Physics of Stellar Winds

from Hot, Luminous Massive Stars

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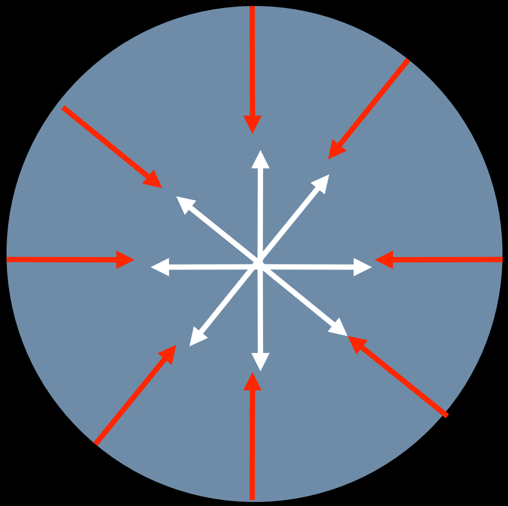
Types of Stellar Winds

- **Solar-type Coronal Winds**
  - Low M_{dot} ~10^{-14} M_{sun}/yr ; V_{inf} ~ V_{esc} ~ 500 km/s
  - Thermally driven with V_{sound} ~ V_{esc}
- **Cool (super) giant (super)winds**
  - Low V_{∞} ~10's of km/s < V_{esc} ; high M_{dot} ~= 10^{-4} - 10^{-8} M_{sun}/yr
  - Driven by pulsation and/or dust ?
- **Radiatively driven winds of hot stars (OB, WR, LBV)**
  - High V_{∞} (~3 Vesc = 2000-3000 km/s) >> V_{sound} ~ 10 km/s
  - High M_{dot} (10^{-4} - 10^{-8} M_{sun}/yr)
- LBVs may have superwind phases (up to 1 M_{sun}/yr, e.g. η Car)

Radiative force vs. gravity

Radiative Force

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



Gravitational Force

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

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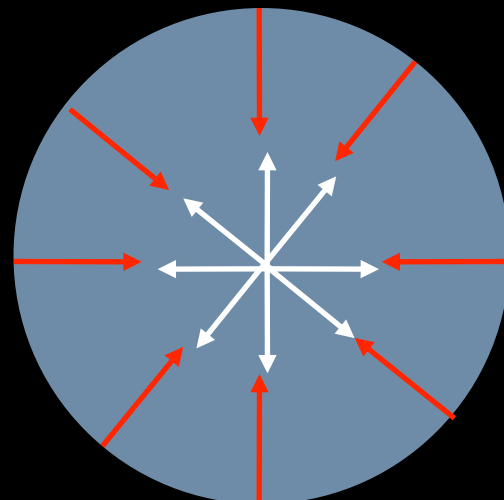

Gravitational Force

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

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

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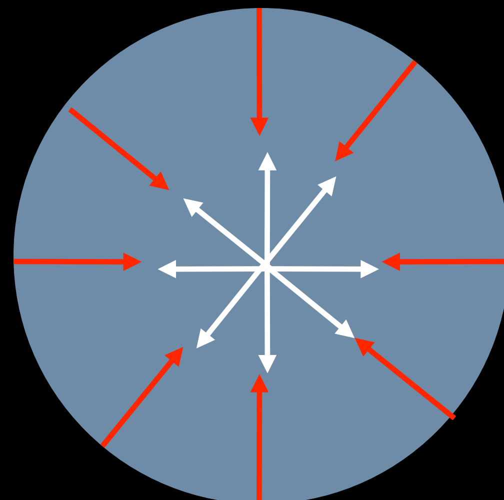

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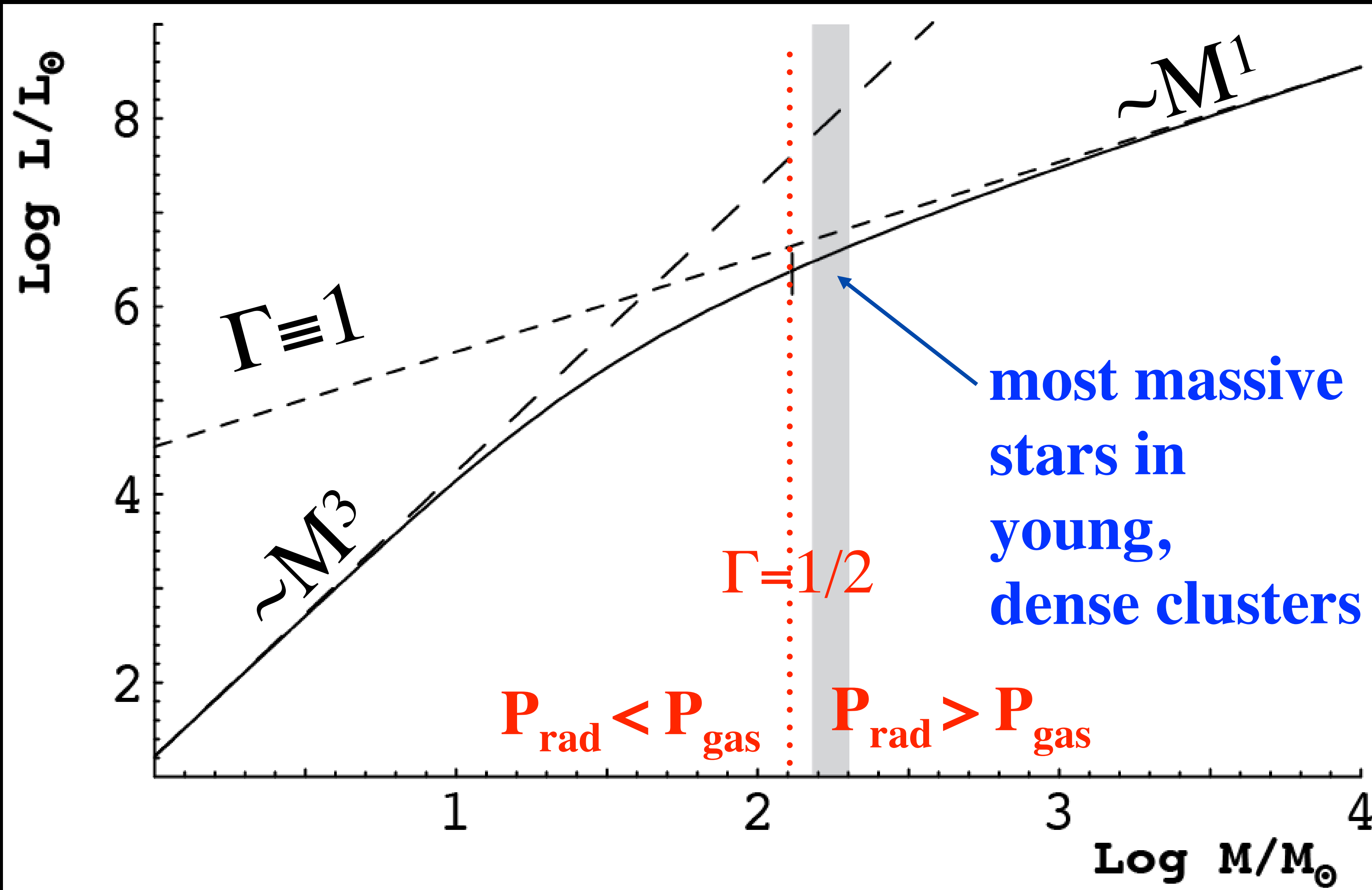
$$\Gamma \simeq 2 \times 10^{-5} \, \frac{L / L_\odot}{M / M_\odot} \, \frac{\overline{\kappa_F}}{\kappa_e}$$

Eddington Standard Model (n=3 Polytrope)



$If\ \Gamma_F \equiv \Gamma > 1,$ steady-state equation of motion (for v>v_{sound}—> 0):

$$v\frac{dv}{dr} = \frac{\kappa L}{4\pi r^2 c} - \frac{GM}{r^2}$$

$$v\frac{dv}{dr} = (\Gamma - 1)\frac{GM}{r^2}$$

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$$\boxed{v_\infty^2 = (\Gamma - 1) v_{esc}^2}$$

“anti-gravity”

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$$4\pi\rho v r^2\, dv = \frac{L}{c}\left(\frac{\Gamma - 1}{\Gamma}\right)\kappa\rho\, dr$$

$$v_\infty^2 = (\Gamma - 1)\, v_{esc}^2$$

"anti-gravity"

$$\dot{M}\, v_\infty = \frac{\tau L}{c}\left(\frac{\Gamma - 1}{\Gamma}\right)$$

"wind momentum"

$$OB : \tau \le 1$$

$$WR : \tau \approx 1 - 10$$

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"wind momentum"

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$$WR : \tau \approx 1 - 10$$

"wind energy"

$$\dot{M}\frac{v_\infty^2 + v_{esc}^2}{2} = \tau\, L\frac{v_\infty}{2c}$$

"photon tiring limit"

$$\tau < \frac{2c}{v_\infty} \simeq 200$$

For wind, need: $$\Gamma > 1 \rightarrow \quad \kappa_F > \kappa_{Edd} \equiv \frac{4\pi GMc}{L}$$

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Rosseland mean

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In optically thin wind: $\kappa_F \simeq \kappa_P \equiv \frac{\int_0^\infty \kappa_\upsilon B_\upsilon d\upsilon}{\int_0^\infty B_\upsilon d\upsilon} \equiv Q\, \kappa_e$

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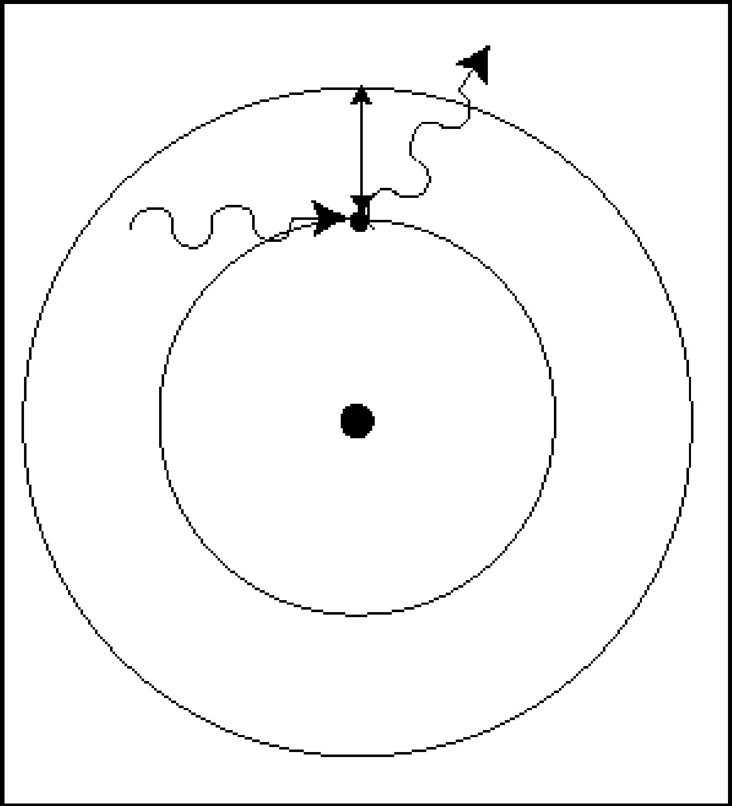
from line opacity: $$Q \sim 2000 \frac{Z}{Z_\odot}$$

cf. Gayley 1995

Driving by Line-Opacity

Optically **thin**



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

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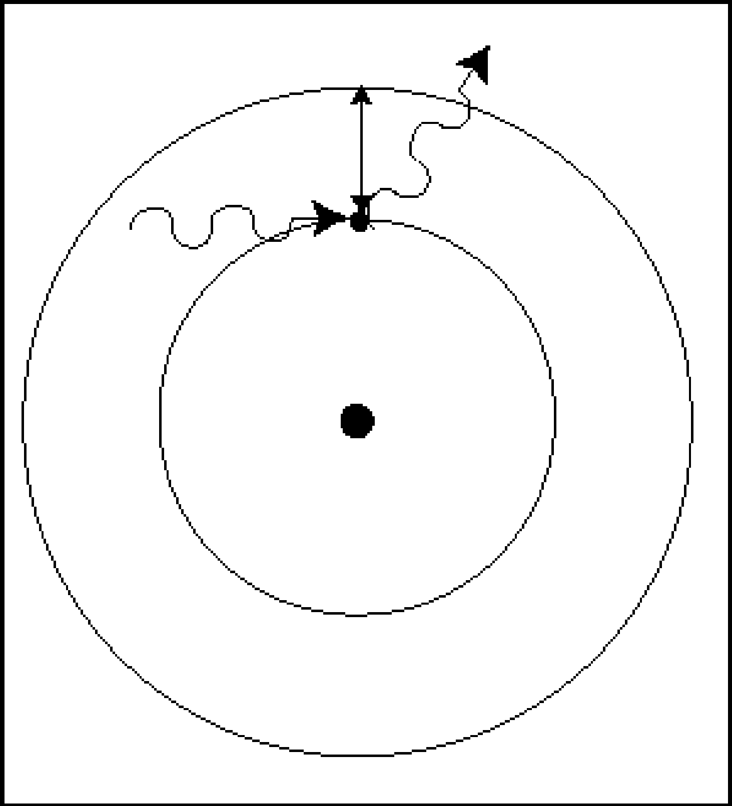

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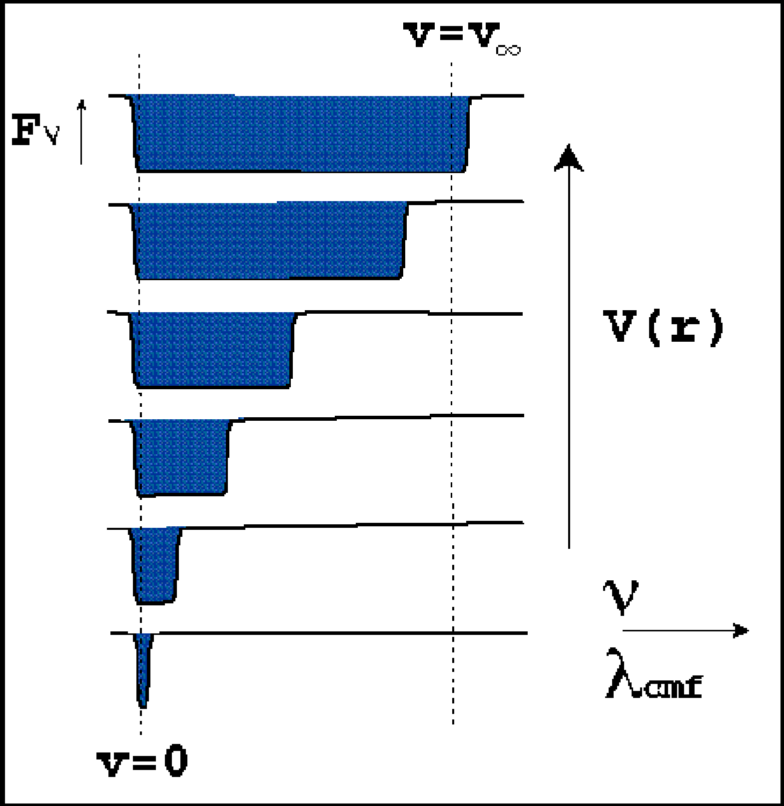
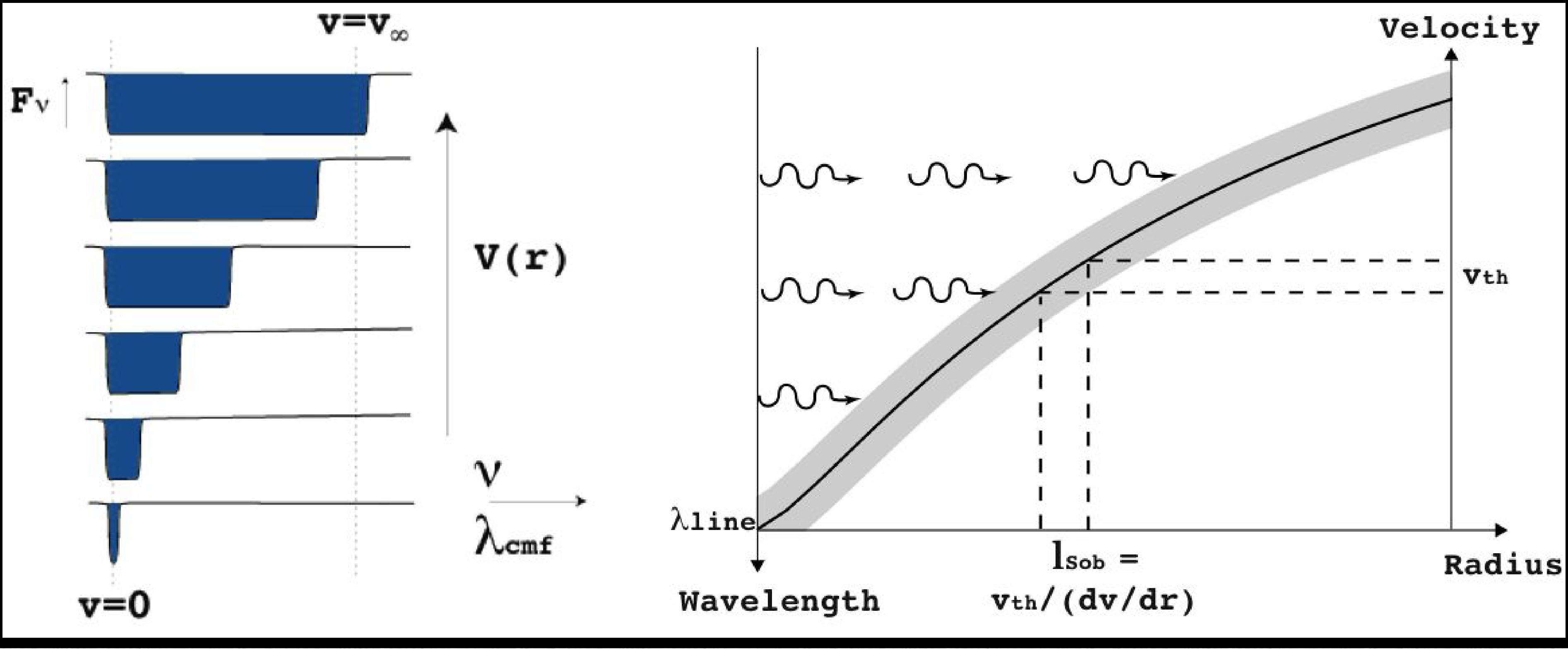


$$\Gamma_{thick} \sim \frac{Q\Gamma_e}{\tau} \sim \frac{1}{\rho}\frac{dv}{dr}$$

Line-driving



For strong, **optically thick** **lines:**

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

$l_{sob} \ll R_*$

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

CAK model of steady-state wind

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

$0 < \alpha < 1$

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

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

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

$\alpha \approx 0.6$

$\overline{Q} \sim Z$

$$\dot{M}_{cak} \approx \frac{L}{c^2}\left(\frac{Q\Gamma_e}{\Gamma_e - 1}\right)^{-1+1/\alpha}$$

Define $\dot{M}_{-6} \equiv \frac{\dot{M}}{10^{-6} M_{\odot}/yr}$ $L_6 \equiv \frac{L}{10^6 L_{\odot}}$

Then for $Q = 1000$:

$$\dot{M}_{-6} \approx 2 L_6 \left(\frac{\Gamma_e}{1-\Gamma_e}\right)^{1/2} \; ; \; \alpha = 2/3$$

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$$\dot{M}_{-6} \approx 30 L_6 \left(\frac{\Gamma_e}{1-\Gamma_e}\right)^{1} ; \; \alpha = 1/2$$

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$\therefore \dot{M}_{cak}$ *very sensitive to value of* α!

NLTE Wind models

- To compute line opacity, need atomic physics and NLTE wind code
  - WM-basic: Pauldrach + ~1985- pres.
  - POWR: Hamman+ ~1990-pres.
  - CMFGEN: Hiller+ ~1990-pres.
  - FastWind: Puls+ ~2000-pres.

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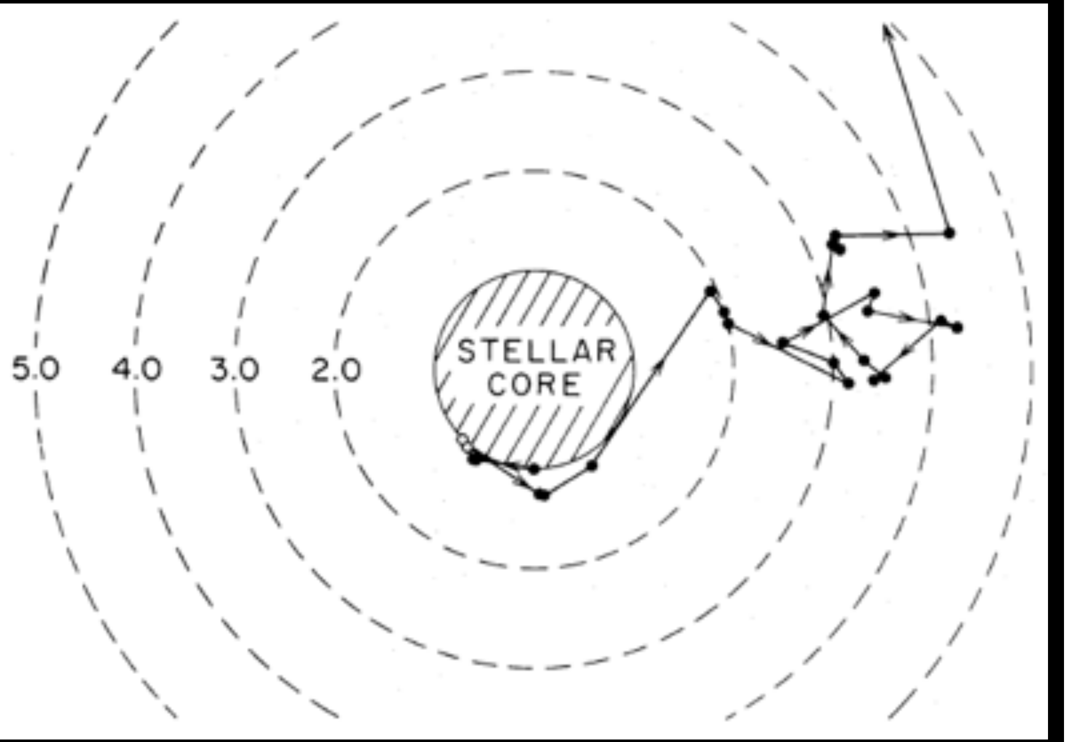
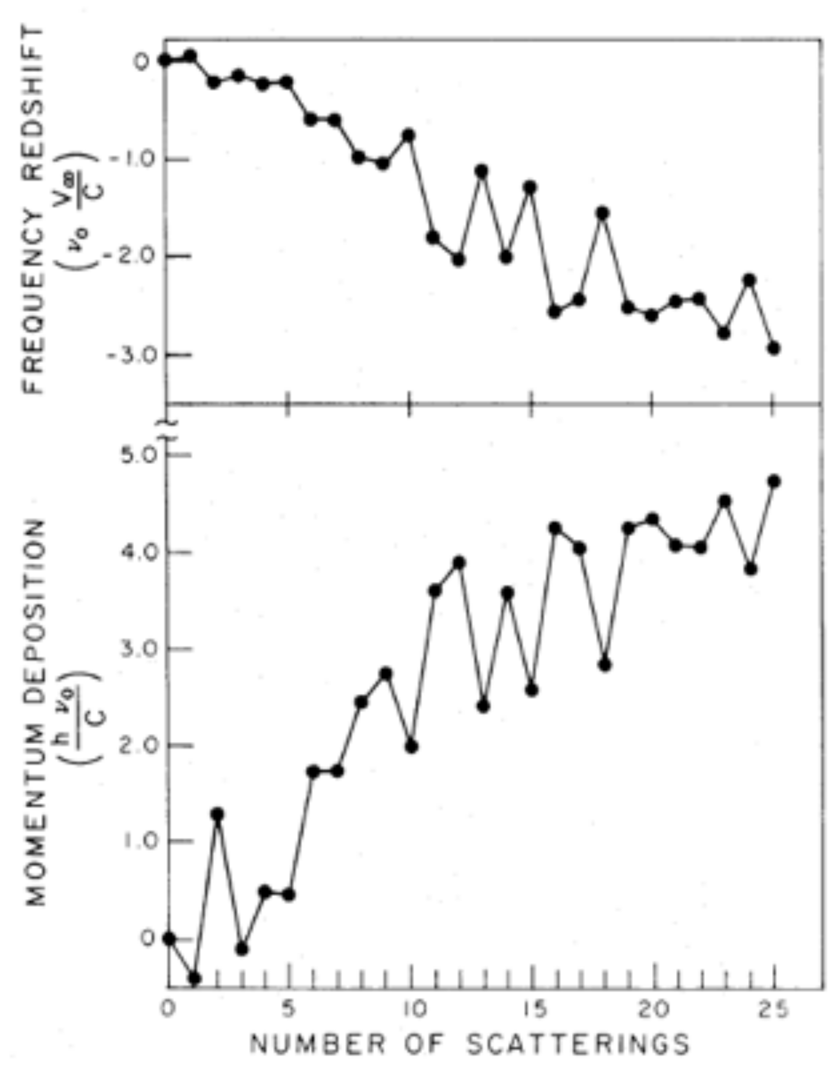
  - FastWind: Puls+ ~2000-pres.
- Solve with wind dynamics
  - Vink+ 2001-present: Monte Carlo + ISA NLTE
    - => recipe for M_{dot} & V_{inf}
  - Graefener 2005-present: CMF + NLTE

Monte-Carlo models

Abbott & Lucy 1985; LA 93; Vink et al. 2000

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

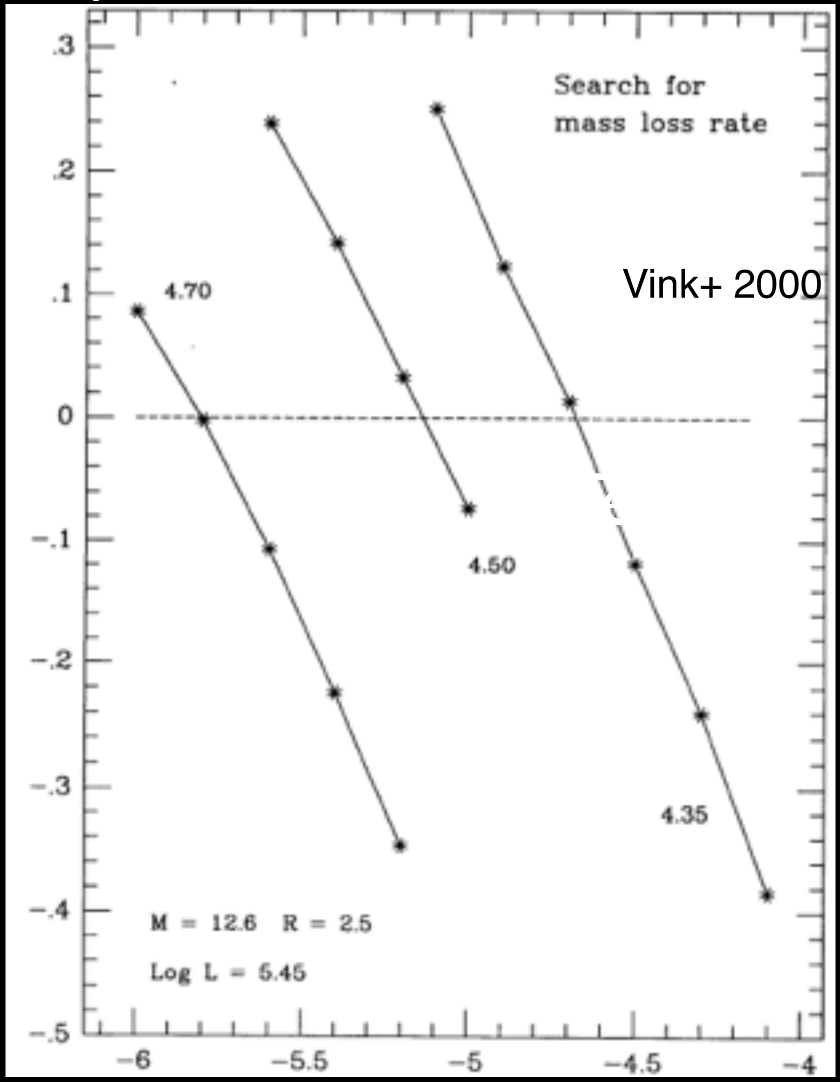




Monte-Carlo models

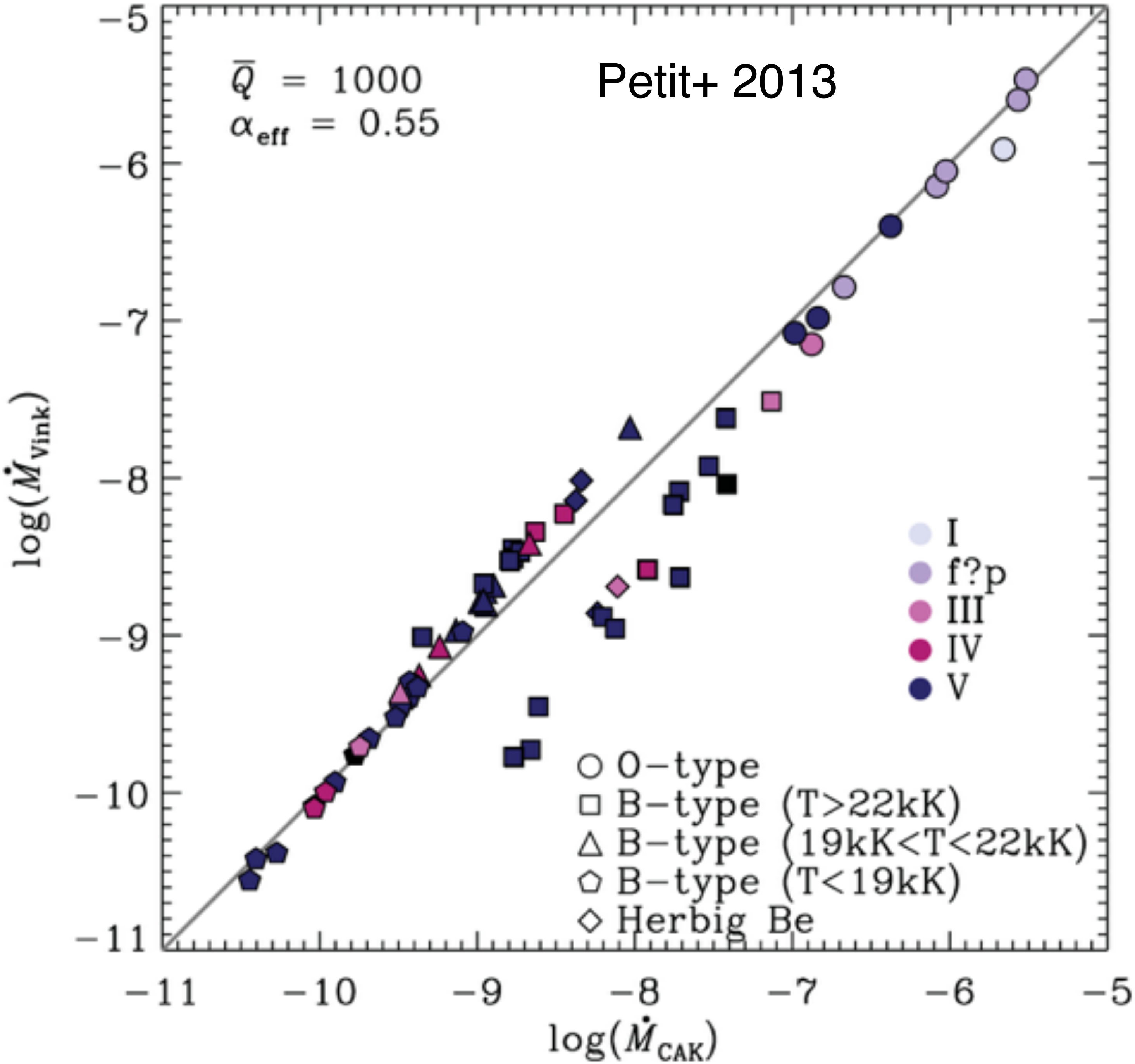
Compute mass loss rate from: $\dot{M} \approx \dfrac{2\dot{W}_{rad}}{V_{esc}^2 + V_{\infty}^2}$

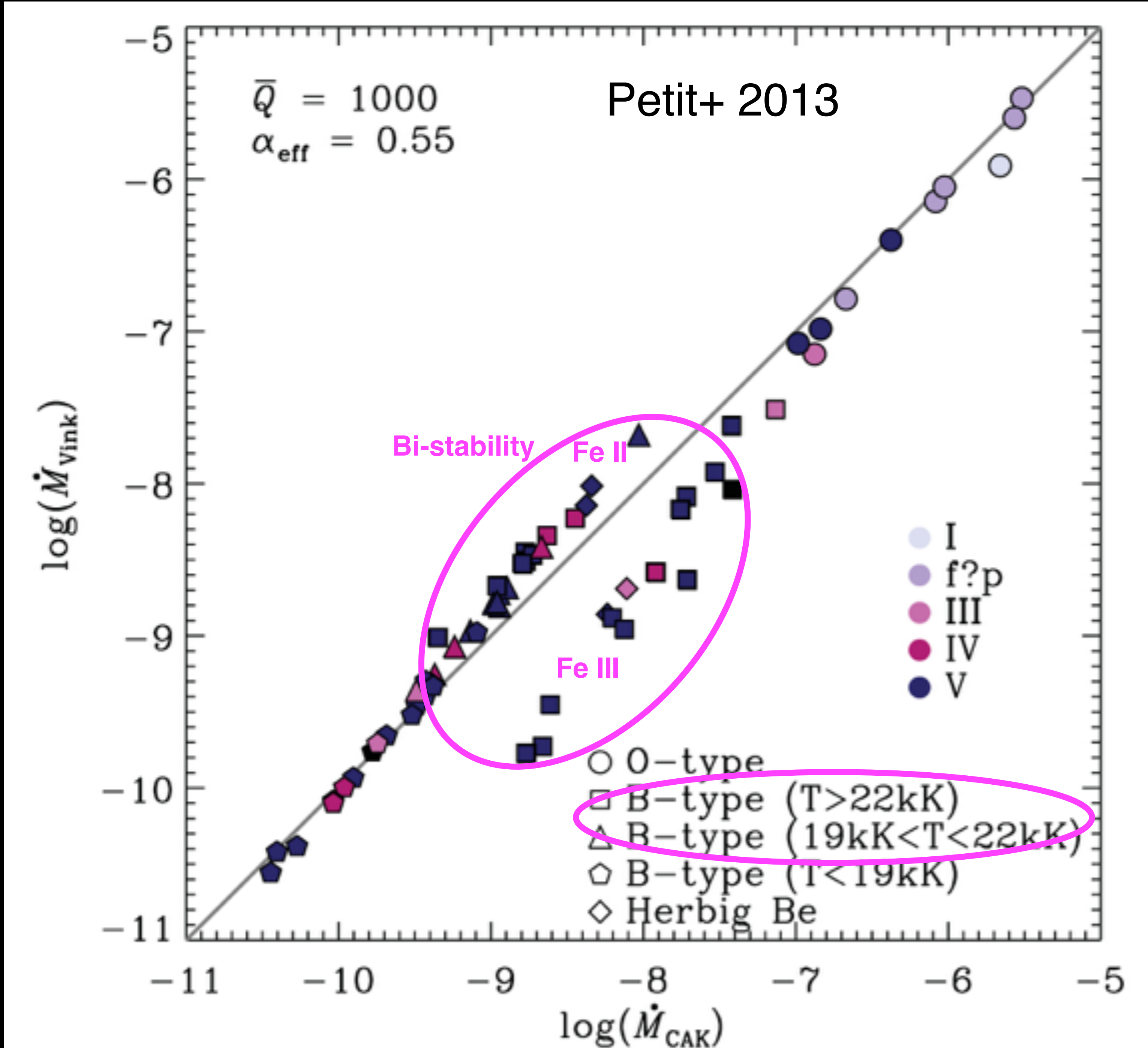
$\log \dfrac{\dot{W}_{rad}}{E_{wind}}$



$\log \dot{M}$

Muller & Vink 2008:
can also infer V_{inf}


$\overline{Q}$ = 1000
α_{eff} = 0.55
Petit+ 2013
I
f?p
III
IV
V
O−type
B−type (T>22kK)
B−type (19kK<T<22kK)
B−type (T<19kK)
Herbig Be
−5
−6
−7
−8
−9
−10
−11
$\log(\dot{M}_{Vink})$
$\log(\dot{M}_{CAK})$



Petit+ 2013
$\overline{Q}$ = 1000
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Bi-stability
Fe II
Fe III
I
f?p
III
IV
V
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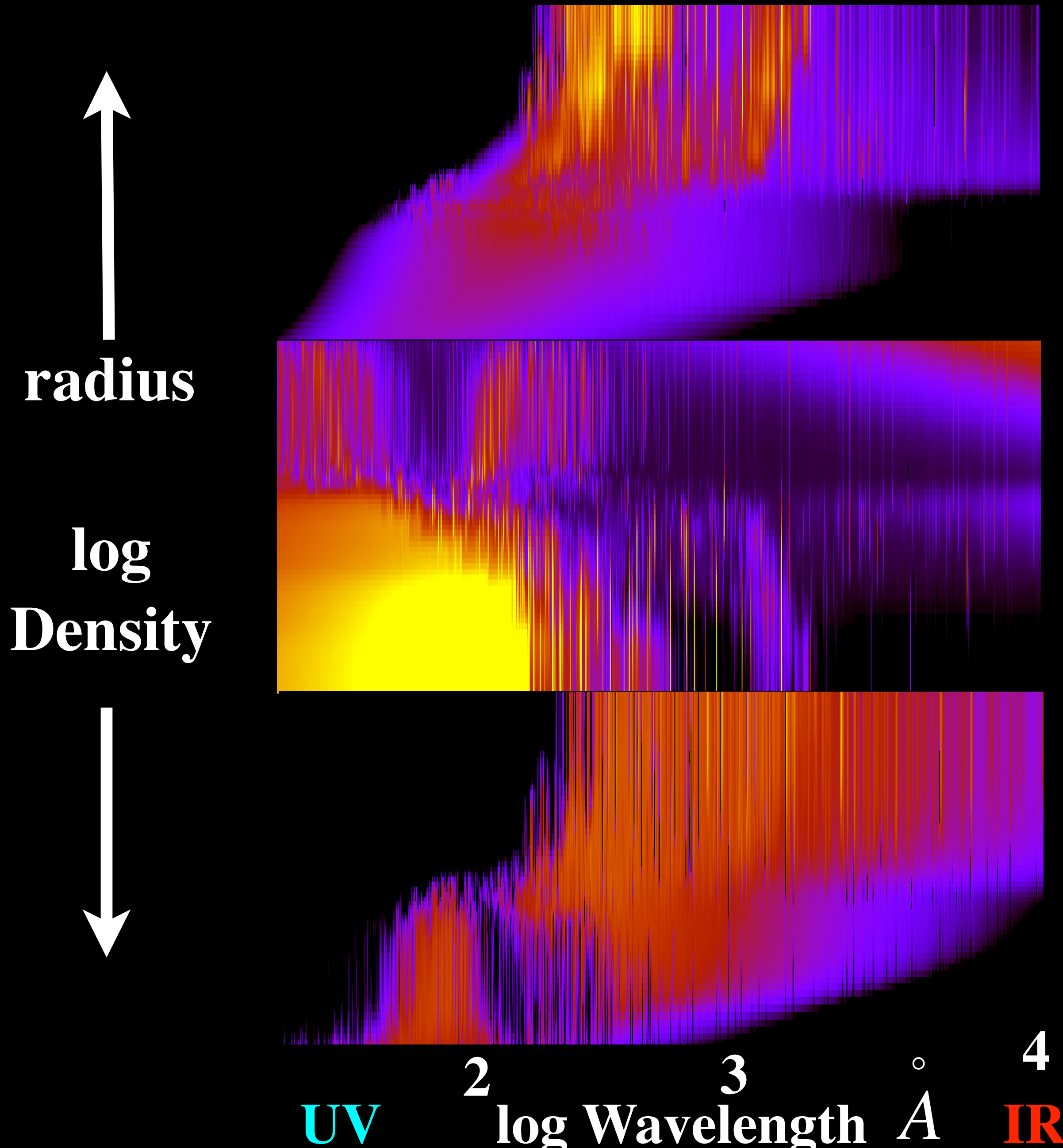
Herbig Be
log($\dot{M}_{Vink}$)
log($\dot{M}_{CAK}$)

Wolf-Rayet Wind Driving

courtesy
G. Graefener



Radiative acceleration

=

Opacity

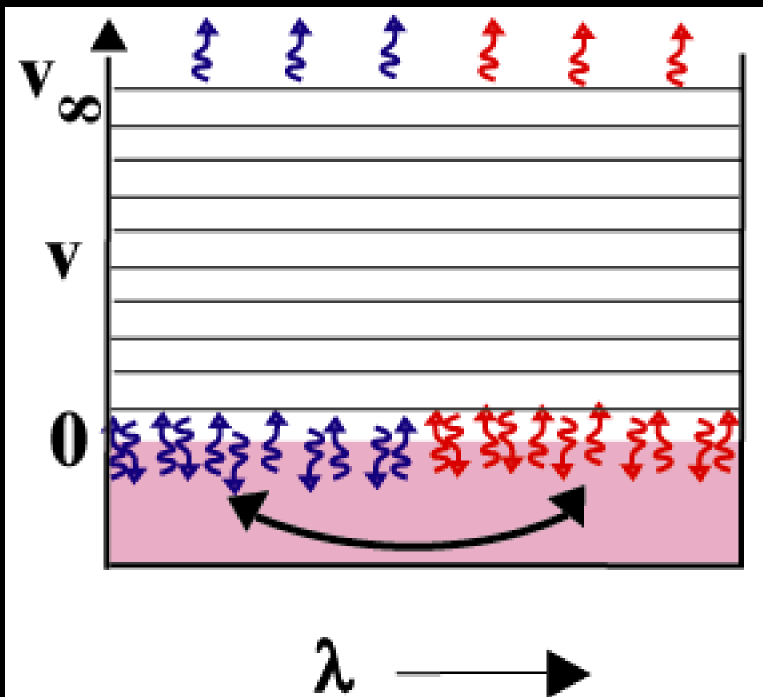
X

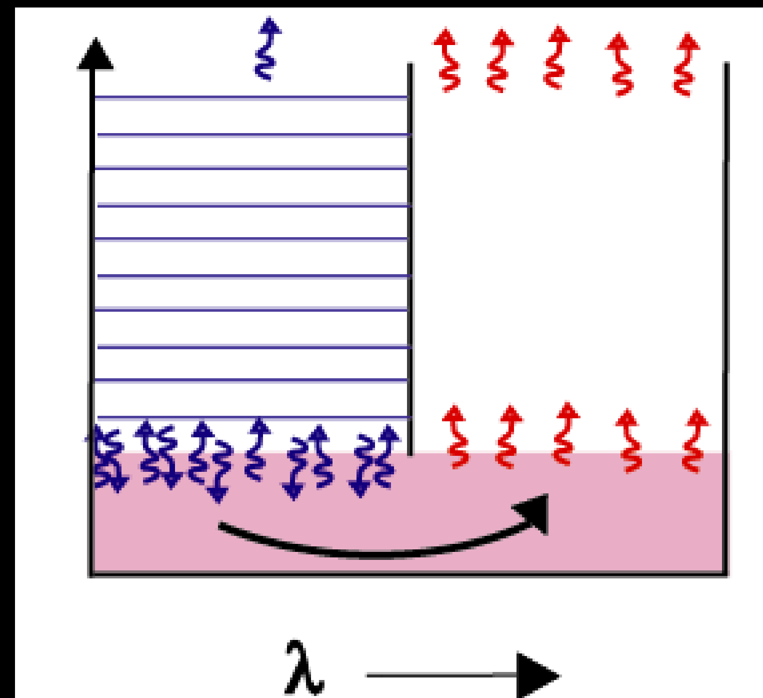
Flux

Multi-line scattering

$$\Delta V = 10 V_\infty$$

photon "leakage"





"Effectively gray" line-distribution

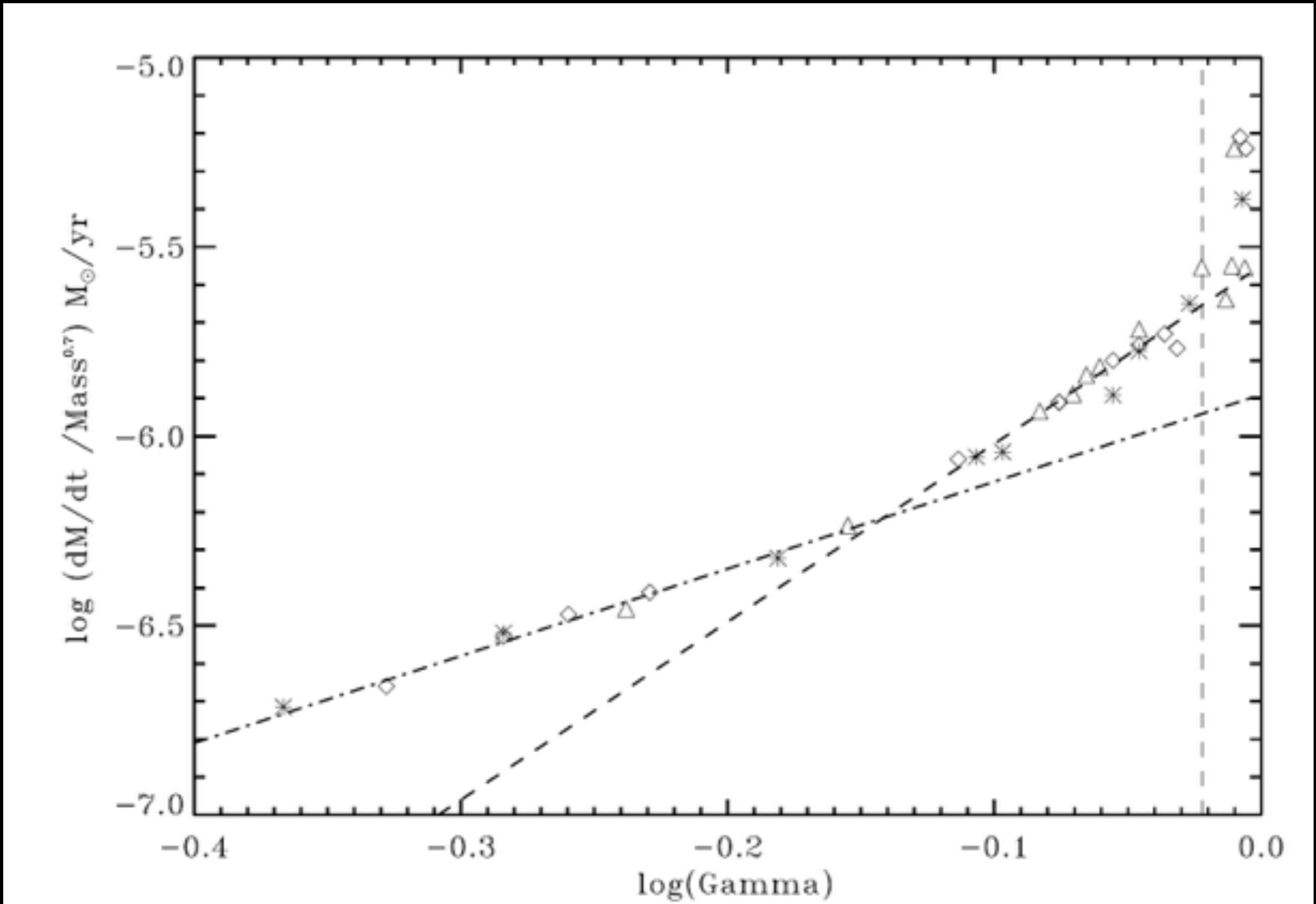
"Bunched" line-distribution

Friend & Castor 1982; Gayley et al. 1995

Onifer &Gayley 2006

Line-Driven Mass Loss near Edd. limit

Vink+ 2011



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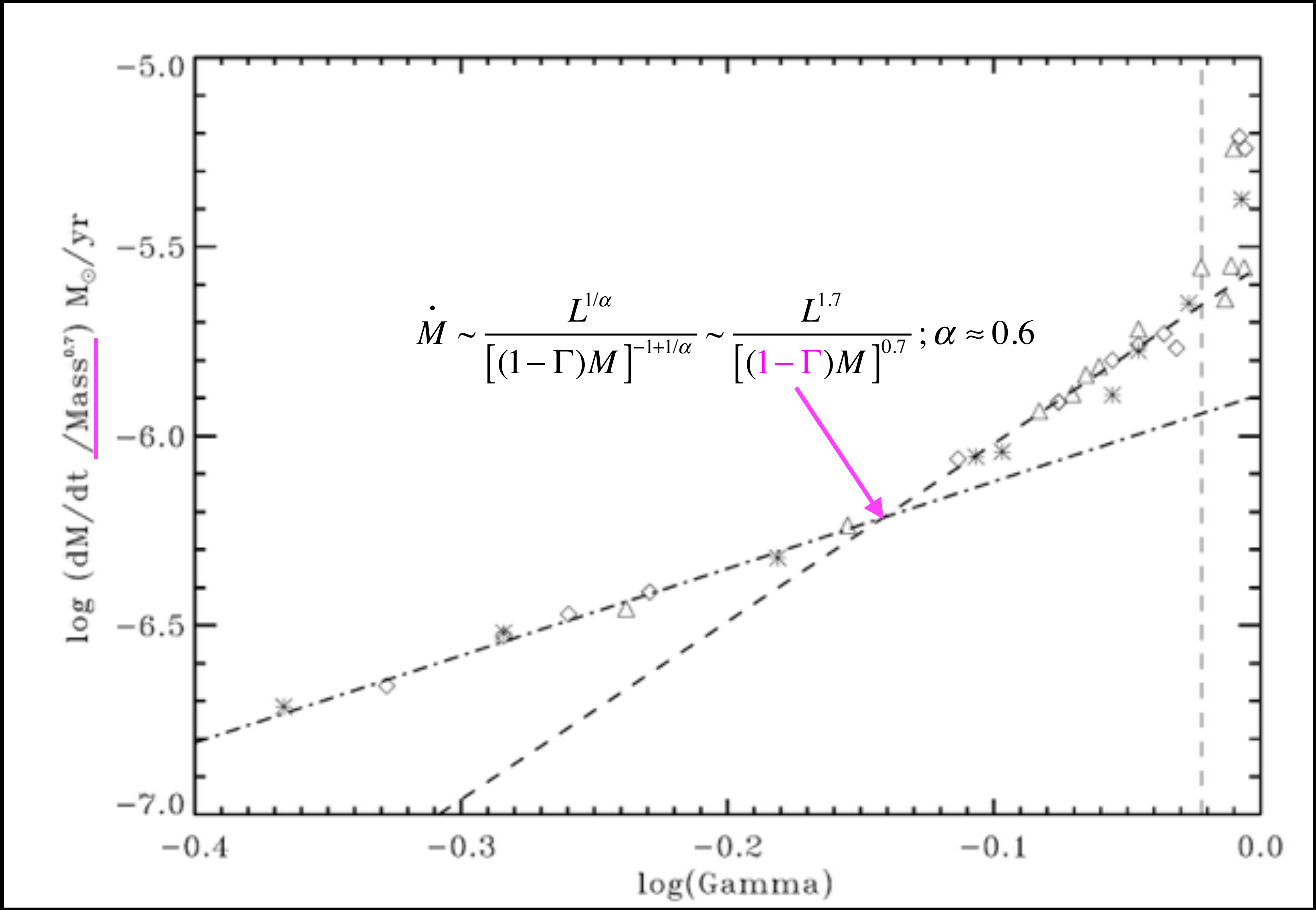


P_{rad}/P_{gas} at sonic base of optically thick wind

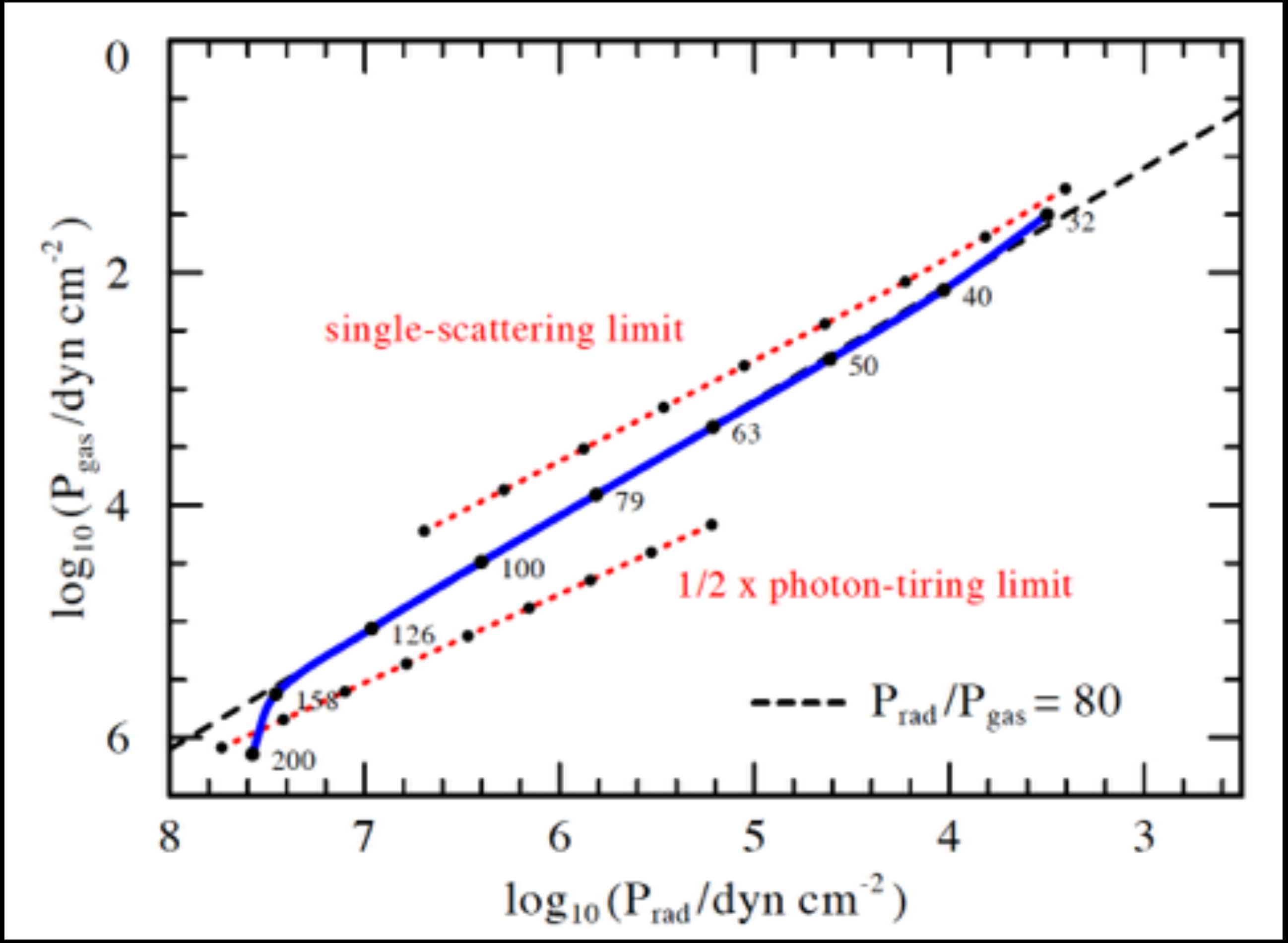
at sonic radius R:

$$P_{gas} = \rho a^2 = \frac{\dot{M}\, a}{4\pi R^2} = \tau \frac{F}{c}\left(\frac{\Gamma - 1}{\Gamma}\right)\frac{a}{v_\infty}$$

$$P_{rad} = \frac{F}{c}\left(\tau + 2/3\right)$$

$$\frac{P_{rad}}{P_{gas}} = \frac{v_\infty}{a}\left(\frac{\tau + 2/3}{\tau}\right)\left(\frac{v_\infty^2}{v_{esc}^2} + 1\right)$$

Graefener & Vink 2013

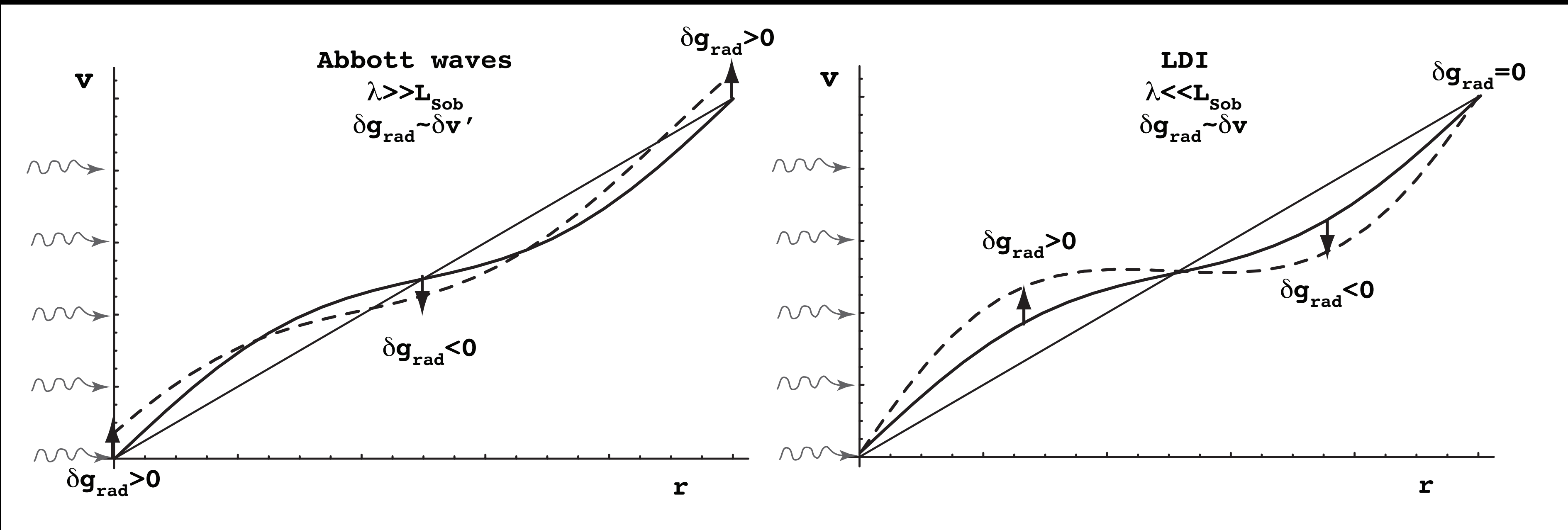


Is line-driving stable?

Carry out linear stability analysis

Response to small-amp. perturbation

Stable | Unstable



Abbott speed

$\delta g_{rad}/\delta v' = -U \simeq -v$

Abbott 1980

Instability growth rate

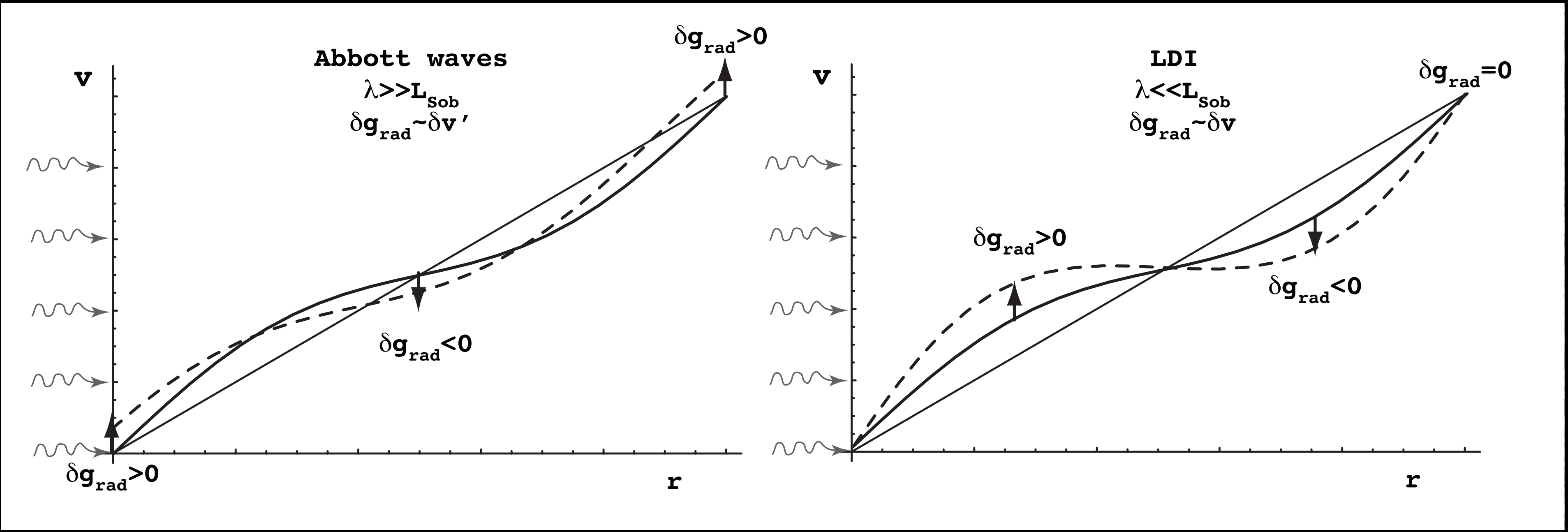
$\delta g_{rad}/\delta v = \Omega$

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

=> e^{100} growth!

Response to small-amp. perturbation

Stable | Unstable



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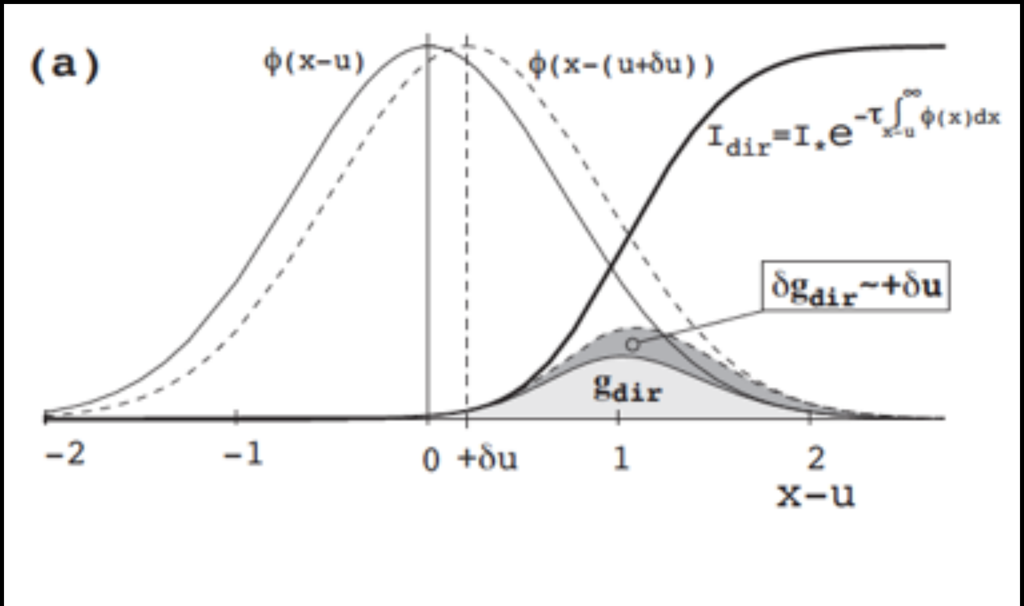
Line-Deshadowing Instability



for $\lambda < L_{sob}$:

$i\omega = \delta g/\delta v = +g_o/v_{th} = \Omega$

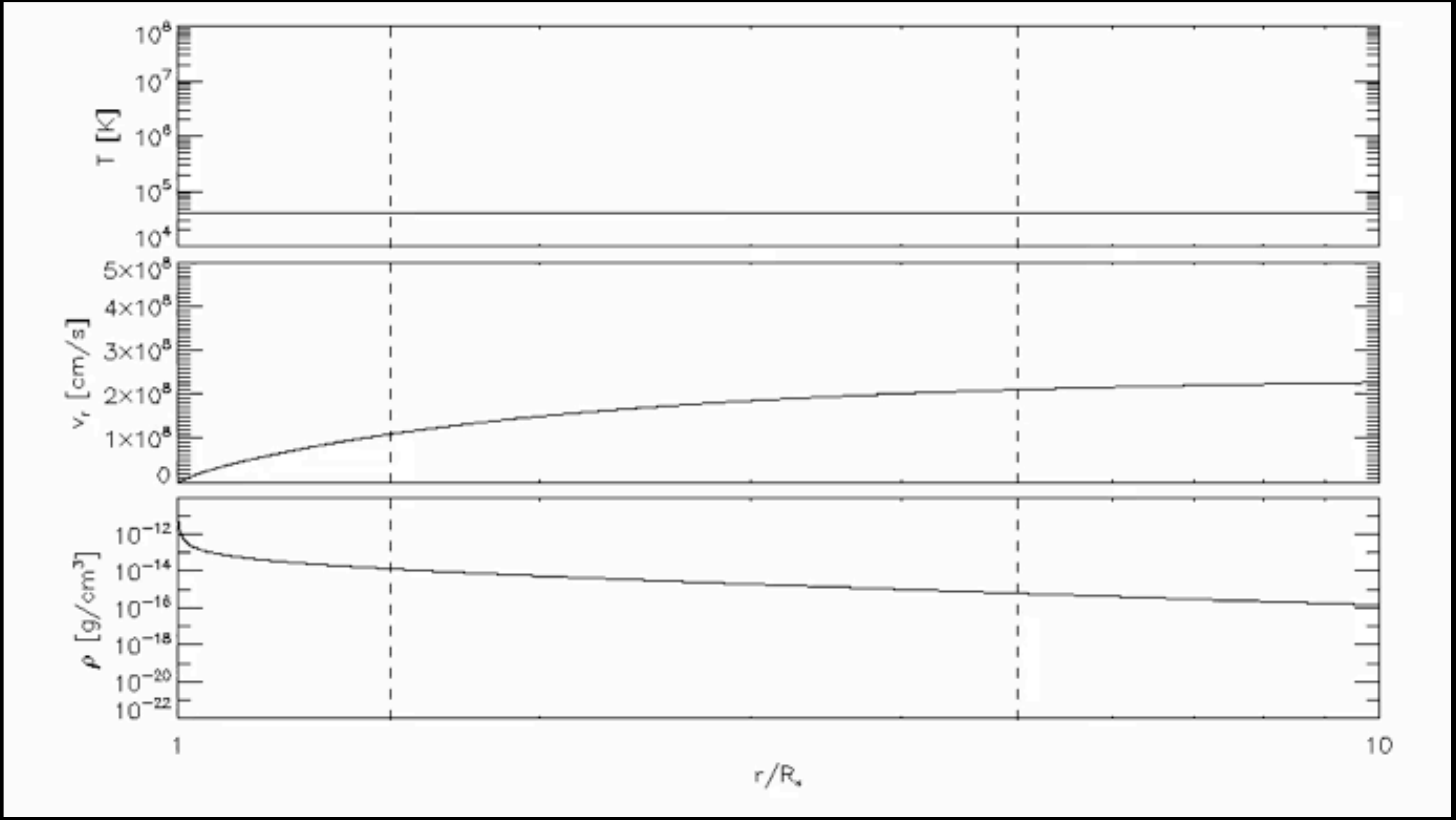
Instability with growth rate

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

=> e^{100} growth!

1D SSF sim of LDI

Smooth Source Function



courtesy J. Sundqvist

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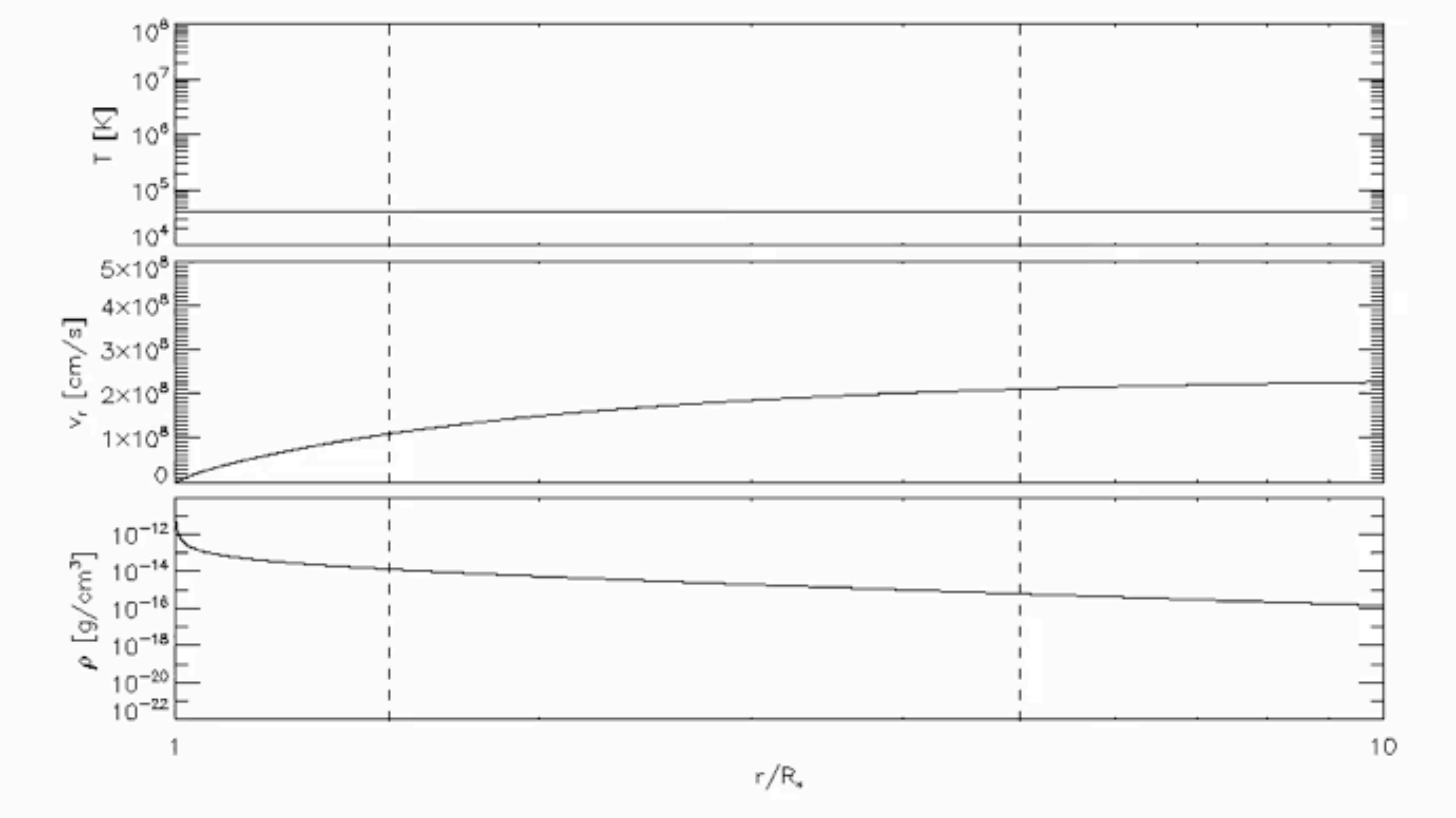
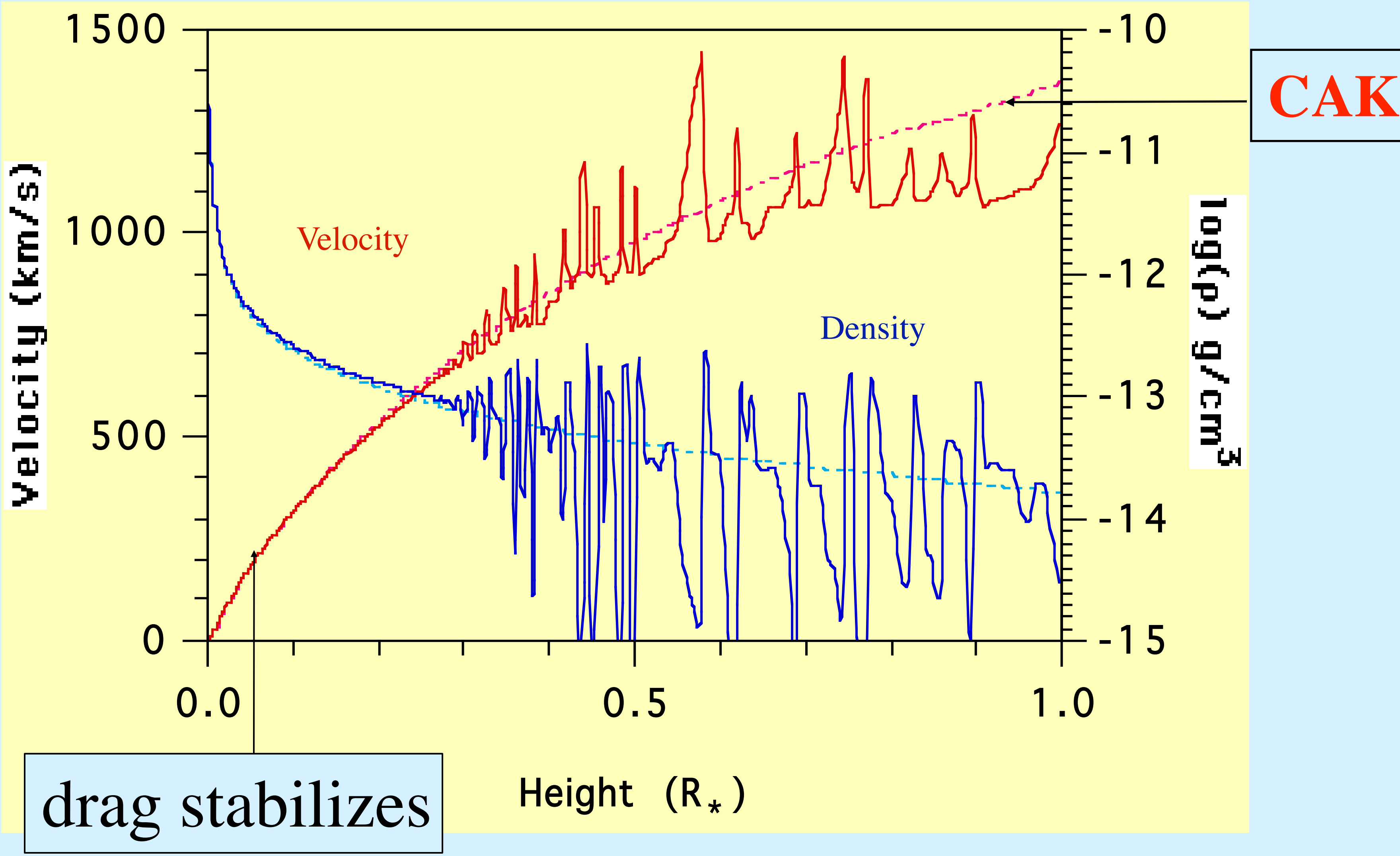


courtesy J. Sundqvist

Time snapshot of SSF instability simulation



but back-scattering also self-excites!

Hydro sims, 2D-R

The radial line-force drives the wind outflow. But in 2-D (or 3-D), you can also have a non-zero lateral radiation force, which may then affect the scales and shapes of clumps.

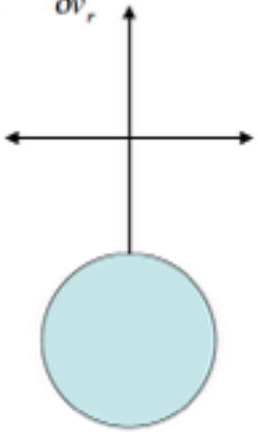
Lateral line-drag

Owocki+ 90

$$\frac{\delta g_r^{dir}}{\delta v_r} + \frac{\delta g_r^{diff}}{\delta v_r} \approx (100-50)\frac{v}{r}$$

net radial instability for:

$$\lambda_r \le L_r = \frac{v_{th}}{dv/dr} \approx \frac{v_{th}}{v} r$$



$$\delta g_\phi^{dir} = 0$$

$$\frac{\delta g_\phi^{diff}}{\delta v_\varphi} \approx -50\frac{v}{r}$$

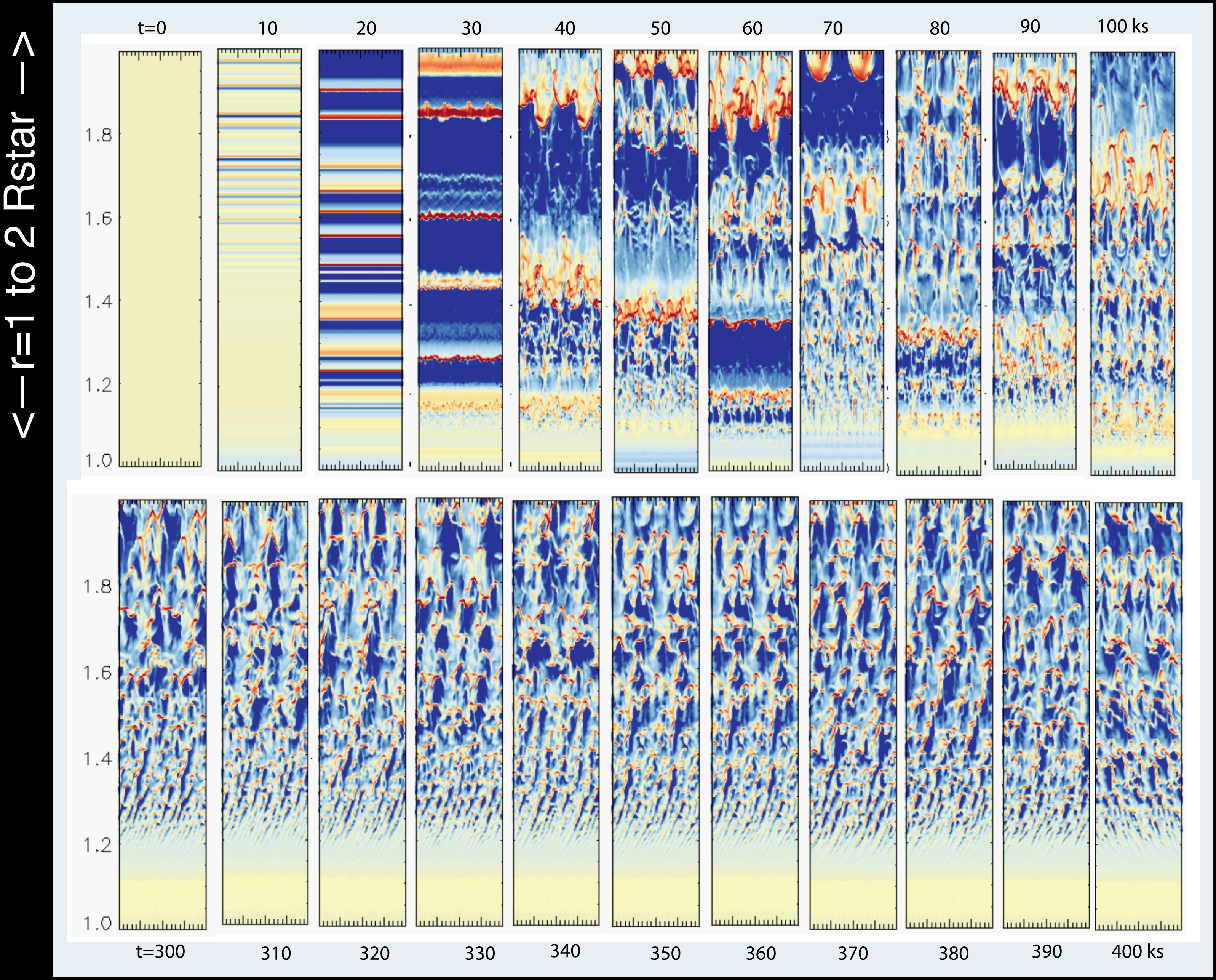
lateral damping for:

$$\lambda_\phi \equiv r\, d\phi \le L_\phi \approx \frac{v_{th}}{v/r}$$

$$d\phi \le \frac{v_{th}}{v} \approx \frac{1}{100} \approx 0.6^o$$

2D-H + 2D-R planar LDI sims

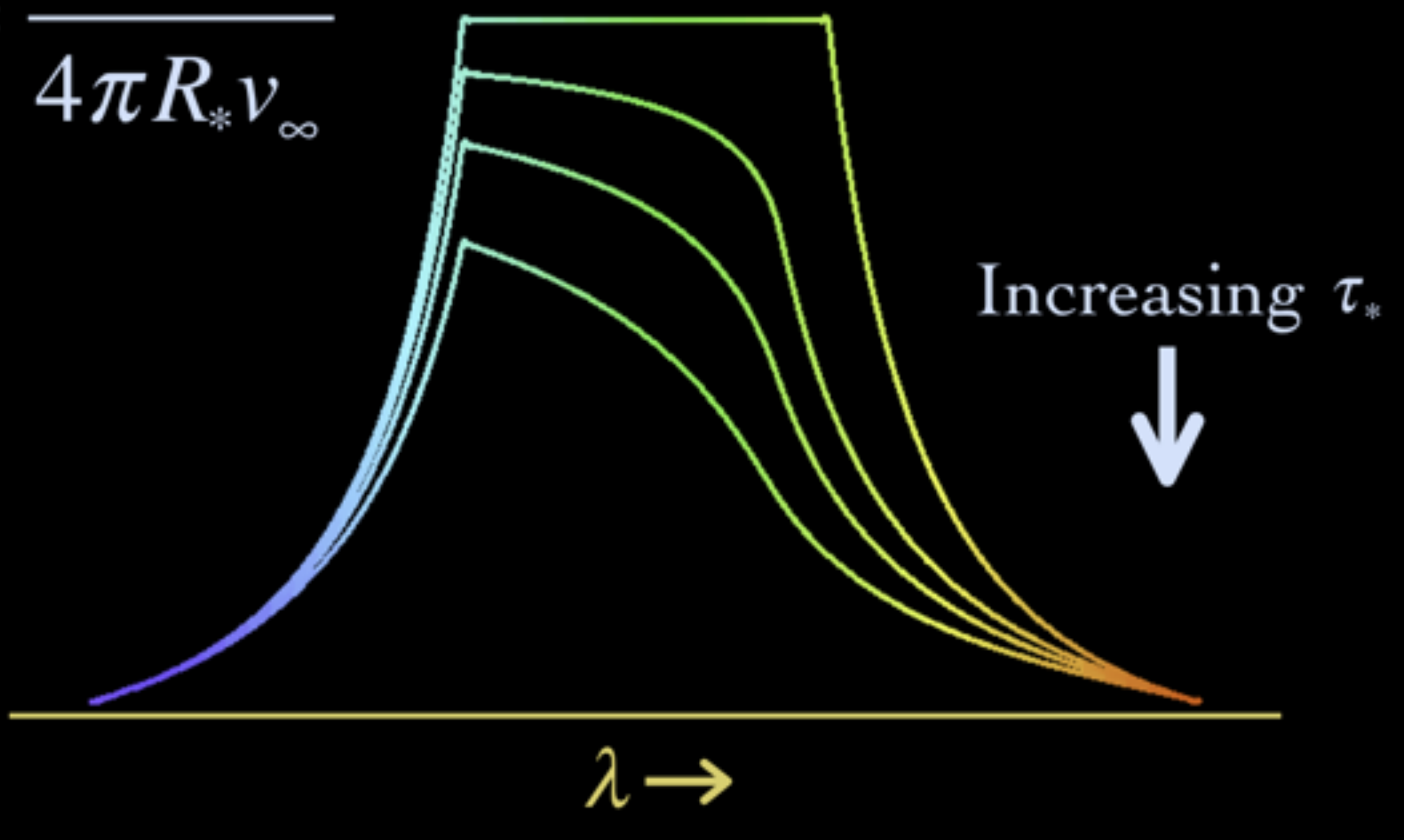
Sundqvist+ in prep.



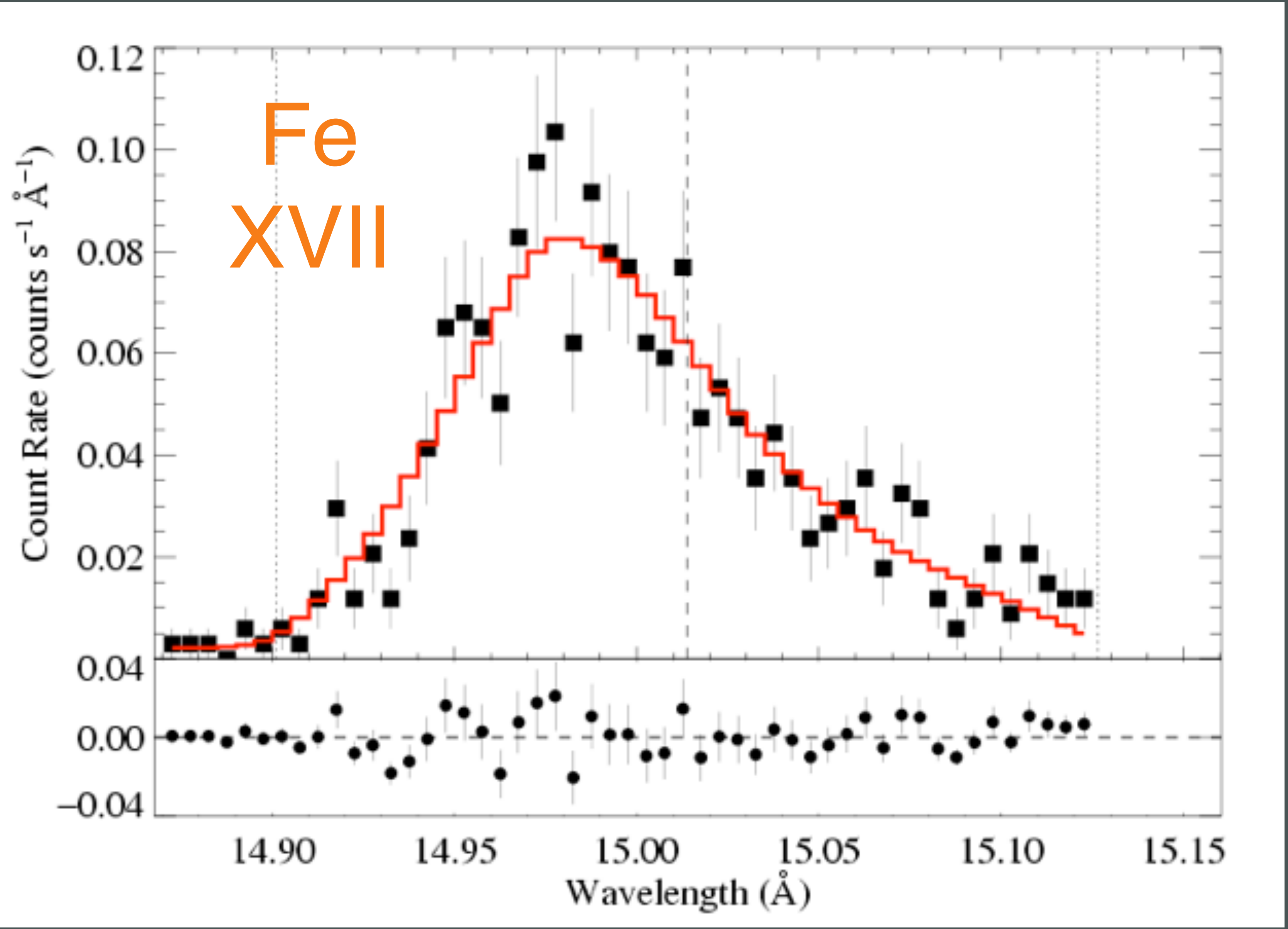
$$\frac{\delta\rho}{\langle\rho\rangle}$$

X-ray emission line-profile

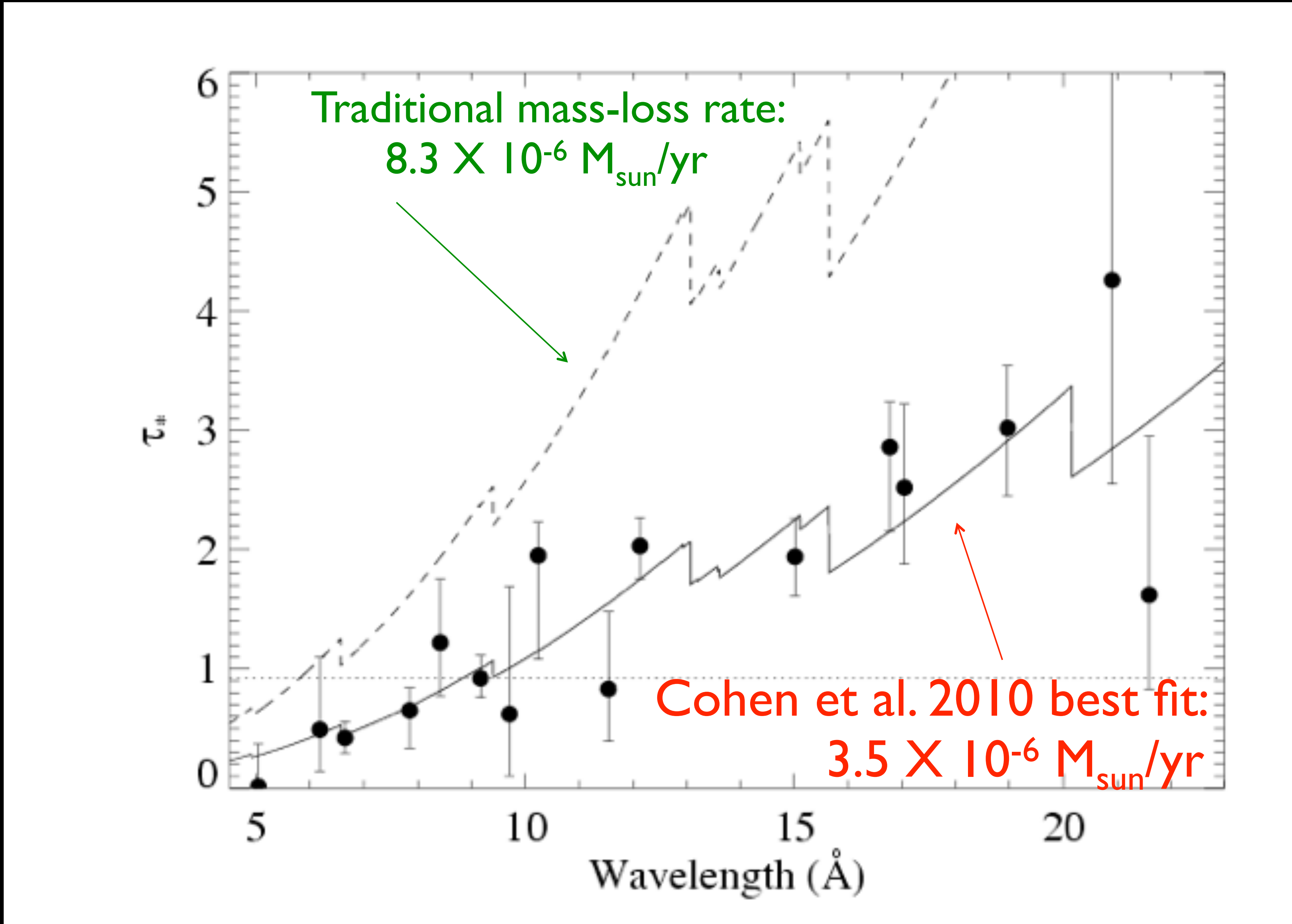
$$\tau_* = \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$



Chandra X-ray line-profile for ZPup



Inferring ZPup M_{dot} from X-ray lines



How are such winds affected by (rapid) stellar rotation?

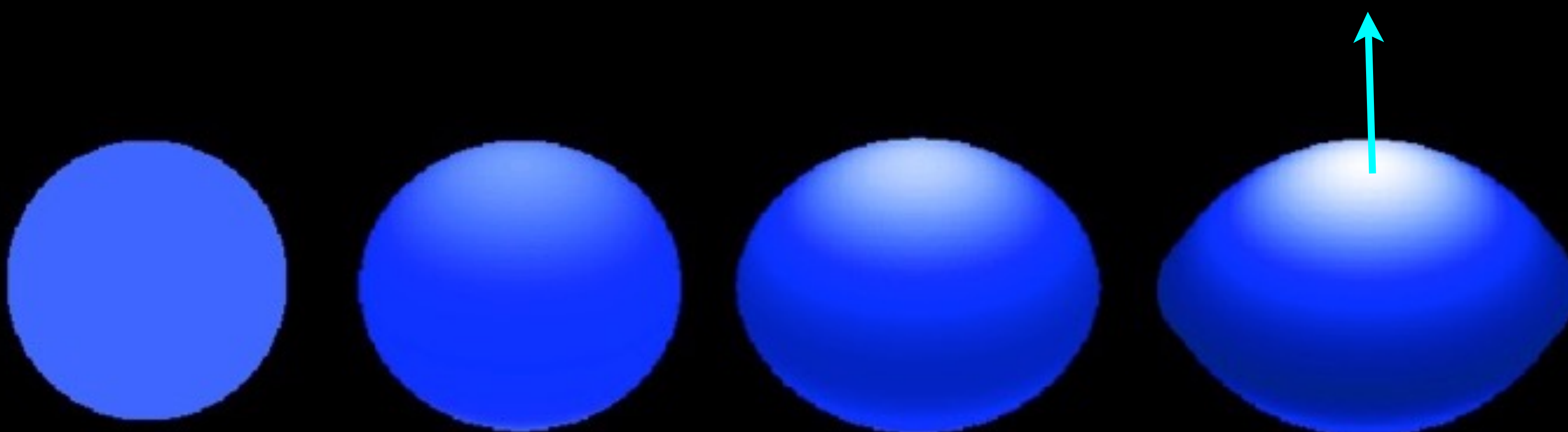
Gravity Darkening

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

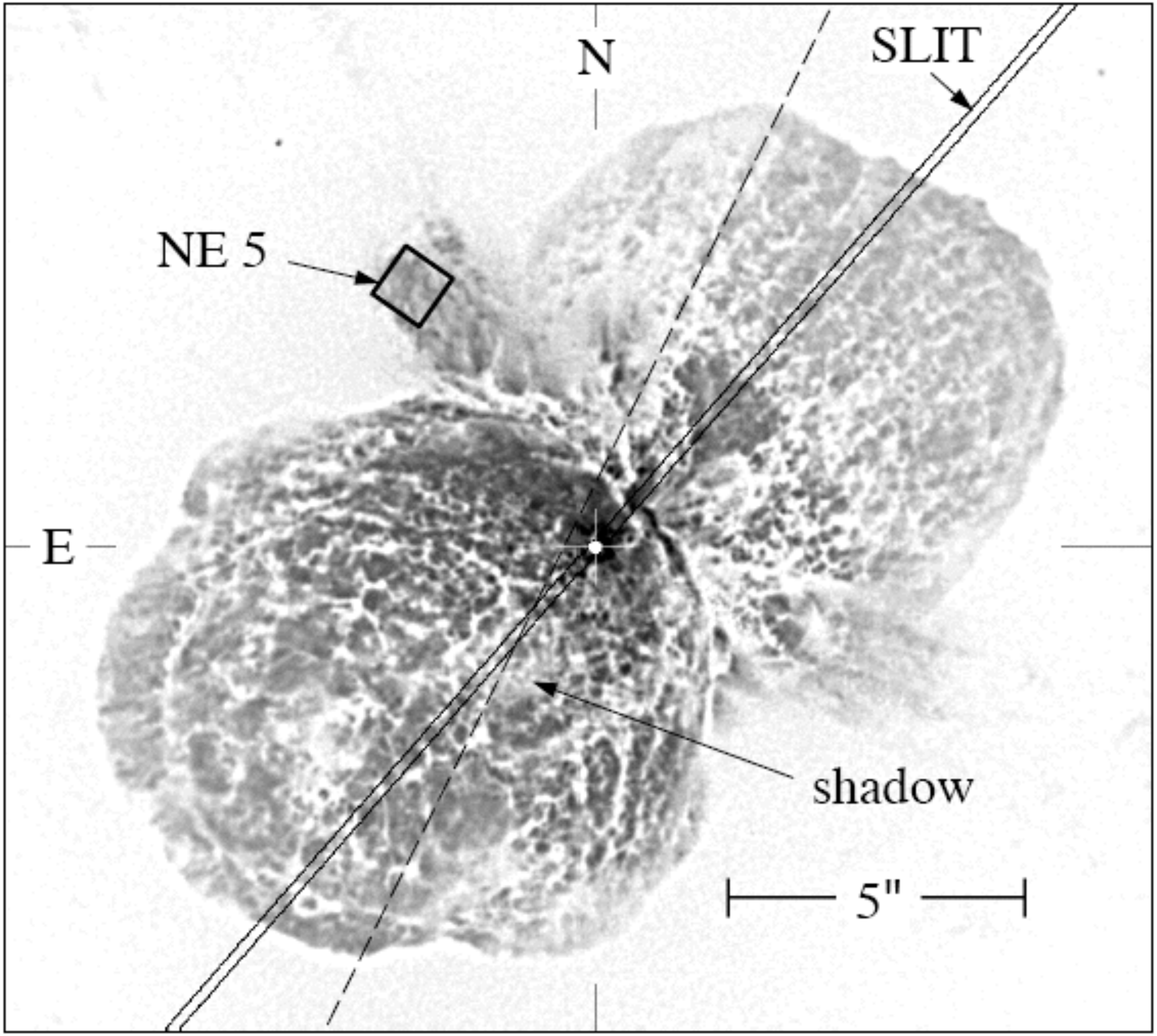
$$\dot{M} \sim F(\theta)$$

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

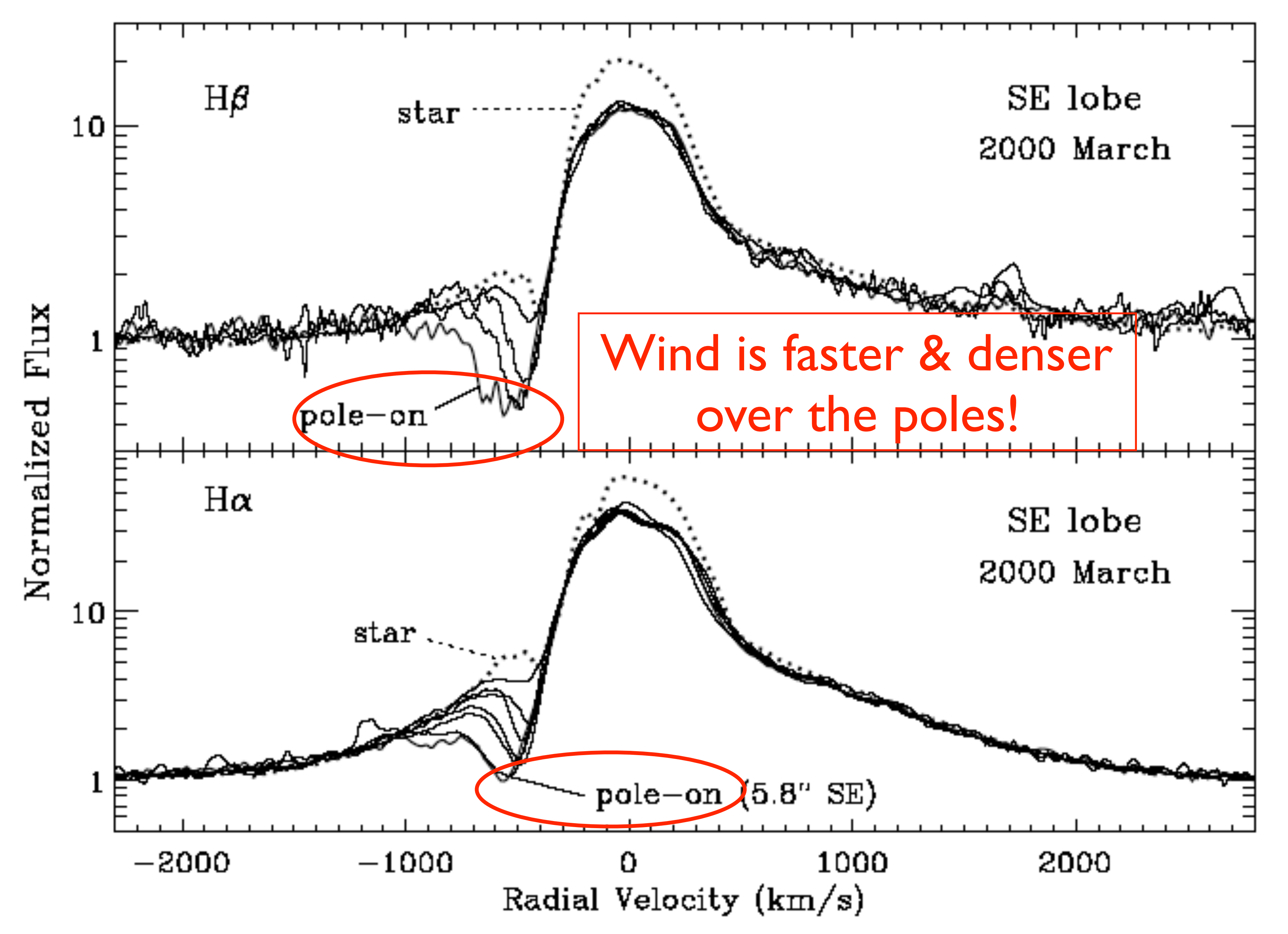
higher at pole!



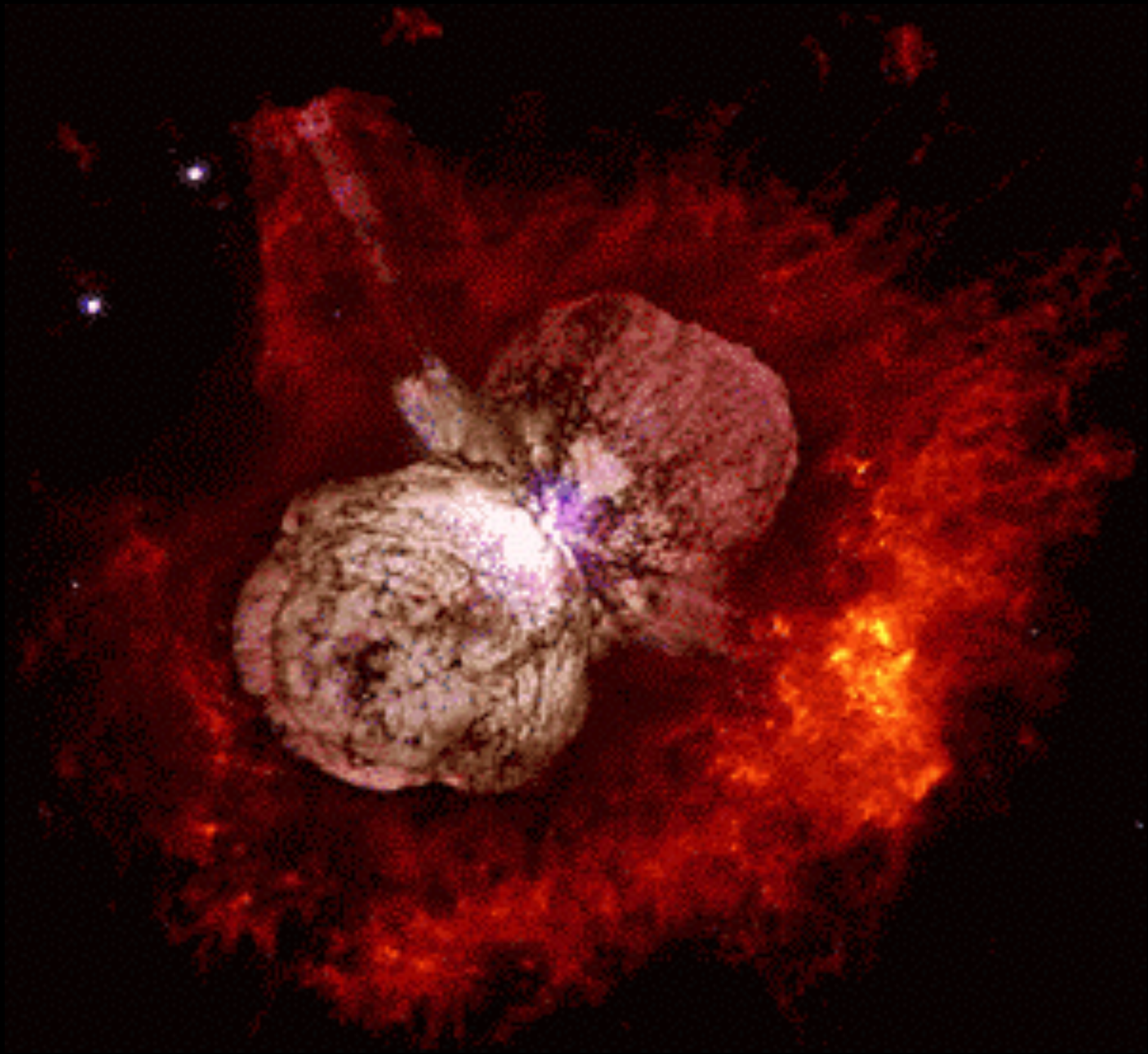
increasing stellar rotation →


N
SLIT
NE 5
E
shadow
5"

Smith et al. 2003

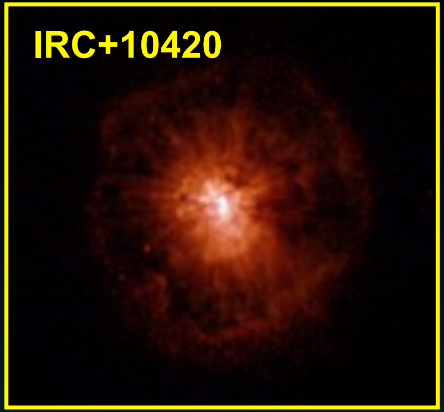


Eta Carinae



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)

3 Key points about η Car's eruption

1. $M_{dot} > 10^3\ M_{dot}(CAK)$

   => can **NOT** be line-driven!

2. $L_{obs} > L_{Edd}$

   => "super-Eddington" (by factor > 5!)

3. $L_{obs} \sim= M_{dot} V^2/2$

   => M_{dot} limited by energy or "photon-tiring"

super-Eddington continuum-driven wind

- Quataert+ 2016
  - add energy E_{dot} > L_{Edd} at at some R_h in envelope
  - tau>>1 => F_{rad}->0, so E_{dot} => rad. enthalpy $h=4P_{rad}/rho$
  - leads to gamma=4/3 polytropic wind
  - But(!), also need to ensure E_{dot} > M_{dot} GM/R_h
- Owocki & Gayley 1997, Owocki, Gayley & Shaviv 2004
  - continuum flux-driven wind with photon tiring

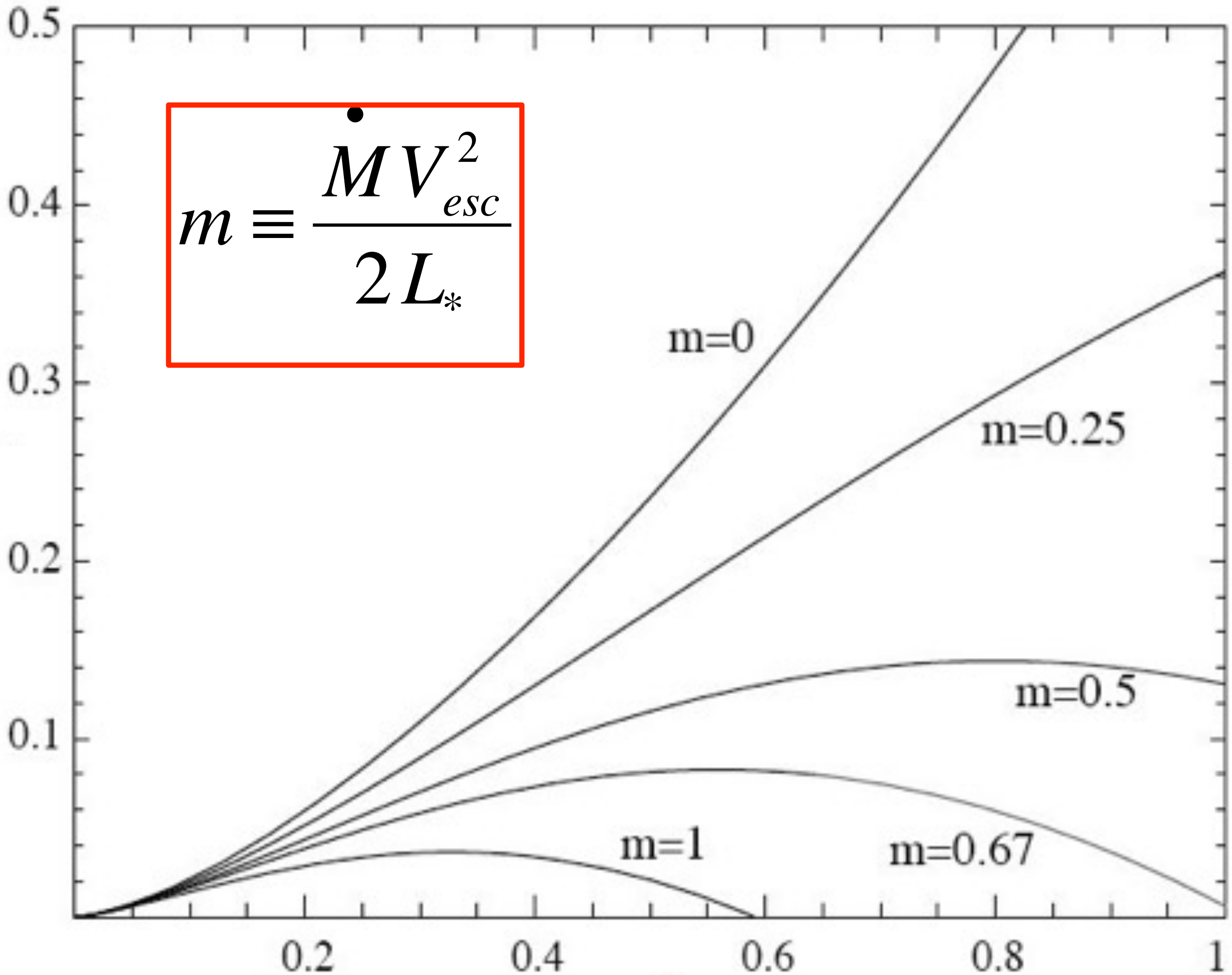
Stagnation of photon-tired outflow

$$\frac{\kappa}{\kappa_{Edd}} = 1 + \sqrt{x}$$

$$L(r) = L_* - \dot{M}\left[\frac{V^2}{2} + \frac{GM}{R} - \frac{GM}{r}\right]$$

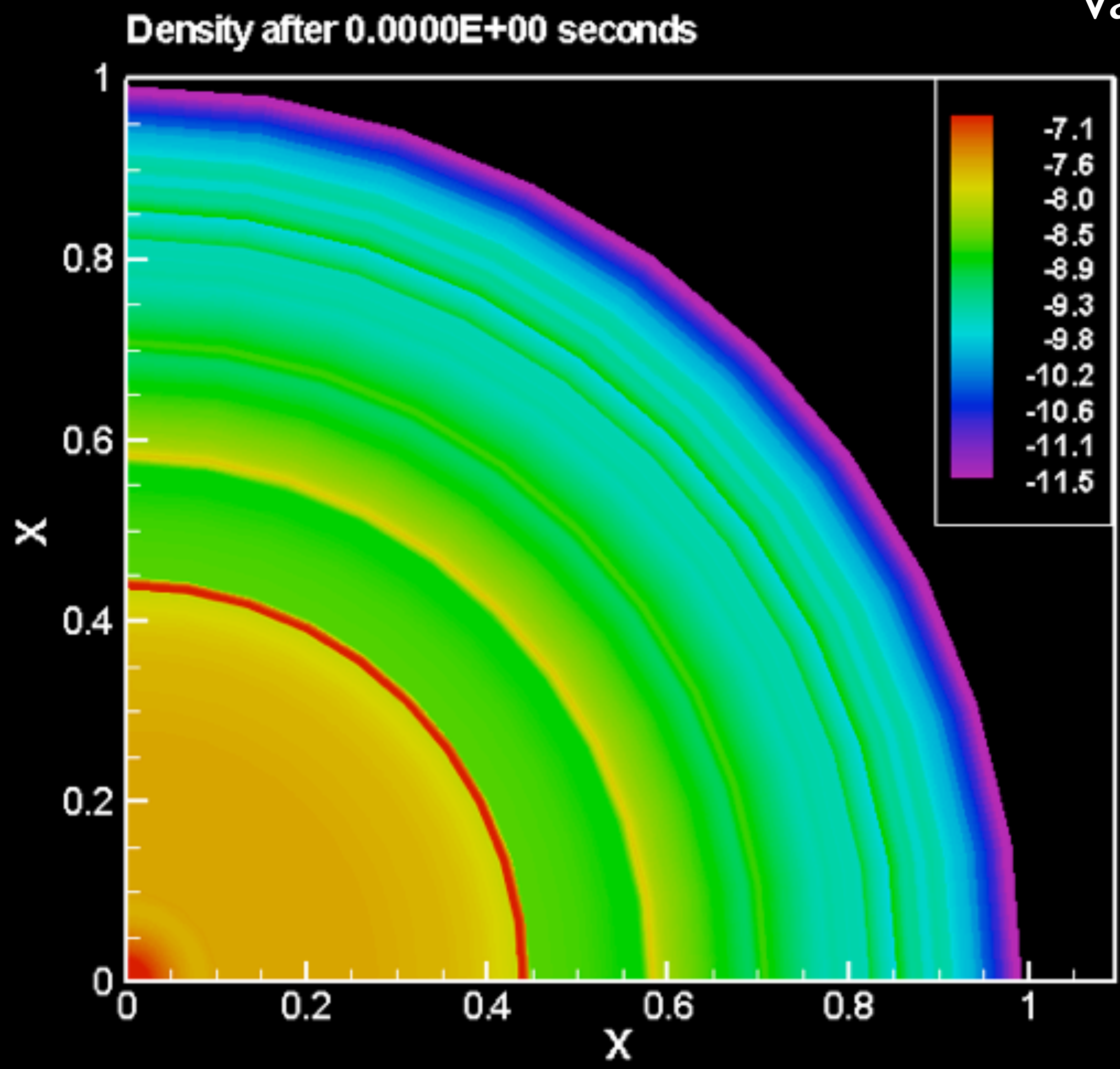
$$m \equiv \frac{\dot{M} V_{esc}^2}{2 L_*}$$

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

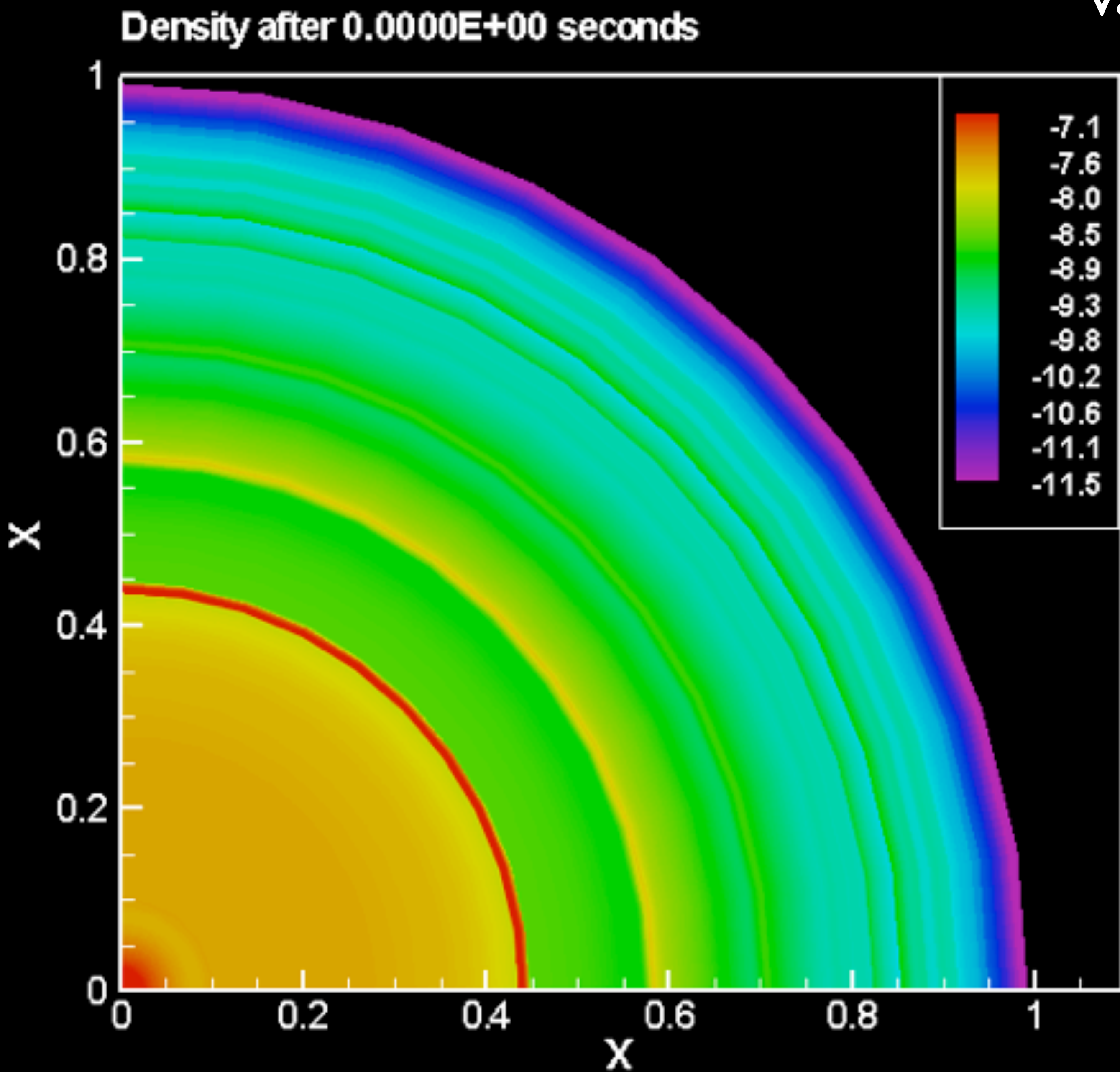


$$x = 1 - R_* / r$$

van Marle+2009



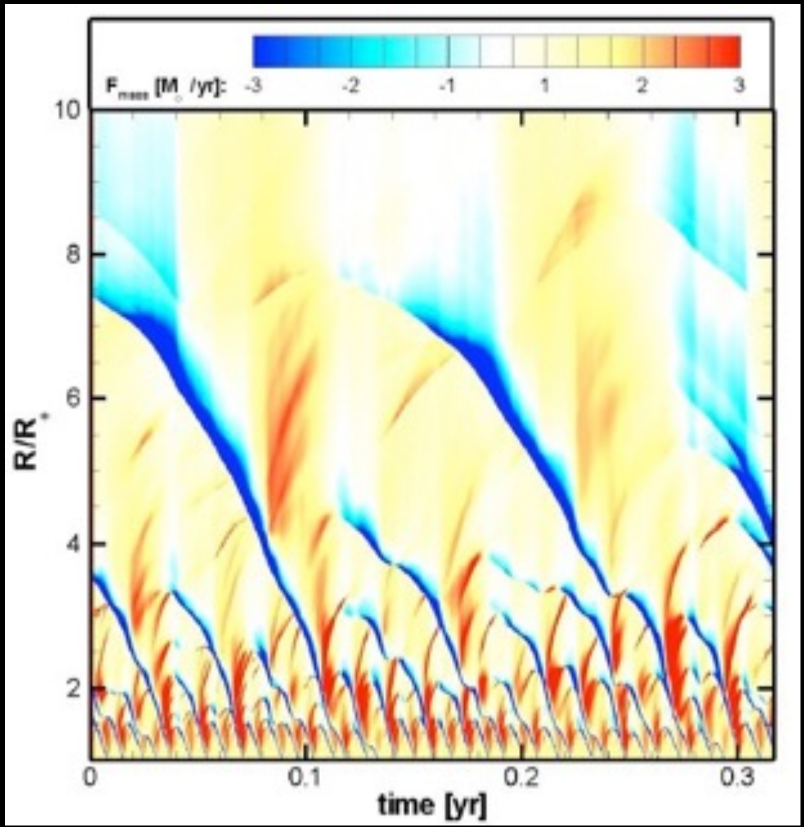
van Marle+2009



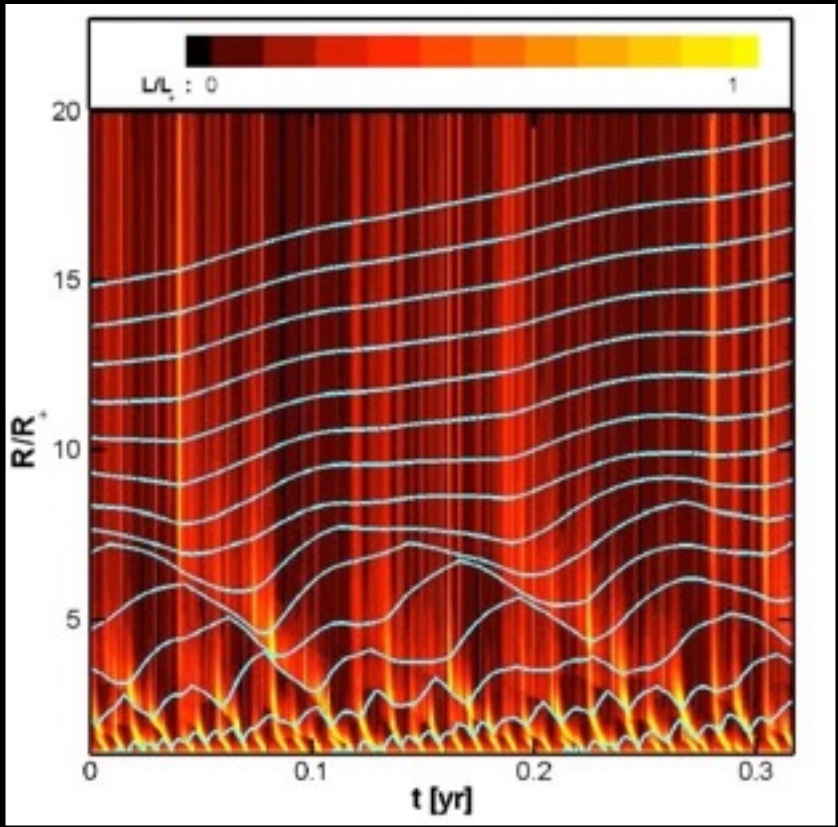
1D Sim of Photon Tiring & Flow Stagnation

van Marle, Owocki & Shaviv 2009

$\dot{M}(r,t)$



$L(r,t)/L_*$



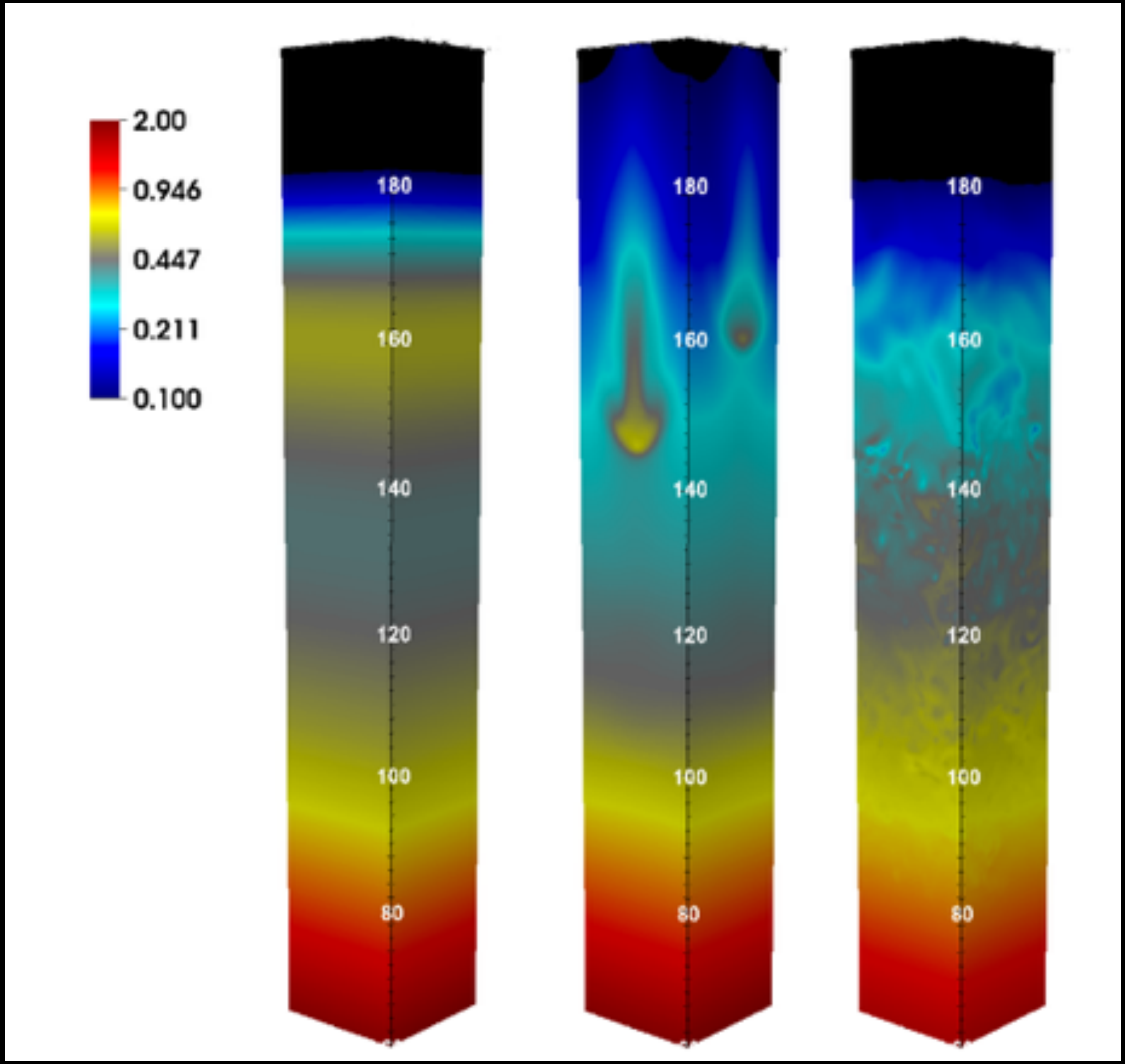
$$\left\langle \dot{M}_\infty \right\rangle \approx \frac{L_*}{V_{esc}^2/2} \qquad V_\infty << V_{esc} \qquad L_{obs} = L_\infty << L_*$$

Jiang+ 2016

"Local Radiation Hydrodynamics Simulations of Massive-Star Envelopes at the Iron Opacity Peak"

Clump structure from instabilities at Iron opacity bump

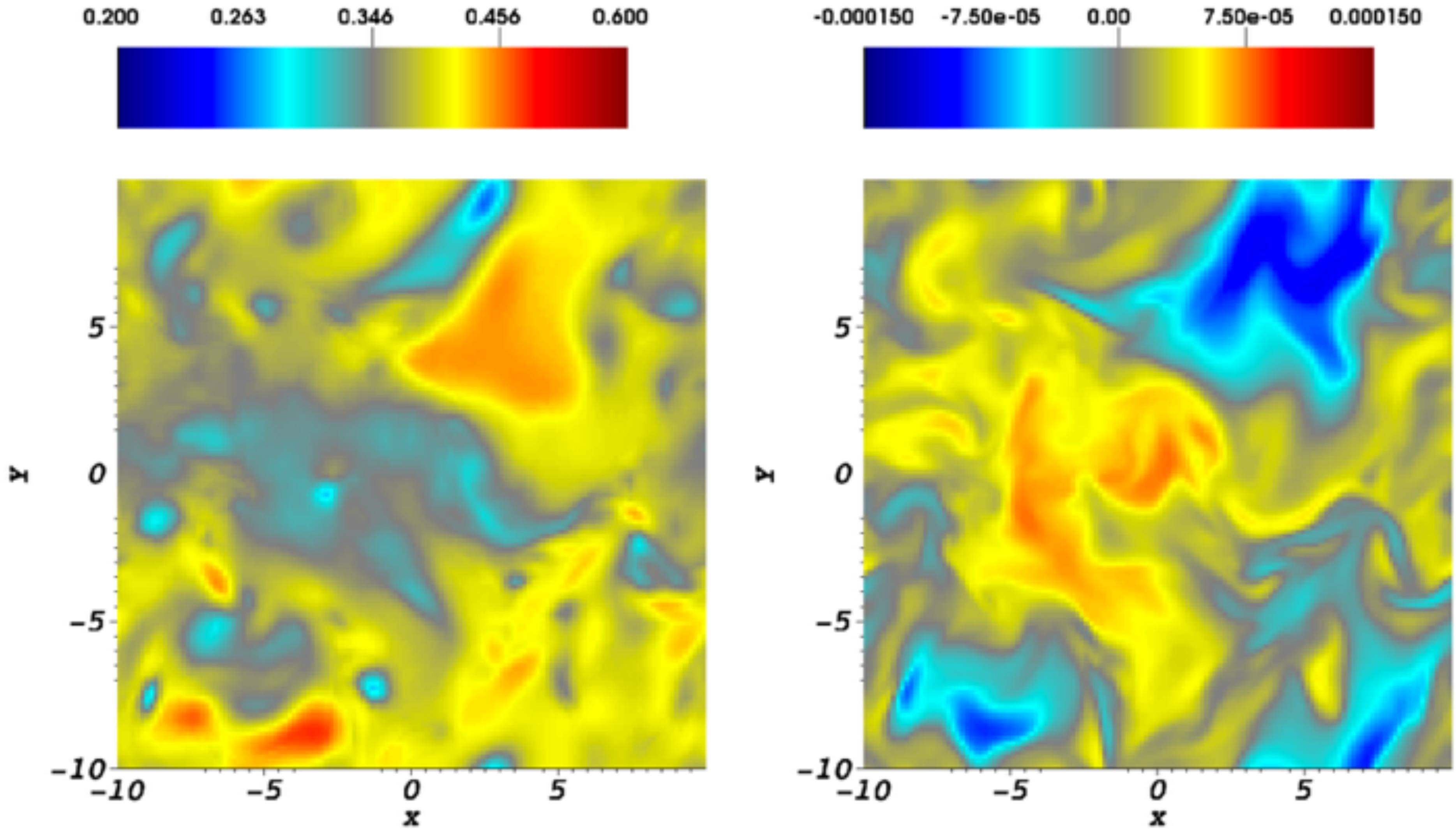
https://goo.gl/3kYbtg



Jiang+ 2016

density

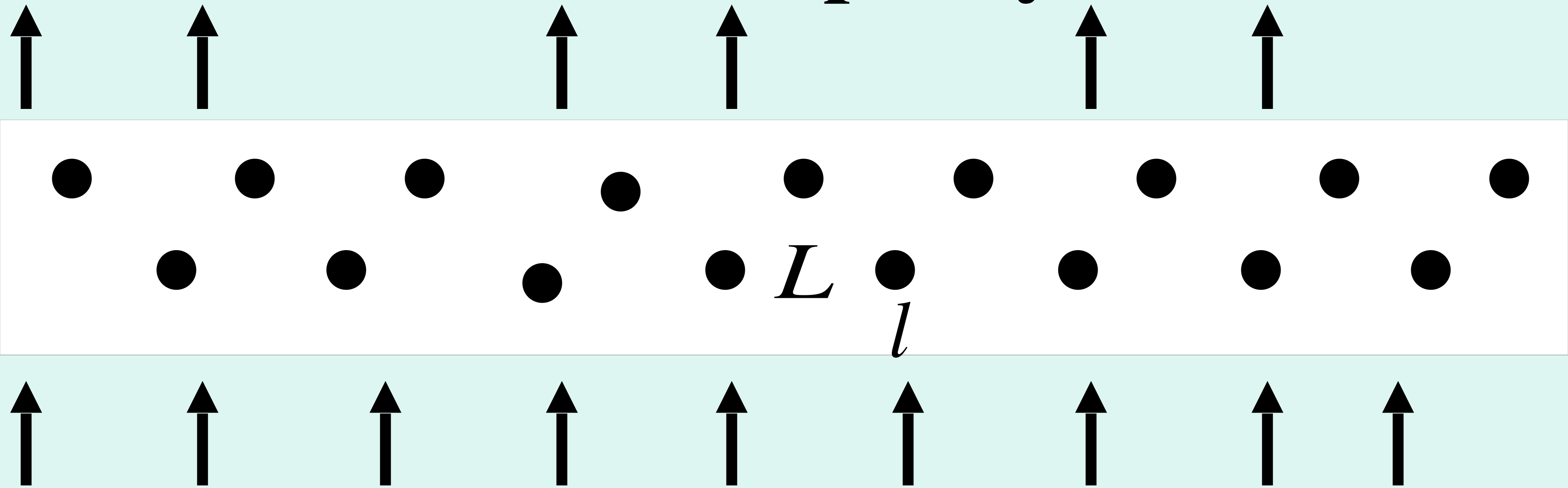
radiative flux



gure 8. Horizontal slices of density ρ (left) and vertical component of the radiation flux $F_{r,z}$ (right) at $z = 140R_\odot$ for the run

Porous opacity

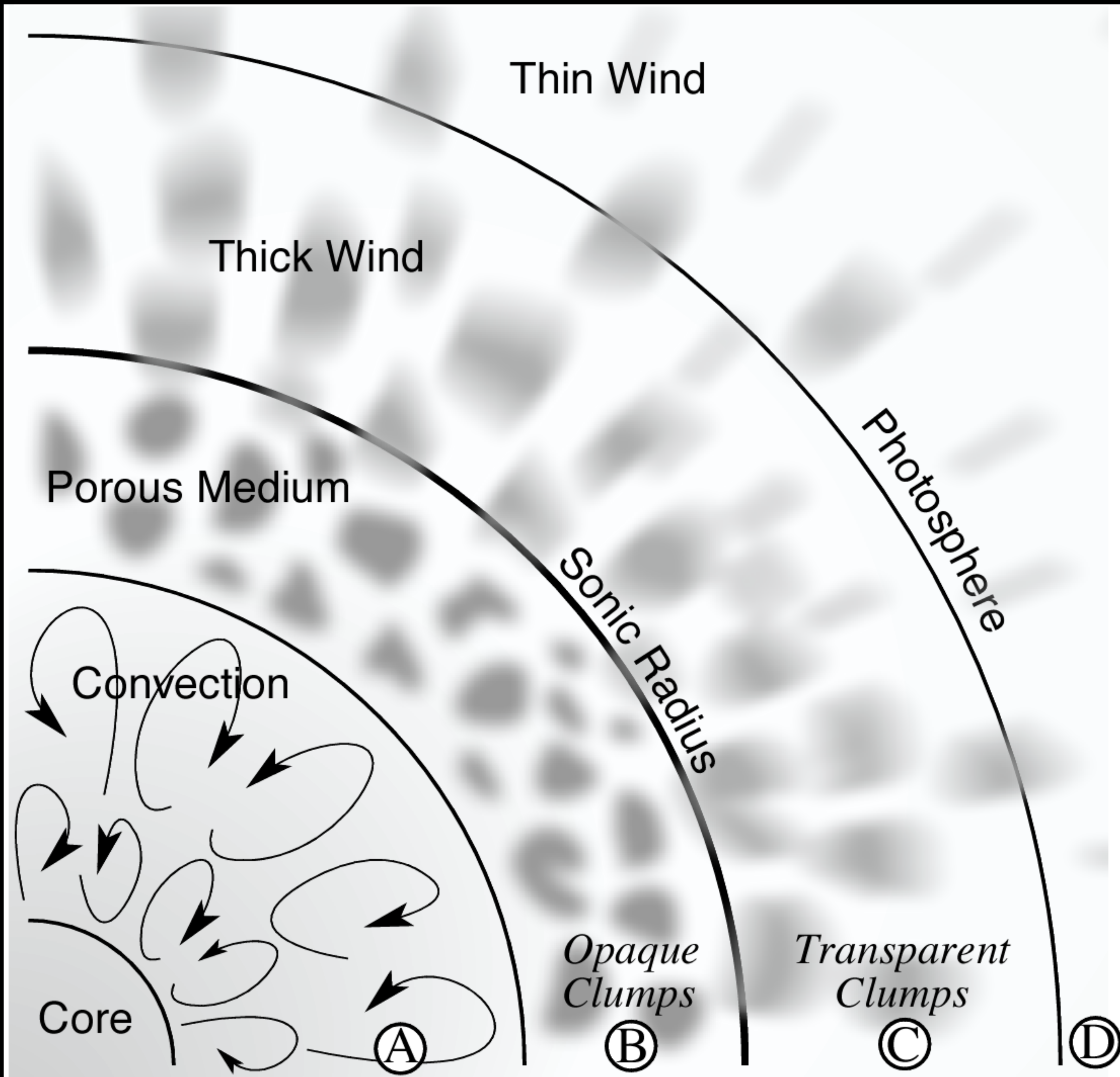
Shaviv 98-03



$$\kappa_{eff} \approx \frac{l^2}{m_b} = \frac{\kappa}{\tau_b} \qquad \tau_b \equiv \kappa \rho_b l >> 1$$

$$= \kappa \frac{1 - e^{-\tau_b}}{\tau_b}$$

O+Shaviv 2012



The Astrophysical Journal, 616:525–541, 2004 November 20

OGS 2004

A POROSITY-LENGTH FORMALISM FOR PHOTON-TIRING–LIMITED MASS LOSS FROM STARS ABOVE THE EDDINGTON LIMIT

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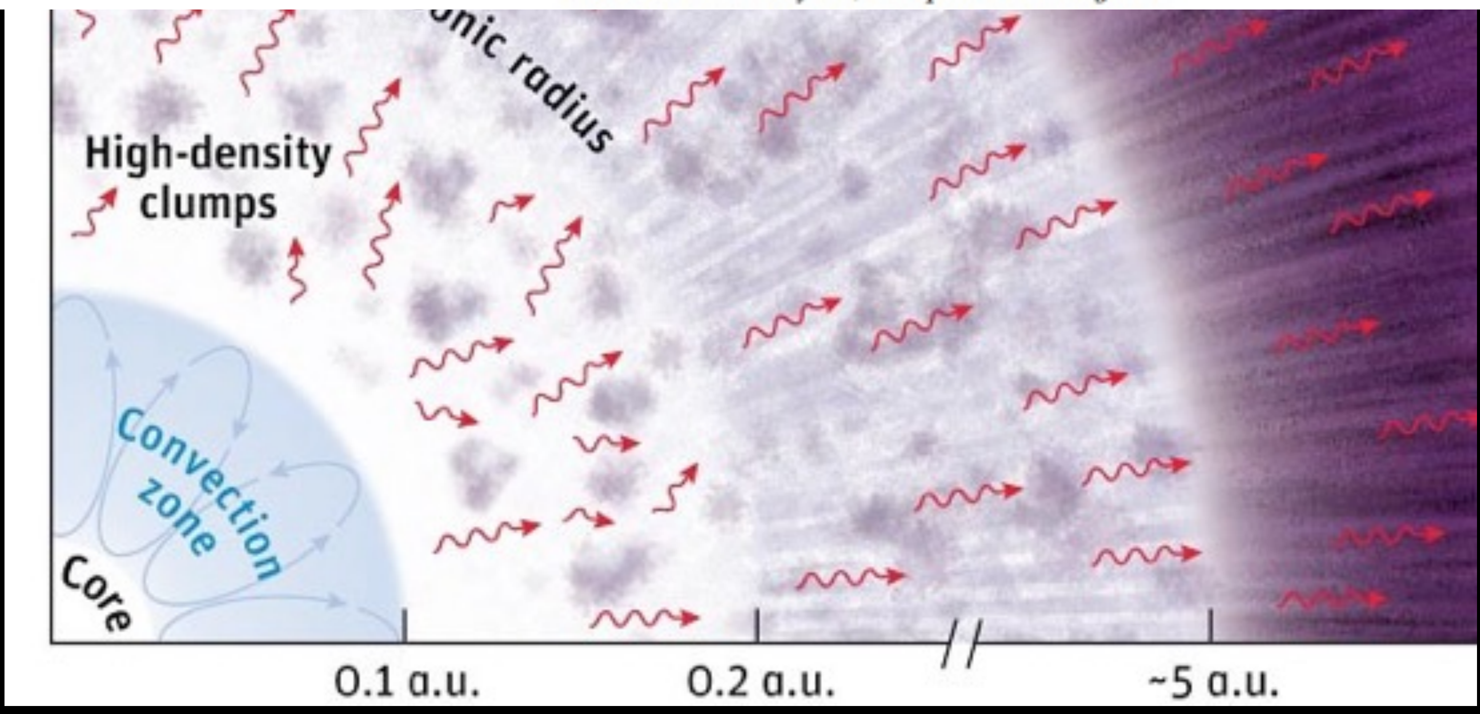

Turbulent Porosity

from LDI sims: $$\frac{\kappa_{eff}}{\kappa} \approx \frac{1}{\sqrt{1+\tau_h}}$$ $$\tau_h \equiv \kappa \rho h$$

$$h = (f_{cl} - 1)\ell$$

"porosity length"

$$f_{cl} \equiv \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

clumping factor

ℓ density auto-correlation length

Porosity regulated mass loss

Porosity reduced
Eddington factor

$$\Gamma_{eff} \equiv \frac{\Gamma}{\sqrt{1+\tau_h}} = 1$$

=> $$\dot{m}_{por} \equiv \frac{\dot{M}_{por}}{\dot{M}_{tir}} \simeq \frac{\Gamma^2 - 1}{\Gamma} \frac{R}{h} \frac{v_s}{c}$$

to keep below
tiring limit

$$\dot{m}_{por} \leq 1$$

requires

$$\rightarrow \quad \frac{h}{R} \geq \frac{\Gamma^2 - 1}{\Gamma} \frac{v_s}{c}$$

Some questions for workshop

- How to unify our understanding of
  - Explosive vs. Eruptive vs. Steady-wind mass loss
    - Failed explosions, failed winds
    - Dynamical vs. Diffusive time scales
  - Energy sources
    - Pre-SN LBVs: nuclear or waves
    - etaCar LBVs: binary merger &/or common env.
  - Momentum transfer
    - via $P_{rad} >> P_{gas}$; optically thick to thin: g_{rad}=kappa F_{rad}/c
  - What determines partition of escape energy?
    - Radiative vs. kinetic vs. potential
  - How different in 3D vs. 1D?
    - Rayleigh-Taylor, porosity

Summary

- Massive star winds driven by line-scattering
  - M_{dot} V_{inf} ~ tau L/c
    - OB winds tau ~< 1 ; WR winds tau~1-10
  - M_{dot} very sensitive to CAK alpha (thin/thick lines)
  - V_{inf} ~ few V_{esc}
- Strong Line-Deshadowing Instability
  - small-scale clumping & embedded soft X-rays
- Eddington limit => LBV's & Eruptions?
  - energy limited, super-Edd, continuum-driven wind
  - failed wind => porosity => regulates M_{dot}
- Explosion vs. wind