Gamma-ray Eclipses from Redback and Black Widow Pulsars

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on behalf of the *Fermi*-LAT collaboration

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Abstract

The ability of the *Fermi* Large Area Telescope (LAT) to identify pulsar-like gamma-ray sources has sparked a huge increase in discoveries of "Spider" millisecond pulsar (MSP) binaries ("Black Widows" and "Redbacks"). These systems are characterised by long radio eclipses due to scattering and absorption by diffuse intra-binary material that has been evaporated from the companion star's surface. Unlike radio emission, gamma-ray pulsations cannot be absorbed or scattered by this diffuse intra-binary material, and therefore the presence of a gamma-ray eclipse provides conclusive evidence that the pulsar passes directly behind the companion star. These subtle gamma-ray eclipses are only just becoming detectable thanks to the duration of the *Fermi* mission. Here we present the results of a search for gamma-ray eclipses from Spider MSPs, including the discovery of significant gamma-ray eclipses from four systems. The detection, or significant exclusion, of a gamma-ray eclipse provides a crucial independent diagnostic for pulsar emission models and Spider optical light curve models, and the new constraints on Spider binary inclination angles lead to robust constraints on their otherwise elusive pulsar masses.

1. Search details

- **30 black widows**, **9 redback**, and **2 transitional** millisecond pulsar binaries detected by the *Fermi* LAT.
- 9+ years of *Fermi*-LAT data (depending on ephemeris length)
- Ephemerides from radio and gamma-ray timing for the upcoming Third *Fermi*-LAT Pulsar Catalogue. (See talk by Matthew Kerr!)
- Photon weights optimised by varying pulsar spectral parameters to maximise pulsation significance (Bruel P., 2019, A&A, 622 A108)
- Poisson log-likelihood (box 2.) used to search for eclipses around each pulsar's superior conjunction (orbital phase = 0.25).

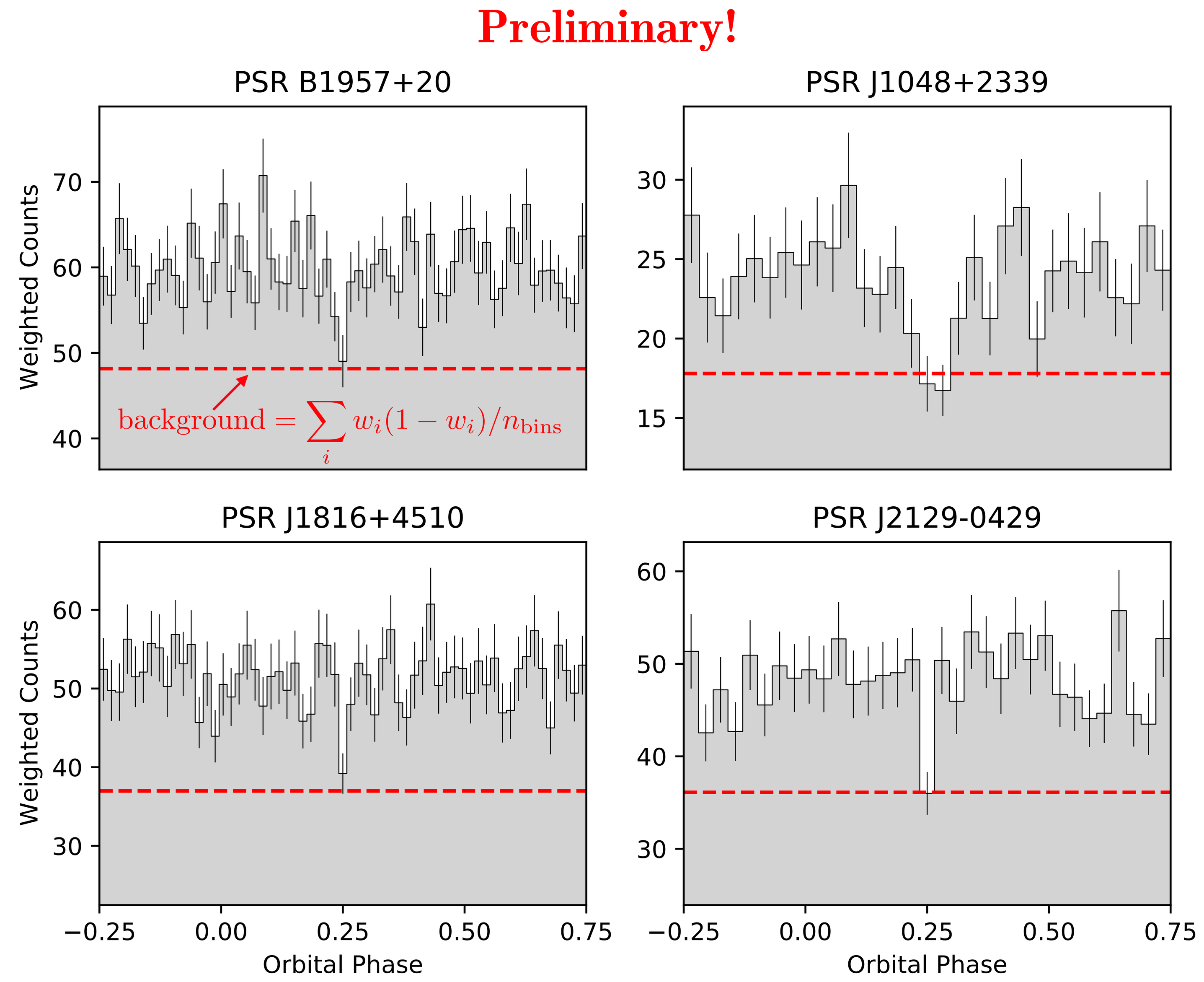
2. Eclipse Detection Statistic

For a set of gamma-ray photons with weights w, the Poisson log-likelihood for an eclipse with width θ and a relative in-eclipse flux α is (Kerr, M., 2019, ApJ, 885, 92; Kennedy M. R. et al. 2020, MNRAS 494, 3912),

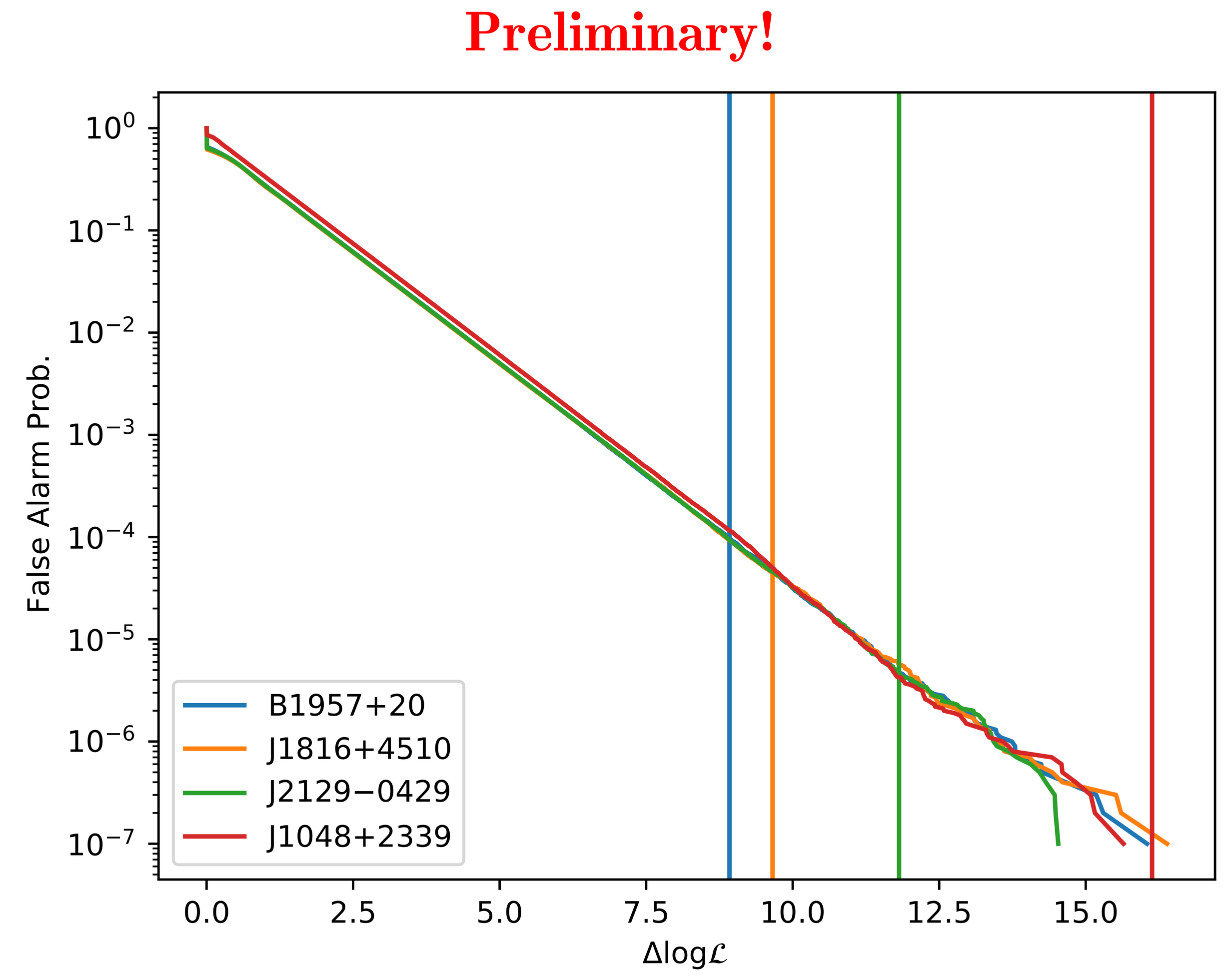
$$\log \mathcal{L}(\alpha,\theta) = \sum_{i\in\Theta} \log\left(w_i\alpha + 1 - w_i\right) + \sum_{i\in\bar{\Theta}} \log\left(w_i \frac{1-\alpha\theta}{1-\theta} + 1 - w_i\right) - \left(\alpha\eta_\Theta + \frac{1-\alpha\theta}{1-\theta}\eta_{\bar{\Theta}}\right)\sum_i w_i \qquad (1)$$

- Penalises log-likelihood for photons in eclipse region
- Increases log-likelihood for photons outside eclipse region
- Accounts for exposure variations over orbital phase

3. Pulsars with Significant Eclipses



4. Eclipse significances



Eclipse significances have been calibrated by searching for eclipses in 10^7 sets of randomly generated photon orbital phases for each pulsar.

Four pulsars are found to have significant eclipses, with false-alarm probabilities $< 10^{-4}$.

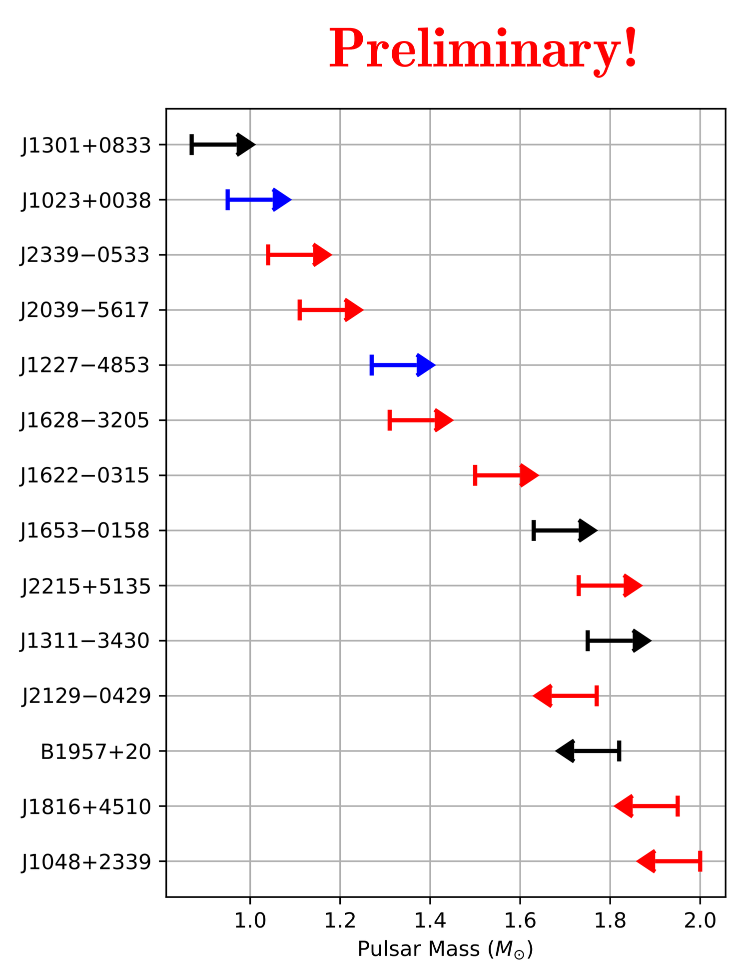
5. Implications

Accurate binary inclination estimates are crucial for measuring neutron star masses (see Box 6.), but have, until now, been extremely difficult to obtain.

For Spiders, these estimates have historically come from optical light curve modelling. However, models for the pulsar's heating effect on the companion cannot yet fully reproduce the asymmetries and variability observed in many systems, and so the resulting inclination estimates have large biases.

Our results provide **robust upper or lower limits on the binary inclination** that depend only on the companion star's Roche-lobe filling factor. These can provide vital independent constraints for optical and X-ray light curve models, and radio/gamma-ray pulse emission models.

6. Neutron Star Mass Constraints



Pulsar mass estimates can be obtained from Spider binaries via the binary mass function,

$$M_{\rm psr} = \frac{K_2^3 P_{\rm orb}(1+q)^2}{2\pi G \sin^3 i}. \qquad (2)$$

The companion's radial velocity K_2 can be measured via optical spectroscopy. Pulsar timing provides the orbital period, $P_{\rm orb}$ and pulsar's semi-major axis, A_1, constraining the mass ratio, $q \equiv M_{\rm comp}/M_{\rm psr} = 2\pi A_1/K_2 P_{\rm orb}$. **The only remaining unknown is the inclination,** i, which takes values between 0° (a face-on orbit) and 90° (edge-on).

The significant detection or exclusion of an eclipse provides lower or upper limits (respectively) on the inclination, and hence **upper or lower limits on the pulsar mass** (respectively).

Fermi Gamma-ray Space Telescope

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