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Protoplanetary Disks: An Overview

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General resources:

Astrophysics of Planet Formation, Armitage, P. J., 2010, Cambridge Univ. Press. (Pedagogical introduction to the theory of planet formation)

Protostar and Planets VI website (most updated in all fields of planetary studies): http://www.mpia-hd.mpg.de/homes/ppvi/

Main references:

Armitage's book: Chapters 2-5

Further reading:

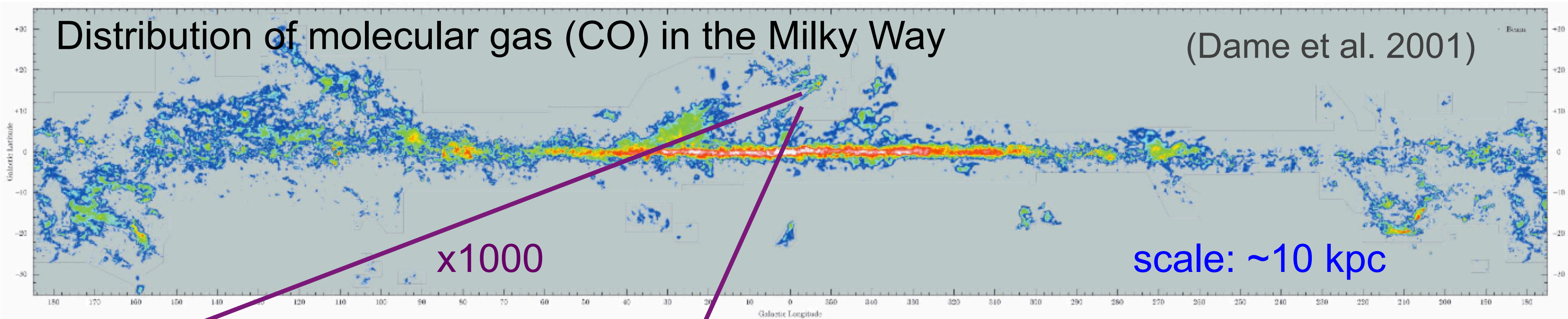
Williams, J. P. & Cieza, L. A., 2011, ARA&A, 49, 67

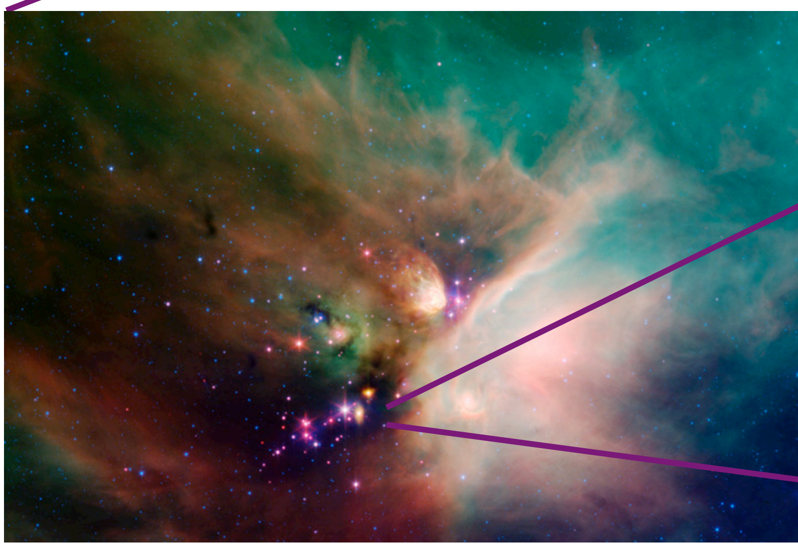
Turner, N. J. et al. review chapter in PPVI, arXiv:1401.7306

Chiang, E. & Youdin, A., 2010, AREPS, 38, 493

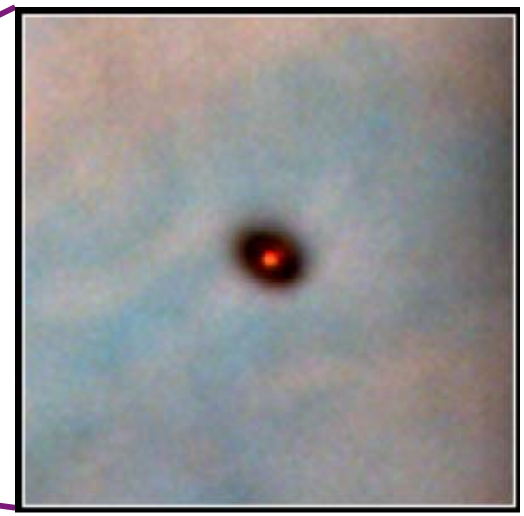
Goldreich, P., Lithwick, Y. & Sari, R., 2004, ARA&A, 42, 549

Protoplanetary disks in the context





x1000



Star forming region (ρ ophiuchus)

Credit: Spitzer space telescope

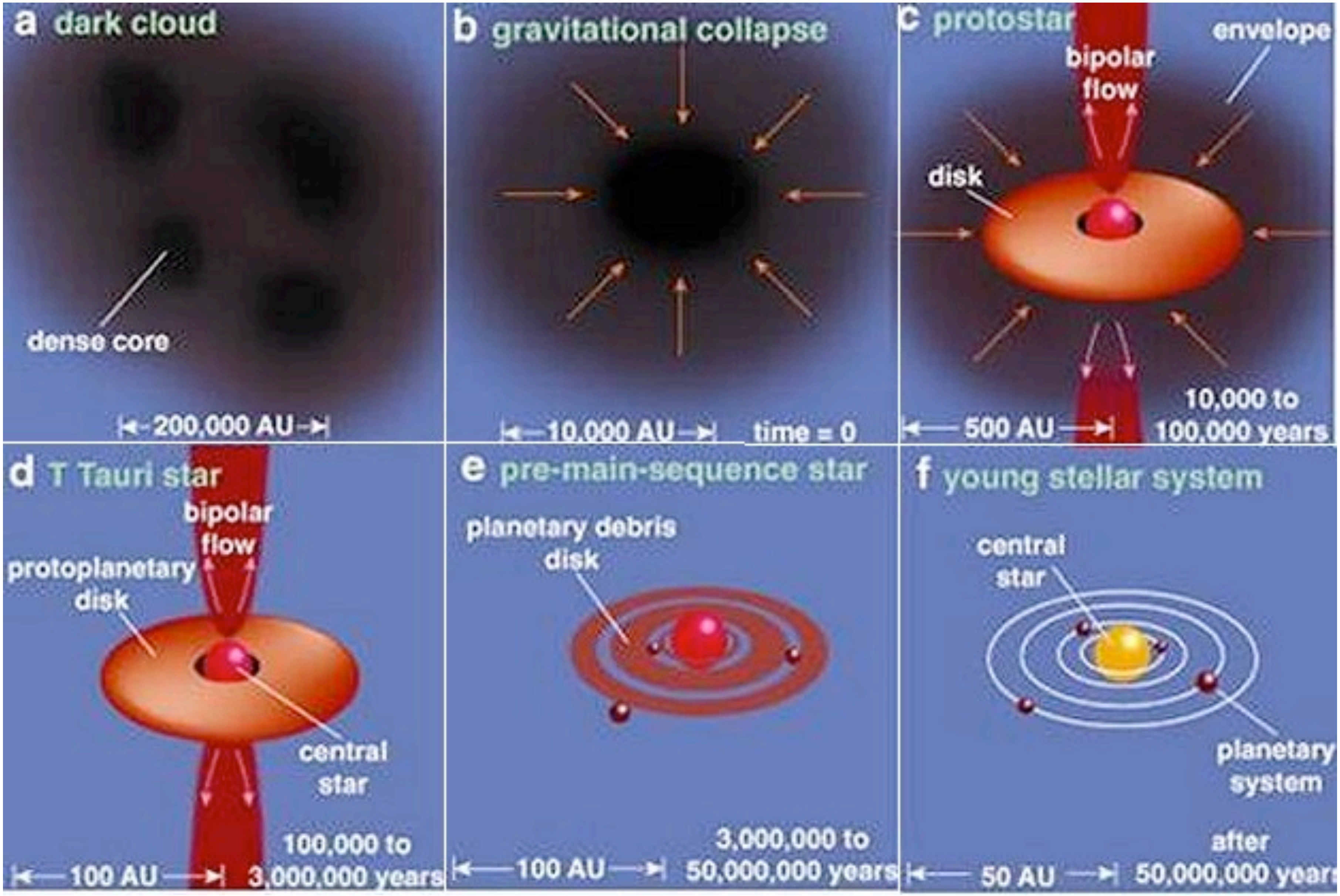
~a few x10 pc

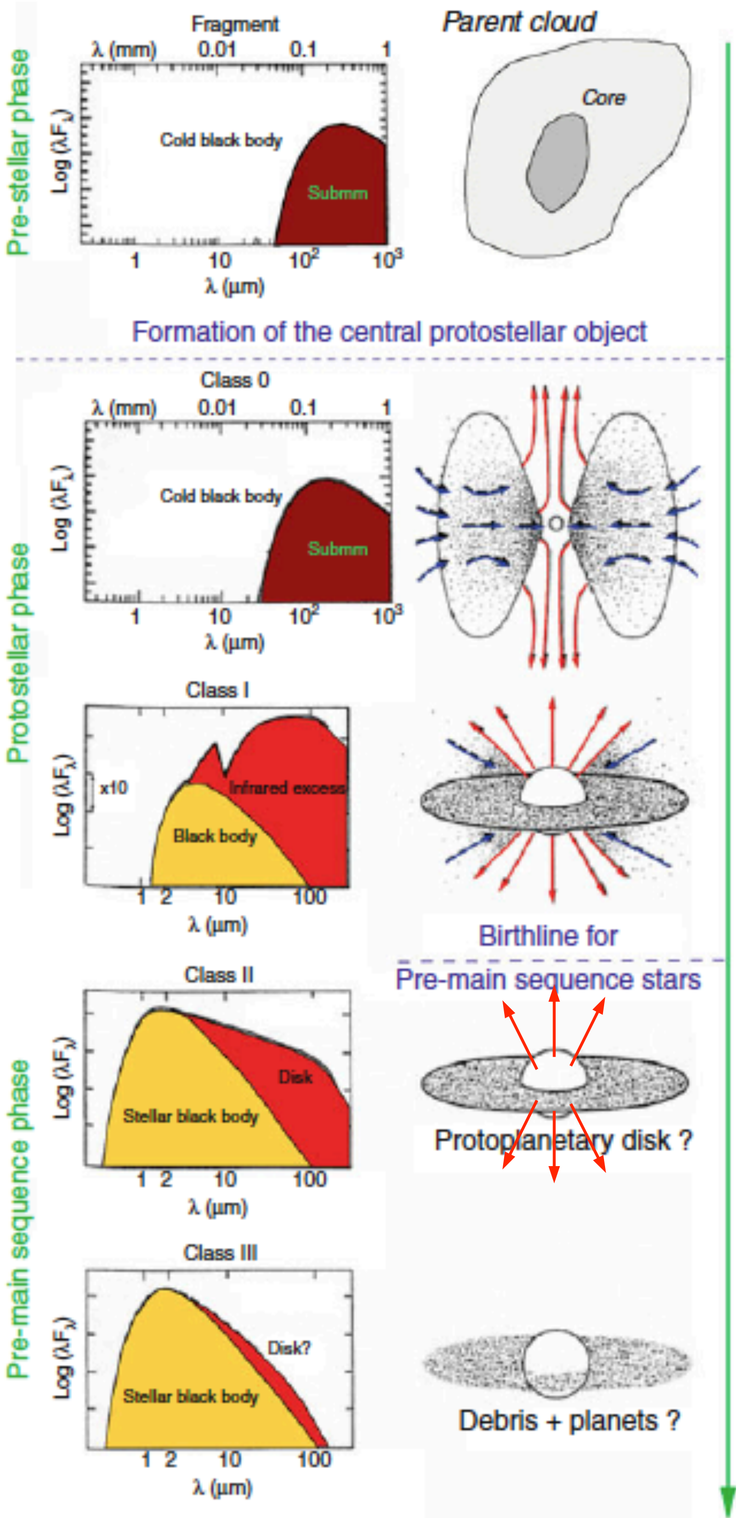
proto-star and its disk

~a few x1000 AU

(1 pc =3.26 light years ~ 2x10^5 AU)

(low-mass) Star and planet formation





Pre-stellar core

$M_{star} = 0$

$\sim 10^6$ yr?

t~ 0 yr

Accreting protostar

$M_{star} << M_{env}$

$<3\times10^4$ yr

Accreting protostar

$M_{star} > M_{env}$

$\sim 2\times10^5$ yr

Classical T Tauri Star

Disk mass $\sim 10^{-3}$-$10^{-1} M_\odot$

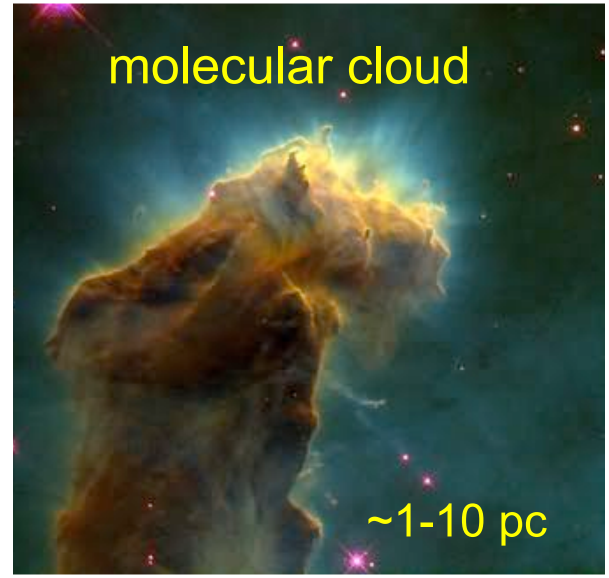
$\sim 3\times10^6$ yr

Weak-line T Tauri Star

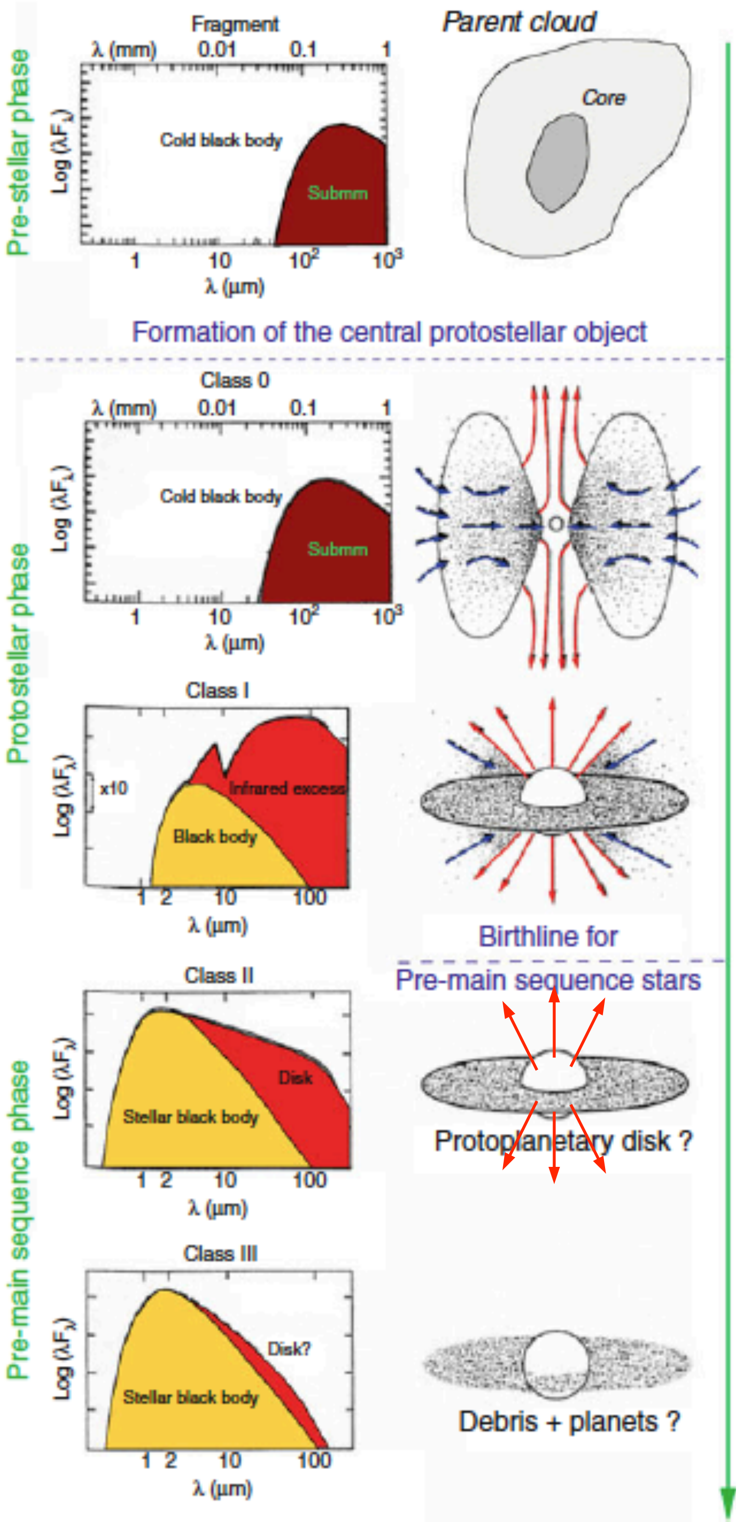
Disk mostly dissipated

$\sim 10^7$ yr?

time



$>10^3\ M_\odot$



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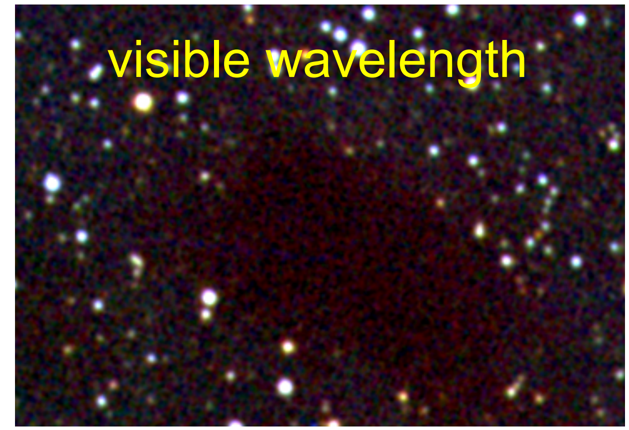
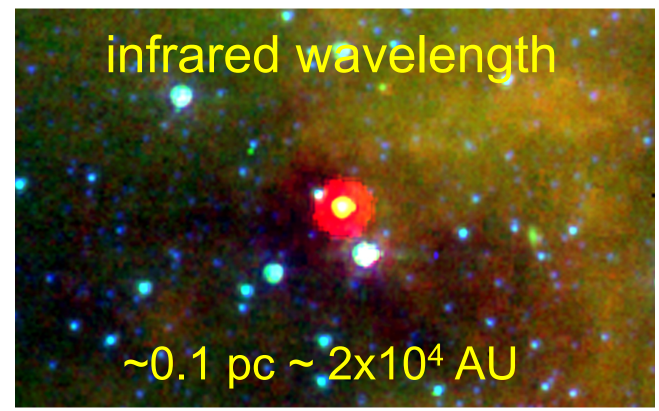
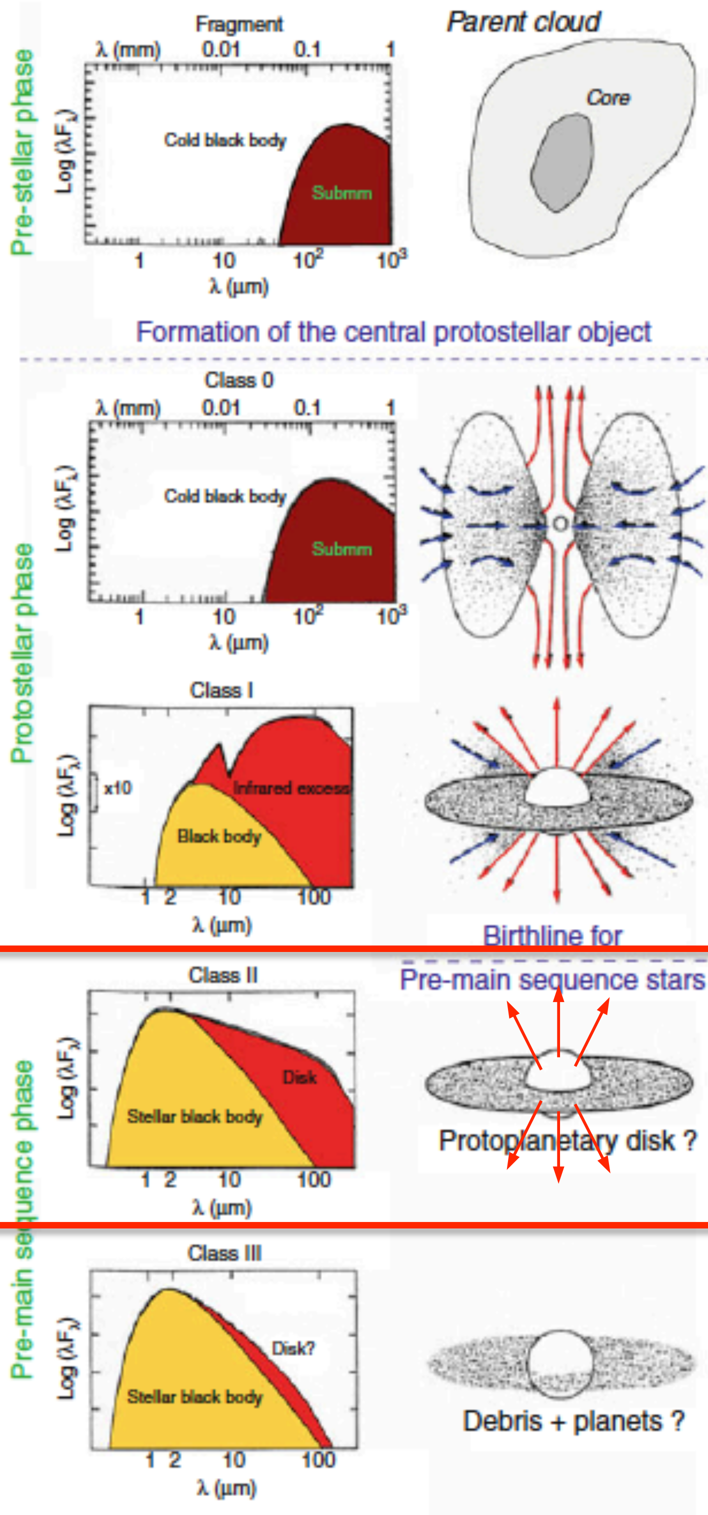
time

star-forming core/class 0 source







Pre-stellar core

$M_{star} = 0$

~10^6 yr?

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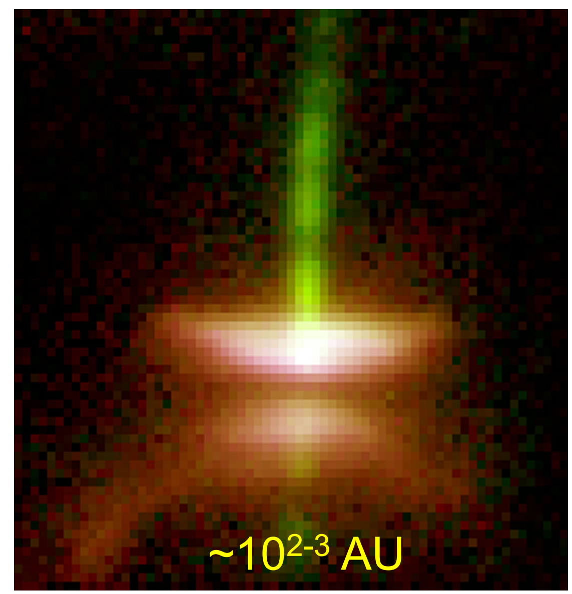
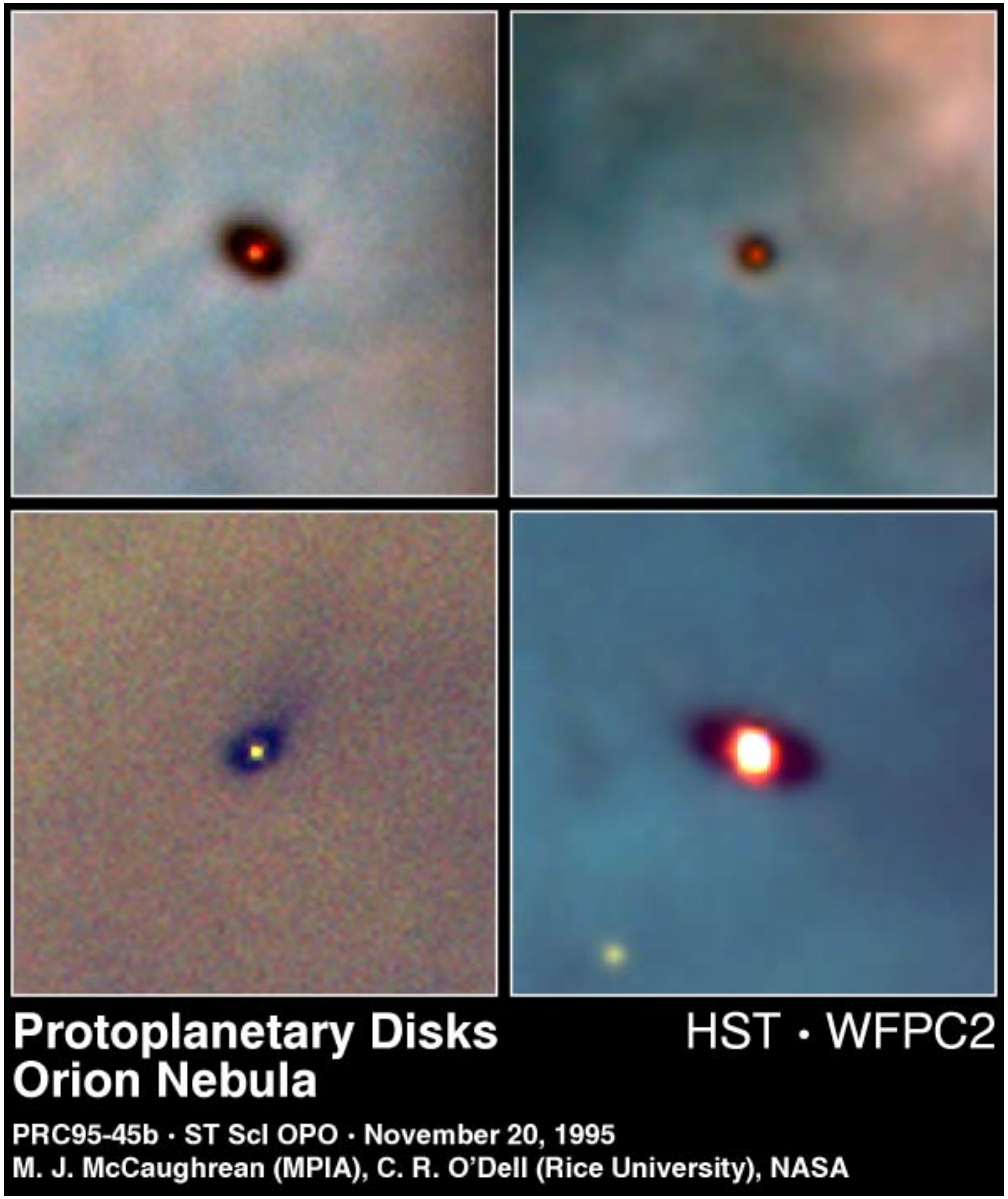
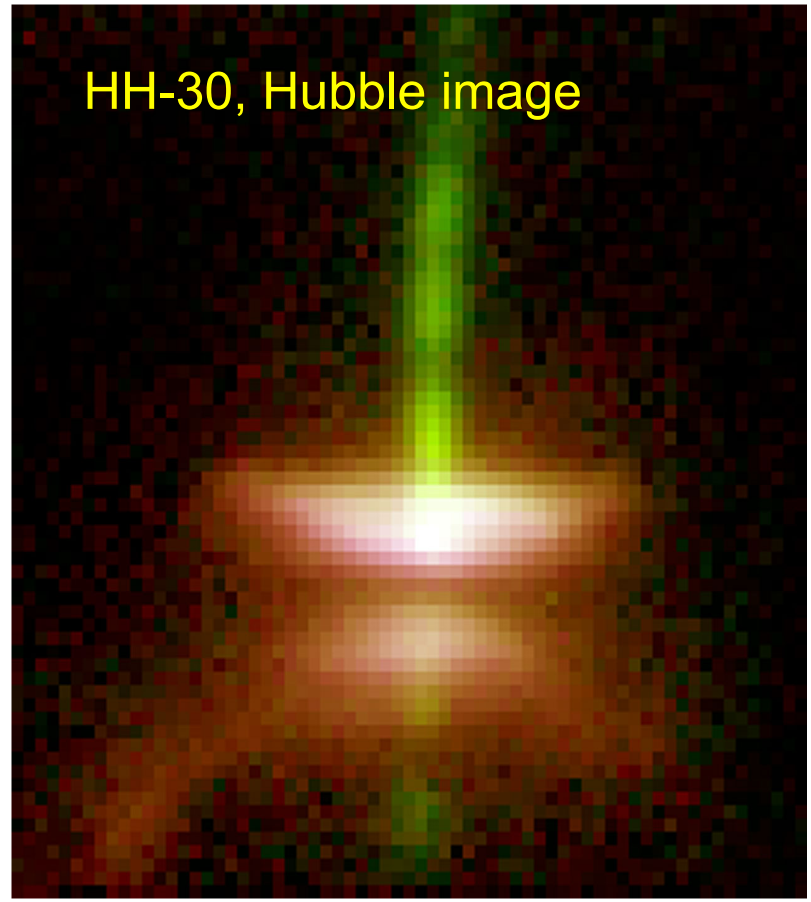


Protoplanetary disks



~1000 AU



~200 AU

Disk formation & size: general considerations

Size of a pre-stellar core: R_{core}~0.05 pc

Rotational to gravitational energy: $\beta_{\text{rot}} \equiv \frac{1}{3}\frac{\omega^2 R^2}{GM/R}$

(assuming uniform density and rotation)

~0.02 (with large scatter).

(Goodman et al. 1993)

By angular momentum conservation, infalling material settles to a disk with size R_{disk}:

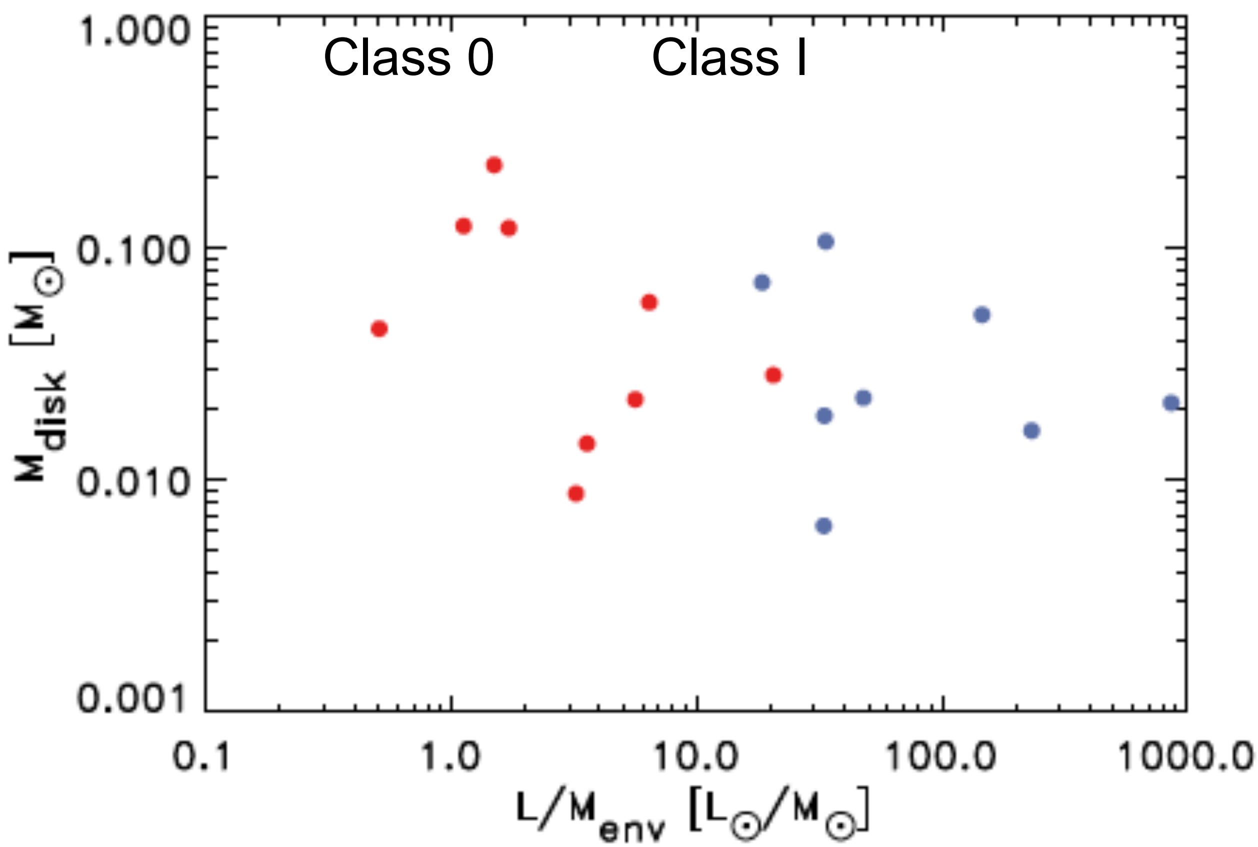
$$J \sim I\omega \sim \sqrt{GMR_{\text{disk}}}$$

$$R_{\text{disk}} \sim \frac{1}{2}\beta_{\text{rot}} R_{\text{core}} \sim 100\text{AU}$$

Disk formation: observations

Difficult because of high extinction.

Need long wavelength (mm) + high resolution.



(Jørgensen et al. 2009)

Disks are formed early in the Class 0 phase.

No significant mass evolution through Class I phase.

Disk formation: outstanding issues

- Luminosity problem: (Kenyon et al., 1990)

  Typical young stellar objects have accretion luminosities that are too low (by a factor of ~10) to build up their mass.

  Solution: accretion is episodic (how?) (e.g., Vorobyov & Basu, 2006, Zhu et al. 2009)

- Magnetic flux problem:

  Conservation of magnetic flux during core collapse would lead to way too strong stellar magnetic fields.

  Solution: magnetic flux must be removed during collapse (how?)

- Magnetic braking catastrophe: (Mellon & Li, 2008)

  Simulations can not form rotationally supported disk because magnetic braking is too efficient.

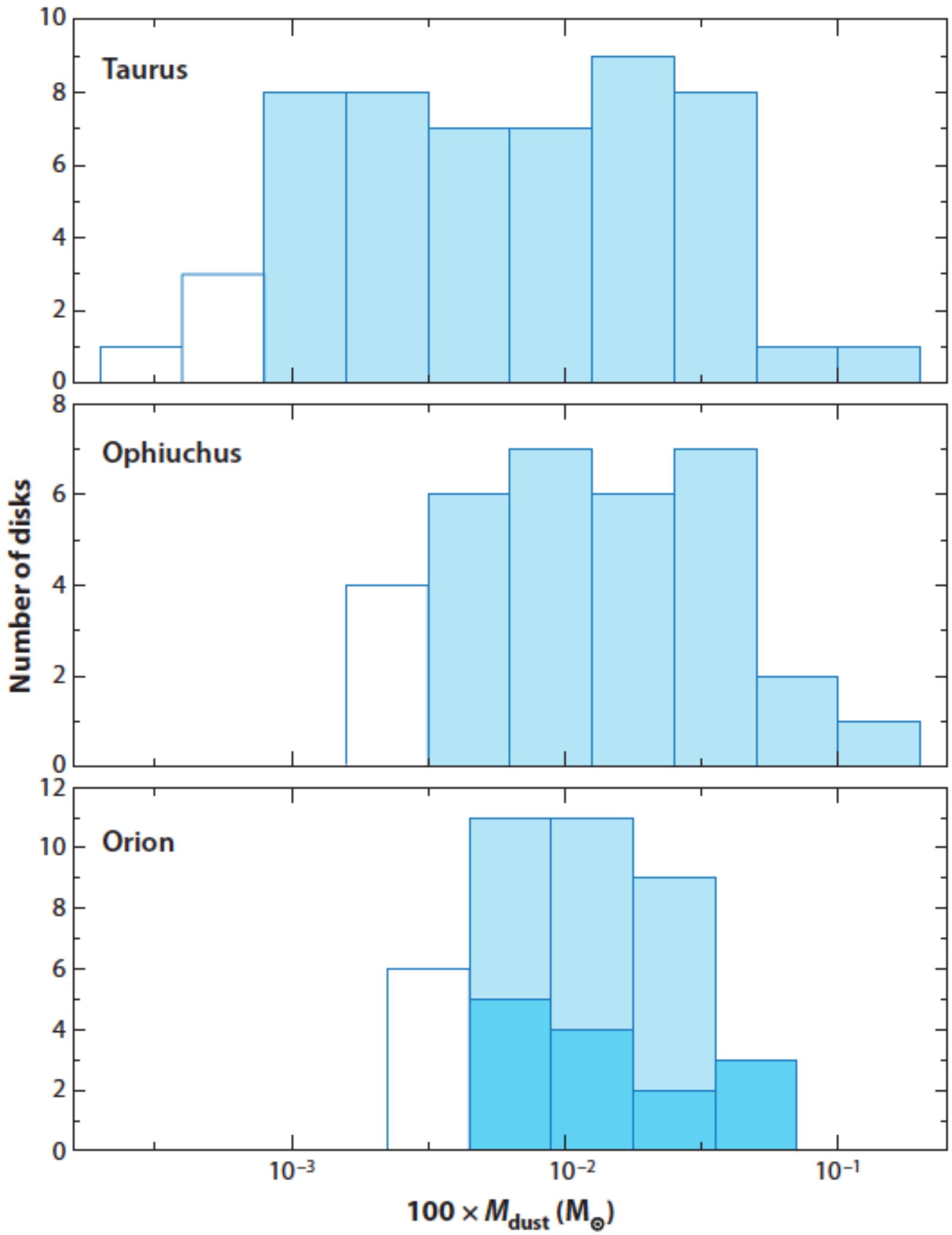
  Solution: misaligned B field and/or turbulent reconnection?

(Hennebelle & Ciardi, 2009; Joos et al., 2012) (Santos-Lima et al., 2012, Seifried et al. 2012)

Disk properties (for class II sources)

- Disk mass
- Disk size and structure (radial and vertical)
- Spectra energy distribution
- Gas content and chemistry
- Disk accretion
- YSO outflow
- Disk lifetime
- Disk dispersal and photoevaporation
- Transition disks

Disk mass



Outer disk is optically thin at mm:

$$\kappa_\nu = 0.1 \left(\frac{\nu}{10^{12}\,\mathrm{Hz}} \right)^\beta \mathrm{cm}^2\,\mathrm{g}^{-1}.$$

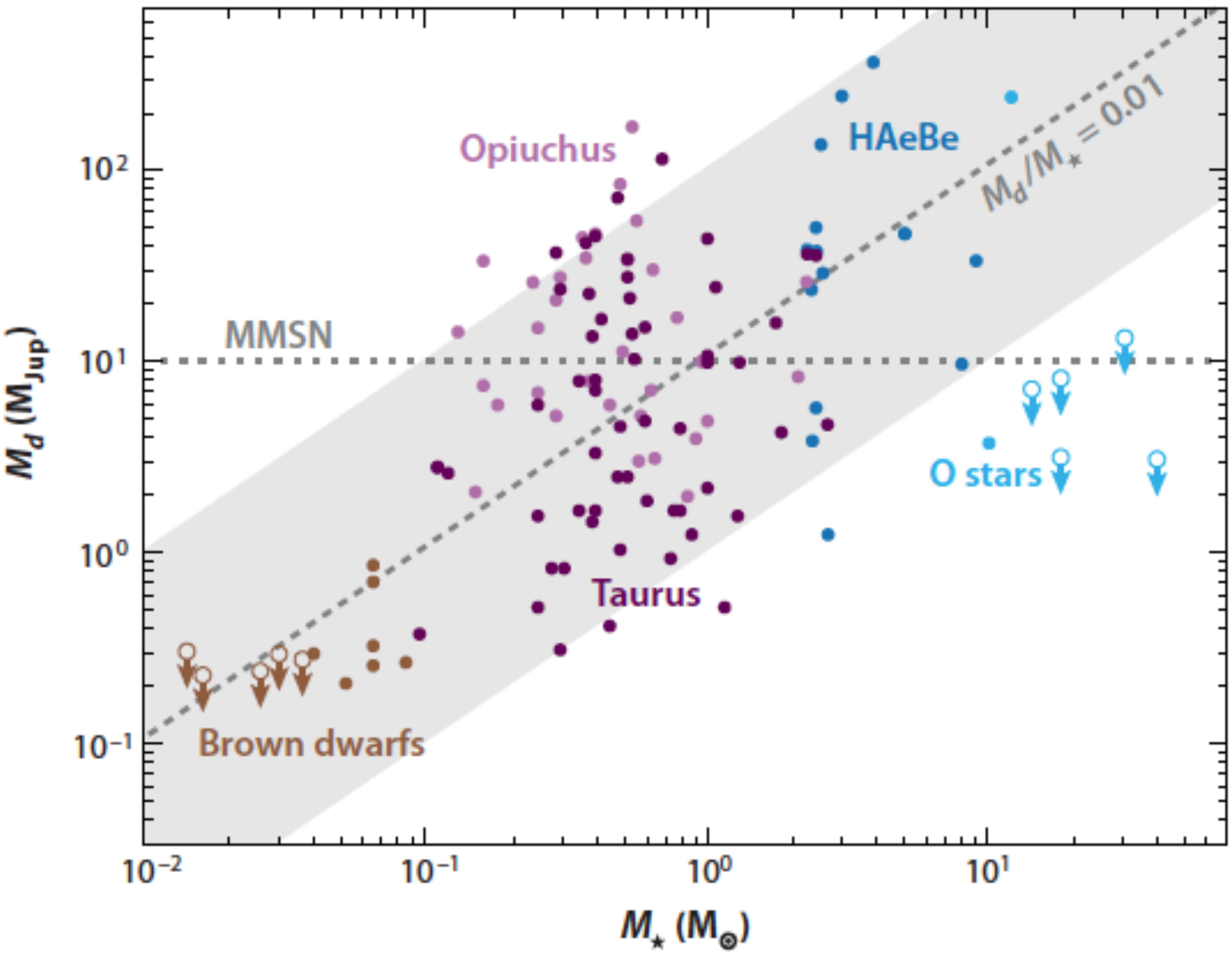
(assuming dust to gas mass ratio 0.01)

$$M(\mathrm{gas}+\mathrm{dust}) = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T)},$$

Disk mass ~0.01 $M_\odot$, with large scatter.

(Williams & Cieza, 2011, ARA&A)

Dependence on stellar mass



(Williams & Cieza, 2011, ARA&A)

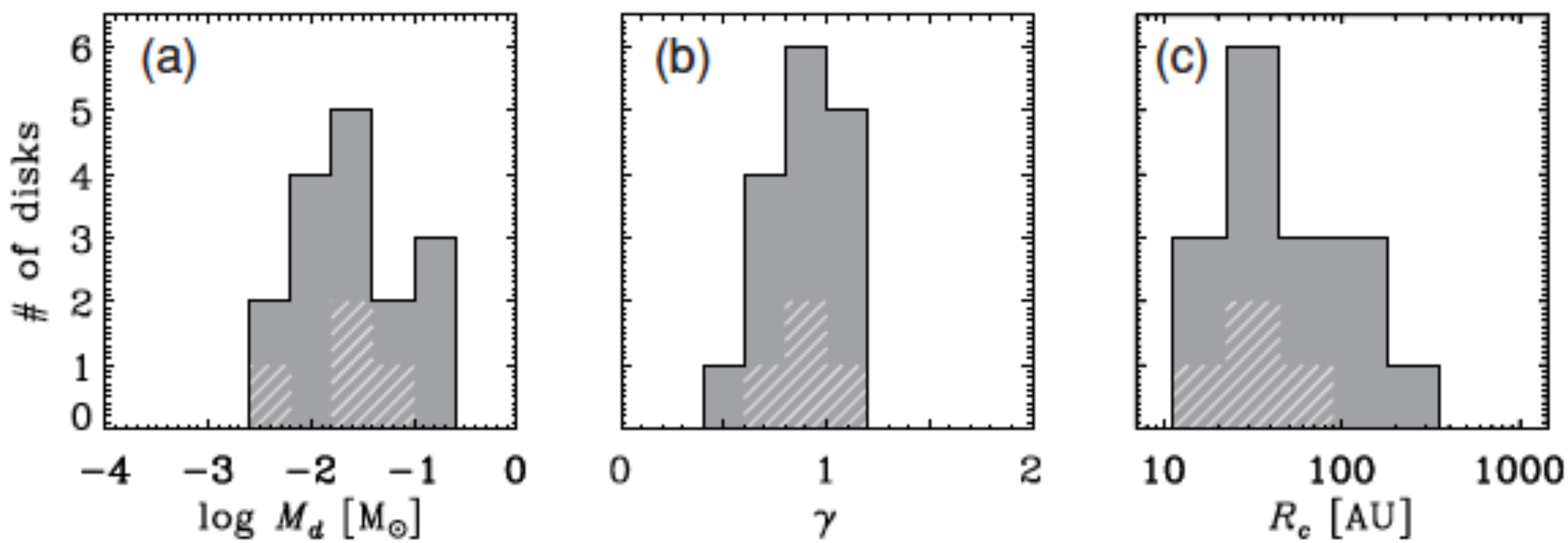
Over a wide mass range, approximately have M_{disk}~$0.01M_*$ with large scatter.

Disk size and structure

Fit mm interferometric data with a exponentially tapered power law:

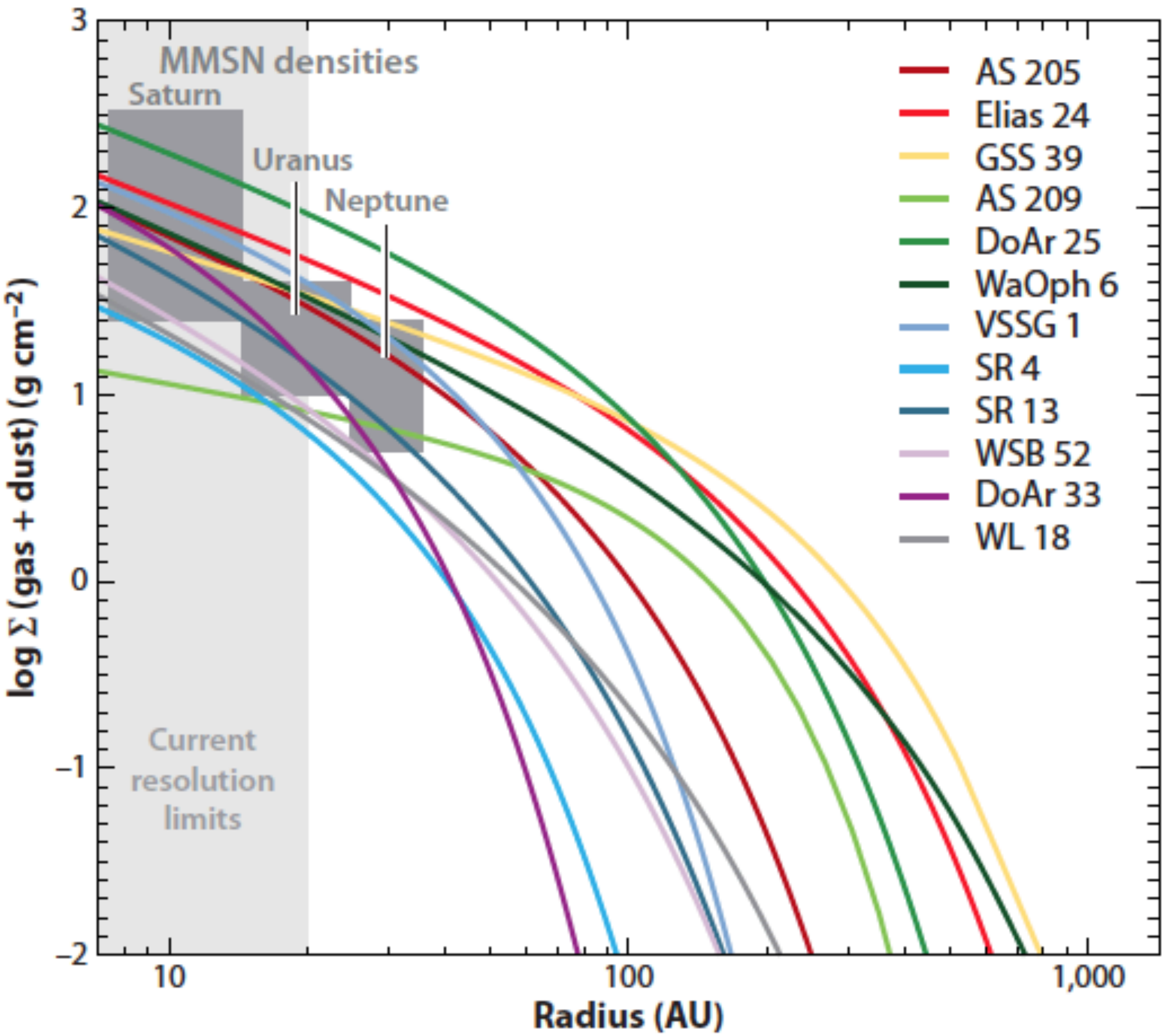
$$\Sigma = (2-\gamma)\frac{M_d}{2\pi R_c^2}\left(\frac{R}{R_c}\right)^{-\gamma}\exp\left[-\left(\frac{R}{R_c}\right)^{2-\gamma}\right],$$

In Ophiochus star-forming region:



(Andrews et al. 2010)

Disk size and structure

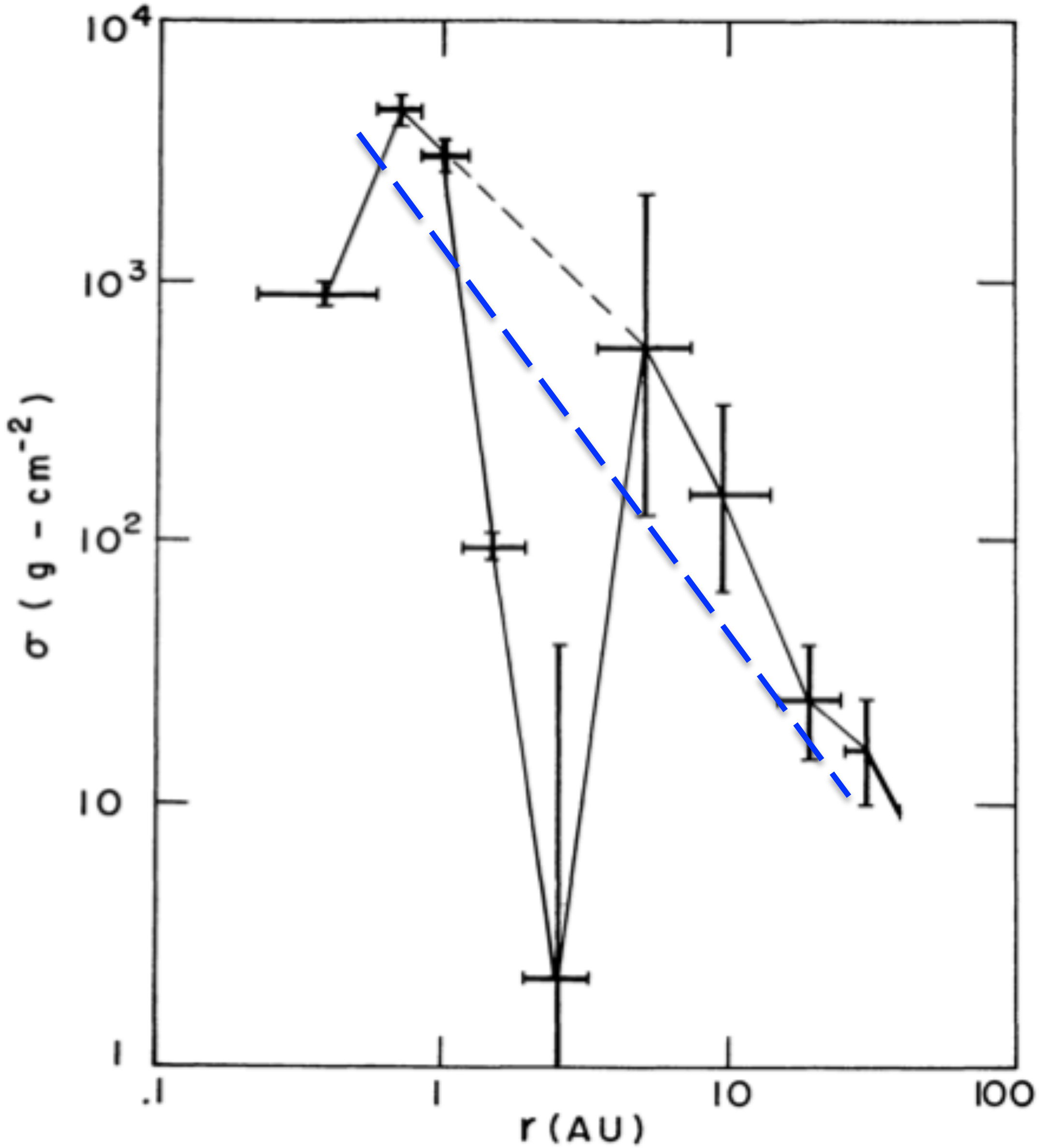


(Andrews et al. 2009,2010)

Outer disk roughly follows R^{-1} profile.

Inner disk (<20 AU) is unresolved (before ALMA) and can be optically thick.

Minimum mass solar nebular (MMSN)



(Weidenschilling 1977; Hayashi 1981)

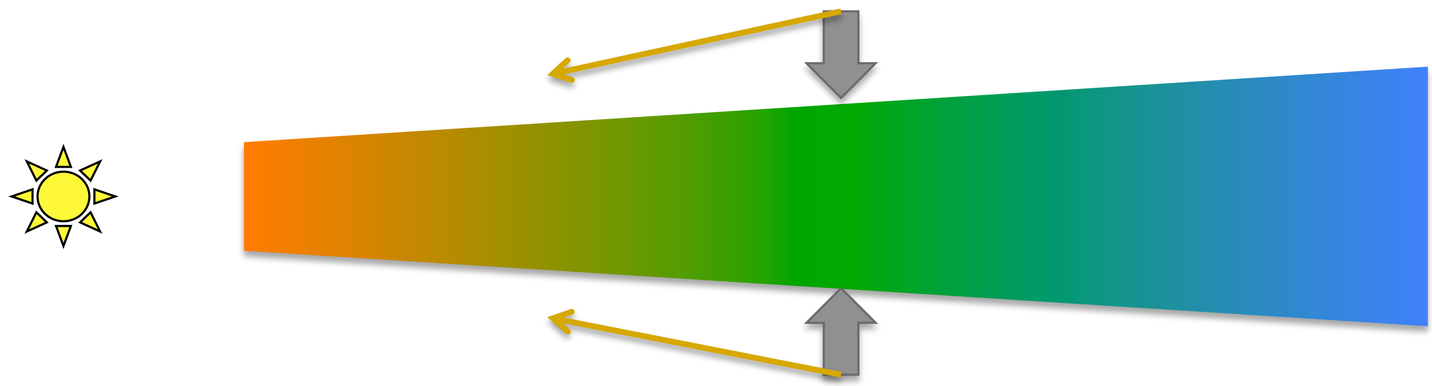
Assume solar-system planets are formed *in-situ*, reconstruct surface density profile by smoothly spreading required gas mass across the disk:

$$\Sigma = 1700 \text{ g cm}^{-2} \cdot r_{\rm AU}^{-3/2},$$

Total mass ~0.01 $M_{\odot}$

Lower mass limit for the pre-solar nebular.

Vertical structure



Vertical gravity:

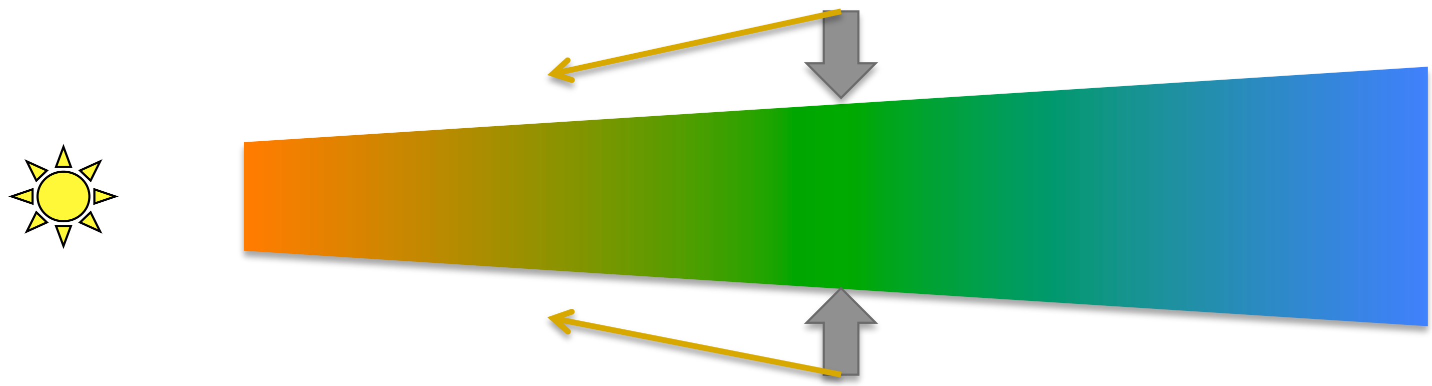
(z<<R)

$$g_z = -\frac{GM_*}{(R+z)^2}\frac{z}{(R^2+z^2)^{1/2}} \approx -\Omega^2 z$$

Pressure support (assuming isothermal EoS $P=\rho c_s^2$):

$$c_s^2 \frac{d\rho}{dz} = \rho g_z$$

Vertical structure



Vertical structure: $$\rho = \rho_0 e^{-z^2/2H^2}$$

Disk scale height (H): $$H = c_s/\Omega$$

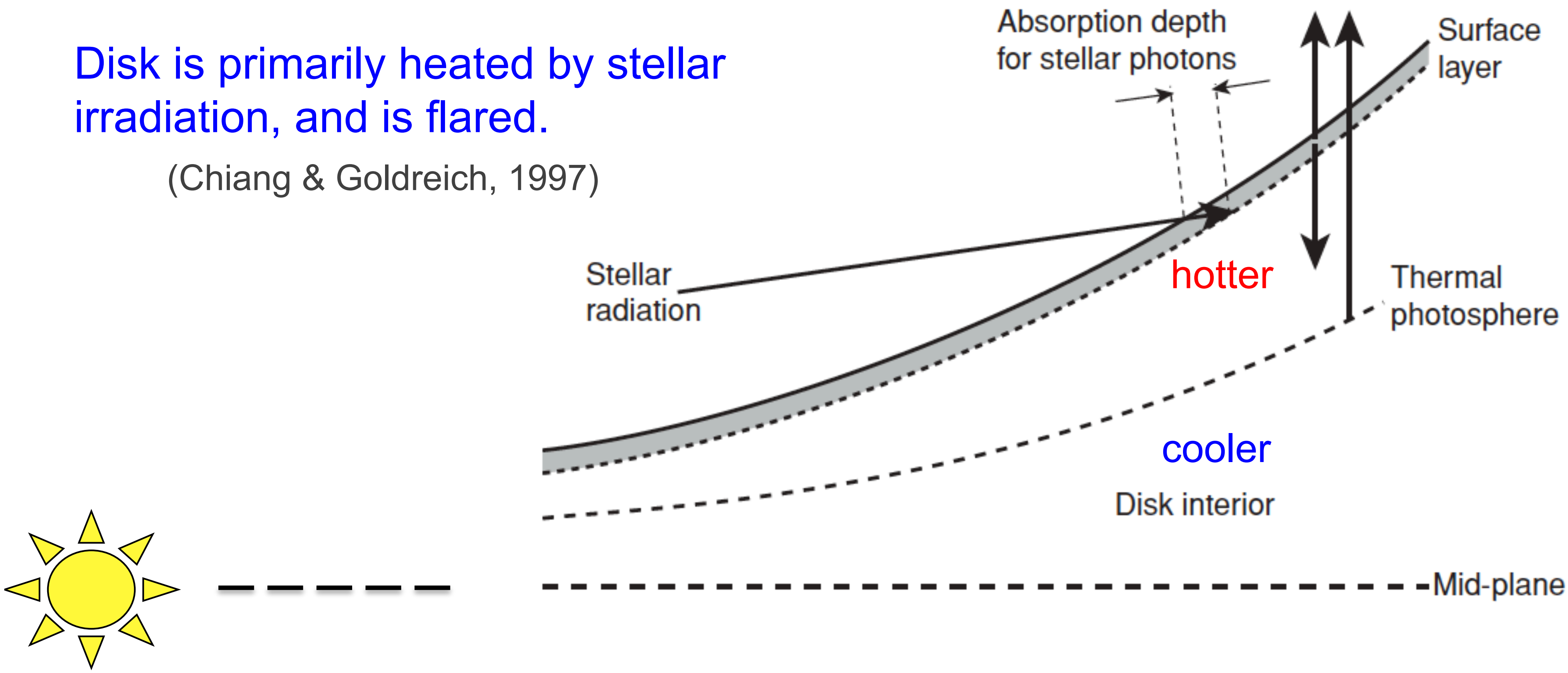
Isothermal sound speed (c_s): $$c_s = \frac{kT}{\mu m_p}$$

$\mu \sim 2.33$
(for molecular gas)

Thermal structure

Disk is primarily heated by stellar irradiation, and is flared.

(Chiang & Goldreich, 1997)



To first order, approximate the disk with isothermal emitting blackbody:

$$\alpha \frac{L_*}{4\pi R^2} \approx \sigma T_{\rm disk}^4 \quad \Rightarrow \quad T_{\rm disk} \sim R^{-1/2}$$

Minimum-mass solar nebular: update

$$\Sigma = 1700 \text{ g cm}^{-2} \cdot r_{\text{AU}}^{-3/2}, \quad T = 280 \text{ K} \cdot r_{\text{AU}}^{-1/2}$$

$$v_K = 30 \text{ km s}^{-1} \cdot r_{\text{AU}}^{-1/2}, \quad c_s = 1.0 \text{ km s}^{-1} \cdot r_{\text{AU}}^{-1/4}$$

Vertically isothermal:

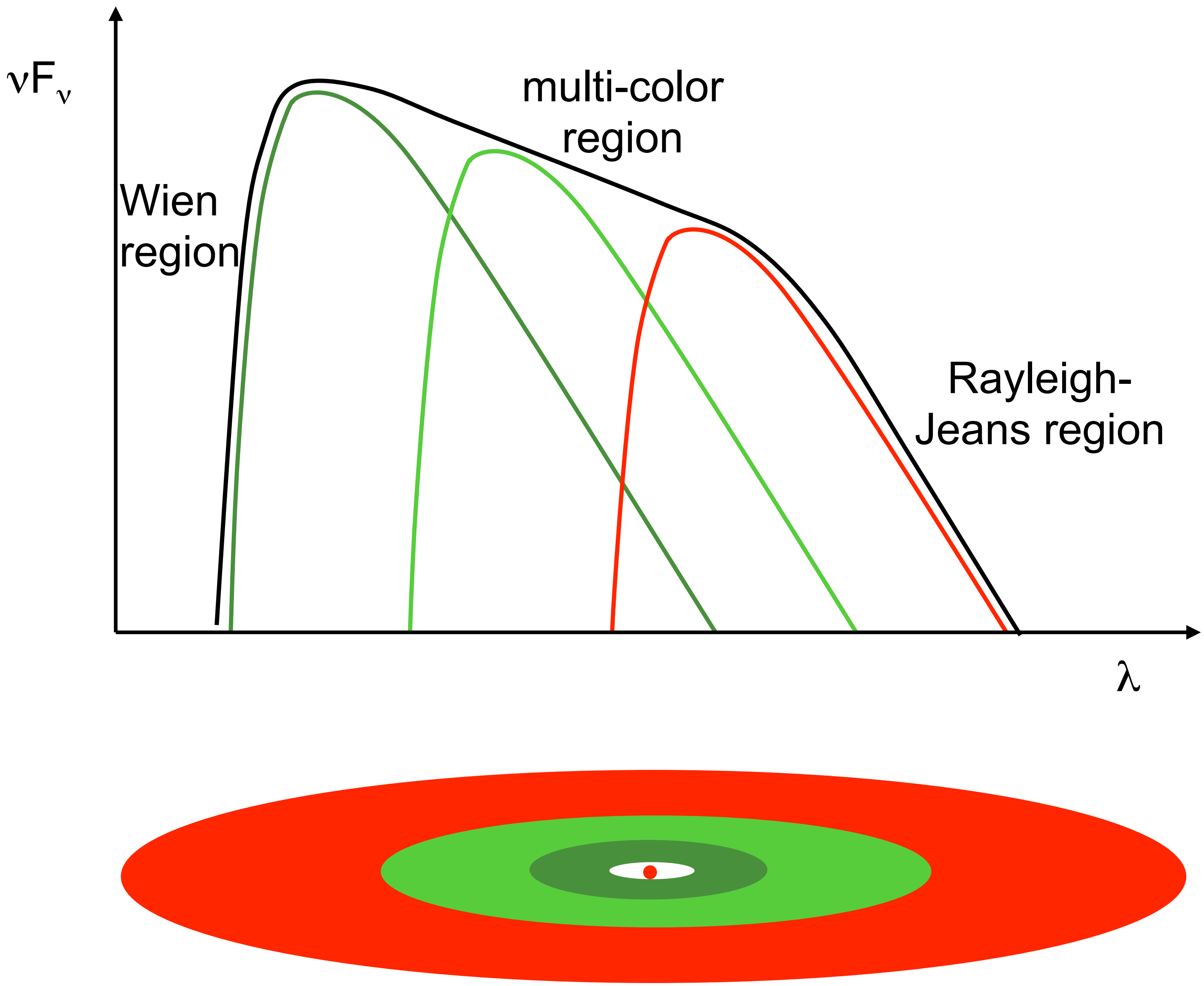
Disk is flared

$$H = c_s/\Omega, \qquad H/r = 0.03 r_{\text{AU}}^{1/4}$$

$$\rho(r, z) = \rho_0(r) \exp(-z^2/2H^2)$$

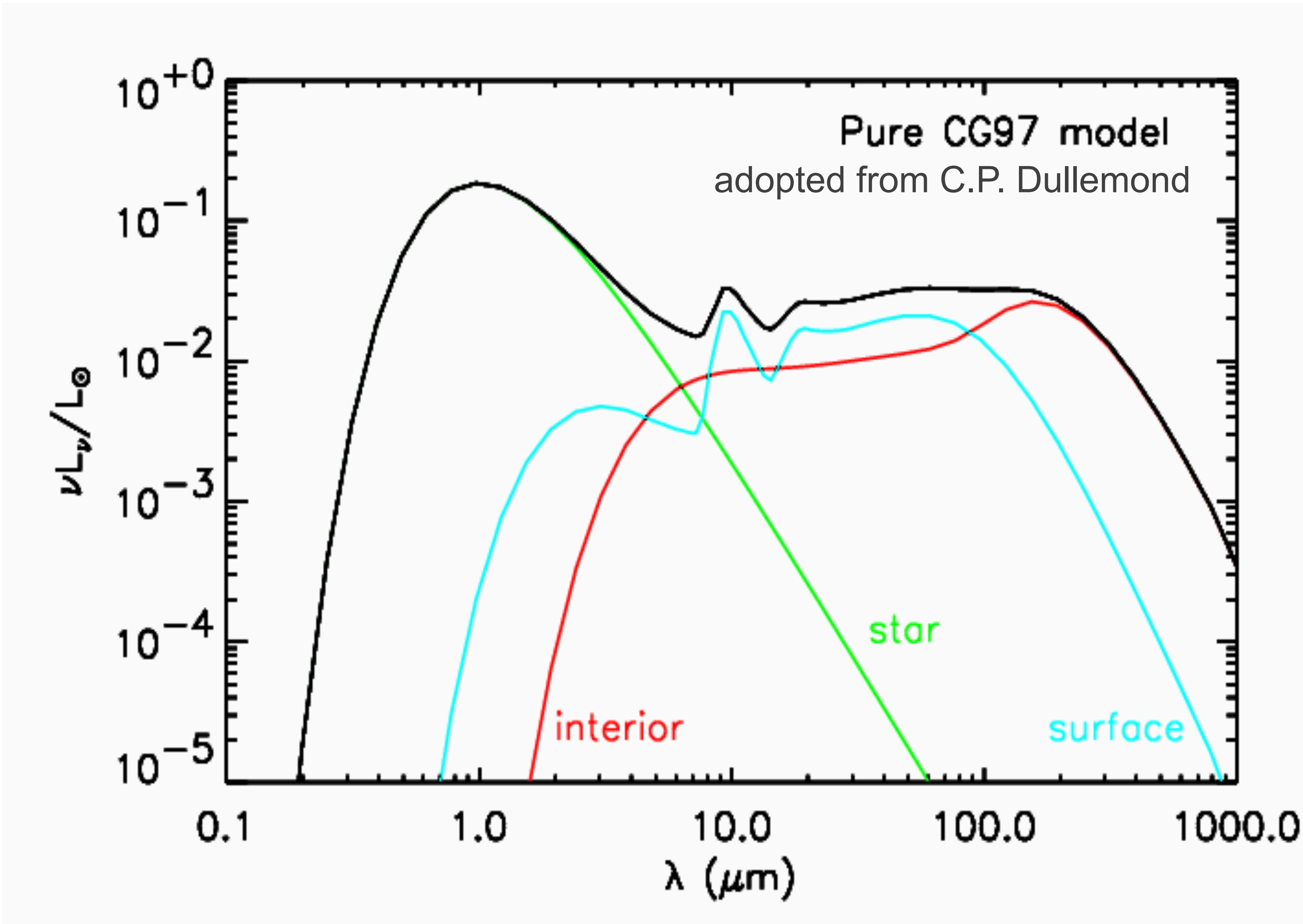
$$\rho_0(r) = 1.4 \times 10^{-9} \text{ g cm}^{-3} \cdot r_{\text{AU}}^{-11/4}$$

Multi-color blackbody disk spectra



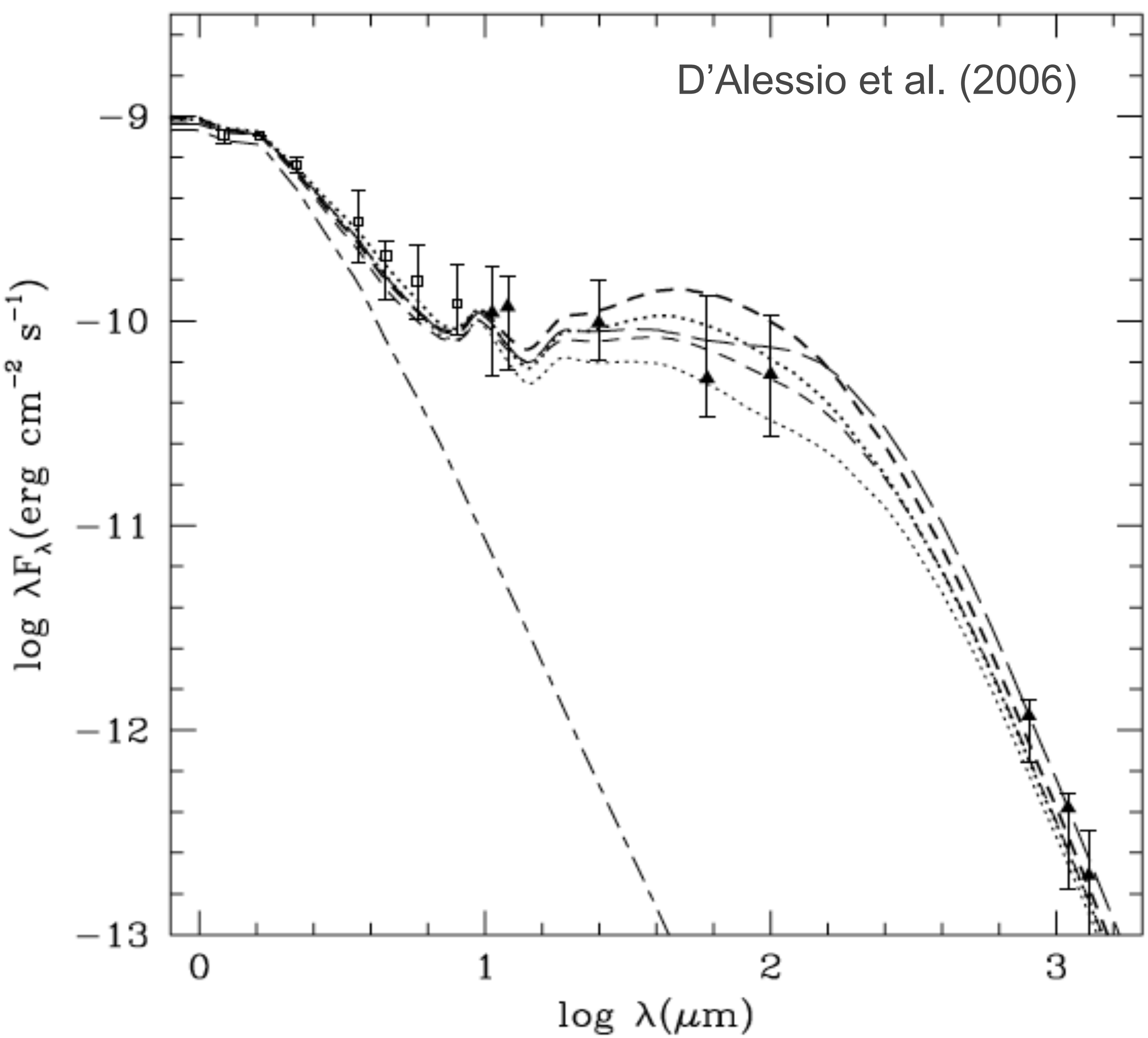
adopted from C.P. Dullemond

Spectral energy distribution (SED)



(Chiang & Goldreich, 1997)

The business of SED modeling



To constrain:

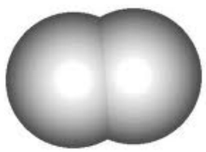
- Dust composition, size, abundance and distribution
- Disk size, surface density and temperature
- Viewing geometry

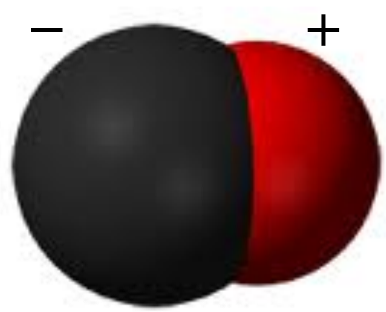
Parameters are highly degenerate but show evidence of grain growth and settling.

Gas in protoplanetary disks

- Gas contains ~99% of disk mass, but the primary gas species, H_2, does not have a permanent electric dipole moment -> radiate very weakly.

H_2





CO

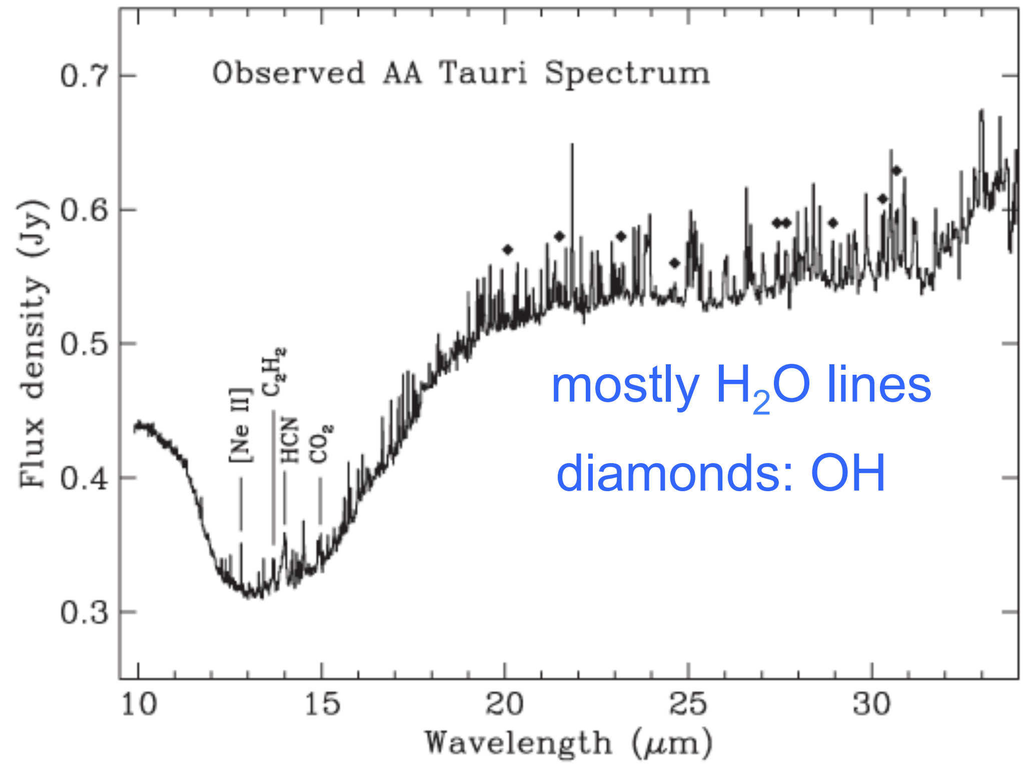
- Other major molecules, particularly CO, do radiate efficiently, although most cases they are optically thick (can not be used to measure disk mass).

For a uniform temperature slab in thermal equilibrium:

$$I_\nu = I_\nu(0)e^{-\tau_\nu} + B_\nu(T_{\rm exc})(1 - e^{-\tau_\nu})$$

IR emission lines

- The surface layer of the inner disk is heated strongly by stellar X-ray, UV radiation, allowing molecular (ro-vibrational) emission lines to stand out (in the near-mid IR).

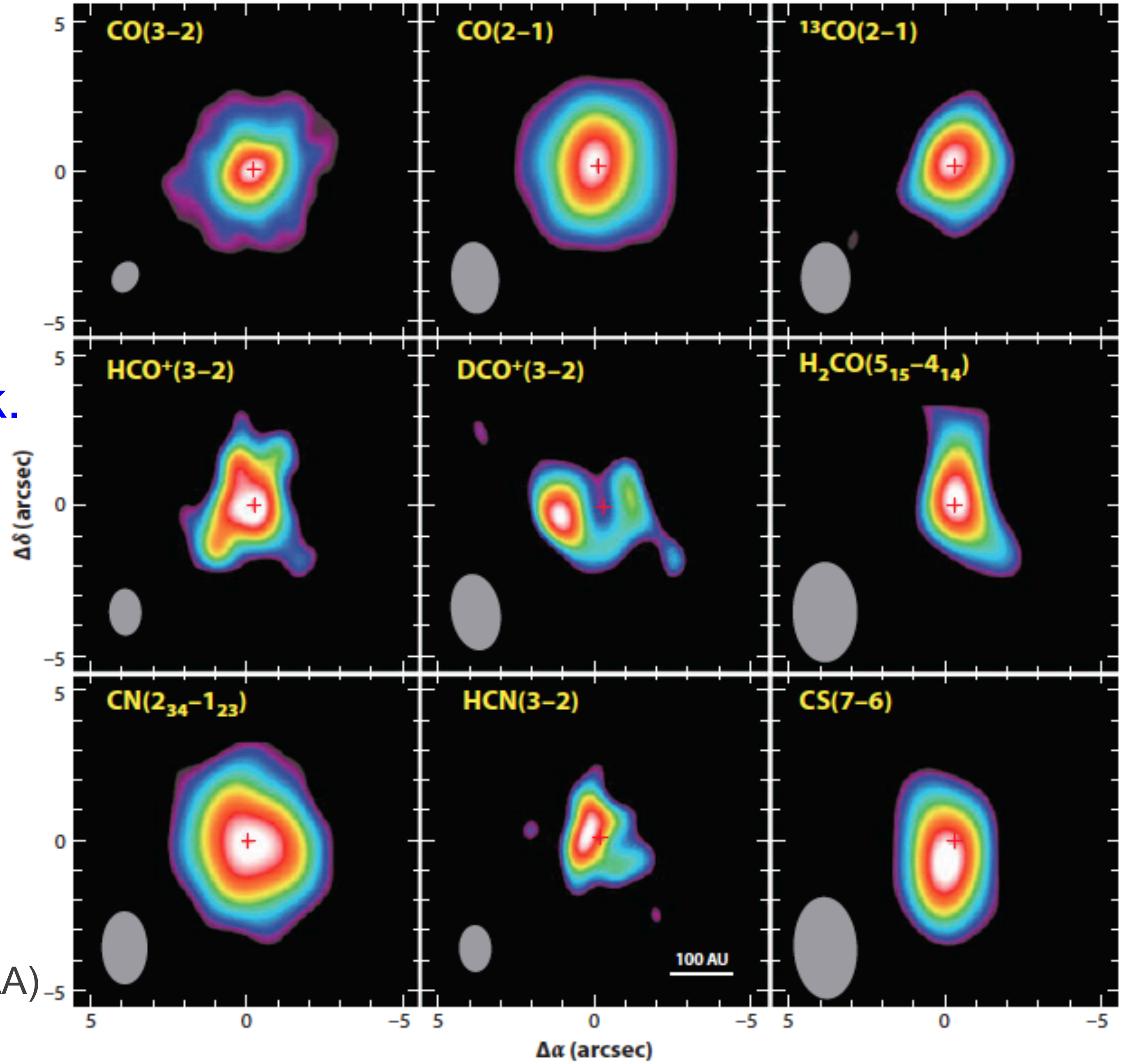


(Carr & Najita, 2008, Sci)

Molecule	T (K)	N (10^{16} cm^{-2})	R^* (AU)	Abundance to CO
H_2O	575 ± 50	65 ± 24	2.1 ± 0.1	1.3
OH	525 ± 50	8.1 ± 5.2	2.2 ± 0.1	0.18
HCN	650 ± 100	6.5 ± 3.3	0.60 ± 0.05	0.13
C_2H_2	650 ± 150	0.81 ± 0.32	0.60†	0.016
CO_2	350 ± 100	0.2 –13	1.2 ± 0.2	0.004 – 0.26
CO	900 ± 100	49 ± 16	0.7 ± 0.1	1.0

Gas content in sub-mm

- Molecular rotational lines can easily be thermally excited (many are in mm): powerful gas probes of the cold outer disk.
- To probe the disk interior, to use isotopologs, or ionized species.

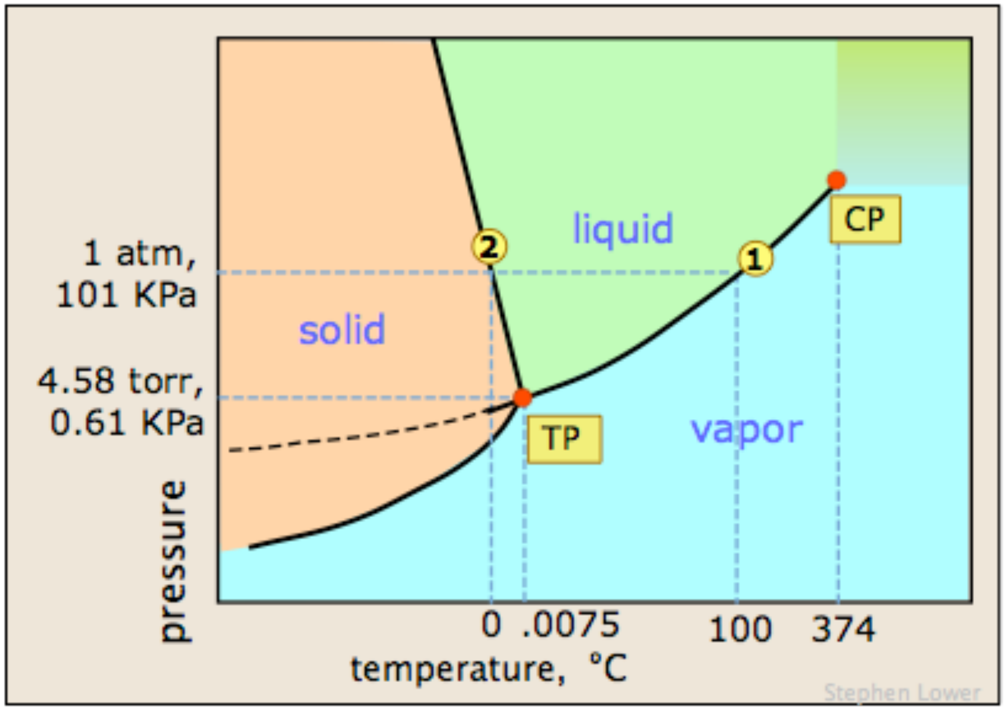


Williams & Cieza (2011, AR&AA)

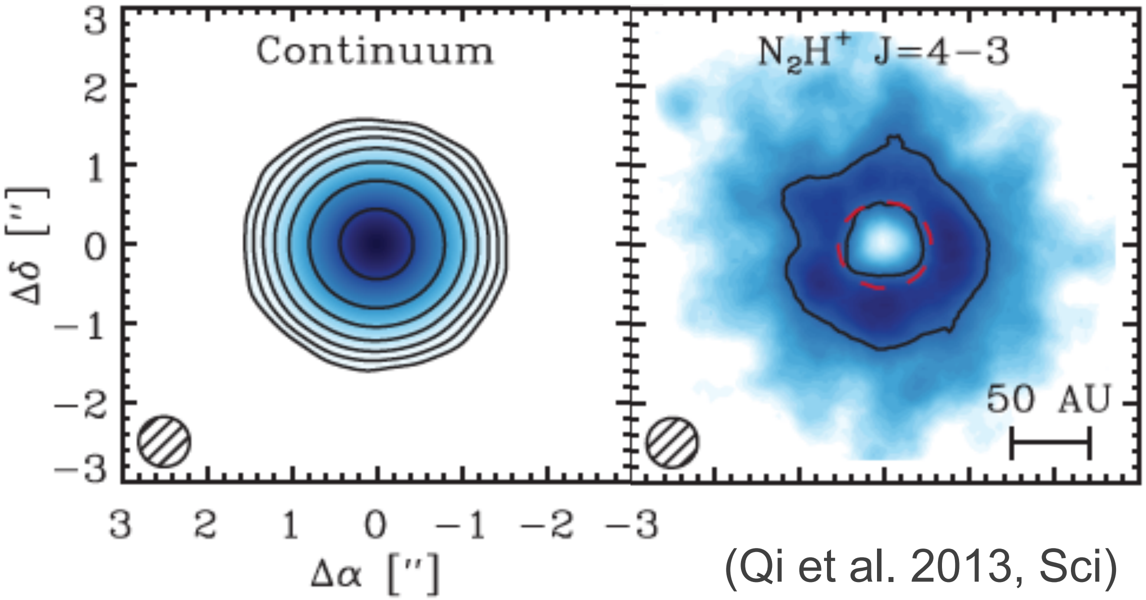
Snowline

Snowline: water freezes out to ice at ~150-170K in PPDs ($P \sim 10^{-6}$ bar).

Evidence of snowline at ~2.7 AU during solar system formation.



Detection of H_2O snowline in other disks has not been achieved, but detection of CO snowline (~17K) has been reported (by ALMA):

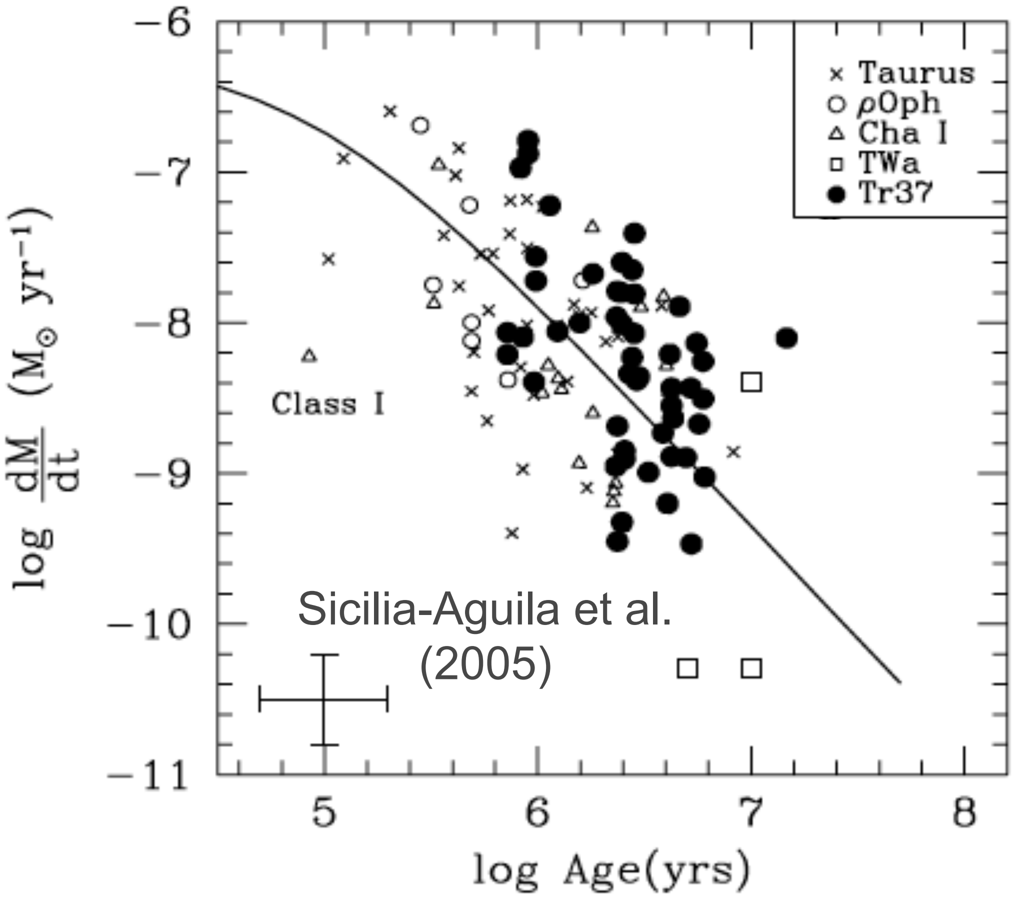


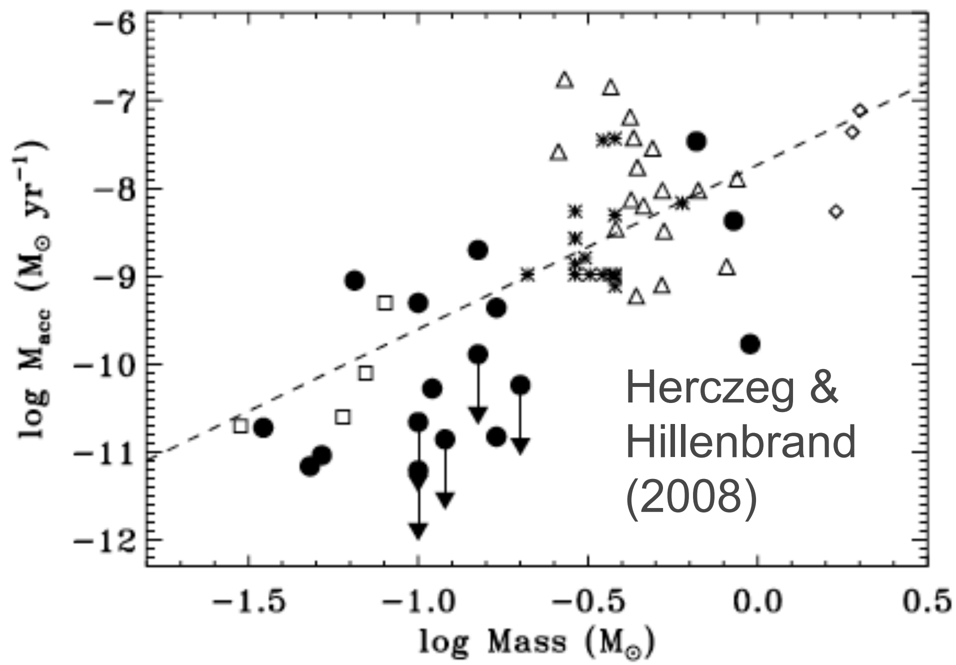
N_2H^+: can easily be destroyed by CO.

$N_2H^+ + CO \Rightarrow HCO^+ + N_2$

(Qi et al. 2013, Sci)

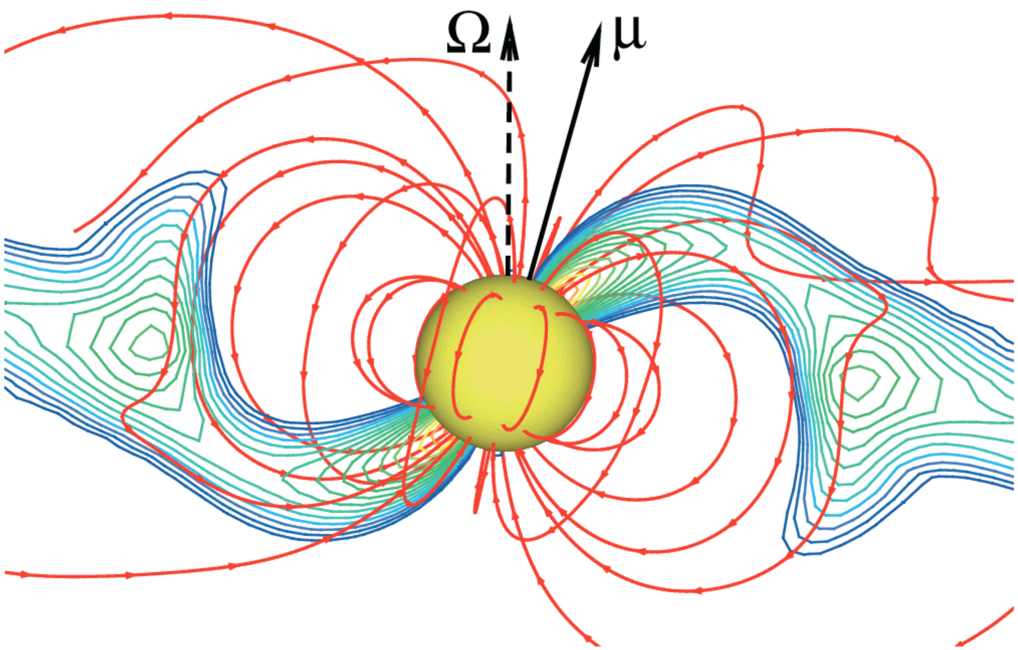
Accretion rates





- Typical accretion rate ~ $10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$ with large scatter.
- Age dependence, dependence on protostellar mass.

Magnetospheric accretion



Romanova et al. 2004

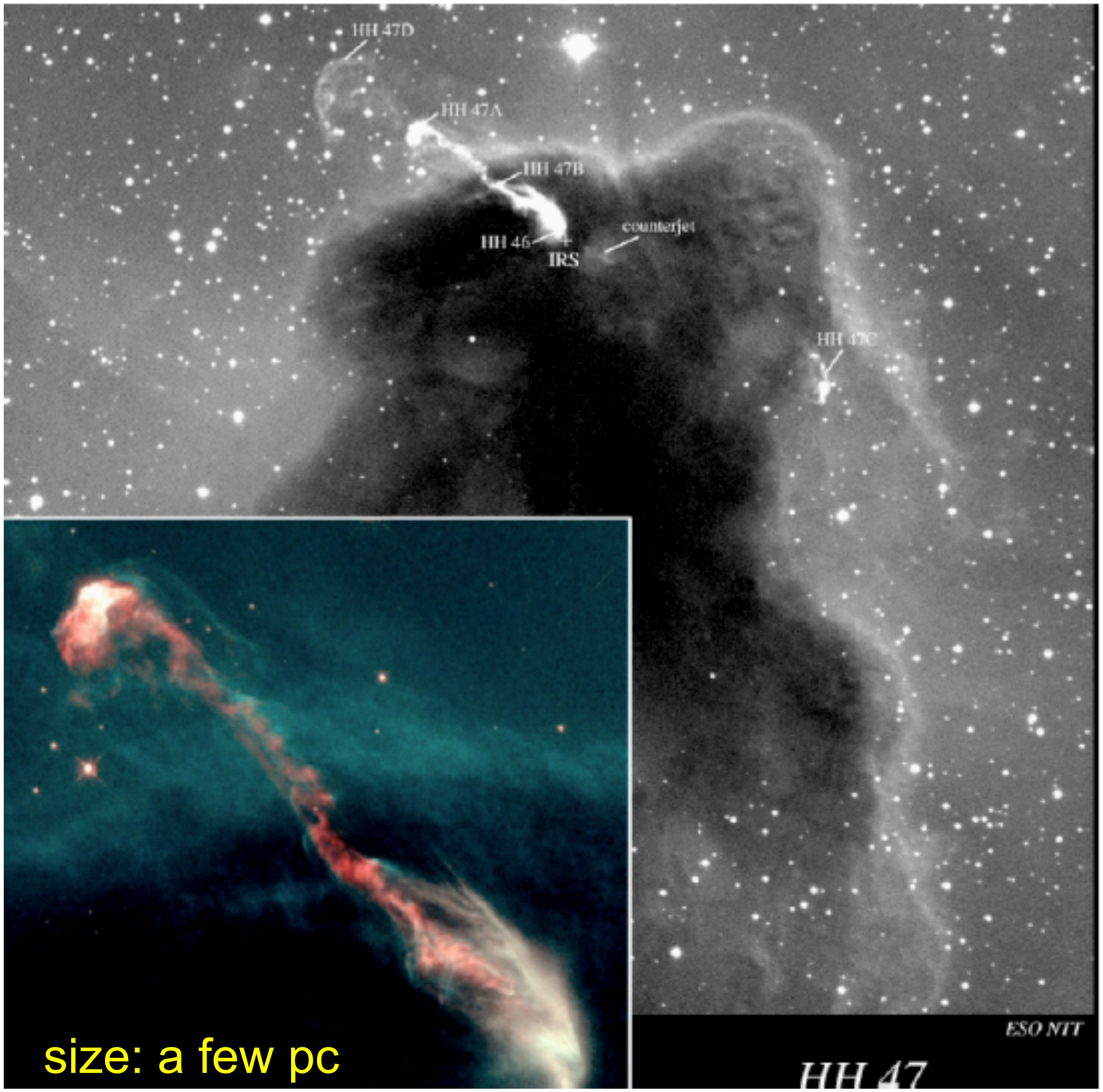
The disk is truncated at ~5R*, entering the stellar magneto-sphere, material flows along stellar magnetic field to stellar surface.

Release of gravitational energy => heat and radiation:

$$L_{\rm acc} \approx 0.8 \frac{GM\dot{M}}{R_*}$$

- Accretion shock -> excess UV radiation + line emission on top of stellar photospheric emission. (e.g., Calvet & Gullbring, 1998)
- Accretion luminosity correlates with various line diagnostics, $H\alpha$ or other emission lines (e.g., Muzerolle, Herczerg, Mohanti)

Jets and outflows

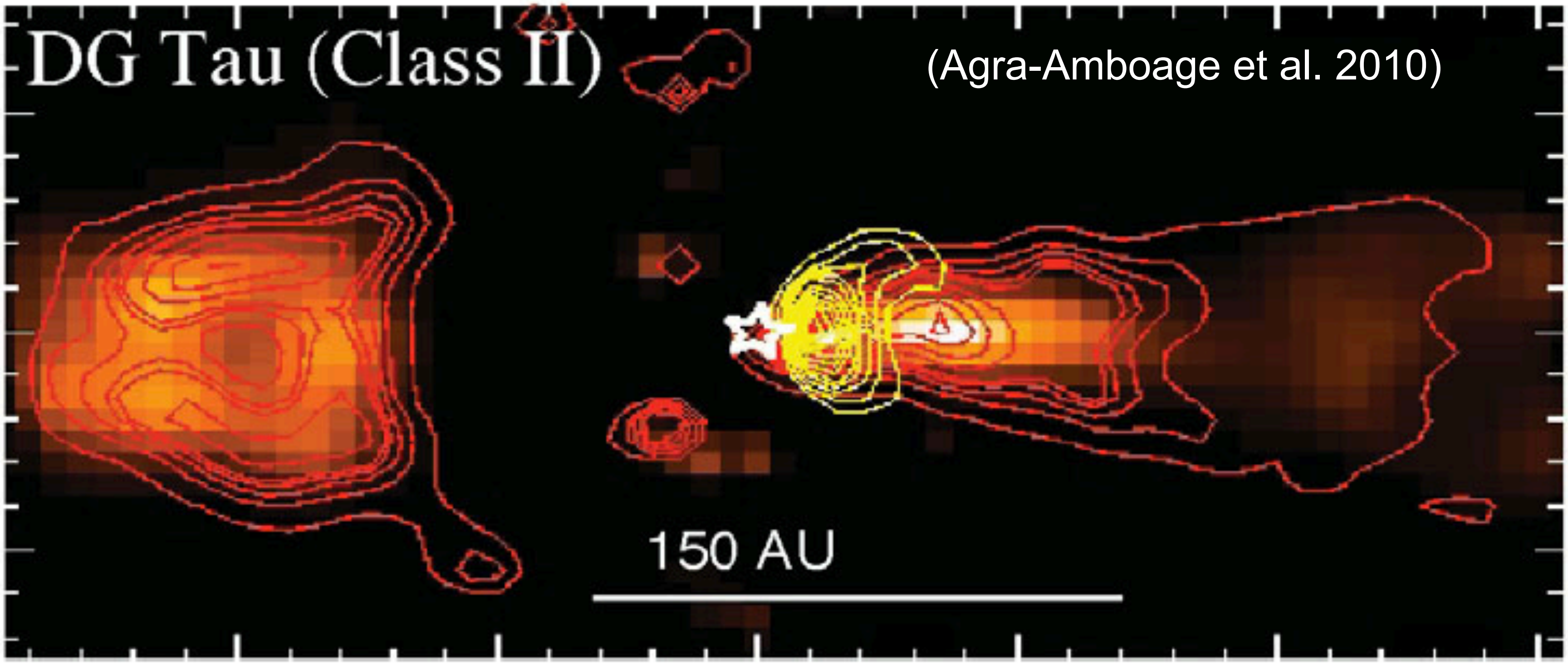


Herbig-Haro objects:

Nebular resulting from YSO jets traveling into their parent cloud/ISM.

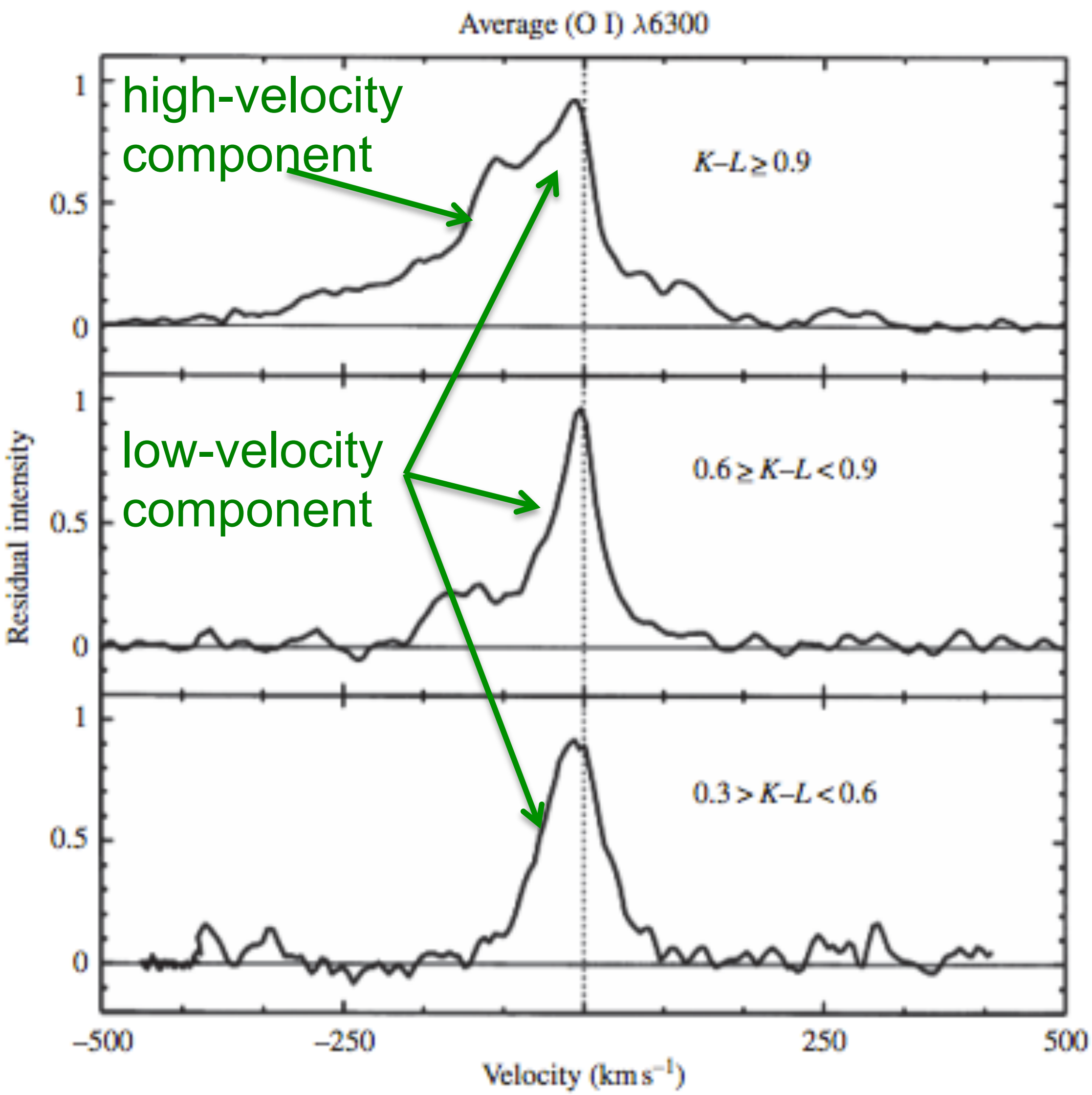
What's the central engine?

Jets and outflows



- Highly collimated high-velocity component + wide-angle low-velocity component (LVC).
- The LVC is very likely to originate from the inner disk (0.3-4AU for DG Tau, Bacciotti et al.2002, Anderson et al.2003)

Wind signature from forbidden lines

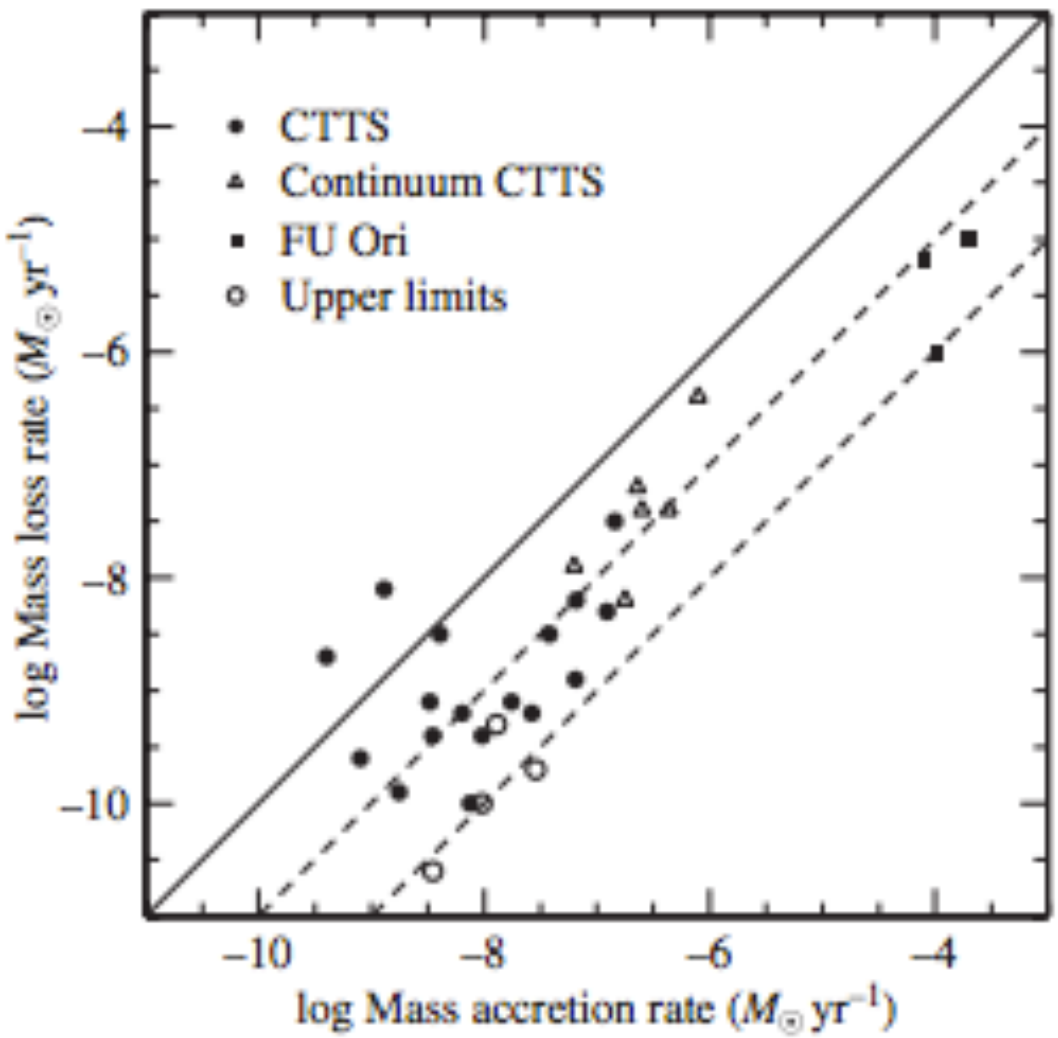


Large IR excess, more actively accreting disks

Little IR excess, less active disks

(Hartigan et al. 1995, adopted from L. Hartmann's book)

Association of accretion with wind

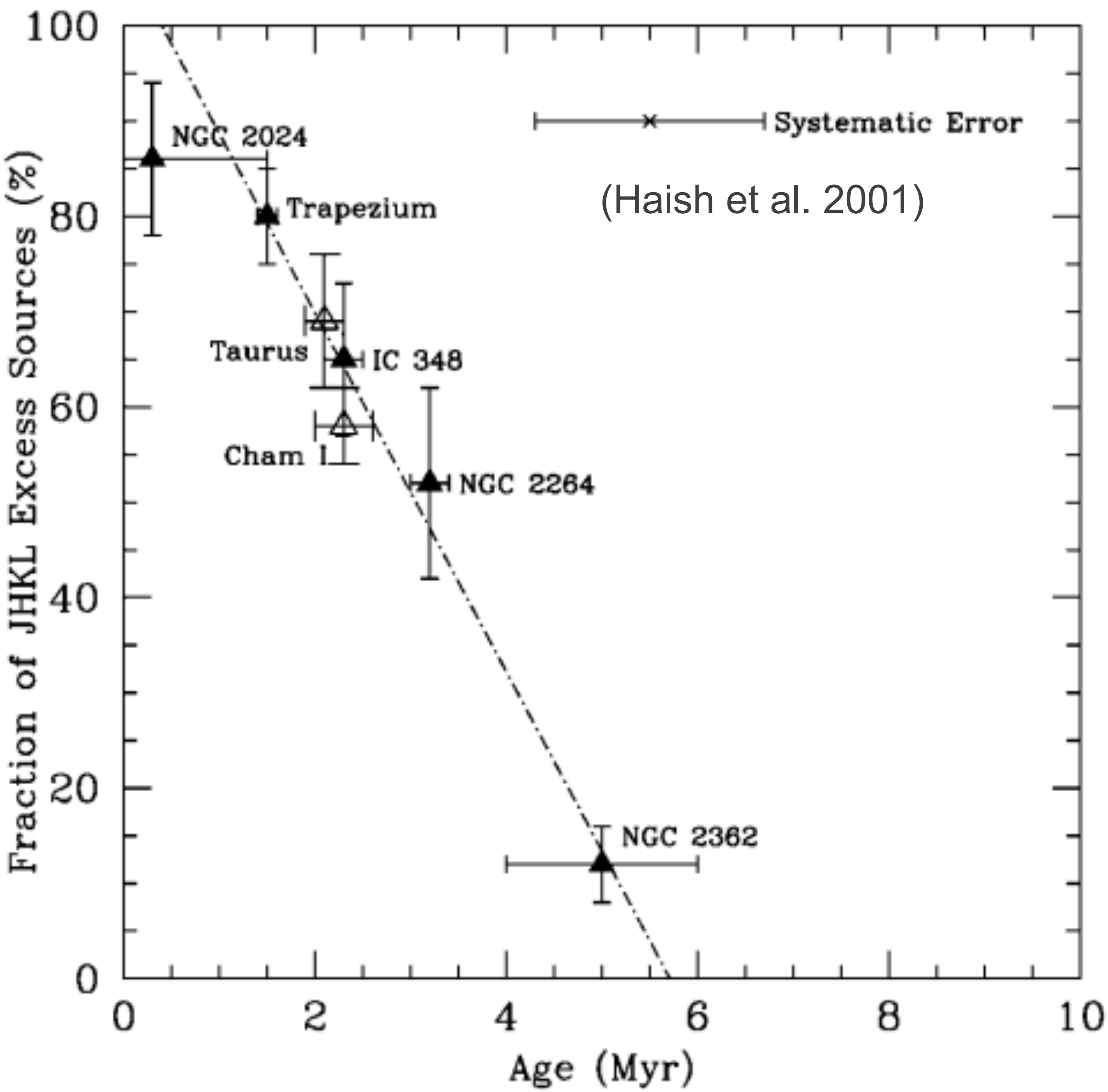


- Outflow is intimately connected to accretion.

$$\dot{M}_{\rm out} \sim 0.1\dot{M}_{\rm acc}$$

(Hartigan et al. 1995, adopted from L. Hartmann's book)

Disk lifetime



(Haish et al. 2001)

Median lifetime:

~3 Myr

Some old systems still possess massive disks (e.g., TW Hydra).

Environmental effects (photoevaporation from nearby OB stars).

Disk dispersal timescale

Observational definition:

$$\tau_{\rm disp} \sim \frac{\overset{<20\%}{\#\text{ of “transition” objects}}}{\text{Total \# of pre-main-sequence stars}} \times \text{ mean age}$$

What are “transition” objects?

(aka., transition disks)

Objects with NO excess in NIR/MIR but have excess in MIR/FIR.

Wolk & Walter (1996): $\tau_{\rm disp} < 10^6$ yr

Weak line T Tauri star (WTTS) with disks

Cieza et al. (2007): $\tau_{\rm disp} \sim 0.4 \times 10^6$ yr

Two-timescale problem:

PPDs survive for several Myr but disappear in much shorter timescale.

Photoevaporation of disks

Energetic photons ionize and strongly heat the surface layer of the disk. If the temperature of the gas in the surface exceeds the escape velocity, then the disk evaporates:

$$r > r_g \sim \frac{GM_*}{c_s^2}$$

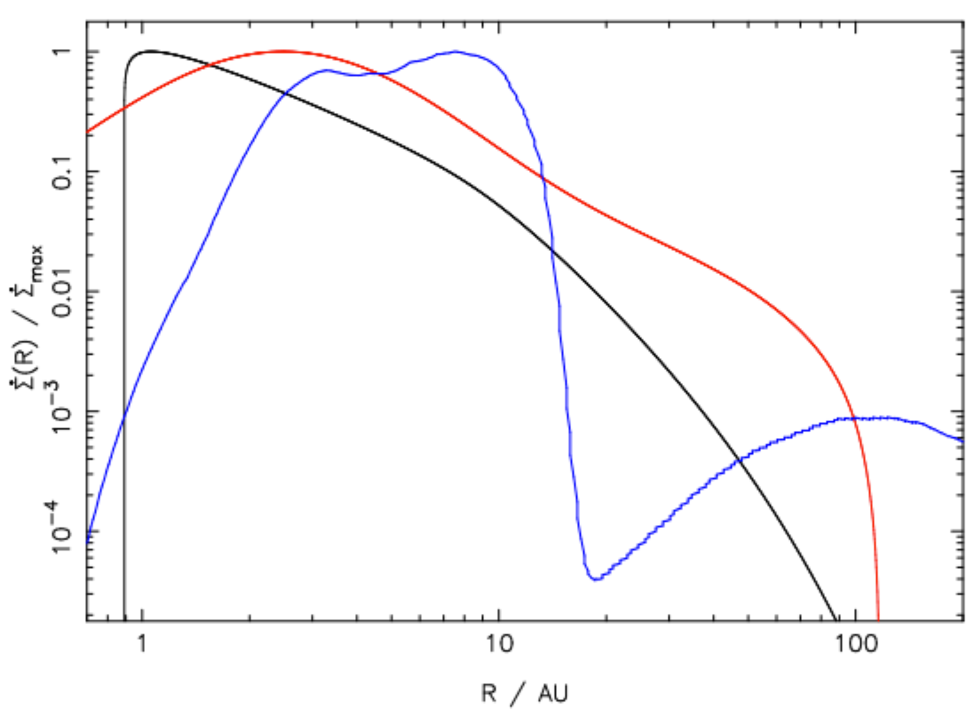
Heating mechanisms:

Mechanism	
extreme-UV (EUV) 13.6 eV < $h\nu$ < 0.1 keV	Indirect constraint ~$10^{41\text{-}44}$ photon/s (Alexander et al. 2005)
X-ray $h\nu$ > 0.1 keV	Dominated by thermal X-ray of 1-5keV, L_X~$10^{28\text{-}32}$ ergs/s. (e.g., Preibisch+ 2005)
far-UV (FUV) 6 eV < $h\nu$ < 13.6 eV	Dominated by line emission (e.g., Lyα), L_{FUV}~$10^{30\text{-}32}$ ergs/s. (Valenti+ 2000, 2003, Bergin+, 2003, Herczeg+ 2004)

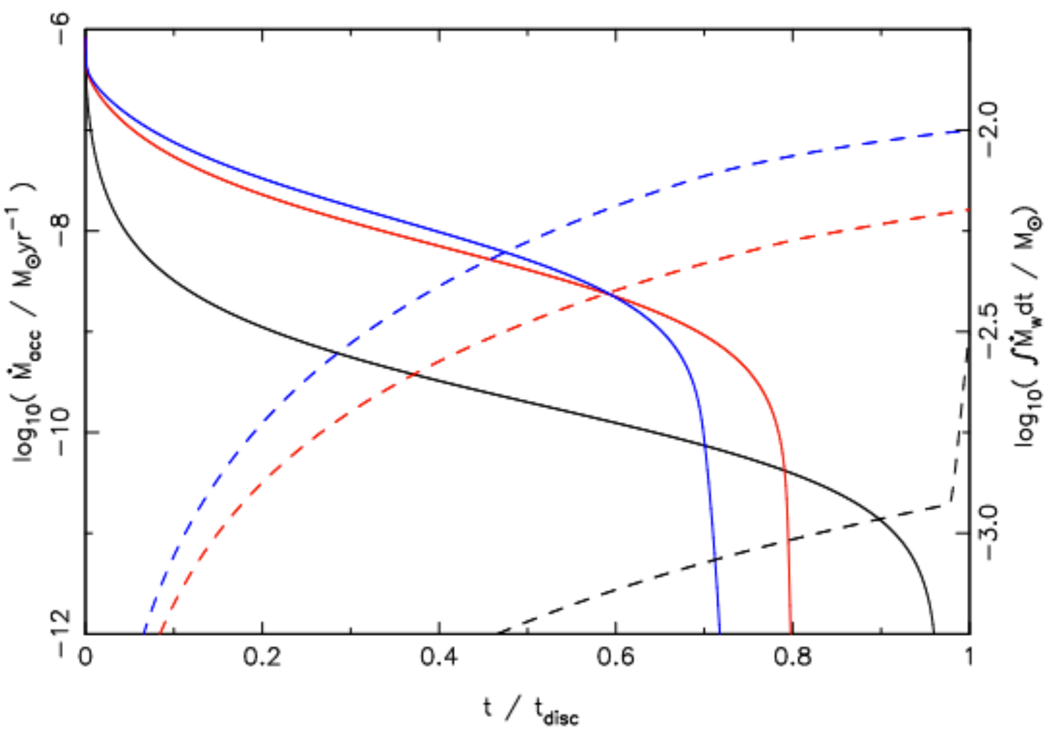
Photoevaporation by nearby massive stars, if present, can be overwhelming.

Photoevaporation of disks

Normalized mass loss profiles



Total mass loss rates



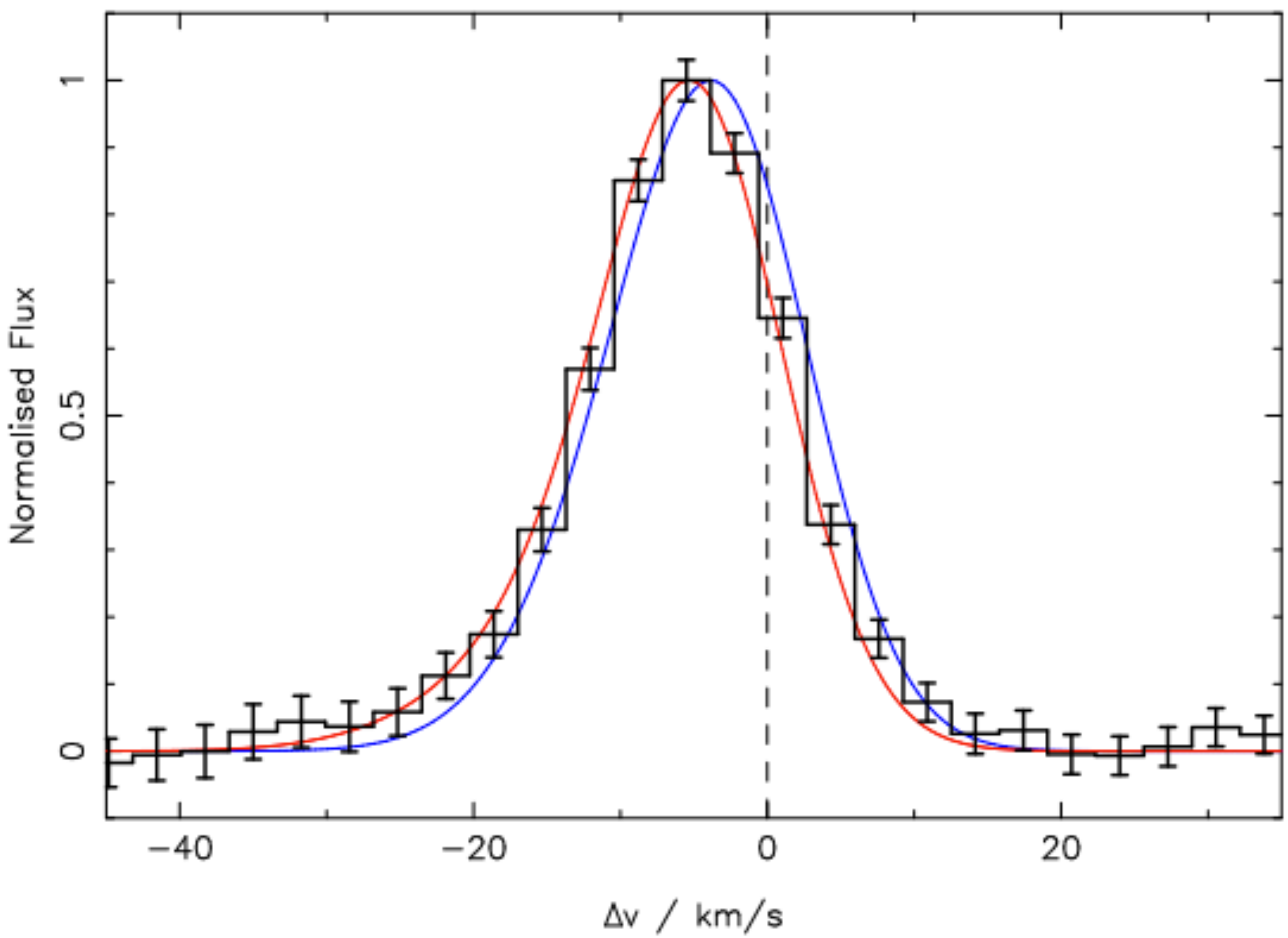
Black: EUV; Blue: FUV; Red: X-ray

(Alexander et al, 2014, PPVI)

General picture: inside-out clearing.

When coupled with viscous evolution, can very quickly evaporate the disk once accretion rate drops below mass loss rate.

Observational evidence



Low-velocity, ionized outflow emanating from the disk.

Similar also seen in other lines (e.g., OI 63μm, CO 4.7μm, Rigliaco+ 2013).

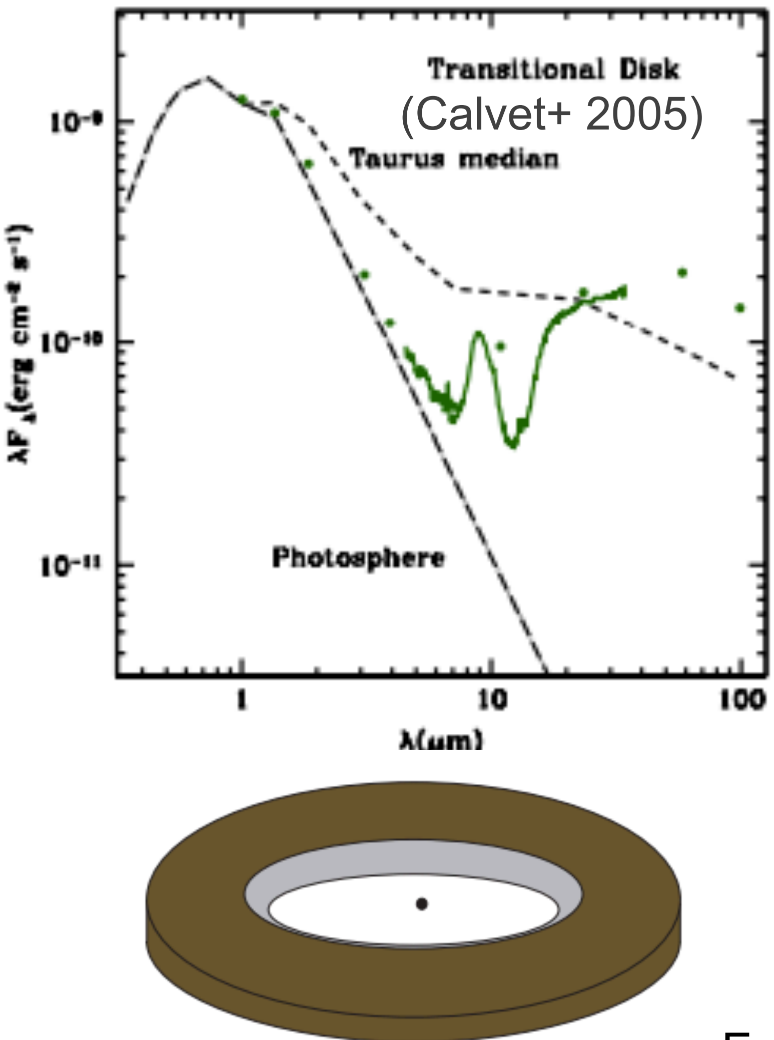
Ne II (12.81μm) line profile from TW Hya (Pascucci+ 2011)

red/blue: normalized flux based on EUV/X-ray photoevaporation models.

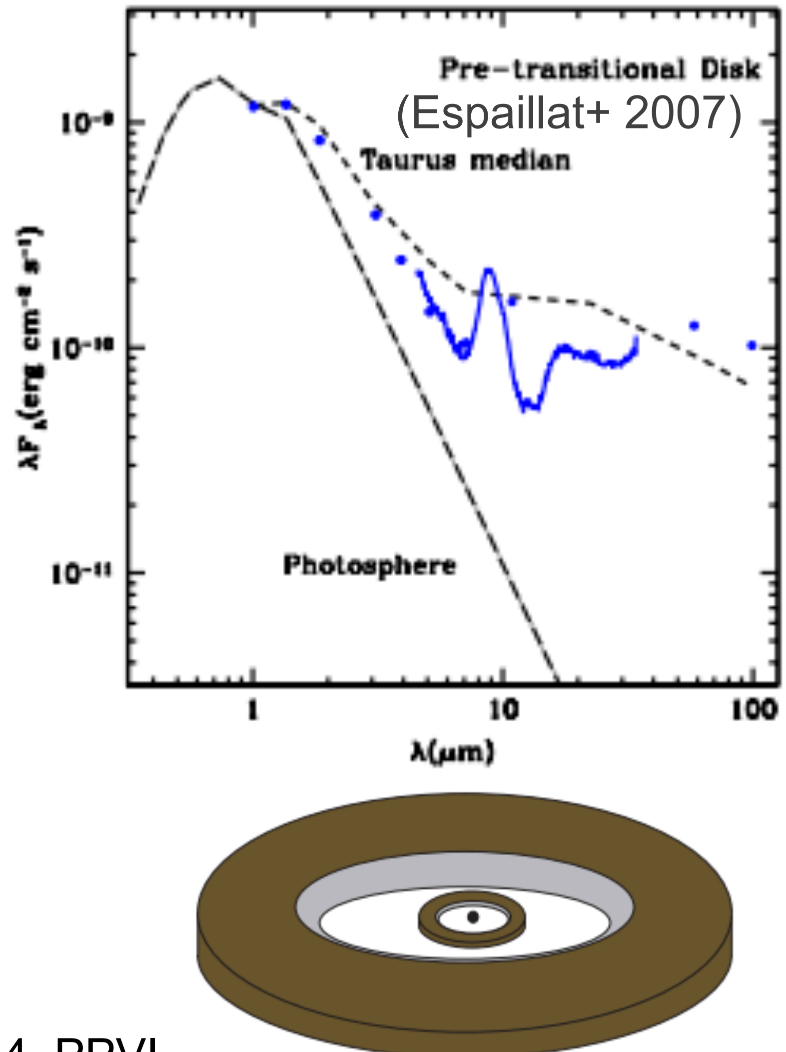
(Alexander 2008; Ercolano & Owen, 2010)

Transition disks

Deficit of NIR and/or MIR flux with respect to the median SED of CTS (Strom et al. 1989)



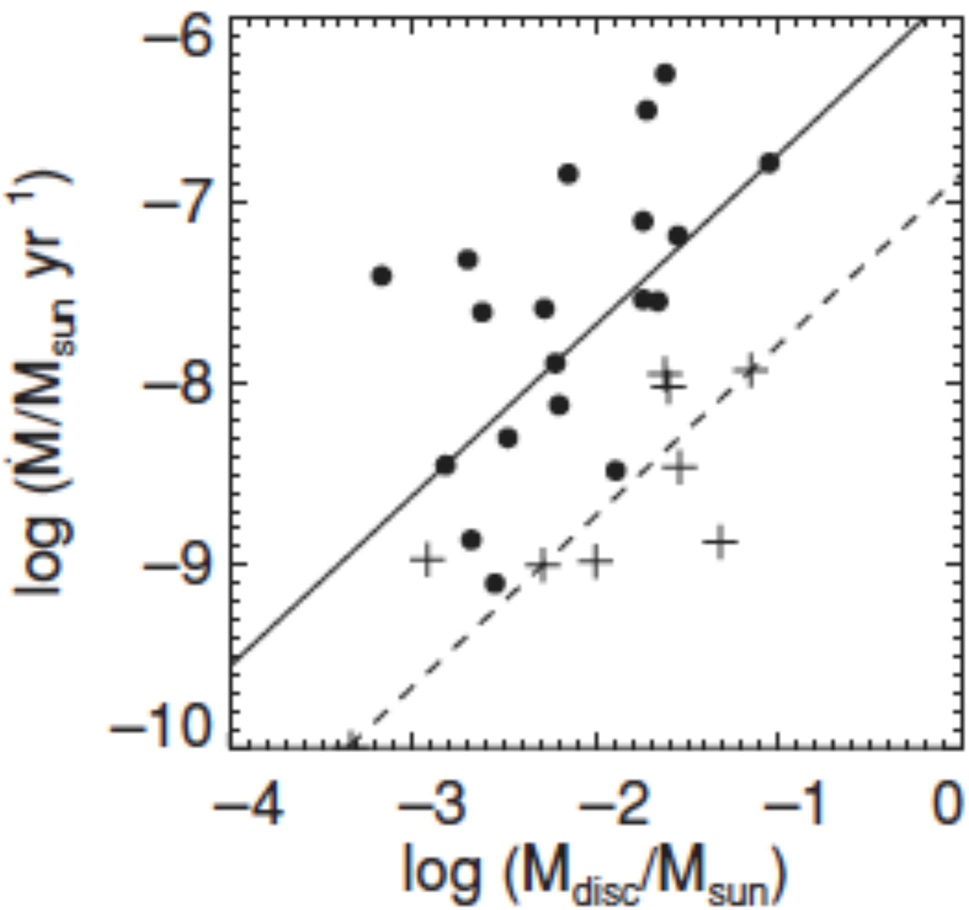
Transitional Disk



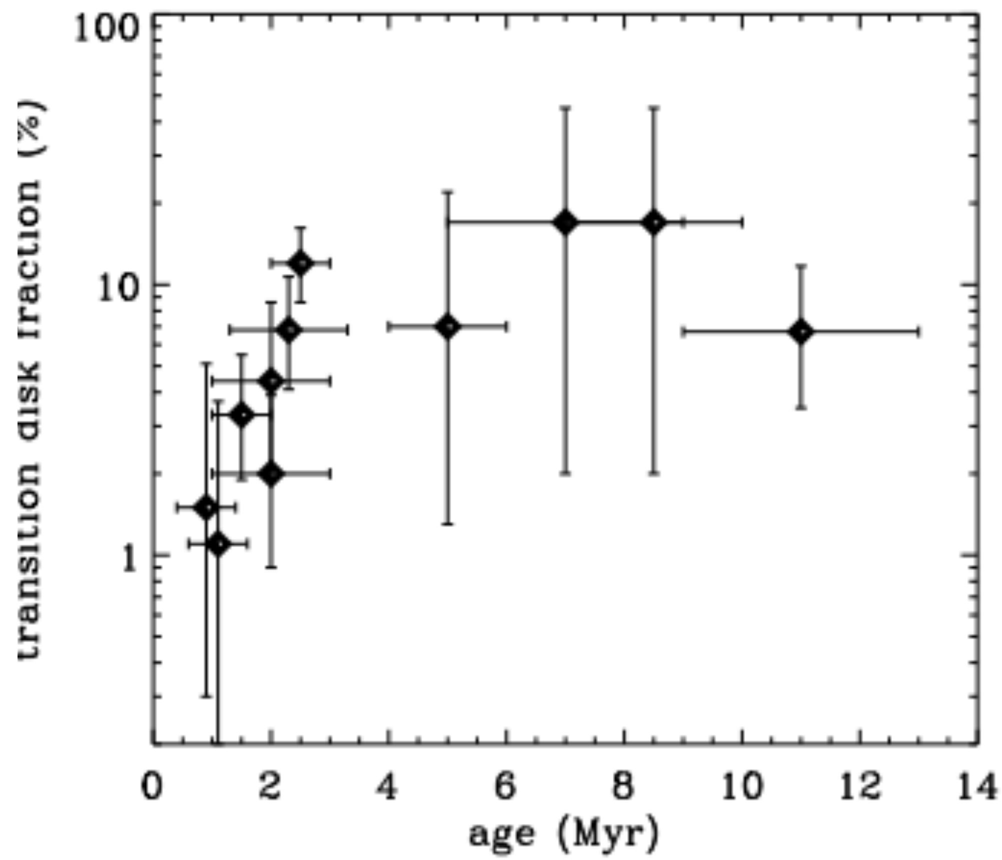
Pre-Transitional Disk

Espaillat+ 2014, PPVI

Demographics



(Najita et al. 2007)



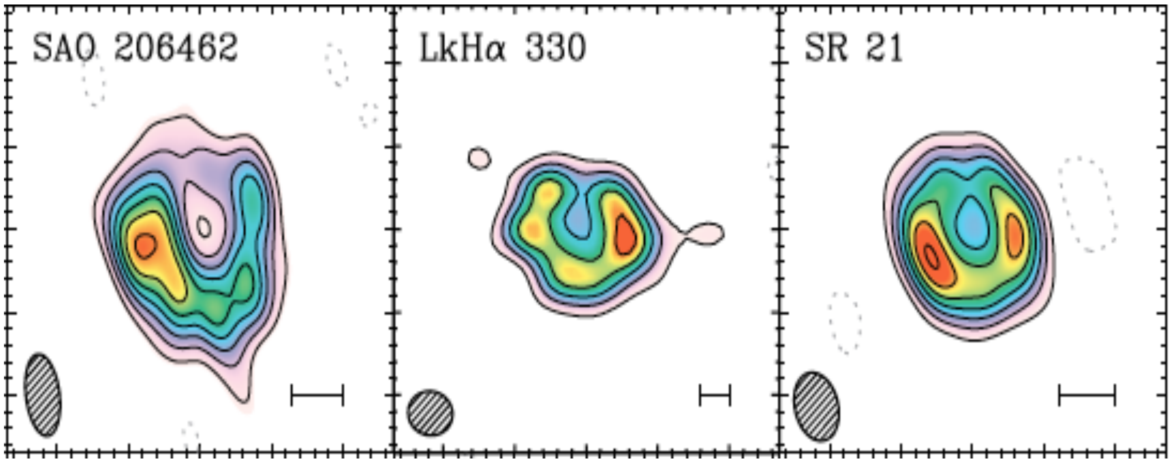
(Espaillat et al. 2014, PPVI)

Transition disks are still actively accreting!

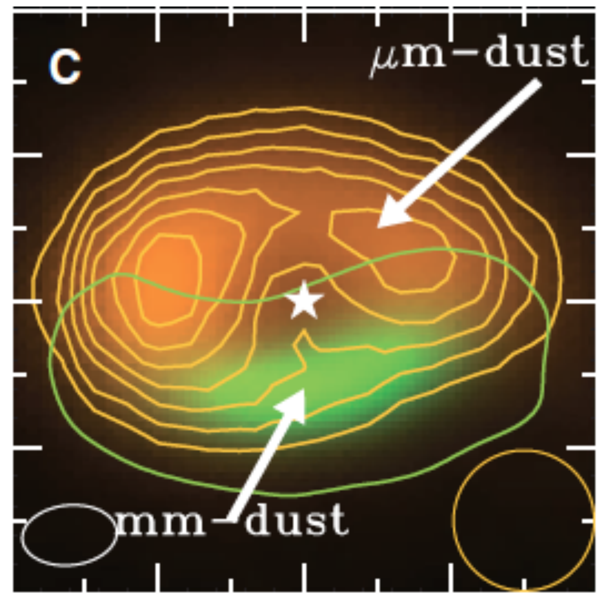
Transition disks constitute of ~10-20% of the disk population.

Resolved images and asymmetries

Sub-mm, 880μm continuum imaging

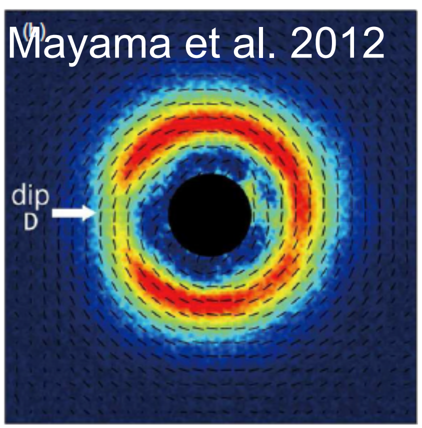


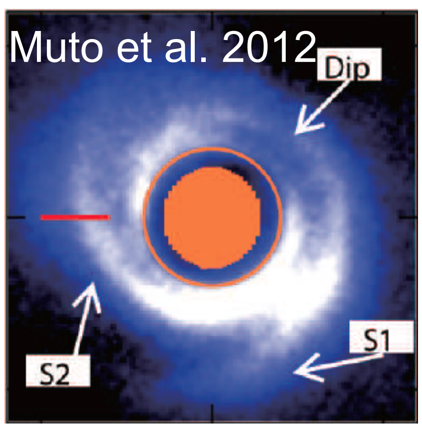
(Andrews et al. 2011)



van der Marel et al. 2013

H-band PDI from the SEEDS project





Dust of different sizes behave very differently!

Mechanisms and puzzles

- **Non-dynamical mechanisms:**
  - Viscous evolution: self-similar evolution, hard to form holes.
  - Grain growth and transport: (e.g., Birnstil+ 2012)

    Hard to simultaneously explain μm and mm cavities.
  - Photoevaporation: (e.g., Alexander & Armitage 2009, Owen+ 2011)

    Works for some cases but not all, especially those with large accretion rates.
- **Dynamical mechanisms:**
  - Multiple planets: (e.g., Zhu+ 2011, Dodson-Robinson & Salyk 2011)

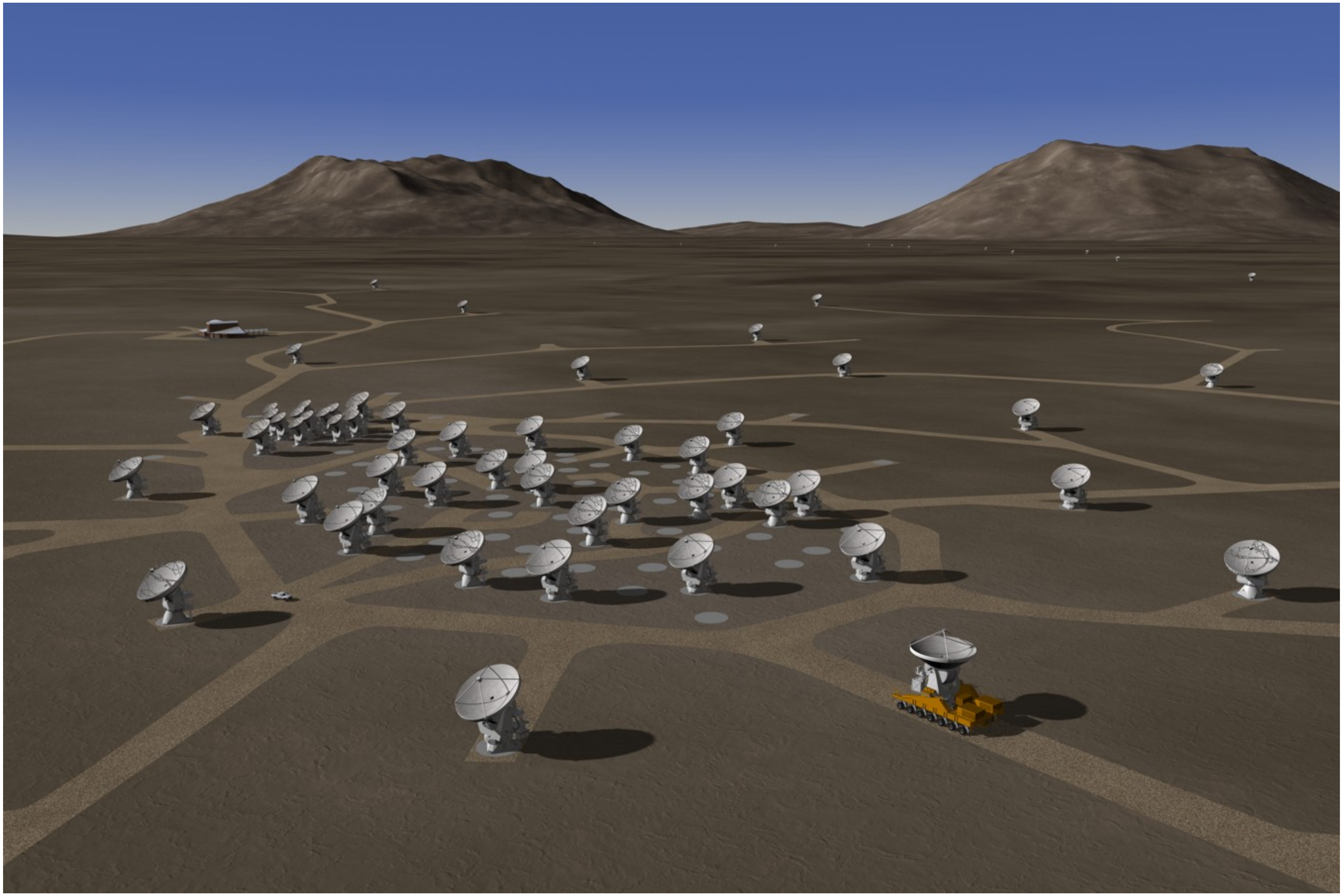
    Still need substantial dust depletion to make the inner disk optically thin.
  - Single planet + dust filtration: (e.g., Rice+ 2006, Zhu+ 2012)

    Large grains “filtered” through disk gaps, small grains penetrate.

Summary on protoplanetary disks

- PPDs form early (~class 0) during star formation.
- From class II phase, total mass ~0.01 stellar mass and size ~100 AU with surface density profile ~r^{-1}.
- Disks are flared, with excess emission from IR to mm from dust.
- Mean lifetime ~3Myr, and followed by rapid dispersal presumably due to photoevaporation.
- Accretion onto the protostar at the rate of ~$10^{-8} M_{\odot}$/yr, which strongly correlates with jet/outflow.
- Transition disks constitute ~10-20% of disk population, may represent late evolution stage, or due to planet formation.
- Broadband SEDs as well as IR-mm spectrum of gas species are major disk probes, which can be substantially boosted from mm and IR interferometry (e.g., ALMA).

Atacama Large Millimeter/sub-mm Array



Location: Chajnantor plain, Chile (altitude ~5000m)