Gamma-ray Variability in Millisecond Pulsar Binaries: Probing Pulsar-Companion Interactions

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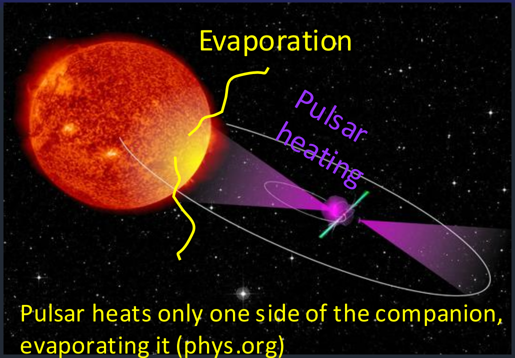
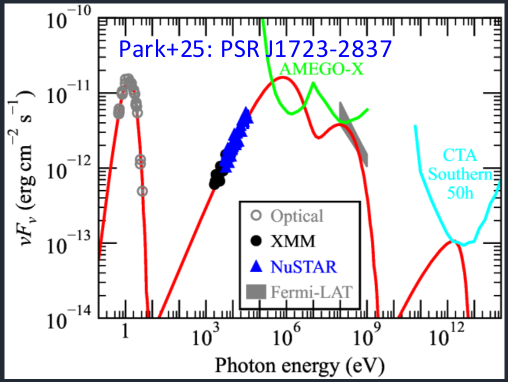
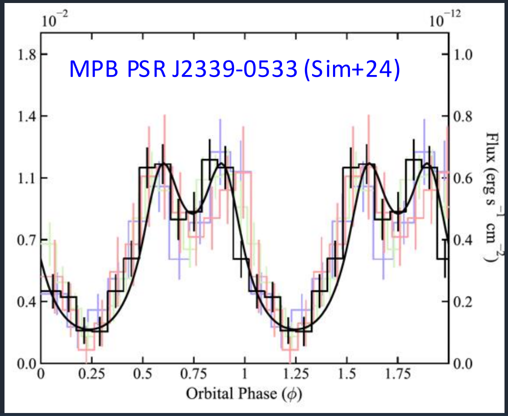
OUTLINE

- **Millisecond Pulsar Binaries (MPBs) – “Spider” Pulsars:** An evolved pulsar actively interacts with its low-mass companion
- **Emission Characteristics of MPBs:** Broadband spectral properties, pulsar wind interactions, and multi-wavelength emission behavior
- **Intra-Binary Shock (IBS) X-ray Emission:** Formation, variability patterns, and basic model
- **Orbitally-Modulated Gamma-Ray (GeV) Signatures:** Observation, model, and implications for pulsar wind
- **Outstanding Challenges and Future Directions:** Intriguing issues and future observations

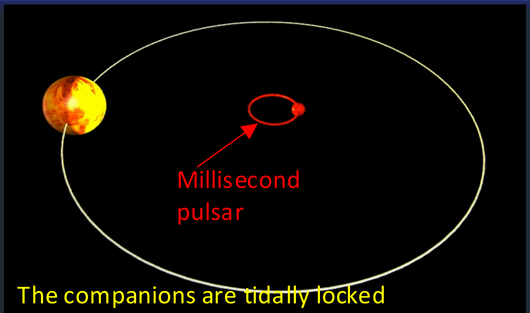


Pulsar heats only one side of the companion, evaporating it (phys.org)

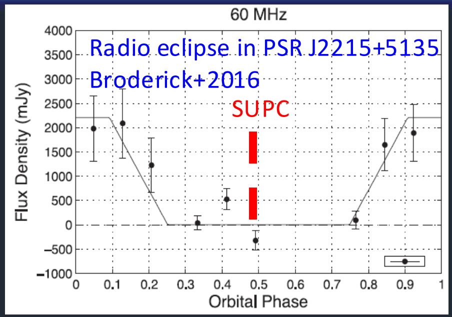


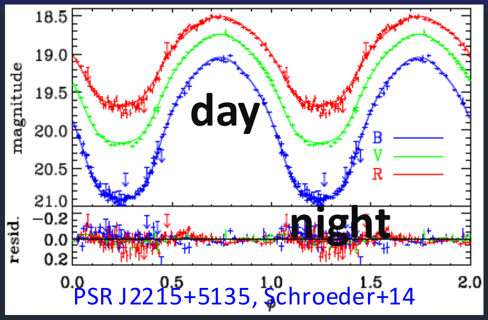


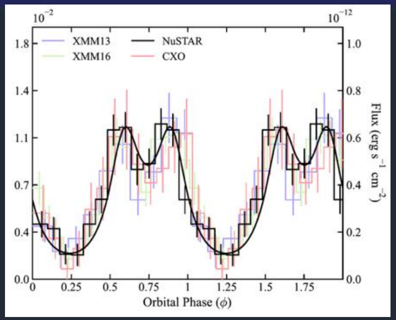
Millisecond Pulsar Binaries provide clues to wind-wind interaction



The companions are tidally locked
https://web.stanford.edu/~dkandel/research.html



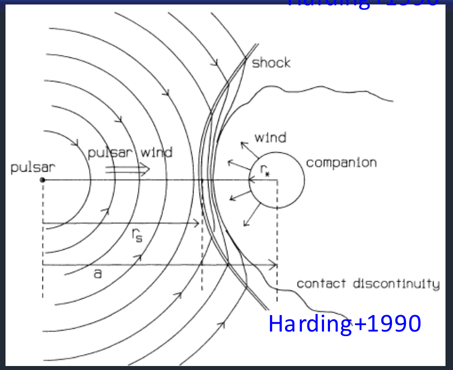




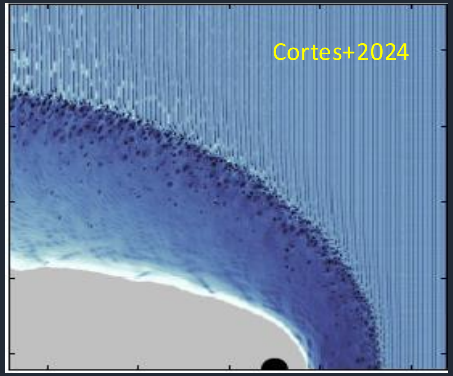
- **<u>MPB (redbacks and black widows)</u>:** A non-accreting millisecond pulsar and a tidally-locked low-mass ($< M_\odot$) companion in a compact, circular orbit ($P_{orb} \leq 1$ day)
- **Interaction between the pulsar and the companion:** leads to diverse observational phenomena such as radio/γ-ray eclipse, companion heating, evaporation, <u>intrabinary-shock emission</u>, and eclipses etc
- **Valuable targets for studies of the interaction:** well-known compact objects, circular and compact orbit, and distinct X-ray light curves

Emission from IBS provides important clues to the interaction

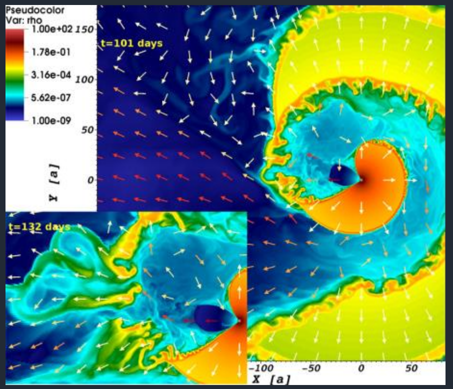
- **IBS formation in MPBs:** Both analytical and numerical models support the existence of IBSs, explaining the shock-driven interactions between pulsar and companion winds



- **Emission modeling:** Phenomenological and numerical IBS-based models have successfully reproduced observed X-ray spectra and light curves of MPBs, validating theoretical predictions

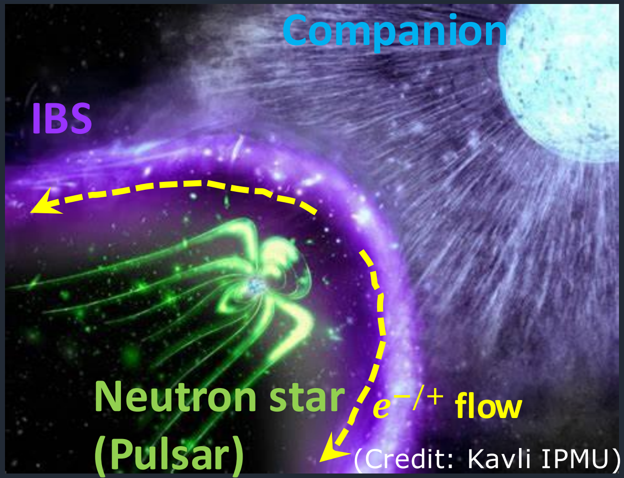


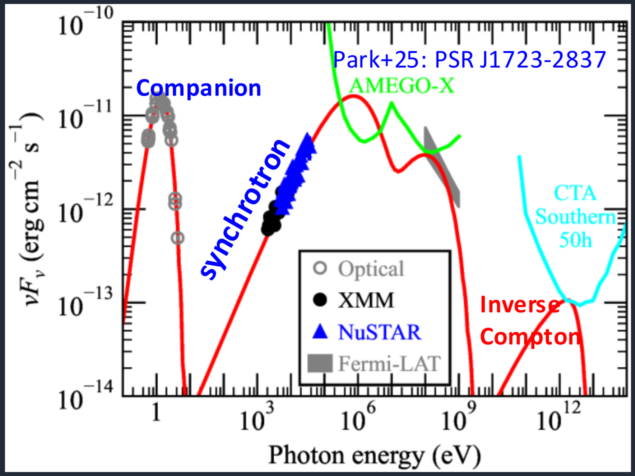
- **High-energy astrophysics and wind-wind interaction:** Studies of MPBs offer crucial insights into wind-wind interactions and the complex shocked flow dynamics, contributing to our understanding of gamma-ray binary phenomena

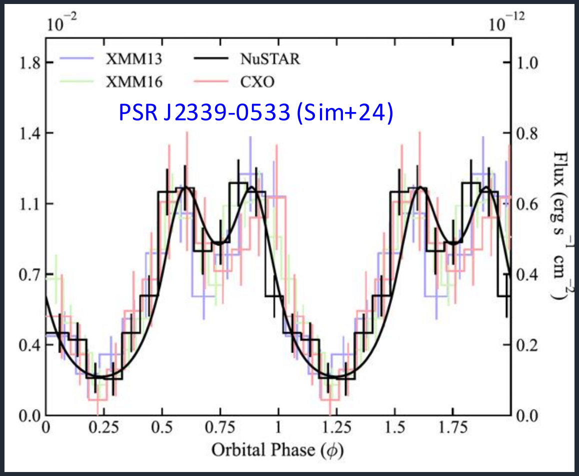


Bosch-Ramon+2017

IBSs can be best probed by X-ray data







Basic scenario for X-ray emission from IBSs

- Shocked electrons flow along the shock, emitting synchrotron X-rays
- Hard PL X-ray spectra ($\Gamma_X \sim 1.1 - 1.3$): magnetic reconnection
- Orbital modulation caused by Doppler beaming of the flow
- These X-ray data provide information on the IBS properties (e.g., B, flow speed, relative wind strength, shock structure, etc)

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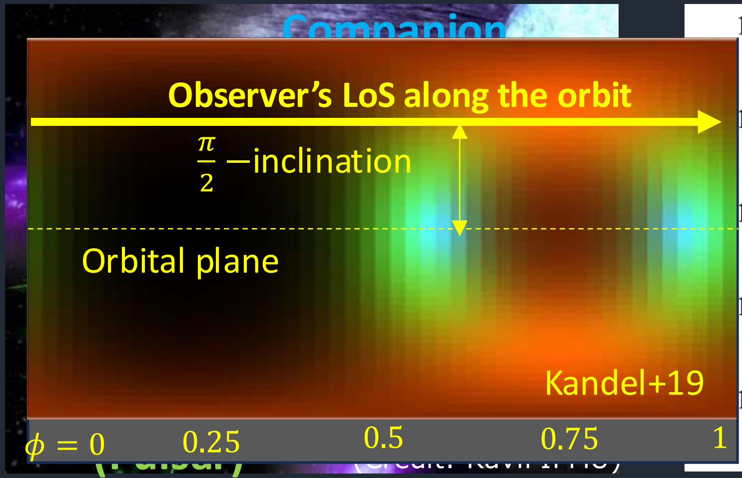

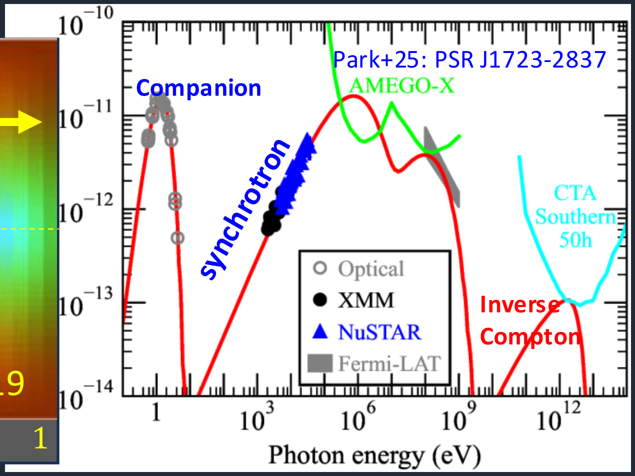

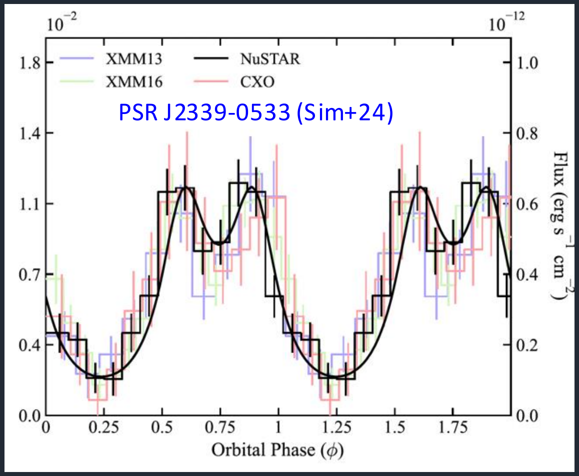

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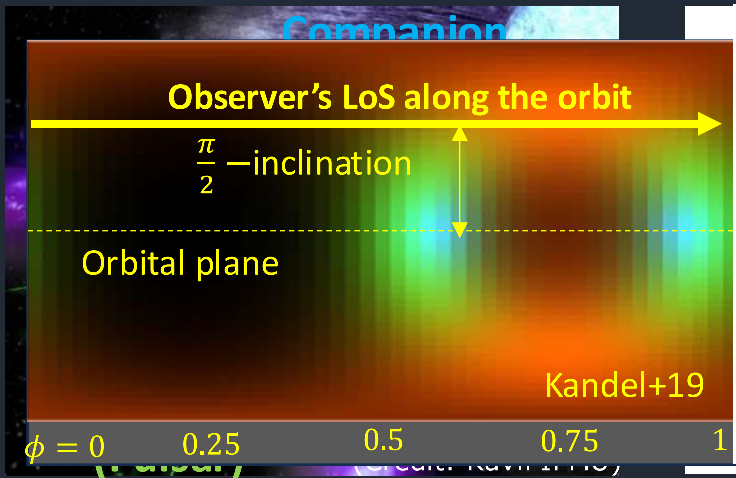

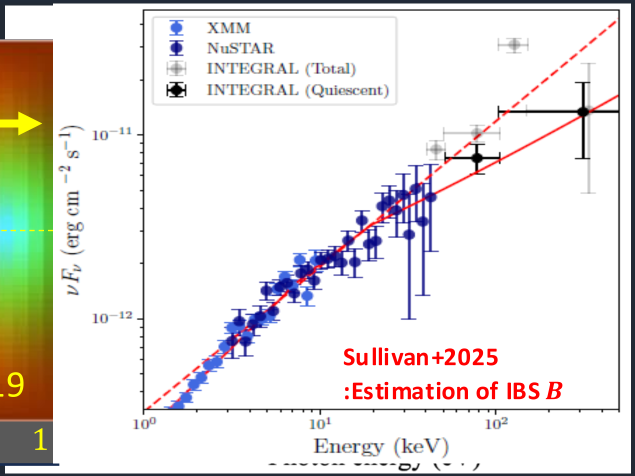

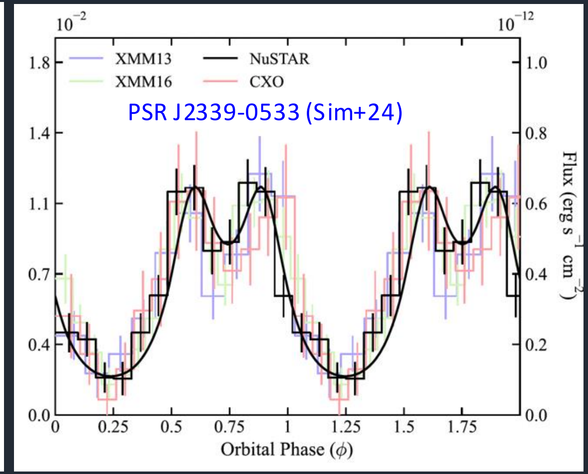

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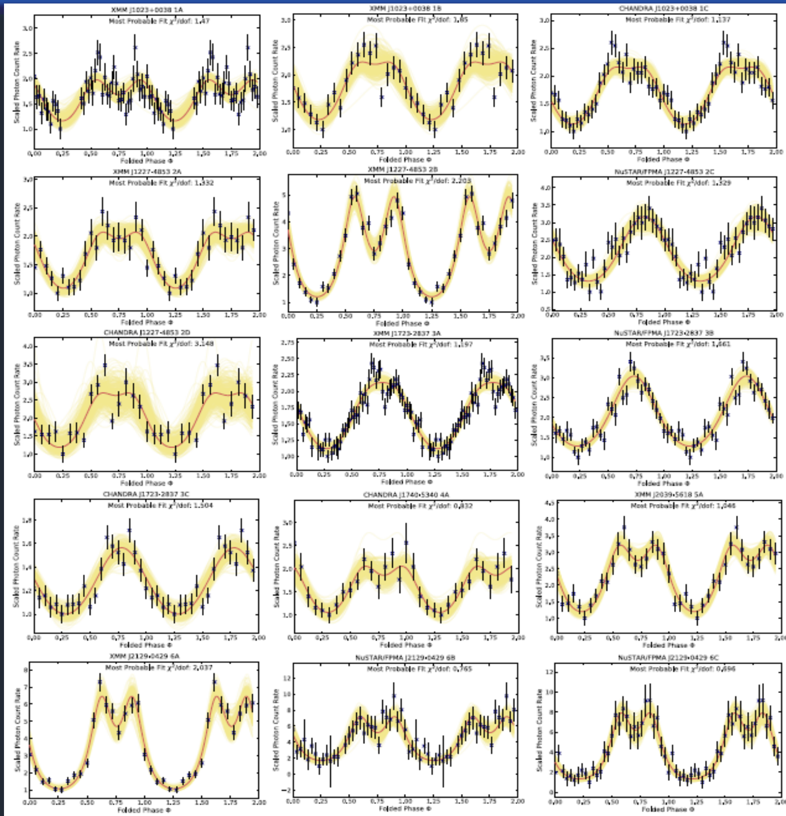
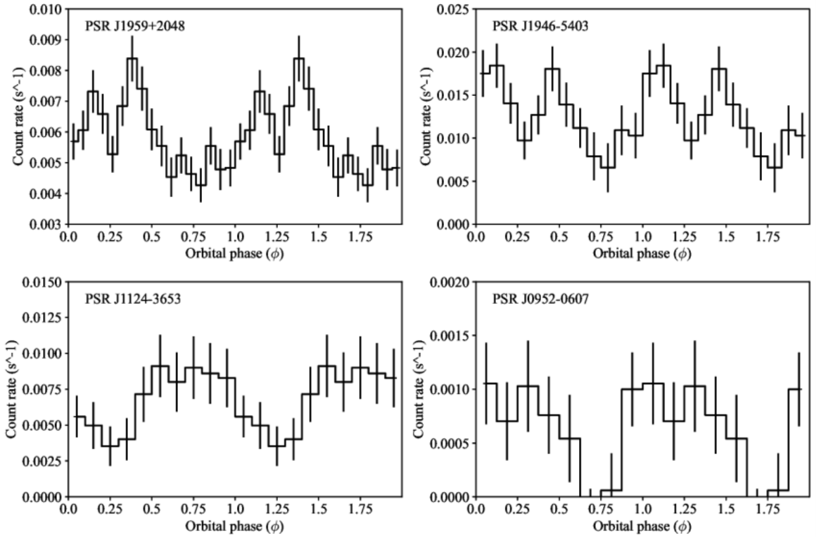
MPBs exhibit light curves that align with the IBS scenario



Redback light curves
(Wadiasingh+17)



Black widow light curves (Sim+2024)

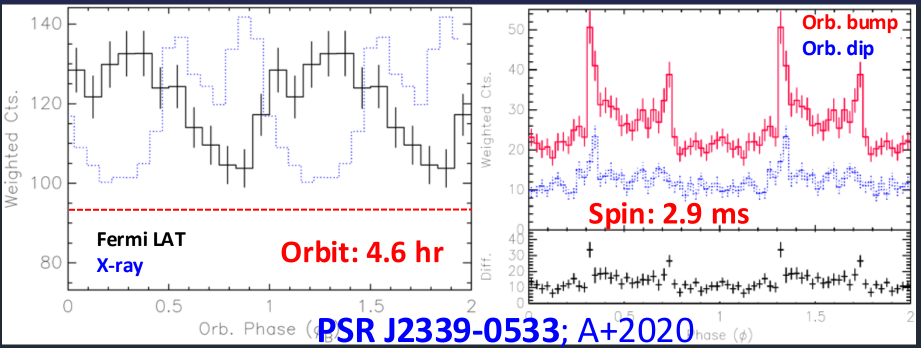
- X-ray spectra and LCs of MPBs share common features
  - ✓ Hard $\Gamma_X < 1.5$ spectrum
  - ✓ Single-to-double peak LC structures
  - ✓ Maximum LC brightness at specific orbital phases

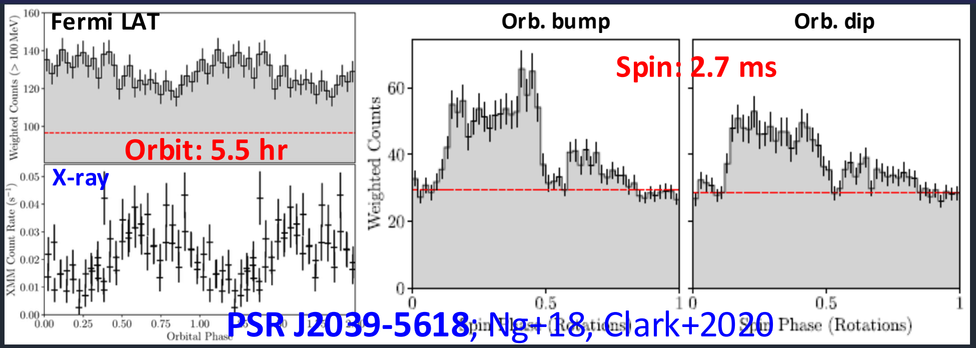
  * These features have been well reproduced by IBS models

- **X-ray emission modeling:** X-ray data in MPBs have been successfully explained through the IBS scenario, providing important insights into the wind-wind interaction

- **Challenges from γ-ray observations:** Detections of orbitally modulated γ-ray signals in MPBs present a challenge to existing IBS models, suggesting additional high-energy emission mechanisms beyond the IBS process

Beyond the IBS X-rays: Non-magnetospheric ~GeV emissions





- Orbitally-modulated γ-ray (~GeV) emissions have been detected in five MPBs (3 RBs and 2 BWs): non-magnetospheric origin for these signals
- The maximum of the γ-ray orbital light curves occurs at $\phi = 0.25$ (pulsar behind the companion)
- In two RBs, the orbitally-modulated γ-ray emissions are accompanied by variations in the pulsar's spin profile.→ these non-magnetospheric emissions also exhibit millisecond-scale structure
- **These Fermi-LAT data can provide new insights into the interaction**

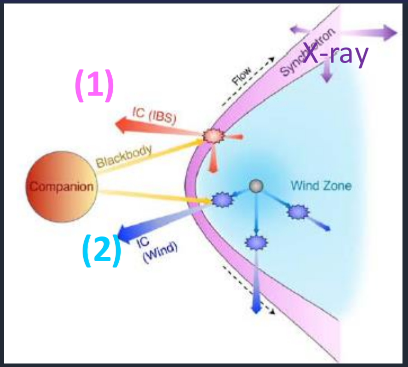
How are the orbitally-modulating gamma rays produced?

Inverse-Compton scenarios

(1) Inverse-Compton (IC) upscattering by IBS electrons

(2) IC by the preshock pulsar-wind electrons

$\phi = 0.25$ 🙂



(1) IC upscattering by IBS electrons

- The measured X-ray spectrum implies that IBS electrons are energetic: $\gamma_e \approx 10^6$
- These electrons would upscatter stellar photons to $\gamma_e^2\, h\nu_{BB} \sim \mathrm{TeV}$ (NOT GeV)

(2) IC upscattering by the preshock pulsar's wind

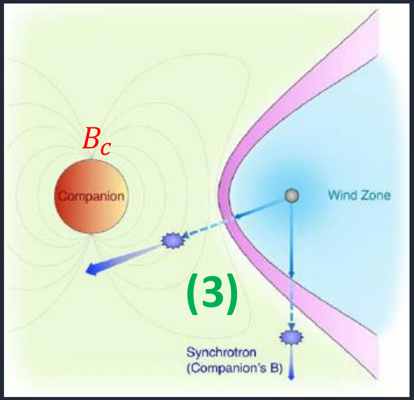
- The preshock wind zone is relatively small, resulting in a short residence time (τ_w)
- The IC flux is estimated to be $F_{IC} \approx$ $10^{-16}\,\frac{\eta_w \dot{E}_{SD,35}\,\gamma_w}{d_{kpc}^2}\left(\frac{u_*}{1\ erg\ cm^{-3}}\right)\left(\frac{\tau_w}{1\ s}\right)\ \mathrm{erg\ s^{-1}\ cm^{-2}}$ (Sim+24)
- The predicted IC flux is lower by orders of magnitude than the observed γ-ray fluxes

These scenarios fail to explain the observed gamma-ray properties!

Synchrotron emission from the companion region

(3) shock-penetration scenario (van der Merwe+20, Sim+24)

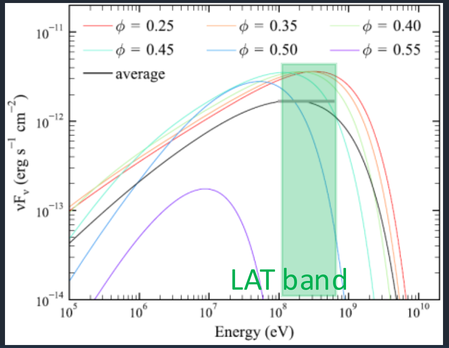
Energetic primary preshock pairs pass through the IBS and emit synchrotron photons under the companion B



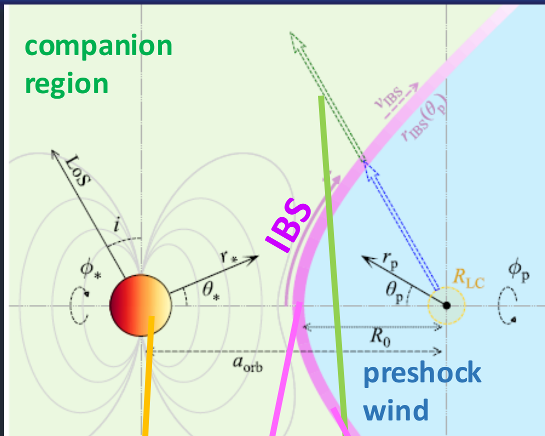
$\phi = 0.25$ 🙂

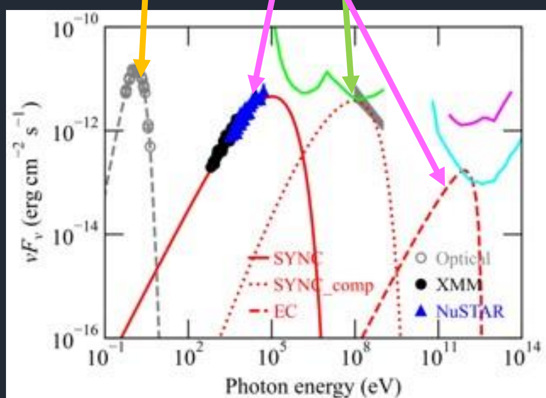
$\phi = 0.5$ 🙂

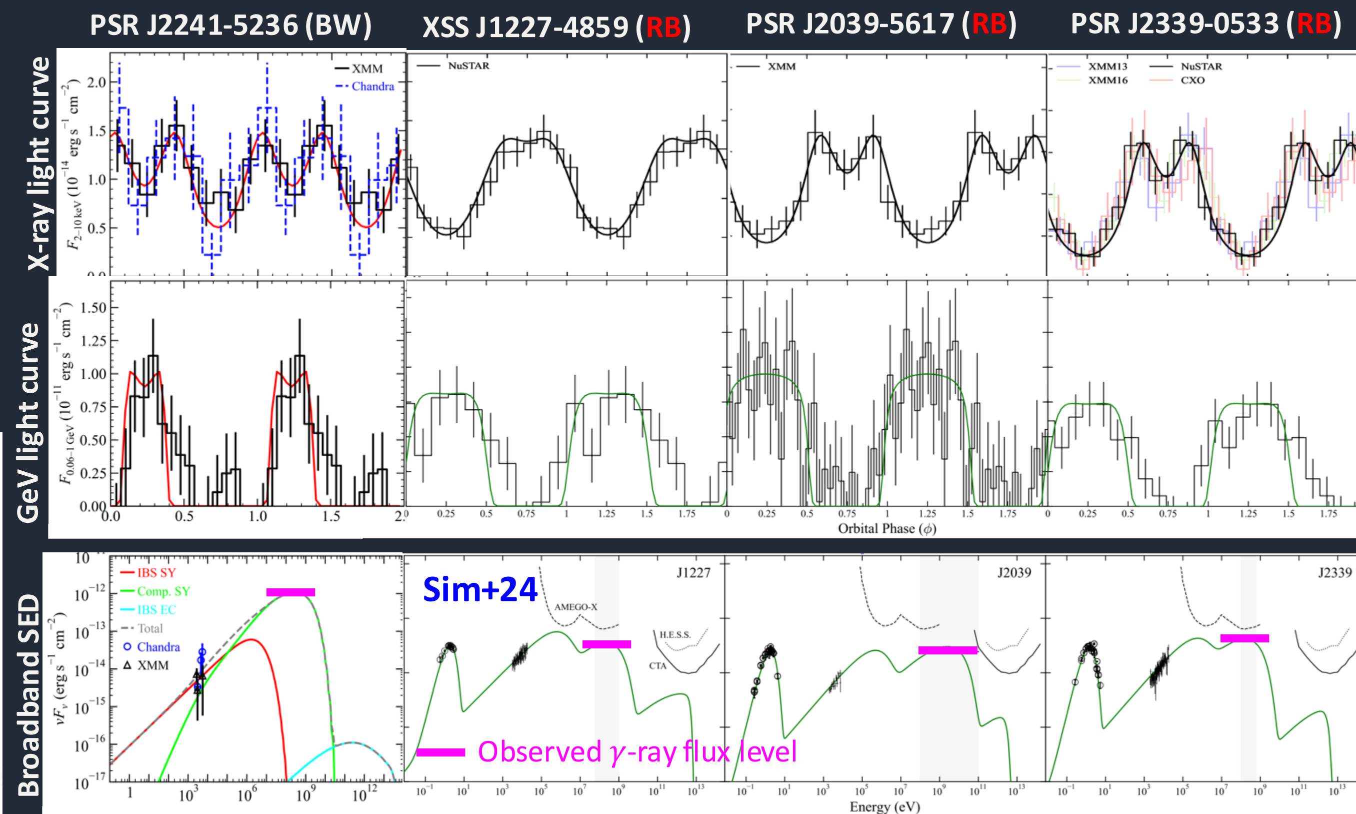
- **Synchrotron emission energy:** $h\nu_{SY} \approx 1.6 \times 10^{-11}\, B_c\, \gamma_e^2$ keV: $\gamma_e \sim 10^{7-8}$ for GeV emission under $B_c \sim 0.1$ kG
- **Generation of $\gamma_e \sim 10^{7-8}$ electrons:** pulsar voltage drop $\Delta V \approx 6.6 \times 10^{12}\, B_{12} P^{-2}$ volts (Ruderman+75, Kalapotharakos+15)
- **Synchrotron cooling time:** $t_{cool} \approx 8 \times 10^{-4} \left(\frac{\gamma_e}{10^8}\right)^{-1} \left(\frac{B}{0.1\ kG}\right)^{-2}$ s; fast enough for producing millisecond variation as well
- **Synchrotron flux:** $F_{SY} = \frac{c\sigma_T \zeta\, \dot{N}_e t_{cool}}{3\pi d^2} \gamma_e^2 U_B \approx 8 \times 10^{-10} \frac{\zeta \eta_p \dot{E}_{SD,35}}{d_{kpc}^2}$ erg s^{-1} cm^{-2}: independent of companion B at the emission site in the cooling dominant regime
- **Orbital modulation:** Changes in the emission "frequency" depending on B $\left(\propto \frac{1}{r_c^3}; \text{dipole}\right)$ at the emission site is the key factor that generates the modulation in the LAT band



The model explains the observed γ-ray data from both BW and RBs







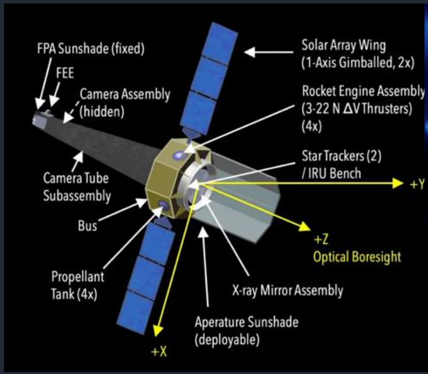
- The phase of X-ray maximum differs between BWs and RBs, but the γ-ray maximum occurs at the same phase ($\phi = 0.25$)

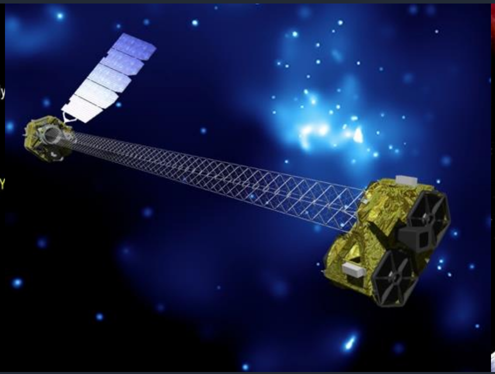
- The Fermi-LAT data require high-energy <u>primaries</u> (10—100 TeV) and a high-B (~kG) companion

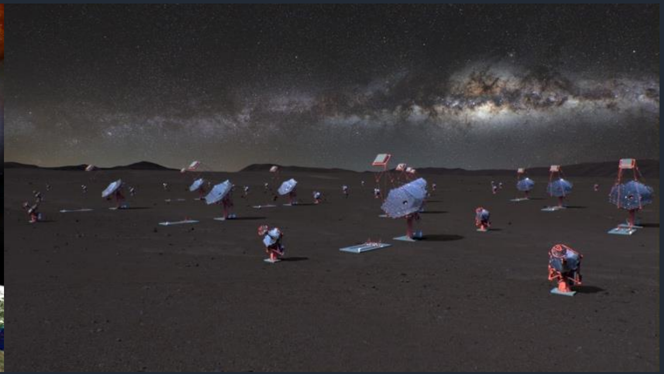
The <u>orbitally modulated γ-ray signals</u> in MPBs may imply

- acceleration of pairs to 10—100 TeV by the pulsars
- their interaction with the companion's strong B

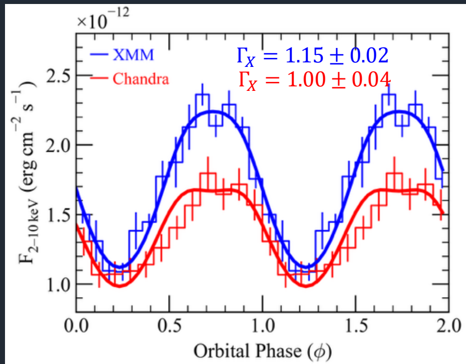
Several other interesting issues warrant attention



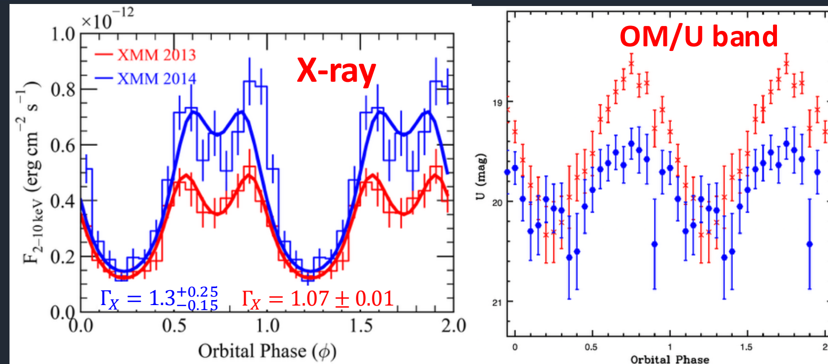




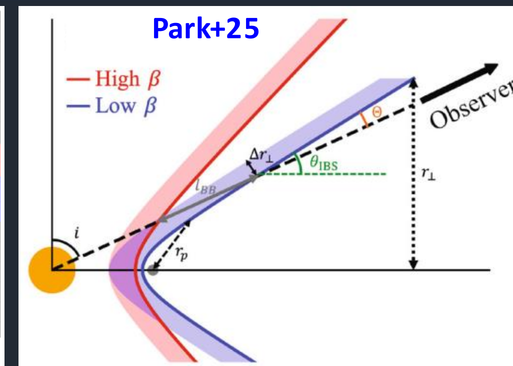
Long-term X-ray and optical variability



PSR J1723-2837; Bogodanov+13

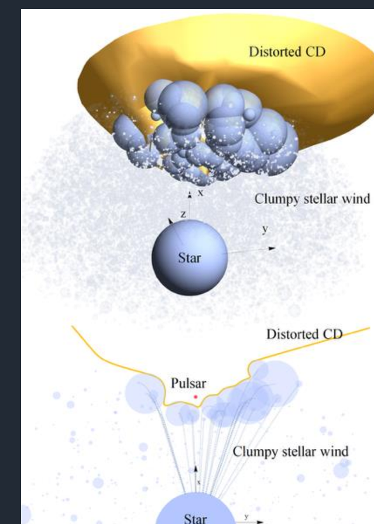


XSS J1227-4859; de Martino+15



- X-ray variabilities have been observed in some MPBs; likely induced by clumpy stellar wind

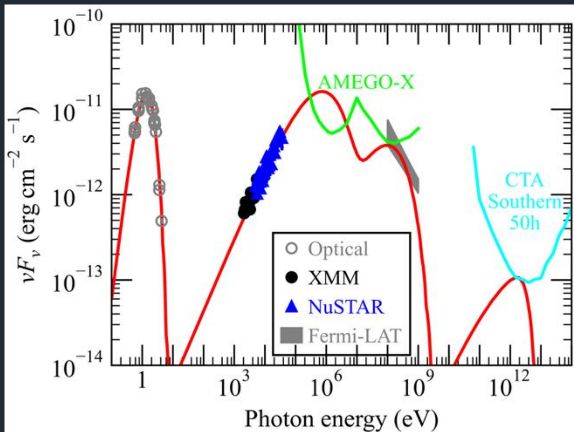
- Intriguingly, F_X-F_O anti-correlation (J1227) in the long-term variability was observed; the IBS blocks the companion's emission (de Martino+15, Park+25) → can provide information on the system inclination



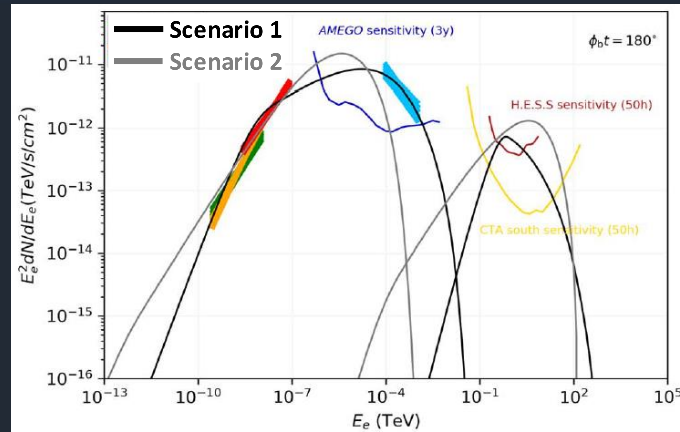
Kefala+23

- Precise measurements of variabilities and their timescales can yield crucial insights into the interaction

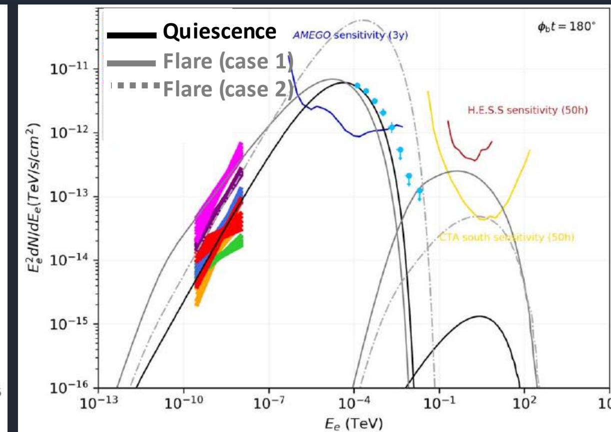
Potential TeV emission from MPBs



PSR J1723-2837 (Park+25)



PSR J1723-2837 (van der Merwe+20)



PSR J1311-3430 (van der Merwe+20)

- X-ray emission from IBS implies high-energy electrons
- IC upscattering by IBS electrons should appear at TeV energies
- The predicted TeV flux depends strongly on the assumed system state (e.g., flare?) and IBS parameters
- CTA may detect a few MPBs, helping understand the IBS better

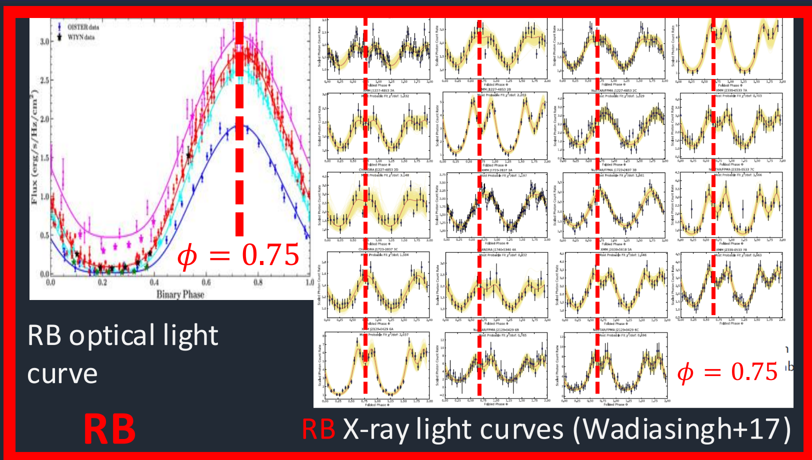
Summary

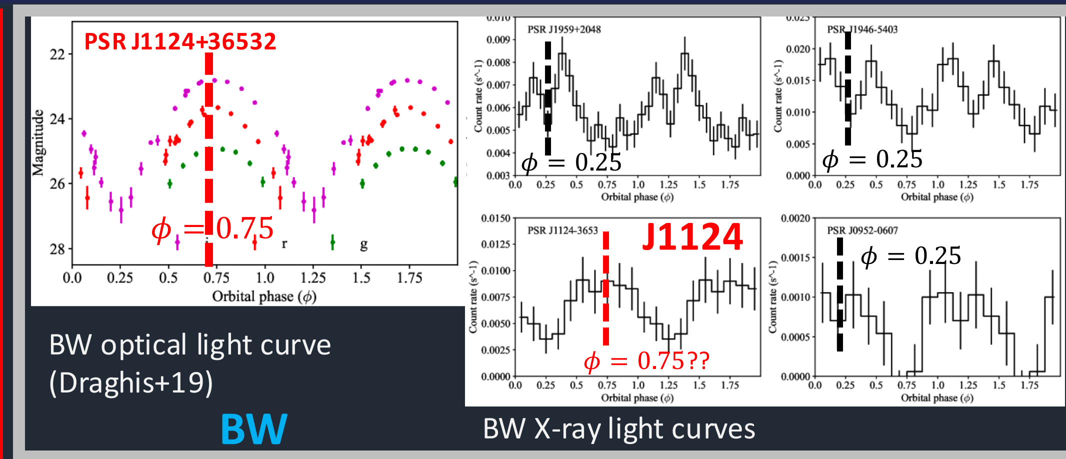
- The orbitally-modulated γ-rays is consistent with the shock-penetrating scenario: MSPs accelerate primary e^{-}/e^{+} to 10—100 TeV energies which interact with companion B

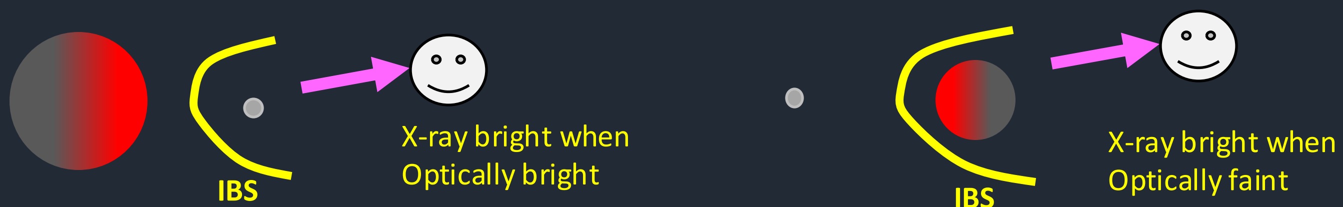
- A comprehensive understanding of pulsar-companion interactions require further observations, detailed emission modeling, and theoretical studies

- IBS models suggest that the CTA will be capable of detecting TeV emission from some MPBs

Different X-ray LC phasing between RBs and BWs?







- **Optical phasing**: Both BWs and RBs exhibit an optical max. at $\phi = 0.75$
- **X-ray phasing** (pulsar-to-companion wind strength ratio β)

 - X-ray max at $\phi = 0.75$ for RB (strong wind) and 0.25 for BW (weak wind)

 - However, **BW J1124 has a max. at $\phi = 0.75$**; Can its $\ll 0.1 M_{\odot}$ companion have a strong wind? Or other factors determine the IBS orientation (e.g., B_c; Wadiasingh+2018) → **Need to confirm the light-curve measurement for J1124**