Physics of Stellar Winds

from Hot, Luminous Massive Stars

Stan Owocki

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- **Solar-type Coronal Winds**
  - Low Mdot ~10^{-14} M_{sun}/yr ; $V_{inf} \sim V_{esc} \sim$ 500 km/s
  - Thermally driven with $a \sim V_{esc}$

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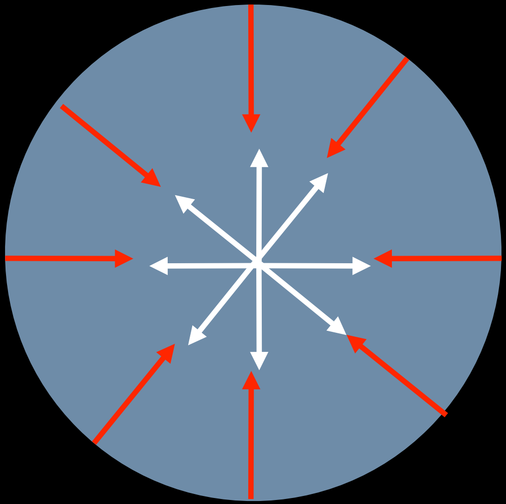
Radiative force vs. gravity

Radiative
Force

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



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

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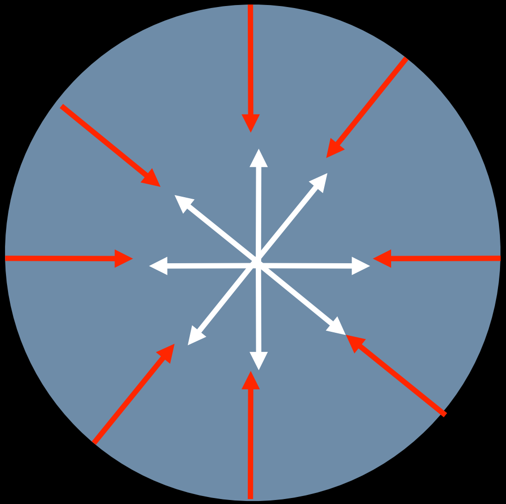

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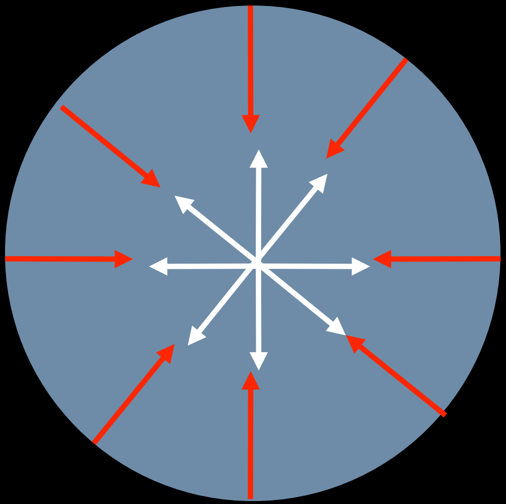

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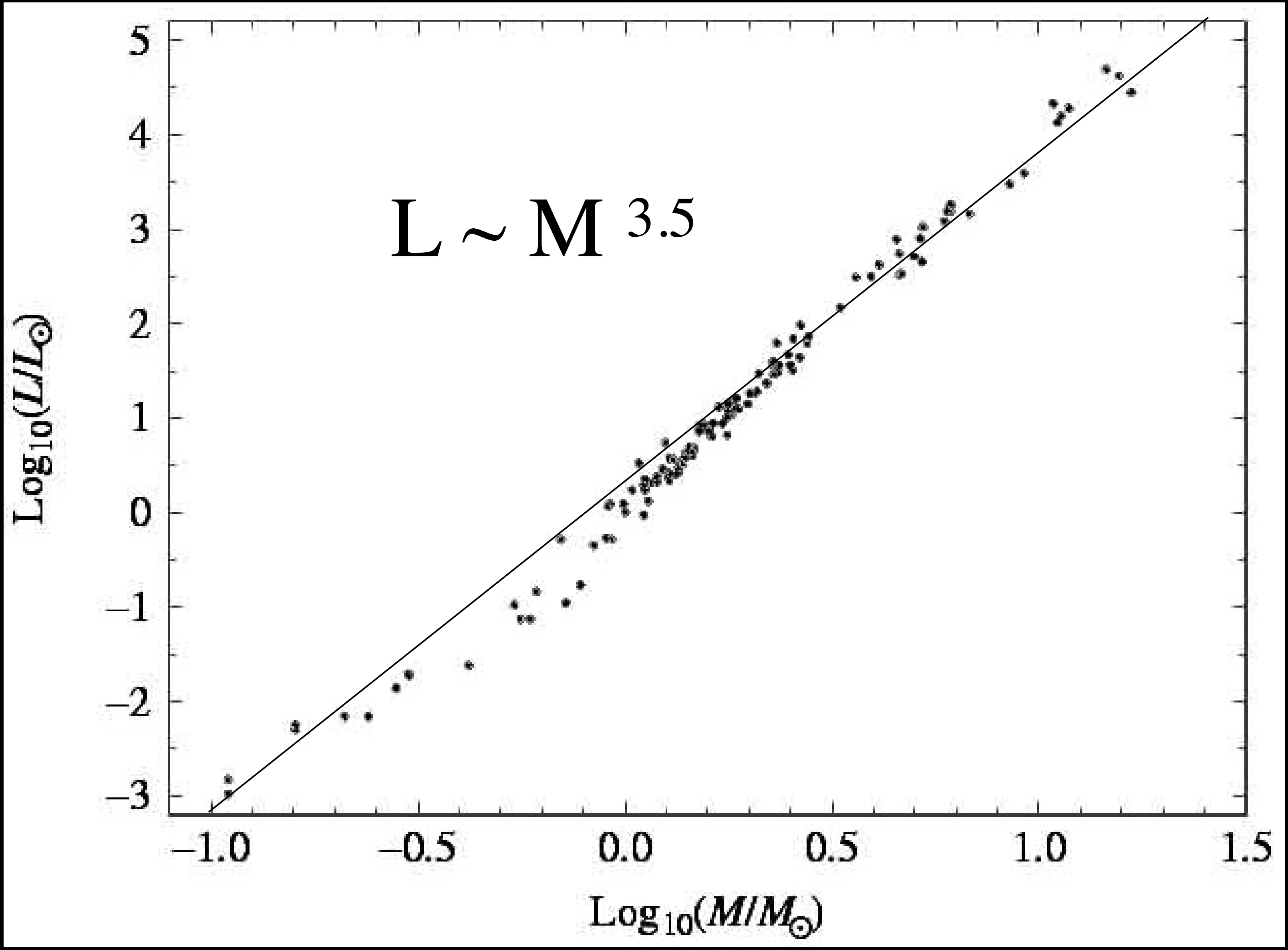
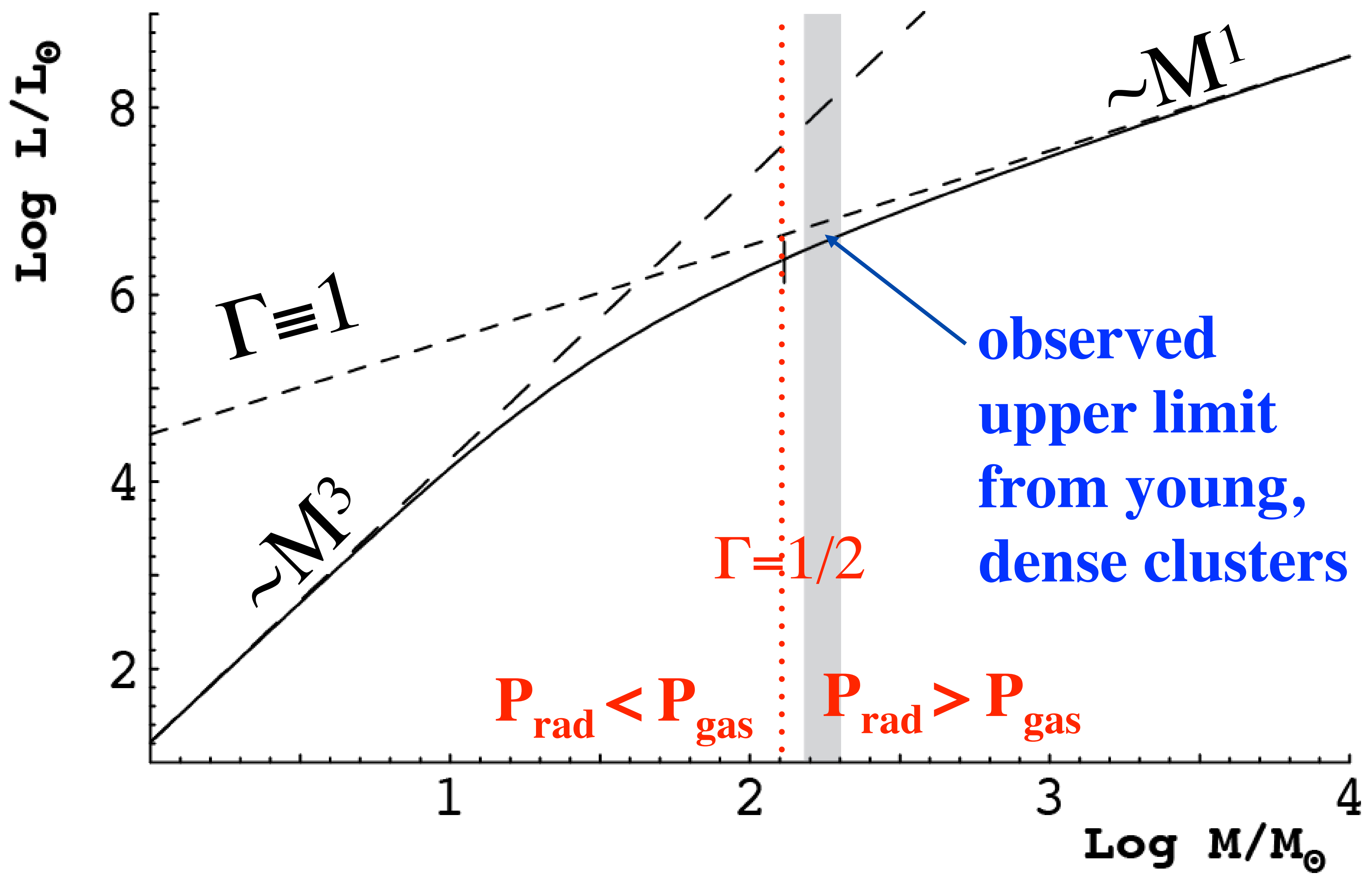
$$\Gamma \simeq 2 \times 10^{-5} \, \frac{L / L_\odot}{M / M_\odot} \, \frac{\overline{\kappa_F}}{\kappa_e}$$

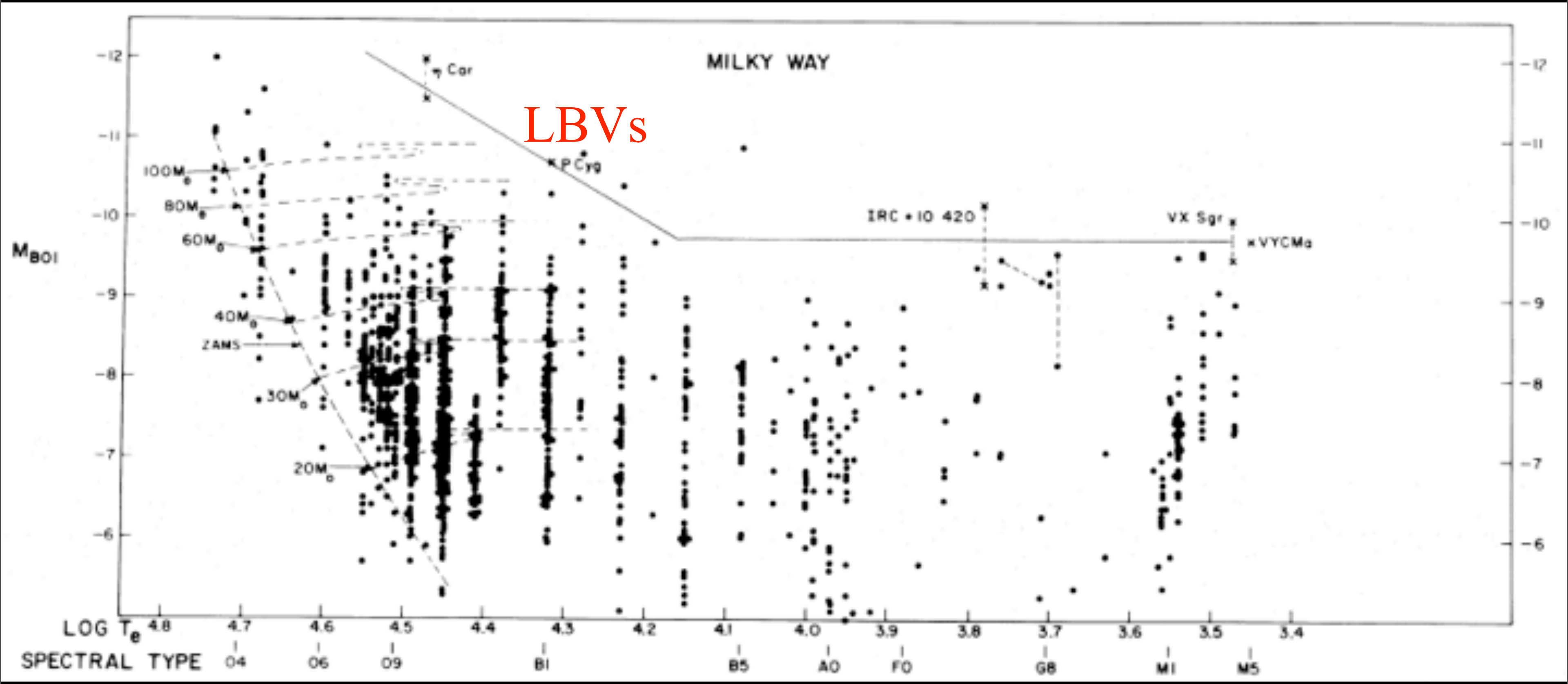
Stellar Luminosity vs. Mass



Eddington Standard Model (n=3 Polytrope)



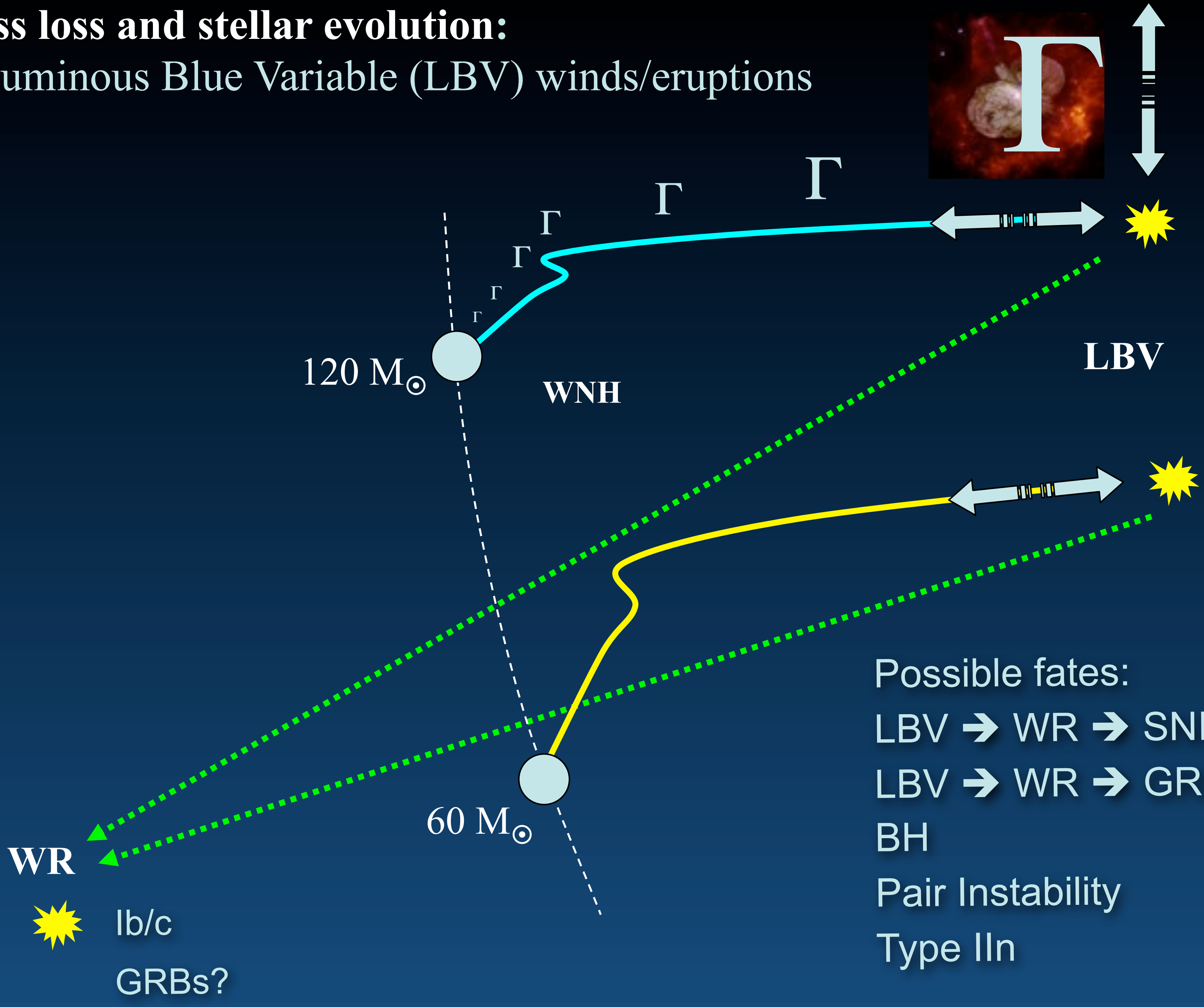
Humphreys-Davidson Limit



LBVs

Mass loss and stellar evolution:

Luminous Blue Variable (LBV) winds/eruptions



Possible fates:

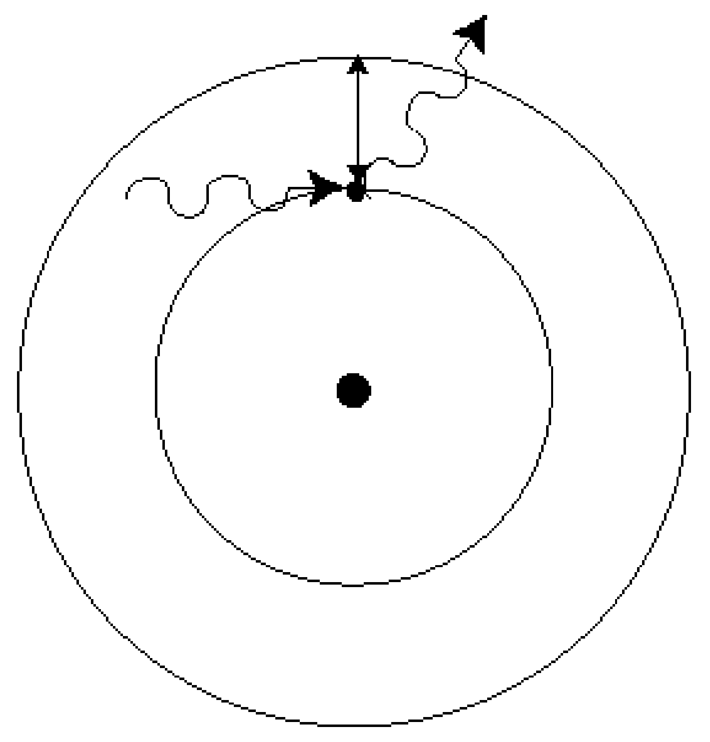
- LBV ➔ WR ➔ SNIbc
- LBV ➔ WR ➔ GRB
- BH
- Pair Instability
- Type IIn

Line-Driven Stellar Winds

- For normal (sub-Eddington stars) wind is driven is 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**



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

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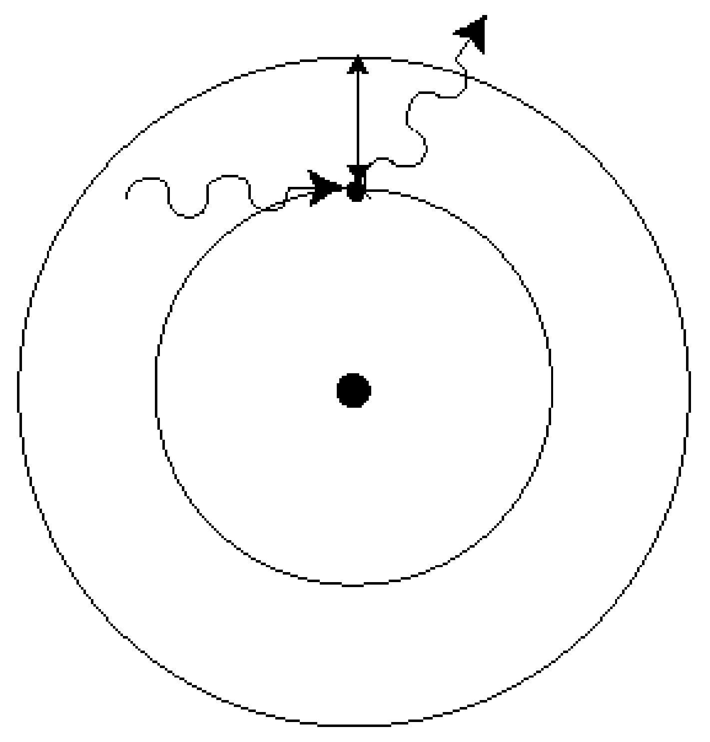
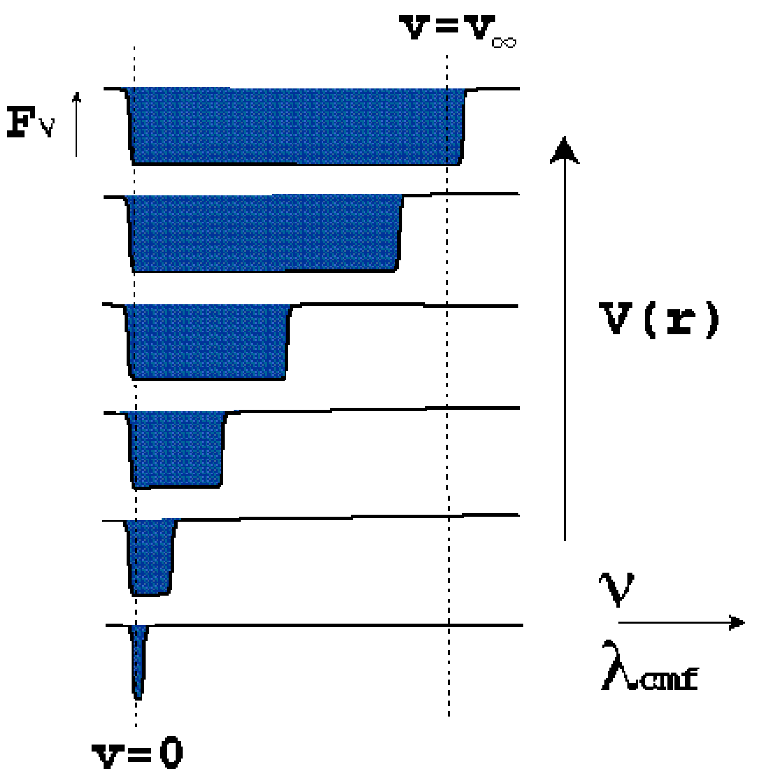


Optically **thick**



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

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

CAK model of steady-state wind

Equation of motion:

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

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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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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Velocity law

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

$$\boxed{\sim v_{esc}}$$

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g

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Wind-Momentum Luminosity law

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

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

$$\alpha \approx 0.6$$

$$\boxed{\bar{Q} \sim Z}$$

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

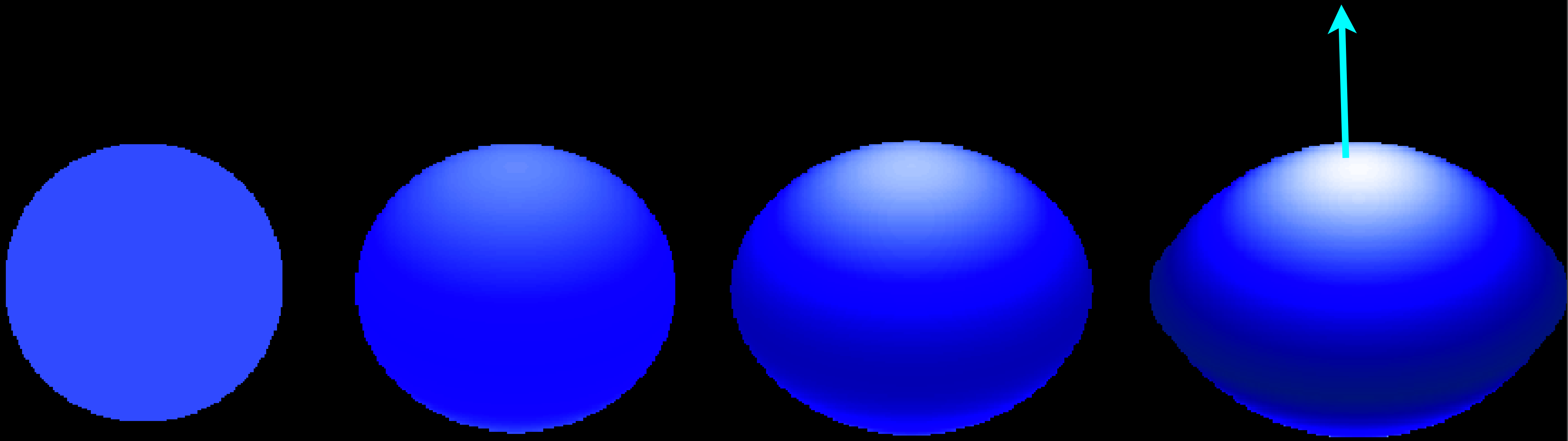
Gravity Darkening

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

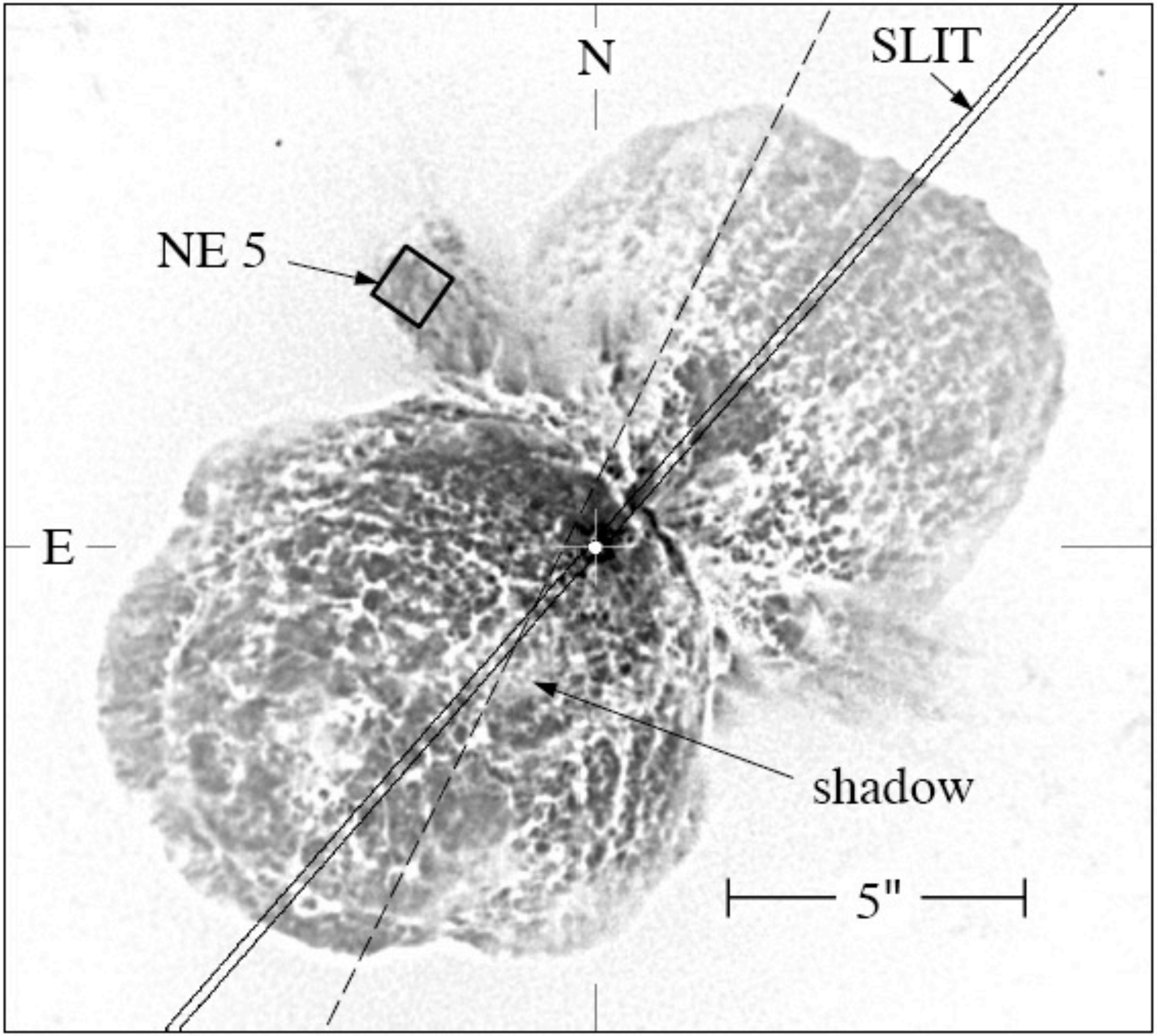
$$F(\theta) \sim g_{eff}(\theta)$$

$$V_{\infty} \sim \sqrt{g(\theta)}$$

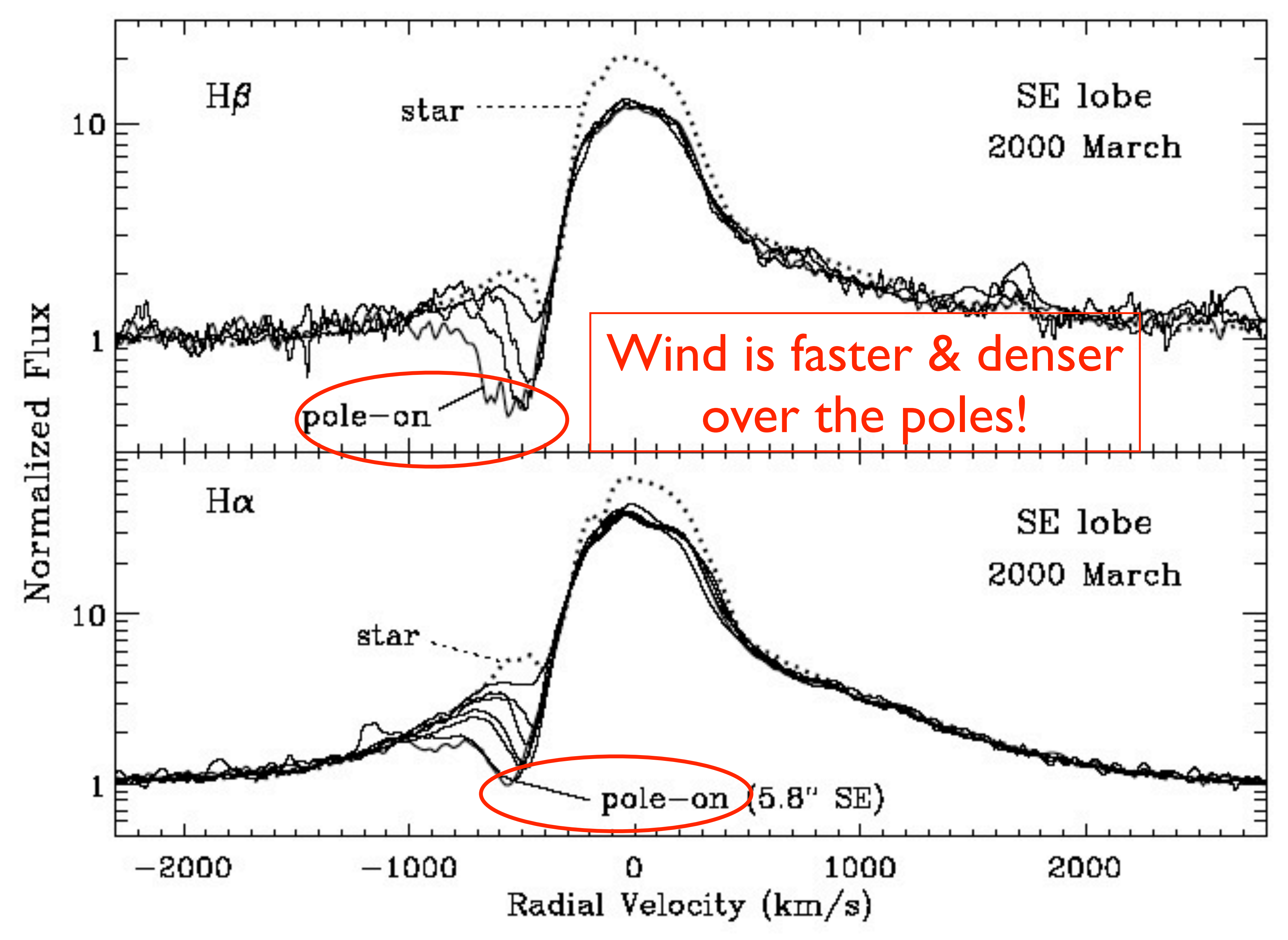
higher at pole!



increasing stellar rotation →


N
SLIT
NE 5
E
shadow
5"

Smith et al. 2003



Wind is faster & denser over the poles!

How are winds affected by a (large-scale) stellar magnetic field?

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

Rigid Field - Hydro Dynamics for $\eta_\star >> 1$

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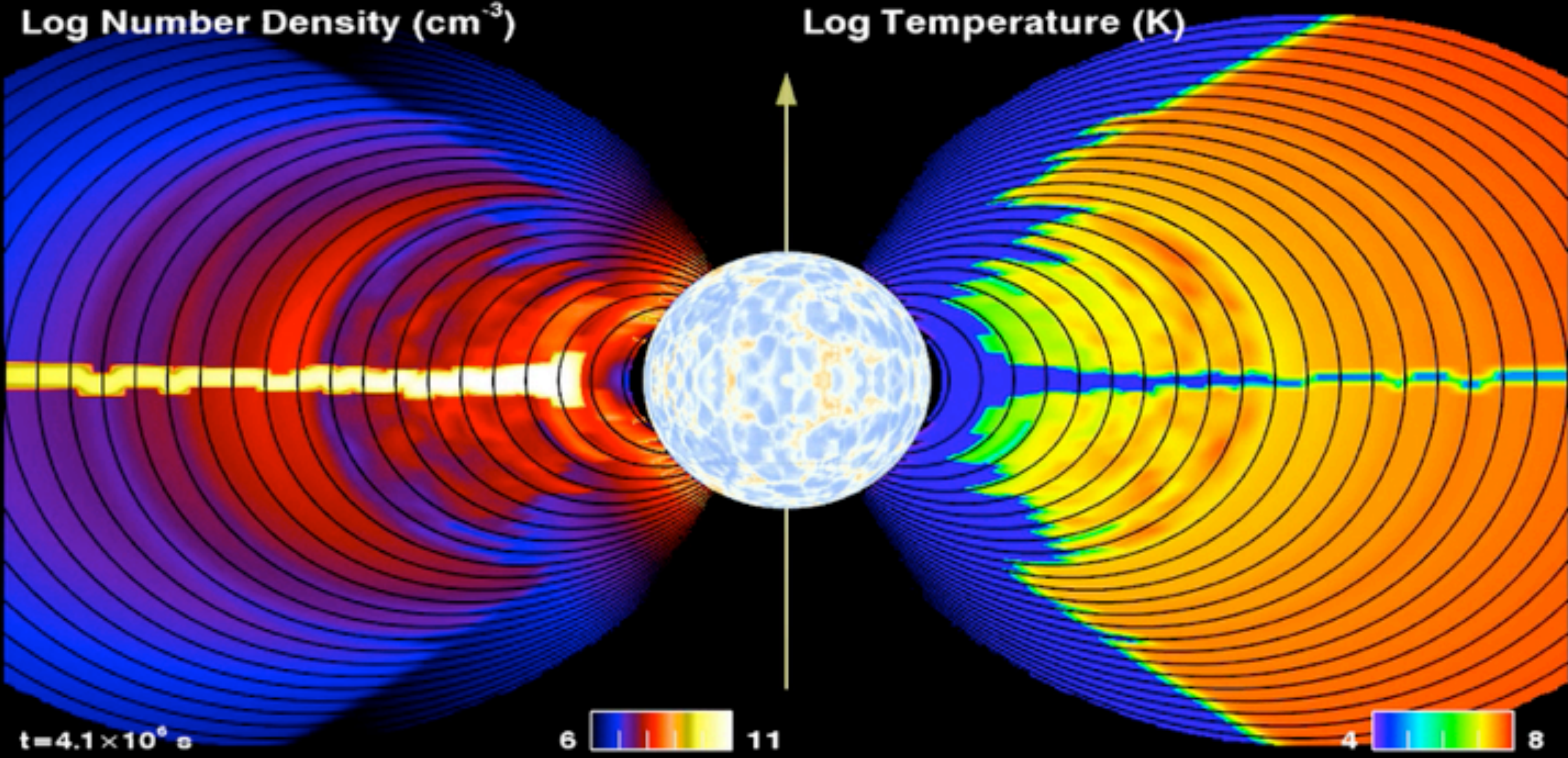

RRM model for σ Ori E

EM +B-field

photometry

$B_{*} \sim 10^4$ G

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

tilt ~ 55^o

Hα

polarimetry

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EM +B-field

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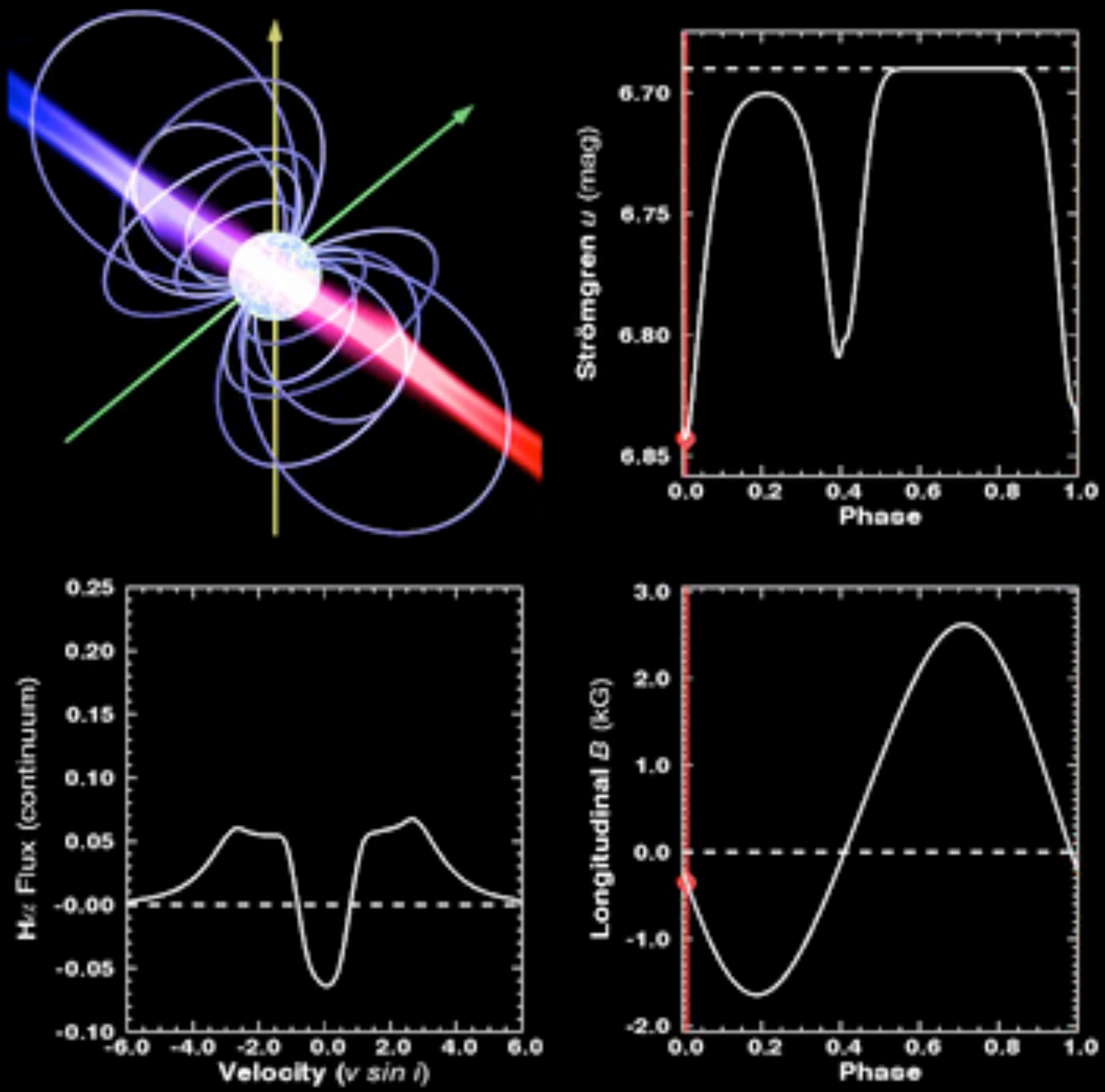

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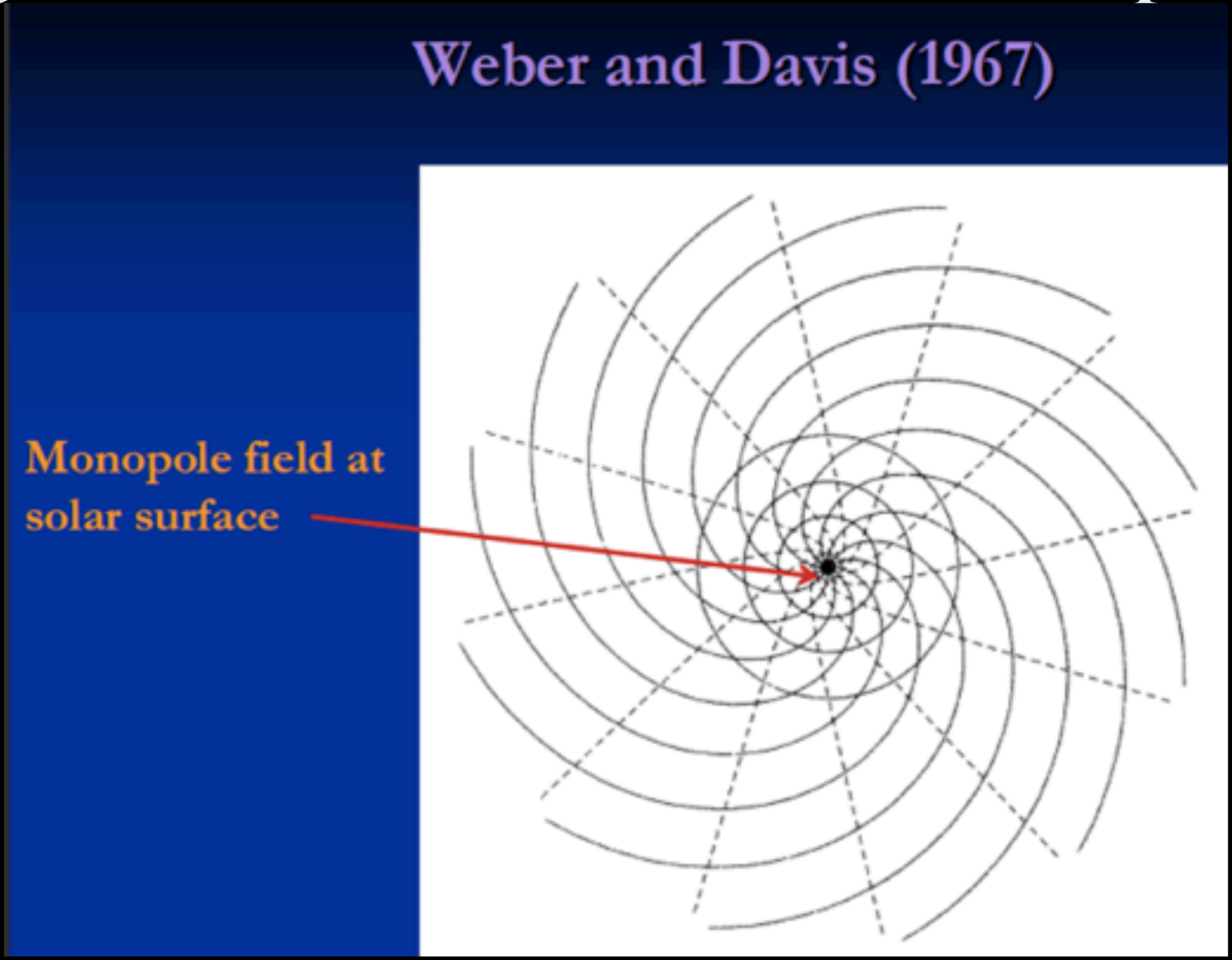
Angular Momentum Loss & Spindown



Weber and Davis (1967)

Monopole field at solar surface

$$\dot{J} = \frac{2}{3}\dot{M}\,\Omega R_A^2$$

Stellar spindown time

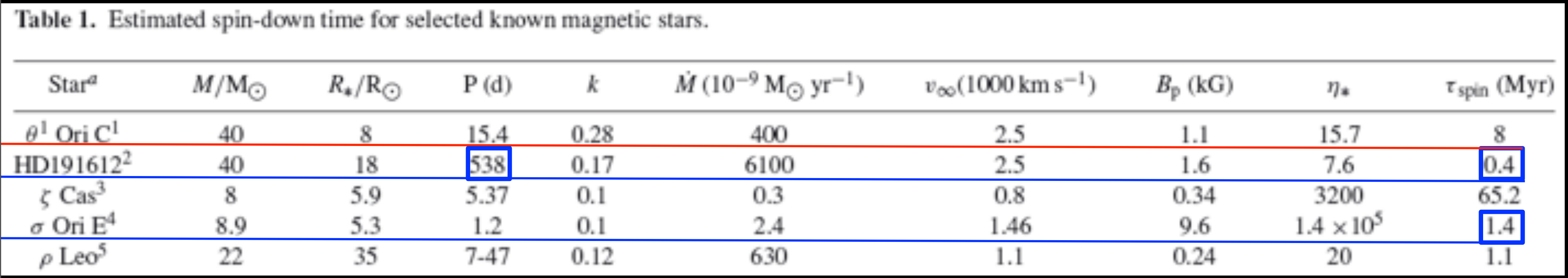


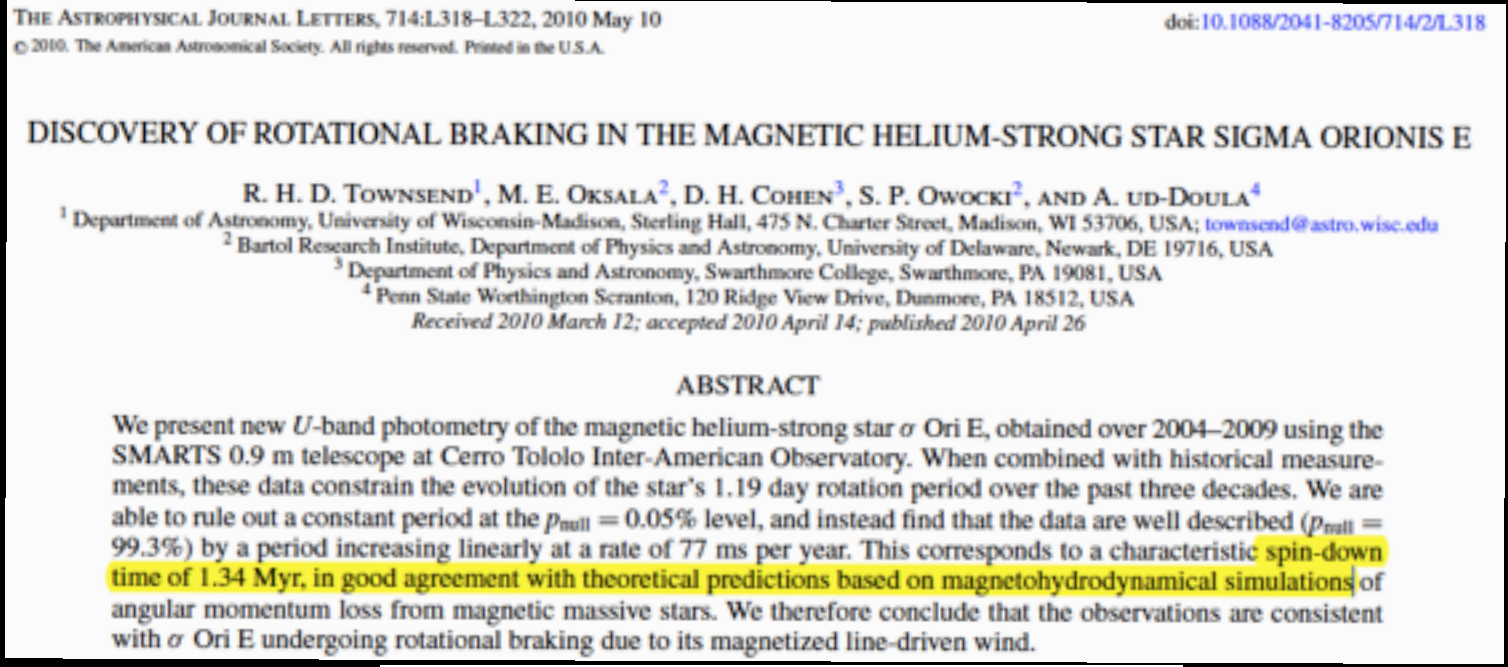
Table 1. Estimated spin-down time for selected known magnetic stars.

Star[a]	$M/M_\odot$	$R_*/R_\odot$	P (d)	k	$\dot{M}$ (10^{-9} $M_\odot$ yr^{-1})	v_∞(1000 km s^{-1})	B_p (kG)	η_*	τ_{spin} (Myr)
θ^1 Ori C[1]	40	8	15.4	0.28	400	2.5	1.1	15.7	8
HD191612[2]	40	18	538	0.17	6100	2.5	1.6	7.6	0.4
ζ Cas[3]	8	5.9	5.37	0.1	0.3	0.8	0.34	3200	65.2
σ Ori E[4]	8.9	5.3	1.2	0.1	2.4	1.46	9.6	1.4×10^5	1.4
ρ Leo[5]	22	35	7-47	0.12	630	1.1	0.24	20	1.1

$$\tau_{spin} \approx \tau_{mass} \frac{\frac{3}{2}k}{\sqrt{\eta_*}}$$

$$\eta_* \equiv \frac{B_*^2 R_*^2}{\dot{M} V_\infty}$$

$$\approx 11 Myr \; \frac{k_{-1}}{B_{kG}} \frac{M_*}{R_*} \sqrt{\frac{V_8}{\dot{M}_{-9}}}$$



The Astrophysical Journal Letters, 714:L318–L322, 2010 May 10
doi:10.1088/2041-8205/714/2/L318

DISCOVERY OF ROTATIONAL BRAKING IN THE MAGNETIC HELIUM-STRONG STAR SIGMA ORIONIS E

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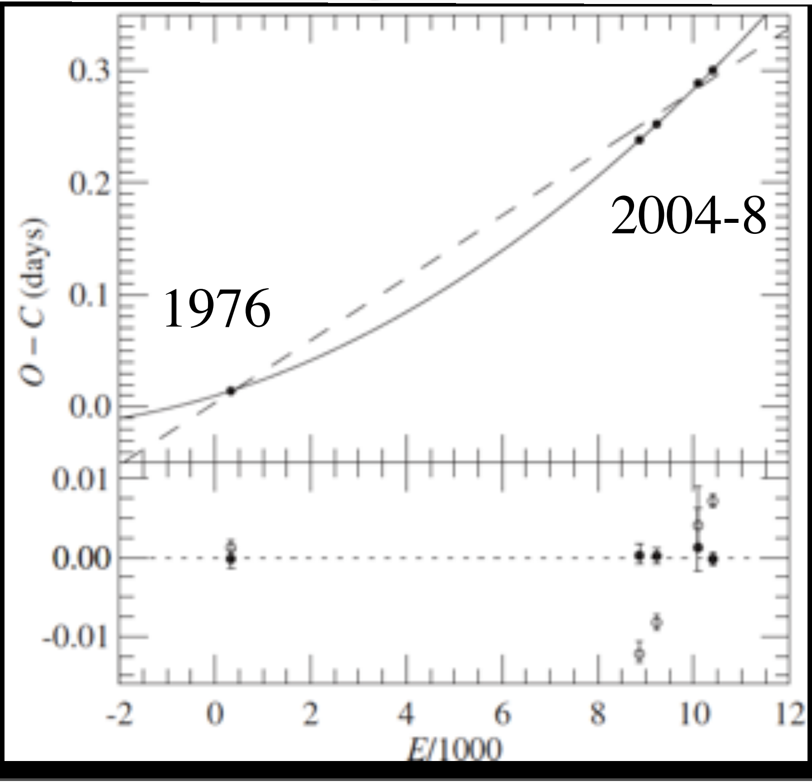
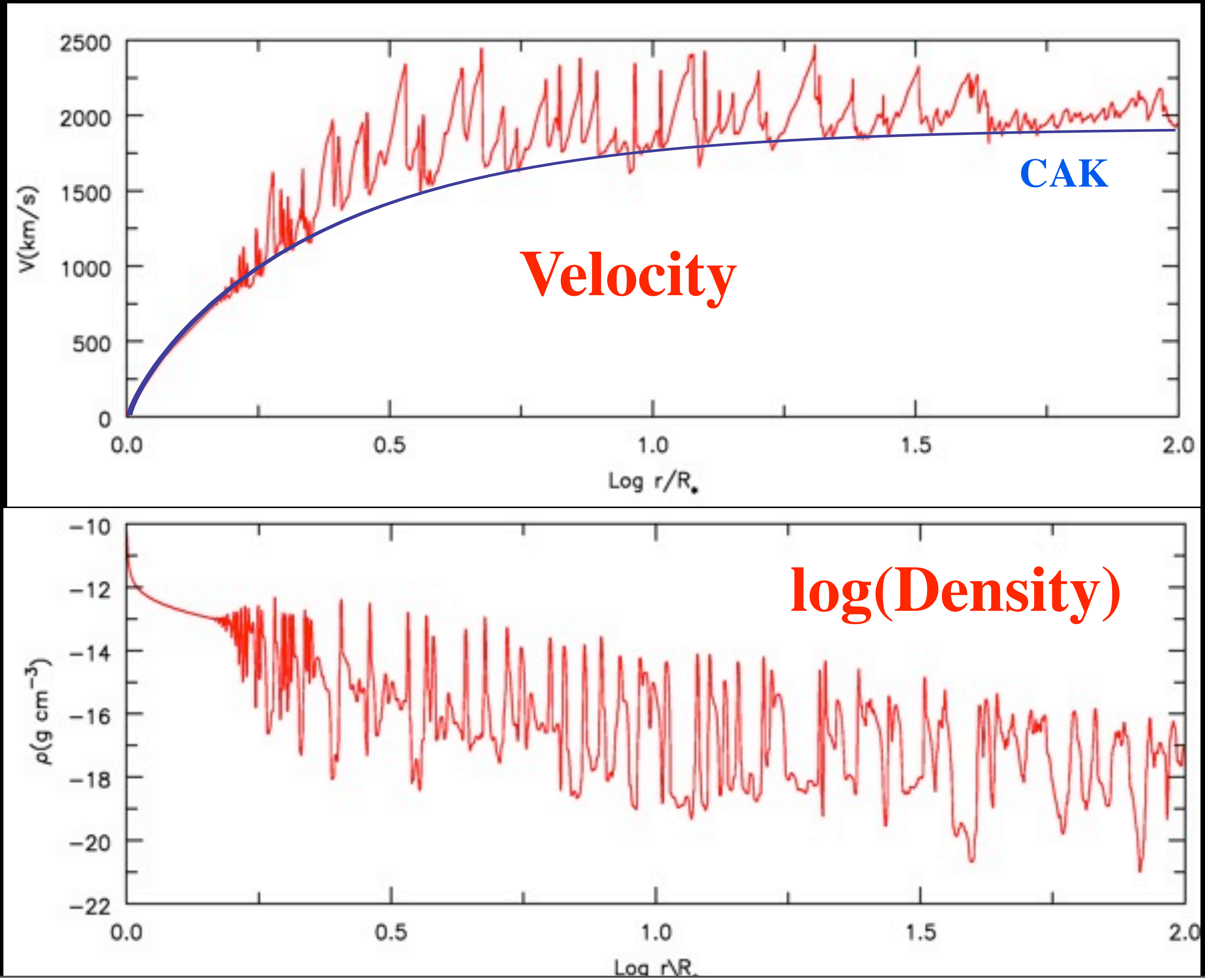
Received 2010 March 12; accepted 2010 April 14; published 2010 April 26

ABSTRACT

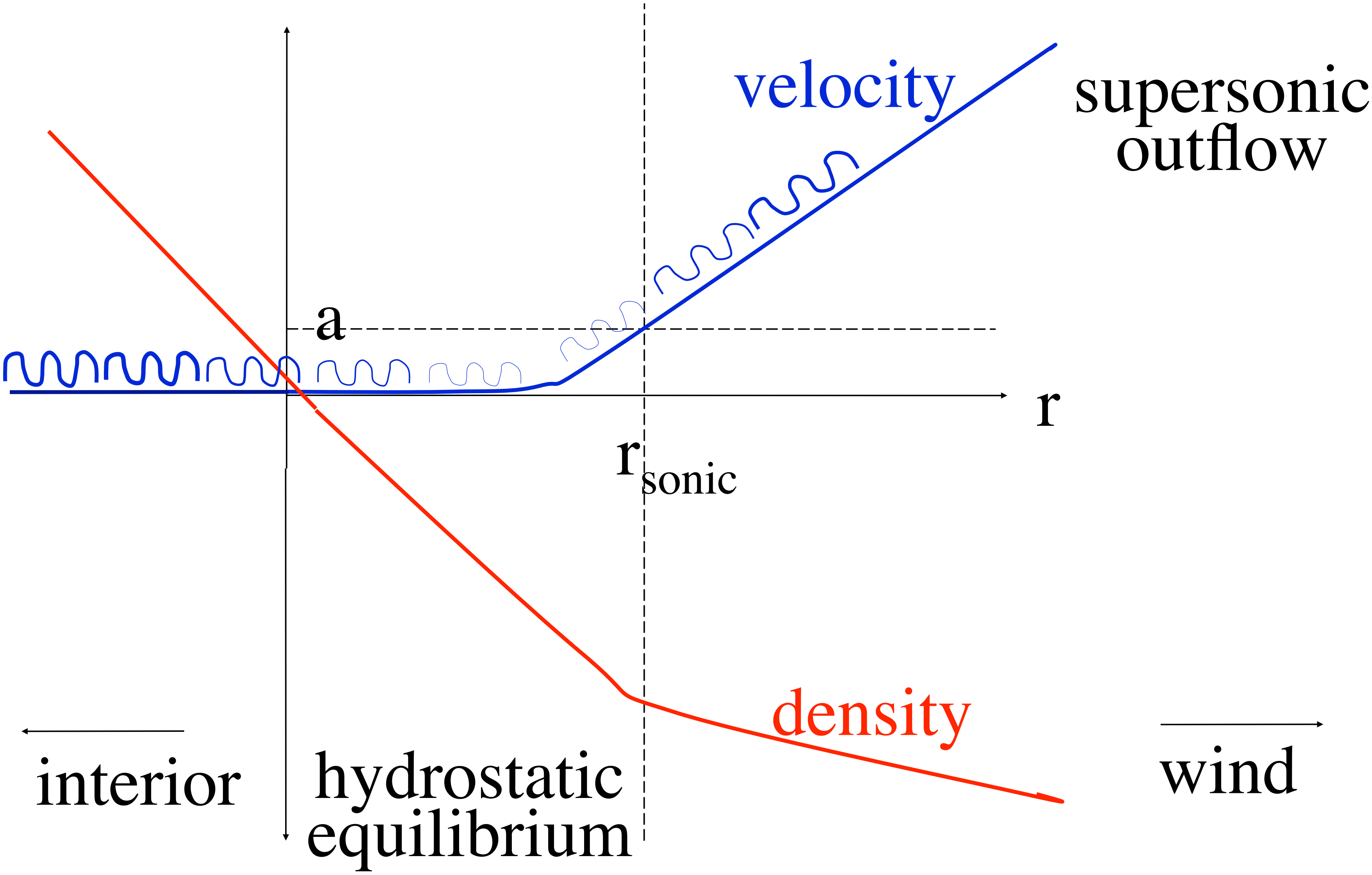
We present new *U*-band photometry of the magnetic helium-strong star σ Ori E, obtained over 2004–2009 using the SMARTS 0.9 m telescope at Cerro Tololo Inter-American Observatory. When combined with historical measurements, these data constrain the evolution of the star's 1.19 day rotation period over the past three decades. We are able to rule out a constant period at the $p_{\rm null} = 0.05\%$ level, and instead find that the data are well described ($p_{\rm null} = 99.3\%$) by a period increasing linearly at a rate of 77 ms per year. This corresponds to a characteristic spin-down time of 1.34 Myr, in good agreement with theoretical predictions based on magnetohydrodynamical simulations of angular momentum loss from magnetic massive stars. We therefore conclude that the observations are consistent with σ Ori E undergoing rotational braking due to its magnetized line-driven wind.



Line-driving intrinsically unstable at small-scales



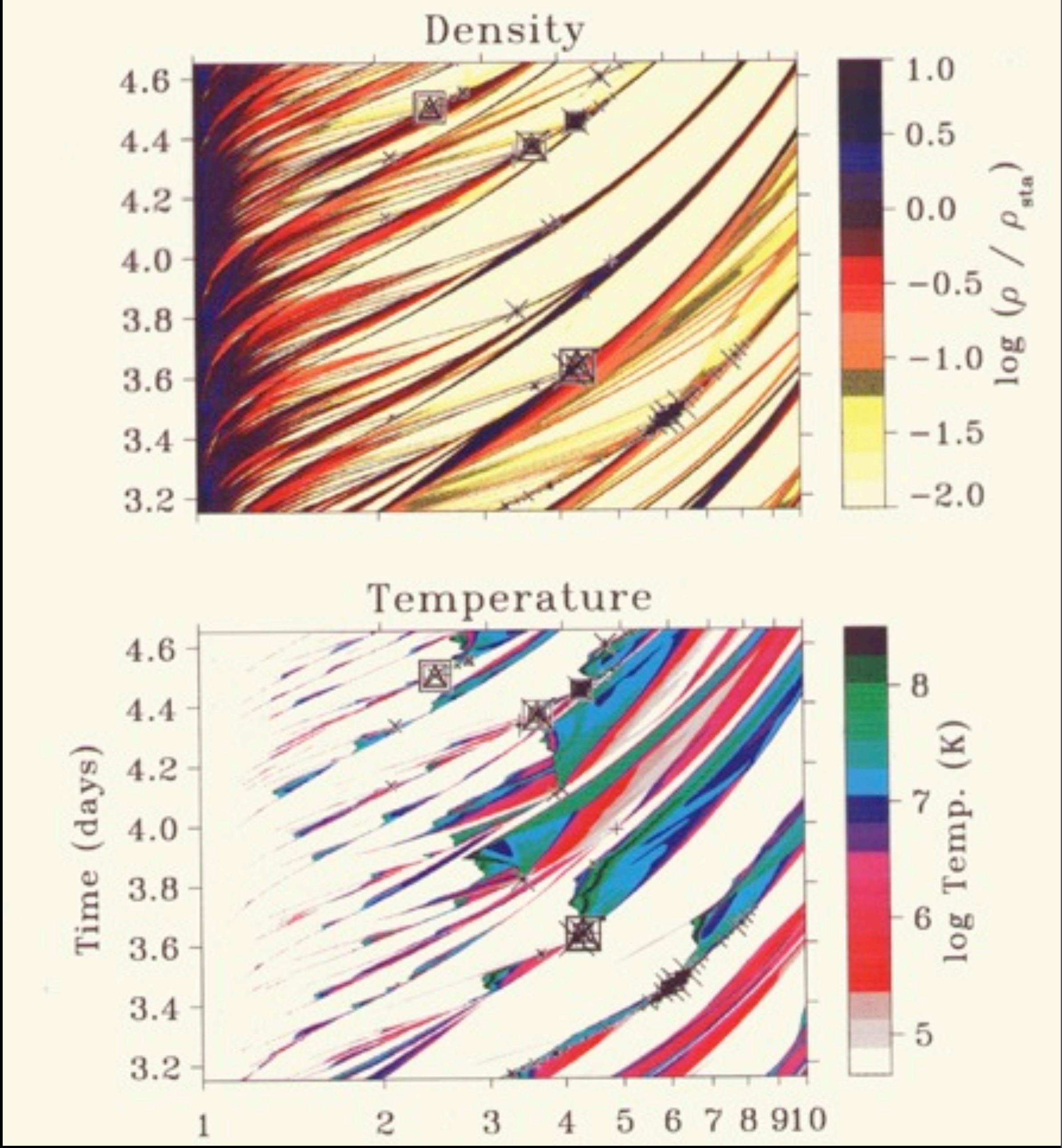
Wave leakage through sonic point



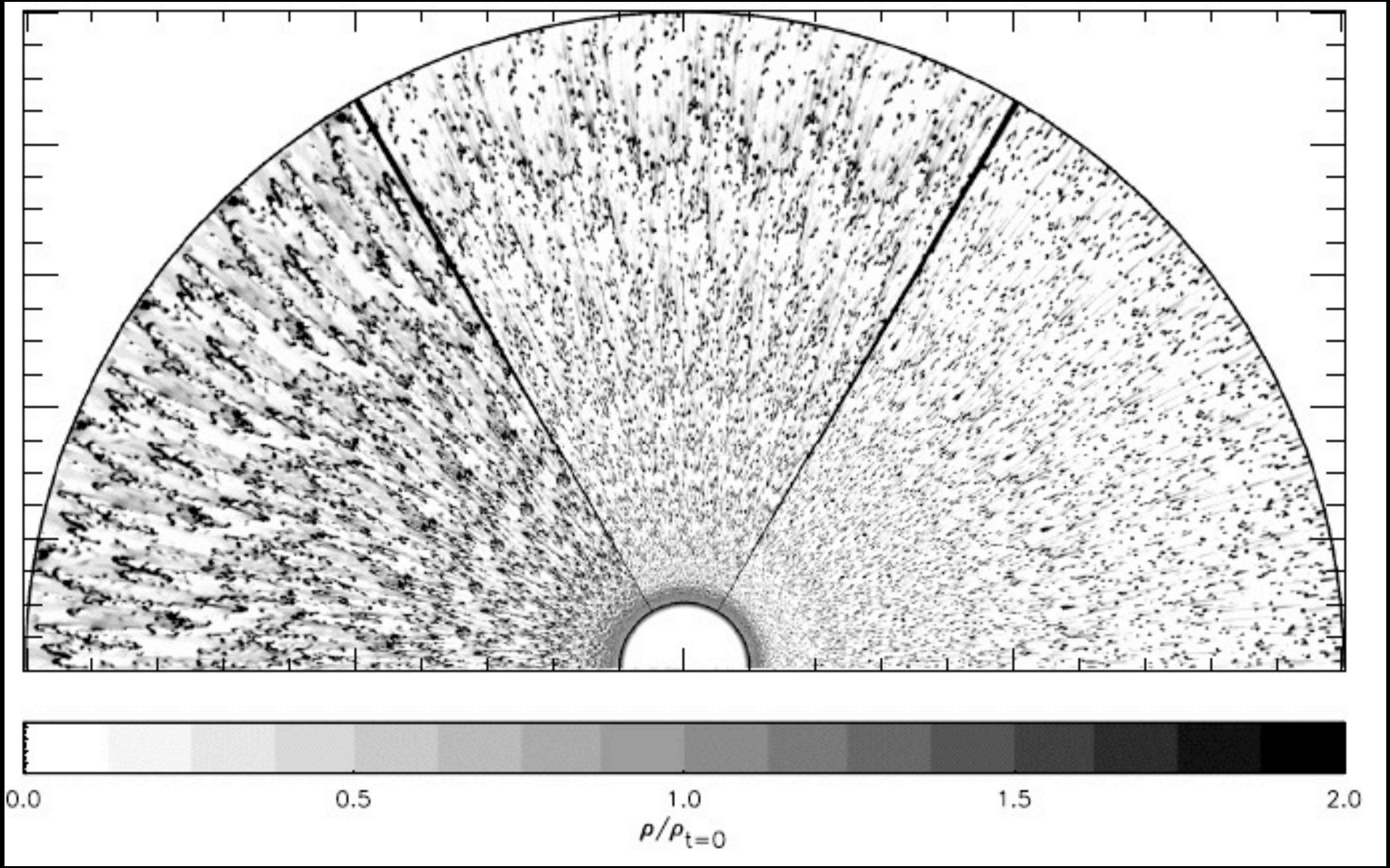
Turbulence-seeded clump collisions

Enhances V_{disp} and thus X-ray emission

Feldmeier et al. 1997



In 2D sims, RT instabilities break shells into clumps

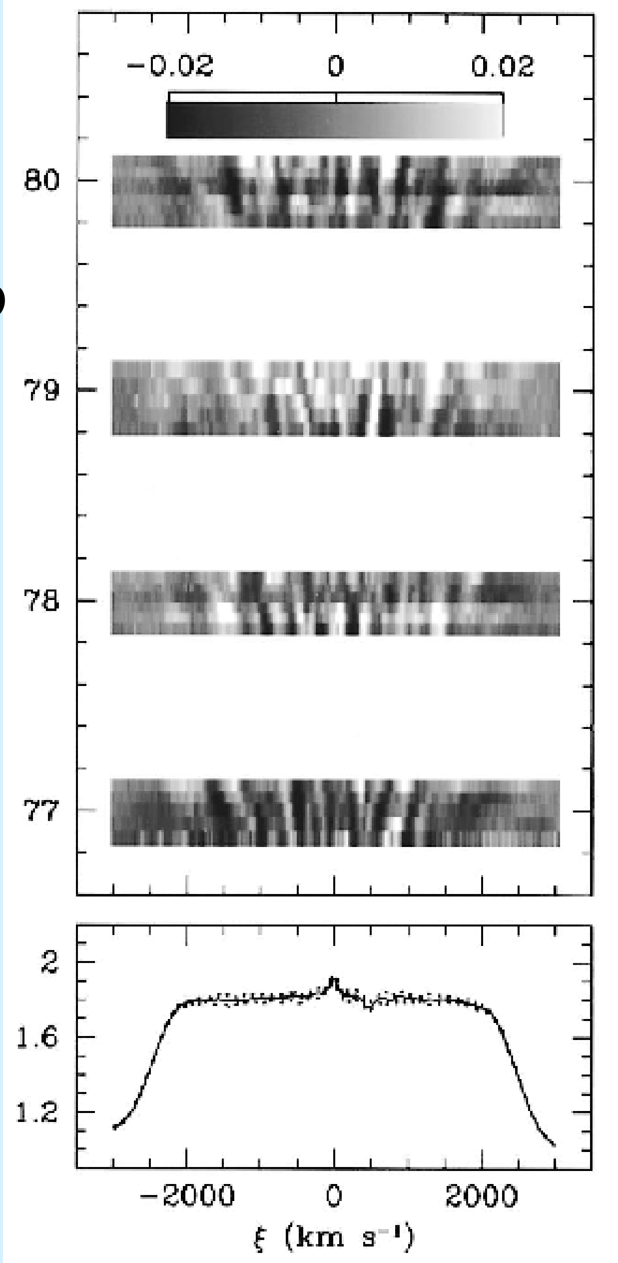


Dessart & Owocki 2005

WR Star Emission Profile Variability

WR 140

Lepine & Moffat 1999



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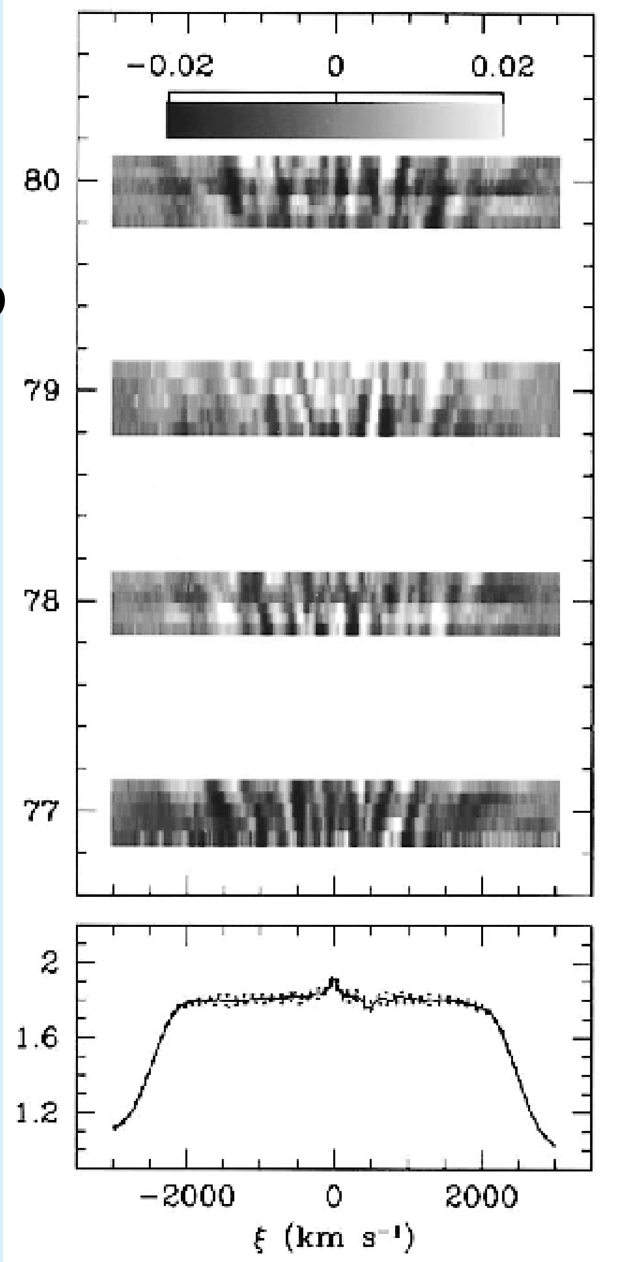
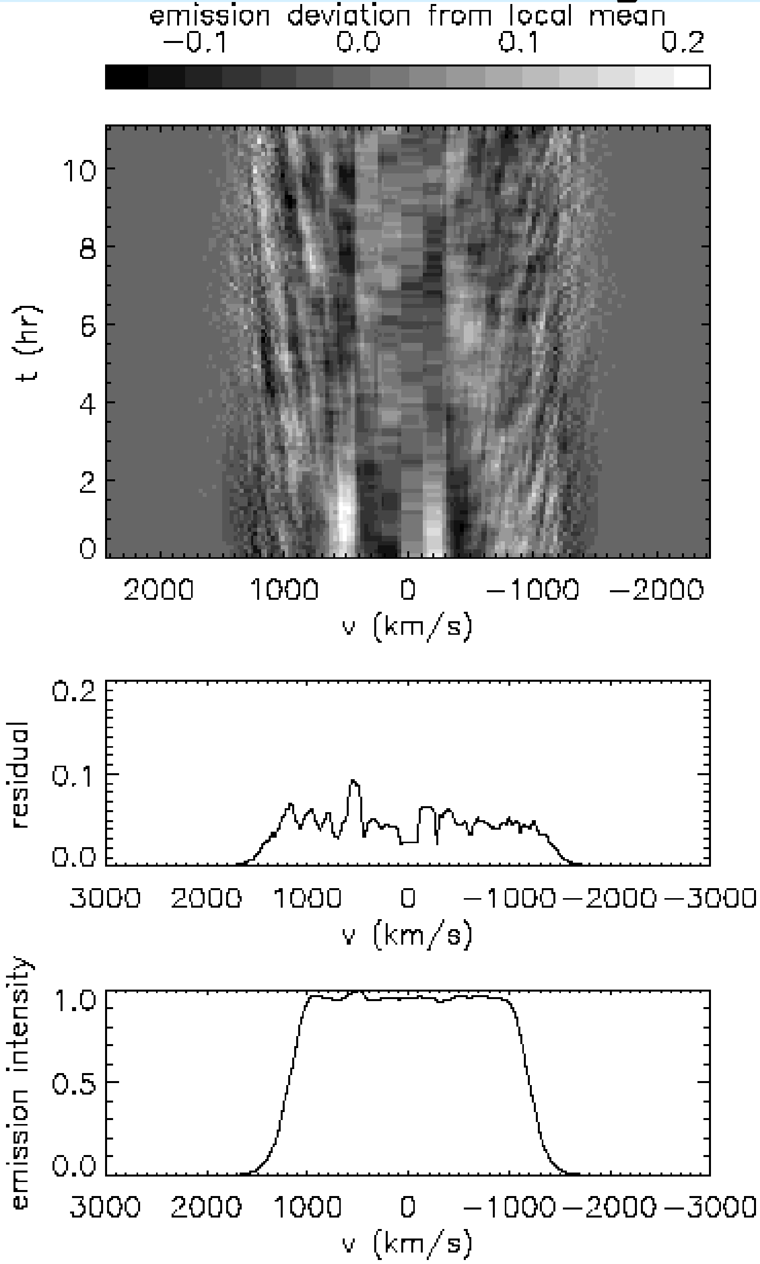


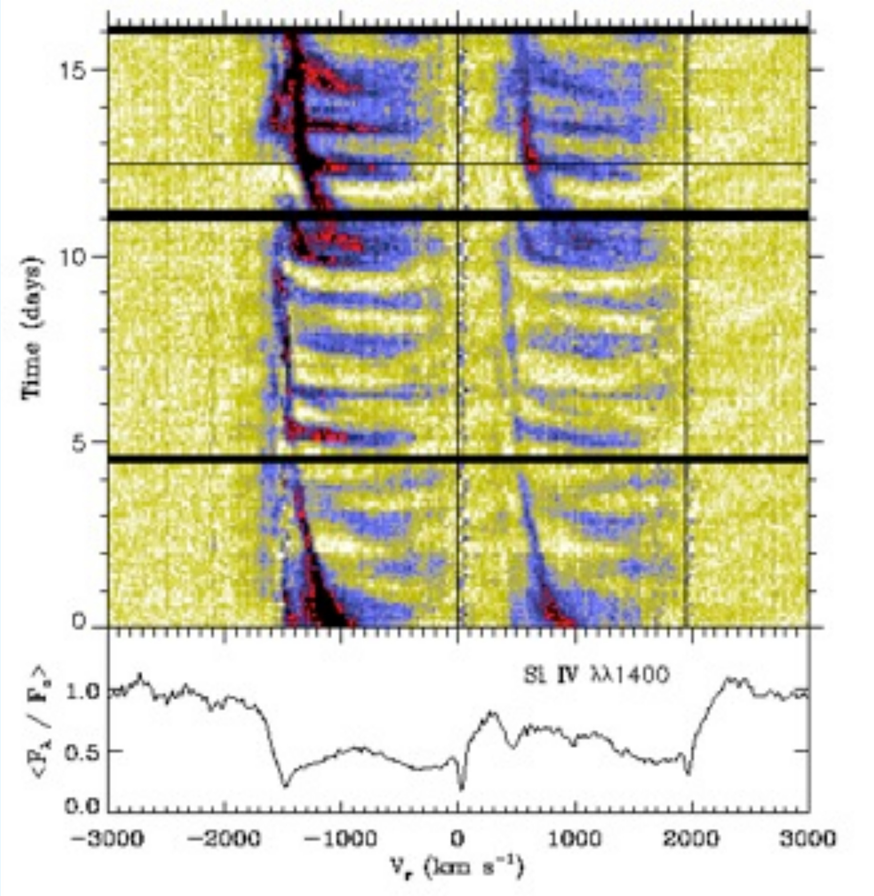
3D "patch" model

Dessart & Owocki 2002

patch size ~3 deg



Discrete Absorption Components: evidence for large-scale wind structure



Monitoring campaigns of P-Cygni lines formed in hot-star winds often show modulation at periods comparable to the stellar rotation period.

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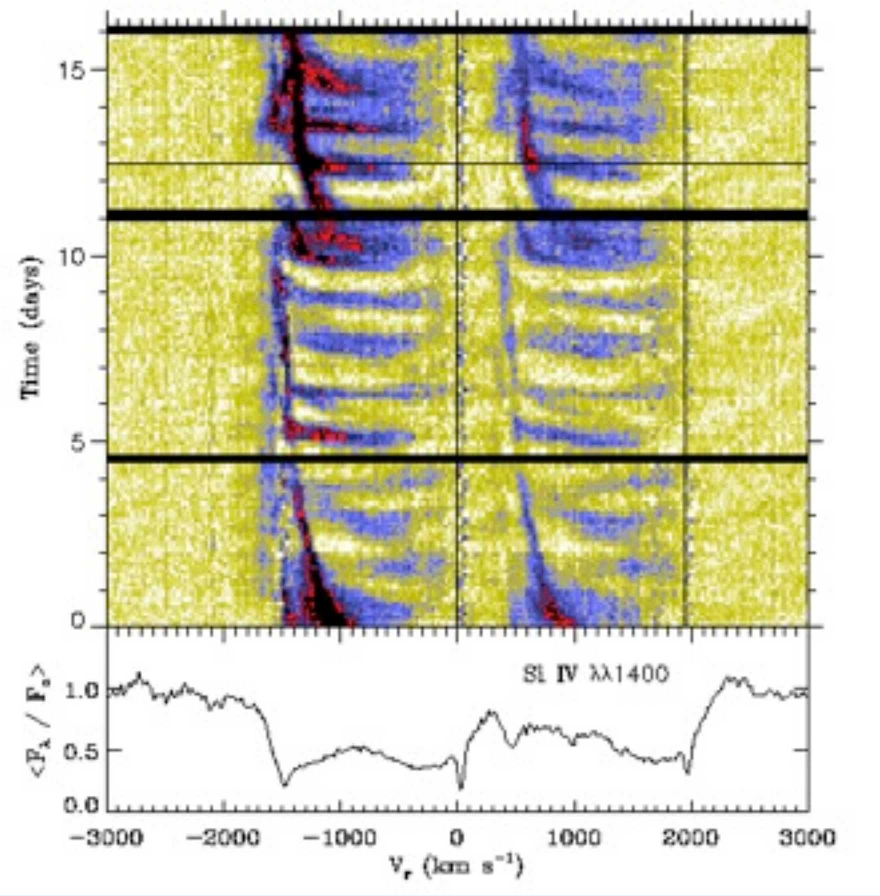
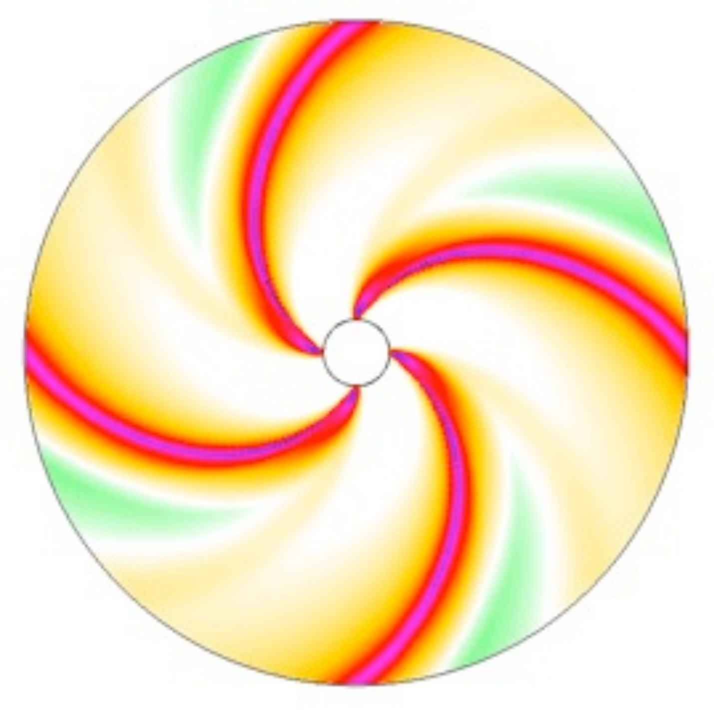


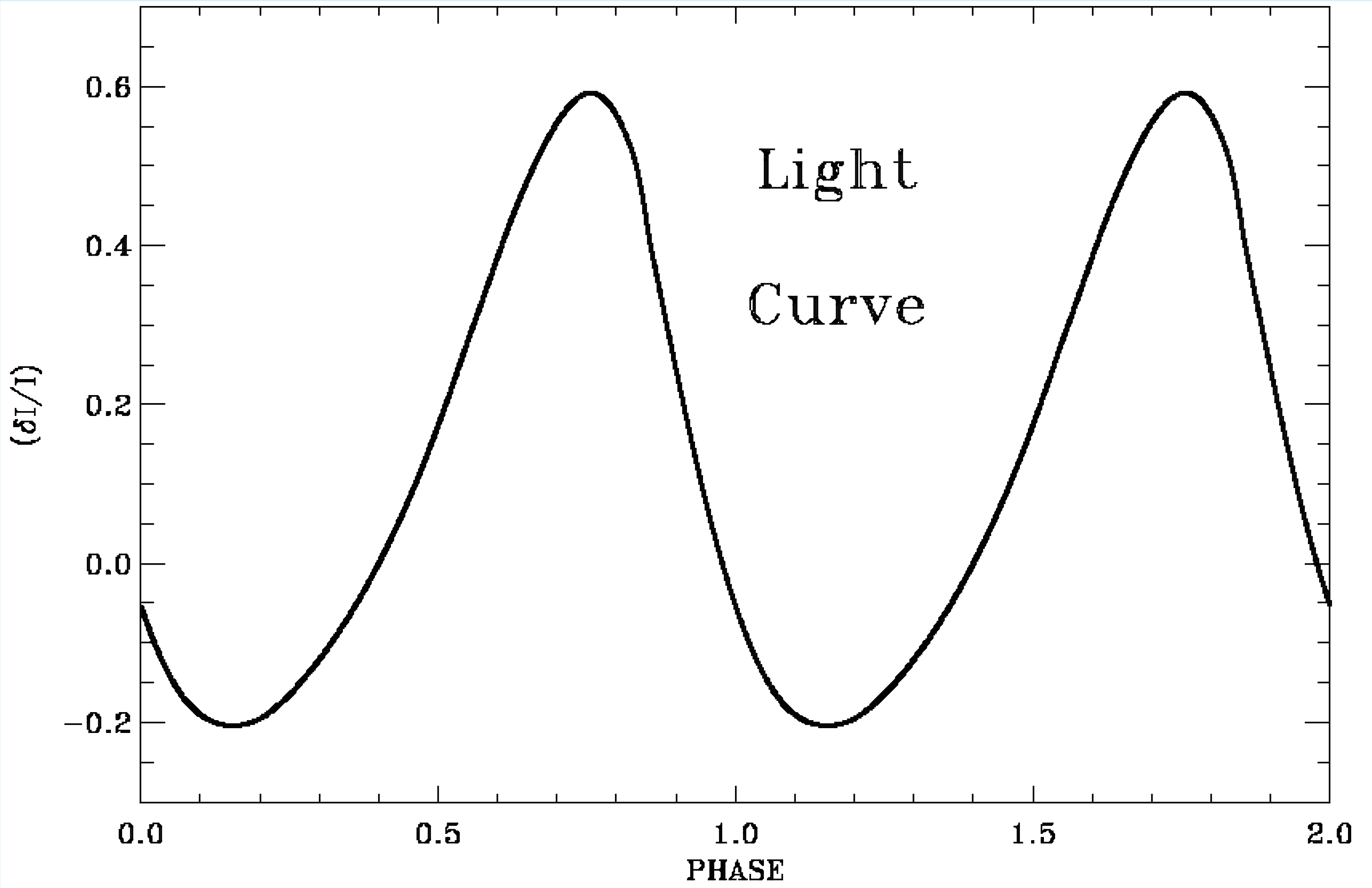


Radiation hydrodynamics simulation of CIRs in a hot-star wind

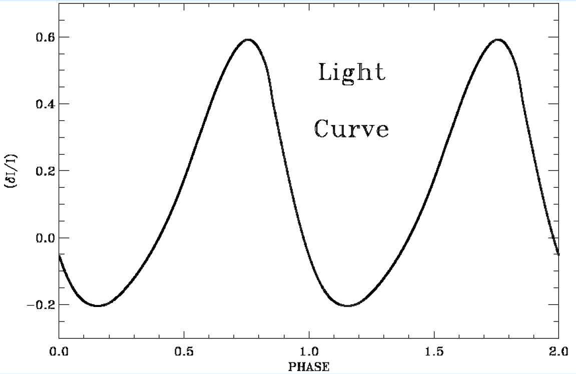
Monitoring campaigns of P-Cygni lines formed in hot-star winds often show modulation at periods comparable to the stellar rotation period.

These may stem from large-scale surface structure that induces spiral wind variation analogous to solar Corotating Interaction Regions.

Radial pulsations in BW Vul

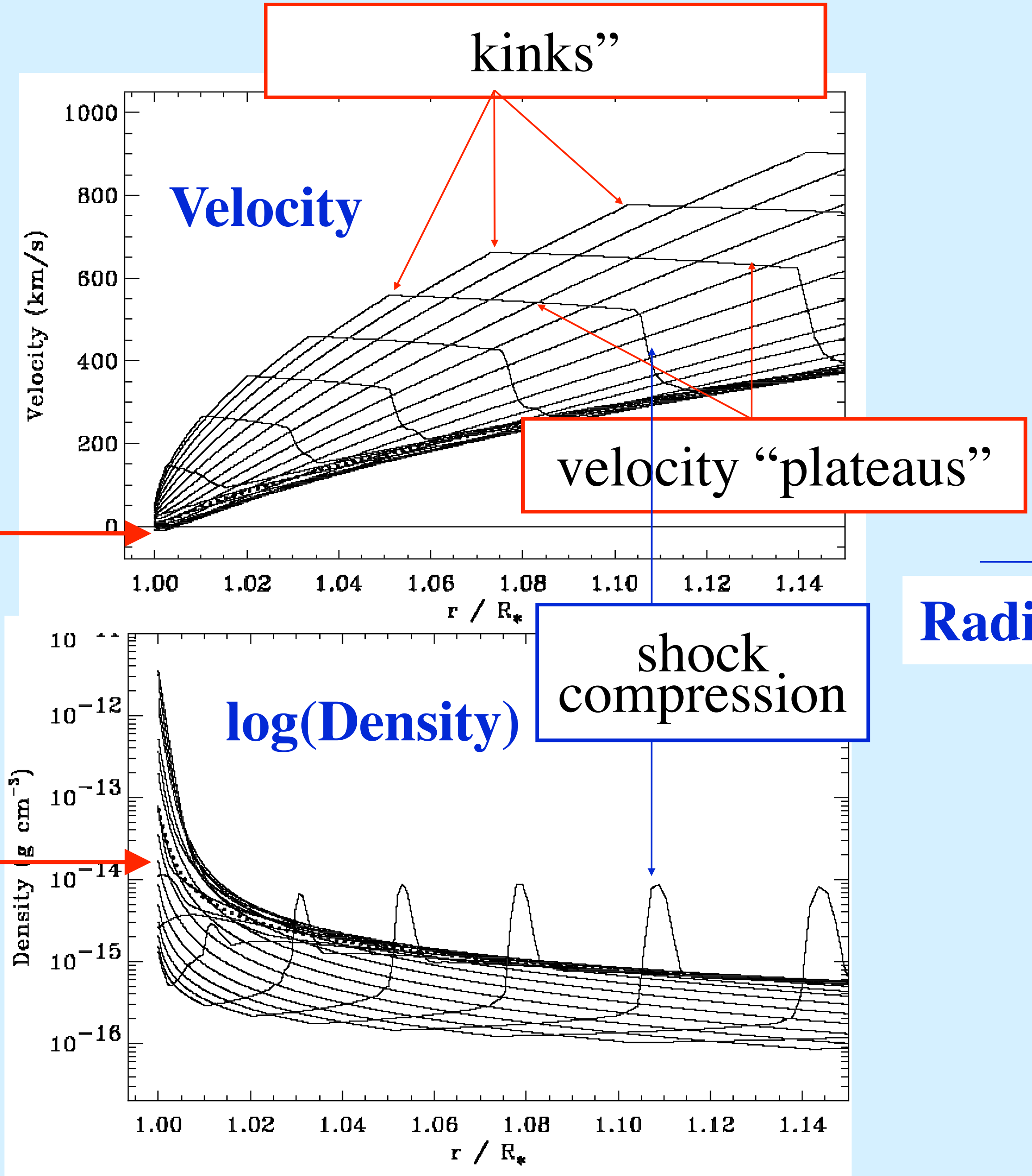


Wind variations from base perturbations in density and brightness



radiative driving modulated by brightness variations

wind base perturbed by $\delta\rho/\rho \sim 50$



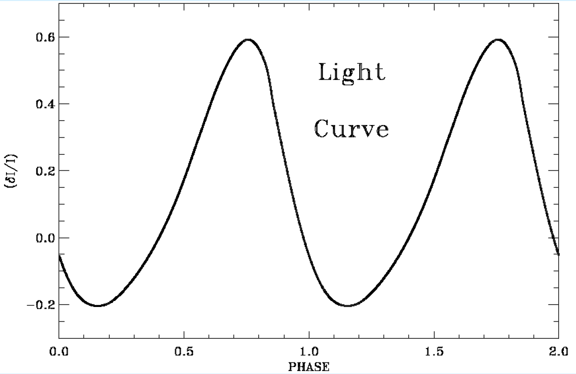
kinks”

velocity “plateaus”

shock compression

Radius

Wind variations from base perturbations in density and brightness



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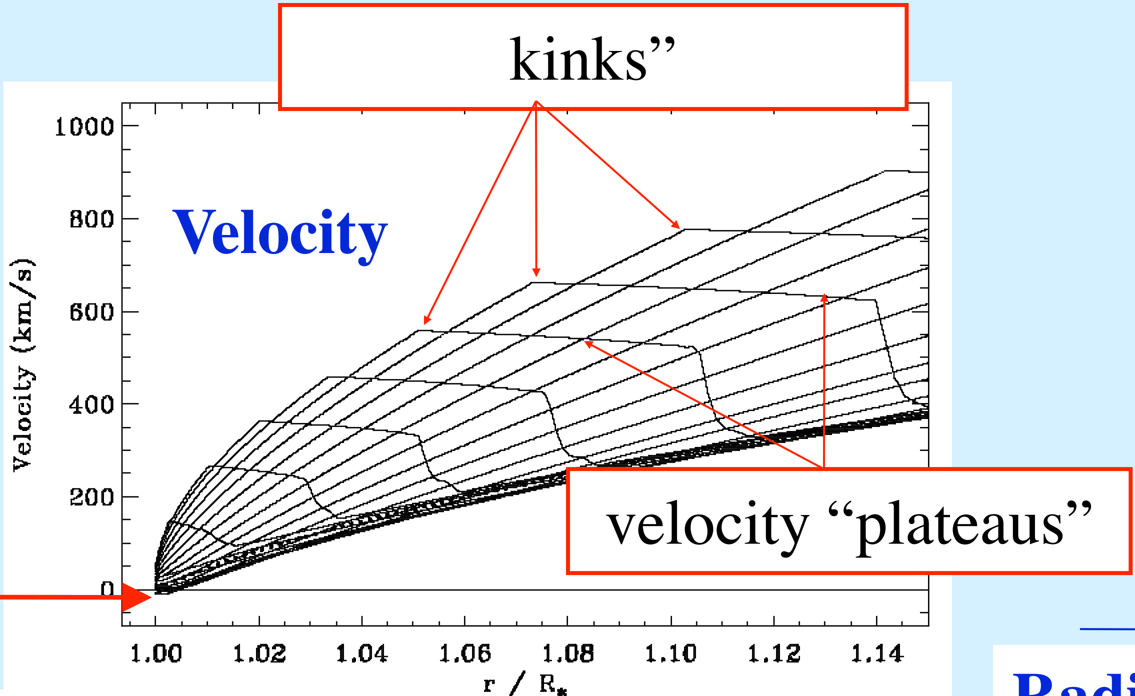

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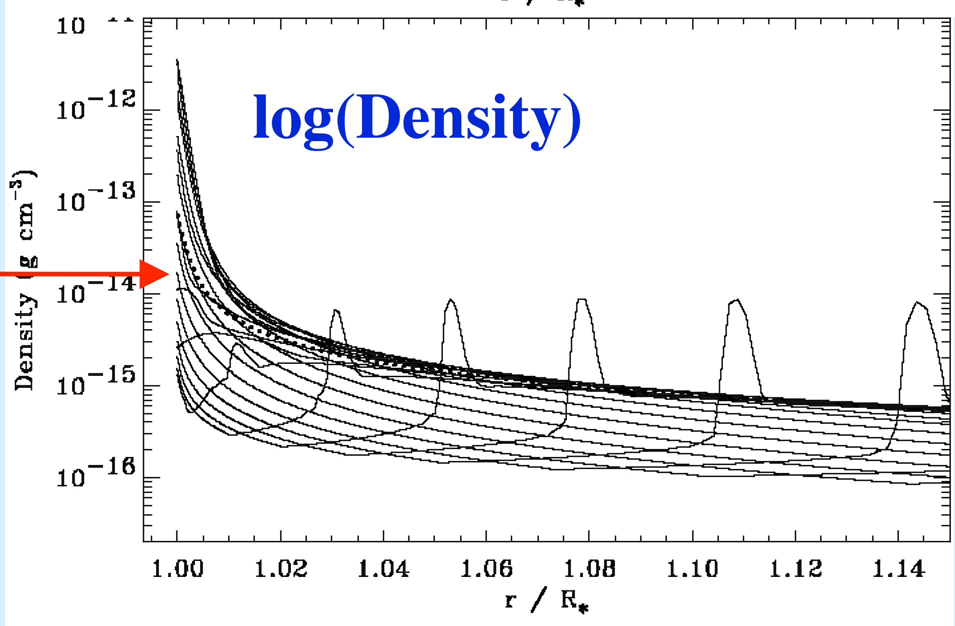
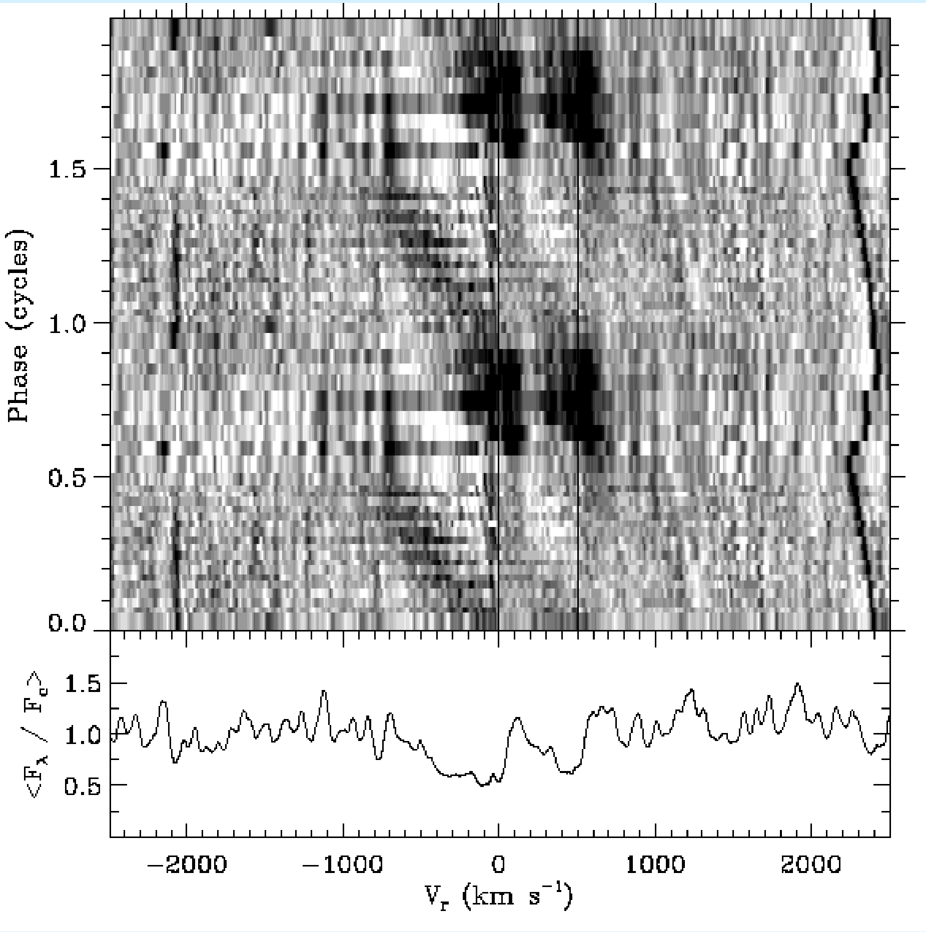


Dynamic spectra

C IV



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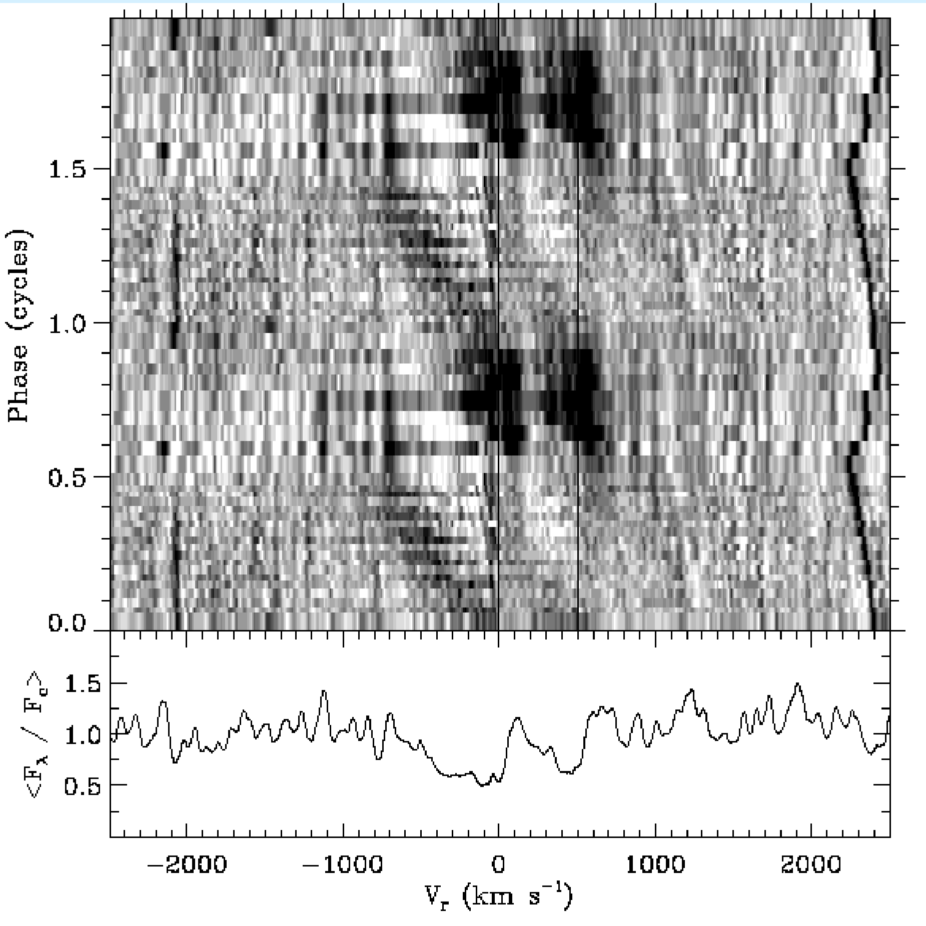
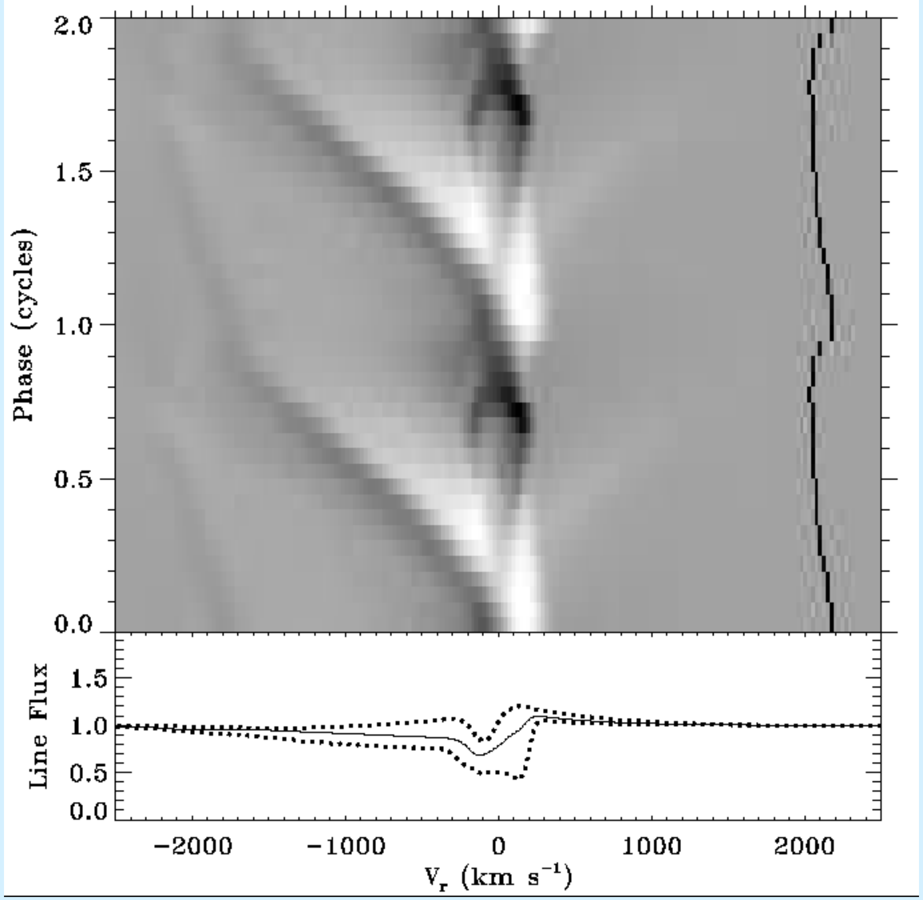


Model line



Massive, Luminous stars:

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


VY CMa


IRC+10420


P Cygni


Pistol Star (Figer et al. 1999)

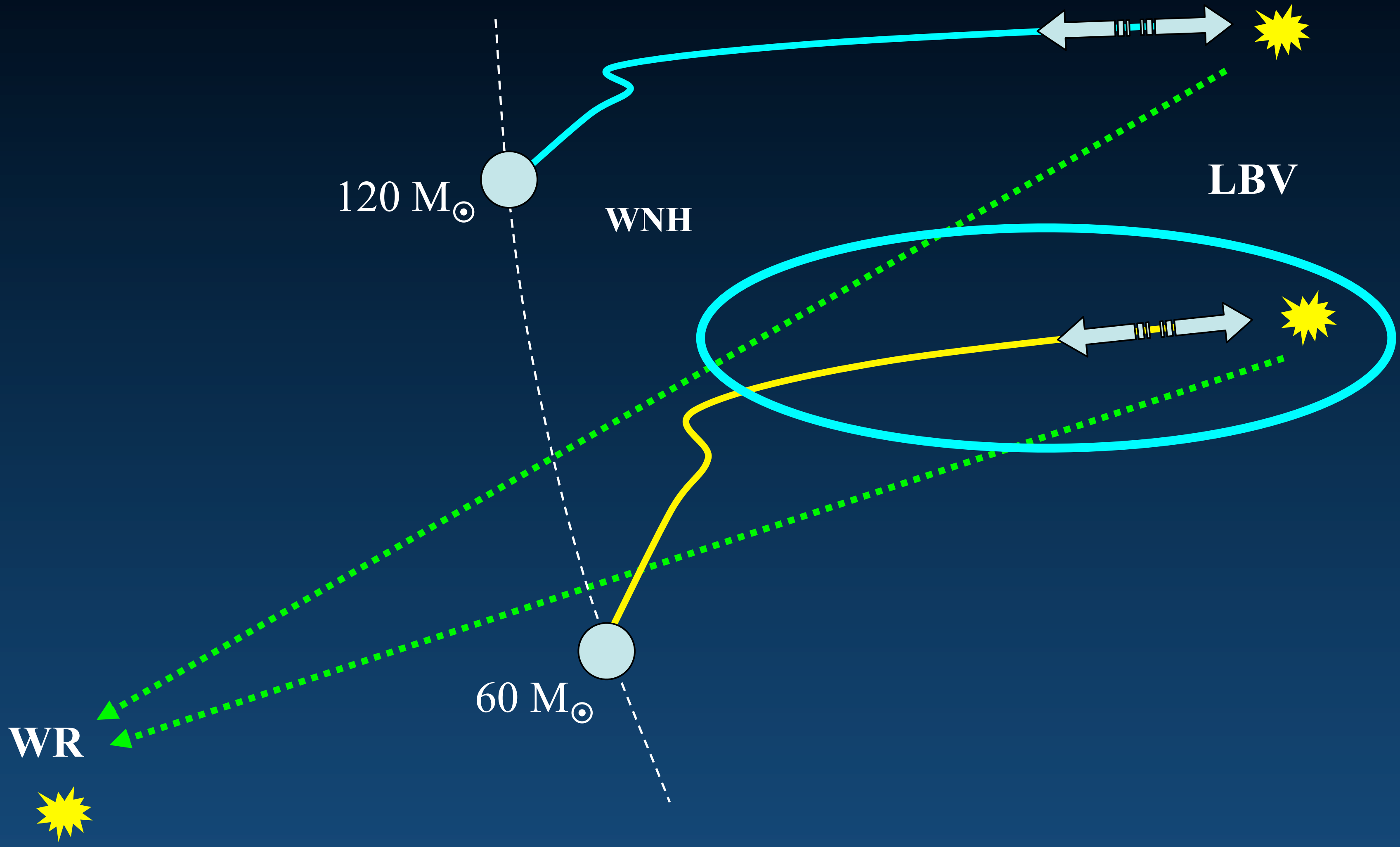

SN1987A
(courtesy P. Challis)


HD 168625
(Smith 2007)

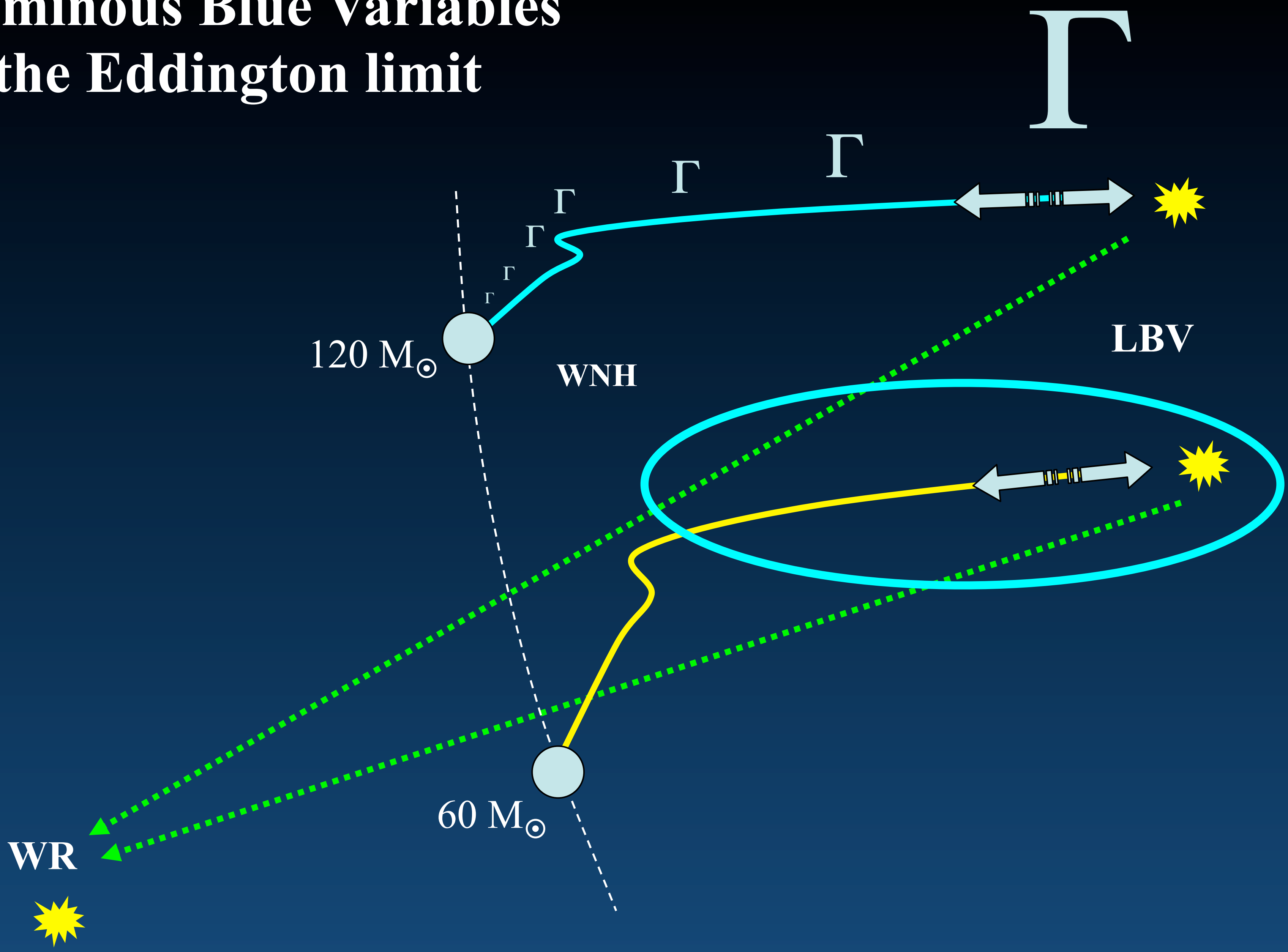

Sher 25
(Brandner et al. 1997)


Eta Car

Luminous Blue Variables & the Eddington limit



Luminous Blue Variables & the Eddington limit



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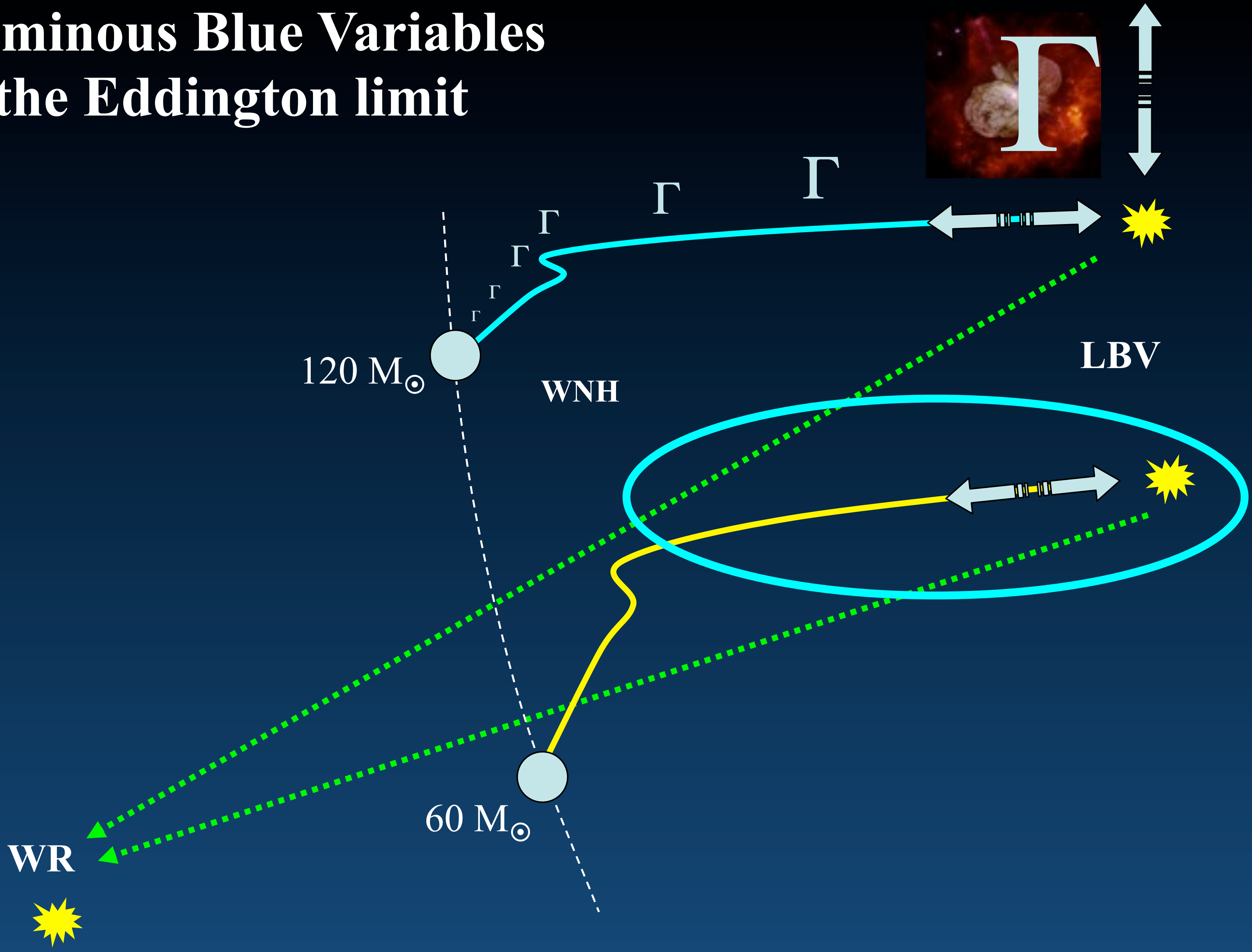
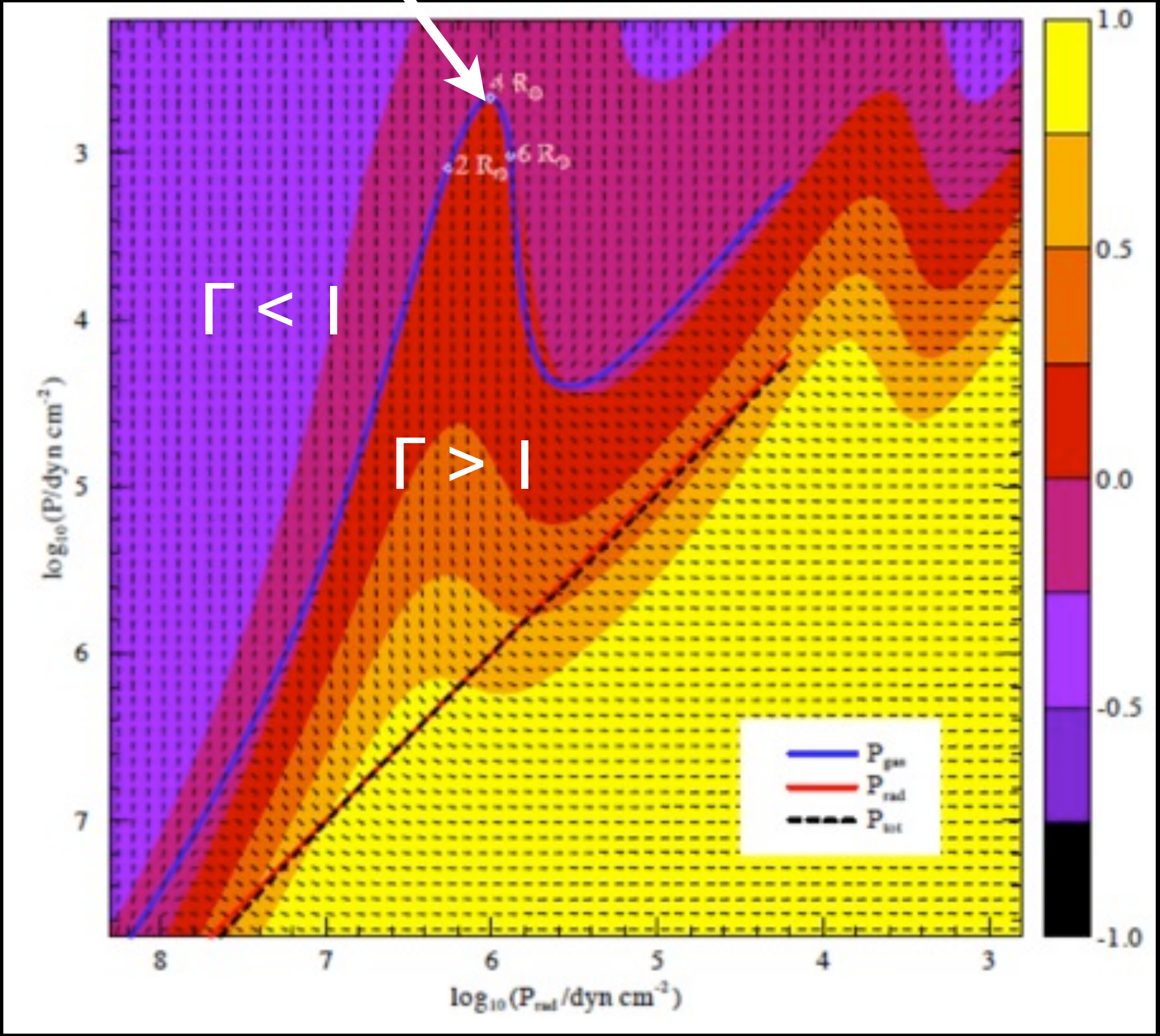


Fe-bump can inflate envelope

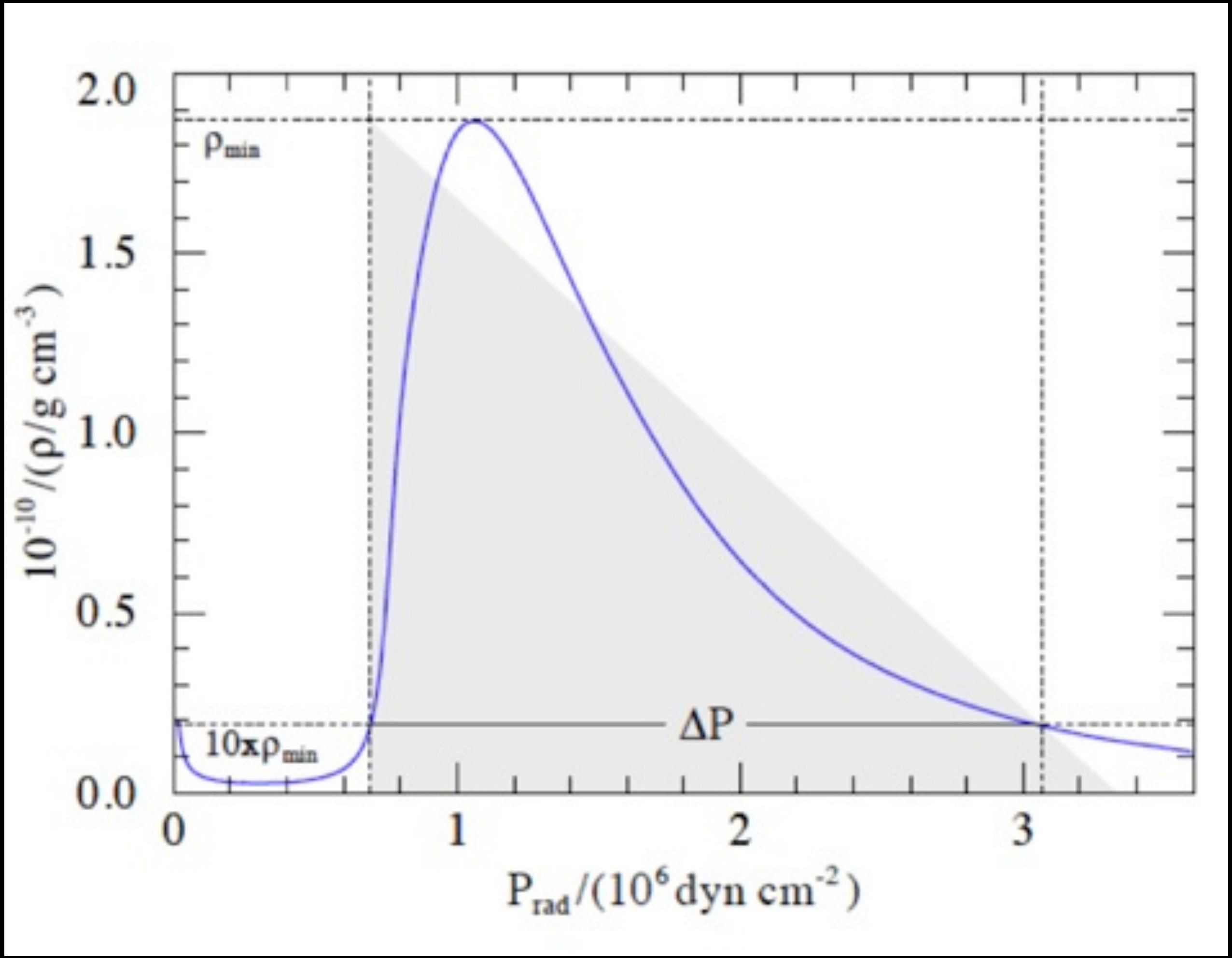


Log Γ

Pgas ↓

← Prad

$R_{out} \longleftarrow R_{in}$



$$1/\rho_{\min}(\Gamma, Z)$$

$$\boxed{\frac{R_{out}}{R_{in}} = \frac{1}{1-W}}$$

$$W \simeq \frac{R_{in}}{GM}\frac{\Delta P}{2\rho_{\min}}$$

Envelope Inflation-Dissipation Cycle

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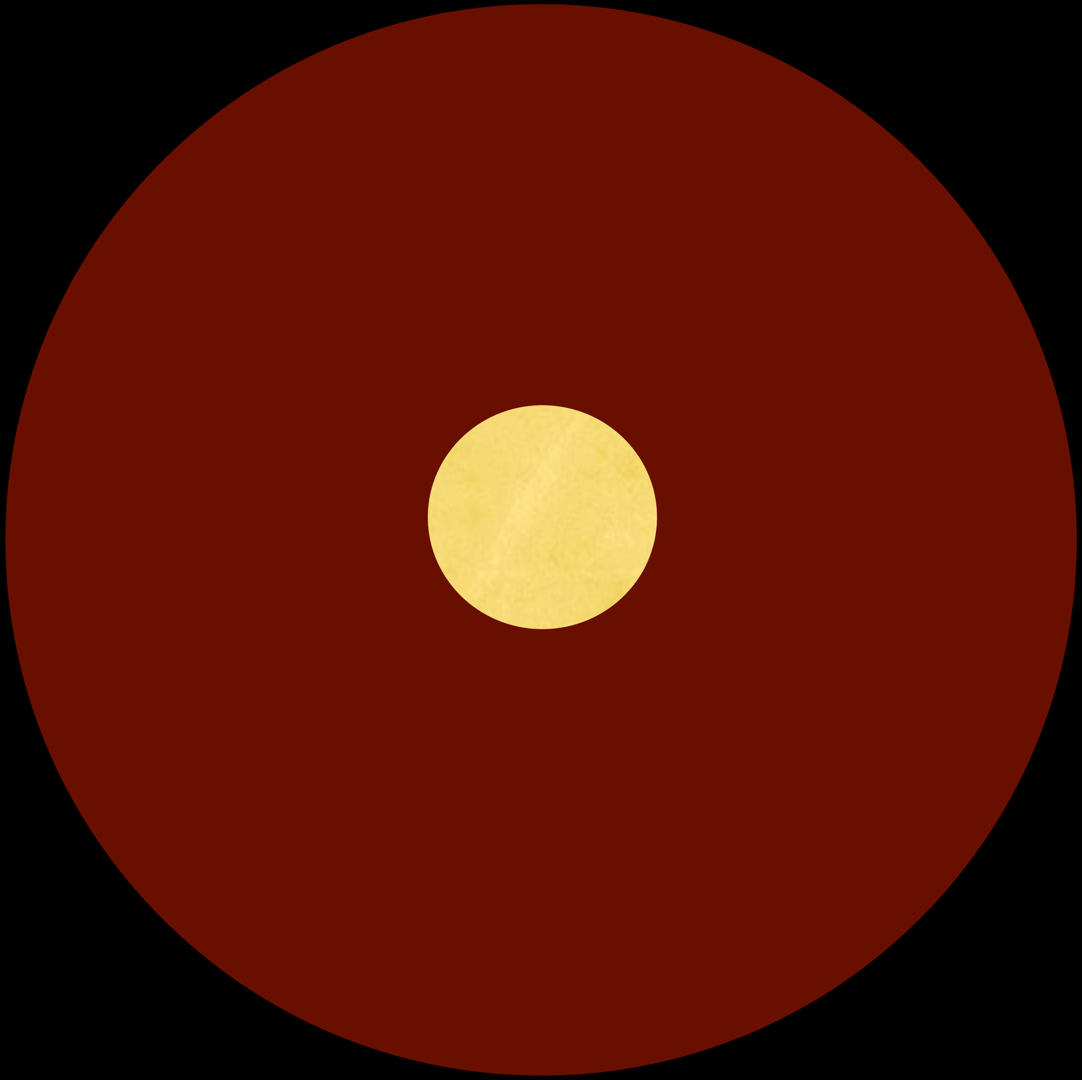
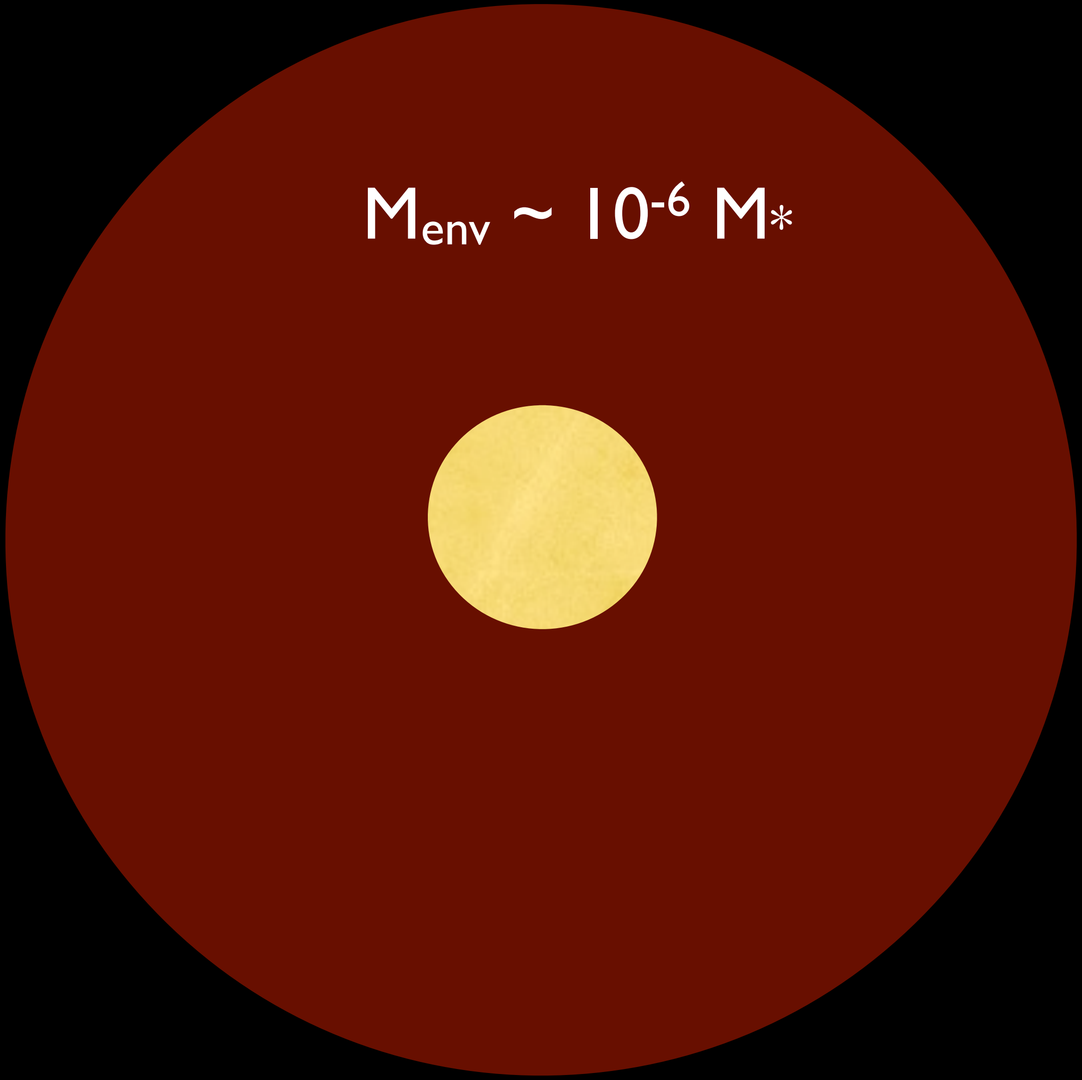
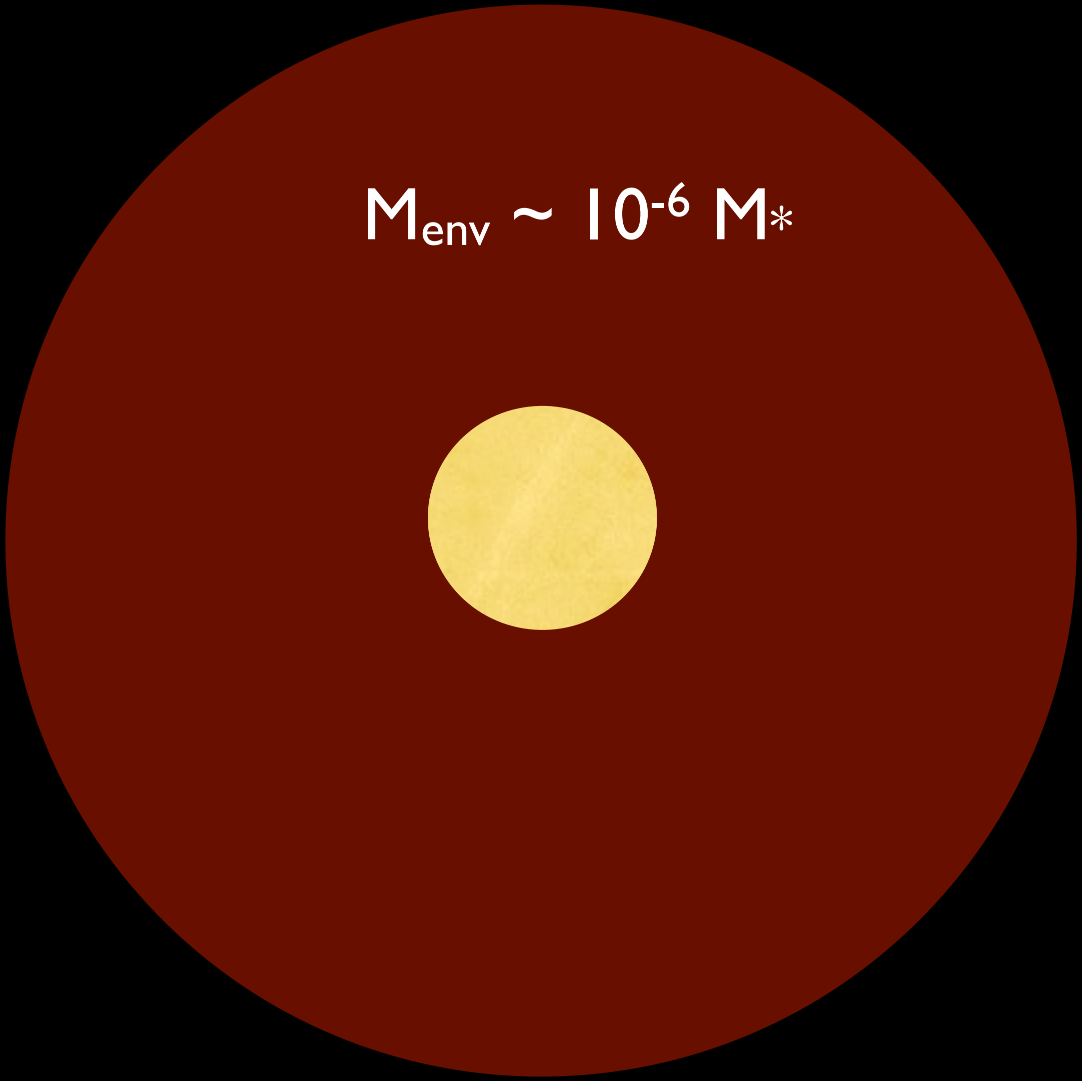


Envelope Inflation-Dissipation Cycle



$M_{env} \sim 10^{-6} M_*$

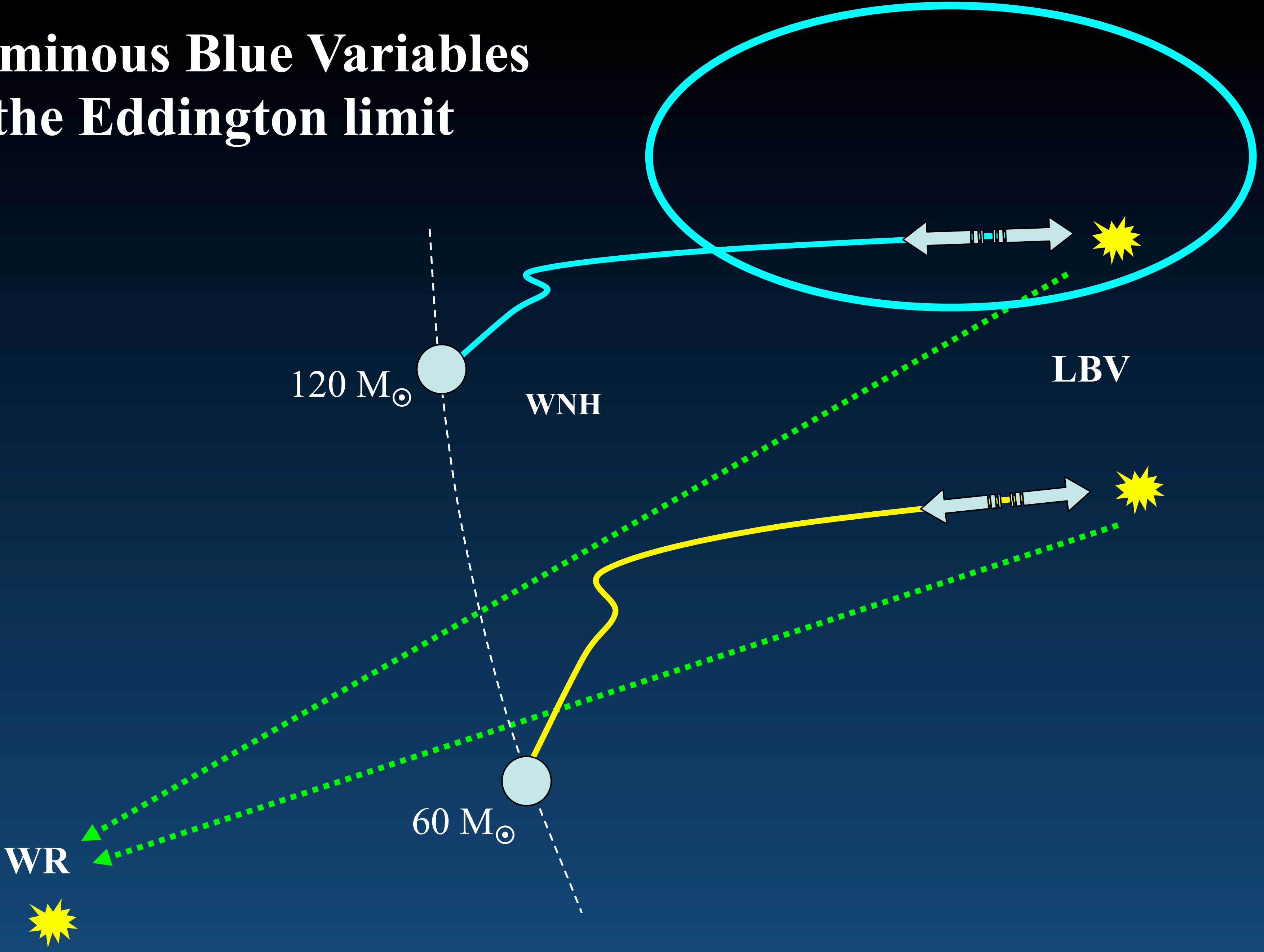
Envelope Inflation-Dissipation Cycle



$M_{env} \sim 10^{-6}\ M_*$

$$T \downarrow \Rightarrow \kappa \uparrow \Rightarrow \dot{M} \uparrow$$

Luminous Blue Variables & the Eddington limit



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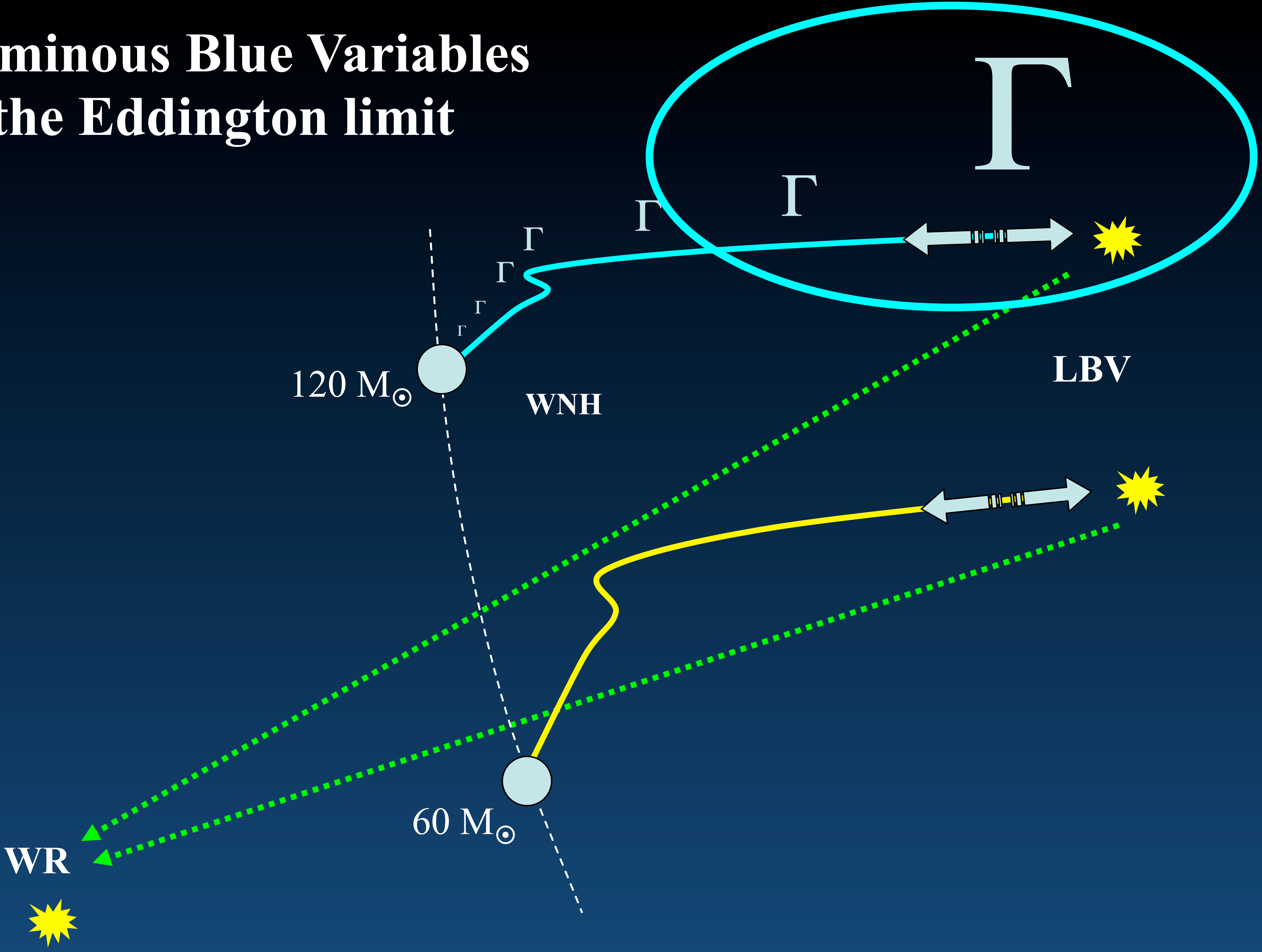
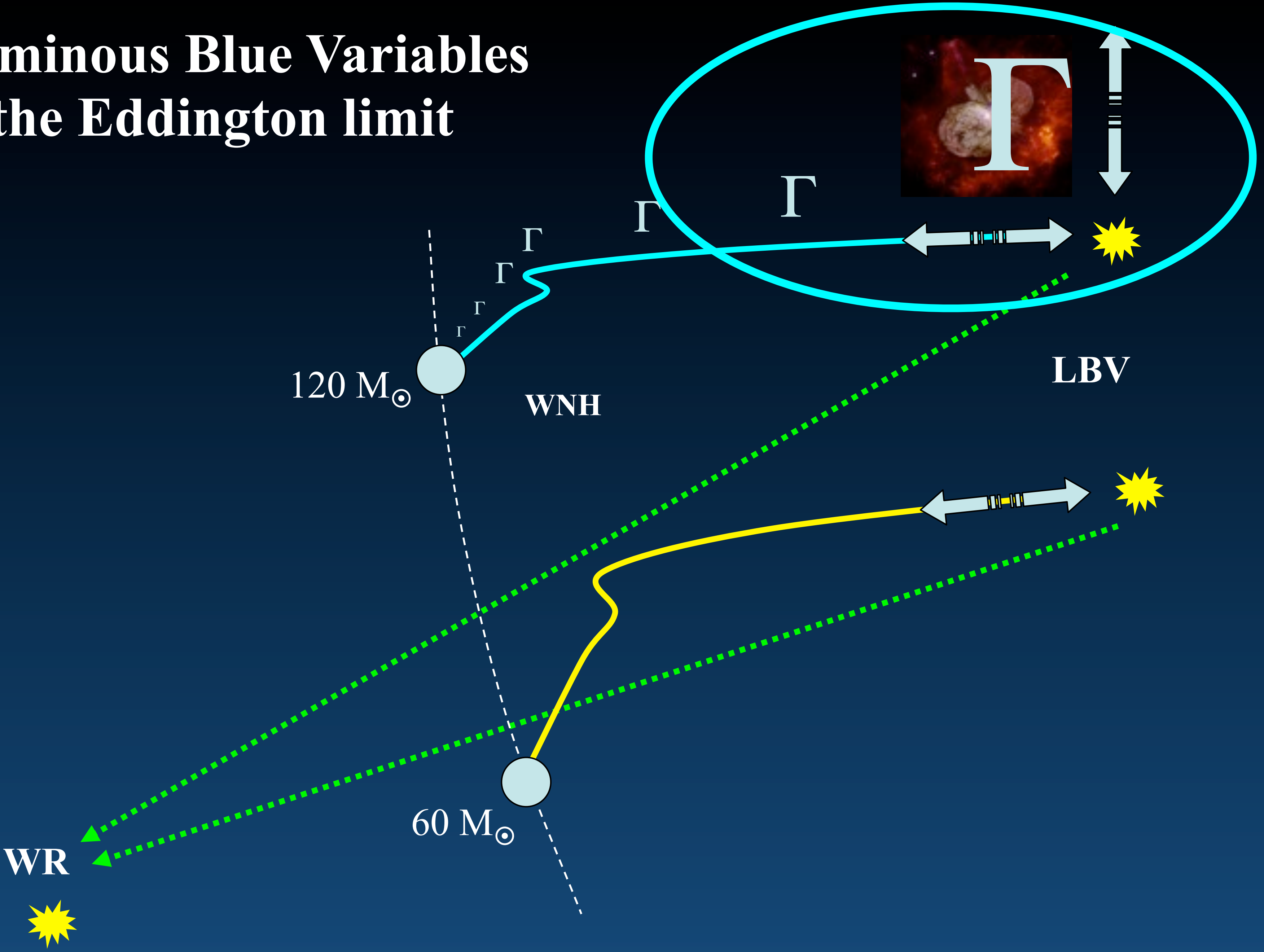
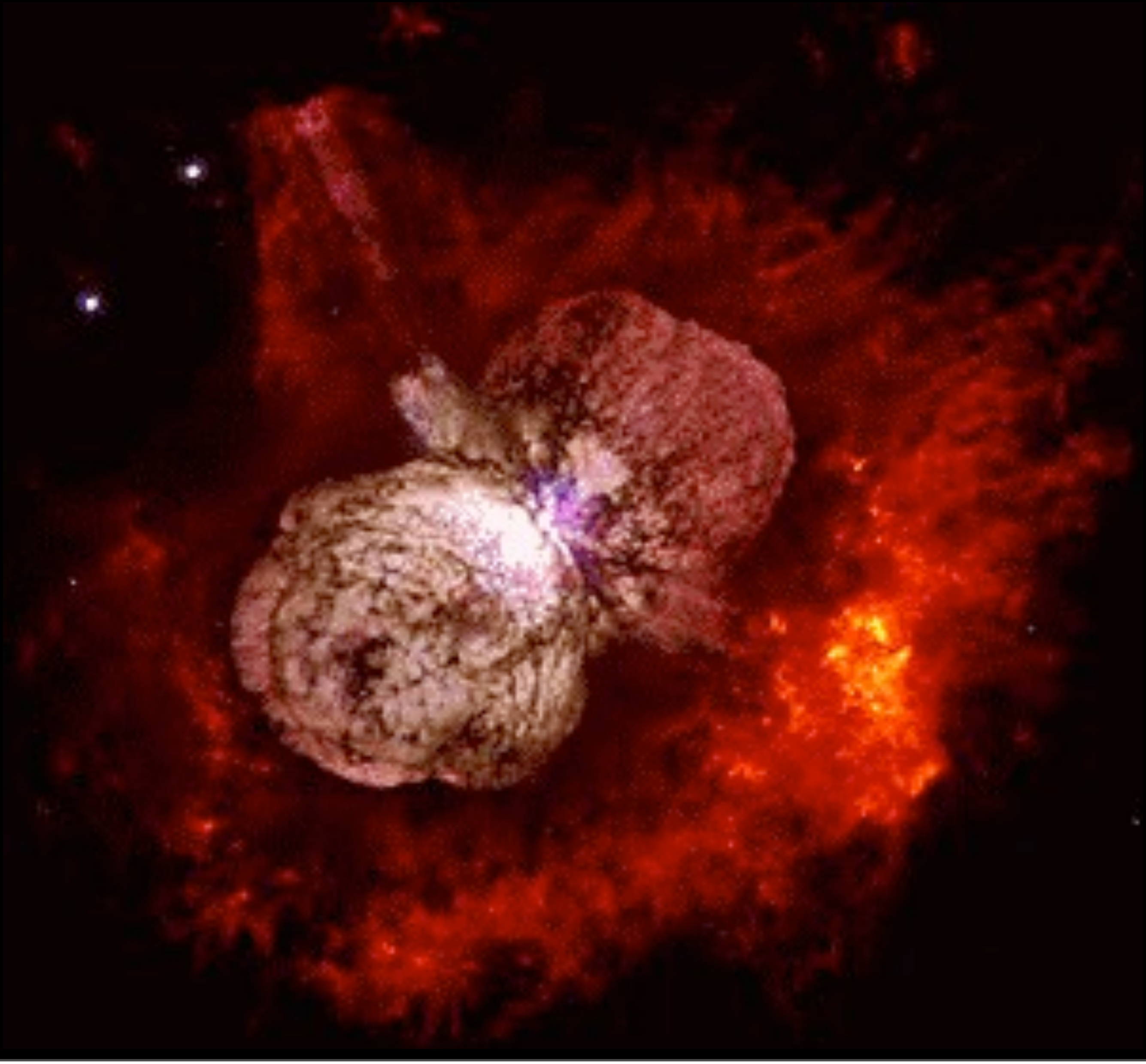


Luminous Blue Variables & the Eddington limit



Eta Carinae



Eta Car's Extreme Properties

Present day:

$$L_{rad} \approx 5 \times 10^6 L_\odot$$

$$\approx L_{\rm Edd}$$

$$\dot{M} \approx 10^{-3} M_\odot/{\rm yr}$$

$$V_\infty \approx 600\,{\rm km/s}$$

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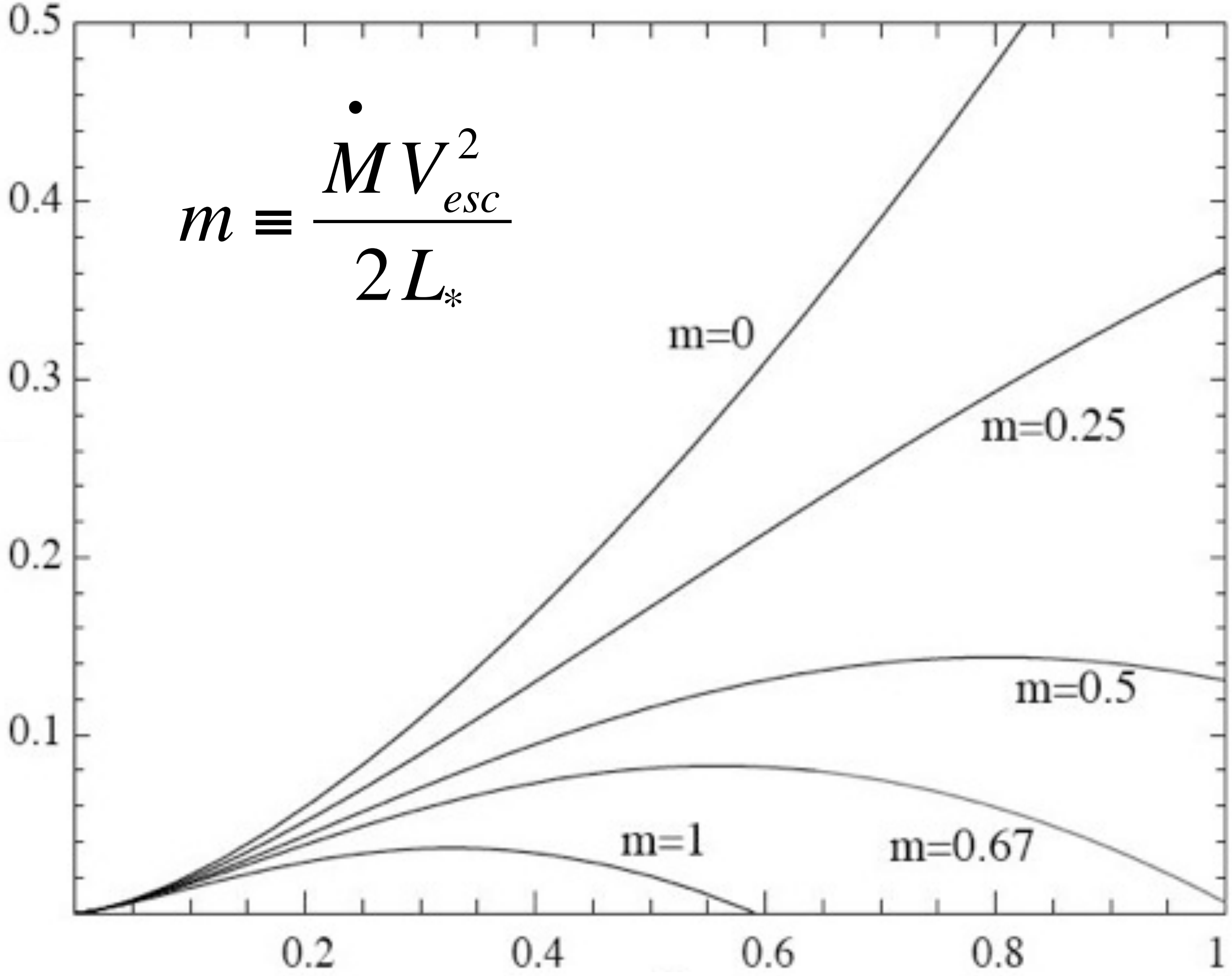
$$\approx L_{kin} = \dot{M} v_\infty^2/2$$

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

Stagnation of photon-tired outflow

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

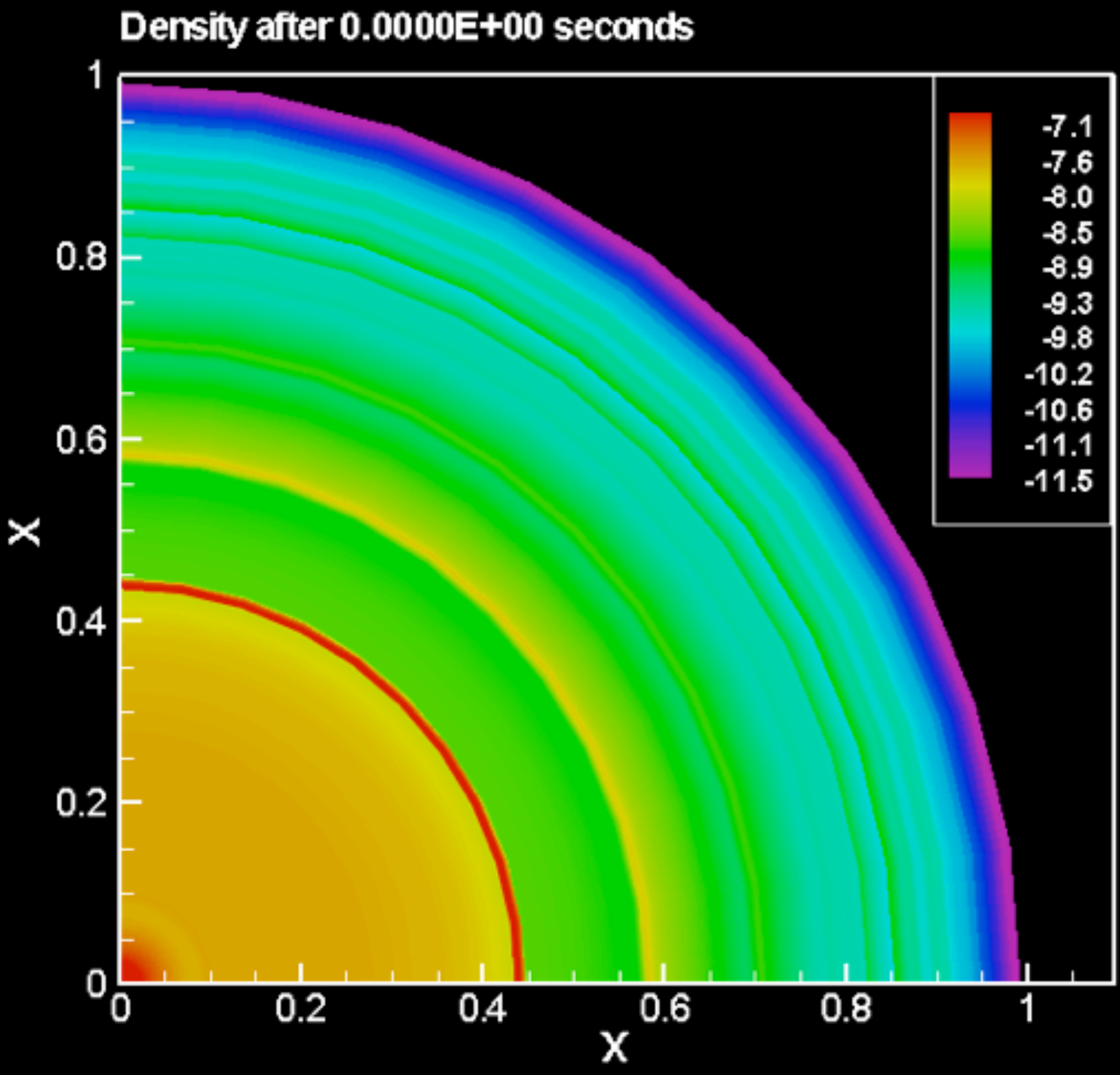
$$L(r) = L_* - \dot{M}\left[\frac{V^2}{2} + \frac{GM}{R} - \frac{GM}{r}\right]$$



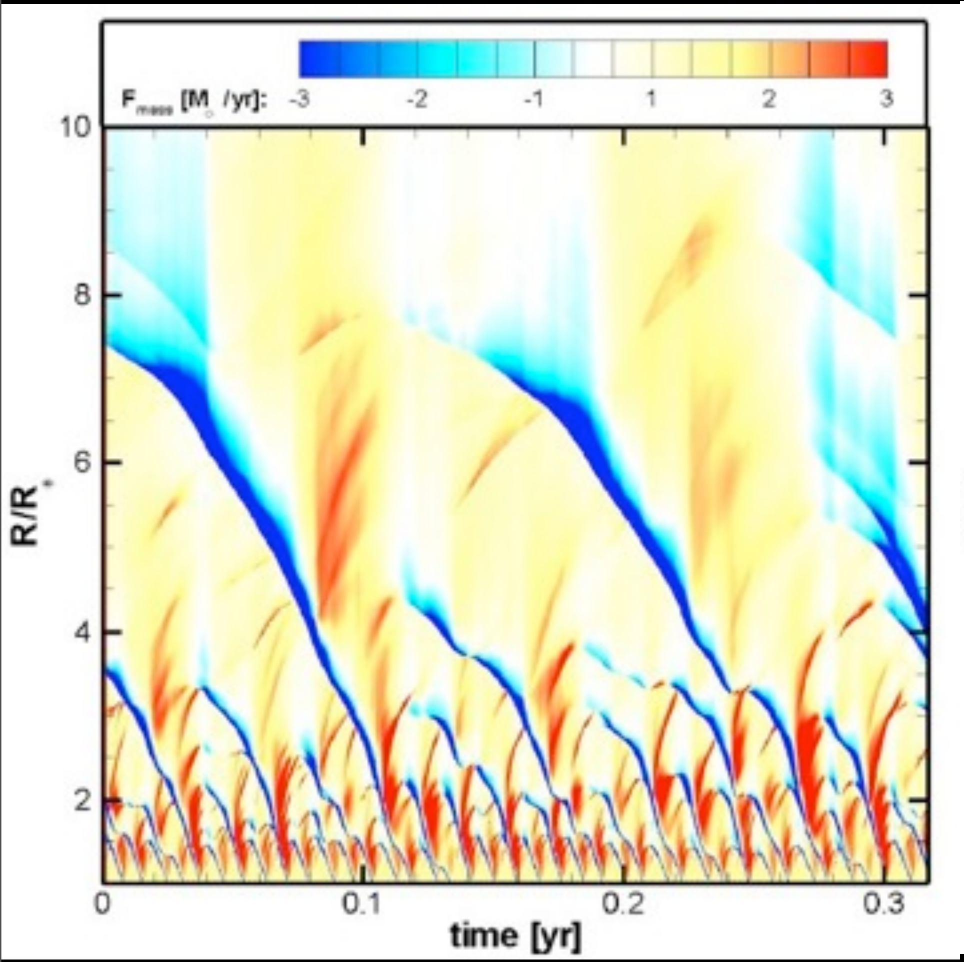
$$m \equiv \frac{\dot{M} V_{esc}^2}{2 L_*}$$

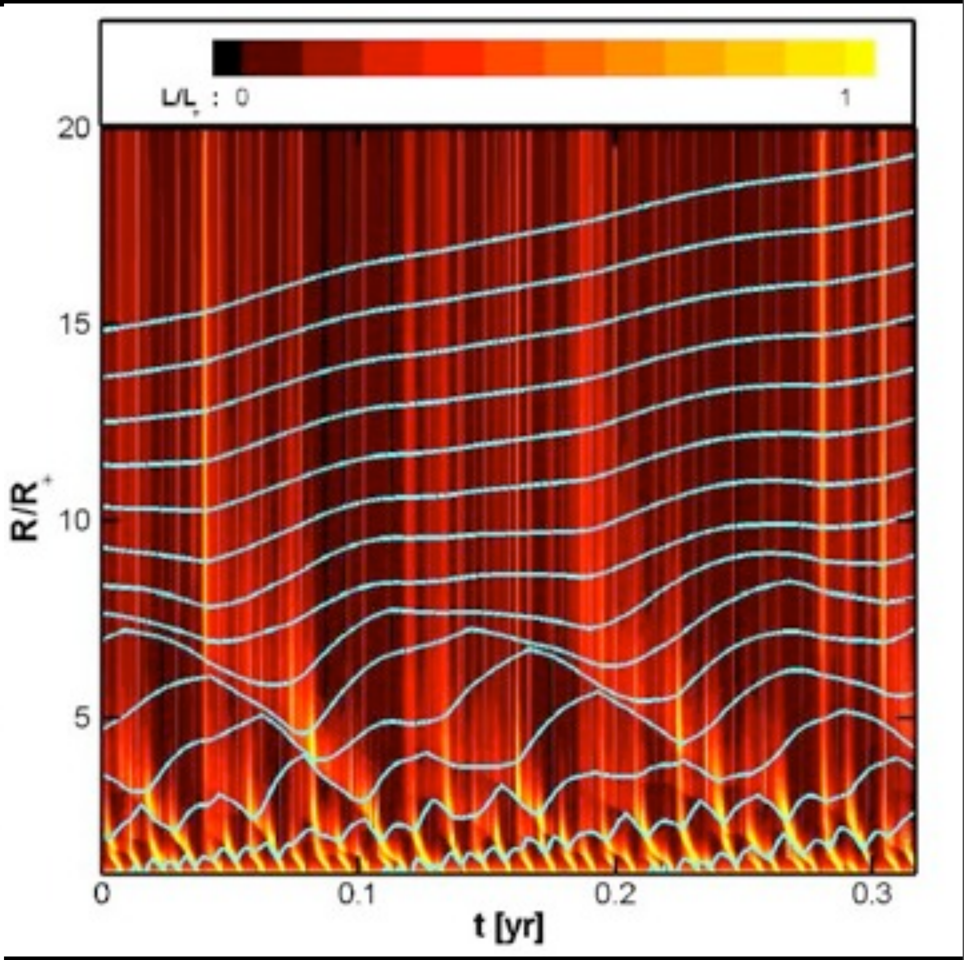
$$\frac{V^2}{V_{esc}^2}$$

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


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

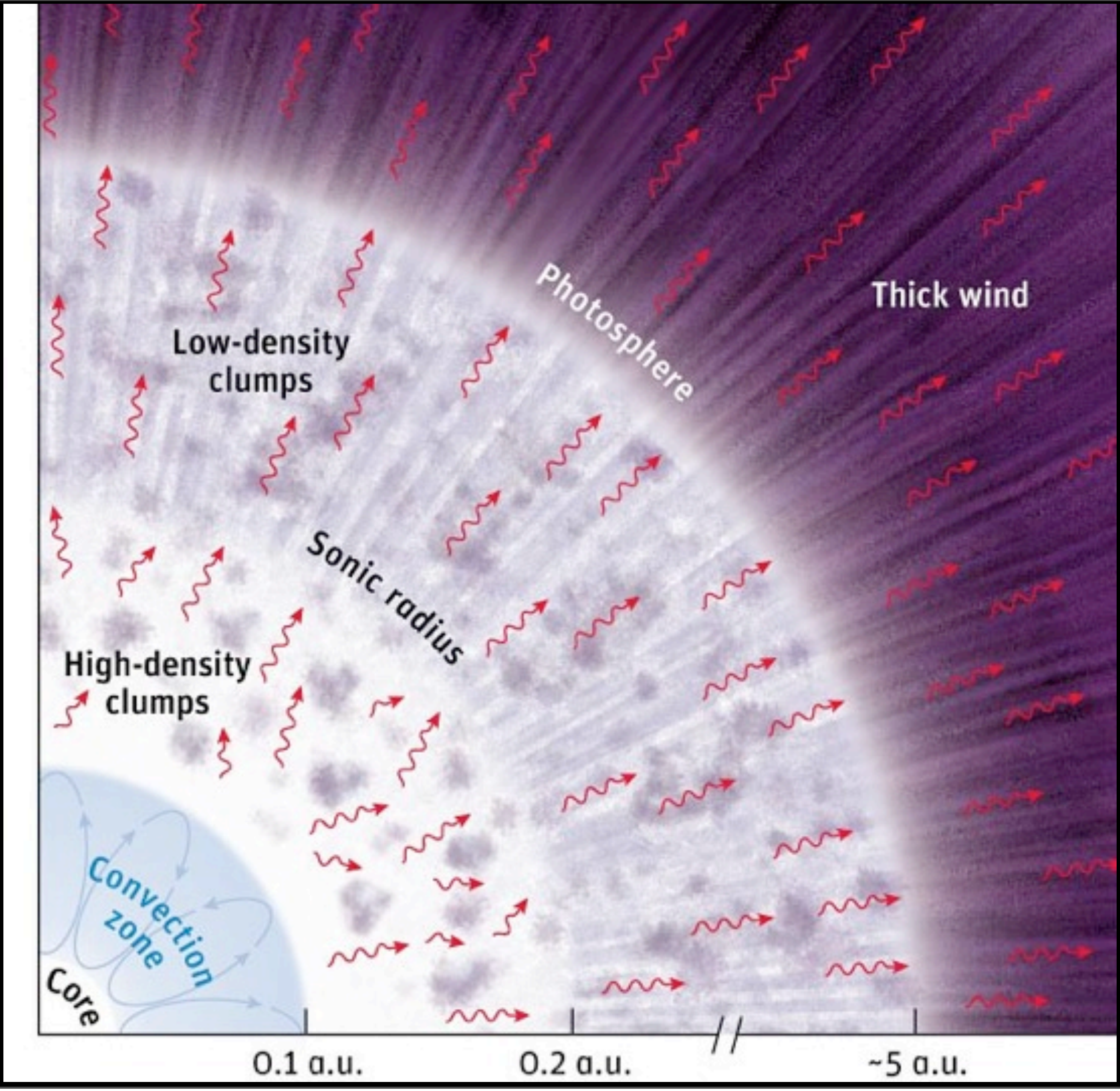
Photon Tiring & Flow Stagnation





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.

Summary

- Massive star winds driven by line-scattering
- Strong Line-deshadowing instability
  - small-scale clumping & embedded soft X-rays
- Large-scale structure from NRP or bright spots
- Rapid rotation => faster denser polar wind
- Eddington limit => LBV & Eruptions

- Wind magnetic channeling + rotation
  - centrifugally supported magnetospheres
- Magnetic spindown over 1 Myr