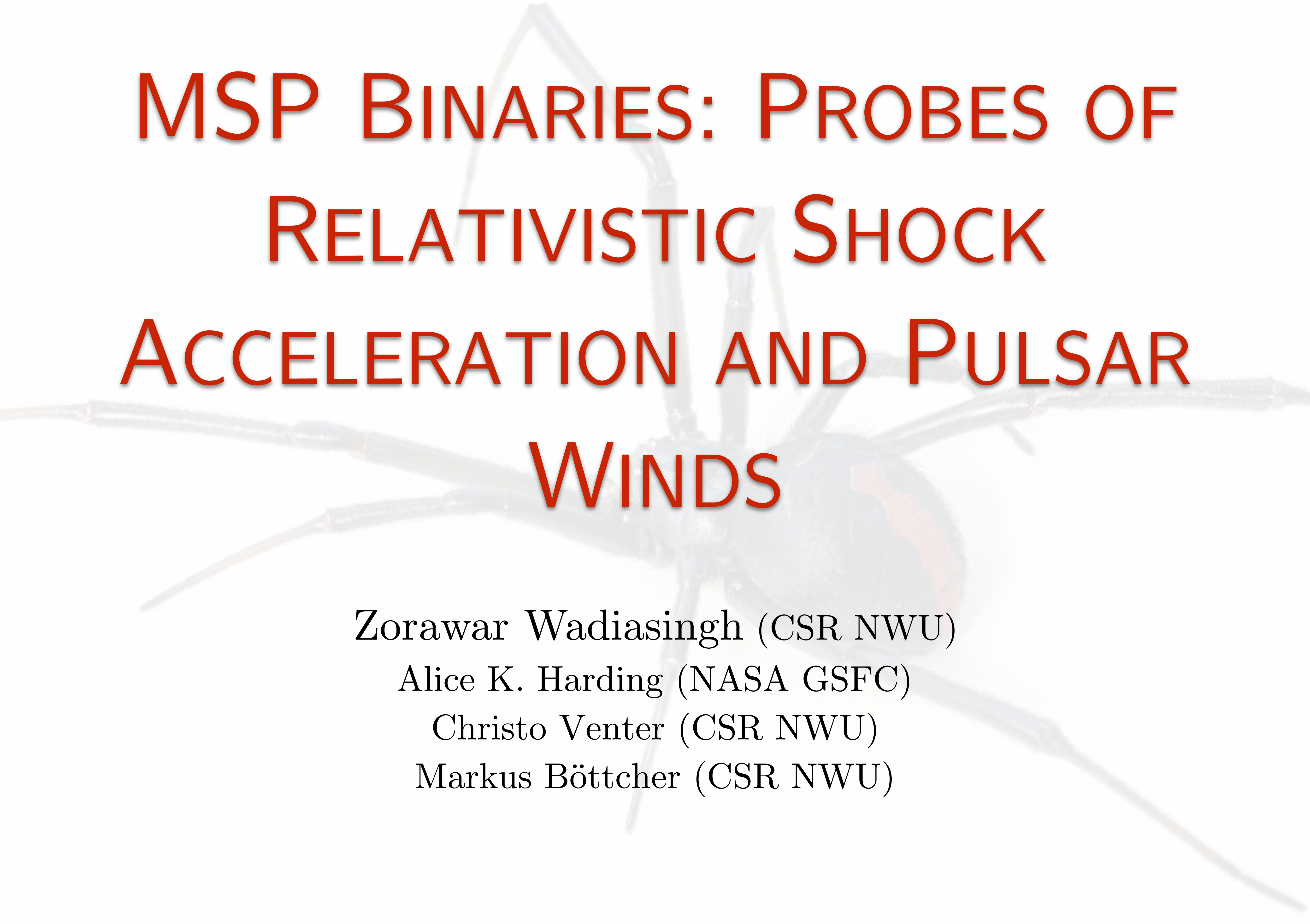


MSP Binaries: Probes of Relativistic Shock Acceleration and Pulsar Winds

Zorawar Wadiasingh (CSR NWU)
Alice K. Harding (NASA GSFC)
Christo Venter (CSR NWU)
Markus Böttcher (CSR NWU)

Black Widows & Redbacks

Nearly all *circular* orbits (see Paul Ray's poster for an exception)

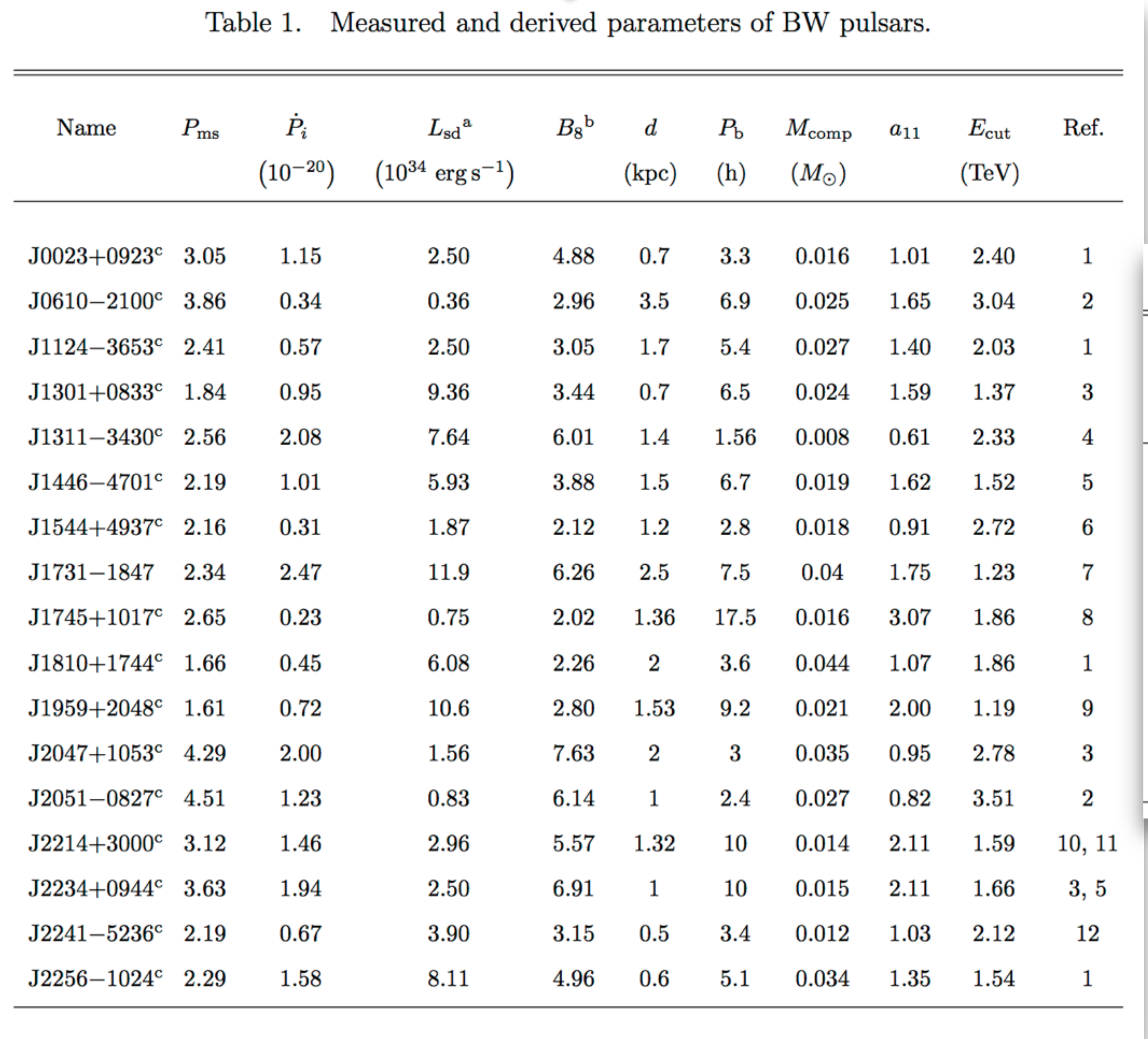


Table 1. Measured and derived parameters of BW pulsars.

Name	$P_{\rm ms}$	$\dot{P}_i$ (10^{-20})	$L_{\rm sd}$[a] (10^{34} erg s^{-1})	B_8[b]	d (kpc)	$P_{\rm b}$ (h)	$M_{\rm comp}$ ($M_\odot$)	a_{11}	$E_{\rm cut}$ (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

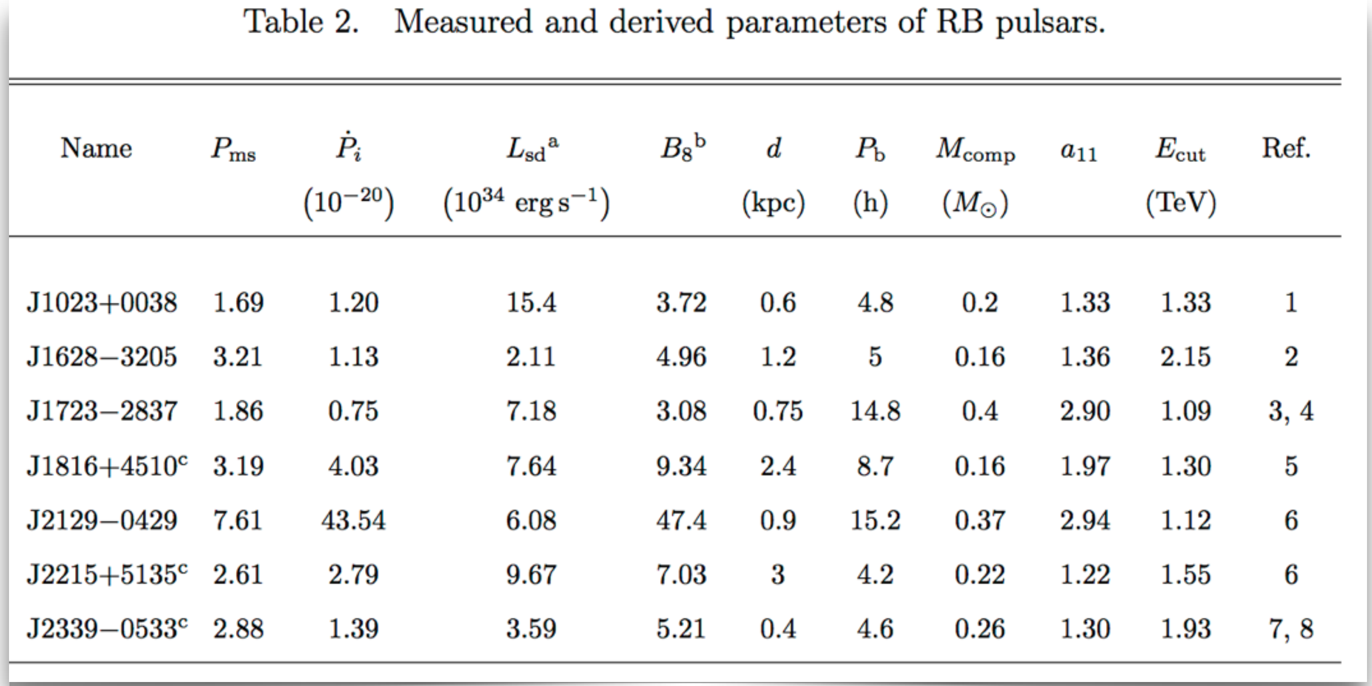


Table 2. Measured and derived parameters of RB pulsars.

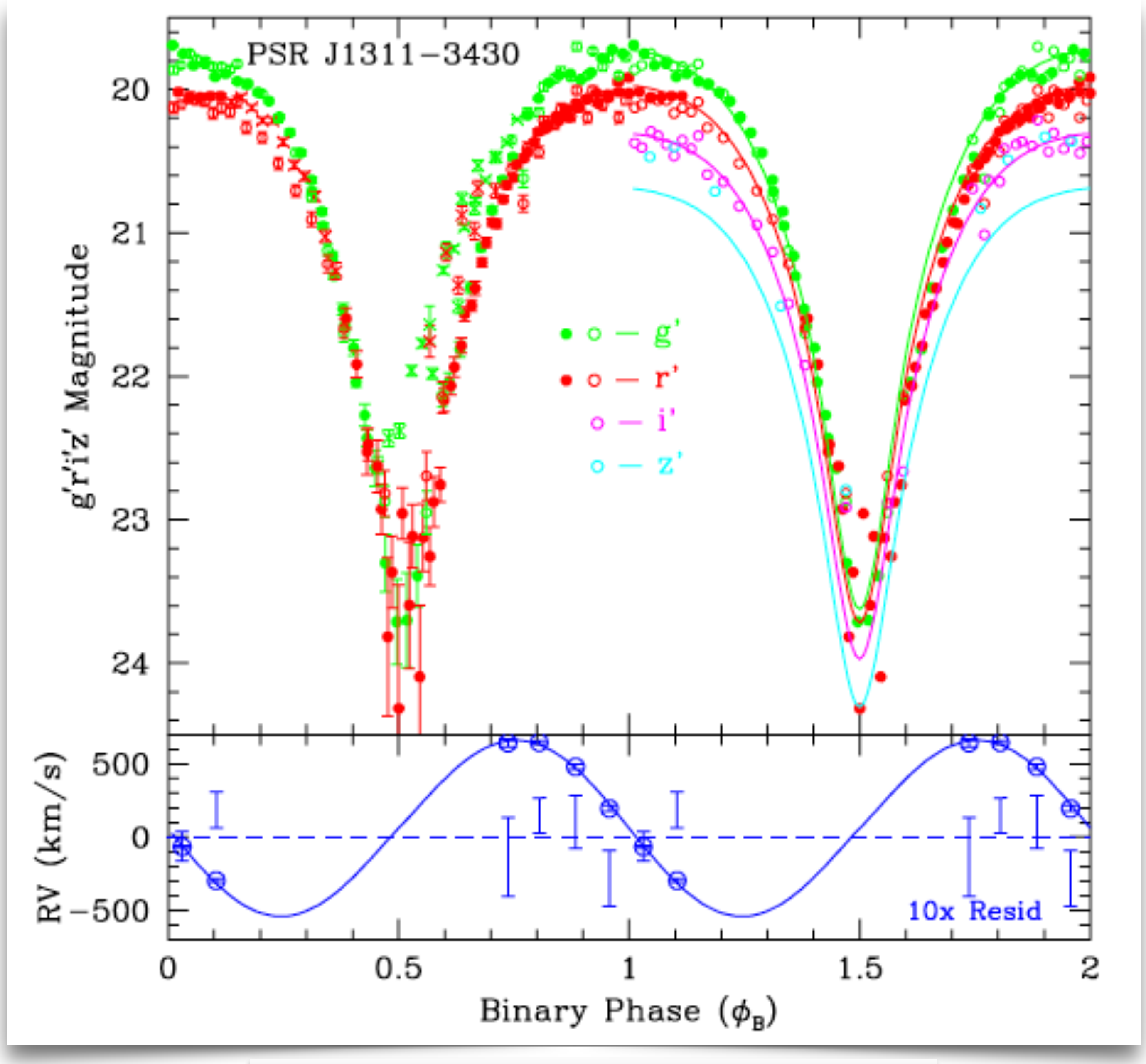
Name	$P_{\rm ms}$	$\dot{P}_i$ (10^{-20})	$L_{\rm sd}$[a] (10^{34} erg s^{-1})	B_8[b]	d (kpc)	$P_{\rm b}$ (h)	$M_{\rm comp}$ ($M_\odot$)	a_{11}	$E_{\rm cut}$ (TeV)	Ref.
J1023+0038	1.69	1.20	15.4	3.72	0.6	4.8	0.2	1.33	1.33	1
J1628−3205	3.21	1.13	2.11	4.96	1.2	5	0.16	1.36	2.15	2
J1723−2837	1.86	0.75	7.18	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)

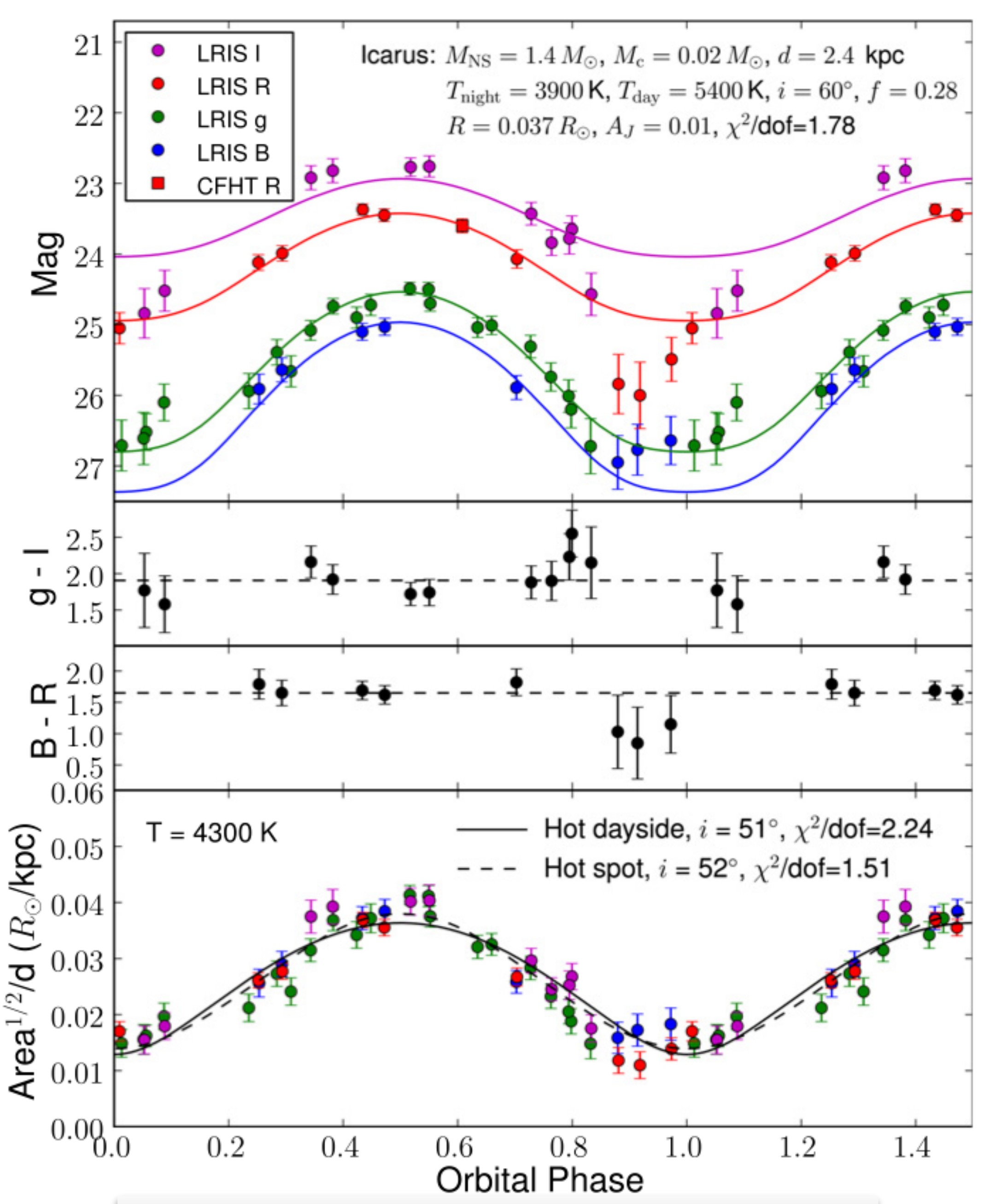
Much of *this* talk is focused on B1957+20/J1959+2048, the *original* Black Widow, but the methods developed here will be applied to more of these systems in the near future

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

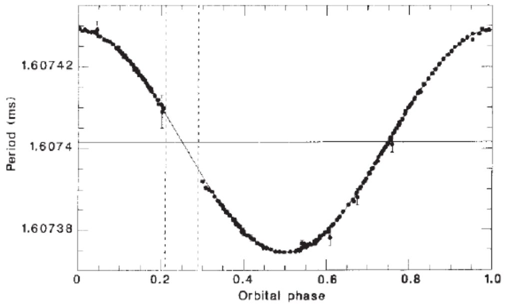


J1311-3430, Romani et al. (2012)



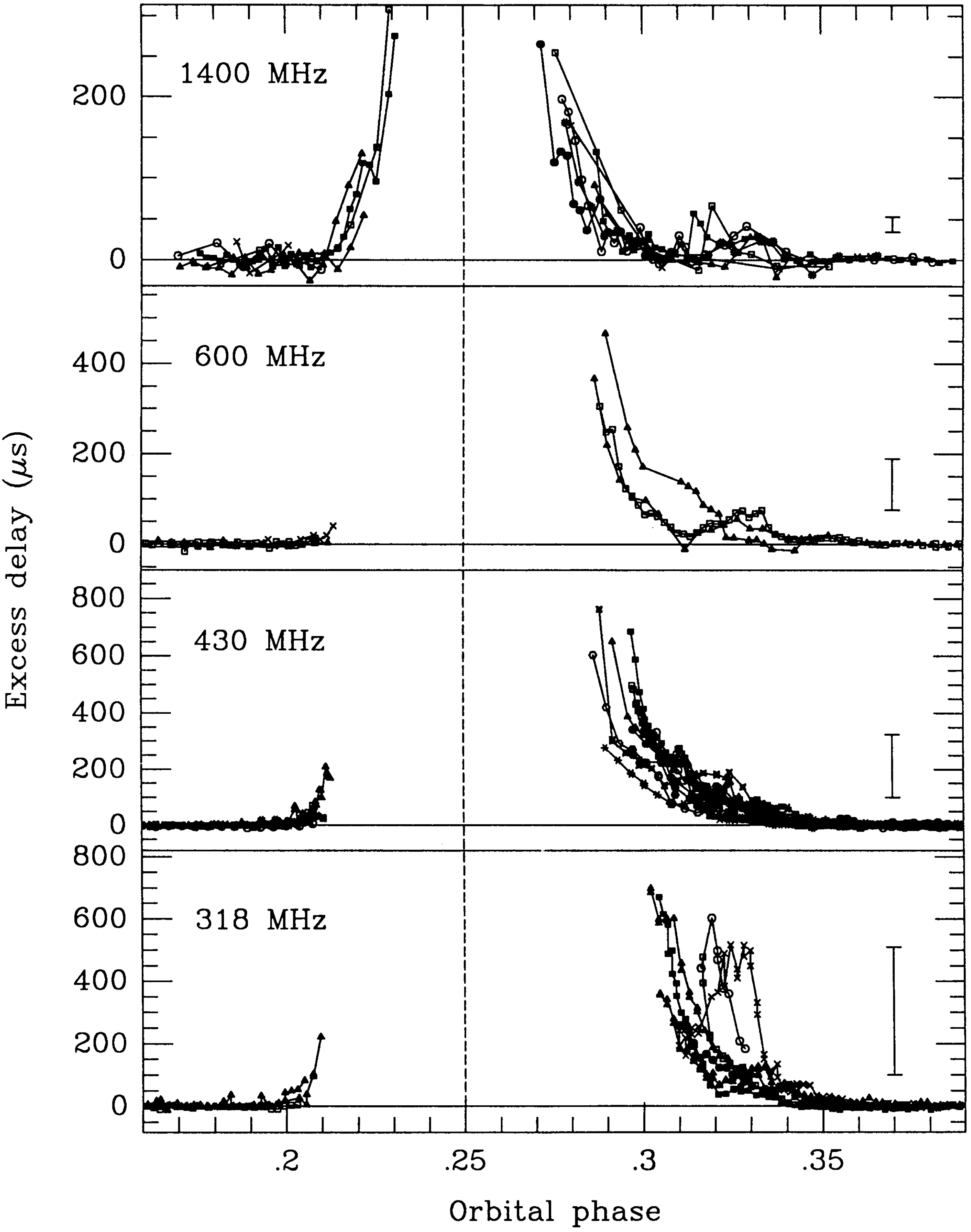
J1544+4937, Tang et al. (2014)

Radio Eclipses

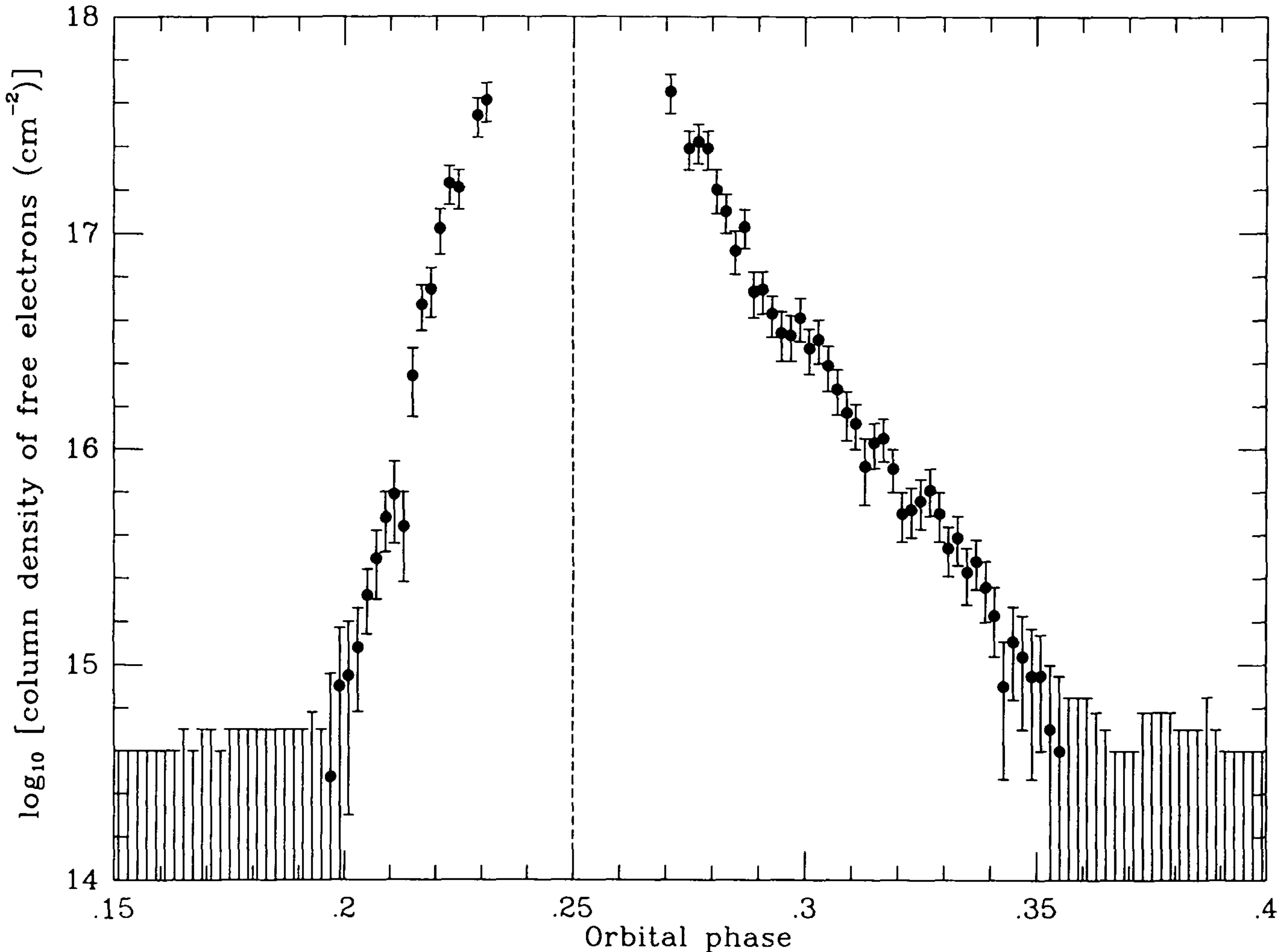


- Many black widows and redbacks show frequency-dependent radio eclipses or shrouding of the MSP over large fractions of their orbit, centered at superior conjunction where the companion is between the observer and MSP

- 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



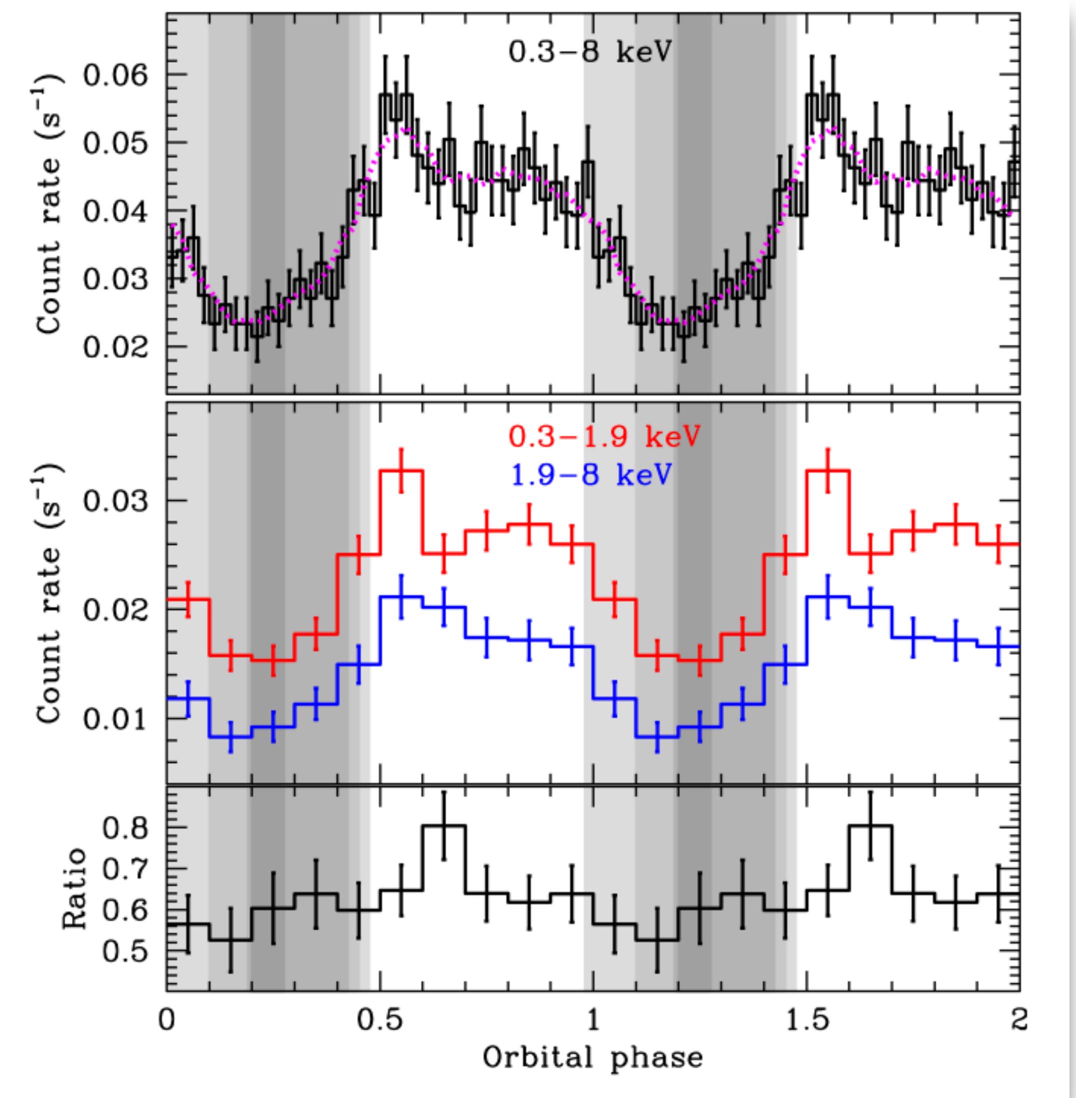
Ryba & Taylor (1991) — B1957+20



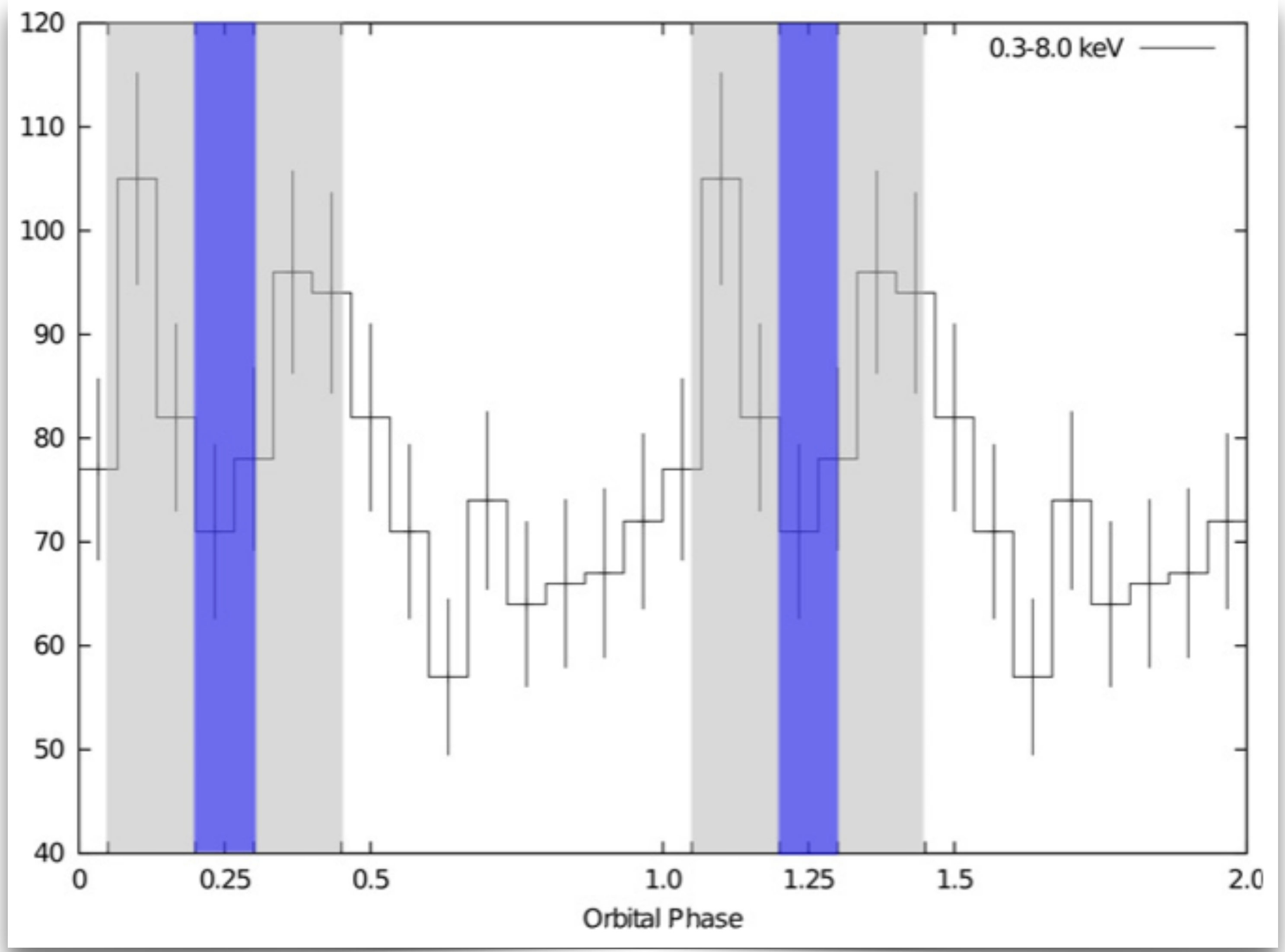
X-ray Observations

- 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 $\Gamma \approx$ 1-1.5 implying very hard underlying electron power-law distributions

J1023+0038 (Bogdanov et al. 2011)

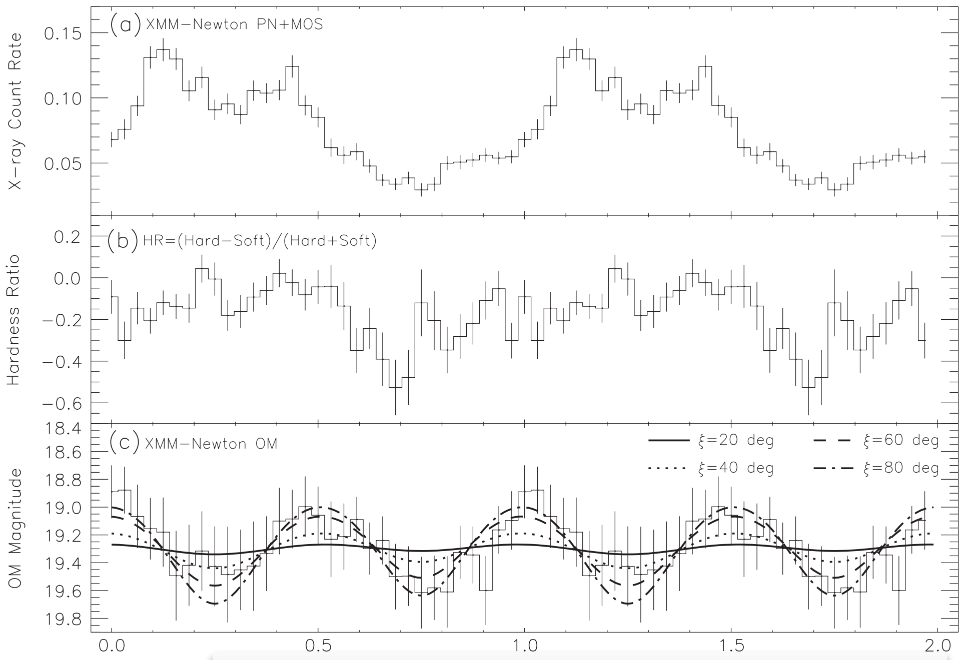


B1957+20 (Huang et al. 2012)

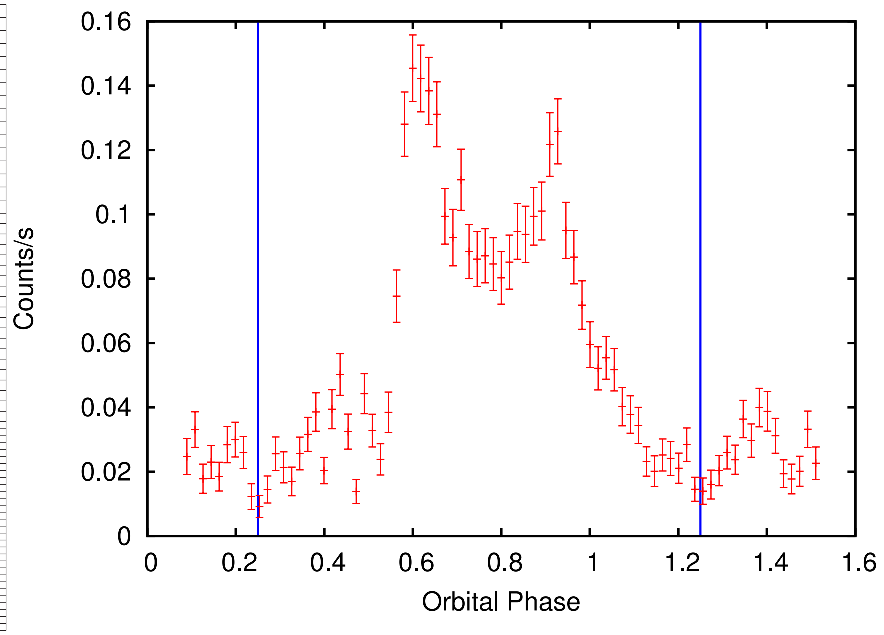


Double-Peaked Soft X-ray Light Curves

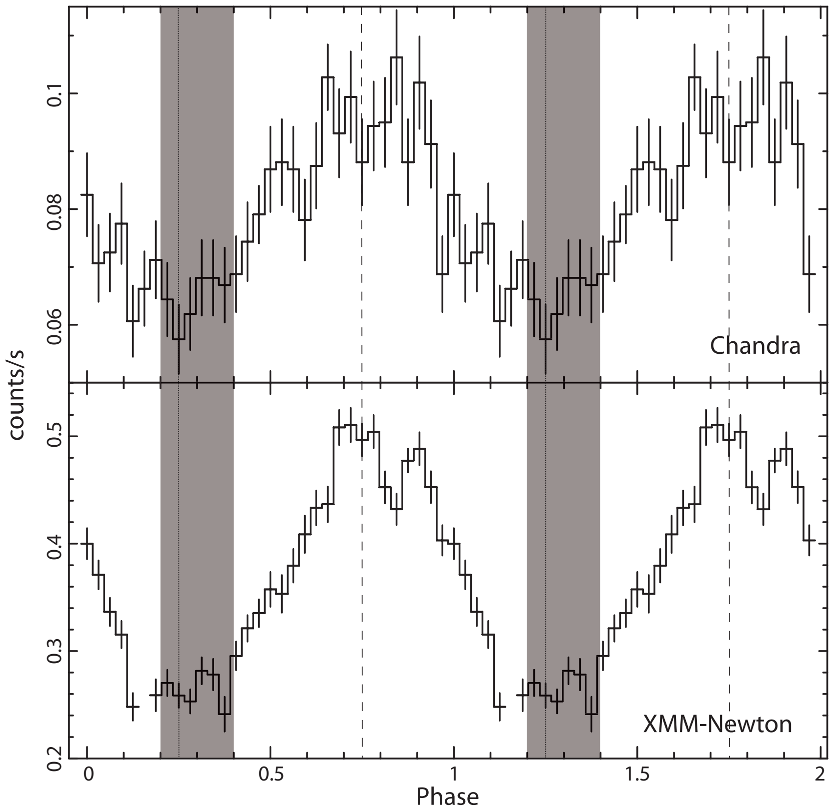
- Centered about inferior or superior conjunction
- Second peak nearly always at a modestly lower flux level



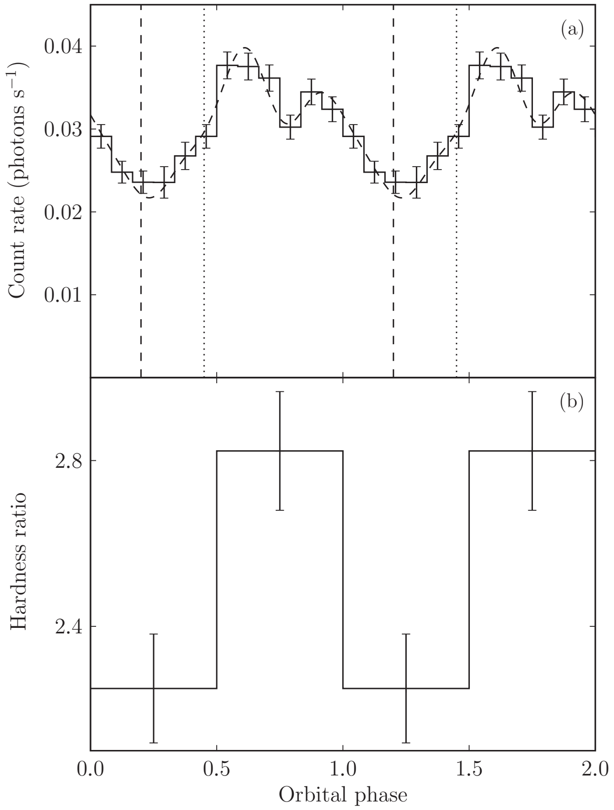
J2129-0429, Hui et al. 2015



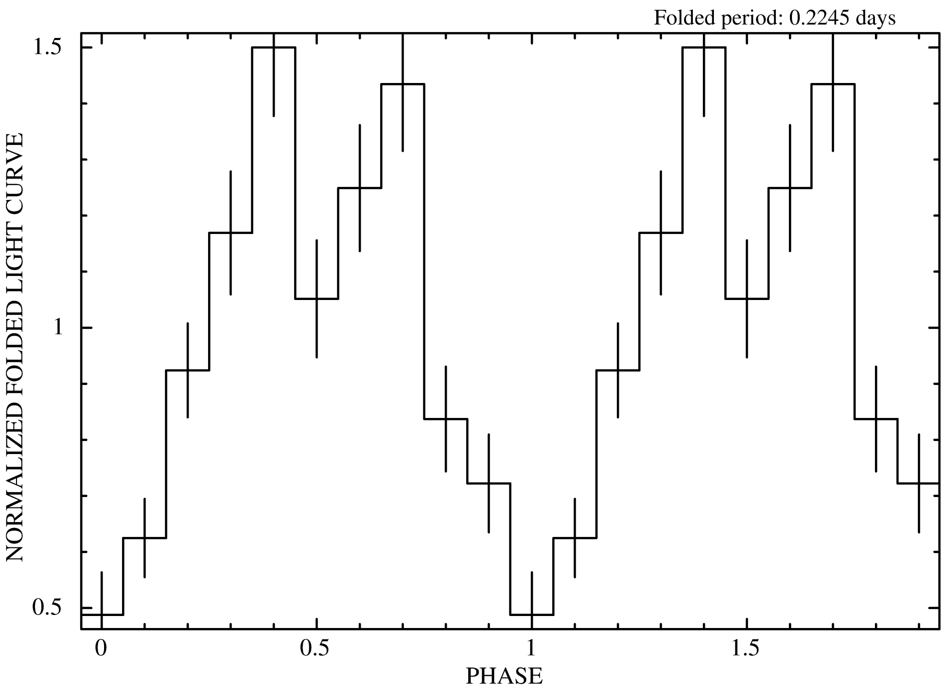
J2129-0429, Roberts et al. 2015



J1723-2837, Hui et al. 2014



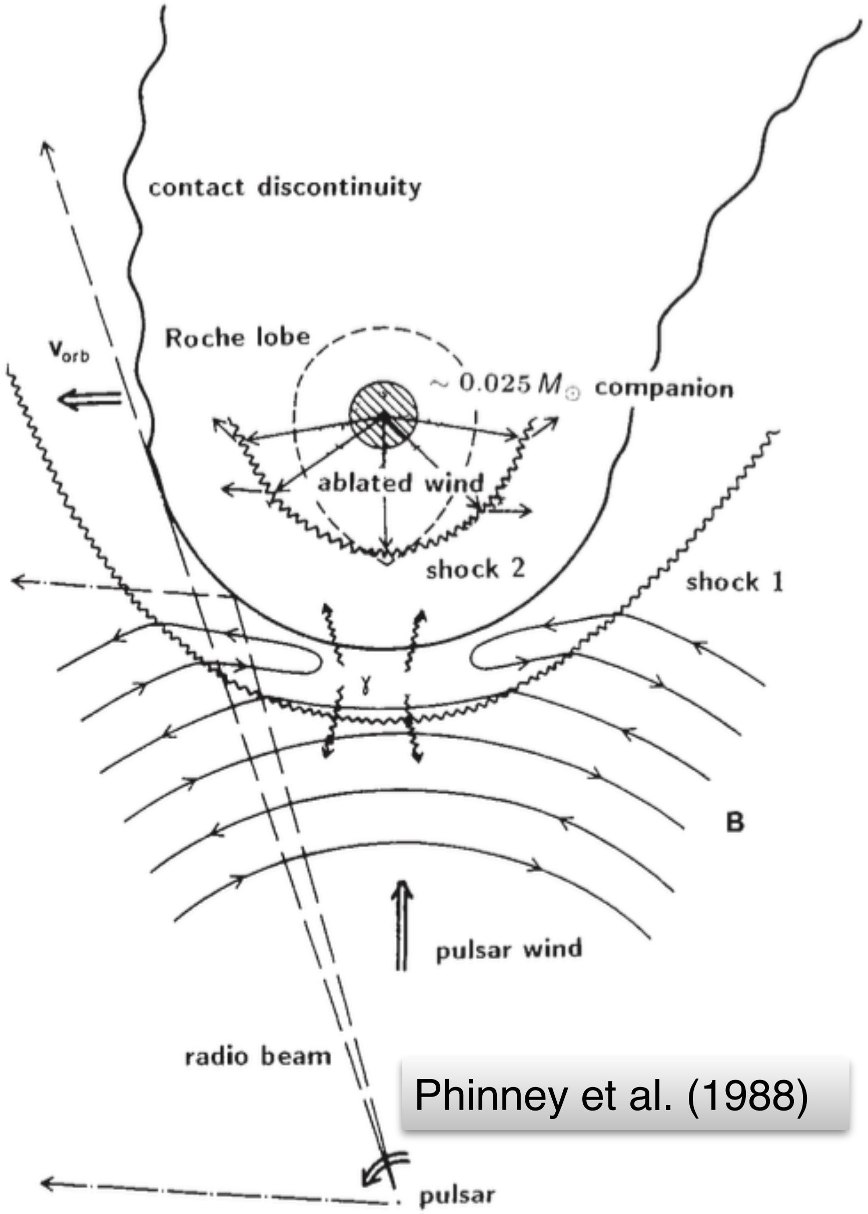
J1023+0038, Archibald et al. 2010



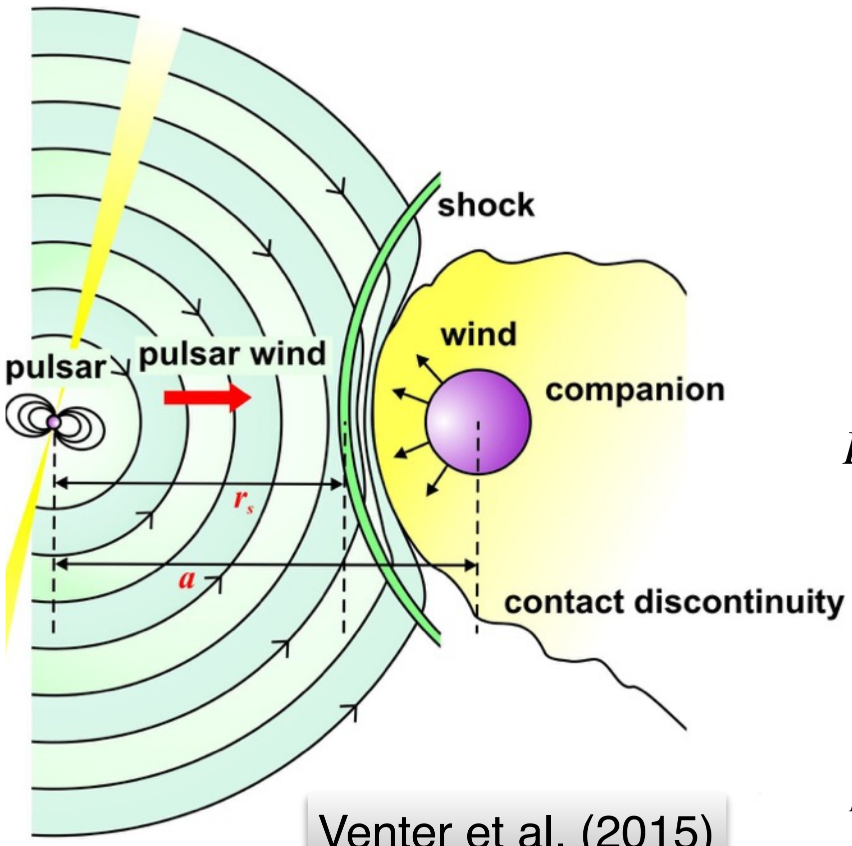
J2039-5618, Salvetti et al. 2015

Particle Acceleration

Shock is only ~10^{11} cm away from the MSP in black widows, contrasted to ~10^{16}-10^{17} cm for PWNe!



Phinney et al. (1988)



Venter et al. (2015)

Shock acceleration spectrum

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

Maximum acceleration energy
(Harding & Gaisser 1990)

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

Normalization

Pair multiplicity

Polar cap flux

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

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

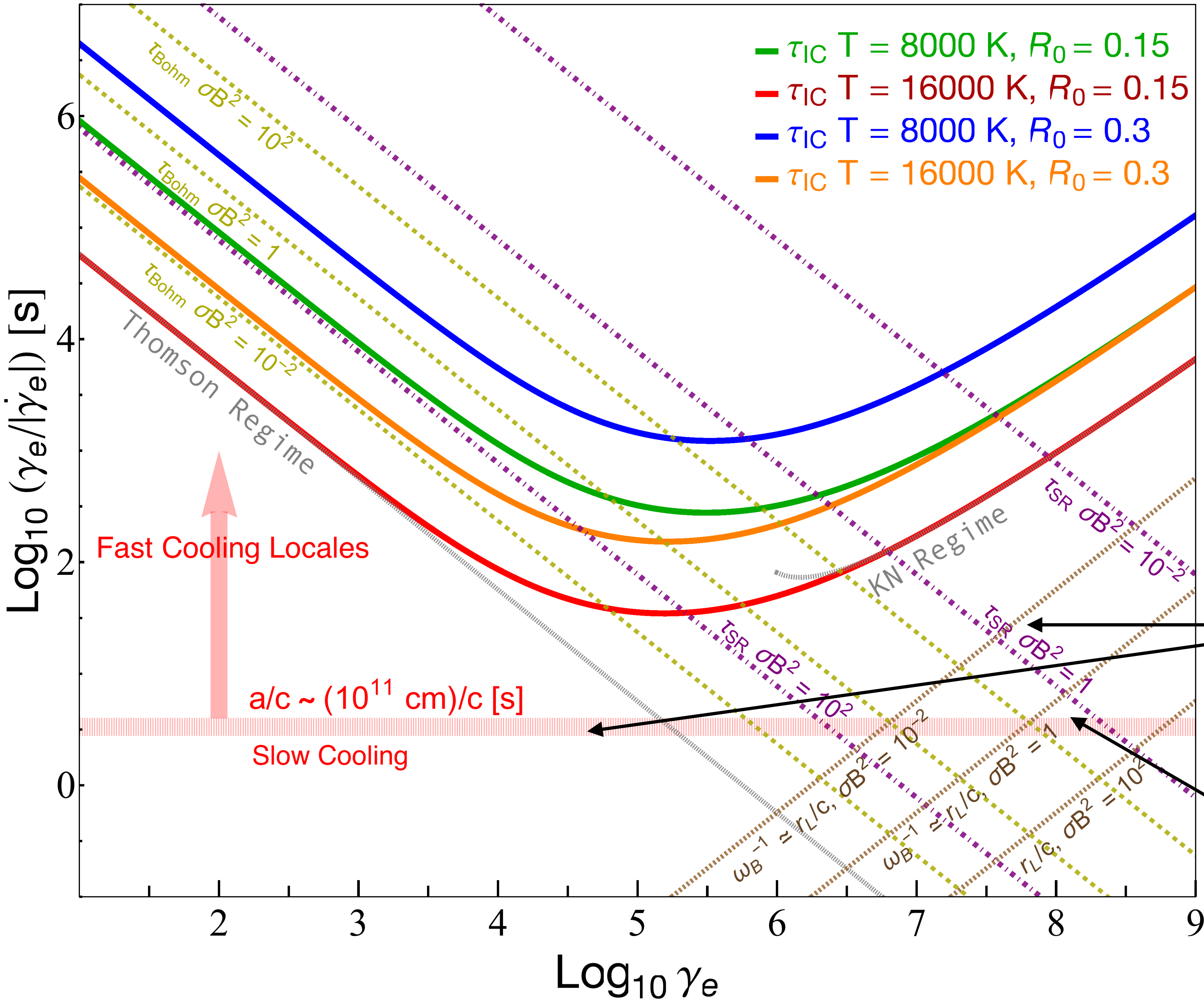
Efficiency

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

Acceleration should be most prolific near the stagnation point

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

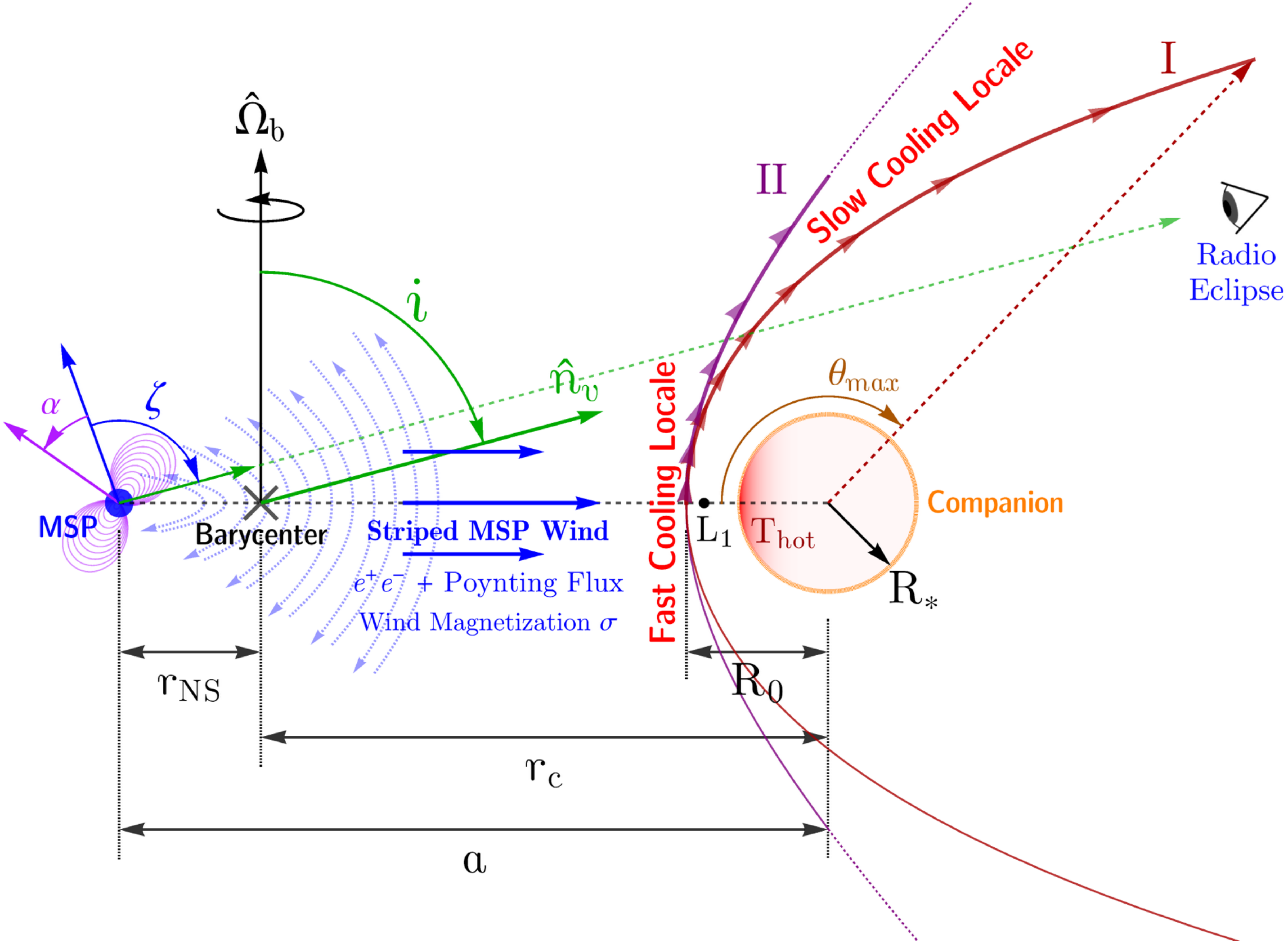


$B_{downstream} \approx 3\sigma^{1/2}B_{up}$ (Kennel & Coroniti 1984)

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

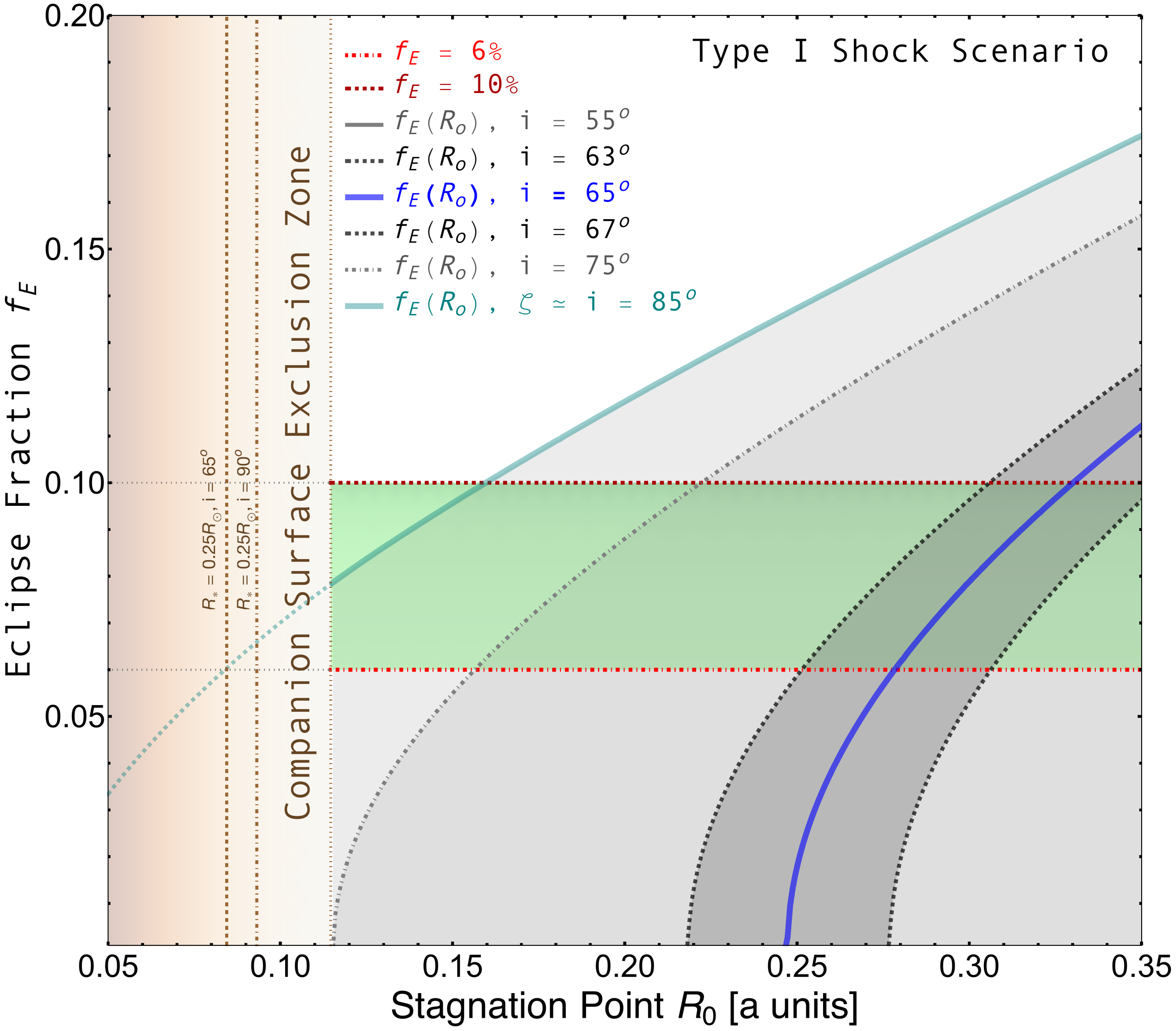
Electrons up to ~TeV, cut-off due to synchrotron burn-off

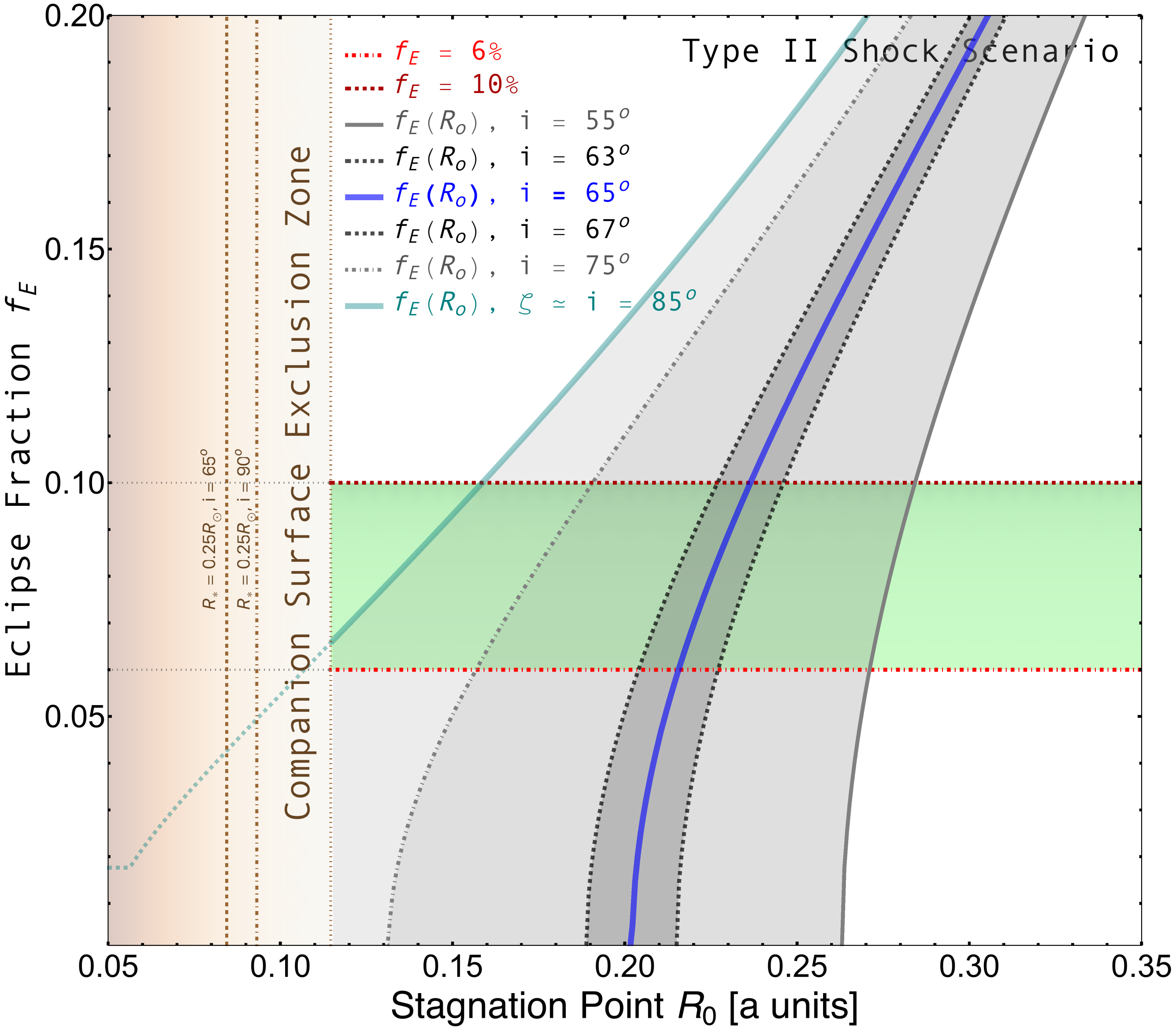
Schematic Geometry



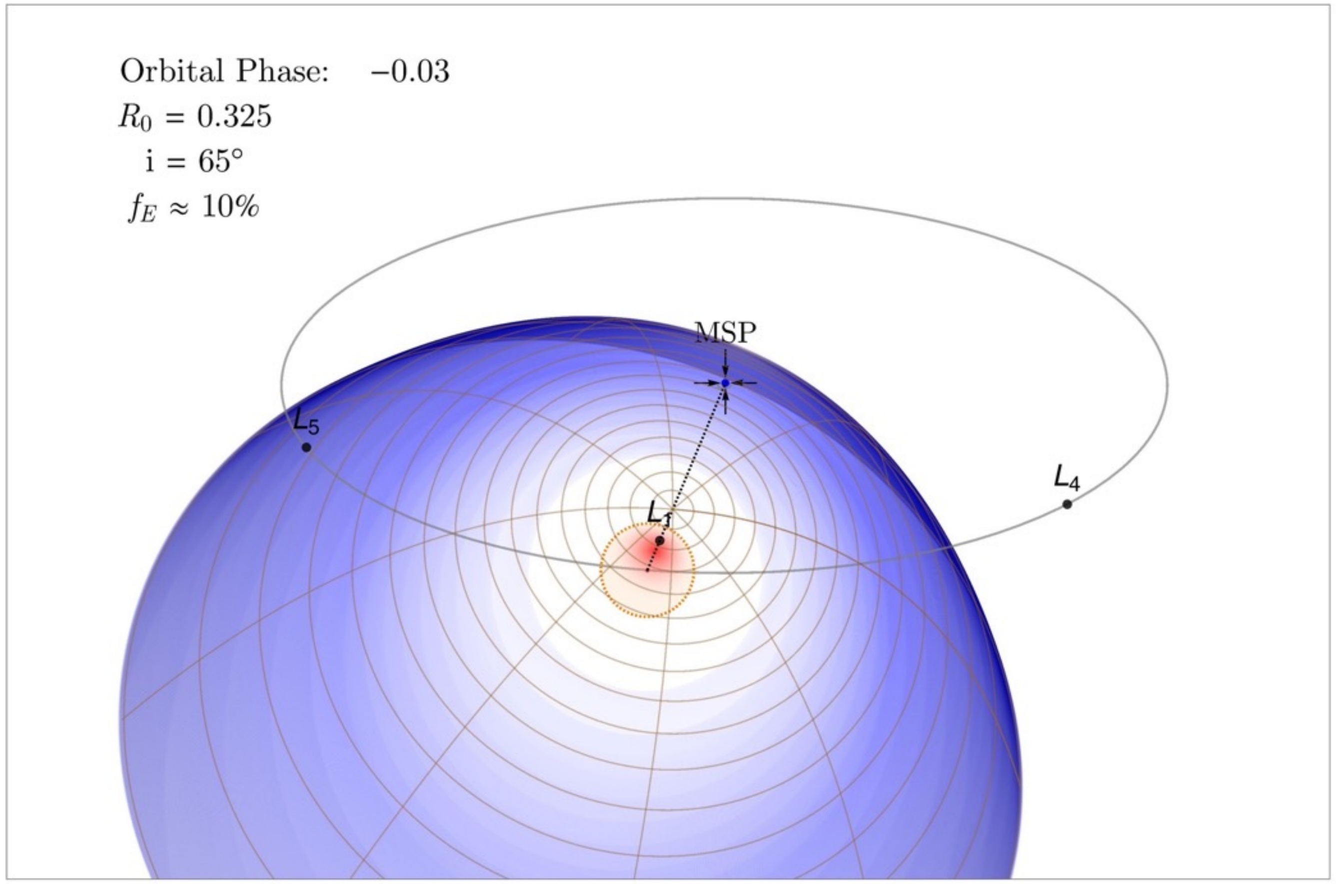
Radio Eclipses by Intrabinary Shocks

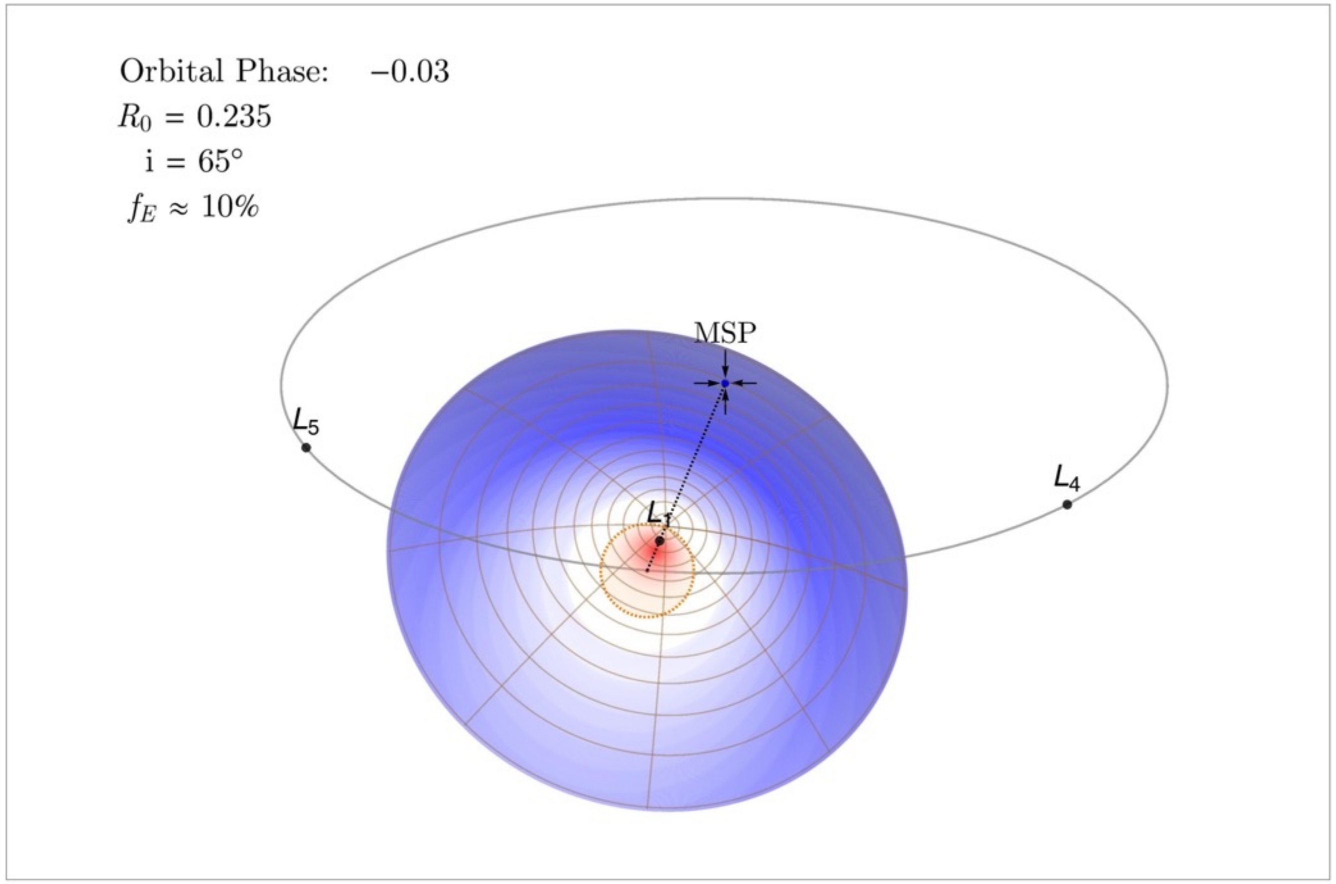
- We model two types of bow shocks, a ”type I” parallel-wind (Wilkin 1996) and “type II” two-spherical-wind shock (Canto et al. 1996) and adopt an optically thick model for eclipses (Rasio et al. 1989)
- One-to-one coupling between eclipse fraction and orbital inclination i for a shock with stand-off 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 $\zeta \approx$ i

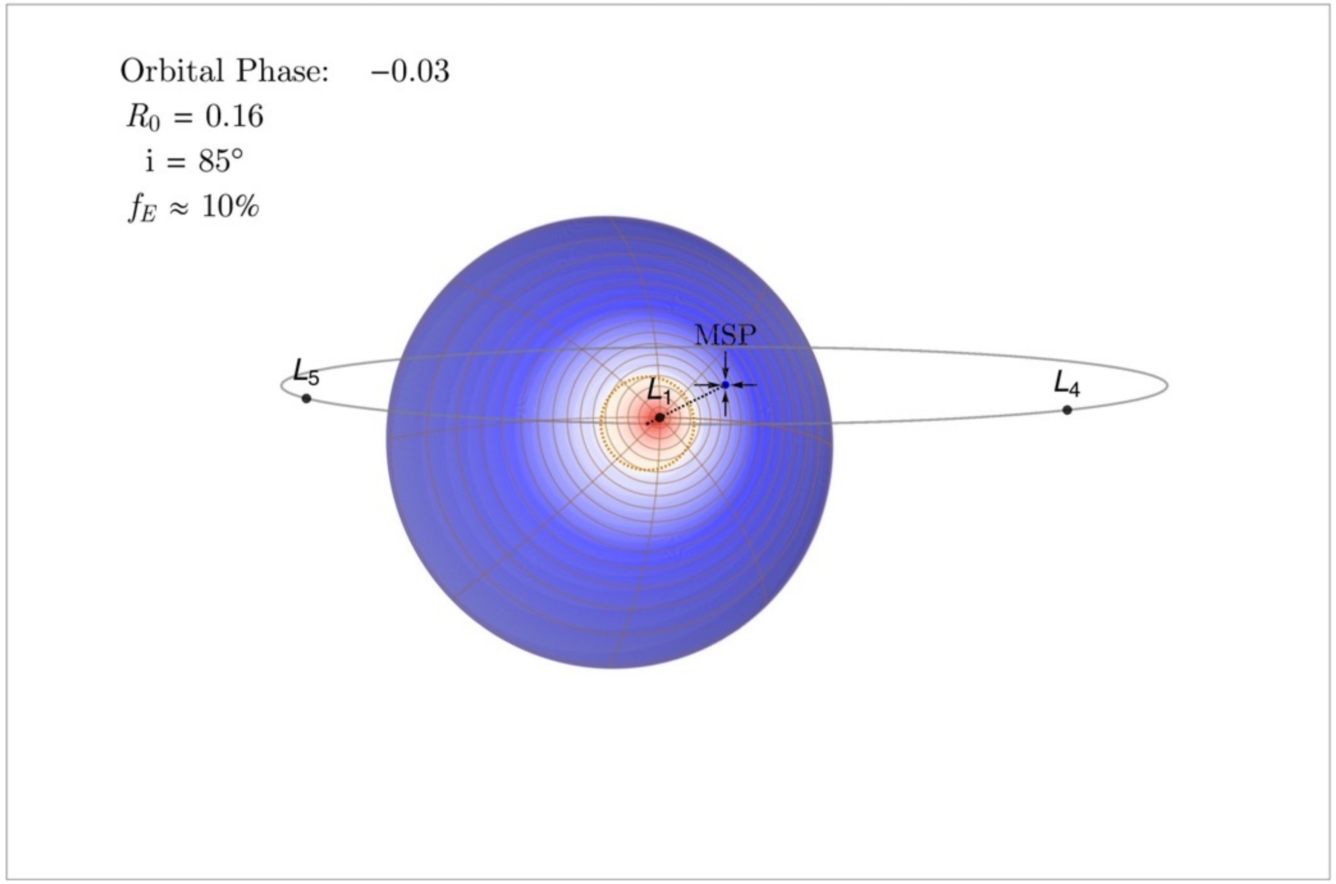


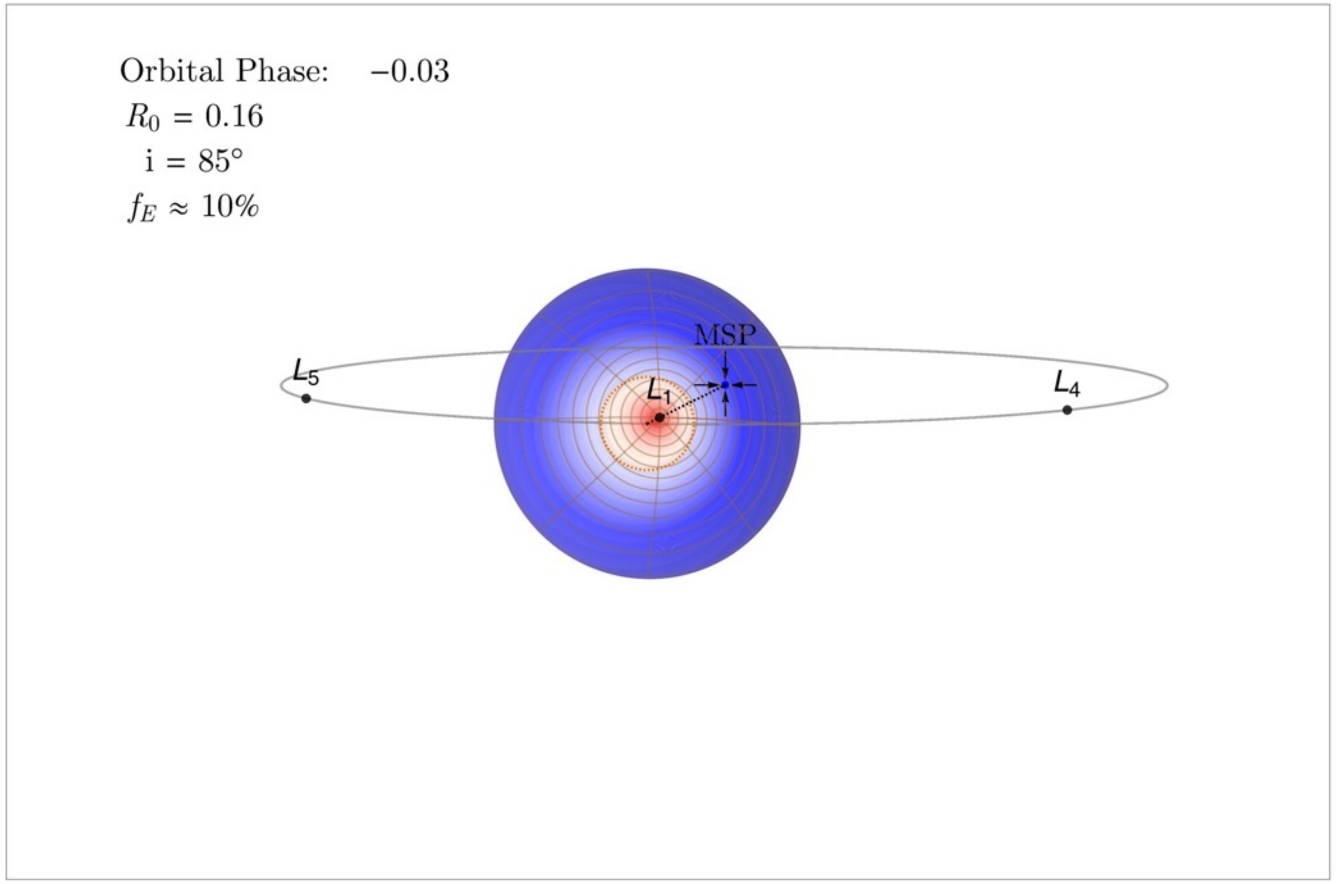


Orbitally Modulated Doppler Boosting

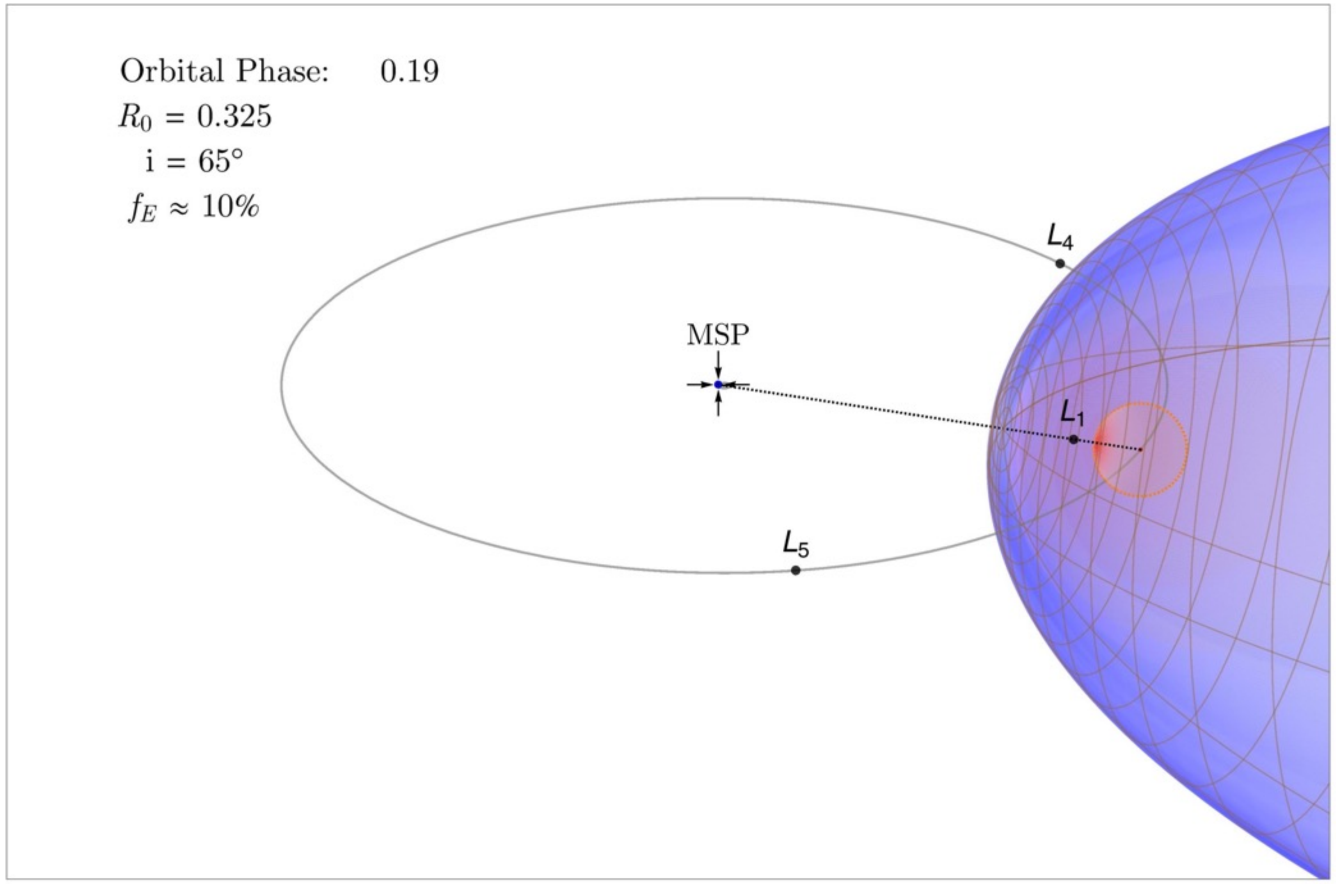


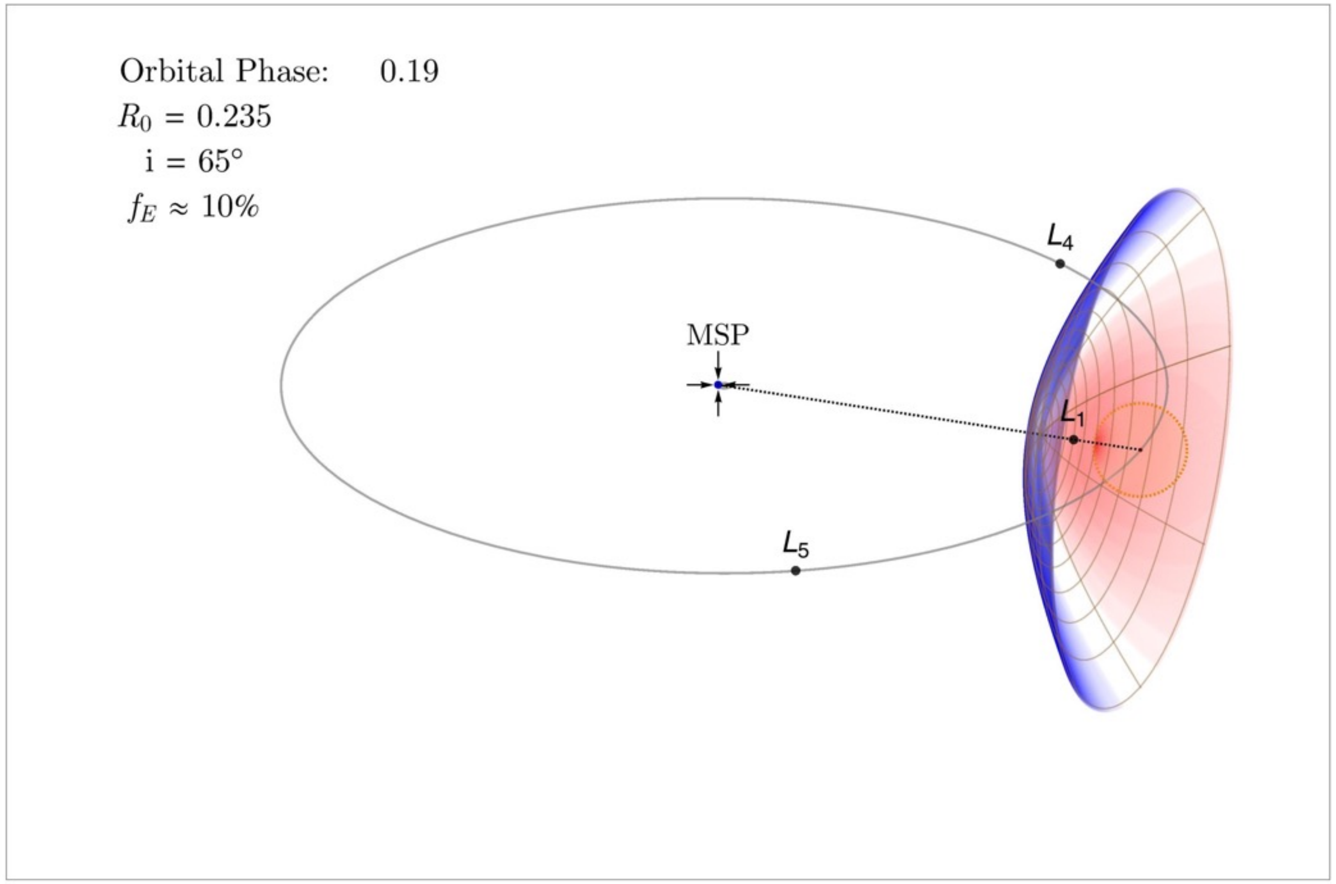


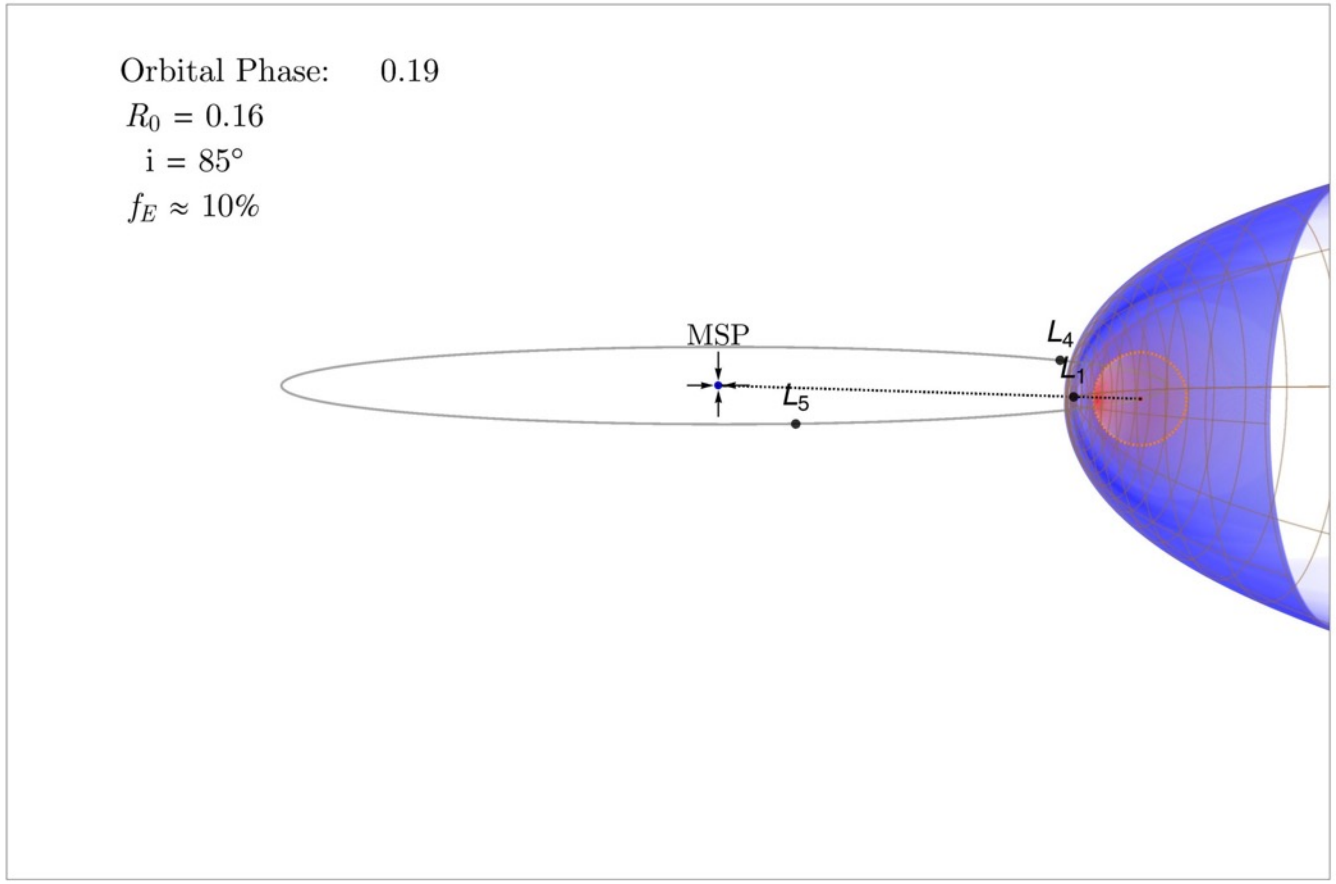


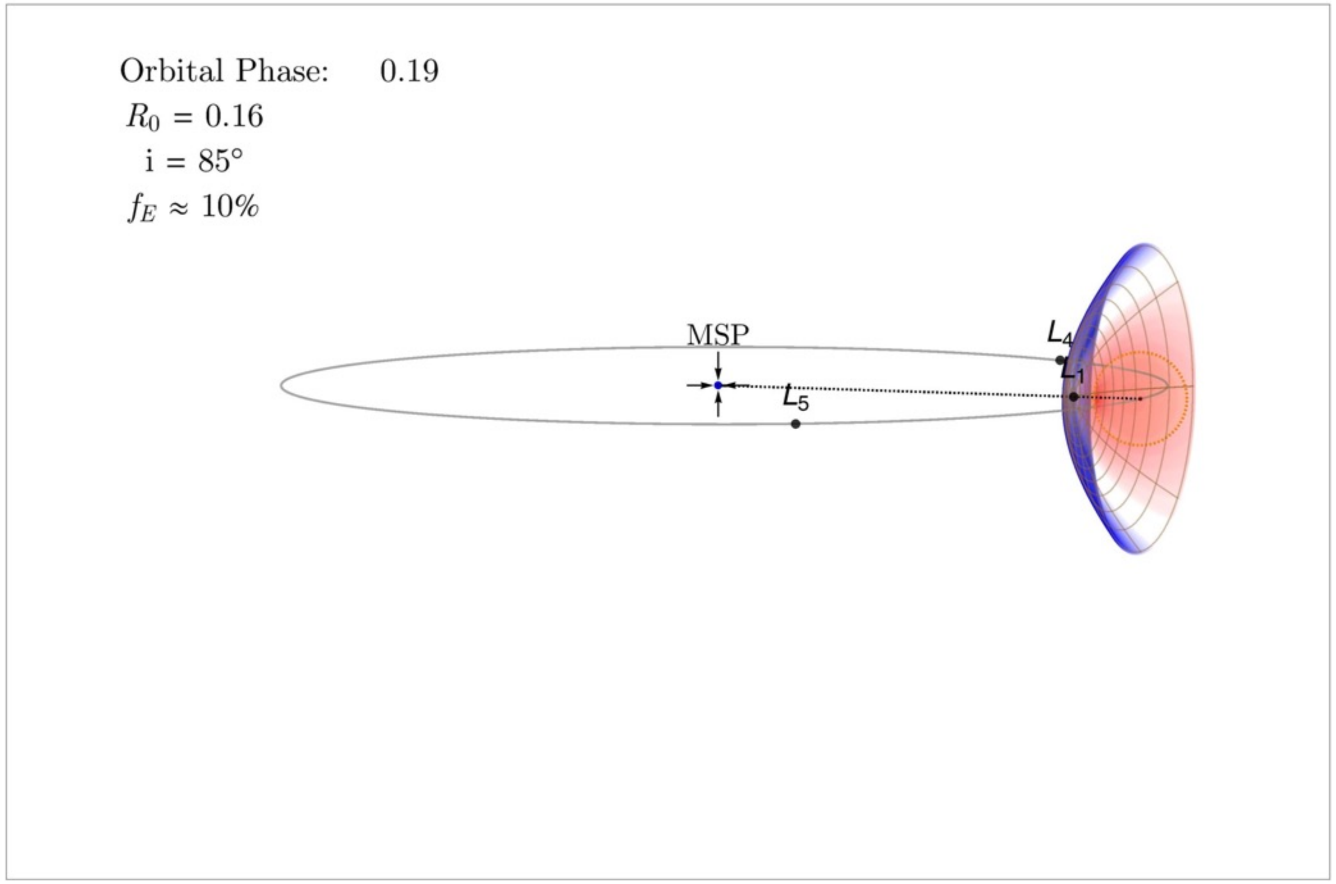


Orbitally Modulated Doppler Boosting



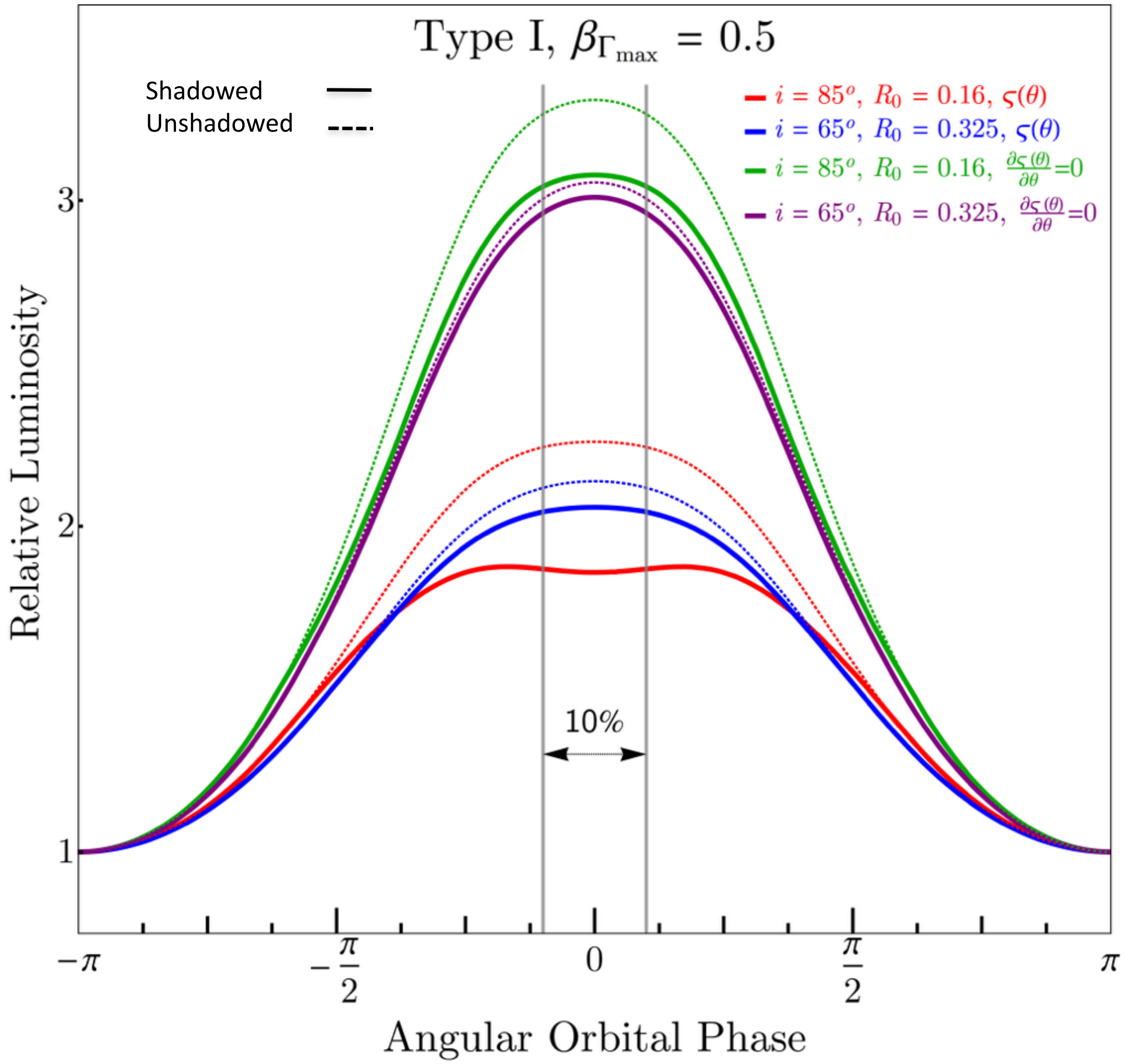


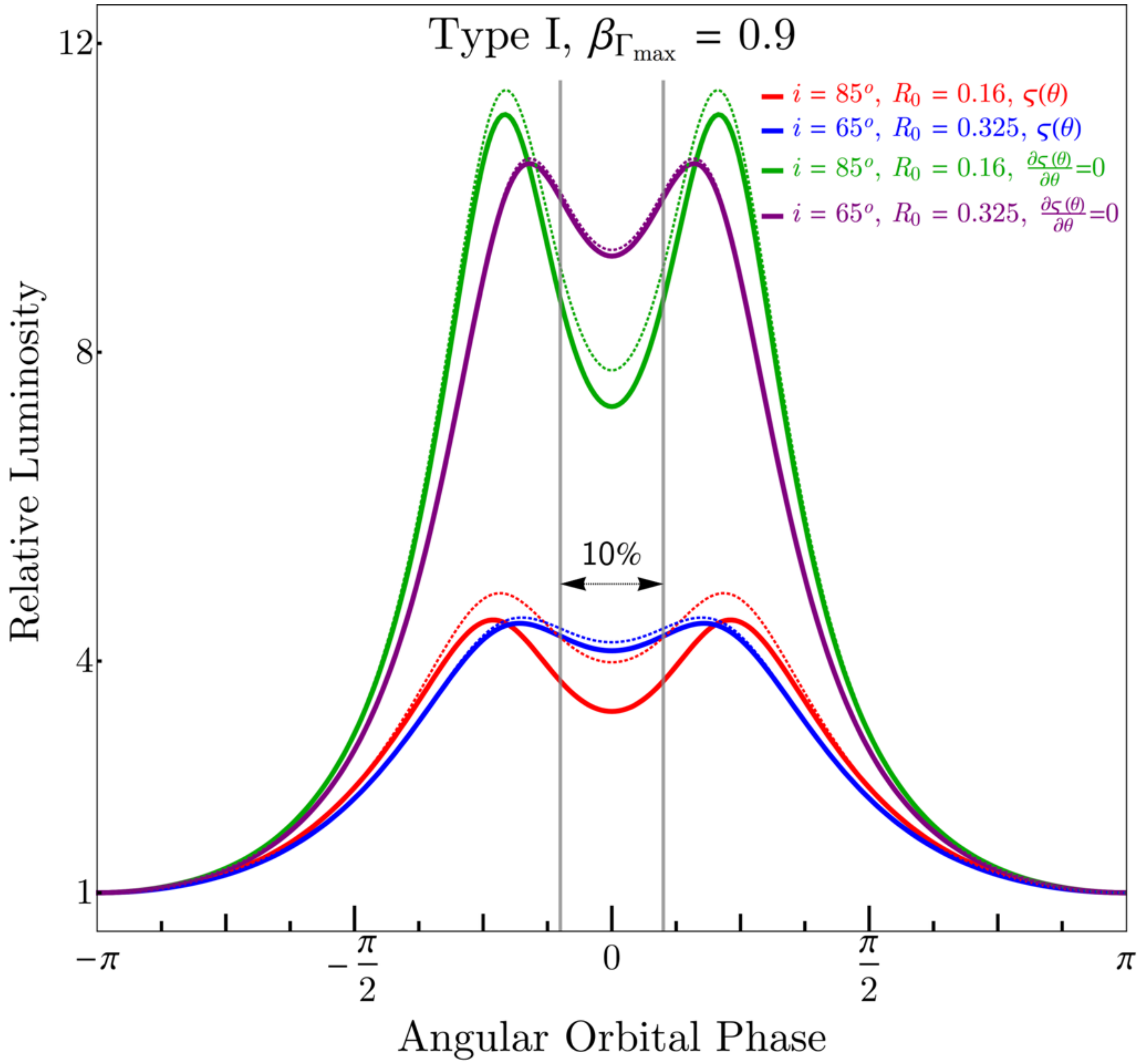




Orbitally Modulated Synchrotron Emission

- 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

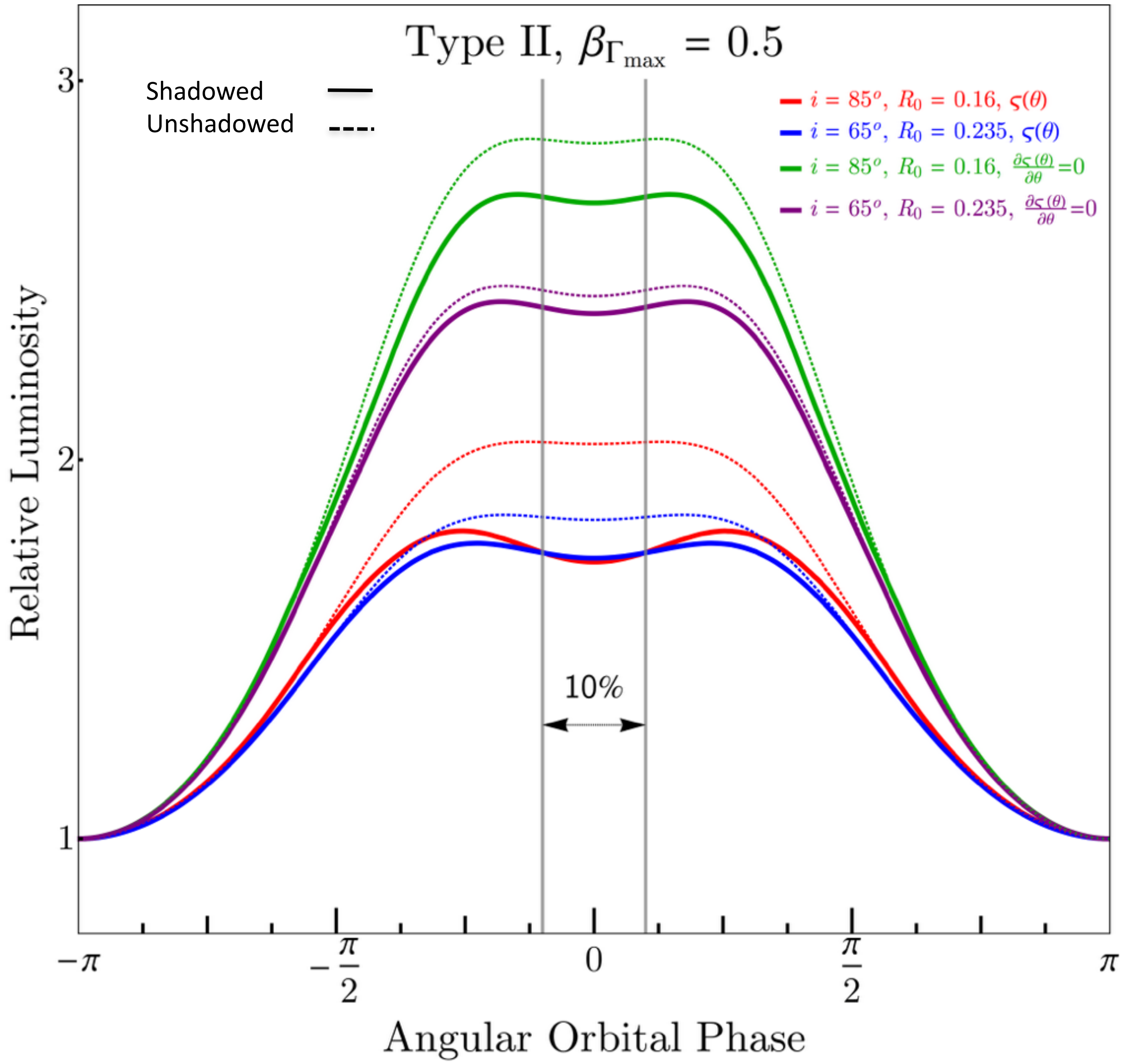


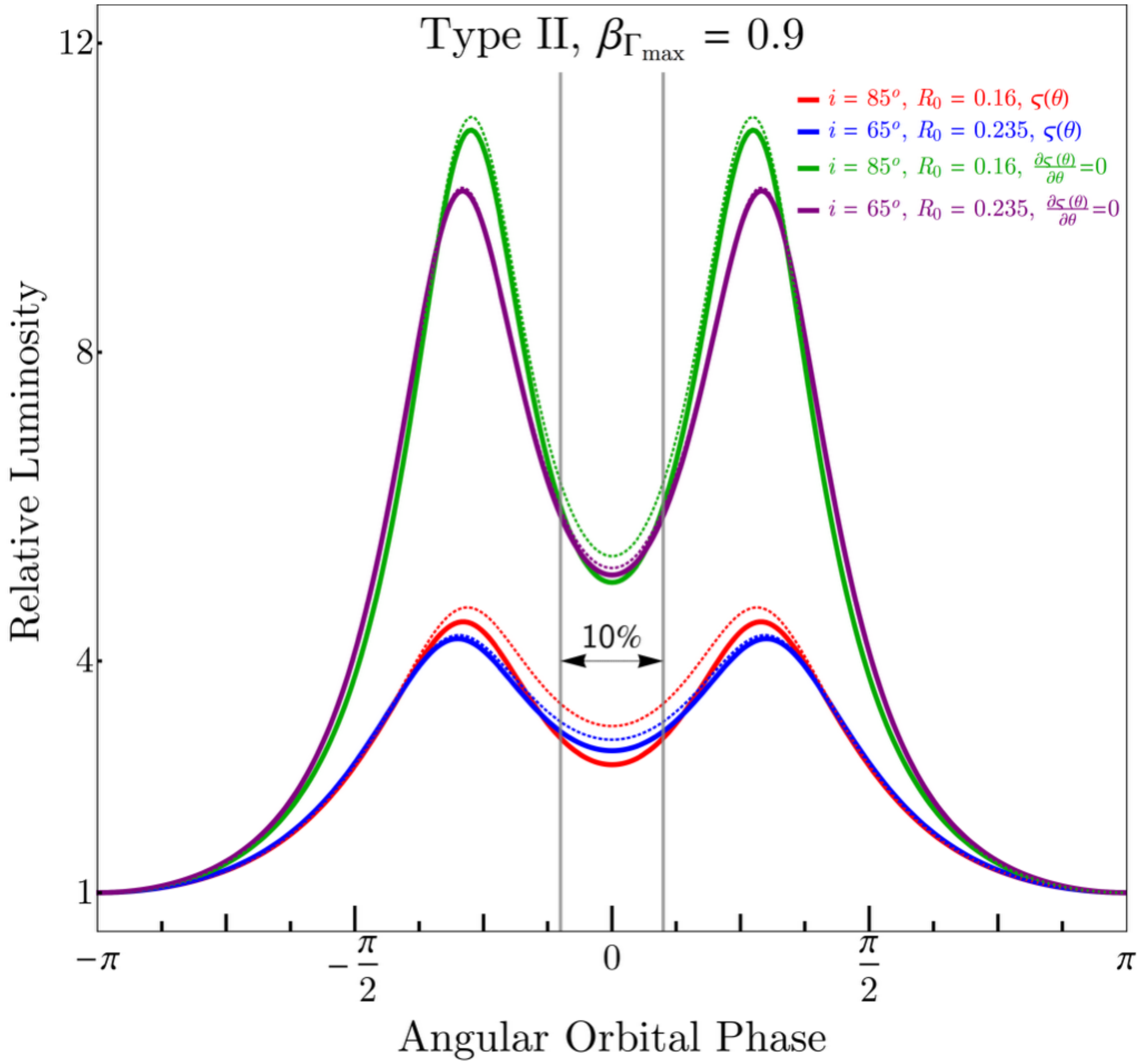


Orbitally Modulated Synchrotron Emission

- 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

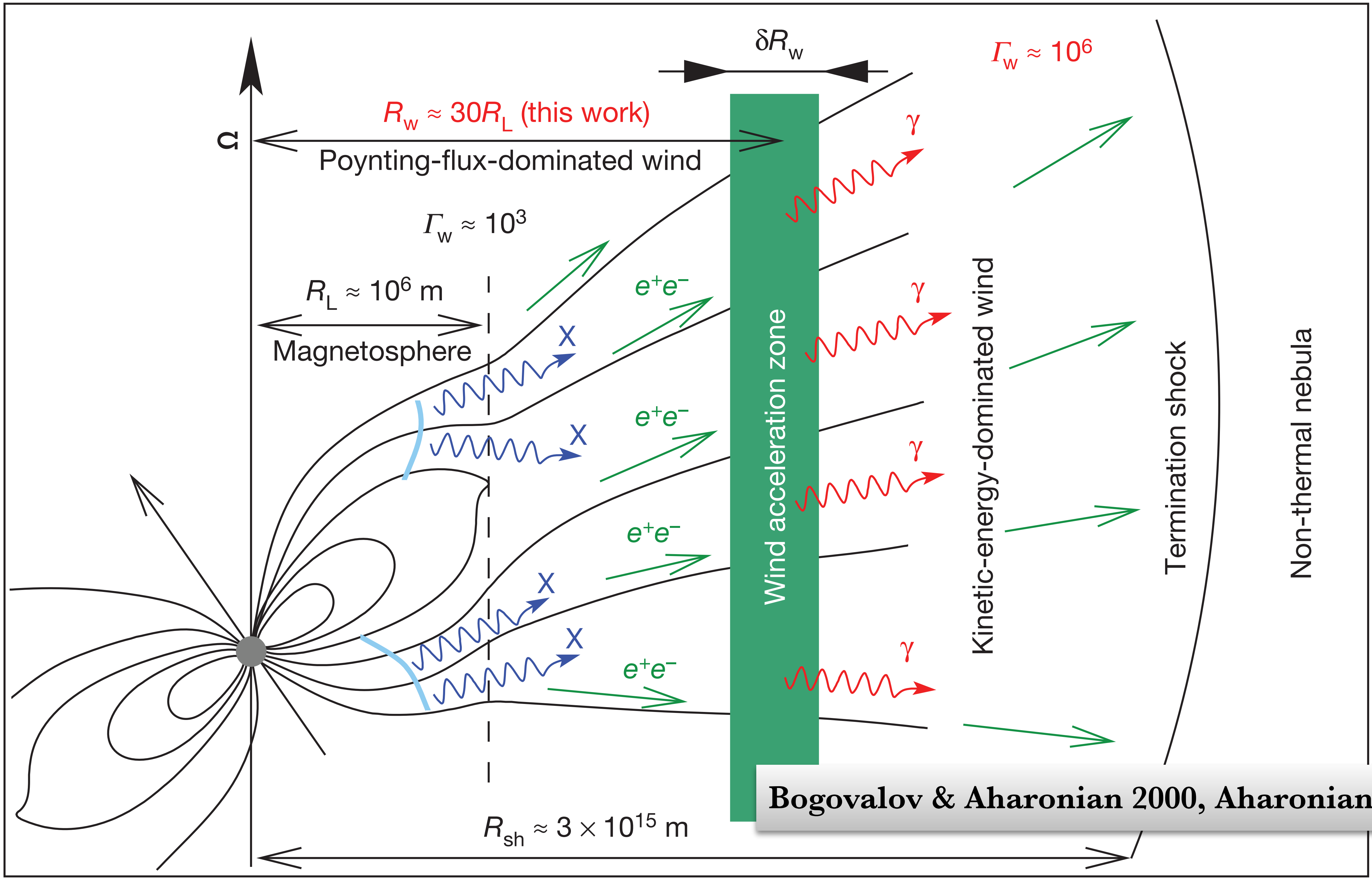
- Optical non-thermal synchrotron emission (and orbitally-modulated *polarization*) could exist depending on the accelerated electron spectrum and level of plasma turbulence in the downstream B

- Companion magnetosphere may influence B or support shock ==> kilogauss fields might be probed with high-resolution spectroscopy of Zeeman line broadening in the IR/optical for some redbacks

- 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 (e.g. Dubus 2013), but much more compact
- Accelerated electrons: shock and possibly upstream pulsar wind



Bogovalov & Aharonian 2000, Aharonian et al. 2012

IC γ-ray Observability & Caveats

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

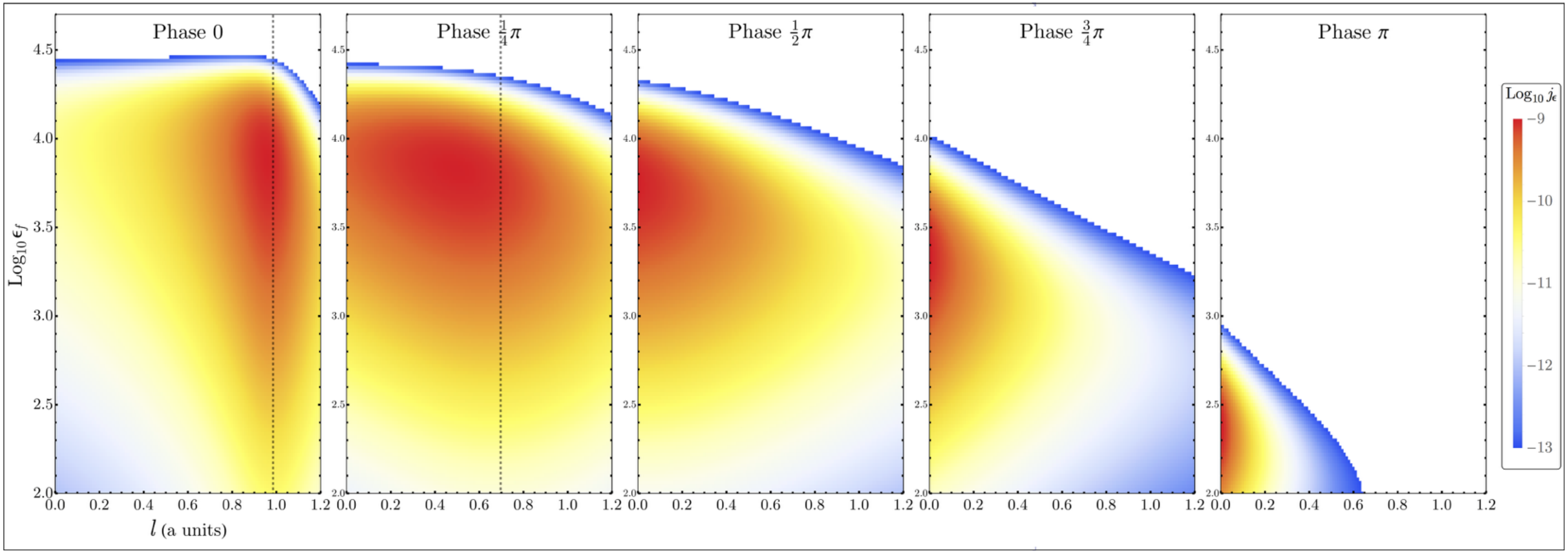
- Orbitally modulated γ-ray emission has been claimed for B1957+20 (Wu et al. 2012) and J1311-3430 (Xing & Wang 2015) but are unconfirmed (6-10 years, Pass 8 and ToOs to optical flares may help)

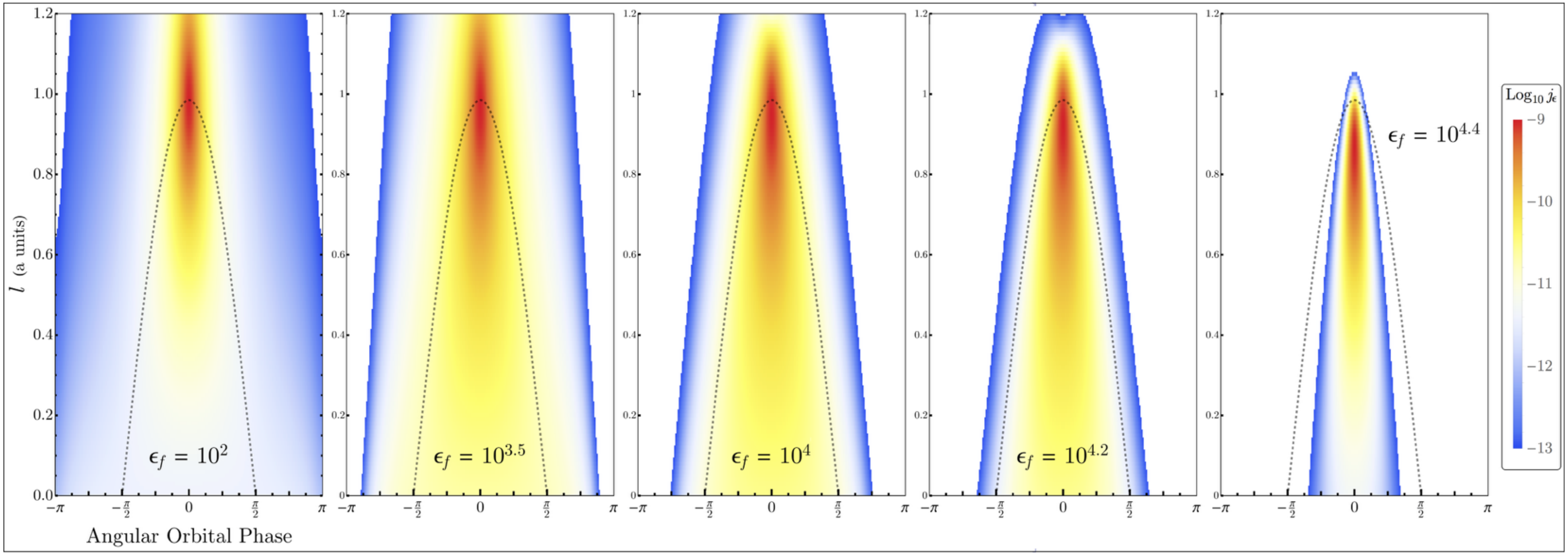
- For most systems, the IC optical depth < 1 on orbital lengthscales $a \sim 10^{11}$ cm, but may exceed unity for hot companions or flaring states where $T_{hot} > 10^4$ K

- Optimistically — IC luminosity ~ $\sigma_T n_\gamma a$ x ηEdot ~ $\eta 10^{33}$ erg/s ==> ~ $\eta 10^{-11}$ 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

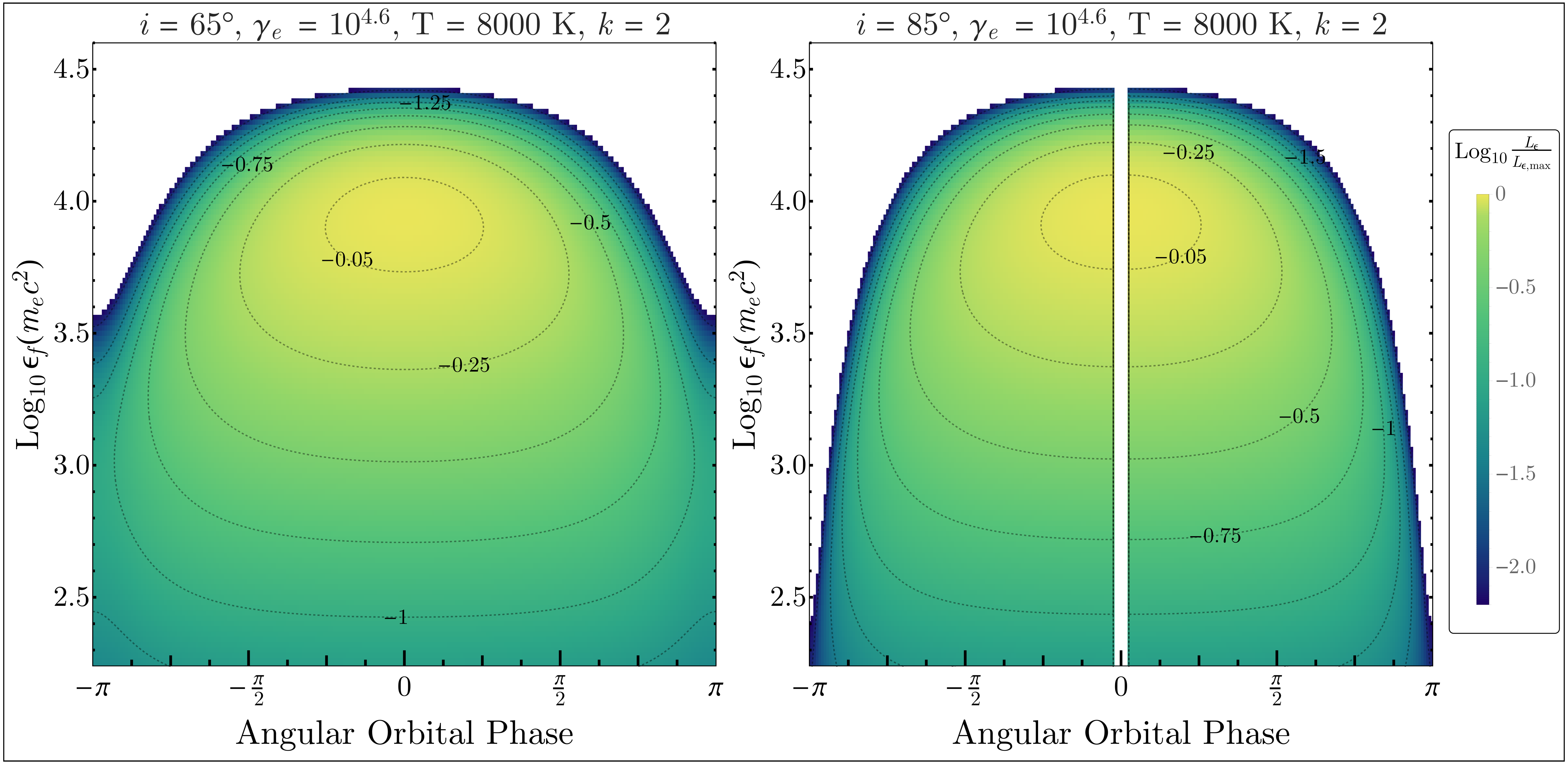
Volume Normalized IC Emissivity - B1957+20





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



Future

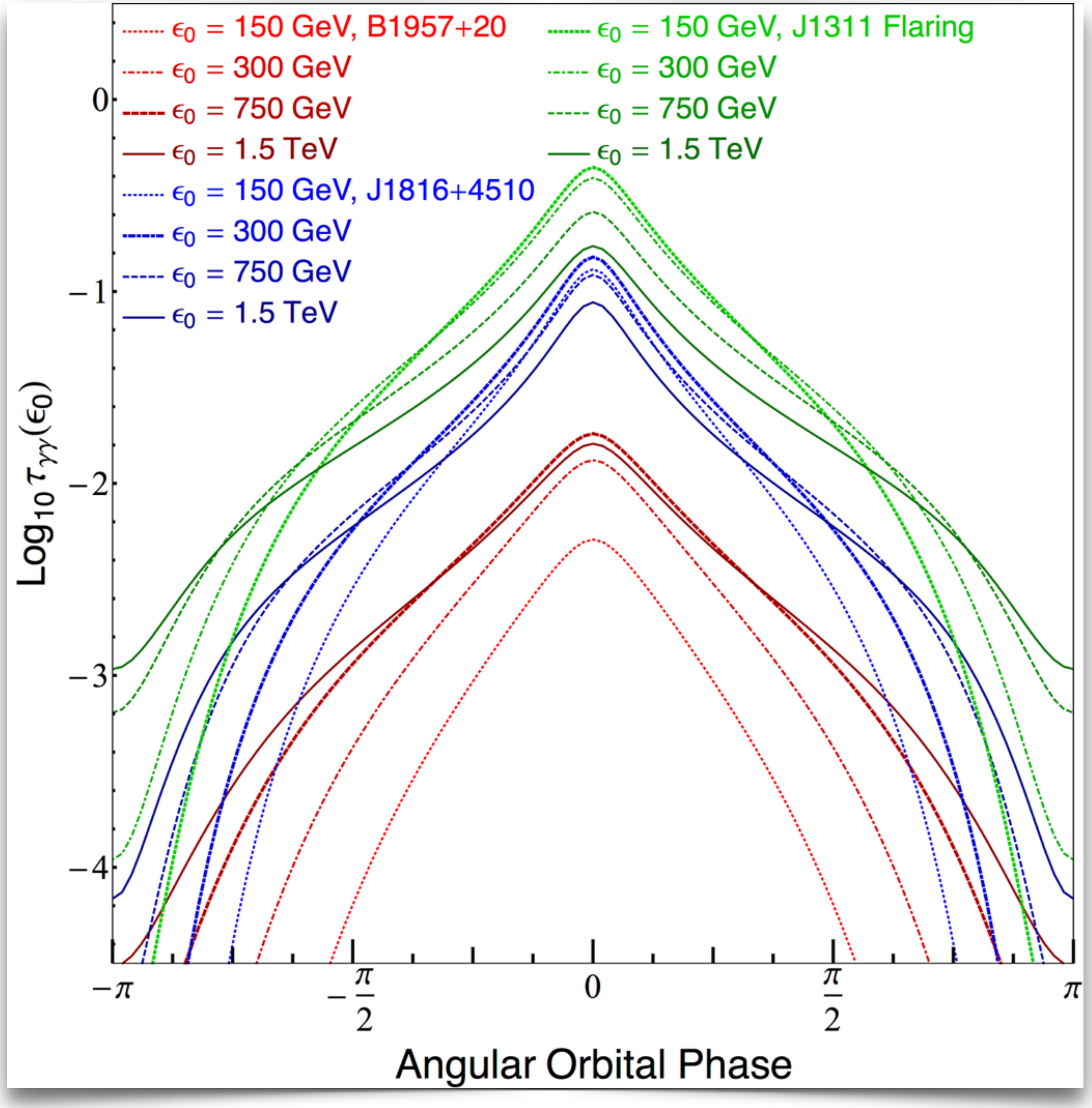
- Steady-state particle transport along the shock and self-consistent synchrotron light curves
- Additional anisotropic IC components and SEDs
- Orbital motion and sweepback effects
- Application to more black widow and redback systems
- Multiwavelength studies are critical for understanding these systems
- Stay tuned!

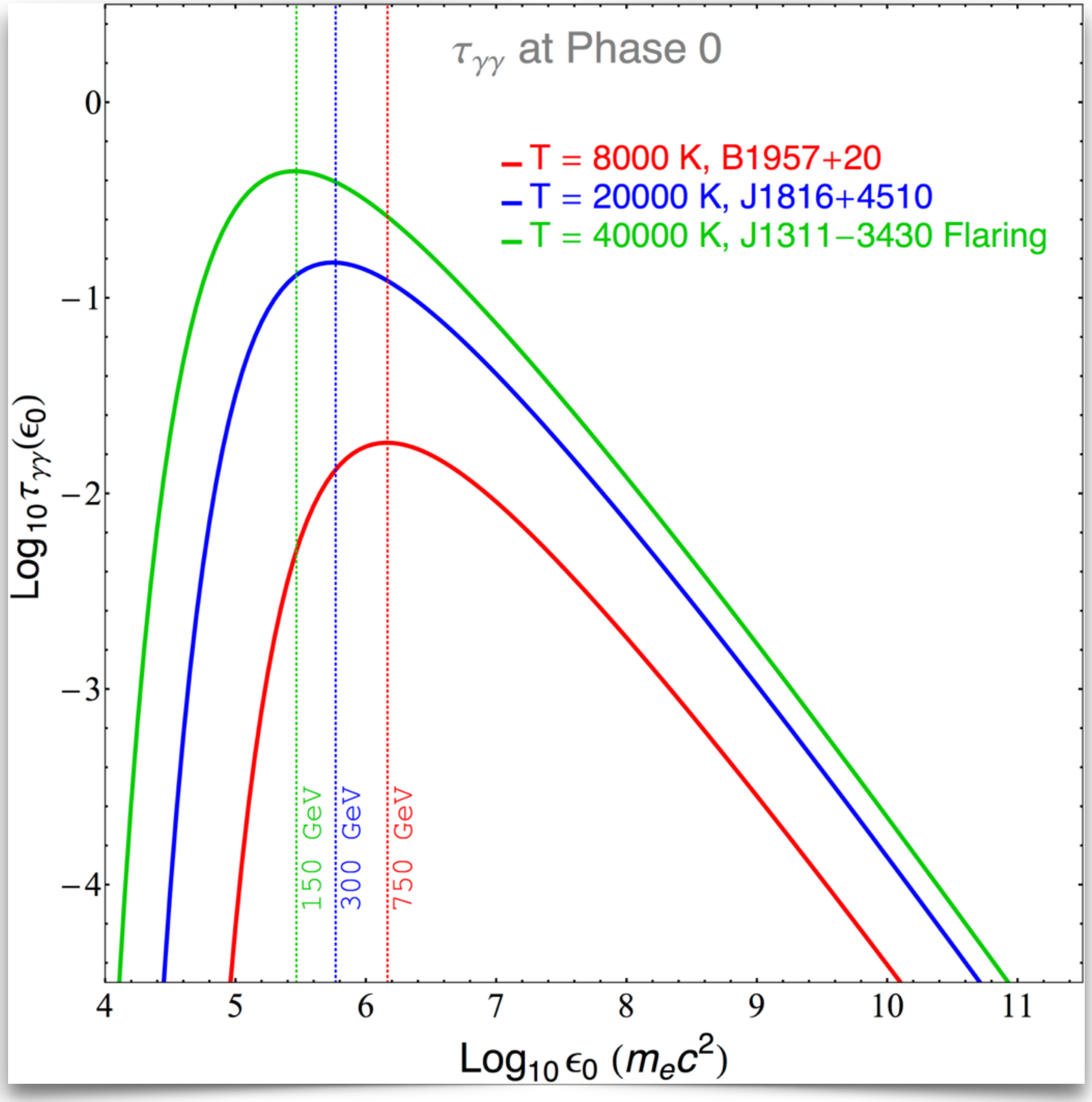
Backup Slides

$\gamma\gamma$ Absorption

- 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} ~ 40000 K

- ε_0 - the energy of the outgoing VHE photon, emitted at stagnation point towards observer

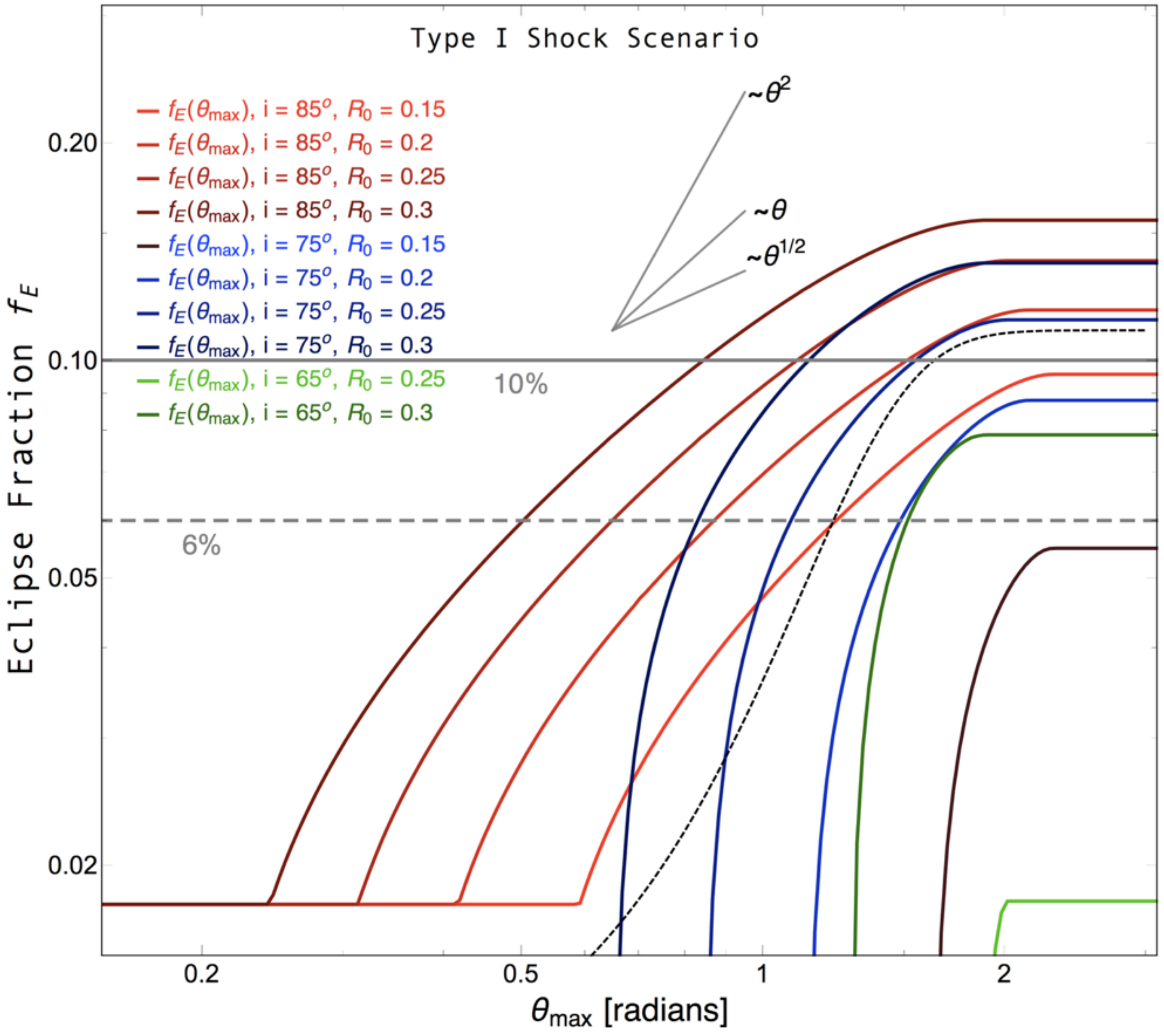


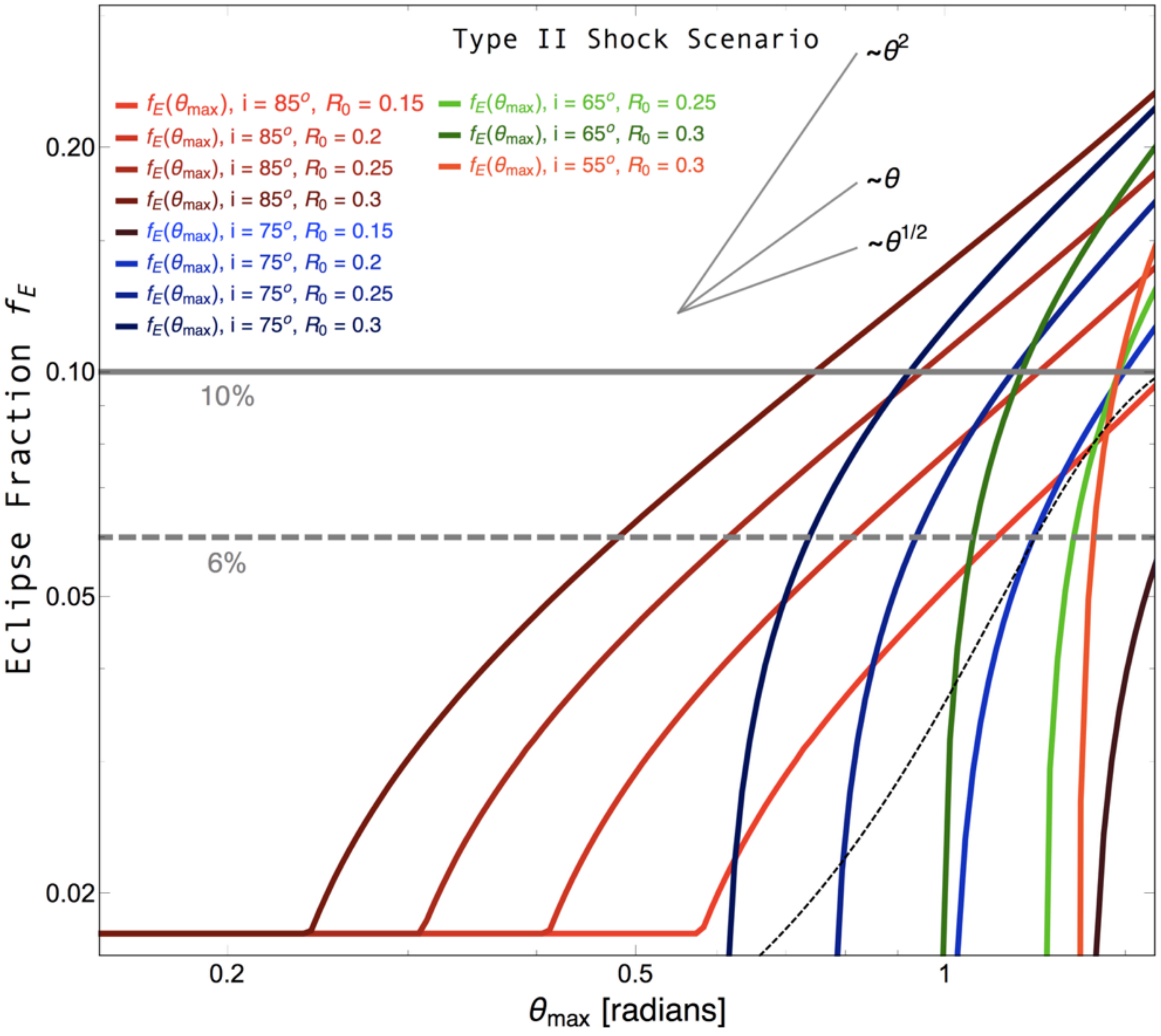


Growth Curve of Radio Eclipses

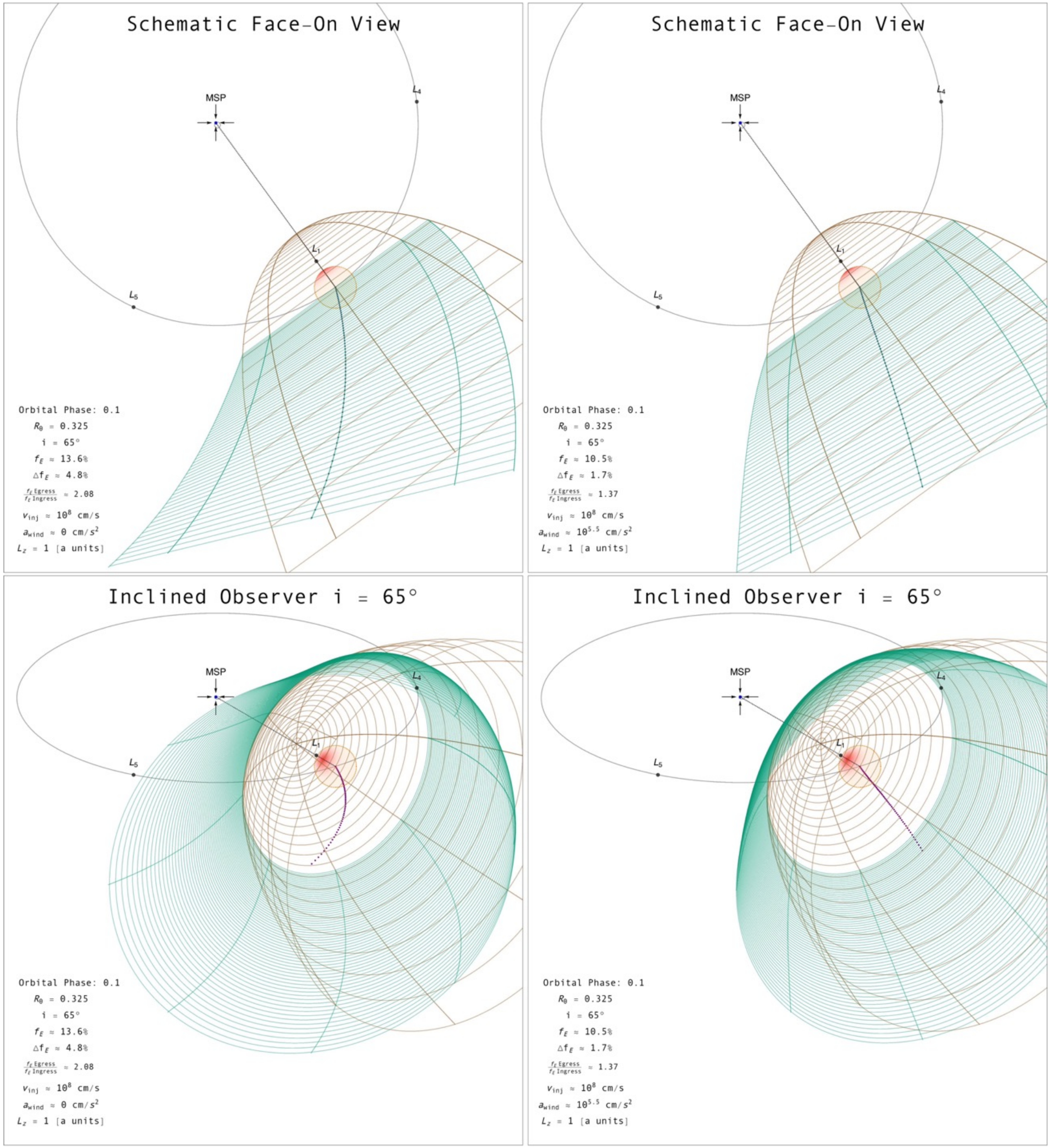
- For the eclipses at ingress, the frequency dependence of the eclipse width can give insight into the spatial dependence of the turbulent plasma and absorption causing the eclipses

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 $\Sigma(\theta) \sim g(\theta)^{-m/n}$



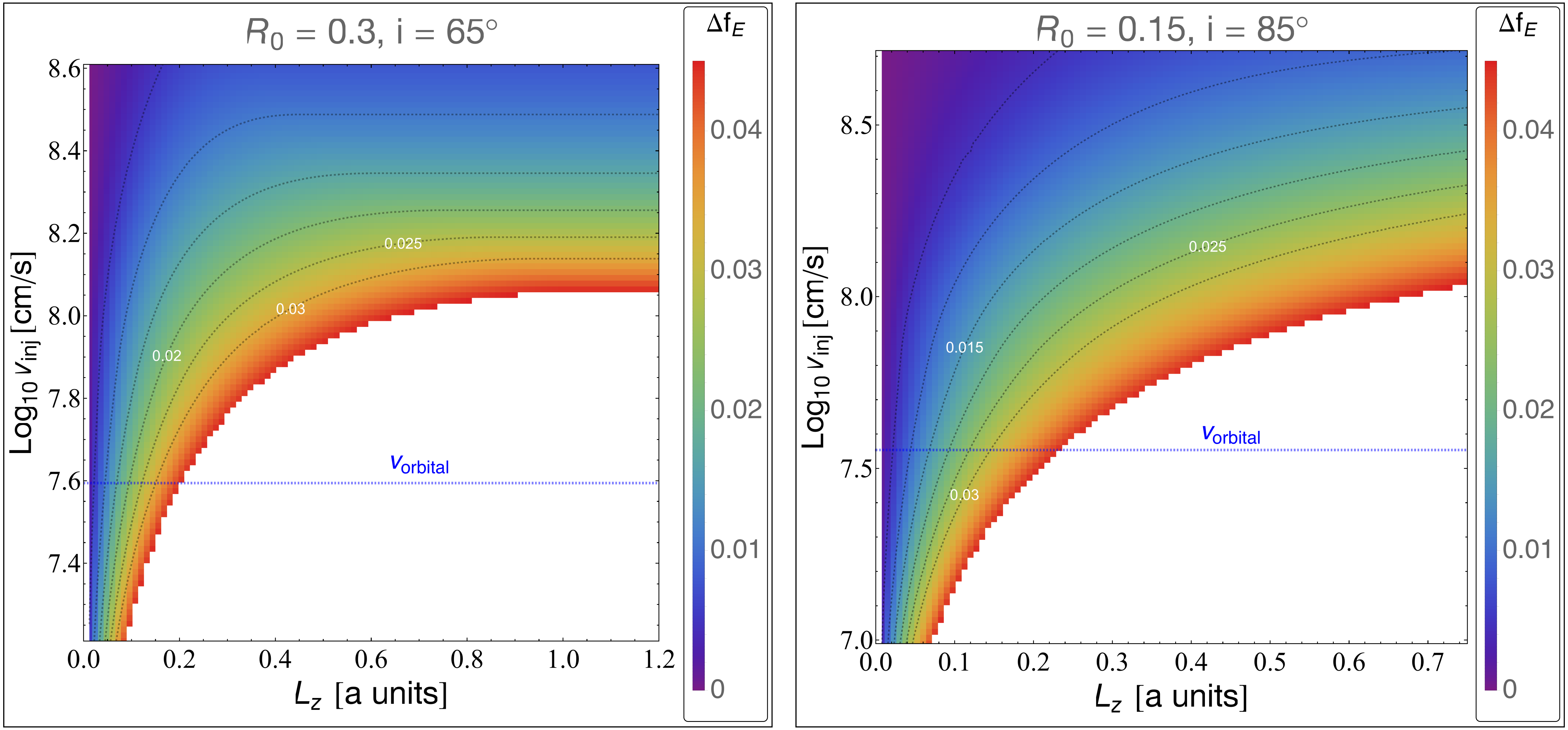


Orbital Sweepback — Ballistic Model



Orbital Sweepback Parameter Exploration

- $\Delta f_E =$ Egress - Ingress eclipse asymmetry
- White — excluded region for B1957+20



Shocked companion wind cometary tail length versus velocity

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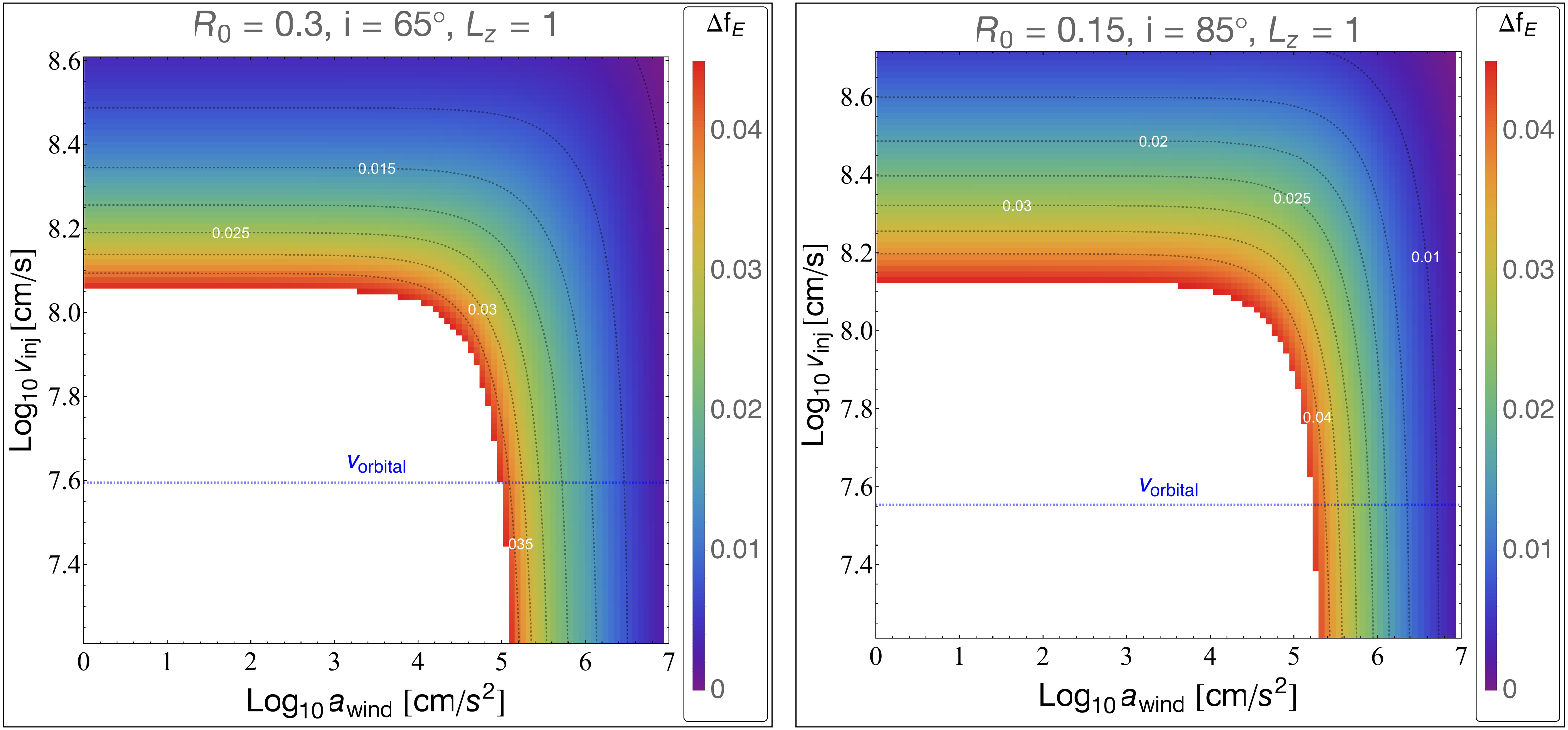

Shocked companion wind cometary tail velocity versus pulsar wind acceleration