Mass Loss from (Hot) Massive Luminous Stars

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Massive Stars in the Whirlpool Galaxy

Henize 70: LMC SuperBubble

Wind-Blown Bubbles in ISM

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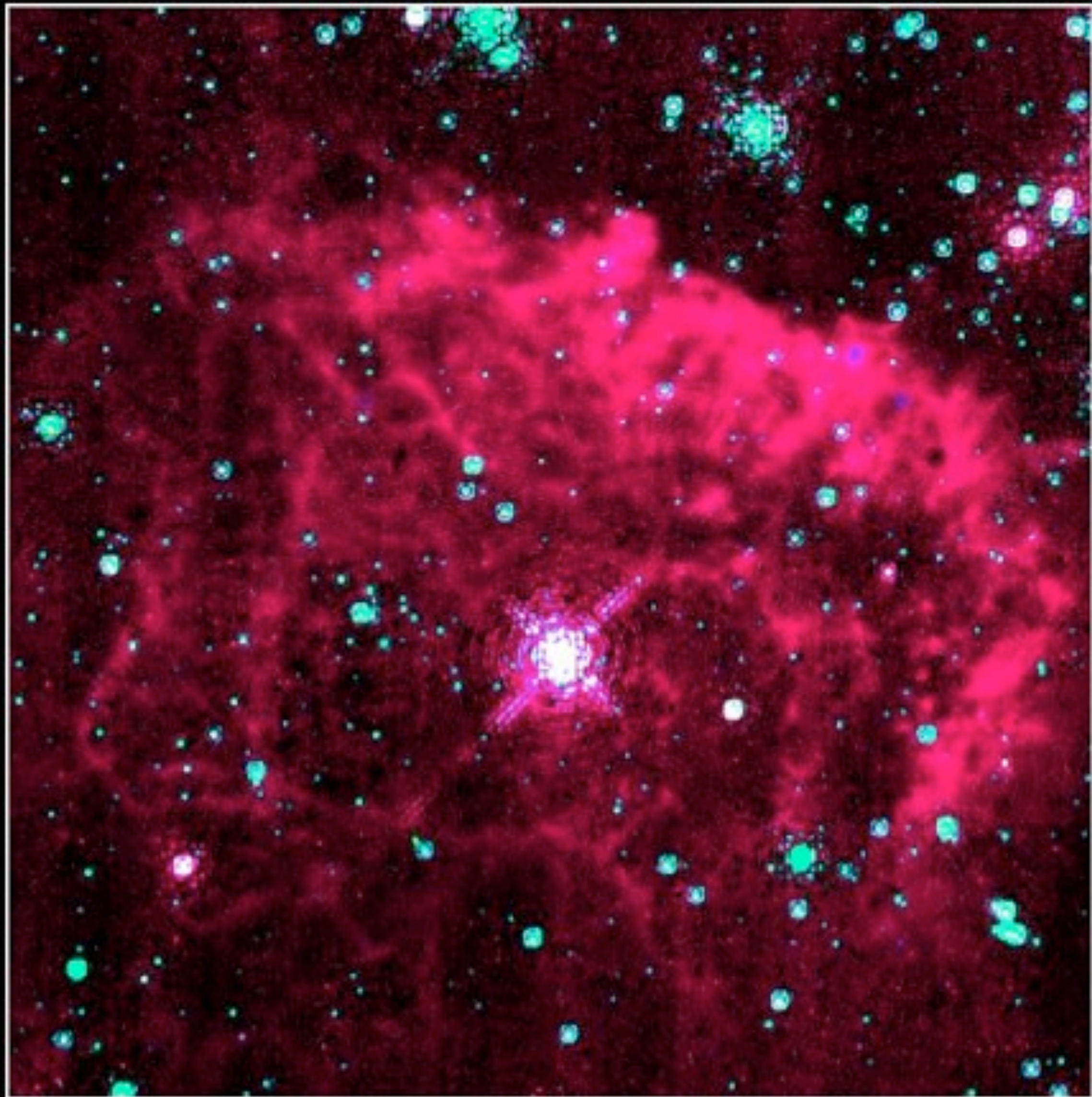
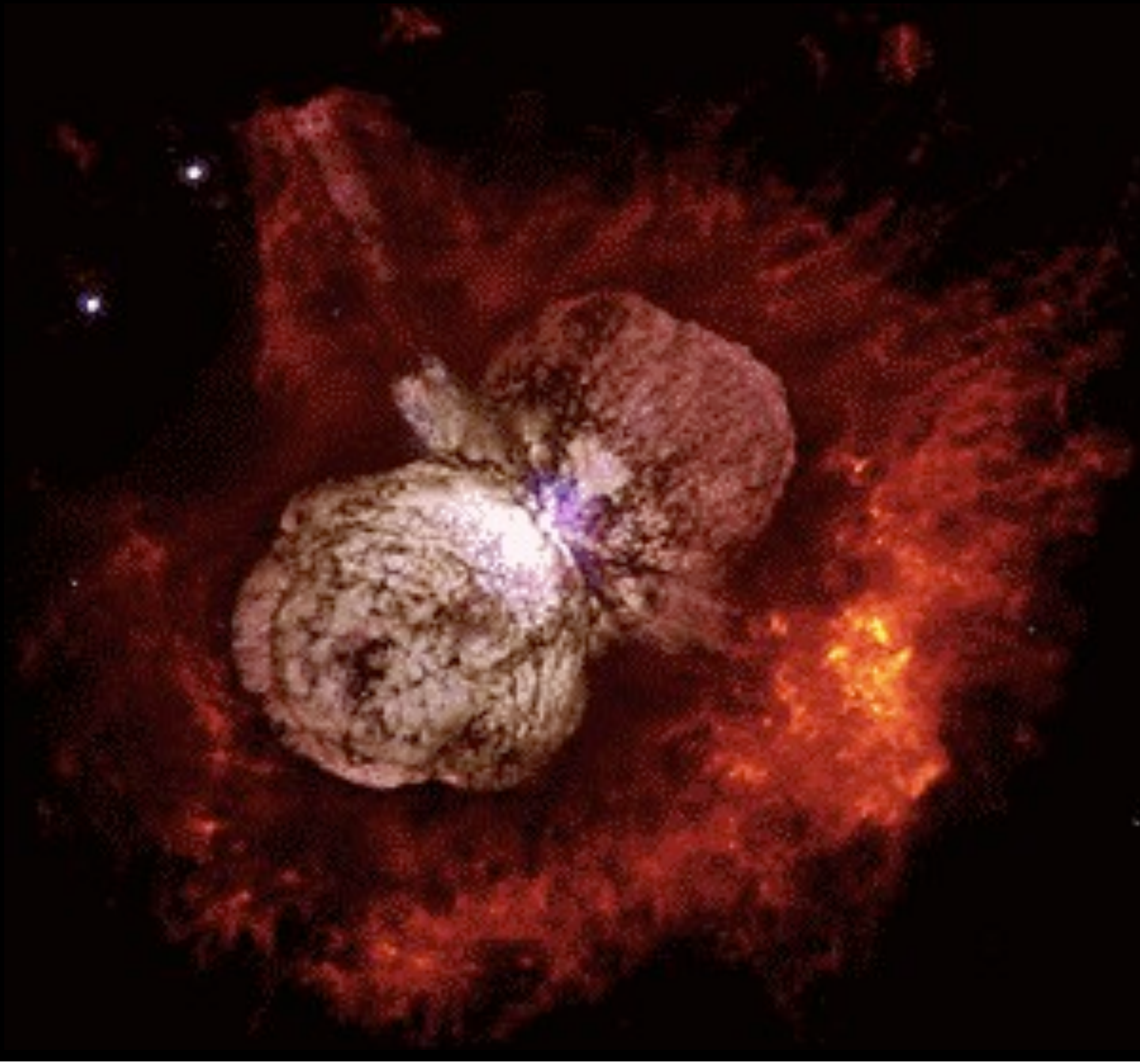
Pistol Nebula

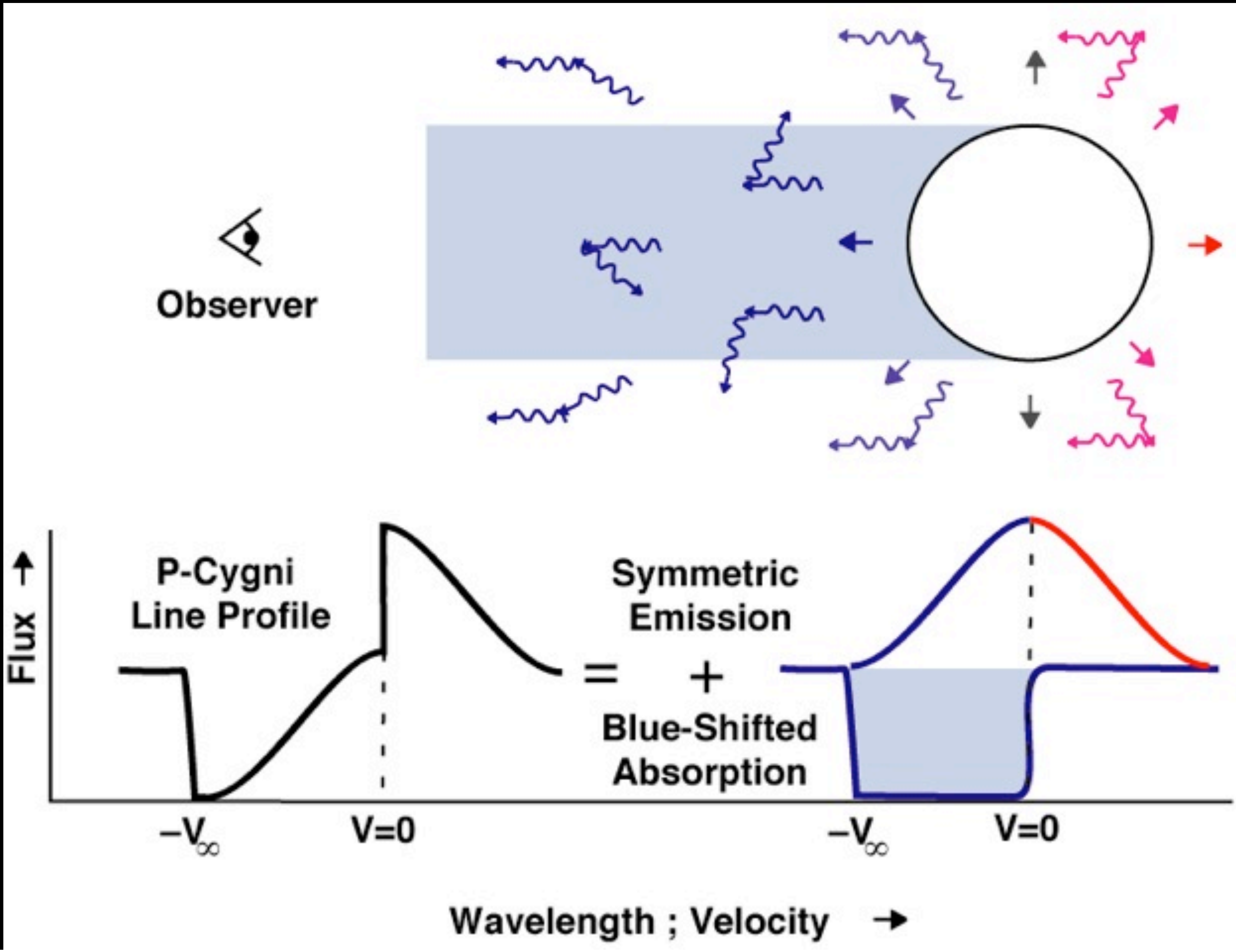


Pistol Nebula and Massive Star HST • NICMOS
PRC97-33 • ST ScI OPO • D. Figer (UCLA) and NASA

Eta Carinae

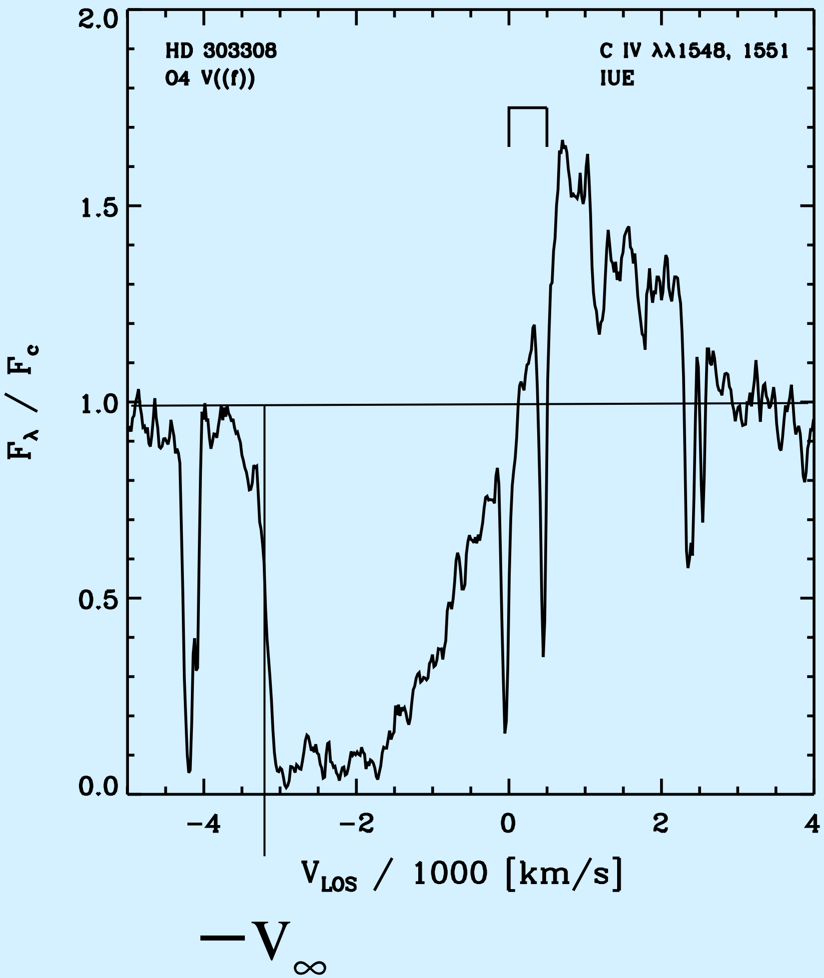


P-Cygni Line Profile

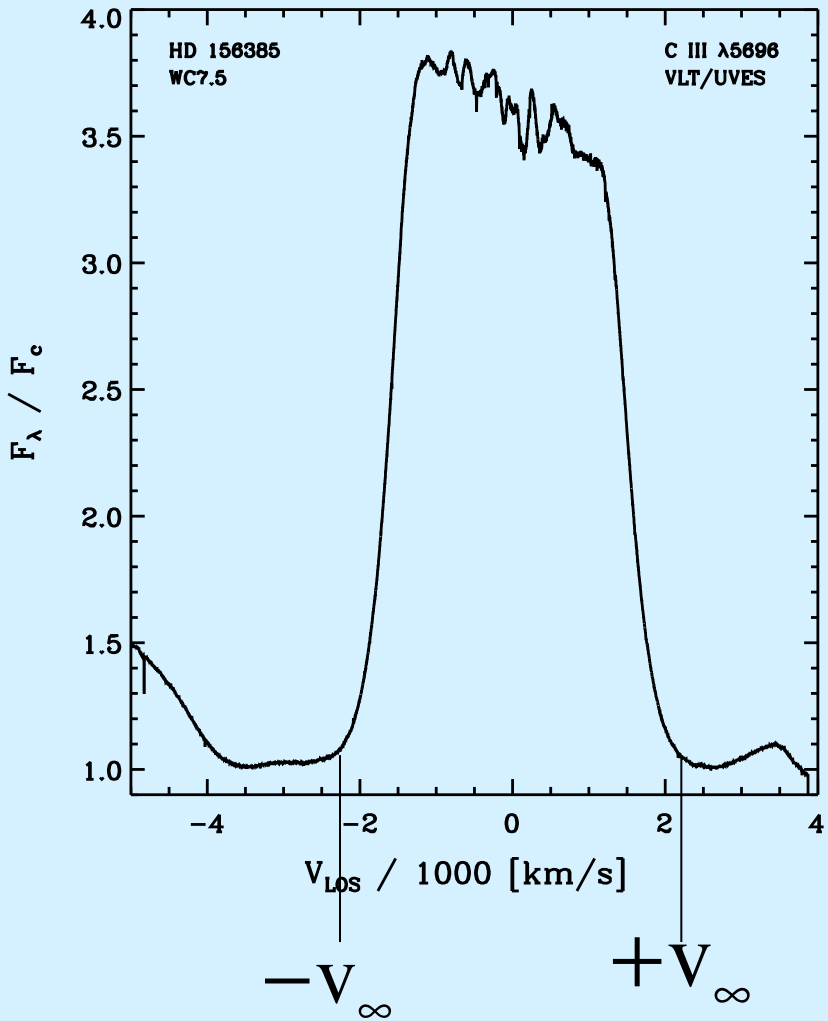


Observed wind line profiles

Resonance line-scattering
O-star P-Cygni profile



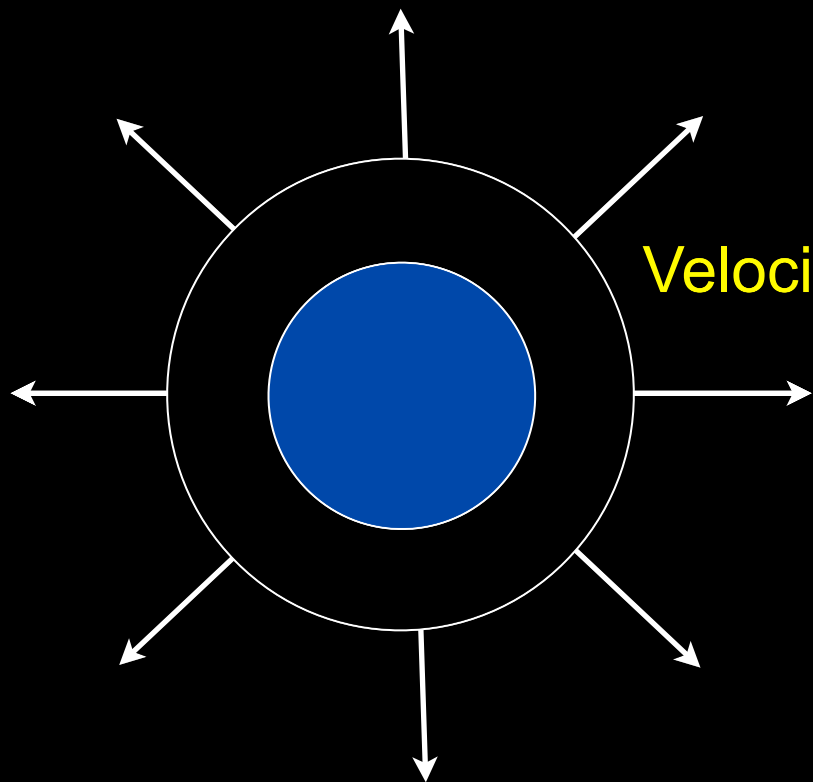
Recombination line
WR-star emission profile



Basic Mass Loss Properties

Mass Loss rate $\dot{M} = 4\pi\rho v r^2$

Terminal speed v_∞



Velocity law $v(r)$

Massive-Star Mass Loss

1. OB Winds

$\dot{M} \sim 10^{-9} - 10^{-6} \frac{M_\odot}{yr}$

– opt. thin $\tau_c < 1$

$v_\infty \sim 1000 - 3000\, km/s$

2. Wolf-Rayet Winds

$\dot{M} \sim 10^{-6} - 10^{-5} \frac{M_\odot}{yr}$

– opt. thick $\tau_c > 1$

$v_\infty \sim 1000 - 3000\, km/s$

3. Luminous Blue Variable (LBV) Eruptions

-very opt. thick $\tau_c \gg 1$

$\dot{M} \sim 10^{-5} - 1 \frac{M_\odot}{yr}$!!

$v_\infty \sim 50 - 1000\, km/s$

Q: What can drive such extreme mass loss??

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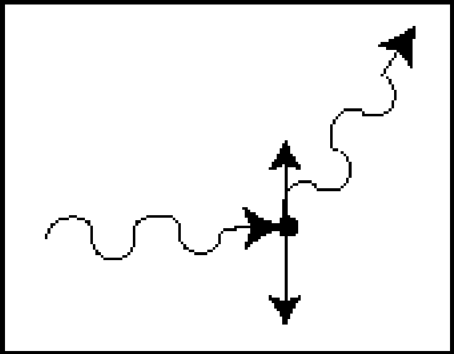
A: The force of light!

- light has momentum, p=E/c
- leads to "Radiation Pressure"
- radiation force from gradient of P_{rad}
- gradient is from opacity of matter
- opacity from both Continuum & Lines

Continuum opacity from Free Electron Scattering



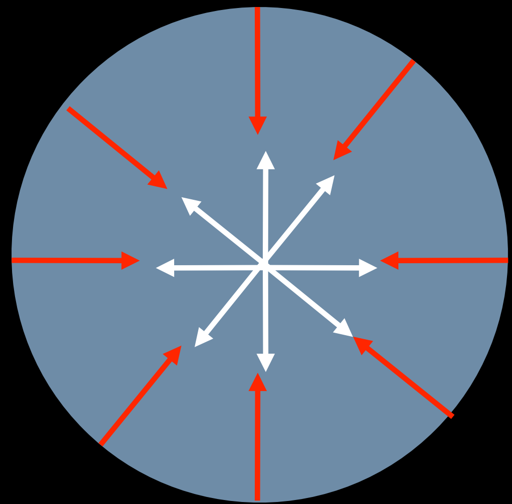
Thompson Cross Section

$\sigma_{Th} = 8\pi/3\ r_e^2 = 2/3$ barn$= 0.66 \times 10^{-24}$ cm^2

$$\kappa_e = \frac{\sigma_{Th}}{\mu_e} = 0.2(1+X) = 0.34\,\frac{cm^2}{g}$$

Radiative acceleration vs. gravity

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



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

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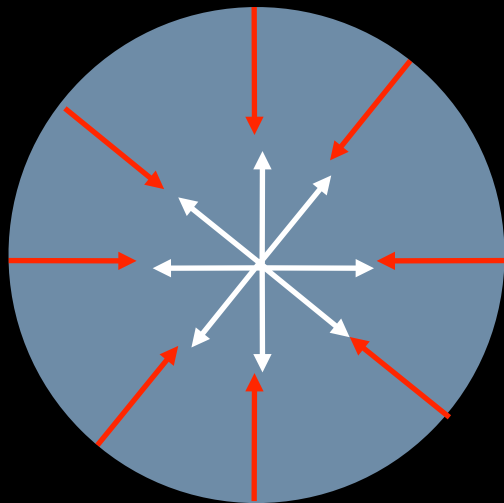

$$\frac{GM}{r^2}$$

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

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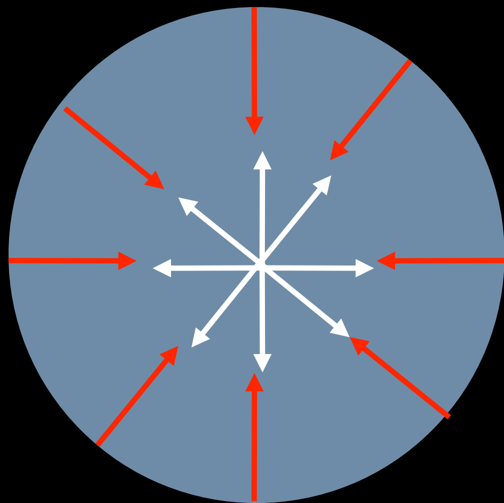

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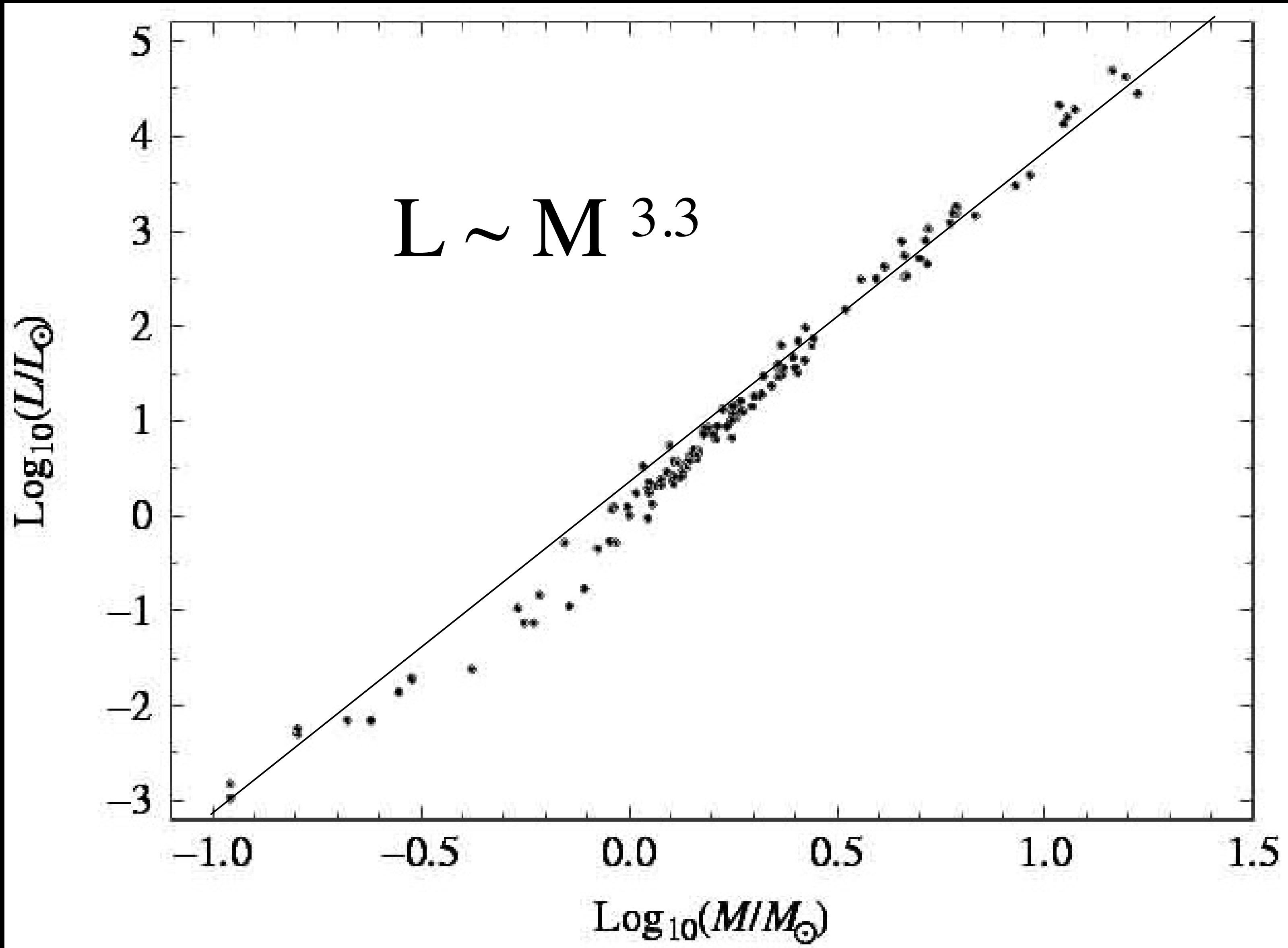
$$\Gamma \simeq 2 \times 10^{-5} \frac{L / L_\odot}{M / M_\odot} \frac{\overline{\kappa_F}}{\kappa_e}$$

Stellar Luminosity vs. Mass



Basic Stellar Structure -> L ~ M^3

cf. Lecture by Prof. Sugimoto

Hydrostatic equilibrium (Γ<<1):

$$\frac{dP_{gas}}{dr} = -\rho g$$

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$$\frac{dP_{rad}}{d\tau} = \frac{F}{c}$$

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Radiative diffusion:

$$\frac{dP_{rad}}{d\tau} = \frac{F}{c} \quad \Rightarrow \quad \frac{T^4}{\kappa M / R^2} \sim \frac{L}{R^2}$$

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$$L \sim \frac{M^3}{\kappa}$$

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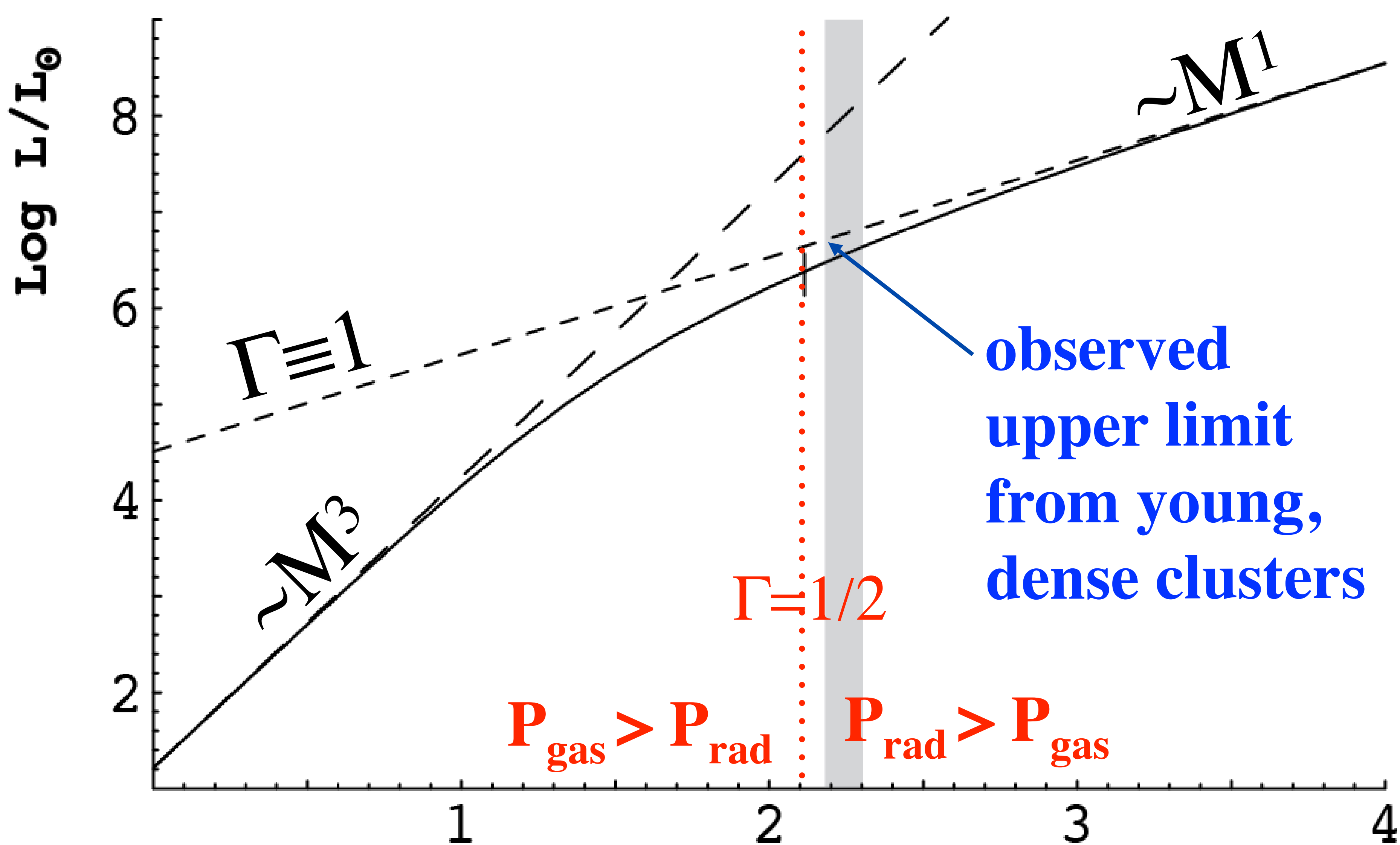
$$L \sim \frac{M^3}{\kappa}(1-\Gamma)^4$$

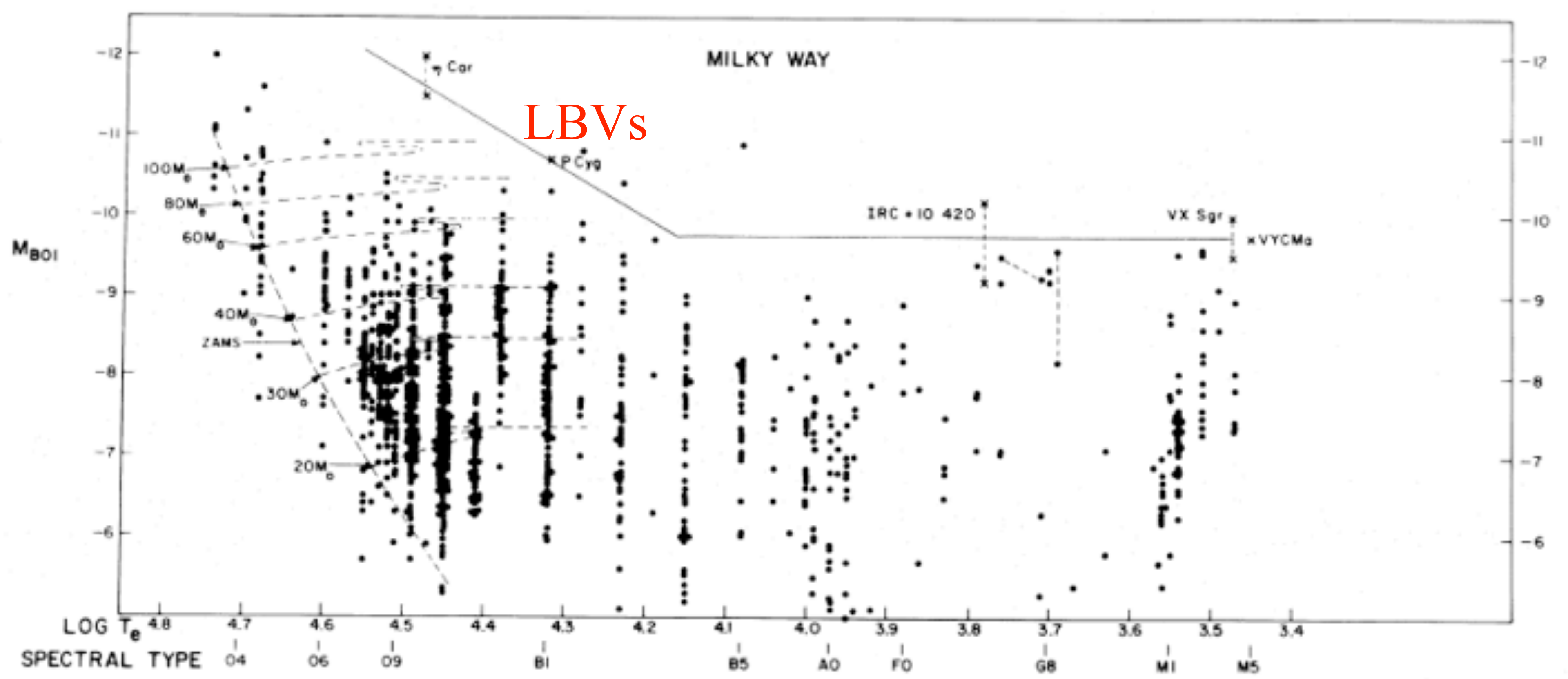
Eddington Standard Model (n=3 Polytrope)



Owocki & van Marle 2008, IAUS, 250, 71

Wednesday, January 12, 2011

Humphreys-Davidson Limit



Humphreys & Davidson 1979, ApJ, 232, 409

Key points

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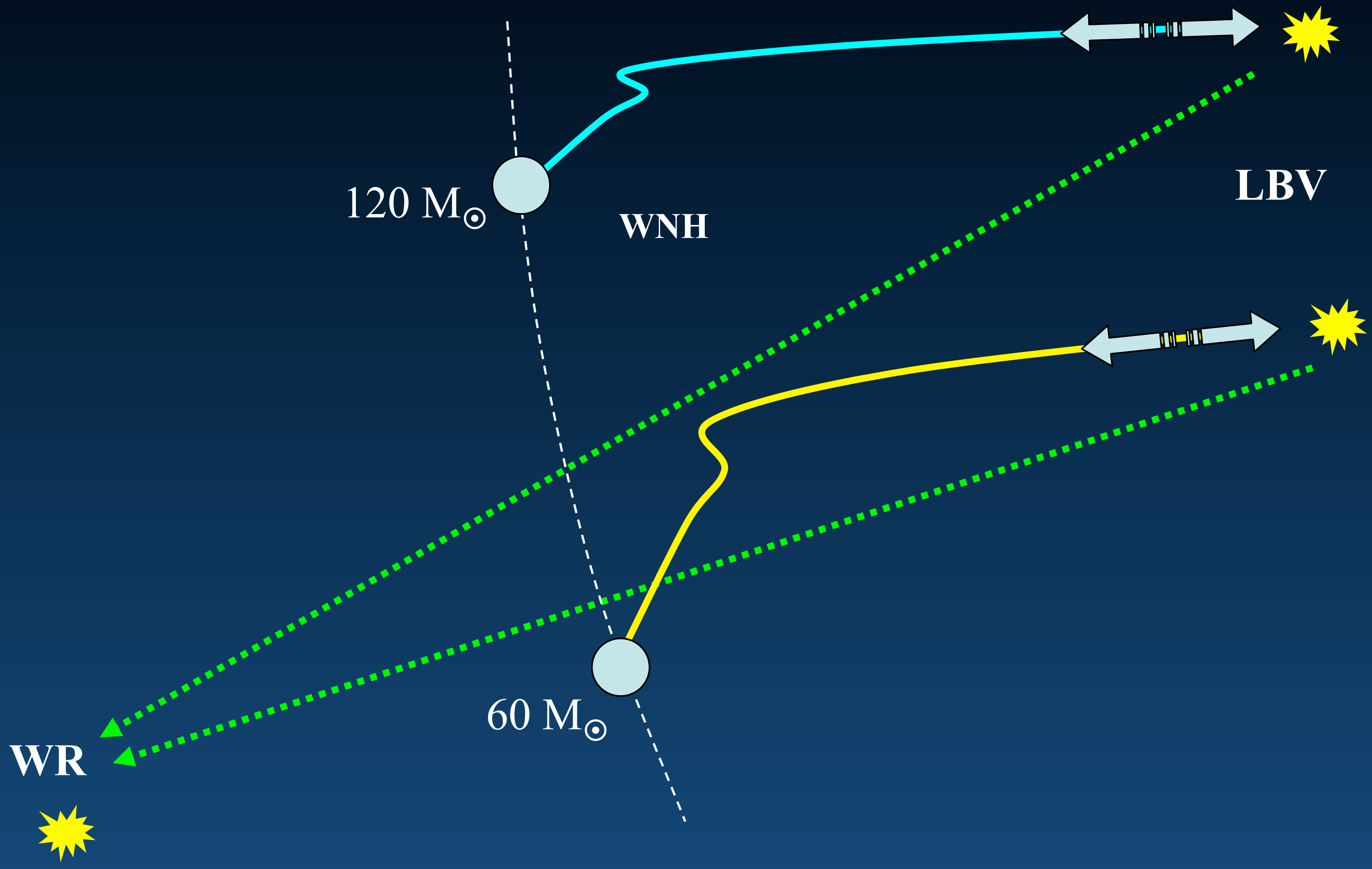
- Suggests natural explanation why we don't see stars much more luminous (& massive)

- $P_{rad} > P_{gas}$ => Instabilities => Extreme mass loss

Mass loss and stellar evolution:

Luminous Blue Variable (LBV) winds/eruptions



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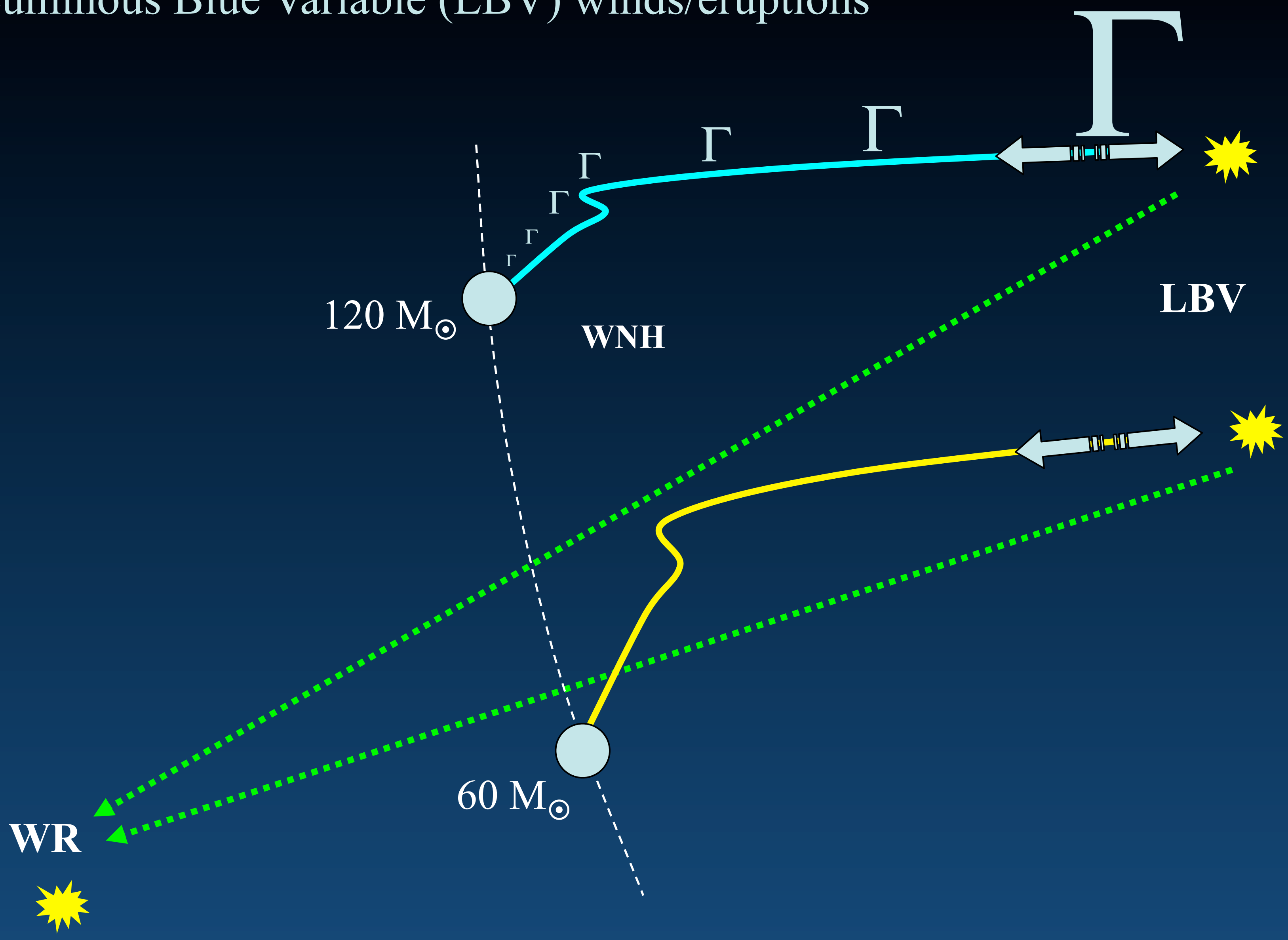

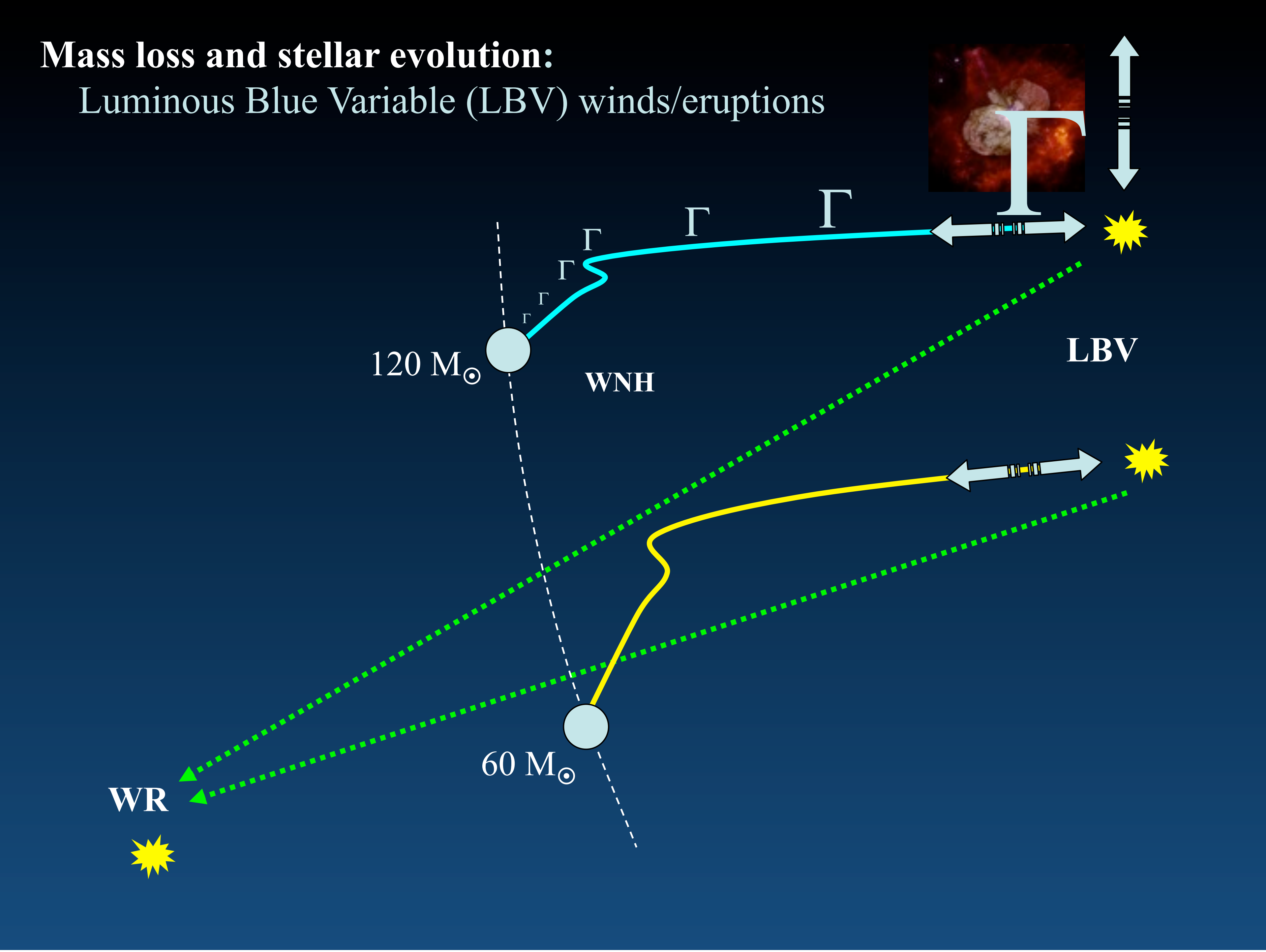
Mass loss and stellar evolution:
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Γ
Γ
Γ
Γ
Γ
Γ
Γ
120 M☉
WNH
LBV
60 M☉
WR

Mass loss and stellar evolution:

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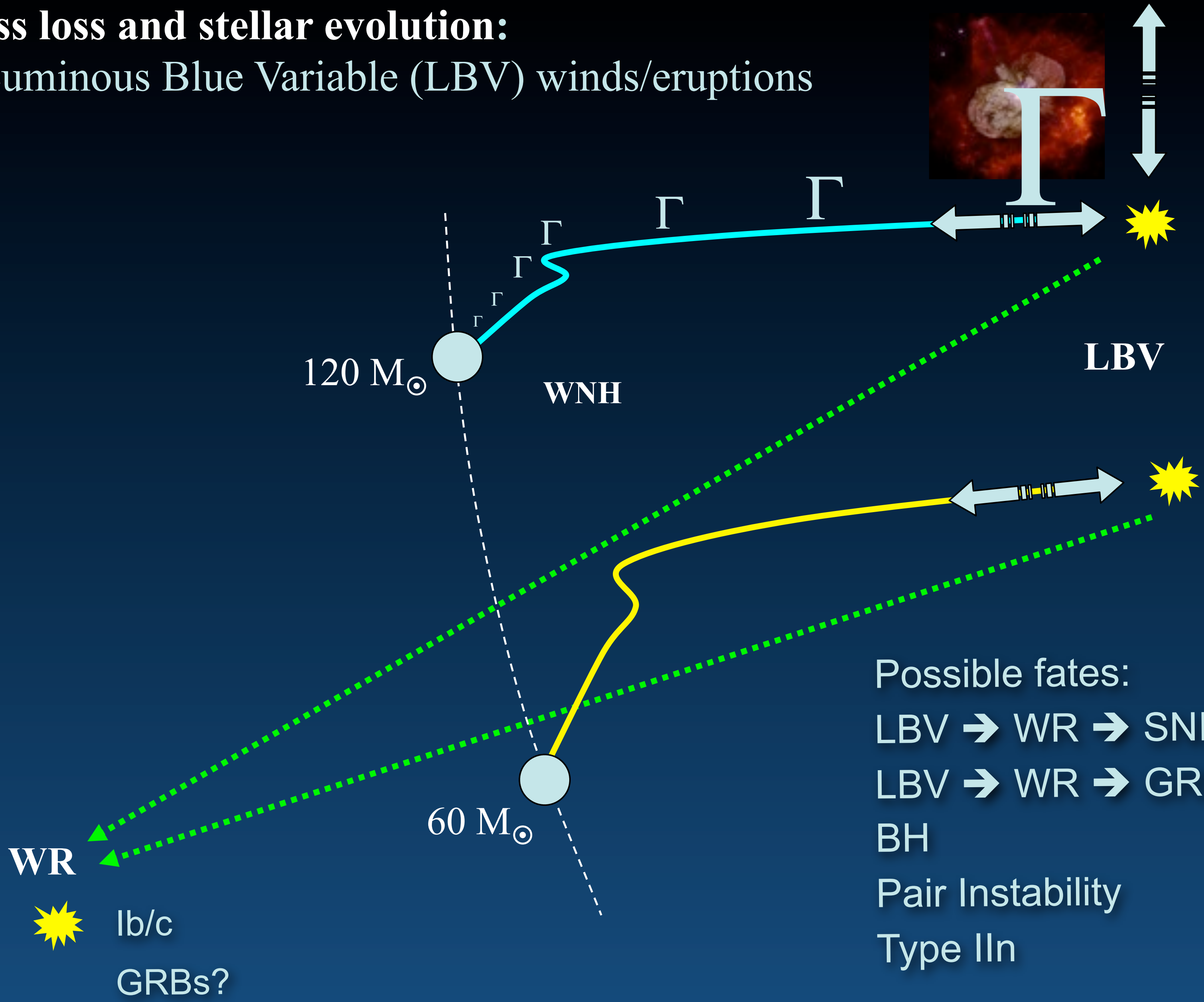

Possible fates:

LBV ➔ WR ➔ SNIbc

LBV ➔ WR ➔ GRB

BH

Pair Instability

Type IIn

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- But before trying to understand LBV eruptive mass loss, let's consider ways to get a steady, radiatively driven wind.
- Key requirement is for Gamma to increase above unity near the stellar surface.
- Two options:
  - Assume continuum opacity to increase outward
  - More naturally: Desaturation of line-opacity

Steady Wind Acceleration

Sound speed $a \equiv \sqrt{P / \rho}$

$$s = \frac{a^2}{v_{esc}^2} \approx 0.001 \frac{T_4}{M / R} \ll 1$$

Scale by gravity:

Accel. $$\frac{dw}{dx} = \Gamma - 1$$

$$x \equiv 1 - \frac{R}{r} \qquad w \equiv \frac{v^2}{v_{esc}^2}$$

Pot. En. **Kin. En. / Escape En.**

Steady Wind Acceleration

Sound speed $a \equiv \sqrt{P/\rho}$

$$s = \frac{a^2}{v_{esc}^2} \approx 0.001 \frac{T_4}{M/R} \ll 1$$

If we neglect gas pressure, steady force balance is simply:

$$v \frac{dv}{dr} = -\frac{GM}{r^2} + g_{rad}$$

Scale by gravity:

Accel.

$$\boxed{\frac{dw}{dx} = \Gamma - 1}$$

$$x \equiv 1 - \frac{R}{r}$$

Pot. En.

$$w \equiv \frac{v^2}{v_{esc}^2}$$

$$\frac{\textbf{Kin. En.}}{\textbf{Escape En.}}$$

Simplest example of radiatively driven wind

Zero sound speed limit (a=0) with constant "anti-gravity" $\Gamma > 1$

$$w' = \Gamma - 1$$

Integrate with B.C. $w(0) = 0$

$$w(x) = w_\infty x$$

$$\mathrm{v}(r) = \mathrm{v}_\infty \left(1 - \frac{R}{r}\right)^{1/2}$$

$$\mathrm{v}_\infty = \sqrt{w_\infty}\,\mathrm{v}_e = \sqrt{\Gamma - 1}\,\mathrm{v}_e$$

Note: Density independence leaves mass loss rate undetermined.

And ignores energy requirement (photon "tiring").

The “beta” velocity law

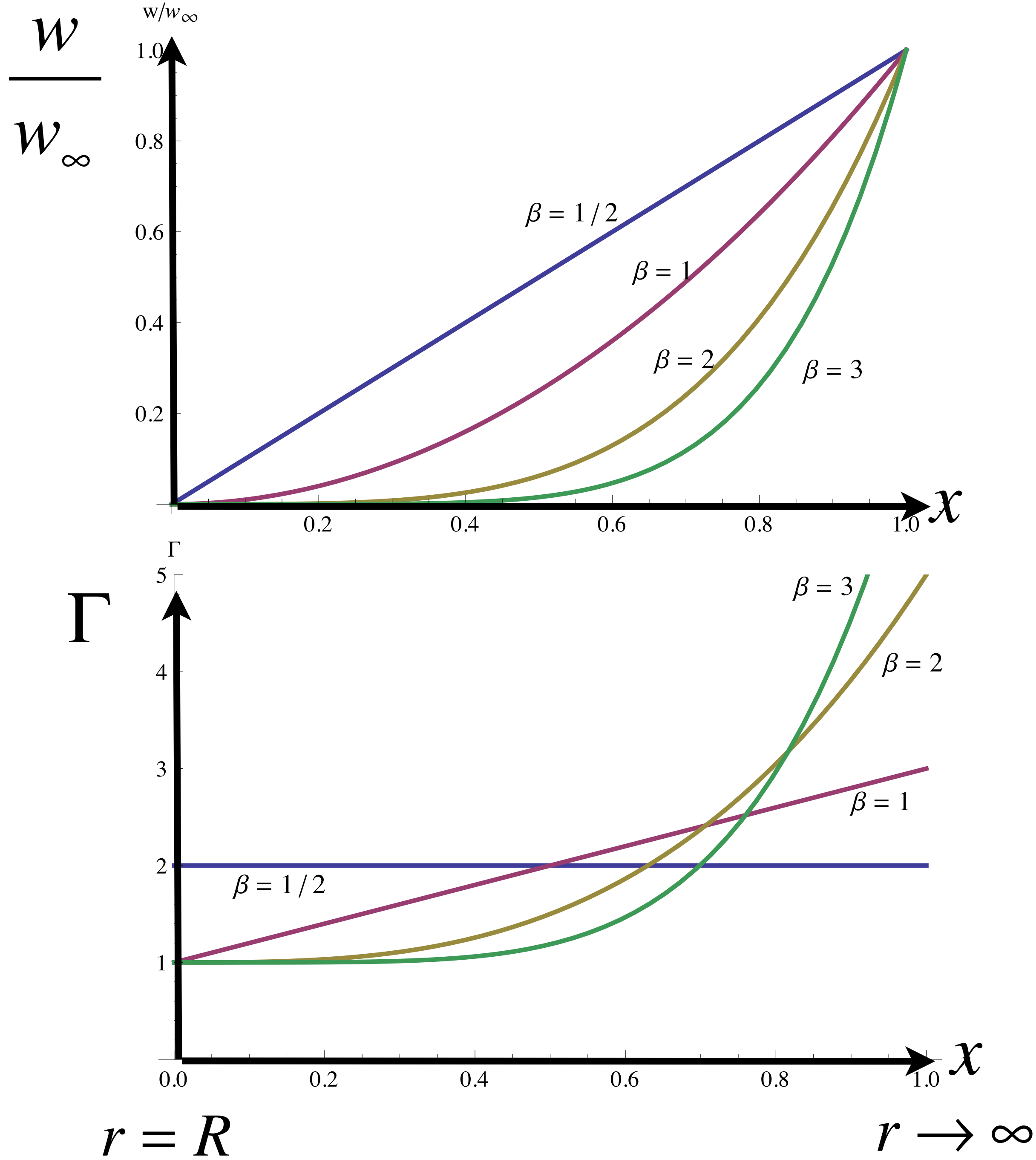
Empirical fitting law:

$$\mathrm{v(r)} = \mathrm{v}_\infty \left(1 - \frac{R}{r}\right)^\beta$$

$$w(x) = w_\infty x^{2\beta}$$

Dynamically requires a specific radial increase in opacity:

$$\Gamma(x) = 1 + w' = 1 + 2\beta w_\infty x^{2\beta - 1}$$



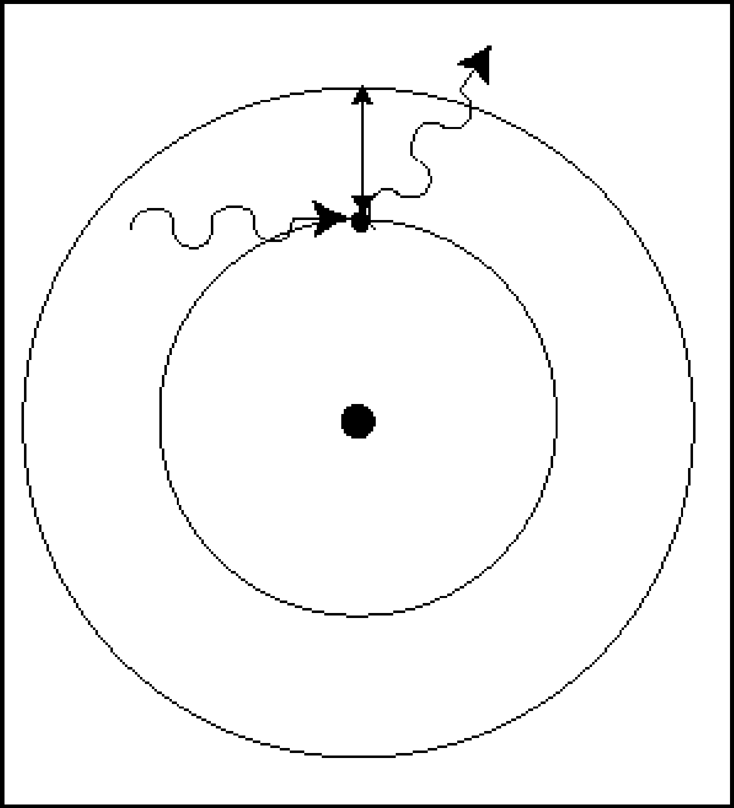
w/w∞
w/w∞
1.0
0.8
0.6
0.4
0.2
β = 1/2
β = 1
β = 2
β = 3
0.2
0.4
0.6
0.8
1.0
x
Γ
Γ
5
4
3
2
1
β = 3
β = 2
β = 1
β = 1/2
0.0
0.2
0.4
0.6
0.8
1.0
x
r = R
r → ∞

Line-Driven Stellar Winds

- A more natural model is for wind to be driven by line scattering of light by electrons bound to metal ions
- This has some key differences from free electron scattering...

Driving by Line-Opacity

Optically **thin**



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

Owocki 2009, AIPC, 1171, 173

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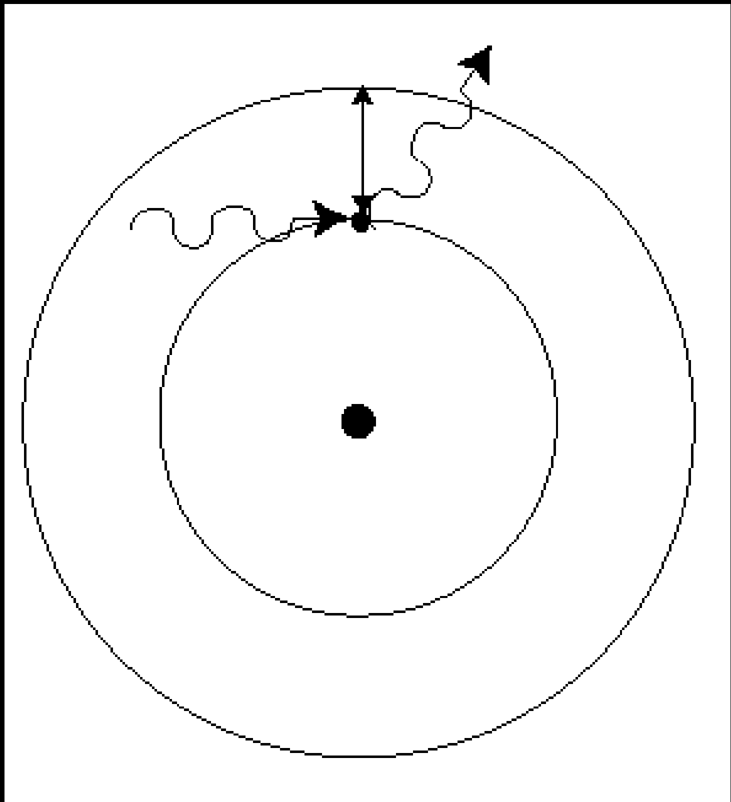

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Owocki 2009, AIPC, 1171, 173

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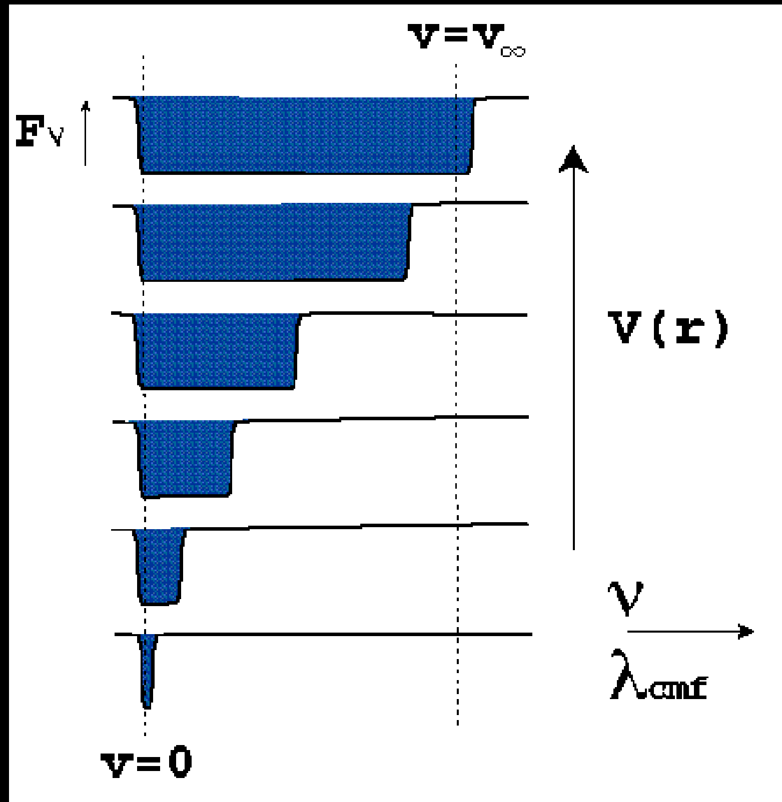
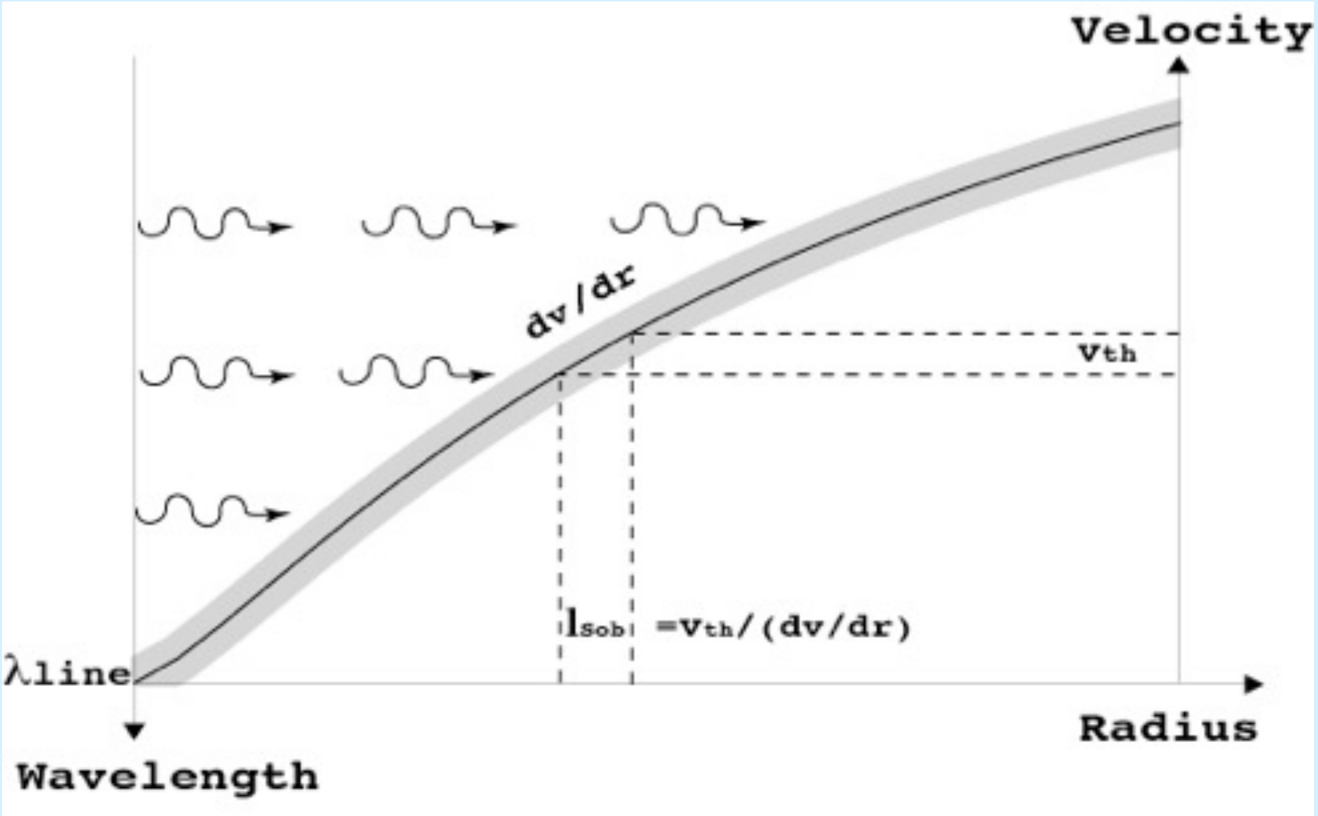


$$\Gamma_{thick} \sim \frac{\bar{Q}\Gamma_e}{\tau} \sim \frac{1}{\rho}\frac{dv}{dr}$$

Optically Thick Line-Absorption in an Accelerating Stellar Wind



$L_{sob} \ll R_*$

For strong, optically thick lines:

$$g_{thick} \sim \frac{g_{thin}}{\tau} \sim \boxed{\frac{1}{\rho}\frac{dv}{dr}}$$

$$\tau \equiv \kappa\rho \boxed{\frac{v_{th}}{dv/dr}} \sim \frac{v_{th}}{v_\infty} R_*$$

CAK model of steady-state wind

Equation of motion:

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

inertia **gravity** **CAK line-force**

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inertia — gravity — CAK line-force

$0 < \alpha < 1$
CAK ensemble of thick & thin lines

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CAK ensemble of thick & thin lines

inertia ≈ gravity ≈ CAK line-force

g_{CAK} ≈ gravity

Mass loss rate

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

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inertia ≈ gravity

Velocity law

$$v(r) \approx v_\infty (1 - R_* / r)^\beta \qquad \beta \approx 0.8$$

$\sim v_{esc}$

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CAK ensemble of thick & thin lines

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

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

$$\dot{M}\,\mathrm{v}_\infty \sim \bar{Q}^{-1+1/\alpha} L^{\frac{1}{\alpha}}$$

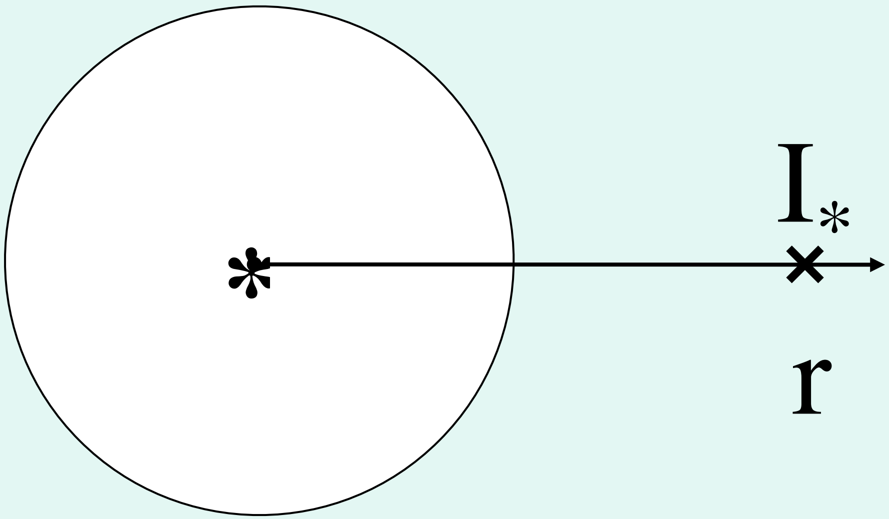
$$\sim Z^{0.6} L^{1.7}$$

$\alpha \approx 0.6$

$\bar{Q} \sim Z$

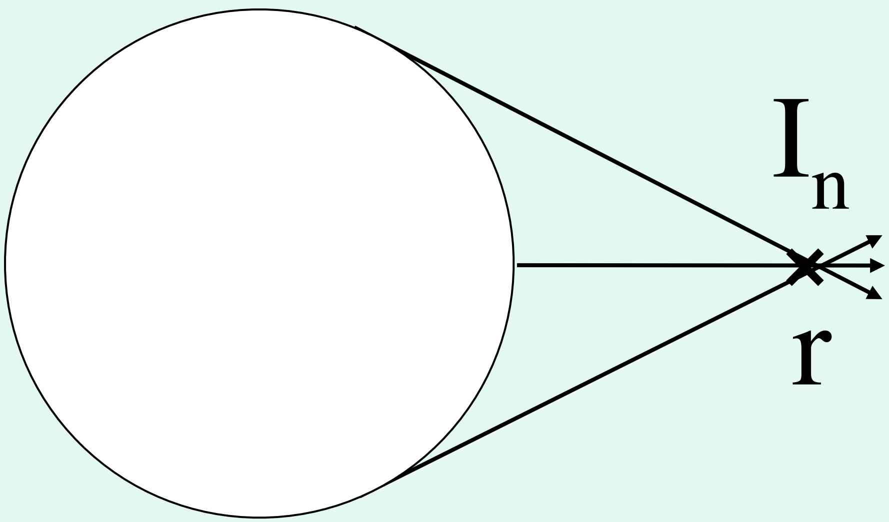
Point-star vs. Finite-disk

Point-star approx.



$g_r \sim I_* (dv/dr)^\alpha$

Finite-disk integration



$g_r \sim I_n (dv_n/dn)^\alpha$

Finite-disk reduction of CAK mass loss rate

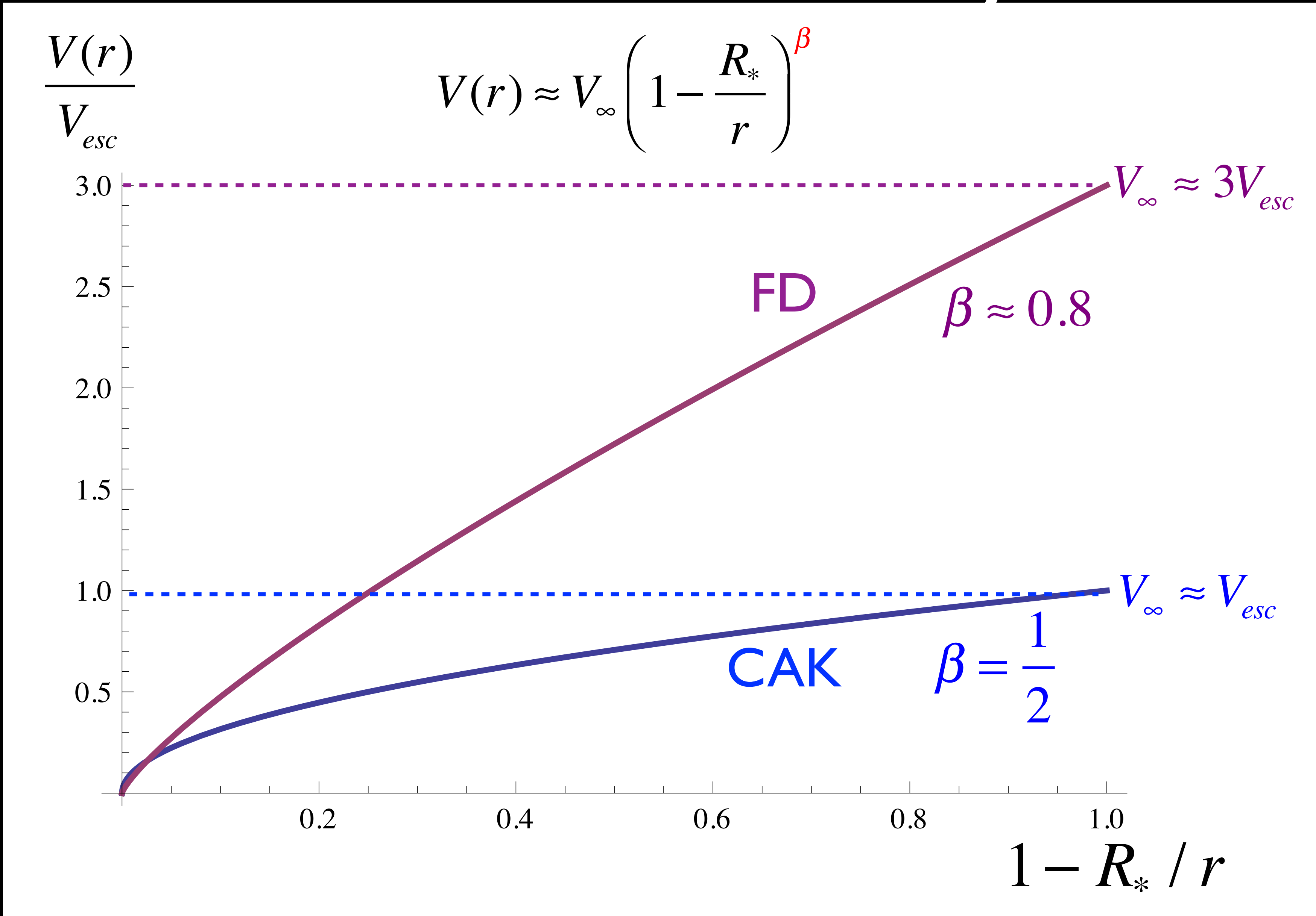
$$w' + 1 = f_d C \, w'^{\alpha} \qquad C \sim 1/\dot{M}^{\alpha}$$

Finite-disk reduction of CAK mass loss rate

$$w' + 1 = f_d C \, w'^{\alpha} \qquad C \sim 1/\dot{M}^{\alpha}$$

$$\dot{M}_{fd} = f_{d*}^{1/\alpha} \dot{M}_{CAK} = \frac{\dot{M}_{CAK}}{(1+\alpha)^{1/\alpha}} \approx \dot{M}_{CAK}/2$$

CAK vs. FD velocity law



Effect of finite gas-pressure on CAK wind

$$\left(1 - \frac{s}{w}\right) w' + 1 = \frac{f C_c}{(1 + \delta m)^\alpha} w'^\alpha \qquad s \equiv \frac{a^2}{V_{esc}^2} \approx 0.001$$

Effect of finite gas-pressure on CAK wind

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Perturbation expansion of FD-CAK soln in s<<1 gives:

$$\delta m \approx + \frac{4\sqrt{1-\alpha}}{\alpha} \frac{a}{V_{esc}} \approx +0.1$$

increases M_{dot} ~ 10%

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$$\delta v_\infty \approx -\frac{2}{\sqrt{1-\alpha}}\frac{a}{V_{esc}} \approx -0.1$$

decreases Vinf ~ 10%

Summary: Key CAK Scaling Results

Mass Flux:

$$\dot{M} \sim \frac{L^{1/\alpha}}{g_{eff}^{1/\alpha - 1}}$$

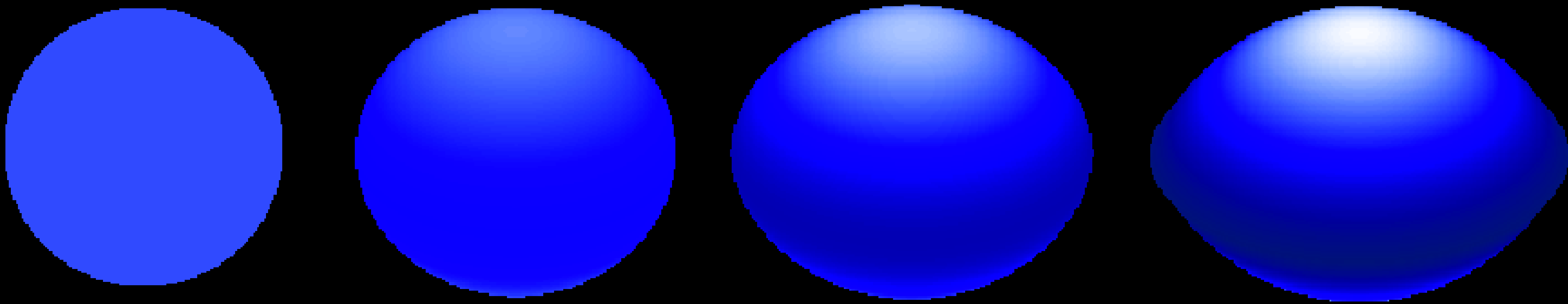
Wind Speed:

$$V_\infty \sim V_{esc} \sim \sqrt{g_{eff}}$$

How is stellar mass loss affected by (rapid) stellar rotation?

Gravity Darkening

increasing stellar rotation →



$$F(\theta) \sim g_{eff}(\theta)$$

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 $\alpha = 1/2$

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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**

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highest at **equator**

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

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

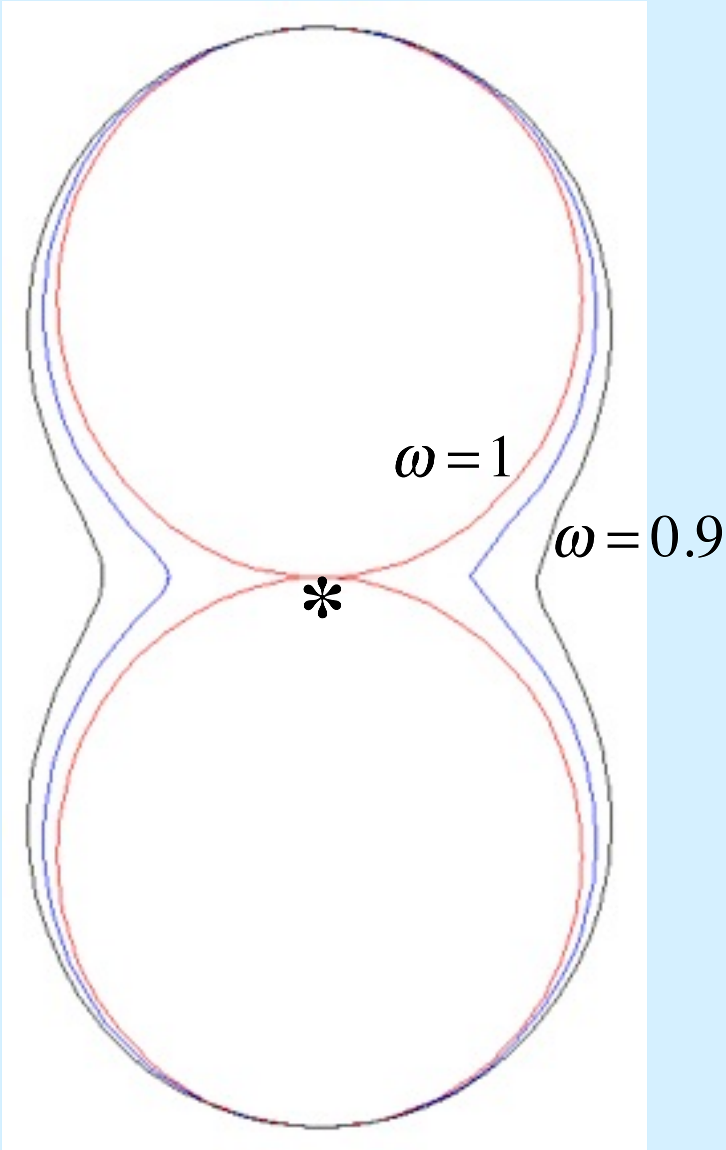
highest at **pole**

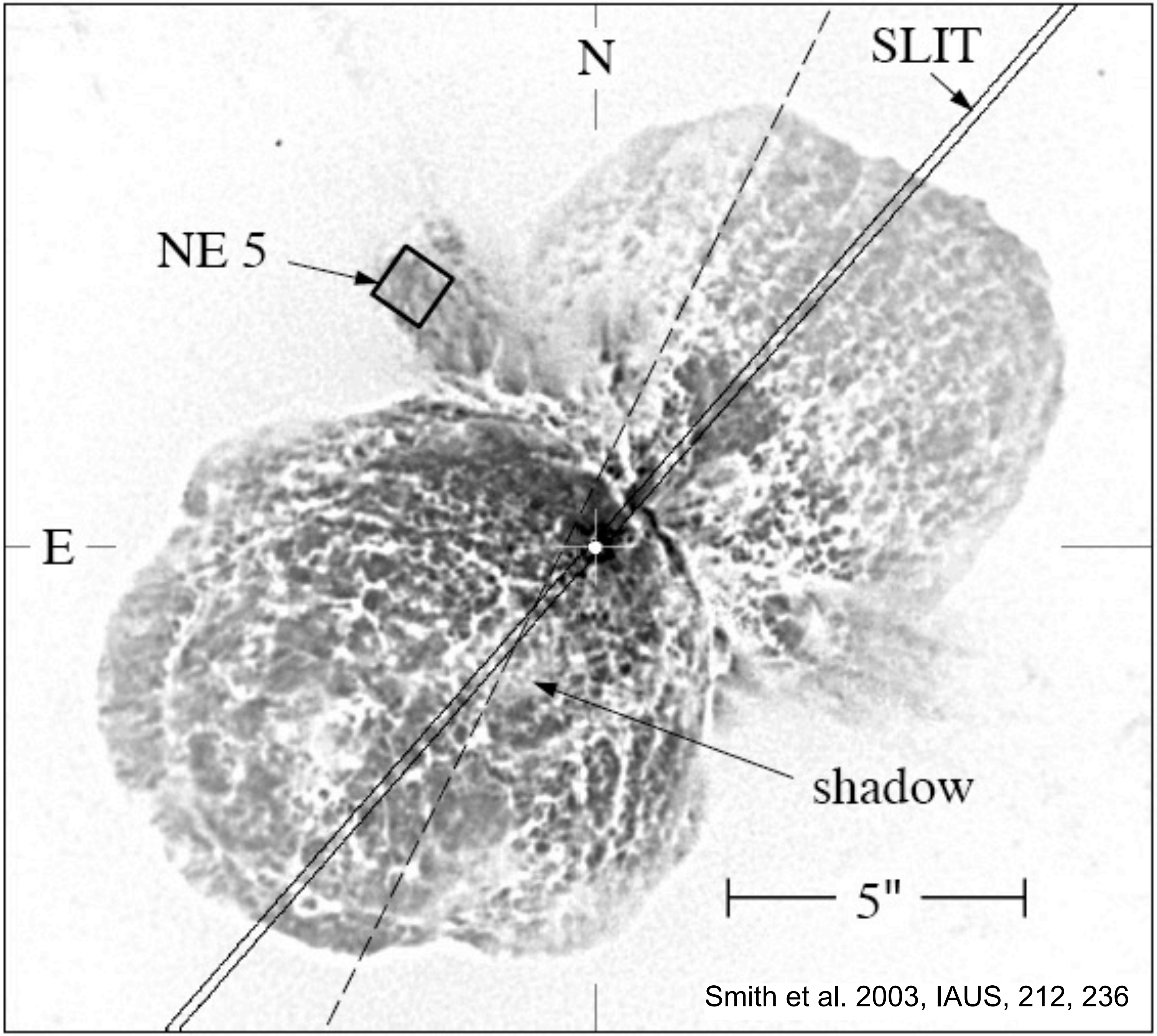
Effect of rotation on flow speed

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

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

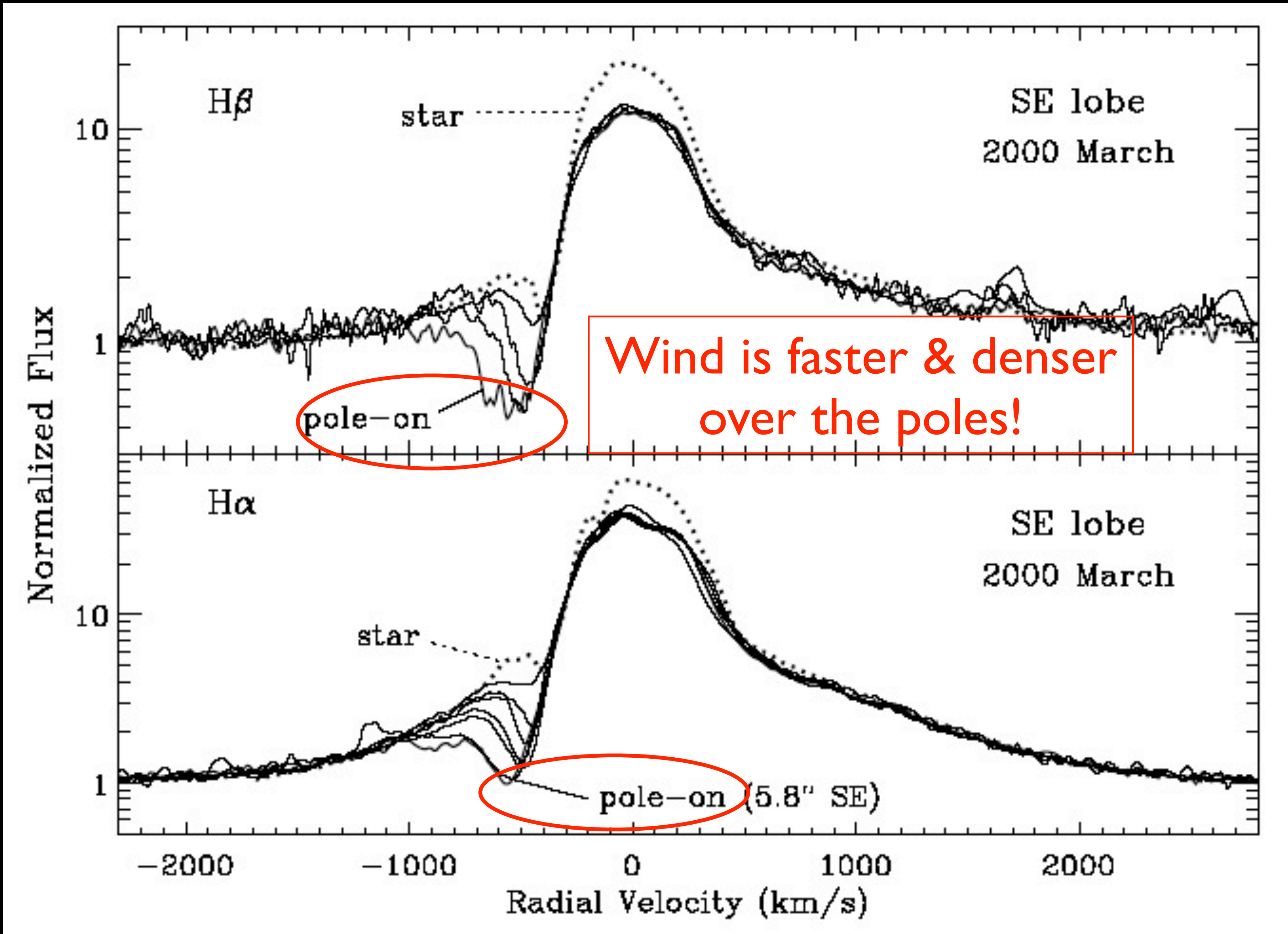
$$\omega \equiv \Omega / \Omega_{crit}$$





Smith et al. 2003, IAUS, 212, 236

Smith et al. 2003



Be stars

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

Hydrogen spectrum

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• Emission intensity split into blue and red peaks

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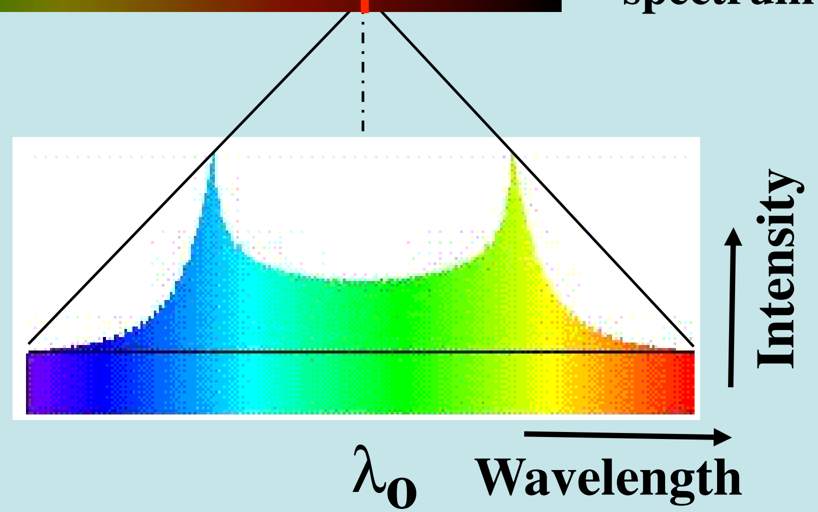

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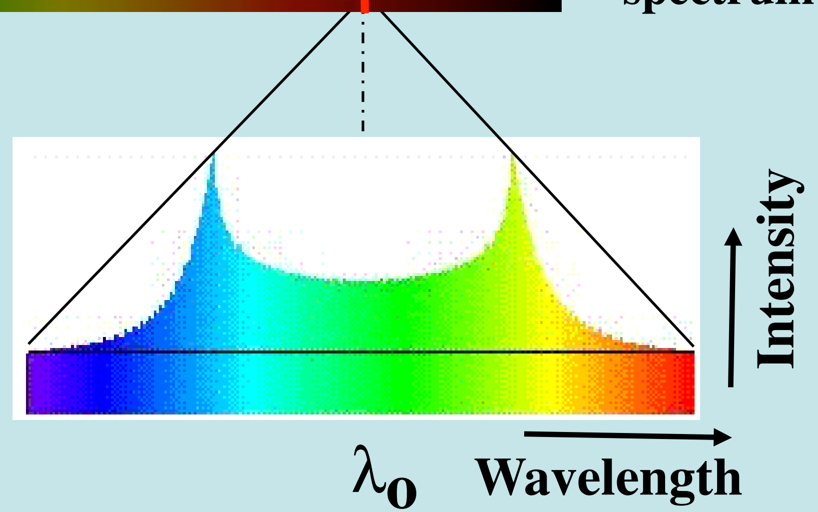

- From Doppler shift of gas moving toward and away from the observer .

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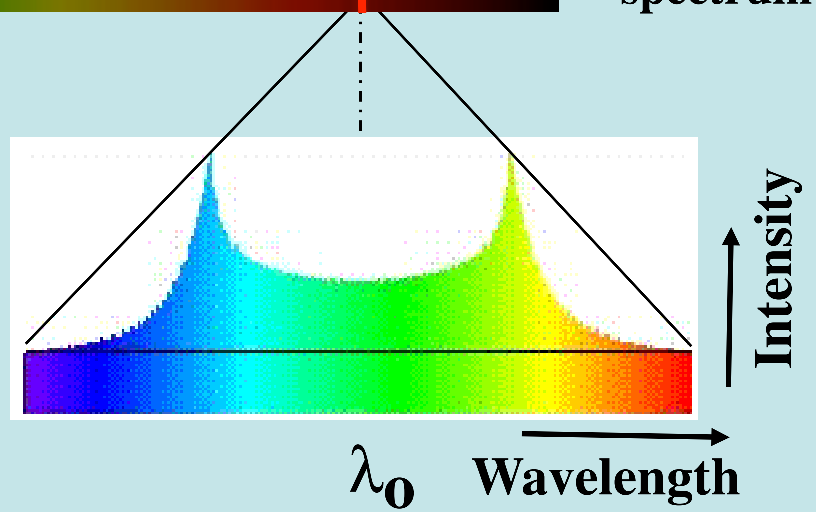

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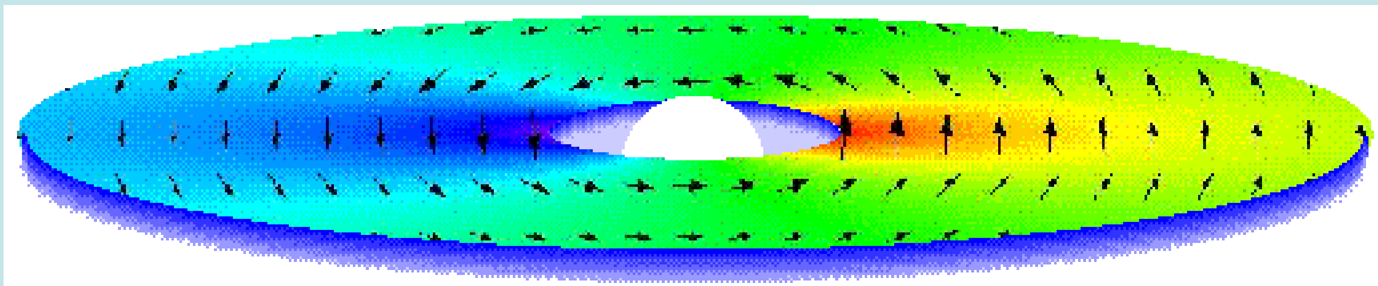

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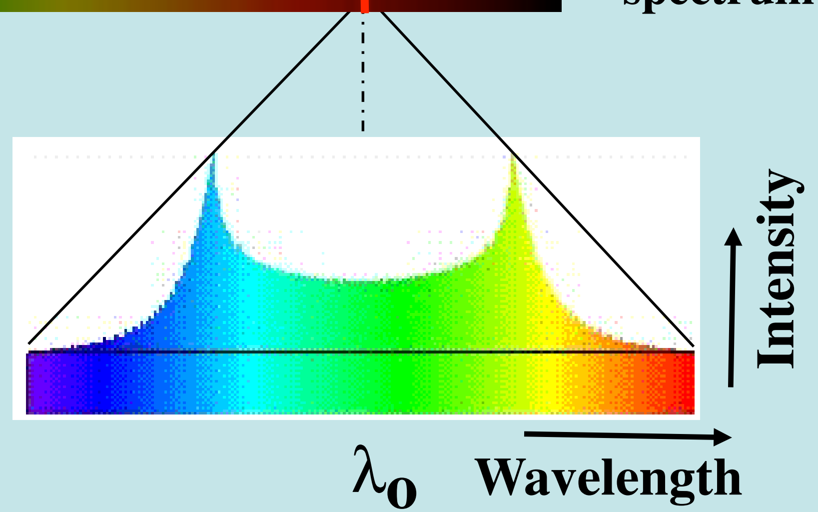

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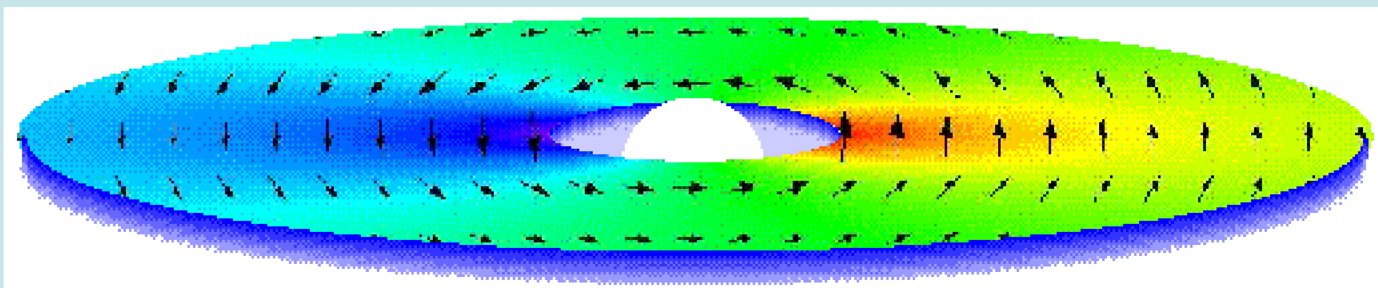
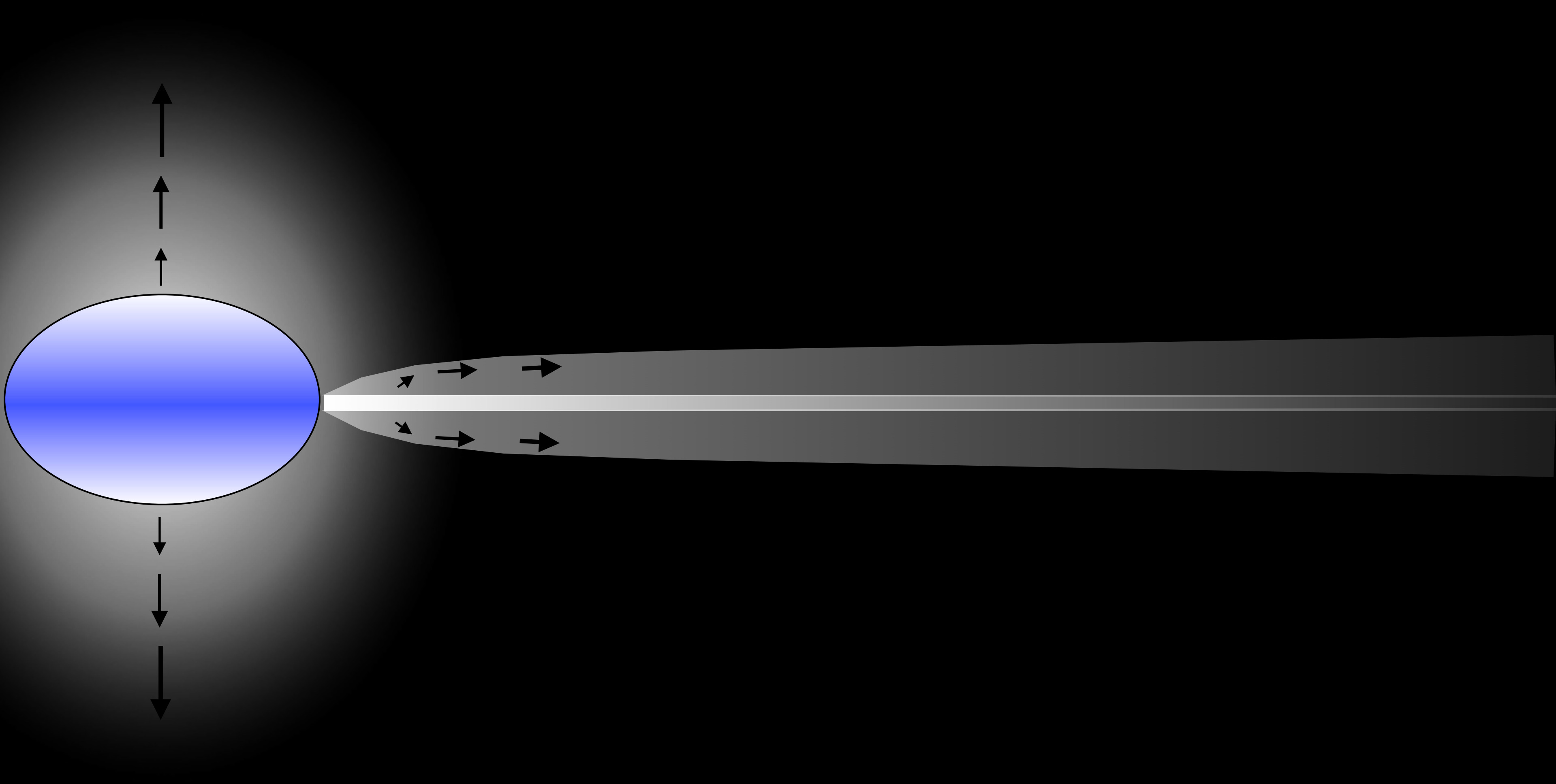


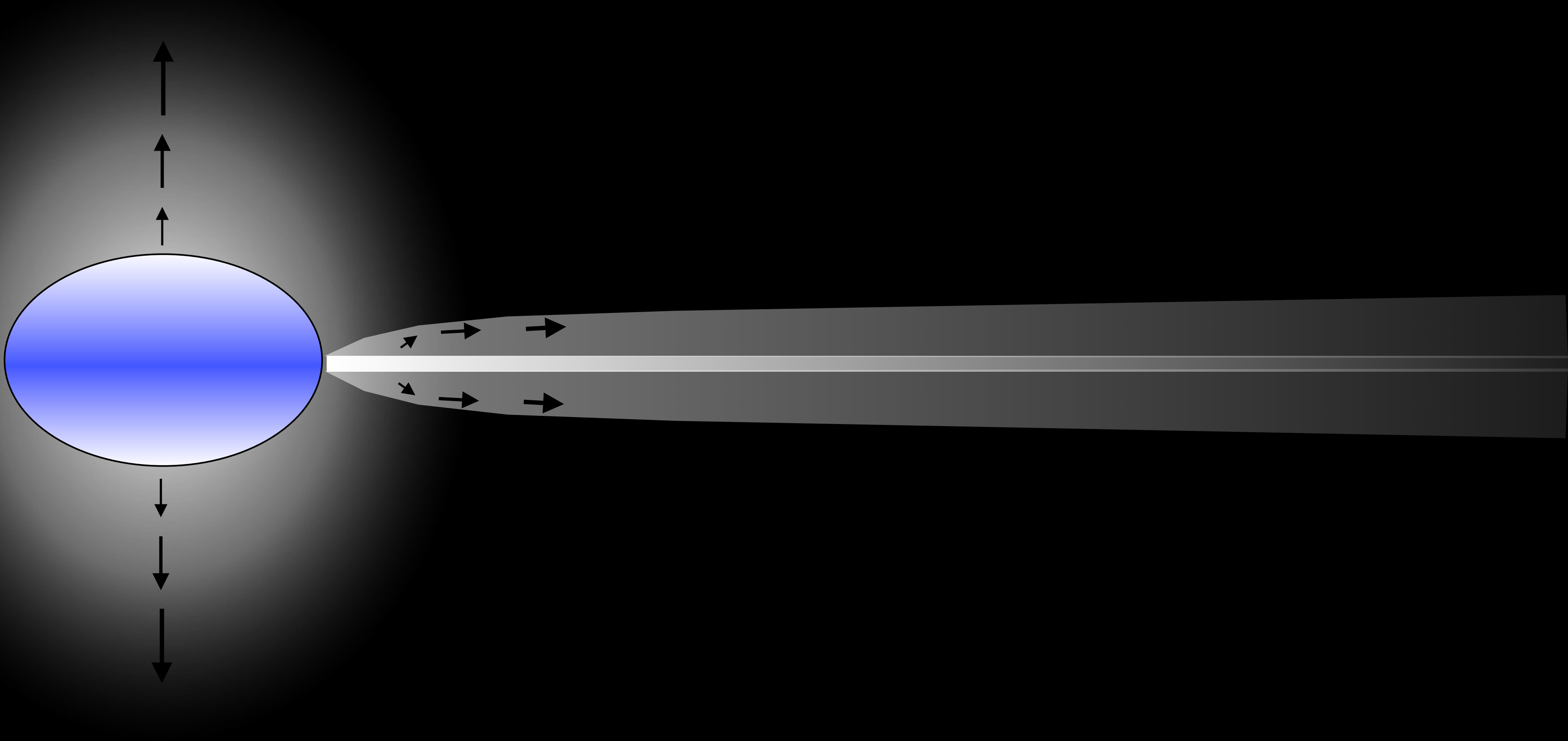
- **Indicates a disk of gas orbits the star.**

3 components of Be star circumstellar gas



3 components of Be star circumstellar gas

gravity brightened poles
drive denser polar wind



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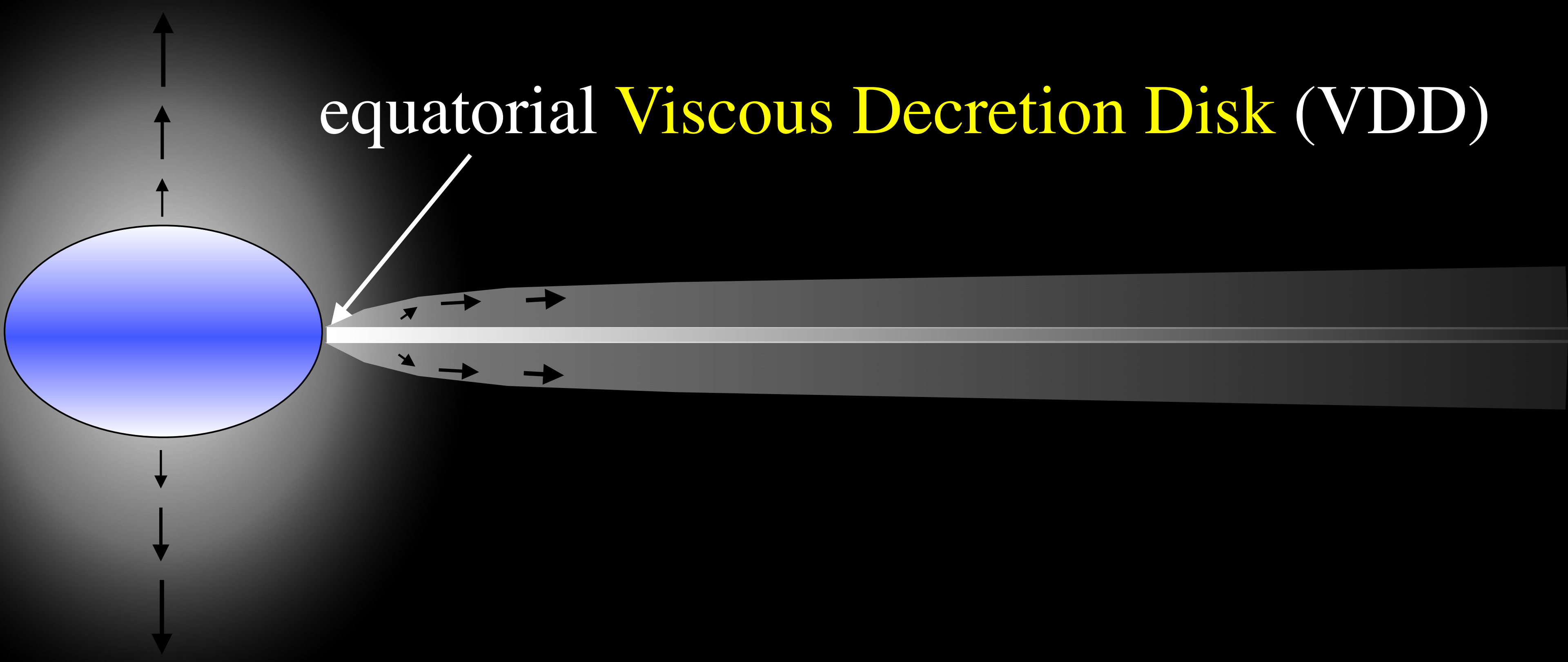

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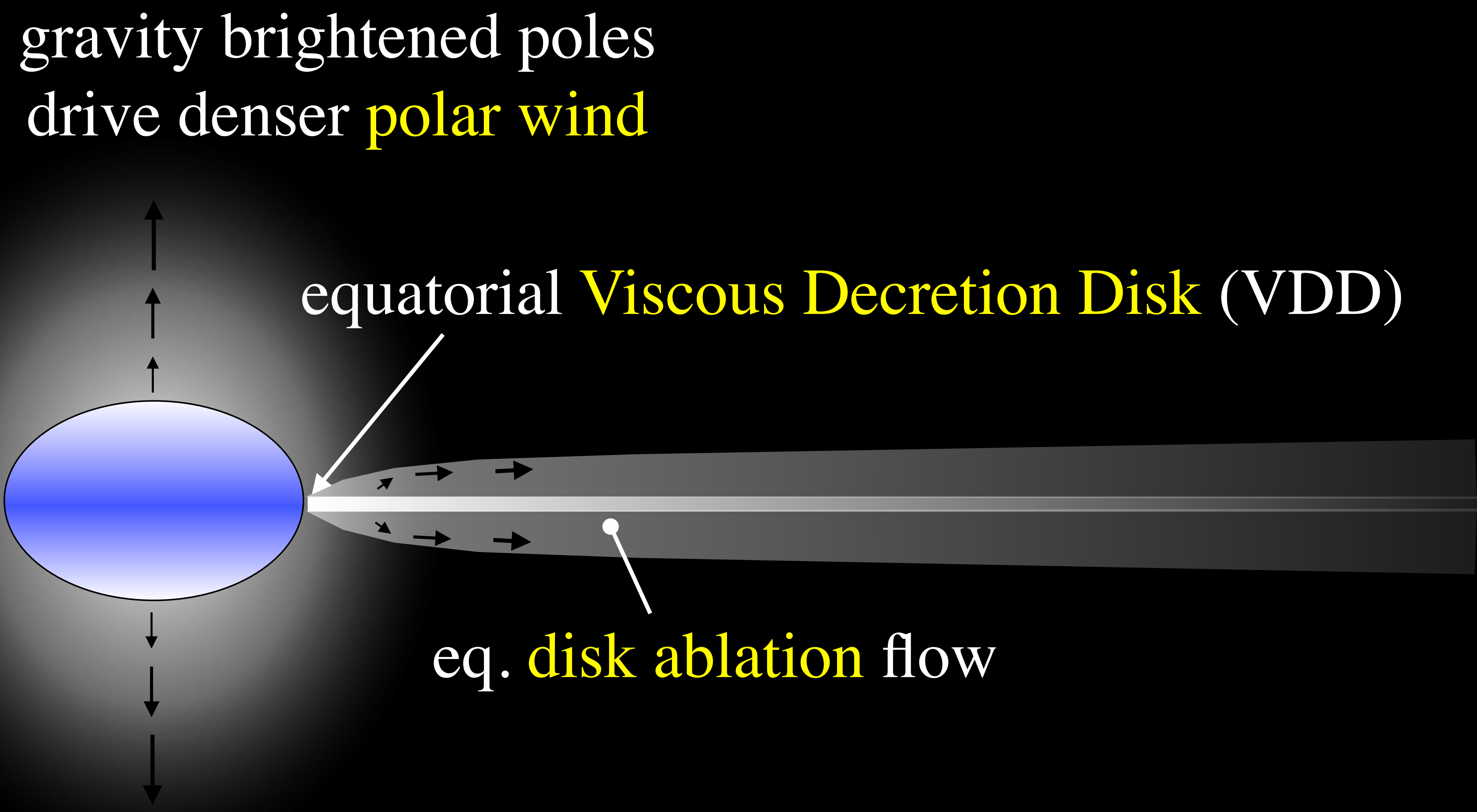

Wolf-Rayet winds

- WR winds have $\dot{M} V_\infty > L / c$
- Requires multiple scattering

$$\dot{p}_{rad} = \tau \frac{L}{c}$$

for lines separated by $\Delta V < V_\infty$

$$\tau = \frac{V_\infty}{\Delta V}$$

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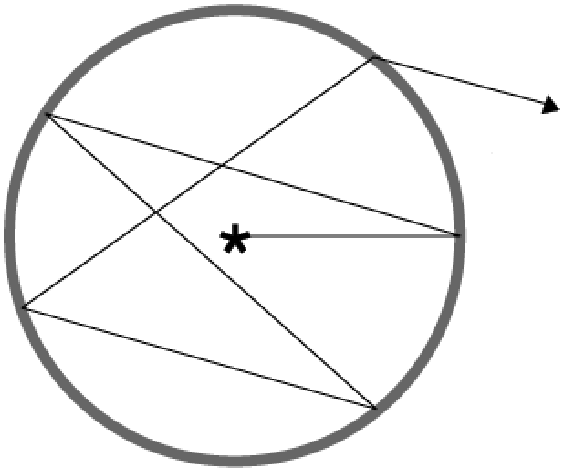

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Gayley et al. 1995, ApJ, 442, 296

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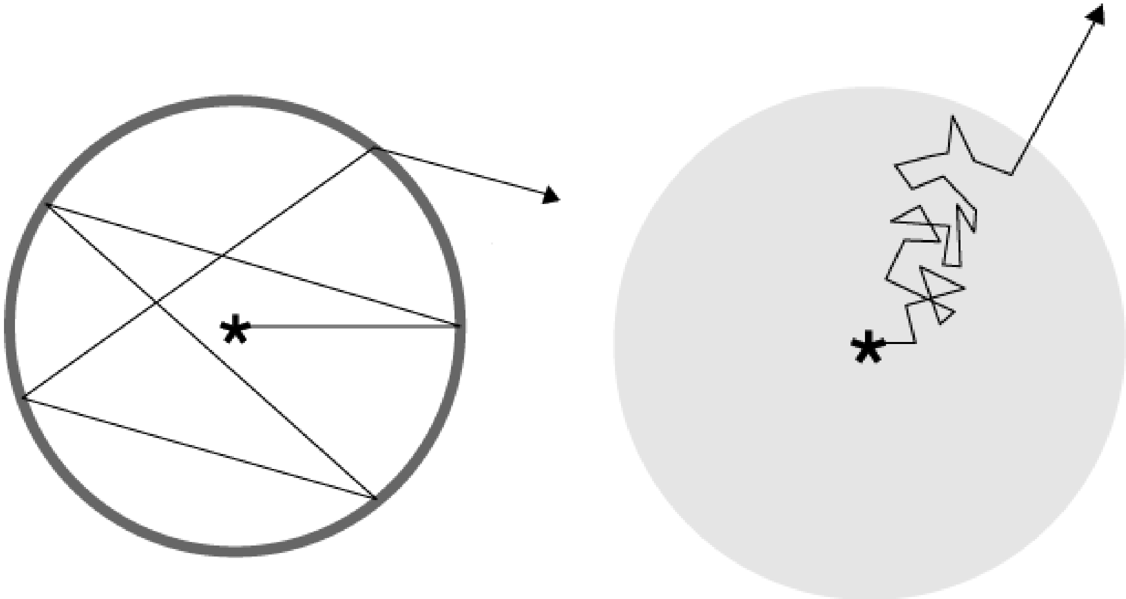

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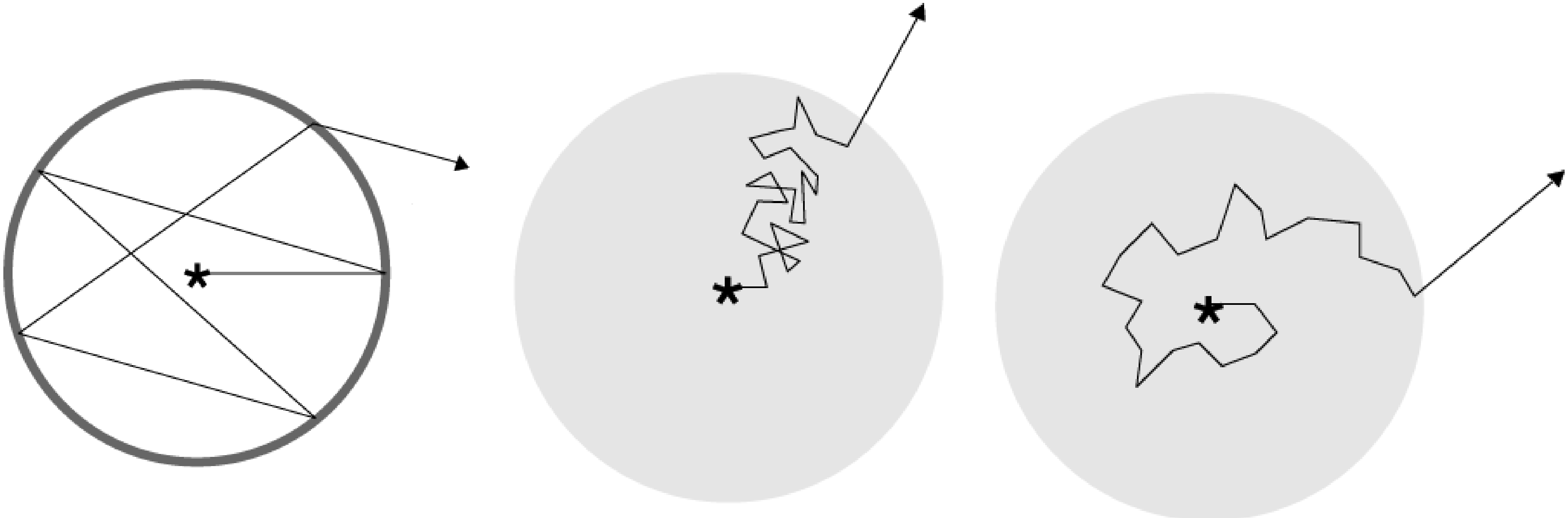

for lines separated by $\Delta V < V_\infty$

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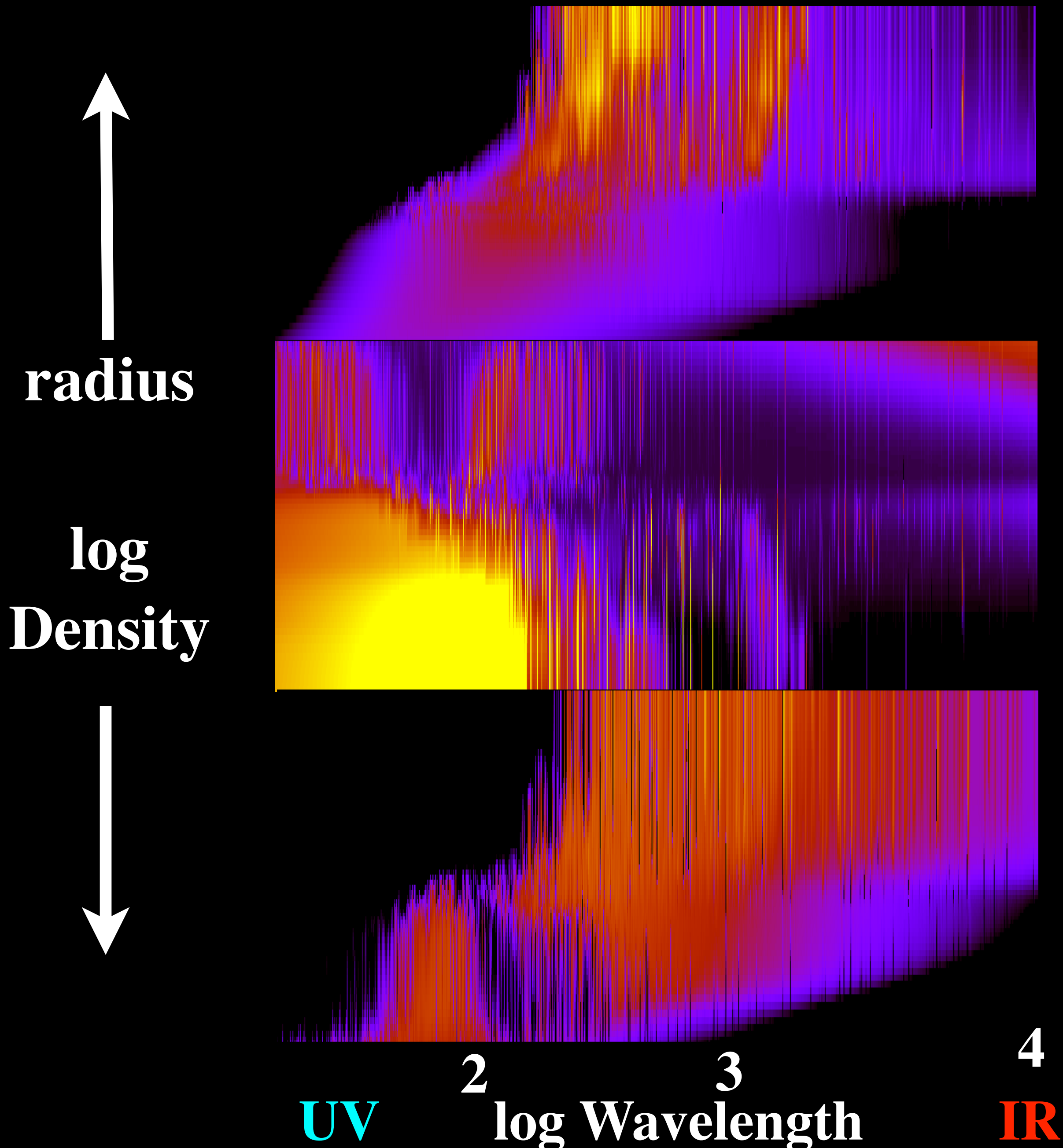
Gayley et l. 1995, ApJ, 442, 296

Wolf-Rayet Wind Driving

courtesy G. Graefener



Radiative acceleration

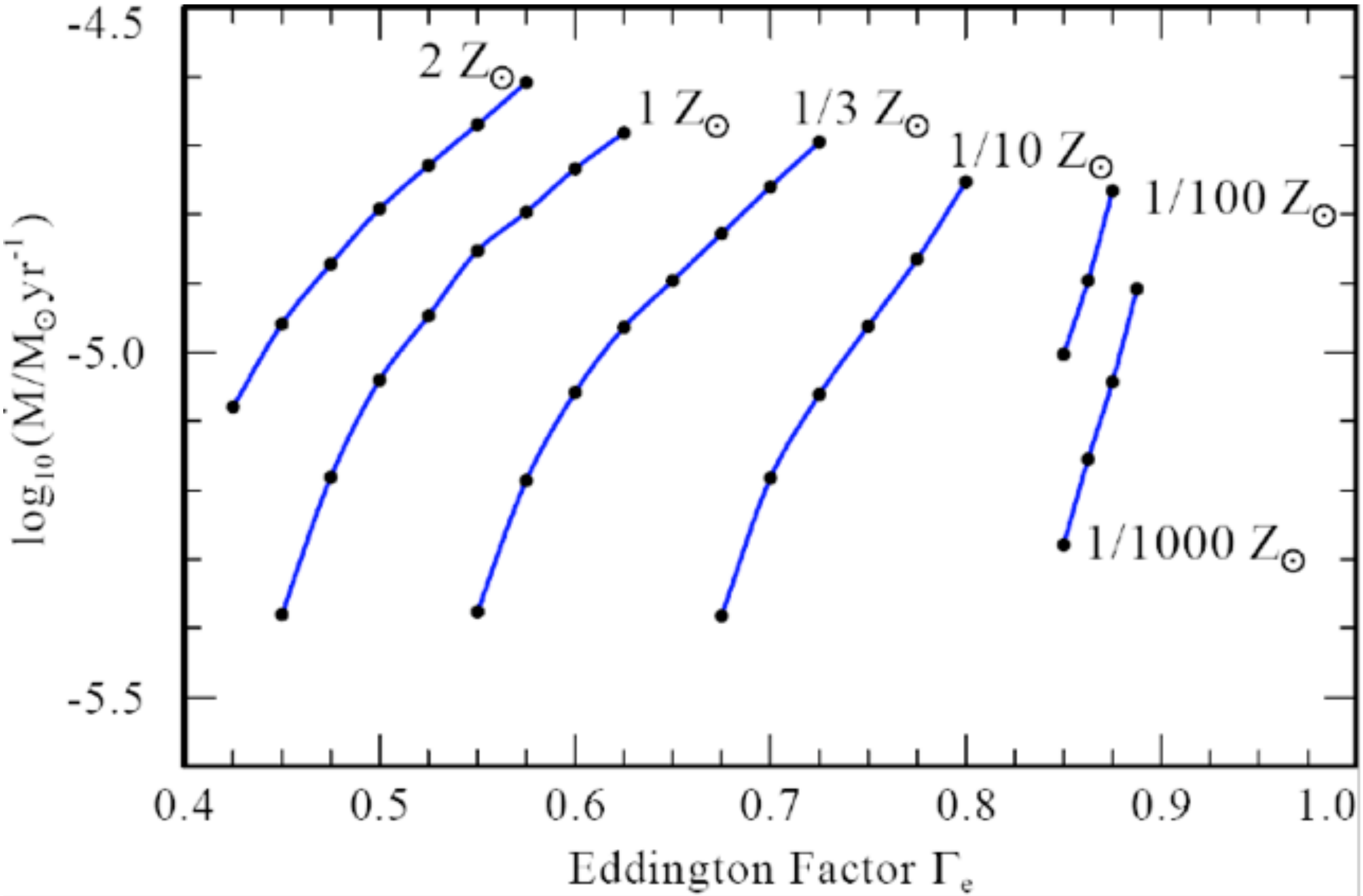
=

Opacity

X

Flux

Mdot increases with Γ_e

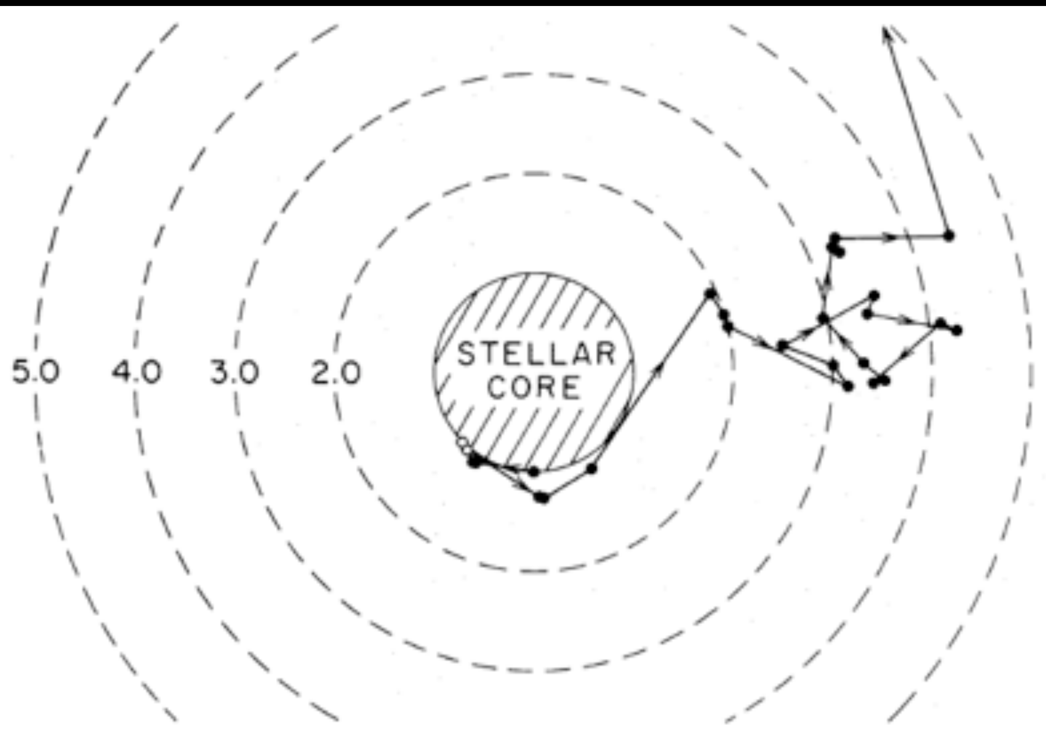


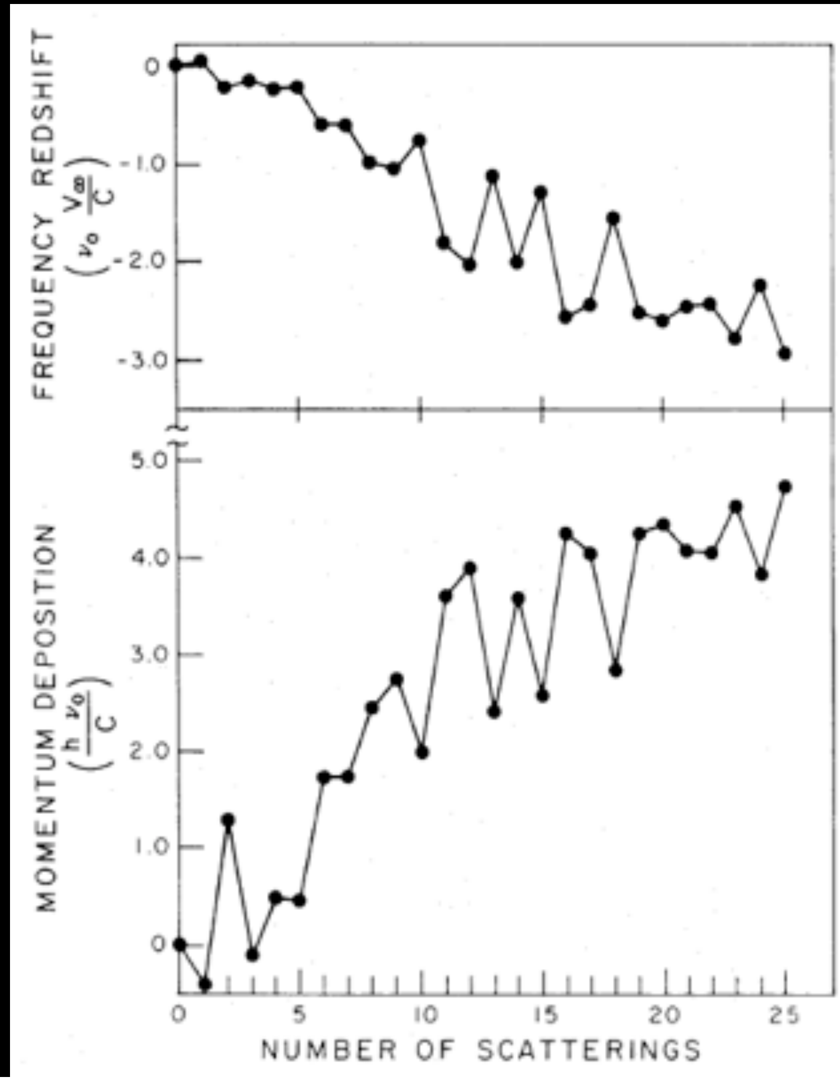
Graefener & Hamman 2005

Monte-Carlo models

Abbott & Lucy 1985; LA 93; Vink et al. 2001

Assume beta velocity law, use MC transfer through line list to compute global radiative work W_{rad} and momentum p_{rad}



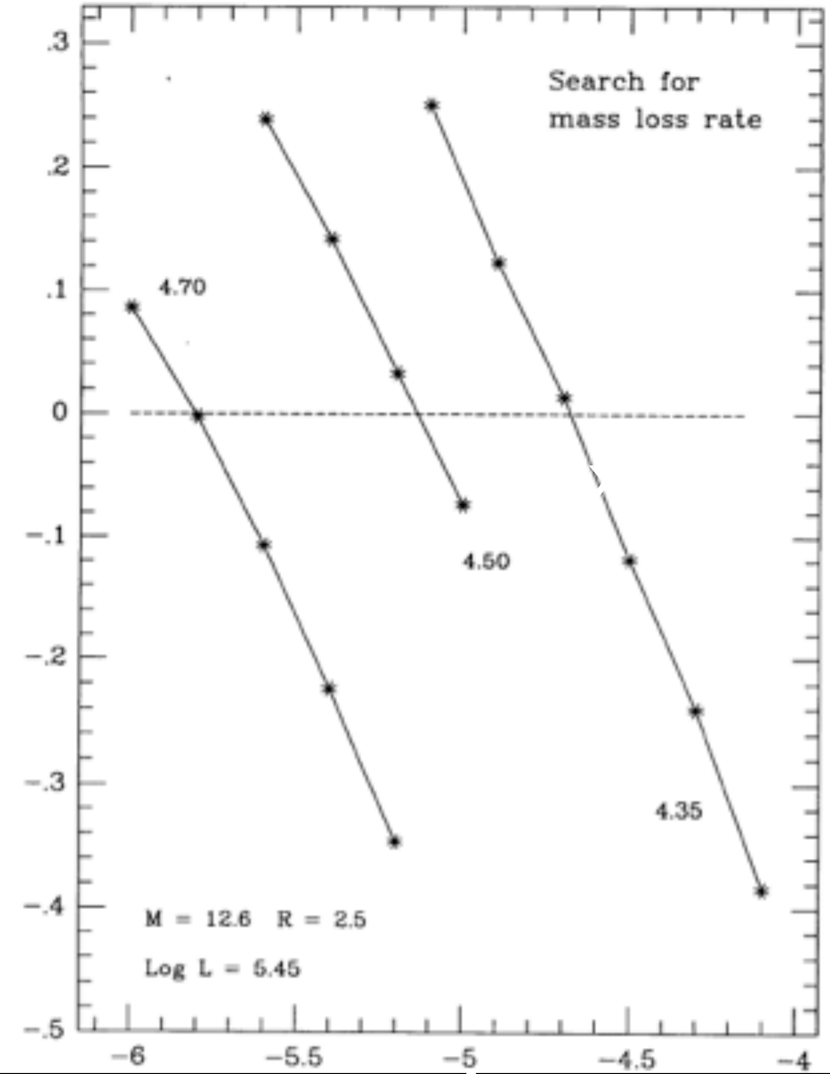


Monte-Carlo models

Then compute mass loss rate from:

$$\dot{M} \approx \frac{2\dot{W}_{rad}}{V_{esc}^2 + V_\infty^2}$$

$$\log \frac{\dot{W}_{rad}}{E_{wind}}$$

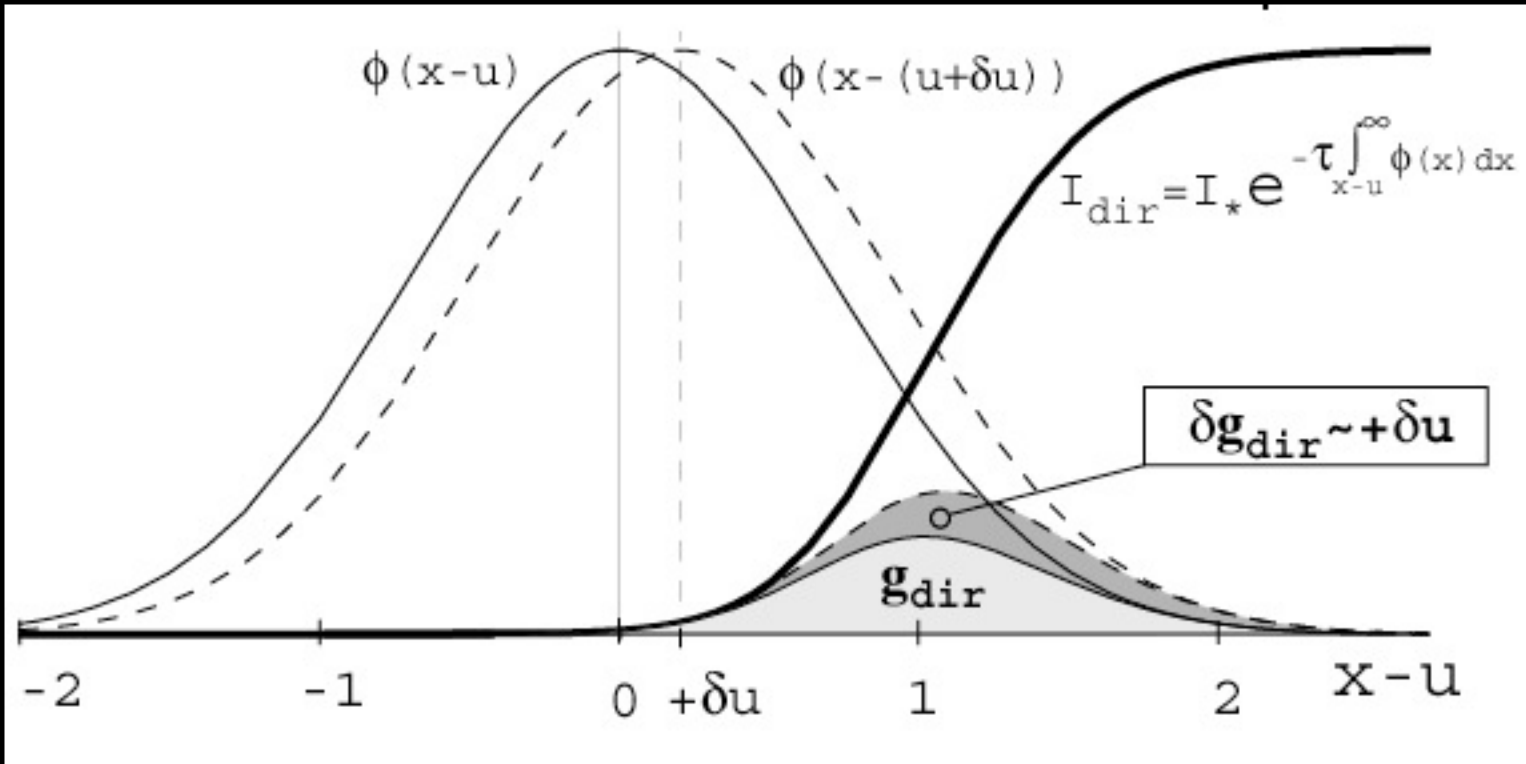


$$\log \dot{M}$$

NOTE:
Global
not local
soln of EOM

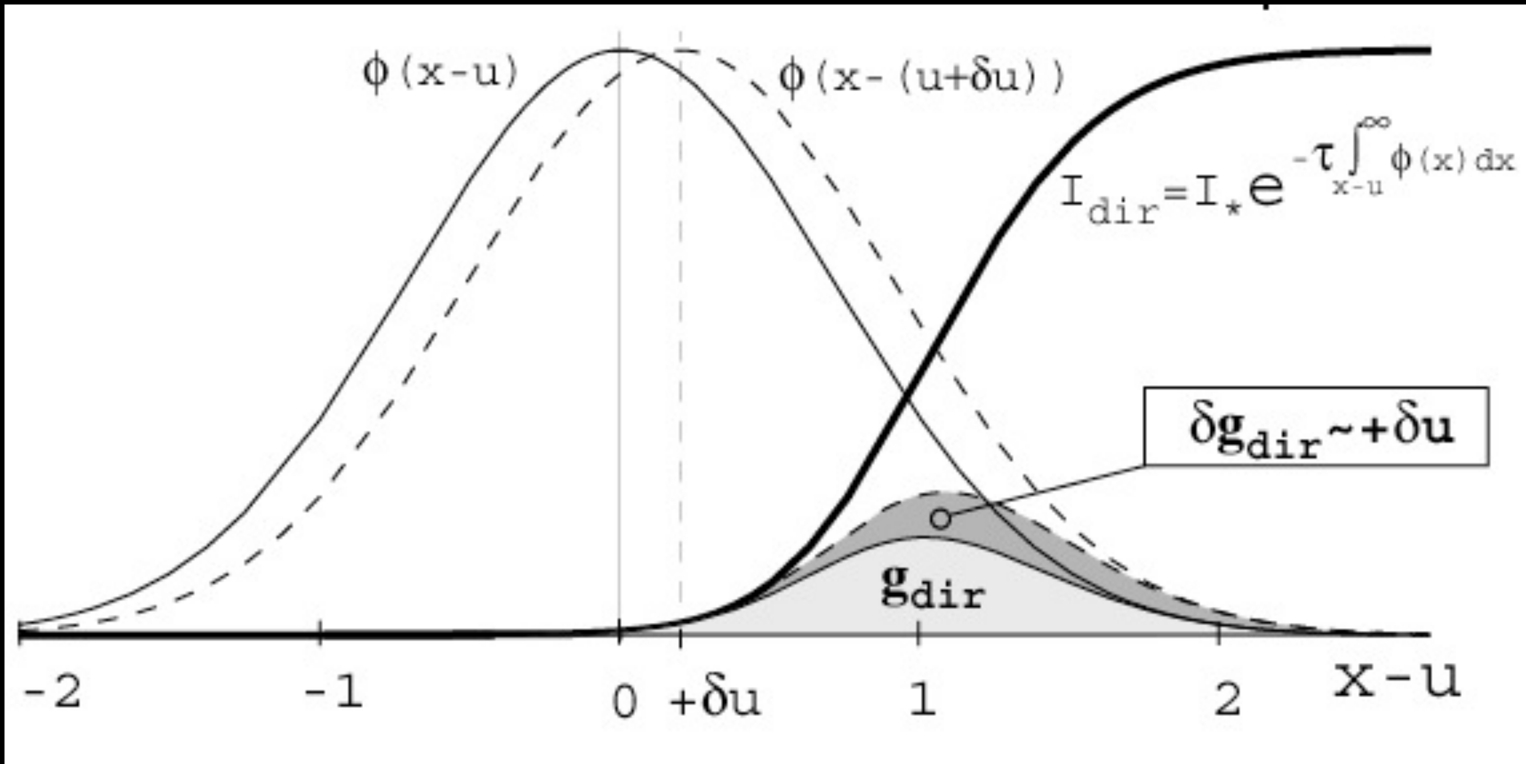
Lucy & Abbott 1993, ApJ, 405, 738

Line-Deshadowing Instability



Owocki 2009, AIP, 1171, 173

Line-Deshadowing Instability



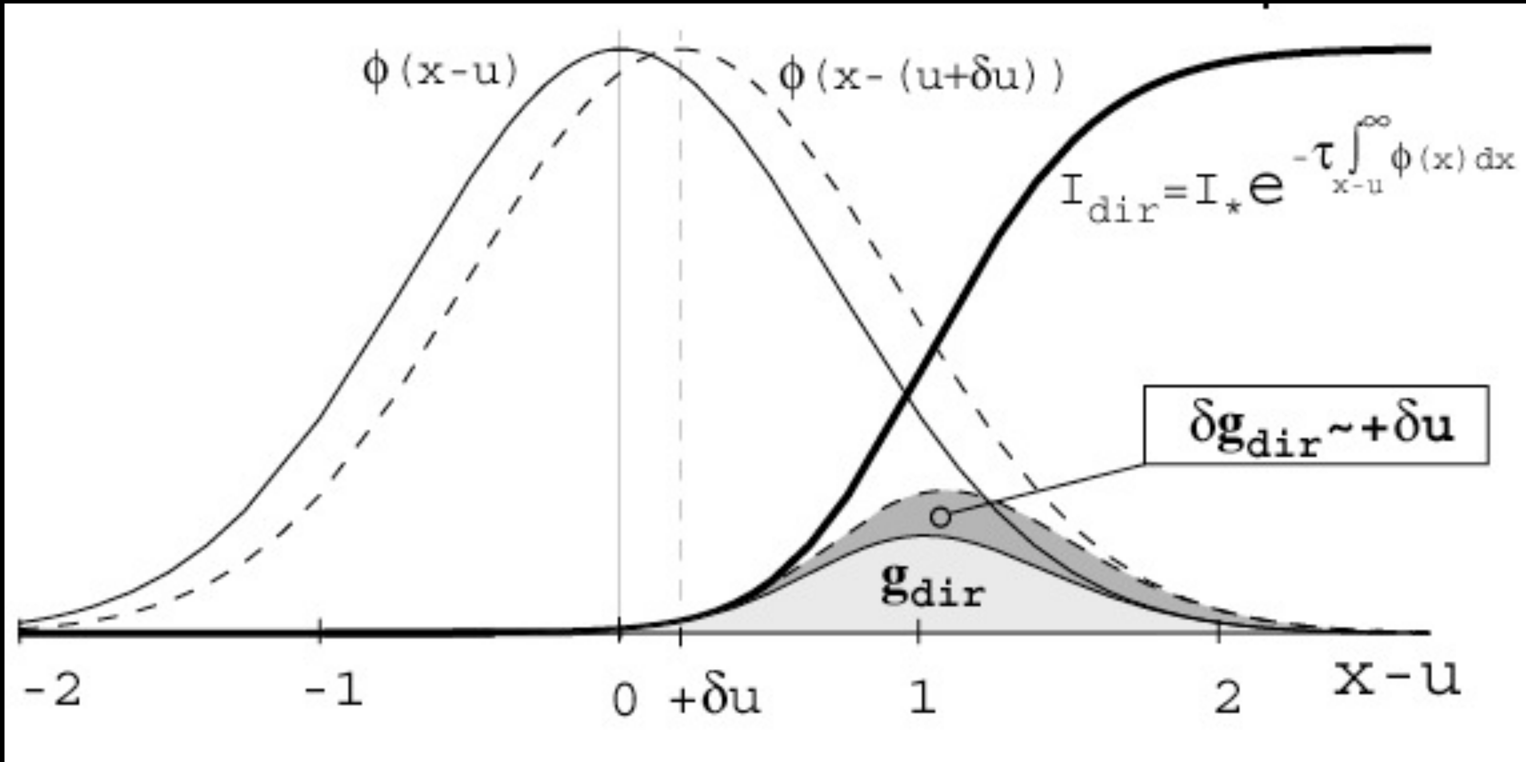
Owocki 2009, AIPC, 1171, 173

for $\lambda < L_{sob}$:

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

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

Line-Deshadowing Instability



Owocki 2009, AIPC, 1171, 173

for $\lambda < L_{sob}$:

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

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

Instability with growth rate

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

=> e^{100} growth!

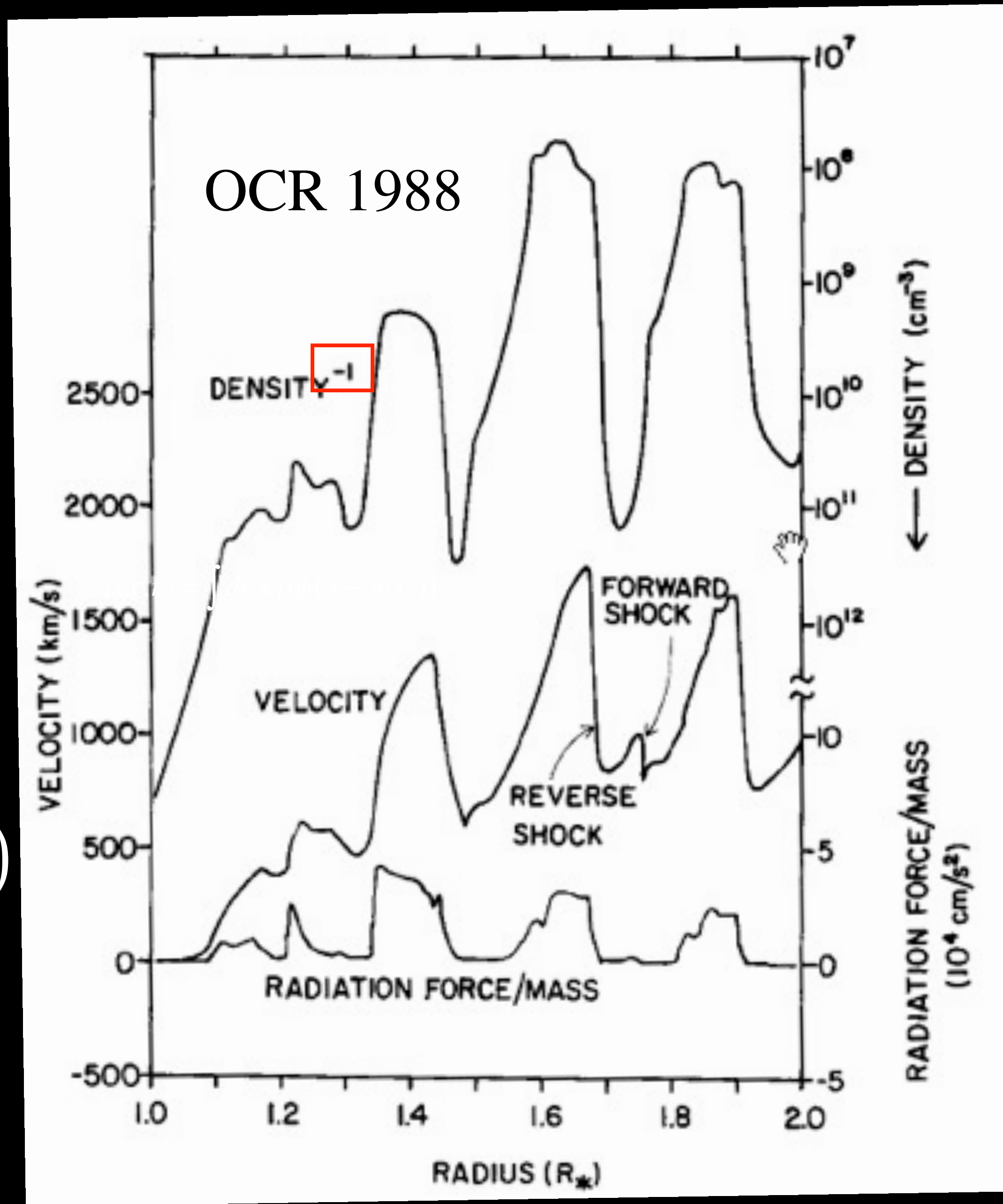
Non-linear structure for pure-absorption model

Direct force

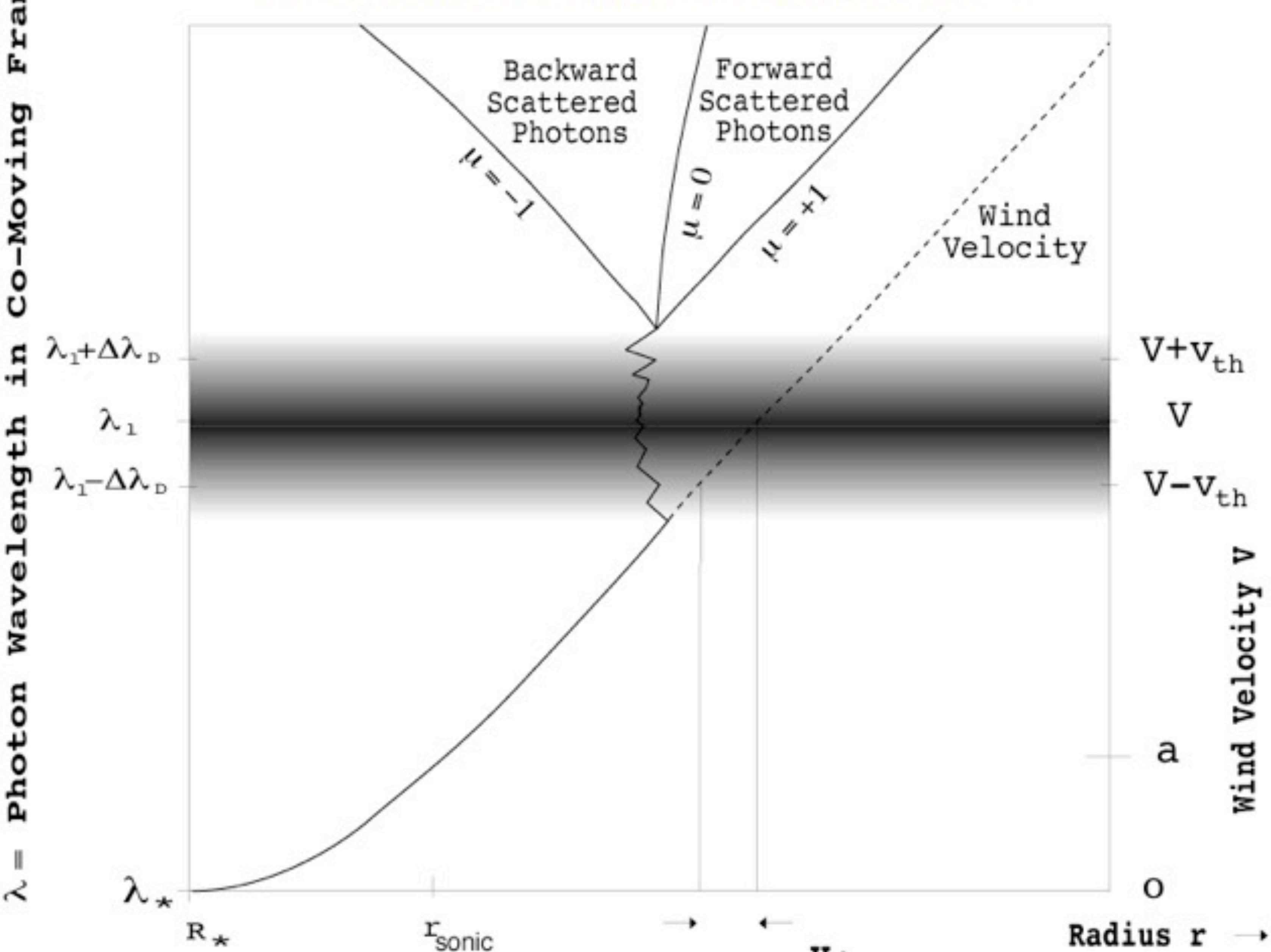
$$g_{dir} \sim \frac{g_{thin}}{t(x,r)^{\alpha}}$$

Integral optical depth

$$t(x,r) = \int_R^r dr\, \kappa \rho \phi\left(x - u(r')\right)$$



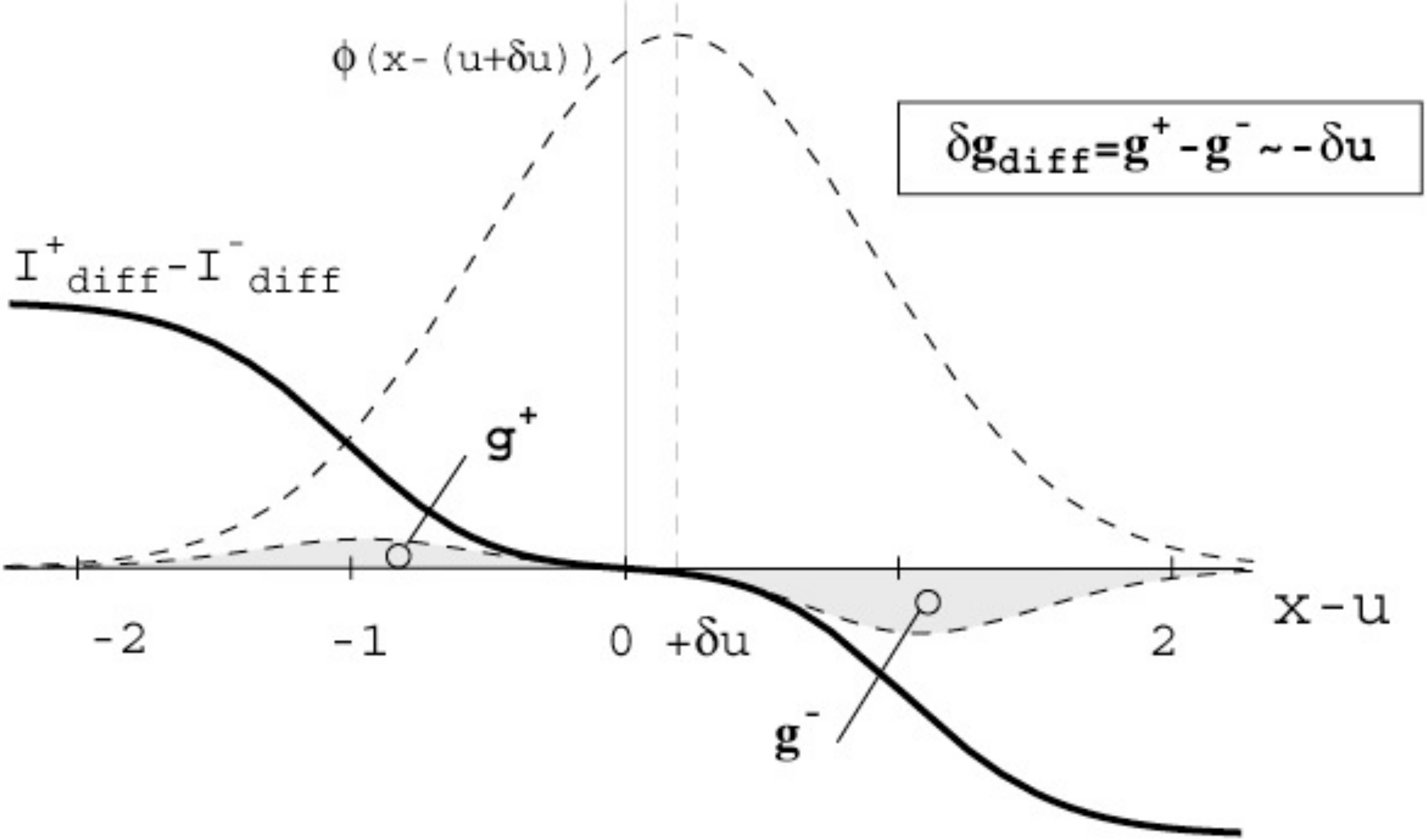
Line-Scattering in an Expanding Wind



$$L = \frac{v_{th}}{dv/dr} << r$$

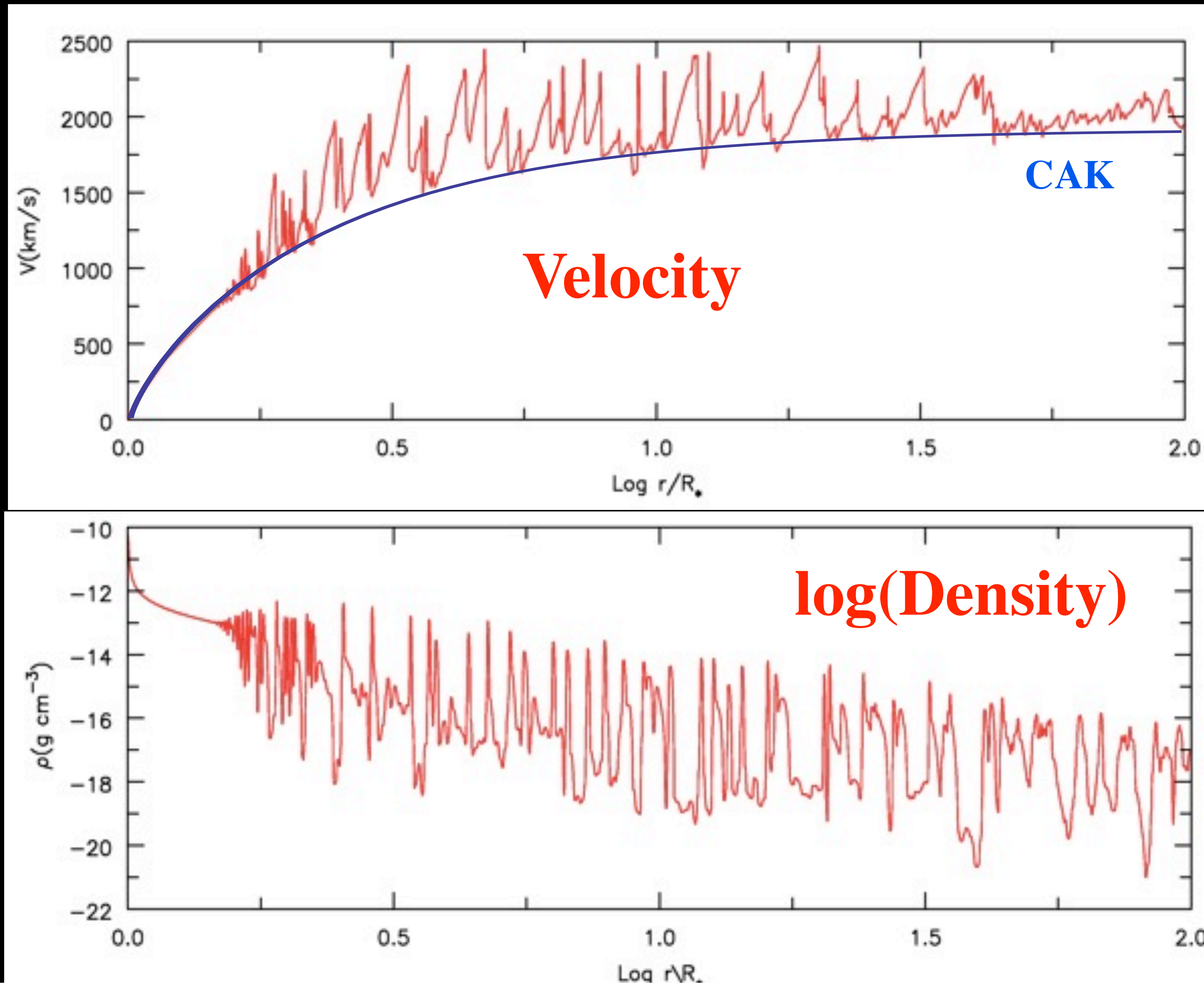
Gayley & Owocki 1994, ApJ, 434, 684

Diffuse Line-Drag

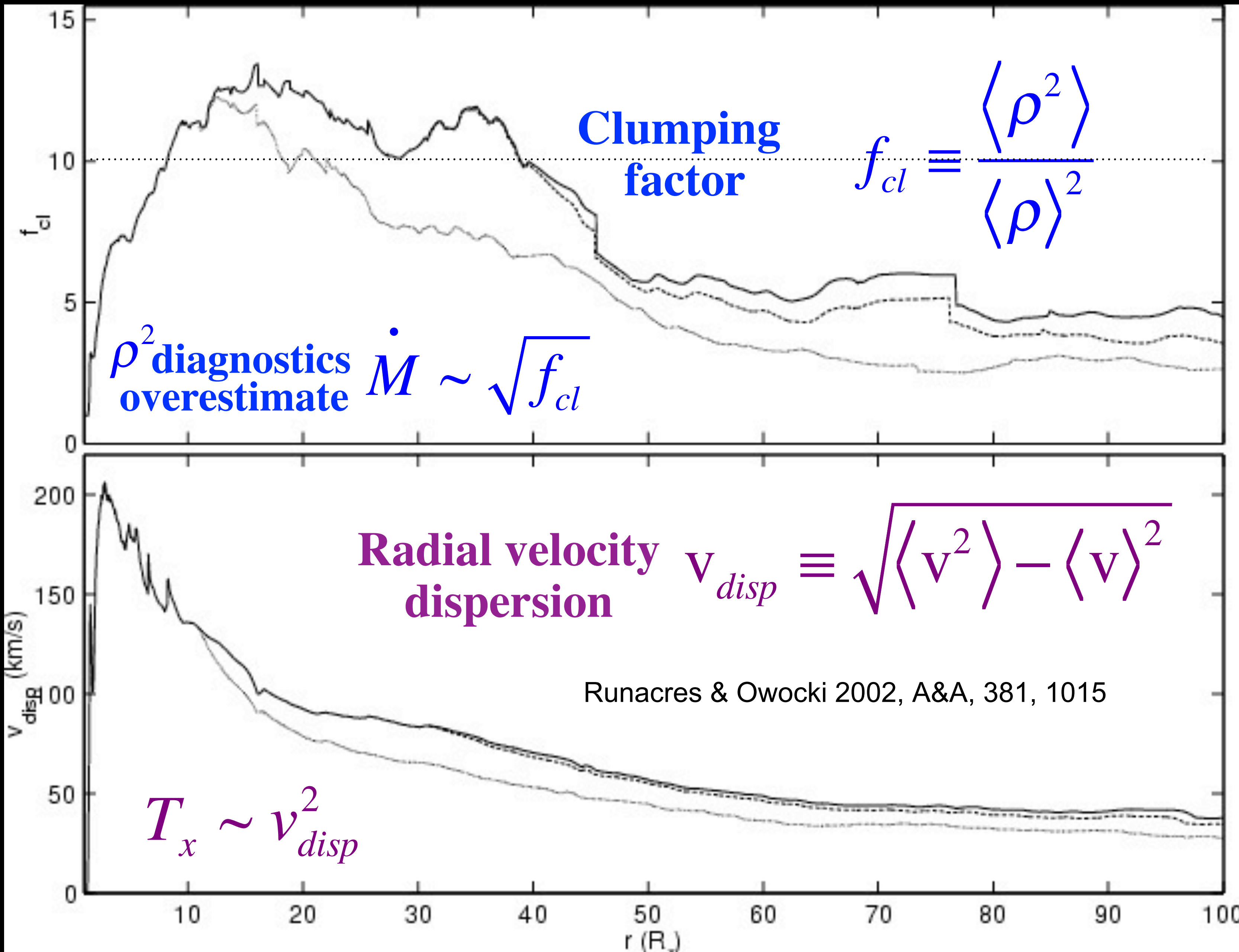


Owocki 2009, AIPC, 1171, 173

Time snapshot of wind structure vs. radius



Clumping vs. radius

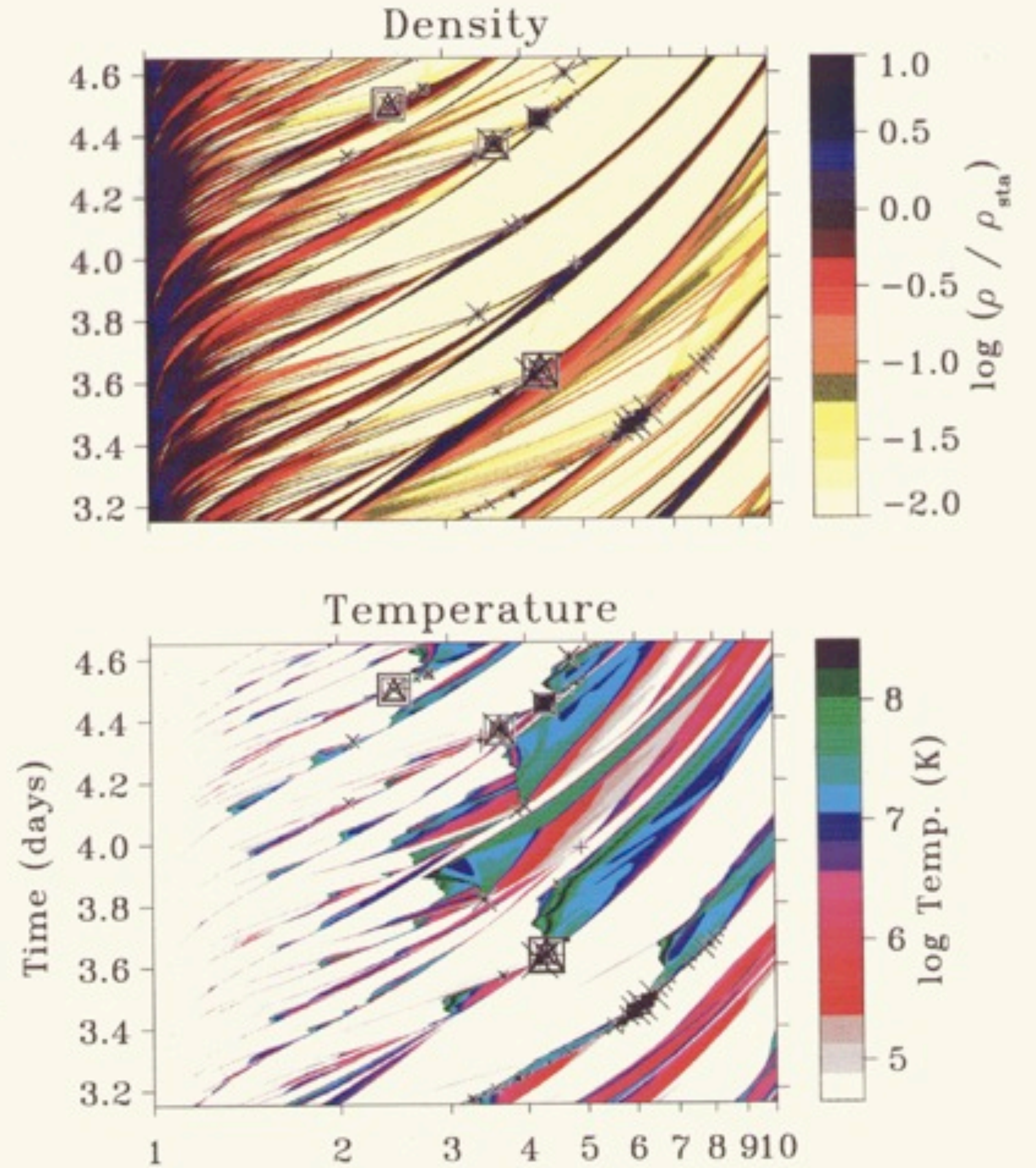


Wednesday, January 12, 2011

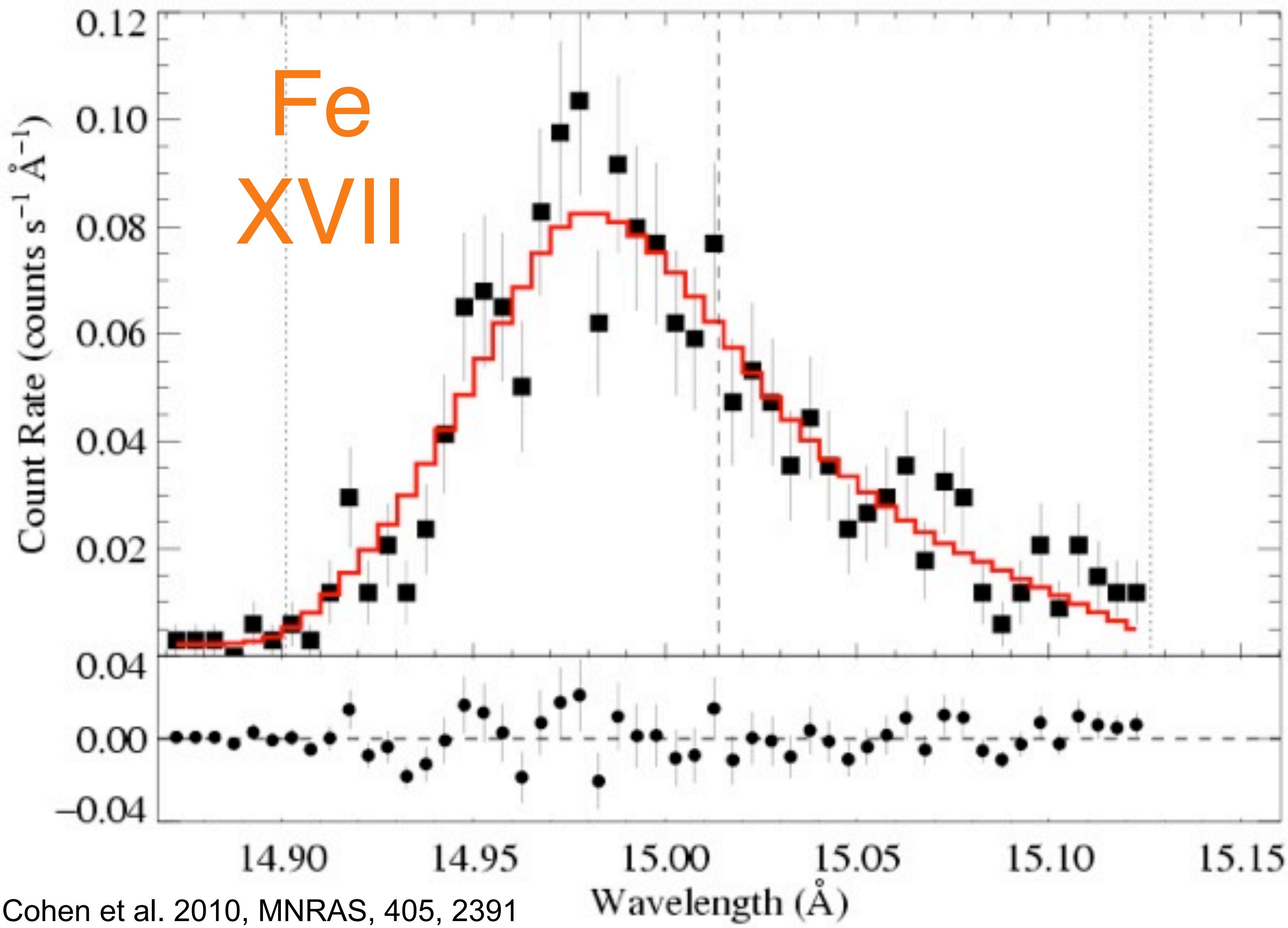
Turbulence-seeded clump collisions

Enhances V_{disp} and thus X-ray emission

Feldmeier et al. 1997

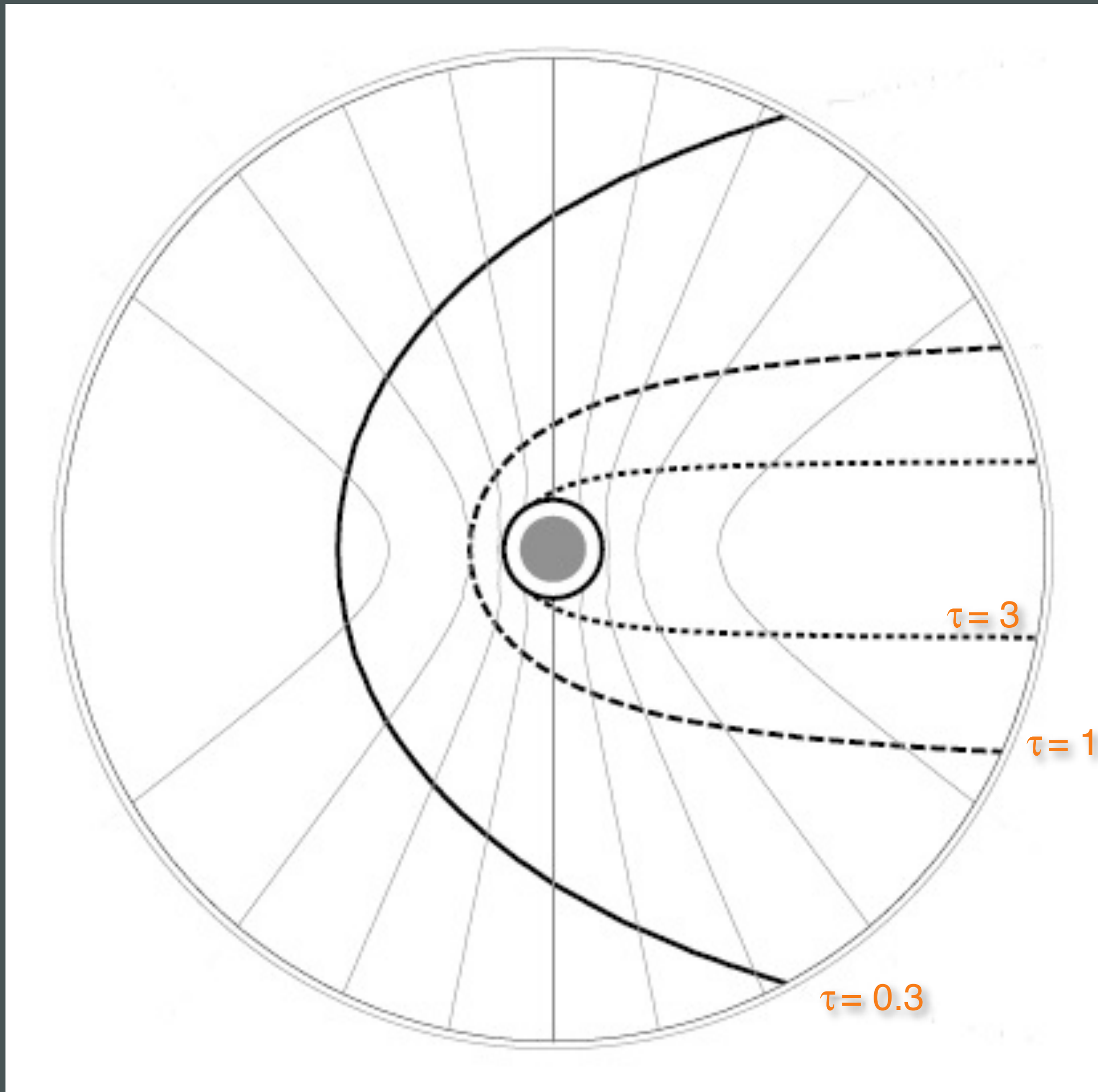


Chandra X-ray line-profile for ZPup



Cohen et al. 2010, MNRAS, 405, 2391

observer
on left

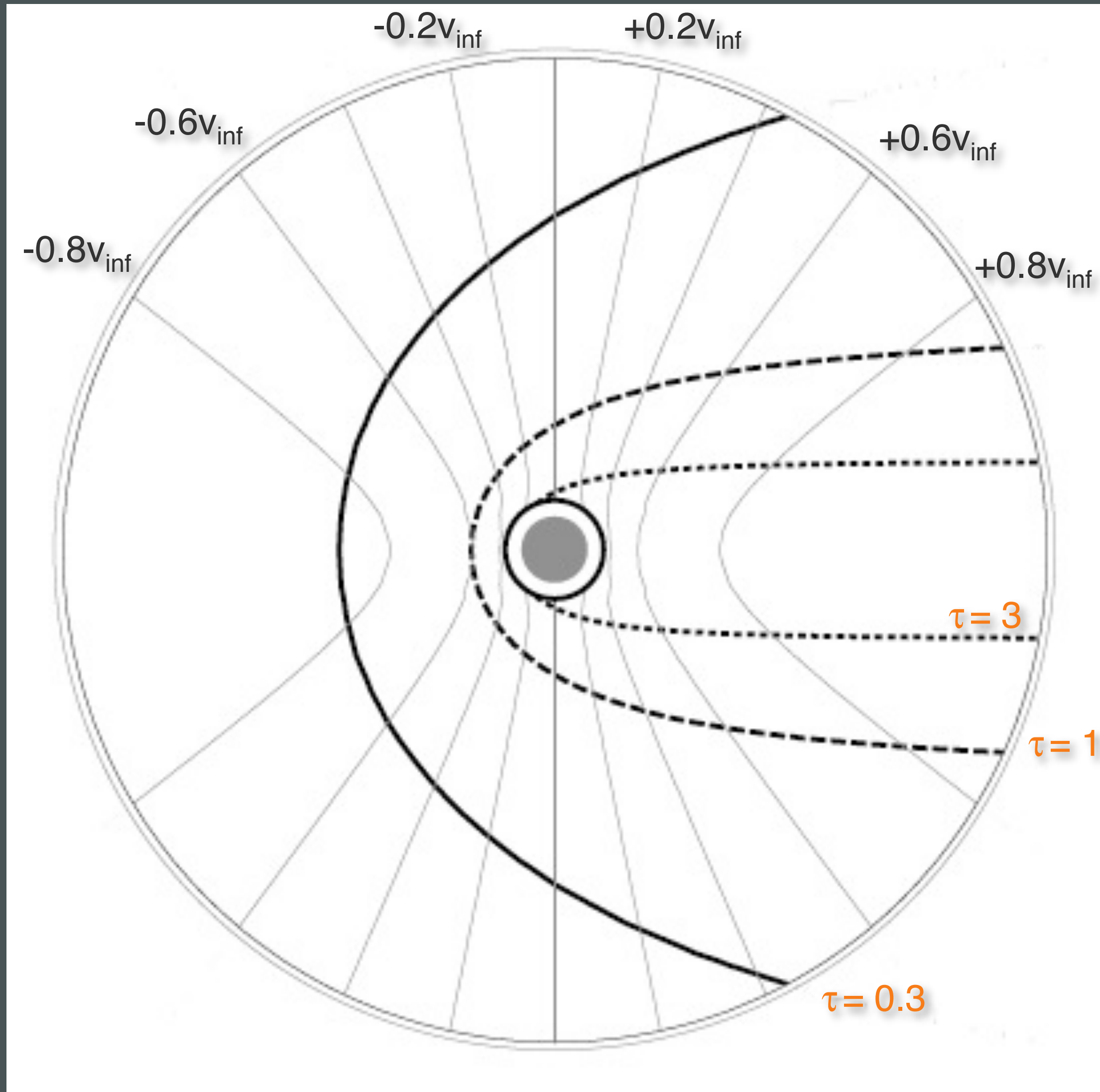


optical
depth
contours

Cohen et al. 2010, MNRAS, 405, 2391

isovelocity contours

observer on left

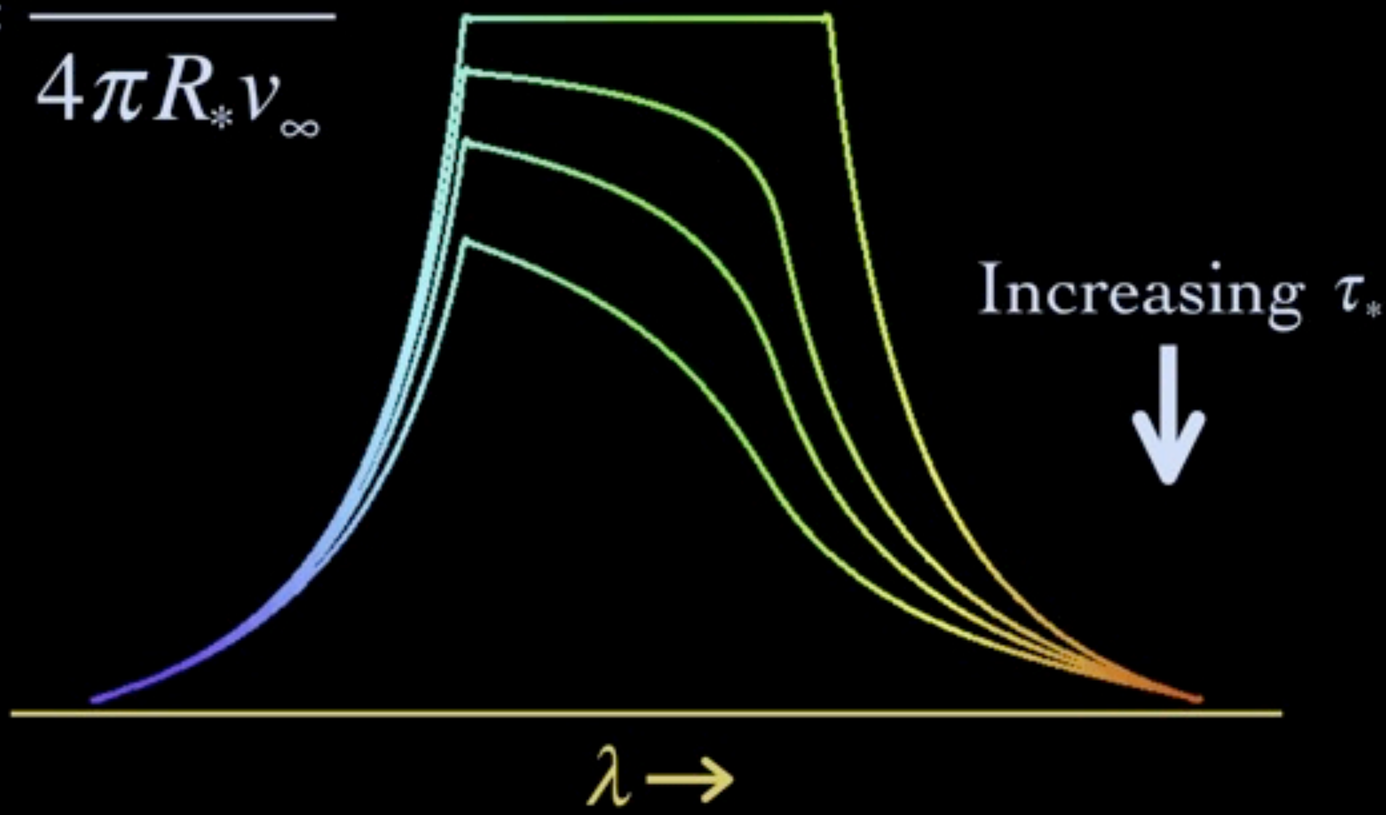


optical depth contours

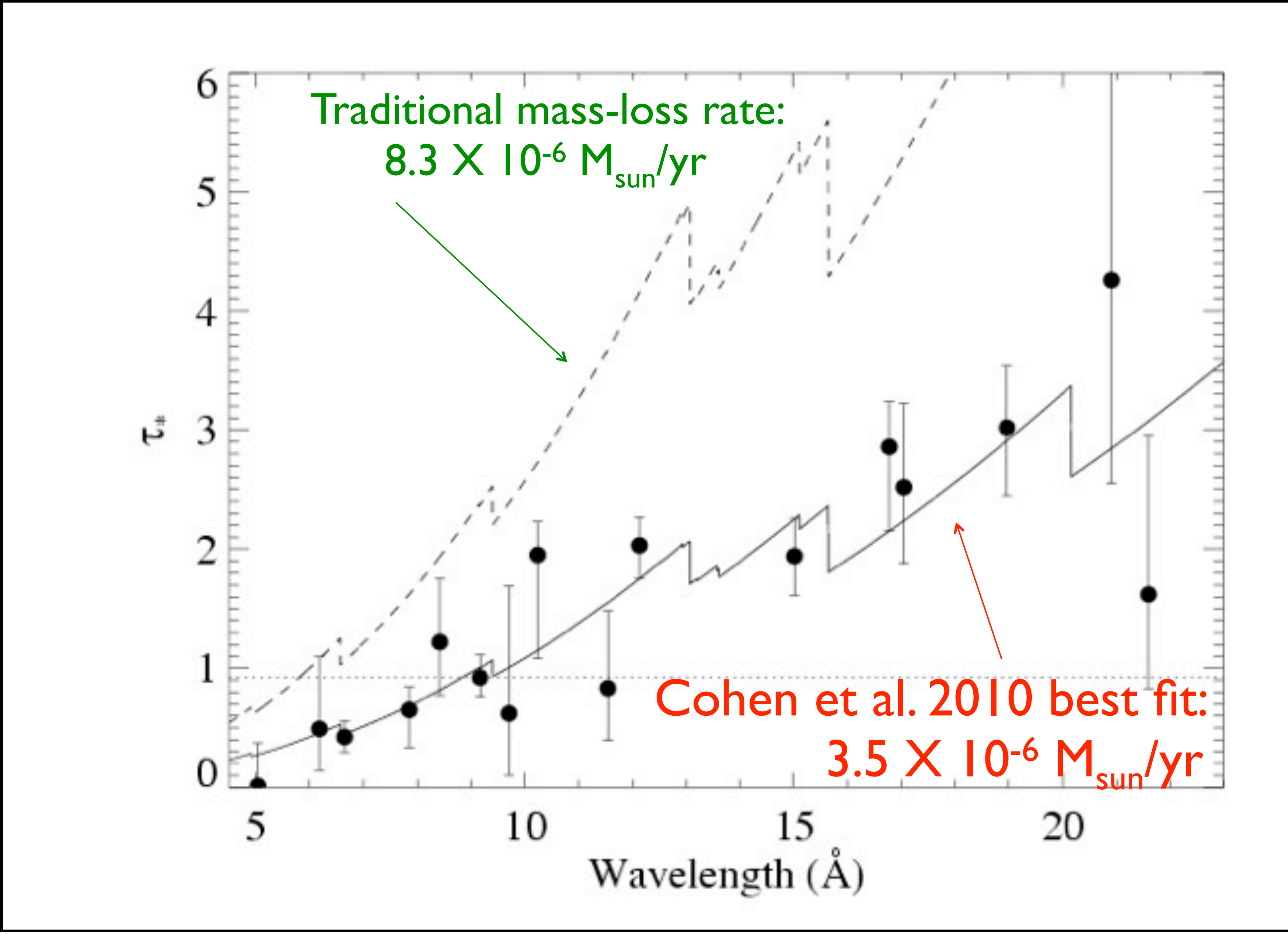
Cohen et al. 2010, MNRAS, 405, 2391

X-ray emission line-profile

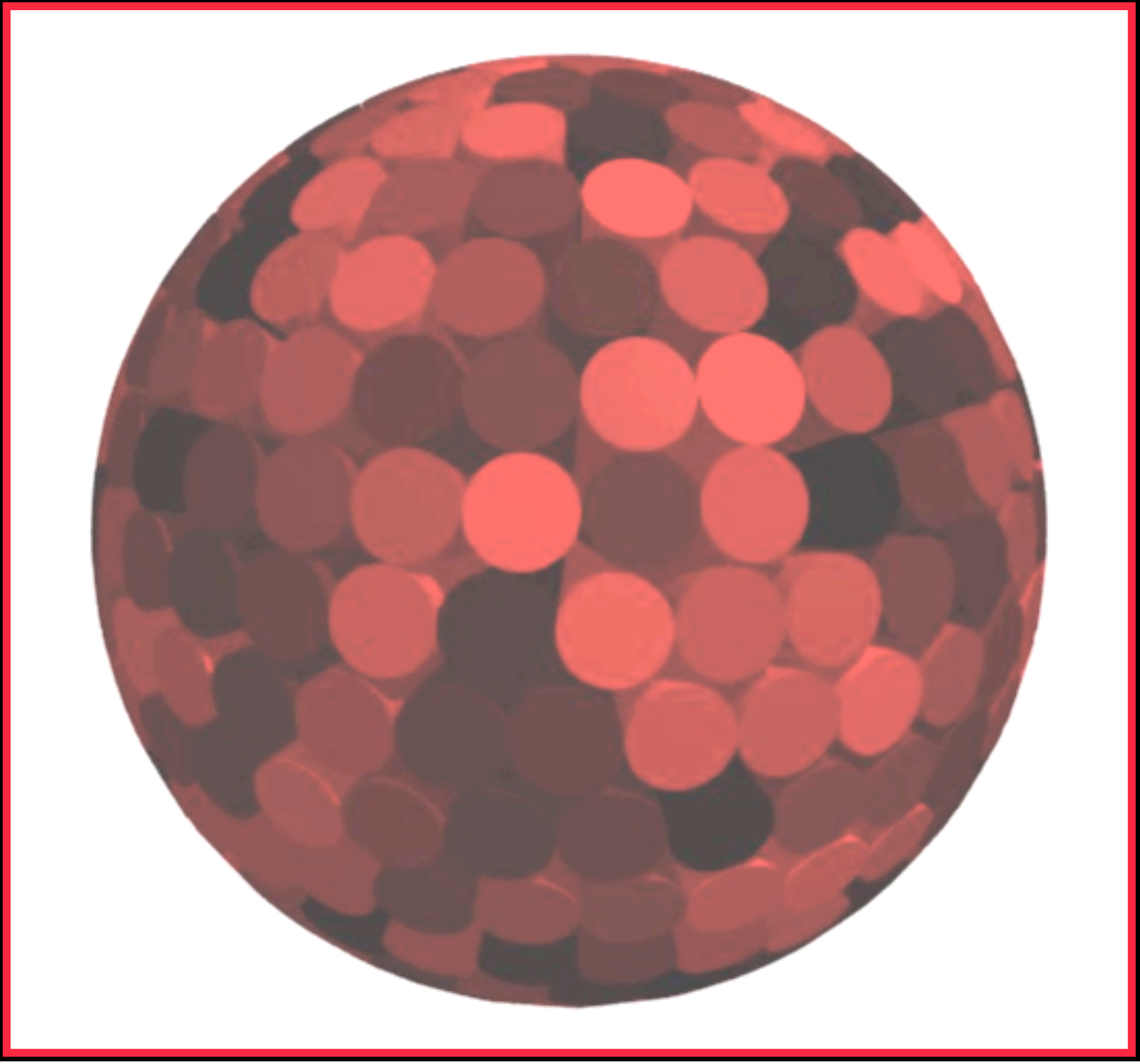
$$\tau_* = \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$



Inferring ZPup Mdot from X-ray lines



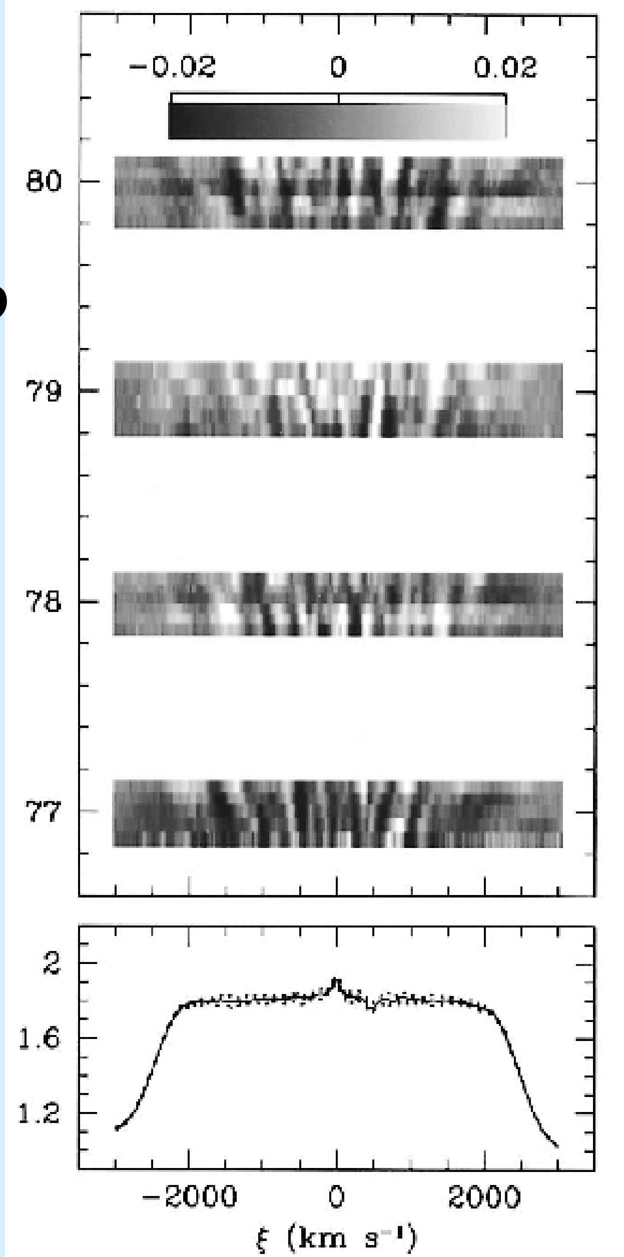
Extension to 3D: the "Patch Method"



WR Star Emission Profile Variability

WR 140

Lepine & Moffat 1999



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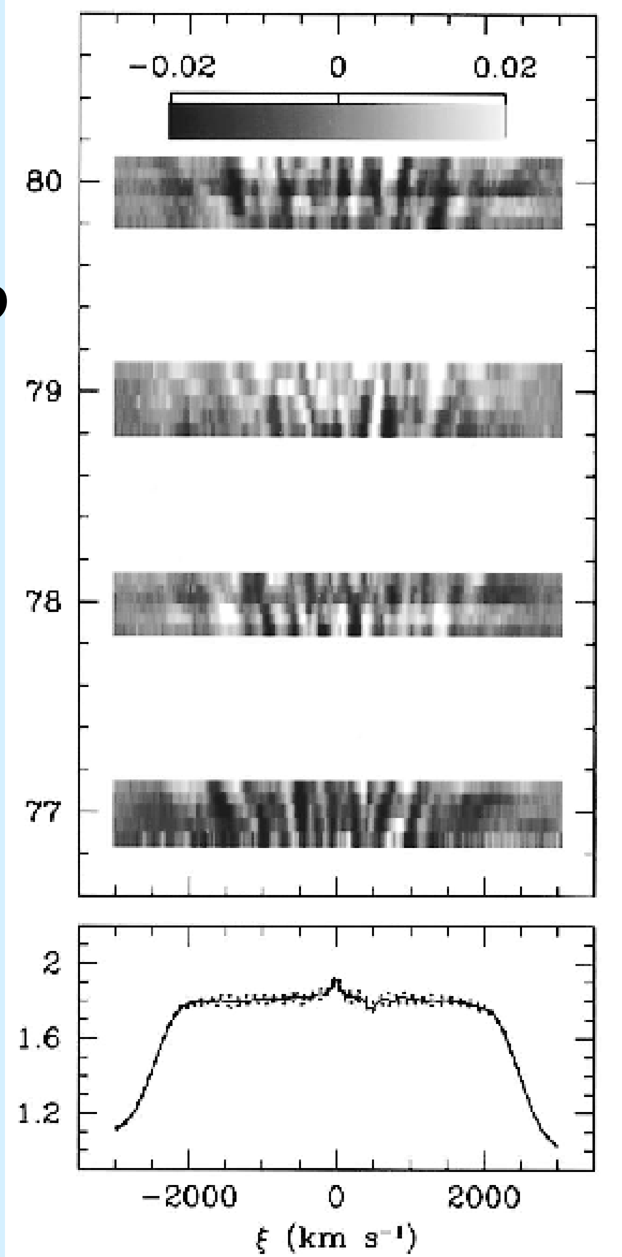
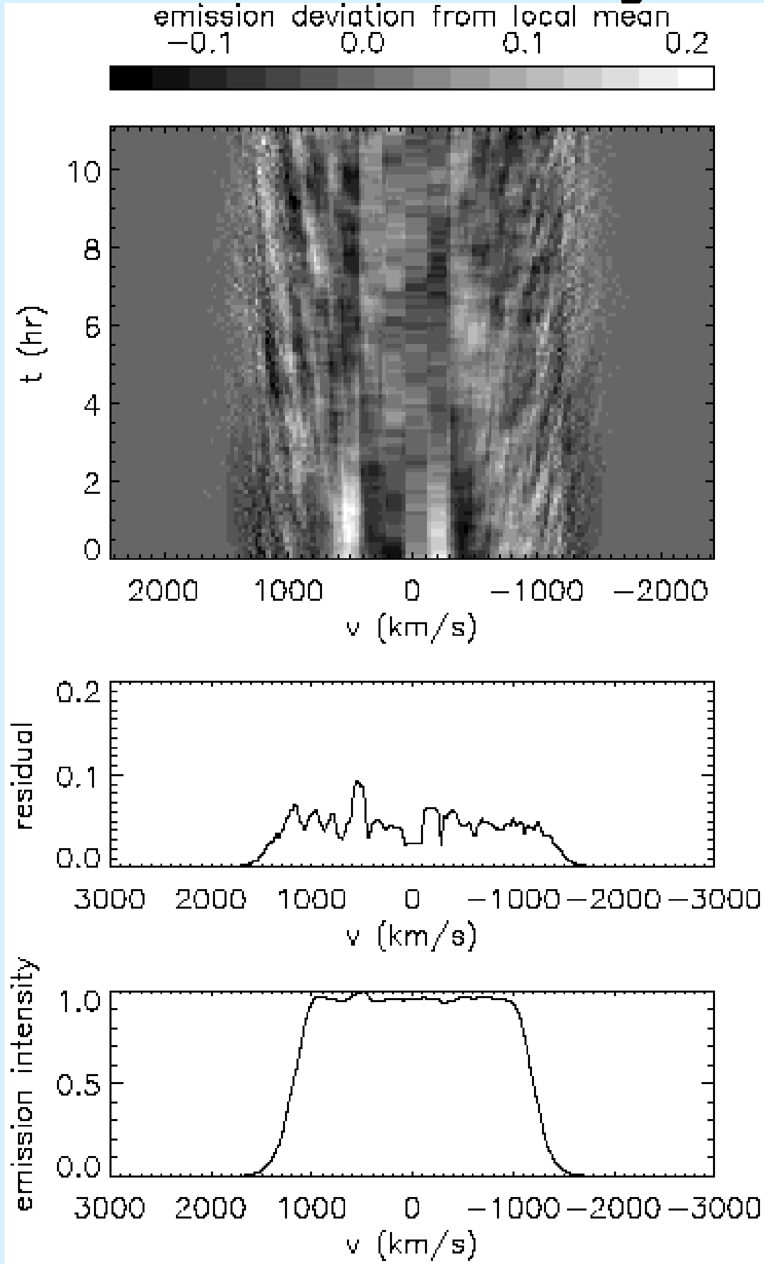


3D "patch" model

Dessart & Owocki 2002

patch size ~3 deg



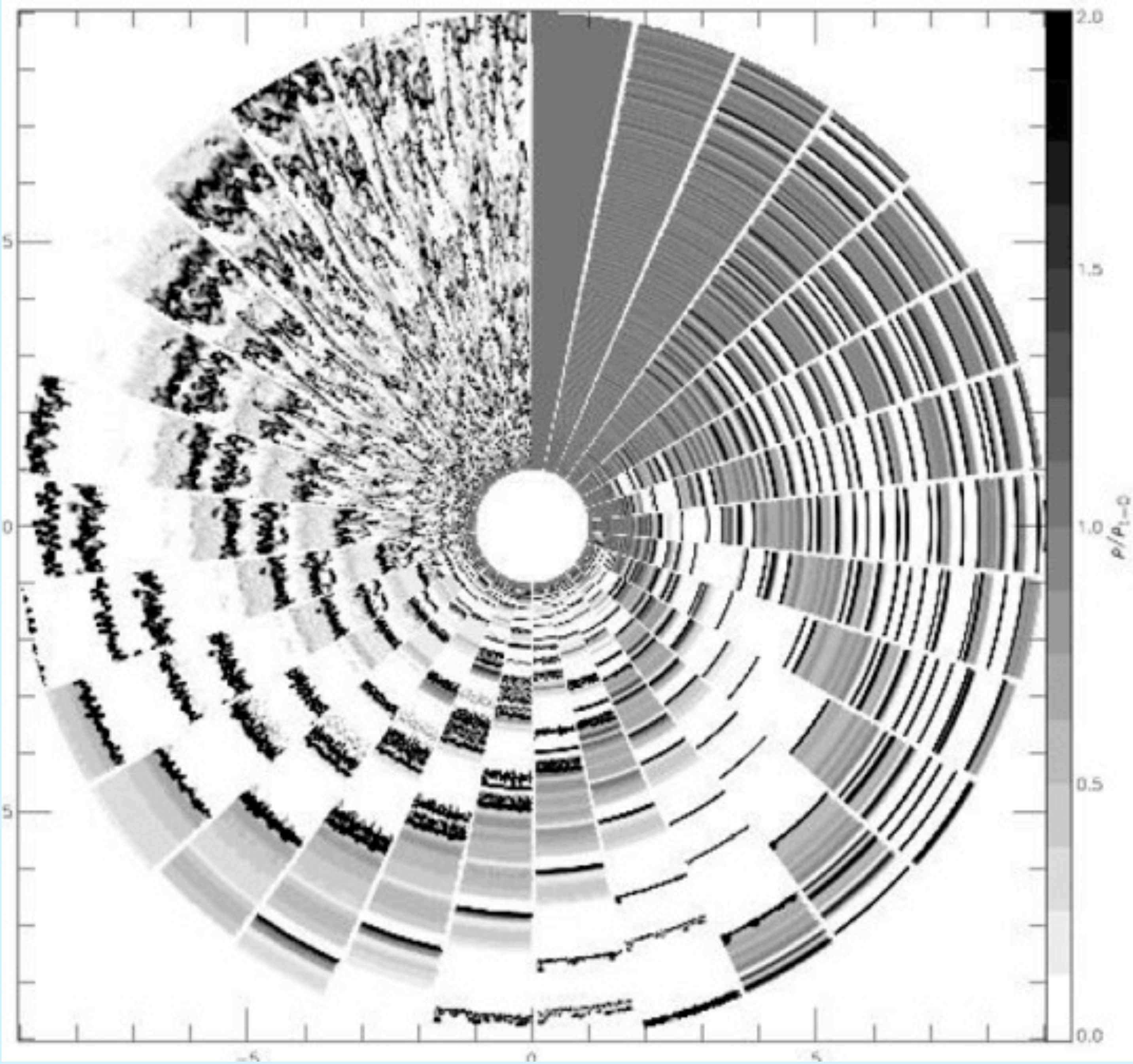
2D-H + 1D-R

nr=1000

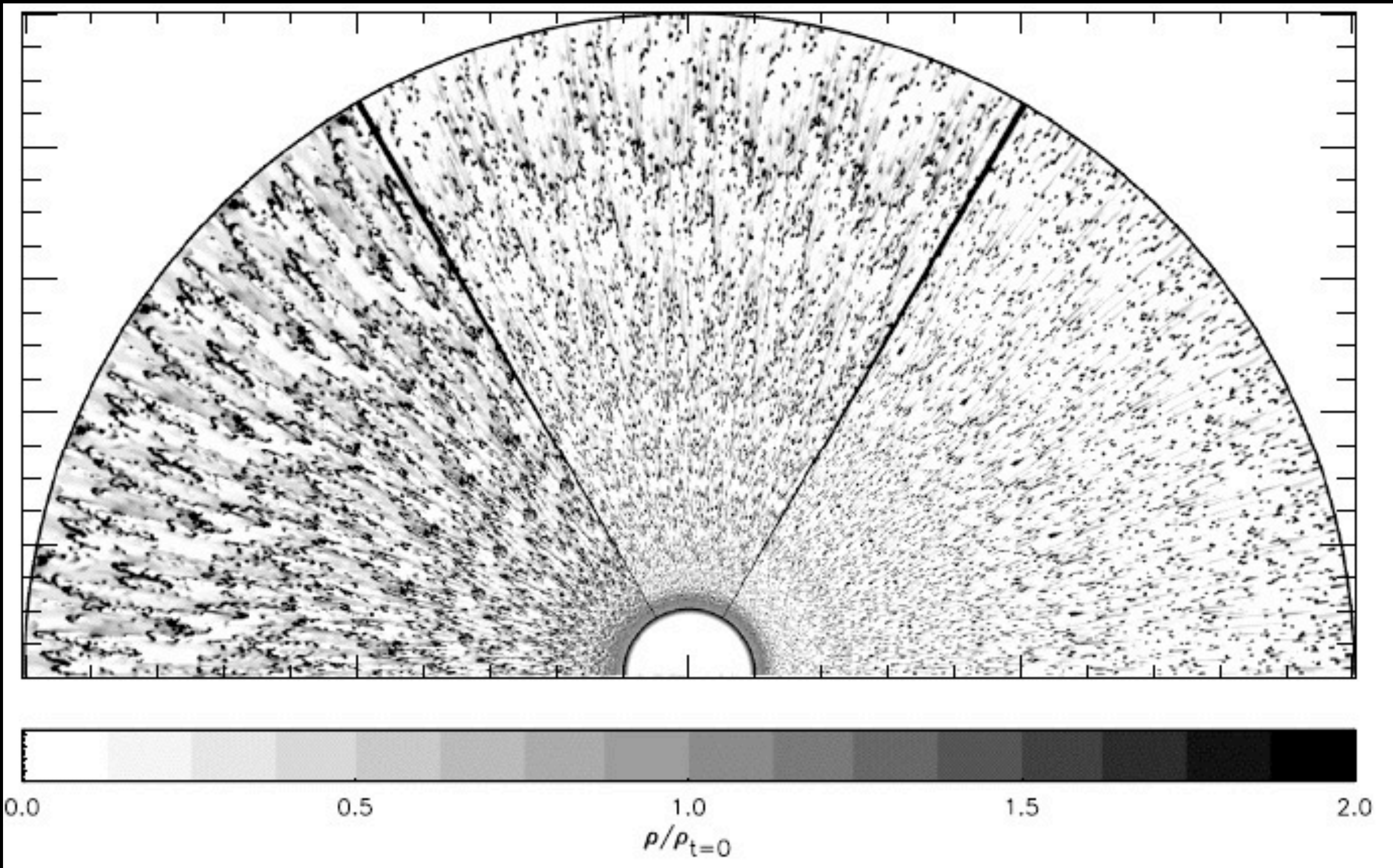
nϕ=60

Δϕ=12deg

Dessart & Owocki 2003

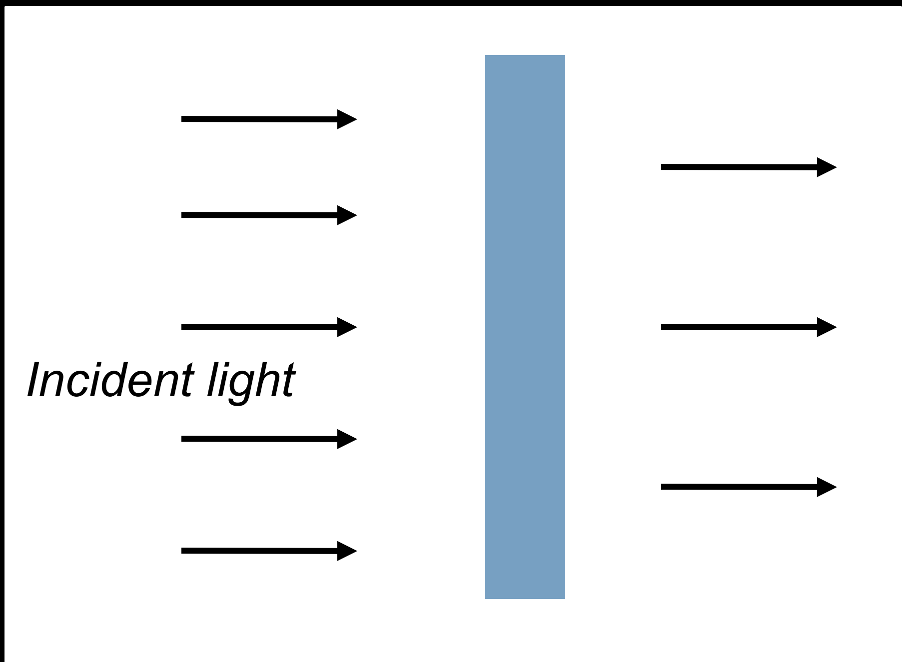


Dessart & Owocki 2005



Porosity

Porosity



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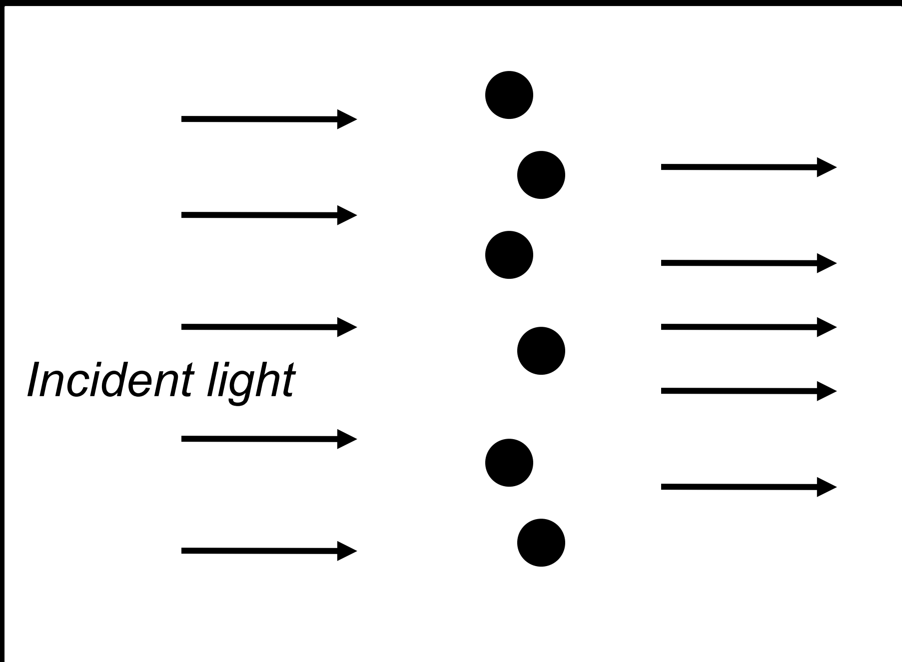
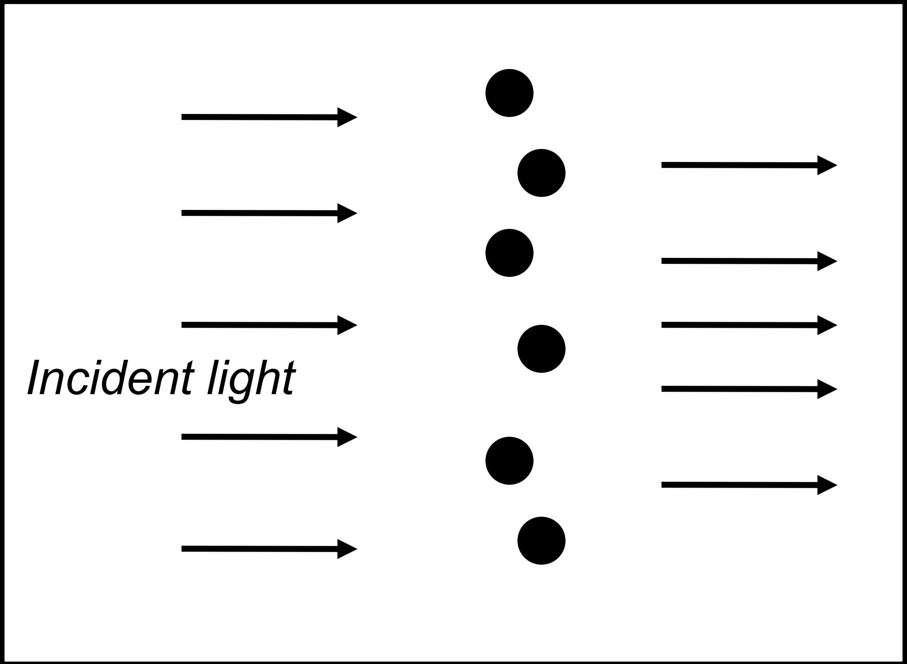
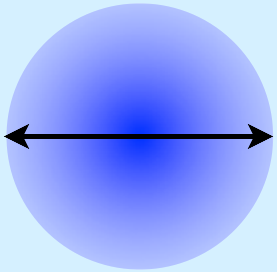


Porosity



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

Porous opacity from optically thick clumps



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

$$\tau_b \equiv \kappa \rho_b \ell = \kappa \rho \, \ell / f$$

"porosity length" h

$$\kappa_{eff} \equiv \frac{\sigma_{eff}}{m_b} = \kappa \, \frac{1 - e^{-\tau_b}}{\tau_b} \approx \frac{\kappa}{\tau_b} \quad ; \tau_b >> 1$$

clump size $\ell = 0.05r$ $\ell = 0.1r$ $\ell = 0.2r$

Porous envelopes

$h = 0.5r$

Porosity length

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

$h = r$

vol. fill factor

$f_{vol} \equiv (\ell / L)^3$

$= 1/f_{cl}$

$h = 2r$

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

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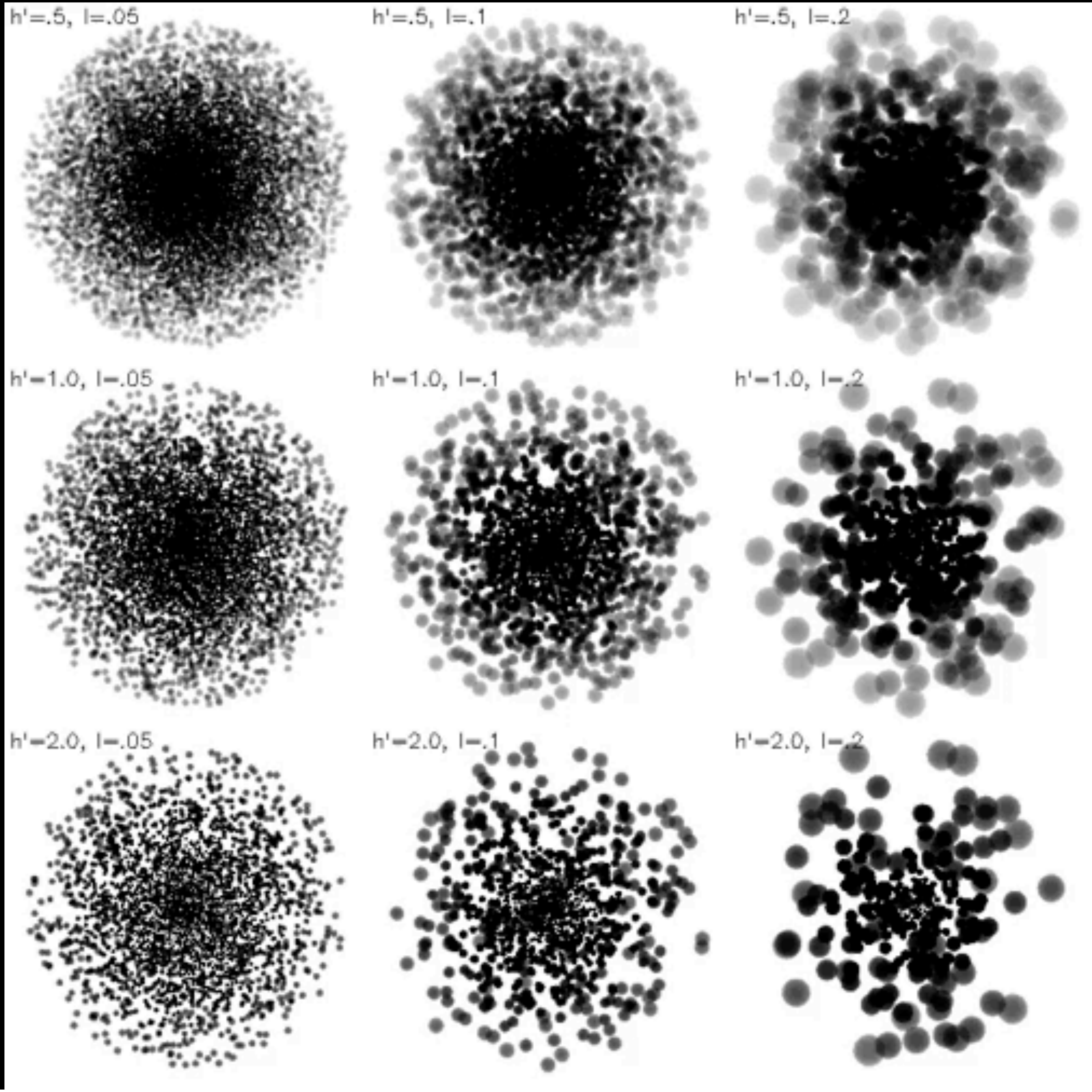
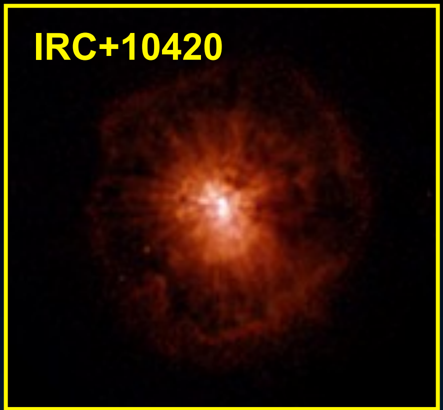


Super-Eddington
Continuum-Driven Winds

mediated by “porosity”

Massive, Luminous stars:

Several $M_\odot$ of circumstellar matter resulting from brief eruptions, expanding at about 50-600 km/s.

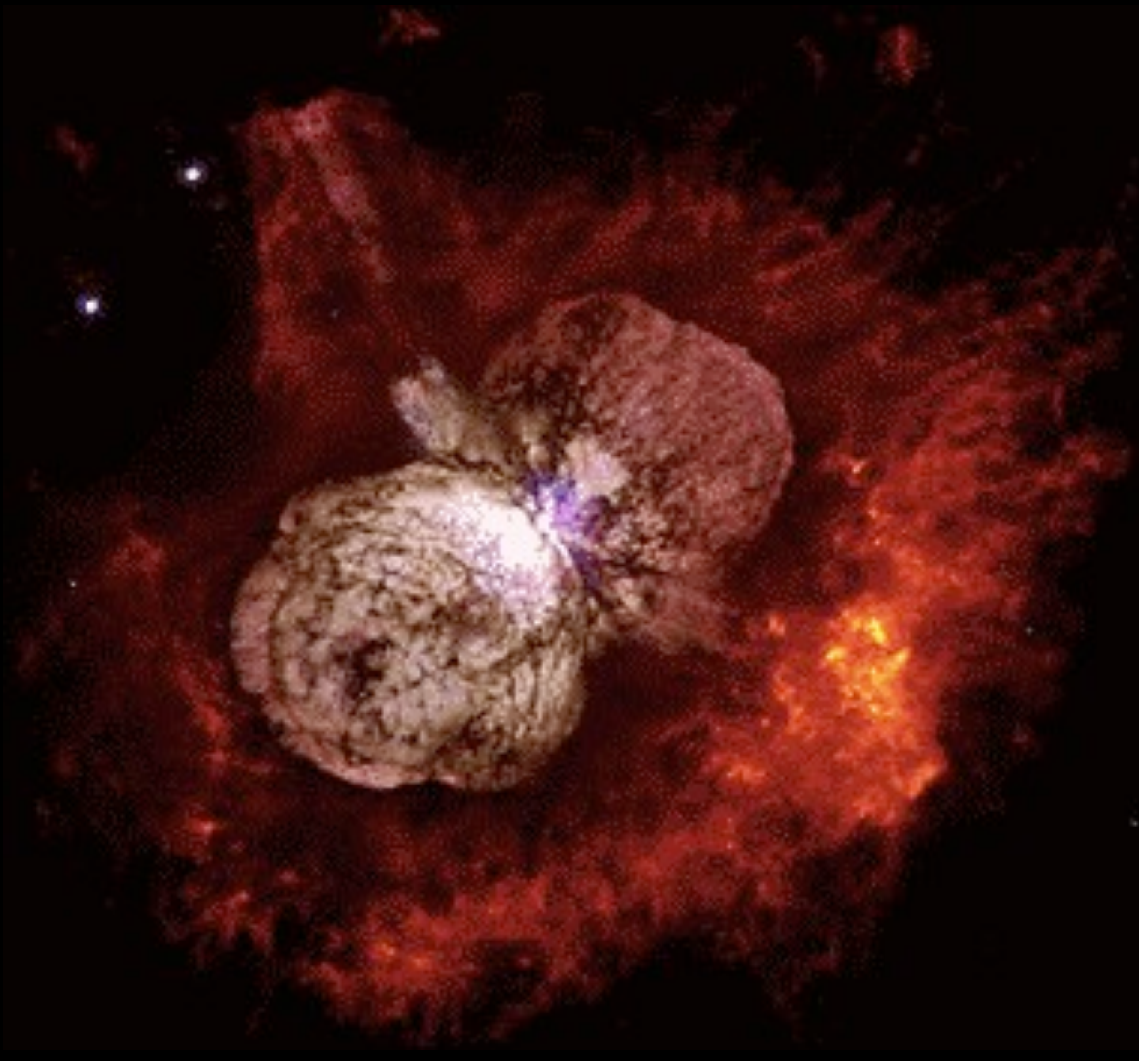


SN1987A
(courtesy P. Challis)

HD 168625
(Smith 2007)

Sher 25
(Brandner et al. 1997)

Eta Carinae



Eta Car's Extreme Properties

Present day:

$$L_{rad} \approx 5 \times 10^6 L_\odot$$
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$$\dot{M} \approx 10^{-3} M_\odot/\text{yr}$$
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$$\approx L_{kin} = \dot{M} v_\infty^2/2$$

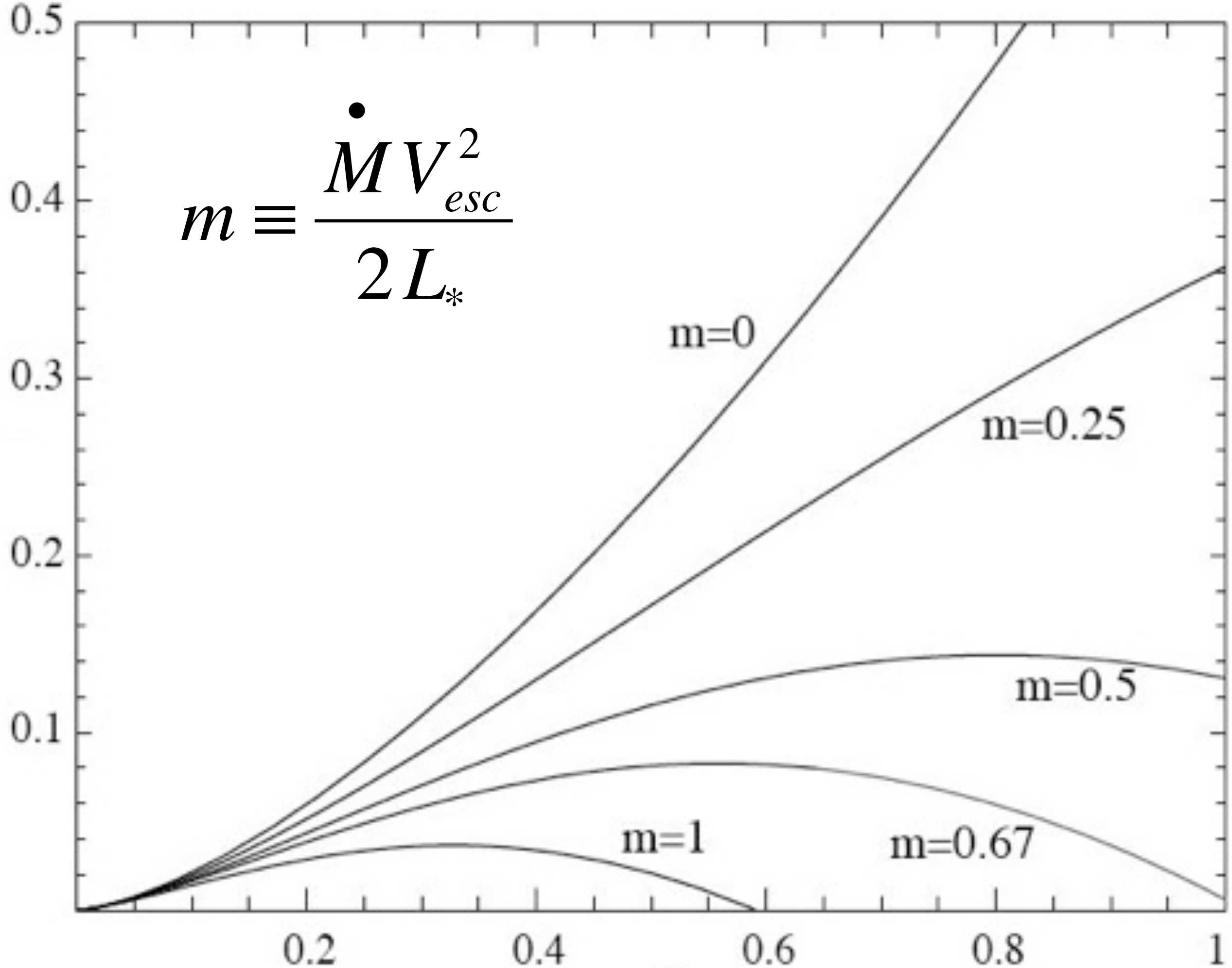
=> Mass loss is energy or "photon-tiring" limited

Stagnation of photon-tired outflow

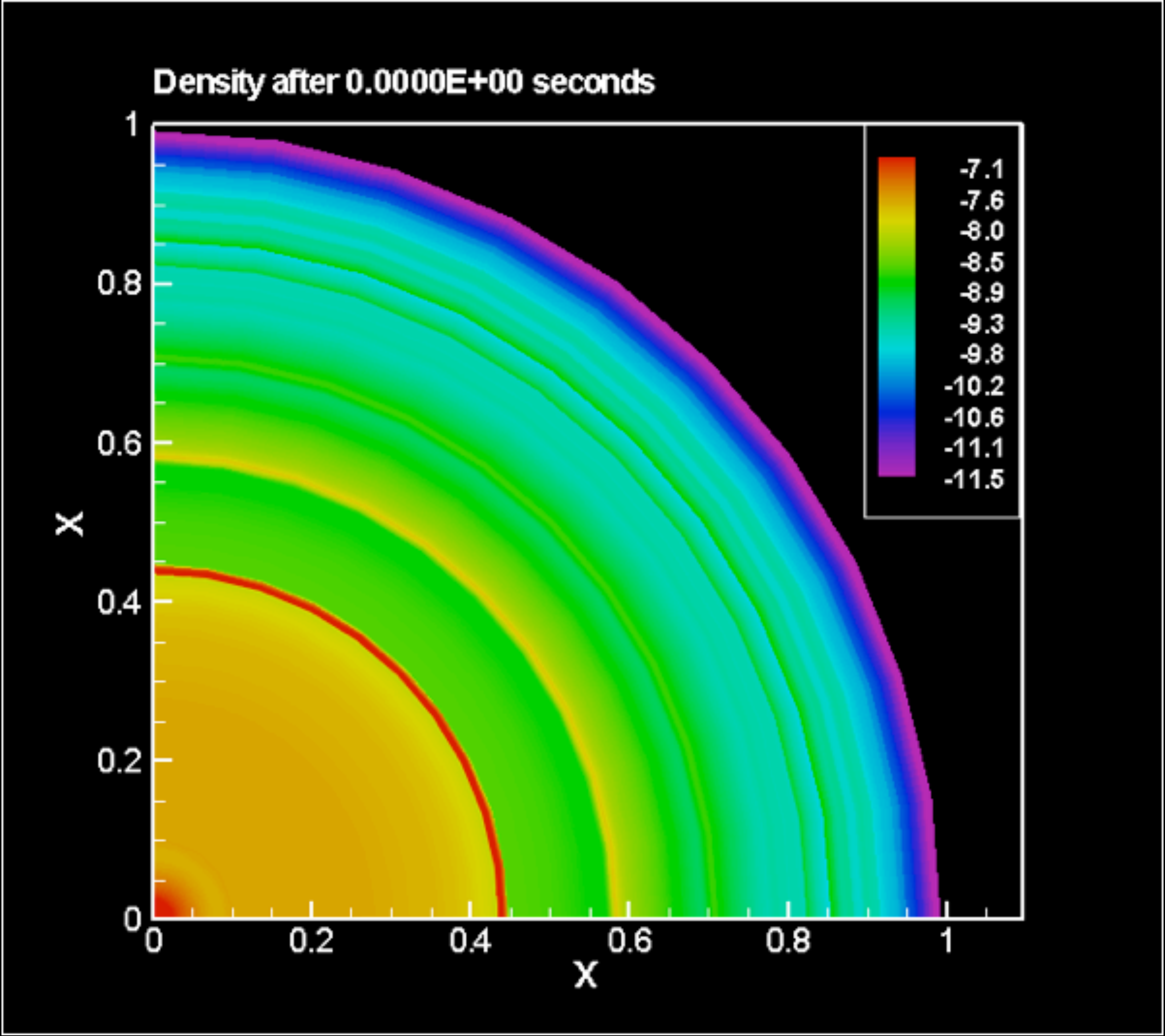
$$\frac{\kappa}{\kappa_{Edd}} = 1 + \sqrt{x} \qquad L(r) = L_* - \dot{M}\left[\frac{V^2}{2} + \frac{GM}{R} - \frac{GM}{r}\right]$$

$$m \equiv \frac{\dot{M} V_{esc}^2}{2 L_*}$$

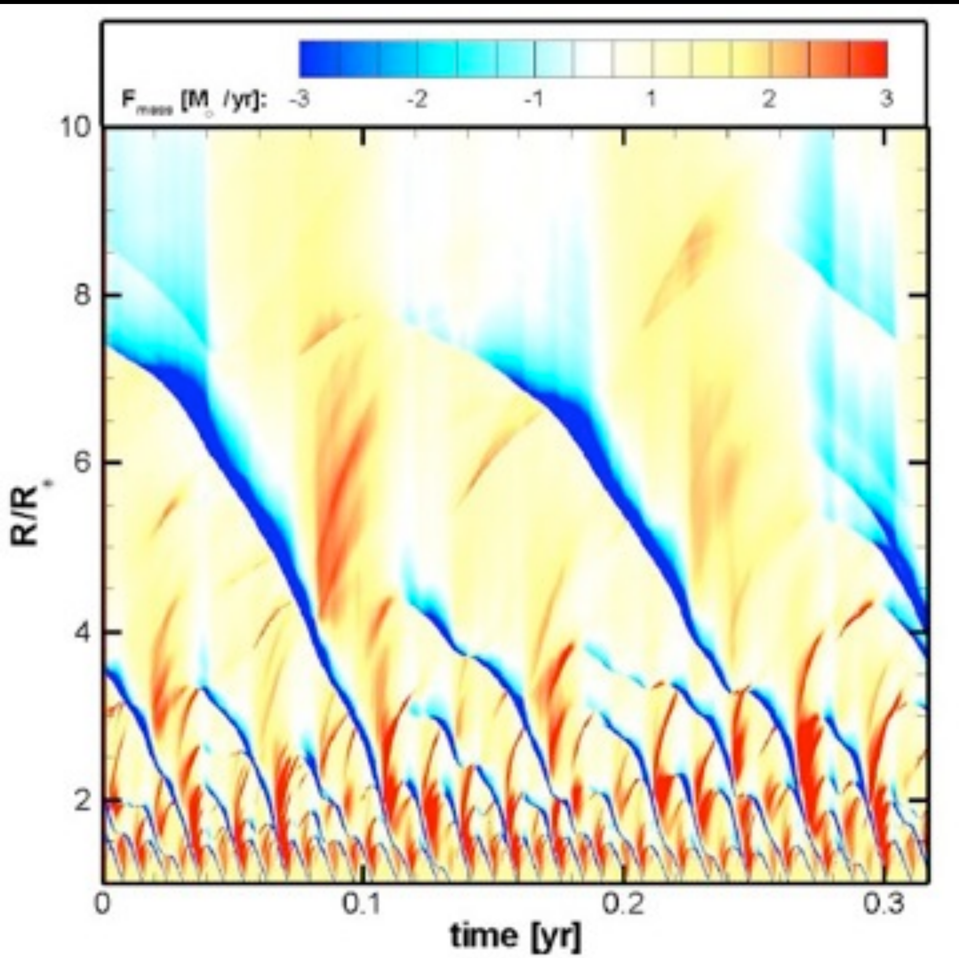
$$\frac{V^2}{V_{esc}^2}$$

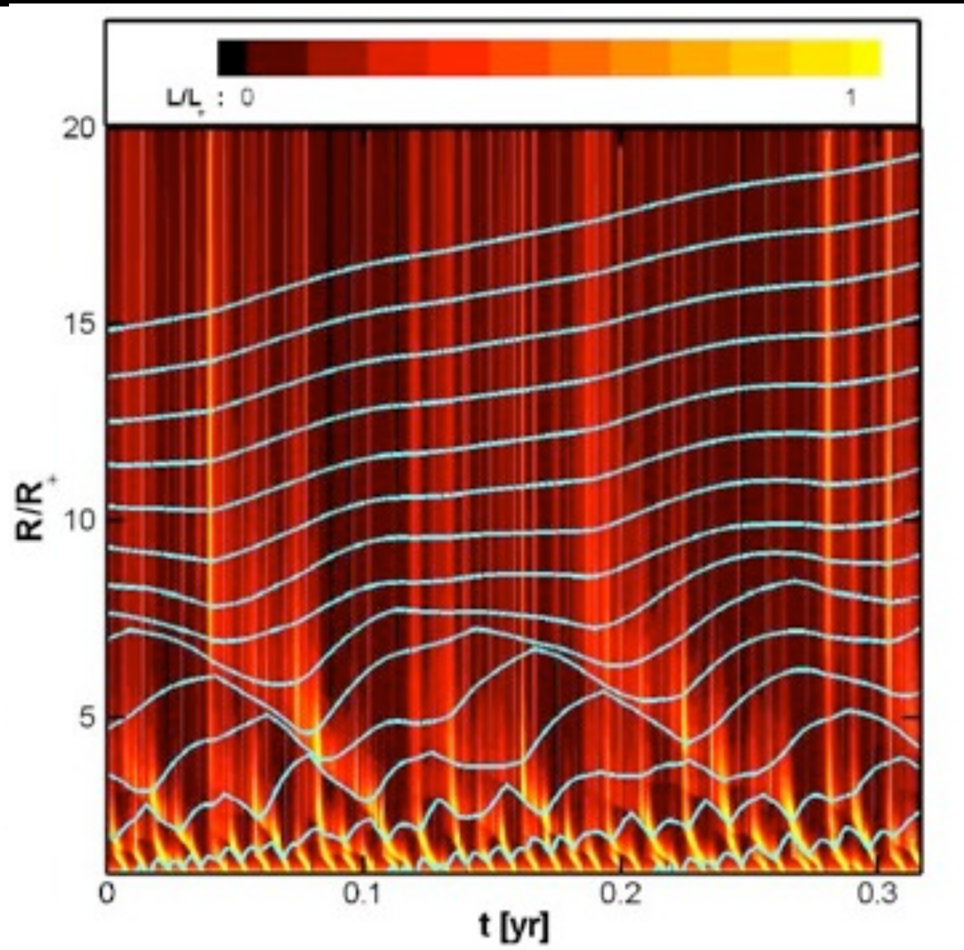


$$x = 1 - R_* / r$$


Density after 0.0000E+00 seconds
1
0.8
0.6
0.4
0.2
0
X
0
0.2
0.4
0.6
0.8
1
X
-7.1
-7.6
-8.0
-8.5
-8.9
-9.3
-9.8
-10.2
-10.6
-11.1
-11.5

Photon Tiring & Flow Stagnation

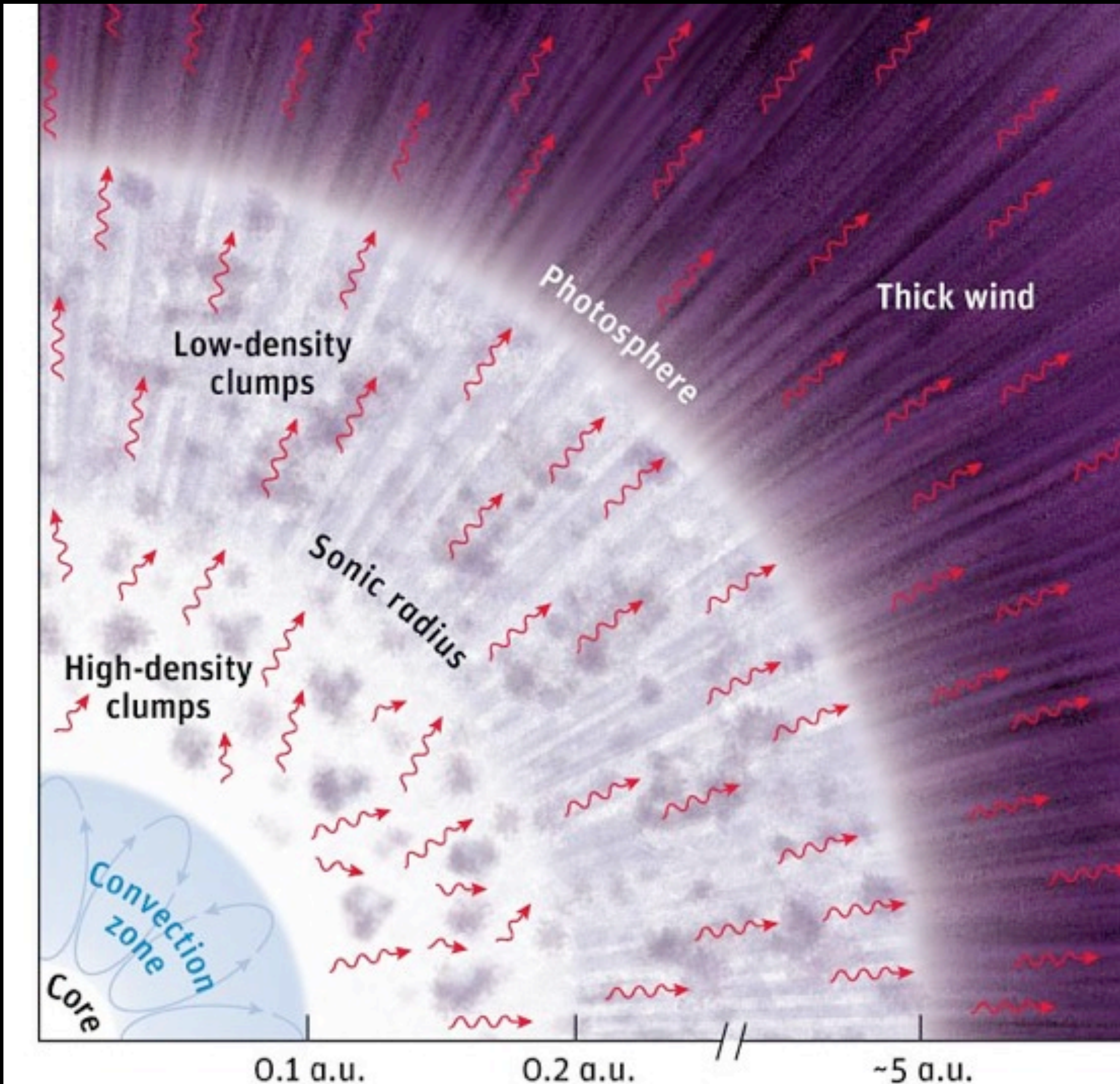




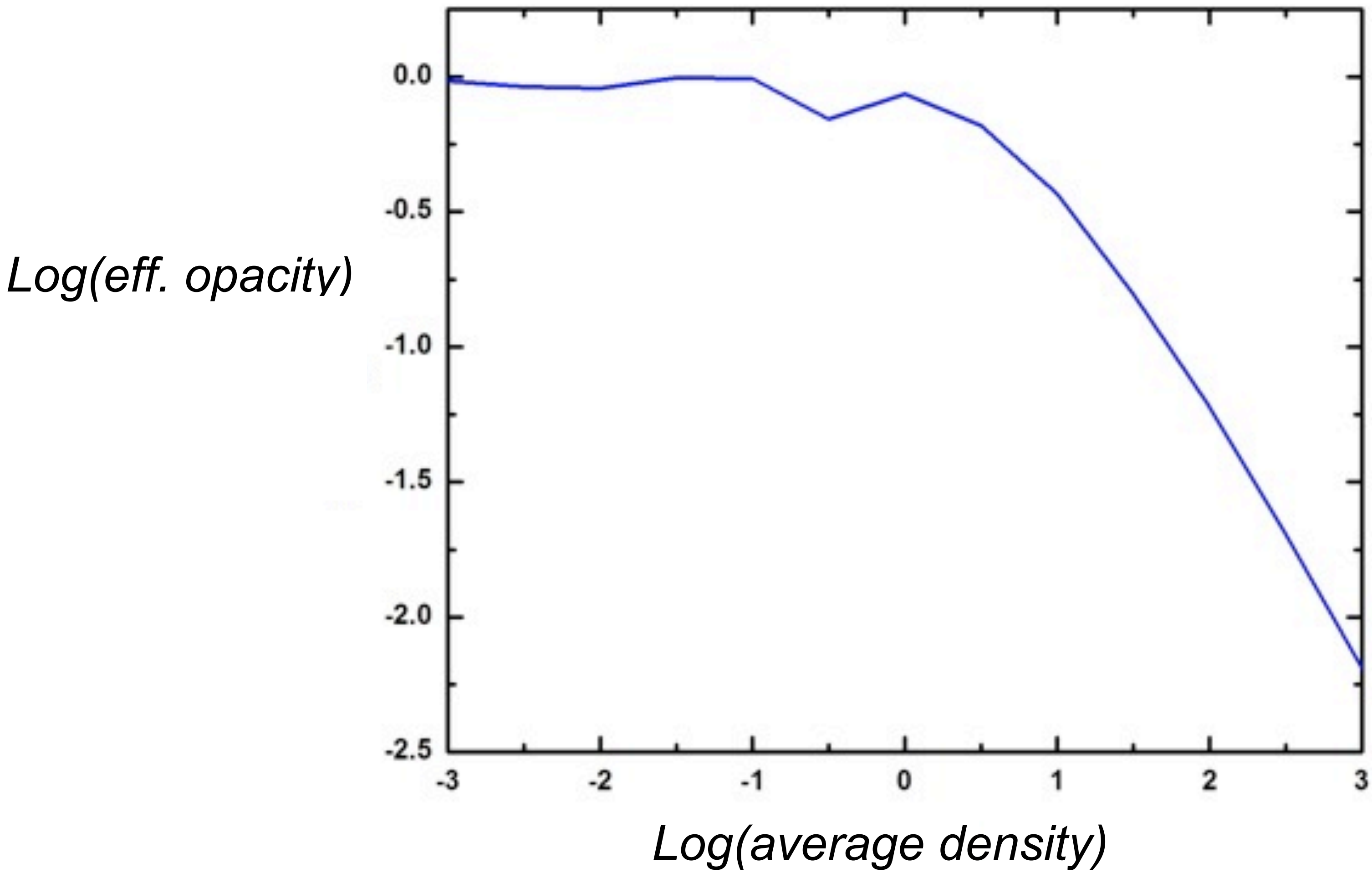
van Marle et al. 2009, MNRAS, 394, 595

Fluidized Bed

Spiegel 2006


Thick wind
Photosphere
Low-density clumps
Sonic radius
High-density clumps
Convection zone
Core
0.1 a.u.
0.2 a.u.
~5 a.u.

Monte Carlo results for eff. opacity vs. density in a porous medium



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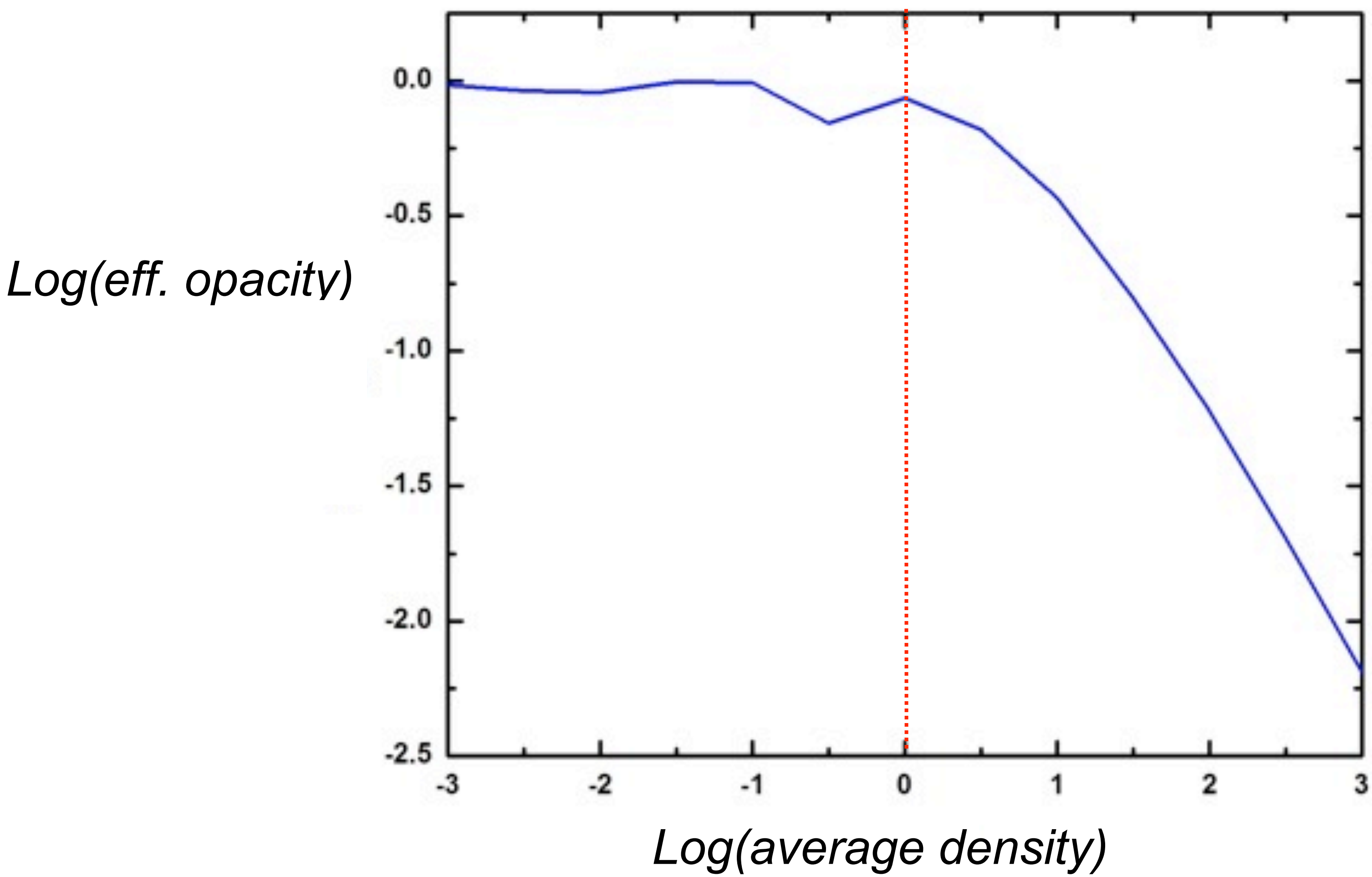

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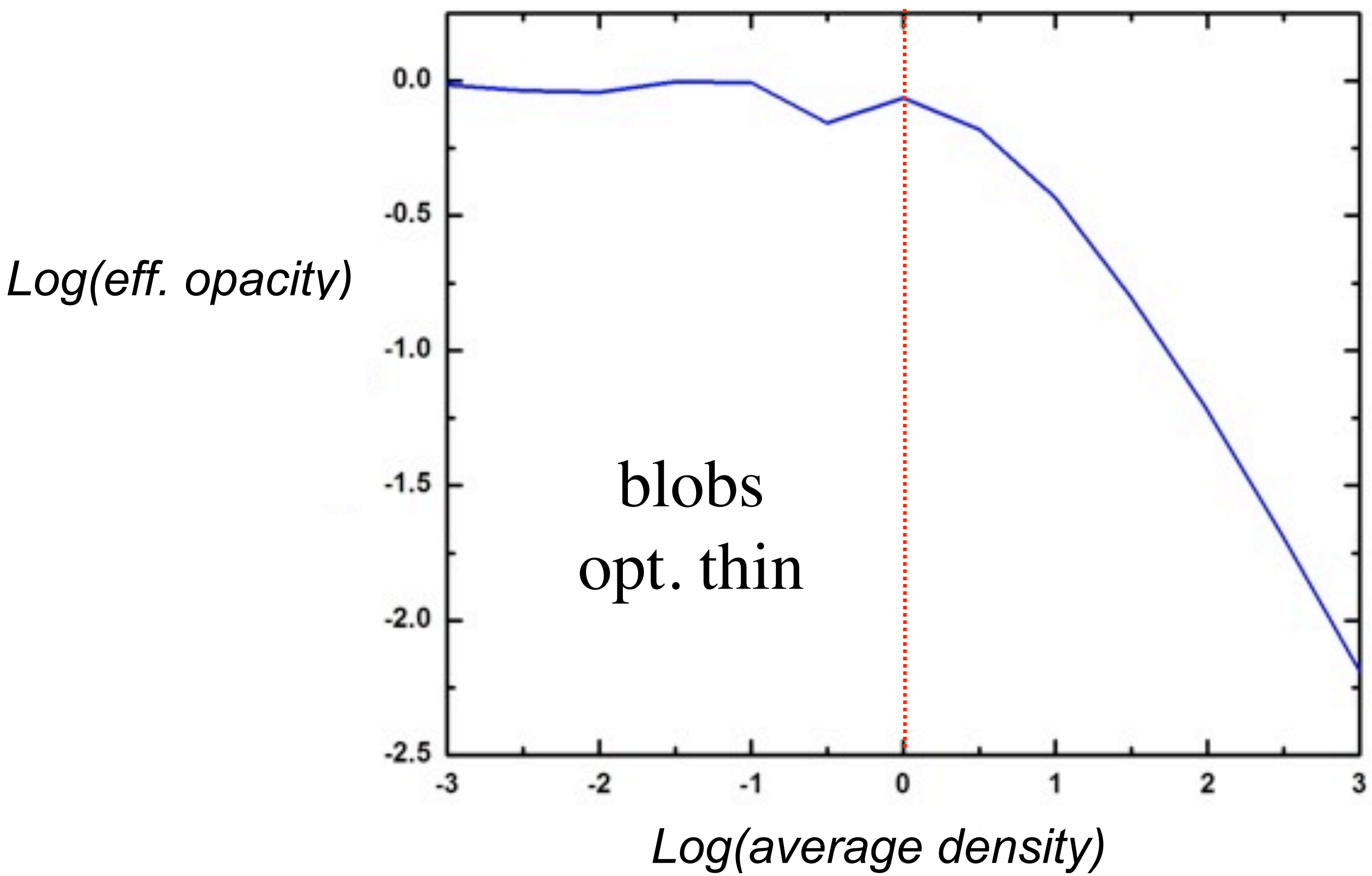

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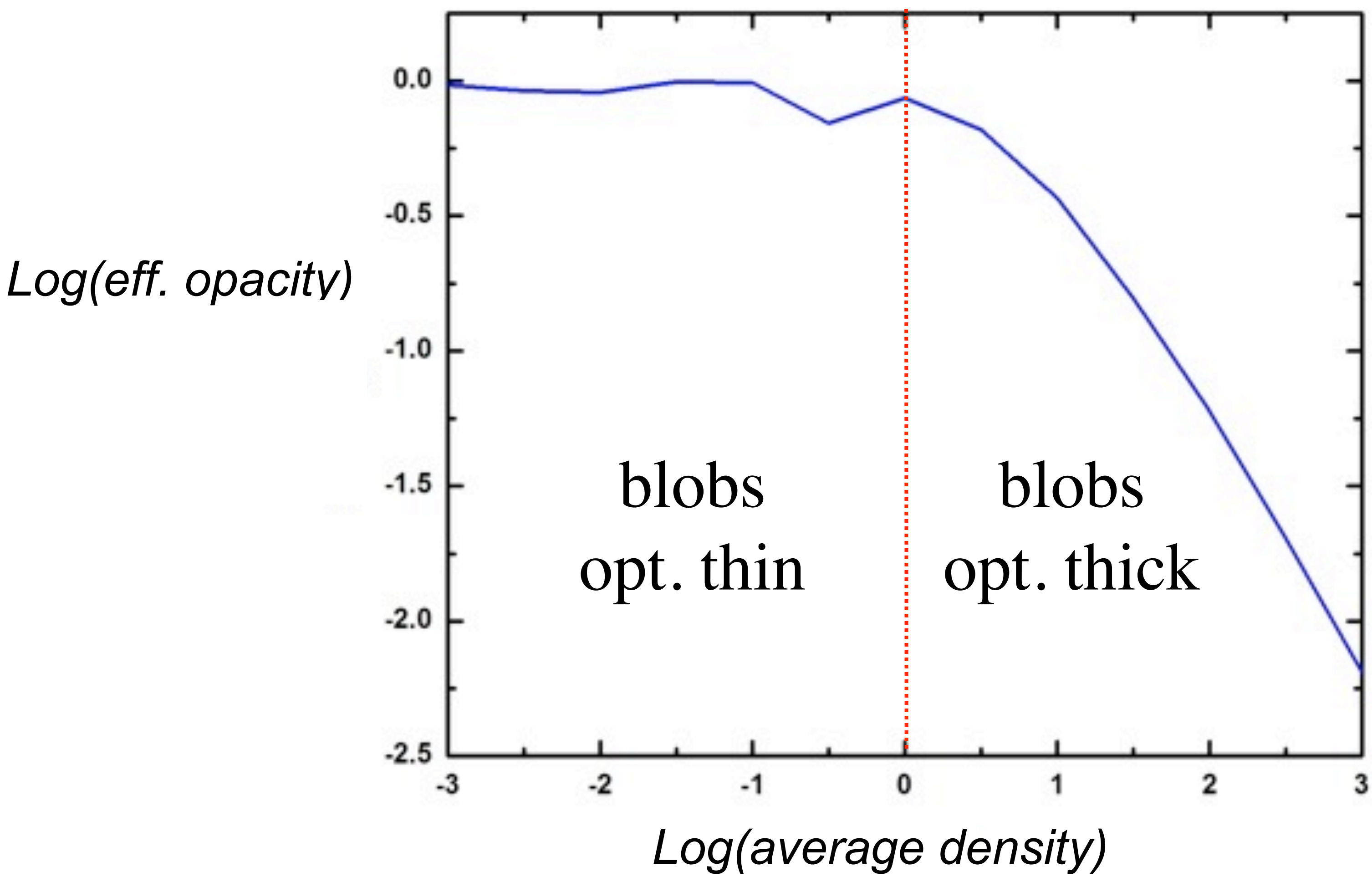

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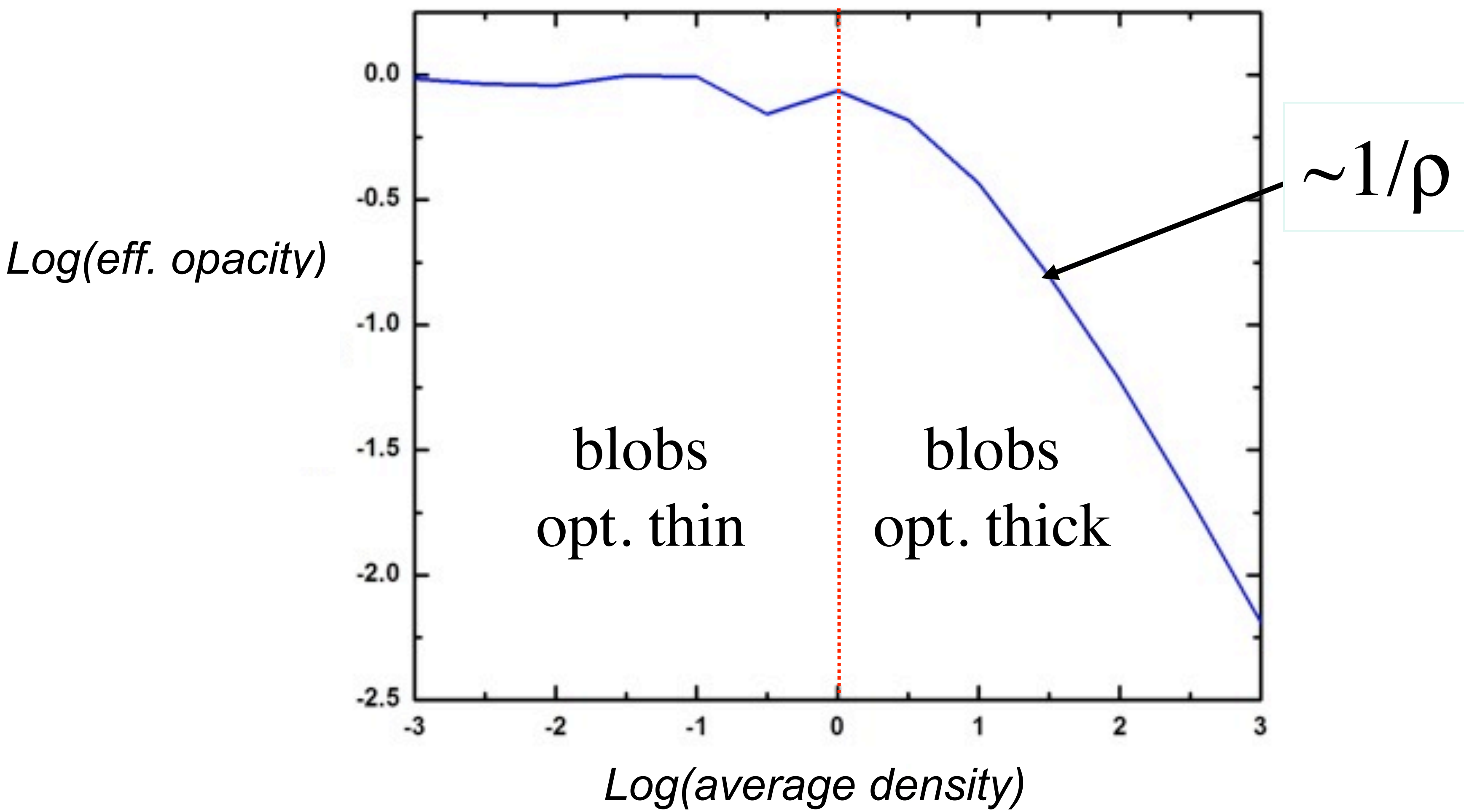

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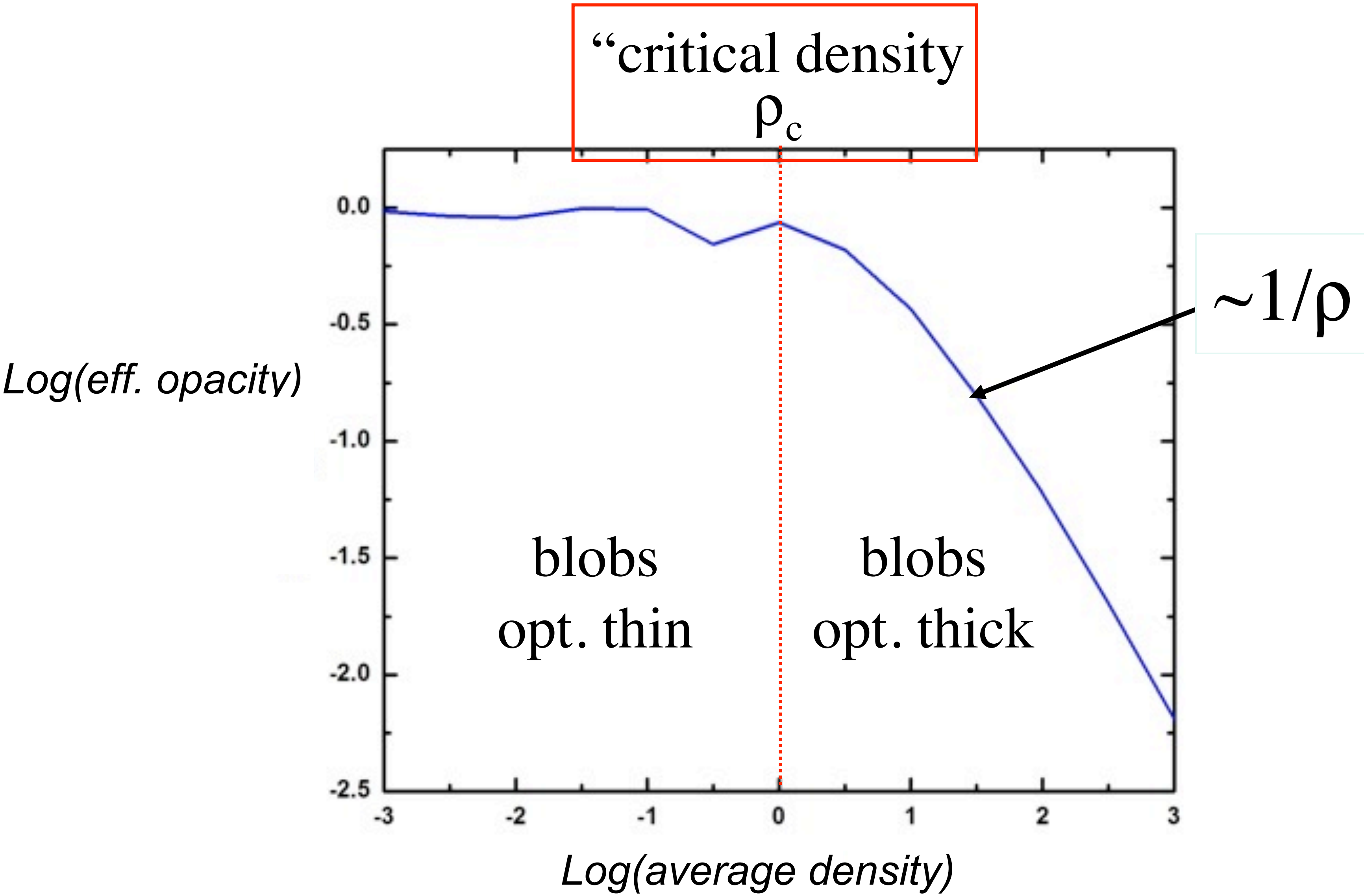

Power-law porosity

At sonic point: $$\Gamma_{eff}(r_S) = \Gamma\left(\frac{\rho_c}{\rho_S}\right)^{\alpha} \equiv 1$$

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$$\dot{M}_{CAK} \approx \frac{L_*}{c^2}\left(\bar{Q}\Gamma\right)^{-1+1/\alpha}$$

Effect of gravity darkening on porosity-mediated mass flux

$$\dot{m} \equiv \frac{\dot{M}}{4\pi R^2}$$

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

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highest at **pole**

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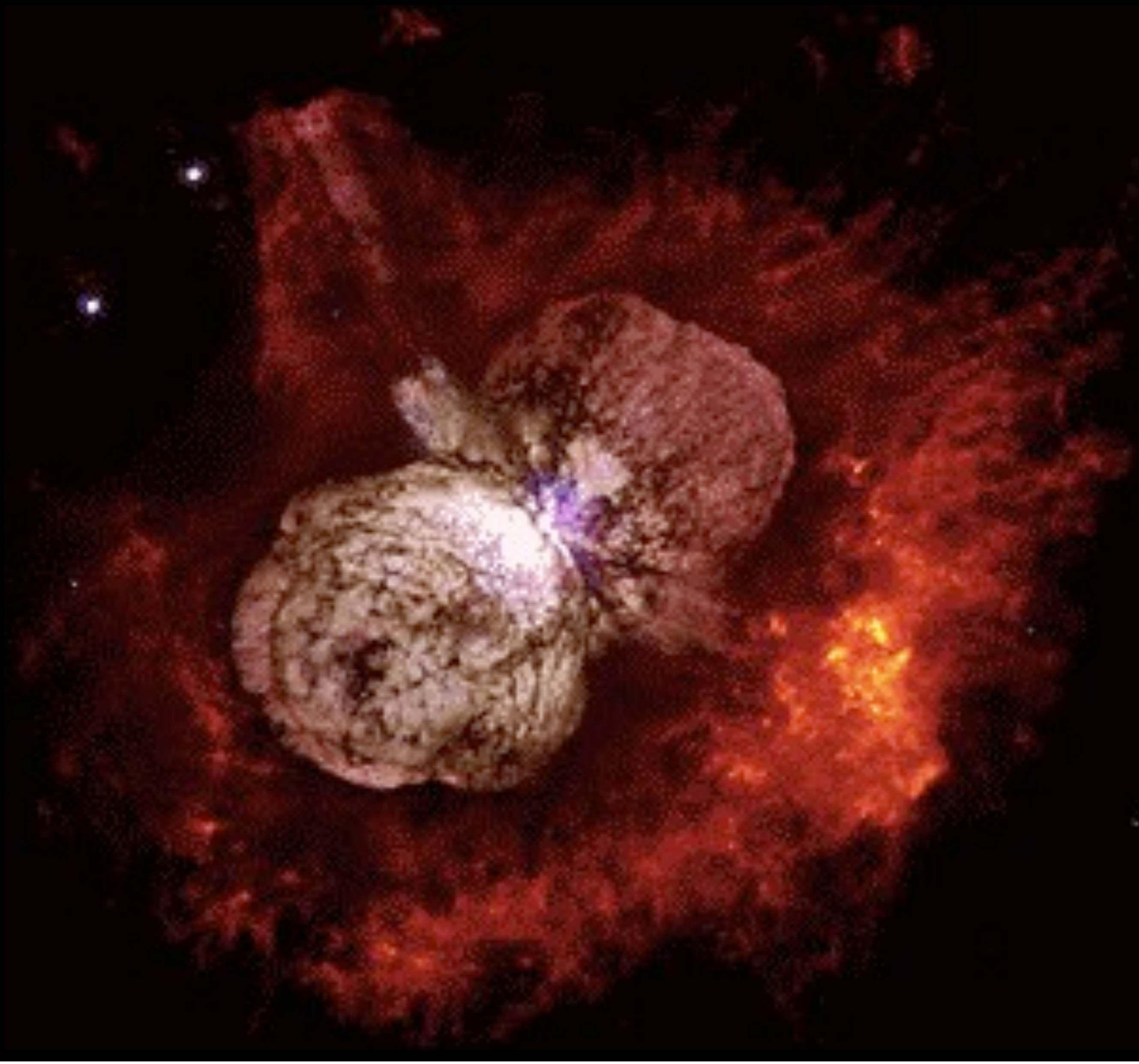
$$\dot{m}(\theta) \sim F(\theta)$$

highest at **pole**

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

highest at **pole**

Eta Carinae



Summary Themes

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- Continuum vs. Line driving

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- Prolate vs. Oblate mass loss

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- Continuum vs. Line driving
- Prolate vs. Oblate mass loss
- Porous vs. Smooth medium

End Lecture 1

References 1

- Humphreys, R.-M. & Davidson, K. 1979, Studies of luminous stars in nearby galaxies. III - Comments on the evolution of the most massive stars in the Milky Way and the Large Magellanic Cloud, ApJ, 232, 409
- Smith, N. et al. 2003, The stellar wind geometry of η Carinae, IAUS, 212, 236
- Smith, N. et al. 2003, Latitude-dependent Effects in the Stellar Wind of η Carinae, ApJ, 586, 432
- Graefener, G. & Hamman, W.-R. 2006, The metallicity dependence of WR wind models, ASPC, 353, 171
- Abbott, D.-C. & Lucy, L.-B. 1985, Multiline transfer and the dynamics of stellar winds, ApJ, 288, 679
- Lucy, L.-B. & Abbott, D.-C. 1993, Multiline transfer and the dynamics of Wolf-Rayet winds, ApJ, 405, 738
- Vink, J.-S. 2001, Mass-loss predictions for O and B stars as a function of metallicity, A&A, 369, 574
- Owocki, S.-P. et al. 1988, Time-dependent models of radiatively driven stellar winds. I - Nonlinear evolution of instabilities for a pure absorption model, ApJ, 335, 914
- Runacres, M.-C. & Owocki, S.-P. 2002, The outer evolution of instability-generated structure in radiatively driven stellar winds, A&A, 381, 1015
- Feldmeier, A. et al. 1997, A possible origin for X-rays from O stars., A&A, 322, 878
- Cohen, D.-H. et al. 2010, A mass-loss rate determination for ζ Puppis from the quantitative analysis of X-ray emission-line profiles, MNRAS, 405, 2391
- Lepine, S. & Moffat, A.-F.-J. 1999, Wind Inhomogeneities in Wolf-Rayet Stars. II. Investigation of Emission-Line Profile Variations, ApJ, 514, 909
- Dessart, L. & Owocki, S.-P. 2002, Wavelet analysis of instability-generated line profile variations in hot-star winds, A&A, 393, 991

References 2

- Dessart, L. & Owocki, S.-P. 2003, Two-dimensional simulations of the line-driven instability in hot-star winds, A&A, 406, 1
- Dessart, L. & Owocki, S.-P. 2005, 2D simulations of the line-driven instability in hot-star winds. II. Approximations for the 2D radiation force, A&A, 437, 657
- Spiegel, E.-A. 2006, Phenomenological photofluiddynamics, EAS, 21, 127
- Owocki, S. 2009, Radiation Hydrodynamics of Line-Driven Winds, AIPC, 1171, 173
- van Marle, A.-J. et al. 2009, On the behaviour of stellar winds that exceed the photon-tiring limit, MNRAS, 394, 595
- Owocki, S. & van Marle, A.-J. 2008, Luminous Blue Variables & Mass Loss near the Eddington Limit, IAUS, 250, 71
- Gayley, K.-G. et al. 1995, Momentum deposition on Wolf-Rayet winds: Nonisotropic diffusion with effective gray opacity, ApJ, 442, 296
- Gayley, K.-G. & Owocki, S.-P. 1994, Acceleration efficiency in line-driven flows, ApJ, 434, 684