Xrays from Massive-Stars

Stan Owocki
University of Delaware
Newark, Delaware USA

Collaborators

- Asif ud-Doula
- Chris Russel
- Dyan Kee
- Marc Gagne
- Jon Sundqvist
- David Cohen

Collisional shock-heated X-ray emission

Rough rule of thumb:

$$\frac{T_x}{10MK} \approx \frac{E_x}{1kev} \approx \left(\frac{V}{1000\mathrm{km/s}}\right)^2$$

E_X ~ 2-10 kev => V~3000 km/s => Colliding wind binaries

E_X ~ 0.5-1 kev => V ~ 700 km/s => Intrinsic instabilities

E_X ~ 1-3 kev => V~ 1000 km/s => Magnetic confinement

Radiative cooling

$$\frac{t_{cool}}{t_{exp}} \approx \frac{V_8 d_{12}}{\dot{M}_{-7}}$$

Stevens+ 1992

$$V_8 \equiv \frac{V}{10^8 \mathrm{cm/s}} = \frac{V}{1000 \mathrm{km/s}}$$

$$d_{12} \equiv \frac{d}{10^{12} \mathrm{cm}} \approx \frac{d}{0.1 \mathrm{au}}$$

$$\dot{M}_{-7} \equiv \frac{\dot{M}}{10^{-7} M_{\odot}/yr}$$

Colliding Wind Shock X-ray emission

$$\chi \equiv \frac{t_{cool}}{t_{\exp}} \approx \frac{l}{r} \gg 1$$

Adiabatic shock for binary separation D

$$L_X \sim \int \rho^2 \, dV \sim \left(\frac{\dot{M}}{V_\infty} \right)^2 \int_R^D \frac{r^2 dr}{r^4} \sim \frac{1}{D}$$

$$\chi \equiv \frac{t_{cool}}{t_{\exp}} \approx \frac{l}{r} \ll 1$$

Radiative shocks: insensitive to D

$$L_x \lesssim L_{wind} \equiv \dot{M} v_\infty^2 / 2$$

for 1-D spherical, laminar shock

THE ASTROPHYSICAL JOURNAL, 386:265–287, 1992 February 10

COLLIDING WINDS FROM EARLY-TYPE STARS IN BINARY SYSTEMS

IAN R. STEVENS[1]
Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771; and Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England

JOHN M. BLONDIN[2]
Department of Astronomy, University of Virginia, Charlottesville, VA 22903

AND

A. M. T. POLLOCK
Computer & Scientific Co., Ltd., 34 Westwood Road, Sheffield S11 7EY, England

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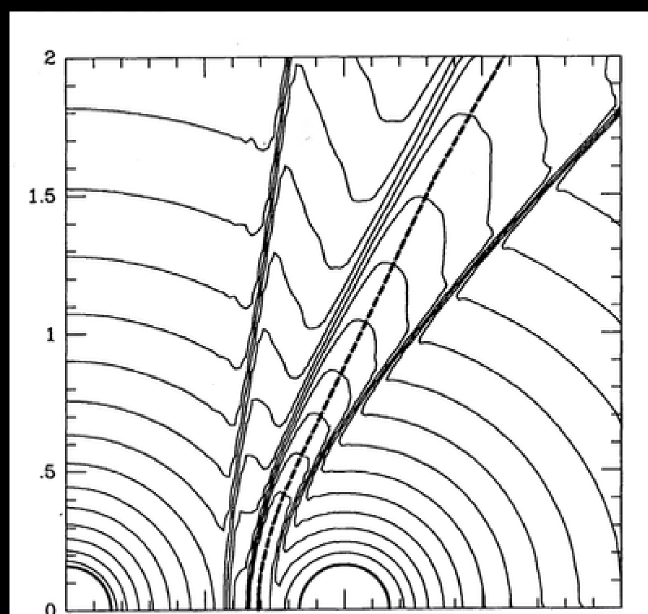
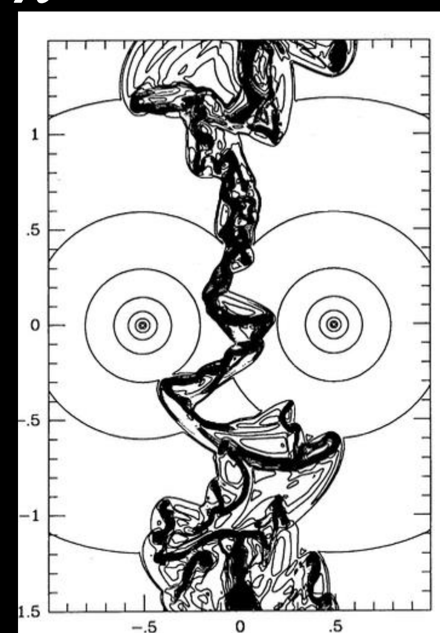
$$\chi = \frac{t_{\rm cool}}{t_{\rm esc}} \approx \frac{v_8^4\, d_{12}}{\dot{M}_{-7}}\,,$$

$\chi \gg 1$; adiabatic



$\chi \ll 1$; radiative



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Suppression of X-rays from radiative shocks by their thin-shell instability

Nathaniel Dylan Kee,[1★] Stanley Owocki[1] and Asif ud-Doula[2]

[1] *Department of Physics and Astronomy, Bartol Research Institute University of Delaware, Newark, DE 19716, USA*
[2] *Penn State Worthington Scranton, Dunmore, PA 18512, USA*

for planar shock, expect

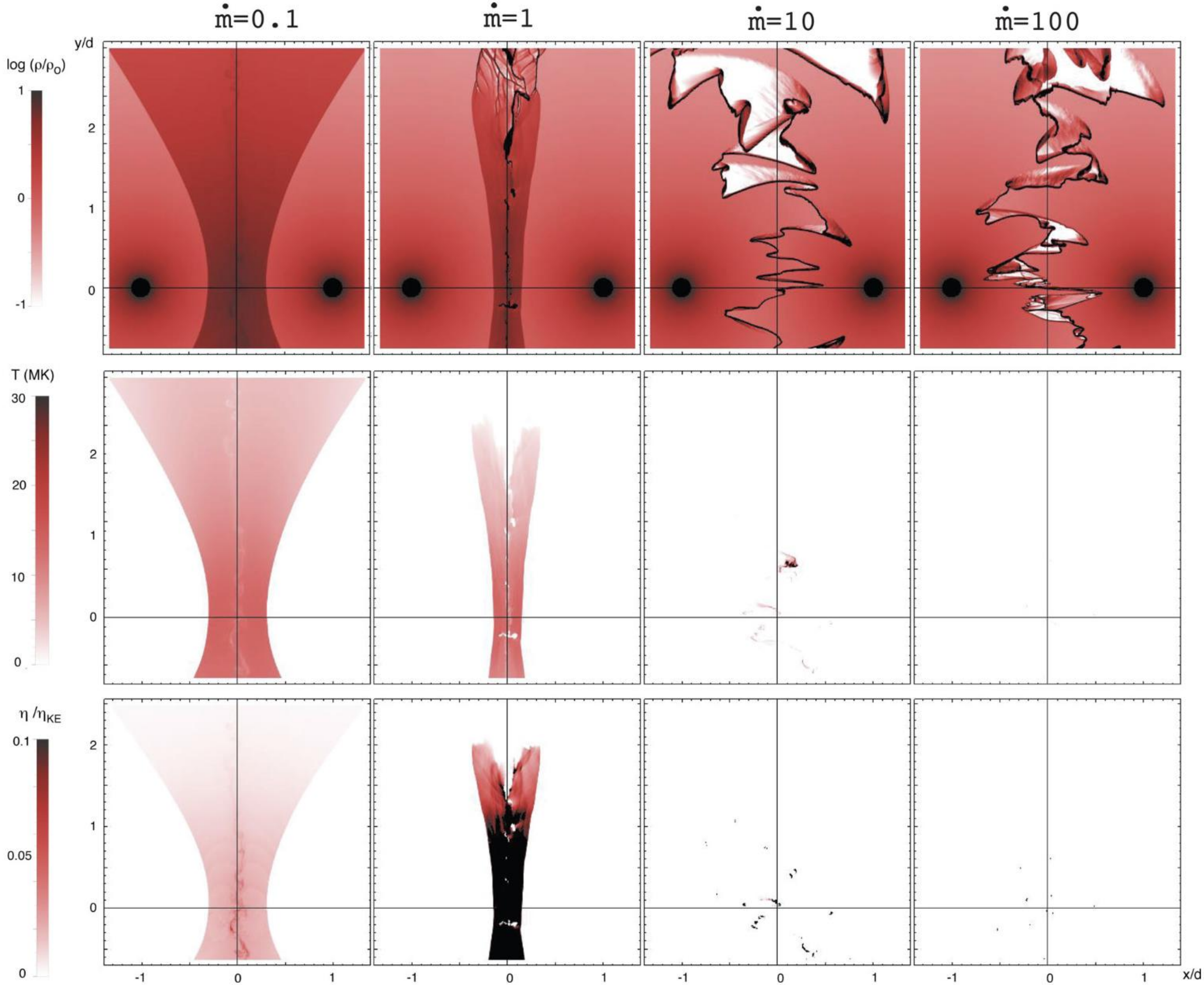
$$\frac{L_x}{L_{KE}} \approx \frac{\dot{m}^2}{1+\dot{m}}$$

$$\dot{m} \equiv 1/\chi$$

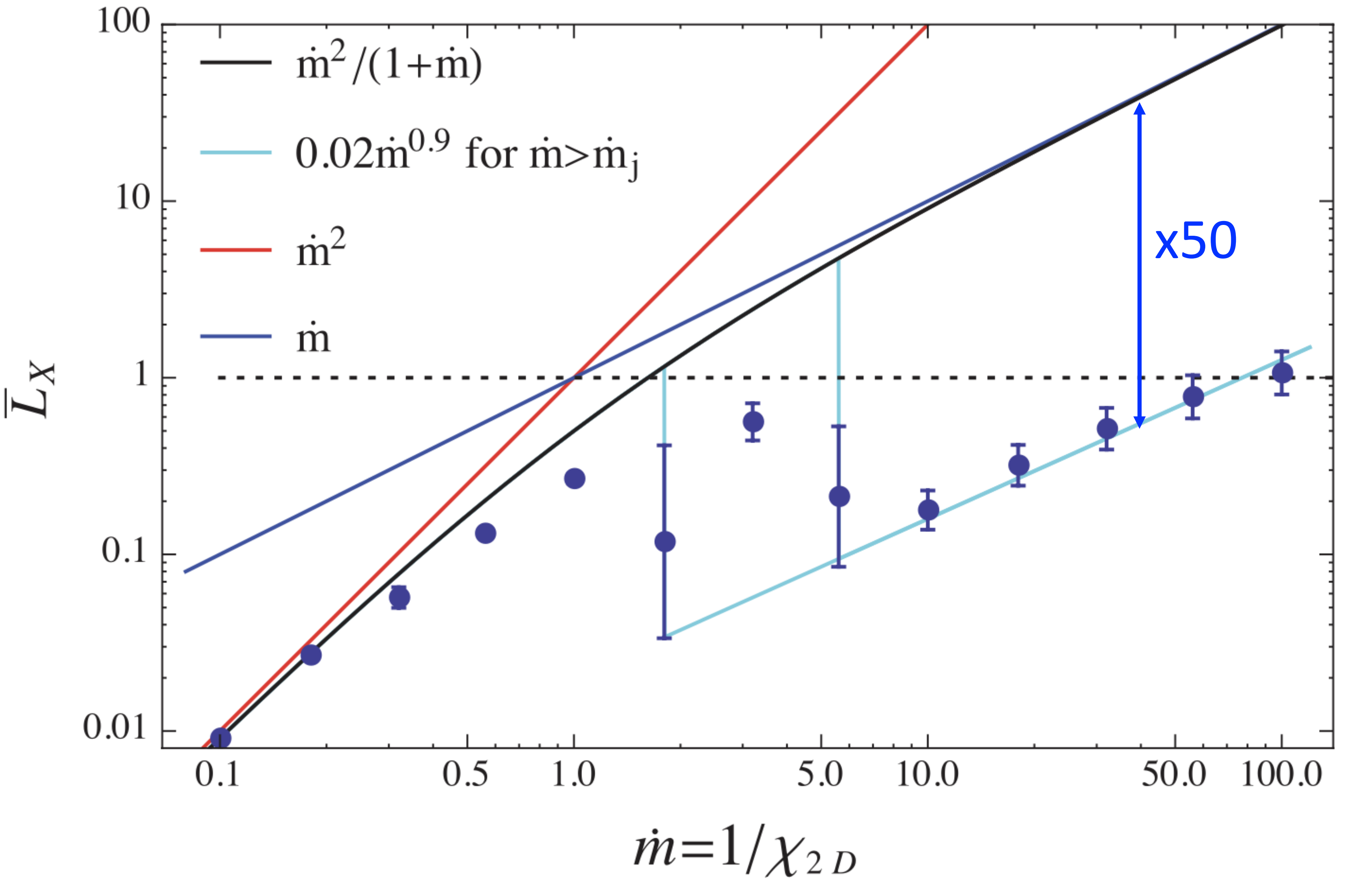
$$\chi = \frac{t_{\rm cool}}{t_{\rm esc}} \approx \frac{v_8^4 \, d_{12}}{\dot{M}_{-7}} ,$$

but for $\dot{m} \gg 1$, thin-shell gives

$$\frac{L_x}{L_{KE}} \approx \frac{\dot{m}}{50}$$

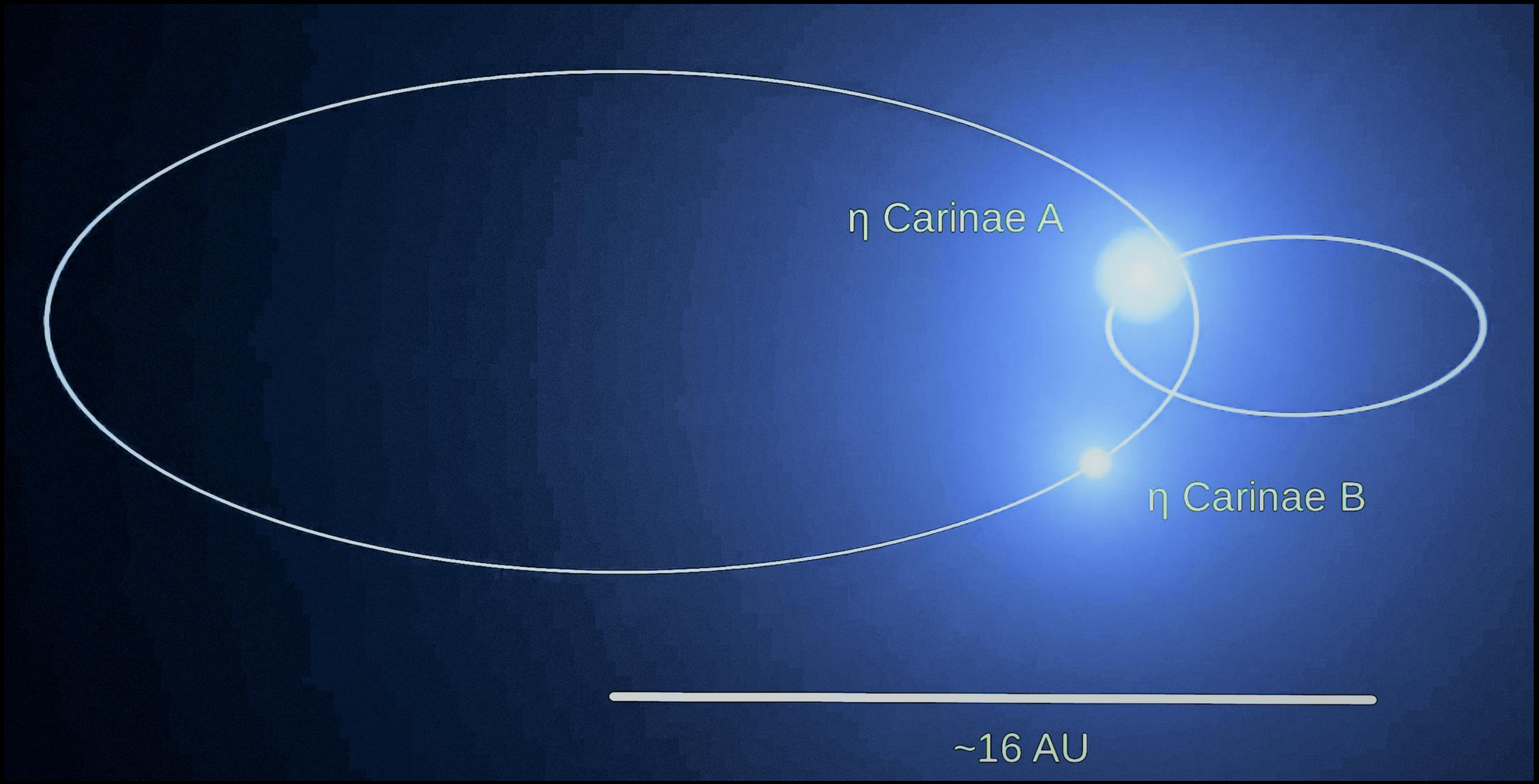


ṁ=0.1
ṁ=1
ṁ=10
ṁ=100
log (ρ/ρ$_0$)
1
0
-1
T (MK)
30
20
10
0
η /η$_{KE}$
0.1
0.05
0
y/d
x/d
-1
0
1
2



100
10
1
0.1
0.01
$\bar{L}_X$
$\dot{m}^2/(1+\dot{m})$
$0.02\dot{m}^{0.9}$ for $\dot{m}>\dot{m}_j$
$\dot{m}^2$
$\dot{m}$
x50
0.1
0.5
1.0
5.0
10.0
50.0
100.0
$\dot{m}=1/\chi_{2D}$

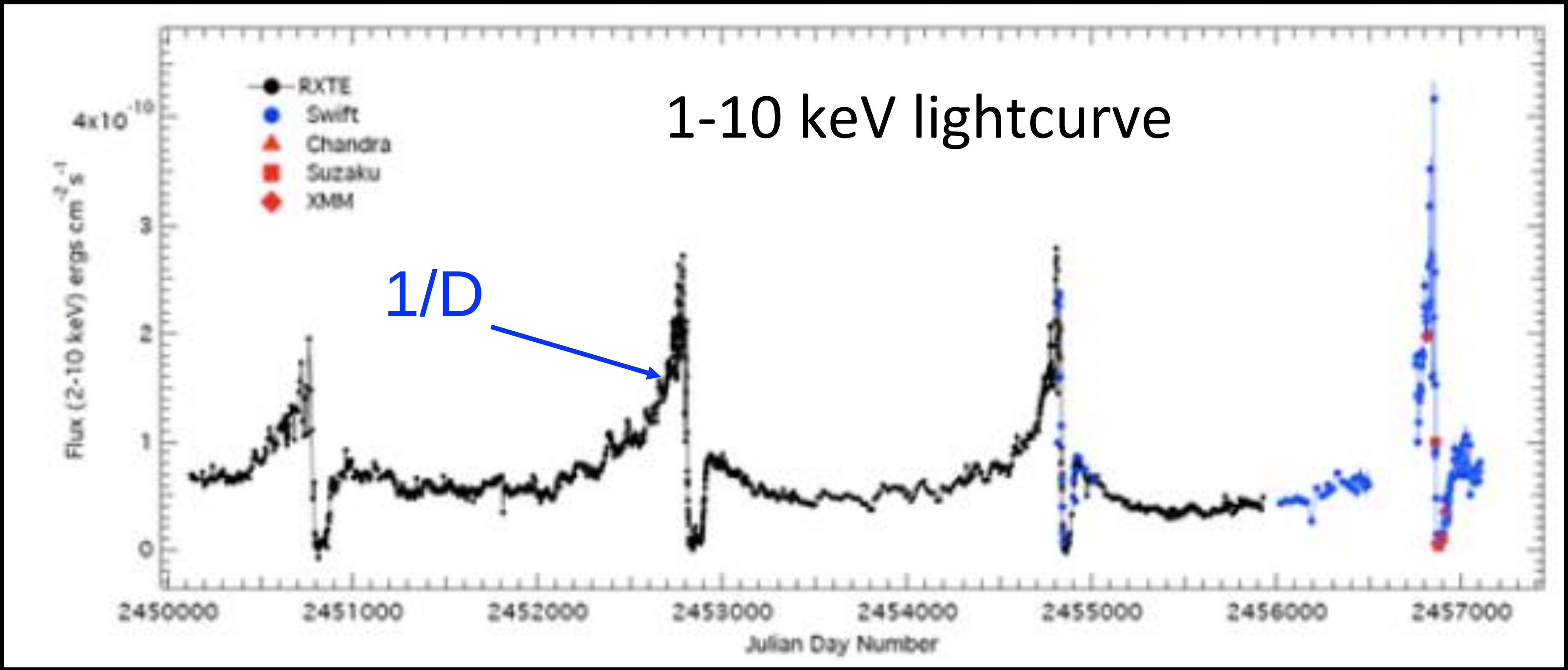
Colliding winds in eta Carinae



5.54 yr (2023 d) binary, a~16au, e=0.9

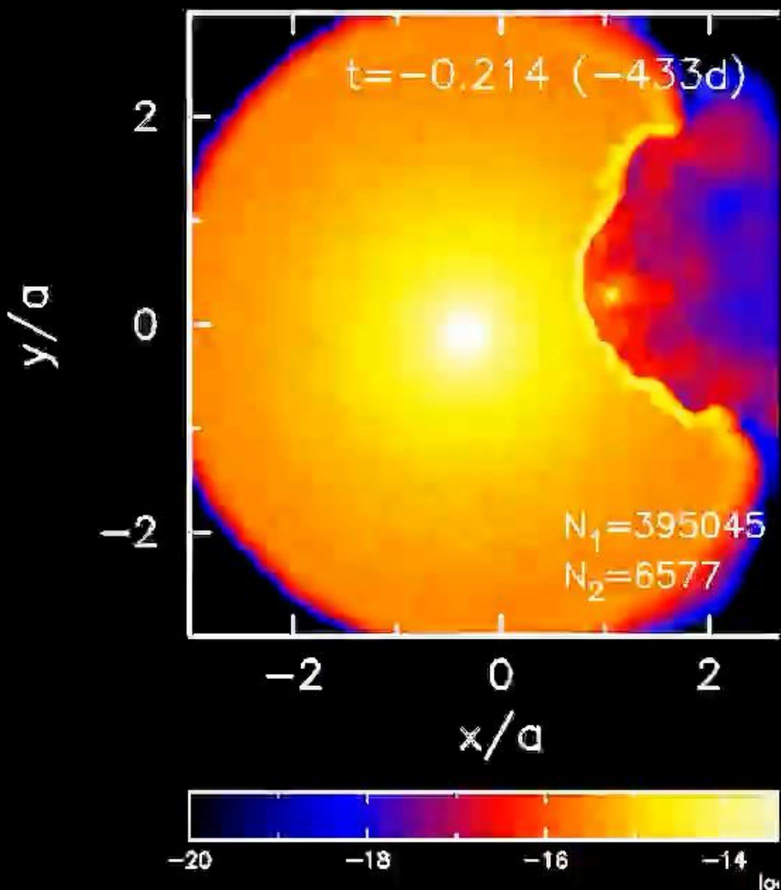
$M_A + M_B \sim 130\ M_\odot$

5.54 yr (2023 d) binary

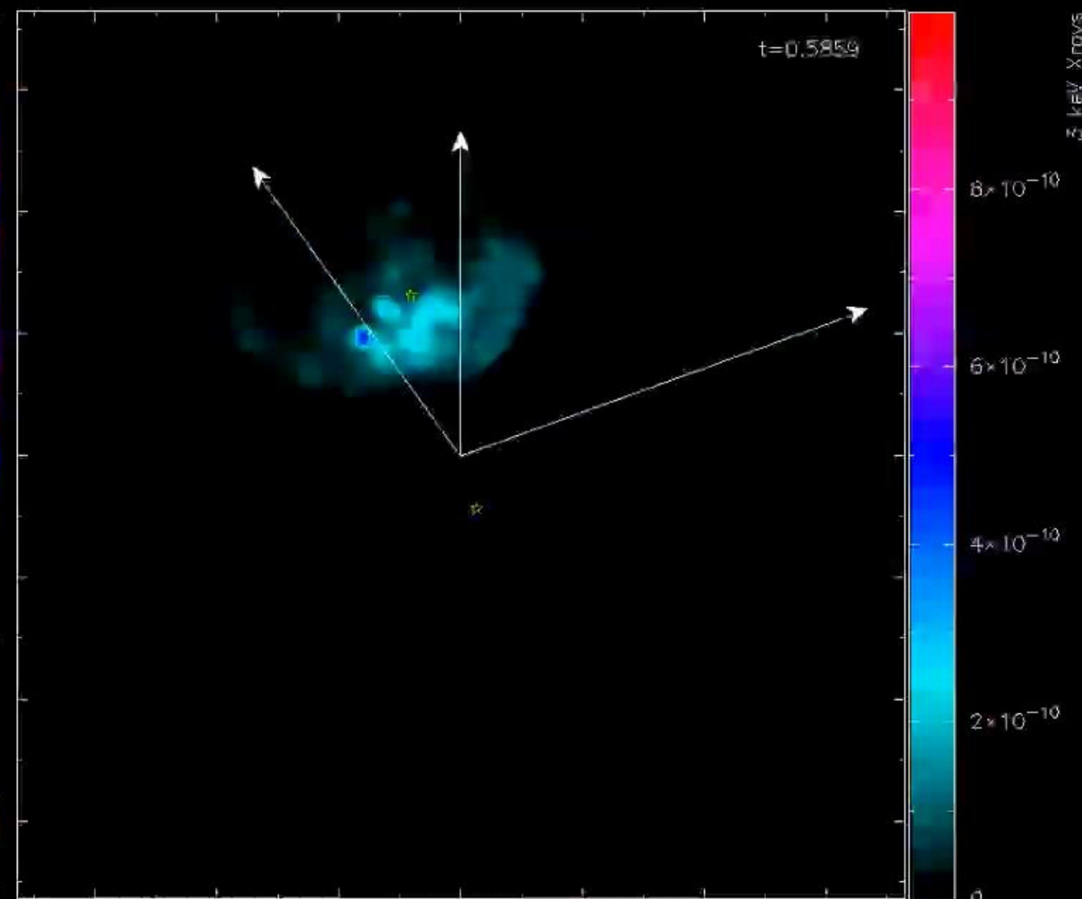


1998 2003 2009 2014

density

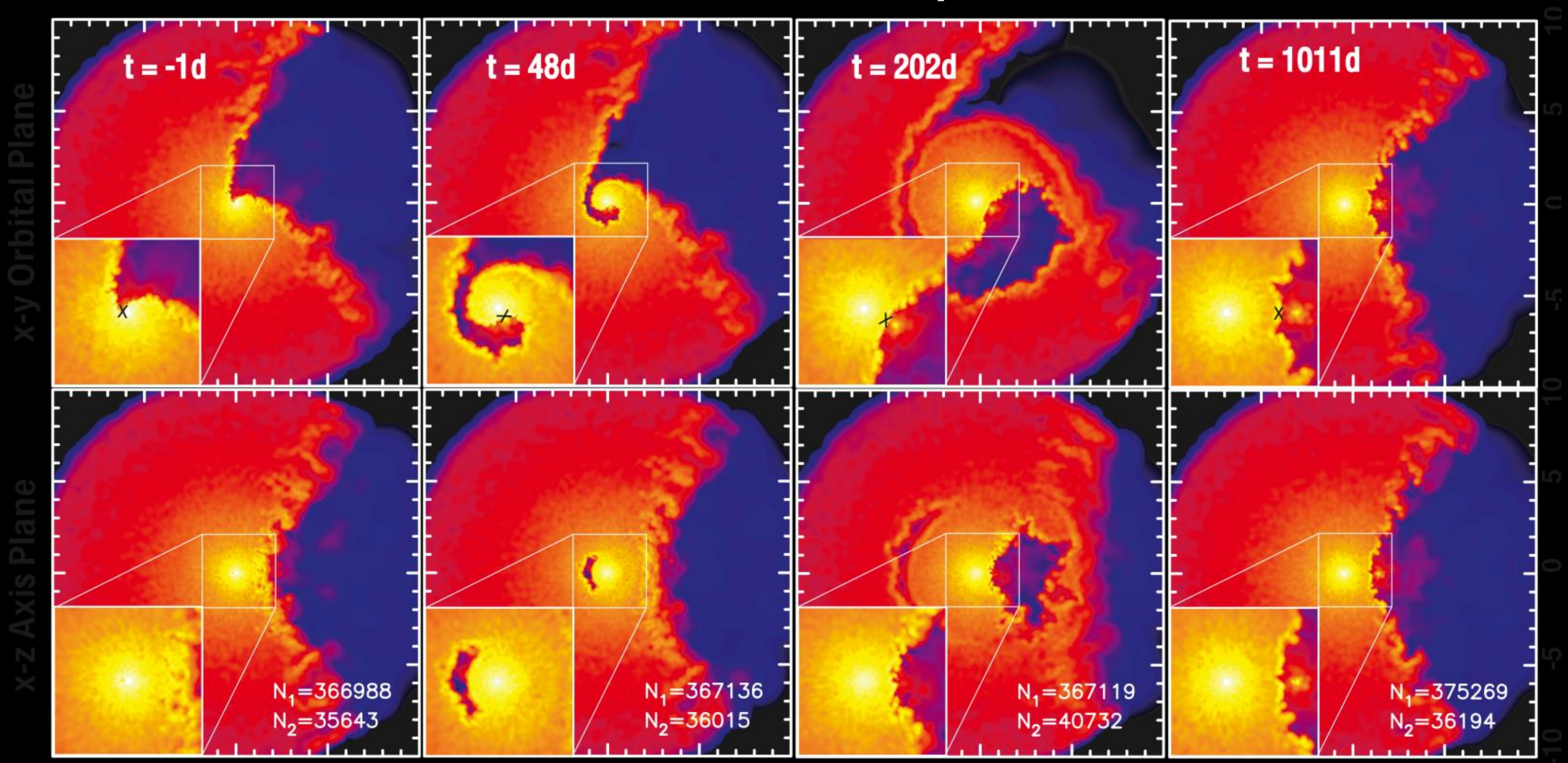


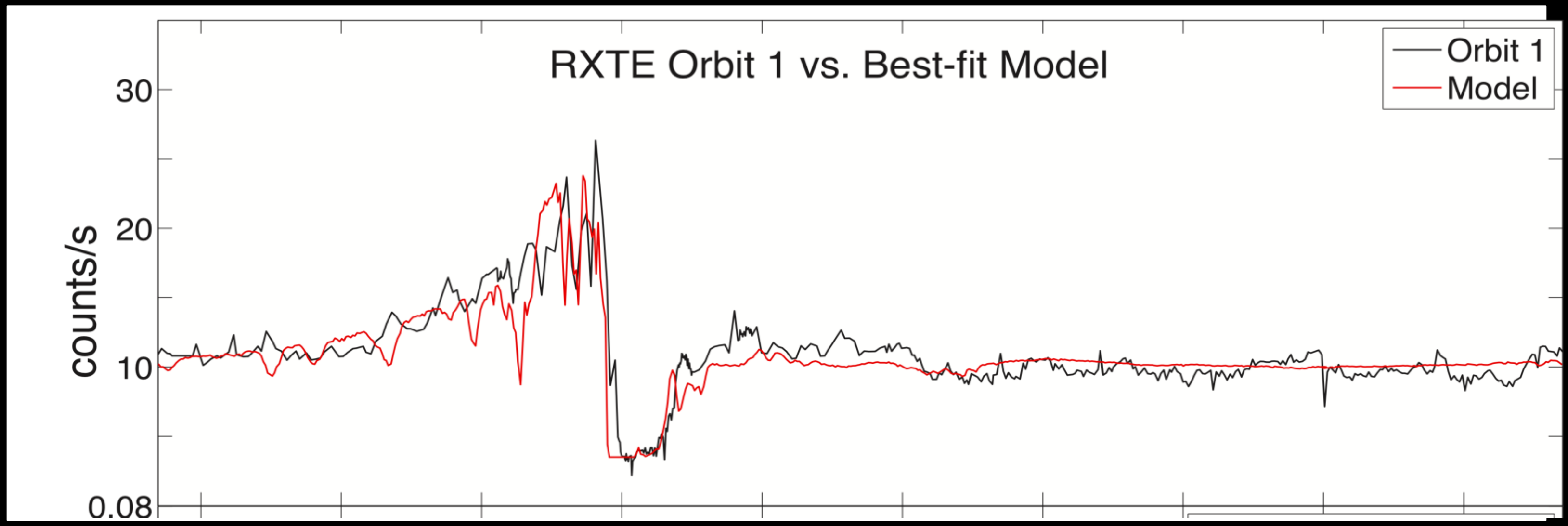
X-rays



courtesy C. Russel

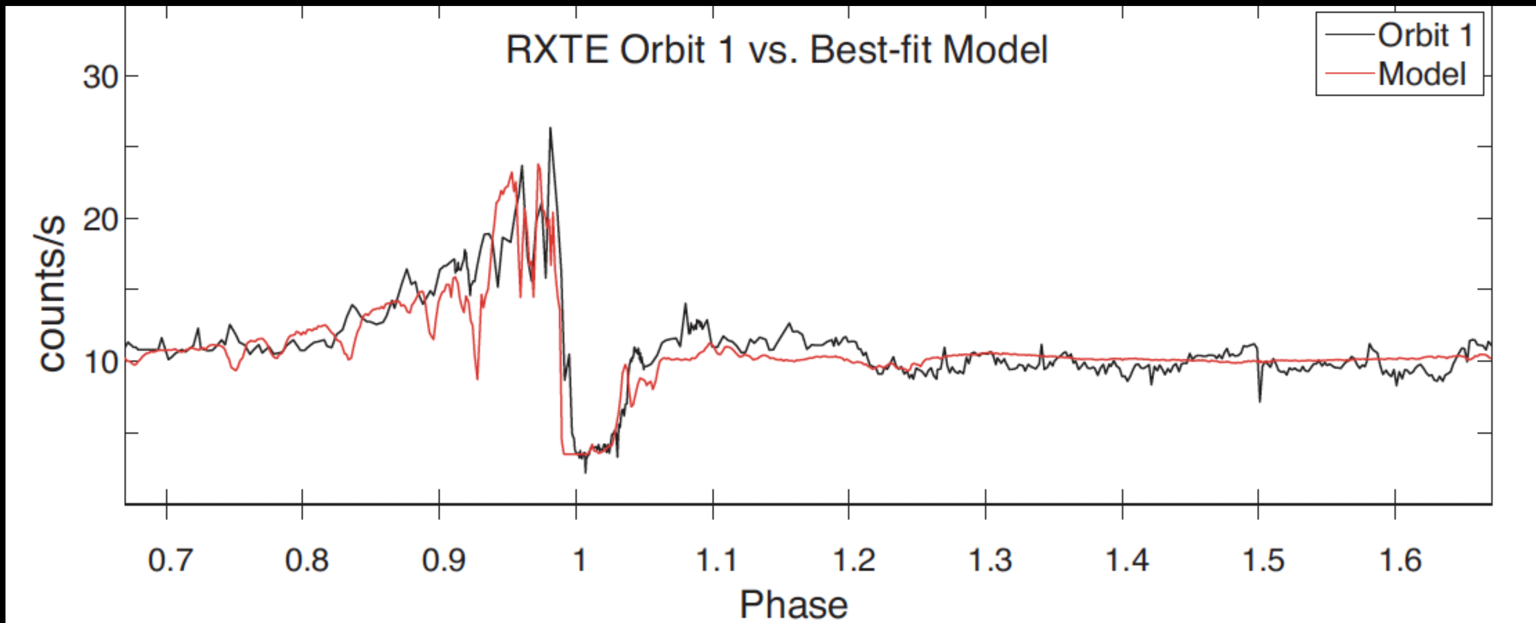
3D SPH sim of η Car CWB





1-10 kev X-ray lightcurve from 5.54 yr (2023 d) binary

C. Russel, UDel Ph.D. thesis 2014



$$\dot{M}_A = 10^{-3}\,\frac{M_\odot}{\mathrm{yr}} \qquad \dot{M}_B = 10^{-5}\,\frac{M_\odot}{\mathrm{yr}}$$

$$V_A = 600\,\frac{\mathrm{km}}{\mathrm{s}} \qquad V_B = 3000\,\frac{\mathrm{km}}{\mathrm{s}}$$

$$L_A = 5\times 10^6 L_\odot \qquad L_B < 10^6 L_\odot$$

Star B likely a stripped WR star

X-rays from single OB Stars

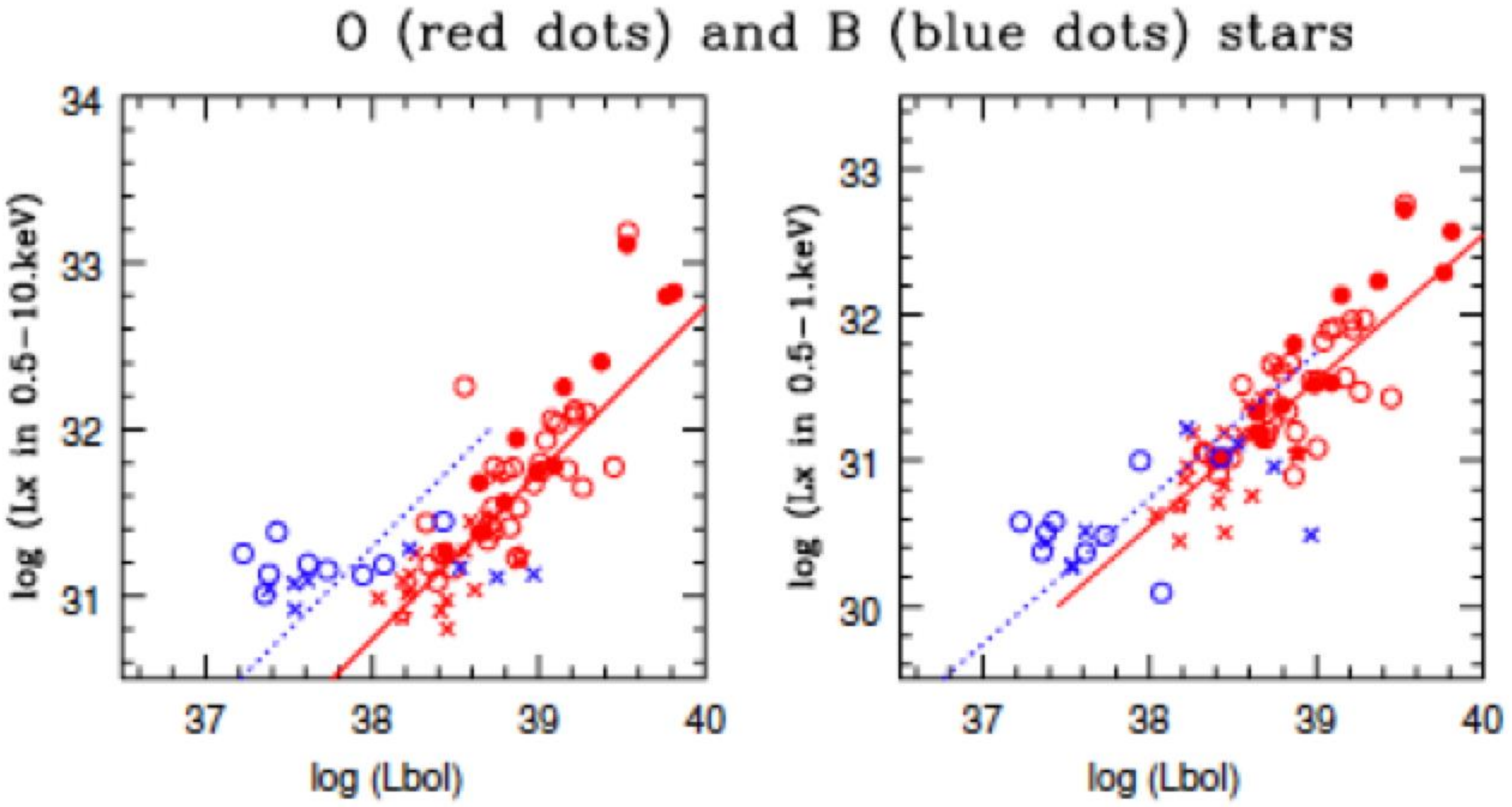
- Single O-stars emit soft (~0.5 kev) X-rays
- Thought to arise from Embedded Wind Shocks
- EWS arise from intrinsic Line-Driving Instability

- Observed scaling is $L_x \sim 10^{-7} L_{bol}$
- EWS theory predicts $L_x \sim M_{dot}/V_\infty \sim (L_{bol})^{1.7}$

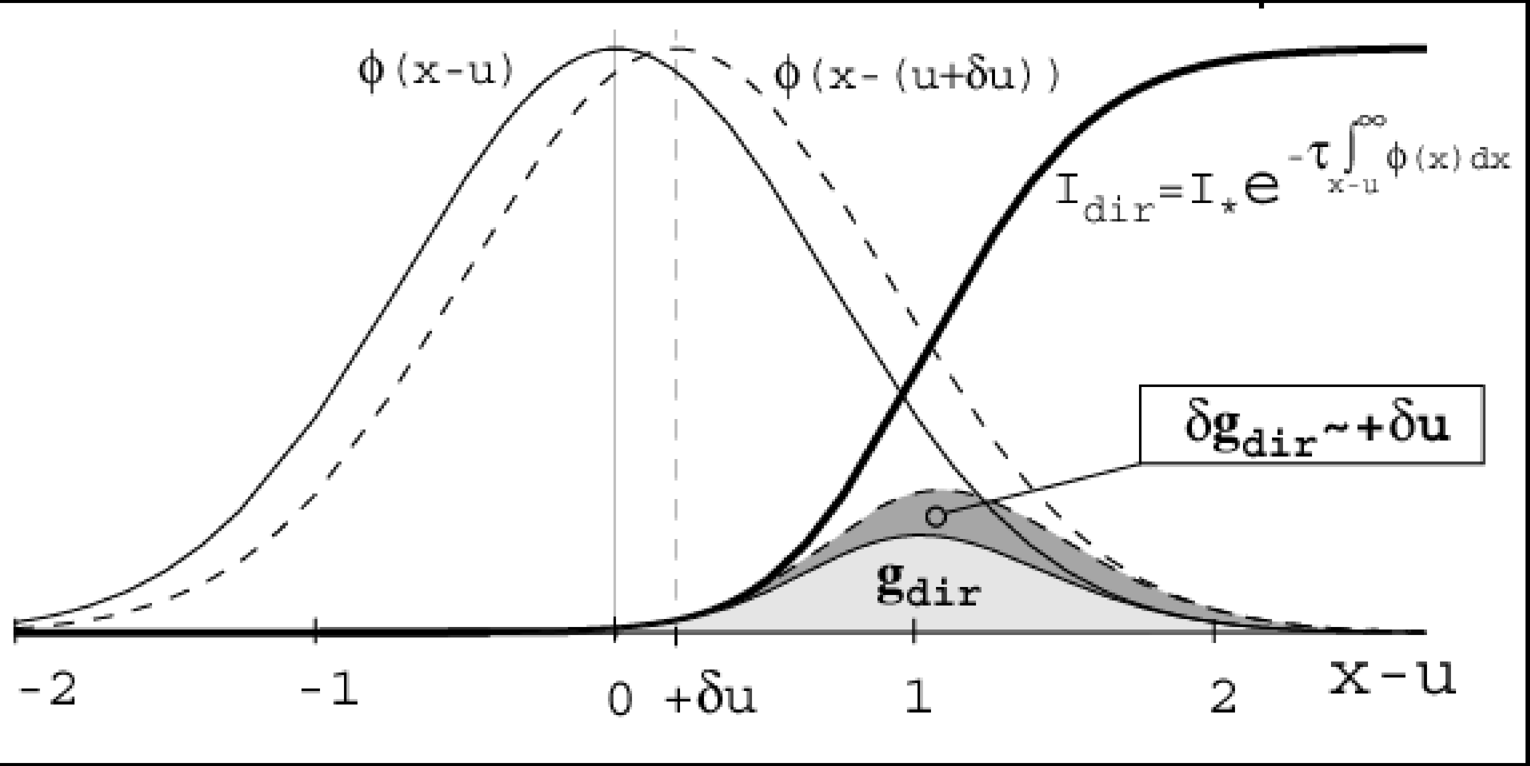
- Reconcile here with "thin shell mixing" of shocks

$L_x \sim 10^{-7} L_{bol}$ for Chandra observations of Carina OB stars

Naze et al. 2011



Line-Deshadowing Instability



for $\lambda < L_{sob}$:

$i\omega = \delta g / \delta v$

$= +g_o / v_{th} = \Omega$

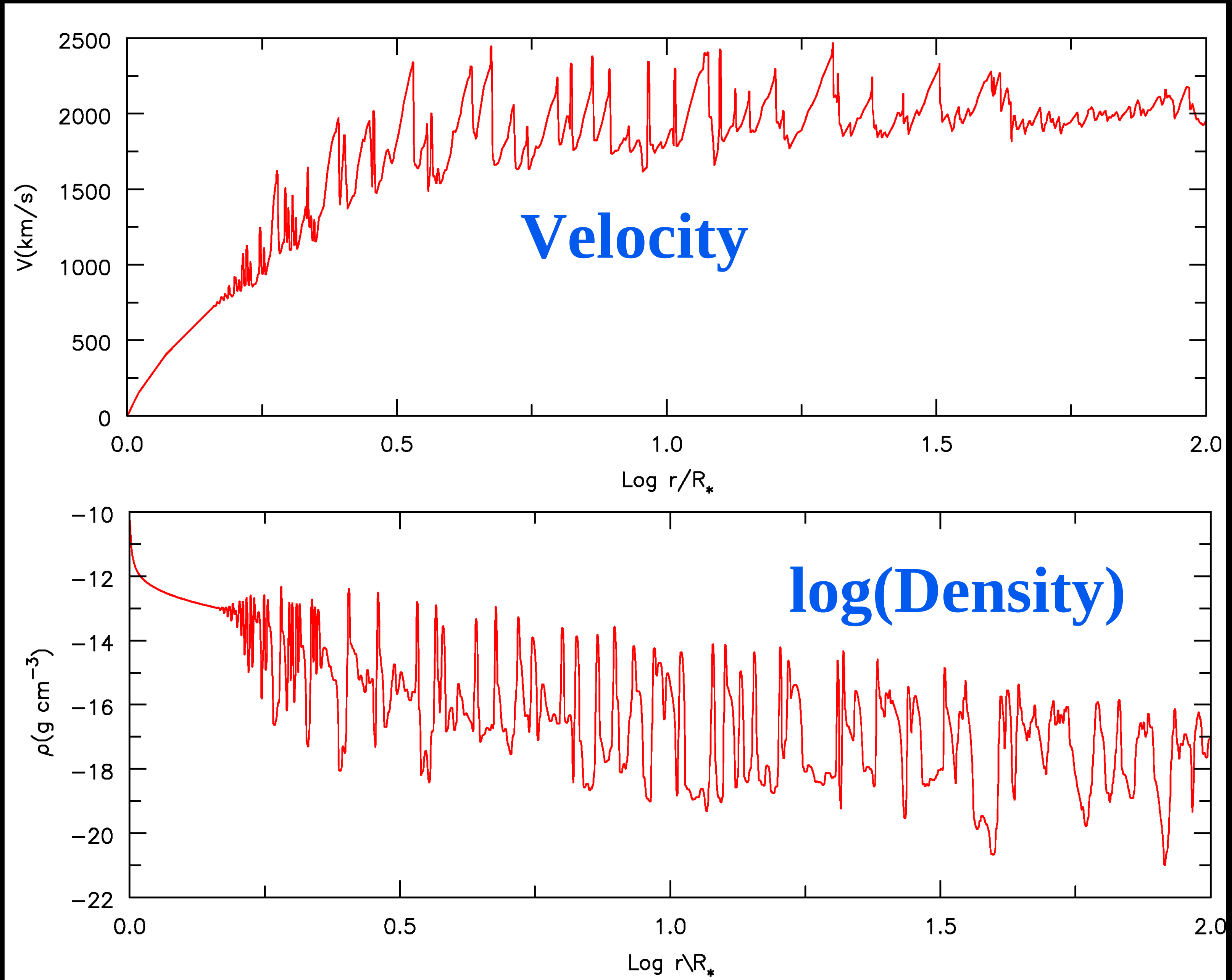
→

Instability with growth rate

$\Omega \sim g_o/v_{th} \sim v v'/v_{th} \sim v/L_{sob} \sim 100\ v/R$

e^{100} growth!

Time snapshot of wind structure vs. radius

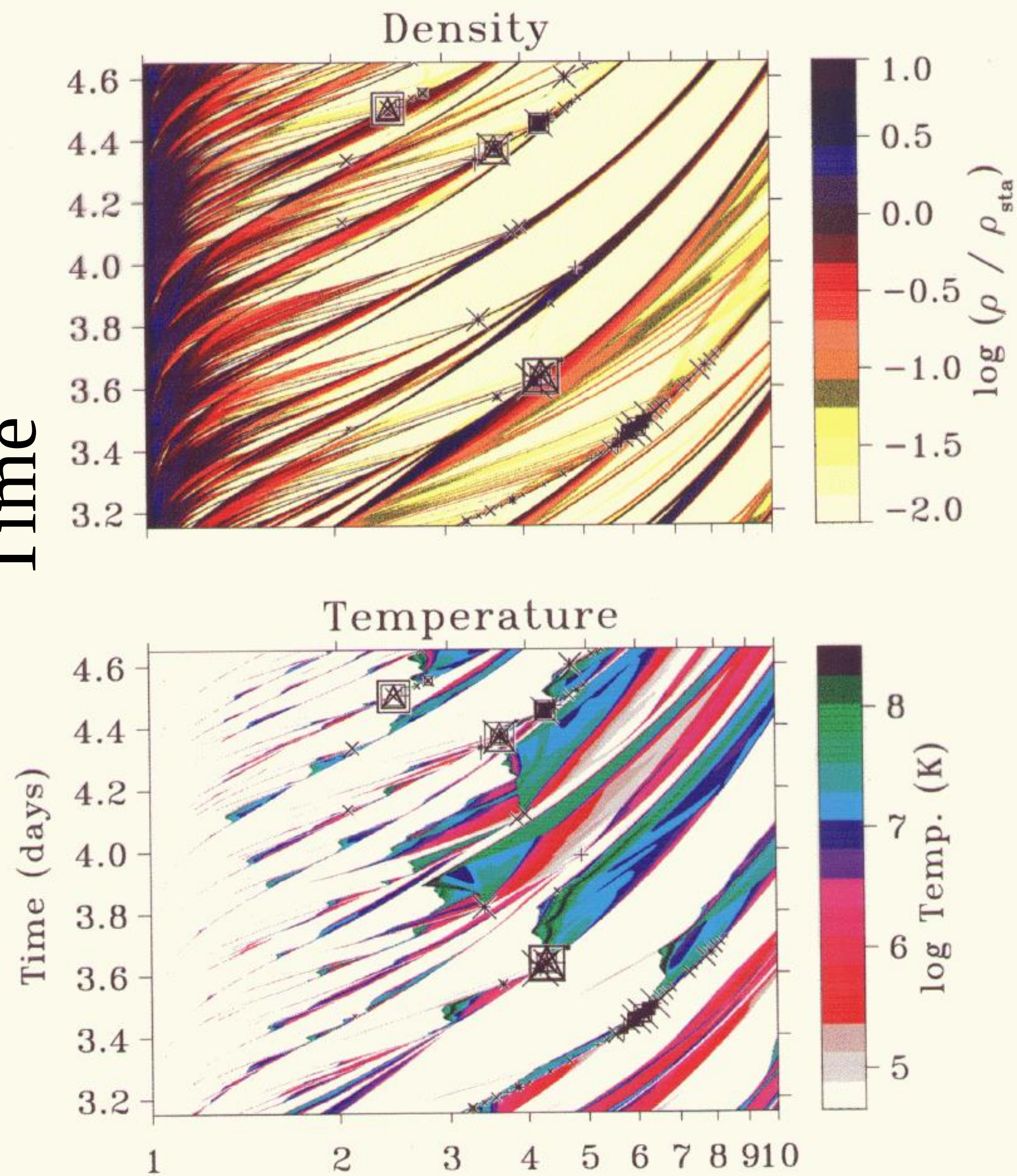


Turbulence-seeded clump collisions

Enhances V_{disp} and thus X-ray emission

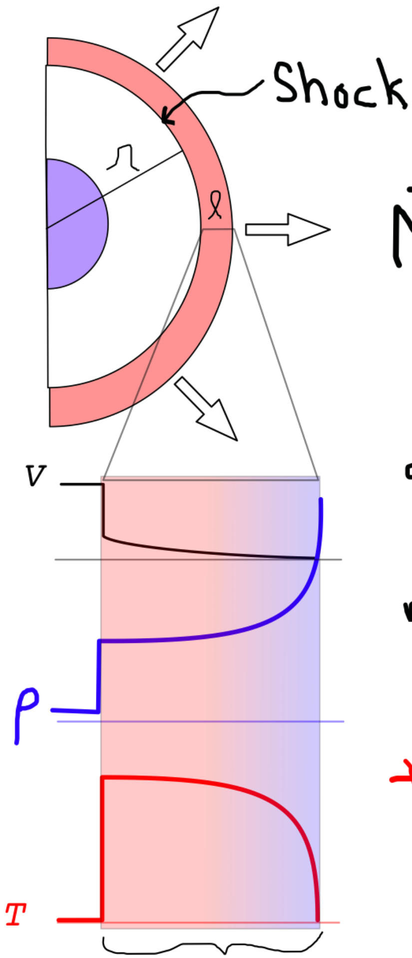
Feldmeier et al. 1997

Time



Radius

Shock cooling & thin-shell mixing



$\ell \sim \frac{m_s}{\rho} \sim \frac{1}{\dot M}$

$\dot M \sim L_{Bol}^{1/\alpha} \sim L_{Bol}^{1.7}$ $\qquad L_x \sim f_x \dot M \Delta v^2$

adiabatic $\ell \gg r$ $\qquad f_x \sim \frac{r}{\ell} \Rightarrow$ $\qquad L_x \sim \dot M^2 \sim L_{Bol}^{3.4}$

radiative $\ell \ll r$ $\qquad f_x \sim$ const. $\qquad L_x \sim \dot M \sim L_{Bol}^{1.7}$

+

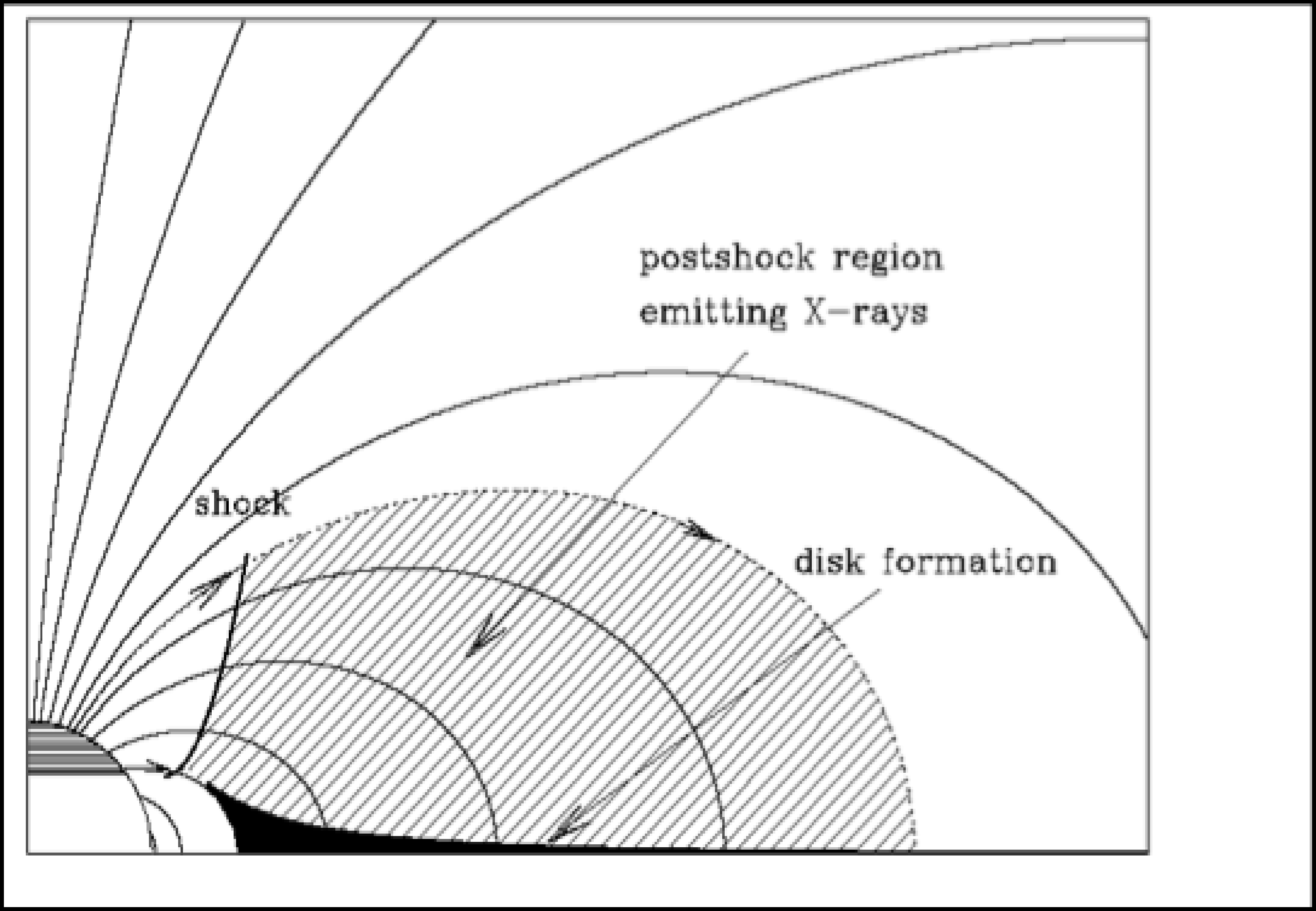
thin-shell mixing $\qquad f_x \sim \left(\frac{\ell}{r}\right)^m$ $\qquad L_x \sim \dot M^{1-m} \sim L_{Bol}^{\frac{1-m}{\alpha}}$

if $m \simeq 1-\alpha \simeq 0.4$

$$L_x \sim L_{Bol}^{\frac{1-m}{\alpha}} \sim L_{Bol}$$

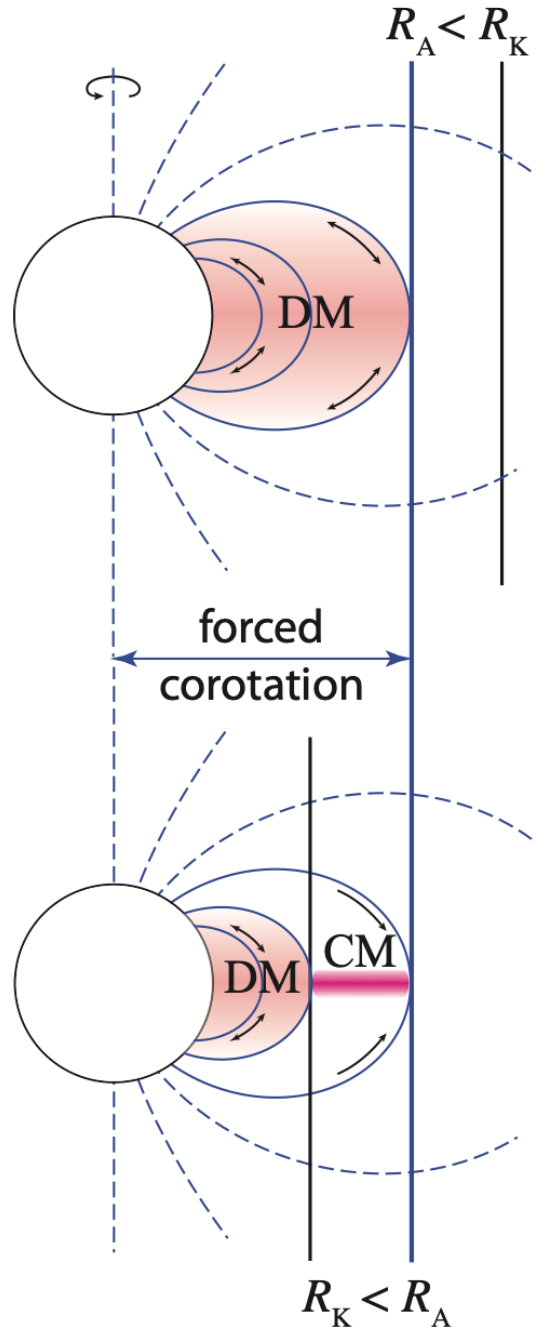
X-rays from Magnetically Confined Wind-Shocks

Babel & Montmerle 1997



Dynamical
Magnetospheres
$R_A < R_K$

Centrifugal
Magnetospheres
$R_K < R_A$

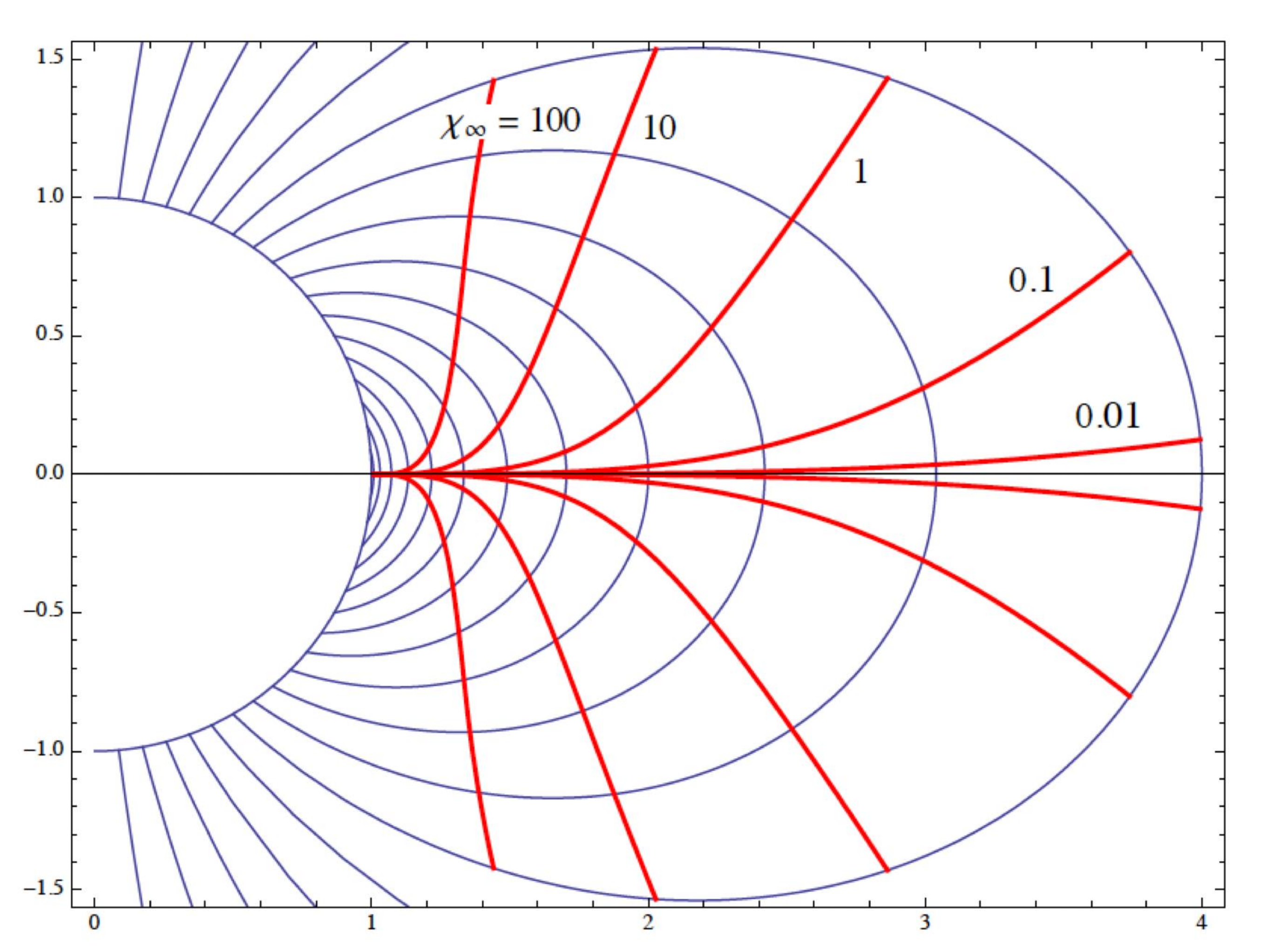


Shock retreat in a DM

χ_∞ measures in cooling inefficiency

$$\chi_\infty \equiv \frac{15\pi}{128}\,\frac{V_\infty^4 R_*}{\dot{M}\Lambda_m}$$

$$\approx 0.034\,\frac{V_8^4\,R_{12}}{\dot{M}_{-6}}$$



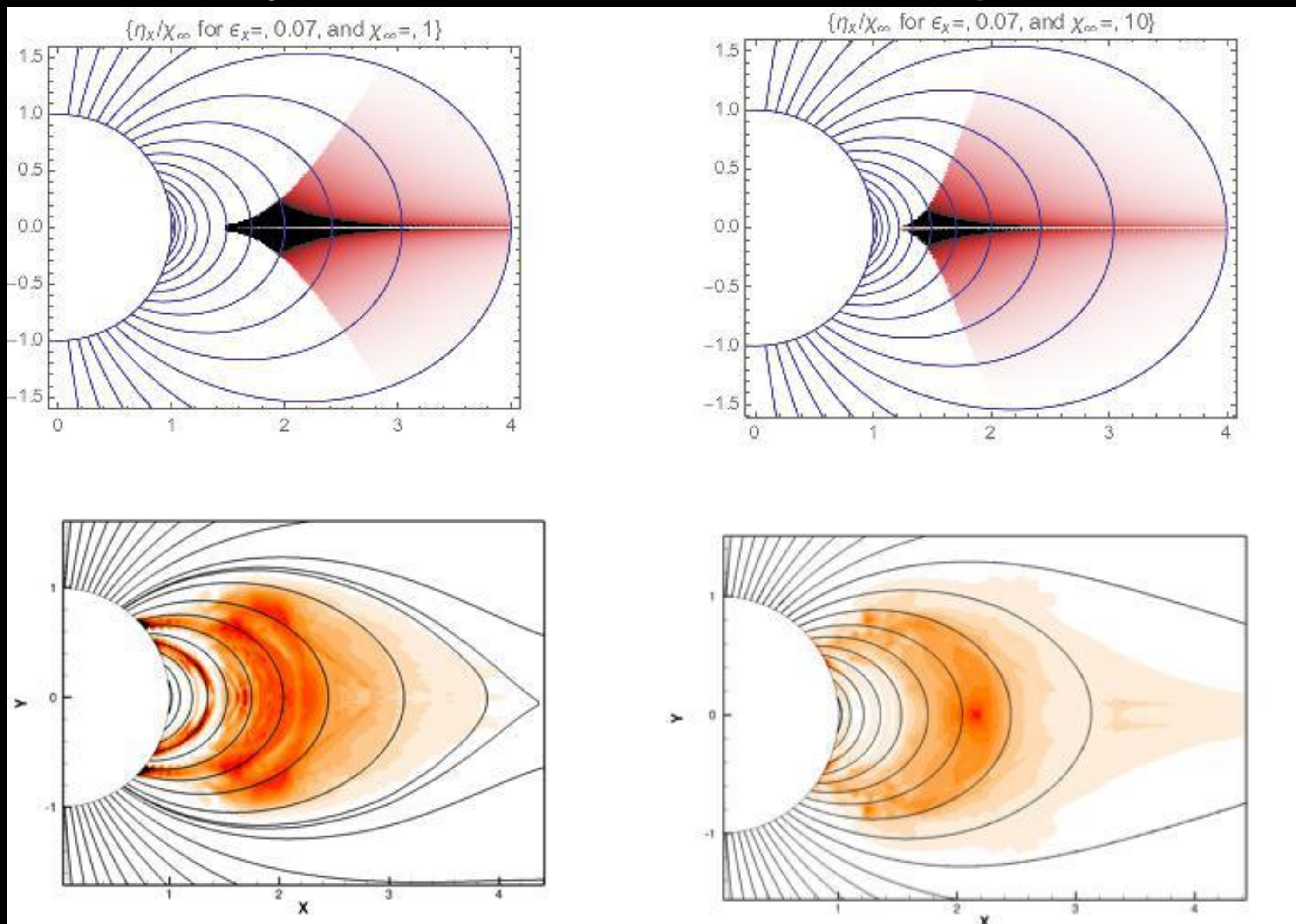
ADM vs. MHD: X-ray emissivity

moderate cooling — weak cooling

$\chi_\infty = 1$ — $\chi_\infty = 10$

ADM

MHD



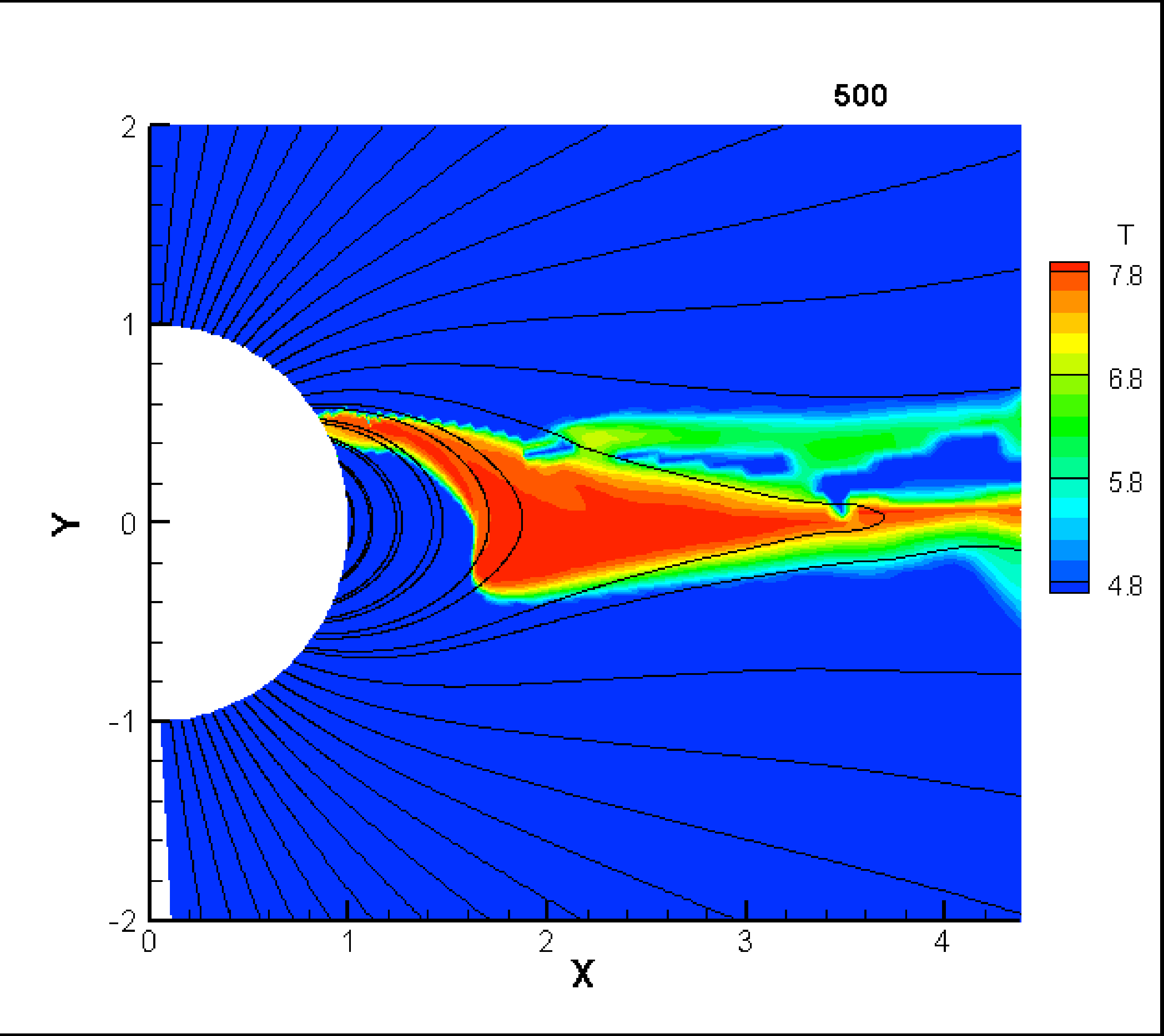
Magnetically Confined Wind Shocks

log T

no
rotation
but now with
Radiative
Cooling

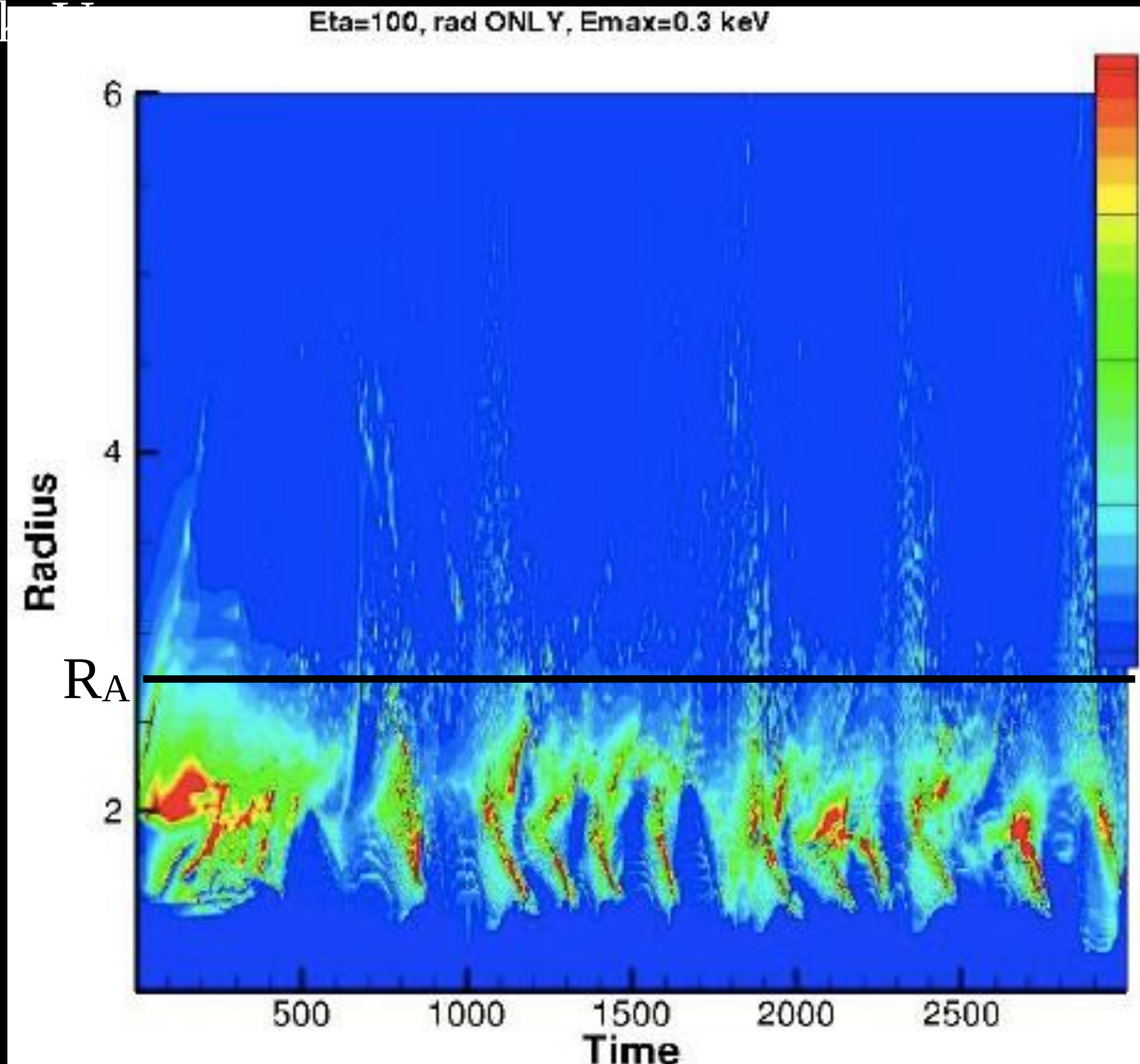
~ 2 kev
X-rays fit
Chandra
spectrum

for Θ^1 Ori C

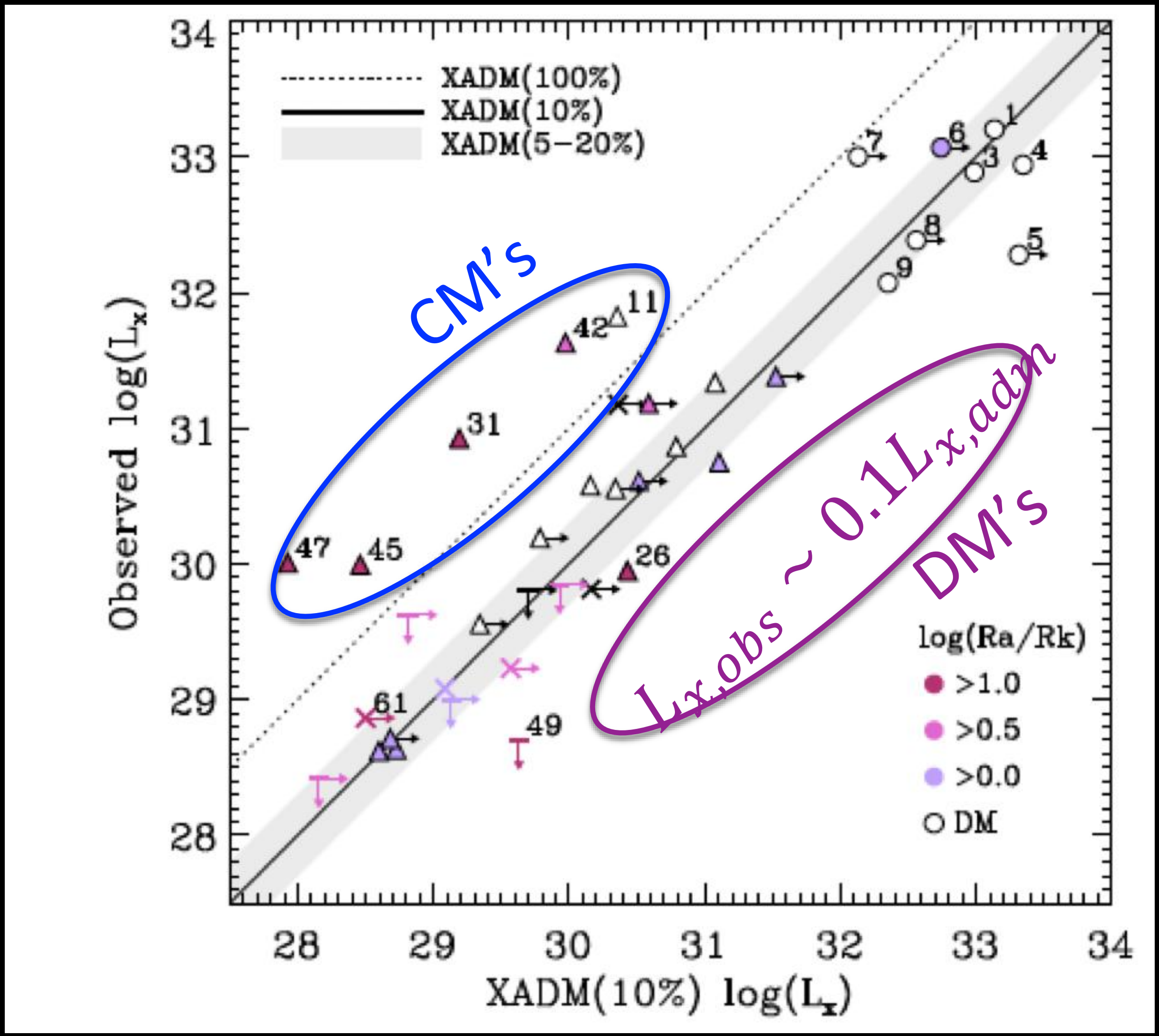


2D MHD: energy w/ rad cooling

r,t variation of (theta-averaged) X-rays > 0.3 keV



Lx vs. Mdot: obs. vs. XADM theory



Naze' et al. 2014

Cuadra+08
Cuadra+15

Hydro models of wind collisions in gc cluster

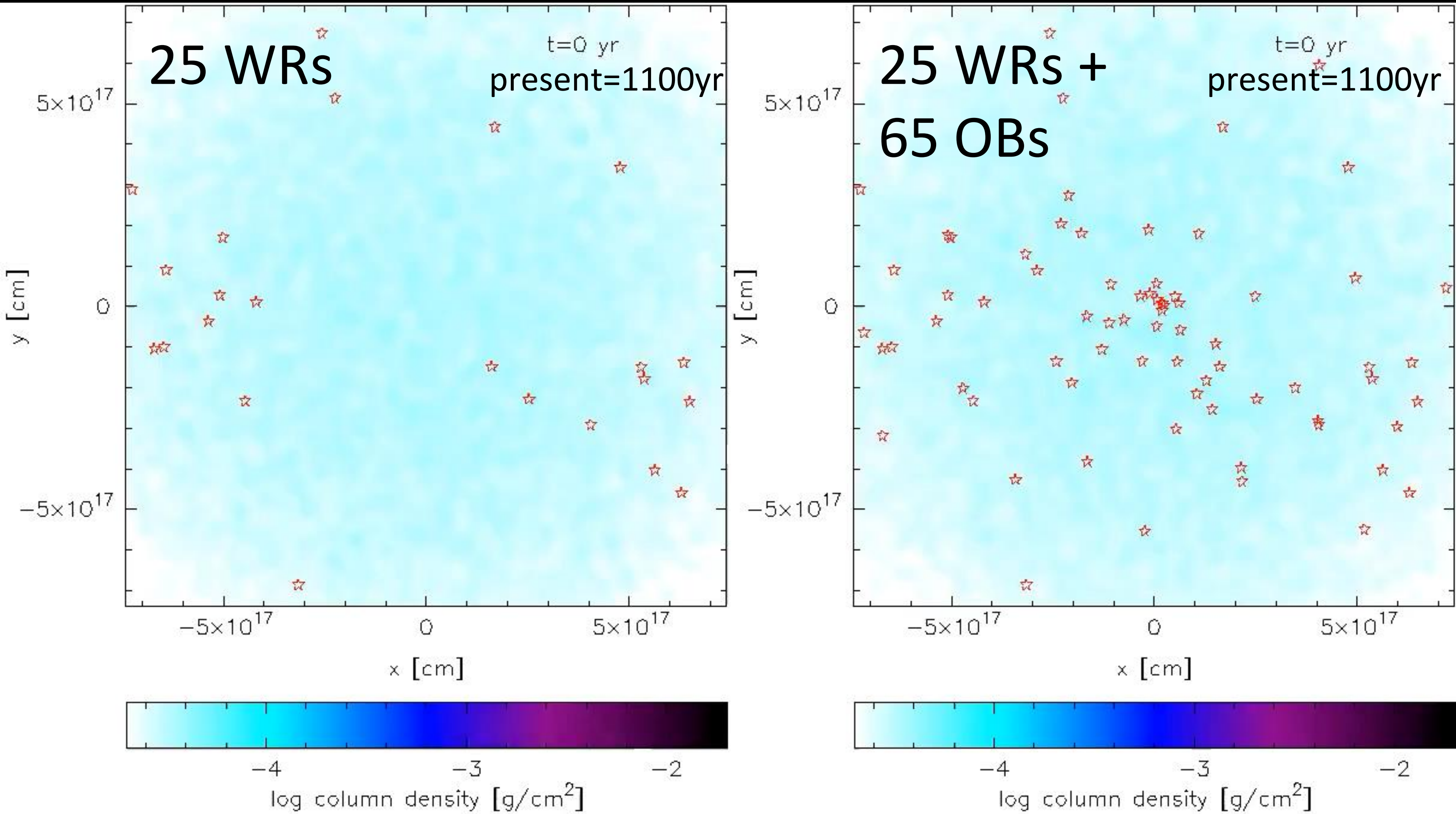
- ~30 Wolf-Rayet stars
- 60+ earlier massive stars

} smorgasbord of colliding winds

- Input constraints: orbital and wind properties from infrared
  Paumard+06, Martin+07, Gillessen+17
  Outbursts from Sgr A* Ponti+10, Clavel+13, Chuard+18

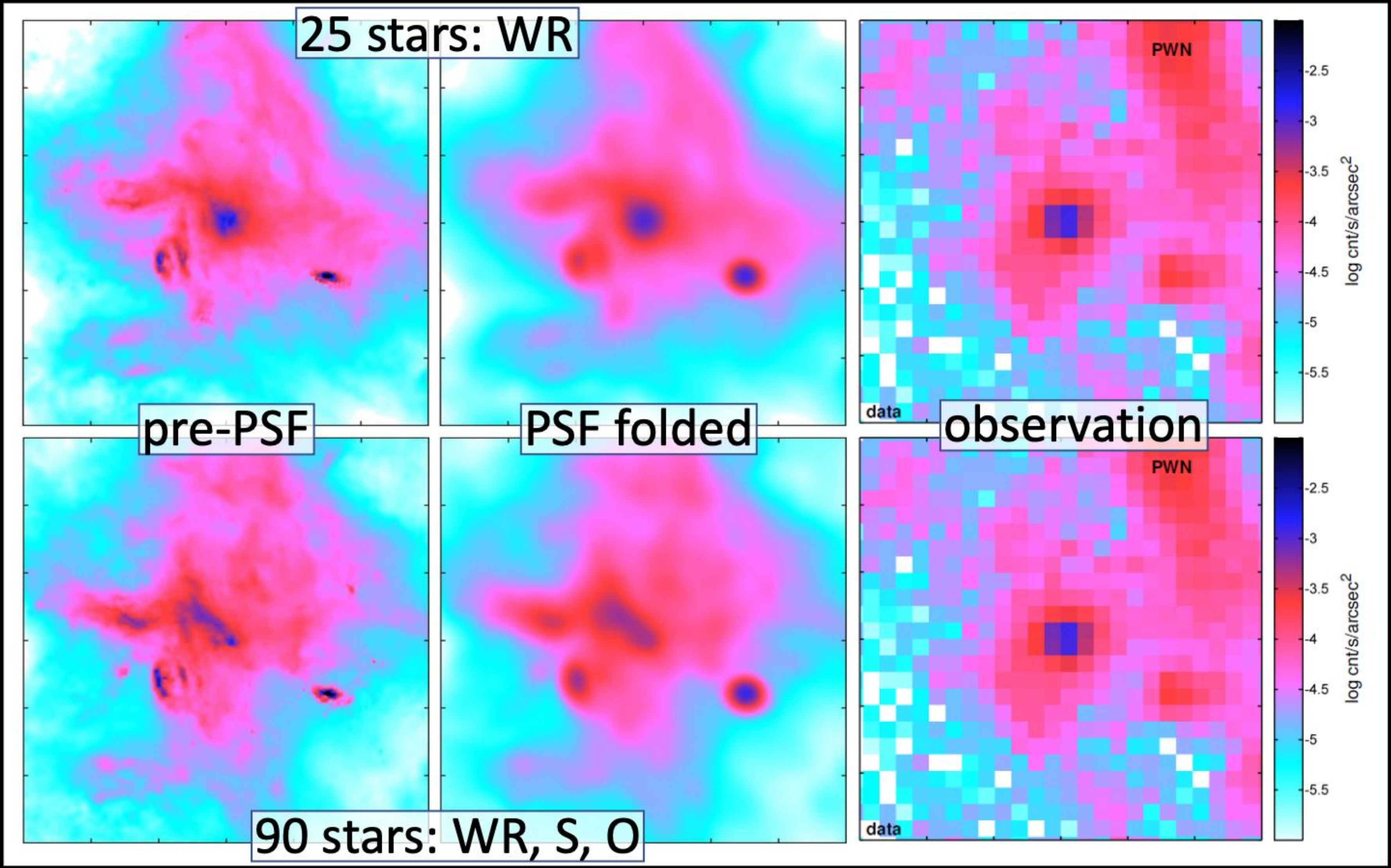
- Hydro simulation → Result is ρ and T in central parsec

- Output constraints: thermal X-ray emission from Chandra
  Wang+13


25 WRs
t=0 yr
present=1100yr
25 WRs +
65 OBs
t=0 yr
present=1100yr
5×10^{17}
0
-5×10^{17}
y [cm]
x [cm]
log column density [g/cm^2]
-4
-3
-2

X-rays – 25 vs 90 stars

4-9 keV HETG 0th-order
1pc x 1pc



Summary

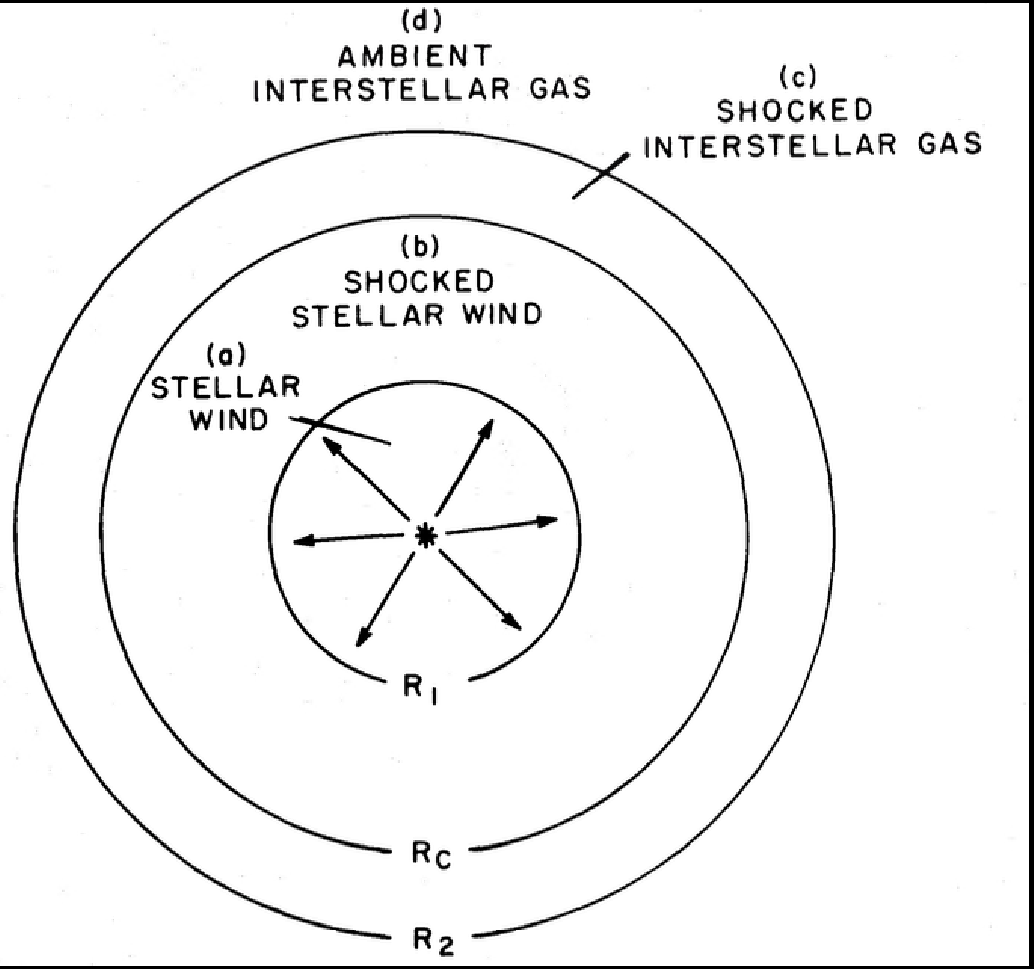
- Colliding wind X-rays
  - $E_x \approx \text{kev}(V/1000)^2$; $L_x \lesssim L_{wind} \equiv \dot{M}V_\infty^2/2$

- Embedded wind shock X-rays
  - $E_x \approx 0.5\text{kev}$; $L_x \sim 10^{-7} L_{bol} \sim L_{bol}^{(1-m)/\alpha}$

- Magnetically Confined Wind Shocks
  - $E_x \approx (1-2)\text{kev}$; $L_x \sim 0.1 L_{XADM}$

- Galactic center wind cluster X-rays

Weaver+ 1977


(d)
AMBIENT
INTERSTELLAR GAS
(c)
SHOCKED
INTERSTELLAR GAS
(b)
SHOCKED
STELLAR WIND
(a)
STELLAR
WIND
R1
RC
R2

Questions for cluster wind models

- How do multiple wind collisions turn into "superwind"
  - $T_x \approx 10\text{MK}(V/1000)^2$; $V_w \approx 3000 km/s$
  - driven by radiation or gas pressure?
  - latter should be adiabatically cooled
  - origin of B-field; O vs WR
  - slow rotation weakens Parker spiral

- Role of Radiative Cooling
  - Adiabatic shocks: "Energy driven"
  - Radiative shocks: "Momentum driven"
  - But how can $\chi \equiv t_{cool}/t_{exp} \approx v_8^4 d_{12}/\dot{M}_{-7}$ be <1?
  - e.g. d~pc~3e18 cm => $\chi \approx 3000 v_8^4/\dot{M}_{-4}$
  - mass loading from clumpy ISM??