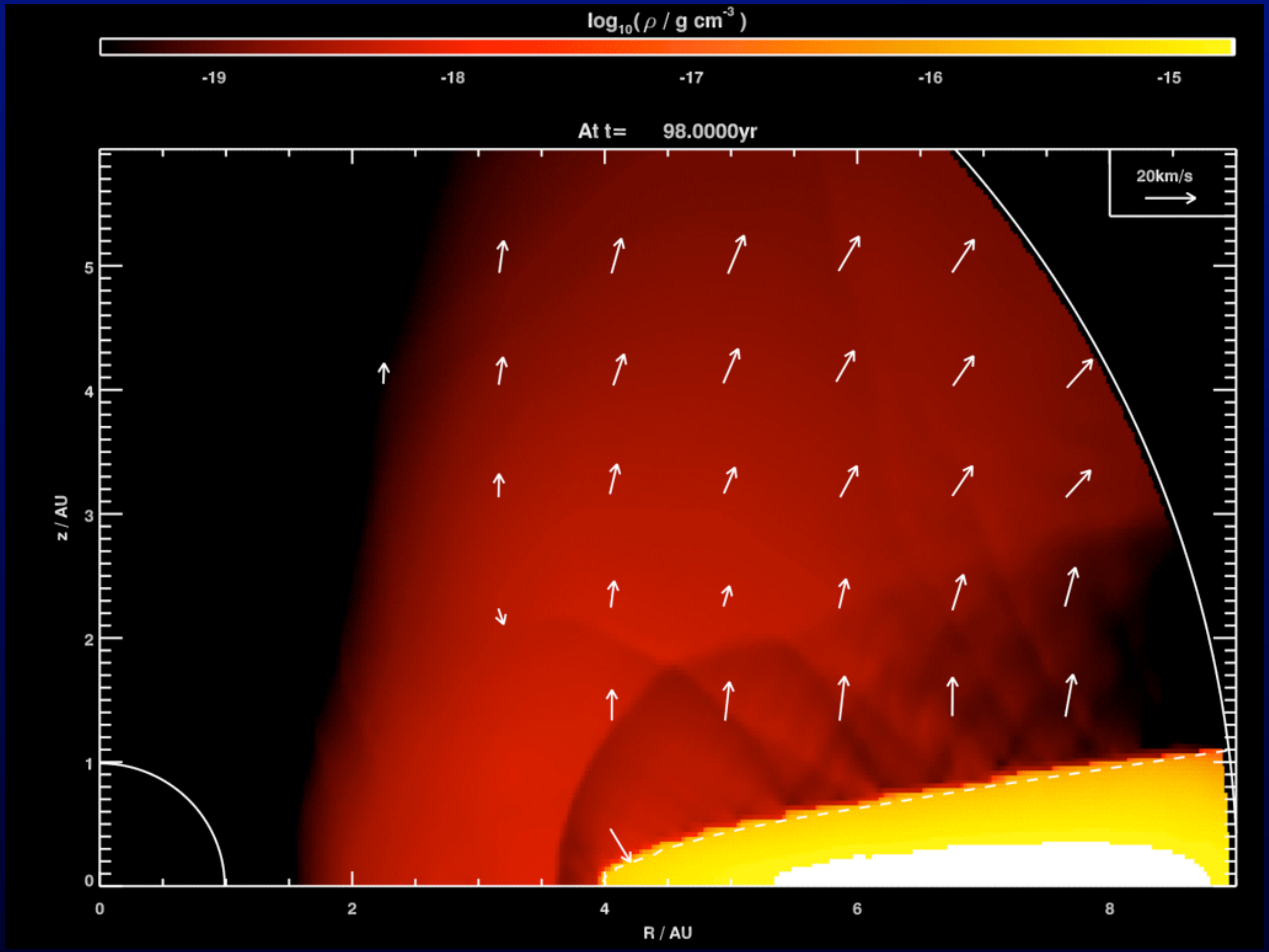
The evolution of gas discs



Richard Alexander
Sterrewacht Leiden

Cathie Clarke, Jim Pringle (Cambridge)
Phil Armitage (Colorado), Pascale Garaud (Santa Cruz)

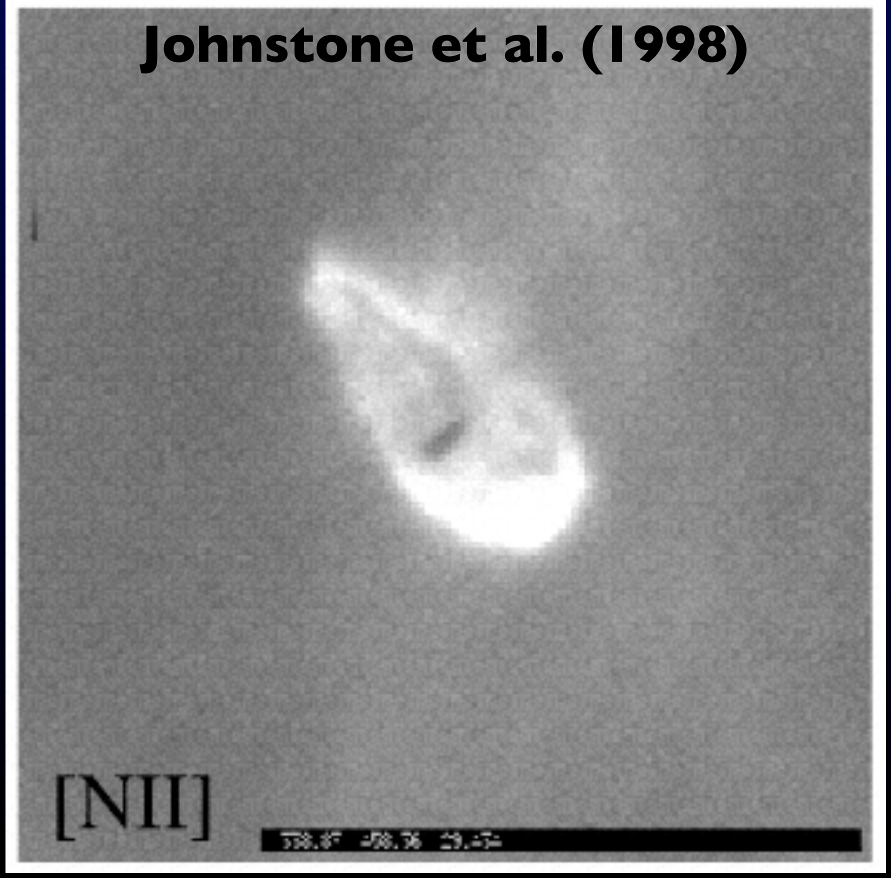
Observational Constraints

(see talk by Williams)

- Disc lifetimes are ~Myr (gas and dust tracers).
- Lifetimes are diverse: some discs live for <1Myr; CTTs & WTTs co-exist at similar ages.
- Disc masses range from >0.1$M_{\odot}$ to $\leq$0.001$M_{\odot}$.
- Accretion rates span >$10^{-7}M_{\odot}yr^{-1}$ to $\leq 10^{-10}M_{\odot}yr^{-1}$.
- Termination of accretion roughly simultaneous with disc clearing.
- Discs are cleared rapidly (in ~10^5yr), across entire radial extent of disc.
- Observations of ***gas*** disc evolution are very limited.

Gas evolution processes

- Various processes can affect evolution of gas discs.
- Hollenbach et al. (PPIV), consider all and conclude that:
  - Viscous evolution dominates for radii $\leq$ 10AU.
  - Photoevaporation dominates for radii $\geq$ 10AU.
- Photoevaporation by O-stars is responsible for the "proplyd" phenomenon seen in the ONC.



Johnstone et al. (1998)

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- Photoevaporation by O-stars is responsible for the "proplyd" phenomenon seen in the ONC.
- In this talk I will discuss only "central star" photoevaporation.

Disc photoevaporation

- UV radiation creates a hot layer on disc surface.
- Outside some critical radius, hot gas is unbound and flows as a wind (Hollenbach et al. 1994, 2000).
- Length scale:

$$R_{\rm g} = \frac{GM_*}{c_{\rm s}^2}$$

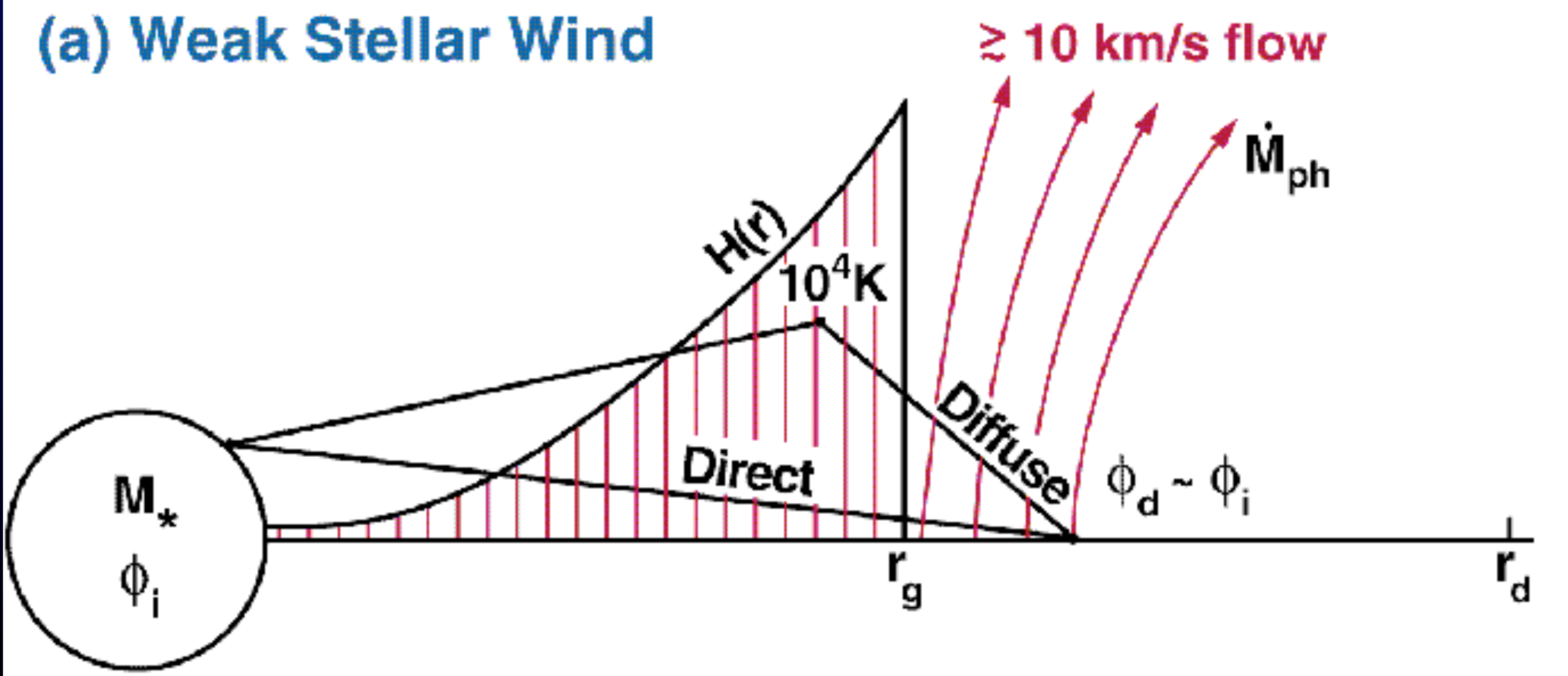
- Two important cases: EUV (ionizing) and FUV (1000-2000Å). For T Tauri parameters:

$$R_{\rm g,EUV} \approx 5{\rm AU} \qquad R_{\rm g,FUV} \approx 100{\rm AU}$$

- Recent reviews: Dullemond et al. (2007 - PPV); RDA (2008).

Disc photoevaporation

- EUV is the "easy" case:
  - Radiative transfer is straightforward (Strömgren criterion)
  - Flow is isothermal (10^4K)
  - Solution insensitive to underlying disc structure or accretion rate
  - Analytic models agree reasonably well with numerical simulations



Hollenbach et al. (1994, 2000)

Disc photoevaporation

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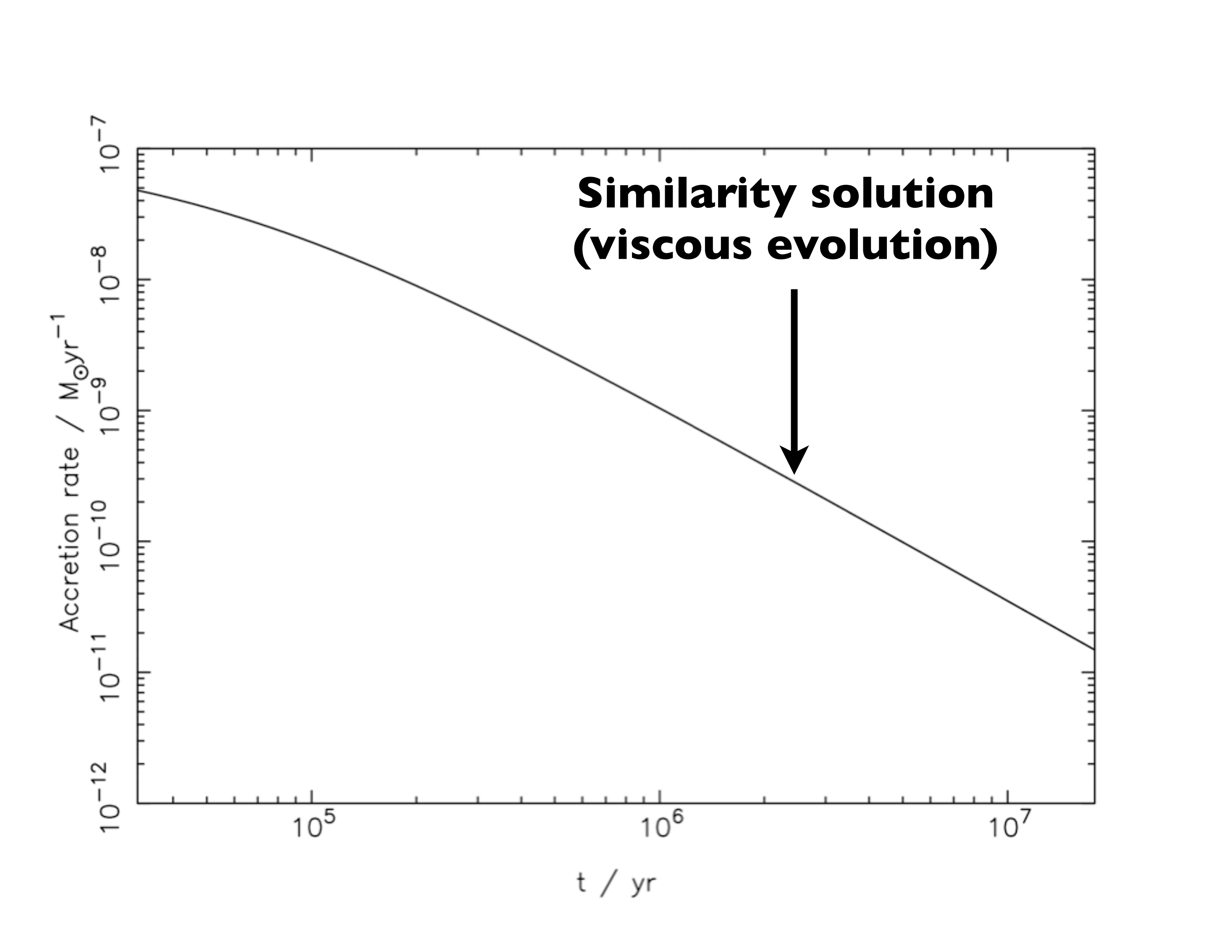
- FUV is the "hard" case:
  - Radiative transfer is complex (PDR-like, 2-D, $T_{dust} \neq T_{gas}$)
  - Thermal physics in atmosphere depends on underlying disc structure
  - Incident radiation field depends on accretion rate
  - Flow structure is complex ($R_{disc} \approx R_g$)

EUV + viscous evolution

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

- For TT parameters, EUV drives a wind at ~$10^{-10} M_{\odot} yr^{-1}$ from beyond 1-2AU.
- Wind rate constant, accretion rate declines with time.
- Eventually, wind dominates and inner disc drains rapidly (due to viscosity).
- Satisfies the "two-timescale" constraint: rapid clearing after long lifetime (the "UV-switch").



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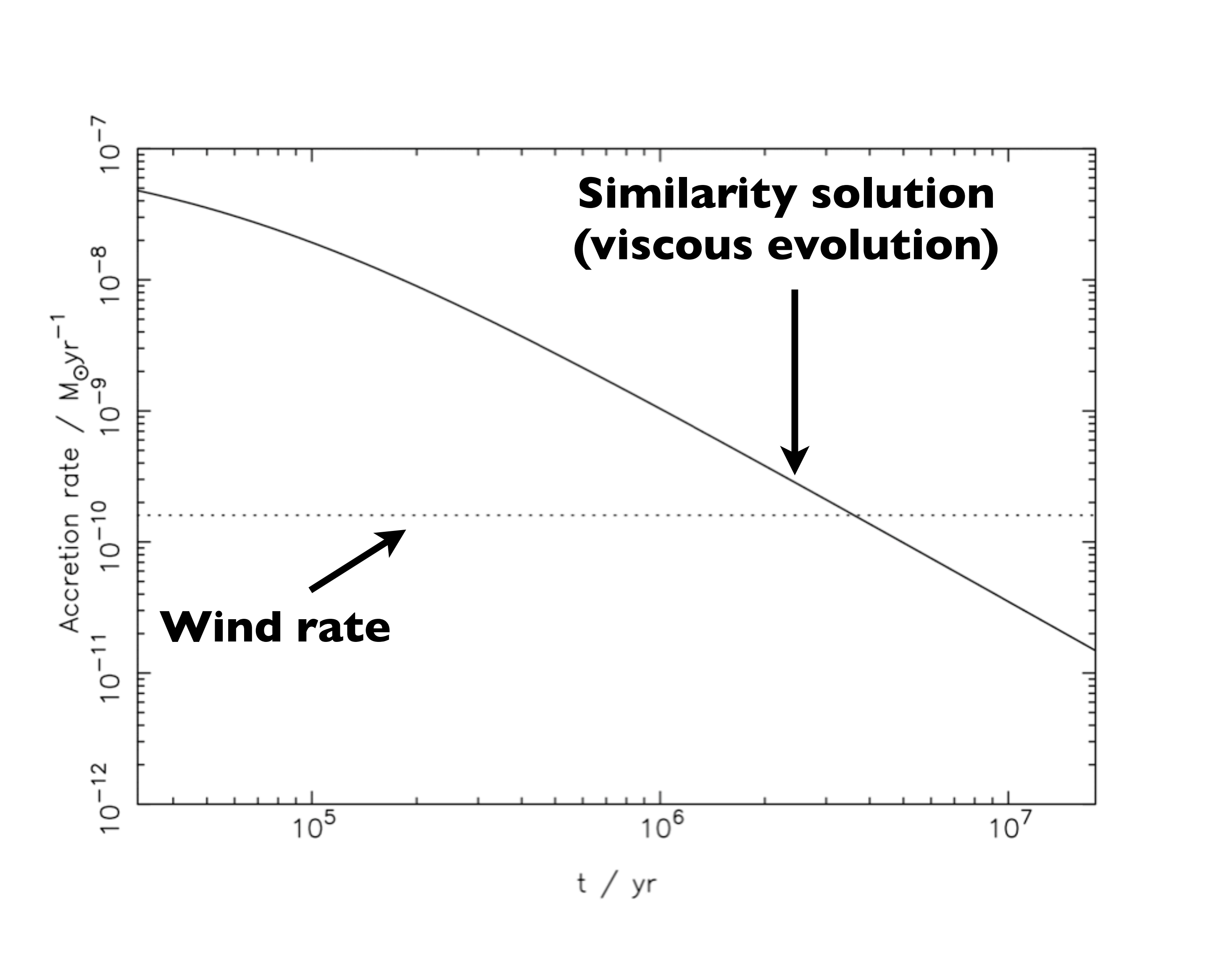

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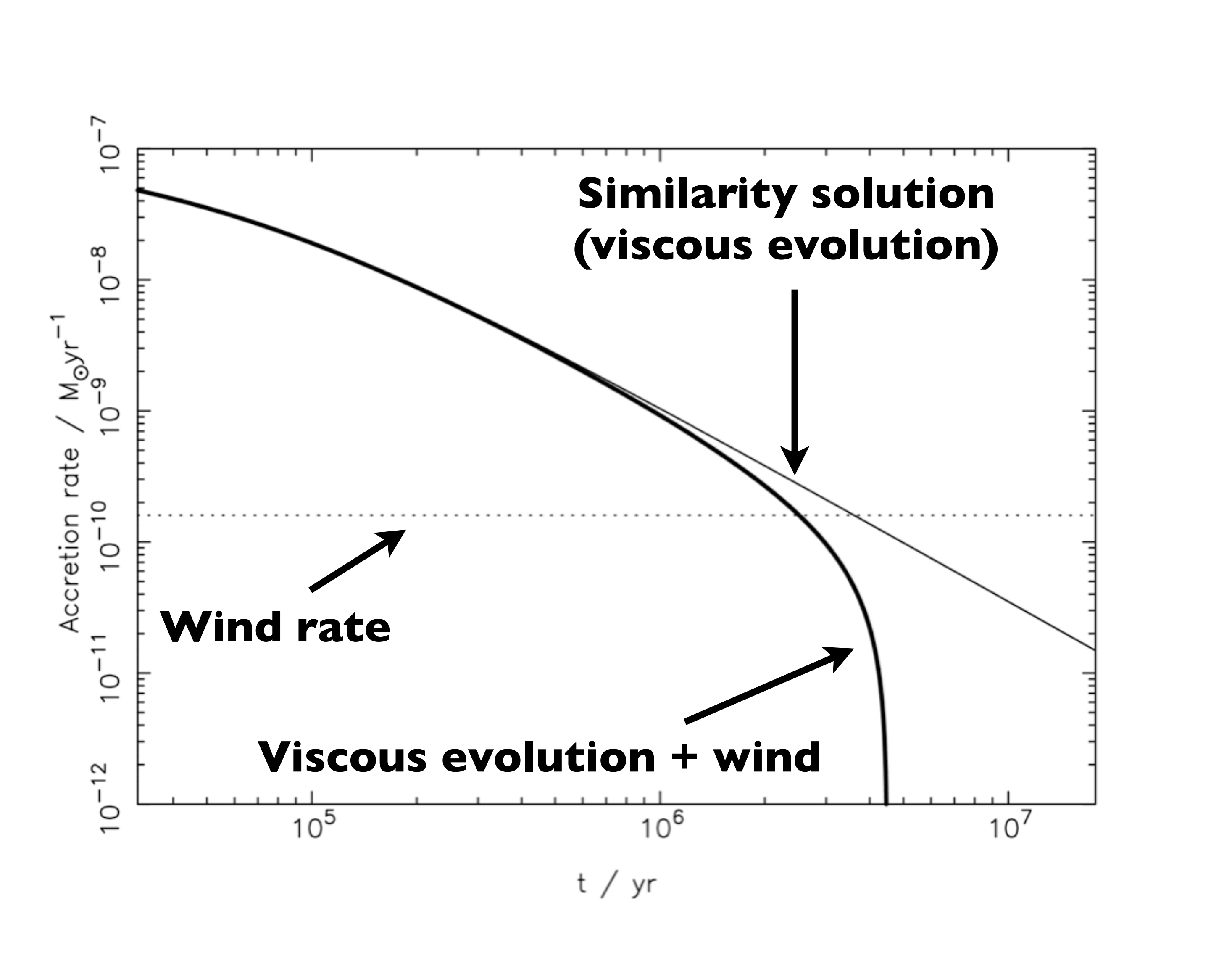
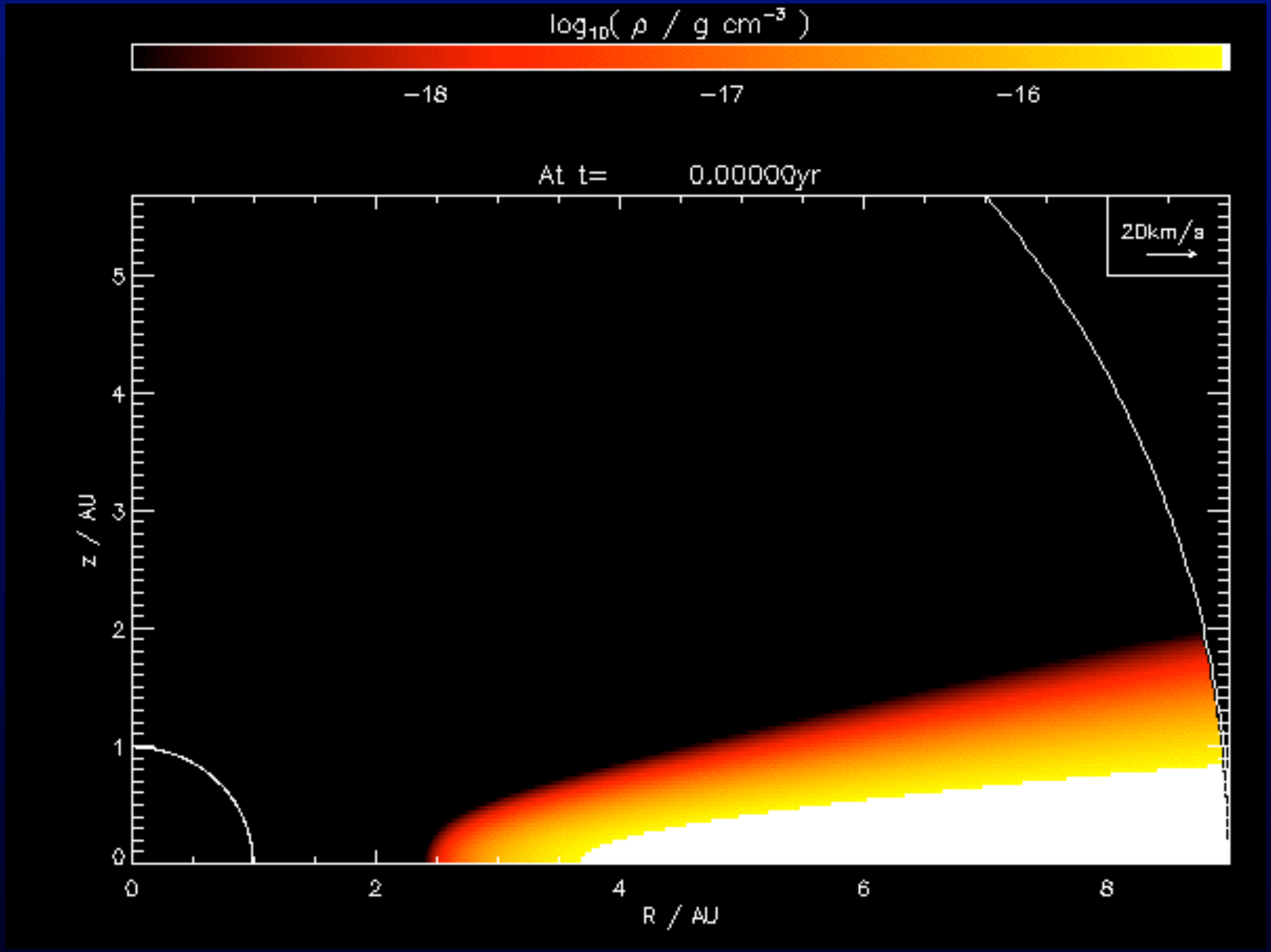


Direct photoevaporation

RDA, Clarke & Pringle (2006a)



- Once inner disc has drained, radiative transfer problem chances.
- Direct irradiation of inner disc edge leads to factor of ~10 increase in wind rate.
- Disc is cleared rapidly from inside-out...

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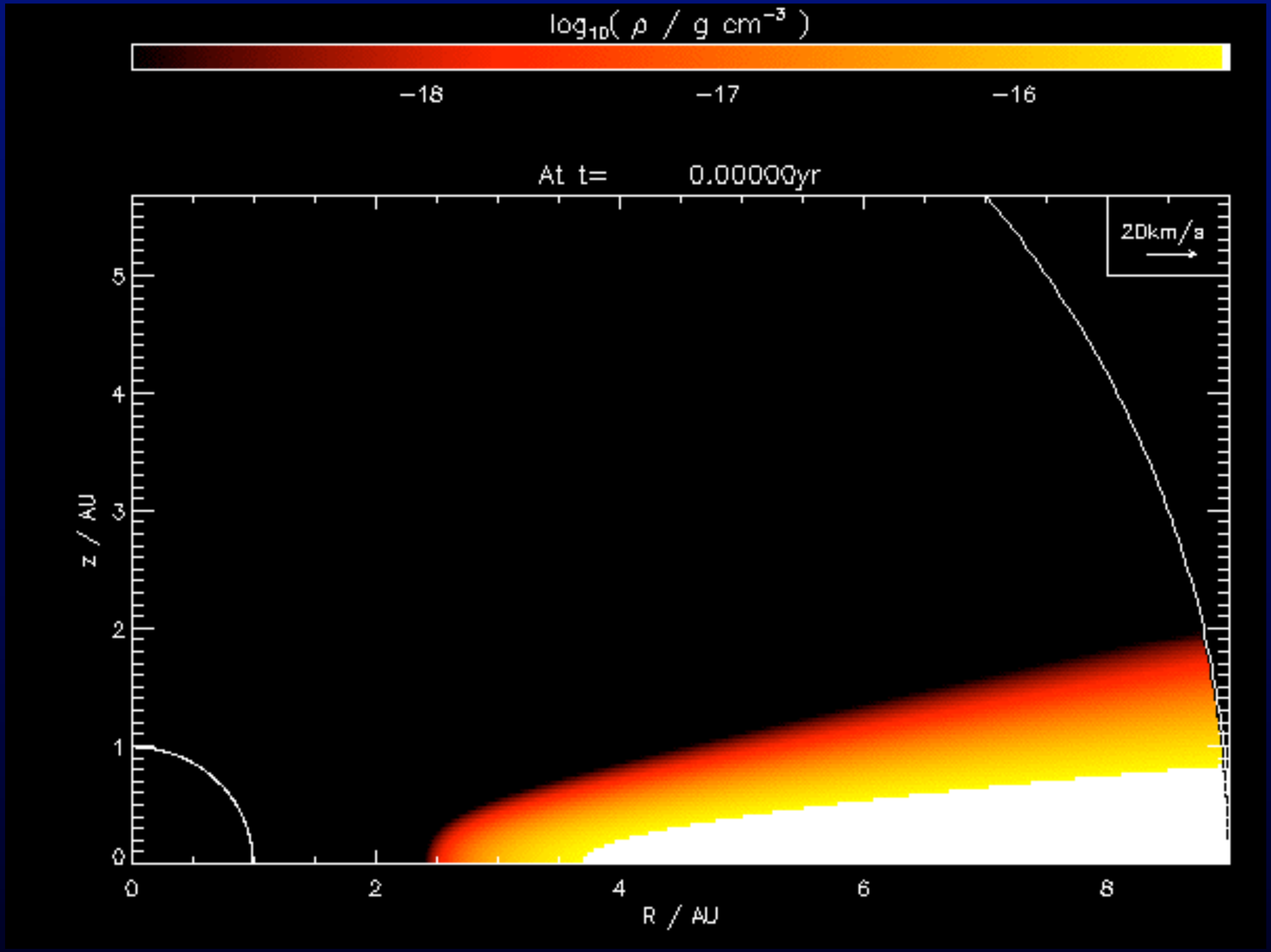

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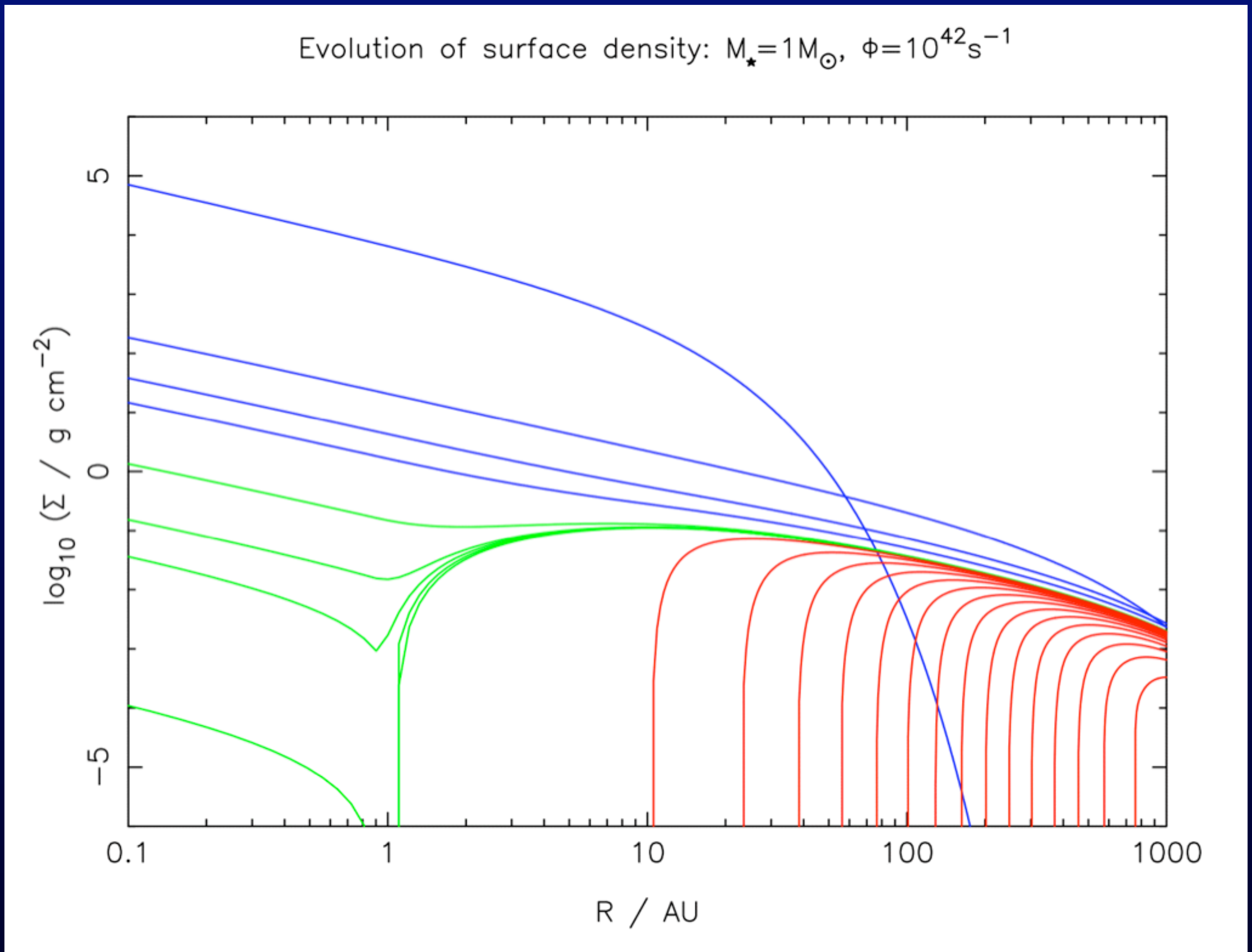
Gas disc evolution model

RDA, Clarke & Pringle (2006b)



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

- "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 (~10^5yr).
  - Inner hole, wind clears outer disc (few 10^5yr).

Timescales and toy SED models show good agreement with data

FUV photoevaporation

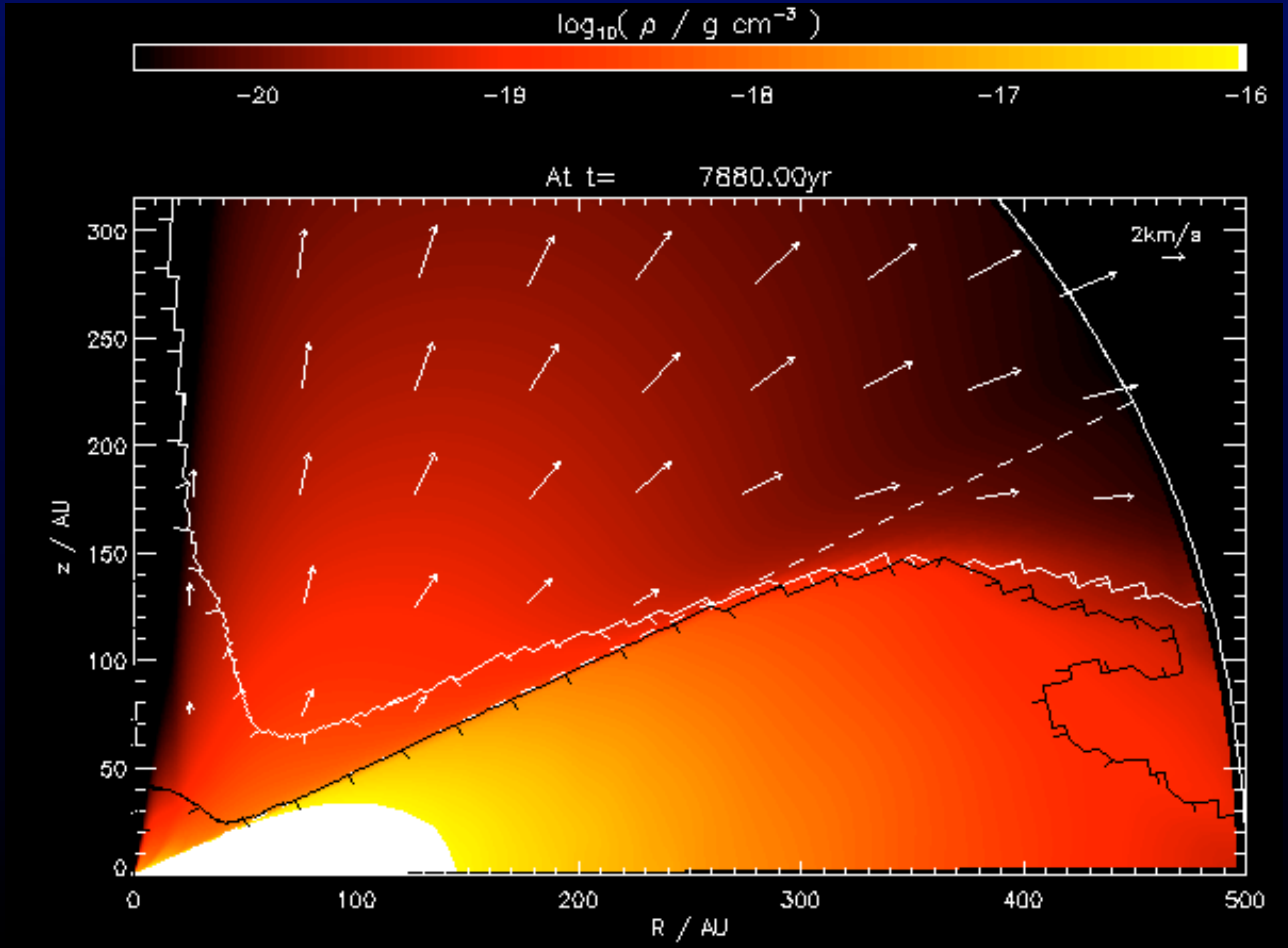
- No complete models to date.
- Two approaches:
  - Detailed radiative transfer, "toy" hydrodynamics
  - Detailed hydrodynamics, "toy" radiative transfer
- Mass loss concentrated near outer edge of disc (>50AU). Estimated mass-loss rates are ~$10^{-8} M_{\odot} yr^{-1}$:

$$\dot{M}_{\mathrm{wind}} \times t_{\mathrm{disc}} \gtrsim 0.01 \mathrm{M}_{\odot}$$

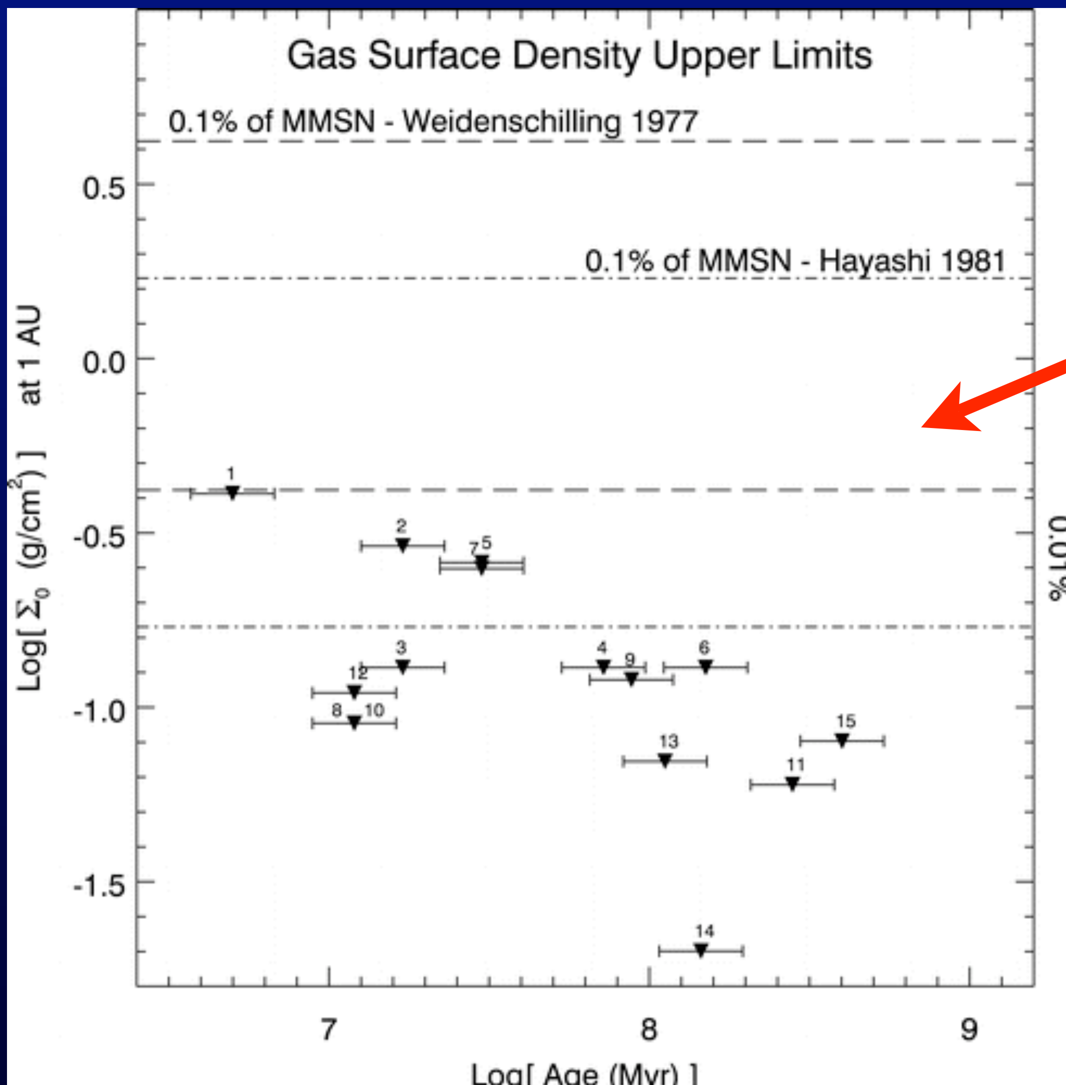
- PDR-like region gives rise to strong emission lines, especially in mid/far-IR (e.g. Gorti & Hollenbach 2008).

FUV photoevaporation

- Work in progress...
- Flow structure is complex - sonic surface is not where simple estimates suggest.



Observing disc photoevaporation



Pascucci et al. (2006)

Gas in inner discs:

FEPS upper limits on gas masses in evolved systems within a factor of ~10 of model predictions (Hollenbach et al. 2005; Pascucci et al. 2006).

Estimates of ionizing flux:

Small sample of bright sources suggest ~$10^{42\text{-}43}$photon/s (RDA et al. 2005); new data suggest somewhat smaller values (Herczeg et al., 2007b; in prep.).

HST COS will improve data greatly.

Emission lines:

Models predict that FUV (and X-ray) irradiation should produce strong emission lines ([OI], H_2, CO, etc.) from PDR-like disc atmosphere (e.g. Gorti & Hollenbach 2008). Excellent Herschel/SOFIA targets.

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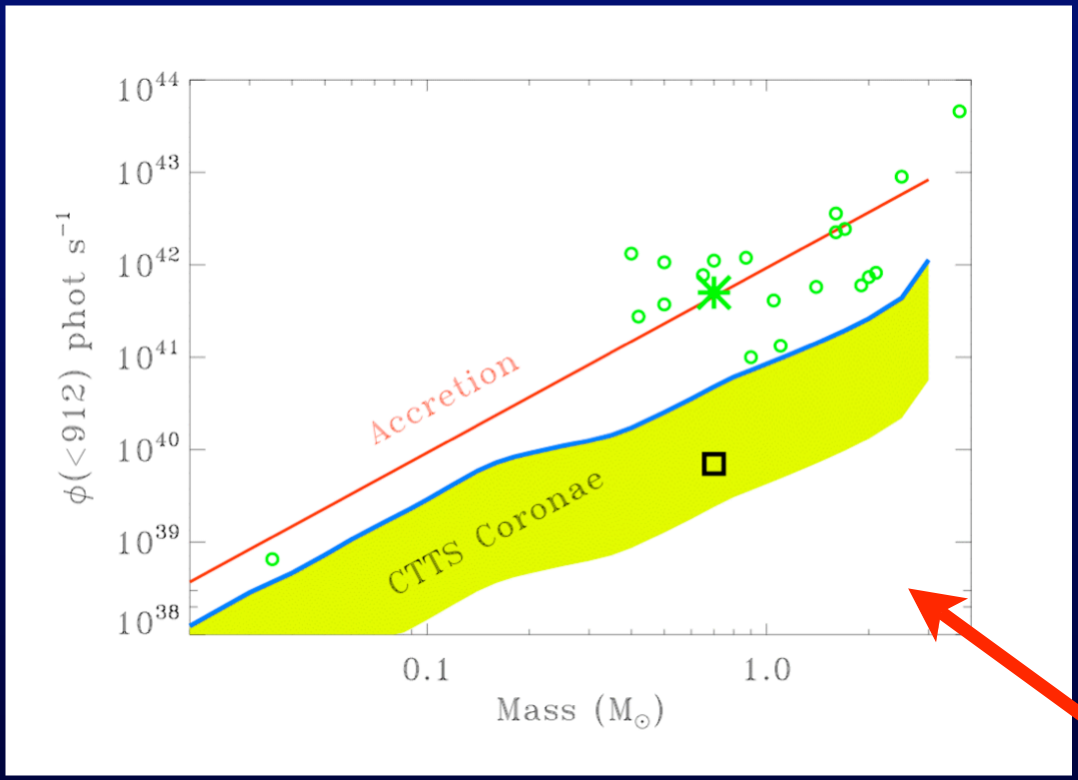

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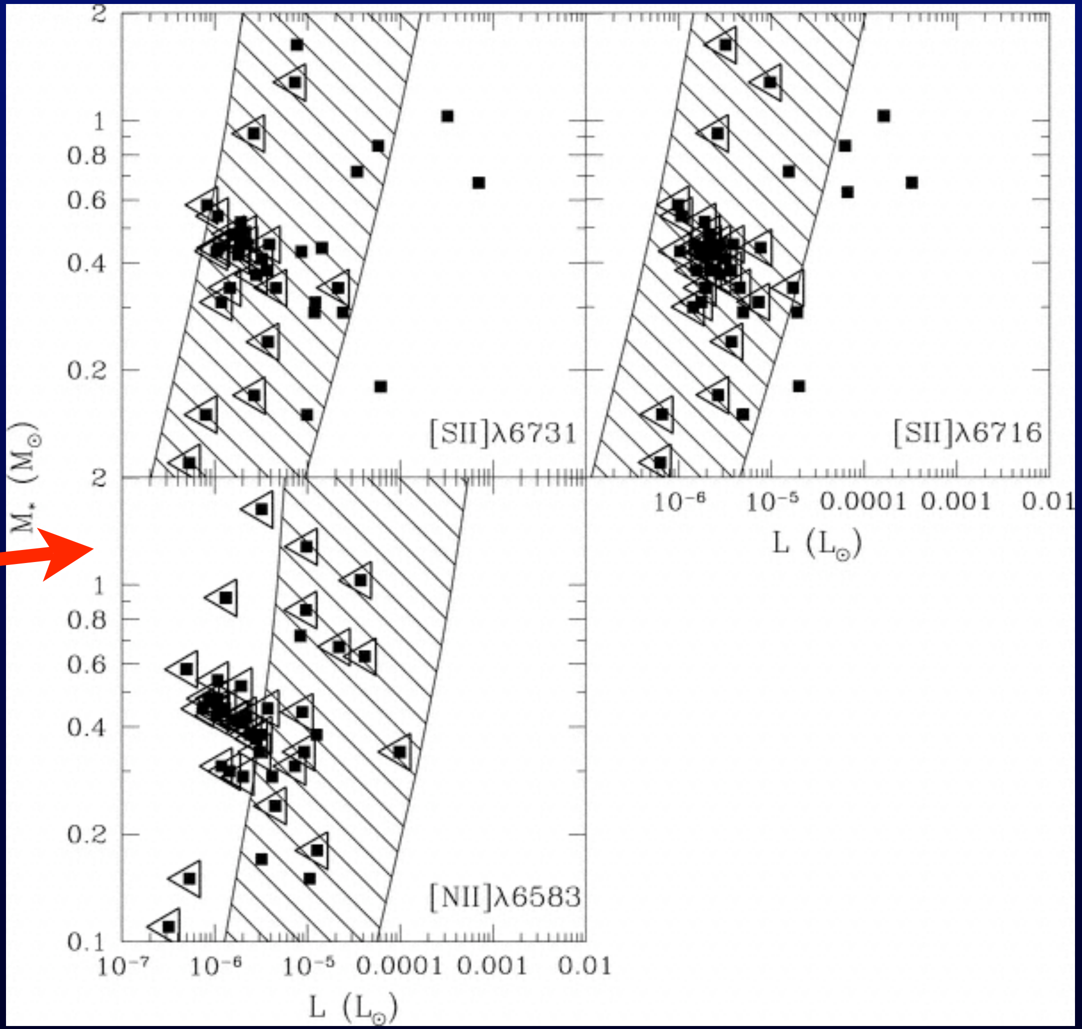
Observing disc photoevaporation

- EUV wind should give produce forbidden line emission from ionized species: [SII], [OIII], [NeII], etc.
- Models provide good fits to low-resolution optical data.
- New instruments capable of resolving velocities <10km/s.
- Current and future observations should unambigiously detect the velocity signature of the wind.



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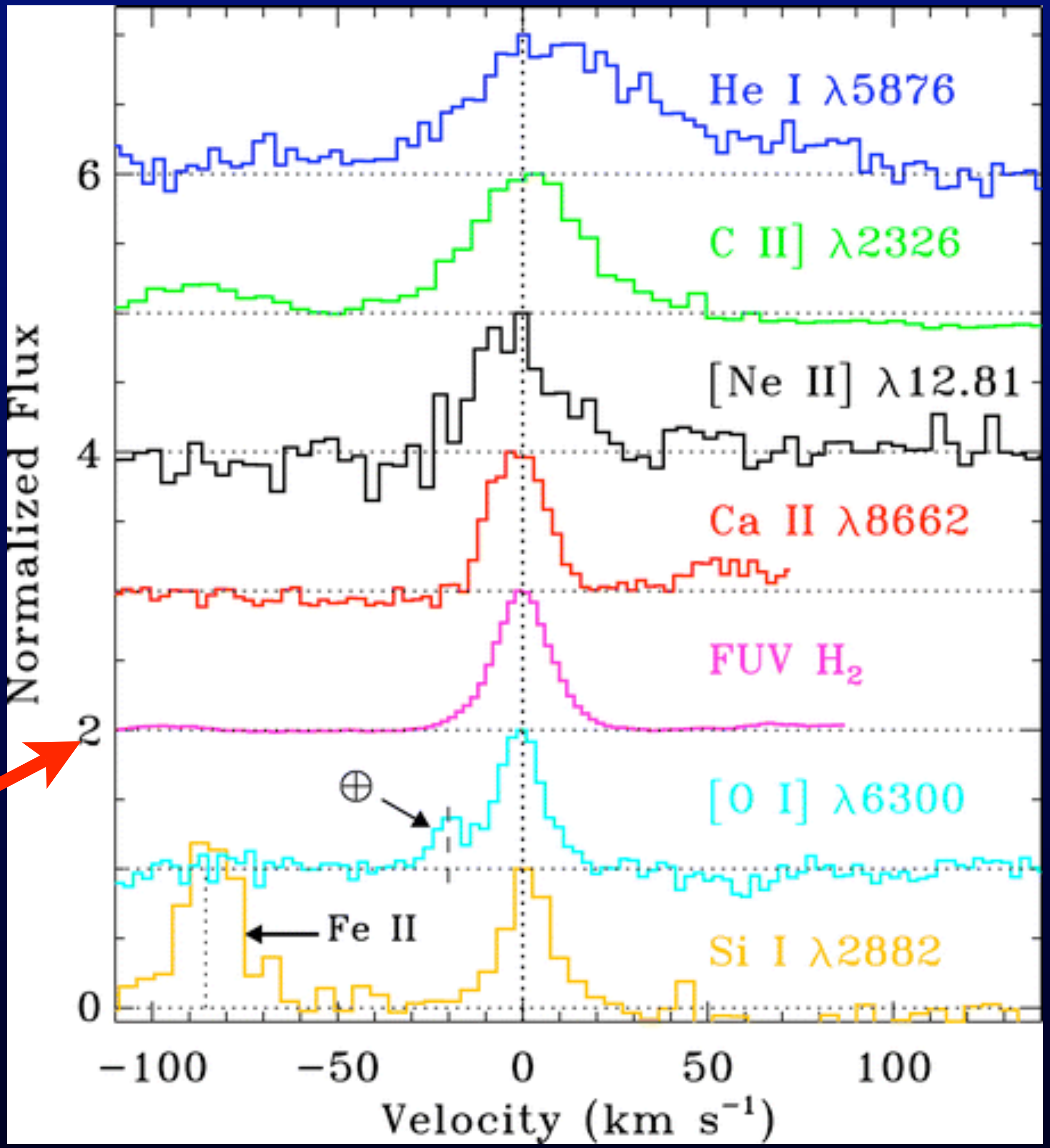

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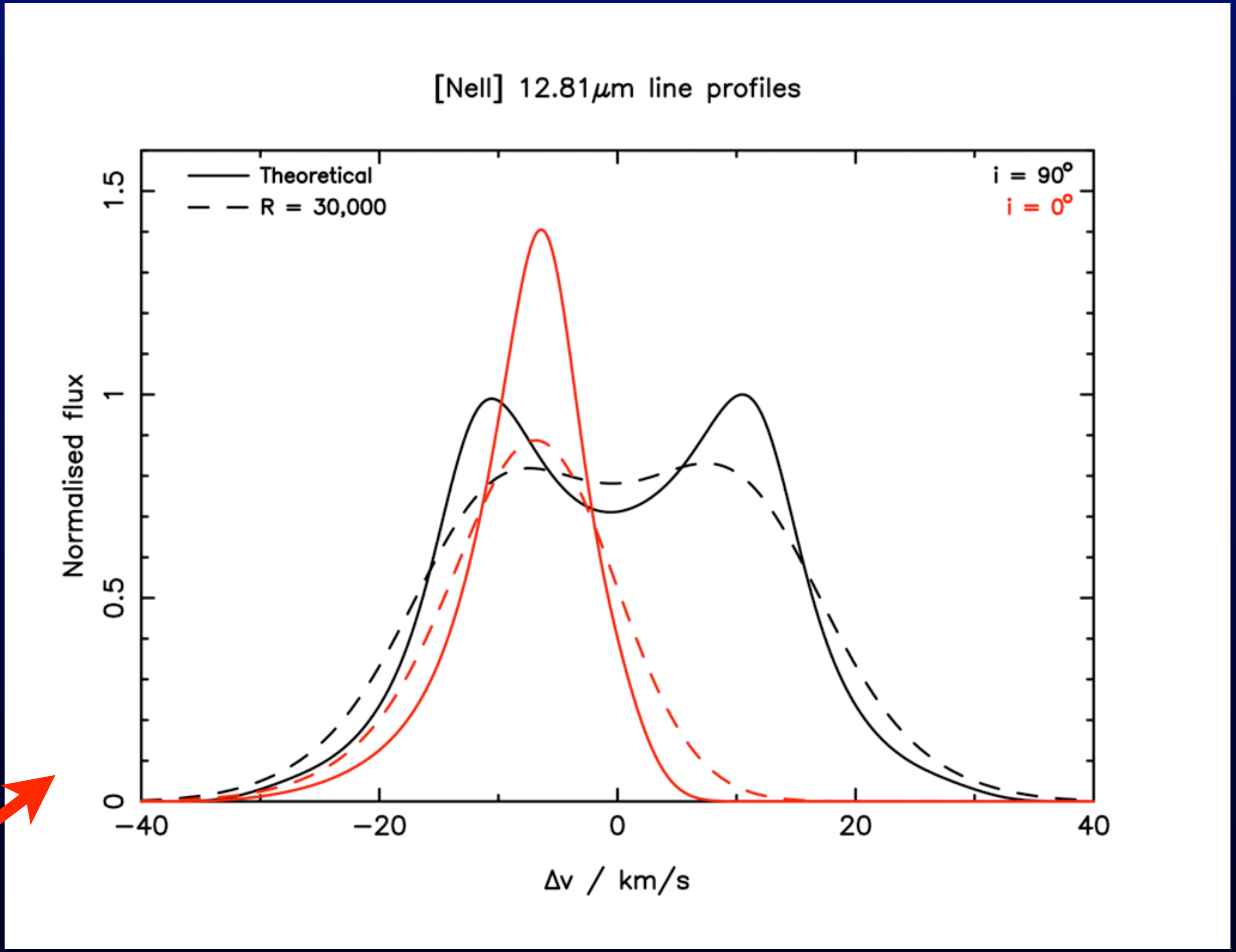
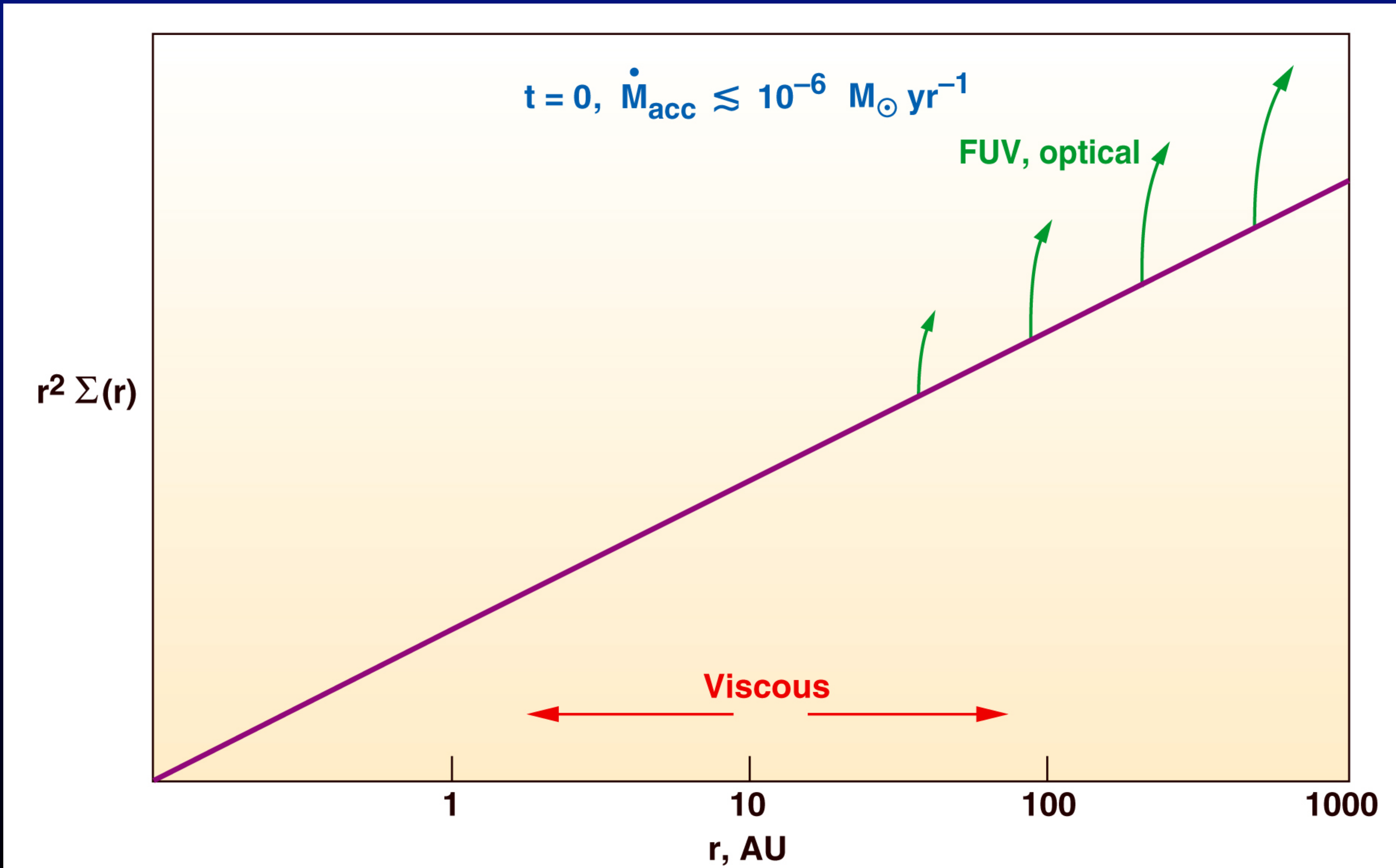


RDA, in prep.

Schematic picture of (gas) disc evolution

Figures courtesy of David Hollenbach



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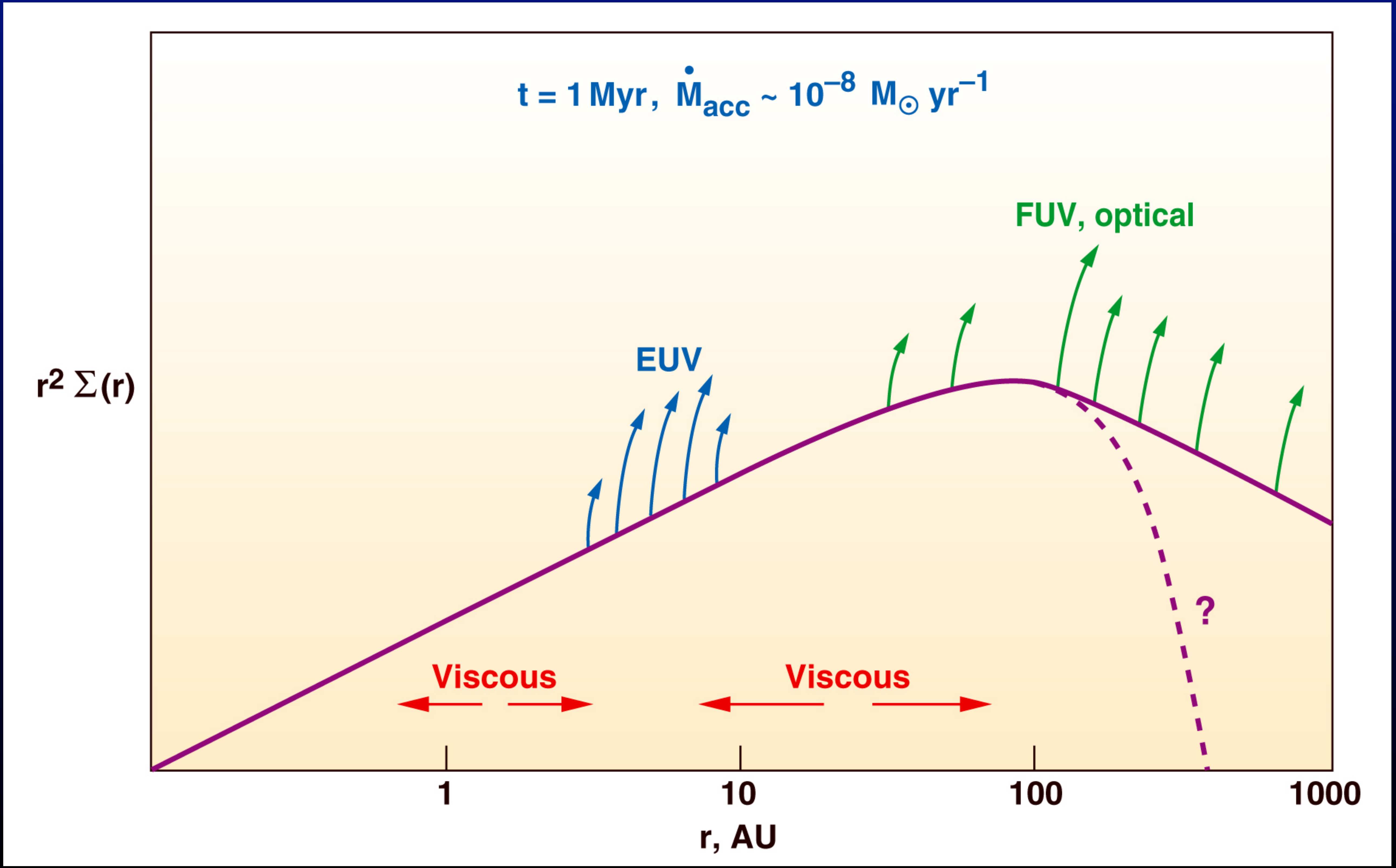

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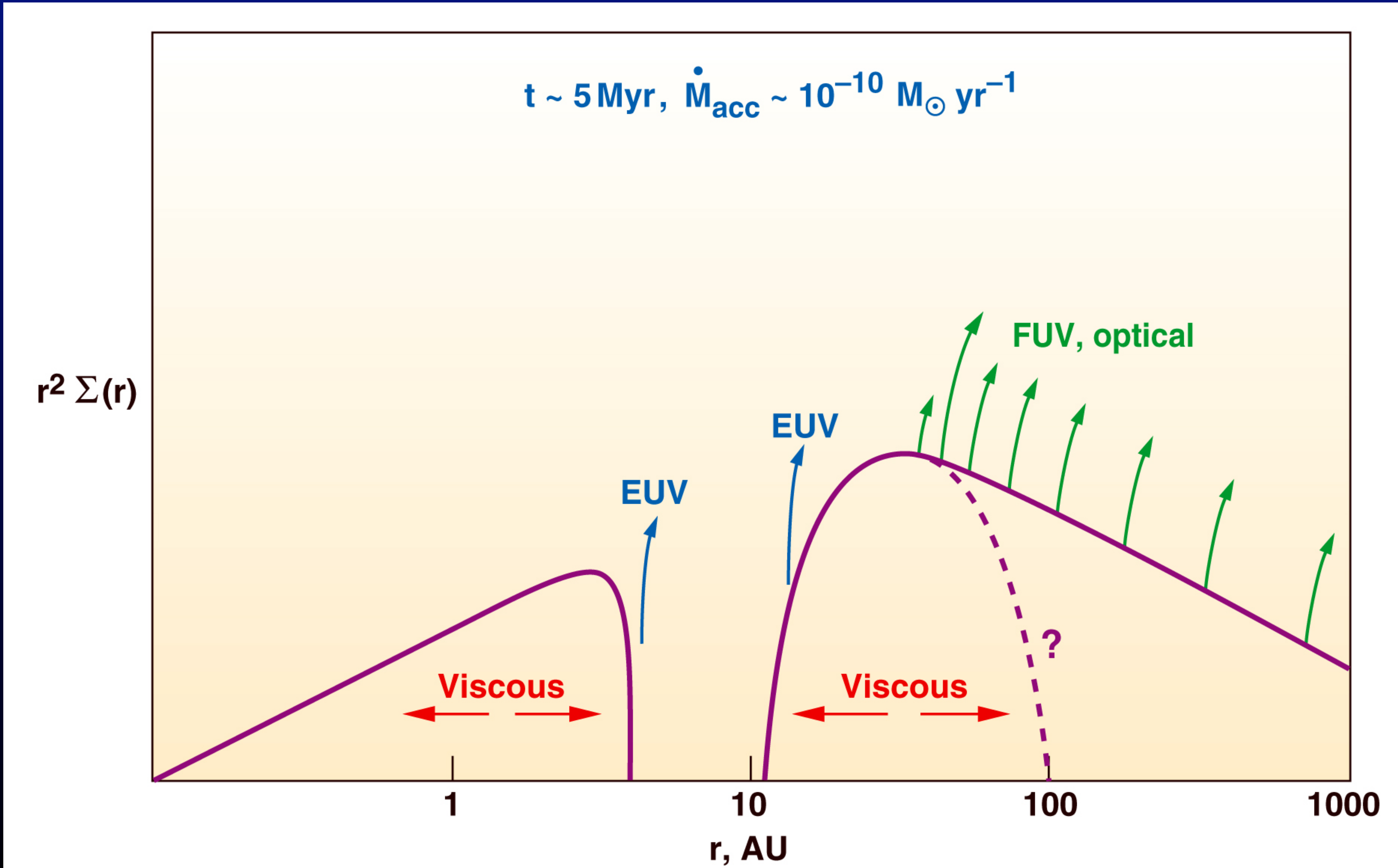

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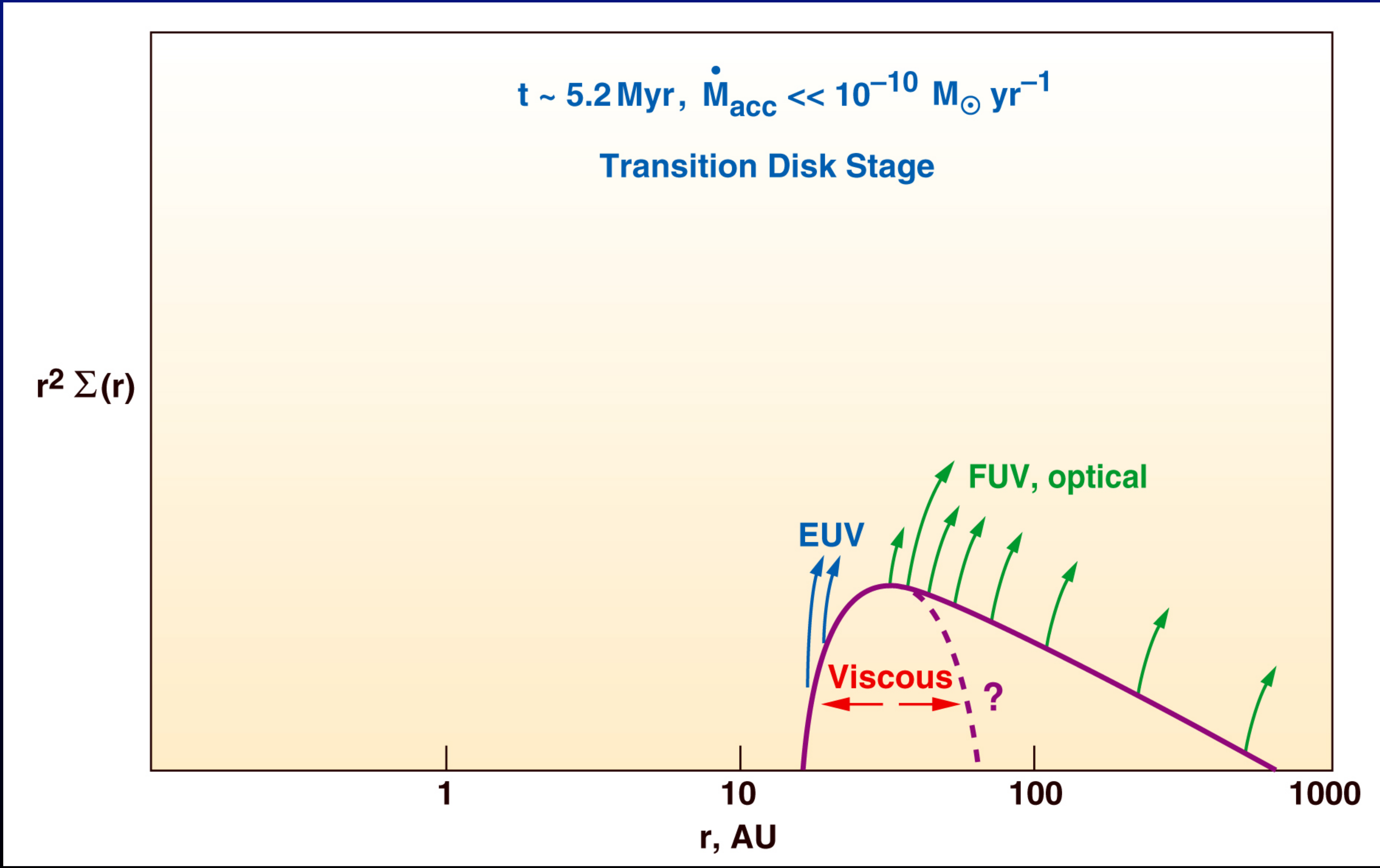

Disc evolution: summary

- Protoplanetary discs evolve, primarily due to “viscosity”.
- During this viscous evolution phase, dust evolution and/or planet formation occur.
- At late times EUV photoevaporation becomes significant and clears the (gas) disc. Such models satisfy available constraints on timescales, and reproduce observed data well.
- Models of FUV photoevaporation remain in progress. Seems likely that this wind can remove a significant fraction of the disc mass over a ~Myr lifetime.
- Observations of gas emission lines should provide critical tests of current theoretical models.