On the Expected Orbitally-modulated TeV Signatures of Spider Binaries

C. Venter[1], A. Kopp[1], Z. Wadiasingh[2,3,4,1],
A.K. Harding[5], M. Baring[6]

[1]Centre for Space Research, North-West University
[2]Department of Astronomy, University of Maryland
[3]Astrophysics Science Division, NASA Goddard Space Flight Center
[4]Center for Research and Exploration in Space Science and Technology, NASA/GSFC
[5]Theoretical Division, Los Alamos National Laboratory
[6]Department of Physics and Astronomy - MS 108, Rice University

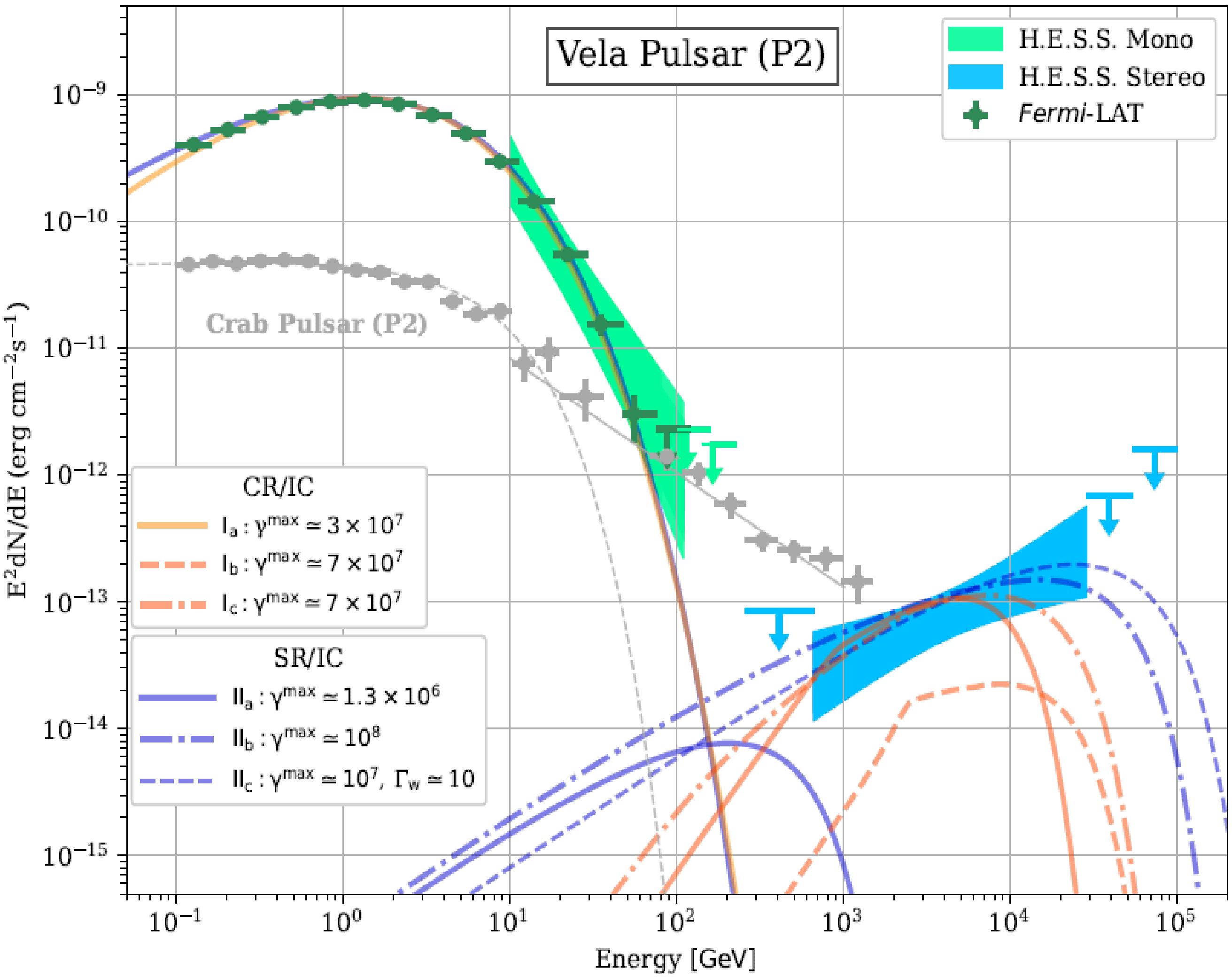
8th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy, Milan, Italy, 2 – 6 September 2024

Science Motivation

s://www.sci.news/astronomy/fermi-gamma-ray-eclipses-spider-binary-systems-11600.html

Science Motivation (I)

- **H.E.S.S. detected a pulsed ~20 TeV component from the Vela pulsar: constrains maximum energy of radiating particles!**



Aharonian et al. (2023)

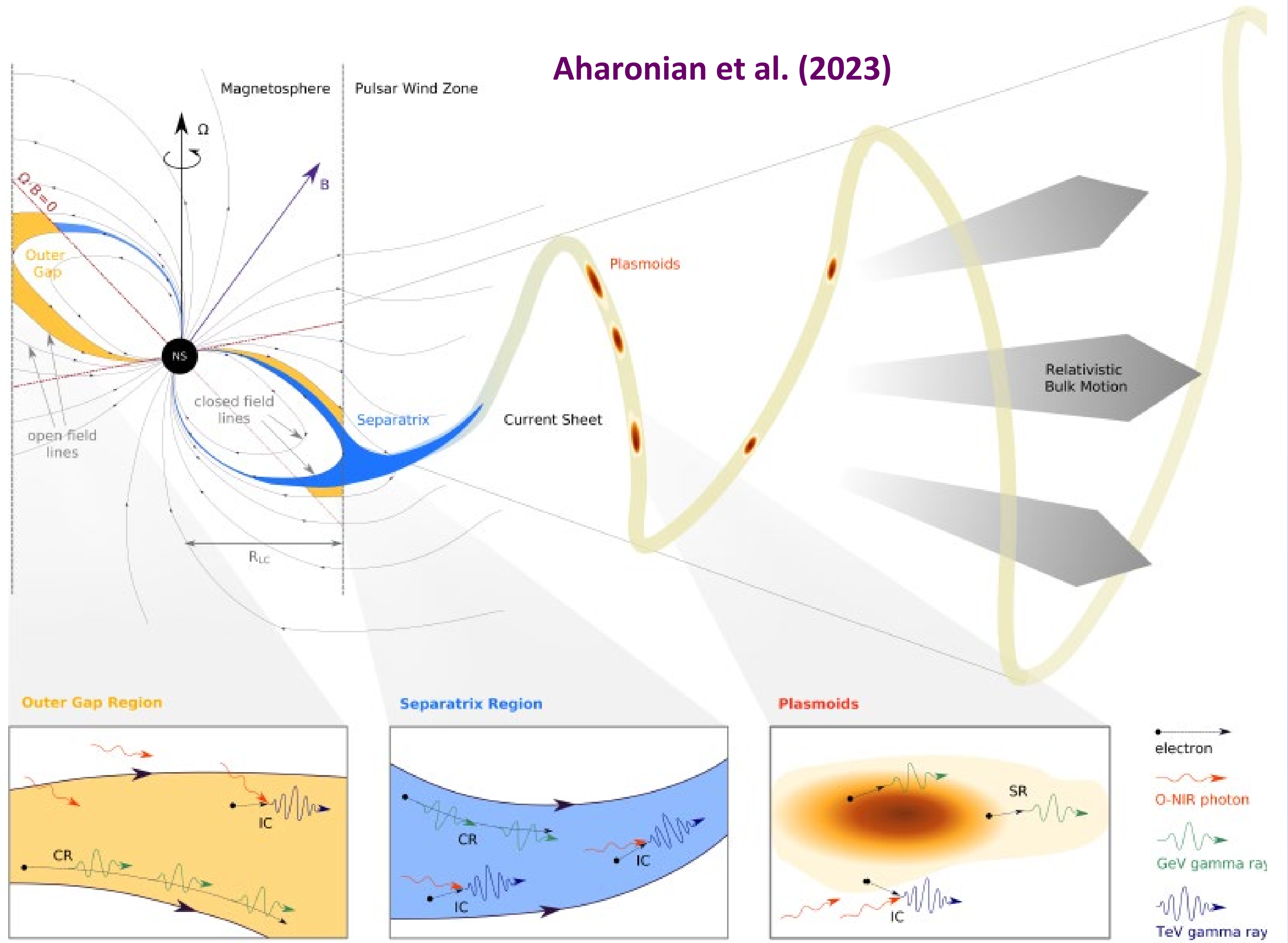
Science Motivation (I)

- Location of energy dissipation : ‘striped wind’ / current sheet
- Looking for <u>other</u> novel sources with TeV signatures that can probe:

✓ Pulsar wind composition

✓ Shock physics, relativistic acceleration processes

✓ Interaction between pulsar and companion



Science Motivation (II)

<u>Some VHE / UHE Pulsar contributions @ γ2024:</u>

- **Reviews** (Cos-B, HAWC, VERITAS, PeVatrons, pulsars): G. Kanbach; S. Casanova; A. Furniss; F. Aharonian; A.K. Harding
- **Multi-GeV / Multi-TeV Pulsations** from PSR J1509-5850, Vela, PSR B1706-44 with H.E.S.S.: M. Regeard, A. Djannati-Ataï
- **VHE pulsations** from the Crab & Geminga pulsars with LST-1: R. Lopez-Coto, P.K.H. Yeung, G. Ceribella, G. Brunelli, T. Saito
- **PWN studies:** K. Egg; S.T. Spencer; S. Kato
- **TeV halos:** G. Giacinti; D. Zheng
- **VHE gamma rays from accreting neutron stars:** L Ducci, P Romano, Prof. A. Santangelo, S. Vercellone
- **Gamma-ray binaries:** T. Tanaka
- **LIV constraints:** C. Plard, S. Caroff
- **Multi-messenger emission from pulsar glitches**: M. Razzano
- **Modelling (SCR, PIC, vacuum, electrospheres):** D. Íñiguez-Pascual, D. Torrest, D. Viganò; A. Timokhin; T.A. Oliveira Gomes, J. Goulart Coelho; T. Francez, F. Mottez, G. Voisin

"Pulsar wind": Multi-TeV particles

Science Motivation (III)

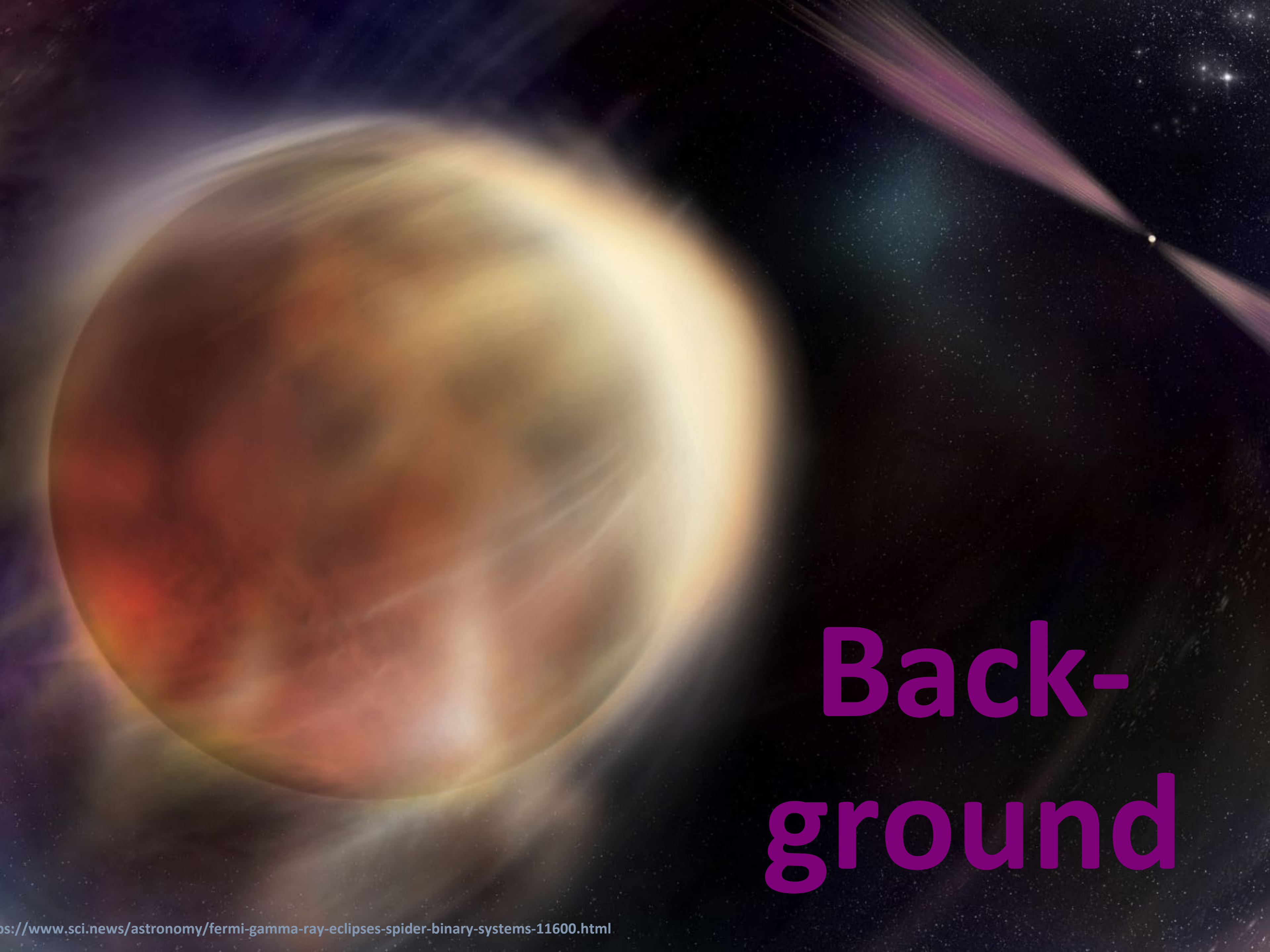
- **3PC:** ~50 *Fermi* spiders and candidates
- Multi-wavelength **follow-up**
- Novel source class
- **Labs** of relativistic physics
- Rich multi-wavelength phenomenology
- **Links:**
  - ✓ Evolutionary link with tMSPs
  - ✓ Probing recycling scenario
  - ✓ Sources of terrestrial leptonic cosmic rays
  - ✓ EOS constraints
  - ✓ PTA / FRB Science

3rd *Fermi* LAT Pulsar Catalog

Smith et al. (2023)

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

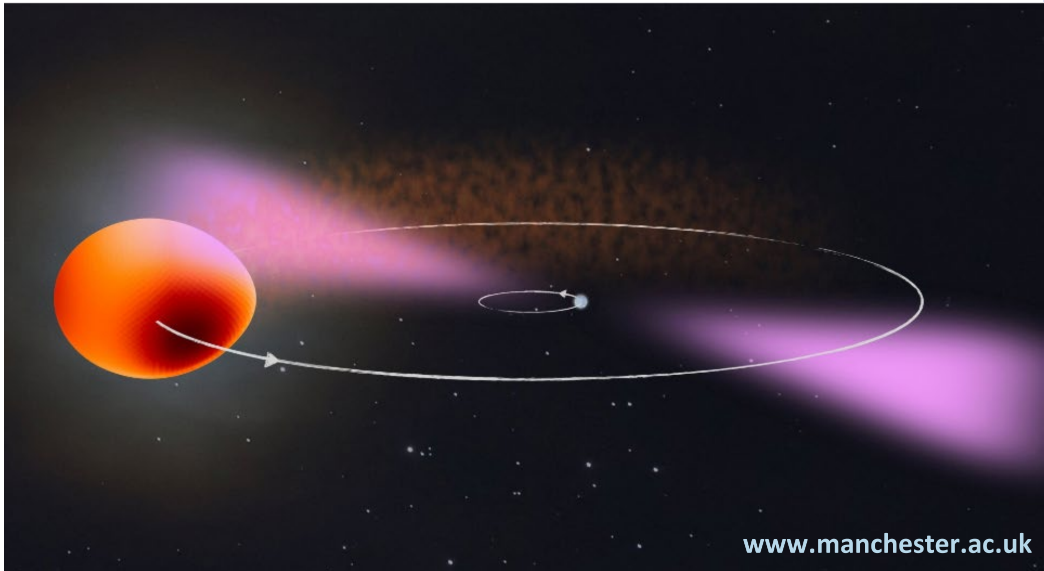


Back-ground

ps://www.sci.news/astronomy/fermi-gamma-ray-eclipses-spider-binary-systems-11600.html

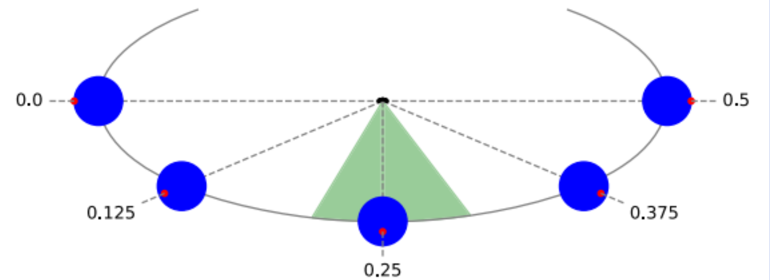
Spider Binaries

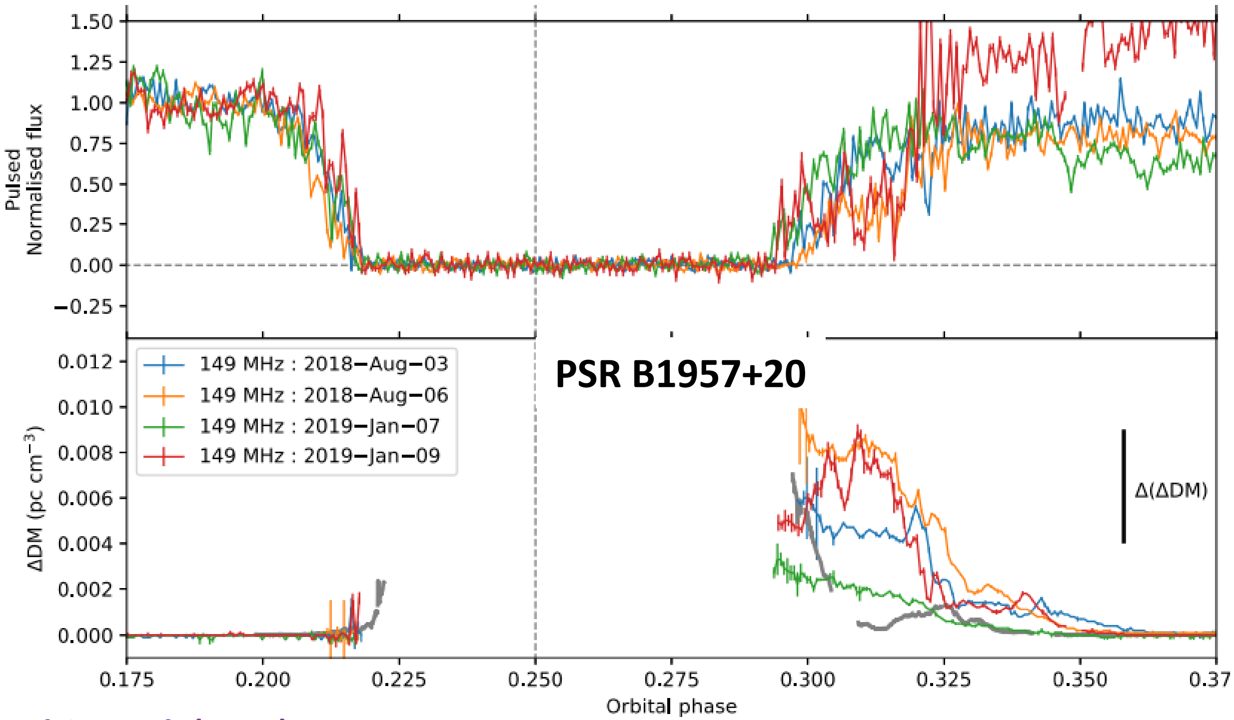
- Actual Black widow (BW) & Redback (RB) spiders: may devour male partners (rarely, though; and opposite).
- Analogy: similar behaviour among MSP binary systems.
- Tight binaries: P_{orb} < 24 h.
- Intense pulsar wind heats tidally-locked companion and excites companion wind / ablates it.
- Flares on companion star: variable heating. Hot 'day side'.
- Interaction of pulsar and companion winds forms an intra-binary shock – site for particle acceleration.
- BWs: smaller, lower-mass semi-degenerate companions (<0.05M_{sun}, P_b < 10 h) than RBs (~0.2M_{sun}, P_b < 1 d) cf. Roberts (2013).

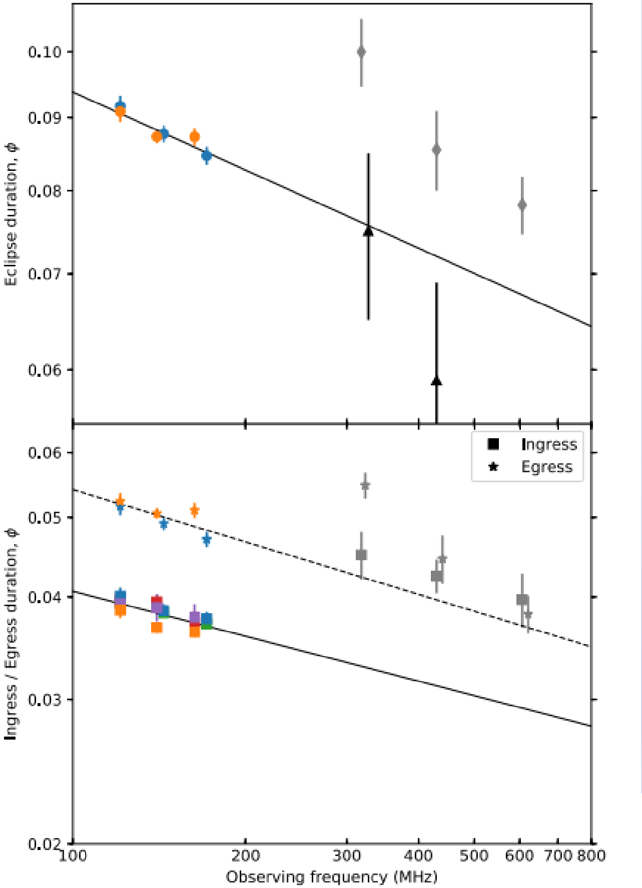


Radio Properties

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



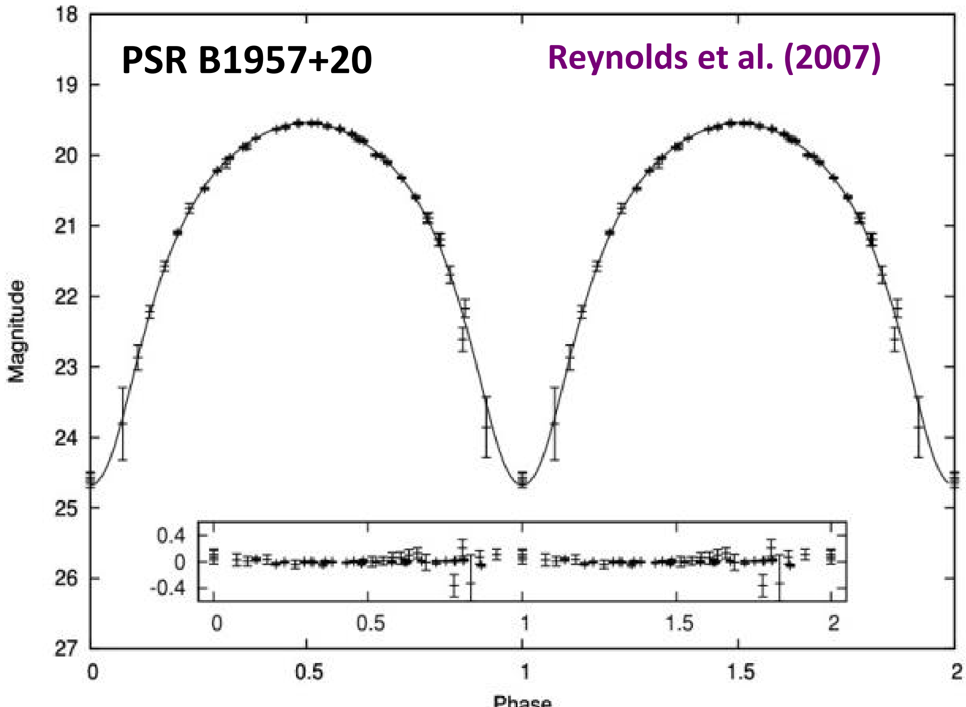


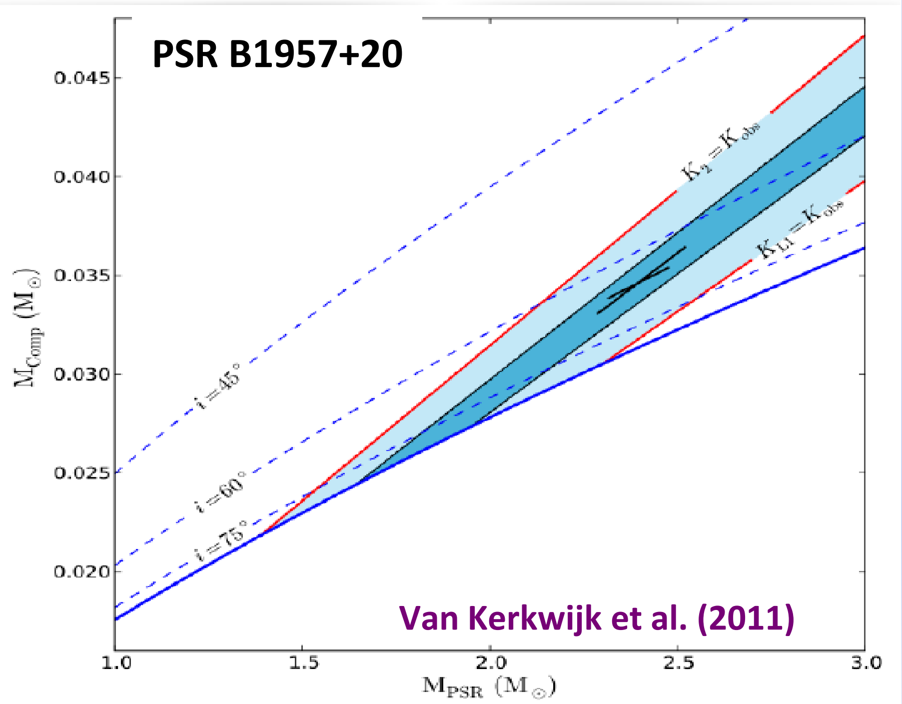


Polzin et al. (2020)

Optical Properties

- Spectroscopic radial velocity: constrains mass ratio *q*.
- Photometry + model of anisotropic heating: model LCs to constrain inclination *i* (biases: uncertain heating pattern, variability).
- Heating: Variable, skewed shock or wind chanelling (Cho et al. 2018).
- Typical T_{comp} ~ 10^3 - 10^4 K; flaring states.
- Radio + optical mass functions: constrain pulsar mass M_{PSR}.

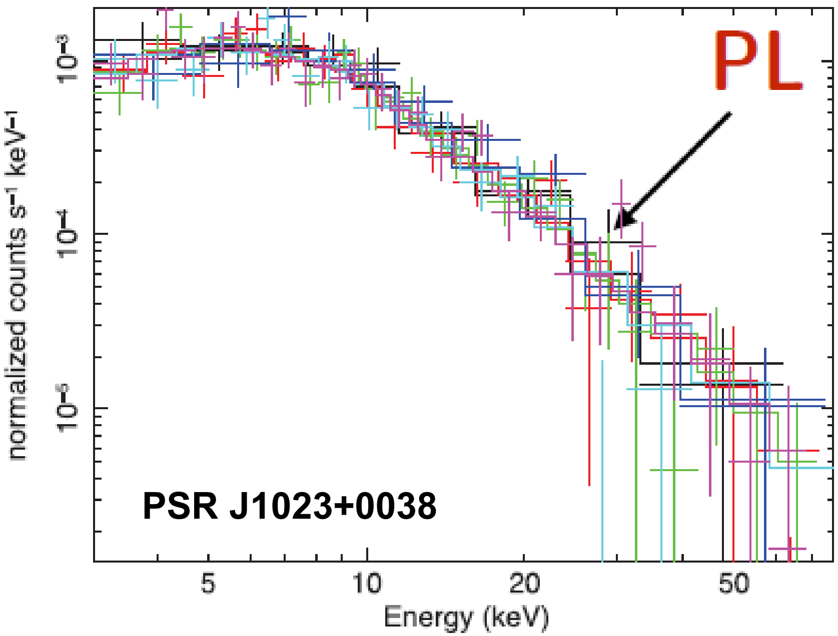




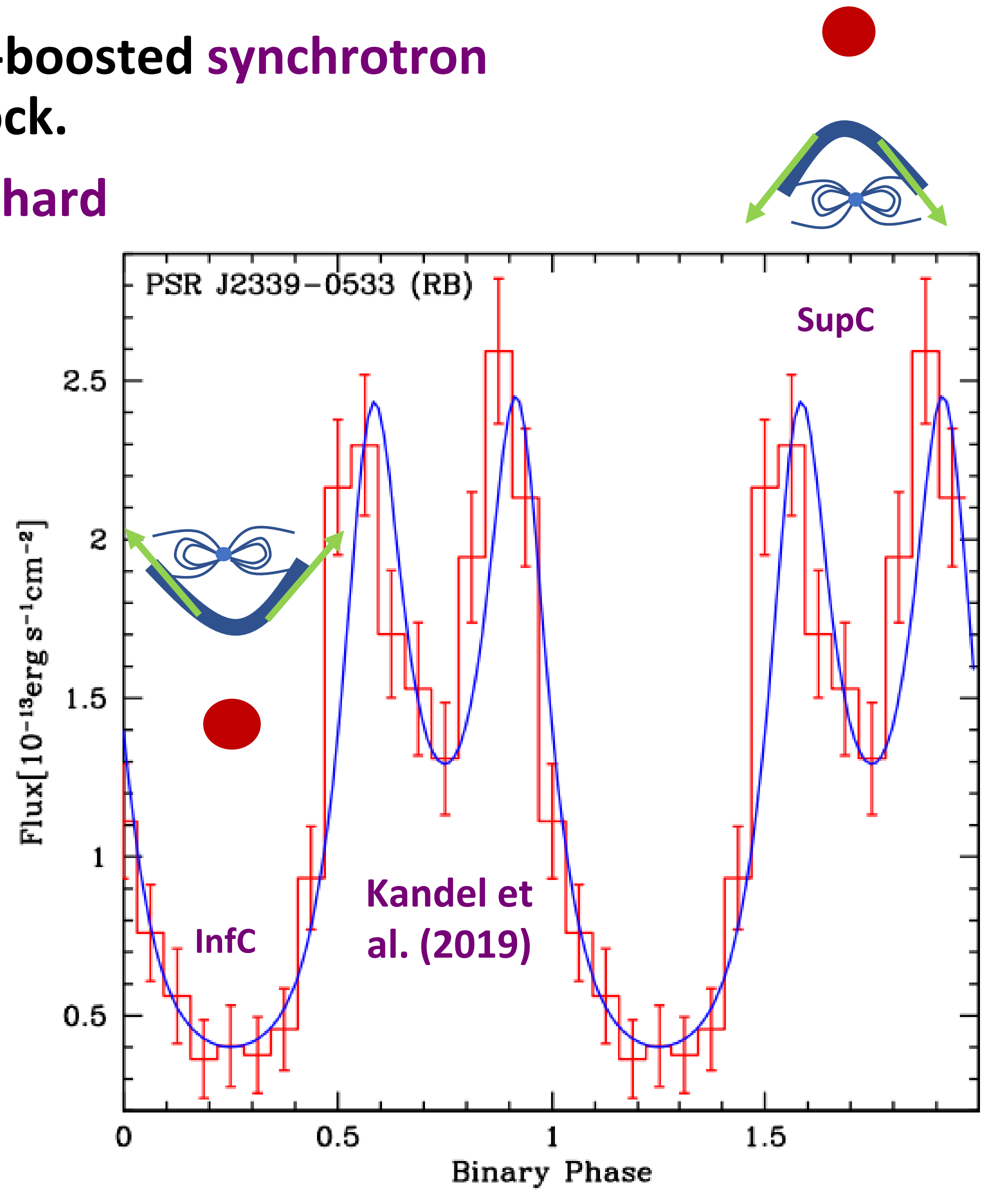
Credit: Z Wadiasingh

X-ray Modulation

- **Double-peaked** emission: Doppler-boosted synchrotron emission from the intra-binary shock.
- Hard power laws: emission due to hard underlying electron spectrum.
- Spectra extending up to 80 keV: constraints on B_{sh} ~ 1 G.

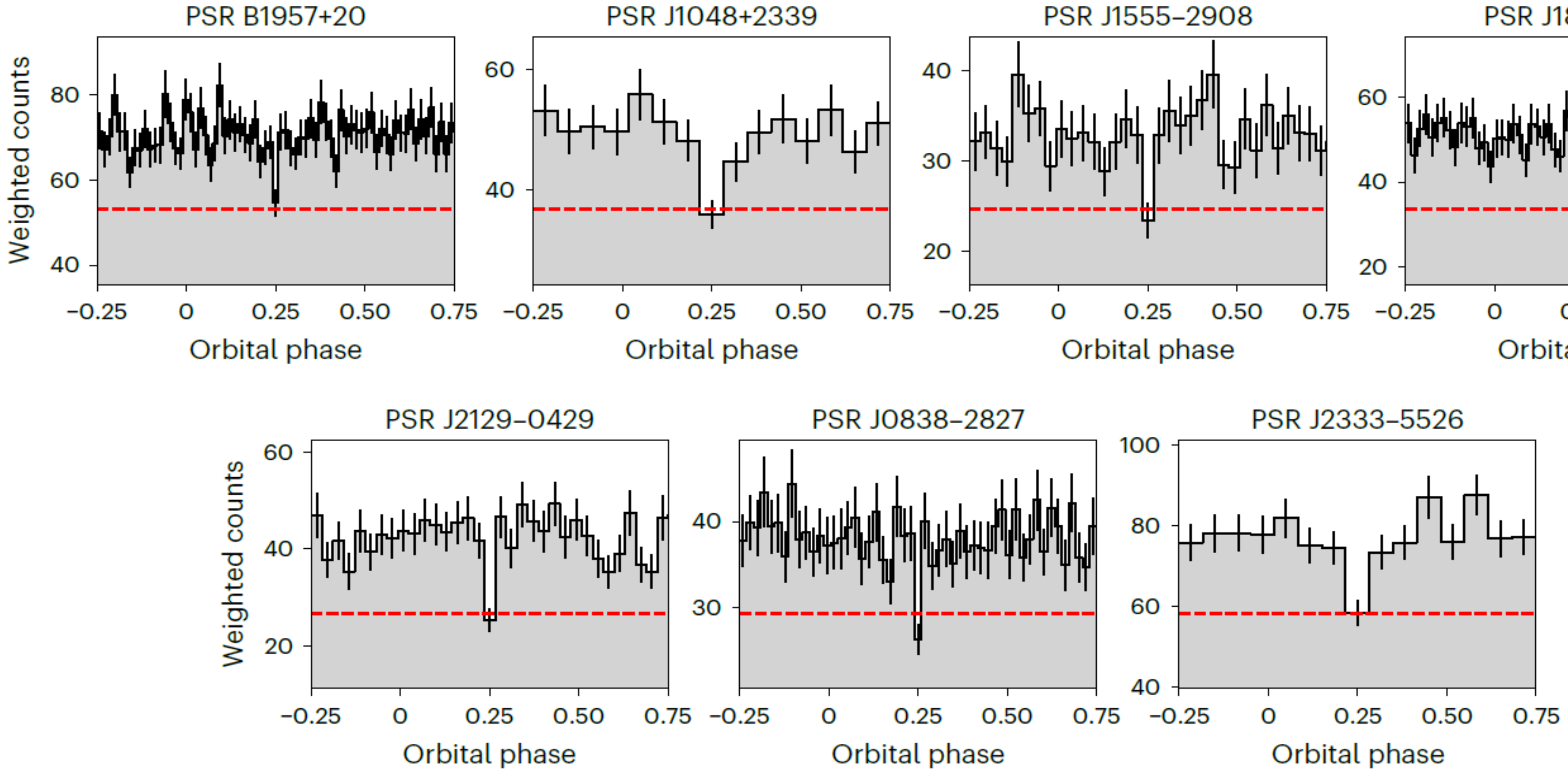


Tendulkar et al. (2014)

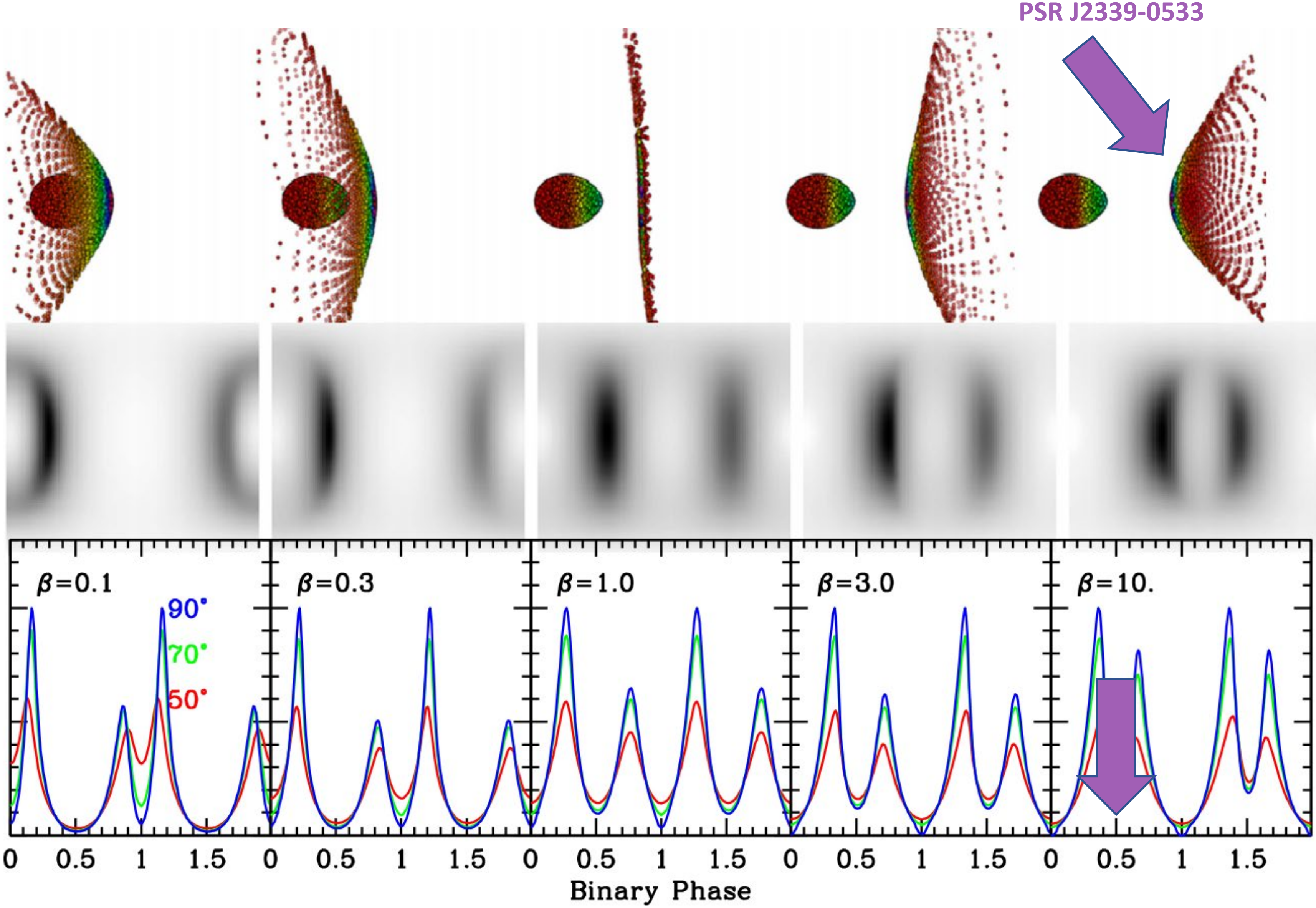


Gamma-ray Properties

- **Gamma-ray eclipses in 7 spider systems (out of 49), including PSR B1957+20, due to occultations by companion**
- **Limiting *i* and provide robust limits on the M_{PSR} (circumventing uncertainties in optical heating model) – EOS constraints**
  (Clark et al. 2023)

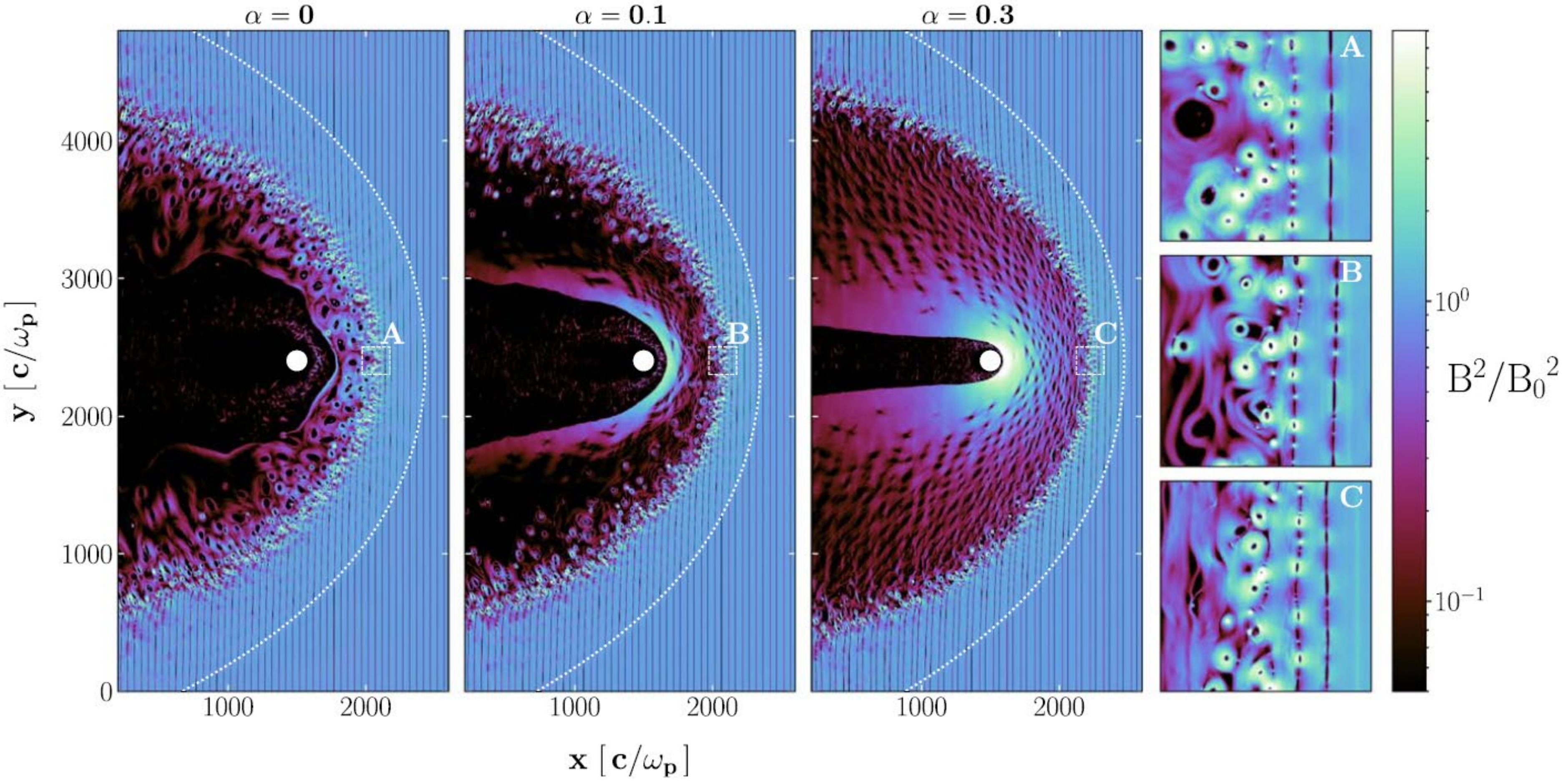


Intra-binary Shock

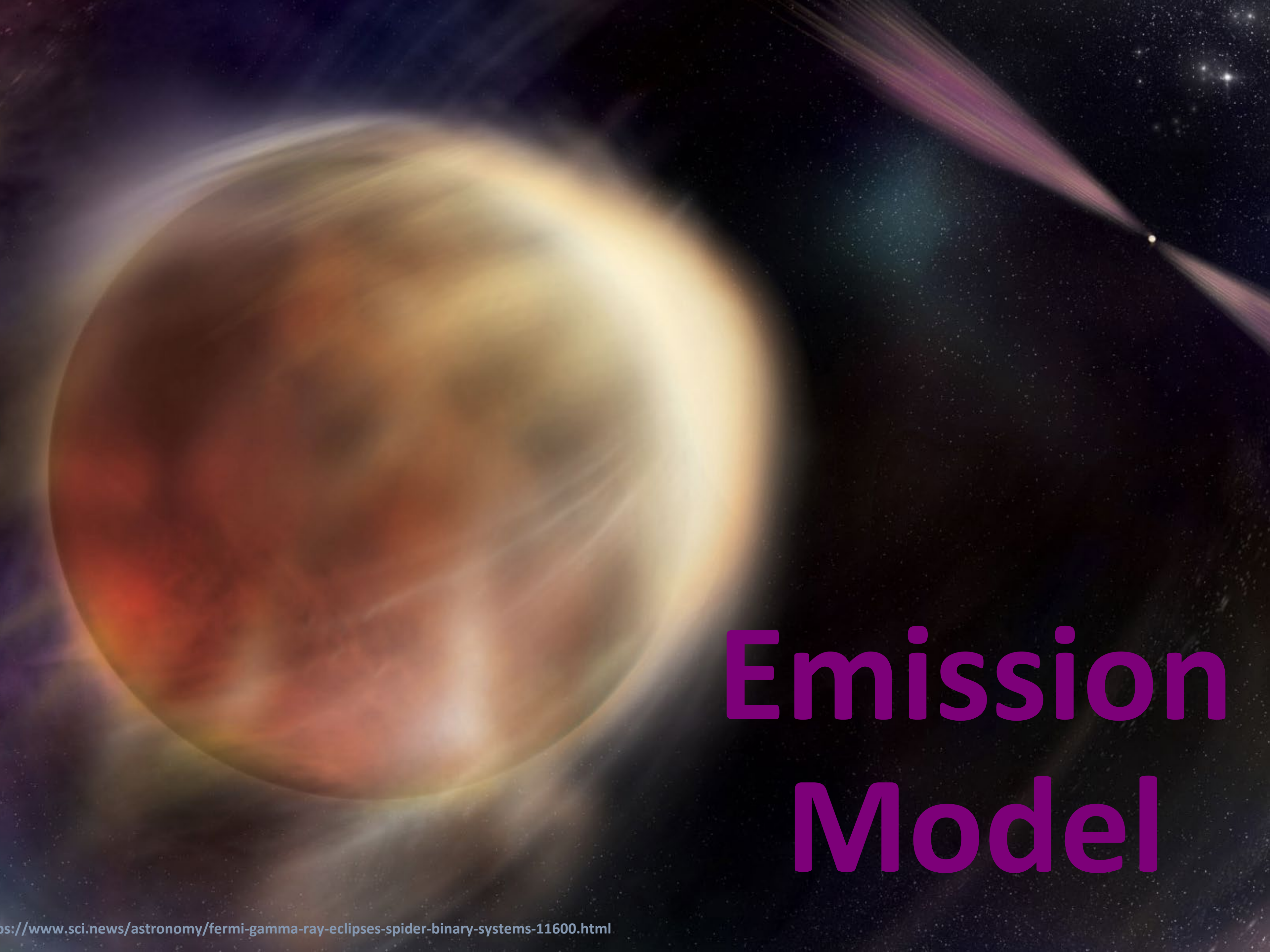


Romani & Sanchez (2016)

Intra-binary Shock



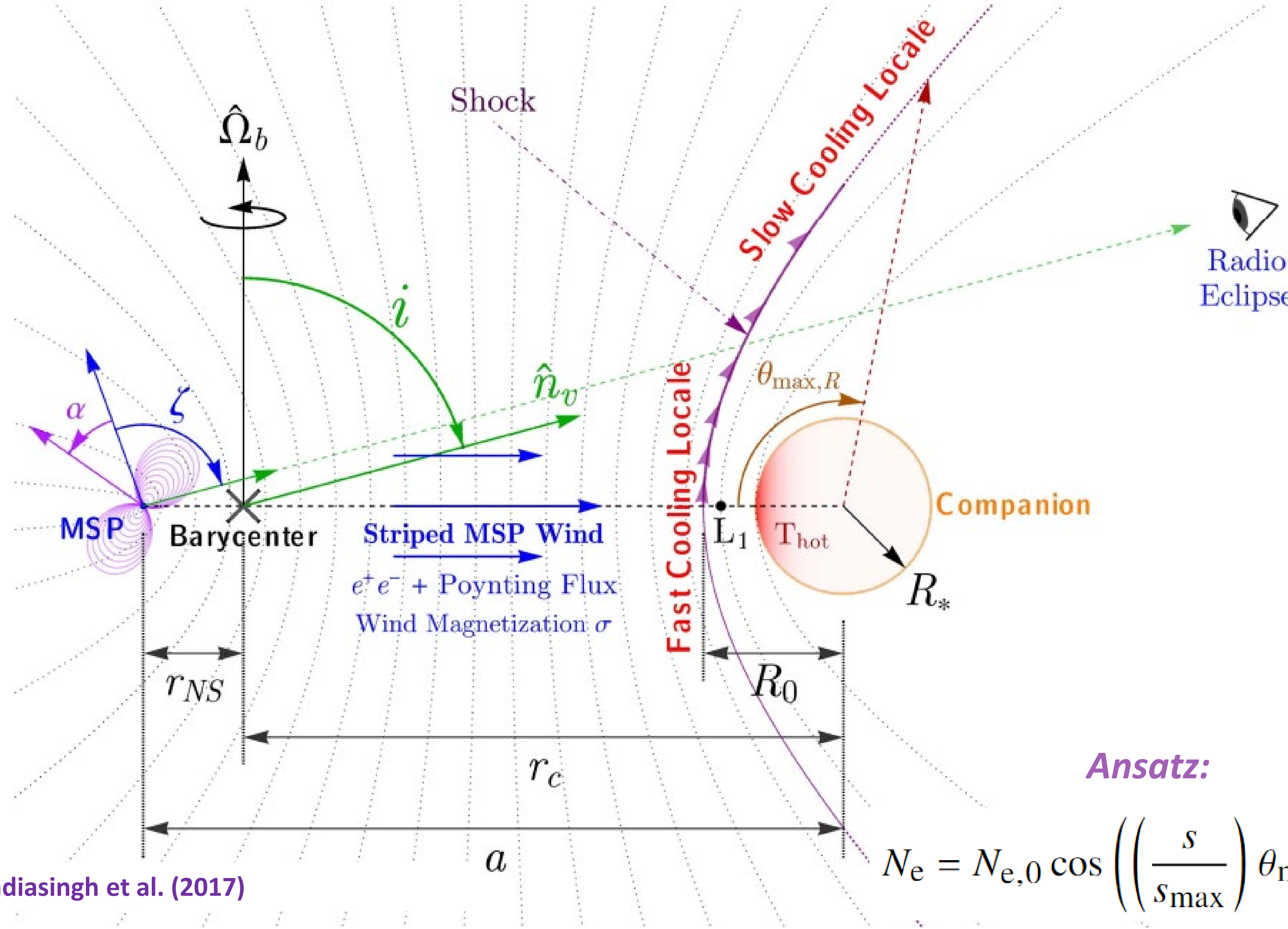
Cortés & Sironi (2022)



Emission Model

ps://www.sci.news/astronomy/fermi-gamma-ray-eclipses-spider-binary-systems-11600.html

Emission Geometry



Ansatz:

$$N_e = N_{e,0} \cos\left(\left(\frac{s}{s_{\max}}\right)\theta_{\max}\right)$$

Wadiasingh et al. (2017)

Different Shocks

Wilkin (1996):
Plane + spherical wind

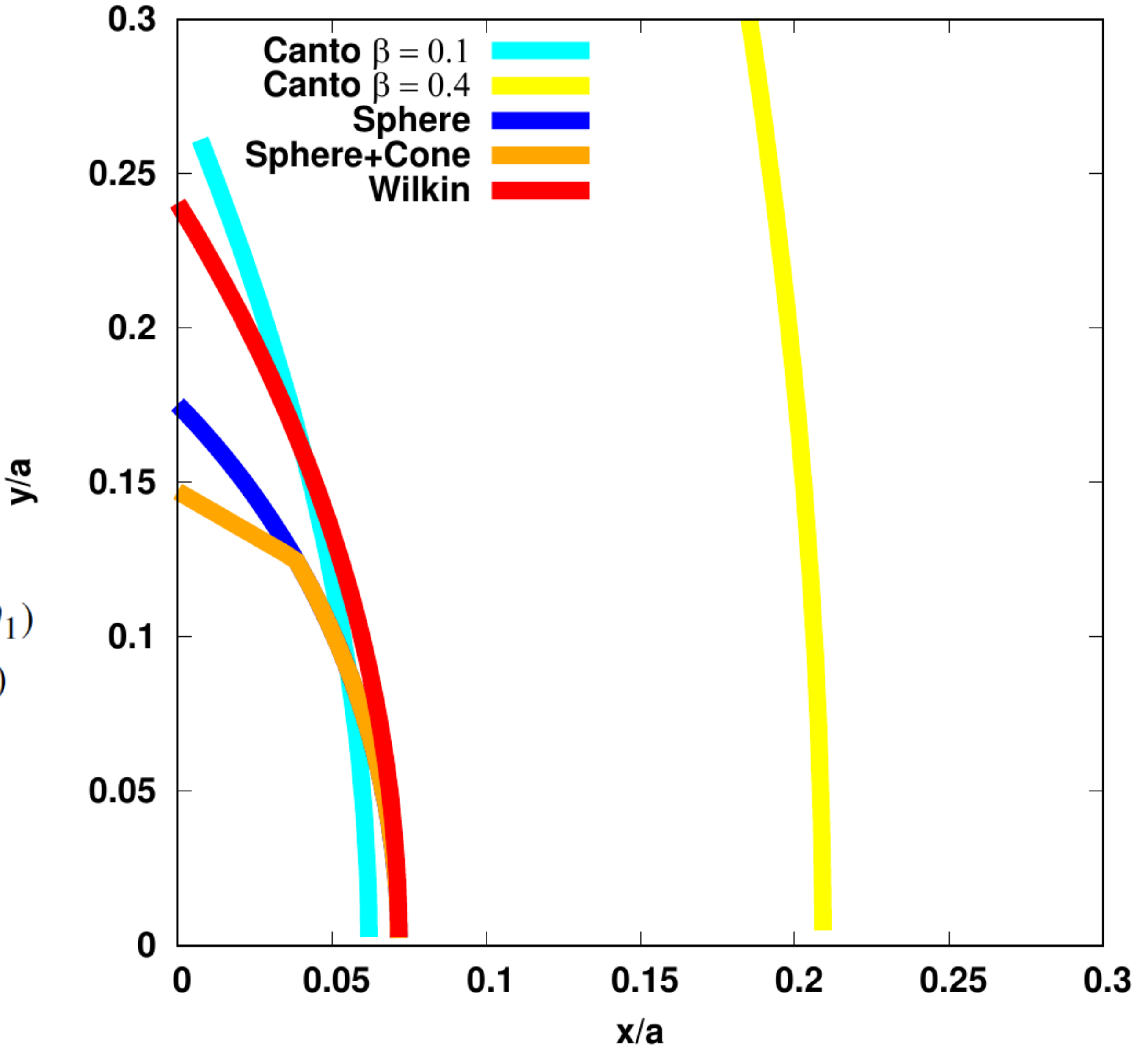
$$R(\theta) = R_0 \csc\theta \sqrt{3\,(1 - \theta\cot\theta)}$$

Cantó et al. (1996):
Two spherical winds

$$\begin{aligned} R(\theta) &= a \sin\theta_1 \csc(\theta + \theta_1) \\ \theta_1 \cot\theta_1 &= 1 + \beta(\theta\cot\theta - 1) \\ \beta &= \frac{\dot{M}_1 v_1}{\dot{M}_2 v_2}, \end{aligned}$$

$$R_0 = \frac{\beta^{1/2} D}{1 + \beta^{1/2}}$$

$$\theta_\infty - \tan\theta_\infty = \frac{\pi}{1-\beta}$$



Particle Transport

$$\frac{\partial N_e}{\partial t} = -\vec{V} \cdot \left(\vec{\nabla} N_e\right) + \kappa(E_e)\nabla^2 N_e + \frac{\partial}{\partial E_e}\left(\dot{E}_{e,tot} N_e\right) - \left(\vec{\nabla} \cdot \vec{V}\right) N_e + Q$$

Solid Angle & Diffusion:

Van der Merwe et al. (2020)

$$Q_{PSR}(E_e) = Q_0 E_e^{-\Gamma} \exp\left(-\frac{E_e}{E_{cut}}\right)$$

$$Q_1 = \left(\frac{1}{4\pi}\int_0^{2\pi}\int_{\lambda_1}^{\lambda_2} \sin\lambda \, d\lambda \, d\phi\right) Q_{PSR} = \frac{1}{2}\left(\cos\lambda_1 - \cos\lambda_2\right) Q_{PSR}$$

$$Q_i = \frac{1}{t_{diff}} \frac{dN_{e,i-1}}{dE_e} + \frac{1}{2}\left(\cos\lambda_i - \cos\lambda_{i+1}\right) Q_{PSR}, \quad i > 1$$

Normalisation – Current and Energetics:

$$\dot{N}_{GJ} = \frac{B_{PSR} 4\pi^2 R_{PSR}^3}{2ceP^2} \qquad \dot{N}_{II} = M_{\pm} \dot{N}_{GJ}$$

$$\int_{E_{min}}^{\infty} Q_{PSR} \, dE_e = (M_{\pm} + 1)\dot{N}_{GJ} \qquad \int_{E_{min}}^{\infty} E_e Q_{PSR} \, dE_e = \eta_p \dot{E}_{rot}$$

Beaming

Transforming between co-moving and lab frames:

$$\frac{dN_e}{d\gamma_e} \approx \frac{dN'_e}{d\gamma'_e}$$

$$\Omega'_{\rm beam} = 4\pi$$

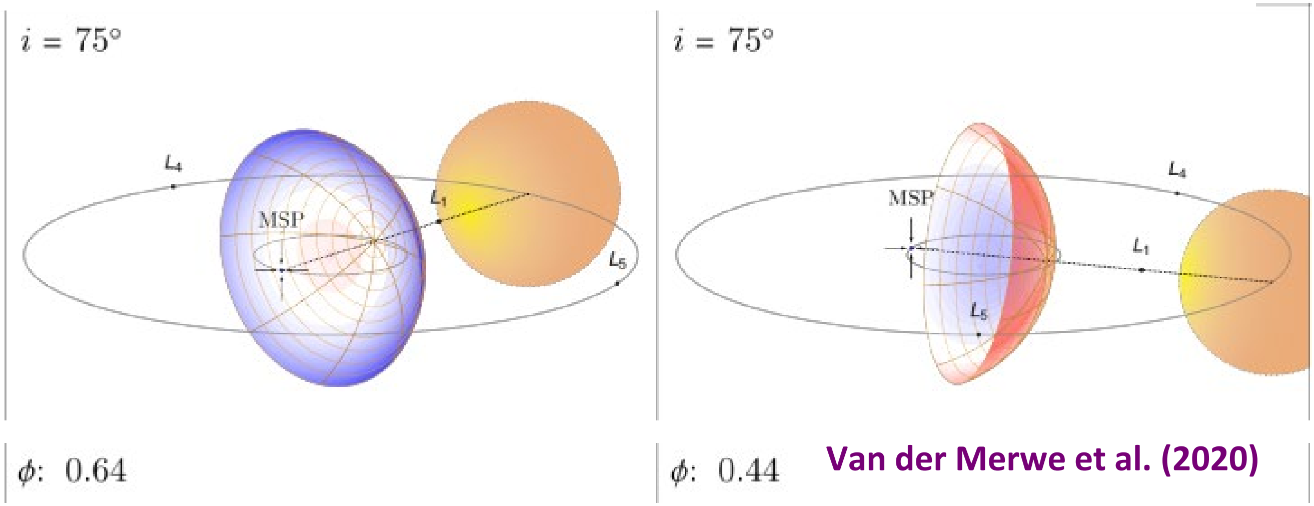
$$u'_x = \sin\theta,$$
$$u'_y = \cos\theta\cos\phi_z$$
$$u'_z = \cos\theta\sin\phi_z$$

$$p_\Gamma \equiv \Gamma\beta_\Gamma = (\Gamma\beta)_{\rm max}\left(\frac{\theta}{\theta_{\rm max,X}}\right)$$

$$\vec{u} = \Lambda_i \Lambda_{\Omega_b t}\vec{u}\,' = \begin{pmatrix} \sin i & 0 & \cos i \\ 0 & 1 & 0 \\ -\cos i & 0 & \sin i \end{pmatrix} \begin{pmatrix} \cos(\Omega_b t) & -\sin(\Omega_b t) & 0 \\ \sin(\Omega_b t) & \cos(\Omega_b t) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u'_x \\ u'_y \\ u'_z \end{pmatrix}$$

$$\delta = \frac{1}{\Gamma\left(1 - \beta\vec{n}\cdot\vec{u}\right)}$$

$$F_\nu = \delta^3 F_{\nu'}$$



Van der Merwe et al. (2020)

Calibration

s://www.sci.news/astronomy/fermi-gamma-ray-eclipses-spider-binary-systems-11600.html

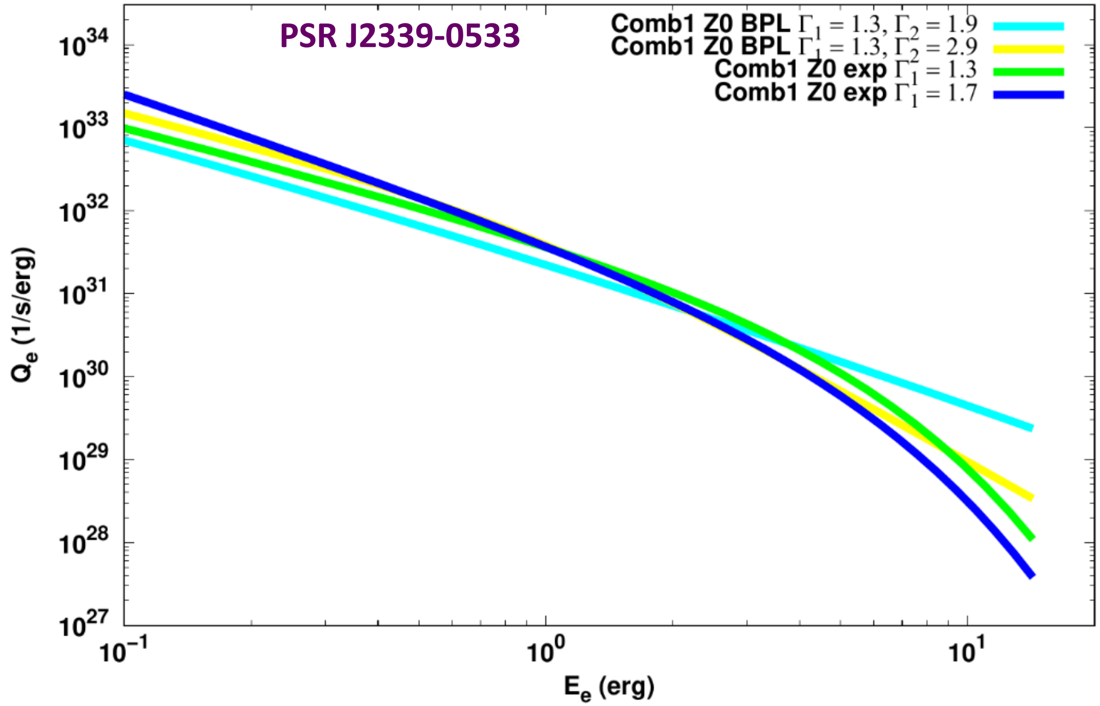
Calibration…

- ✓ Code versions
- ✓ Injection spectrum – correct parametrisation (BPL)
- ✓ θ vs μ grid, different shocks: difficult to compare zones
- ✓ Energy and phase grids:
  - Nearest neighbour (interpolation)
  - Binning (pile-up)
  - Extending the grid (δ)
- ✓ Parameter combinations
- ✓ Div(v)

Results

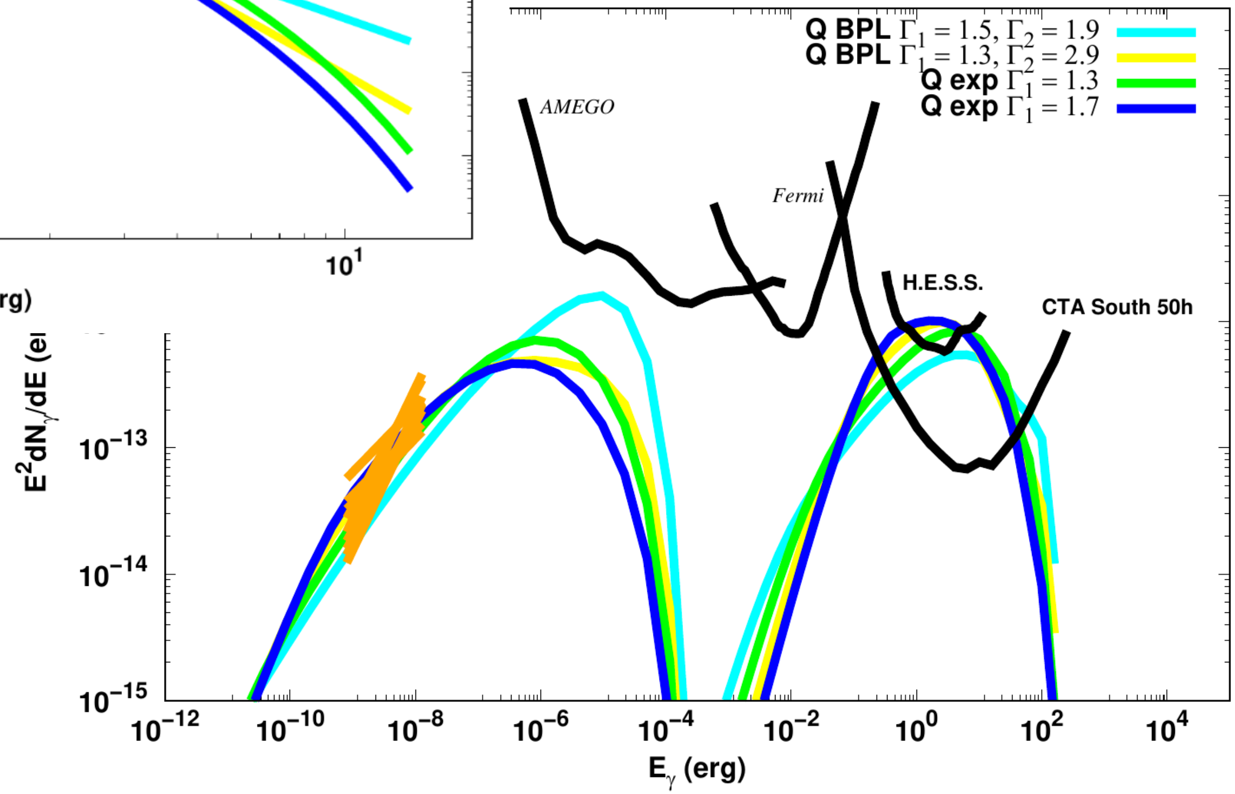
ps://www.sci.news/astronomy/fermi-gamma-ray-eclipses-spider-binary-systems-11600.html

Injection Spectrum

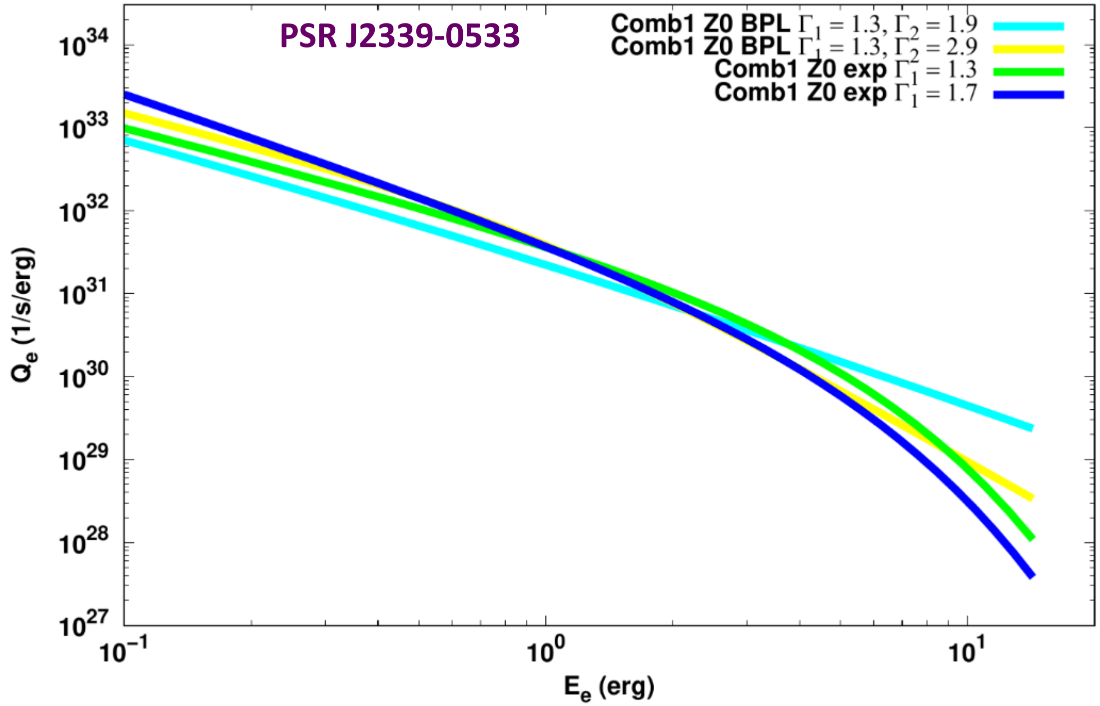


$$Q = Q_0 E^{-\Gamma_1} \exp\left[-\left(\frac{E}{E_c}\right)^b\right]$$

$$Q = Q_0 \left(\frac{E}{E_b}\right)^{-\Gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^{(-\Gamma_1+\Gamma_2)/f}\right)^{-f}$$

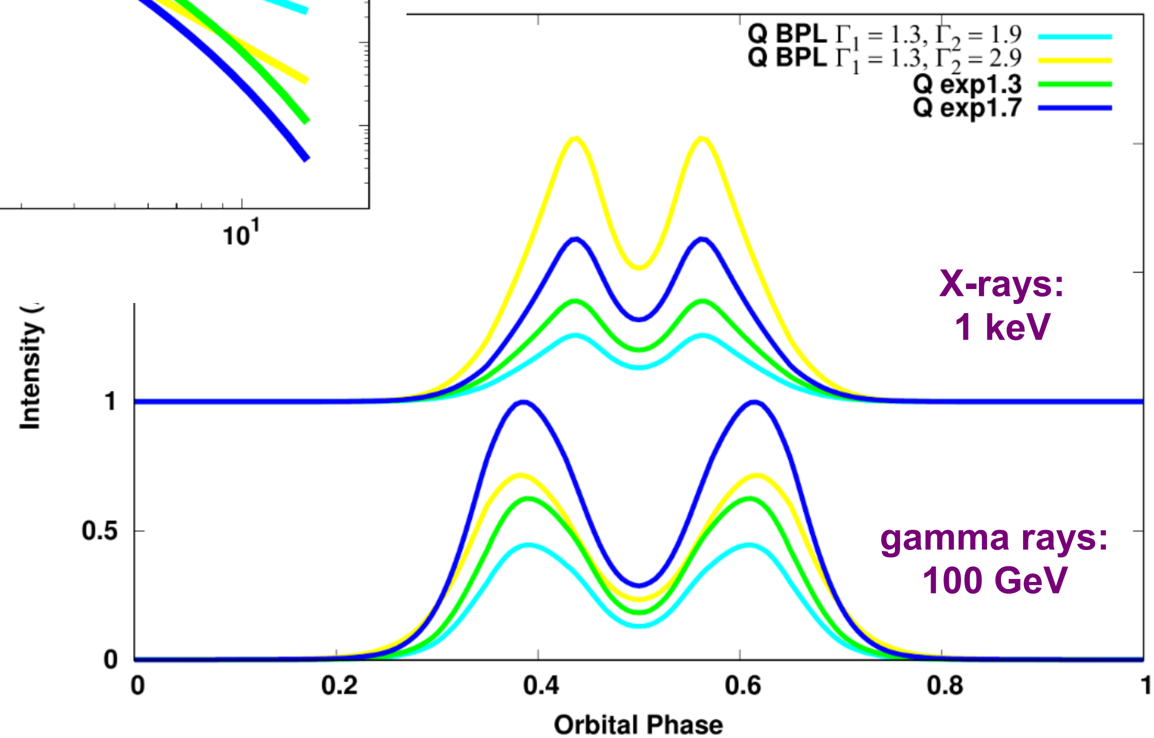


Injection Spectrum

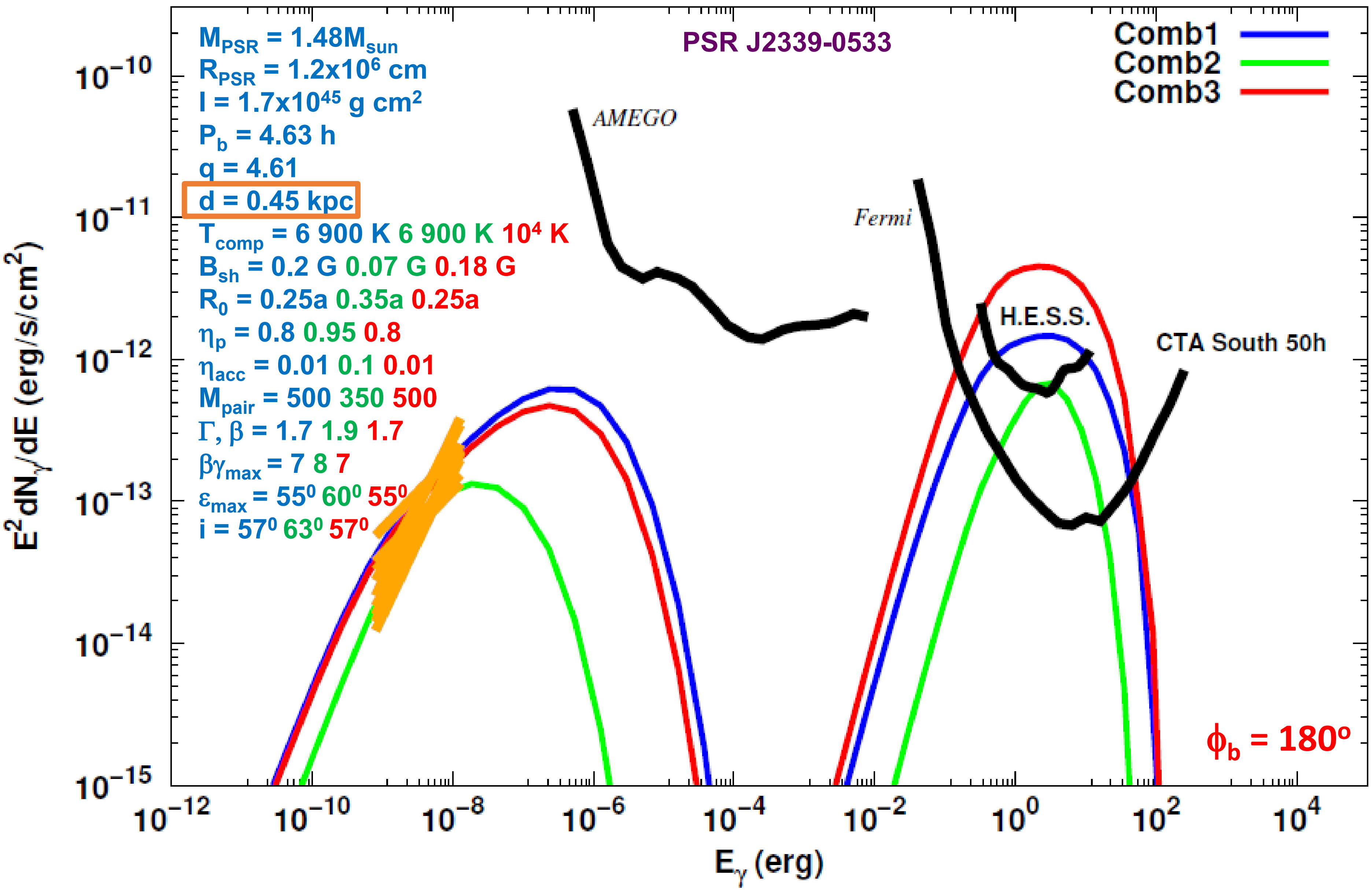


$$Q = Q_0 E^{-\Gamma_1} \exp\left[-\left(\frac{E}{E_c}\right)^b\right]$$

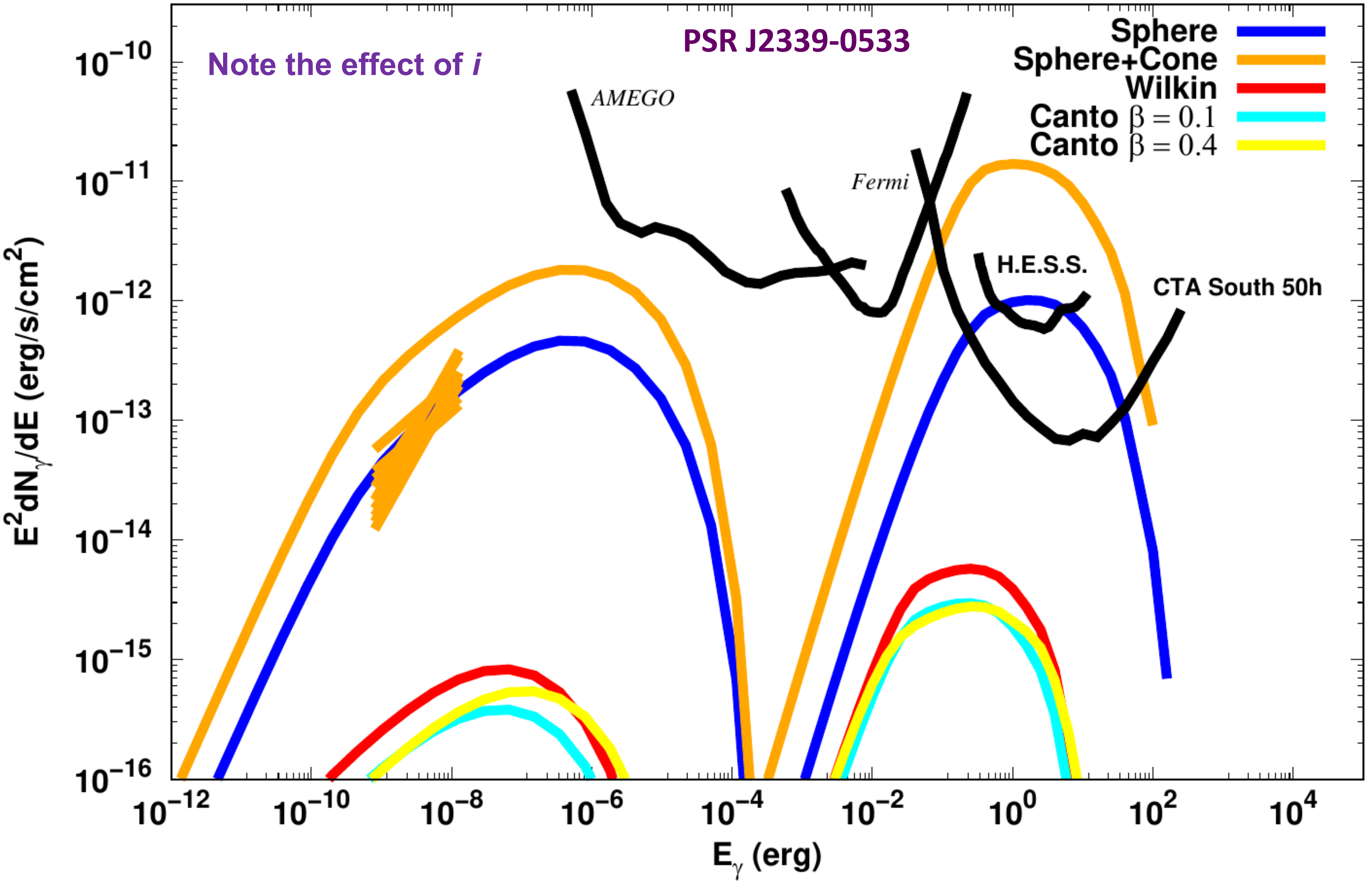
$$Q = Q_0 \left(\frac{E}{E_b}\right)^{-\Gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^{(-\Gamma_1+\Gamma_2)/f}\right)^{-f}$$



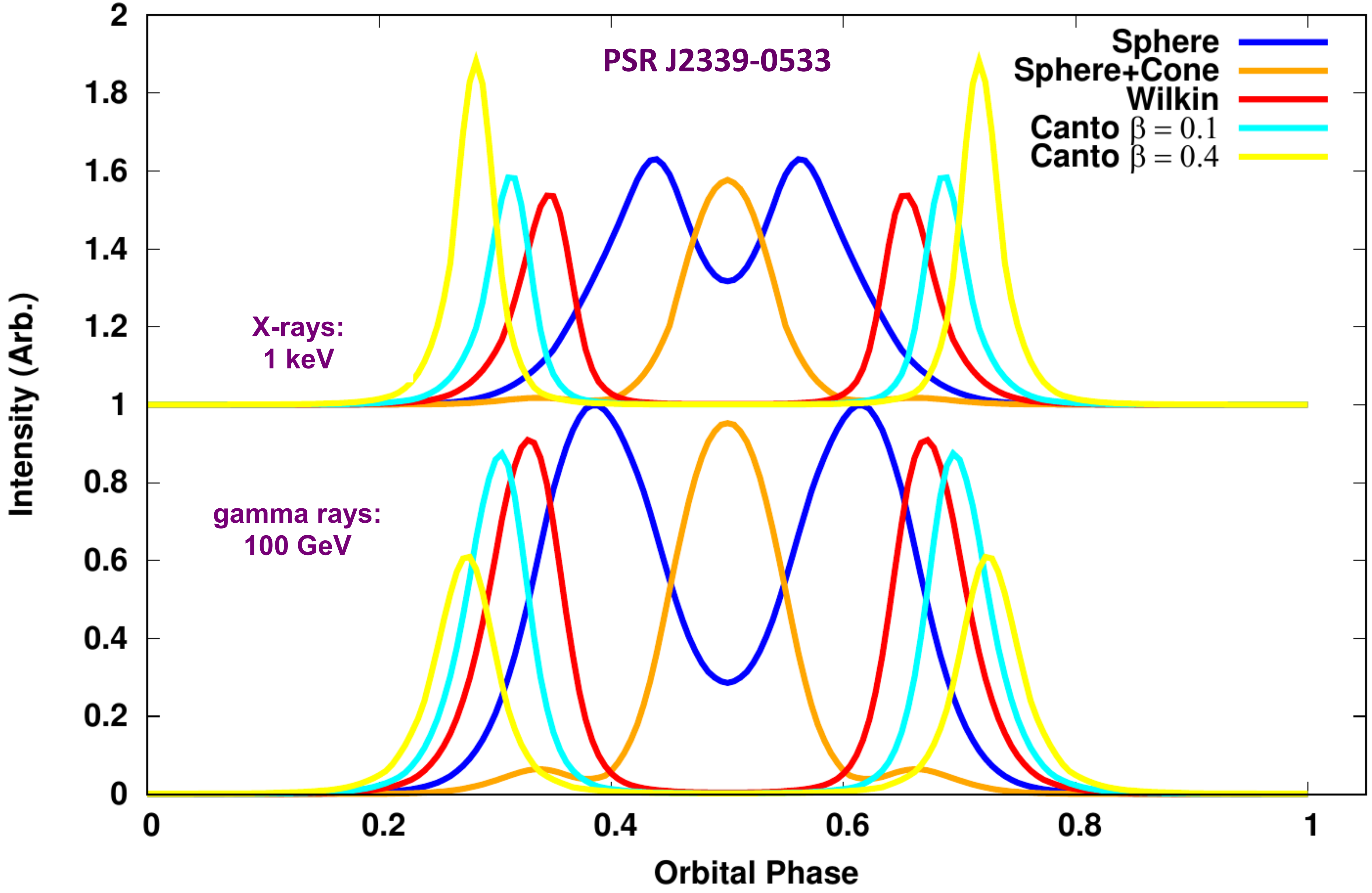
Different Parameters



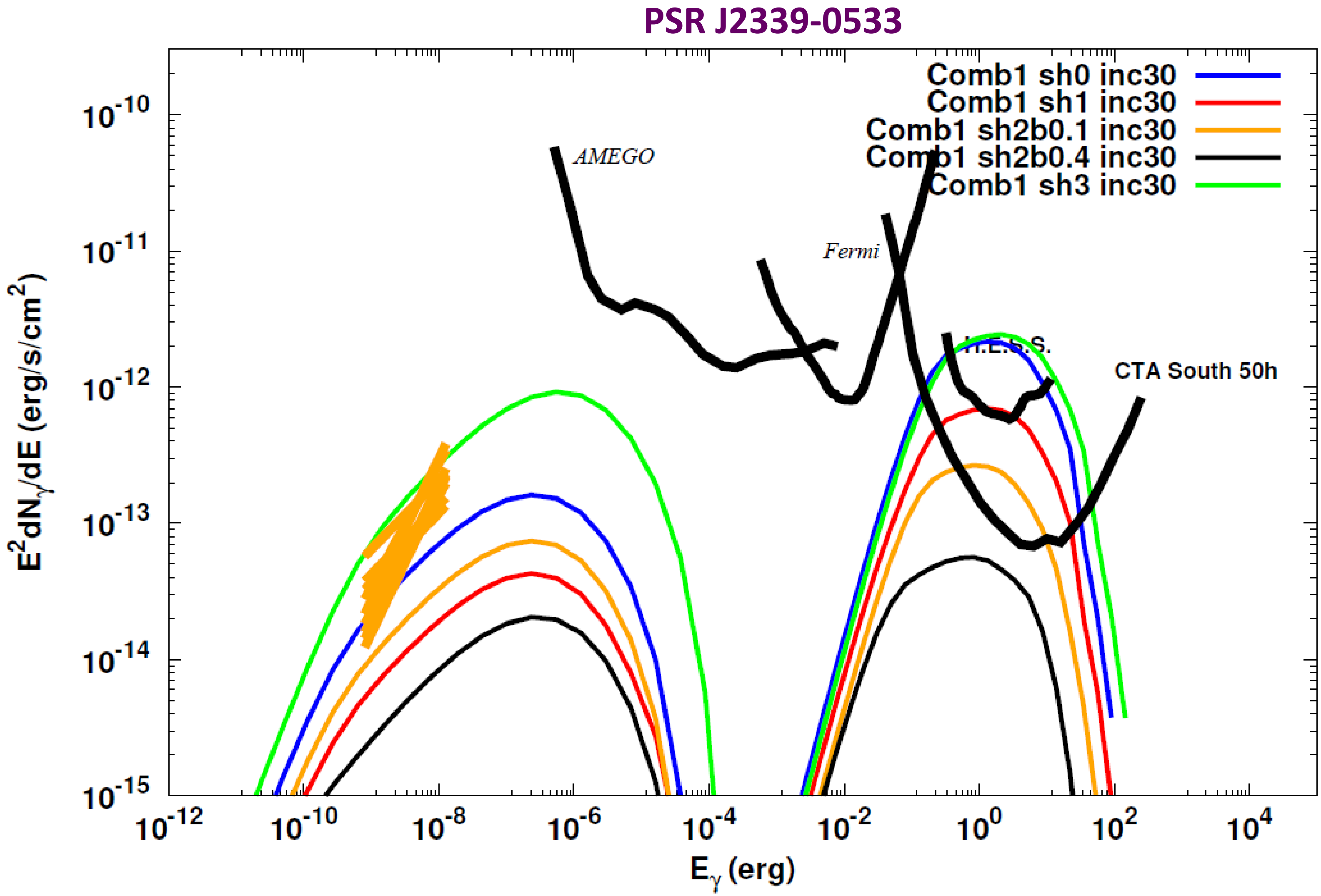
Different Shocks



Different Shocks

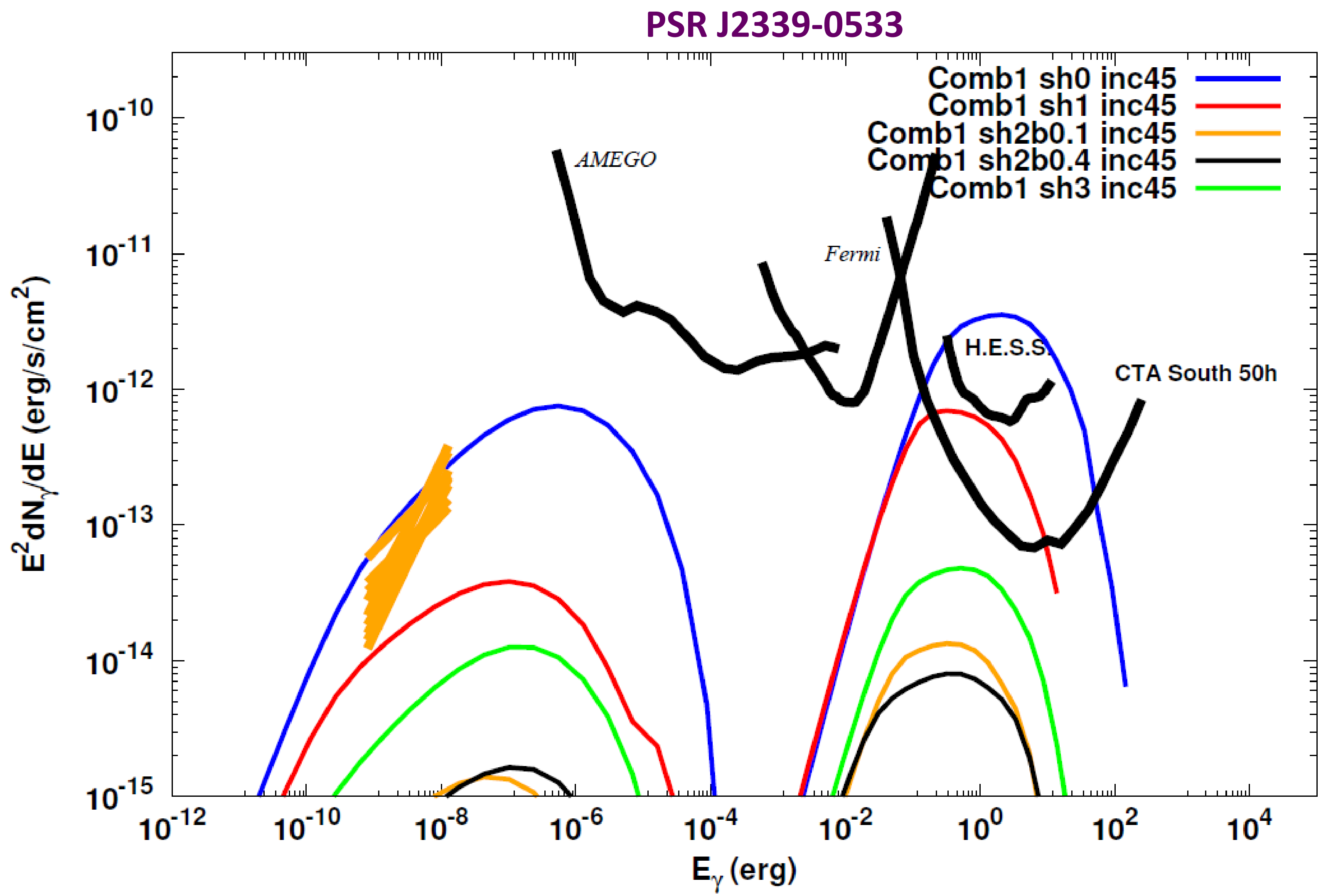


Effect of *i*

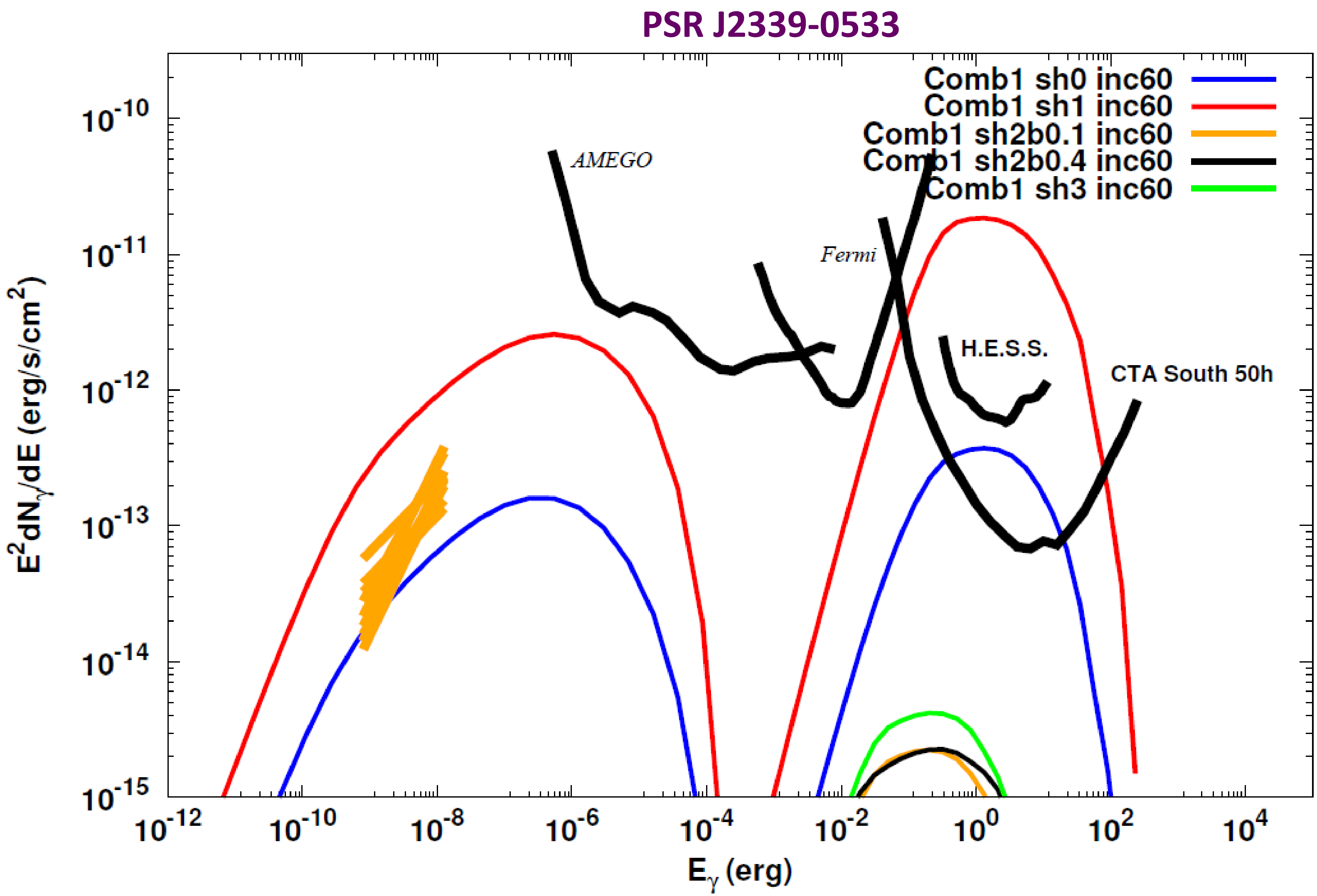


PSR J2339-0533
Comb1 sh0 inc30
Comb1 sh1 inc30
Comb1 sh2b0.1 inc30
Comb1 sh2b0.4 inc30
Comb1 sh3 inc30
AMEGO
Fermi
H.E.S.S.
CTA South 50h
$E^2 dN_\gamma/dE$ (erg/s/cm^2)
E_γ (erg)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}

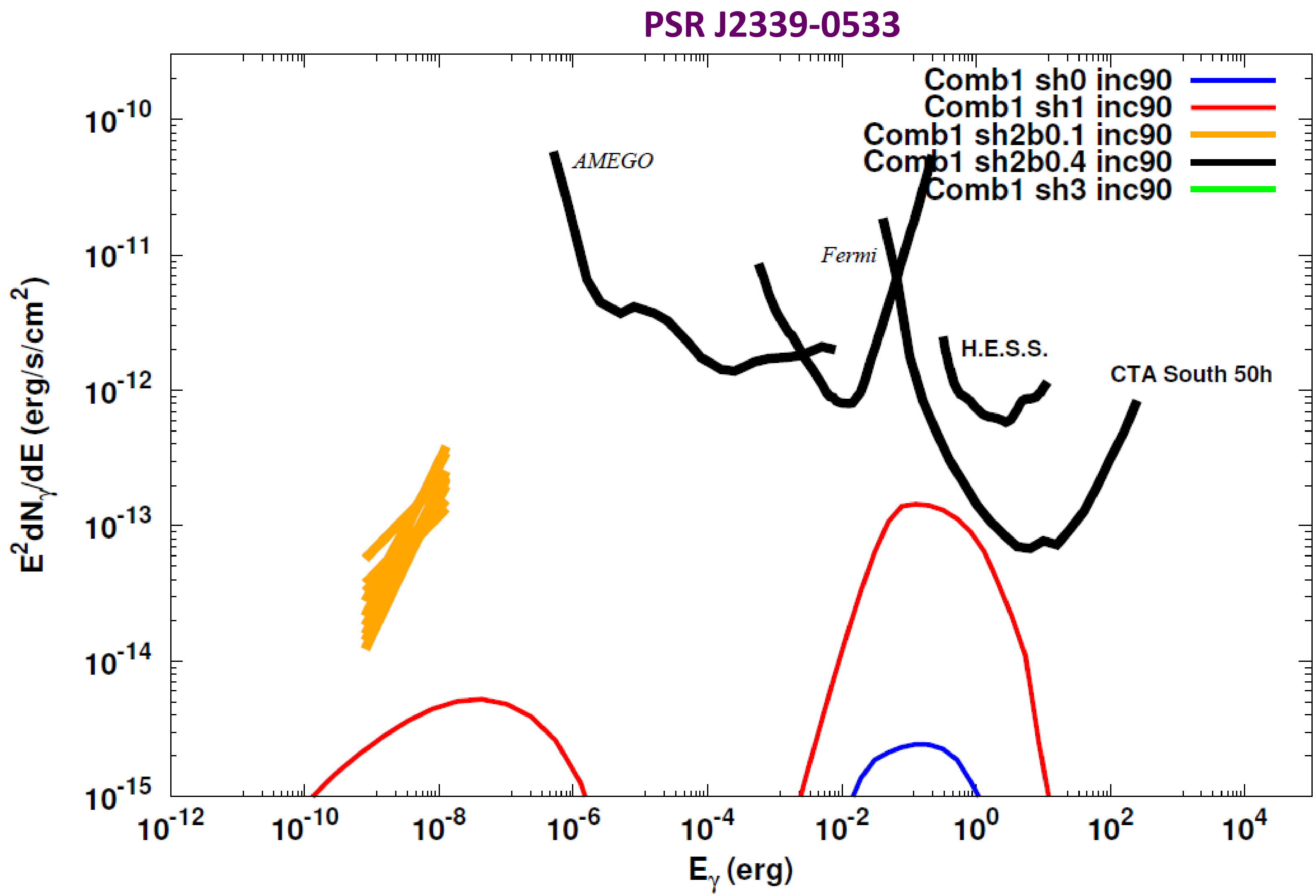
Effect of *i*


PSR J2339-0533
Comb1 sh0 inc45
Comb1 sh1 inc45
Comb1 sh2b0.1 inc45
Comb1 sh2b0.4 inc45
Comb1 sh3 inc45
AMEGO
Fermi
H.E.S.S.
CTA South 50h
$E^2 dN_\gamma/dE$ (erg/s/cm^2)
E_γ (erg)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}

Effect of *i*

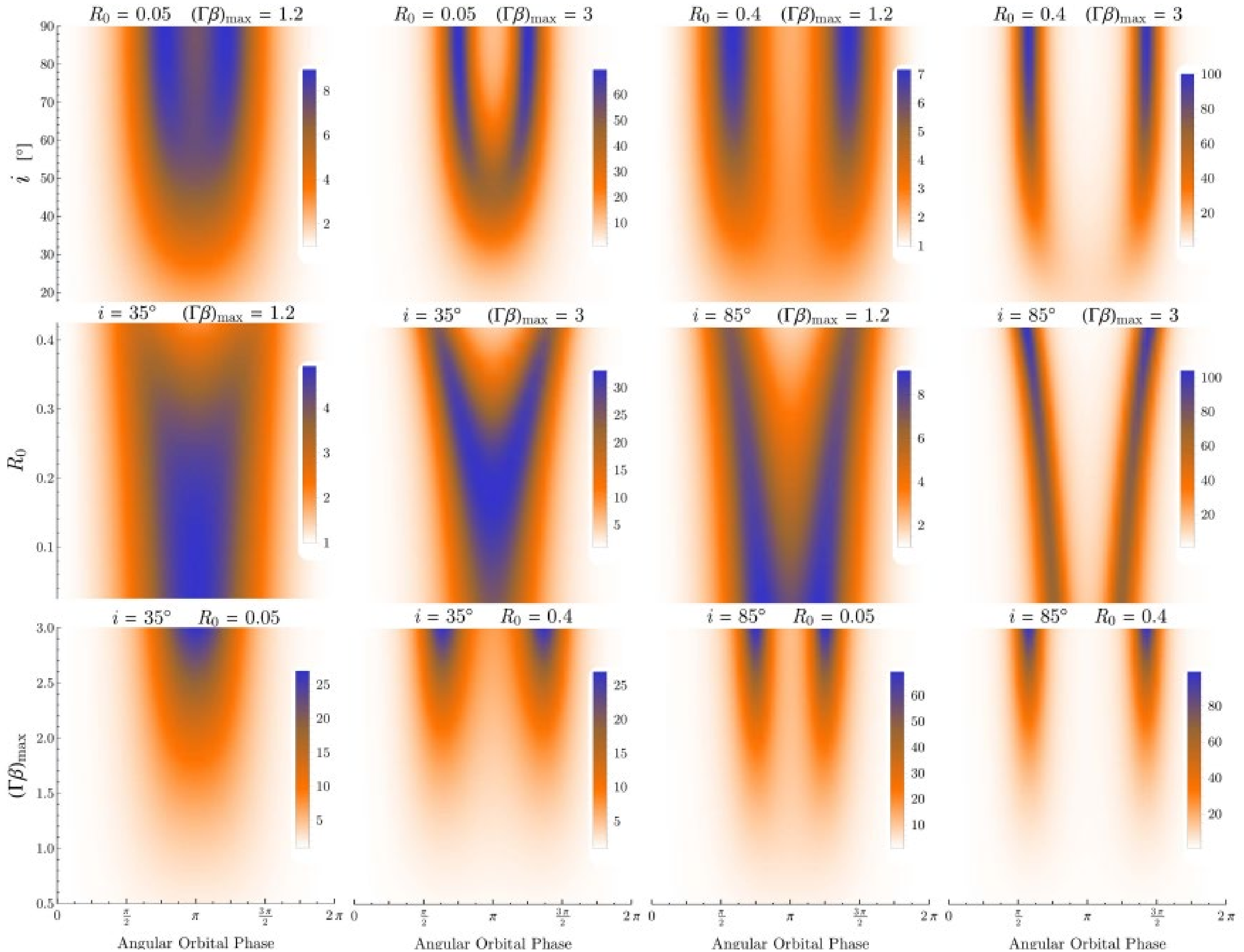

PSR J2339-0533
Comb1 sh0 inc60
Comb1 sh1 inc60
Comb1 sh2b0.1 inc60
Comb1 sh2b0.4 inc60
Comb1 sh3 inc60
AMEGO
Fermi
H.E.S.S.
CTA South 50h
E^2dN_γ/dE (erg/s/cm^2)
E_γ (erg)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}

Effect of *i*


PSR J2339-0533
Comb1 sh0 inc90
Comb1 sh1 inc90
Comb1 sh2b0.1 inc90
Comb1 sh2b0.4 inc90
Comb1 sh3 inc90
AMEGO
Fermi
H.E.S.S.
CTA South 50h
E^2dN_γ/dE (erg/s/cm^2)
E_γ (erg)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}

To Do….

- **3D data cubes: $F(i,\phi,E_\gamma)$**
- **Cuts:**
  - ✓ **Skymaps of shock emission**
  - ✓ **LCs**
  - ✓ **Spectra**

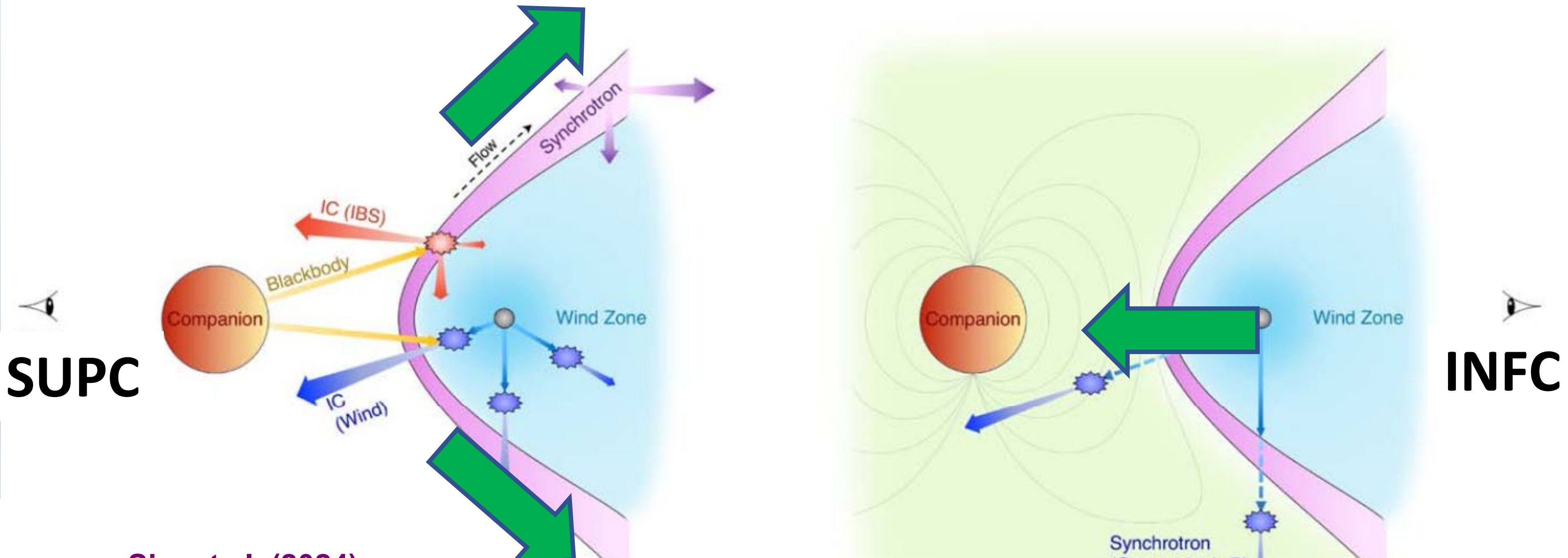


Wadiasingh et al. (2017)

Future Work

<u>3 REDBACKS</u>: (XSS J12270-4859, PSR J2039-5617, and PSR J2339-0533)

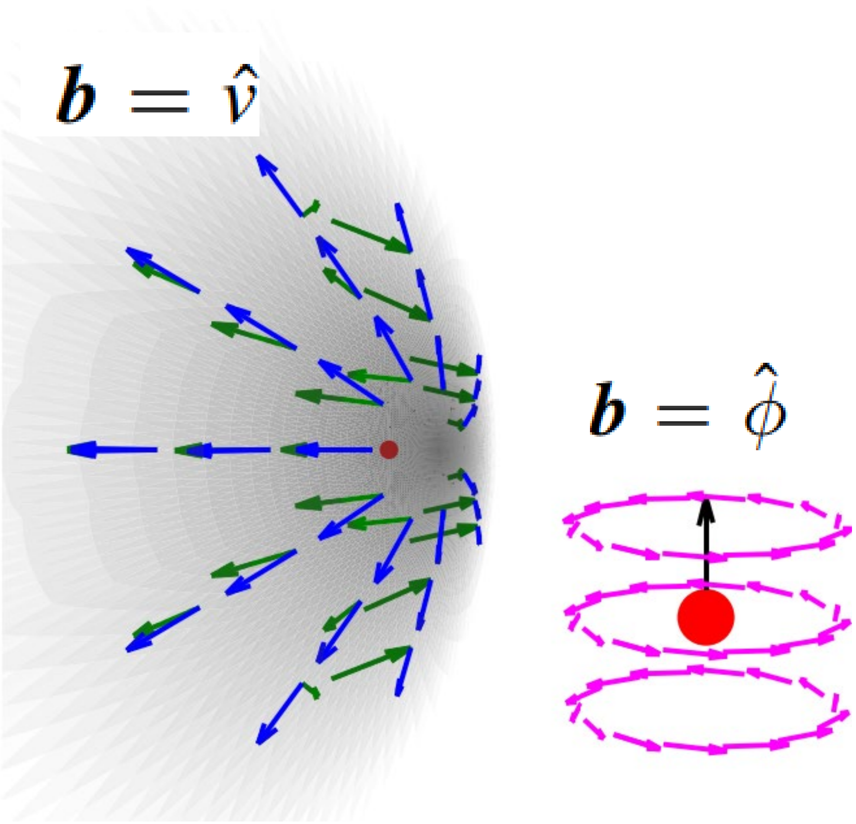
- **X-ray LCs: minimum at INFC**
- **GeV orbital modulation, LCs maximum at SUPC**
- **Particles passing through shock into companion magnetosphere, SR: γ ~1e8 (0.1 PeV)**

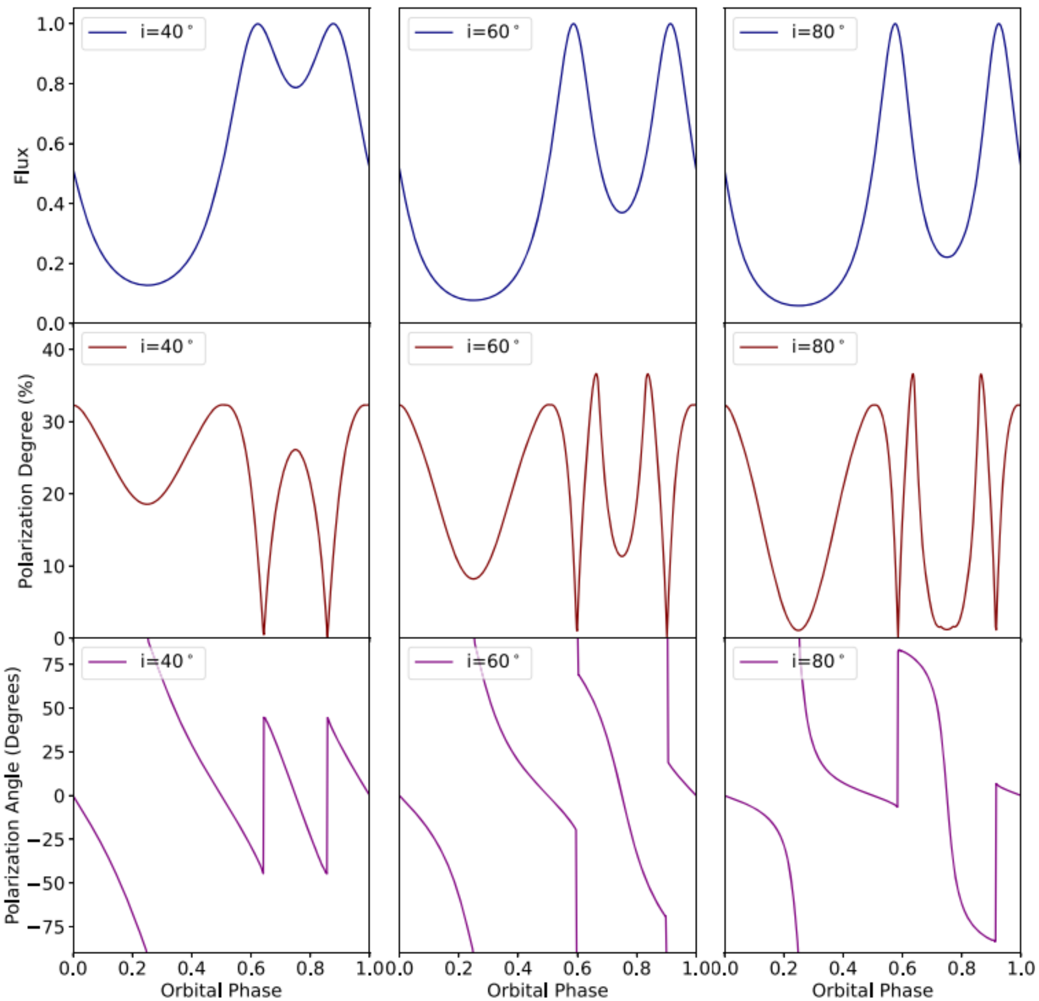


Sim et al. (2024)

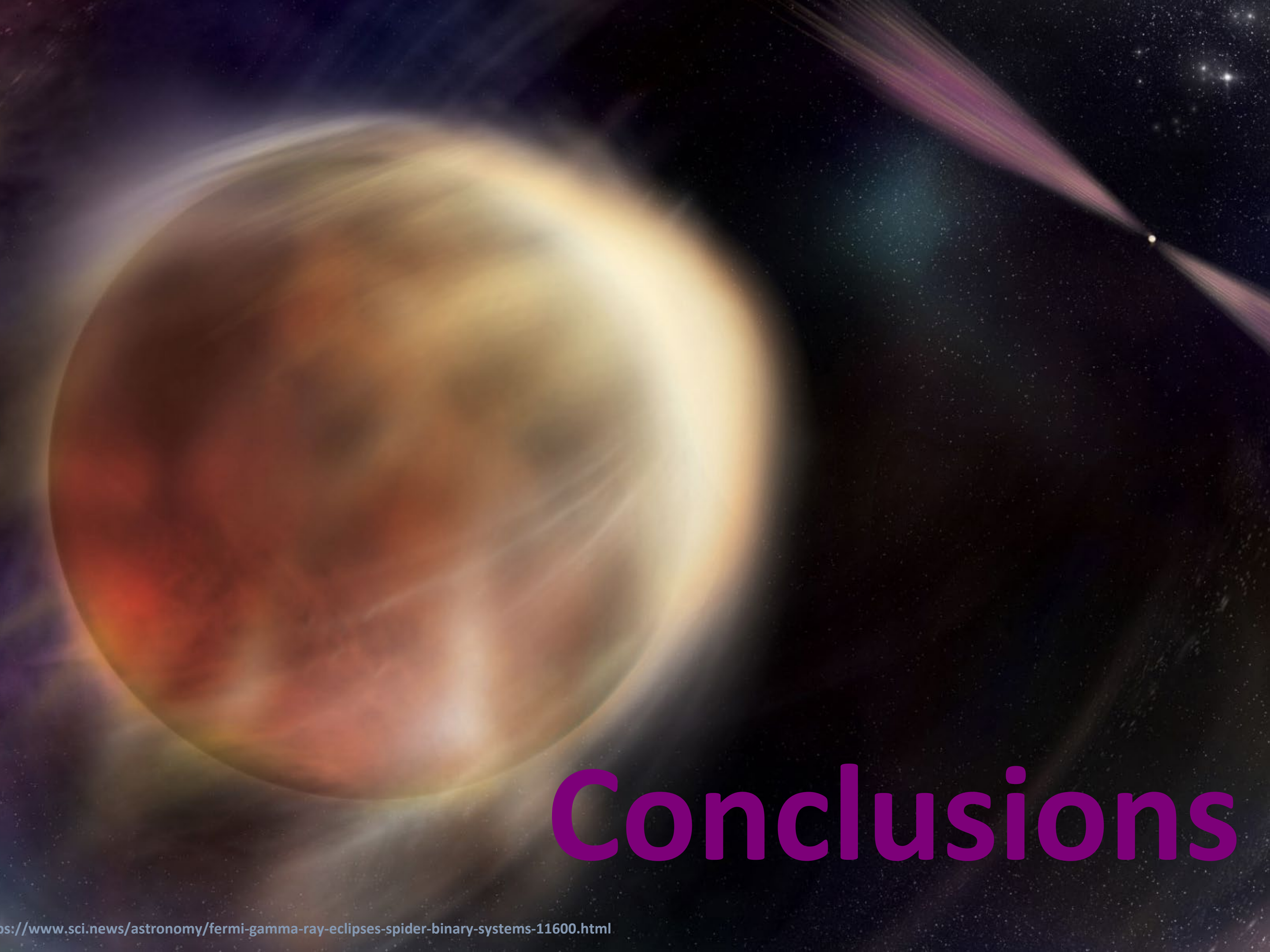
Future Work

- Modelling the (X-ray) polarisation from the interbinary shocks of spiders





Sullivan & Romani (2023)

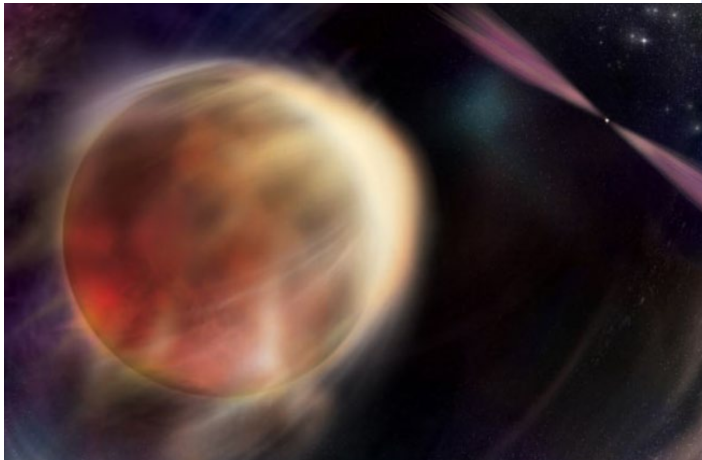


Conclusions

s://www.sci.news/astronomy/fermi-gamma-ray-eclipses-spider-binary-systems-11600.html

Conclusions

- ‘Spider binaries’ are **promising targets** with rich multi-wavelength phenomenology
- **Improving** the emission model in several ways:
  - Injection spectrum
  - SR kernel
  - Shock geometry (future: sweepback?)
  - Code efficiency / accuracy
- Looking for **‘new’ sources** to probe pulsar wind
- Nearby (d), energetic ($\dot{E}$), flaring (T) sources will be **brightest** ones modulating in TeV band (also for CTA).
- **Future:** add spectral components, eclipses, companion heating, polarisation, LIS



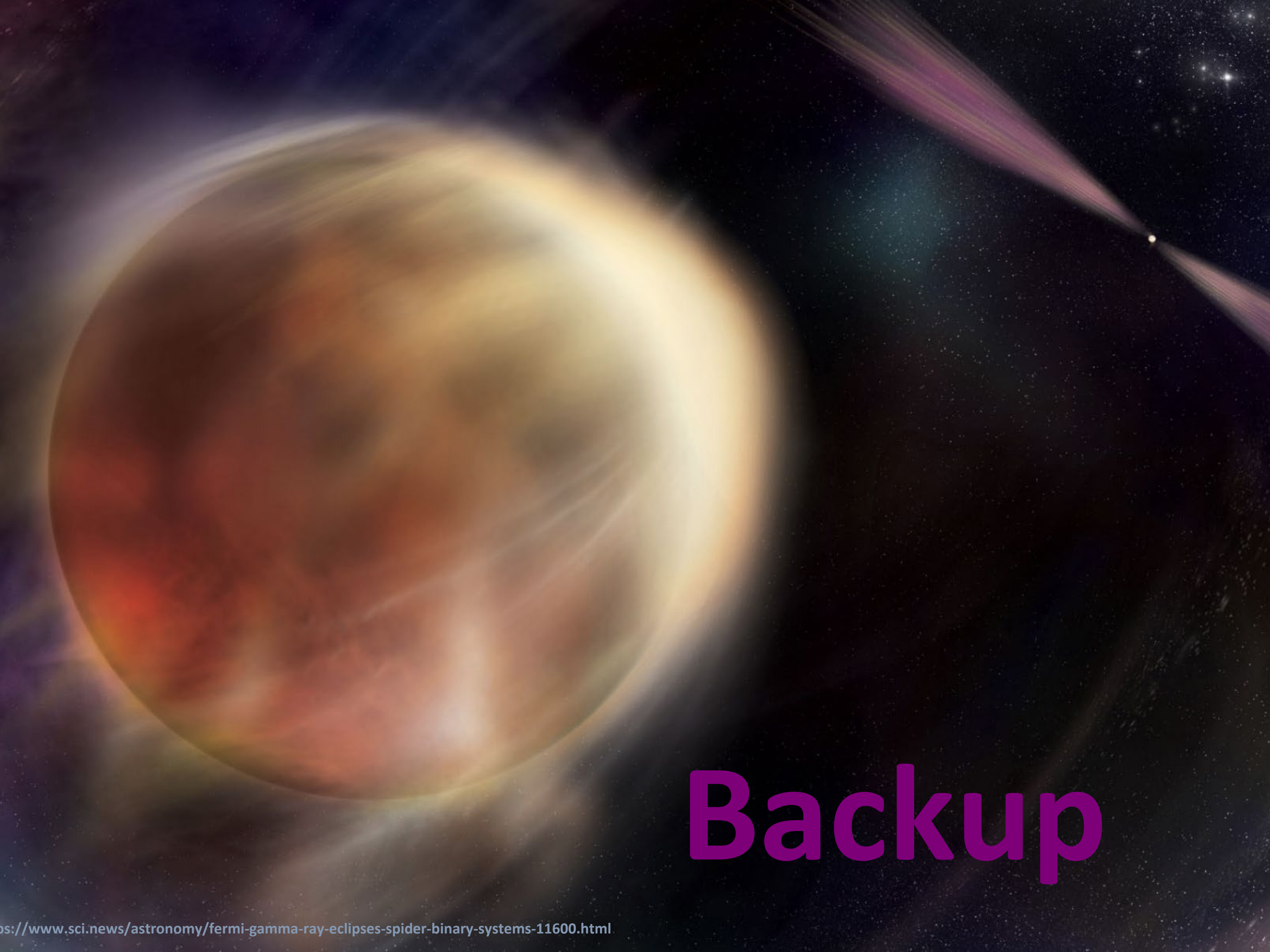
Thanks!

NRF National Research Foundation | RISA Research and Innovation Support and Advancement

This work is based on the research supported wholly/in part by the National Research Foundation (NRF) of South Africa (grant number 99072). The grantholder acknowledges that opinions, findings, and conclusions or recommendations expressed in any publication generated by the NRF supported research is that of the author(s), and that the NRF accepts no liability whatsoever in this regard.

https://generationvoyage.fr/visiter-dome-milan/

“Through Him all things were made; without Him nothing was made that has been made” (John 1:3).



Backup

s://www.sci.news/astronomy/fermi-gamma-ray-eclipses-spider-binary-systems-11600.html

Black Widow Spiders

- Many different species worldwide in the black-widow group (the genus Latrodectus. These species do not all behave alike.
- Most past observations of mating took place in laboratory cages, where males could not escape!
- Hunger and a drive for the best reproductive options drive male black widows of certain species to devour “unsuitable” mates.

Western Black Widows, Latrodectus hesperus.
Females weigh 10-160 times as much as males.

- The only known Latrodectus species in which mate cannibalism in nature is the rule are in the Southern Hemisphere. US: mate cannibalism occurs sometimes in Latrodectus mactans, the eastern (southern) black widow, but most males survive. In the other two black species, mate cannibalism has never been observed in the wild!