Properties of circumstellar disks

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http://konkoly.hu/staff/kospal/teaching.html

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Main literature

Jonathan P. Williams & Lucas A. Cieza
Annu. Rev. Astron. Astrophys. 2011, 49:67−117
(Chapter 4)

Protoplanetary Disks and Their Evolution

Jonathan P. Williams and Lucas A. Cieza

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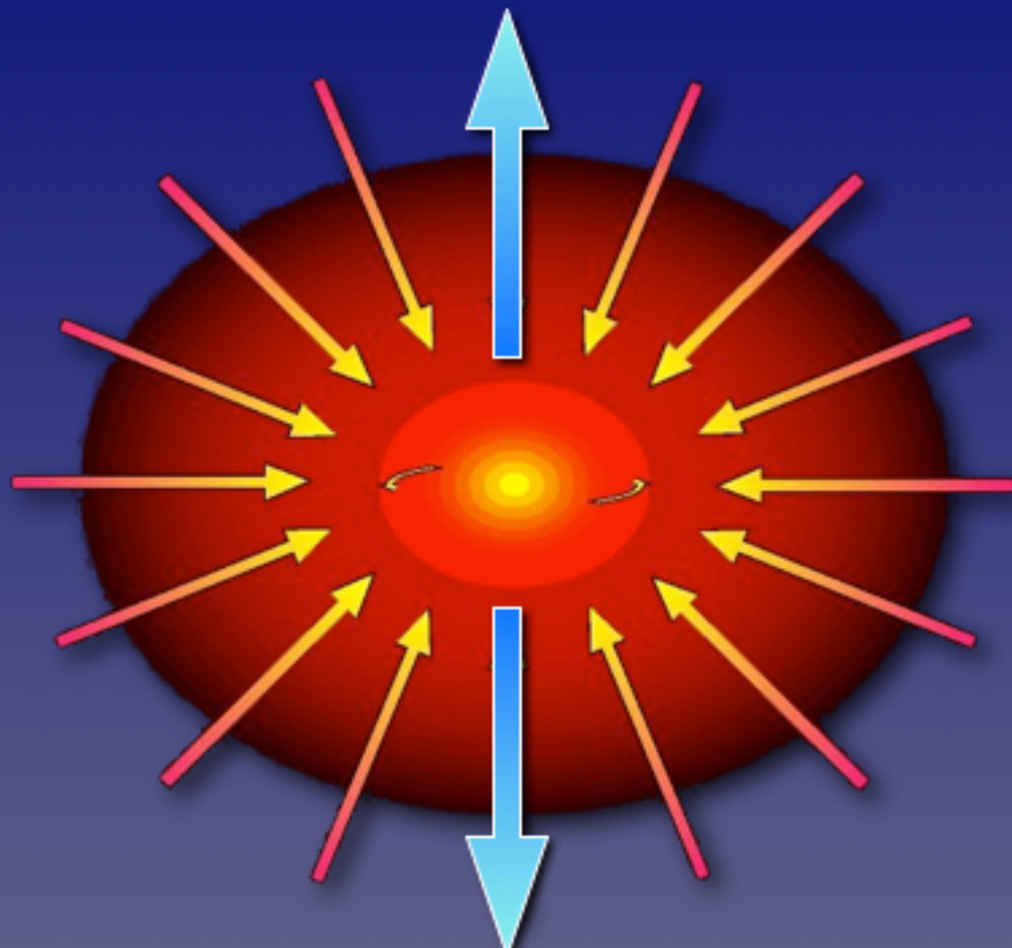
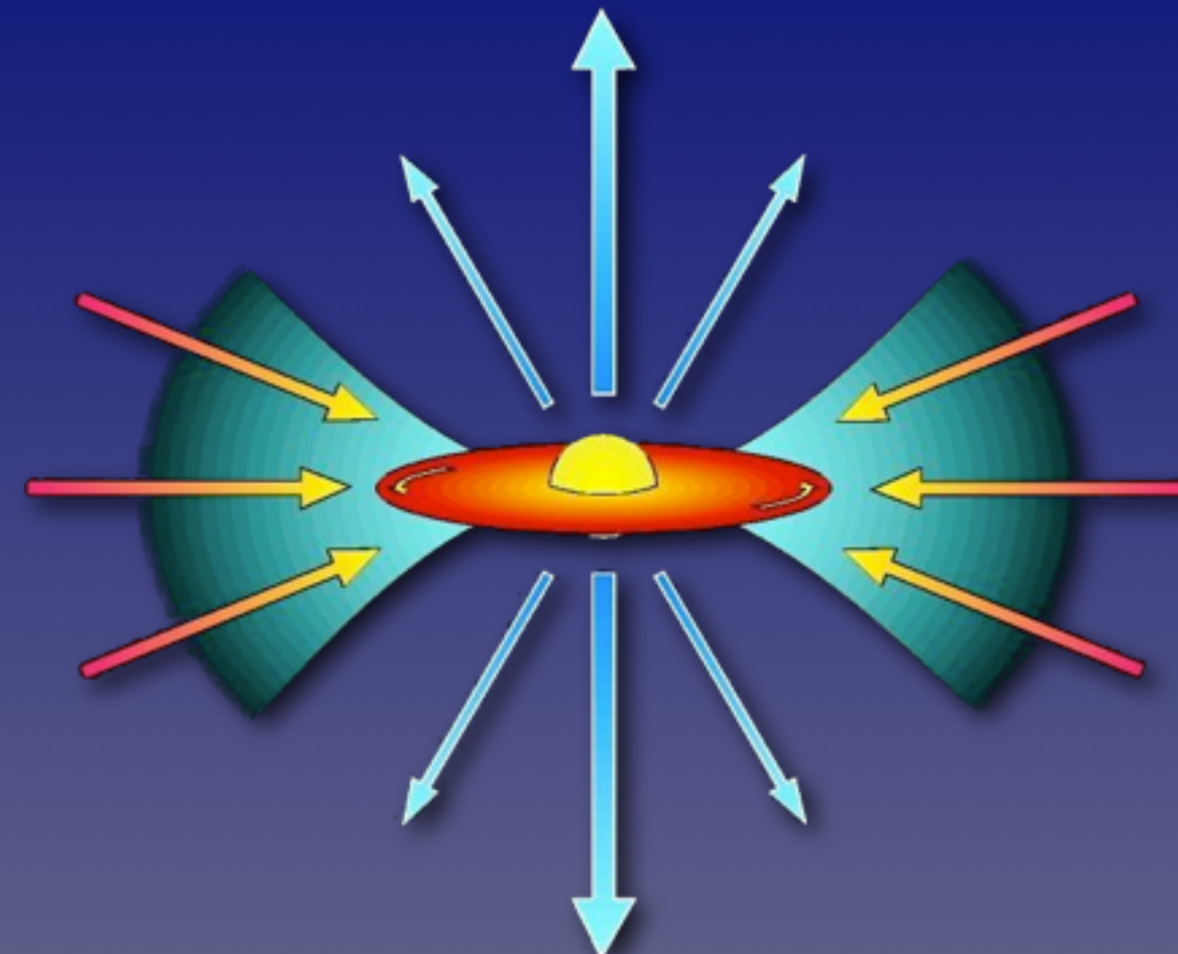
The isolated star formation paradigm

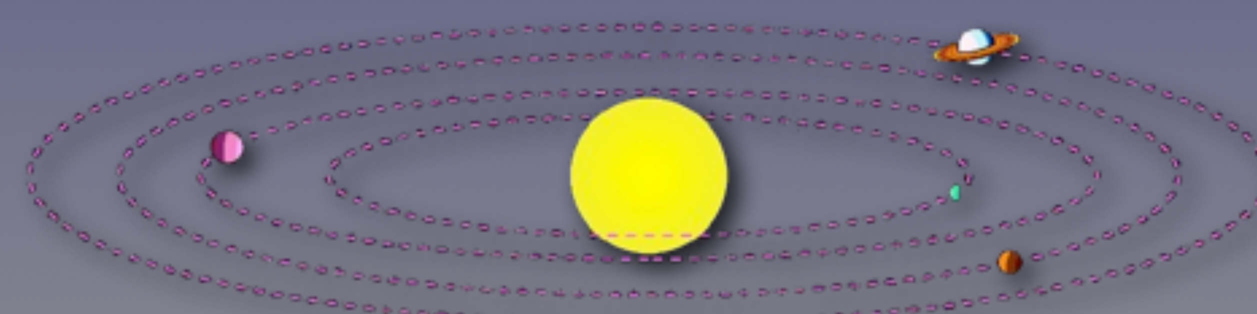


Class 0:
10^4 yrs; 10-10^4 AU; 10-300 K



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

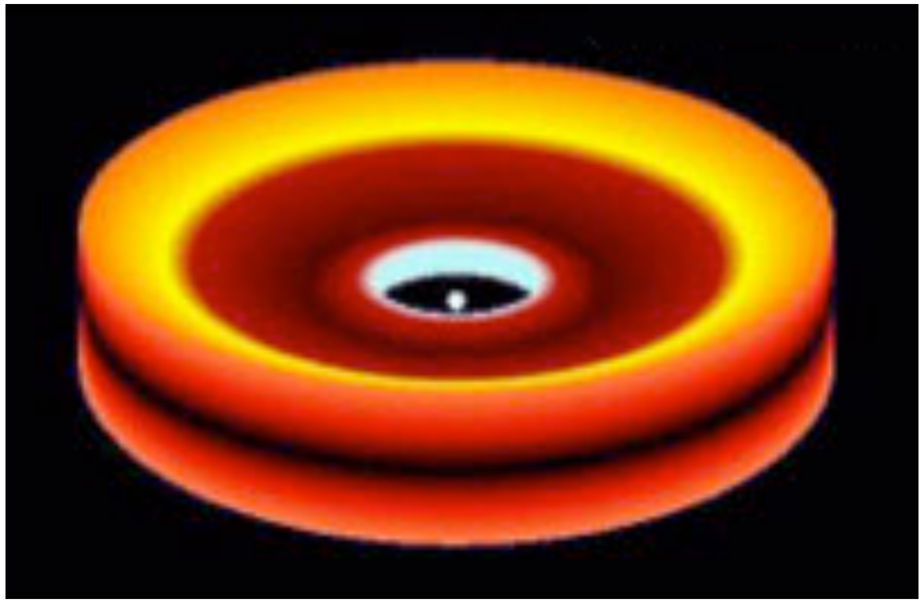
Class II-III:
$10^{6\text{-}7}$ yrs; 1-100 AU; 100-5000 K



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

After Shu, Adams, & Lada

Class II disks

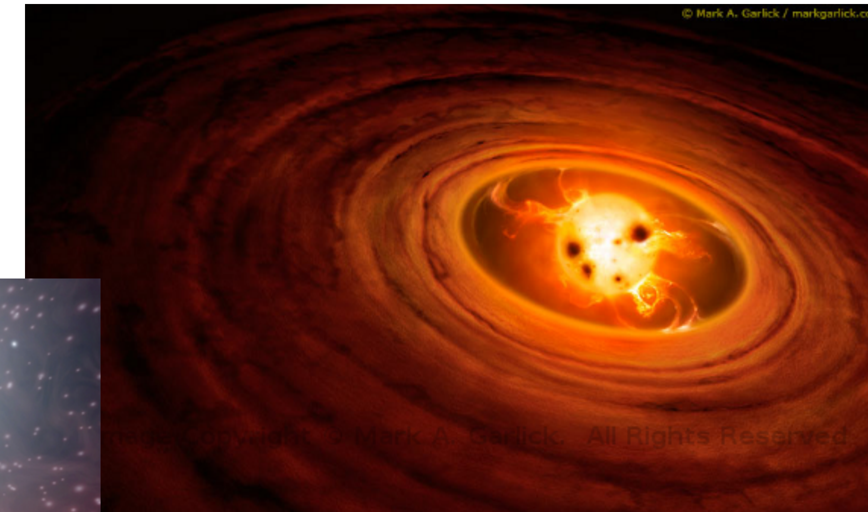


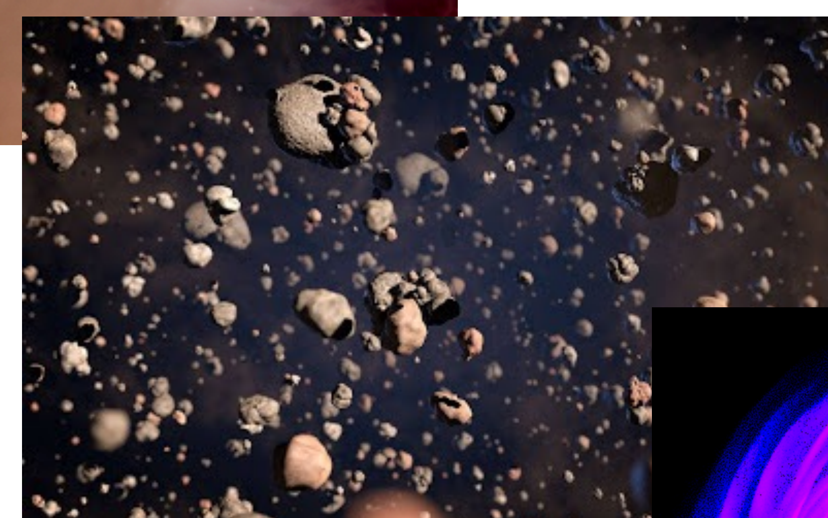
- Class 0 + Class I stage phase lasts about 0.5 Myr
- By the end of the Class I phase, the envelope disperses
- Star formation process is almost over (accretion may be still on-going at a low rate)
- Disk mass is typically only a few % of the stellar mass → protoplanetary disk, not protostellar disk

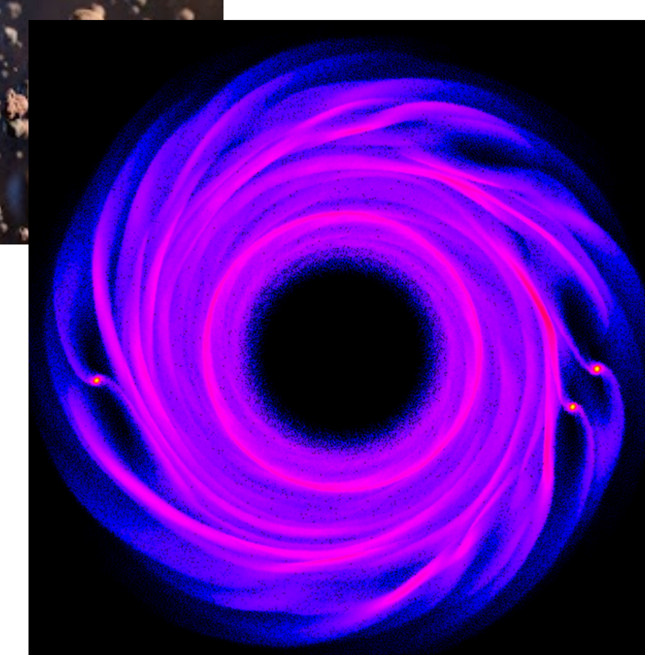
Processes during disk evolution

Major processes that govern the disk evolution:

- accretion onto the star
- photoevaporation
- agglomeration into larger bodies
- dynamical interactions with stellar or planetary companions

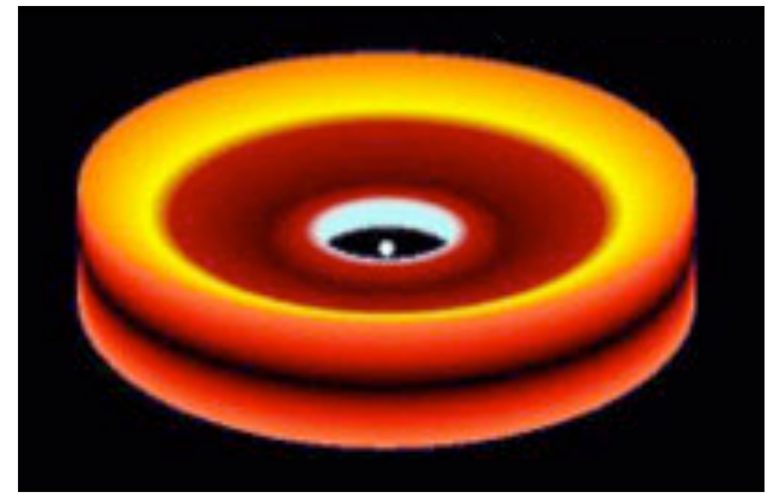




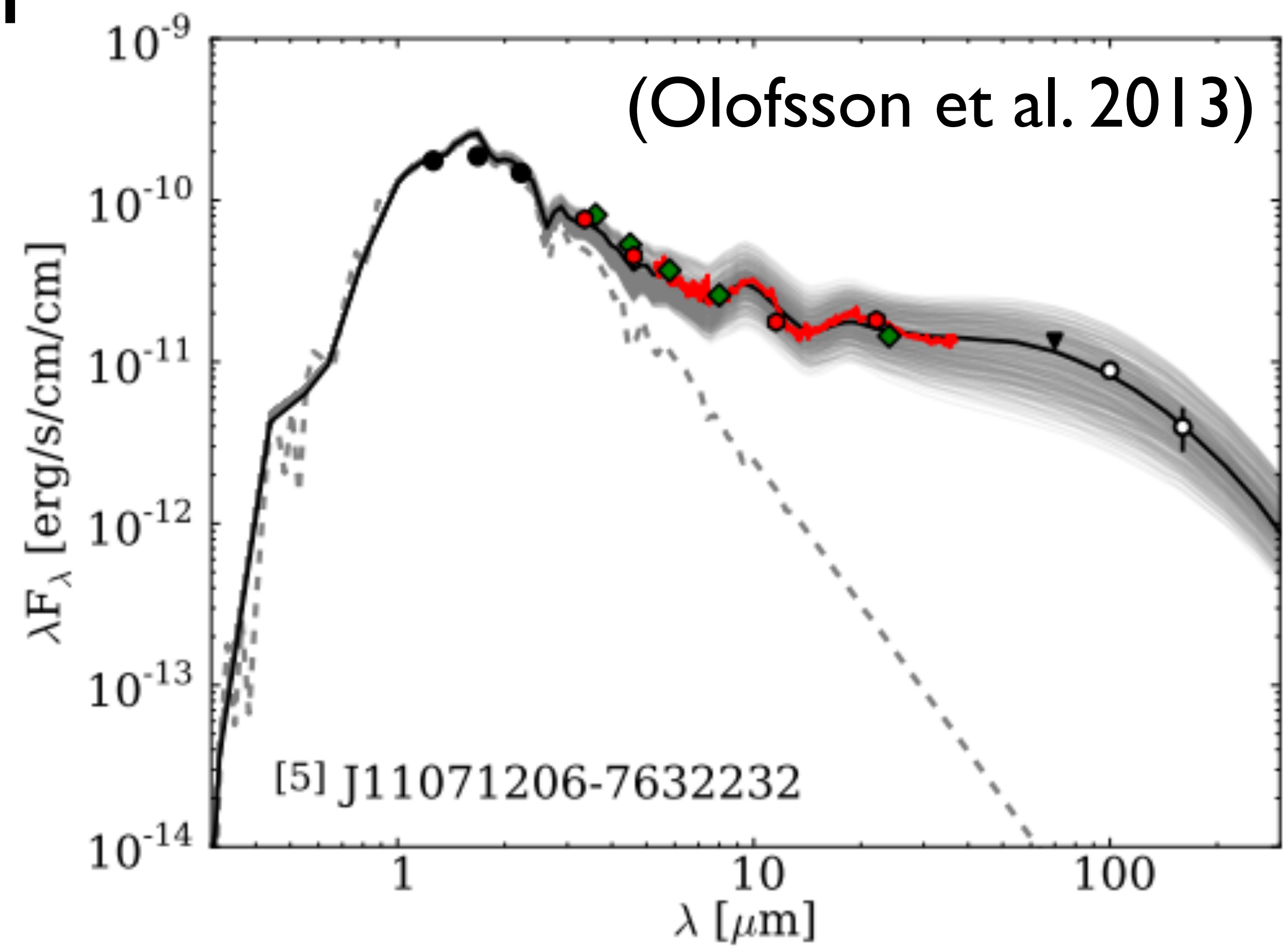


SED of Class II disks

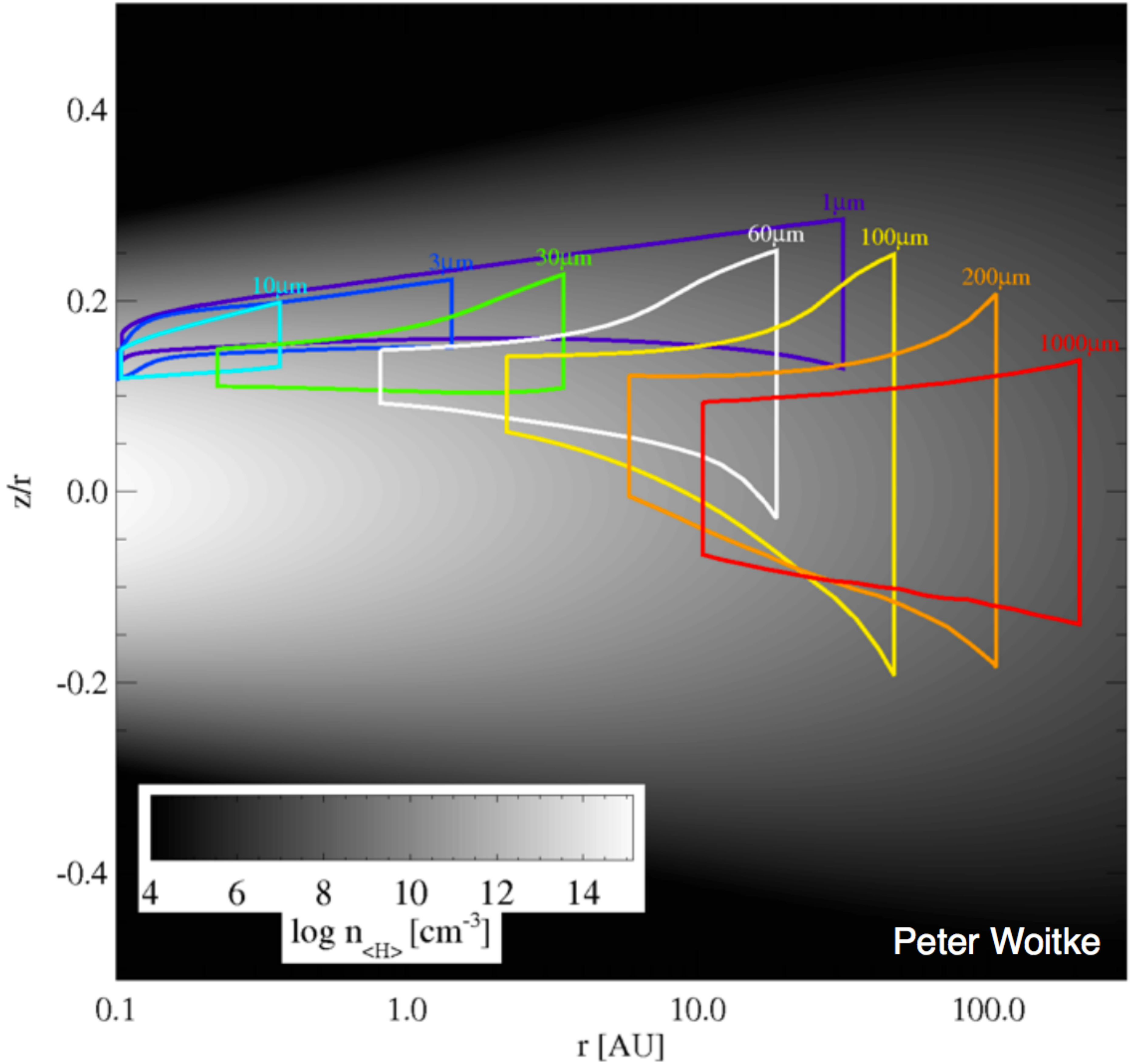
- Extinction is low → stellar properties can be observed in the optical/near-IR



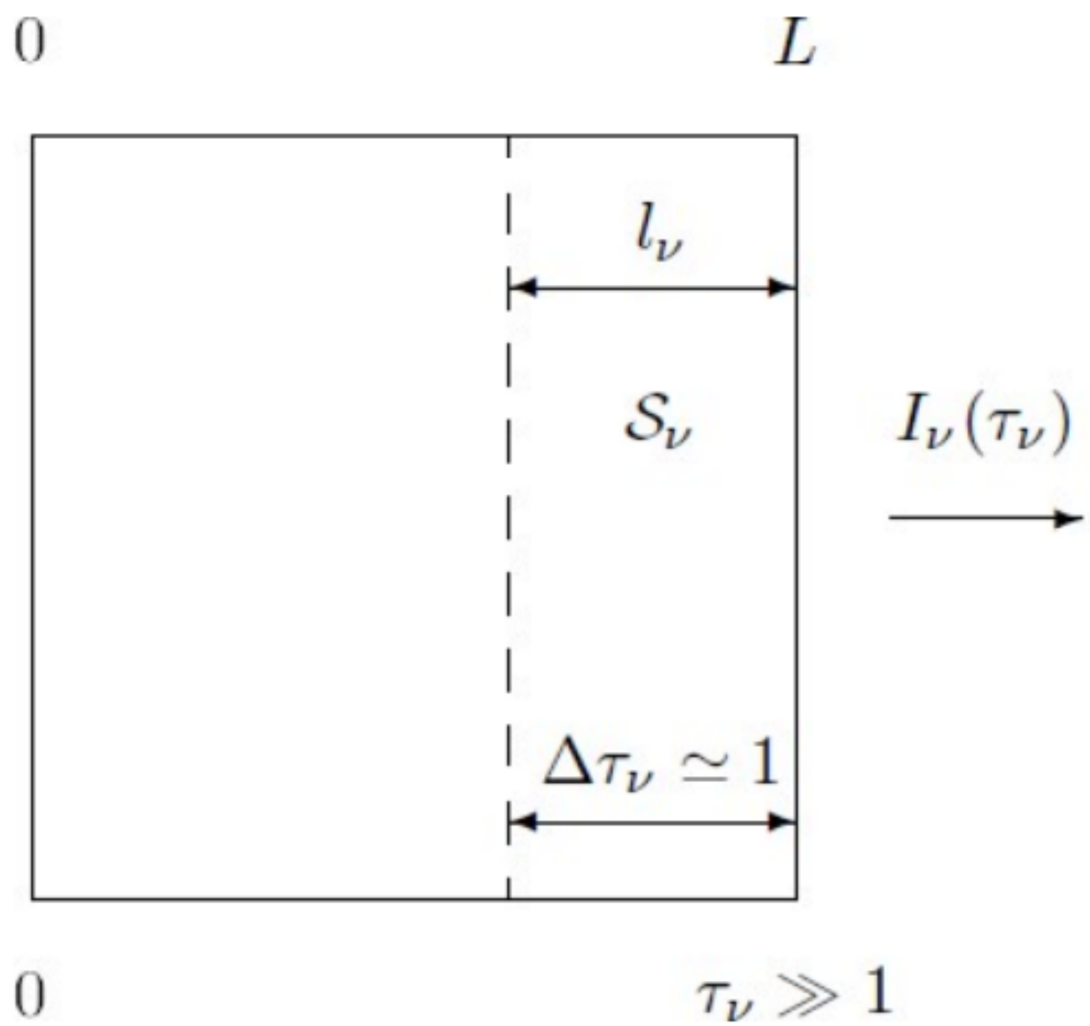
- What other information can we get from the SED?
  - Disk mass?
  - Disk size?
  - Disk structure?
  - Disk compostion?



Origin of disk emission vs λ



Disk mass: radiative transfer



(Robert Estalella)

$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + \mathcal{S}_\nu \left(1 - e^{-\tau_\nu}\right)$$

Optically thin limit ($\tau_\nu \ll 1$):

intensity is proportional to the optical depth i.e. to the column density of the emitting material

$$I_\nu \simeq I_\nu(0) + \mathcal{S}_\nu \tau_\nu$$

Optically thick limit ($\tau_\nu \gg 1$):

radiation is coming from a thin surface layer with $\Delta\tau_\nu = 1$; no information on the inside of the source $I_\nu \simeq \mathcal{S}_\nu$

(S_ν : source function)

Disk mass: dust thermal emission

- Flux density of a source with thermal emission from dust, at temperature T_d and solid angle Ω_S:

$$S_\nu = B_\nu(T_\mathrm{d})\,(1 - e^{-\tau_\nu})\,\Omega_\mathrm{S}$$

- Absorption coefficient (opacity) per unit mass density (gas + dust) and unit length: κ_ν

$$\tau_\nu = \kappa_\nu \int_\mathrm{visual} \rho\, dl$$

- Approximation for κ_ν: power law of frequency with exponent β (β is usually between 1 and 2, depending on the dust properties):

$$\left[\frac{\kappa_\nu}{\mathrm{cm^2\ g^{-1}}}\right] = 0.1 \left[\frac{\nu}{1000\ \mathrm{GHz}}\right]^\beta$$

Disk mass: dust thermal emission

- We can assume optically thin emission at submm and mm wavelengths (usual observations at 870 µm / 345 GHz, 1.3 mm / 230 GHz, 2.7 mm / 110 GHz)
- In the Rayleigh-Jeans approximation, the flux density can be expressed in terms of the mass of the source:

$$S_\nu = \frac{2k\nu^2}{c^2} T_\mathrm{d} \tau_\nu \Omega_\mathrm{S} = \frac{2k\nu^2}{c^2} T_\mathrm{d} \kappa_\nu \frac{A}{D^2} \int \rho \, dl = \frac{2k\nu^2}{c^2} T_\mathrm{d} \kappa_\nu \frac{M}{D^2}$$

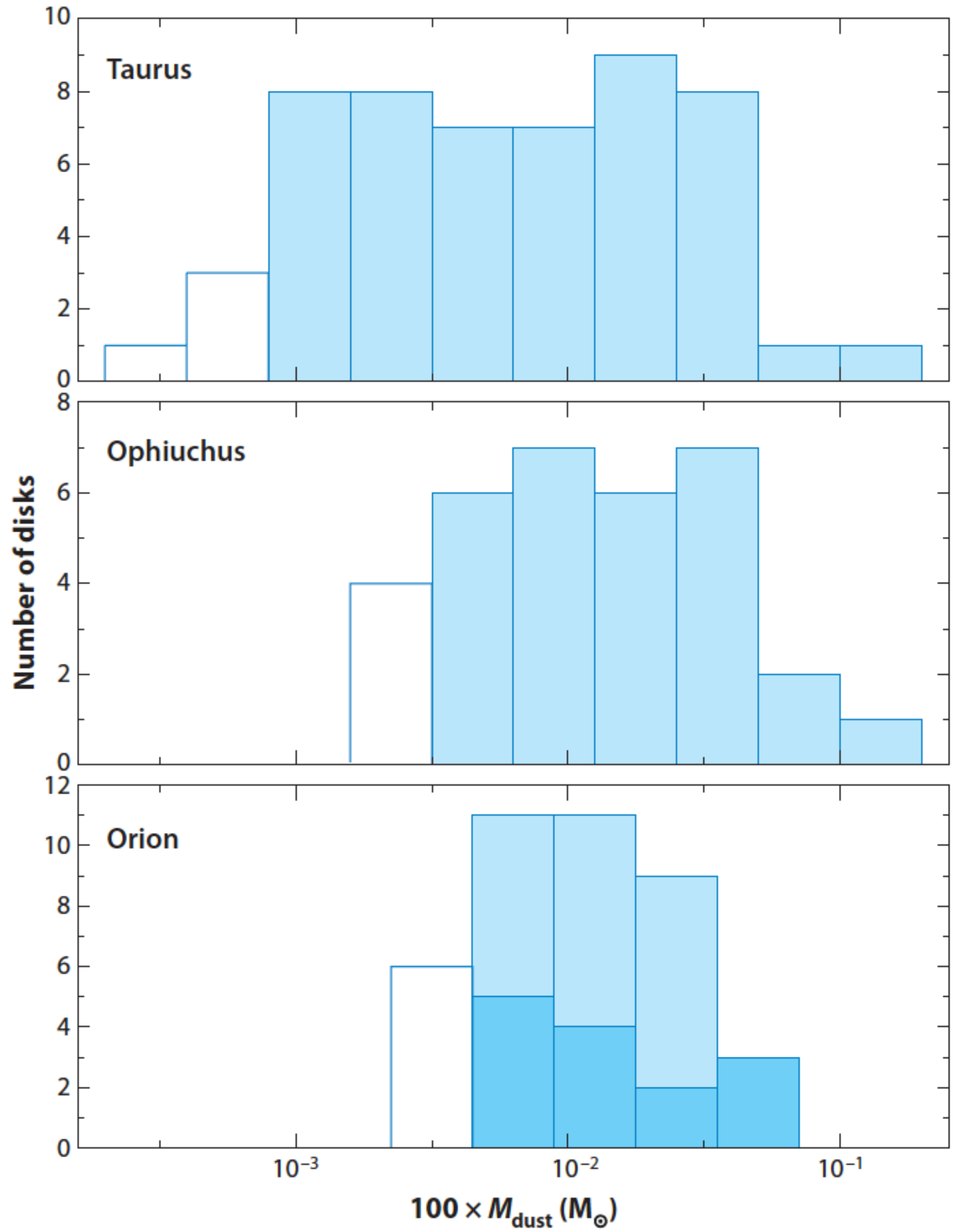
- In practical units:

$$\left[\frac{M}{M_\odot}\right] = 1.6 \times 10^{-6} \left[\frac{\nu}{1000\ \mathrm{GHz}}\right]^{-(2+\beta)} \left[\frac{S_\nu}{\mathrm{Jy}}\right] \left[\frac{T_\mathrm{d}}{\mathrm{K}}\right]^{-1} \left[\frac{D}{\mathrm{pc}}\right]^2$$

Disk mass distribution

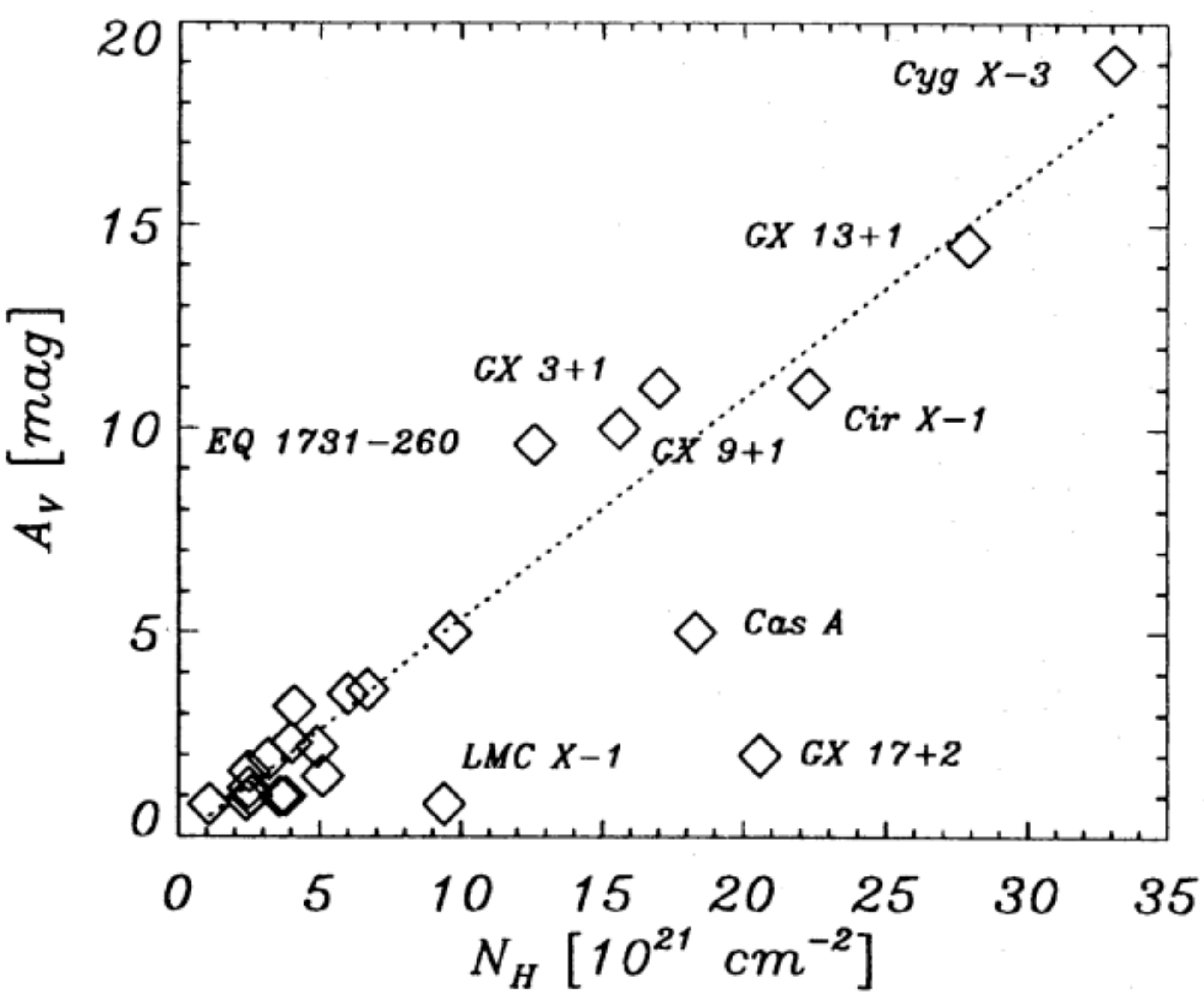
- Large mm surveys:
  Beckwith et al. (1990) for Taurus-Auriga
  André & Montmerle (1994) for Ophiuchus
- Andrews & Williams (2005, 2007)
- Median M_{disk} / M_{star} = 0.01
- Mass distribution in log mass bins: flat until 50 M_{Jup} (0.05 M_{Sun})

Disk mass distribution



Uncertainties in disk mass

- Gas-to-dust ratio is assumed to be interstellar (100); in reality: ratio in disks may be < 100 → if we assume 100, we overestimate disk mass!



(Predehl & Schmitt 1995)

$$\left[\frac{\kappa_\nu}{\mathrm{cm^2\ g^{-1}}}\right] = 0.1 \left[\frac{\nu}{1000\ \mathrm{GHz}}\right]^\beta$$

- H is very difficult to detect in disks, other molecules are used, e.g. CO (requires assumption on H_2/CO ratio)

Uncertainties in disk mass

- Hidden mass in large grains → underestimation
- Rule of thumb: observations at λ are sensitive to grains with sizes of < 3λ (Mie theory)

$$\left[\frac{\kappa_\nu}{\mathrm{cm^2\ g^{-1}}}\right] = 0.1\left[\frac{\nu}{1000\ \mathrm{GHz}}\right]^\beta$$

- Optical properties of dust grains: Draine & Lee (1983)
- Dust opacities for protostellar cores: Ossenkopf & Henning (1994)

Uncertainties in disk mass

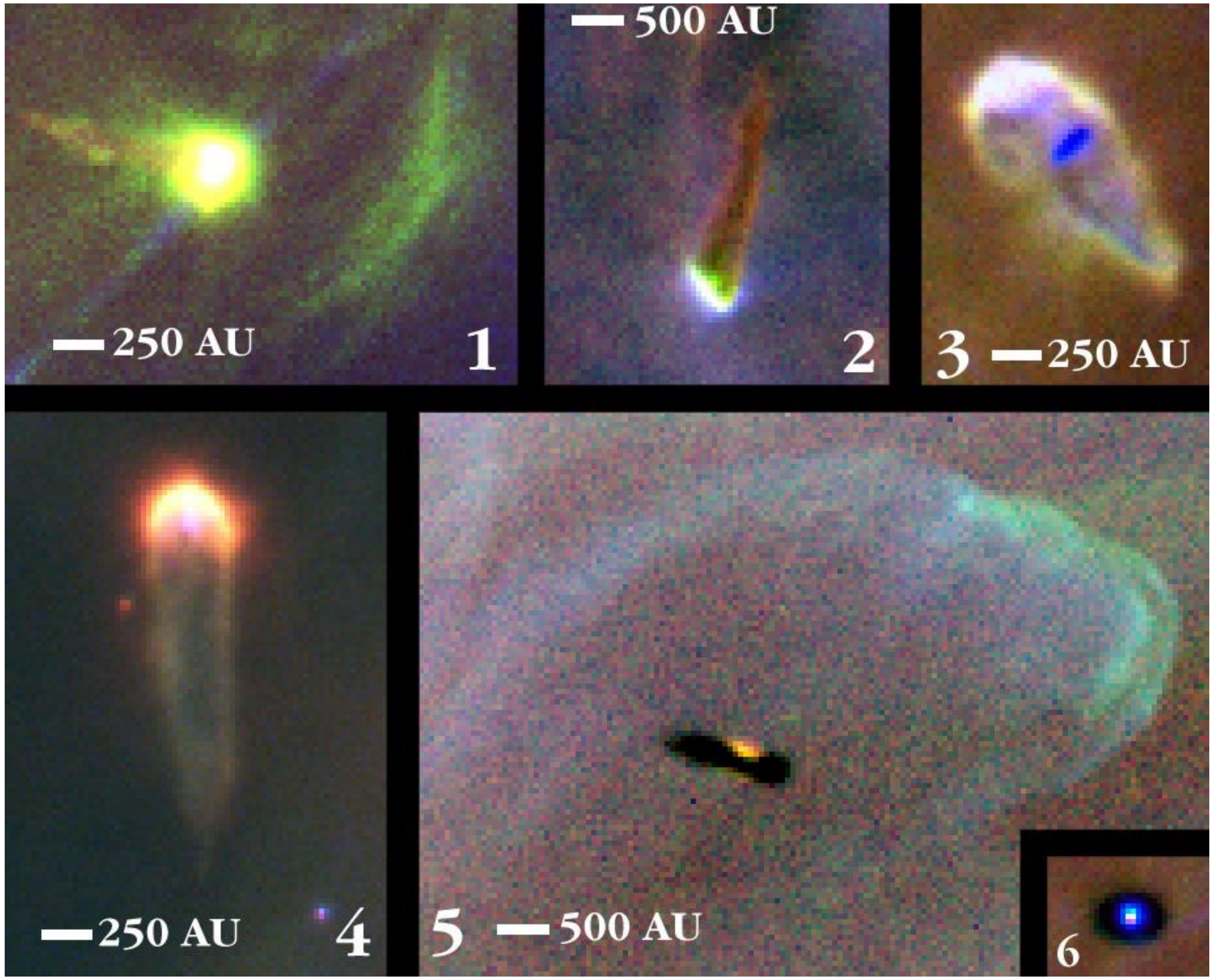
- Indications for severe underestimation:
    - measured disk masses are lower than what is expected by integrating the accretion rate over the protostellar age
    - not enough massive disks to match the statistics on the incidence of exoplanets

Disk radius: direct measurement

NASA, ESA and L. Ricci (ESO)

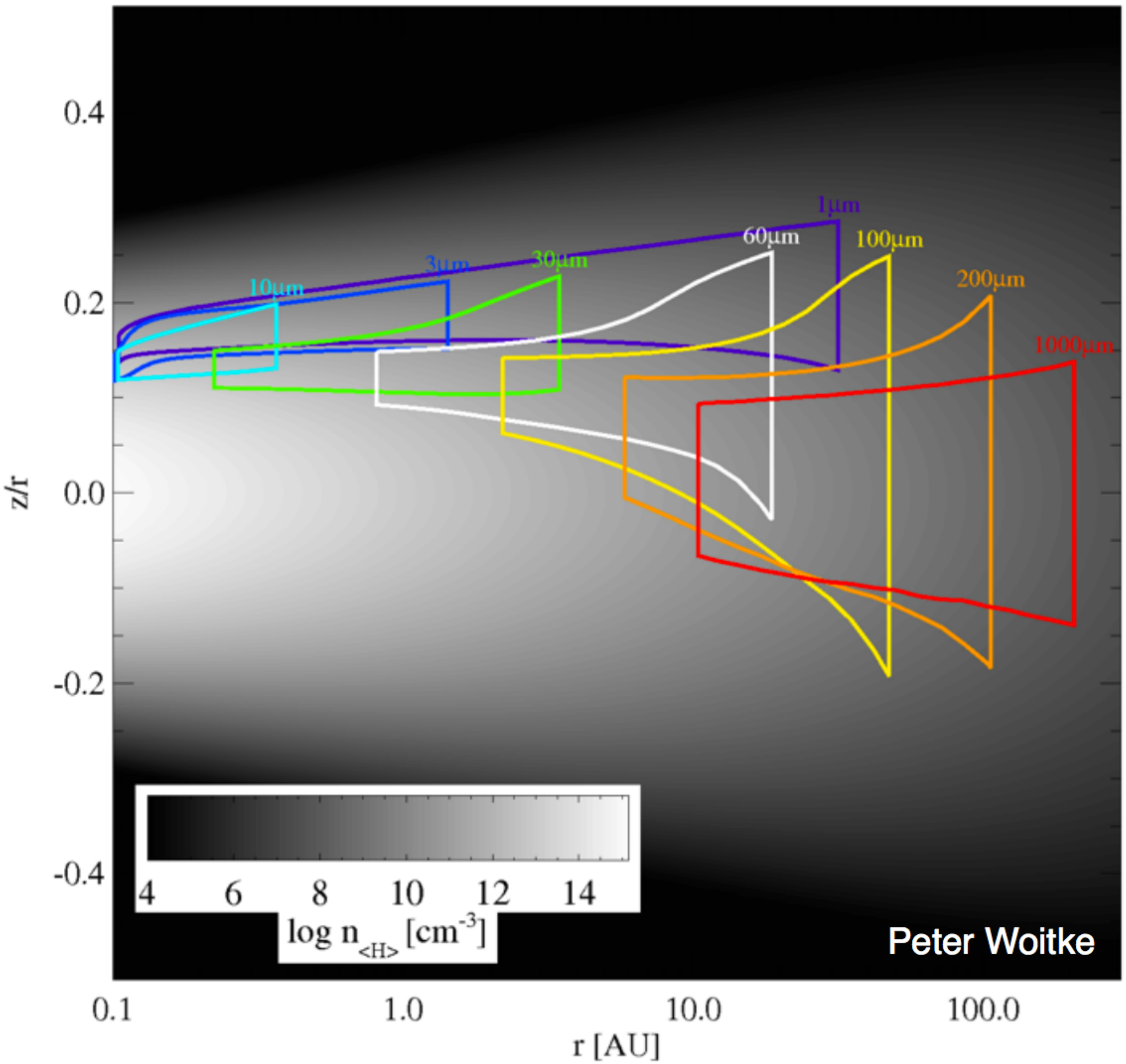
Disk radii in Orion

- Disk silhouettes in Orion: disks are directly visible against a bright background
- Radii: between 50 and 194 au
- Median radius: 75 au
- Is this typical?



NASA, C.R. O'Dell and S.K. Wong (Rice University)

Disk radius: detect resolved disk emission



Difficult to measure, because outer parts are cold and faint

Solution: interferometry

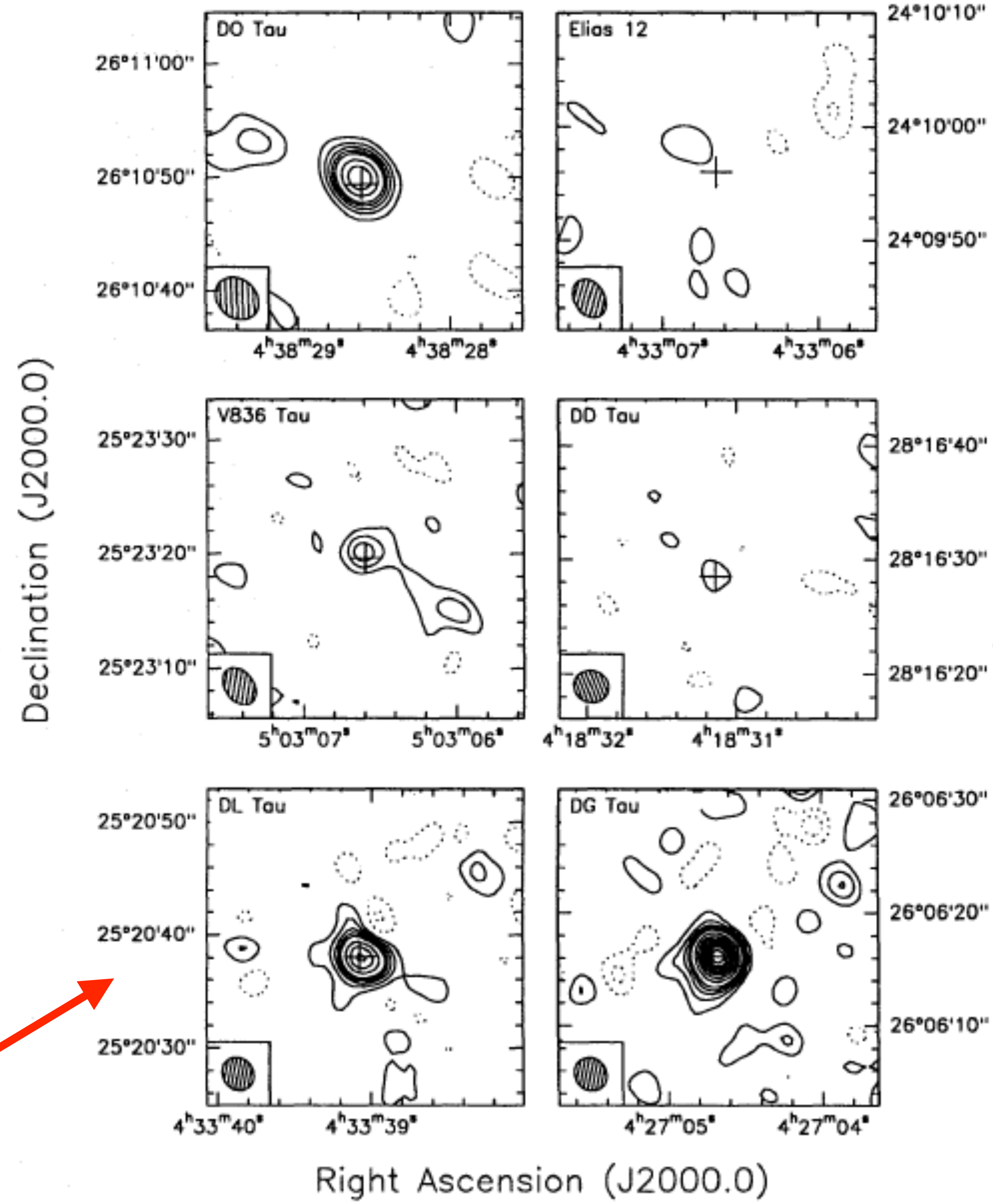
- Angular resolution of an antenna: $\theta = k \lambda / D$
  λ: observing wavelength
  D: diameter of the antenna
  k = 70 (if θ is measured in degrees)
  k = 1.22 (if θ is measured in radians)
- If we want a resolution of 1″ or better at 1 mm, we need a 800 m diameter antenna or larger!
- Not possible with a single dish, but possible with interferometry

Interferometry

- Interferometer: combines the signal from several telescopes/antennas
- Array works like a giant telescope
- Resolution is determined by the distance between the antennas (baseline) and not the diameter of the antennas

Interferometric surveys

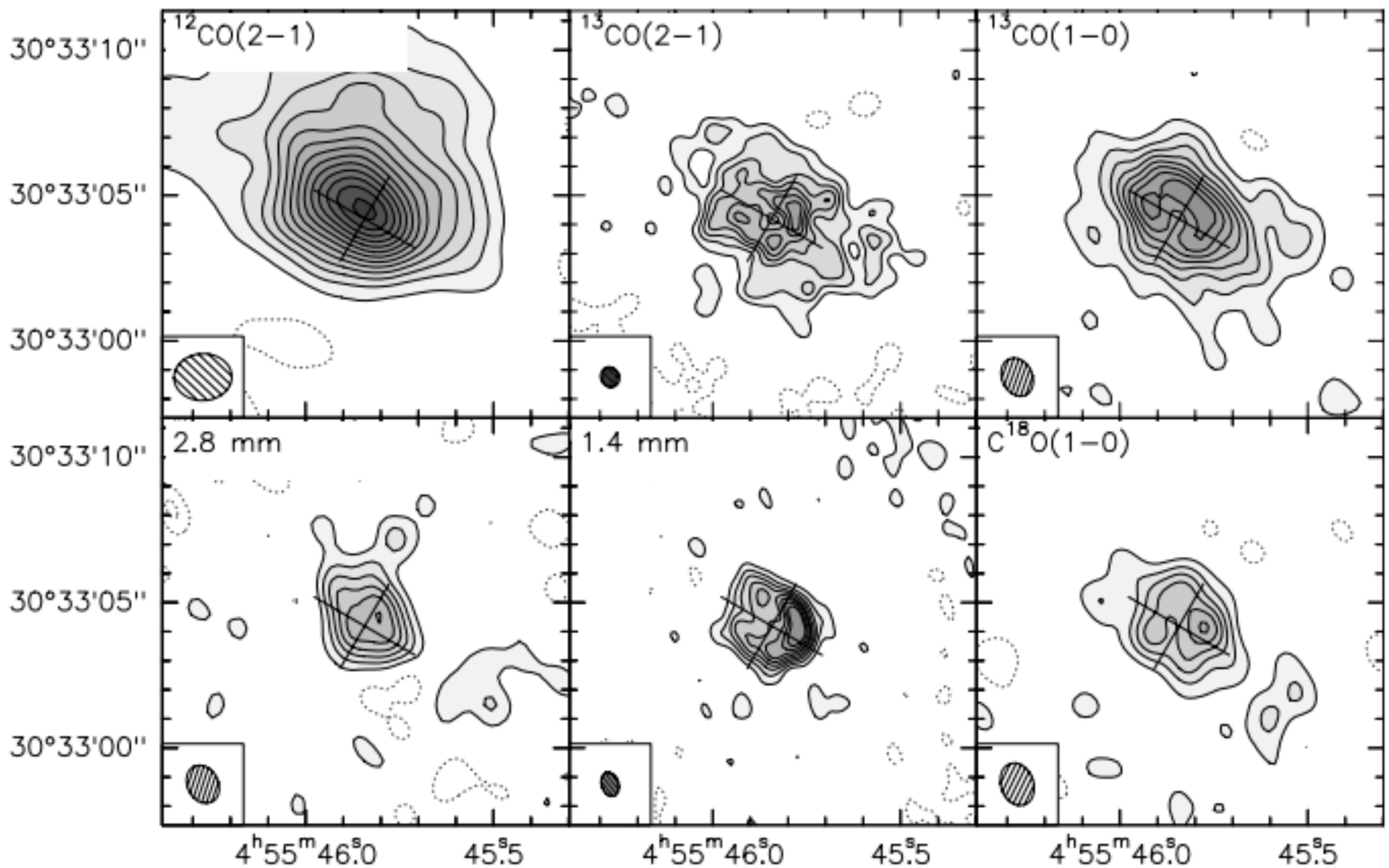
- First large interferometric survey: Dutrey et al. (1996)
- Typical disk sizes in Taurus (d=150 pc): 1 − 2″ (r = 75 − 150 au)



2.7 mm dust continuum

Dust size vs. gas size

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

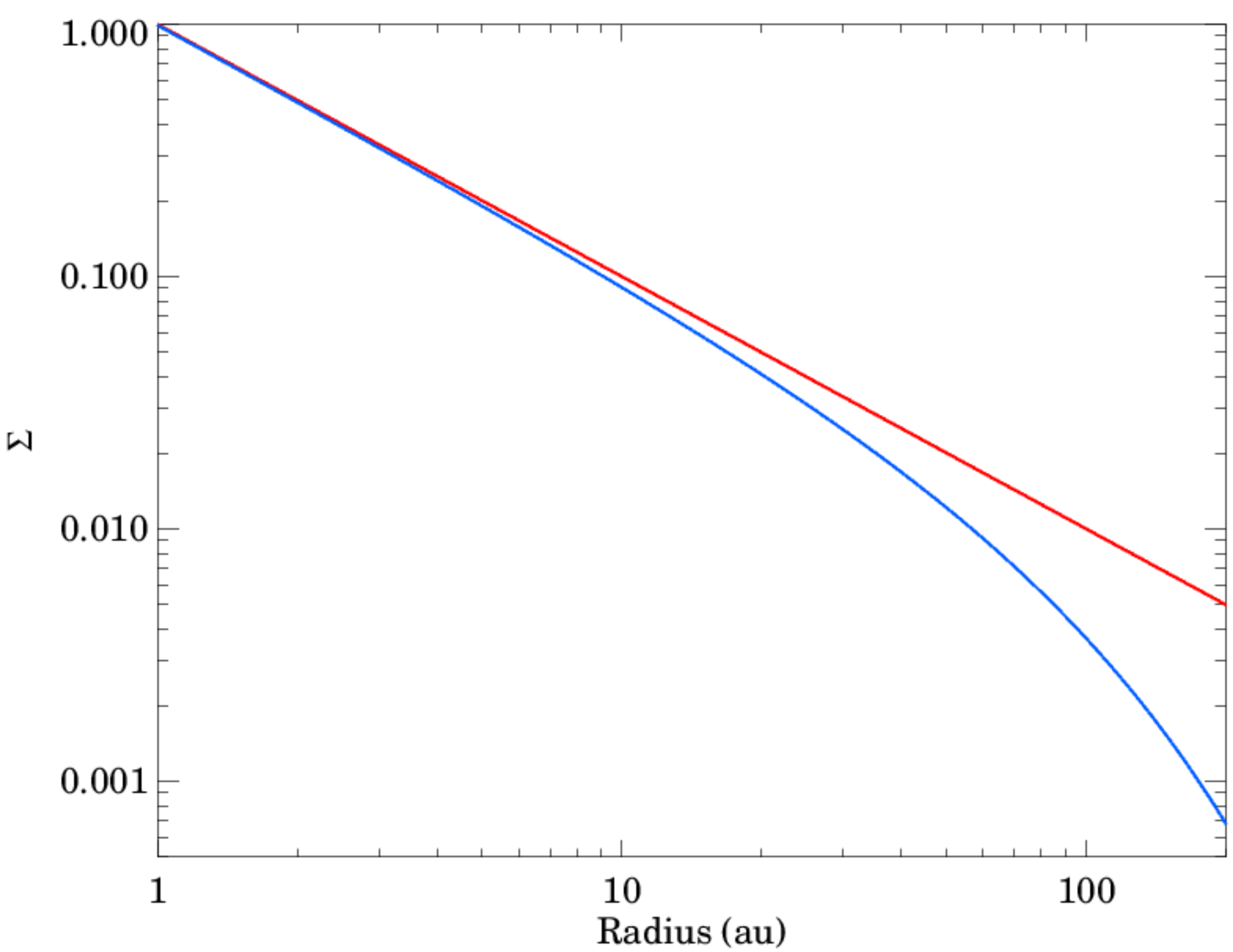


AB Aur (Pietu et al. 2005)

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:



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

Dust size vs. gas size

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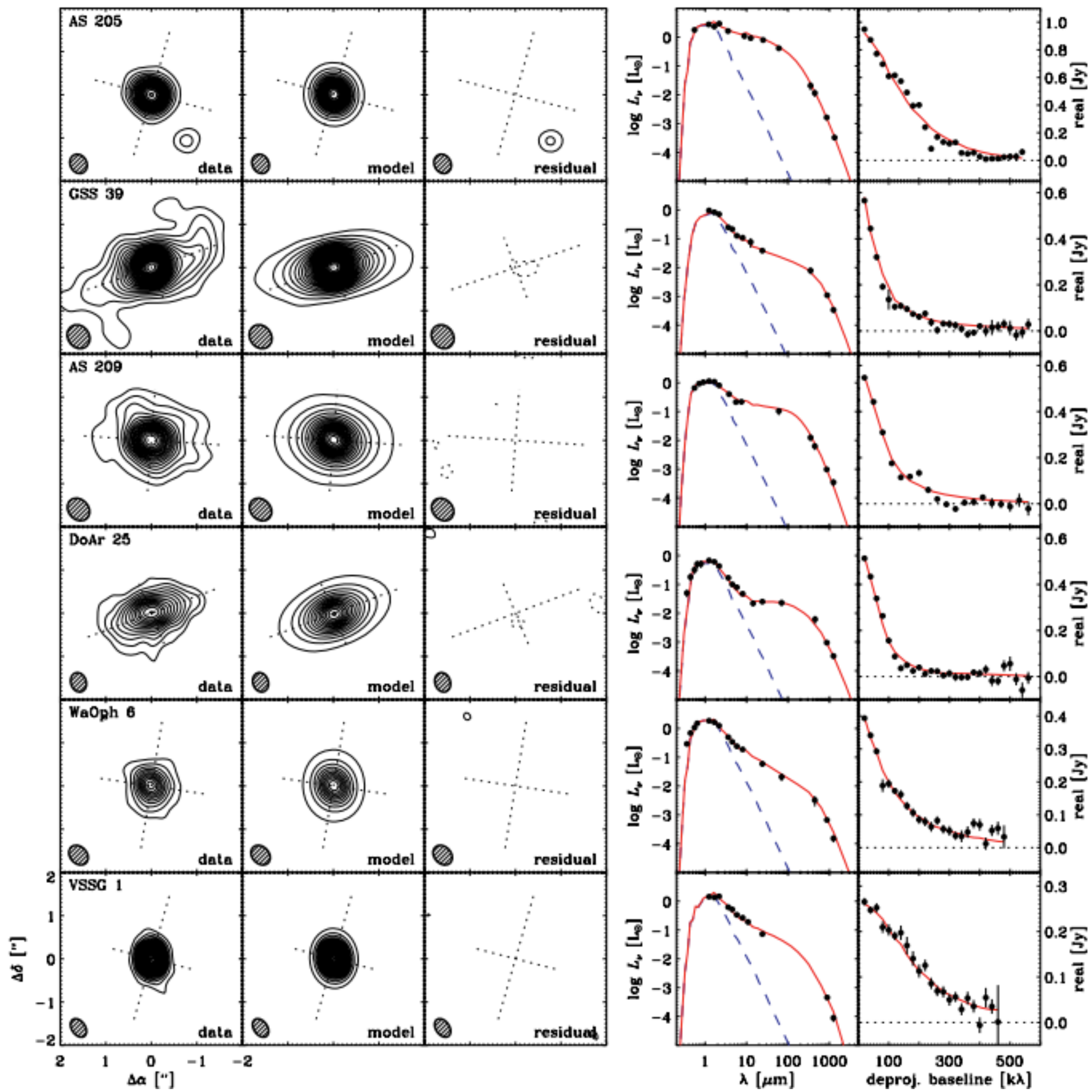
- Rc: characteristic radius where the density profile begins to steepen significantly from a power law, typically Rc = 30 − 200 au
- Apparent size discrepancy! mm continuum is optically thin, CO line emission is optically thick → can be detected further out

Parameter correlations

- Andrews et al. (2009, 2010): 16 disks in Ophiuchus
- Rc = 14 − 198 au
- Between disk size and disk mass:

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

- Between disk size and stellar properties: no correlation



Disk structure – Σ

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

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

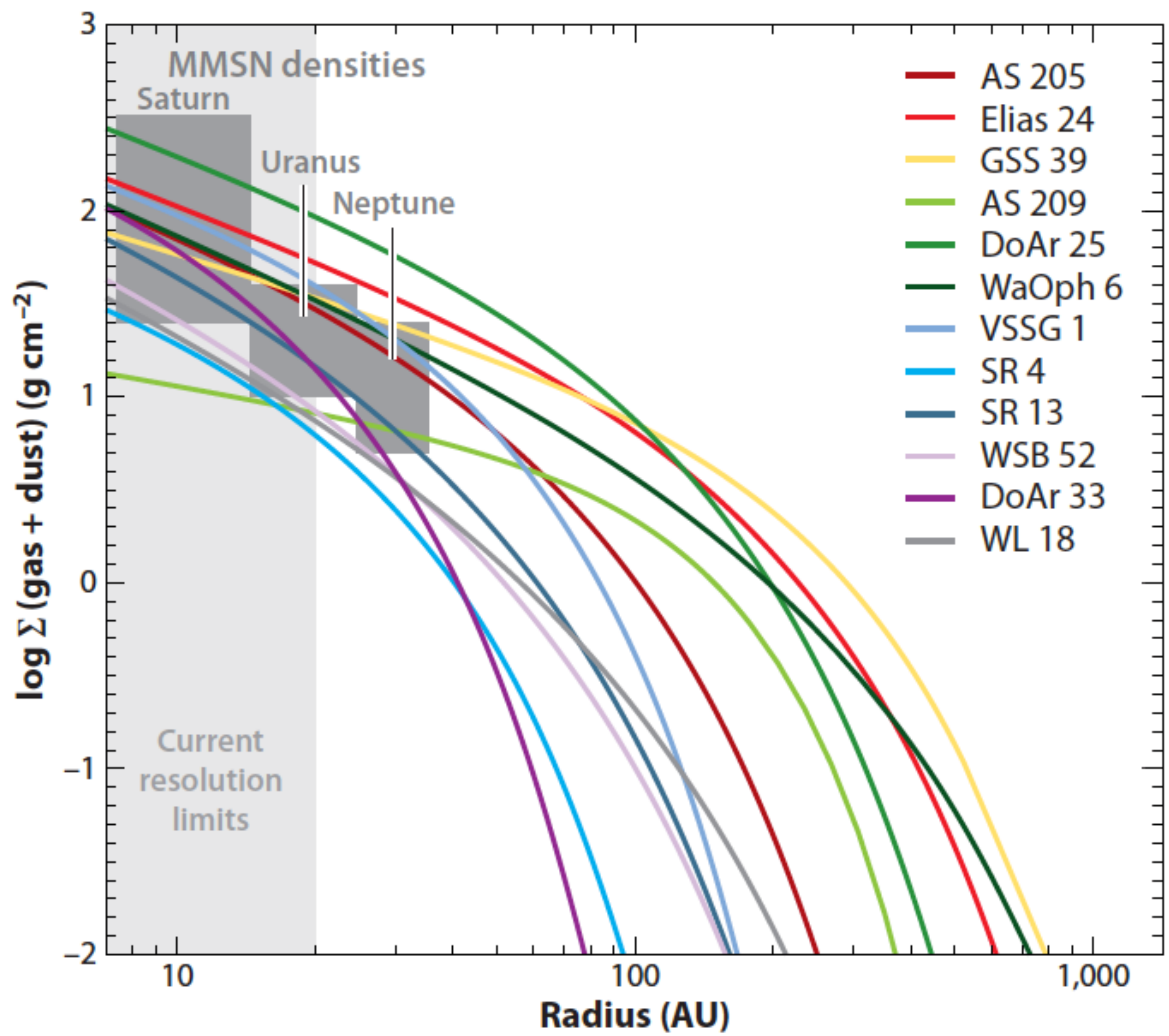
- Approximates $\Sigma \sim R^{-\gamma}$ for $R \ll R_c$
- $\gamma = -0.8 \ldots 0.8$ (mean 0.1)
- Σ distribution is quite flat

Σ distribution

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

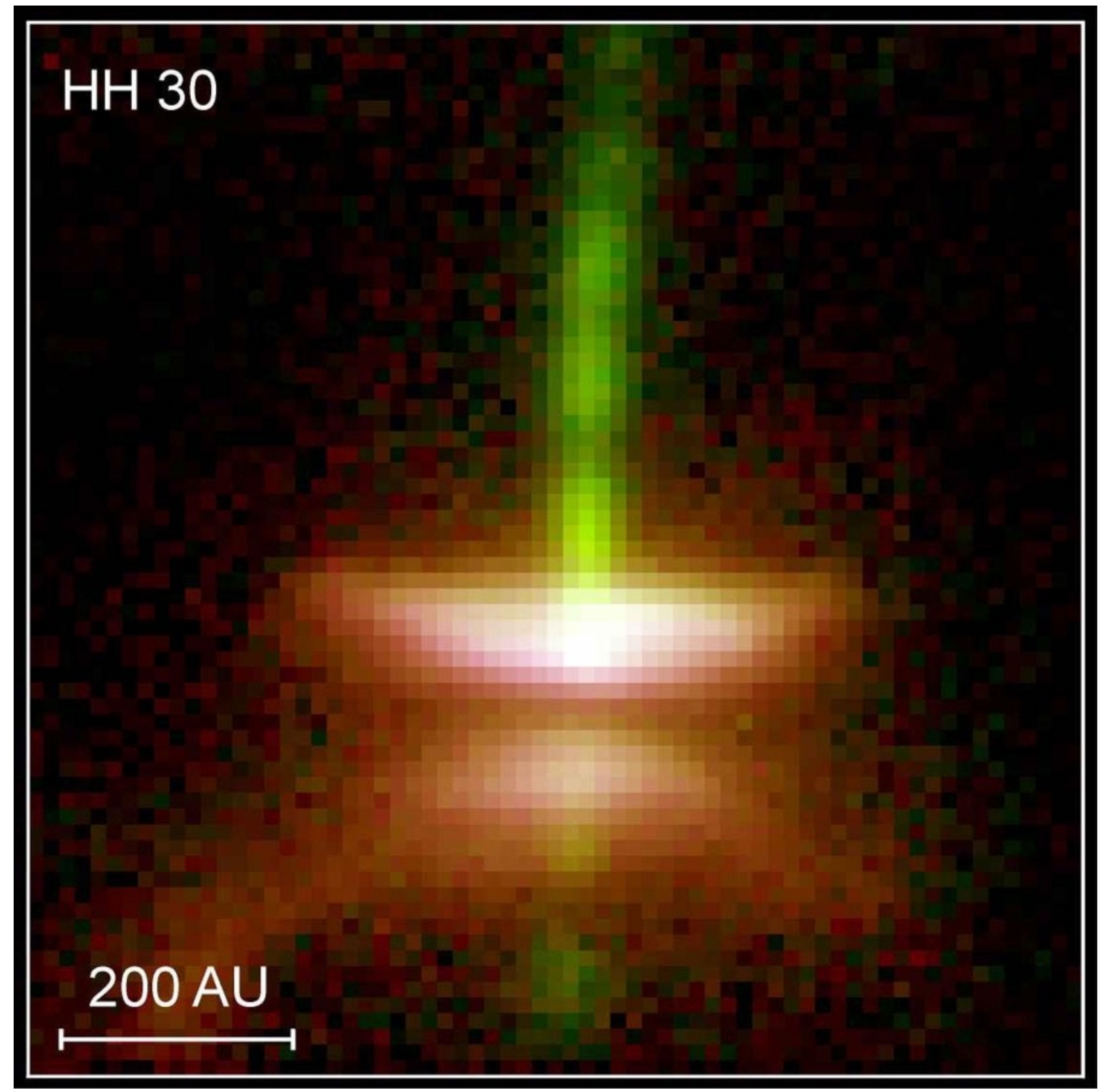
$$Q(R) = c\,\Omega / \pi G \Sigma$$

- Class II are typically gravitationally stable



Disk structure − H

H − vertical scale height

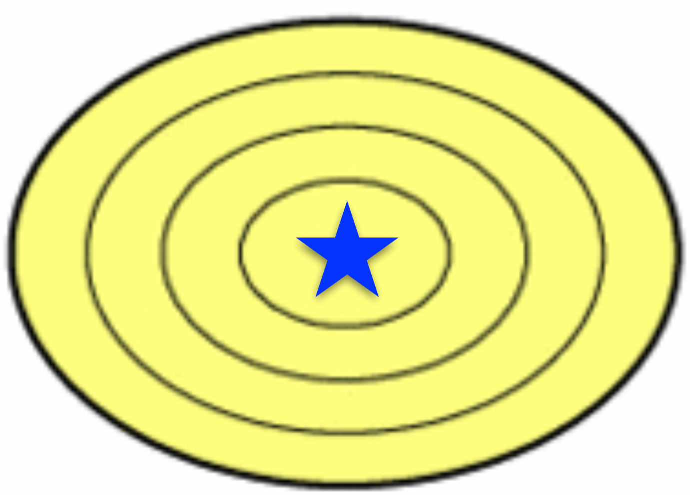


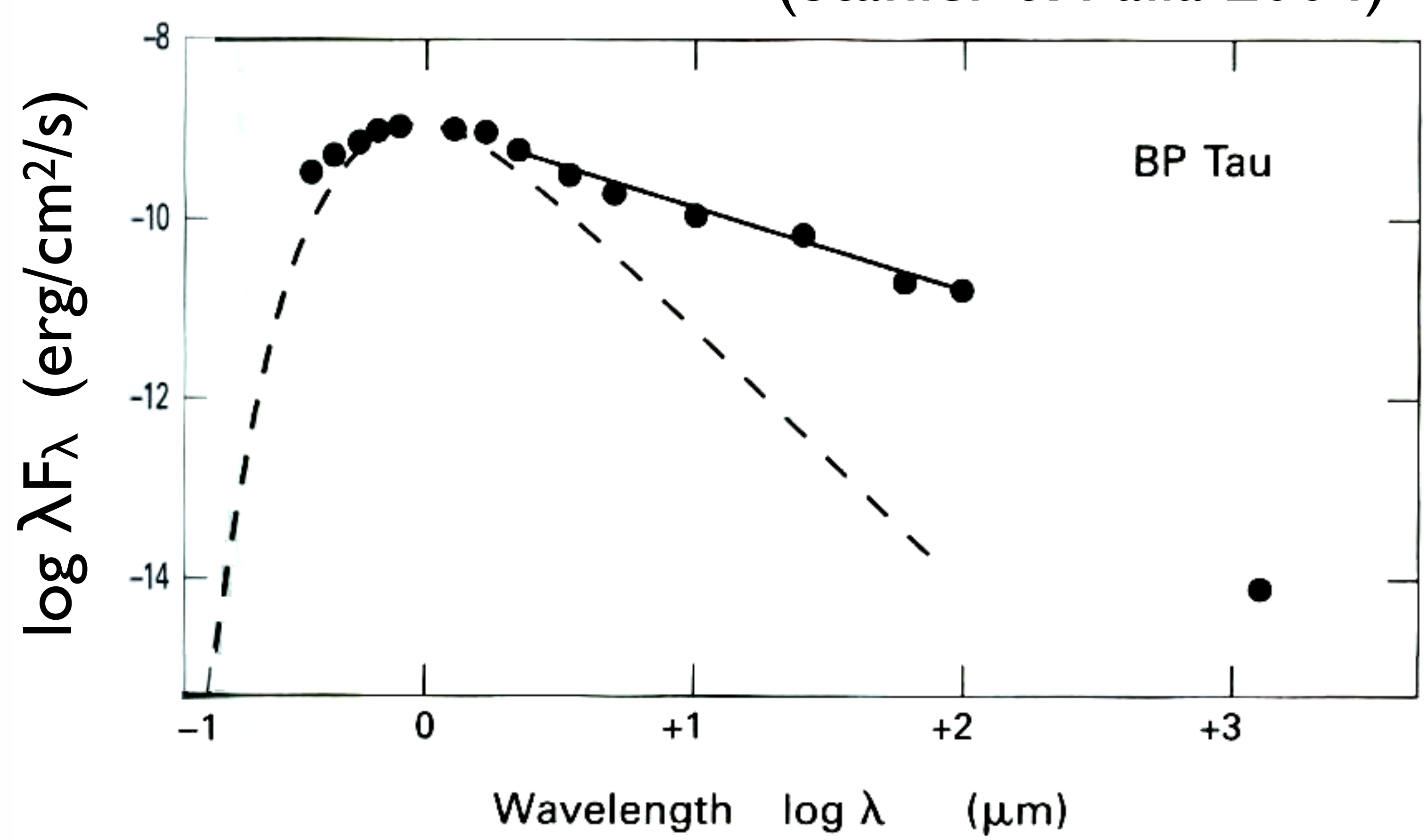
(Burrows et al. 1996)

Disk structure – H

- Disks were first assumed to be flat
- If $T(r) \sim r^{-q} \;\rightarrow\; \lambda F_\lambda \sim \lambda^{(2-4q)/q}$
- For both a passive, flat irradiated disk, or an active accreting disk, theoretically q = 3/4
- Resulting SED shape: $\lambda F_\lambda \sim \lambda^{-4/3}$

(Stahler & Palla 2004)



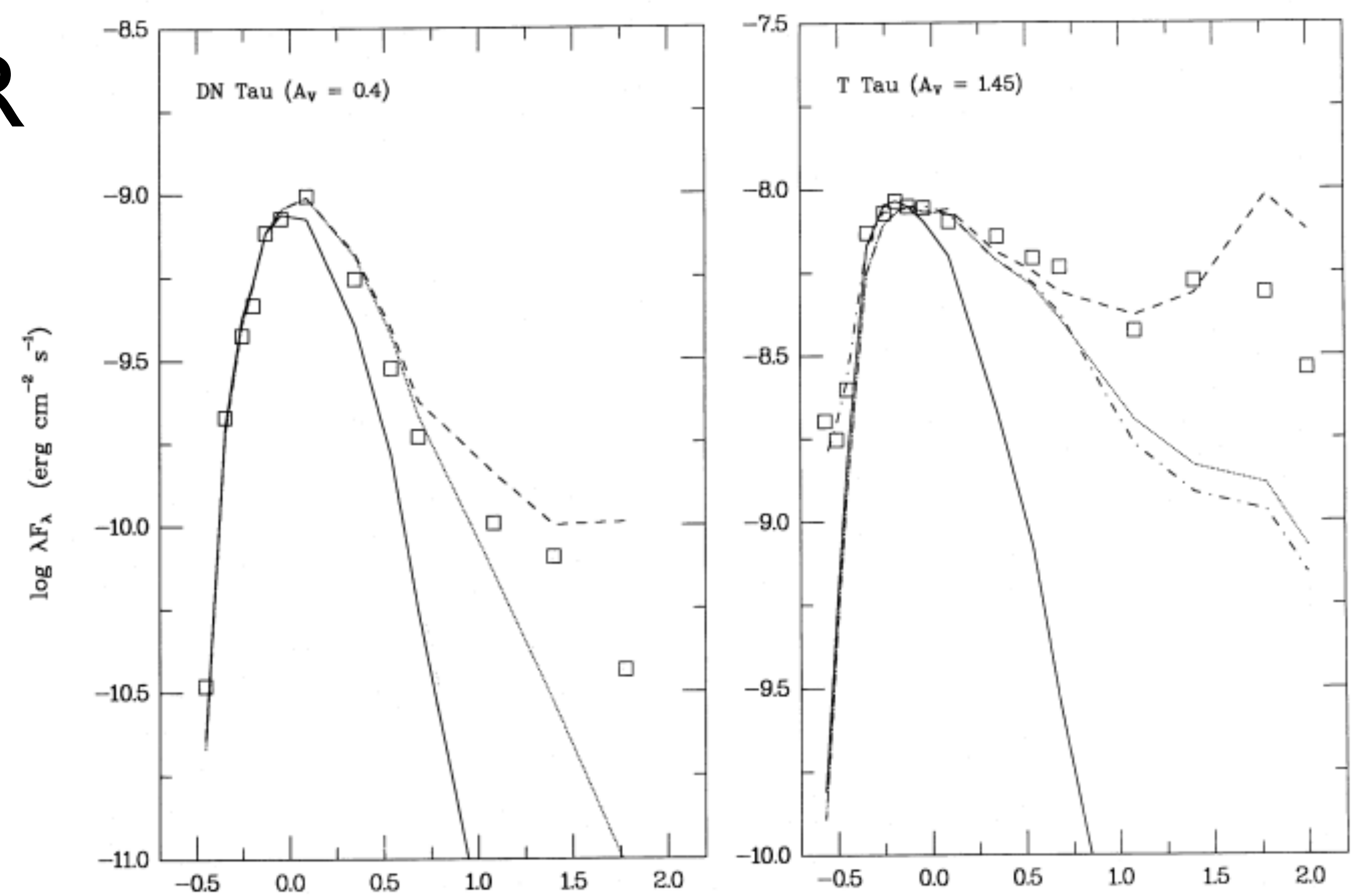


Disk structure – H

- Not all disks look like $\lambda F_\lambda \sim \lambda^{-4/3}$
- First idea of a flared disk: Kenyon & Hartmann (1987)
- H must increase with R
- Density:

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

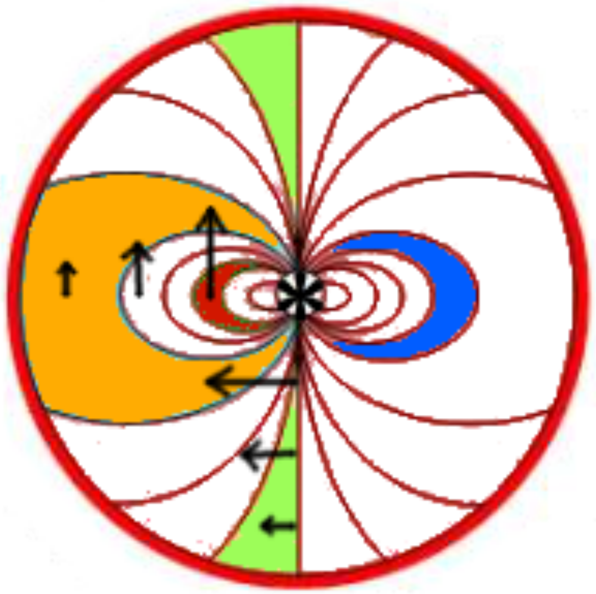
- Scale height is power-law: $H \sim R^h$, with $h = 1.3 \ldots 1.5$

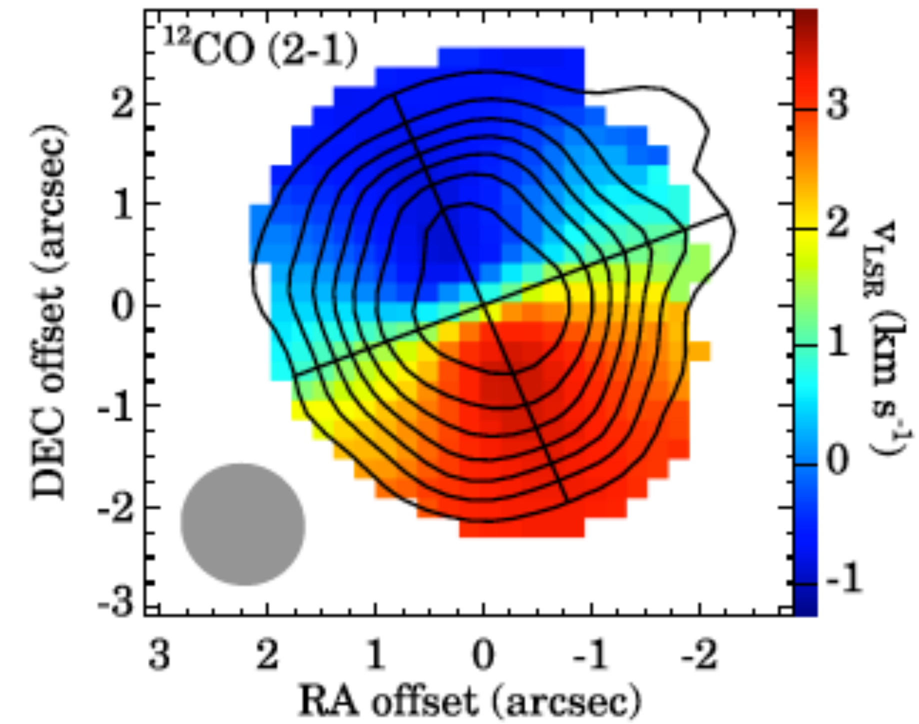


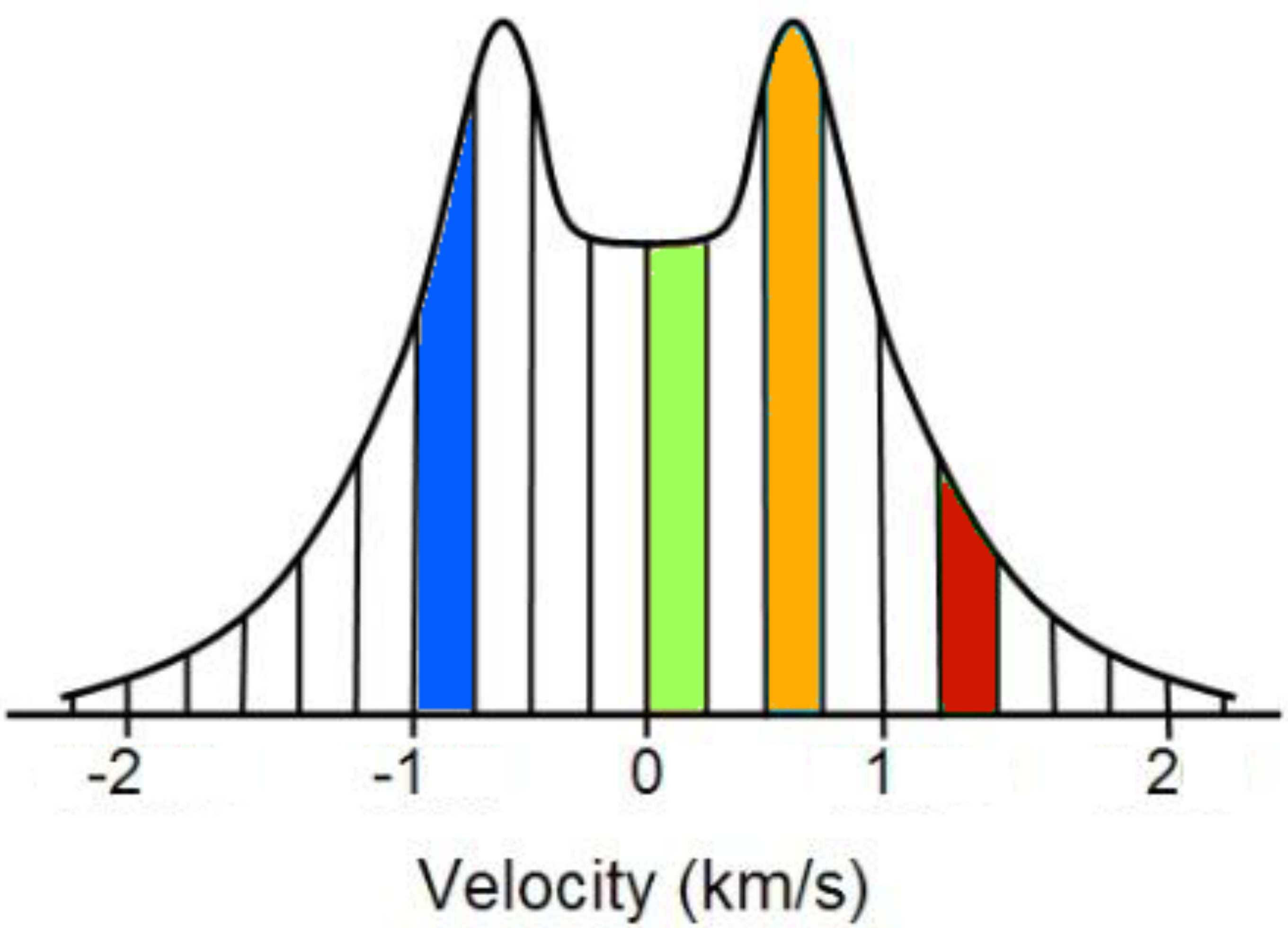
Disk structure – v

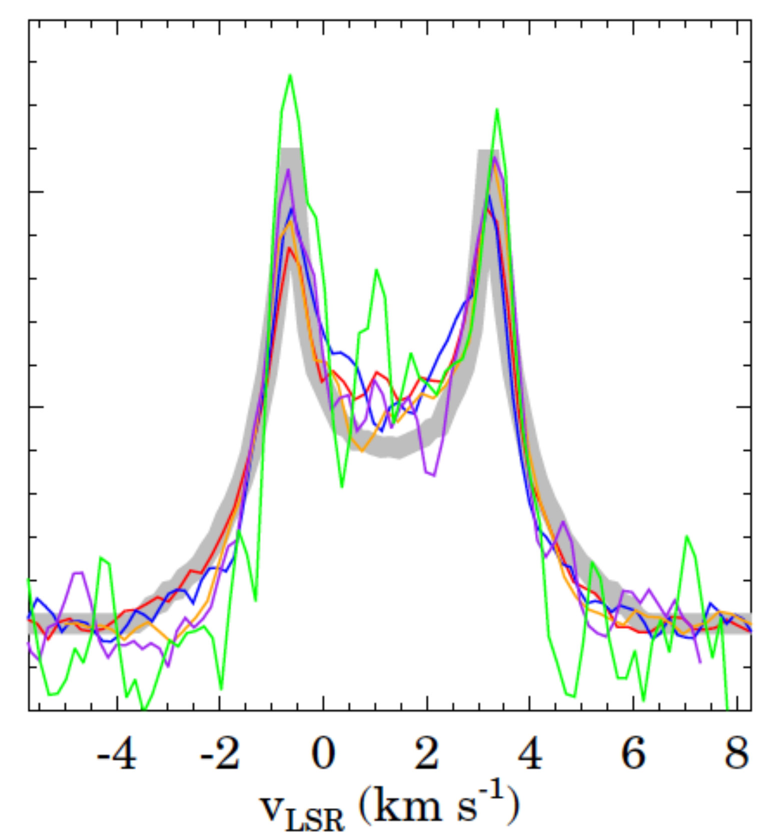
- In Class II: $M_{disk} \ll M_{star}$
- Expectation: Keplerian velocity field ($v \sim r^{-0.5}$)
- Method: spectral line observations
- Challenge: target needs to be bright enough for the individual channel maps to have high S/N ratio; no background cloud / envelope contamination
- Done for a handful of disks
- Now almost routine task with ALMA

Keplerian velocity profile



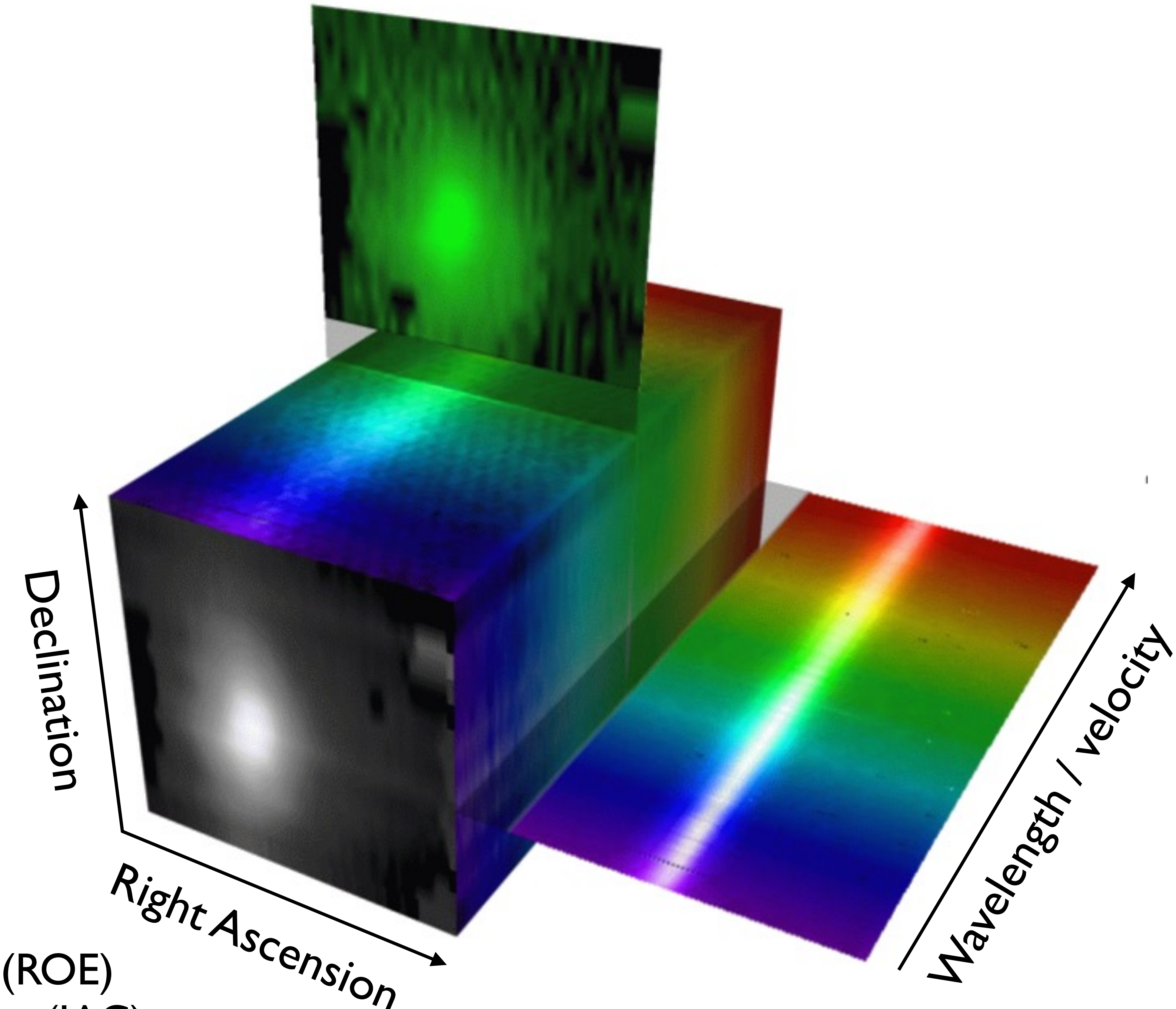






HD 21997 (Kóspál et al. 2013)

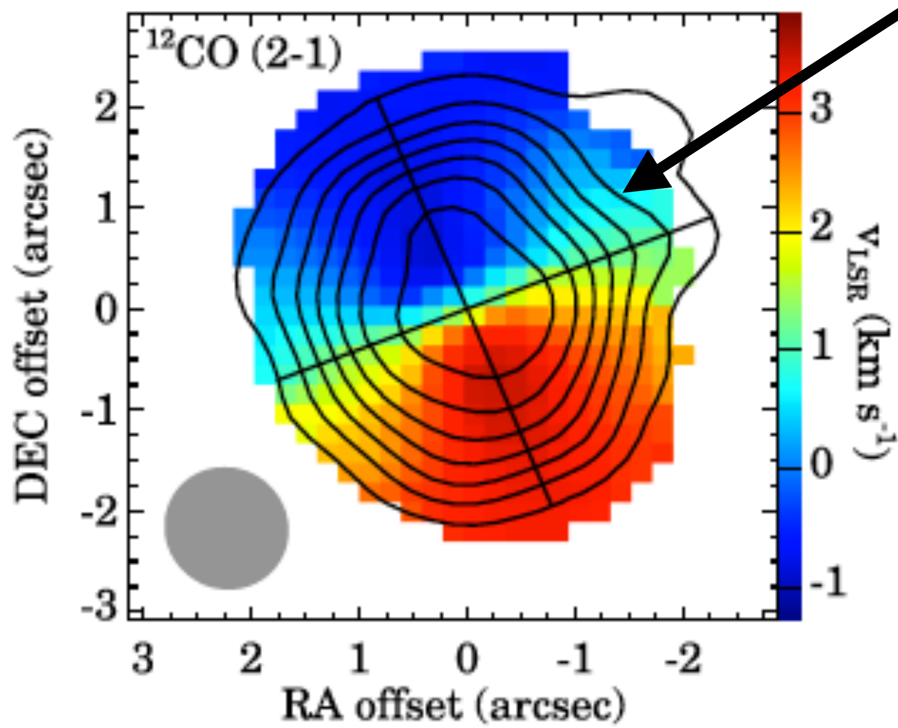
Interferometric data cube



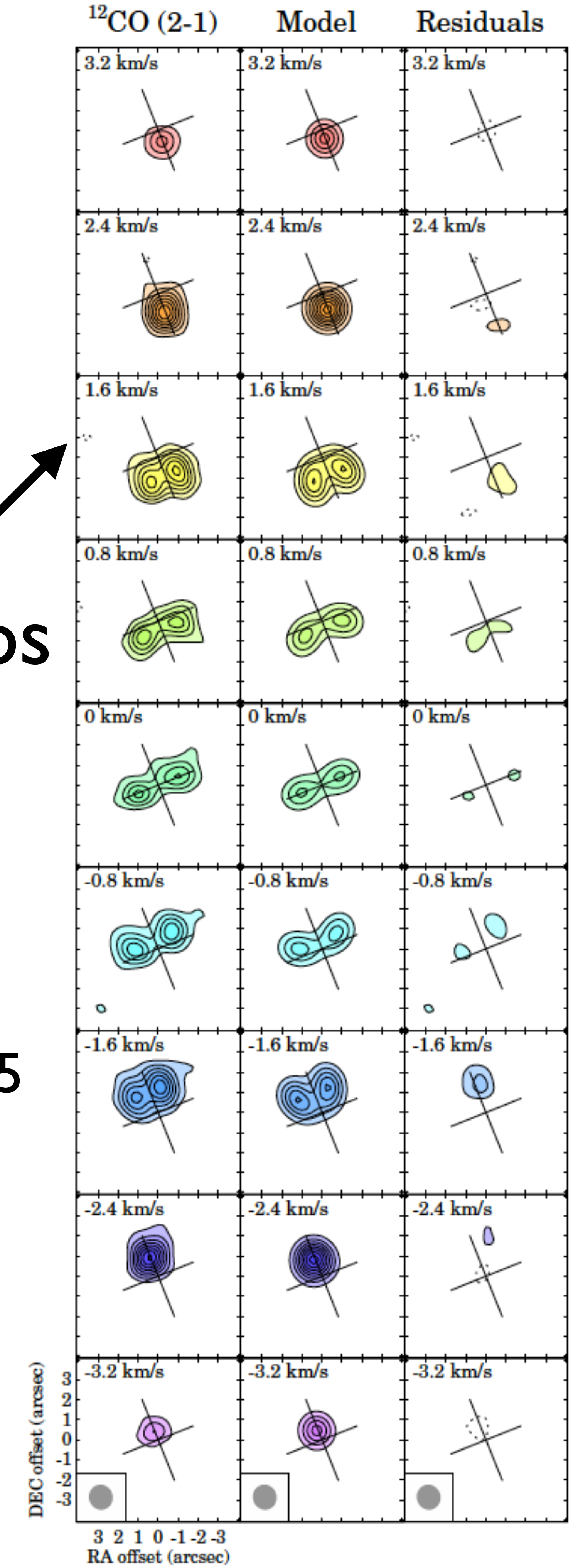
Credit: Stephen Todd (ROE)
and Douglas Pierce-Price (JAC)

Disk rotation

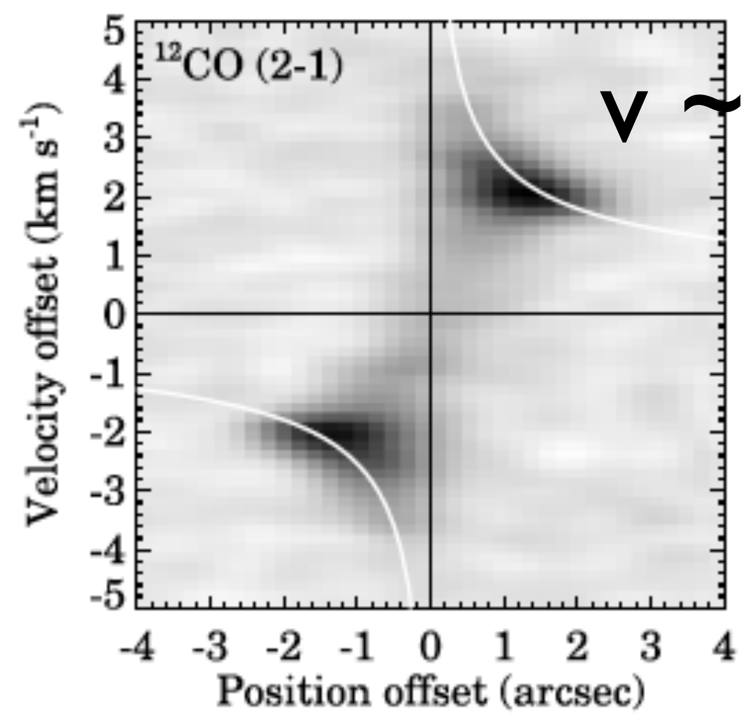
Velocity map
(first moment map)



Channel maps



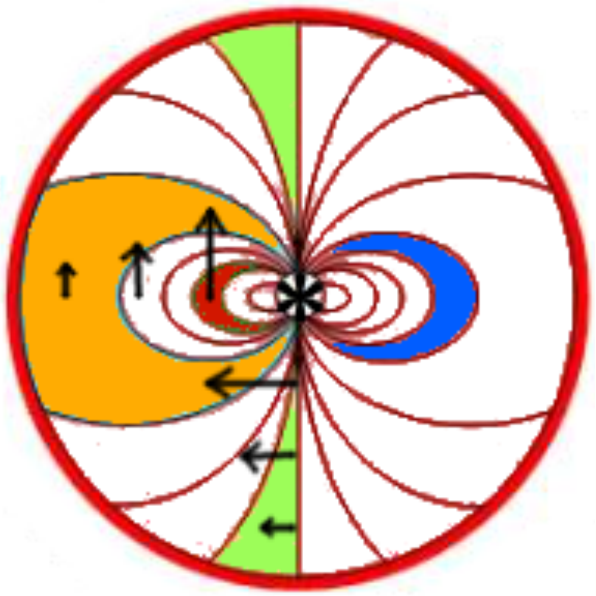
Position-velocity diagram

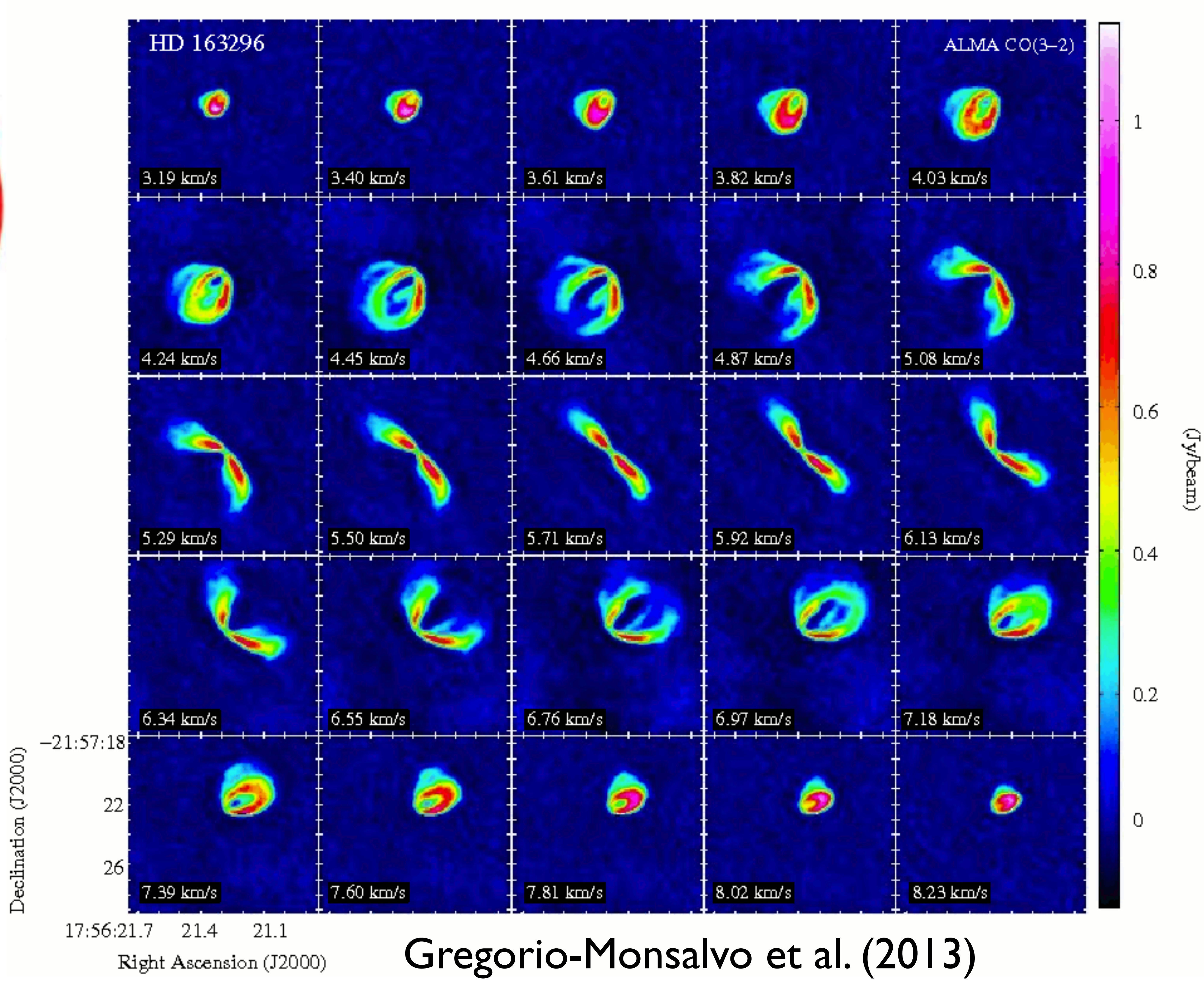


$v \sim r^{-0.5}$

HD 21997, Kóspál et al. (2013)

Disk rotation

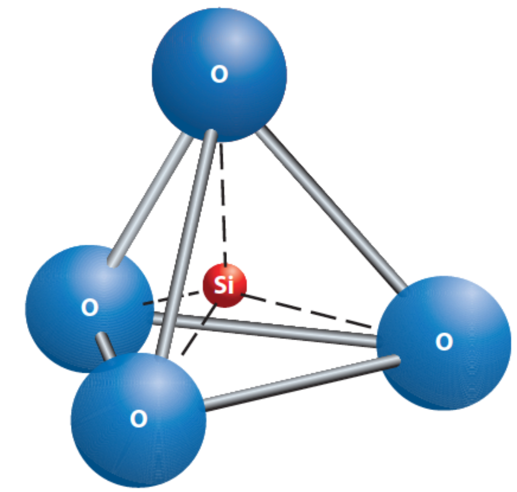


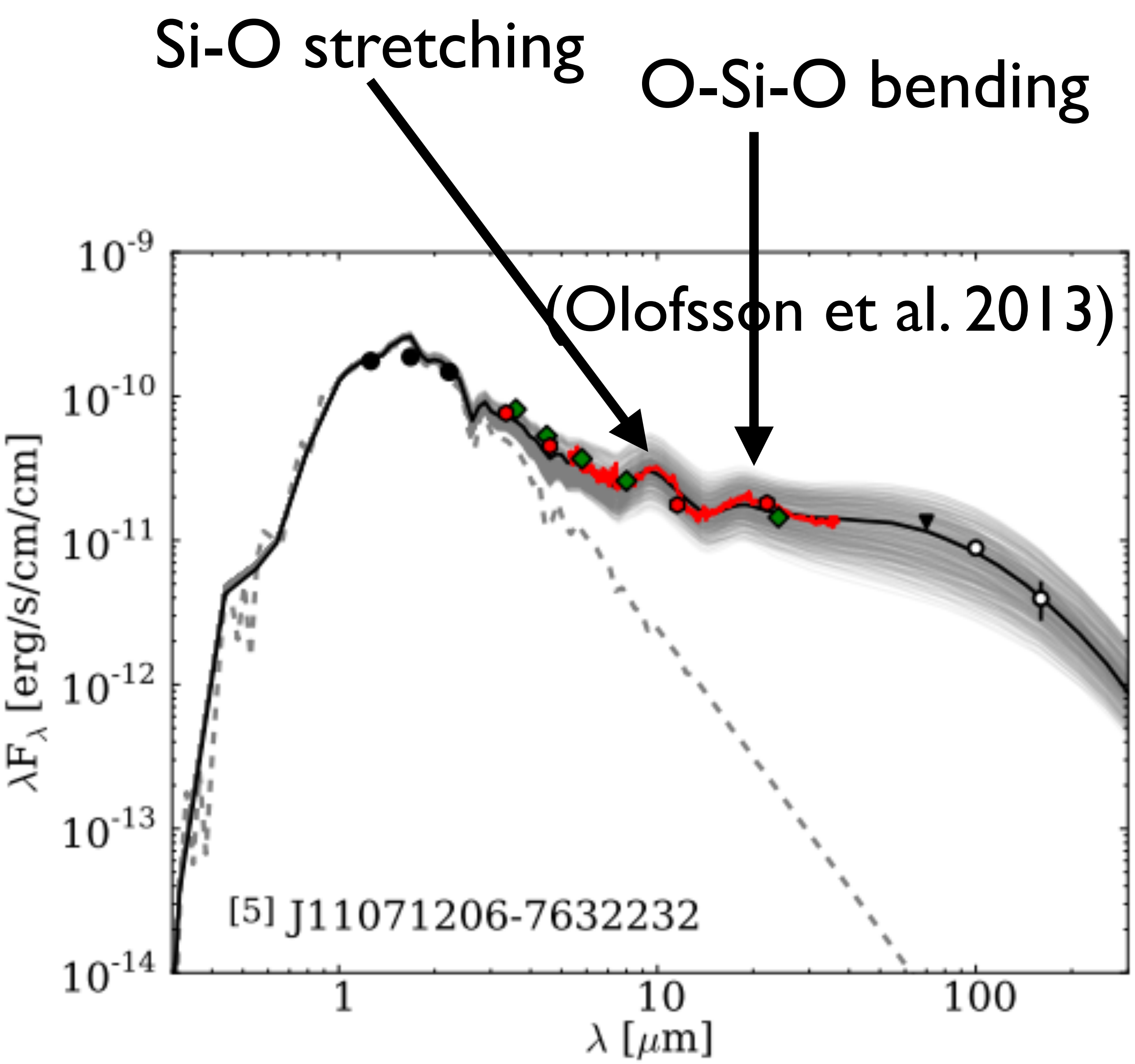


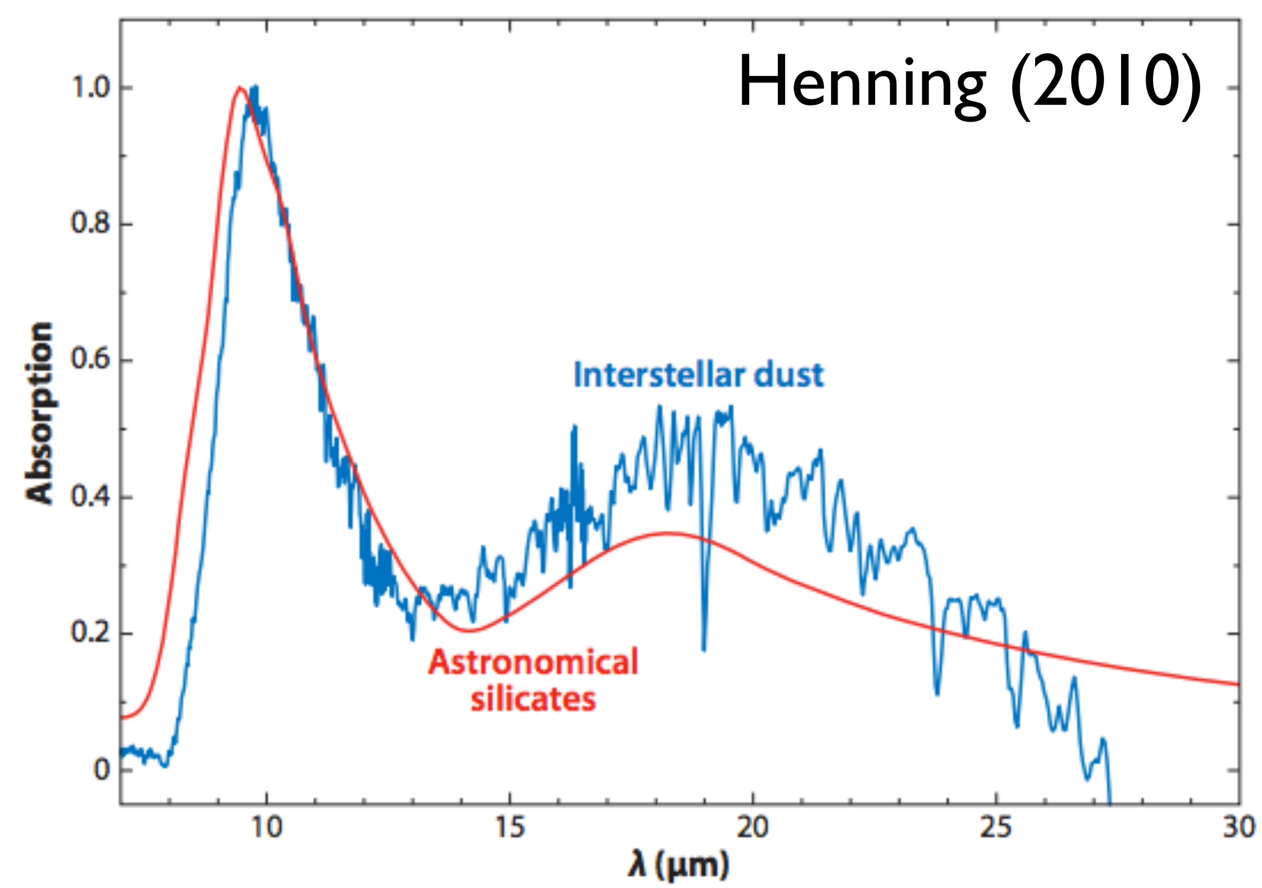
Gregorio-Monsalvo et al. (2013)

Disk composition – dust

- Dust dominates the opacity + dust makes the planets
- Composition: mainly silicates (SiO_4)

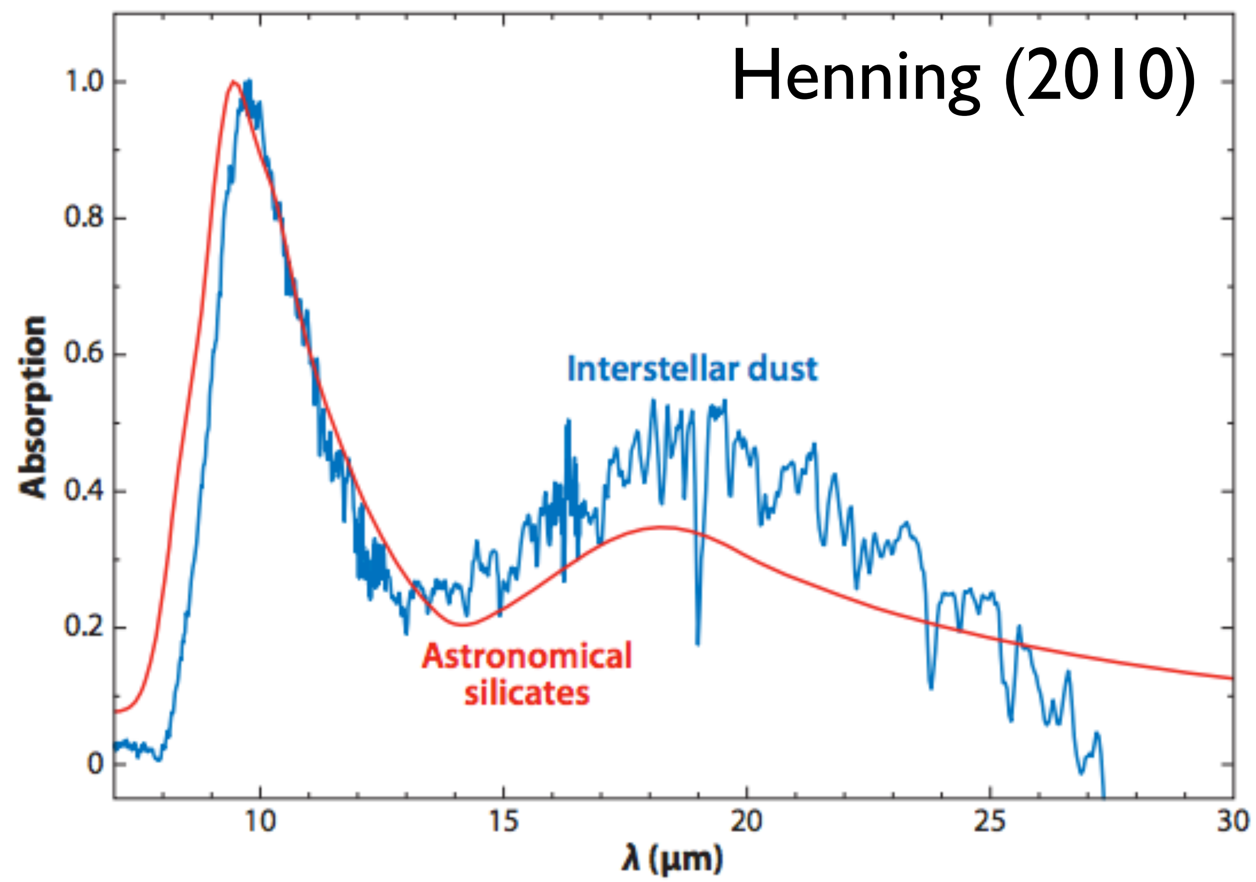






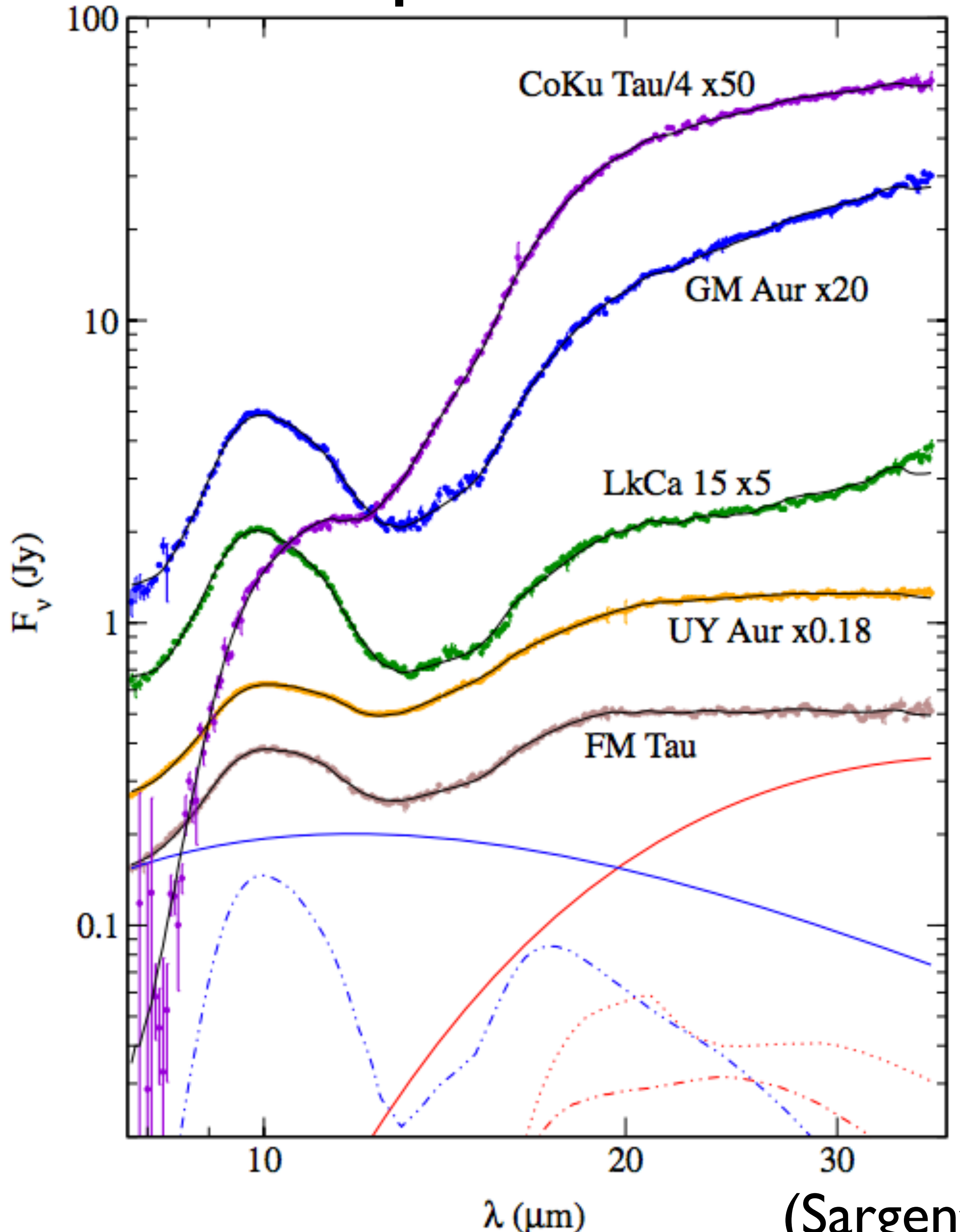
Interstellar dust

- Dust in the ISM: small (submicron-size) and amorphous
- In young stellar objects, there is evidence for dust processing:
  - Crystallization (amorphous → crystalline)
  - Grain growth (submicron → mm)

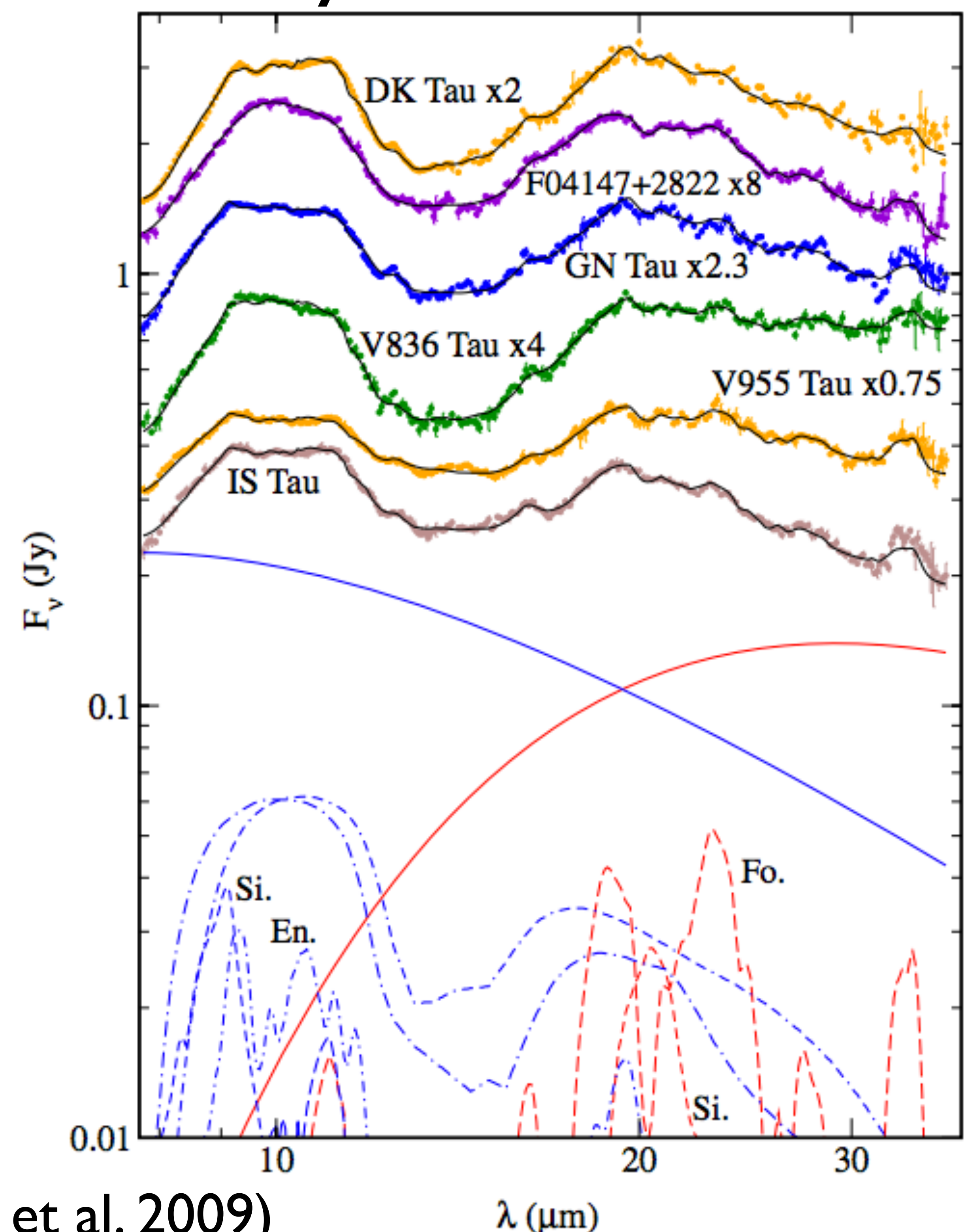


Dust processing

Amorphous silicates



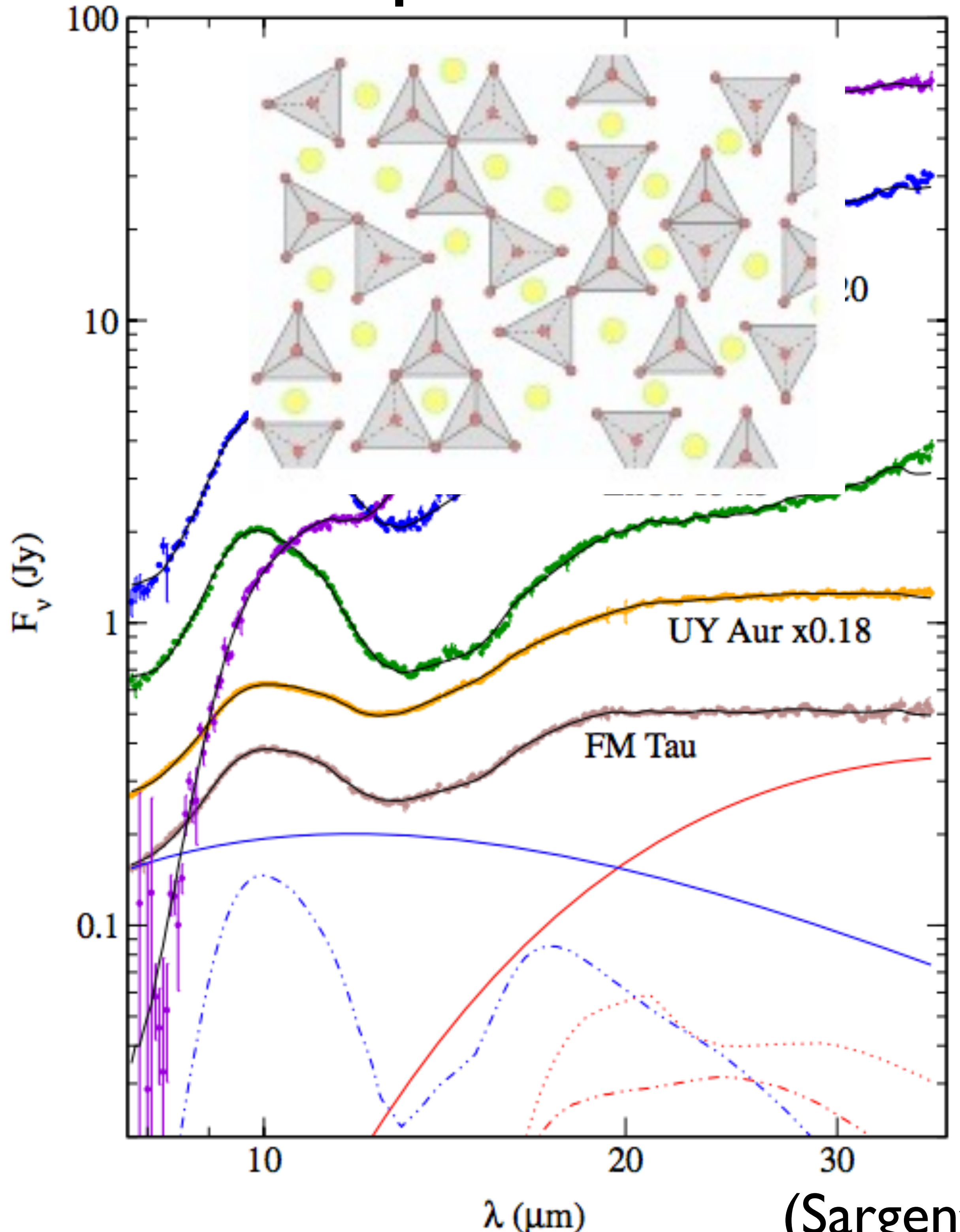
Crystalline silicates



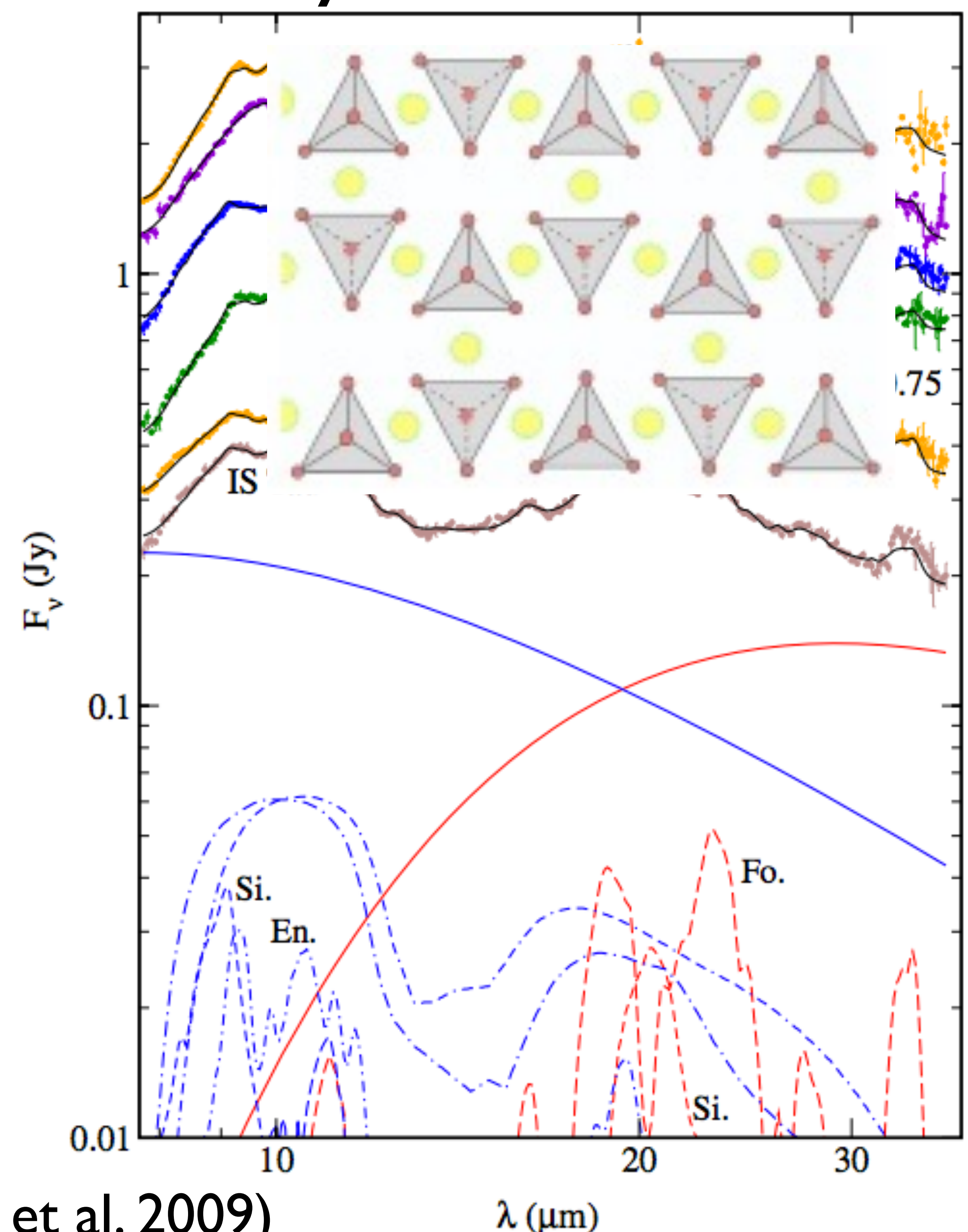
(Sargent et al. 2009)

Dust processing

Amorphous silicates

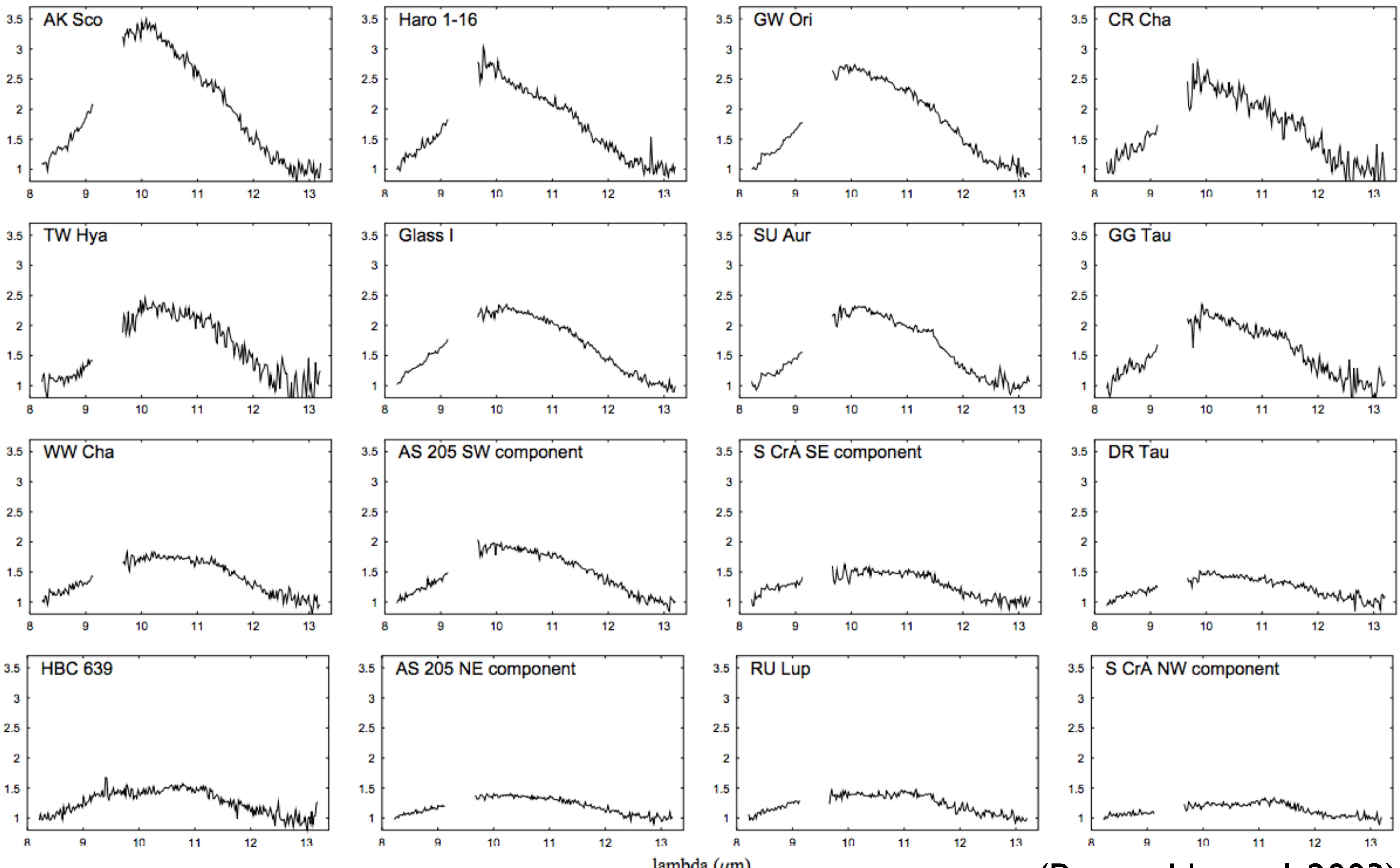


Crystalline silicates



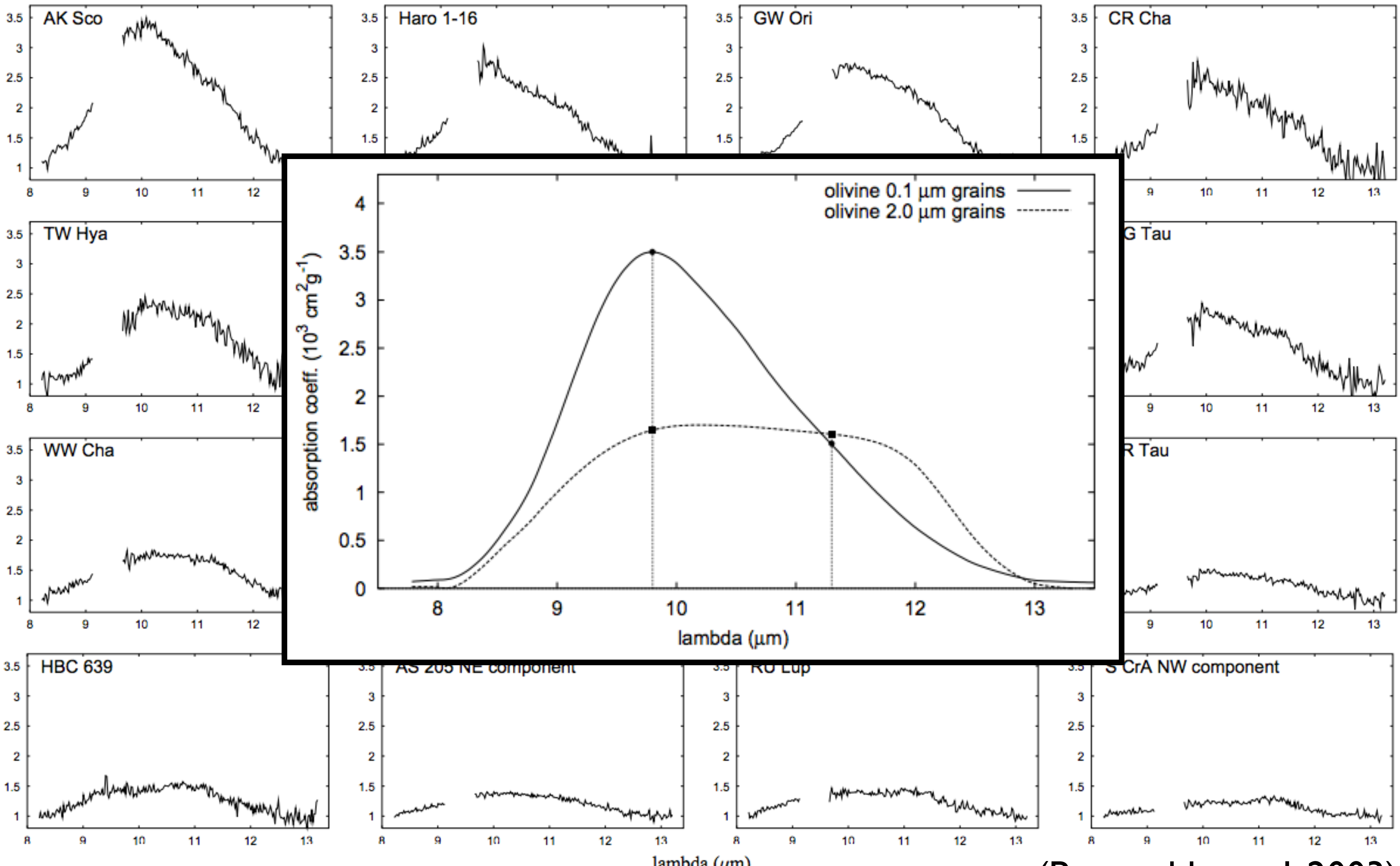
(Sargent et al. 2009)

Grain growth



(Przygodda et al. 2003)

Grain growth

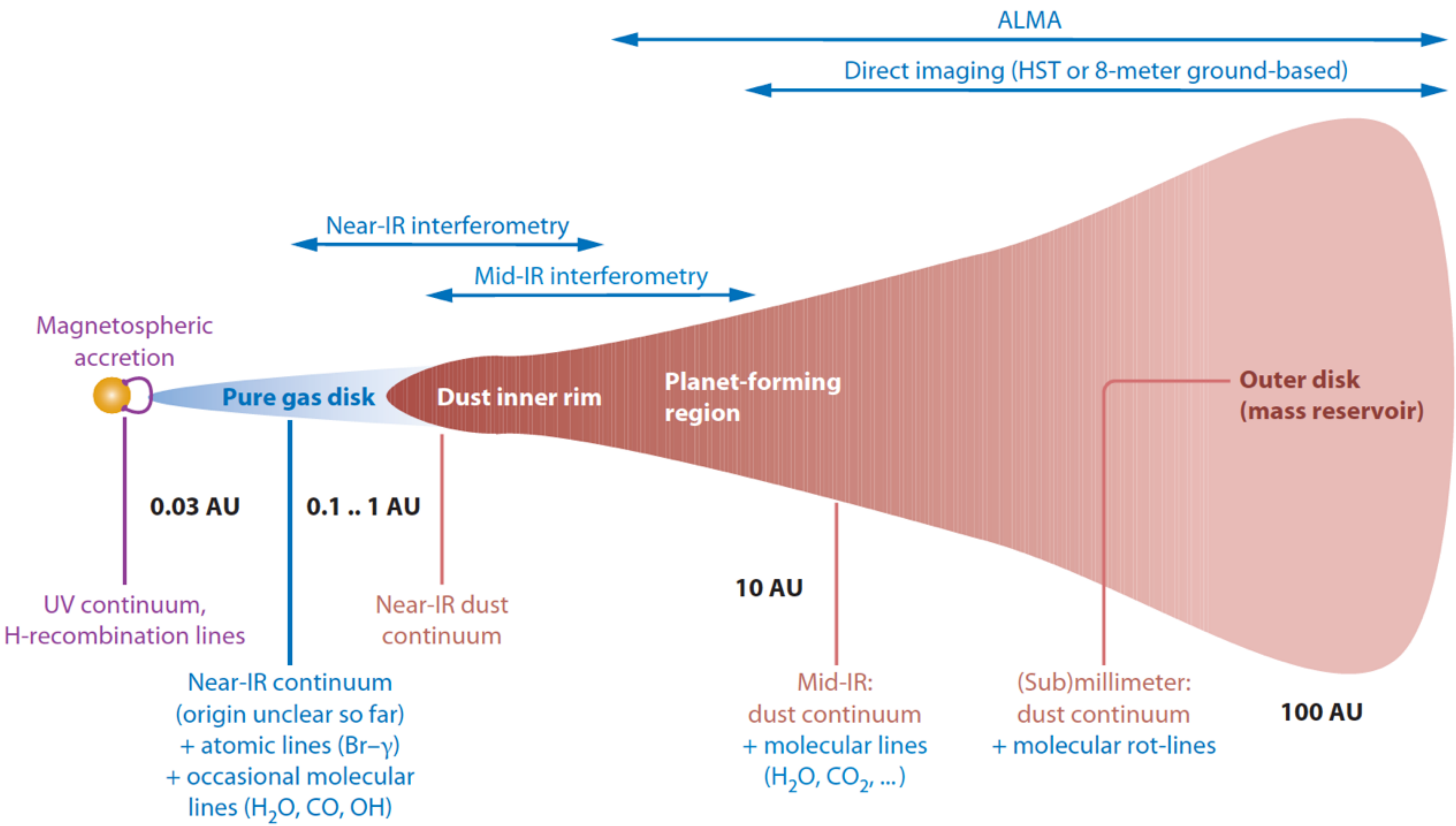


(Przygodda et al. 2003)

Disk composition – gas

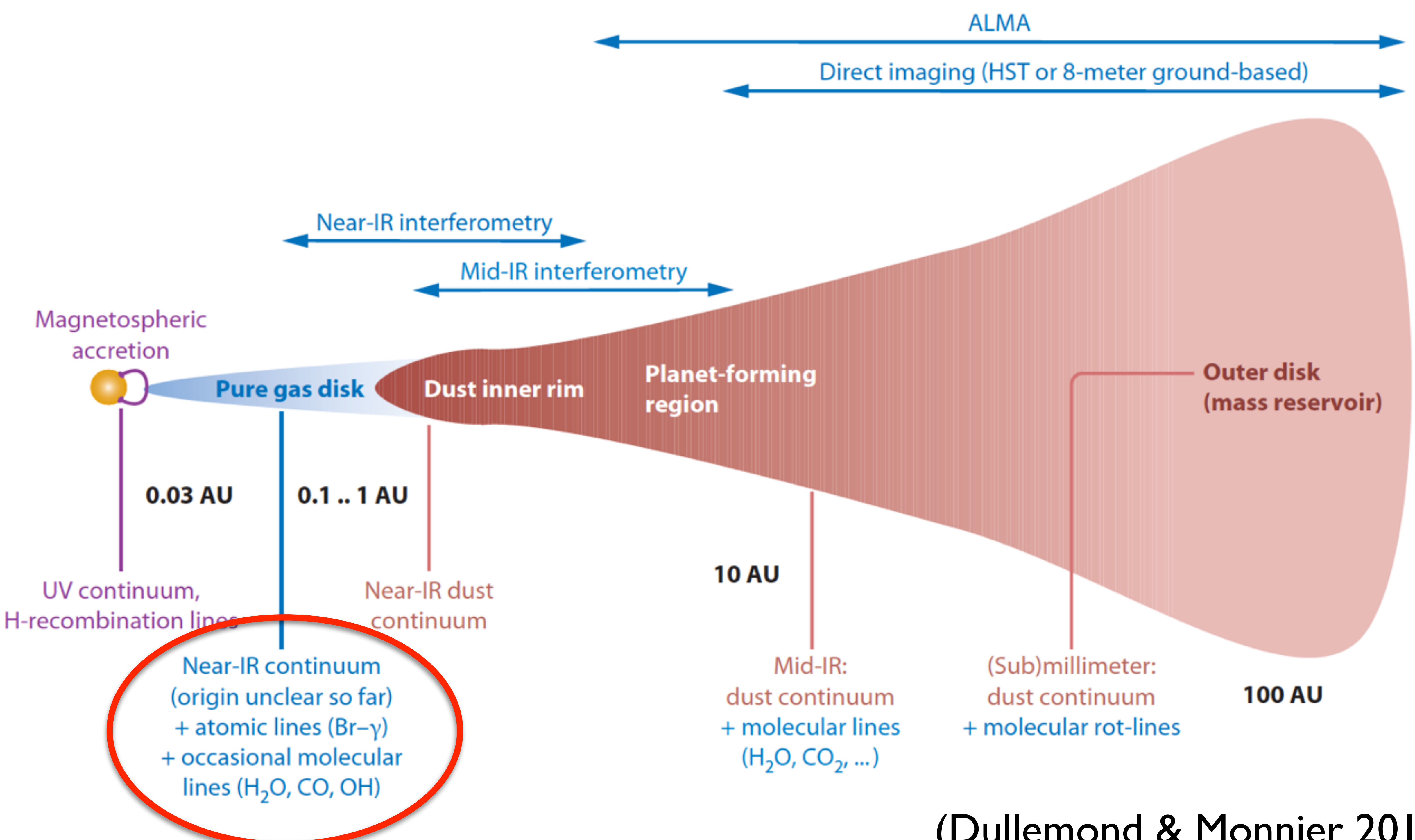
- Interstellar gas-to-dust mass ratio: 100
- 99% of the total mass of ISM
- 99% of the total mass of disks (at least initially)
- Difficult to detect (H_2 has no easily observable lines)
- Ways to observe the gas:
    - Disk accretion (recombination lines, excess hot continuum)
    - MIR molecular lines
    - FIR molecular lines

Disk composition – gas



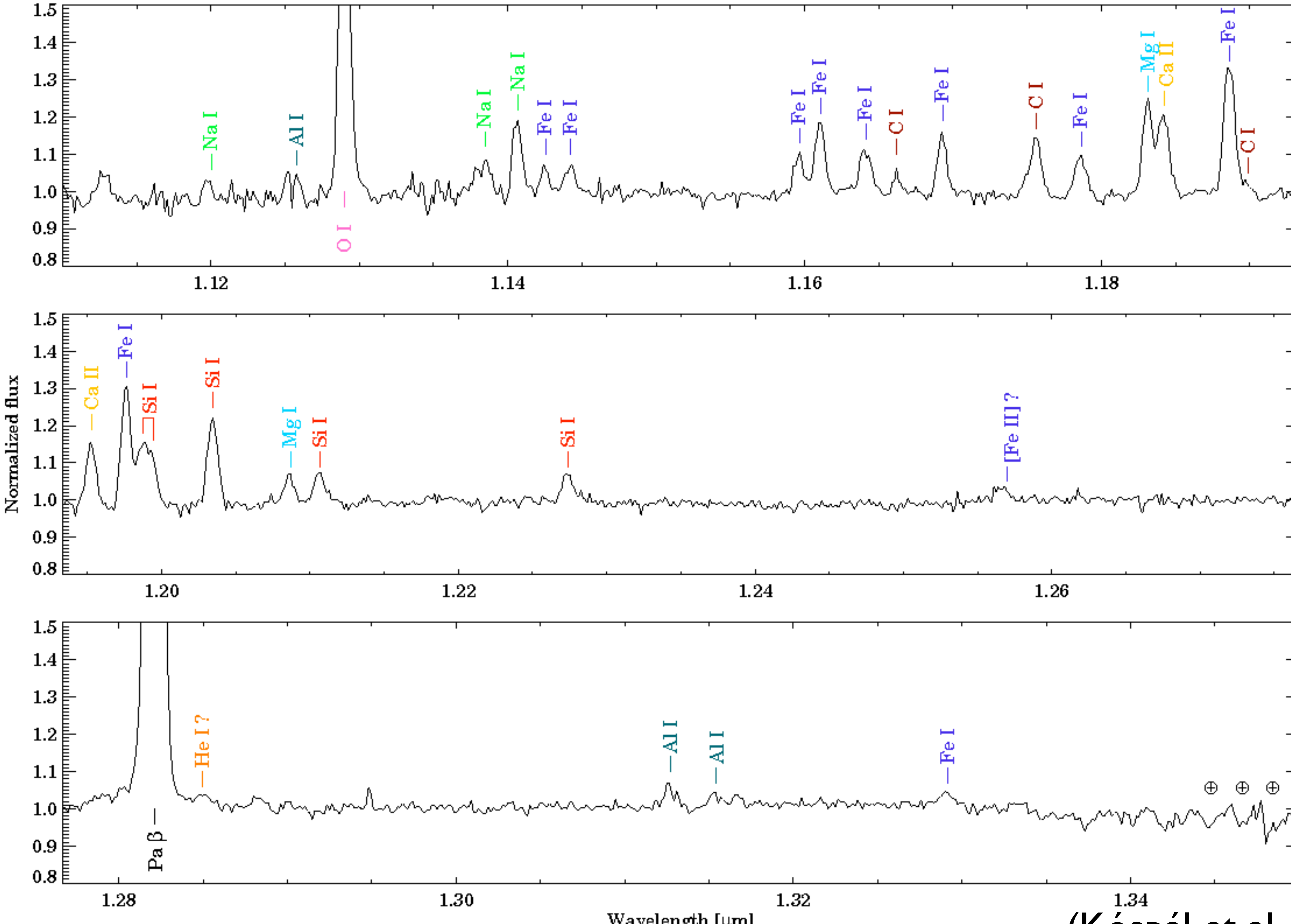
(Dullemond & Monnier 2010)

Disk composition – gas



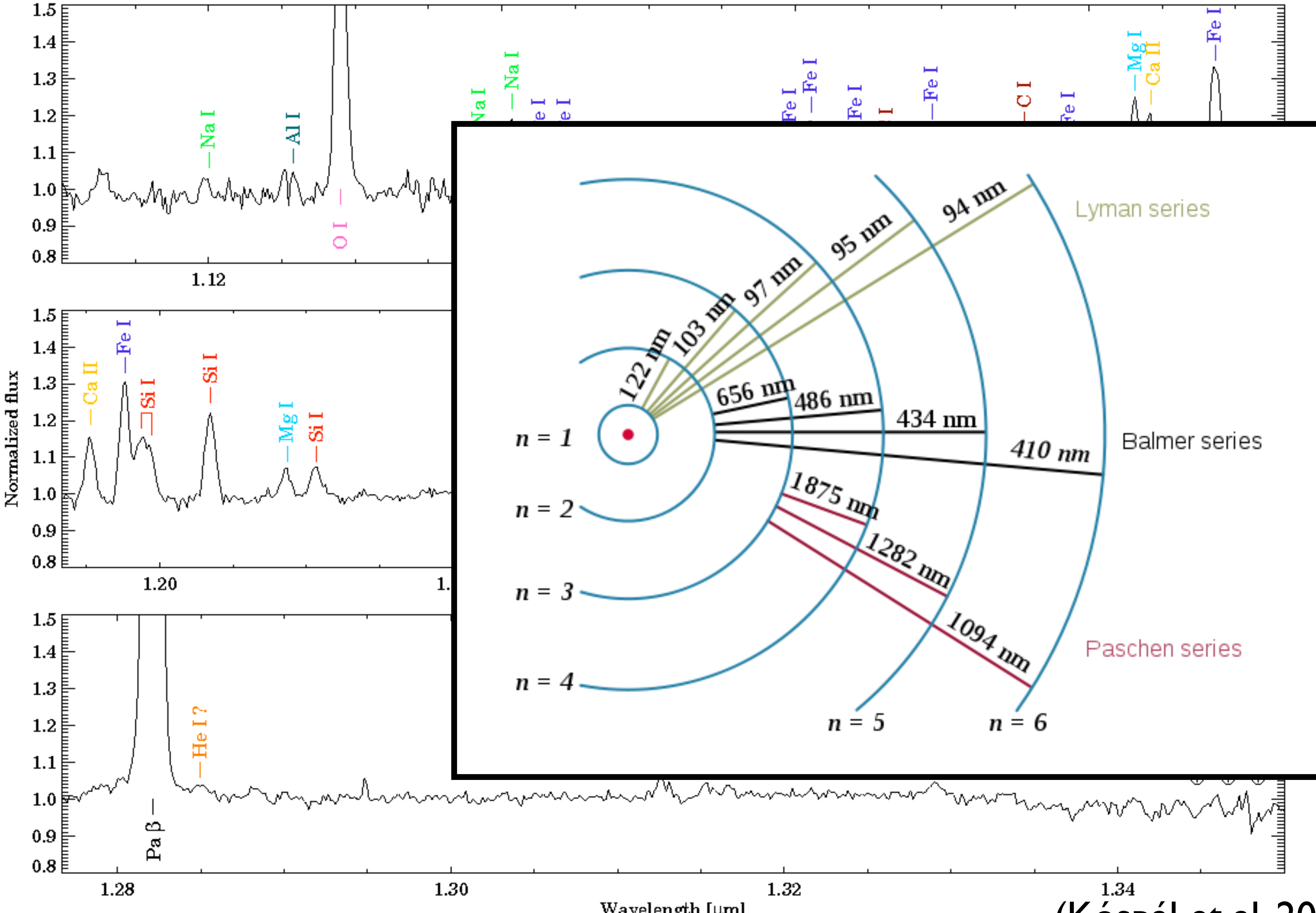
(Dullemond & Monnier 2010)

Near infrared lines



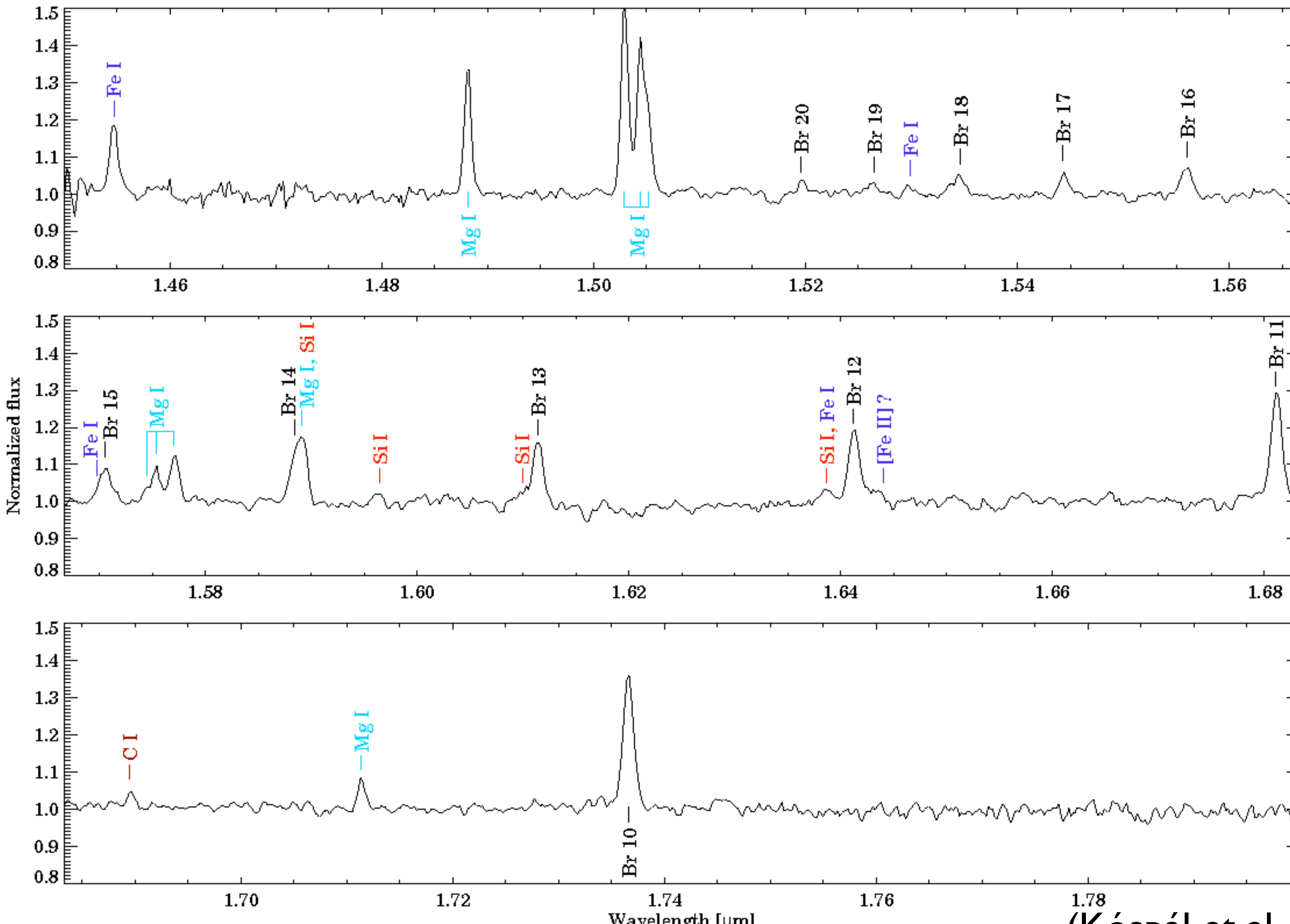
(Kóspál et al. 2012)

Near infrared lines



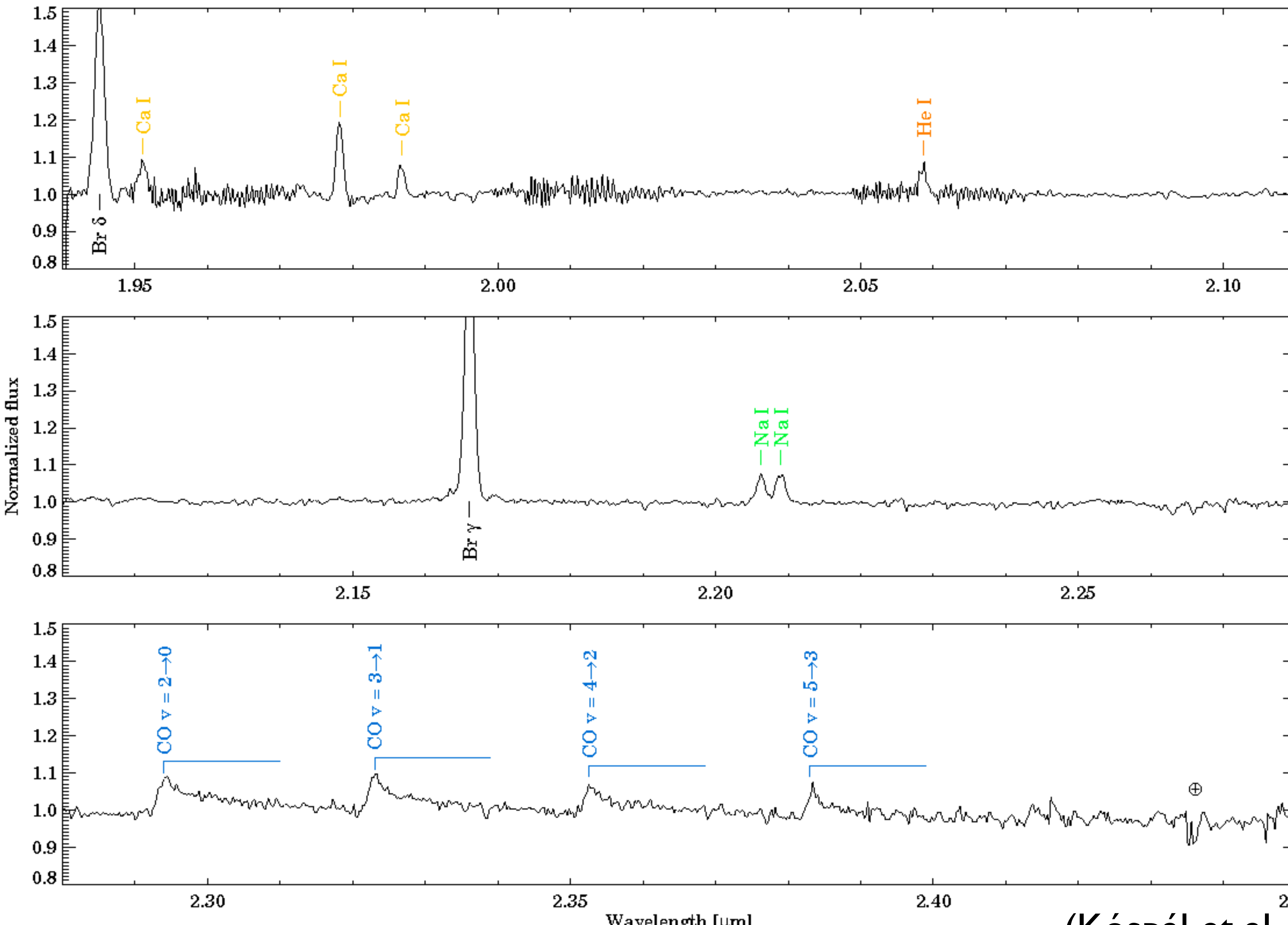
(Kóspál et al. 2012)

Near infrared lines



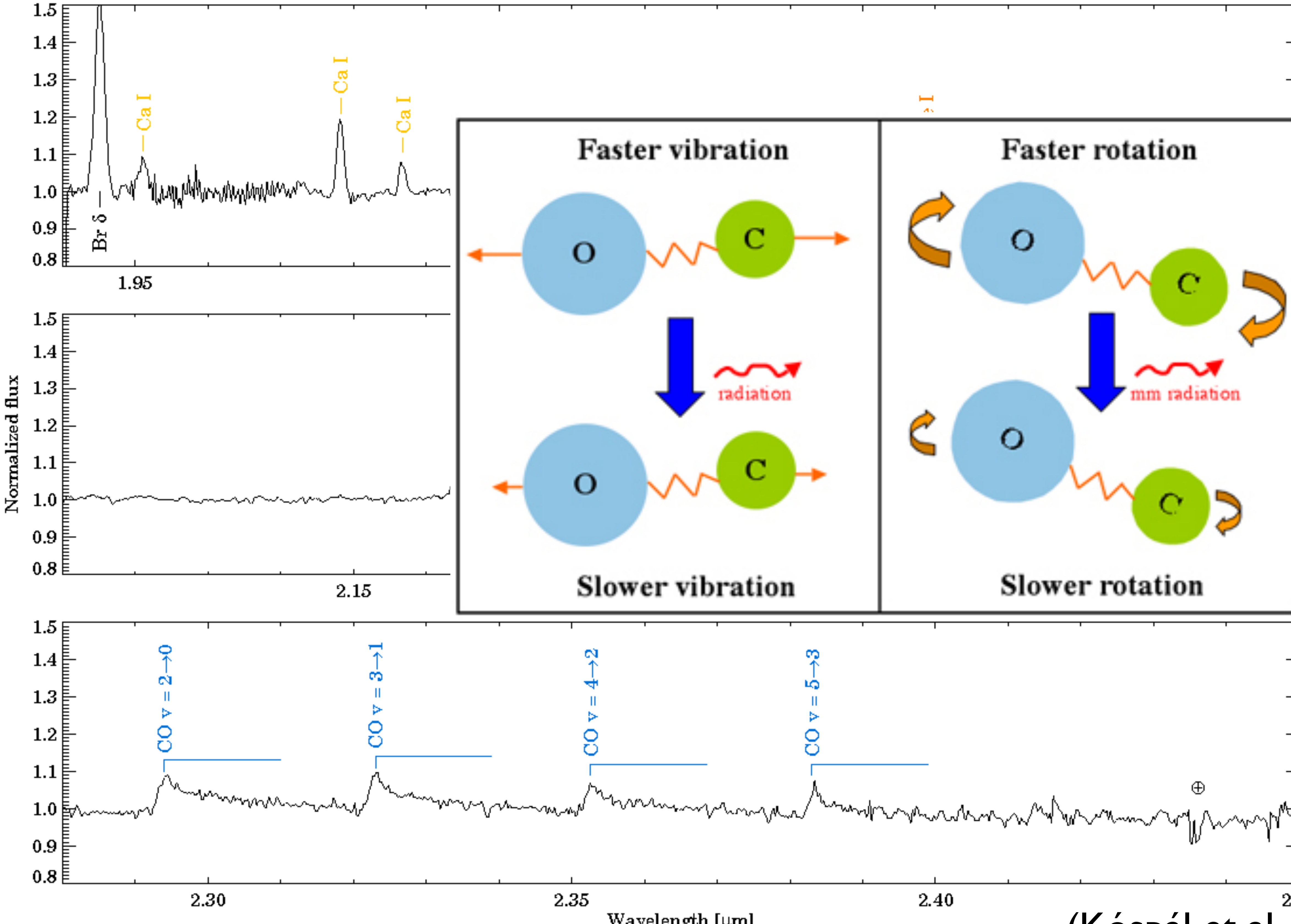
(Kóspál et al. 2012)

Near infrared lines



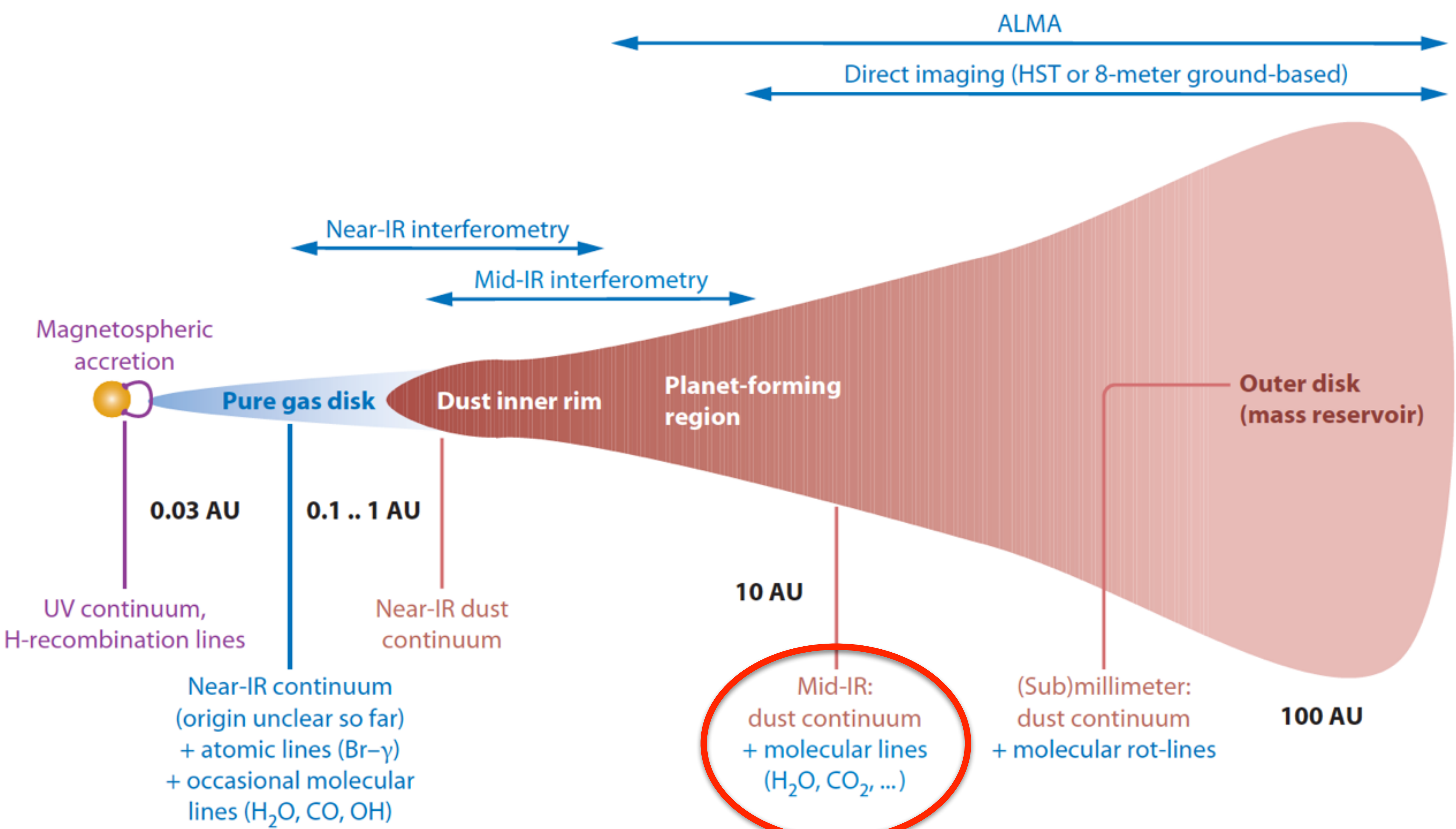
(Kóspál et al. 2012)

Near infrared lines



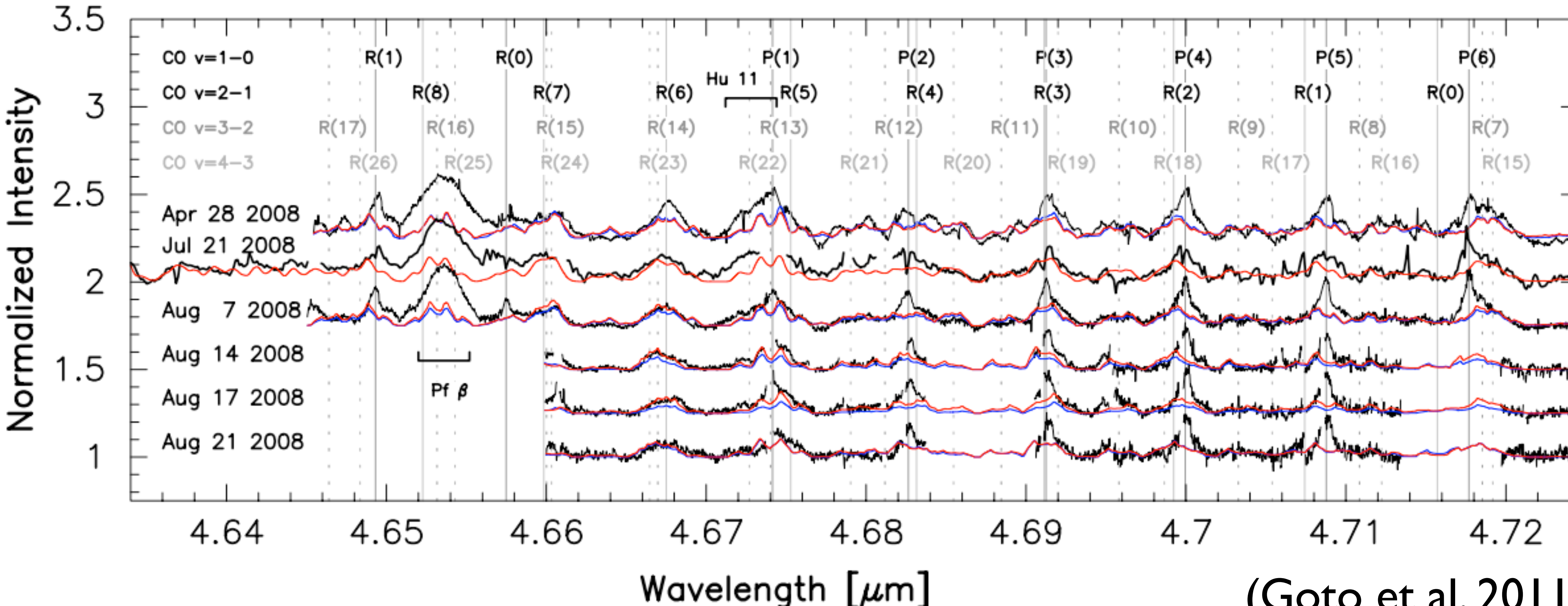
(Kóspál et al. 2012)

Disk composition – gas



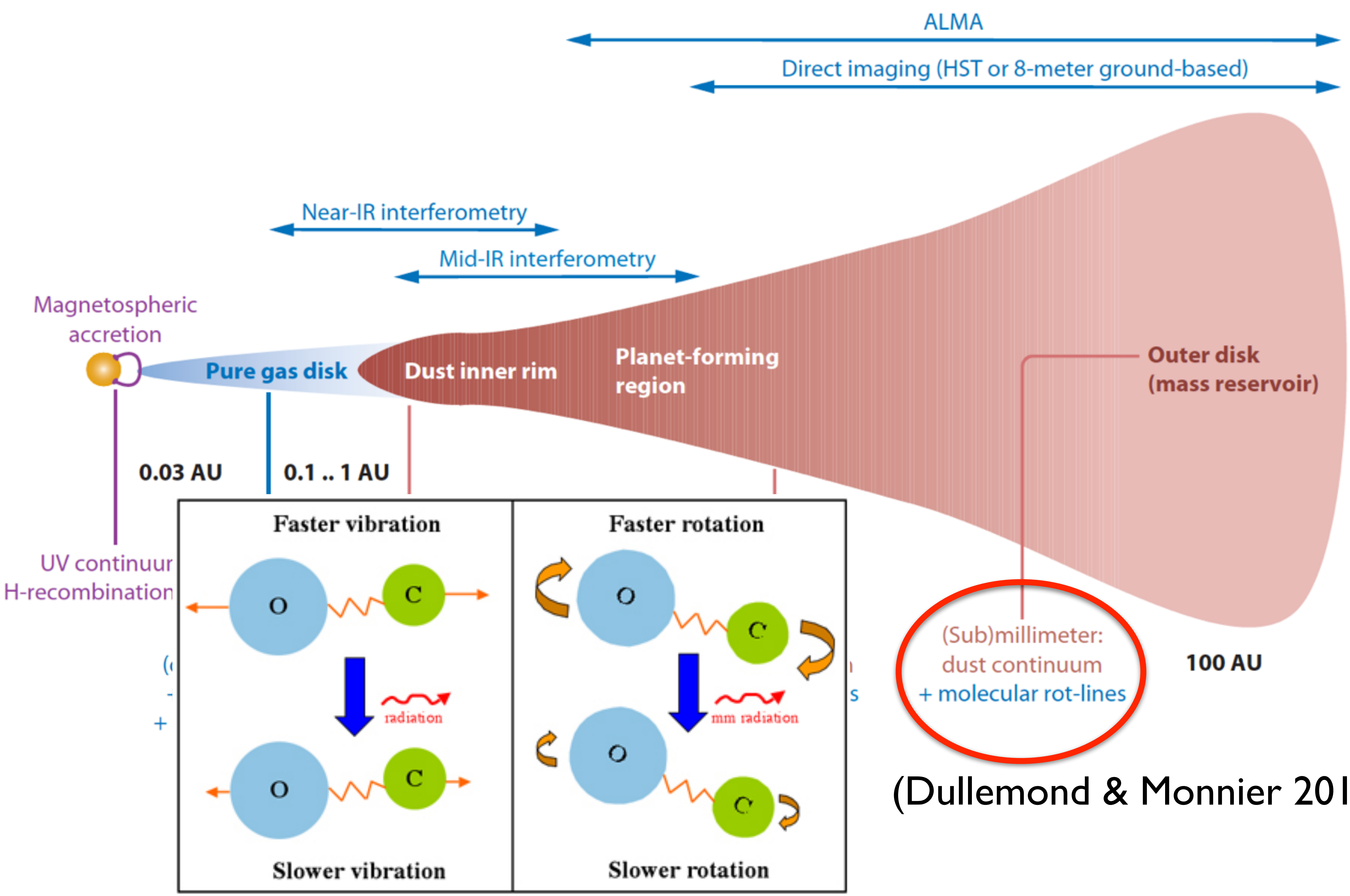
(Dullemond & Monnier 2010)

Mid-infrared lines



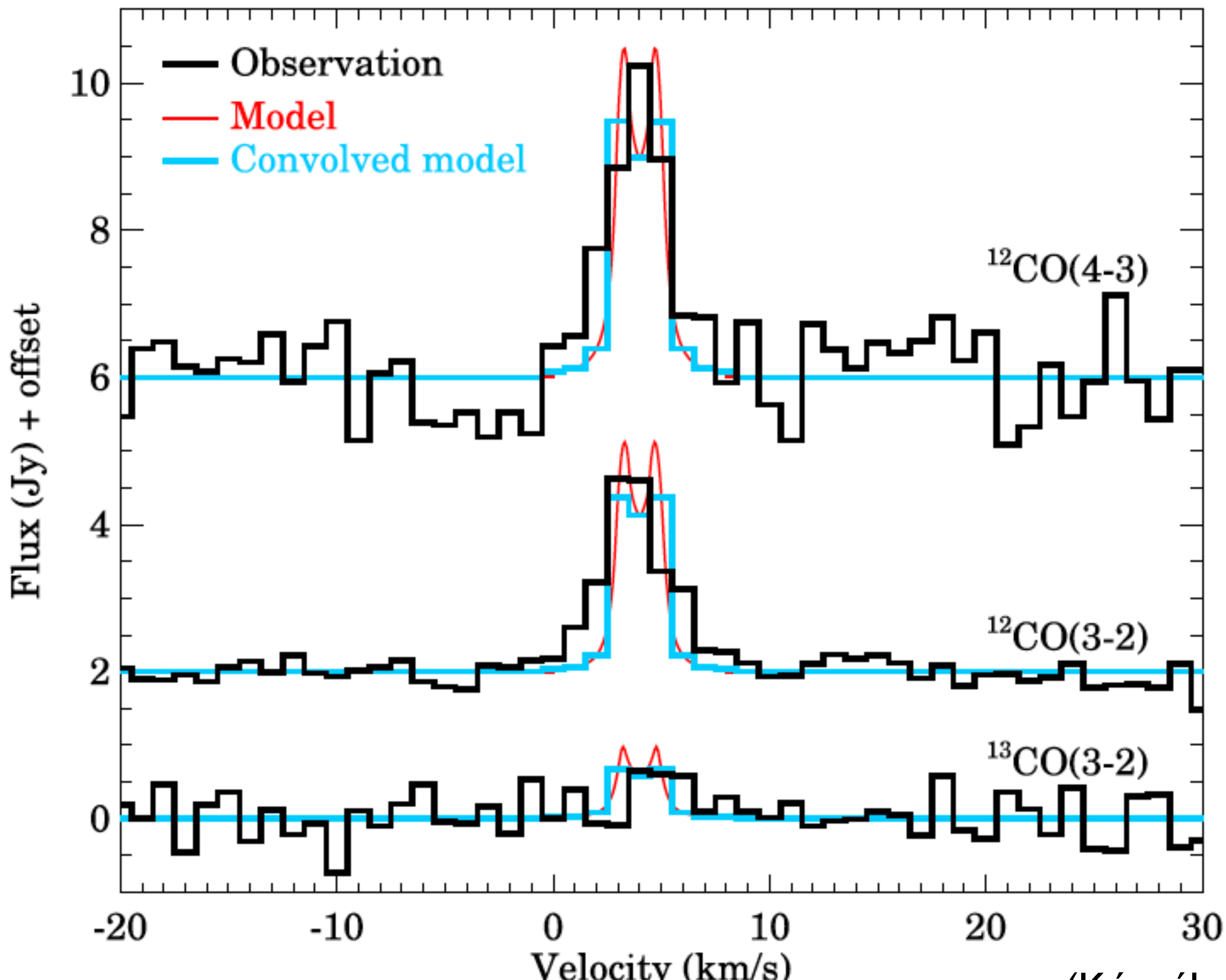
(Goto et al. 2011)

Disk composition – gas



(Dullemond & Monnier 2010)

Millimeter lines



(Kóspál et al. 2016)

Disk composition – gas

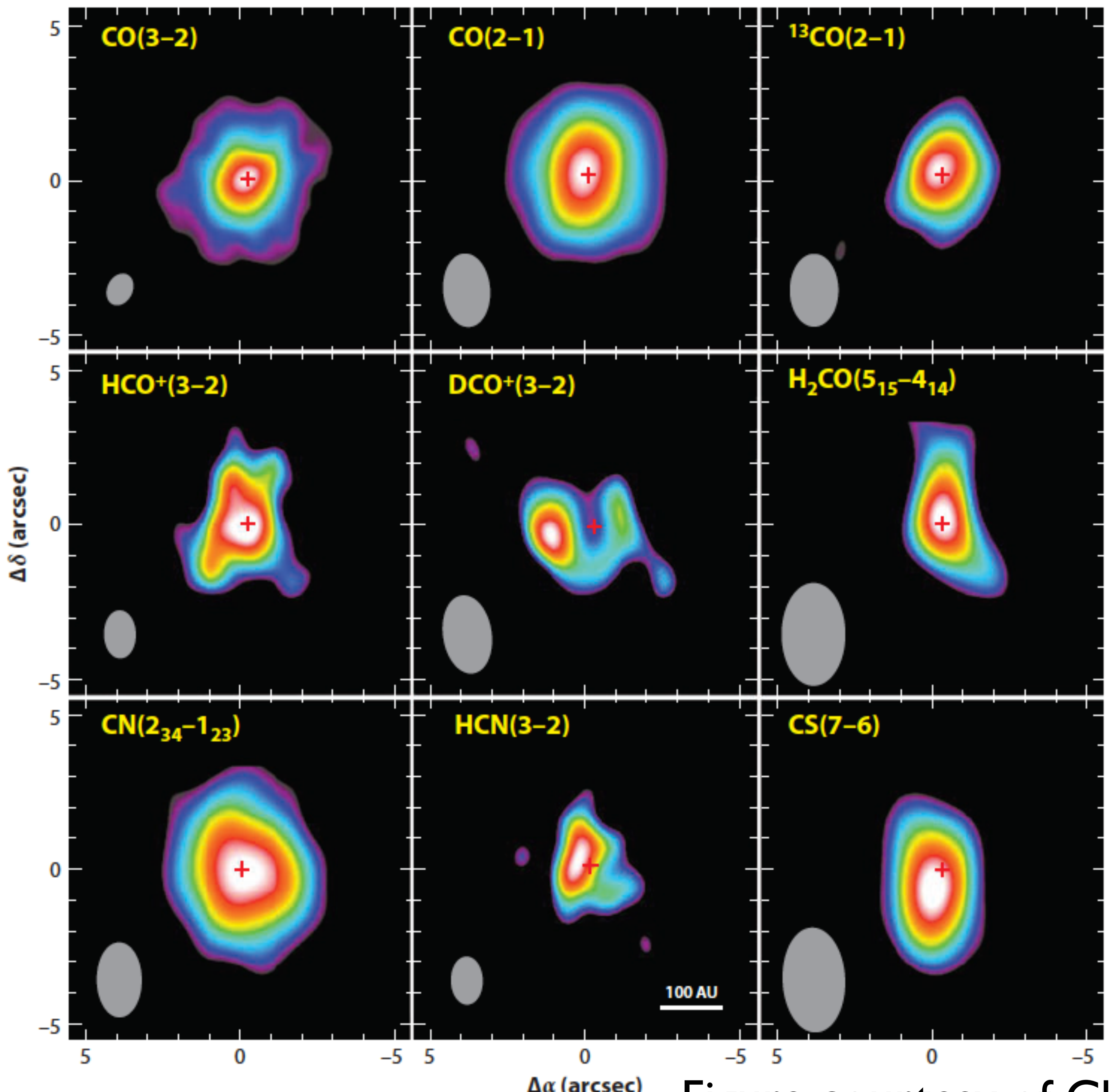
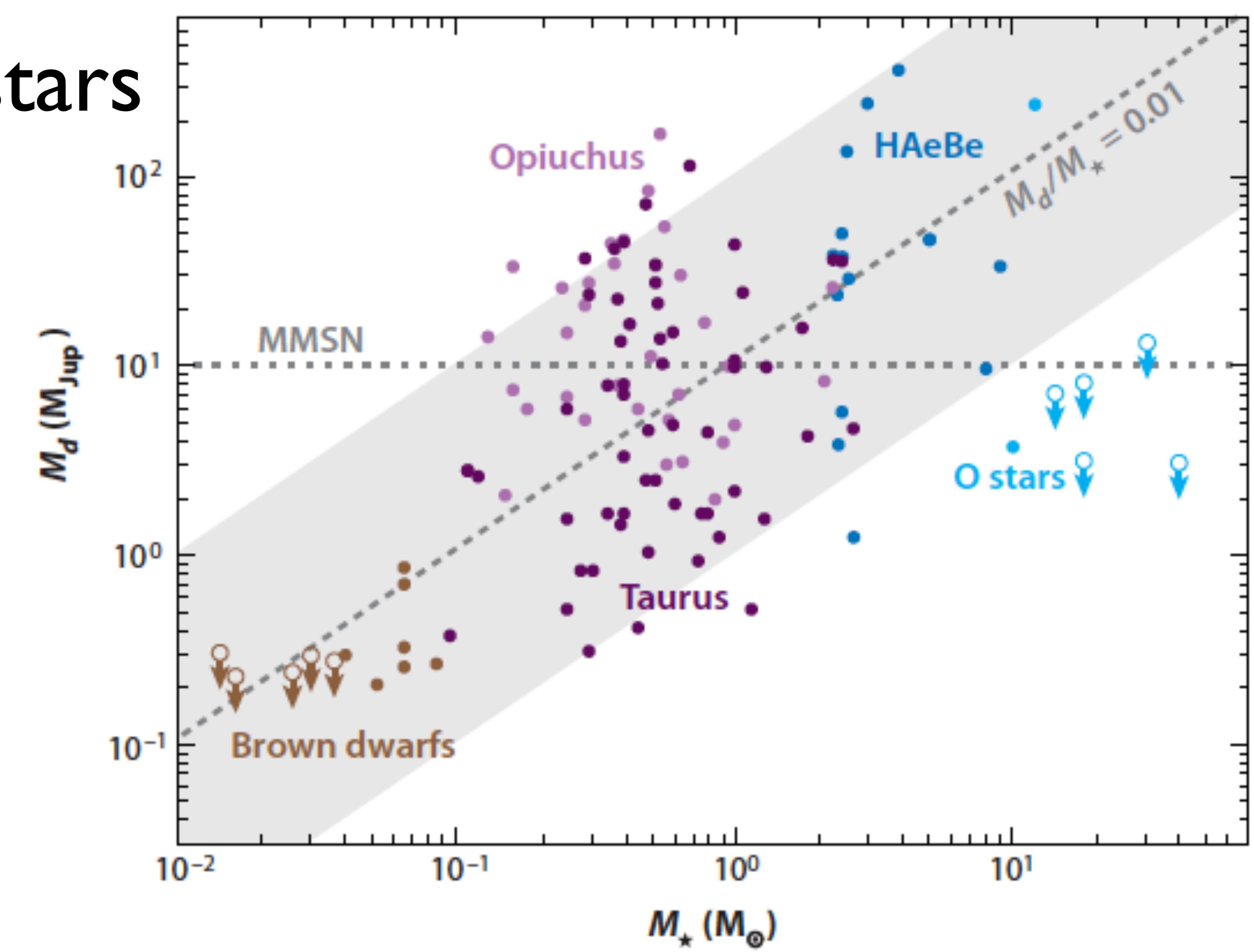


Figure courtesy of Charlie Qi

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
- $M_{disk} / M_{star} \sim 0.01$



More massive stars?

- $M_{disk} / M_{star} < 10^{-4}$ for $M_{star} > 10\ M_{\odot}$
- No disks around optically visible O stars? Why?
    - High photoevaporation rate (disk disappears by the time the star becomes visible)
    - Different star formation mechanism than for lower-mass stars
      Cause?
- Some new results: a Keplerian-like disk around AFGL 4176 (Johnston et al. 2015)