Variable high-energy emission in intrabinary shock of various pulsar binaries

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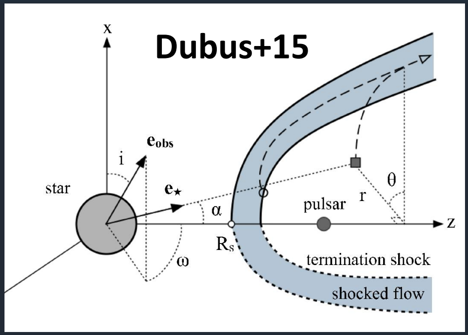
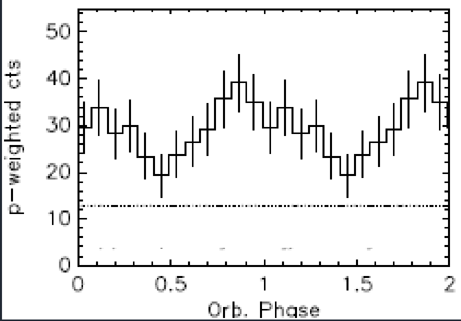
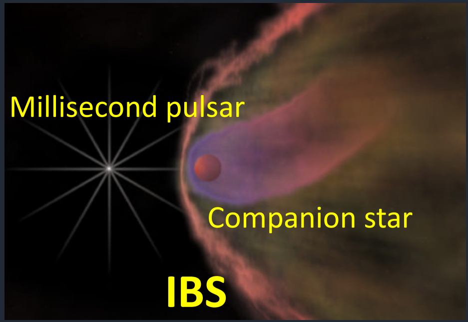
OUTLINE

- Intrabinary shock in gamma-ray binaries
- Millisecond pulsar binaries: BWs, RBs
- IBS signatures in pulsar binaries
- Gamma rays in pulsar binaries
- Issues toward understanding gamma-ray modulation in pulsar binaries
- Summary

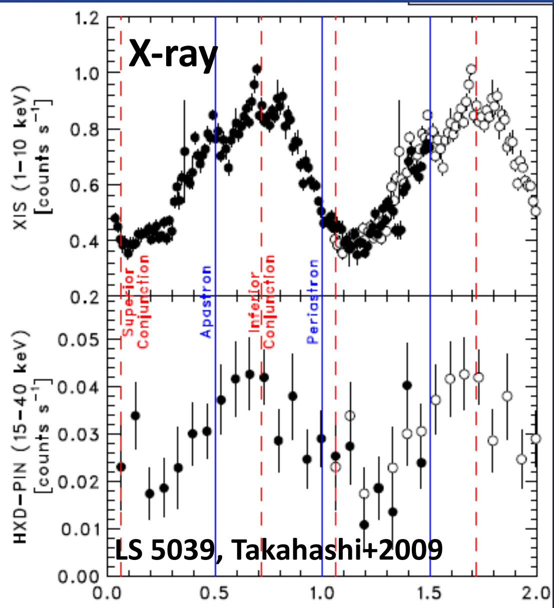


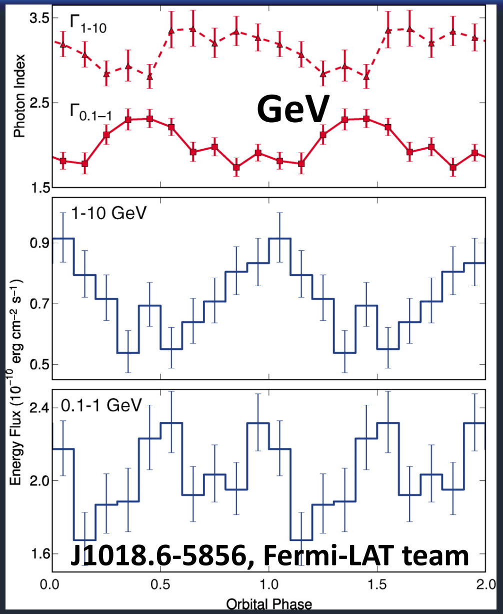


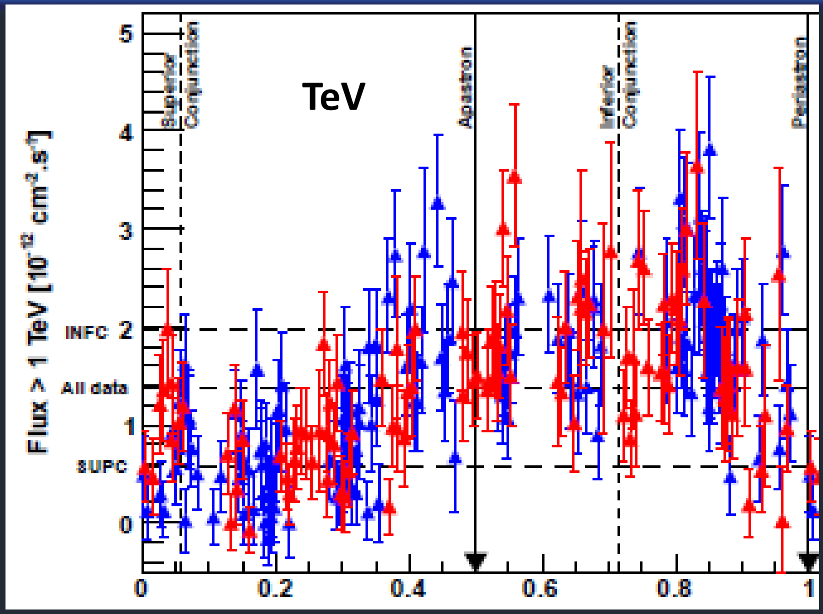


https://aasnova.org/2017/09/01/how-a-black-widow-consumes-its-companion/

Variable HE emission has been seen in gamma-ray binaries



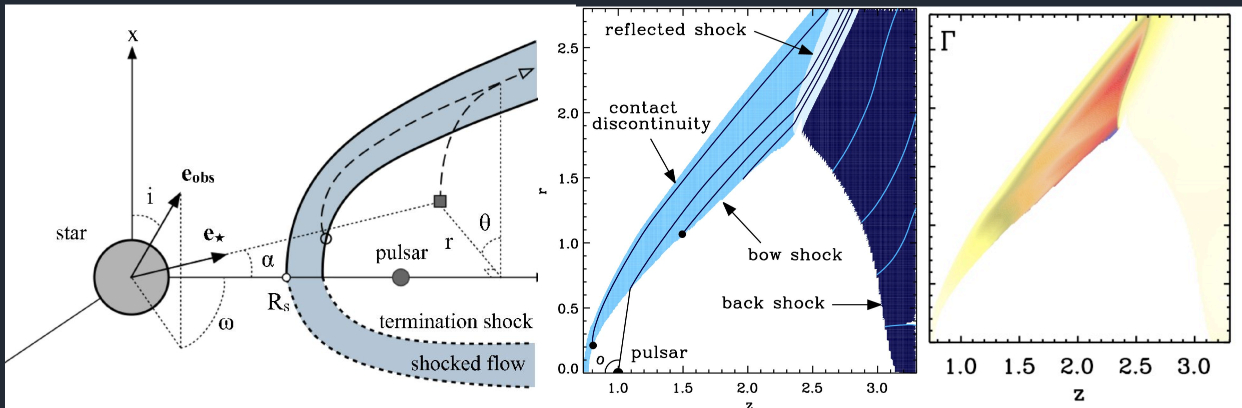




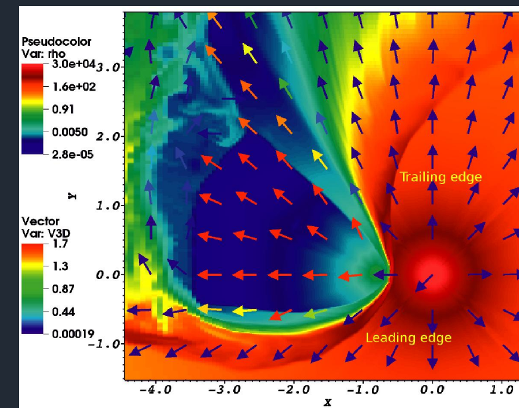
LS 5039, Mariaud+2015

- Gamma-ray binaries show variability in the Radio to TeV band
- The nature of the compact object is known for only a few sources
- In some systems, the compact object is assumed to be a pulsar. It is then believed that interaction between the pulsar's and the companion's winds is responsible for the emission

Recent studies further our understandings of the systems



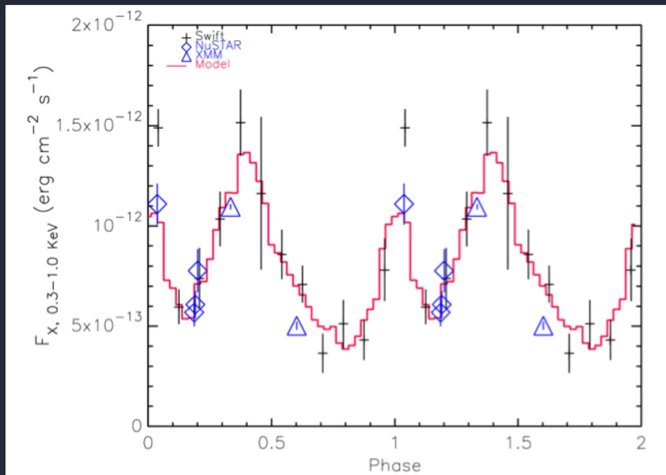
Dubus+15: RAMSES-RHD simulations, see also Bogovalov+2008

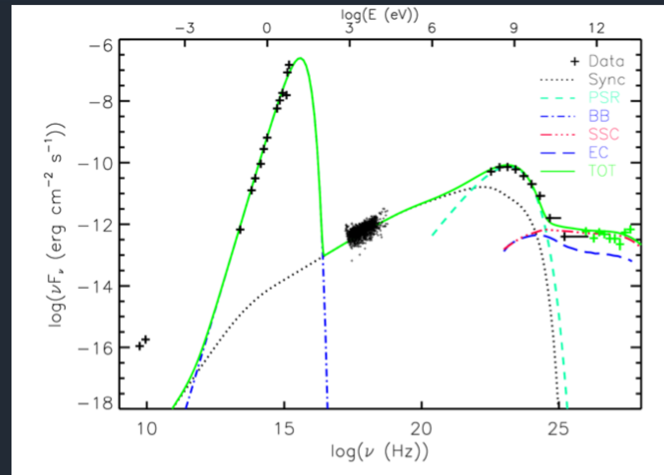


Bosch-Ramon+15: PLUTO-RHD simulations

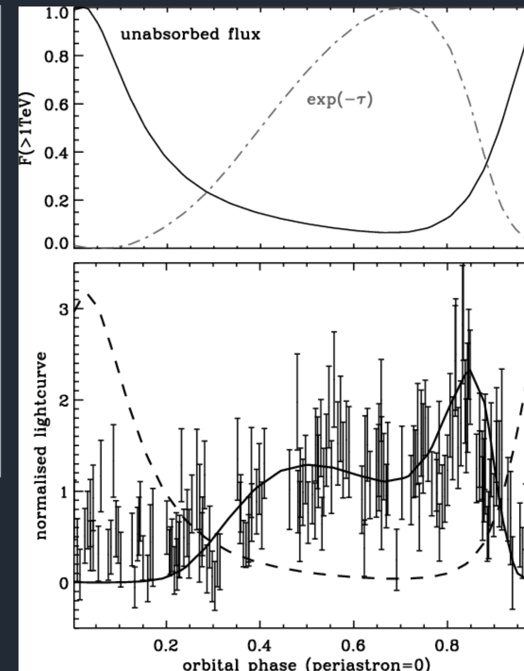
- For some gamma-ray binaries with an assumed pulsar, intrabinary shock (IBS) models are used to explain the SED and orbital modulation
- In the IBS models, wind-wind interaction forms shock which accelerates electrons to very high energies
- The electrons flow along the shock; the detailed flow properties are studied with RHD simulations (e.g., flow shape and bulk Γ)

IBS scenarios have been applied to gamma-ray binaries





ar17: 1FGL J1018.6-5856



Dubus+08

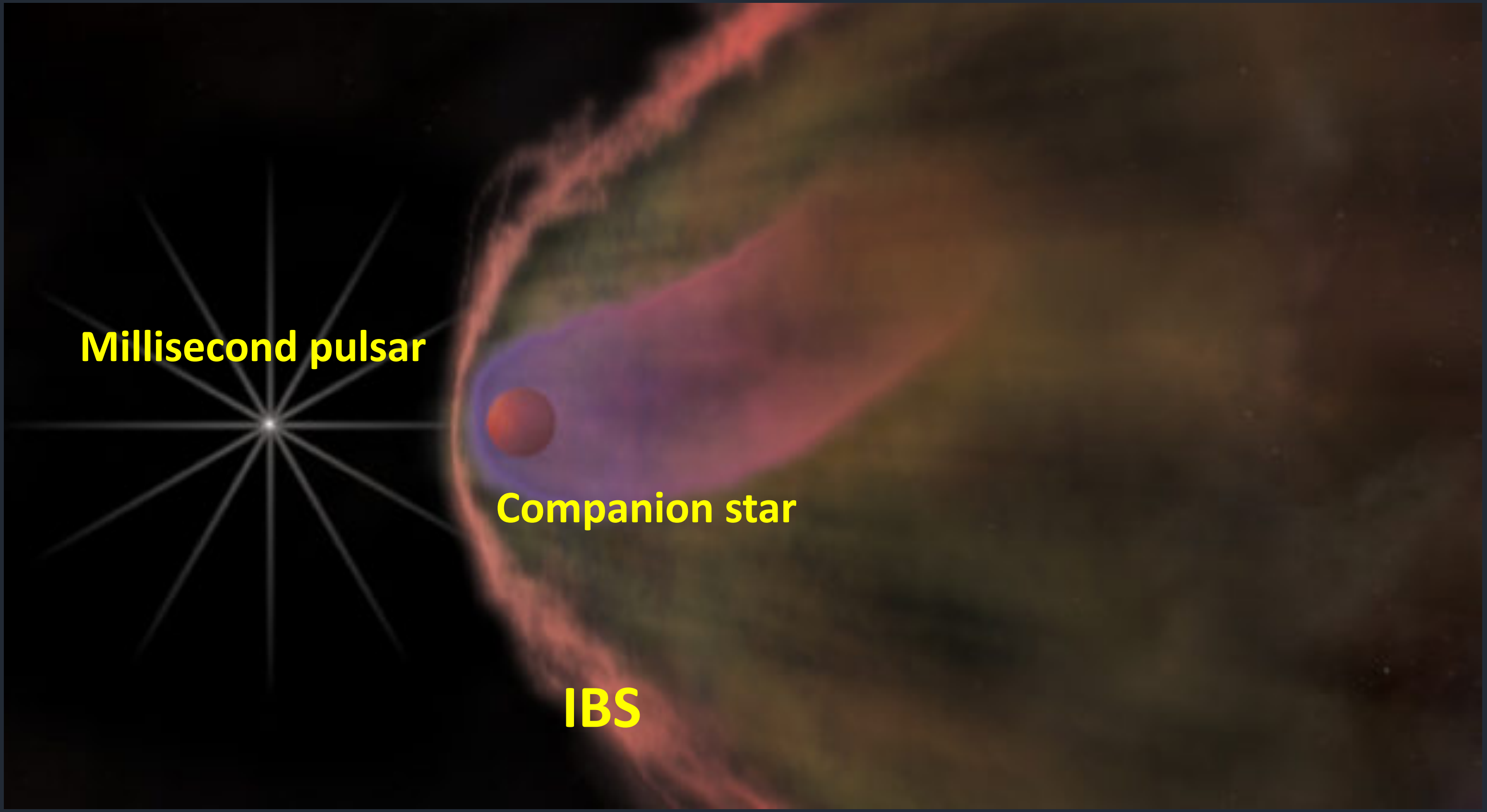
- The basic IBS scenarios are used to explain high-energy emission in gamma-ray binaries

- Basically, X-rays are produced in the shocked flow, and beaming and orbital eccentricity produce the modulation

- Gamma-ray emission can be produced by external-Compton and/or self-Compton in the flow. Here $\gamma - \gamma$ absorption is important for variability

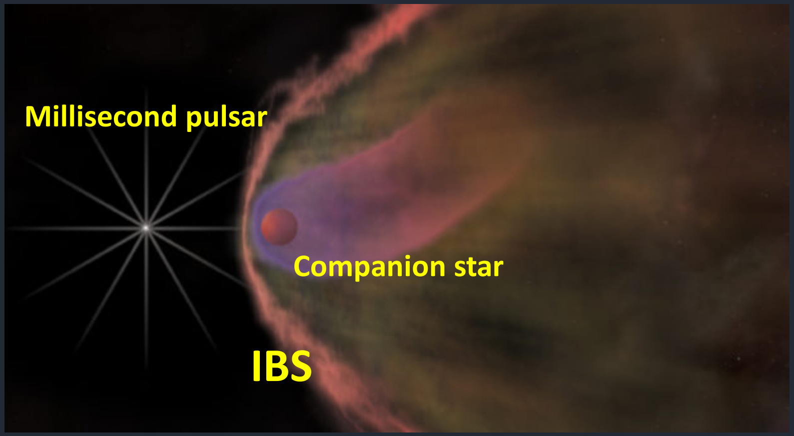
Almost the same physics applies to other systems

PULSAR BINARIES



https://aasnova.org/2017/09/01/how-a-black-widow-consumes-its-companion/

The same IBS scenario applies to pulsar binaries



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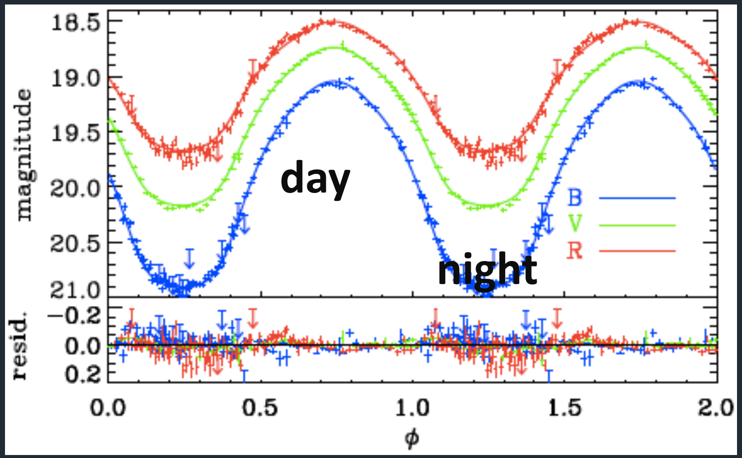
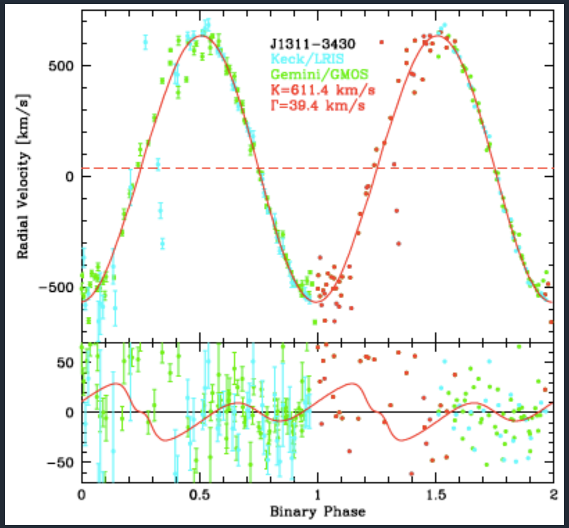


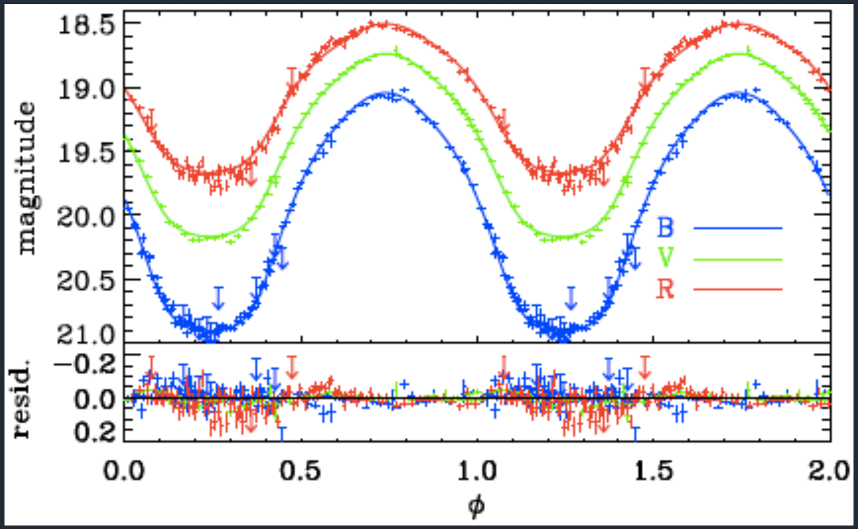
PSR J2215+5135, Schroeder+14

- A recycled pulsar (millisecond) in a tight orbit $(P_B \sim hr - day)$ with a light stellar companion $\left(M_C < M_\odot\right)$: black widows (BW) $M_C \leq 0.1\ M_\odot$ and redbacks otherwise. 30—40 systems are known and the list is growing.
- The pulsar irradiation of the facing side of the companion (day-night cycle) induces stellar wind
- Pulsar and stellar winds interact to form intrabinary shock (IBS)

Pulsar binaries may harbor massive neutron stars



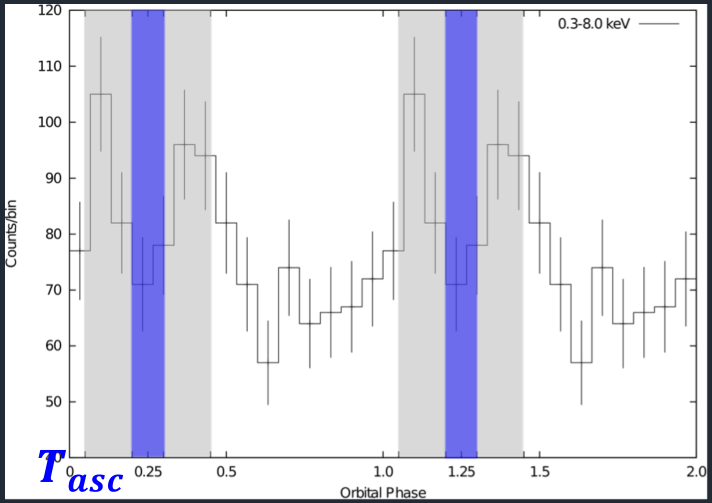
PSR J1311-3430, Romani+15



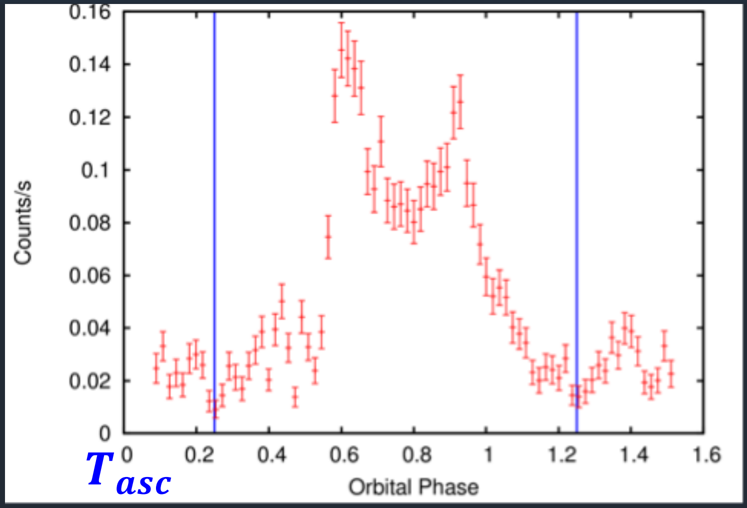
PSR J2215+5135, Schroeder+14

- **Orbital parameters of the binaries via optical light-curve modeling are used for neutron star mass estimation (anisotropic heating + ellipsoidal modulation)**
- $M_{psr} > 2M_\odot$ **was inferred for a few pulsar binaries: e.g., PSR B1957+20 (van_k+12), PSR J2215+5135 (sh14), PSR J1311—3430 (r+15)**
- **This method is subject to large systematic uncertainties due to the heating pattern correction** $M_{psr} = (K_{corr}/sini)^3$ **(e.g., r+15)**

IBS is also prominent in some other pulsar binaries



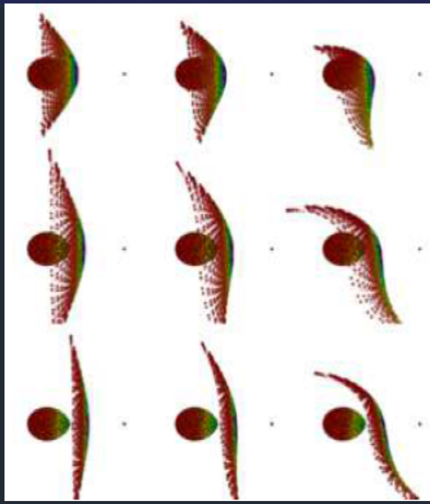
BW PSR B1957+20 , Huang+12



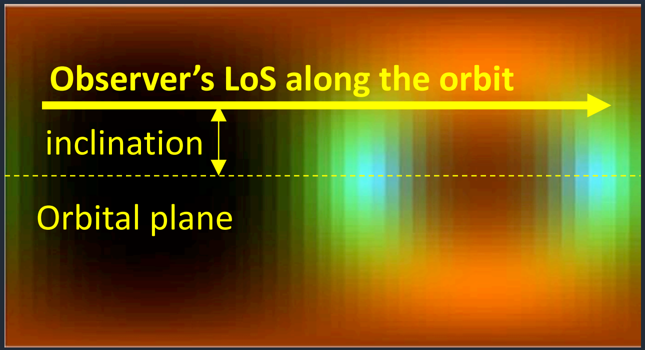
RB PSR J2129—0429, Roberts+15

- These pulsar binaries shows strong X-ray signature of IBS
- The double-peaked X-ray light curves are believed to be formed by the shock geometry; Earth LoS crosses the shock tangent twice per orbit
- Hence, IBS models almost identical to those used for gamma-ray binaries are developed and applied to these systems, and provided estimates of the system parameters (e.g., inclination)

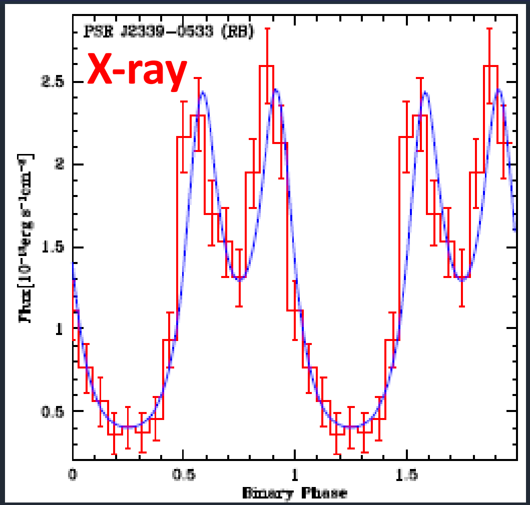
IBS models are successful to explain the X-ray emission



Romani+16

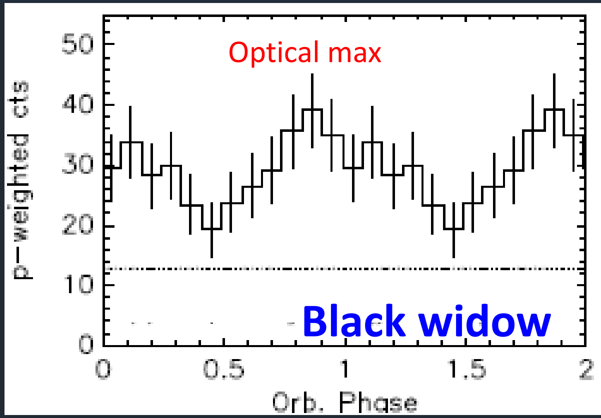


Kandel+19

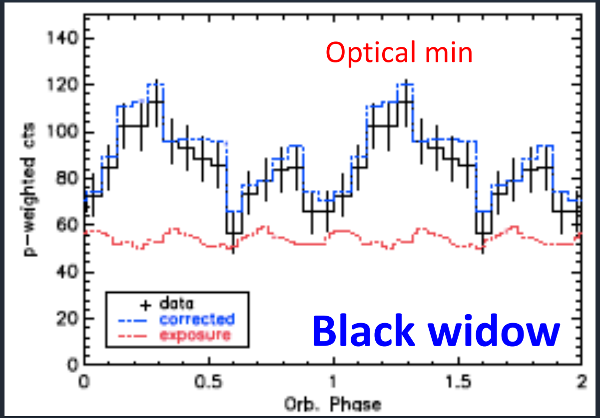


- Conic IBS is formed due to interaction of the winds
- Particle flow along the shock produces ring emission in the sky
- The observer sees bright emission when the LoS crosses the shock tangent: 0—2 peaks in the X-ray light curve
- This explains the X-ray emission very well

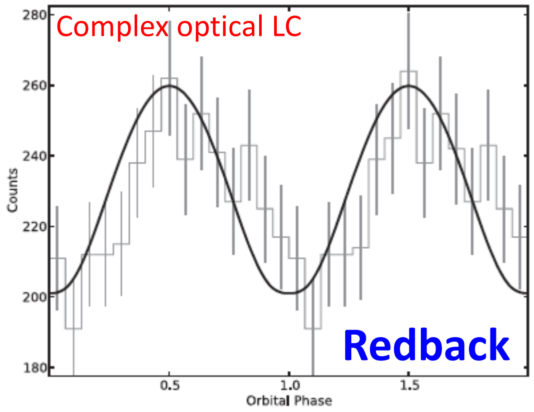
We start to see GeV modulation in PSR binaries



J1311-3430; An+17



J2241-5236; An+18

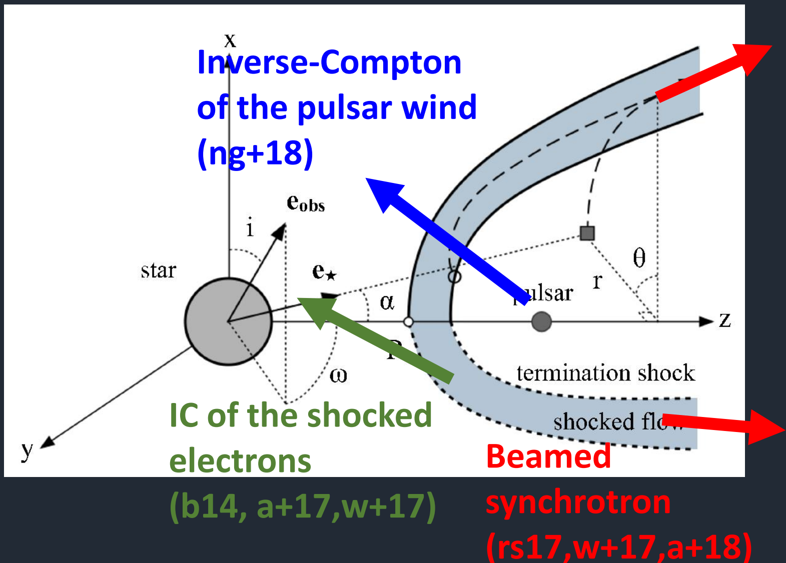


J2039-5618; Ng+18,
Complex Optical, Salvetti+2015l

- **Fermi-LAT follow-up studies of pulsar binaries revealed ~GeV modulation in some PSR binaries**
- **The light curves look simple, but peak phases are different; the modulation is seen in various phases: optical max (J1311) or min (J2241)**
- **There are only 4 PSR binaries with gamma-ray modulation claimed, but the significances all relatively low $(p > 10^{-6})$: the gamma-ray spectrum is not well measured due to pulsar contamination**

Some processes are suggested for the gamma rays

- **Beamed synchrotron radiation** may produces modulating low-energy (< a few 100 MeV) gamma rays in IBS similar to the X-ray emission

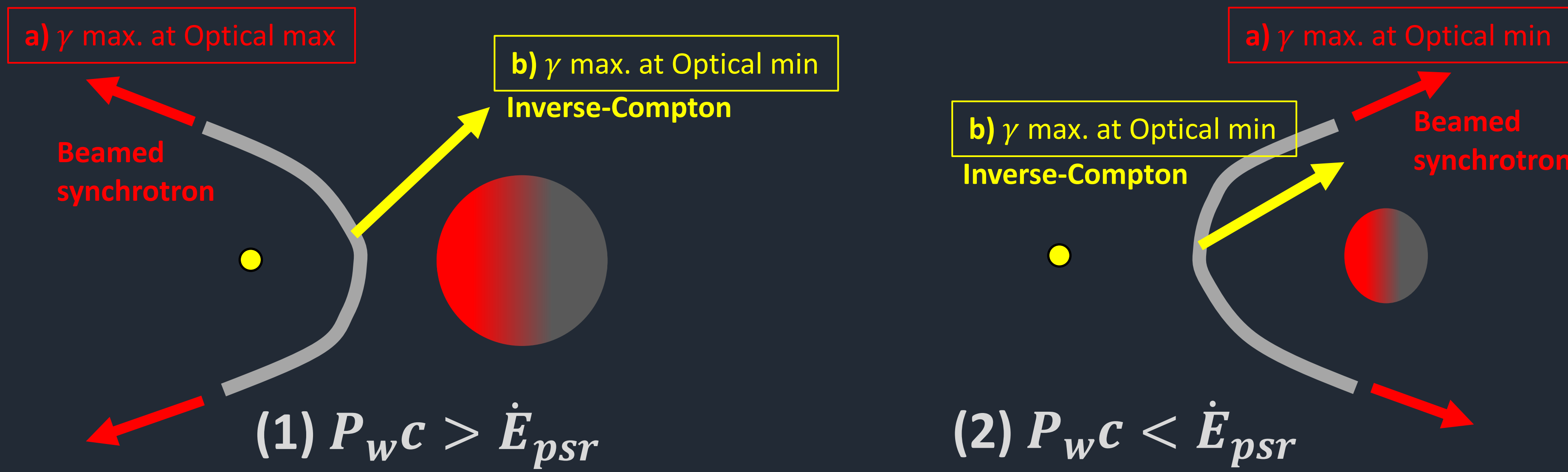


- **Inverse-Compton upscattering of the stellar photons by the pulsar's wind** produces modulating gamma-ray signals

- **The same inverse-Compton upscatternig by the IBS** electrons produces gamma-rays

- These seem to be speculative yet, and more work is needed

Depending on the wind strengths, IBS may curve to either direction



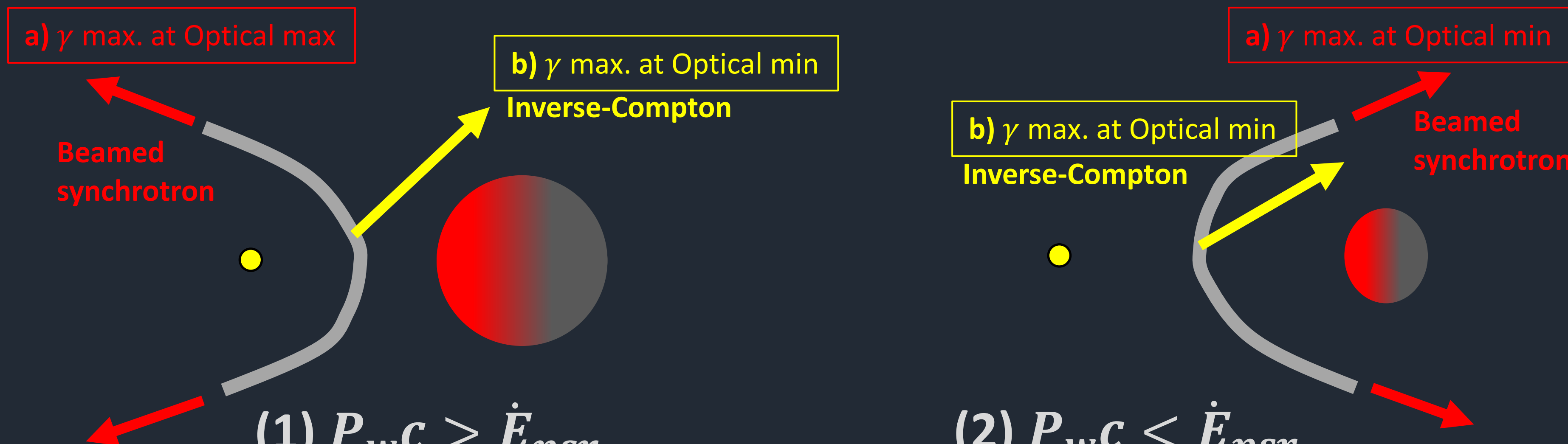
- **Stellar wind momentum flux $P_w c$ vs. pulsar energy loss $\dot{E}_{psr}$**

(1) $P_w c > \dot{E}_{psr}$: shock bends toward the pulsar (gamma-ray binaries, redbacks?)

(2) $P_w c < \dot{E}_{psr}$: shock bends toward the pulsar (black widows?)

- **The gamma-ray phasing depends on the shock direction and the emission mechanism**

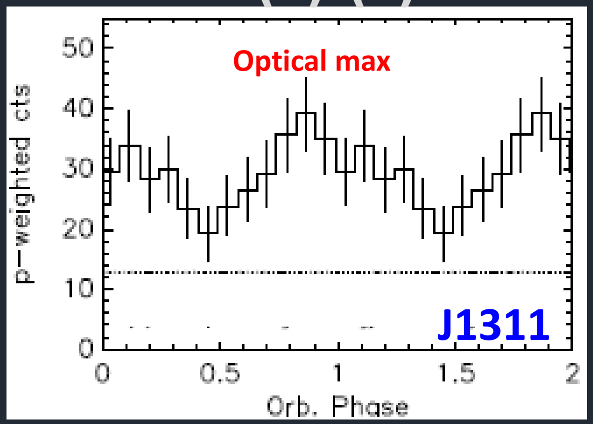
This scenario can qualitatively explain the gamma-ray modulations



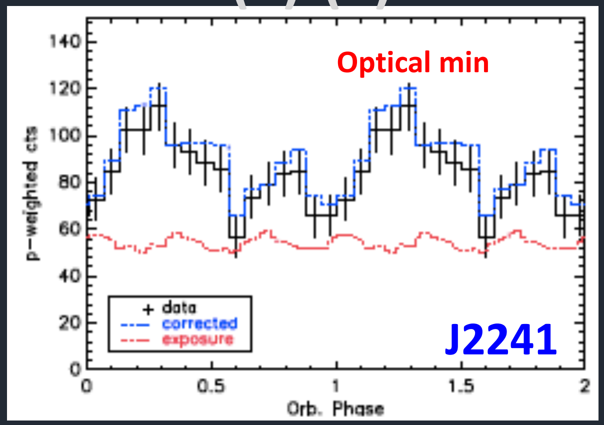
(1) $P_w c > \dot{E}_{psr}$

(2) $P_w c < \dot{E}_{psr}$

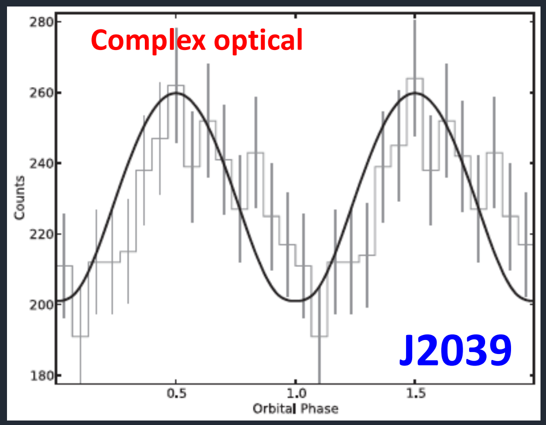
(1)-(a)?



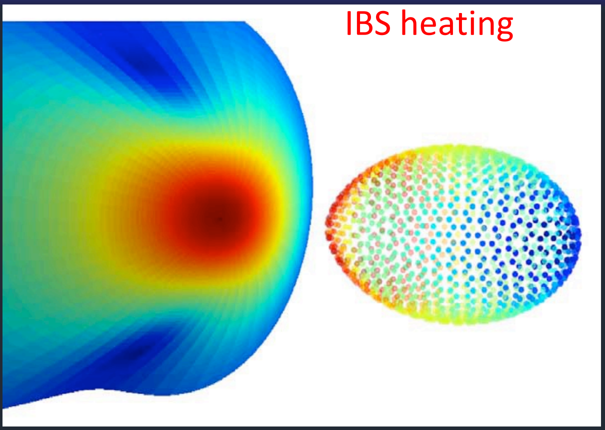
(2)-(a)?



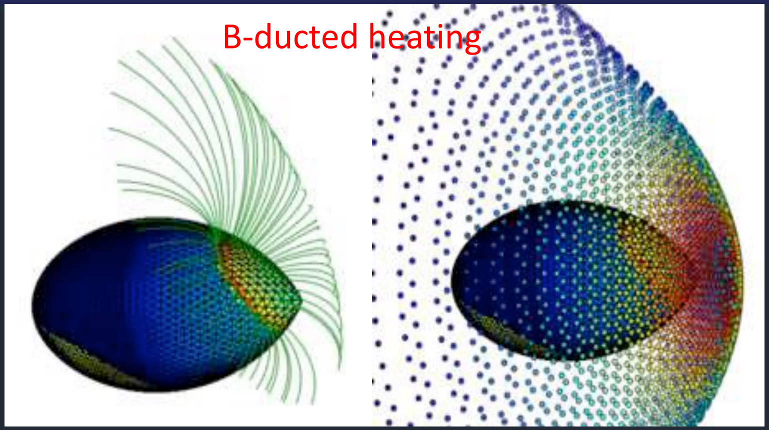
Complex



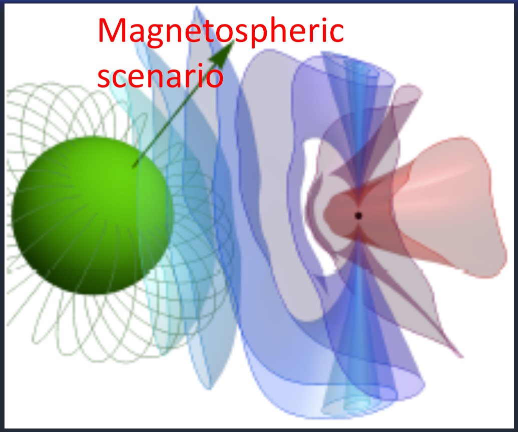
Detailed modeling is more complicated



Romani+16



Sanchez+17



Wadiasingh+19

- Companion heating mechanism is not well known:
  direct beam, IBS heating (rs16), B-ducted heating (sr17)

- The heating is related to the anisotropic stellar wind profile. In addition pulsar wind may be anisotropic and companion B may be important (kra19, w19), making the IBS shape complicated

- More details of shock structure and flow in the shock are needed

Towards understanding of high-energy emission in PSR binaries

- **Companion heating:** optical light curve can give some hints
- **Stellar and pulsar wind profiles:** simple isotropic-isotropic wind interaction seems to work. But some modification are needed
- **Acceleration and flow of particles in the shock:** X-ray data can tell us about the shock direction and basic flow properties. RHD simulations can help (e.g., dlf15, bbp15)
- **Which gamma-ray emission mechanism dominates?**
  Need more sources with higher significance of gamma-ray modulation
  Emission models that can explain from the optical to the gamma-ray emission (optical to X-ray: rs16)
- **Observationally isolating the IBS emission:** Fermi-LAT keeps collecting data. Future soft-γ missions (AMEGO, e-ASTROGAM), VHE observations?

Summary

- The list of gamma-ray binaries is growing, and these sources have helped us to understand IBS physics better
- Variable gamma-ray emission is seen in low-mass pulsar binaries. They have a known compact object, and so can provide better samples for IBS studies
- The orbitally-modulated GeV emission in some pulsar binaries is not yet very well explained; this can give us new insights into IBS physics
- There are still many things to know about pulsar binaries; more observations and RHD studies can help to further our understandings of the variable gamma-ray emission in Galactic sources