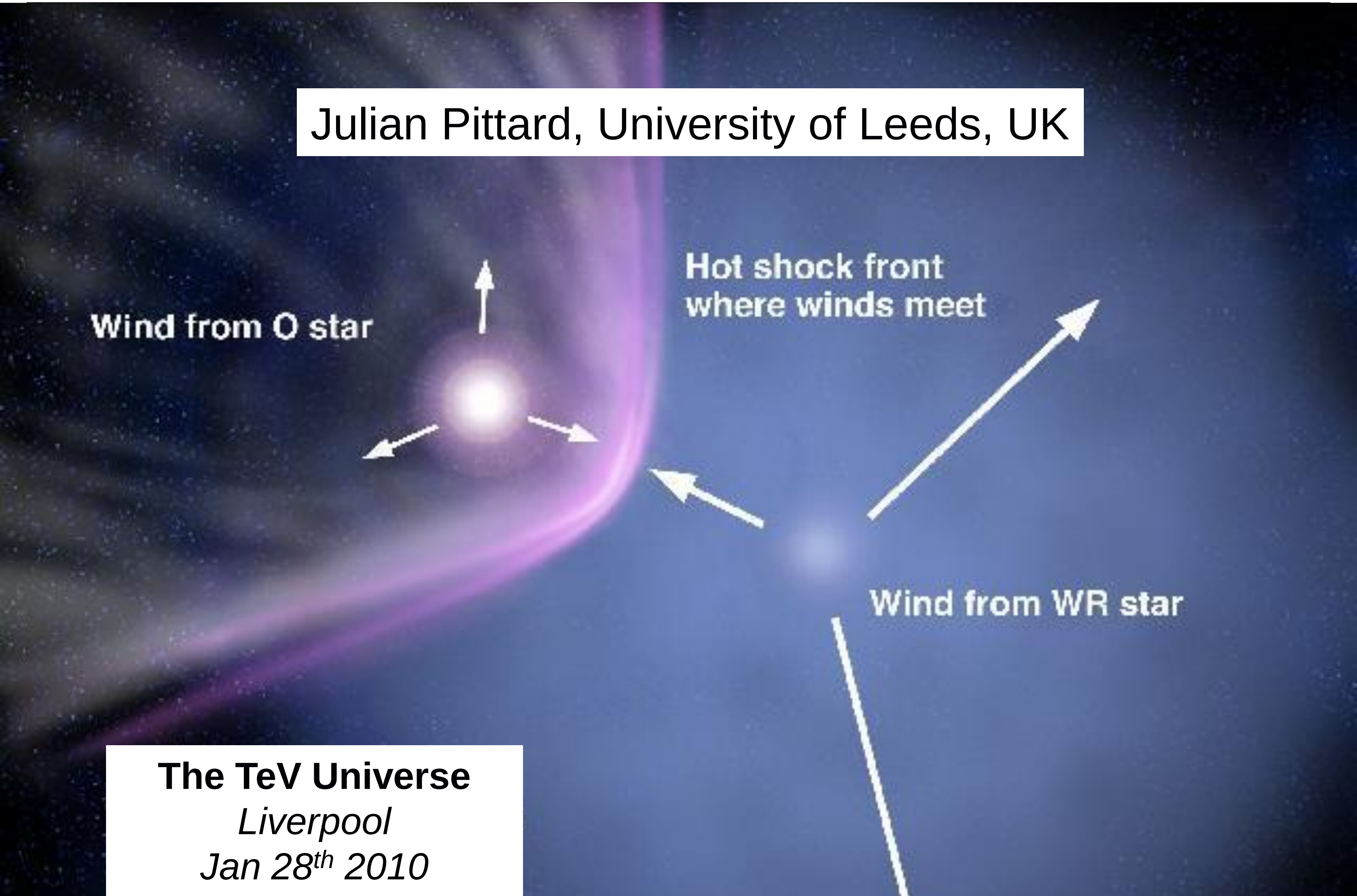
Studies of Colliding Stellar Winds

Julian Pittard, University of Leeds, UK



The TeV Universe
Liverpool
Jan 28th 2010

Outline

I. Taste of the interesting hydrodynamics

II. Particle acceleration in CWBs

III. A phenomenological model

IV. Conclusions and further work

Why study CWBs?

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CWBs probe wide range of interesting shock physics

System	Orbital Period (d)	Separation (AU)	Density (cm^{-3})	χ_{WR}	χ_{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

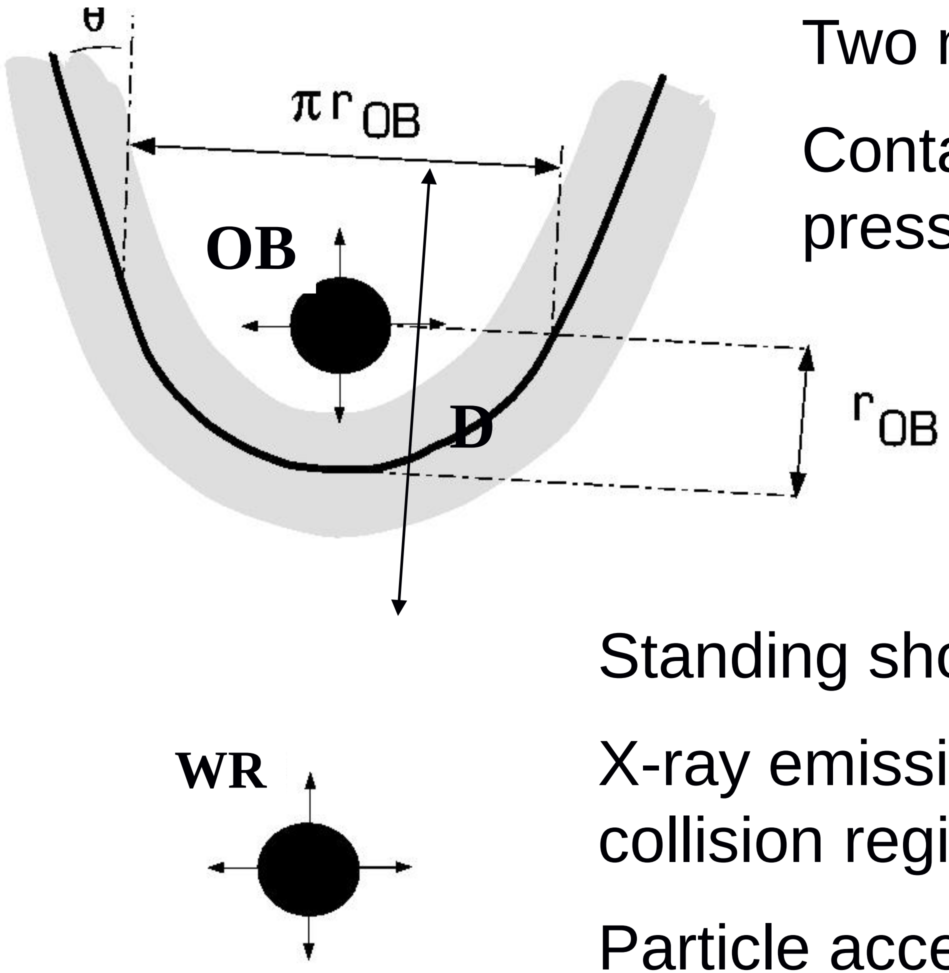
2 different regimes determined by characteristic *cooling parameter*,

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

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

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

Cartoon of a wind-wind collision



Two massive stars with stellar winds

Contact discontinuity where ram pressures are equal

$$\frac{r_{OB}}{D} = \frac{\eta^{1/2}}{1+\eta^{1/2}}$$

Standing shocks on either side of the CD

X-ray emission from shock-heated gas in collision region

Particle acceleration occurs somewhere in the interaction region

Why study CWBs?

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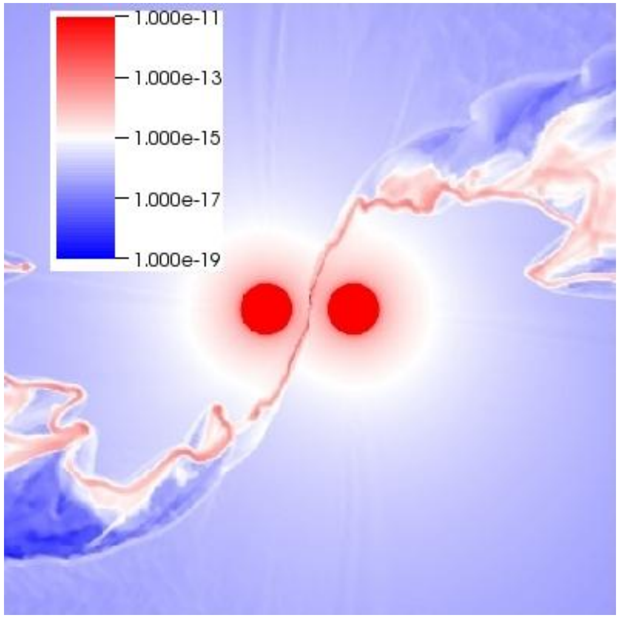
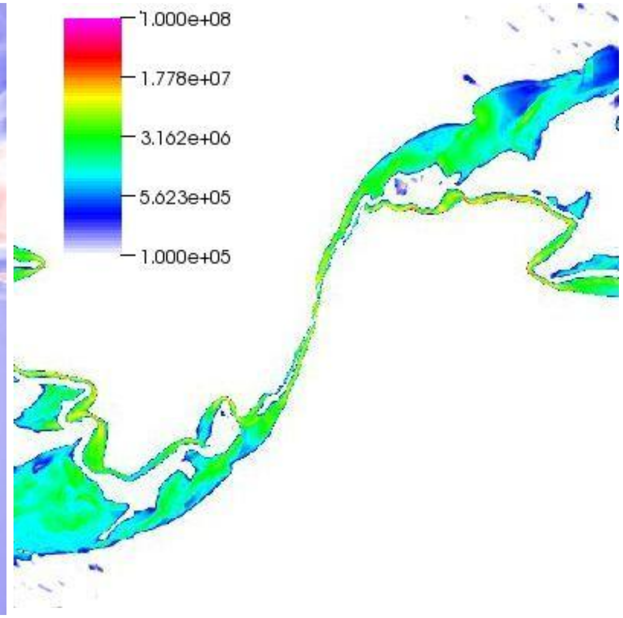
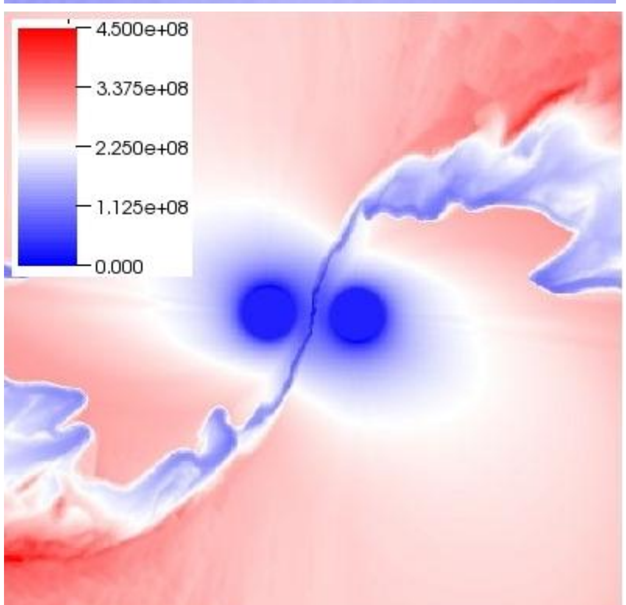




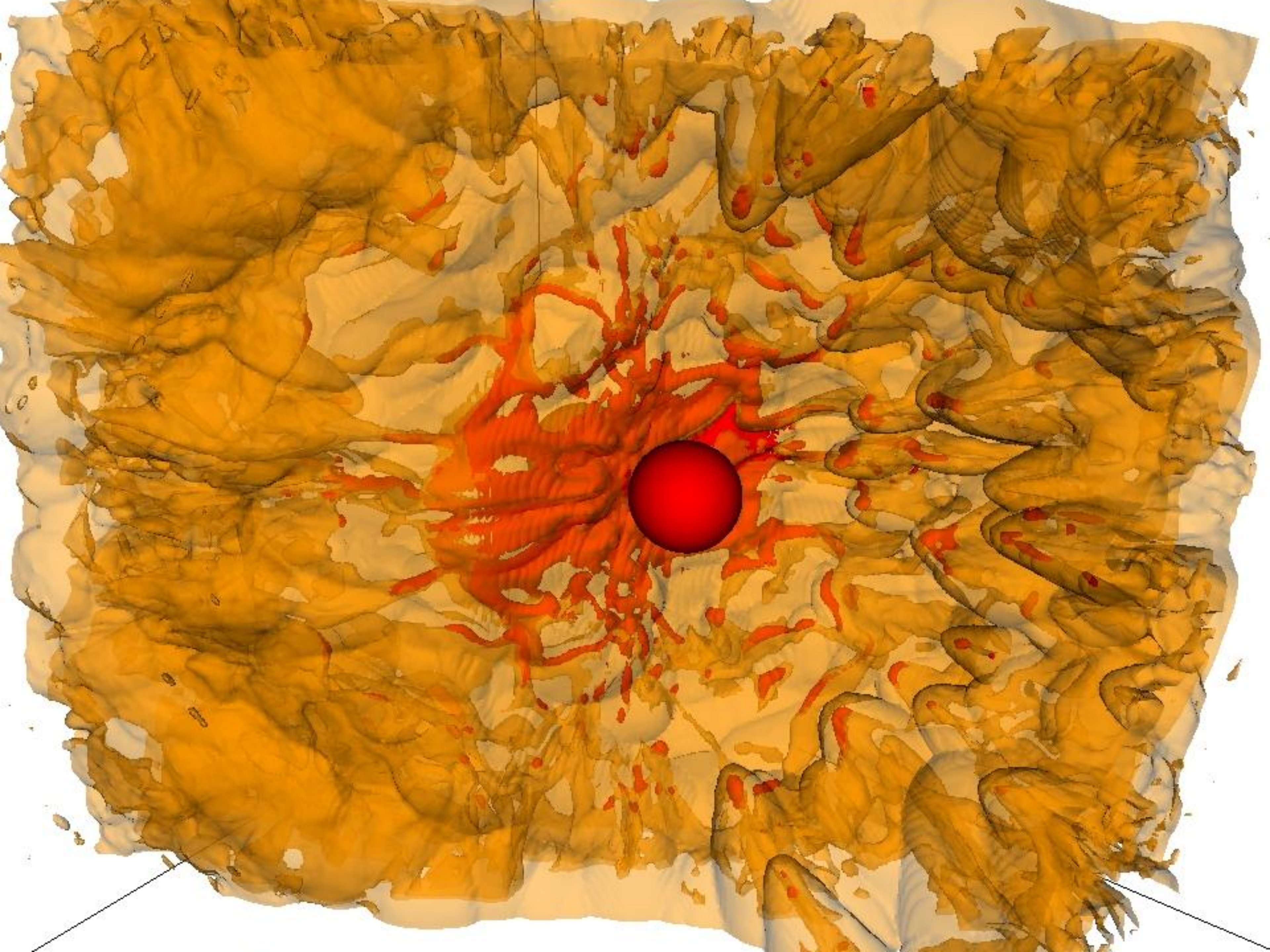
O6V + O6V, P=3d,
Dsep = 35 Rsun
$\chi << 1$



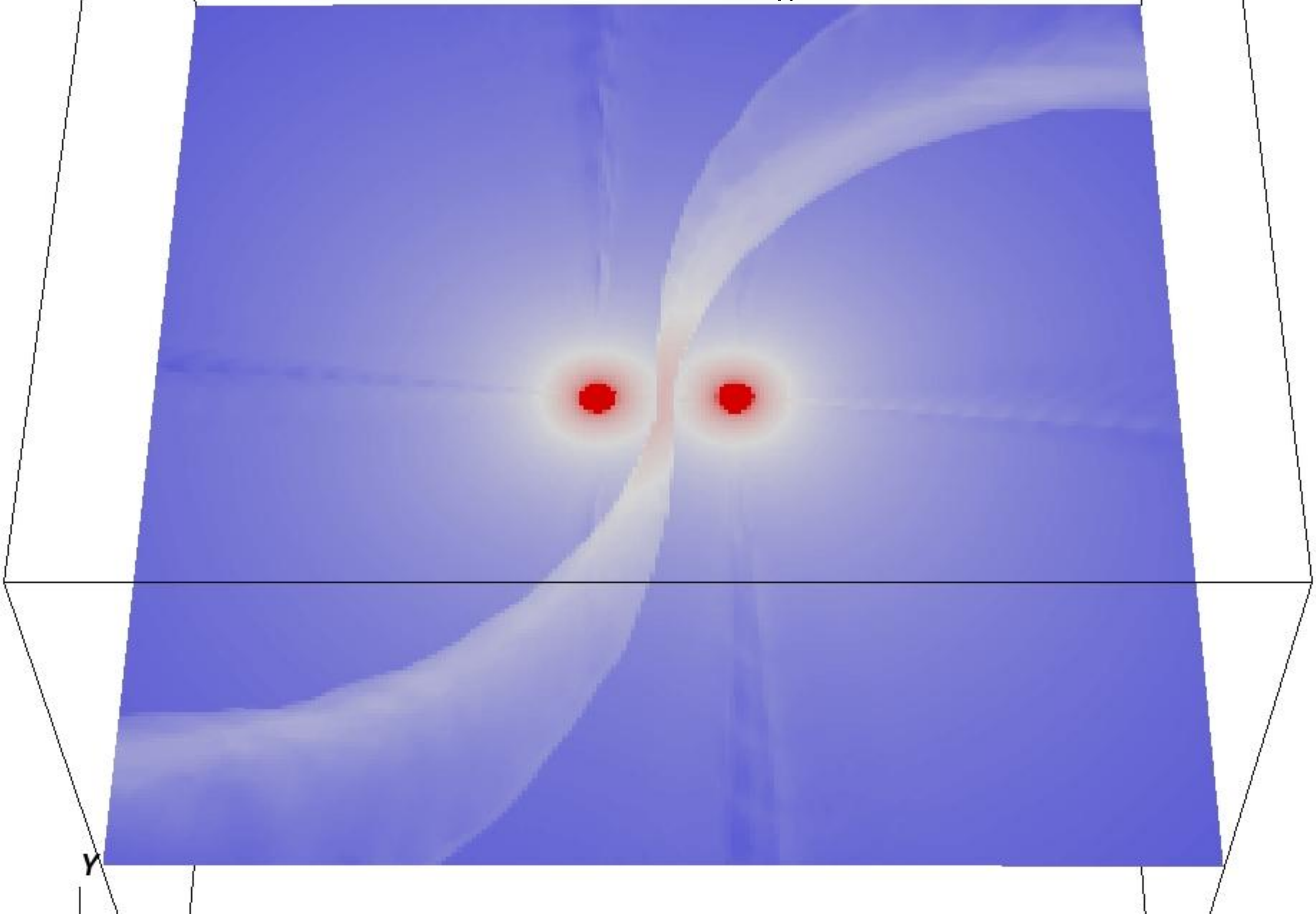
Cold plasma inside WCR

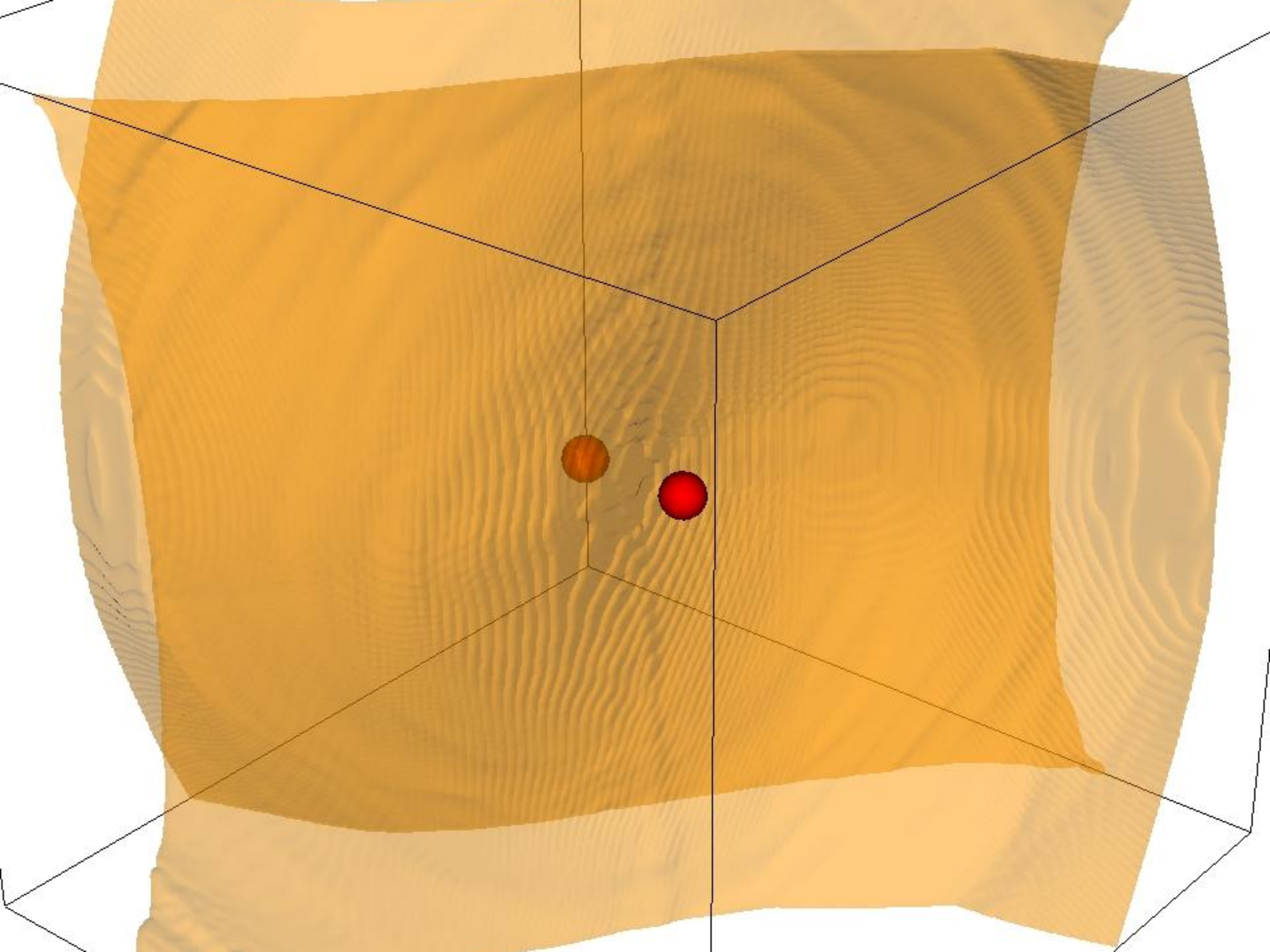
Wind speeds higher where radiative flux reinforced, relatively smaller in shadows behind stars

Leading side of WCR arms less susceptible to instabilities



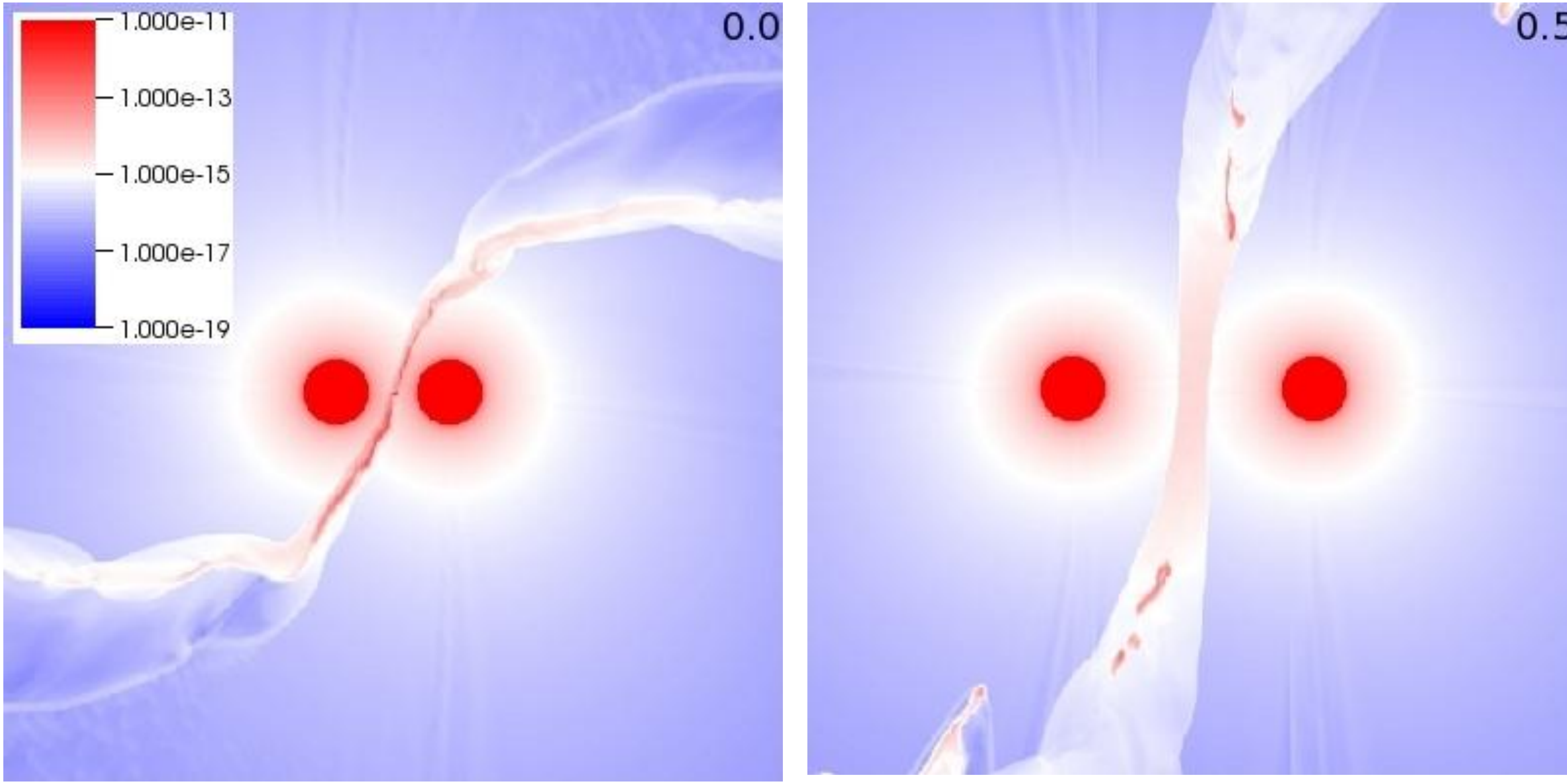
O6V + O6V, P=10d, Dsep=76.4 Rsun,
vshk ~ 2000 km/s, χ~40



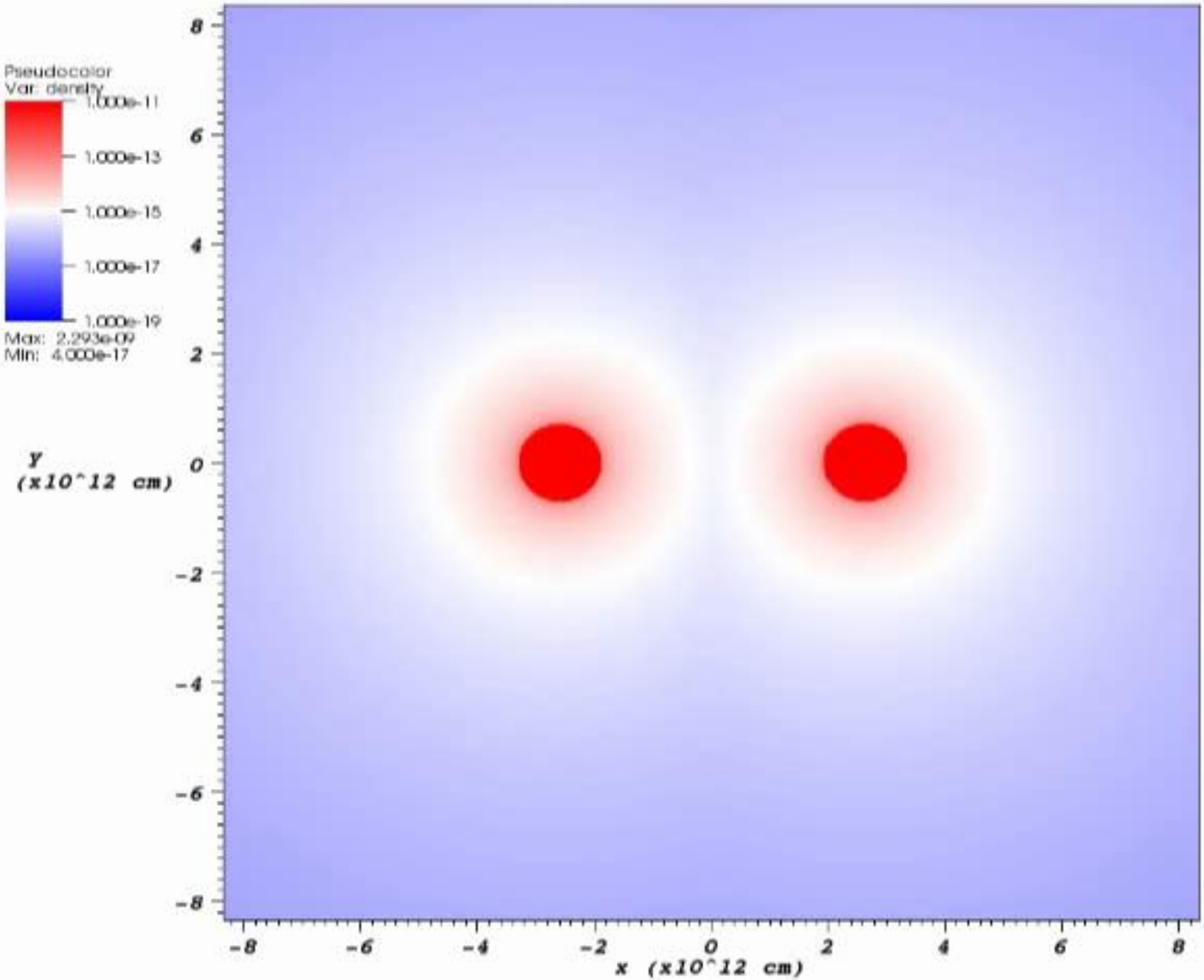


Why study CWBs?

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



Pittard (2009)



Pseudocolor
Var: density
1.000e-11
1.000e-13
1.000e-15
1.000e-17
1.000e-19
Max: 2.293e-09
Min: 4.000e-17
y (x10^12 cm)
x (x10^12 cm)

Eta Carinae: density movie

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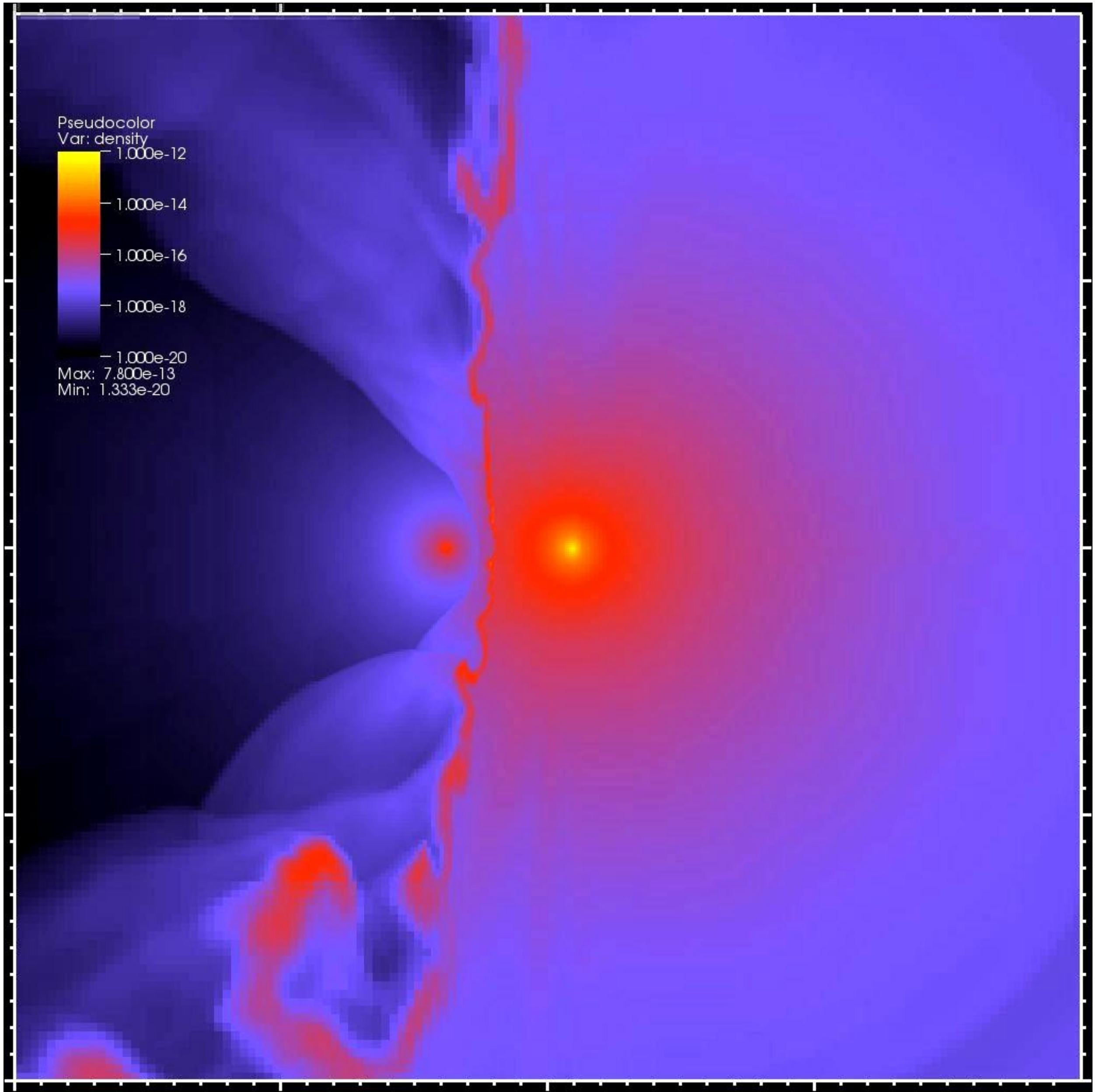

Parkin et al., in preparation

Terminal speed winds

Why study CWBs?

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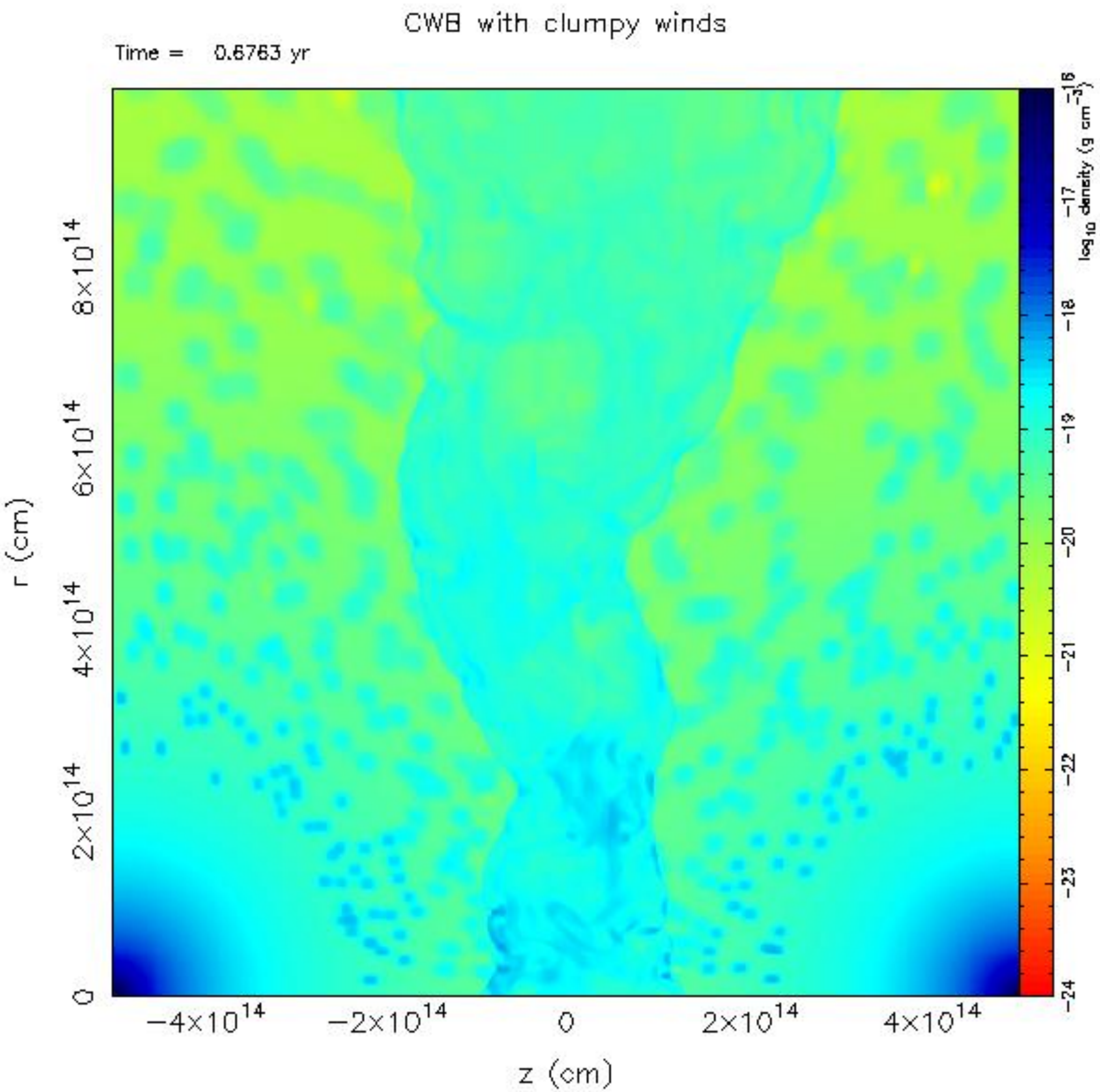

Clump destruction in adiabatic CWBs

Implications for particle accn?

Reconnection?

Stochastic accn?

Why study CWBs?

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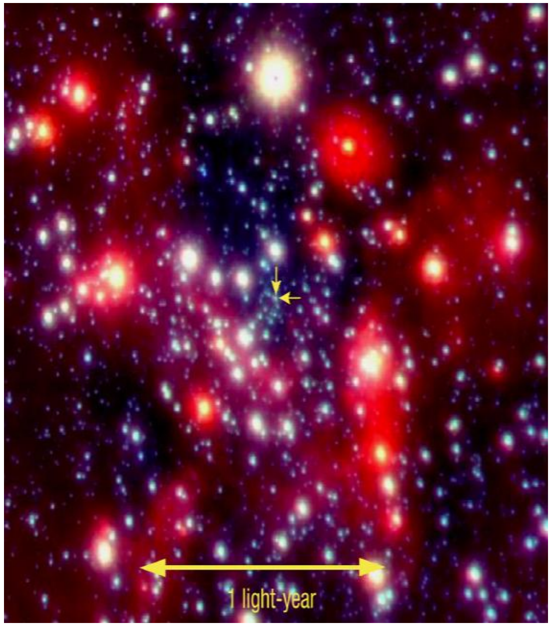
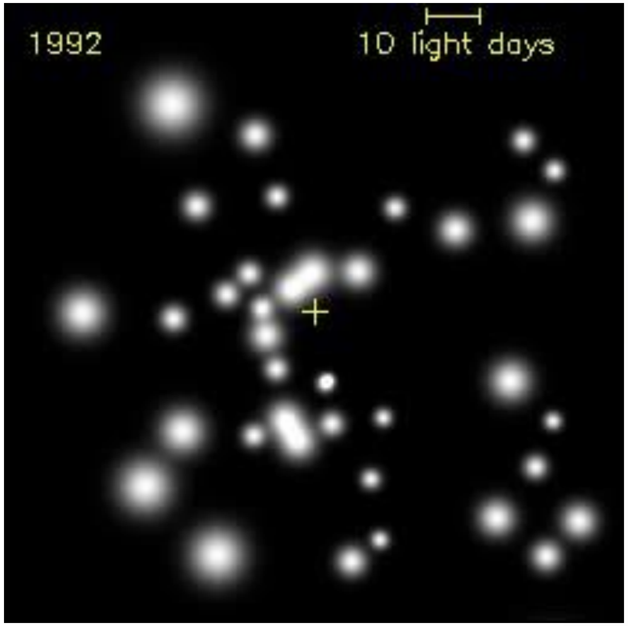
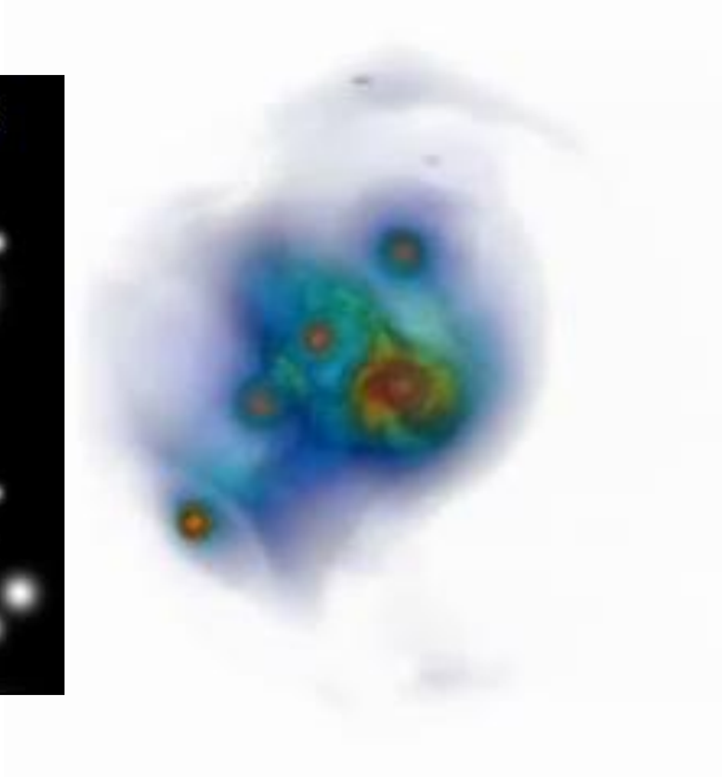
Multiple colliding winds in stellar clusters e.g. Carinae, Westerlund1/2, M17 etc.

Another example is the central cluster around Sgr A*







MPE / R. Genzel et al.

Coker & Pittard

Evidence for particle acceleration…

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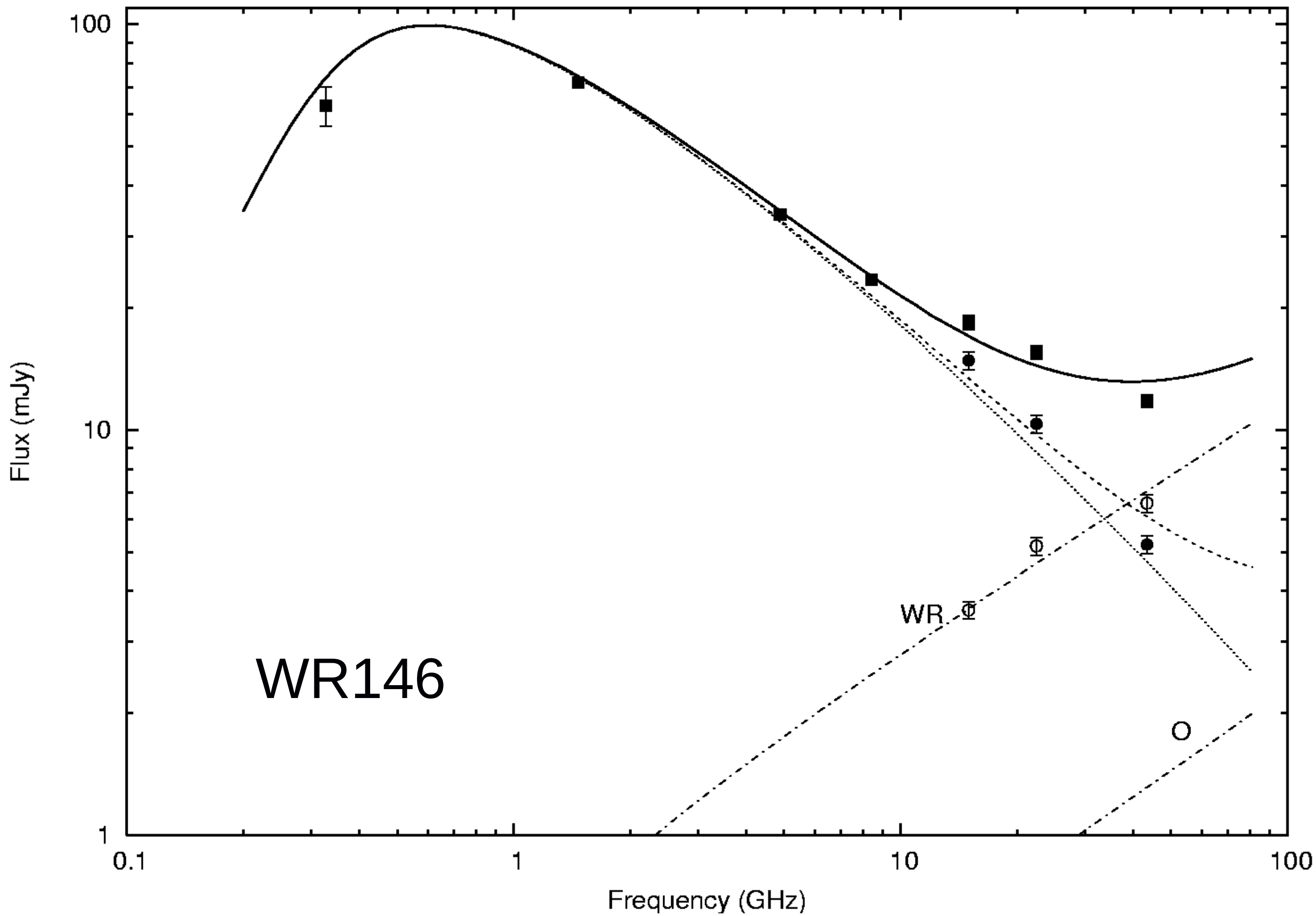
- WR 146 - brightest radio CWB – NT emission dominates



WR 146 radio obs

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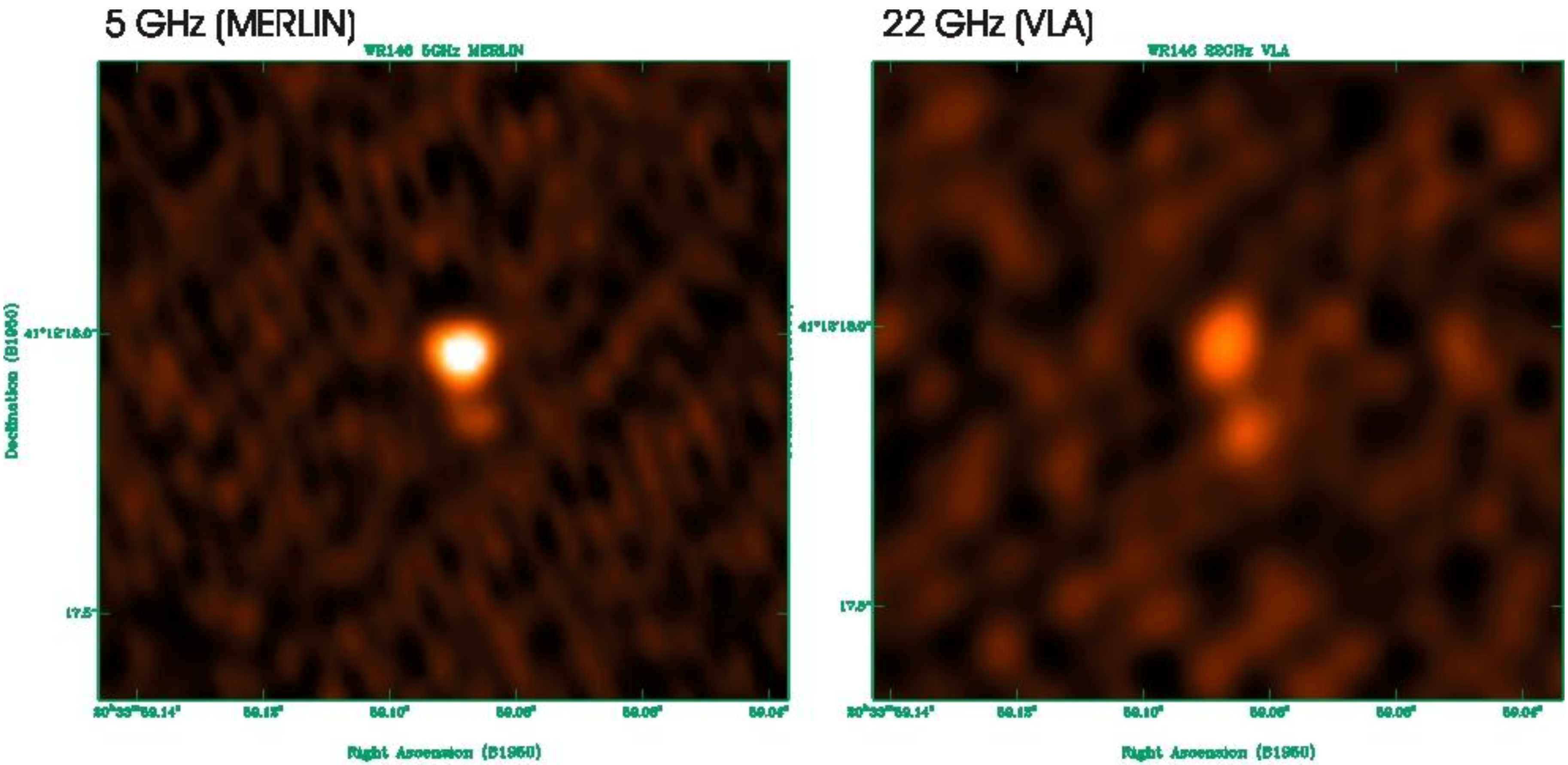
Spatially resolved thermal and NT components



Dougherty et al. (1996, 2000)

Evidence for particle acceleration…

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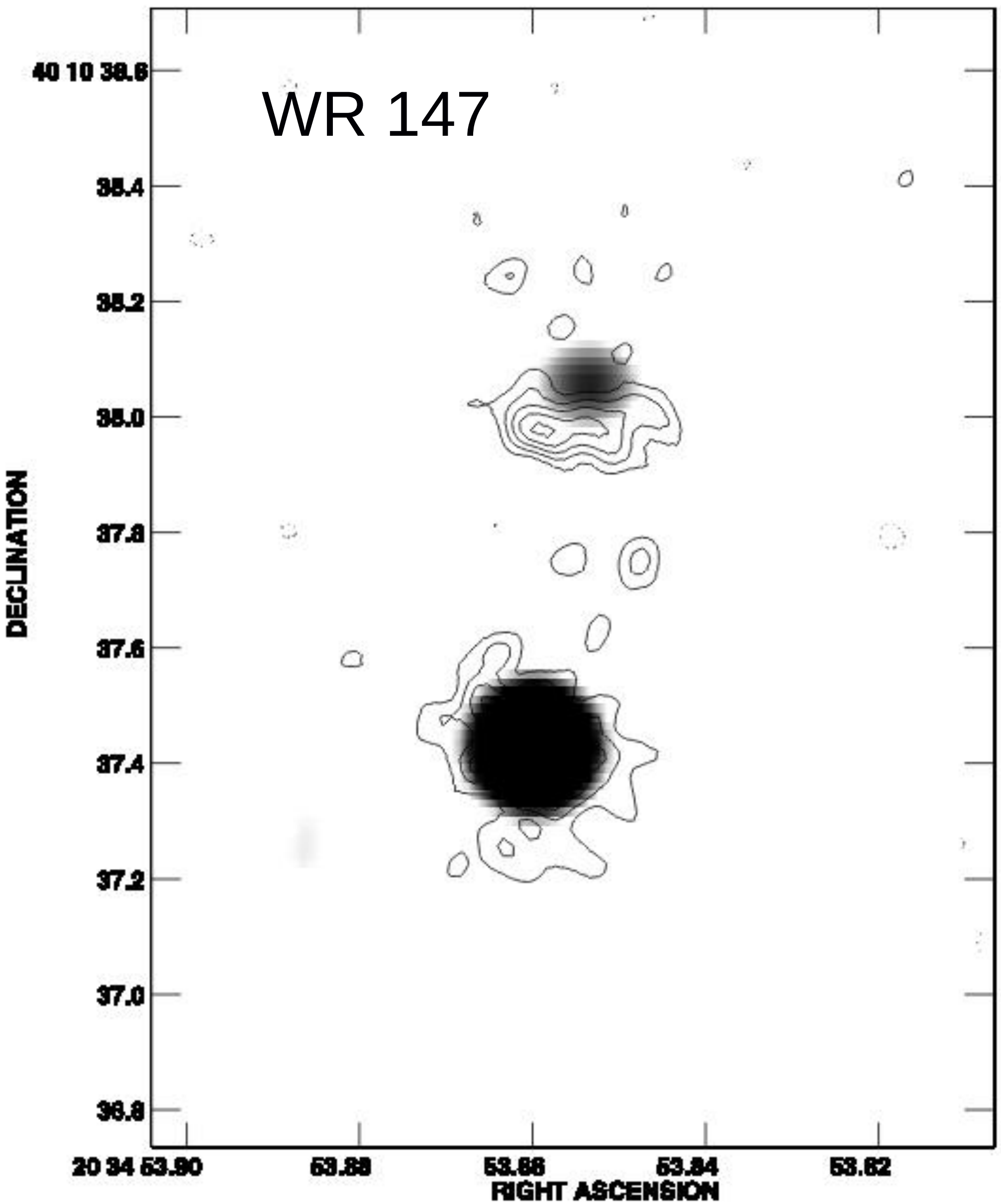

WR147: WR+OB binary

High resolution observations
- MERLIN @ 5GHz:

50 mas = 77AU @ 650pc

Two components, one thermal, one non-thermal

NT emission => relativistic electrons + magnetic fields

NT emission consistent with wind-collision position

Williams et al. (1997)

Evidence for particle acceleration…

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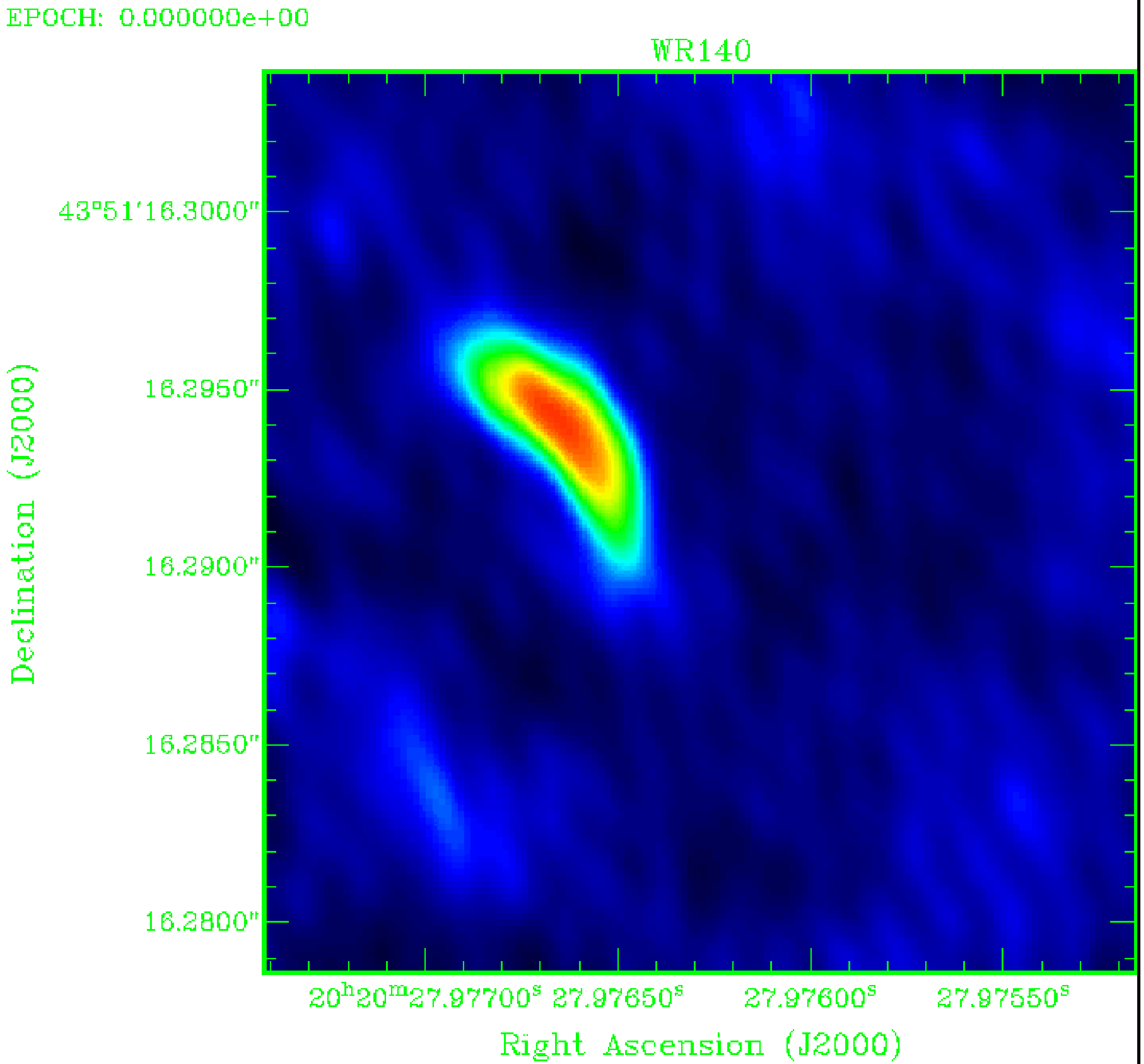

WR 140

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

Orbit size ~ 2-28 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

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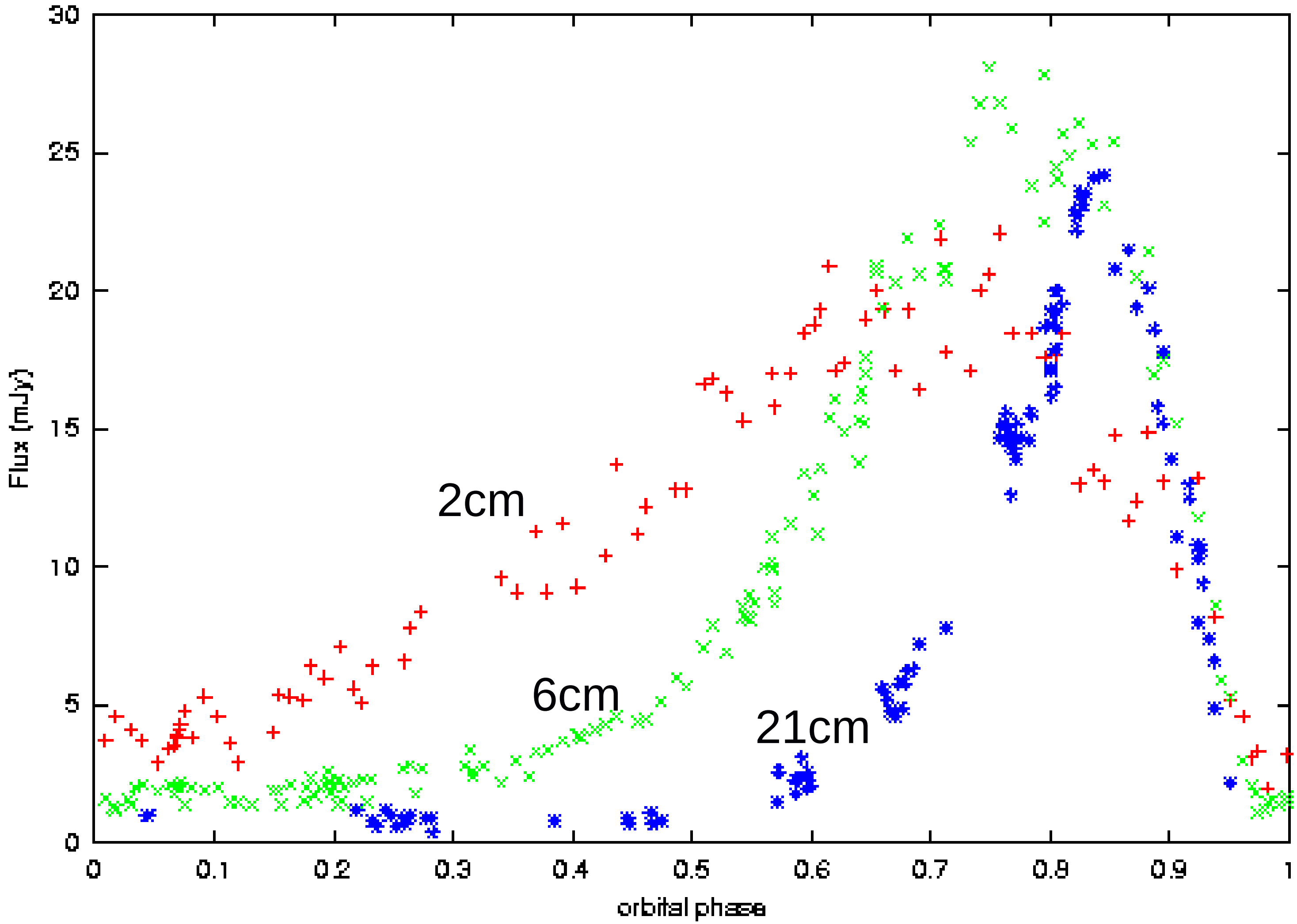

8 years of VLA (White & Becker 1995) +
WSRT (Williams et al 1991) data

Visibility of NT emission vs. binary period

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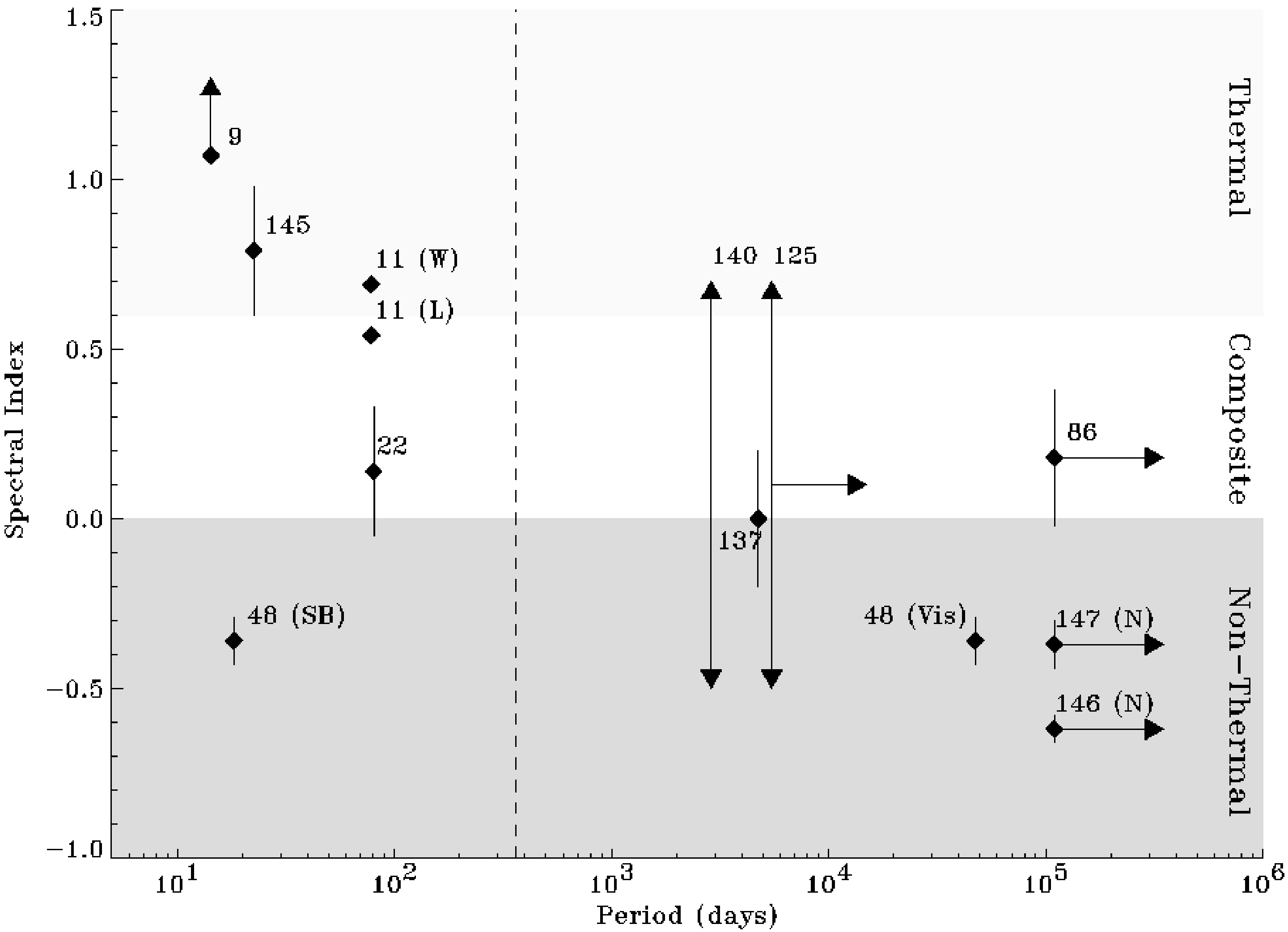


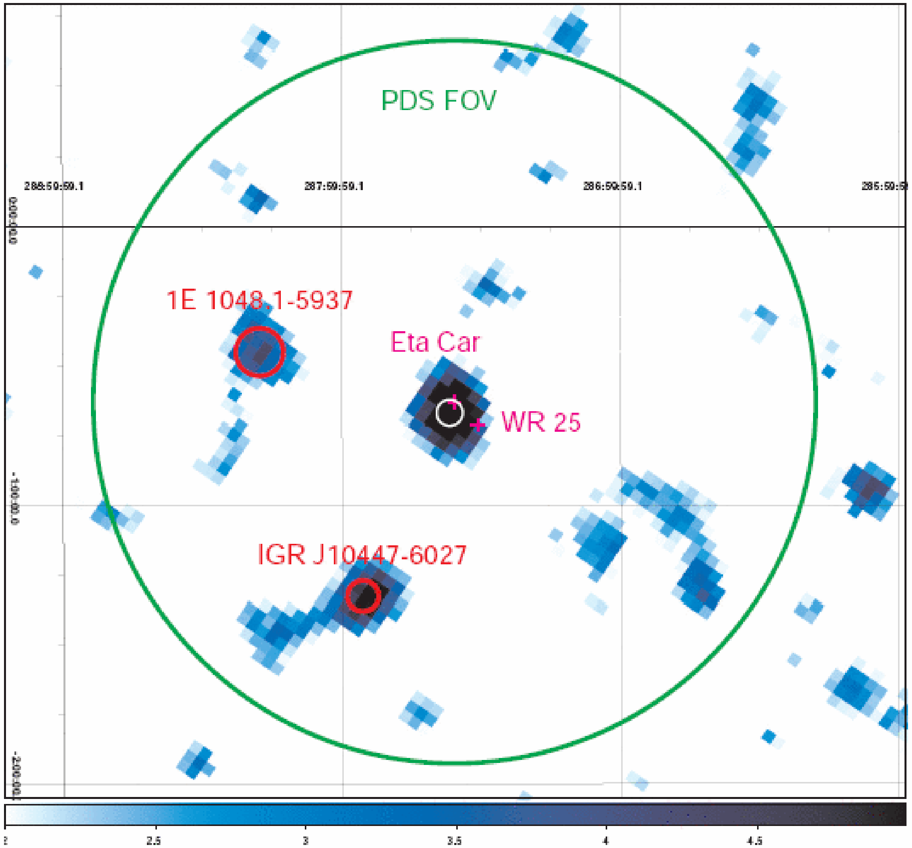
Thermal

Non-thermal

Dougherty & Williams (2000)

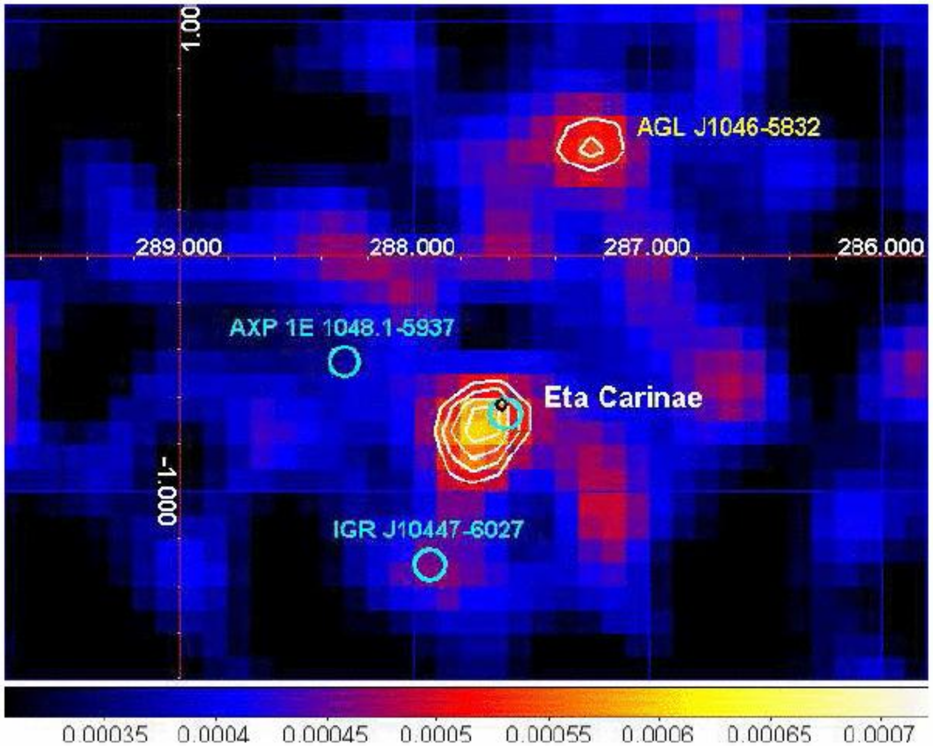
Higher Energy NT Emission

Eta Car INTEGRAL



Leyder et al. (2008)

AGILE



Tavani et al. (2009)

Previous models

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Early models of NT emission were simple

Radio:

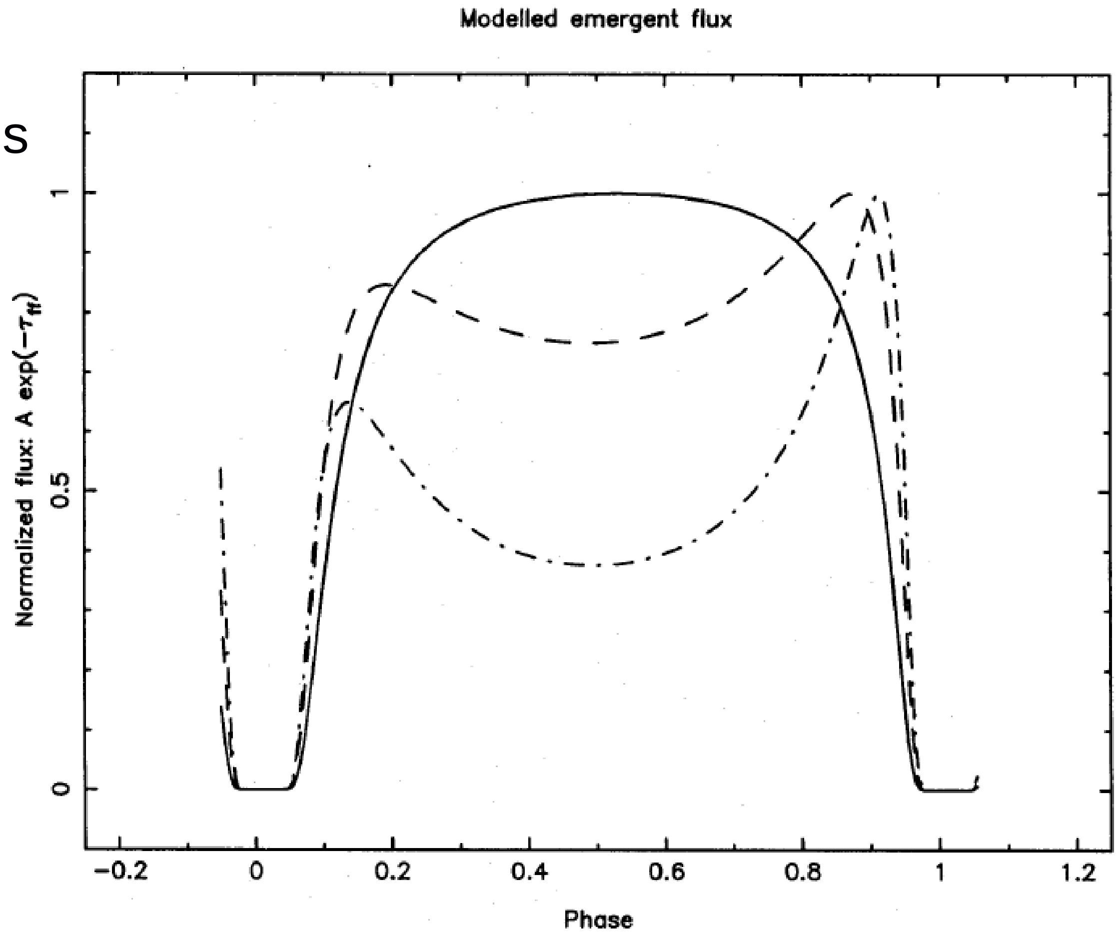
- Point source non-thermal emission, spherically symmetric winds –

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

- 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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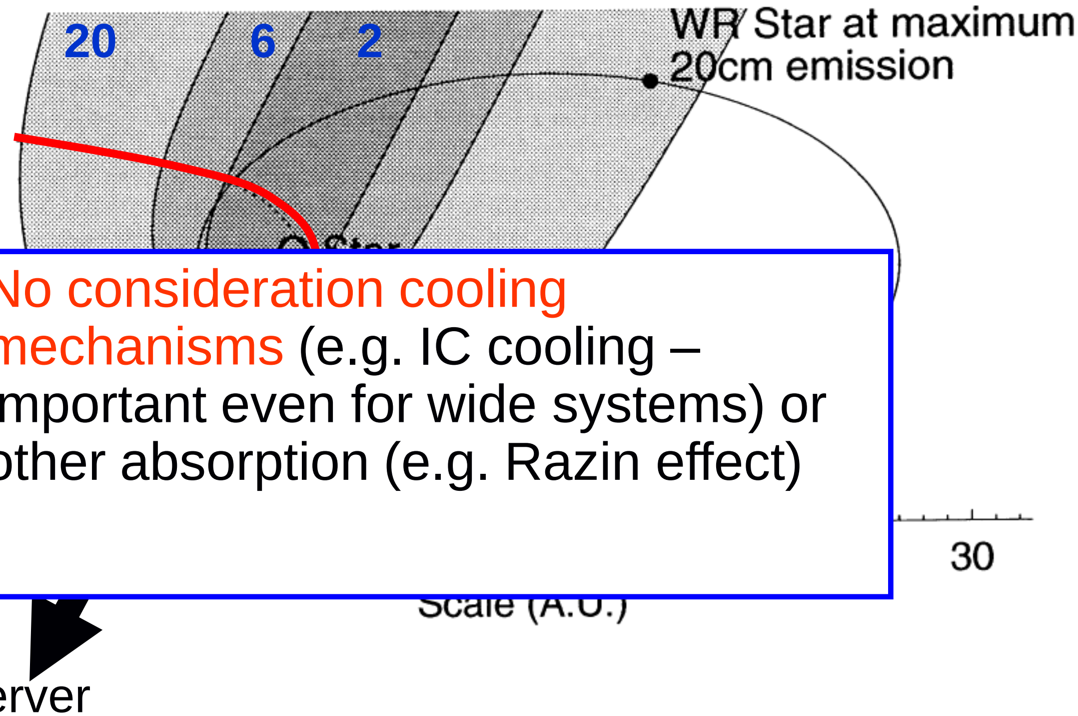
- maintains analytic solutions

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

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



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

Previous models

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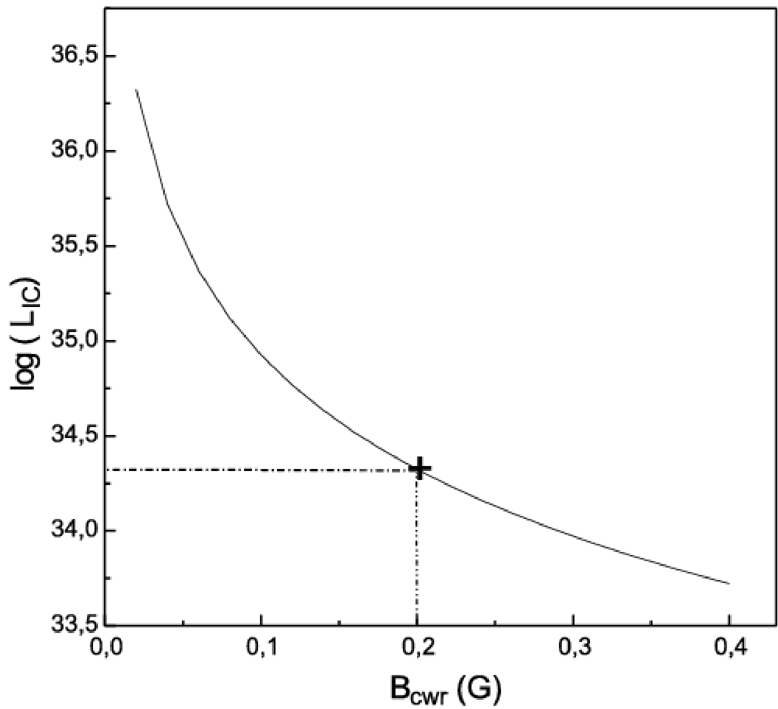
NT X-ray/γ-ray:

$$\frac{L_{sync}}{L_{ic}} = \frac{U_B}{U_{ph}}$$



Benaglia & Romero (2003)

Issues: L_{ic} is highly sensitive to the assumed B-field

Need the intrinsic (NOT observed) L_{sync}

More recently, Reimer and co-workers have used a two-zone model to approximate the acceleration of the NT particles and their advection downstream with the post-shock flow – however, the spatial representation remains crude.

A phenomenological model

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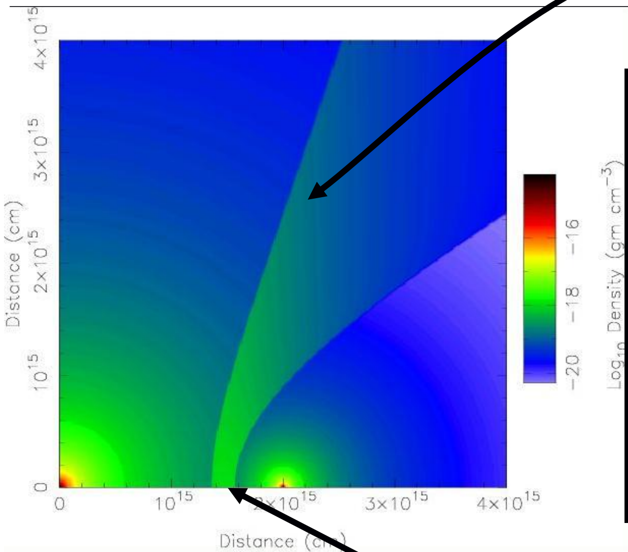
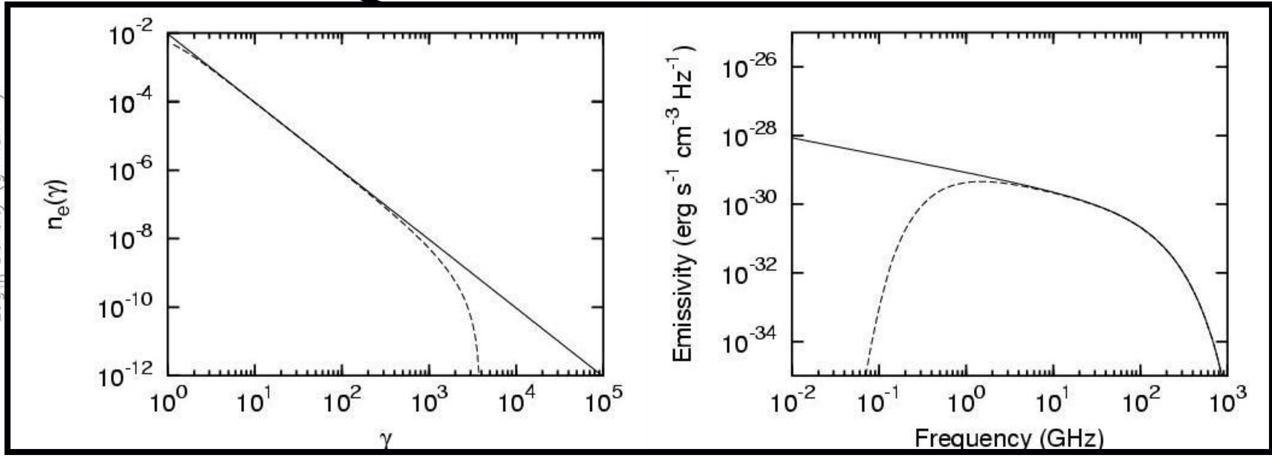
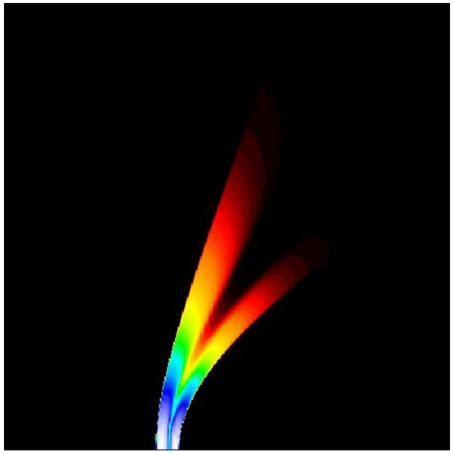
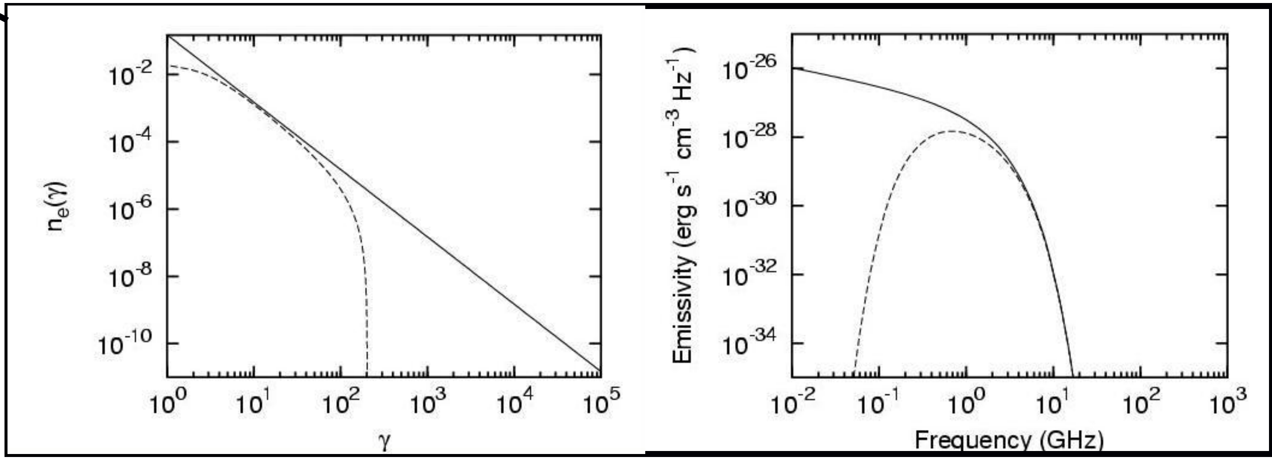








1.6 GHz emission map

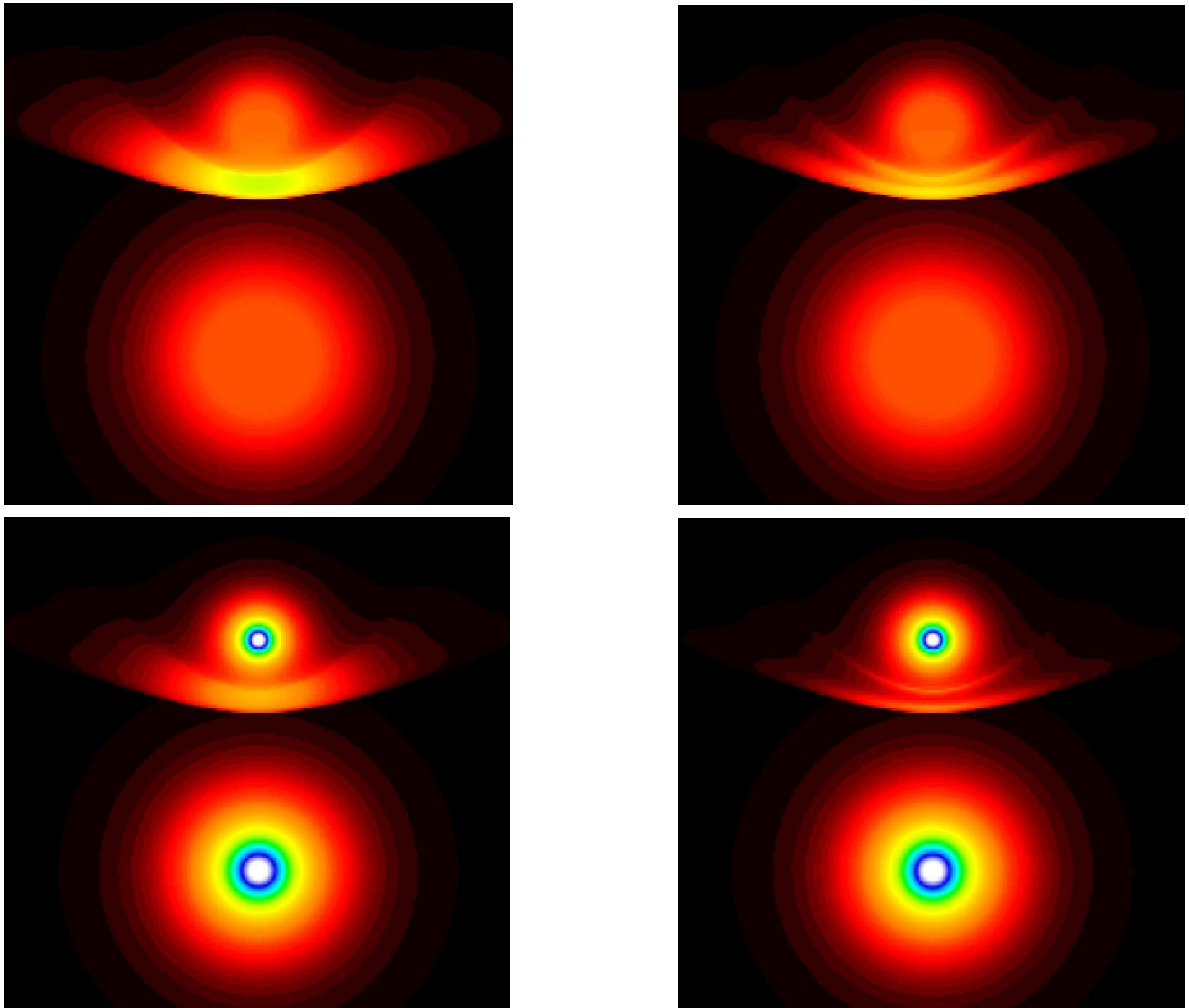
Pittard et al. (2006)

Example synthetic emission maps

No IC cooling | With IC cooling

1.6 GHz

22 GHz



Spectral fits to WR140 spectra

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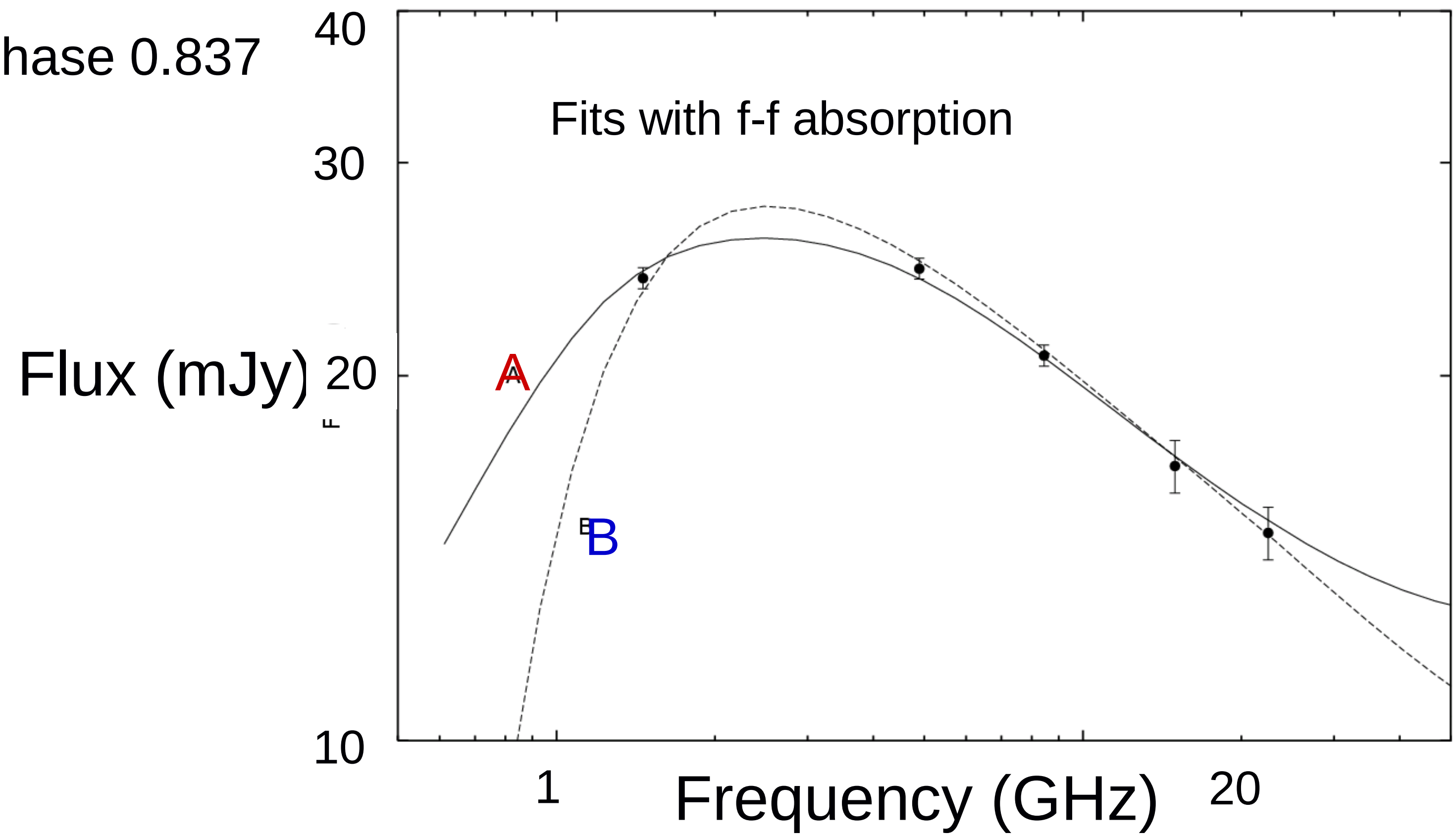
Phase 0.837



Pittard et al. (2006)

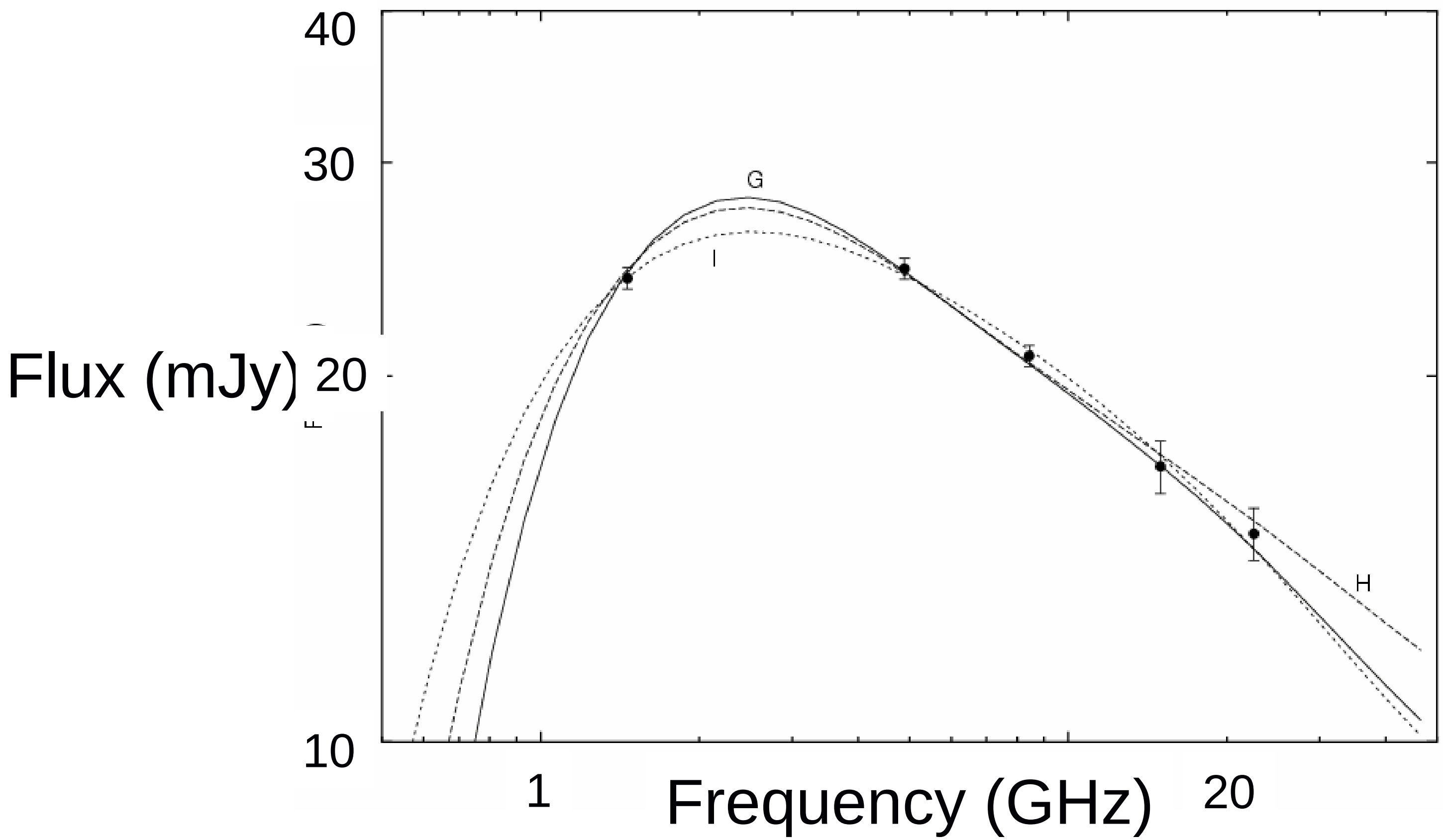
Model A: η=0.22, p=1.4, ζ_e=1.4x10^{-3}, ζ_B=0.05

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 Razin



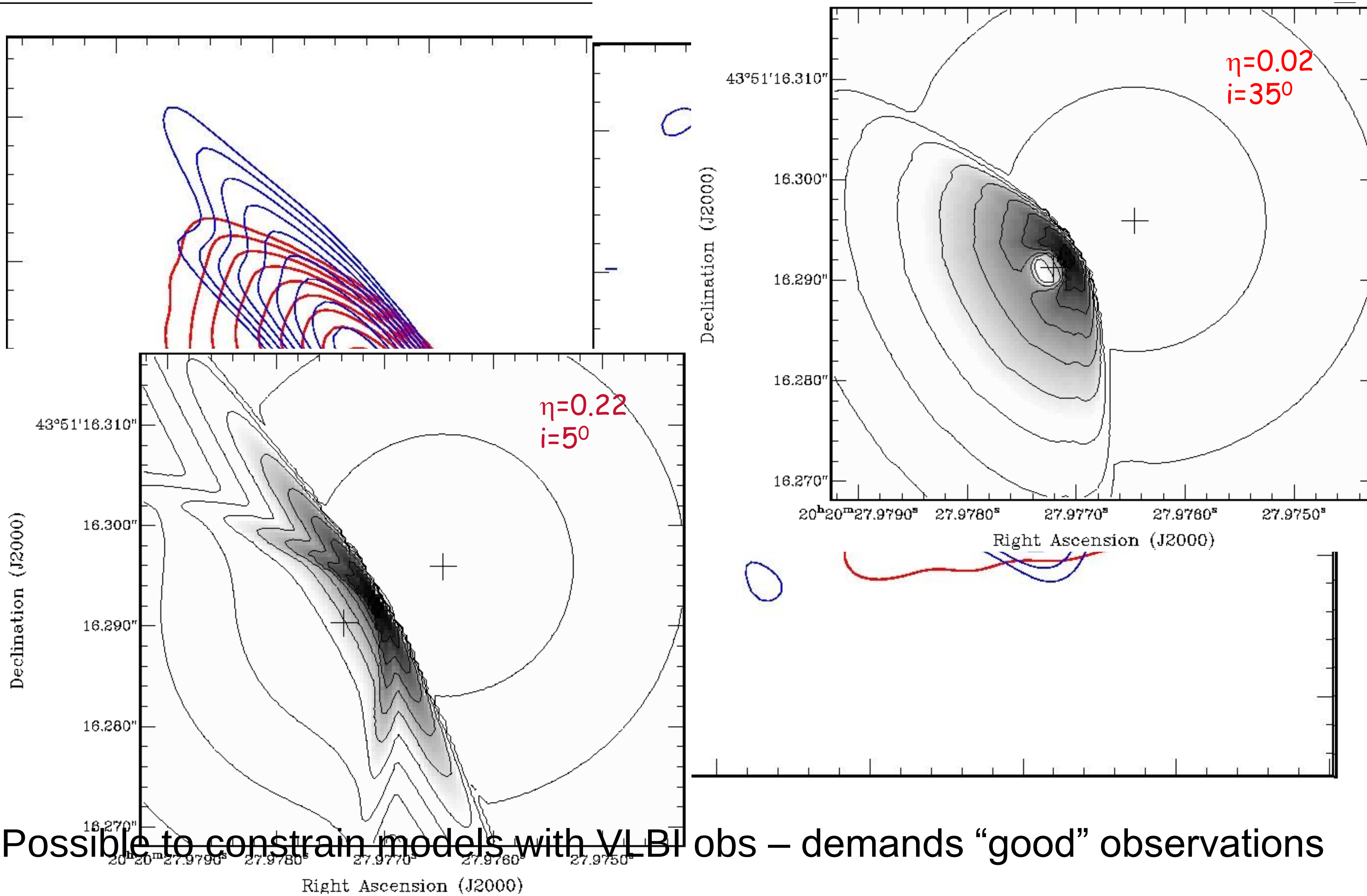
Model G: η=0.11, p=2.0, ζ_e=0.22, ζ_B=2.6x10^{-4}

Model I: η=0.0353, p=1.4, ζ_e=0.14, ζ_B=1.0x10^{-3}

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

We can obtain fits with p = 2!

Modelling 8 GHz VLBA observations



Possible to constrain models with VLBI obs – demands "good" observations

Gamma-ray absorption

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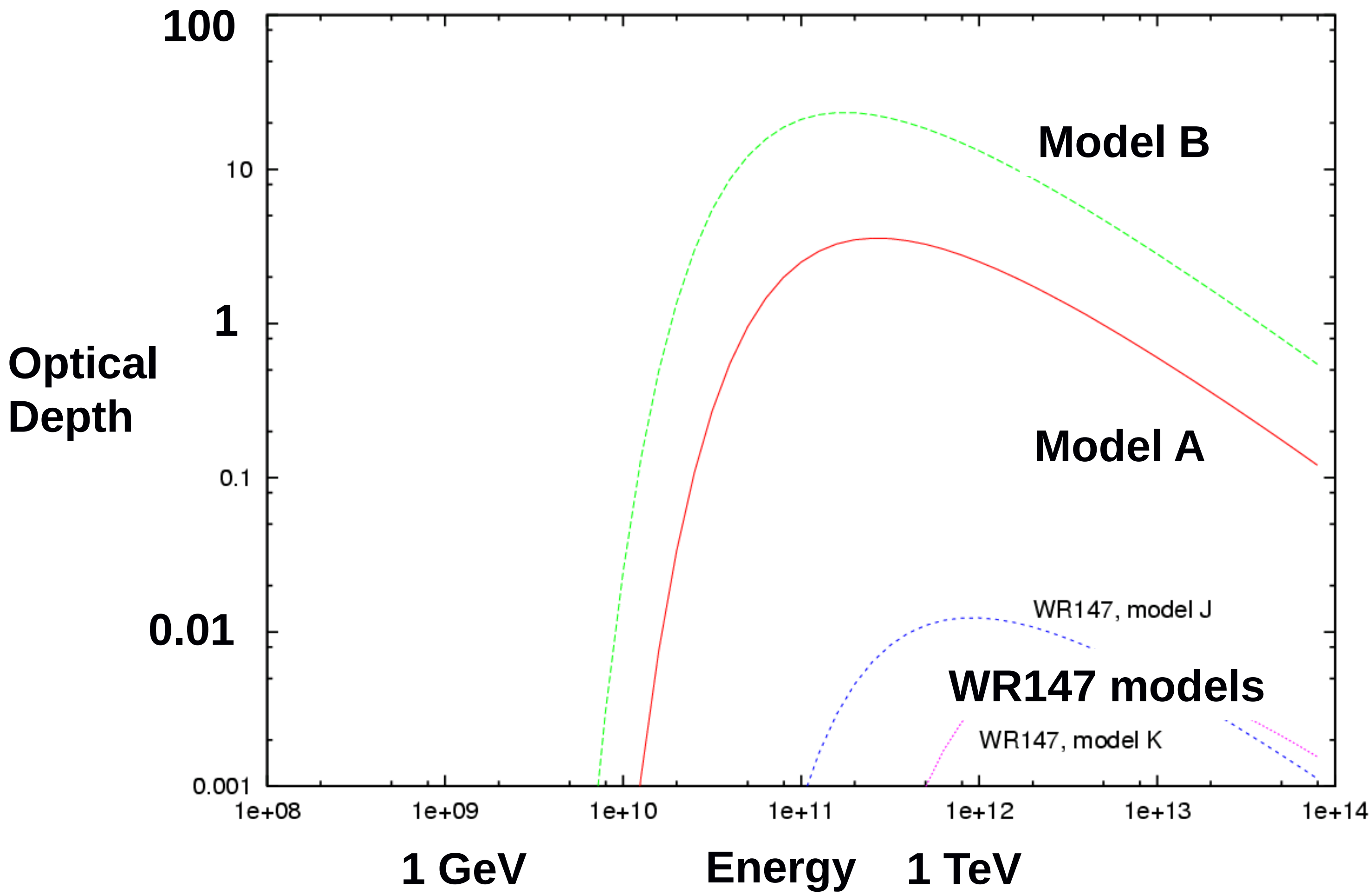
Two-photon pair production: $\gamma + \gamma_* \rightarrow e^- + e^+$



Pair production in electric field of charged nuclei is negligible

High energy emission at phase 0.837

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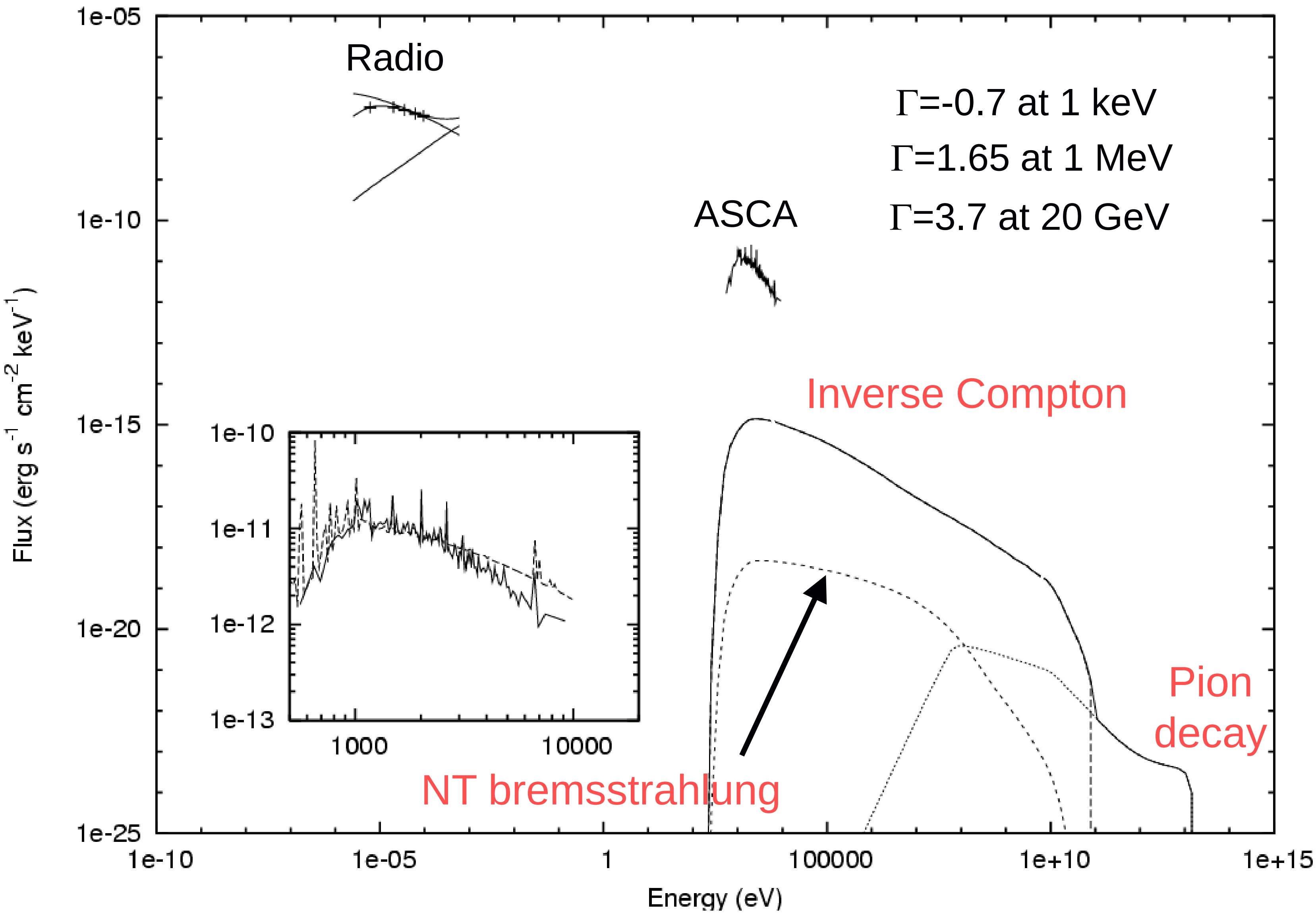

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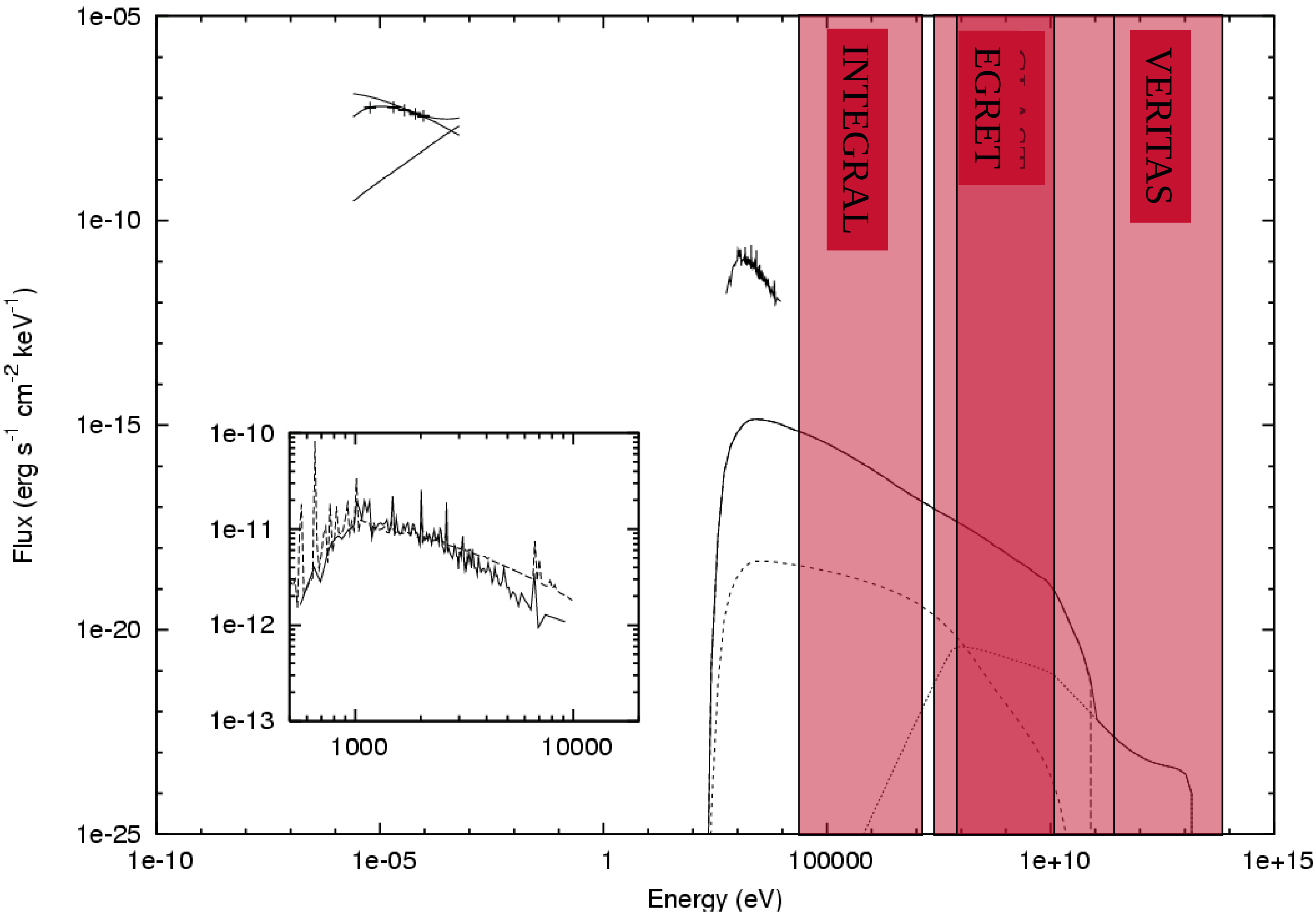

Predicted luminosities and fluxes

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Mechanism	Total emission ($erg\,s^{-1}$)	EGRET (100MeV-10GeV) ($erg\,s^{-1}$)	EGRET (100MeV-10GeV) ($photons\,s^{-1}\,cm^{-2}$)	INTEGRAL IBIS (15keV-10MeV) ($photons\,s^{-1}\,cm^{-2}$)	GLAST (20MeV-300GeV) ($photons\,s^{-1}\,cm^{-2}$)
Inverse Compton	3.5×10^{33}	2.1×10^{33}	5.4×10^{-9}	2.7×10^{-6}	1.5×10^{-8}
Rel. bremsstrahlung	1.8×10^{30}	3.2×10^{29}	2.5×10^{-12}	2.0×10^{-9}	2.1×10^{-11}
π^0 decay	6.8×10^{31}	9.8×10^{30}	1.3×10^{-11}	3.9×10^{-14}	1.8×10^{-11}
Total	3.6×10^{33}	2.1×10^{33}	5.4×10^{-9}	2.7×10^{-6}	1.5×10^{-8}

Predicted EGRET flux is 50x lower than 3EG J022+4317

Do not predict a detection (>100 yr for 5σ)

Fermi 5σ sensitivity at E > 100MeV for a 2yr all-sky survey is 1.6 x 10^{-9} ph s^{-1} cm^{-2}

High-energy observations are critical to establishing some model parameters

Model discrimination

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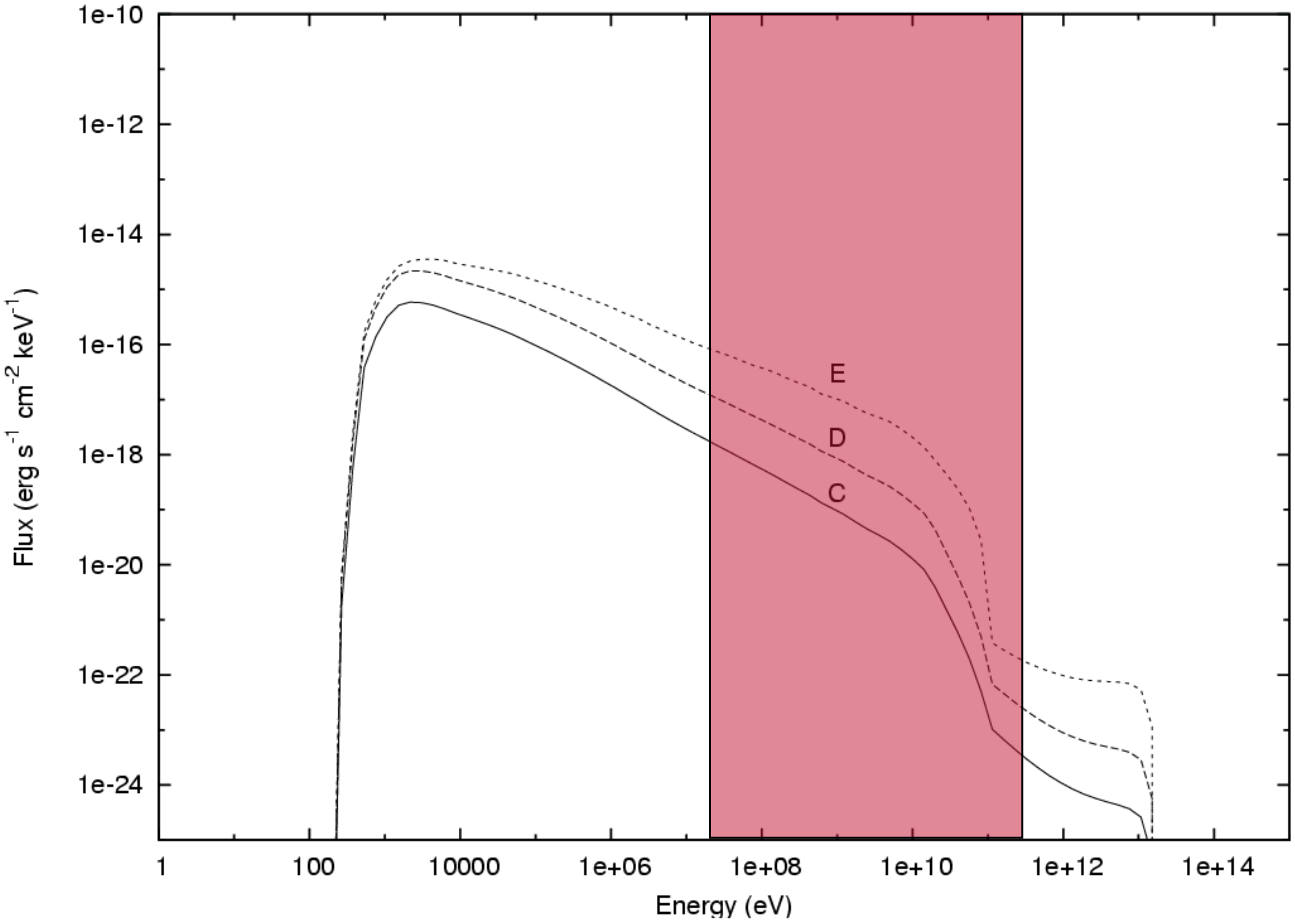
Fermi will be able to discriminate between models



Will place constraints on the spectral index and B-field

Model discrimination

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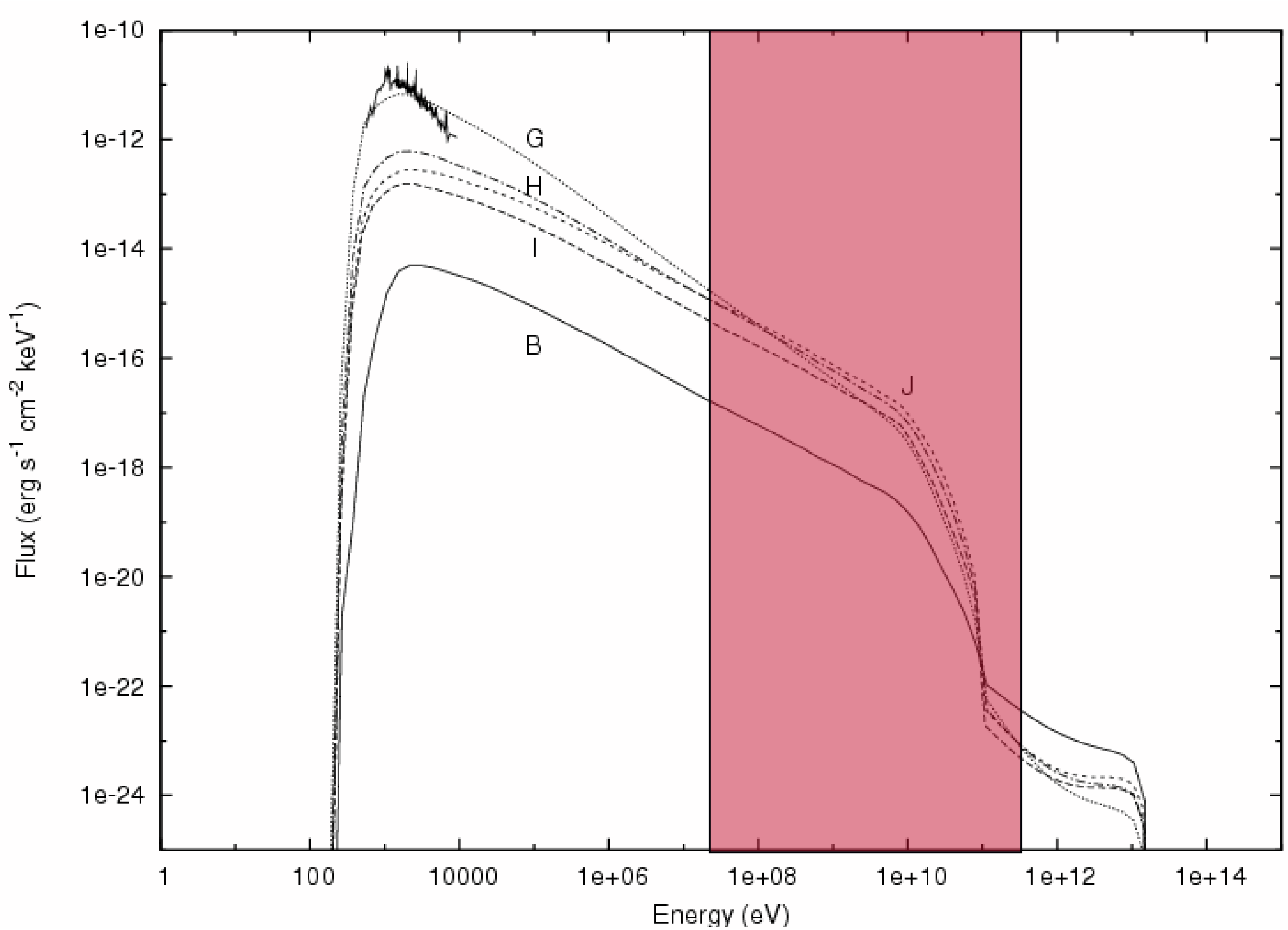
Model B is likely a lower limit



Flux at TeV energies in VERITAS band

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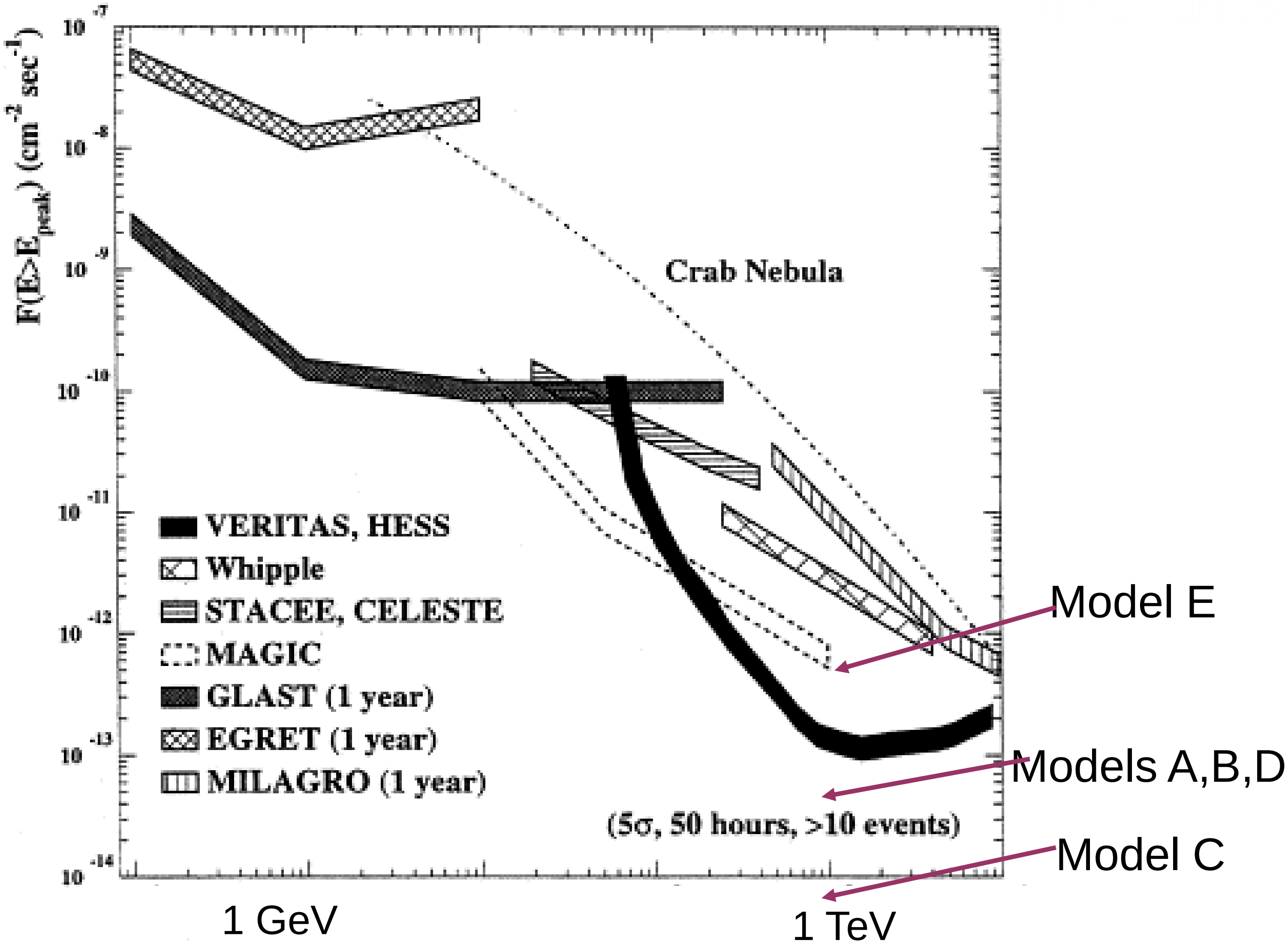

Conclusions

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Colliding winds in early-type binaries are important laboratories for investigating shock physics 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, VERITAS/HESS/Magic, 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