Protoplanetary Disks and Their Evolution

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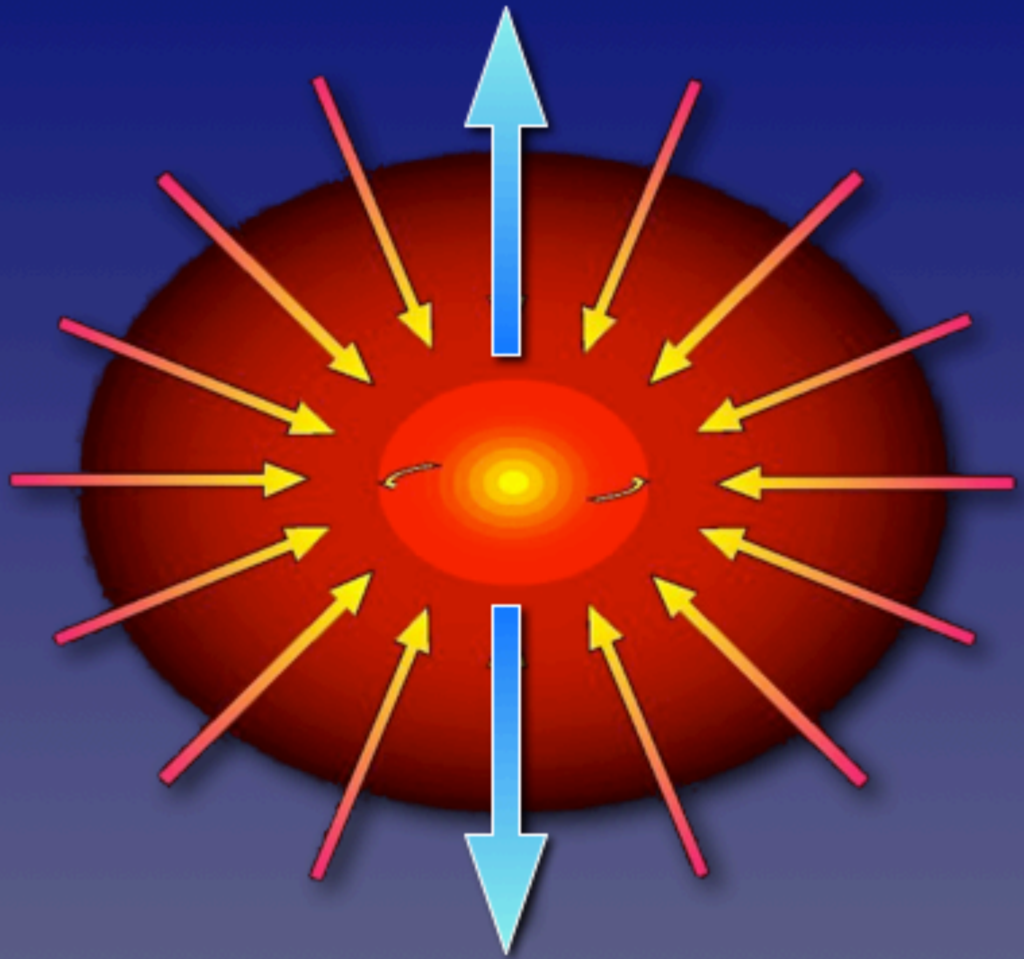
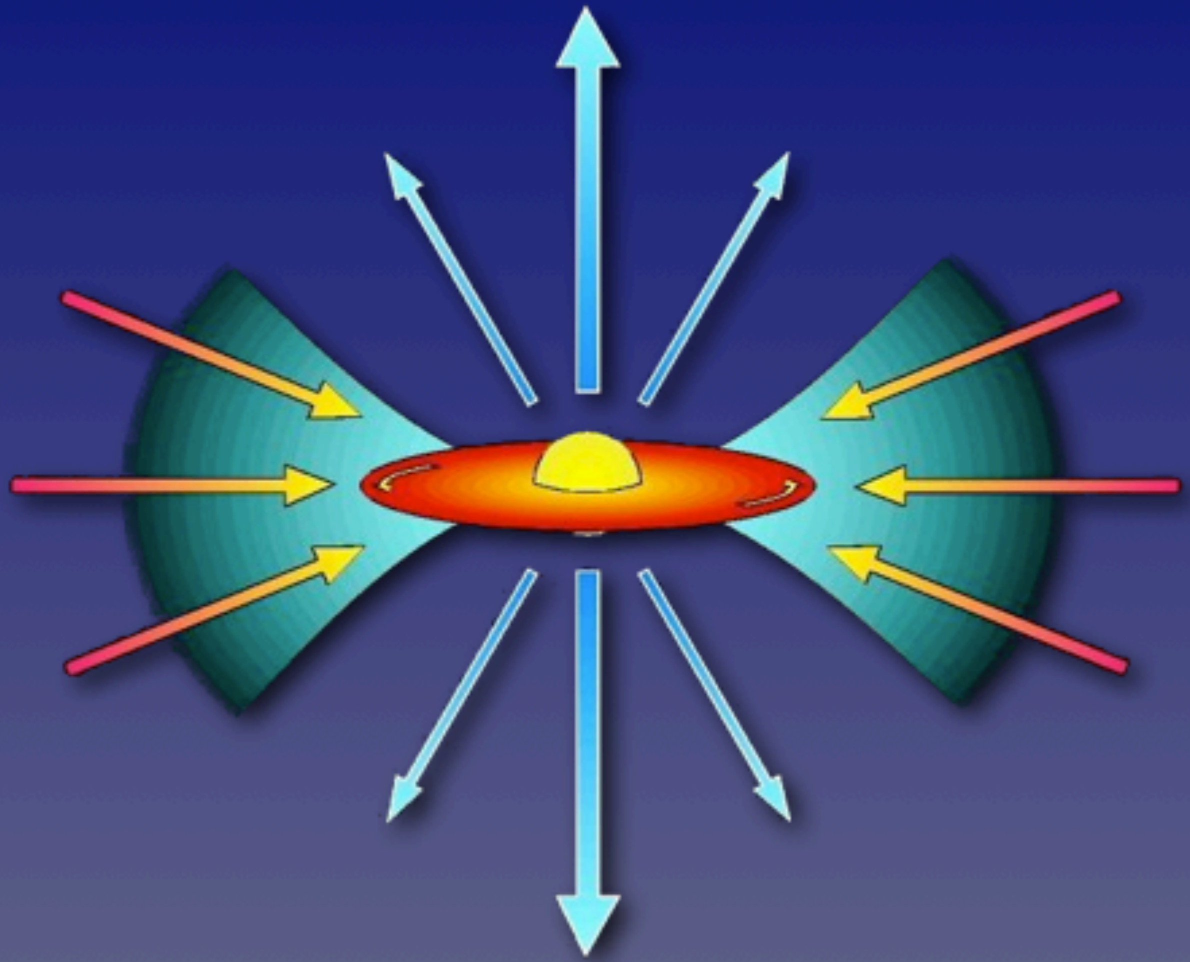
Circumstellar disks

- Disks accompany the birth of all low-mass stars
- Present for millions of years
- Their material builds up the star & planets
- Emit at IR and mm wavelengths → measure mass, size, structure, composition

The isolated star formation paradigm

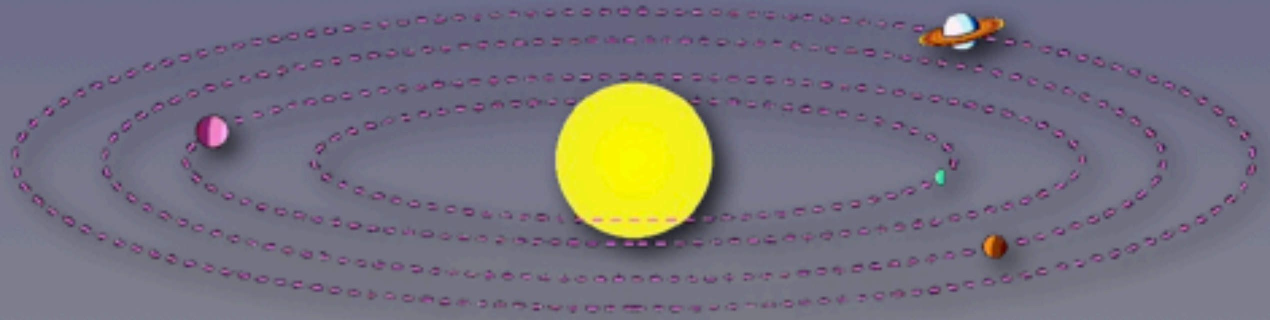


Class 0:
10^4 yrs; 10-10^4 AU; 10-300 K



Class I-II:
10^{5-6} yrs; 1-1000 AU; 100-3000 K

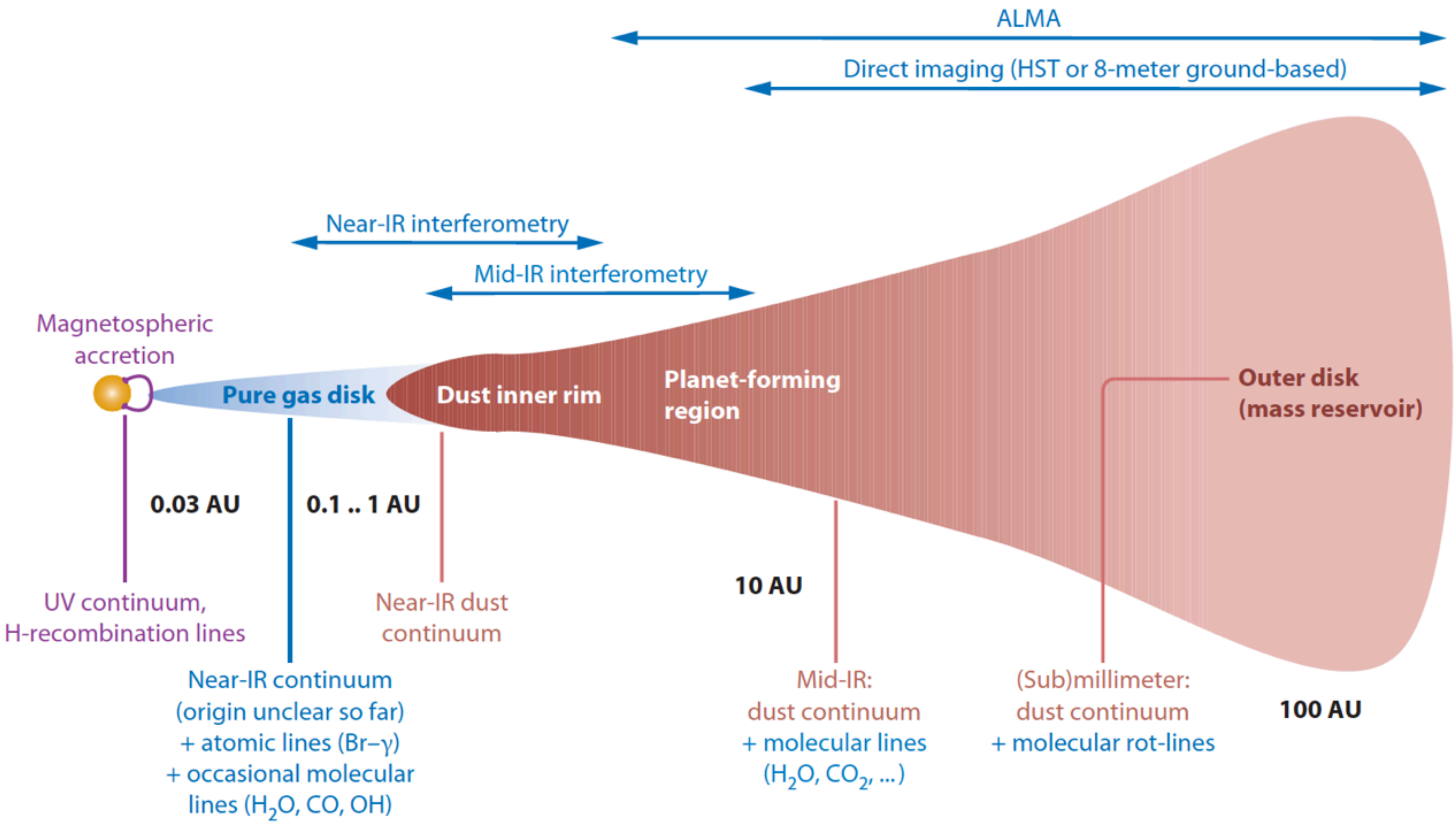
Class II-III:
10^{6-7} yrs; 1-100 AU; 100-5000 K



Class IV:
10^{7-9} yrs; 1-100 AU; 100-5000 K

After Shu, Adams, & Lada

Circumstellar disks



ALMA

Direct imaging (HST or 8-meter ground-based)

Near-IR interferometry

Mid-IR interferometry

Magnetospheric accretion

Pure gas disk

Dust inner rim

Planet-forming region

Outer disk (mass reservoir)

0.03 AU

0.1 .. 1 AU

10 AU

100 AU

UV continuum,
H-recombination lines

Near-IR continuum
(origin unclear so far)
+ atomic lines (Br–γ)
+ occasional molecular
lines (H_2O, CO, OH)

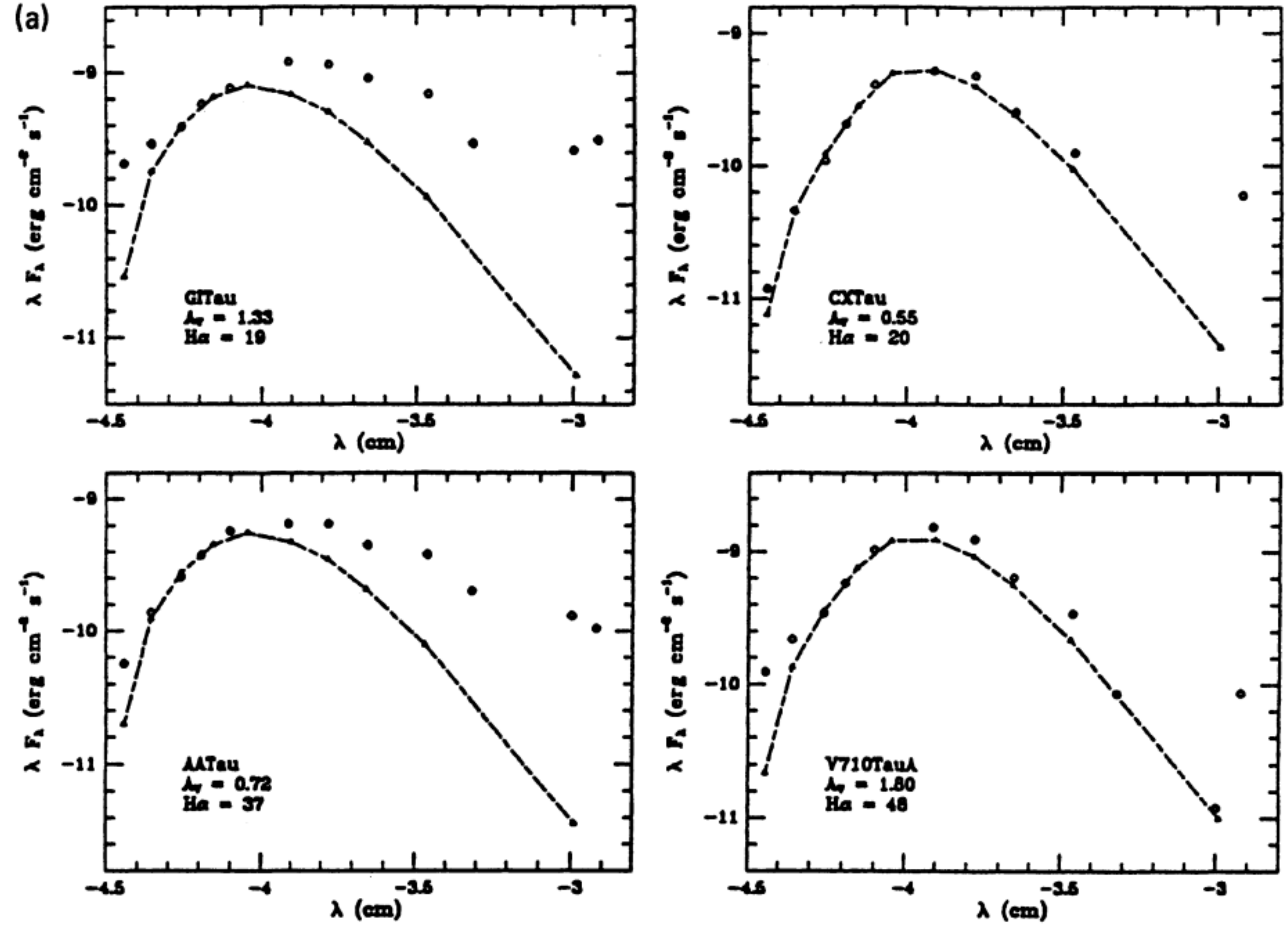
Near-IR dust
continuum

Mid-IR:
dust continuum
+ molecular lines
(H_2O, CO_2, ...)

(Sub)millimeter:
dust continuum
+ molecular rot-lines

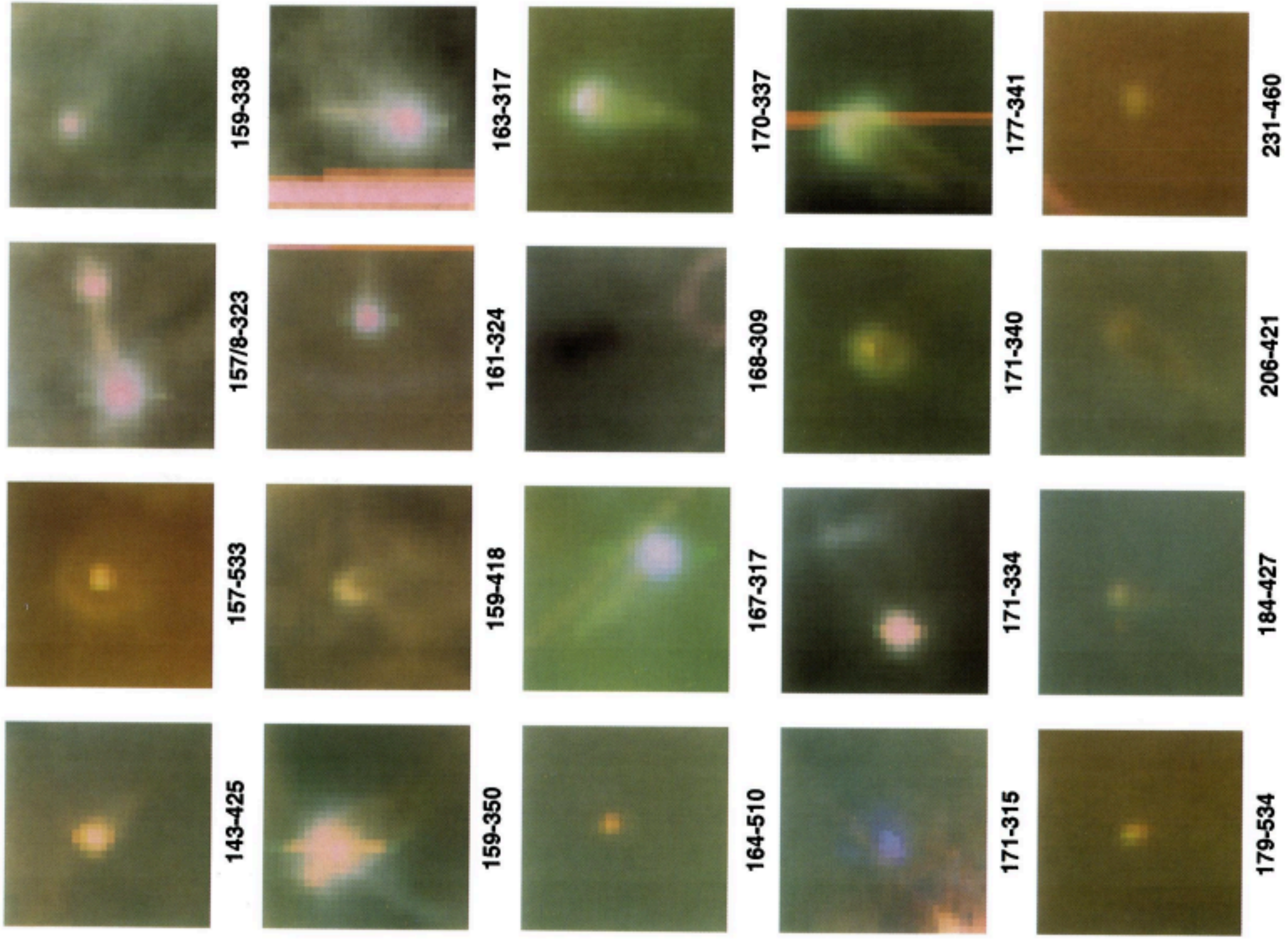
Dullemond & Monnier 2010

First statistical studies



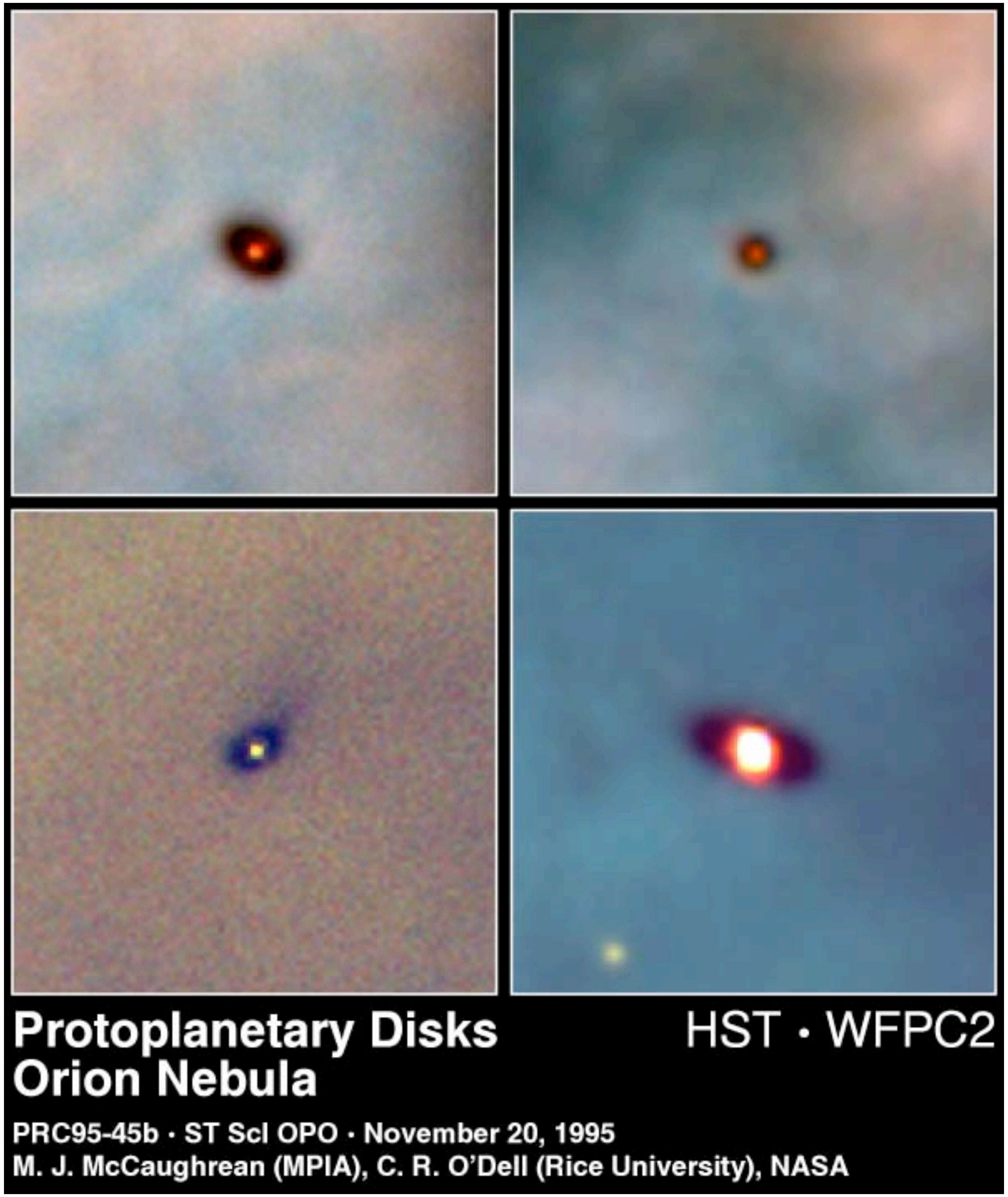
Strom et al. 1989

Evidence for flatness



O'Dell & Wen (1994)

Evidence for flatness



Protoplanetary Disks
Orion Nebula

HST • WFPC2

PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

McCaughrean & O'Dell (1995)

New discoveries

- Infrared Space Observatory (ISO)
- Spitzer Space Telescope
- Herschel Space Observatory
- Ground-based mm interferometers: SMA, PdBI, CARMA, ALMA

Info on disks

- Regular reviews: Protostars & Planets conference series
- ARA&A papers:
    - cosmic silicates (Henning 2010)
    - inner disks (Dullemond & Monnier 2010)
    - debris disks (Wyatt 2008)
    - dynamical processes (Armitage 2011)

Circumstellar disks

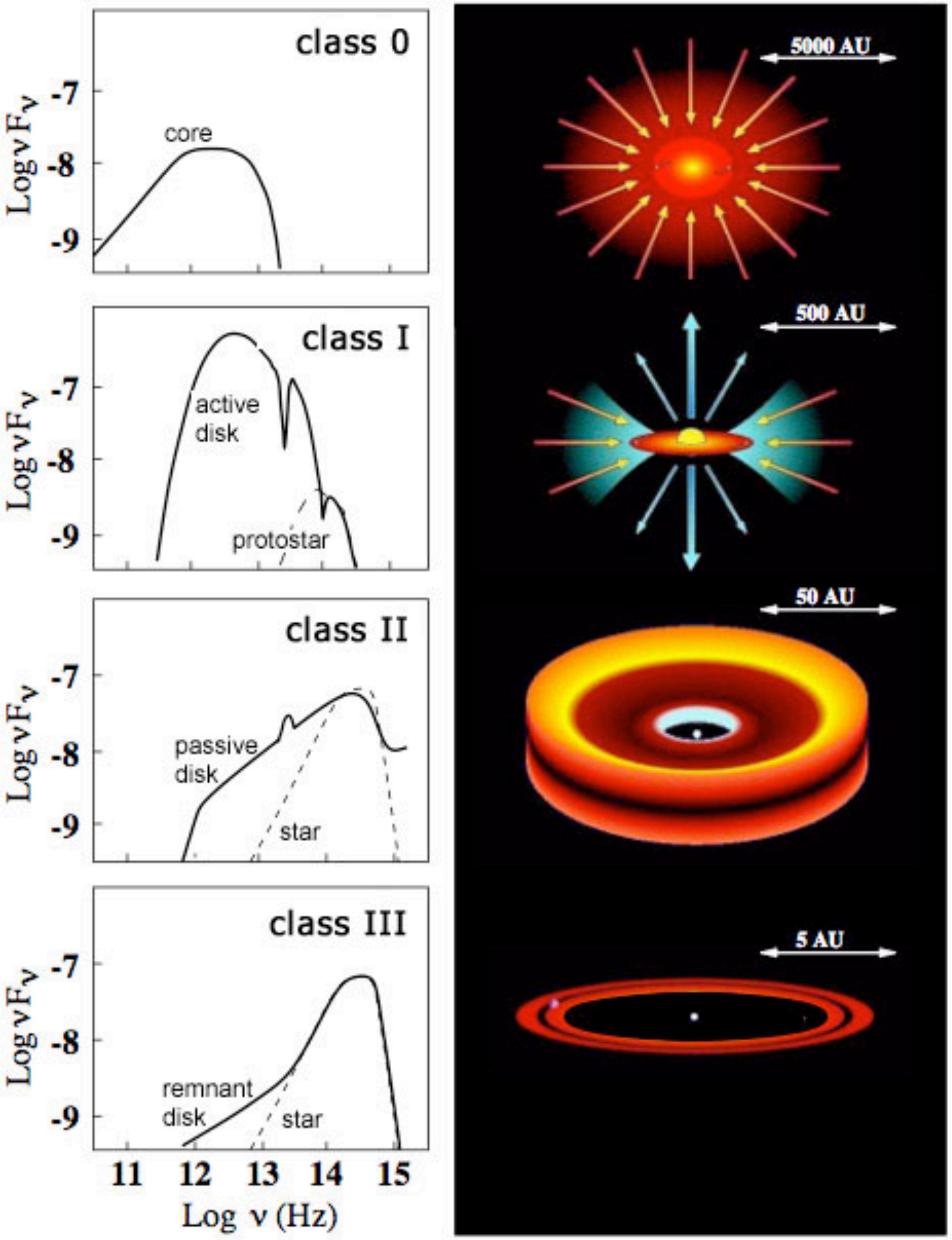
1. Intro
2. YSO classification
3. Formation of disks
4. Properties of disks
5. Disk lifetimes
6. Processes governing disk evolution
7. Transitional disks, end state of disk evolution
8. Summary
9. Future directions

Classification of YSOs

- IR-based classification: Lada & Wilking (1984)
- Class I-II-III
- Spectral slope between 2 and 25 µm

$$\alpha_{\mathrm{IR}} = \frac{d\log \nu F_\nu}{d\log \nu} = \frac{d\log \lambda F_\lambda}{d\log \lambda}$$

- Flat spectrum; Class 0
- CTTS / WTTS EW(Hα) ~ 10 Å



Classification of YSOs

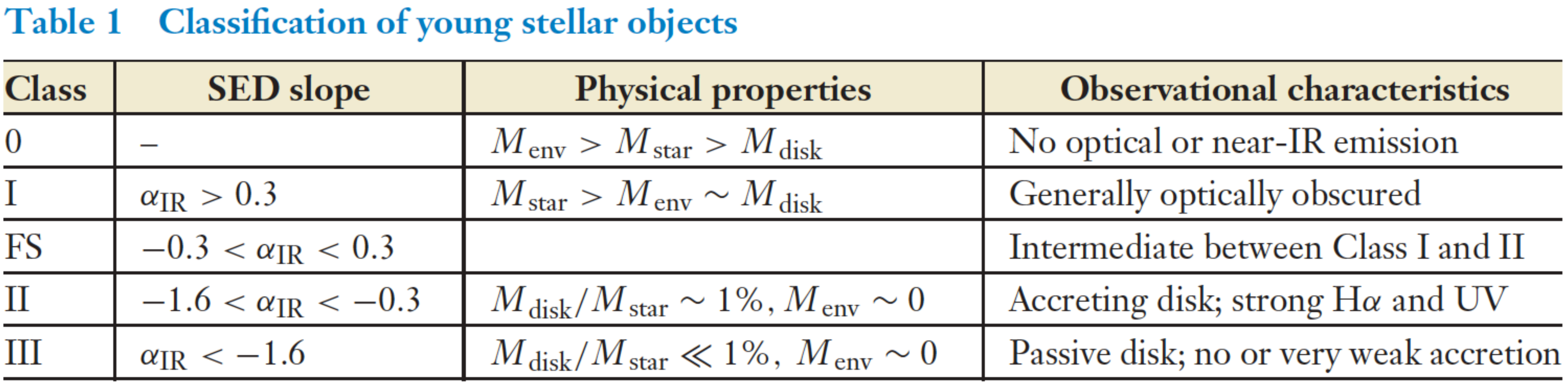


Table 1 Classification of young stellar objects

Class	SED slope	Physical properties	Observational characteristics
0	–	$M_{\rm env} > M_{\rm star} > M_{\rm disk}$	No optical or near-IR emission
I	$\alpha_{\rm IR} > 0.3$	$M_{\rm star} > M_{\rm env} \sim M_{\rm disk}$	Generally optically obscured
FS	$-0.3 < \alpha_{\rm IR} < 0.3$		Intermediate between Class I and II
II	$-1.6 < \alpha_{\rm IR} < -0.3$	$M_{\rm disk}/M_{\rm star} \sim 1\%, M_{\rm env} \sim 0$	Accreting disk; strong Hα and UV
III	$\alpha_{\rm IR} < -1.6$	$M_{\rm disk}/M_{\rm star} \ll 1\%,\ M_{\rm env} \sim 0$	Passive disk; no or very weak accretion

Problems:

- SED is ambiguous: objects with different amount/distribution of material can have similar SEDs
- Example: edge-on disks are highly extincted → seem less evolved

Disk formation

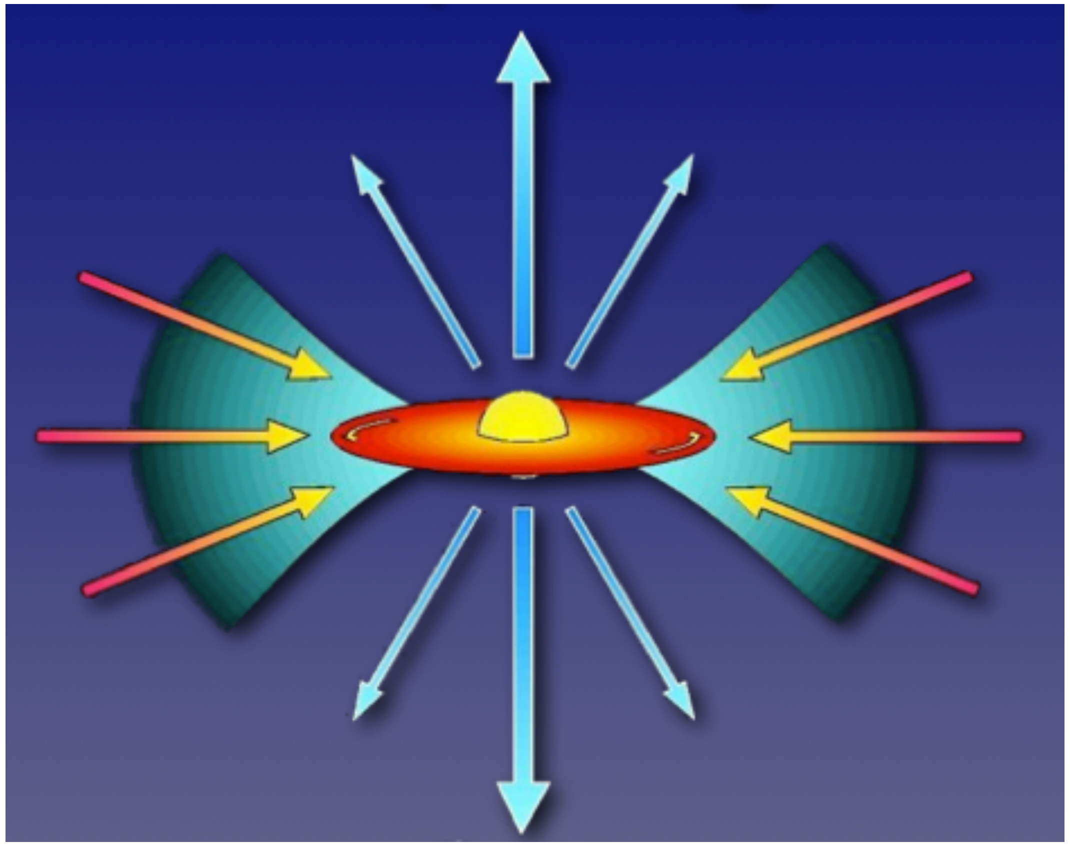
Theoretical calculations: Terebey, Shu & Cassen (1984)

- Uniformly rotating isothermal sphere
- Equilibrium is unstable to collapse
- Disks grow rapidly with time: $R(t) \sim \Omega^2 t^3$
- Various masses and sizes
- Role of magnetic field: unclear, but doesn't support the cloud from collapsing
- Disks form within 10^4 years

Disk formation

Observations

- Disks are visible due to polar cavity in the envelope



- Inward motions in cores? Observed.
- Direct detection of gas flow onto a disk? Not observed yet.
- Imaging embedded disks: long wavelength to see through the envelope; >arcsec resolution to match disk sizes → mm interferometers

Rapid transport in disks

- Jørgensen et al. (2009): 1.1mm continuum survey of 20 embedded YSOs
- Disk flux is typically 4x higher in Class 0 than in Class I.
- Class 0 sources are also hotter.
- Masses in both Class 0 and Class I are the same $\sim 0.02 - 0.1\ M_\odot$; median disk mass = $0.04\ M_\odot$.
- Envelope mass declines by x10 from Class 0 to Class I
- Material is rapidly transported through the disk

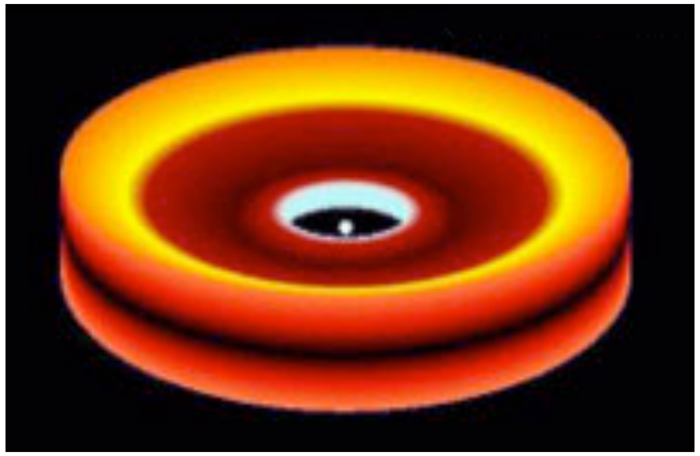
Rapid transport in disks

- Cause of rapid transport: disk instability
- Gravitational instability during early formation
- Sporadic bursts of high accretion (FU Orionis)
- Prevents the disk from growing too much in mass
- Another evidence for episodic accretion: envelope infall rates are > 10x higher than disk accretion rates in Class I YSOs → mass builds up in the disks until it bursts
- Episodic accretion: possible solution for the luminosity problem

From Class I to Class II

- Class 0 + Class I phase lasts about 0.5 Myr
- By the end of Class I, envelope disperses
- Disk mass is typically 0.01 M_{star}
- Star formation process is effectively over
- Disk: protoplanetary, not protostellar
- Disk material:
    - accretes onto the star
    - disperses due to photoevaportion
    - coagulates into larger bodies

Properties of Class II disks



- Extinction is low → stellar properties can be observed in the optical/near-IR
- Minimum mass solar nebula: lowest mass primordial disk that could have formed the solar system (computed by scaling planetary composition to cosmic abundances)
- MMSN = $0.01 - 0.07\ M_\odot$
- $\Sigma \sim r^{-3/2}$

Disk mass: basics

- Best determined from (sub)millimeter observations
- Dust continuum emission is optically thin for most of the disk
- Optical depth:

$$\tau_\nu = \int \rho \kappa_\nu ds = \kappa_\nu \Sigma$$

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

where Σ is the projected surface density
β is related to dust size and composition

- Dust continuum emission is optically thin for most of the disk

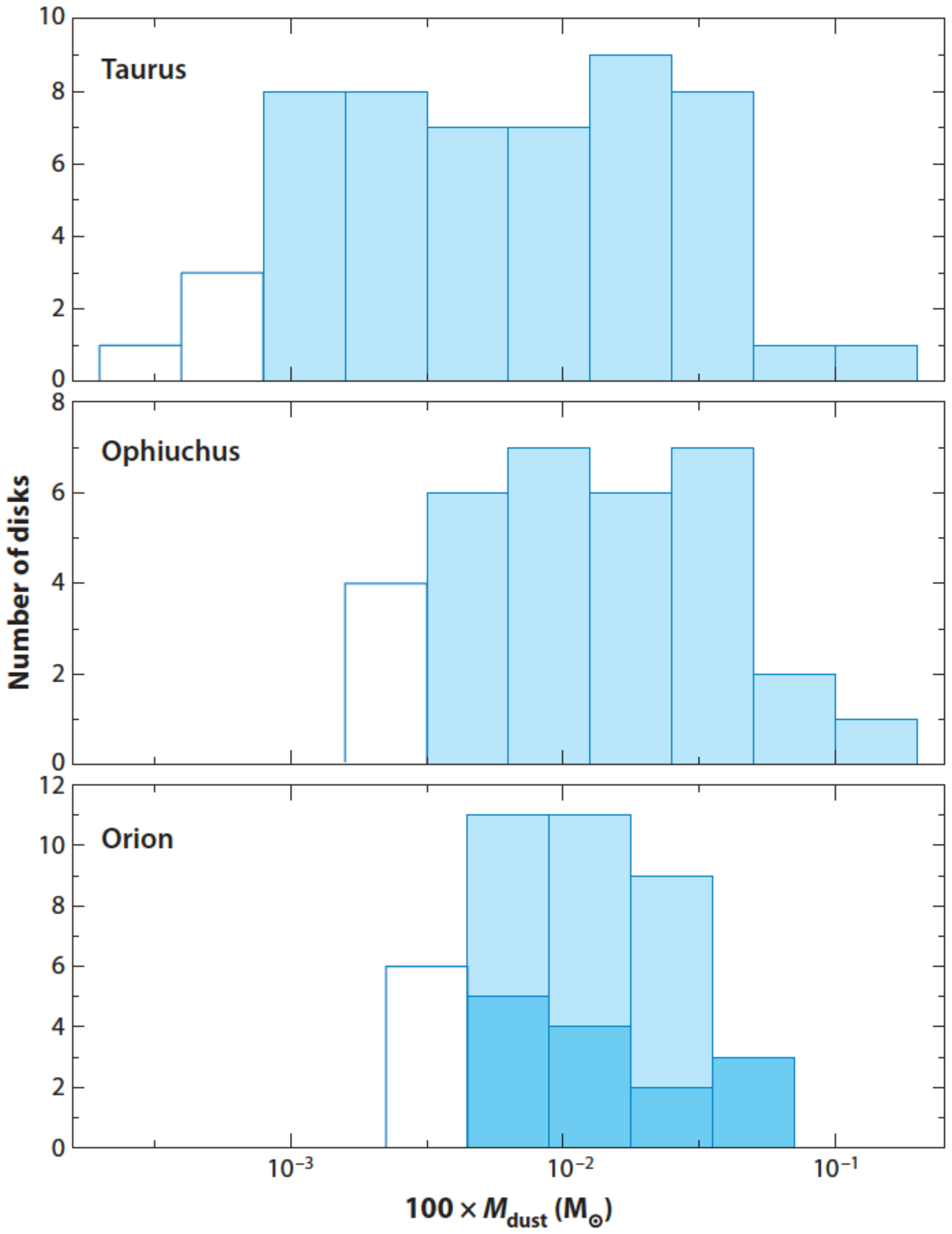
Optically thin emission

- In circumstellar disks: $\beta \sim 1$
- κ(1 mm) = 0.03 $\mathrm{cm^2 g^{-1}}$
- τ(1 mm) = 1 where Σ = 30 $\mathrm{g\ cm^{-2}}$
- Corresponds to 10 AU in the MMSN
- Corresponds to 0.07″ in Taurus
- Disks are larger than this → most of the resolved emission is optically thin
- Disk mass: $M\,(\mathrm{gas}+\mathrm{dust}) = \dfrac{F_\nu d^2}{\kappa_\nu B_\nu(T)}$ $\qquad B_\nu \approx 2\nu^2 kT/c^2$

Disk mass distribution

- Large mm surveys:
  Beckwith et al. (1990) Taurus-Auriga
  André & Montmerle (1994) Ophiuchus
- Andrews & Williams (2005, 2007)
- Median disk mass for Class I YSOs: 5 M_{Jup}
- Median M_{disk} / M_{star} = 0.009
- Mass distribution in log mass bins: flat until 50 M_{Jup}

Disk mass distribution

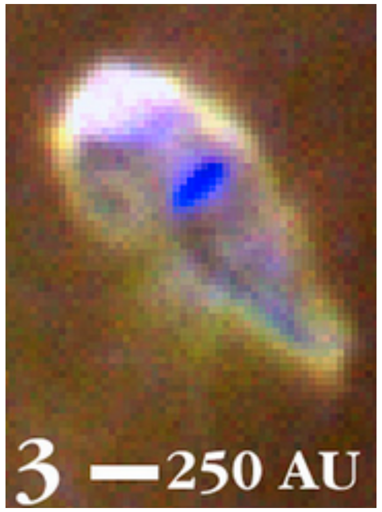


Uncertainties in mass

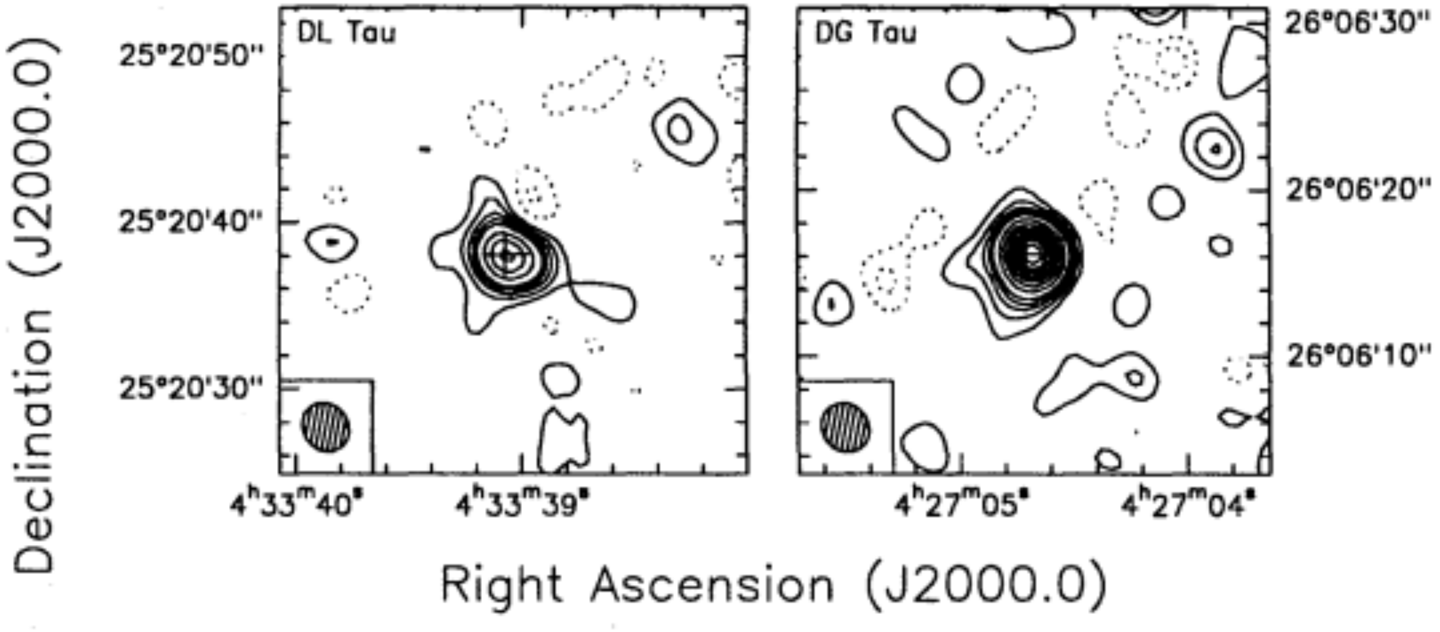
- Gas-to-dust ratio is assumed to be interstellar (100) → overestimation
- Hidden mass in large grains → underestimation
- Rule of thumb: observations at λ is sensitive to grains with sizes of < 3λ
- Indications for severe underestimation:
    - measured disk masses are lower than what is expected by integrating the accretion rate over the protostellar age
    - not enough massive disks to match the statistics on the incidence of exoplanets

Disk radius

- Difficult to measure: outer parts are cold and faint
- Disk silhouettes in Orion:
  radii between 50 and 194 au
  median radius of 75 au

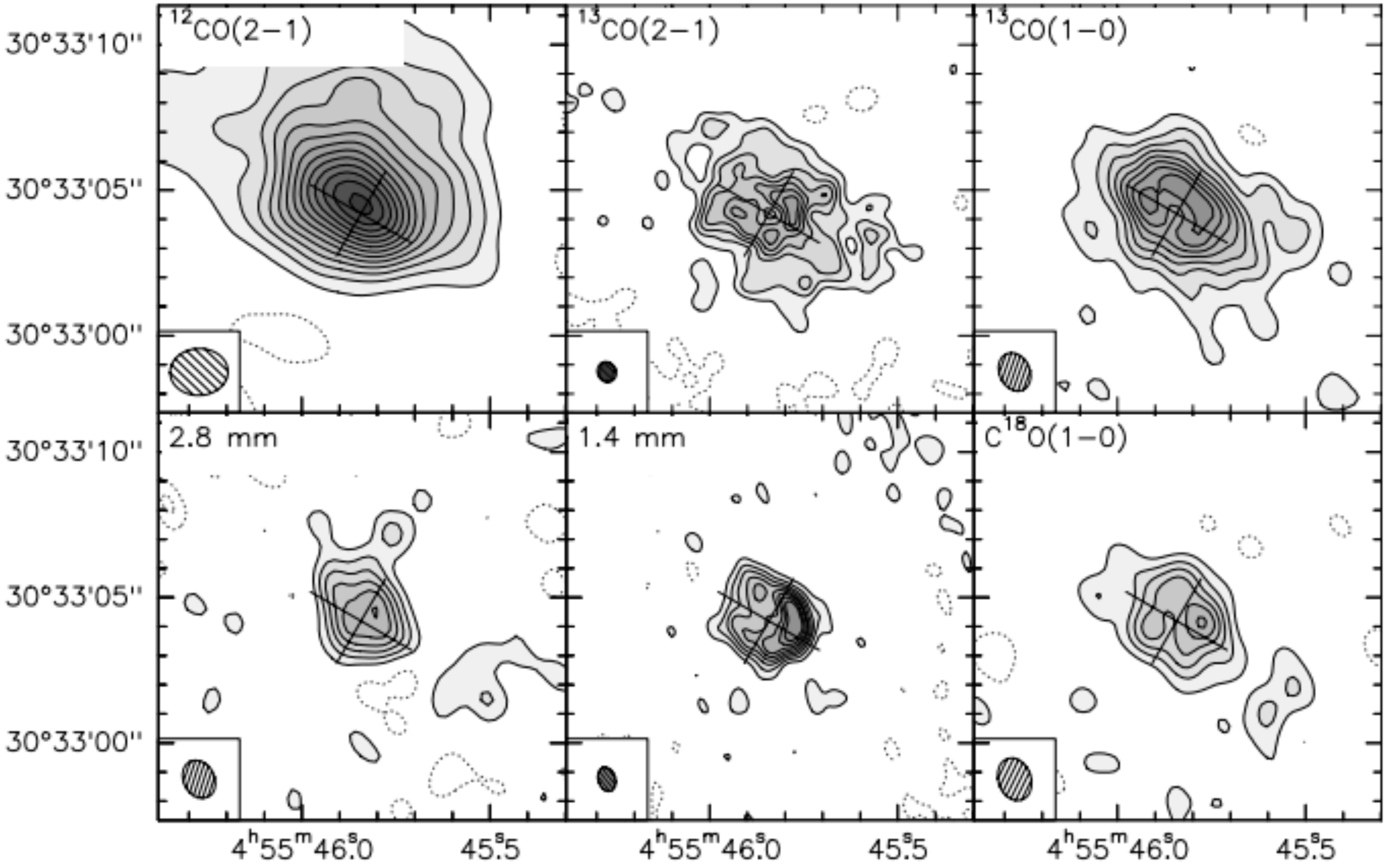


- Millimeter disk images: requires interferometry
- First large interferometric survey: Dutrey et al. (1996):
  typical disk sizes in
  Taurus: 1 − 2″
  (r = 75 − 150 au)



Dust size vs. gas size

- Problem: dust sizes ≠ gas sizes (size from CO lines larger than from dust continuum)



AB Aur Pietu et al. (2005)

Dust size vs. gas size

- Possible solutions:
- Change in the gas-to-dust ratio or dust opacity at a certain radius
- Exponentially tapered density profile:

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

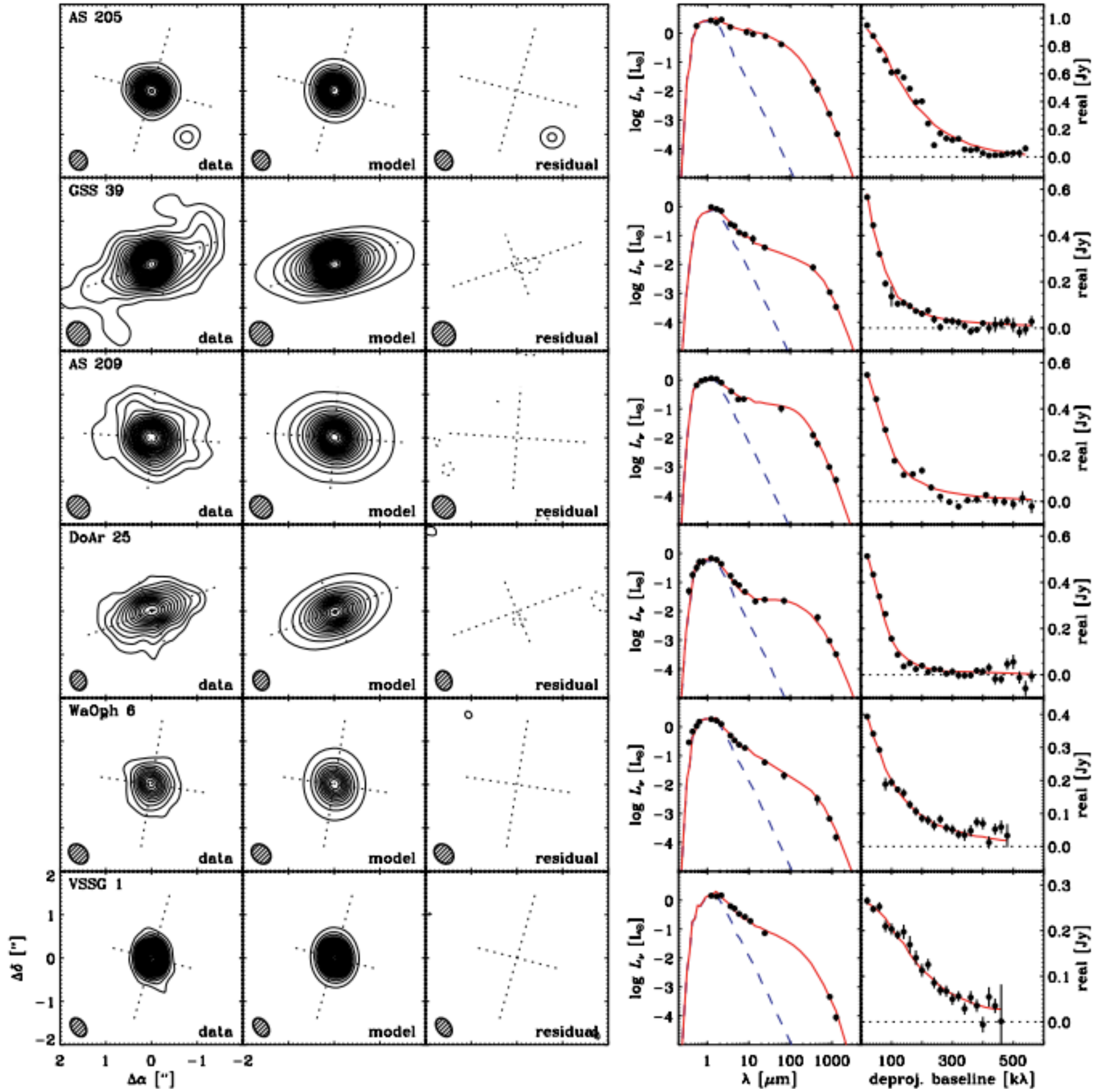
- Apparent size discrepancy! mm continuum is optically thin, CO line emission is optically thick → can be detected further out
- Rc: characteristic radius where the density profile begins to steepen significantly from a power law, typically Rc = 30 − 200 au

Parameter correlations

- Between disk size and disk mass:

$$M_d \propto R_c^{1.6\pm0.3}$$

- Between disk size and stellar properties: no correlation



Andrews et al. (2009)

Disk structure – Σ

- Resolved mm image of the disk → total mass + radial mass distribution
- Usual parametrization: power law: $\Sigma \sim R^{-p}$
- $p = 0 \ldots 1$
- Exponentially tapered edge

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

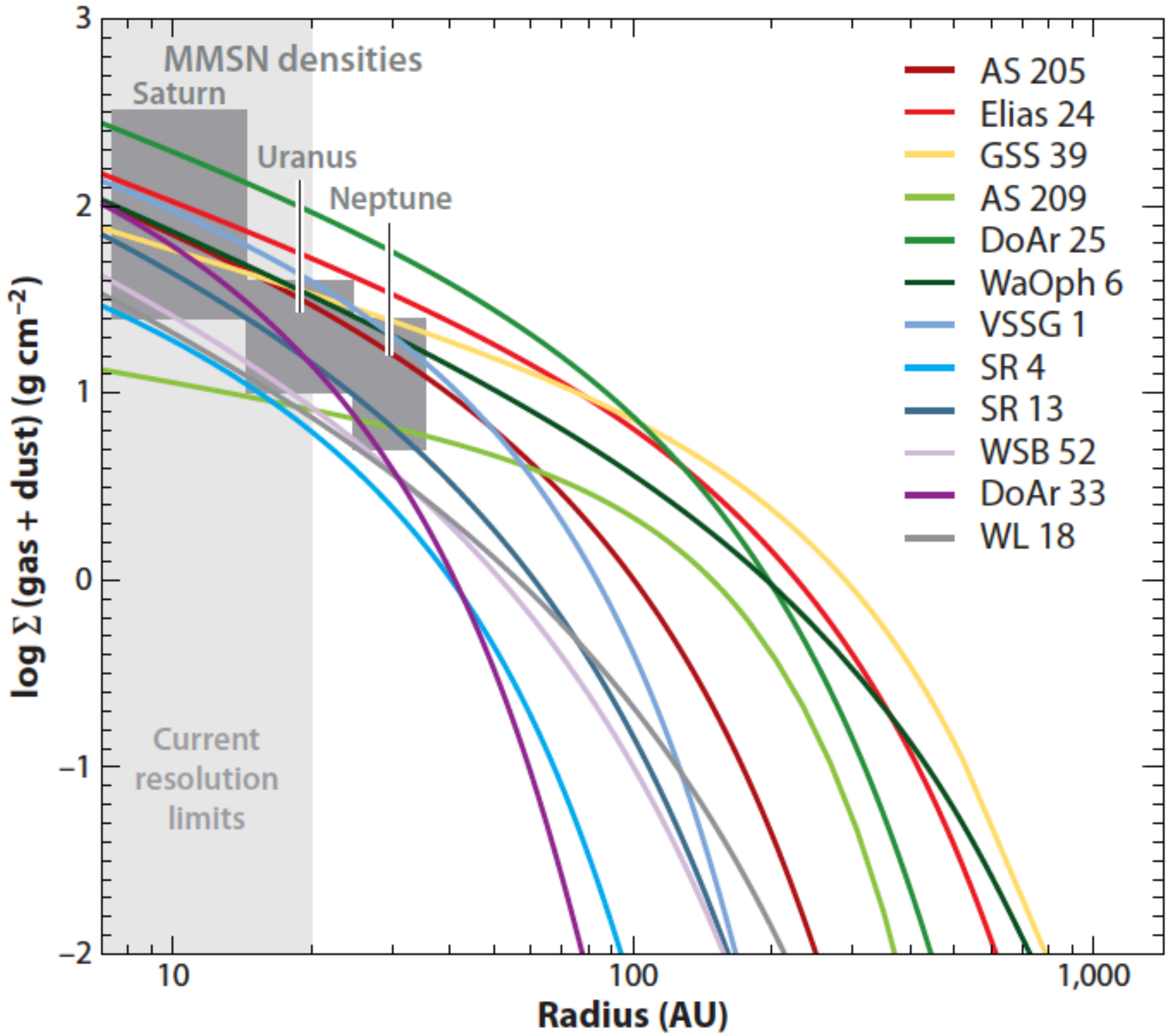
- Approximates $\Sigma \sim R^{-\gamma}$ for $R \ll R_c$
- $\gamma = -0.8 \ldots 0.8$ (mean 0.1)
- Σ distribution is quite flat (cf. p=1.5 for MMSN)

Σ distribution

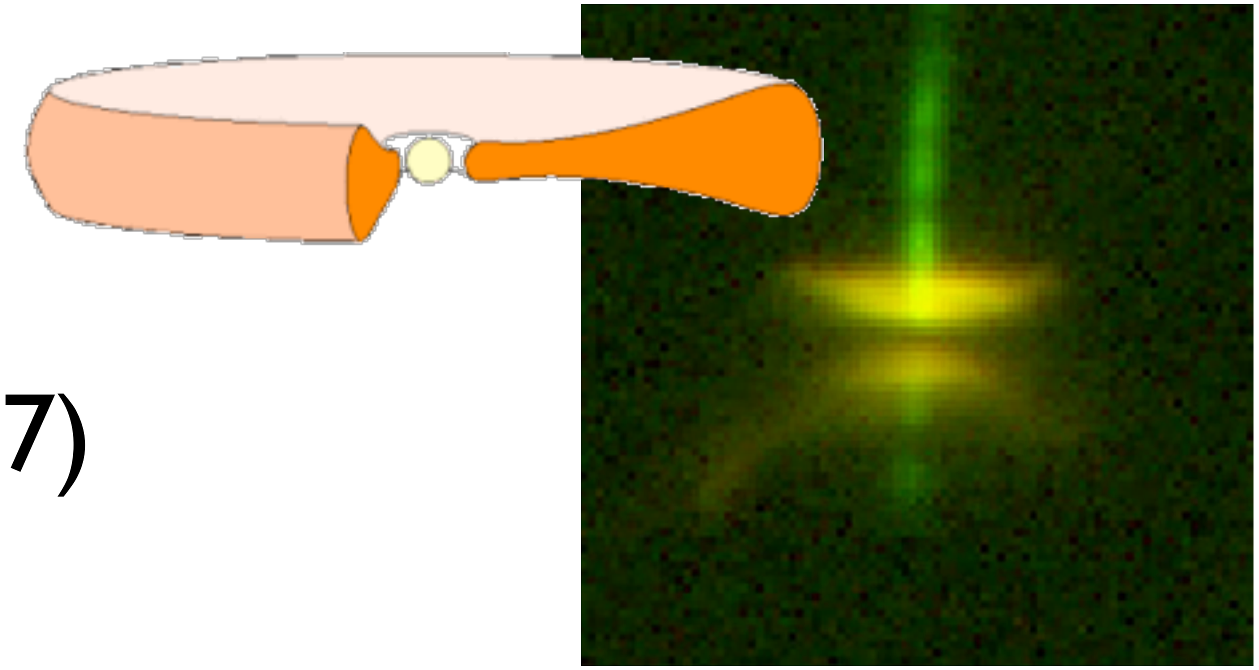
- p exponent for MMSN is very uncertain
- Let's compare directly the absolute value of Σ at different radial distances
- $\Sigma = 10 \ldots 100\ \mathrm{g\ cm^{-2}}$ at 20 au
- Good match
- Toomre parameter:

$$Q(R) = c\,\Omega/\pi G\Sigma$$

- Class II are typically gravitationally stable



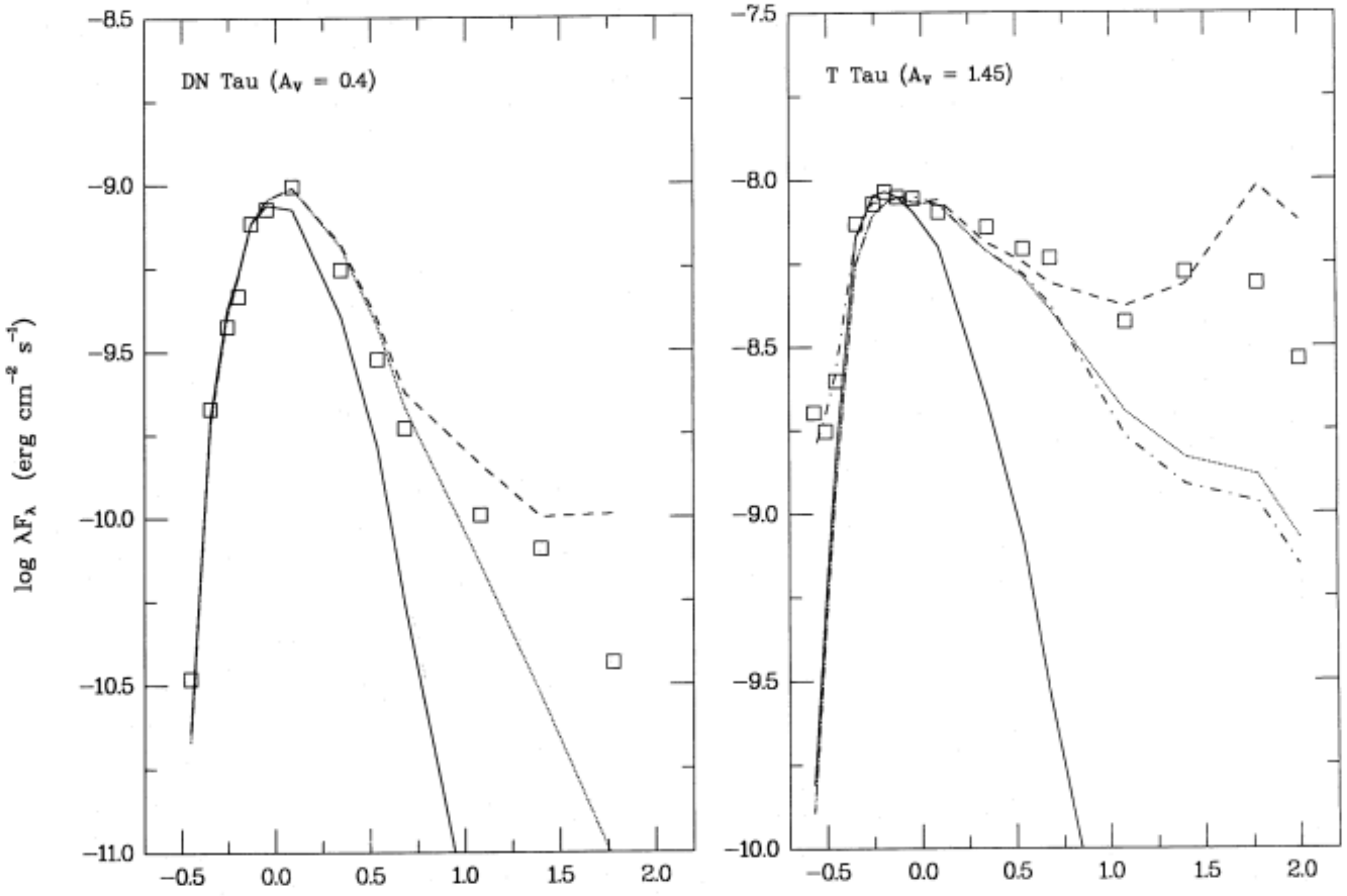
Disk structure − H



- H − vertical scale height
- First idea of a flared disk: Kenyon & Hartmann (1987)
- H must increase with R
- Density:

$$\rho(R, Z) = \frac{\Sigma(R)}{\sqrt{2\pi}\,H} \exp\left(-\frac{Z^2}{2H^2}\right)$$

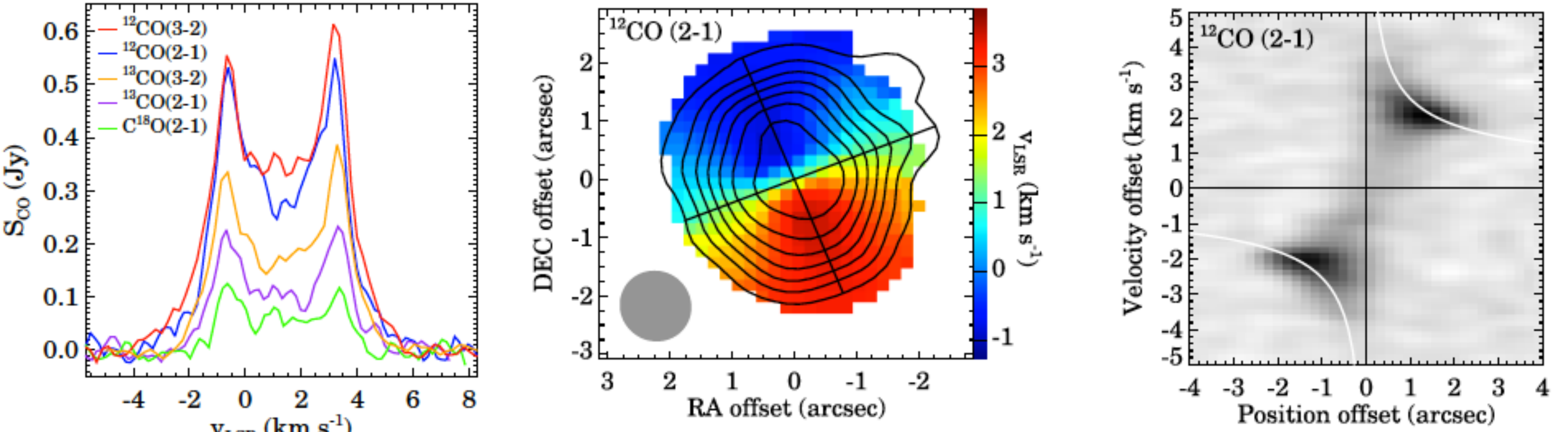
- Scale height is power-law: H ~ R^h, with h = 1.3 ... 1.5

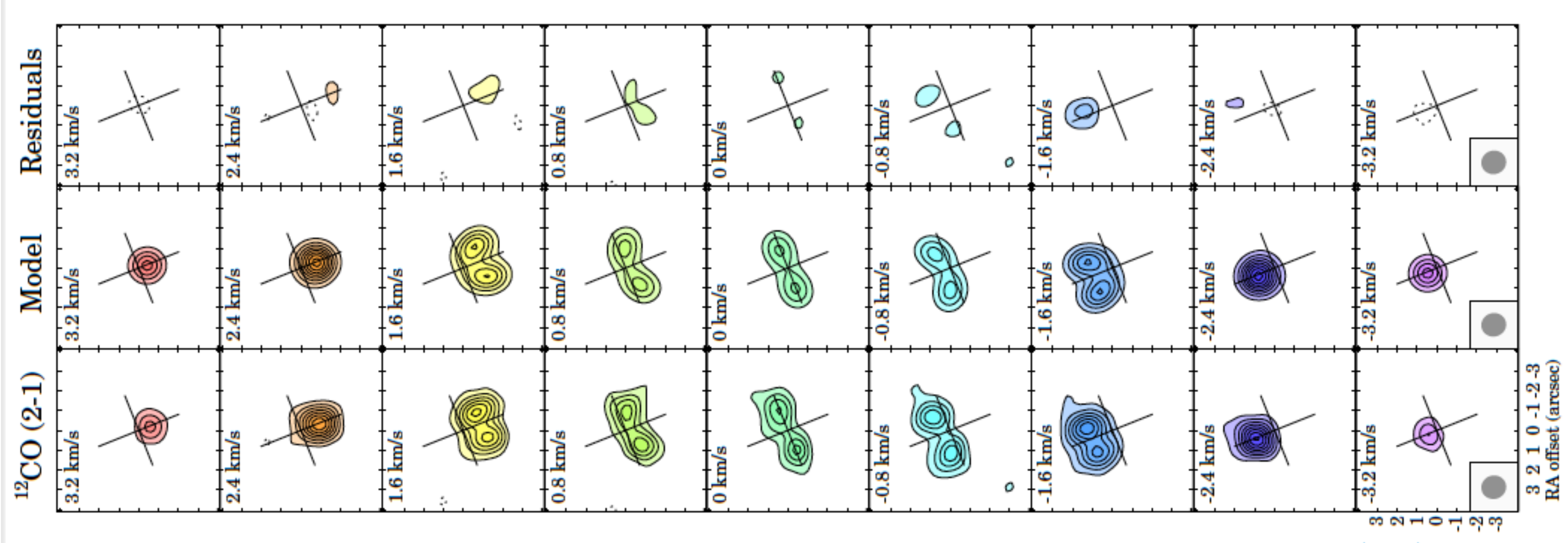


Disk structure − v

- In Class II: $M_{disk} \ll M_{star}$
- Expectation: Keplerian velocity field
- Method: spectral line observations
- Challenge: target needs to be bright enough for the individual channel maps to have high S/N ratio; no background cloud / envelope contamination
- Done for a handful of disks
- Now almost routine task with ALMA

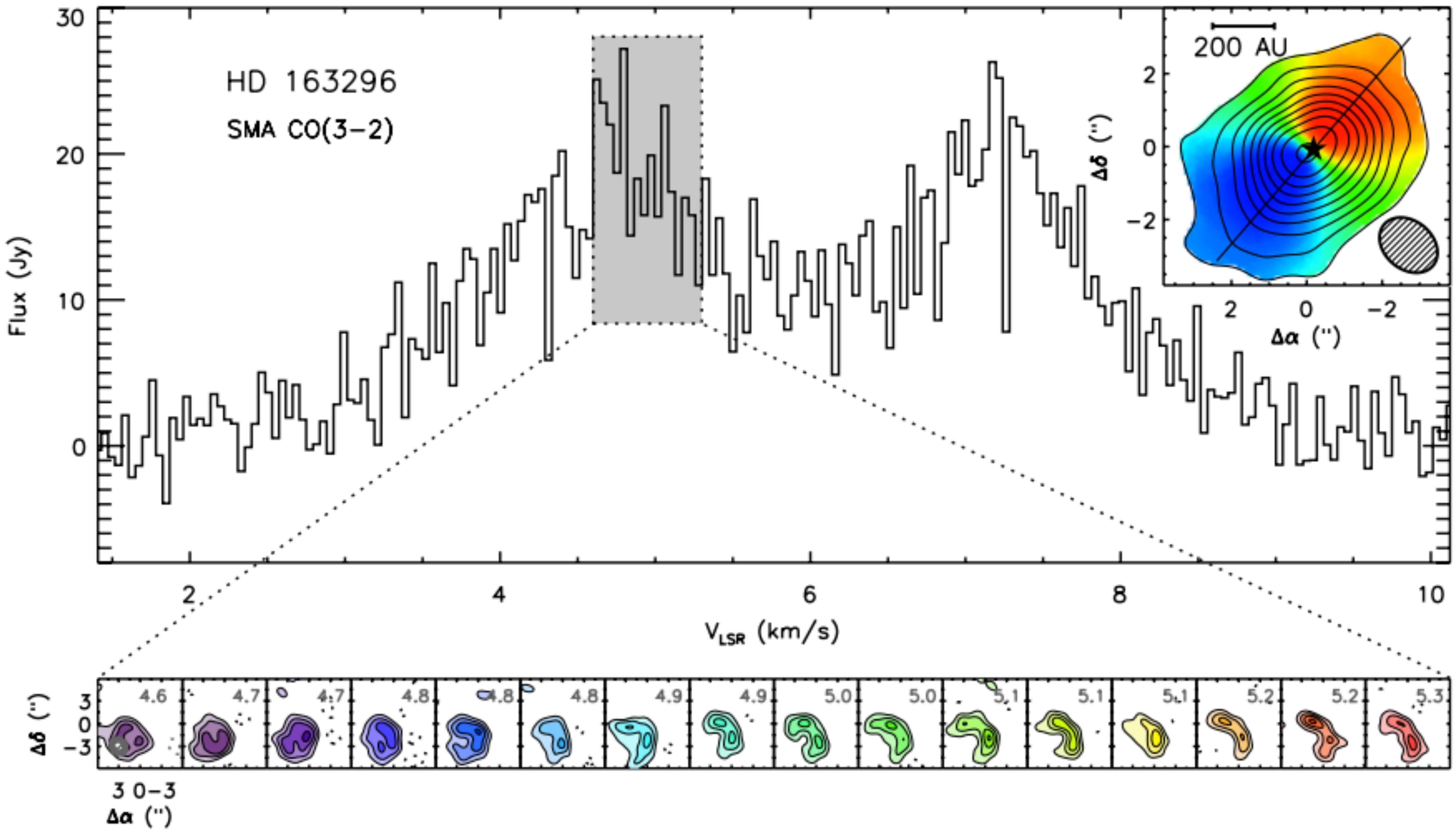
Disk rotation





HD 21997, Kóspál et al. (2013)

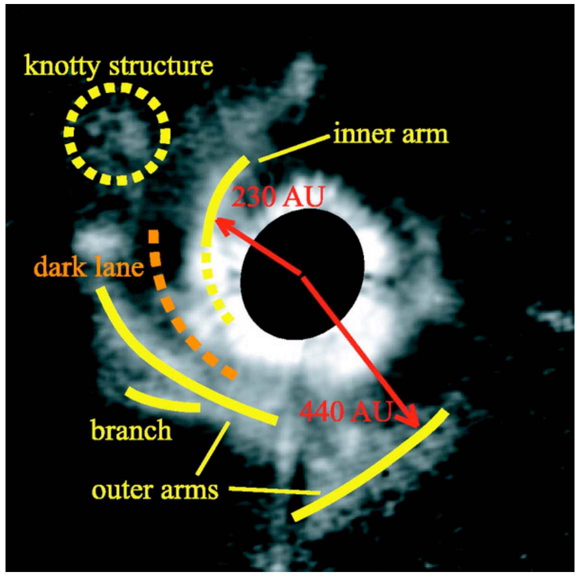
Line broadening

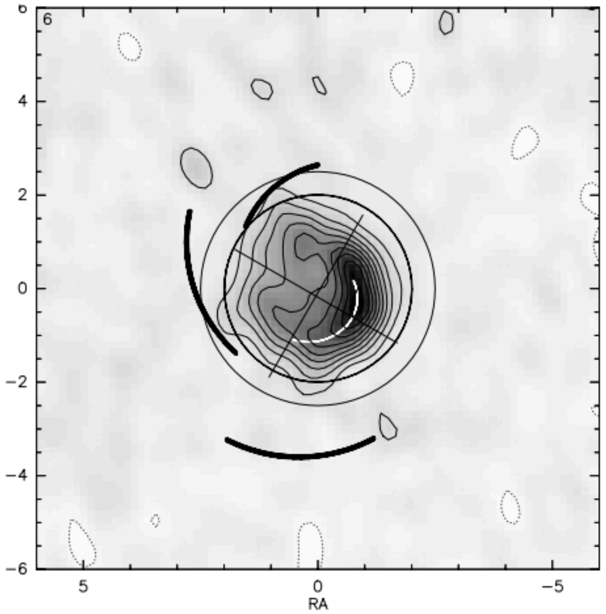


- Typically: rotational + thermal
- HD 163296: evidence for turbulent broadening (Hughes et al. 2011)

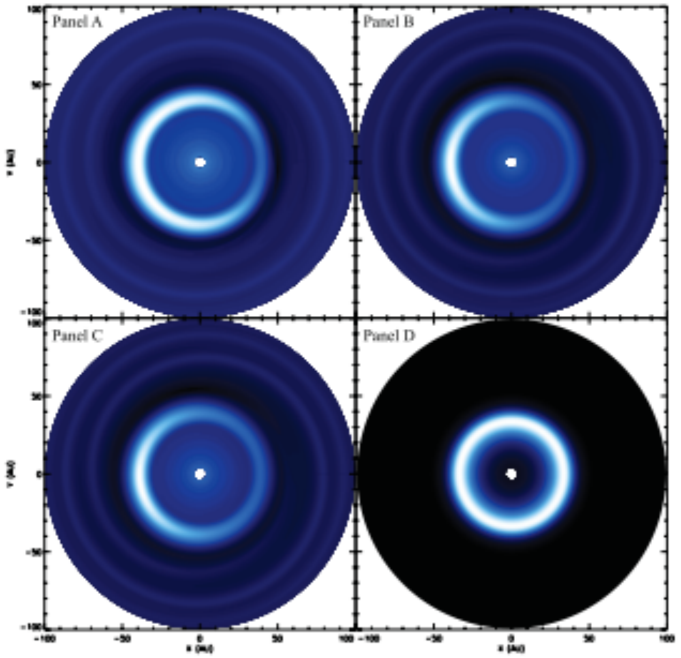
Azimuthal symmetries?

- Azimuthal variations are interesting because they would indicate additional effects:
  - self-gravity
  - protoplanets
  - dust traps
  - vortices

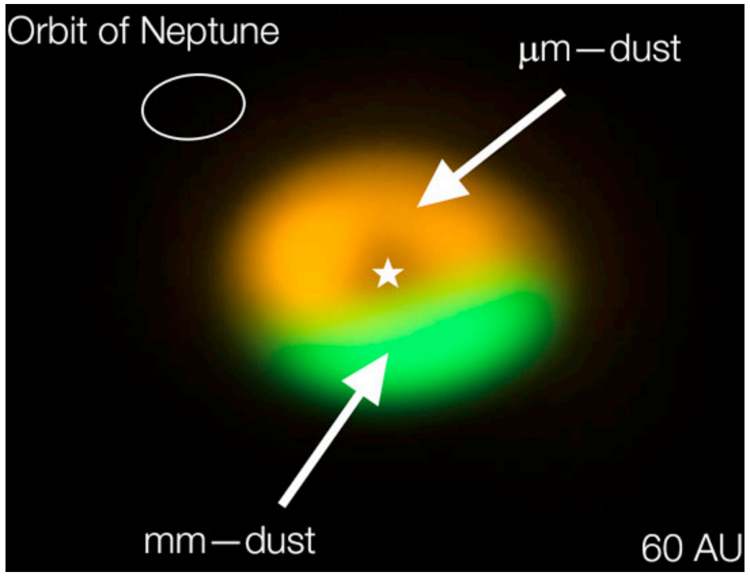




Regály et al. 2012

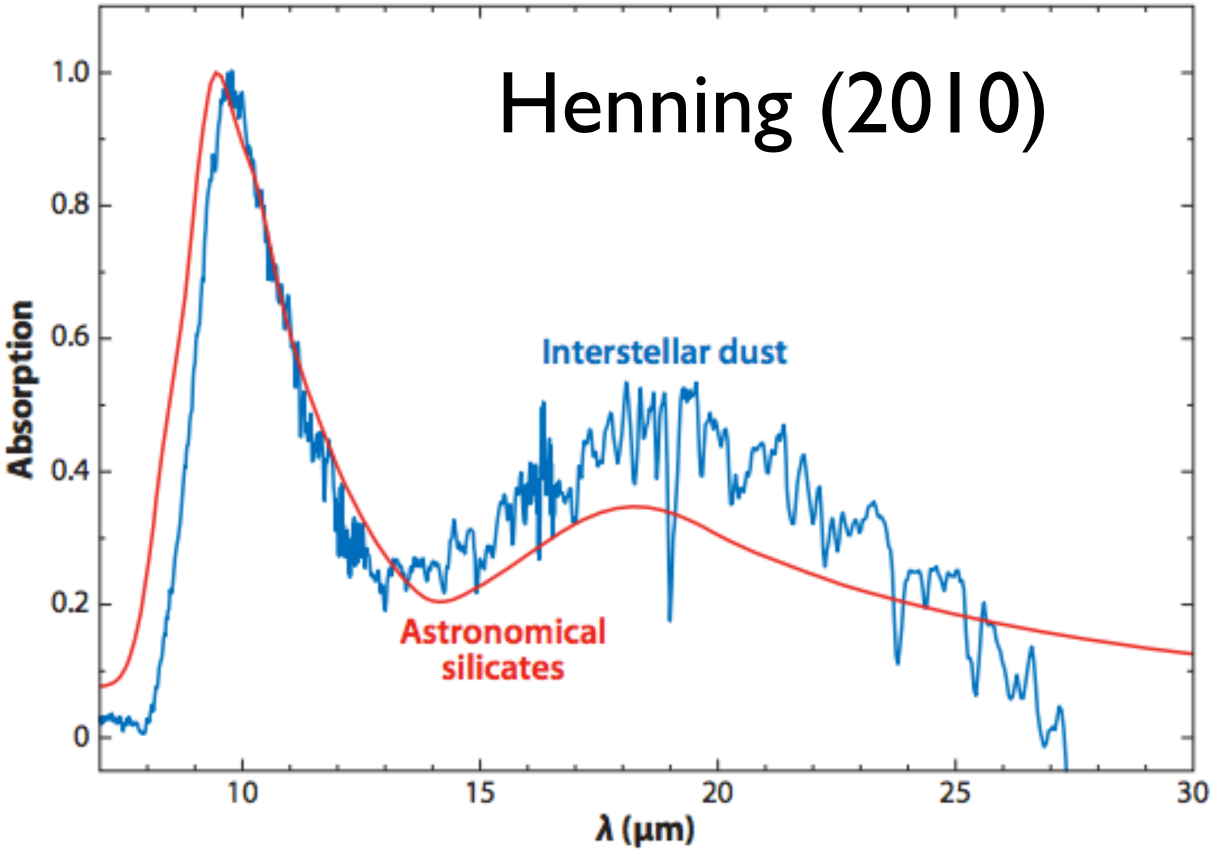


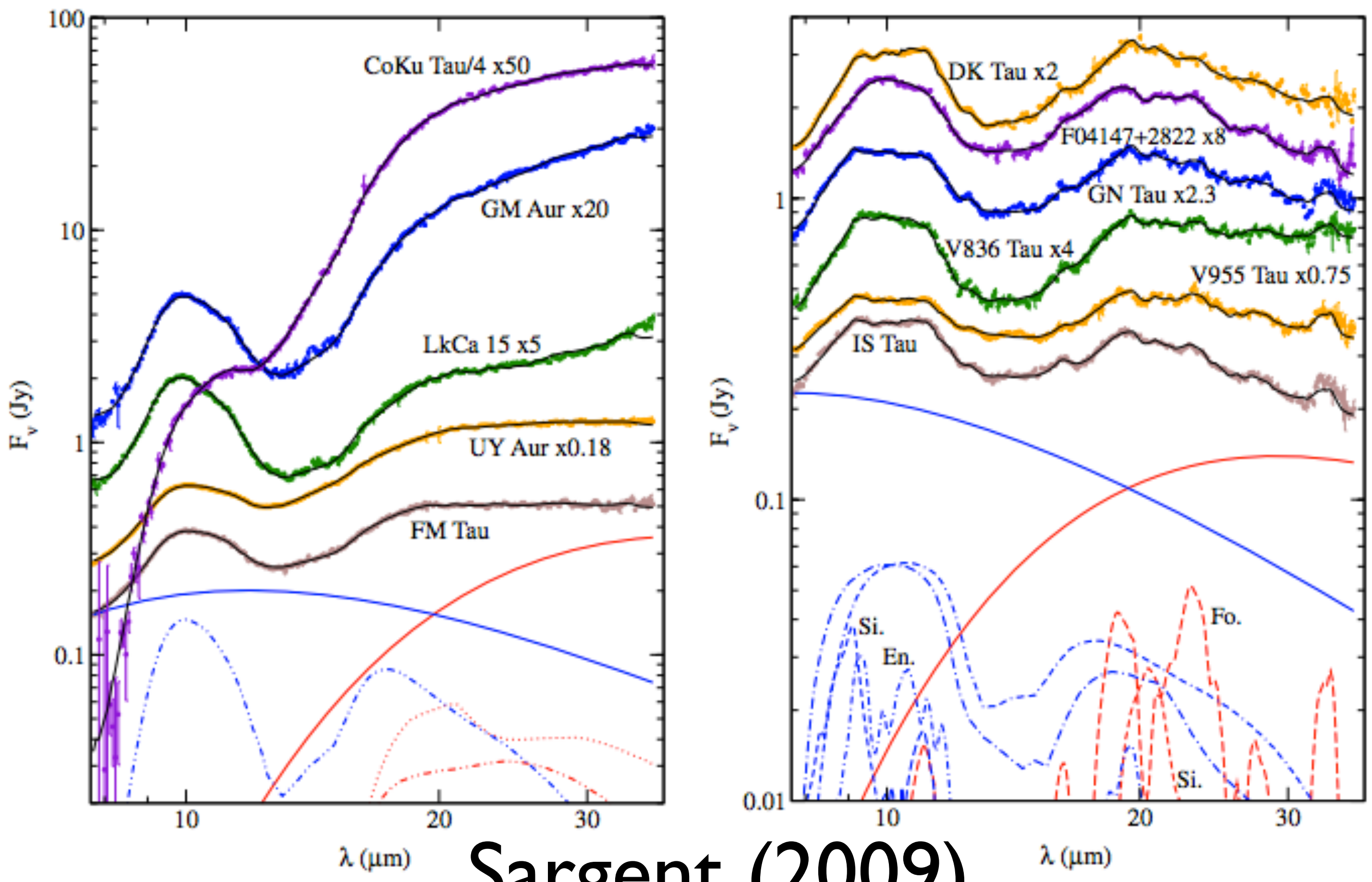
van der Marel et al. (2013)



Disk composition – dust

- Dust dominates the opacity + dust makes the planets
- Mainly silicates
- Dust processing (amorphous → crystalline)
- Grain growth (submicron → mm)

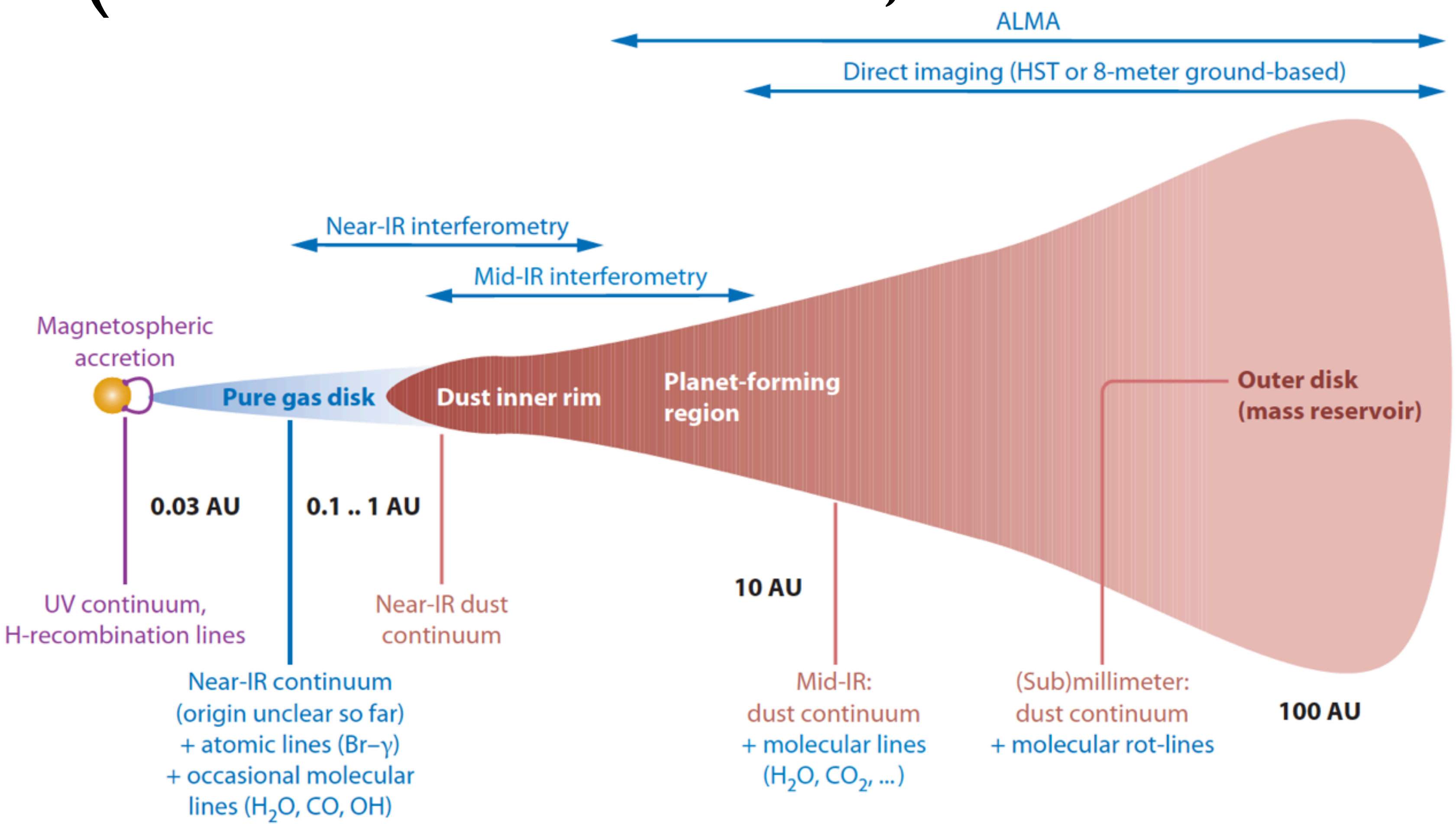

Henning (2010)



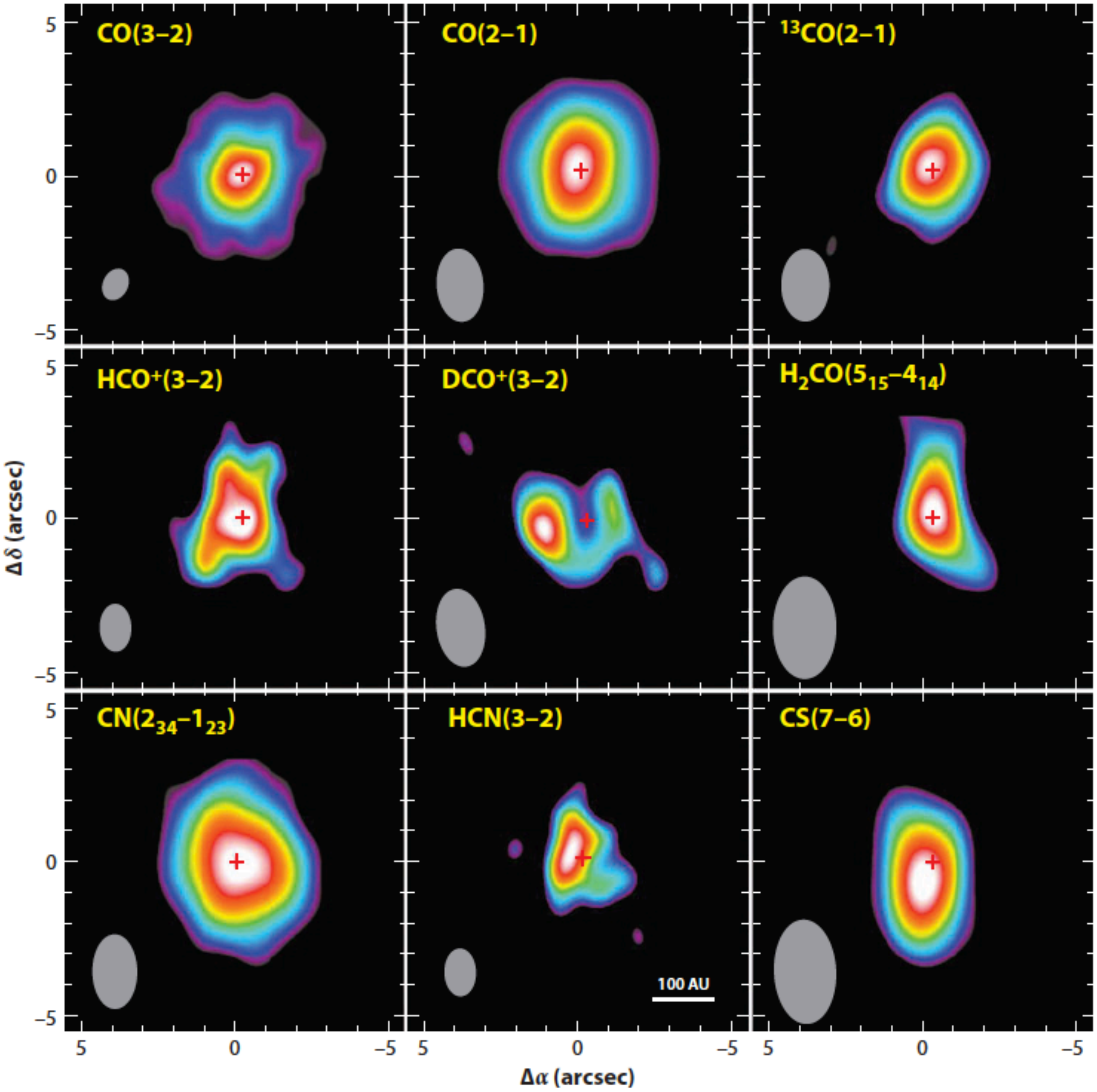
Sargent (2009)

Disk composition – gas

- 99% of the total mass of ISM
- 99% of the total mass of disks (at least initially)
- Difficult to detect (H_2 has no easily observable lines)
- Ways to observe the gas:
  - Disk accretion (recombination lines, excess hot continuum)
  - MIR mol. lines
  - FIR mol. lines

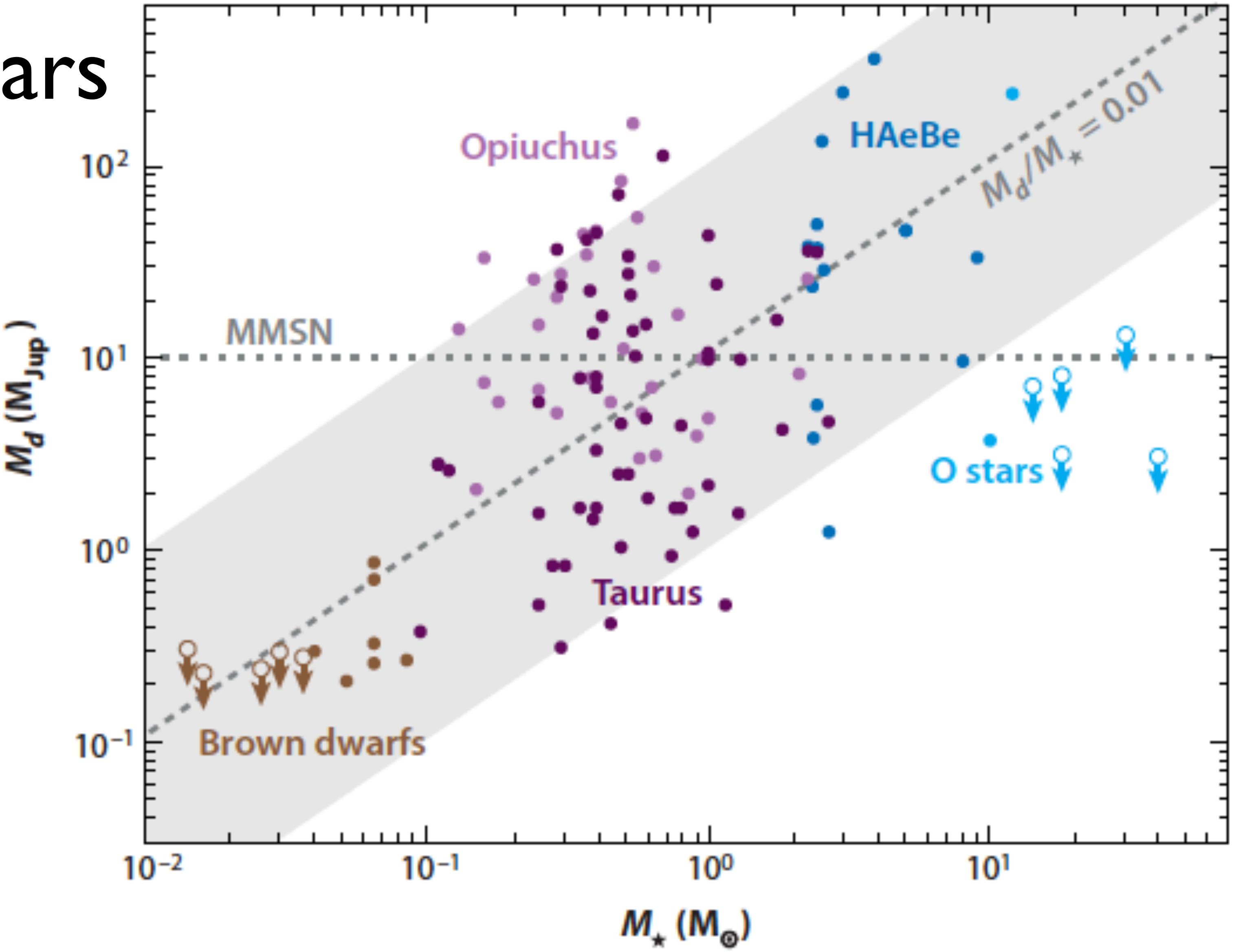


Disk composition – gas



Dependence on stellar mass

- Disks have been detected around
  - Brown dwarfs
  - T Tauri stars of various masses
  - Herbig Ae/Be stars
- Expectation: higher mass stars require more mass to pass through their disks
- $M_{disk} / M_{star} \sim 0.01$



Dependence on stellar mass

- What about more massive stars?
- No disks around optically visible O stars
- $M_{disk} / M_{star} < 10^{-4}$ for $M_{star} > 10\ M_{\odot}$
- Cause?
  - High photoevaporation rate (disk disappears by the time the star becomes visible)
  - Different star formation mechanism than for lower-mass stars

Dependence on stellar mass

- No clear correlation between disk size and stellar mass
- Scale height - stellar mass? Disks around lower mass stars tend to be flatter