Colliding Winds and Non-thermal Emission

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TOSCA Workshop
Siena
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Colliding Wind Binaries (CWBs)

I. A taste of the interesting hydrodynamics
   i. Key parameters, cooling, instabilities, orbital effects, radiative driving
   ii. 3D simulations

II. Observations and models of Non-Thermal Emission

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): set by wind momentum ratio, $\eta = \frac{\dot{M}_2 v_2}{\dot{M}_1 v_1}$

Two 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 for KH instability)

(Stevens+ 92)

Eccentricity – introduces "time lag" effects

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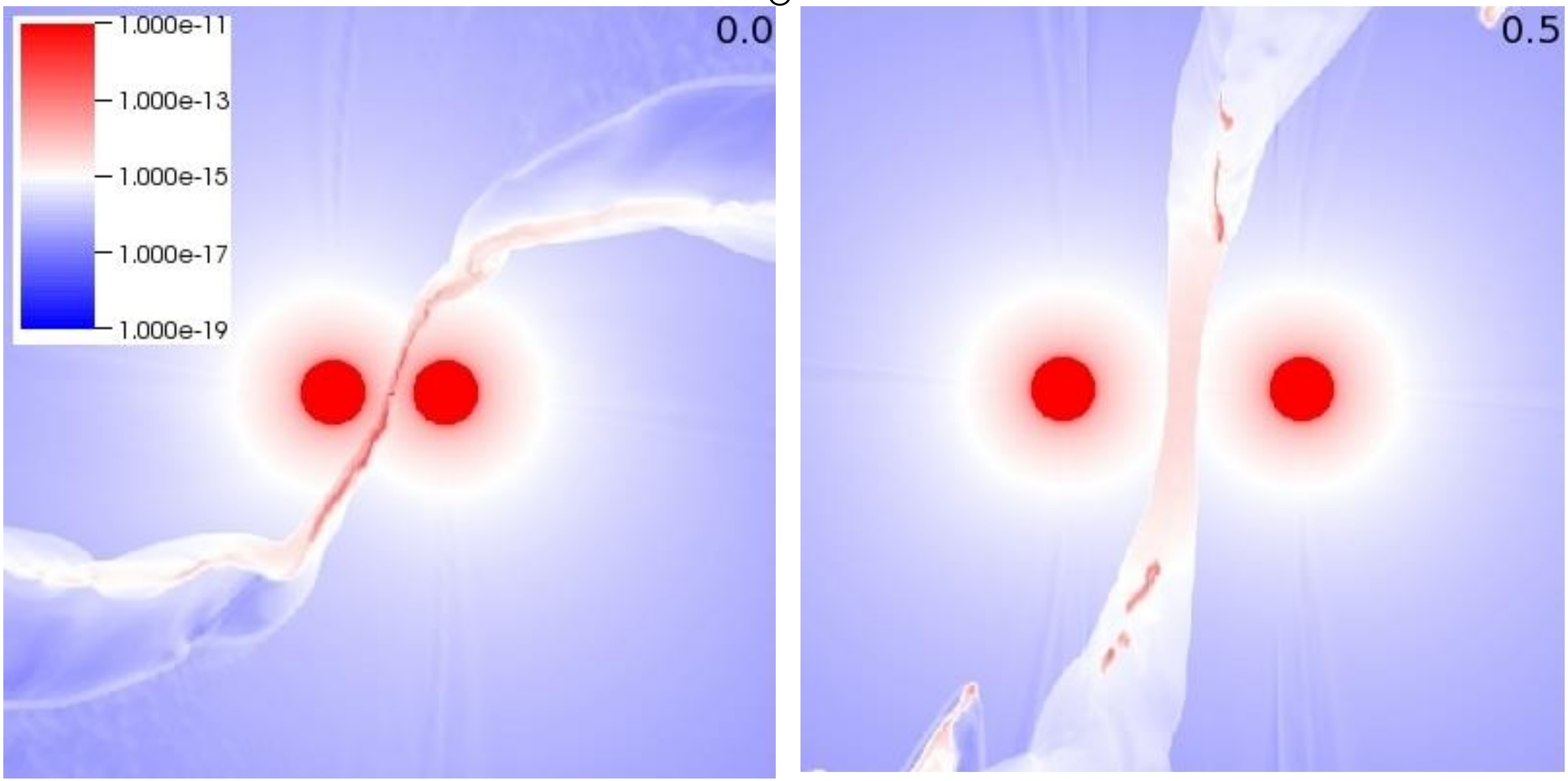
O6V + O6V, P = 6.1 d, d_{sep} = 35-75 $R_{\odot}$, e = 0.36



$v_{1,2}$ = 740 – 1630 km s^{-1} (with inhibition)
$\chi_{1,2}$ = 0.4 - 20

(Pittard 09)

Eccentricity – introduces "time lag" effects

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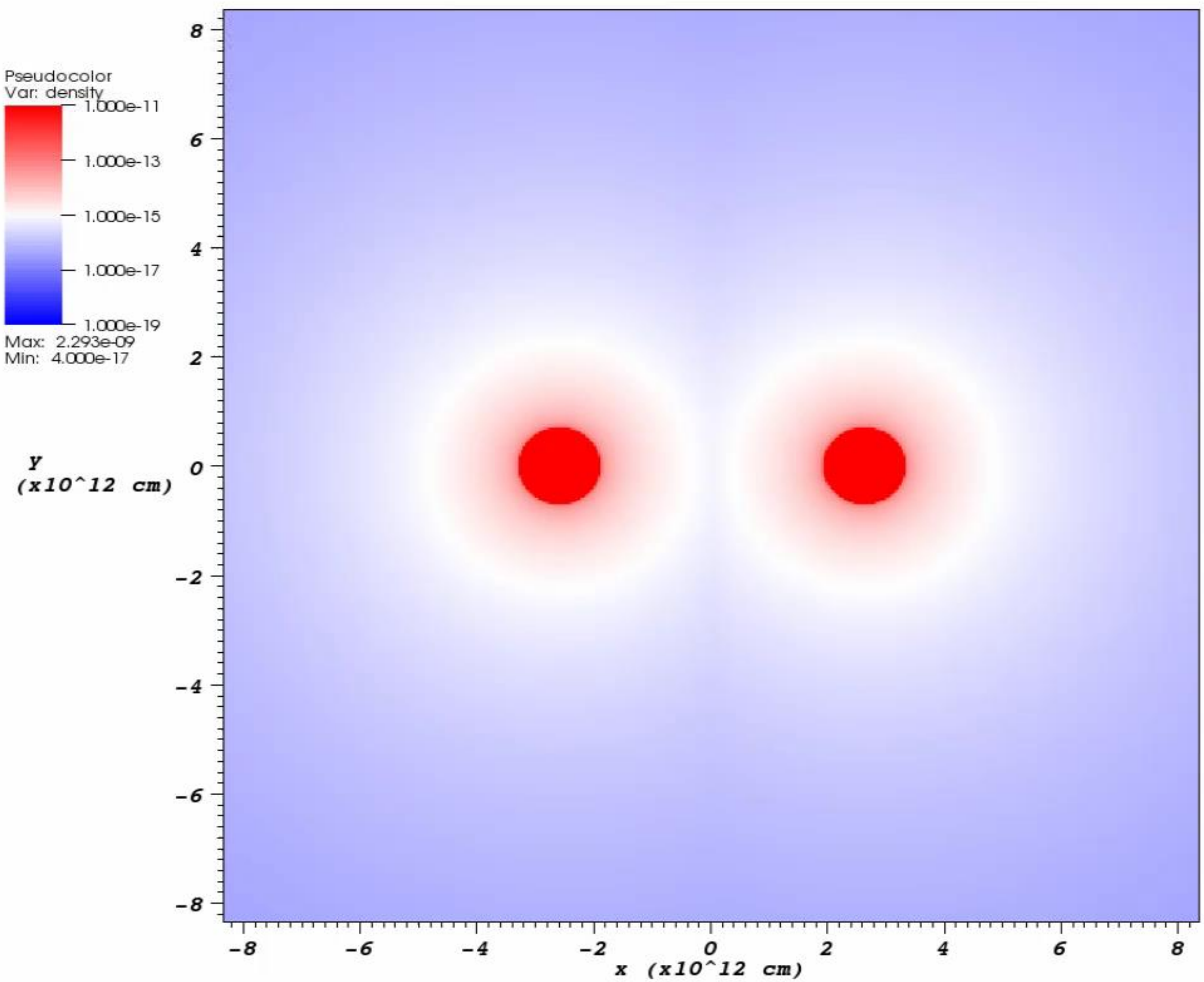

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(Pittard 09)

WR 22 – terminal speed winds

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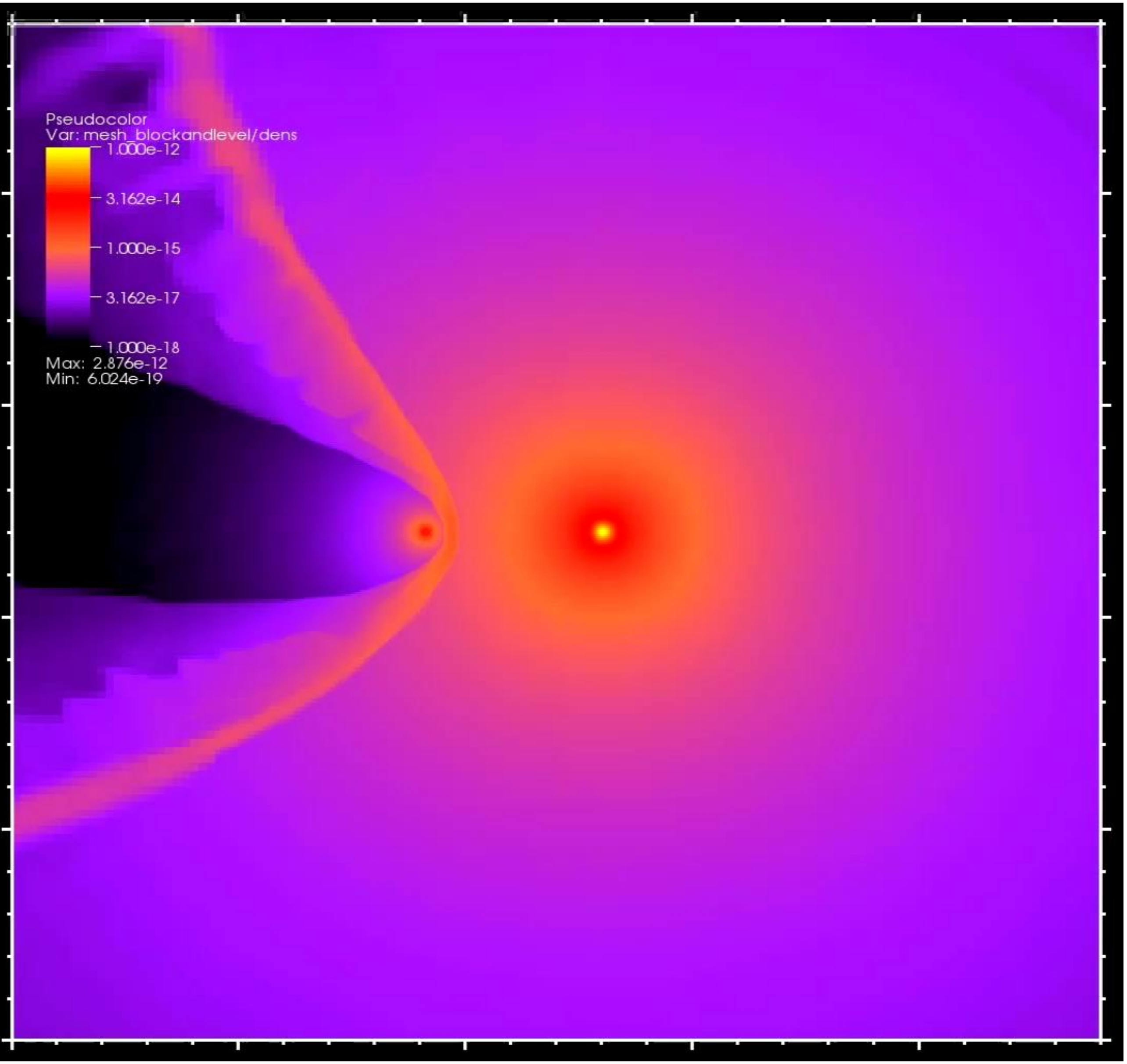

WN7 + O9V

P = 80.3d, e = 0.56, a = 1.68 AU

M = 72 + 25.7 $M_\odot$

Mdot = 1.6e-5, 2.8e-7 $M_\odot$ yr^{-1}

v_∞ = 1785, 2100 km s^{-1}

χ_{WR} = 0.7-2.5, χ_O = 75-270

Terminal velocity winds

1. Wind balance maintained around entire orbit.
2. Post-shock plasma is hot.
3. Shocked O9 wind does not significantly cool.

(Parkin+ 11)

WR 22 – radiative driving

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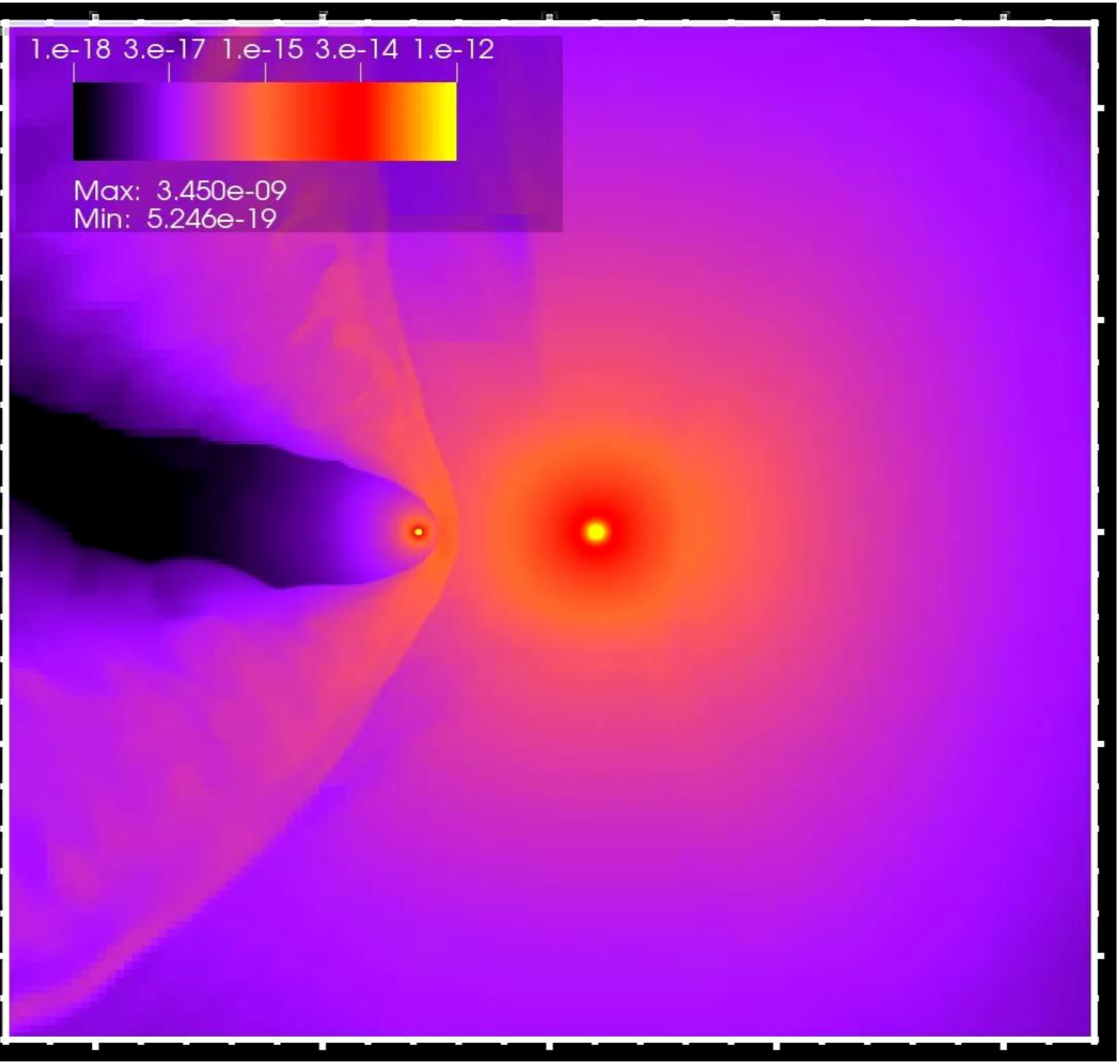

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Radiatively driven winds

1. Collide before reaching terminal speed.
2. Post-shock plasma is cooler and denser.
3. Shocked O wind now also strongly radiates around periastron.
4. WCR collapses onto O star at periastron.

(Parkin+ 11)

WR22 – radiative driving

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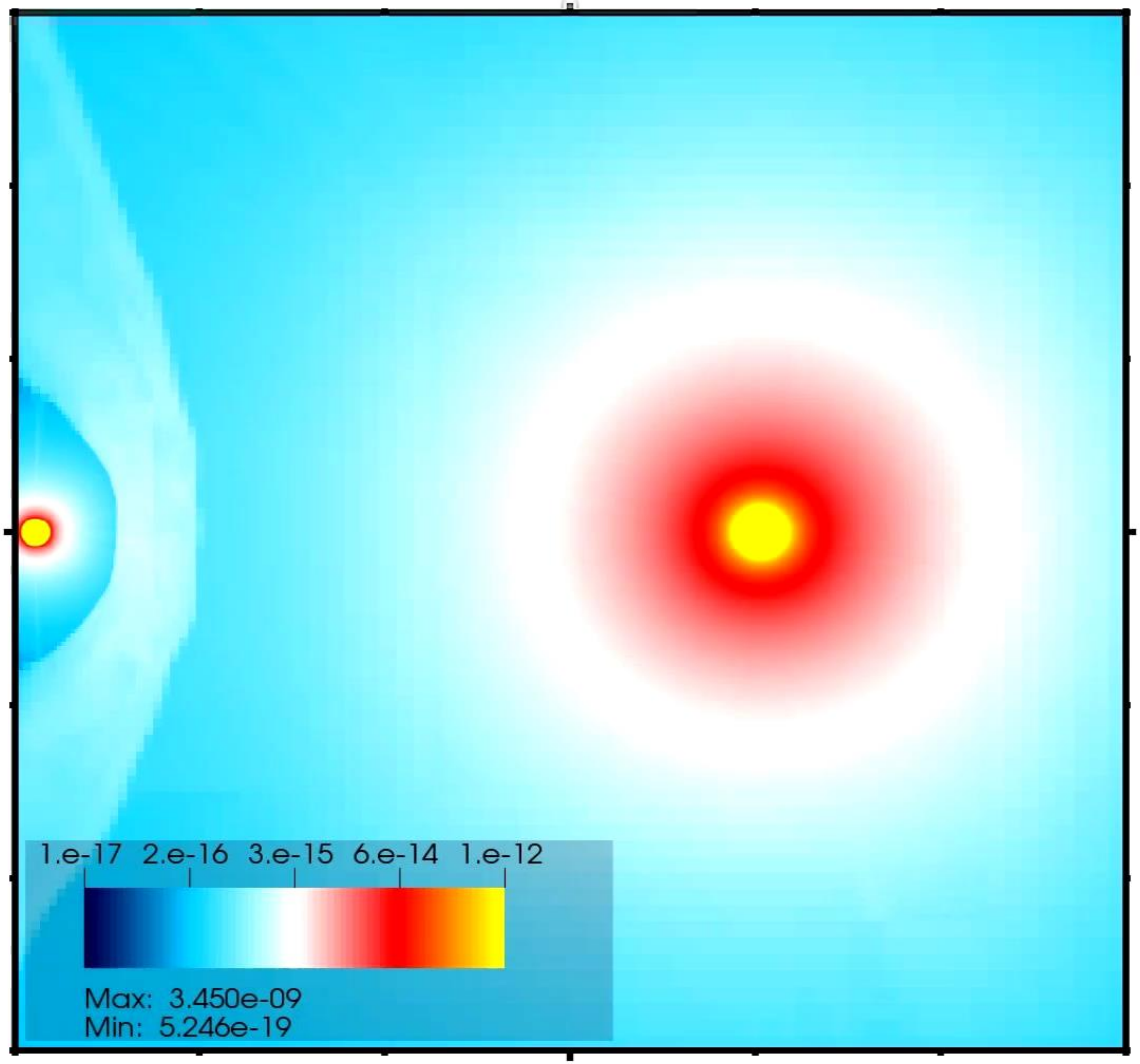

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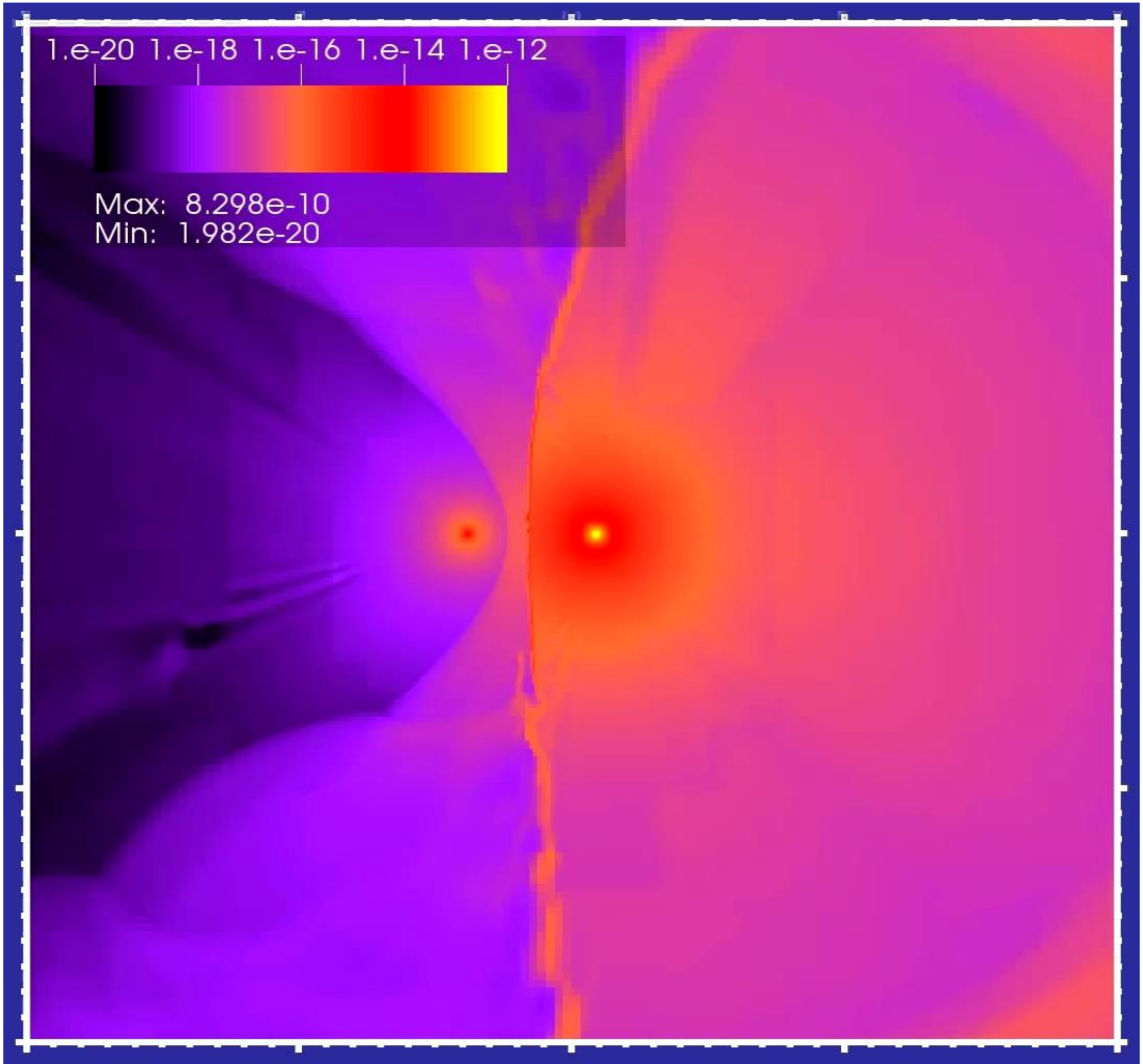
v_∞ = 1785, 2100 km s^{-1}

As the stars approach periastron the ram pressure of the WR wind increasingly overwhelms the O star's wind, pushing the WCR deeper into the O star's wind acceleration region, and triggering radiative cooling in its postshock wind. The subsequent growth of powerful NTSIs which massively disrupt the WCR is followed by a collapse of the WCR onto the O star between $\varphi \simeq 0.95$–1.05.

(Parkin+ 11)

Eta Car



LBV + ? (WR/O)

P = 2024 d, e ~ 0.9, a ≈ 15.0 AU

M = 120 + 30 $M_\odot$

Mdot = 4.8e-4, 1.4e-5 $M_\odot$ yr^{-1}

V_∞ = 500, 3000 km s^{-1}

$\chi_{LBV} << 1$

$\chi_{WR/O\ (peri)} < 13$, $\chi_{WR/O\ (ap)} < 250$

(Parkin+ 11)

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First Direct Proof of Colliding Winds Model

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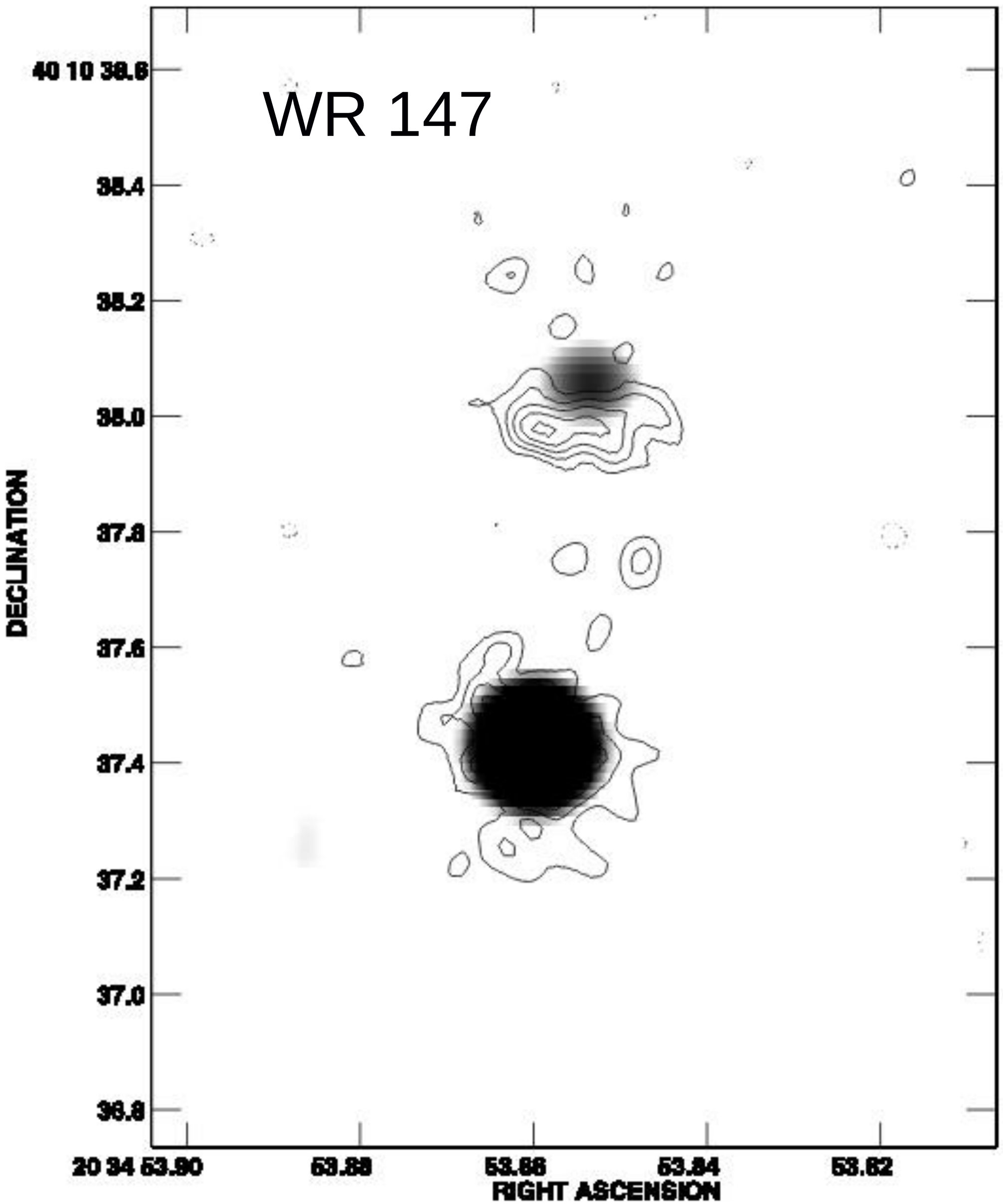

WR147: WR+OB binary

Grey-scale: **UKIRT K-band**

Contours: 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+ 97)

WR 146 – a very bright CWB in the radio

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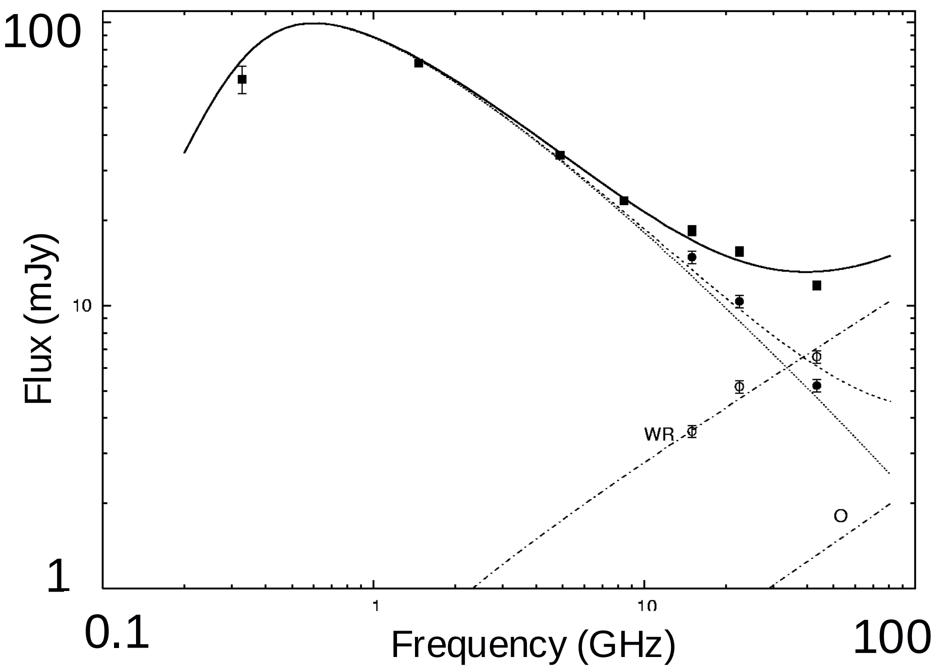

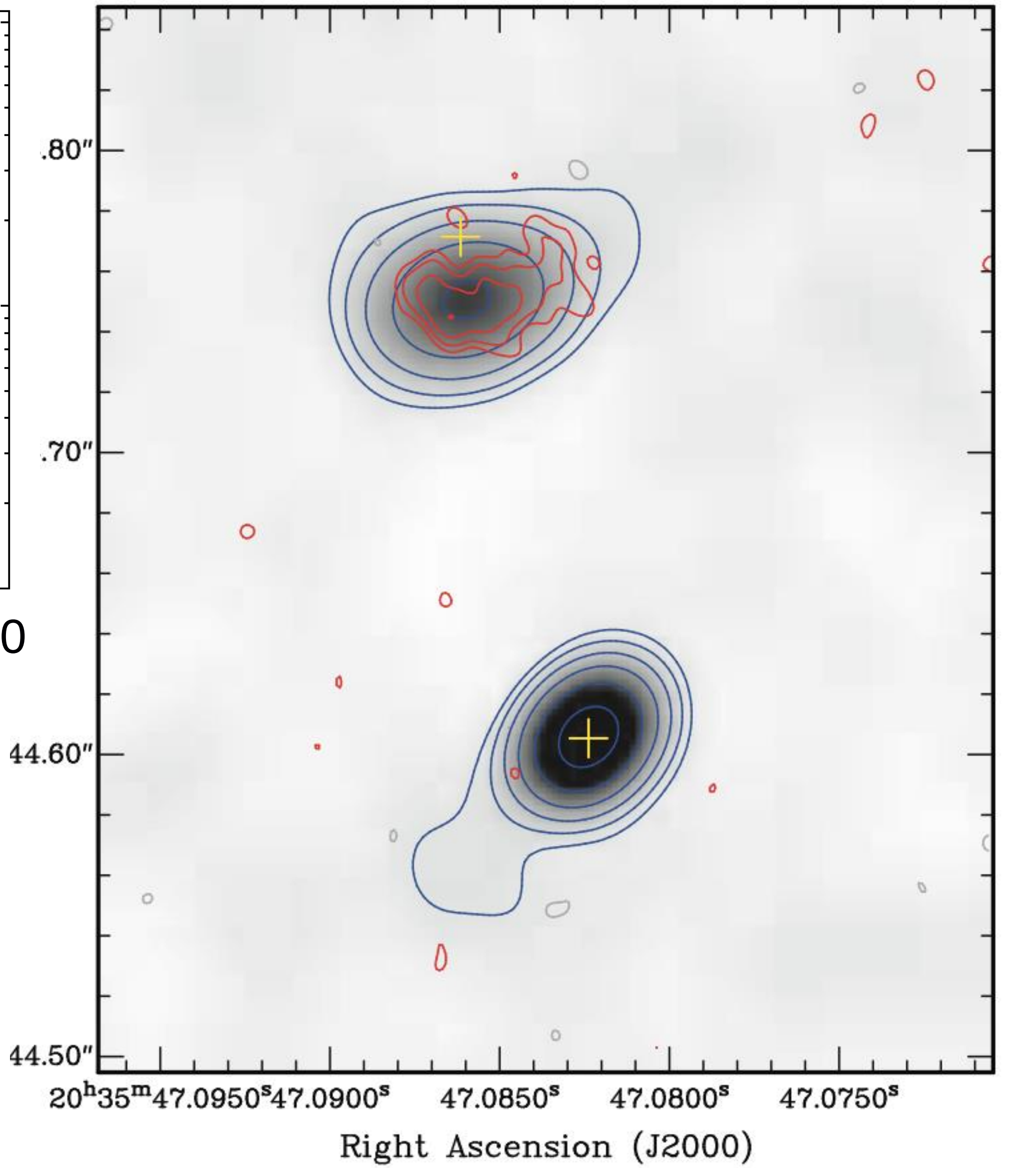

VLA 43-GHz shows the southern thermal source that is associated with the WR star and the northern non-thermal emission from the WCR.

VLBA 8.6-Ghz reveals the structure of the WCR.

Yellow crosses mark the positions of the two stars.

Courtesy Sean Dougherty

WR140 – the particle acceleration laboratory

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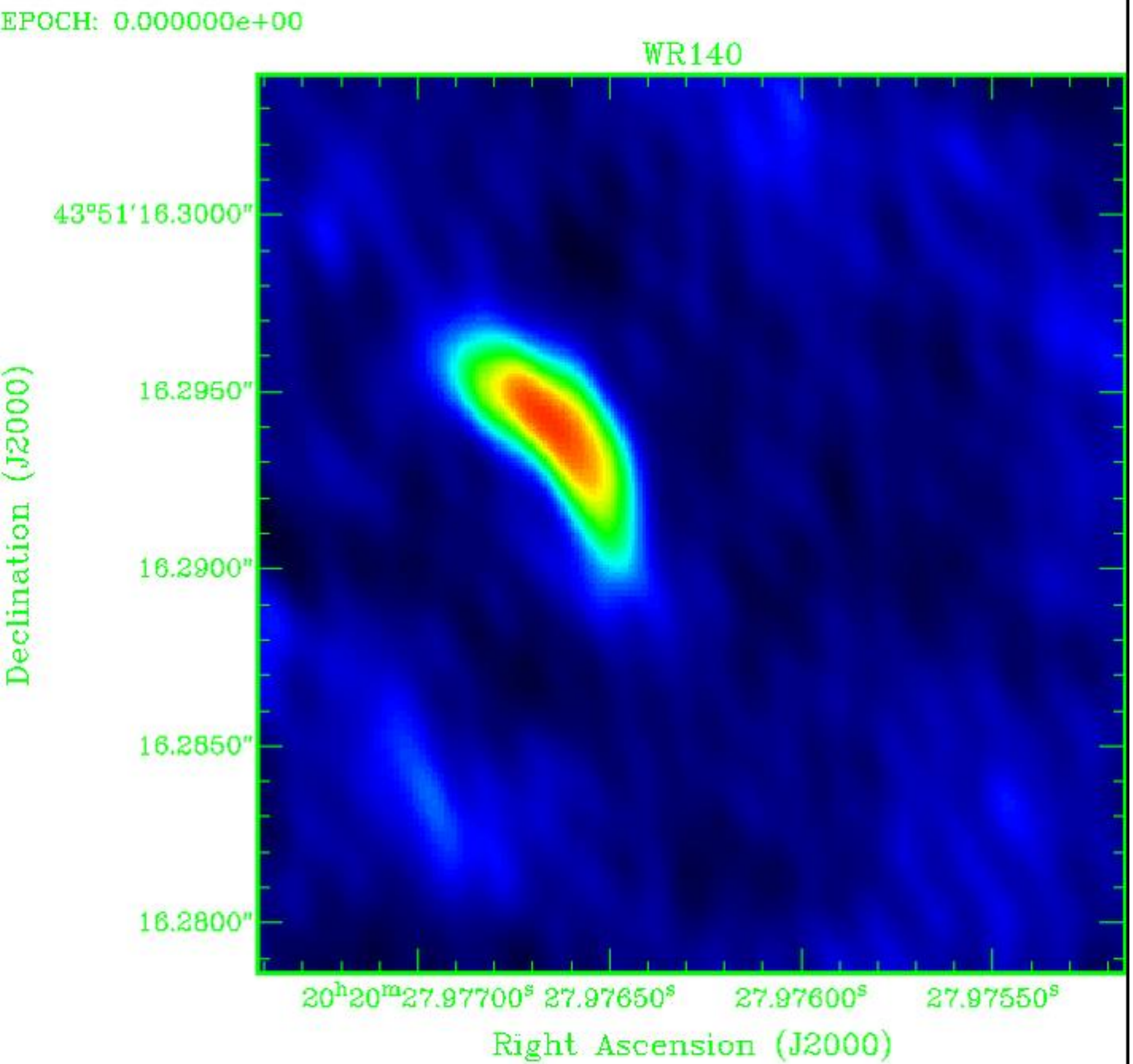

WR + O in a 7.9 year, eccentric (e ~ 0.9) orbit

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+ 05)

The radio light curve of WR140

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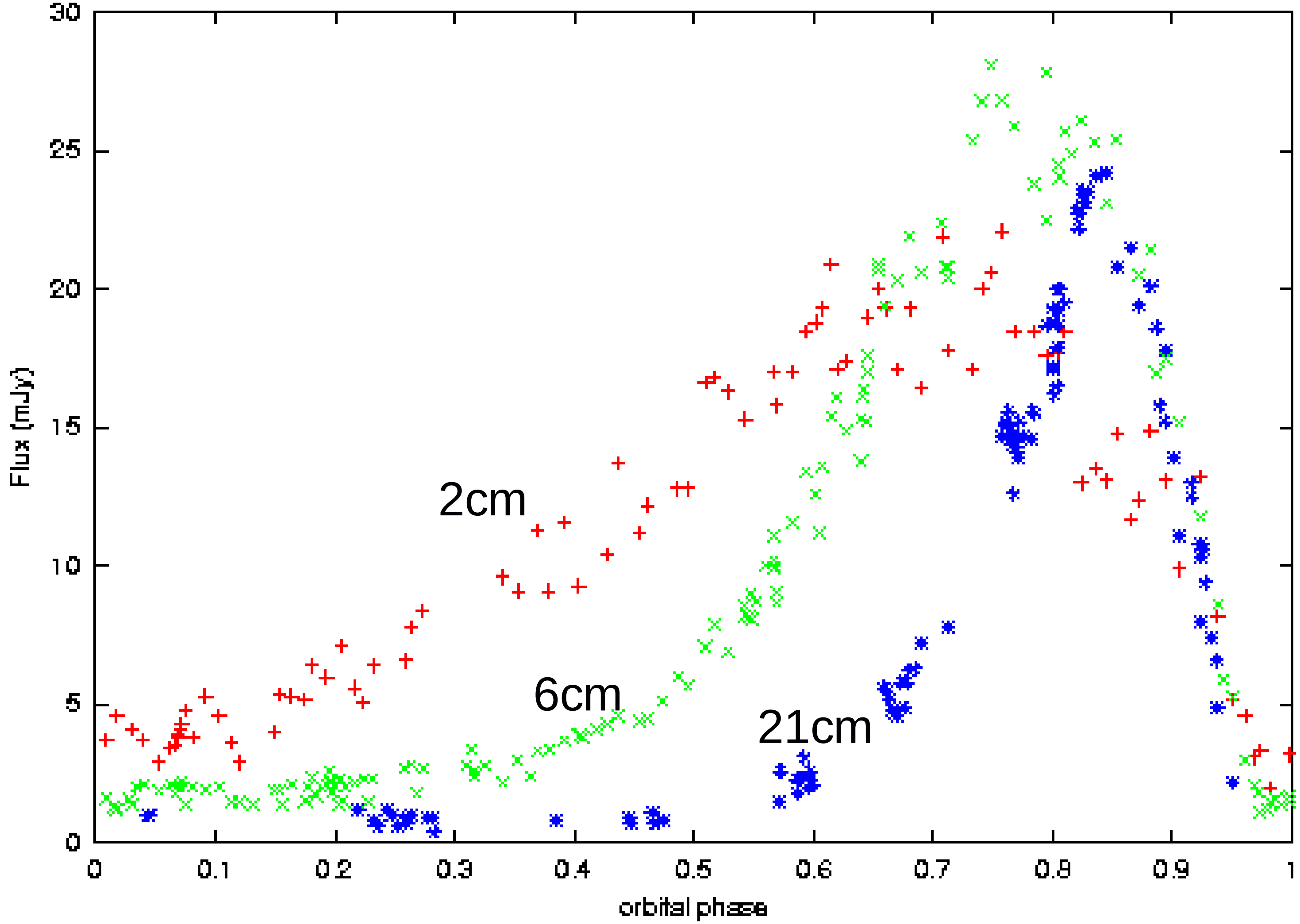

8 years of VLA (White+ 95) + WSRT (Williams+ 91) data

Early Models

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Early models of NT emission were simple

Radio:

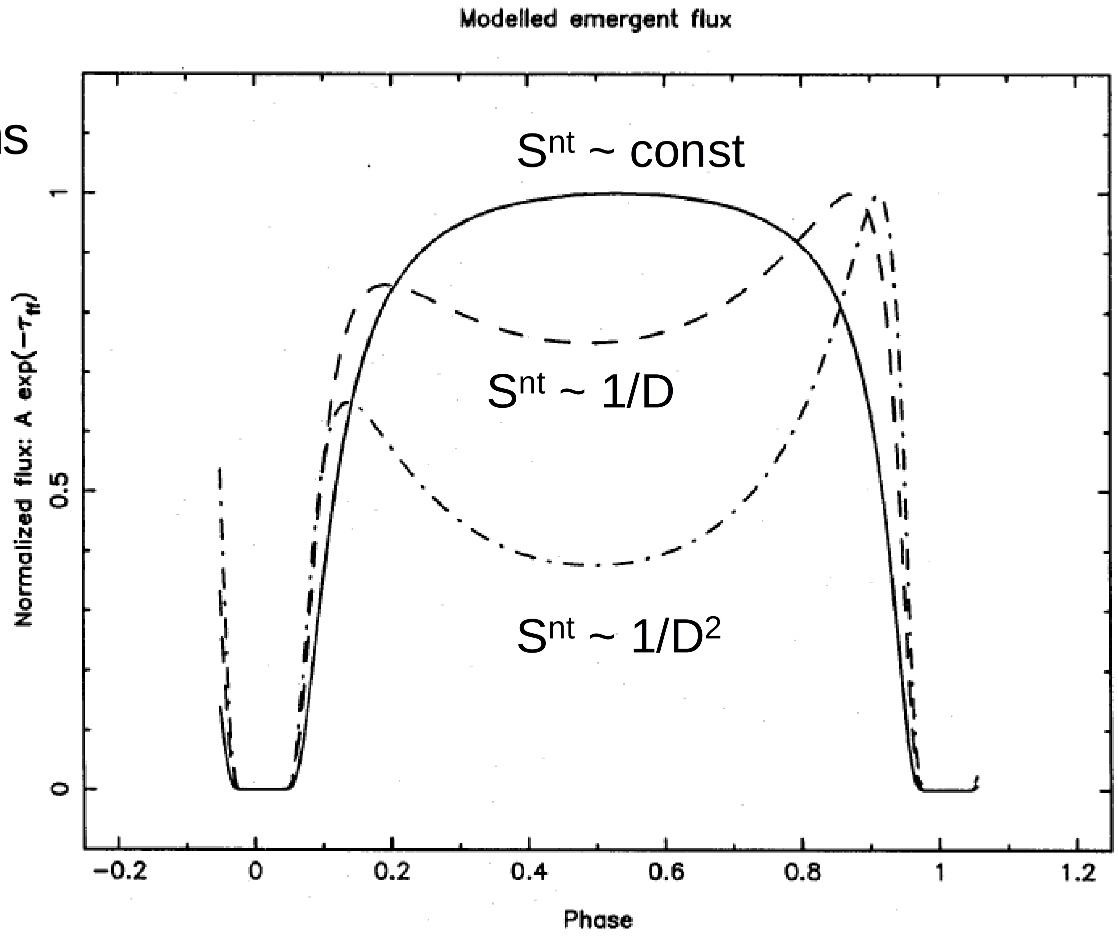
- Point source non-thermal emission, spherically symmetric winds –

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

- maintains analytic solutions

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

(Williams+ 90)



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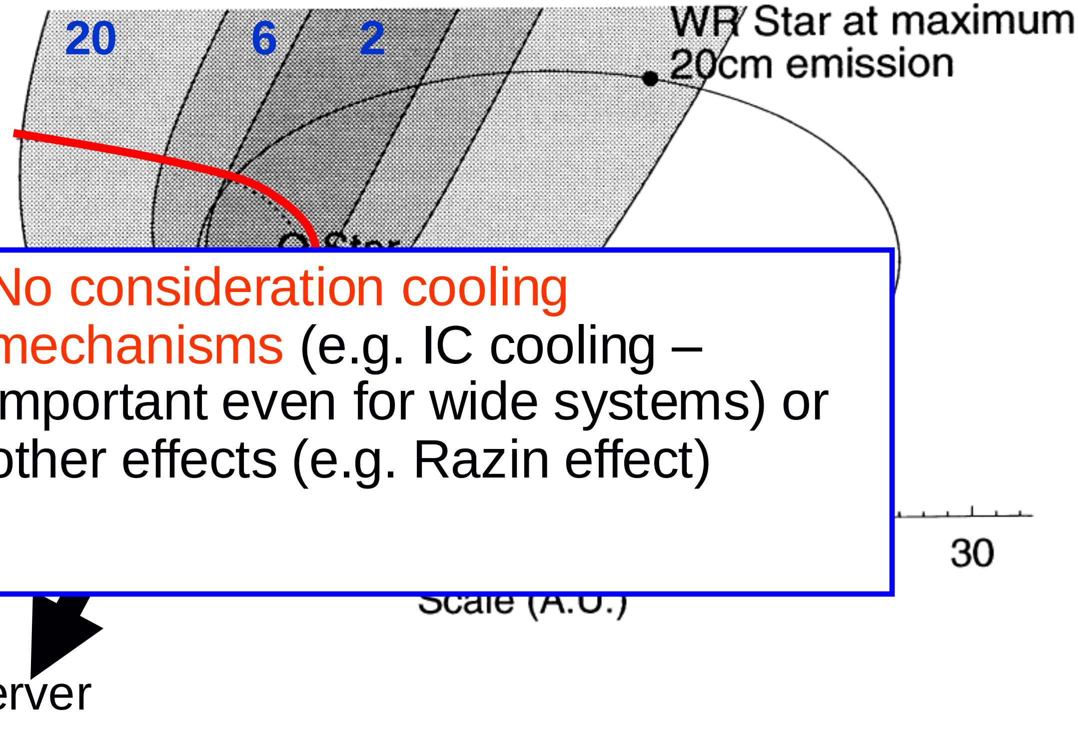
White+95 pointed out that even the O wind has significant opacity



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

The first spatially-extended model

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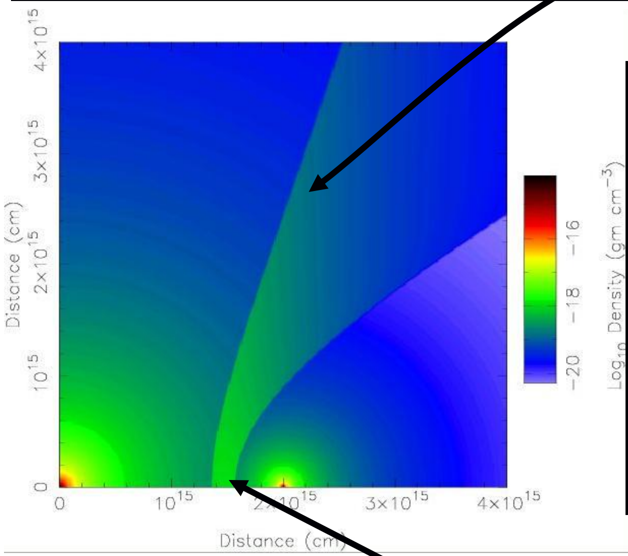
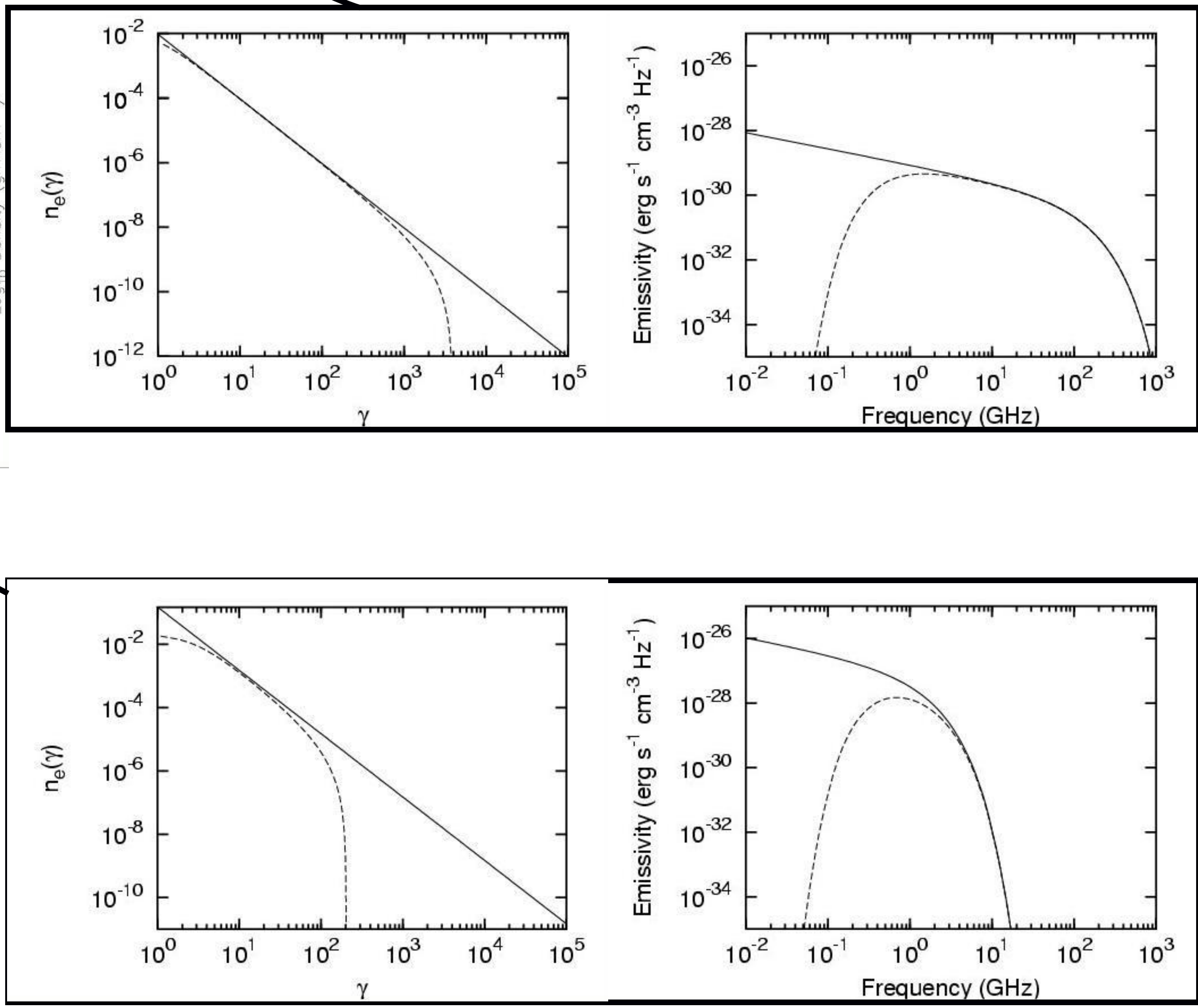
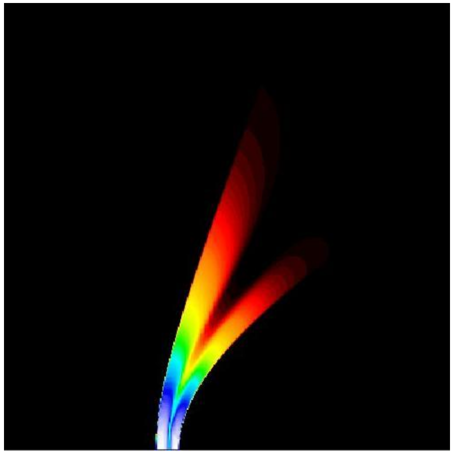






1.6 GHz emission map

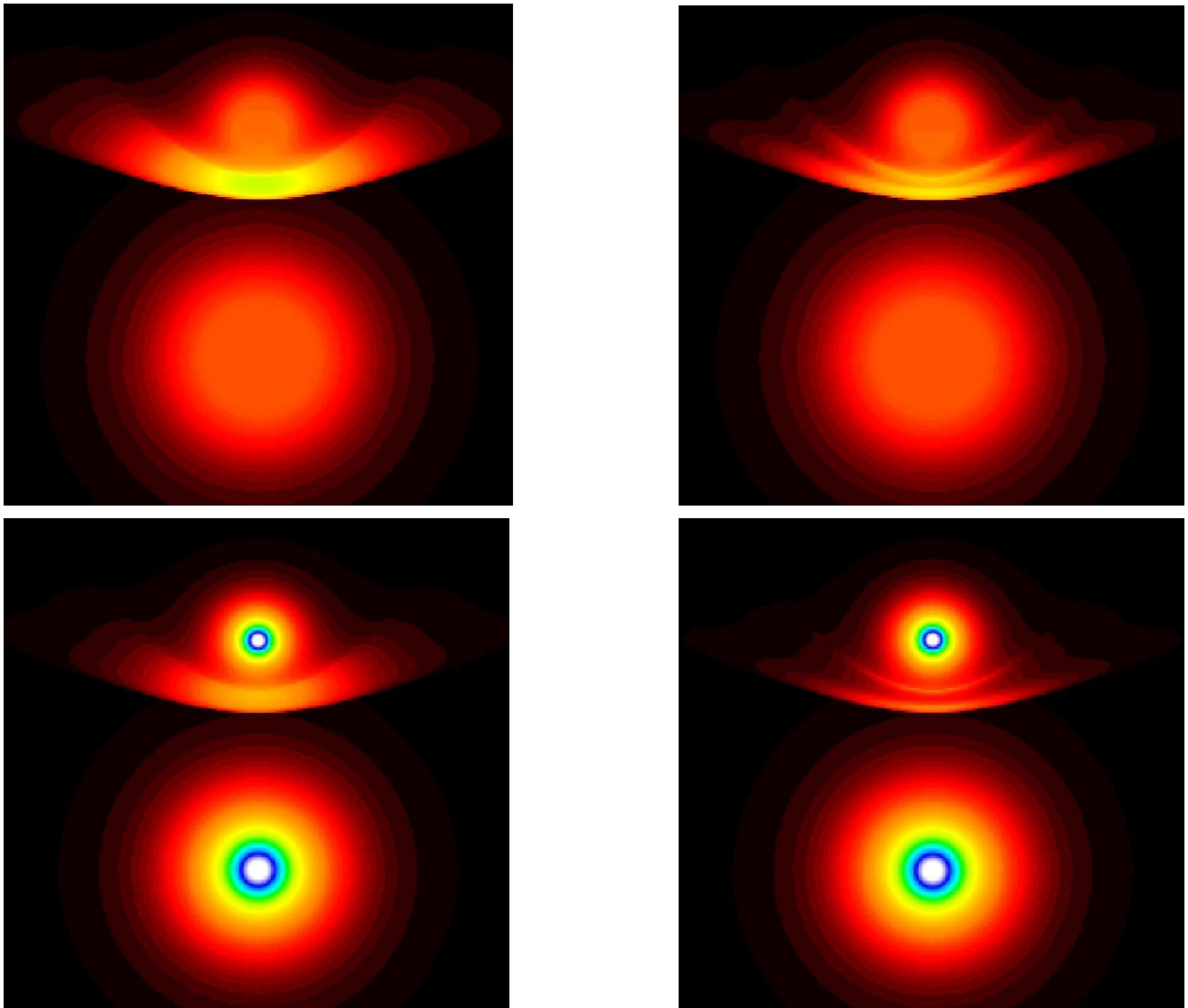
(Pittard+ 06)

Example synthetic emission maps

No IC cooling | With IC cooling

1.6 GHz

22 GHz



NT (keV) emission from ηCar

(Hamaguchi, Corcoran, Pittard+, 2018, Nat. Ast., 2, 731)

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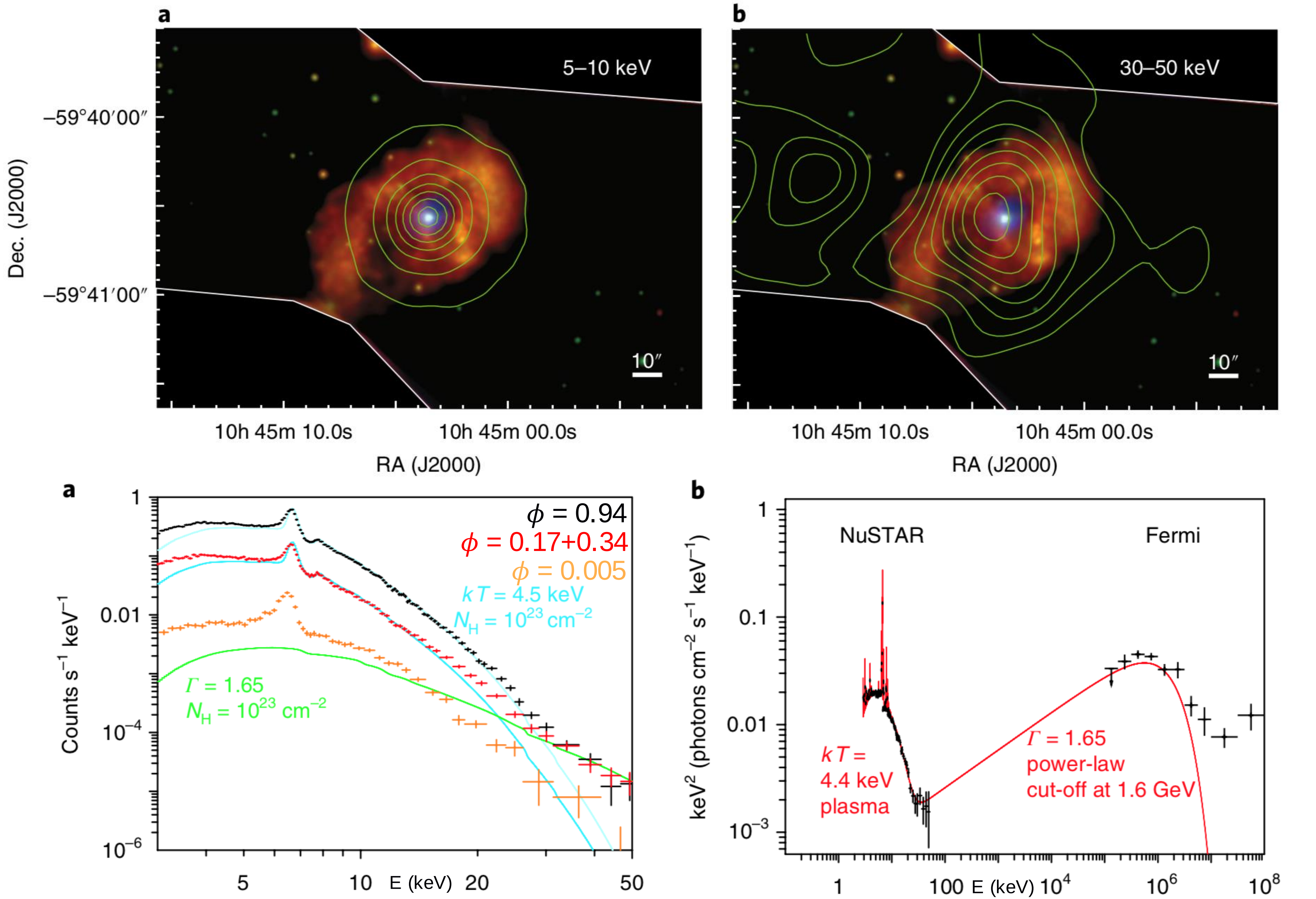

NT (keV) emission from ηCar
(Hamaguchi, Corcoran, Pittard+, 2018, Nat. Ast., 2, 731)

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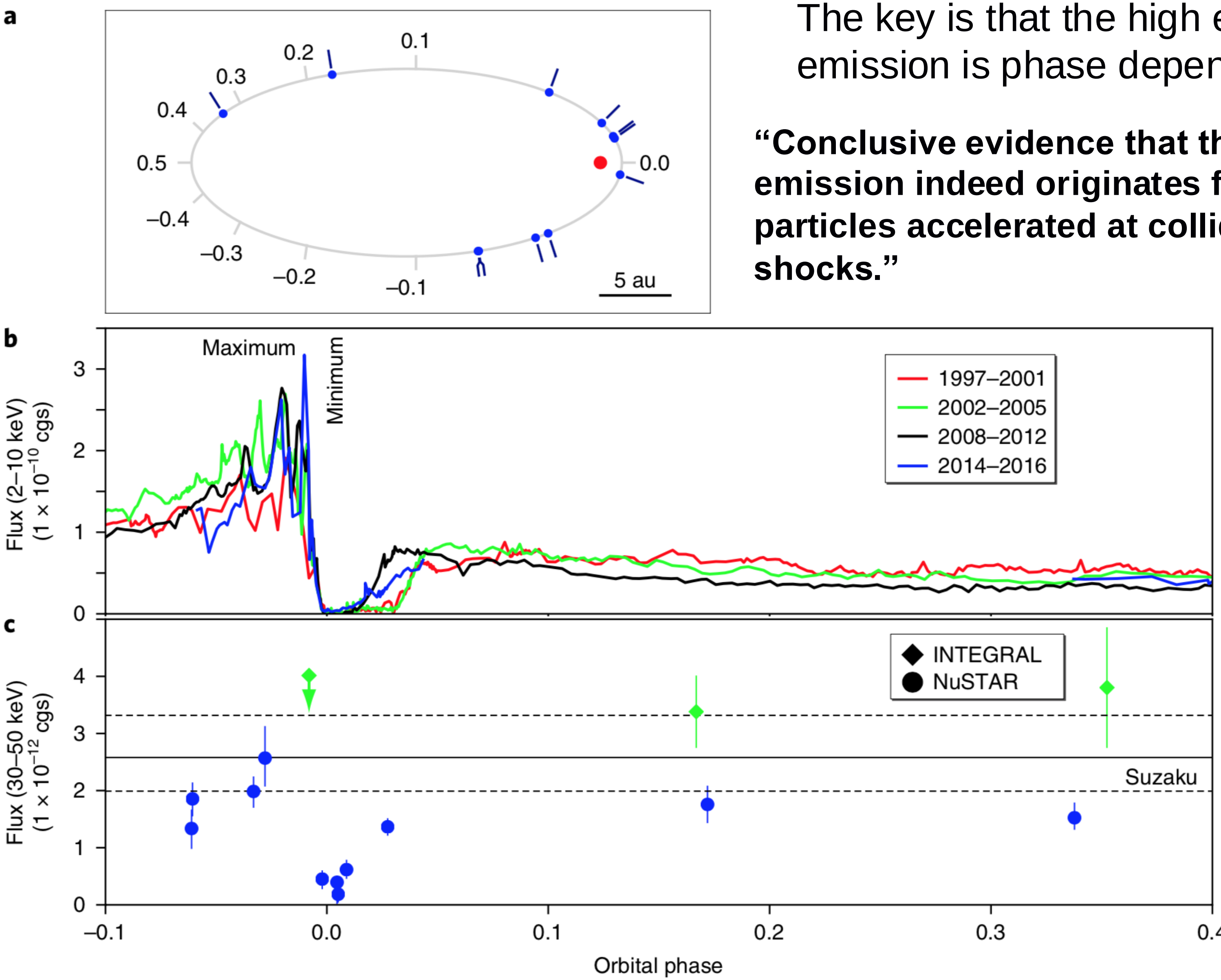
The key is that the high energy NT emission is phase dependent.

"Conclusive evidence that the high-energy emission indeed originates from non-thermal particles accelerated at colliding wind shocks."

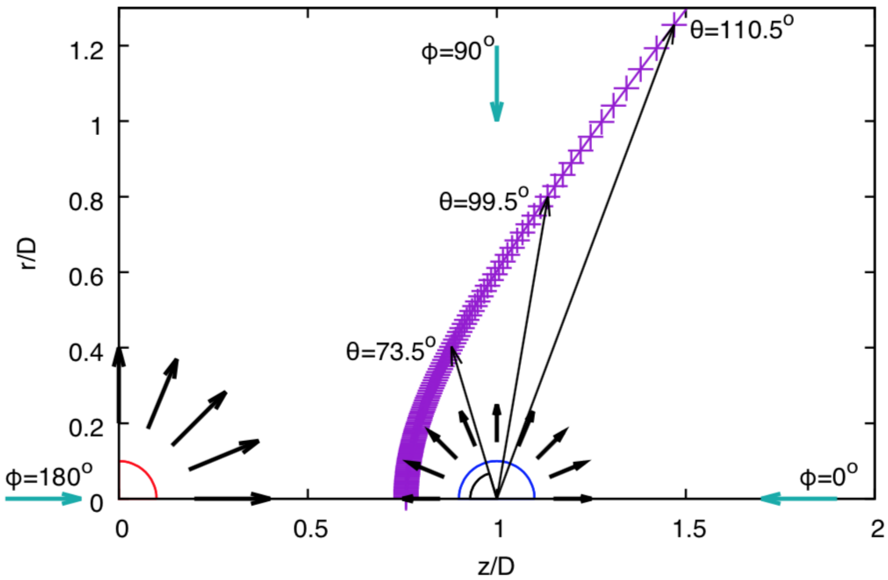


Outside of periastron the NuSTAR emission is roughly constant.

Likely due to the high energy electrons cooling quickly.

We wish to construct a model that has the main geometrical features but that isn't tied to an expensive 3D HD/MHD simulation.

Pittard+ (2021)



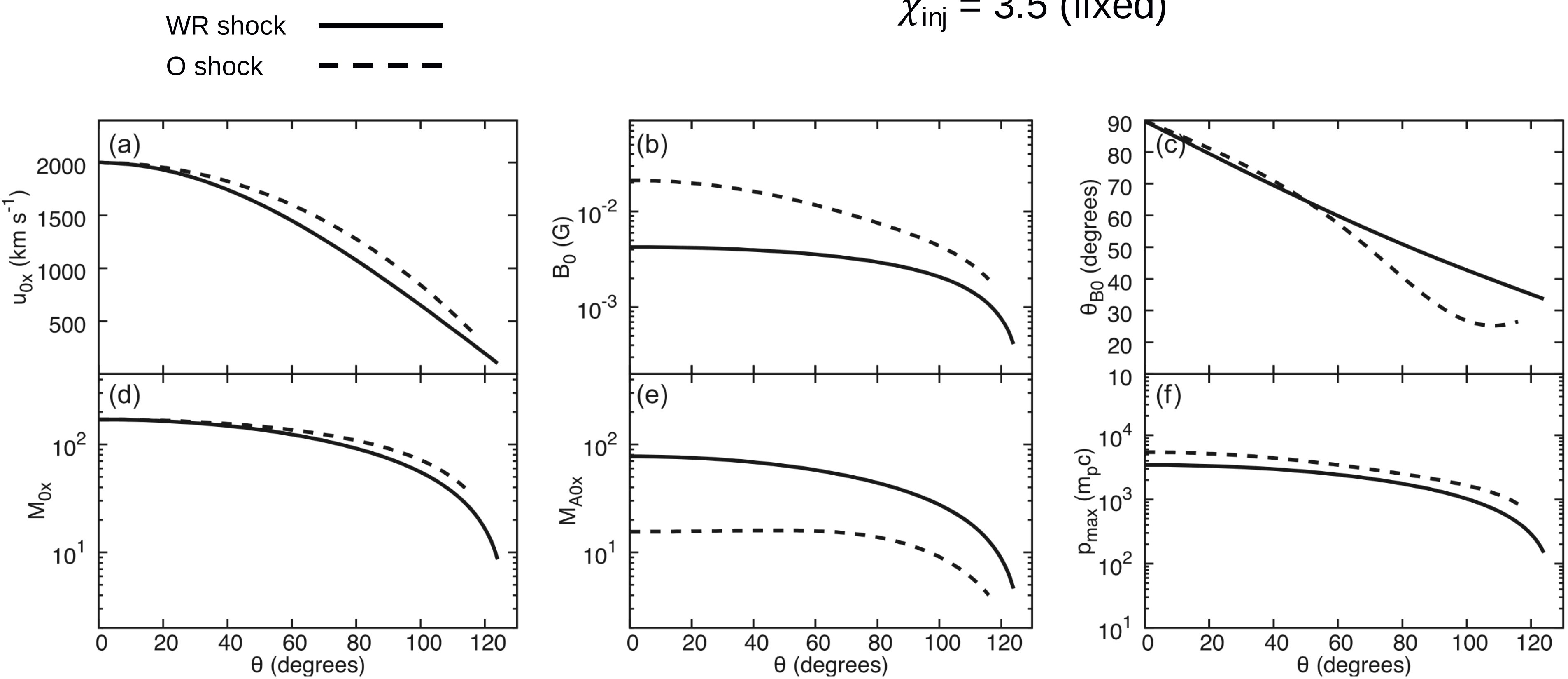
Model description/assumptions:

- Axisymmetric. Winds collide at terminal speed. No radiative inhibition/braking effects.
  - ➢ long period systems.
- Position of the CD from Canto+ (1996). Assume shocks are coincident.
- Solve the diffusion-advection equation at the shocks using the semi-analytic method of Blasi+ (2005), modified by Grimaldo+ (2019) for a uniform background B-field. Valid for oblique shocks and includes magnetic field amplification and back-reaction.
- Assume that scattering centres move relative to the fluid at the Alfven velocity.
- Solve the kinetic equation to obtain the downstream particle distributions. Includes secondary electron generation.
- All major NT emission processes included (synchrotron, relativistic bremmsstrahlung, anisotropic IC, neutral pion decay), plus free-free and $\gamma\gamma$ absorption.

“Standard model” parameters and shock properties

Parameter	WR star	O star
$\dot{M}$ ($M_\odot$ yr^{-1})	2×10^{-5}	2×10^{-6}
v_∞ (km s^{-1})	2000	2000
L ($L_\odot$)	2×10^5	5×10^5

D_{sep} = 2 x 10^{15} cm
T = 40,000 K for both stars
B_* = 100 G
V_{rot} = 200 km s^{-1} => Toroidal field
Shocks almost perpendicular on axis
B_0 = 4 mG (WR) and 20 mG (O)
χ_{inj} = 3.5 (fixed)



NT emission from the “standard model”

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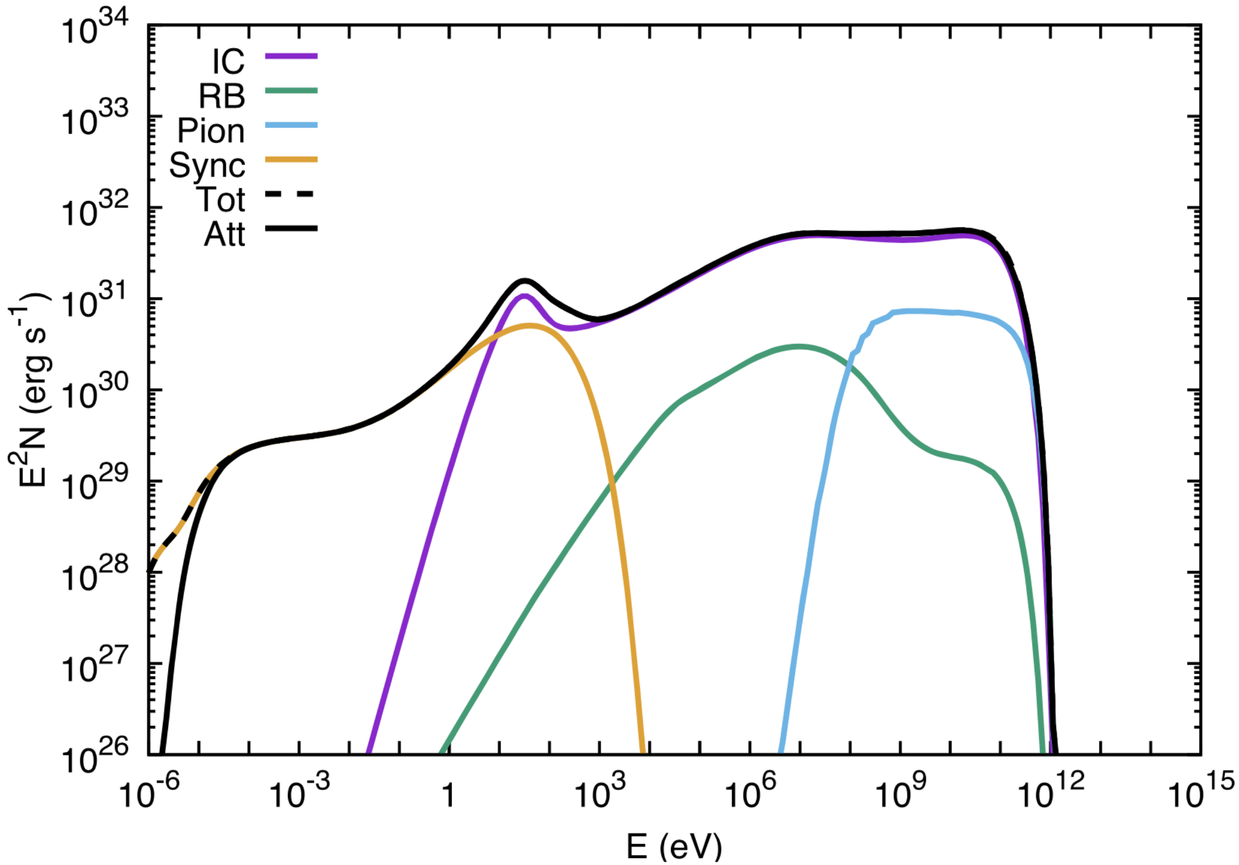

The emission from particles accelerated at the WR shock dominates.

The Razin effect causes the low frequency turnover in this case.

$\gamma - \gamma$ absorption is negligible.

Dependence on stellar separation, D_{sep}

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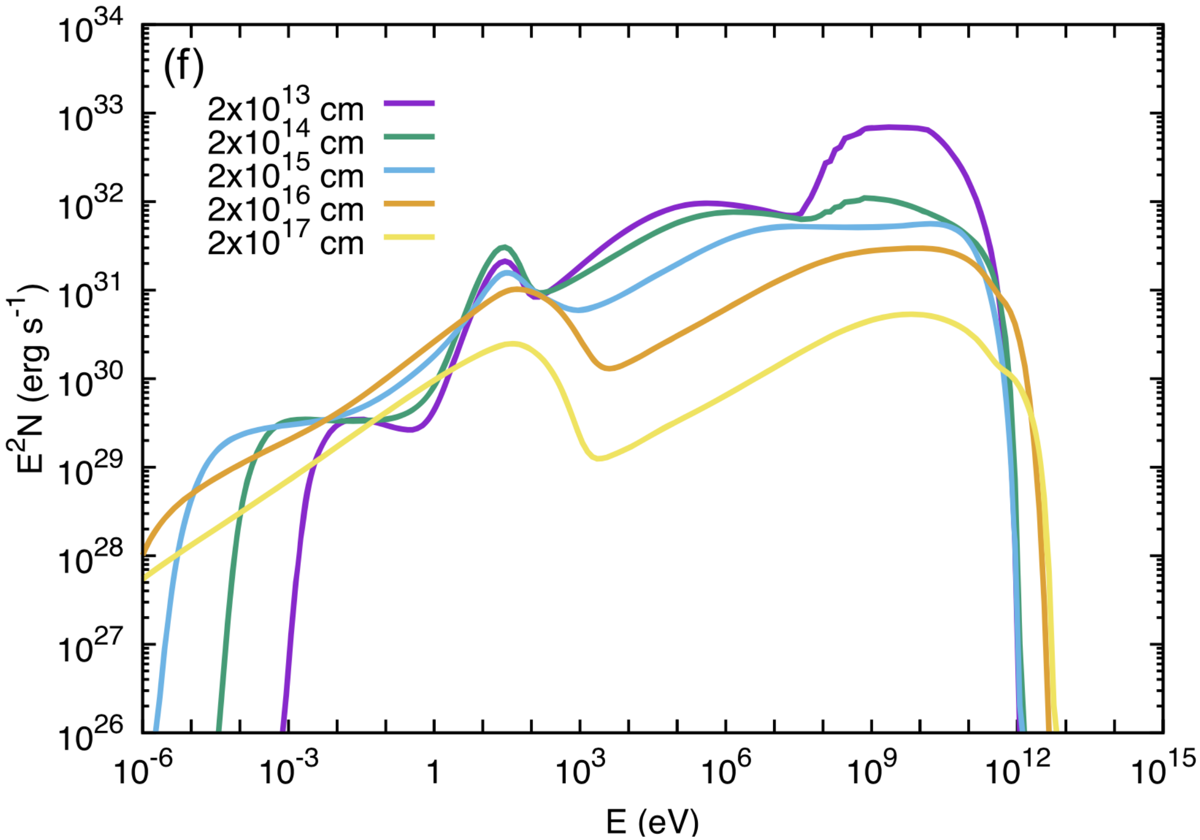
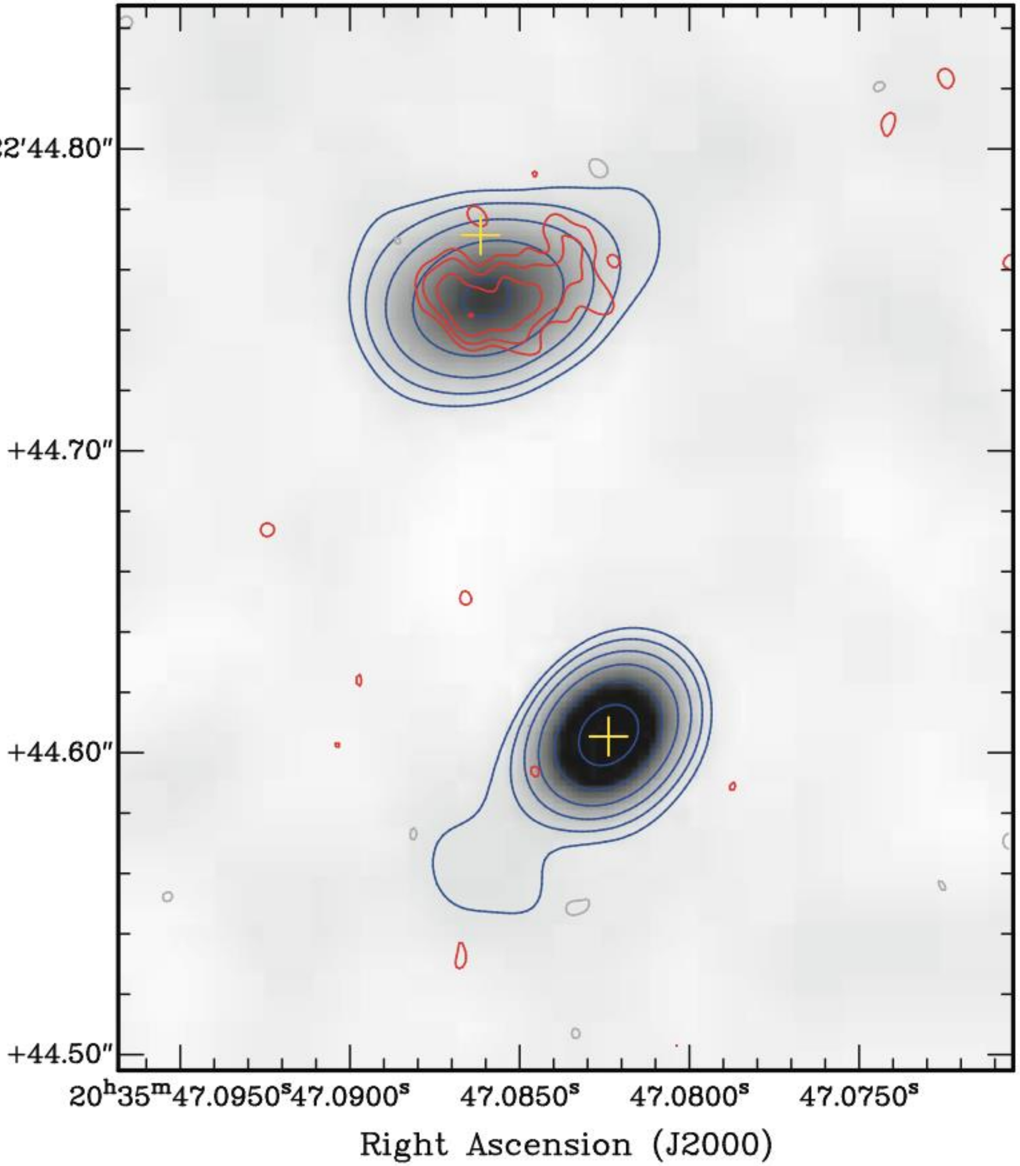


Decreasing D_{sep} causes the π^0-decay emission to increase ($\propto D^{-1}$).
The IC emission also increases but plateaus at low separations.
The synchrotron emission shows quite complicated non-linear behaviour.
The low frequency turnover is still dominated by the Razin effect ($\nu_R \propto D^{-1}$).
$\gamma - \gamma$ absorption becomes important at $D_{sep} < 10^{14}$ cm.

Application to WR 146



Parameters in final model

Parameter	WR star	O star
$\dot{M}$ ($M_\odot\,yr^{-1}$)	2×10^{-5}	4×10^{-6}
v_∞ (km s^{-1})	2800	1600
L ($L_\odot$)	2.3×10^5	7.9×10^5
T_{eff} (K)	49 000	32 000
R_* ($R_\odot$)	6.6	28.9
X	0.0	0.7381
Y	0.744	0.2485
Z	0.256	0.0134
B_* (G)	140	14
v_{rot}/v_∞	0.1	0.1
f	1.0	1.0

To match the low frequency synchrotron downturn we needed to set $D_{sep} = 1.2\text{x}10^{16}$ cm (i = 76°; i = 0° is face-on). This necessitated a doubling of the O-star mass-loss rate to match the normalization of the synchrotron emission.
Finally, B_* was adjusted to match the synchrotron flux and turnover.

Application to WR 146

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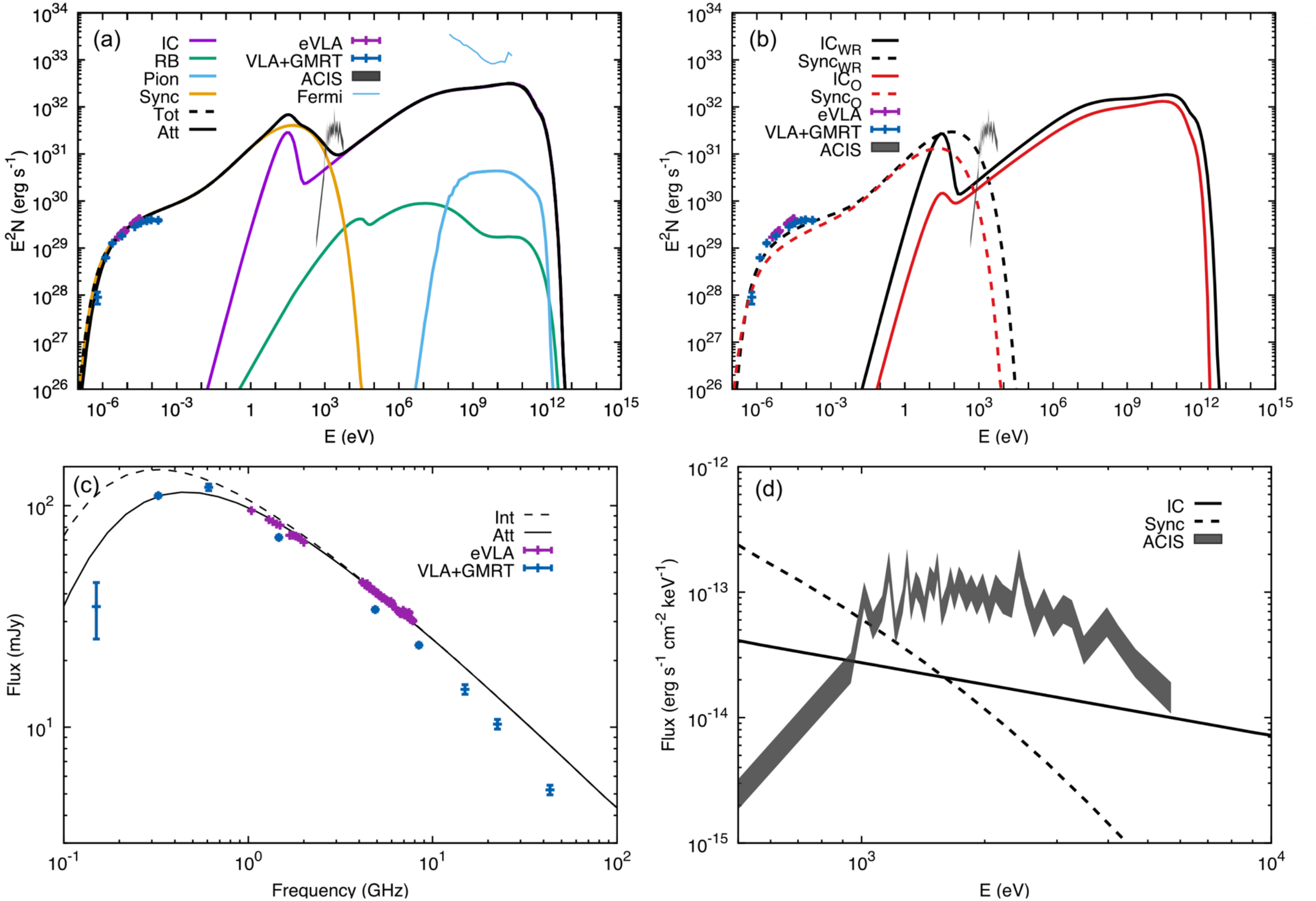

30% of the wind power perpendicular to the shocks goes into CRs.

Observations and modelling of Apep (WN+WC)

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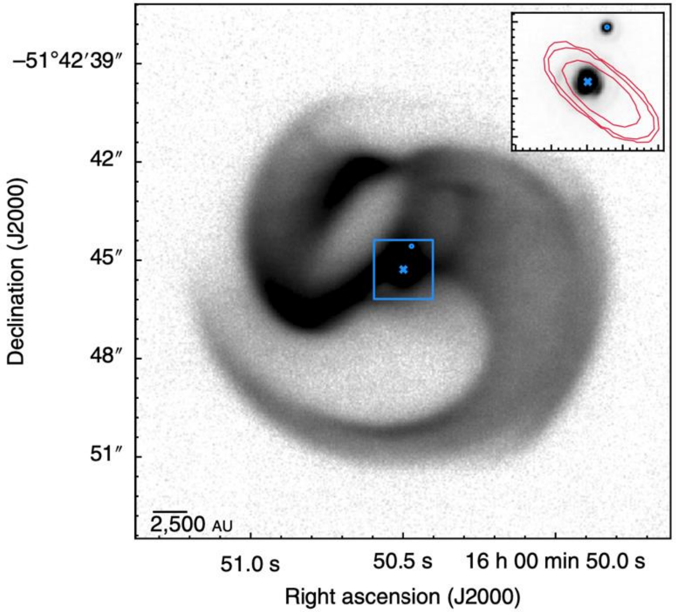


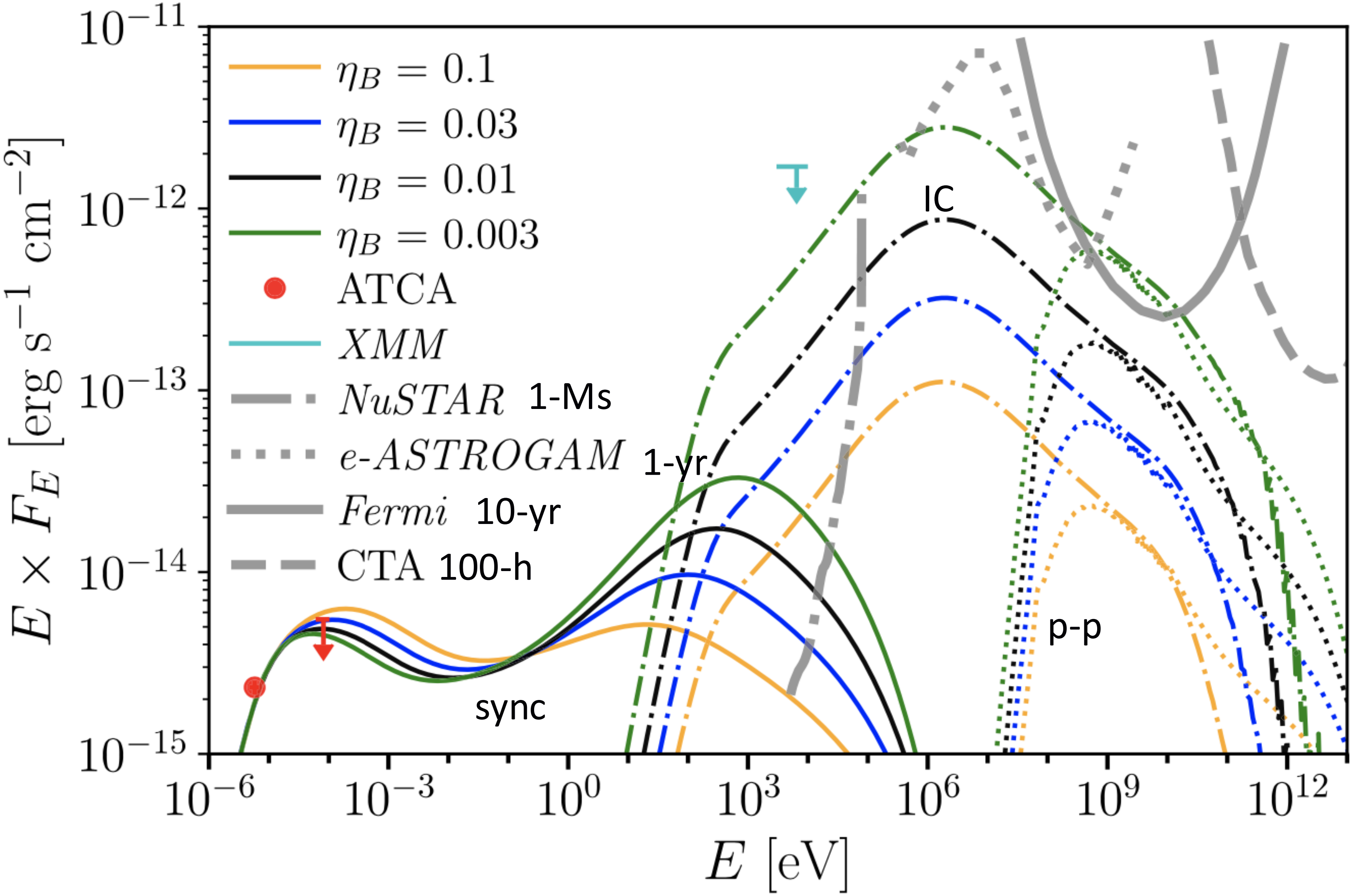
VISIR 8.9 µm Callingham+19

WN wind dominates

Parameters:

Parameter	Value
Distance	$d = 2.4^{+0.2}_{-0.5}$ kpc
Projected system separation	$D_{\rm proj} = 47 \pm 6$ mas
Projection angle	$\psi = 85°$
Wind momentum rate ratio	$\eta = 0.44 \pm 0.08$
Stellar temperature	$T_{\rm eff,WN} = 65\,000$ K
Stellar radius	$R_{\rm WN} = 6\,R_\odot$
Wind terminal velocity	$v_{\infty,\rm WN} = 3500 \pm 100$ km s^{-1}
Wind mass-loss rate	$\dot{M}_{\rm WN} = (4 \pm 1) \times 10^{-5}\,M_\odot$ yr^{-1}
Wind mean atomic weight	$\mu_{\rm WN} = 2.0$
Stellar temperature	$T_{\rm eff,WC} = 60\,000$ K
Stellar radius	$R_{\rm WC} = 6.3\,R_\odot$
Wind terminal velocity	$v_{\infty,\rm WC} = 2100 \pm 200$ km s^{-1}
Wind mass-loss rate	$\dot{M}_{\rm WC} = (2.9 \pm 0.7) \times 10^{-5}\,M_\odot$ yr^{-1}
Wind mean atomic weight	$\mu_{\rm WC} = 4.0$

Observations and modelling of Apep (WN+WC)



Modelled non-thermal SED of Apep for different values of η_B

del Palacio+22

Observations and modelling of Apep (WN+WC)

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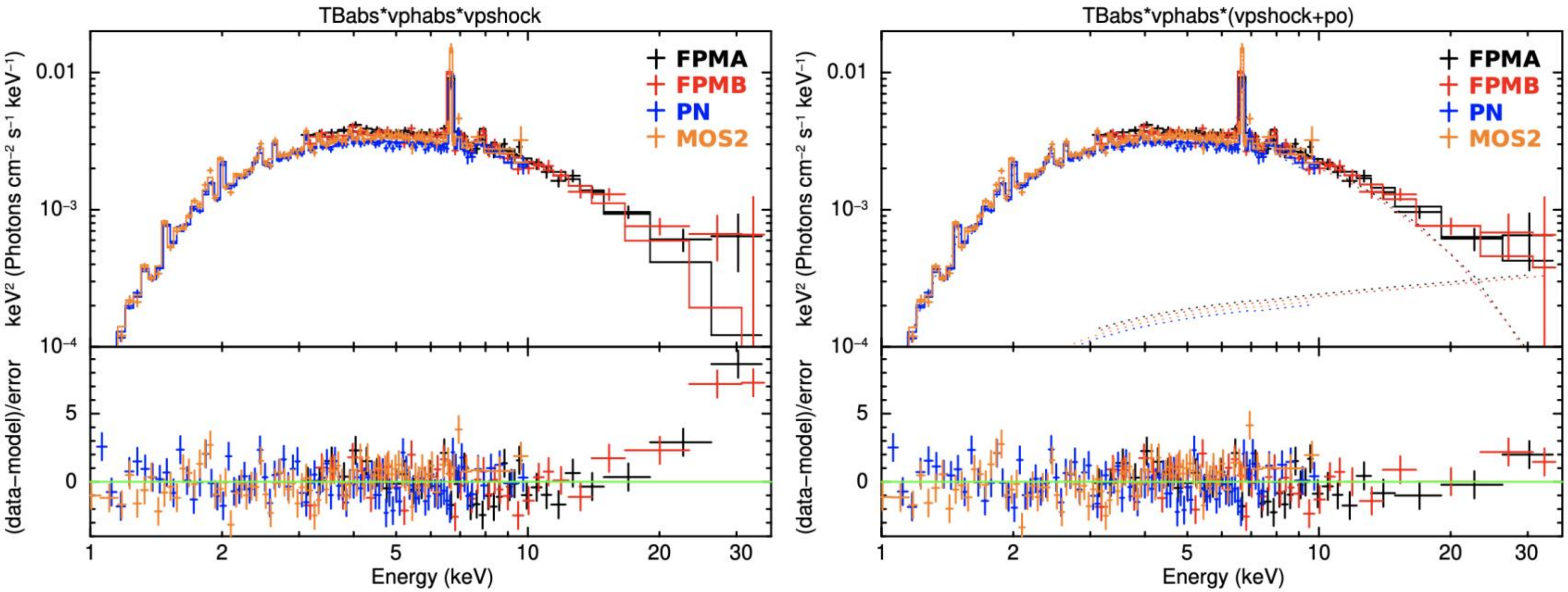

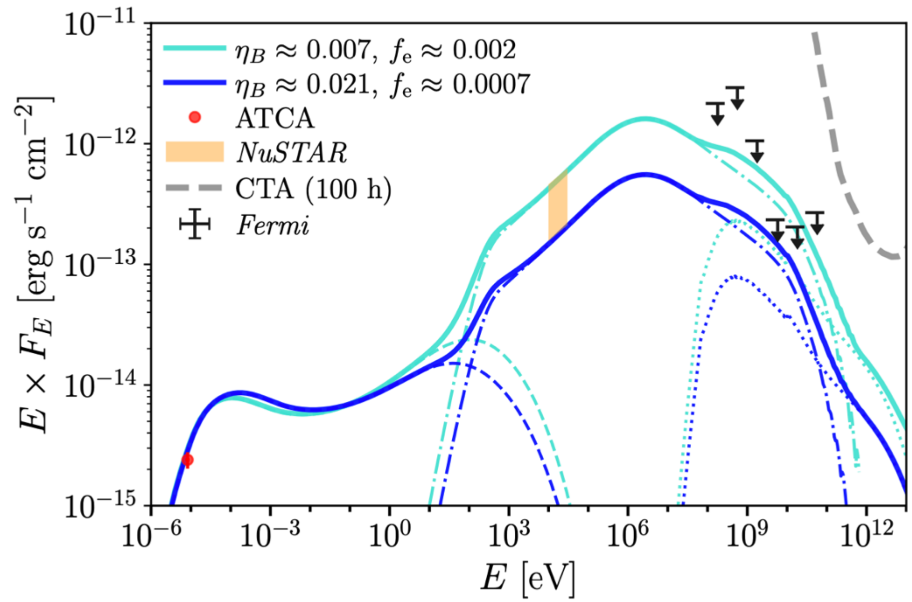

Detected NT X-rays with NuSTAR.

The value of η_B is now much more constrained.

The energy density of NT protons likely exceeds the magnetic energy density.

del Palacio+23

Summary

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

Highly eccentric systems are particularly useful (but challenging to simulate!)

Our understanding of the wind dynamics has come a long way in recent years, but there are still some puzzles to work out, e.g.:

1. Fraction of energy going into NT particles?
2. How well can models simultaneously fit the observed thermal and NT emission?

Lots of systems with data that theoretical models can be applied to, but few systems are observationally well-constrained.

Exciting time – observations in the near future should dramatically improve in quality and quantity, and there are lots of ways that theoretical models can be further improved.