High-Energy Emission from Spider Binaries

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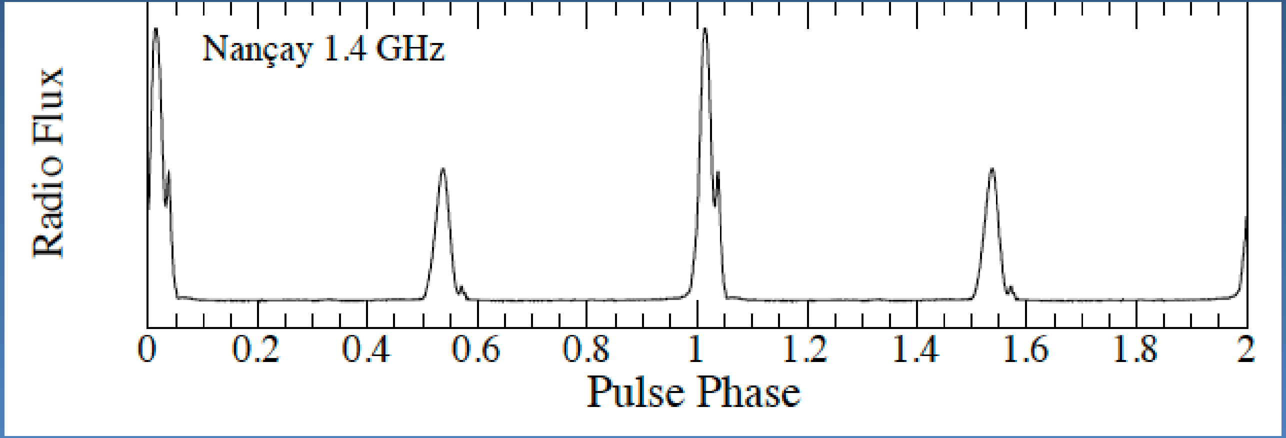
What are millisecond pulsars?

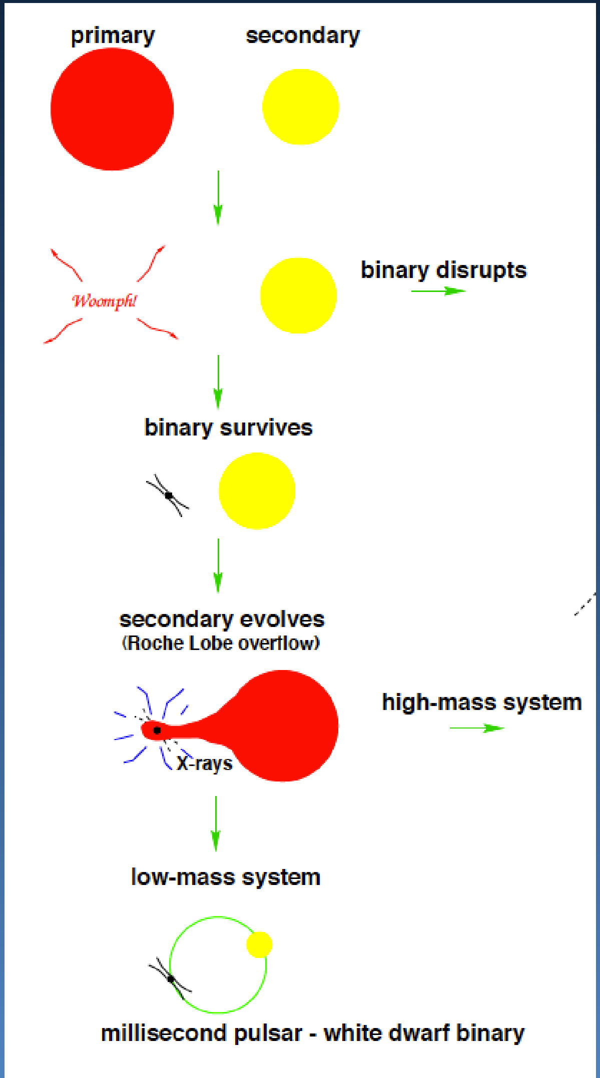
- First detected MSP – PSR J1939-2134 (Backer 1982)
  - P = 1.558 ms, rotation-powered
  - In binary system
  - Very low Pdot (and surface B_0) – but energetic, $E_{sd} = 10^{36}$ erg/s
  - Near NS break-up frequency!



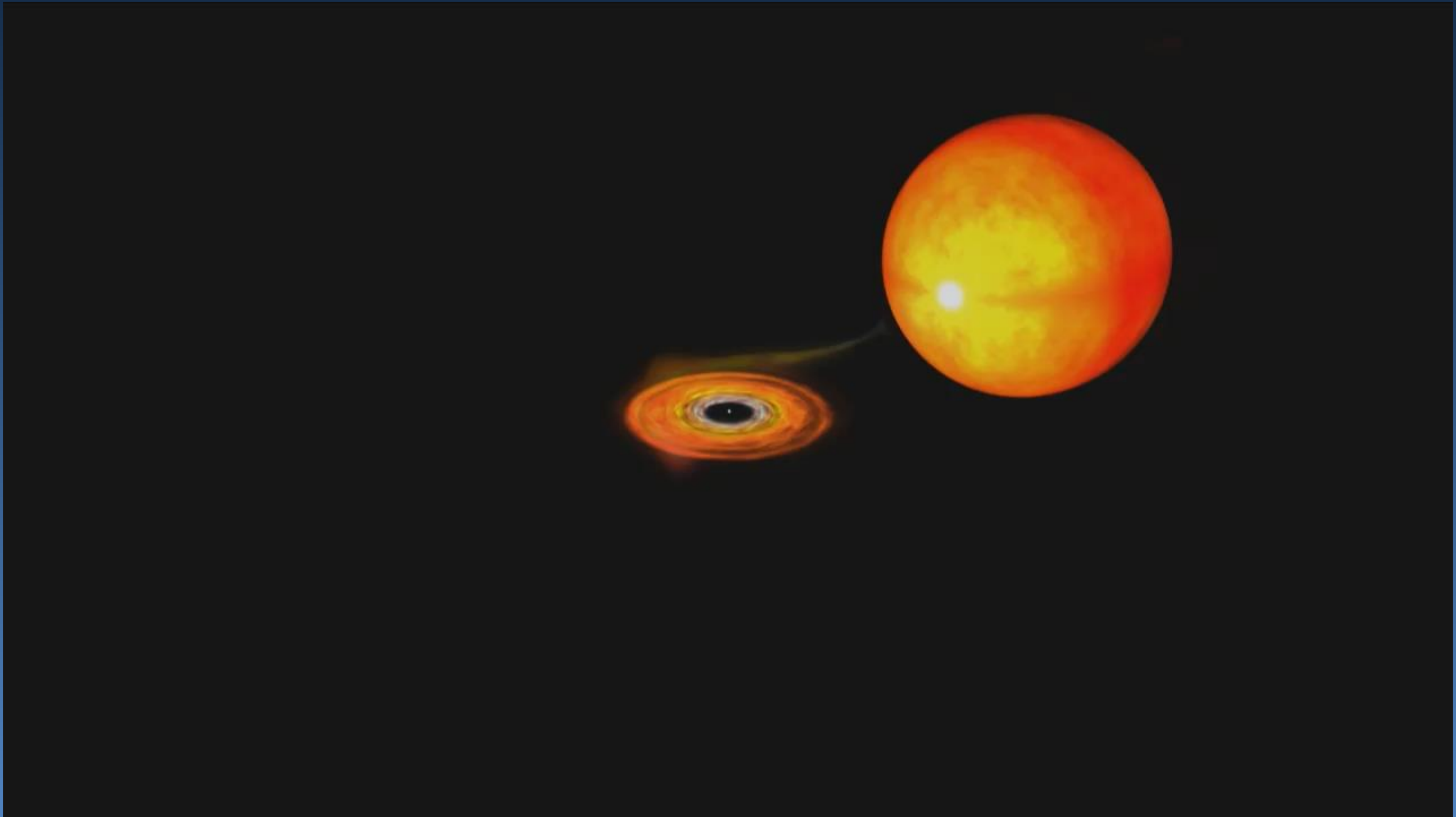
Binary spin-up model

Alpar et al. (1982)

Low-mass X-ray binary



Spin-up of a millisecond pulsar



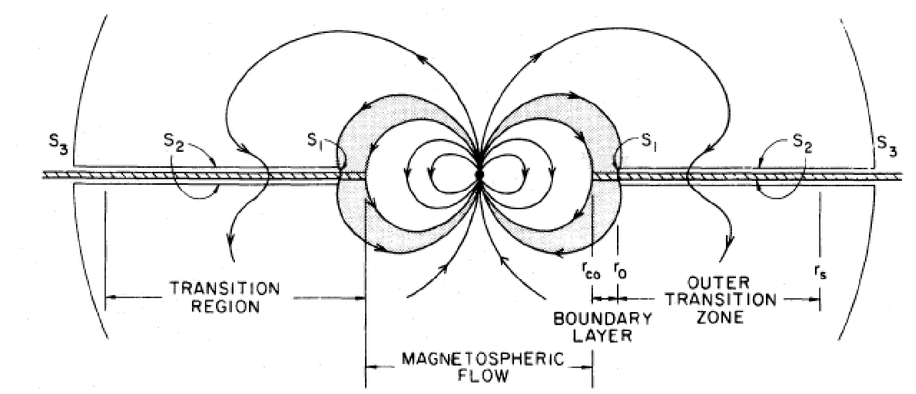
Binary spin-up model

(Davison & Ostriker 1973, Alpar et al. 1982)

Equilibrium period = Keplerian velocity at the Alfven radius

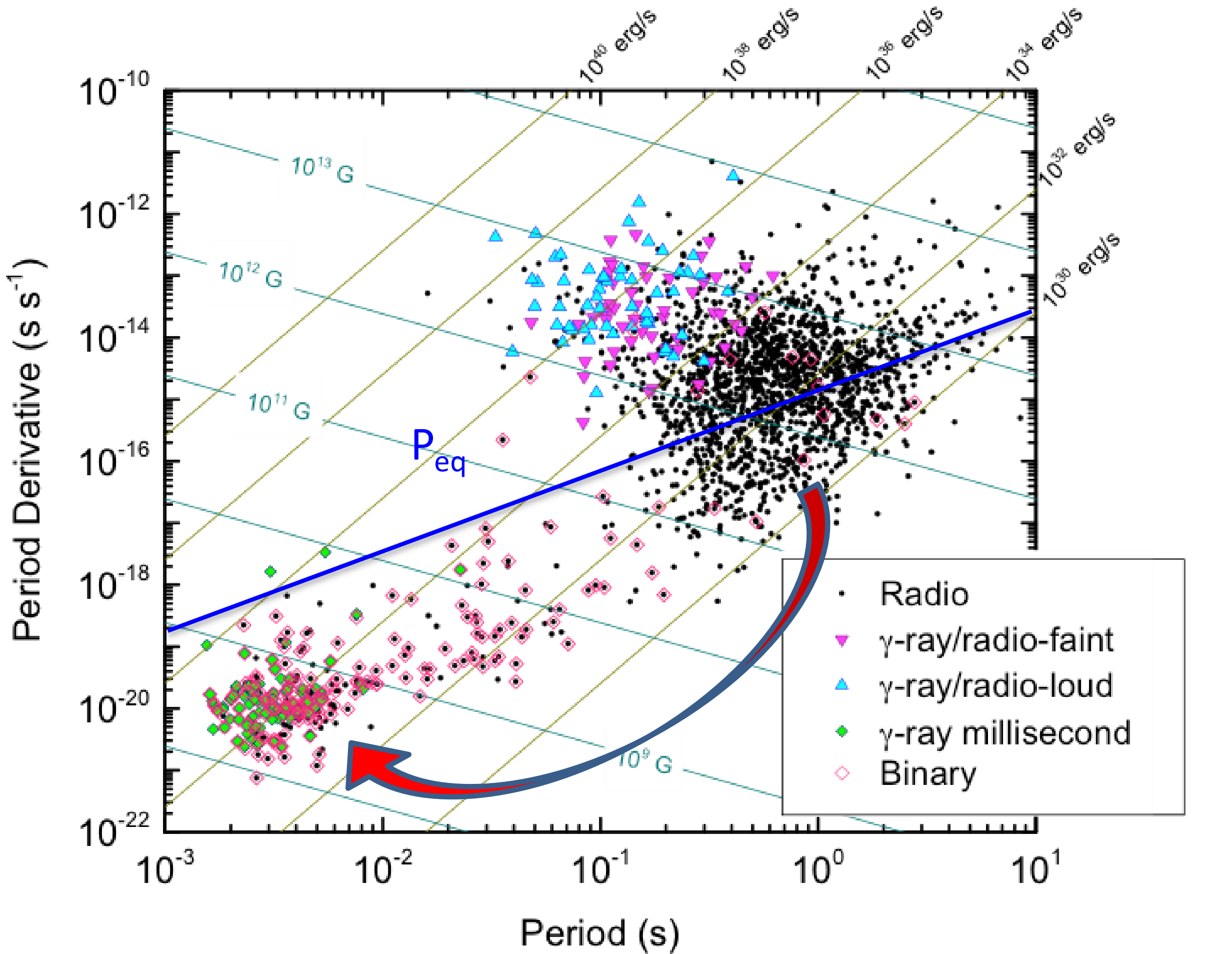
$$\Omega_{eq} = \left(\frac{GM}{R_A^3}\right)^{1/2} \qquad \frac{B^2}{8\pi} = \rho v^2 \Rightarrow R_A = \left(\frac{B_0^4 R^{12}}{8GM\dot{M}_a^2}\right)^{1/7}$$

$$P_{eq} \approx 6\times10^{4}\,s\,B_8^{6/7} R_6^{18/7} \left(\frac{M}{M_{solar}}\right)^{-5/7} \dot{M}_{17}^{-3/7}$$



Ghosh & Lamb 1979

MSPs: recycled from the graveyard



- ~424 field MSPs
  ~ 80% binary
- 128 are γ-ray pulsars
- Spin periods
  1.5 - ~ 100 ms
- Magnetic fields ~ 10^8 – 10^{10} G
- Ages 10^8 – 10^9 yr
- "Recycled" pulsars spun-up by binary companion stars

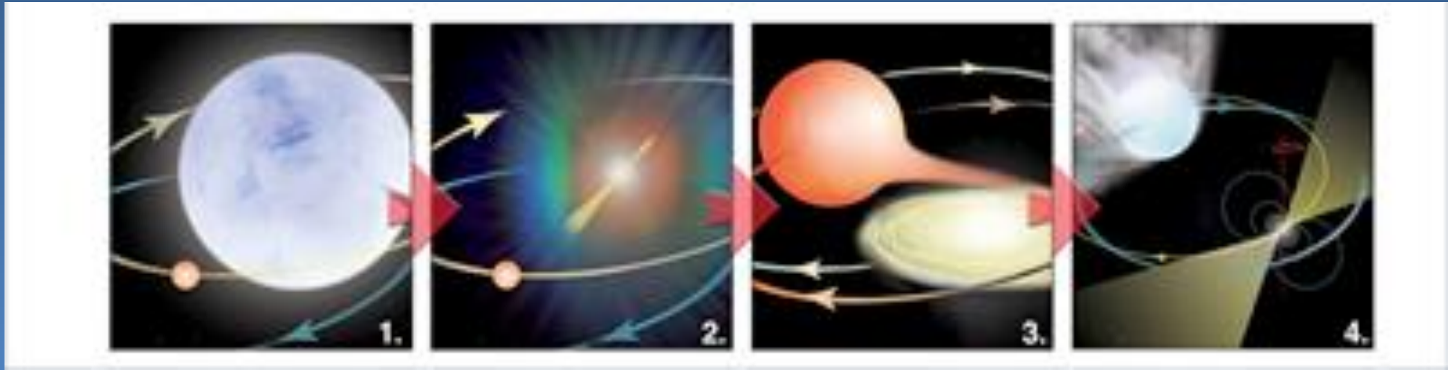
Transitional MSPs

- Discovery of accreting MSPs (Wijnands & van der Klis 1998)
  - Evolutionary progenitors of radio MSPs
  - ~20 presently known: spin frequencies ~100 – 700 Hz

- MSP accretion/spin-down in transition (Archibald et al. 2009)

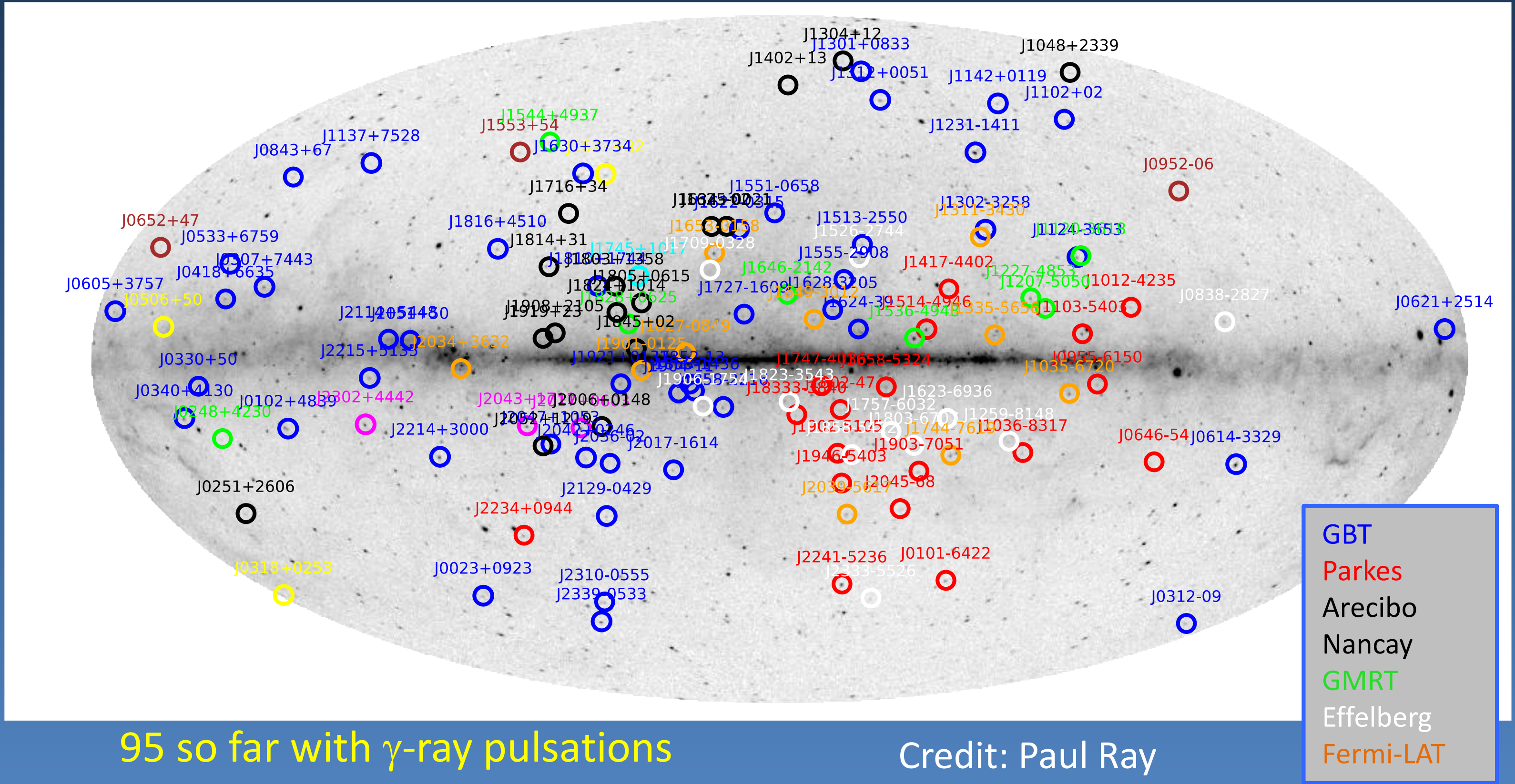
Newly discovered radio PSR J1023+0038 was accreting source FIRST J102347.67+003841.2 in 2002

Two other tMSPs and several candidates found since



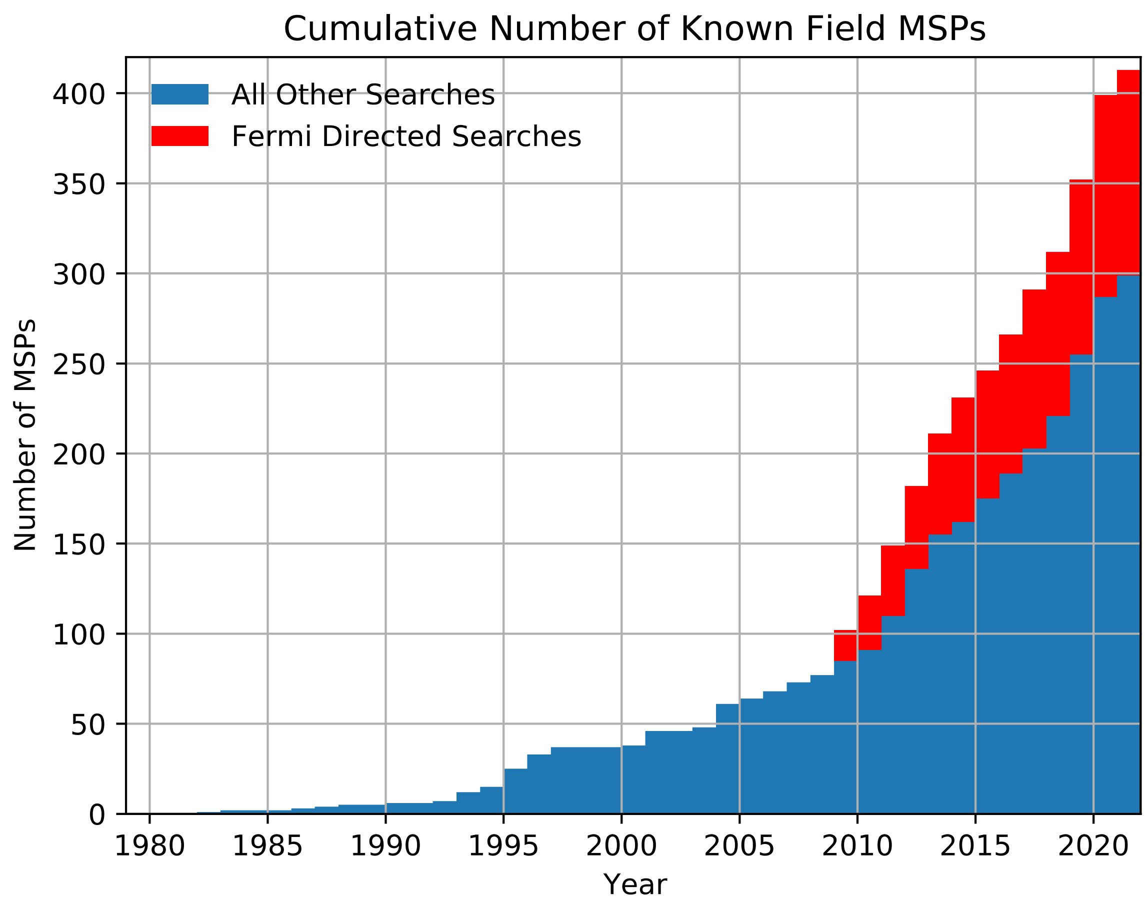
MSPs discovered in Fermi unID sources

126 new radio MSPs discovered in Fermi unidentified sources!



95 so far with γ-ray pulsations

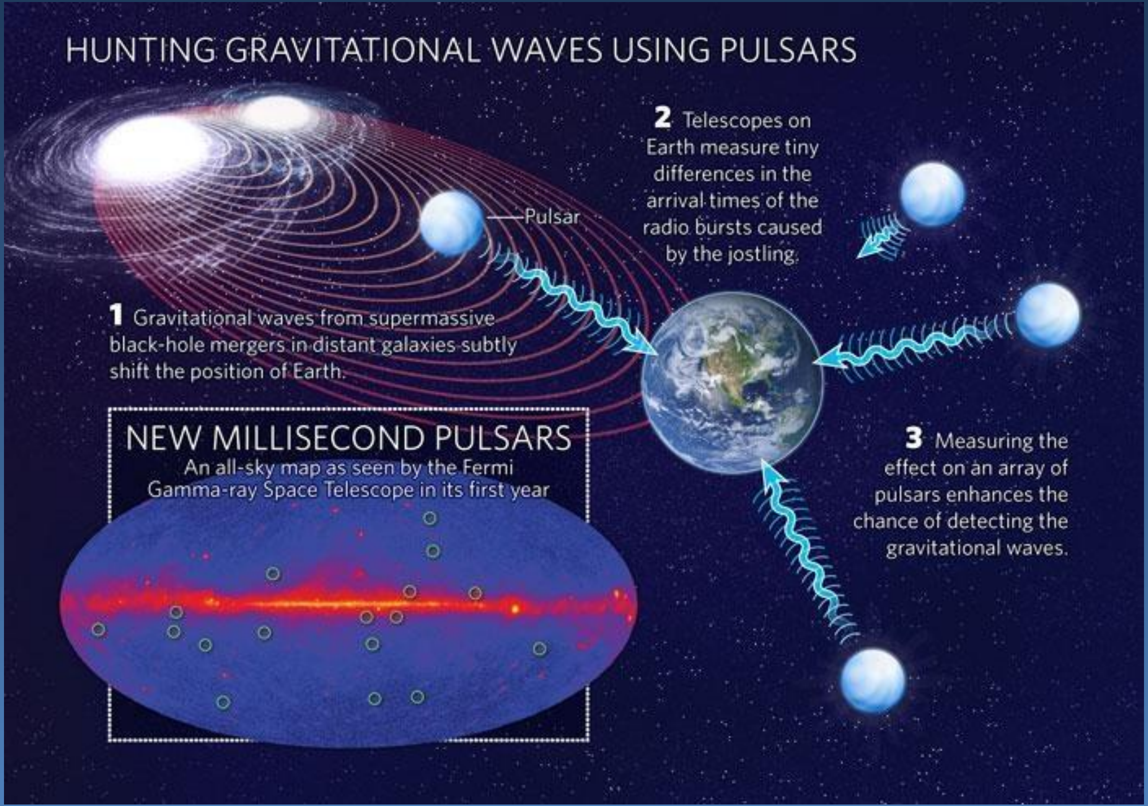
Credit: Paul Ray



Cumulative Number of Known Field MSPs
All Other Searches
Fermi Directed Searches
Number of MSPs
Year
0
50
100
150
200
250
300
350
400
1980
1985
1990
1995
2000
2005
2010
2015
2020

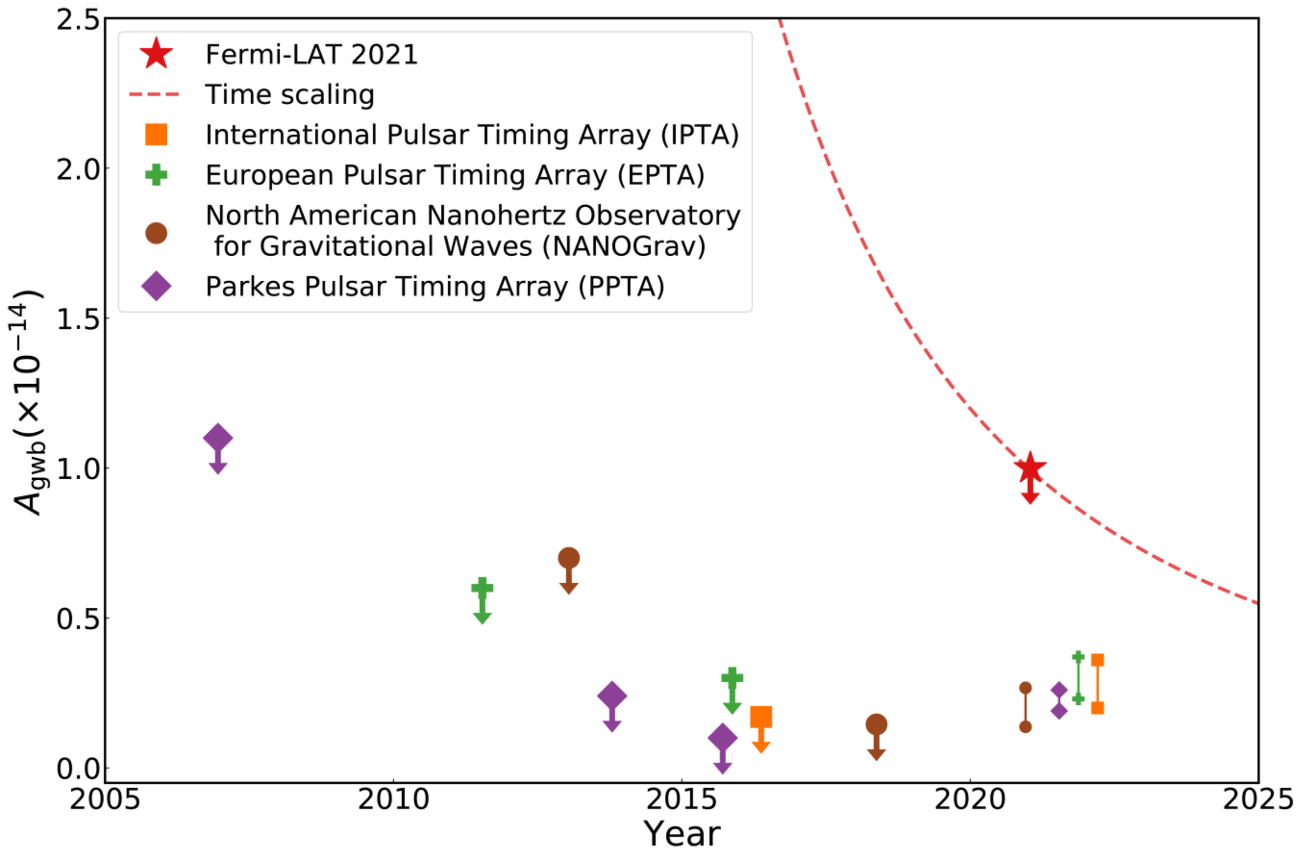
Gamma-ray MSPs and gravitational waves

Radio pulsar timing arrays



Gamma-ray MSPs and gravitational waves

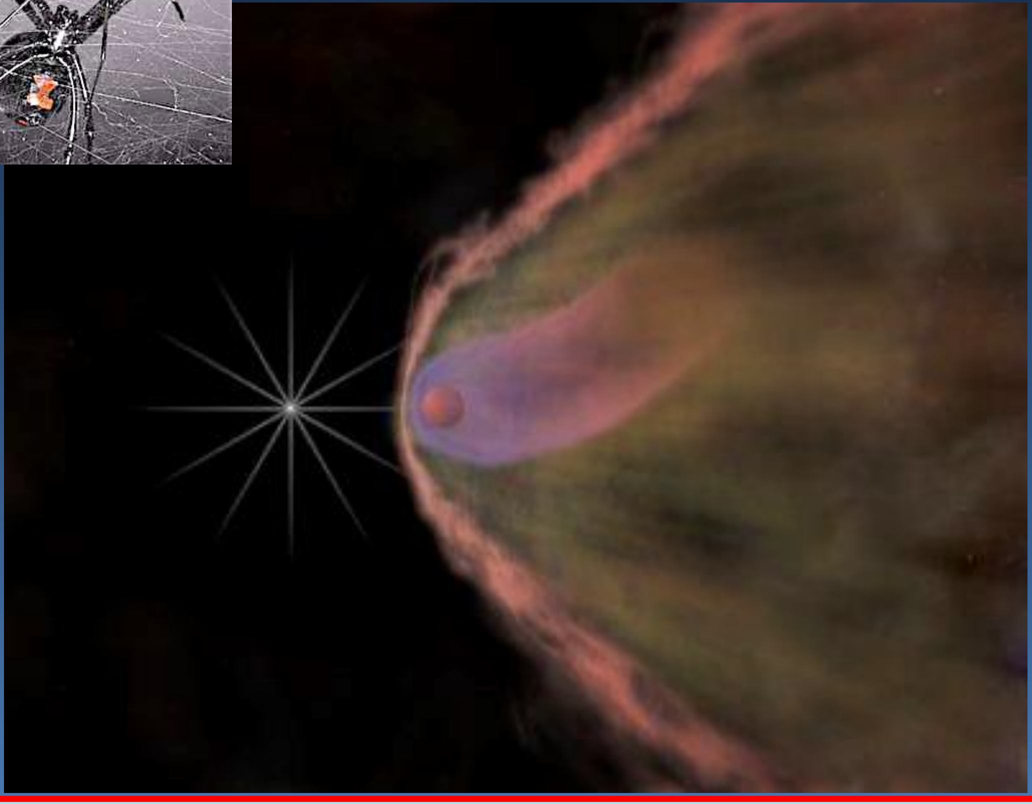
Ajello et al. (Fermi Collaboration) 2022



Gamma-ray pulsar timing array!

- 12.5 years of Fermi data
- 35 bright MSPs
- Limit on stochastic GW signal < 10^{-14}
- Will reach radio timing array limit in 2 years!

Spider millisecond pulsars

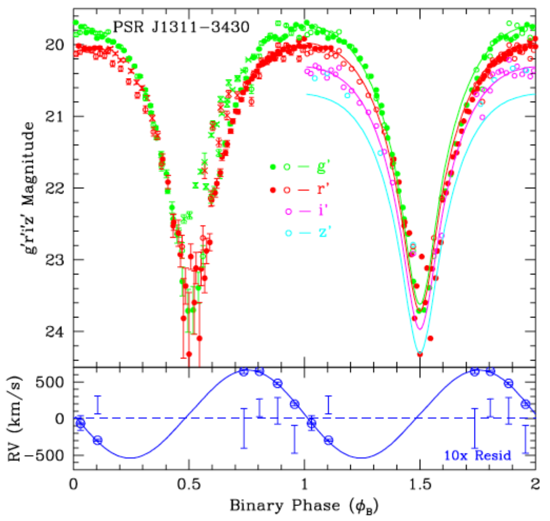


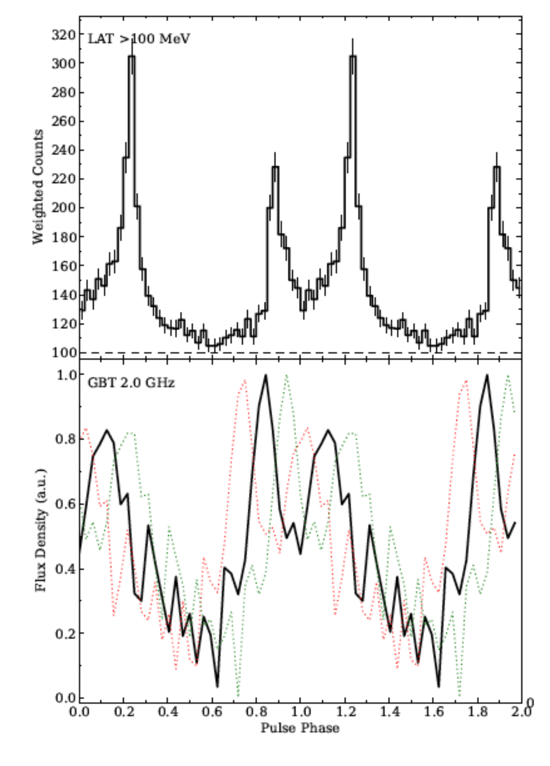
- Black Widows - MSPs with very low-mass binary companions
  - 10 – 80 Jupiter masses ($< 0.1\ M_\odot$)
- Pulsar wind ablates companion by exciting stellar winds
- Redbacks (cousins)
  - $> 0.1\ M_\odot$ companions

Before Fermi launch: 3 Black Widows, 1 Redback
Now: 31 Black Widows, 12 Redbacks – Total of 43!

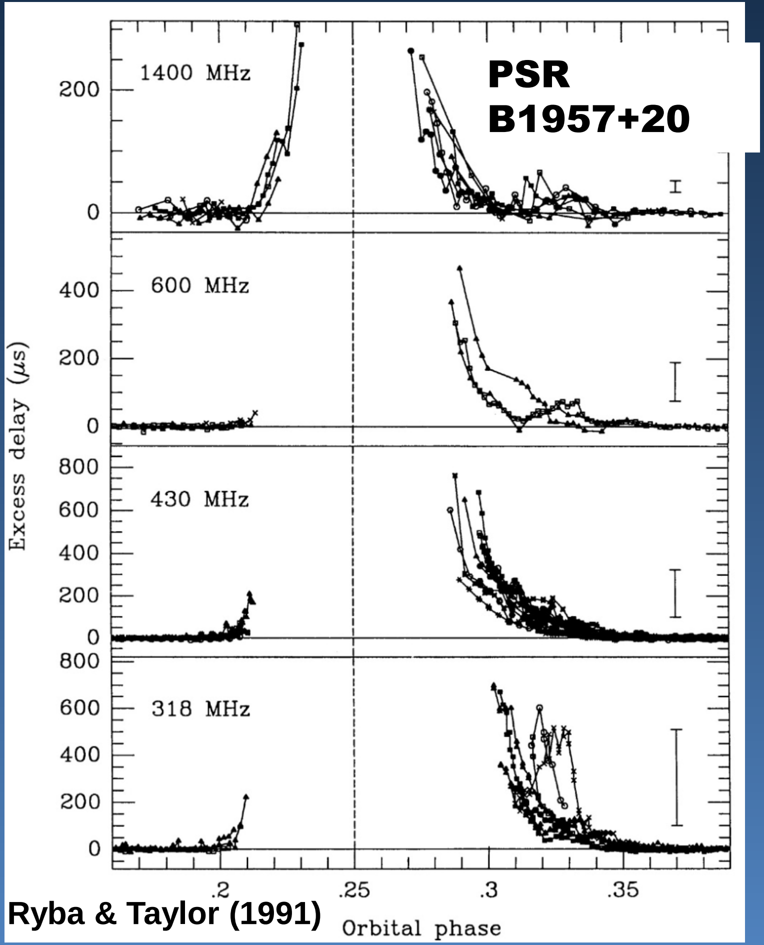
Fermi 'web' catches Black Widow

- Optical orbital modulation found in 2FGL J1311.7-3429 (Romani et al. 2012)
- First MSP J1311-3430 discovered in γ-ray blind search of 2FGL J1311.7-3429 (Pletsch et al 2012)
- But not a radio quiet pulsar! (Ray et al. 2012)
- Tiny companion (0.008 $M_{\odot}$) and smallest known orbit (1.5 hr – Earth/Sun distance!)





Radio properties

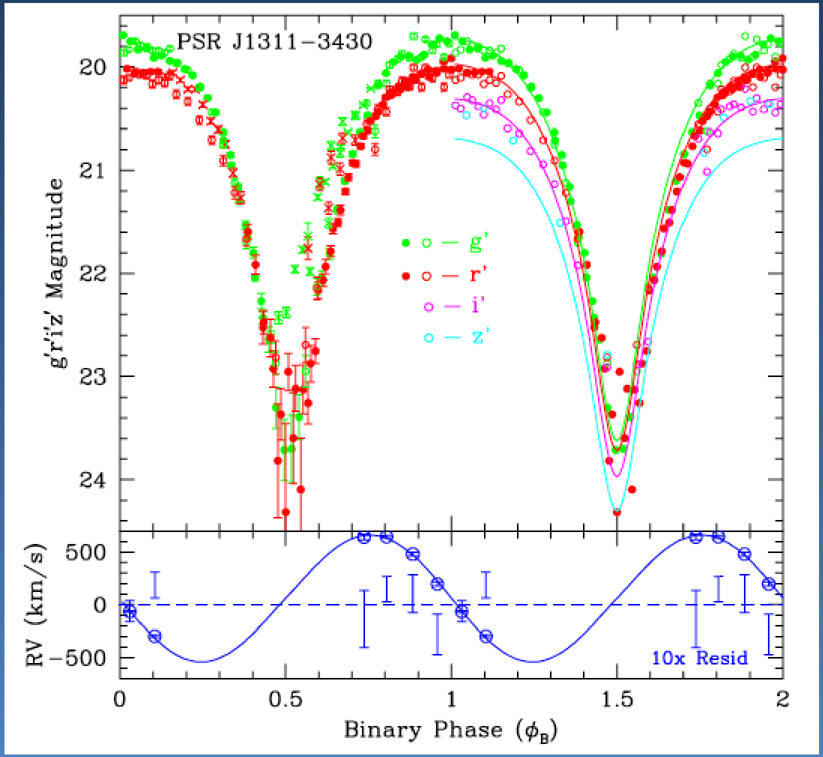


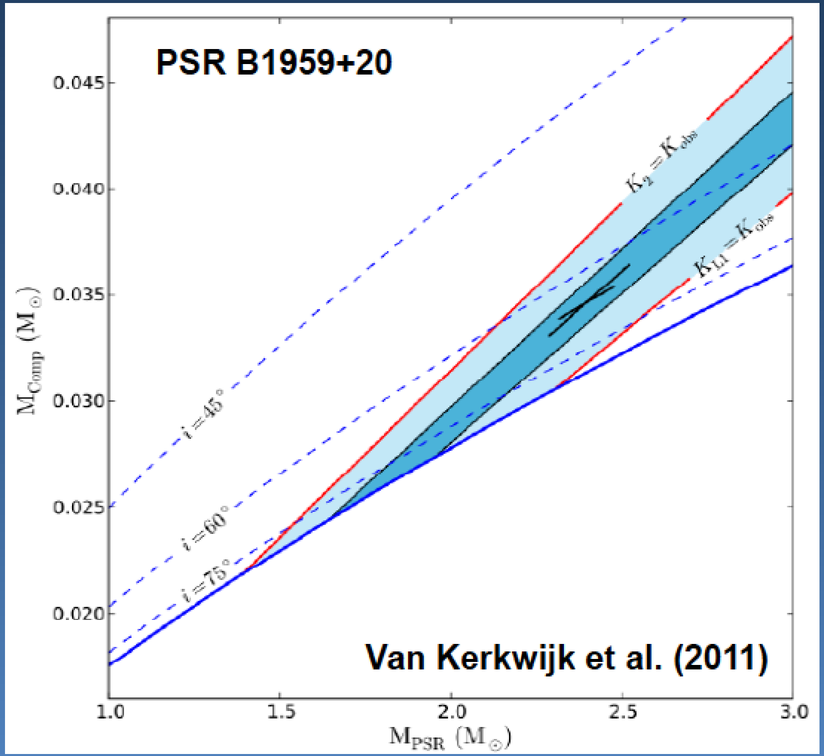
Ryba & Taylor (1991)

- **Frequency-dependent radio eclipses (disappearance of radio pulses).**
- **Shrouding of MSP pulsed radio emission by intra-binary material.**
- **Phase of eclipse discriminates shock orientation.**
- **Asymmetry of eclipse decreases with frequency: higher frequency observations probe denser regions closer to the shock.**

Optical observations of the stellar companion

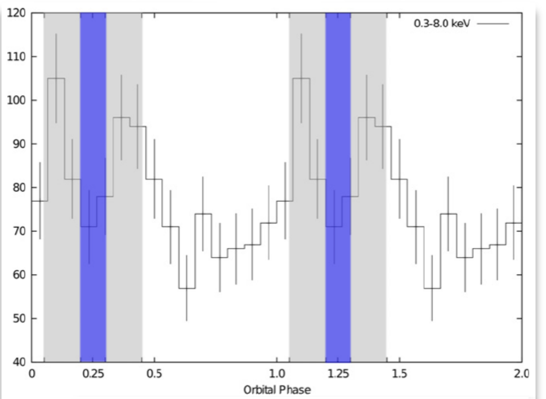
- Optical light curve modeling can constrain orbital inclination and mass ratio
- Companion temperature as high as few times 10^4 K on heated side



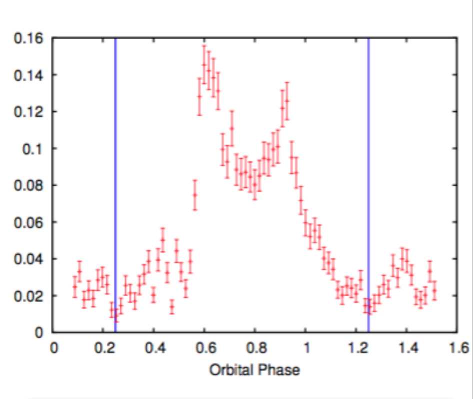


Double-peaked soft X-ray light curves

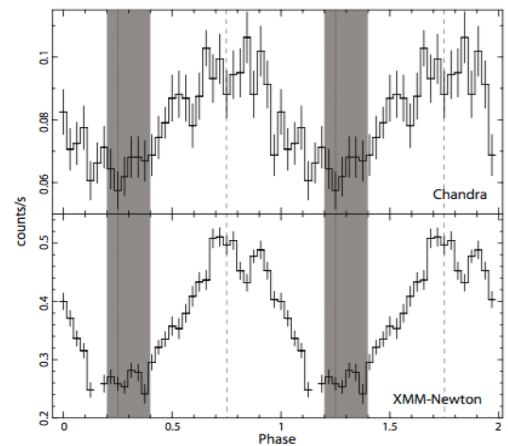
- Flux minimum around superior (BWs) or inferior (RBs) conjunction
- Spectral indices $\Gamma \sim 1 - 1.5$
- Synchrotron, modulated by Doppler boosting



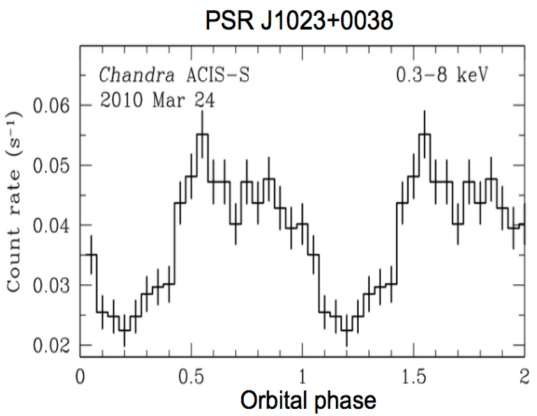
B1957+20 Huang et al. 2012



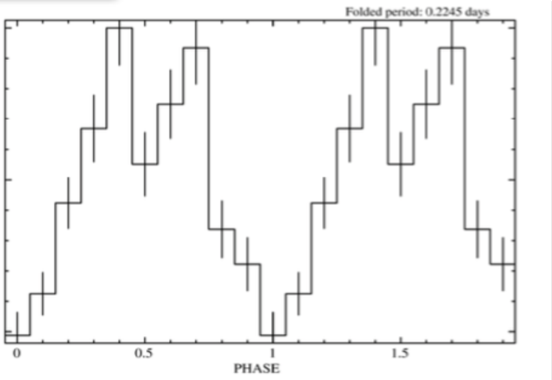
J2129-0429, Roberts et al. 2015



J1723-2837, Hui et al. 2014



J1023+0038, Archibald et al. 2010

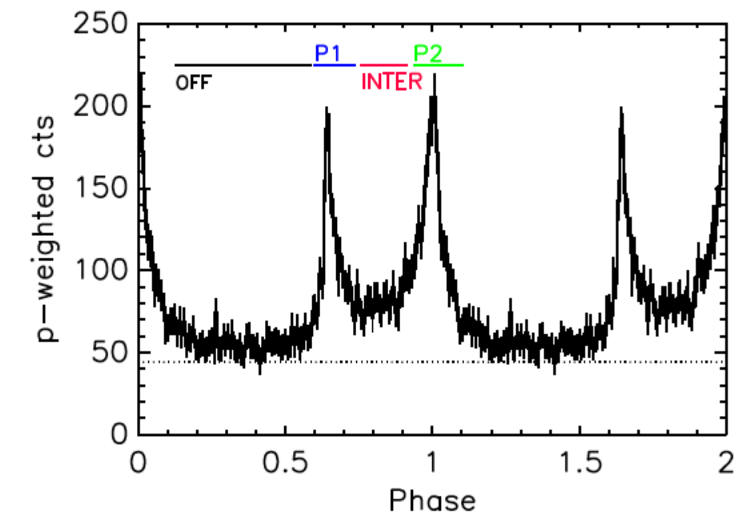


J2039-5618, Salvetti et al. 2015

Gamma-ray properties

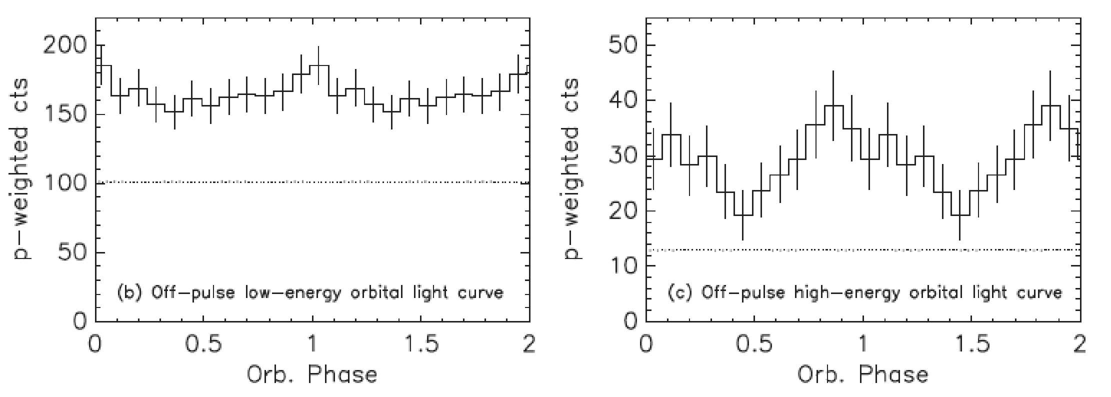
An et al. 2017

Fermi pulsar light curve



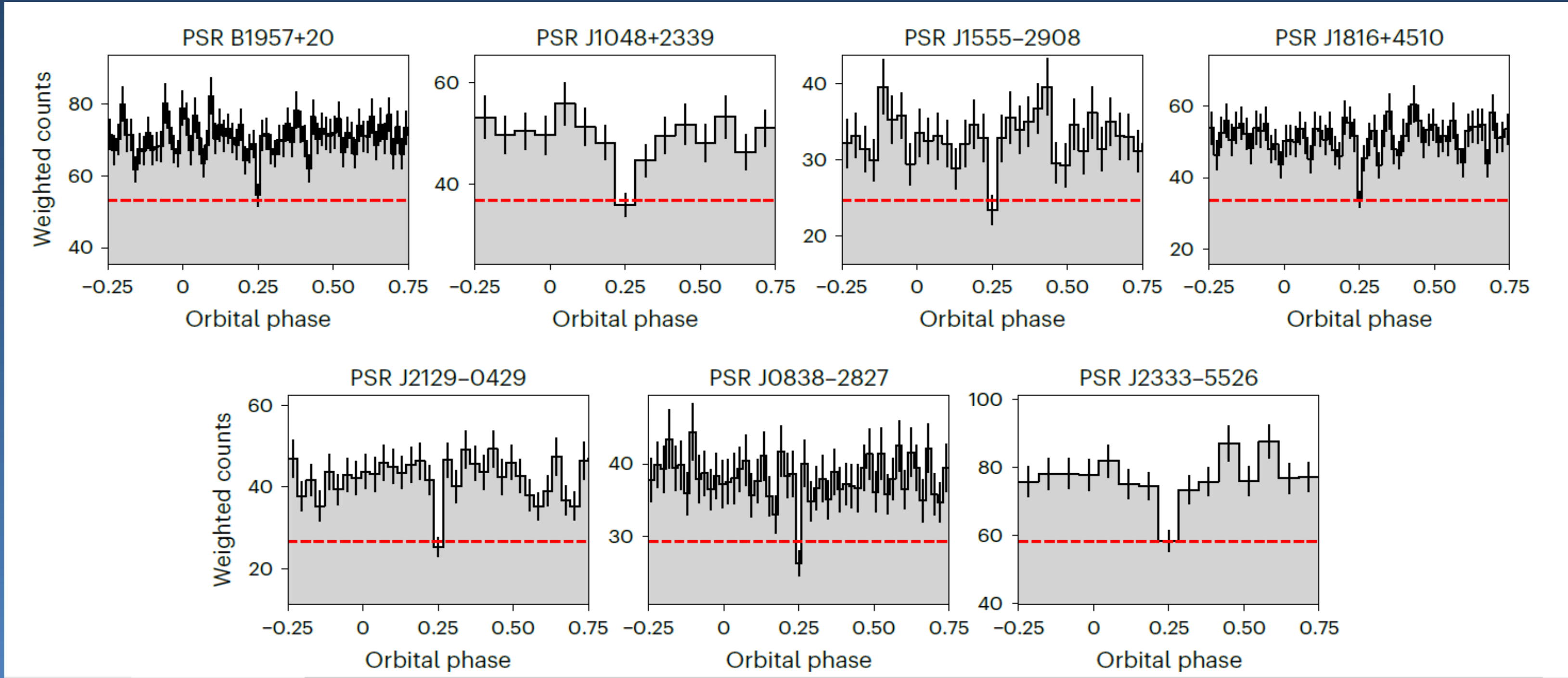
PSR J1311-3430 orbital modulation

Fermi off-pulse light curve

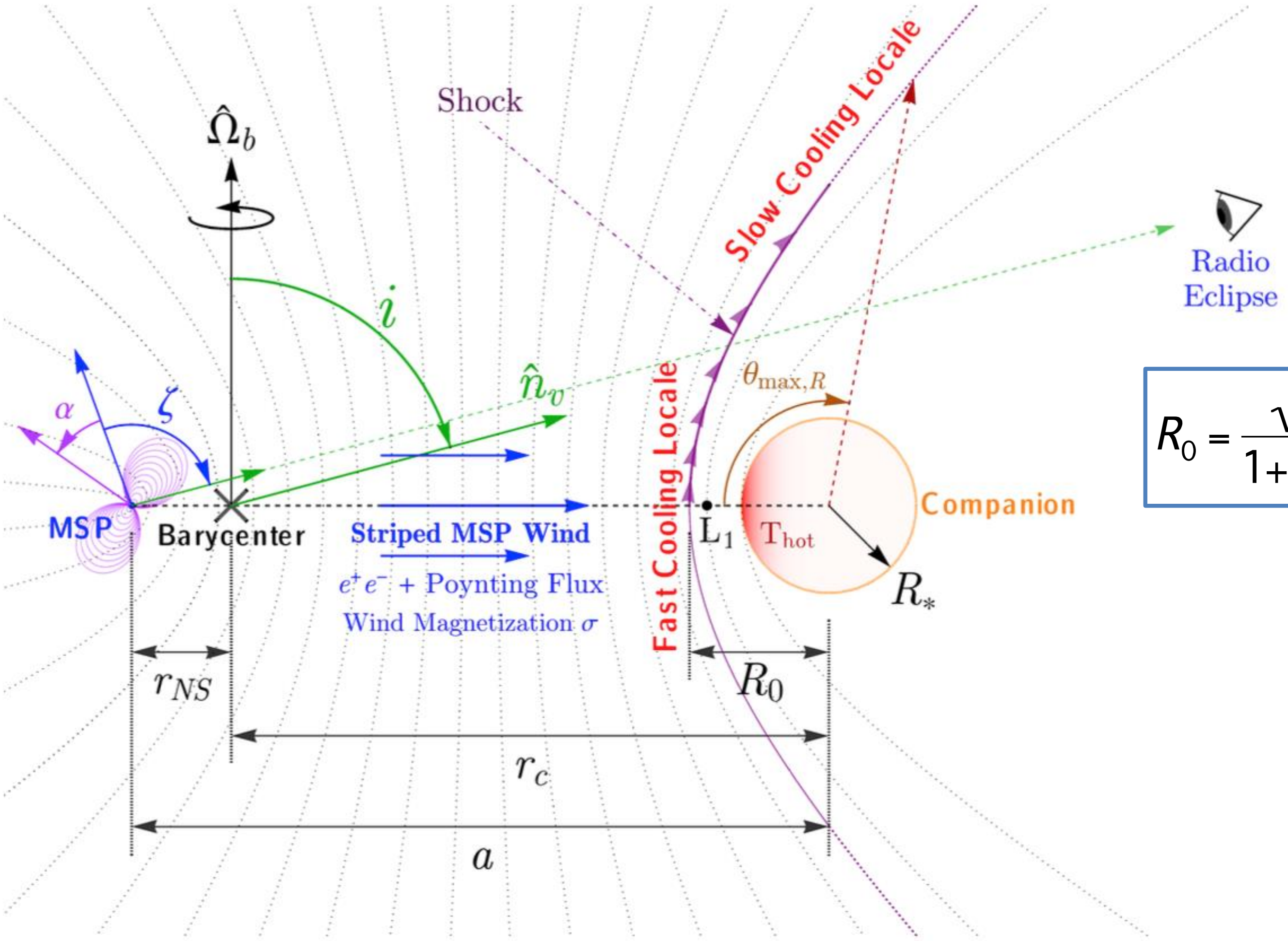


Gamma-ray eclipses

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



Black widow and Redback binaries



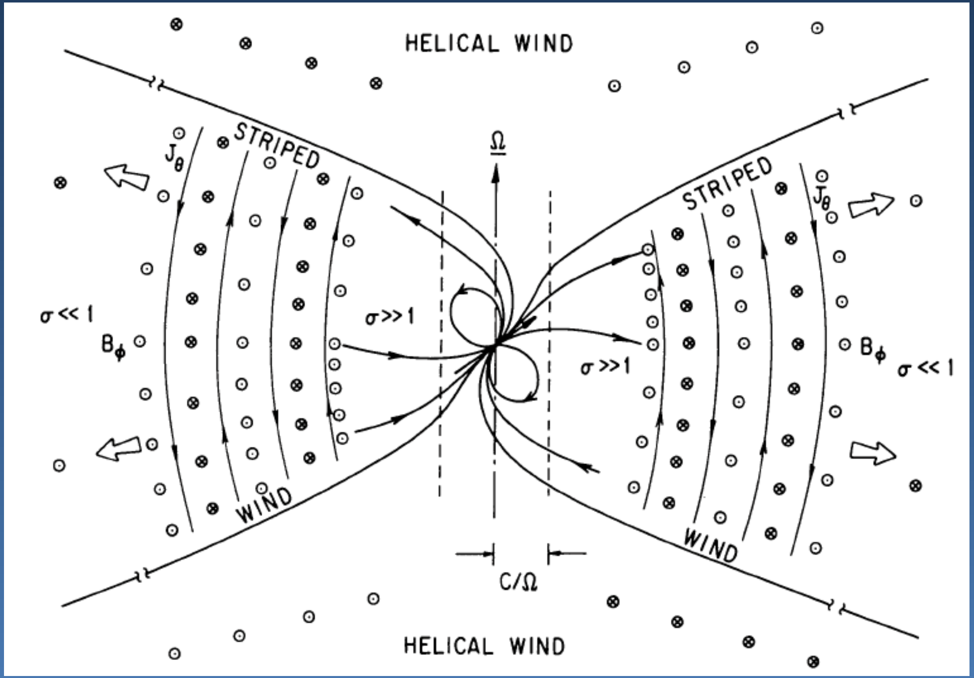
Harding & Gaisser 1990

$$R_0 = \frac{\sqrt{\eta_w}}{1+\sqrt{\eta_w}} \qquad \eta_w = \frac{P_{comp}}{\dot{E}_{SD}/c}$$

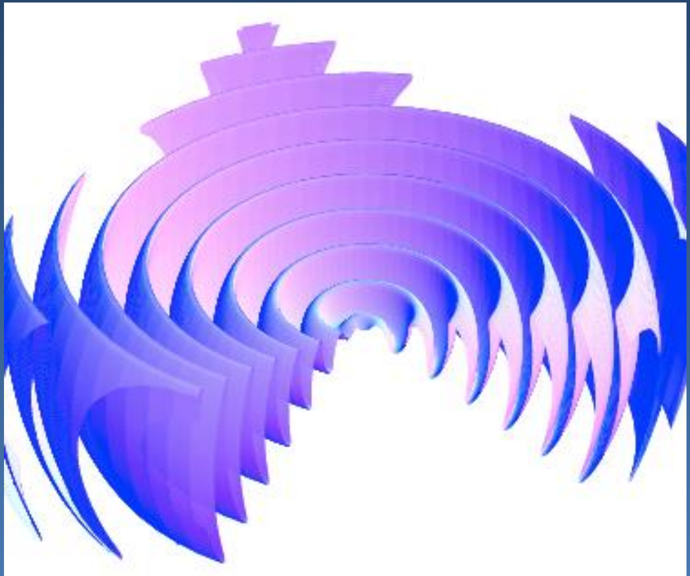
If $\eta_w < 1$, shock surrounds companion

If $\eta_w > 1$, shock surrounds the MSP

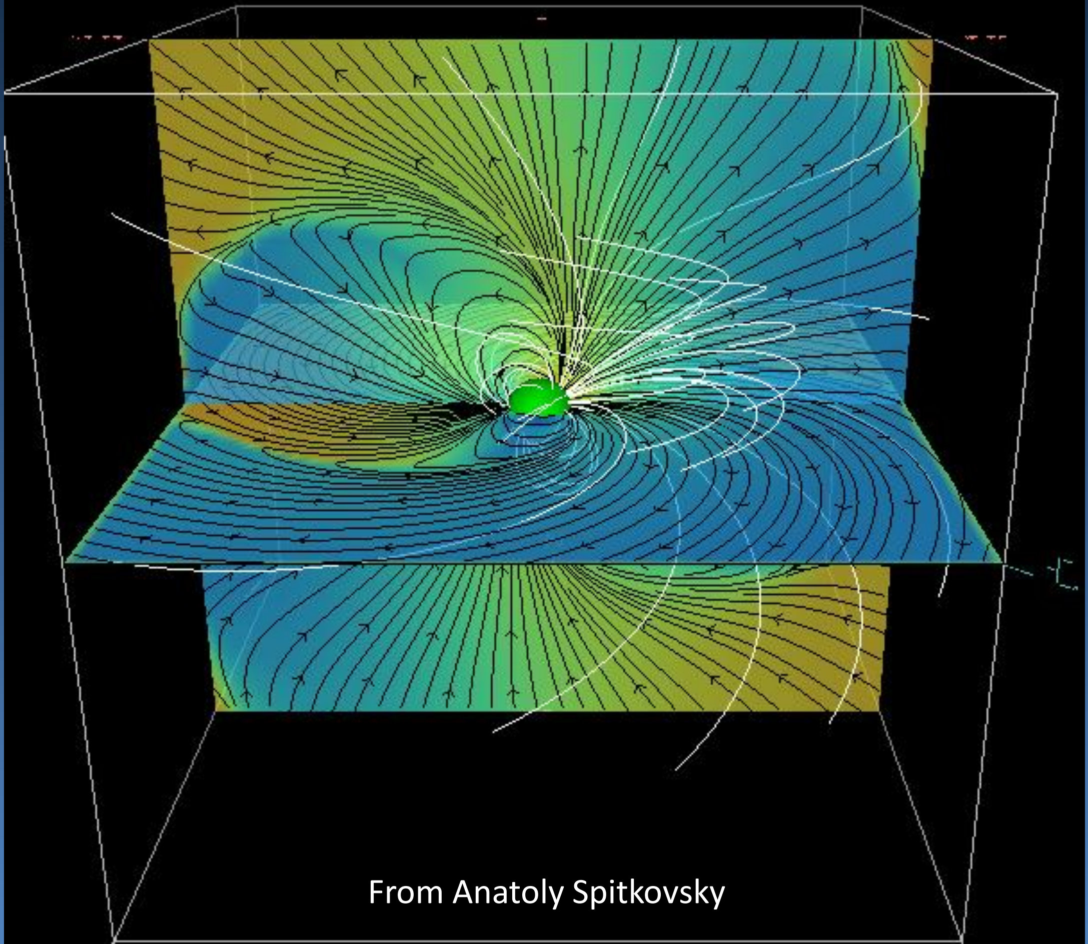
Pulsar striped wind



Coroniti 1990



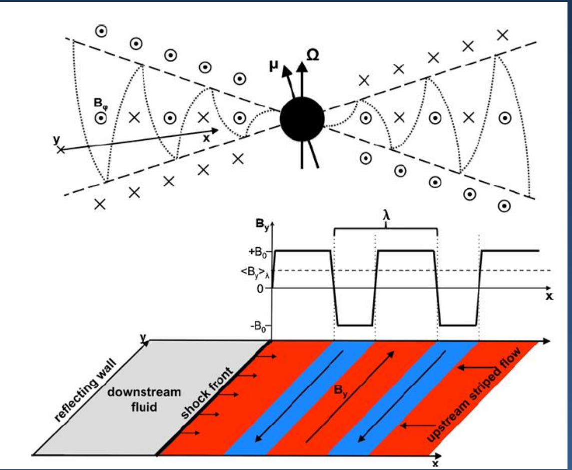
3D pulsar magnetosphere

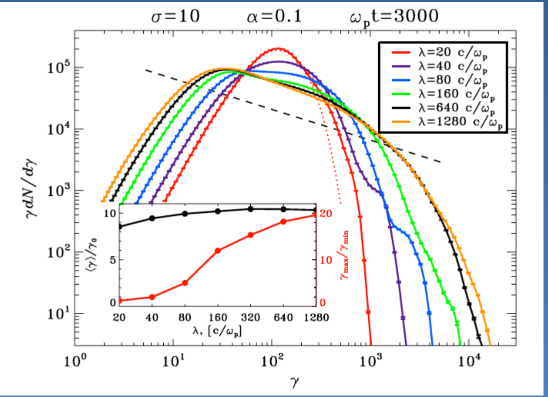


From Anatoly Spitkovsky

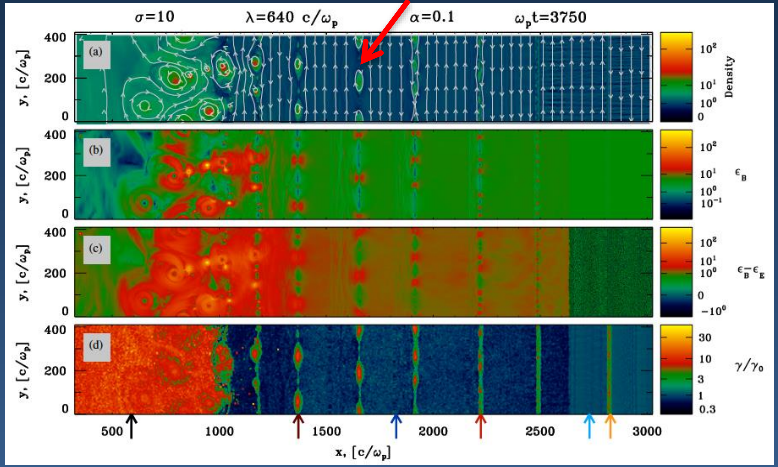
Shock-driven reconnection

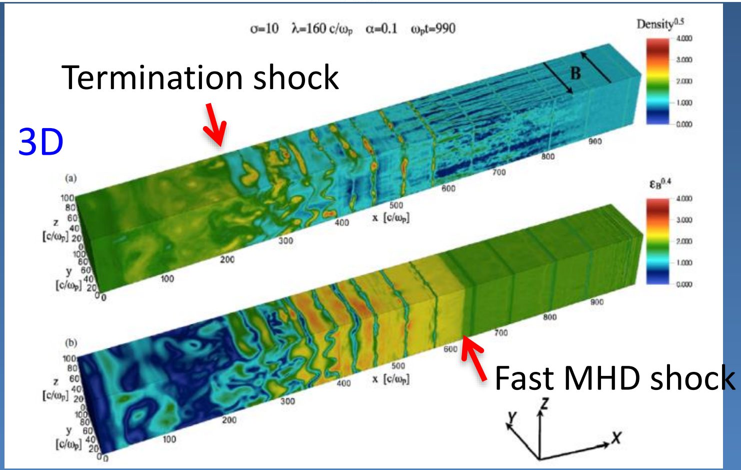
Sironi & Spitkovsky 2011





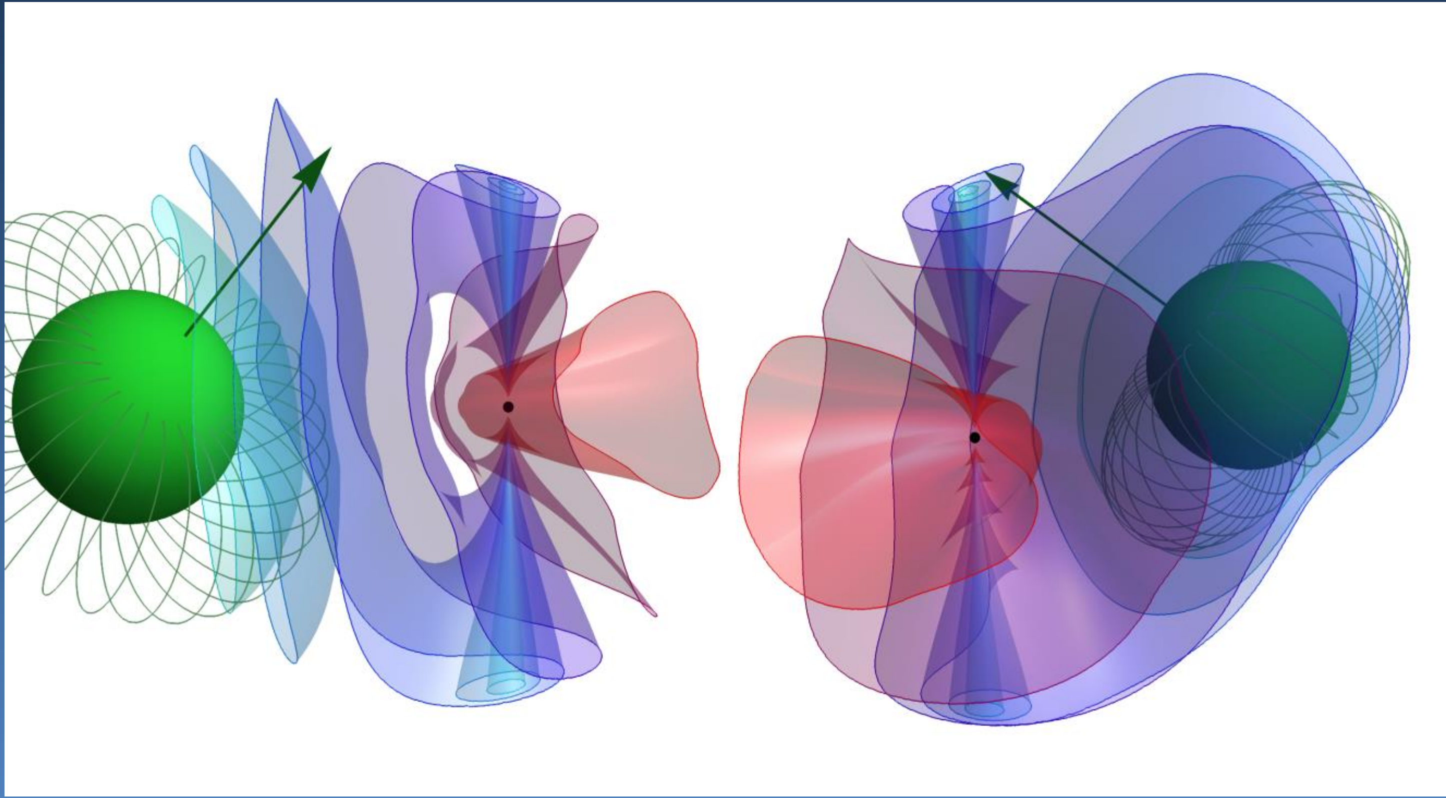
2D Particles accelerated at X-points where E > B





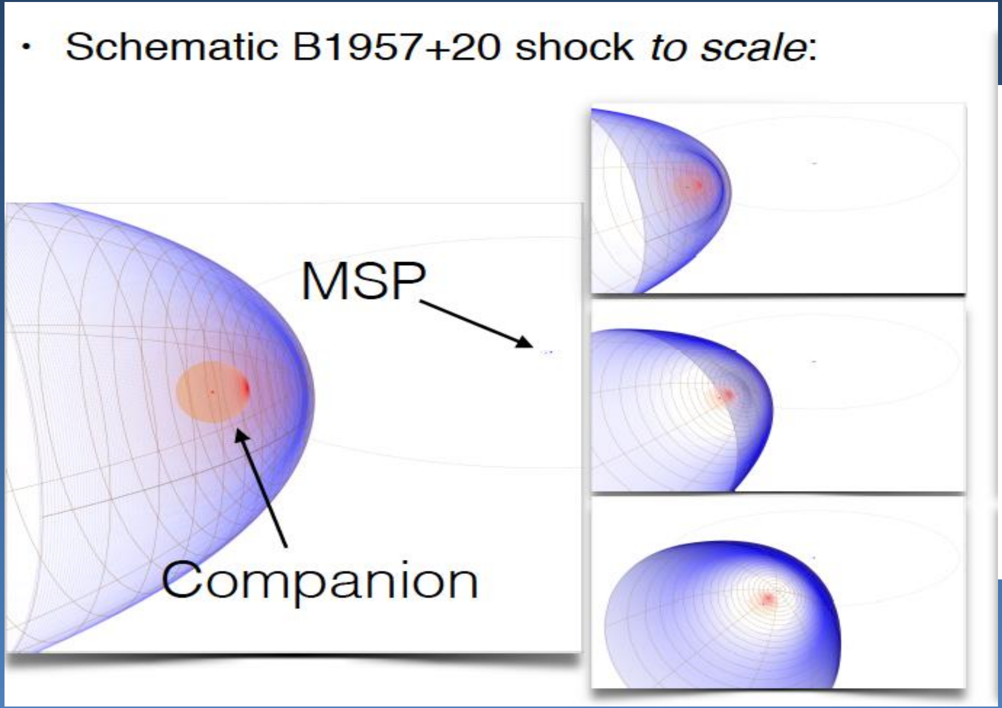
Magnetic pressure of companion

Wadiasingh et al. 2018

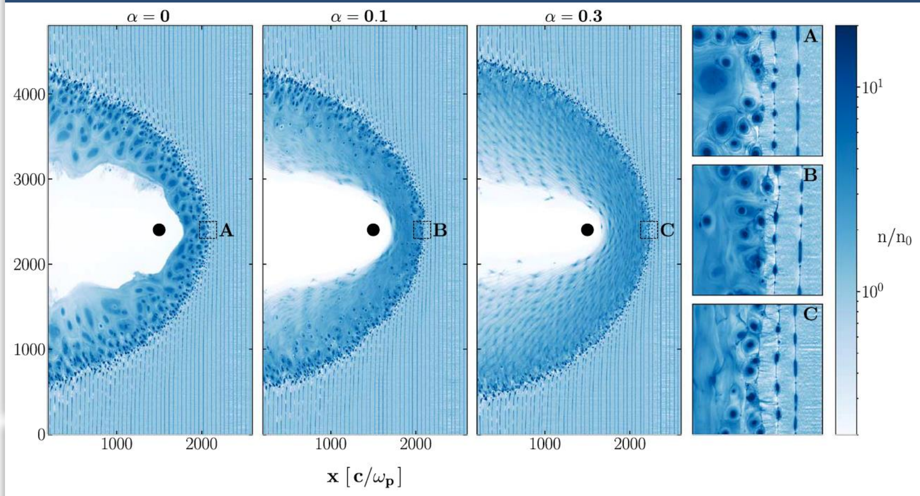


Shock geometry

Use analytic solution for shock geometry from isotropic colliding winds (Canto et al. 1996)



PIC simulations (Cortez & Sironi 2022)



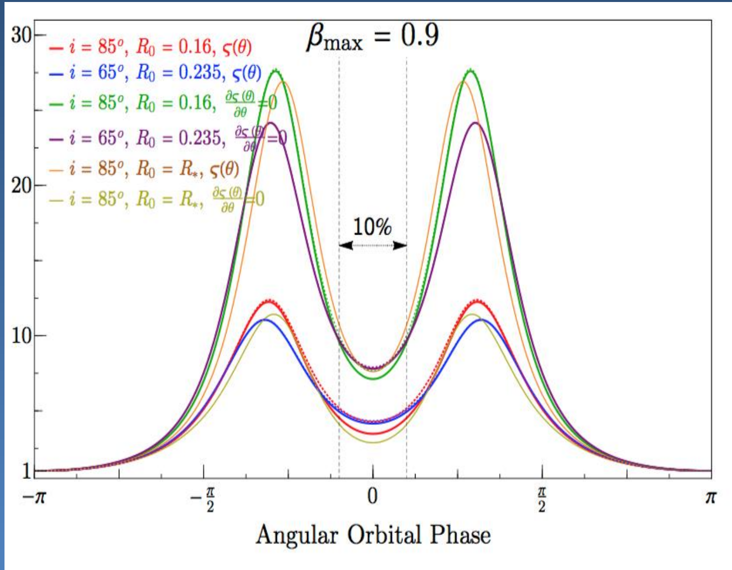
Orbitally modulated synchrotron emission

Wadiasingh et al. 2017

- Doppler boosting produces a double-peaked light curve for high bulk flow velocity centered on inferior conjunction
- Bulk flow β_{max} > 0.5 needed for doubled-peaked light curves

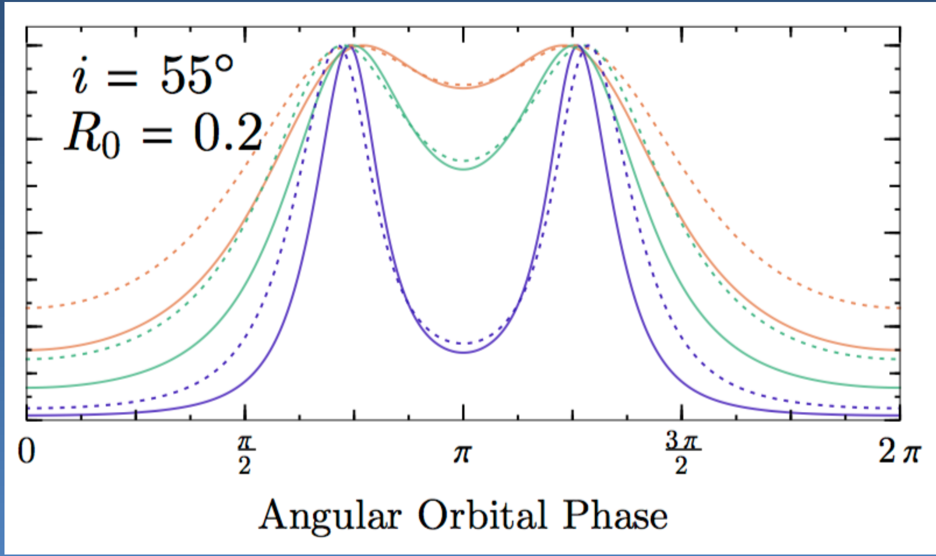
Shock surrounding companion (e.g. B1957+20)

Light curve centered on superior conjunction

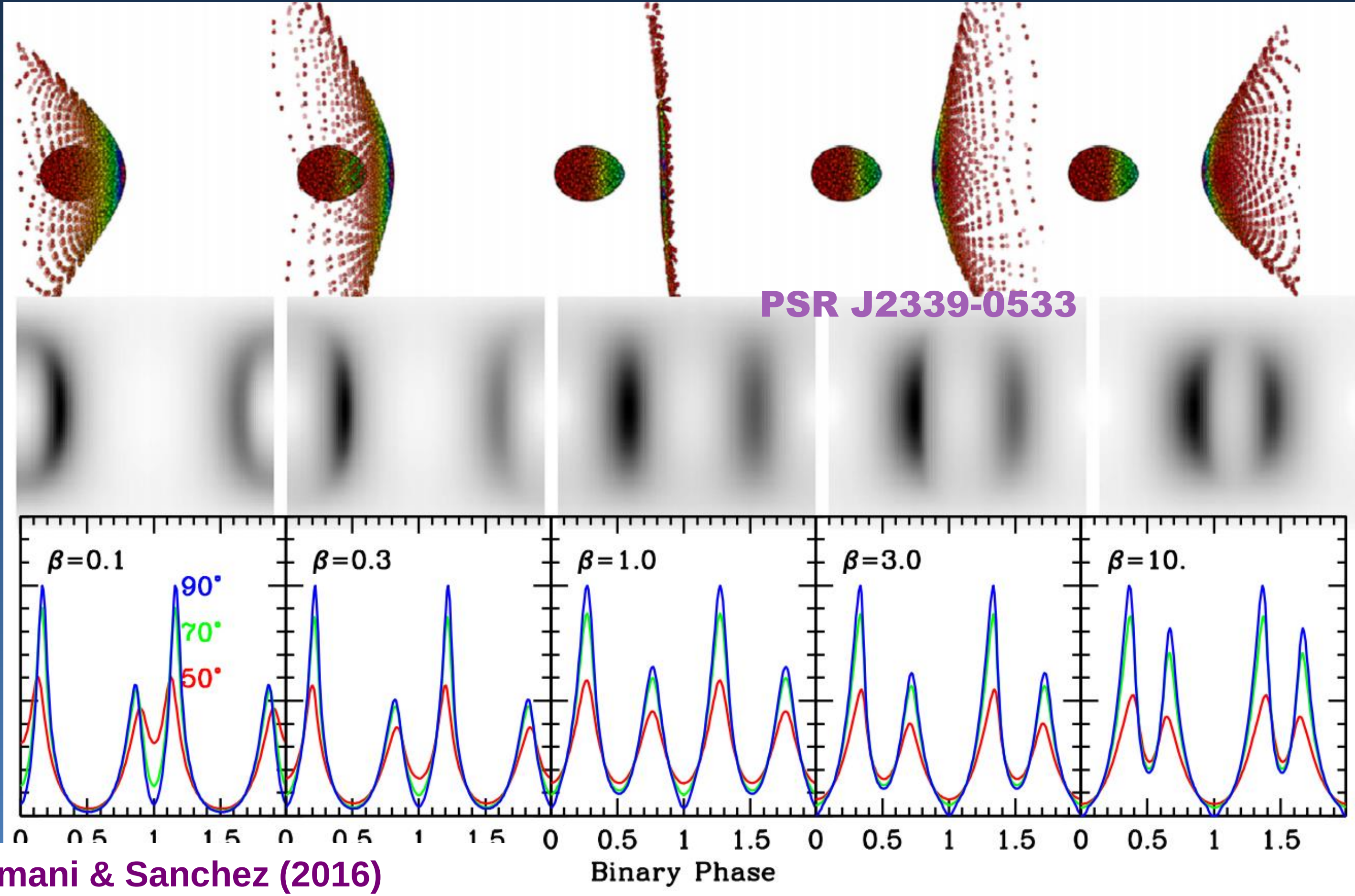


Shock surrounding pulsar (e.g. J1023+0038)

Light curve is centered on inferior conjunction



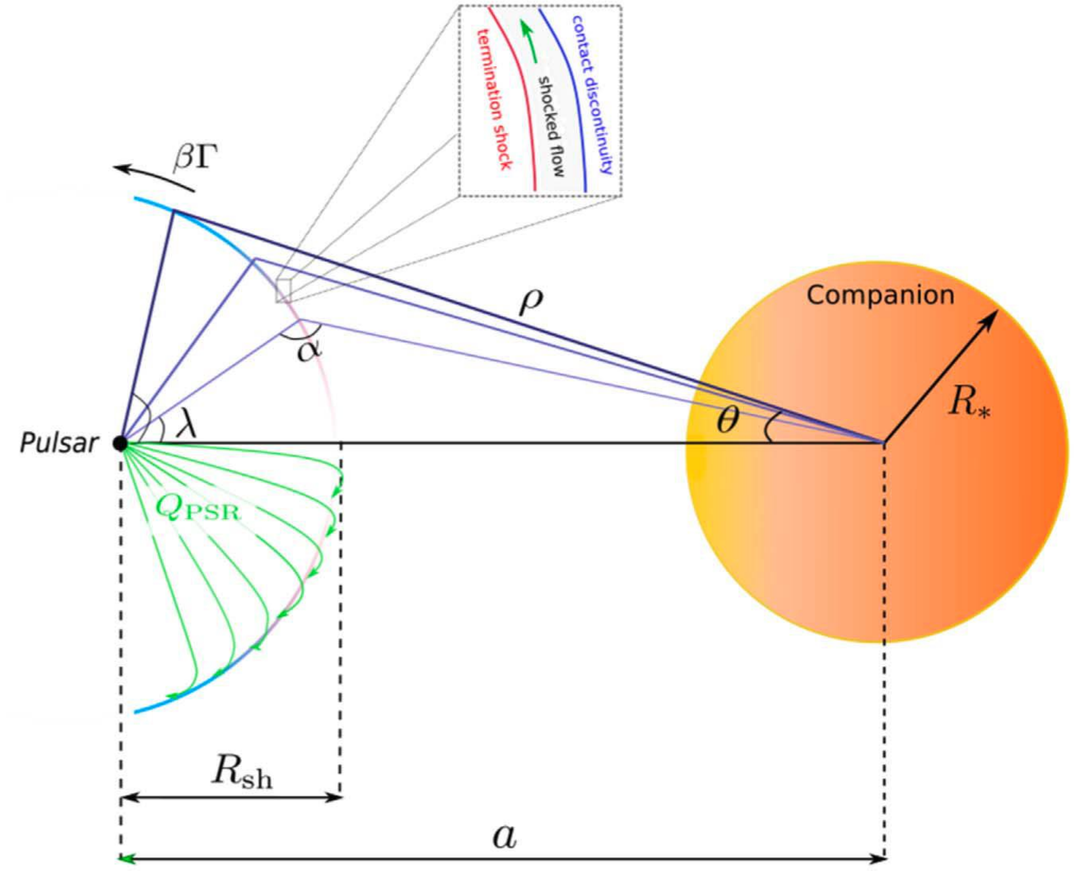
Intrabinary shock emission



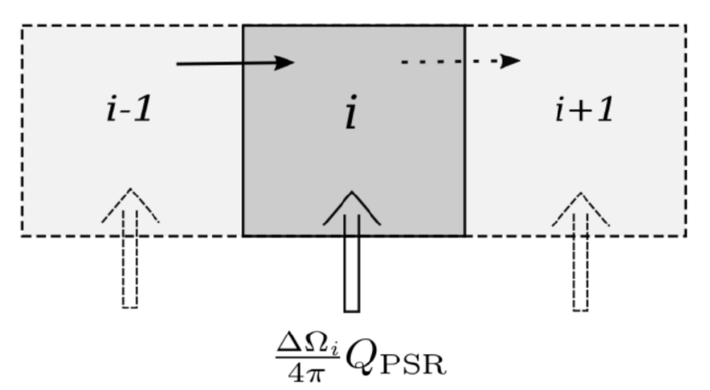
Romani & Sanchez (2016)

Shock emission model

Van der Merwe et al. 2020



Particle transport



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

$$\int_{\gamma_{\rm e,min}}^{\infty} Q_{\rm PSR}\, d\gamma_{\rm e} = (M_{\pm} + 1)\dot{N}_{\rm GJ},$$

$$m_{\rm e}c^2 \int_{\gamma_{\rm e,min}}^{\infty} \gamma_{\rm e} Q_{\rm PSR}\, d\gamma_{\rm e} = \eta_{\rm p}\dot{E}_{\rm rot},$$

$$\frac{\partial N_{\rm e}}{\partial t} = -\vec{V} \cdot \left(\vec{\nabla} N_{\rm e}\right) + \kappa(\gamma_{\rm e})\nabla^2 N_{\rm e} + \frac{\partial}{\partial \gamma_{\rm e}}\left(\dot{\gamma}_{\rm e,tot} N_{\rm e}\right) - \left(\vec{\nabla} \cdot \vec{V}\right) N_{\rm e} + Q$$

$$0 = -\frac{N_{{\rm e},i}}{\tau_{{\rm ad},i}} - \frac{N_{{\rm e},i}}{\tau_{{\rm diff},i}} - \frac{N_{{\rm e},i}}{\tau_{1,i}} - \frac{N_{{\rm e},i}}{\tau_{2,i}} - \frac{N_{{\rm e},i}}{\tau_{{\rm rad},i}} + Q_i$$

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

Maximum acceleration energy

"Hillas" criterion – $R_{sh} = r_g$

$$\gamma^{\rm H}_{\rm e,\,max} \approx \frac{eR_{\rm sh}B_{\rm sh}}{m_{\rm e}c^2} \sim 2\times10^8 \left(\frac{R_{\rm sh}}{10^{10}\ {\rm cm}}\right)\left(\frac{B_{\rm sh}}{10\ {\rm G}}\right)$$

Polar cap voltage drop

$$\gamma^{\rm P}_{\rm e,\,max} = \frac{e\Phi_{\rm open}}{m_{\rm e}c^2} \sim 5\times10^8 \left(\frac{P}{5\times10^{-3}\ {\rm s}}\right)^{-2}\left(\frac{R_{\rm PSR}}{10^6\ {\rm cm}}\right)^3\left(\frac{B_{\rm PSR}}{10^9\ {\rm G}}\right)$$

Synchrotron loss-limited diffusive shock acceleration

$$\gamma^{\rm acc}_{\rm e,\,max} = \frac{3}{2}\sqrt{\frac{\epsilon_{\rm acc}B_{\rm cr}}{\alpha_{\rm f}B_{\rm sh}}} \sim 4\times10^7\epsilon_{\rm acc}^{1/2}\left(\frac{B_{\rm sh}}{10\ {\rm G}}\right)^{-1/2}.$$

$$\epsilon_{\rm acc} \equiv r_{\rm g}/\lambda(\gamma_{\rm e}) \leq 1$$

Reconnection in striped wind

$$\gamma^{R}_{e,max} = \gamma_0\sigma_{sh} \approx 6\times10^3\left(\frac{B_{sh}}{10G}\right) P_{ms}\,\gamma_0/\kappa$$

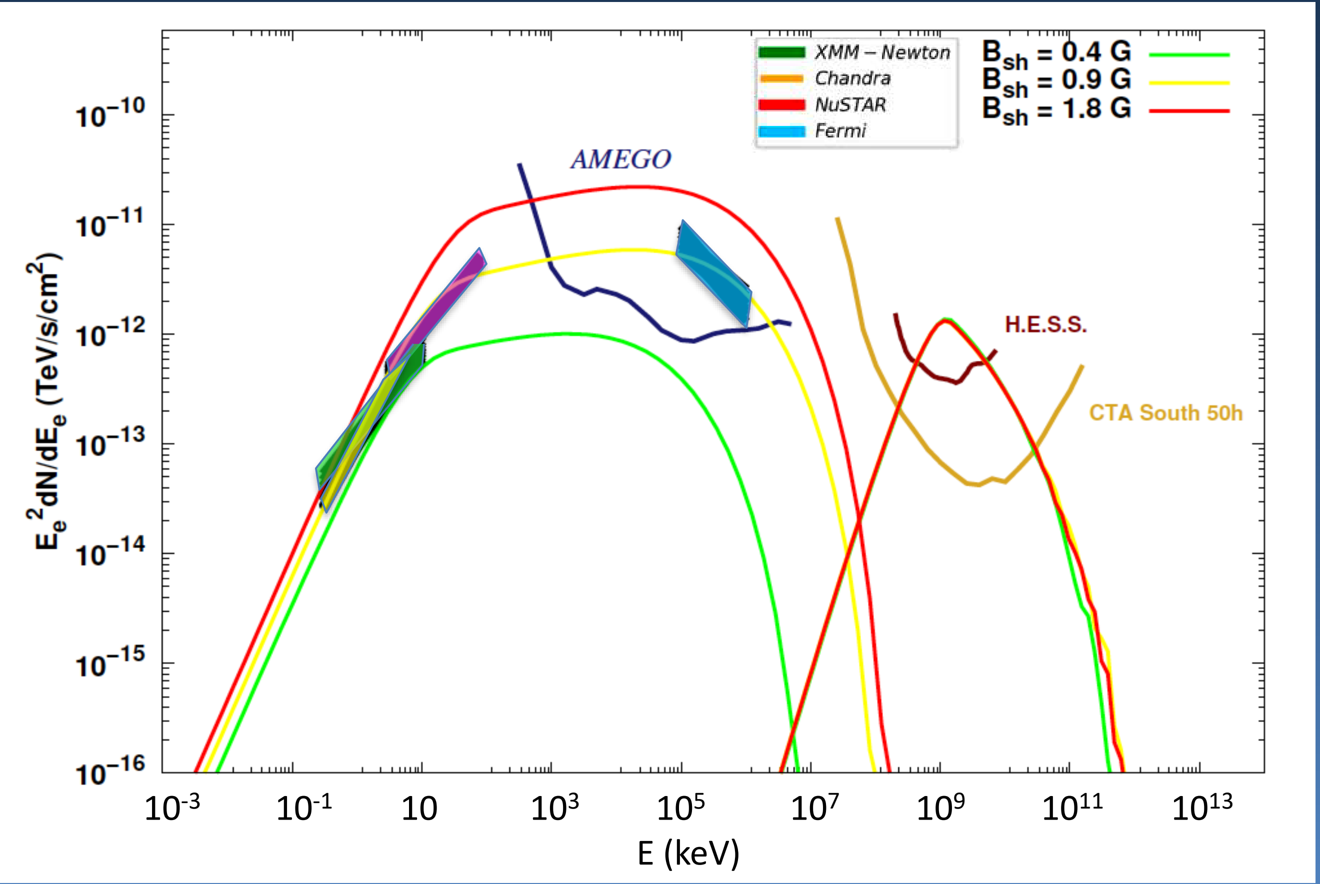
Model parameters

		J1311-3430 Quiescent	J1311-3430 Flaring	J1723-2837	J1959+2048	J2339-0335
Parameters	Symbols	Values				
Pulsar mass	M_{psr} ($M_{\odot}$)	2.0	2.0	2.0	2.0	2.16
Pulsar radius	R_{NS} (cm)	1.0e6	1.0e6	1.0e6	1.0e6	1.0e6
Orbital period	P_b (hr)	1.56	1.56	14.8	9.17	4.60
Mass ratio	q	180	180	3.5	70	18.2
Shock radius	R_{0} (units of a)	0.5	0.4	0.3	0.4	0.3
B-field at the shock	B_{sh} (G)	1.3	1.2	0.8	1.9	0.6
Companion Temperature	T_{comp} (K)	12000	45000	6000	8500	6000
Pair multiplicity	M_{pair}	1000	5000	1000	8000	500
Maximum particle conversion efficiency	$\eta_{p,max}$	0.9	1.0	1.5	0.9	0.7
Pulsar period	P (ms)	2.56	2.56	1.86	1.60	2.88
Pulsar period derivative	$\dot{P}$ (s/s)	2.1e-20	2.1e-20	7.6e-21	1.7e-20	1.4e-20
Index of injected spectrum	Γ	1.8	1.6	2.6	2.5	1.9
Distance	d (kpc)	1.40	1.40	0.72	1.73	1.10 → 0.45!
Bulk flow momentum	$\beta_{\Gamma,max}$	4.0	10	6.0	3.0	12.0
Inclination angle	i (degrees)	60	60	40	65	54

PSR J1723-2873 (RB)

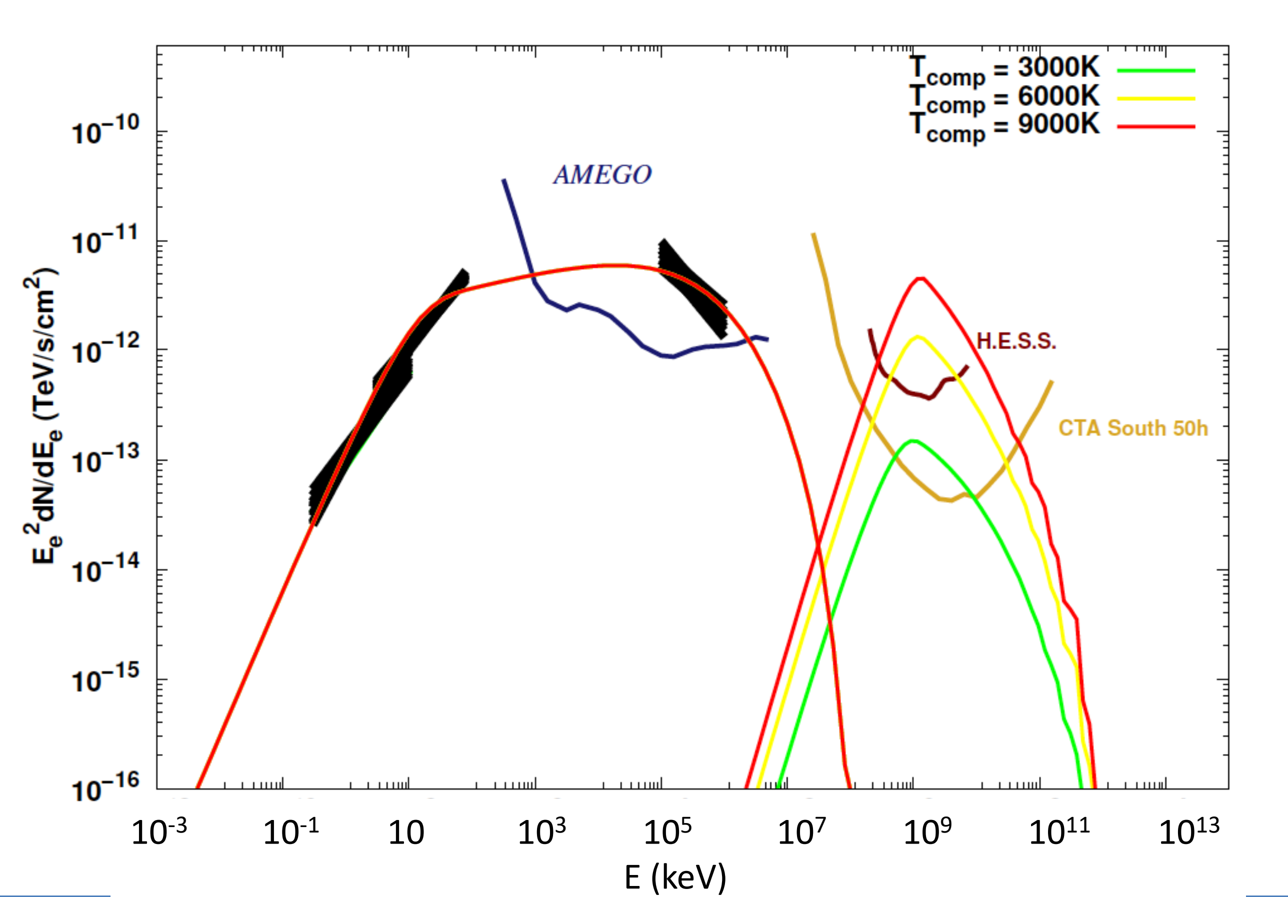
Van der Merwe et al. 2020

Dependence on B at shock

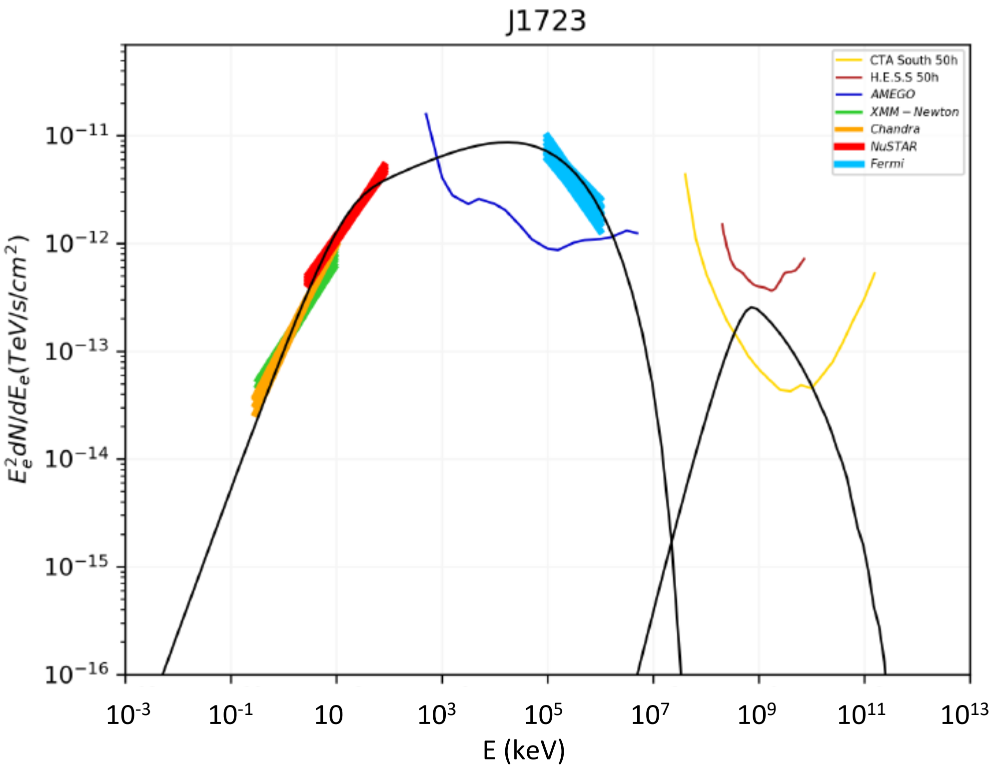


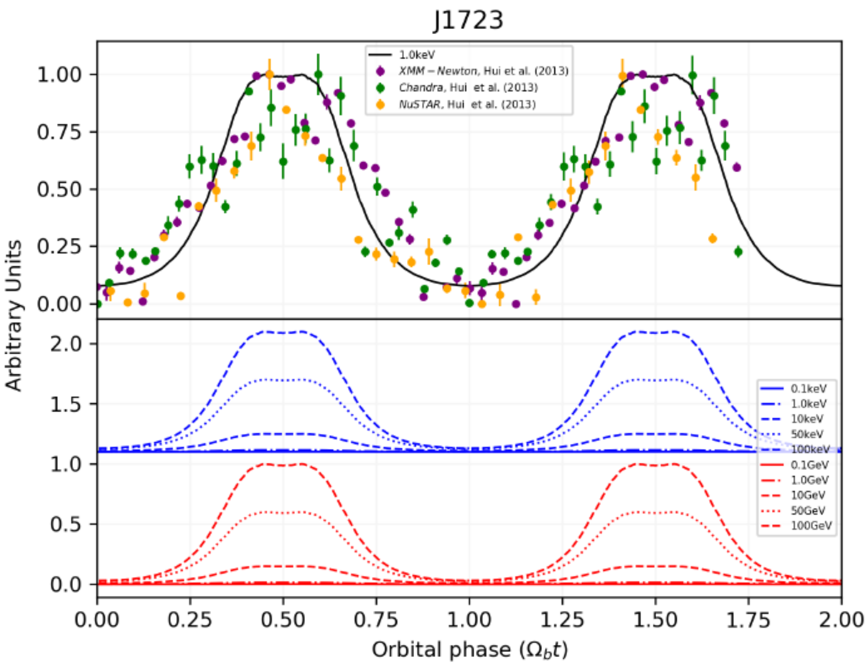
PSR J1723-2873 (RB)

Dependence on temperature of companion

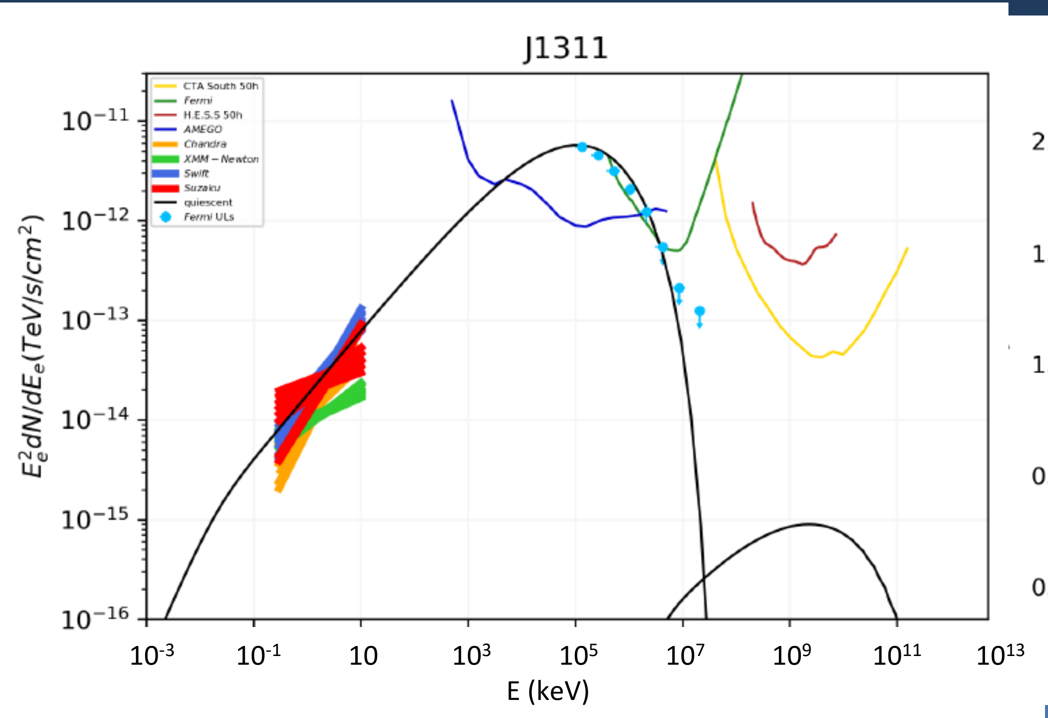


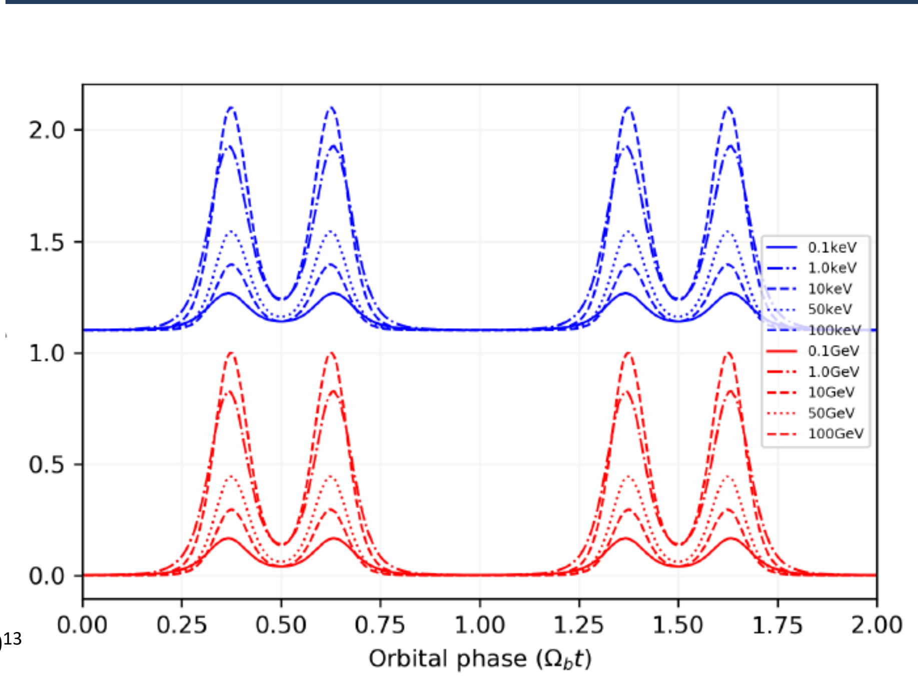
PSR J1723-2873 (RB)



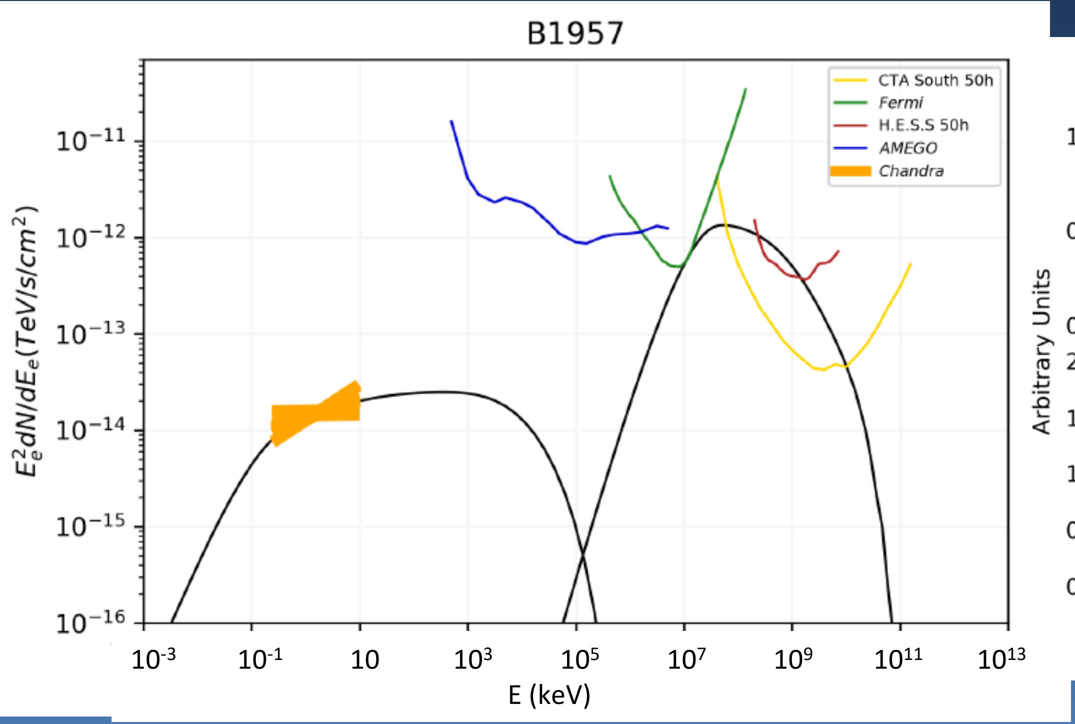


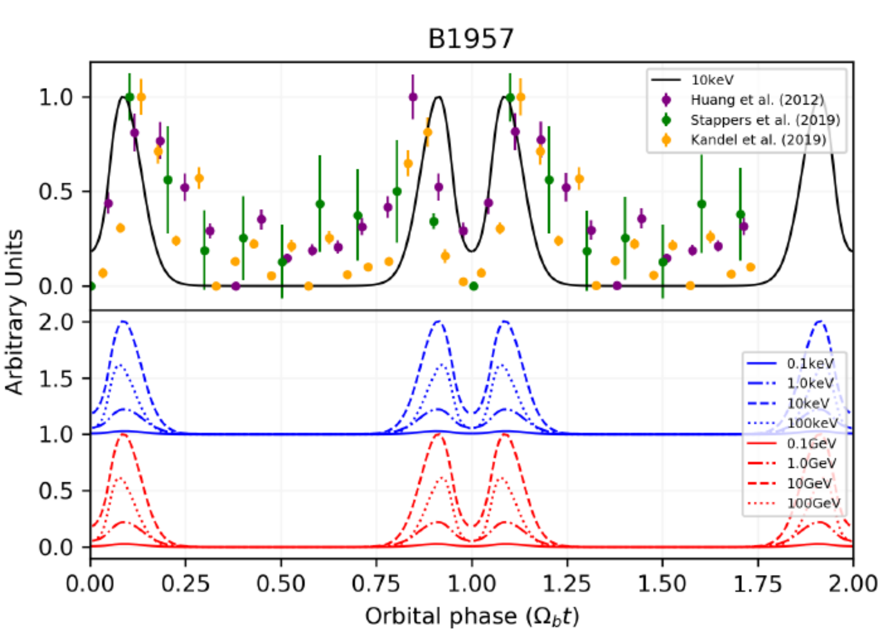
PSR J1311-3430 (BW)



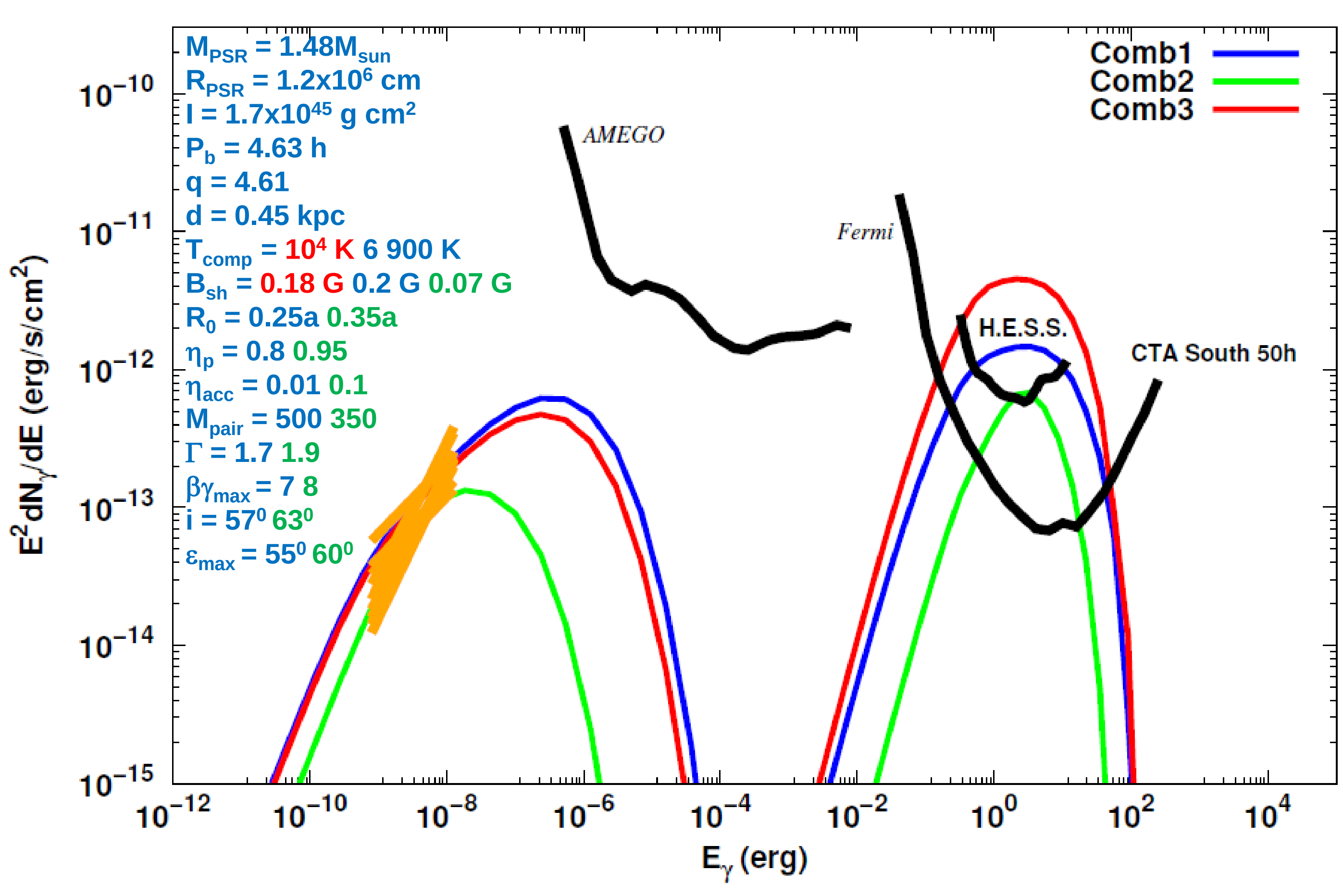


PSR B1957+20 (BW)

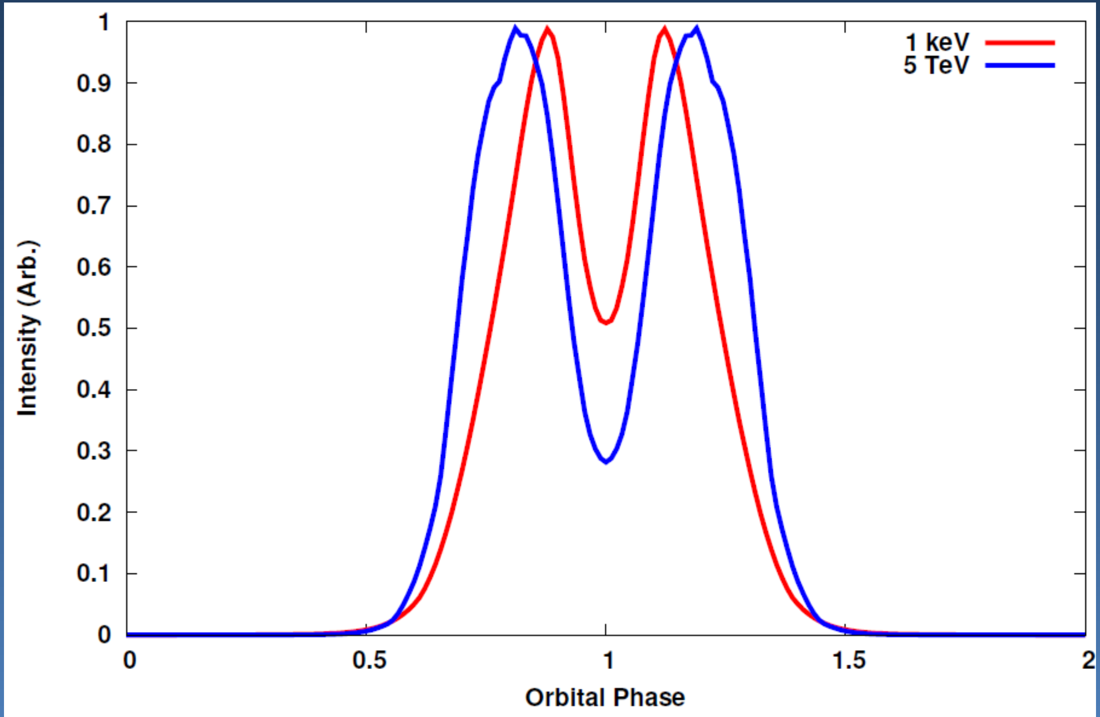




PSR J2339-0533 (RB)



PSR J2339-0533 (RB)



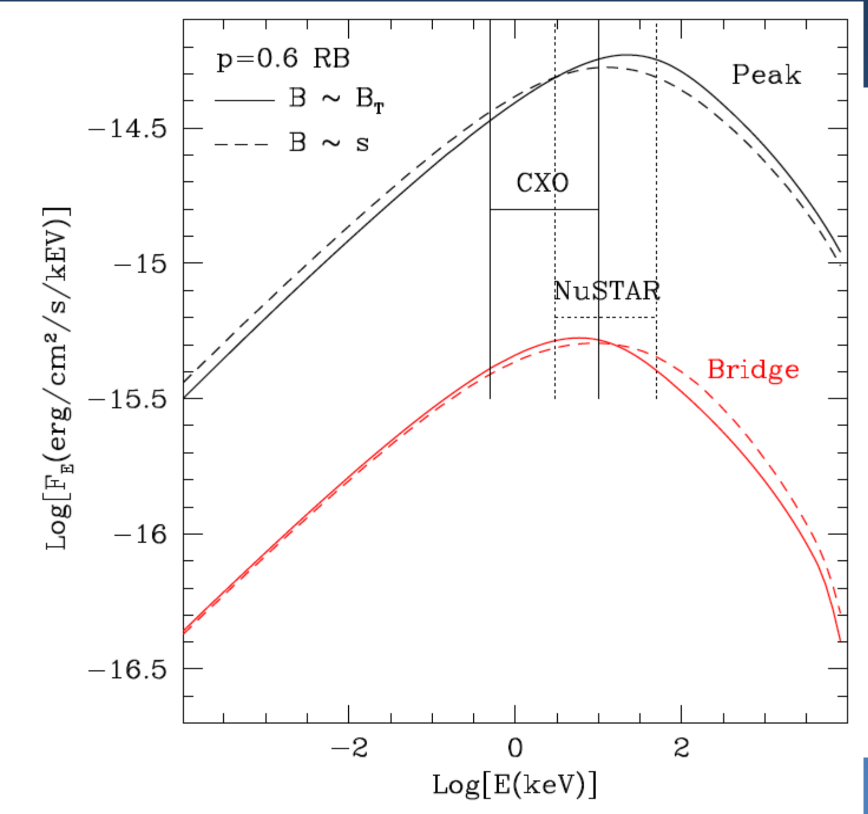
What is the shock acceleration mechanism?

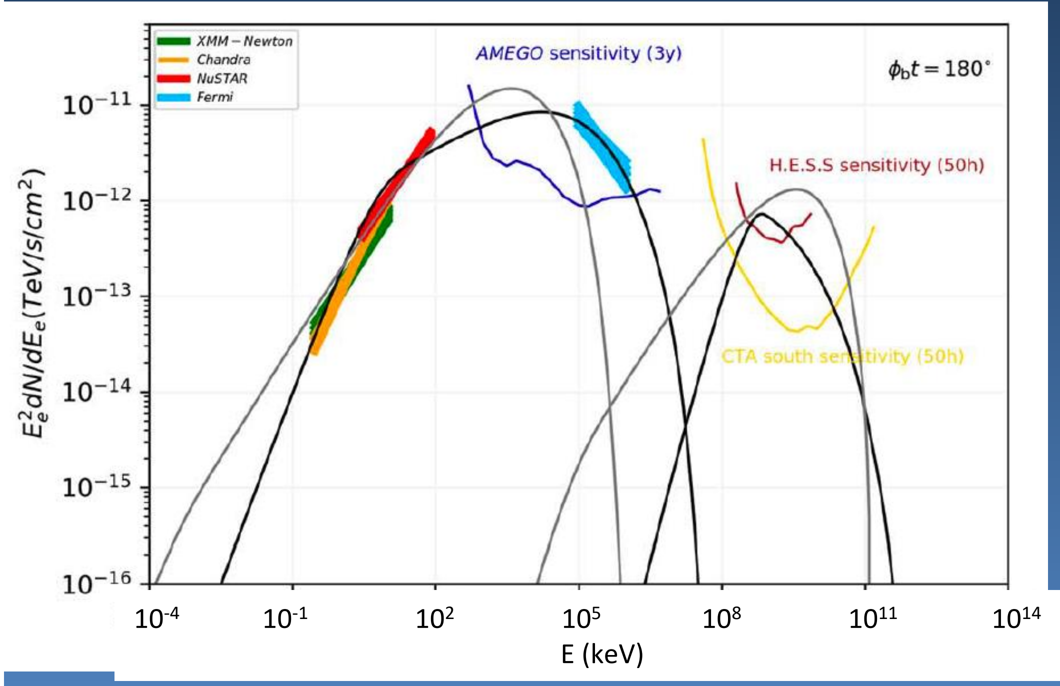
Reconnection? (Kandel, Romani & An 2019)

$\gamma_{max} \sim \sigma_w \gamma_w \sim 10^4$

Diffusive shock acceleration? (Van der Merwe 2020)

$$\gamma_{max} \sim 4 \times 10^7 \epsilon_{acc}^{1/2} \left(\frac{B_{sh}}{10\ \mathrm{G}} \right)^{-1/2}$$





What is the shock acceleration mechanism?

Reconnection

Particle spectrum as hard as $p \sim 1.0$

Photon SR index $\alpha = -(p + 1) / 2 \sim -1$

Diffusive shock acceleration

Particle spectrum $p \sim 2.0$ for compression ratio $r \sim 4$

But if injected spectrum is $p = p_0 < 2.0$, accelerated particle spectrum will be $p = p_0$ (Jones & Ellison 1991)

MSP pair spectra have $p_0 \sim 1.5$

Photon SR index $\alpha \sim -1.25$

Summary

- A large fraction of millisecond pulsars discovered by Fermi – many are redbacks and black widows
- Doppler boosting of synchrotron emission produces double-peaked light curve seen in black widow and redback binaries
- Intrabinary shock acceleration mechanism not resolved:
  - Shock-driven reconnection – $\gamma_e^{max} \sim 10^{4\text{-}5}$
  - DSA - $\gamma_e^{max} \sim$ few 10^6
  - Proton acceleration??
- Detection of TeV emission from spiders will support DSA model