Theory and Observations of Colliding Wind Binaries

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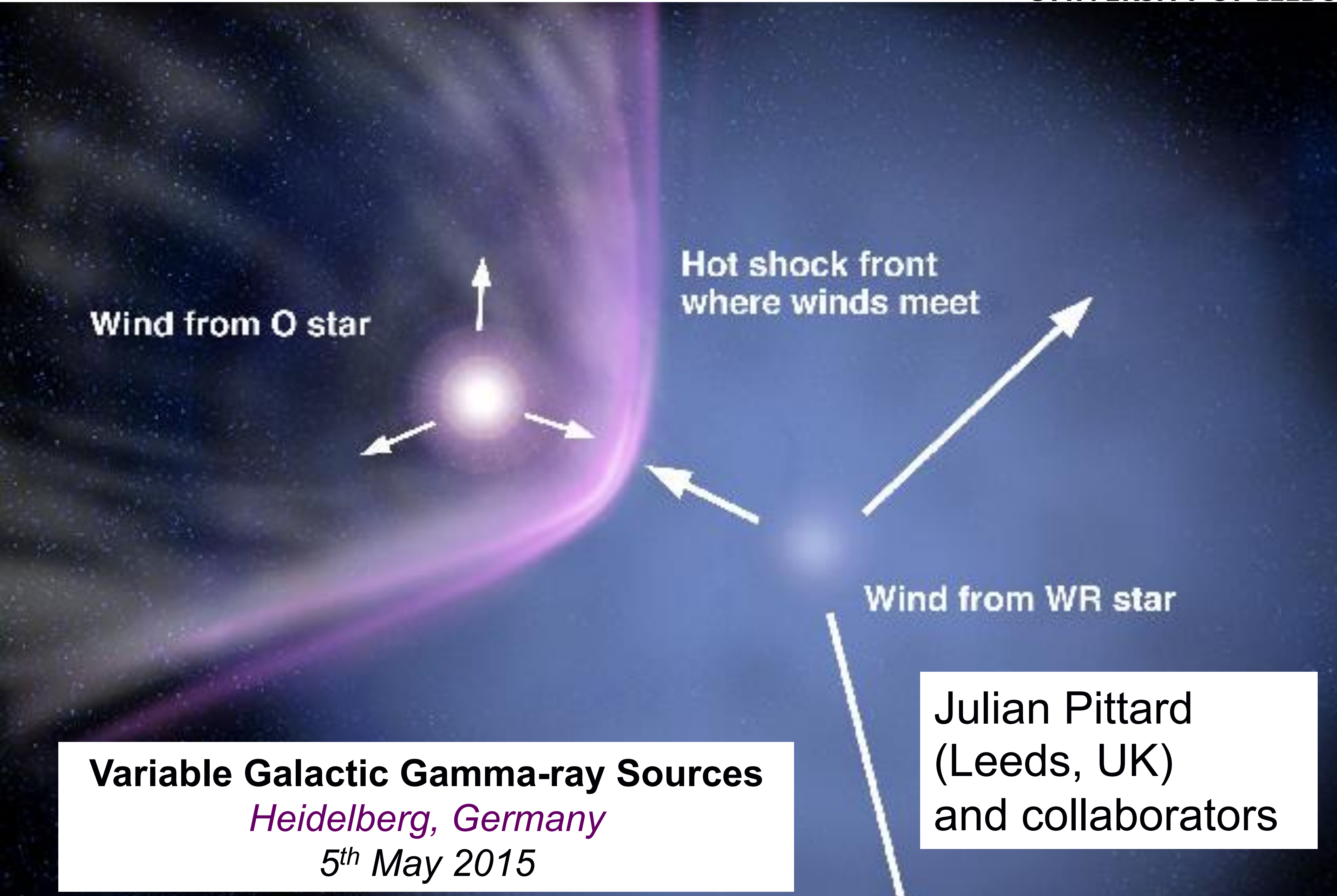

Julian Pittard
(Leeds, UK)
and collaborators

Variable Galactic Gamma-ray Sources

Heidelberg, Germany

5th May 2015

Outline

I. A taste of the interesting hydrodynamics

II. Particle acceleration in CWBs

III. Conclusions and further work

CWBs are hugely diverse

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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

Winds may achieve ram-pressure balance, or the stronger wind may overpower the weaker (for all or part of the orbit)

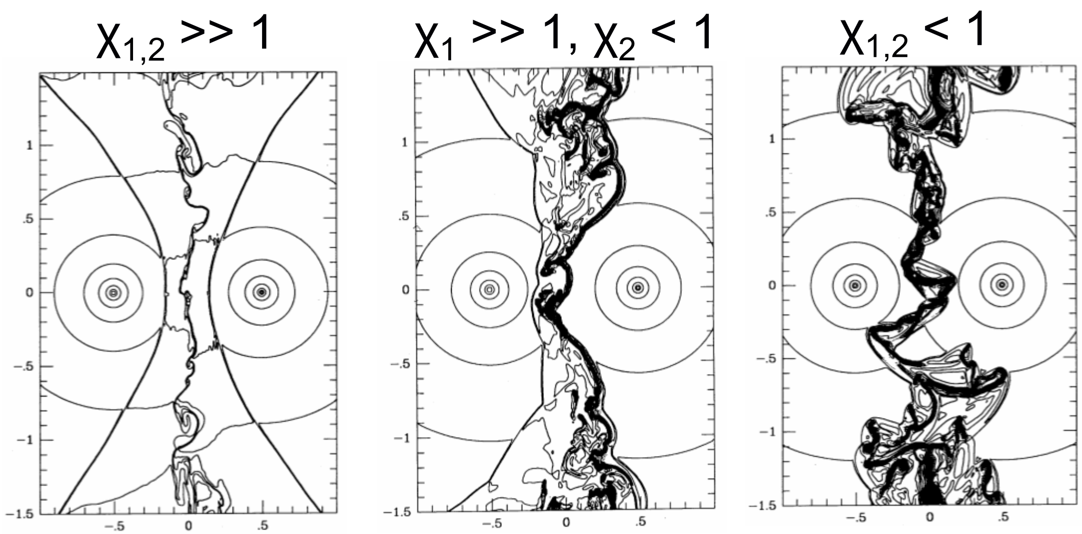
2 different regimes determined by characteristic *cooling parameter*,

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

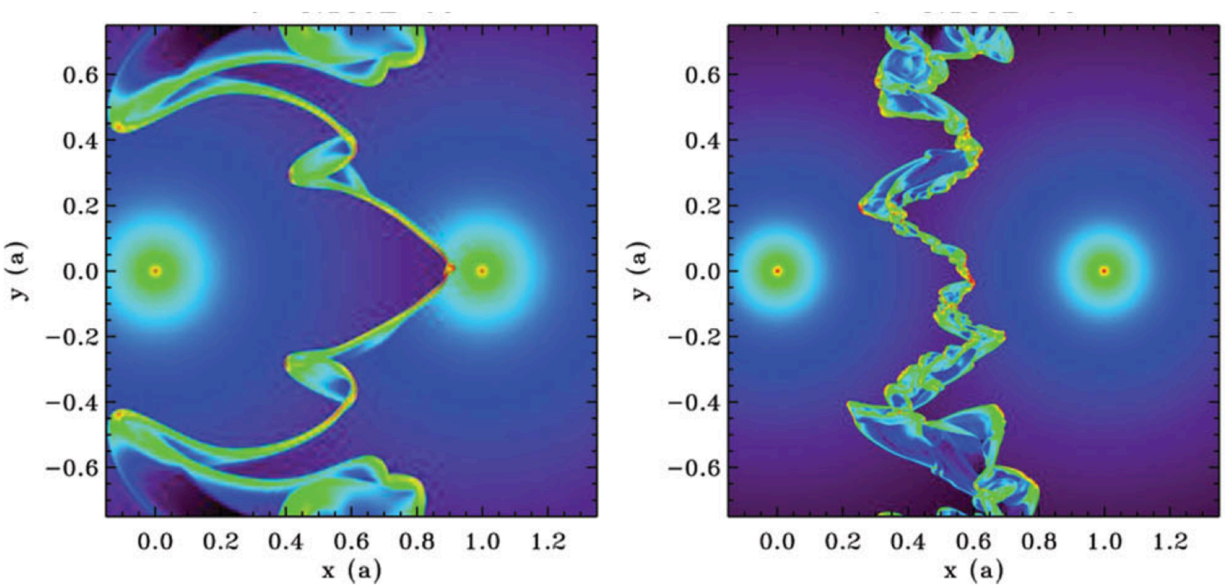
i) $\chi << 1$ - shocked wind highly radiative, wind-collision region (WCR) subject to thin shell instabilities

ii) $\chi >> 1$ - cooling mostly due to adiabatic expansion, WCR stable (except KH instability)

Dynamical Instabilities

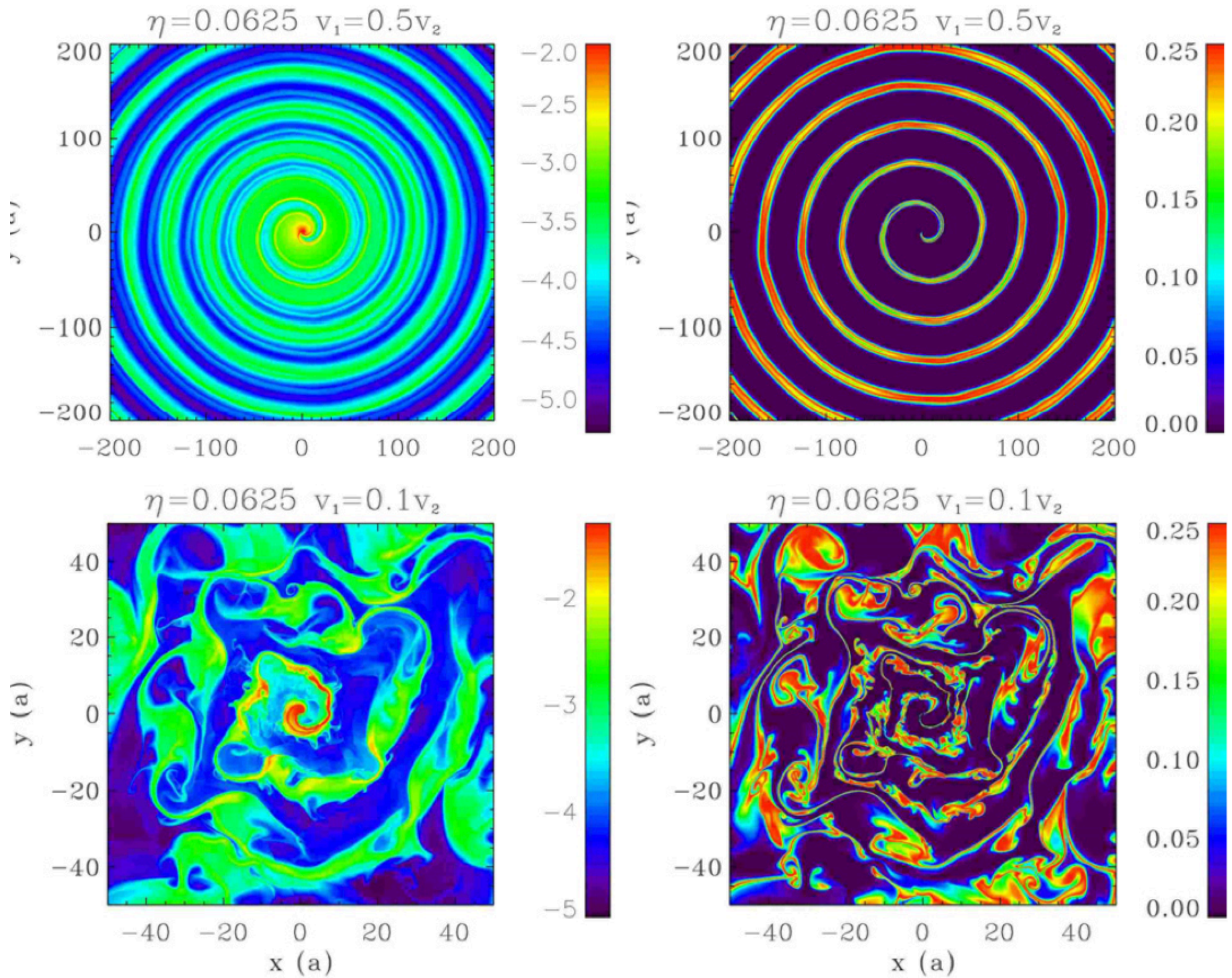


Stevens et al. (1992)



Lamberts et al. (2012)

Spiral structure



2D calculations
Lamberts+ (2012)

3D simulations with radiative driving

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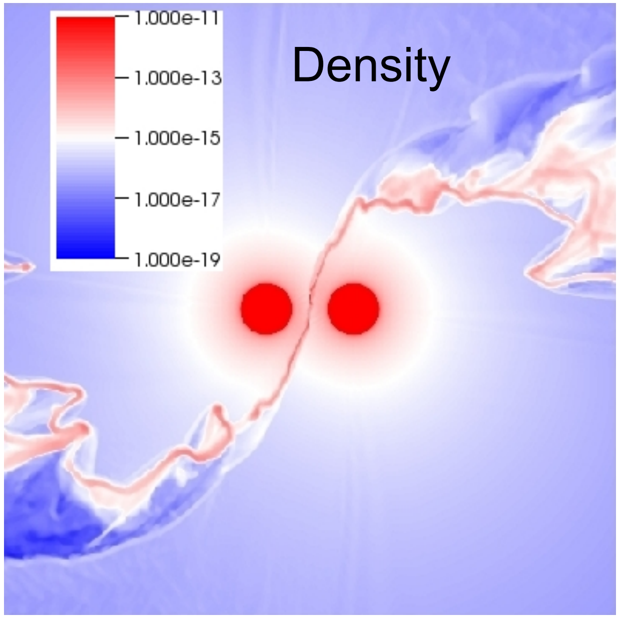
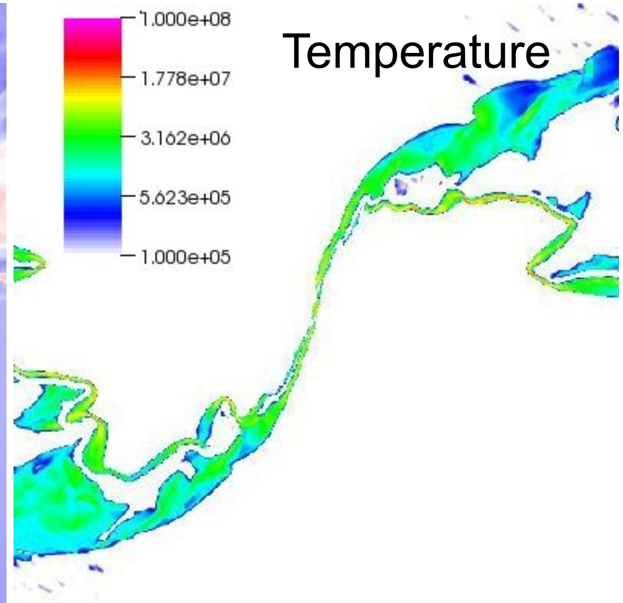
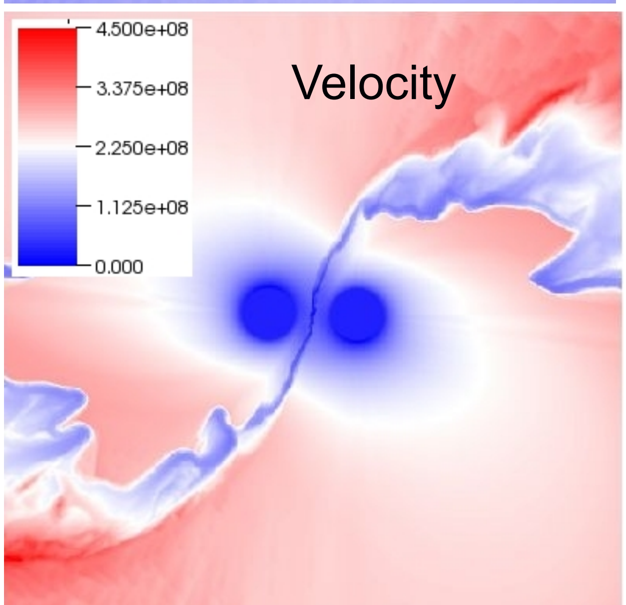




O6V + O6V, P=3d,
Dsep = 35 Rsun
$\chi \ll 1$



Cold plasma inside WCR

Wind speeds faster where radiative flux reinforced, relatively slower in shadows behind stars

Leading side of WCR arms less susceptible to instabilities

Pittard (2009)

Eccentricity – introduces “time lag” effects

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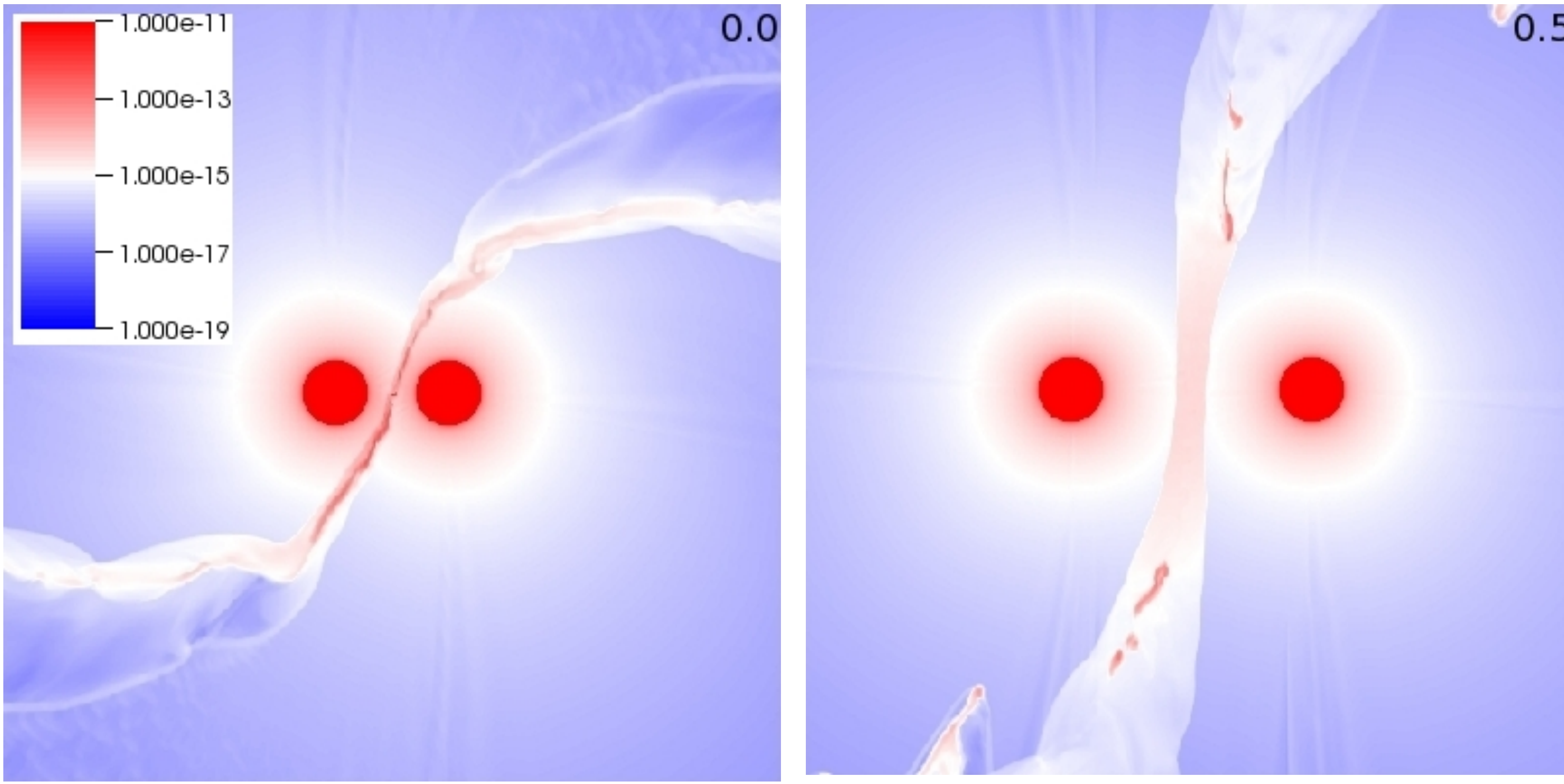
O6V + O6V, P=6.1d, dsep = 35-75 Rsun, e=0.36



Pittard (2009)

X-ray Hysteresis in Eccentric Systems

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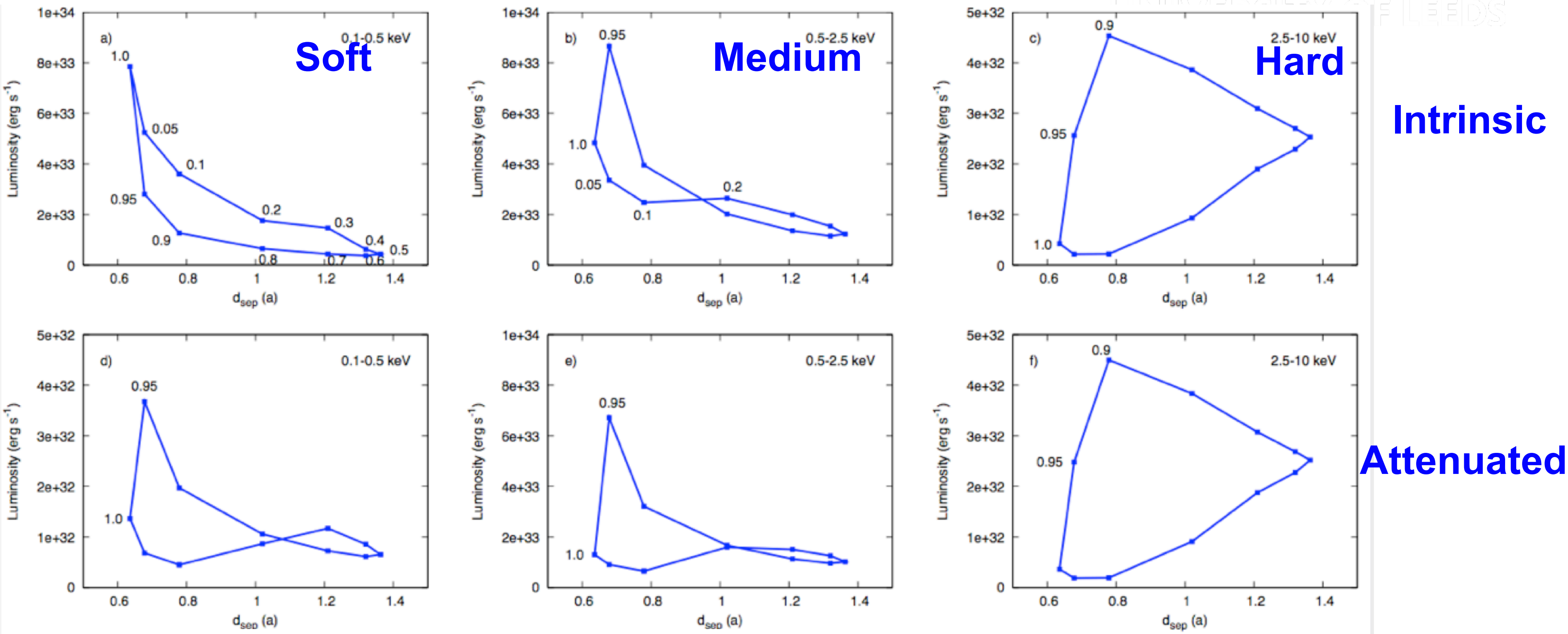

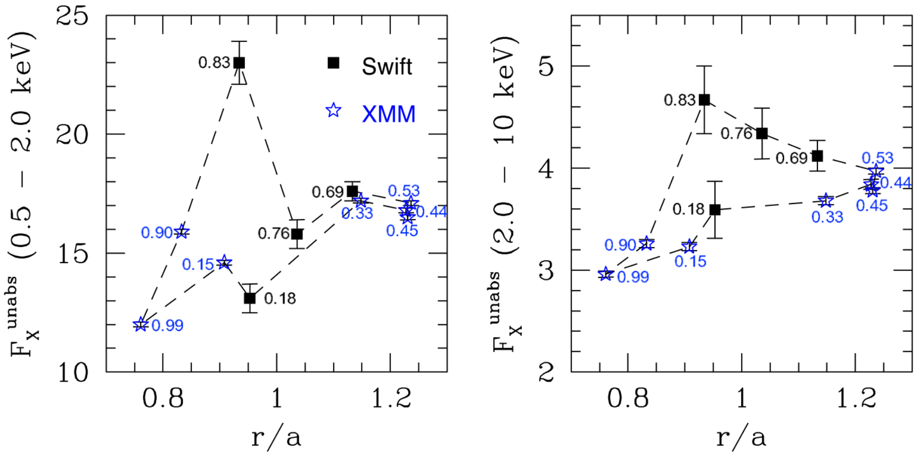

- Hysteresis now seen for the first time! Cyg OB2#8A (Cazorla+2014)
- Phase-behaviour is a little different to current theoretical models (of a generic system)
- Need dedicated model of this system

CygOB2 No. 9

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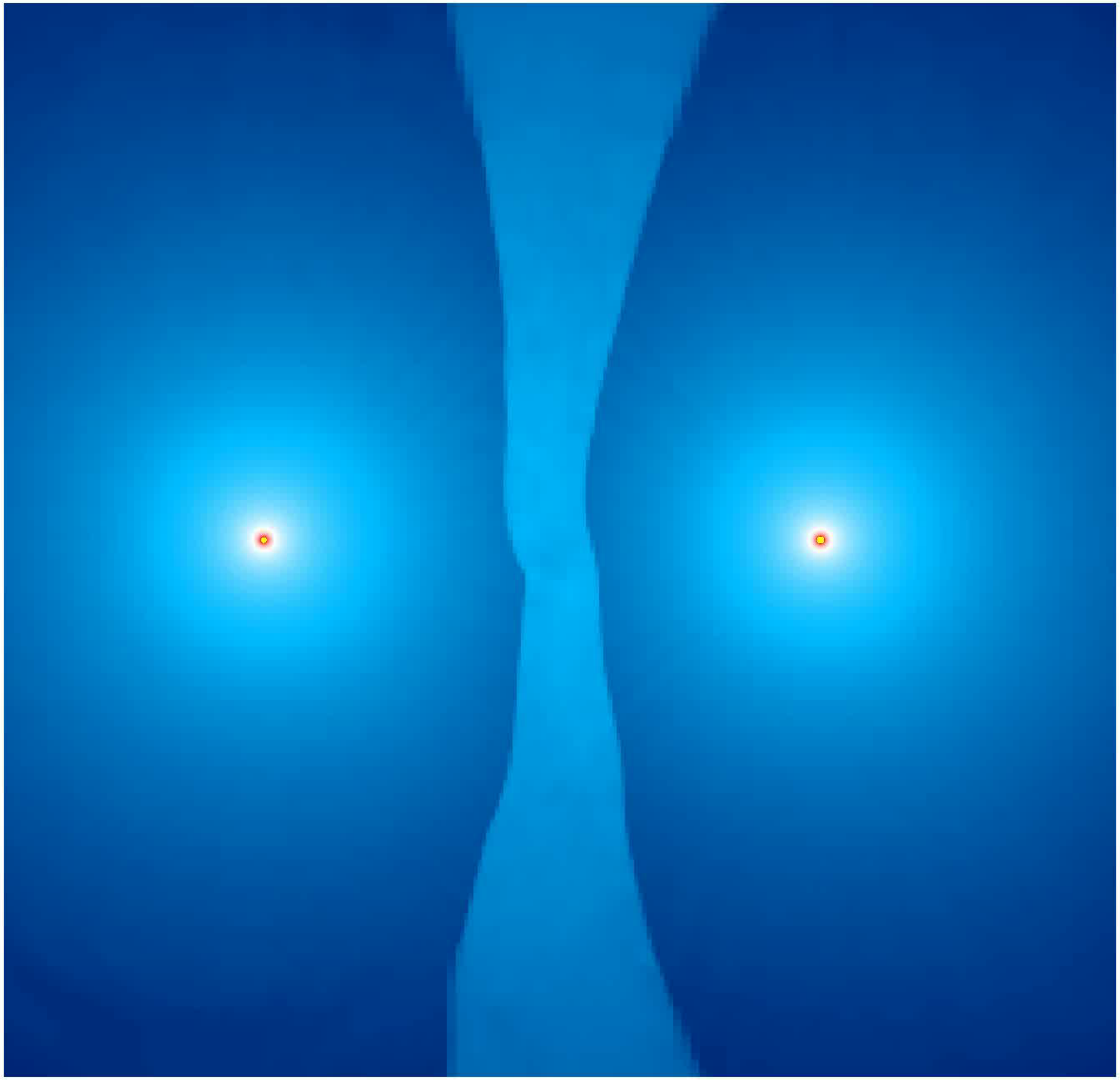

O5.5I + O3.5III
P = 860 d
e = 0.71
a = 8.0 AU

Post-shock plasma is expected to have $T_e < T_i$. Best fit to X-ray data indicates $T_e/T_i = 0.1$.

Parkin et al. (2014)

WR22

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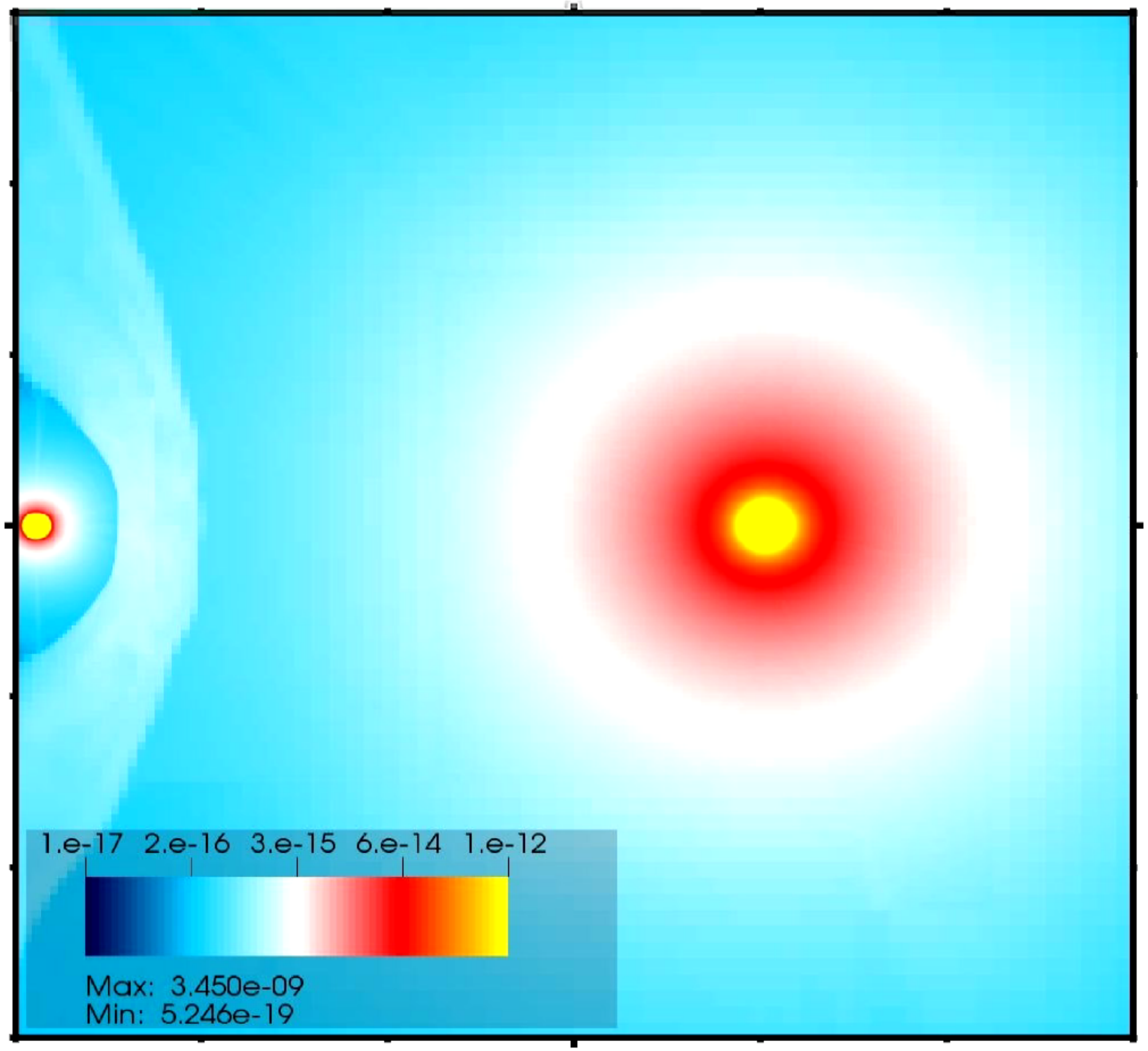
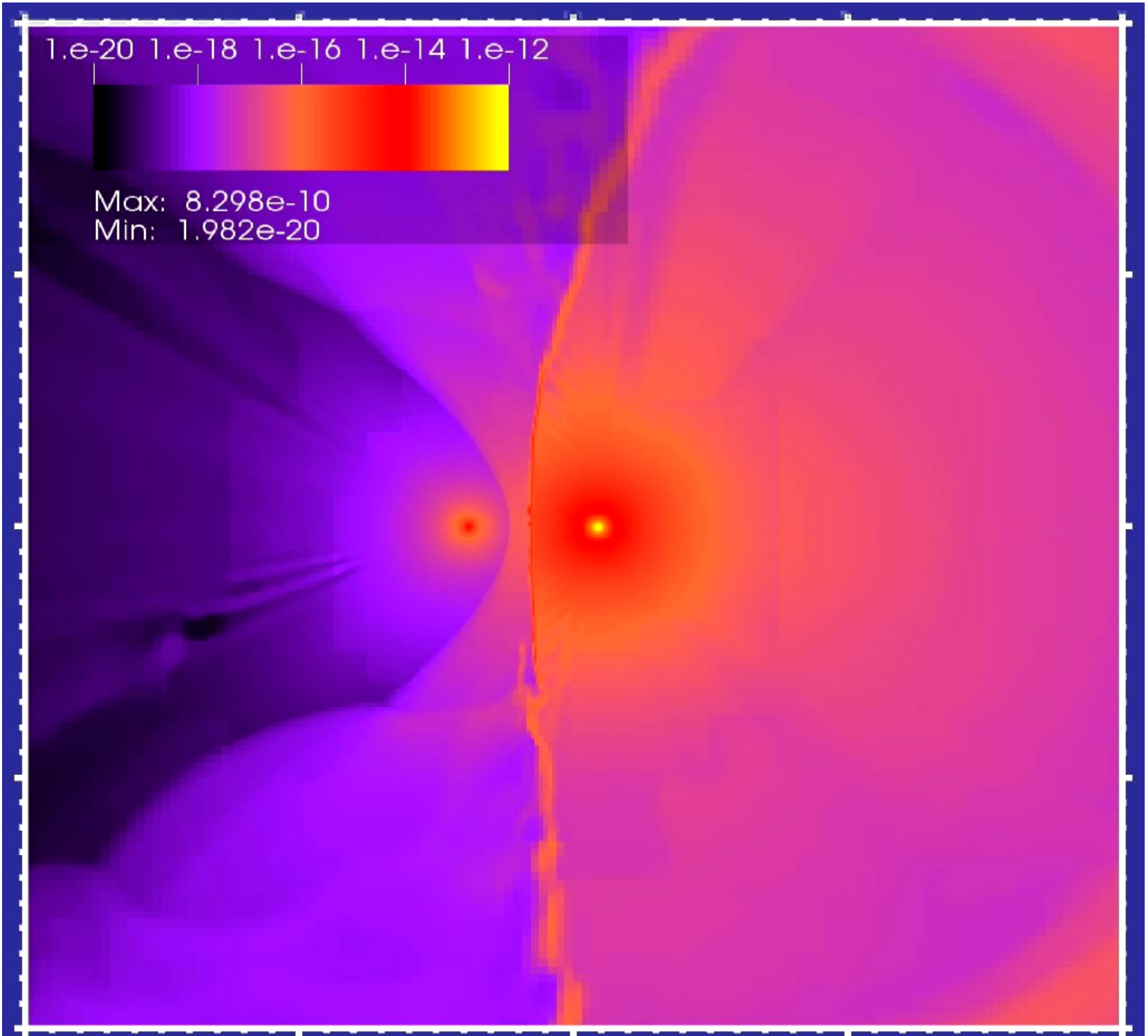
WN7 + O9V
P = 80.3d
e = 0.56
a = 1.68 AU



Parkin & Gosset (2011)

Eta Car



LBV + ? (WR/O)
P = 2024 d
e ~ 0.9
a ≈ 15.0 AU

Parkin et al. (2011)

Interaction of clumpy winds?

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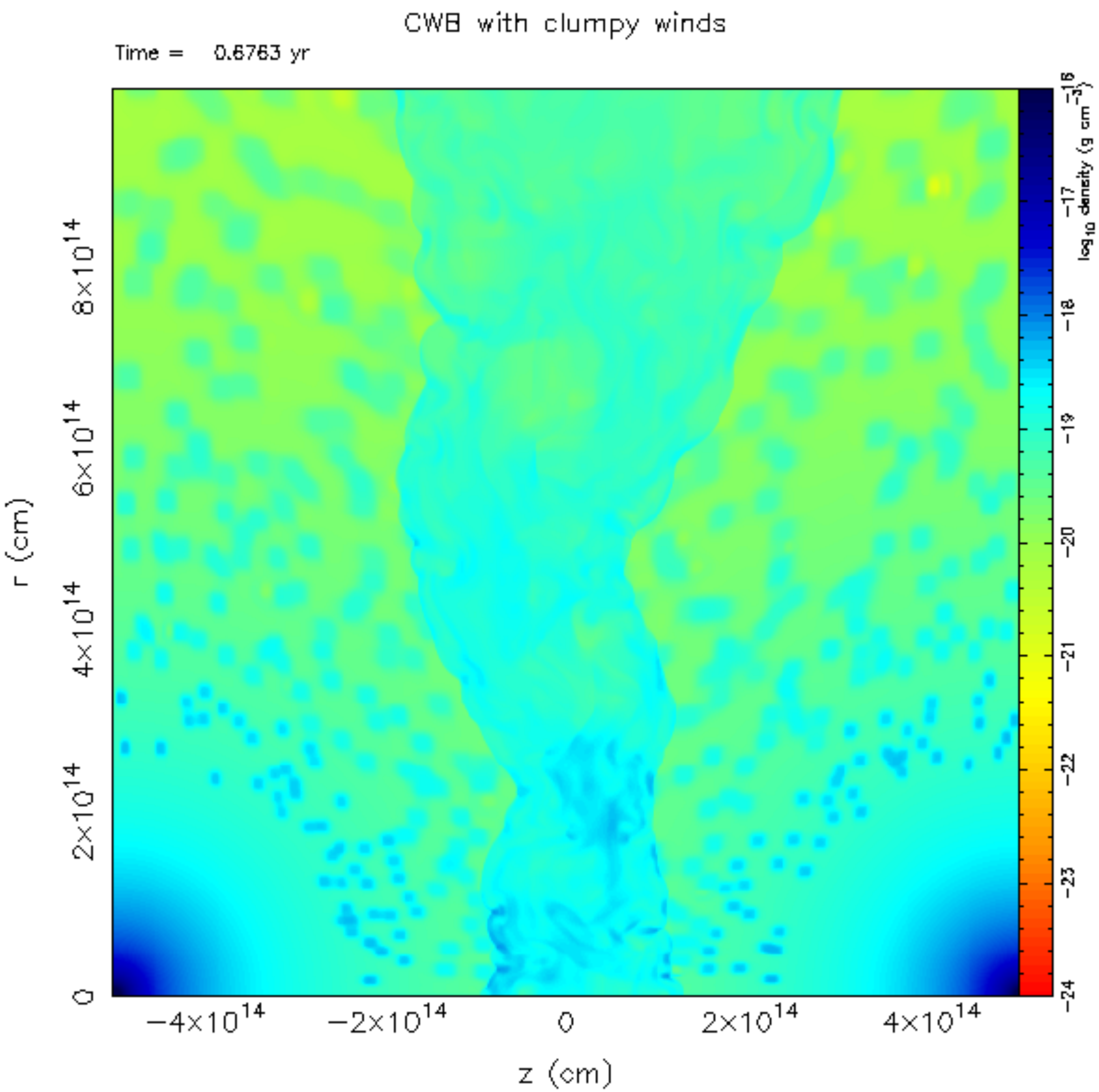


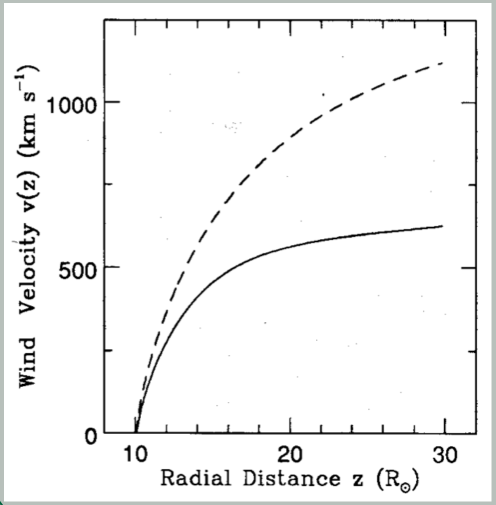
Clump destruction in adiabatic CWBs (Pittard 2007)

How about in radiative CWBs?

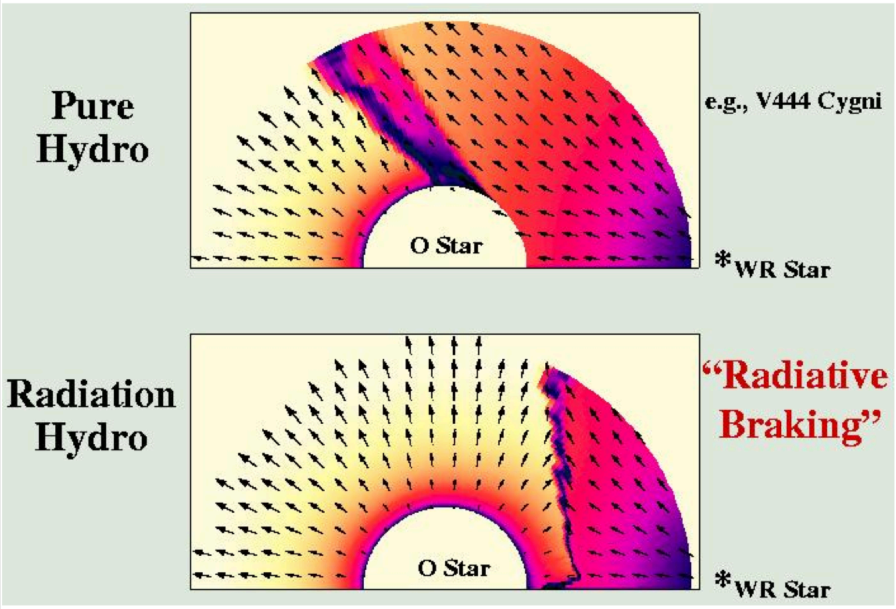
Also implications for particle accn?
Reconnection?
Stochastic accn?

Radiative coupling effects

Radiative inhibition
(Stevens & Pollock 1994)
Pre-shock velocities decrease
Mdot may decrease or increase

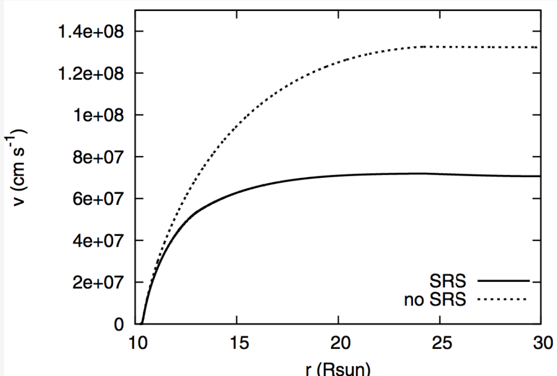


Reflection needs to be considered (Gayley+ 1999)



Radiative braking (Owocki & Gayley 1997)
More powerful than inhibition
Highly non-linear to effective opacity of wind

Self-regulated shocks Parkin & Sim (2013)
Enhanced ionization of winds by the WCR reduces radiative driving – can greatly increase the range of separations where wind-star collisions occur (also may make radiative braking less effective)



Outline

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First Direct Proof of Colliding Winds Model

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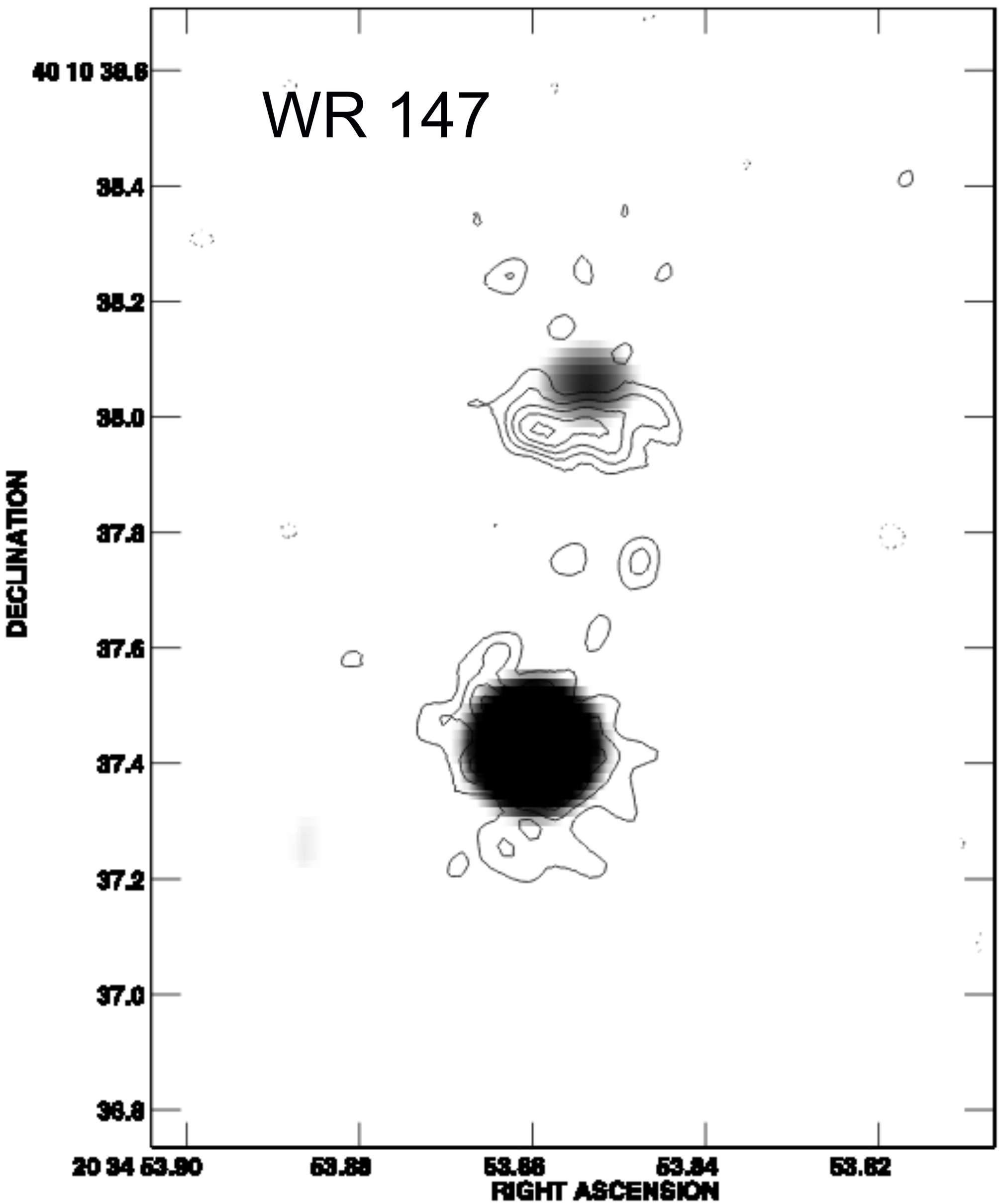

WR147: WR+OB binary

High resolution observations
- MERLIN @ 5GHz:

50 mas = 77AU @ 650pc

Two components, S is thermal, N is non-thermal

NT emission => relativistic electrons + magnetic fields

NT emission consistent with wind-collision position

Williams et al. (1997)

WR 146 - brightest radio CWB

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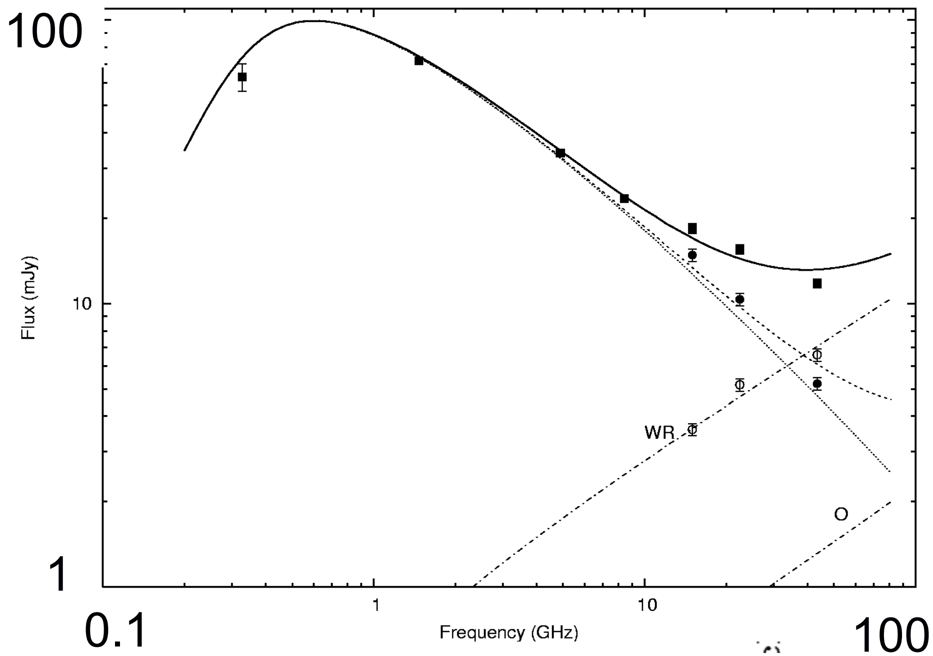

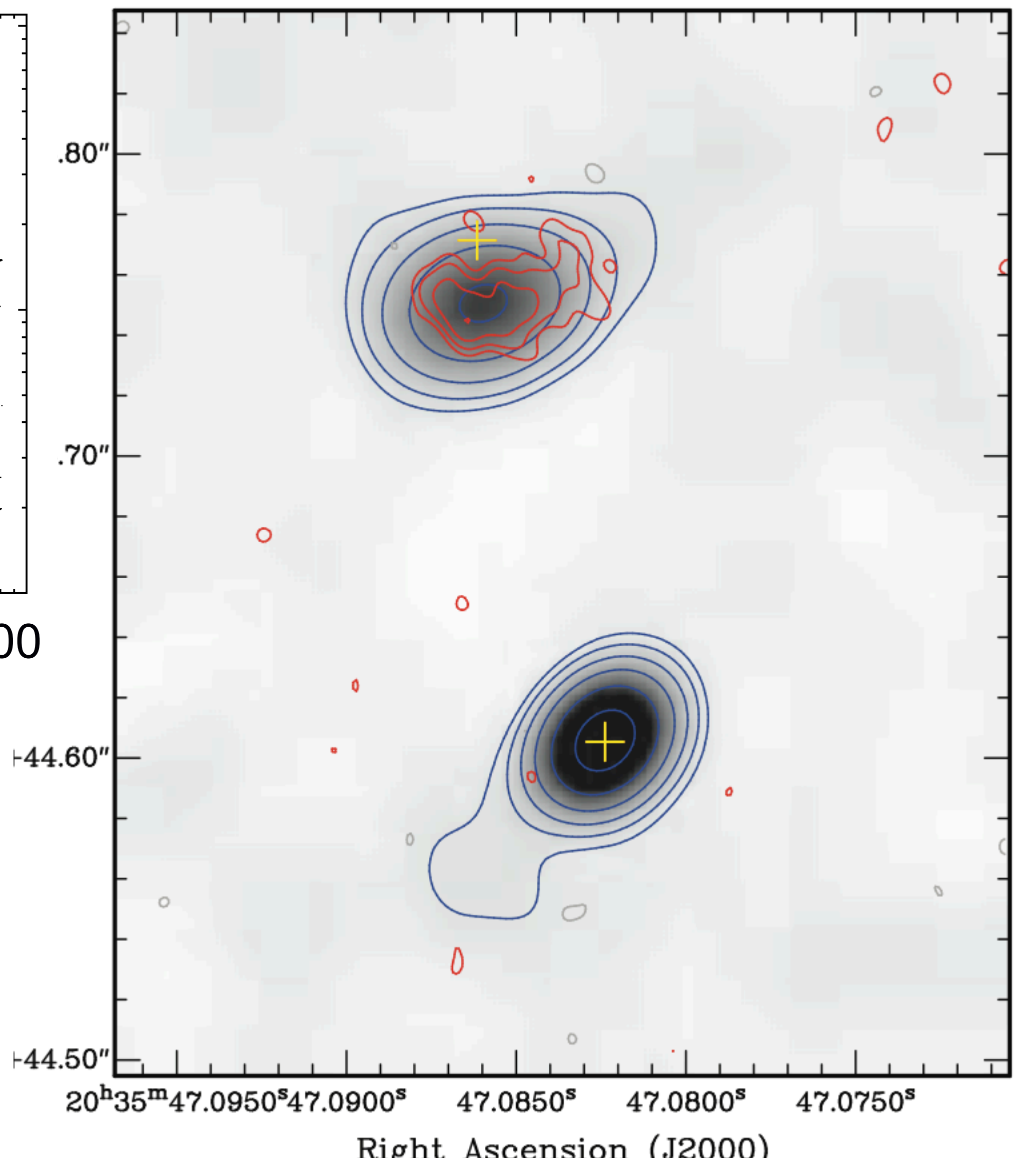

VLA 43-GHz shows the southern thermal source that is associated with the WR star and the northern non-thermal emission from the WCR.

VLBA 8.6-Ghz reveals the structure of the WCR.

Crosses mark the relative location of the two stars.

Courtesy Sean Dougherty

WR140 – the particle acceleration laboratory

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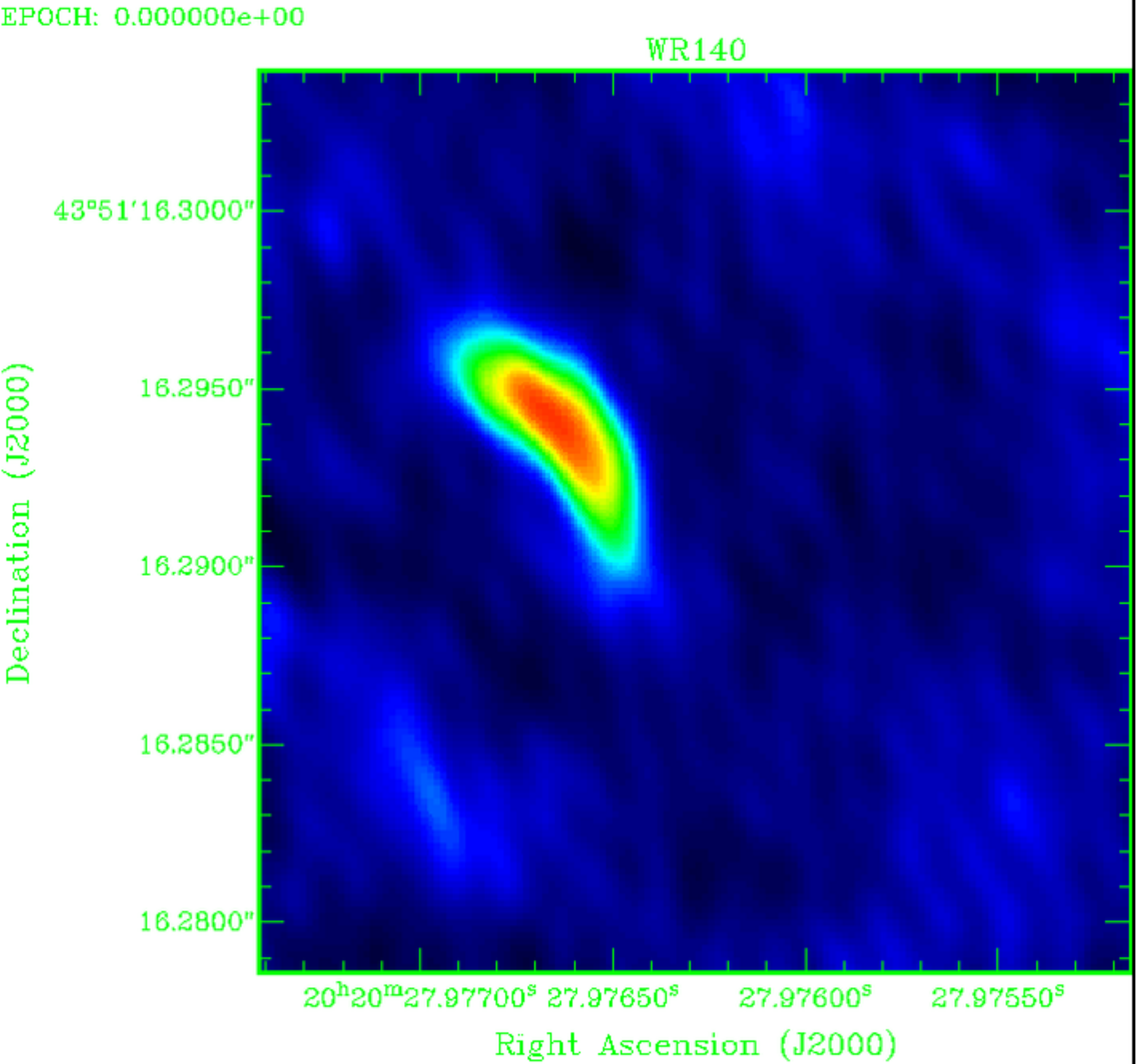

WR + O in a 7.9 year, eccentric (e ~ 0.9) orbit

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

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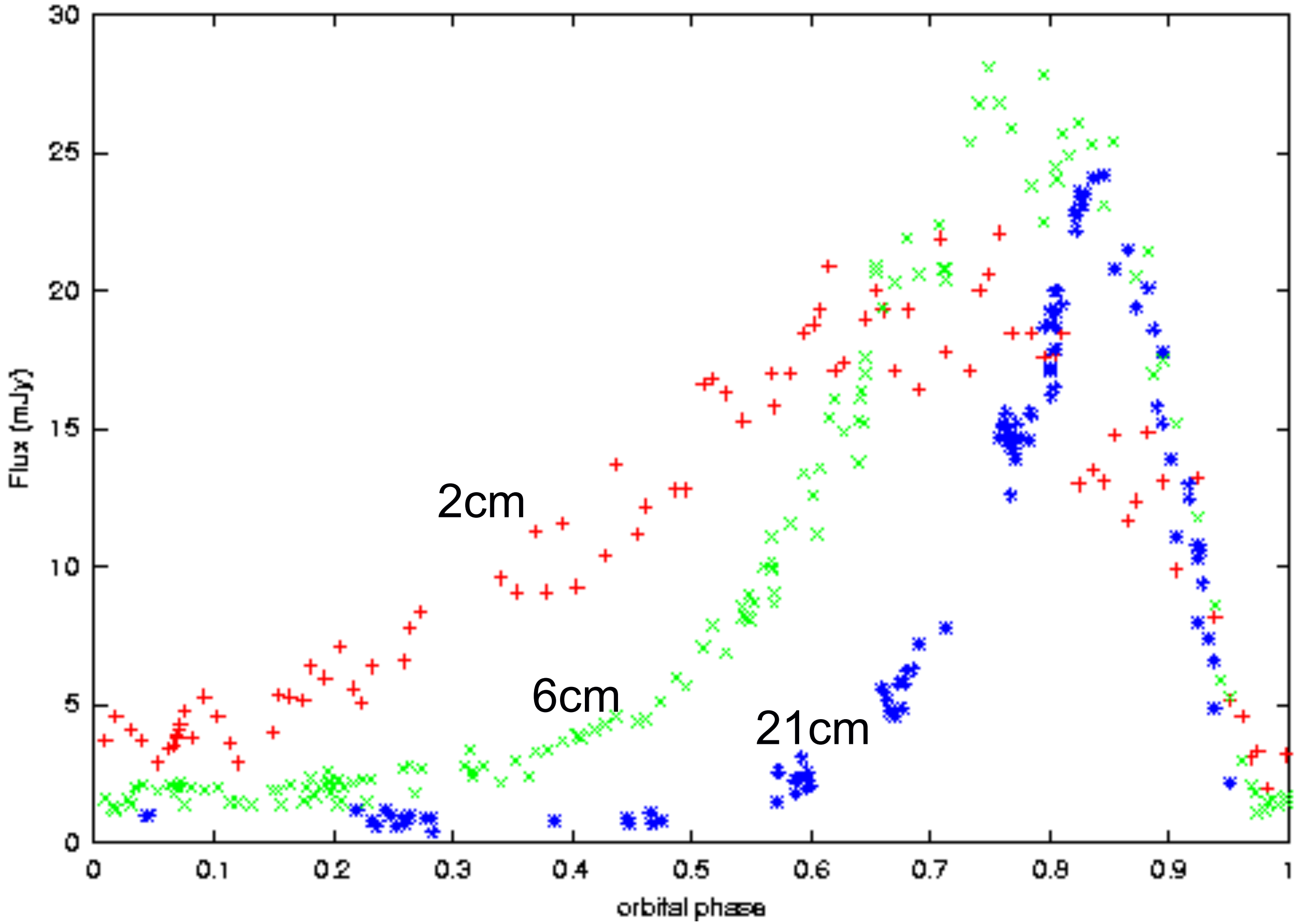

8 years of VLA (White & Becker 1995) +
WRST (Williams et al 1991) data

Visibility of NT emission vs. binary period

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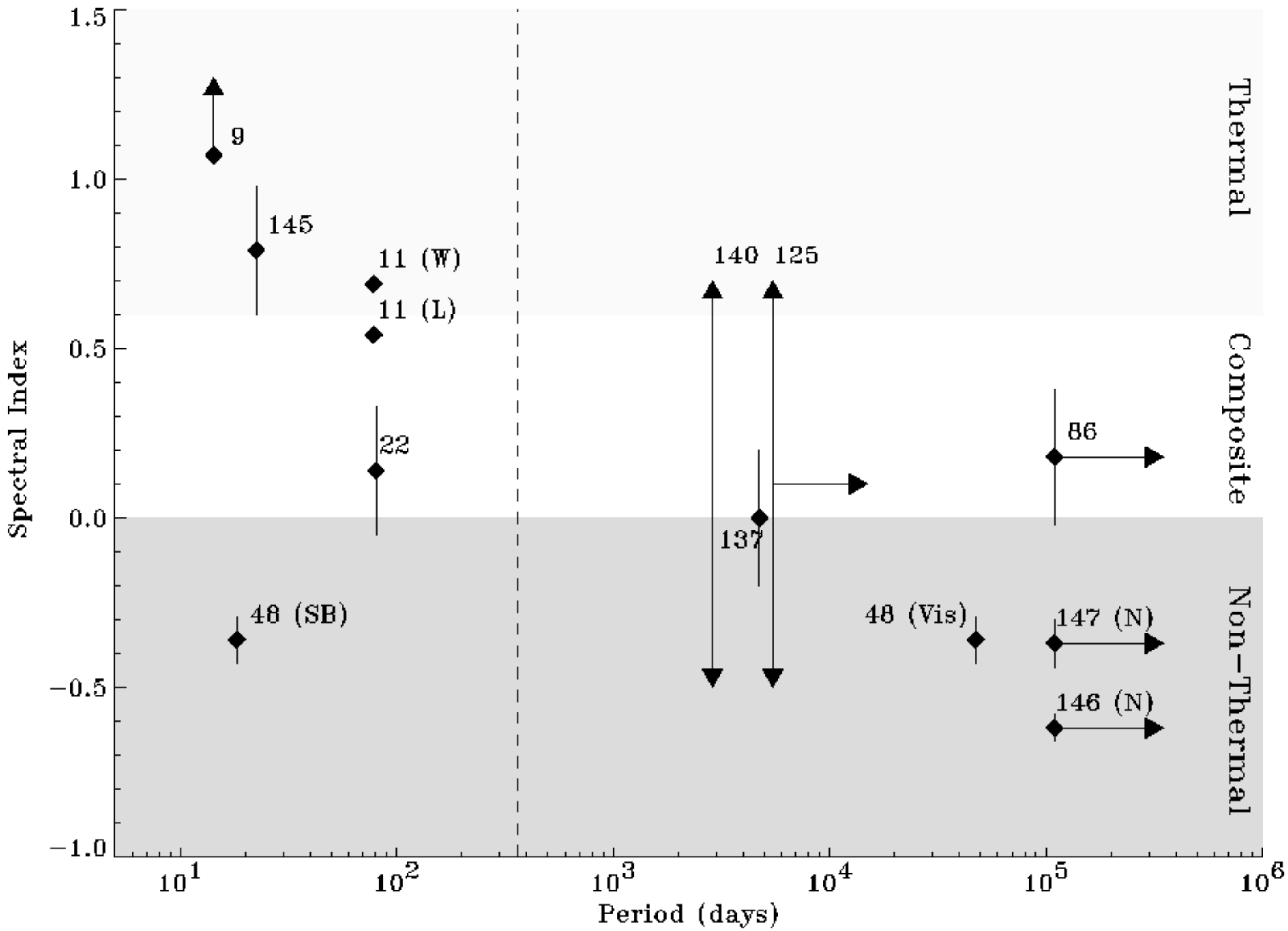

Thermal

Non-thermal

Dougherty & Williams (2000)

Models

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Early models of NT emission were simple

Radio:

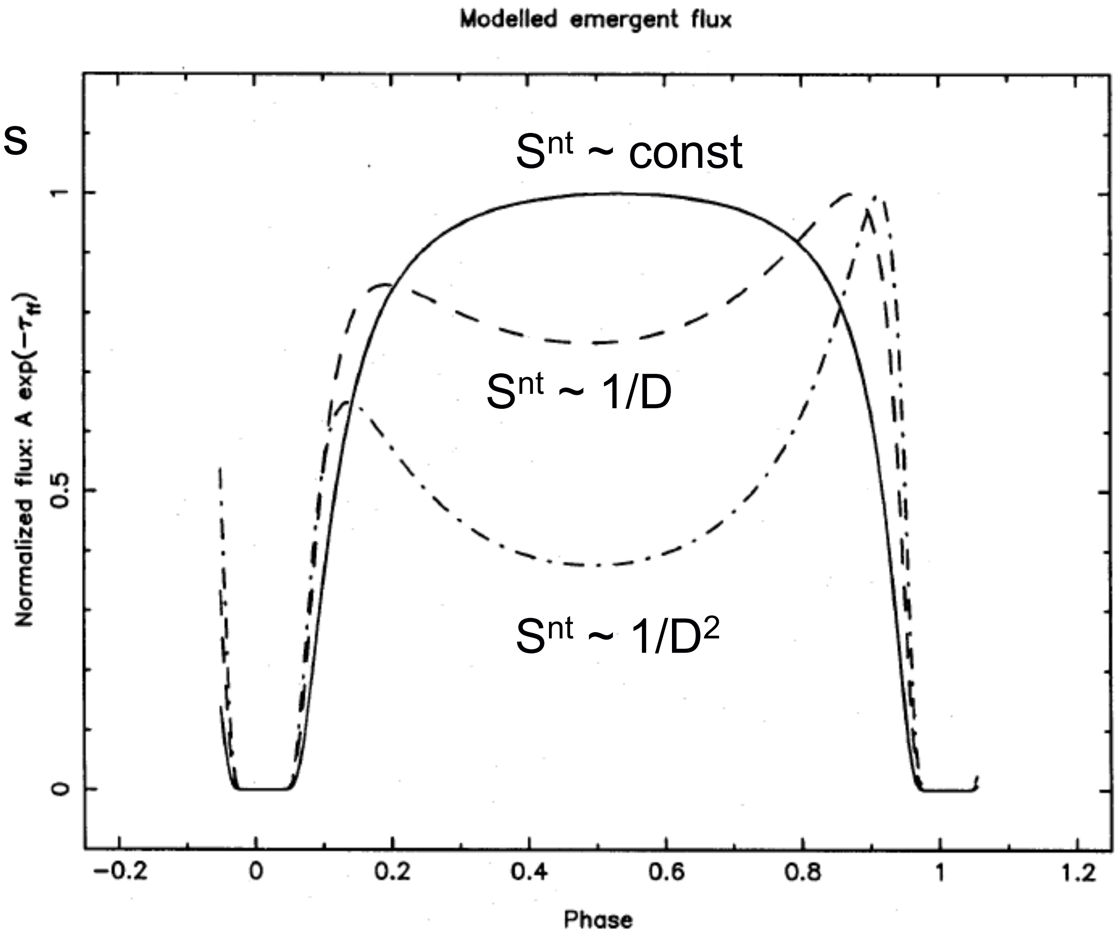
- Point source non-thermal emission, spherically symmetric winds –

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

- 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)



Previous models

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Early models of NT emission were simple

Radio:

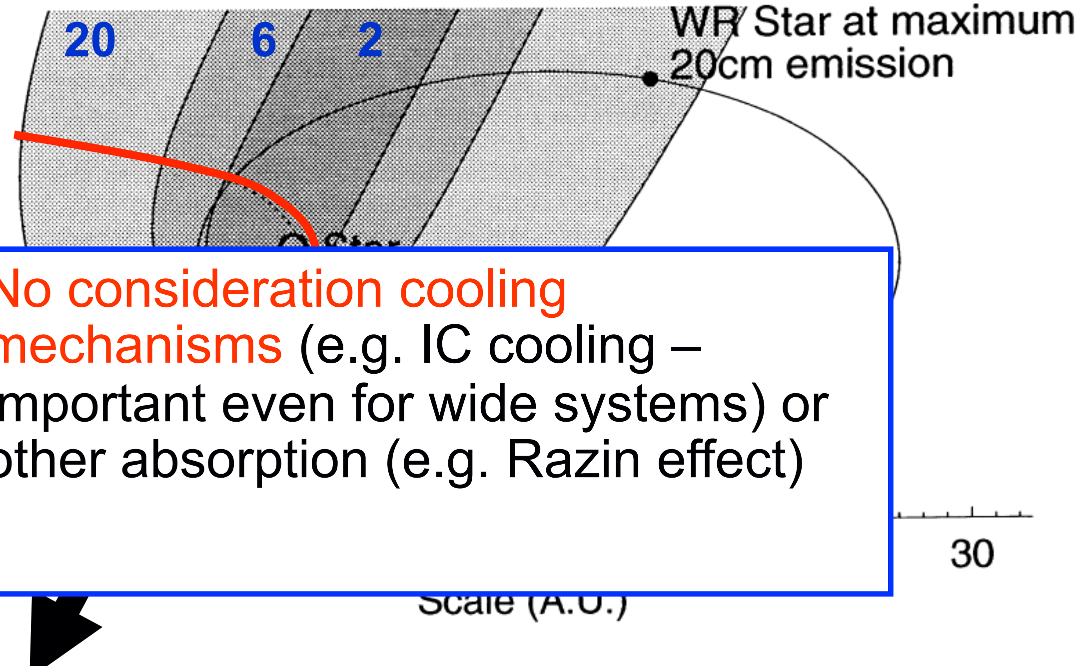
- Point source non-thermal emission, spherically symmetric winds –

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

- maintains analytic solutions

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

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)

A phenomenological model

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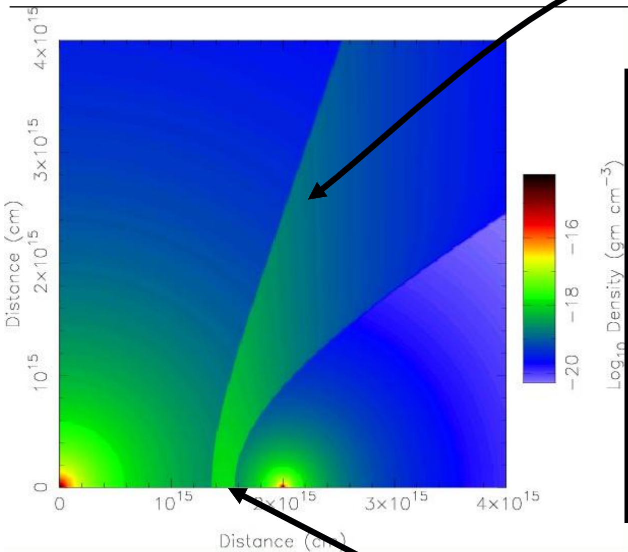
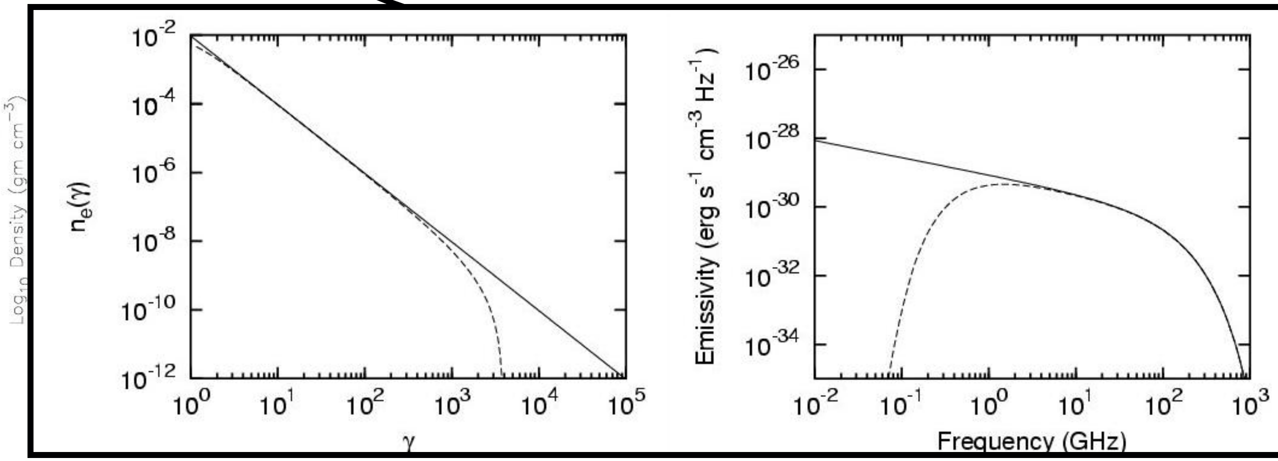
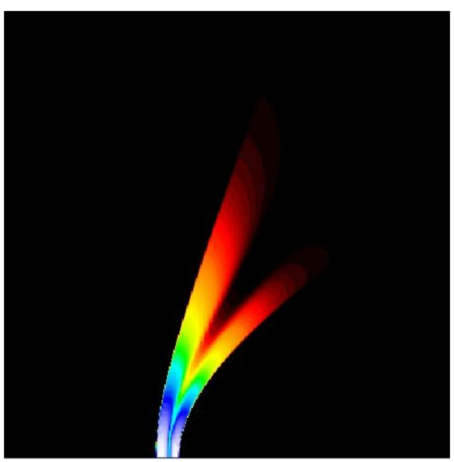
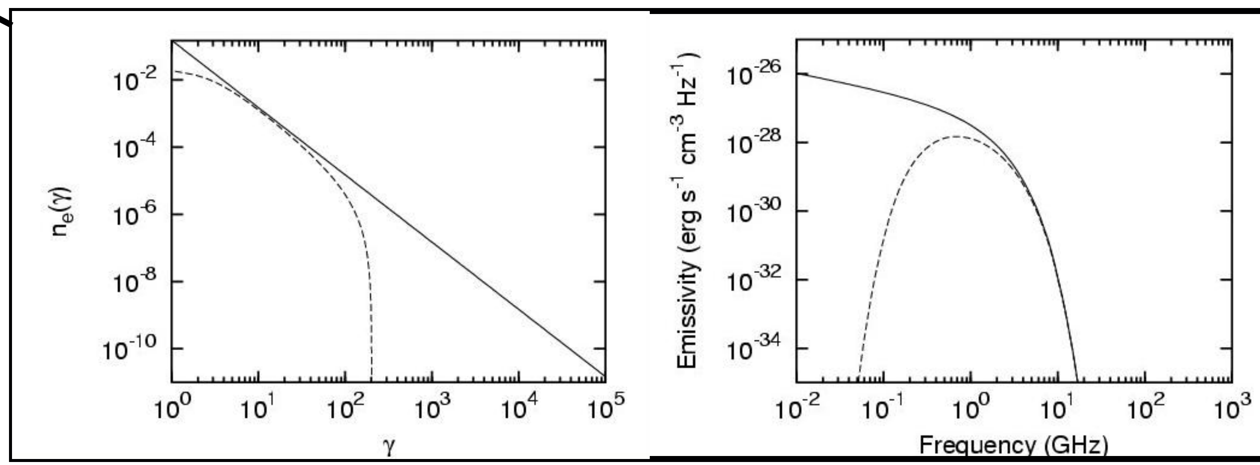








1.6 GHz emission map

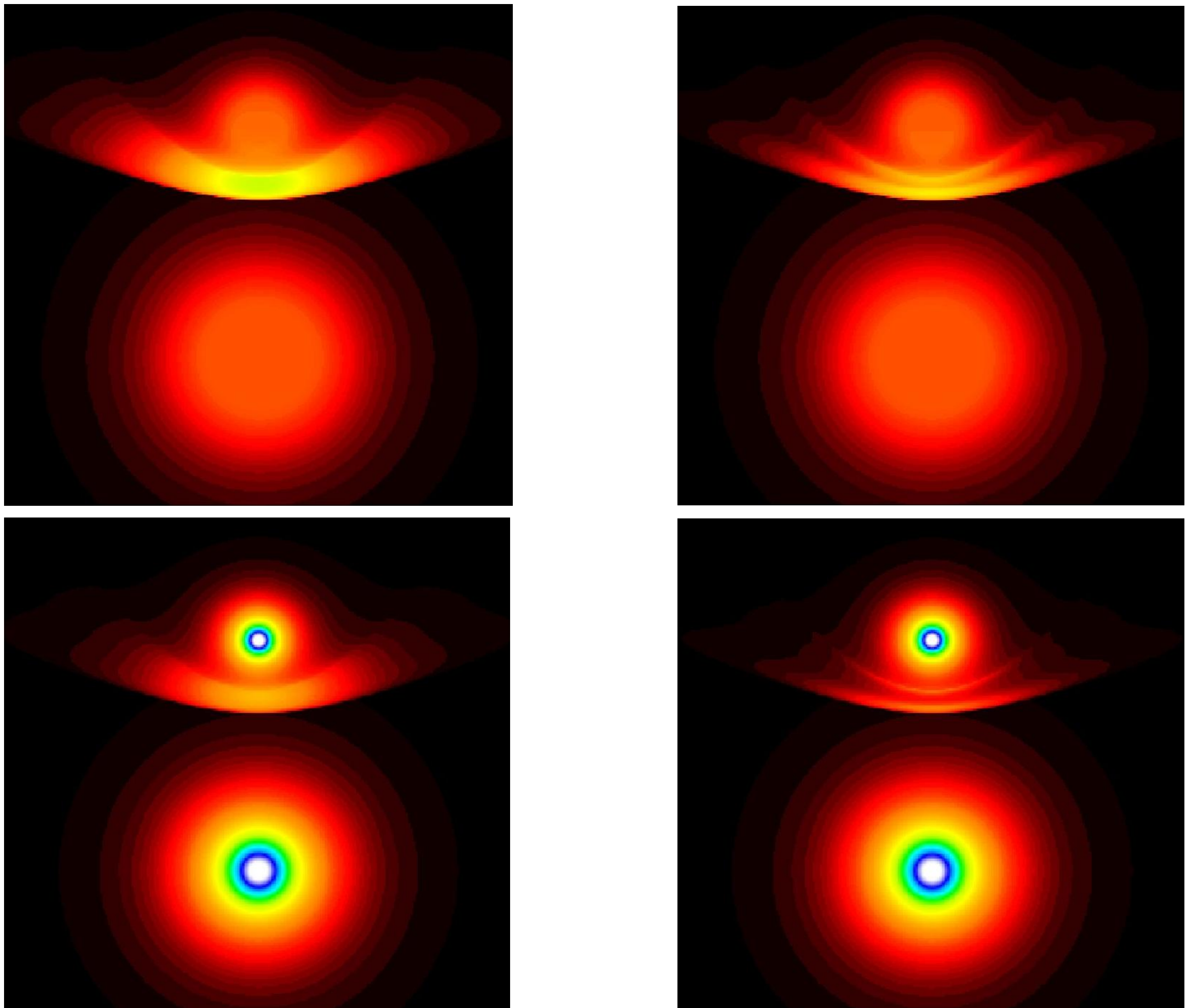
Pittard et al. (2006)

Example synthetic emission maps

No IC cooling | With IC cooling

1.6 GHz

22 GHz



Spectral fits to WR140 spectra

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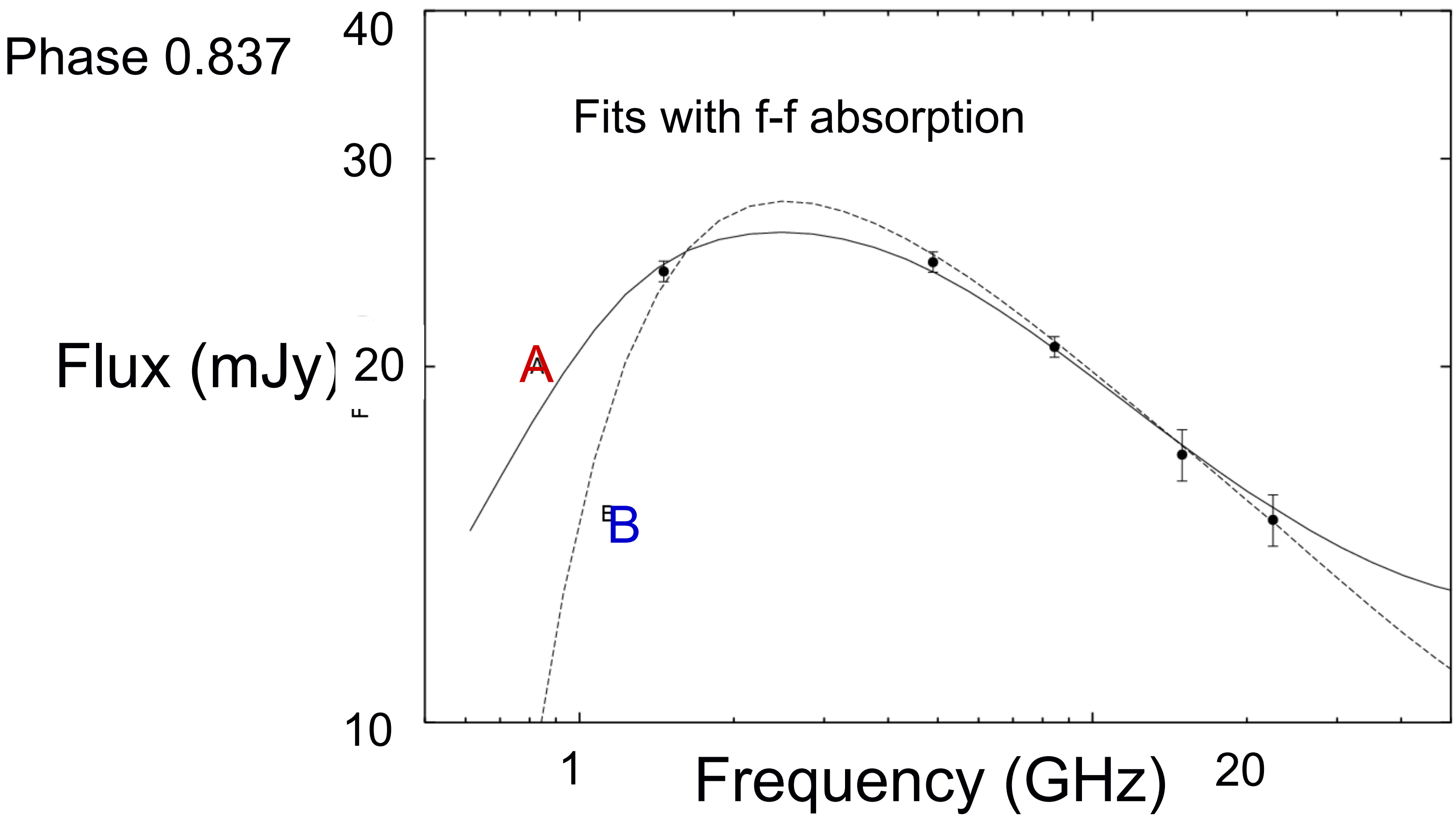


Pittard et al. (2006)

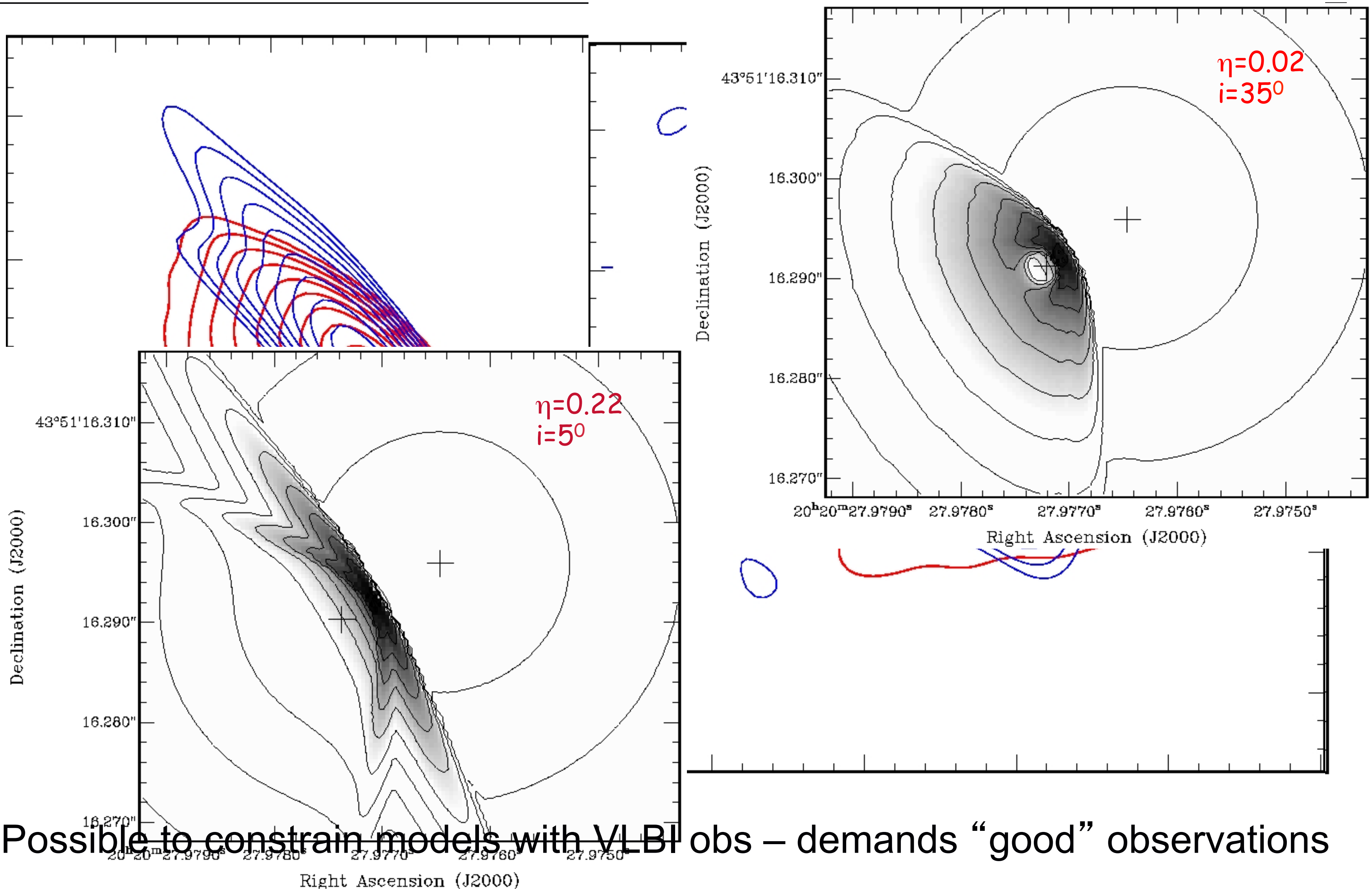
Model A: η=0.22, p=1.4, ζ_e=1.4x10^{-3}, ζ_B=0.05

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!

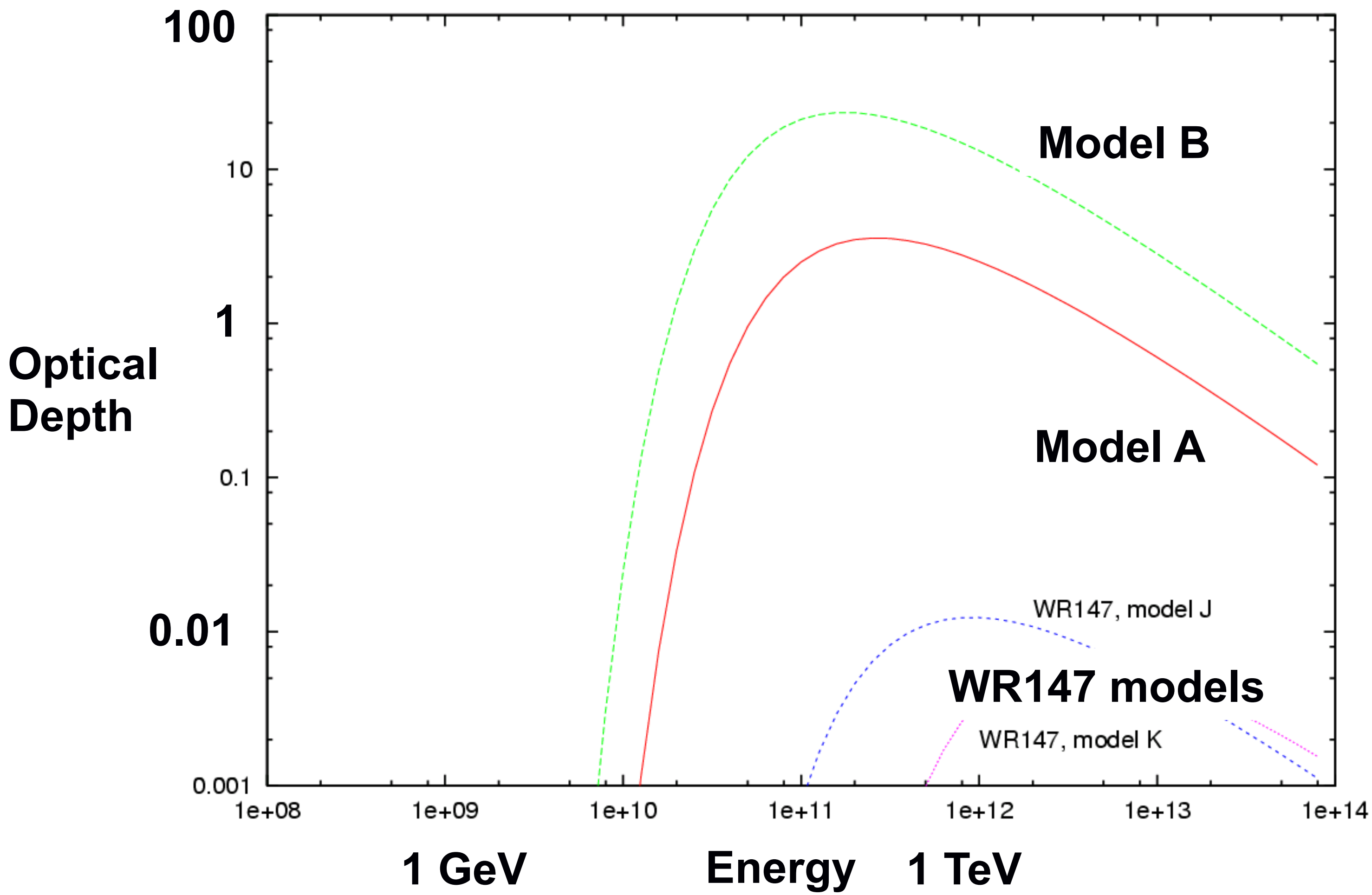
Modelling 8 GHz VLBA observations



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

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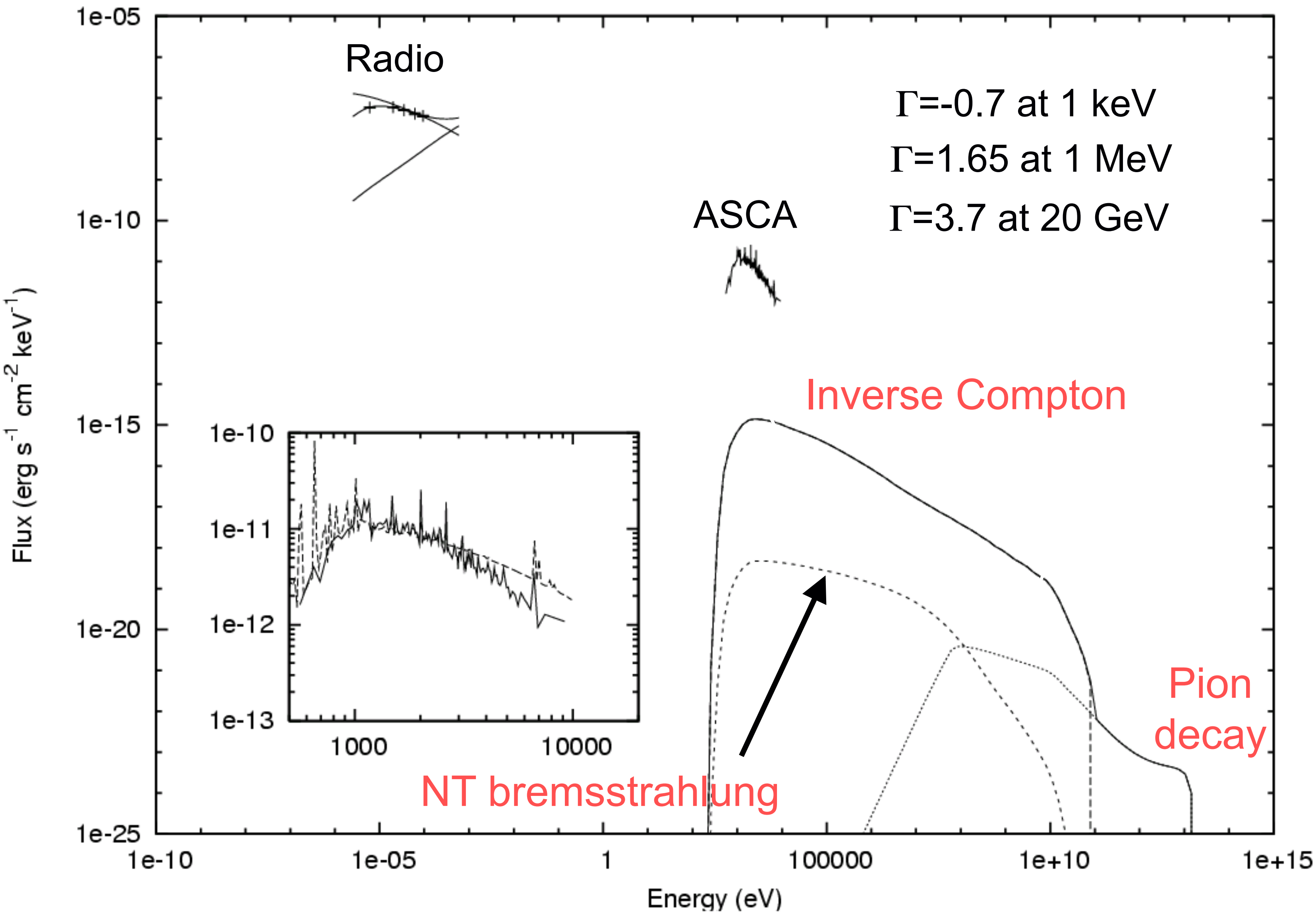
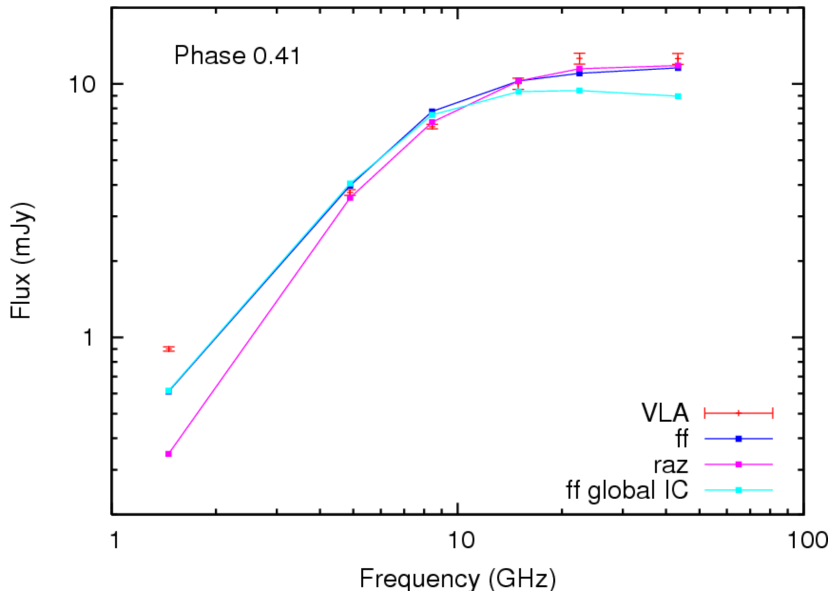
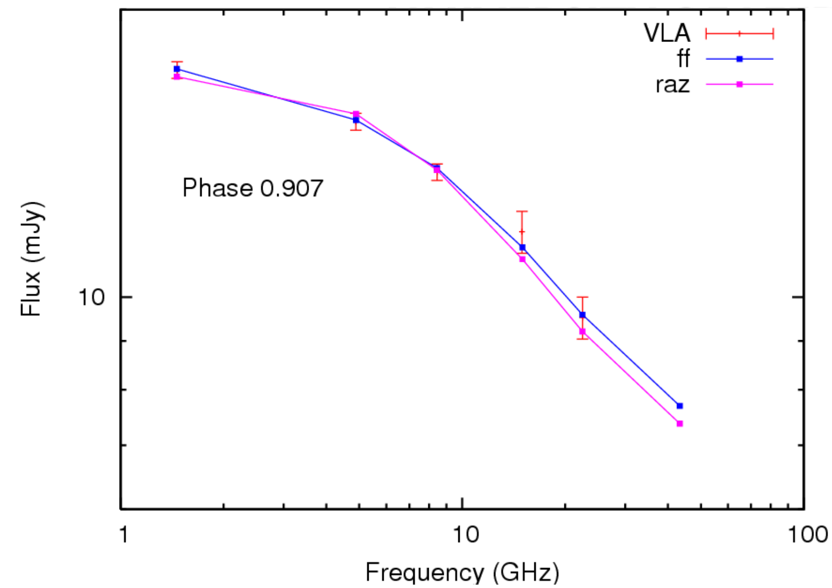
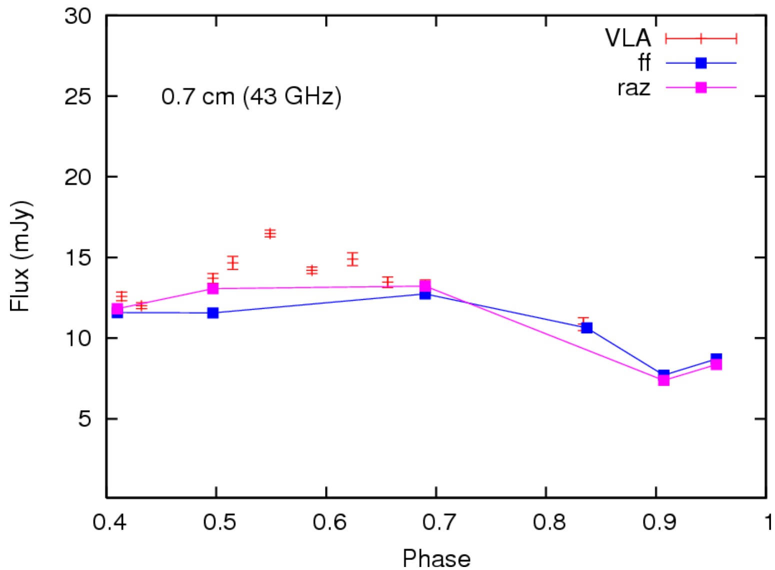
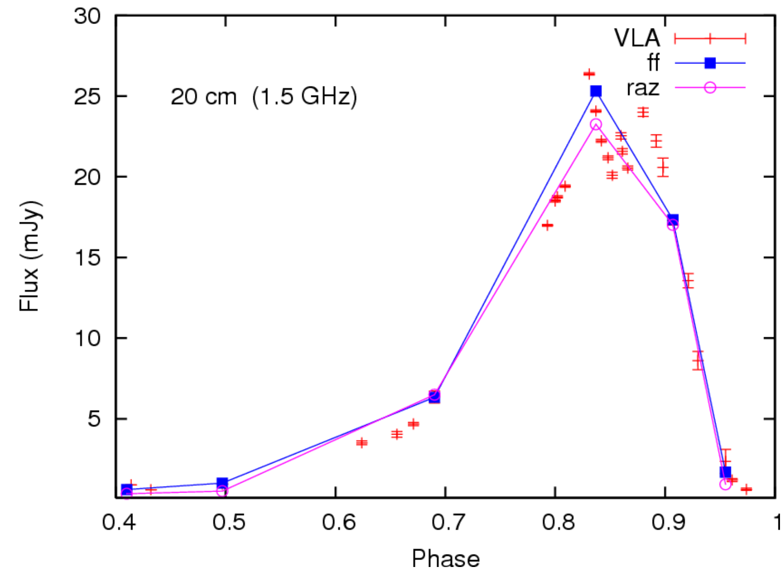


Fits at phase 0.41 and 0.907 and lightcurves









Conclusions and future work

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Colliding wind binaries are incredibly diverse, and are important laboratories for investigating shock physics and particle acceleration

Highly eccentric systems – like WR140 – are particularly useful

Our understanding of the wind dynamics has come a long way in recent years.

There are still some puzzles to work out, e.g.:

1. X-ray emission from close binaries (2 component wind vs. NTSI suppression of X-rays vs. something else?)
2. Particle Acceleration (2^{nd} order Fermi vs. reconnection, efficiency, what really controls whether we see NT emission or not?)
3. Dust formation (not discussed in this talk…)

One hopes that these puzzles will be gradually worked out…