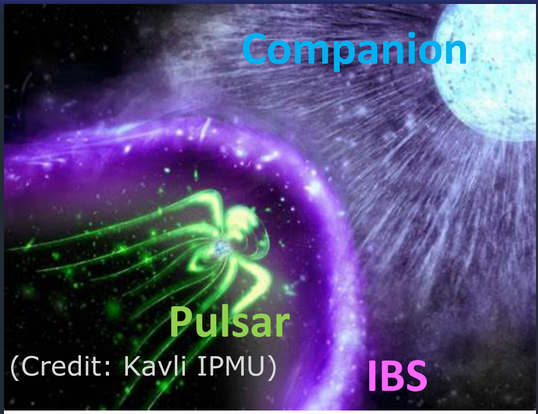
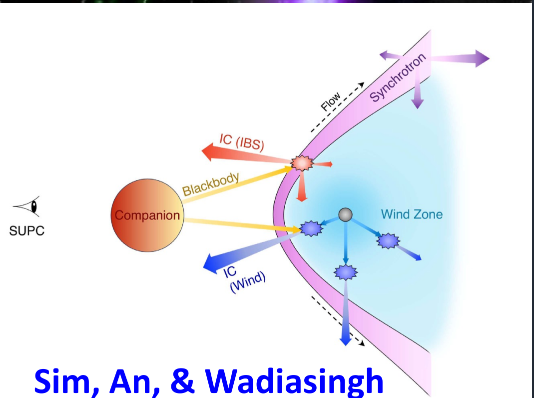
Orbitally modulating gamma-ray signals in redback pulsar binaries

Hongjun An
Chungbuk National University
6/20/24

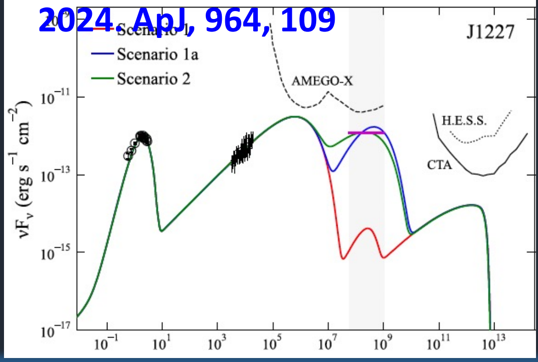
OUTLINE

- Millisecond pulsar binaries: BWs, RBs
- Radiative processes operating in pulsar binaries
- An emission model for X-rays and gamma rays from pulsar binaries
- Constraints obtained by modeling high-energy emission from RBs
- Further studies necessary to understand pulsar binaries better
- Summary

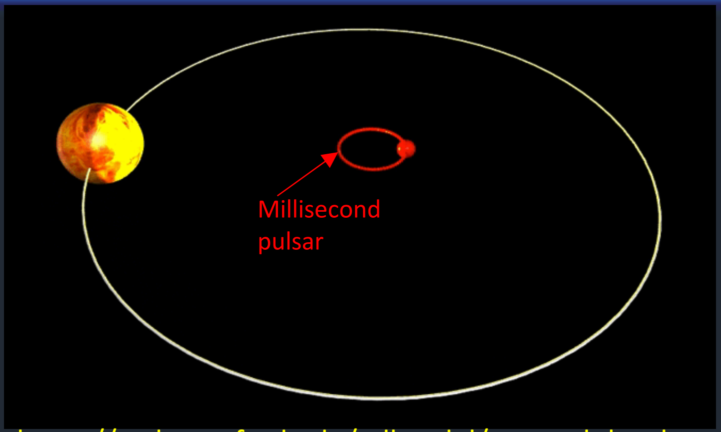




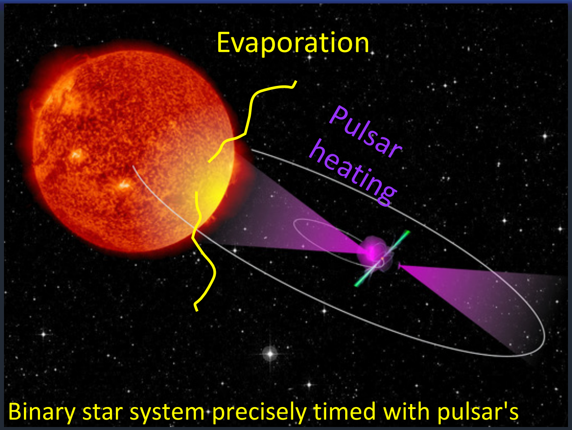
Sim, An, & Wadiasingh 2024, ApJ, 964, 109



Millisecond pulsar binaries are descendants of LMXBs



https://web.stanford.edu/~dkandel/research.html



Binary star system precisely timed with pulsar's gamma-rays (phys.org)

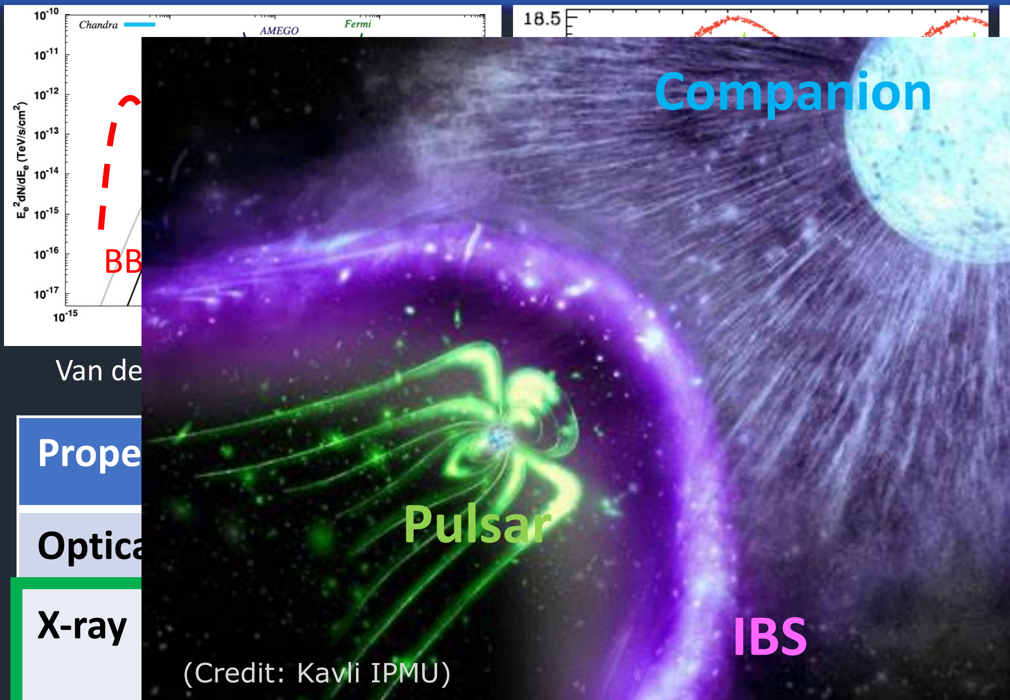
(NASA Goddard Flight Center)

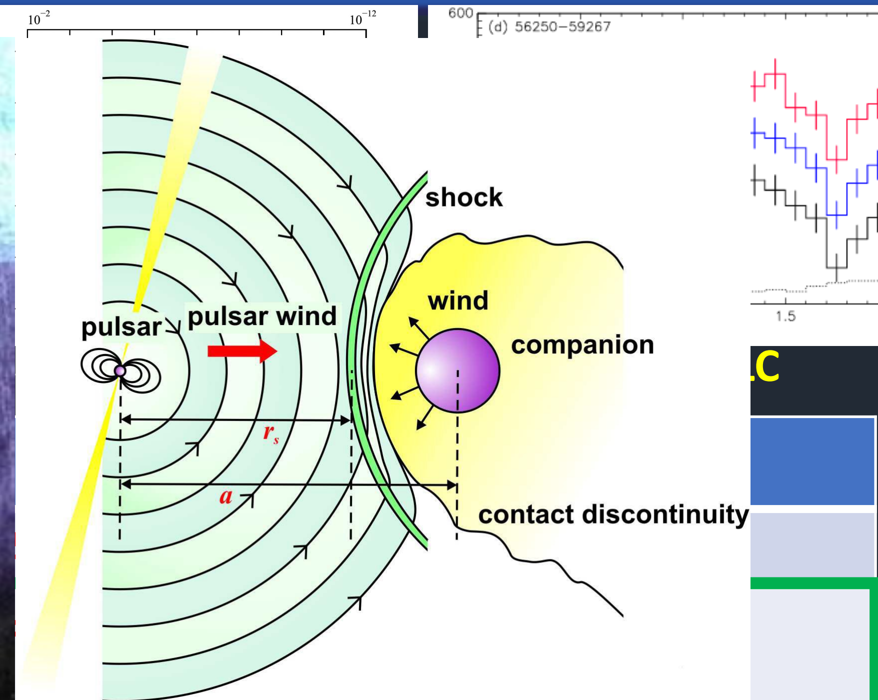
- **Millisecond pulsar binary: A millisecond pulsar and a tidally-locked low-mass ($\ll M_{\odot}$) companion in a tight, circular orbit ($P_{orb} \leq 1$ day)**

- **Such a binary is formed when a $M_c \sim M_{\odot}$ companion has transferred its mass and angular momentum over a period of $\geq$ Gyr, causing the pulsar to spin up→ millisecond spin (Alpar+82)**

- **These binaries are called Redback ($M_c \geq 0.1 M_{\odot}$) or Black Widow ($\mathrm{M_c} < 0.1 M_{\odot}$)**

Broadband observational properties of pulsar binaries



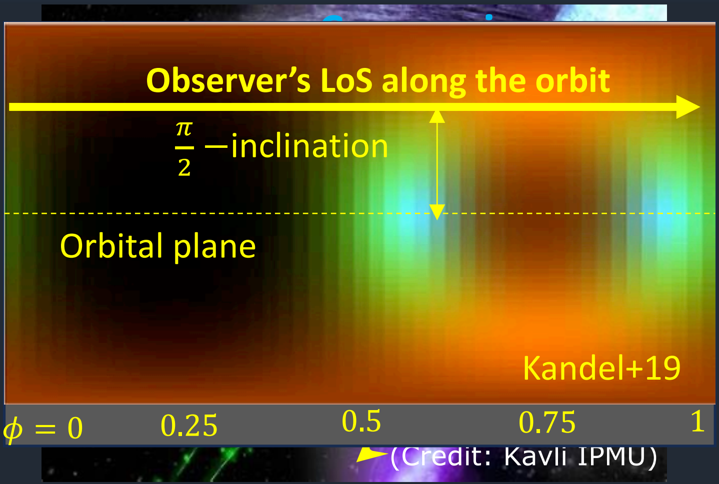


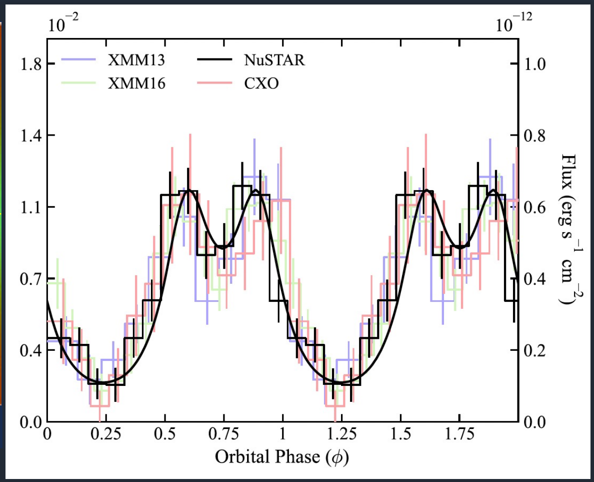
Van de

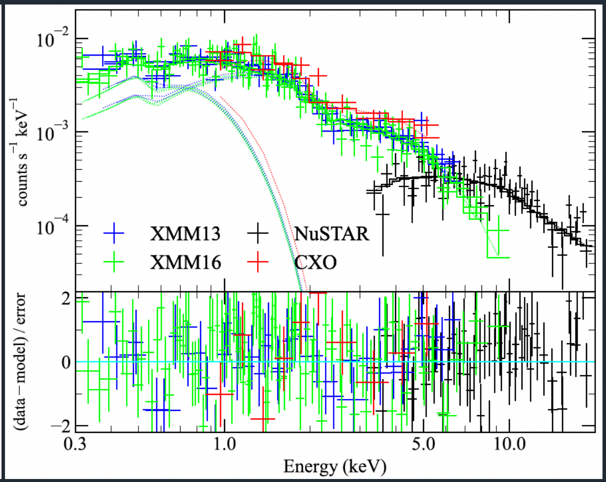
Prope			
Optica			
X-ray			
GeV	PSR PLEXP+??	Orbitally-constant pulsar emission is dominant. Orbital modulation was seen in a few systems	PSR IBS?

- The broadband SED is important, but the multi-band orbital modulation is the key to understanding these systems
- In particular, the modulating gamma rays are not well understood

Hard non-thermal X-ray emission is produced in the IBS



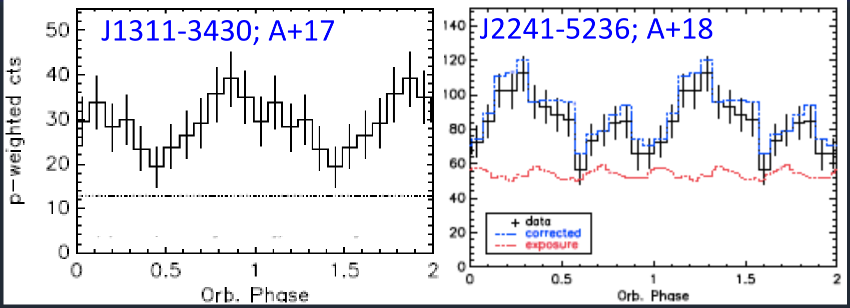




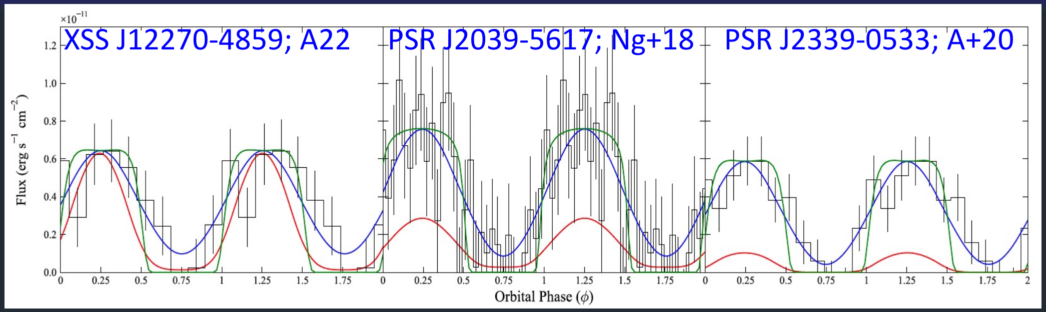
(Sim+24)

- **Interaction between companion's and pulsar's winds produces a hollow cone IBS**
- **Relativistic pulsar-wind $e^{-/+}$ are accelerated to high energies at the IBS, and they flow along the conic surface to the tail and emit synchrotron X-rays**
- **This X-ray emission is Doppler-boosted in the flow direction; this effect produces an emission ring pattern in the sky: double-peaked LCs**
- **The X-ray spectra generally exhibit hard PL emission ($\Gamma_X < 1.5$), possibly suggesting acceleration by magnetic reconnection in the IBS**

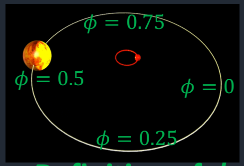
≲GeV orbital modulation is observed in PSR binaries



BWs



RBs



Definition of ϕ

Observer

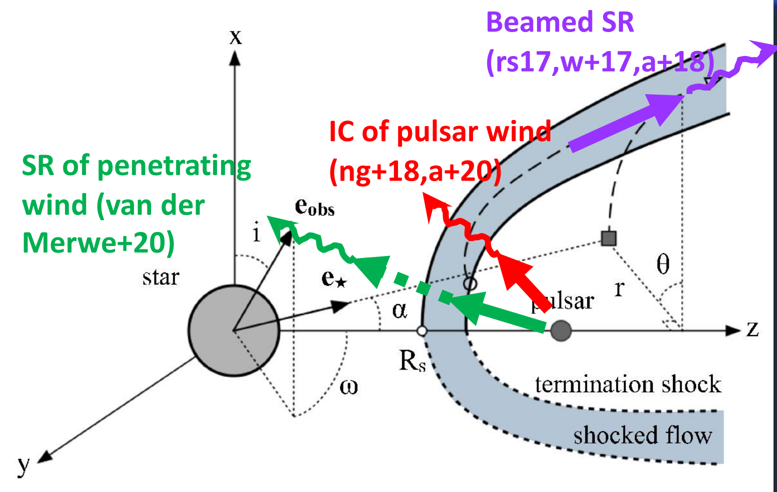
- **Fermi-LAT studies of pulsar binaries have uncovered <u>≈GeV orbital modulation</u> in some PSR binaries**
- **Their light curves have a single bump with a max. at $\phi \approx 0.25$**
- **The gamma-ray spectra for the "modulating" signal have not been well measured due to contamination by bright pulsed emission**
- **How are these <u>*orbitally-modulating*</u> GeV signals produced?**

Scenarios for the modulating X-rays and gamma rays

X-ray emission: synchrotron from IBS

Gamma-ray emission:

(1) Inverse-Compton (IC) upscattering of the stellar photons by the pulsar's wind (2) beamed synchrotron emission from the IBS electrons



- Challenges to these gamma-ray scenarios:

Simple calculations show

(1) For the given pulsar energy budget, IC emission from the preshock wind seems insufficient (e.g., a+20, Clark+20)

(2) Beamed synchrotron emission from the IBS is expected to have a maximum at phase 0.75 like X-rays: no good for Redbacks (a+17, van der Merwe+20)

Due to these difficulties, a new scenario was proposed (van der Merwe+20):

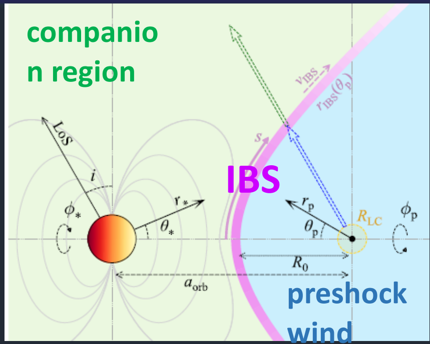
(3) Part of the pulsar wind particles may penetrate the IBS and emit synchrotron radiation under influence of the companion's B (Sanchez+17, Wadiasingh+18)

- These scenarios have been used qualitatively, but they have not been seriously tested with GeV data
- We attempt to test them using a phenomenological emission model

We constructed a multi-zone IBS model

Electrons

- The pulsar accelerates electrons to high energies: $\gamma_p \dot{N}_p m_e c^2 = \eta_p \dot{E}_{SD}$ (to accommodate scenario (3))
- Most of these primary electrons turn into low-energy electrons (secondary) with a pair multiplicity $\mathcal{M}$



- The primaries have a large gyro radius, and thus they pass through the IBS and propagate into the companion region, interacting with a strong B of the companion (3)
- The secondaries are injected into the IBS, and they are accelerated

IBS properties

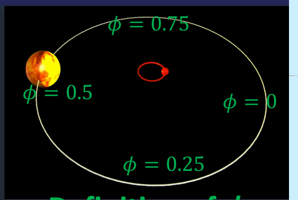
- The shape computed analytically (Canto et al. 1996; isotropic winds)
- B and bulk flow speed are prescribed to be $B_0 r_p^{-1}$ and $\Gamma_{IBS} = 1 + \frac{s}{l_s}(\Gamma_\mathrm{D} - 1)$

Companion: assumed to have a strong dipolar B ($B_{surf} \sim \mathrm{kG}$) (Sanchez+17, Kansabanik+21)

The model computes emission from electrons in 'multi zones' within each region, accounting for number/energy conservation, and radiative cooling

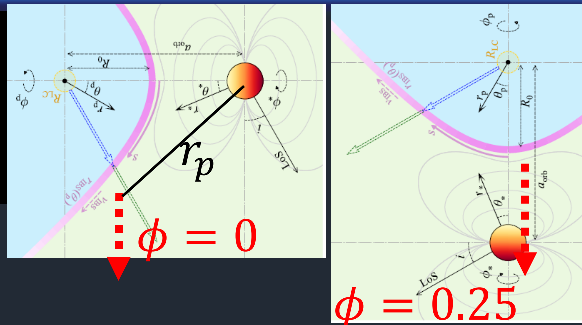
We applied this model to high-energy data from three RBs

Both emission and cooling are important in scenario (3)

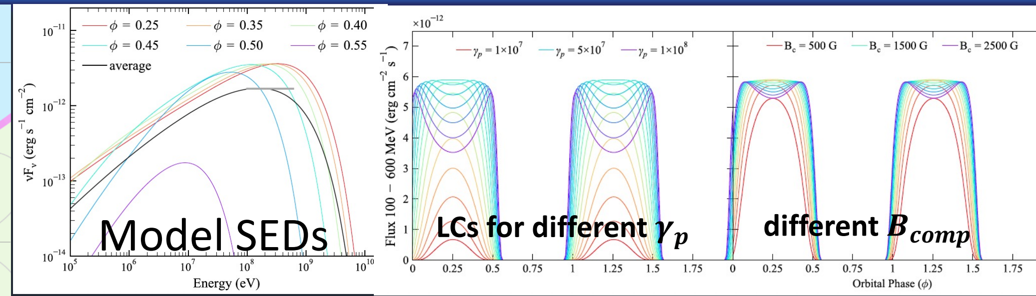


Definition of ϕ

Observer



Scenario (3): Synchrotron γ rays



Predicted LC and SED under Scenario 3

Computations of SED/LC for scenarios (1) & (2) are straightforward since cooling is weak

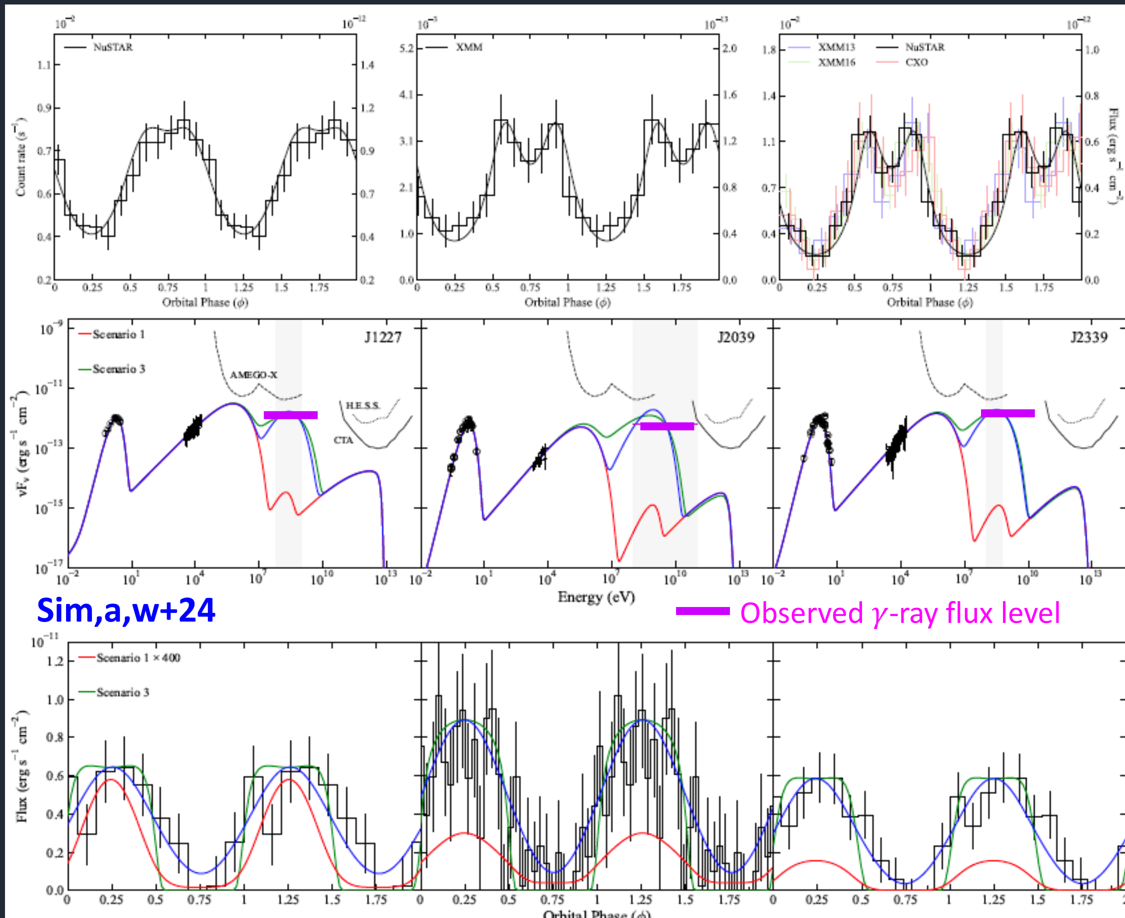
In Scenario (3), (synchrotron from shock-penetrating electrons)

- **Because of strong companion B, cooling is significant in this scenario**
- **The complex interplay between the emission and loss processes determines the shapes of the SED and LC; diverse LCs and SEDs can be reproduced**
- **E.g., the variation in B (due to r_p; $B \propto r_p^{-3}$) across the orbital phases induces the orbital modulation to the gamma-ray emission**

Modeled three RBs for which both X-ray and GeV LCs were measured

XSS J1227-4859 | PSR J2039-5617 | PSR J2339-0533

X-ray light curve | Broadband SED | GeV light curve



Input parameters: pulsars and orbits

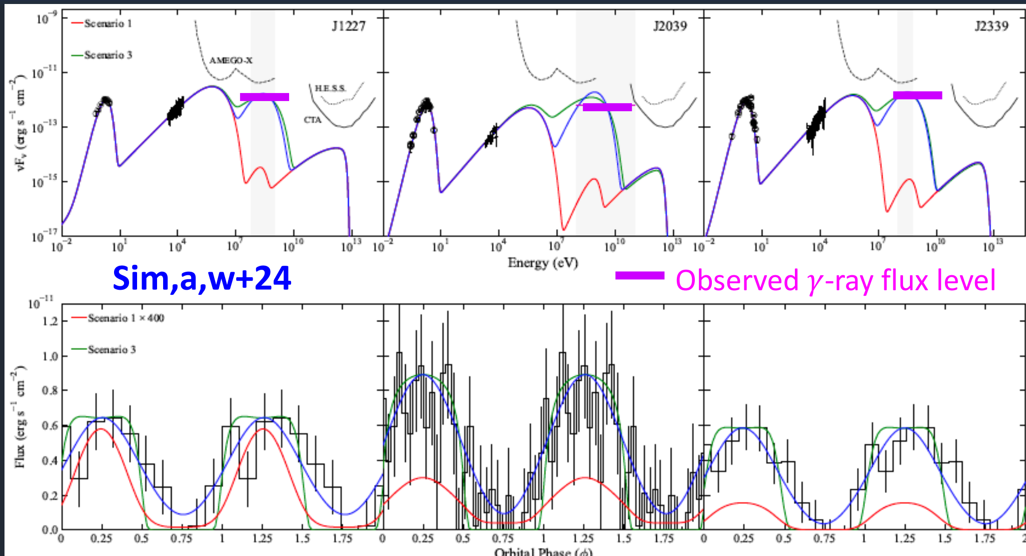
Property	Unit(s)	J1227	J2039	J2339
$\dot{E}_{SD}$	10^{34} erg s^{-1}	9.0	2.5	2.3
η_γ	...	0.05	0.21	0.18
P_B	day	0.288	0.228	0.193
T_{ASC}	MJD	57139.0716	56884.9670	55791.9182
M_*	$M_\odot$	0.27	0.18	0.32
R_*	$R_\odot$	0.29	0.30	0.35
T_*	K	5700	5500	4500
a_{orb}	10^{11} cm	1.5	1.2	1.2
i	deg	54.5	69	70
d	kpc	1.37	1.7	1.1

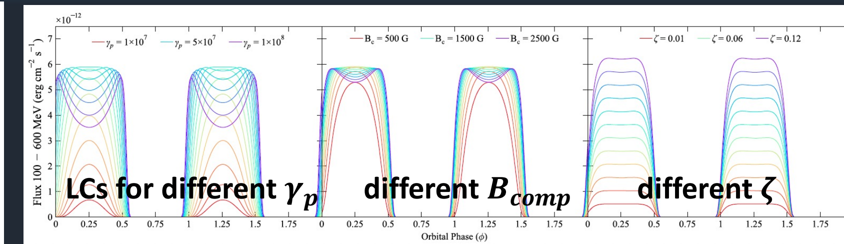
Inferred parameters: pulsar winds and IBSs

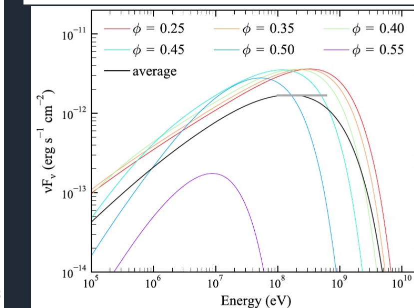
Property	Unit	J1227	J2039	J2339
Common to Scenarios 1 and 3				
p_1	...	1.56	1.34	1.37
$\gamma_{s,min}$	...	16	1	1
$\gamma_{s,max}$	10^6	10	6	6
γ_w	10^4	0.82	2.14	1.61
Γ_D	...	1.15	1.37	1.45
β	...	0.20	0.24	0.20
Scenario 1				
B_s	G	1.93	3.30	3.80
η_w	...	0.95	0.79	0.82
η_s	...	0.95	0.79	0.82
Scenario 3				
B_s	G	1.97	3.70	4.10
η_w	...	0.92	0.67	0.73
η_s	...	0.92	0.67	0.73
B_c	kG	2.35	1.52	1.39
η_p	...	0.95	0.79	0.82
ζ	...	0.03	0.15	0.11
γ_p	10^7	7	20	4
$\mathcal{M}$	10^3	8.6	9.5	2.5

- The X-ray data constrain the IBS properties: B~a few G, $\gamma_{e,max} \approx 10^7$, $\beta = \frac{\dot{E}_{SD}}{\dot{M} v_W c} \approx 0.2$, and $\Gamma_D \approx 1.3$ for these three RBs

Gamma-ray data favor scenario (3)







Predicted LCs and SEDs under Scenario 3

Scenario (1): IC by pulsar wind predicts correct LC shapes but very low gamma-ray flux

Modification to (1): Deceleration of the preshock bulk speed (blue curves).

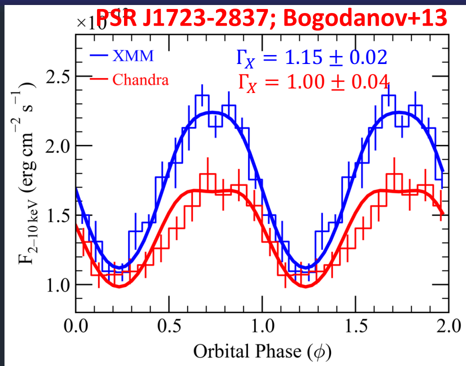
The data require a huge deceleration than prediction (PIC simulations; Sironi+11), to a level in which formation of an IBS seems problematic

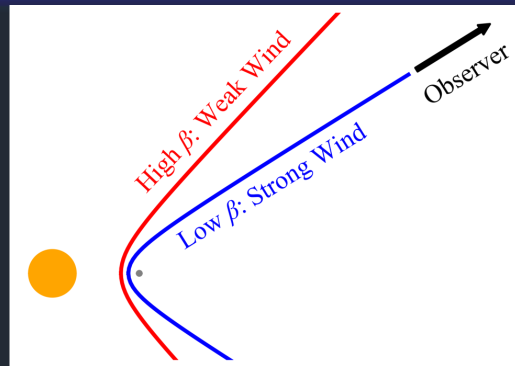
Scenario (2): has the LC maximum at phase 0.75 for these redbacks (as expected)

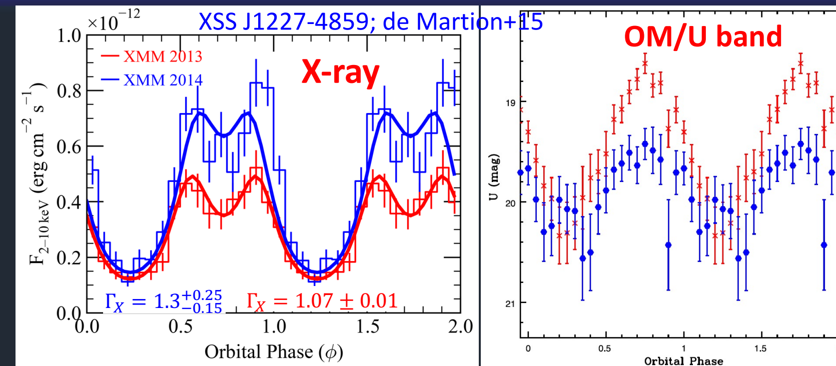
Scenario (3): The SY emission from shock-penetrating primaries can readily explain both the gamma-ray flux and light curve

- Scenario (3) requires high energy primaries ($\sim 100\ TeV$) and a high-B (~kG) companion
- This scenario predicts various LCs and SEDs depending on the model parameters

Further studies are necessary: Long-term X-ray variability







- Variations in stellar winds ($\beta = \frac{\dot{E}_{SD}}{\dot{M} v_W c}$) can explain the long-term X-ray flux variability

- F_X - F_O anti-correlation (J1227) discovered thanks to the XMM-Newton's capability of simultaneous X-ray and optical observations may give important clues to the long-term variability

- The spectral change accompanied by the flux variability (J1723 and J1227) may provide additional insights into these systems

- There are many more to be studied

Summary

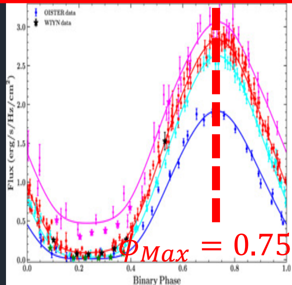
- Our IBS emission modeling of the orbitally modulating GeV signals from some RBs suggests that millisecond pulsars may accelerate electrons to $\sim$100 TeV and that these electrons may pass through the IBS and interact with the companion's ~kG B

- X-ray data provide crucial information on the IBS properties. IBS B is inferred to be ~G. Electrons in the IBS seems to have TeV energy

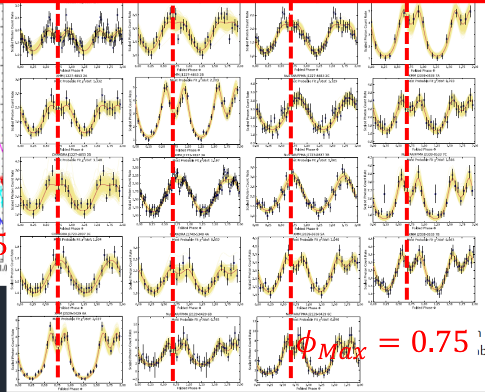
- There are some intriguing features that the current IBS model cannot explain; further observations and theoretical studies (MHD/PIC; e.g., Cortes+22) are warranted

- The list of pulsar binaries is growing, and these sources can help us understand interaction between the low-mass star, pulsar, pulsar wind structure, and IBS

Distinction between RBs and BWs?

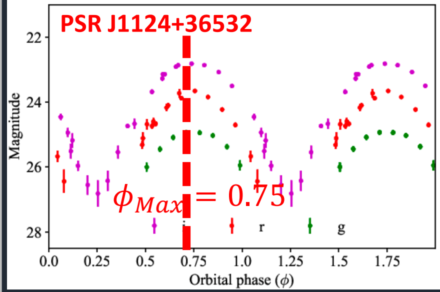


RB optical light curve



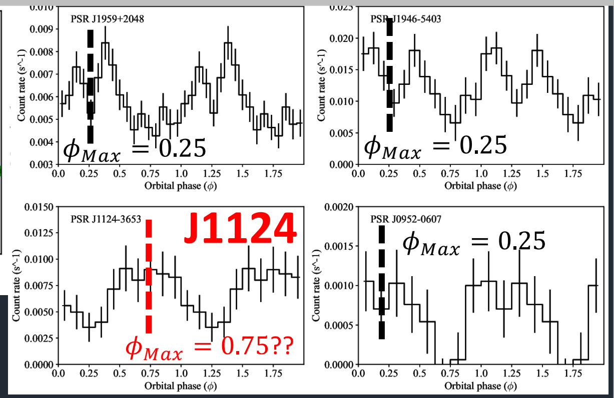
RB

RB X-ray light curves (Wadiasingh+17)



BW optical light curve (Draghis+19)

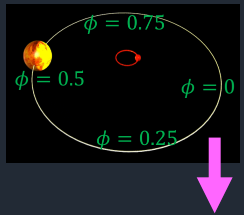
BW



BW X-ray light curves

X-ray bright when Optically bright

X-ray bright when Optically faint



- **Optical phasing**: Both BWs and RBs exhibit an optical max. at $\phi_{Max} = 0.75$ 

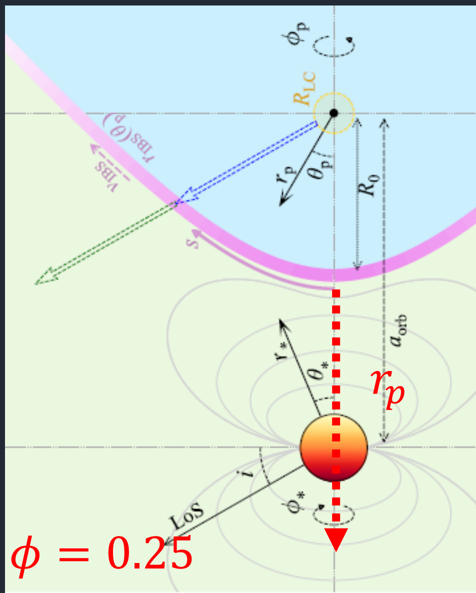
- **X-ray phasing** (pulsar-to-companion wind strength ratio β)

-All RBs with a measured X-ray LC have a max at $\phi_{Max} = 0.75$

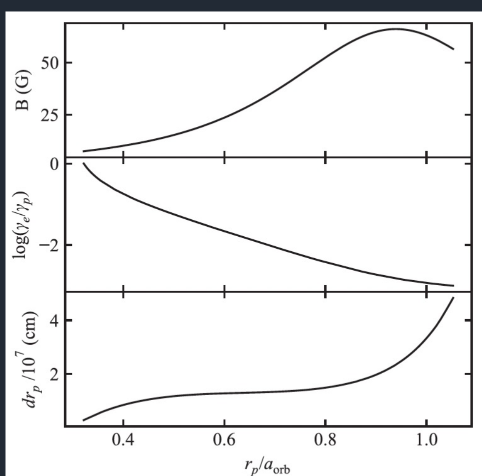
-3 out of 4 BWs have an X-ray max. at $\phi_{Max} \approx 0.25$, but **J1124 has a max. at $\phi_{Max} = 0.75$**

- Redbacks are generally brighter than black widows in the X-ray band

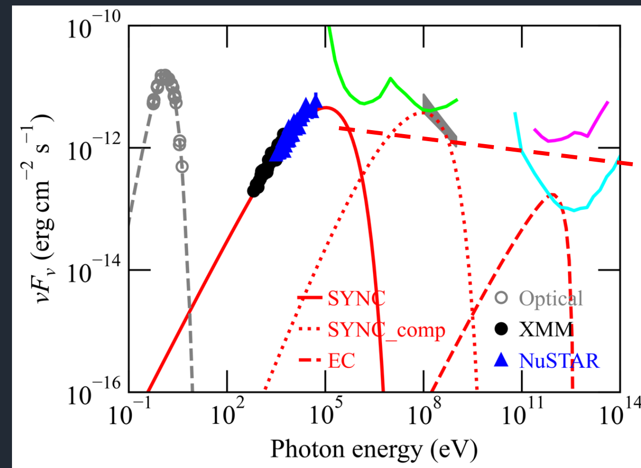
BACKUP



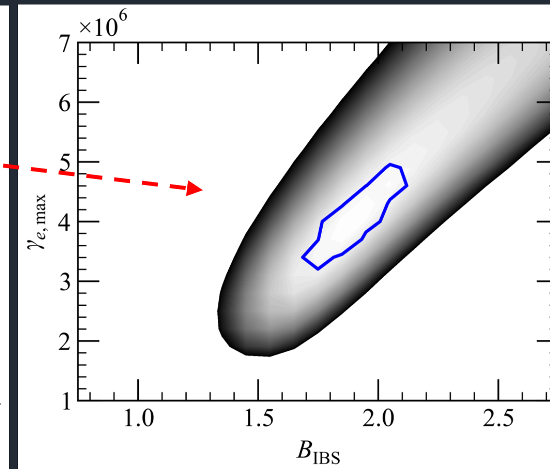
ϕ_p
R_{LC}
r_p
θ_p
R_0
a_{orb}
r_*
θ_*
r_p
i
LoS
ϕ_*
$\phi = 0.25$



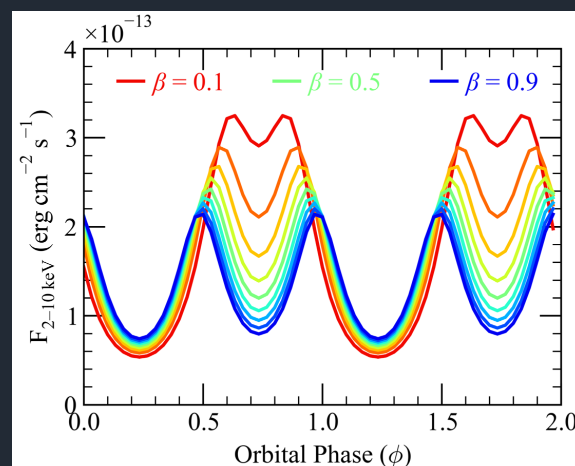
B (G)
50
25
0
$\log(\gamma_e/\gamma_p)$
−2
$dr_p/10^7$ (cm)
4
2
0.4
0.6
0.8
1.0
r_p/a_{orb}



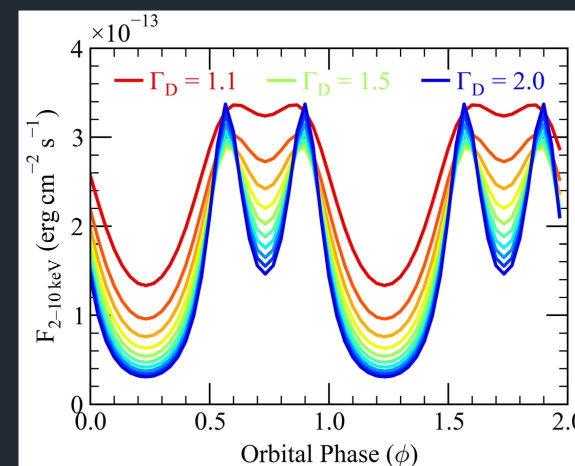
νF_ν (erg cm^{-2} s^{-1})
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
10^{14}
Photon energy (eV)
SYNC
SYNC_comp
EC
Optical
XMM
NuSTAR



$\times 10^6$
$\gamma_{e,\max}$
1
2
3
4
5
6
7
1.0
1.5
2.0
2.5
B_{IBS}



$\times 10^{-13}$
$\beta = 0.1$
$\beta = 0.5$
$\beta = 0.9$
$F_{2\text{–}10\,keV}$ (erg cm^{-2} s^{-1})
0
1
2
3
4
0.0
0.5
1.0
1.5
2.0
Orbital Phase (ϕ)



$\times 10^{-13}$
$\Gamma_D = 1.1$
$\Gamma_D = 1.5$
$\Gamma_D = 2.0$
$F_{2\text{–}10\,keV}$ (erg cm^{-2} s^{-1})
0
1
2
3
4
0.0
0.5
1.0
1.5
2.0
Orbital Phase (ϕ)