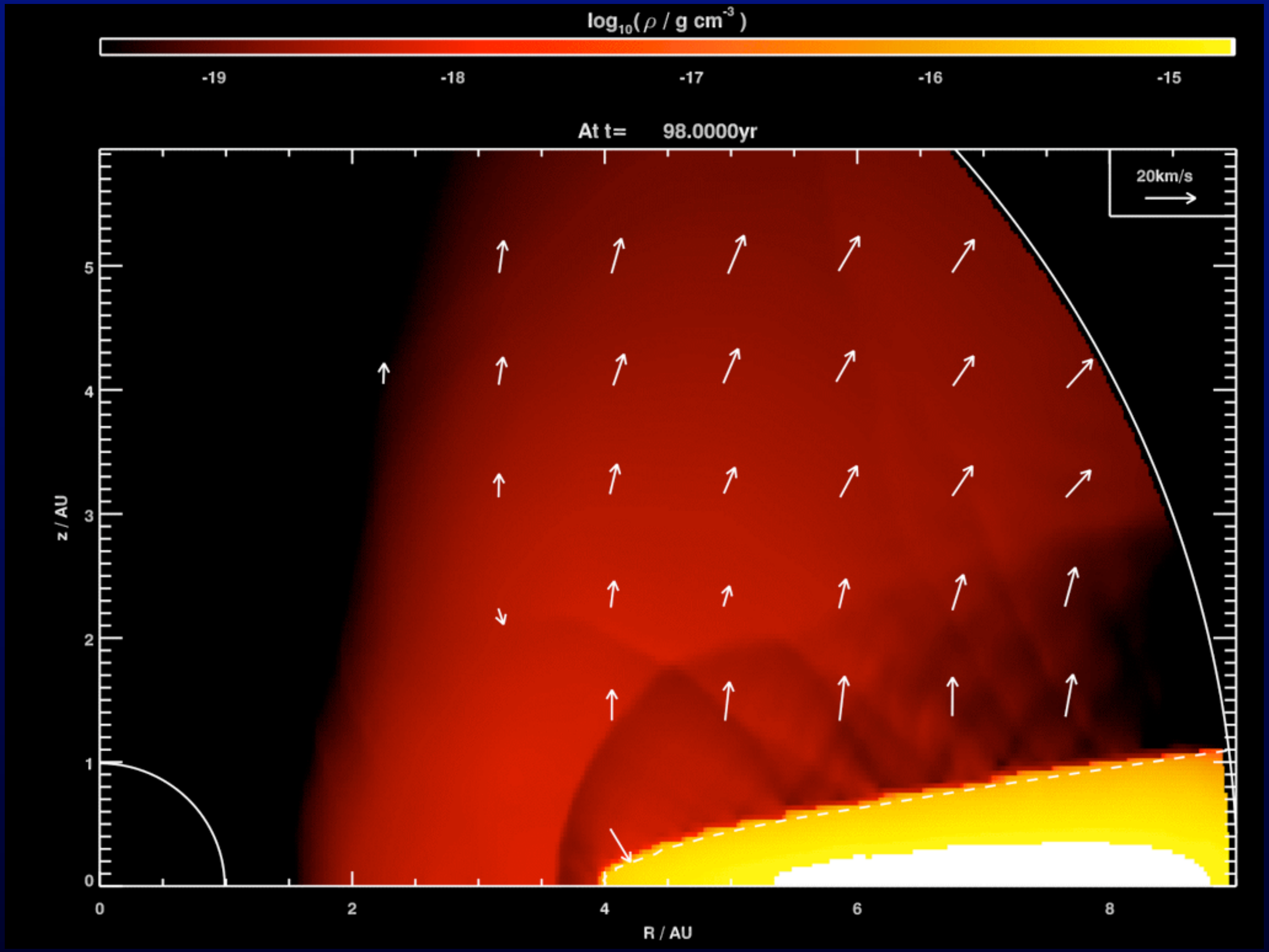
Evolution & dispersal of gas discs



Richard Alexander
Sterrewacht Leiden

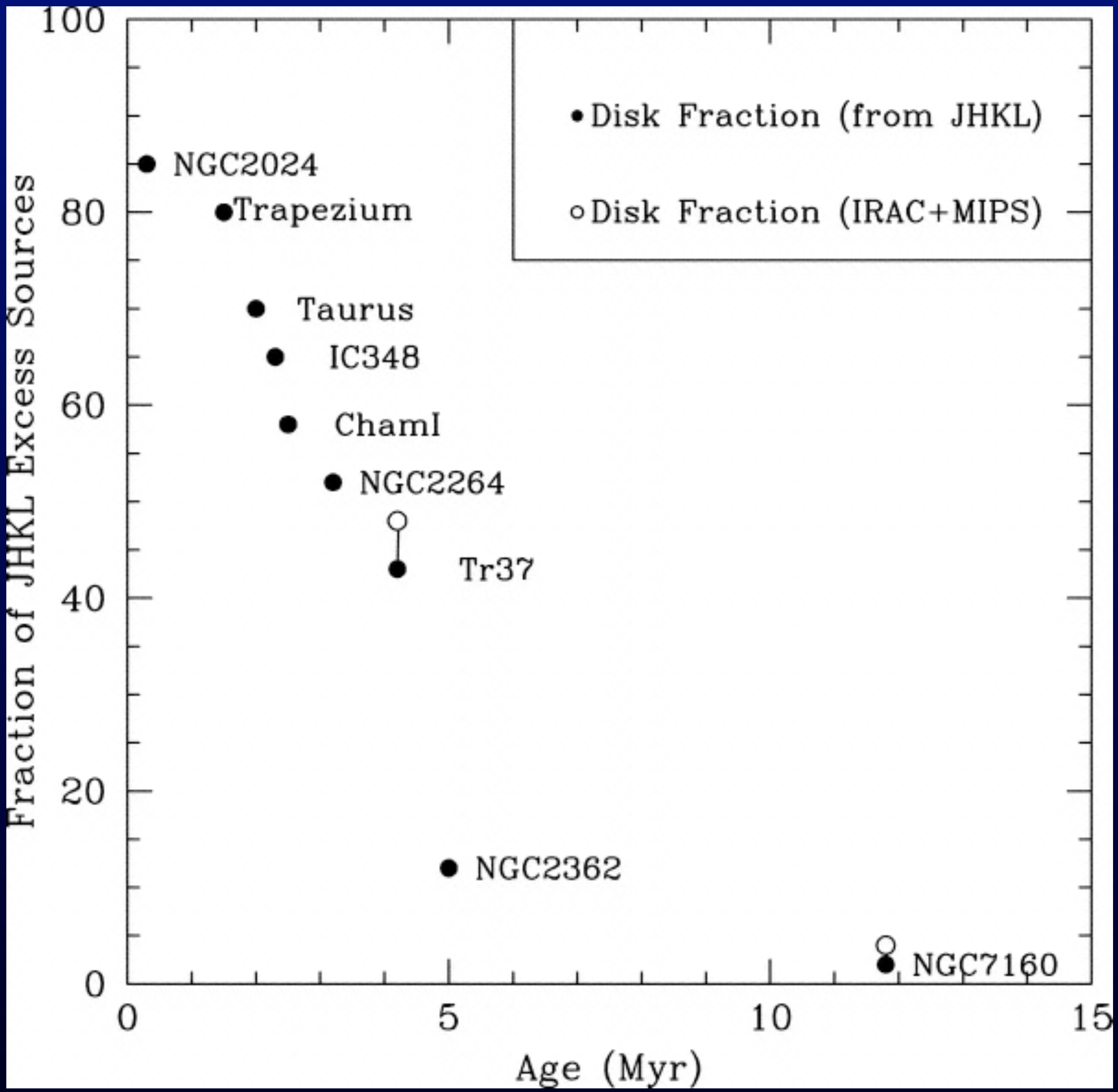
Cathie Clarke, Jim Pringle (Cambridge)
Phil Armitage (Colorado), Barbara Ercolano (Cambridge)

Sterrewacht Leiden

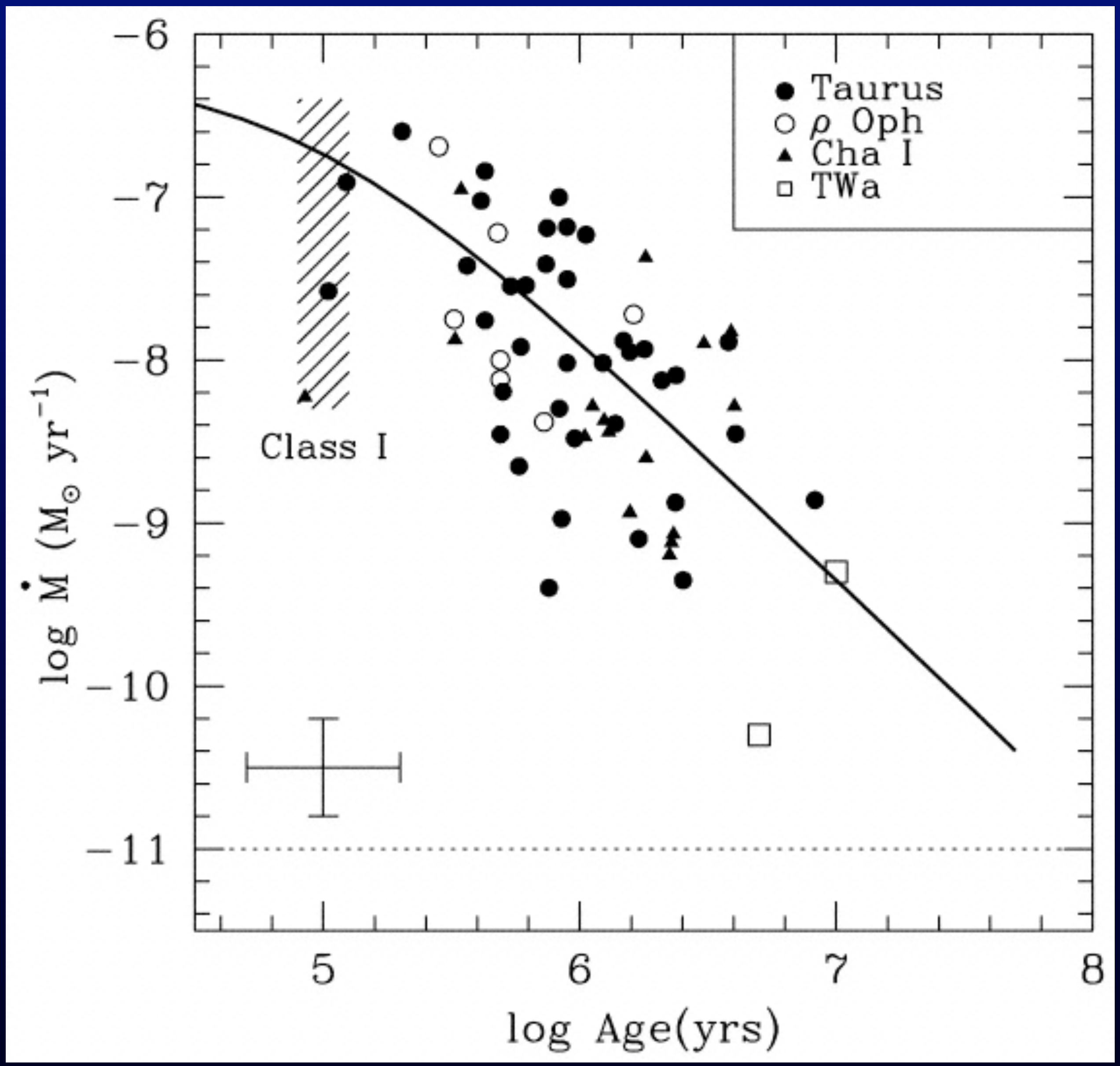
Outline

- (Gas) disc evolution theory
  - Observational motivation: timescales & observed properties
  - Basic theory: viscous accretion + photoevaporation
  - Recent models and work in progress
- Observational diagnostics
  - [NeII] emission as a tracer of photoevaporation
- "Transitional" discs
  - Statistical studies and selection biases
  - Discriminating between models
- Summary / speculative hand-waving

Observations of disc evolution



Sicilia-Aguilar et al. (2006)



Muzerolle et al. (2000)

Observational constraints

- 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 $>0.1M_\odot$ to $\leq 0.001M_\odot$.
- Accretion rates span $>10^{-7}M_\odot yr^{-1}$ to $\leq 10^{-10}M_\odot yr^{-1}$.
- Termination of (gas) accretion roughly simultaneous with (dust) disc clearing.
- Discs are cleared rapidly (in $\sim 10^5$yr), across entire radial extent of disc.
- Observations of ***gas*** disc evolution are very limited.

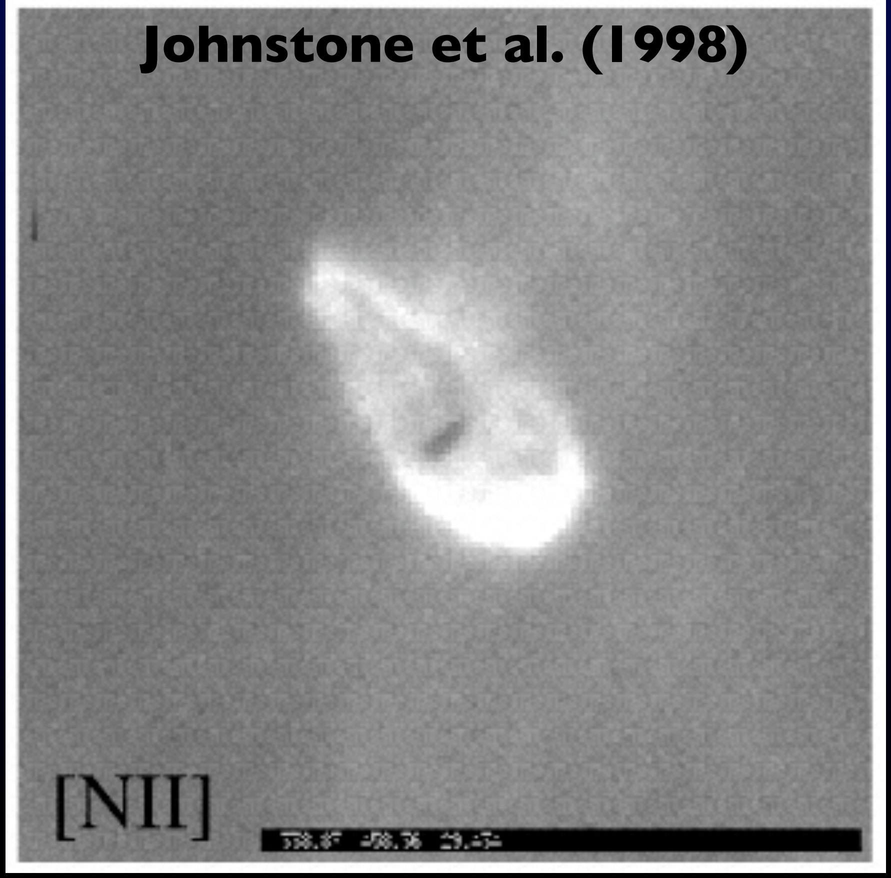
See talks by Calvet, Hernandez, Furlan

Gas evolution processes

- Various processes can affect evolution of gas discs.
- Hollenbach et al. (PP4), considered all and concluded that:
  - "Viscous" evolution dominates for radii ≤ 10AU.
  - Photoevaporation dominates for radii ≥ 10AU.
- Photoevaporation by O-stars is responsible for the "proplyd" phenomenon seen in the ONC.

(See talk by Williams)

Johnstone et al. (1998)



Gas evolution processes

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  - "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.
- In this talk I will treat TTs as isolated objects (only "central star" photoevaporation; neglecting cluster dynamics; etc.).
- I will also assume that angular momentum transport ("viscosity") can be modelled using an $\alpha-$prescription.

Disc photoevaporation

- High-energy irradiation 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:

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

- Important cases: EUV (ionizing), FUV (1000-2000Å) and X-ray. For a typical T Tauri star:

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

- Recent reviews: Dullemond et al. (PP5); RDA (2008a).

See posters by Gorti, Hollenbach, Ercolano, Drake

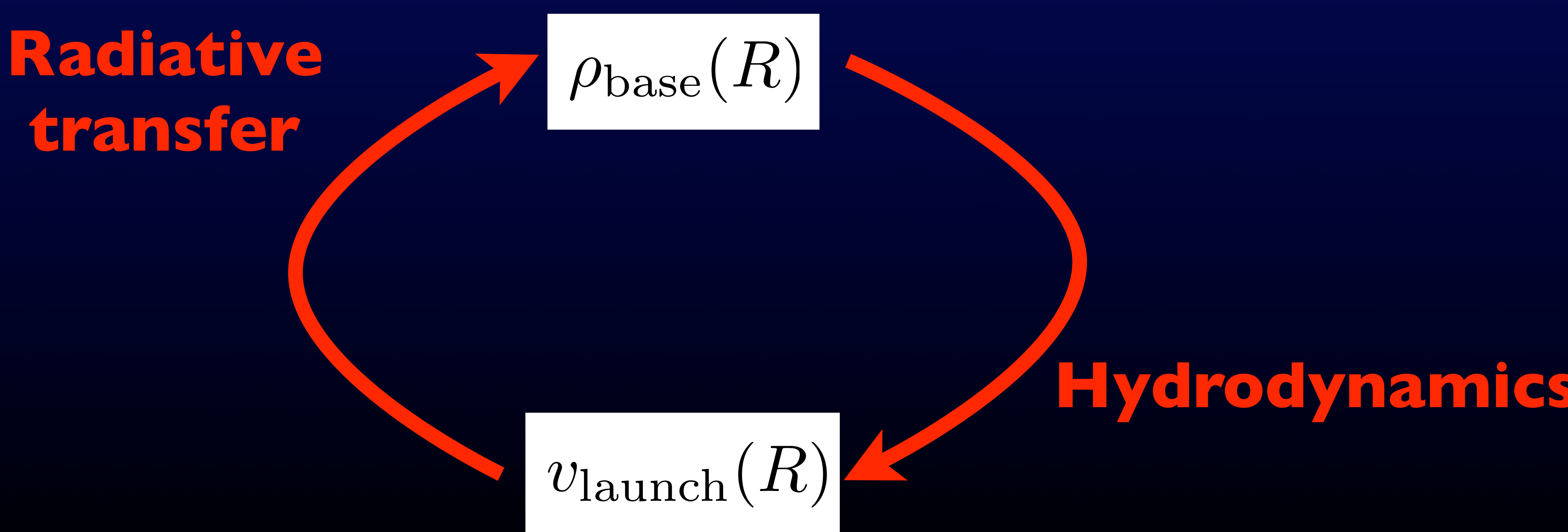
Disc photoevaporation

- Models aim to compute mass-loss profile of the wind.

$$\dot{M}_{\mathrm{wind}} = \int 2\pi R \dot{\Sigma}_{\mathrm{wind}}(R) dR$$

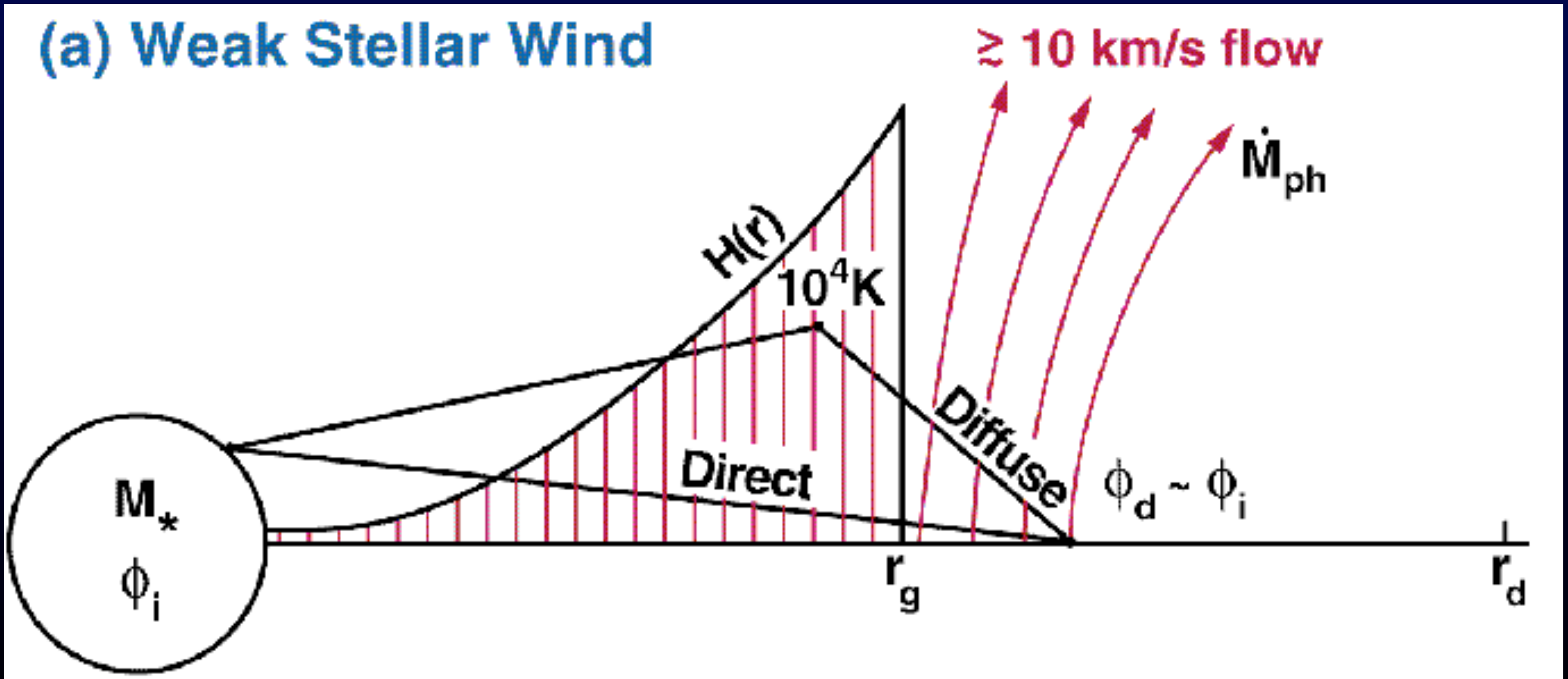
$$\dot{\Sigma}_{\mathrm{wind}}(R) = 2\rho_{\mathrm{base}}(R) v_{\mathrm{launch}}(R)$$

- In general, this is a complicated problem:



Disc photoevaporation

- EUV is the "easy" case:
  - Radiative transfer is simple (Strömgren criterion), ρ_{base} well-defined.
  - Flow is isothermal (10^4K).
  - Wind is 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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  - Flow is isothermal (10^4K).
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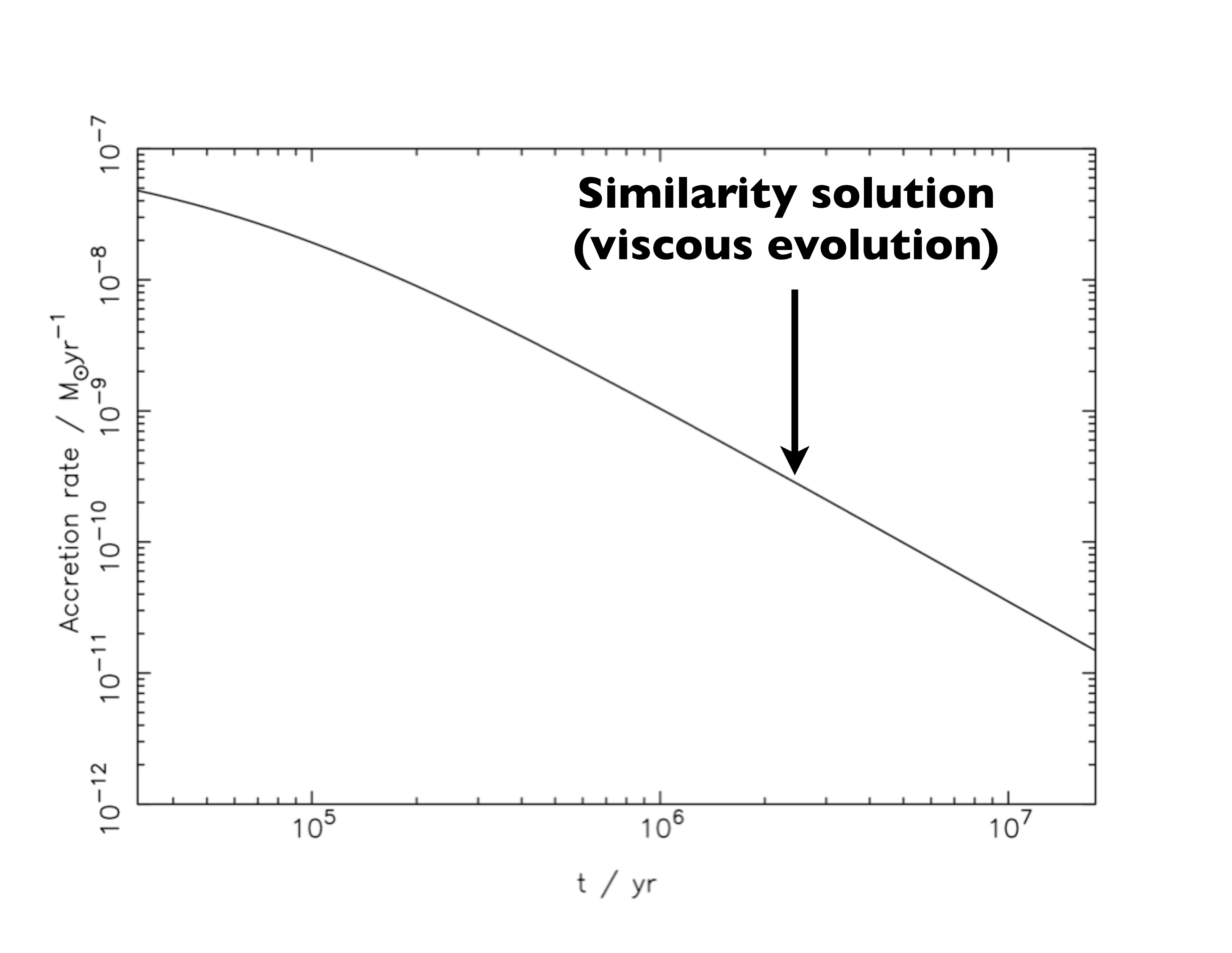
  - Analytic models agree reasonably well with numerical simulations.

- FUV & X-rays are 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 FUV radiation field depends on accretion rate.
  - Flow geometry 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 $\sim 10^{-10} M_{\odot} yr^{-1}$ 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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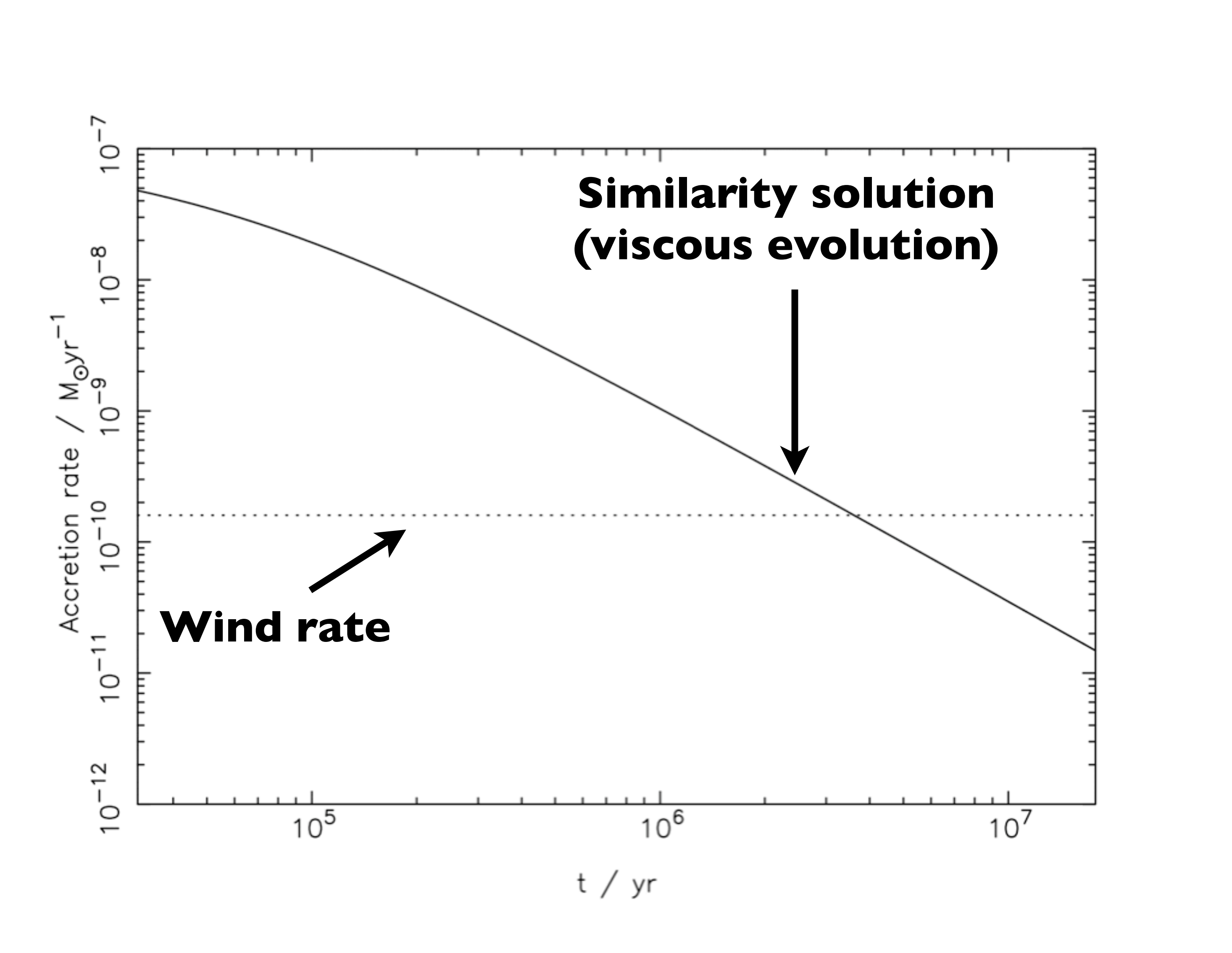

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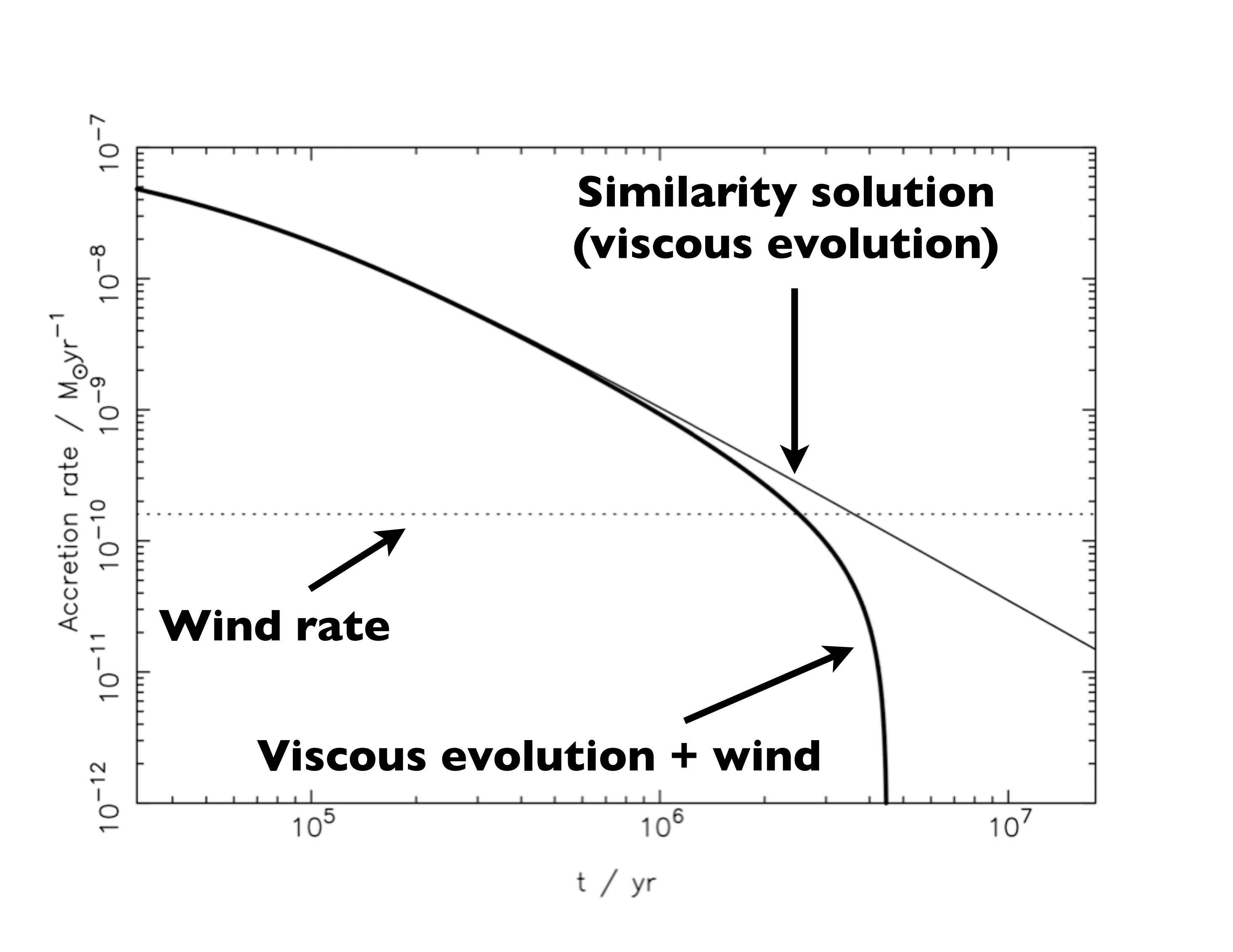
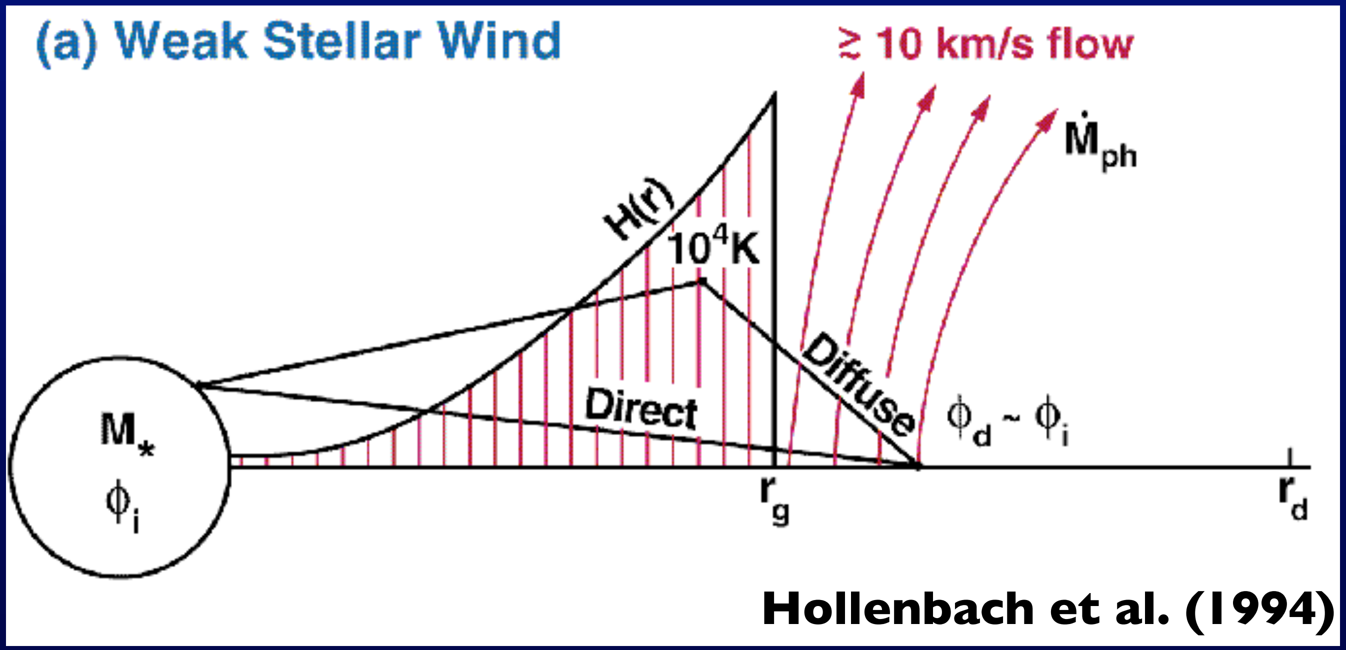
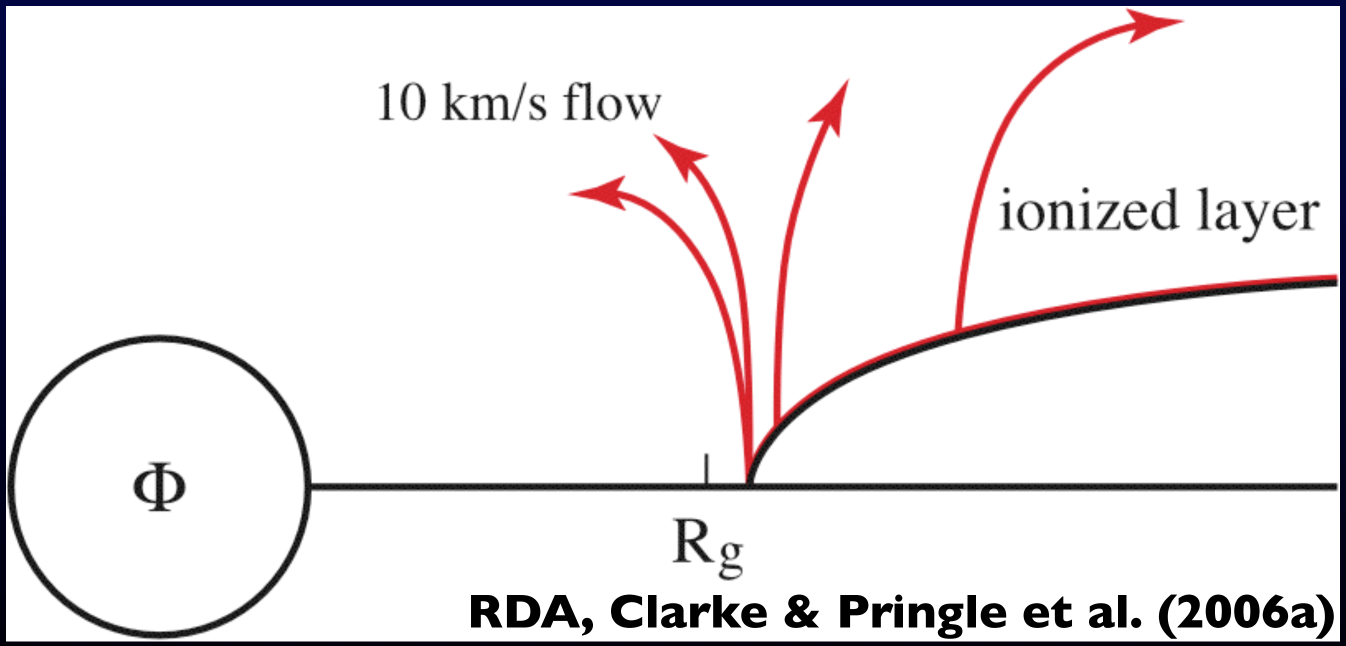


The outer disc: direct irradiation

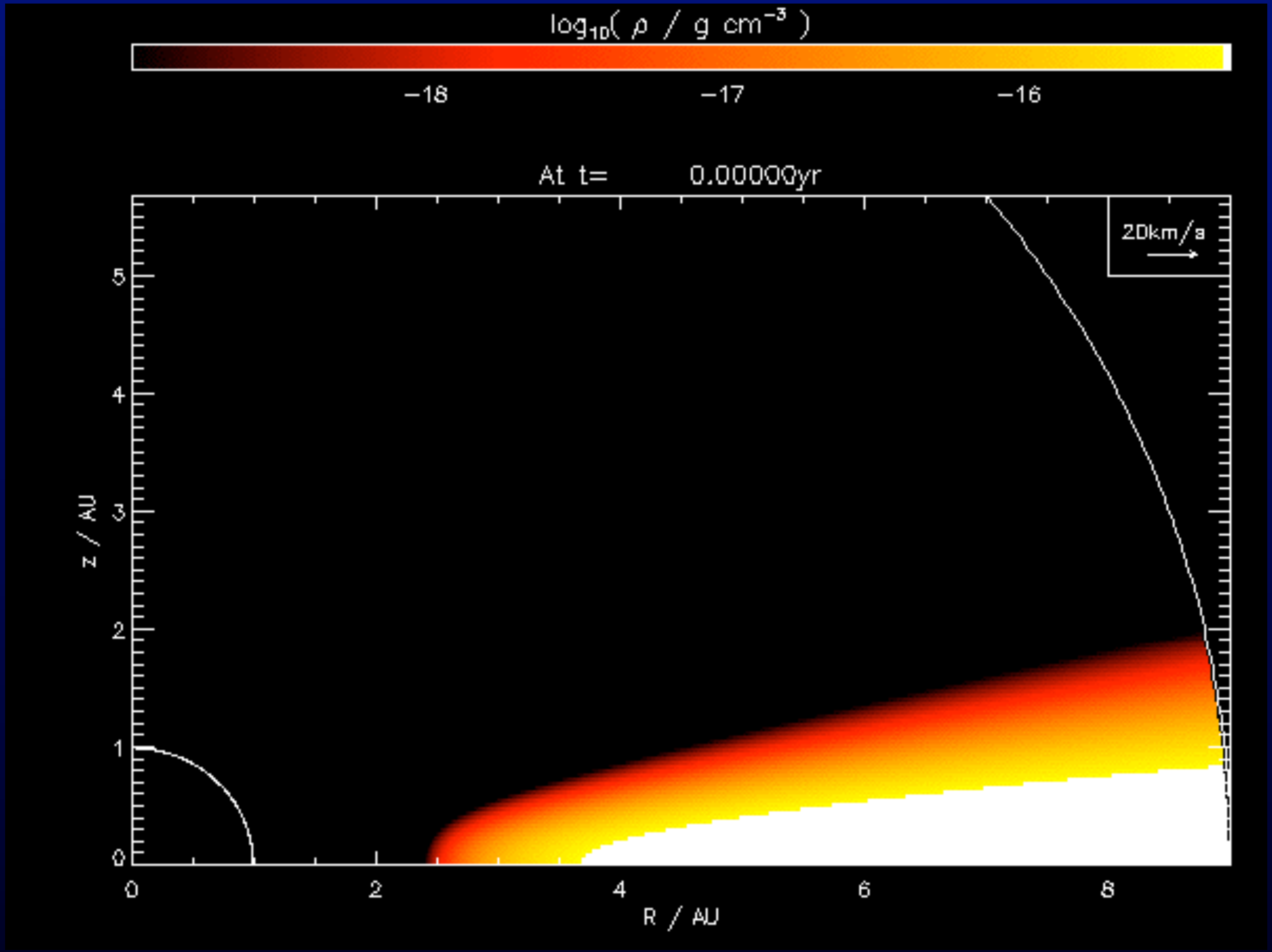




- In static wind model disc is assumed to be optically thick to ionizing photons, so the diffuse (recombination) field dominates the wind.
- After the inner disc has drained, radiative transfer problem changes: direct radiation field dominates the wind.

Direct photoevaporation

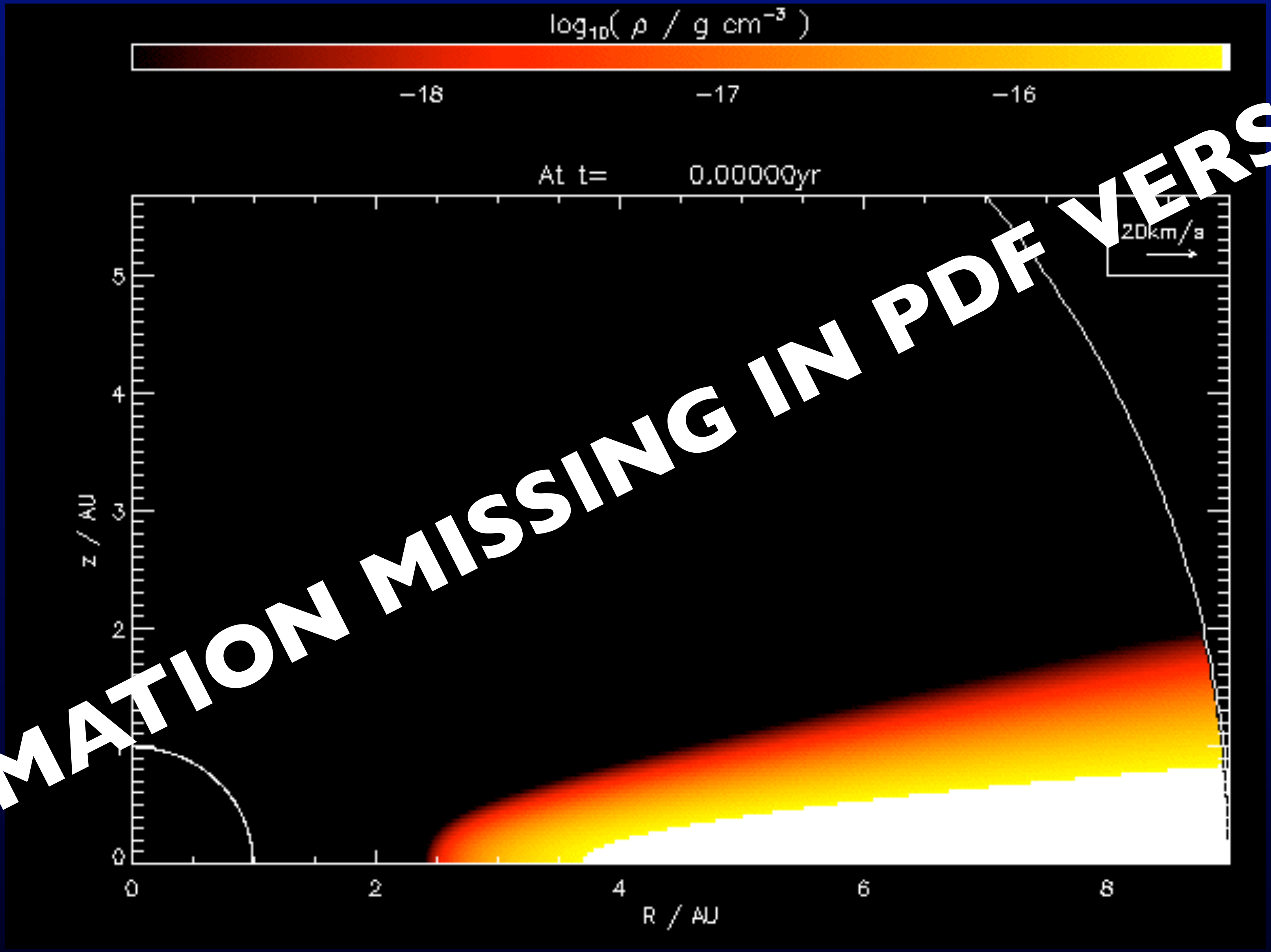
RDA, Clarke & Pringle (2006a)



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

Direct photoevaporation

RDA, Clarke & Pringle (2006a)



ANIMATION MISSING IN PDF VERSION

- Once inner disc has drained, radiative transfer problem changes.
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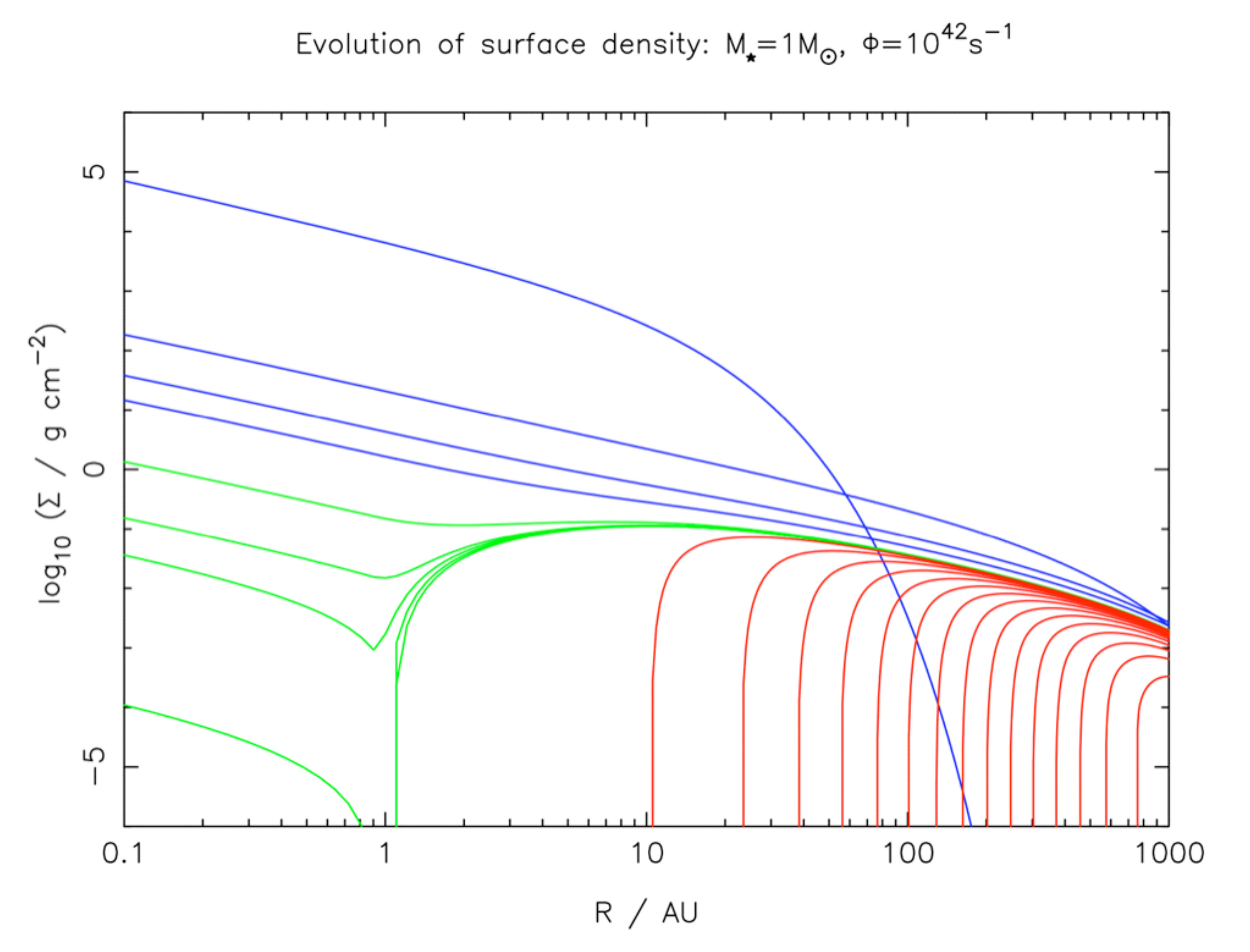
EUV + viscous evolution

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, time-dependent models to date.
- Two (complementary) approaches:
  - Detailed radiative transfer, simplified hydrodynamics.
  - Detailed hydrodynamics, simplified radiative transfer.
- Mass loss concentrated near outer edge of disc (>50AU). Calculated mass-loss rates are ~$10^{-8} M_{\odot} yr^{-1}$ (Gorti & Hollenbach 2008b):

$$\dot{M}_{\rm wind} \times t_{\rm disc} \sim 0.01 \rm M_{\odot}$$

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

See posters by Gorti, Hollenbach, Ercolano, Drake

FUV photoevaporation

- No com
- Two (co
  - Detaile
  - Detaile
- Mass los (>50AU). Calculat rti & Hollenb
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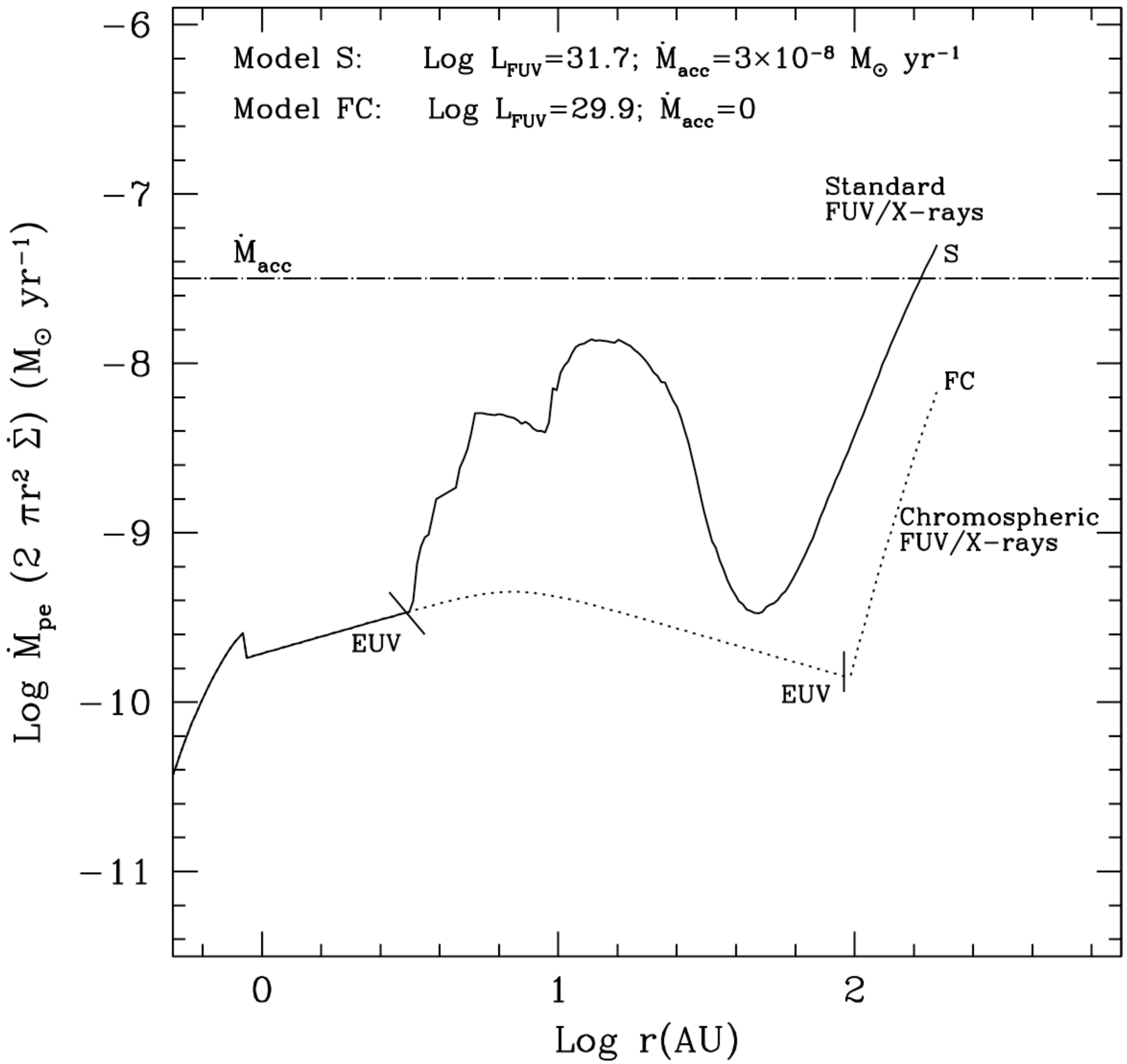
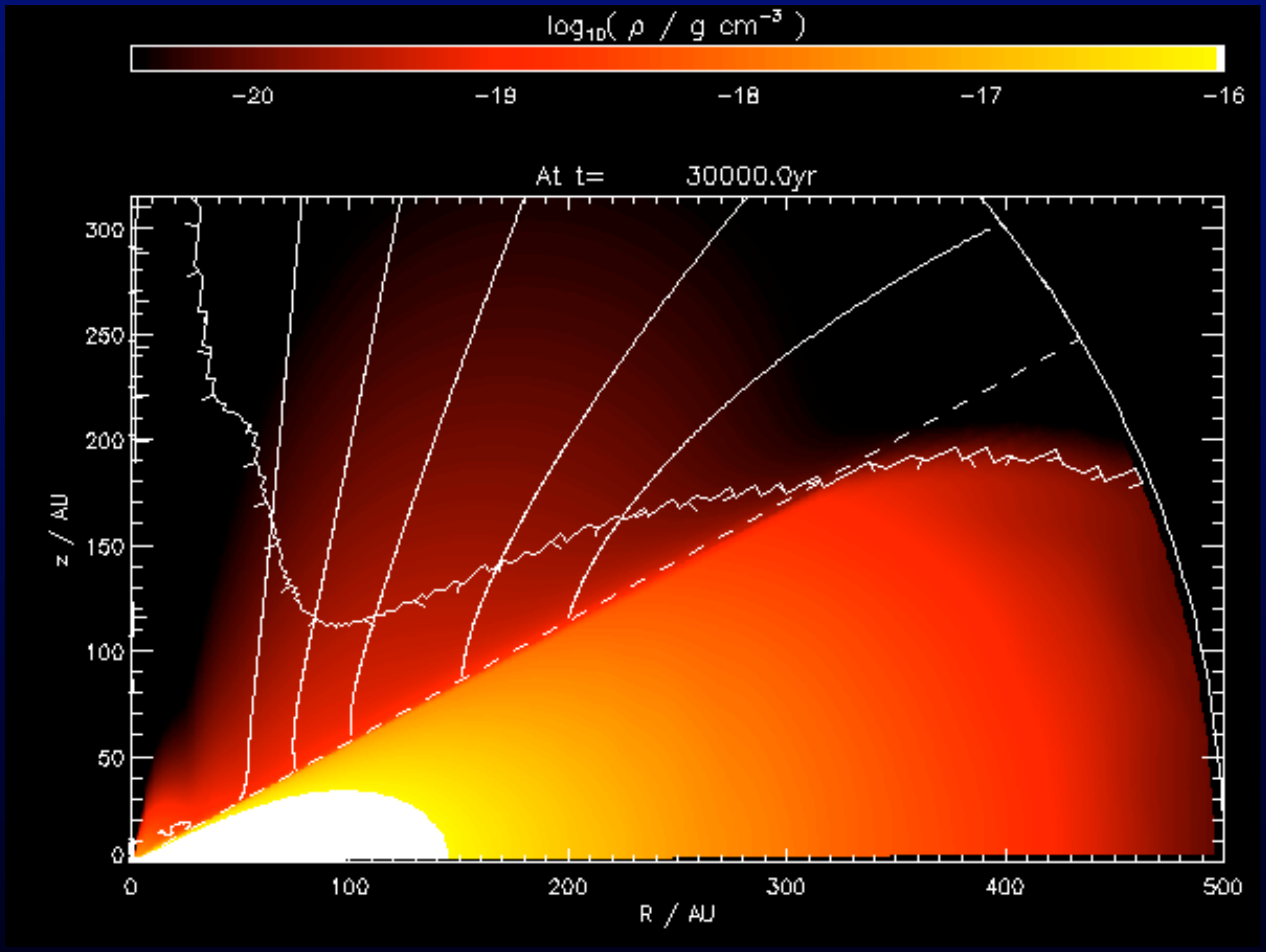


Gorti & Hollenbach (2008b)

See posters by Gorti, Hollenbach, Ercolano, Drake

FUV photoevaporation

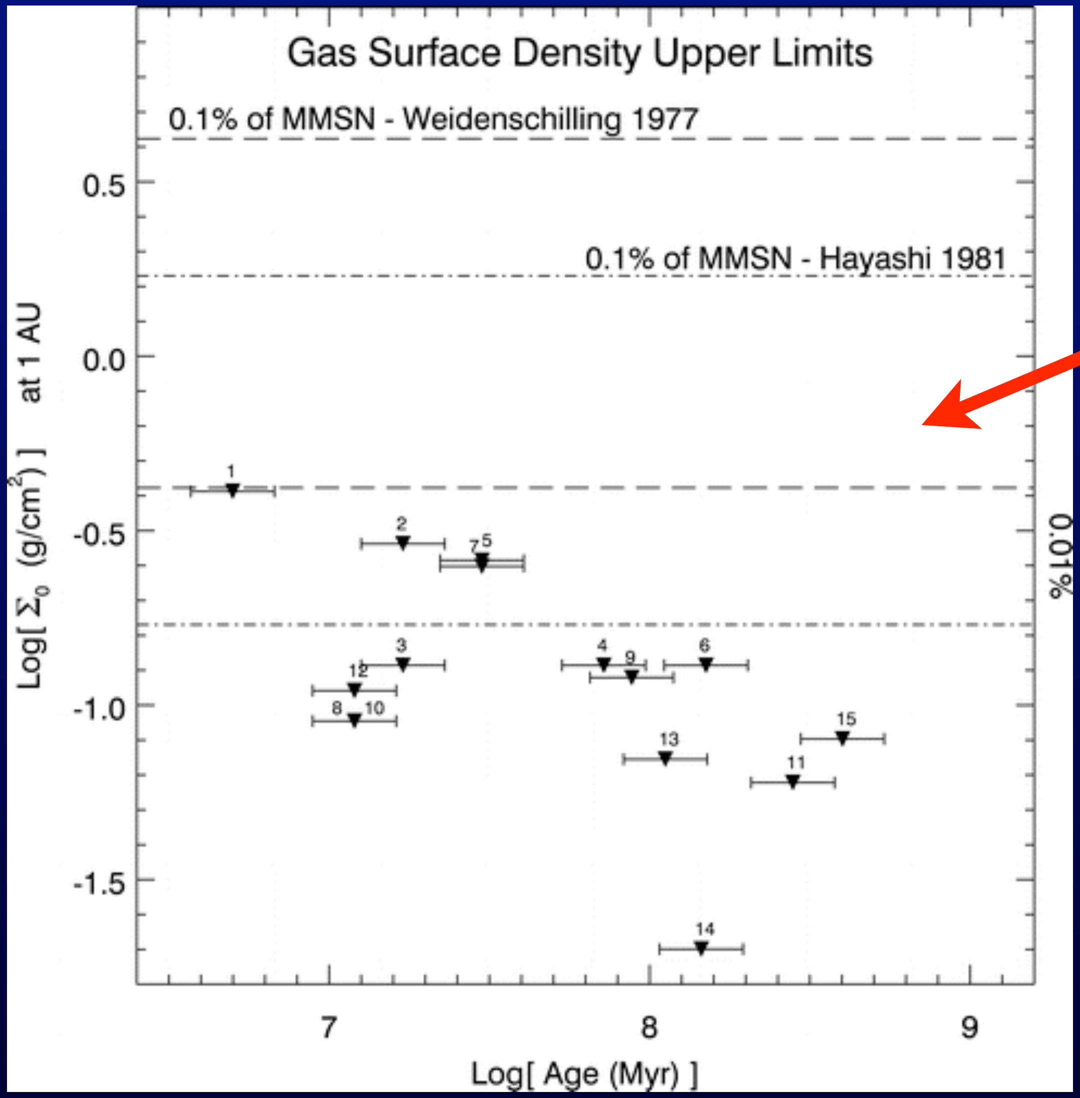
RDA & Clarke (in prep.)



$$T = T_0 \exp\left(-\frac{A_V}{A_{V,crit}}\right)$$

- Flow is complex: solution depends on flow topology, and cannot usually be computed analytically.
- Hydro models with "toy" heating used to try and understand flow dynamics.
- Work in progress: no widely-applicable analytic result (yet).

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 2008a). Excellent *Spitzer*/*Herschel*/SOFIA targets.

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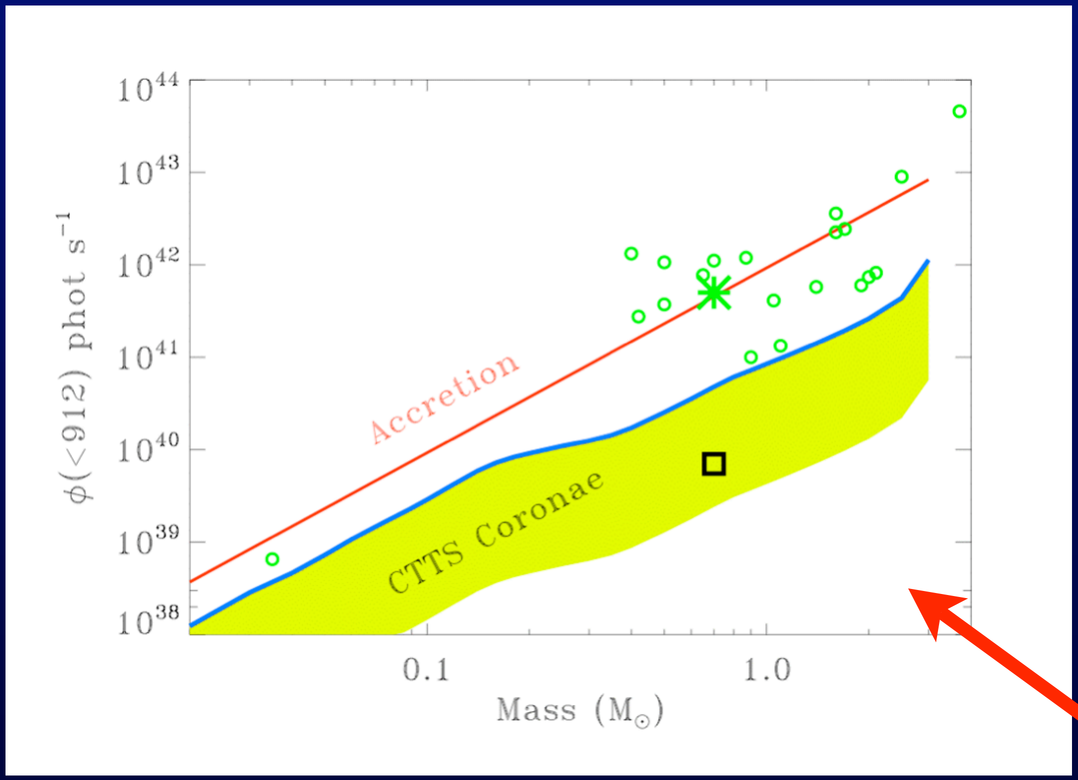

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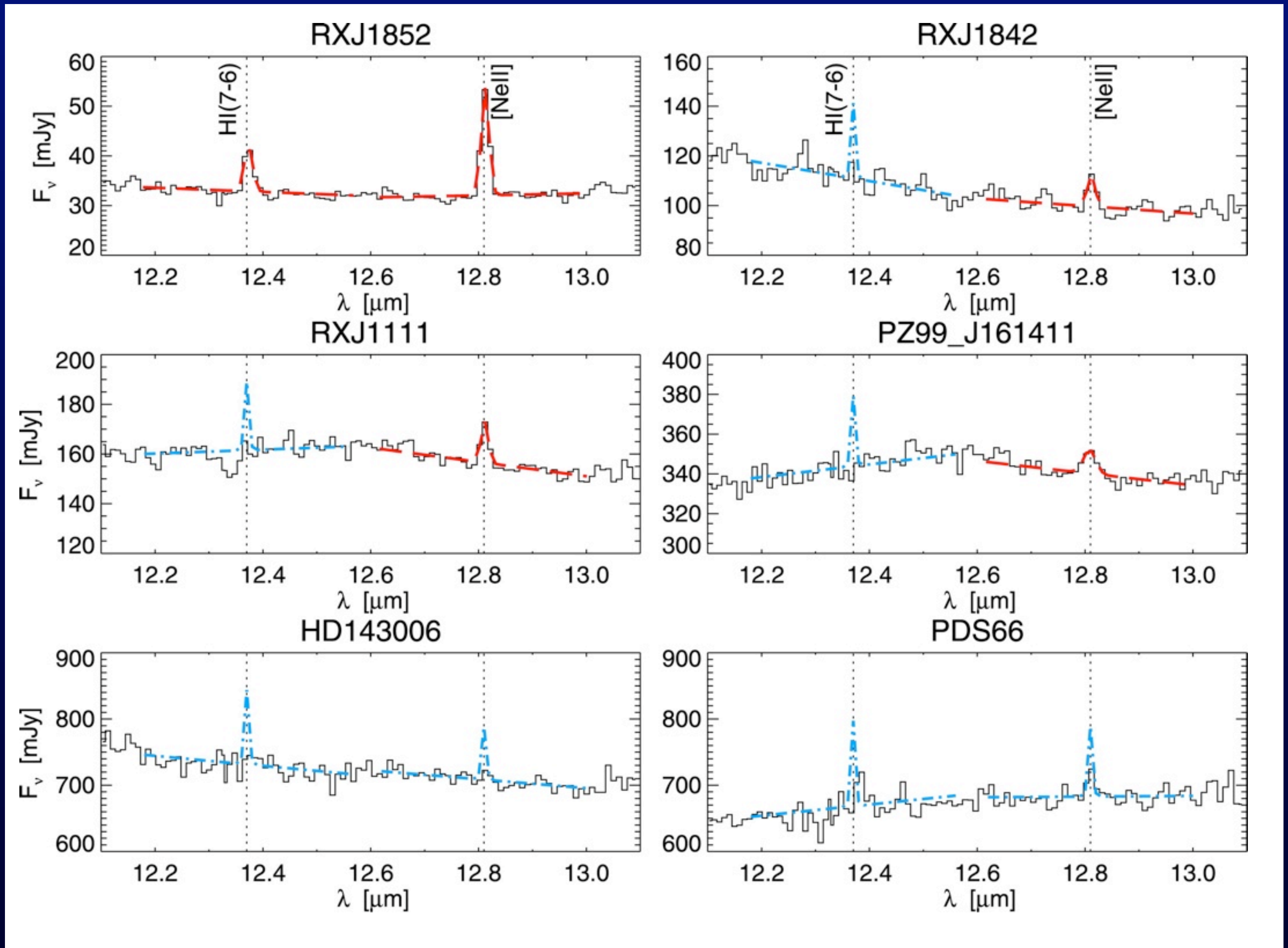
[NeII] emission



Pascucci et al. (2007); see also Lahuis et al. (2007)

(Detected) line fluxes ≈ 10^{-6}–$10^{-5}L_\odot$

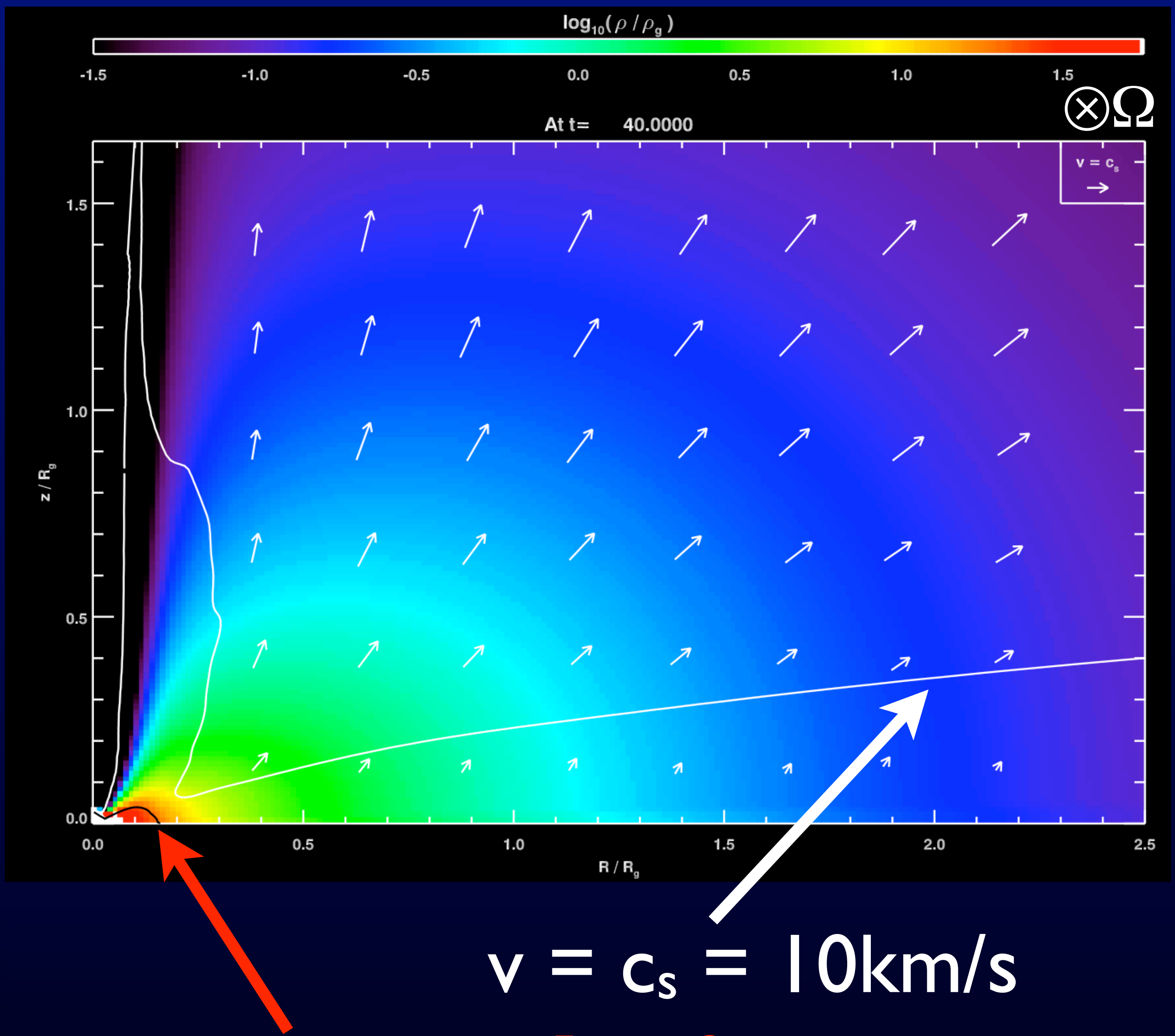
Equivalent widths ≈ 50–500Å

- *Spitzer* has detected the [NeII] 12.81μm line towards >20 young, ~solar-mass stars.
- Ionization potential of Ne is 21.56eV: line must come from low-density photo-ionized gas.
- Falls in 8-13μm atmospheric window: can be observed from the ground at echelle resolution.
- Does [NeII] emission trace an ionized disc wind?

See talk by Güdel; poster by Hollenbach

Modelling [NeII] line profiles

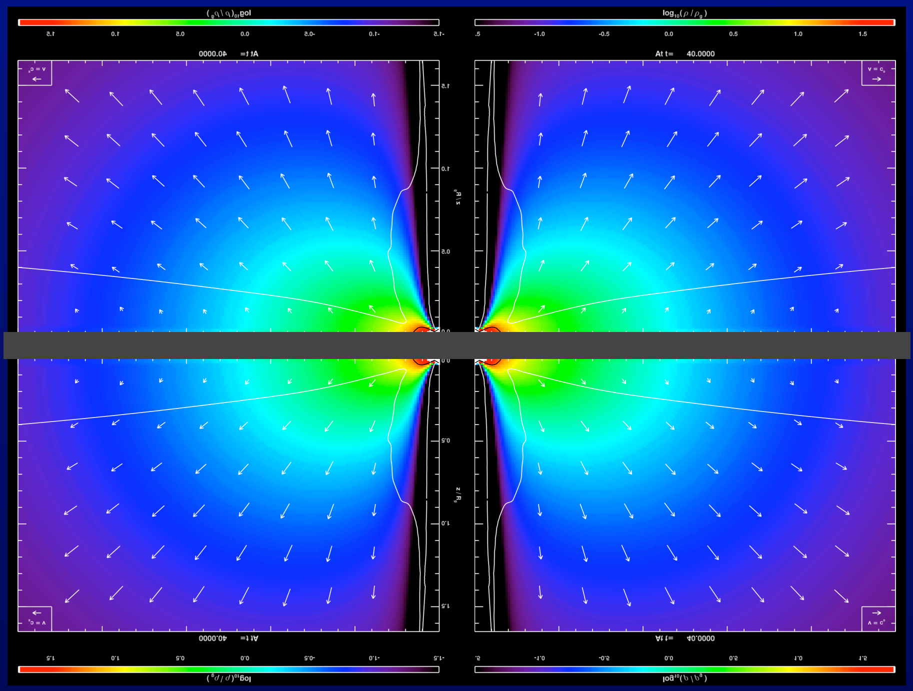
RDA (2008b)



- Use existing hydrodynamic model of EUV wind (Font et al. 2004) to model line profiles.
- Critical density of [NeII] 12.81μm line is well-matched to density in wind.
- Emission dominated by gas in "launching region": 0.1-2R_g.
- Ideal tracer of photoevaporation.

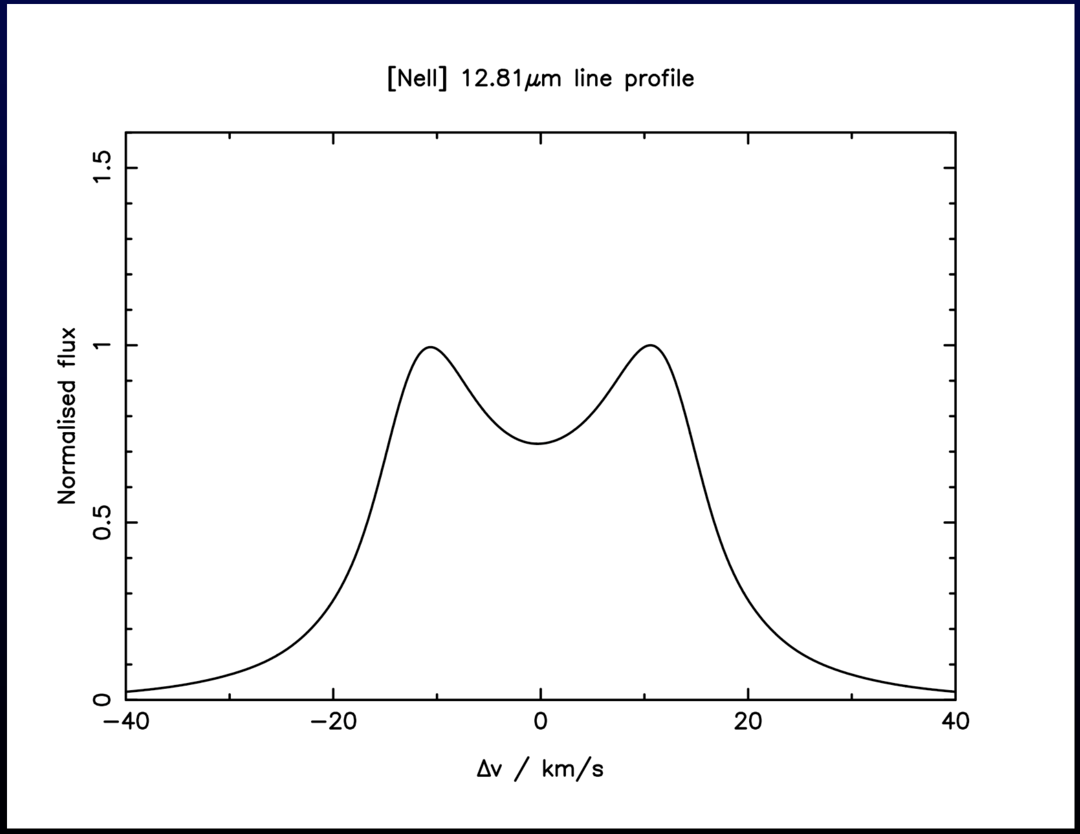
$$R_g = 8.9\left(\frac{M_*}{M_\odot}\right)\mathrm{AU} \qquad n_g \simeq 3\times10^4\left(\frac{\Phi}{10^{41}\mathrm{s}^{-1}}\right)^{1/2}\left(\frac{M_*}{1M_\odot}\right)^{-3/2}\mathrm{cm}^{-3}$$

Results

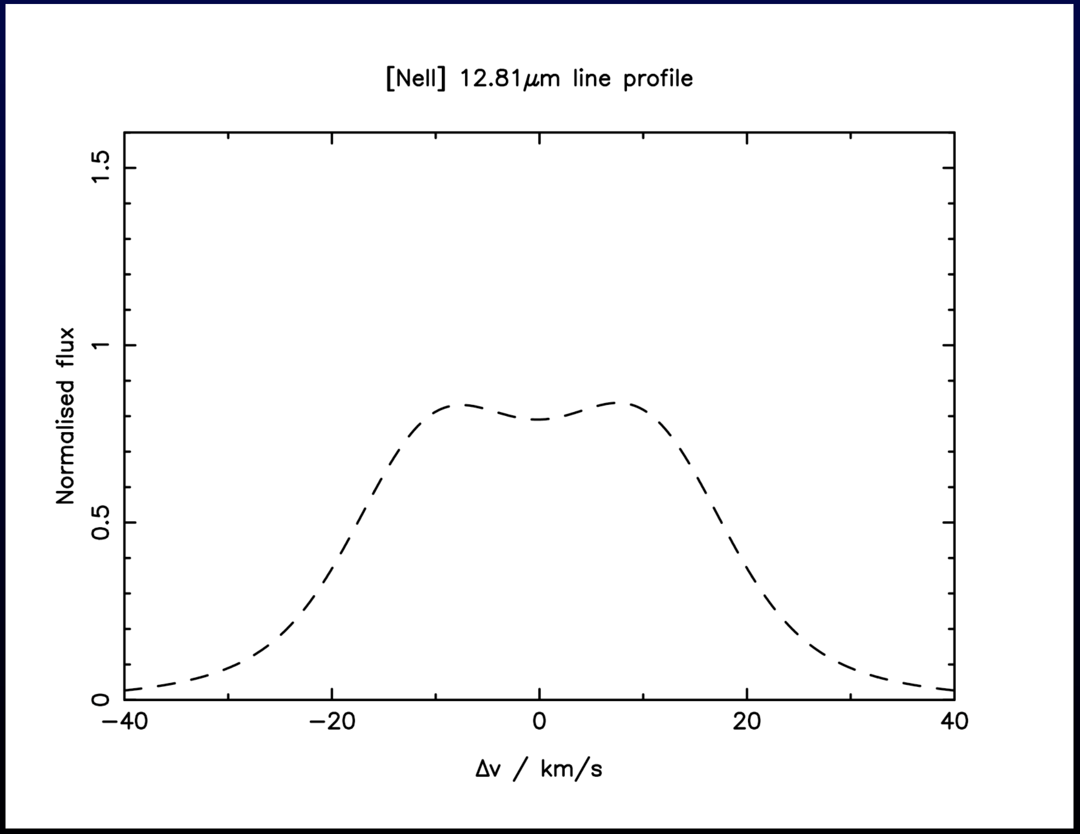


i = 90°

Theoretical profile



R = 30,000



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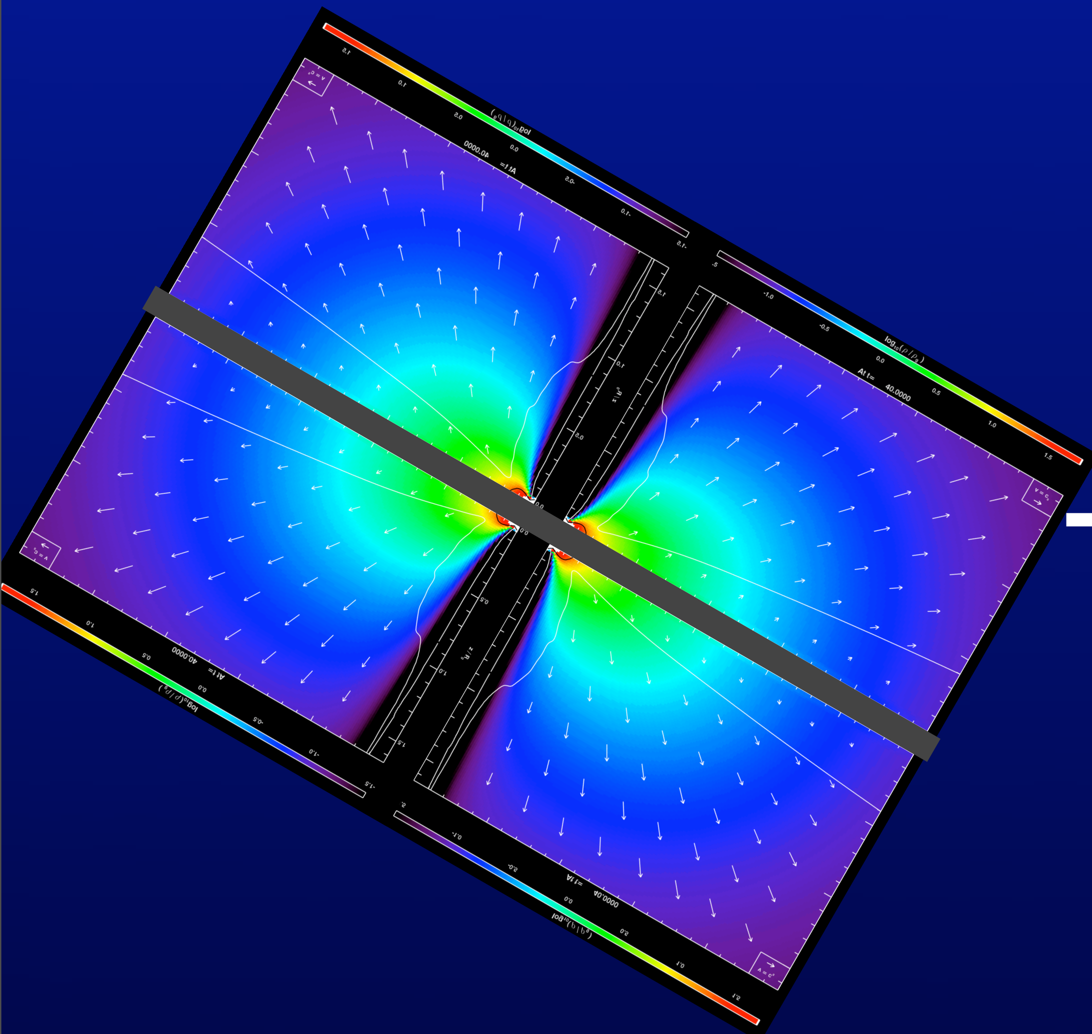
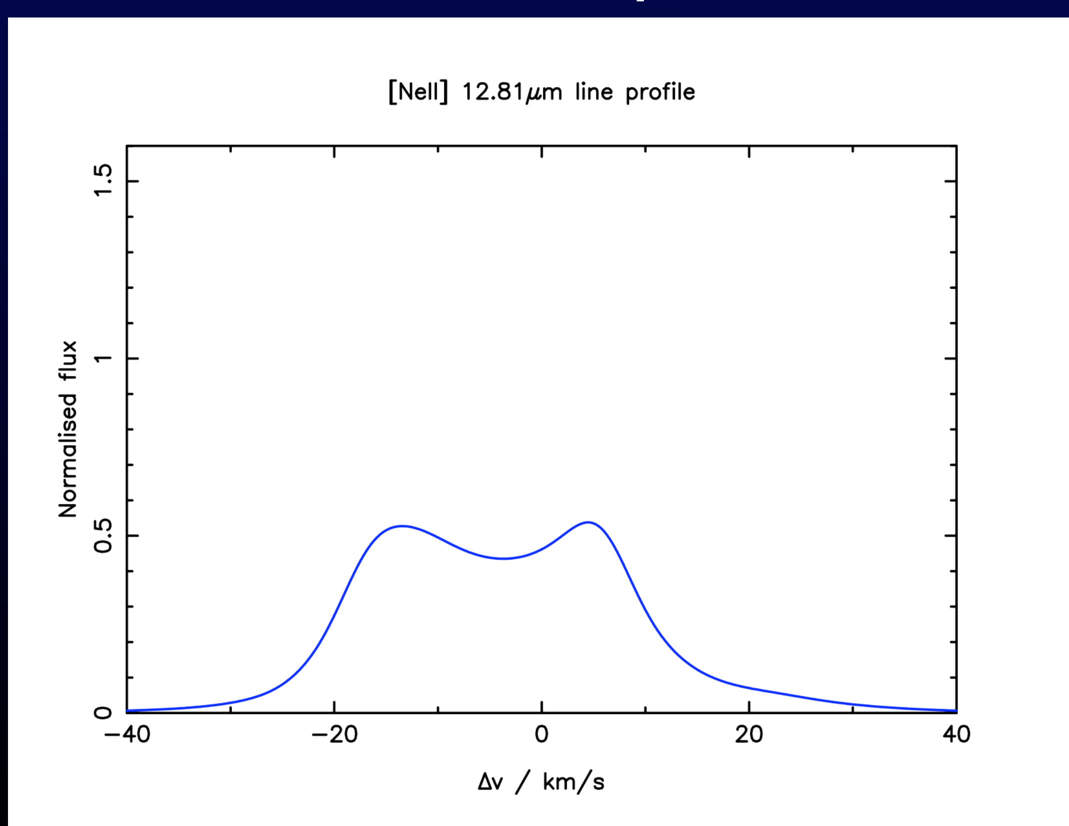
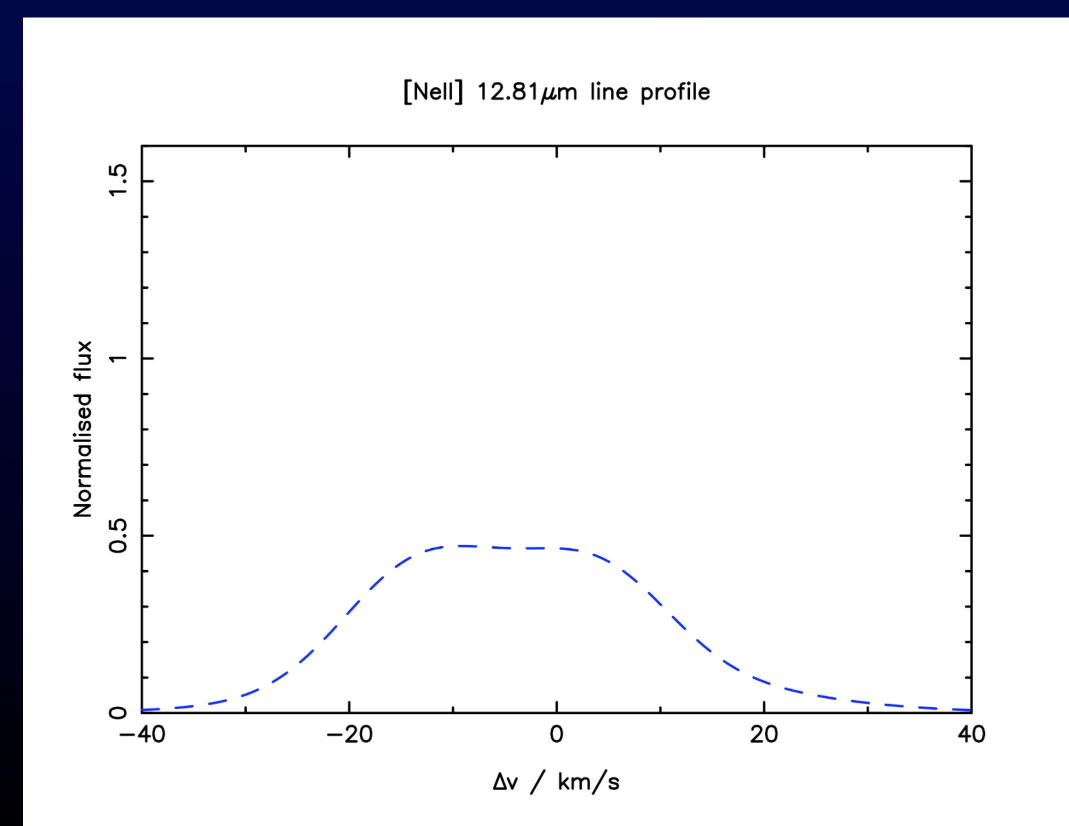


i = 60°

Theoretical profile



R = 30,000



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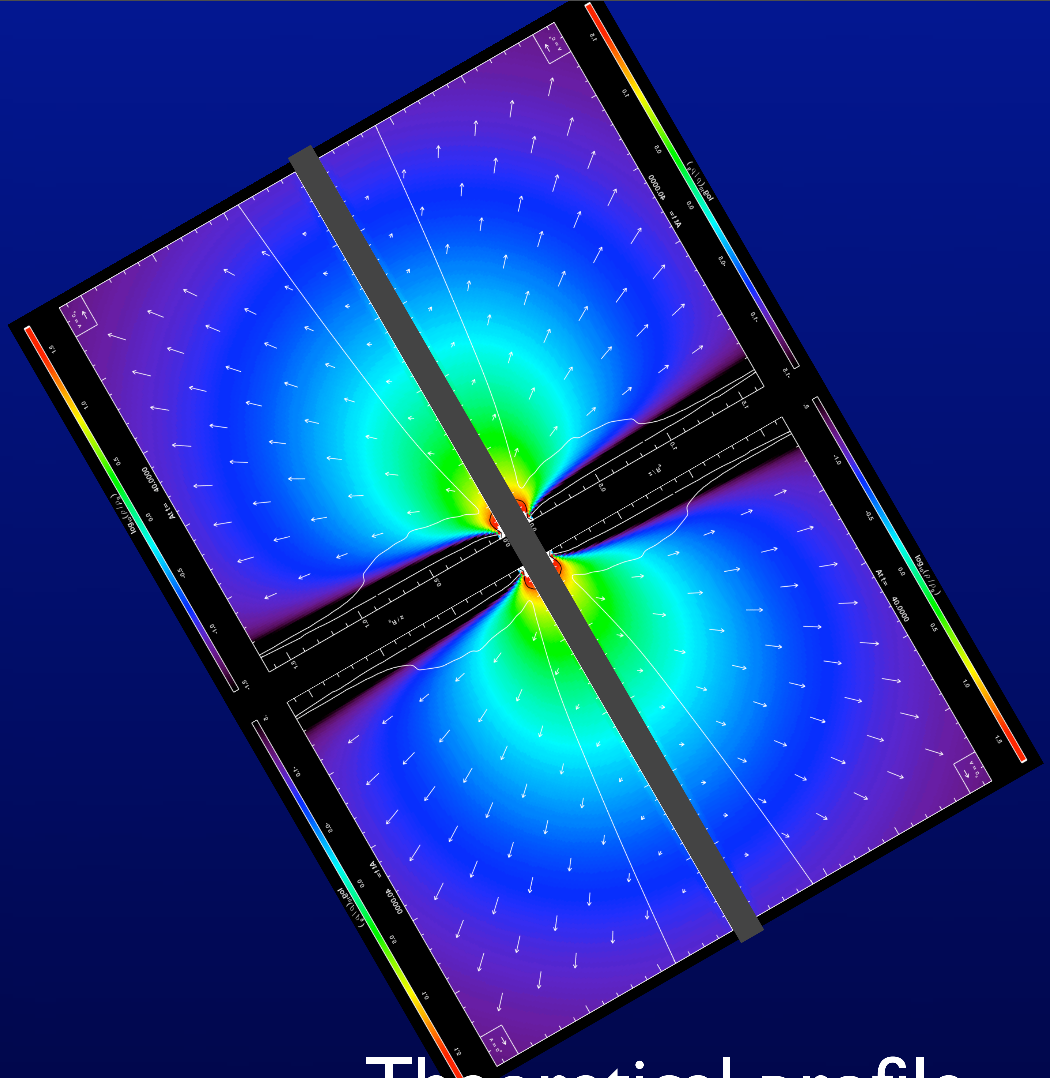
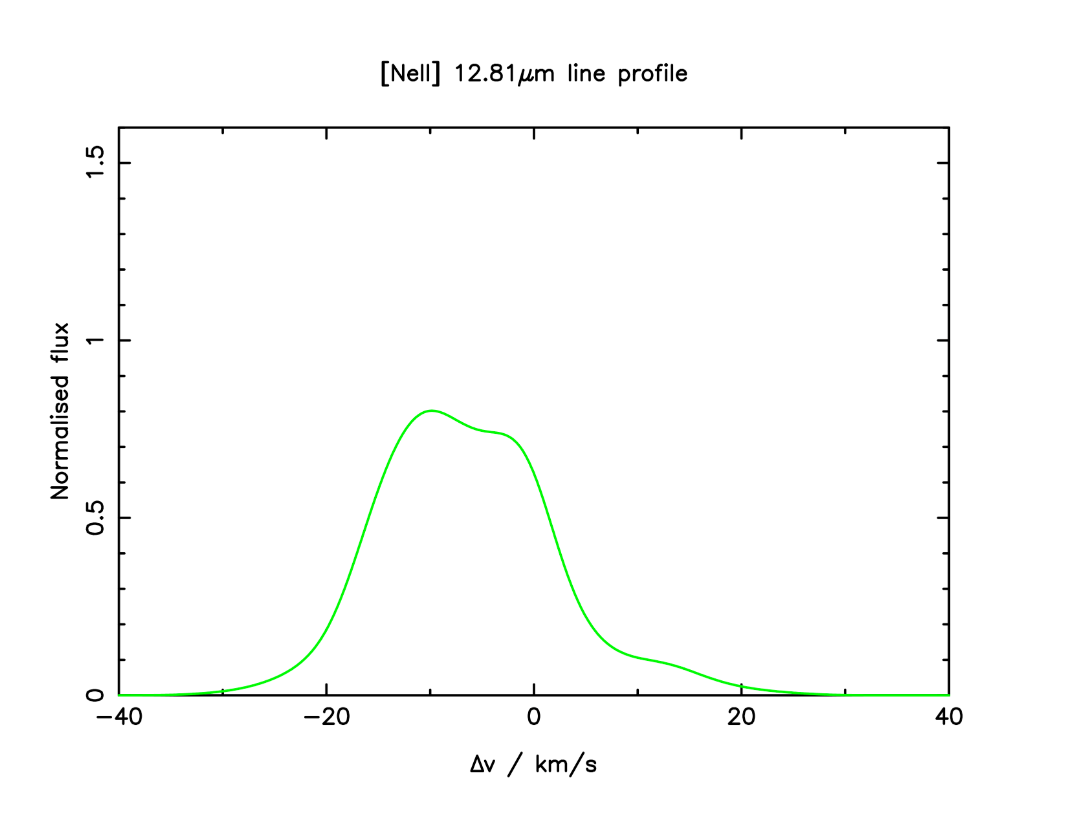
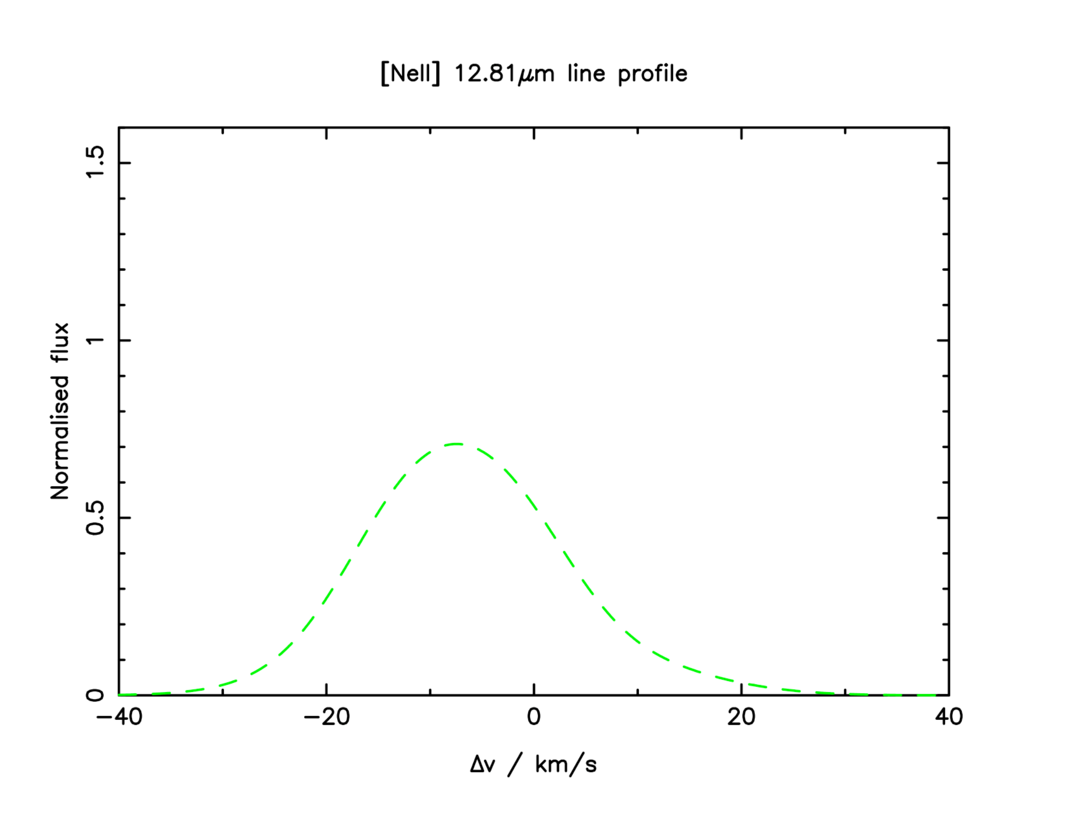


i = 30°

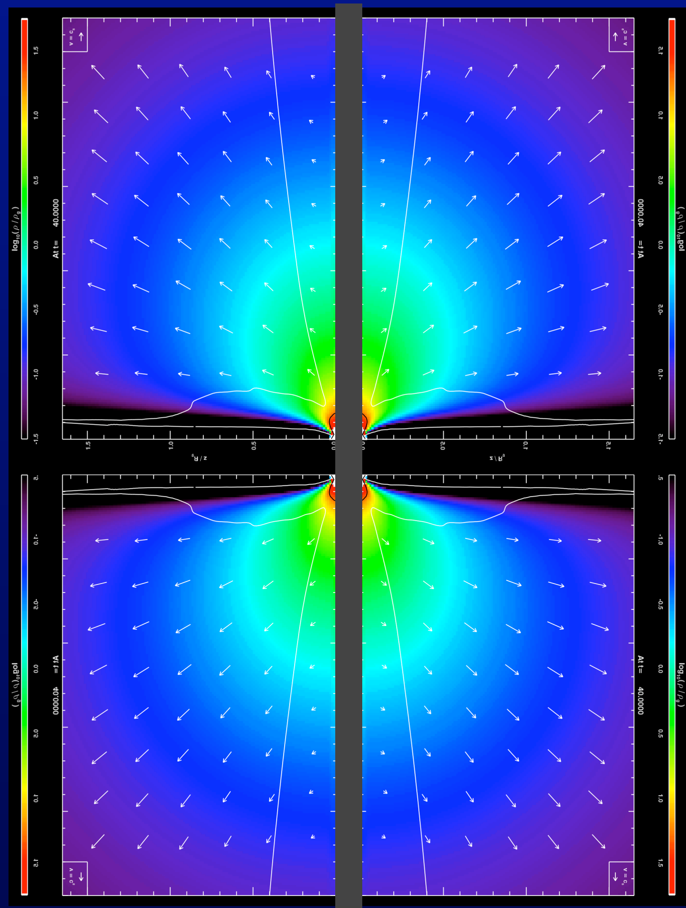
Theoretical profile

R = 30,000



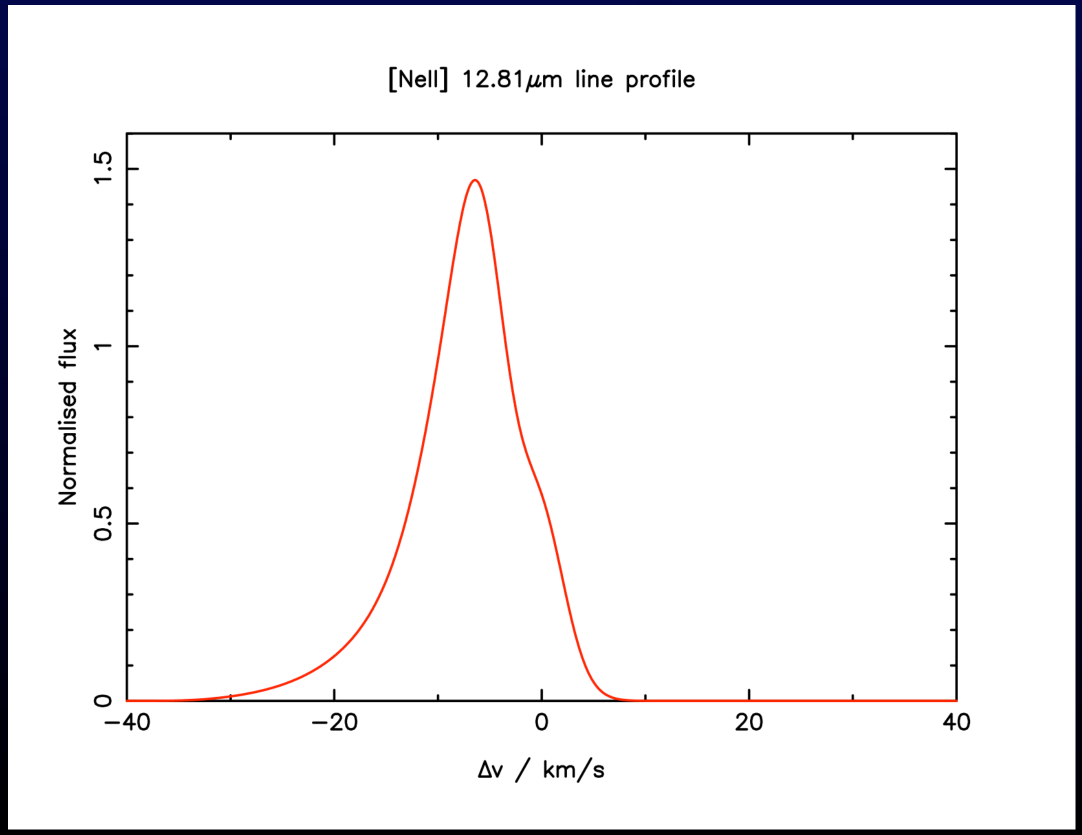


Results

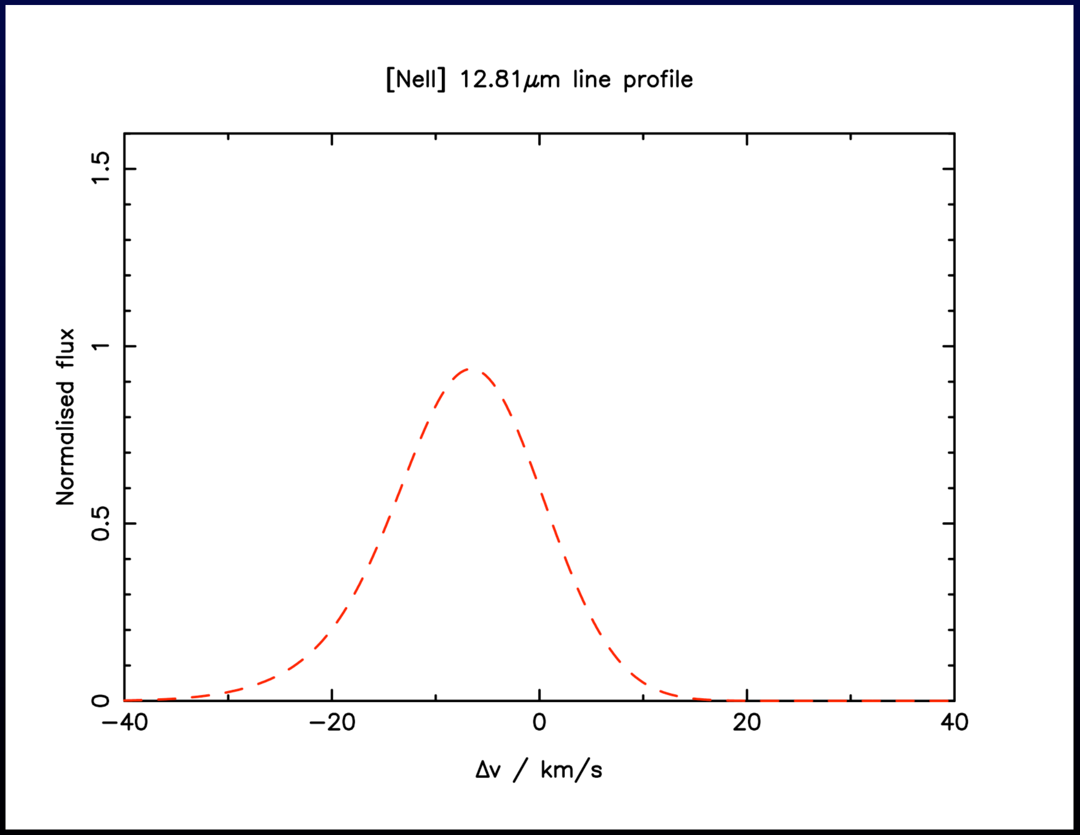


$i = 0°$

Theoretical profile



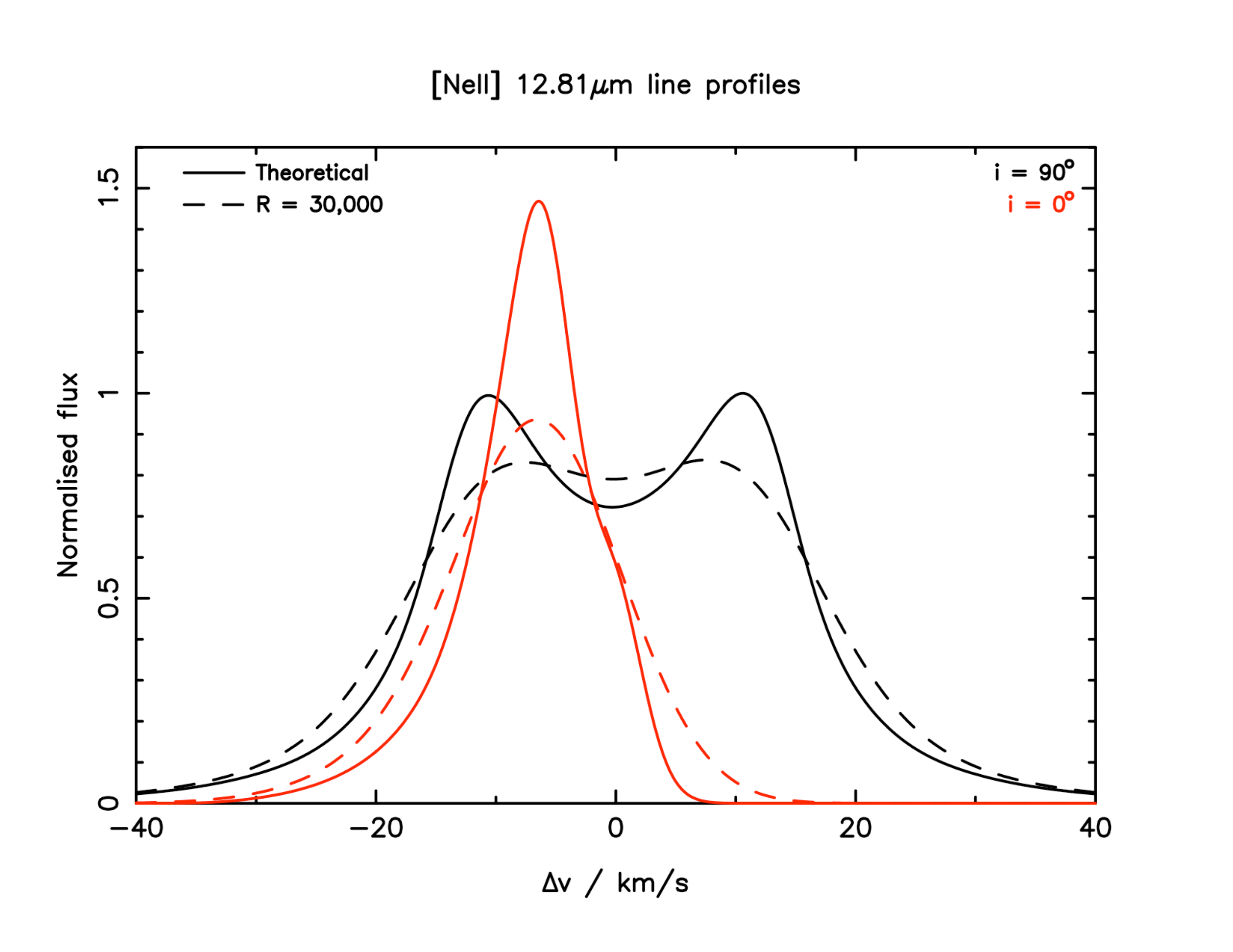
R = 30,000



Results

RDA (2008b)

- Edge-on profile is dominated by rotation. Similar to profile from bound disc atmosphere (Glassgold et al. 2007).
- Face-on profile is broad (~10km/s), and blue-shifted by ~7km/s.
- This blue-shift is unique to the wind, and is detectable at resolution $\lambda/\Delta\lambda \geq 30{,}000$.
- Predicted line luminosities (few$\times 10^{-6} L_\odot$) consistent with *Spitzer* observations.



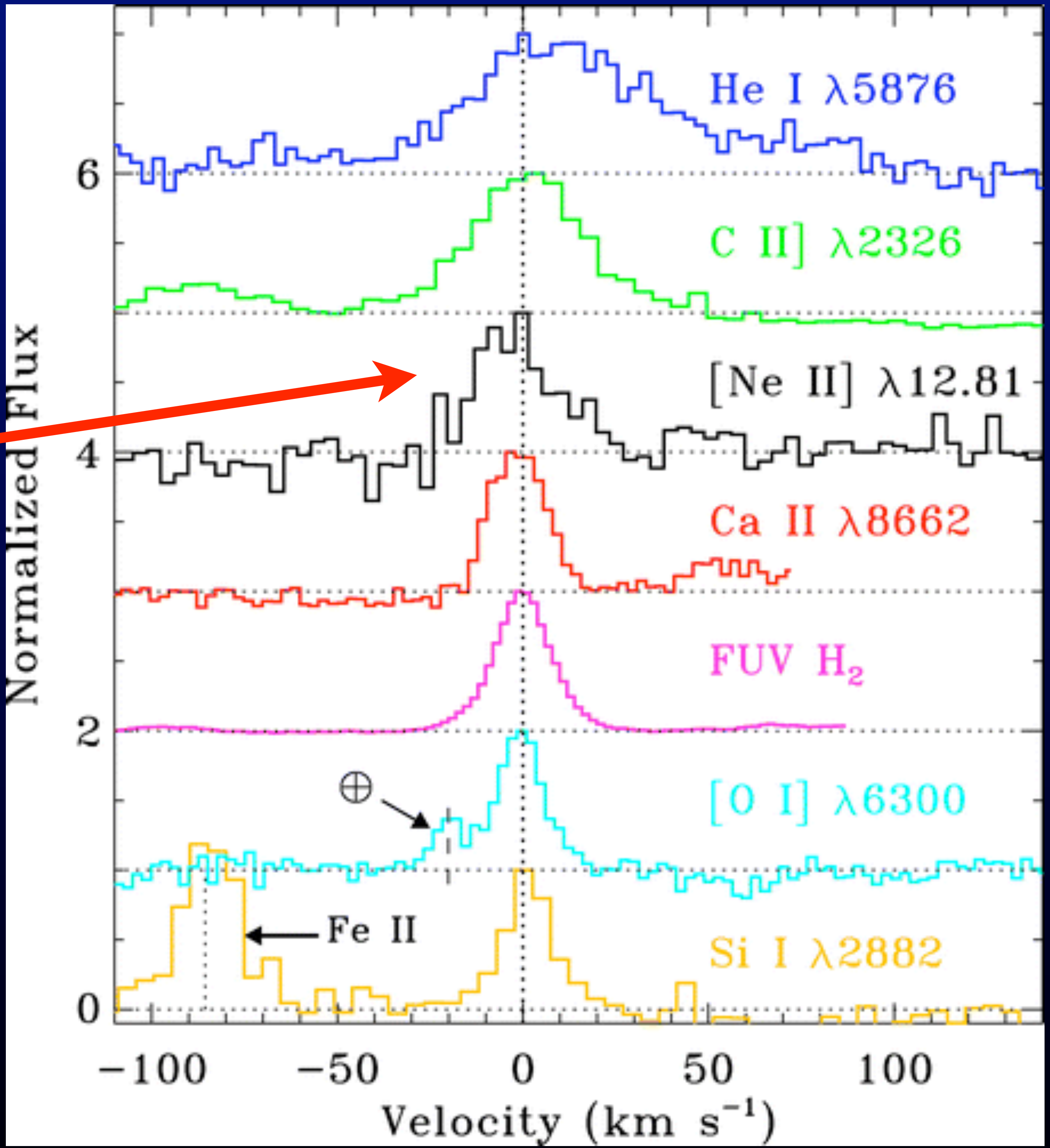
Comparison to (the!) observation

- In real data, wind profile will be combined with emission from bound, X-ray-ionized atmosphere (at v=0). Net blue-shift likely 2–5km/s.
- Line observed at R~30,000 in TW Hya (i = 4–7°):

FWHM = 21±4 km/s

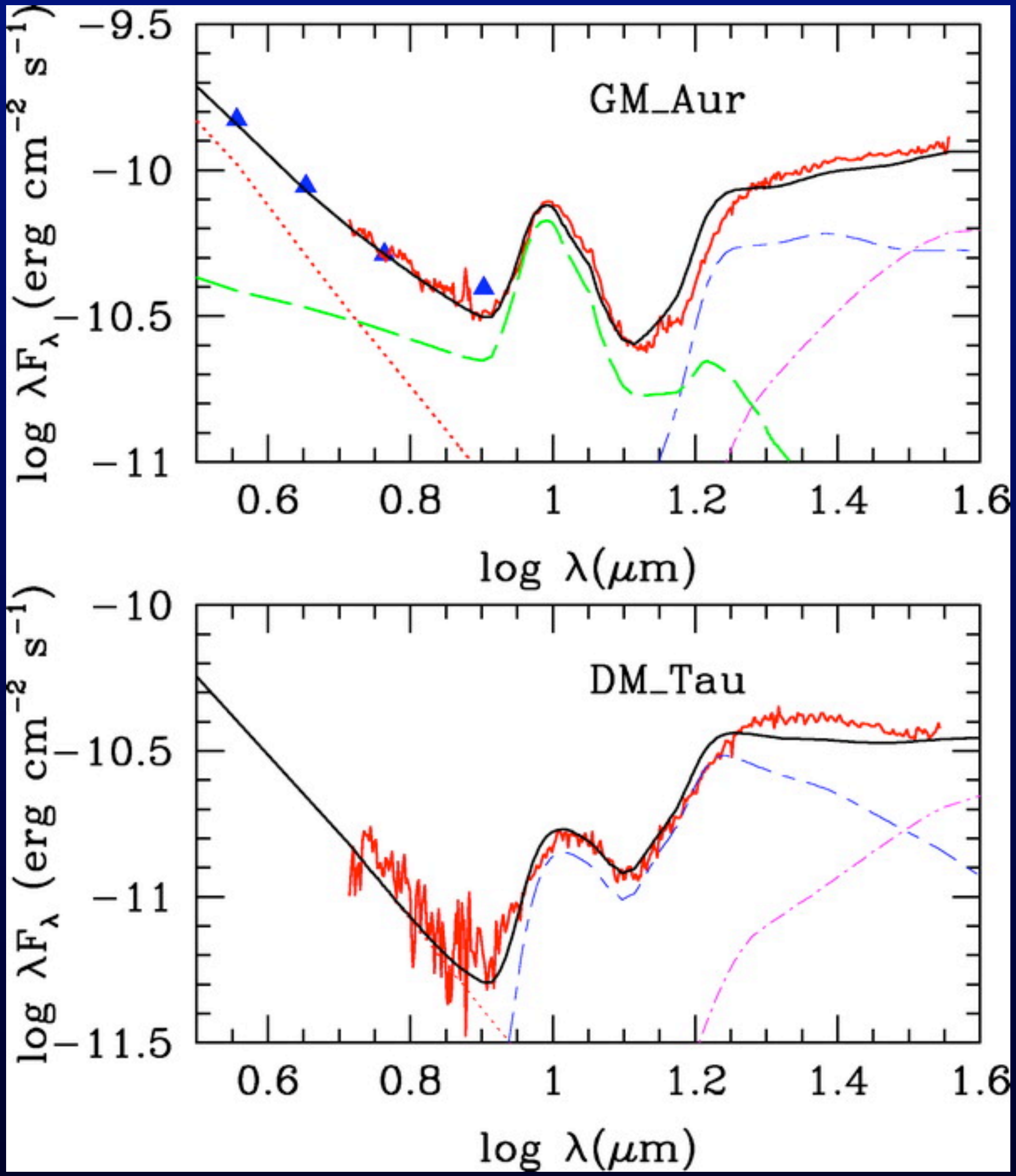
Blue-shift = 2±3 km/s

- Further similar observations scheduled in coming months...



Herczeg et al. (2007)

“Transition discs”



Calvet et al. (2005)

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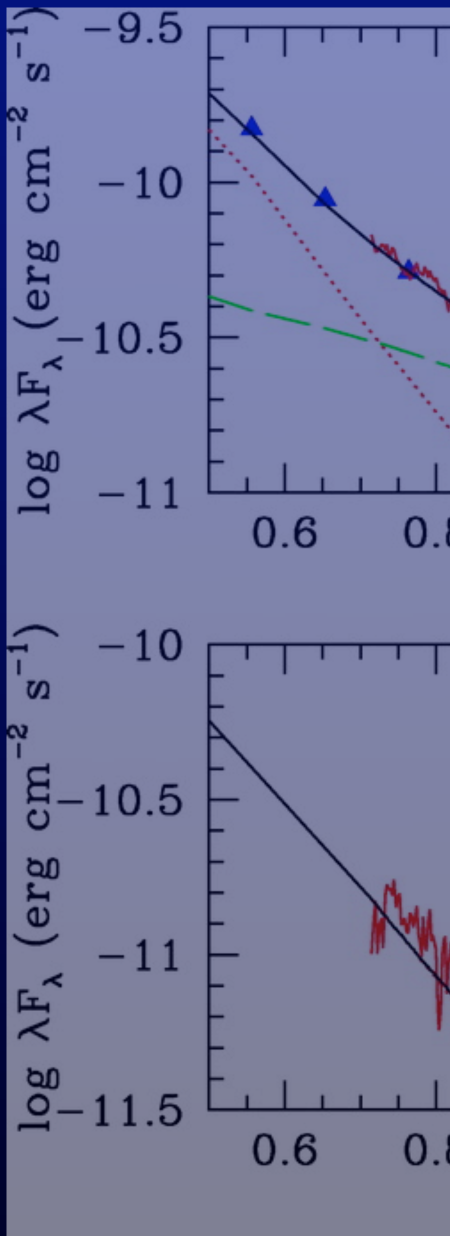
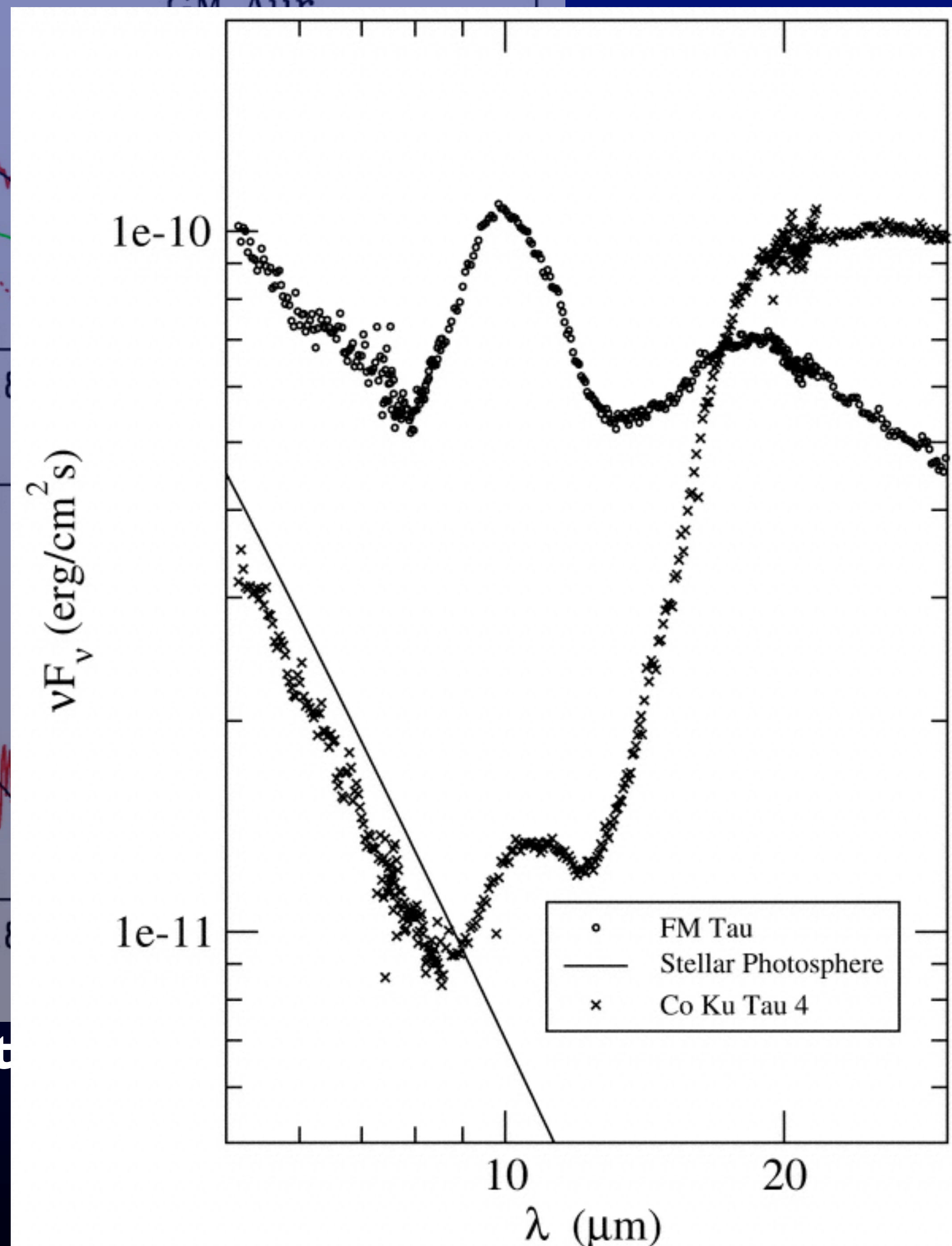


Calvet



Forrest et al. (2004)

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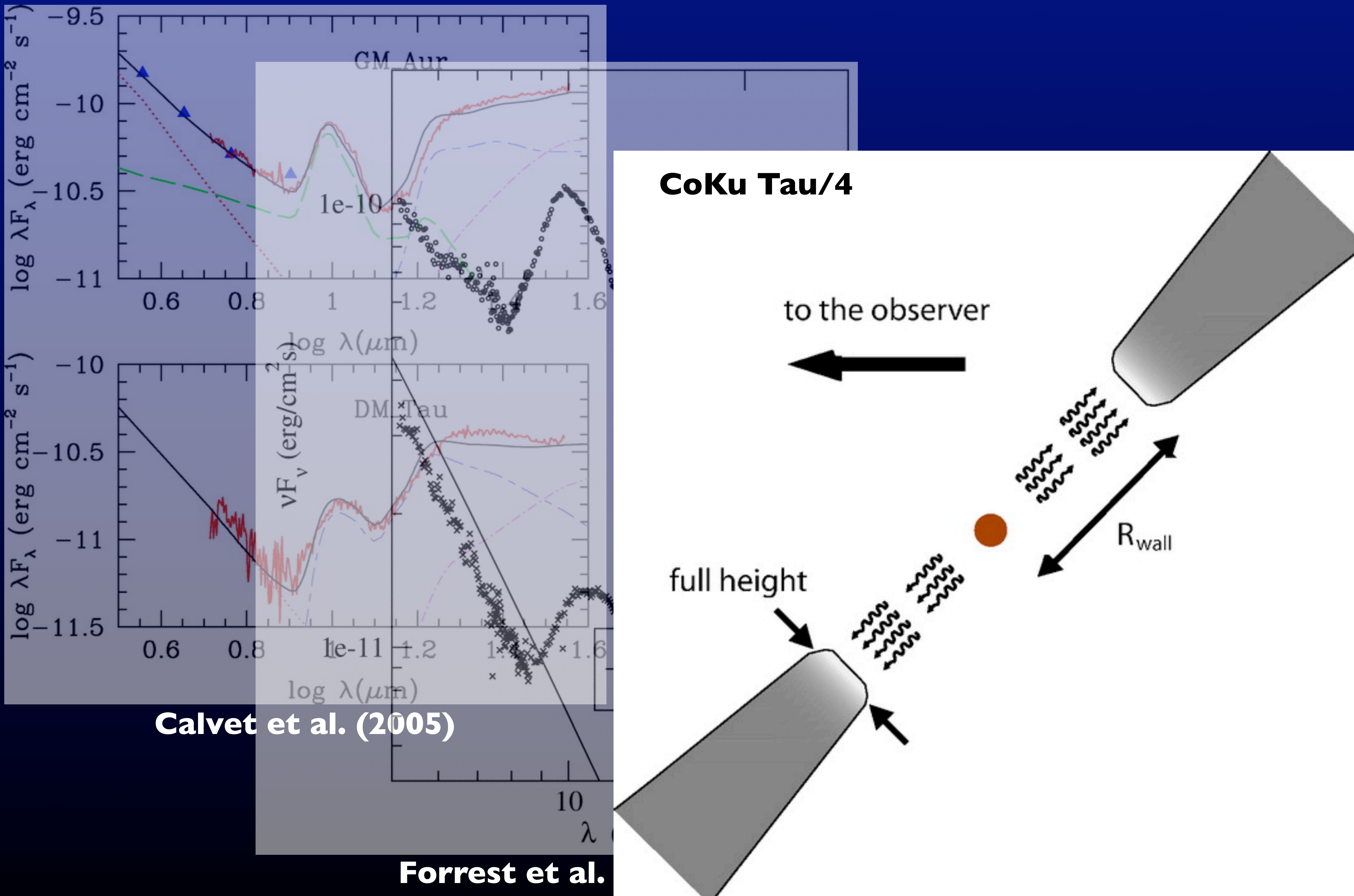

Calvet et al. (2005)

Forrest et al.

d’Alessio et al. (2005)

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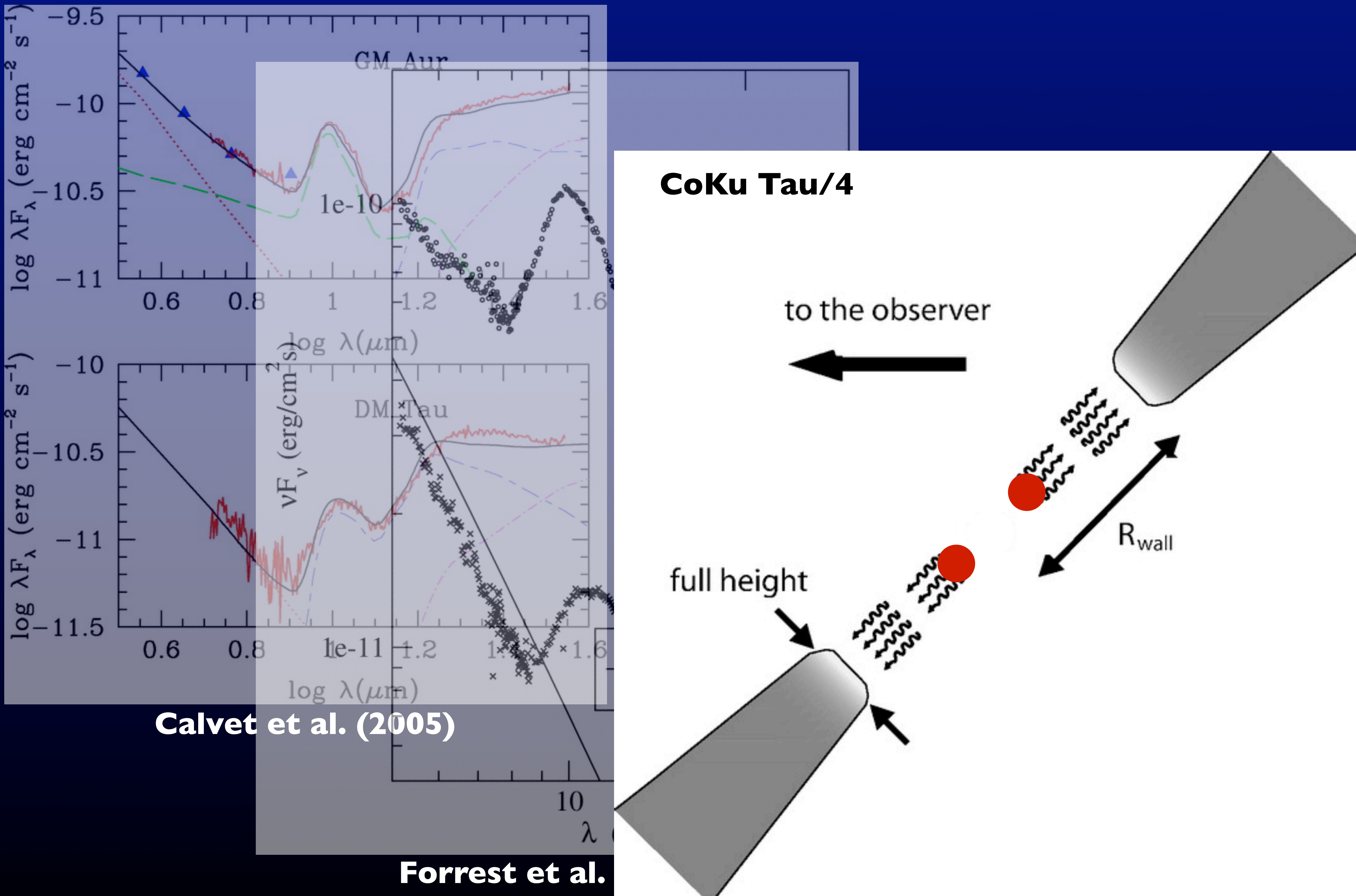

Calvet et al. (2005)

Forrest et al.

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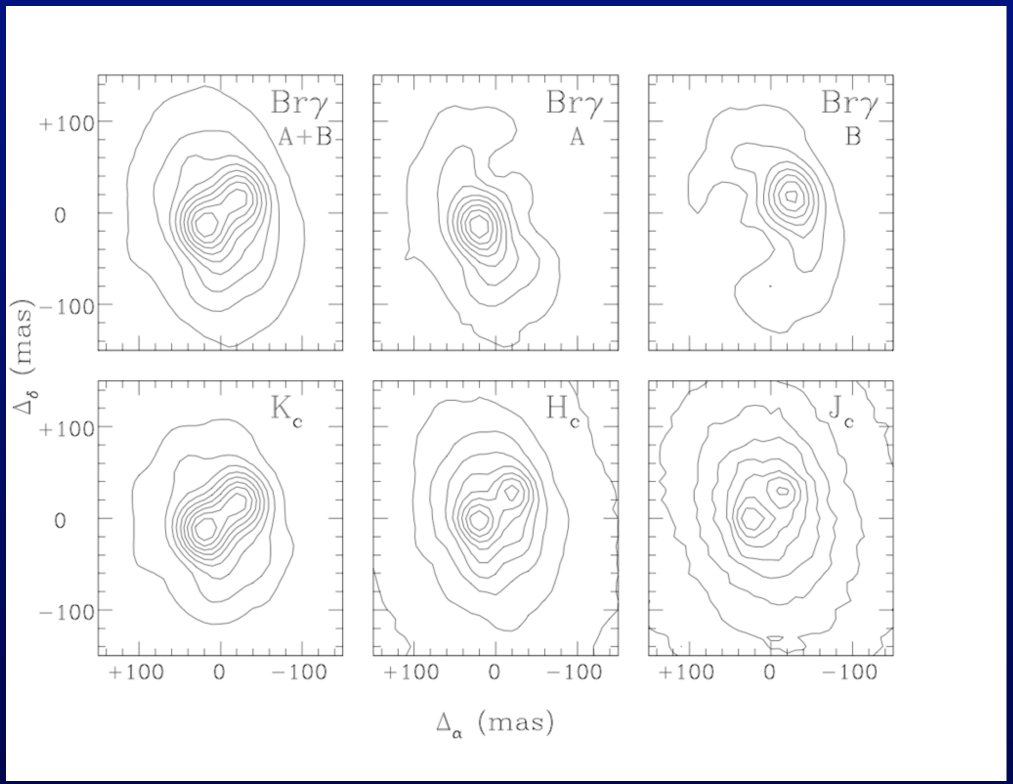
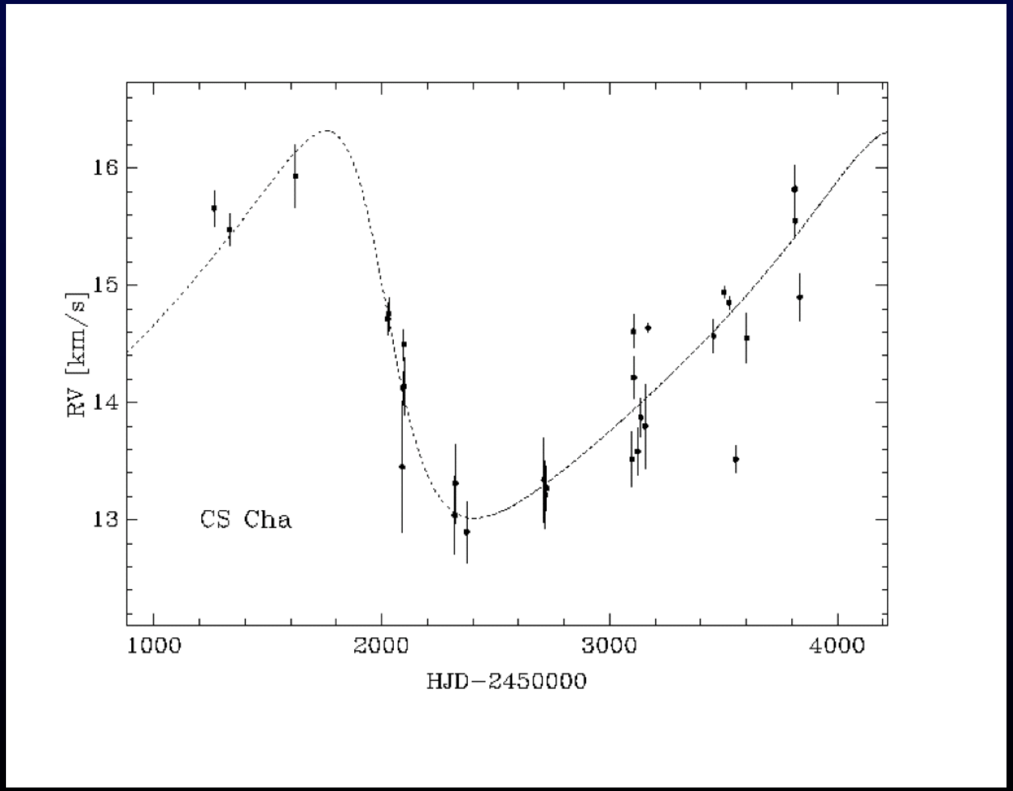
"Transitional" or binaries?



CoKu Tau/4: Ireland & Krauss (2008)



CS Cha: Guenther et al. (2007)

- It seems that a significant fraction of "transitional" discs may in fact be circumbinary discs:
  - CoKu Tau/4: equal mass binary ($M \sim 0.6 M_\odot$), separation ~ 8AU.
  - CS Cha: $\sim 0.1 M_\odot$ secondary, $\sim 0.9 M_\odot$ primary, separation ~ 4AU.
- Binaries with a wide range of properties can result in "transitional" SEDs.
- A cautionary note:
  10-15% of G- to K-type MS stars are binaries with separations 1AU< a <10AU (Duquennoy & Mayor 1991; Halbwachs et al. 2003).

See talk by Kraus

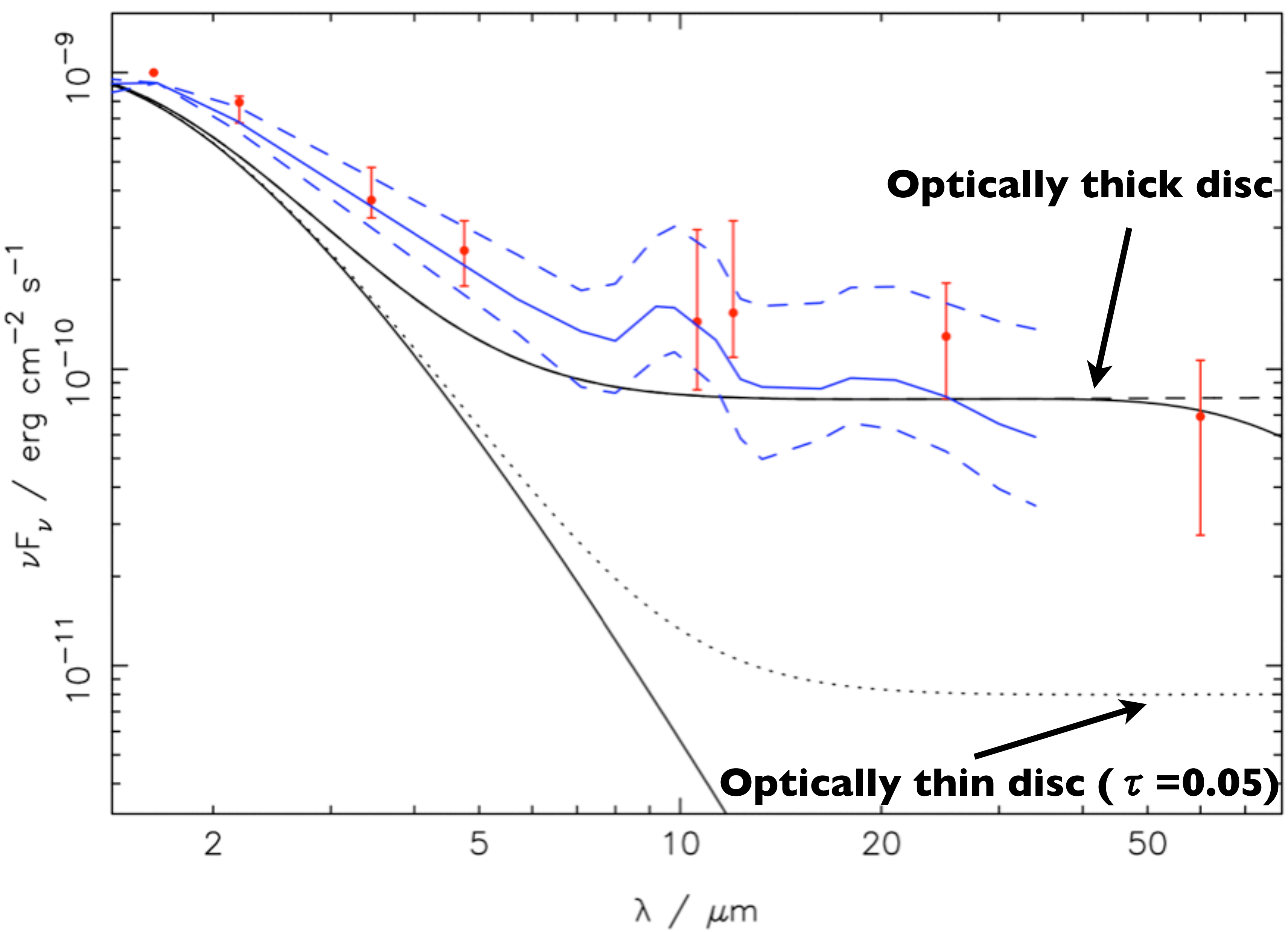
Models of transitional discs

- Several models exist for making gaps/holes in discs, all of which predict similar observable SEDs:
  - Dynamical clearing by companions: planets or binaries.
  - Photoevaporation/viscous clearing.
  - X-ray illumination of inner edge (Chiang & Murray-Clay 2007).
  - Photophoresis (Krauss et al. 2007; Krauss & Wurm 2005).
- Dust settling/growth also gives rise to "transitional" SEDs, especially if wavelength coverage is limited.
- Statistical approach seems most promising, but selection effects are crucial: need to separate holes/gaps from settling/growth (and remove binaries).

Identifying samples

RDA (2008a)

Median SED of Taurus CTTs - photometric / Spitzer IRS



Data from d'Alessio et al. (1999) & Furlan et al. (2006)

See talk by Scholz (BDs)

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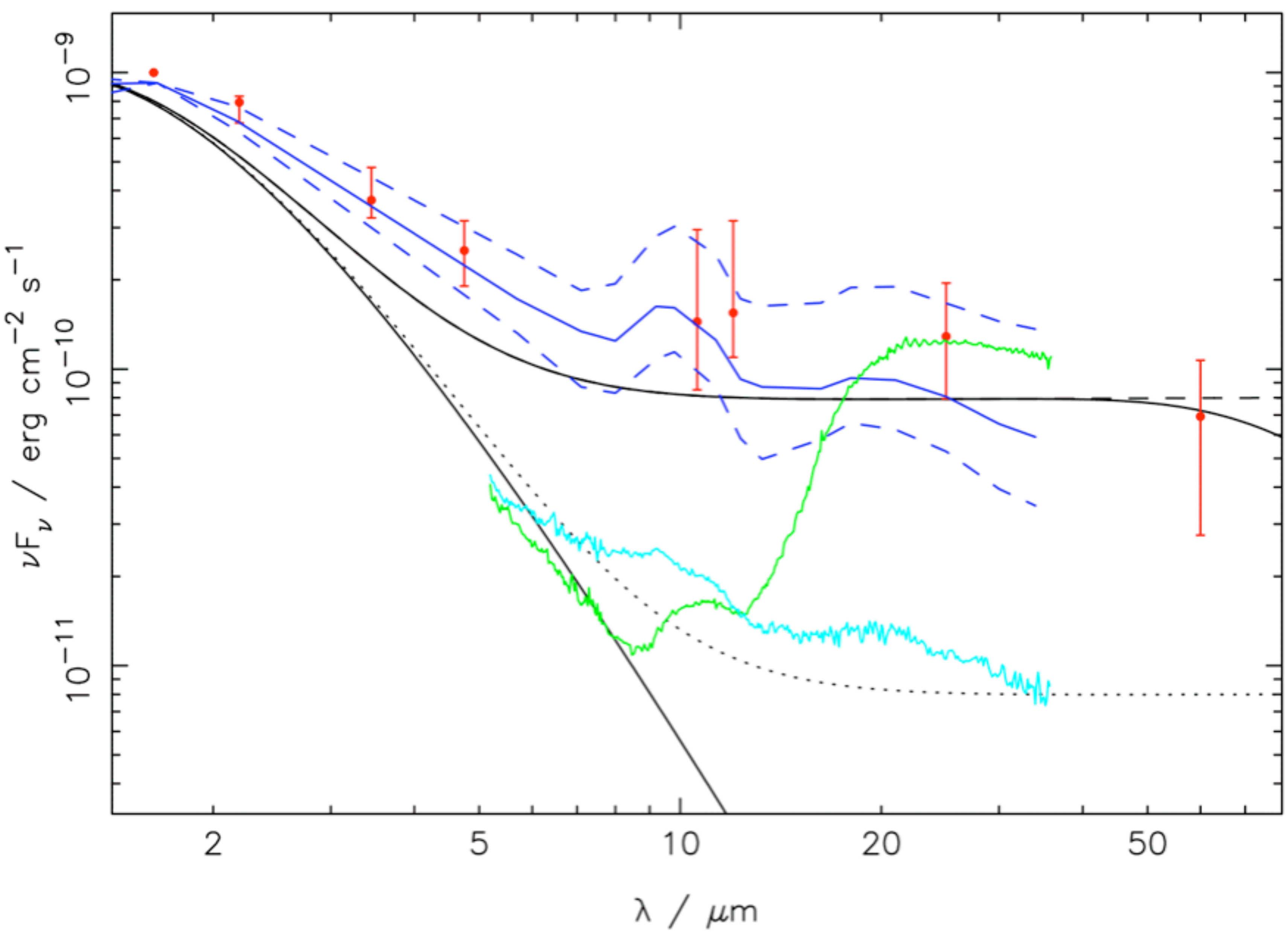

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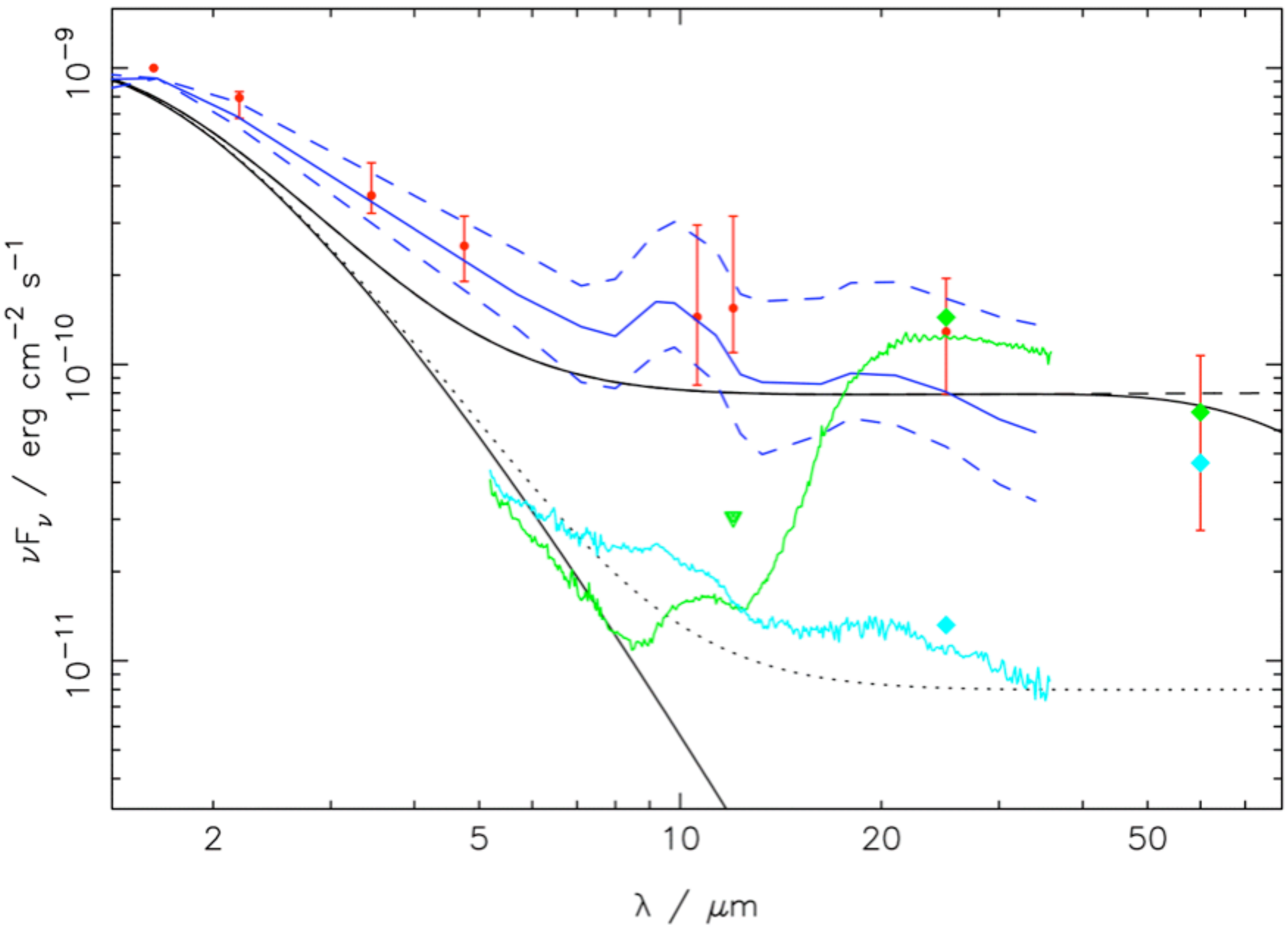

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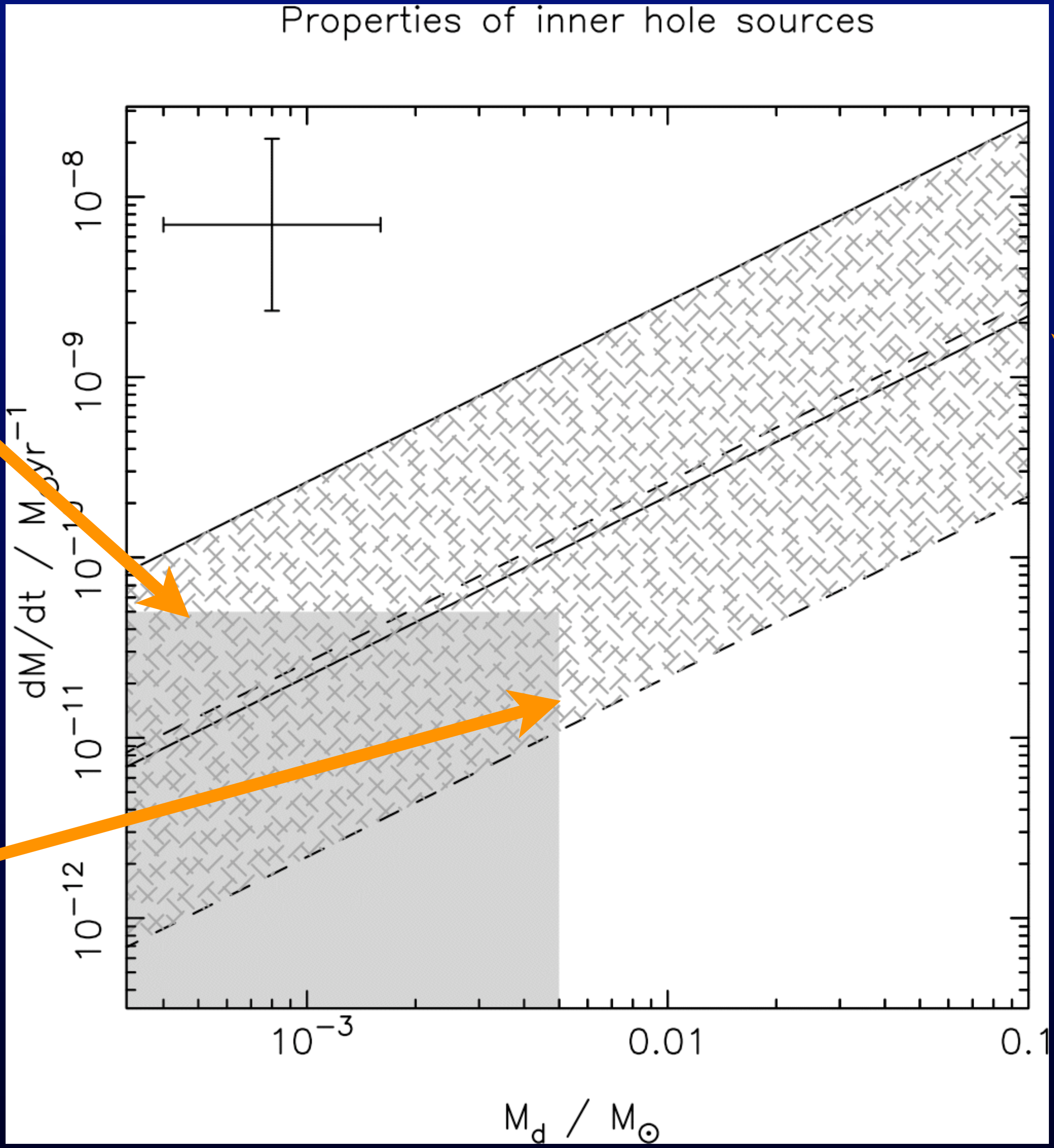
Discriminating between models

RDA & Armitage (2007); updated with data from Najita et al. (2007) & Cieza et al. (2008)

$\dot{M}_{\rm acc} \lesssim \dot{M}_{\rm wind}$



Decreasing α
Increasing M_P

Wind rate + viscosity gives disc mass

- Disc masses + accretion rates should distinguish between different models of "inner hole" systems (RDA & Armitage 2007; Najita et al. 2007).
- Selection biases seem to be dominant in current samples.

See talks by Chiang, Brittain, Najita, Muzerolle; *many* posters

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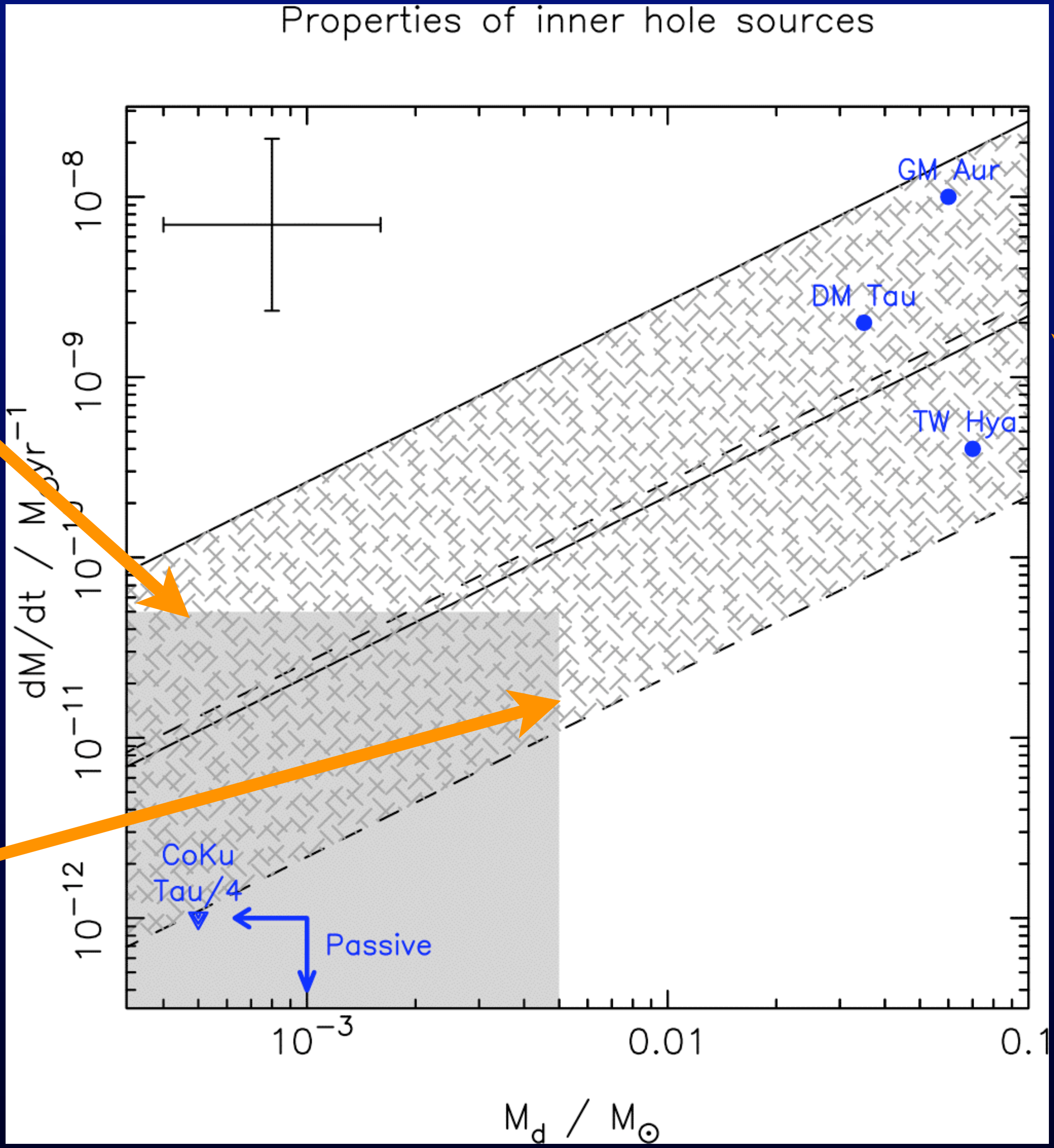

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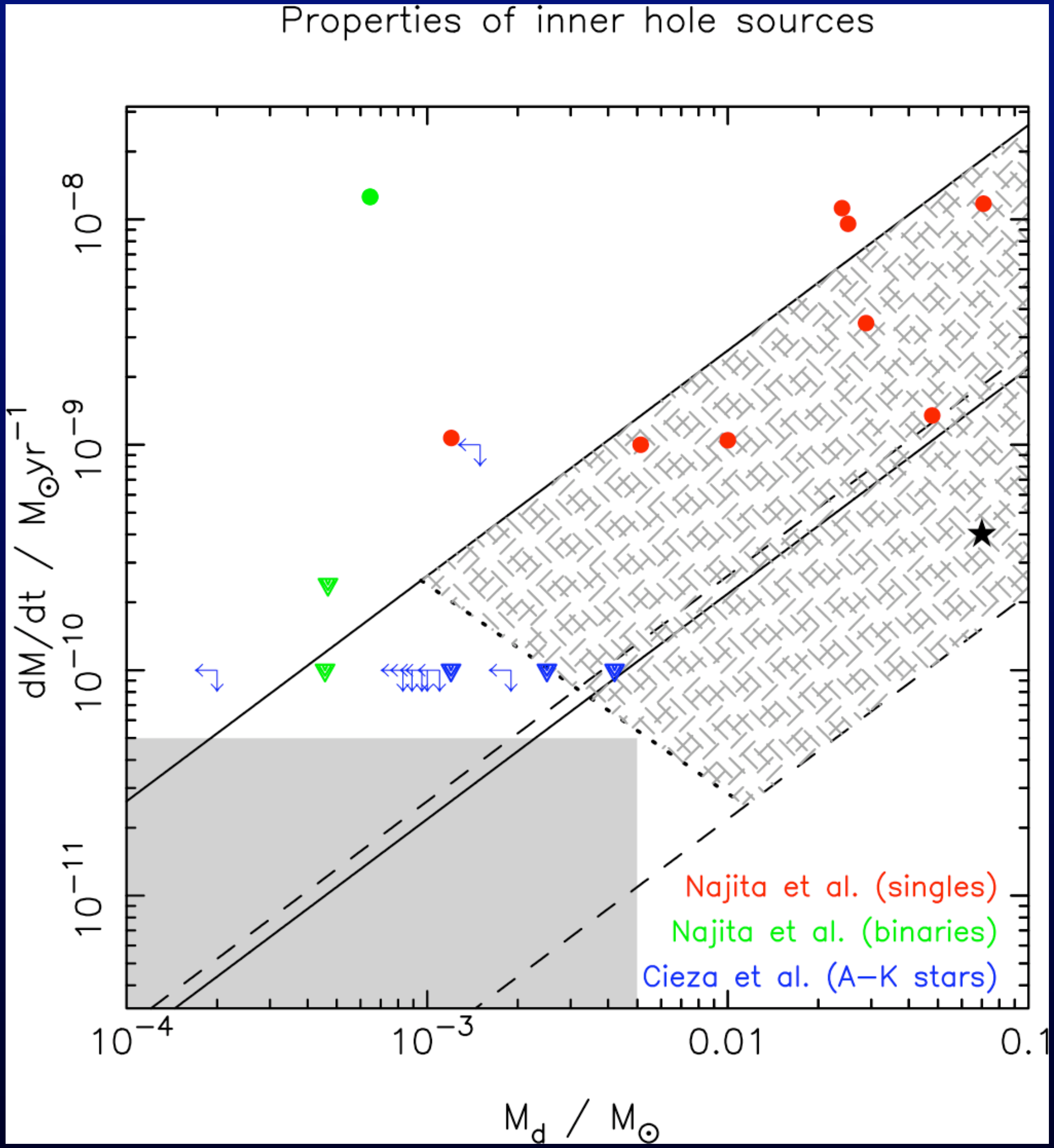

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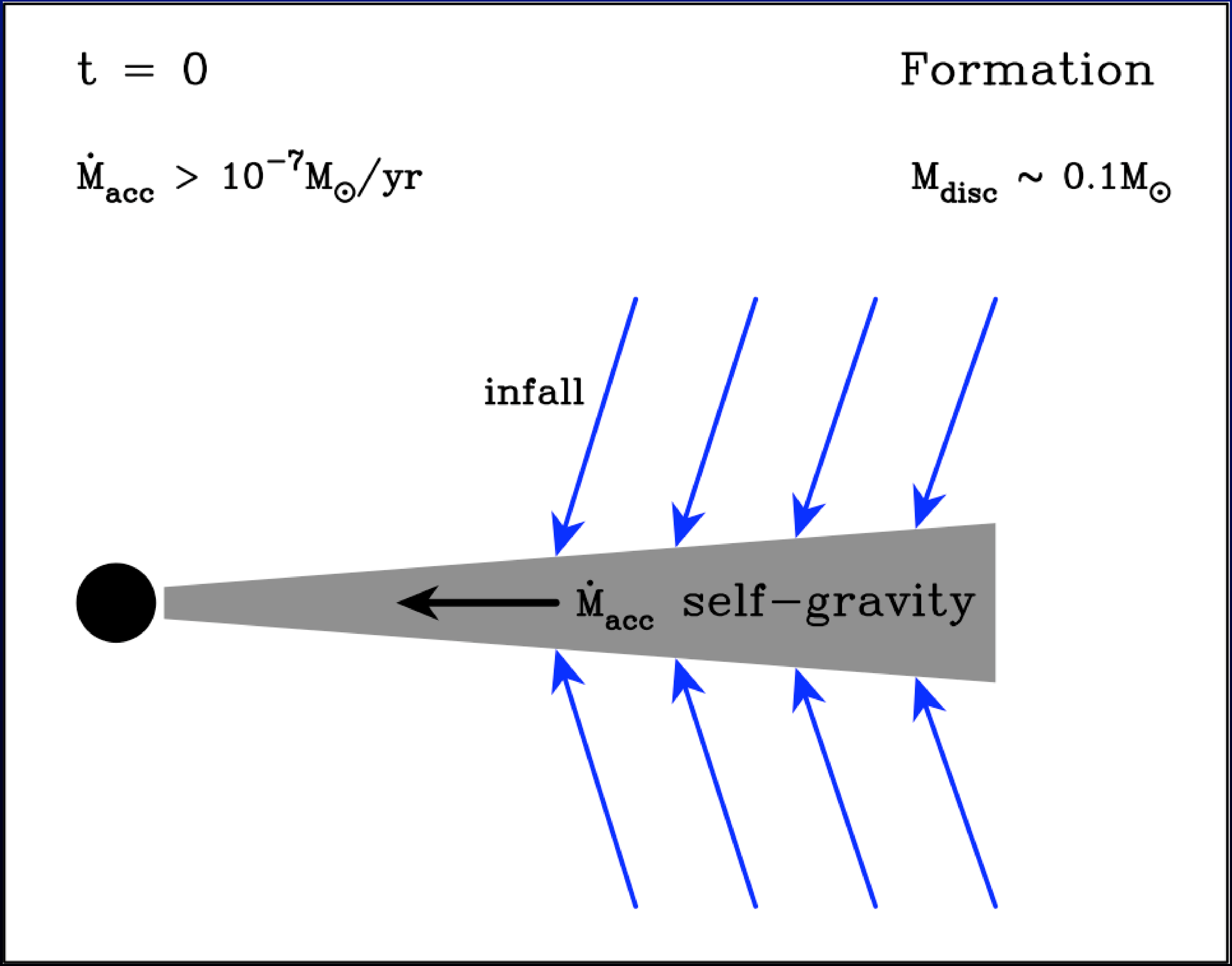
Schematic picture of disc evolution



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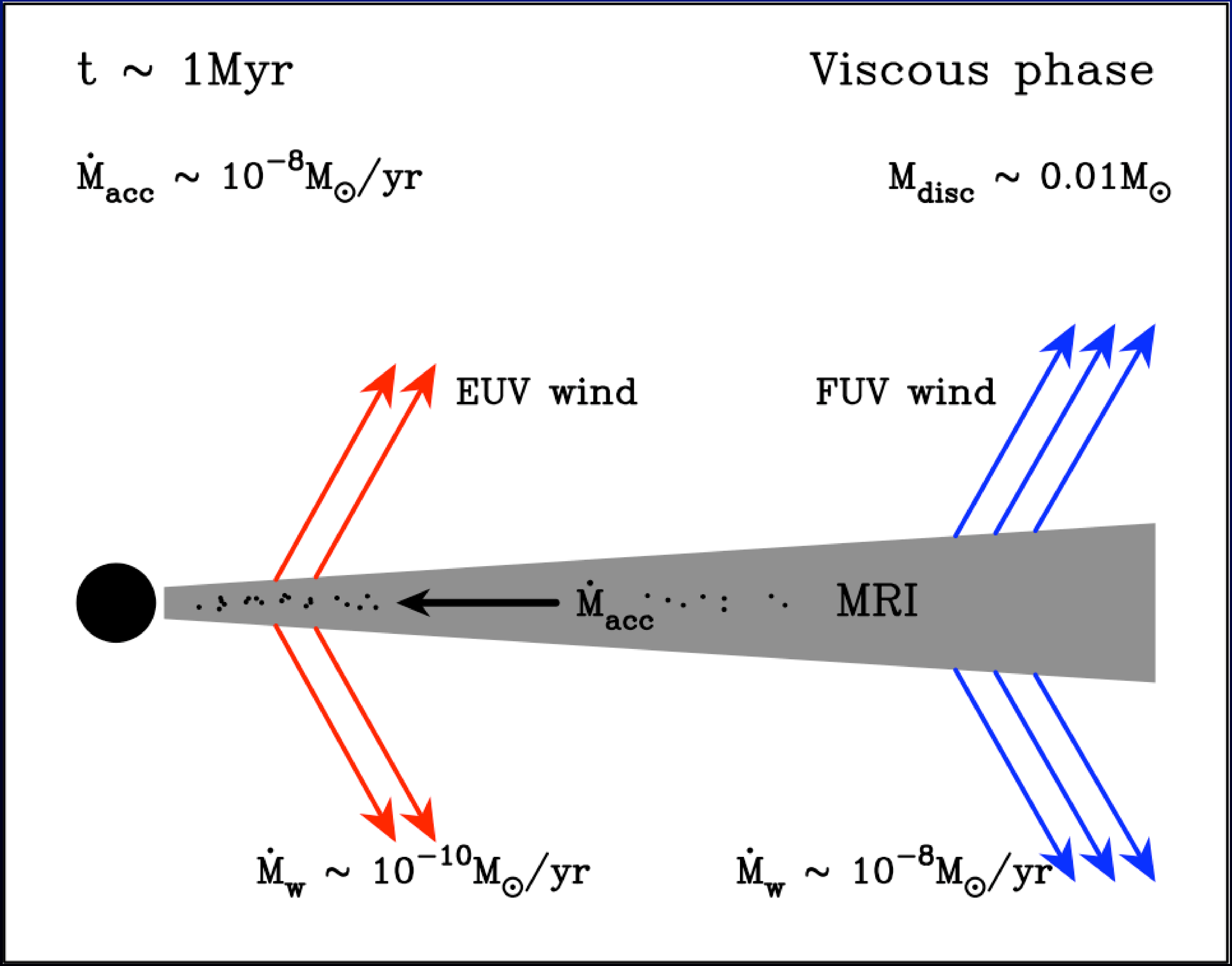

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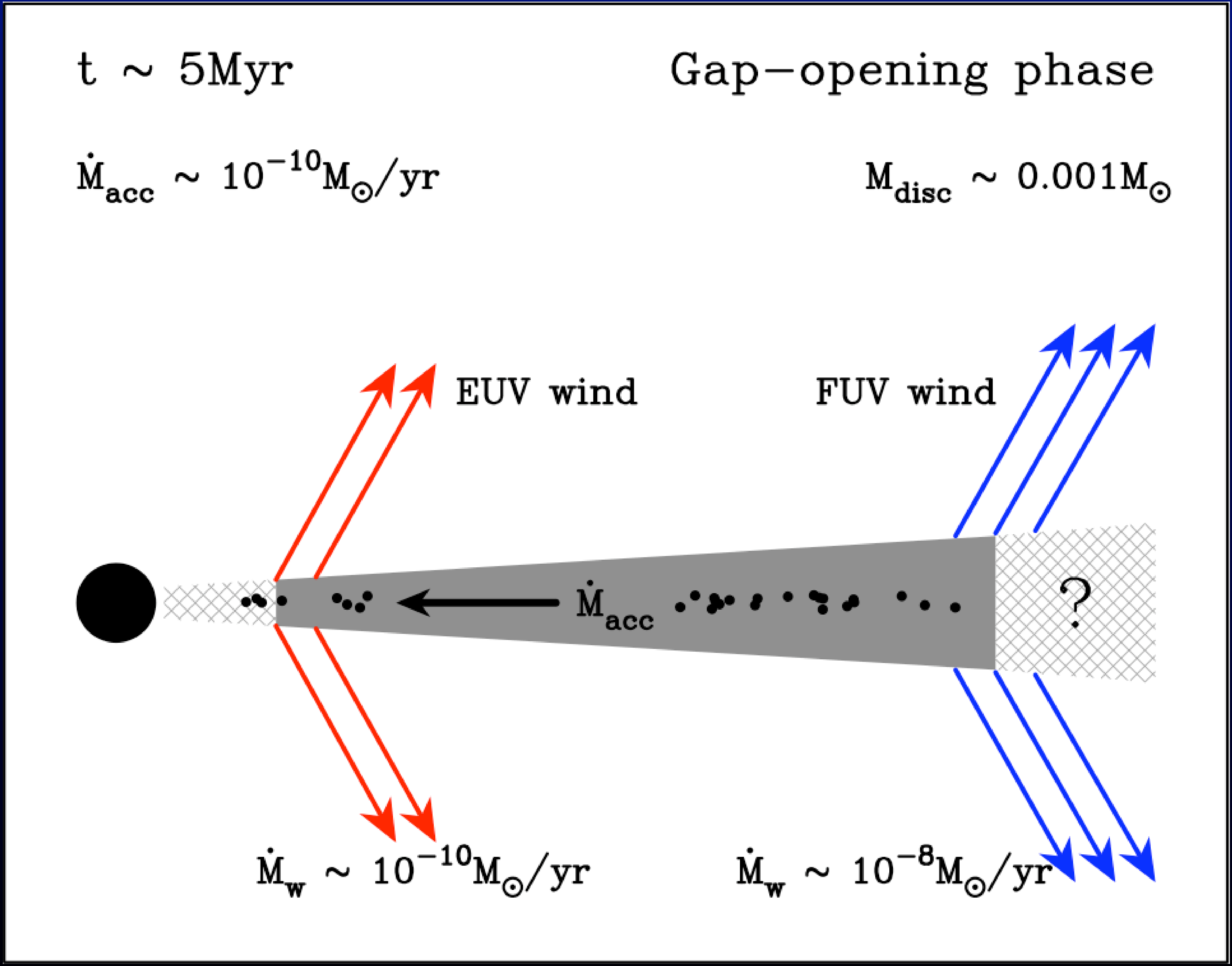

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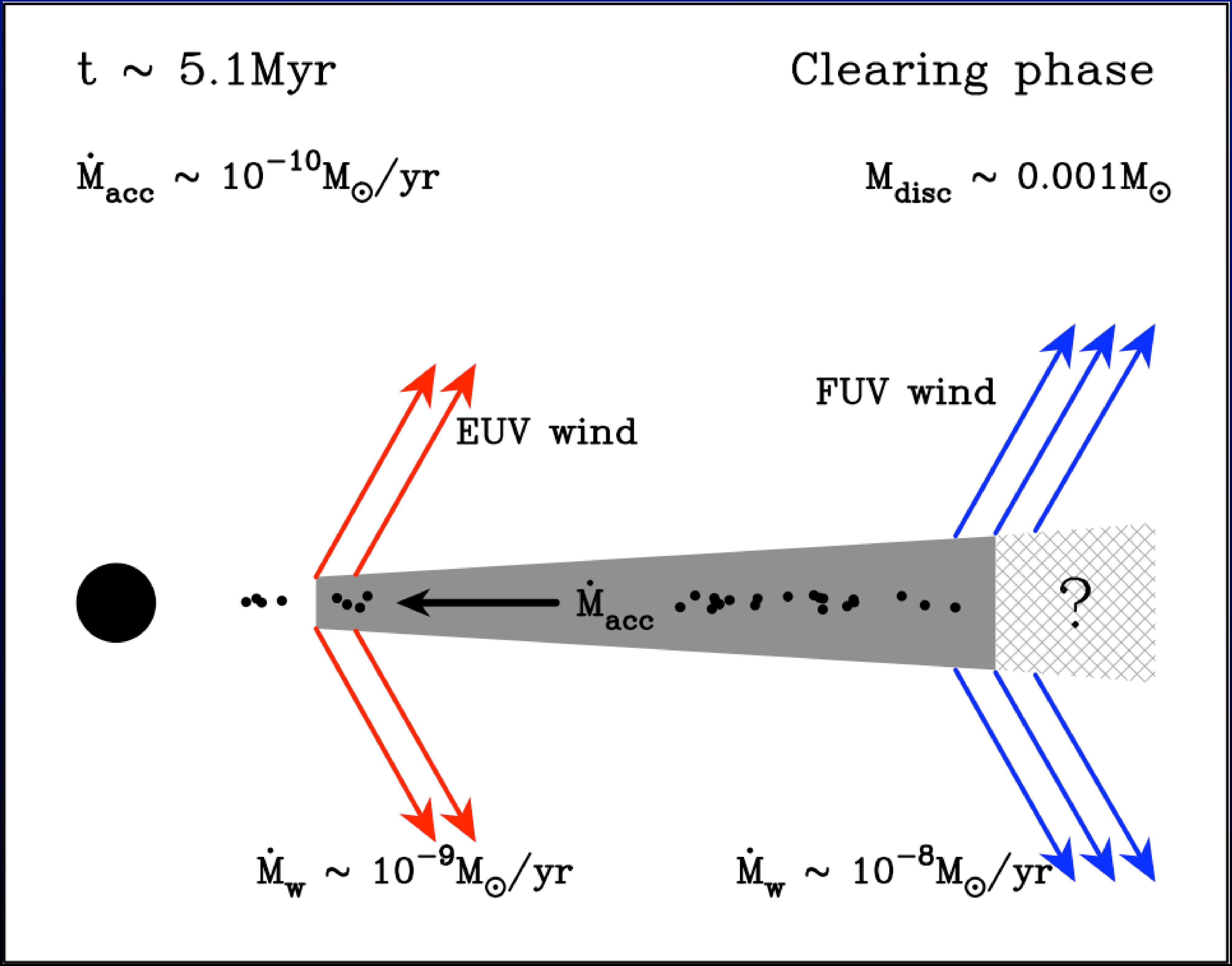

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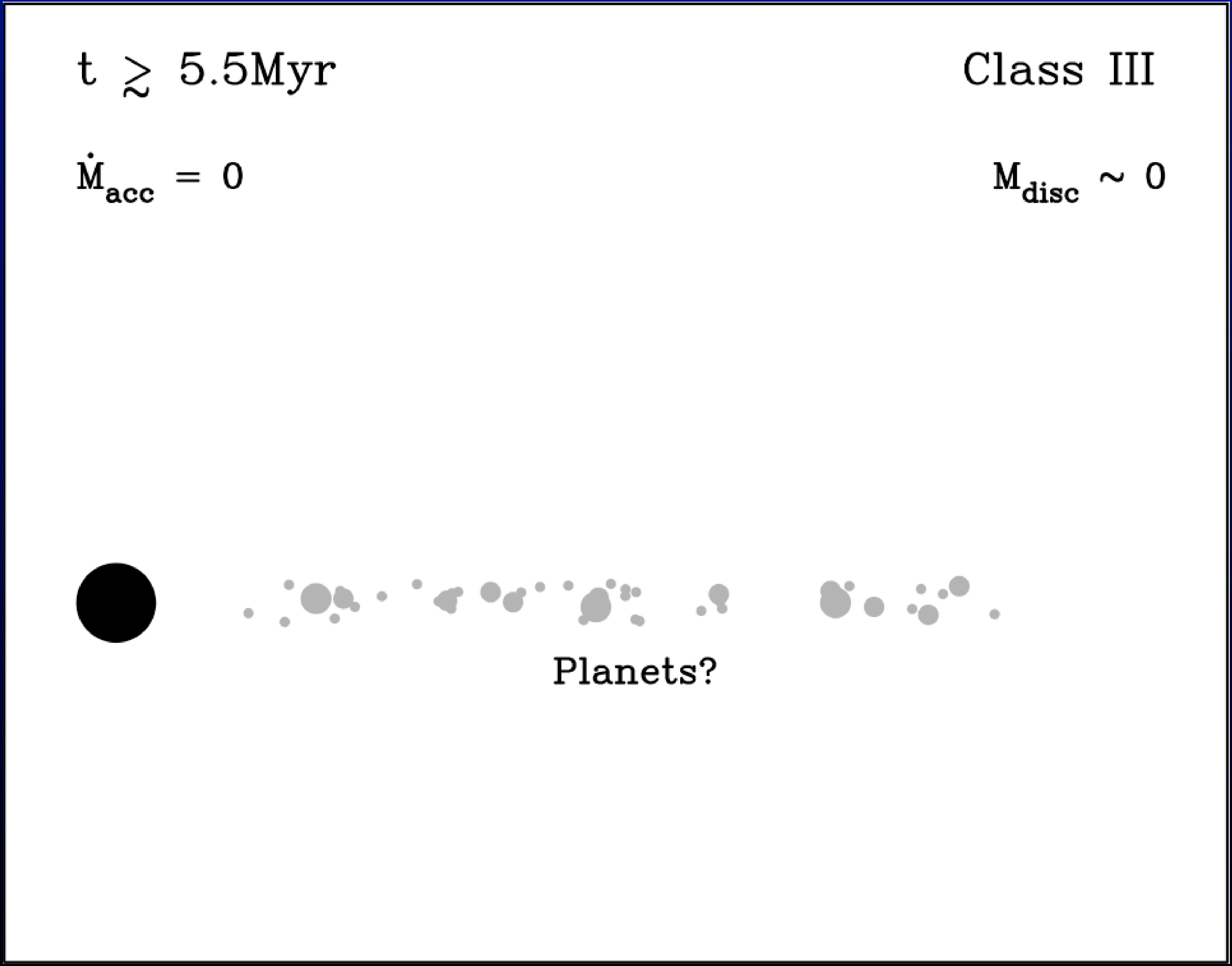

Summary

- Protoplanetary discs evolve, primarily due to "viscosity".
- During this viscous evolution phase, dust grains grow and evolve, and planets (may) form.
- 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 (gas) mass over a ~Myr lifetime.
- Various proposed observations should provide critical tests of current theoretical models in the near future.