The Properties of Winds from Massive Stars

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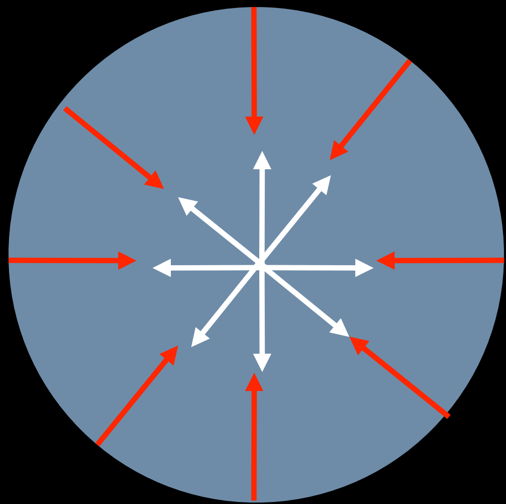
& many more...

Key properties of massive-star winds

- $M_{dot} \sim 10^{-10}$-10^{-4} M_{sun}/yr;
  - $V_{inf} \sim 3\ V_{esc} \sim$ 1000-3000 km/s
- sometimes (e.g. Be stars) rotationally distorted
  - polar wind & equatorial "decretion disk"
- highly clumped & moderately "porous"
  - filling factor $f_{vol} \sim 0.1$
  - mfp ~ "porosity length" $h \sim \ell/f_{vol} \sim$ 1-10% R_*

Radiative force vs. gravity

Radiative Force



Gravitational Force

$$g_{rad} = \int_0^\infty d\nu \, \frac{\kappa_\nu F_\nu}{c}$$

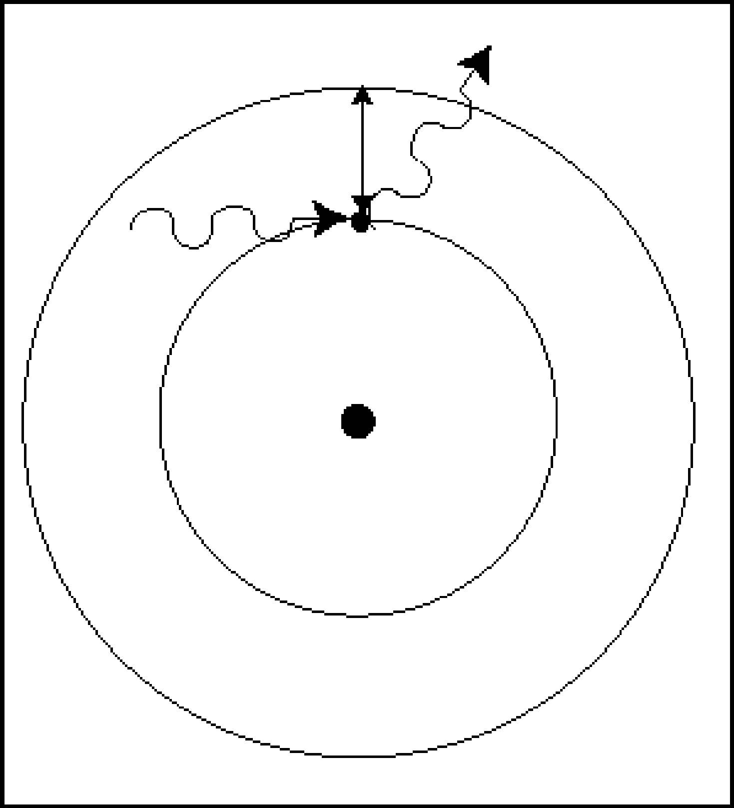
$$\frac{GM}{r^2}$$

$$\Gamma_e \equiv \frac{g_e}{g} = \frac{\kappa_e L / 4\pi r^2 c}{GM / r^2} = \frac{\kappa_e L}{4\pi GMc}$$

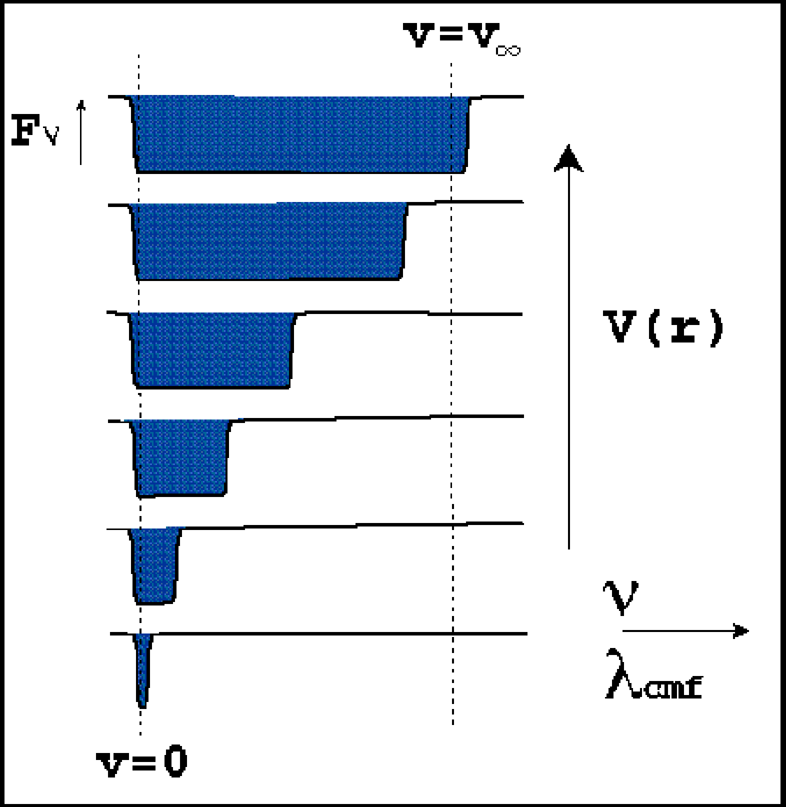
$$\Gamma \simeq 2 \times 10^{-5} \frac{L / L_\odot}{M / M_\odot} \frac{\overline{\kappa_F}}{\kappa_e}$$

Driving by Line-Opacity

Optically thin



Optically thick



$$\Gamma_{thin} \sim Q\Gamma_e \sim 1000\,\Gamma_e$$

$$\Gamma_{thick} \sim \frac{Q\Gamma_e}{\tau} \sim \frac{1}{\rho}\frac{dv}{dr}$$

CAK model of steady-state wind

Equation of motion:

$$\mathrm{v}\mathrm{v}' \approx -\frac{GM(1-\Gamma)}{r^2} + \frac{\overline{Q}L}{r^2}\left(\frac{r^2\mathrm{v}\mathrm{v}'}{\dot{M}\overline{Q}}\right)^{\alpha}$$

$0<\alpha<1$

CAK ensemble of thick & thin lines

inertia ≈ gravity ≈ CAK line-force

g_{CAK} ≈ gravity

Mass loss rate

$$\dot{M} \approx \frac{L}{c^2}\left(\frac{\overline{Q}\Gamma}{1-\Gamma}\right)^{\frac{1}{\alpha}-1}$$

inertia ≈ gravity

Velocity law

$$\mathrm{v}(r) \approx \mathrm{v}_\infty (1-R_*/r)^\beta \qquad \beta \approx 0.8$$

$\sim \mathrm{v}_{esc}$

Wind-Momentum Luminosity law

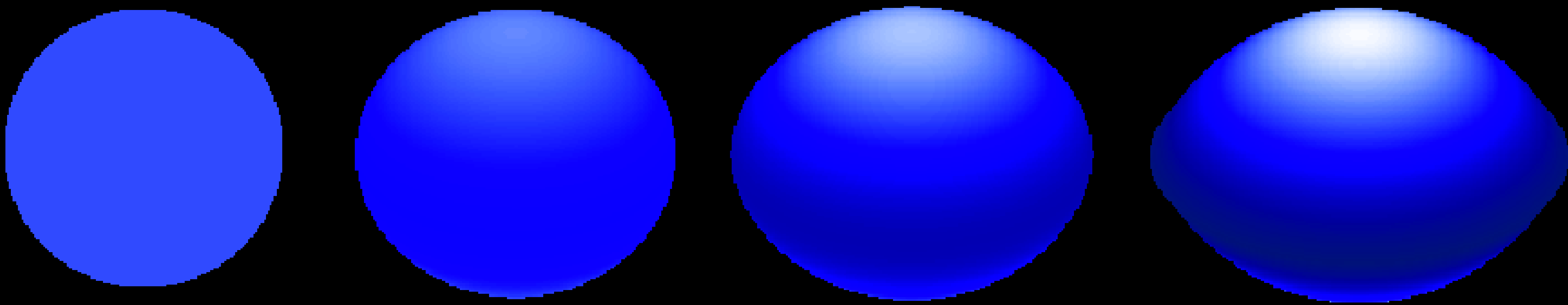
$$\dot{M}\,\mathrm{v}_\infty \propto L^{\frac{1}{\alpha}}$$

$\alpha \approx 0.6$

How is such a wind affected by (rapid) stellar rotation?

Gravity Darkening

increasing stellar rotation →



Effect of gravity darkening on line-driven mass flux

Recall:

$$\dot{m}(\theta) \sim \frac{F(\theta)^{1/\alpha}}{g_{eff}(\theta)^{1/\alpha - 1}} \sim \frac{F^2(\theta)}{g_{eff}(\theta)}$$

e.g., for $\alpha = 1/2$

w/o gravity darkening,
if F(θ)=const.

$$\dot{m}(\theta) \sim \frac{1}{g_{eff}(\theta)}$$

highest at **equator**

w/ gravity darkening,
if $F(\theta) \sim g_{eff}(\theta)$

$$\dot{m}(\theta) \sim F(\theta)$$

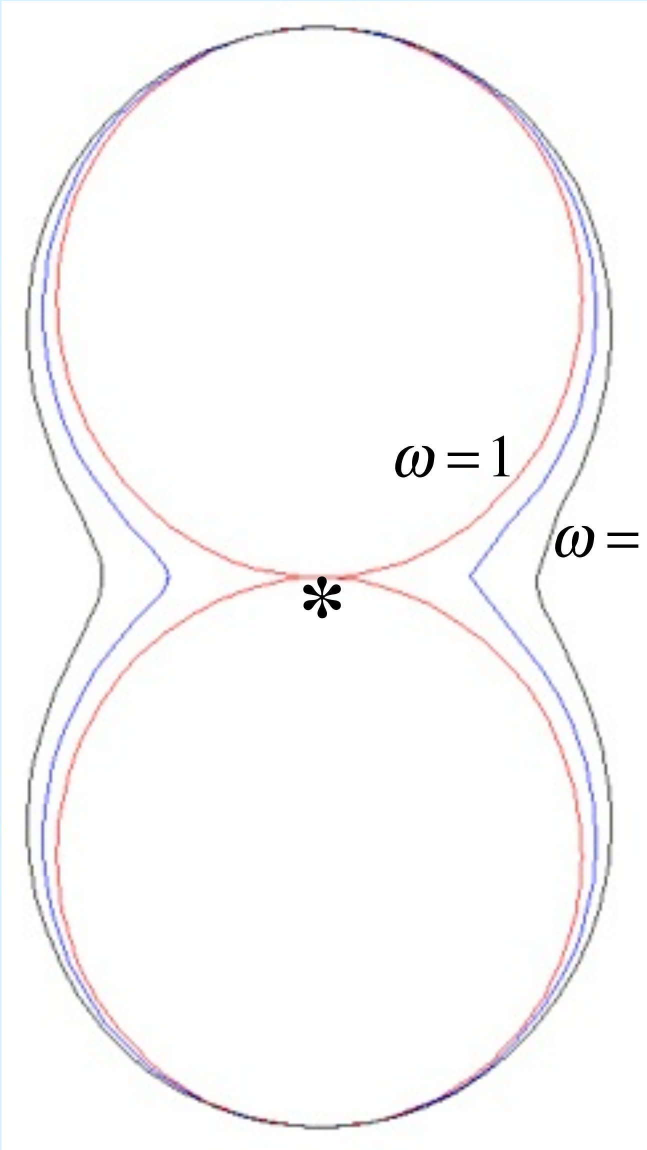
highest at **pole**

Effect of rotation on flow speed

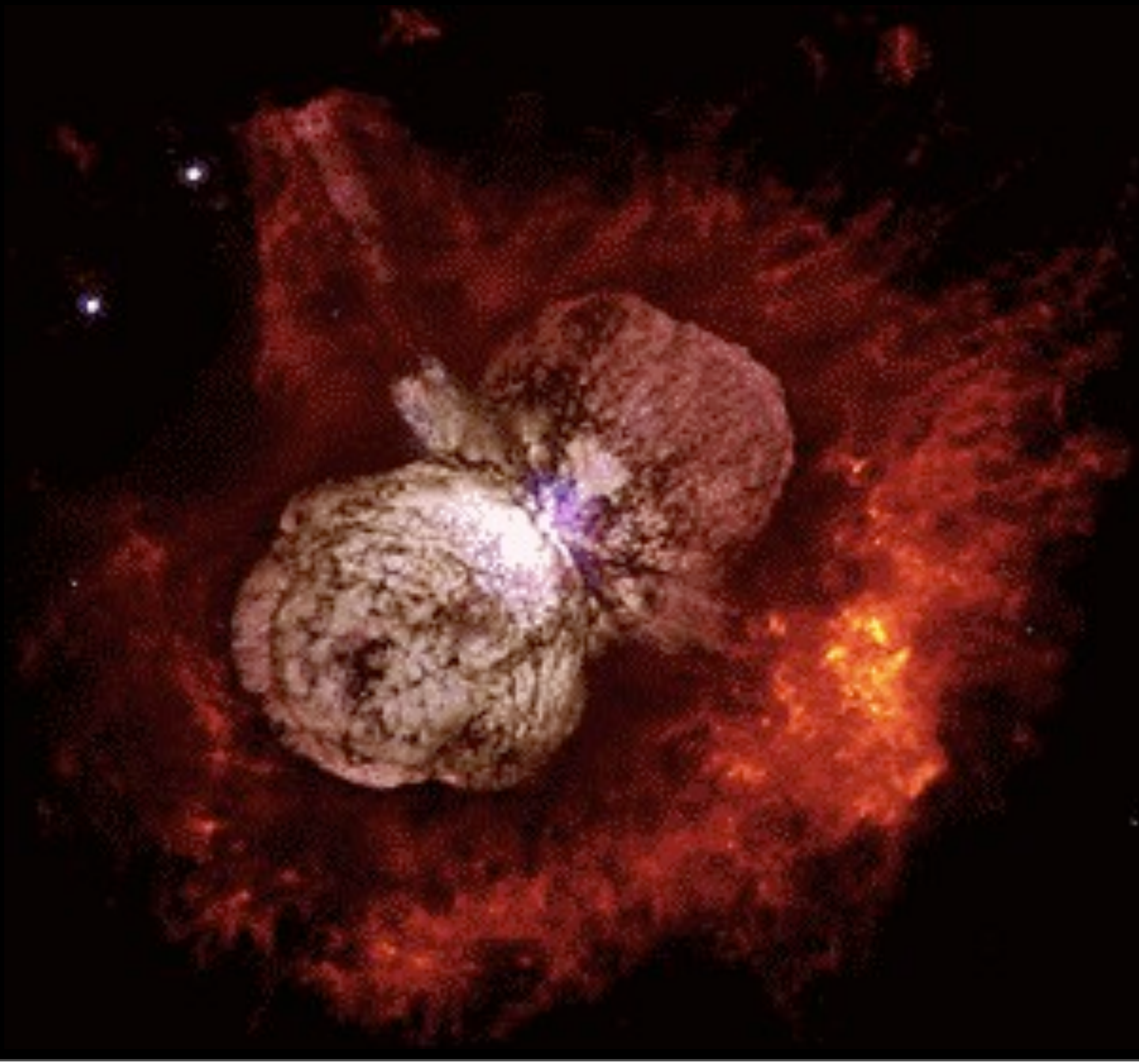
$$V_\infty(\theta) \sim V_{eff}(\theta) \sim \sqrt{g_{eff}(\theta)}$$

$$g_{eff}(\theta) \sim 1 - \omega^2\, Sin^2\theta$$

$$\omega \equiv \Omega / \Omega_{crit}$$



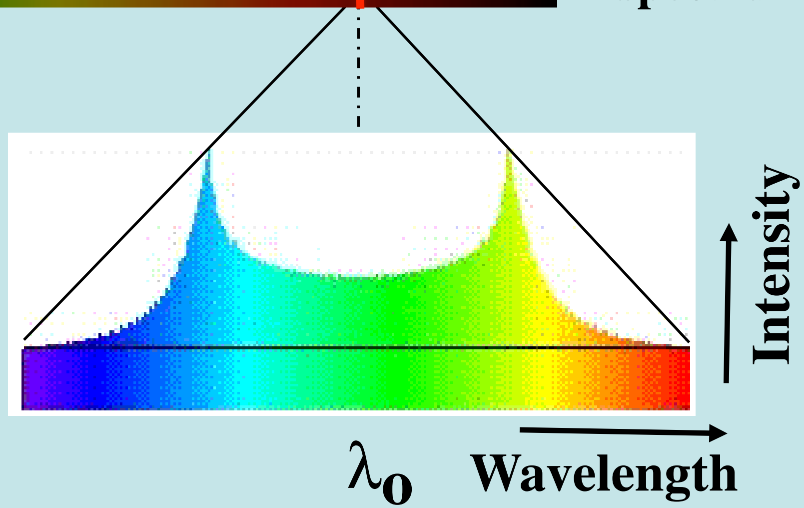
Eta Carinae



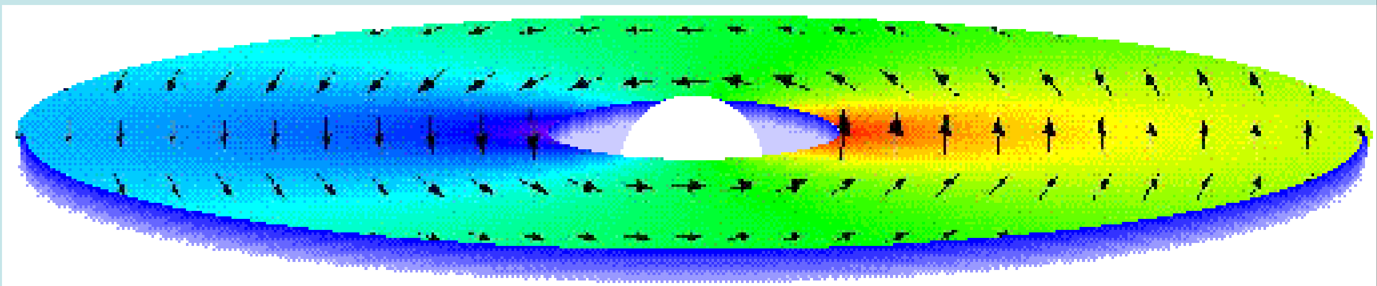
Be stars

- Hot, bright, & rapidly rotating stars of mass ~ 3-10 Msun
- The " e" stands for emission lines in the star's spectrum

- Emission intensity split into blue and red peaks

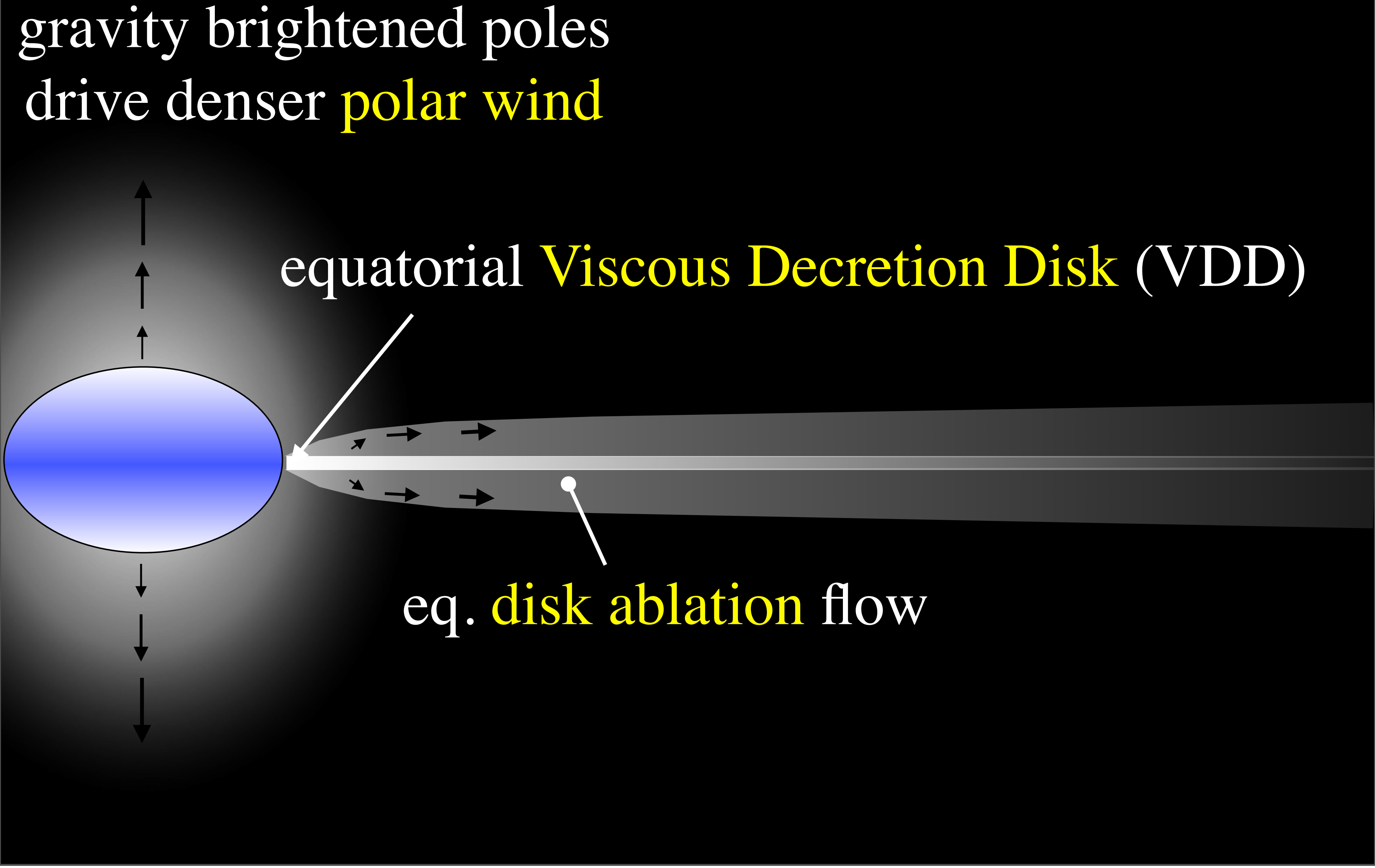


- From Doppler shift of gas moving toward and away from the observer .

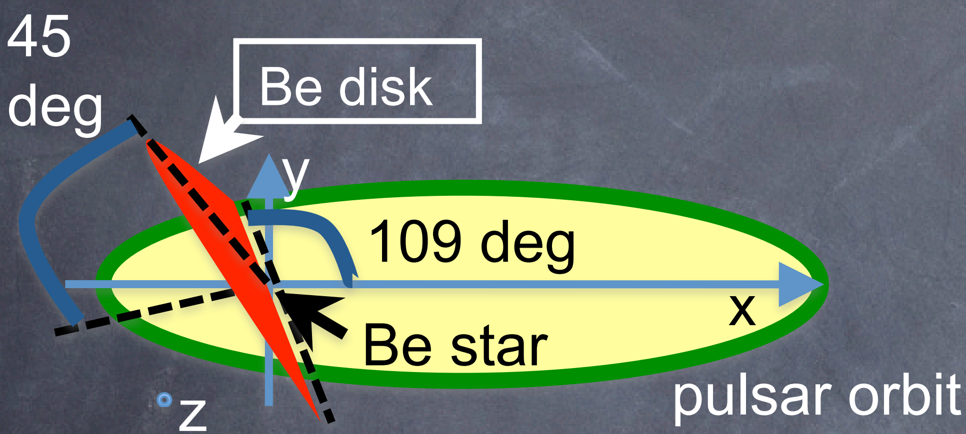


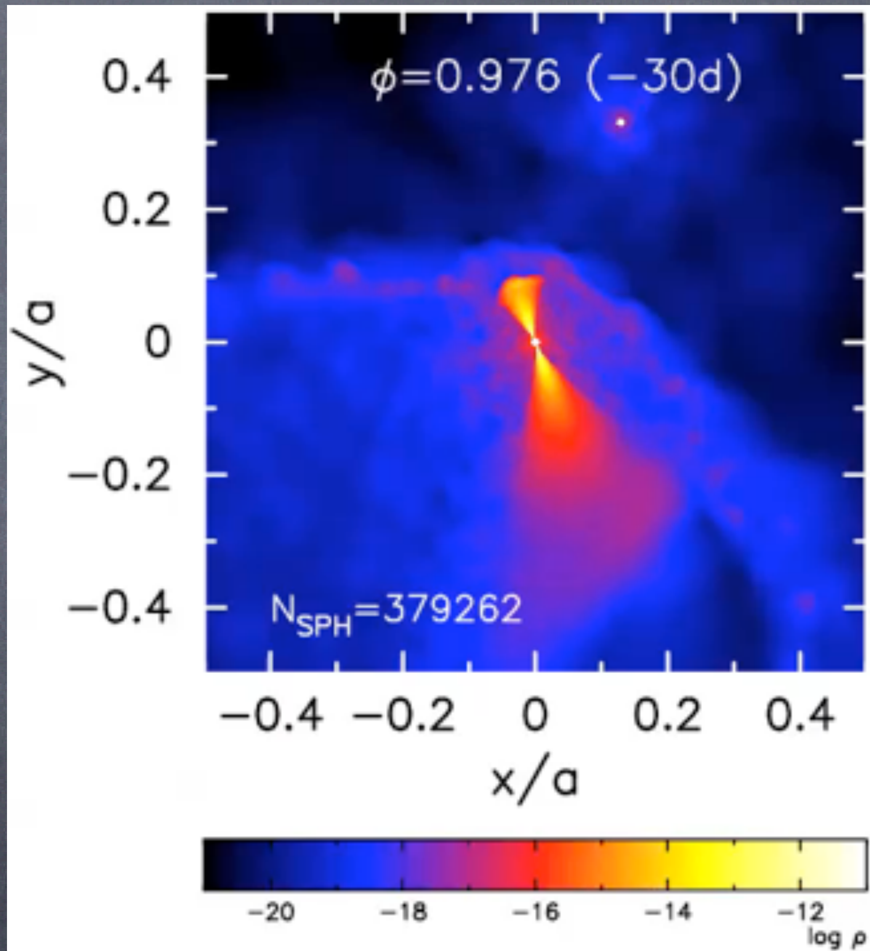
- Indicates a disk of gas orbits the star.

3 components of Be star circumstellar gas



B1259-63 = misaligned Be-pulsar system.





see talk by A. Okazaki

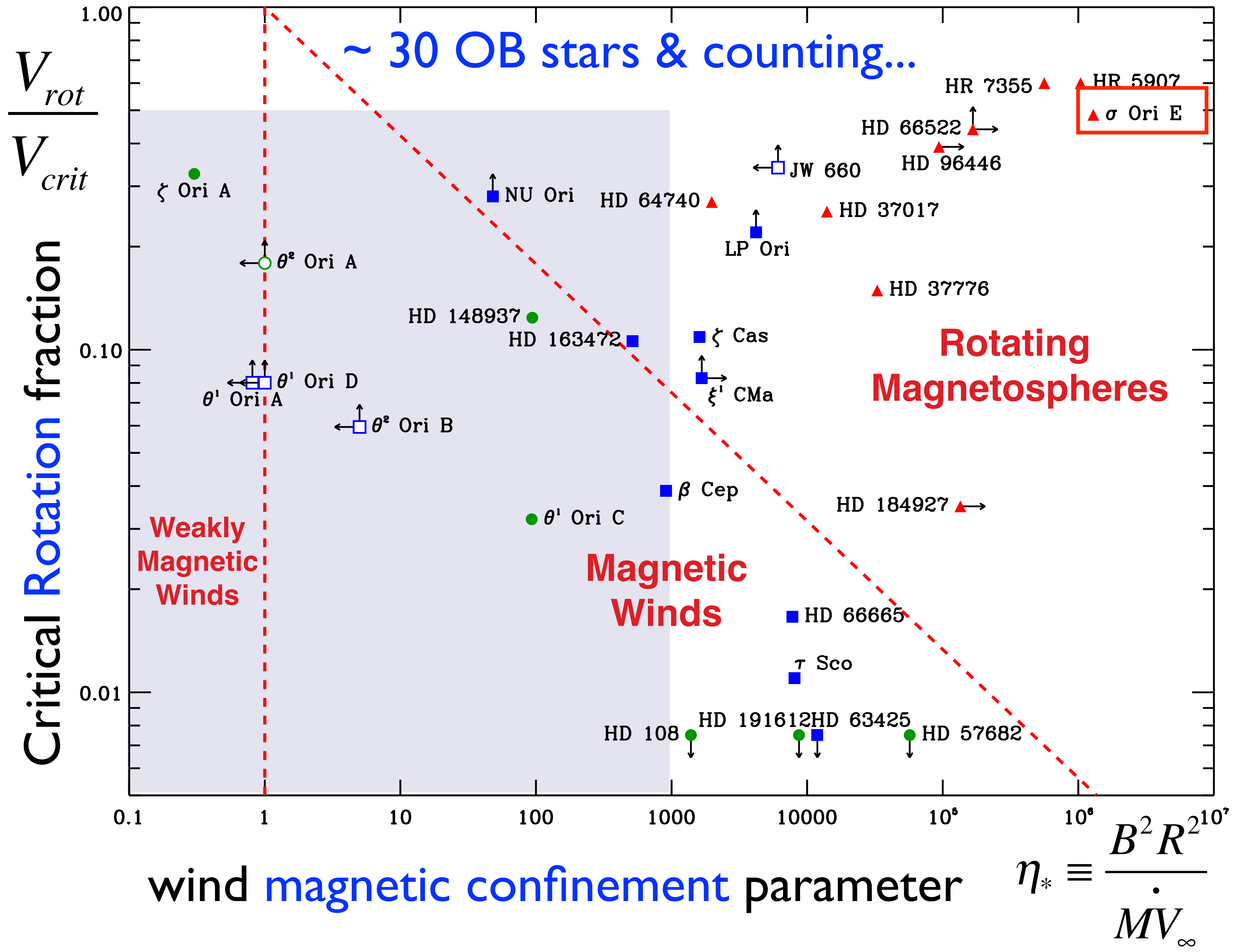
MiMeS

Magnetism in Massive Stars

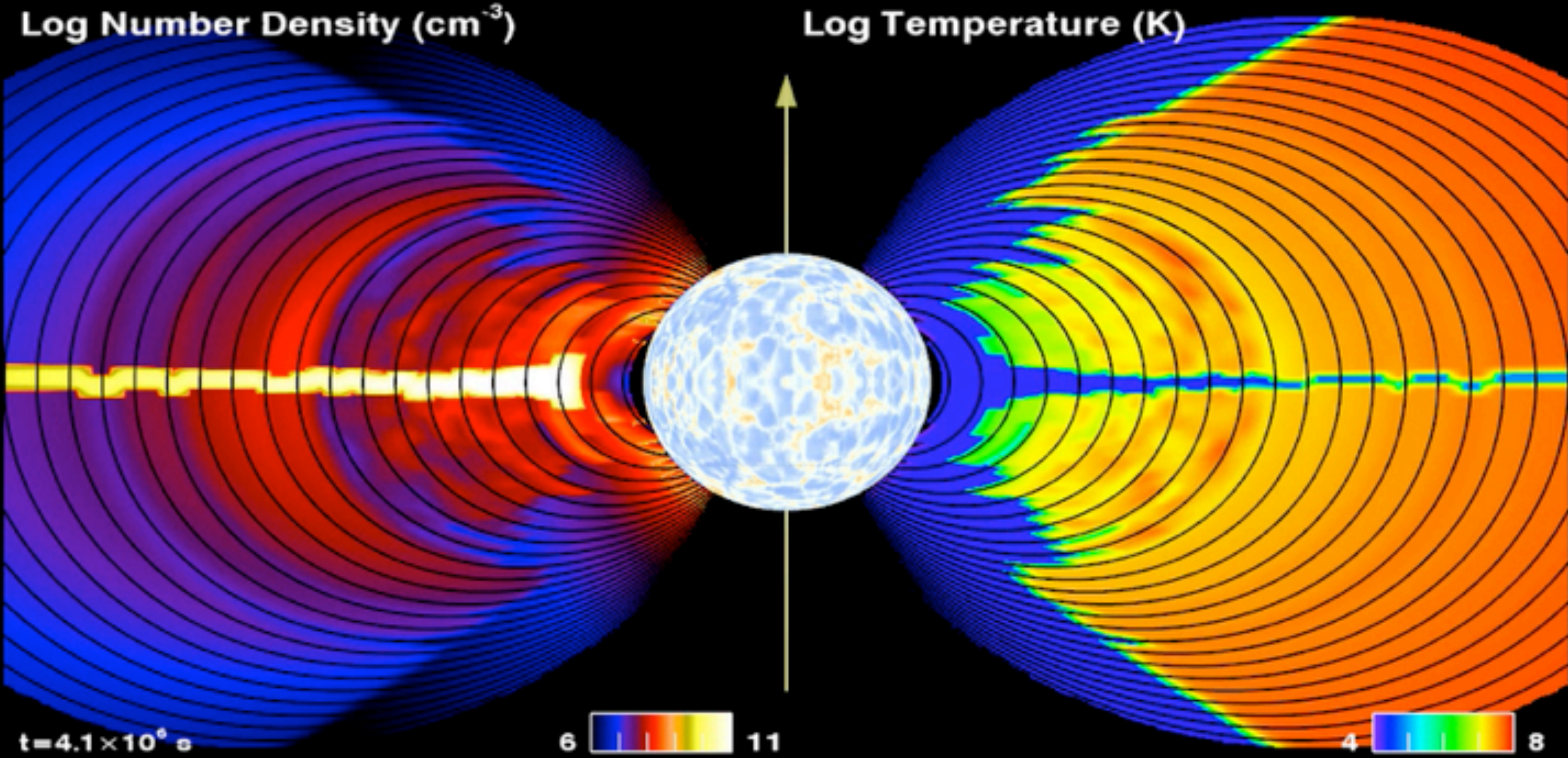
P.I.: Gregg A. Wade, Royal Military College

50+ Co-Is, 2008-2012, CFHT Allocation: 640 hours

http://www.physics.queensu.ca/~wade/mimes/MiMeS__Magnetism_in_Massive_Stars.html

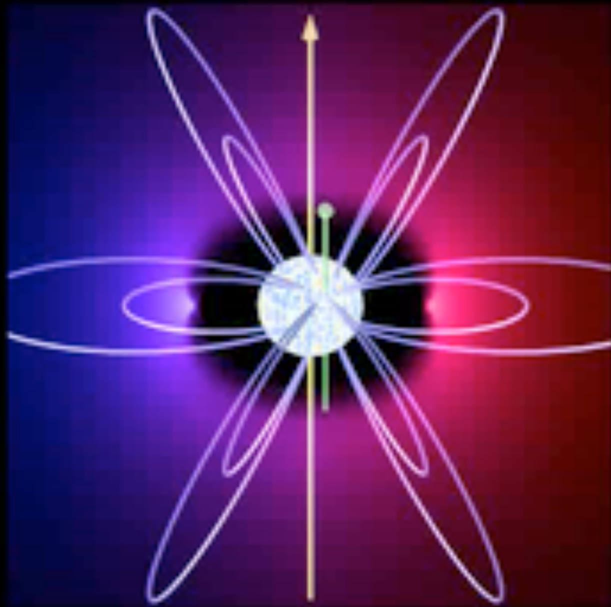

~ 30 OB stars & counting...
Critical Rotation fraction
$\frac{V_{rot}}{V_{crit}}$
1.00
0.10
0.01
0.1
1
10
100
1000
10000
10^5
10^6
10^7
wind magnetic confinement parameter
$\eta_* \equiv \frac{B^2 R^2}{\dot{M} V_\infty}$
Weakly Magnetic Winds
Magnetic Winds
Rotating Magnetospheres
HR 7355
HR 5907
σ Ori E
HD 66522
HD 96446
JW 660
ζ Ori A
NU Ori
HD 64740
HD 37017
LP Ori
θ² Ori A
HD 37776
HD 148937
HD 163472
ζ Cas
θ¹ Ori D
θ¹ Ori A
ξ¹ CMa
θ² Ori B
β Cep
HD 184927
θ¹ Ori C
HD 66665
τ Sco
HD 108
HD 191612
HD 63425
HD 57682

Rigid Field - Hydro Model

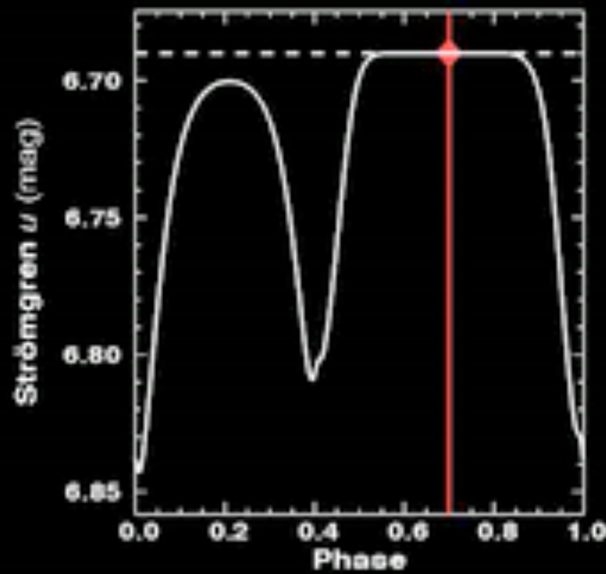


σ Ori E

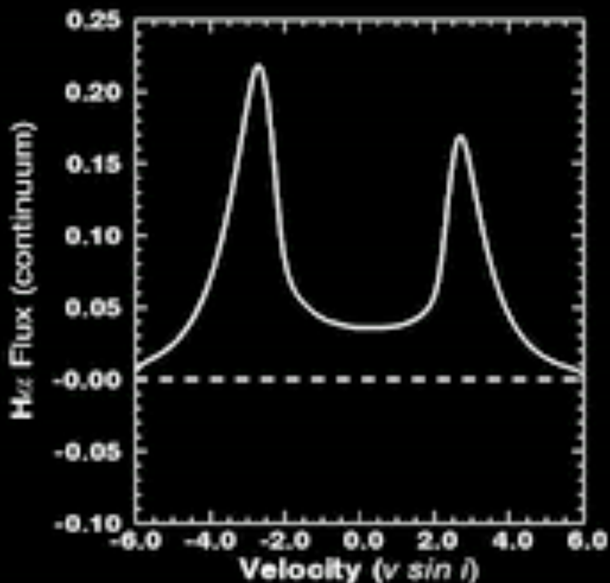
EM +B-field



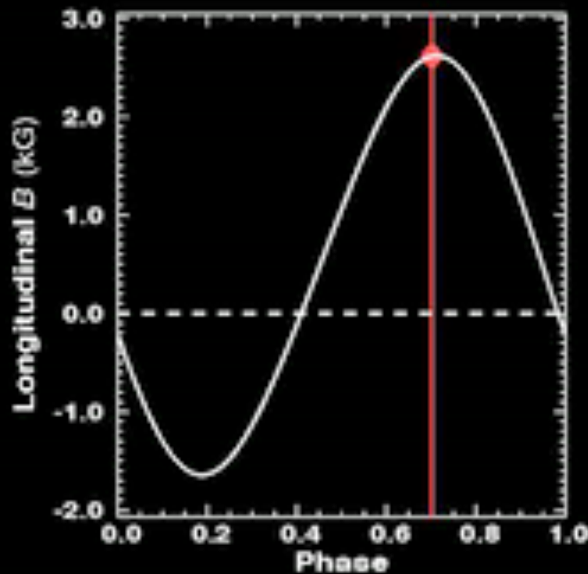
photometry



Rigidly Rotating Magnetosphere



Hα

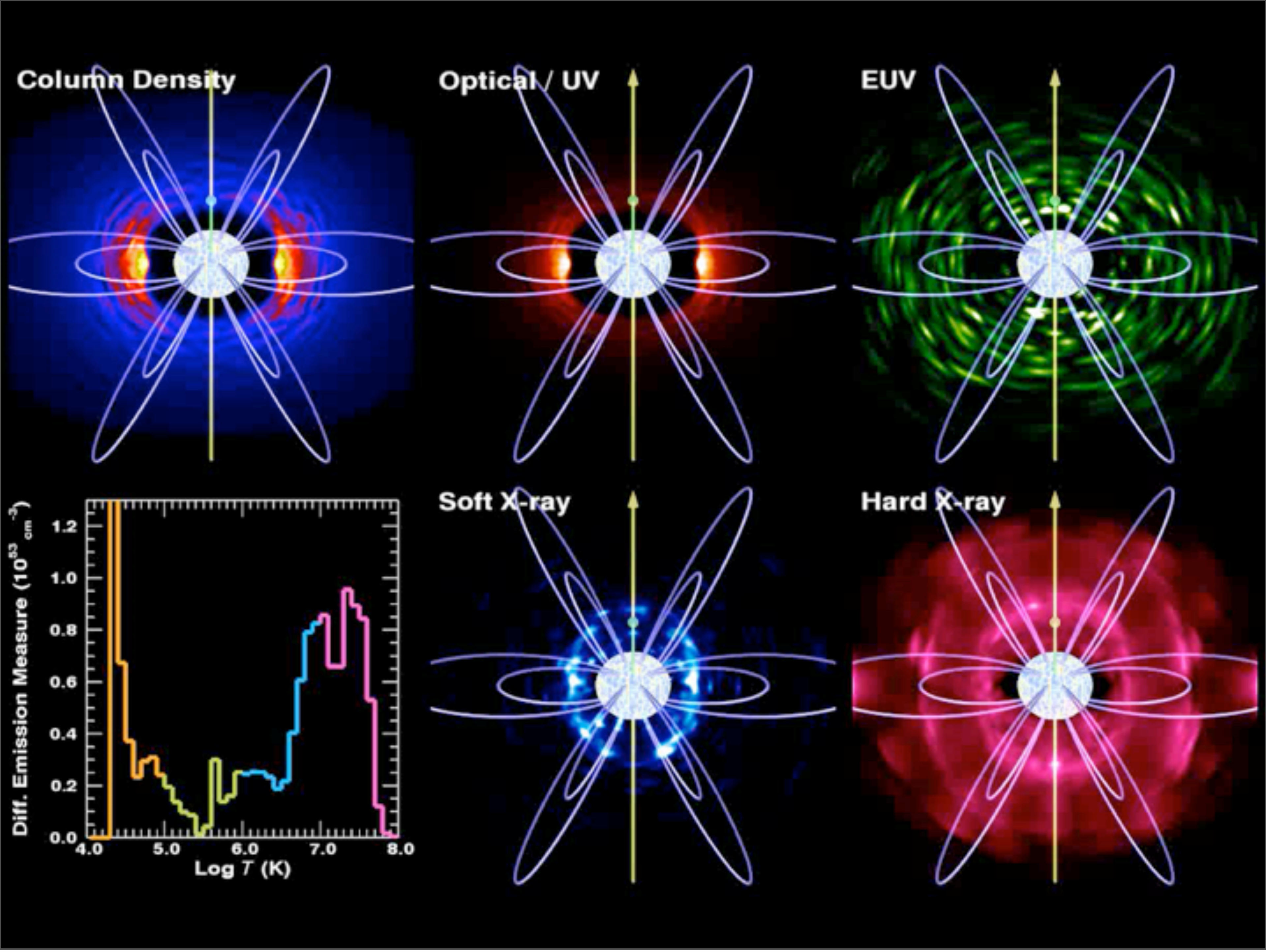


polarimetry

$B_* \sim 10^4$ G

$=> \eta_* \sim 10^6$!

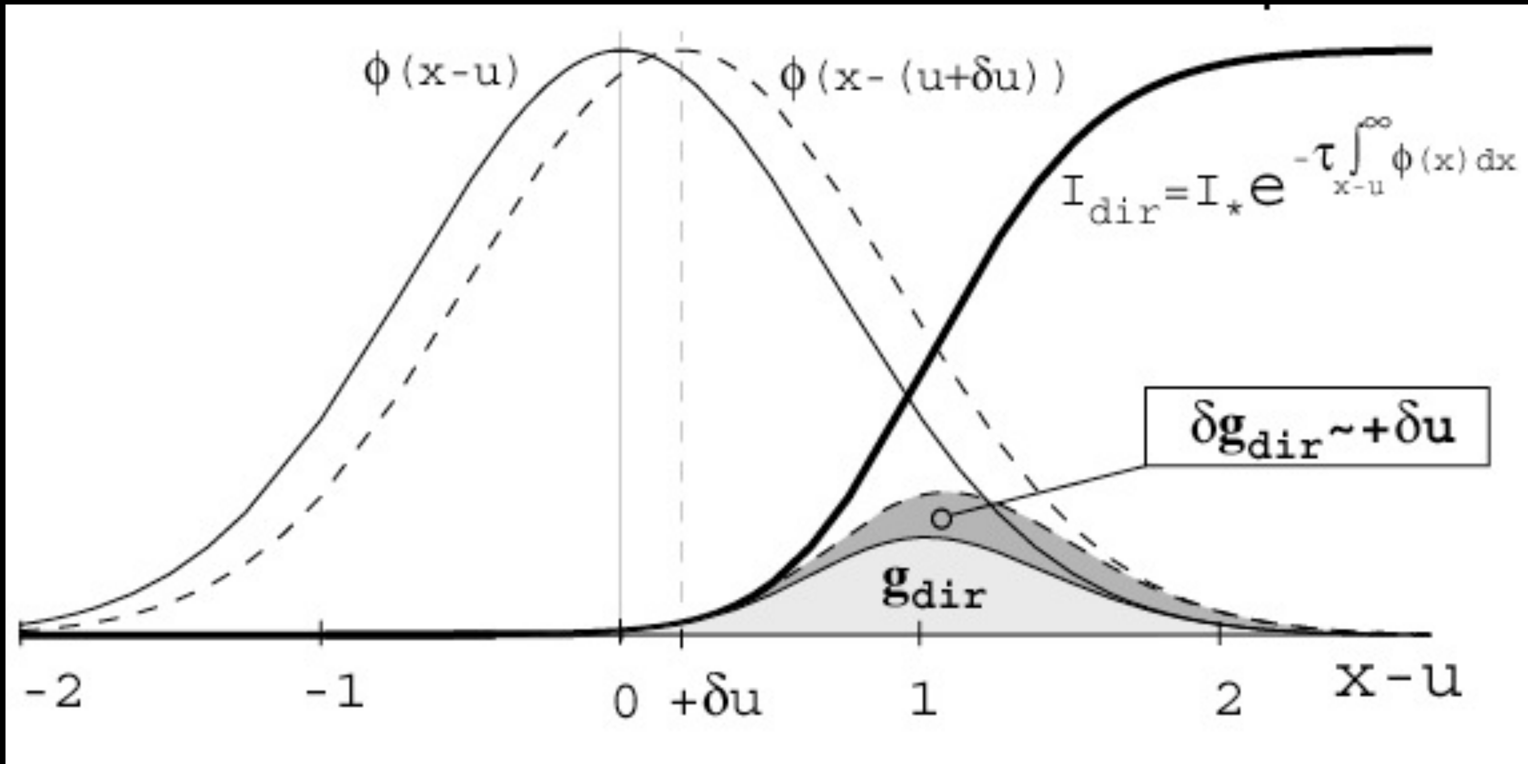
tilt ~ 55^o


Column Density
Optical / UV
EUV
Soft X-ray
Hard X-ray
Diff. Emission Measure (10^53 cm^-3)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
4.0
5.0
6.0
7.0
8.0
Log T (K)

Back to 1D models of non-magnetic winds
&
“Line-Deshadowing” Instability

- Leads to:
  - clumping
  - porosity
  - soft X-ray emission

Line-Deshadowing Instability



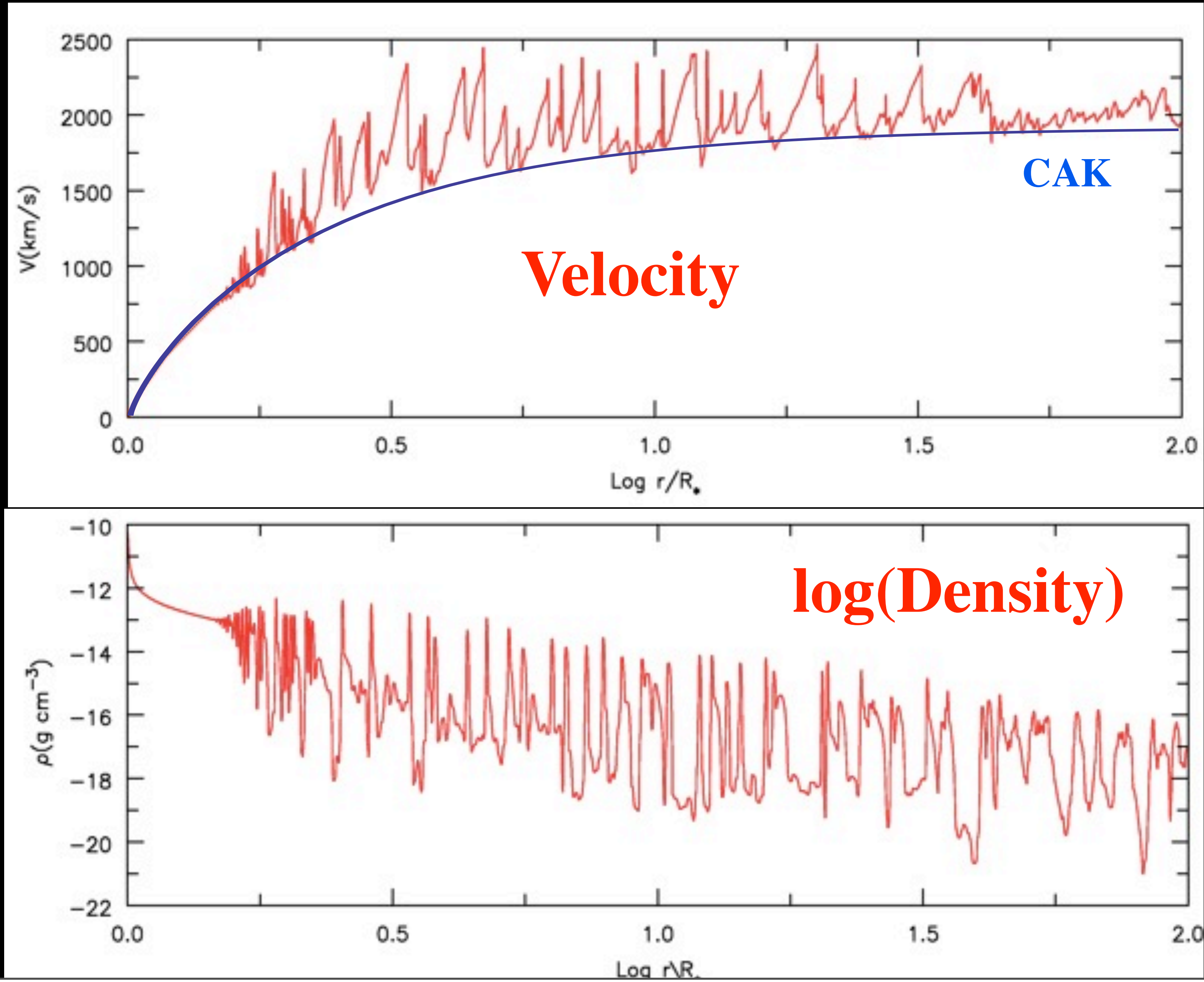
for $\lambda < L_{sob}$:

Instability growth rate

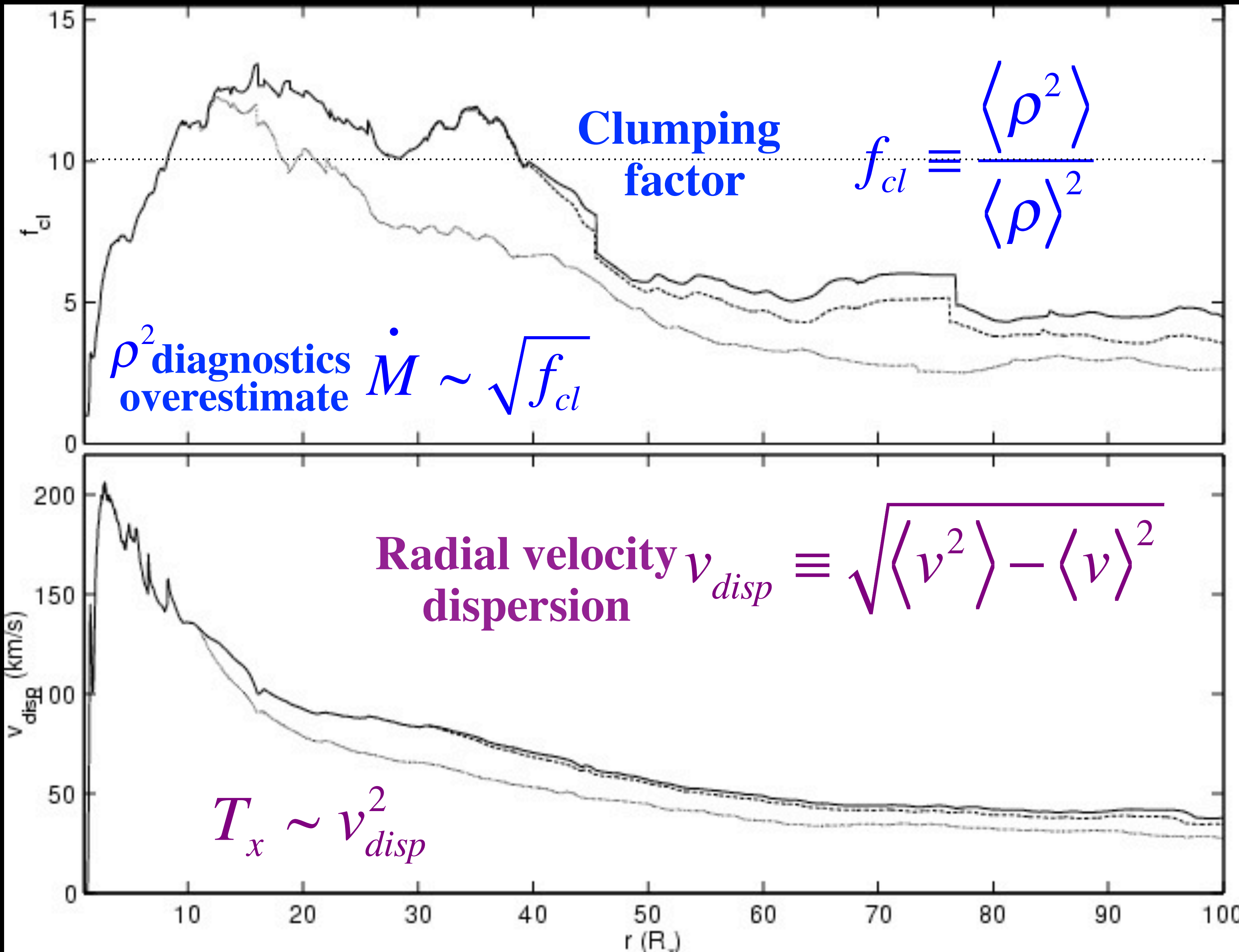
$$\Omega \sim g_o/v_{th} \sim vv'/v_{th} \sim v/L_{sob} \sim 100\ v/R$$

=> e^{100} growth!

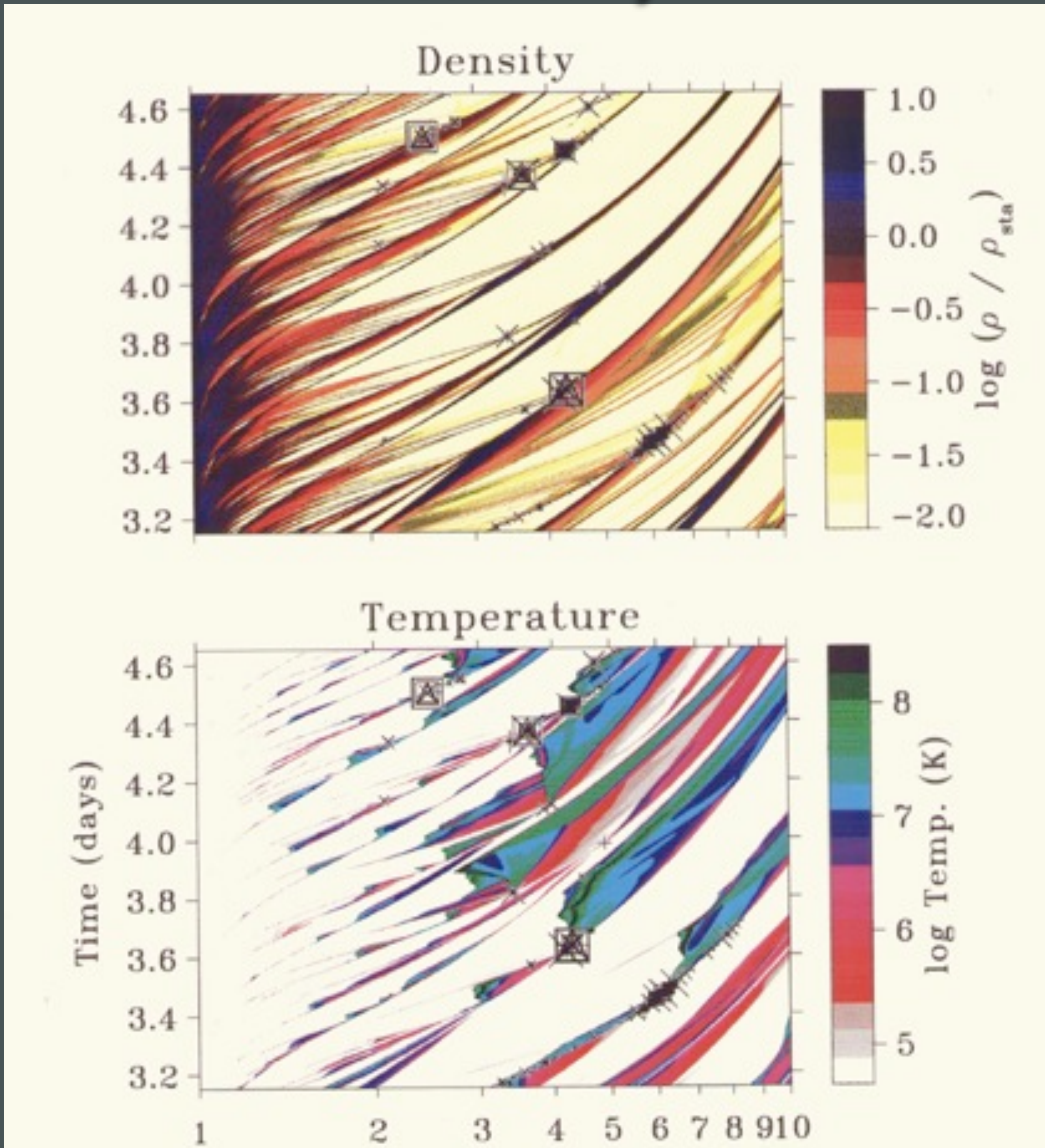
Time snapshot of wind structure vs. radius



Clumping vs. radius



Shell-shell collisions seeded by turbulence at the base of the wind flow



Time

Radius

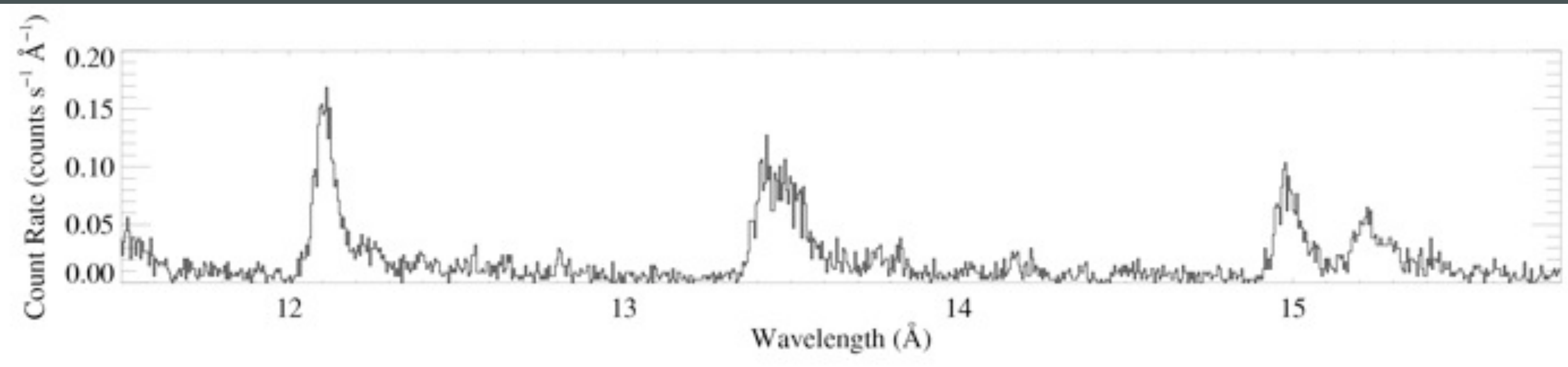
Feldmeier, et al. 1997

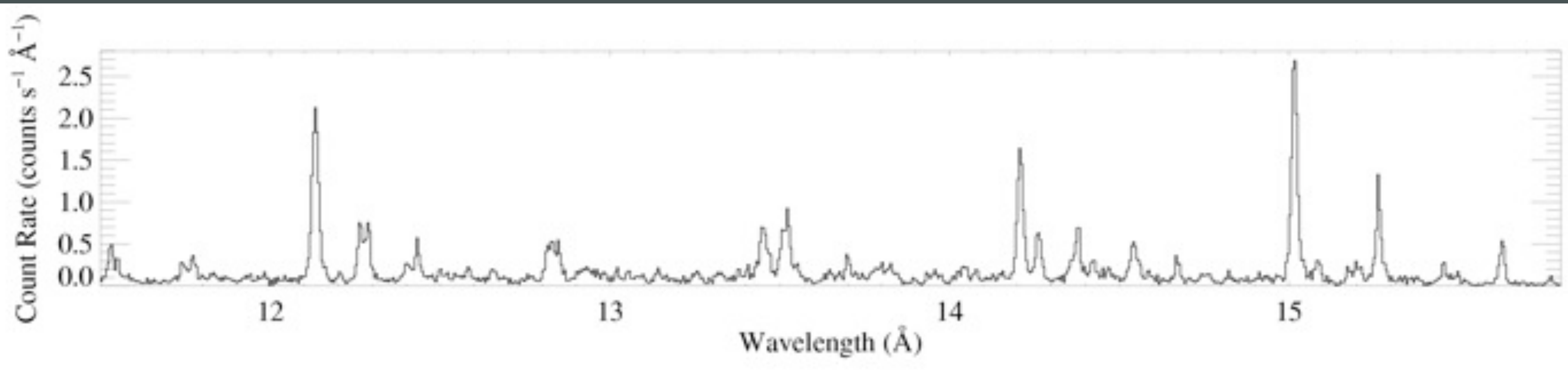
T~ 5-10 MK

=> 0.5-1 keV X-rays

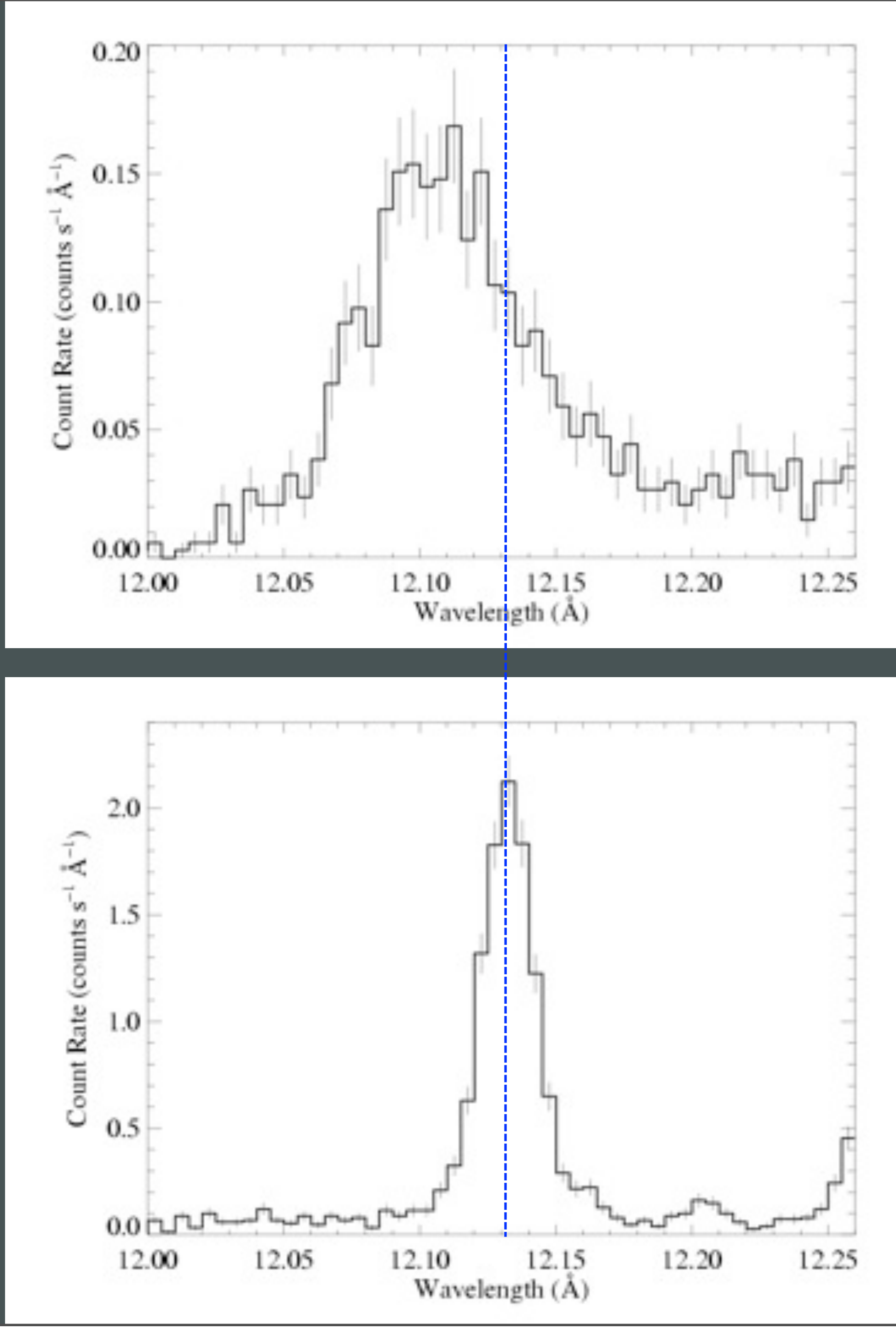
Chandra spectra
Hot-star ζ Pup: wind shock X-rays lines (broad)

Ne X   Ne IX   Fe XVII





Cool-star Capella: coronal X-rays lines (narrow)



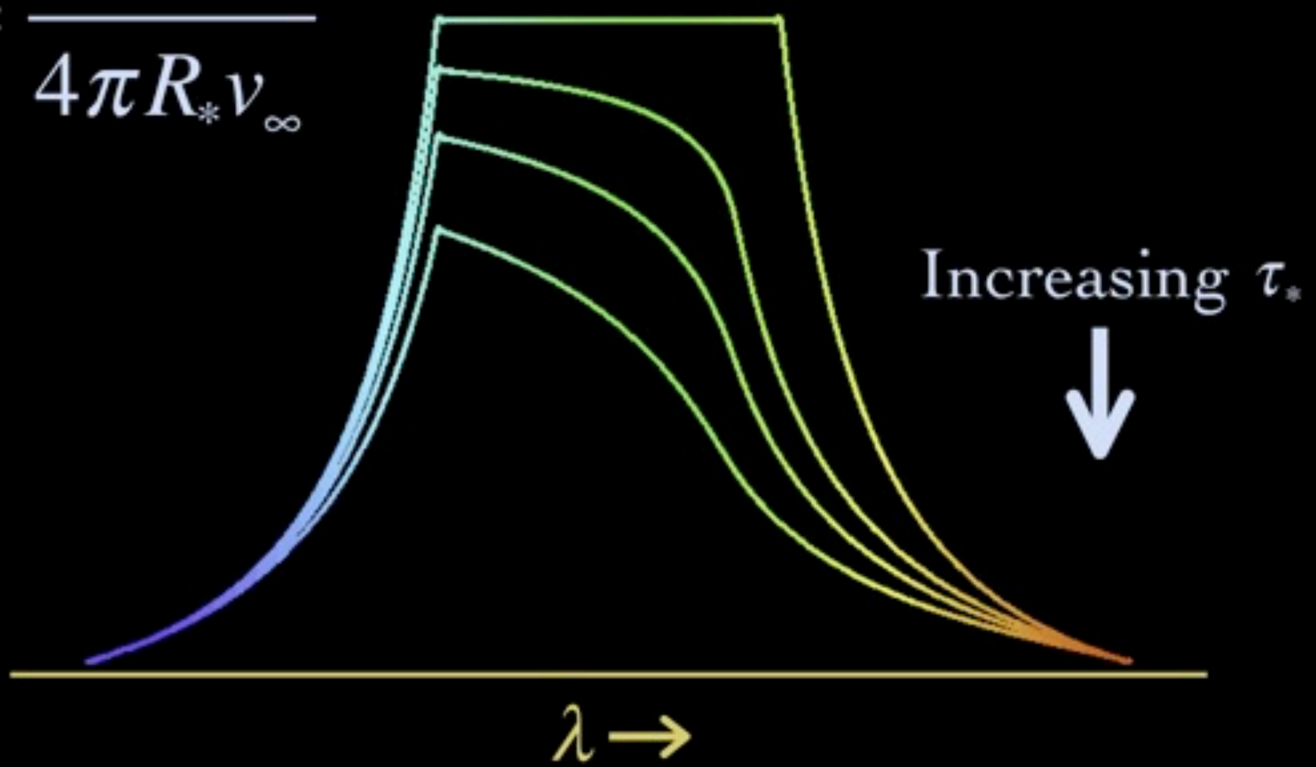
ζ Pup
high-mass

Ne X Ly α
broad,
skewed,
blue shifted

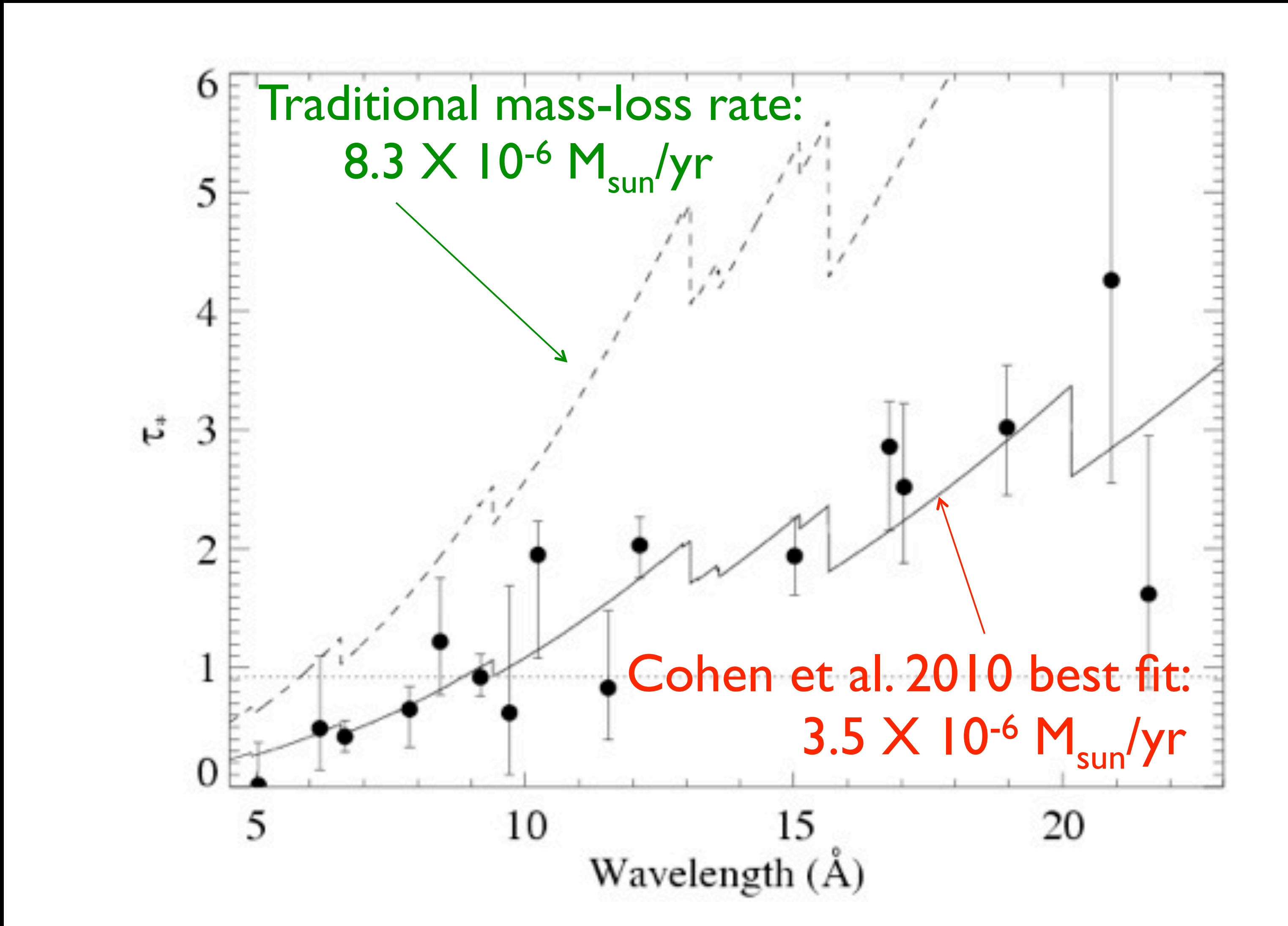
Capella
low mass
unresolved

Wind Profile Model

$$\tau_* = \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

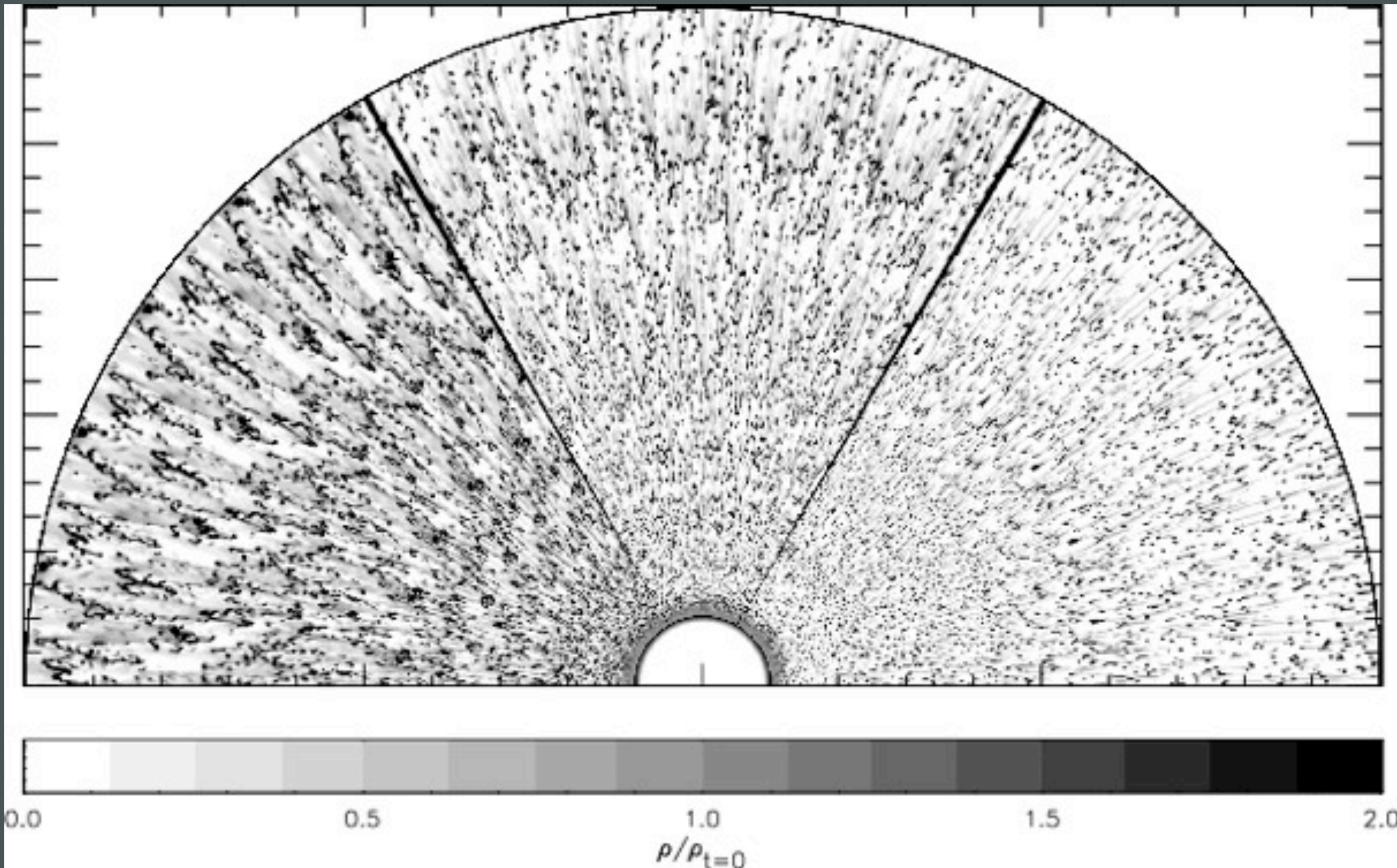


Inferring ZPup M_{dot} from X-ray lines



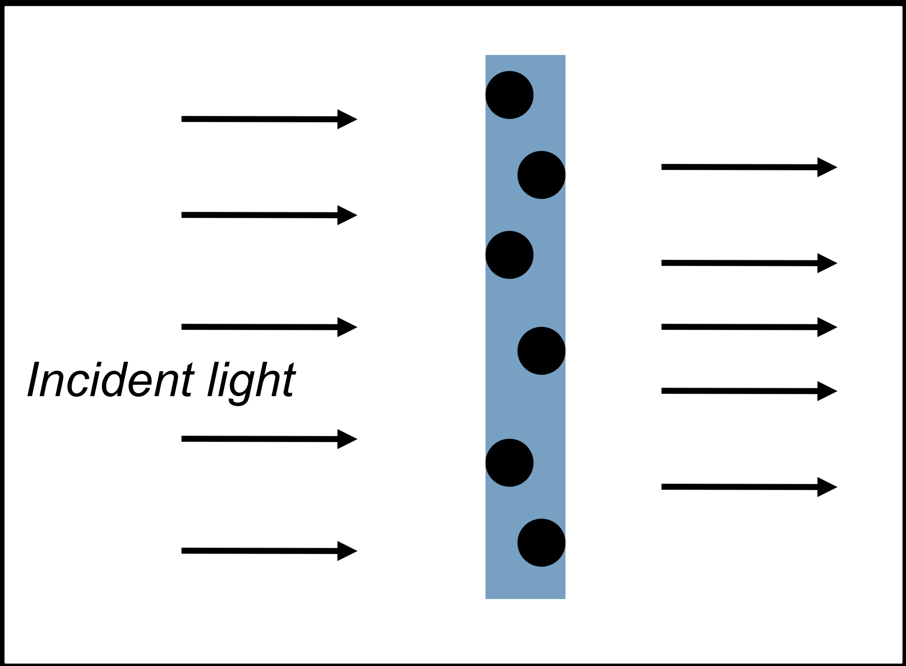
$$\dot{M} \sim \sqrt{f_{cl}} \rightarrow f_{cl} \approx 6$$

Resulting small-scale density clumping in 2-D simulations



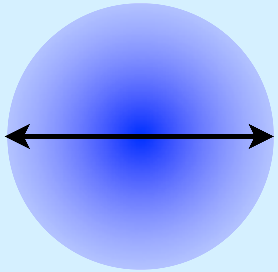
Dessart & Owocki 2003, *A&A*, 406, L1

Porosity



- *Same amount of material*
- *More light gets through*
- *Less interaction between matter and light*

Porous opacity from optically thick clumps



ℓ

$$\sigma_{eff} \approx \ell^2 \, [1 - e^{-\tau_c}]$$

$$\tau_c \equiv \kappa \rho_c \ell = \kappa \rho \ell / f_{vol}$$

"porosity length" h

$$\kappa_{eff} \equiv \frac{\sigma_{eff}}{m_c} = \kappa \, \frac{1 - e^{-\tau_c}}{\tau_c}$$

$$\kappa_{eff} \approx \frac{\kappa}{\tau_c} \quad ; \tau_c >> 1$$

Porosity length = mfp

$$\text{mfp} = 1/\ell^2 n_c$$

$$= L^3/\ell^2$$

$$= \ell/f_{vol}$$

$$= h = \text{porosity length}$$

clump size ℓ =0.05r ℓ =0.1r ℓ =0.2r

Porous envelopes

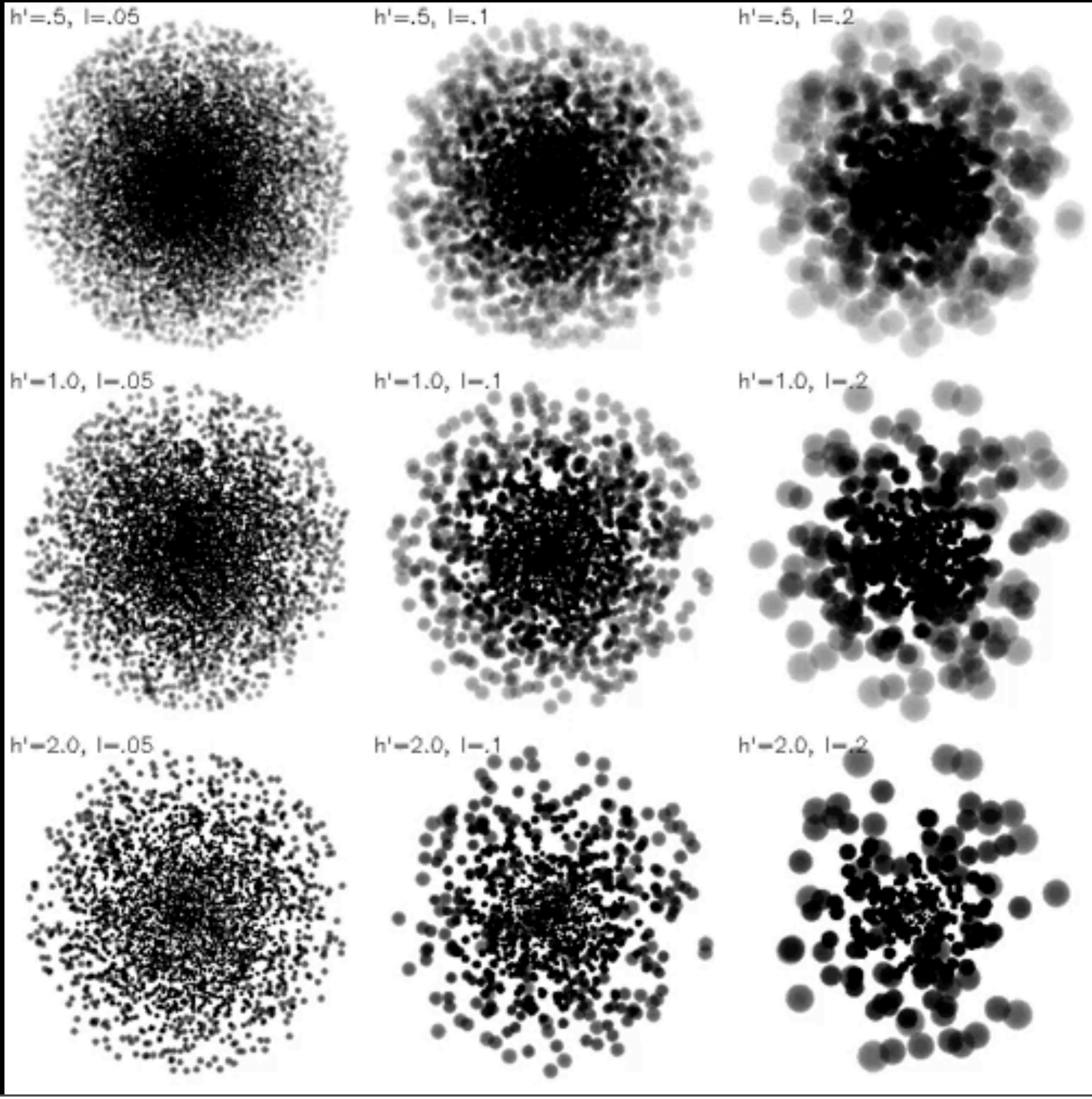
h=0.5r

Porosity length
$h \equiv \ell / f_{vol}$

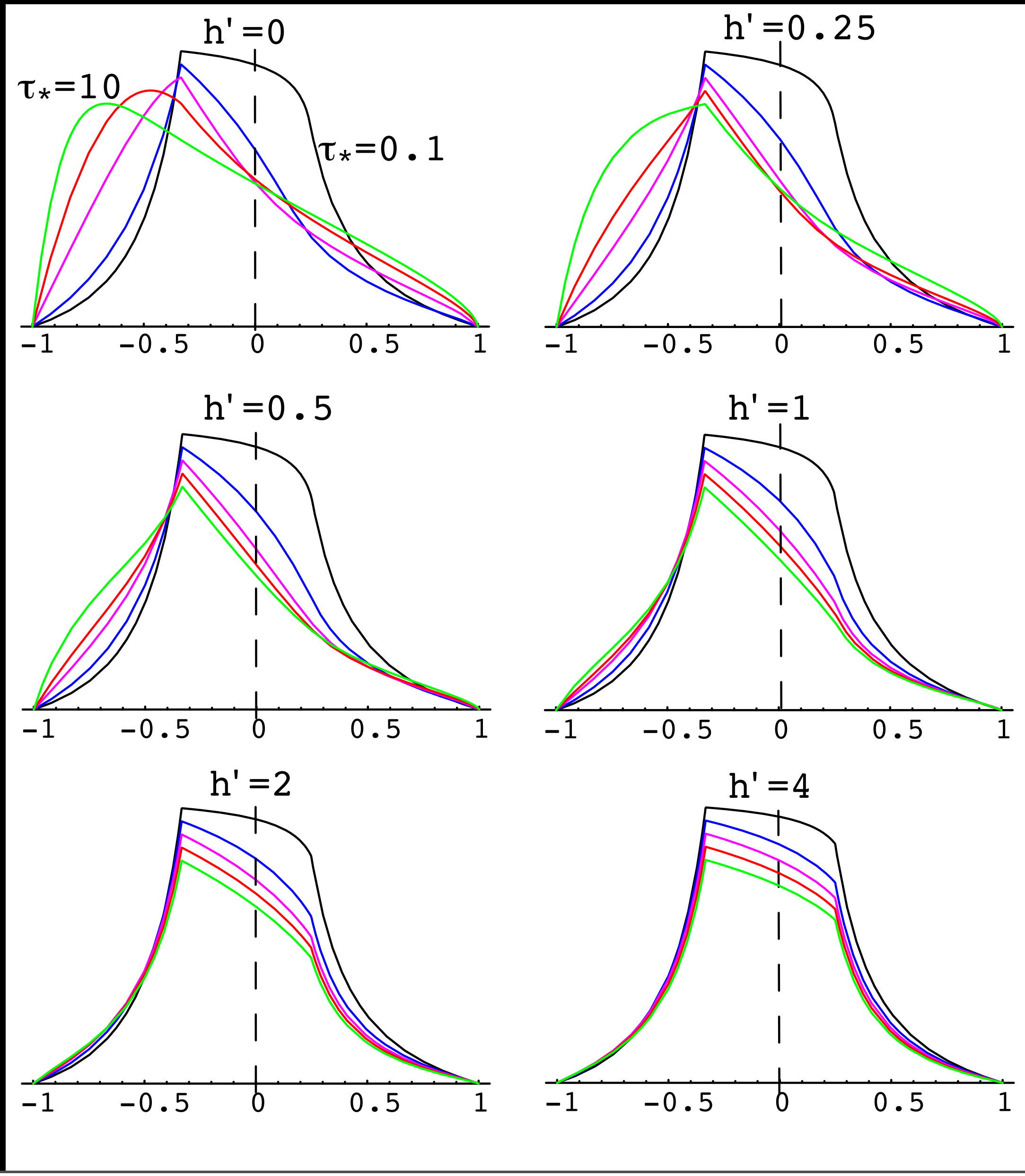
h=r

vol. fill factor
$f_{vol} \equiv (\ell / L)^3$
$= 1/f_{cl}$

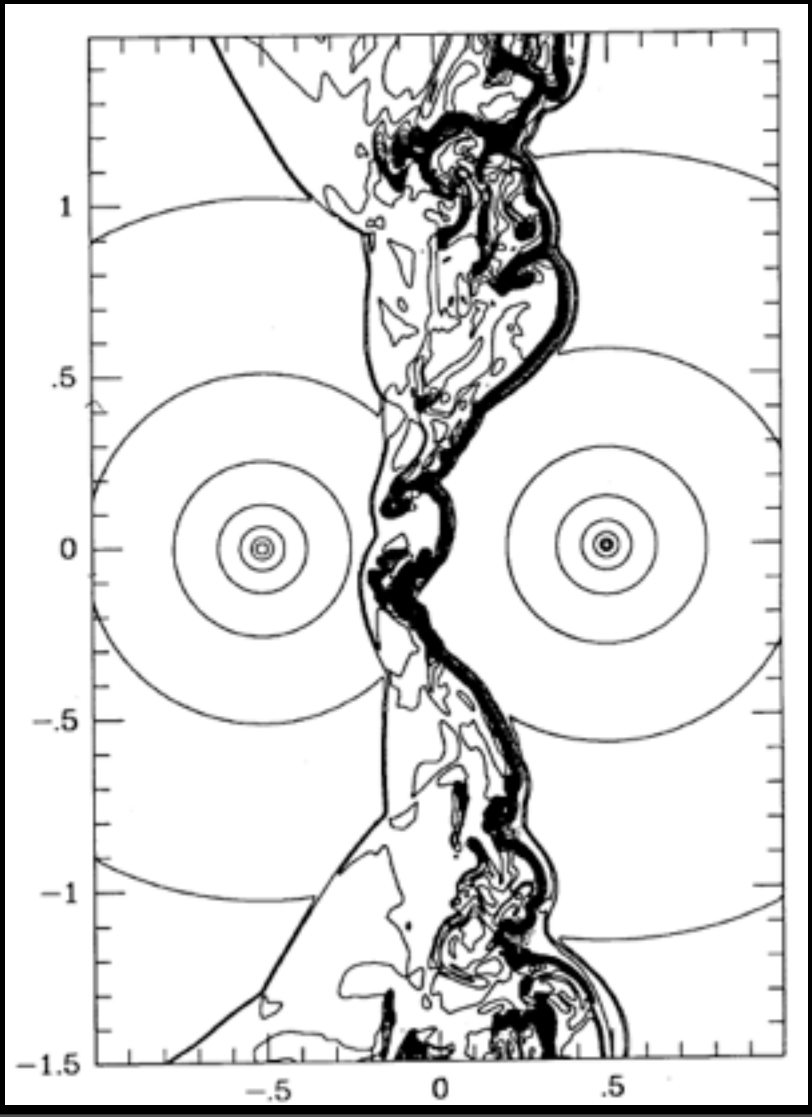
h=2r



Porosity's effect on X-ray line profiles

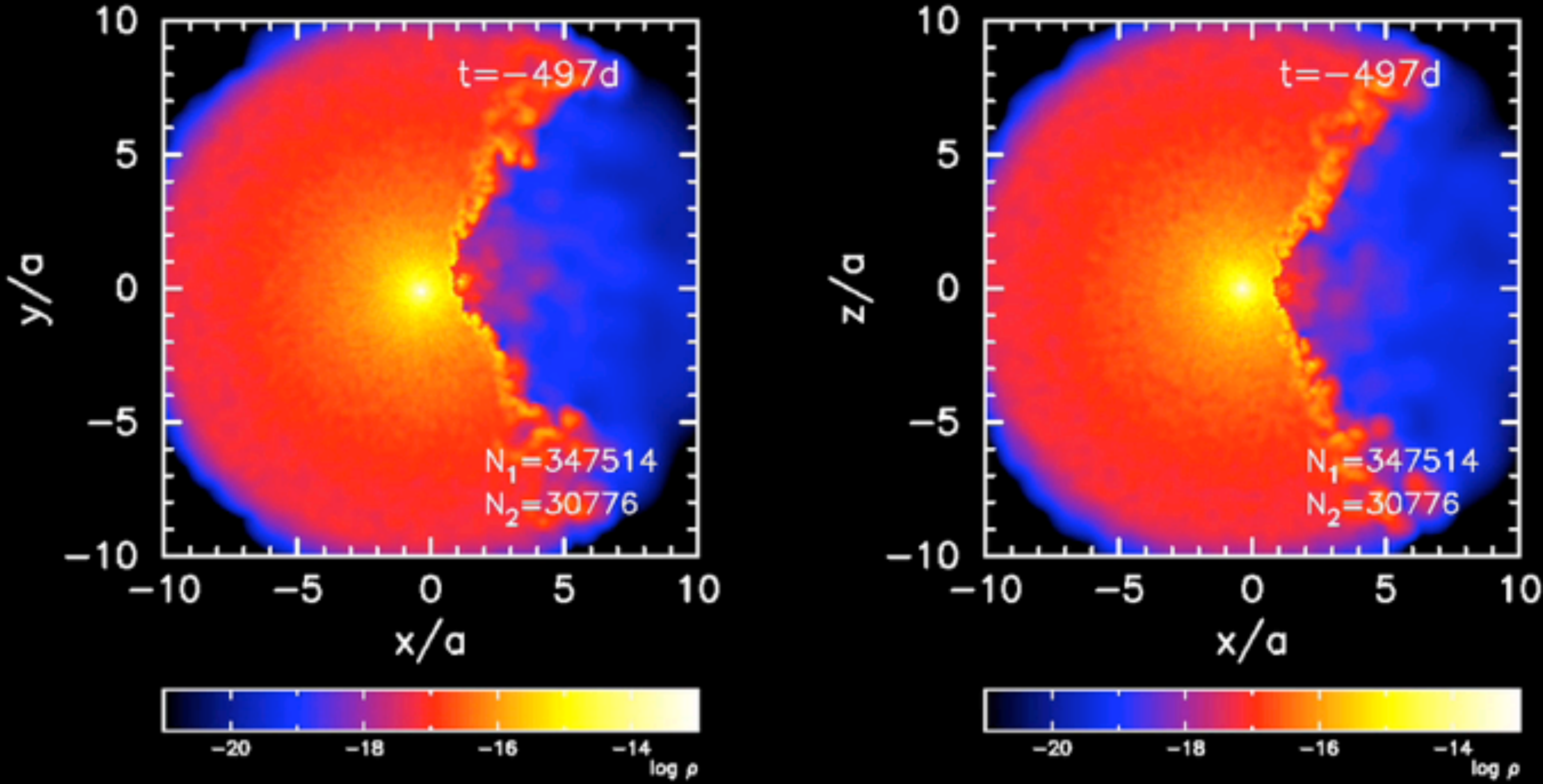


X-rays from Colliding Wind Binaries



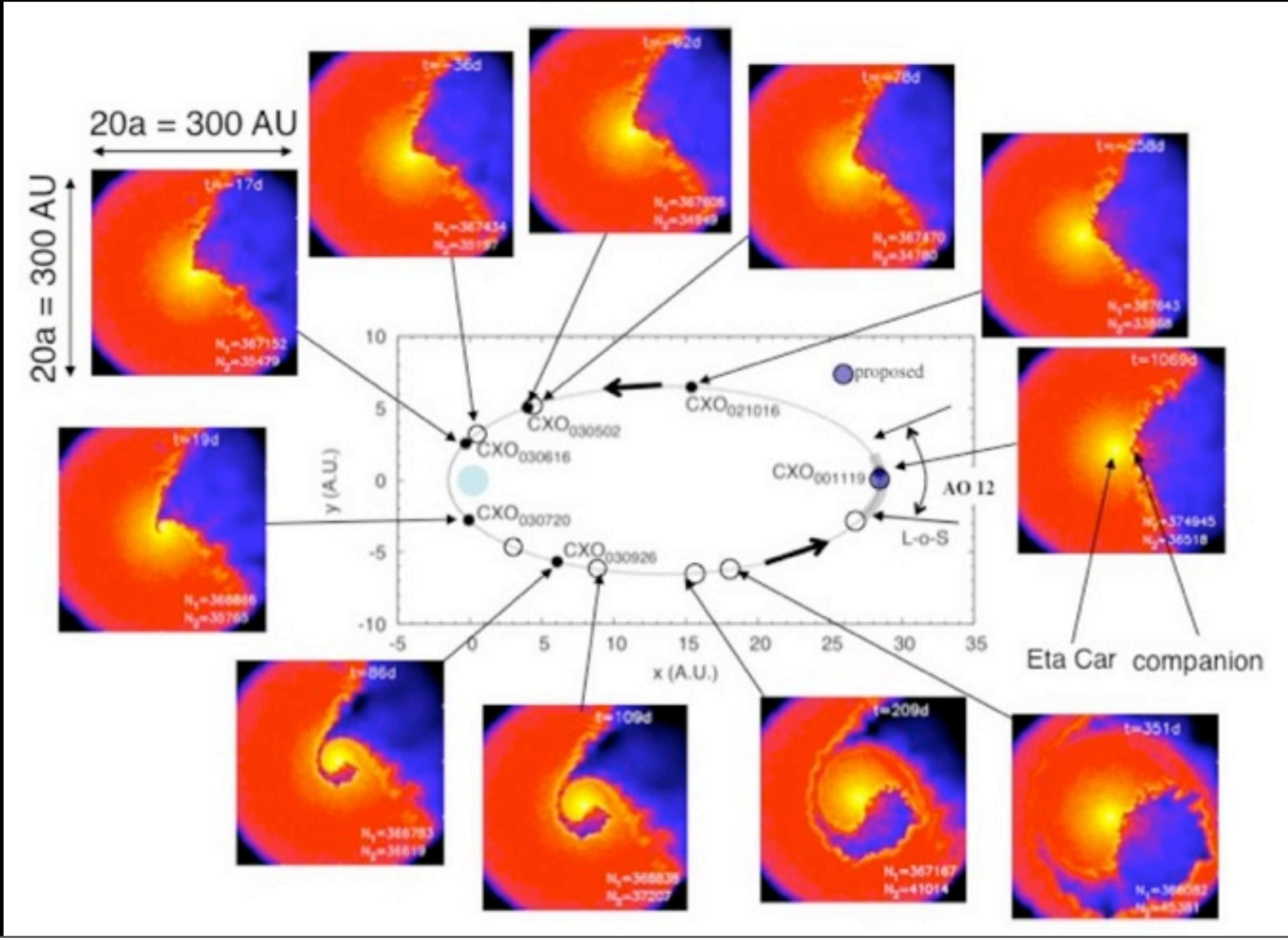
Stevens et al. 1992

3D SPH sim of CWB in eta Car

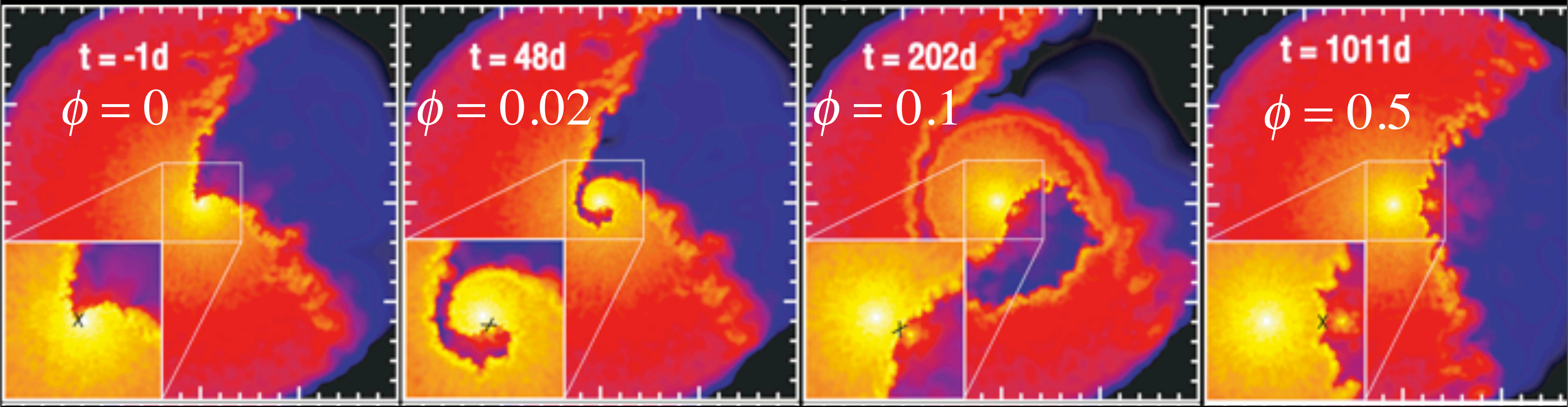


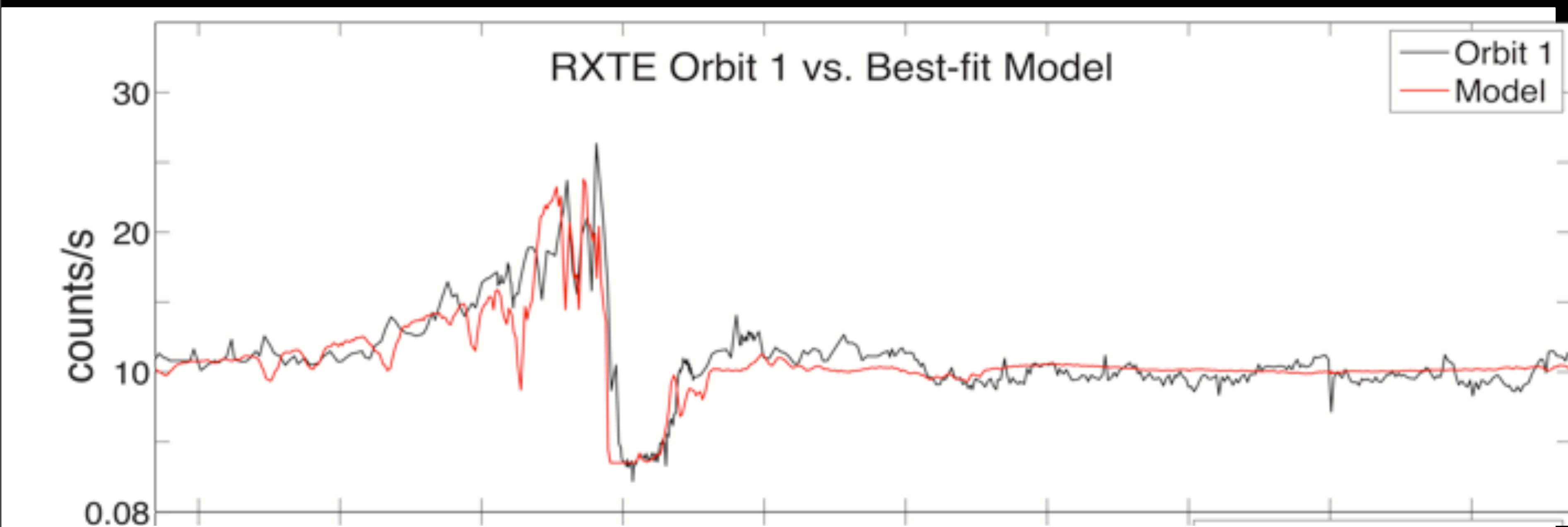
http://www.bartol.udel.edu/~owocki/xfr/eta_car_r10-full.mov

3D SPH sim of η Car CWB



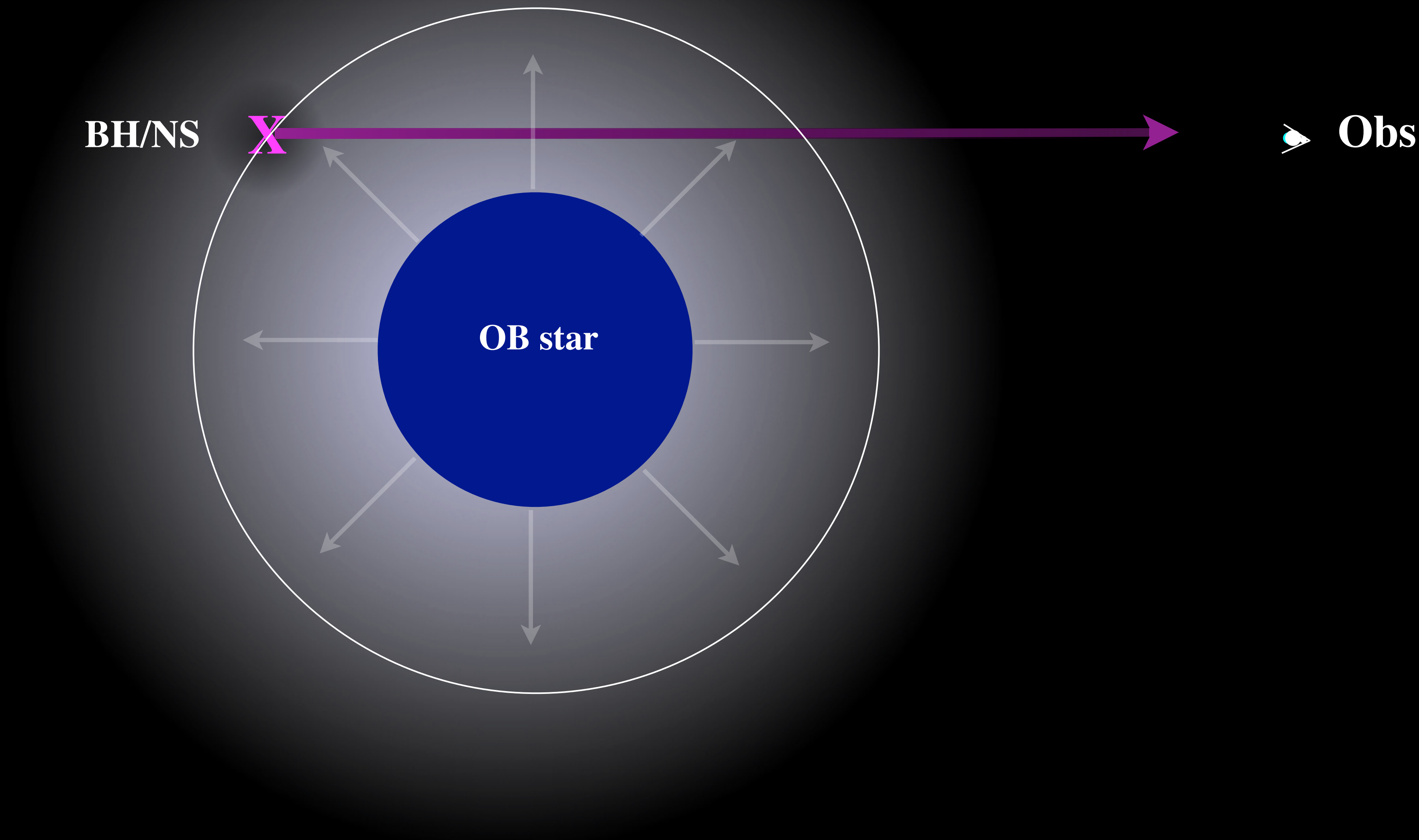
3D SPH sim of η Car CWB





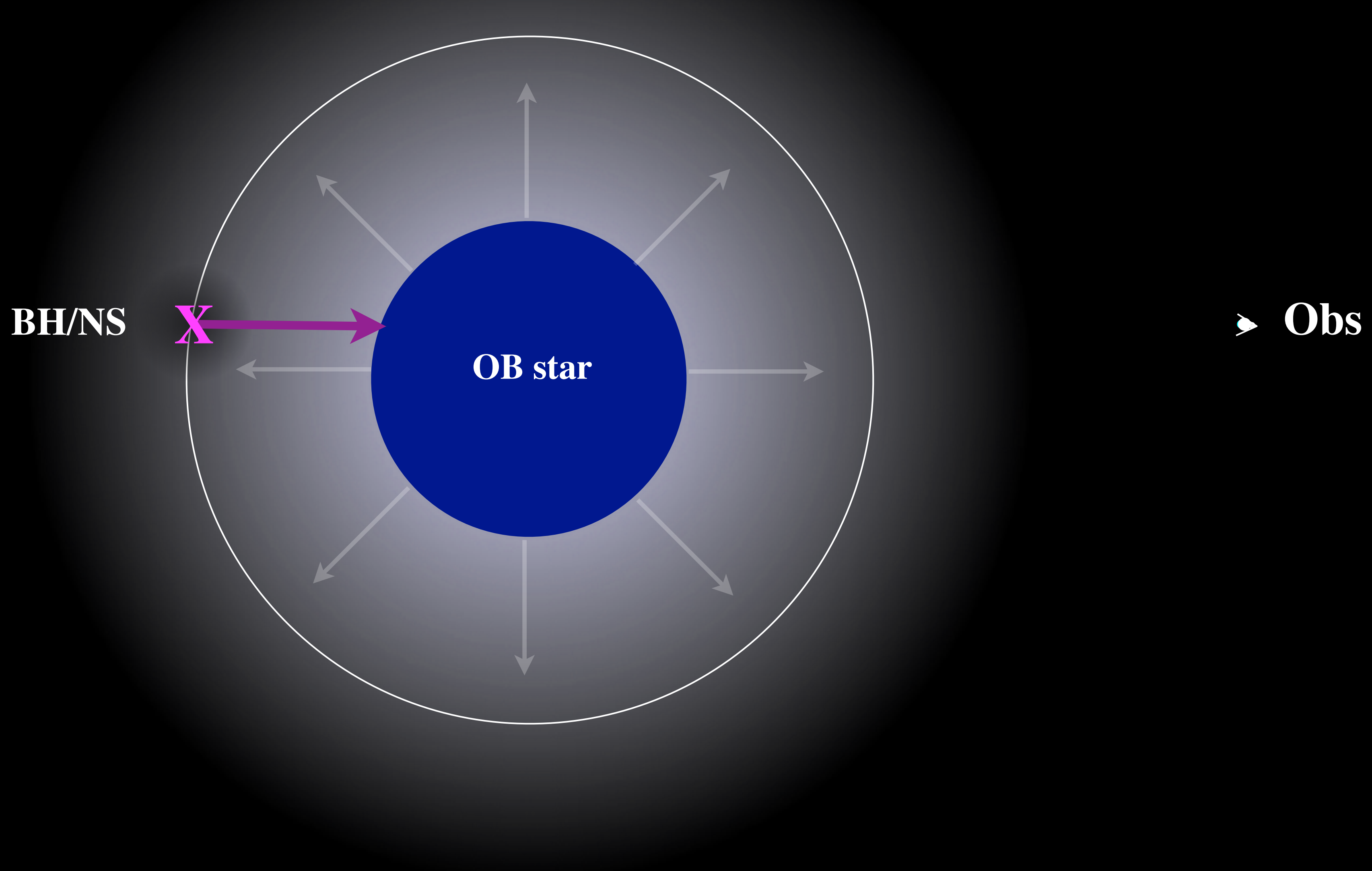
High-Mass X-Ray Binary

partial absorption by stellar wind

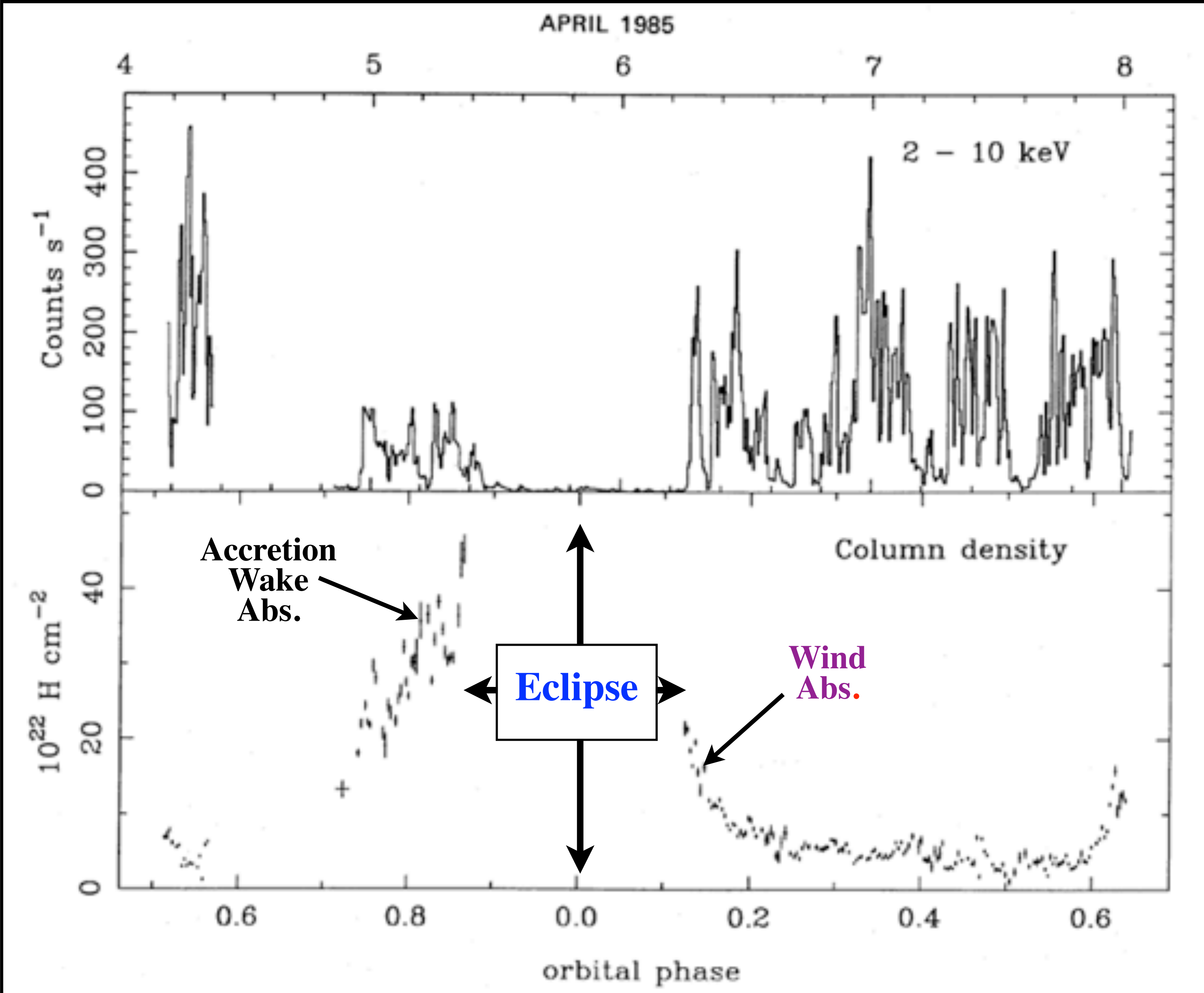


High-Mass X-Ray Binary

full absorption by stellar Eclipse



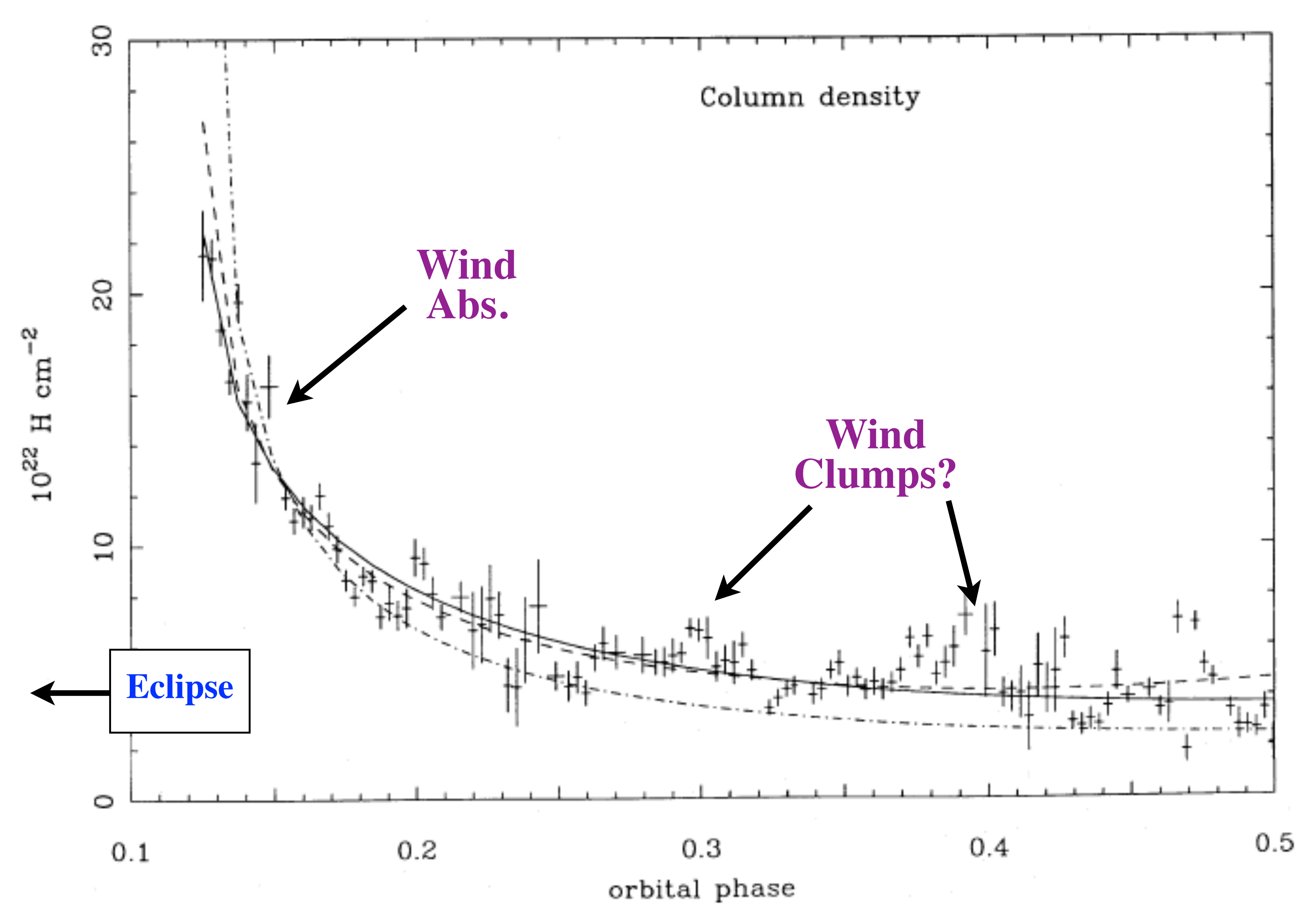
HMXRB X-ray light curve



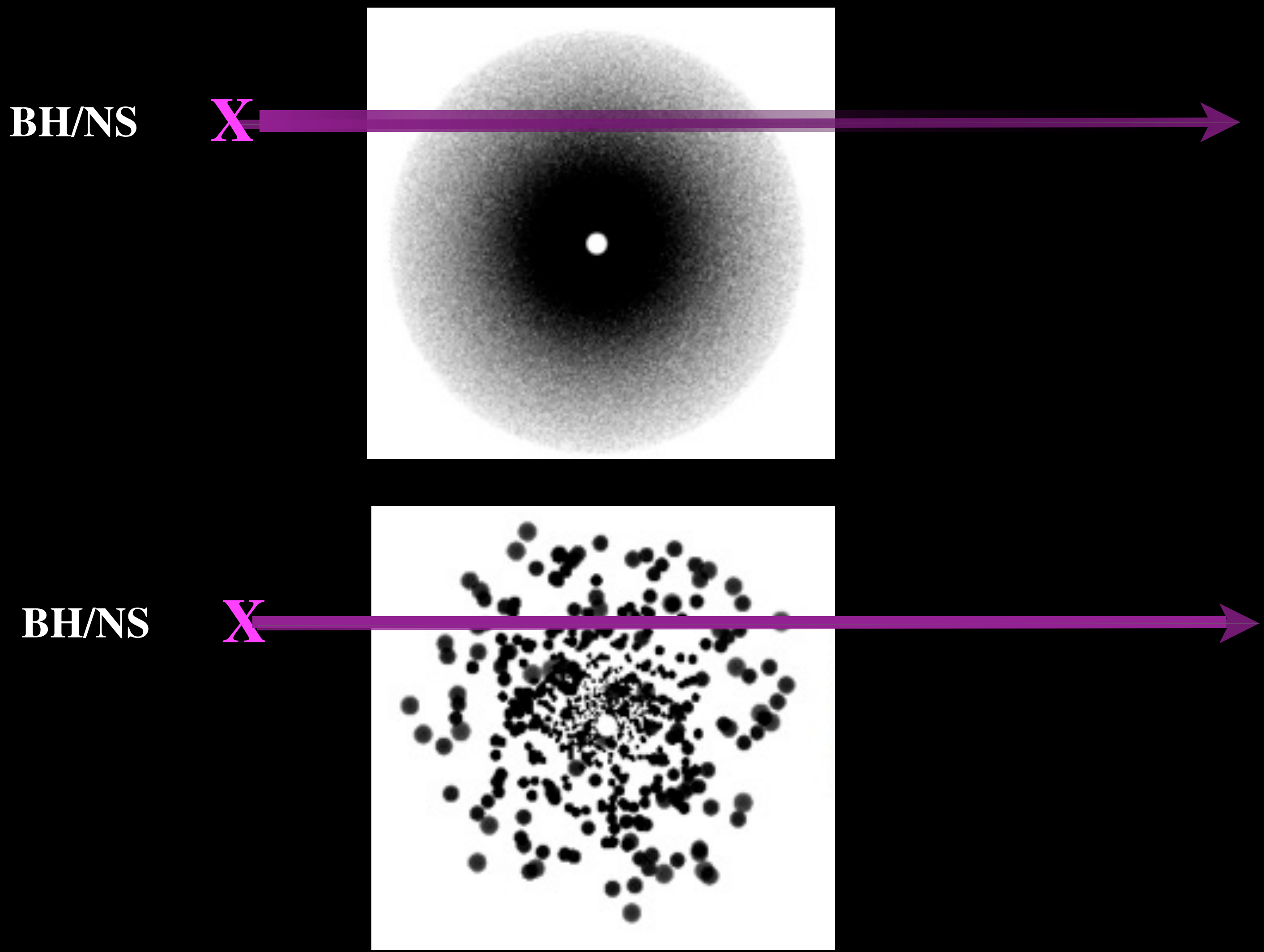
4U 1700-37
HD 153919

Haberl et al. 1989

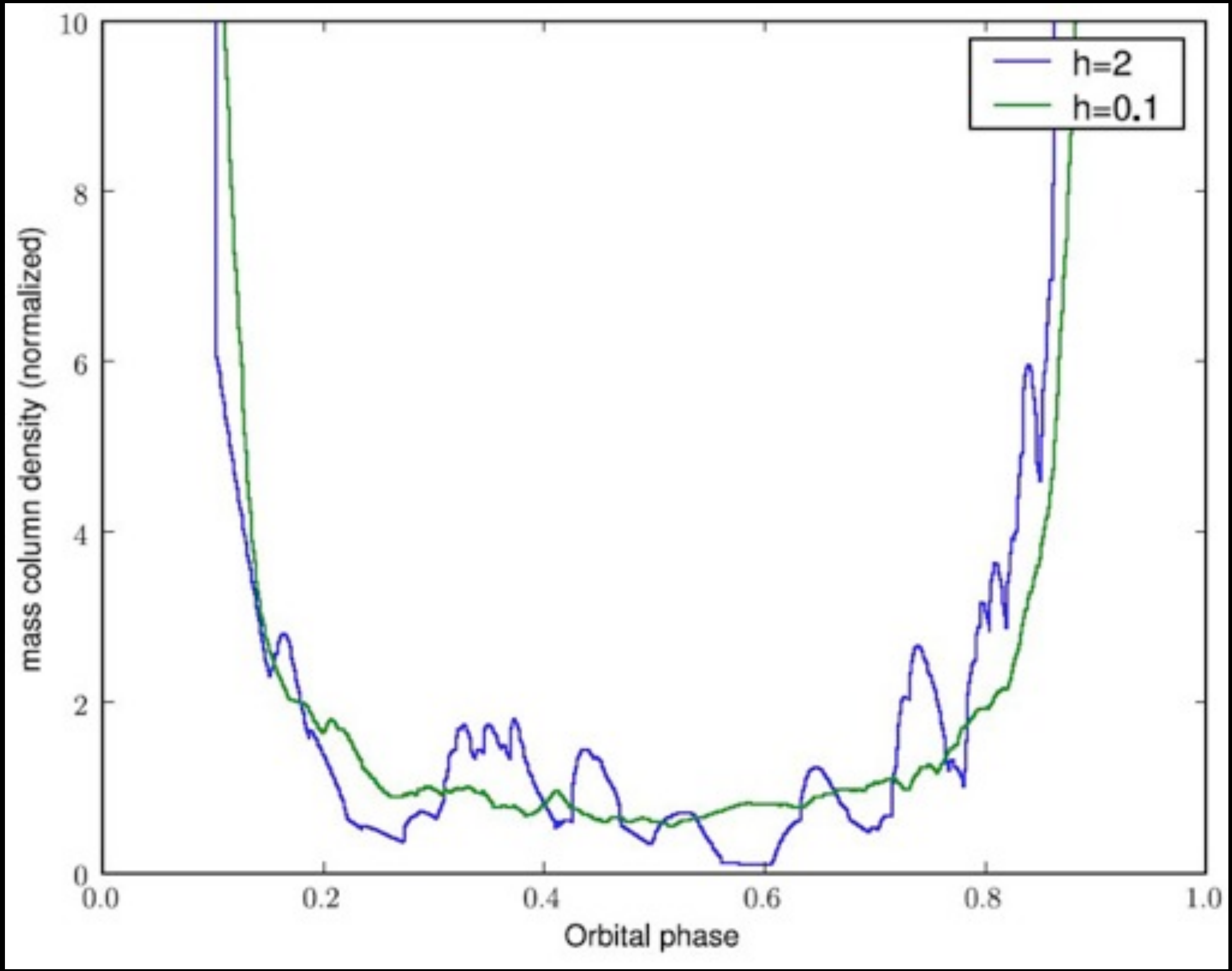
HMXRB light curve fluctuations



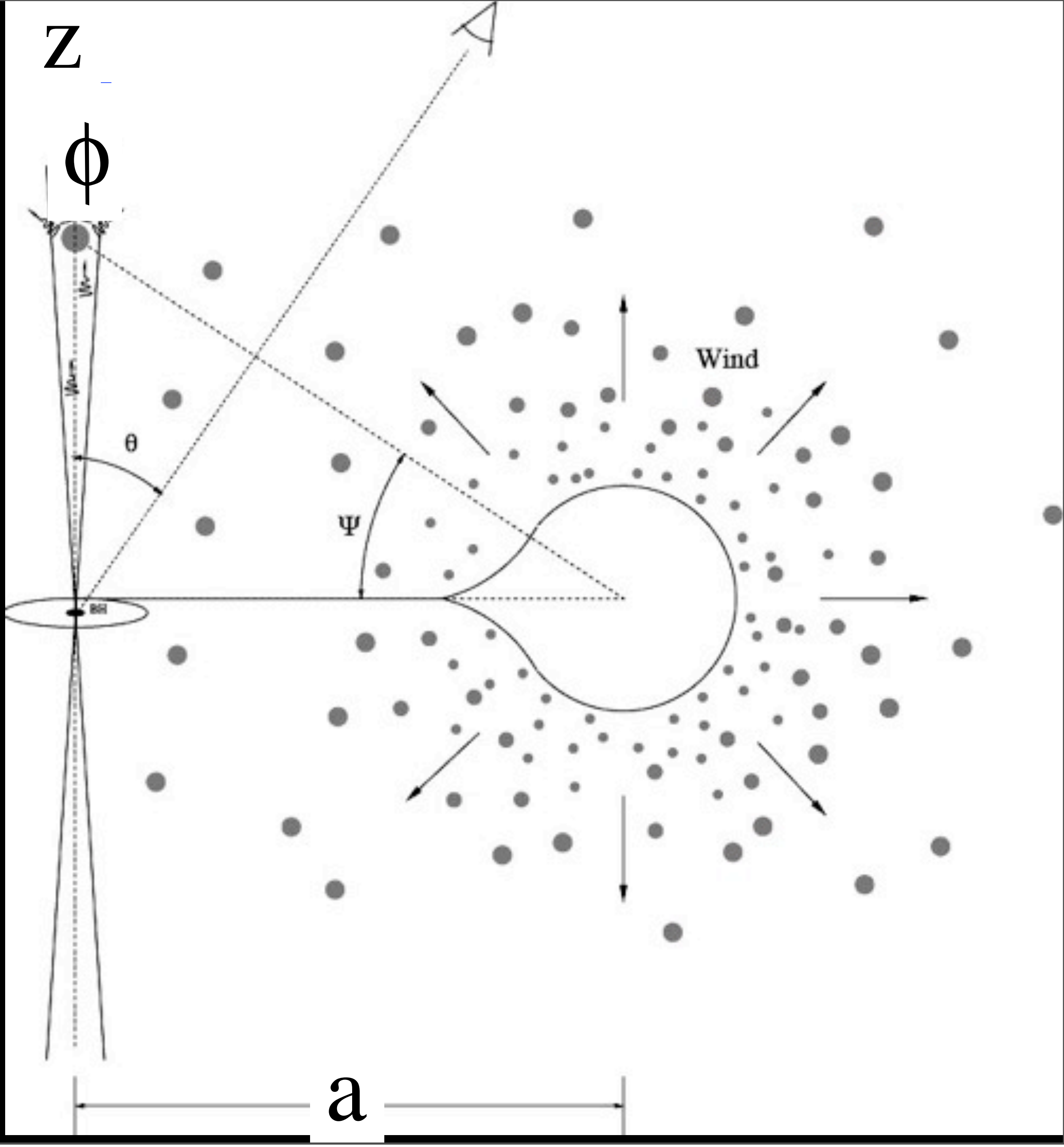
X-ray absorption in smooth vs. porous wind



Porosity Model for how wind clumps perturb light curve mass column



γ-ray emission in HMXRB with clumpy wind



γ-ray fluctuation from wind clumps

$$L_\gamma = L_j \sigma \int_0^\infty n(z)\, dz$$

 # clumps $\Delta N_c = \dfrac{\Delta z}{\boxed{h}}$ **mfp**

$$\delta L_\gamma \sim \sqrt{N_c}$$

$$\boxed{\frac{\delta L_\gamma}{L_\gamma} = \frac{\sqrt{\int_0^\infty n^2 h\, dz}}{\int_0^\infty n\, dz} = \sqrt{\frac{h}{\pi a}}}$$

Typical example

narrow jet with: l=h/10=0.03a

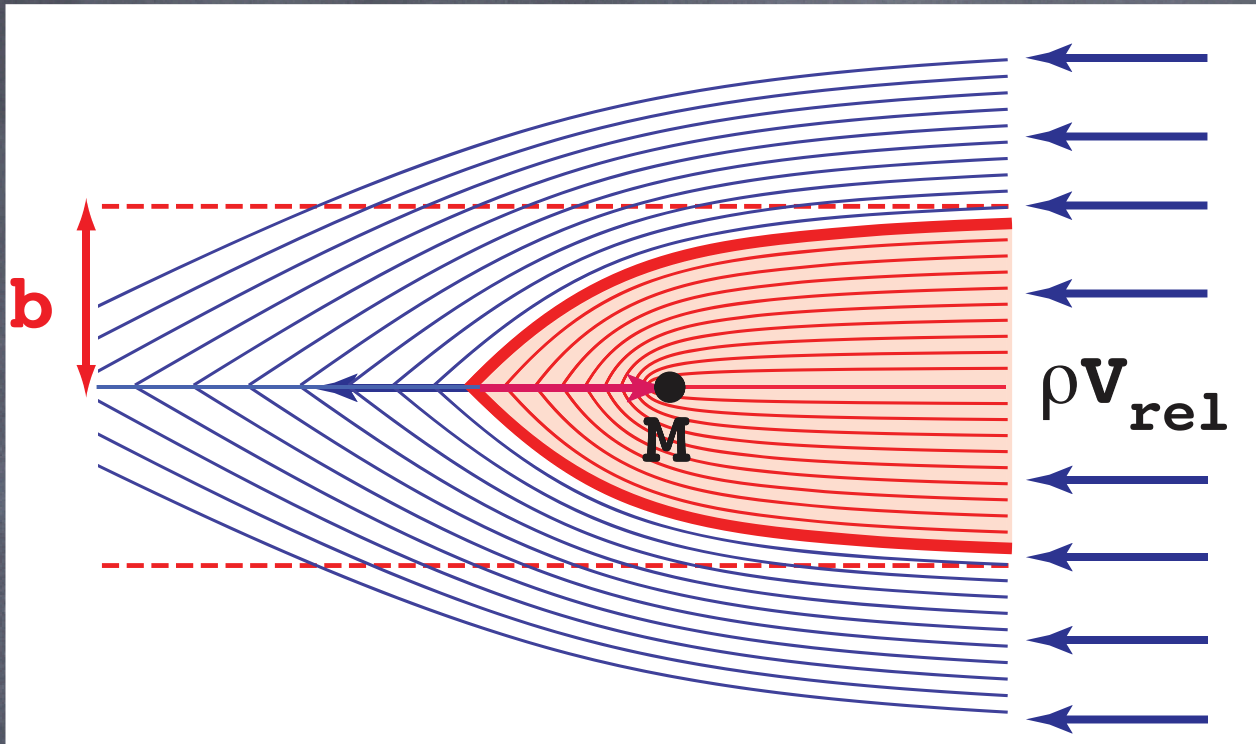
$$\frac{\delta L_\gamma}{L_\gamma} \approx \sqrt{\frac{h}{\pi a}} \approx 0.1 = 10\%$$

Modeling TeV gamma-rays from LS 5039: An Active OB Star at the Extreme

Stanley P. Owocki (BRI, Univ. Delaware)
Atsuo T. Okazaki (Hokkai-Gakuen Univ.)
Gustavo E. Romero (U. Nacional La Plata)

talk at Paris IAUS 272 July 2010

Bondi-Hoyle-Lyttleton (BHL) Accretion



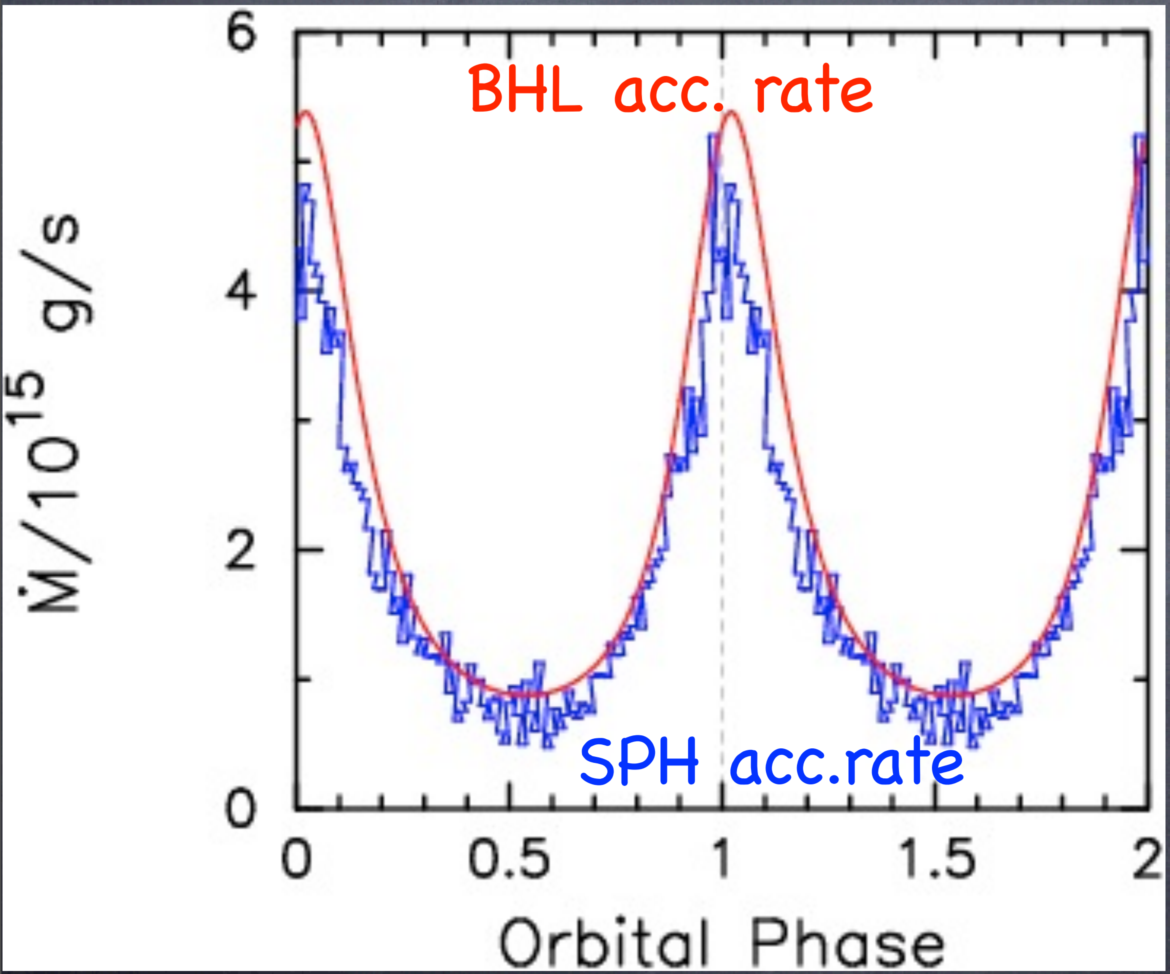
Bondi radius

$$b = \frac{GM_{BH}}{V_{rel}^2/2}$$

BHL accretion rate

$$\dot{M}_{BHL} = \rho V_{rel} \pi b^2 = \frac{G^2 M_{BH}^2 \dot{M}_w}{V_{rel}^3 V_w d^2}$$

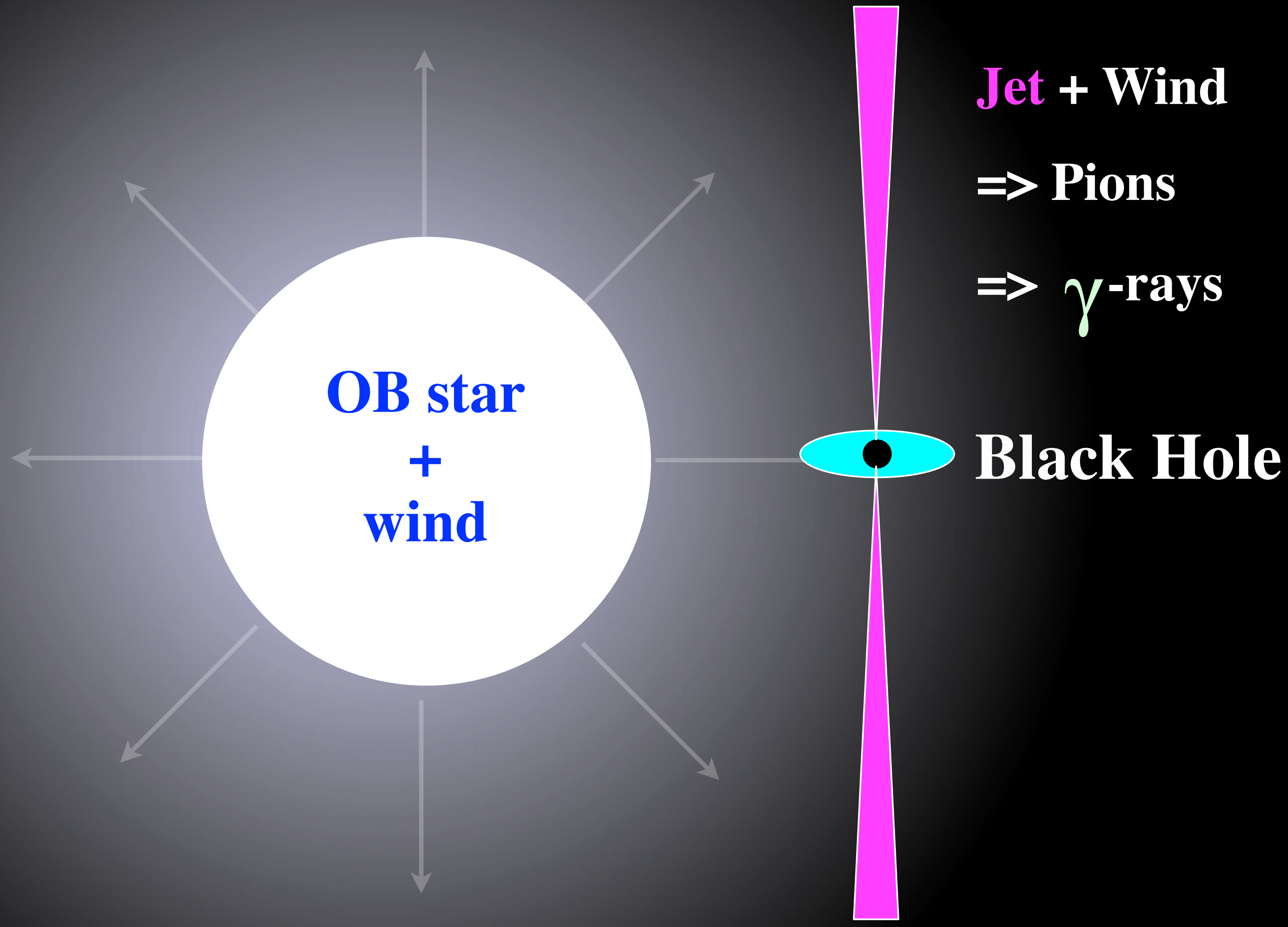
Orbital variation of SPH accretion closely follows Bond-Hoyle-Lyttleton rate



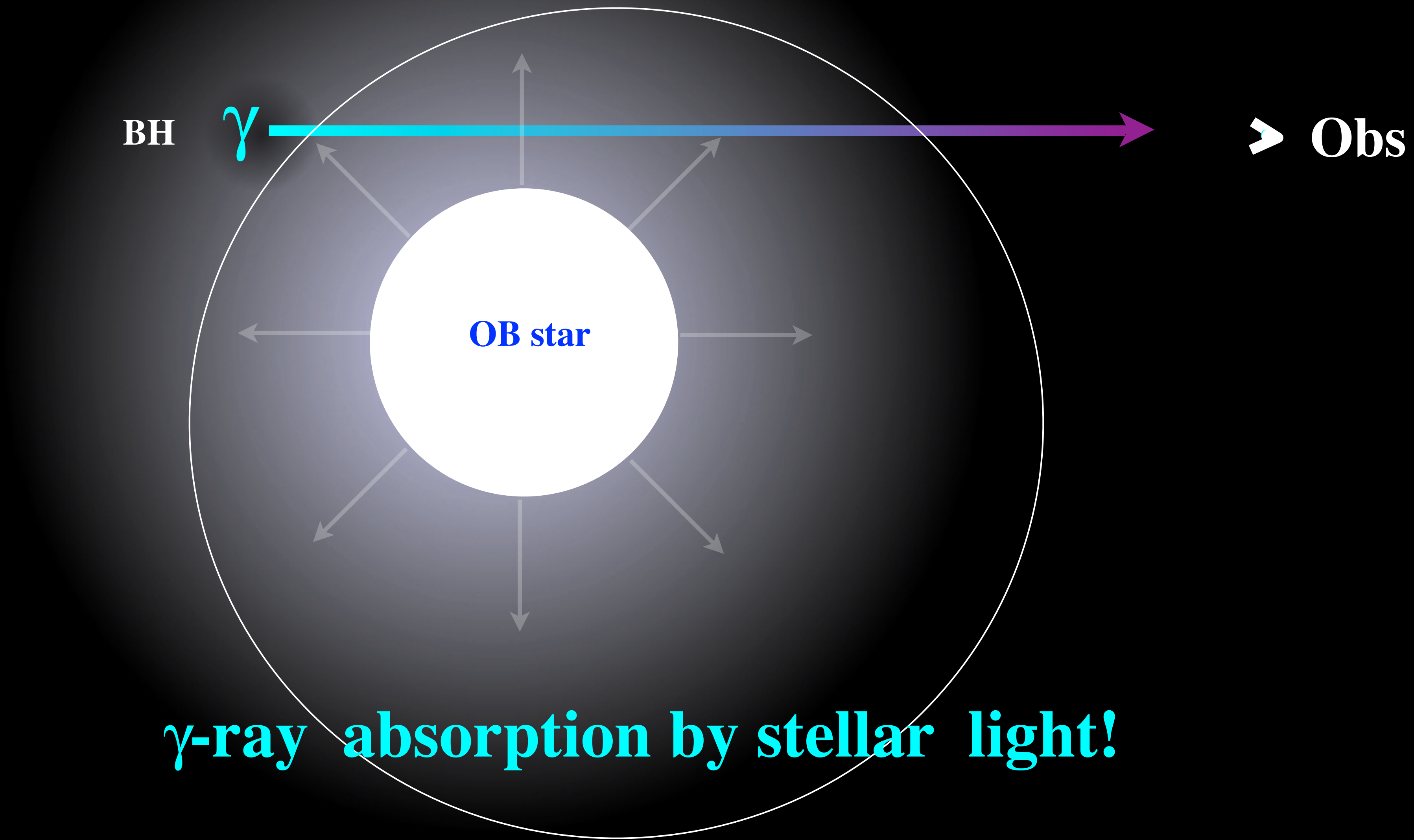
$$\dot{M}_{BHL} = \frac{G^2 M_X^2 \dot{M}_w}{V_{rel}^3 V_w d^2}$$

$$\beta = 1$$

MicroQuasar Model

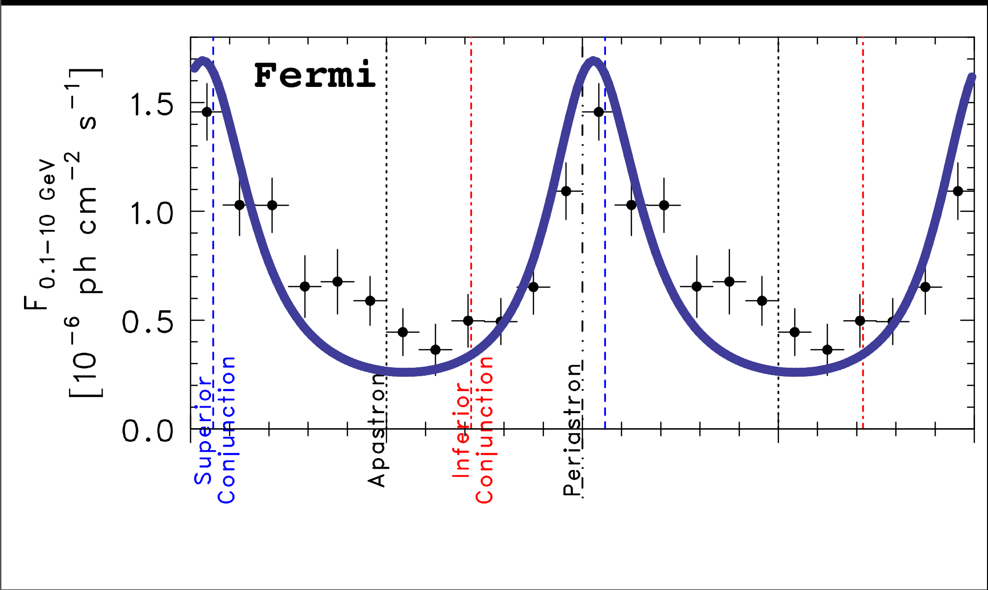


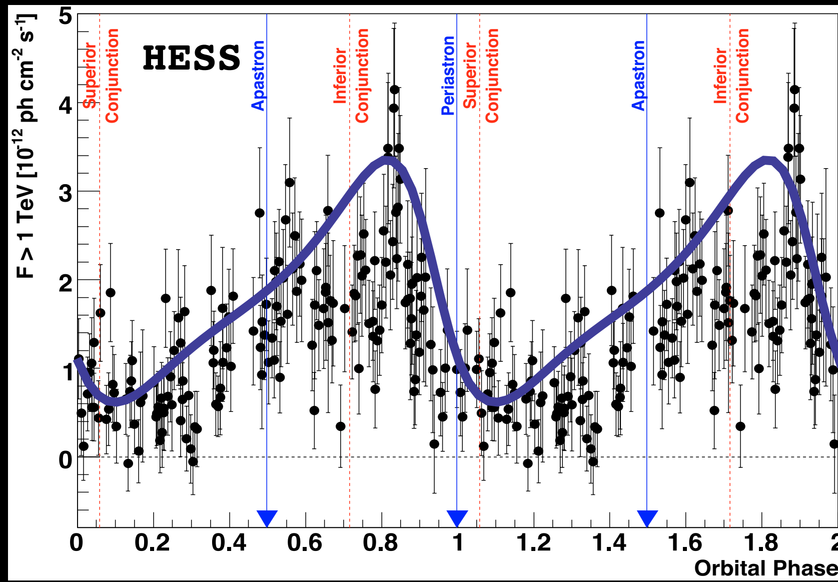
γ–γ Absorption



γ-ray absorption by stellar light!

LS 5039 γ-ray light curves



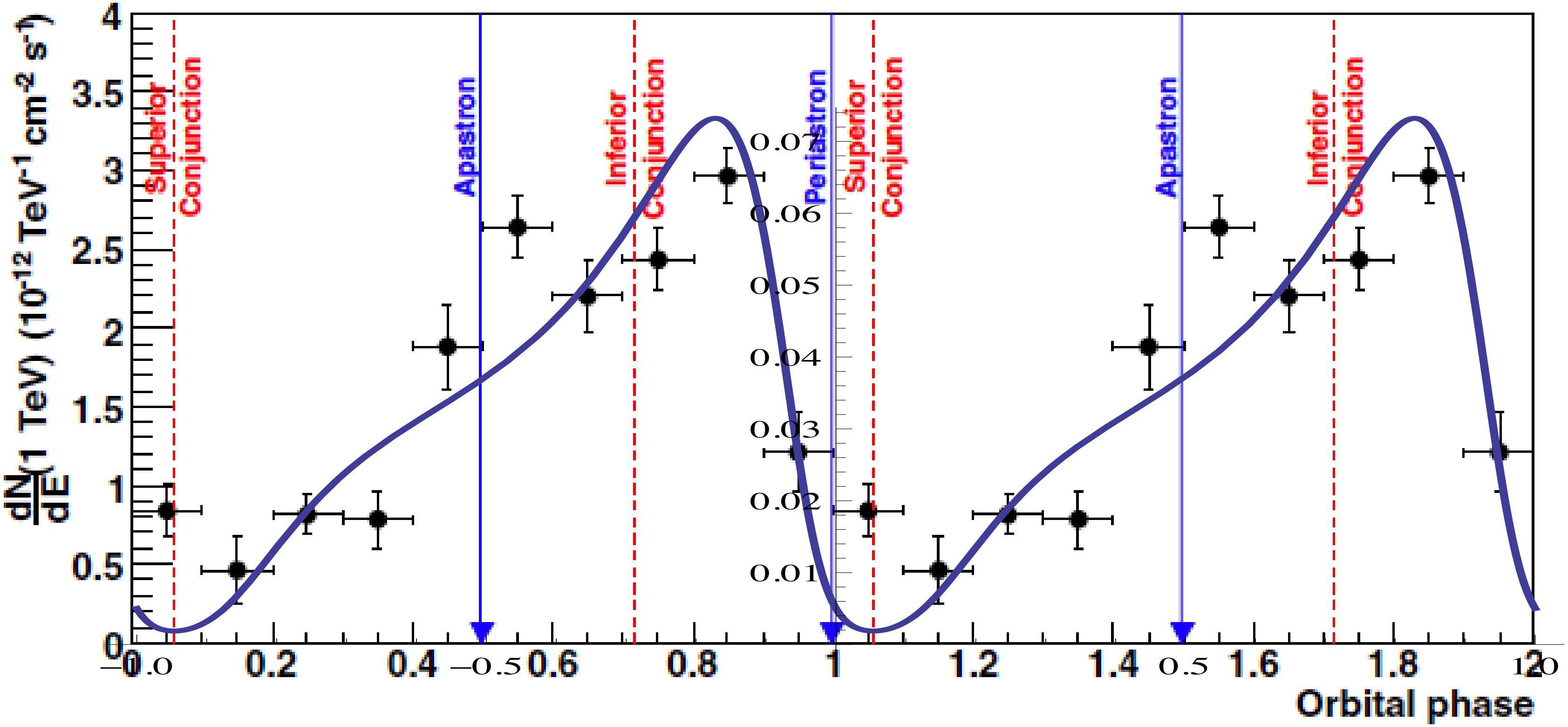


E=0.1-10 GeV:
below threshold for
γ–γ with stellar UV
NO ABS

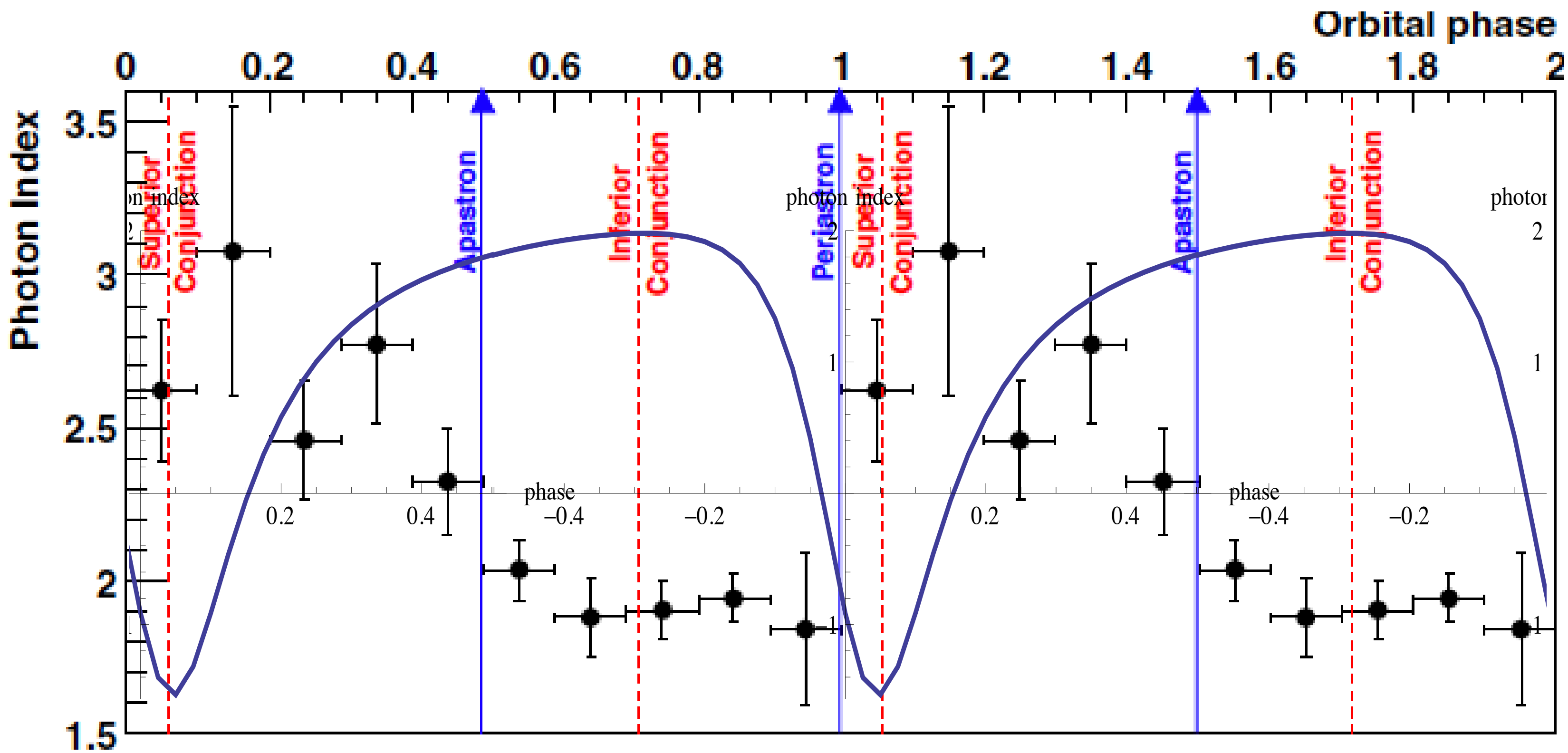
E > 1 TeV:
above threshold for
γ–γ with stellar UV
γ–γ ABS

HESS

normalization at E= 1 TeV



HESS photon index:



Need to include **Photon Cascade**

Summary

- Winds unstable => clumps, soft X-rays
- Colliding Winds in Binaries => harder X-rays
- Be CSM = polar wind + eq. VDD + ablation
- Porosity length h=size/f_{vol} key clump parameter
- In HMXRB => fluctuations in X-ray light curve
- Microquasar jets => γ-rays w/ fluct. ~ Sqrt[h/a]
- MQ model fits Fermi & HESS l.c. for LS5039
- But fitting spectrum requires photon cascade