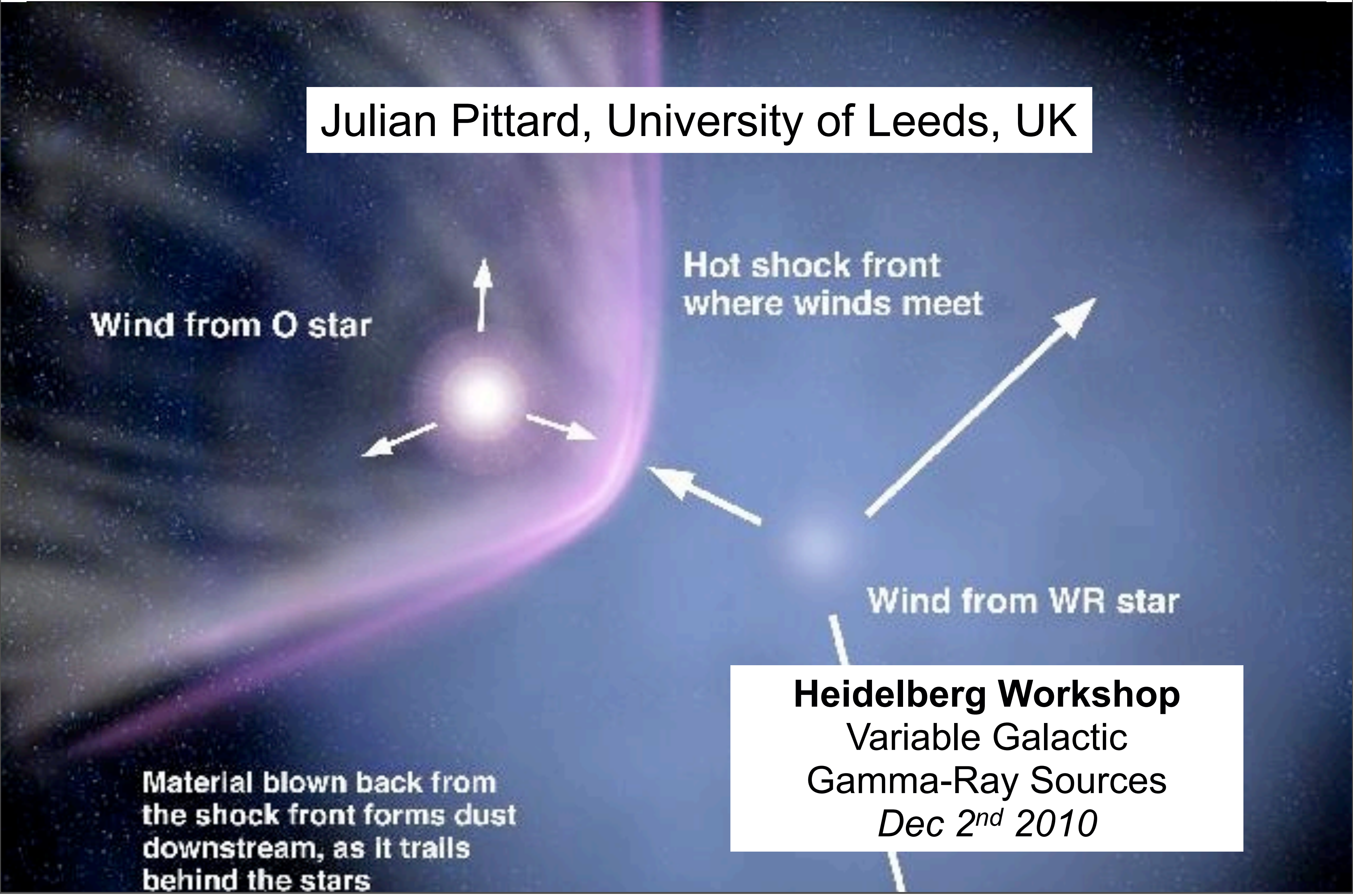
Massive Star Colliding Winds: Spectral and Variability Behaviour

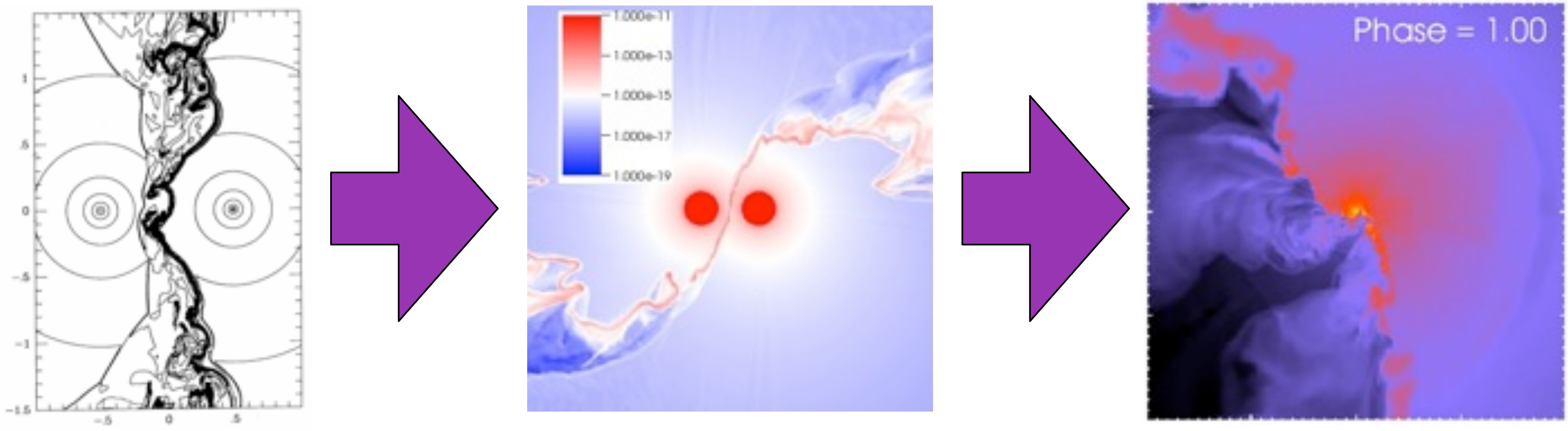
Julian Pittard, University of Leeds, UK



Heidelberg Workshop
Variable Galactic
Gamma-Ray Sources
Dec 2nd 2010

Outline

I. Overview of Dynamical Models and Studies



II. Recent Models of X-ray, Radio, Non-thermal Emission

CWBs are a very diverse population

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System	Orbital Period (d)	Separation (AU)	Density (cm^{-3})	$\chi_{\rm WR}$	$\chi_{\rm O}$
WR 139 (V444 Cyg)	4.2	0.2	$\sim 10^{10}$	<<1	?
WR 11 (γ^2 Vel)	78.5	0.81-1.59	$\sim 10^{9}$	~0.5-1	~250-500
WR 140	2899	~1.7-27.0	$\sim 10^{9}$-10^{7}	~2-50	~150-2000
Eta Car	2024	~1.5-30	$\sim 10^{12}$	<<1	~1-50
WR 147	$>10^{5}$	>410	$\leq 10^{4}$	>30	>1000

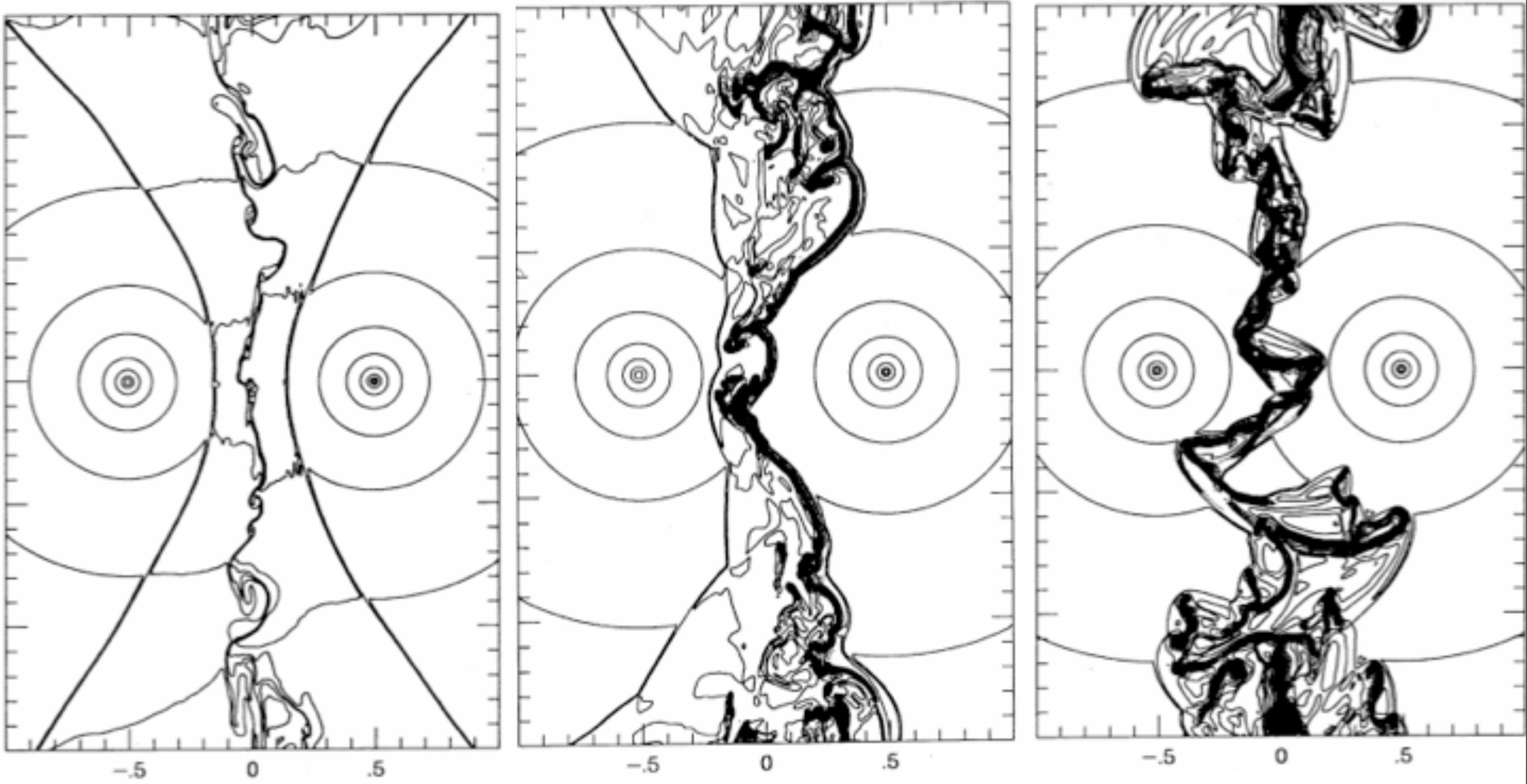
2 different regimes determined by characteristic cooling parameter,

$$\chi = \frac{t_{\rm cool}}{t_{\rm dyn}} \approx \frac{v_8^4 D_{12}}{\dot{M}_{-7}}$$

i) $\chi < 1$ - shocked wind highly radiative, $L_{\rm x} \propto \dot{M} v^2$, faster wind dominates X-ray emission

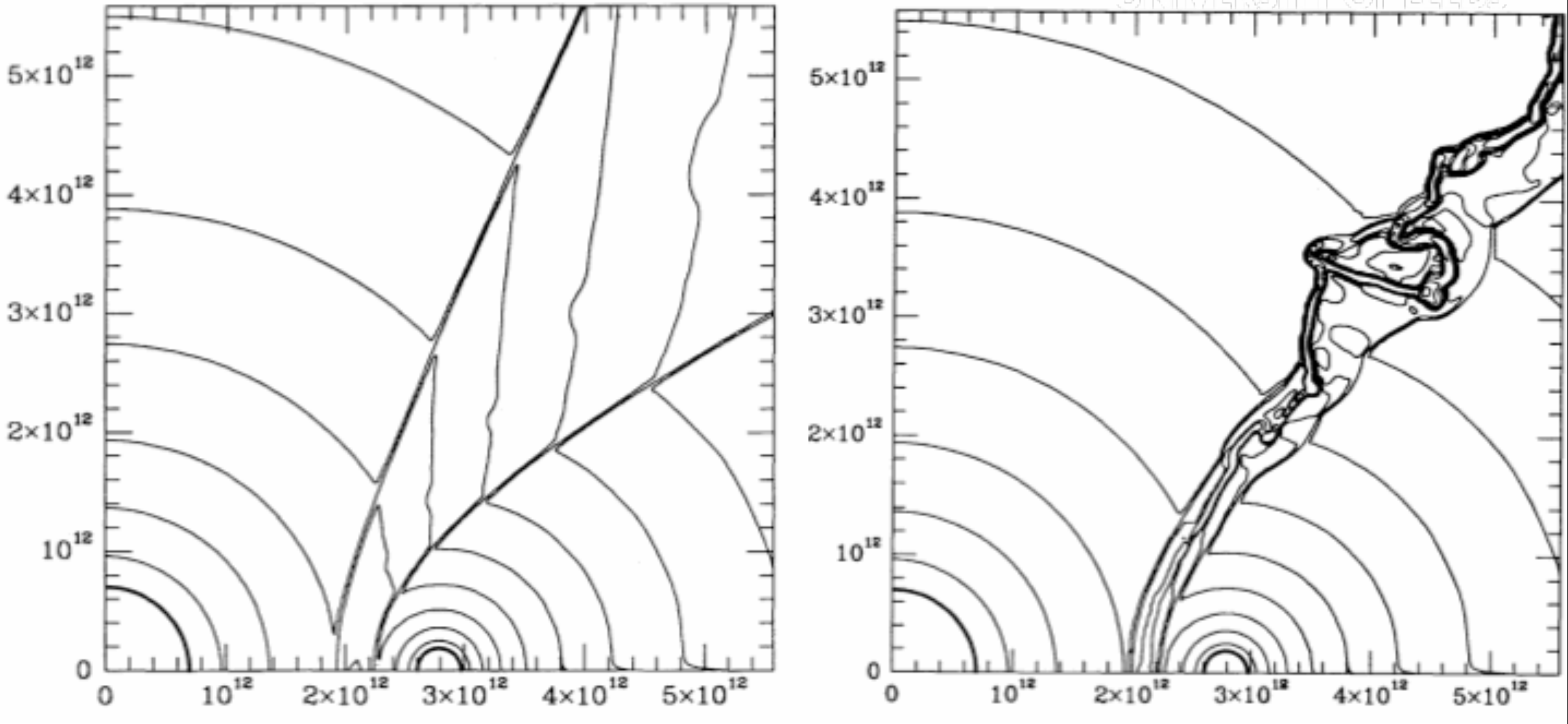
ii) $\chi >> 1$ - cooling mostly due to adiabatic expansion, $L_{\rm x} \propto \frac{\dot{M}^2}{v^{3.2} D}$, stronger wind dominates X-ray emission

Dynamical Instabilities



Stevens et al. (1992)

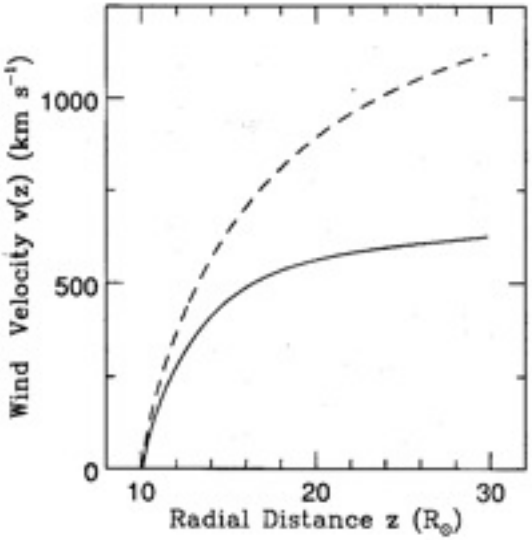
Early models



Stevens et al. (1992)

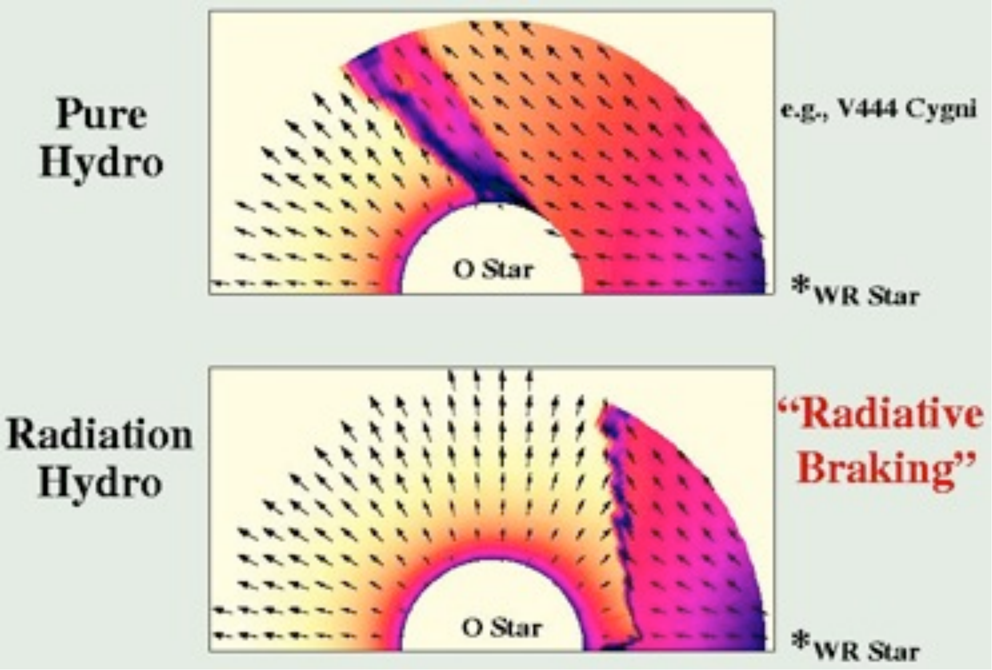
2D, axisymmetric, no orbital motion or radiative driving of winds

Radiative Driving Effects



<u>Radiative Inhibition</u> (Stevens & Pollock 1994)

- Pre-shock velocities always decrease
- $\dot{M}$ can increase or decrease (but reflection needs to be considered!)

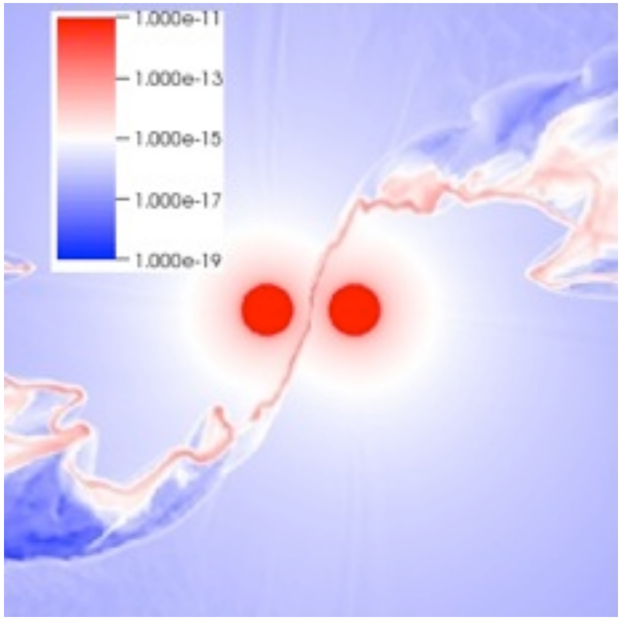


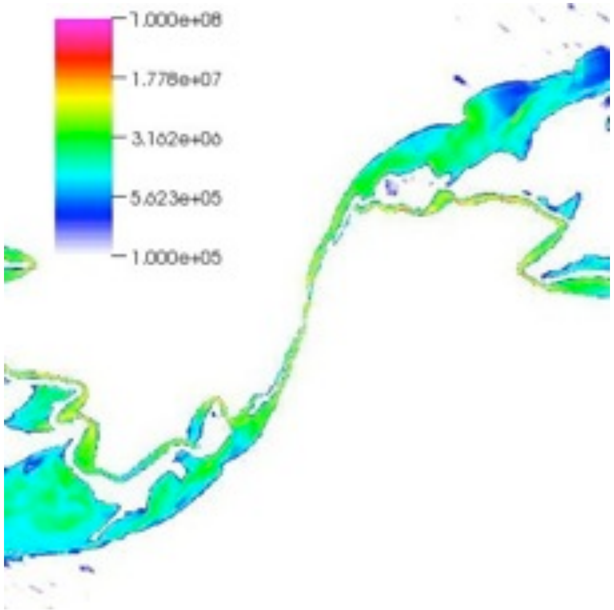
<u>Radiative Braking</u>

(Owocki & Gayley 1997)

- More powerful than inhibition
- Highly non-linear to effective opacity of the wind

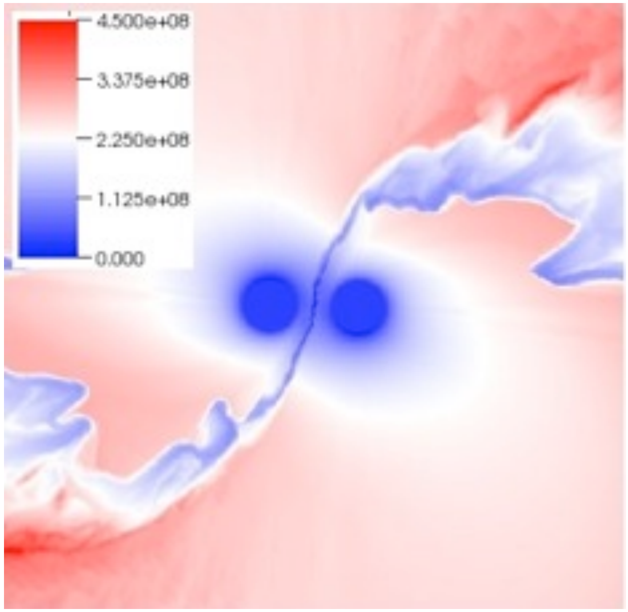
Structure of the Wind Collision Region





O6V + O6V, P=3d,
Dsep = 35 Rsun
$\chi \ll 1$

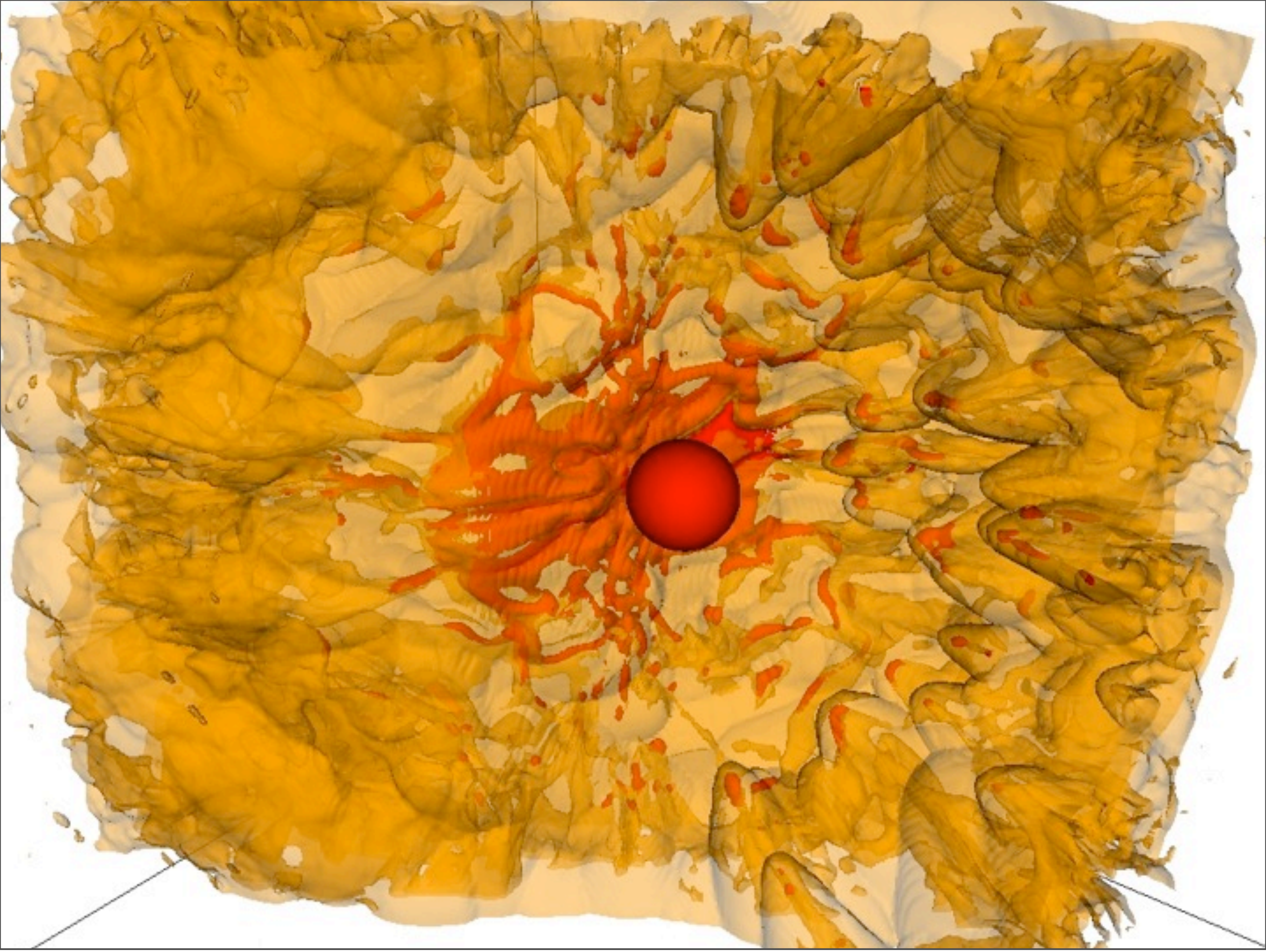
Pittard (2009)



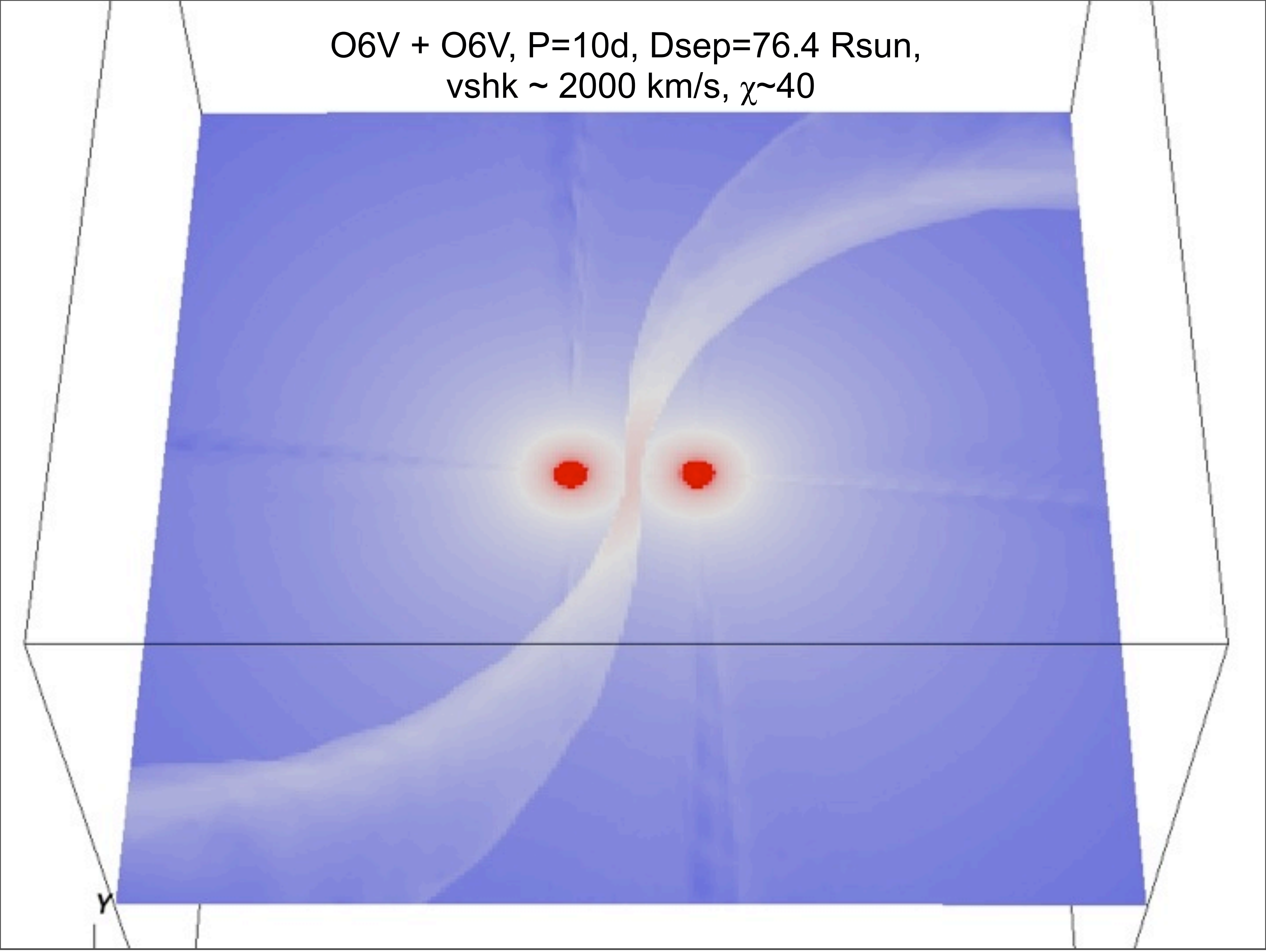
Cold plasma inside WCR

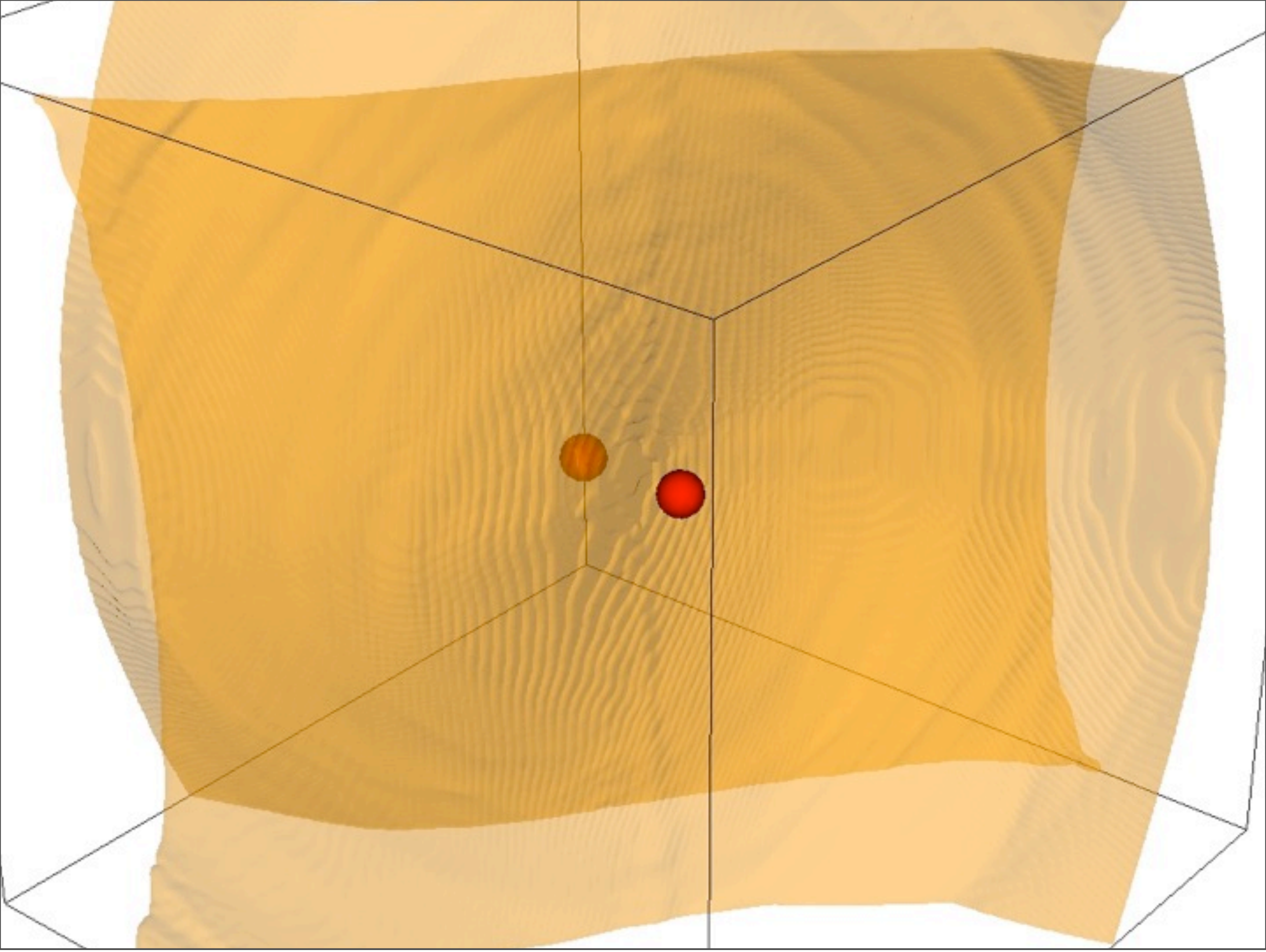
Wind speeds higher where radiative flux reinforced, relatively smaller in shadows behind stars

High inertia causes the dense shell to move to the trailing edge of the WCR



O6V + O6V, P=10d, Dsep=76.4 Rsun, vshk ~ 2000 km/s, χ~40





Behaviour of the WCR in an eccentric system

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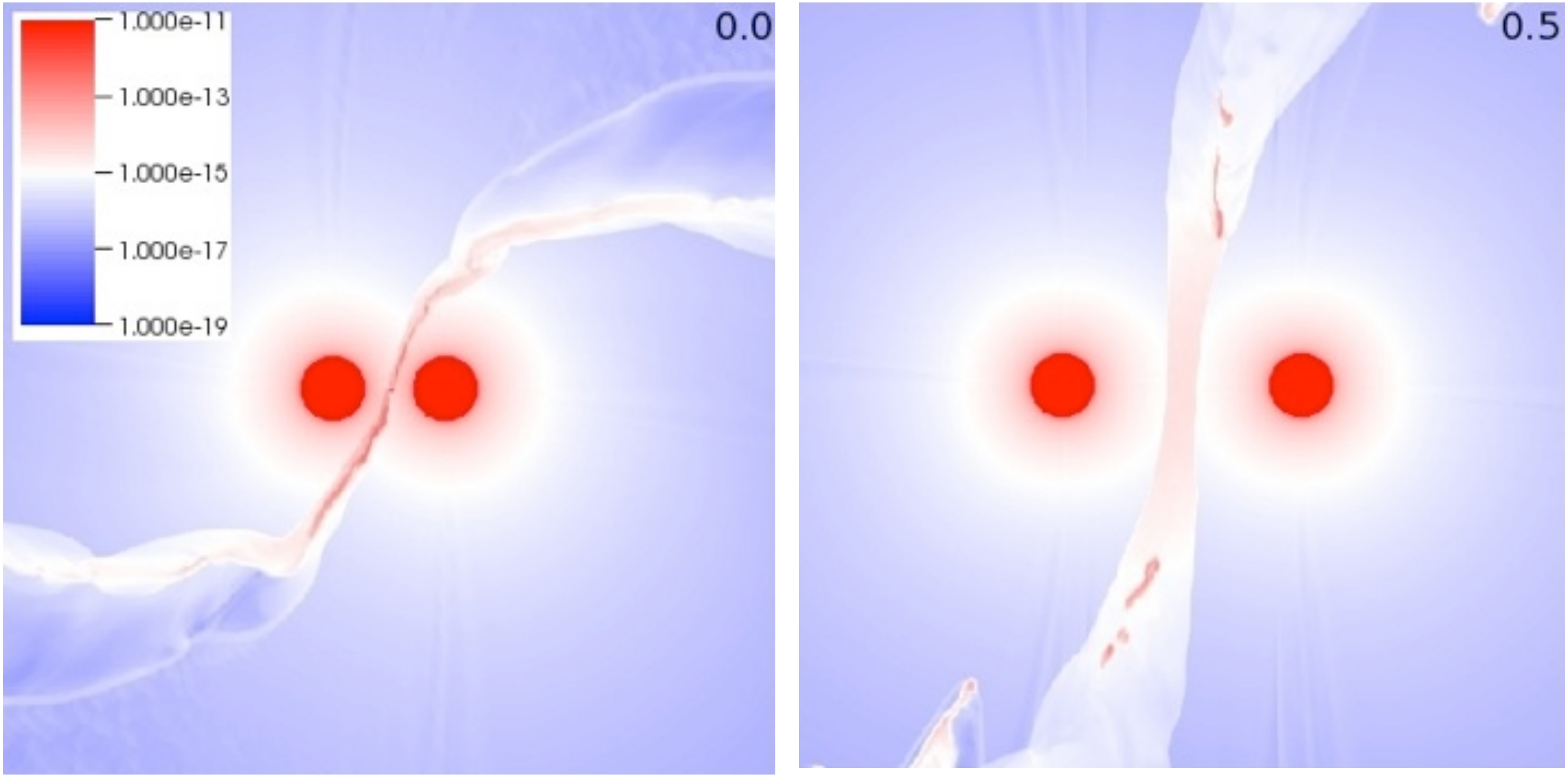
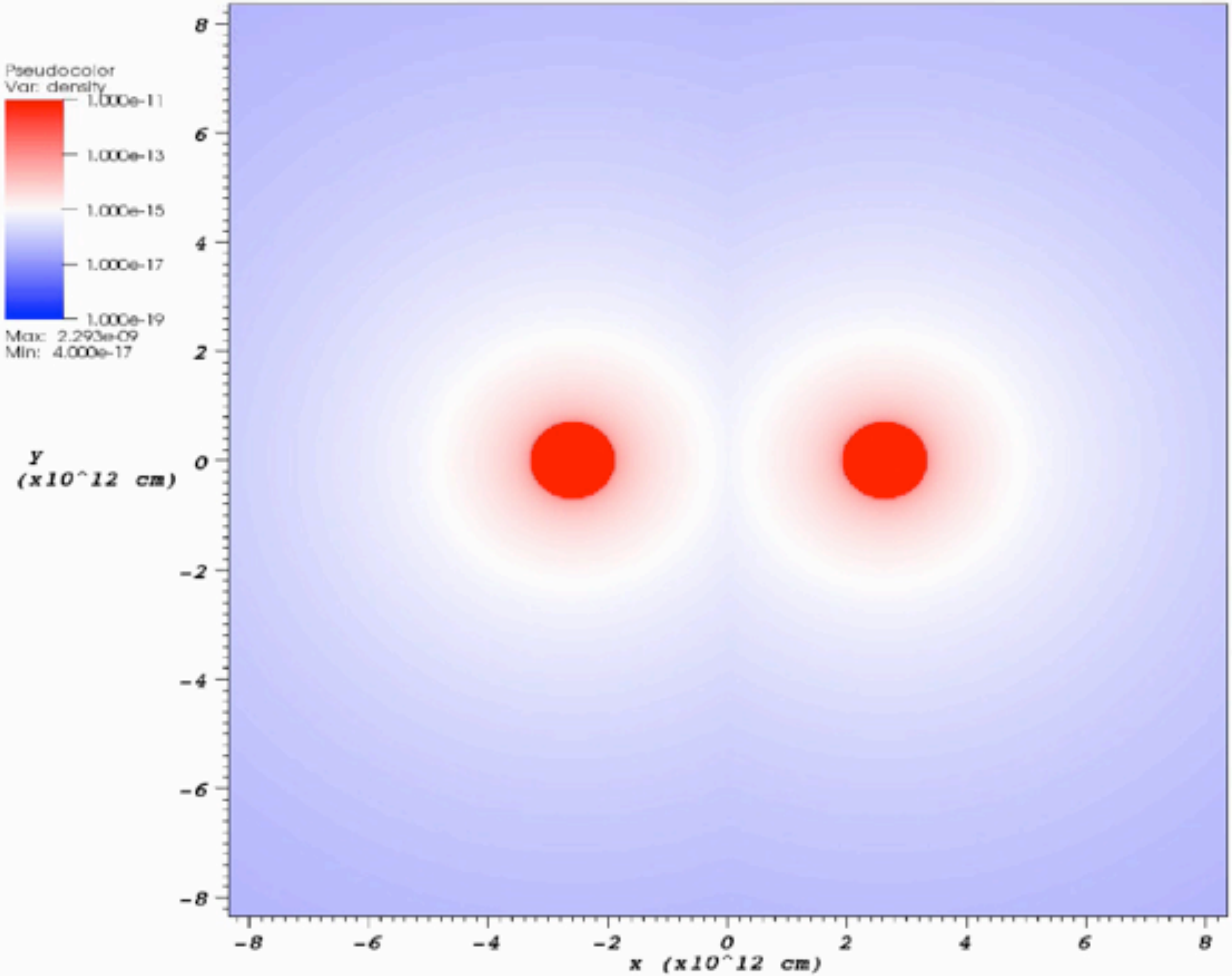
O6V + O6V, P=6.1d, dsep = 35-75 Rsun, e=0.36



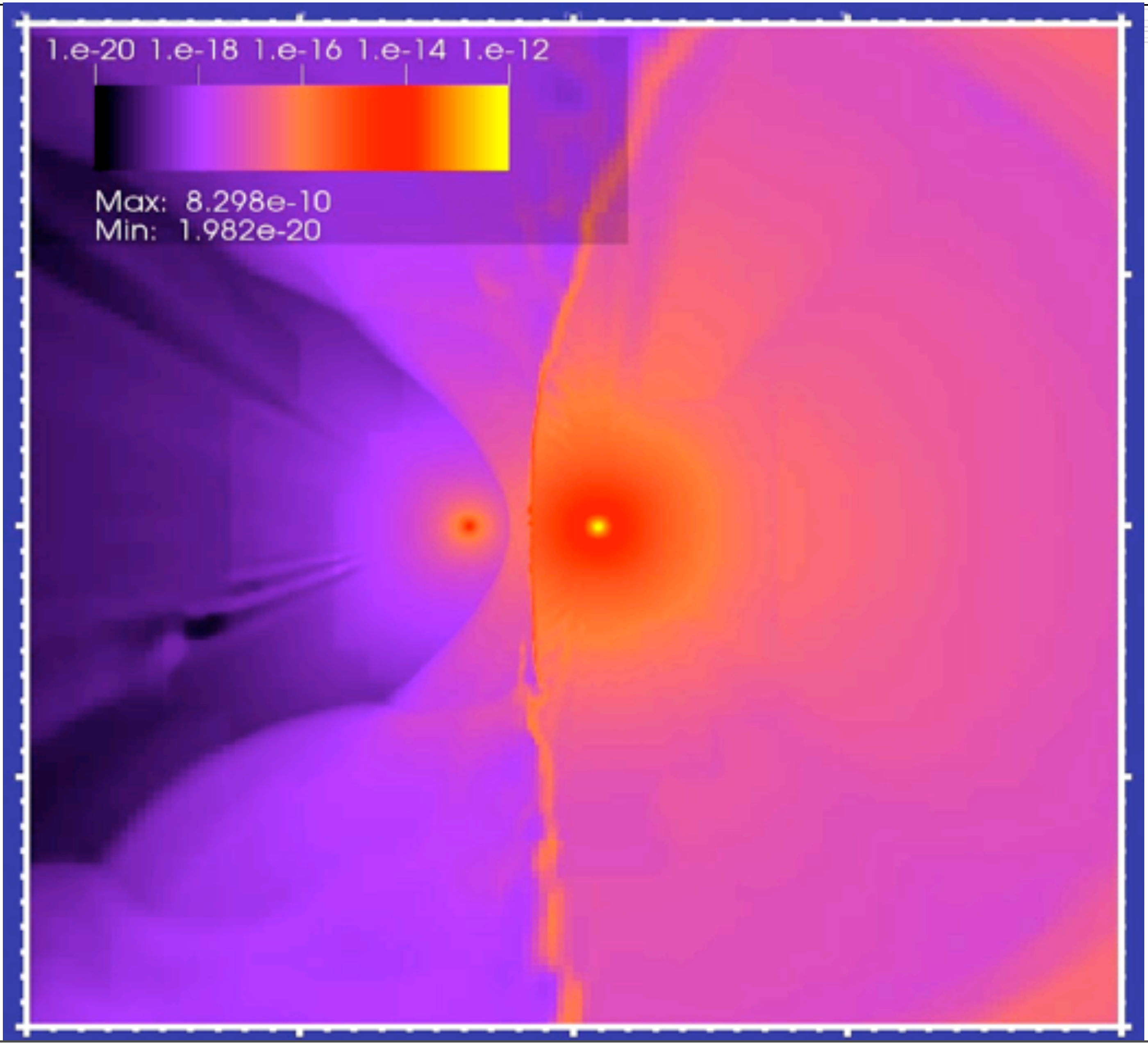
Pittard (2009)

O6V + O6V, e=0.3, P=6.1d

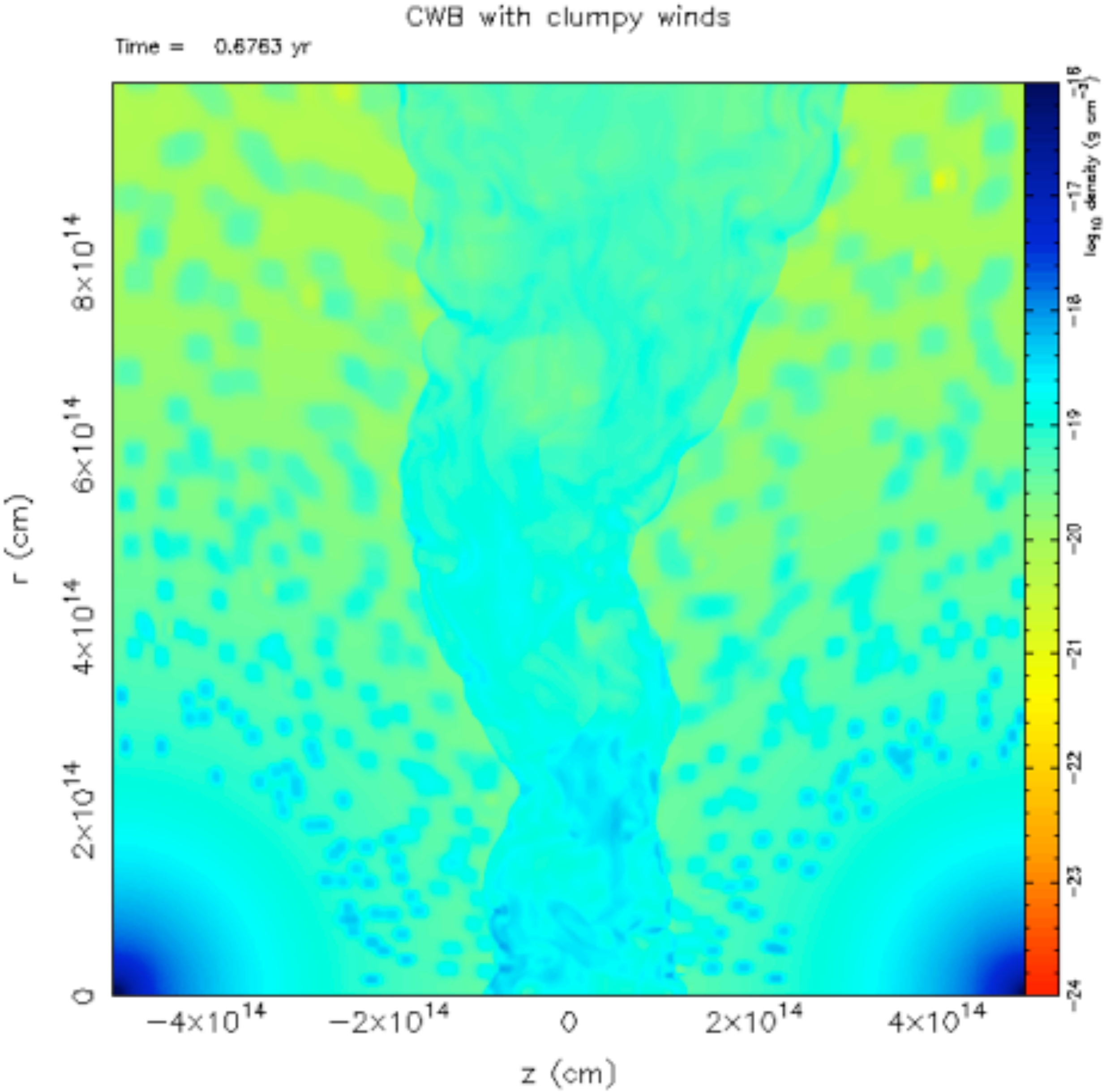


3D AMR model of Eta Carinae

Parkin et al. (2010, accepted)



Clump destruction in adiabatic CWBs



Implications for particle accn?

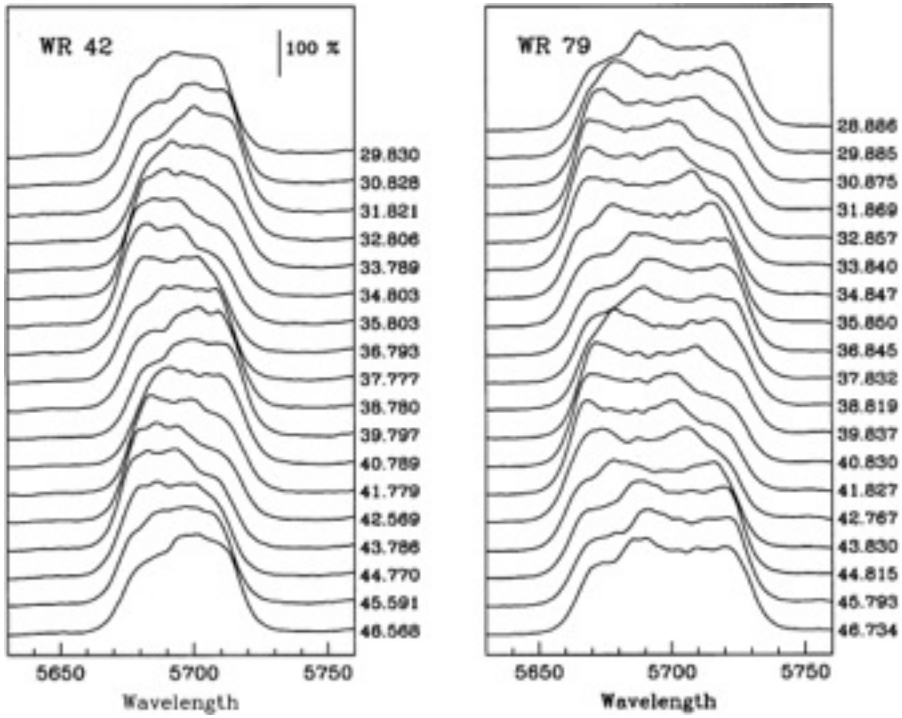
Reconnection?

Stochastic accn?

Part II: Application of Models

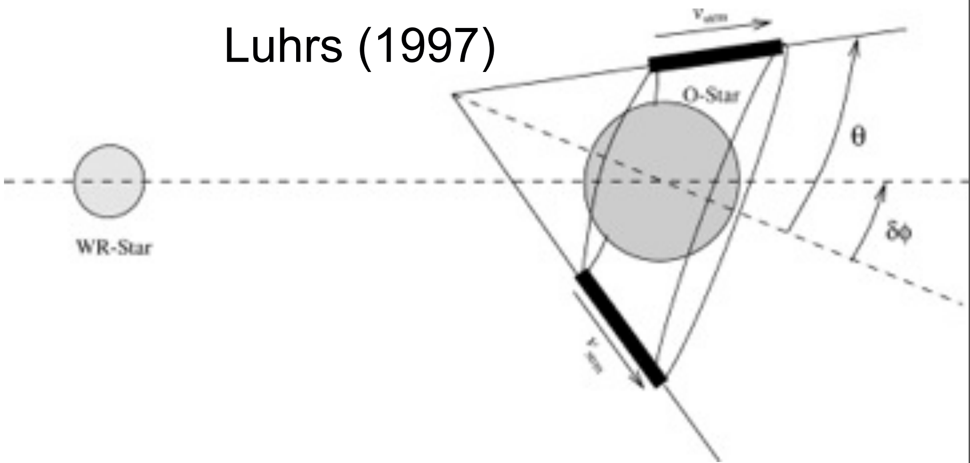
Line Profile Variability: IR, Optical, UV

- Many WR binaries show signs of variability in *excess* emission on top of flat-topped emission lines
- Extra emission from wind material flowing along the shock cone and cooling



Hill et al. (2000)

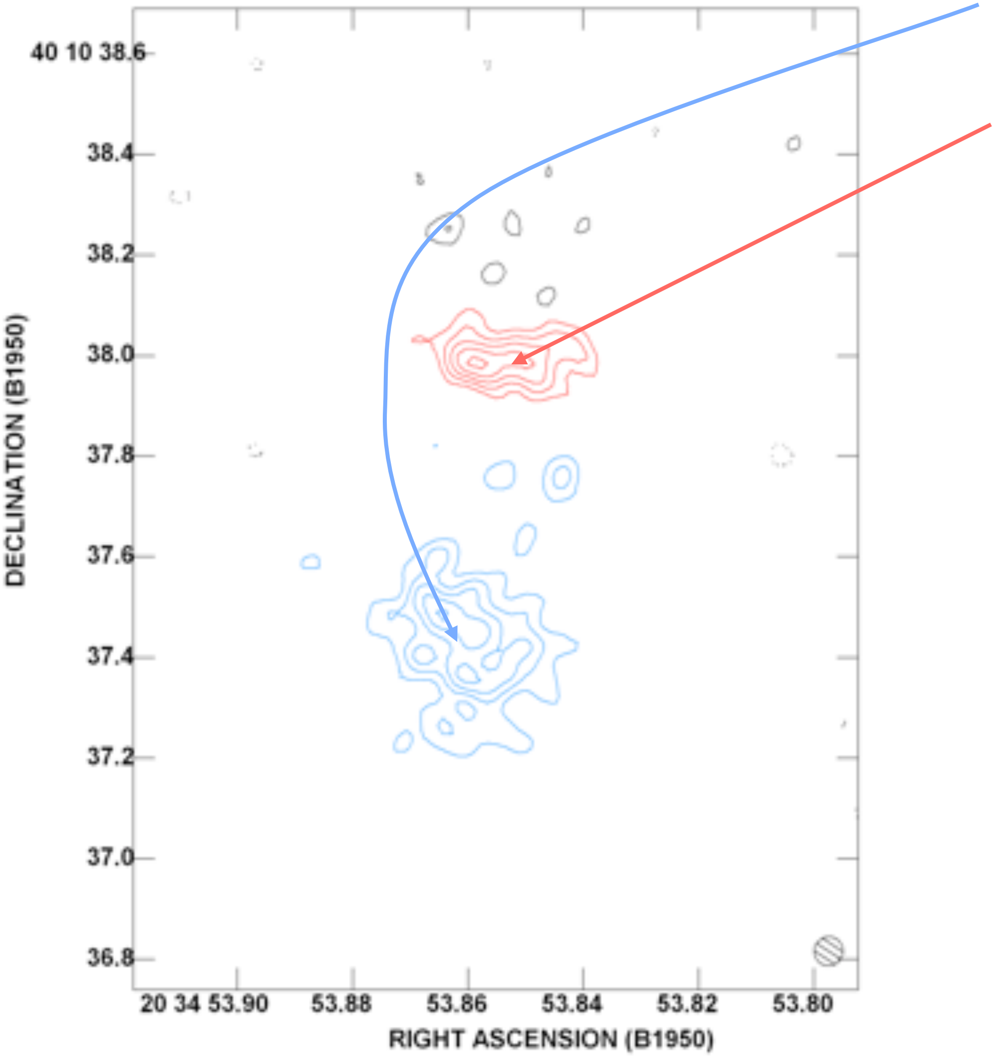
Luhrs (1997)



- The excess emission (on top of the underlying flat-top line) can be parameterized by two quantities:
  - FW (full width of the excess emission, at some suitable height)
  - RV (mean radial velocity of the entire excess emission)

- Fitting the observed profiles yields:
  - orbital inclination, i
  - shock half-opening angle, θ
  - shock skew, $\delta\theta$

Radio structure of the WR+OB CWB - WR 147



Two components, one thermal, one non-thermal

High resolution observations - MERLIN @ 5GHz:

50 mas = 77AU @ 650pc

WR+OB binary

NT emission => relativistic electrons + magnetic fields

NT emission consistent with wind-collision position

Williams et al. (1997)

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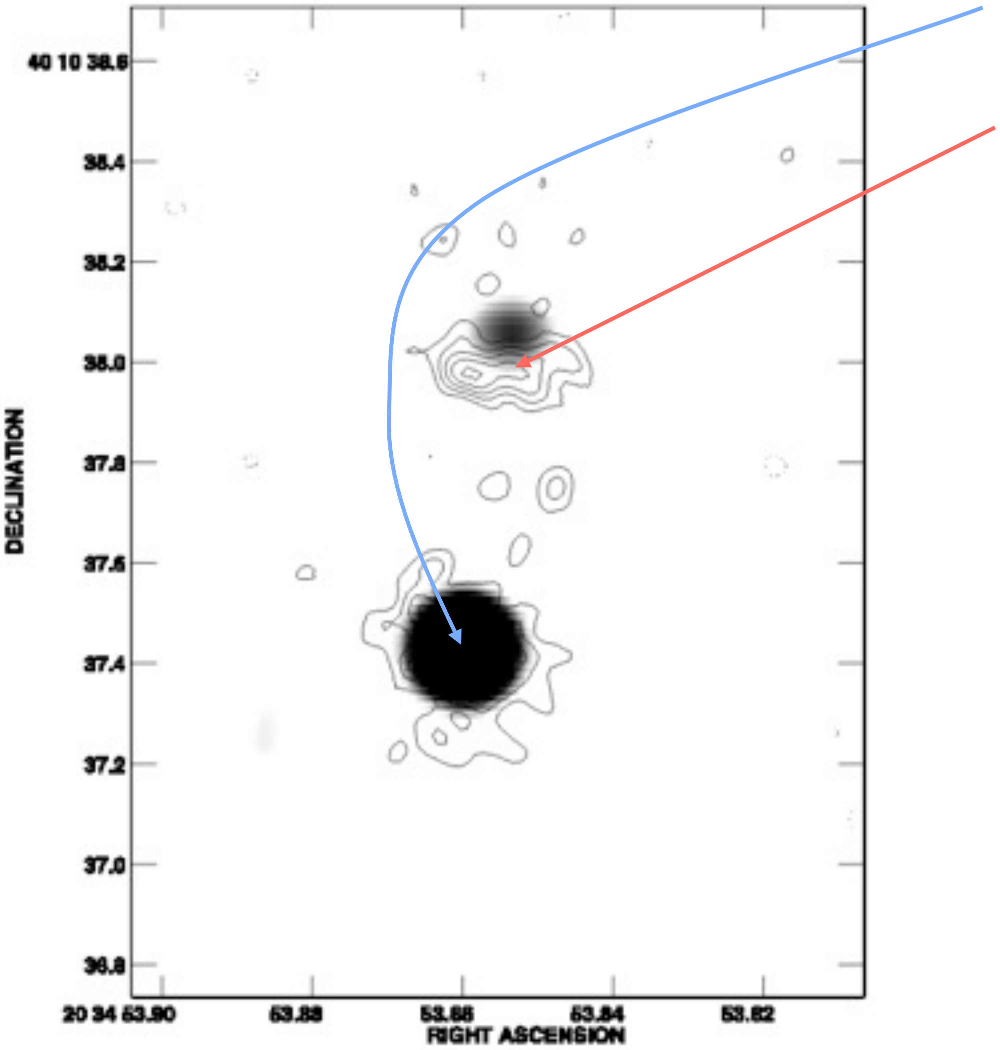

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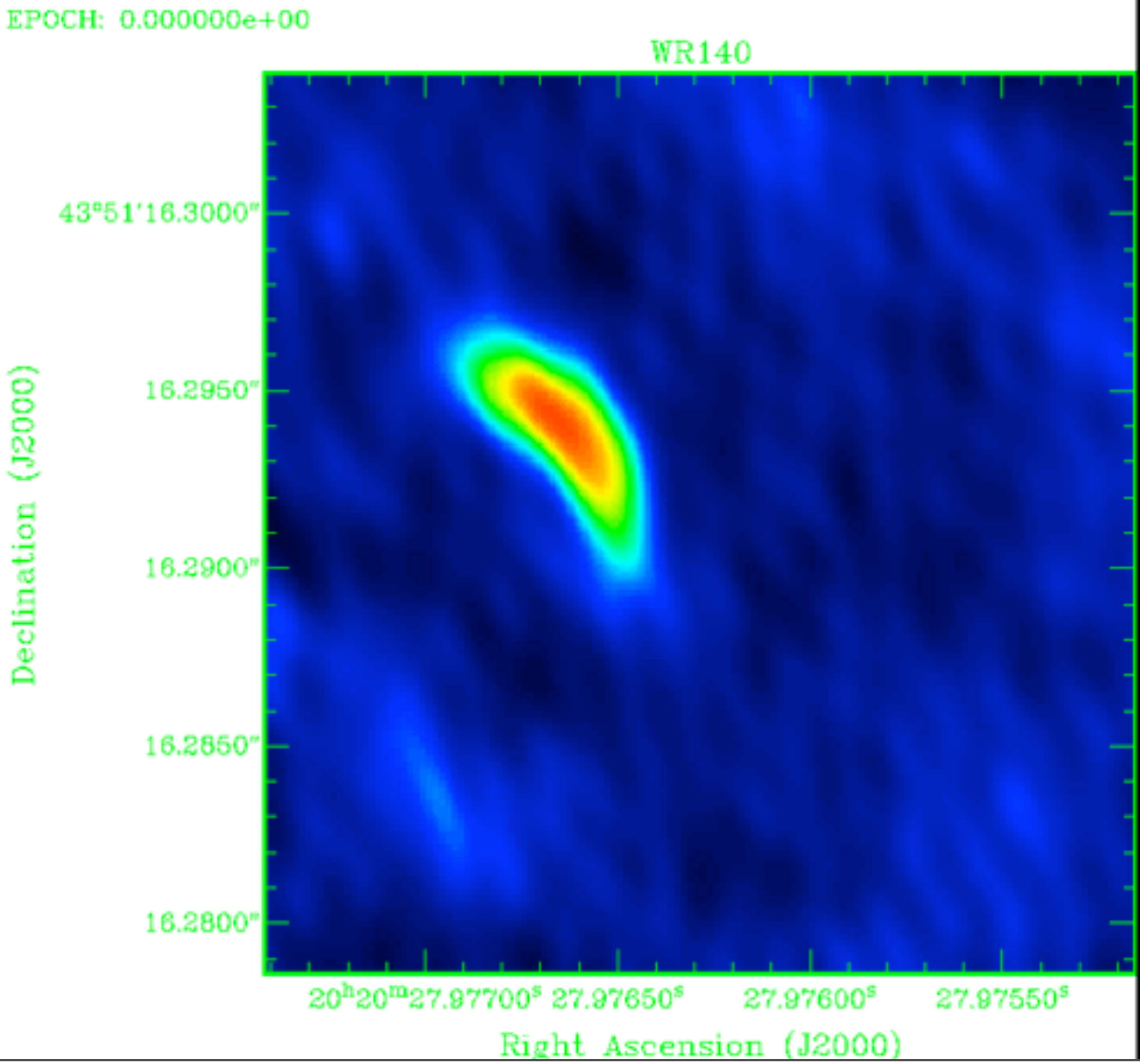
WR140 – VLBA obs



WR 140

WR + O in a 7.9 year, eccentric (e ~ 0.9) orbit

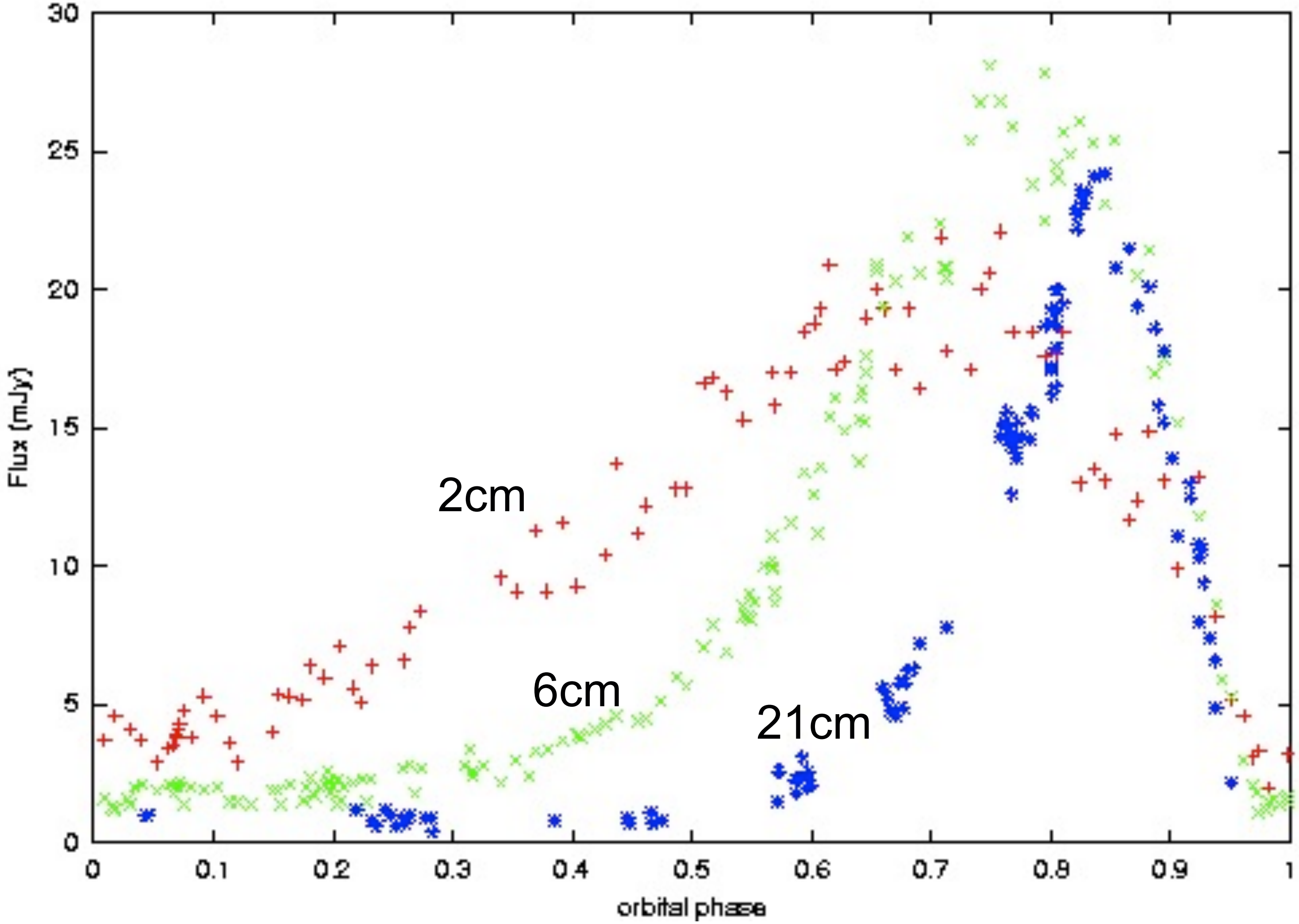
Orbit size ~ 1.5-28 AU

Radio-bright; dramatic variations in radio emission as orbit progresses

State of the Art imaging!
23 epochs @ 3.6 cm
Phase ~ 0.74 -> 0.93
(Jan 1999 to Nov 2000)
Resolution ~ 2 mas
Linear res ~ 4 AU

Dougherty et al. (2005)

The radio light curve of WR140



8 years of VLA (White & Becker 1995) +
WSRT (Williams et al 1991) data

Previous Models of Radio Emission

Early models of NT emission were simple

Radio:

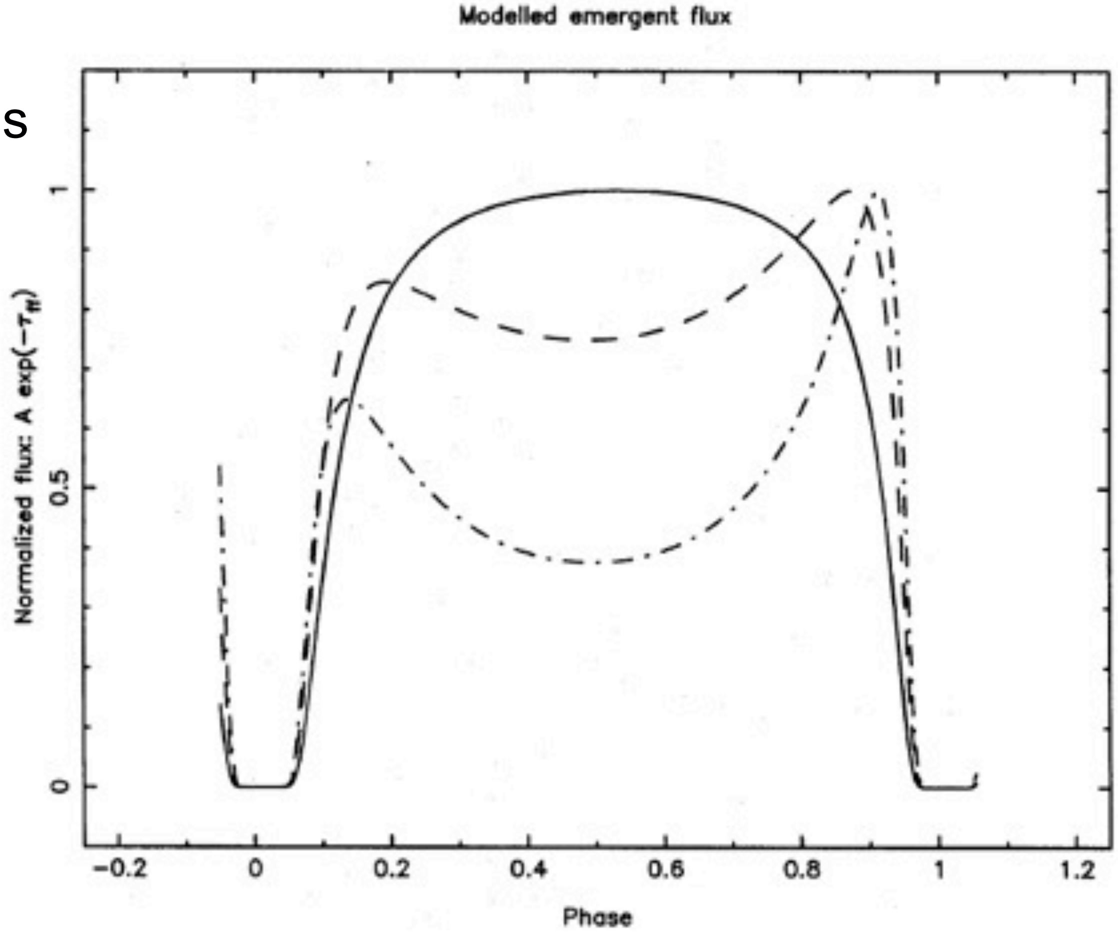
- Point source non-thermal emission, spherically symmetric winds –

$$S_\nu^{\mathrm{obs}} = S_\nu^{\mathrm{thermal}} + S_\nu^{\mathrm{nt}} e^{-\tau_\nu^{\mathrm{ff}}}$$

- maintains analytic solutions

A more complex model would account for the hole in the WR wind carved out by the O wind

Williams et al. (1990)



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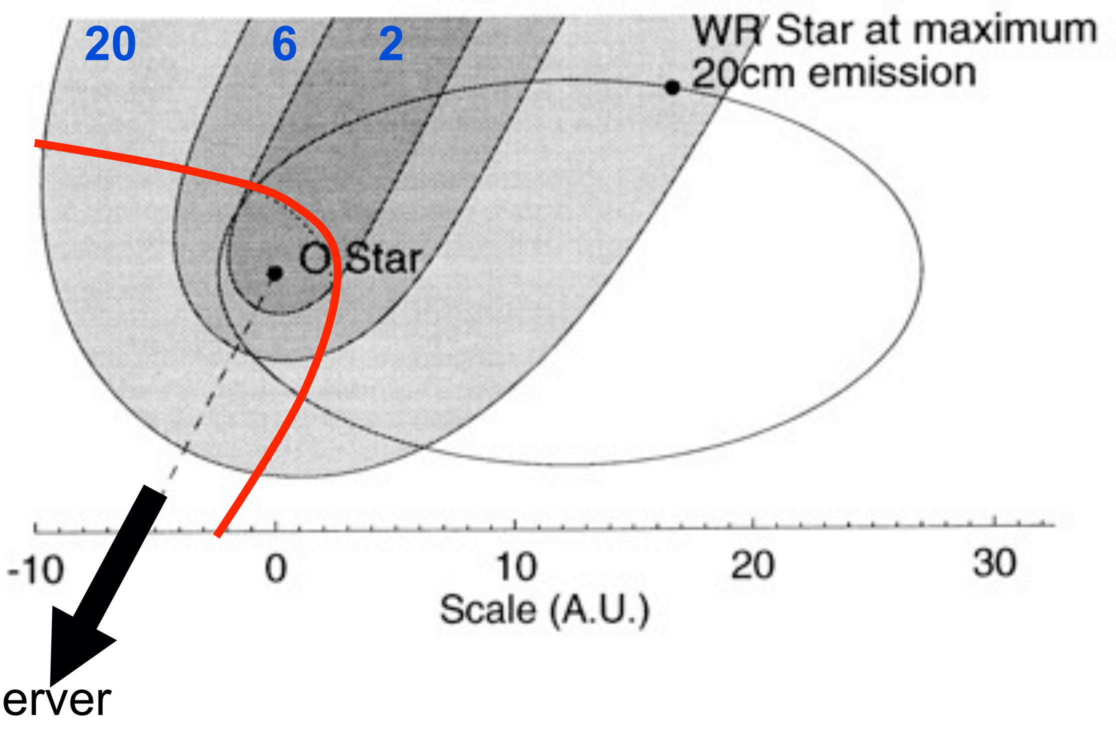
White & Becker (1995) pointed out that even the O wind has significant opacity



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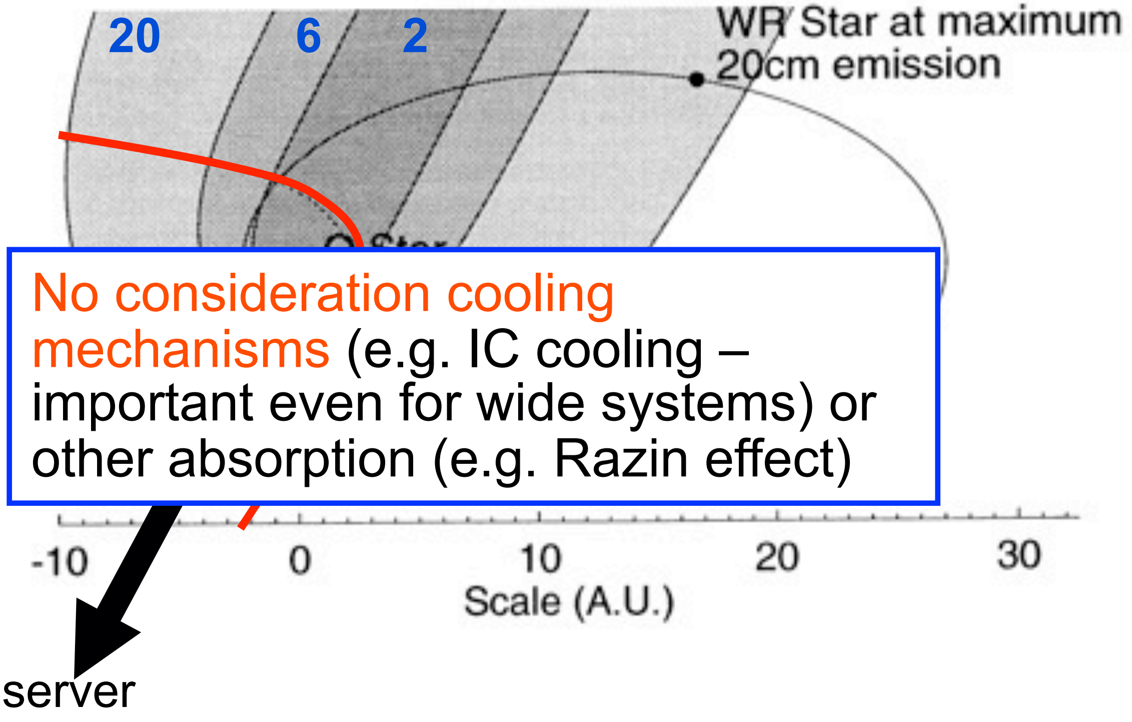
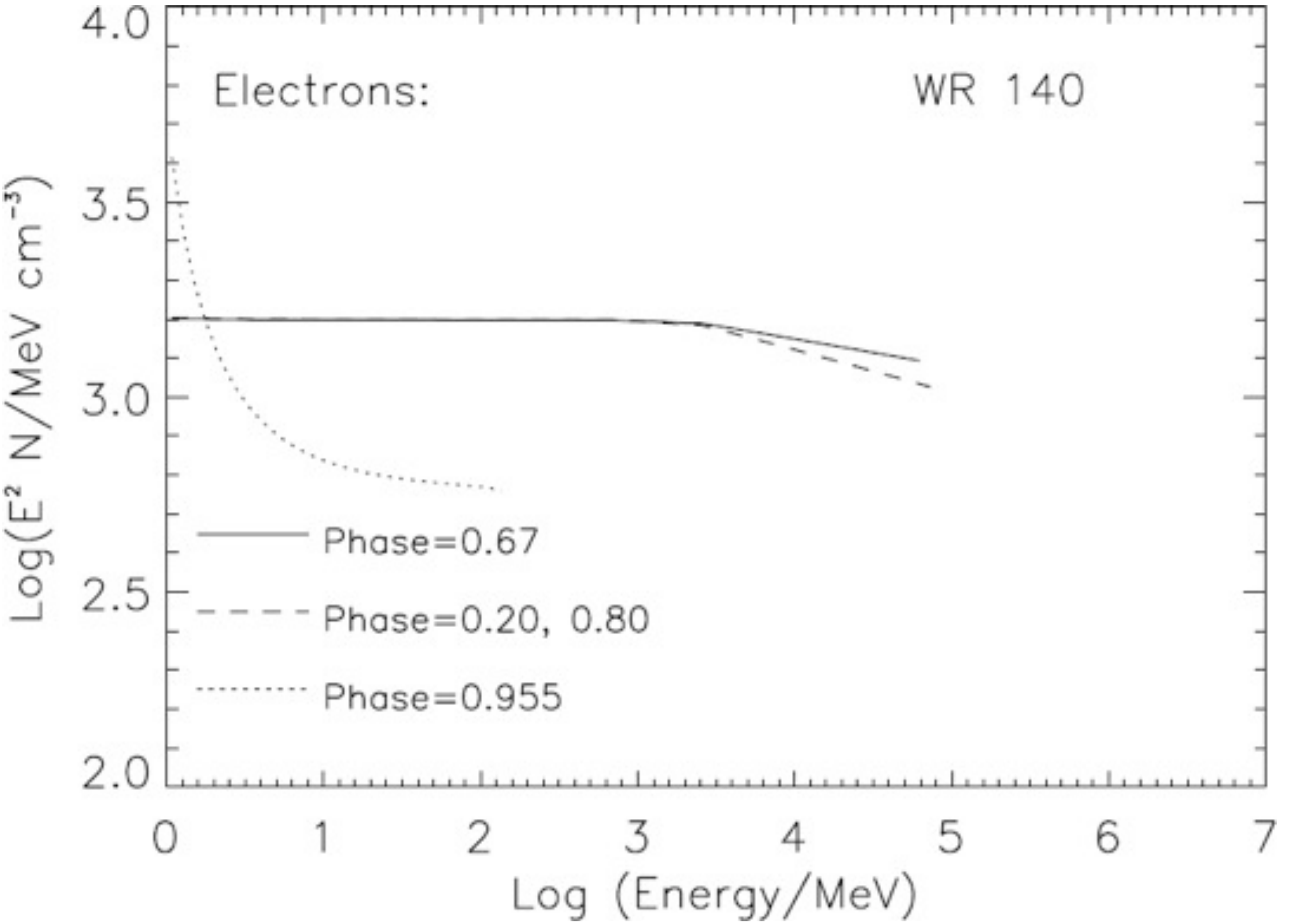


No consideration cooling mechanisms (e.g. IC cooling – important even for wide systems) or other absorption (e.g. Razin effect)

More Recent Models

NT X-ray/γ-ray: Reimer et al. (2006)



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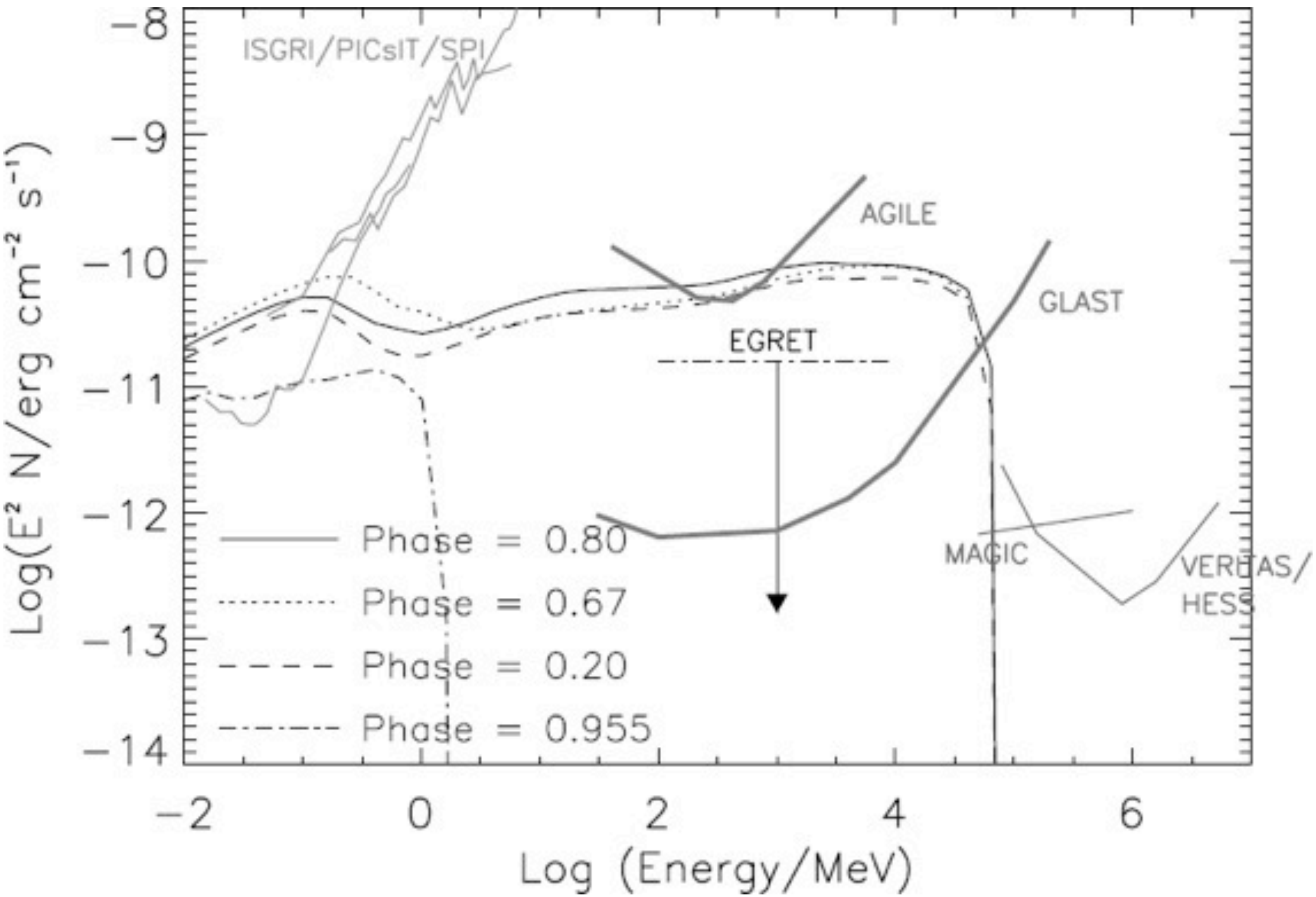
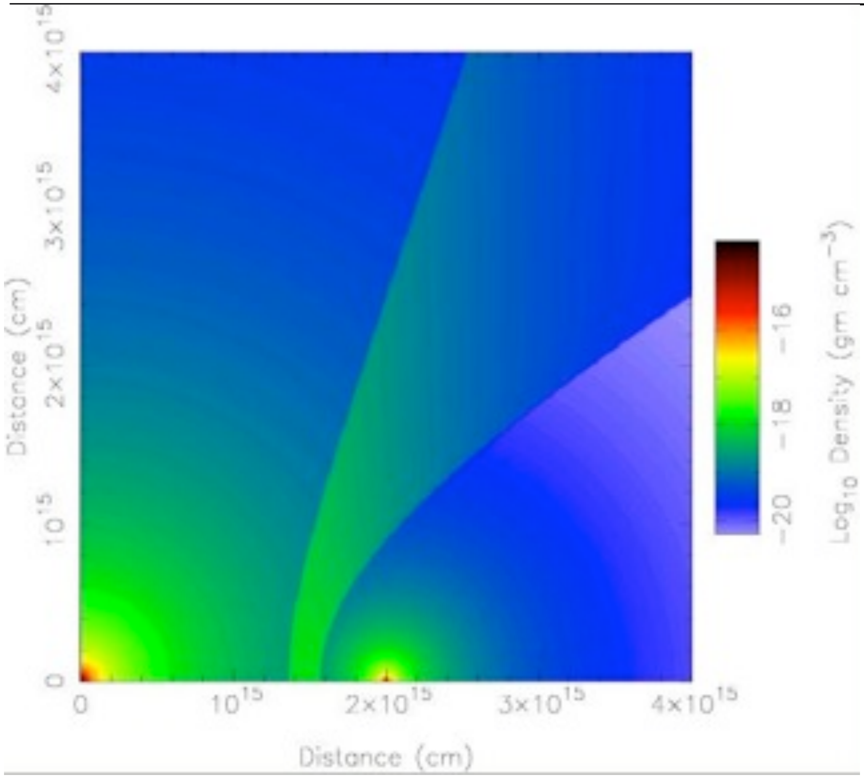
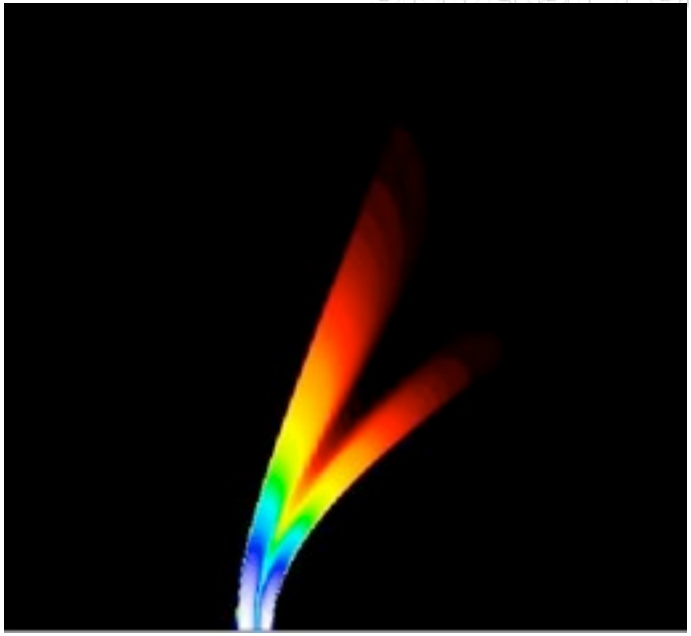
NT X-ray/γ-ray: Reimer et al. (2006). IC spectra



A Phenomenological Model

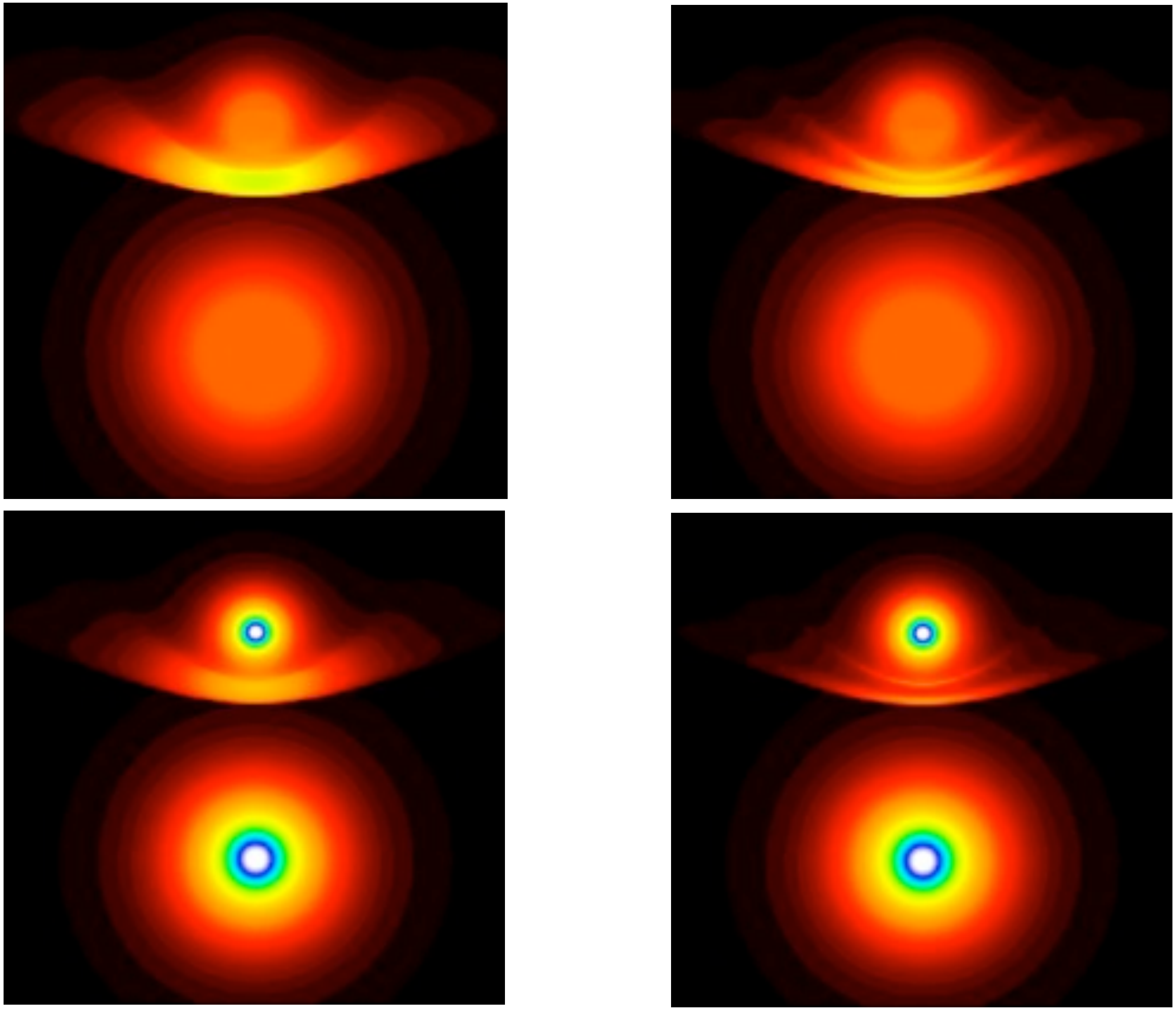




1.6 GHz emission map of
synchrotron emission

Dougherty et al. (2003), Pittard et al. (2006)

Example Synthetic Emission Maps



No IC cooling

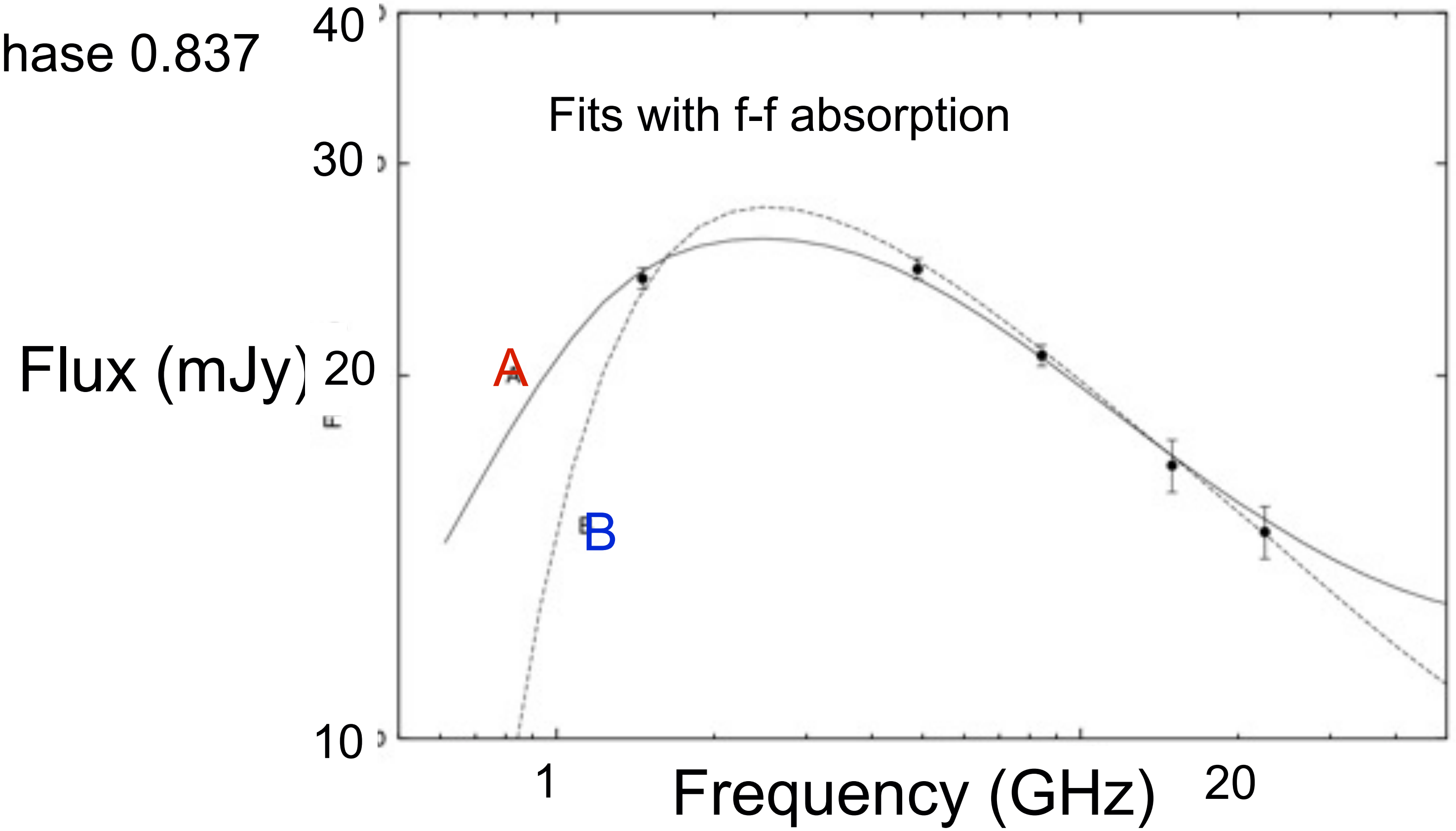
With IC cooling

1.6 GHz

22 GHz

Spectral fits to WR140 spectra

Phase 0.837



Pittard et al. (2006)

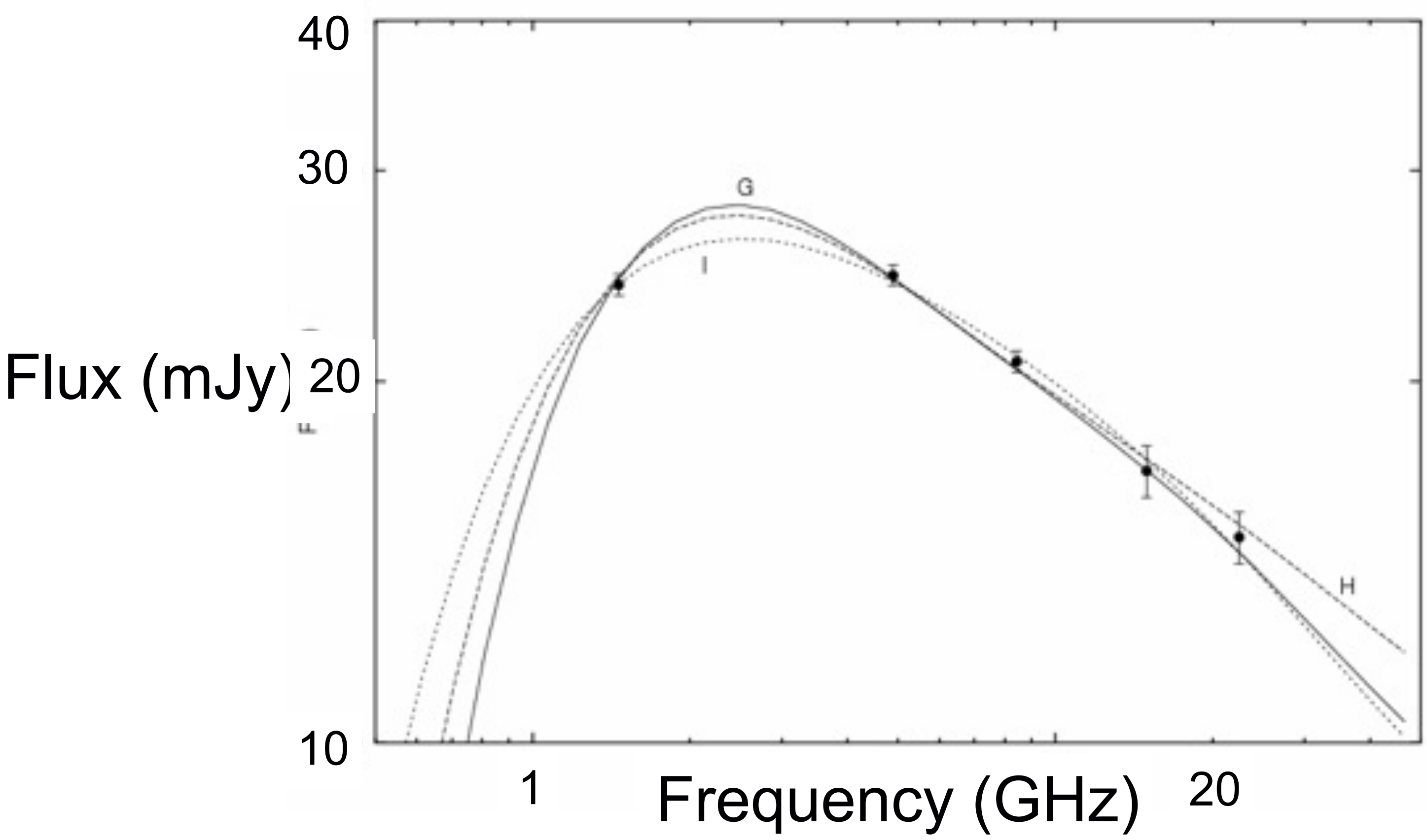
Model A: η=0.22, p=1.4, ζ_e=1.4x10^{-3}, ζ_B=0.05

Model B: η=0.02, p=1.4, ζ_e=5.4x10^{-3}, ζ_B=0.05

A caveat – p and ζ_B are ill-constrained parameters in these models

Crucially, we cannot obtain fits with p = 2!

Fits with the Razin effect causing the low freq. turnover



Model G: $\eta=0.11$, $p=2.0$, $\zeta_e=0.22$, $\zeta_B=2.6\times10^{-4}$

Model I: $\eta=0.0353$, $p=1.4$, $\zeta_e=0.14$, $\zeta_B=1.0\times10^{-3}$

Again – p and ζ_B are ill-constrained in these models

We can obtain fits with p = 2!

Modelling 8 GHz VLBA observations

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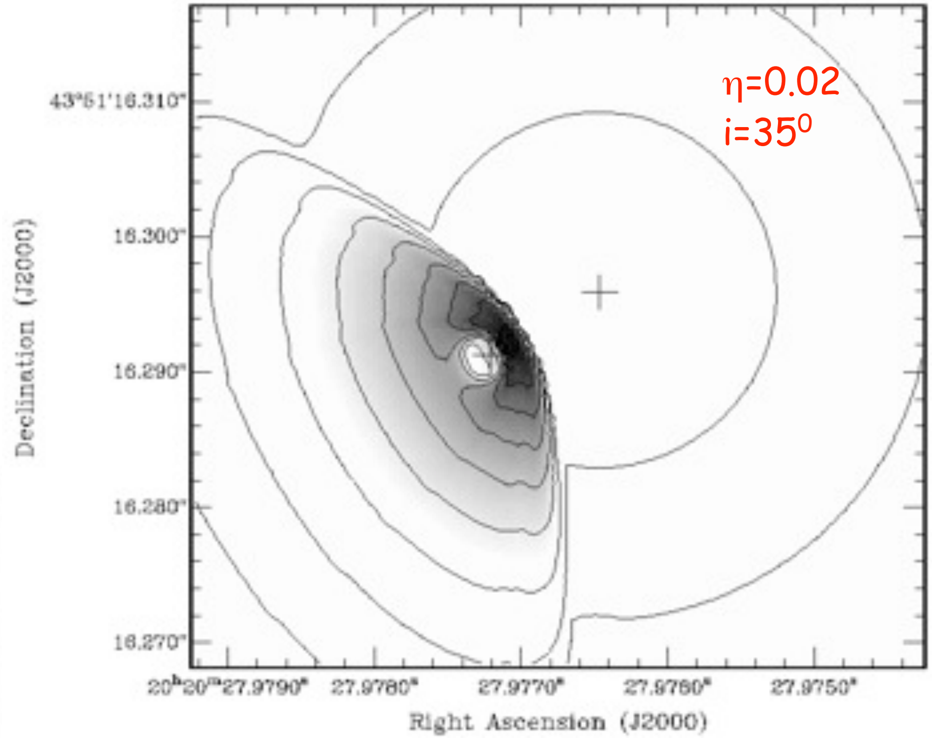

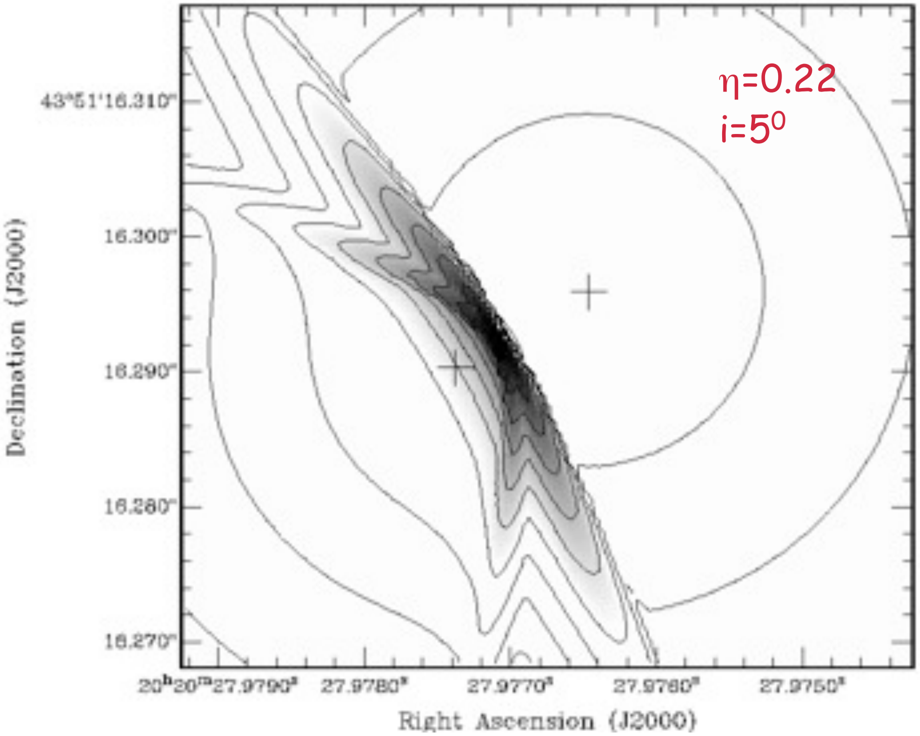

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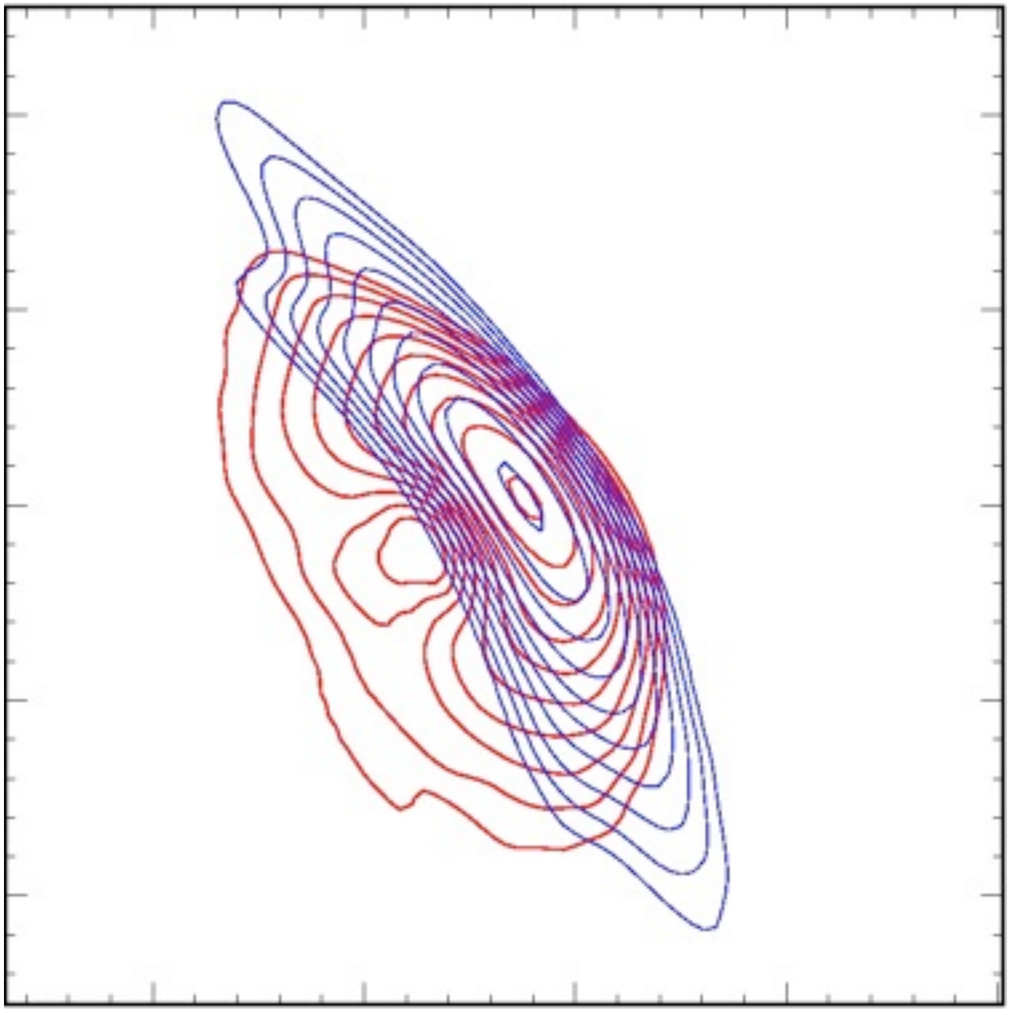

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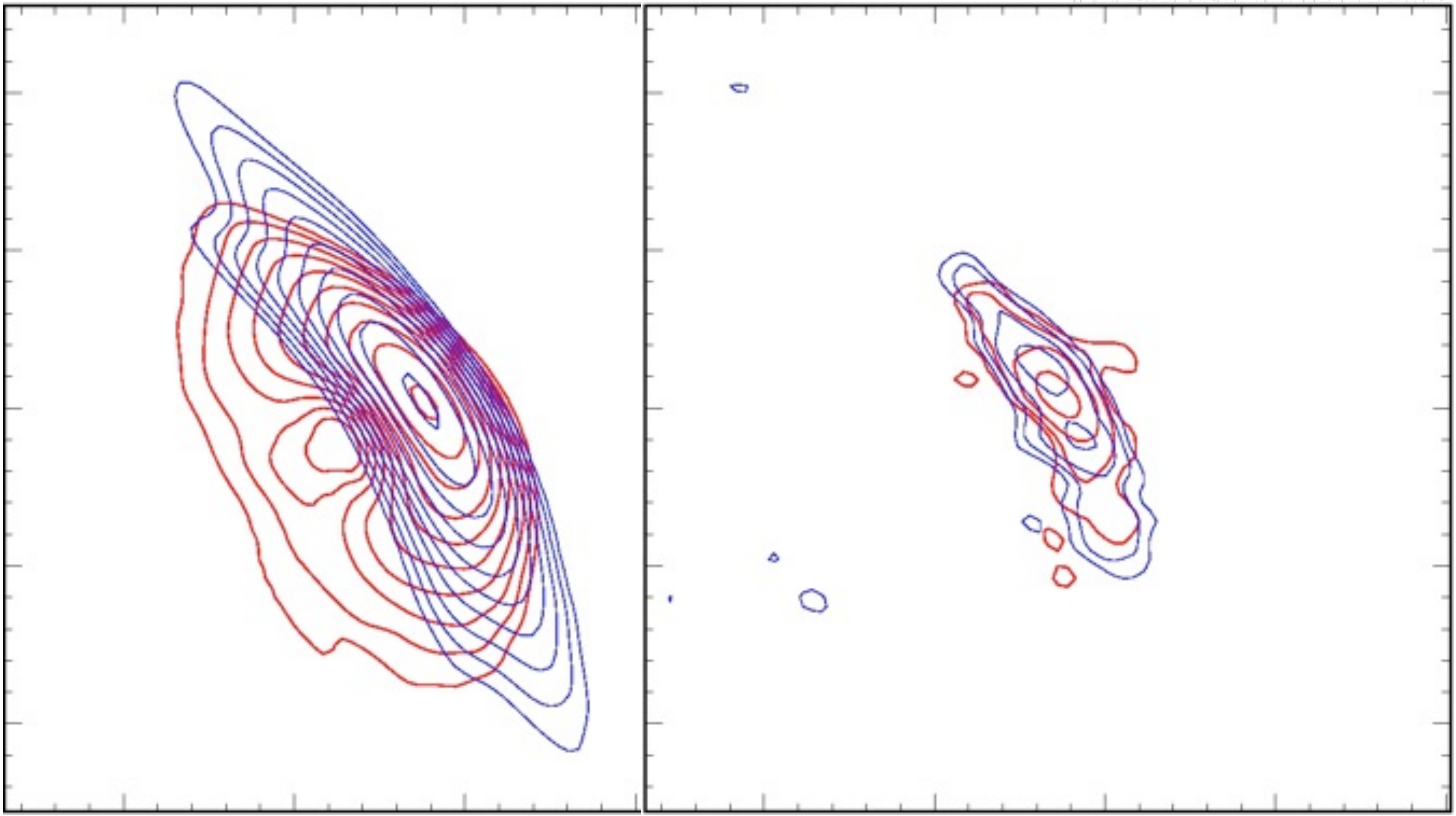

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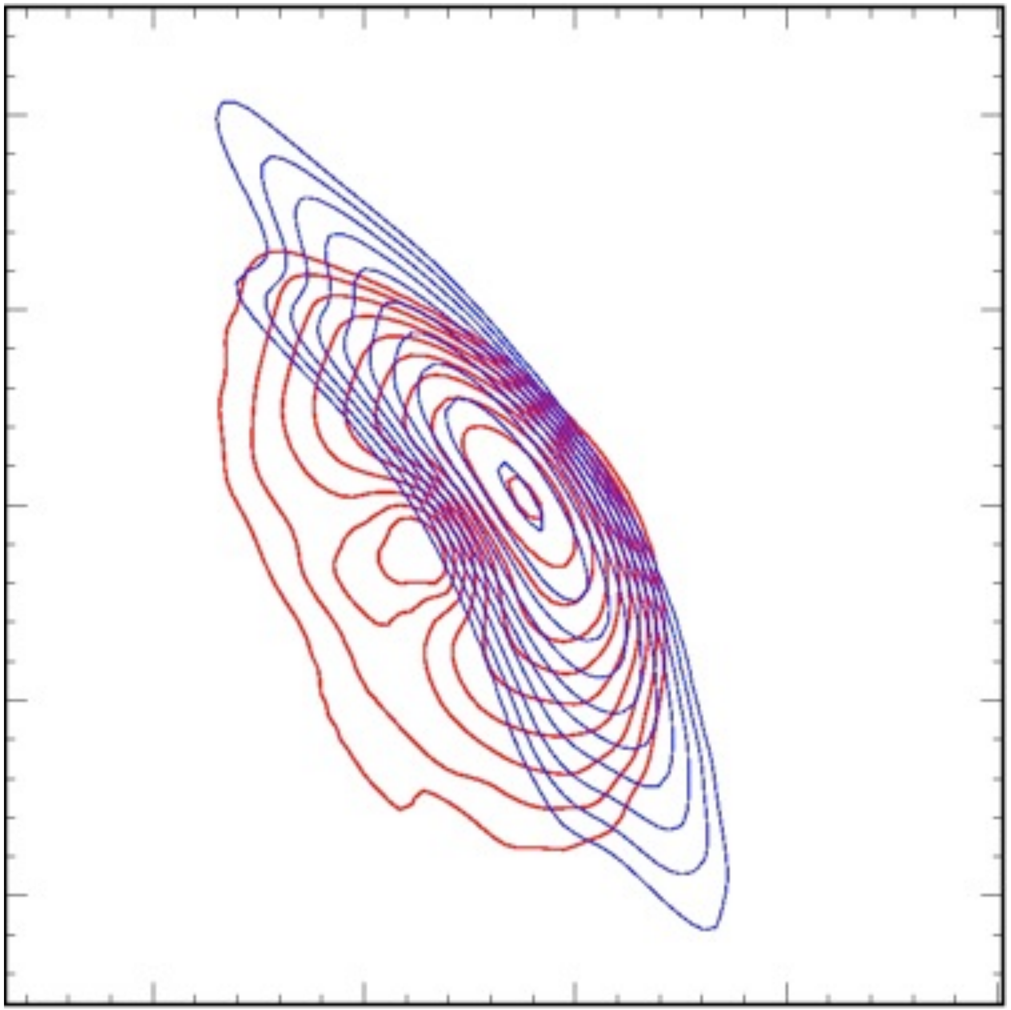

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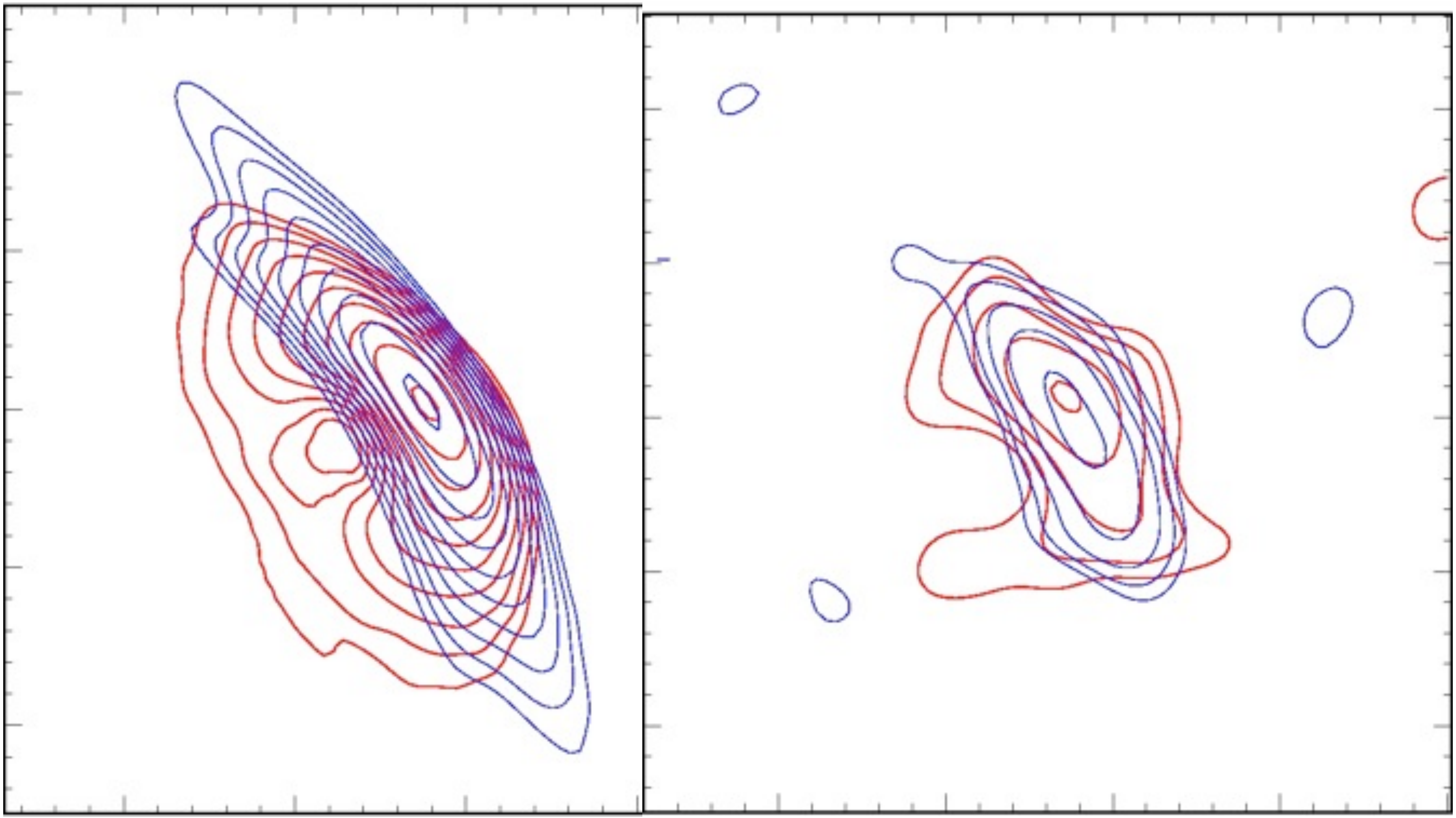

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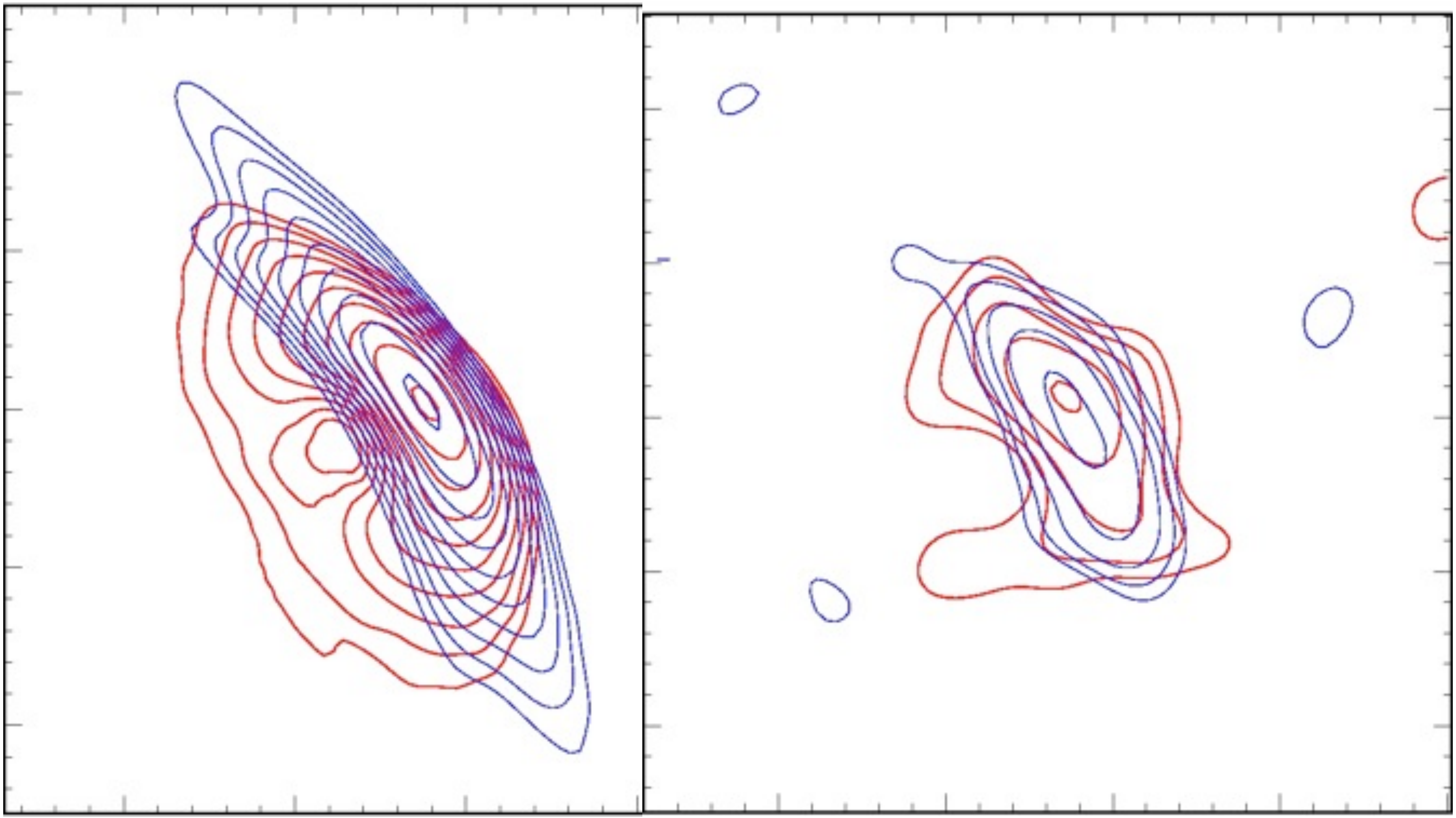
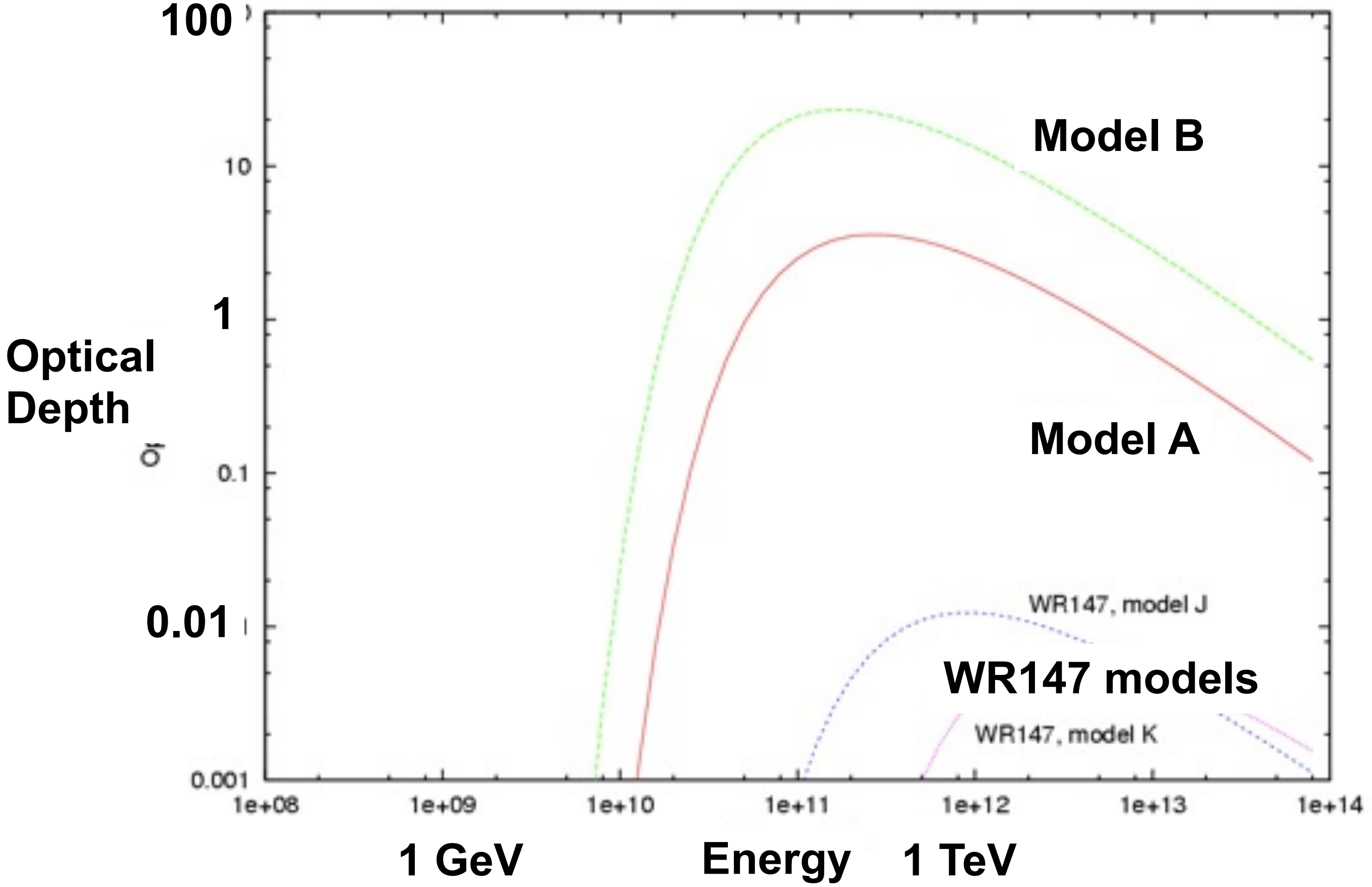


Possible to constrain models with VLBI obs – demands “good” observations

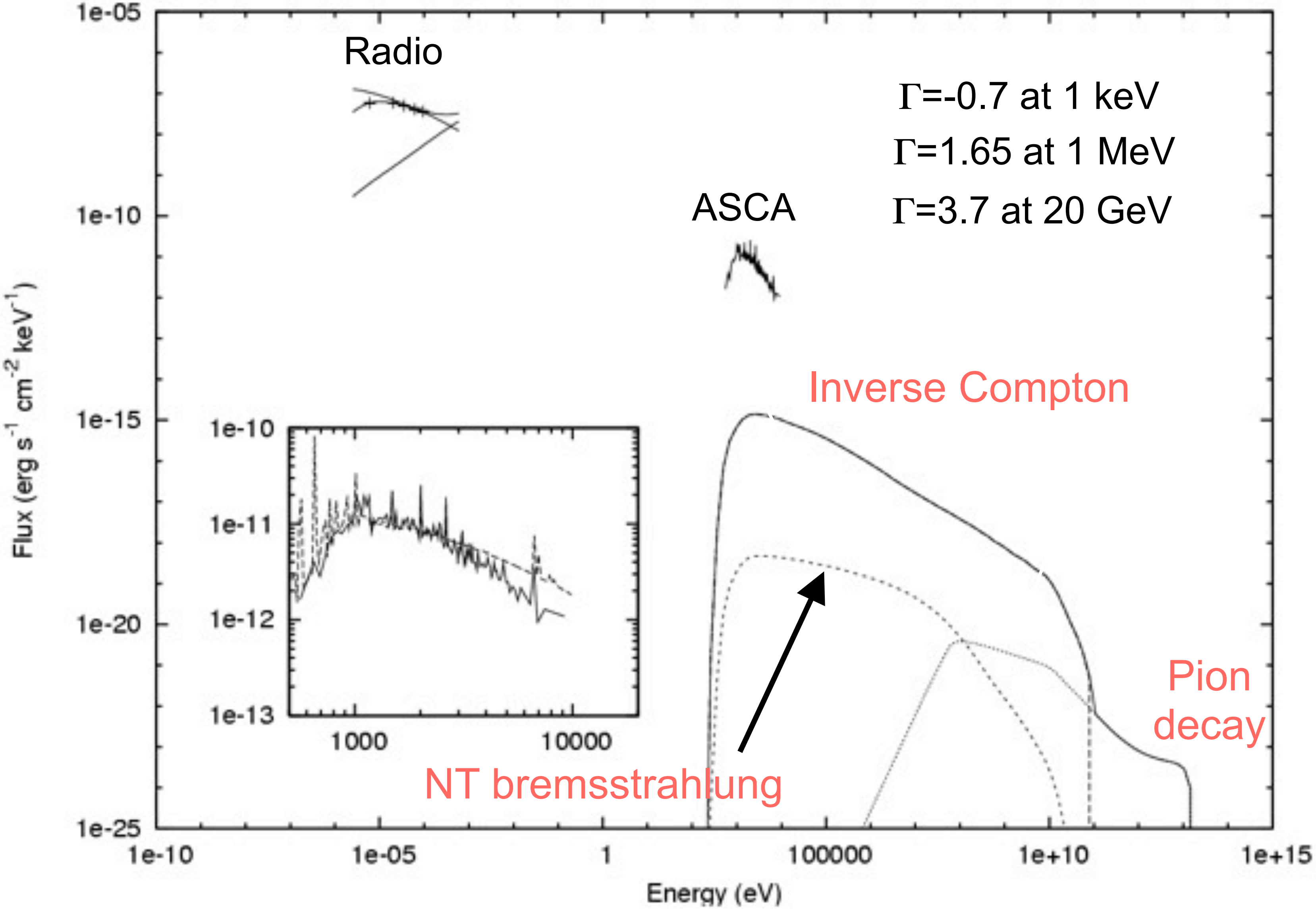
Gamma-ray absorption

Two-photon pair production: $\gamma + \gamma_* \rightarrow e^- + e^+$



Pair production in electric field of charged nuclei is negligible

High energy emission at phase 0.837



Γ=-0.7 at 1 keV

Γ=1.65 at 1 MeV

Γ=3.7 at 20 GeV

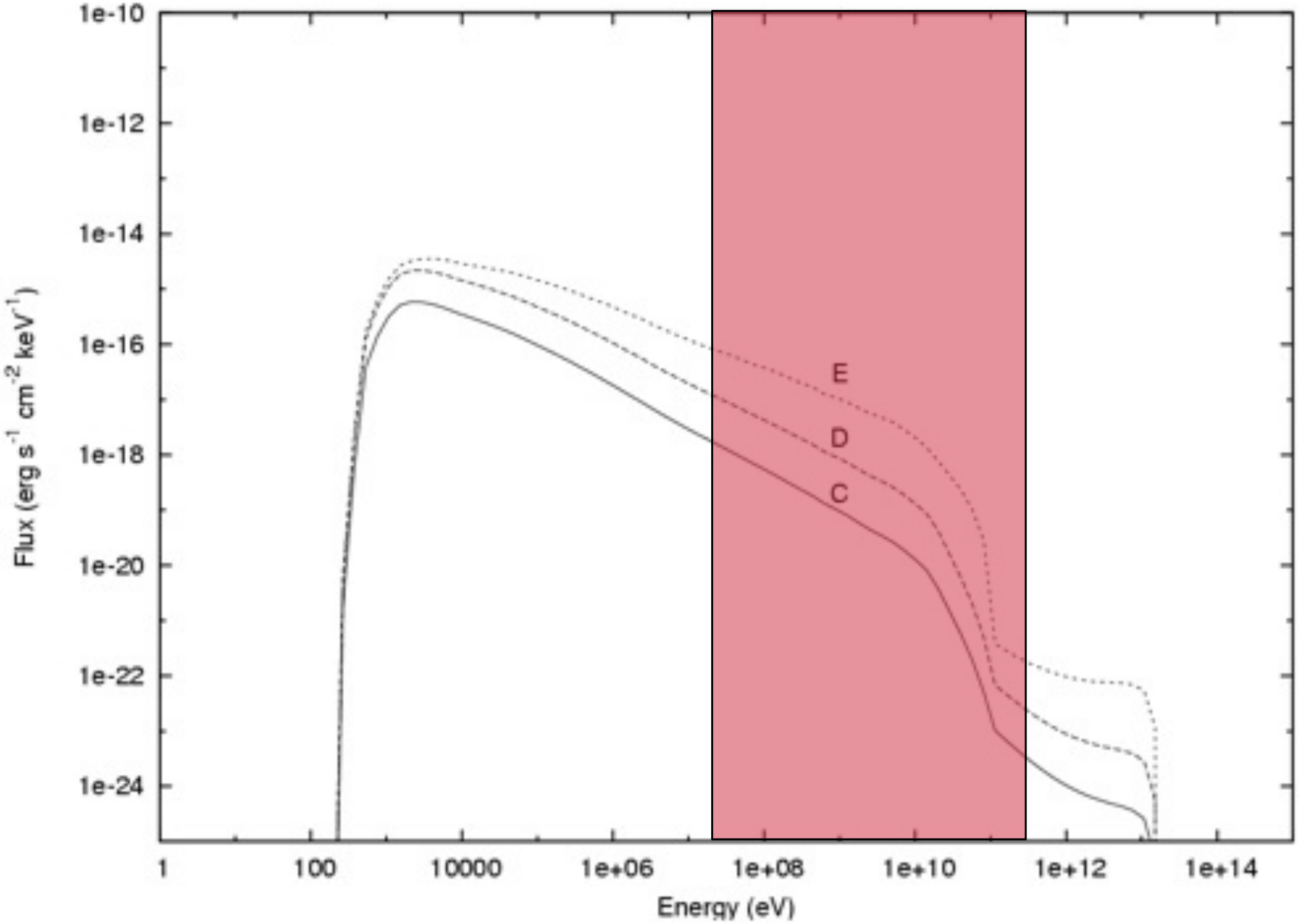
Inverse Compton

NT bremsstrahlung

Pion decay

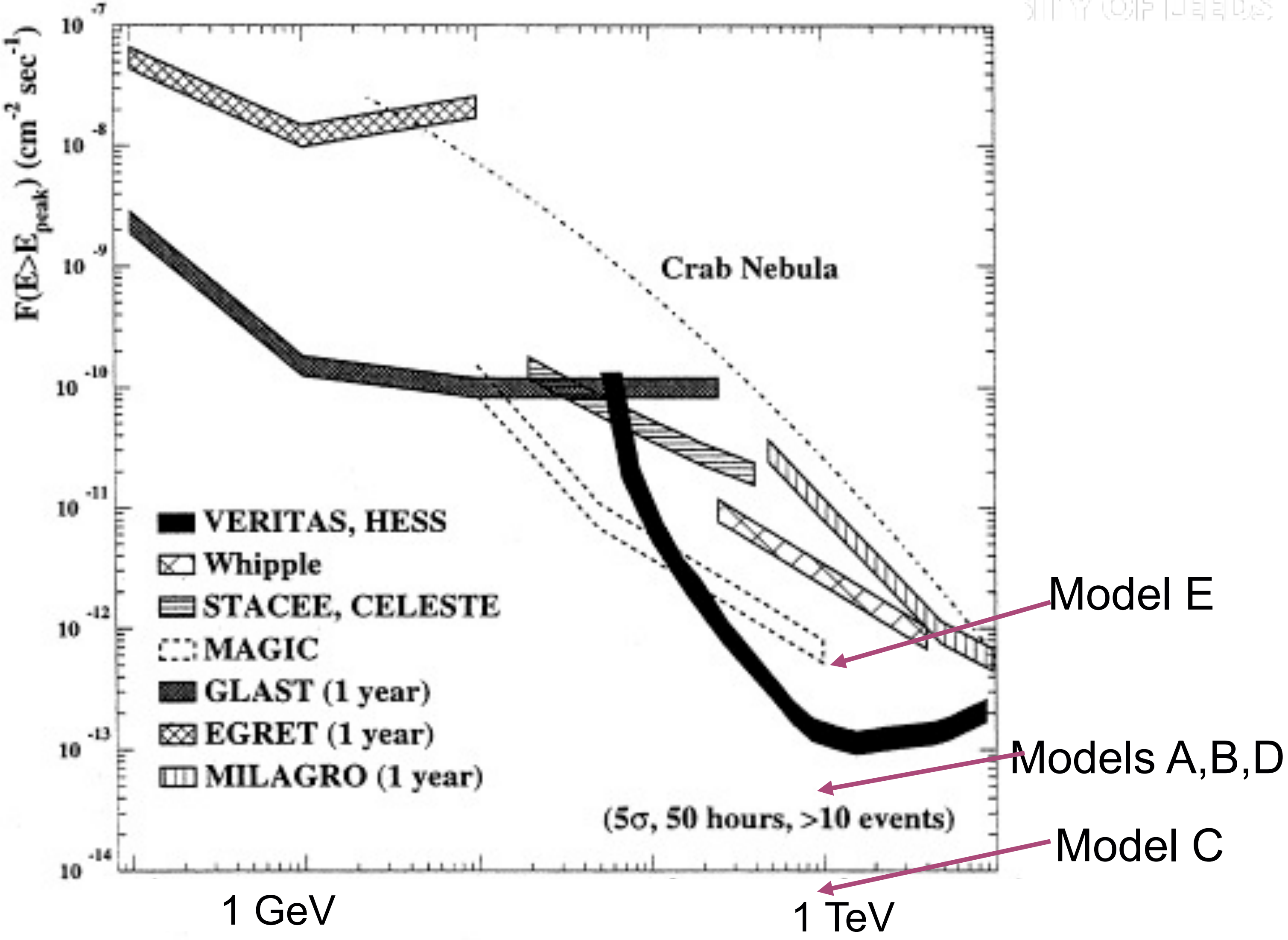
Model discrimination

Fermi will be able to discriminate between models

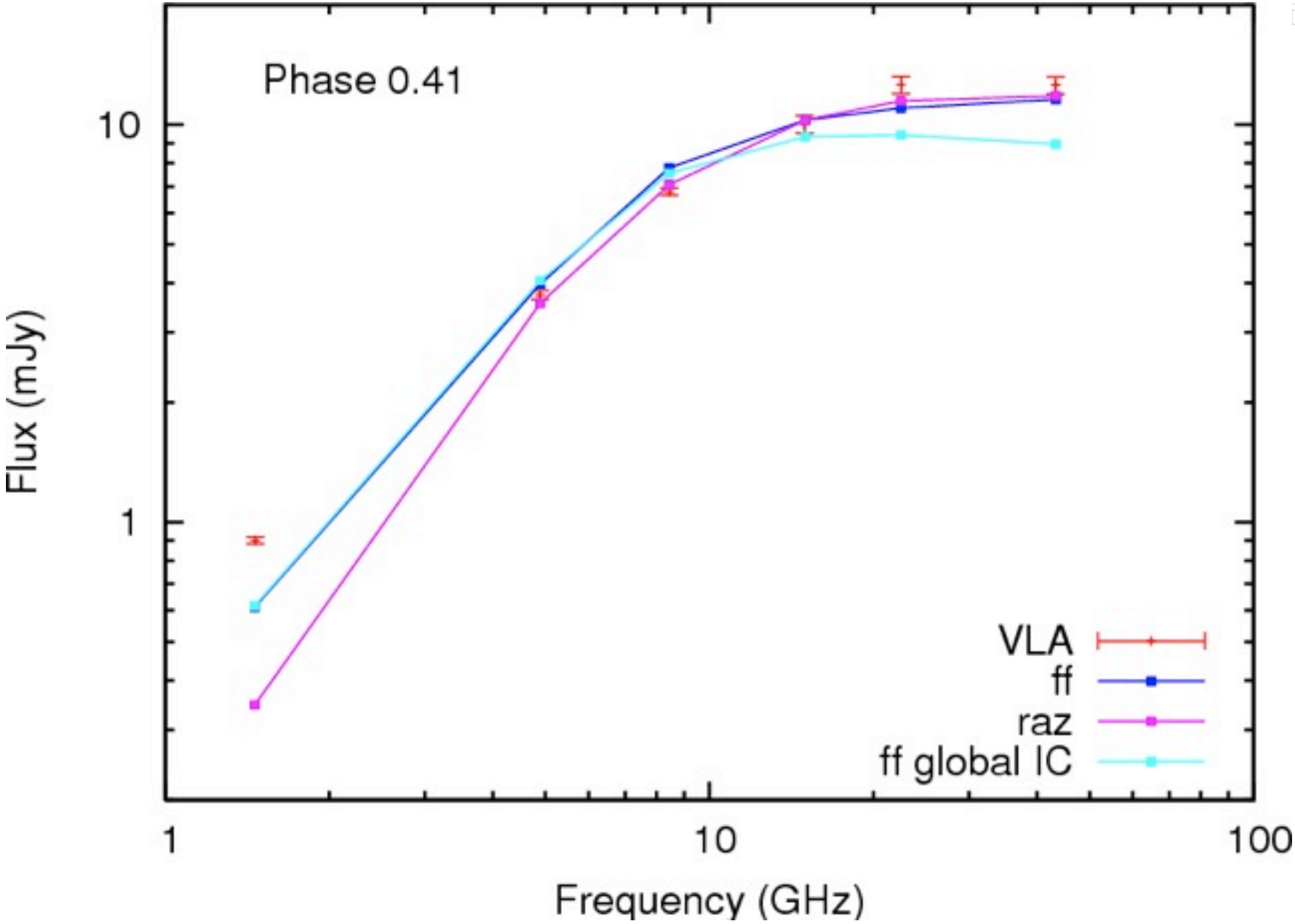


Will place constraints on the spectral index and B-field

Flux at TeV energies in VERITAS band



Fits at other phases?



Fits at other phases?

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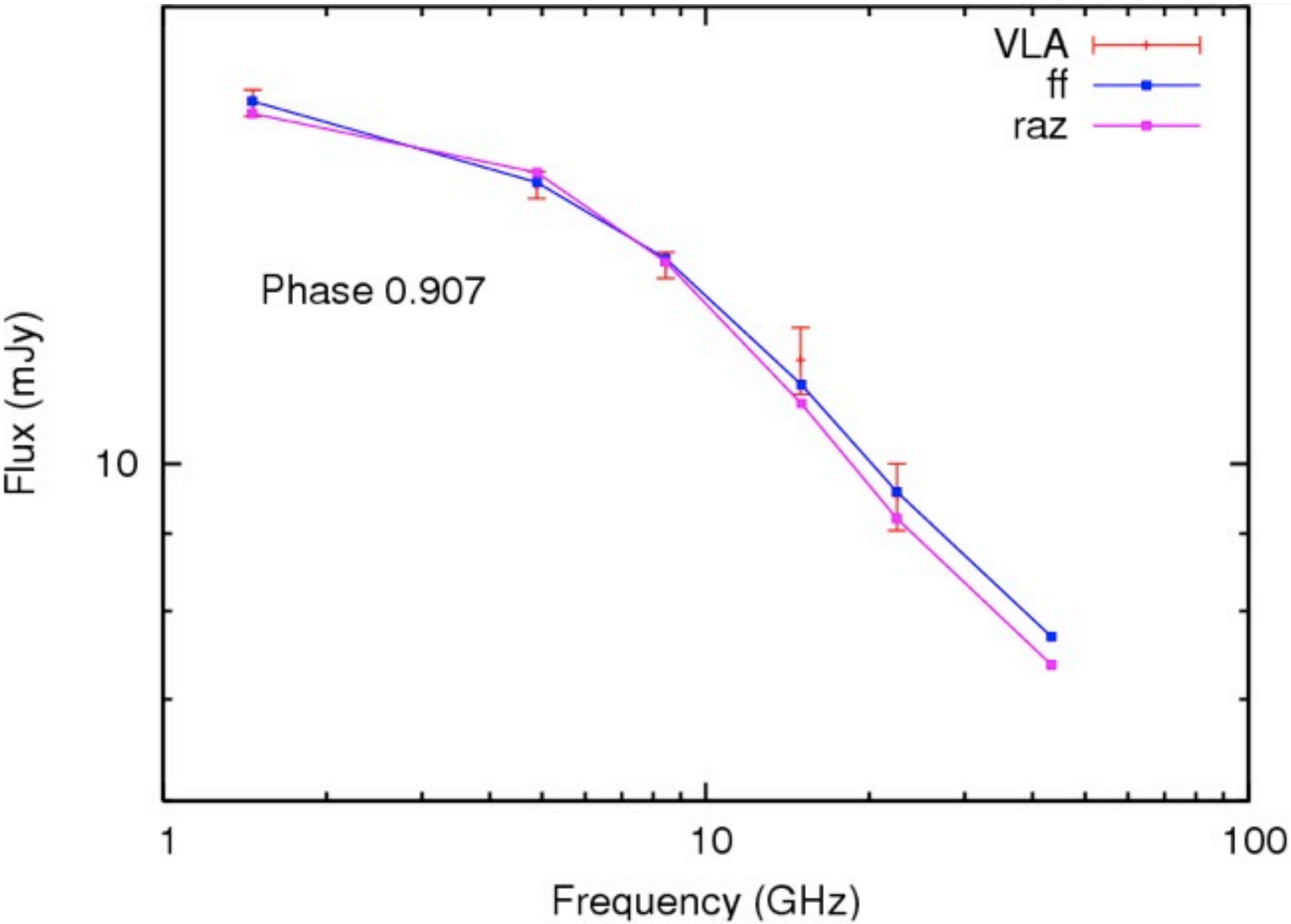
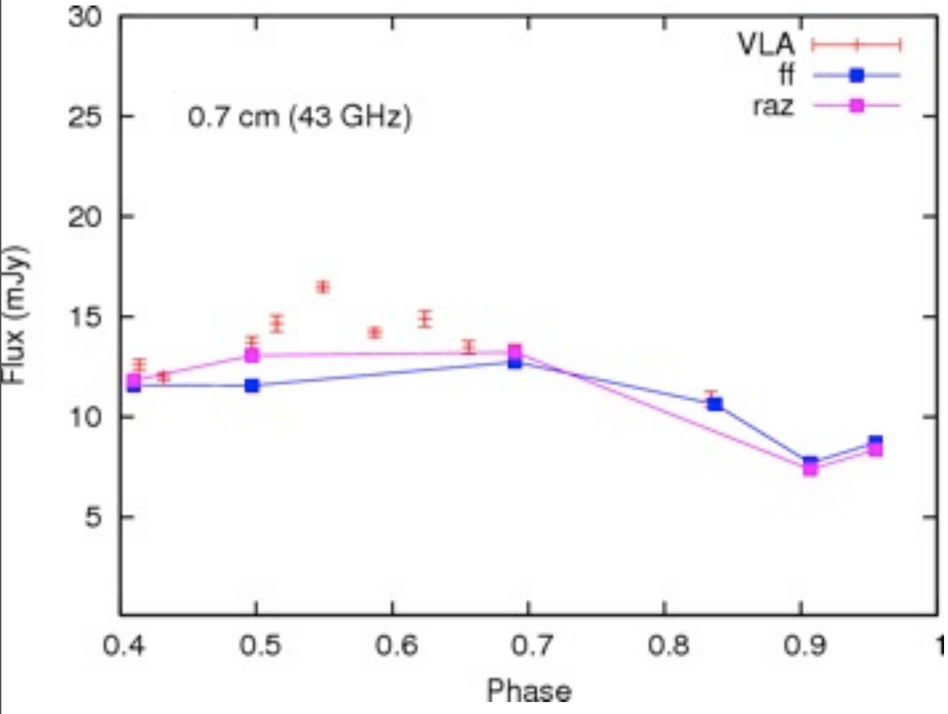
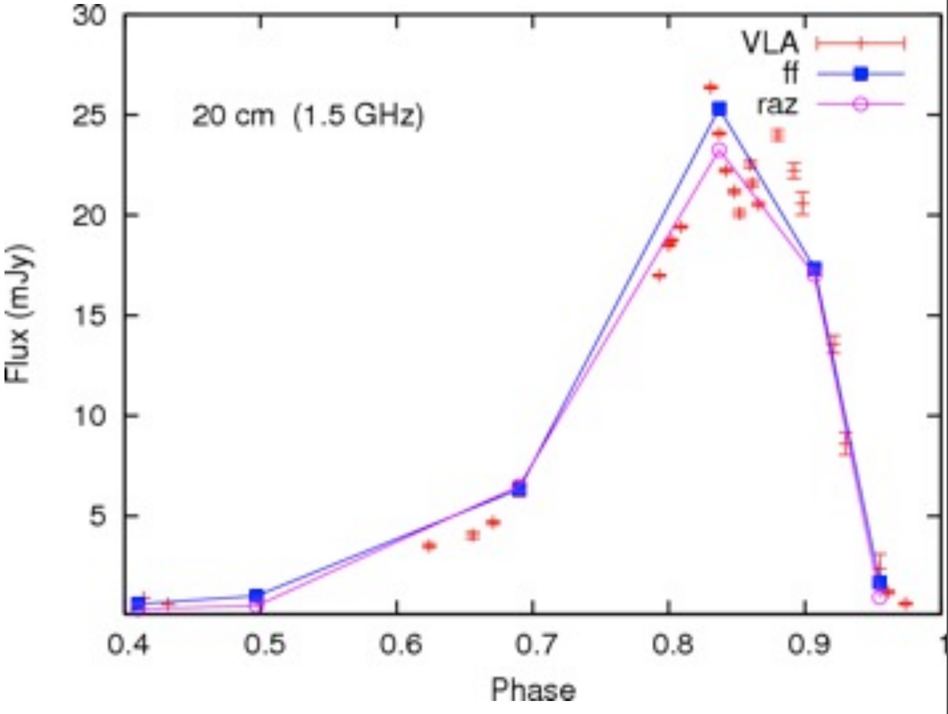


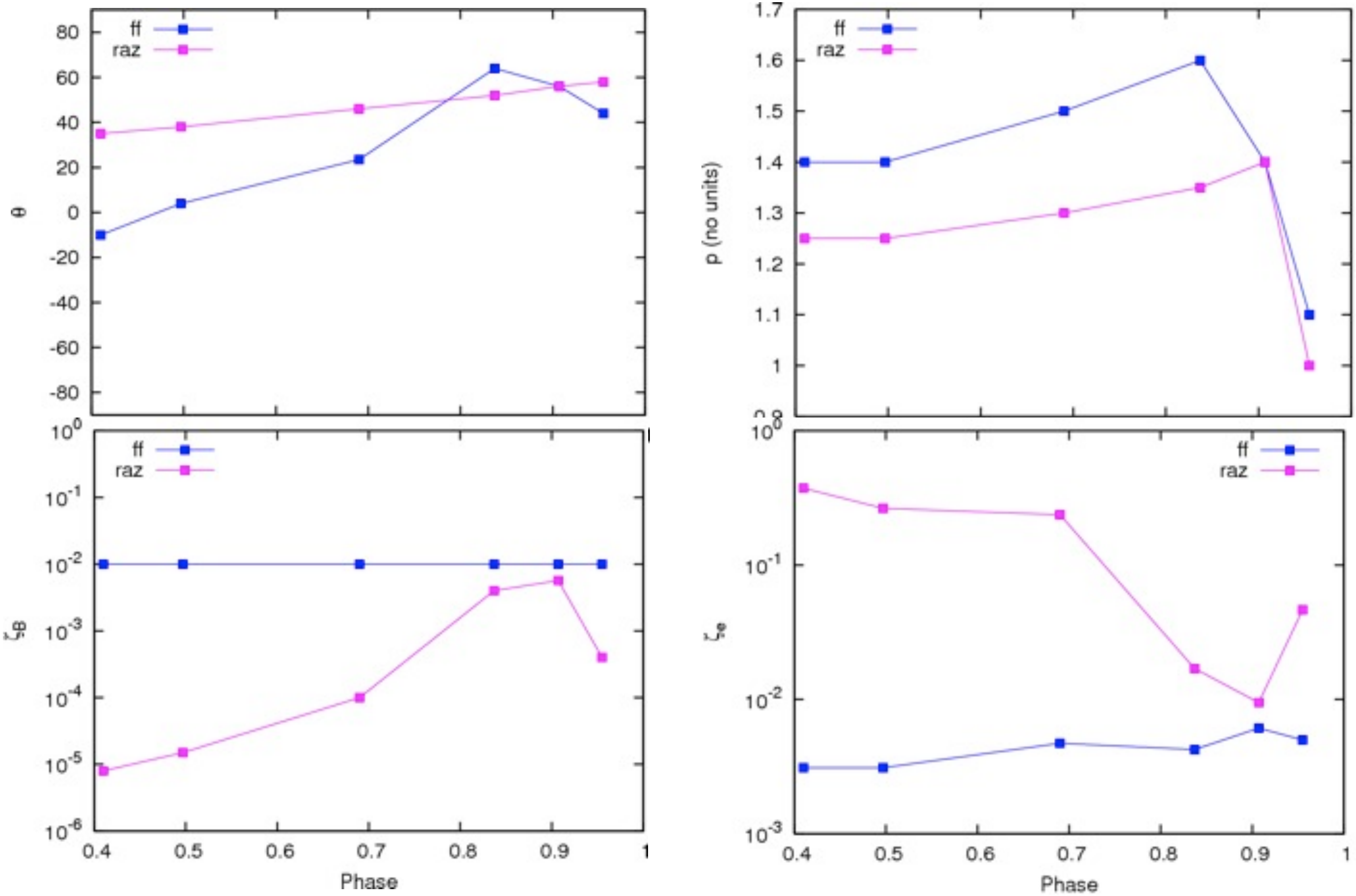
Model comparison to lightcurves

Match is now quite good….





Phase variation in model parameters



Summary

Colliding stellar winds in early-type binaries are important laboratories for **investigating high Mach Number shock physics** (ionization and temperature equilibration timescales) and particle acceleration

Highly eccentric systems – like WR140 – are particularly useful

Models of radio/X-ray/γ-ray emission provide insight into particle acceleration efficiencies, and the strength of the B-field

Exciting period (Fermi, EVLA, CTA)

Expect to see large variations in the high energy NT emission with phase

Expect to see high energy NT emission from many more sources

May see NT radio emission even from short period (~10d) O+O binaries?