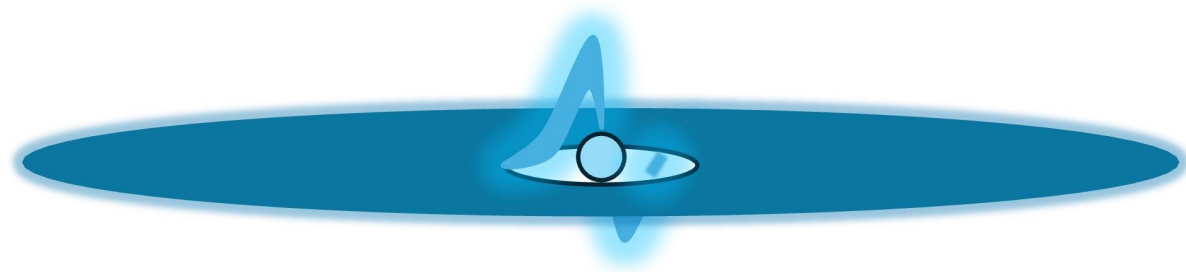
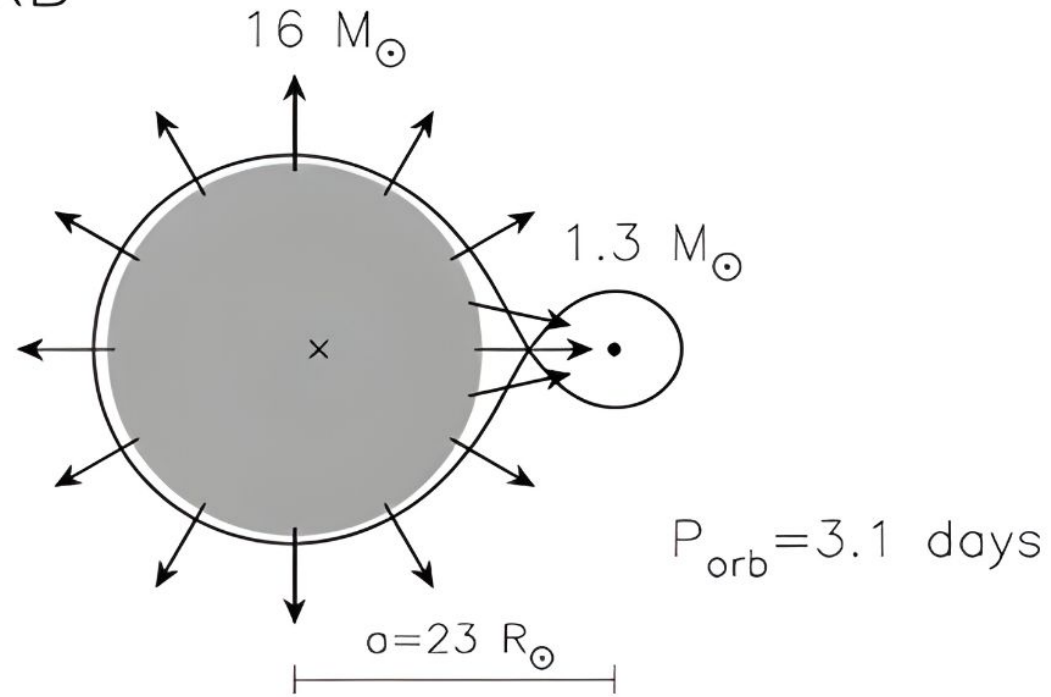
Randy Loberger

"Probing Abnormal Dipping Behavior in the X-ray Binary, Cen X-3"

X-ray Emission from Accreting Neutron Stars

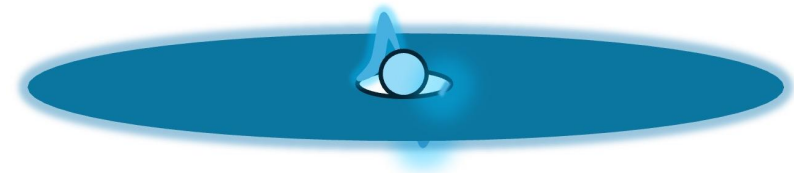
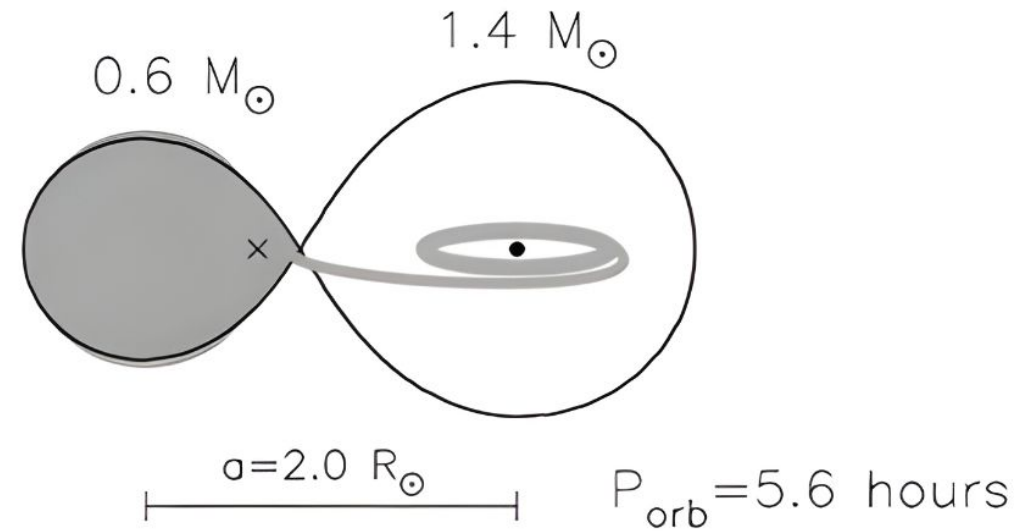


HMXB

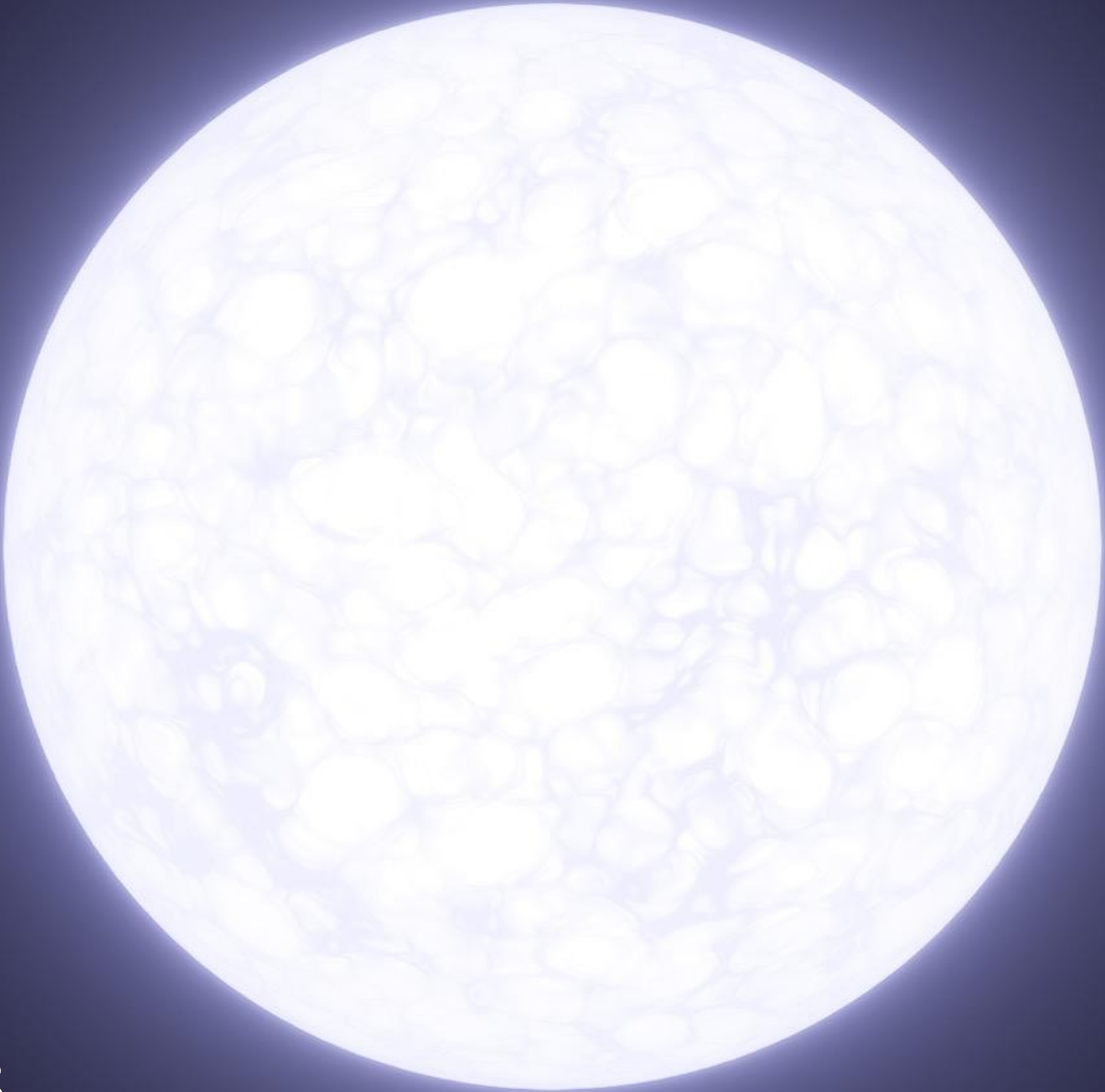


- Short-lived variable accretion ($10^5 - 10^6 \text{ yrs}$)
- Strong magnetosphere blocks accretion disk
- Massive, hot accretion columns

LMXB



- Long-term stable accretion ($10^7 - 10^9 \text{ yrs}$)
- Weaker magnetosphere allows the disk to get closer
- Small, cooler accretion columns



• Cen X-3

Cen X-3

$P = 4.8 \text{ s}$

$B \sim 10^{12} \text{ G}$



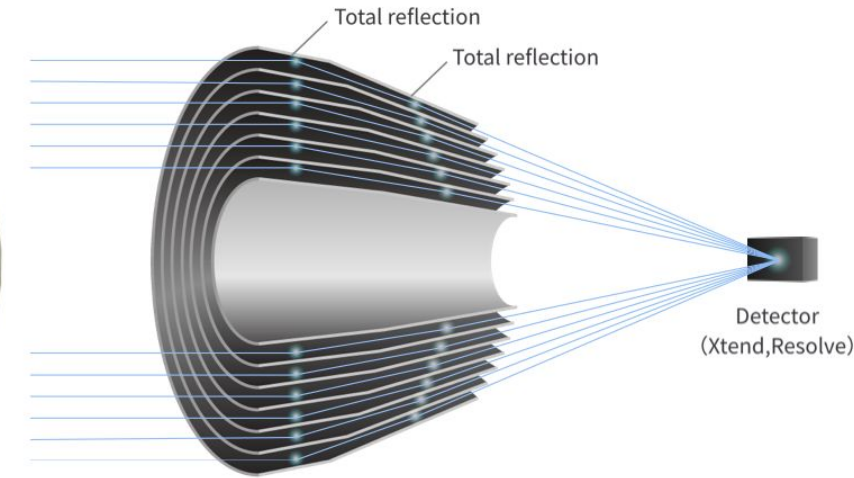
• Example Pulsar

Example Pulsar

$P = 10 \text{ ms}$

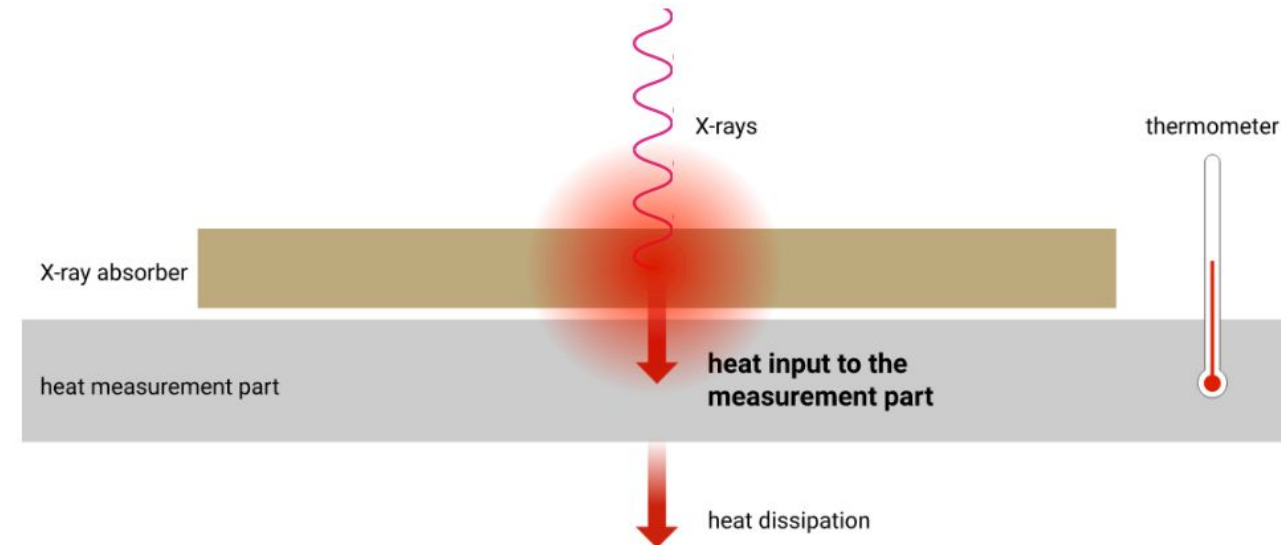
$B \sim 10^9 \text{ G}$

X-ray Imaging and Spectroscopy Mission (XRISM)

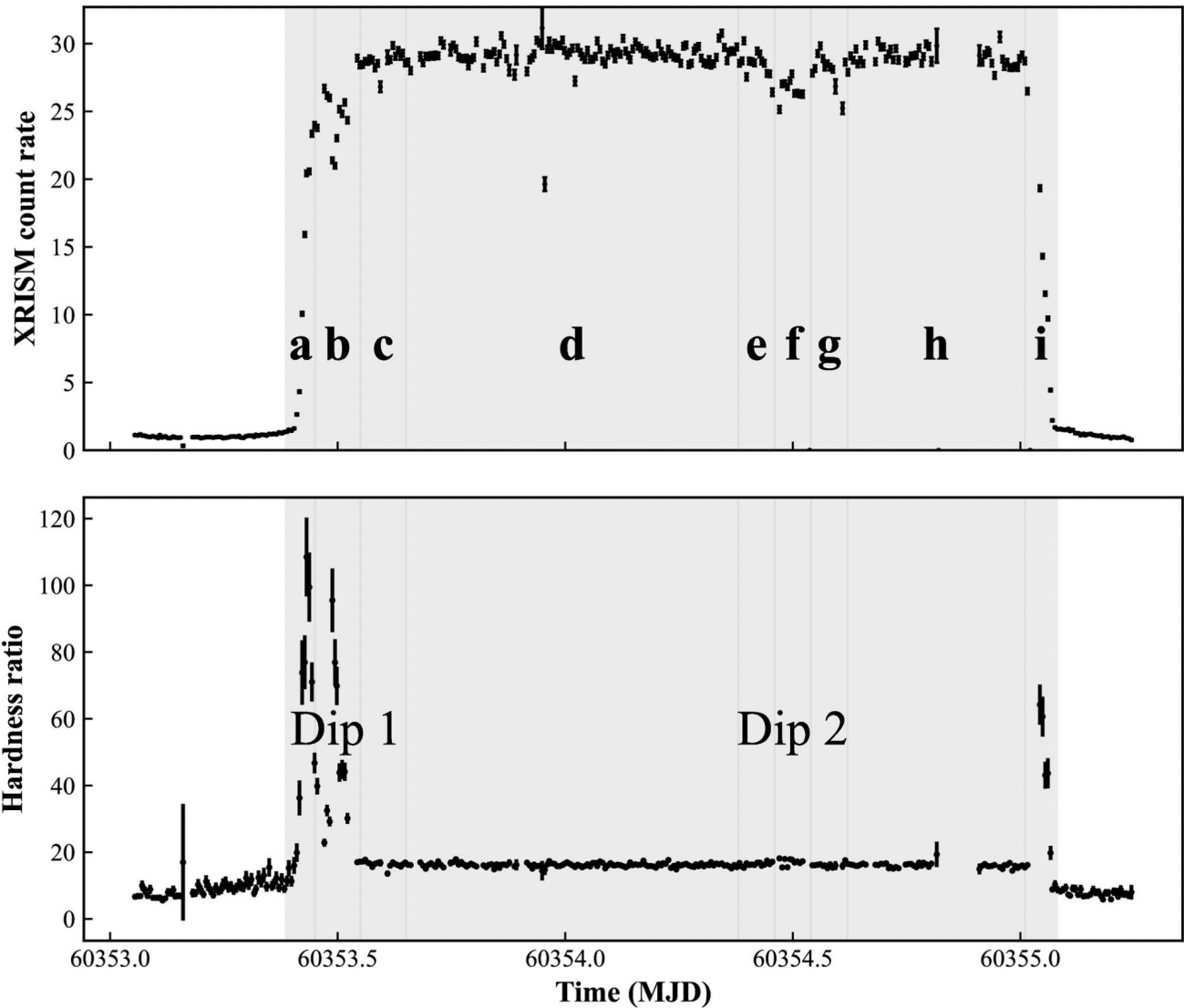


- Bumps on the gold reflecting surface are less than one millionth of a millimeter
- Microcalorimeter is controlled at 50mK and takes <1ms to cool after an X-ray hit

Instrument	Timing Resolution	Spectral Resolution
Susaku (XIS)	7.8 ms – 8 s	0.12 @ 6 keV
XRISM Resolve	1 ms	0.005 @ 6 keV (25x!)



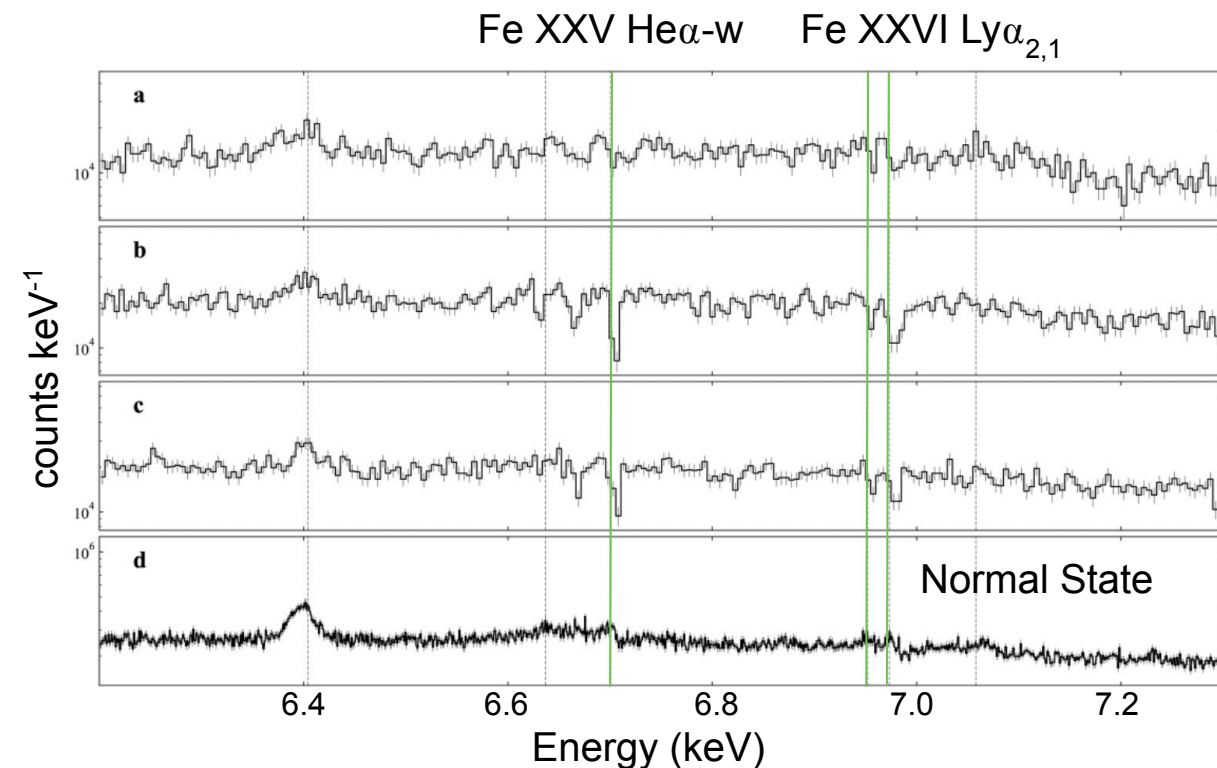
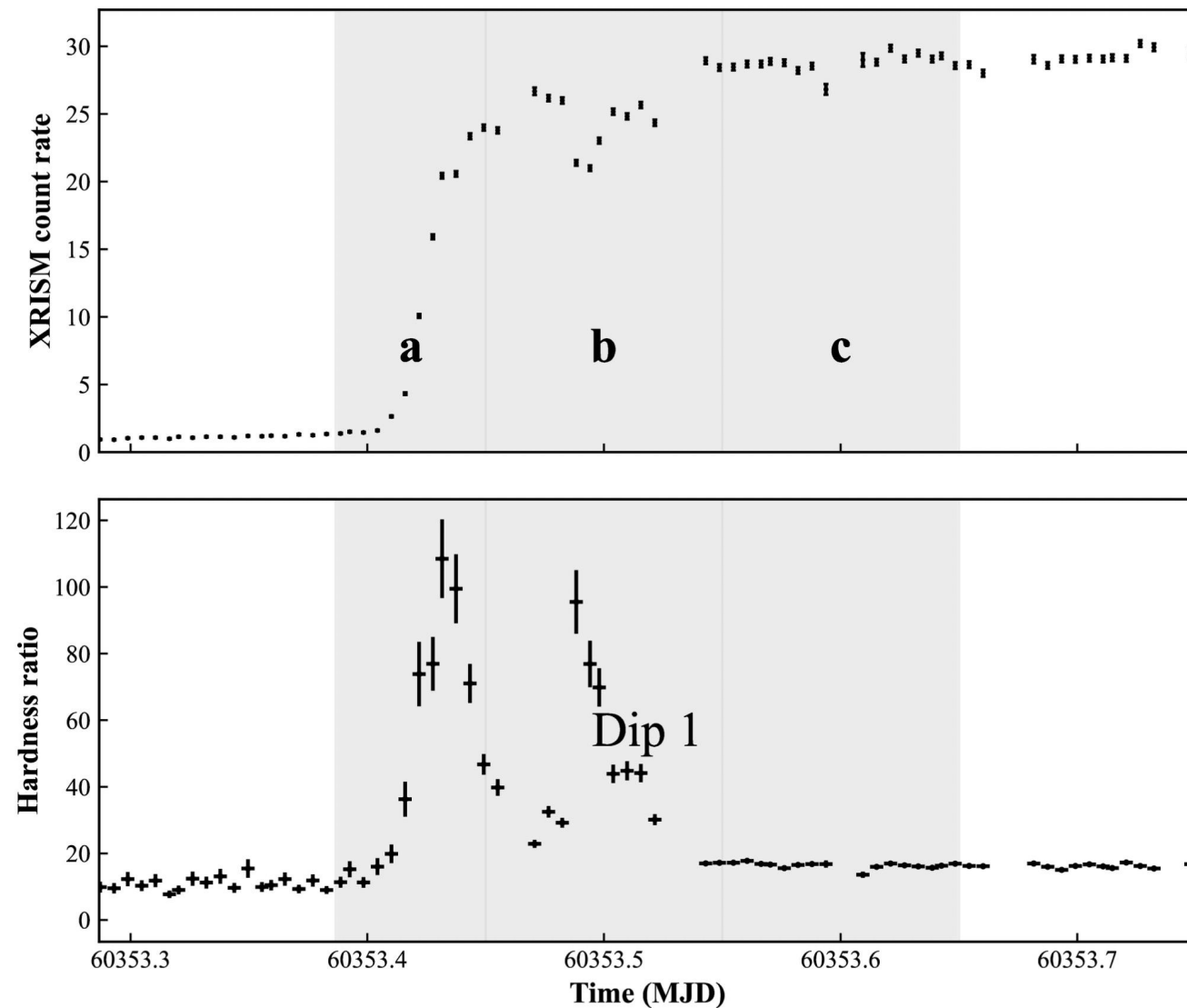
Dips spotted, two different mechanisms?



- The orbital period is 2.09 days
- Pulsar spin period: 4.8 sec
- Companion: $21 M_{\odot}$, $13 R_{\odot}$
- Zones to the left of segment *a* and the right of segment *i* are eclipsing phases (the neutron star behind the companion)

	Dip 1	Dip 2
Timescale	Very Short	Long
Shape	Sharp	Broad
Hardness Ratio (HR)	Increases	No Change

Dip 1: The Technicals

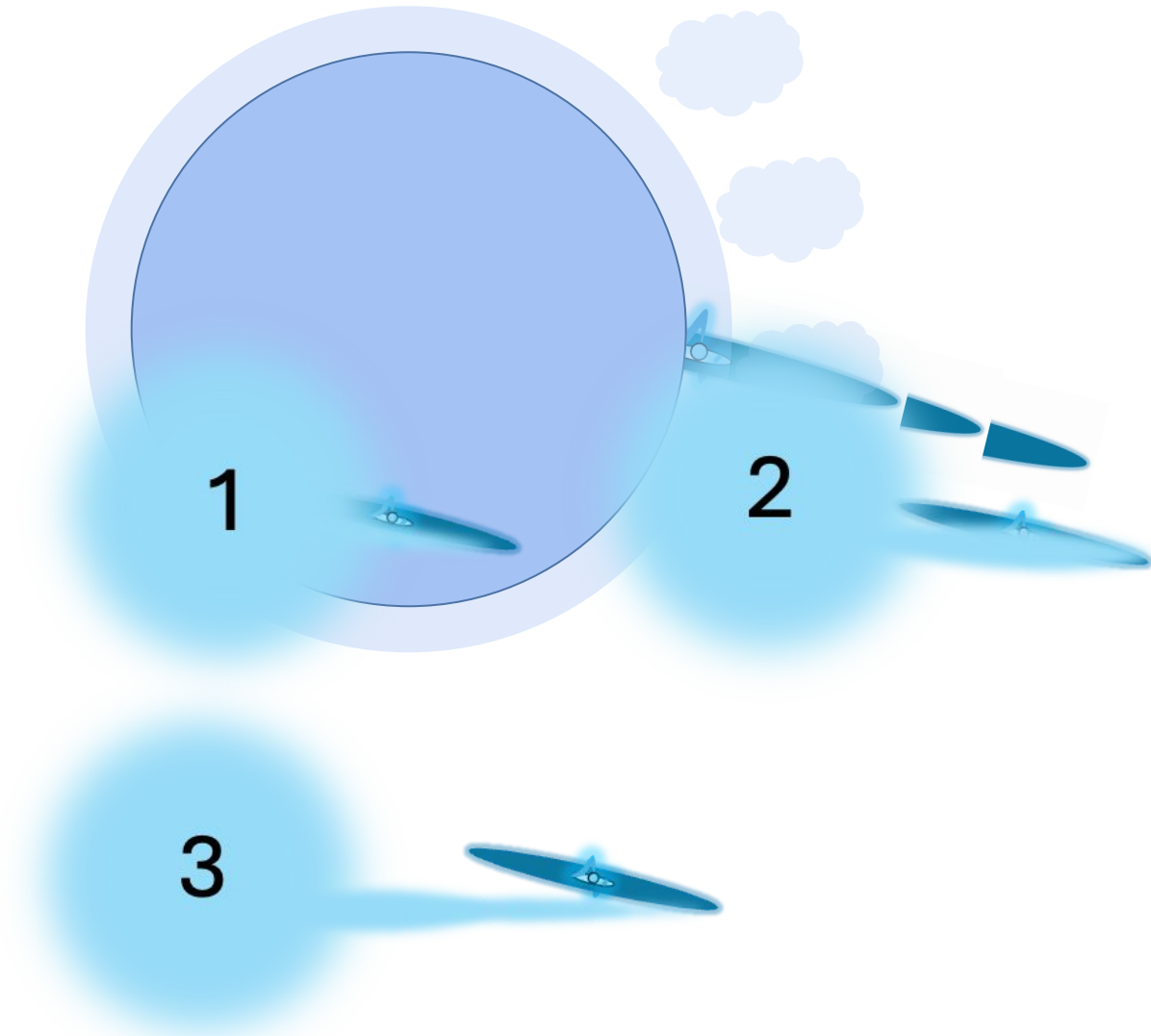
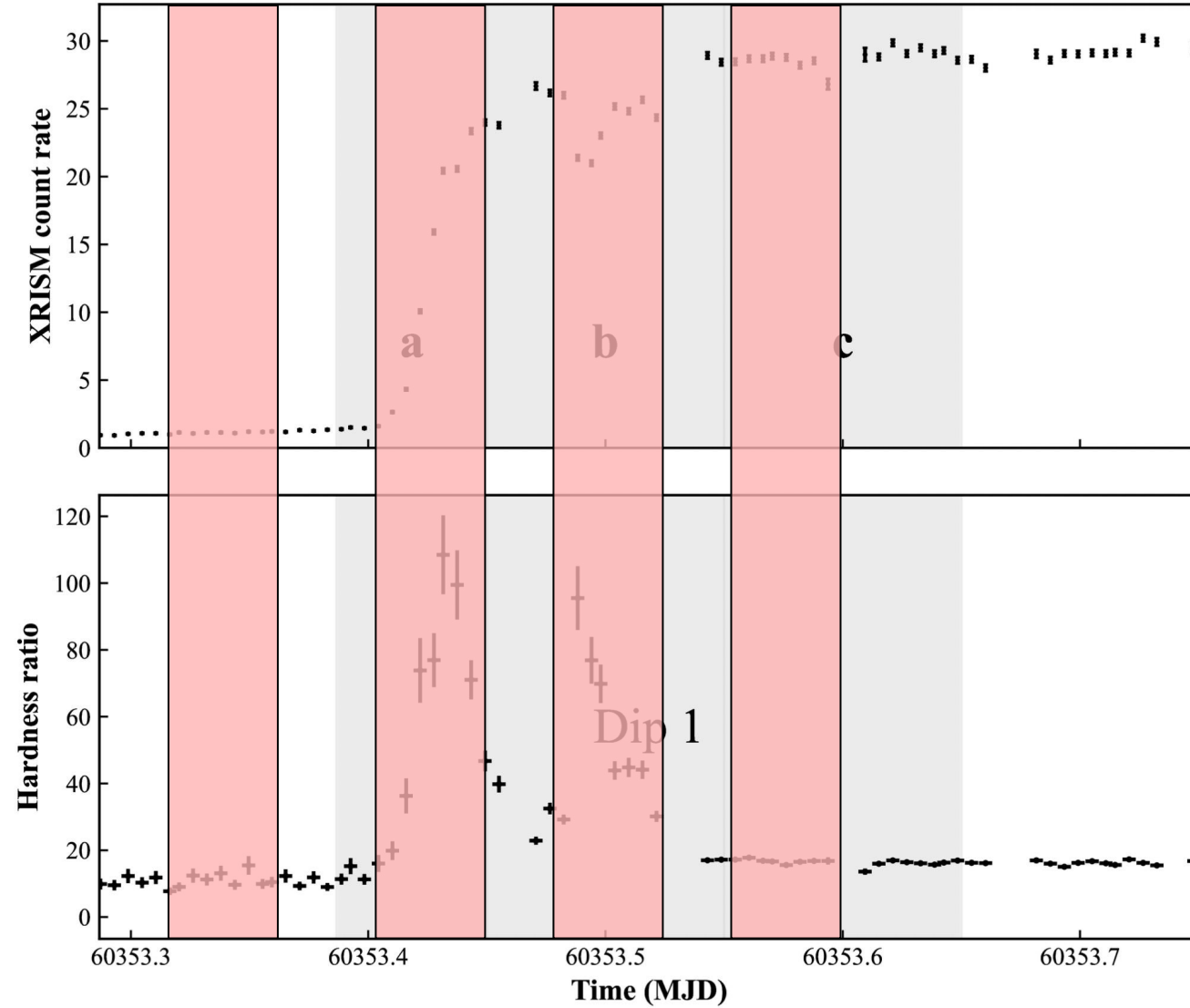


- Fe XXV and Fe XXVI absorption during the dip, not present in normal state

Scenario 1: Partially ionized clump in the wind

Scenario 2: Accretion stream blocking LOS

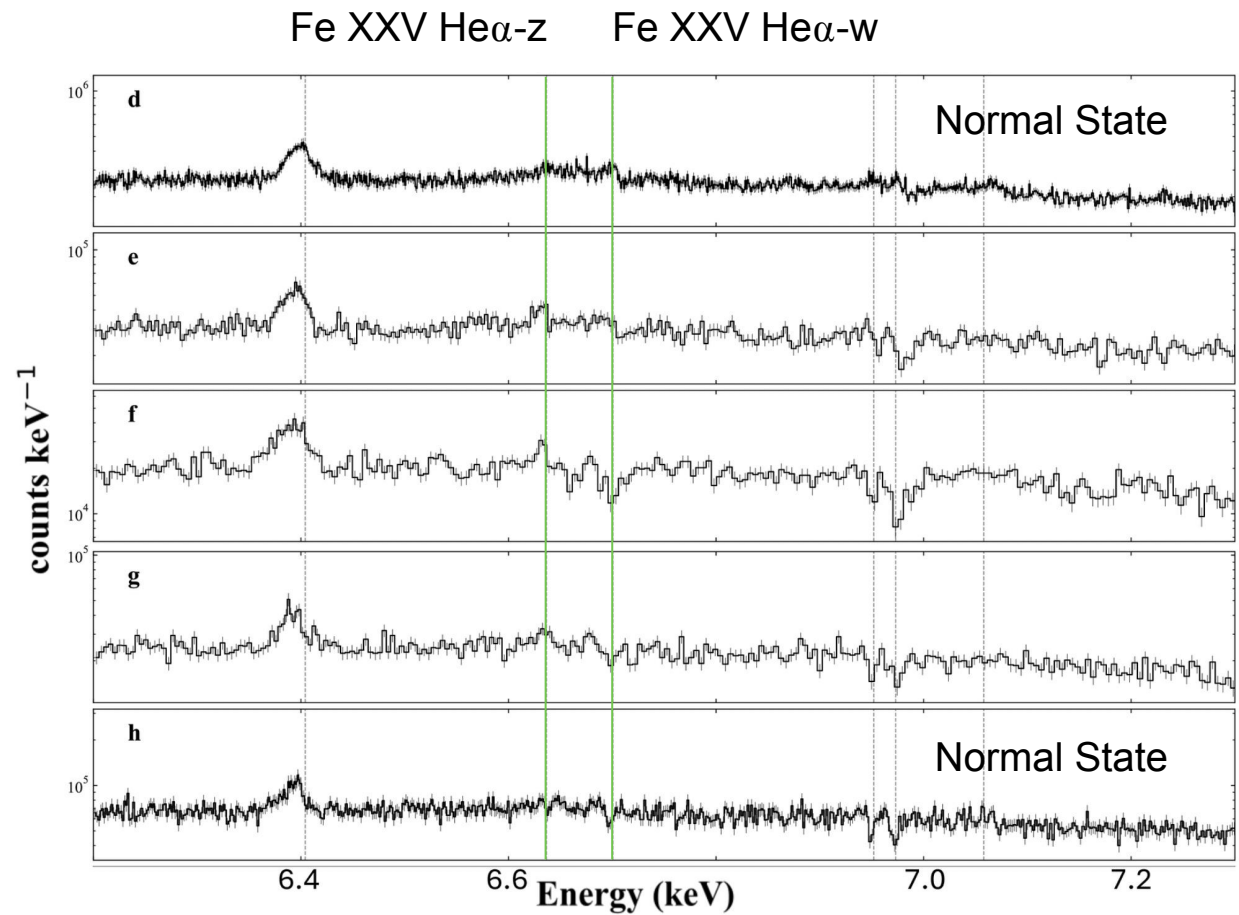
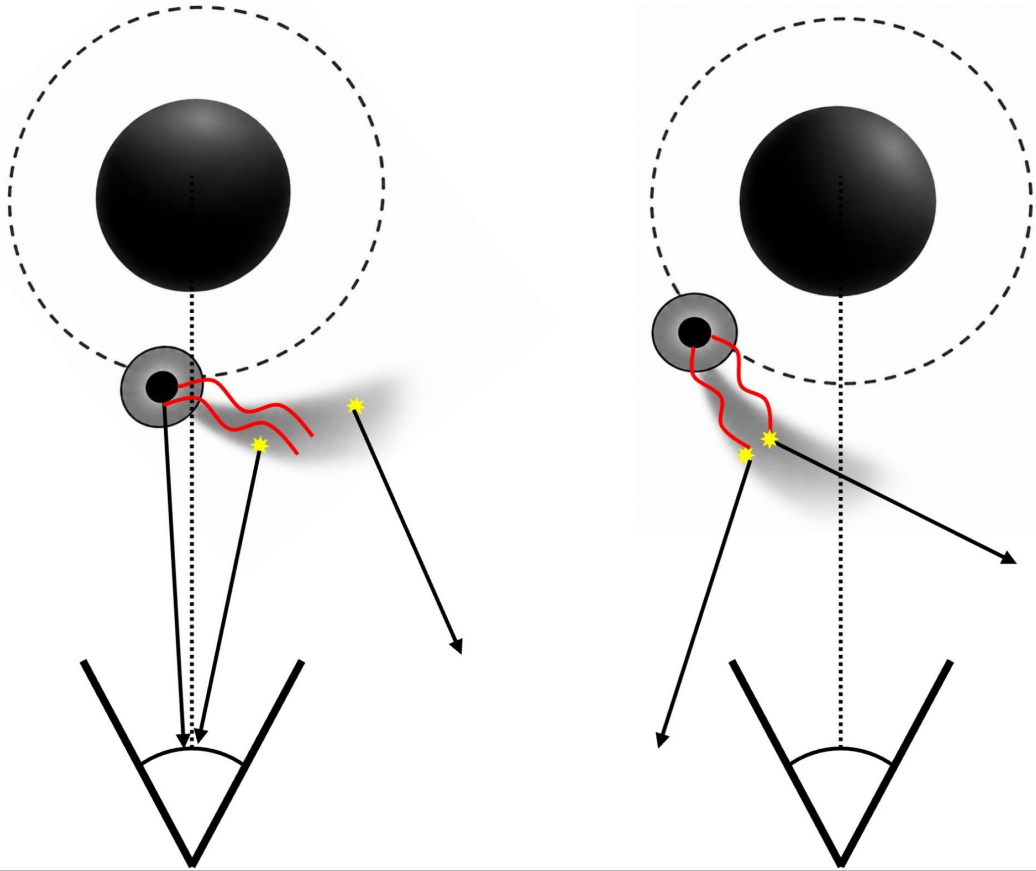
Dip 1: Visually



Dip 2: The Technicals

Main Lines to Watch:

- Fe XXV He α -z (Recombination Line)
- Fe XXV He α -w (Resonance Line)



- Fe XXV He α -z emission due to the wake being photoionized by X-rays from the neutron star
- During the dip, the wake intersects the LOS, photons are resonantly scattered out of our LOS

Limitations and Assumptions

- Only 1 XRISM observation, the Fe lines are out at 6-8 keV, only XRISM has the spectral resolution needed to probe this
- For Dip 1, there is signs that this dip appeared in other X-ray instrument light curves at different times, but there isn't enough spectral resolution to probe further
- For now, it's hard to distinguish between Dip 1 being caused by a dense clump in the wind or an accretion stream blocking our LOS
- The flux of Cen X-3 varies by 10x, this could change the characteristics of whatever is causing the dip, specifically the wake, making it harder to pin down

Future Work

The Imaging X-ray Polarimetry Explorer (IXPE) to test Dip 2 (470 ks, 2.5 orbits)

- If we see a rise in the polarization degree around the phase of the wake, this would imply single scattering in an ionized wake
- If there's no rise, this may point to a multiple scattering event and would largely contradict the wake theory which is currently supported by our observation as well as hydrodynamic simulations

Questions?

Afternoon II | 03:00 PM - 03:15 PM

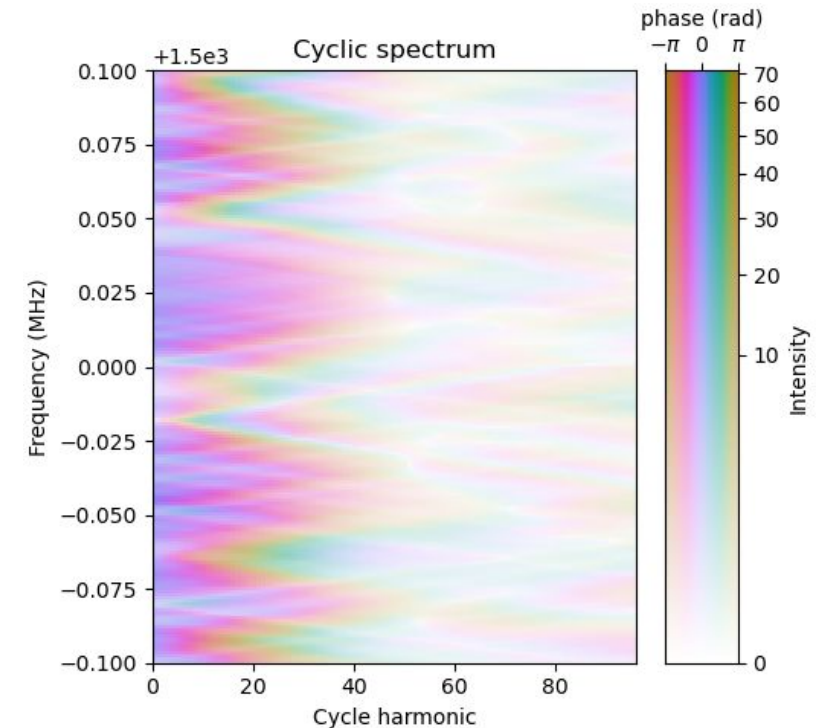
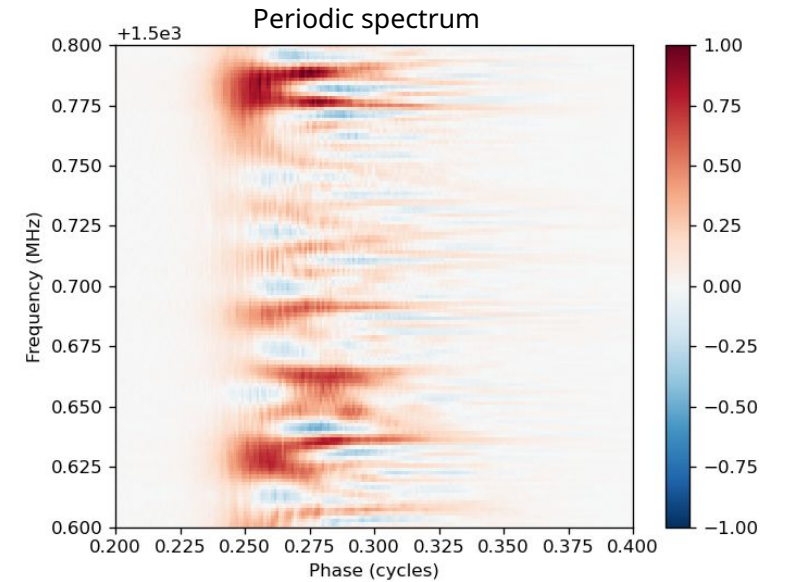
Ross Jennings

"Cyclic Spectroscopy for Pulsar Scintillometry"

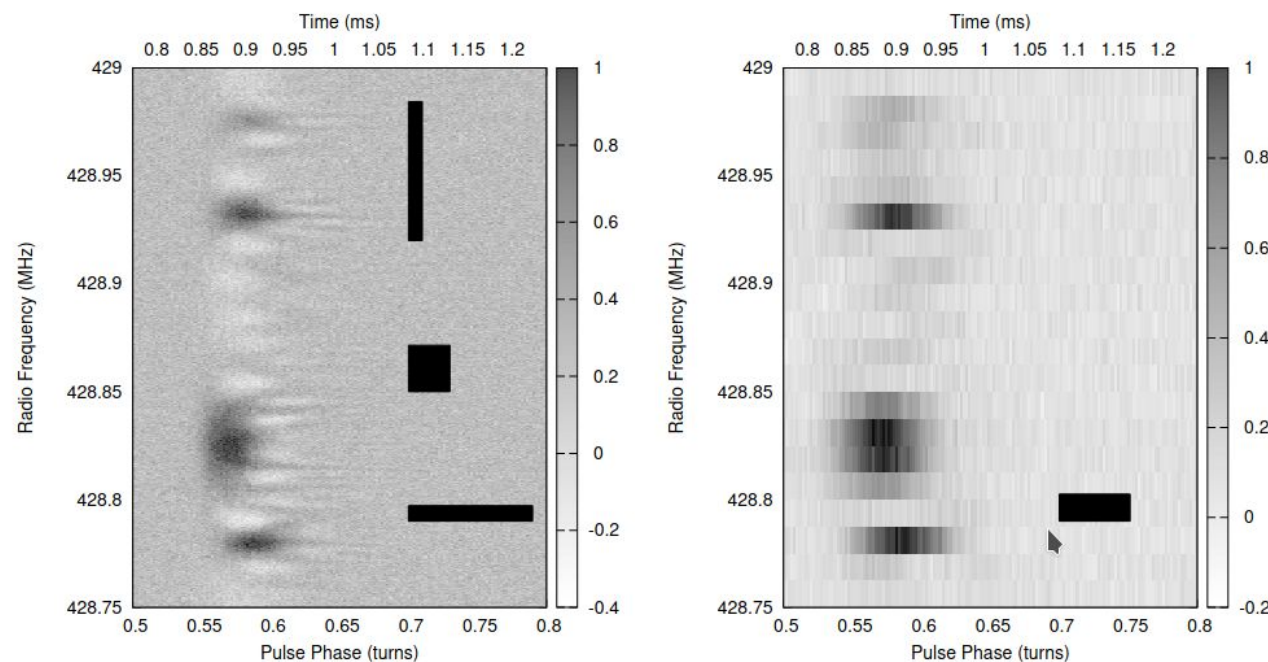
What is cyclic spectroscopy?

A specialized signal processing technique for characterizing *cyclostationary* signals.

- *Cyclostationary* = “statistically periodic” (stationary, for fixed pulse phase). **Pulsar signals are cyclostationary!**
- *Cyclic spectrum* = power spectrum, plus more information, indexed by *cycle frequency* (harmonics of pulse frequency).
- *Periodic spectrum* = Fourier transform of cyclic spectrum wrt cycle frequency. Roughly: intensity vs. frequency and pulse phase.



Why cyclic spectroscopy?



Periodic spectrum

Folded filterbank

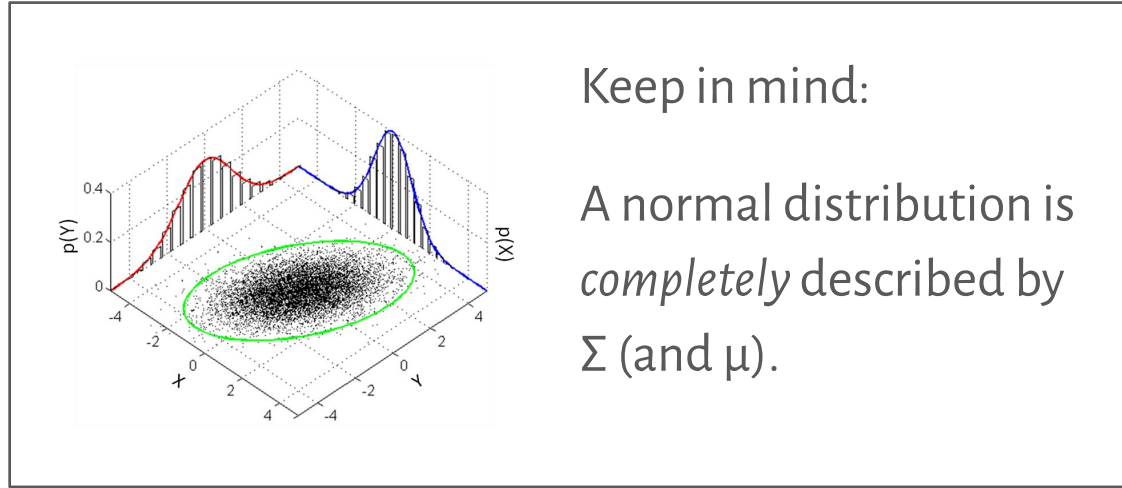
Demorest (2011)

- Much higher frequency resolution for pulsar observations, *without* sacrificing phase resolution!
- Allows deconvolution of the impulse response function $h(t)$ of the interstellar medium!

But, how is this possible?

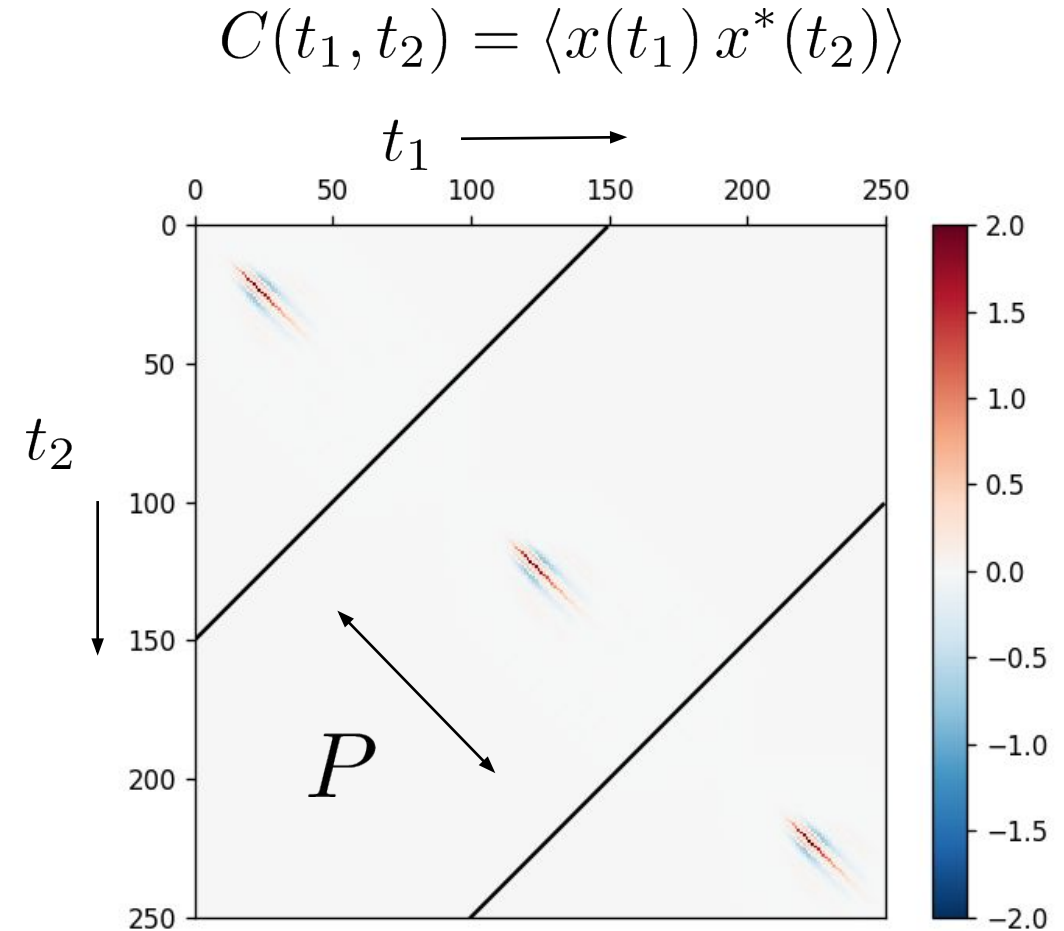
- In a typical filterbank, frequency and time resolution are limited by an “uncertainty principle” because you only get one realization of the signal.
- For a cyclostationary process, you can get around this limit because each pulse is a different realization of the signal!

The covariance matrix of a cyclostationary signal



- For a continuous signal, $\Sigma_{ij} = \langle x_i x_j^* \rangle$ is replaced by $C(t_1, t_2) = \langle x(t_1) x^*(t_2) \rangle$.
- For a cyclostationary signal, shifting both t_1 and t_2 by P is a symmetry:

$$C(t_1 + P, t_2 + P) = C(t_1, t_2).$$

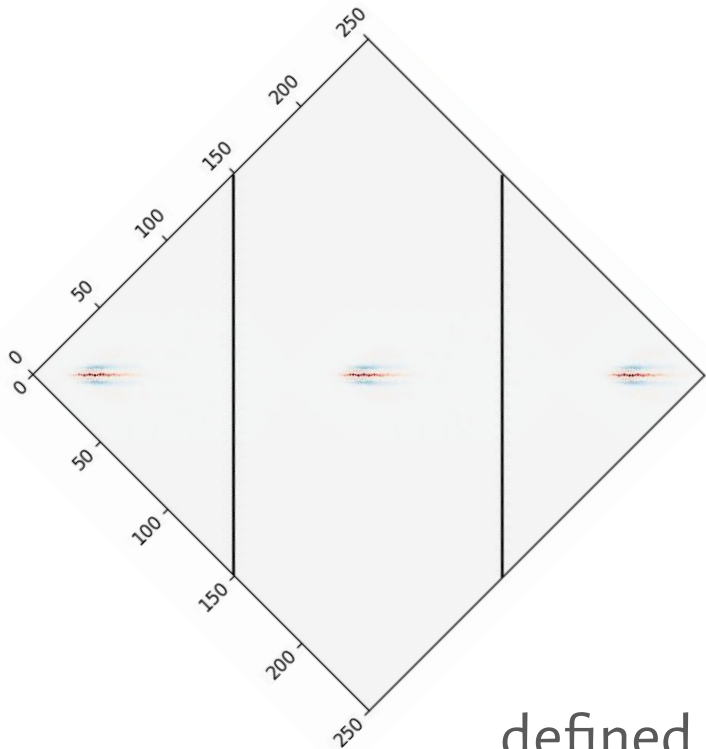


NOTE: $C(t_1, t_2)$ is an *ensemble average* quantity!

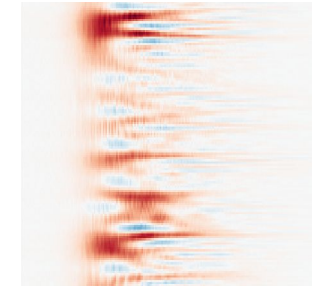
From covariance matrix to cyclic spectrum

A change of coordinates:

$$C(t, \tau) = \left\langle x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) \right\rangle \begin{matrix} \xrightarrow{\mathcal{F}_\tau} \\ \xleftarrow{\mathcal{F}_\nu^{-1}} \end{matrix} Z(t, \nu) = \int_{-\infty}^{\infty} \left\langle x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) \right\rangle e^{-2\pi i \nu \tau} d\tau$$



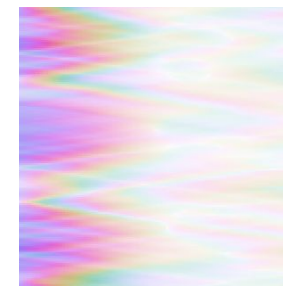
Periodic spectrum



$$\begin{matrix} \mathcal{F}_t \downarrow \\ \uparrow \mathcal{F}_\alpha^{-1} \end{matrix}$$

$$S(\alpha, \nu) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\langle x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) \right\rangle e^{-2\pi i (\alpha t + \nu \tau)} dt d\tau \\ = \left\langle \hat{x}\left(\nu + \frac{1}{2}\alpha\right) \hat{x}^*\left(\nu - \frac{1}{2}\alpha\right) \right\rangle$$

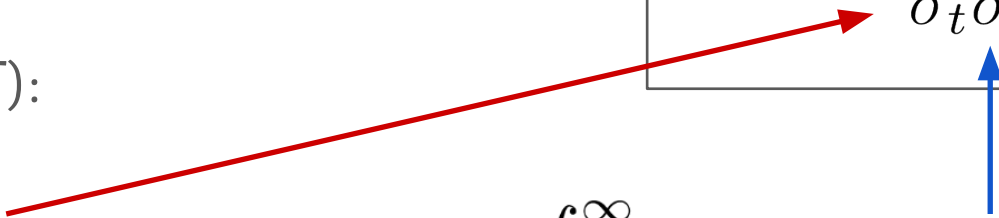
Cyclic spectrum



defined only at *cycle frequencies* ($a_k = k/P$)

The Gabor limit, and how to beat it

A general filterbank setup (STFT):

$$X_w(t, \nu) = \int_{-\infty}^{\infty} x(t') w(t' - t) e^{-2\pi i \nu t'} dt' = \int_{-\infty}^{\infty} \hat{x}(\nu') \hat{w}(\nu - \nu') e^{-2\pi i (\nu - \nu') t} d\nu'$$


Uncertainty principle (Kennard bound):

$$\sigma_t \sigma_\nu \geq \frac{1}{4\pi}$$

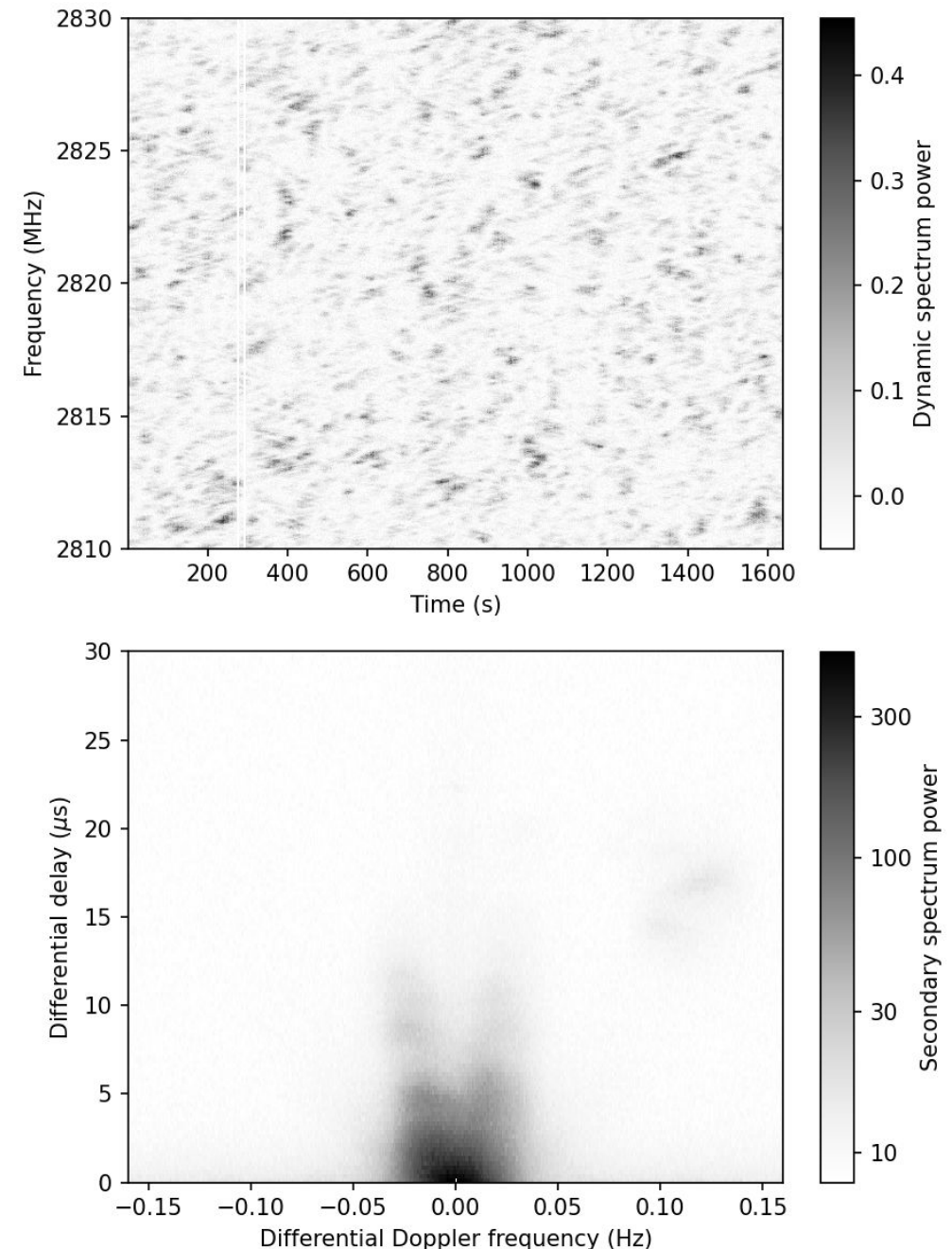
- Can choose window function $w(t)$ arbitrarily, but subject to uncertainty principle:

A narrower $w(t)$ means a wider $\hat{w}(\nu)$.

- Intuitive reason for this: To split the signal into frequencies, you need more than just the value at one point, you need a chunk of finite duration. The longer the chunk, the better you resolve in frequency, but the worse you resolve in time.
- **WORKAROUND:** Instead of using nearby points, use points a whole number of periods away! This only works because of the cyclostationary property.

Diffraction interstellar scintillation

- Pulsars are very nearly point sources, so they are strongly scintillated by the ISM.
- In the strong scintillation regime, there are two separate time scales: diffractive (DISS, minutes to hours) and refractive (RISS, weeks to months).
- DISS of pulsars produces a pattern in the dynamic spectrum whose 2-dimensional Fourier transform (the *secondary spectrum*) shows a characteristic parabolic arc.
- To a first approximation, DISS occurs at a 2D “scattering screen” in the ISM; the curvature of the arc is related to the distance to the screen (as a fraction of the distance to the pulsar).



The cyclic spectrum of a pulsar

Before scintillation:

pulse profile

$$C_x(t, \tau) = p(t) \delta(\tau)$$

$$\Rightarrow S_x(\nu, \alpha) = \hat{p}(\alpha)$$

Scintillation can be represented by convolution with an impulse response function (IRF) $h(t)$, with Fourier transform (filter function) $H(\nu)$:

$$y(t) = x(t) * h(t)$$

$$\hat{y}(\nu) = H(\nu) \hat{x}(\nu)$$

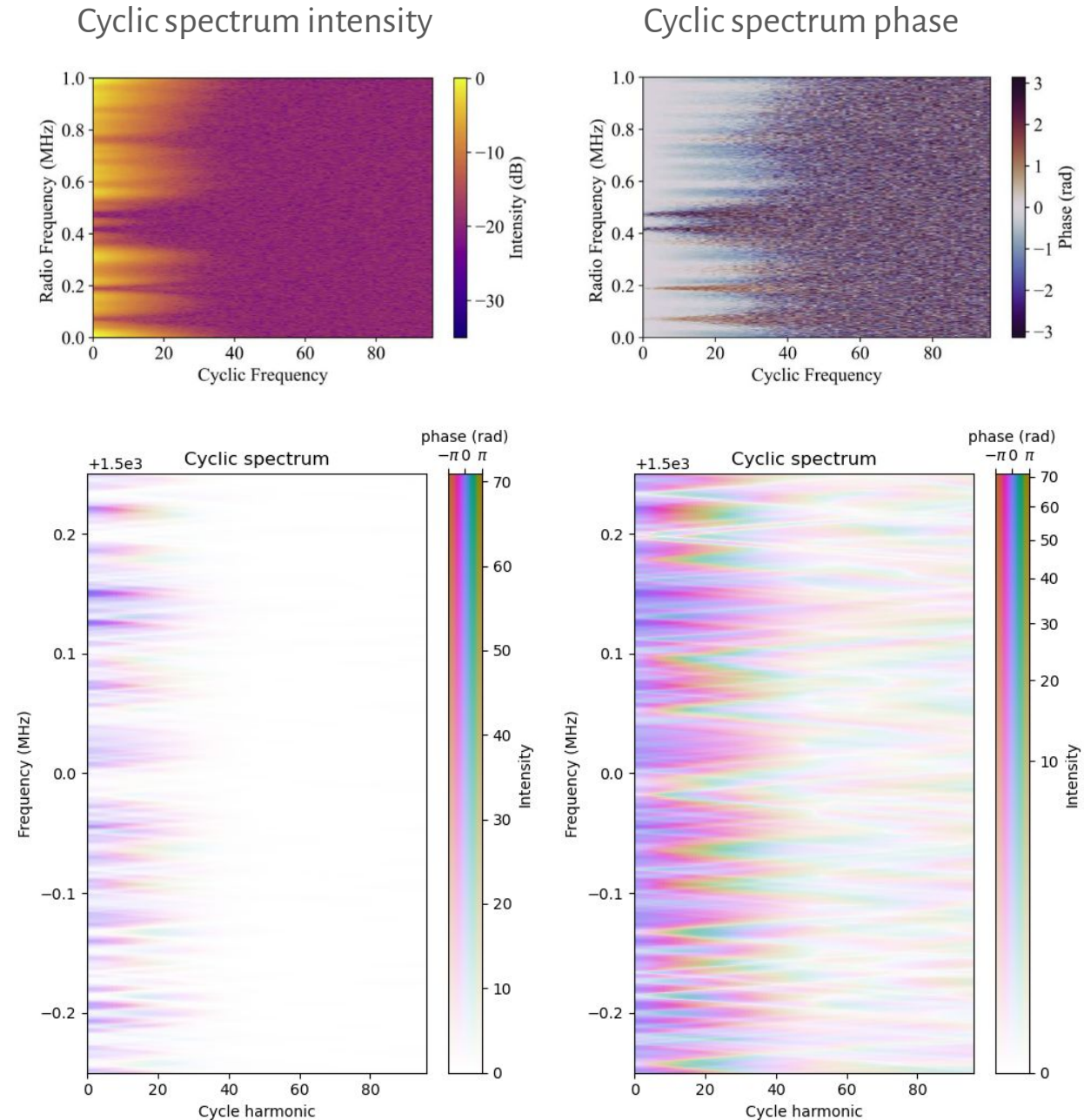
Cyclic spectrum: $\Downarrow$

$$S_y(\nu, \alpha) = \langle \hat{y}(\nu + \frac{1}{2}\alpha) \hat{y}^*(\nu - \frac{1}{2}\alpha) \rangle$$

$$= H(\nu + \frac{1}{2}\alpha) H^*(\nu - \frac{1}{2}\alpha) S_x(\nu, \alpha)$$

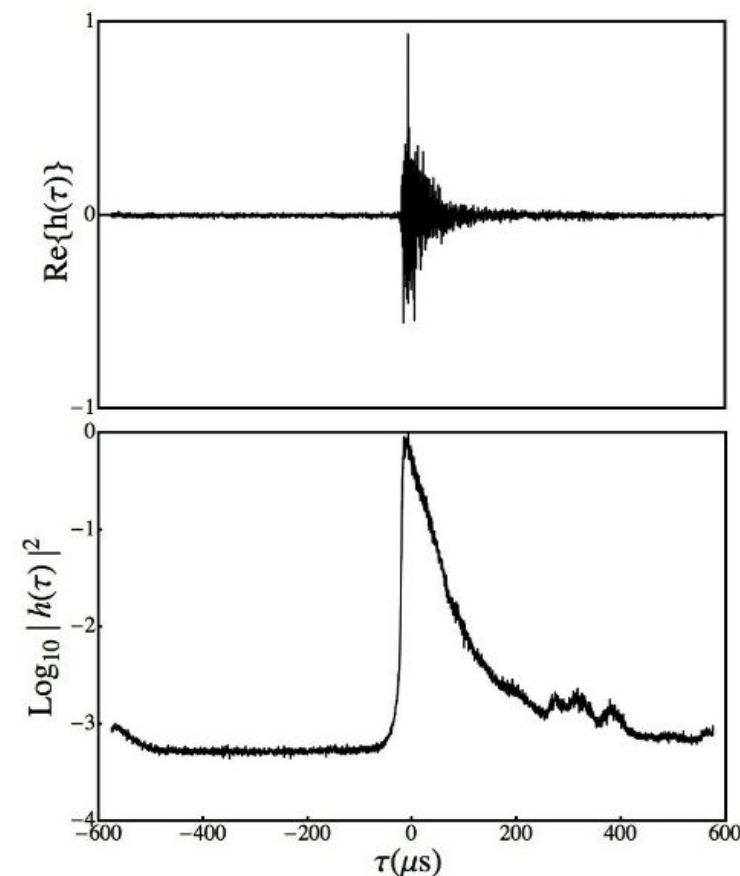
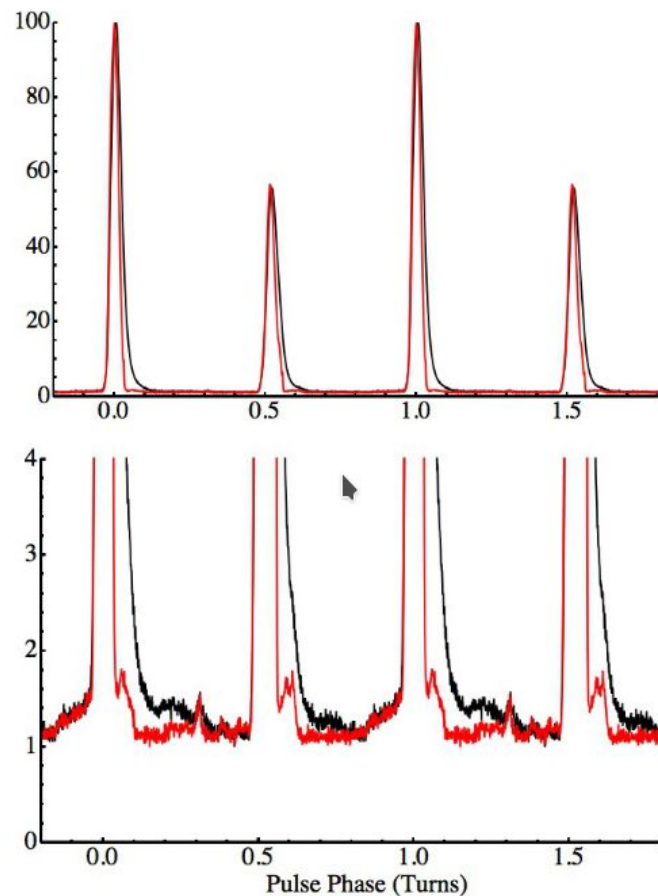
The phase of $H(\nu)$ is (partially) preserved!

Dolch et al. (2021)



Deconvolving the ISM impulse response

- Because the phase $H(\nu)$ is preserved, it can be reconstructed from the observed cyclic spectrum.
- This allows the IRF, $h(t)$, to be fully deconvolved from the intrinsic pulsar emission.
- This is a major advantage compared to traditional methods, which worked with either $|H(\nu)|^2$ or $|h(t)|^2$. (Turner *et al.* 2023).



Walker et al. (2013)

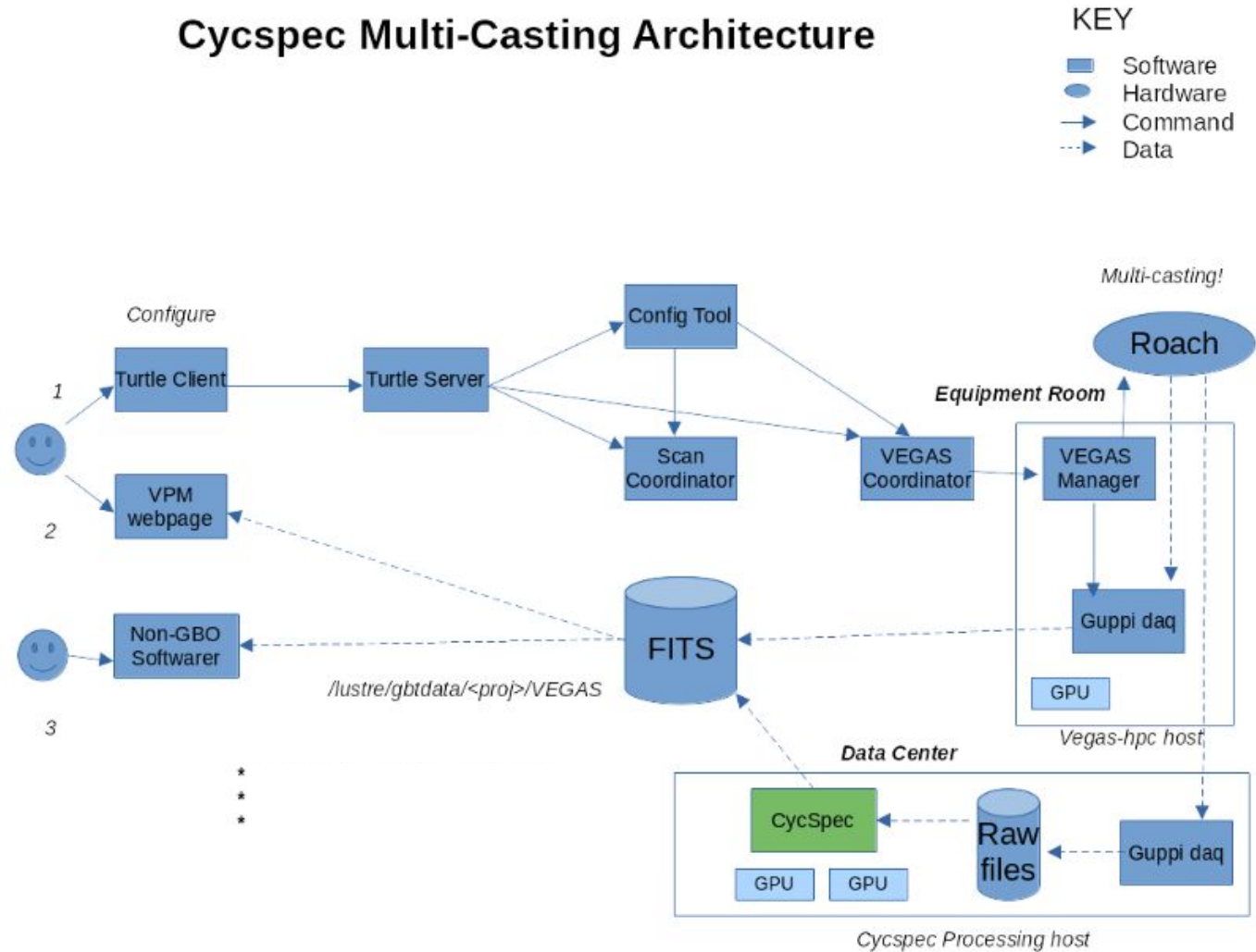
The GBT CS backend



“Cyclops”



“Cyclid”



The GBT CS backend (continued)

Baseband data rate (per bank):

187.5 MHz

× 2 bytes/sample

= 375 MB/s

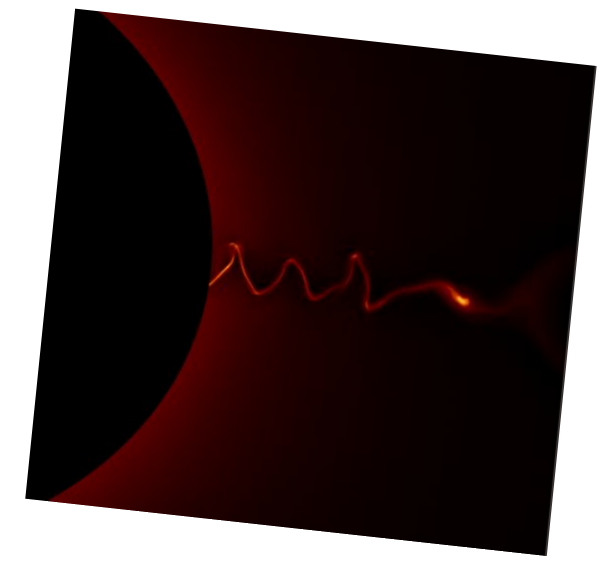
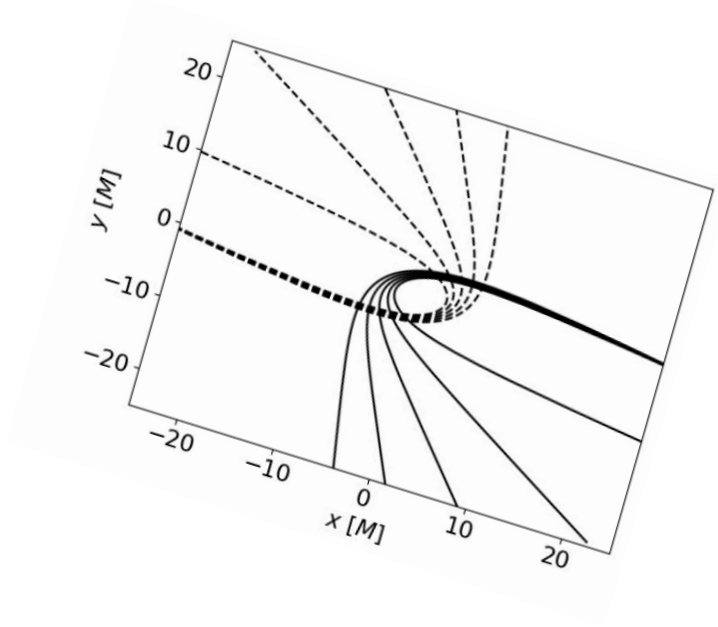
= 1.35 TB/hr

- Important question: Can the processing be done in real time?
- With existing software: no.
- “Quasi-real-time” system: will write baseband data to disk and process afterwards
- Originally, this led to scheduling constraints for CS observing.
- Solution: use multiple GPUs per bank to process multiple scans in parallel.

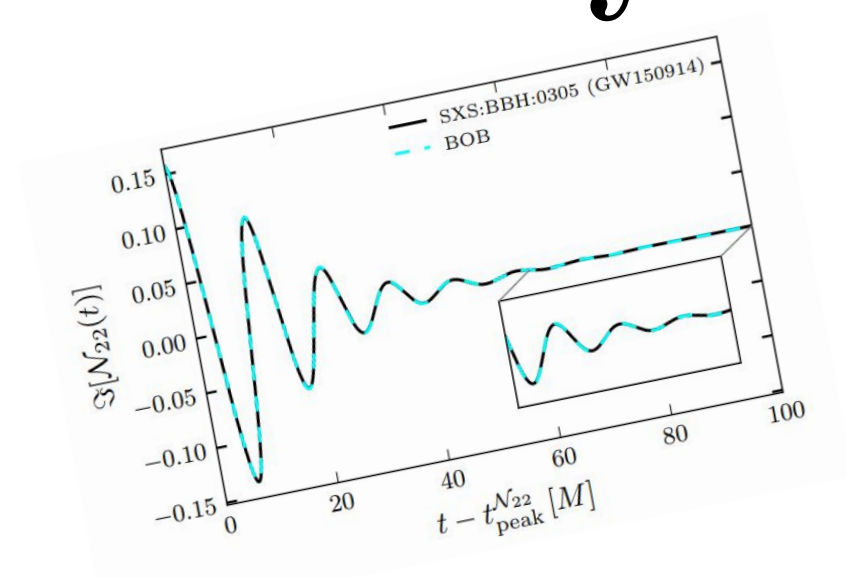
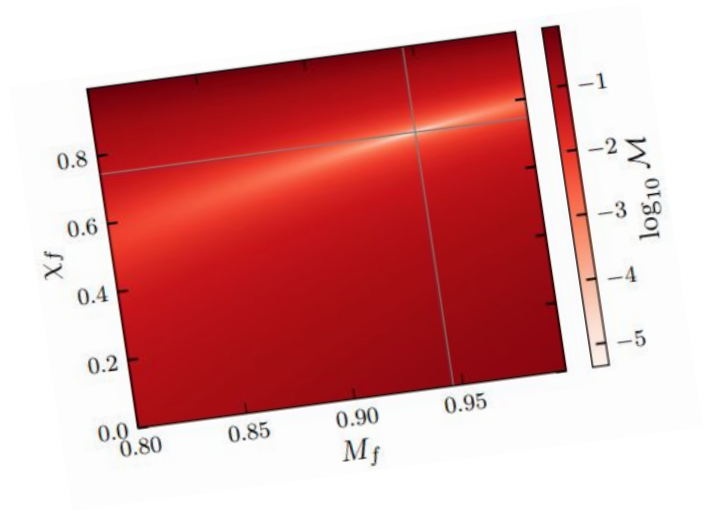
Afternoon II | 03:15 PM - 03:30 PM

Anuj Kankani

"Modeling Extreme Gravity: From Relativistic Plasmas to Gravitational Waves"

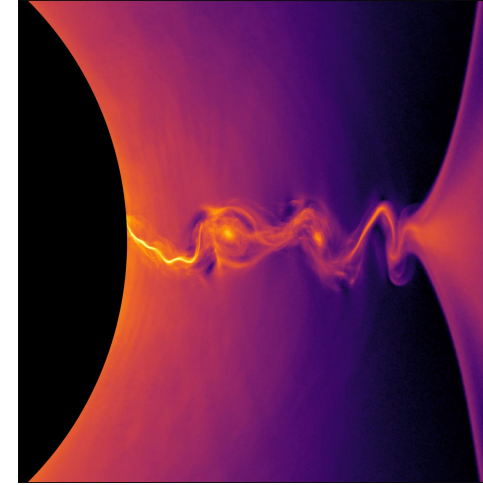


What does Anuj do all day?

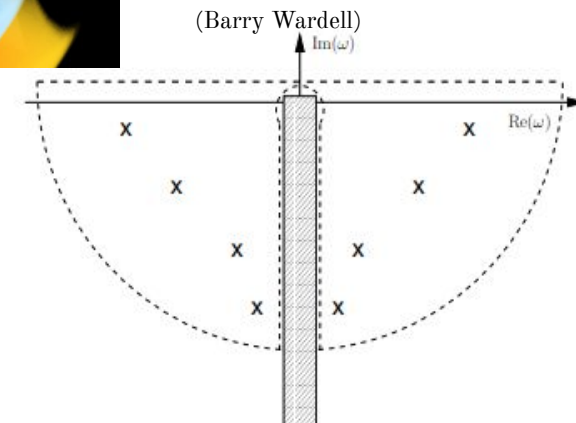
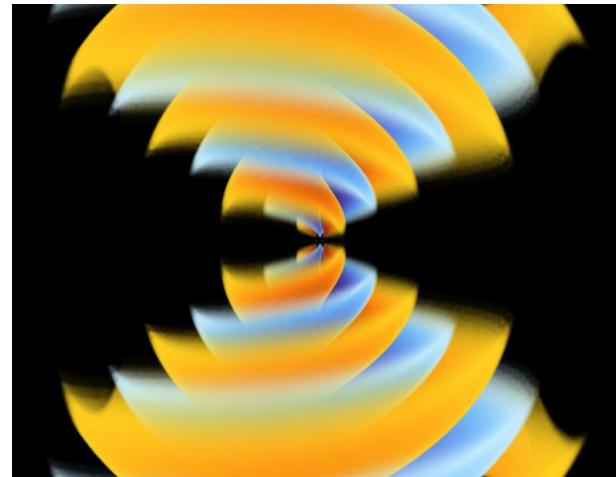


How do I study Black Holes?

- **General Relativistic Particle-in-Cell Methods!**
 - To study BH jets!
- **Numerical Relativity!**
 - To study BH scattering!
- **Analytical Methods!**
 - To study BH mergers!

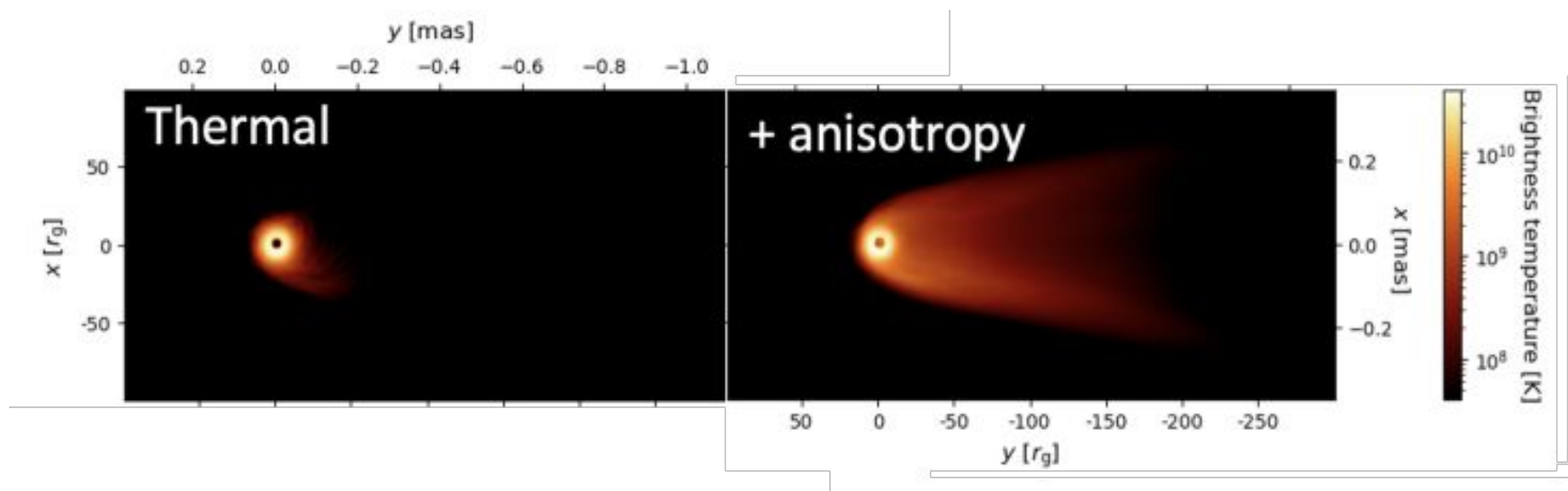


(Kyle Parfrey)



(Emanuele Berti)

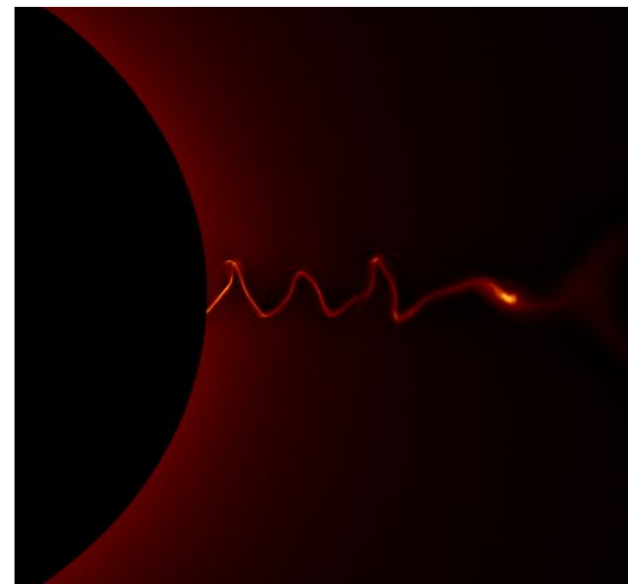
Temperature Anisotropies in the Jet of M87*



(Tsunetoe, Yuh, et al.)

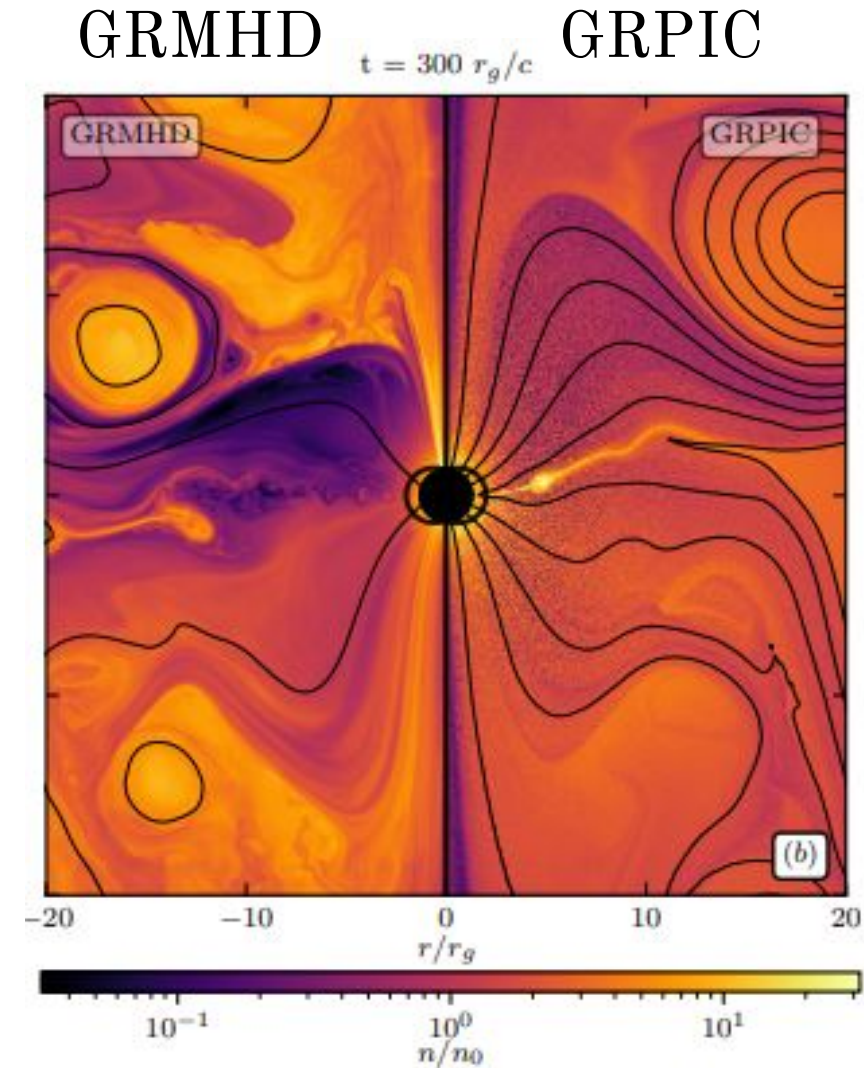
entity

tl;dr: One particle-in-cell code to rule them all.

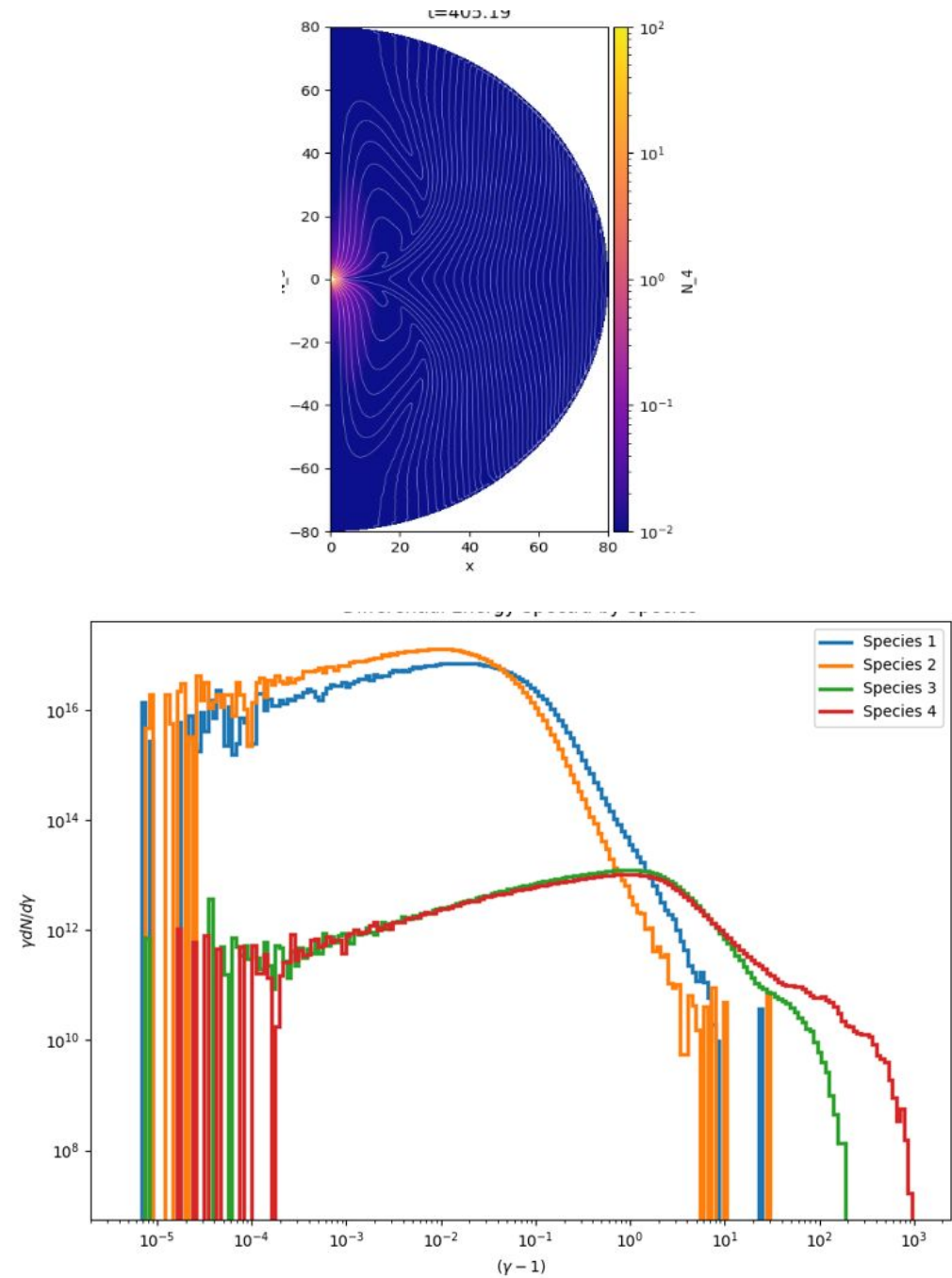
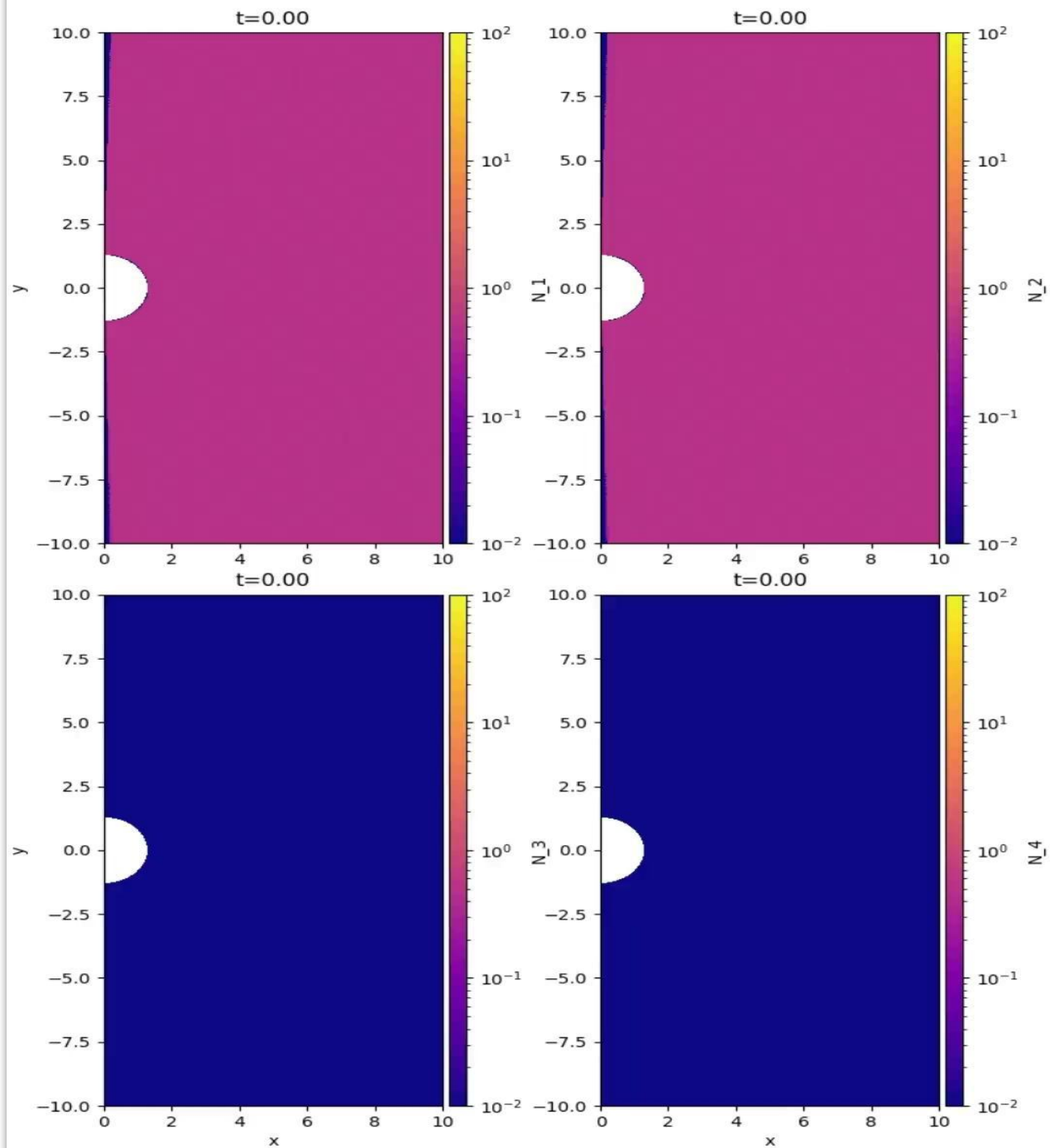


Why GRPIC?

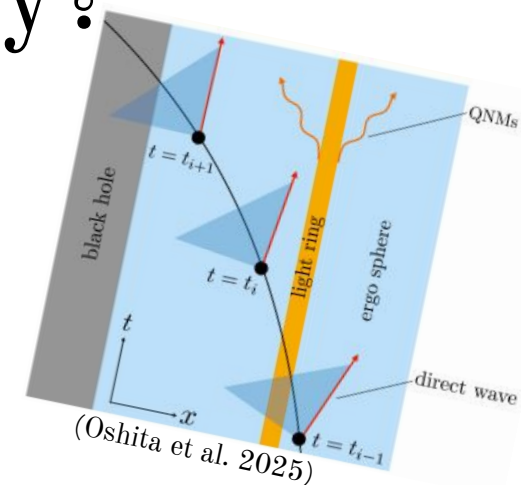
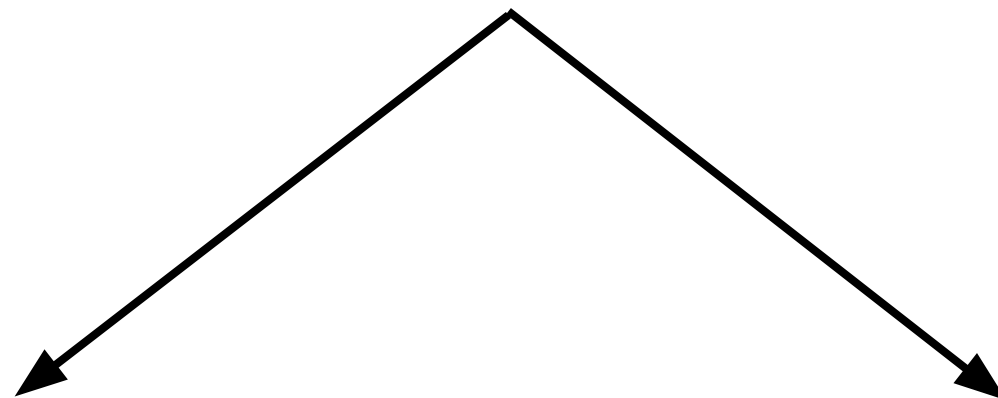
- Plasmas around BHs are effectively collisionless
 - GRMHD is formally inapplicable (but we use it anyway)
- GRPIC allows us to properly study
 - Reconnection!
 - Anisotropies!
 - Particle Acceleration!
- BH accretion, Pulsar emission, FRBs, BH jets ...
- But it's expensive (“curse of scales”)!



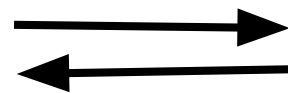
(Galishnikova, et al. 2022)



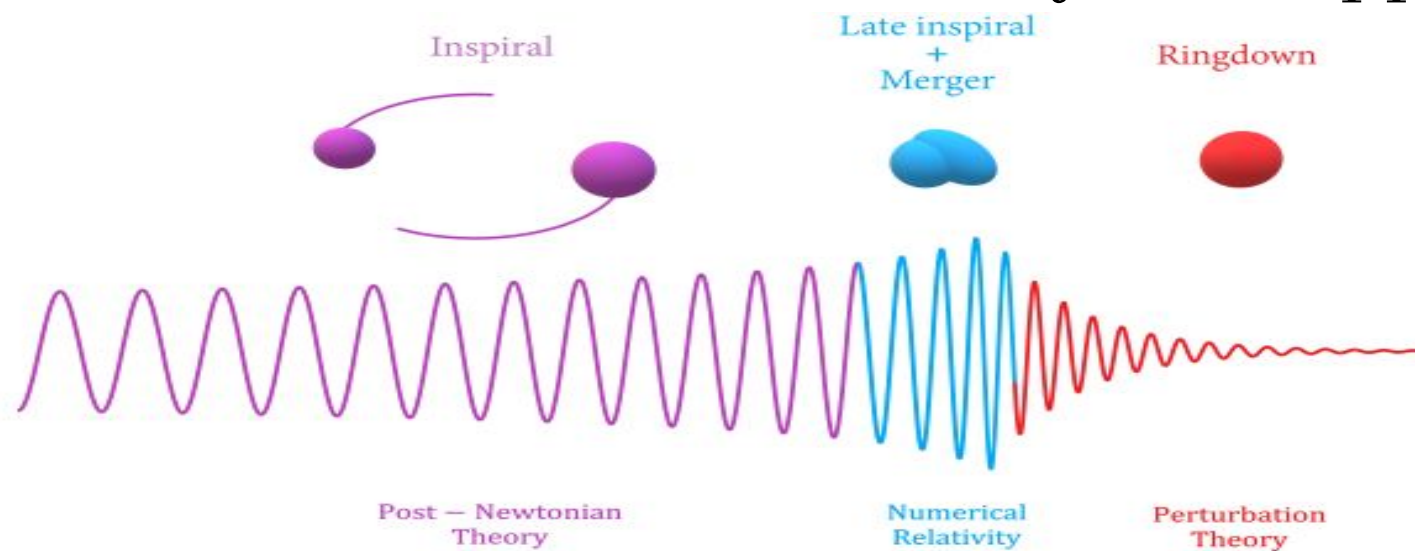
How do we probe strong gravity?



Numerical Relativity

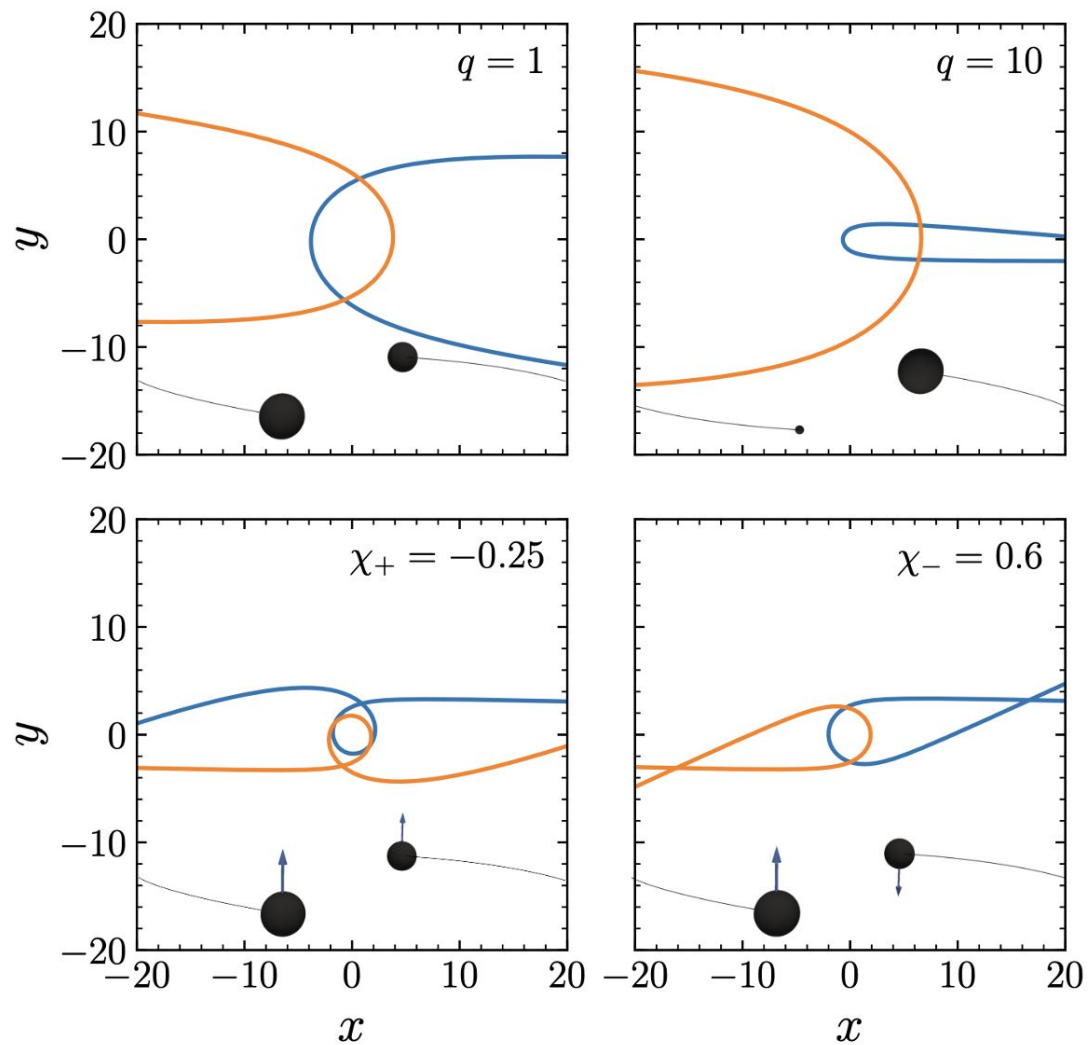


Analytical Approximations

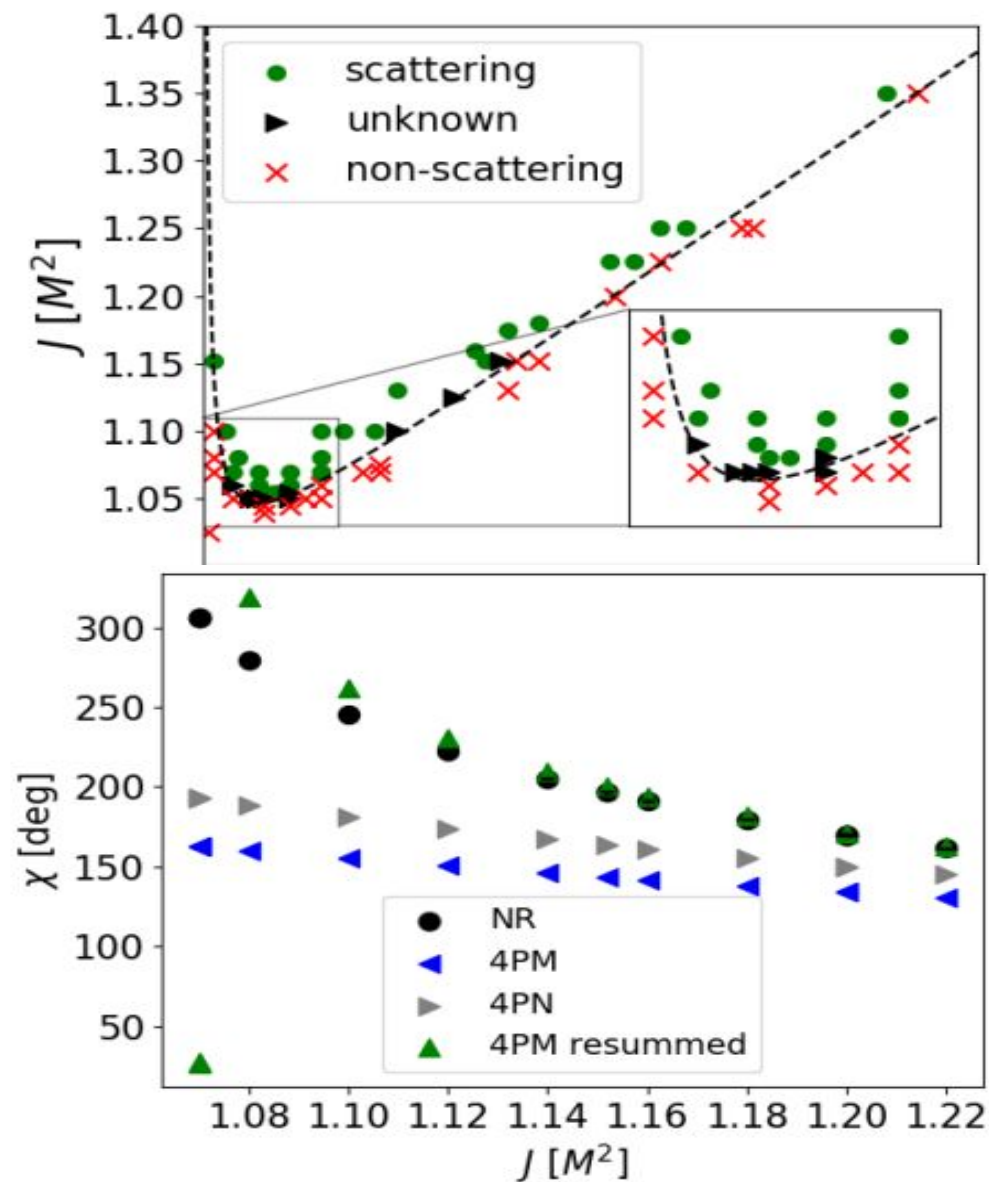


(Cattorini and Giacomazzo 2024)

BH Scattering



(Oliver Long)





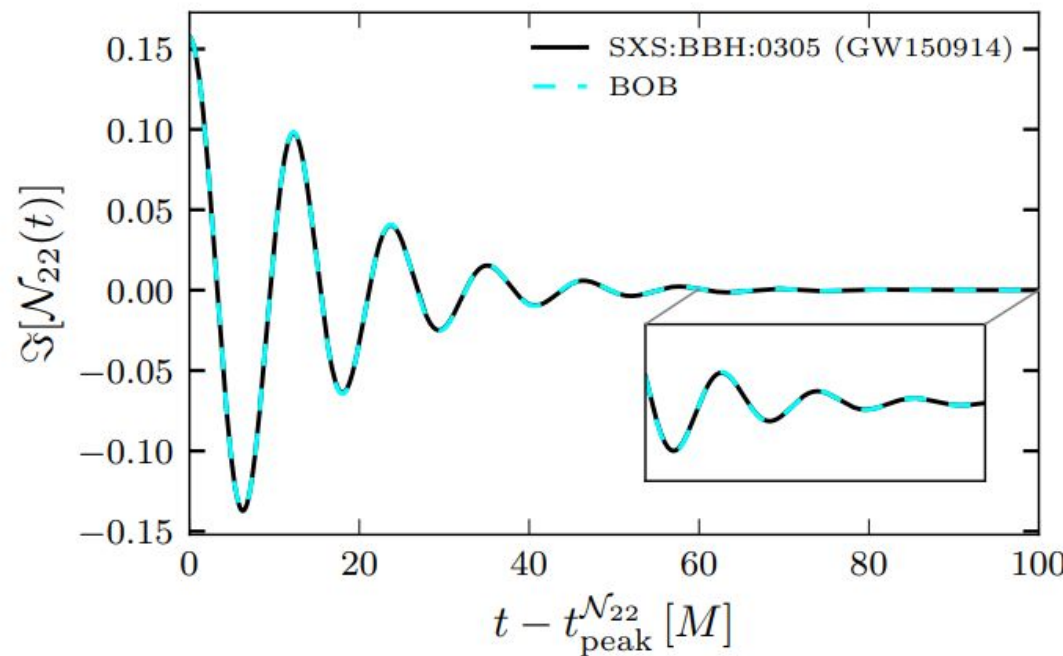
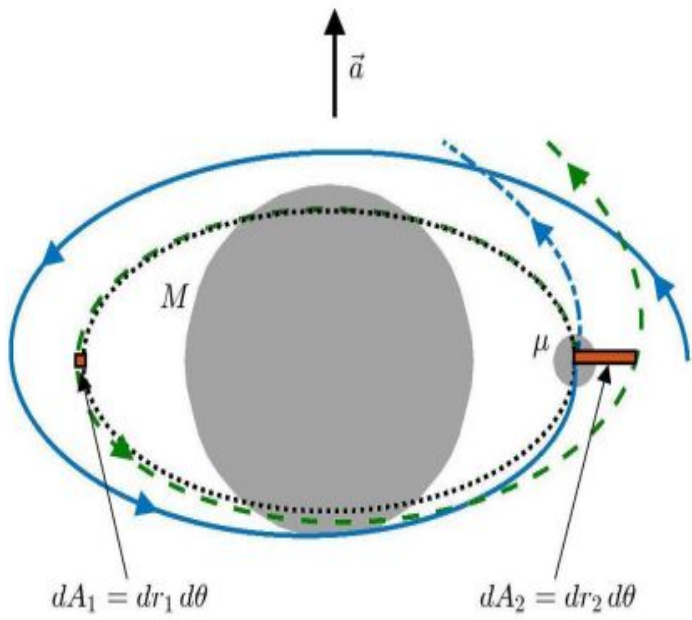
The Backwards One Body Model

$$A = A_p \operatorname{sech}\left(\frac{t - t_p}{\tau}\right)$$

Only 4 Parameters!

$$M_f, \chi_f, A_p, \Omega_0 \approx 0.155$$

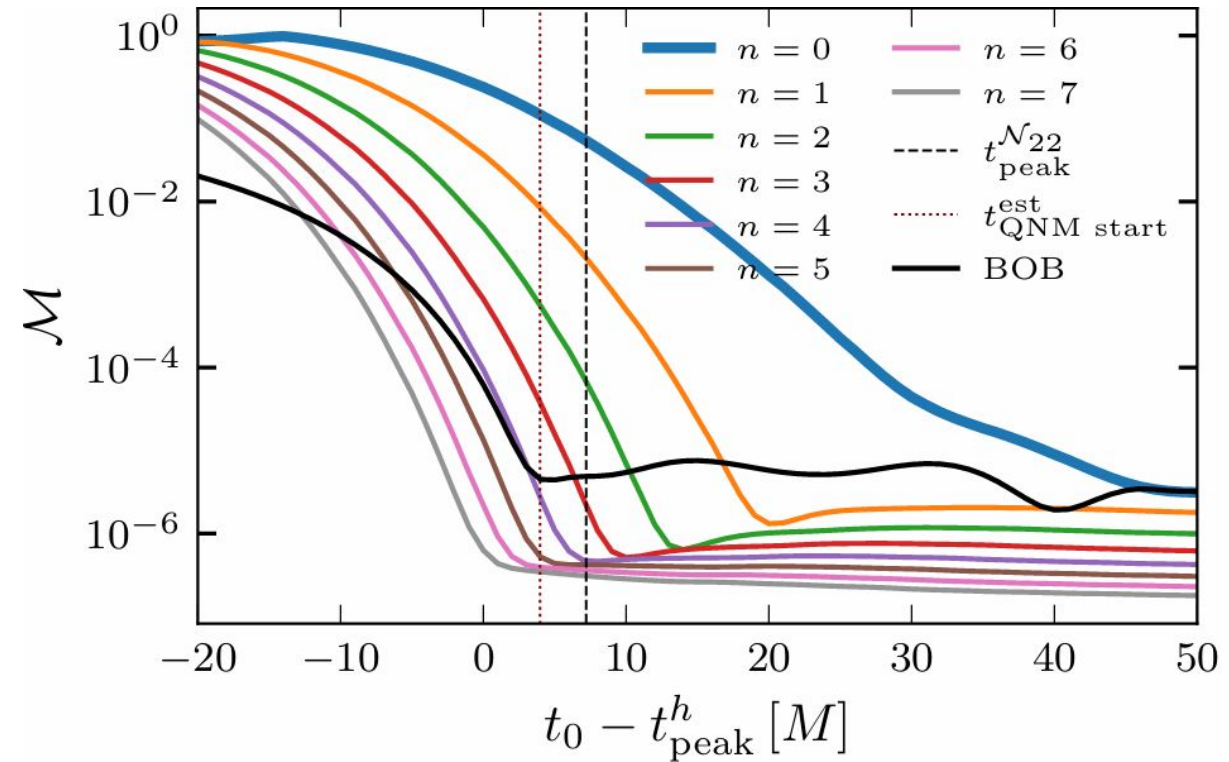
$$\Phi = \frac{\tau}{2} \left[\Omega_{\text{QNM}} \ln \left(\frac{\Omega + \Omega_{\text{QNM}}}{|\Omega - \Omega_{\text{QNM}}|} \right) - \Omega_0 \ln \left(\frac{\Omega + \Omega_0}{\Omega - \Omega_0} \right) \right] + \Phi_0$$



BOB “looks” like QNMs

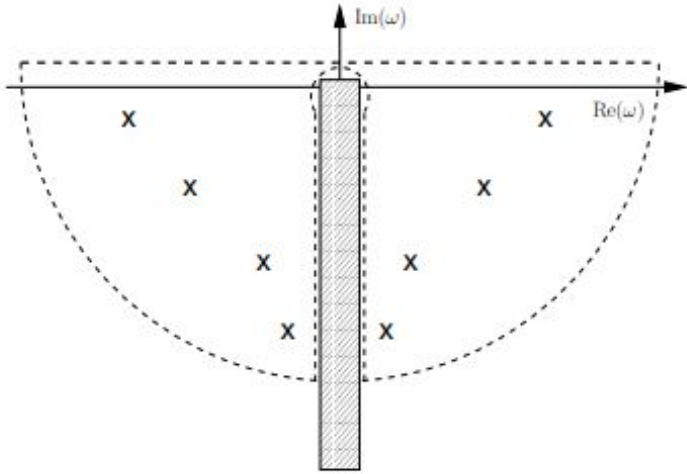
$$2A_p \left(e^{-\frac{t-t_p}{\tau}} - e^{-3\frac{t-t_p}{\tau}} + e^{-5\frac{t-t_p}{\tau}} + \dots \right)$$

BOB “acts” like QNMs



How is BOB related to QNMs ? $\longrightarrow$ BH Perturbation Theory!

$$\frac{d^2 \hat{X}^{(s)}(\omega, r)}{dr_*^2} + V_{\text{eff}}(r) \hat{X}^{(s)}(\omega, r) = I(\omega, r)$$



(Emanuele Berti)

$$X^{(s)}(t, r) = -\text{Re} \left[\sum_n C_n e^{-i\omega_n(t-r_*)} \right]$$

$$\frac{dX^{(s)}(t, r)}{dt} \propto \text{Re} \left[\frac{\alpha}{2\Gamma(1+\beta)\Gamma(-\beta)} \left[\sum_n \frac{(-1)^n \Gamma(n-\beta)\Gamma(1+2\beta-n)}{n!\Gamma(\beta-n)} e^{-i\omega_n(t-r_*)} \right] \right]$$

$$\frac{dX^{(s)}(t, r)}{dt} \propto \text{Re} \left[\frac{\alpha\Gamma(1+2\beta)}{2\Gamma(\beta)\Gamma(1+\beta)} e^{+\alpha\beta(t-r_*)} (1 + e^{-\alpha(t-r_*)})^{-1} F\left(-\beta, -1-\beta; -2\beta; -e^{-\alpha(t-r_*)}\right) \right]$$

$$|\mathcal{N}(t)| \propto \text{sech}\left(\frac{t-t_p}{\tau}\right)$$

NR insights! 

