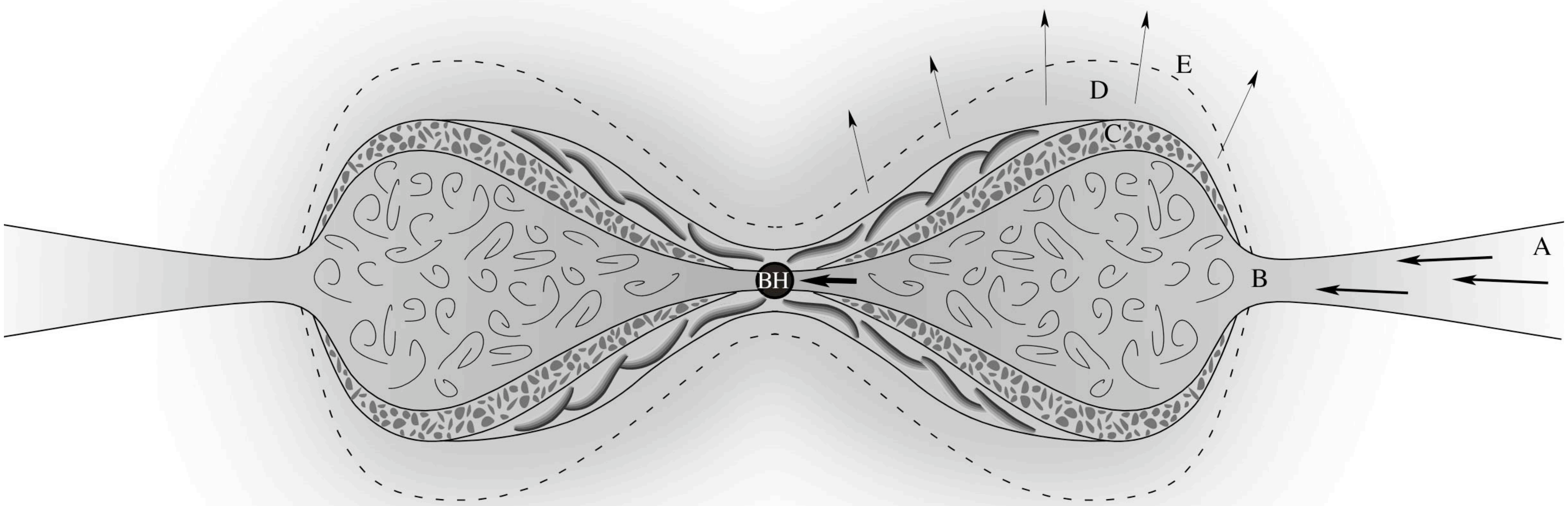
Super-Eddington **Slim** Accretion disks
(and other objects helping us to understand what these accretion disks look like!)



Nir Shaviv
Hebrew University of Jerusalem

Slim Accretion Disk workshop 2018

Synopsis

- Super-Eddington objects in nature
- How can it be?
- What do super-Eddington systems look like?
- Implications to Accretion Systems

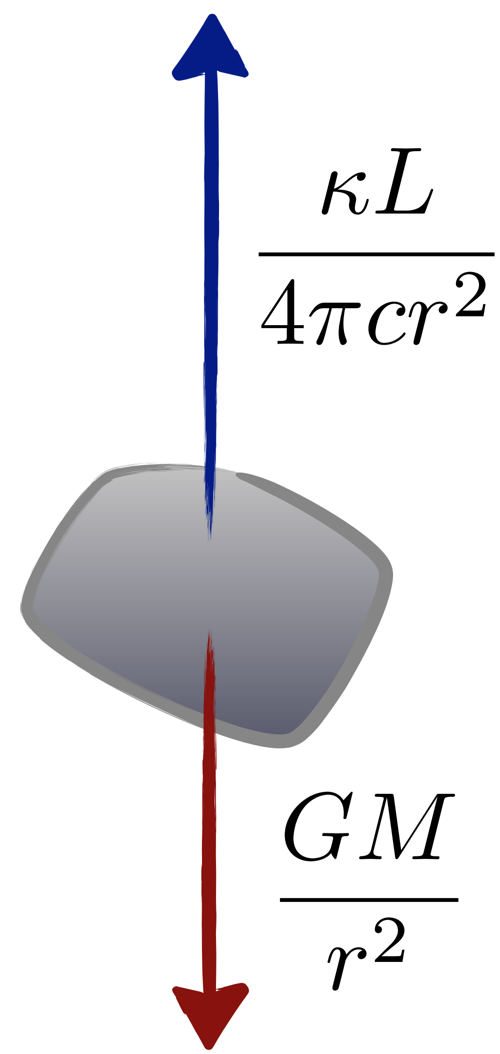
The Eddington Limit

- The Eddington luminosity is the luminosity for which the **radiative force** balances the **gravitational pull**

$$L_{edd} = \frac{4\pi G M c}{\kappa}$$

- Note: For accretion disks effective area is larger, giving higher Ledd:

$$L_{Edd,acc} \approx \left(1 + \ln\left(\frac{R_{out}}{R_{in}}\right)\right) L_{Edd,Sph}$$

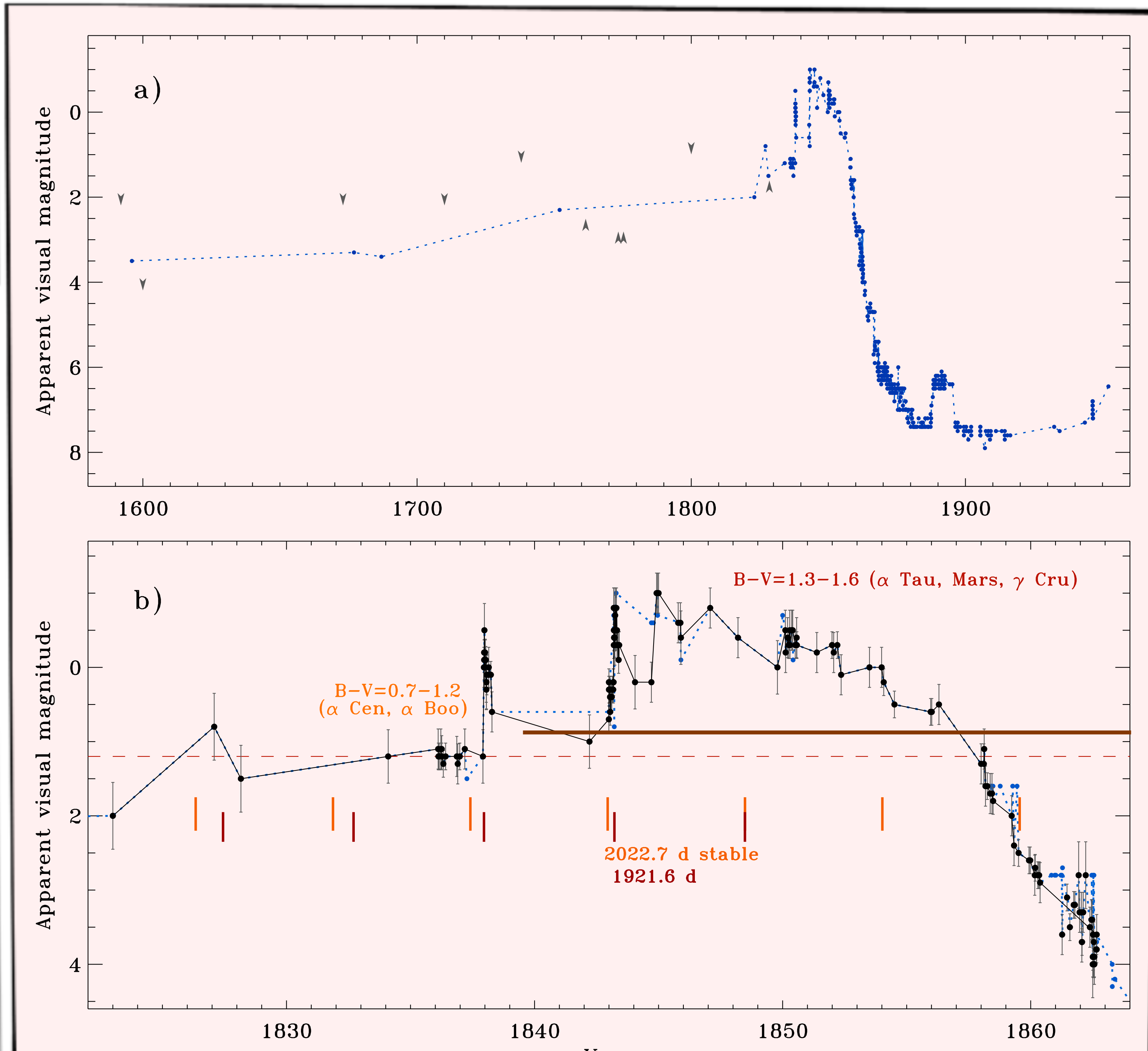


Milne

Why spherical objects first?

- Accretion disks are super-Interesting but more complicated than spherical objects
- We therefore study spherical objects first - Learn how super-Eddington systems behave
- Then apply to Accretion disks

η-Carinae - An LBV

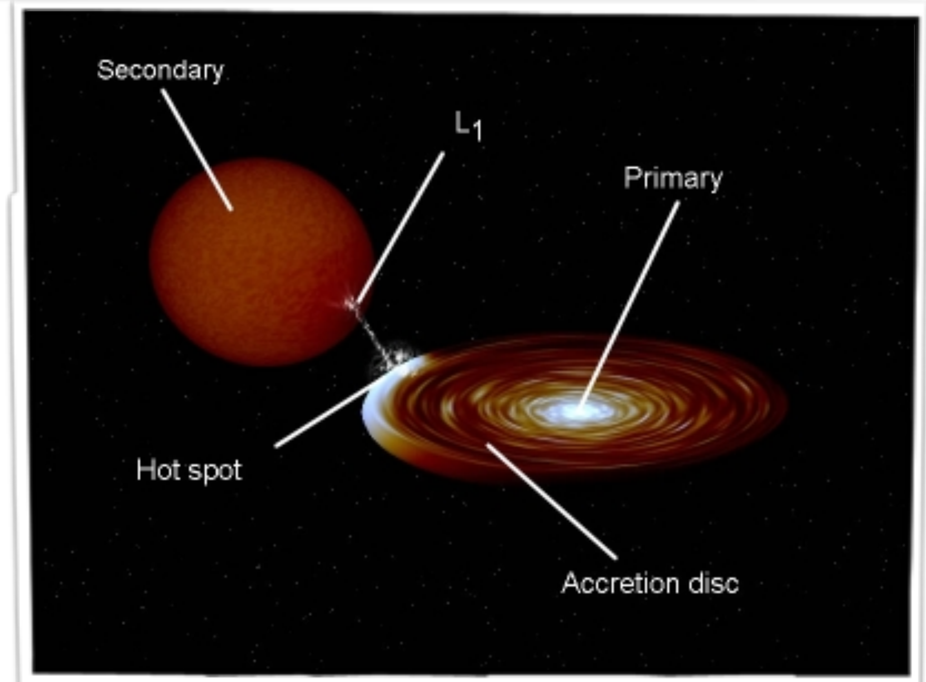


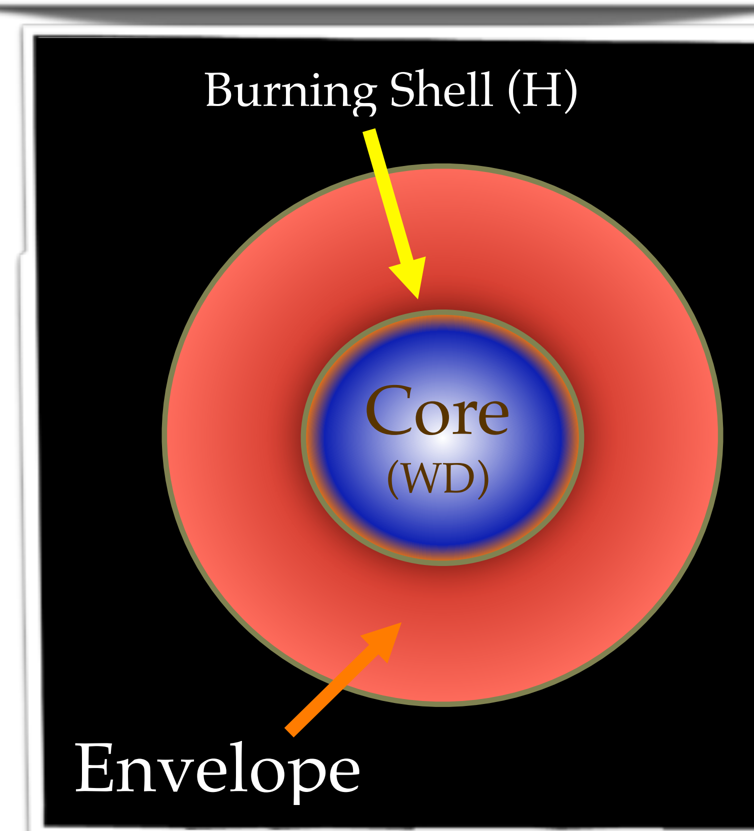
$L_{edd}(M=150M_{sun}\ X=0.55)$

Smith & Frew
2010

Classical Novae

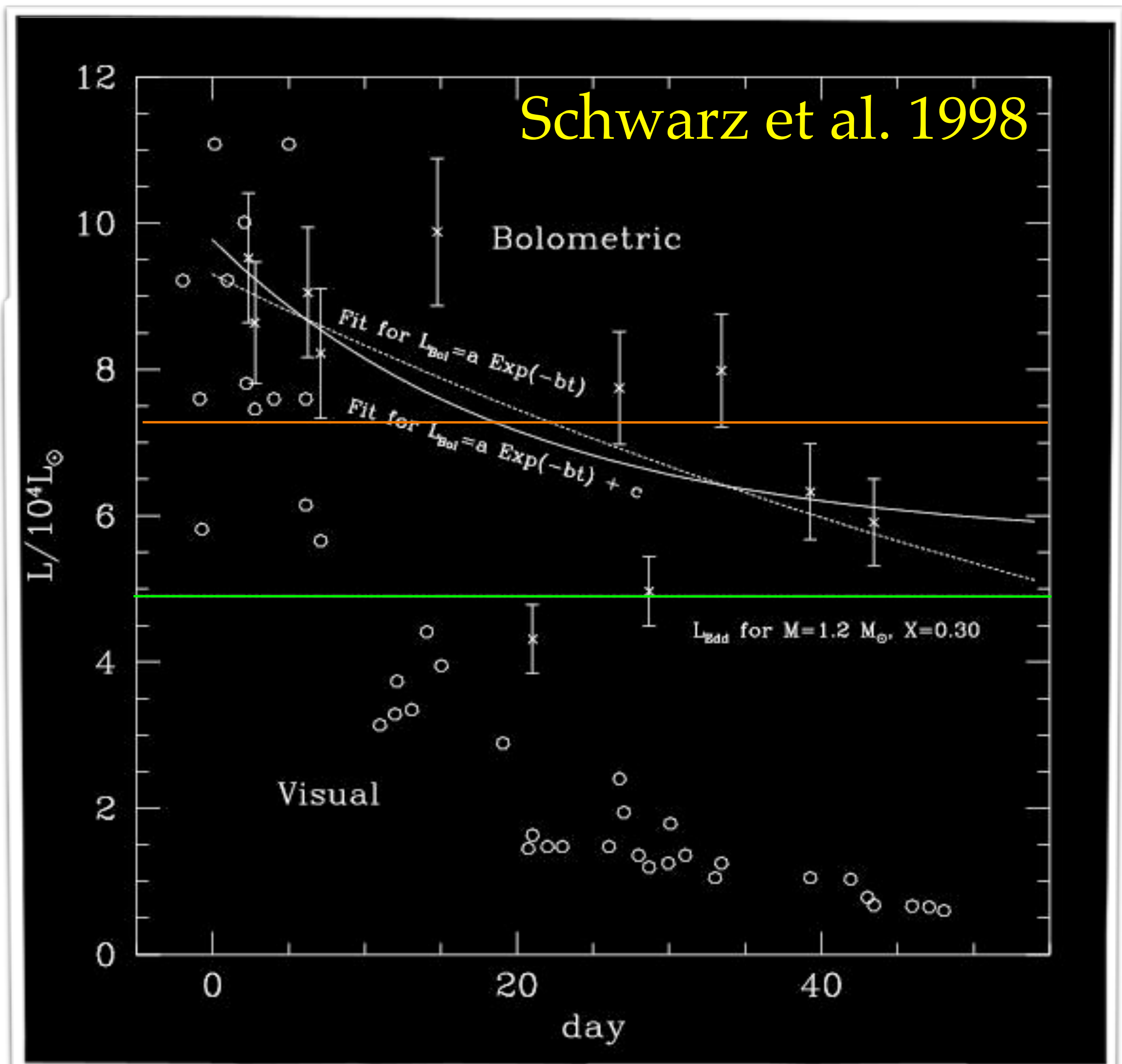
- When enough hydrogen is accreted on a white dwarf, it ignites.
- **Theory:** It should shine close to the Eddington limit (Paczynski 1970)
- **Reality:** Can be up to 20 times the L_{Edd}!





Specific Novae Are Super-Eddington for a long time if observed in UV

Nova LMC 1988#1



Extreme L_{edd}
"upper limit"

($M=1.4M_{sun}$, $X=0$)

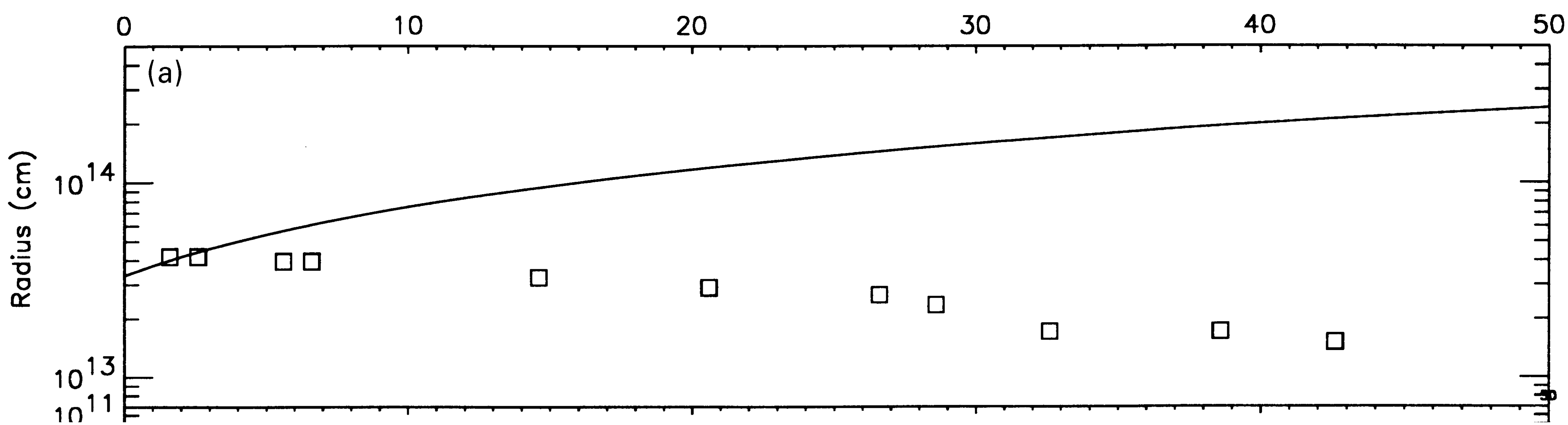
Reasonable L_{edd}
"upper limit"

($M=1.2M_{sun}$, $X=0.3$)

Photospheric radius << v t

Nova LMC 1988#1

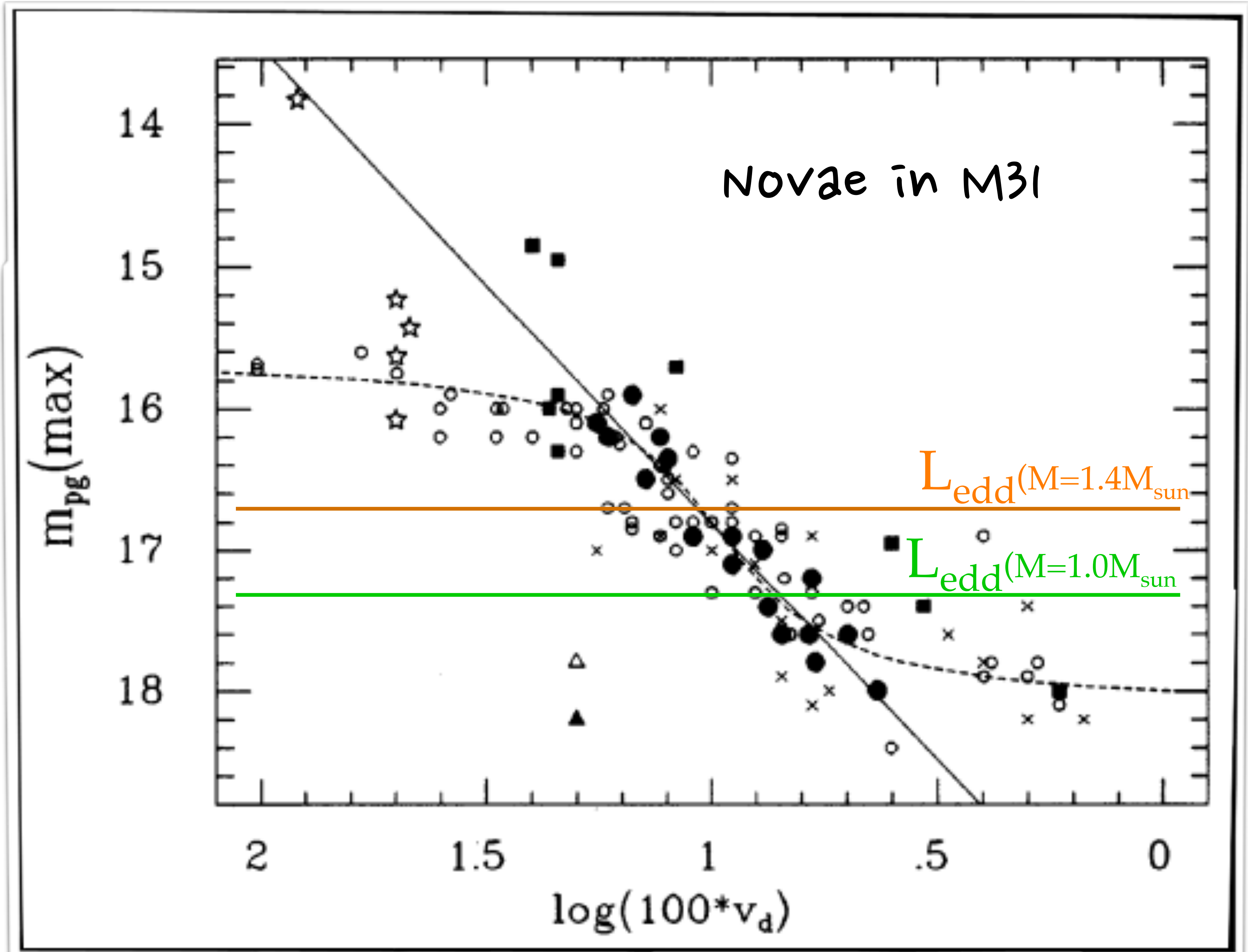
Schwarz et al. 1998



Novae have steady state winds with photospheres at $r_{sonic} \ll r_{ph} \ll v\,t$ (Bath & Shaviv 1976)

Novae have steady state have steady super-Eddington continuum driven winds (Shaviv 2001)

Peak Luminosity of Classical Novae is super-Eddington

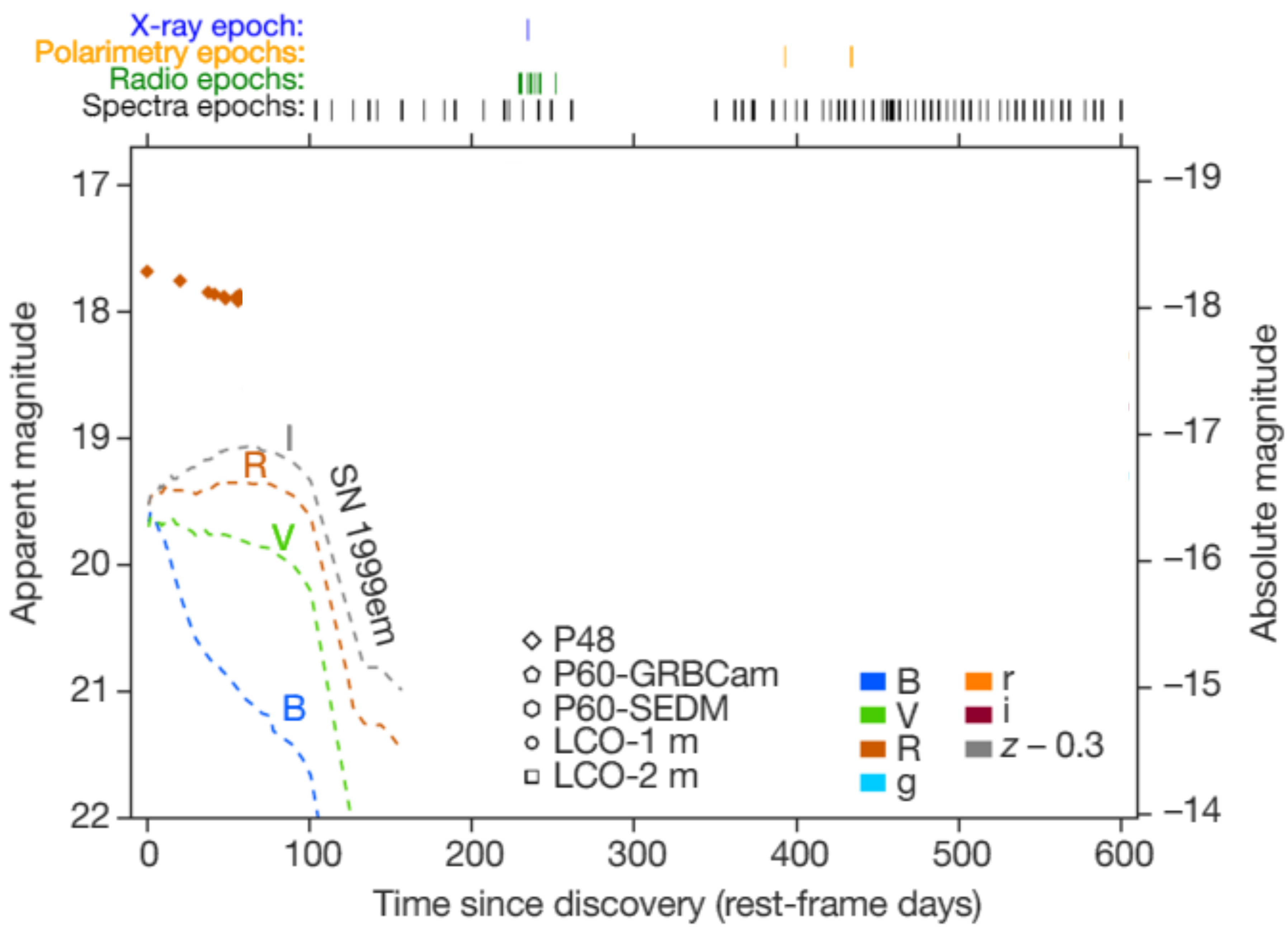


(vd = rate of decline in mags/days = 2 / t_2)

Capaccioli et al. 1989

iPTF14hls

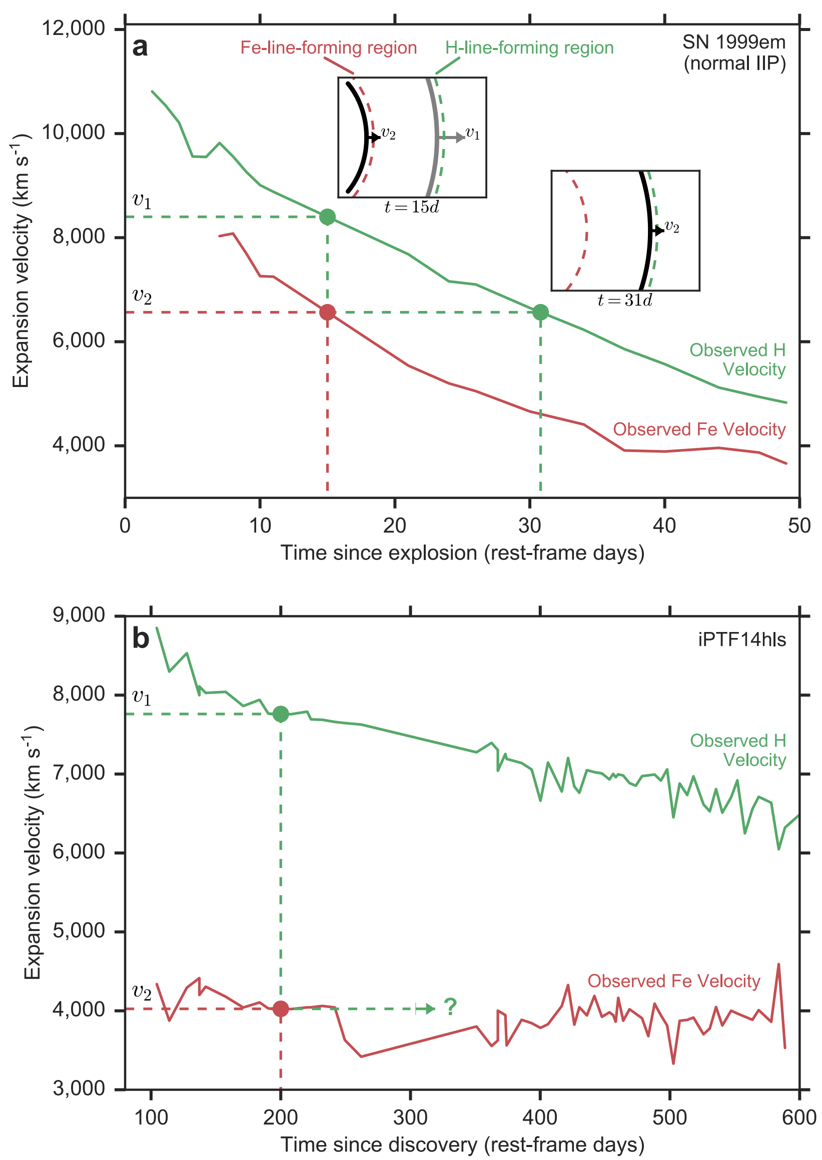
- A supernova?

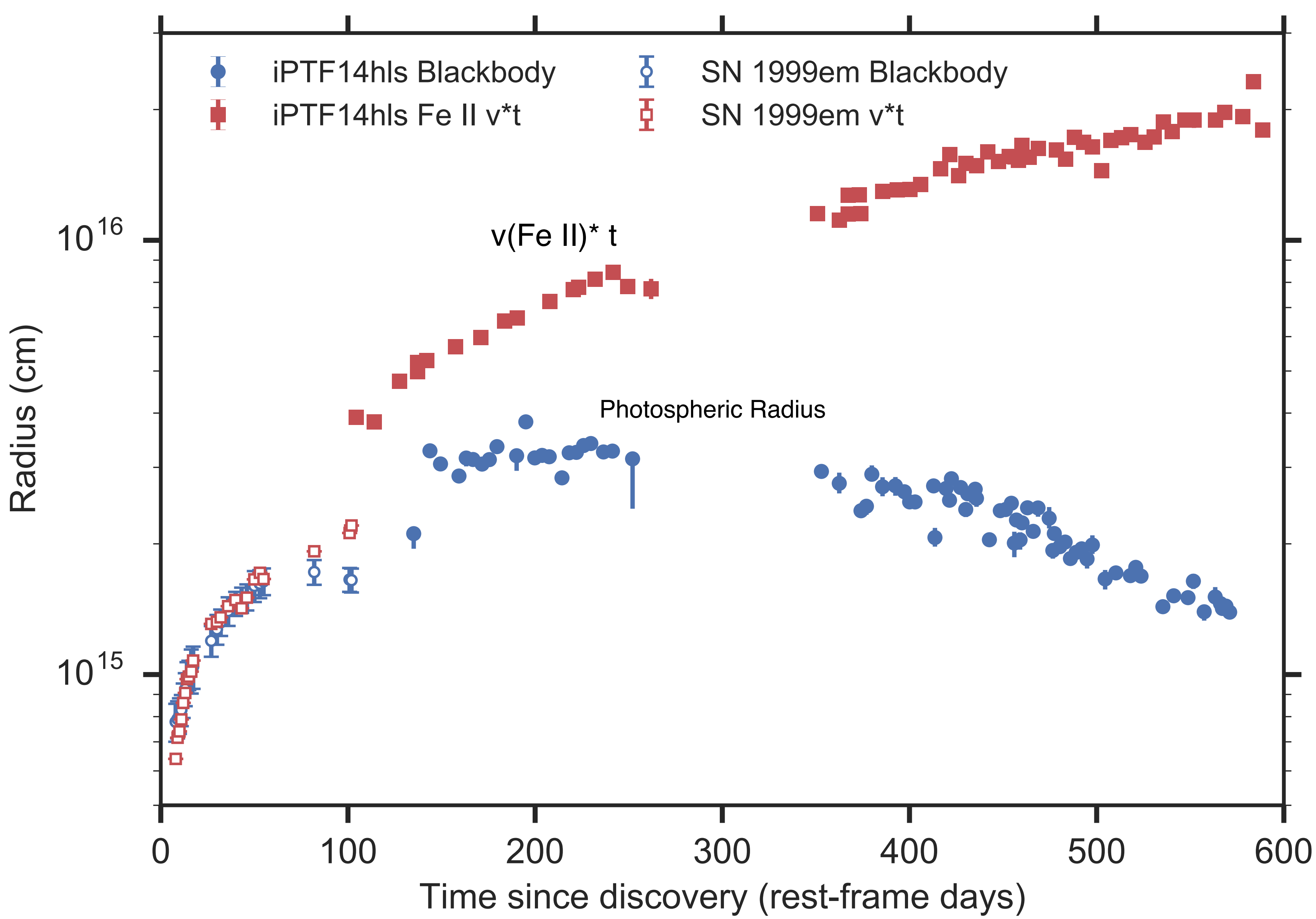


Arcavi et al. 2017

iPTF14hls

- Not a supernova, it has a steady state wind $r_{ph} \ll v\,t$

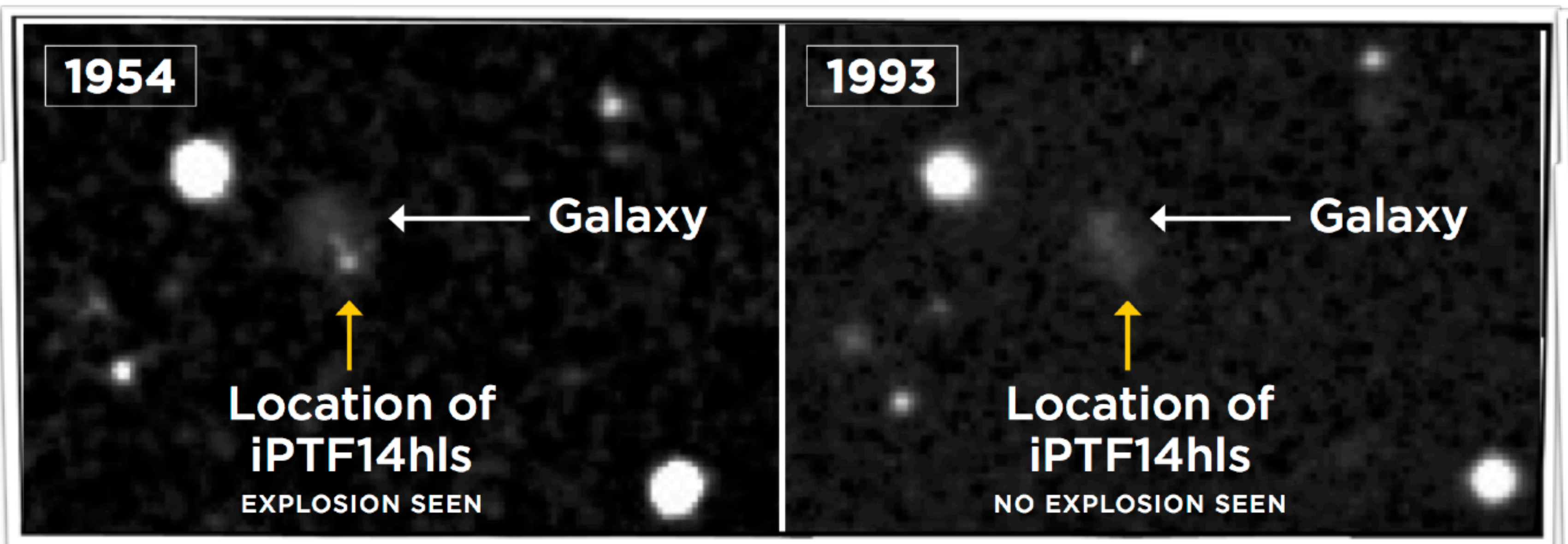




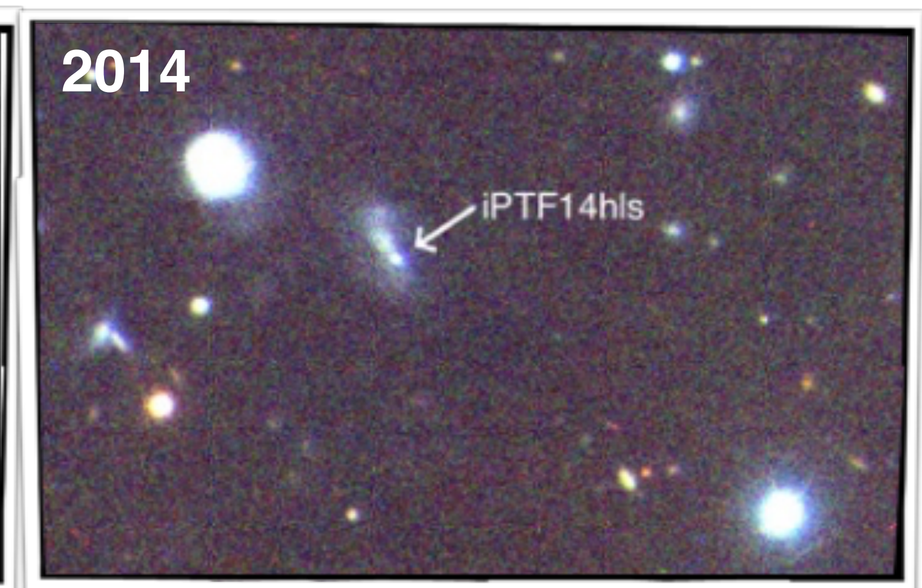
Arcavi et al. 2017

iPTF14hls

- Not a supernova, it is also episodic



Mv ~ -15.5



Mv ~ -18.5
500 Ledd of 100 Msun!

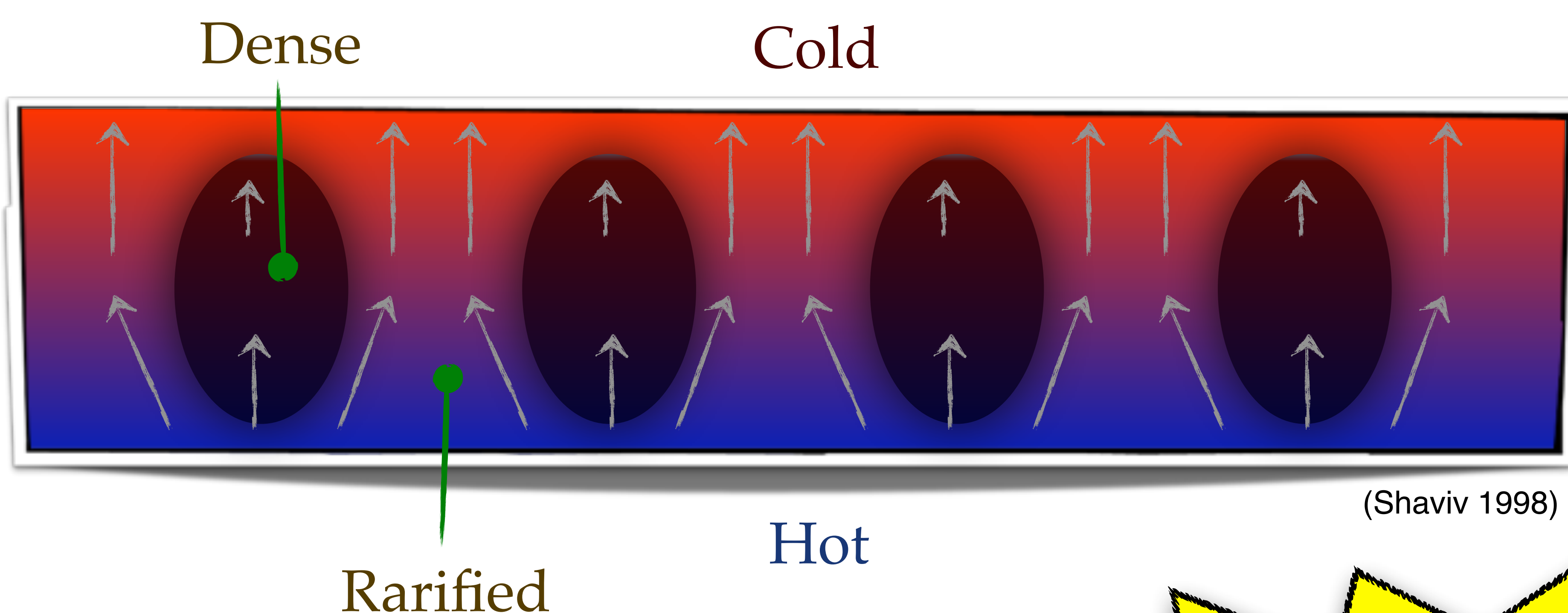
Arcavi et al. 2017

super-Edd in Nature

- LBV Giant Eruptions
- Classical Nova eruptions
- Type IIn (and Ibn) precursors
- Post failed-SN Iax winds from WD remnant
- ULXs (which are not IMBH...)

How can objects be super-Eddington?

- **Secret:** Atmospheres are porous



(Shaviv 1998)

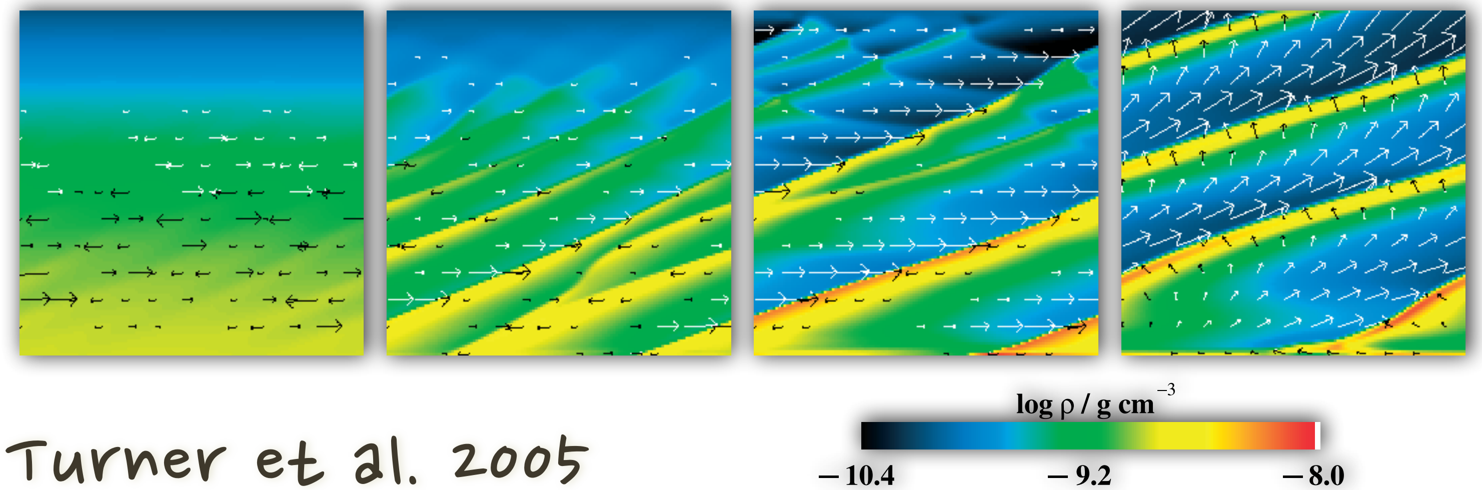
On average, the radiation "sees" a smaller opacity (per unit volume)

$$\kappa_V^{\text{eff}} = \frac{\langle F \kappa_V \rangle_V}{\langle F \rangle_V}$$

NJS 1998

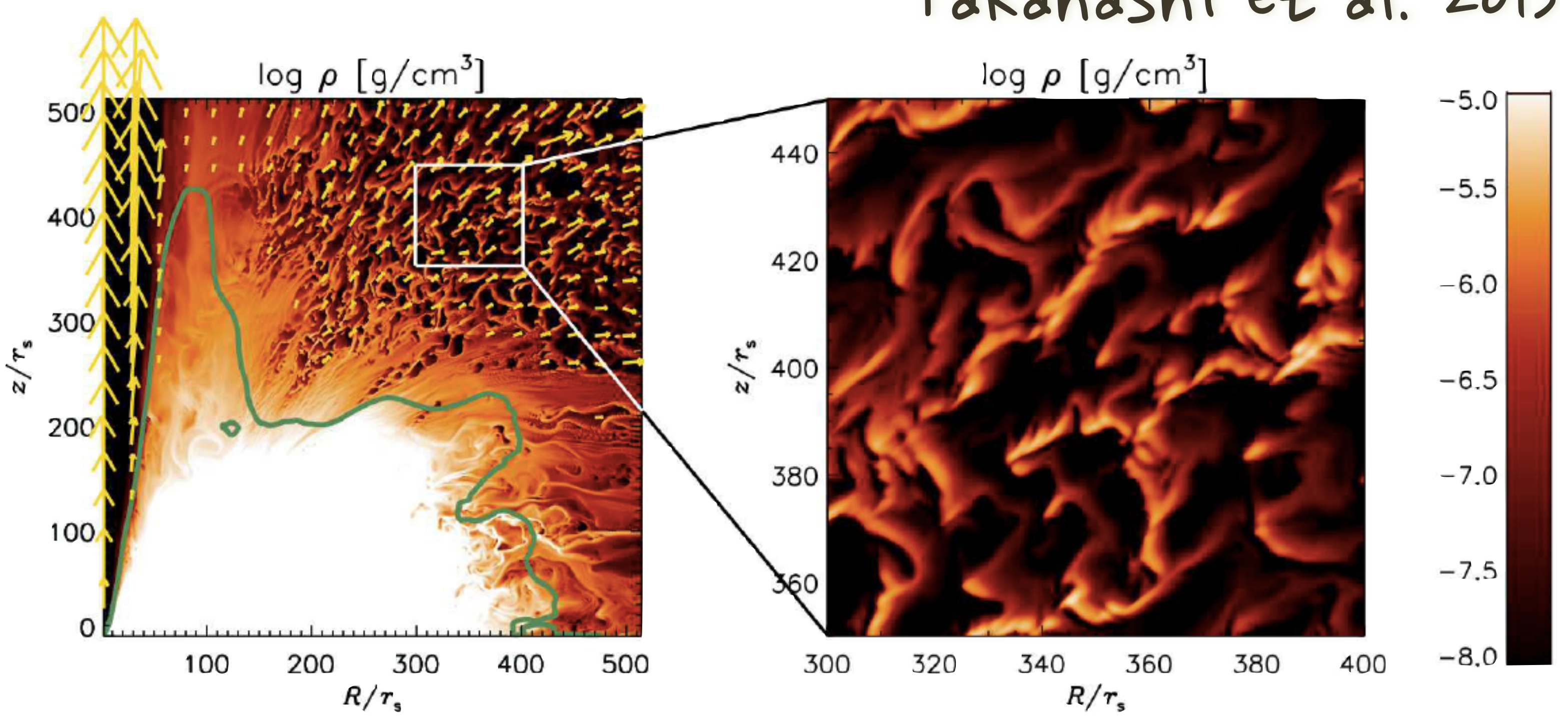
Instabilities close to L_{edd}

- There are many radiative hydrodynamic instabilities under various conditions
- Radiation + Hydro + stratification (NJS, 2001)
- Radiation + B-field (Arons '92, Hsu et al. '97, Gammie '98, Blaes & Socrates '01, Begelman '01)
- s-mode instability under special opacity laws (Glatzel 1994; Papaloizou et al. 1997)

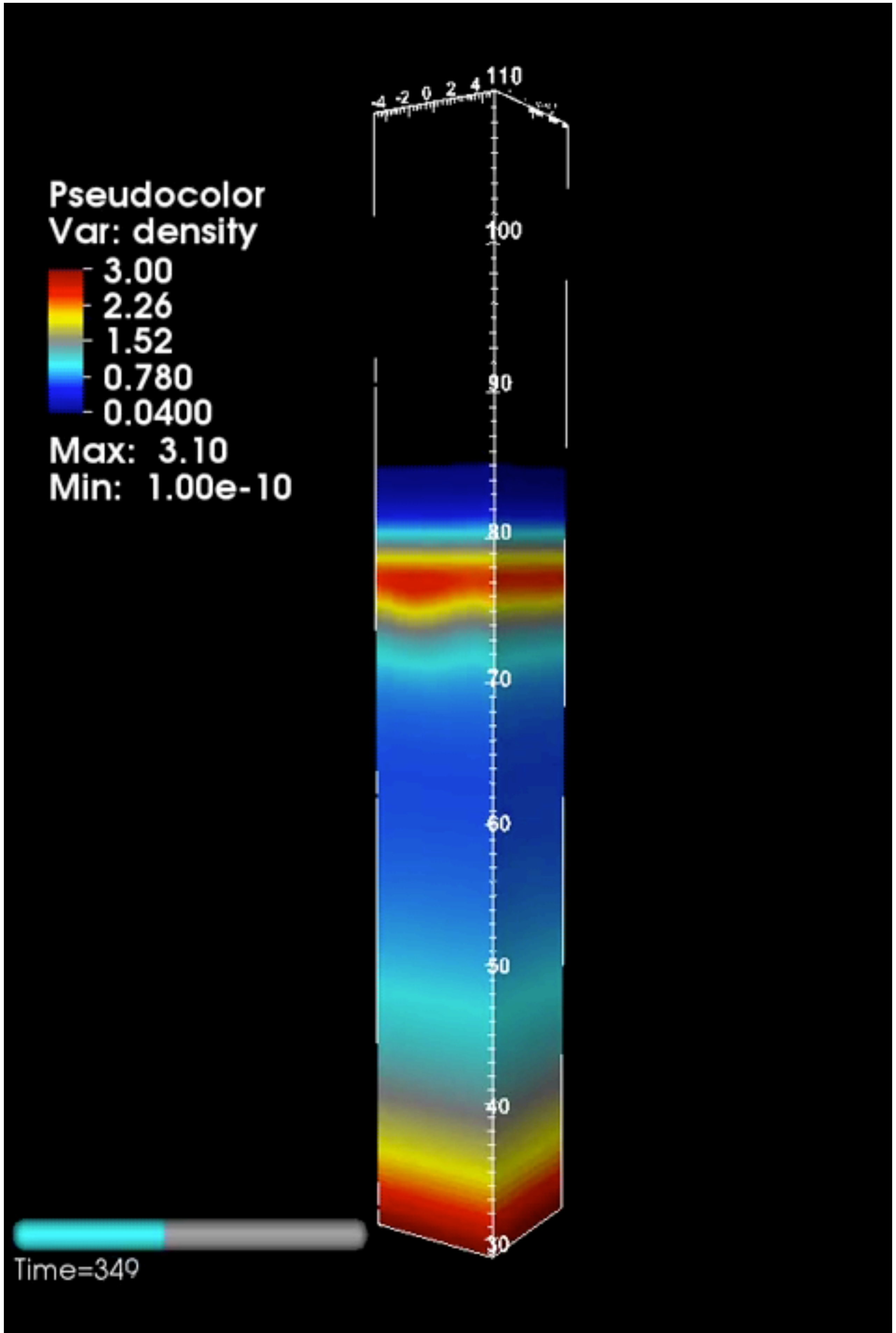


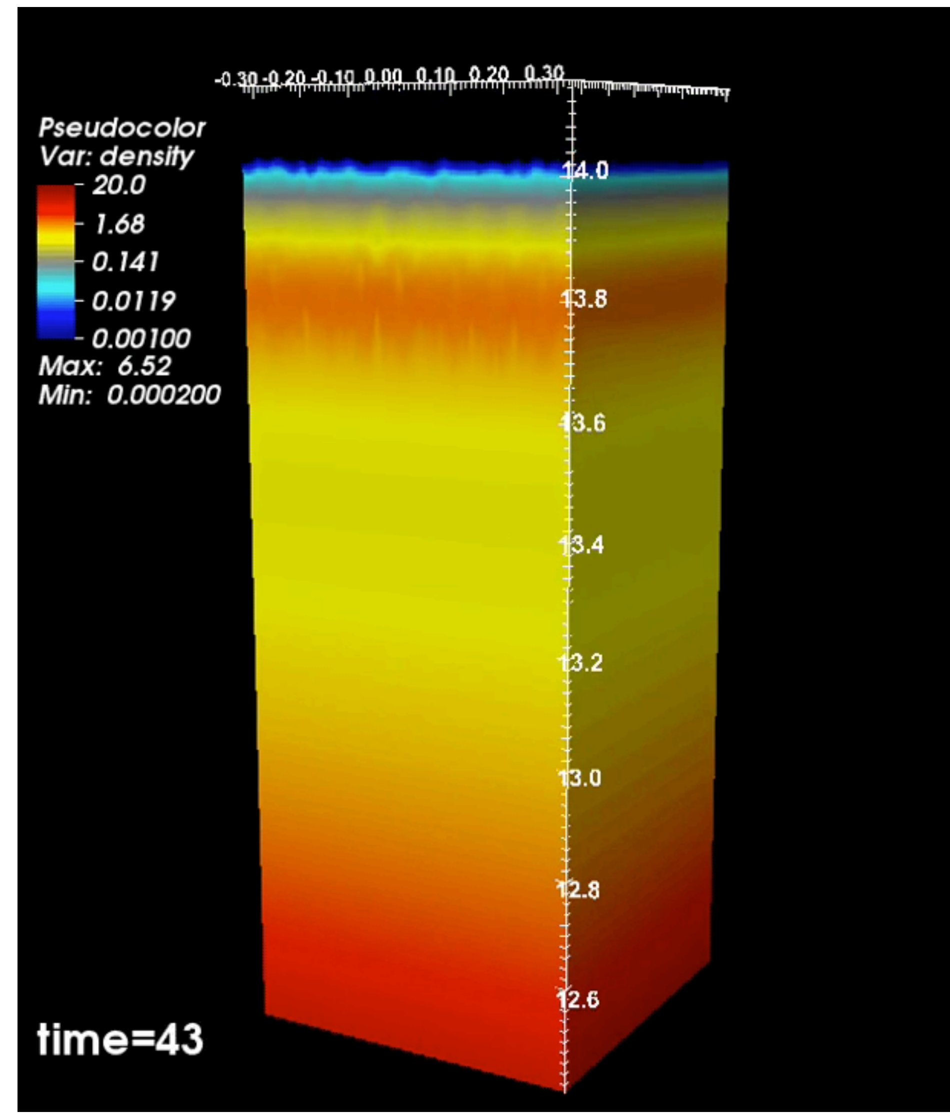
Turner et al. 2005

Takahashi et al. 2013



Instabilities close to L_{edd}





Jiang et al. 2015

Full Picture

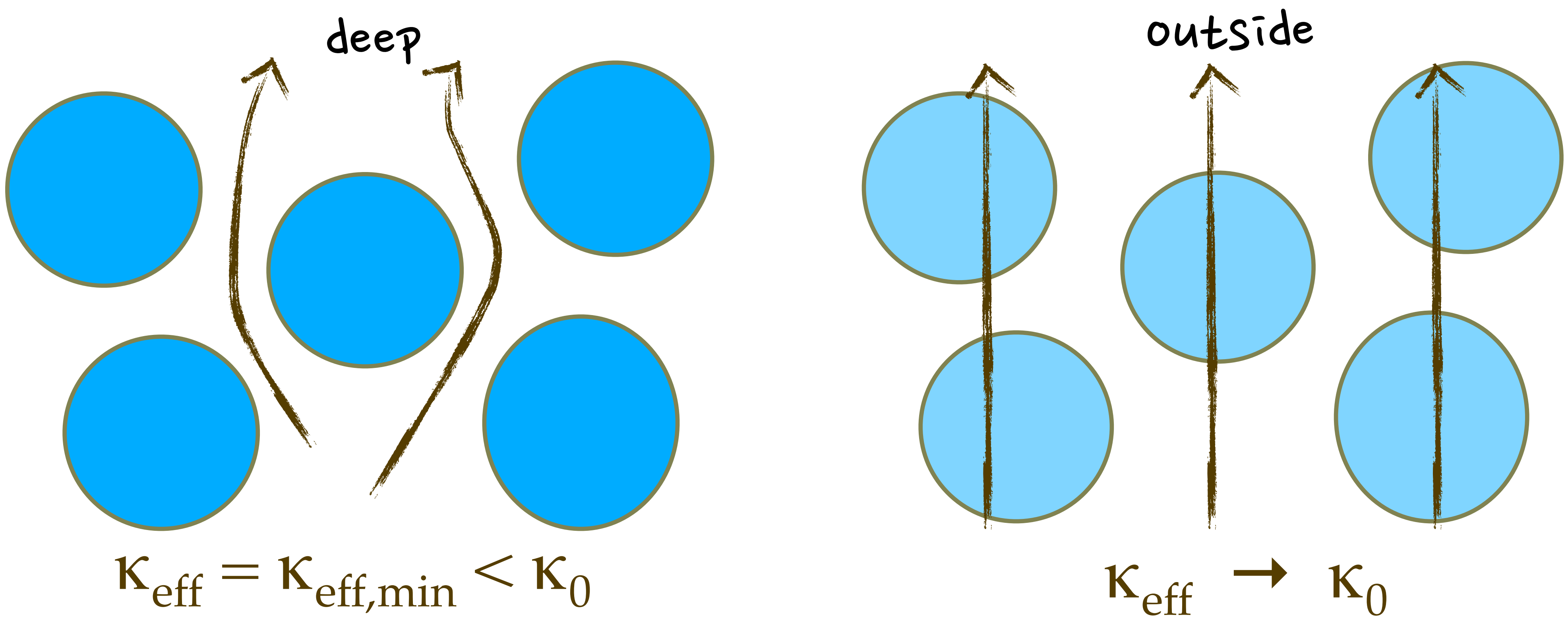
- Atmospheres are **unstable** as they approach the Eddington Luminosity
  - Atmospheres become Inhomogeneous
  - Effective Opacity is Reduced
  - **Effective** Eddington Luminosity is Increased

What do these atmospheres look like?

"...The answer my friends, is blowing in the wind, the answer is blowing in the wind..."

Wind from super-Edd Atmospheres

- Theory predicts wind from region where structure becomes optically thin (transparent)

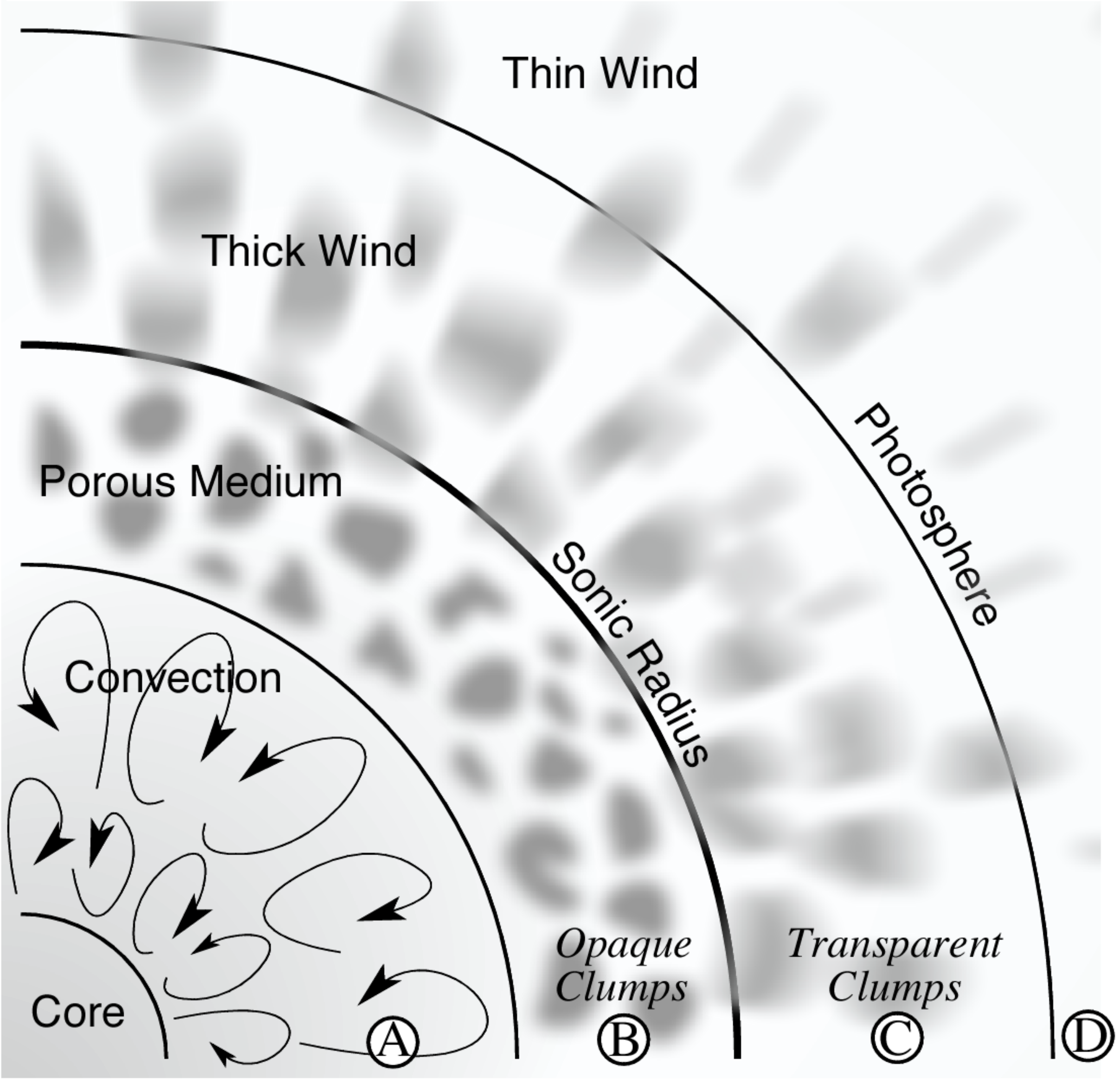


$$\dot{m} = \mathcal{W}\frac{(L - L_{Edd})}{v_s c}$$

NJS (2002)

Structure of Porous atmospheres

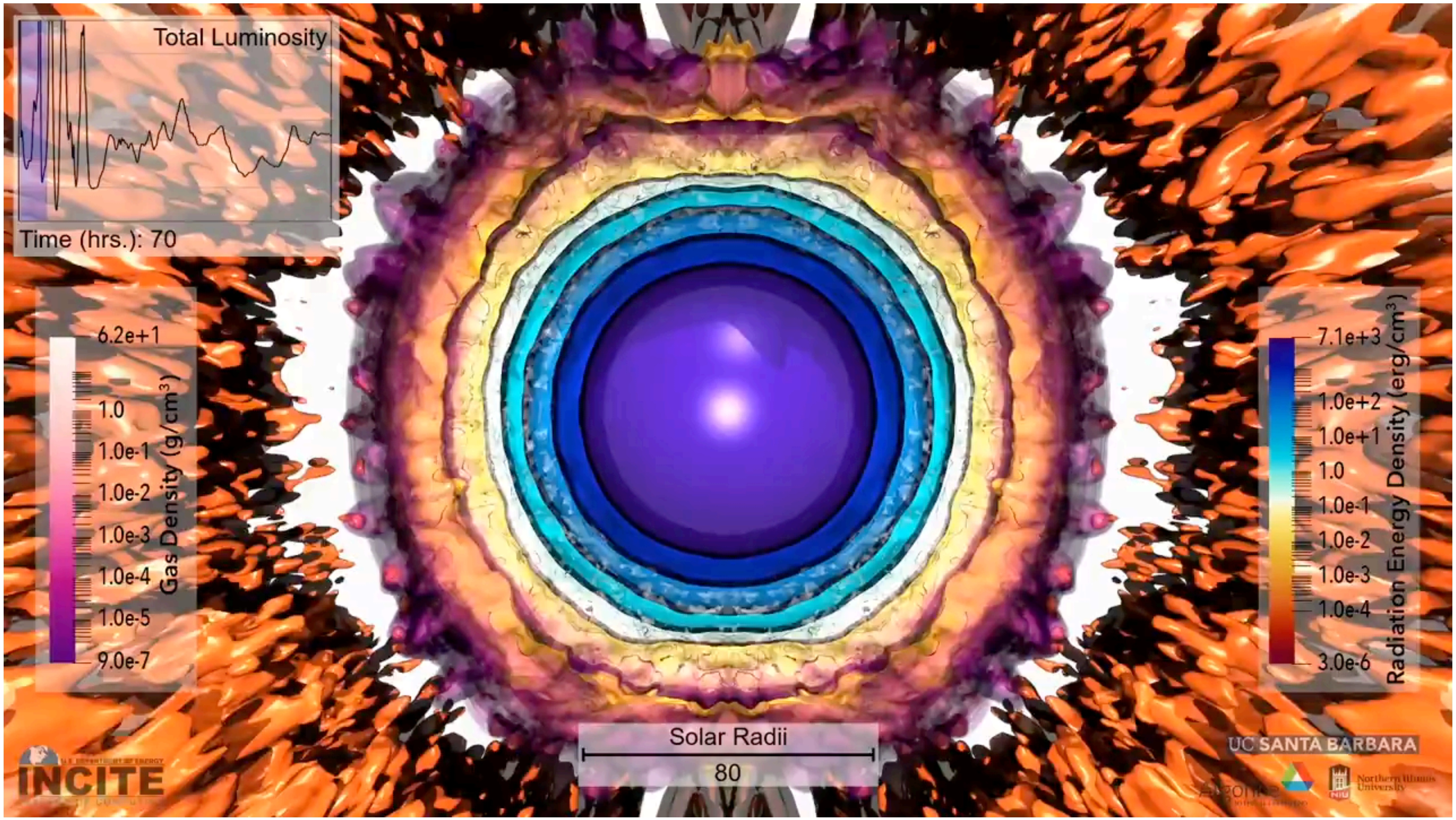
- Prediction:



NJS (2000)

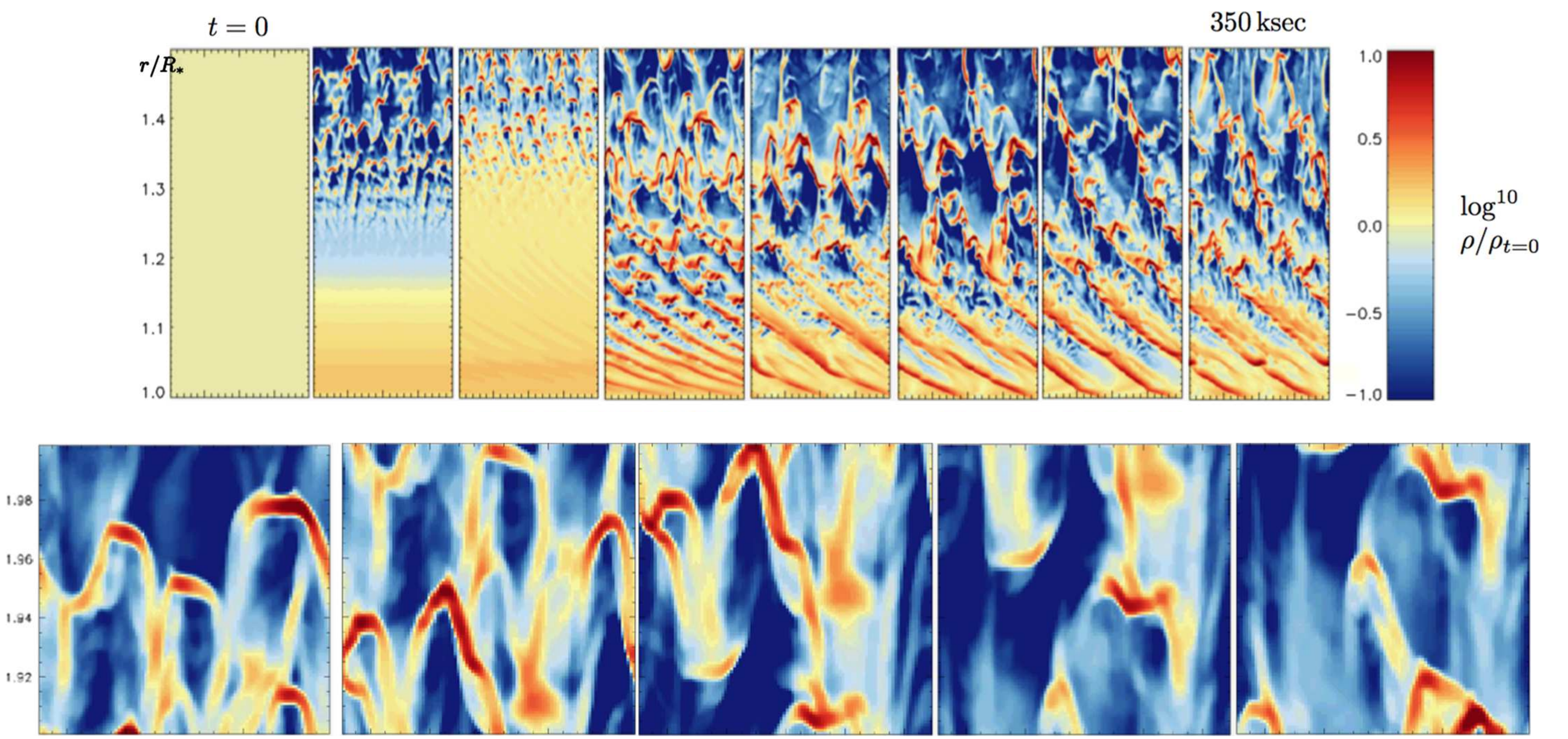
Structure of Porous atmospheres

- 18 years later + 7000 CPU years (!)



Jiang et al. (2018)

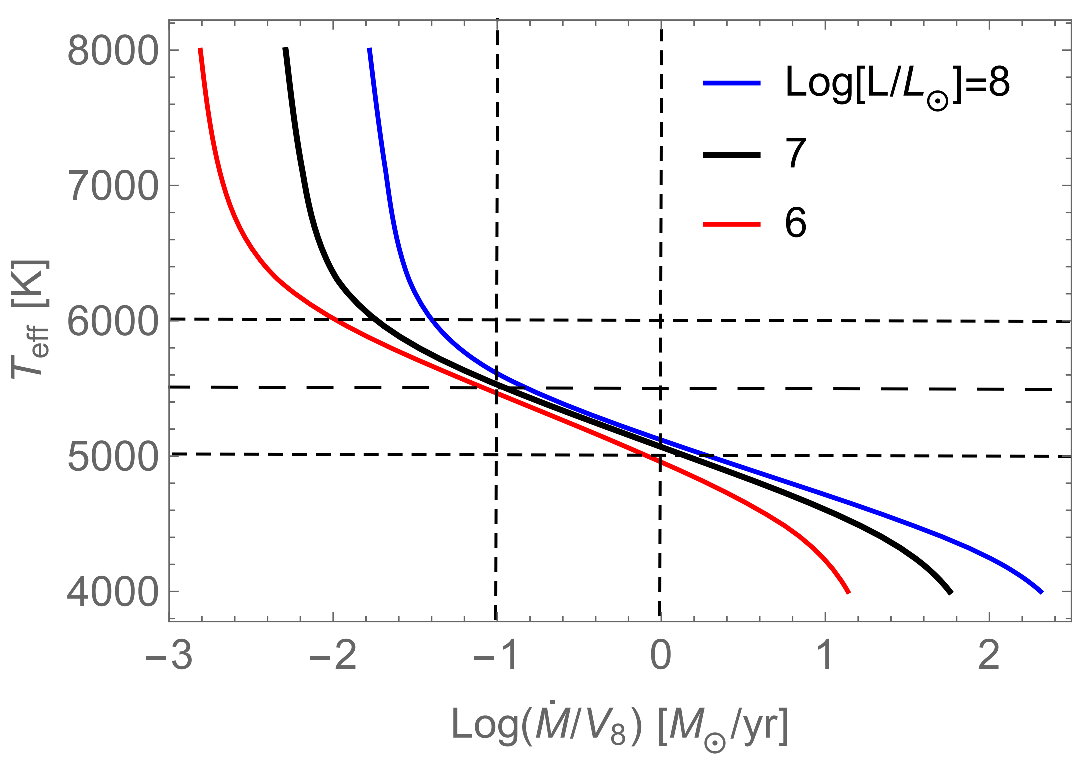
Note: Winds are also unstable

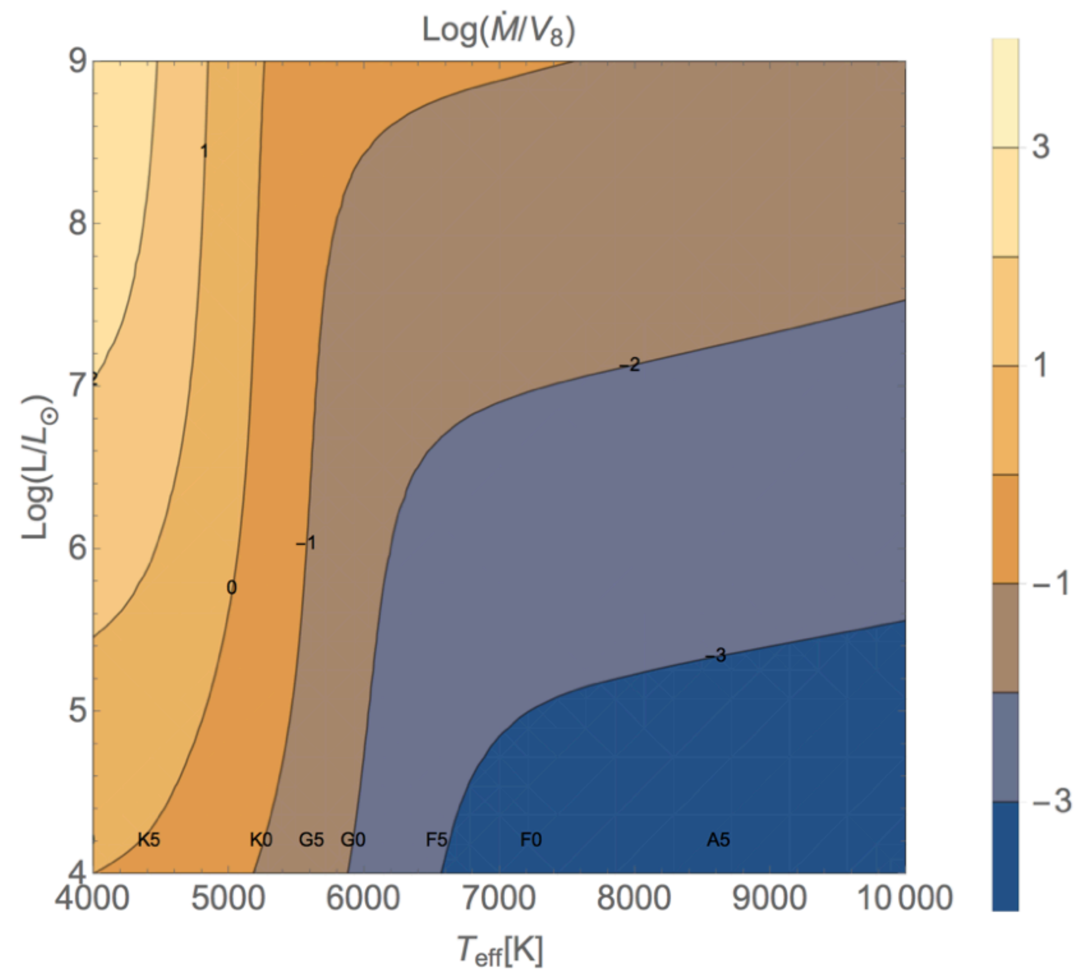


Sundqvist, Owocki & Puls (2018)

photospheres

- In optically thick winds, the photosphere resides in the wind. (Bath & Shaviv 1976)
- For m-dots seen in η Car: One expects $T_{eff} \sim$ 5000K
- This is seen in the light echo (Rest et a. 2012).





Owocki & NS 2016

The Winds

- Given photospheric conditions (L, v, m-dot or Tph, M) we can integrate down until we reach the sonic radius.

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

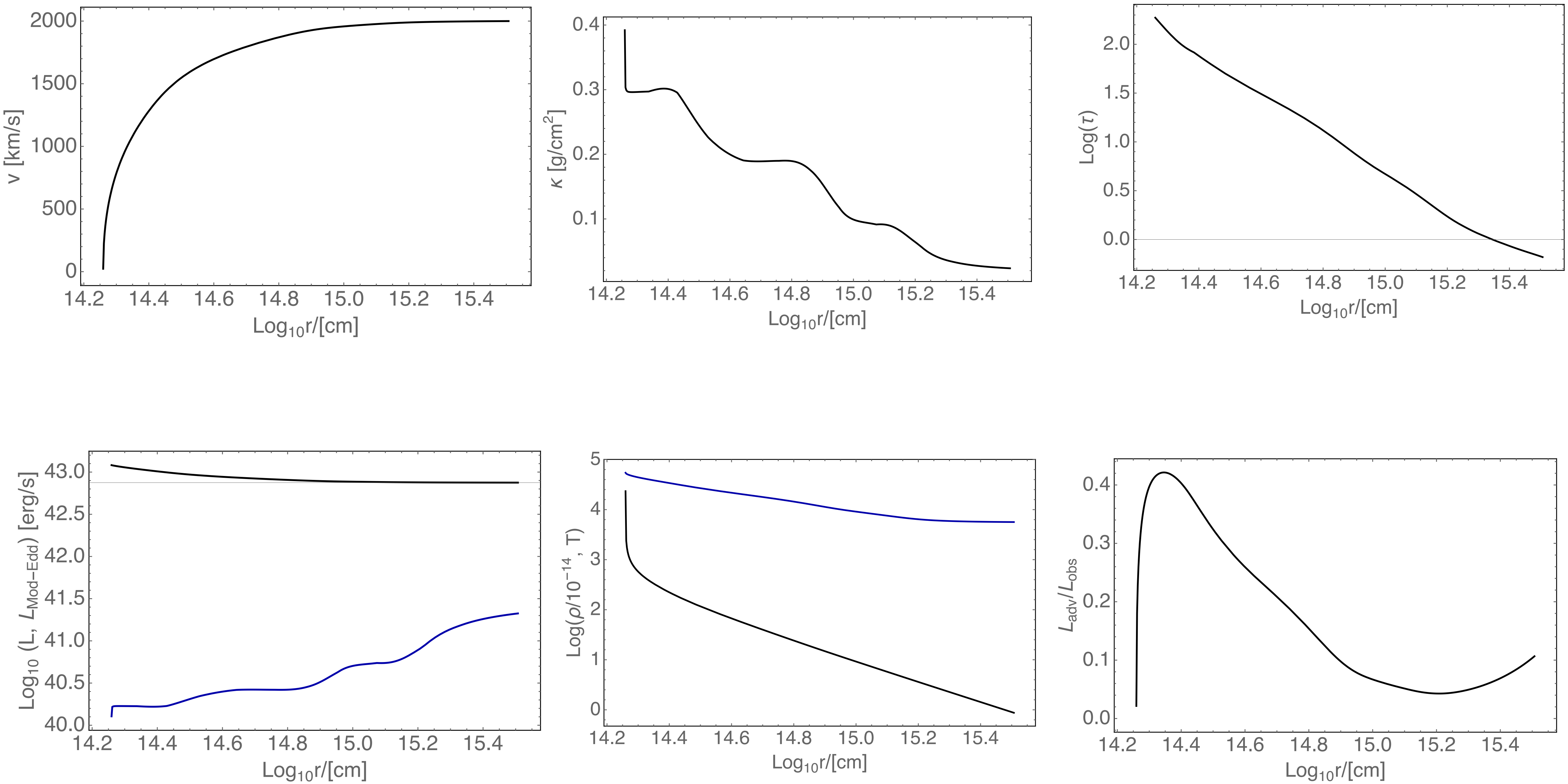
$$v\frac{dv}{dr} = \frac{\kappa}{c}\left(\frac{L}{4\pi r^2} - 4vP_{\rm rad}\right) - \frac{GM}{r^2} - \frac{1}{\rho}\frac{dP}{dr}$$

$$\frac{d}{dr}[\dot{M}(v^2/2 + h_g - GM/r) + L] = 4\pi r^2 \dot{q}$$

$$\frac{dP_{\rm rad}}{dr} = -\frac{\rho\kappa}{c}\left(\frac{L}{4\pi r^2} - 4vP_{\rm rad}\right),$$

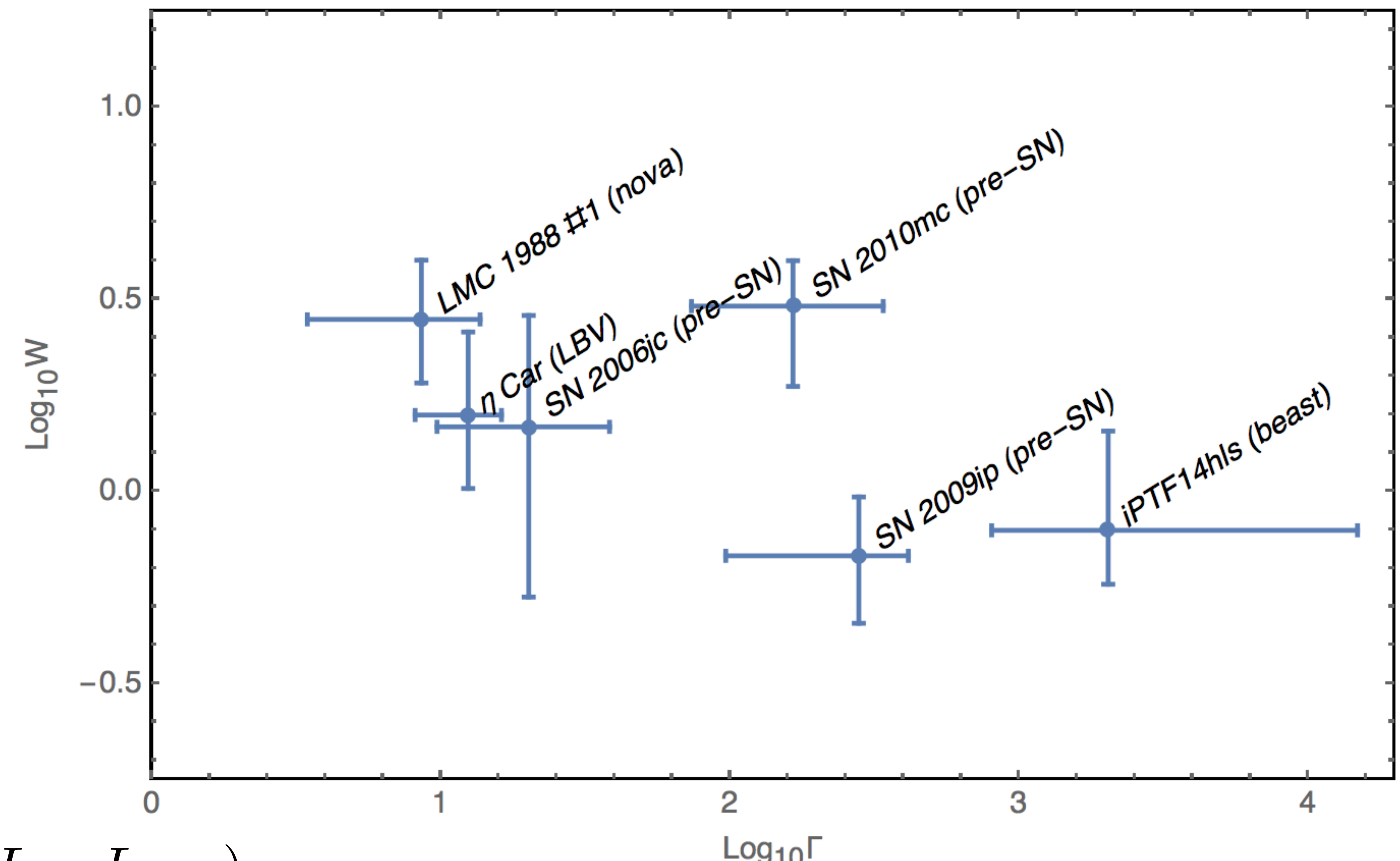
e.g., Owocki, Townsend & Quaraert (2018)

e.g., solution for iPTF14hls



Empirically obtaining W(Γ)

- W is expected to be O(1), and slowly falling with $\mathbf{\Gamma}$ (higher $\mathbf{\Gamma}$, more nonlinear structure, lower effective opacity).



$$\dot{m} = \mathcal{W}\frac{(L - L_{Edd})}{v_s c}$$

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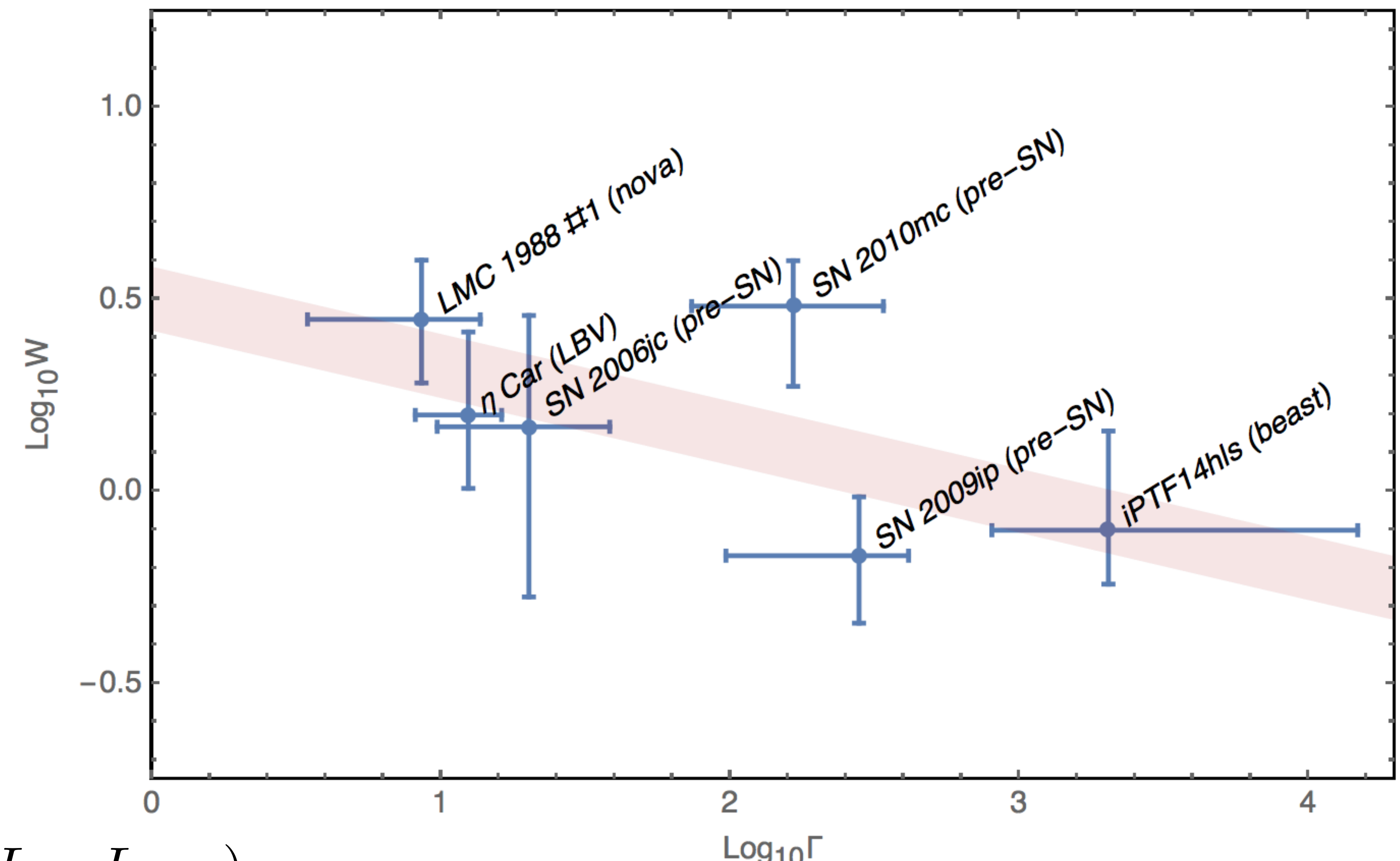
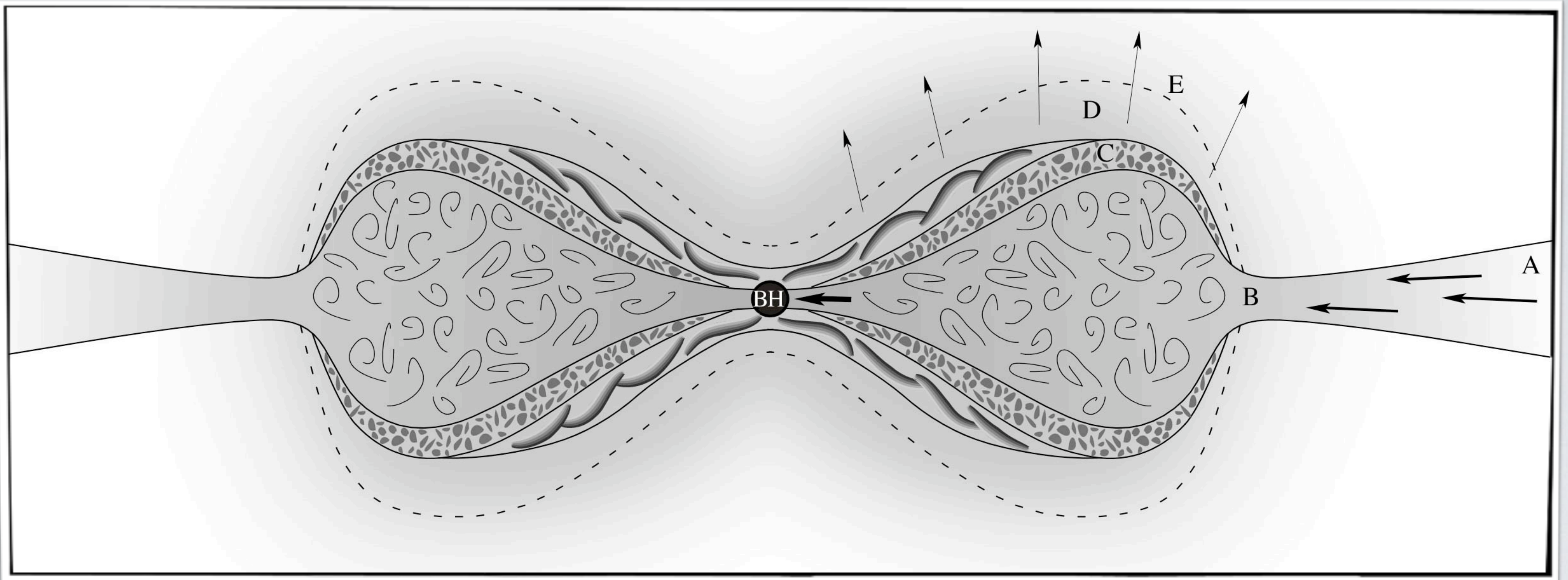


$$\dot{m} = \mathcal{W}\frac{(L - L_{Edd})}{v_s c}$$

W ~ 3 $\Gamma^{-1/6}$

Application to Accretion Disks



Radial Structure: Equations

- Mass conservation,

$$\frac{d\dot{\rm m}}{dr} = 4\pi r \dot{\Phi}_{\rm wind}$$

- Radial momentum,

$$v_r \frac{dv_r}{dr} + \frac{1}{\rho}\frac{dP}{dr} = -\frac{\partial \Psi}{\partial r}$$

- Pseudo-Newtonian potential

$$\Psi = -\frac{GM_{\rm BH}}{R - rg} \qquad R = \sqrt{r^2 + z^2}.$$

Radial Structure

- Angular momentum,

$$\rho v_r \frac{d}{dr}\left(r^2\omega\right) = -\frac{1}{r}\frac{d}{dr}\left(r^2\tau_{r\phi}\right) \qquad \tau_{r\phi} = -\alpha P_{\mathrm{tot}}$$

- Advection,

$$T\frac{ds}{dr} = (F-\phi)\frac{4\pi r}{\dot{m}}$$

Vertical Structure: Hydrostatic region

- Hydrostatic equilibrium,

$$\frac{1}{\rho}\frac{dP}{dz} = -\frac{d\Psi}{dz}$$

- Temperature gradient ,

$$\frac{dT}{dz} = \begin{cases} \frac{\gamma - 1}{\gamma}\frac{dP}{dz}\frac{T}{P}, & \text{in the convective zone,} \\ -\frac{3\kappa_{\text{eff}}\,\rho F}{4acT^3}, & \text{in the radiative zone,} \end{cases}$$

Vertical Structure: Porous Atmosphere

- The effective opacity is

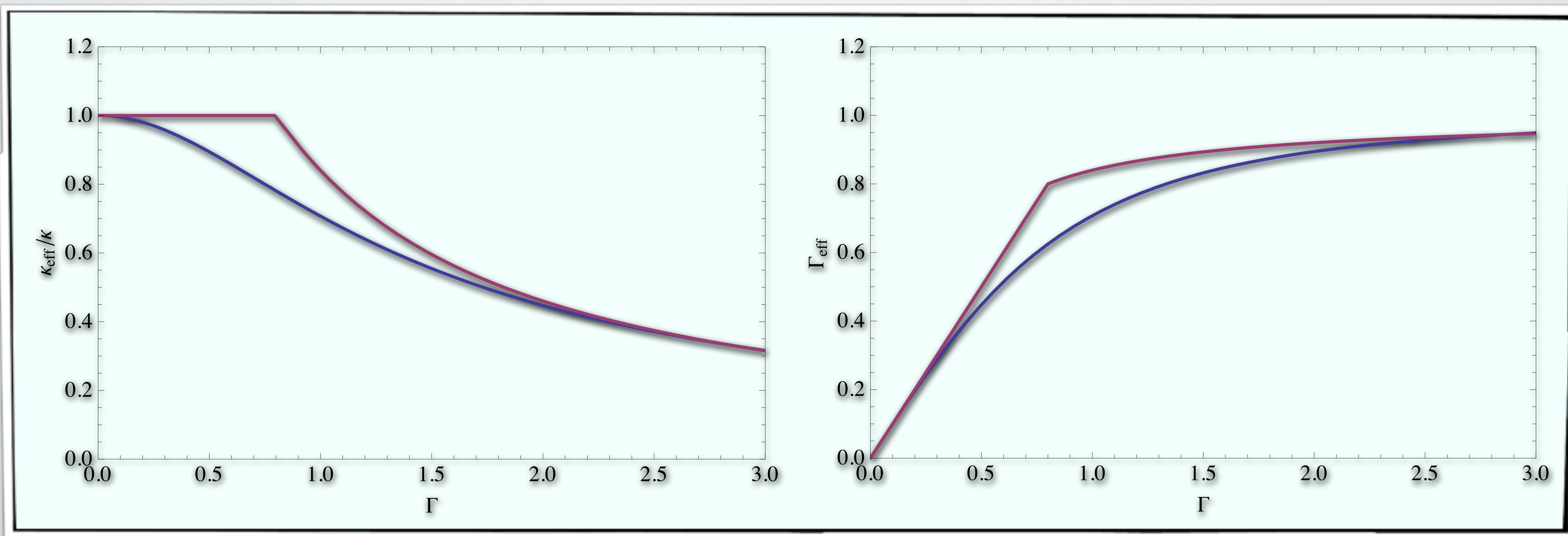
Reduction above Γ_{crit}

$$\frac{\kappa_{\rm eff}}{\kappa_0} = \left(1 - \frac{A}{\Gamma^B}\right)\frac{1}{\Gamma} \quad \text{for} \quad \Gamma > \Gamma_{\rm crit}$$

$$\frac{\kappa_{\rm eff}}{\kappa_0} = 1 \quad \text{for} \quad \Gamma > \Gamma_{\rm crit}$$

Smooth Option:

$$\frac{\kappa_{\rm eff}}{\kappa_0} = \frac{1}{(1+\Gamma^p)^{1/p}}$$



Super-Eddington Winds

- Local mass loss rate,

$$\dot{\Phi} = \mathcal{W} \frac{F - \mathcal{F}_{\rm Edd}}{c v_s}$$

- Equation of motion,

$$\rho v_z \frac{dv_z}{dz} = -\frac{dP}{dz} - \rho g_z$$

- Energy conservation,

$$F(z) = F_{\rm atm} - \dot{\Phi}_{\rm wind} \left(\frac{v_z^2}{2} + \frac{G M_{\rm BH}}{R_{\rm atm}} - \frac{G M_{\rm BH}}{R} \right)$$

Photon Tired winds

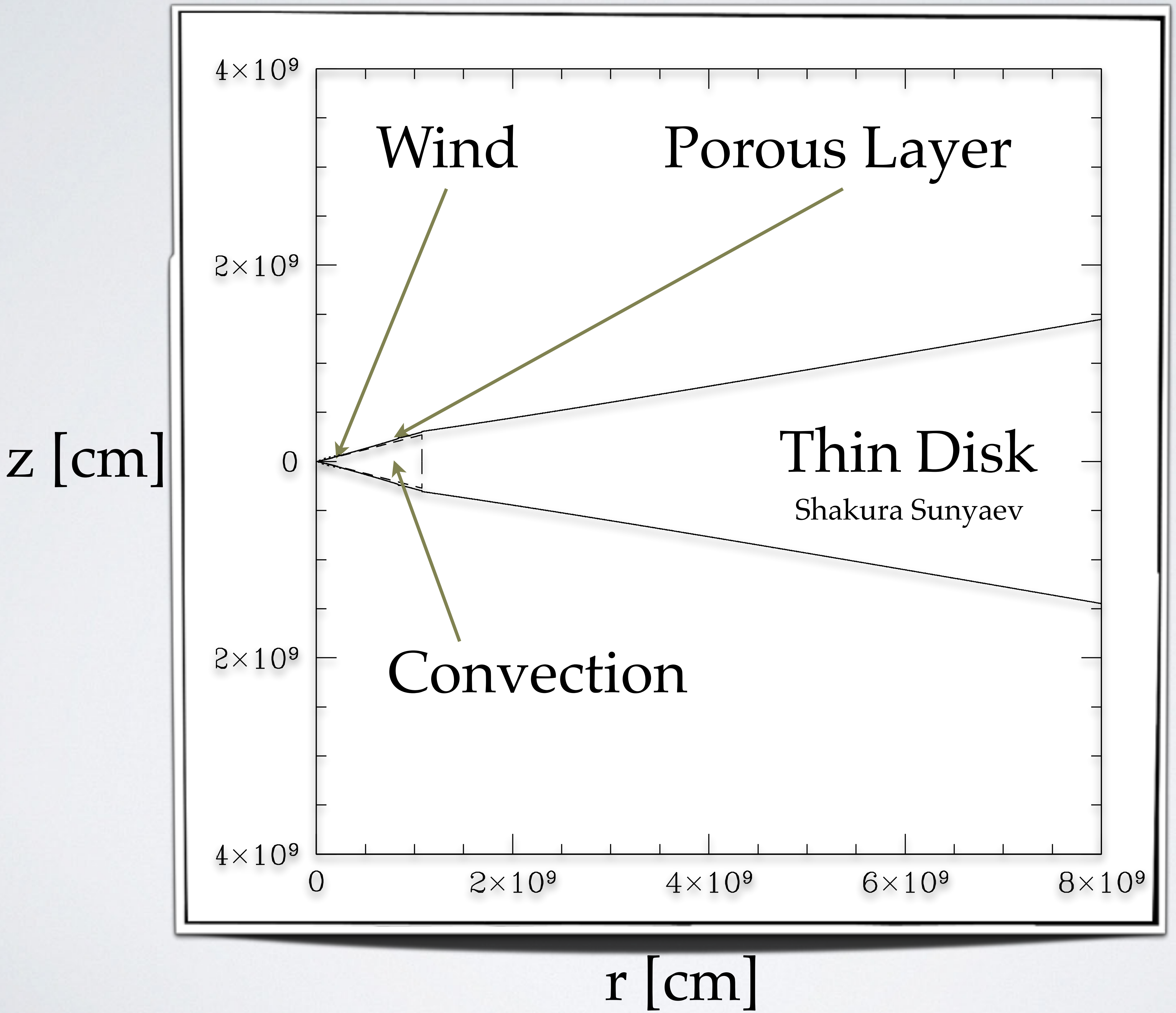
- When available radiative flux at the sonic point F_0 is insufficient, photon tired wind is formed

$$\dot{\Phi}_{\rm tiring} \equiv F/(GM_{\rm BH}/R_{\rm atm})$$

- Actual mass loss is reduced, (van Marle et al. 2009)

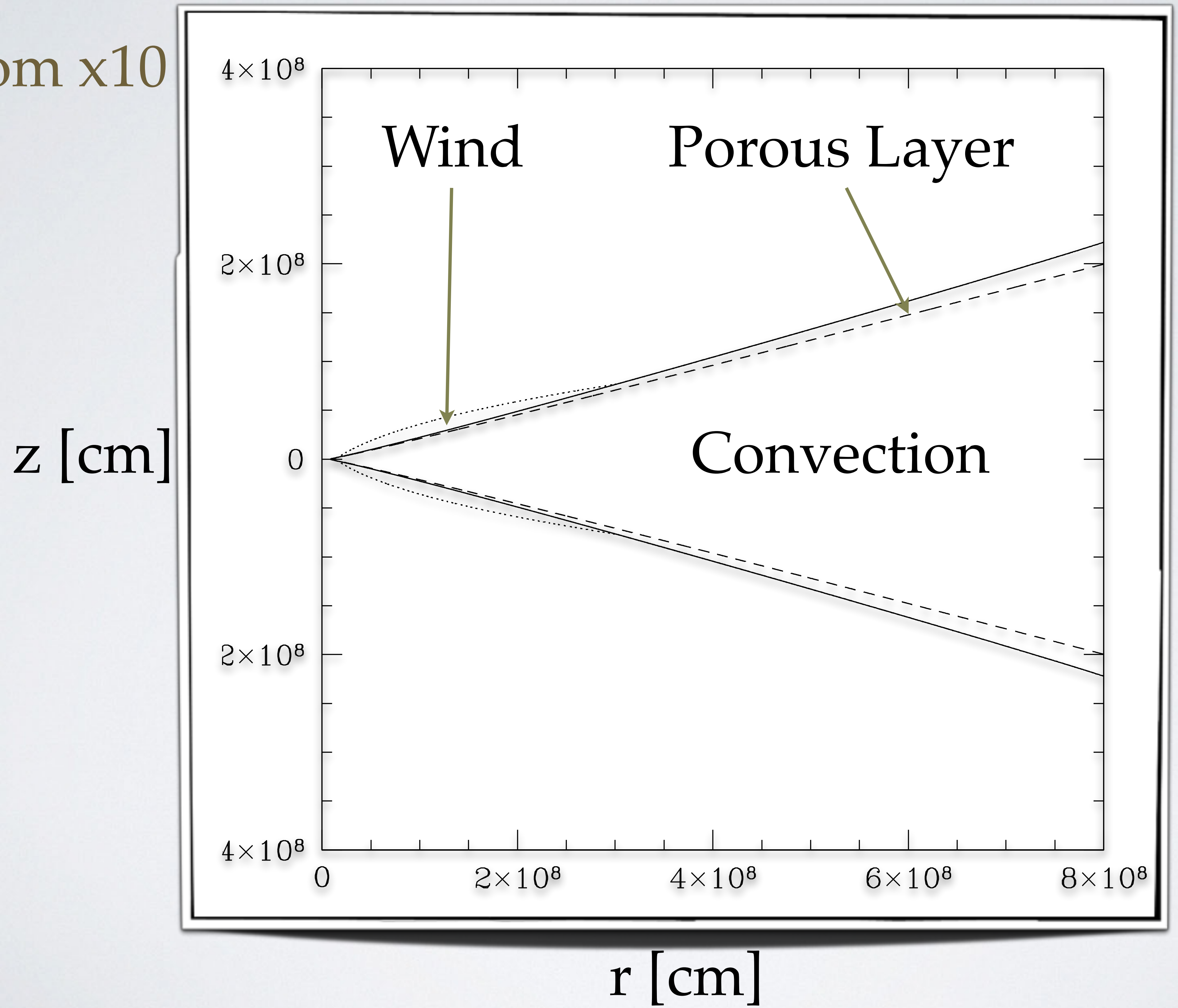
$$\frac{\dot{\Phi}_{\rm wind}}{\dot{\Phi}_{\rm tiring}} \simeq max\left(0.2\left(\frac{F}{F_{\rm Edd}}\right)^{0.6}, 0.9\right)$$

Real Appearance (1:1 Aspect ratio)



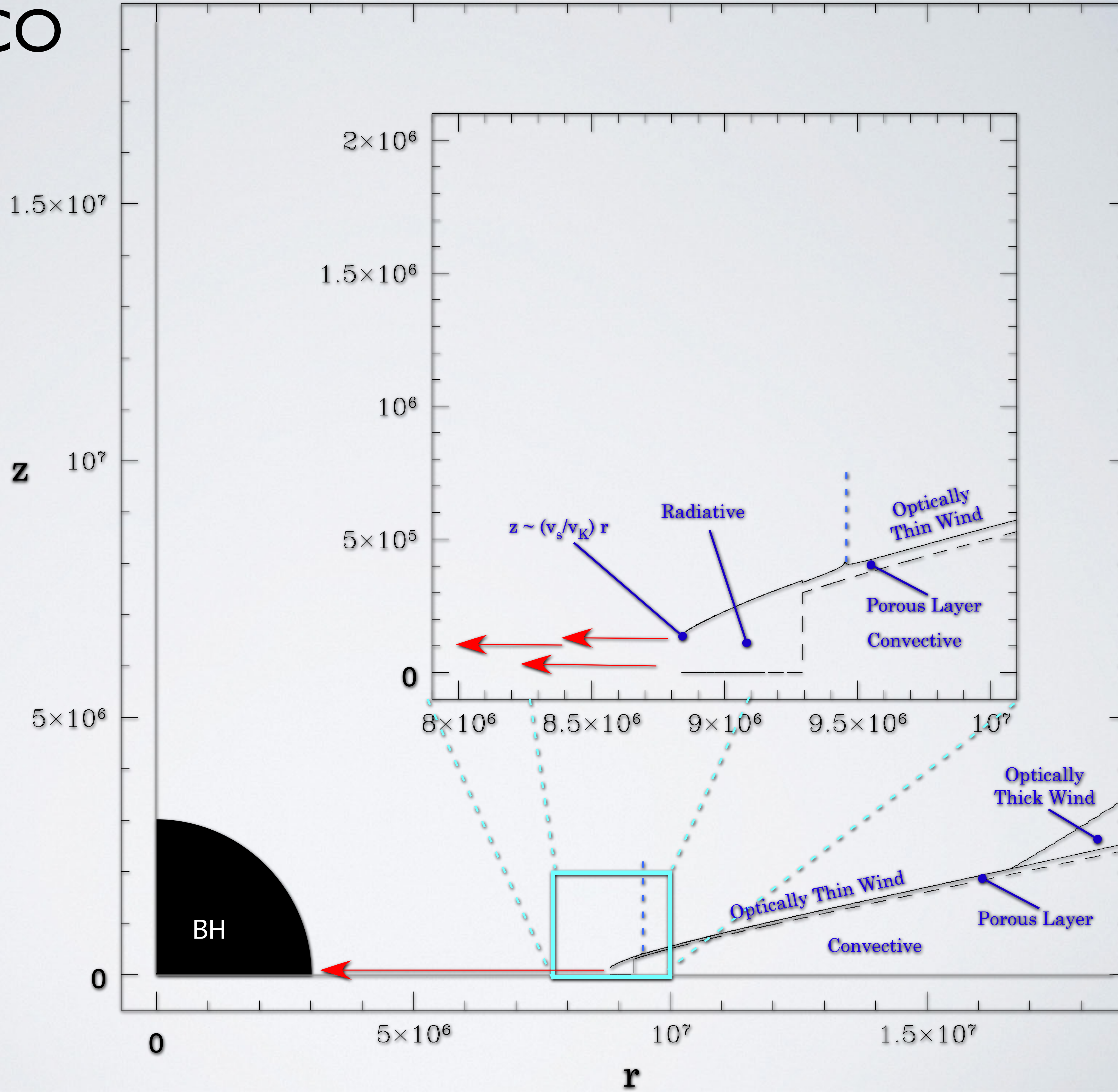
Real Appearance (1:1 Aspect ratio), zoomed in

Zoom x10



Near the ISCO

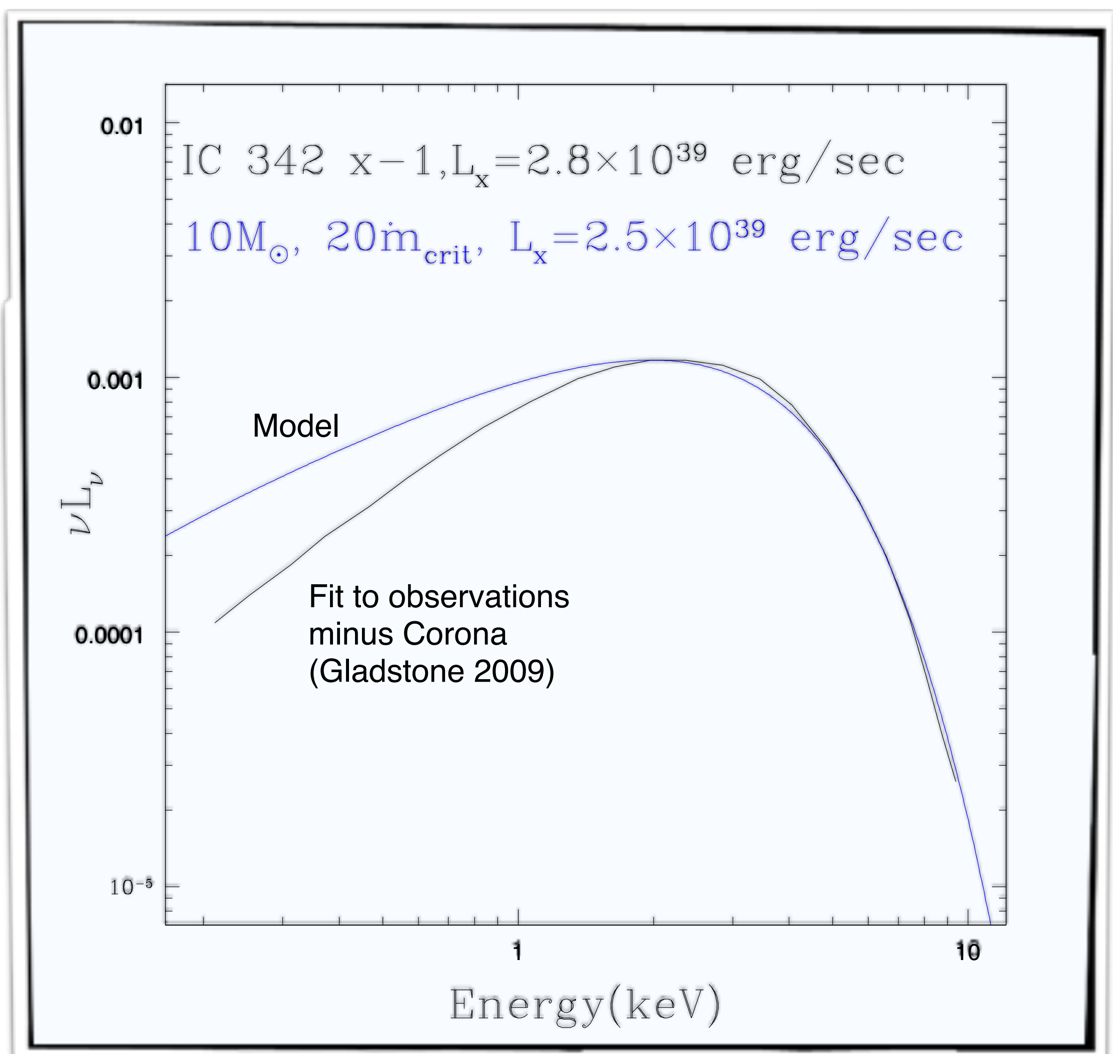
Zoom x400

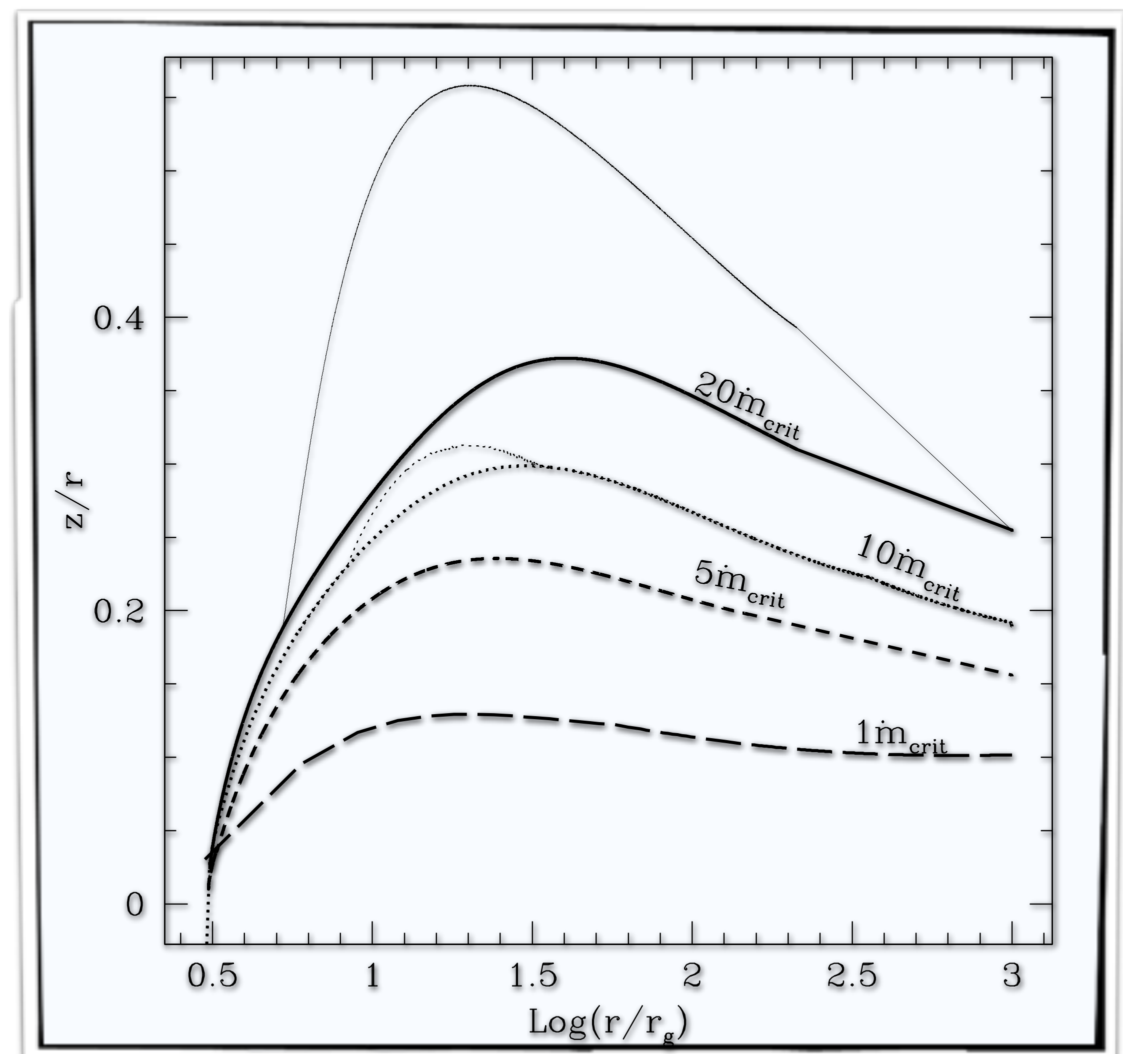


Super-Eddington Slim Accretion

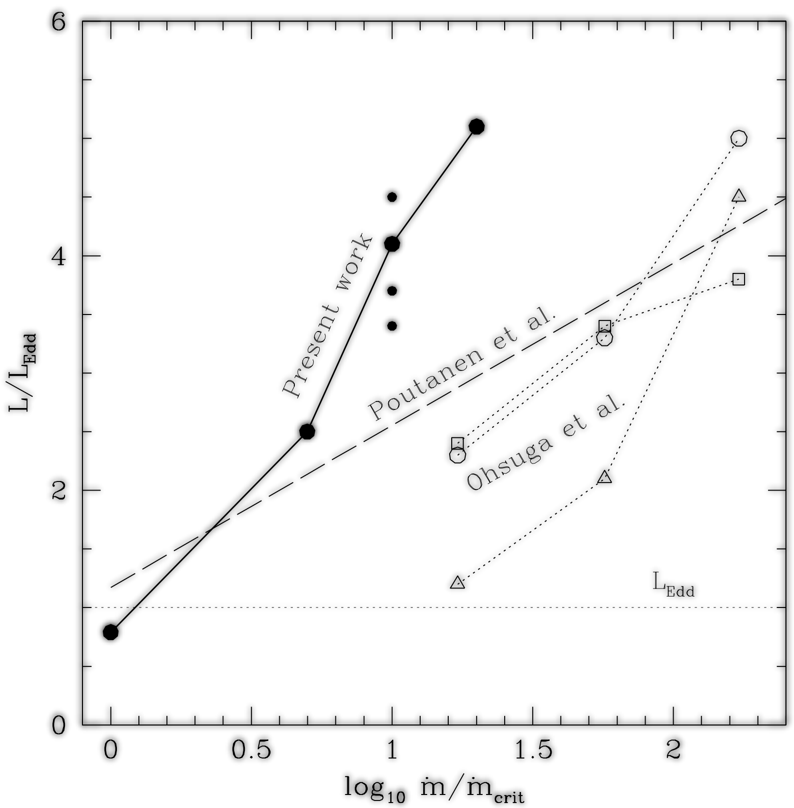
Dotan & Shaviv 2012

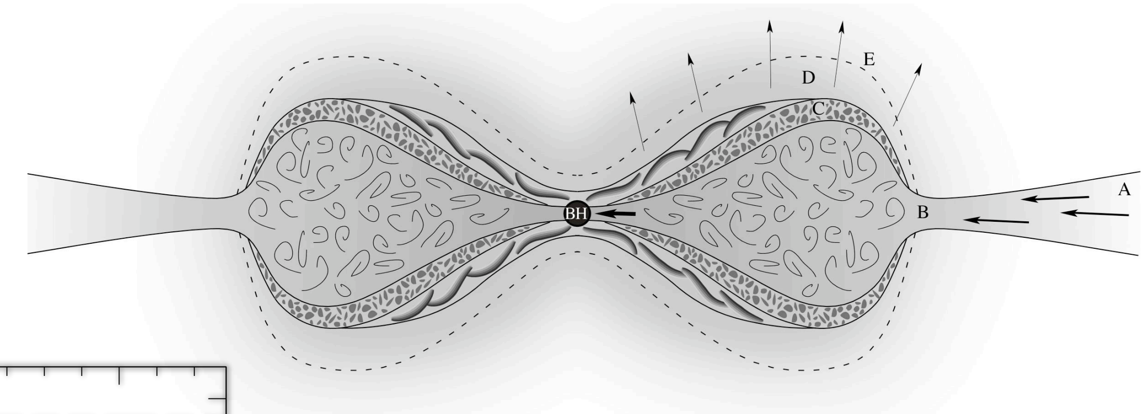
- Super-Edd states allow for super-Eddington accretion
- Predicted X-ray spectrum consistent with observations

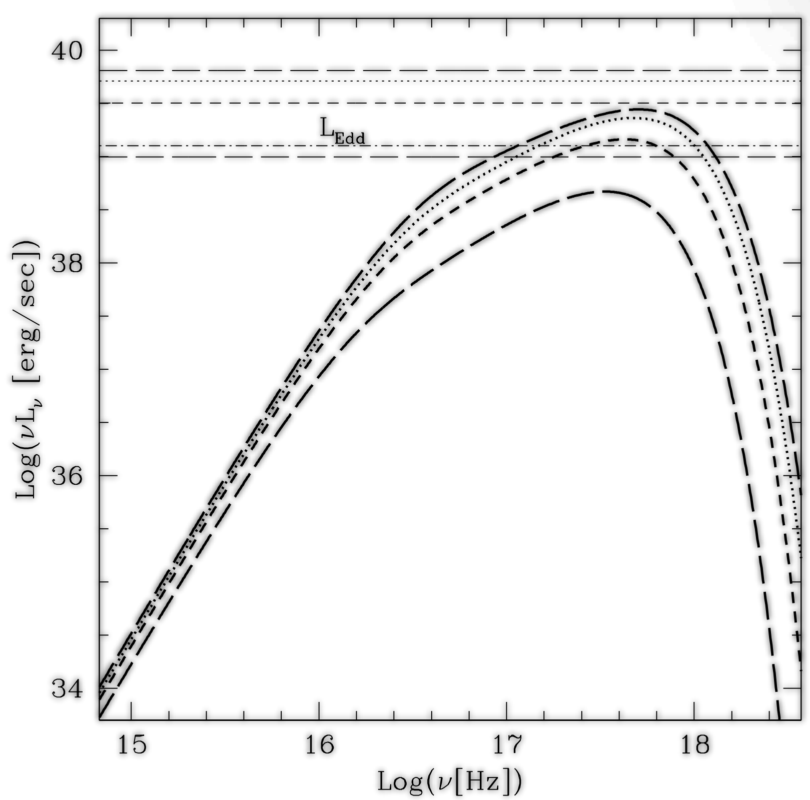


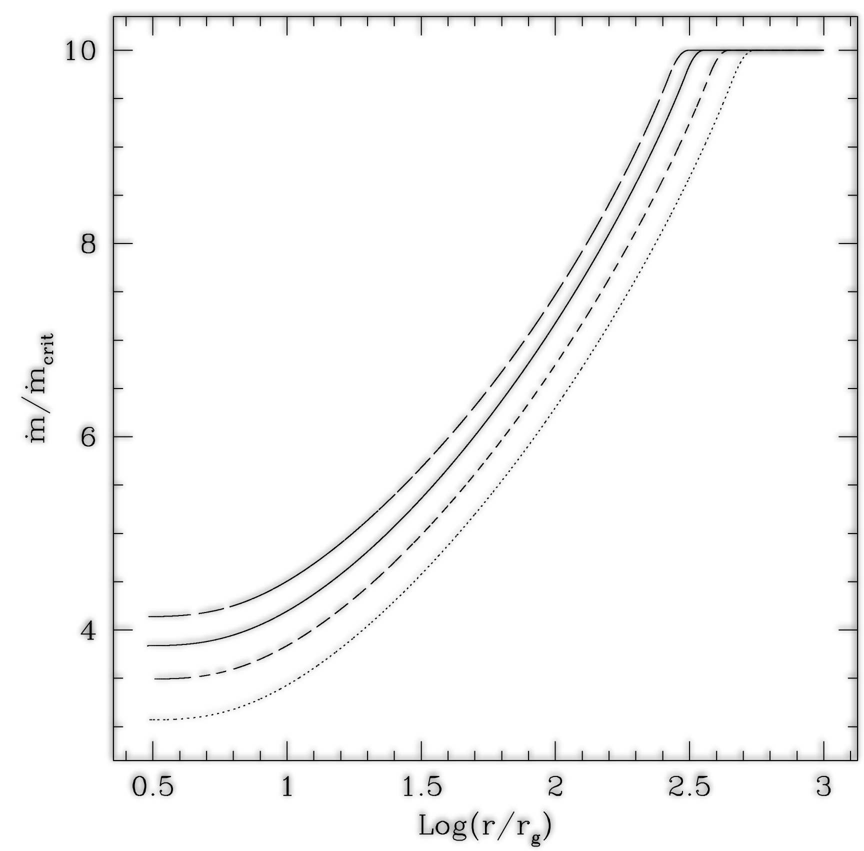


Predicts super-Eddington Accretion





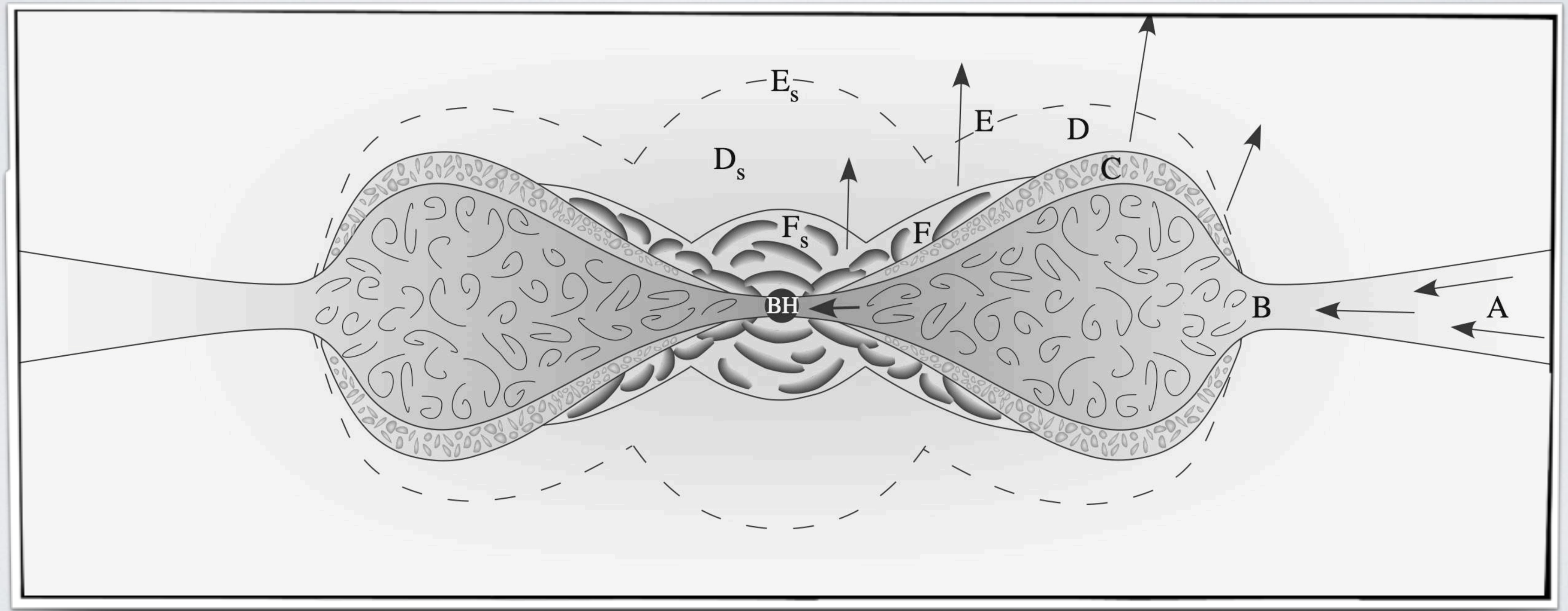




Dotan & Shaviv 2012

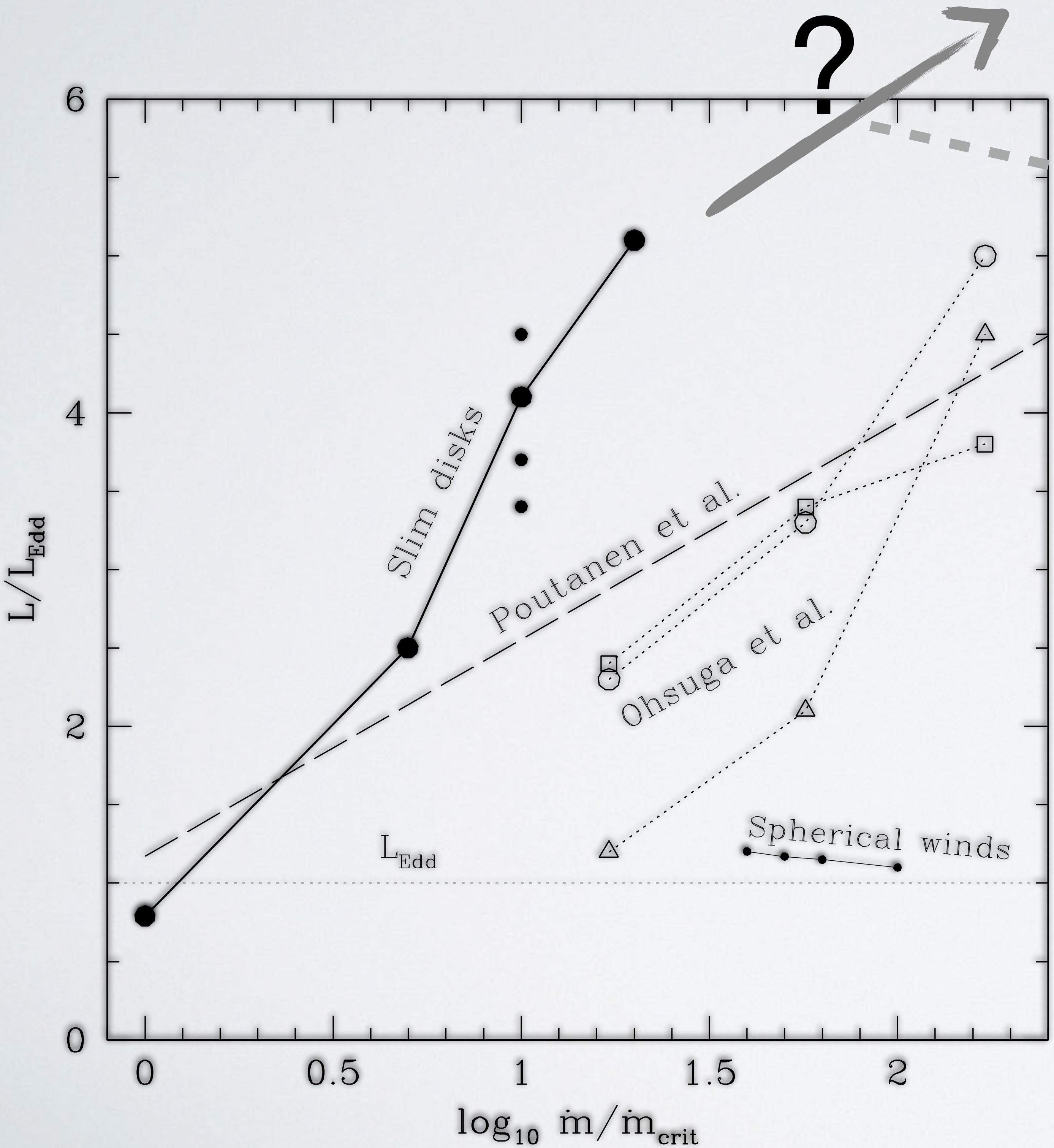
For high accretion rates

- For Mdot > 30 Mcrit, zph > r -> inconsistent solution
- Wind becomes spherical?



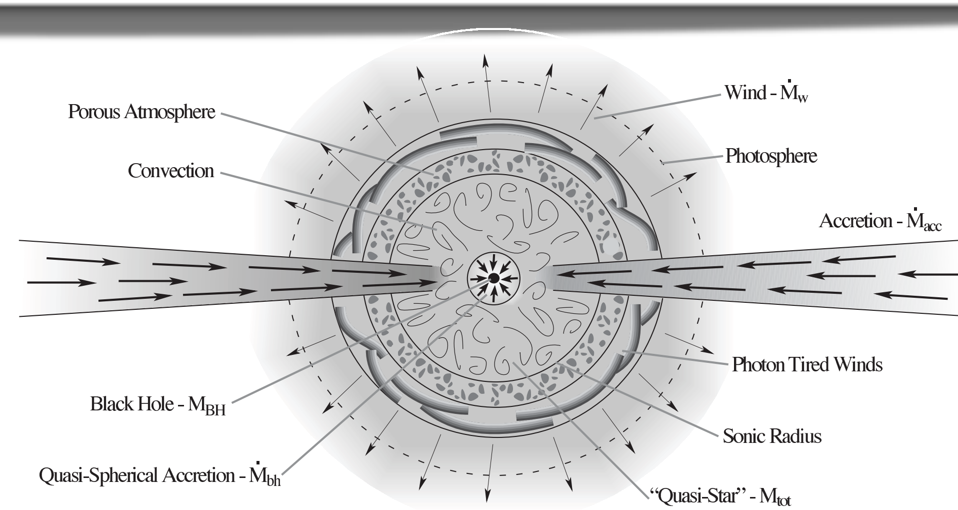
Slim disks with spherical winds

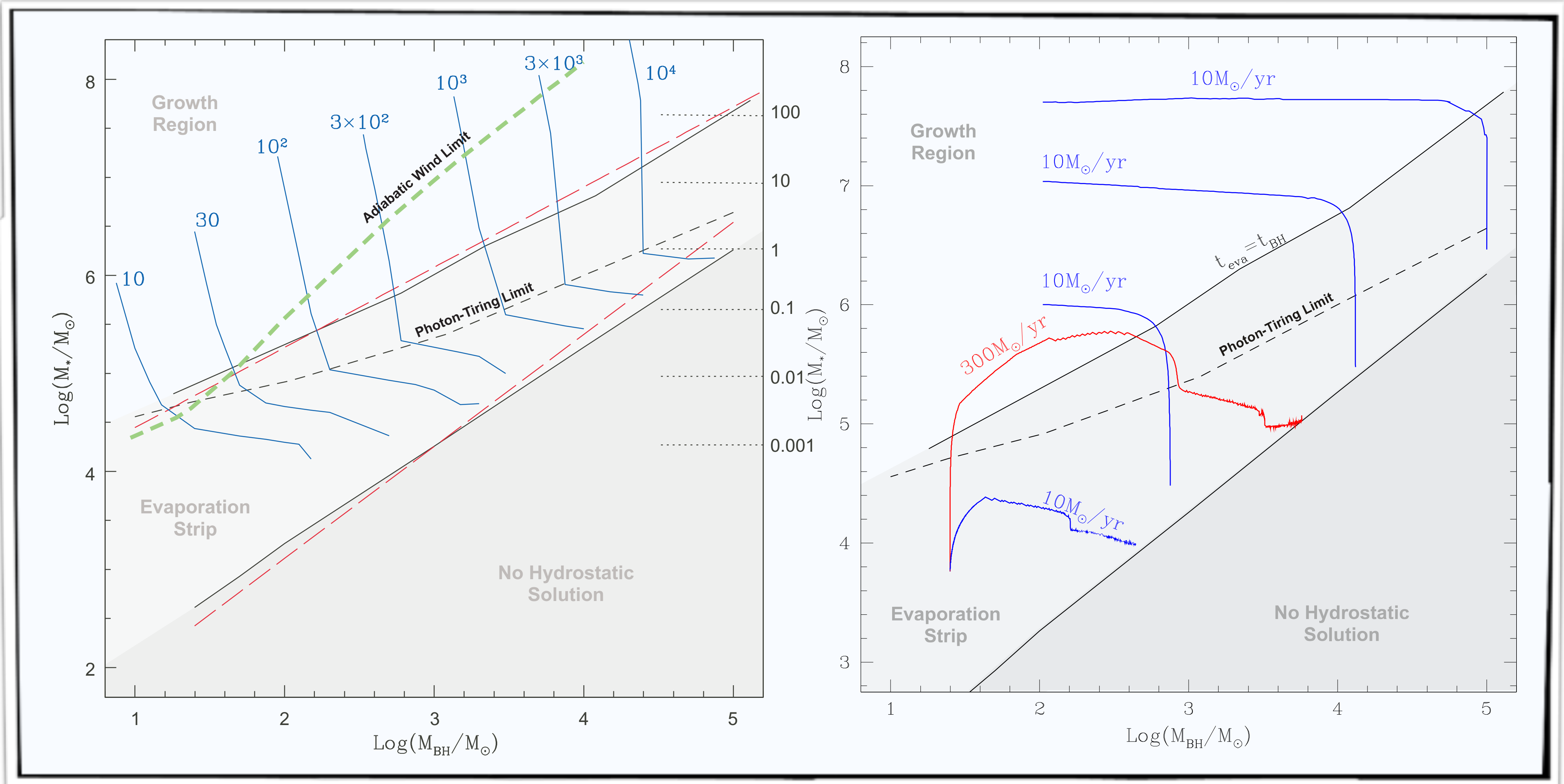
For high accretion rates



Quasi-star accretion

- Another accretion geometry is that of "quasi-stars"





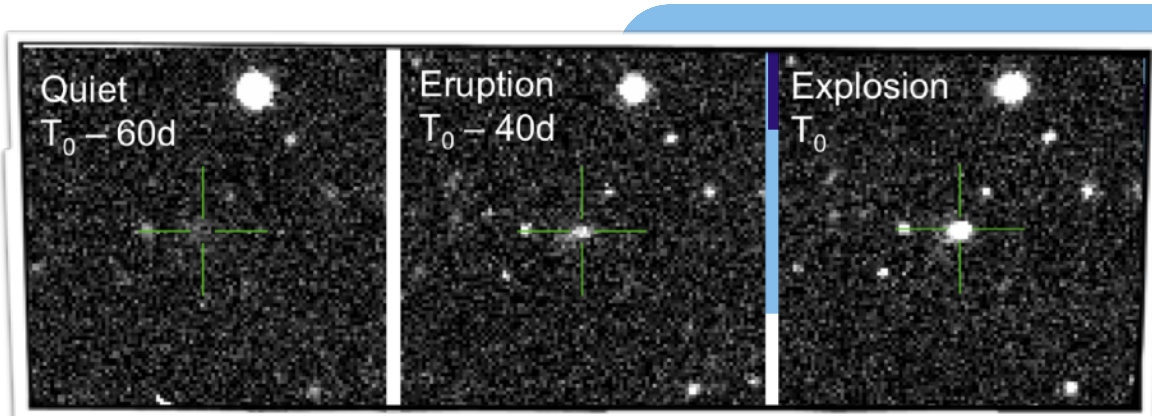
Dotan Rossi & Shaviv 2012

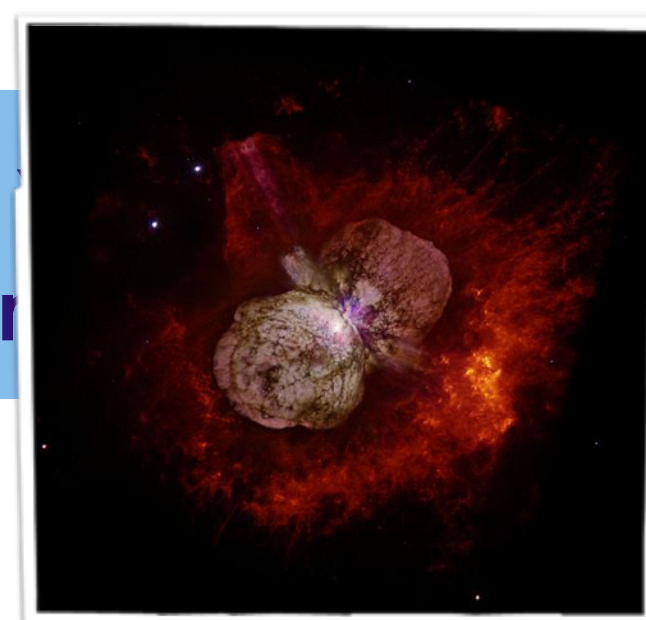
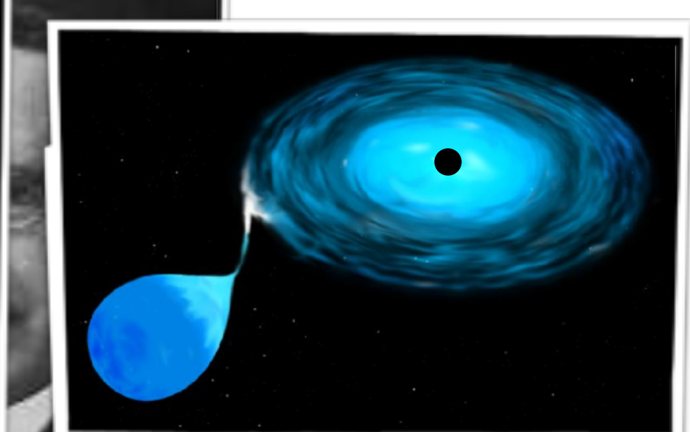
Summary

- The Eddington luminosity is not a limit!
- Super-Eddington states exist
  They have strong winds

$$\dot{m} = \mathcal{W}\frac{(L - L_{Edd})}{v_s c}$$

- Super-Eddington states explain a range of astrophysical phenomena



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- Calanit Dotan & Elena Rossi (Accretion)
- Yair Arcavi & Avishai Gal Yam (IIn pre cursors, SN imposters)