MSP Binaries: Probes of Relativistic Shock Acceleration and Pulsar Winds

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Black Widows & Redbacks

Nearly all *circular* orbits

Table 1. Measured and derived parameters of BW pulsars.

Name	P_{ms}	$\dot{P}_i$ (10^{-20})	L_{sd}[a] (10^{34} erg s^{-1})	B_S[b]	d (kpc)	P_b (h)	M_{comp} ($M_\odot$)	a_{11}	E_{cut} (TeV)	Ref.
J0023+0923[c]	3.05	1.15	2.50	4.88	0.7	3.3	0.016	1.01	2.40	1
J0610−2100[c]	3.86	0.34	0.36	2.96	3.5	6.9	0.025	1.65	3.04	2
J1124−3653[c]	2.41	0.57	2.50	3.05	1.7	5.4	0.027	1.40	2.03	1
J1301+0833[c]	1.84	0.95	9.36	3.44	0.7	6.5	0.024	1.59	1.37	3
J1311−3430[c]	2.56	2.08	7.64	6.01	1.4	1.56	0.008	0.61	2.33	4
J1446−4701[c]	2.19	1.01	5.93	3.88	1.5	6.7	0.019	1.62	1.52	5
J1544+4937[c]	2.16	0.31	1.87	2.12	1.2	2.8	0.018	0.91	2.72	6
J1731−1847	2.34	2.47	11.9	6.26	2.5	7.5	0.04	1.75	1.23	7
J1745+1017[c]	2.65	0.23	0.75	2.02	1.36	17.5	0.016	3.07	1.86	8
J1810+1744[c]	1.66	0.45	6.08	2.26	2	3.6	0.044	1.07	1.86	1
J1959+2048[c]	1.61	0.72	10.6	2.80	1.53	9.2	0.021	2.00	1.19	9
J2047+1053[c]	4.29	2.00	1.56	7.63	2	3	0.035	0.95	2.78	3
J2051−0827[c]	4.51	1.23	0.83	6.14	1	2.4	0.027	0.82	3.51	2
J2214+3000[c]	3.12	1.46	2.96	5.57	1.32	10	0.014	2.11	1.59	10, 11
J2234+0944[c]	3.63	1.94	2.50	6.91	1	10	0.015	2.11	1.66	3, 5
J2241−5236[c]	2.19	0.67	3.90	3.15	0.5	3.4	0.012	1.03	2.12	12
J2256−1024[c]	2.29	1.58	8.11	4.96	0.6	5.1	0.034	1.35	1.54	1

Table 2. Measured and derived parameters of RB pulsars.

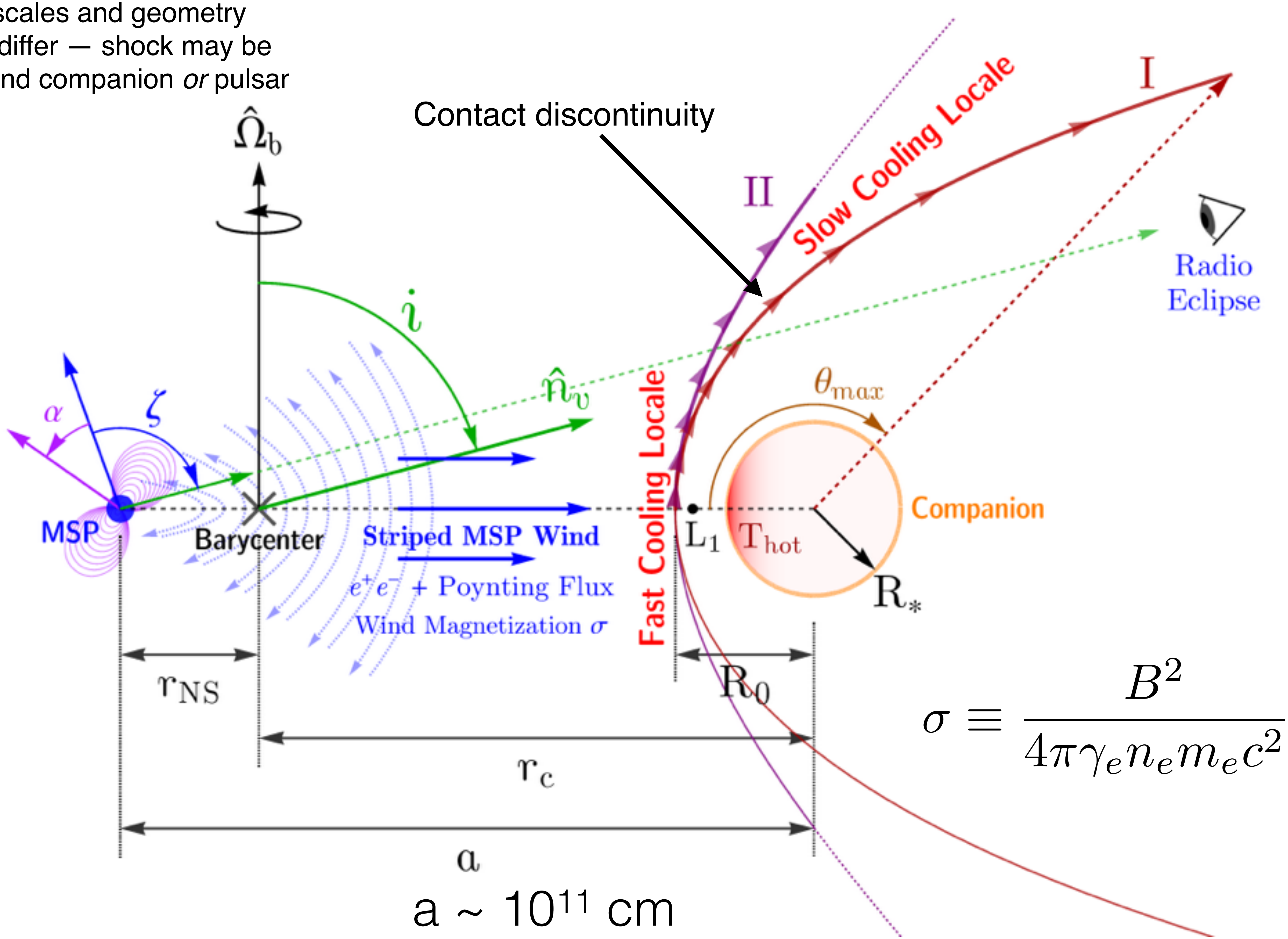
Name	P_{ms}	$\dot{P}_i$ (10^{-20})	L_{sd}[a] (10^{34} erg s^{-1})	B_S[b]	d (kpc)	P_b (h)	M_{comp} ($M_\odot$)	a_{11}	E_{cut} (TeV)	Ref.
J1023+0038	1.69	1.20	15.4	3.72	0.6	4.8	0.2	1.33	1.33	1
J1628−3205	3.21	1.13	2.11	4.96	1.2	5	0.16	1.36	2.15	2
J1723−2837	1.86	0.75	7.18	3.08	0.75	14.8	0.4	2.90	1.09	3, 4
J1816+4510[c]	3.19	4.03	7.64	9.34	2.4	8.7	0.16	1.97	1.30	5
J2129−0429	7.61	43.54	6.08	47.4	0.9	15.2	0.37	2.94	1.12	6
J2215+5135[c]	2.61	2.79	9.67	7.03	3	4.2	0.22	1.22	1.55	6
J2339−0533[c]	2.88	1.39	3.59	5.21	0.4	4.6	0.26	1.30	1.93	7, 8

Venter et al. (2015)

Much of *this* talk is focused on B1957+20/J1959+2048, the *original* Black Widow, but the methods developed here will be applied to more of these systems in the near future

Schematic Geometry

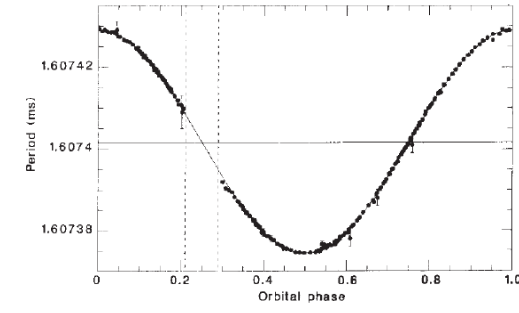
Physics somewhat similar to massive binaries (cf. Dubus) but scales and geometry can differ — shock may be around companion *or* pulsar

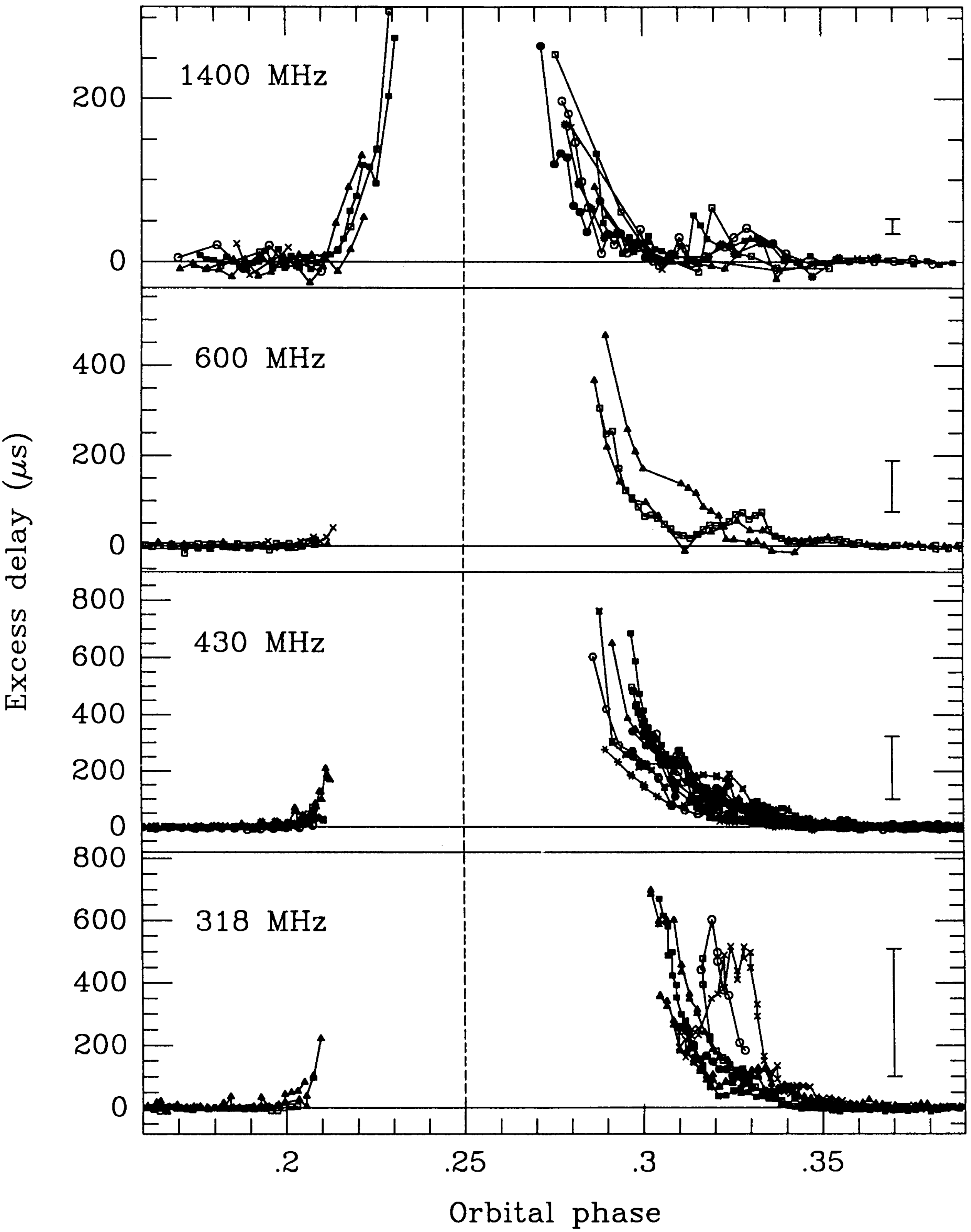


$$\sigma \equiv \frac{B^2}{4\pi\gamma_e n_e m_e c^2}$$

a ~ 10^{11} cm

Radio Eclipses

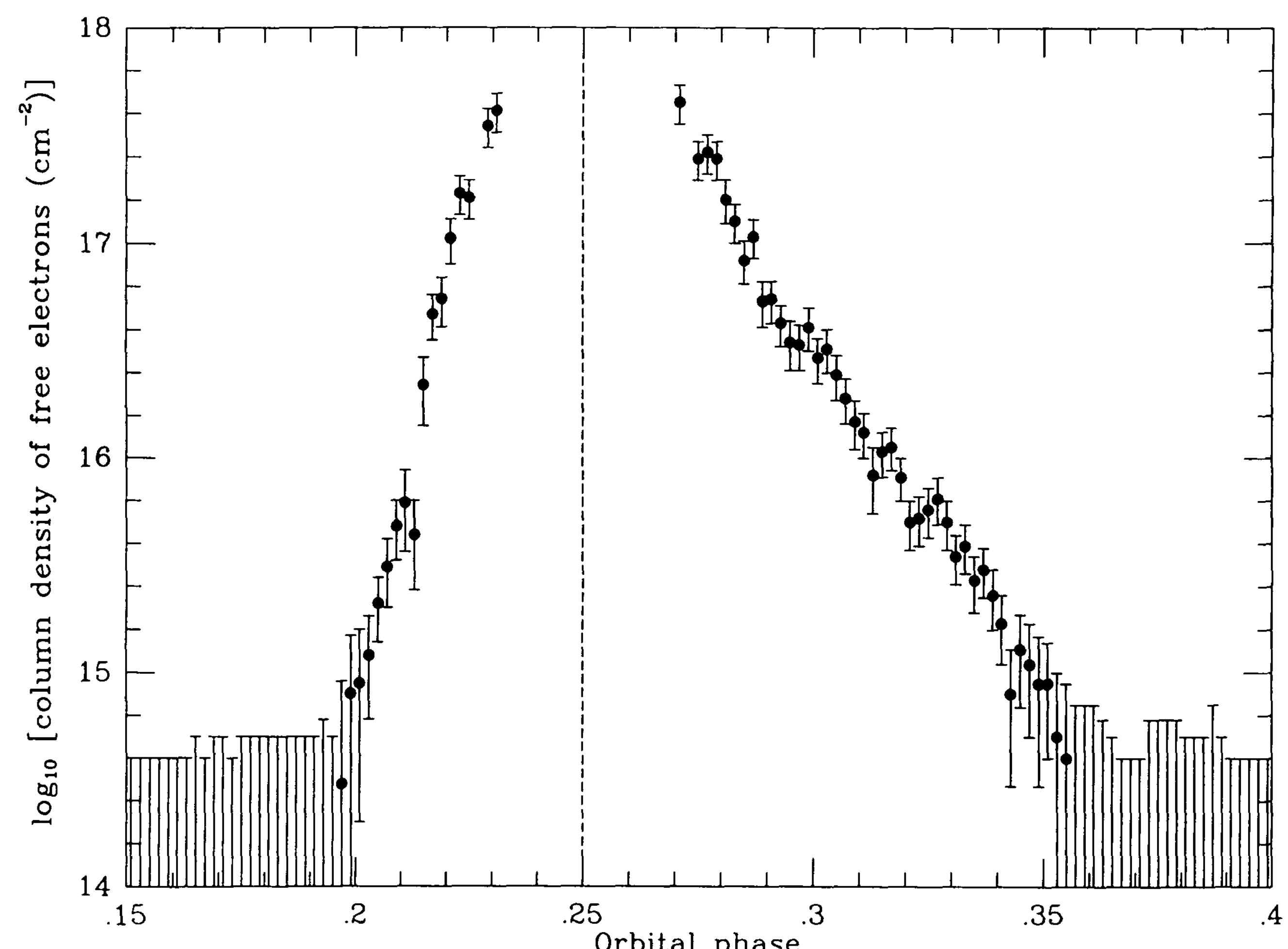




Ryba & Taylor (1991) — B1957+20

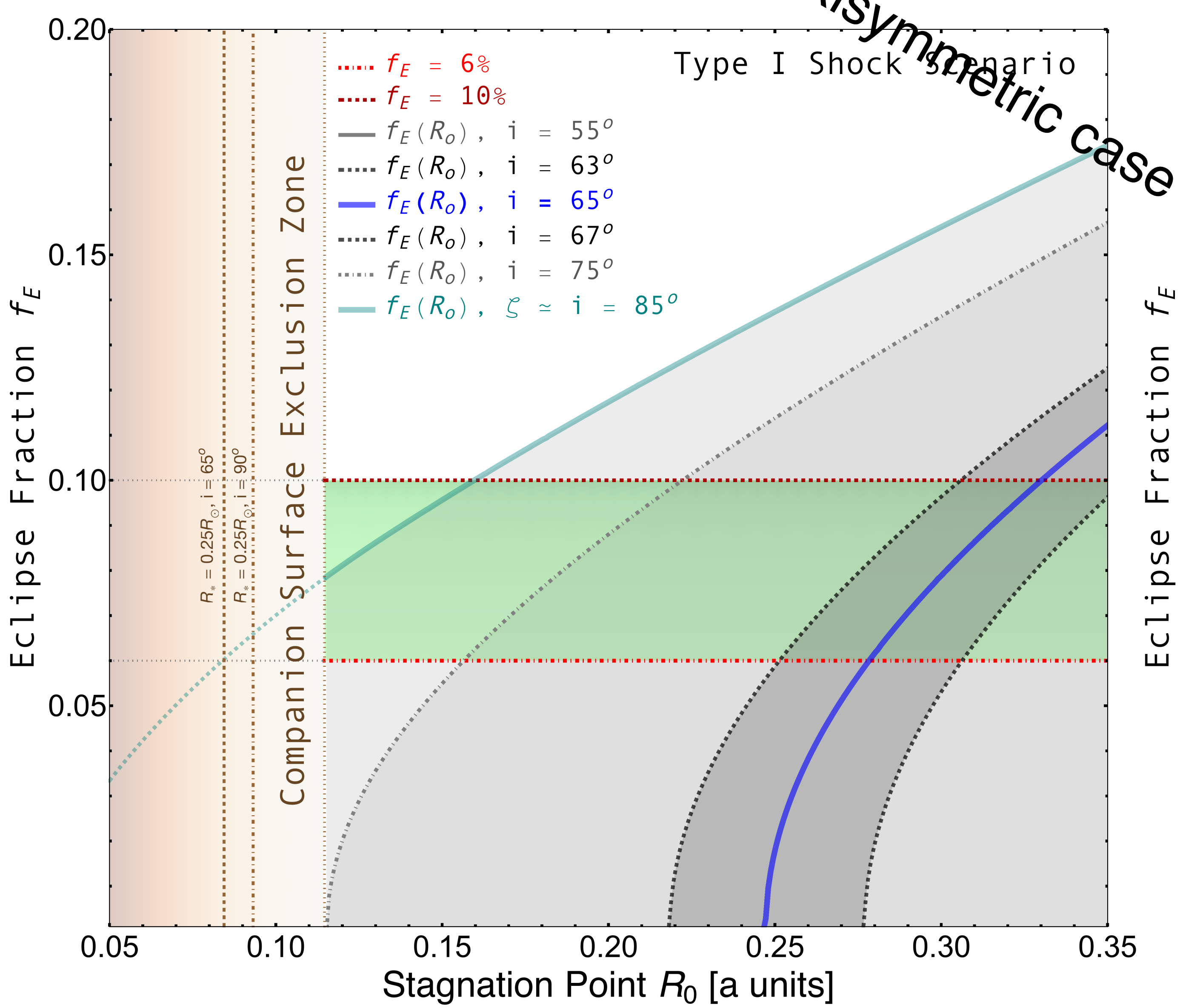
- Many black widows and redbacks show frequency-dependent radio eclipses or shrouding of the MSP over large fractions of their orbit, centered at superior conjunction where the companion is between the observer and MSP

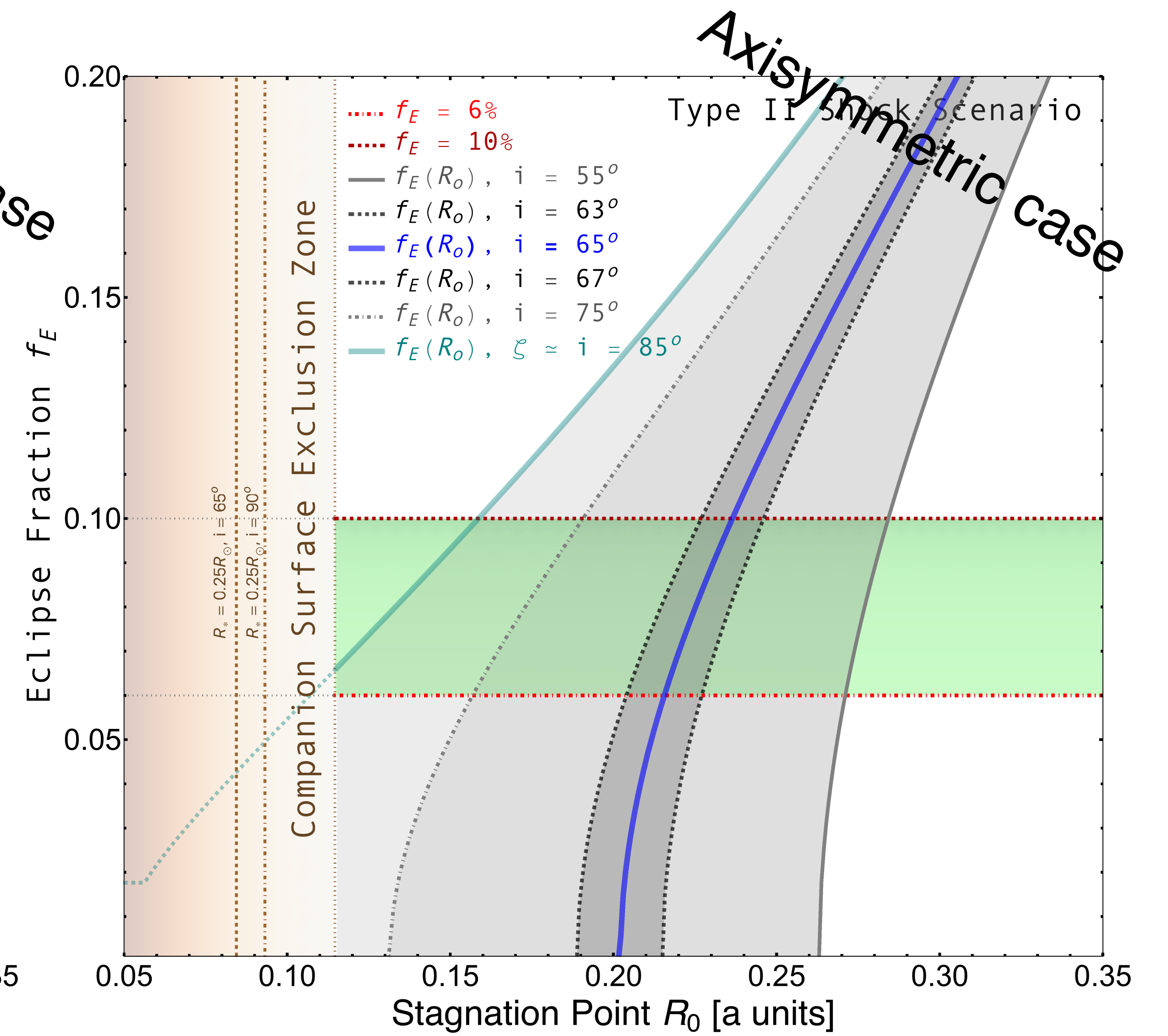
- Ingress-egress shrouding asymmetry tends to always decrease with higher observing frequencies ==> high frequencies probe denser wind regions closer to the shock where asymmetry due to orbital motion is lower



Estimating Shock Containment & Inclination with Radio Eclipses

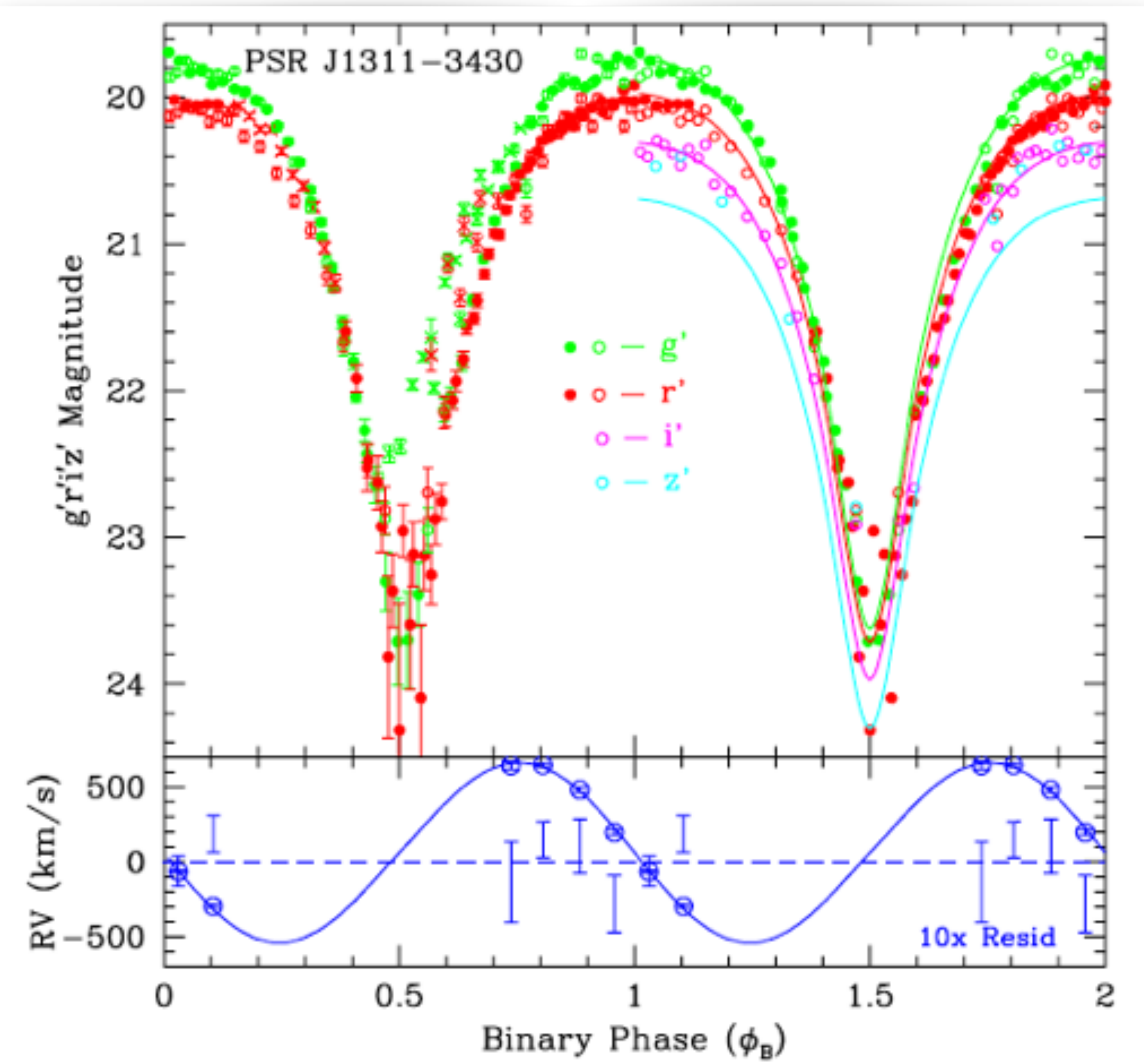
- We model two types of bow shocks, a ”type I” parallel-wind (Wilkin 1996) and “type II” two-spherical-wind shock (Canto et al. 1996) and adopt an optically thick model for eclipses (Rasio et al. 1989)
- One-to-one coupling between eclipse fraction and orbital inclination i for a shock with stand-off distance R_0 — R_0 values compatible with kilogauss companion magnetospheres or thermally driven winds
- B1957+20: 6-10% eclipse fraction (green band)
- Blue line: 65° ± 2° (Reynolds et al. 2007) with looser limits 55°-75° (van Kerkwijk et al. 2011)
- Cyan line: i ≈ 85° found from outer-magnetospheric pulsed γ-ray light curve modeling of the MSP (Johnson et al. 2014) if ζ ≈ i



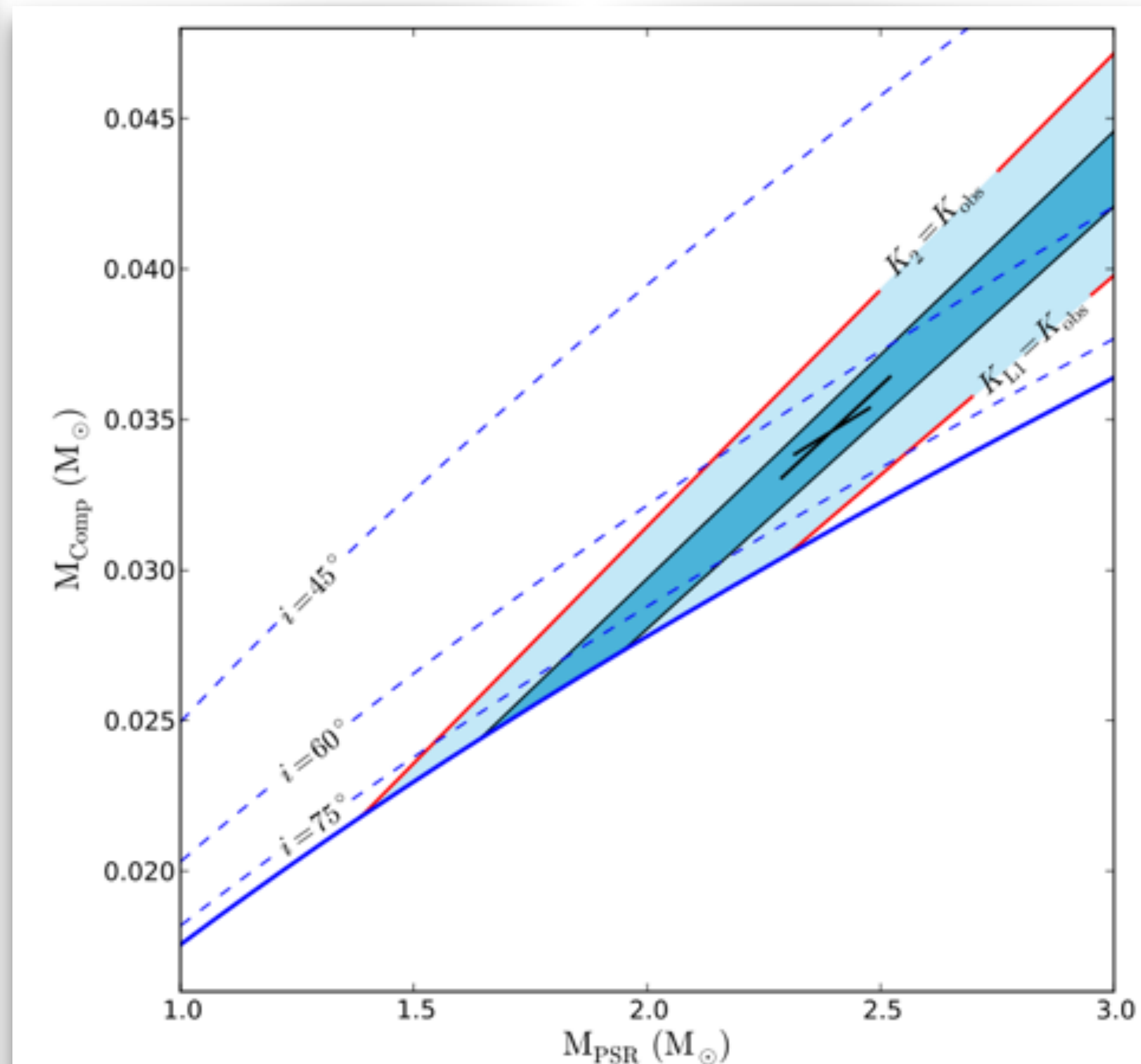


Optical Observations of the Stellar Companion

- Photometry with a model of anisotropic heating can constrain the system inclination
- Spectroscopic radial velocity studies can constrain the mass ratio
- Companion temperature as high as few times 10^4 K on heated side



J1311-3430, Romani et al. (2012)

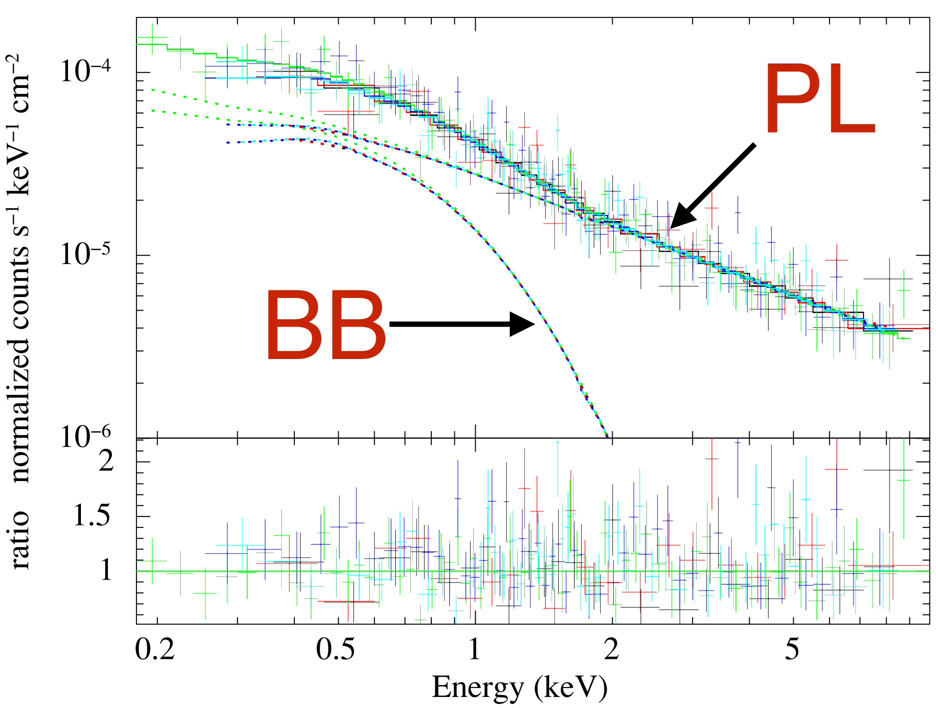


B1957+20, van Kerkwijk et al. (2011)

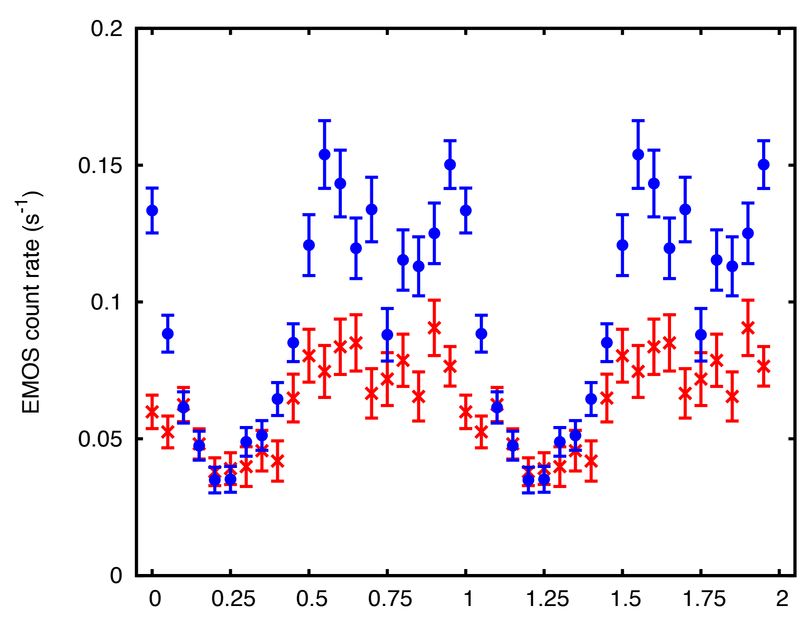
X-ray Observations

- Soft X-ray observations of many black widows and redbacks show a flux minimum around superior or inferior conjunction, and many exhibit double-peaked light curves
- The emission is likely due to synchrotron radiation, modulation by Doppler boosting and/or shadowing by the companion
- Spectral photon indices are typically Γ ≈ 1-1.5 implying very hard underlying electron power-law distributions and efficient acceleration

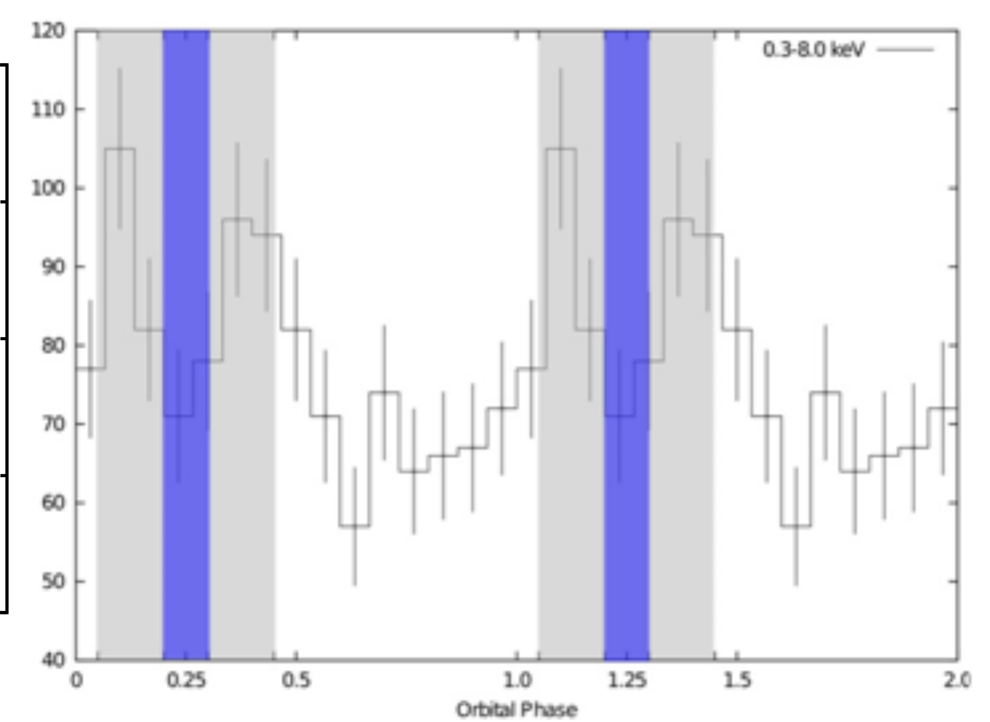
J1023+0038 (rotation-powered state)
Archibald et al. (2010)



J1227-4853, de Martino et al. (2015)

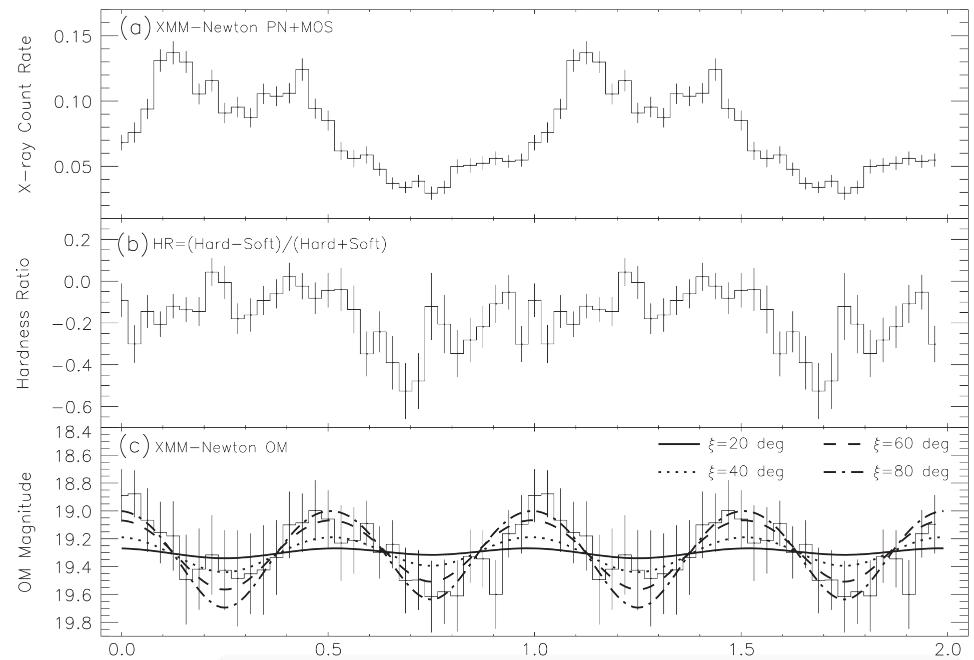


B1957+20, Huang et al. (2012)

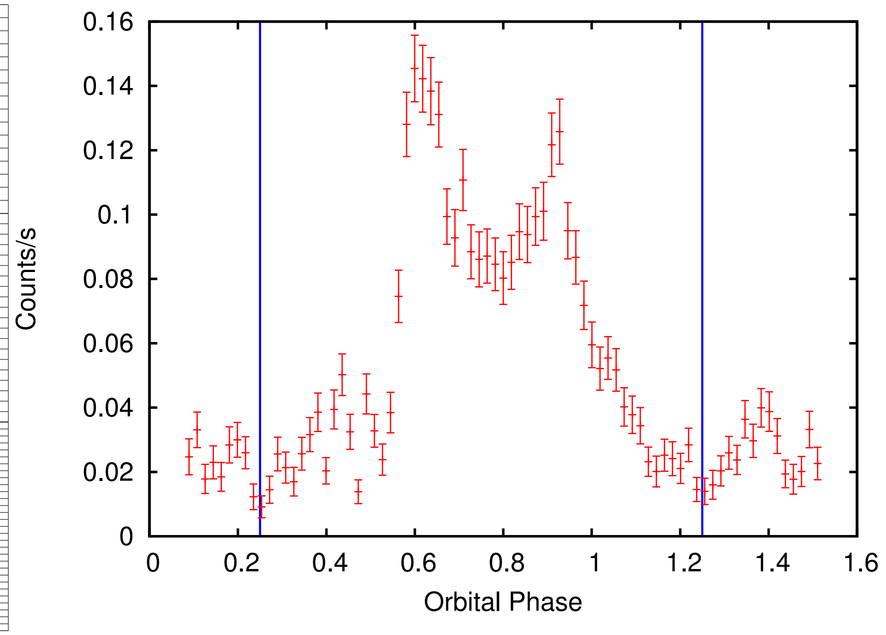


Double-Peaked Soft X-ray Light Curves

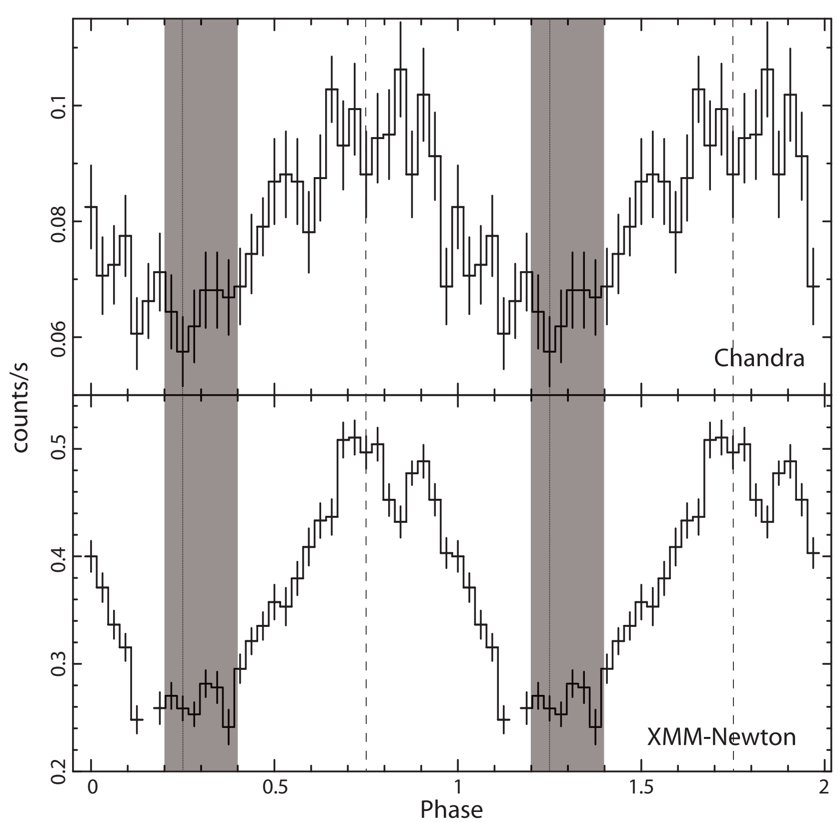
- Centered about inferior or superior conjunction
- Second peak nearly always at a modestly lower flux level



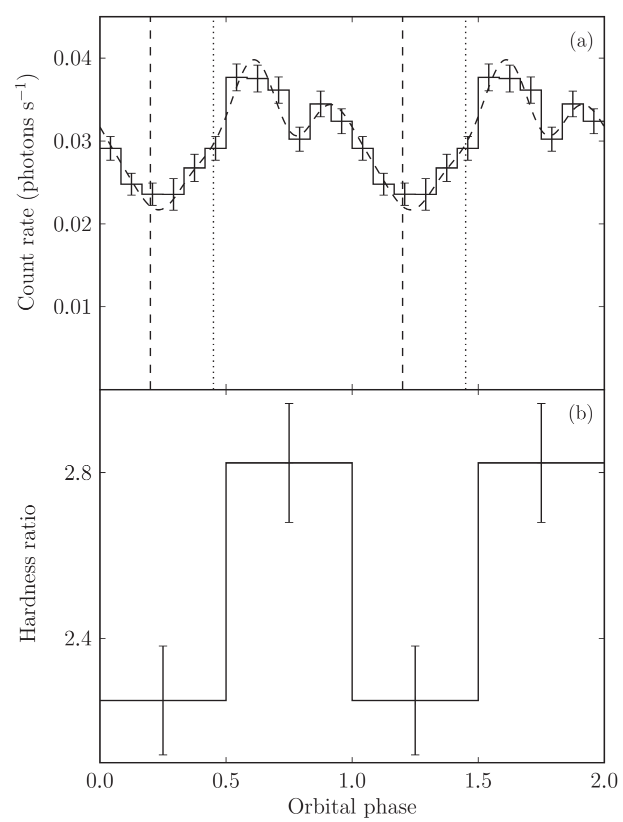
J2129-0429, Hui et al. (2015)



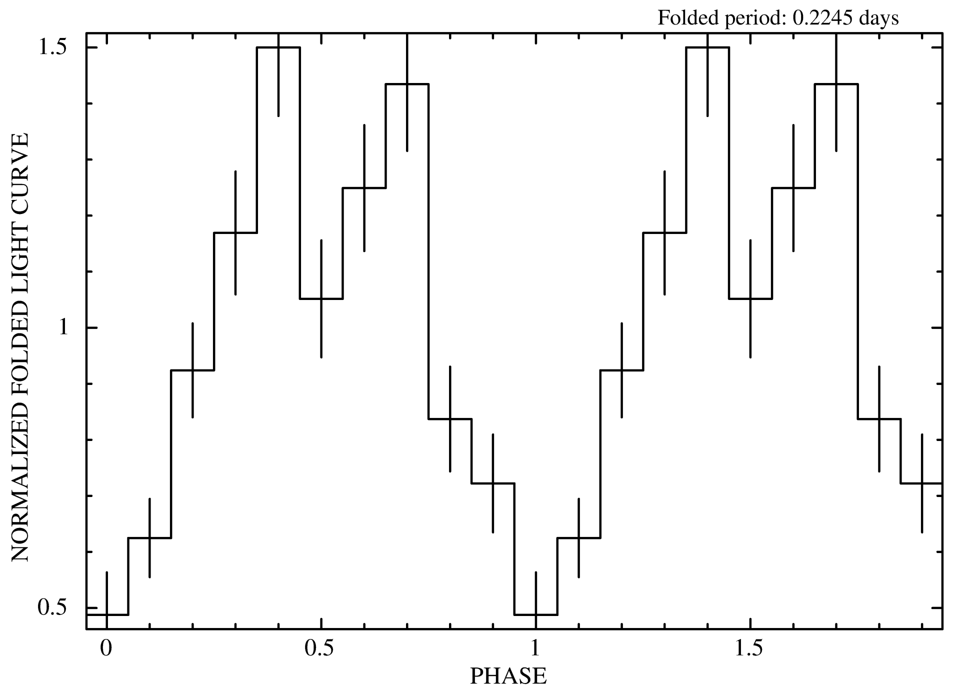
J2129-0429, Roberts et al. (2015)



J1723-2837, Hui et al. (2014)



J1023+0038, Archibald et al. (2010)



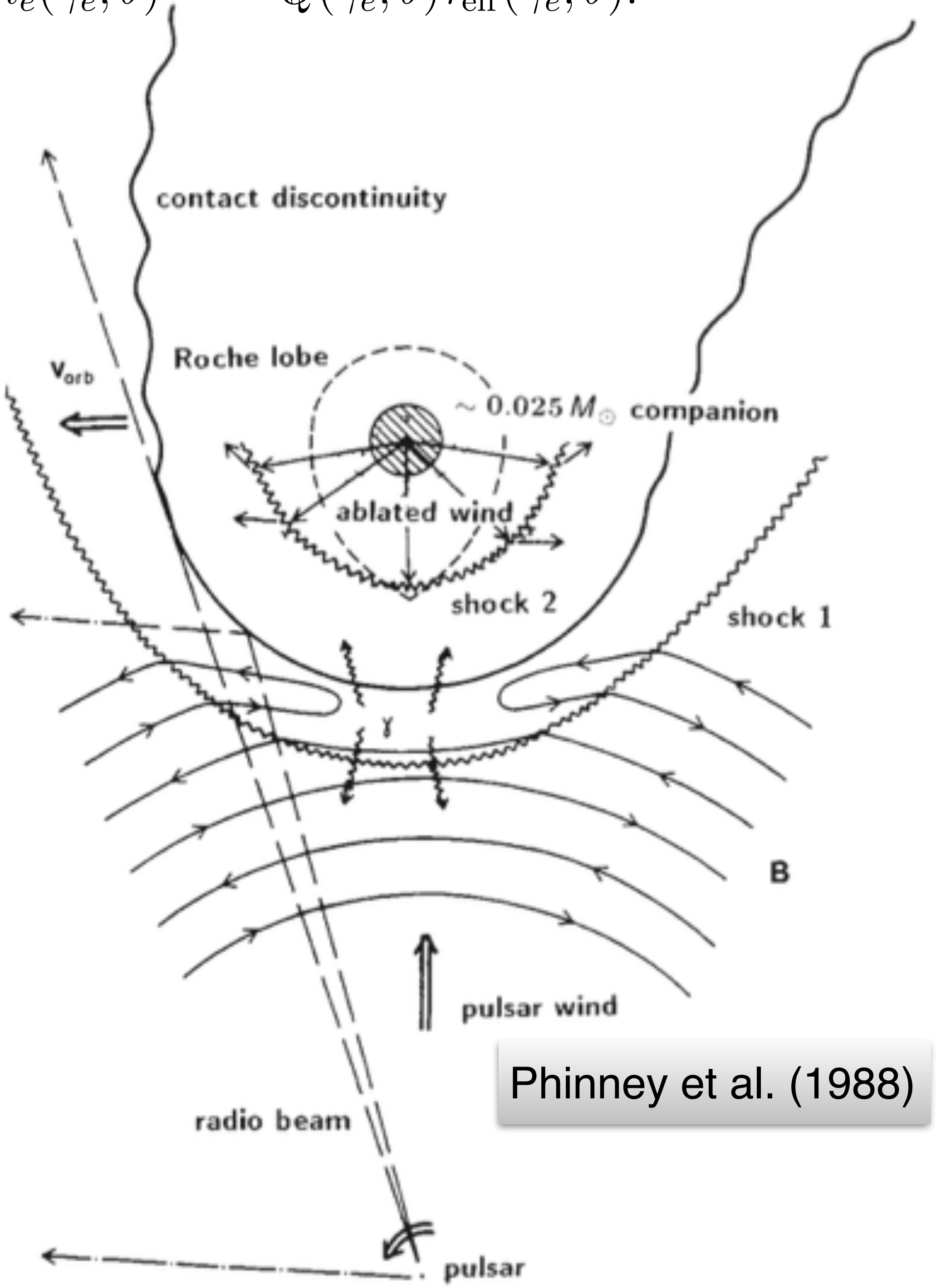
J2039-5618, Salvetti et al. (2015)

Particle Acceleration

Shock is only ~10^{11} cm away from the MSP in black widows, contrasted to ~10^{15}-10^{17} cm for PWNe

$$\tau_{\rm eff} = \left[\frac{1}{\tau_{\mathcal{D}}} + \frac{1}{\tau_{\rm conv}} + \frac{1}{\tau_{\rm ad}} + \frac{1}{\tau_{\rm rad}} + \frac{1}{\tau_{\rm cat}}\right]^{-1}$$

$$n_e(\gamma_e, \theta) \sim Q(\gamma_e, \theta)\tau_{\rm eff}(\gamma_e, \theta).$$



Phinney et al. (1988)

Shock acceleration spectrum

$$N_p(E) = Q_0 E^{-2} \exp(-E/E_{\max})$$

Maximum acceleration energy

(Harding & Gaisser 1990)

$$E_{\max} = 2.6\ \text{TeV}\ B_8^{-1/2} P_{ms} a_{11}^{-1/2} \left(\frac{a}{r_s}\right)^{1/2} \sqrt{\frac{3(\xi-1)}{\xi(\xi+1)}}$$

Normalization

$$\int_{E_{\min}}^{\infty} N_p(E)dE = M_+ \dot{n}_{GJ}$$

$$\int_{E_{\min}}^{\infty} N_p(E)E\, dE = \eta_p \dot{E}$$

Pair multiplicity

Polar cap flux

Efficienc

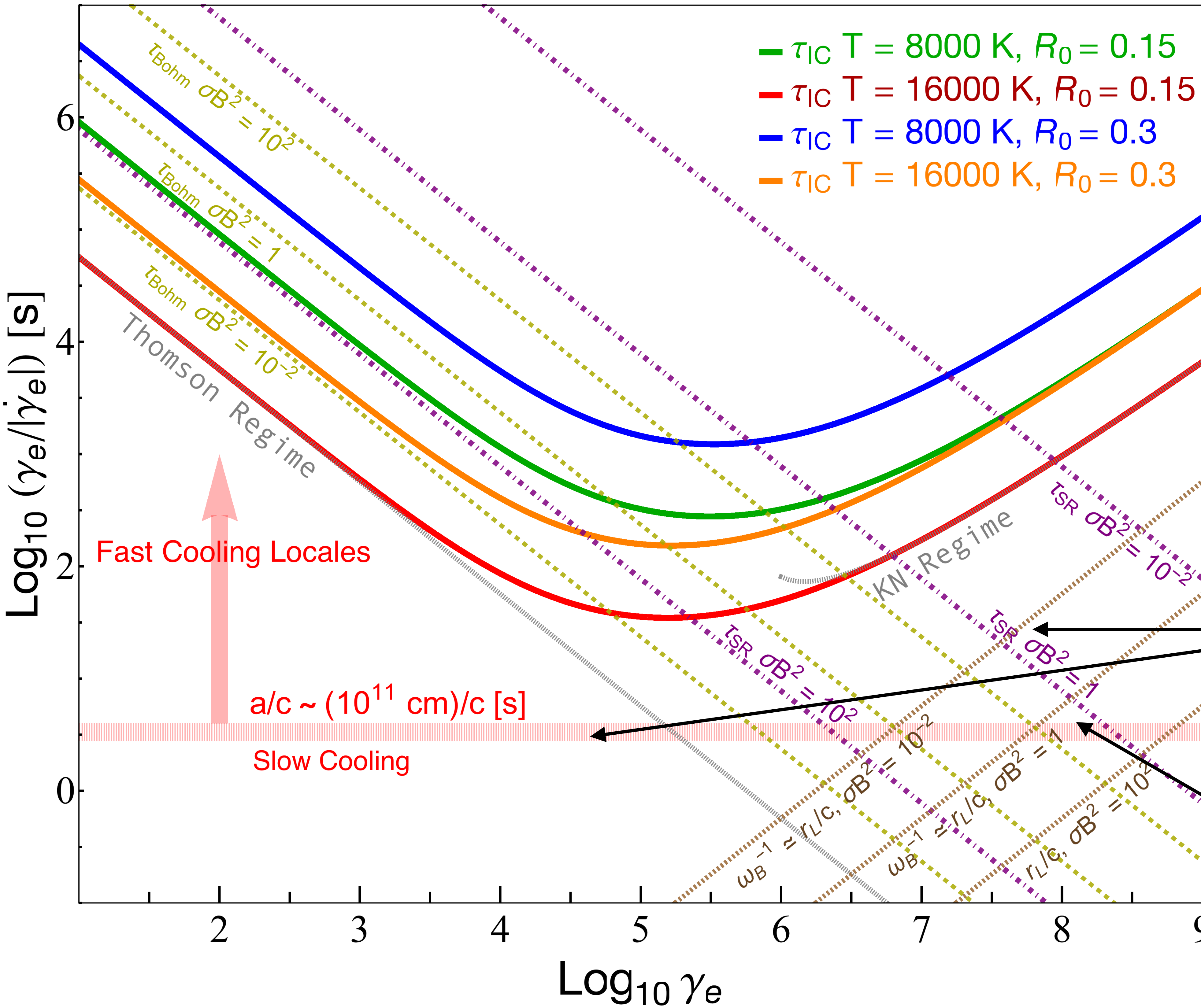
The shock is quasi-perpendicular, relativistic and possibly magnetically dominated σ >> 1 upstream — reconnection or DSA?

Emission & particle cooling should be most prolific near the stagnation point

Some regions may be a shear flow

Electron Timescales in the Intrabinary Shock

- Inverse Compton cooling timescale τ_{IC} computed at the stagnation point — Klein-Nishina reductions allow SR cooling to dominate IC cooling at high Lorentz factors

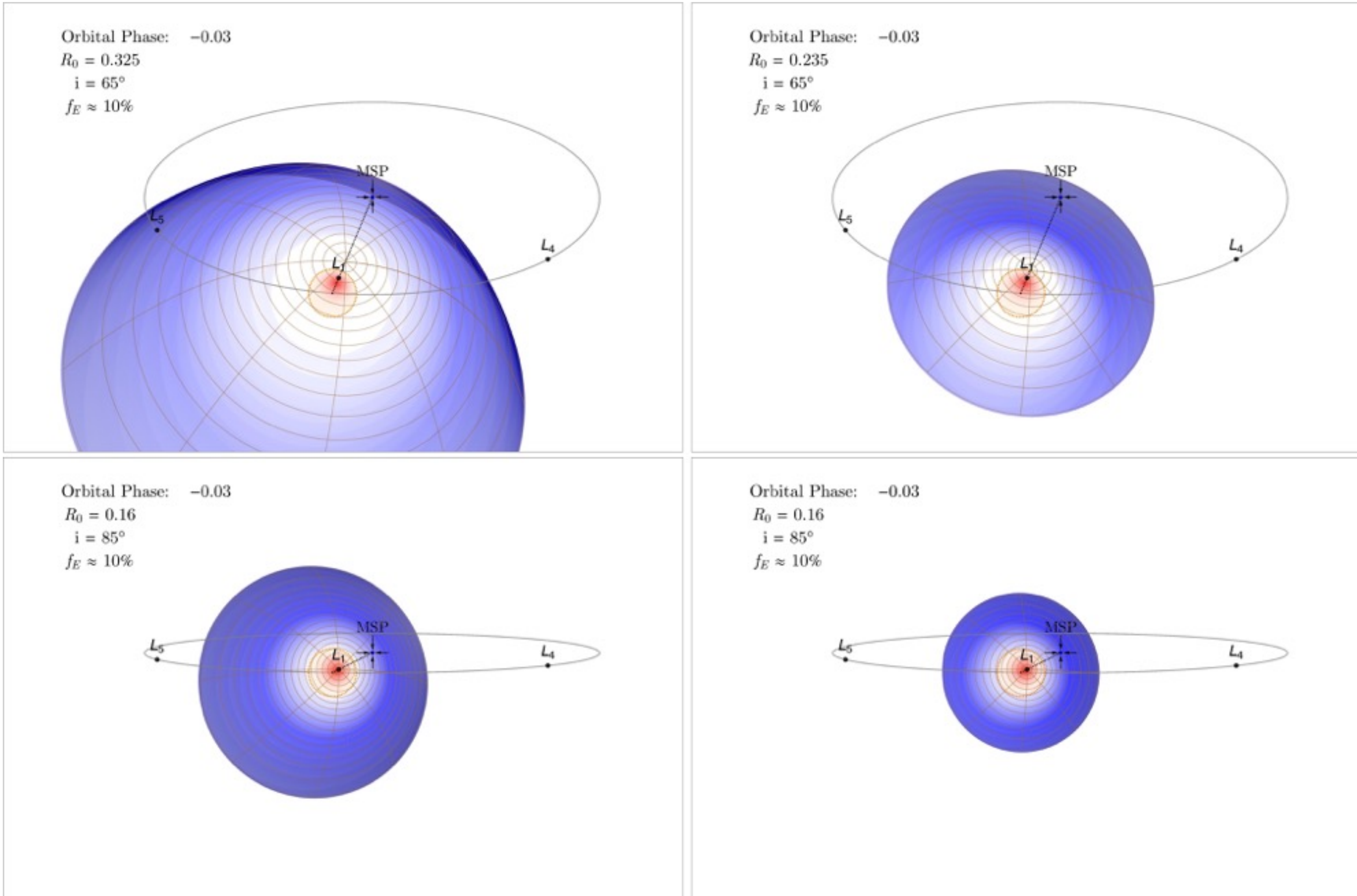


$B_{downstream} \approx 3\sigma^{1/2}B_{up}$ (Kennel & Coroniti 1984)

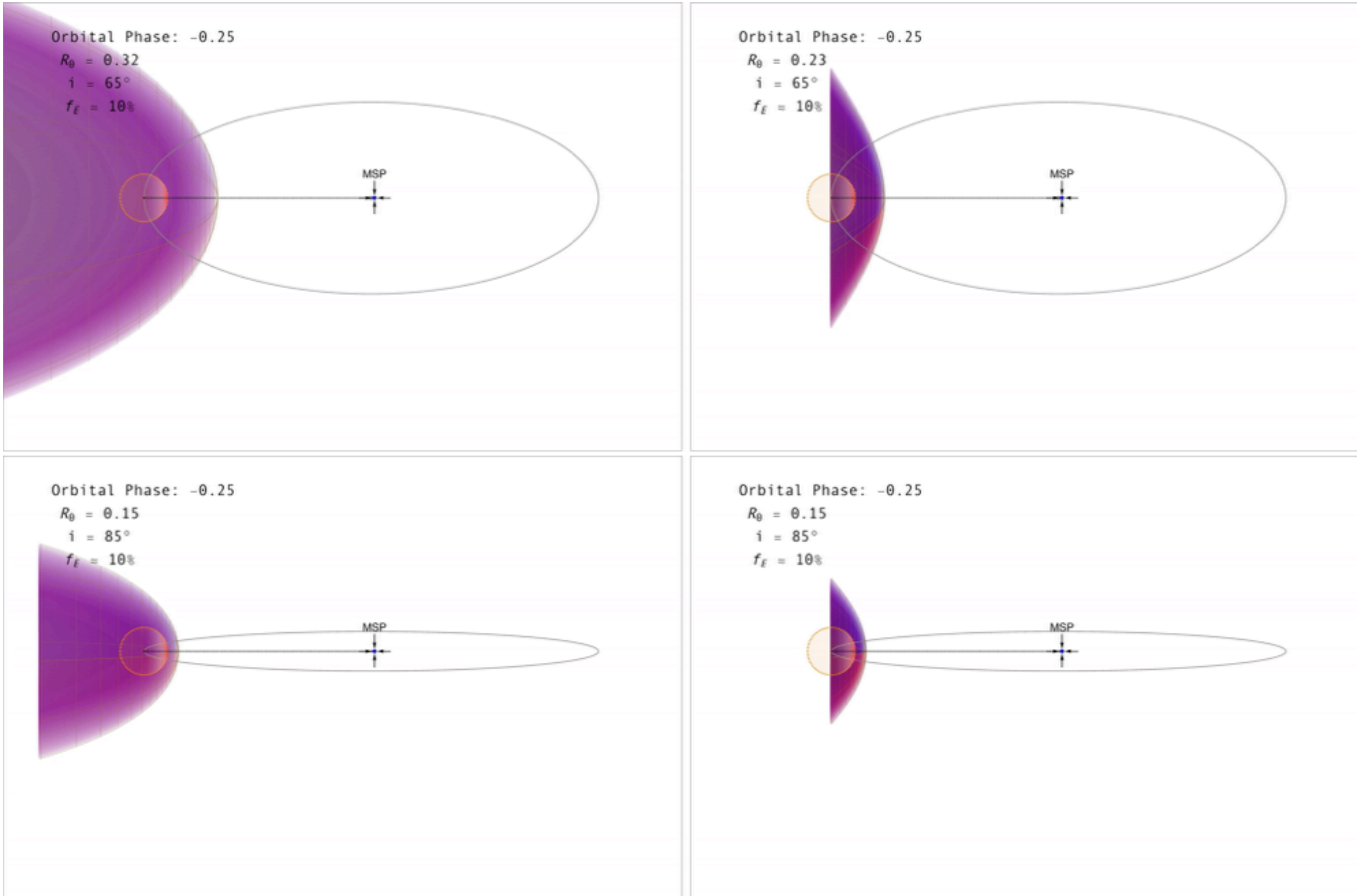
Fastest timescales: spatial convection a/c and τ_{SR}

Electrons up to ~TeV, cut-off due to synchrotron burn-off

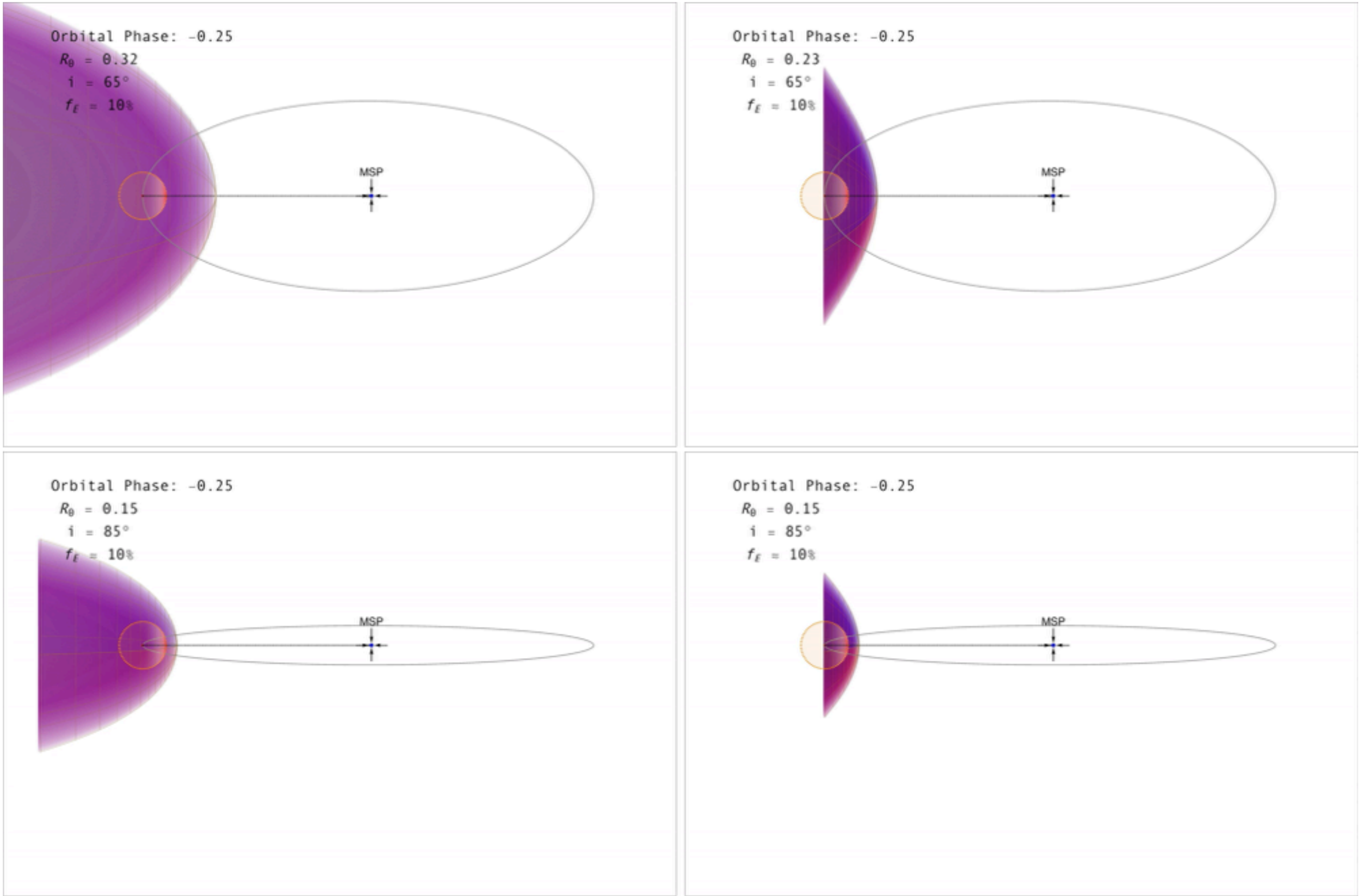
Orbitally Modulated Doppler Boosting — B1957+20 (*to scale*)



Orbitally Modulated Doppler Boosting — B1957+20 (*to scale*)

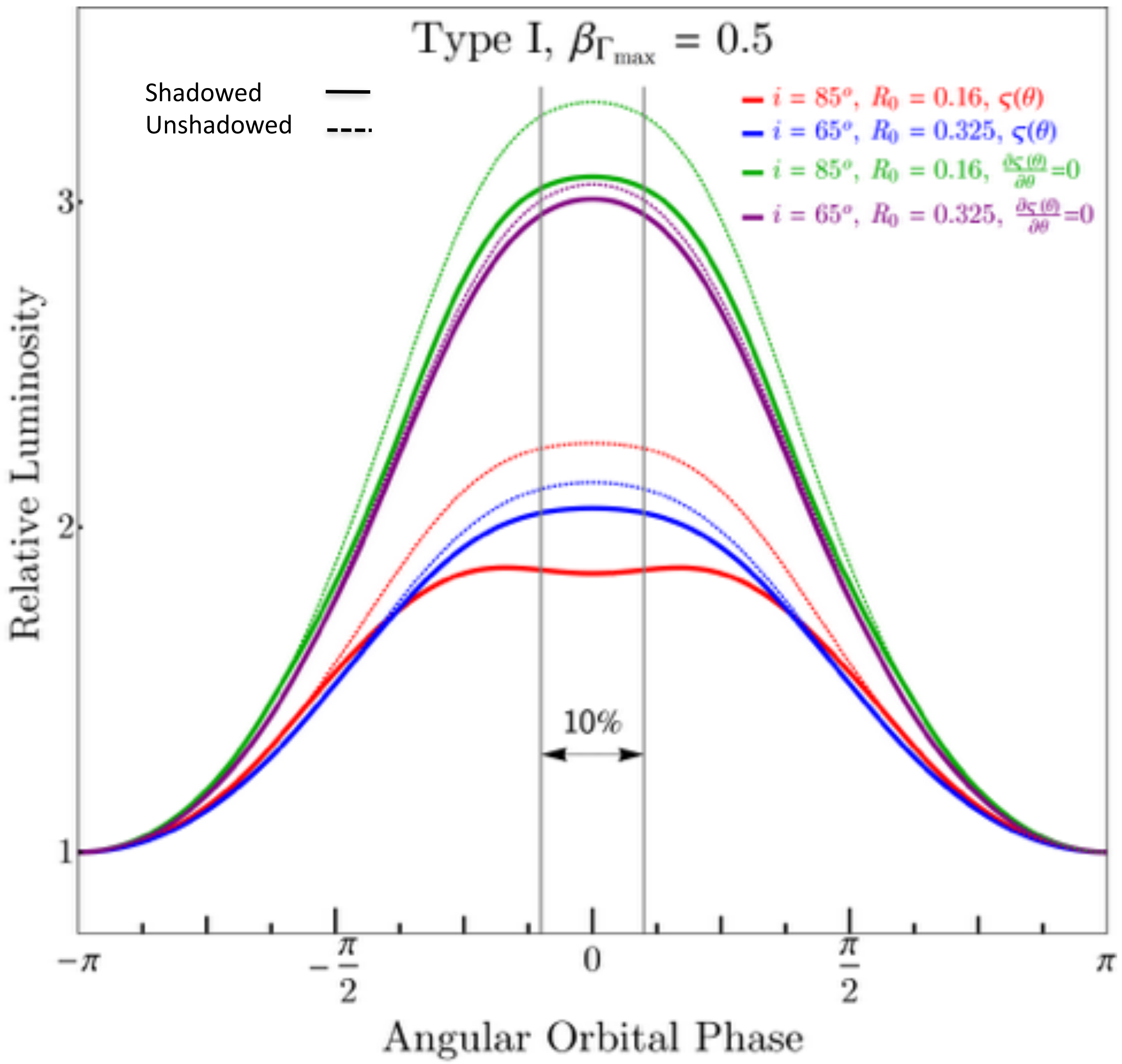


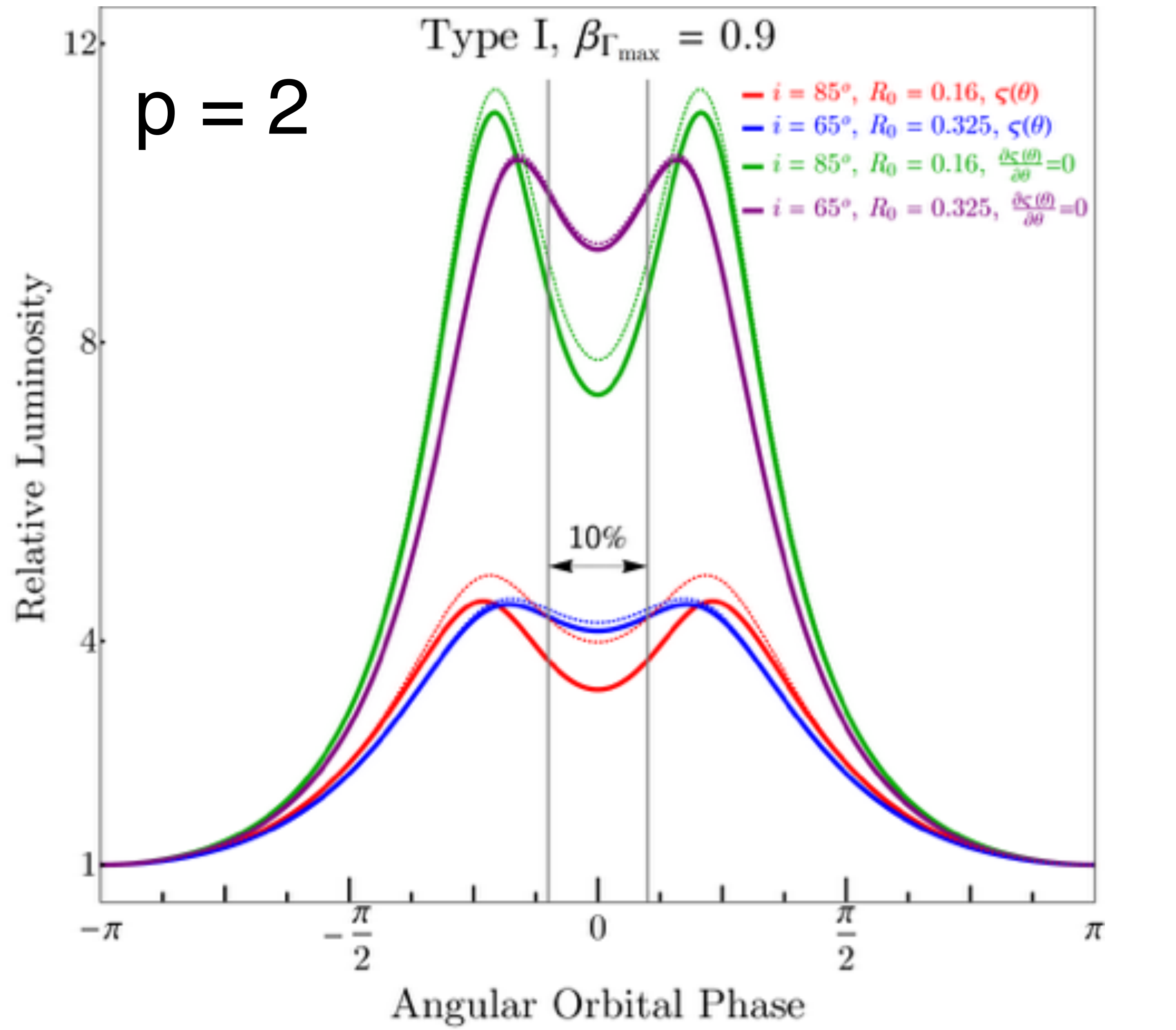
Orbitally Modulated Doppler Boosting — B1957+20 (*to scale*)



Orbitally Modulated Synchrotron Emission

- If the bulk velocity along the shock is high enough, doppler boosting produces a characteristic double-peaked light curve
- For where the stagnation point R_0 is close to the companion, shadowing can be a strong influence
- Below: Orbitally modulated SR emission for B1957+20 at a fixed energy where the emission is a power law, with shadowed and unshadowed fluxes joined and dotted curves, respectively

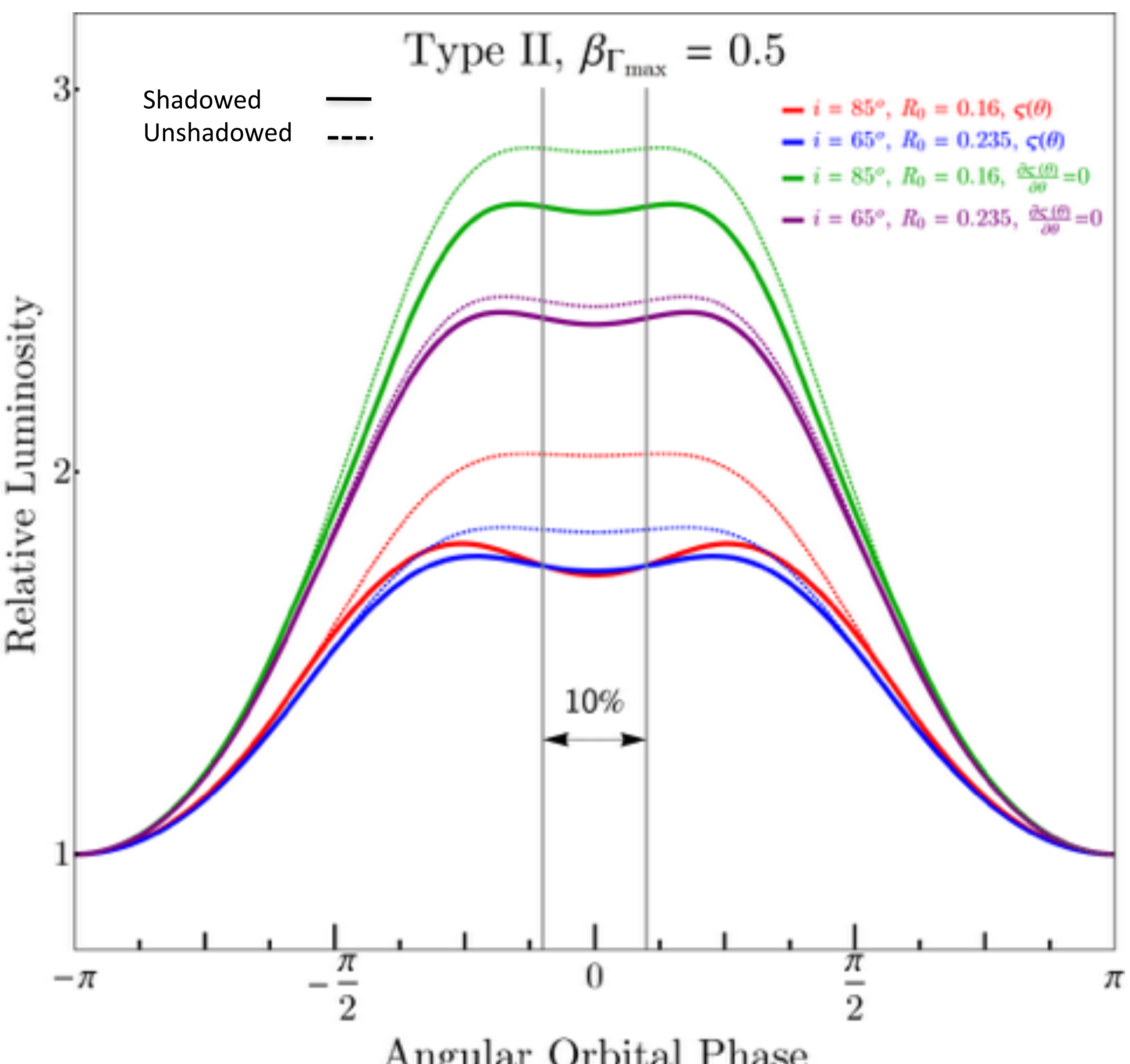


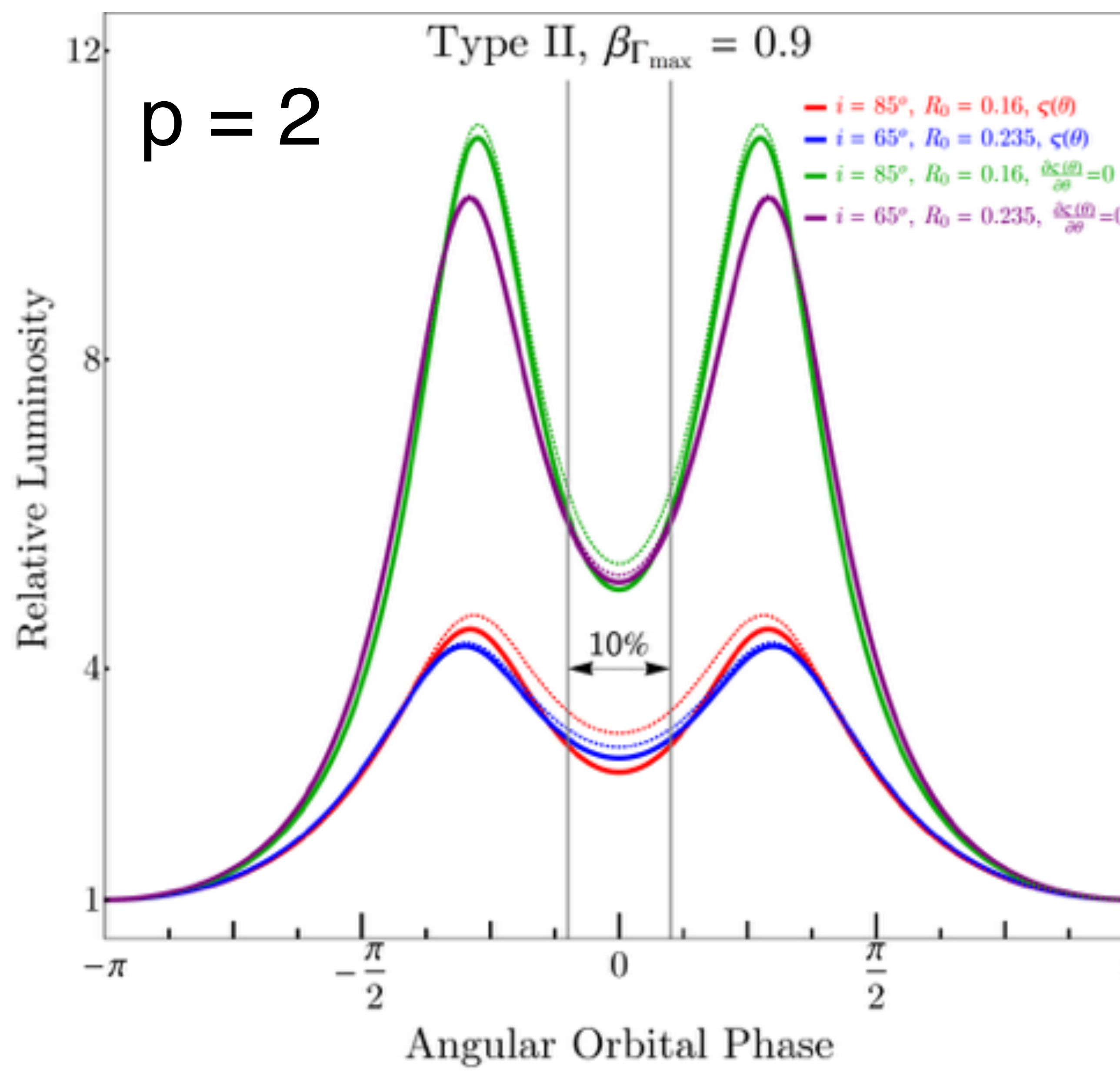


Orbitally Modulated Synchrotron Emission

- Complex interplay between the shock shape, R_0, shadowing, bulk Lorentz factor, and electron density along the shock controls the light curve modulation

- The type II shock scenario yields more significant modulation than the cone-like type I scenario, with a different peak separation for a given inclination





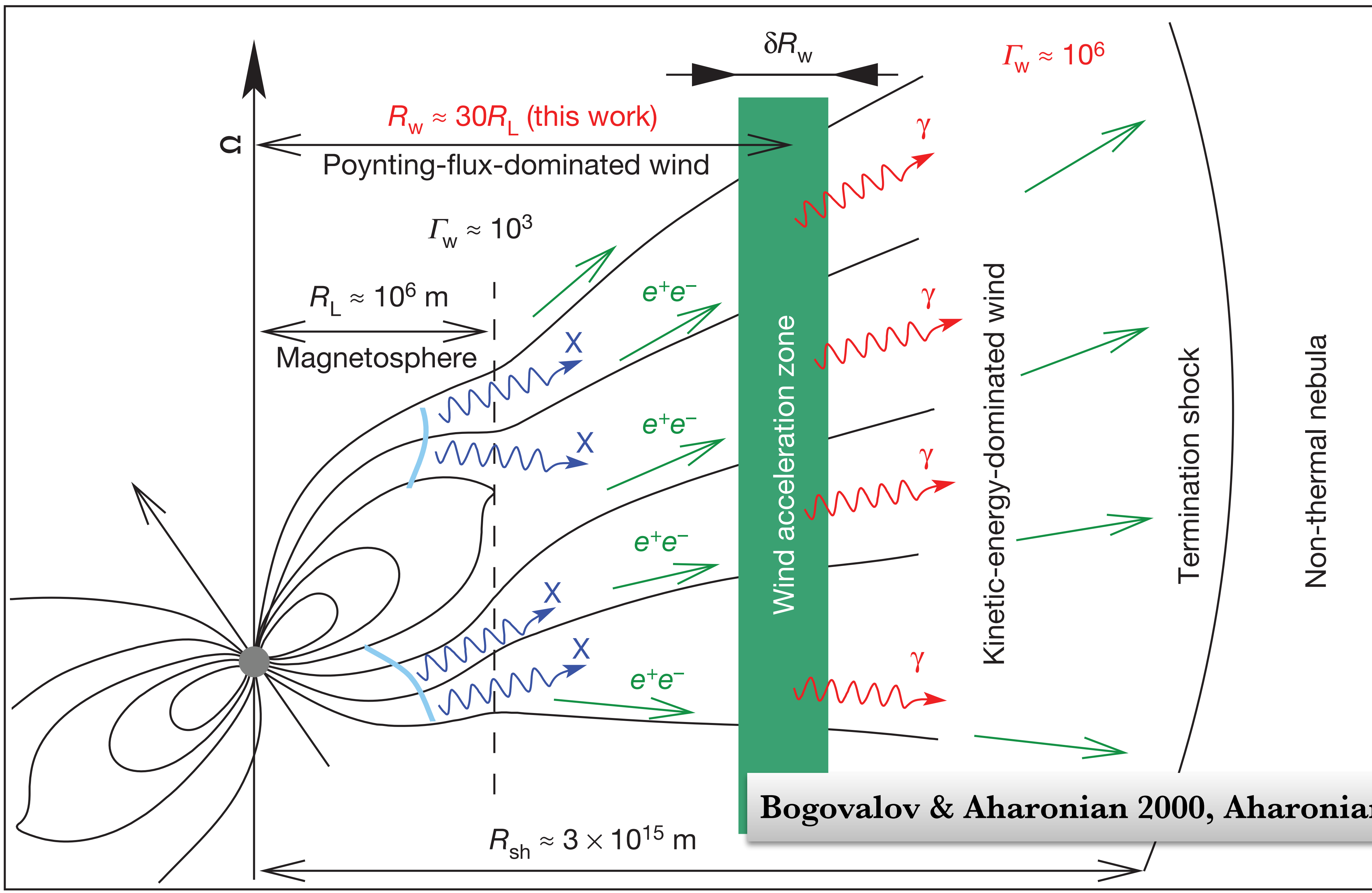
SR Discussion

- Must originate from the shocked MSP wind (mildly relativistic) rather the shocked companion wind (nonrelativistic)
- A natural path to produce double-peaked light curves and spectral hardening
- Redbacks where the double peaks are centered around inferior conjunction imply a scenario where the shock surrounds the pulsar ==> consistent with >50% radio eclipse fractions (e.g. J1023+0038 in non-accreting state, Archibald et al. 2009) and LMXB state transition
- Optical non-thermal synchrotron emission (and orbitally-modulated *polarization*) could exist depending on the accelerated electron spectrum and level of plasma turbulence in the downstream B
- Need MeV instrument to ascertain acceleration efficiency and location of synchrotron peak — ComPair, AdEPT, etc
- Lower second peak possibly due to absorption or asymmetric particle acceleration/transport in the shock induced by orbital motion

Inverse Compton

- IC target photon fields: companion (optical/UV), shock synchrotron (X-ray), MSP
- Similar physics to TeV binaries, but much more compact
- Accelerated electrons: shock and possibly upstream pulsar wind (e.g. dissipation in the current sheet)

e.g.



Bogovalov & Aharonian 2000, Aharonian et al. 2012

IC γ-ray Observability & Caveats

- Energetics governed by pulsar Edot & orbital modulation critically dependent on inclination

- Orbitally modulated γ-ray emission has been claimed for B1957+20 (Wu et al. 2012) and J1311-3430 (Xing & Wang 2015) but are unconfirmed (6-10 years, Pass 8 and ToOs to optical flares may help)

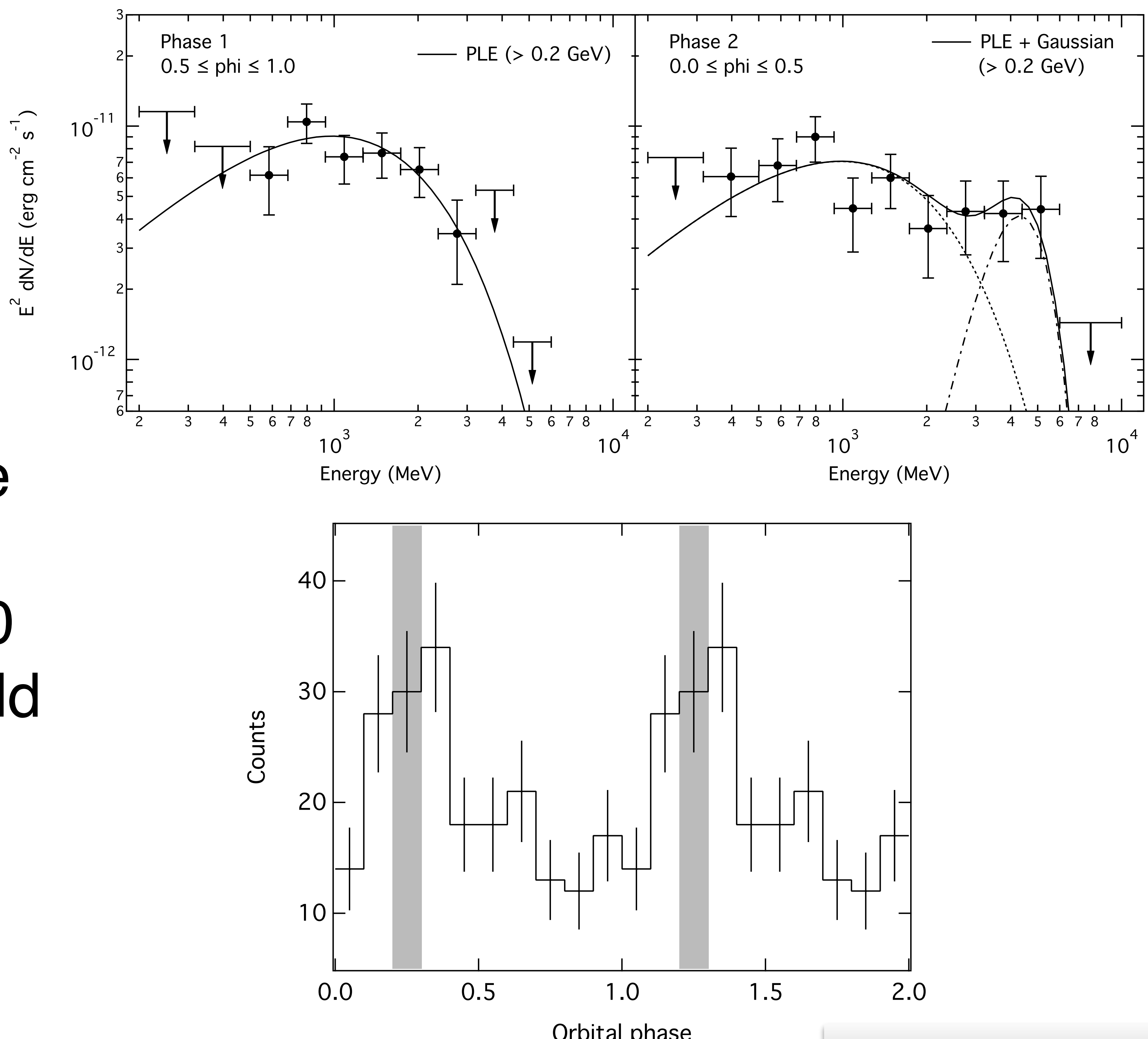
- For most systems, the IC optical depth < 1 on orbital lengthscales $a \sim 10^{11}$ cm, but may exceed unity for hot companions or flaring states where $T_{hot} > 10^4$ K

- Optimistically — IC luminosity $\sim \sigma_T n_\gamma a \times \eta \dot{E} \sim \eta 10^{33}$ erg/s ==> $\sim \eta 10^{-9}$ ergs/s/cm^2 for d=2 kpc with efficiency η dumped into e^+e^- and emission is beamed, n_γ should include both thermal and synchrotron photons targets

- Focus should be on nearby systems with high X-ray luminosities, hot companions and flaring states, and near edge-on inclinations

Inverse Compton - B1957+20

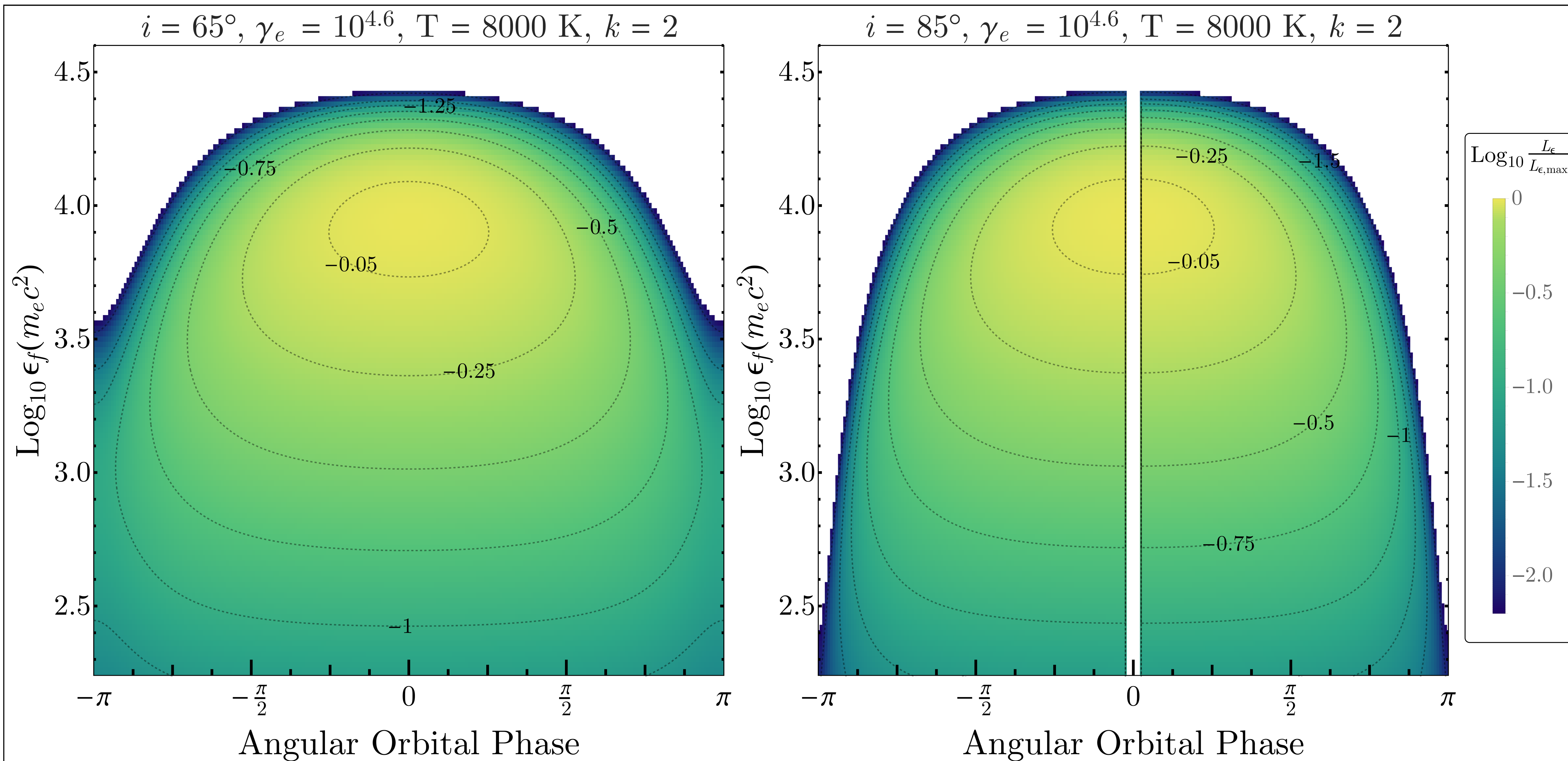
- Only ~ 2-3-sigma significance (post-trials) and <u>unconfirmed</u> by the main collaboration — Pass 8 and 6-10 years of data should confirm or refute



Wu et al. (2012)

Orbitally Modulated Cold Wind IC — B1957+20

- Horizontal cuts — light curves; vertical cuts — spectra
- Occultation by the companion of the emission region may be important for inclinations near edge-on
- General agreement with Bednarek (2014)

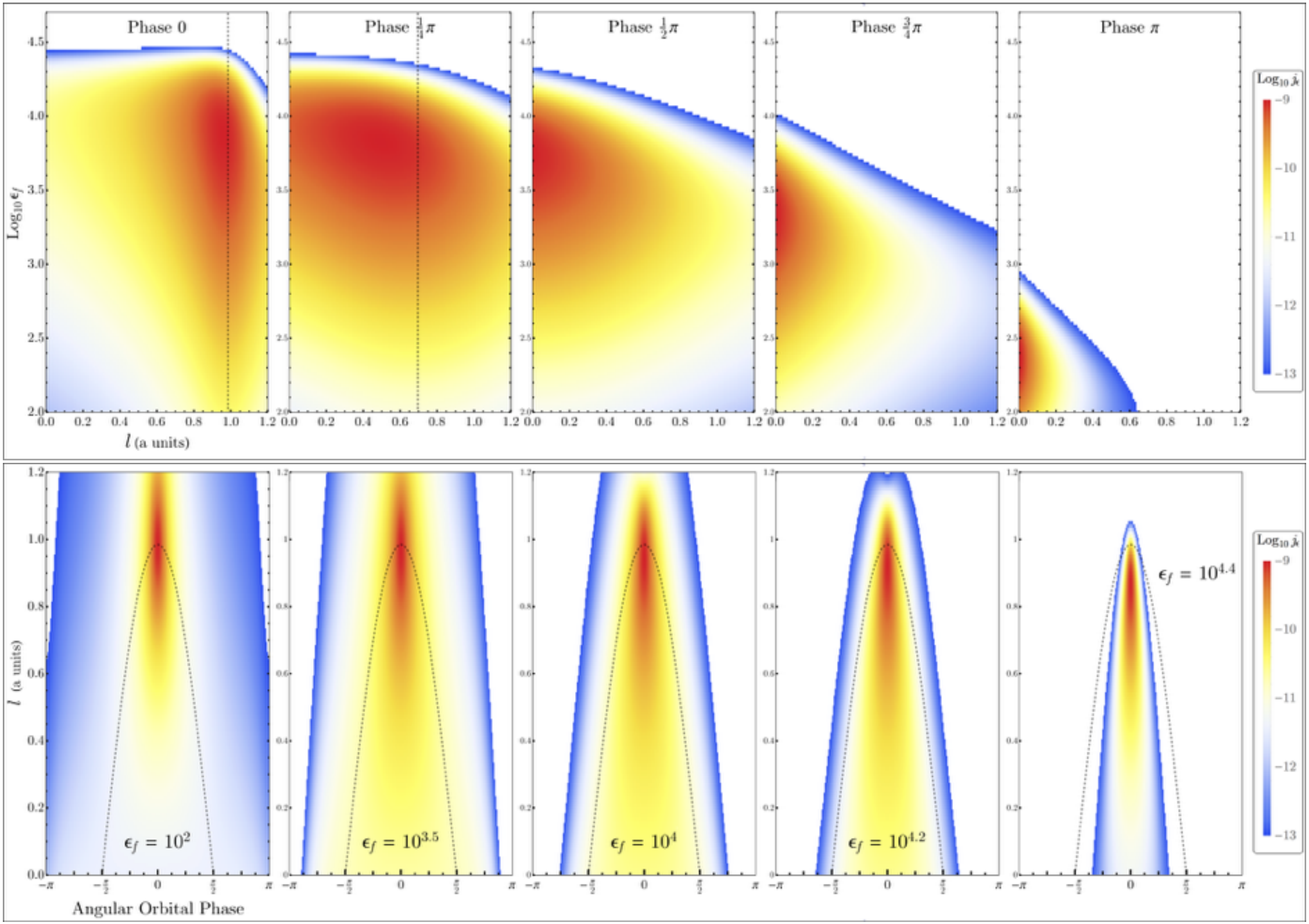


Future

- Steady-state particle transport along the shock and self-consistent synchrotron light curves
- Additional anisotropic IC components and SEDs
- Relativistic MHD shock structure
- Orbital motion and sweepback effects
- Application of machinery to more eclipsing black widow and redback systems
- Stay tuned!

Backup Slides

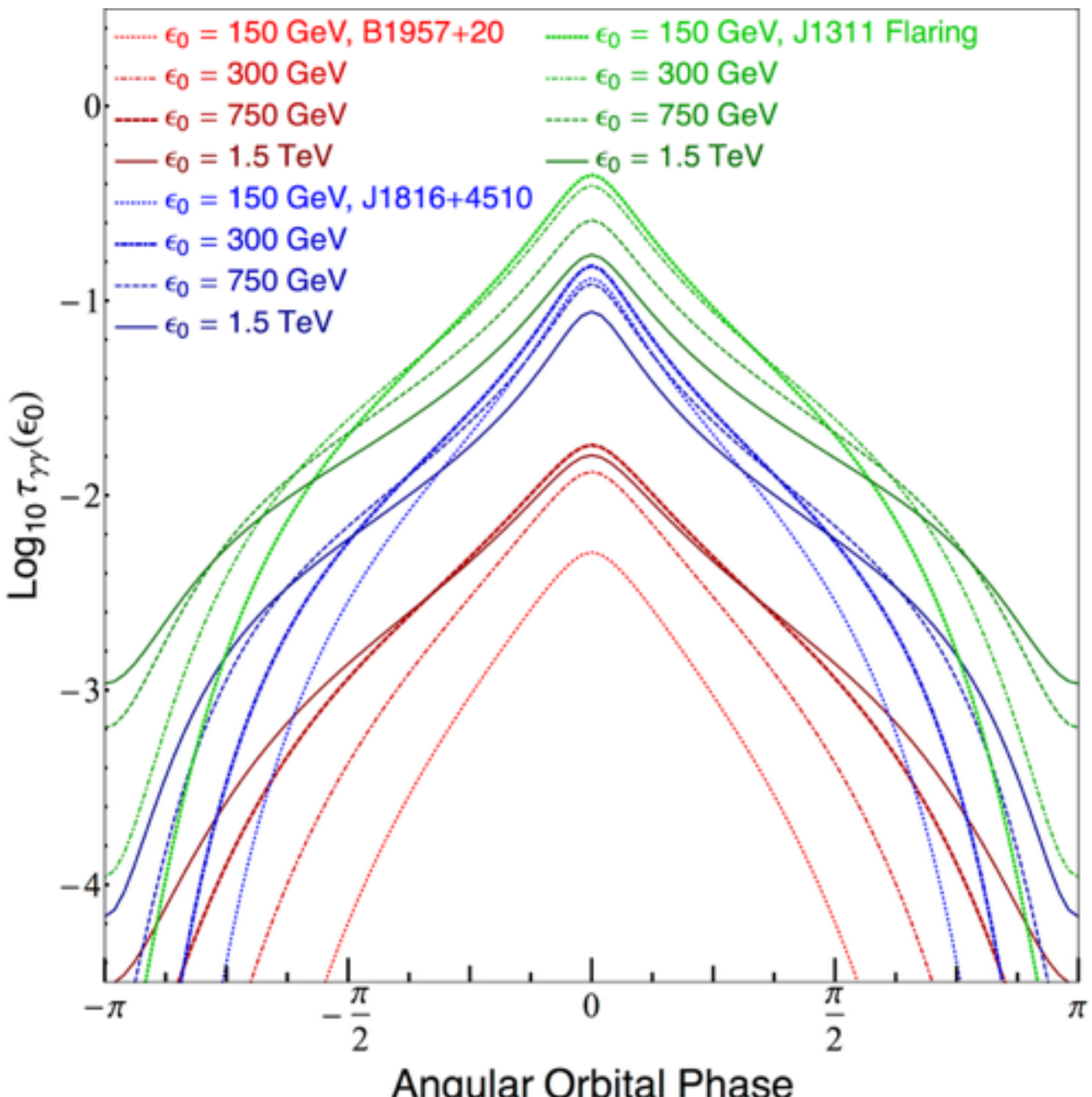
Volume Normalized IC Emissivity - B1957+20

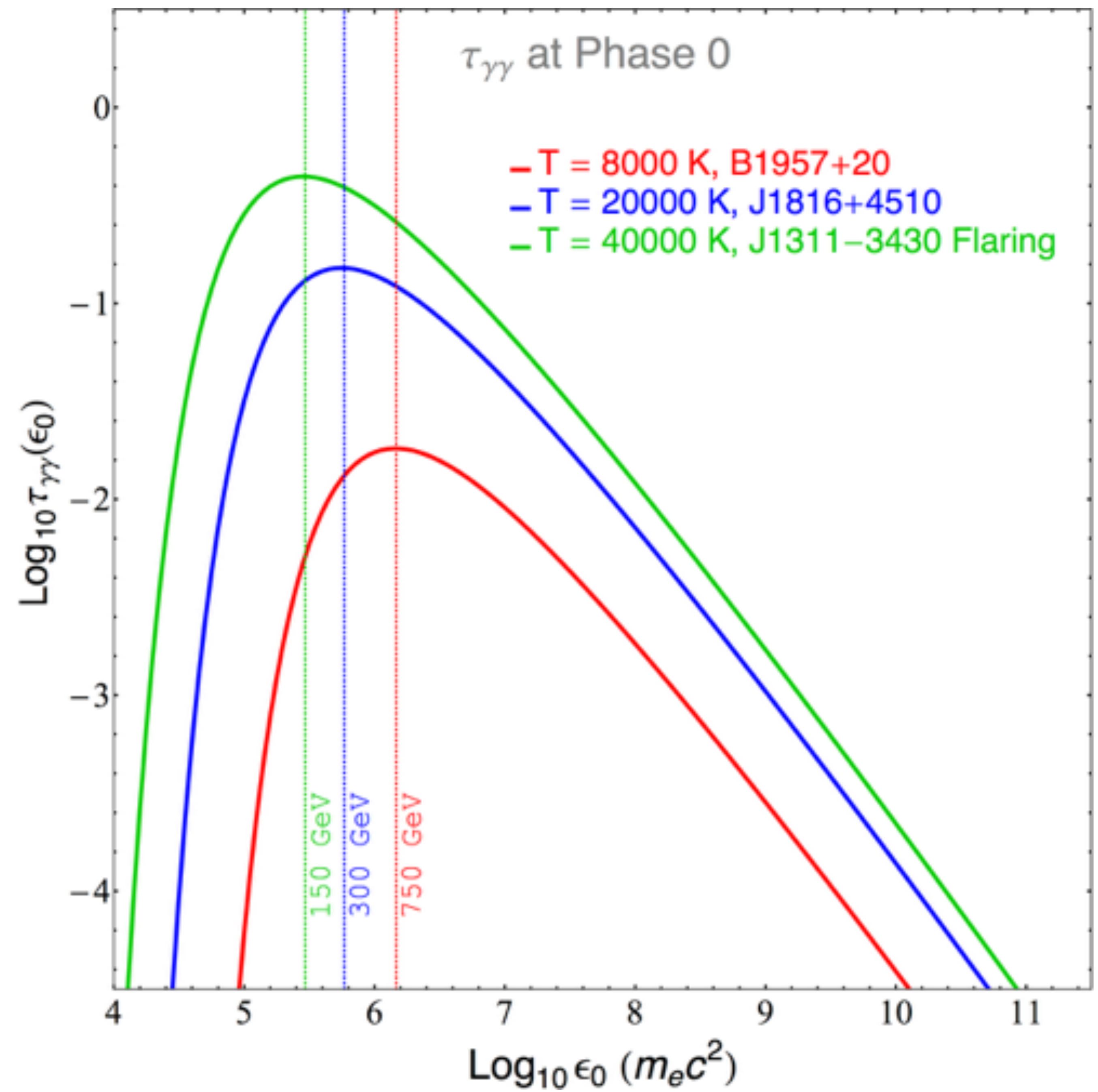


γγ Absorption & Pair Creation

- Although temperatures of black widow and redback companions can be high, due to their small size, absorption is insignificant except perhaps for J1311-3430 in a flaring state, where $T_{eff} \sim 40000$ K
- ε_0 - the energy of the outgoing VHE photon, emitted towards observer from ~ 0.2*a* near the companion

$$\tau_{\gamma\gamma}(\epsilon_0) = \int_0^\infty d\ell' \int_{\mu_-}^{\mu_+} d\mu_{\gamma\gamma}(1-\mu_{\gamma\gamma}) \int_{2/[\epsilon_0(1-\mu_{\gamma\gamma})]}^\infty d\varepsilon_s \frac{\partial\sigma_{\gamma\gamma}(\epsilon_0,\varepsilon_s,\mu_{\gamma\gamma})}{\partial\mu_{\gamma\gamma}} n_\gamma(\varepsilon_s) f(\mu_{\gamma\gamma},\ell')$$





Growth Curve of Radio Eclipses — Frequency Mapping

- For the eclipses at ingress, the frequency dependence of the eclipse width can give insight into the spatial dependence of the turbulent plasma and absorption causing the eclipses

If the eclipse fraction $f_E \sim g(\theta) \propto \nu^{-n}$ with optical depth $\tau \sim \Sigma\,\sigma$ and absorption cross section $\sigma \sim \nu^{-m}$, then $\Sigma(\theta) \sim g(\theta)^{-m/n}$