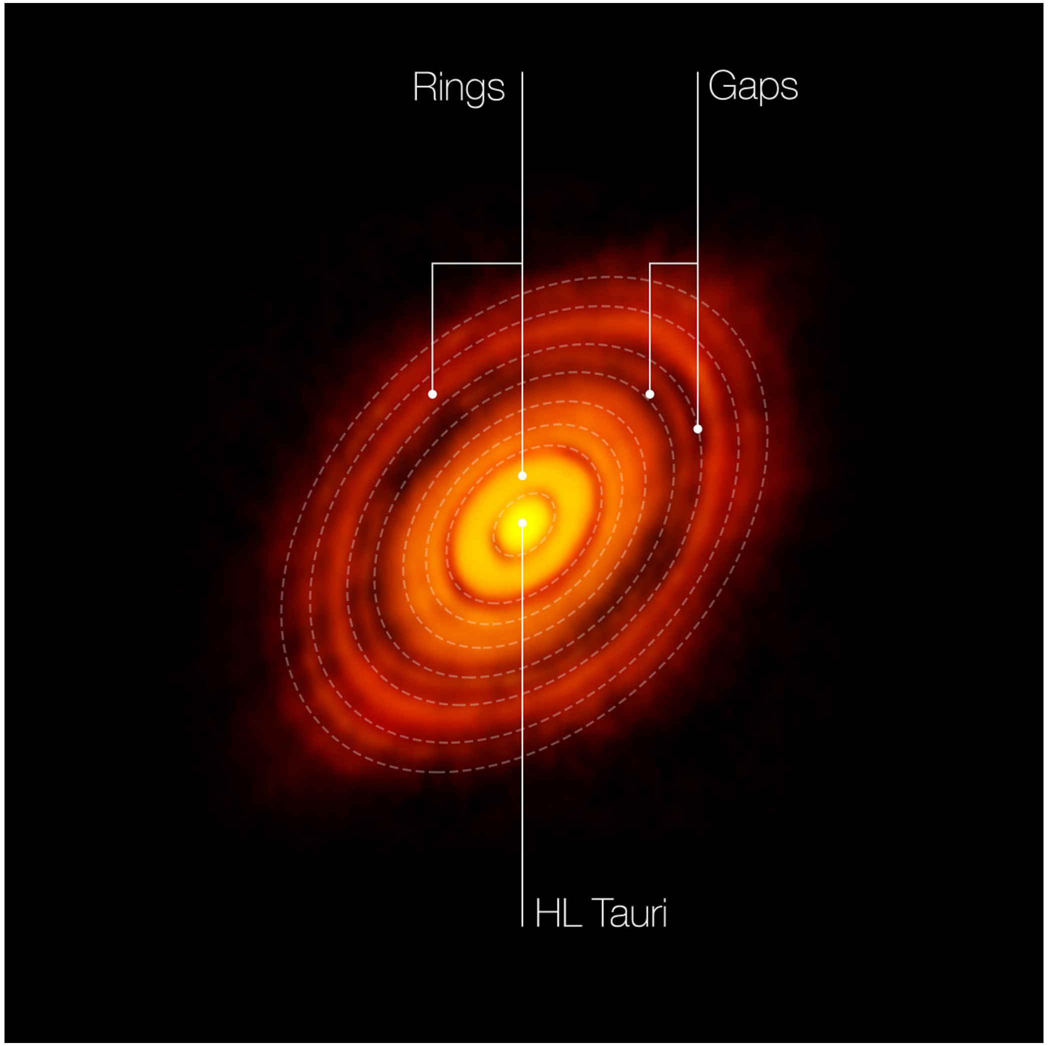
Protoplanetary Accretion Disks – The Most Iconic Image



Protoplanetary Gas Disks – Accretion Disks I

Formation of a disk

Let us assume that collapsing material has specific angular momentum j and falls in gravitational field of mass M:

$R = j^2/G\,M$

$(mv^2/R = GM\,m/R^2 \rightarrow v^2 = GM/R \rightarrow \omega^2 R^2 = GM/R$

Specific angular momentum: $j = R^2\,\omega \rightarrow j^2/R^2 = GM/R\,)$

Let us assume that the material comes from position r_0 in a cloud core with uniform rotation $\Omega \rightarrow j = \Omega\, r_0^2 \sin\theta$ (θ – angle from rotation axis)

- Material close to rotation axis has low angular momentum -> falls close to star
- Mass falling from $\theta = \pi/2$ will fall to maximum „centrifugal radius“: $R_c = \Omega^2 r_o^4/GM$

Disk Formation in Shu's Collapse Solution

Shu`s similarity solution:

$M = m_0 c_s^3 t / G$ in a region with radius

$r_0 = (m_o/2) c_s t \quad (r_0^4 = m_0^4/16 \; c_s^4 t^4)$

This results in ($R_c = \Omega^2 r_o^4 / G M$):

$R_c = \Omega^2 \; m_0^4/16 \; c_s^4 t^4 \; 1/(m_0 c_s^3 t) = \Omega^2 \; m_0^3 c_s t^3/16$

Or: $R_c = 0.3$ au $(T/10 \text{ K})^{1/2} (\Omega/10^{-14} s^{-1})^2 \; (t/10^5 \text{ yr})^3$

Important: $R_c \sim t^3$

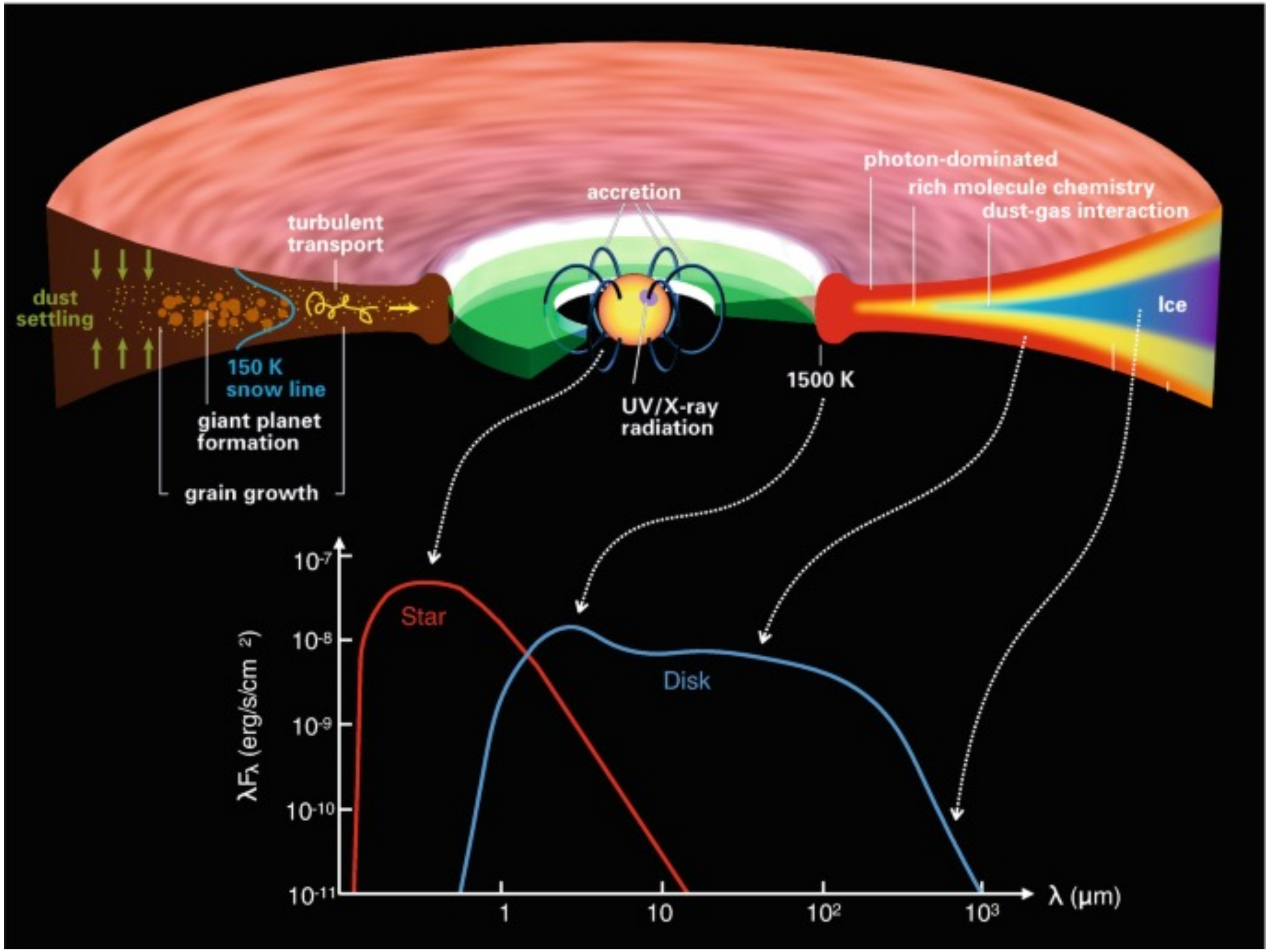
Initially most of the mass falls close to the center because material has small angular momentum. As collapse proceeds material from larger radii is added and material is then added to a a „disk" rather than to the „star".

How to observe a disk?

NIRCAM/JWST Image of protostar L 1527 In Taurus

Disk seen as an extinction silhouette

Structure of a Disk



How to observe a disk ? The Challenges

- Disks have very low masses (typical values – 10^{-2} M_{sun}, scales with stellar mass)
- Disks have small angular dimensions:
  Solar system (100 au) at a distance of 140 pc (nearest star-forming regions) would have angular size of 0.“7 arcsec. Emission from hot inner regions even smaller

Best spatial resolution:

ALMA Long Baselines:	0“.025 at 870 μm (thermal dust emission, better resolution recently reached @ high frequencies)
VLT SPHERE (Extreme AO):	0“.027 at 1 μm (scattered light)
VLTI GRAVITY:	0“.003 at 2 μm

Historically (1990):

Strom & Strom (1989) – Detection of IR excess

Beckwith et al. (1990) - Detection of millimetre dust emission

$S_\nu = \tau(\nu)\, B_\nu(\nu,T)$ (Dust emission at long wavelengths is optically thin)

$\tau(\nu) \sim \kappa(\nu) \sim \lambda^{-\beta}$ $\beta = 2$ for many materials

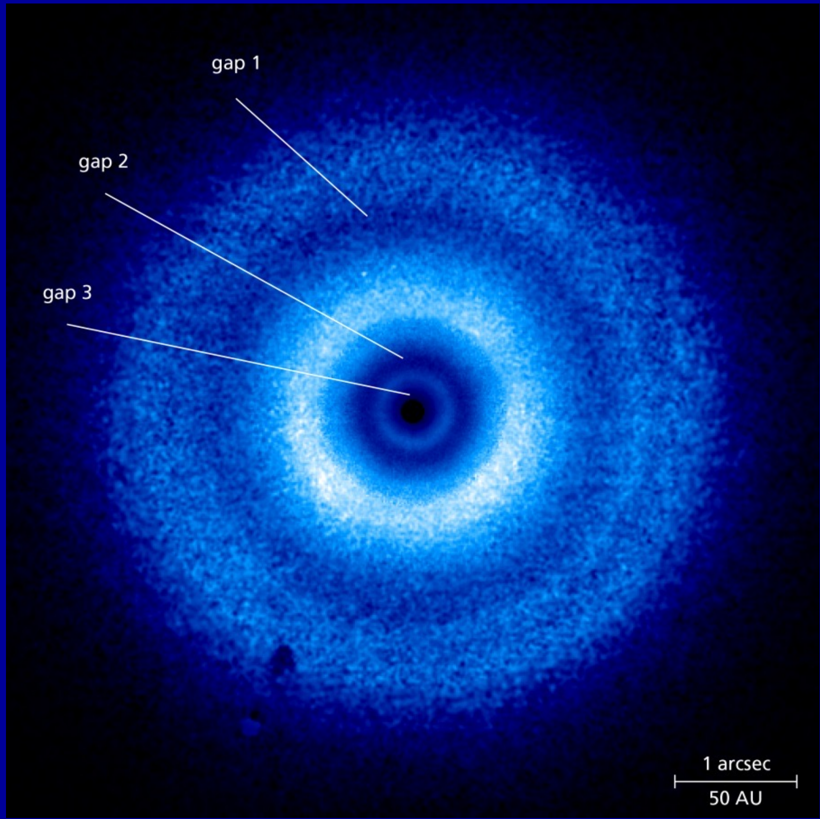
Emission in sphere would be optically thick in the visible, but T Tauri stars visible → Disk

VLTI Facility @ Paranal (Chile – 2600 m)

ALMA Facility @ Chajnantor (Chile – 5000 m)

66 movable radio dishes of 12m diameter distributed over a largest distance of 16 km
Recently 5 milli-arcsec spatial resolution at highest frequency (Band 10: 787 – 950 GHz)

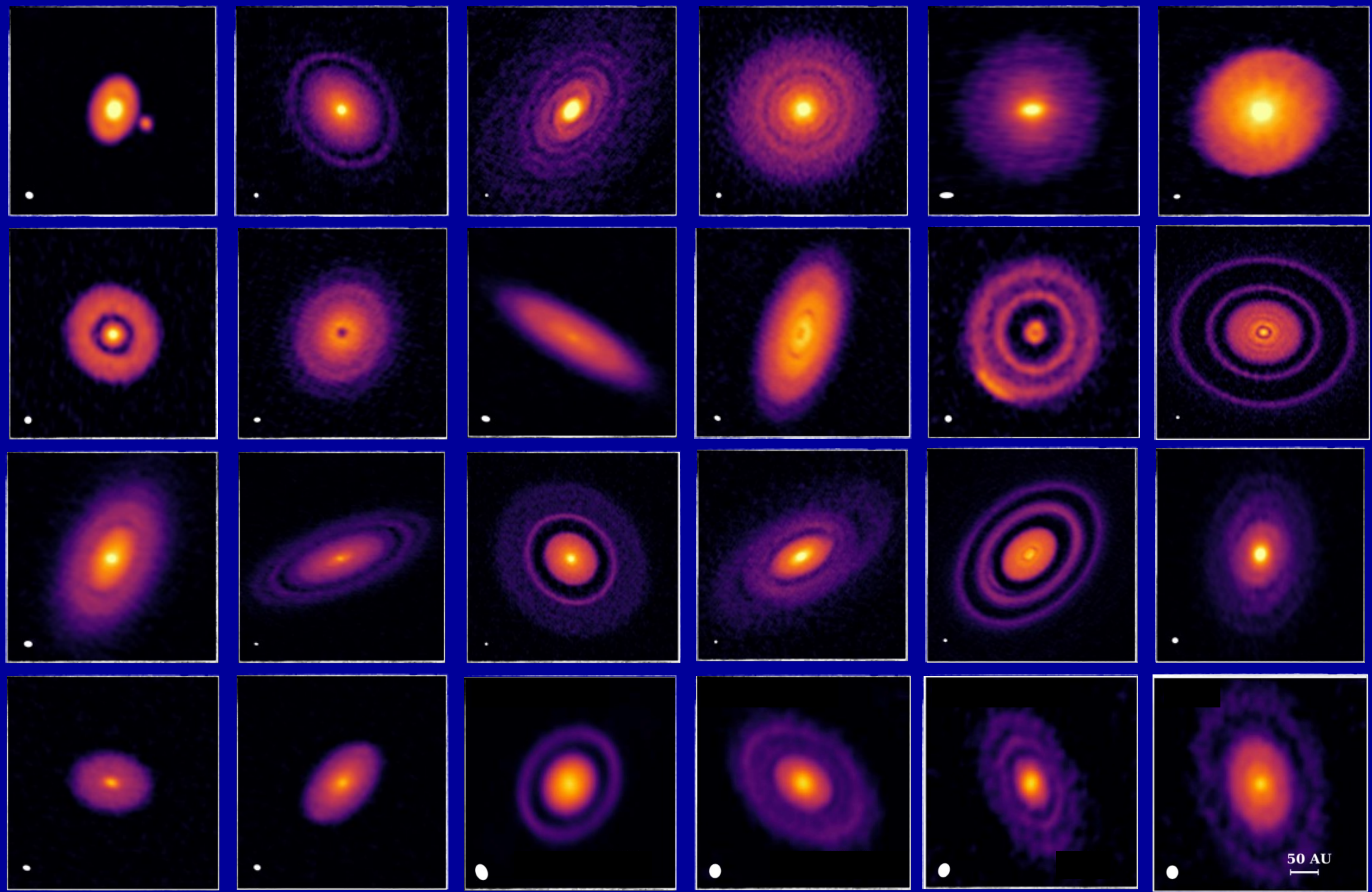
Scattered Light Image of a Disk



TW Hydrae Ring World – SPHERE/IRDIS @ H band with apodized Lyot coronograph (40 marcsec- 2.4 a.u.)

van Boekel, Henning, Menu et al. (2017)

Disk Substructures: ALMA at 1.25 mm



Resolution: 0.035 arcsec; Andrews et al. 2018; Long et al. 2018

How to observe a disk ?

- Indirectly: Bipolar molecular flows and high-velocity optical jets
- Direct images at near-IR wavelengths and at submillimeter/millimeter wavelengths
- Images in polarized light
- Observations of rotational transitions of molecular gas (CO, CS, …) (ALMA)
- Ro-vibrational transitions at infrared wavelengths (JWST)

Typical masses/radii/ages of disks around T Tauri stars:

- 10^{-2} M_{sun} (Large uncertainties: Dust opacity & dust/gas mass ratio); dependence on stellar mass
- 100 au with large spread.
- Lifetime: Median value is few Myrs.

Analysis of the spectral energy distribution (SED):

$$\nu S_\nu = \cos\theta / D^2 \int_{r1}^{r2} \nu B_\nu(\nu, T(r)) (1-\exp(-\tau(\nu)/\cos\theta))\, 2 \pi r^2 \, dr$$

($\theta = 0^0$ – Disk is seen „pole-on“)

How to observe a disk ?

- In the IR – dust disks are optically thick:

  νS_ν determined by $T(r)$

  Let us assume $T(r) \sim r^{-q}$ and $S_\nu \sim \nu^\alpha$ then $\alpha = 4 - 2/q$

- In the mm – dust disks are optically thin:

  $S_\nu \sim \nu^\alpha$ $\kappa(\nu) \sim \nu^\beta$

  Rayleigh Jeans approximation: $\beta = \alpha - 2$

  One can get constraints on opacity and dust grain size!

Flat and flared disk

Flat Disk

a) Accretion disk (actively heated): $T(r) \sim r^{-3/4}$

b) Passively heated disk: $T(r) \sim r^{-3/4}$

The two heating mechanisms cannot be distinguished by SED analysis!

Data indicate that outer disk regions are hotter than anticipated from flat disk solution: Disks are flared!

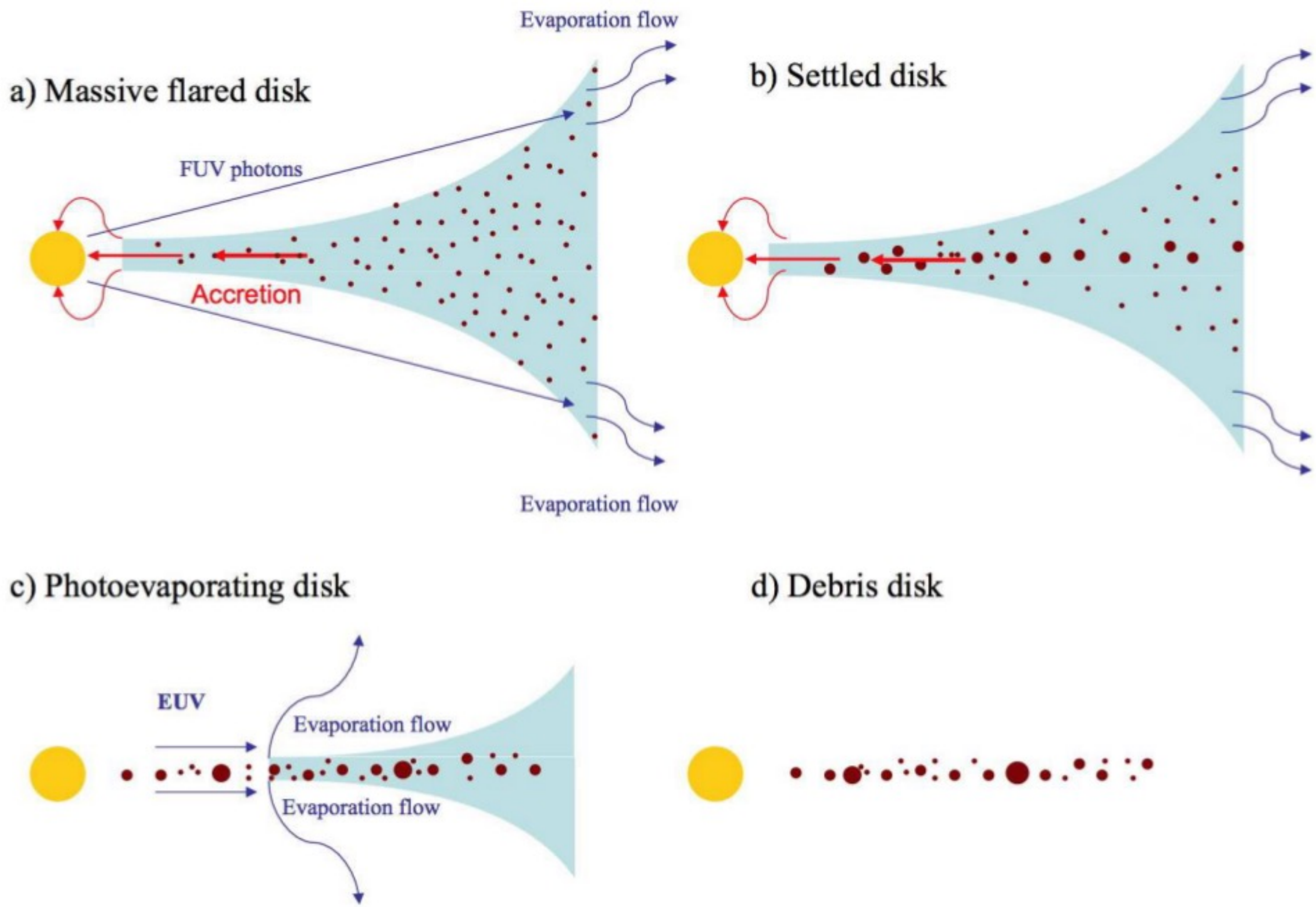
Scale height of a disk: $E_{vert,grav} = E_{therm}$

$h/r \; Gm_{star}/r = k \; T(r)$ Let us assume $T(r) \sim r^{-3/4}$

$h \sim k/G \; M_{star} \; r^{5/4}$

Radiation transfer models: Stellar radiation (NIR) + Disk surface (MIR) + Disk interior (Millimetre wavelengths); In addition: grain sedimentation and gap formation

Disk structure



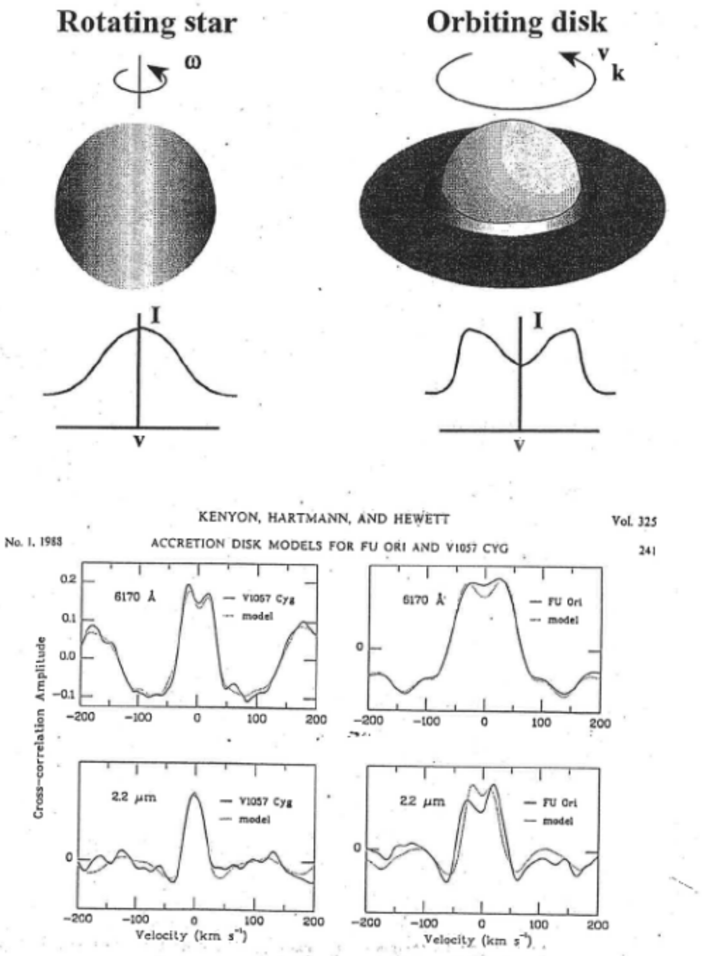
Williams & Cieza (2011)

Gas Disks

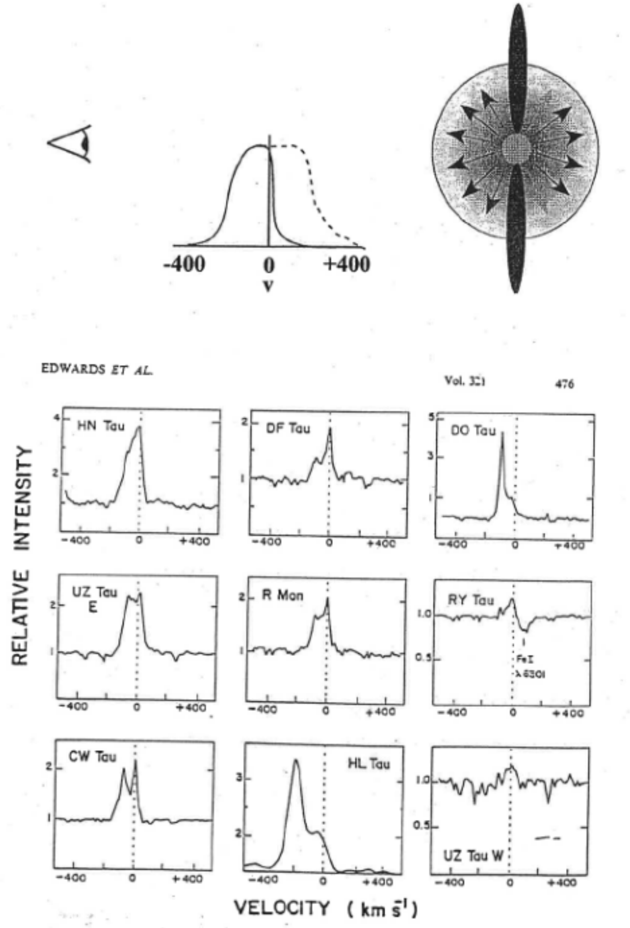
a) Optical „double“ profiles (Hartman & Kenyon)
b) Profiles of forbidden lines, e.g. [OI] – Red part is blocked (Appenzeller & Edwards)
c) MM interferometry with high spectral resolution → Keplerian velocity profiles
d) NIR spectroscopy with high spectral resolution → Keplerian velocity profiles

Gas Disks

Inner Disk Optical Lines



Circumstellar Emission Lines



Gas Disks – Keplerian Velocities

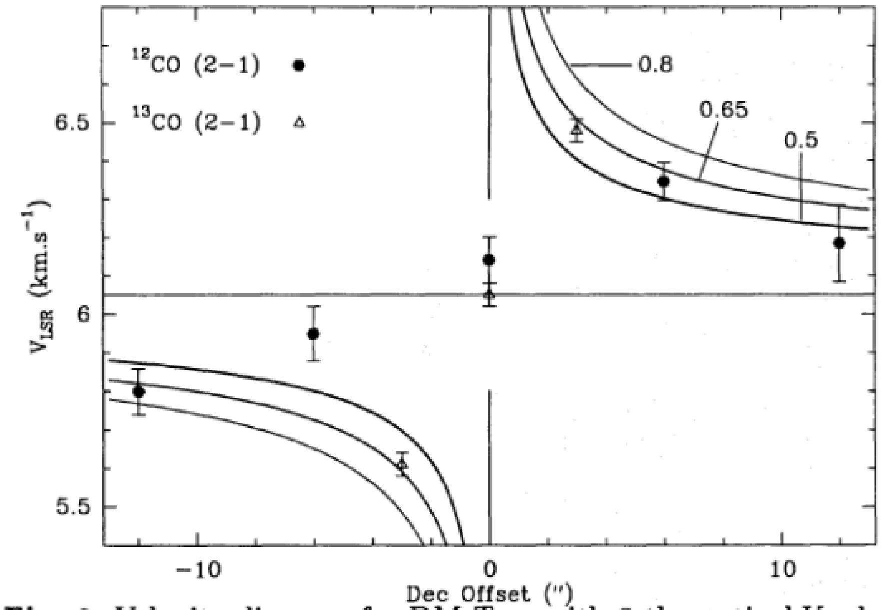
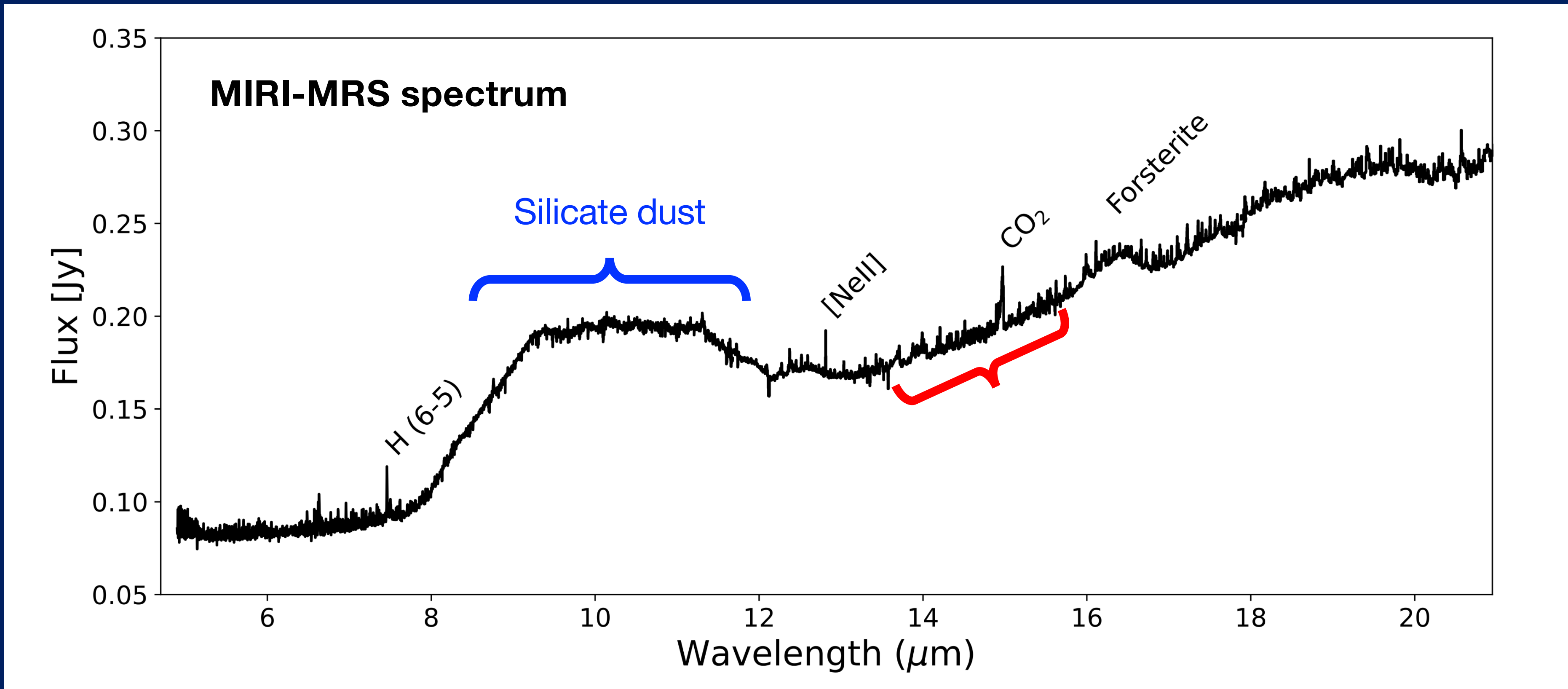


Fig. 3. Velocity diagram for DM Tau, with 3 theoretical Keplerian rotation curves superimposed. The open triangles indicate velocities derived from the ^{13}CO J = 2 → 1 spectrum toward DM Tau, and were assigned to offsets ±3″ since for Keplerian rotation the two peaks represent emission from the outer edge of the disk.

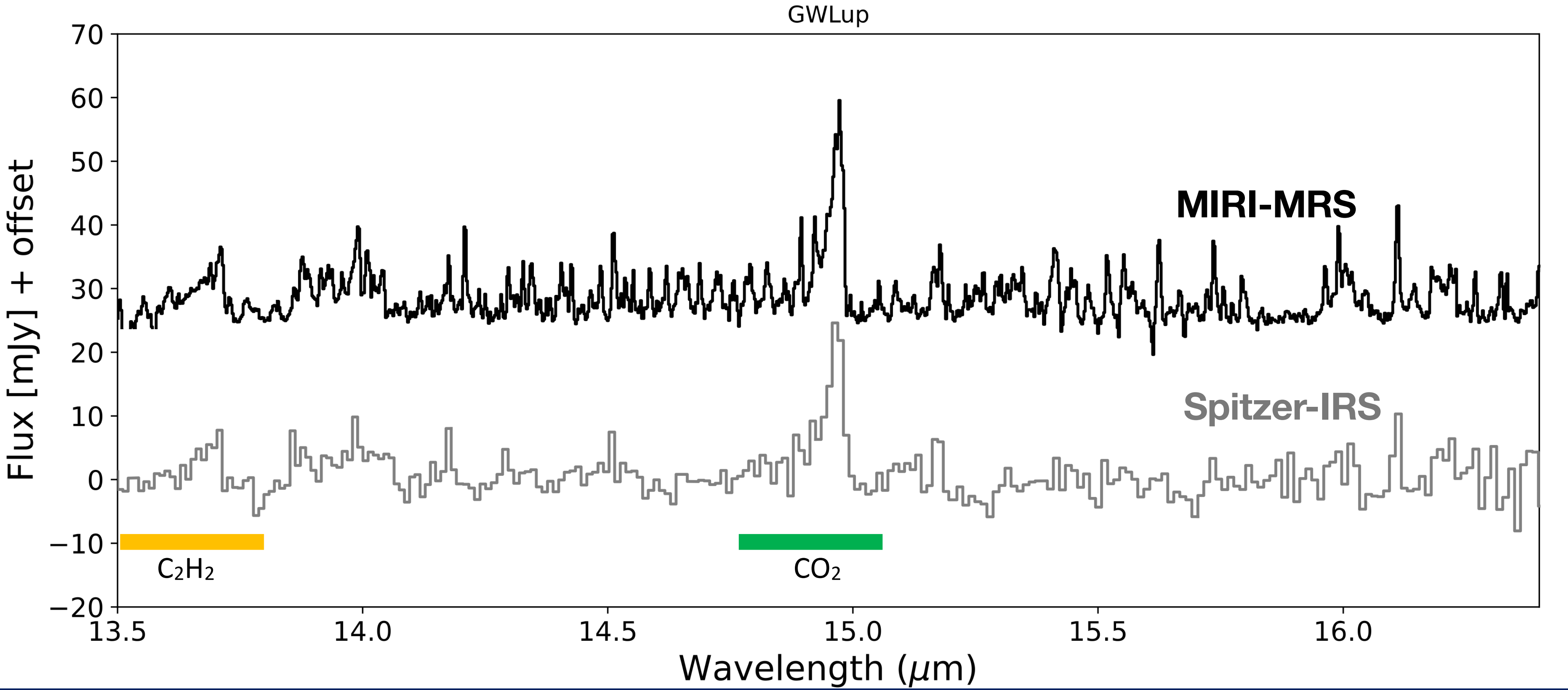
30 degrees from face-on: DM Tau (Guilloteau & Dutrey 1994)

GW Lup – A Disk around a T Tauri Star in Lupus



Detected molecules: CO_2, H_2O, HCN, C_2H_2, OH; $N(CO_2)/N(H_2O) \sim 0.7$

The GW Lup Disk



Grant et al. submitted

Fitting procedure with slab models

Fit one species

Subtract emission

Repeat for the next molecule

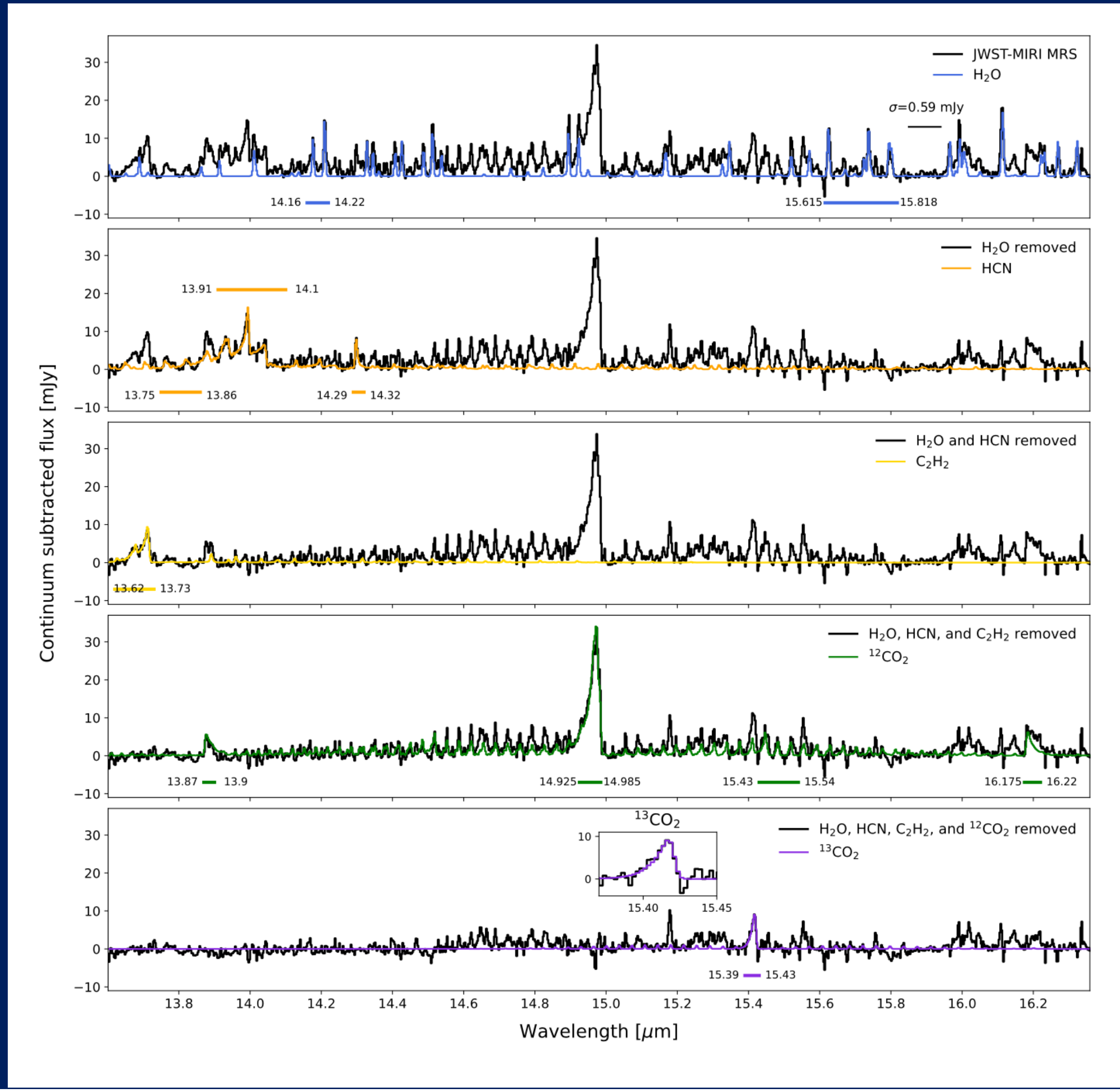
H_2O

HCN

C_2H_2

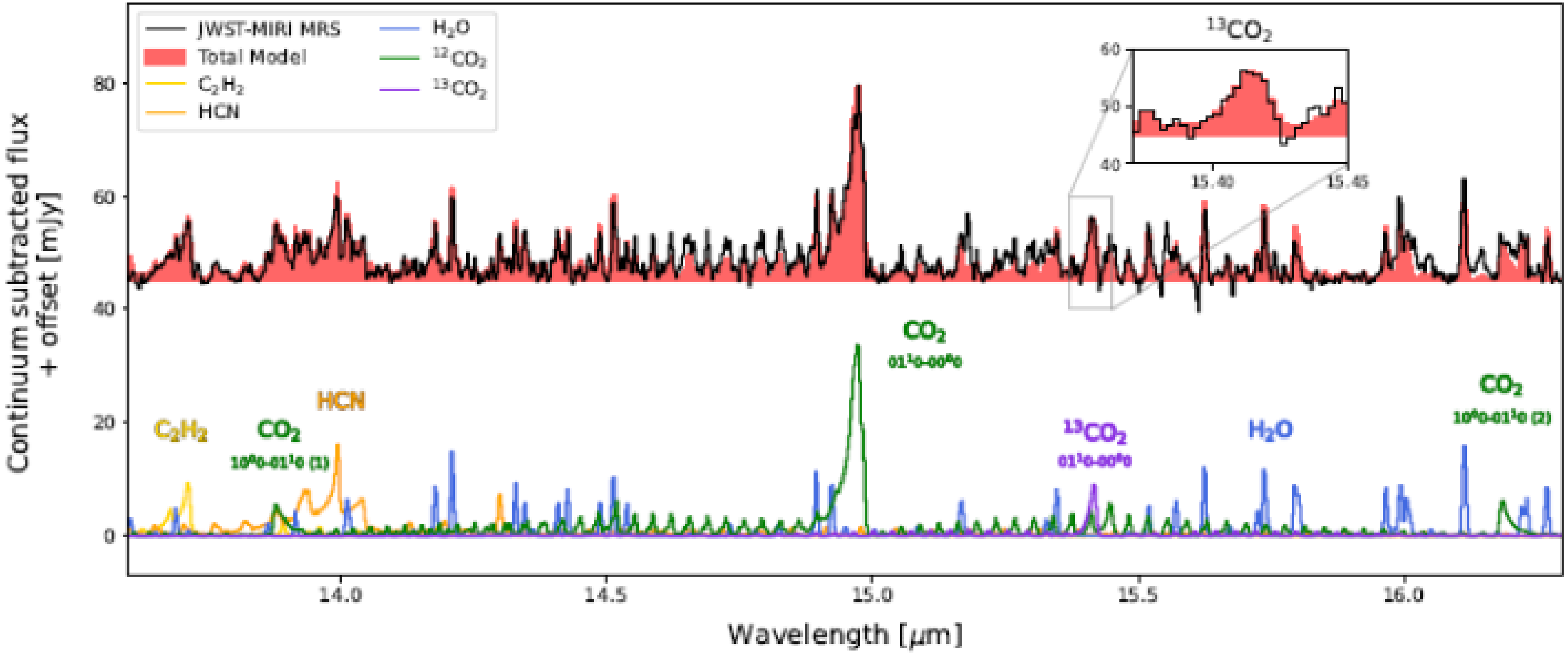
$^{12}CO_2$

$^{13}CO_2$



Grant et al. (2023)

CO_2 and $^{13}CO_2$ Detection

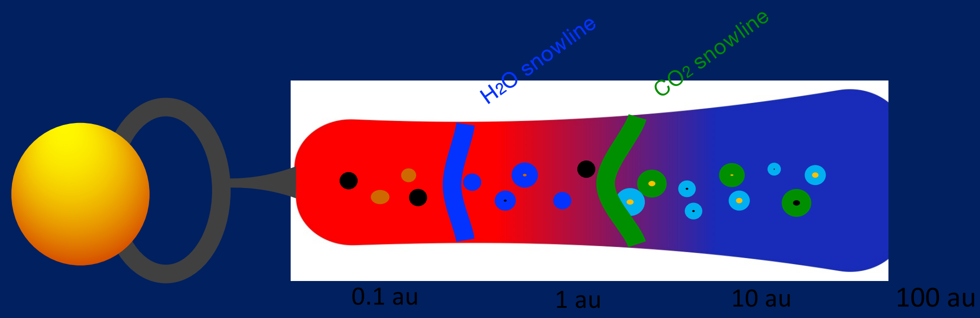


CO_2: T ~ 400 K and N ~ 2.2x10^{18} cm^{-2} at 0.11 au

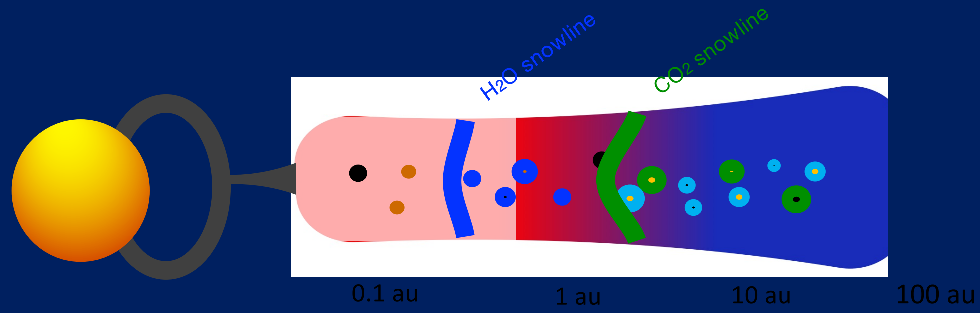
Why is CO_2 so strong compared to H_2O in GW Lup?

Relatively high CO_2/H_2O ratio of 0.7: Inner cavity between H_2O and CO_2 ice line?
=> Gas distribution affects the observed line strength!
=> Synergy with VLTI (spatial information) and CRIRES$^+$ (kinematics)

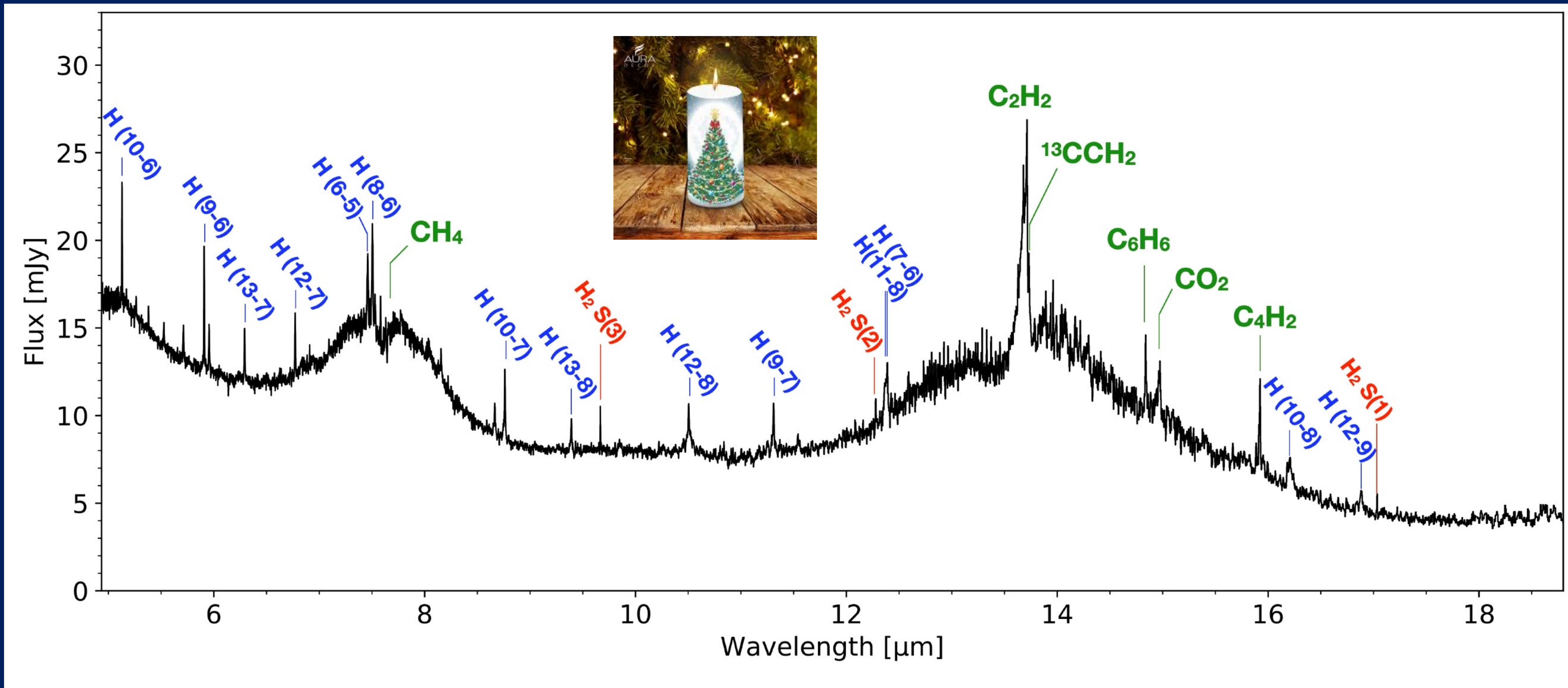
« Normal « T Tauri system



Disk around GW Lup



Spectrum of Disk around Low-Mass Star



JWST-MINDS Project – Tabone et al. (2023, Nature Astronomy)
2MASS-J16053215-1933159 in Upper Sco (M5 star)
Theory: Mah et al. (2023)