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

Why should we care about dust?

- Dust is most of what we see when we observe protoplanetary discs.
- Dust dominates disc opacity, so thermal structure of the disc depends on dust heating & cooling.
- Most(ish) heavy elements in discs are in solid phase, so "dust" is the primary absorber of high-energy photons. Dust therefore has a strong influence on gas disc evolution via the MRI.
- Dust represents the "building blocks" for planets.

What forces affect dust in discs?

- Dust "grains" in discs are subject to two main forces:
  - Gravity
  - Aerodynamic drag
- Crucially, however, dust is NOT subject to gas pressure. This is the origin of most differential gas-dust dynamics.
- Drag force on an individual (spherical) grain is:

$$F_{\mathrm{D}} = -\frac{1}{2} C_{\mathrm{D}} \,.\, \pi s^2 \,.\, \rho_{\mathrm{g}} v^2$$

- Drag coefficient C_D is simple in Epstein regime (depends only on thermal velocity of gas); depends on Reynolds number in Stokes regime.

Vertical settling (no turbulence)

- Useful to define "stopping timescale". In Epstein regime:

$$t_{\rm s} = \frac{mv}{|F_{\rm D}|} = \frac{\rho_{\rm d}}{\rho_{\rm g}} \frac{s}{v_{\rm th}}$$

- This is ~1s for micron-sized grains, so such grains are very well coupled to the gas. Often write $T_s = t_s \Omega_k$ (dimensionless).

- Equate vertical forces (gravity and drag):

$$m\Omega_{\rm K}^2 z = \frac{4}{3}\pi s^2 v_{\rm th}\rho_{\rm g} v$$

$$m = \frac{4}{3}\pi s^3 \rho_{\rm d}$$

$$t_{\rm settle} = \frac{z}{v_{\rm settle}} = \frac{v_{\rm th}}{\Omega_{\rm K}^2}\frac{\rho_{\rm g}(z)}{\rho_{\rm d}}\frac{1}{s}$$

- For micron-sized grains, this results in settling timescales of order 10^5yr. Expect significant sedimentation of grains > 1μm over disc lifetime. (Turbulent effects: lectures by Hubert Klahr.)

Radial drift

Whipple (1972); Weidenschiling (1977); Takeuchi & Lin (2002)

- Two regimes:
  - **"Dust":** small particles are well-coupled to the gas, orbit at gas velocity. Migrate relative to gas because they don't feel pressure gradients.
  - **"Rocks":** larger particles poorly-coupled to gas, orbit at Keplerian velocity. Gas is sub-Keplerian, so rocks feel a "headwind" drag force.
- Gas orbital velocity is sub-Keplerian:

$$\frac{v_{\phi,\mathrm{gas}}^2}{R} = \frac{GM_*}{R^2} + \frac{1}{\rho_\mathrm{g}}\frac{dP}{dR}$$

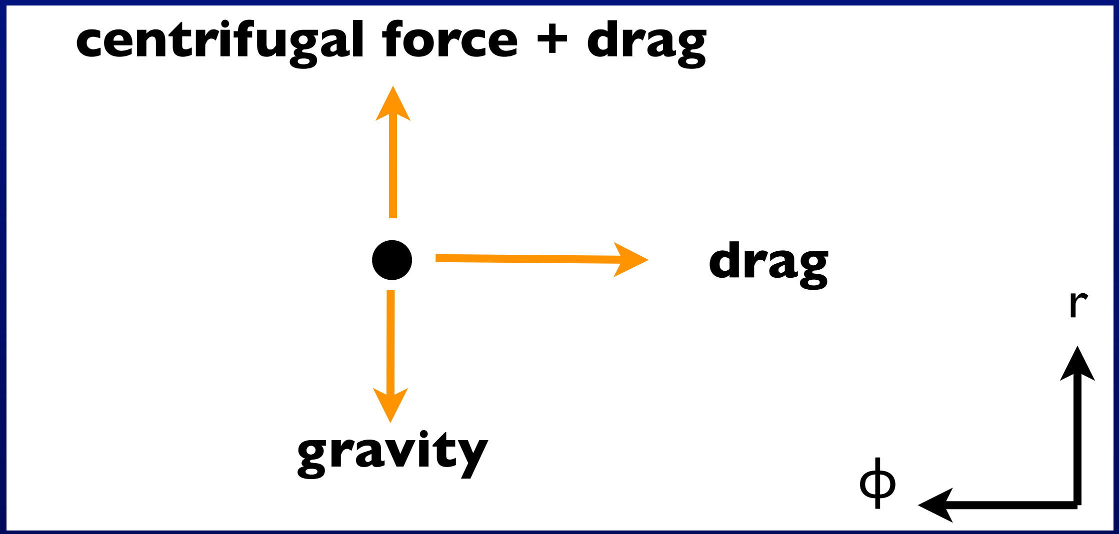
- If $P \sim R^{-n}$ and disc is locally isothermal, then

$$v_{\phi,\mathrm{gas}} = v_\mathrm{K}(1-\eta)^{1/2} \quad , \quad \eta = n\frac{c_\mathrm{s}^2}{v_\mathrm{K}^2}$$

- Gas is typically sub-Keplerian by ~100ms^{-1} at 1AU. This is small fraction (~0.1%), but causes a STRONG HEADWIND!

Radial drift

Whipple (1972); Weidenschiling (1977); Takeuchi & Lin (2002)



$$\frac{dv_{\mathrm{r,d}}}{dt} = \frac{v_{\phi,\mathrm{d}}^2}{r} - \Omega_K^2 r - \frac{1}{t_\mathrm{s}} v_{\mathrm{r,d}}$$

$$\frac{d}{dt}(r v_{\phi,\mathrm{d}}) = -\frac{r}{t_\mathrm{s}}(v_{\phi,\mathrm{d}} - v_{\phi,\mathrm{g}})$$

- Assume particles spiral in on ~circular orbits: $v_{\phi,\mathrm{d}} \simeq v_{\phi,\mathrm{g}} \simeq v_\mathrm{K}$
- Azimuthal EoM becomes: $v_{\phi,\mathrm{d}} - v_{\phi,\mathrm{g}} \simeq -\frac{1}{2}\frac{t_\mathrm{s} v_\mathrm{K}}{r} v_{\mathrm{r,d}} = -\frac{1}{2} T_\mathrm{s} v_{\mathrm{r,d}}$
- Radial EoM LHS is negligible (to O(h^2/r^2)), so:

$$\frac{v_{\phi,\mathrm{d}}^2}{r} - \frac{v_{\phi,\mathrm{g}}^2}{r} - \eta\frac{v_\mathrm{K}^2}{r} - \frac{1}{t_\mathrm{s}} v_{\mathrm{r,d}} \simeq 0$$

$$\frac{2v_\mathrm{K}}{r}(v_{\phi,\mathrm{d}} - v_{\phi,\mathrm{g}}) - \eta\frac{v_\mathrm{K}^2}{r} - \frac{1}{t_\mathrm{s}} v_{\mathrm{r,d}} \simeq 0$$

Radial drift

Whipple (1972); Weidenschiling (1977); Takeuchi & Lin (2002)

$$-\frac{v_{\mathrm{K}}}{r} T_{\mathrm{s}} v_{\mathrm{r,d}} - \eta \frac{v_{\mathrm{K}}^2}{r} - \frac{1}{t_{\mathrm{s}}} v_{\mathrm{r,d}} \simeq 0$$

- Substituted first term from azimuthal EoM. Now divide by (v_K/r), and note that: $T_s = t_s \Omega_{\mathrm{K}} = t_s \frac{v_{\mathrm{K}}}{r}$

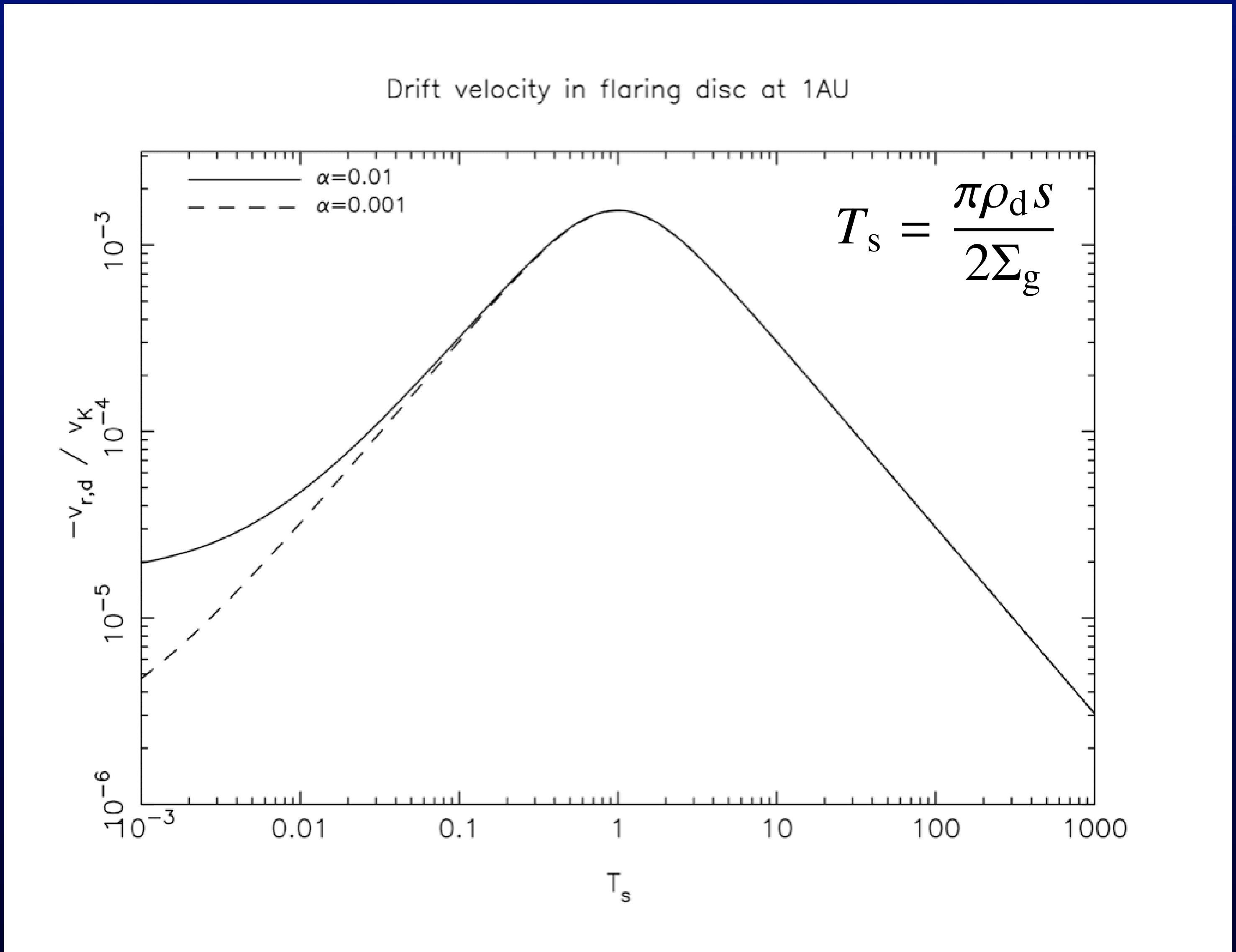
$$v_{\mathrm{r,d}} T_s + v_{\mathrm{r,d}} T_s^{-1} = -\eta v_{\mathrm{K}}$$

$$v_{\mathrm{r,d}} = -\frac{\eta v_{\mathrm{K}}}{T_s + T_s^{-1}}$$

- $v_{r,g}$ depends only on viscosity, and η only on gas pressure.
- Plot in terms of: T_s scales linearly with particle size, but also depends on conditions in gas disc.

Radial drift

Whipple (1972); Weidenschiling (1977); Takeuchi & Lin (2002)



- At the peak, this leads to large drift velocities, ~1000cm/s.
- For $dM/dt = 10^{-8} M_\odot yr^{-1}$ & $\alpha=0.01, T_s=1$ corresponds to a size of ~85cm. As disc evolves the peak shifts to smaller grains (lower gas density).
- Decay timescales at peak are *very* short, ~150yr at 1AU.

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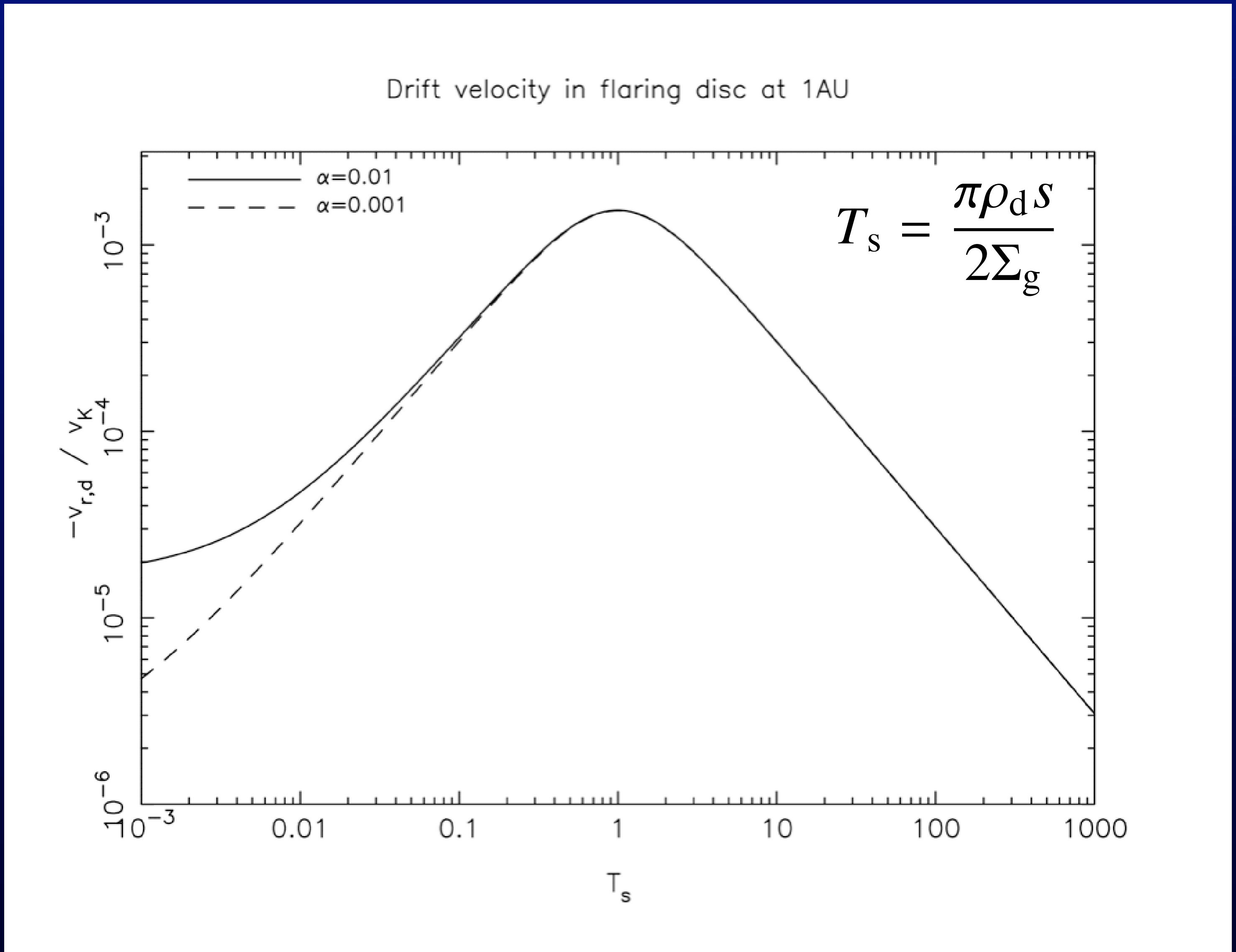

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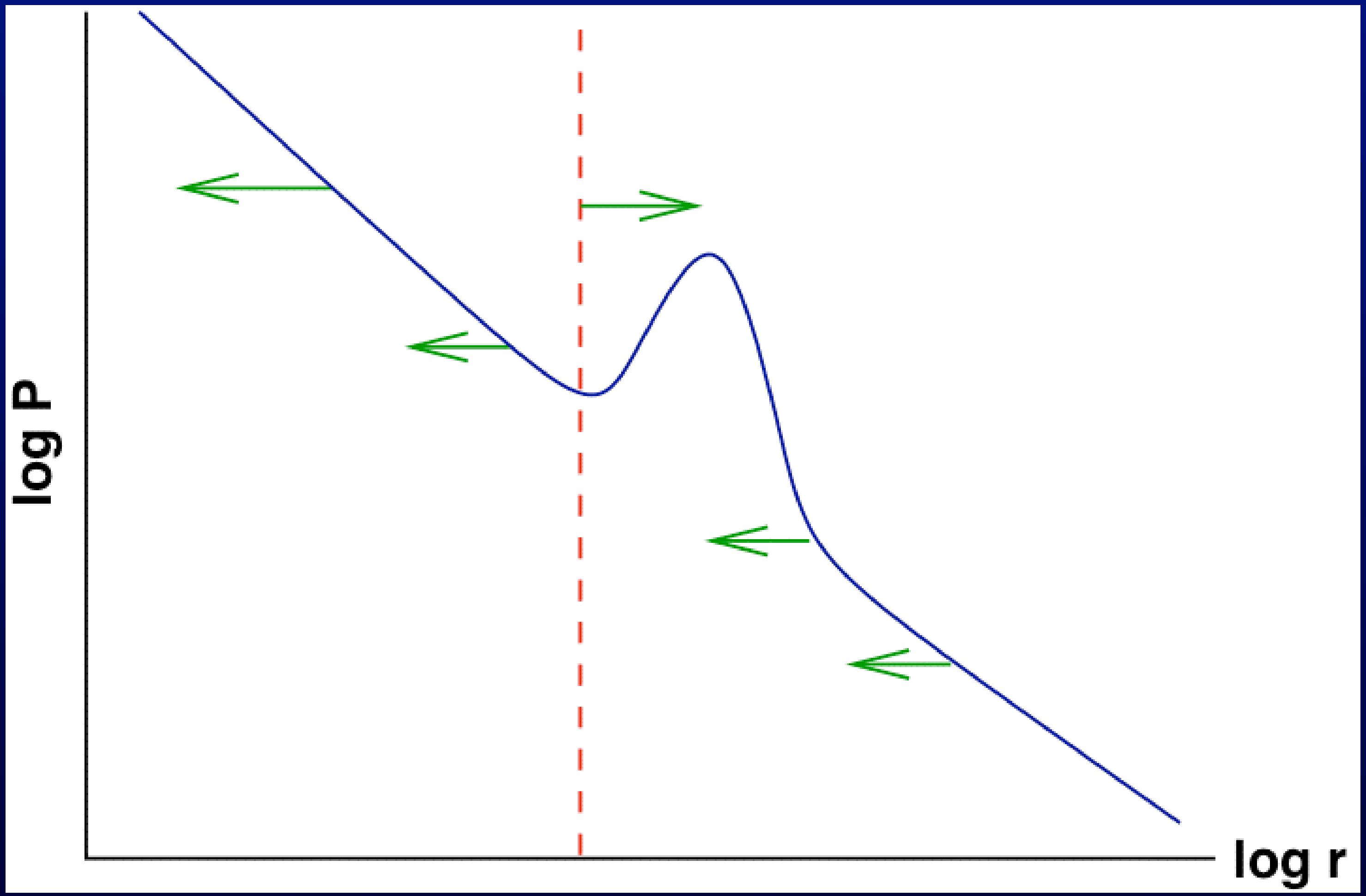
Planetesimal formation must occur very rapidly to overcome this barrier.

This is often referred to as the "metre-size problem".

Radial drift in "turbulent" discs



Armitage (2007)

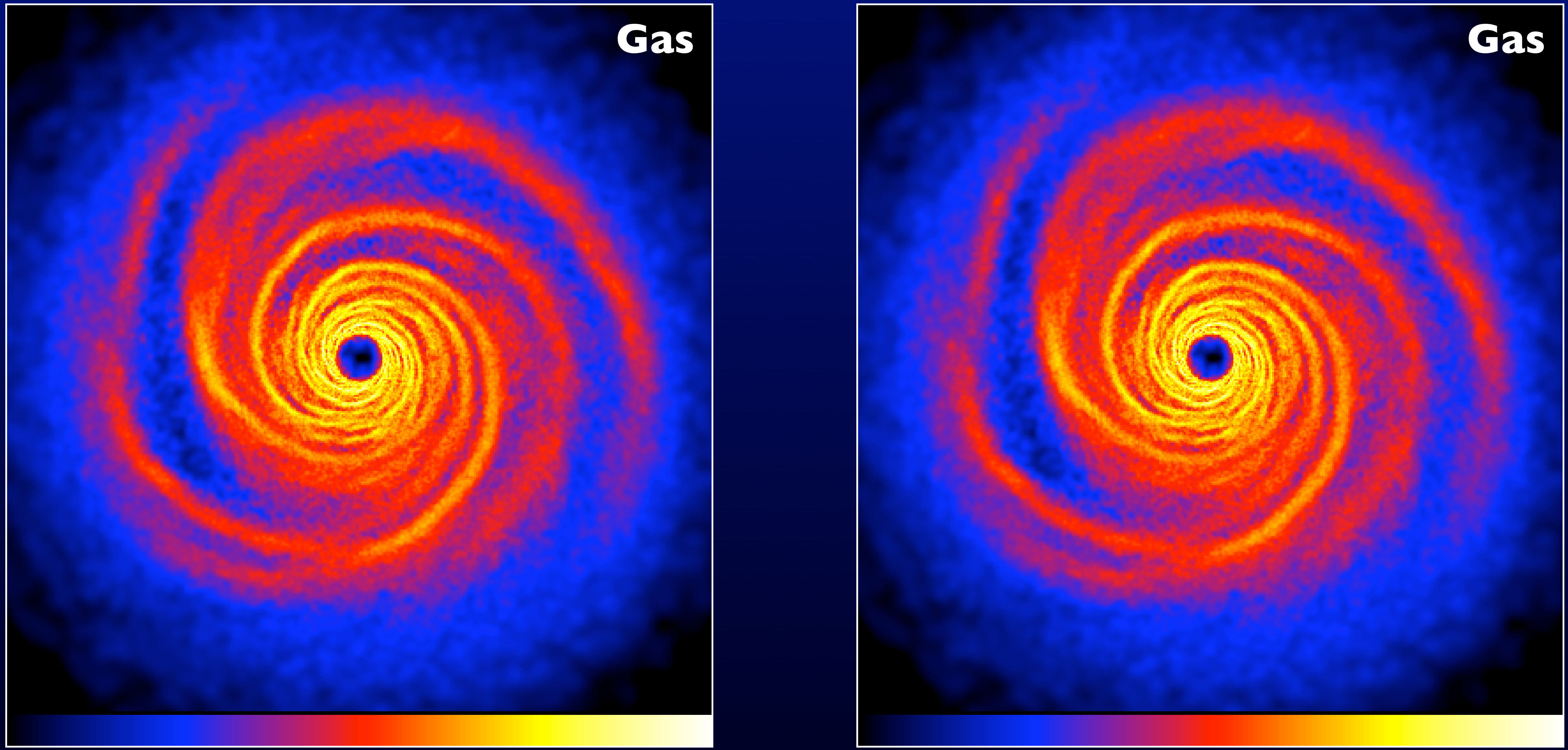
If local pressure maximum has length-scale Δr, then pressure gradient ($\sim P/\Delta r$) exceeds global pressure gradient ($\sim P/r$). "Concentration timescale" is therefore shorter than the drift timescale by $\sim(r/\Delta r)^2$.

- In quiescent, viscous discs pressure gradient is outwards, so all gas is sub-Keplerian and particles drift inwards.
- In general, however, particle drift opposes pressures gradient: particles move towards pressure *maxima*.
- If disc is not quiescent, this can cause significant enhancements of the local dust/gas ratio for particles with $T_s \sim 1$.

Radial drift in “turbulent” discs

Haghighipour & Boss (2003); Rice et al. (2004, 2006); Durisen et al. (2005)

Figures from Rice, Lodato et al. (2004)



Concentration of particles in this manner can dramatically increase collision rates, and *may* provide a solution to the metre-size problem.

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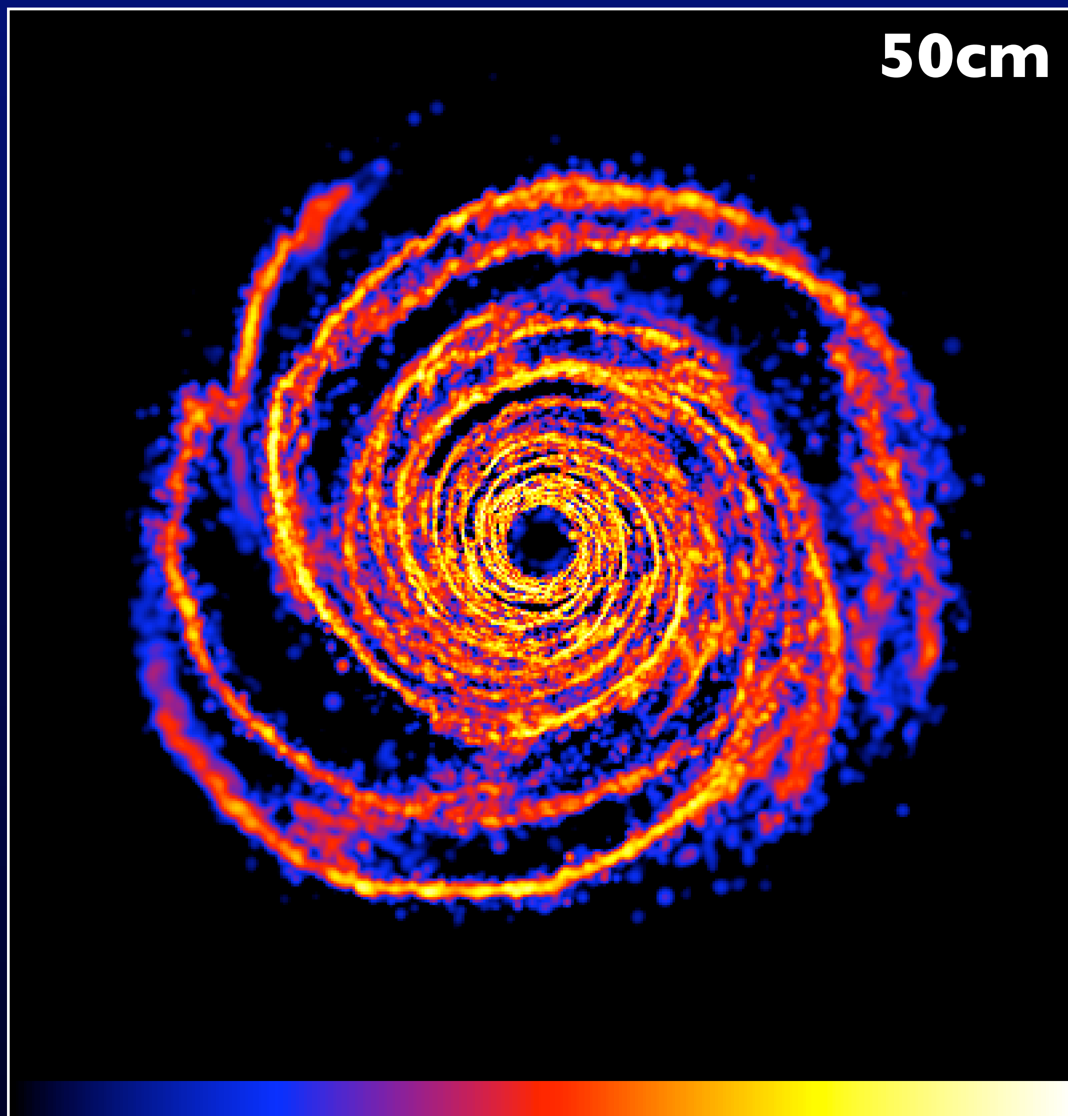

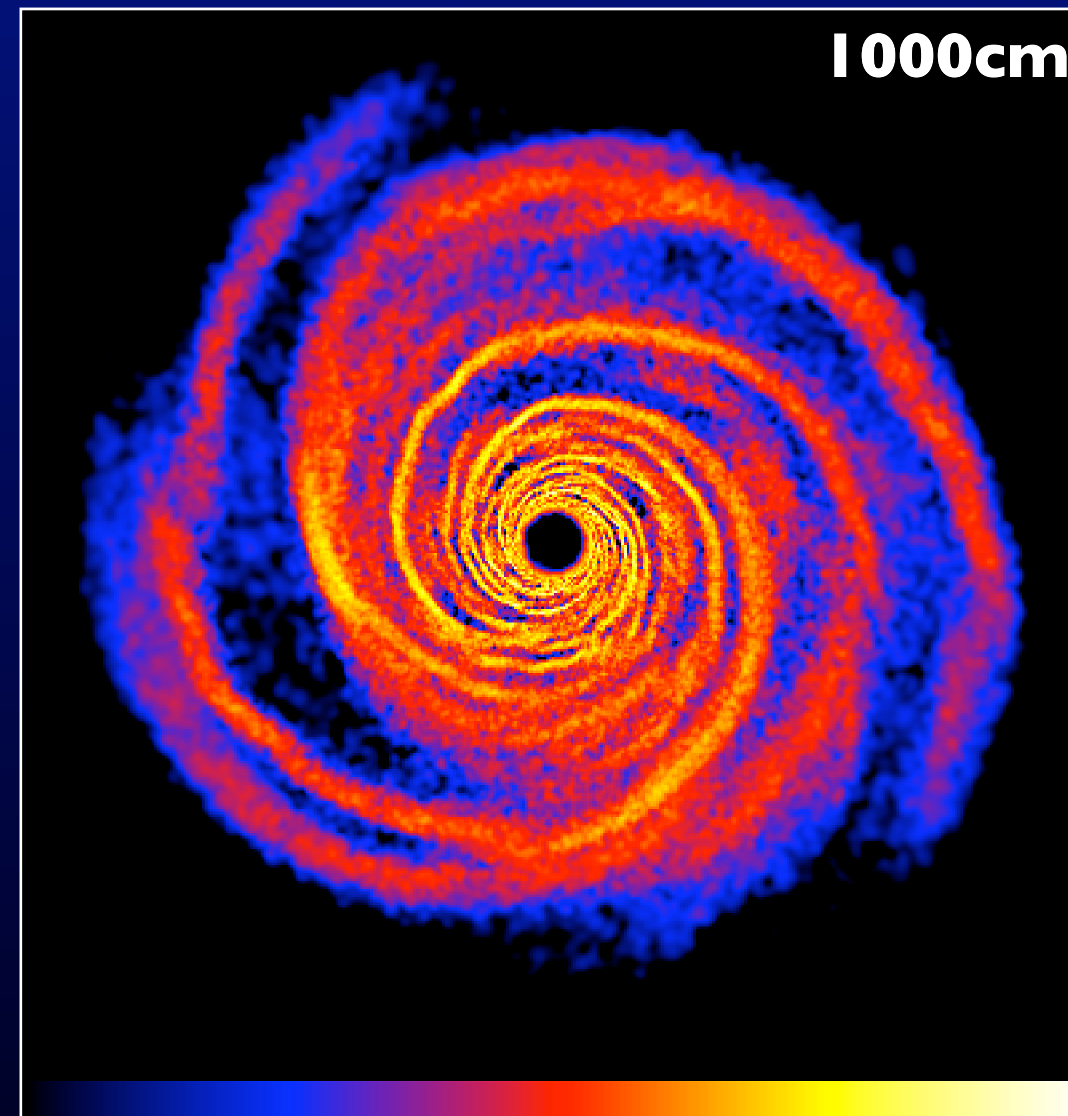

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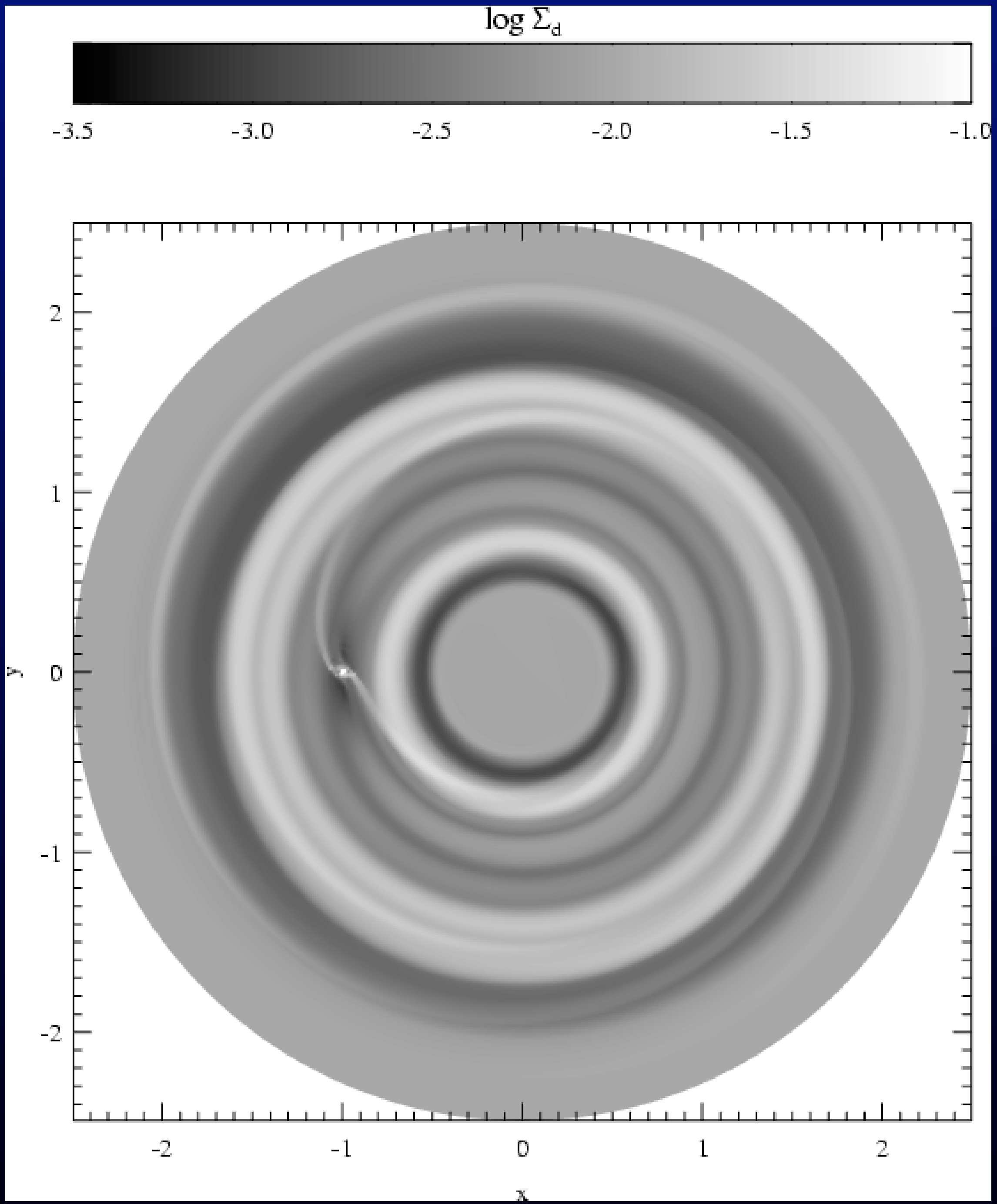
Clumping in planet-induced structure

e.g. Pardekooper & Mellema (2004,2006); Rice et al. (2006)

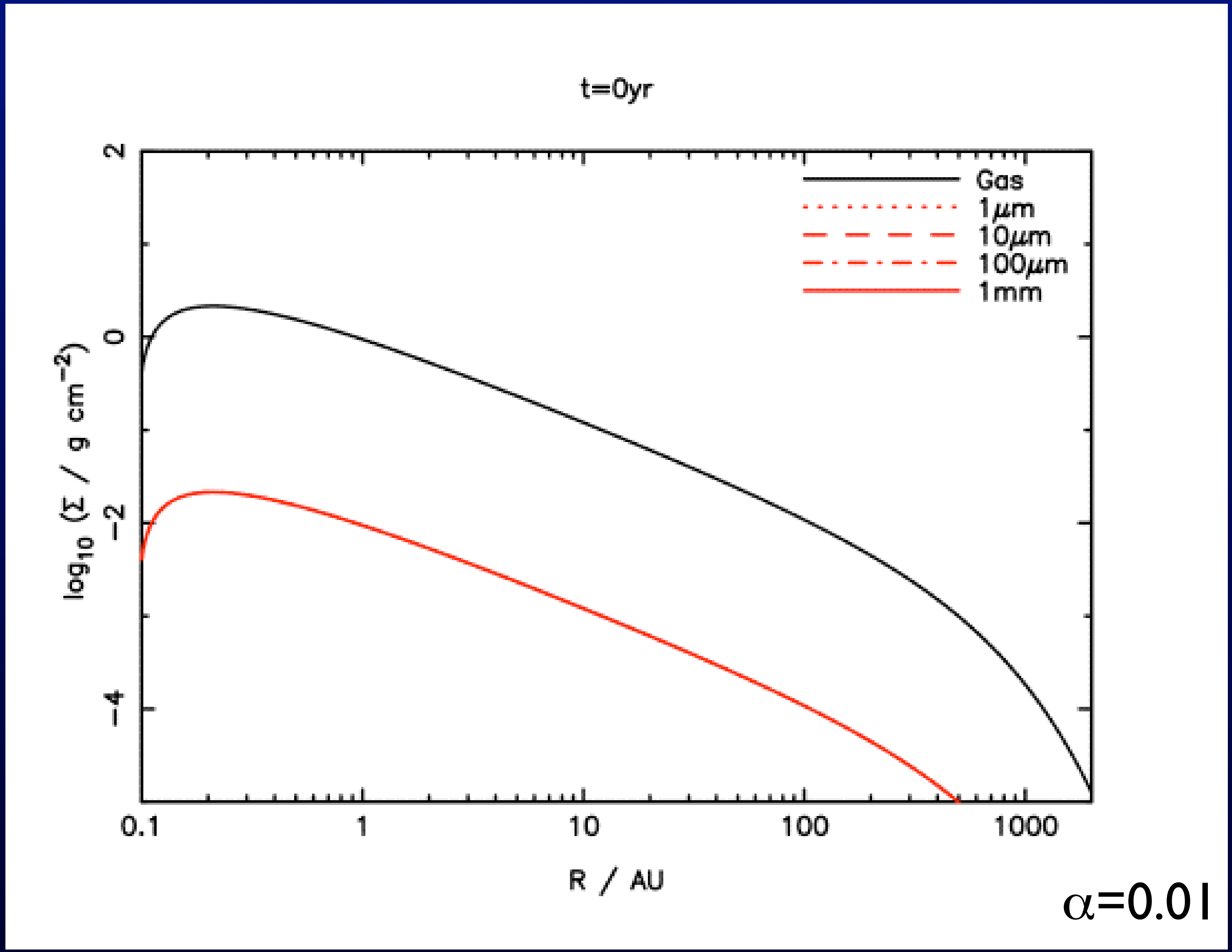


Pardekooper & Mellema (2006)

- Presence of a planet alters structure of gas disc: spiral arms for low-mass planet; tidal gap for massive planet.
- Dust is concentrated in these local pressure maxima.
- Low-mass planet makes dust spiral arms.
- In gap-opening case, tend to starve inner region of dust and reduce local dust-to-gas ratio (Rice et al. 2006).

“Sweeping-up” of small grains

RDA & Armitage (2007); see also Garaud (2007)



- Clearing phase of gas disc: viscosity + photoevaporative wind.
- “Two-fluid” model of dust, similar to Takeuchi et al. (2005).
- Once gap opens, pressure gradients concentrate dust at disc edge.

Grain growth & planetesimal formation

e.g. Lissauer (1993); Youdin & Shu (2005); Dullemond & Dominik (2005); Dominik et al. (PPV)

- In standard theory, dust grains agglomerate to form planetesimals via "sticking" collisions.
- This model is viable, but many parameters are very uncertain. Sticking and fragmentation probabilities are especially problematic. (Growth to cm sizes seems OK, but larger grains stick much less efficiently.)
- Many theories invoke some variant of the Goldreich-Ward (1973) mechanism: grav. instability in a thin dust layer.
- Problems exist here also, primarily in how to concentrate the dust sufficiently. Various suggestions exist in the literature: settling, radial drift (Youdin & Shu 2005), photoevaporation (Throop & Bally 2005), etc.

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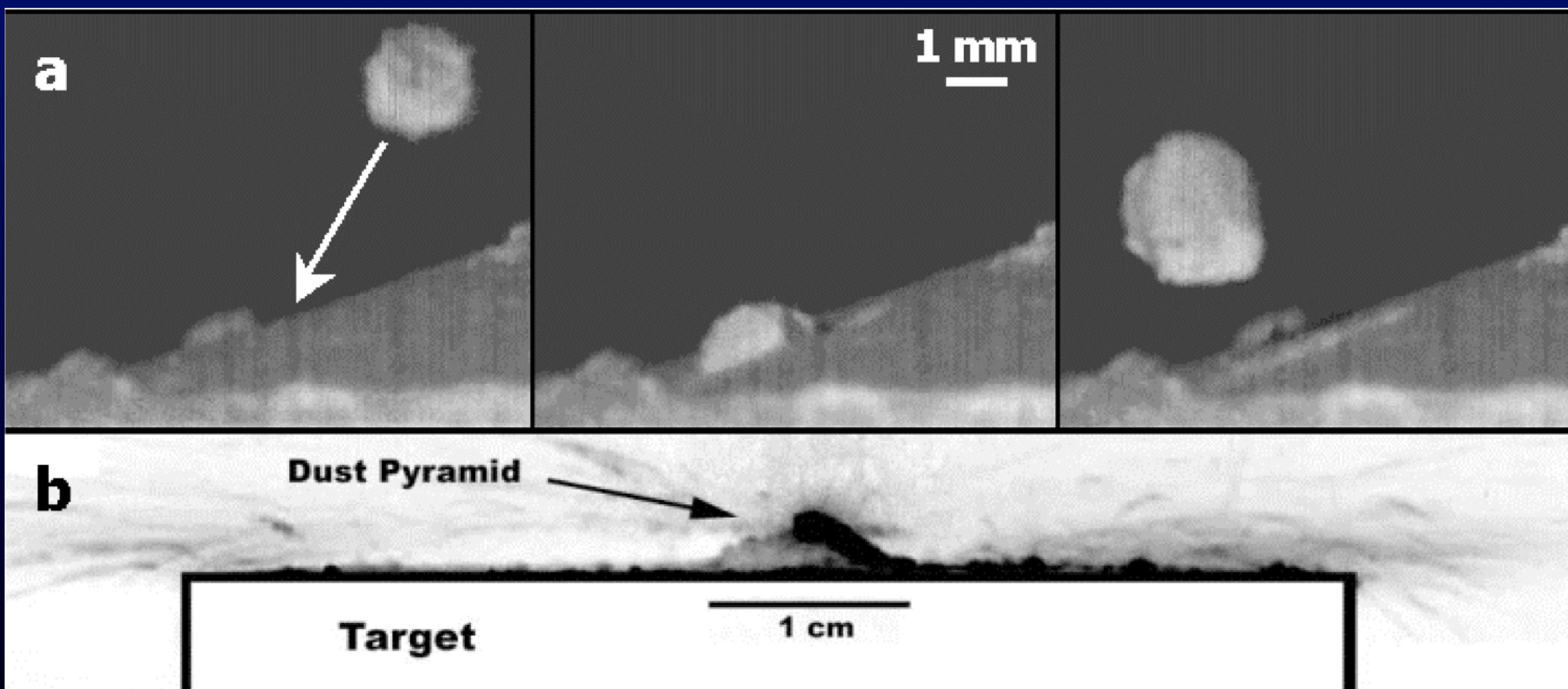


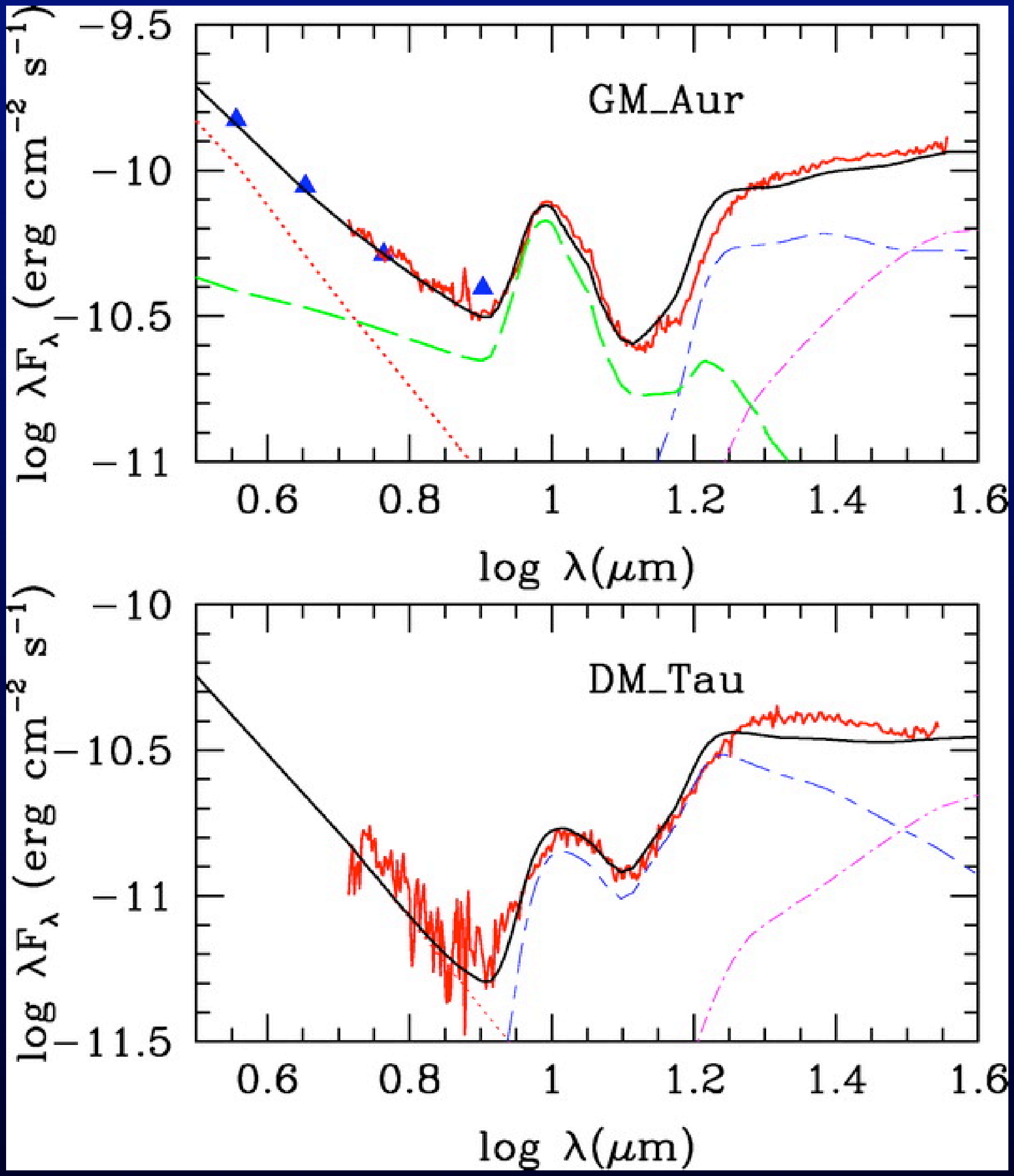
Dominik et al. (2007); experiments by Langkowski & Blum

photoevaporation (Throop & Bally 2005), etc.

Dust dynamics: summary

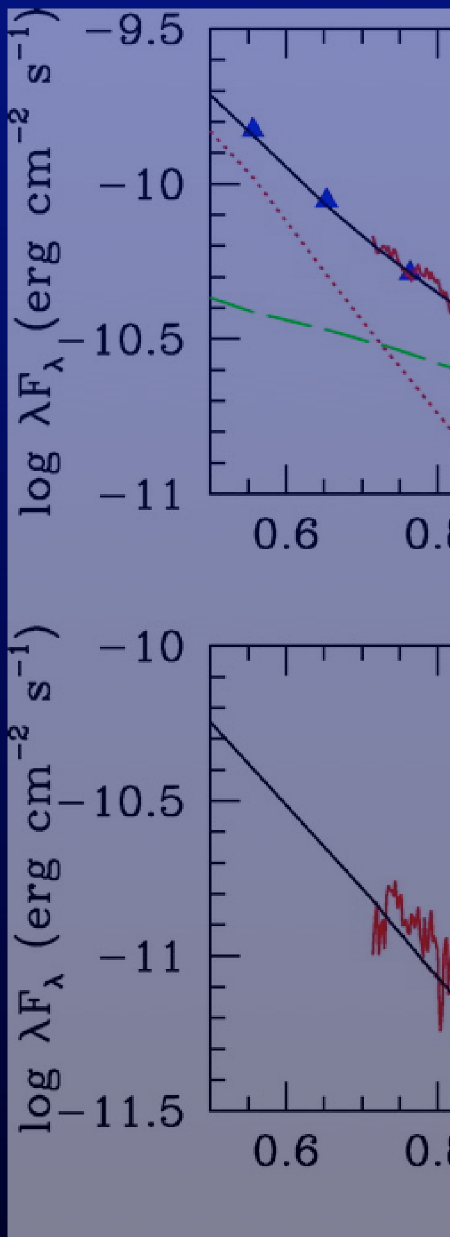
- Gas-grain interactions dominated by aerodynamic drag, arising because grains don't feel gas pressure.
- Grains with $T_s \sim 1$ are most susceptible to radial drift, and decay on very short timescales (<1000yr).
- Growth to ~mm-cm size (agglomeration) can occur in <1Myr.
- Planetisemal formation must occur sufficiently rapidly to overcome the "metre-size barrier".
- Effects of turbulence may be significant (see lectures by Klahr).
- Planetesimal formation still very poorly understood. Models exist, but all have their associated problems.

“Transition discs”

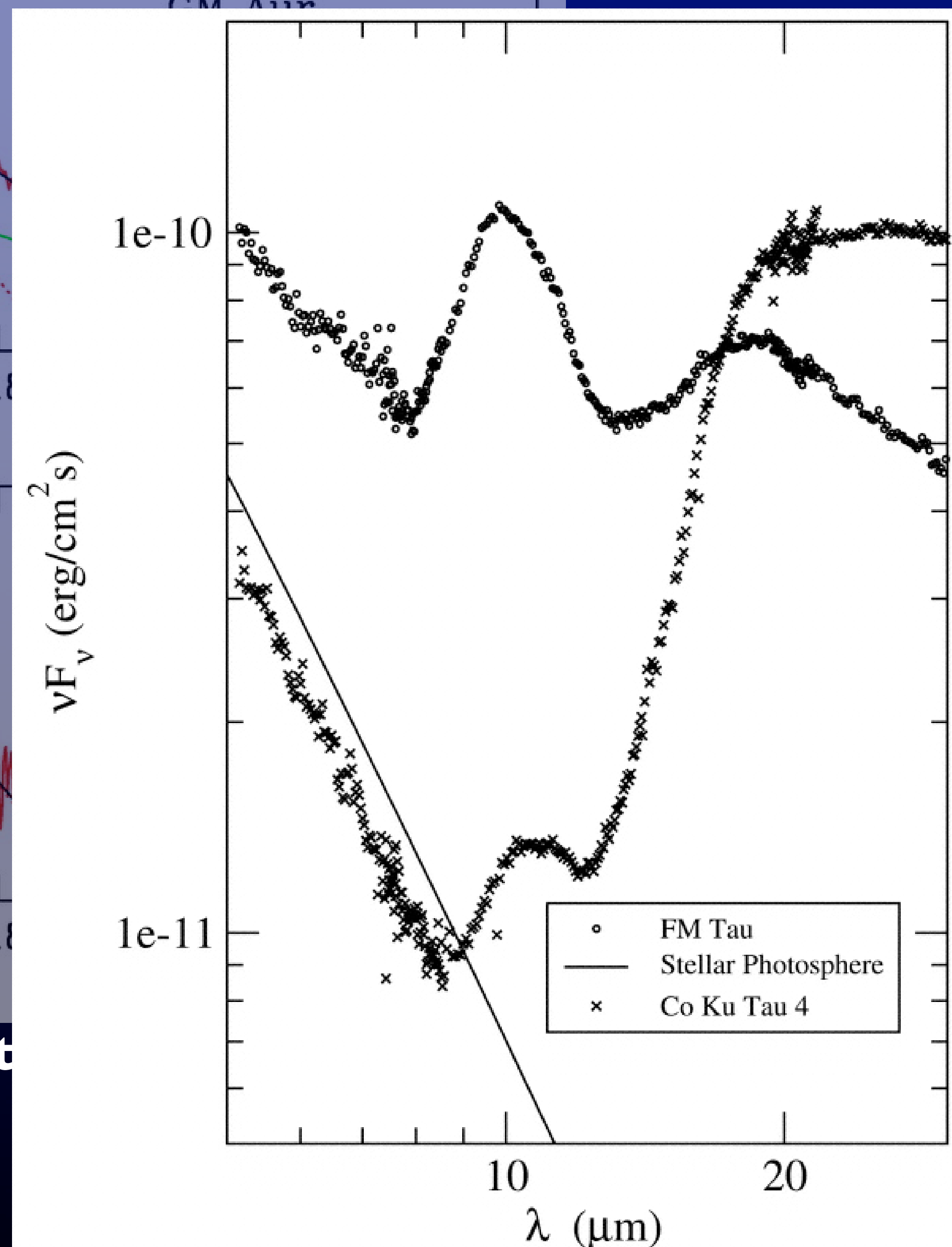


Calvet et al. (2005)

“Transition discs”

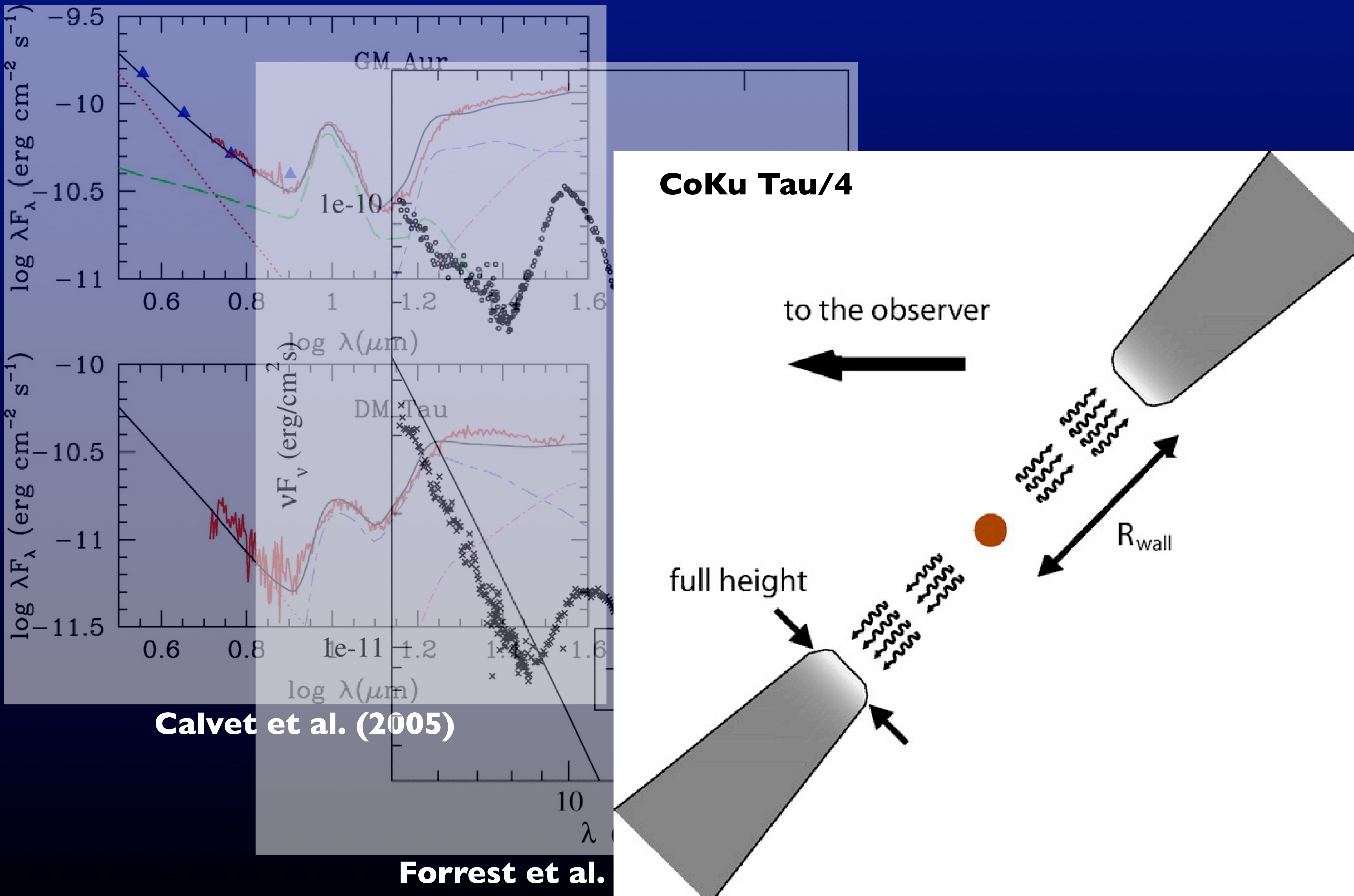


Calvet



Forrest et al. (2004)

“Transition discs”

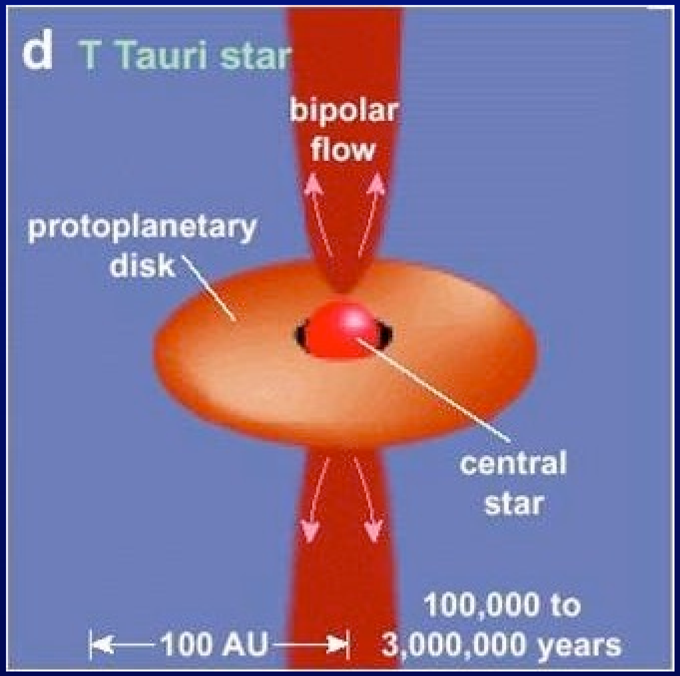


Calvet et al. (2005)

Forrest et al.

d’Alessio et al. (2005)

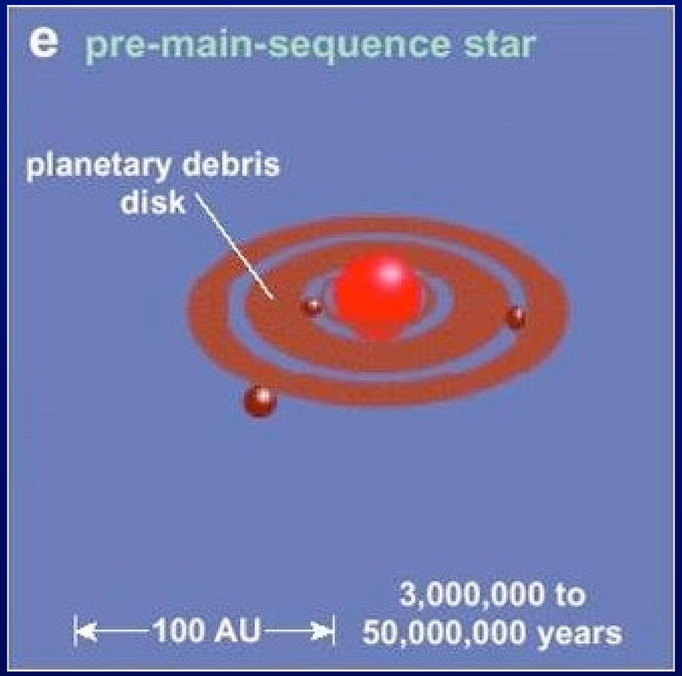
Why do we care?



Optically thick disc

Classical T Tauri (CTT)

IR Class II



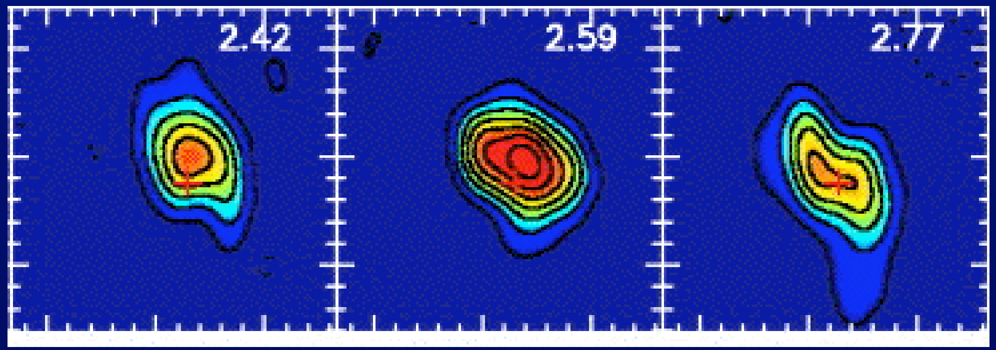
Dispersed disc/planets?

Weak-lined T Tauri (WTT)

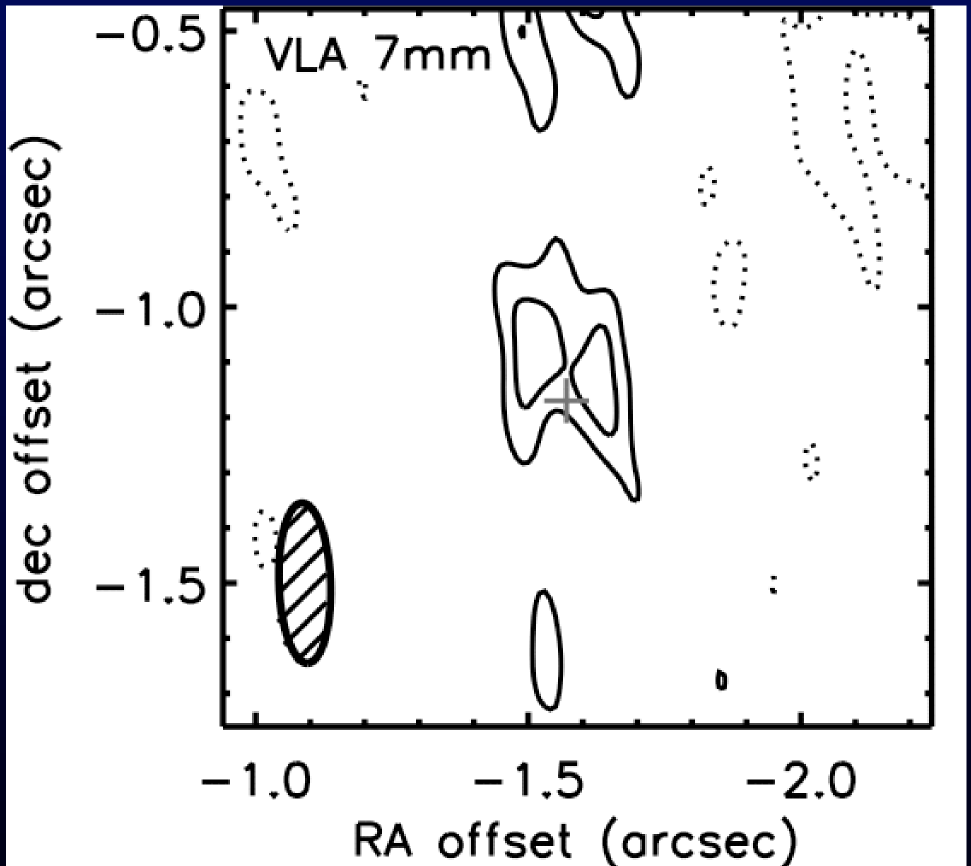
IR Class III

- CTTs evolve into WTTs, and the transition is fast.
- Objects "caught in the act" of clearing provide a key test for models.

Need spatially resolved data...



Qi et al. (2004): CO J=3-2 line (SMA)



Hughes et al. (2007): 7mm continuum (VLA)

- As we will see, SEDs are essentially degenerate between different models.
- Spatially resolved observations are key to breaking these degeneracies.
- 1AU at 140pc ⇔ 7mas.
- Existing (sub-)mm observations have already resolved some spatial structure.
- Ideal (faint) targets for optical/IR interferometry!

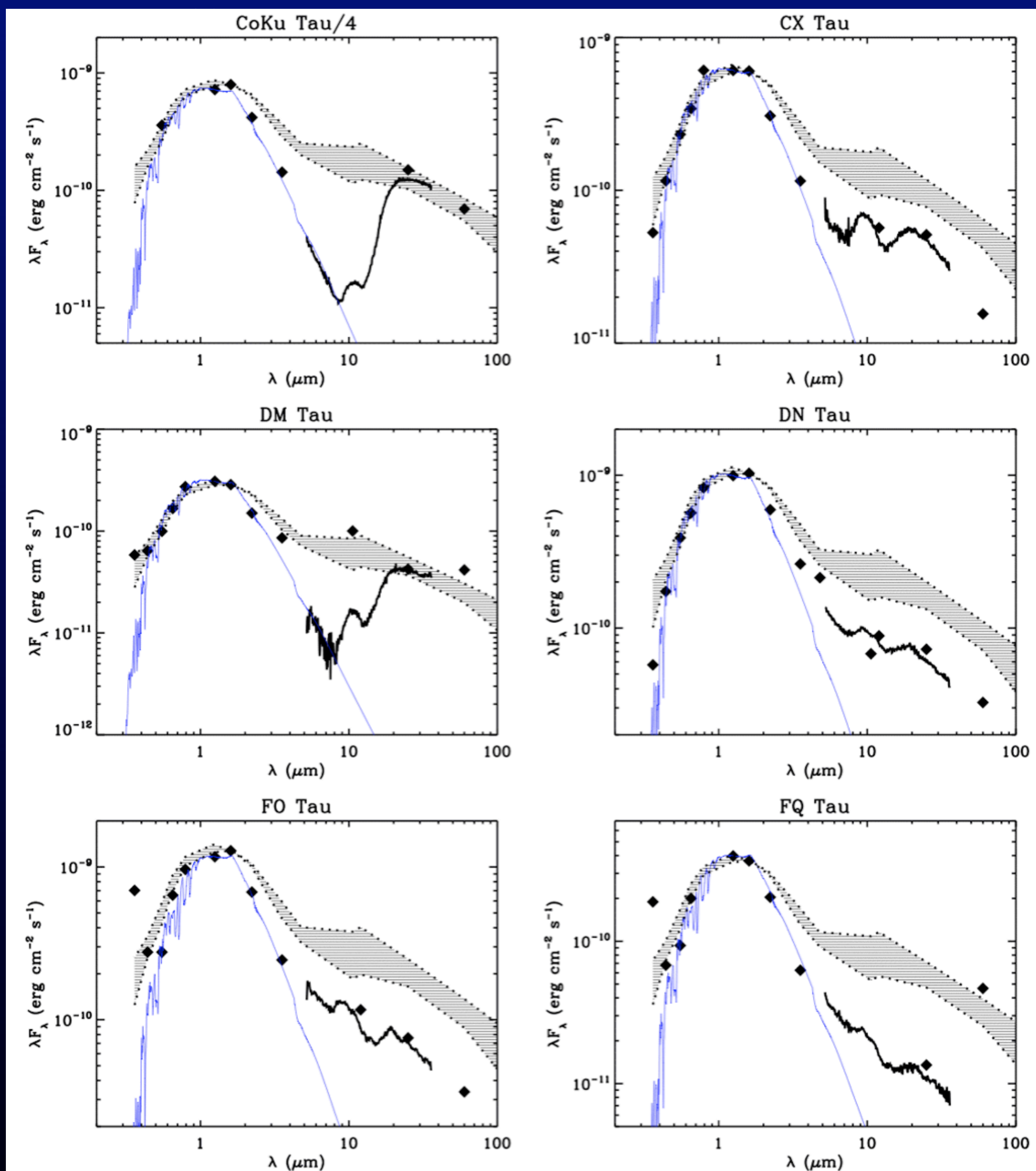
What is a "transitional" disc?

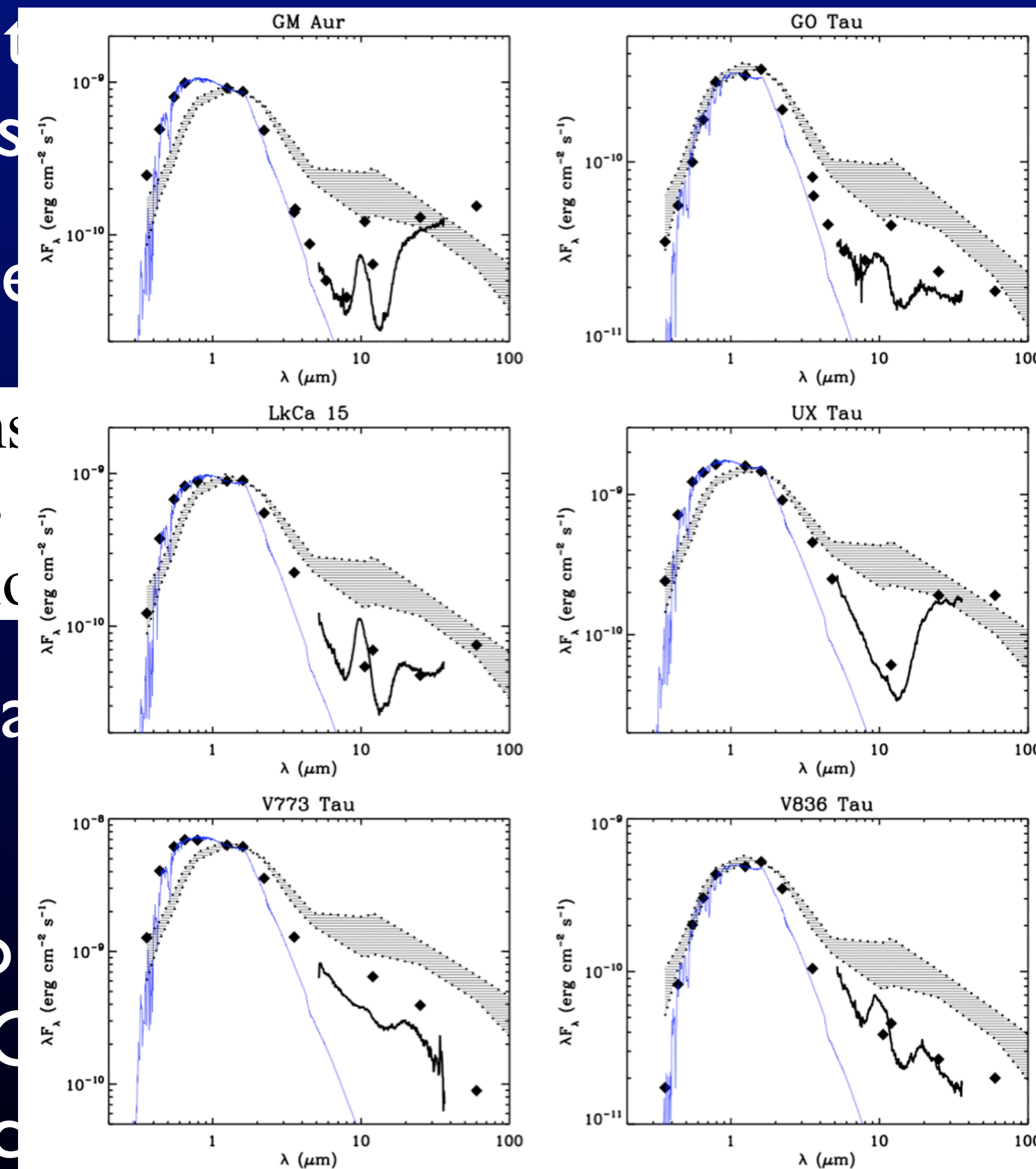
- "Properties between those typical of CTTs & WTTs" - little consistency in how this is defined observationally.
- Najita et al. (2007) adopt the following definition:

> "Objects are classed as transition objects if they show weak or no infrared excess shortward of 10μm and a significant excess at longer wavelengths."

- Based on Spitzer IRS spectra, they classify 12 objects in Taurus as "transitional".
- Demographically, these 12 objects show systematically lower accretion rates than CTTs of the same disc mass. Only 2/12 however, are spectroscopic WTTs.

What is a “transitional” disc?





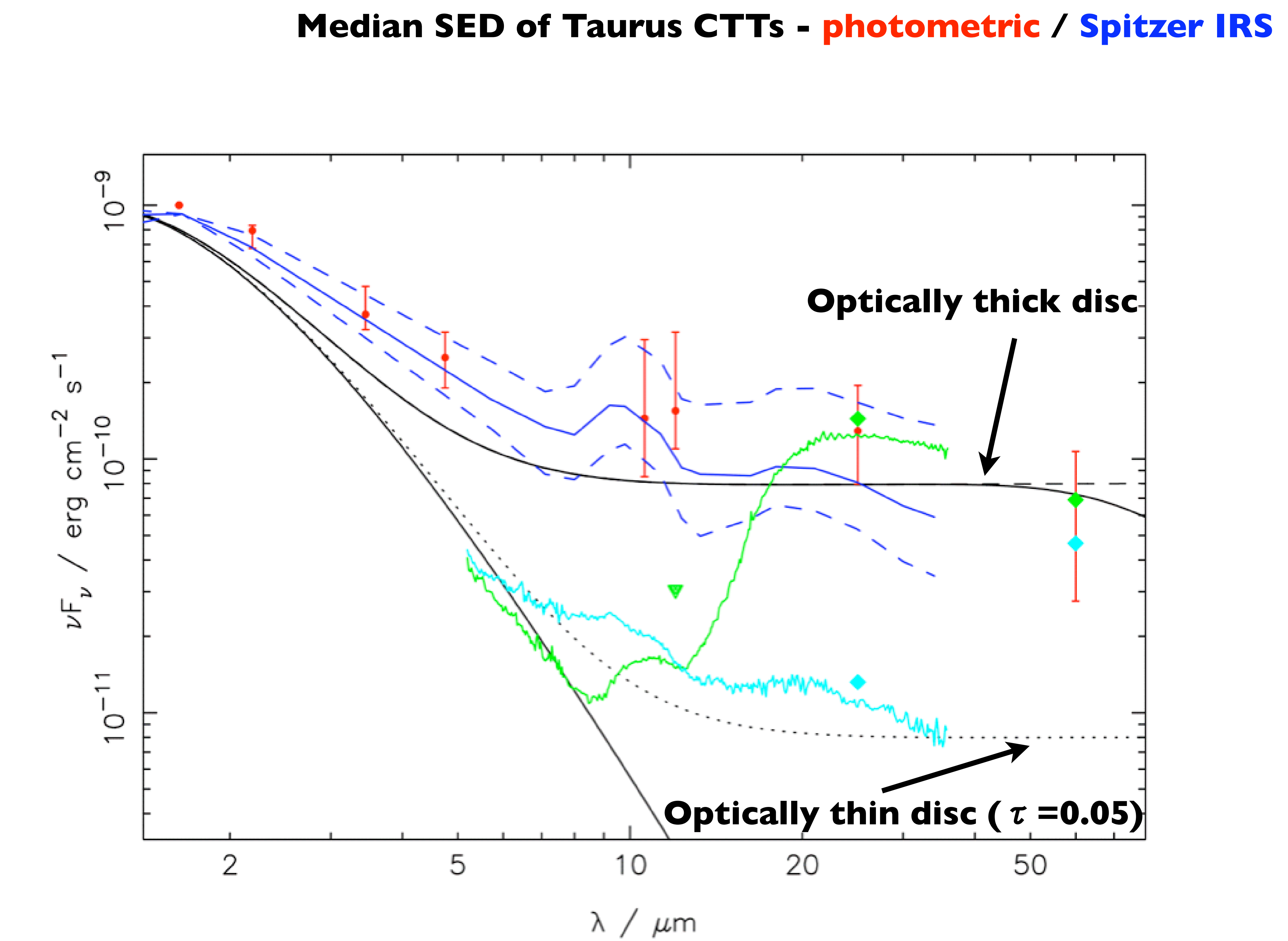
What is a "transitional" disc?

- I prefer a more model-based definition:

> "Transition objects have discs which are optically thin at shorter wavelengths and optically thick at longer wavelengths."

- Such a definition removes potential selection biases due to observed wavelength ranges, and requires a real physical change in the radial structure of the disc.
- This is more stringent that the Najita et al. (2007) criterion: only 6 of their 12 objects meet satisfy it.
- Unbiased samples will require observations at longer wavelengths: Spitzer is not sensitive to large "holes" (>20 -50AU, depending on spectral type).

What is a "transitional" disc?



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

What is a "transitional" disc?

- Physically, transitional SEDs are consistent with a hole or gap in the (dust) disc.
- Dust settling/growth can also give rise to a weakened IR excess: optical depth criterion should reject such objects.
- Several models for transition objects exist:
  - Clearing by planets
  - Photoevaporation/viscous clearing
  - Others: photophoresis, dust settling, MRI enhancement, etc.
- All such models predict very similar SEDs in the IR, so how do we distinguish between different modes?

Disc clearing by planets

e.g. Papaloizou & Lin (1984); Takeuchi et al. (1996); Nelson et al. (2000)

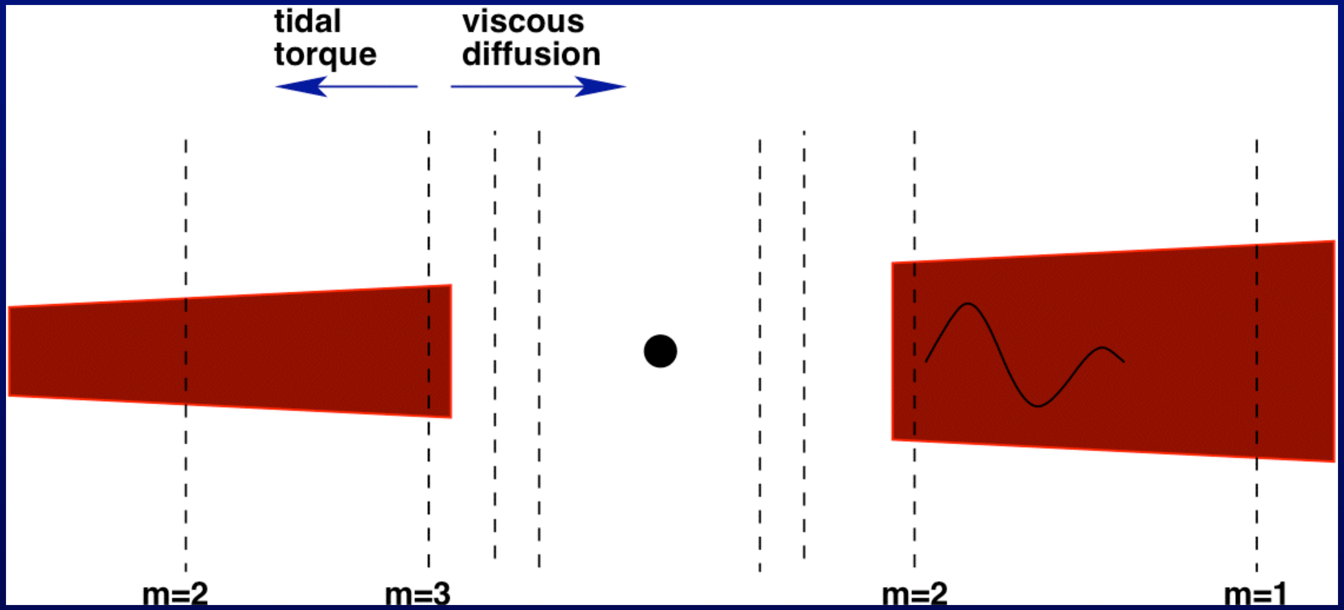


Figure from Armitage (2007)

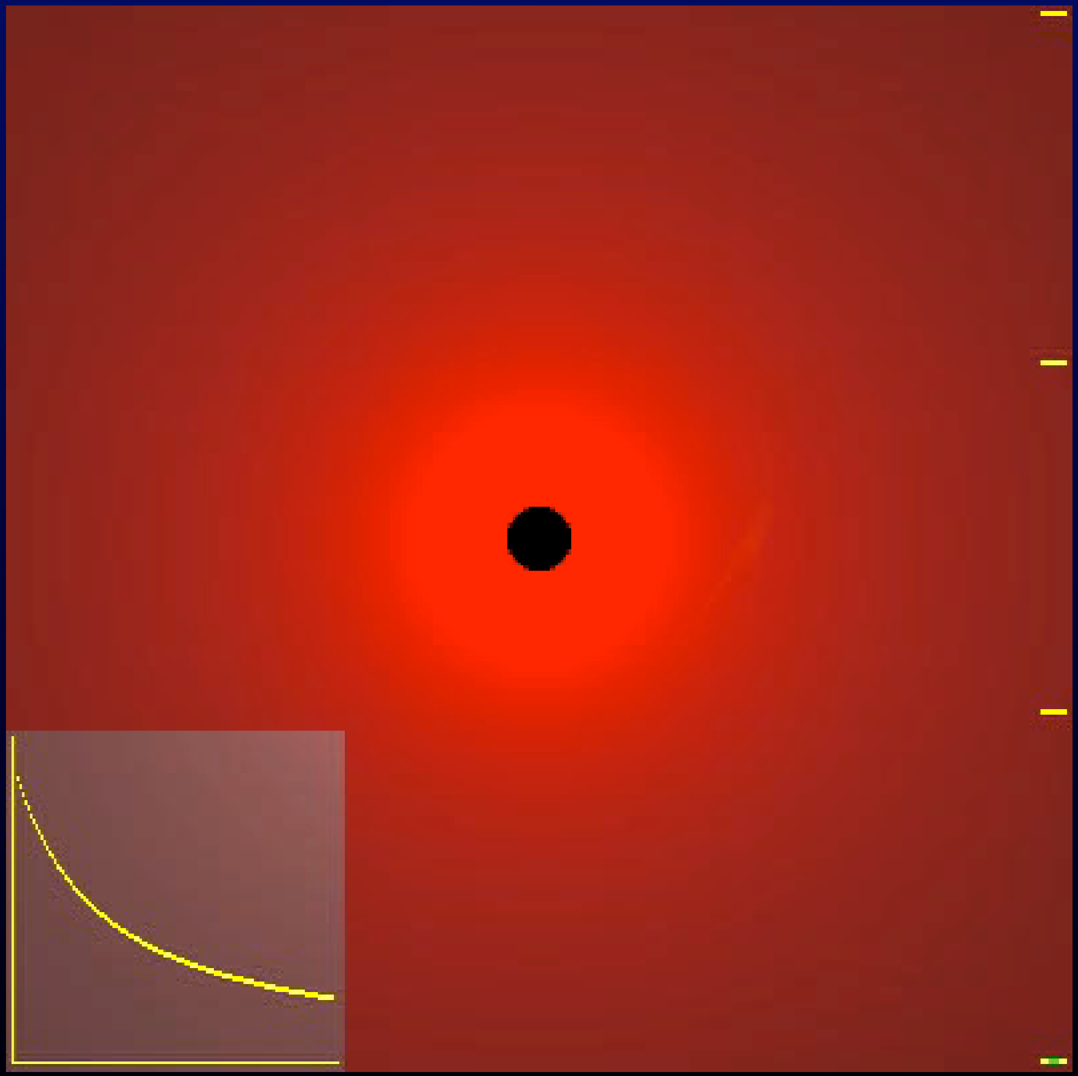
Gap-opening criterion is essentially that the tidal torques from the planet must exceed the viscous torques in the disc. Can be written as:

$$q \gtrsim \frac{40}{\mathcal{R}} \simeq 40\alpha \left(\frac{H}{R}\right)^2$$

- A sufficiently massive planet will open a gap in a disc, resulting in a "transitional" appearance.
- Gap-opening criterion is independent of surface density.
- Once gap opens planet undergoes Type II migration. Accretion across gap is a strong function of planet mass.
- For α=0.01, planets more massive than ~0.5MJup will open a gap.

Disc clearing by planets

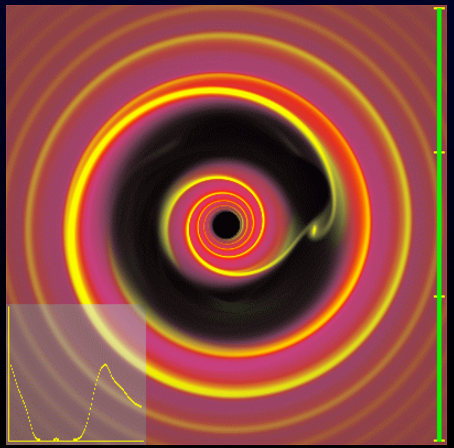
- Dynamical effect of a planet in a disc is to clear a gap or hole on a short (dynamical) timescale (e.g. Rice et al. 2003; Quillen 2004; Varnière et al. 2006).



Armitage (2005)

Disc clearing by planets

- Dynamical effect of a planet in a disc is to clear a gap or hole on a short (dynamical) timescale (e.g. Rice et al. 2003; Quillen 2004; Varnière et al. 2006).
- Models of these holes are consistent with observed infrared SEDs (e.g. Rice et al. 2003, 2006).
- Models usually assume presence of planet, and do not consider formation issues.
- Not clear whether accretion will persist across the gap over long timescales (see Lubow & d'Angelo 2006).



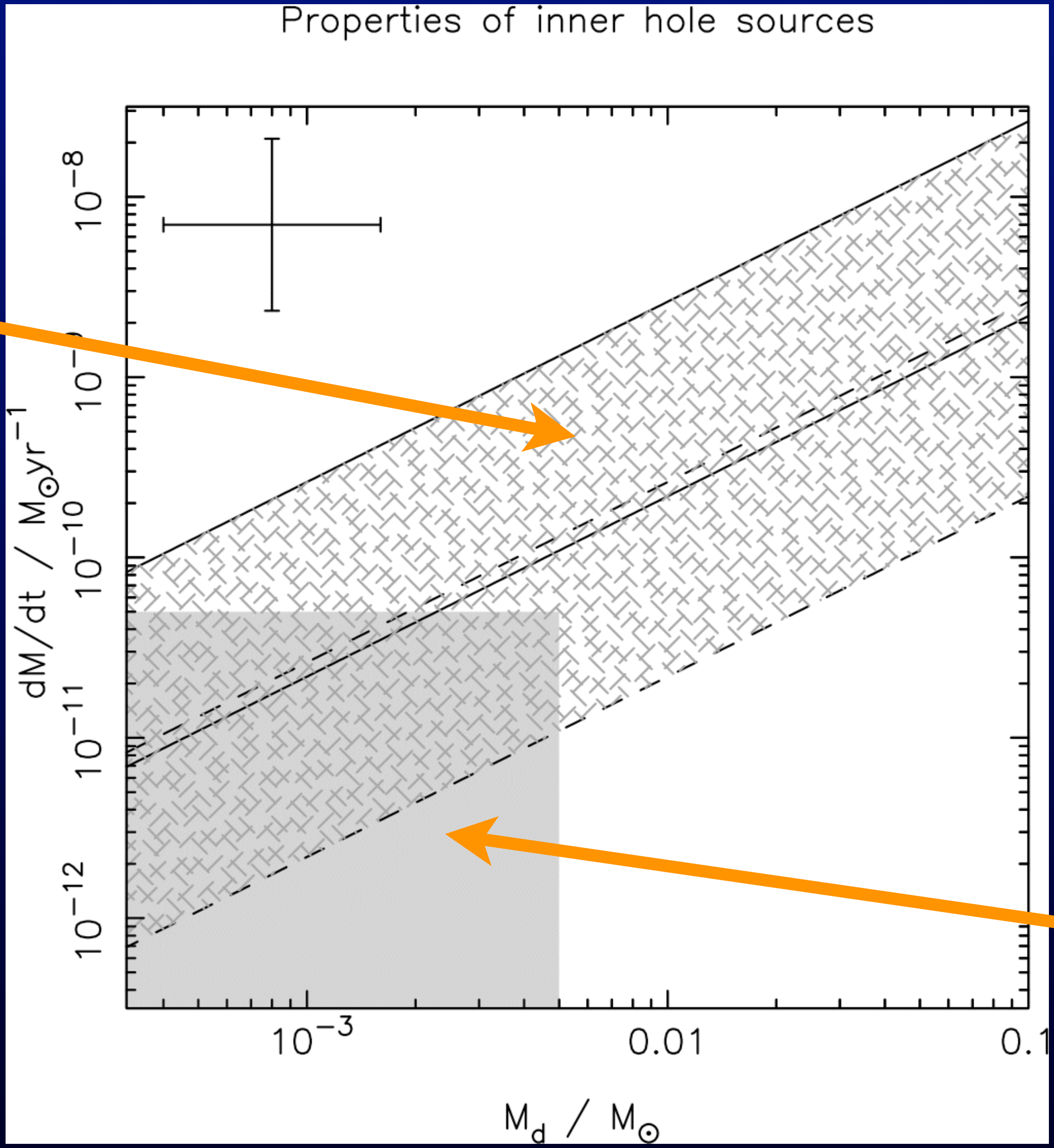
Properties of inner hole models

- Planet-induced gaps/holes:
  - Disc masses typical of CTTs.
  - Accretion across gap likely ("leaky barrier"), although strong function of planet mass (e.g. Lubow & d'Angelo 2006).
  - Reduced dust/gas ratio inside gap (in <mm grains, Rice et al. 2006).
  - Hole sizes typically few planet radii, so <30-50AU.
- "Photoevaporated" holes:
  - Hole sizes ~uniformly distributed (≥1.5AU).
  - Little or no accretion ($\leq 10^{-10} M_{\odot} yr^{-1}$).
  - Low disc mass (~ few M_{Jup}).
  - Should represent ~1-10% of total (CTT+WTT) population.

Discriminating between models

RDA & Armitage (2007); see also Najita et al. (2007)

Allowed range for embedded planets



Allowed range for photoevaporation

- Explore range of allowed parameters: accretion rates and disc masses.
- Combine with toy planet+disc model to compare to data. (Planet model adapted from Lubow et al. 1999 and Lubow & d'Angelo 2006).

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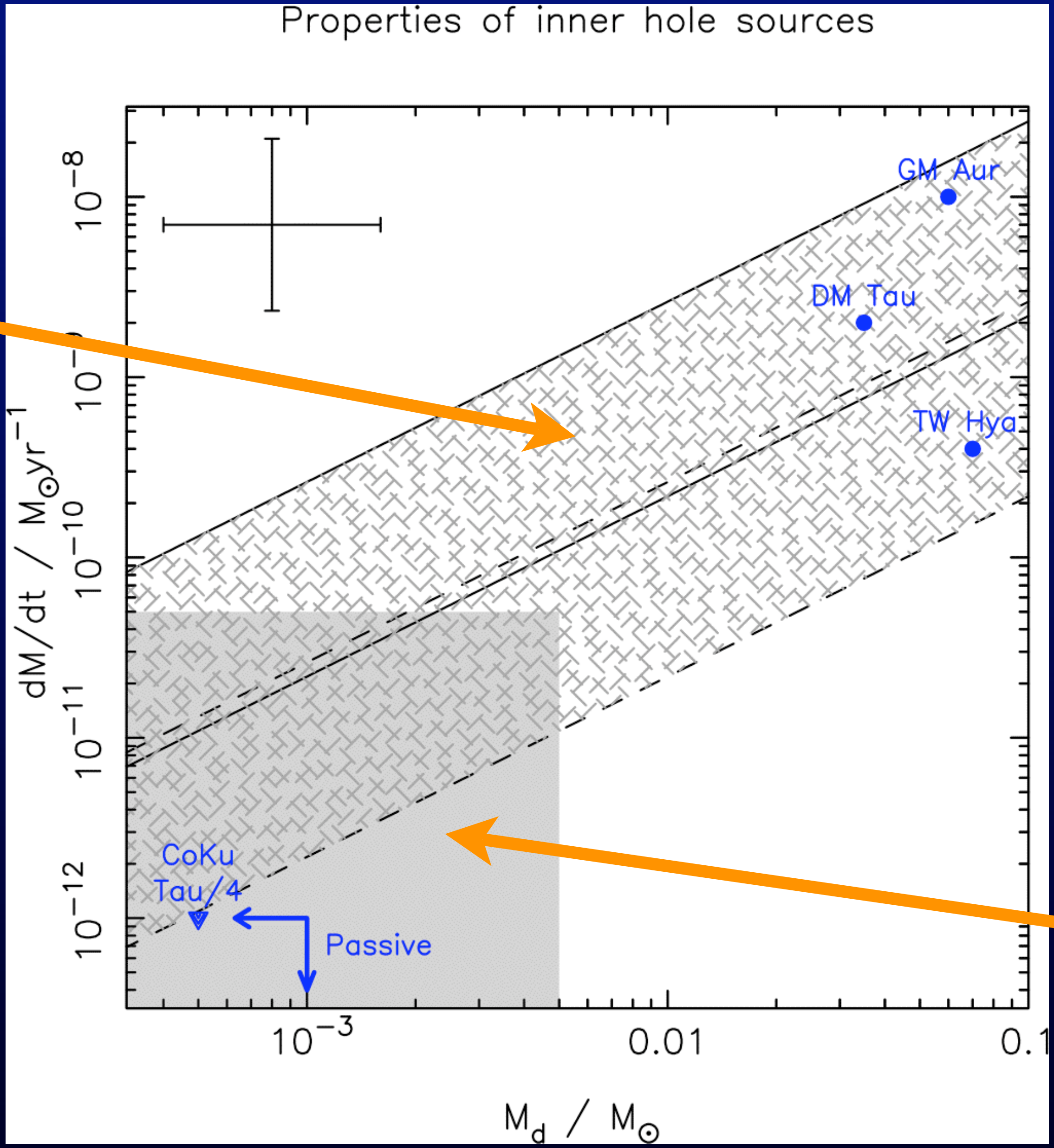

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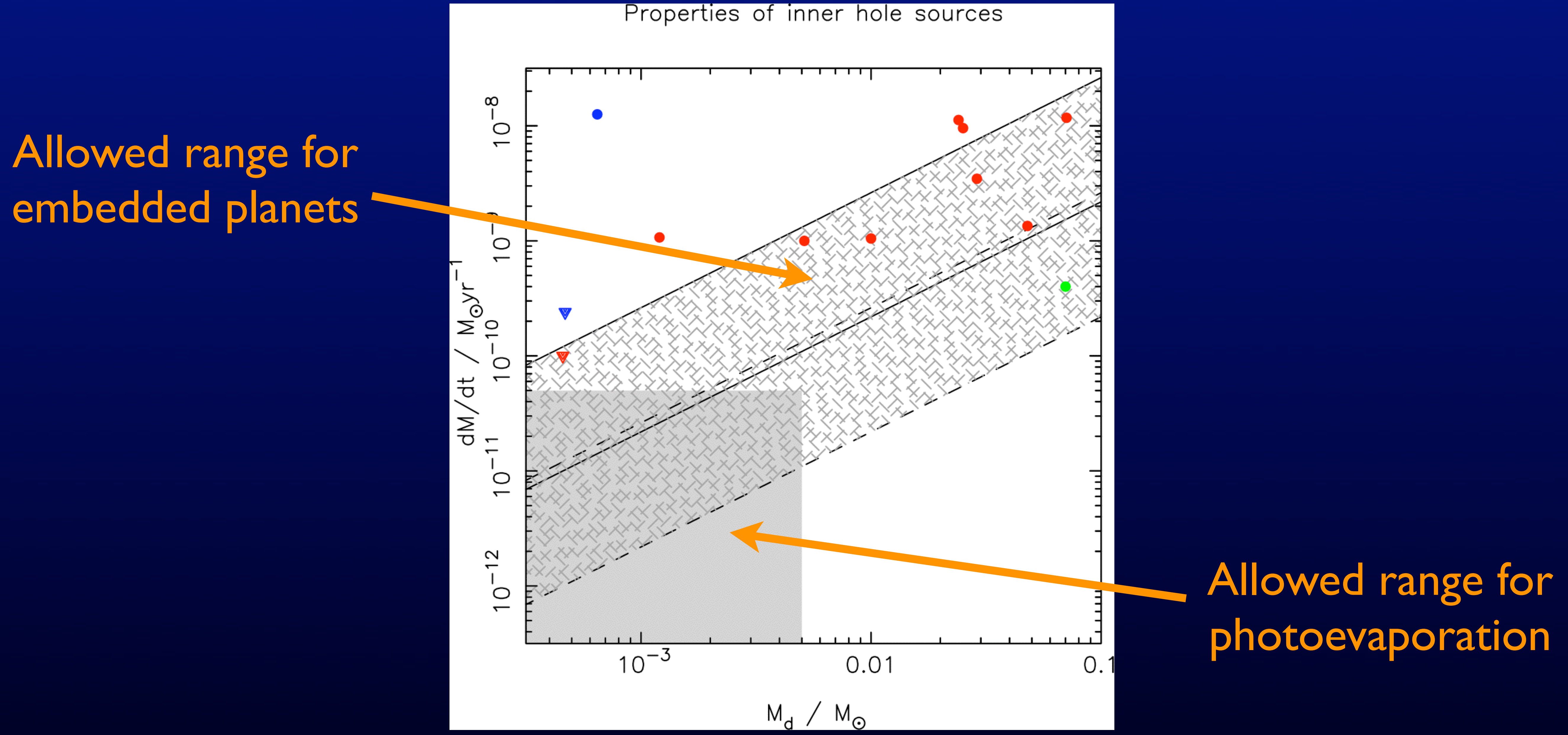

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Transition discs: summary

- Current data suggest that accreting:non-accreting ratio in transition objects is between 1:1 & 3:1 (Sicilia-Aguilar et al. 2006; Najita et al. 2007).
- No single object definitively matches any model(!): statistical approach seems best.
- Currently number statistics are poor (~15 objects known), and selection biases unclear.
- Multi-wavelength data essential: need more disc masses and accretion rates (especially meaningful upper limits for WTTs).
- Spatial scale (~10AU) makes these ideal(ish) targets for the VLTI!

Recommended reading...

- Observations: Beckwith et al. (1990); Kenyon & Hartmann (1995); Haisch et al. (2001); Andrews & Williams (2005).
- Theory: Pringle (1981); Hollenbach et al. (1994); Hartmann et al. (1998); Clarke et al. (2001); Weidenschilling (1977).
- *Evolution of the protoplanetary cloud and formation of the earth and the planets*, Safronov (1969).
- Recent reviews:
  - PPIV: Hollenbach et al., Calvet et al., Clarke et al.
  - PPV: Dullemond et al., Meyer et al.; Najita et al., Natta et al., Dominik et al.
- Other: lecture notes by Phil Armitage (astro-ph/0701485)