The theory of Colliding Stellar Winds

Models of the X-Ray and Radio Emission

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X-Ray and Radio Connections, 3rd Feb 2004

Motivation for observations of massive stars

- Hot massive stars are of key importance in the evolution of the ISM of galaxies
  - evolve rapidly - major source of heavy elements to the ISM
  - high UV photon luminosity - the main source of ionizing radiation to nearby ISM

$$L_{BOL} \sim 10^{39-40} erg/s$$

  - have massive stellar winds - major source of mechanical energy to the ISM

$$L_{wind} = (1/2)\dot{M}\, v_{\infty}^{2} \sim 10^{37-38} erg/s$$

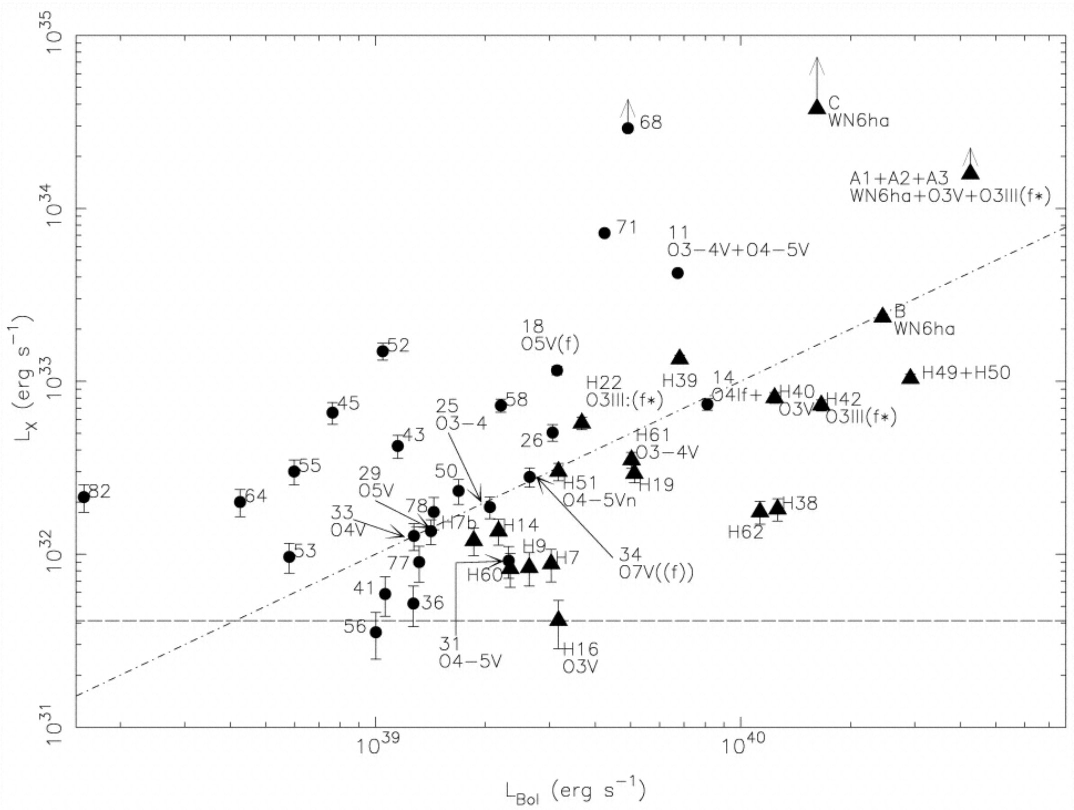
  - evolve to SN

  - hot stars completely dominate the characteristics of young galaxies

- Understanding the nature of their evolution is fundamental to our understanding of the evolution of young galaxies.
- A high proportion of massive stars occur in binary systems
- Massive star binaries offer the potential for us to determine many properties of O-type and Wolf-Rayet (WR) stars and their winds
- A variety of phenomena related to the collision of the two winds can be observed

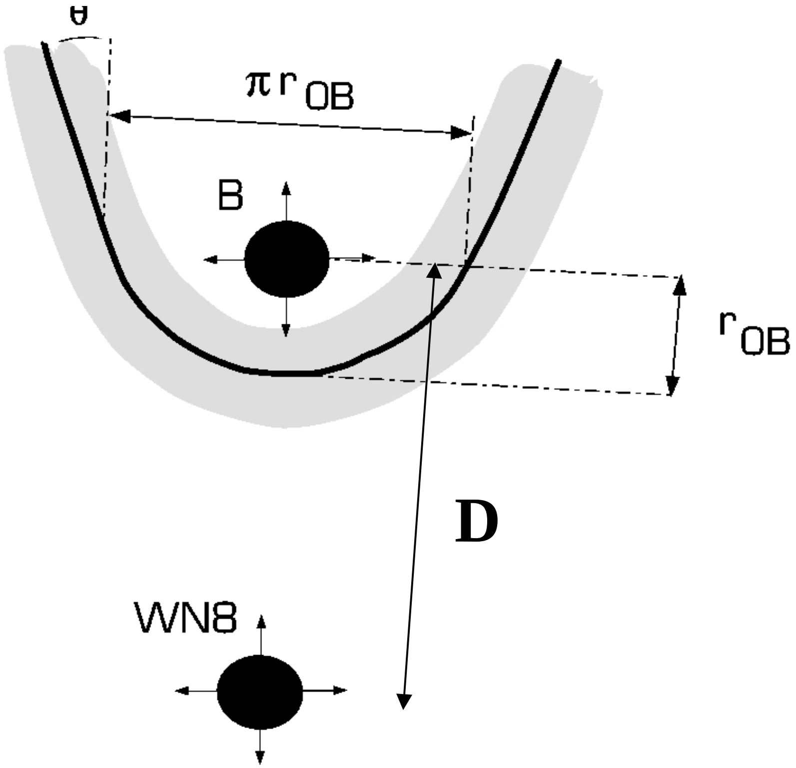
X-ray Emission

- Single OB and WR stars are X-ray sources
- Emission is generally soft (kT ~ 0.2 keV), and non-variable
- For OB stars, X-ray emission scales with bolometric luminosity, but large scatter (e.g. NGC3603, Moffat et al. 2002)



- For binaries, X-ray emission tends to be harder (kT ~ 1-2 keV) and more luminous, and shows orbital variability

Cartoon of a wind-wind collision



- Theoretical concept (Prilutskii & Usov 1976; Cherepashchuk 1976)
- 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 at the shocks

- X-ray emission properties from binary systems consistent with colliding winds picture
  - *eccentric orbits* (e > 0.0) - changing orbital separation, D, causes intrinsic emission to vary
  - *anisotropic absorption* - changing line of sight
  - *photospheric eclipses* - if system is short period

X-ray emission in binaries

Early numerical modelling: Lebedev & Myasnikov (1988), Luo etal (1990), Stevens etal (1992)

2 different regimes determined by characteristic *cooling parameter*,

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

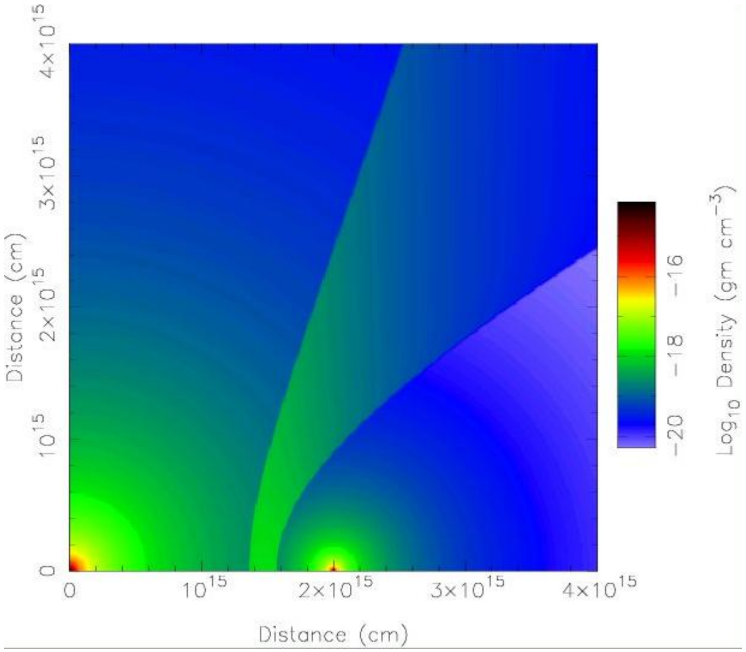
i) $\chi << 1$ - shocked wind highly radiative, $L_x \propto \dot{M} v^2$, faster wind dominates emission

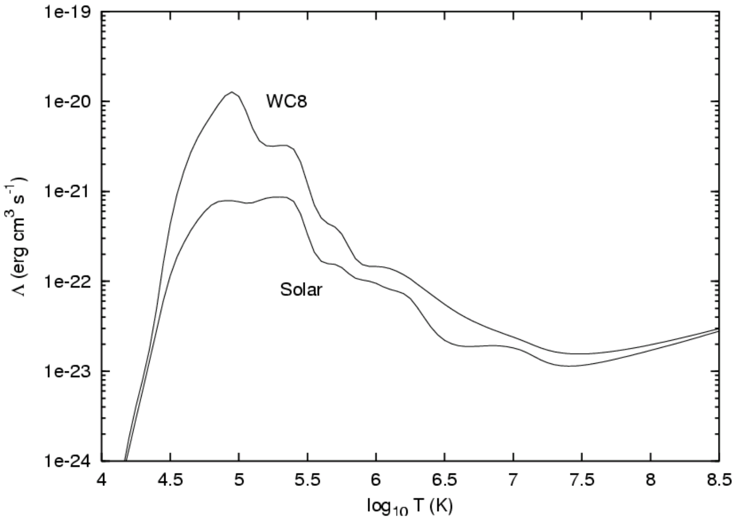
ii) $\chi >> 1$ - cooling mostly due to adiabatic expansion, $L_x \propto \frac{\dot{M}^2}{v^{3.2} D}$, stronger wind dominates emission

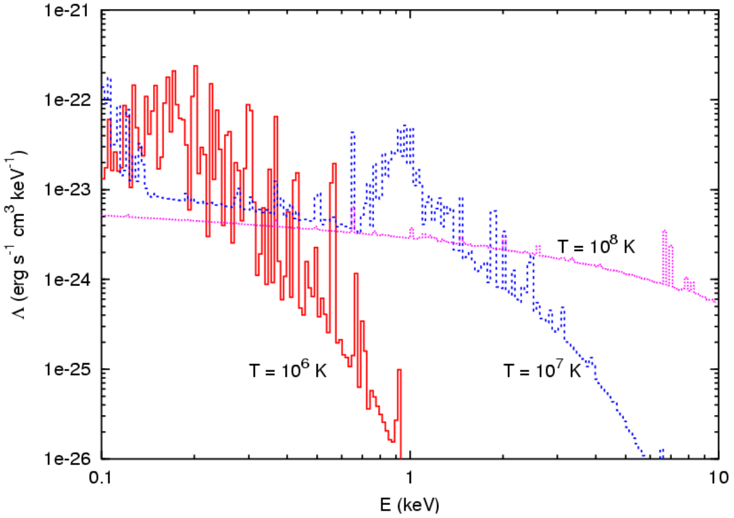
Pittard & Stevens (2002)

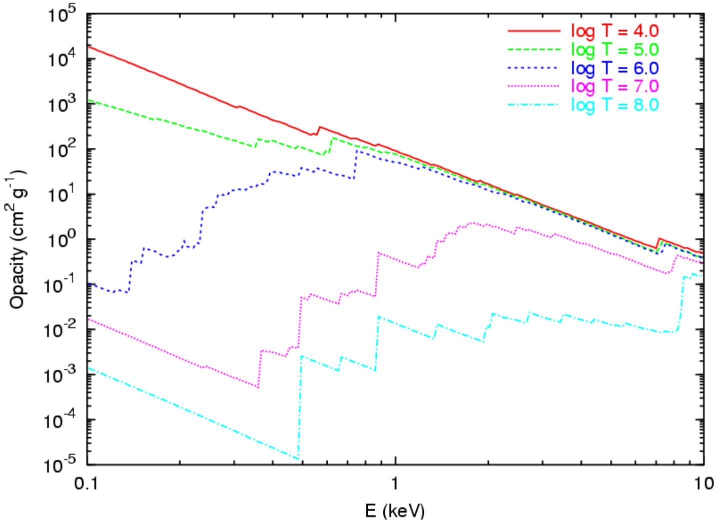
System	**Orbital Period (d)**	**Separation (AU)**	**Density (cm^{-3})**	χ_{WR}	χ_{O}
WR 139 (V444 Cyg)	4.2	0.2	$\sim 10^{10}$	<<1	?
WR 11 (γ^2 Vel)	78.5	0.81-1.59	$\sim 10^{9}$	~0.5-1	~250-500
WR 140	2899	~1.7-27.0	$\sim 10^{9}$-10^{7}	~2-50	~150-2000
WR 147	$>10^5$	>410	$\leq 10^4$	>30	>1000

Ingredients for simulating X-ray emission from Colliding Winds

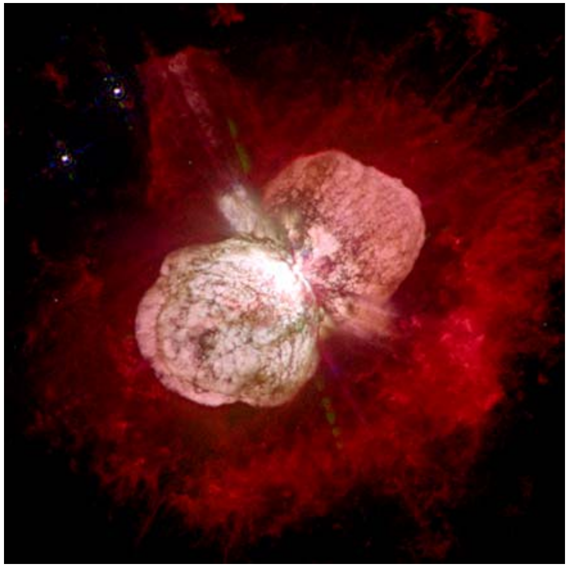








Colliding Winds emission in Eta Carinae?



One of the most luminous ($L = 5 \times 10^6 L_{sol}$) and massive stars in our Galaxy

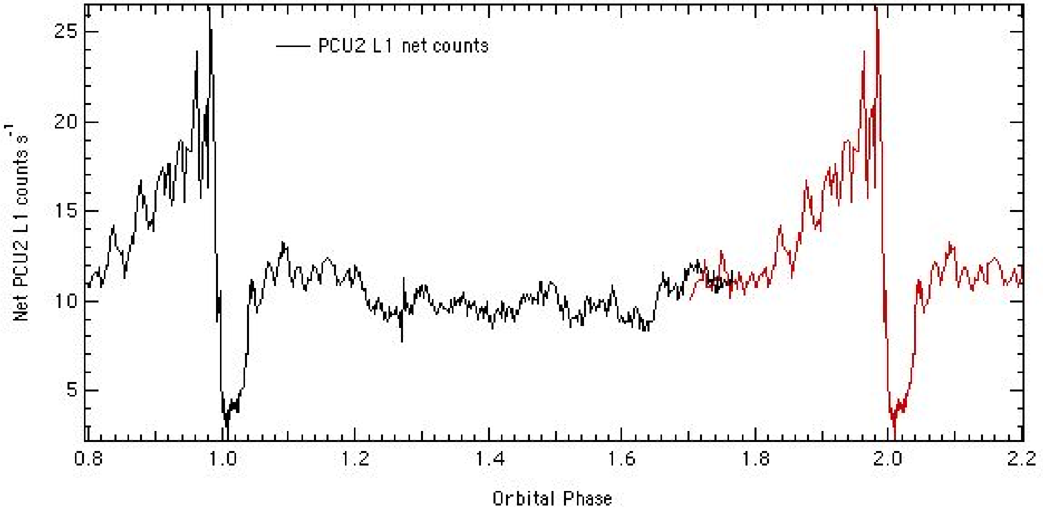
Underwent a series of giant eruptions in the 1840s, and again in the 1890s

Central star(s) hidden behind obscuring nebula

Long thought to be an LBV

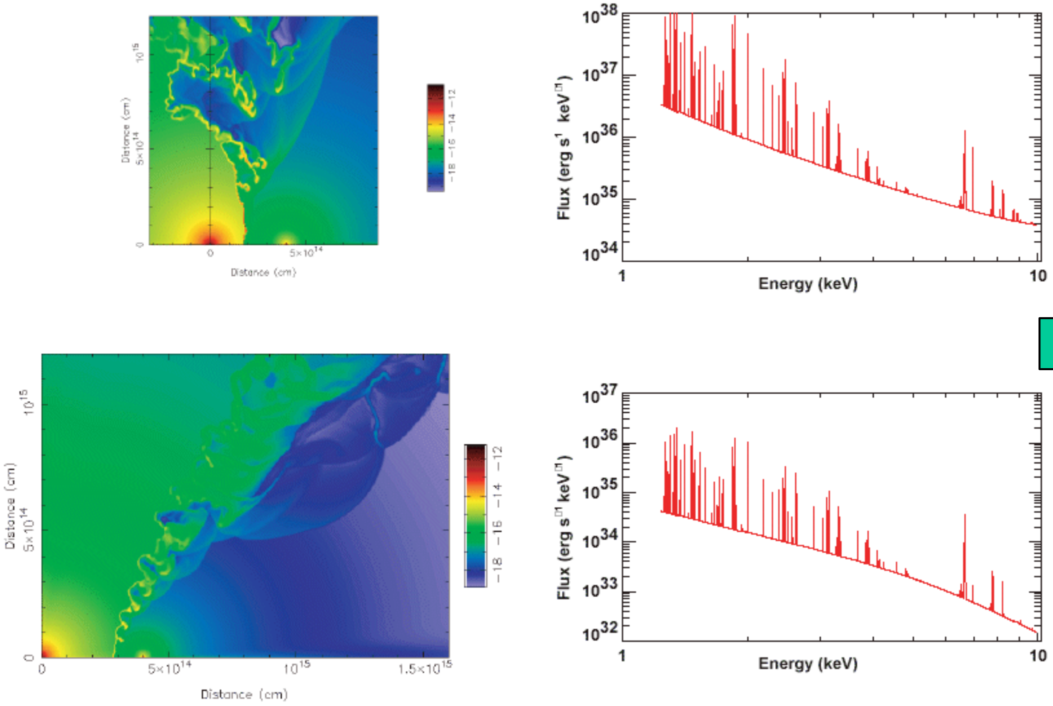
5.5 yr periodicity noticed in optical lines (Damineli 1997)

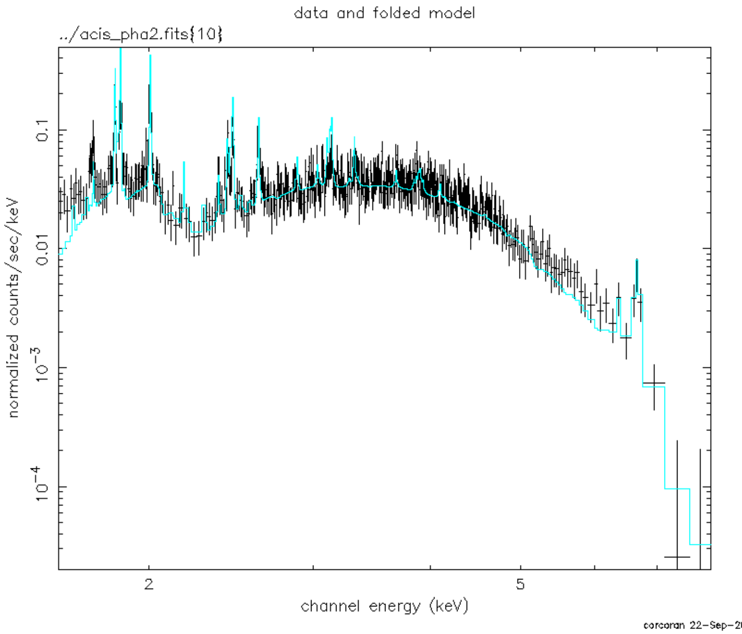
- Continuous X-ray monitoring with RXTE since 1996
- Emission closest to star is strong, hard, highly absorbed and variable
- Small-scale qausi-periodic outbursts



Corcoran et al.

In 'Hot Pursuit' of η Carinae





Parameter	Value
η	0.2 (fixed)
M_O (M_{sol} /yr)	1.0 (±0.1) x 10^{-5}
V_O (km/s)	3000 ± 350
N_H (cm^{-2})	7.7 (±0.2) x 10^{22}
Normalization	1.16

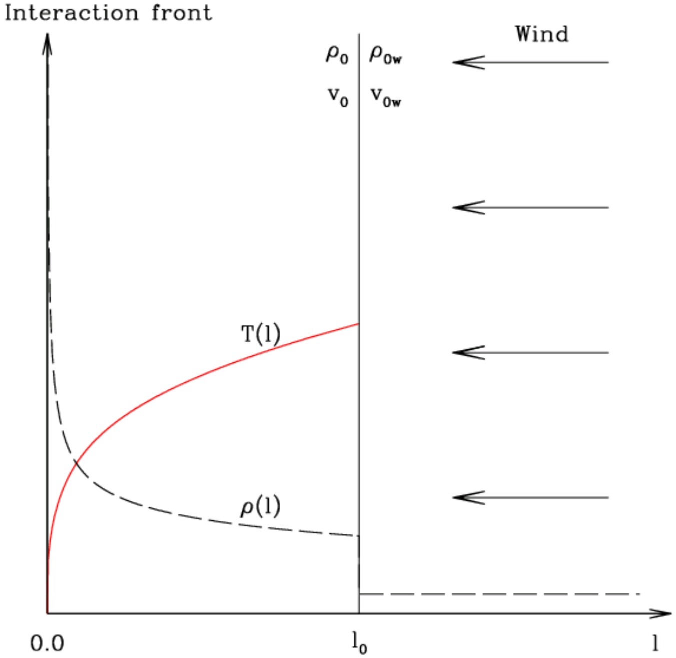
$$\dot{M}_1 \approx 2.5\text{x}10^{-4} M_{sol}\, yr^{-1}$$

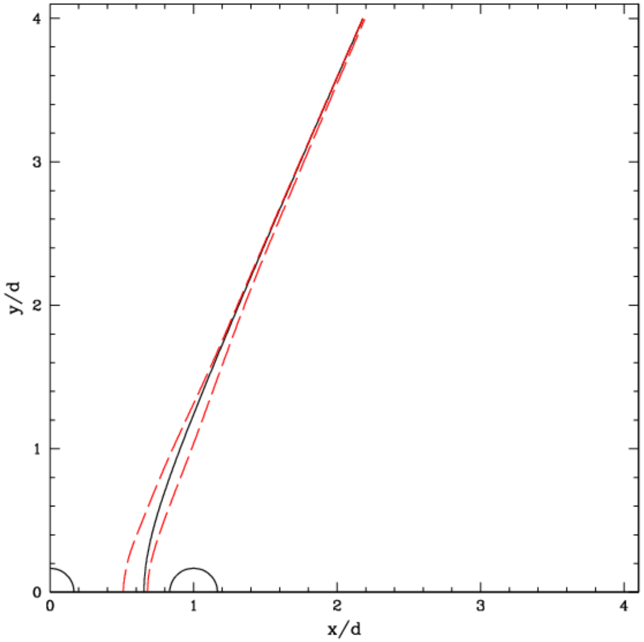
Pittard & Corcoran (2002)

Modelling X-ray emission from highly radiative systems

- Impossible with hydro codes
- Need to use a steady-state approach
- Separate small-scale shock emission calculation from large-scale structure

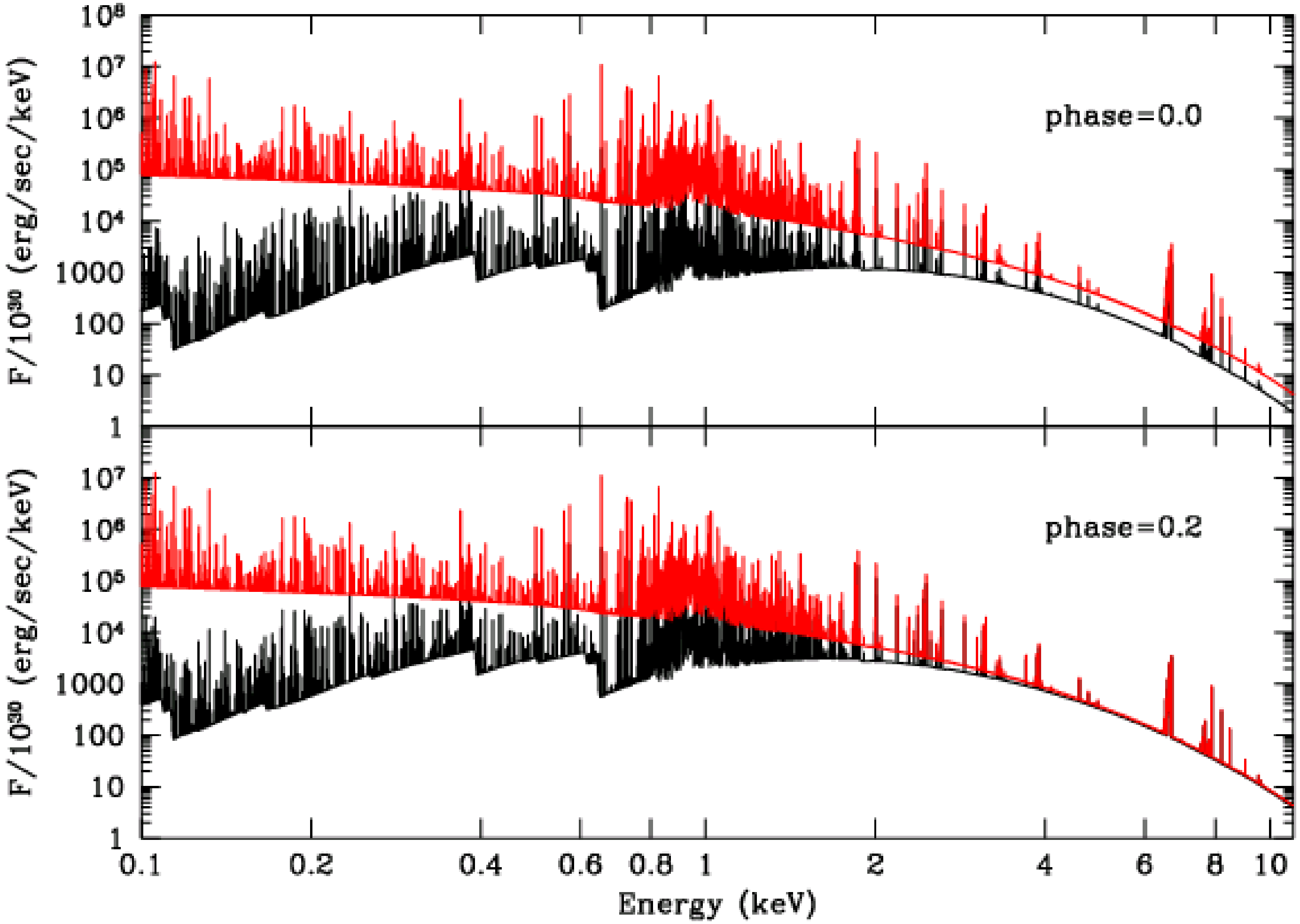
$$\frac{5k}{2\mu m_p}\rho v\frac{dT}{dl}=-n_e n_H \Lambda(T)$$





Antokhin, Owocki & Brown (2004)

Example spectra:



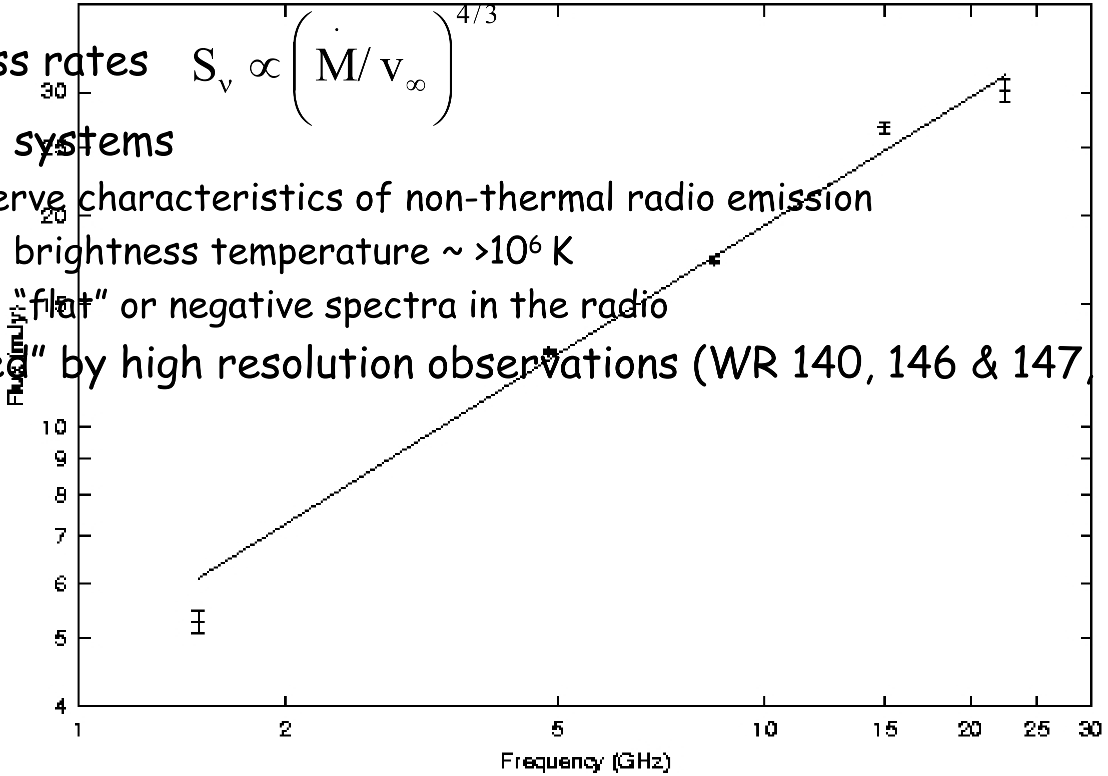
Observations of V444 Cyg in the near future…

Radio Observations of Massive stars

- thermal emission from winds
  - positive spectra from IR to radio
  - brightness temperature ~ 10^4 K
  - large photospheric radii

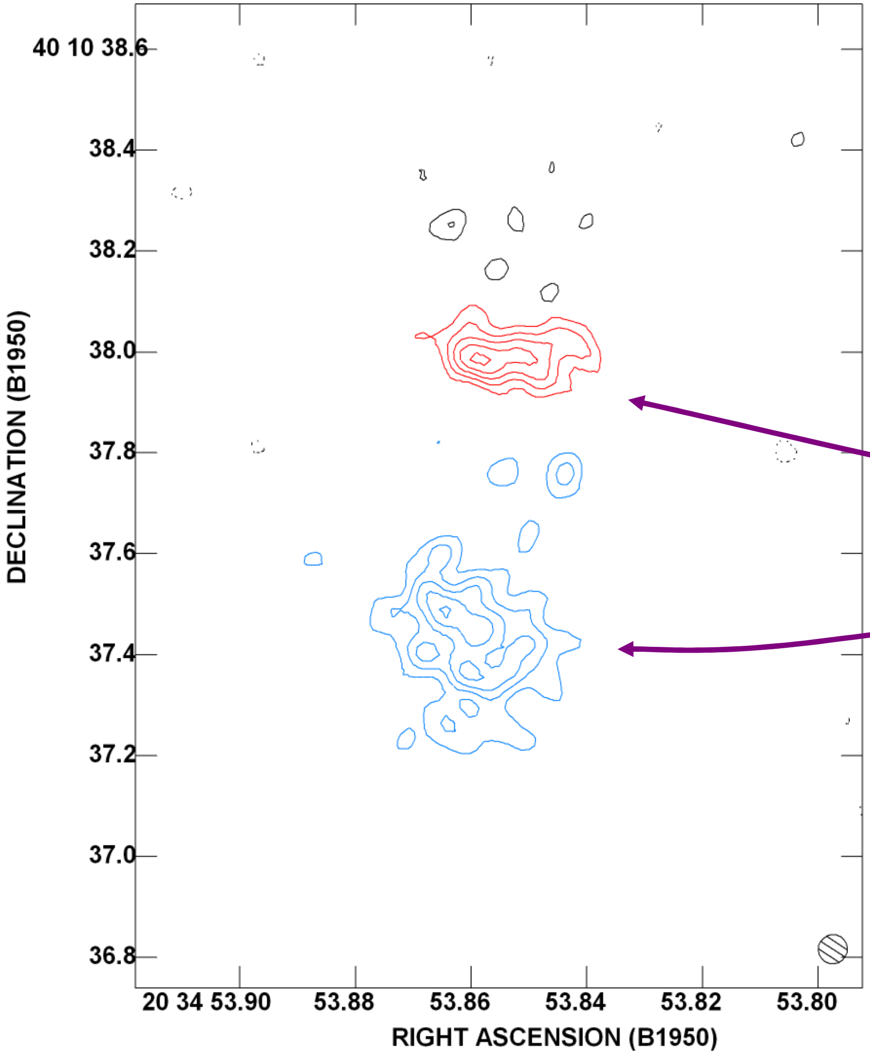
$$S_\nu \propto \nu^\alpha \quad \alpha = +0.6 \Rightarrow \rho_{ions} \propto r^{-2}$$

λ (cm)	**ν (GHz)**	**R_{WR} (AU)**	**R_O (AU)**
2	15	30	2
6	5	60	5
20	1.6	100	10



- mass loss rates $S_\nu \propto \left(\dot{M}/v_\infty\right)^{4/3}$
- in a few systems
  - observe characteristics of non-thermal radio emission
    - brightness temperature ~ >10^6 K
    - "flat" or negative spectra in the radio
- "resolved" by high resolution observations (WR 140, 146 & 147, V729 Cyg)

Direct Imaging in Radio



- High resolution observations of WR147
  - MERLIN @ 5GHz:
  - 50 mas = 50AU @ 1kpc
  - two components – one thermal + one non-thermal

Williams, Dougherty et al. 1997

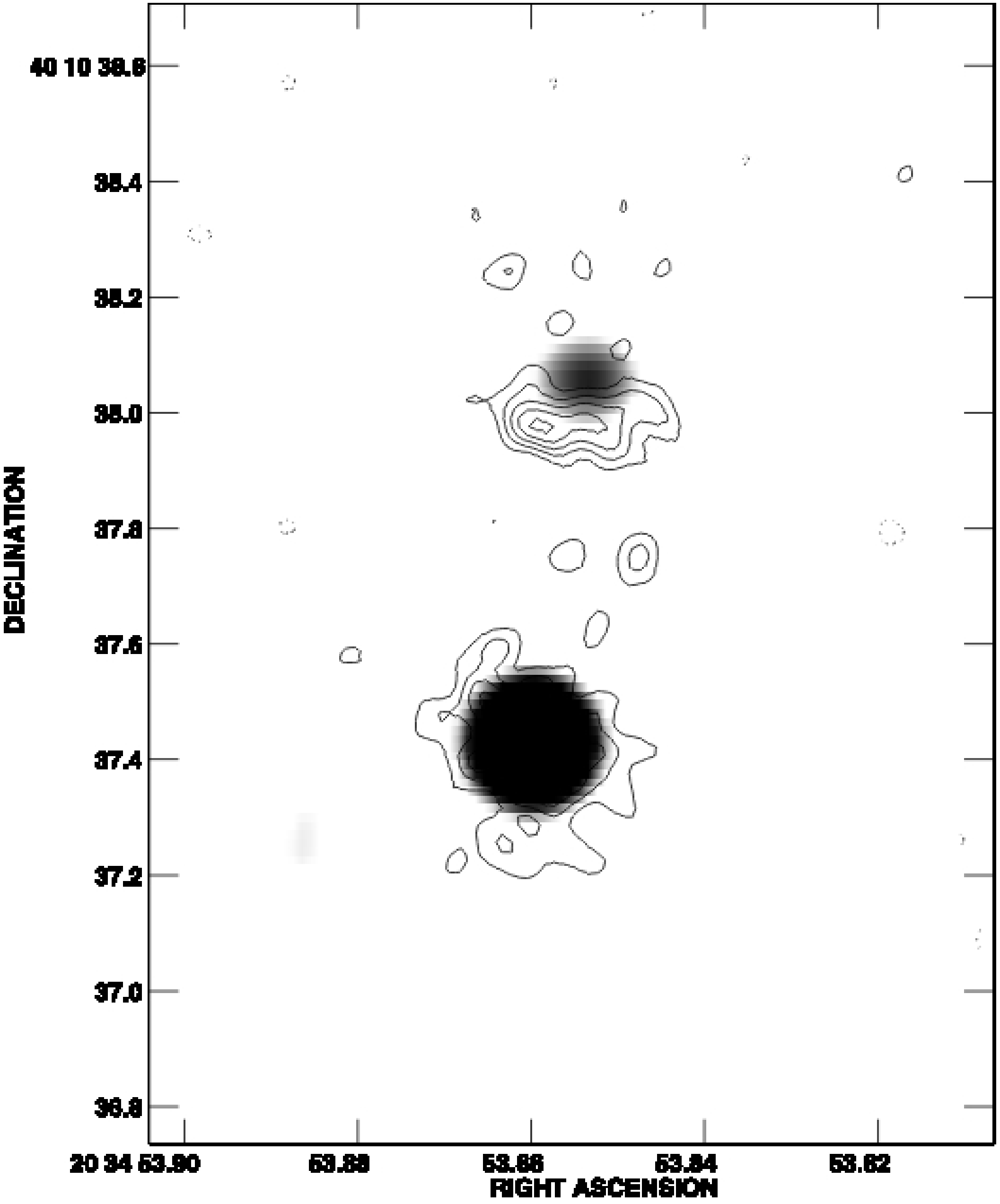
Overlay of radio and IR

Contours: MERLIN 5GHz

Grey: UKIRT K-band shift+add

If southern star is the WR star then northern star lies just to the N of the non-thermal emitting region

Also consistent with subsequent HST imaging (Niemela et al. 1998)



Wind-collision and particle acceleration

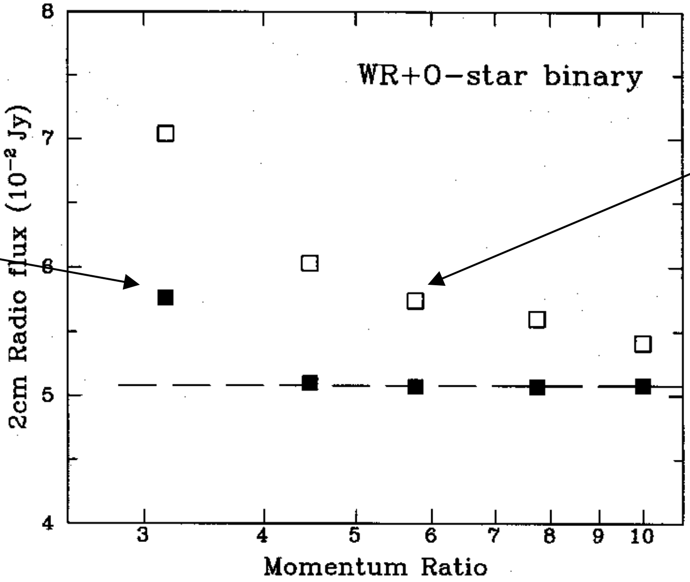
- Identification of wind-wind collision as the source of non-thermal radio emission
- Stationary shocks --> excellent laboratories for the study of particle acceleration - in turn the collision region provides a probe of the circumstellar envelopes
- For non-thermal emission we require relativistic electrons
  => need to accelerate from ~1000km/s to ~c
- Fermi acceleration at the shock
  - produces a power-law electron energy distribution - attractive
  - for a strong shock

$$\partial N \sim E^{-2}\,\partial E \;\Rightarrow \alpha = -0.5$$

  - close to what is observed
- Additional possibility for the colliding wind case
  - magnetic compression near the CD (Jardine, Allen & Pollock 1996)
- High sensitivity VLBI may provide the means to determine the site of the accelerated particles - shock or CD?
  - for WR147 - 2 mas at 630 pc
  - experiment for SKA + VLBI

Models of the interaction region

- Models to date have been relatively simple
  - Stevens (1995) investigated effect of binarity on *thermal* emission
  - two radially mal point source
    - OK for s
    - Fails to



WR-star in front

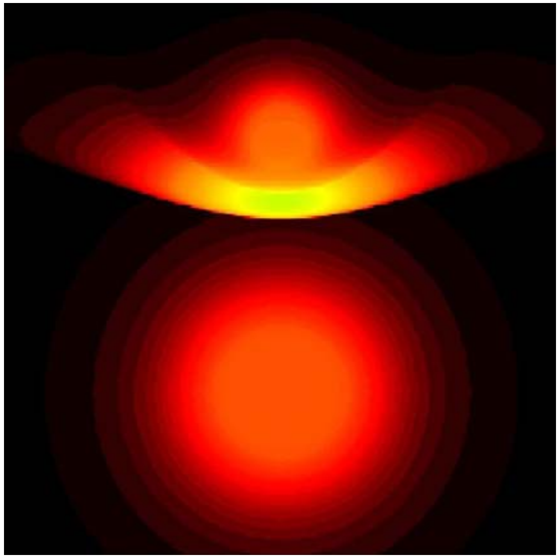
O-star in front

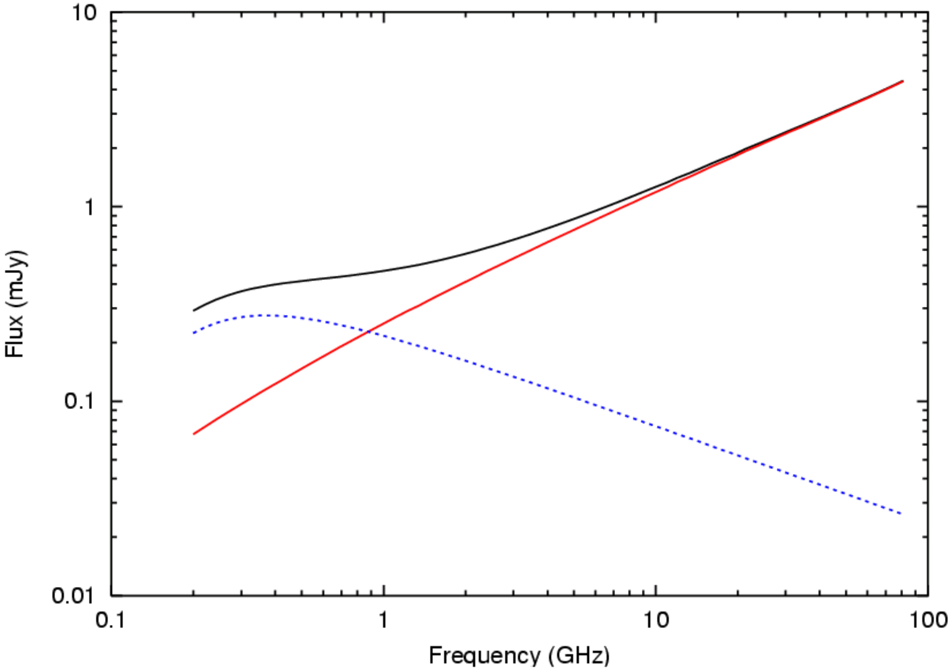
- Use hydro mo non-thermal emission
  - constrainec
  - assume cyli tic index=5/3
  - add non-the on-thermal energy = fraction x thermal energy, and equipartition between magnetic energy density
  - assume magnetic field highly tangled
  - p = 2 energy spectrum, $\gamma < 10^5$ frozen into flow
  - include Razin effect, SSA, ff-absorption
  - ray-tracing radiative transfer code to get model radio images

Constraints from radio data - consistency check against X-ray data

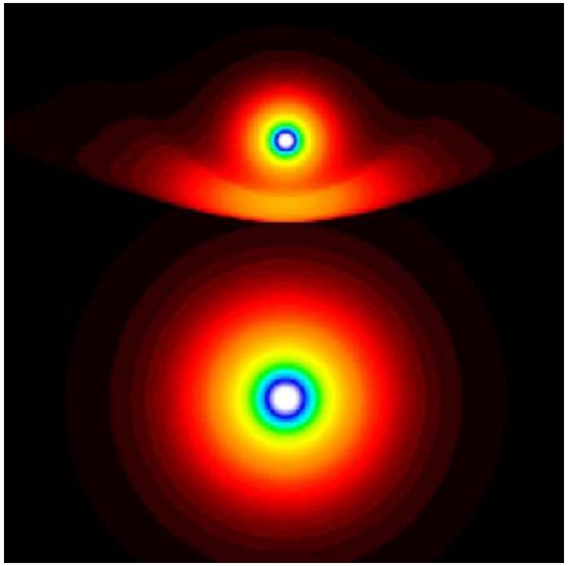
Intensity and spectral distributions of “standard model”

1.6 GHz





22 GHz



Dougherty et al (2003)

‘Standard’ model: $\dot{M}_{\mathrm{WR}} = 2\mathrm{x}10^{-5}\,\mathrm{M}_{\mathrm{sol}}\mathrm{yr}^{-1}$

$\dot{M}_{\mathrm{OB}} = 2\mathrm{x}10^{-6}\,\mathrm{M}_{\mathrm{sol}}\mathrm{yr}^{-1}$

$v_{\infty(\mathrm{WR,OB})} = 2000\mathrm{kms}^{-1}$

$D_{\mathrm{sep}} = 140\mathrm{AU}$

$\xi = 10^{-4}$

n_{max} = 4x10^5 cm^{-3}

T_{max} = 2x10^8 K

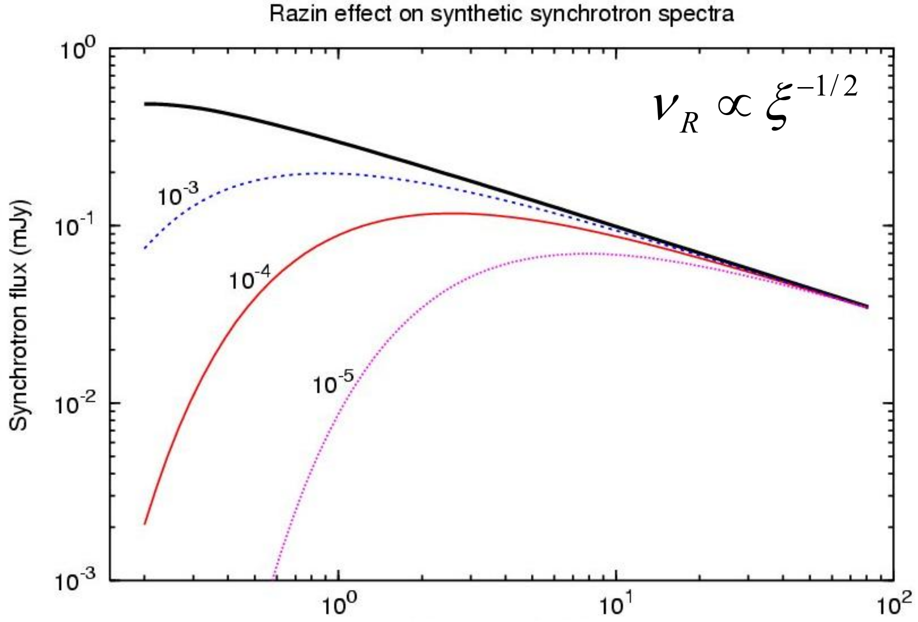
B_{max} = 6 mG

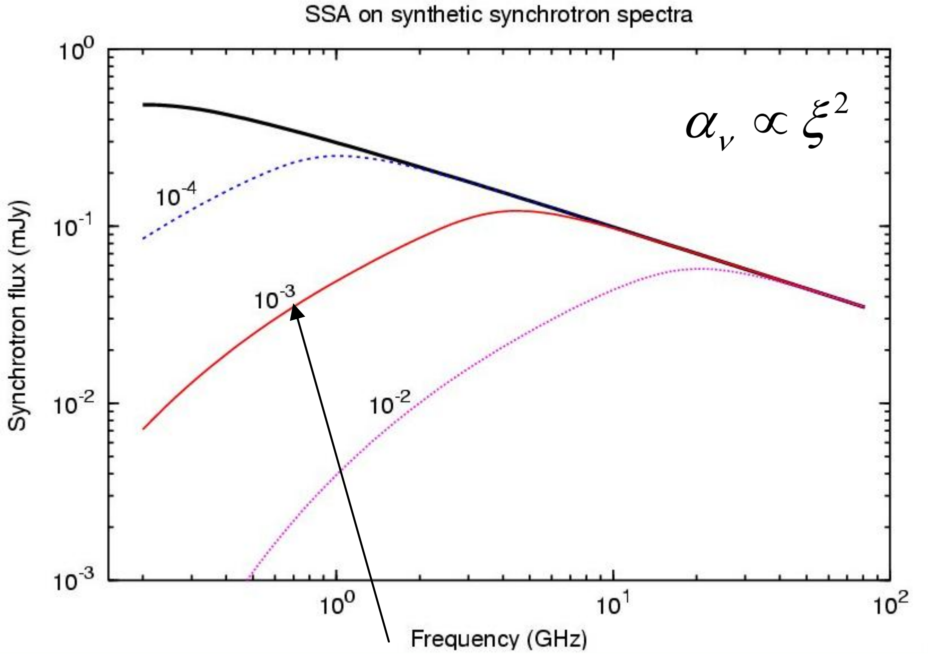
ν_c = 250 MHz (γ=100)

ν_c = 25 GHz (γ=1000)

B_* ~ 100 G

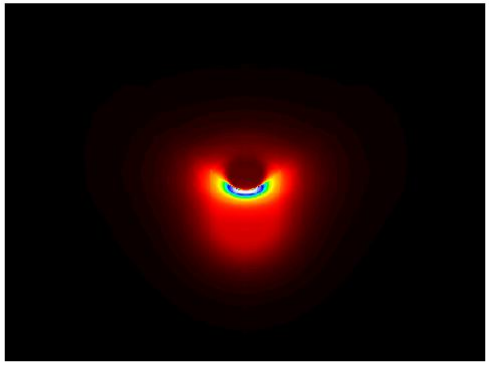
Influence of the Razin effect and SSA


Razin effect on synthetic synchrotron spectra

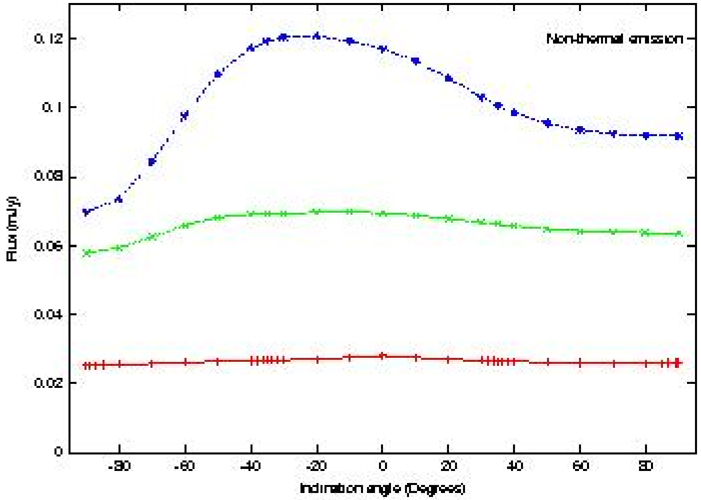

SSA on synthetic synchrotron spectra

Slope ~ +1 (c.f. +2.5 if optically thick)

Effect of Inclination

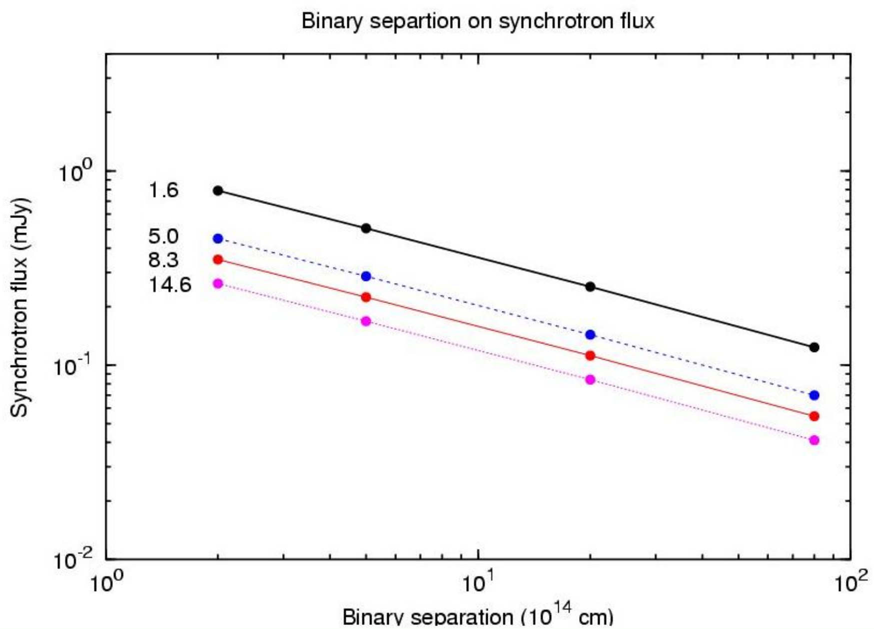


i = 35°



Change in NT flux with inclination angle
1.6 GHz (blue), 5 GHz (green), 22 GHz (red)

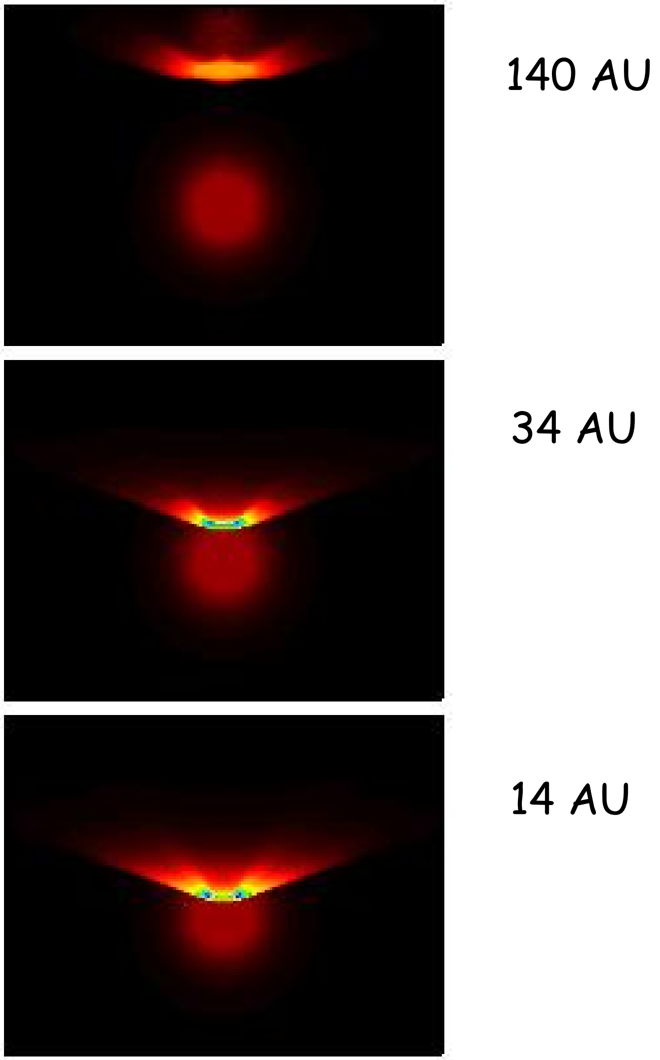
Effect of Binary Separation



$$P(\nu) \propto \xi^{3/4} n^{3/4} \nu^{-1/2} \propto D^{-1/2} \nu^{-1/2}$$

Turnover frequencies:

$$\nu_{ff} \propto D^{-10/7}, \nu_R \propto D^{-1}, \nu_{SSA} \propto D^{-1}$$



i=0 (250x185 mas)

Modelling WR 147

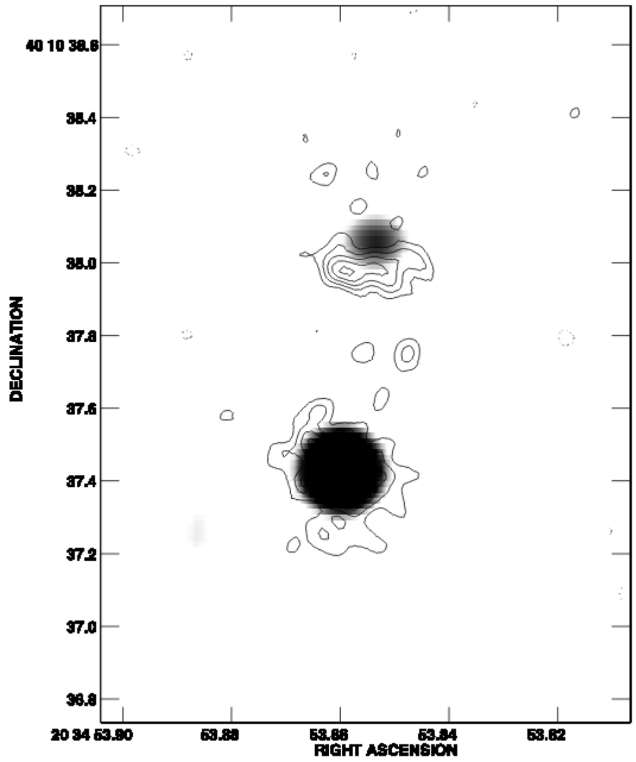
- One of two systems where thermal and NT spatially resolved
- Amongst the brightest WR stars at radio frequencies
- Best observed of all massive binary systems: 353 MHz – 42.9 GHz

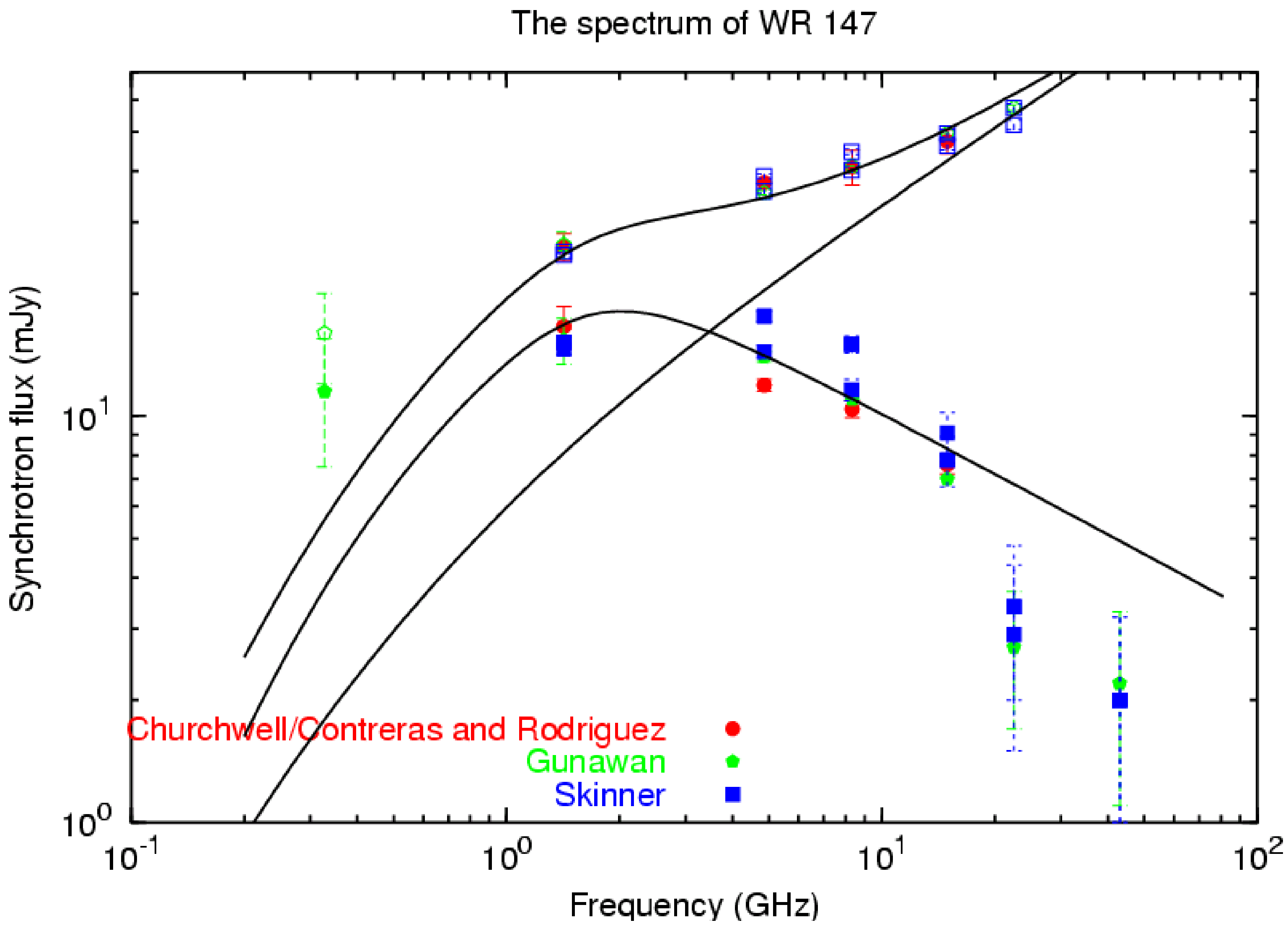
Flow time ~ 2yr => IC losses unimportant for γ < 400

$$\dot{M}_{\mathrm{WR}} = 2\mathrm{x}10^{-5}\,\mathrm{M}_{\mathrm{sol}}\mathrm{yr}^{-1} \qquad v_{\infty(\mathrm{WR})} = 950\mathrm{kms}^{-1}$$

$$\dot{M}_{\mathrm{OB}} = 4\mathrm{x}10^{-7}\,\mathrm{M}_{\mathrm{sol}}\mathrm{yr}^{-1} \qquad v_{\infty(\mathrm{OB})} = 1000\mathrm{kms}^{-1}$$

$$D_{\mathrm{sep}} = 410/\cos i\,\mathrm{AU}$$





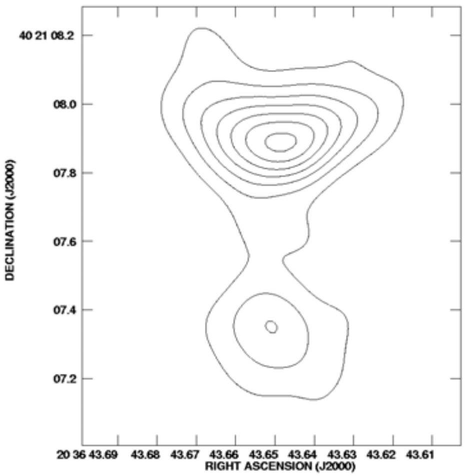
$\xi \sim 10^{-2}$, $f = 0.14$, $B_{max} = 2\text{-}4$ mG

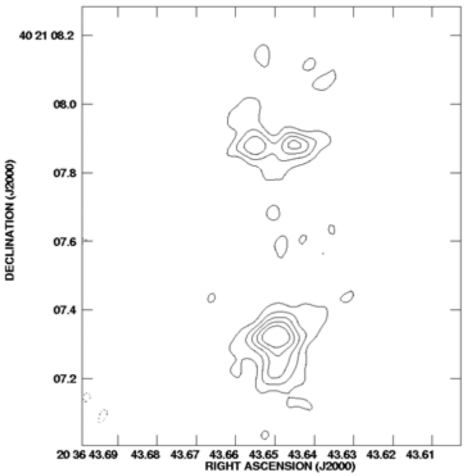
Simulated vs. real images of WR 147

1.6 GHz

5 GHz

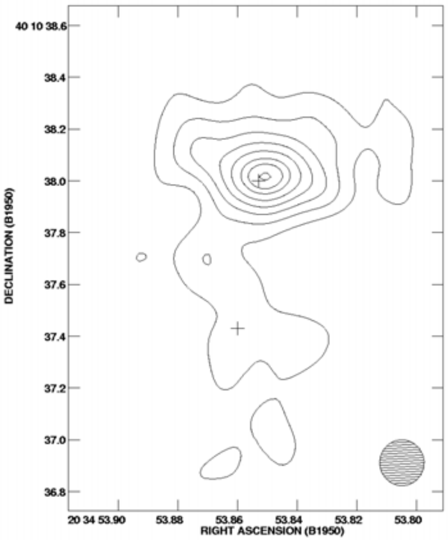
Simulated

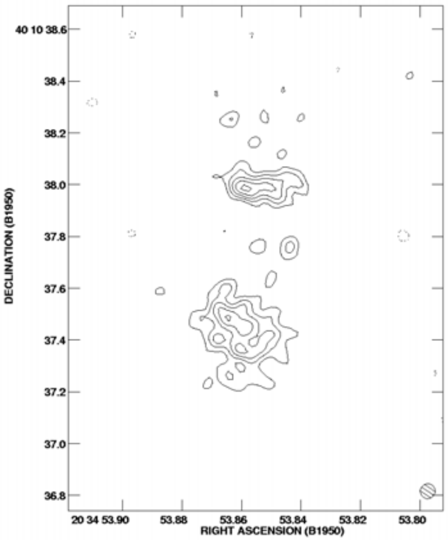




Find that $i \sim 0-30^{o}$ preferred

Real



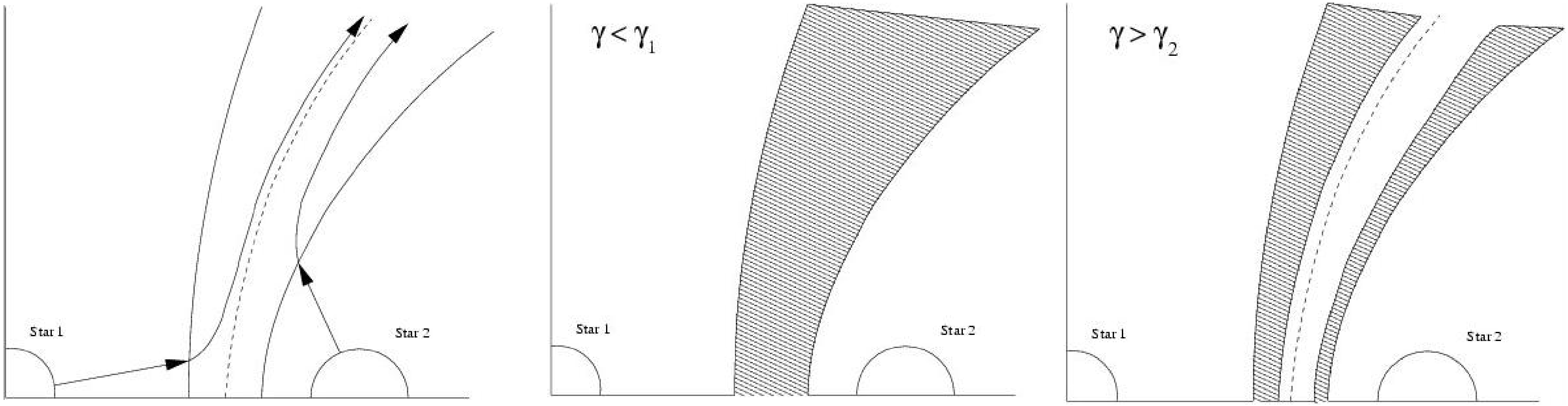


The Effect of IC cooling

In colliding wind binaries, $\frac{P_{sync}}{P_{ic}} = \frac{U_B}{U_{ph}}$

Rate of energy loss: $\left.\frac{d\gamma}{dt}\right]_{ic} \propto \gamma^2$

Distribution of relativistic electrons ($\gamma_1 << \gamma_2$):



Cyclosynchrotron emission

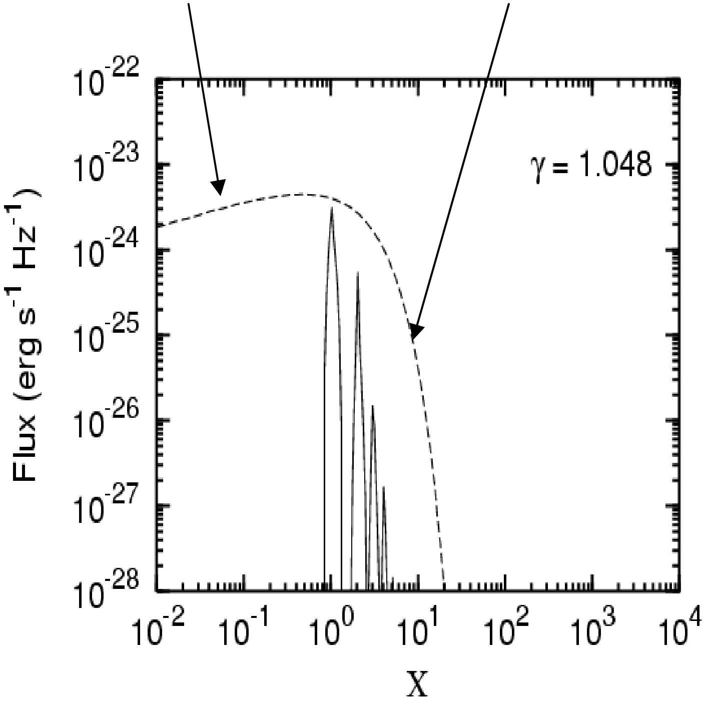
Cyclotron emission is a series of delta functions

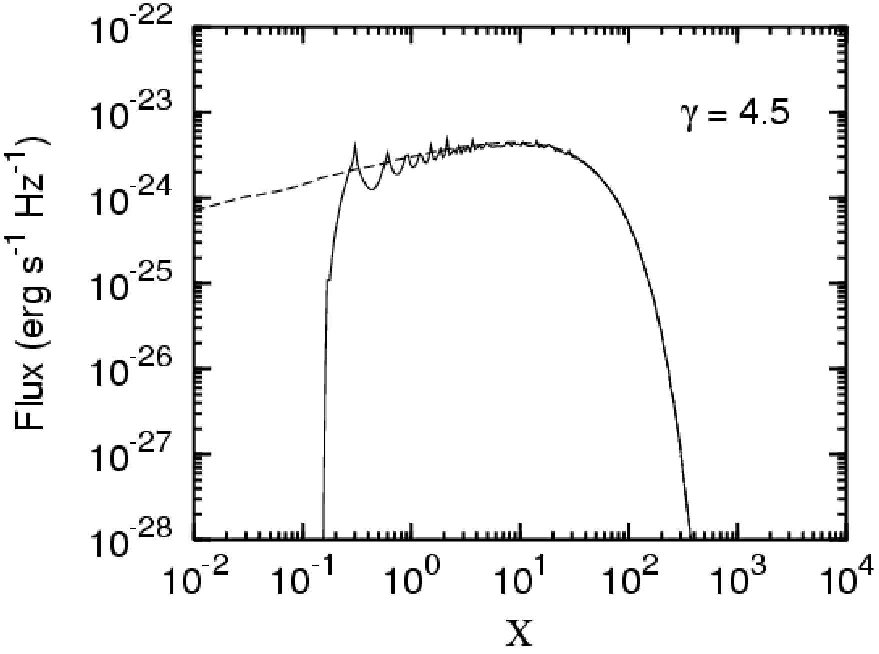
Cyclotron frequency: $\nu_b = \dfrac{eB}{2\pi m_e c}$ Orbital frequency: $\nu_o = \dfrac{\nu_b}{\gamma}$

Synchrotron emission from e$^-$: $P(\nu) = \dfrac{\sqrt{3}e^3 B \sin\alpha}{m_e c^2} F(\nu / \nu_c)$ $\nu_c = \dfrac{3\gamma^2 eB \sin\alpha}{4\pi m_e c}$

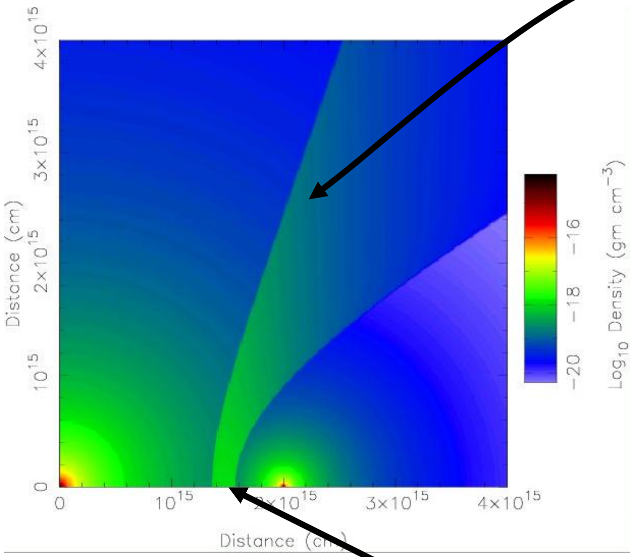
Define: $\chi = \dfrac{\nu}{\nu_b} = \dfrac{\nu}{\gamma \nu_o} = \dfrac{3\gamma^2}{2}\dfrac{\nu}{\nu_c}$

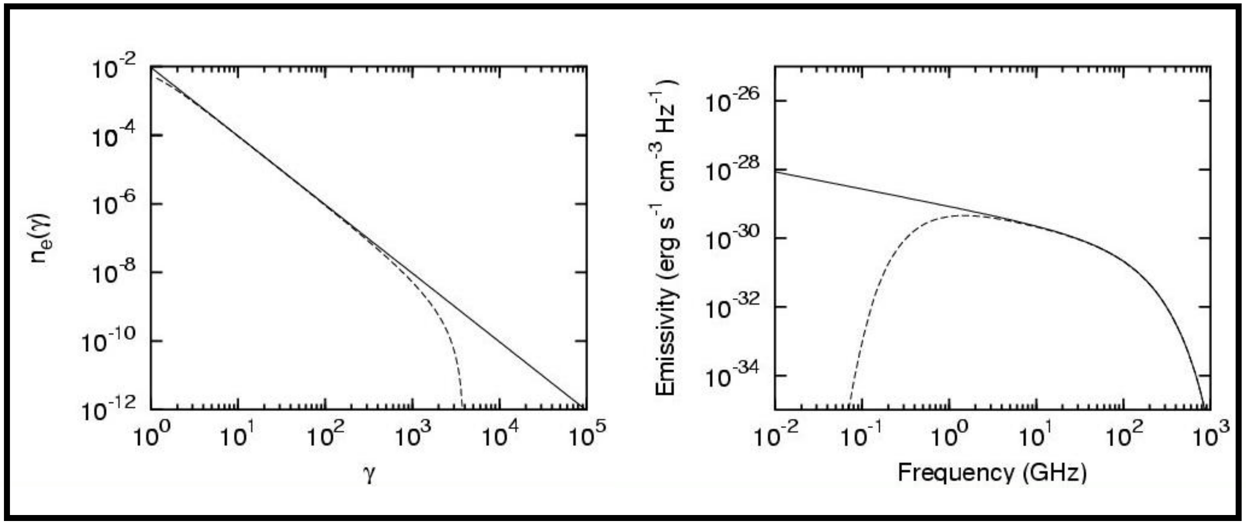
$F \propto \nu^{1/3}$ $F \propto e^{-\nu}\nu^{1/2}$

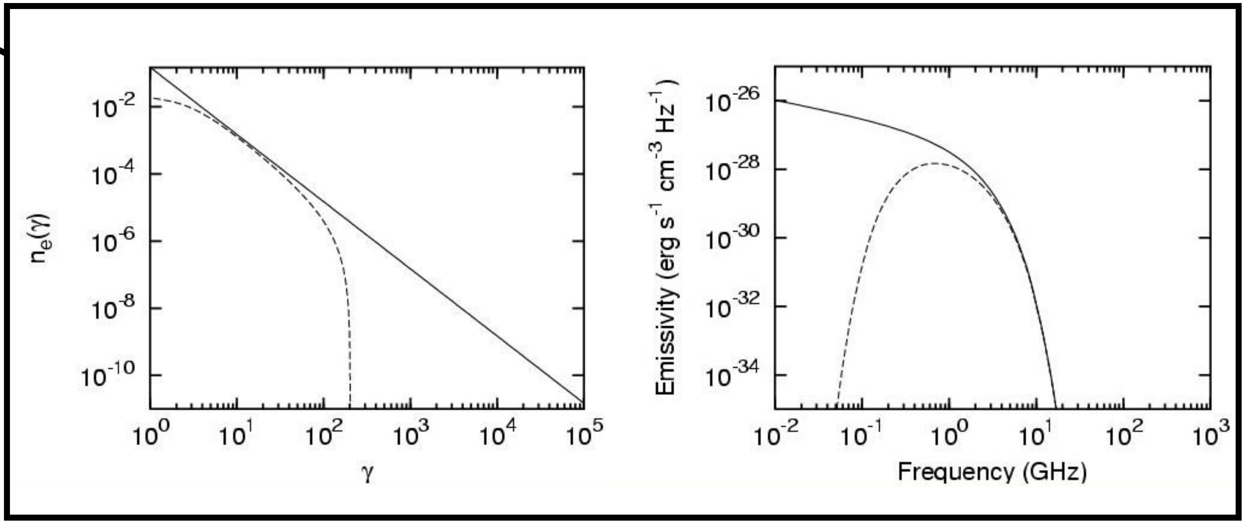


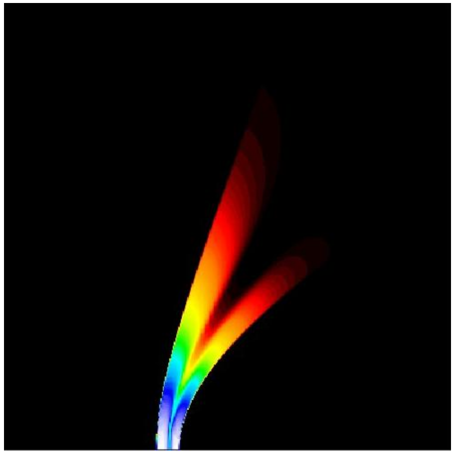


Salient features of modelling IC and coulombic cooled spectra

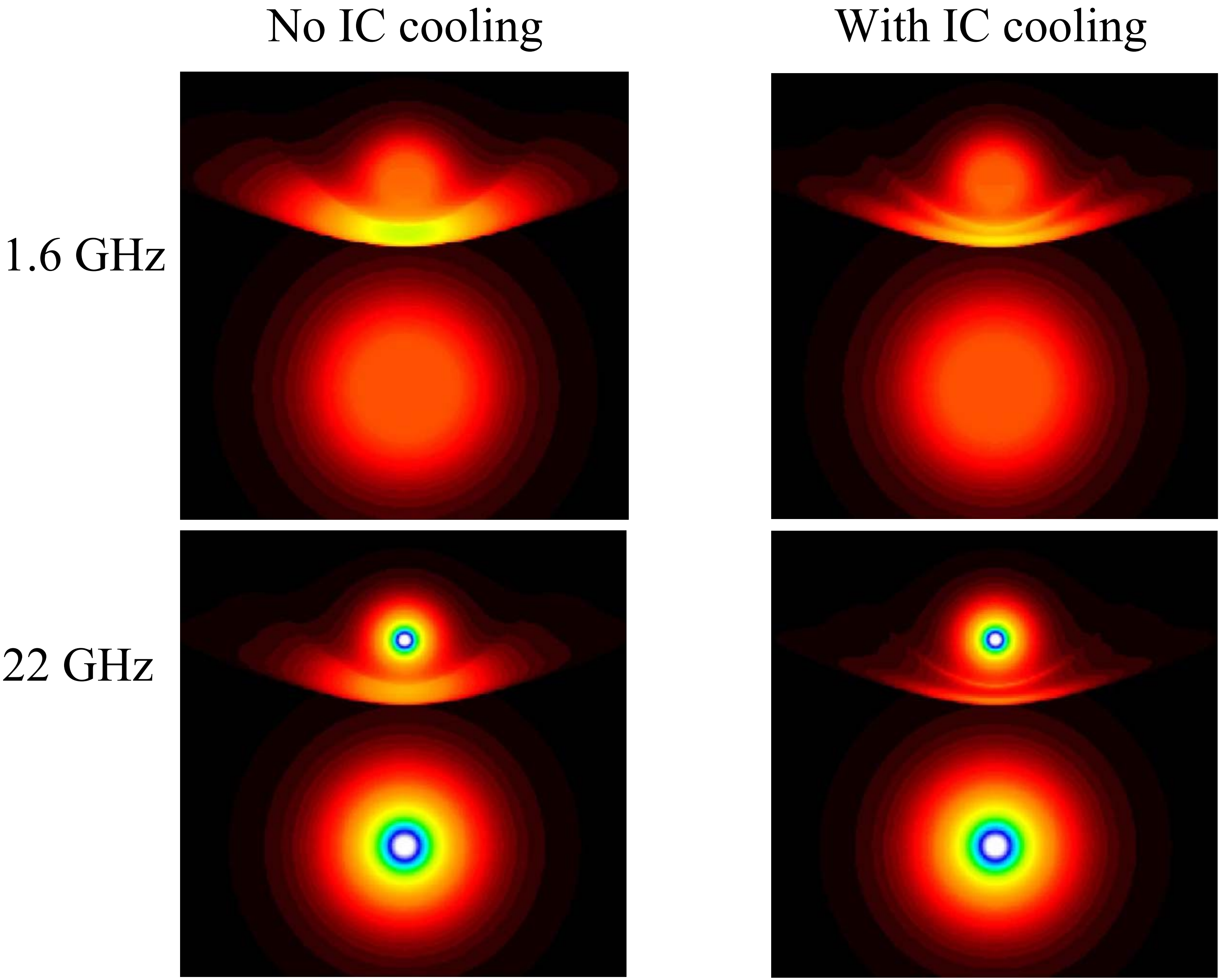




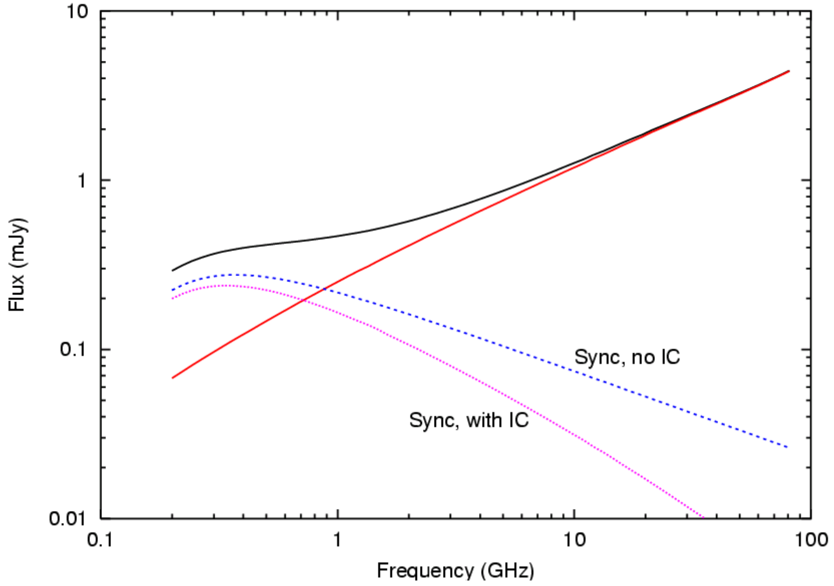




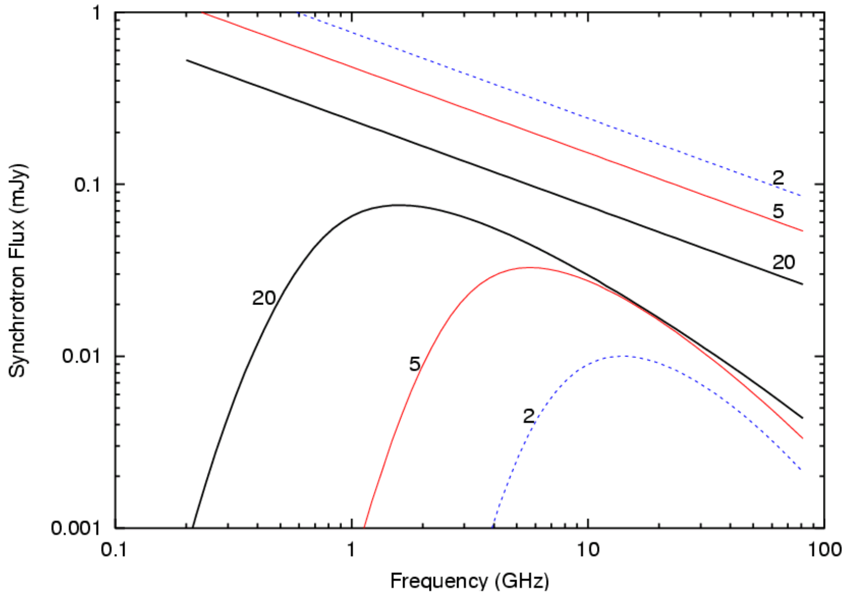
1.6 GHz emission map


No IC cooling
With IC cooling
1.6 GHz
22 GHz

IC cooling on spectral distribution



$D_{sep} = 2 \times 10^{15}$ cm

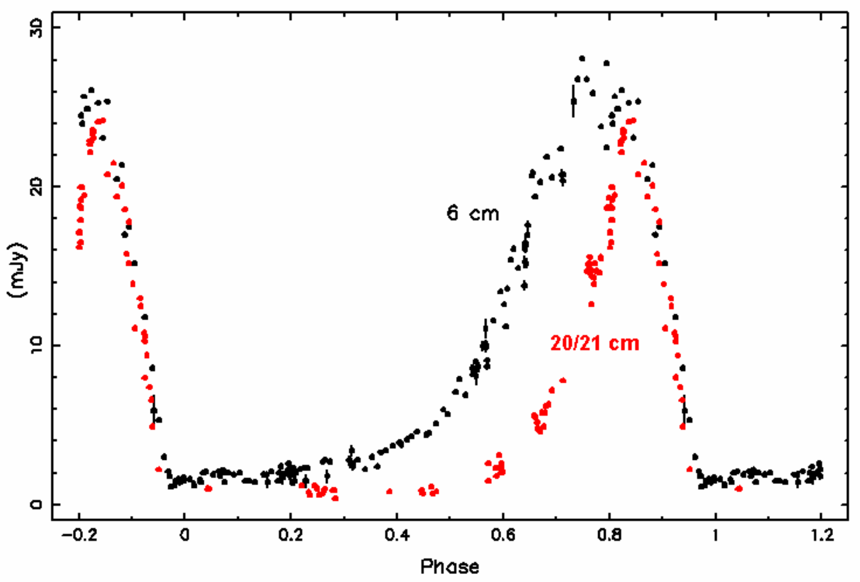


D_{sep} (10^{14} cm)

New models of WR147 to be made soon… However, our main goal is to model WR140!

The radio emission from WR 140

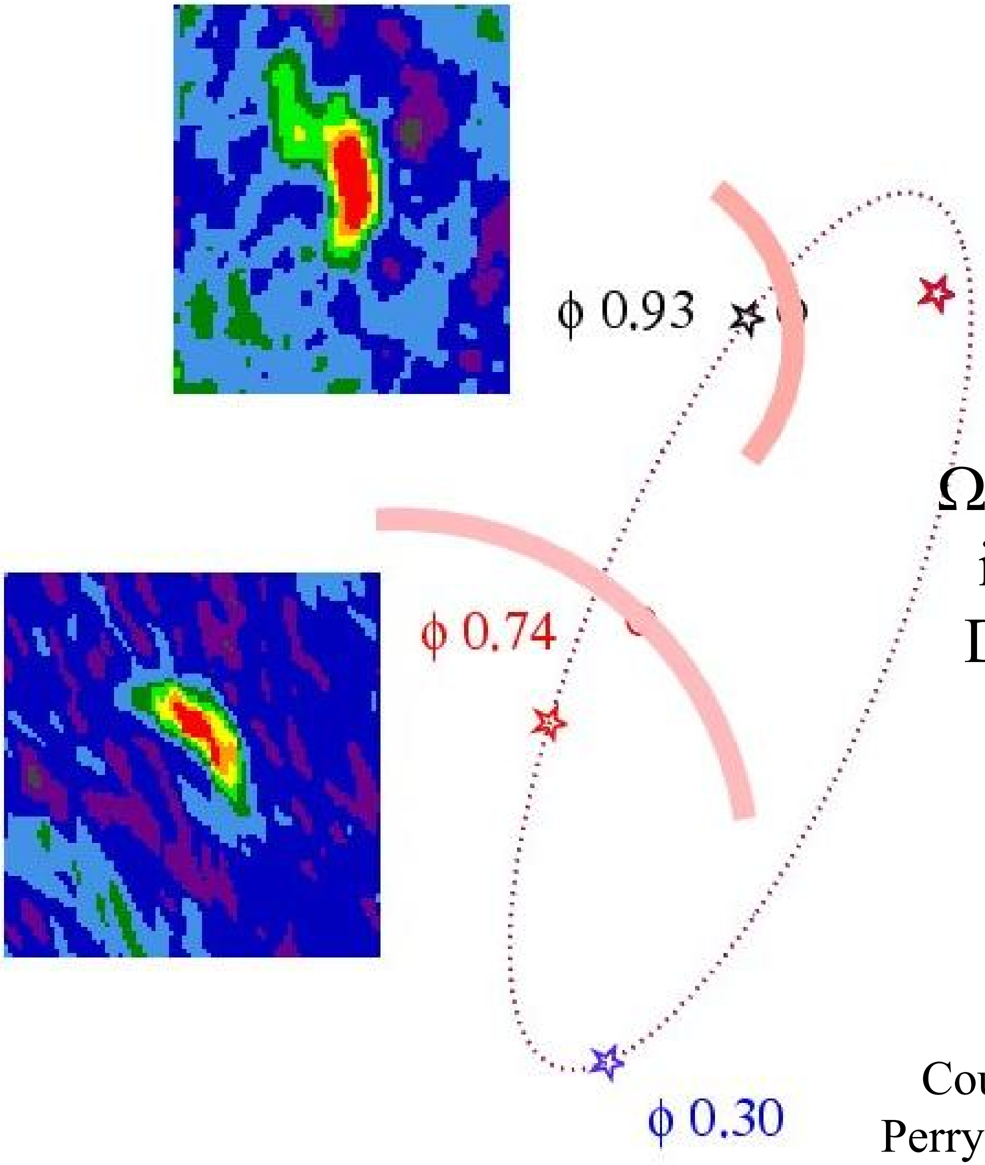
- Reasons why non-thermal emission is clearly seen in WR146 and 147
  - the systems are very wide (if they are actually "binary")
  - free-free opacity along l.o.s. to the wind-collision zone is small
- WR 140 is an eccentric system
  - variable circumstellar extinction by virtue of orbiting in and out of the radio photosphere



8 yrs of VLA observations
@ 1 observation/month!
(White & Becker 1995)

Is a colliding wind origin consistent with these observations?

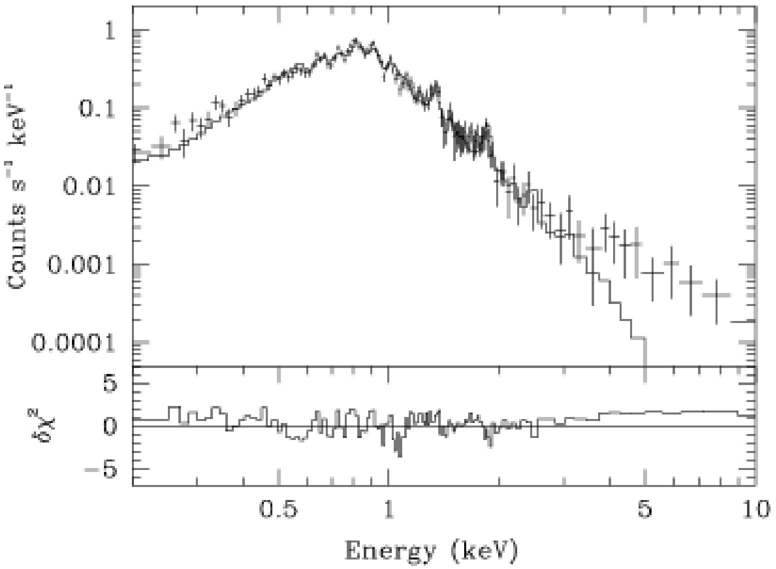
VLBA images of WR140



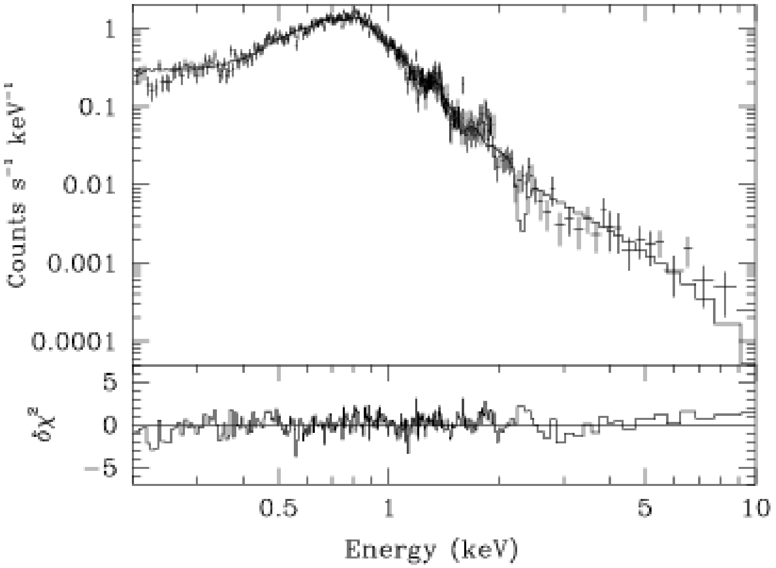
Ω = 343-355°
i = 55-75°
D = 1.7 kpc

Courtesy of Tony Beasley,
Perry Williams, John Monnier,
et al.

X-ray/Radio Connections



EPIC-MOS2: wind * 2-T



EPIC-pn: wind * (1-T + power law)

9 Sgr (O4V)

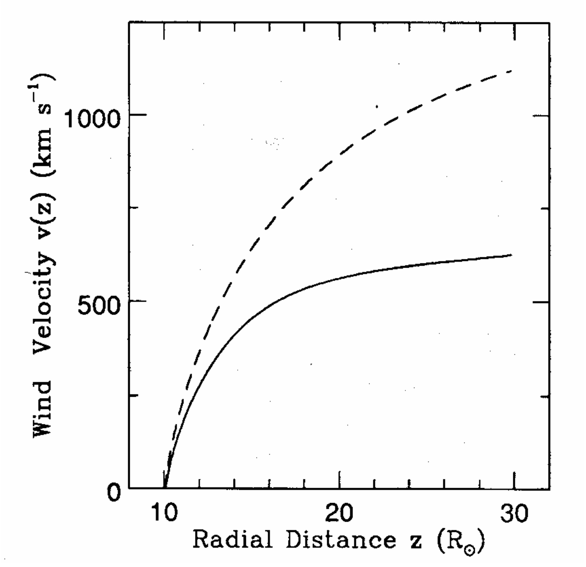
- Displays NT radio emission
- Bulk of X-ray emission is thermal
- First clear evidence for a NT hard X-ray tail
- Photon index, Γ ≥ 2.9
- Low compression ratio
- Or perhaps it is a CWB?

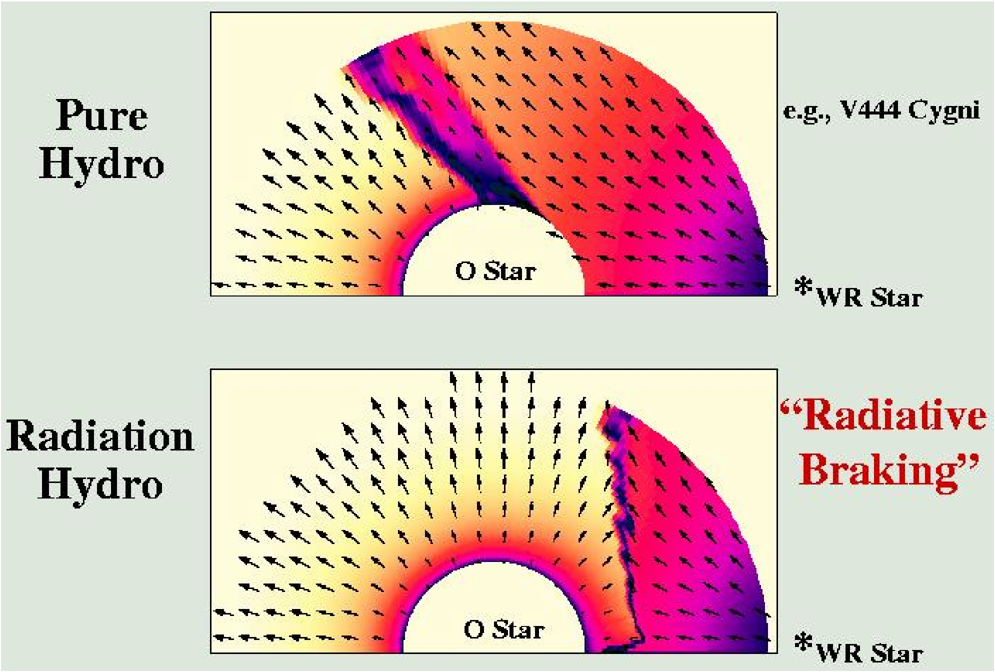
Rauw et al. (2002)

Future Work I: Radiative Driving Effects

Radiative Inhibition (Stevens & Pollock 1994)

- Pre-shock velocities always decrease
- $\dot{M}$ can increase or decrease



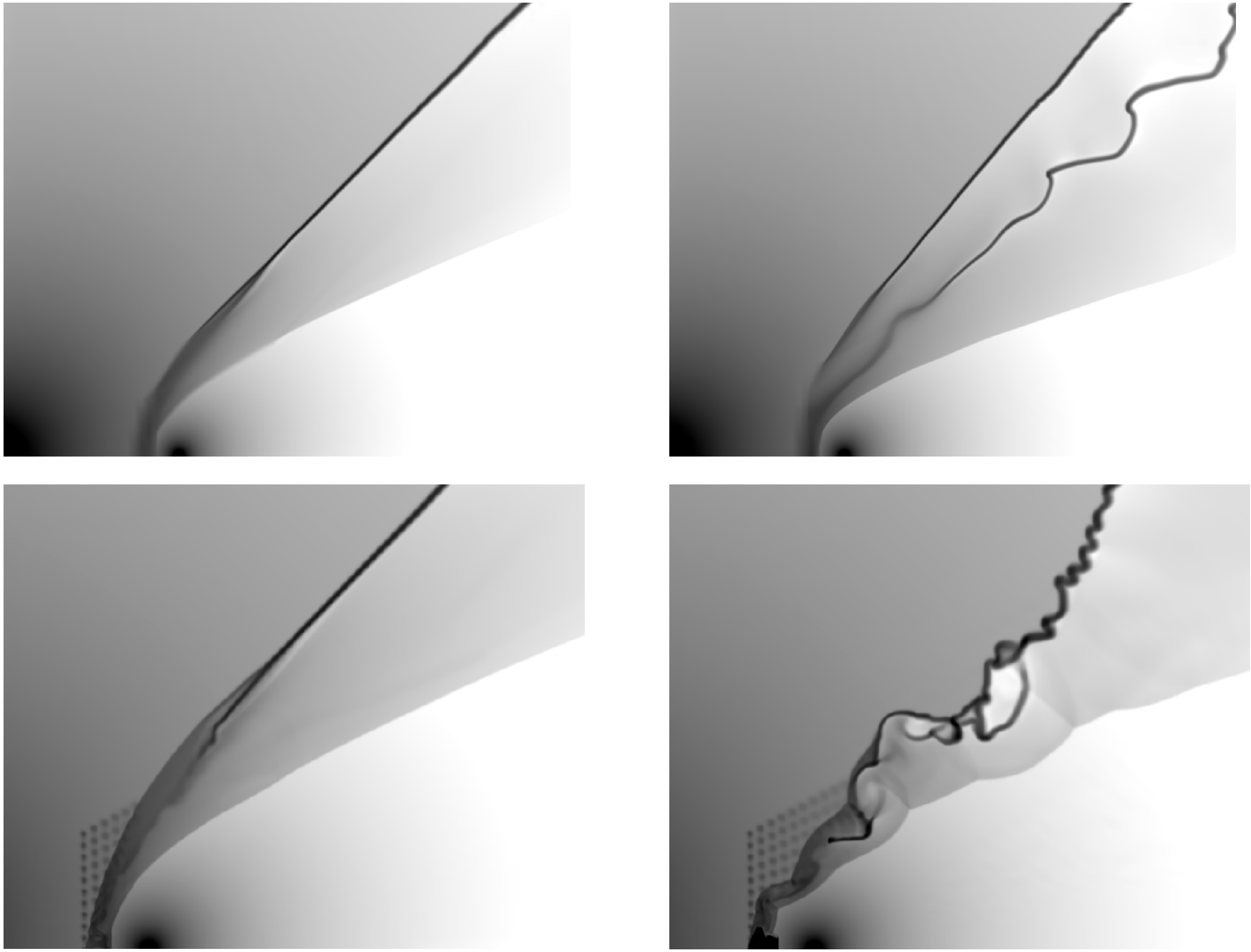


Radiative Braking

(Owocki & Gayley 1997)

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

Future Work II: Effects of clumping



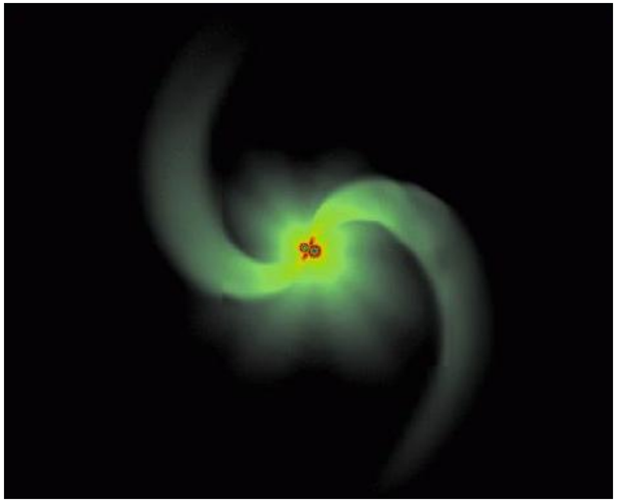
Single clump

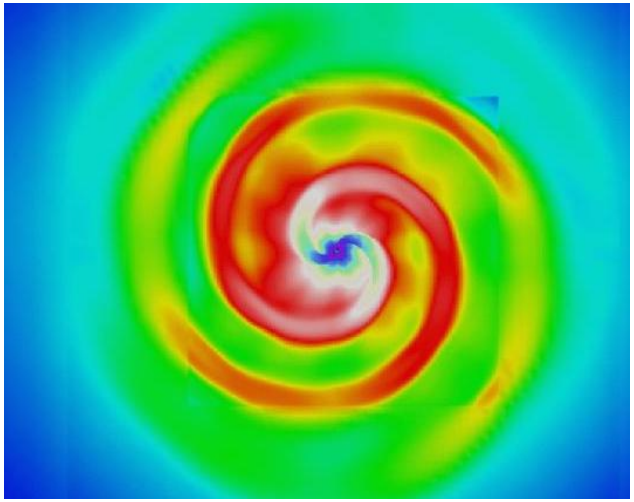
Multiple clumps

Courtesy Rolf Walder

Future Work III: 3D Hydro Modelling

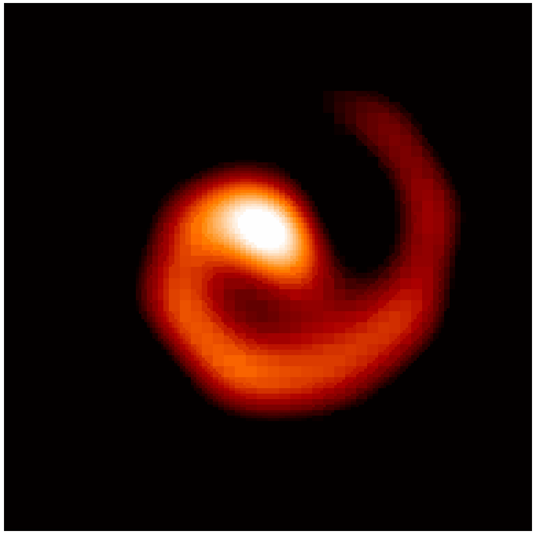
3D simulations using AMR



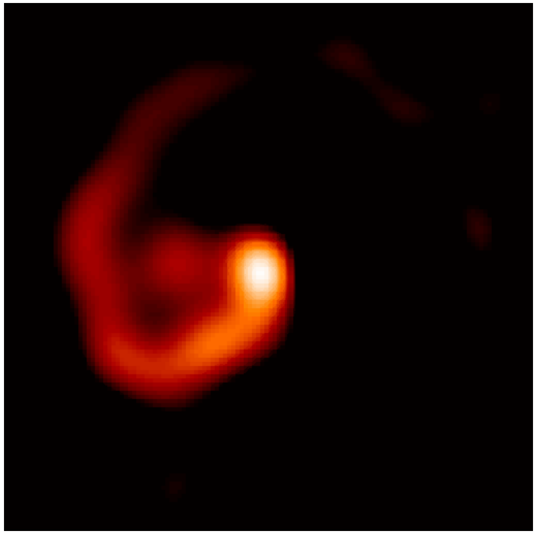


Courtesy Rolf Walder

WR104 - 220 days

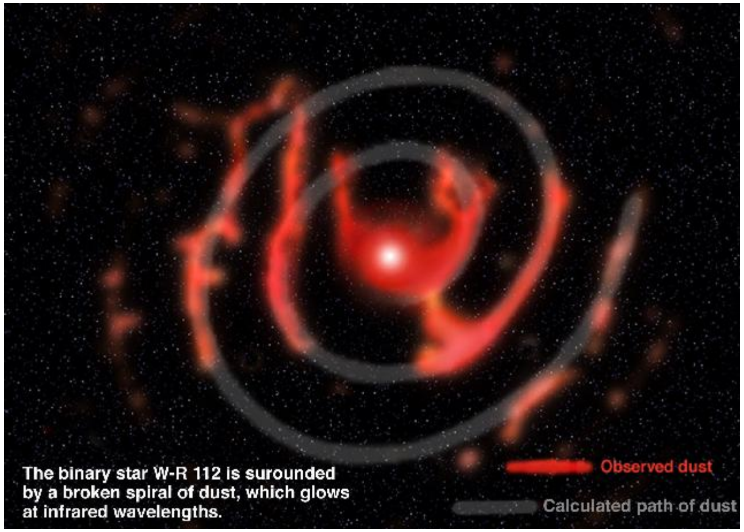


WR98a - 1.5 yrs



Tuthill, Monnier & Danchi 1999

WR112 - 25yrs



The binary star W-R 112 is surounded by a broken spiral of dust, which glows at infrared wavelengths.

Marchenko, Moffat, Doyon, Vacca, Cote 2002

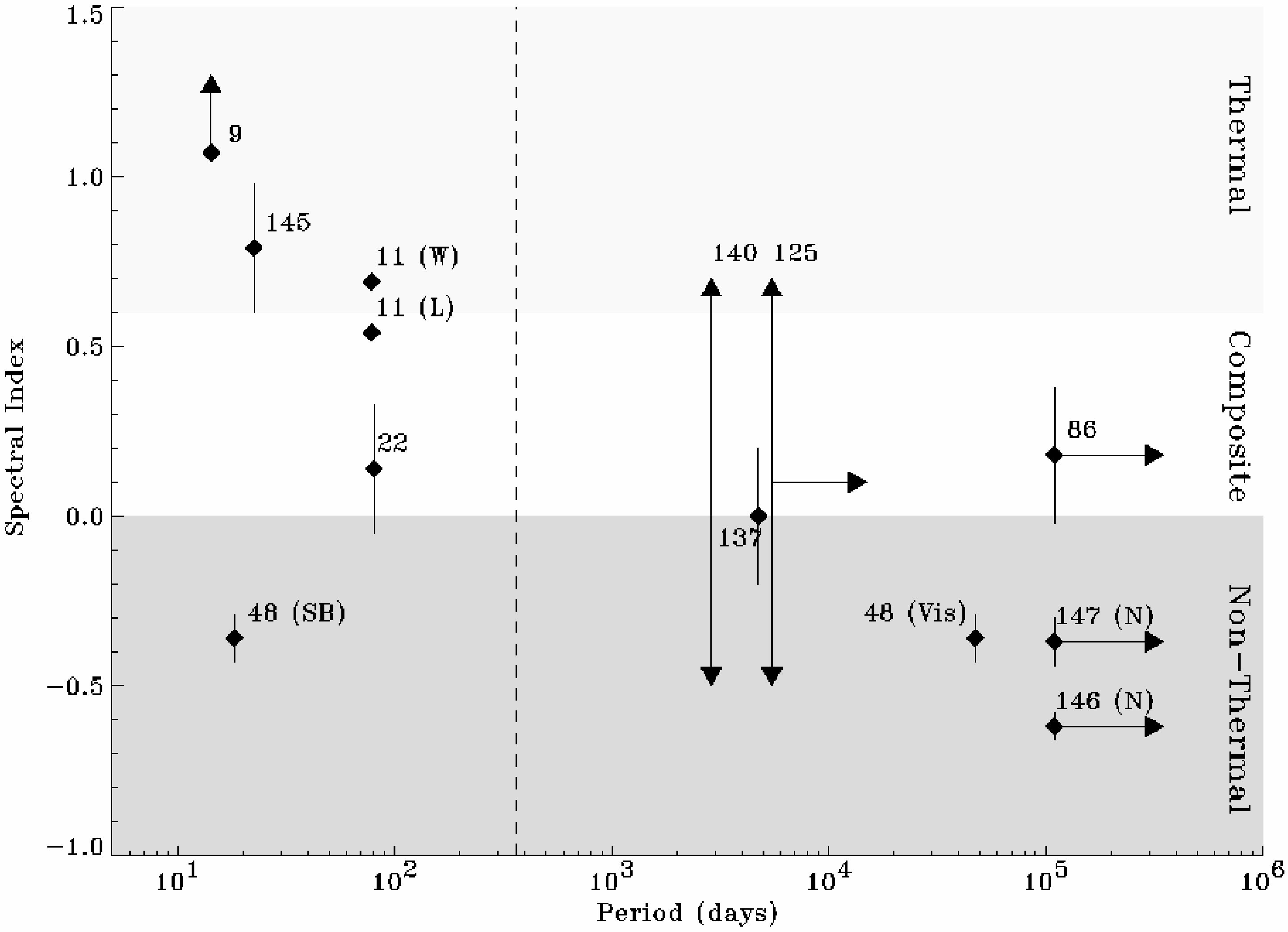
Conclusions

- **Colliding winds** in early-type binaries occur with a wide range of conditions
- This inherent diversity allows us to investigate many phenomena
- Modelling can help us to identify previously unknown binaries, can allow us to infer wind properties, and can be used to test our understanding of the relevant physical processes which occur in these systems

Future work

- Detailed comparison between latest X-ray data and hydro models (to include radiative forces, 3D, non-equilibrium effects)
- Further radio modelling, including comparison of synthetic images with those from VLBA imaging
- Profile modelling of X-ray lines and extension to IR/optical and UV (FUSE) data
- Models which are consistent from X-ray through to radio regimes - prediction of hard X-ray/γ-ray fluxes from IC scattering

Dependence on visibility of non-thermal emission with binary period



Thermal

Non-thermal

Dougherty & Williams 2000

Summary of diagnostics

- Non-thermal emission in 2 WR stars, and at least one O-star system (Cyg OB2 #5), which is spatially resolved in wind-wind collision regions
- Of 11 WR systems with non-thermal emission, 10 are binaries
  - binaries are required to get non-thermal emission in massive stars
- WC subtypes exhibit dust emission
  - can be episodic, or in some cases imaged (the `pinwheels' - spatial scale well suited to new generation of large telescopes and adaptive optics systems)
- Excess emission in some IR/optical/UV lines
  - variability consistent with origin in wind-wind collision
- Excess X-ray emission over single massive stars
  - characteristically harder, and variable
  - now have the capability to resolve lines
- INTEGRAL
  - may detect gamma-rays from Compton upscattering of stellar UV photons by relativistic electrons in wind collision zone

Non -thermal emission in massive stars : does it require a companion?

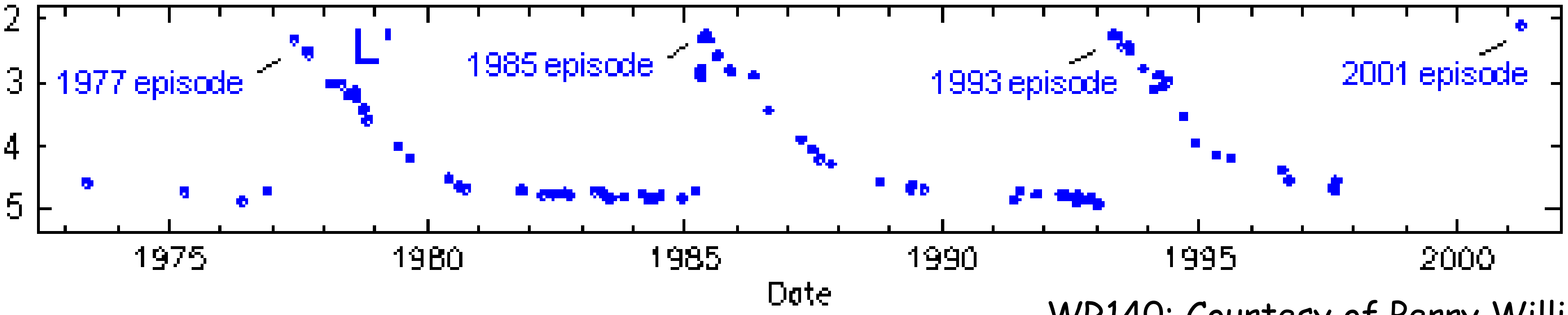
- In spatially resolved WR-systems, non-thermal emission is from a wind-collision region
- Are all systems with non-thermal emission binary systems?
  - 25 WR stars - mixture of both single and binary with measured radio continuum spectra
  - 11 systems have spectra identifying non-thermal emission (at some epoch for variables)
    - 11, 48, 98a, 104, 105, 112, 125, 137,140, 146, 147
    - ***10 of these 11 WR stars have OB-binary companions!***
- Not all binaries are non-thermal emitters
  - free-free absorption along l.o.s

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

  - appearance of non-thermal emission is dependent on optical depth
  - optical depth dependent on size of the orbit relative to the radio photosphere

Dust Formation: IR observations

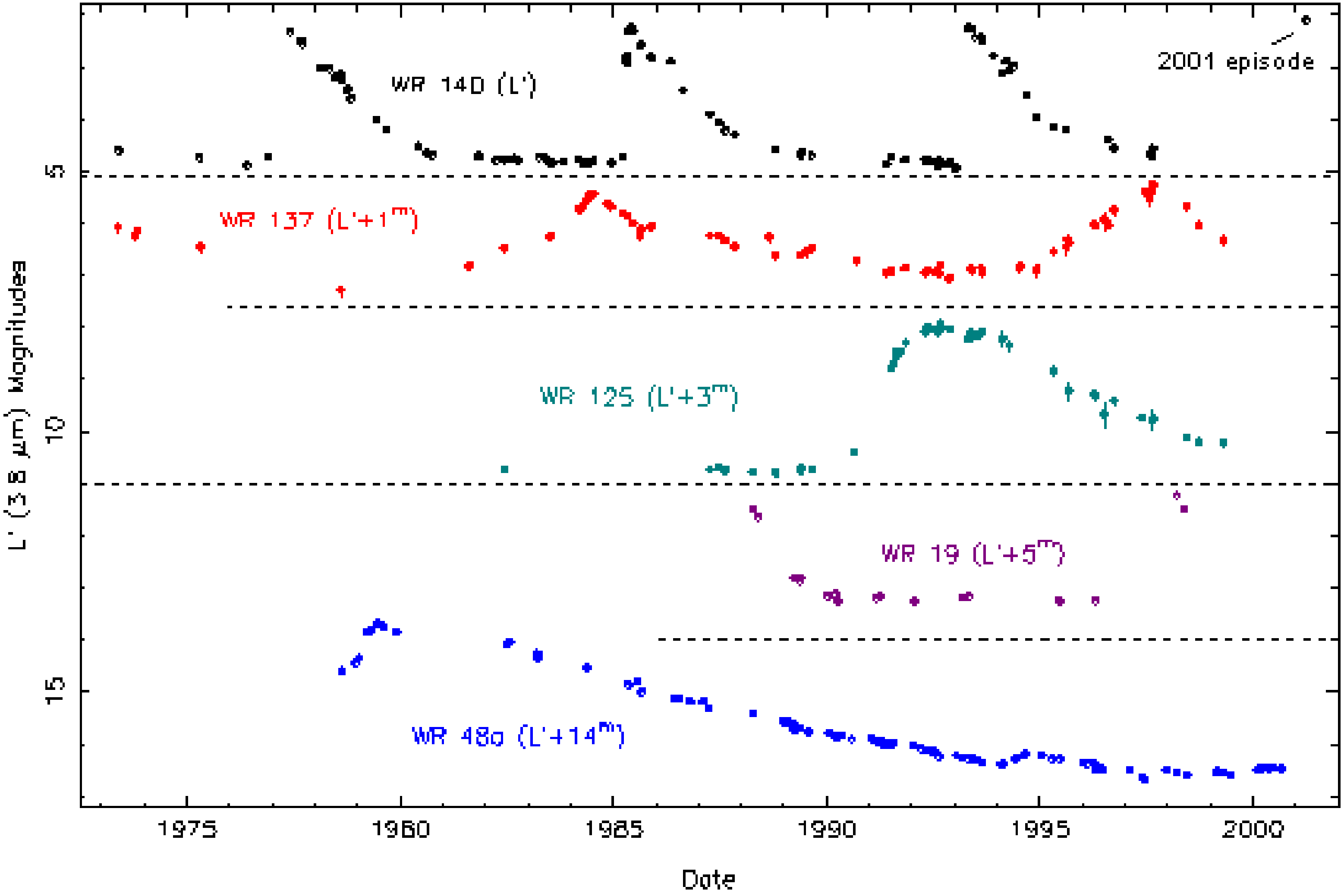
- Dust emission! - in WC subtypes
  - to survive sublimation by UV radiation, need to be ~ 100 AU from star
  - at this distance stellar wind density too low to form grains (Cherchneff & Tielens 1995)
    - need compression of wind material
  - carbon dust - "soot"
  - T_{dust} ~ 1000 K
  - persistent "dusters" - include WR 98a, 104, 112
  - episodic dust makers - 7 in total, including WR 48a, 125, 137, 140



WR140: Courtesy of Perry Williams

- Sharp IR rise near periastron passage - 3×10^{-8} M_{sol} of dust @ T_{dust}~1100K
- Dust formation triggered by compression (40 x 4) near periastron passage

Similar WC-type binary systems



Non-thermal
P=7.9yrs

Non-thermal
P=13.05 yr

Non-thermal
P>18yrs

NT? P=10.1yr

NT? P>22yr