Structure of Wind-Wind Collision Shocks in Massive Binaries

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Talk Outline

- Systems with colliding winds
- 3-D modeling of colliding winds
  - Interaction front ~ Archimedean spiral
  - Highly asymmetric spiral structure in highly eccentric CWBs
    - η Carinae
    - WR 140
- Summary

Colliding winds in massive binaries

Massive stars have strong winds driven stron line radiation.

➡ In binaries consisting of two massive stars, two winds collide and form complicated shock structures, from which high energy emission arise

Colliding Winds (CW)

occur in binaries with

- OB stars
- LBV (luminous blue variable) stars
- Wolf-Rayet stars

In addition, CW also occurs in

- Single or double pulsar with pulsar winds

Progress in dynamical modeling of CWB

1990s-early 2000s

Much progress done in dynamical modeling, but most of them limited to 2-D

Recent progress in 3-D dyn. modeling

- Grid-based: Pittard (1999); Walder, Folini (2003); Lemaster+ (2007); Pittard (2010); Parkin+ (2011)
- SPH: Okazaki et al. (2008)

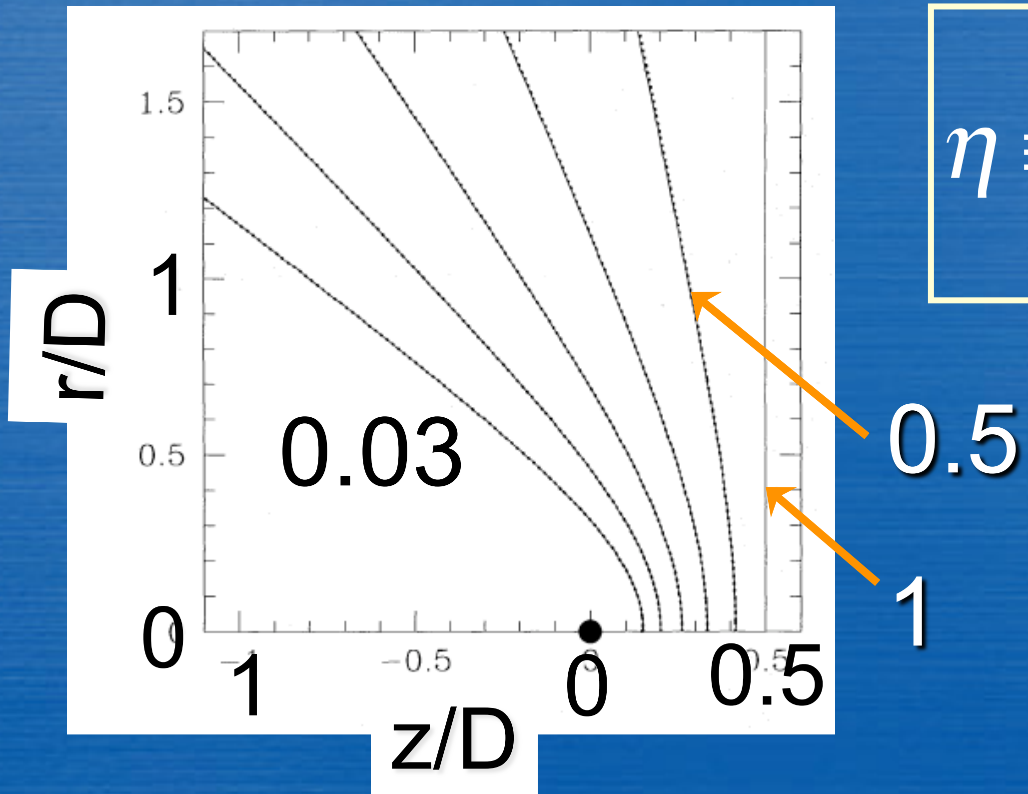
Why do we need 3-D dynamical modeling of CWB?

Having a 3-D dynamical model is essential to understand structure of colliding winds in:

- massive binaries with optically thick winds/nebula and/or high *e* (e.g., η Carinae and WR 140)
- Gamma-ray binaries with competing scenarios (CWB vs. MQ) or needs to identify particle acceleration sites.

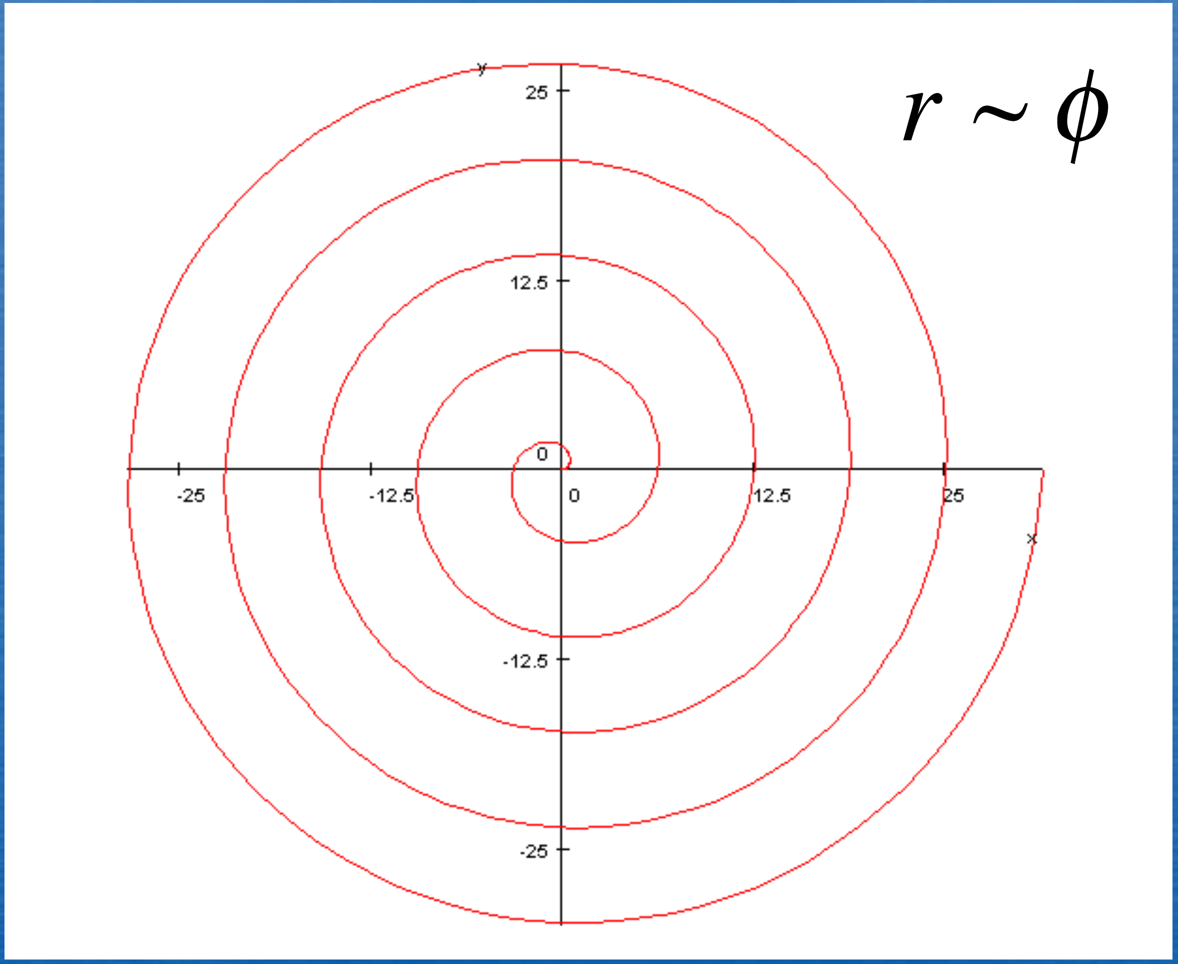
Shape of the steady interaction front without orbital motion

Momentum balance determines the bow shock structure (e.g., Canto+ 1996)



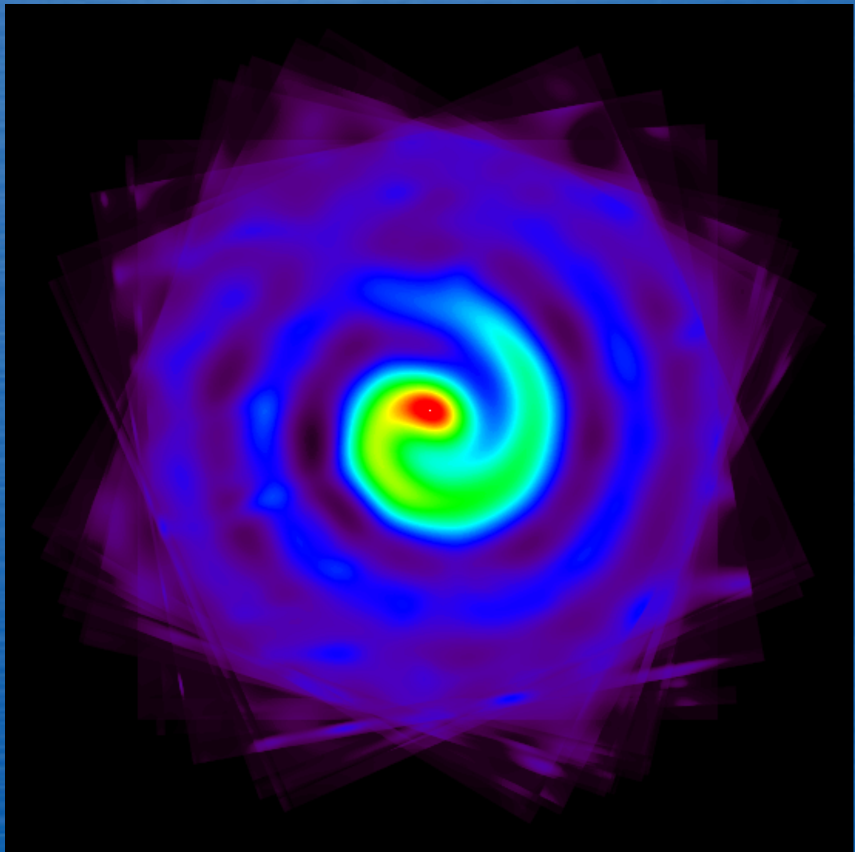
$$\eta \equiv \frac{\dot{M}_2 v_2}{\dot{M}_1 v_1}$$

Interaction front with orbital motion ~ Archimedean spiral



Dust formation region around a massive star

WR 104



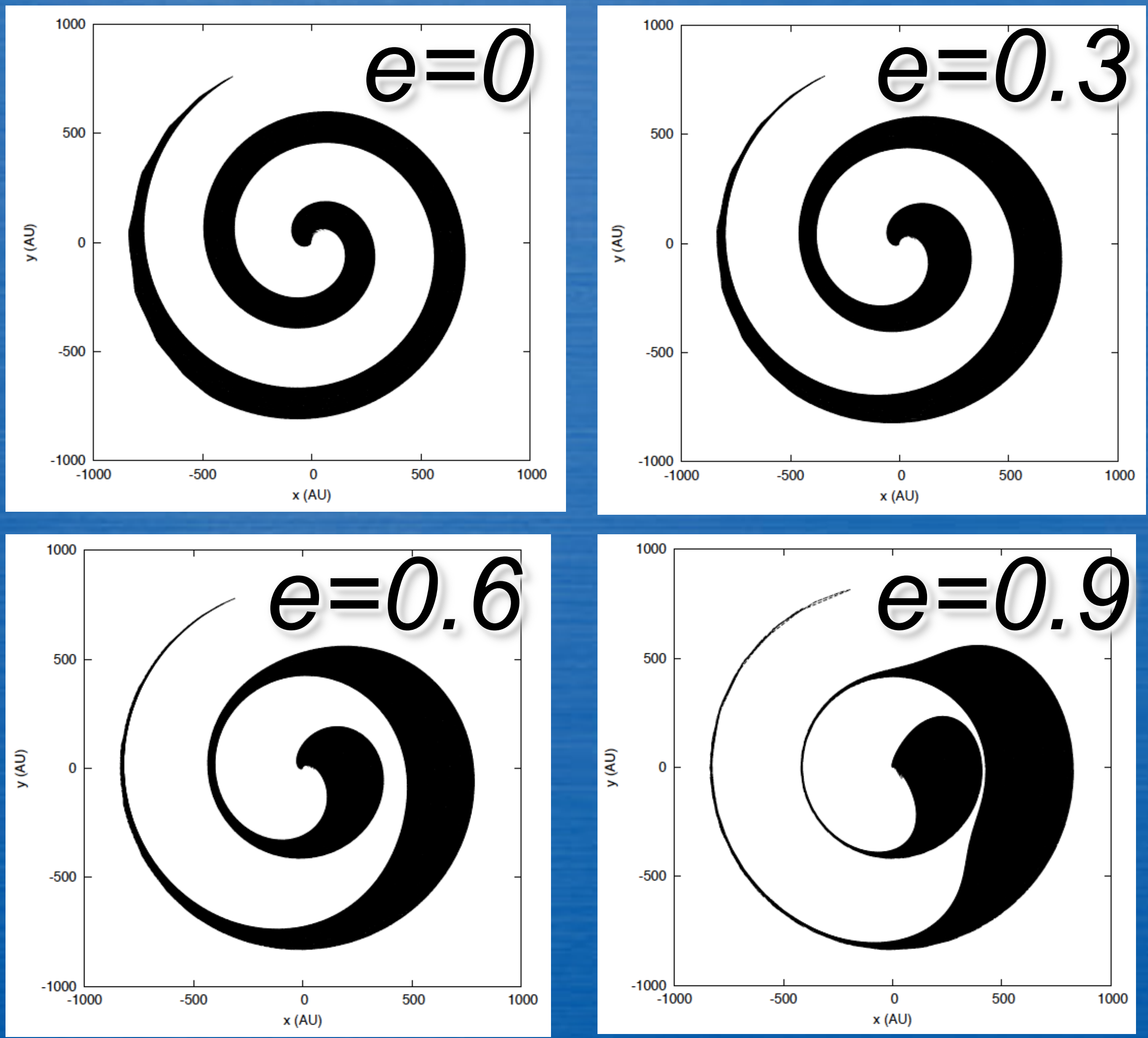
(Tuthill+ 2008)

Colliding winds in a massive binary (WR+O) can form dust

↑

Strong cooling at strong shocks?

Semi-analytical model of interaction surface with orbital motion



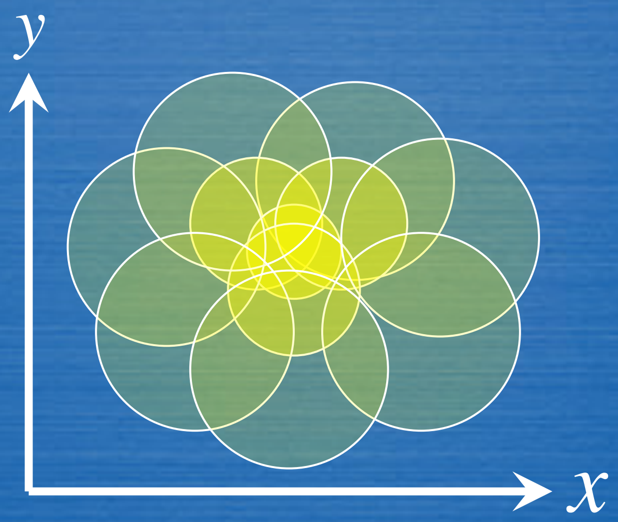
Asymmetry in spiral structure is more remarkable for a higher orbital eccentricity

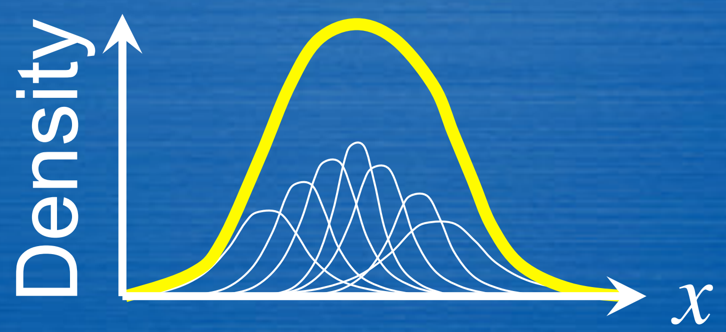
(Parkin & Pittard 2008)

3-D Numerical modeling of highly eccentric CWB with SPH

Smoothed Particle Hydrodynamics (SPH) method is:

- A particle method that divides the fluid into a set of discrete "fluid elements" (=particles)
- Flexible in setting various initial configurations





Numerical model

- 3-D SPH code with the standard artificial viscosity: $\alpha_{\mathrm{SPH}} = 1, \beta_{\mathrm{SPH}} = 2$
  (Bate+ 1995)
- w/ or w/o optically-thin radiative cooling
- wind velocity: beta law

$$v_{\mathrm{w}} = v_{\infty}\left(1 - R_{*} / r\right)^{\beta} \ \text{with}\ \beta = 0, 1$$

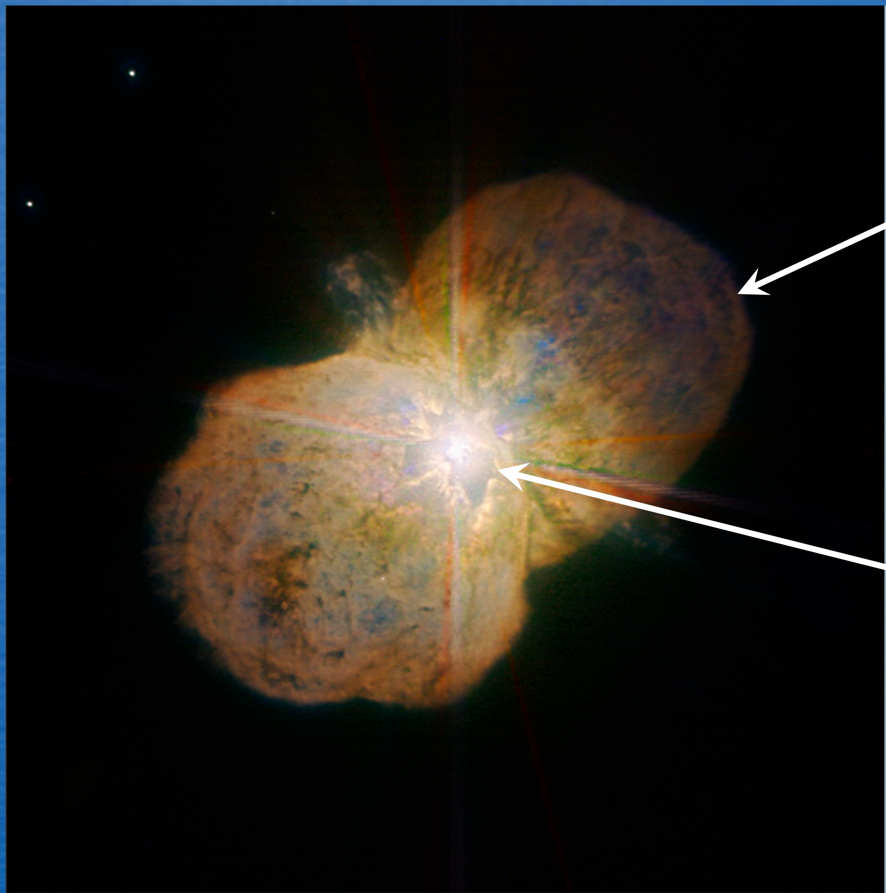
Case study (1) η Carinae

- LBV: supermassive ($M \geq 10^2 M_\odot$) & superluminous ($L \sim 5 \times 10^6 L_\odot$)
- Greatt mass ejection of $\sim 10 M_\odot$ in mid-1800's ⇨ the Homunculus nebula
- Optical lines & X-ray light curves show variations with a 5.54 yr periodicity

  ⇨ η Carinae is a binary with

  $$P_{\rm orb} = 5.54 \text{ yr} \;\; \& \;\; e \sim 0.9$$

η Carinae obscured by the Homunculus nebula



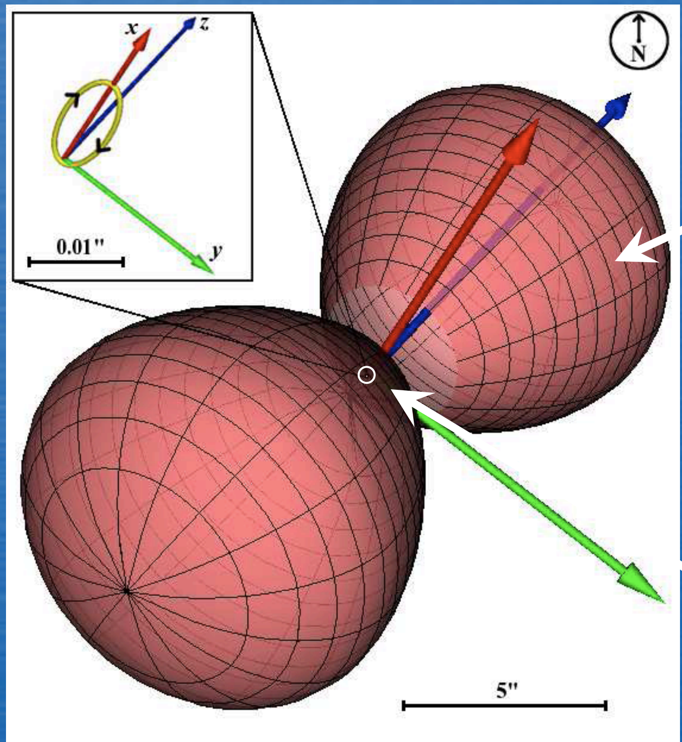
Eta Carinae (NACO/VLT)

ESO Press Photo 17a/08 (27 May 2008)

Homunculus, the remnant of a great eruption in 1840’s

Stars can’t be seen directly

Binary orbital axis roughly aligned with the Homunculus nebula axis



(Madura+ 2011)

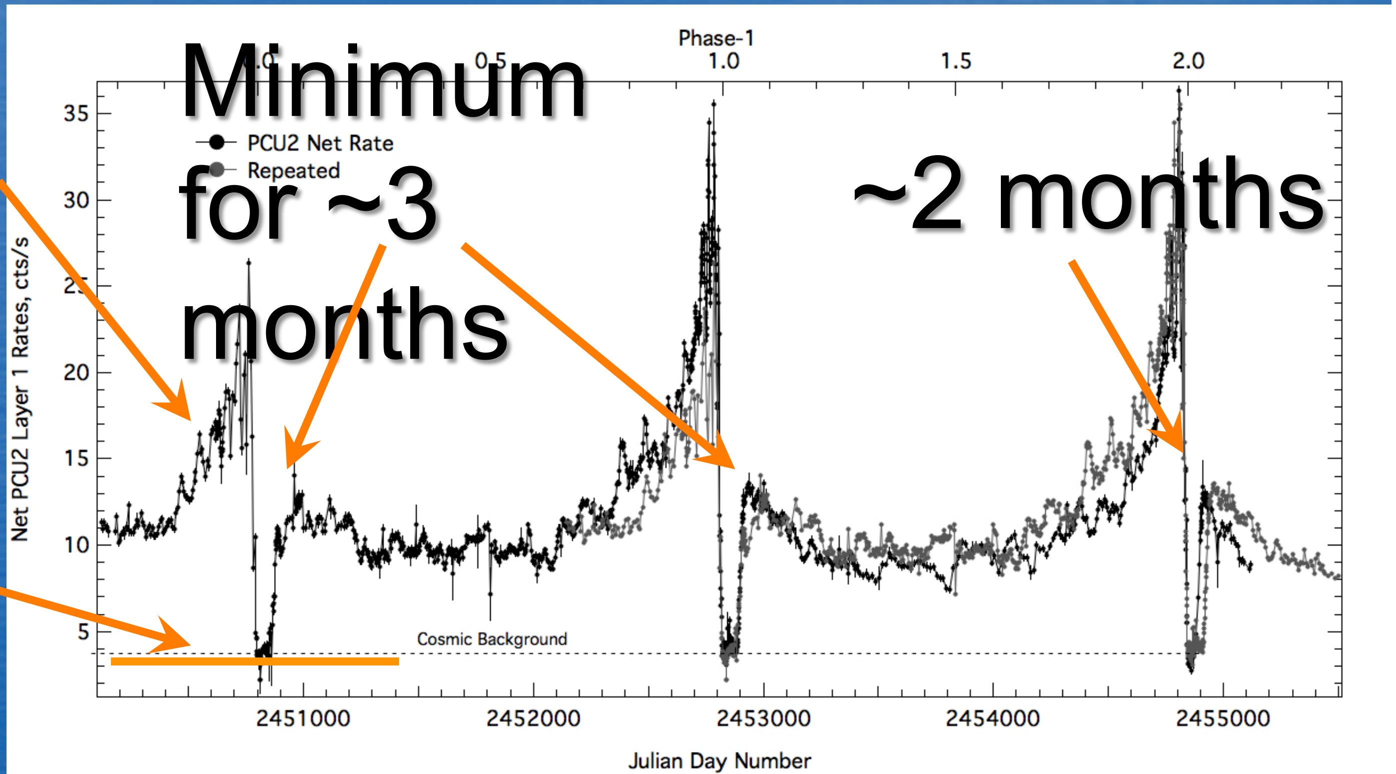
Homunculus, the remnant of a great eruption in 1840's

binary

RXTE light curve vs. orbital phase (1996-2009)

Gradual rise before periastron

Minimum ≠ 0

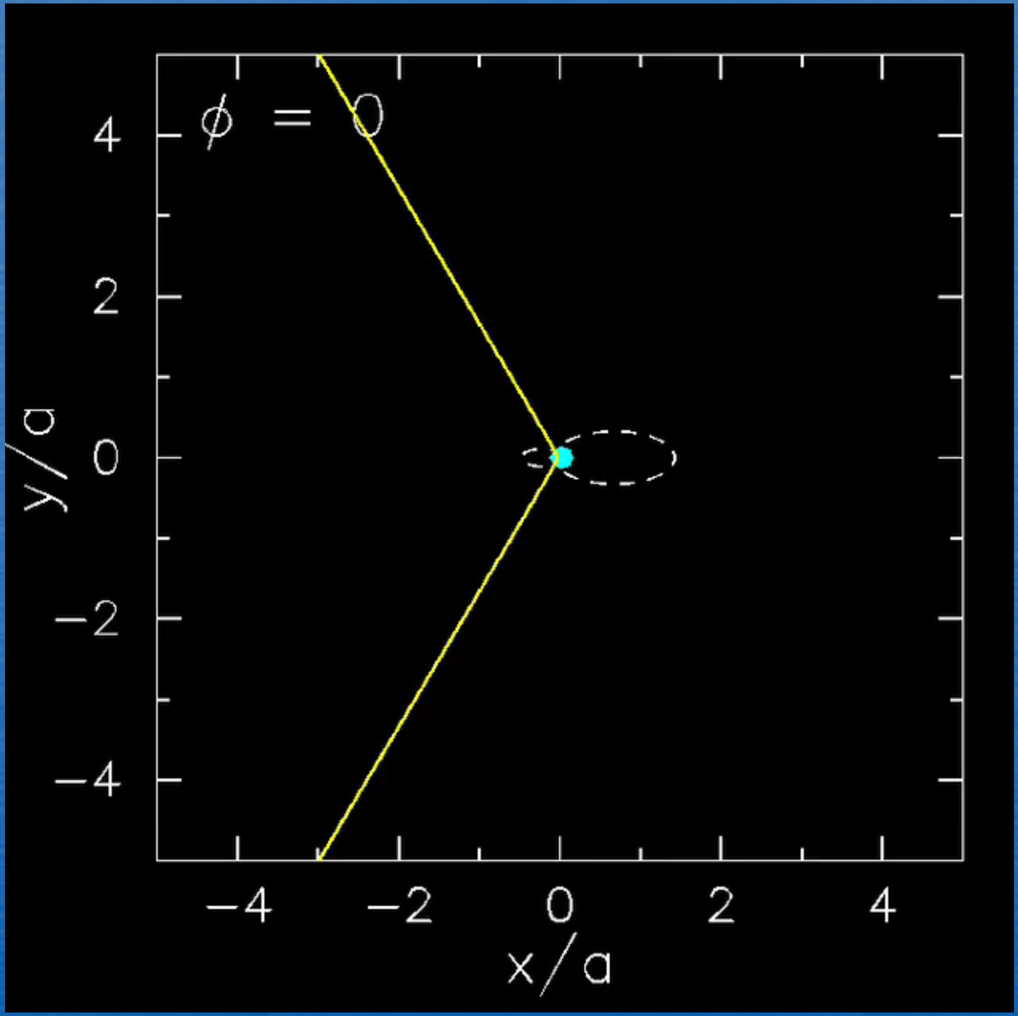


http://asd.gsfc.nasa.gov/Michael.Corcoran/eta_car/etacar_rxte_lightcurve/index.html

Stellar and wind parameters of η Carinae

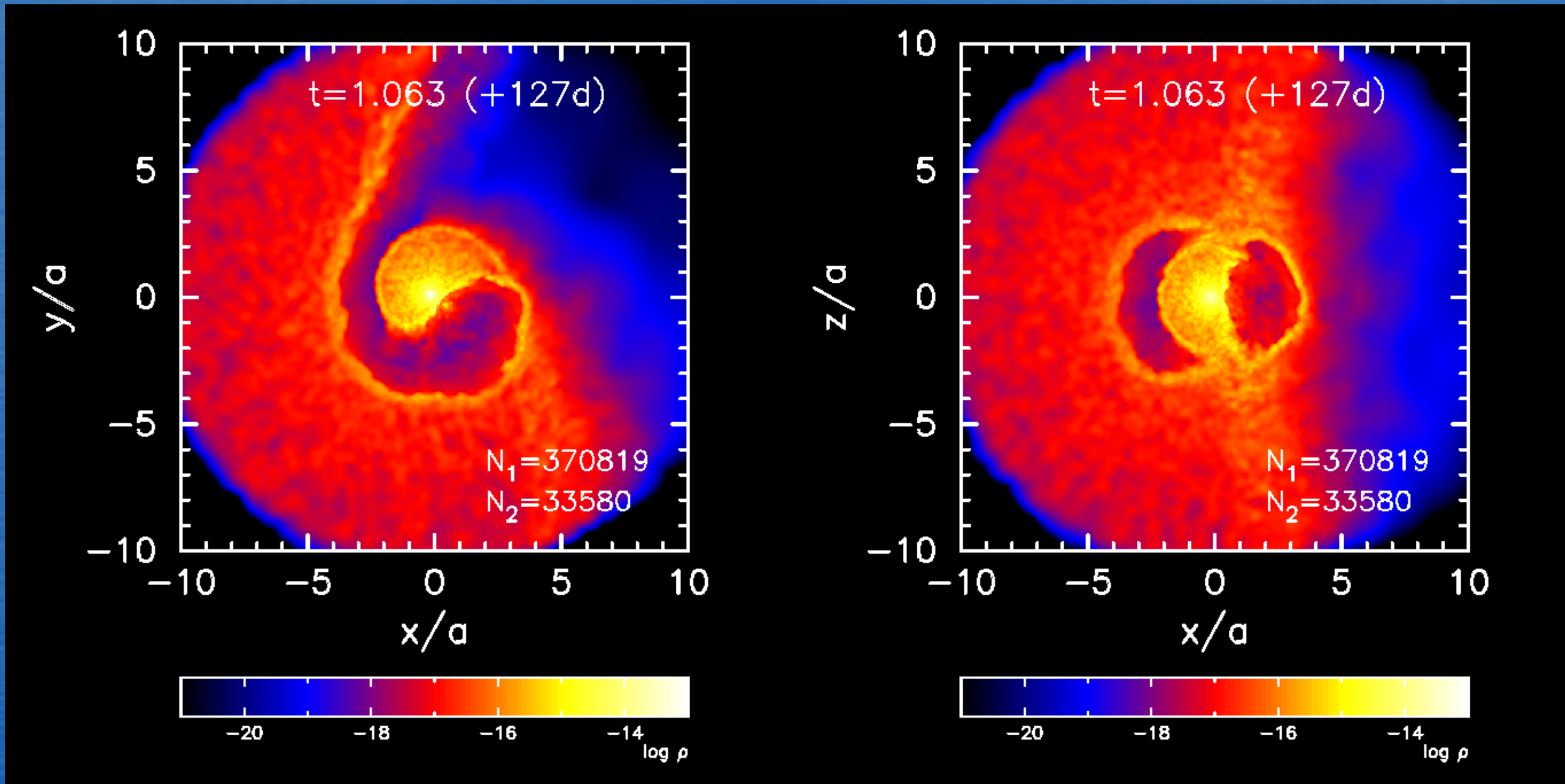
	η Car A	η Car B
$M / M_{\odot}$	90	30
$R / R_{\odot}$	90	30
$\dot{M}$ $(M_{\odot} / \mathrm{yr})$	2.5×10^{-4}	10^{-5}
V_{wind} (km/s)	500	3,000
T_{wind} (K)	3.5×10^{4}	3.5×10^{4}

Simple approach w/o orbital motion



3-D adiabatic simulation within $r = 10a$ (~0.07 arcsec)

← ~300 au ⟶

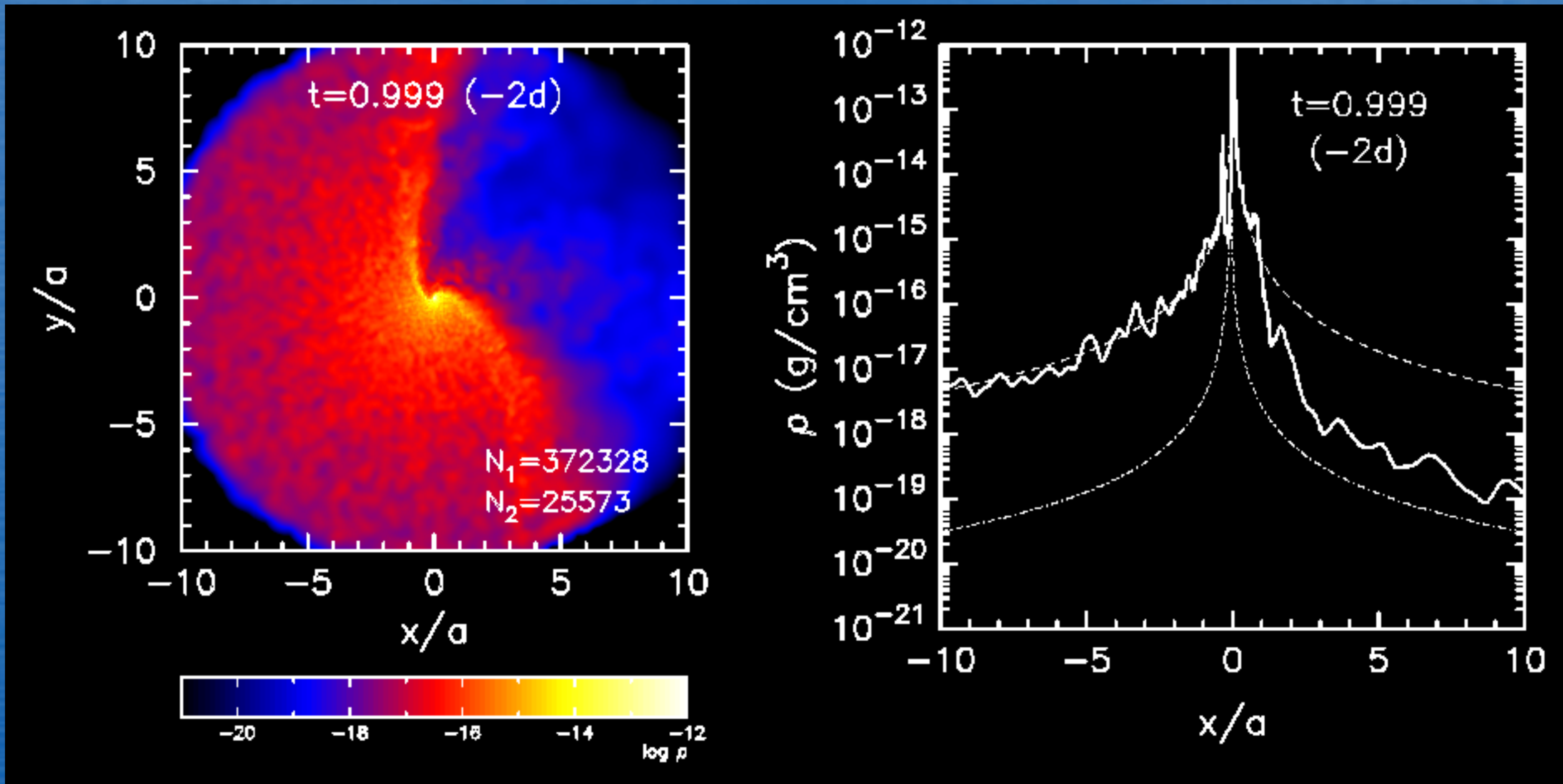


Density on the orbital plane

Density on the axis plane

3-D adiabatic simulation within $r = 10a$ (~0.07 arcsec)

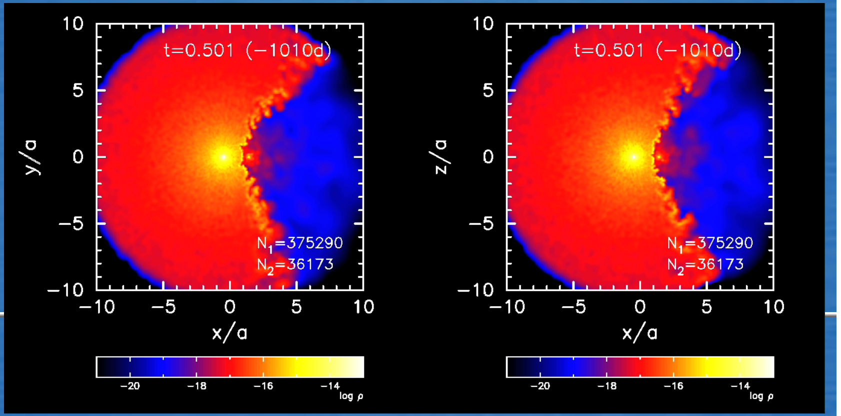
← ~300 au →



Density on the orbital plane

Density on the semi-major axis

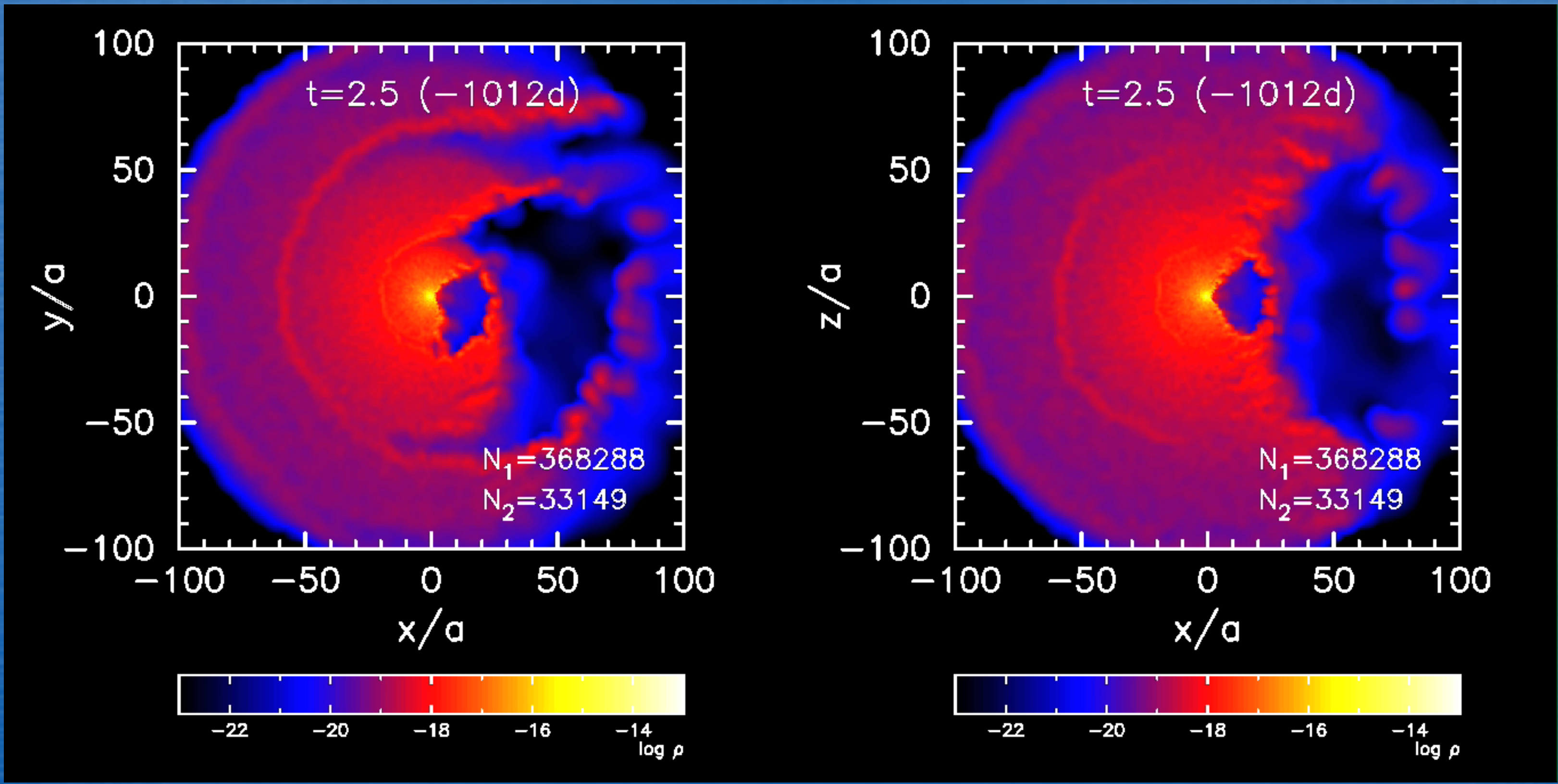
Summary of eta Car wind-wind collision



- Low-density, fast wind from the secondary carves out high-density, slow wind from the primary
- Because of high eccentricity, the cavity is very thin on the periastron side, while it occupies a large volume on the apastron side

Simulation within $r = 100a$ (~0.7 arcsec)

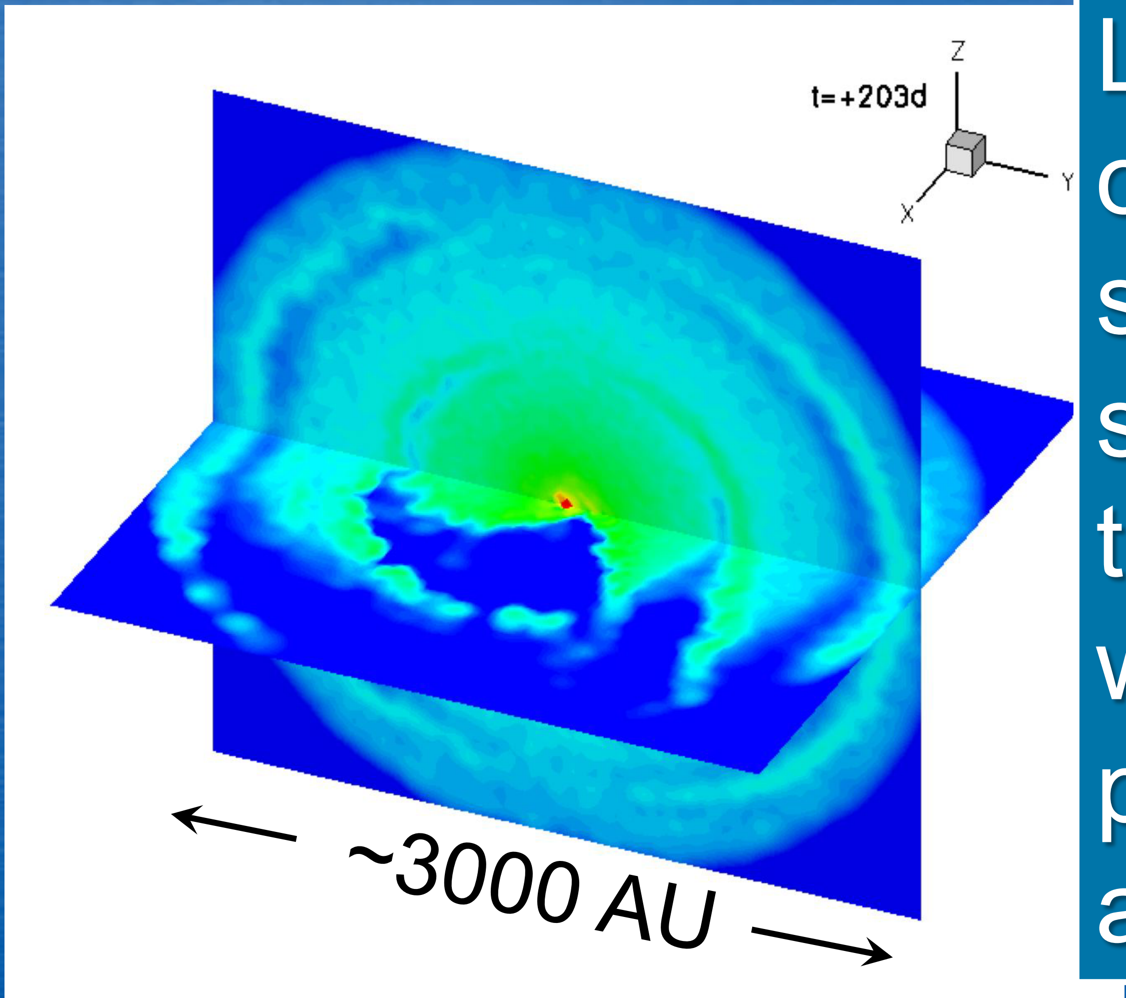
←~3000 au→



Density on the orbital plane

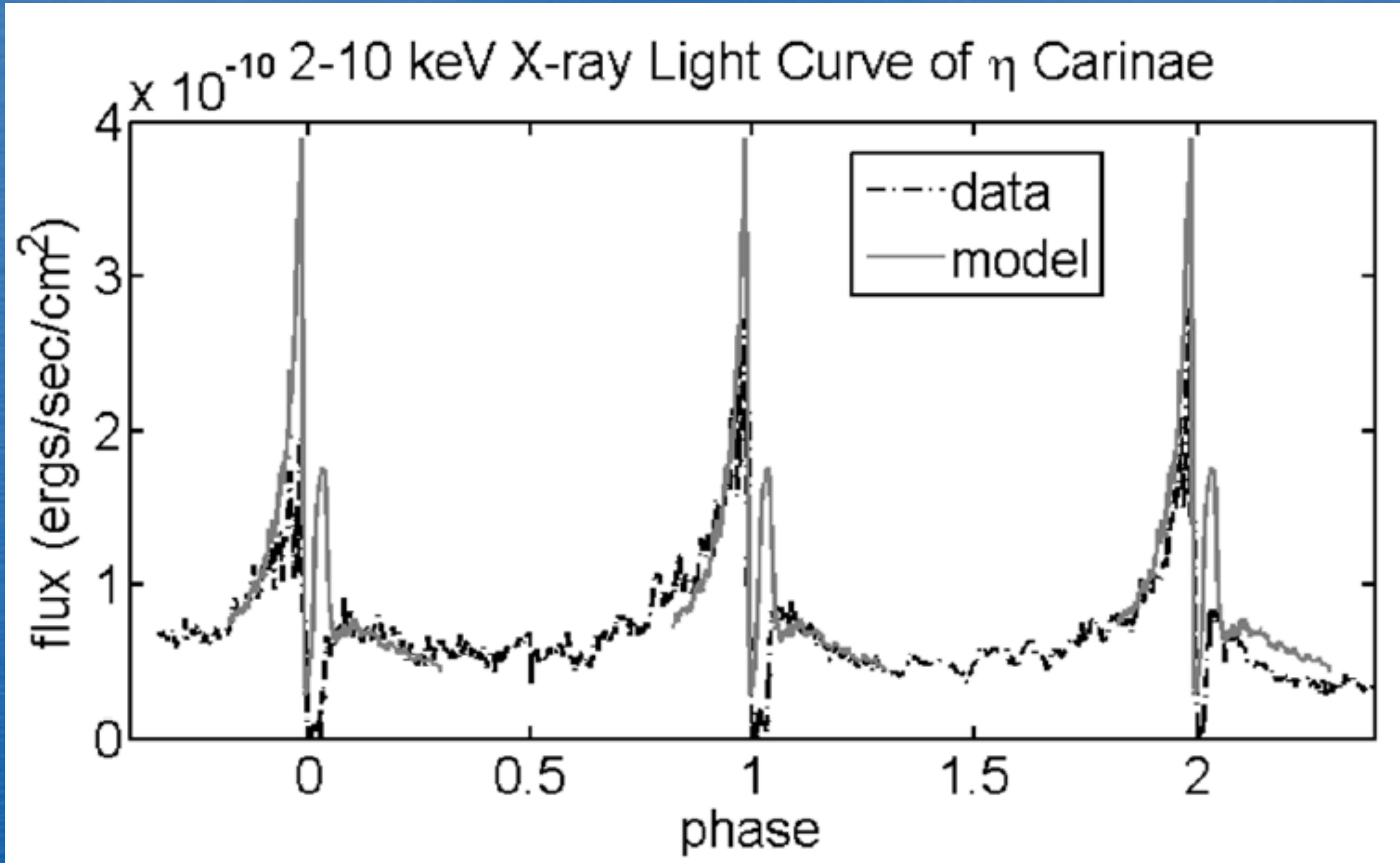
Density on the *x*-*z* plane

3-D wind structure from simulation within $r = 100a$ (~0.7 arcsec)



Large cavities of similar shape separated by thin, primary wind region are present at apastron side

Model RXTE light curve (w/ radiative cooling) vs. observed light curve



(Russell+ 2011)

Episodic post-shock dust formation

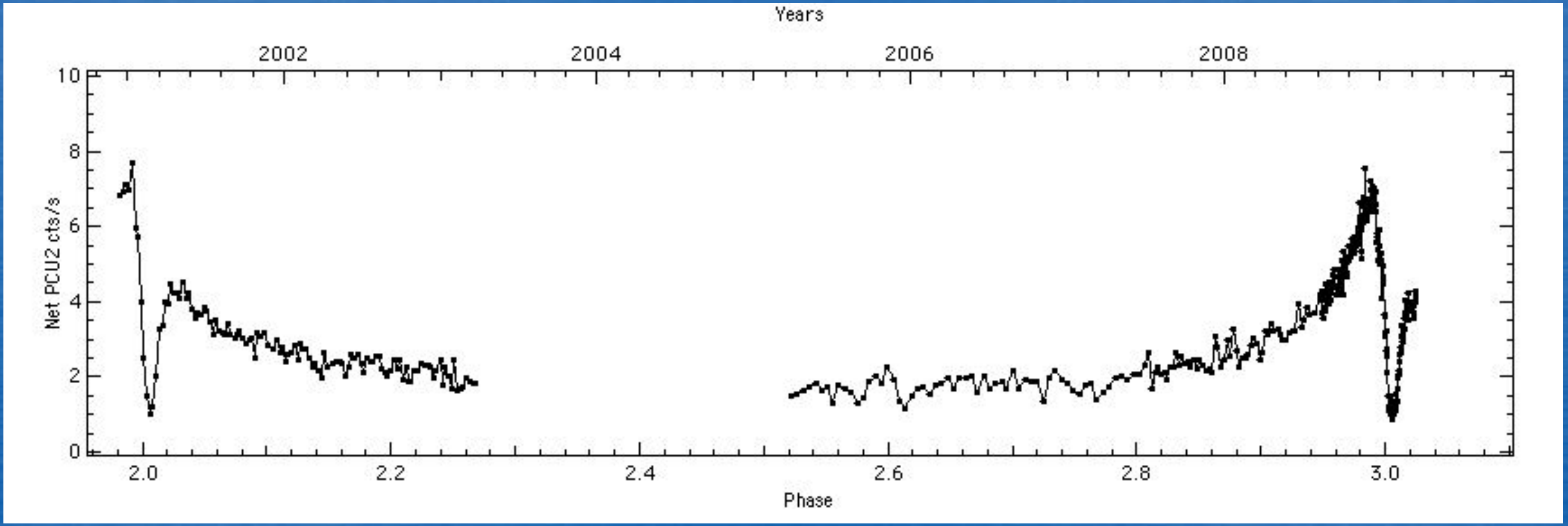
(Smith 2010)

- Eta Car shows broad peaks in JHKL photometry, roughly correlated with times of periastron passage.
- These peaks have IR SEDs consistent with emission from hot dust at 1400–1700 K.
- The excess SEDs are inconsistent with the excess being entirely due to free-free wind or photospheric emission.

Case study (2) WR 140

- A WR binary: WC7 + O4-5V
- Transient dust formation at periastron
  ⇔ Wind-wind collision
- Radial velocities, IR and X-ray lightcurves vary with 7.9 yr periodicity
- Deep X-ray minimum at periastron, similar to that of η Car

RXTE X-ray lightcurve of WR 140 (2001-2009)

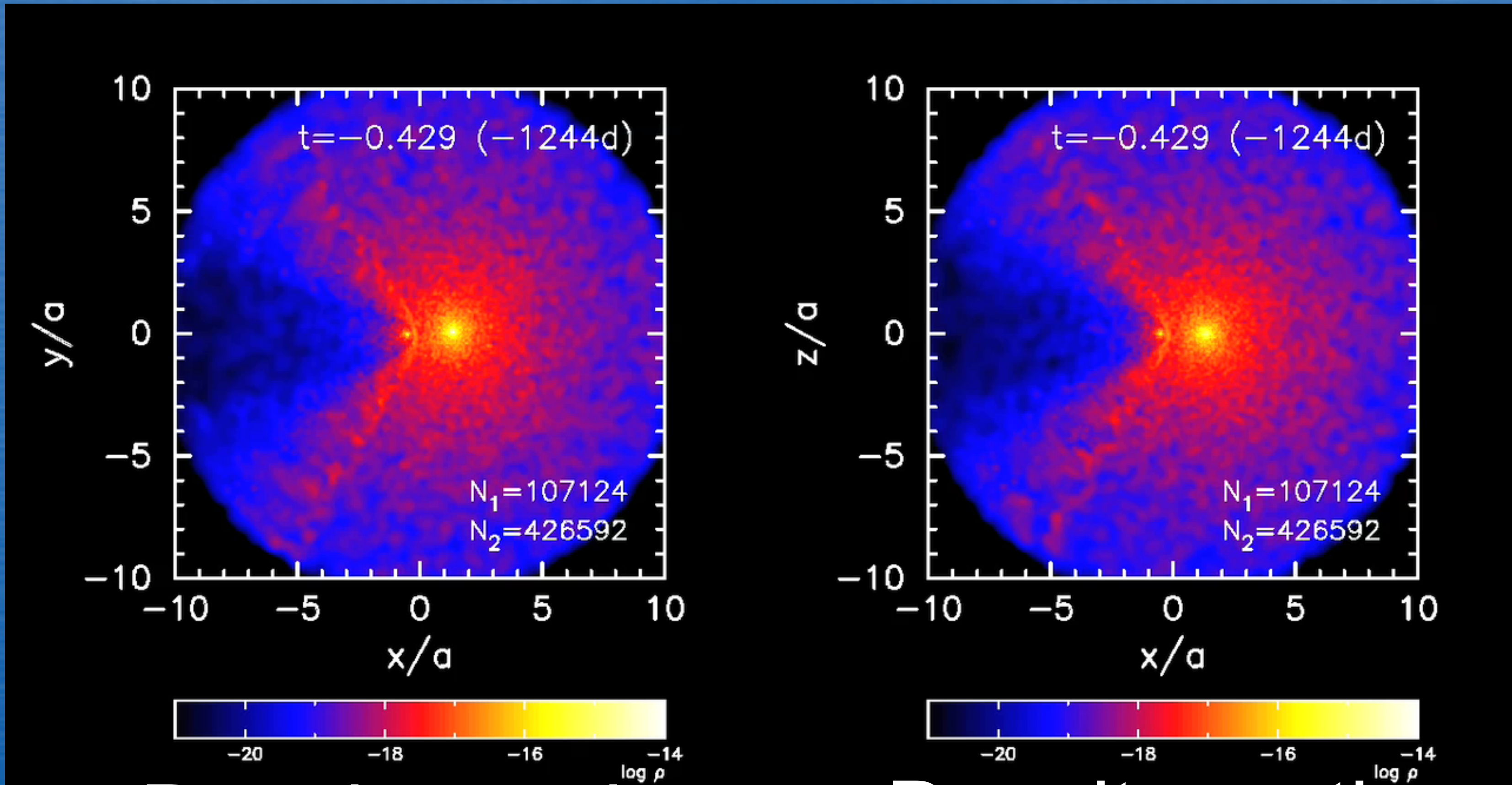


http://asd.gsfc.nasa.gov/Michael.Corcoran/wr140/wr140_rxte_lightcurves/index.html

Stellar, wind & binary parameters

	O4-5V	WC7
$M / M_\odot$	50	19
$R / R_\odot$	12	13
$\dot{M}$ $(M_\odot / \mathrm{yr})$	1.2x10^-6	3.8x10^-5
V_{wind} (km/s)	3,200	2,860
T_{wind} (K)	42,000 (initially)	
P_{orb} (yr)	7.94	
e	0.881	

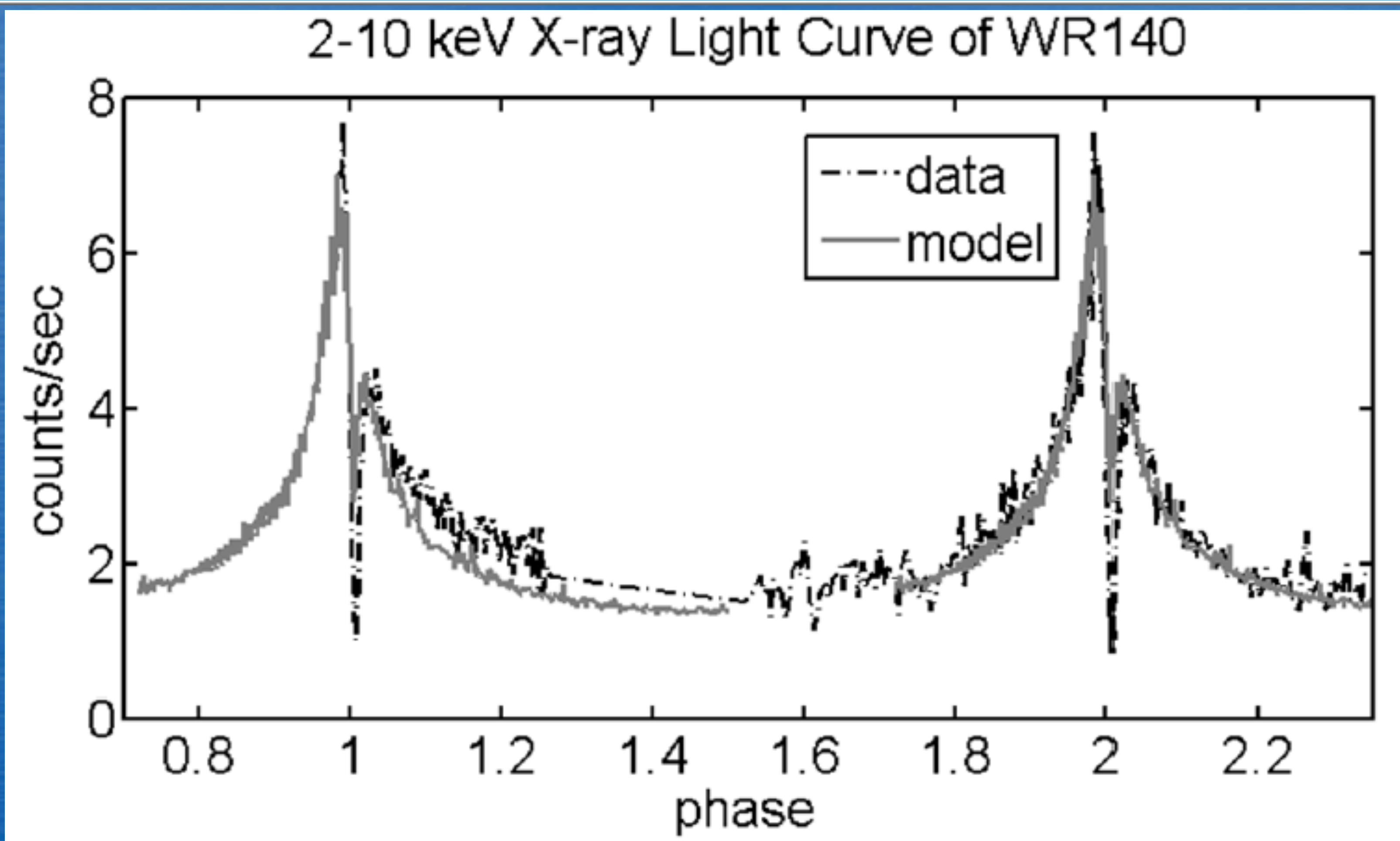
SPH Simulations of WR 140 (*r* <10*a*)



Density on the orbital plane

Density on the *x-z* plane

Model RXTE light curve vs. observed light curve



(Russell+ 2011)

Summary

- Constructing 3-D dynamical models is essential to understand the behavior of colliding-wind binaries.
- 3-D SPH sims reproduce observed X-ray light curve of WR 140, but the fit is not ery good for eta Car.
- Formation of dust in strong shocks at periastron remains an open question.