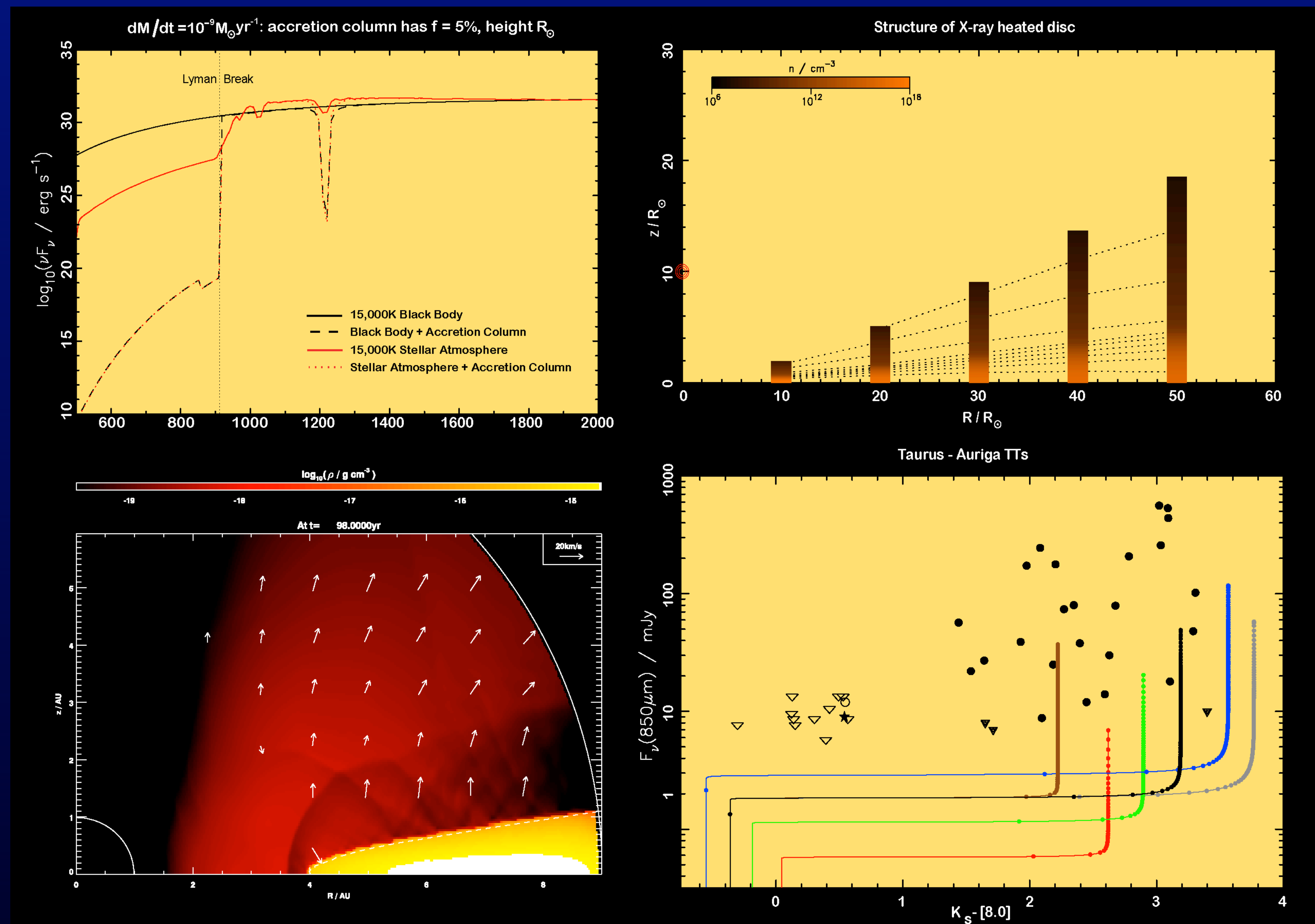
Evolution & dispersal of gas & dust discs



Richard Alexander

JILA, University of Colorado

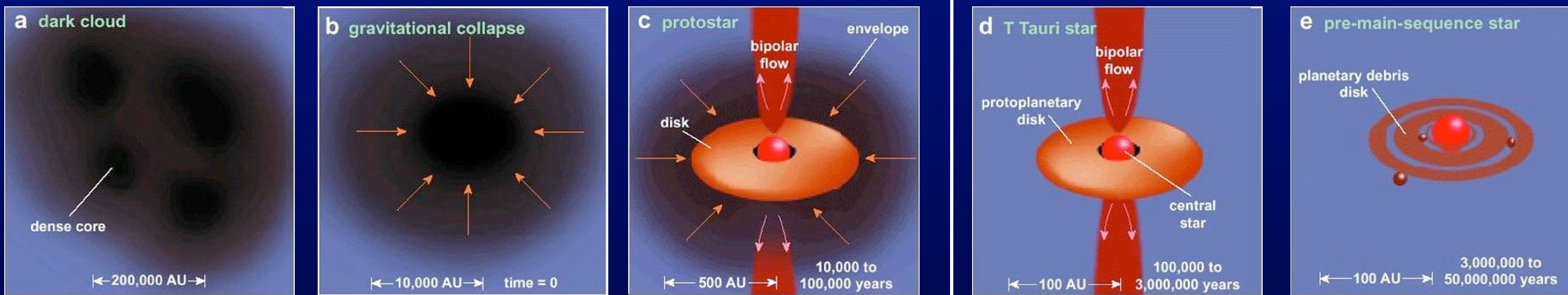
"Circumstellar discs at high angular resolution"

Porto, June 1st 2007

Outline

- Introduction
  - Observational motivation; constraints on timescales
  - Mechanisms driving disc evolution (qualitative)
- Gas dynamics
  - Basic photoevaporation theory
  - Evolutionary models; comparison to observations
- Dust dynamics (and growth)
  - Forces affecting dust: diffusion, gas-drag, settling
  - Introduction to grain growth and planetesimal formation
- "Transition" discs
  - Observational review
  - Comparison to models

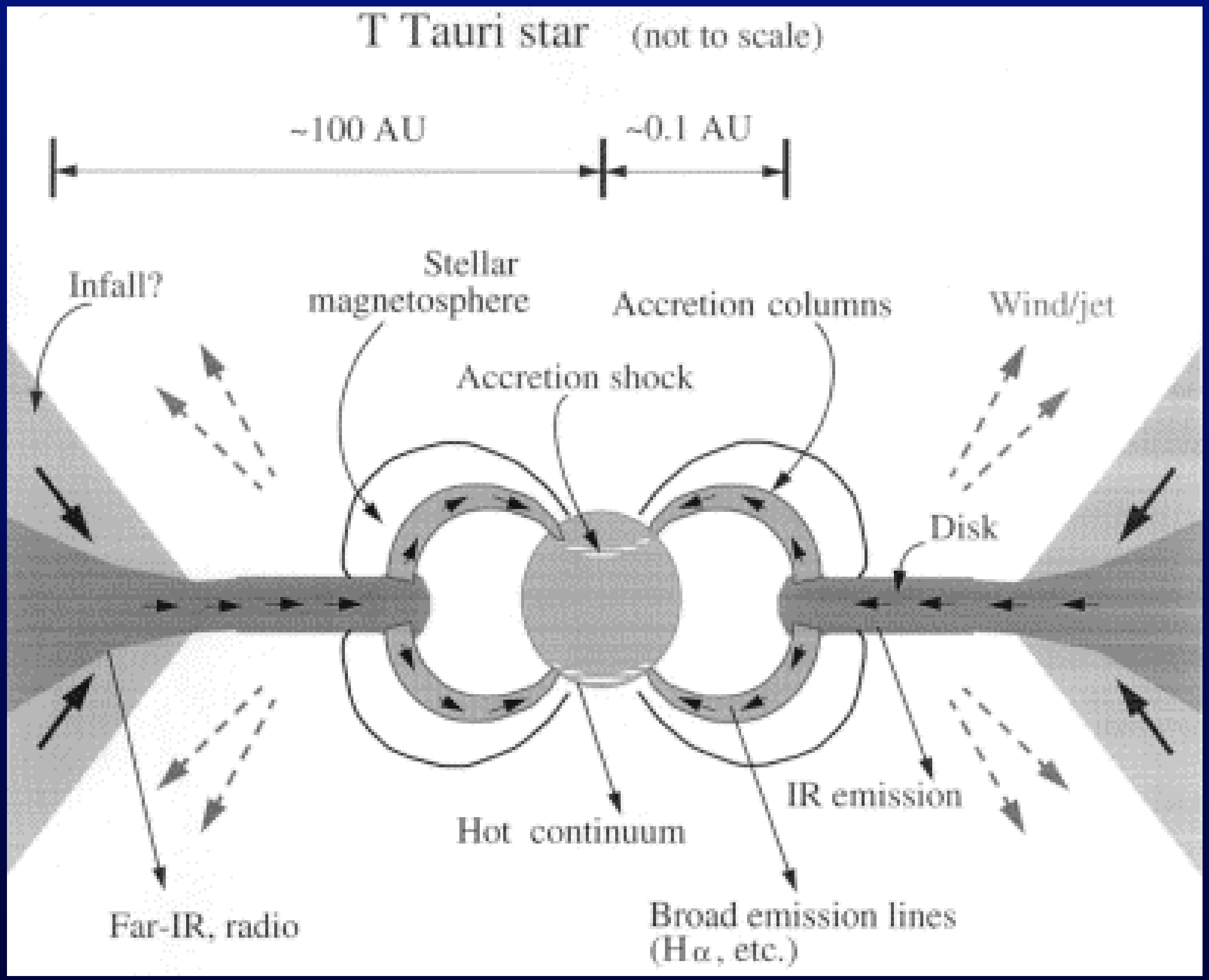
Background: The Star Formation Paradigm



Dense cores/ dark clouds of molecular gas	Pre-stellar core with infalling envelope	Protostar with bipolar outflow	Optically thick disc	Dispersed disc/planets?
			Classical T Tauri (CTT)	Weak-lined T Tauri (WTT)
	(IR) Class 0	IR Class I	IR Class II	IR Class III

Figures from Blitz (2004), after Shu et al. (1987)

What can we observe?



Hartmann (1998)

Gas accretion (<0.1AU): UV continuum, broad emission lines (e.g. Calvet & Gullbring 1998; Muzerolle et al. 2000)

Warm gas (~0.1AU): CO fundamental, H_2 electronic transitions (e.g. Najita et al. 2003; Herczeg et al. 2004)

Warm dust (<1AU): IR emission (e.g. Kenyon & Hartmann 1995; many others)

Cold gas (>10AU): CO rotational transitions, H_2 rotational transitions(?) (e.g. Körner & Sargent 1995; Dutrey et al. 1996)

Cold dust (>10AU): (sub-)mm continuum (Beckwith et al. 1990; Andrews & Williams 2005).

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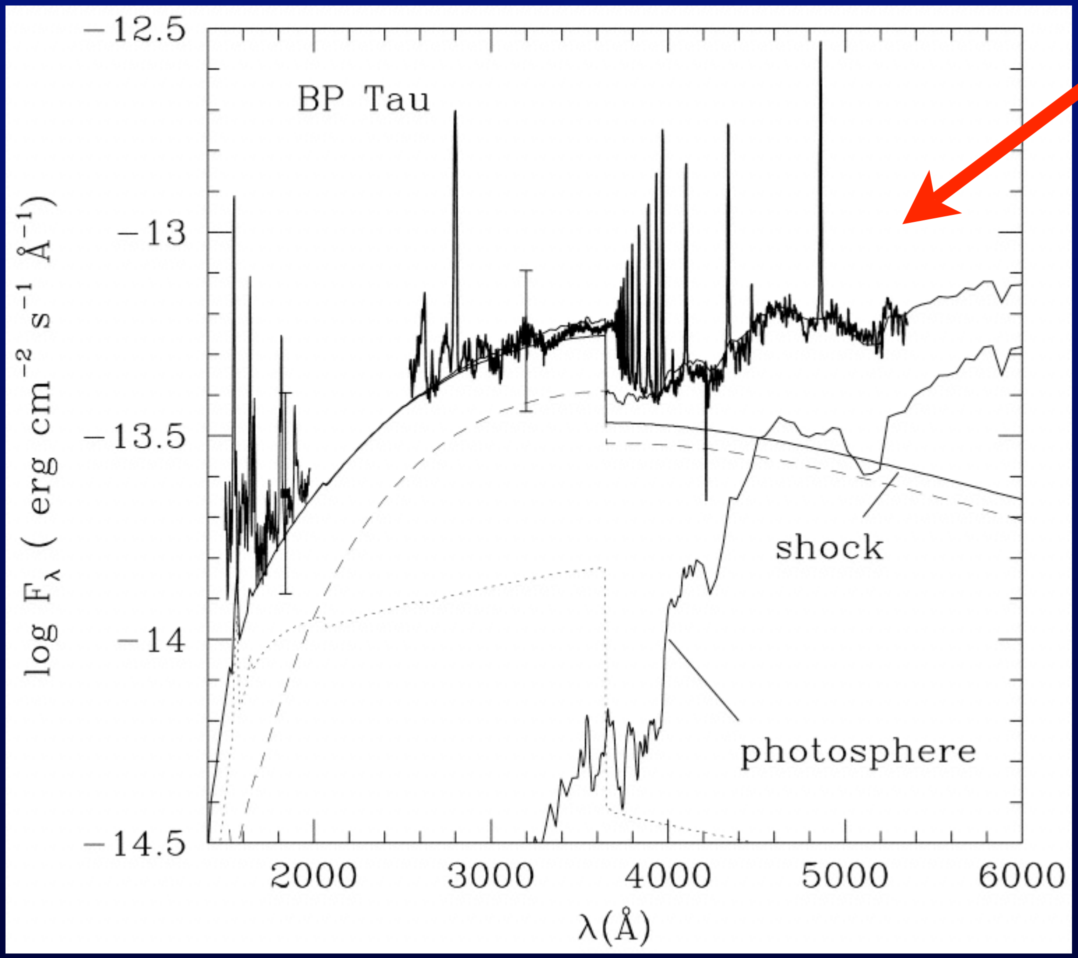

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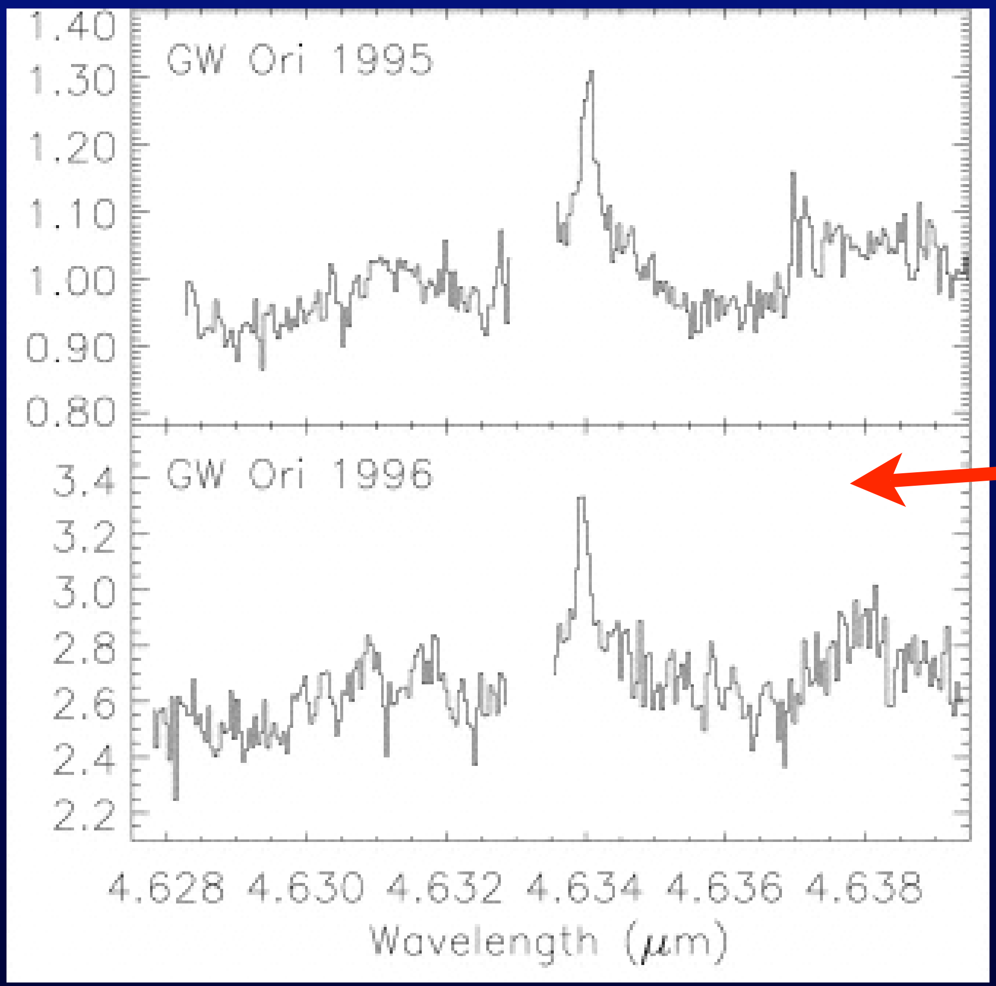

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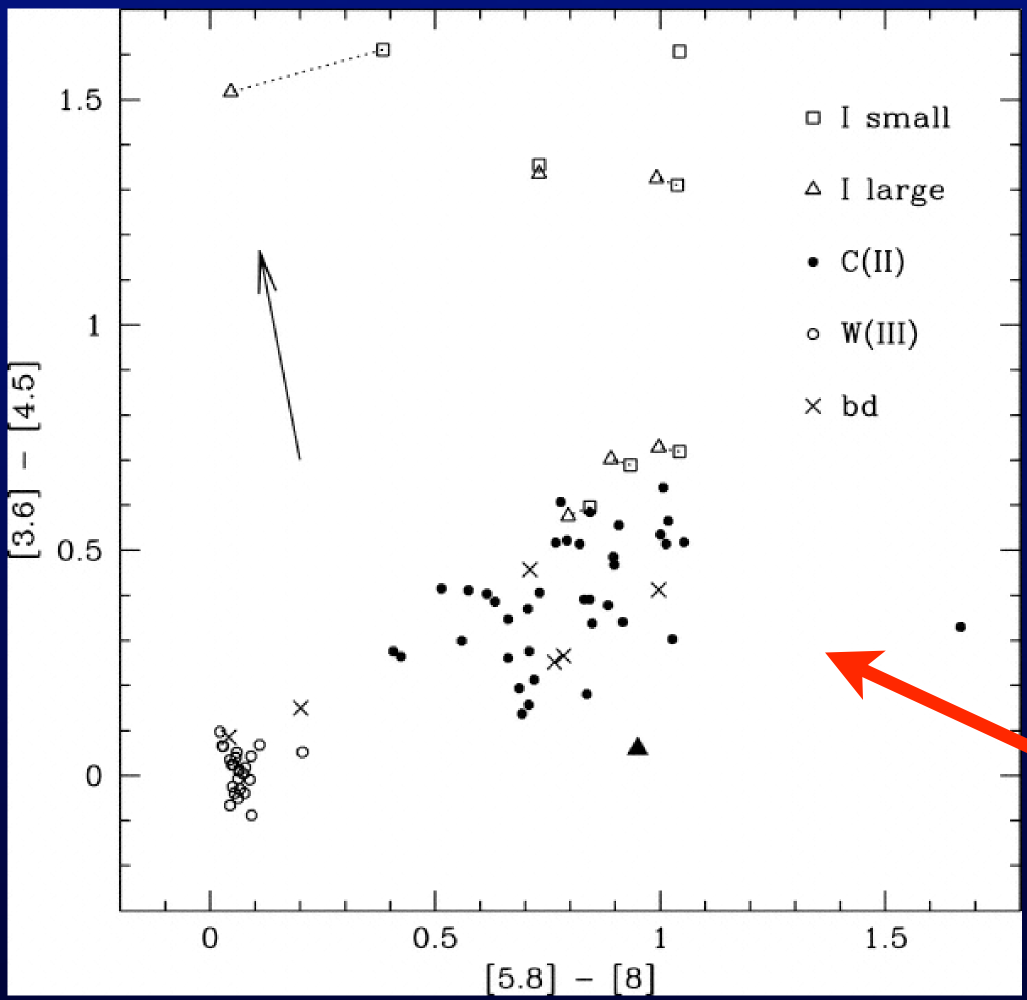

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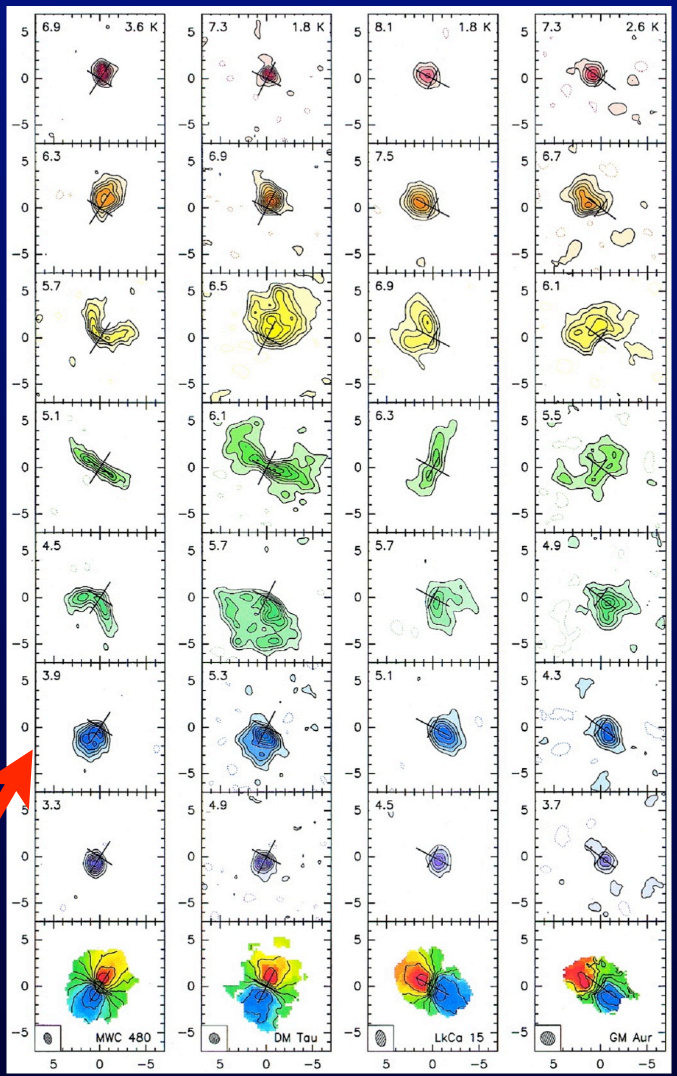

Simon et al. (2000)

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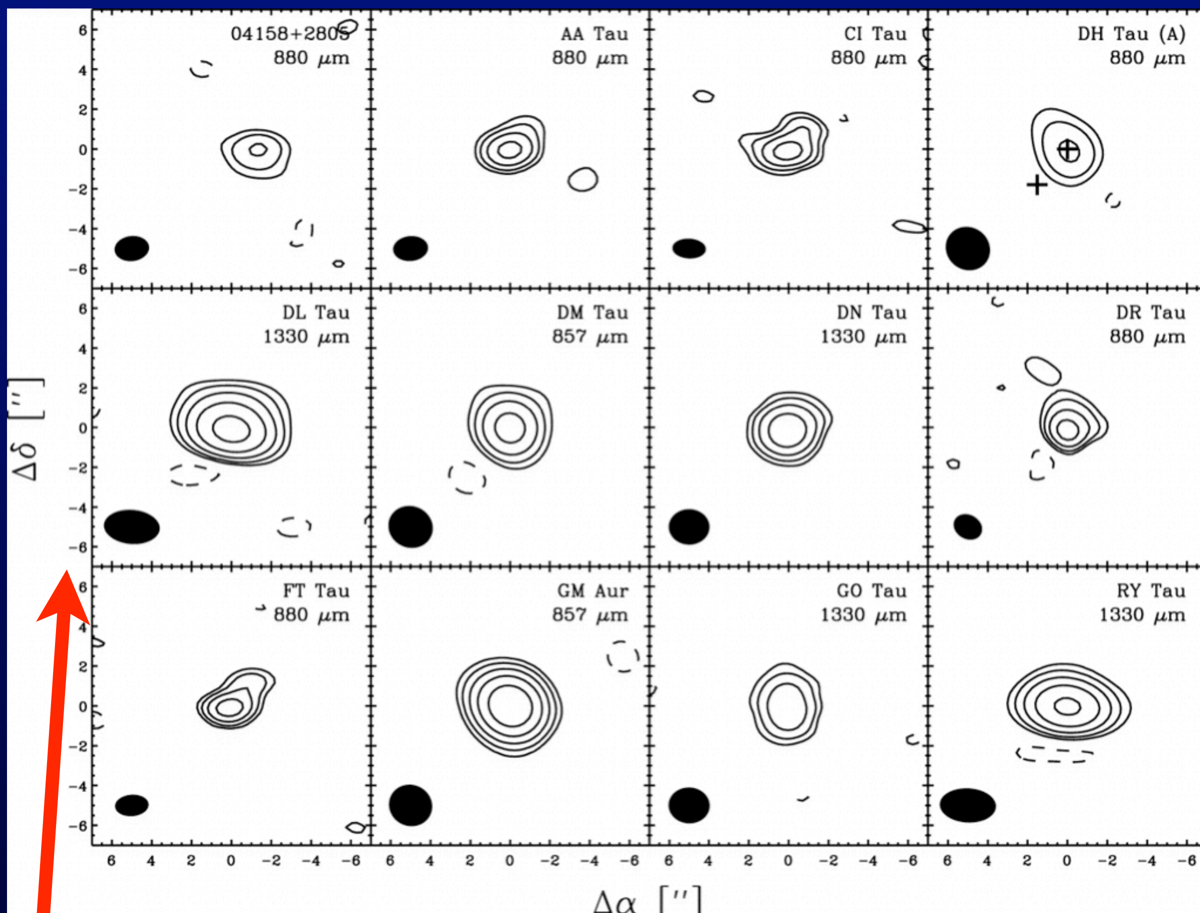

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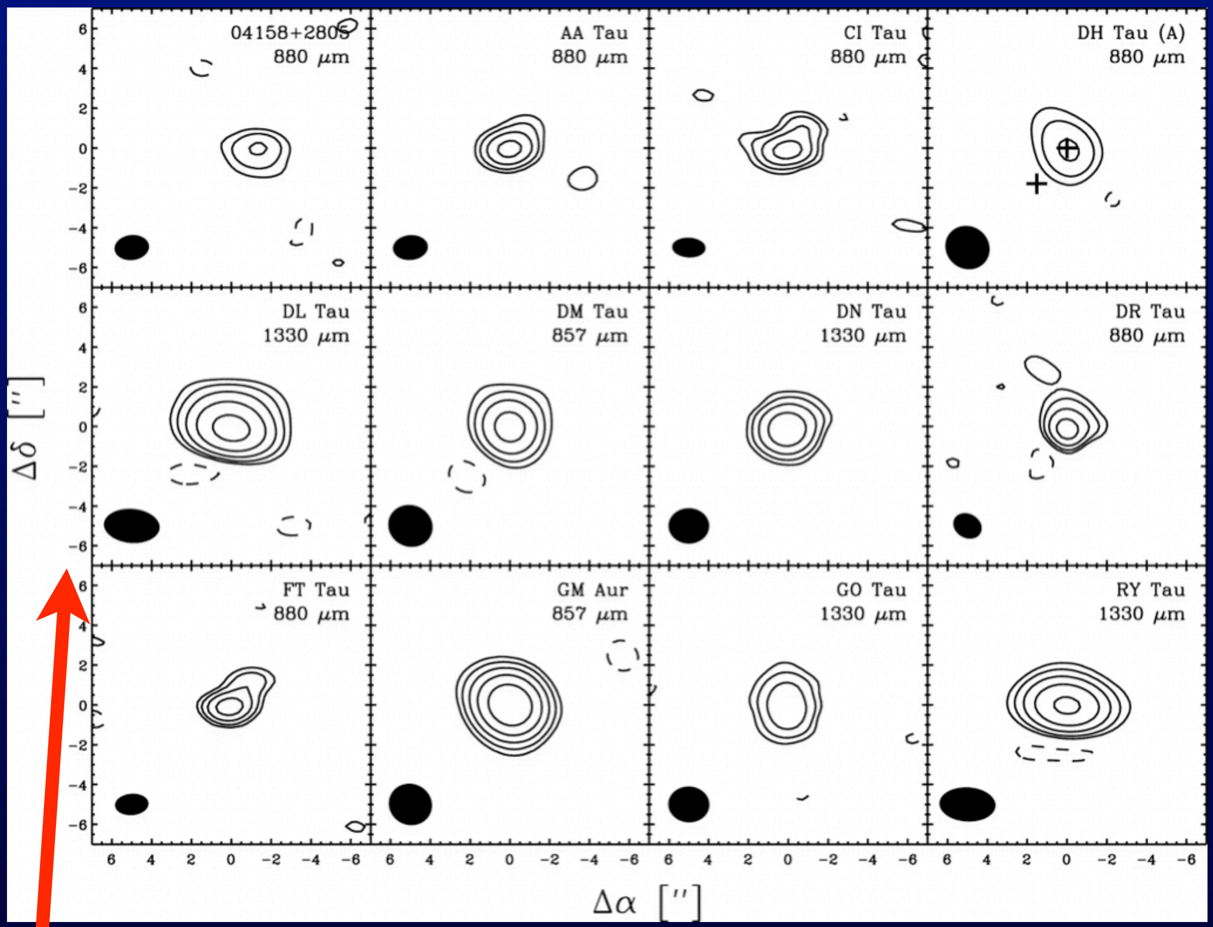

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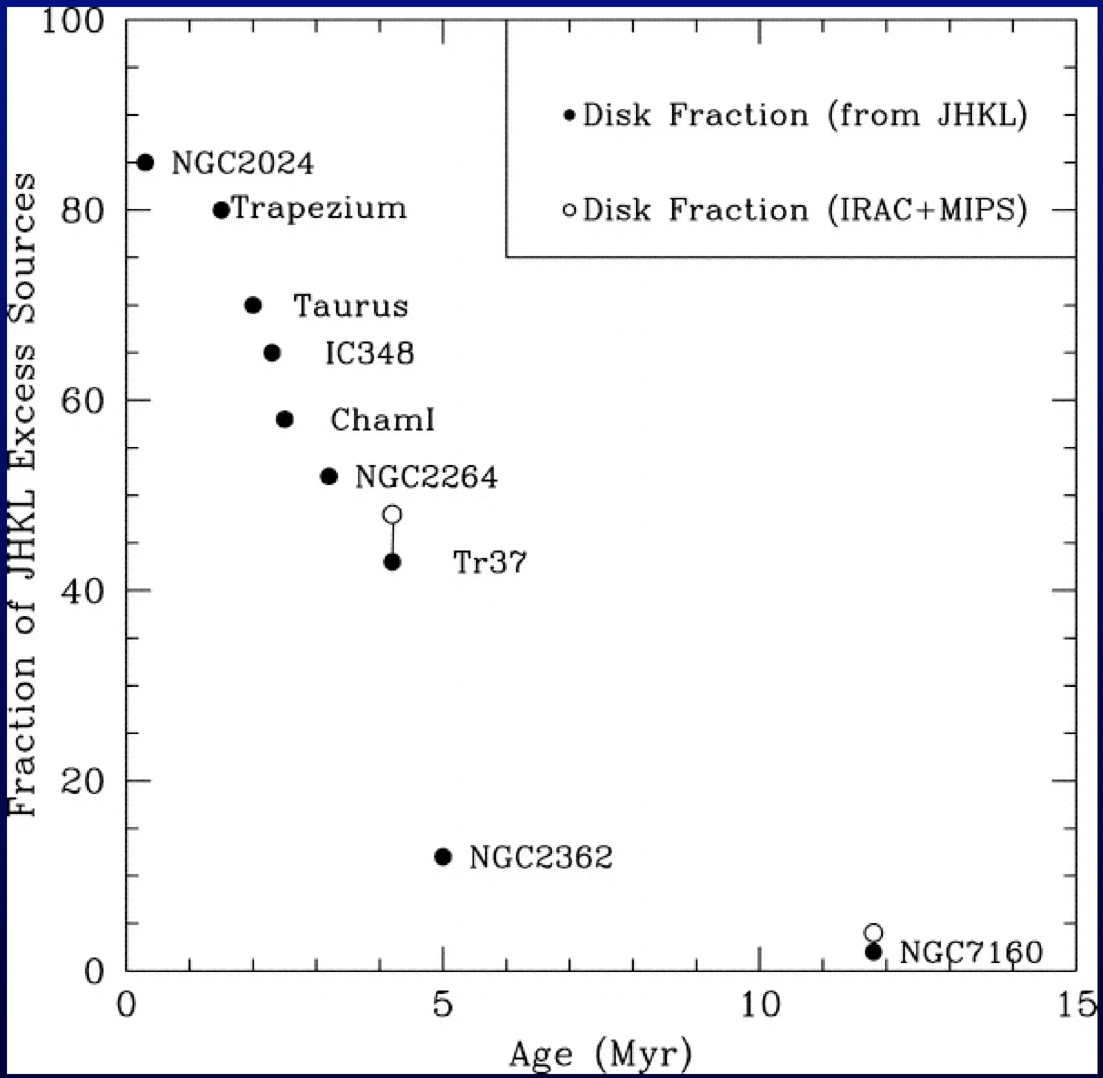
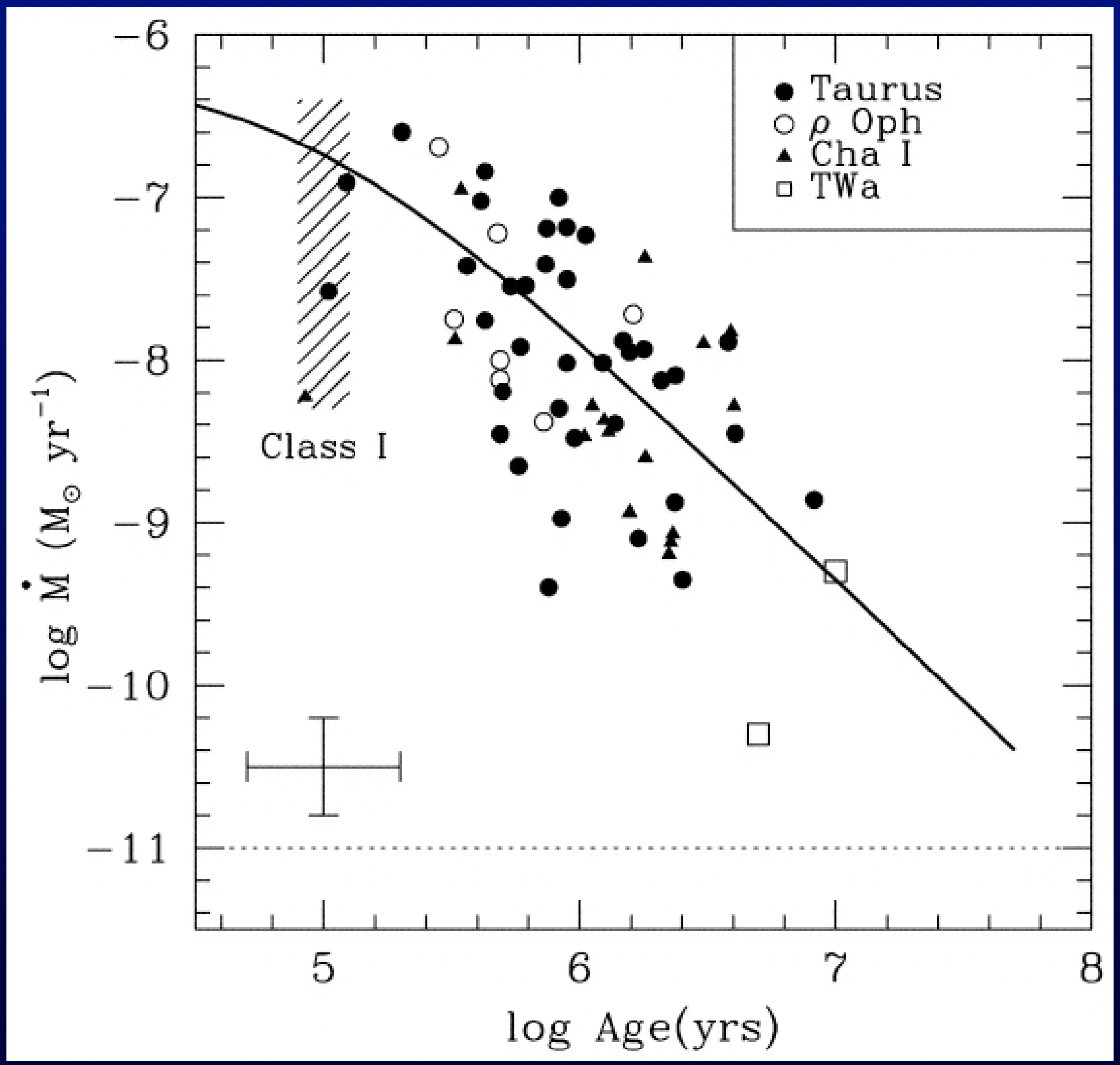
Gas dominates disc mass

Dust dominates disc opacity

Observations of disc evolution



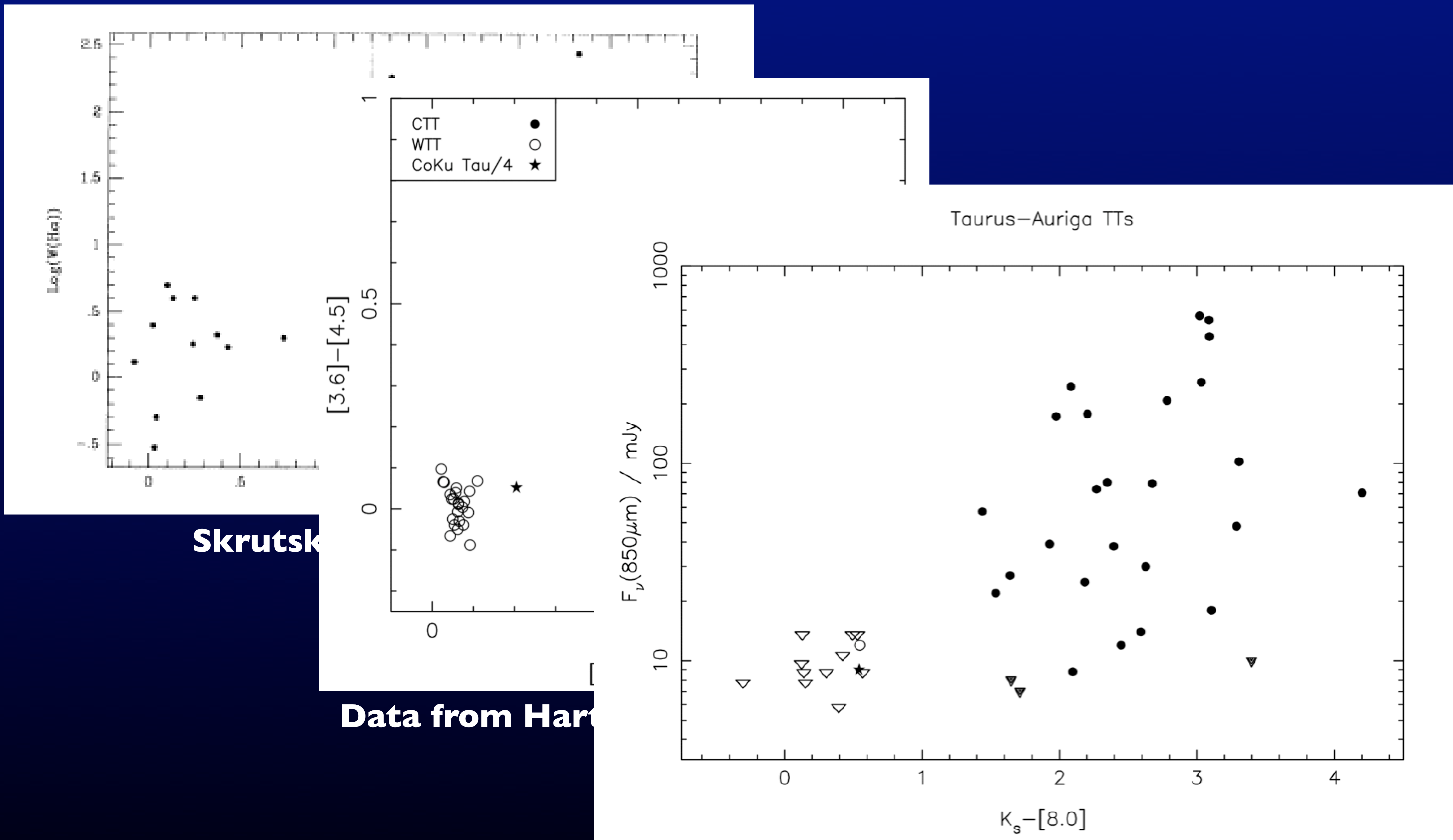
Sicilia-Aguilar et al. (2006)



Muzerolle et al. (2000)

- Typical (viscous) evolutionary timescale is ~few Myr.
- Large scatter in lifetimes: some discs are gone at 1Myr, some discs persist to 10Myr and beyond.

Observations of disc dispersal



Skrutsk

Data from Hart

Data from Hartmann et al. (2005), Andrews & Williams (2005)

Observational Constraints

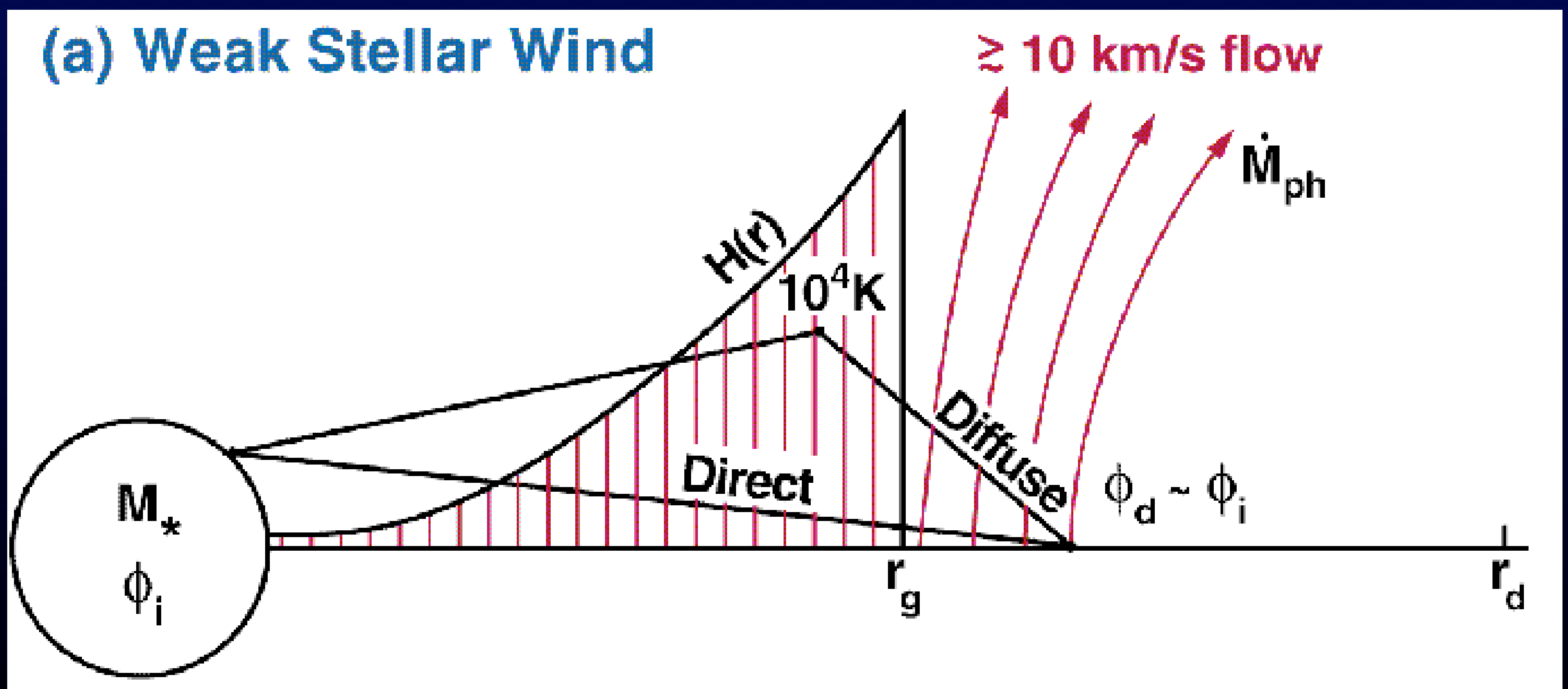
- Disc lifetimes are ~Myr, with large scatter.
- CTTs and WTTs co-exist at same age in same clusters.
- Disc masses range from $>0.1M_{\odot}$ to $\leq 0.001M_{\odot}$.
- Accretion rates span $>10^{-7}M_{\odot}yr^{-1}$ to $\leq 10^{-10}M_{\odot}yr^{-1}$.
- Termination of accretion roughly contemporaneous with disc clearing.
- Discs are cleared rapidly (in $\sim 10^{5}$yr), across entire radial extent of disc.
- Although most stars form in clusters, disc evolution does not appear to depend strongly on environment (at least in clusters such as the ONC, e.g. Eisner & Carpenter 2006).

What processes affect (gas) disc evolution?

- “Viscous” evolution, due to radial transport of angular momentum. (See lectures by Lodato, Ferreira.)
- Disc winds/jets, which can remove angular momentum from disc (e.g. Shu et al. PPIV, Königl & Pudritz PPIV).
- Dynamical interactions with other stars: tidal stripping of disc (e.g. Clarke & Pringle 1993; Scally & Clarke 2002).
- Evaporation by energetic photons, from both star and cluster (e.g. Hollenbach et al. 1994, rest of this lecture!).
- Hollenbach et al. (PPIV), consider all and conclude that:
  - Viscous evolution dominates for radii ≲ 10AU.
  - Photoevaporation dominates for radii ≳ 10AU.

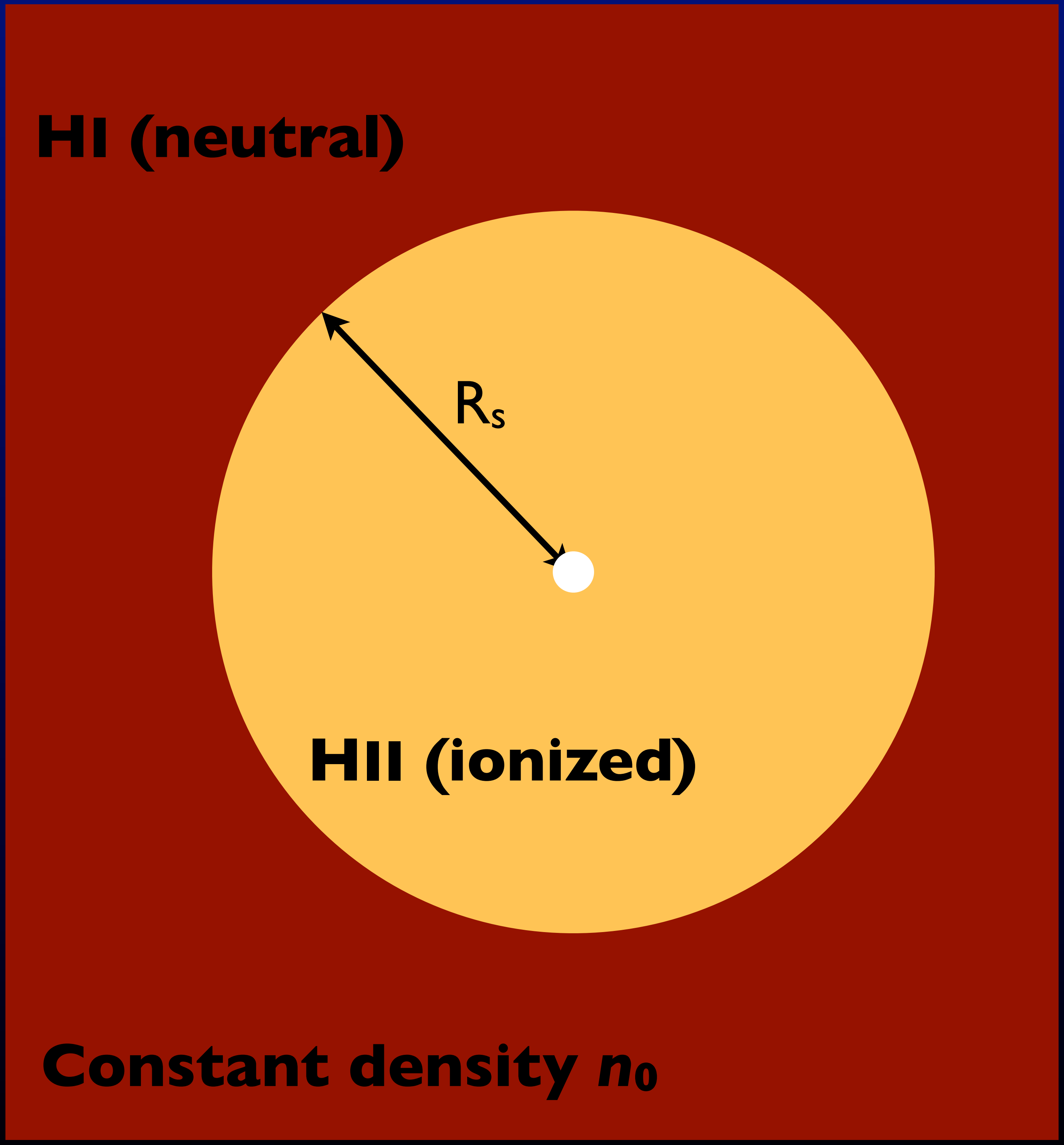
Disc Photoevaporation

- First suggested as long ago as Bally & Scoville (1982)!
- Basic premise: UV/X-ray irradiation heats disc surface to >> midplane temperature.
- Originally applied to massive stars: first detailed models by Hollenbach, Johnstone, Shu et al. in early 1990s.



Hollenbach et al. (1994, 2000)

Recap: the Strömgren sphere



- Within R_s, ionizations (from star) balance recombinations:

$$\Phi = N_{\rm rec} = \int \alpha_{\rm B} n_0^2 dV$$

$$\Rightarrow \Phi = \int_0^{R_{\rm s}} 4\pi r^2 \alpha_{\rm B} n_0^2 dr = \frac{4}{3}\pi R_{\rm s}^3 \alpha_{\rm B} n_0^2$$

$$\Rightarrow R_{\rm s} = \left(\frac{3\Phi}{4\pi\alpha_{\rm B} n_0^2}\right)^{1/3}$$

- Note, however, that this is only the initial radius: the HII region expands with time.

Basic photoevaporation theory

Hollenbach et al. (1994)

- Basic length scale - “gravitational radius”:

$$v_{\mathrm{K}} = c_{\mathrm{s}} \qquad \Rightarrow \qquad R_{\mathrm{g}} = \frac{GM_*}{c_{\mathrm{s}}^2} = 8.9\left(\frac{M_*}{\mathrm{M}_\odot}\right)\mathrm{AU} \quad \text{for} \quad c_{\mathrm{s}} = 10\mathrm{km/s}$$

- Inside R_g, there is a bound disc atmosphere.
- Outside R_g, the ionized gas is unbound and flows as a wind.
- Wind rate depends on density at base of ionized layer:

$$\dot{\Sigma}_{\mathrm{wind}} \simeq \rho c_{\mathrm{s}}$$

Mass-loss rate per unit area

Density at base of ionized layer: compute from ionization balance

10km/s

Basic photoevaporation theory

Hollenbach et al. (1994)

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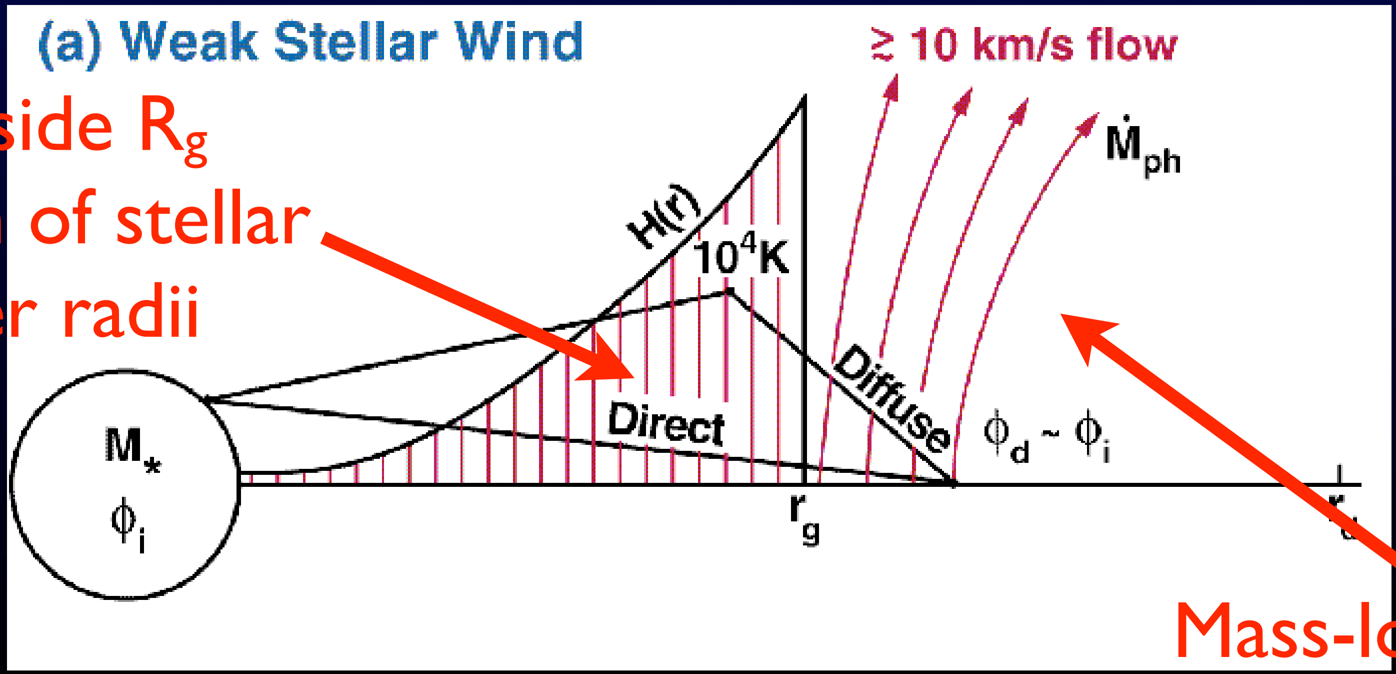
- Inside R_g, there is a bound disc atmosphere.
- Outside R_g, the ionized gas is unbound and flows as a wind.
- Wind rate depends on density at base of ionized layer:

Disc structure inside R_g controls penetration of stellar radiation to larger radii



Mass-loss outside R_g only

Basic (EUV) photoevaporation theory

Hollenbach et al. (1994)

- Ionization balance fixes density at base of atmosphere:

$$\alpha_{\rm B} R^3 n_0^2(R) \propto \Phi \quad , \quad R < R_{\rm g}$$

- Base density (in "bound" region) given by:

$$n_0(R) = n_{\rm g} \left(\frac{R}{R_{\rm g}}\right)^{-3/2} \quad \text{where} \quad n_{\rm g} = C \left(\frac{3\Phi}{4\pi\alpha_{\rm B} R_{\rm g}^3}\right)^{1/2} \quad , \quad R < R_{\rm g}$$

- Beyond R_g we have flow, and recombinations at R_g dominate at all radii. Geometric dilution of flux alters base density:

$$\alpha_{\rm B} R_{\rm g}^3 n_{\rm g}^2 \left(\frac{R_{\rm g}}{R}\right)^2 = \alpha_{\rm B} R^3 n_0^2(R) \quad , \quad R > R_{\rm g}$$

$$n_0(R) = n_{\rm g} \left(\frac{R}{R_{\rm g}}\right)^{-5/2} \quad , \quad R > R_{\rm g}$$

Basic (EUV) photoevaporation theory

Hollenbach et al. (1994)

- Density profile gives wind rate:

$$\dot{\Sigma}_{\rm wind}(R) = 2n_0(R)c_{\rm s}\mu m_{\rm H}$$

- Integrate and re-scale to TT parameters:

$$\dot{M}_{\rm wind} \simeq 4.4 \times 10^{-10} \left(\frac{\Phi}{10^{41}\,{\rm s}^{-1}}\right)^{1/2} \left(\frac{M_*}{1{\rm M}_\odot}\right)^{1/2} {\rm M}_\odot{\rm yr}^{-1}$$

- This analysis considers *static* problem only. More recent studies have included effects of dust (on radiative transfer), and hydrodynamic effects. These give quantitative differences, but qualitative picture remains the same.

More recent advances...

- Hydro effects: smaller "critical radius", sub-sonic launch velocity (e.g. Liffman 2003; Font et al. 2004).

$$R_{\rm crit} = 1.5\left(\frac{M_*}{{\rm M}_\odot}\right){\rm AU} \simeq 0.2R_{\rm g}\ ,\ \dot{M}_{\rm wind} = 1.6\times10^{-10}{\rm M}_\odot{\rm yr}^{-1}\left(\frac{\Phi}{10^{41}{\rm s}^{-1}}\right)^{1/2}\left(\frac{M_*}{1{\rm M}_\odot}\right)^{1/2}$$

- FUV (non-ionizing) heating typically heats to ~1000K, launch radius ~100AU (often > disc radius). PDR-type heating, much more complex radiative transfer problem (e.g. Johnstone et al. 1998; Adams et al. 2004).
- In case of external irradiation FUV (usually) dominates wind. Much success in explaining proplyd phenomenon, and also disc sizes in Orion nebula (e.g. Johnstone et al. 1998, Scally & Clarke 2002; Clarke 2007).

More recent advances...

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$R_{\rm crit} = 1.5$ … $\left(\frac{M_*}{1M_\odot}\right)^{1/2}$

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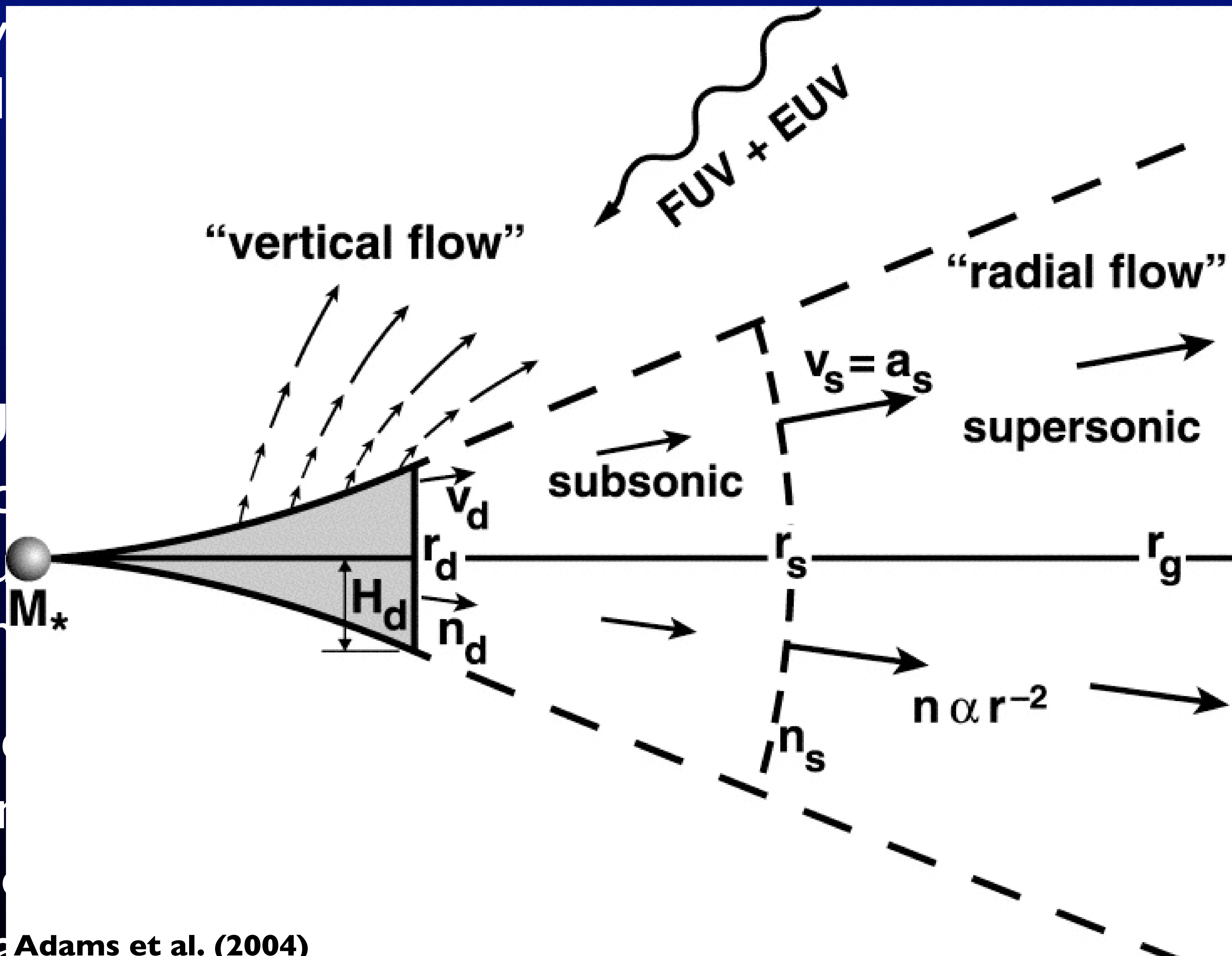
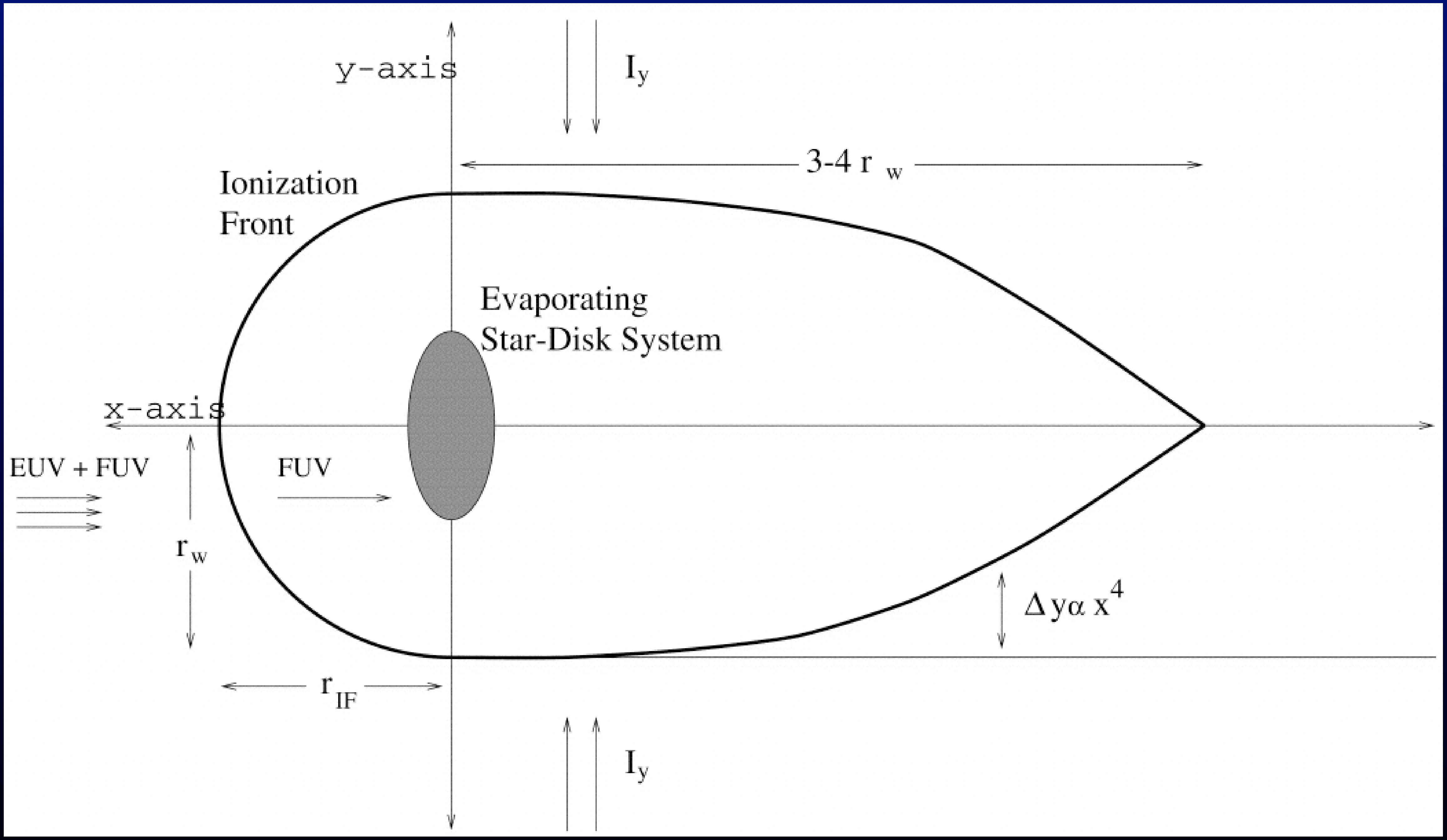


Adams et al. (2004)

External irradiation: the ONC "proplyds"

Johnstone et al. (1998)



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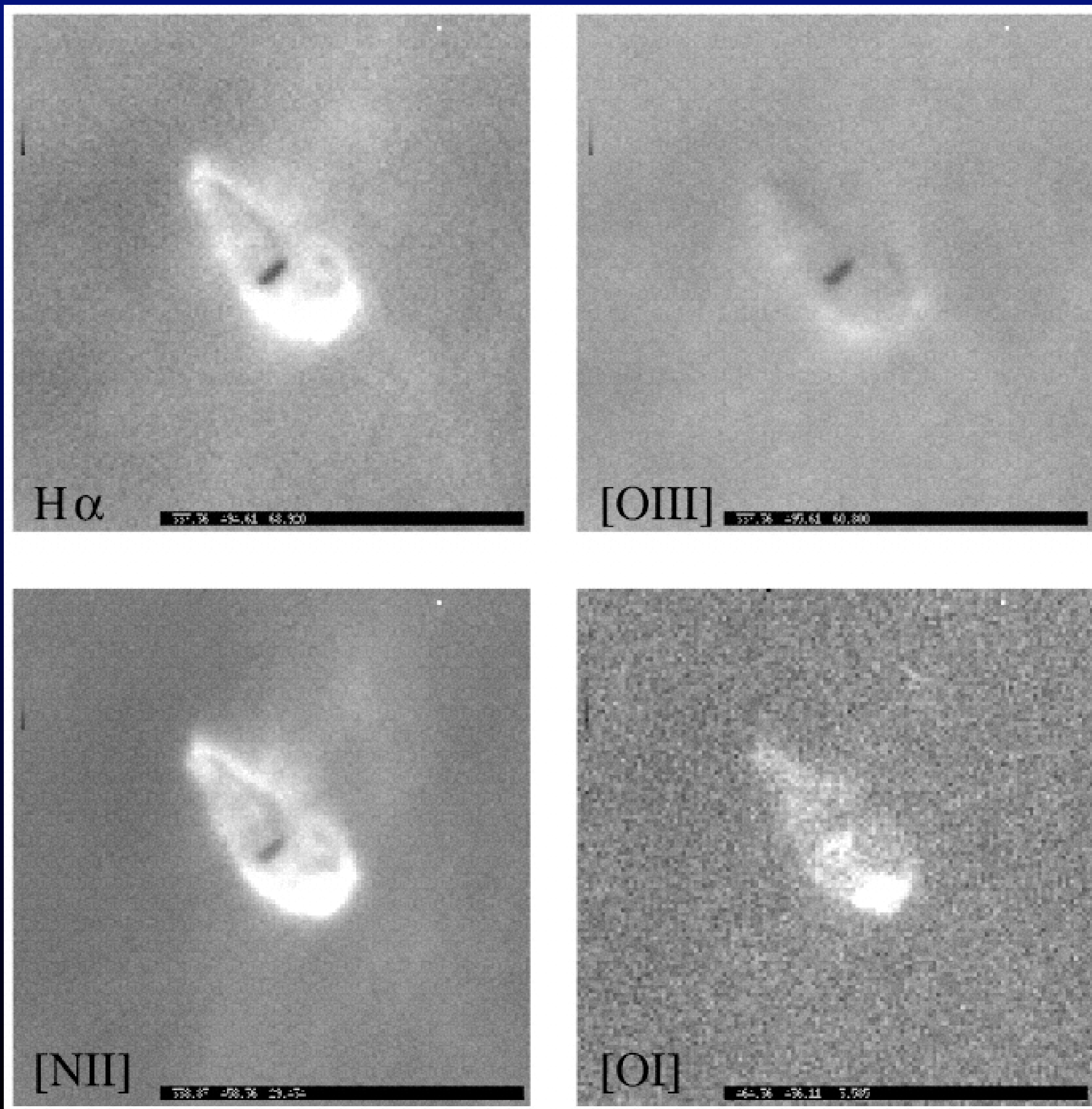
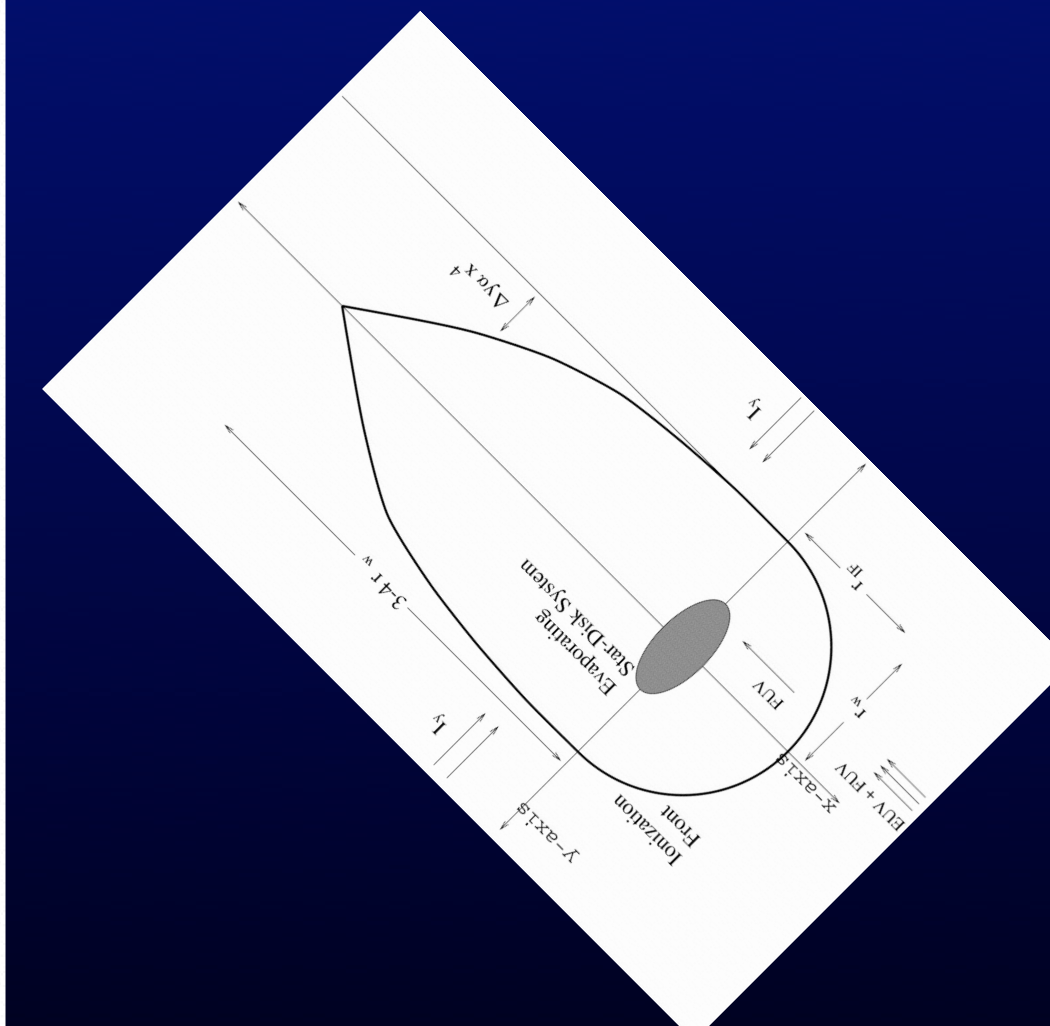
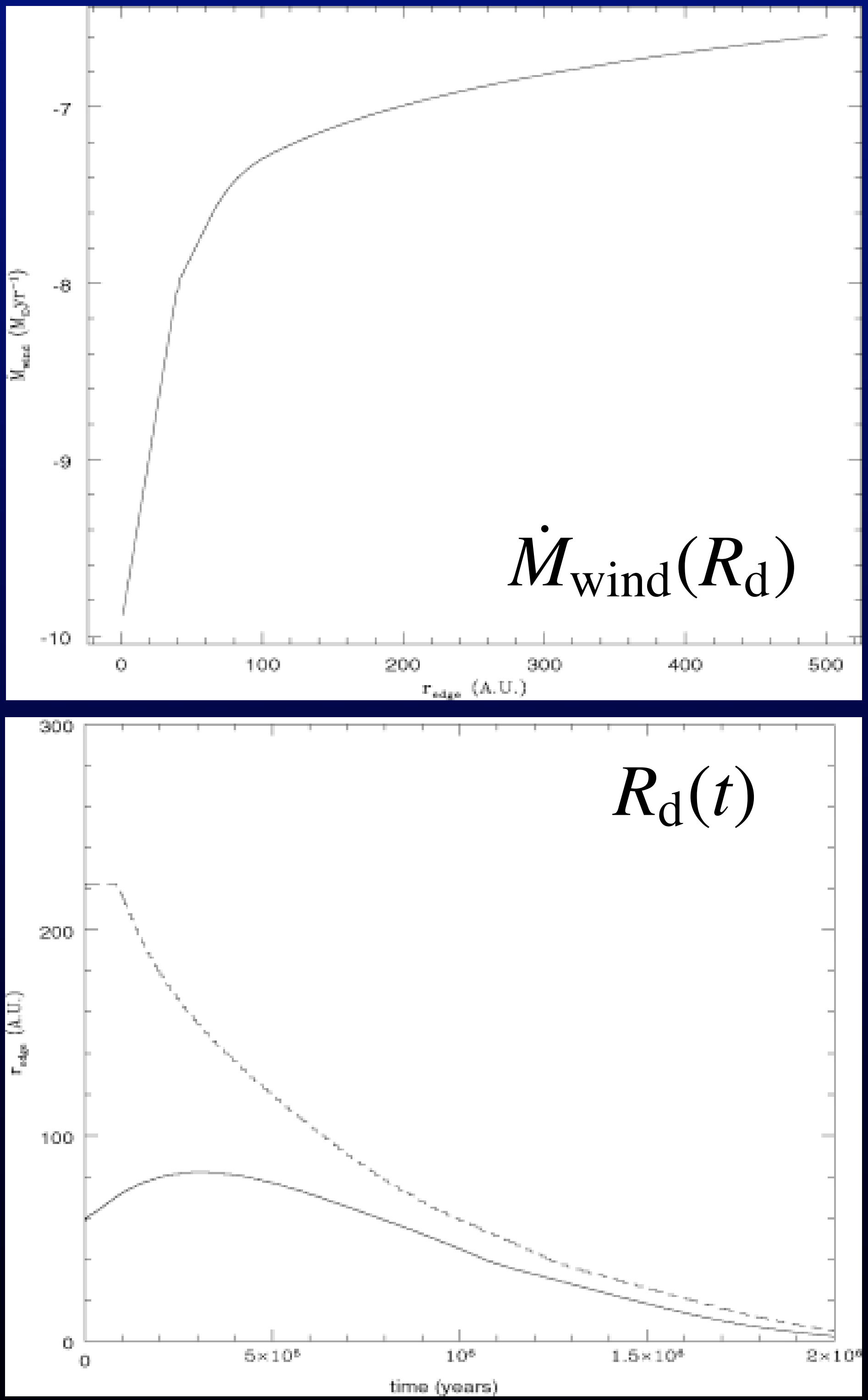




External irradiation + viscosity

Adams et al. (2004); Clarke (2007); Hollenbach & Gorti (in prep.)



Clarke (2007)

- Wind rate from external (FUV) heating is sharp function of radius.
- Discs evolve towards "quasi-steady", where viscous spreading at disc edge matches mass-loss from wind.
- Late time evolution not sensitive to initial disc sizes: dominant factor in evolution is initial disc mass.
- Provides good match to disc size distribution in ONC, and offers possible solution to "proplyd lifetime problem" (Clarke 2007).

Photoevaporation + viscous evolution

Clarke et al. (2001); Matsuyama et al. (2003); Ruden (2004)

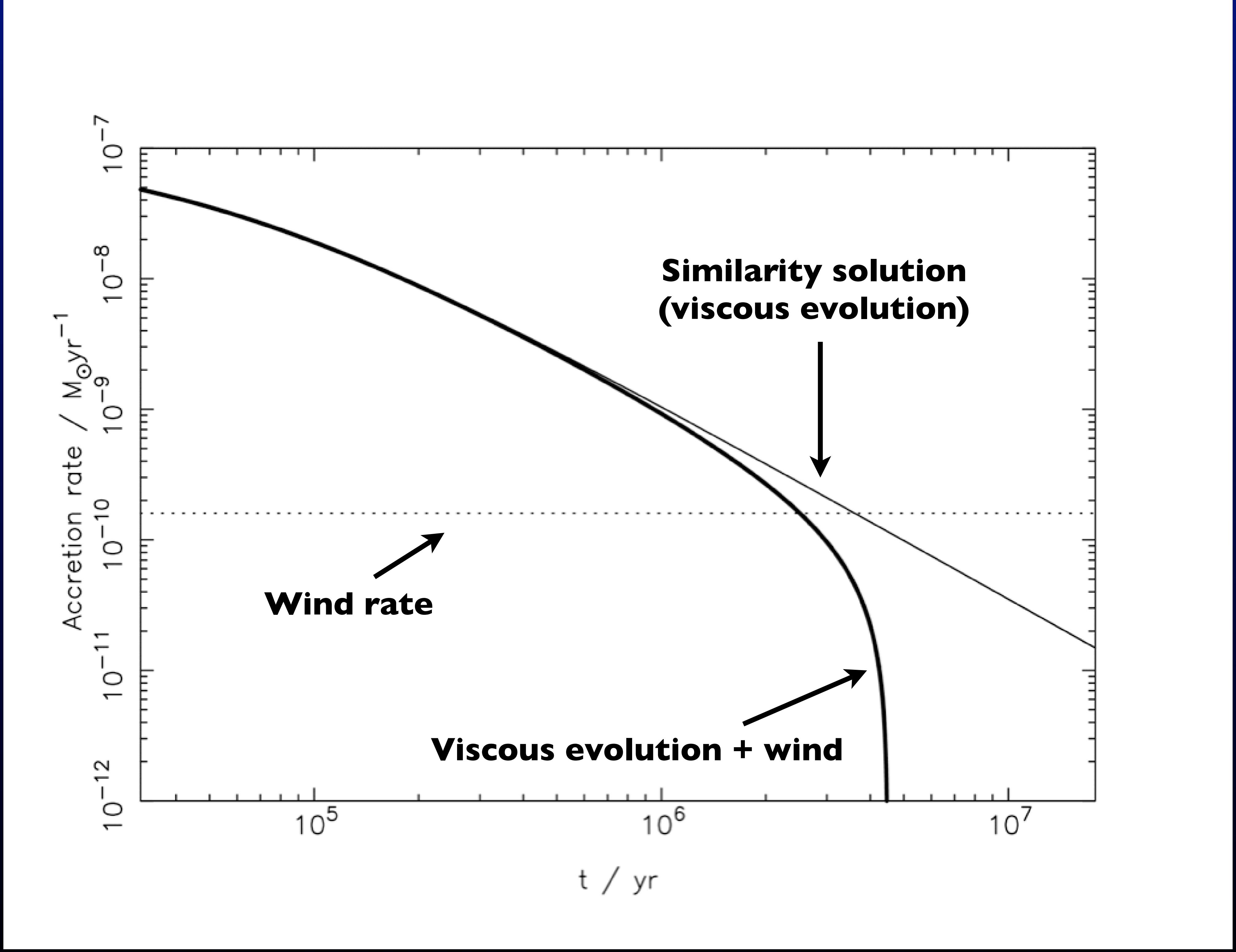
- Clarke et al. (2001) proposed the "UV-switch" model, where the wind interacts with a viscously evolving disc:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}\left(\nu \Sigma R^{1/2}\right)\right] - \dot{\Sigma}_{\mathrm{wind}}(R, t)$$

- As we saw, wind rate only depends on stellar ionizing luminosity, and is ~ constant (see later discussion).
- However, disc accretion rate falls with time. Initially accretion rate >> wind rate, but at late times these become comparable.
- Wind becomes important at late times.

Photoevaporation + viscous evolution

Clarke et al. (2001); Matsuyama et al. (2003); Ruden (2004)



Photoevaporation + viscous evolution

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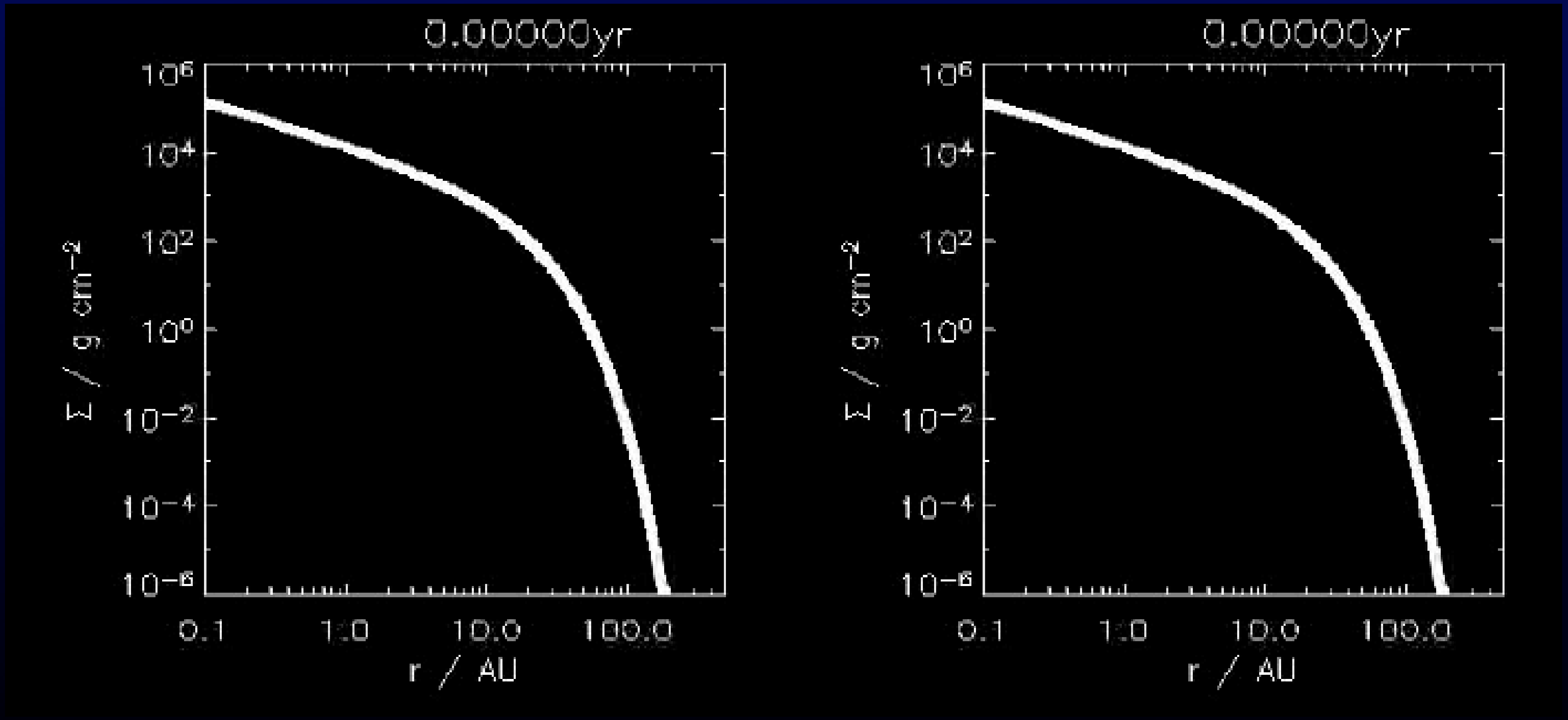
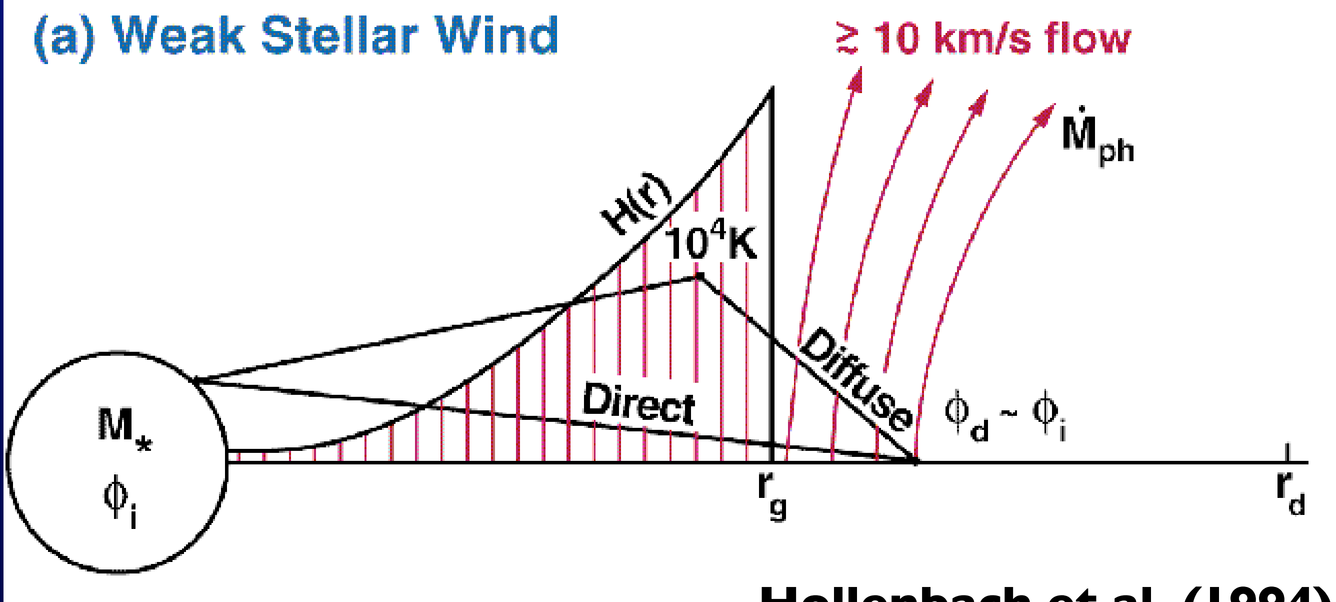
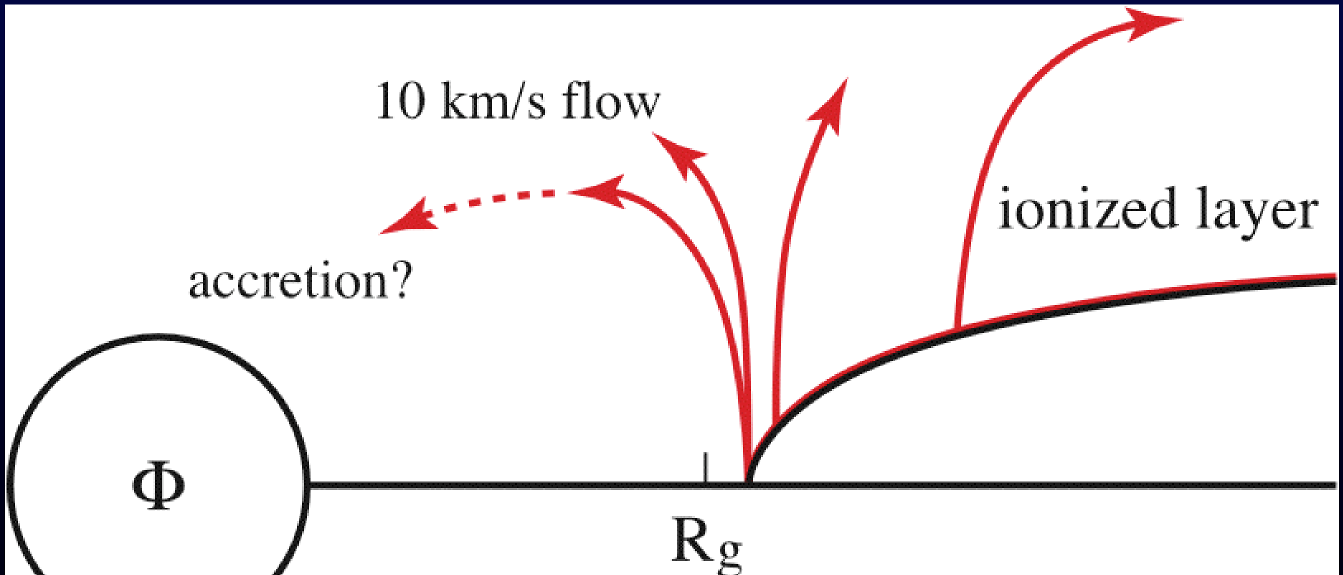
- Clarke et al. (2001) proposed the "UV-switch" model.
- Accretion rate falls as disc evolves. Once the disc accretion rate falls to ~ wind rate the inner disc cannot be resupplied, and drains on a viscous timescale.



The outer disc: direct irradiation



Hollenbach et al. (1994)



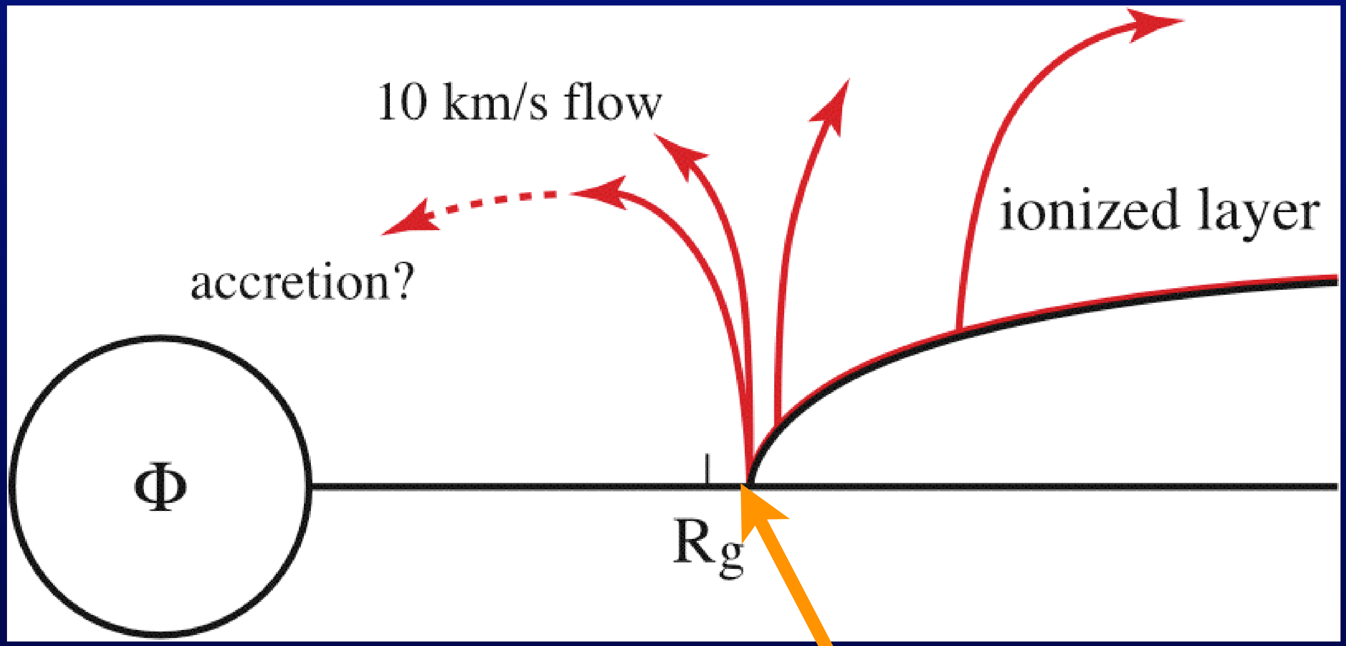
RDA, Clarke & Pringle et al. (2006a)

- In static wind model disc is assumed to be optically thick to ionizing photons, so the diffuse (recombination) field dominates the wind.
- After the inner disc has drained, radiative transfer problem changes: direct radiation field dominates the wind.

Direct photoevaporation

RDA, Clarke & Pringle (2006a)

- Analytic model computes density from ionization balance edge and evaluates mass-loss rate per unit area as ρc_{S} :



$$\frac{1}{2}\Delta\theta.\Phi = \alpha_{\mathrm{B}} n_{\mathrm{in}}^{2}.\Delta V$$

$$\Delta V \simeq 2\pi R.(R\Delta\theta).H$$

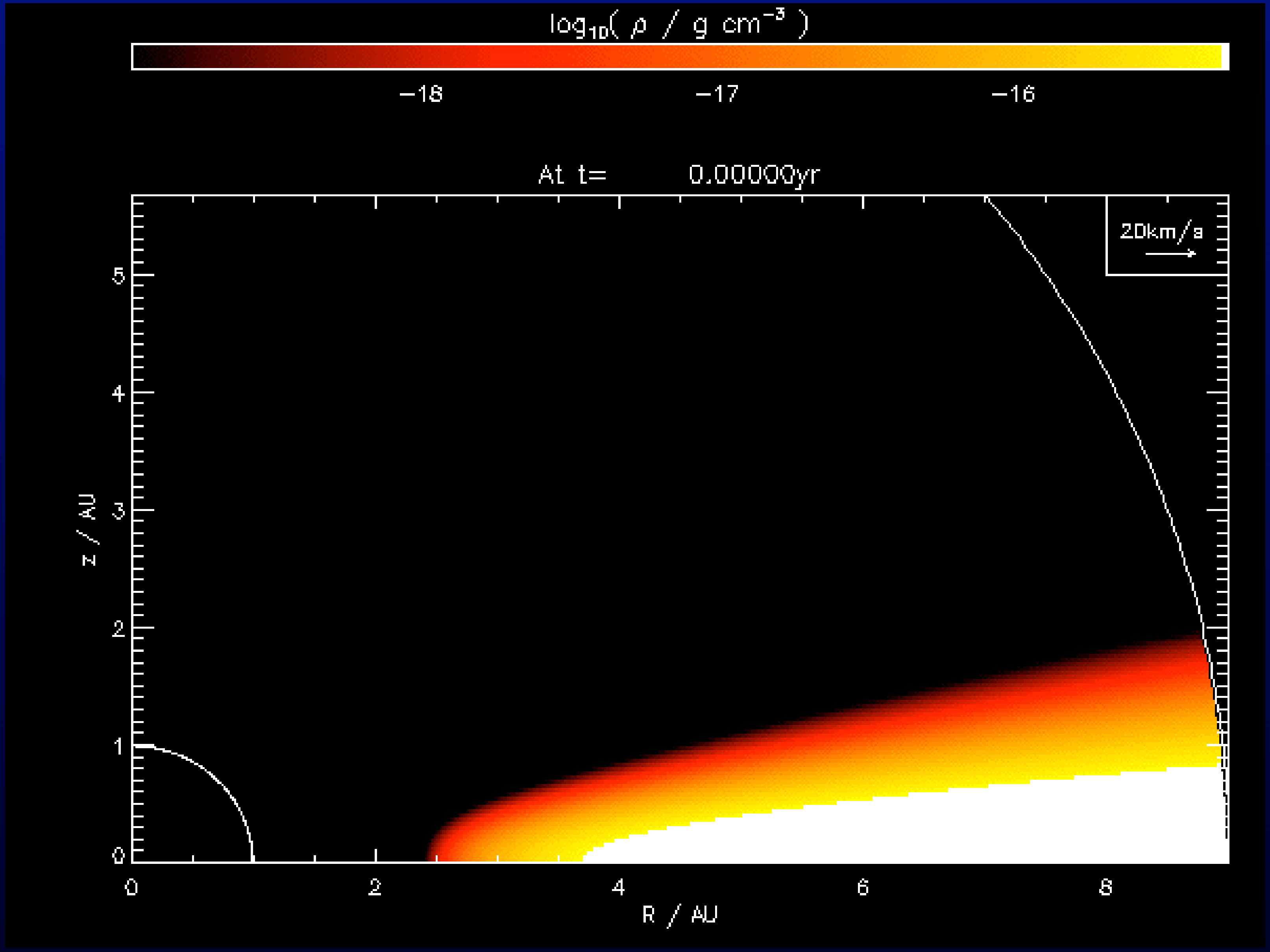
Expect wind rate to increase significantly as disc evolves

$$\dot{M}_{\mathrm{direct}} = 2.35 \times 10^{-9} \mathrm{M}_{\odot}\mathrm{yr}^{-1}\, .\, C \left(\frac{\Phi}{10^{41}\mathrm{s}^{-1}}\right)^{1/2} \left(\frac{R_{\mathrm{in}}}{3\mathrm{AU}}\right)^{1/2} \int_{1}^{R_{\mathrm{out}}/R_{\mathrm{in}}} x f(x) dx$$

Shape function depends on disc structure (especially H(R))

Direct photoevaporation

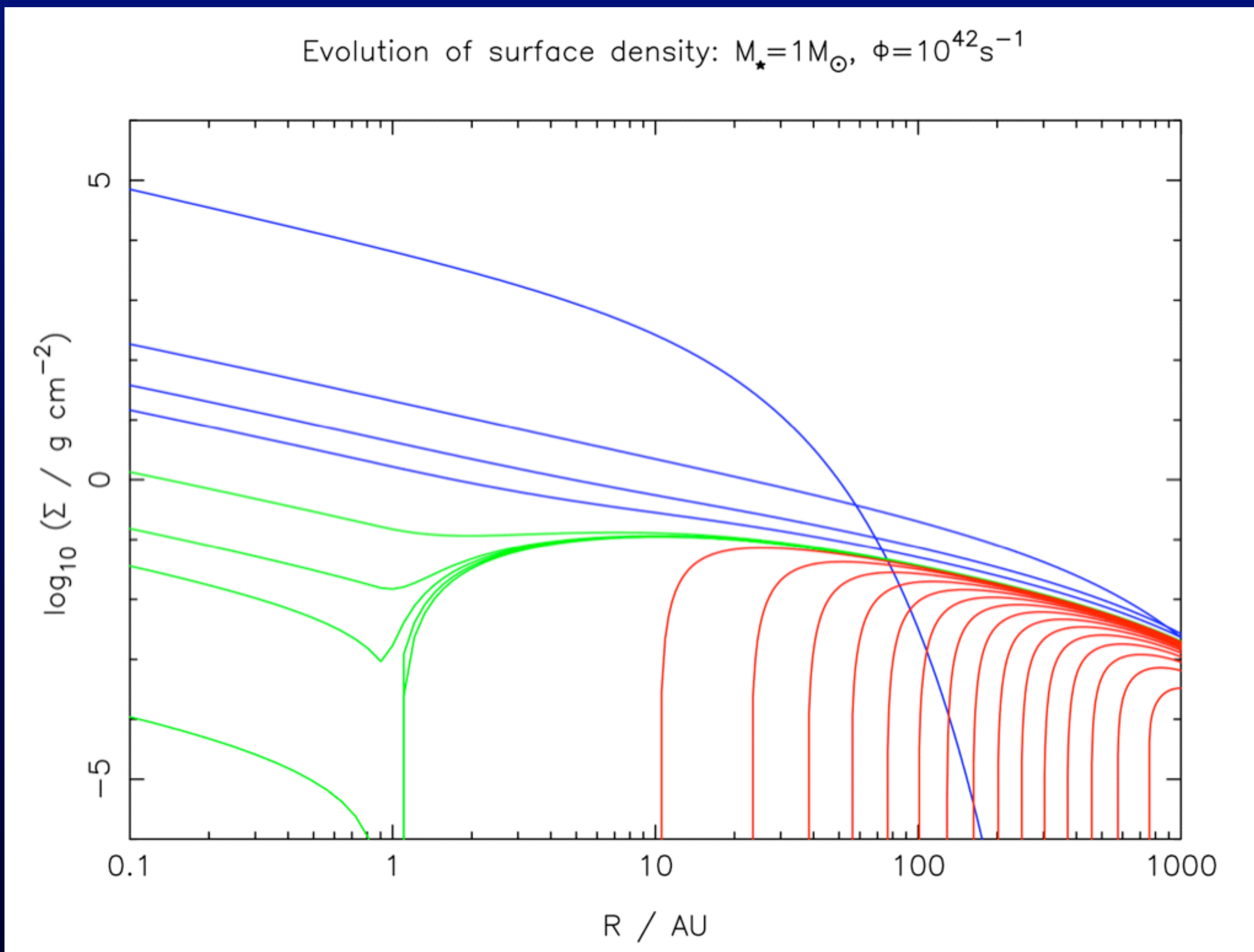
RDA, Clarke & Pringle (2006a)



- Hydrodynamic models with modified version of **ZEUS-2D**.
- Use "on-the-spot" approximation to solve for ionization balance.
- Modify equation of state according to location of ionization front.
- Fit functional form for $\dot{M}_w(R)$ and use in 1-D evolution model.

Gas disc evolution model

RDA, Clarke & Pringle (2006b)



Snapshots at t=0, 2, 4, 5.9, 6.0, 6.01, 6.02, 6.03, 6.04....6.18Myr

Entire disc is dispersed in ~3×10^{5}yr after lifetime of 6Myr

- "Three-stage" model for disc evolution:
  - $\dot{M}_{\rm wind} \ll \dot{M}_{\rm acc}$, wind negligible, viscous evolution (few Myr).
  - $\dot{M}_{\rm wind} \sim \dot{M}_{\rm acc}$, gap opens, viscous draining of inner disc (~10^{5}yr).
  - Inner hole, wind clears outer disc (few 10^{5}yr).
- Use simple prescription to model SED of evolving disc.

Evolutionary timescales

Hartmann et al. (1998); Clarke et al. (2001); RDA, Clarke & Pringle (2006b)

- Assume linear viscosity law, neglect factors of order unity:

$$t_{\rm disc} = t_\nu \left(\frac{\dot{M}_{\rm acc}(0)}{\dot{M}_{\rm wind}}\right)^{2/3}$$

$$t_{\rm inner} = t_\nu \frac{R_{\rm g}}{R_0}$$

$$t_{\rm outer}(R) = \frac{M_{\rm d}(< R)}{\dot{M}_{\rm wind}(R)} = t_\nu(R)\frac{\dot{M}_{\rm acc}}{\dot{M}_{\rm wind}(R)} = t_\nu(R)\left(\frac{R}{R_{\rm g}}\right)^{-1/2}$$

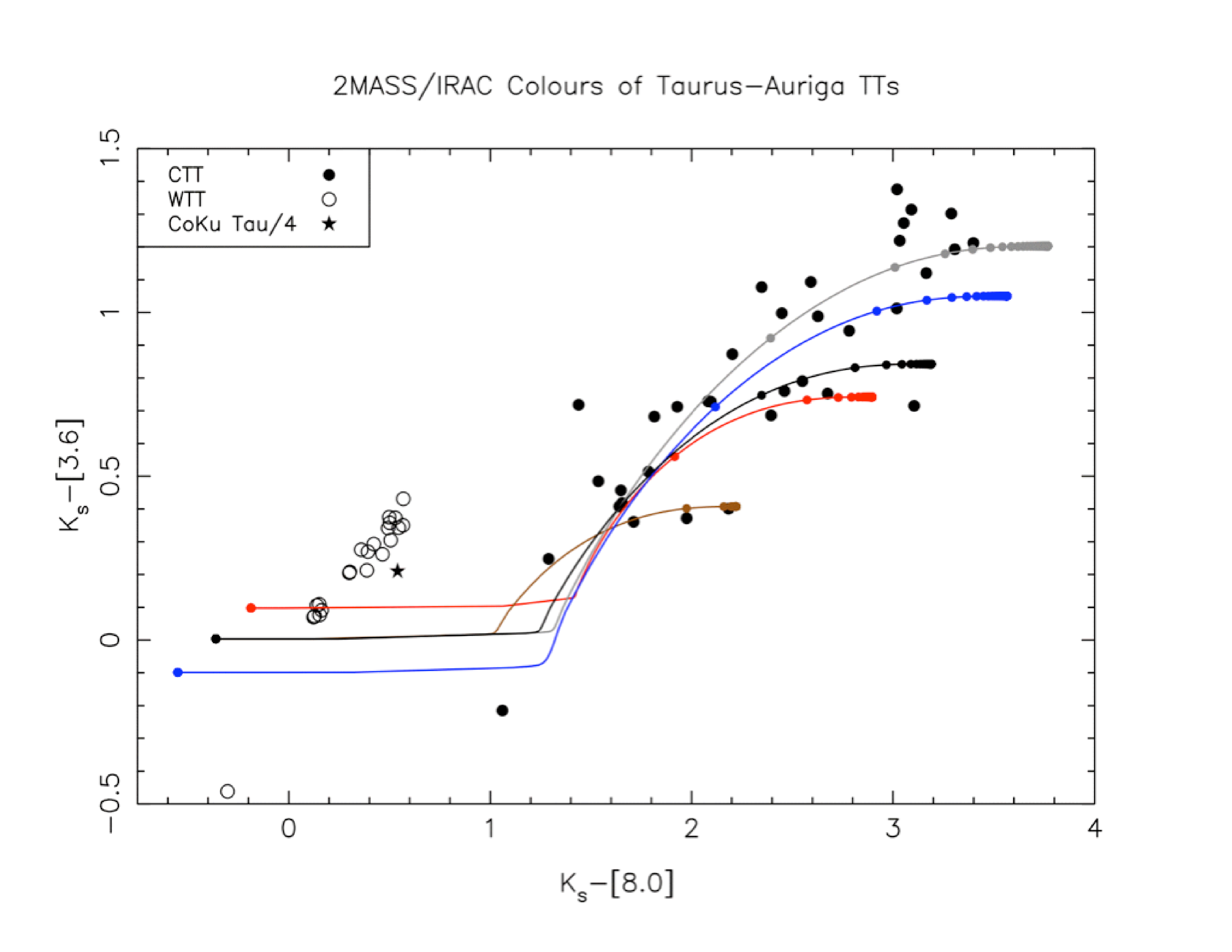
- Successfully reproduces "two-timescale" behaviour:

$$\frac{t_{\rm clearing}}{t_{\rm disc}} = \frac{t_\nu(R_{\rm d})}{t_\nu(R_0)}\left(\frac{R_{\rm d}}{R_{\rm g}}\right)^{-1/2}\left(\frac{\dot{M}_{\rm acc}(0)}{\dot{M}_{\rm wind}}\right)^{-2/3} = \frac{R_{\rm d}}{R_0}\left(\frac{R_{\rm d}}{R_{\rm g}}\right)^{-1/2}\left(\frac{\dot{M}_{\rm acc}(0)}{\dot{M}_{\rm wind}}\right)^{-2/3}$$

- For typical parameters this gives ~5%, which is consistent with the observed fraction of "transition objects".

Evolutionary tracks: near-infrared

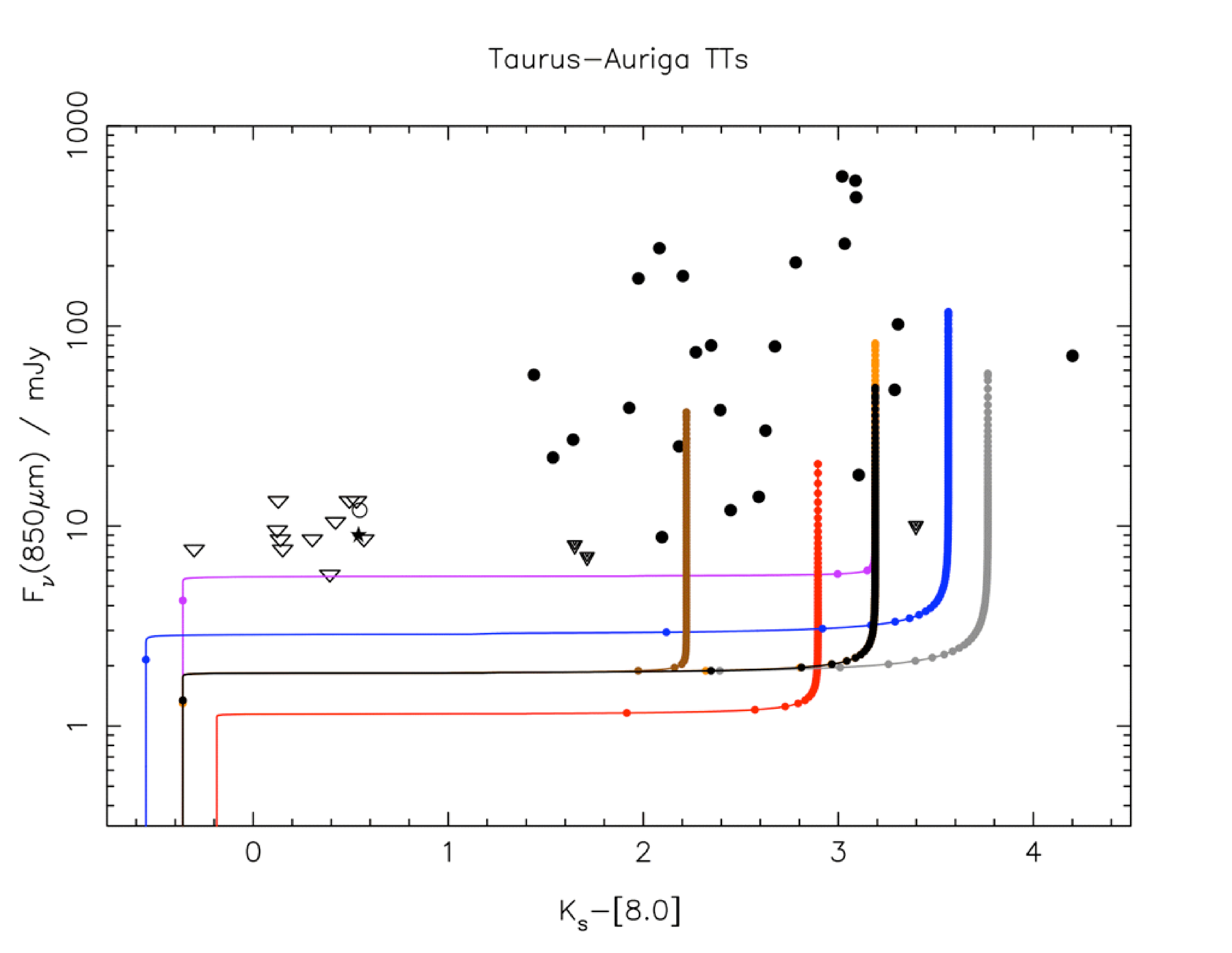
RDA, Clarke & Pringle (2006b)



Data from Hartmann et al. (2005)

Evolutionary tracks: infrared/sub-mm

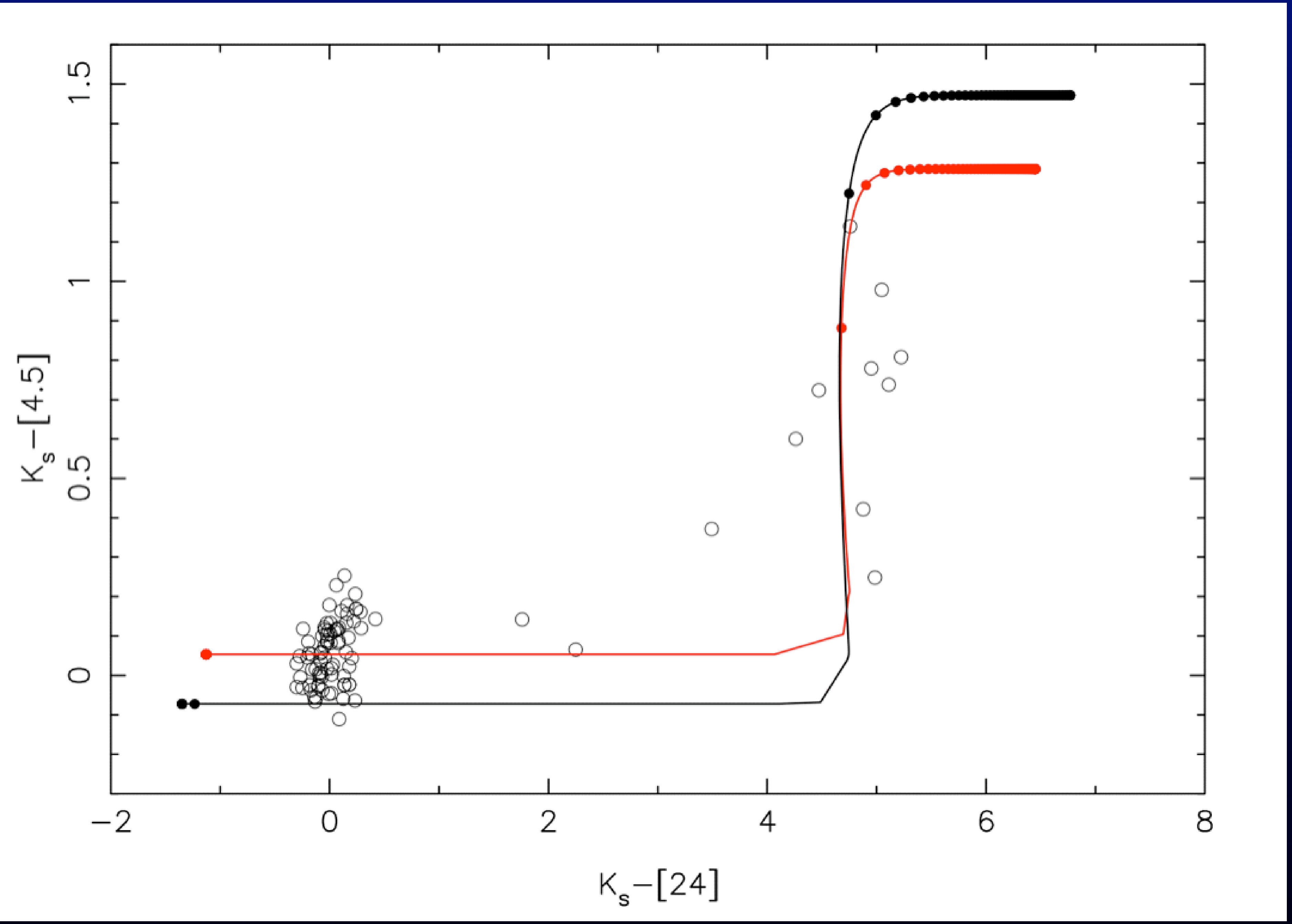
RDA, Clarke & Pringle (2006b)



Data from Hartmann et al. (2005), Andrews & Williams (2005)

Evolutionary tracks: mid-infrared

RDA, Clarke & Pringle (2006b)



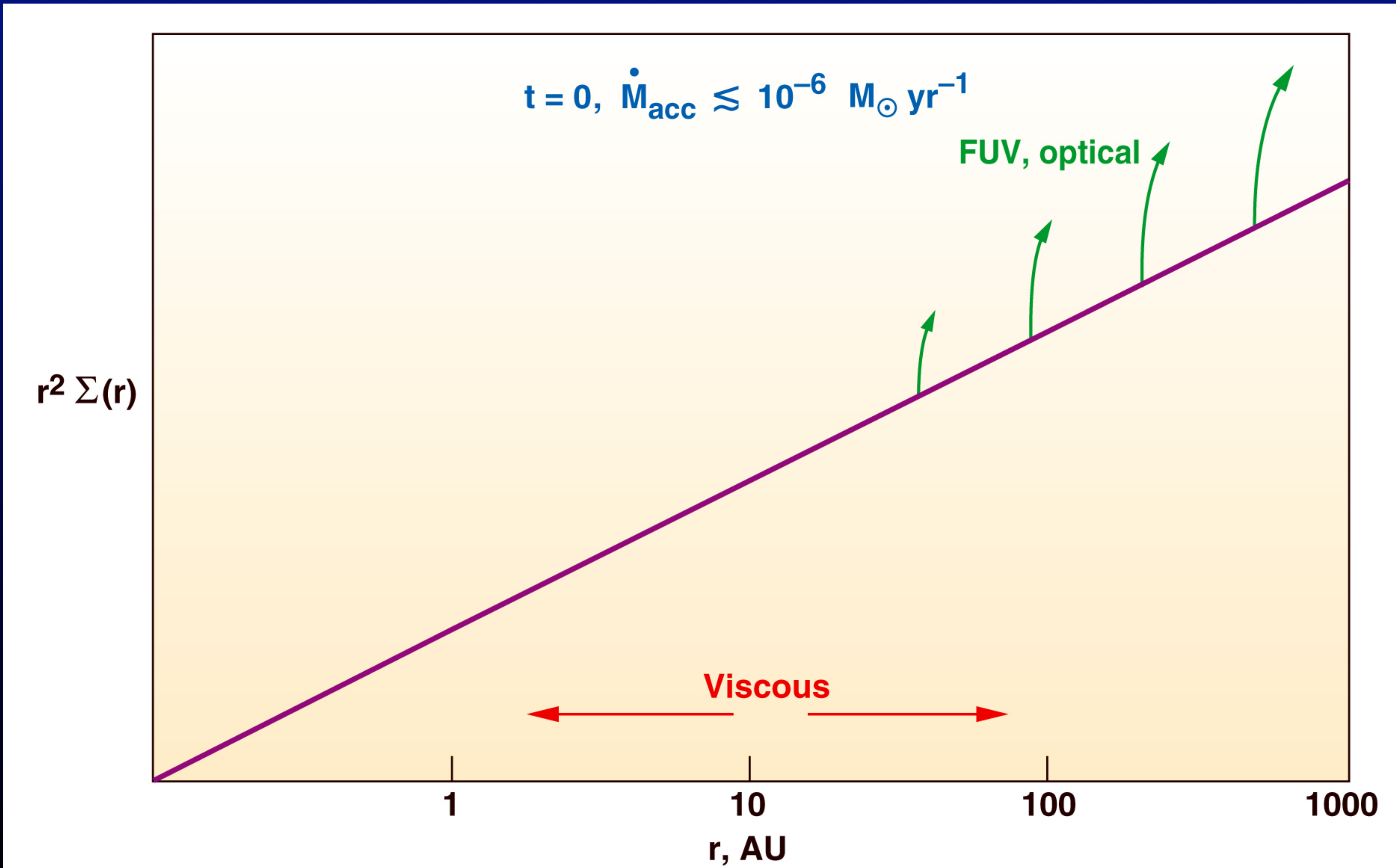
Data from Padgett et al. (2006)

Uncertainty: heating rates

- Biggest uncertainty in photoevaporation models is the stellar UV emission, and especially the ionizing luminosity (<912Å).
- Stellar ionizing flux probably from magnetic/chromospheric activity. Typical values ~$10^{42}s^{-1}$, approx. constant over 10Myr (RDA, Clarke & Pringle 2005).
- However, sample is small: ~10 objects with STIS, ~50 with IUE. More data needed: COS on HST (Sep 2008?) is most promising upcoming instrument.
- "Indirect" measurements such as line emission from winds may be more promising than observations in the UV (e.g. [NeII] line at 12.8μm; Pascucci et al. 2007).

Schematic picture of (gas) disc evolution

Figures courtesy of David Hollenbach



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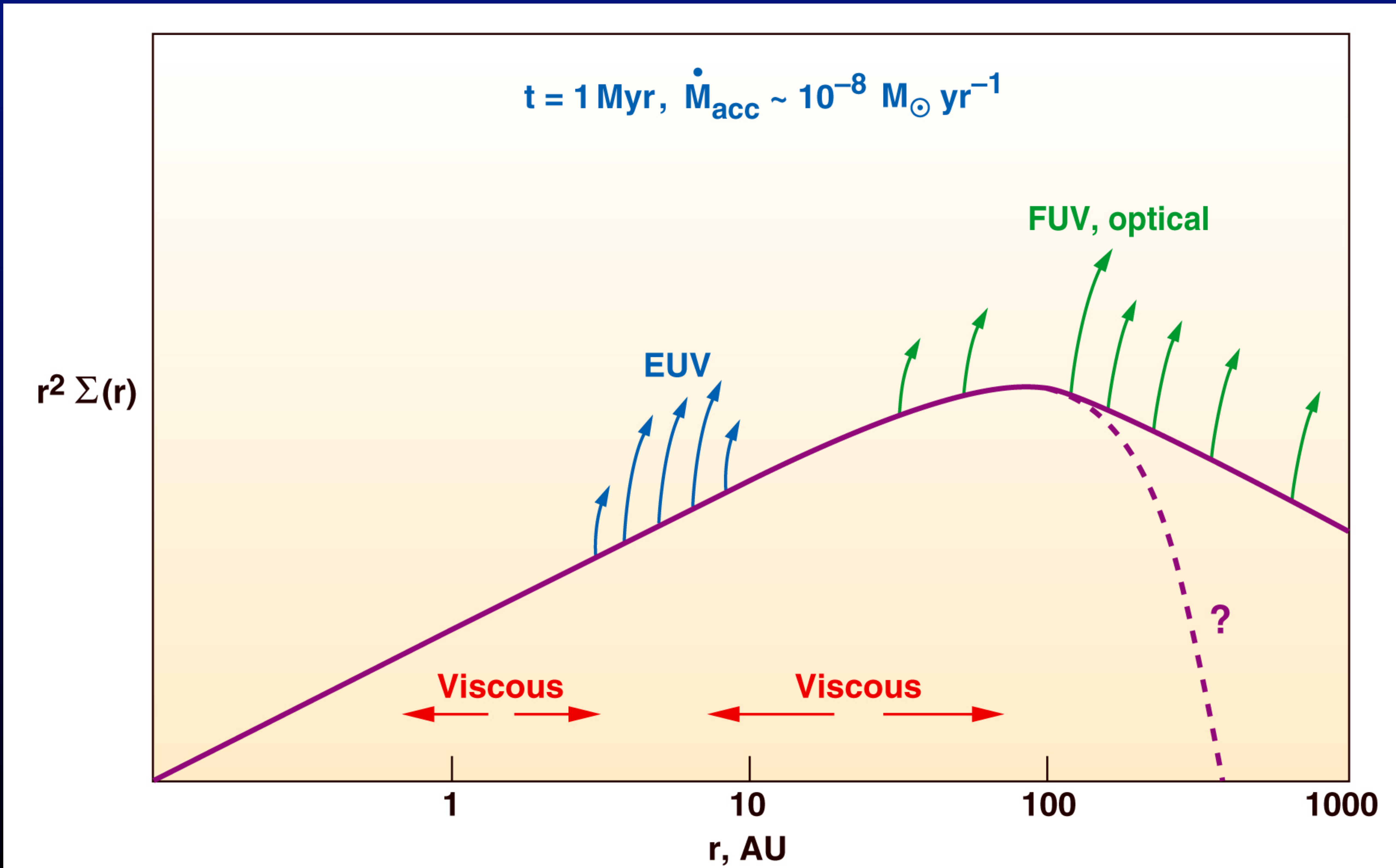

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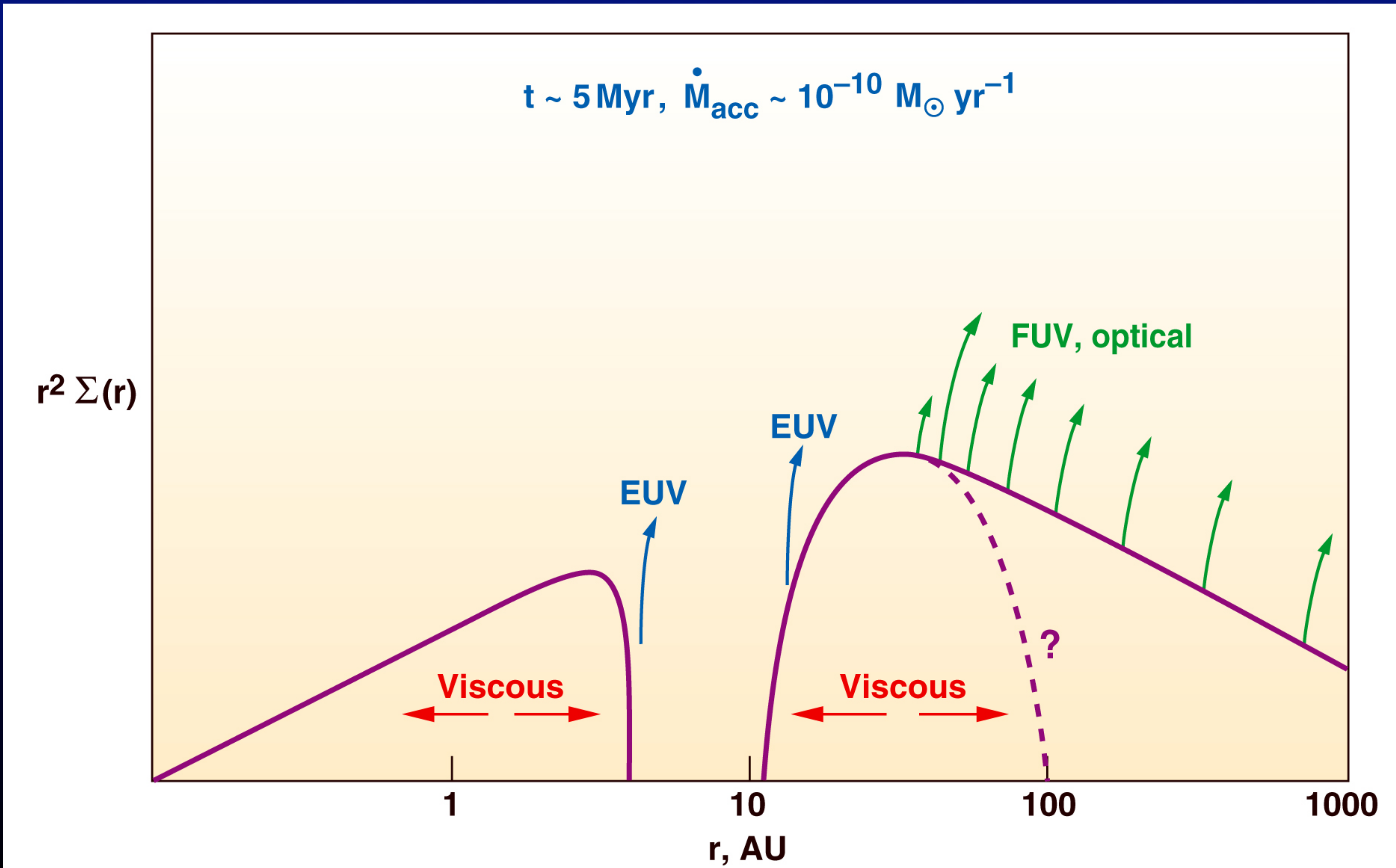

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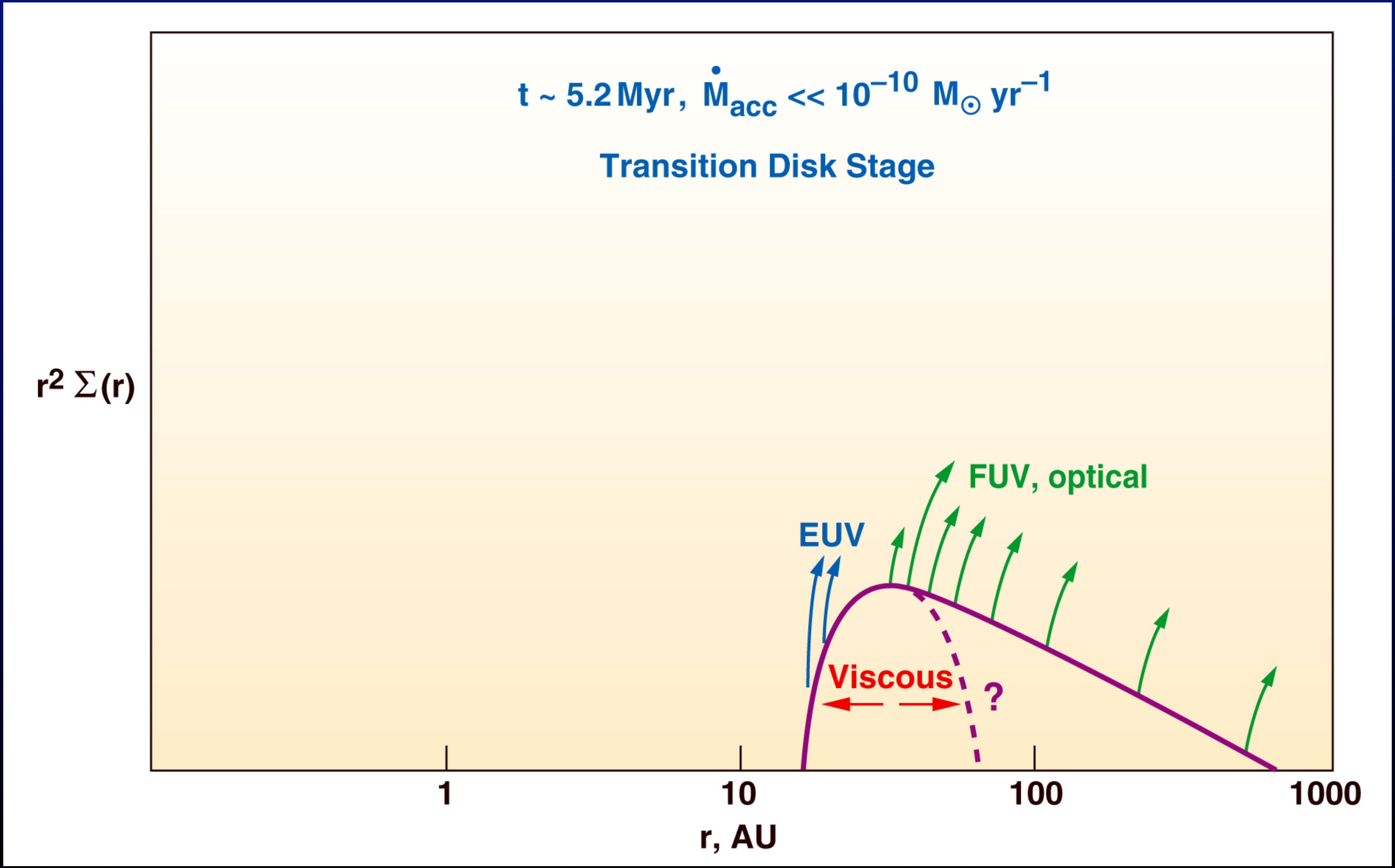

Gas dynamics: summary

- Evolution of gas discs dominated by viscous evolution and photoevaporation.
- Observations demand rapid disc clearing after a long lifetime (the "two-timescale" constraint).
- Photoevaporation by external O stars can explain the proplyds, but only affects a minority of TTs.
- Models which combine photoevaporation by the central star with viscous evolution are able to reproduce many observed properties.
- Biggest uncertainty in these models remains the heating rates - UV fluxes poorly constrained.