Millisecond Pulsars are likely (leptonic, magnetospheric) PeV Particle Accelerators

Zorawar Wadiasingh (UMD, NASA GSFC)
with Minju Sim and Hongjun An (Chungbuk National University, South Korea)

much previous work also involves C. Venter, A. K. Harding, C.J.T. van der Merwe, M. G. Baring, M. Boettcher, P. Kilian and others

Fermi Symposium, Sep 9, 2024

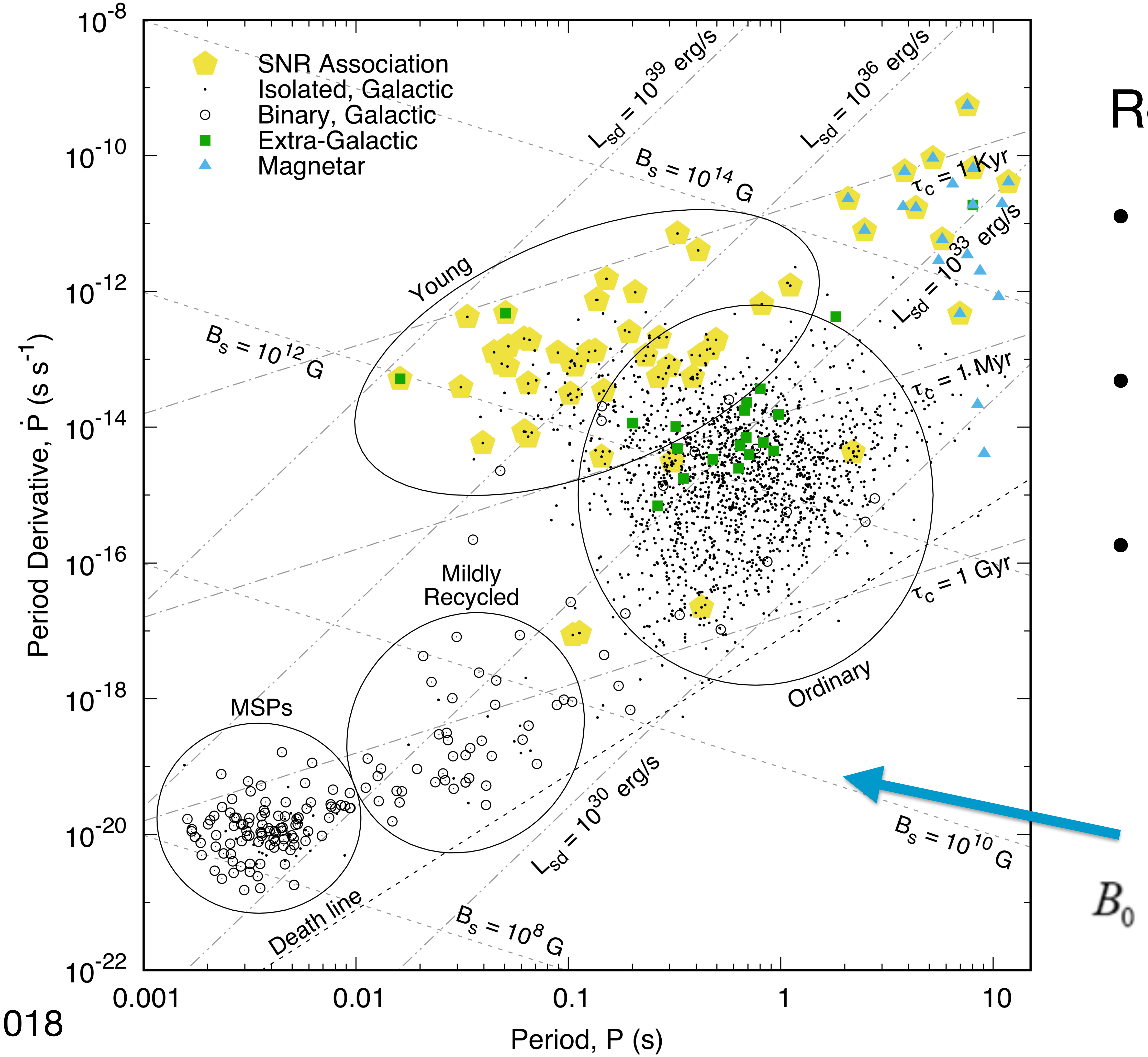
Outline

I will try to convince you from evidence that:

- Spider binaries are extremely interesting and well-constrained+clean laboratories of pulsar wind physics
- Fermi-LAT in recent years has detected something remarkable in three of these systems with *pulsed* orbitally-modulated γ-rays
  - The phasing and flux of these γ-rays **cannot be explained** with models of inverse Compton scattering of the pulsar wind on (companion) photons
  - A workable solution, perhaps the only one, seems to be ~0.1 PeV electron/positrons from the pulsar magnetosphere interacting with a companion magnetosphere
  - The phasing implies these ~0.1 PeV electrons are likely the same ones which produced pulsed GeV signals from pulsars

Some background

The Neutron Star Zoo



Ridolfi 2018

Rotation-powered pulsars

- About 3000 total, ~10% gamma-ray pulsars
- Millisecond pulsars are mostly in binaries
- Fermi-LAT is limited to detecting pulsars above spin down power >10^31 erg/s

$$B_0 = \left(\frac{3Ic^3 P\dot{P}}{2\pi^2 R^6} \right)^{1/2}$$

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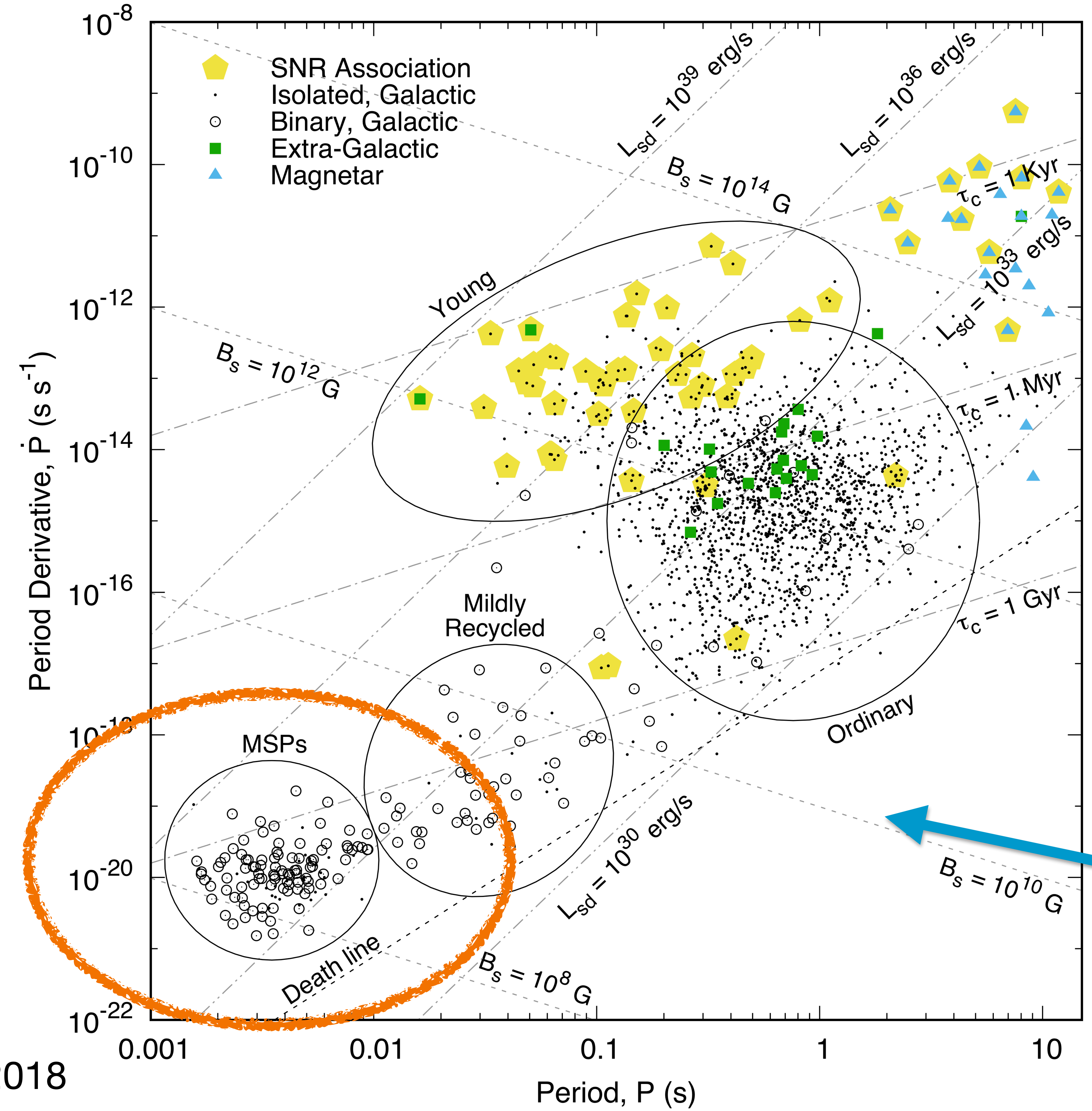

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Fermi pulsars

as of 2024

3rd *Fermi* LAT Pulsar Catalog

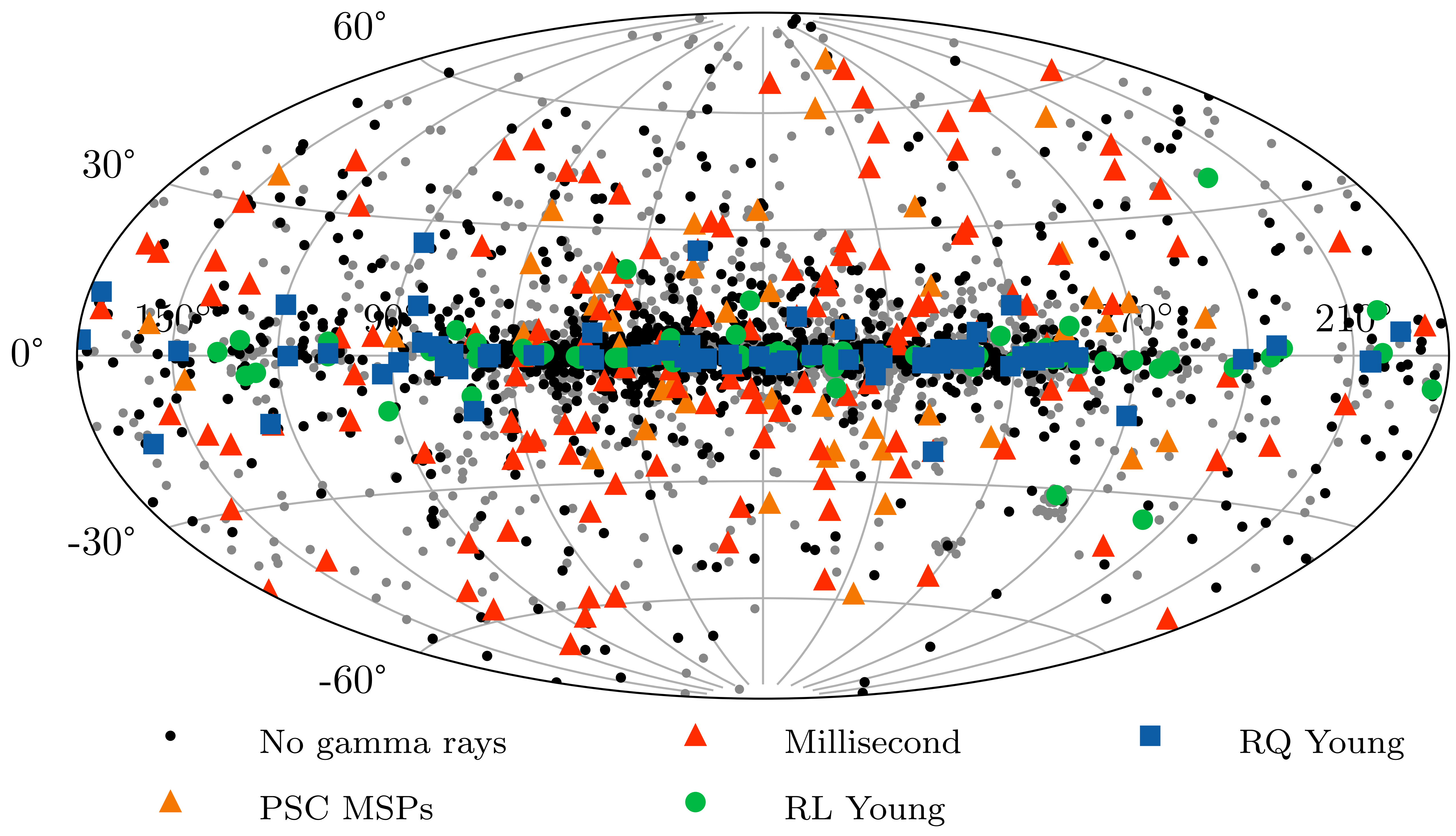
Table 1. Pulsar varieties

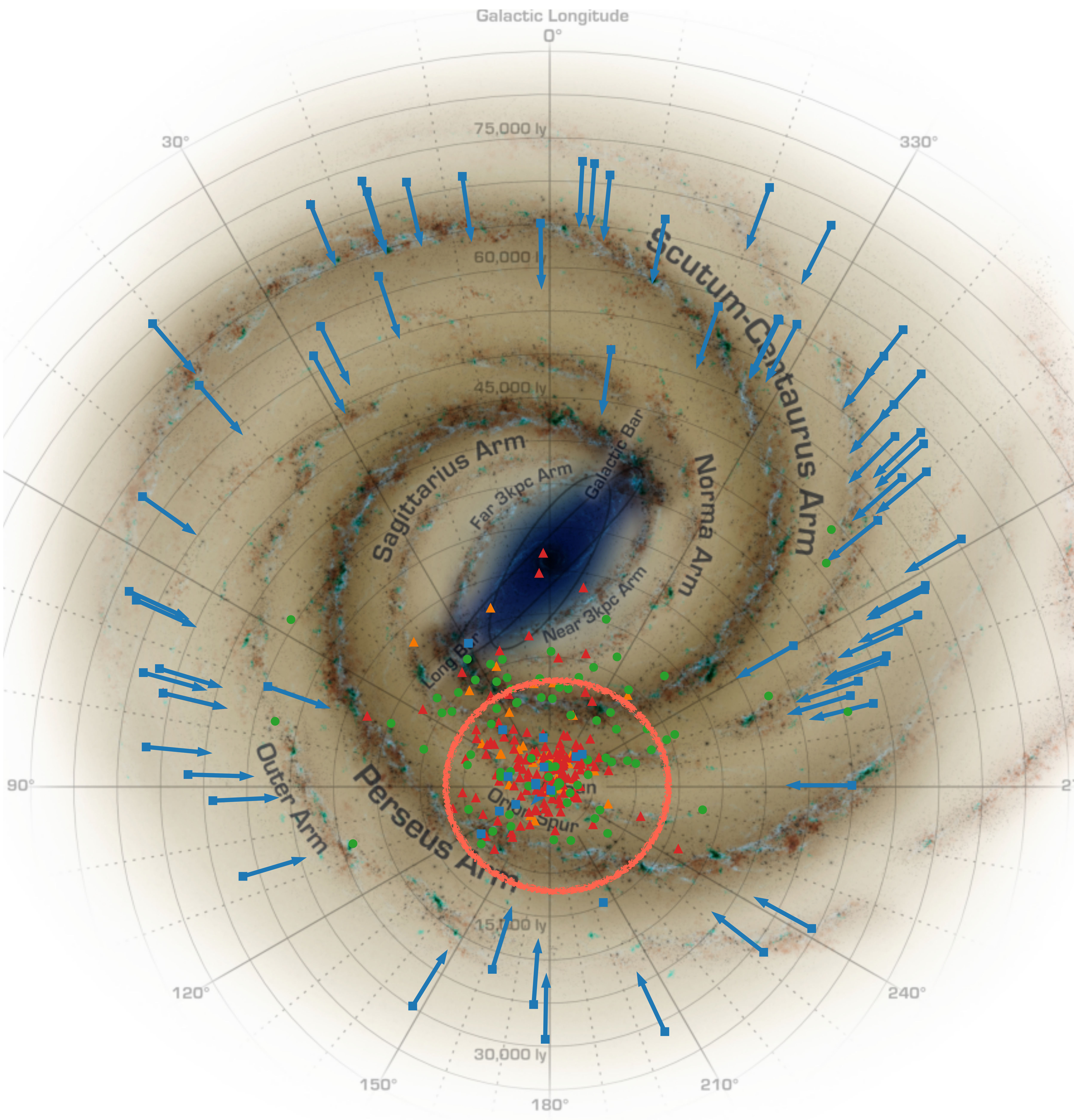
Category	Count	Sub-count
Known rotation-powered pulsars (RPPs)[a]	3436	
with measured $\dot{E} > 3 \times 10^{33}$ erg s^{-1}		762
Millisecond pulsars (MSPs, $P < 30$ ms)	681	
with measured $\dot{E} > 3 \times 10^{33}$ erg s^{-1}		250
Field MSPs[b]		427
MSPs in globular clusters[c]		254
Gamma-ray pulsars in this catalog[d]	**294**	
Spectral fits (with free b parameter)[f]		255 (116)
Profile fits in $\geq$ 1, 2, 6 energy bands		236, 167, 28
Young gamma-ray pulsars	150	
Radio-quiet[e]		70
Gamma-ray MSPs	144	
Isolated, Binary		32, 112
Discovered in LAT blind searches		10
Radio-quiet		6
Black Widows, Redbacks:		32, 13
Radio MSPs discovered in LAT sources	119	
with gamma-ray pulsations		78
waiting for ephemeris phase-connection[d]		33

Smith+2023, 3PC

Fermi pulsars

as of 2024

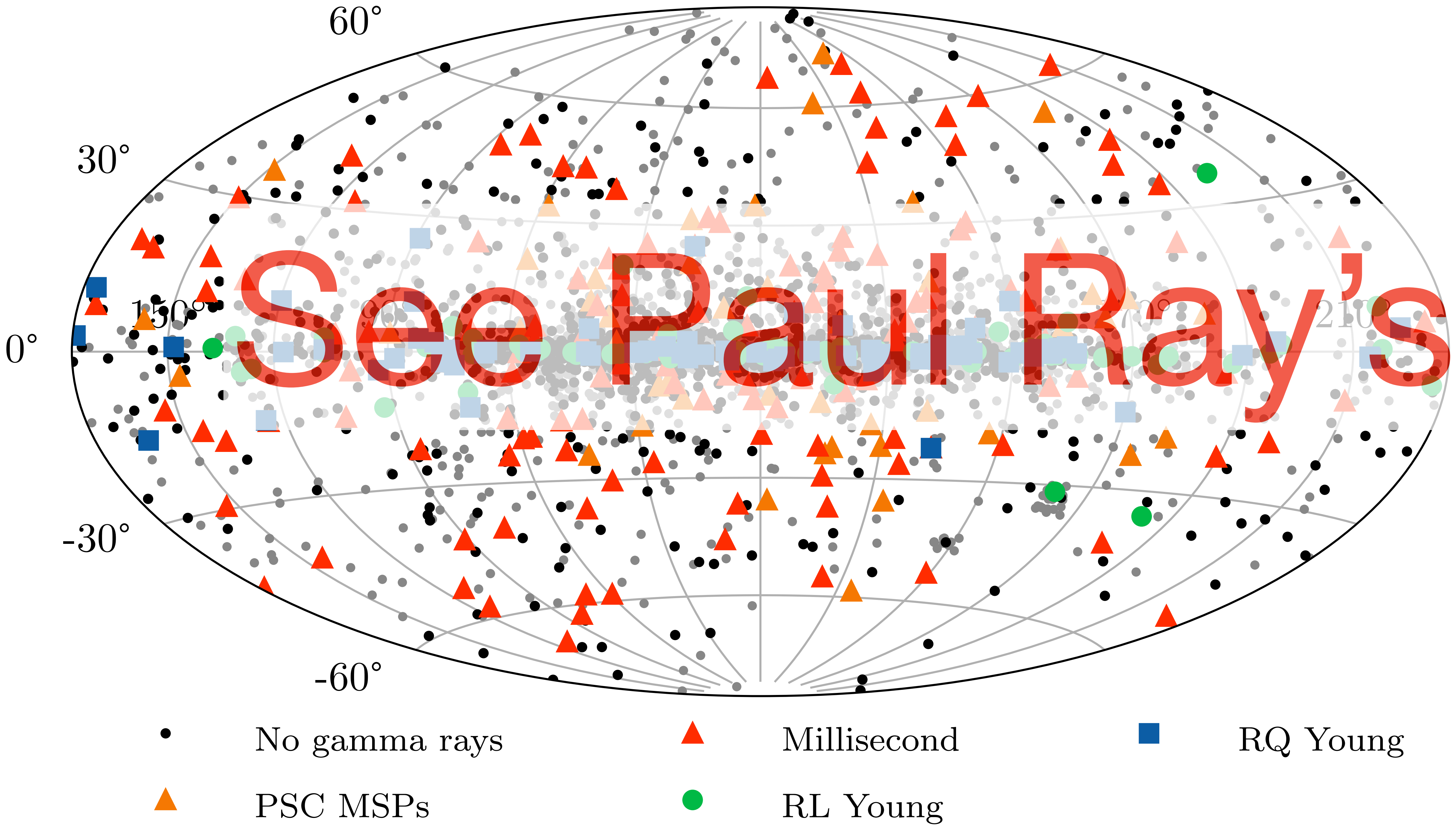




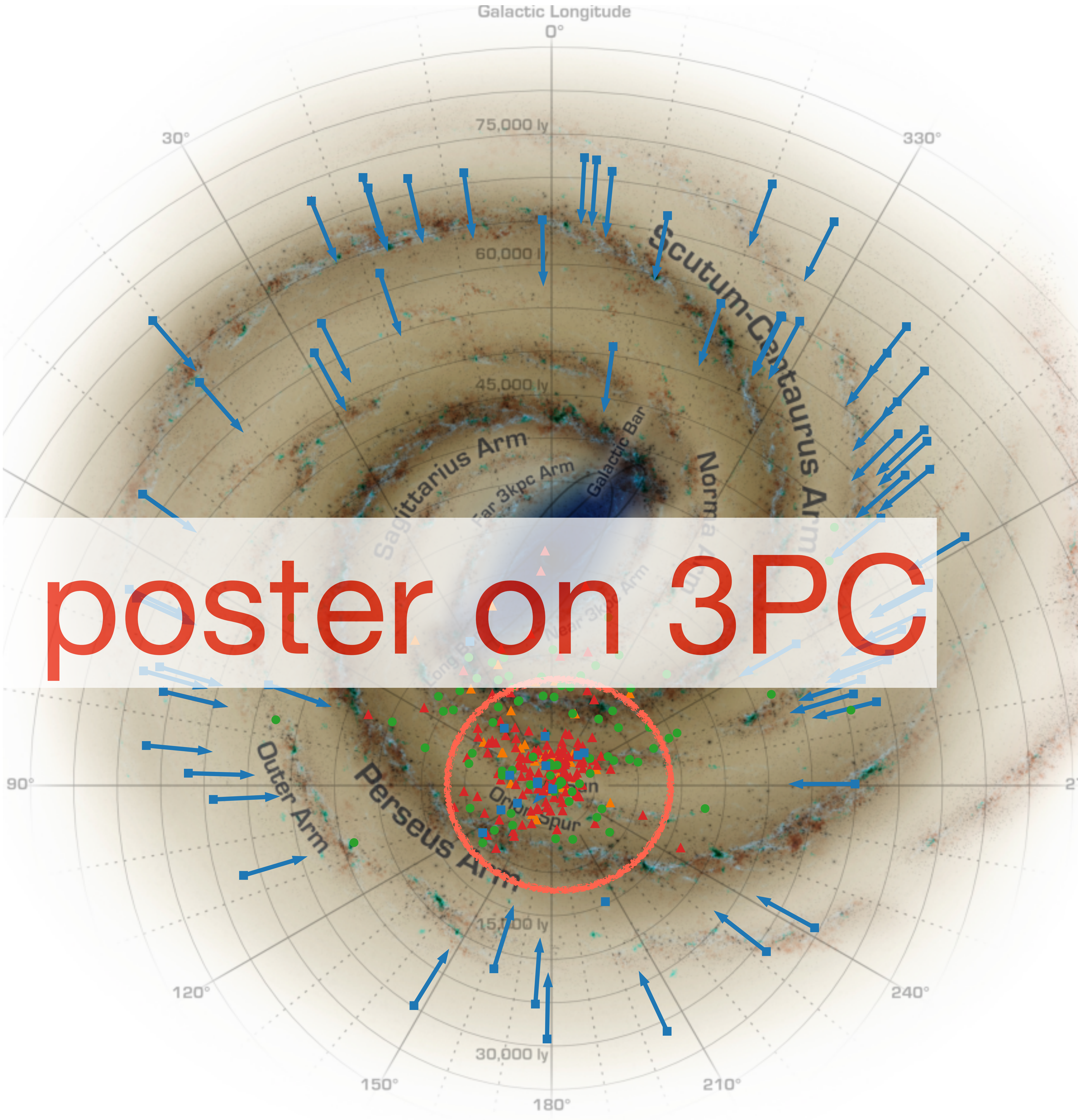
Smith+2023, 3PC

Fermi pulsars

as of 2024



See Paul Ray's poster on 3PC



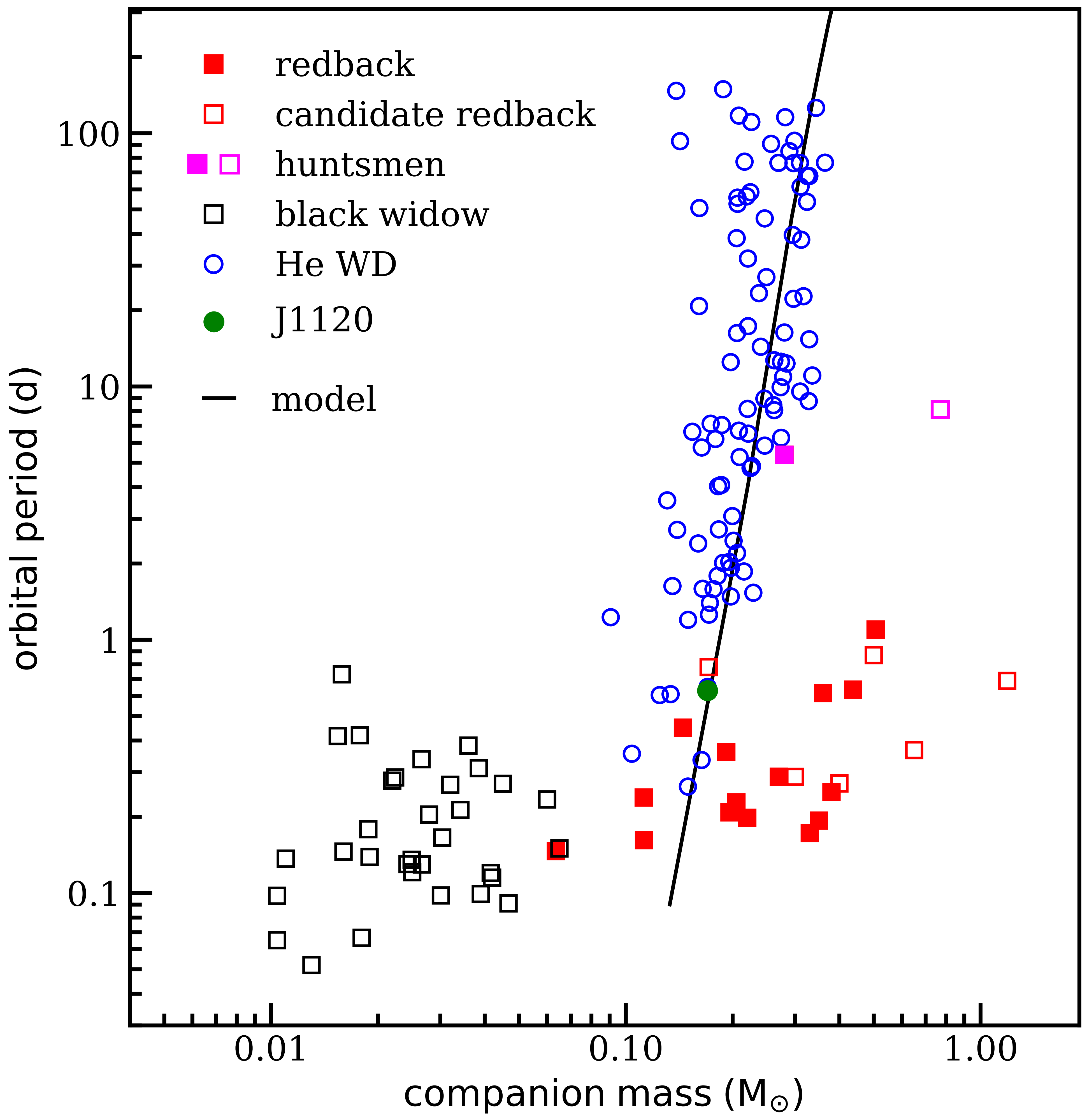
Smith+2023, 3PC

"Spider" millisecond pulsar binaries

Black Widows and Redbacks - "devour" companion

Swihart et al. 2022

- Non-accreting systems, pulsar is active
- Companion is tidally-locked, has a hot "day side"
- Orbital periods <1 day, some as short as 90 minutes
- Black widows: low mass companion 0.01-0.1 M_{sun}, often degenerate/ablated
- Redbacks: higher mass companions of 0.1-1 M_{sun}
  (Mallory Roberts+2011/2013)
- Intrabinary shock between pulsar and companion leads to particle acceleration and orbitally-modulated emission



$$\dot{E}_{\rm MSP} \sim 10^{34} - 10^{35} \text{ erg s}^{-1}$$

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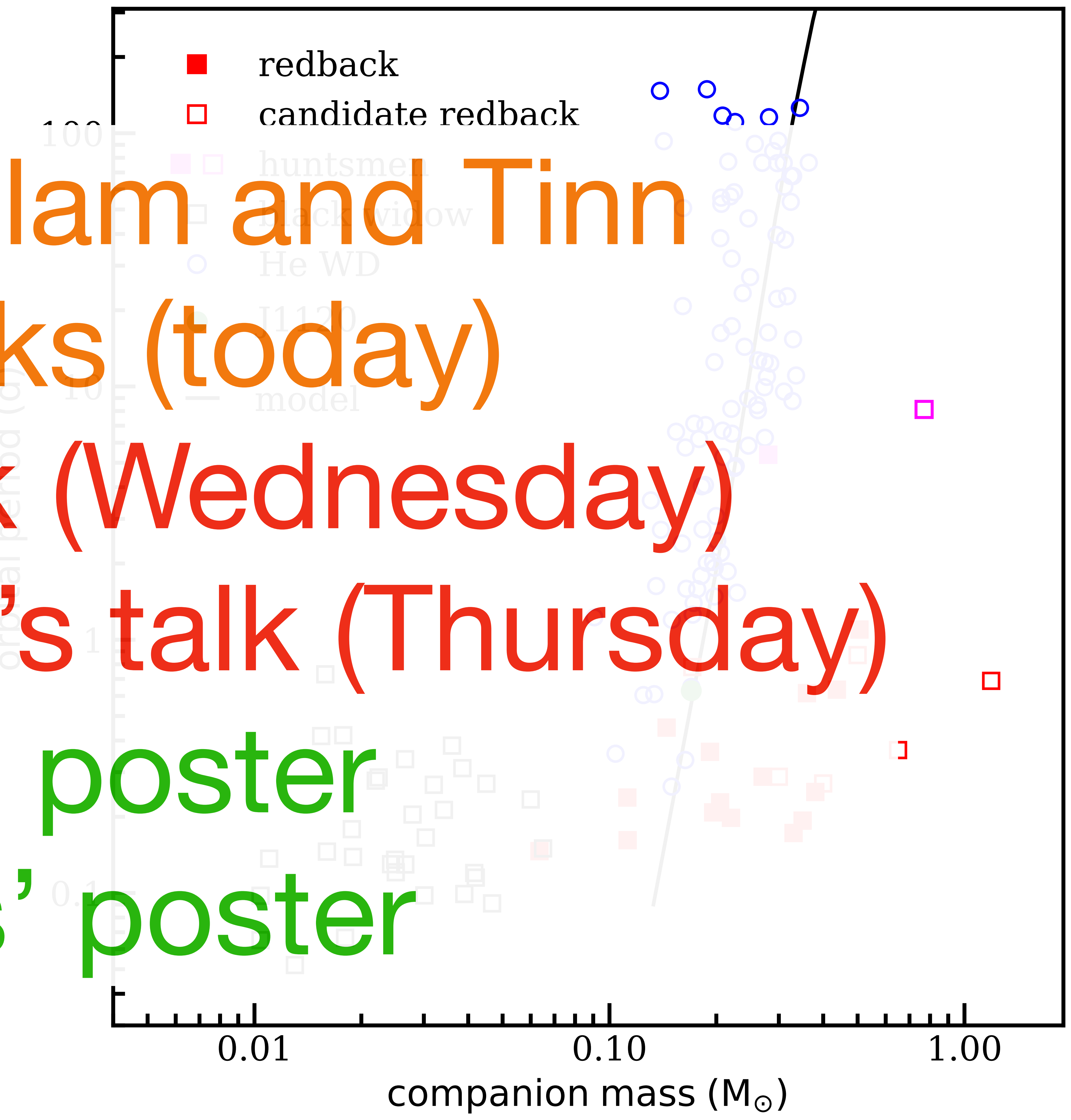


- Non-accreting systems, pulsar is active

See/remember Nazma Islam and Tinn Thongmeearkom's talks (today)

See Marco Turchetta's talk (Wednesday)

See Valentina Richard Romei's talk (Thursday)

See Robin Corbet's poster

See Mallory Roberts' poster

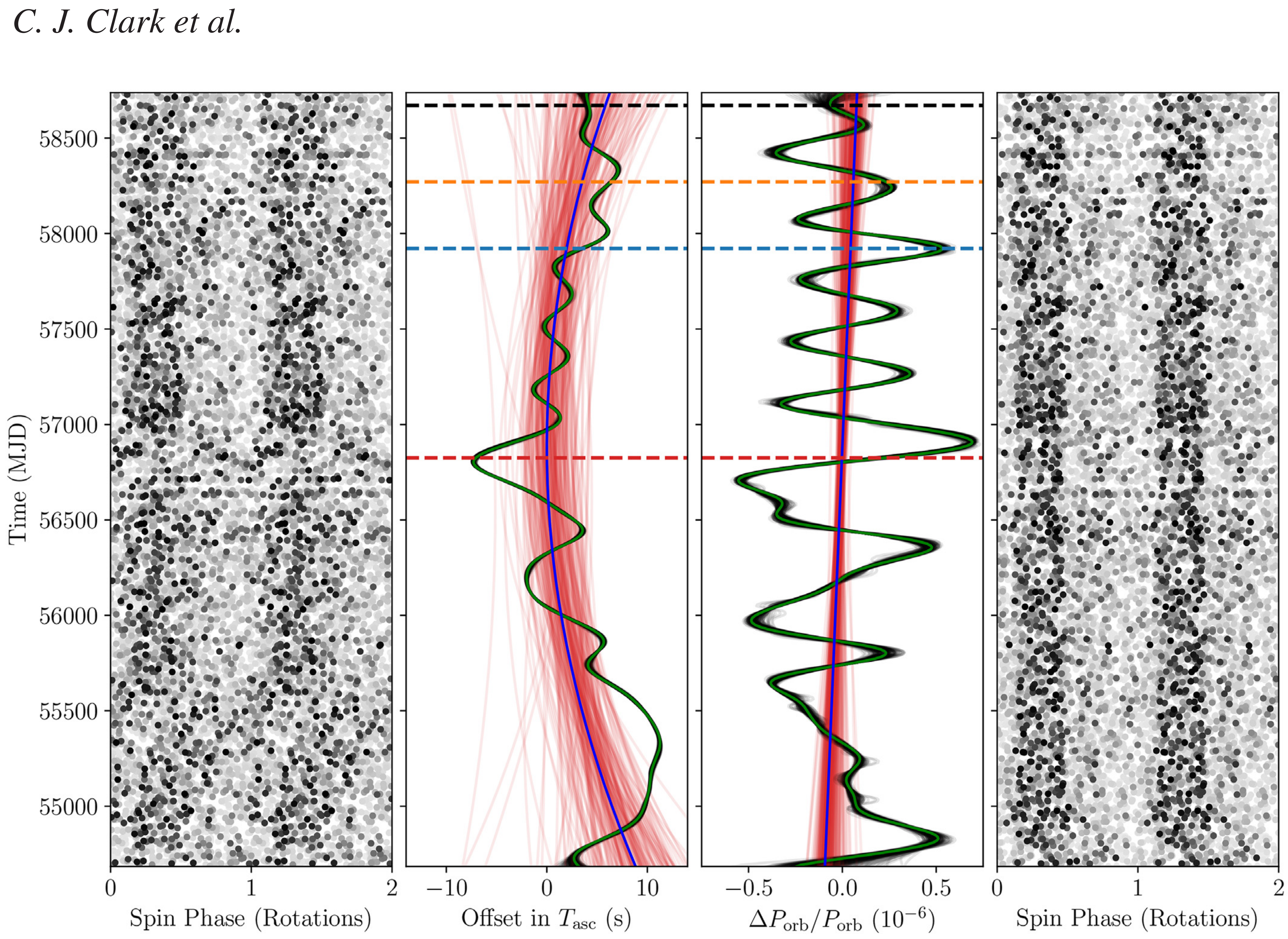
- Intrabinary shock between pulsar and companion leads to particle acceleration and orbitally-modulated emission

$$\dot{E}_{\rm MSP} \sim 10^{34} - 10^{35}\ {\rm erg\ s^{-1}}$$

Low mass stars interiors and convection

via gamma-ray pulsar timing over long timescales

(tidally locked with the MSP, rotating very fast in their short orbital period)



Gamma-ray eclipses of millisecond pulsars

Clark et al. 2023

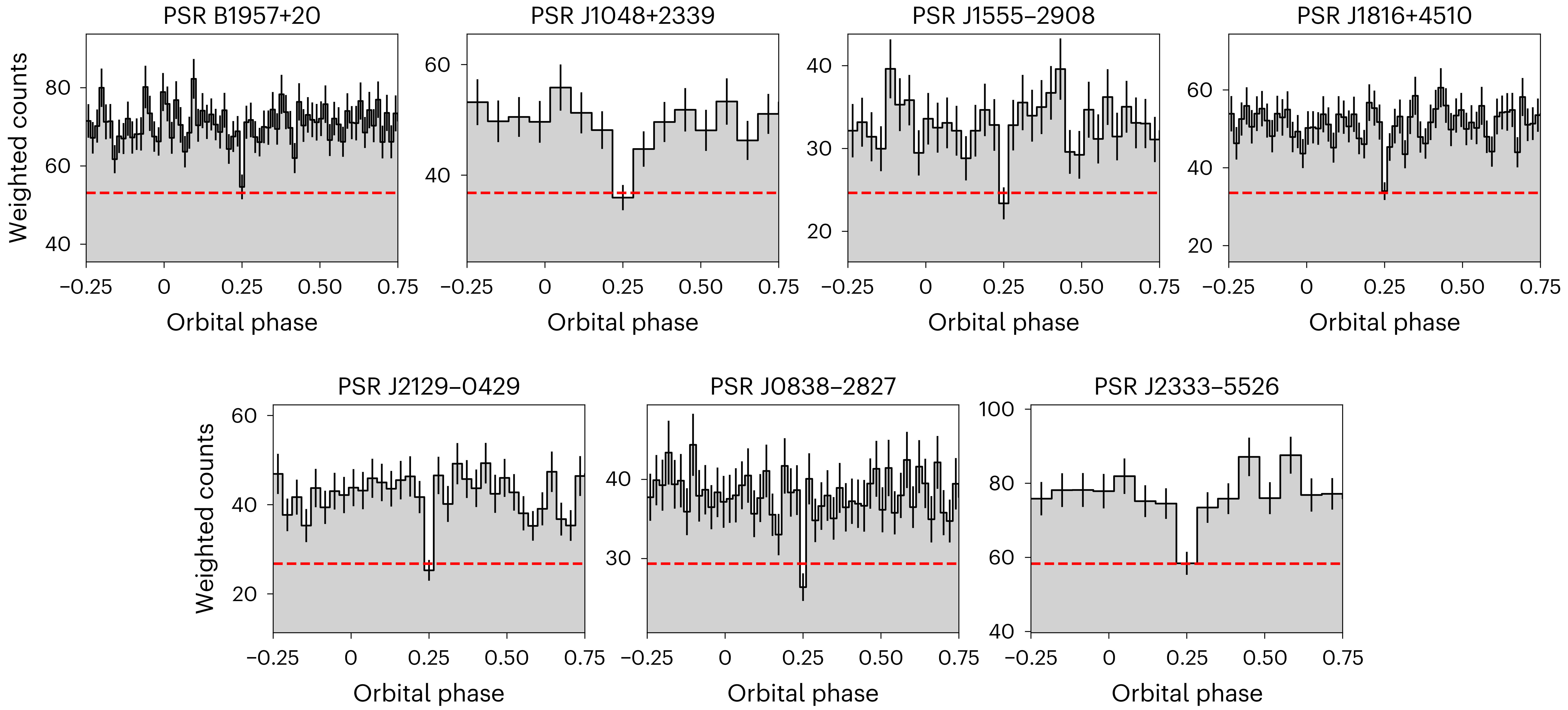


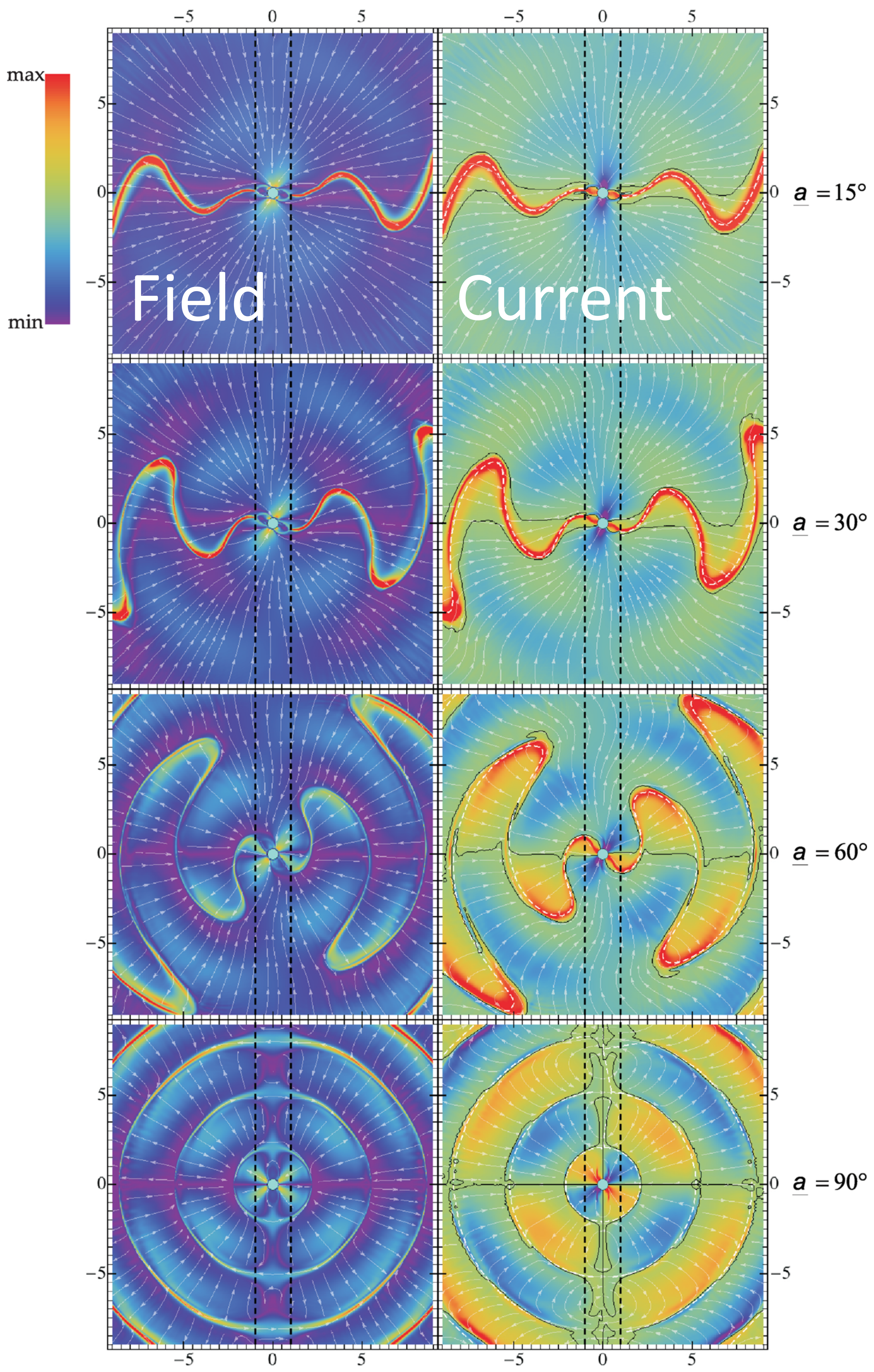
Fig. 1 | Gamma-ray orbital light curves of seven eclipsing spider pulsars. The red dashed lines show the estimated background level. Phase 0 corresponds to the pulsar's ascending node. The phase of the pulsar's superior conjunction, where eclipses would be expected to occur, has been placed at the centre of a phase bin, and is shown at the centre of the plots for emphasis. Bin widths were chosen to be close to the best-fitting eclipse duration. Bin heights show the sum of the photon weights in each orbital phase bin, and error bars show the corresponding 1σ Poisson uncertainties.

Why are “Spider” Binaries Interesting?

- We know pulsar winds are good accelerators and make TeV emission
- Clean systems: circular orbits, many orbits, pulsar well timed, companion radial velocities ==> inclination and component masses constrained
- Fermi gamma-ray pulsations — constrains pulsar magnetic obliquity and also binary inclination (if spin and orbital axes aligned)
- Many of them (~10 now with X-ray obs, ~60 in the radio) and growing
- Study shock acceleration and pulsar winds in oblique shocks
- Doppler boosting along shock necessary to match X-ray LCs. This constrains the character of the pulsar termination shock
- Target photons inverse Compton in the TeV
- Flares of the companion — u~1 to u >> 1 erg/cm^3 — well suited flaring timescales for IACTs
- Double humped SED should peak in the MeV and TeV — some (all?) could be “gamma-ray binaries”
- Promising targets for CTA and MeV concepts

Striped Pulsar Winds

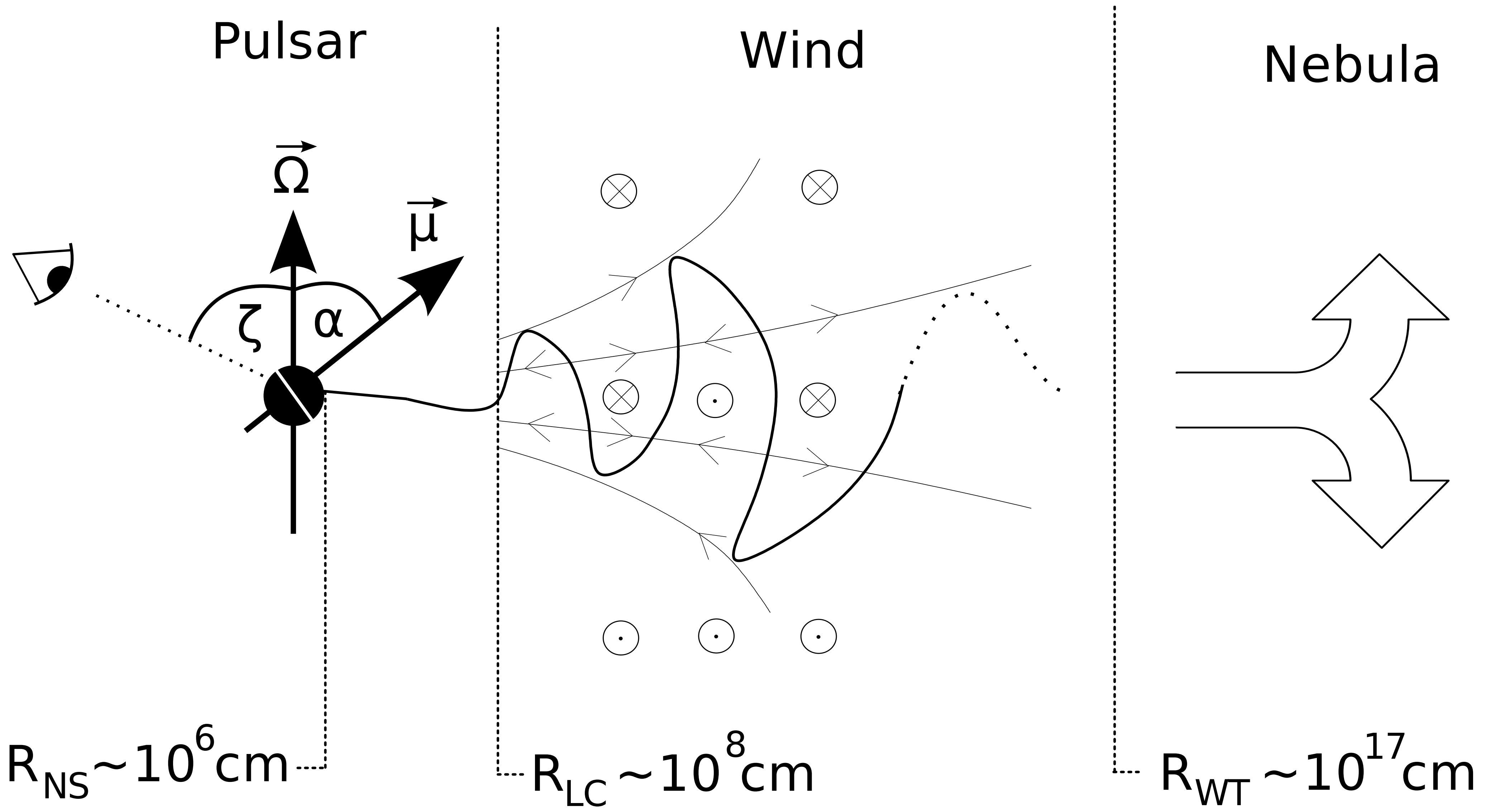
Kalapatharakos+ 2012



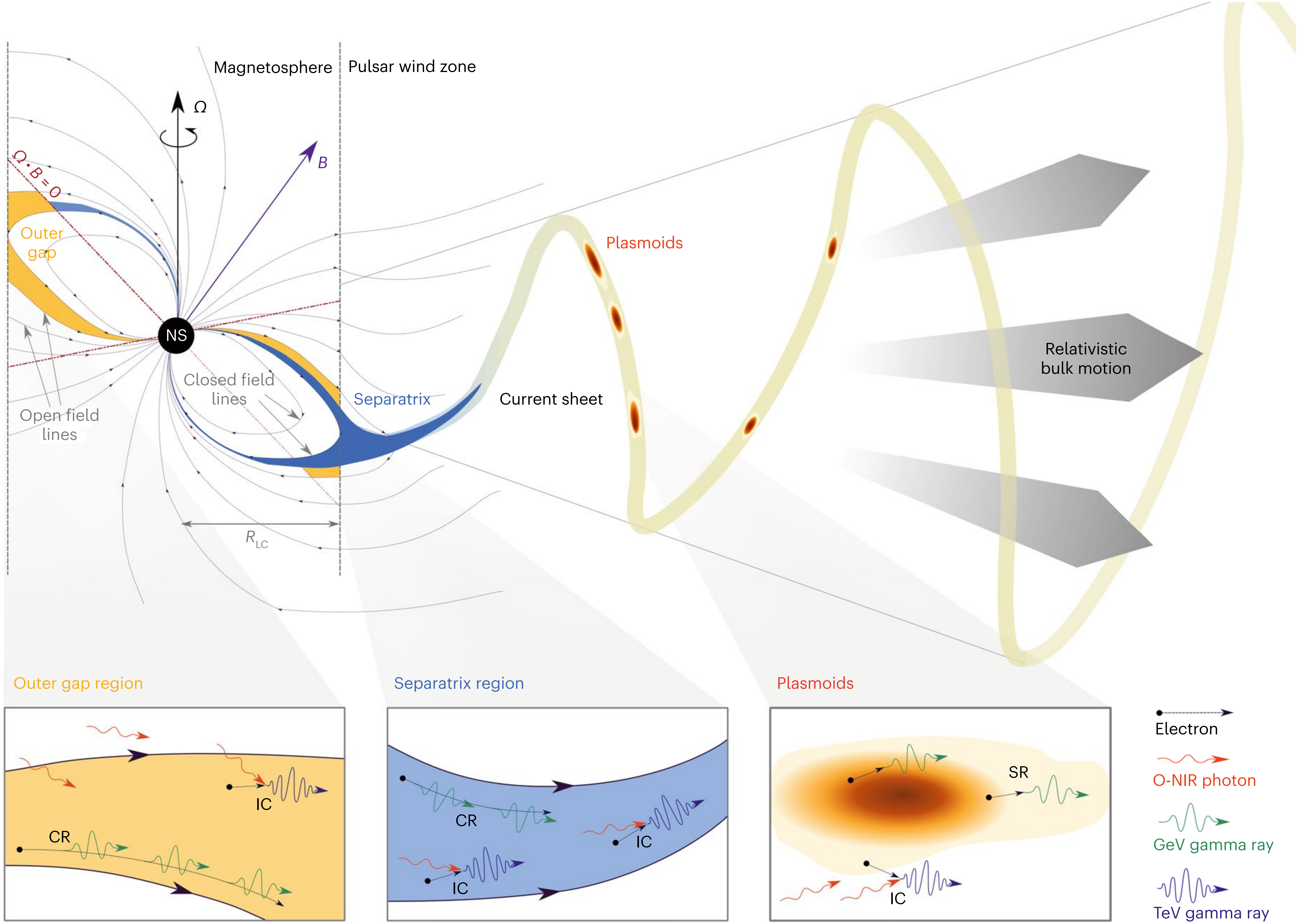
$$\gamma_{\rm open} m_e c^2 \sim \; e\Phi_{\rm open} \sim eB_{\rm LC}R_{\rm LC} \sim 10^{16}\, B_{12}R_6^3P_{33\,{\rm ms}}^{-2} \quad {\rm eV}$$
$$\sim 10^{15}\, B_9R_6^3P_{3\,{\rm ms}}^{-2} \quad {\rm eV}$$
$$\sim 1 - 10\ {\rm PeV}$$

(The maximum irrespective of synchrotron burn-off, or the Hillas criterion which may be more limiting)

Actual voltage realized in the open zone perhaps limited by pair multiplicity, which varies with latitude to the last open field line



Buhler & Blandford 2014



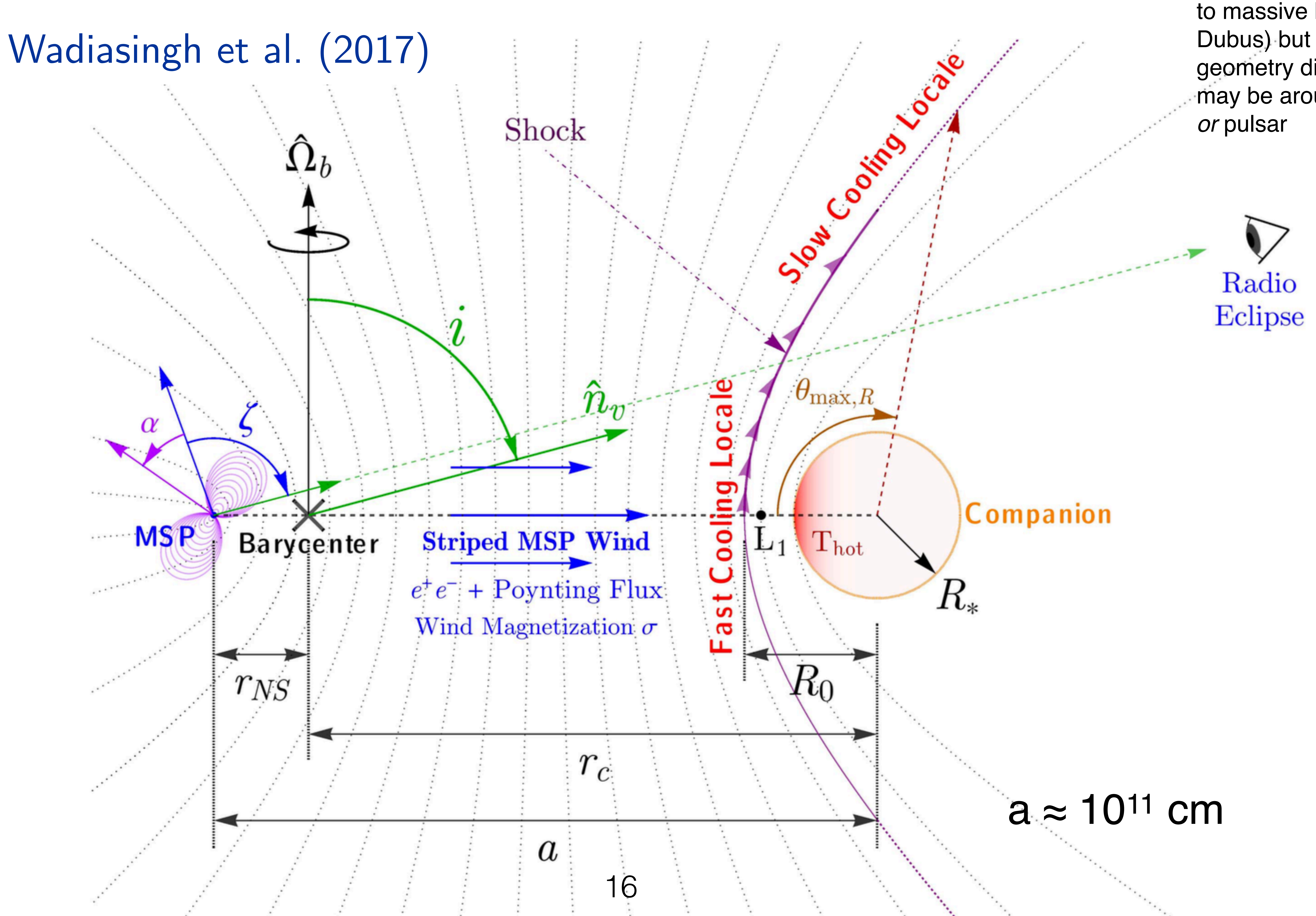
Vela Pulsar

HESS collaboration 2023

A. Djannati-Ataï, E. de Ona Wilhelmi, B. Rudak, C. Venter.

Schematic Geometry (Pulsar State)

Physics somewhat similar to massive binaries (cf. Dubus) but scales and geometry differ — shock may be around companion *or* pulsar



$a \approx 10^{11}$ cm

Characteristic Scales for Shock Models

$$a \sim 10^{11}\ \mathrm{cm} \qquad R_* \sim 0.3a \qquad r_{\mathrm{LC}} \sim 10^{7}\ \mathrm{cm} \sim 10^{-4}a$$

$$T_{\mathrm{comp}} \sim 5000 - 8000\ \mathrm{K}$$

$$B_{\mathrm{w}} \approx \left(\frac{3\dot{E}_{\mathrm{SD}}}{2c}\right)^{1/2}\frac{1}{r_{\mathrm{s}}} = 22\left(\frac{\dot{E}_{\mathrm{SD}}}{10^{35}\ \mathrm{erg\ s^{-1}}}\right)^{1/2}\left(\frac{10^{11}\ \mathrm{cm}}{r_{\mathrm{s}}}\right)\ \mathrm{G} \qquad B_{\mathrm{s}} \gtrsim B_{\mathrm{s,min}} \approx 4.4\ \epsilon_{X,\mathrm{max}}^{1/3}\left(\frac{10^{9}\ \mathrm{cm}}{r_{\mathrm{L}}}\right)^{2/3}\ \mathrm{G}$$

$$\sigma \sim 10^{-5} - 10^{-3} \quad \text{from SED fitting}$$

$$u_B \sim \mathcal{O}(0.1 - 10)\ \mathrm{erg\ cm^{-3}}$$

$$u_{\mathrm{ph}} \sim \mathcal{O}(0.1 - 1)\ \mathrm{erg\ cm^{-3}}$$

$$E_{\mathrm{cut}} \sim 0.1 - 10\ \mathrm{erg} \rightarrow 0.1 - 10\ \mathrm{TeV\ electrons}$$

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See Christo Venter's poster

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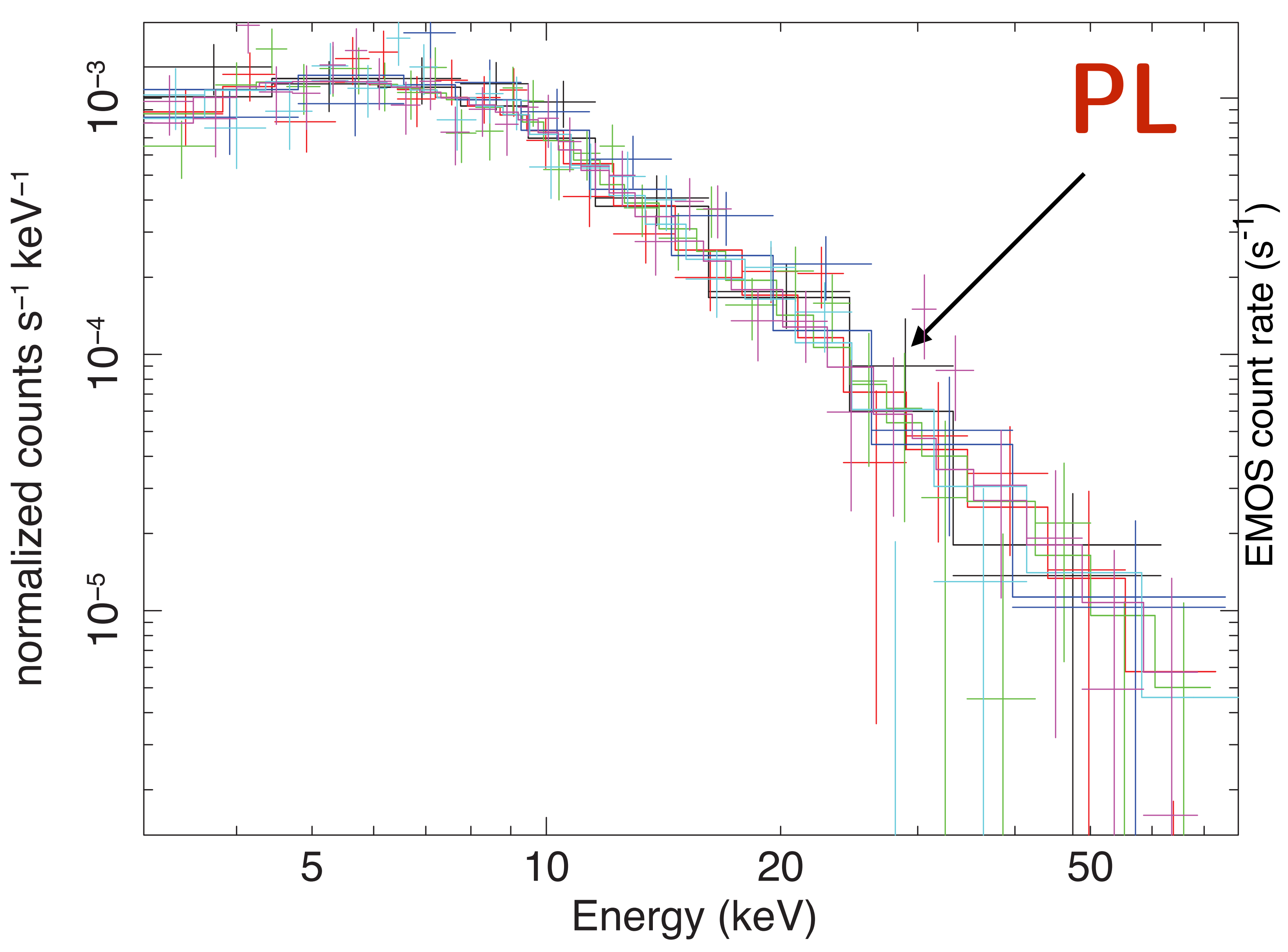
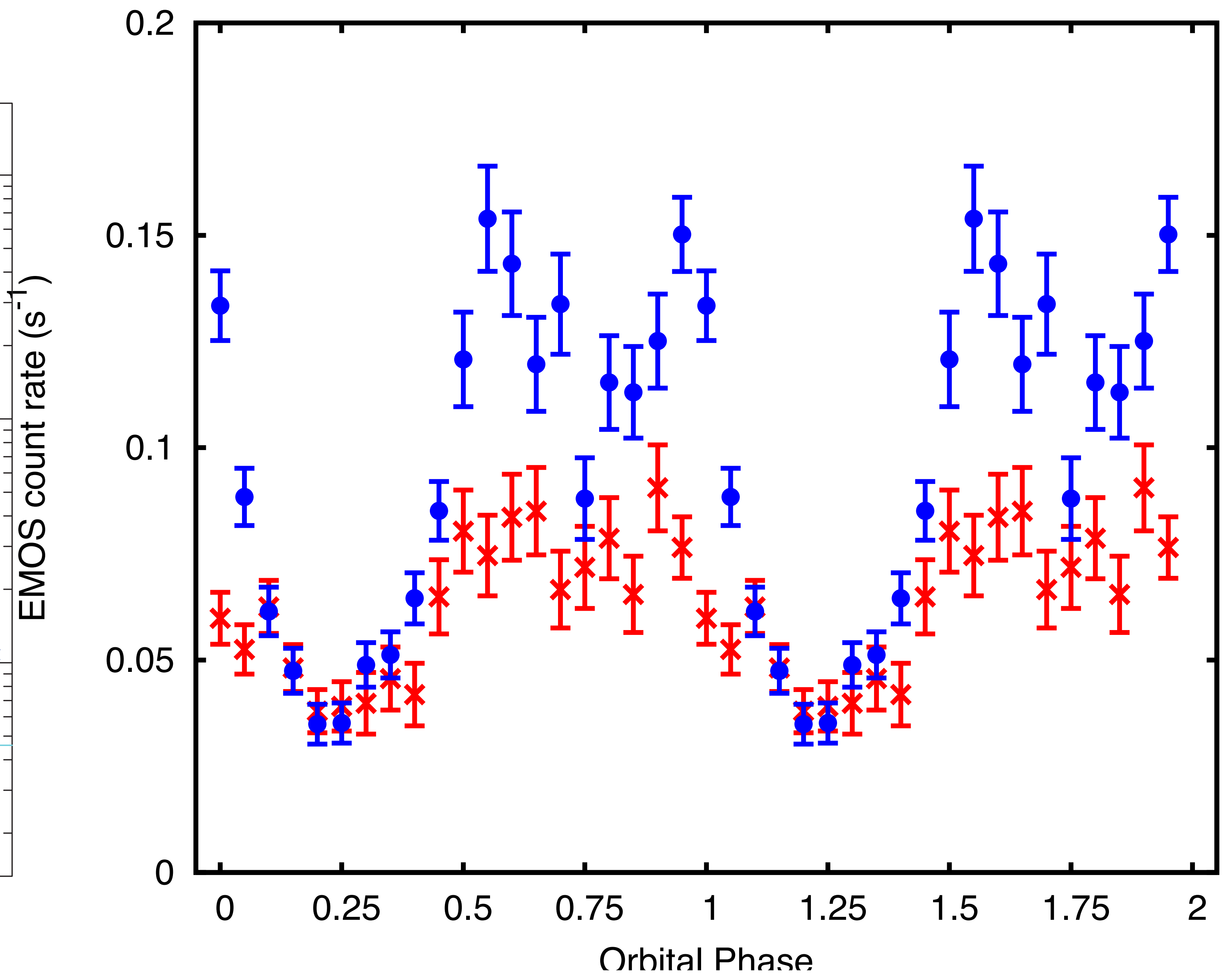
X-ray Observations

- Spectral photon indices are typically Γ ≈ 1-1.5 implying very hard underlying electron power-law distributions and efficient acceleration
- Up to 80 keV NuSTAR PL implies downstream shocked B ≳ 1 G by containment (Hillas criterion) arguments

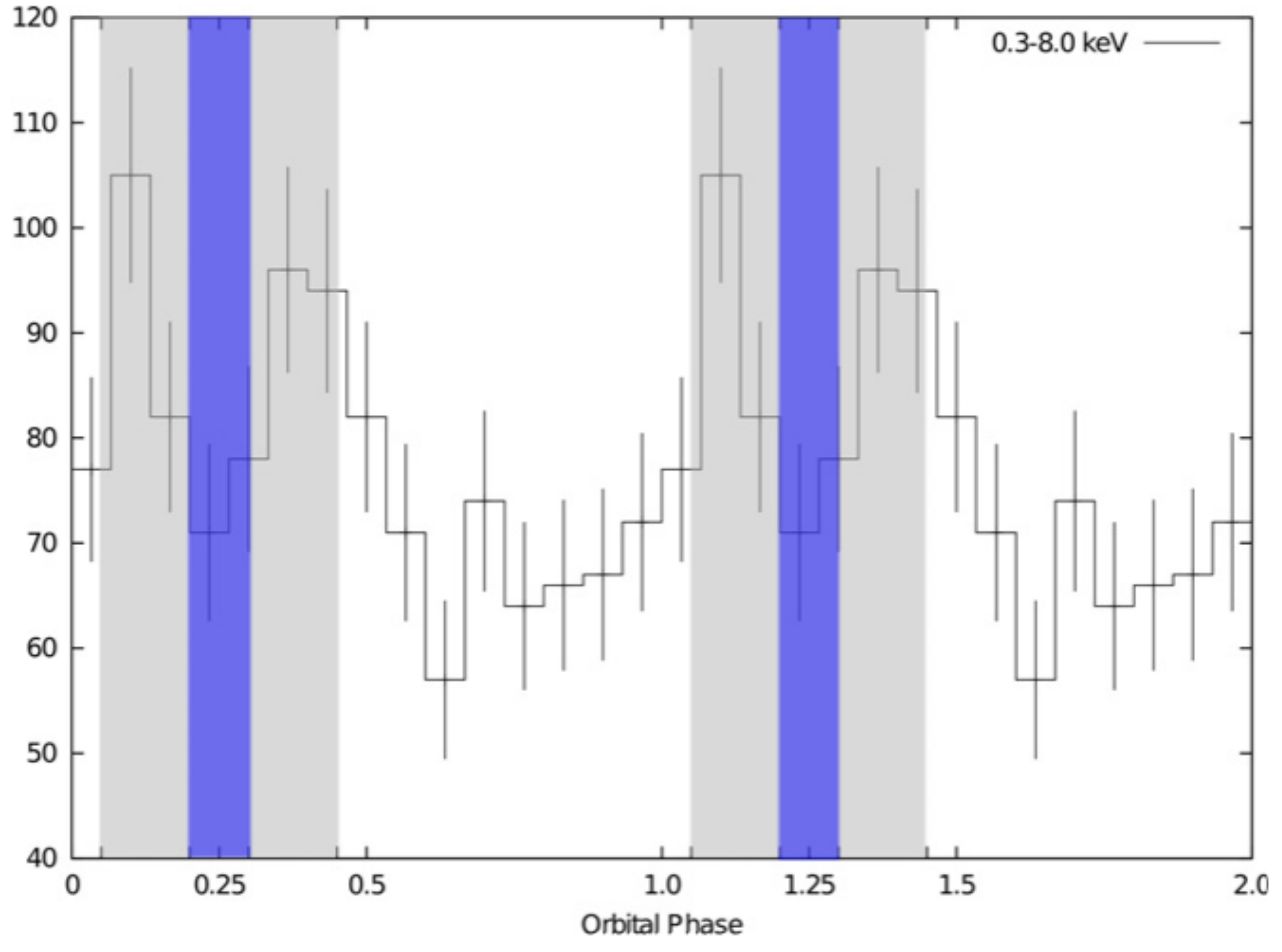
J1023+0038 (rotation-powered state)
Tendulkar et al. (2014)



J1227-4853, de Martino et al. (2015)

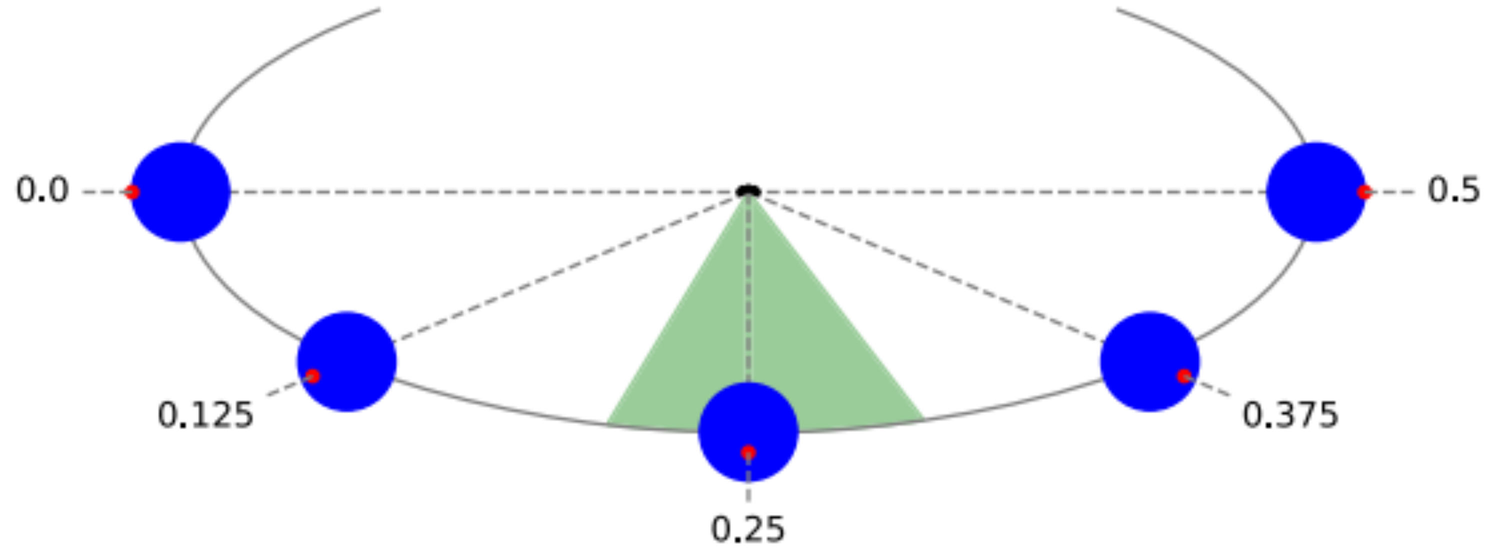


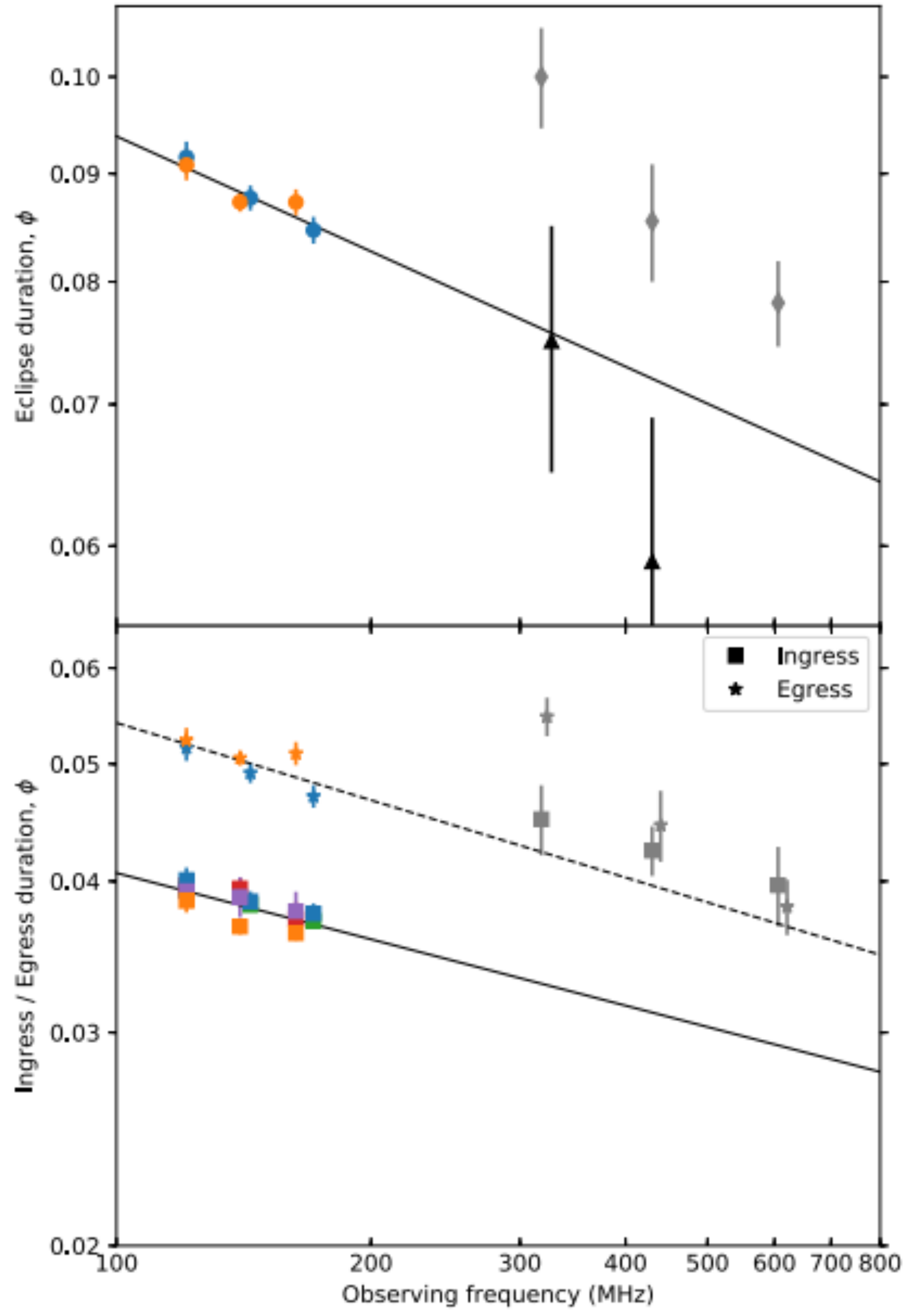
B1957+20, Huang et al. (2012)

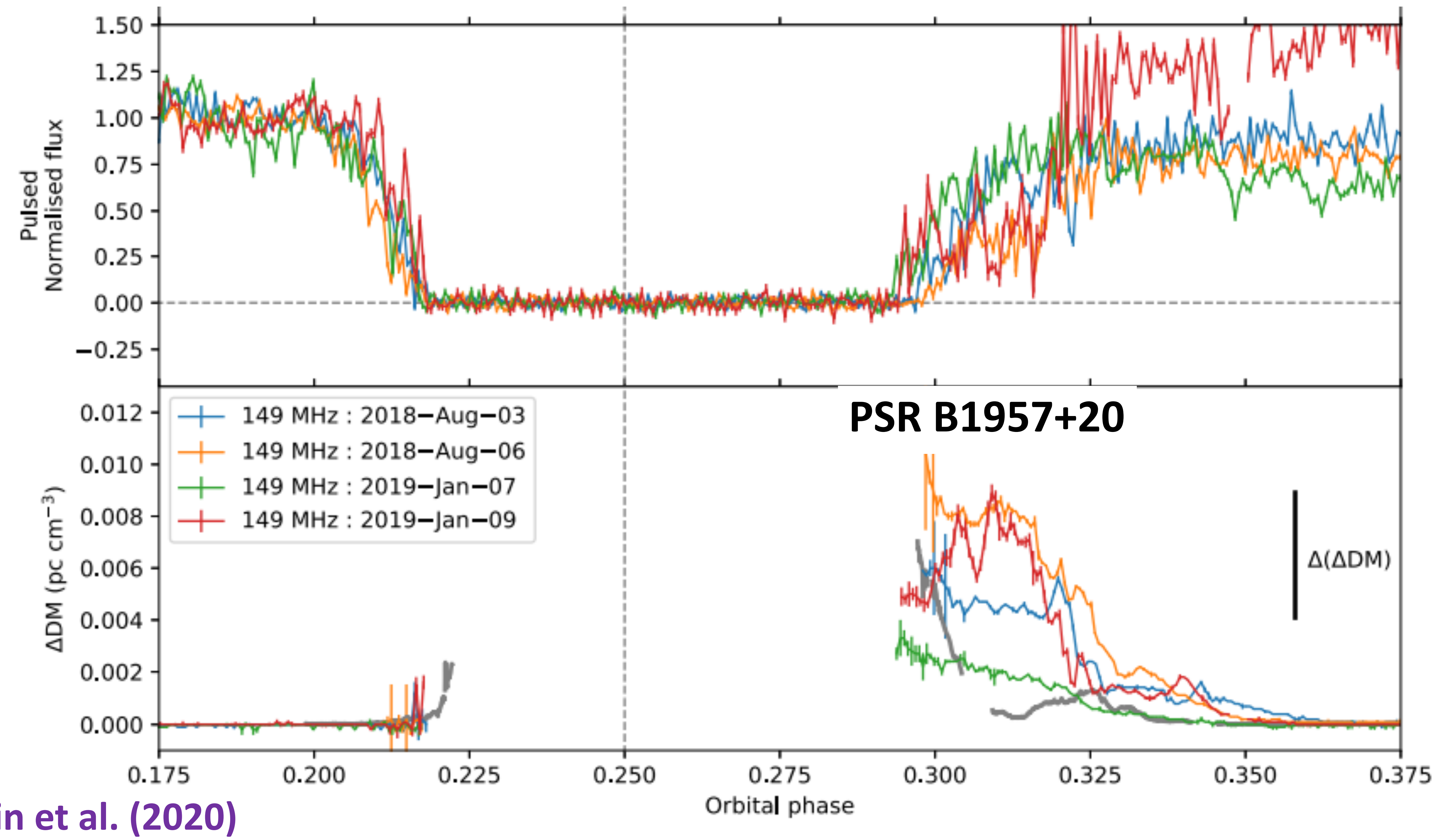


Radio Properties

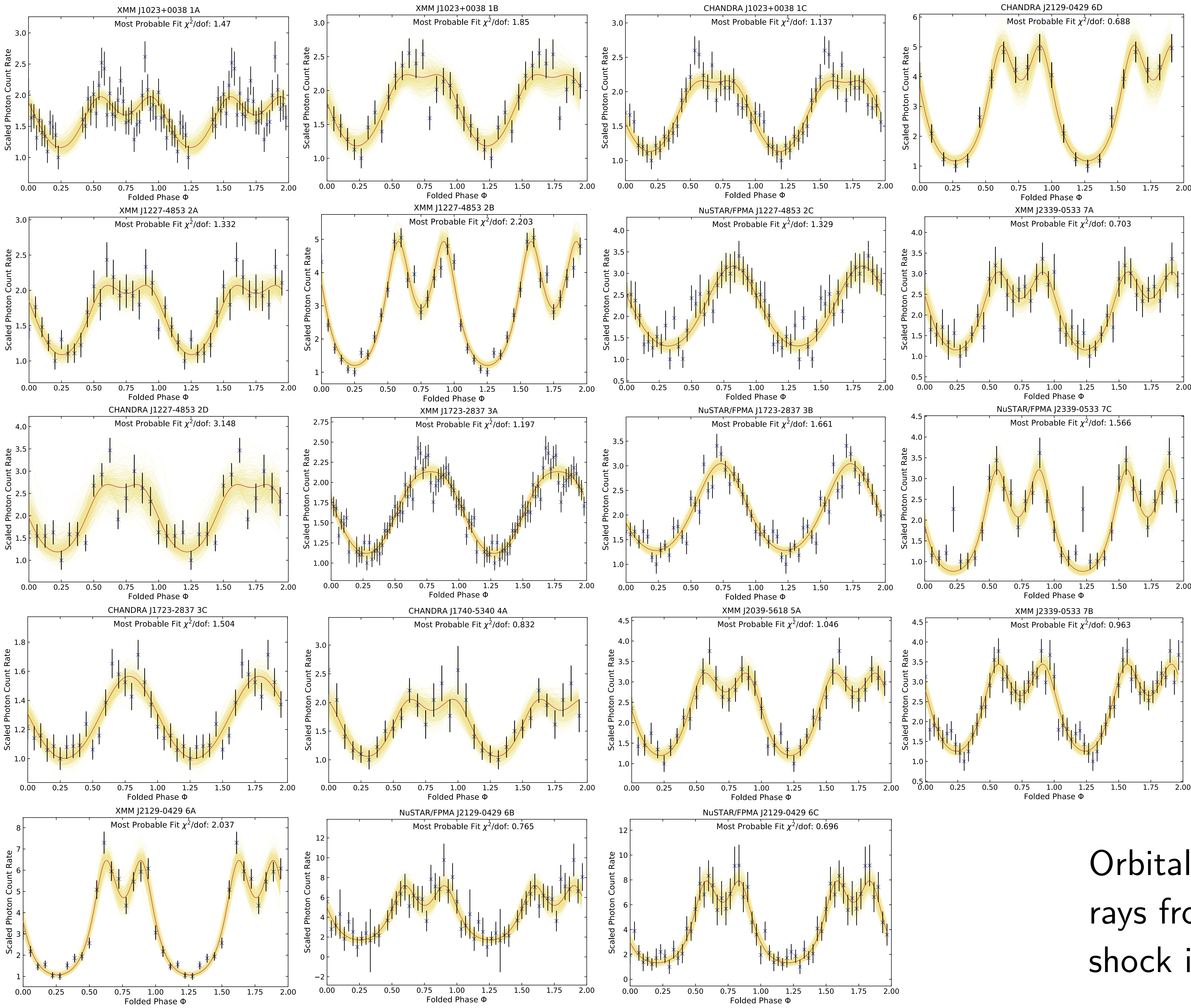
- Frequency-dependent radio **eclipses** (disappearance of radio pulses).
- Shrouding of MSP pulsed radio emission by intrabinary material.
- **H**igher frequency observations probe denser regions closer to the shock.





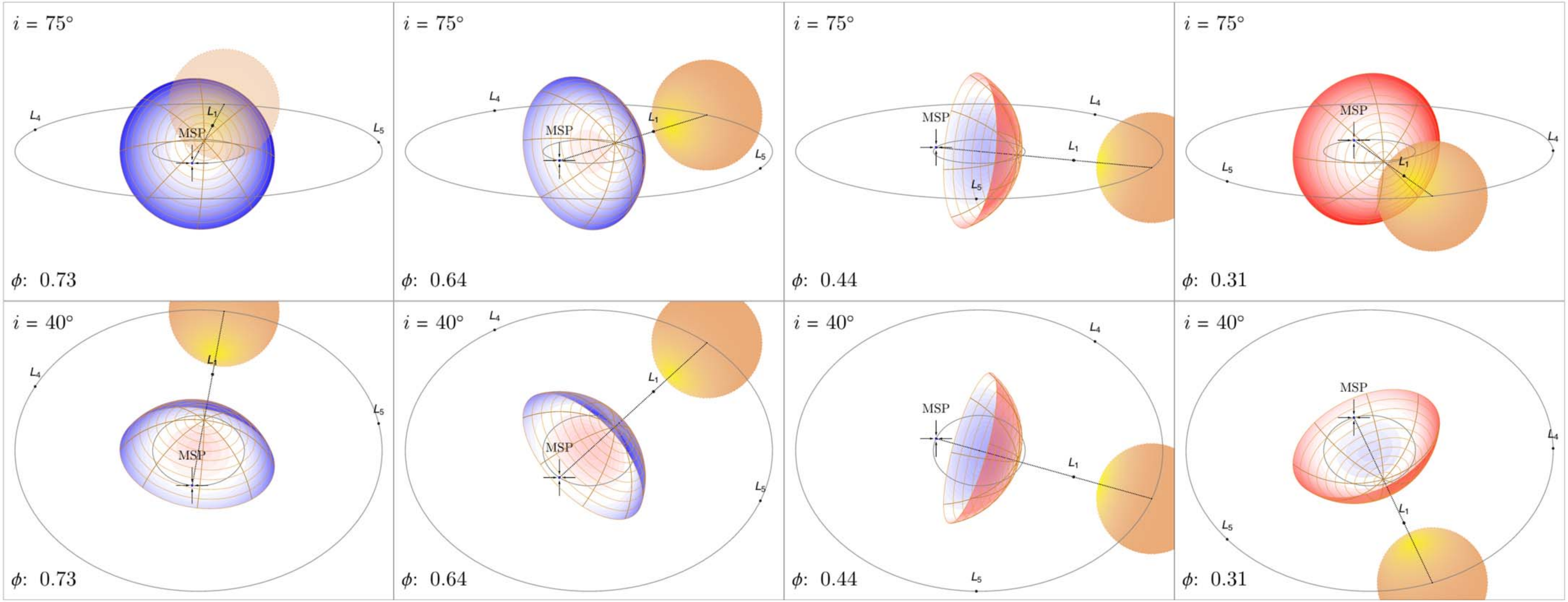


Polzin et al. (2020)



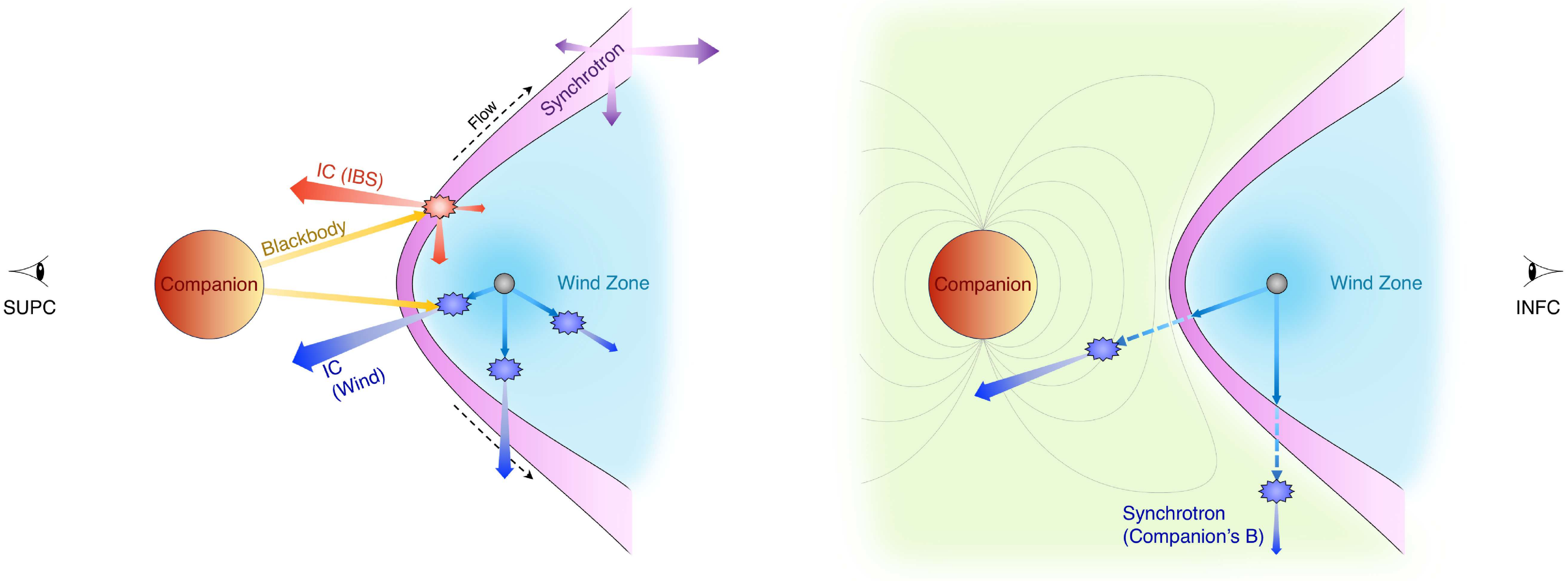
Orbital Modulation of X-rays from the intrabinary shock in redbacks

Model Schematic — Doppler Boosting



Van der Merwe, Wadiasingh, Venter, Harding & Baring;
ApJ 904:91, 2020

Schematic Scenarios



Sim, An, Wadiasingh 2024

ApJ **964** 109

Schematic Scenarios

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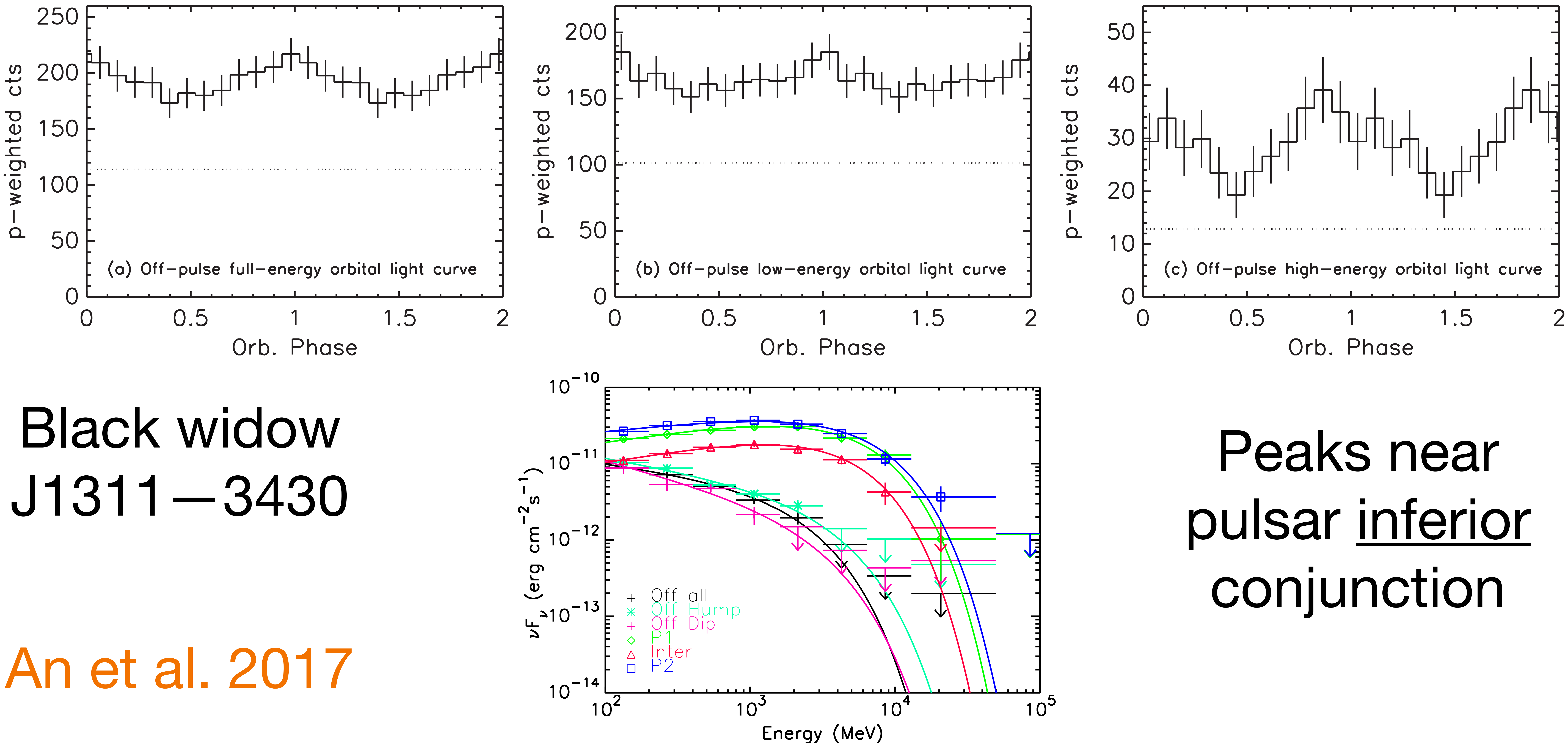
Fermi-LAT Orbital Modulation

Seen in a small subset of spiders



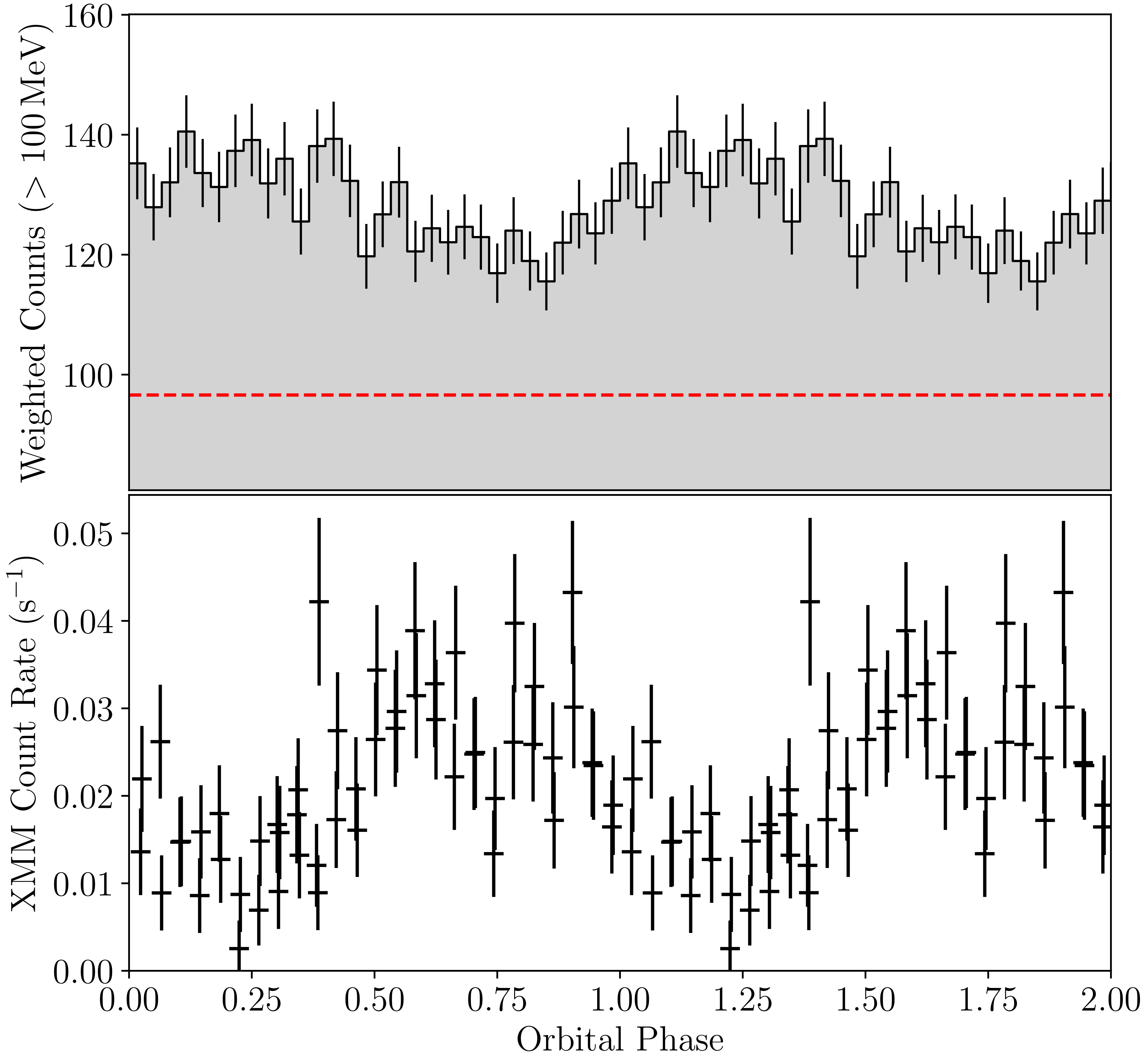
Black widow J1311−3430

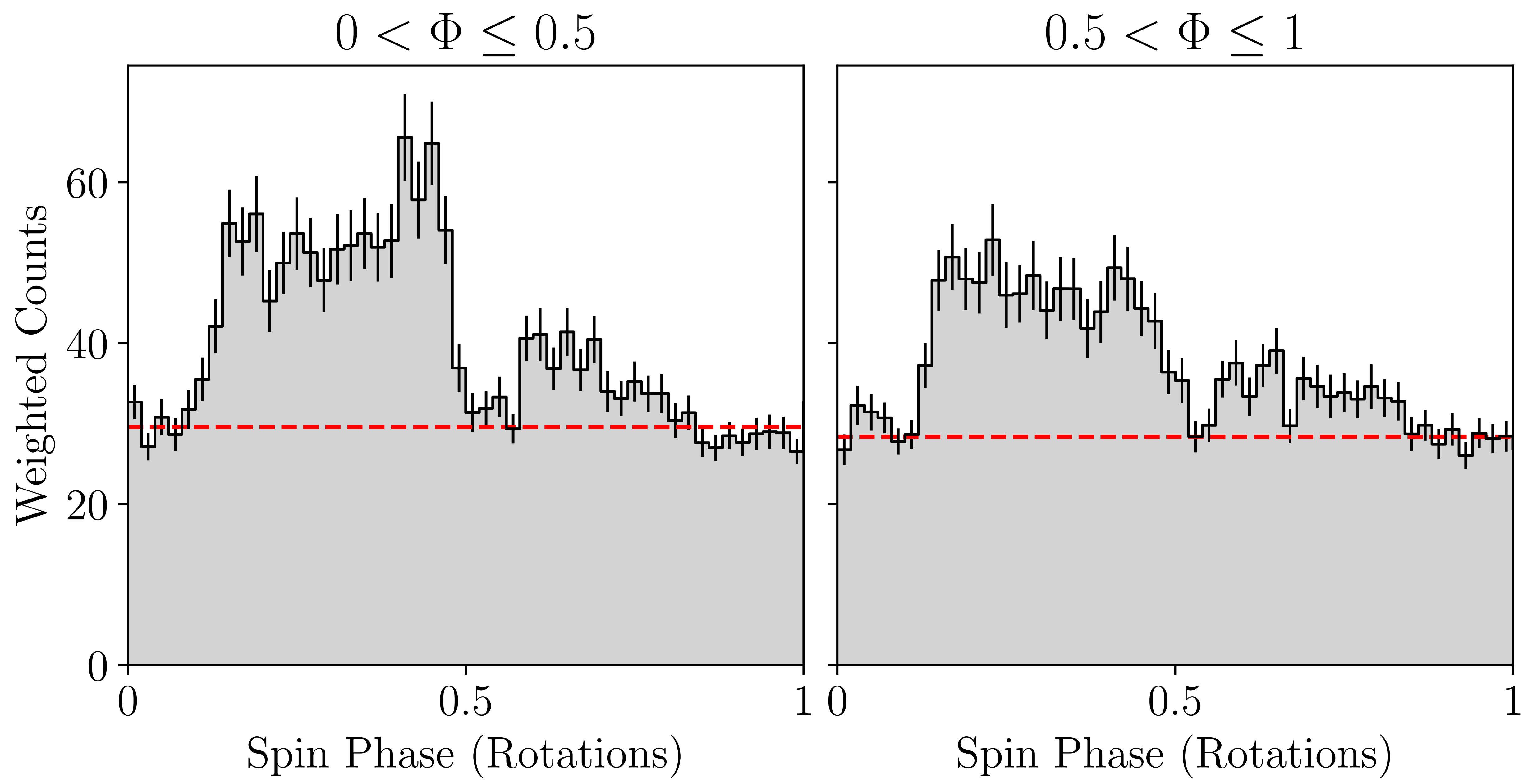
An et al. 2017

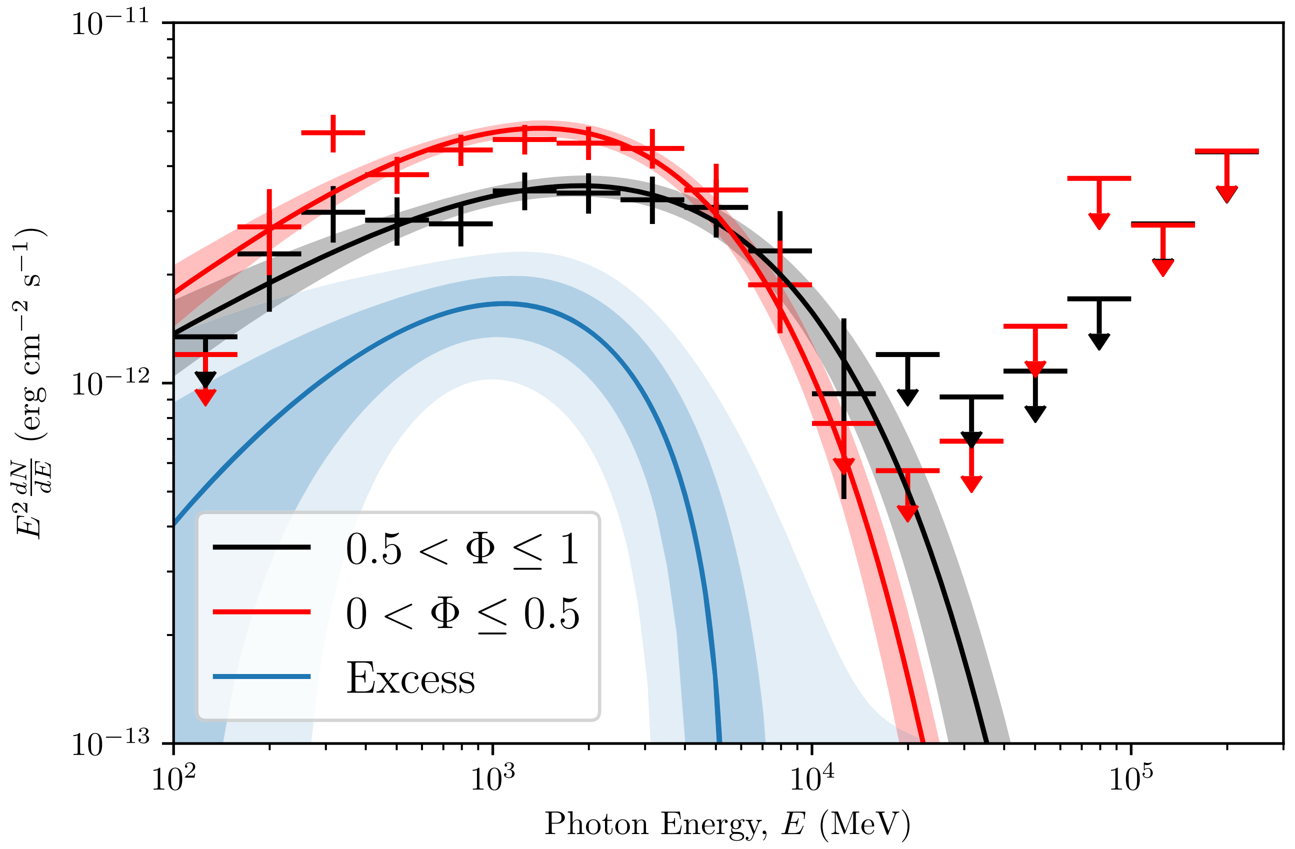
Peaks near pulsar <u>inferior</u> conjunction

Fermi-LAT Orbital Modulation — Pulse Enhancement

Redback J2039−5617

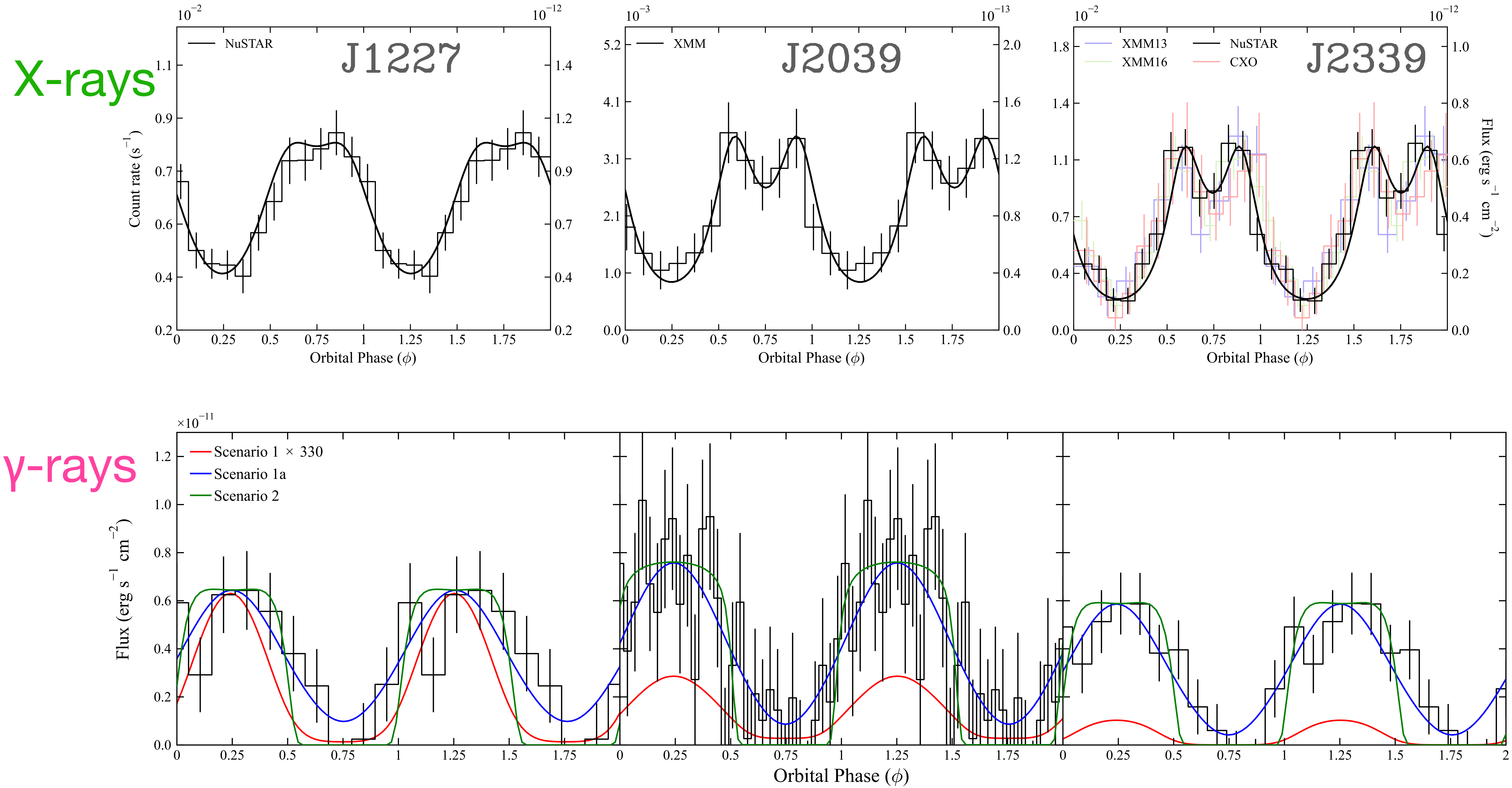






Clark et al. (2021)

Pulsed enhancement near pulsar <u>superior</u> conjunction



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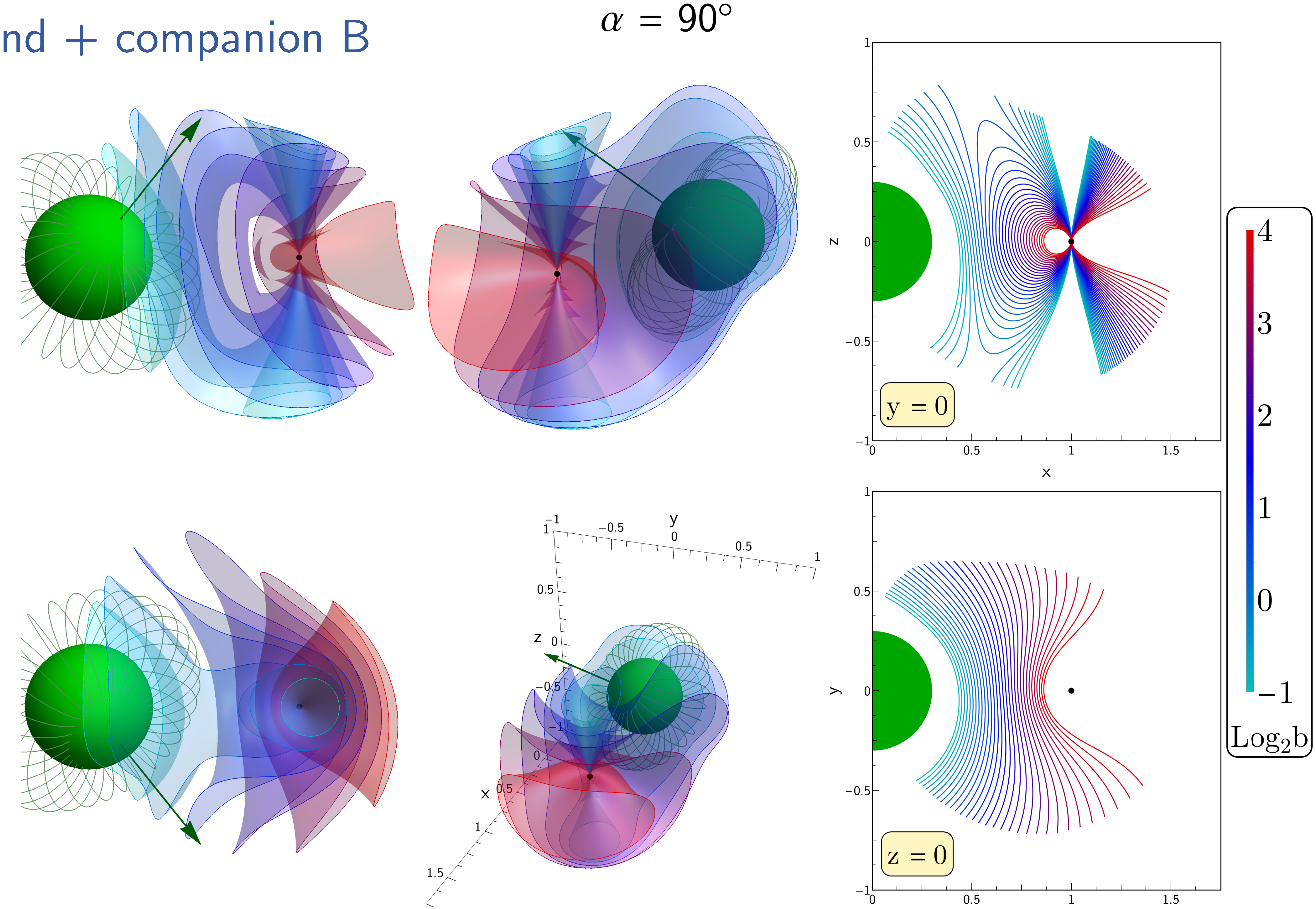
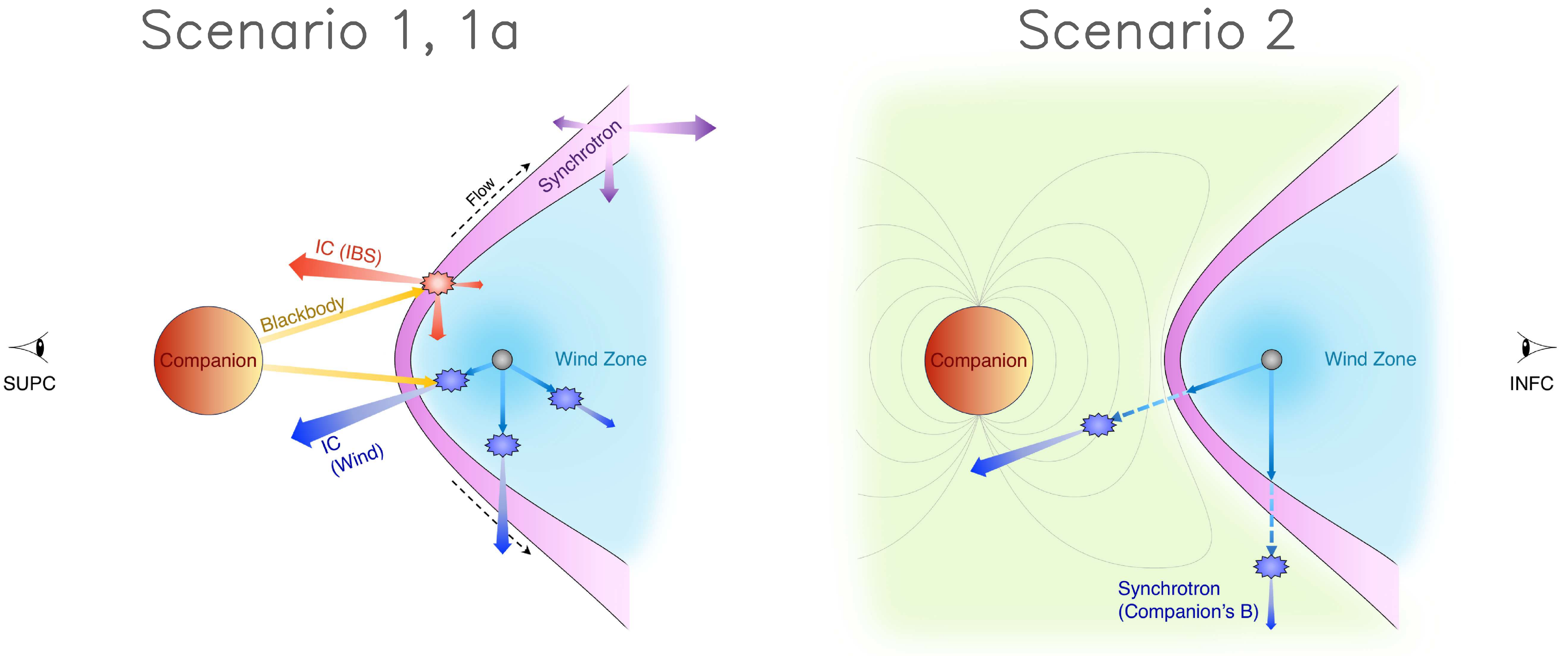
Pulsar Wind + companion B



Wadiasingh et al. (2018)

Inverse Compton (1) versus catastrophic synchrotron (2)



Sim, An, Wadiasingh 2024
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Scenario 1,1a— doesn't work!

Sim, An, Wadiasingh 2024
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- Simply, the optical depth to scattering is not high enough for efficient production of MeV/GeV gamma-rays
- One can "phenomenologically" increase the flux by increasing the particle resident time ==> but then this requires an upstream speed that is too slow to form a shock

$$F_{\mathrm{IC,wind}} = 4\sigma_{\mathrm{T}} c u_* \gamma_w^2 \frac{\eta_w \dot{E}_{\mathrm{SD}} \tau_w}{4\pi d^2 \gamma_w m_e c^2} \approx$$

$$10^{-16} \frac{\eta_w \dot{E}_{\mathrm{SD,35}} \gamma_w}{d_{\mathrm{kpc}}^2} \left(\frac{u_*}{1 \ \mathrm{erg \ cm^{-3}}} \right) \left(\frac{\tau_w}{1 \ \mathrm{s}} \right) \ \mathrm{erg \ s^{-1} \ cm^{-2}},$$

Way too low flux to match observations by 2-3 orders of magnitude

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Sim, An, Wadiasingh 2024
ApJ **964** 109

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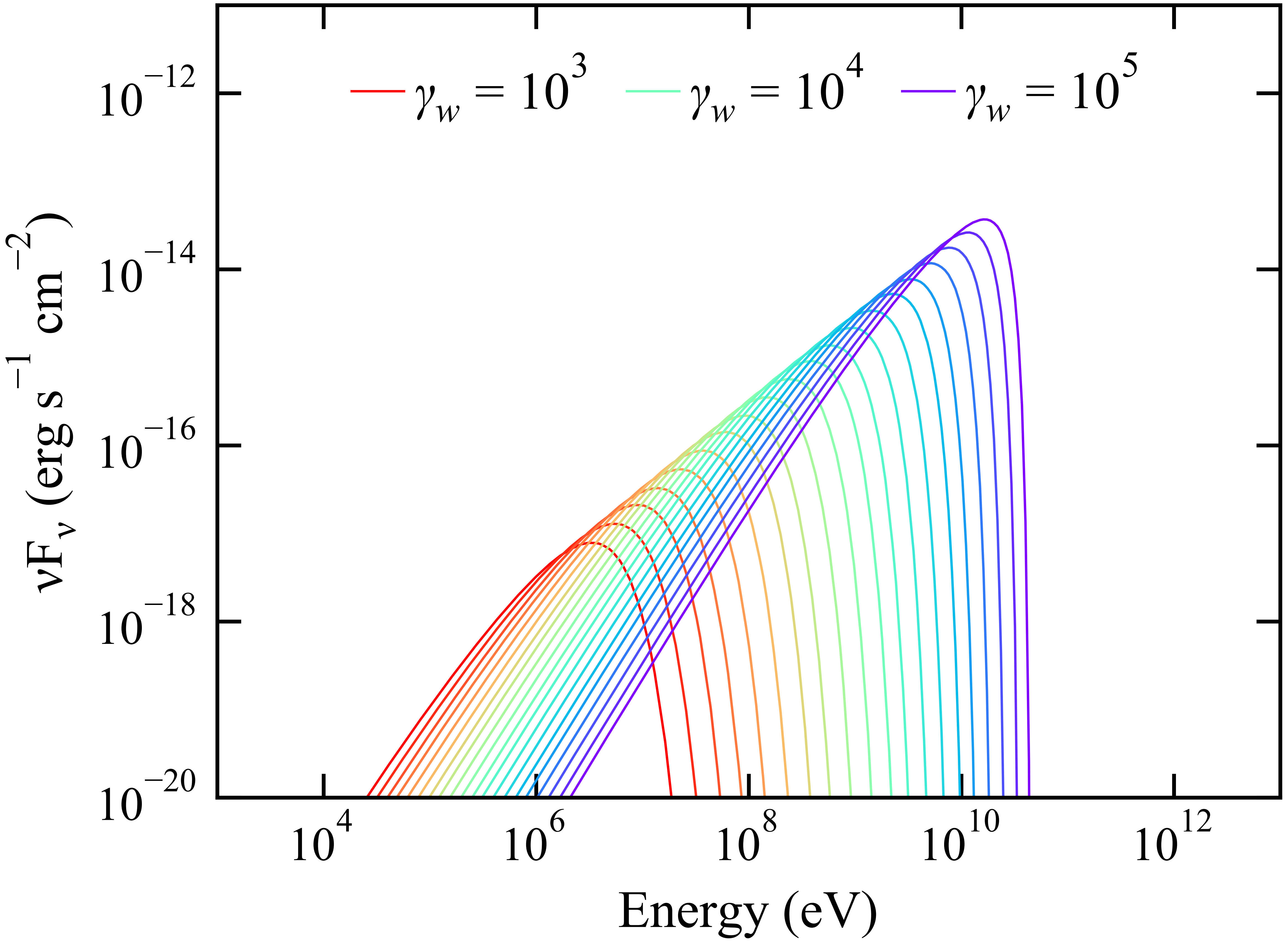


Way too low flux to match observations by 2-3 orders of magnitude

Scenario 2

Sim, An, Wadiasingh 2024
ApJ **964** 109

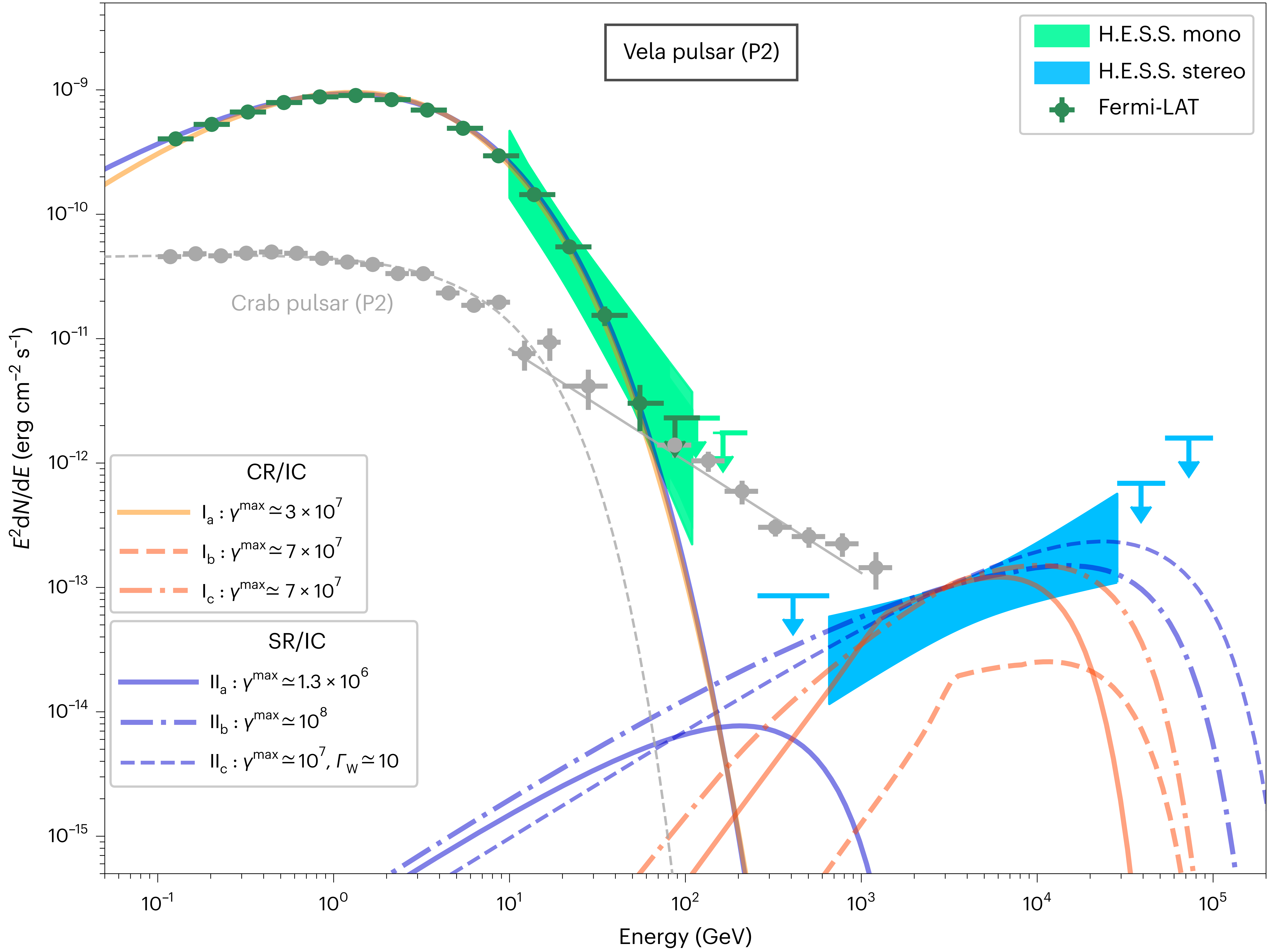
- Originally proposed in van der Merwe+2020 and Clark+2021
- B high enough that particles lose energy in <1 ms — the emission stays in temporal phase with the magnetospheric gamma-rays!
- 10^7-10^8 Lorentz factors also required for pulsed GeV emission in the curvature radio scenario in the current sheet (e.g. Kalapotharakos et al. 2019, 2023) for millisecond pulsars, as corroborated by HESS for the Vela pulsar

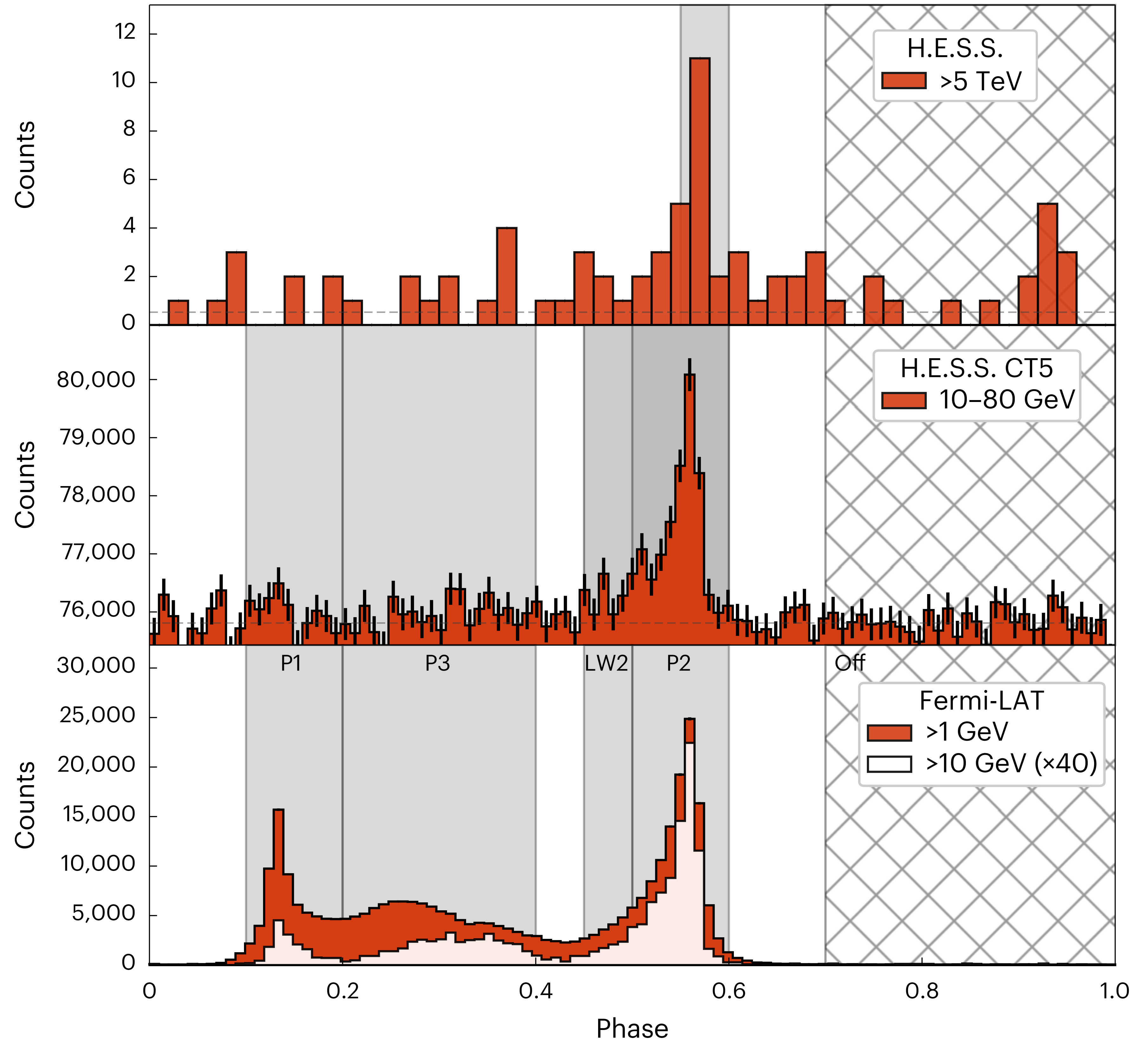
$$t_{\rm cool} \approx 8 \times 10^{-4} \left(\frac{\gamma_p}{10^8}\right)^{-1} \left(\frac{B}{0.1\ {\rm kG}}\right)^{-2}\ {\rm s}.$$

$$F_{\rm SY} = \frac{c\sigma_{\rm T}\zeta \dot{N}_p t_{\rm cool}}{3\pi d^2}\gamma_p^2 U_B$$

$$\approx 8 \times 10^{-10} \frac{\zeta \eta_p \dot{E}_{\rm SD,35}}{d_{\rm kpc}^2}\ {\rm erg\ s^{-1}\ cm^{-2}}$$

HESS Vela Pulsar measurements require multi-TeV particles in the current sheet (in phase with the GeV)





HESS collaboration 2023

A. Djannati-Ataï, E. de Ona Wilhelmi, B. Rudak, C. Venter.

Scenario 2 models

Sim, An, Wadiasingh 2024
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- Originally proposed in van der Merwe+ 2020 and Clark+2021

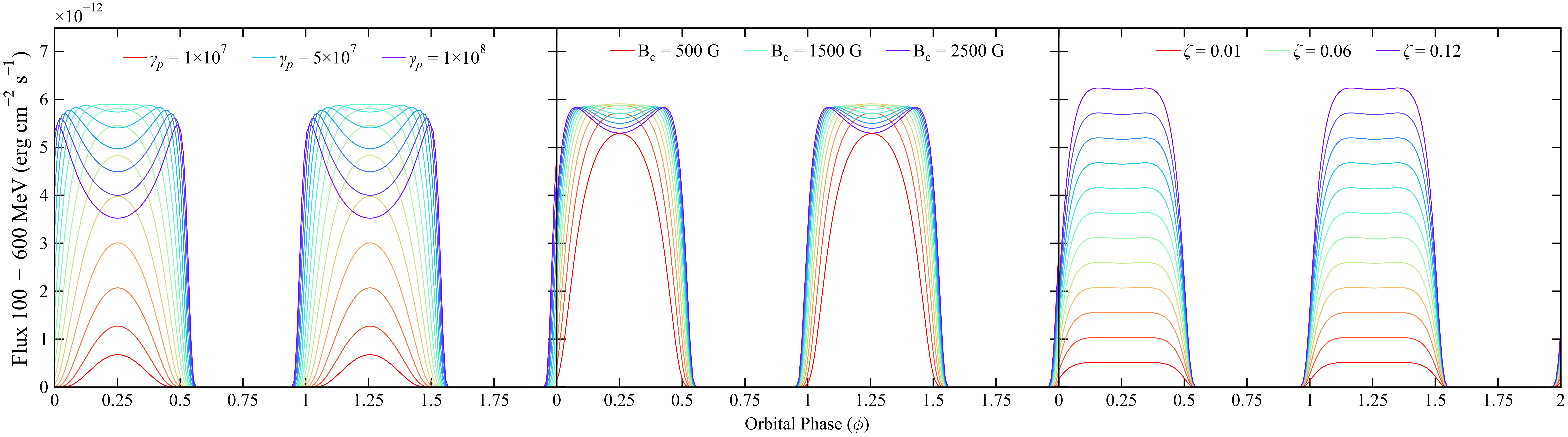
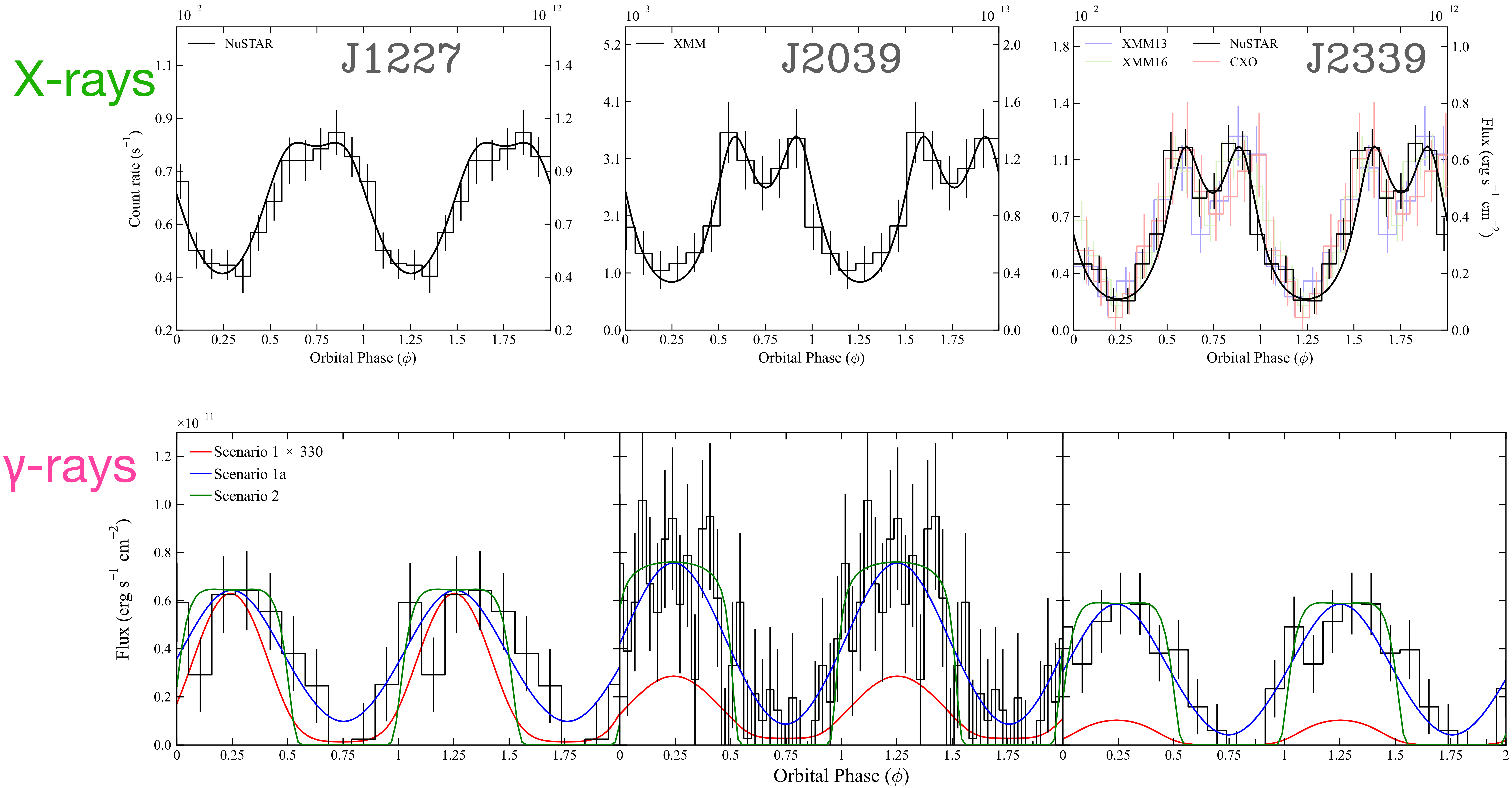


Figure 6. GeV LCs generated through our numerical model (Section 4) based on Scenario 2, employing optimized parameters specific to J2339 (Table 4). Changes in the LCs are attributed to different values of γ_p (left), B_c (middle), and ζ (right), reflecting the diverse parameter space under consideration.



Sim, An, Wadiasingh 2024
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SEDs

Sim, An, Wadiasingh 2024
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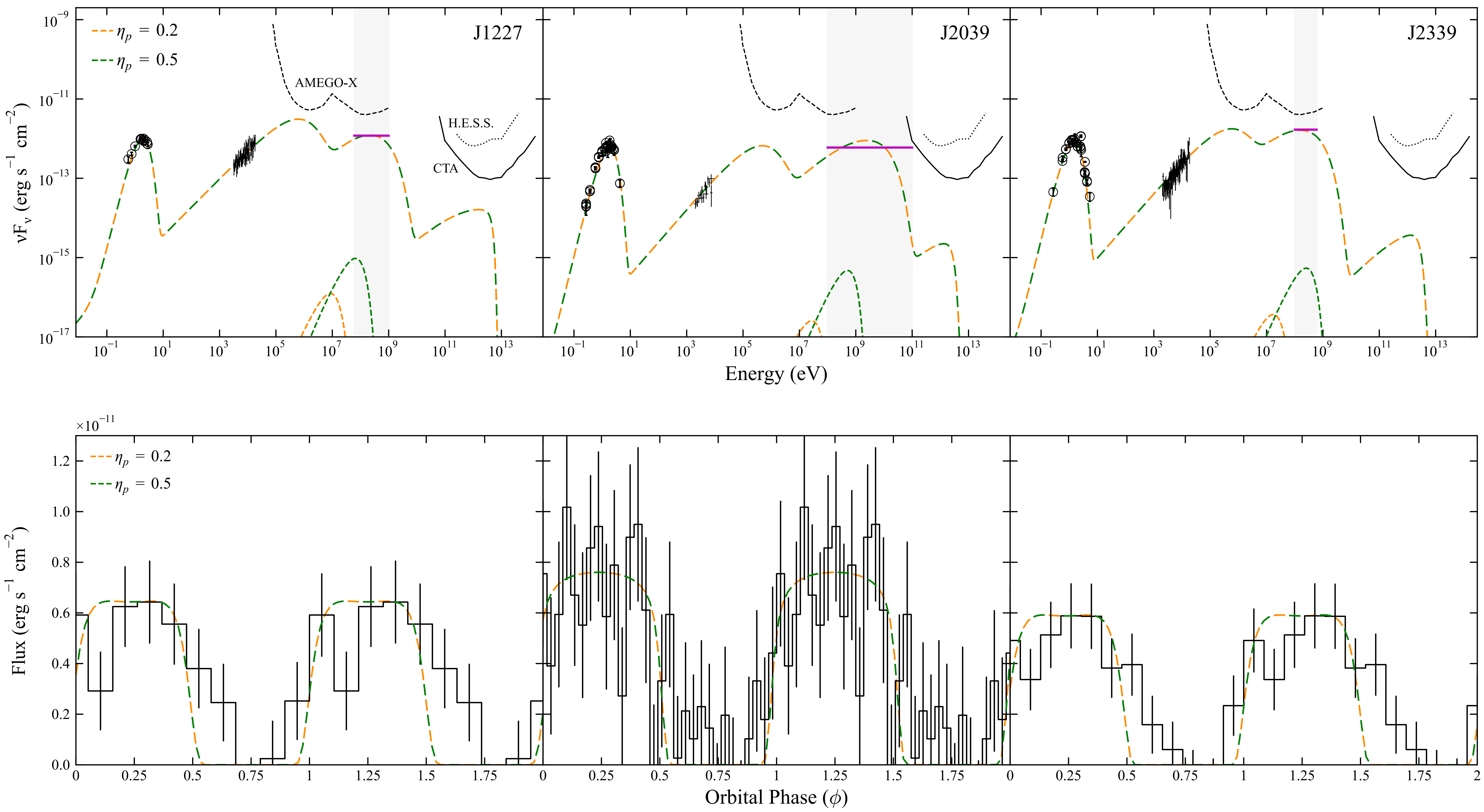
(parameter exploration not attempted, just a reasonable set)



Summary

- Millisecond pulsars appear to be able to accelerate particles to 0.1 PeV energies in their **magnetospheres** (consistent with HESS results of pulsed 20 TeV emission from Vela)
    - We only know this because of LAT and the existence of spiders binaries which allow for additional diagnostics not available in isolated pulsars
- This scenario is also consistent with curvature radiation models (e.g. Kalapotharakos et al. 2018) of pulsed GeV, but not purely synchrotron models with high multiplicity (lower Lorentz factor) in the current sheet
- Redback companions seem to have strong (kilogauss) magnetic fields — this is not surprising given how far they are rotating (synchronized/locked with orbit)
- **Future:** GeV gamma-rays could be used to map stellar magnetic fields in these systems, possibly see how they correlated with orbital period timing variations —> probe convective interiors of low-mass stars
- **Future:** Protons?