Protoplanetary Disks and Their Evolution

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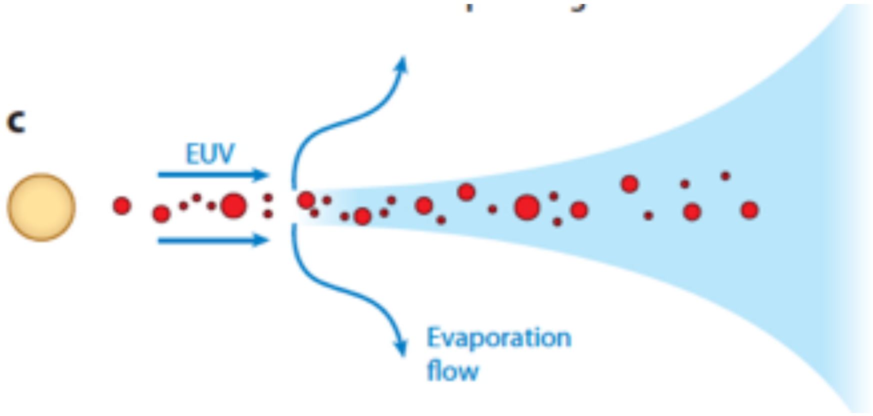
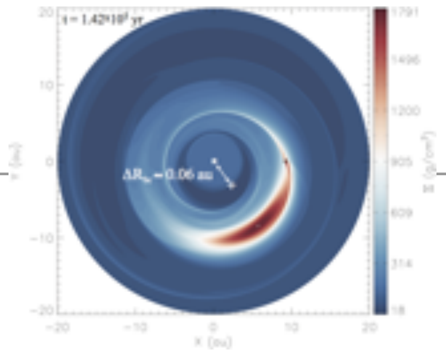
Annual Review of Astronomy and Astrophysics, Vol. 49, pp. 67–117, 2011





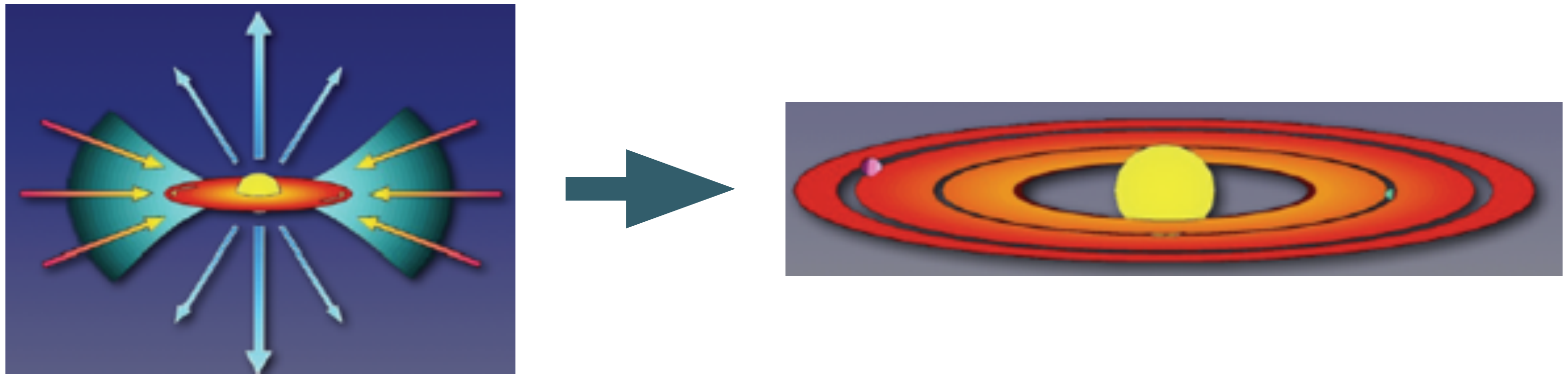
Section 6-7

Ábrahám Péter

Accretion processes, 2014. október 8.

Disk evolution

Understanding the physical processes that drive the evolution of primordial circumstellar disks from optically thick to optically thin is crucial for our understanding of planet formation.



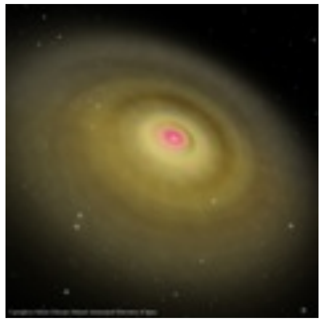
Main processes:

- viscous accretion
- dust settling and coagulation
- dynamical interaction with companions and planets
- photoevaporation by UV and X-ray radiation

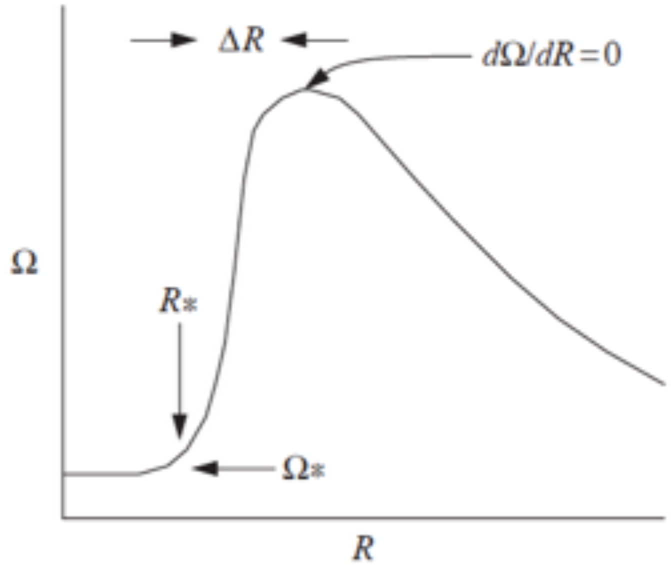
Viscous transport

- **The most important evolution process**
  - Accretion from the inner disk onto the star
  - Physical mechanisms that drive radial transport

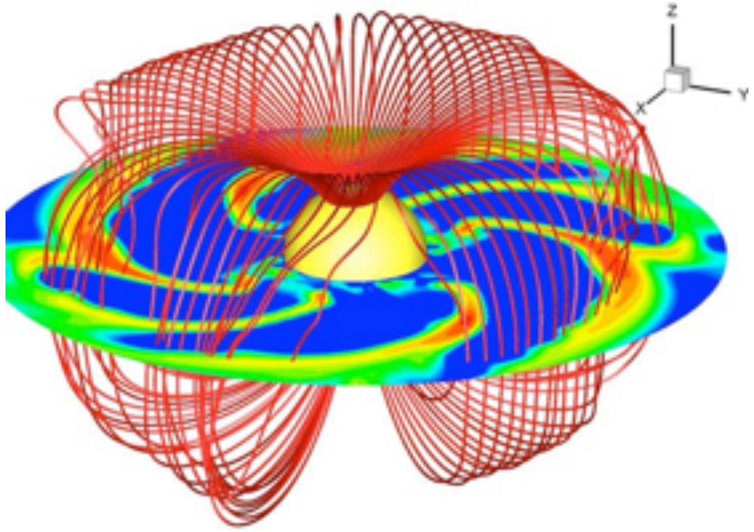
Magnetospheric accretion



Credit: Subaru Telescope



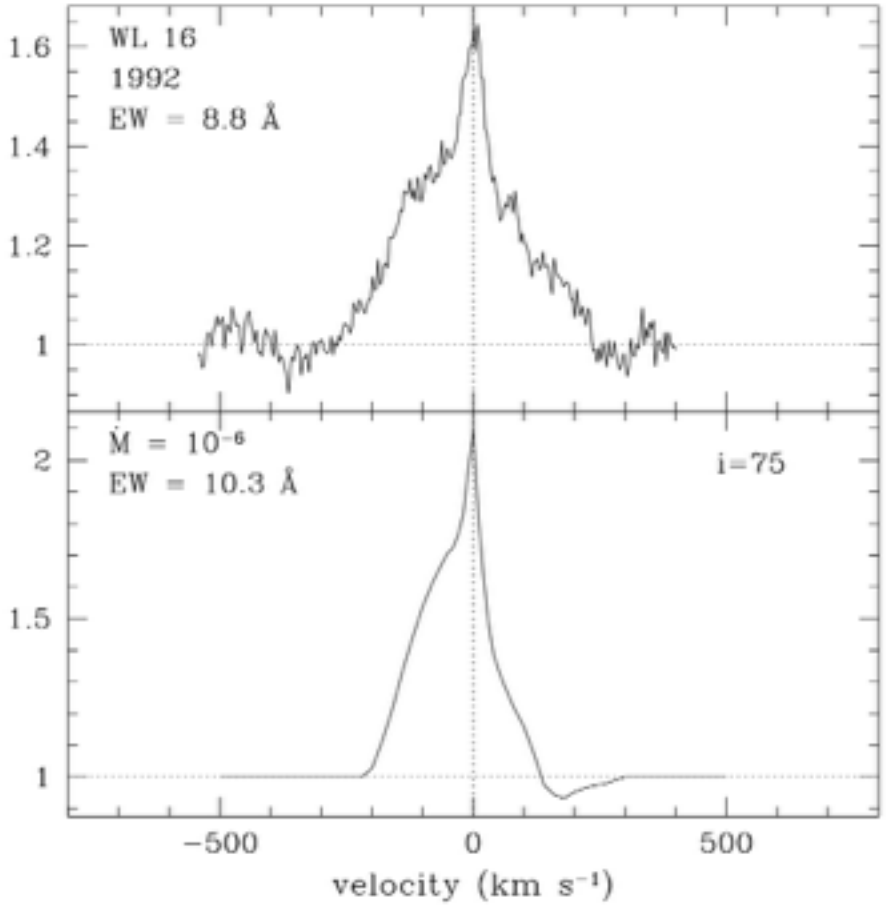
- Early models: boundary layer
  - → hot material, UV excess
- Magnetospheric accretion
- stellar magnetic field truncates the disk
- gas infall along magnetic lines @ free-fall
- high latitude accretion shocks
- X-ray/EUV radiation immediately absorbed, producing UV-optical excess, consistent with observations
- if accretion occurs in magnetic “columns”, or if the magnetic axis is misaligned with the rotation axis, photometric changes appear



Credit: M. Romanova

Magnetospheric accretion: line profiles

- Classical T Tauri stars exhibit strong emission lines with large line widths, and sometimes inverse P Cygni profiles
- H alpha, Br gamma, Ca II, …
- redshifted absorption component at several hundred km/s indicates infall (observed in many CTTSs)
- boundary layer cannot produce high enough accretion velocities



Br gamma in WL 16. Credit: Muzerolle et al. 1998.

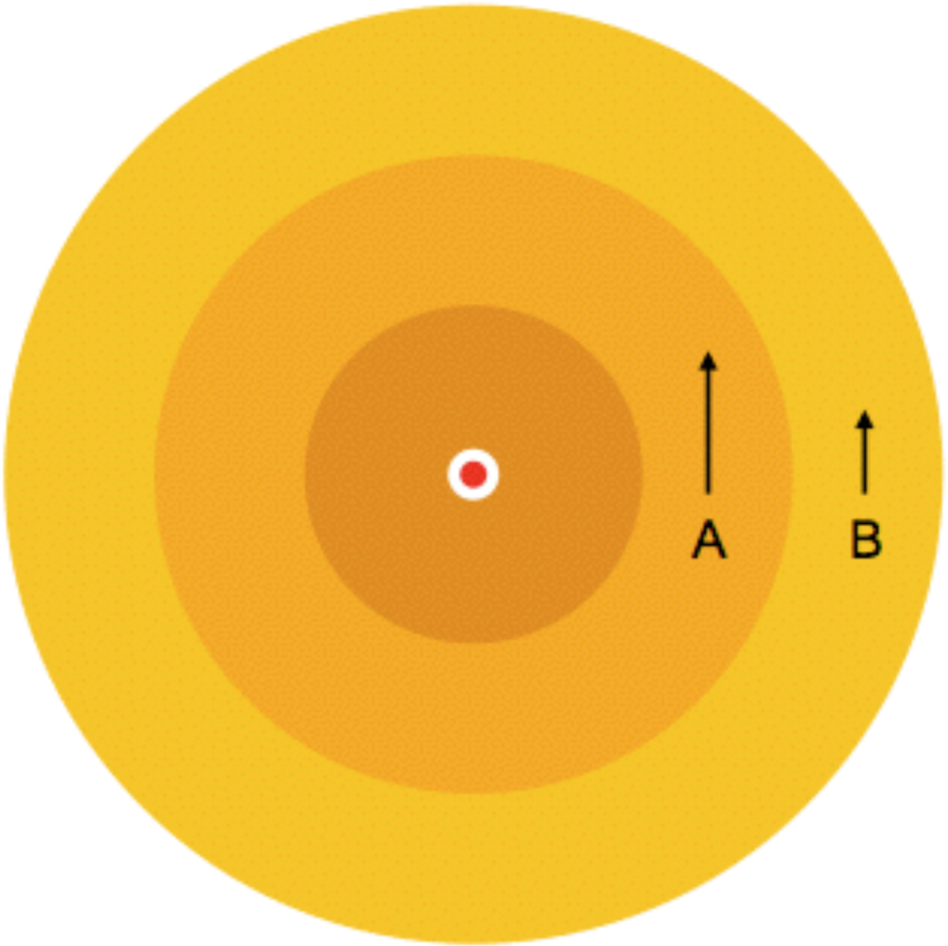
- infall along the magnetic lines will be on ballistic trajectories with free-fall velocity - consistent with observations
- line radiative transfer can reproduce line width and central peak
- redshifted absorption depends on geometry, and is not always seen

The angular momentum problem

- Angular momentum of 1 $M_\odot$ in 10 AU disk:
  3×10^{53} cm^2/s
- Angular momentum of 1 $M_\odot$ in 1 $R_\odot$ star:
  <<6×10^{51} cm^2/s (=breakup-rotation-speed)
- Original angular momentum of disk = 50x higher than maximum allowed for a star
- Angular momentum is strictly conserved!
- Two possible solutions:
  - Torque against external medium (via magnetic fields?)
  - Very outer disk absorbs all angular momentum by moving outward, while rest moves inward.
    Need *friction through viscosity!*

Outward angular momentum transport

Ring A moves faster than ring B. Friction between the two will try to slow down A and speed up B. This means: angular momentum is transferred from A to B.



Specific angular momentum for a Keplerian disk:

$$l = rv_\phi = r^2\Omega_K = \sqrt{GM_* r}$$

So if ring A looses angular momentum, but is forced to remain on a Kepler orbit, it must move inward! Ring B moves outward, unless it, too, has friction (with a ring C, which has friction with D, etc.).

Molecular viscosity? No!

Problem: molecular viscosity is virtually zero

Reynolds number

$$\mathrm{Re} = \frac{\langle u \rangle L}{\nu}$$

L = length scale
<u>= typical velocity
ν = viscosity

Molecular viscosity:

$$\nu = \langle u_T \rangle l_{\mathrm{free}}$$

l_{free} = m.f.p. of molecule
$\langle u_T \rangle$= velo of molecule

Typical disk (at 1 AU): N=1x10^{14} cm^{-3}, T=500 K, L=0.01AU

Assume (extremely simplified) $\sigma_{H_2} \approx \pi(1\mathrm{Ang})^2$.

$$\langle u_T \rangle = \sqrt{\frac{3kT}{\mu m_p}} = 2.3\,\mathrm{km/s} \qquad l_{\mathrm{free}} = \frac{1}{N\sigma} = 32\,\mathrm{cm}$$

$$\nu = 7.3 \times 10^6\ \mathrm{cm^2/s} \qquad \boxed{\mathrm{Re} = 4.7 \times 10^9}$$

Turbulent viscosity

Problem with turbulence as origin of viscosity in disks is: most stability analyses of disks show that the Keplerian rotation stabilizes the disk: *no turbulence!*

Debate has reopened recently:
- Non-linear instabilities
- Baroclynic instability? (Klahr et al.)

But most people believe that turbulence in disks can have only one origin: *Magneto-rotational instability (MRI)*

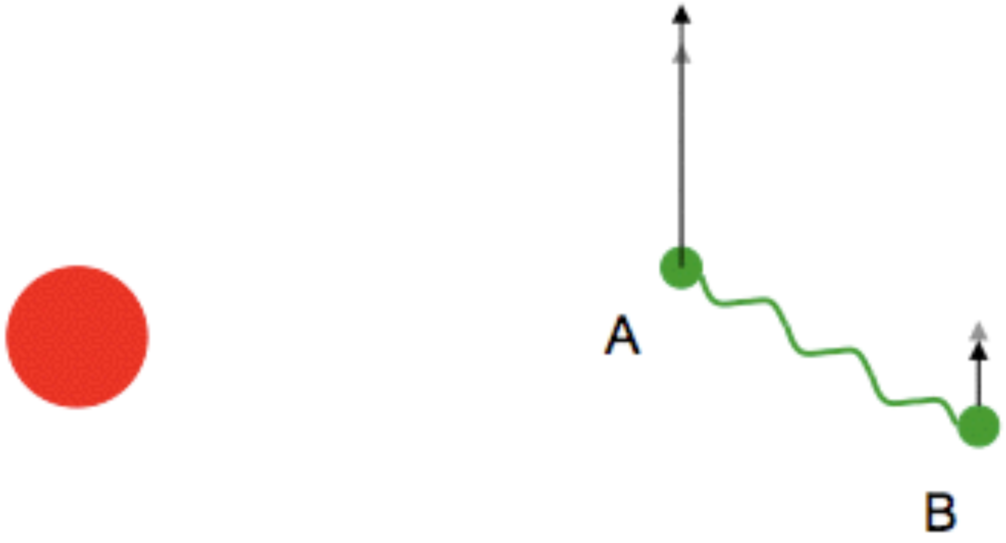
Magneto-rotational instability (MRI)

(Also often called Balbus-Hawley instability)

Highly simplified pictographic explanation:

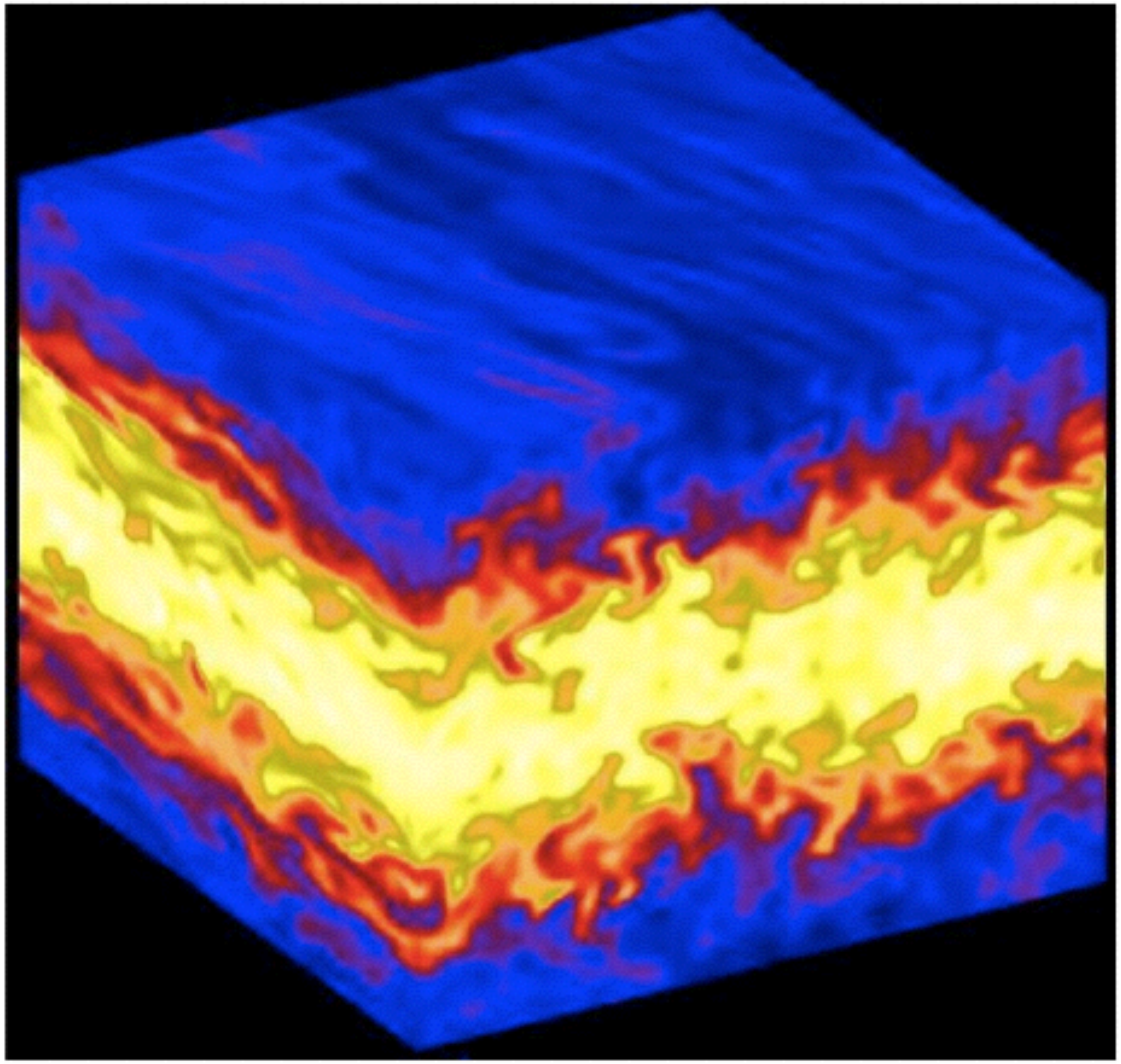
If a (weak) pull exists between two gas-parcels A and B on adjacent orbits, the effect is that A moves inward and B moves outward: a pull causes them to move apart!

The lower orbit of A causes an increase in its velocity, while B decelerates. This enhances their velocity difference! This is positive feedback: an instability.



Causes turbulence in the disk

Magneto-rotational instability



Johansen & Klahr (2005); Brandenburg et al.

Viscous transport

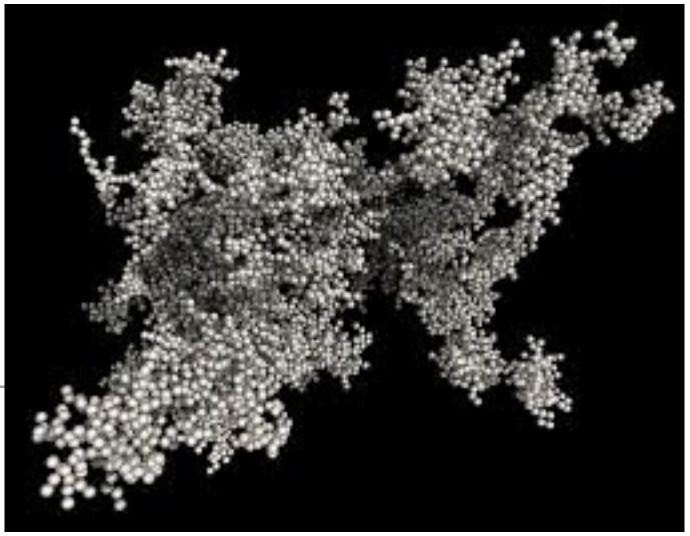
- **The most important evolution process**
  - Accretion from the inner disk onto the star
  - Physical mechanisms that drive radial transport
- Current models broadly consistent with observed disk mass, size, and decrease of accretion rate over time

BUT!

Secural disk evolution models run into the two-timescale problem, and fail to explain the variety of SEDs.

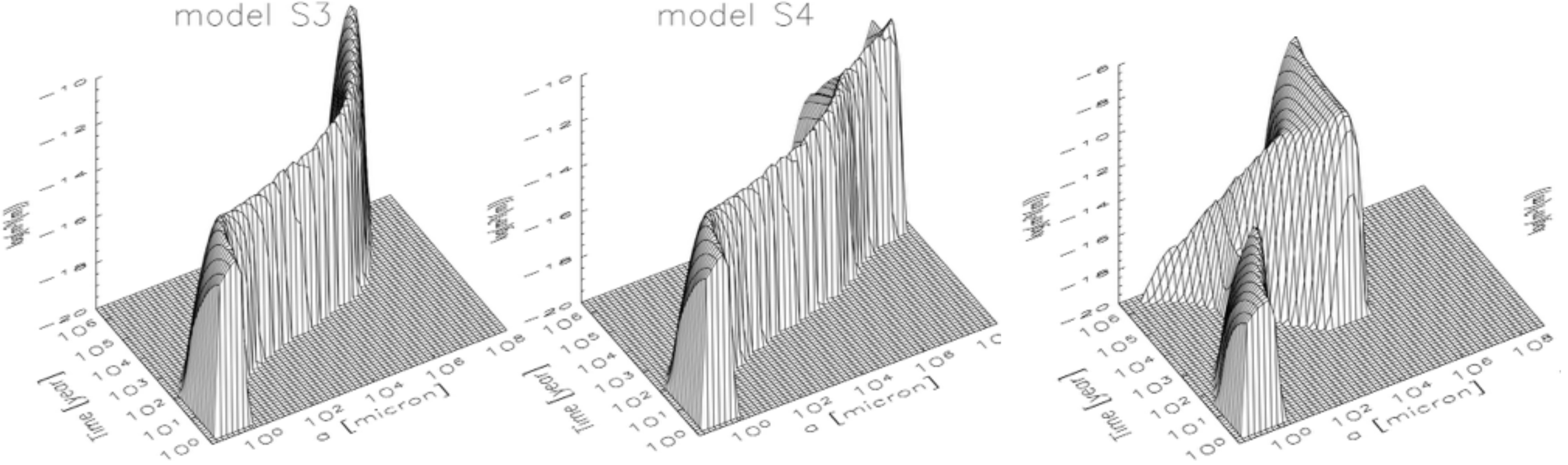
➡ other physical processes must also be in action!

Grain growth and dust settling

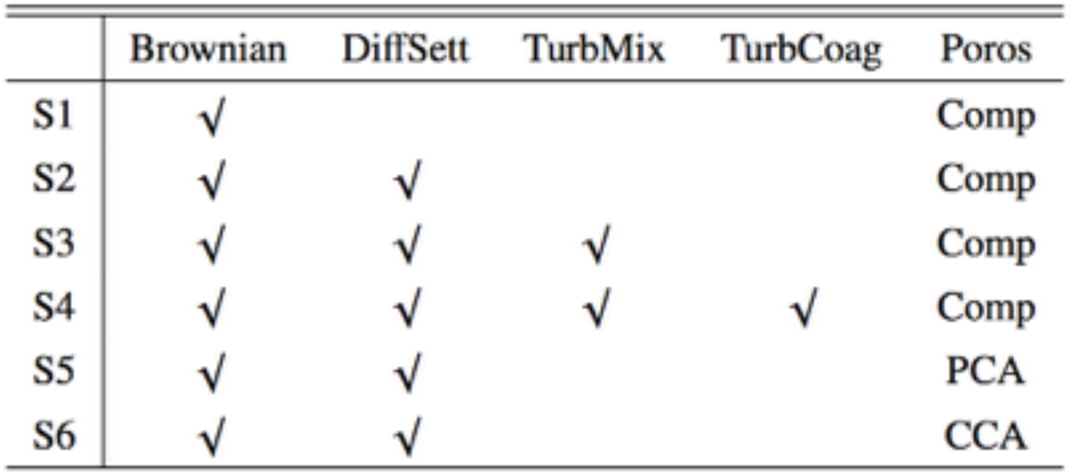


- small (0.1 micron) grains are swept with the gas
- later grains collide and stick together, and start feeling the headwind of the sub-Keplerian rotating gas disk
- slowed down, they settle towards the mid plane
- it would accelerate further grain growth, leading to a stratified disk
- because of turbulence, vertical stirring and mixing is expected
- ignoring fragmentation and radial drift, very efficient coagulation would occur (Dullemond & Dominik 2005)
- including Brownian motion, differential settling, and turbulence all small (<100 um) grains would be removed within 10^4 years!
- this is not the case, small grains must be replenished

Grain growth



Dullemond & Dominik 2009



	Brownian	DiffSett	TurbMix	TurbCoag	Poros
S1	√				Comp
S2	√	√			Comp
S3	√	√	√		Comp
S4	√	√	√	√	Comp
S5	√	√			PCA
S6	√	√			CCA

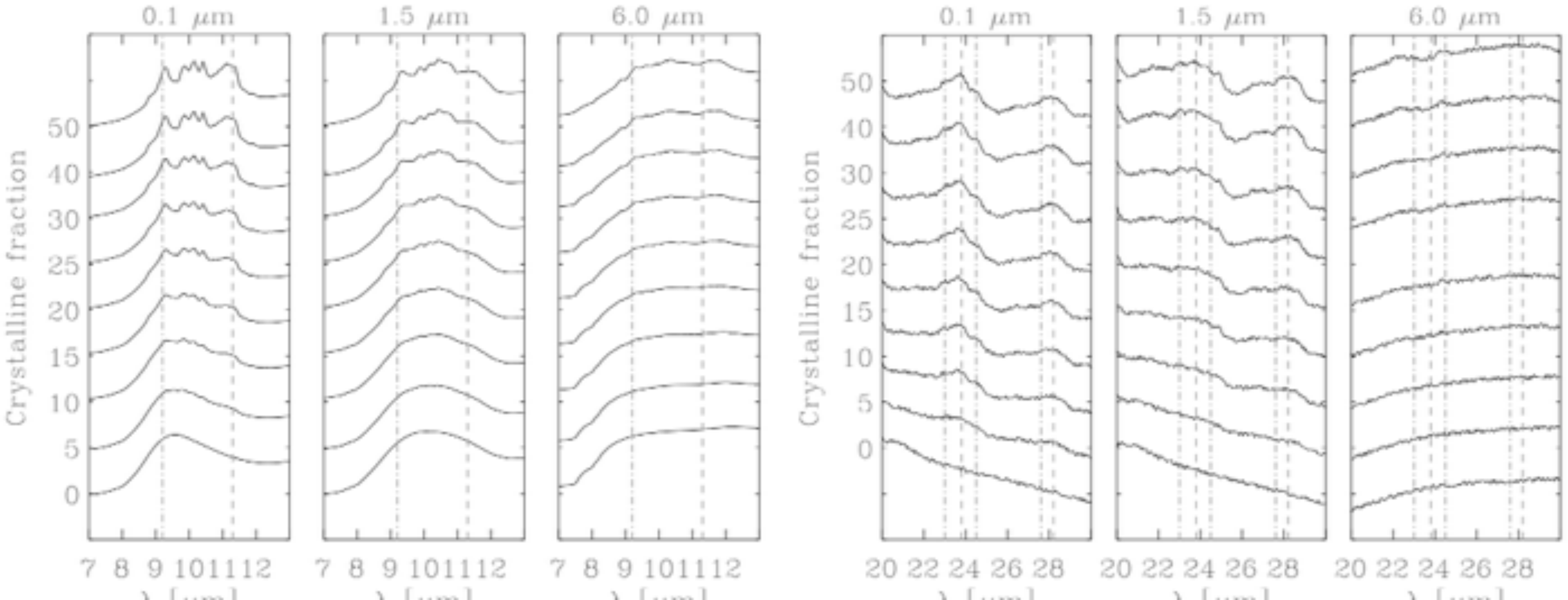
It is necessary to assume fragmentation and radial drift

meter-size barrier: destructive collisions and rapid inward migration

one of the largest challenges of planet formation history

Grain growth from submicron to micron

- the 9.7 and 18.5 um spectral features of silicates, related to Si-O stretching and O-Si-O bending modes, are sensitive for size
- smallest grains exhibit strong and narrow peak, larger one exhibit weaker and broader features
- Spitzer spectra of the upper layers of many disks: presence of micron-sized grains, absence of submicron sized grains
- either grain growth from submicron ISM particles is efficient, or sub micron grains are removed from disk upper layer by stellar wind and radiation pressure

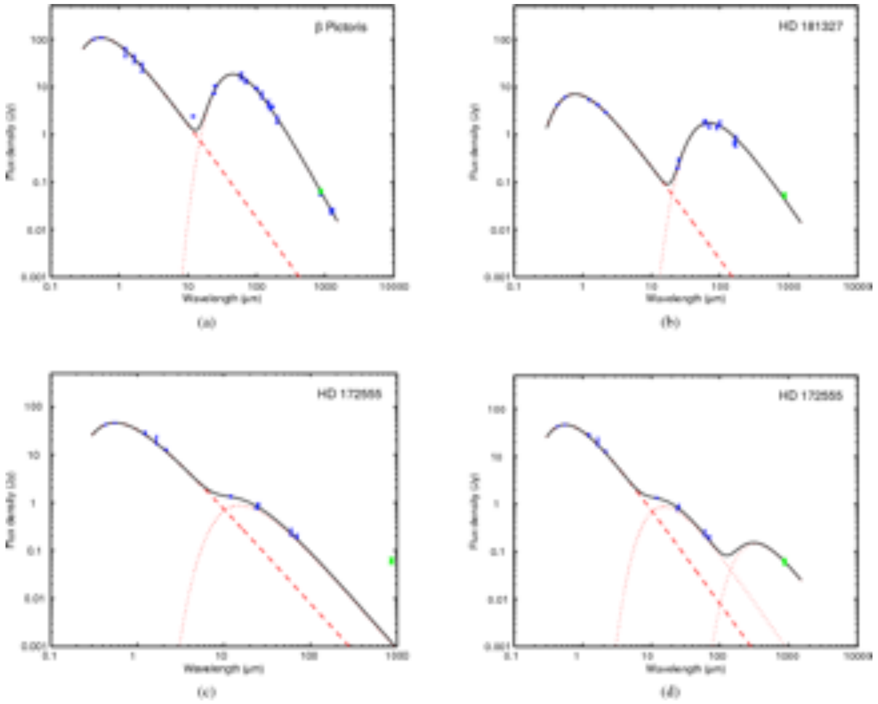


Grain growth from submicron to micron

- signatures of grain growth and crystallization are seen from very early stages
- But no correlation between disk age and dust properties!
- characteristics of dust grains depend on a balance between growth and fragmentation. Thus balance persists through the primordial phase
- similar balance between crystallization and amorphization?

Grain growth from micron to millimetre

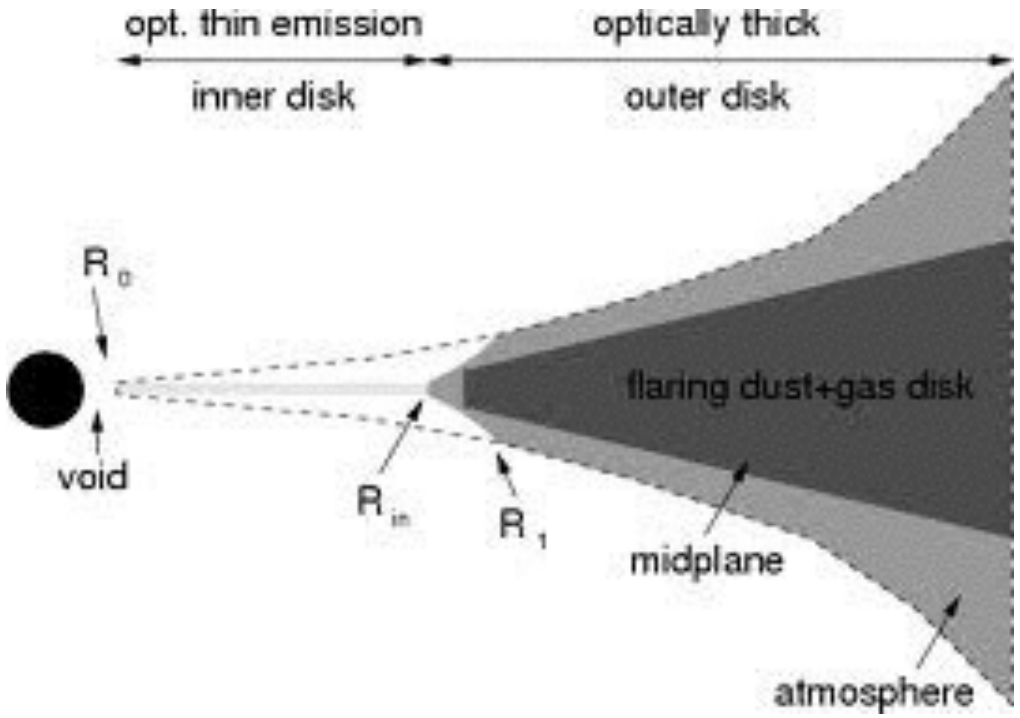
- a measure of grain growth is the slope of the SED at millimeter wavelengths
- diffuse ISM: alpha = 4; protoplanegtary disks: alpha = 2-3 (BB: 2)
- presence of substantially larger grains than in the ISM. Implication: grains growth by 3 orders of magnitude in size
- some growth occurs in dense molecular clouds
- 7 mm survey of Taurus (Rodmann et al. 2006) show shallow slopes
- even larger grains seen at centimeter wavelengths (TW Hya, WW Cha)



Nilsson et al. 2009

Dust settling

- protoplanetary disks are flared, but many TTau stars exhibit less mid-IR radiation than expected for a disk in hydrodynamic equilibrium: reduced scale height and flaring angle
- mid-infrared slopes are indicators of dust settling
- survey of ~80 Taurus T Tau stars (Furlan et al. 2006): most cases dust depletion factors of 100-1000 in the surface layers
- McClure et al. (2010): in Ophiuchus dust settling at already 0.3 Myr!



Ratzka et al. 2007

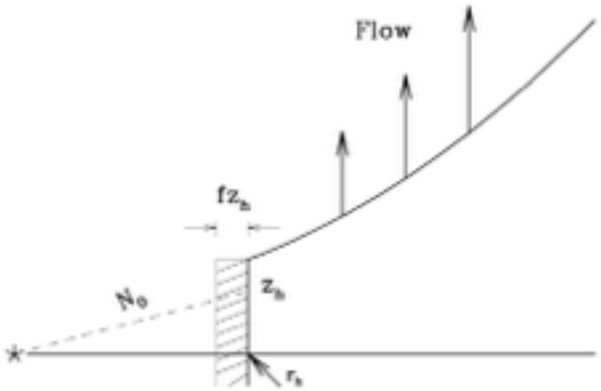
Photoevaporation by the central star

- Driven by **far-UV** (FUV: 6 eV < *hv* < 13.6 eV); **extreme-UV** (EUV: 13.6 eV < *hv* < 0.1 keV), and **X-ray** (*hv* > 0.1 keV) photons
- they affect the disk in different ways, and their relative contribution is not known
- **UV-switch models** (e.g. Clarke, Gendrin & Sotomayor 2001) combine viscous evolution with EUV photoevaporation
- EUV can ionise the surface disk layer: “Strömgren zone” with T~10^4 K. In CTTSs, thermal velocity of ionized hydrogen exceeds escape velocity at R > 10 AU
- at early evolutionary phases in falling hydrogen blocks EUV
- later, as accretion drops with time, (1) EUV can penetrate the inner region and illuminates the outer disk; (2) photo evaporation rate exceeds disk accretion (10^-9 - 10^-10 Msun/yr)

Photoevaporation by the central star

- the inner disk drains on a viscous timescale (<10^5 yr), and an inner hole of a few AU radius is formed
- the inner edge of the disk is directly exposed to EUV radiation, and the disk is rapidly evaporated from inside out
- modern models include also X-ray and

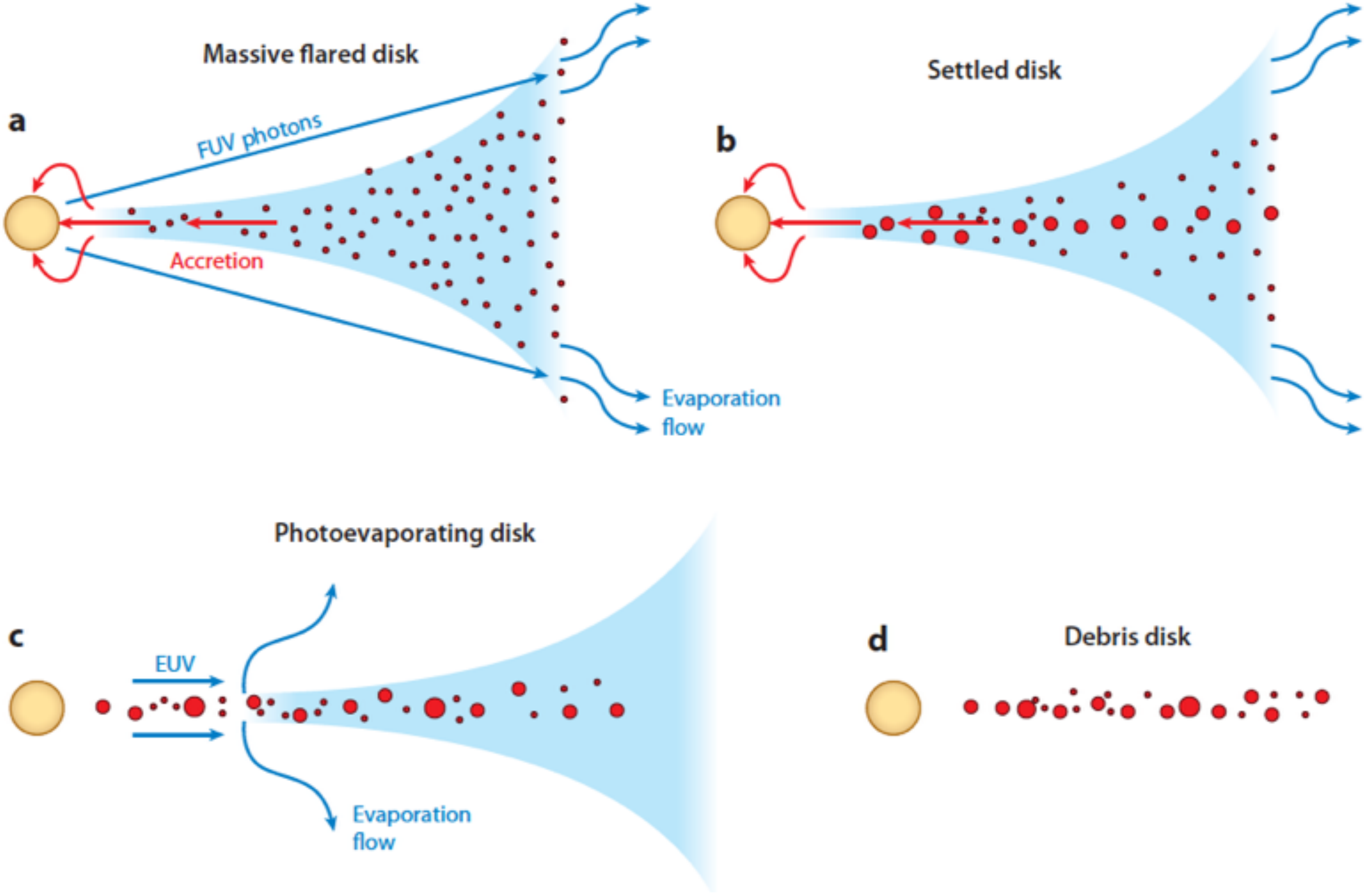
  FUV (e.g. Gorti & Hollenbach 2009)
- they penetrate deeper and further (tens of AU)



- predict photoevaporation rates of 10^-8 Msun/yr, tis the inner hole forms early in the disk’s accretion history
- prediction: relatively massive disks with large inner holes, with no or little accretion
- BUT disks around WTTSs tend to be smaller →in reality photoevaporation rate must be lower.

Evolutionary paths

- while not all disks follow the evolutionary path, many of them follow a common sequence of events

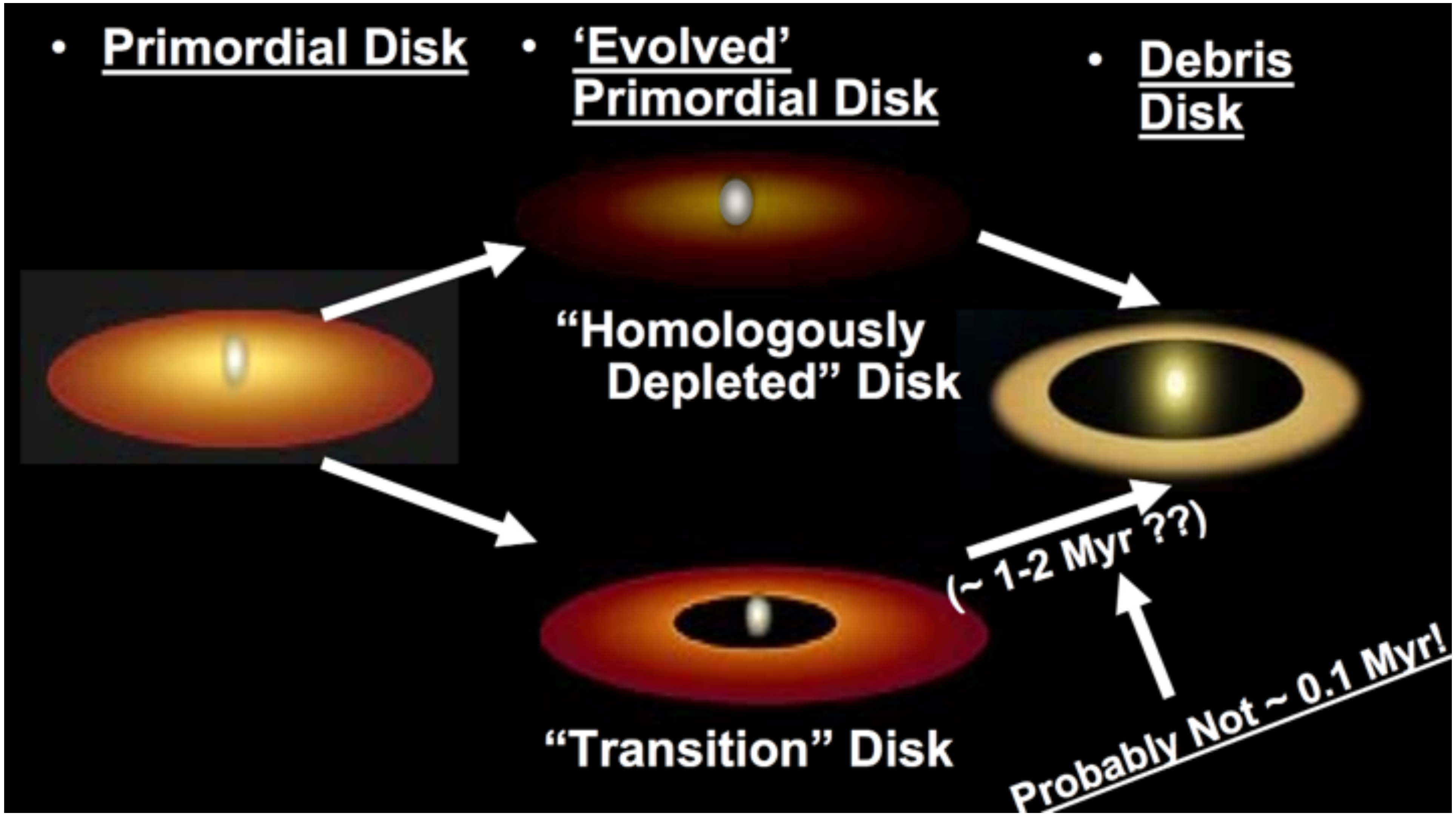


The age factor

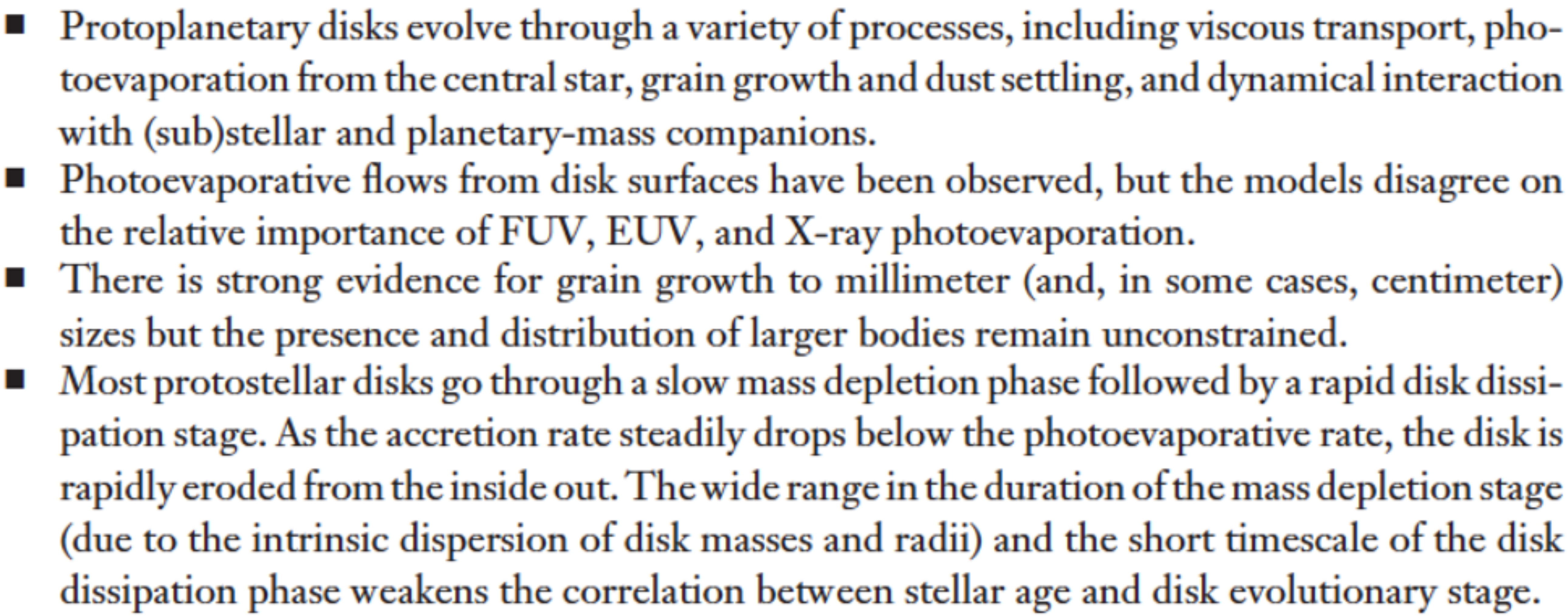
- the correlation between the ages of pre-main sequence stars and the evolutionary status of their disks is surprisingly weak
- in a given cluster of any age between 1 and 10 Myr, almost all stages can be found
- Extremes: disk-less WTTS in the core of rho Ophiuchus, and the gas-rich TW Hya disk
- Possible explanation: large diversity in the duration of the mass depletion phase, and short timescale of the disk dissipation phase
- e.g. circumprimary disks in medium-separation binaries possess truncated disks with small radii, which evolve very fast
- initially massive, isolated disks can keep gas up to 10 Myr

Alternative evolutionary paths

- there are some disks which do not follow the typical sequence
- e.g. accreting objects with cleared out inner disk but massive outer disk (DM Tau, GM Aur,…) - the hole is too big for current theory
- dynamical clearing by a companion?



Summary on disk evolution



- Protoplanetary disks evolve through a variety of processes, including viscous transport, photoevaporation from the central star, grain growth and dust settling, and dynamical interaction with (sub)stellar and planetary-mass companions.
- Photoevaporative flows from disk surfaces have been observed, but the models disagree on the relative importance of FUV, EUV, and X-ray photoevaporation.
- There is strong evidence for grain growth to millimeter (and, in some cases, centimeter) sizes but the presence and distribution of larger bodies remain unconstrained.
- Most protostellar disks go through a slow mass depletion phase followed by a rapid disk dissipation stage. As the accretion rate steadily drops below the photoevaporative rate, the disk is rapidly eroded from the inside out. The wide range in the duration of the mass depletion stage (due to the intrinsic dispersion of disk masses and radii) and the short timescale of the disk dissipation phase weakens the correlation between stellar age and disk evolutionary stage.

Transition disks

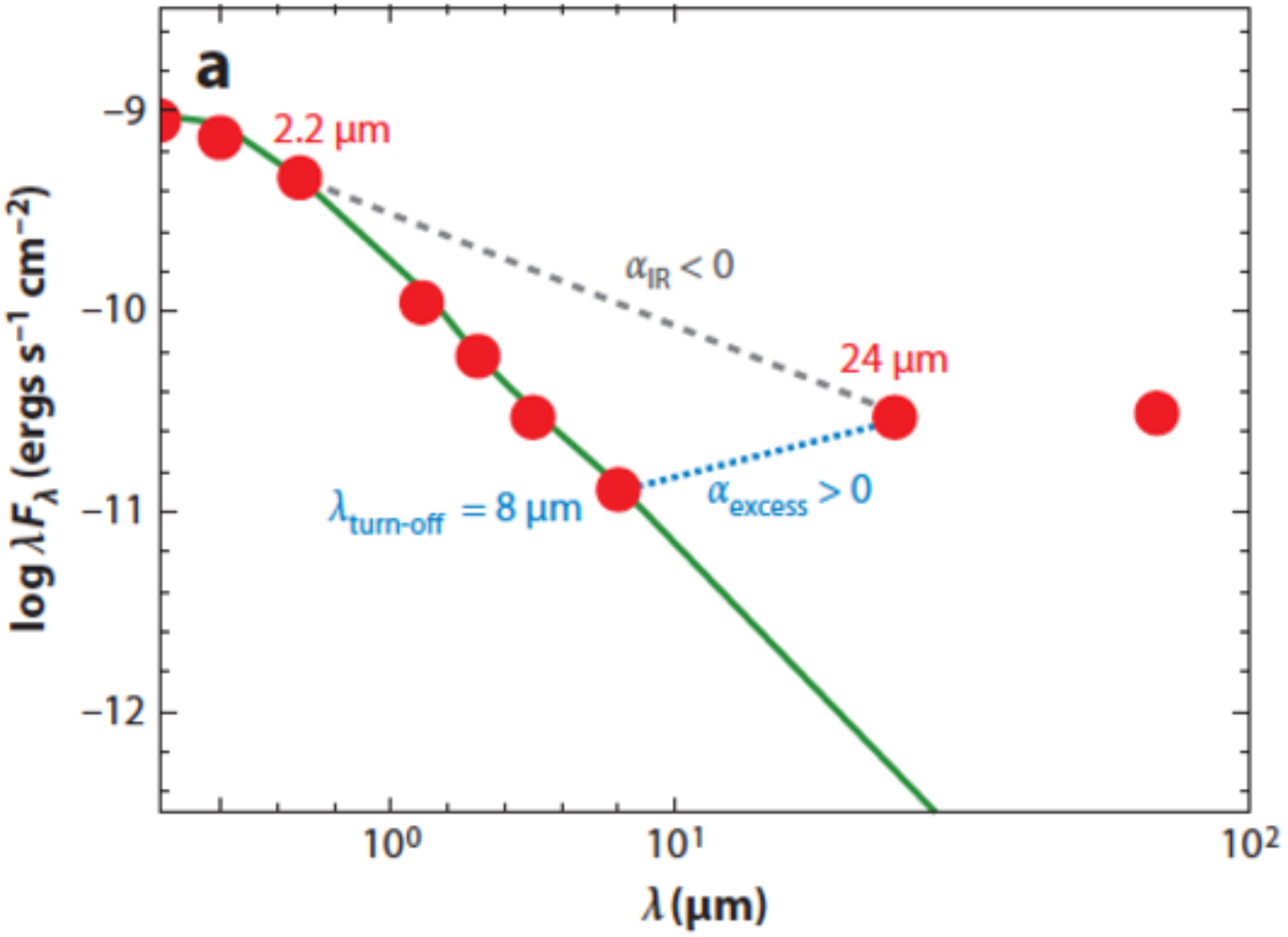
Objects with little or no excess at <10um, but significant excess at >10um (Strom et al. 1989)

Lack of NIR emission: inner hole? Early phase of planet formation?

Special attention in disk studies

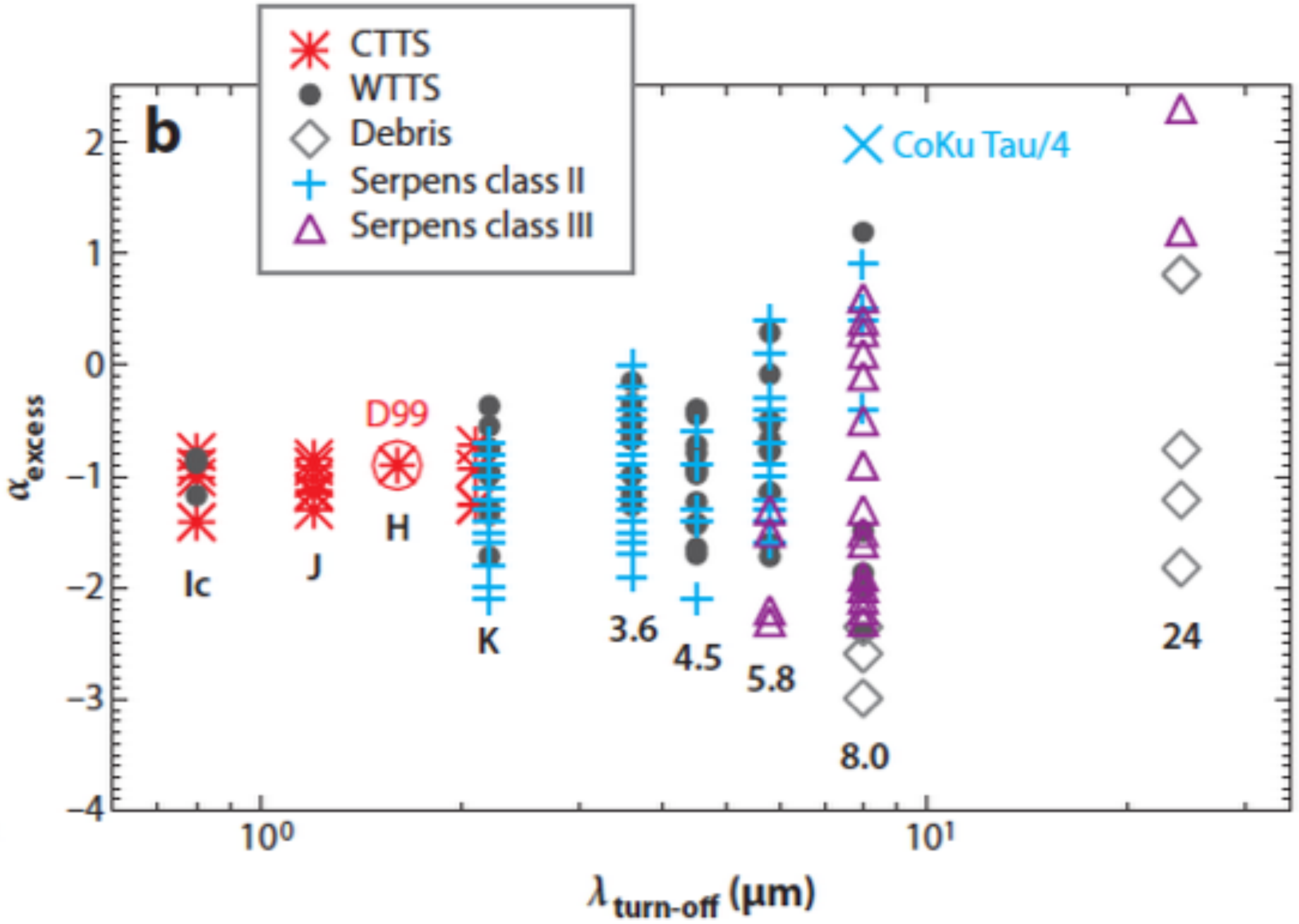
The diversity of the SEDs

- large variety of SED morphologies which do nto follow Class I-III
- two-parameter scheme (Cieza et al. 2007):
  - most restrictive definition: no NIR excess, steep MIR slope, strong FIR excess
  - more relaxed: some weak NIR excess may be present
  - most general: significant decrement at any wavelength wrt. the median SED

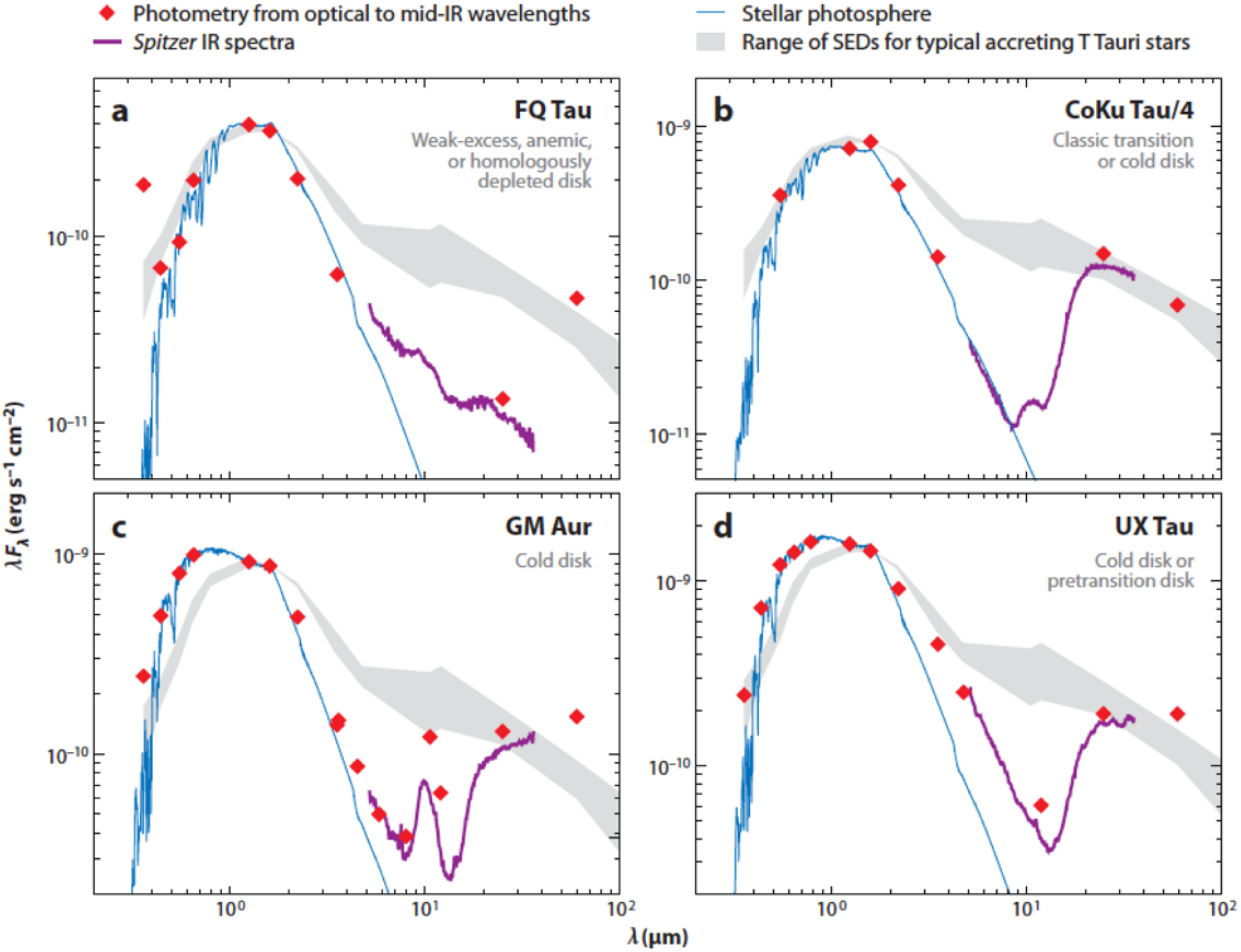


Subclasses of transition disks

- classical, cold, anemic, pre transitional



- disks with no inner hole are rather similar to each other
- disks with inner hole are more diverse

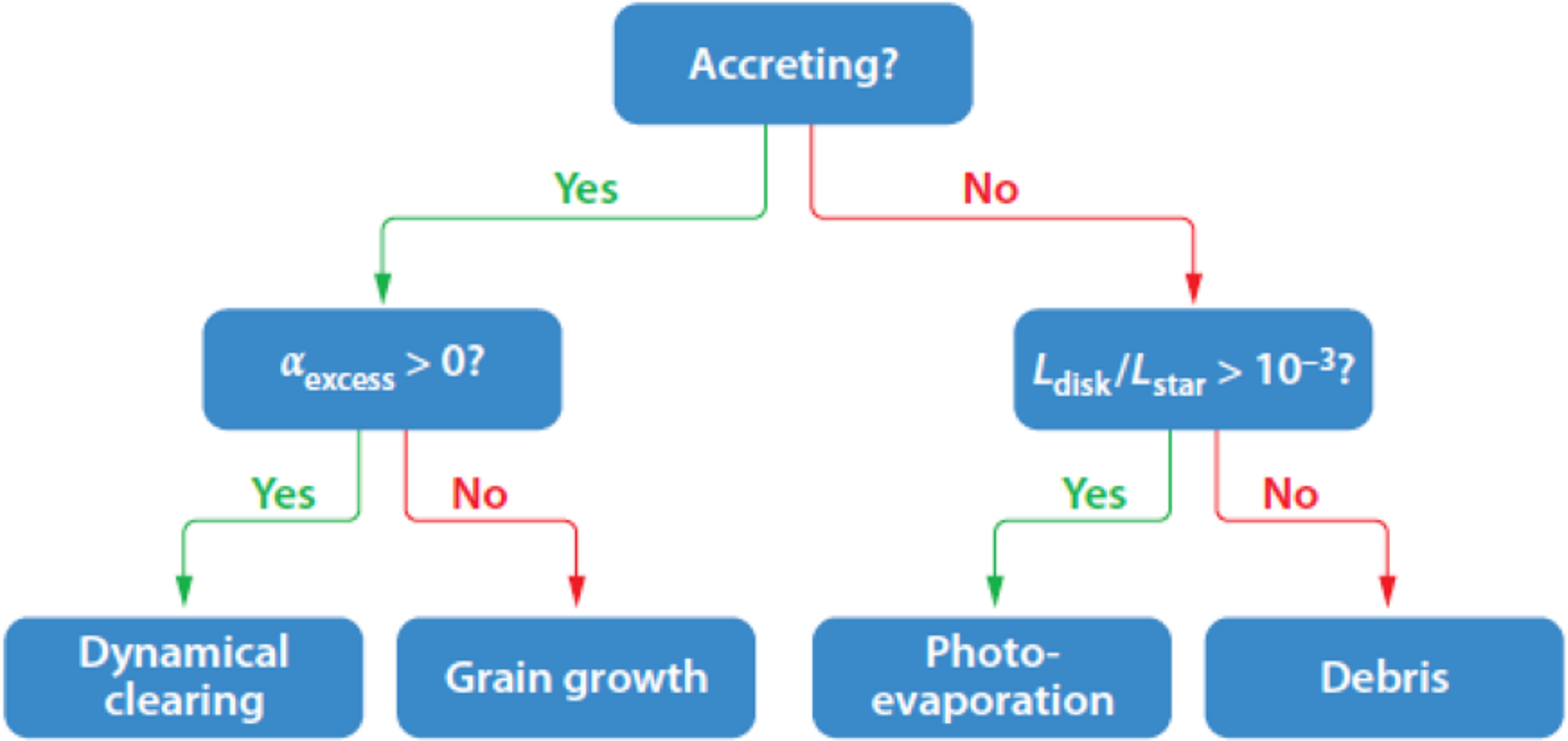

Photometry from optical to mid-IR wavelengths
Spitzer IR spectra
Stellar photosphere
Range of SEDs for typical accreting T Tauri stars
a
FQ Tau
Weak-excess, anemic, or homologously depleted disk
b
CoKu Tau/4
Classic transition or cold disk
c
GM Aur
Cold disk
d
UX Tau
Cold disk or pretransition disk
λF_λ (erg s^{-1} cm^{-2})
10^{-9}
10^{-10}
10^{-11}
λ (μm)
10^0
10^1
10^2

Incidence

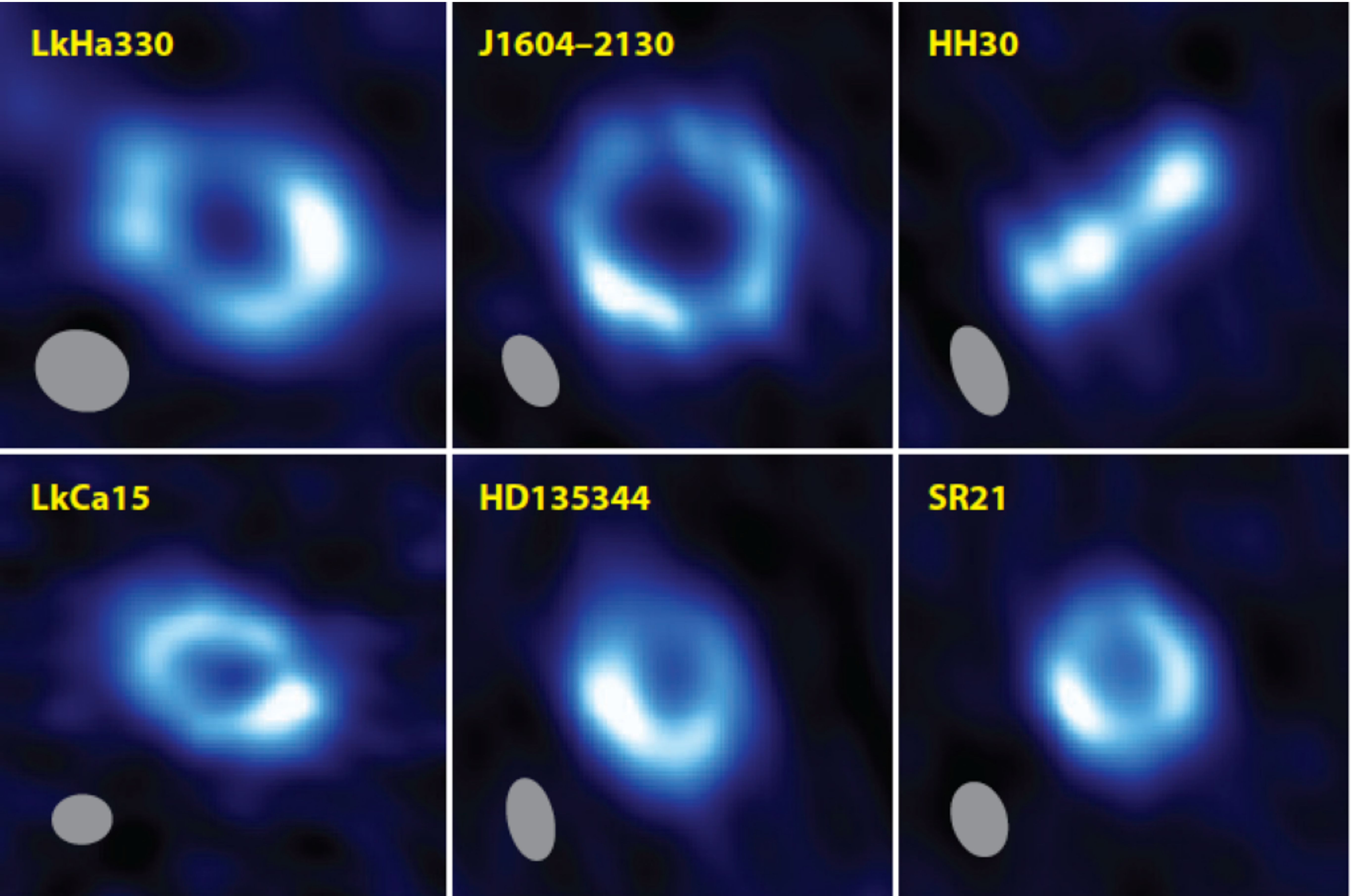
- not straighforward (different definitions, incomplete samples, AGB and Be stars, edge-on protoplanetary disks)
- nearby star-forming regions: fraction is >10-20%
- anemic disks outnumber shat-edge disks by 2-3
- cold disks: 5-10%
- anemic disks are more frequent in old clusters (understandable, as disks loose matter during evolution)
- the evolutionary path through the transition phase is either uncommon or rapid
- very likely they represent the evolutionary phase of disk dissipation

Physical processes

- which are the dominant processes in creating a transition disk?



Resolved images



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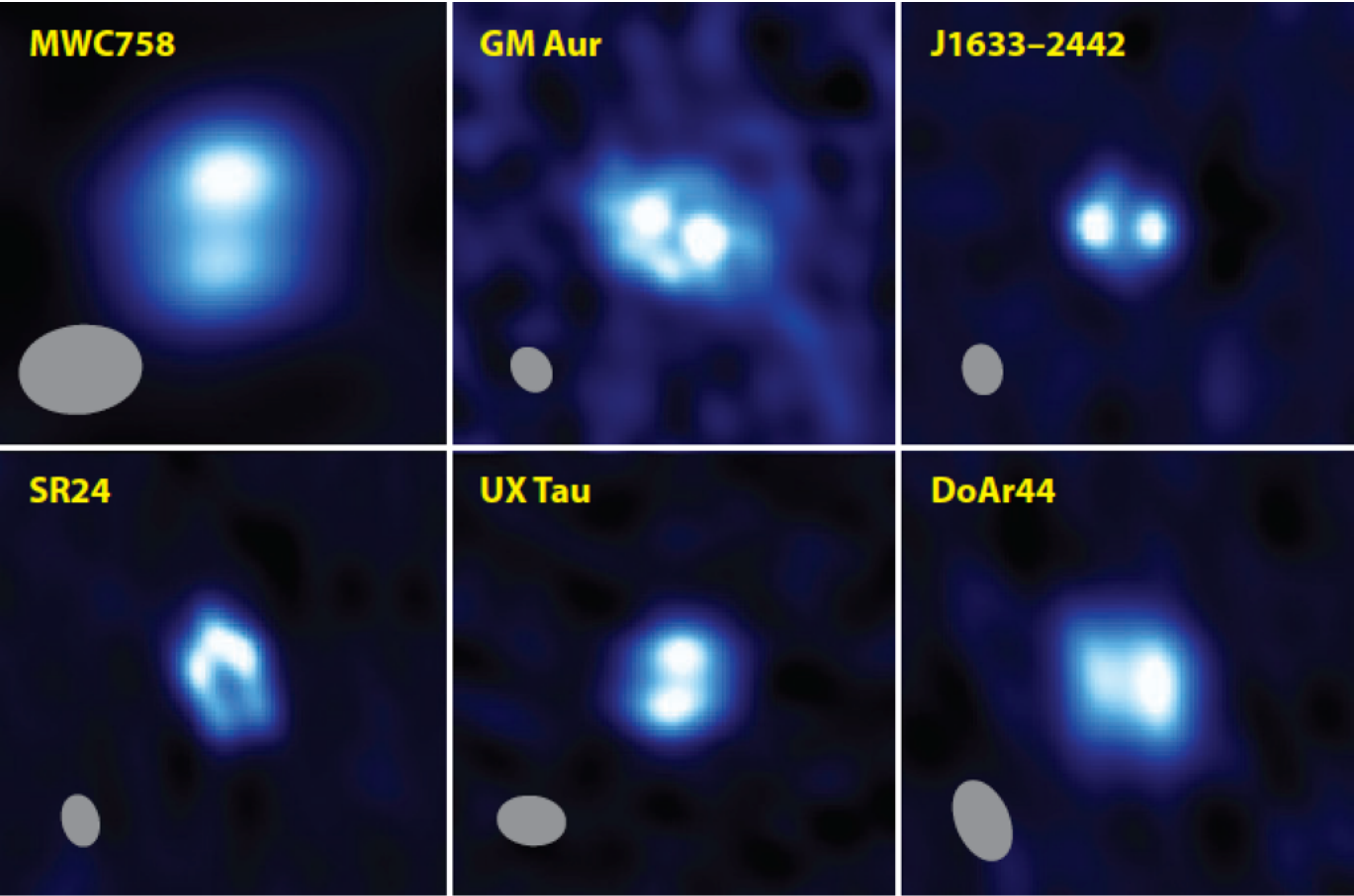

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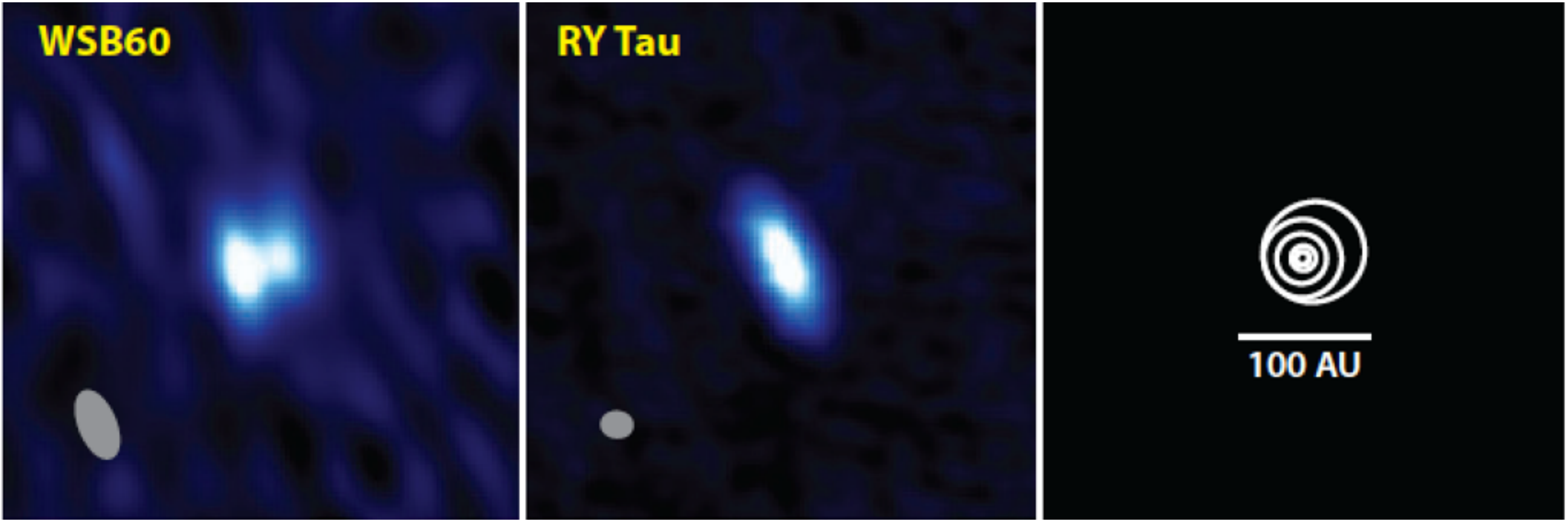
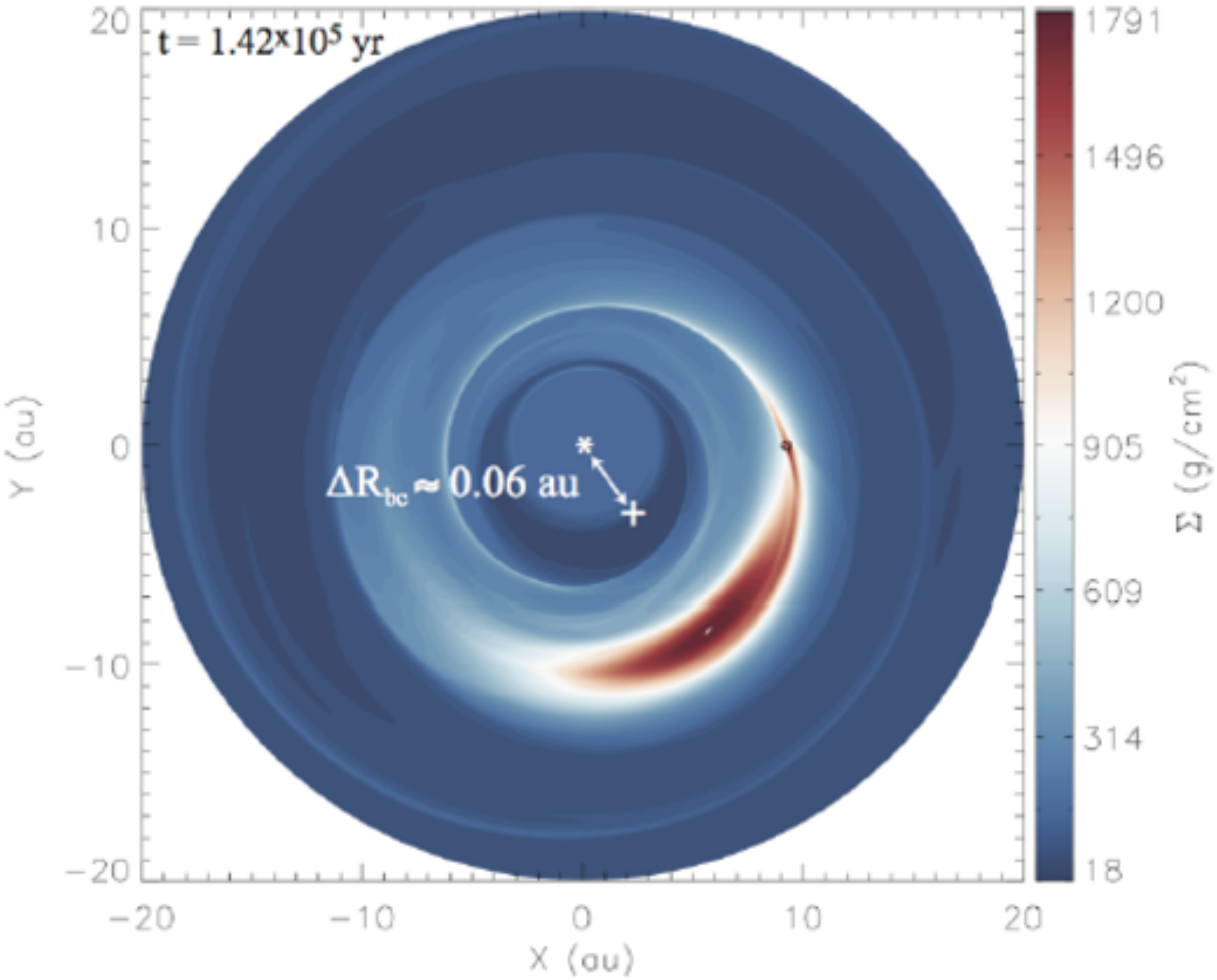


Gas in transitional disks

- millimeter interferometry can locate both the dust and gas (CO) component
- ALMA brings new results
- In some cases the dust central cavity is also gas-free (e.g. GM Aur, Dutrey et al. 2008)
- However, warm CO gas (mid-IR fundamental band) can be observed in the central hole (SR 21, HD 135344, TW Hya; Pontoppidan et al. 2008)

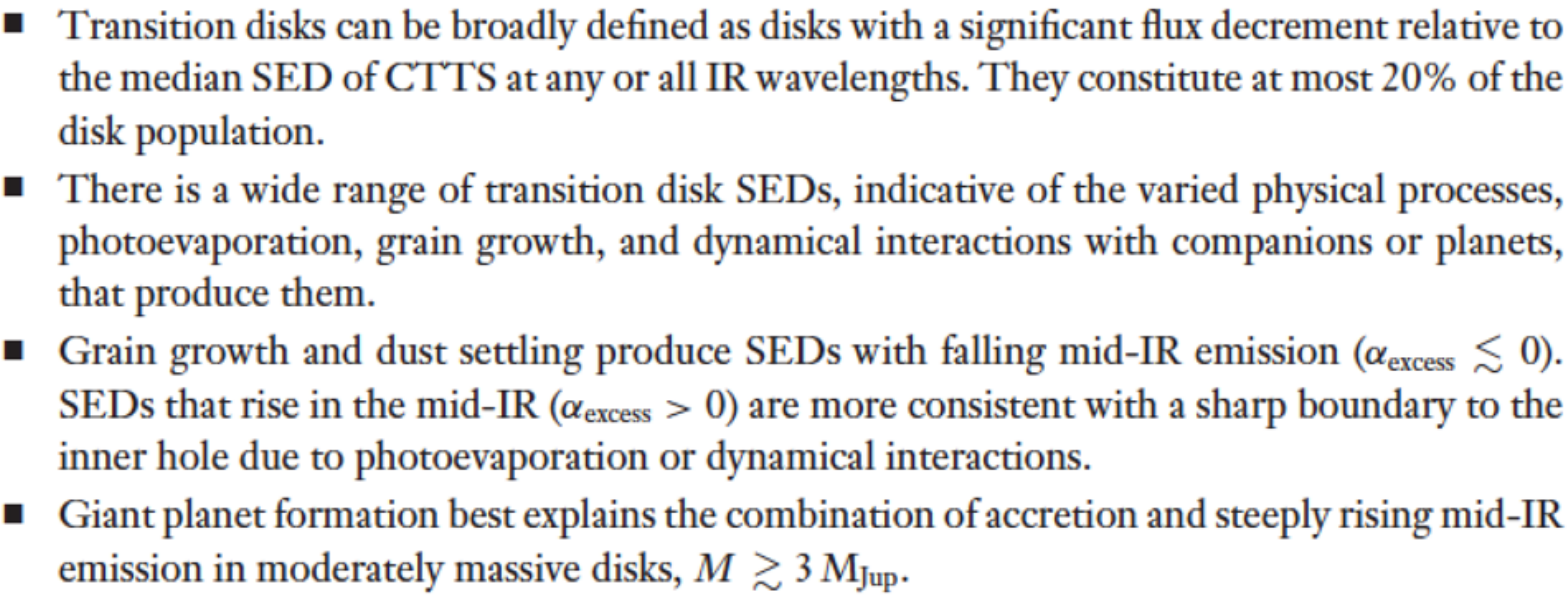
Hints for giant planets

- azimuthal asymmetries in the images may suggest the presence of giant planets
- radial gaps, density waves, spiral arms, warps



Regály et al. 2013

Summary on transitional disks



- Transition disks can be broadly defined as disks with a significant flux decrement relative to the median SED of CTTS at any or all IR wavelengths. They constitute at most 20% of the disk population.
- There is a wide range of transition disk SEDs, indicative of the varied physical processes, photoevaporation, grain growth, and dynamical interactions with companions or planets, that produce them.
- Grain growth and dust settling produce SEDs with falling mid-IR emission ($\alpha_{\mathrm{excess}} \lesssim 0$). SEDs that rise in the mid-IR ($\alpha_{\mathrm{excess}} > 0$) are more consistent with a sharp boundary to the inner hole due to photoevaporation or dynamical interactions.
- Giant planet formation best explains the combination of accretion and steeply rising mid-IR emission in moderately massive disks, $M \gtrsim 3\ \mathrm{M_{Jup}}$.

Summary

- Observations of protoplanetary disks is challenging: small size, low mass, cold temperature
- Mid-IR optically thick emission: census, occurrence, lifetime
- Millimeter-wave optically thin emission: disk mass, disk structure
- Many competing physical processes, a variety of evolutionary pathways