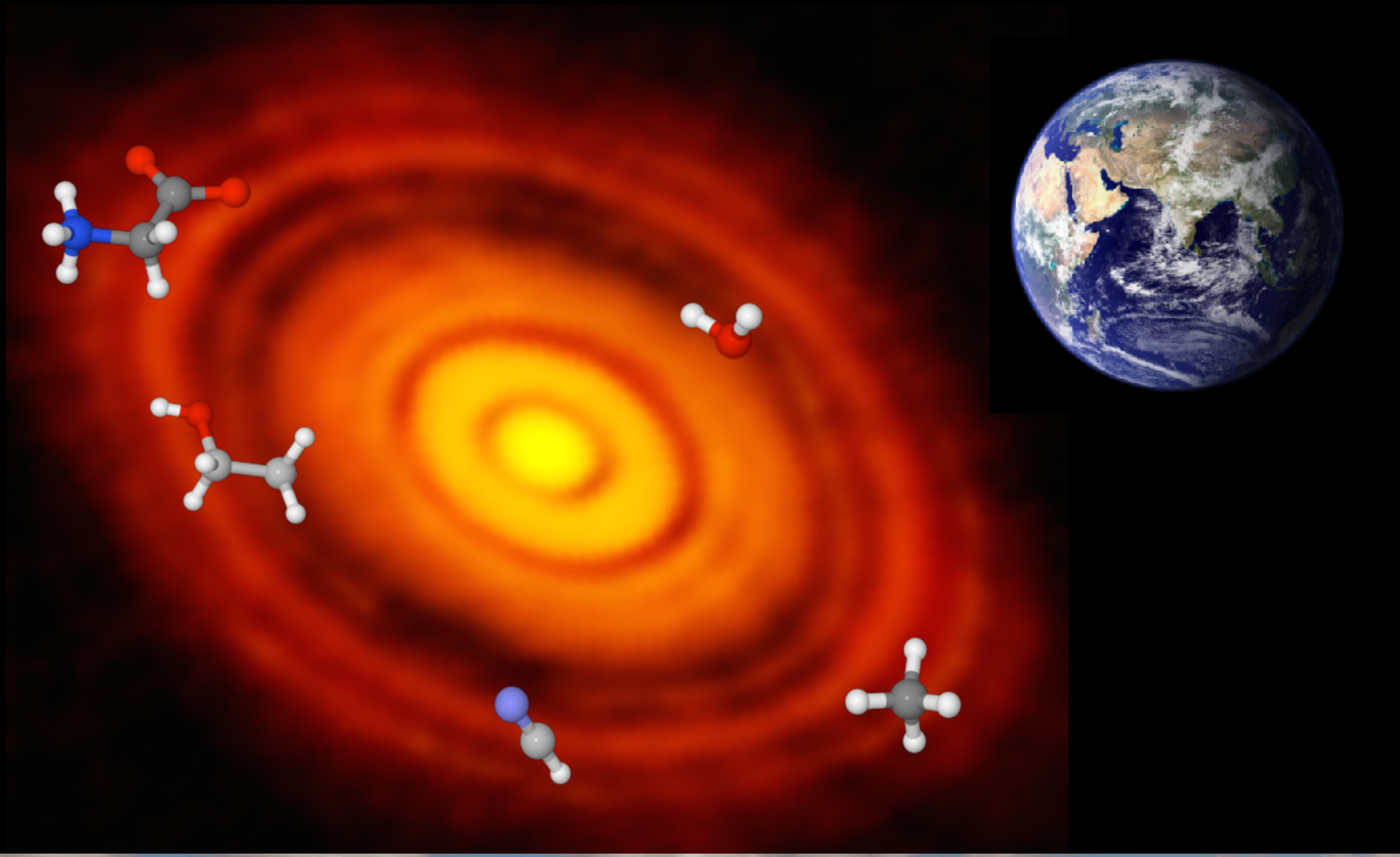
Lecture 12: Protoplanetary disks

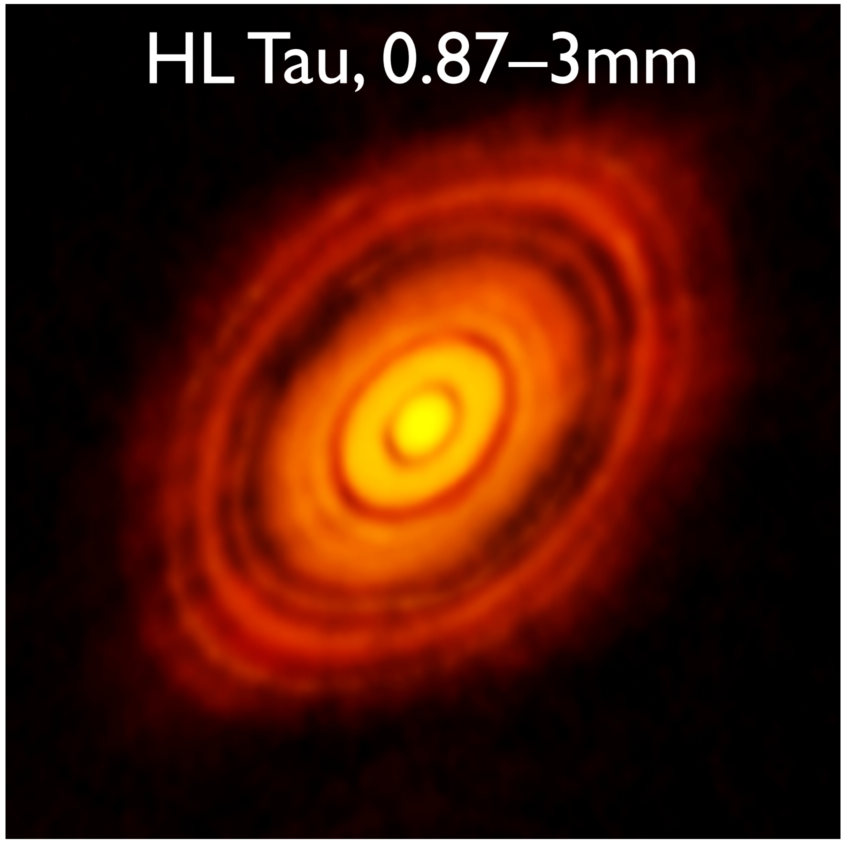


Outline

- History and basic information
- Disk physics
- Disk chemistry
- New era of discoveries with ALMA and JWST

Confusing nomenclature

- **„Protoplanetary disk“ (PPD)**
- **„Planet-forming disk“**
- „Solar nebula“
- „Circumstellar disk“
- „Accretion disk“
- „Proplyd“
- „Transitional disk“
- „Debris disk“
- NOT THE SAME AS „Planetary nebula“!


HL Tau, 0.87–3mm


Cat’s Eye Nebula, optical

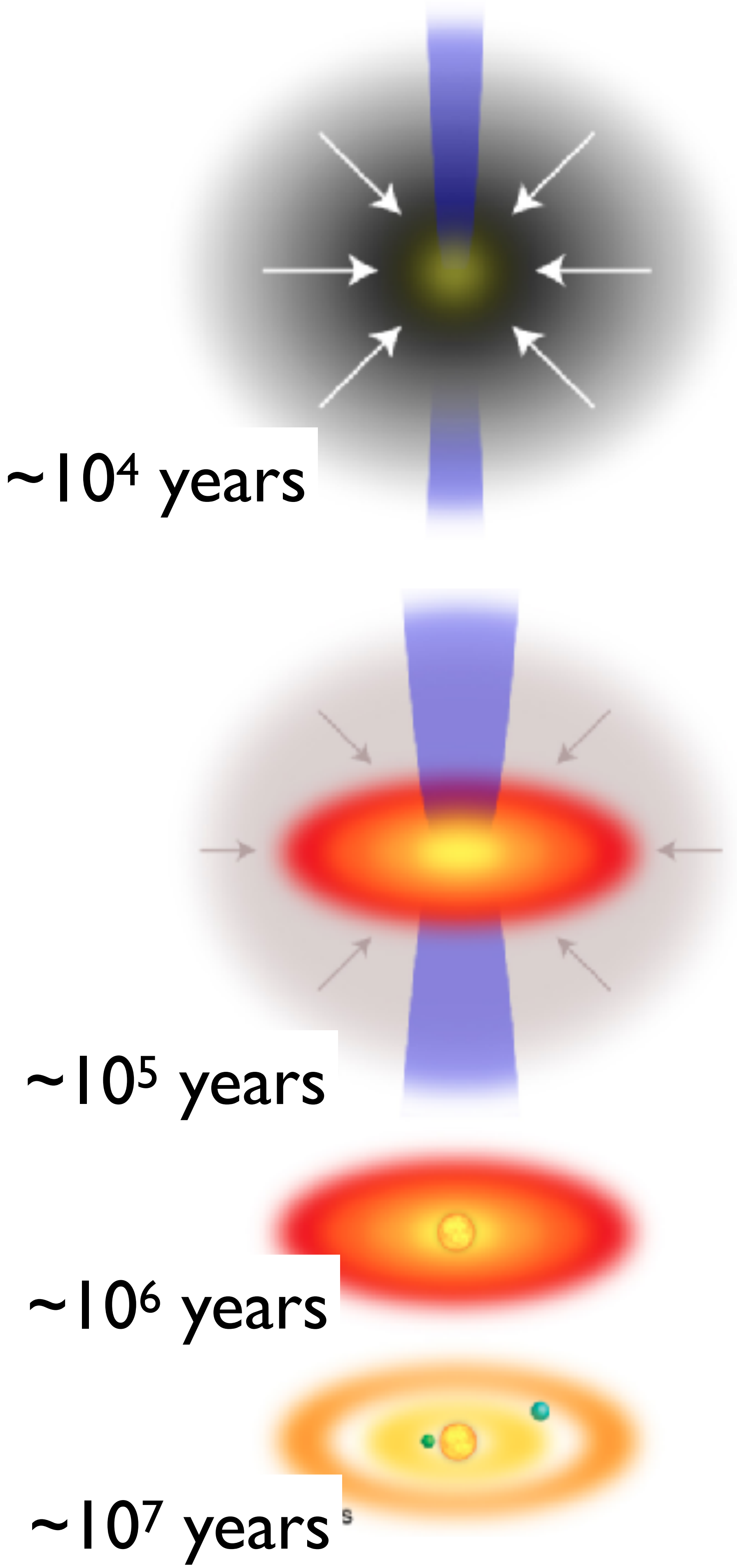
Nebular hypothesis of planet formation

- First idea by Swedenborg, E. „Philosophical and Mineralogical Works“ (1734)
- Kant, I. „ Allgemeine Naturgeschichte und Theorie des Himmels“ (1755)
- Laplace, P.–S. „Exposition du Système du Monde“ (1796)
- Solar system formed from a rotating gas cloud (nebula) ⇒ coplanar planetary orbits, planets rotate in the same direction as Sun

Immanuel Kant
(1724 – 1804)

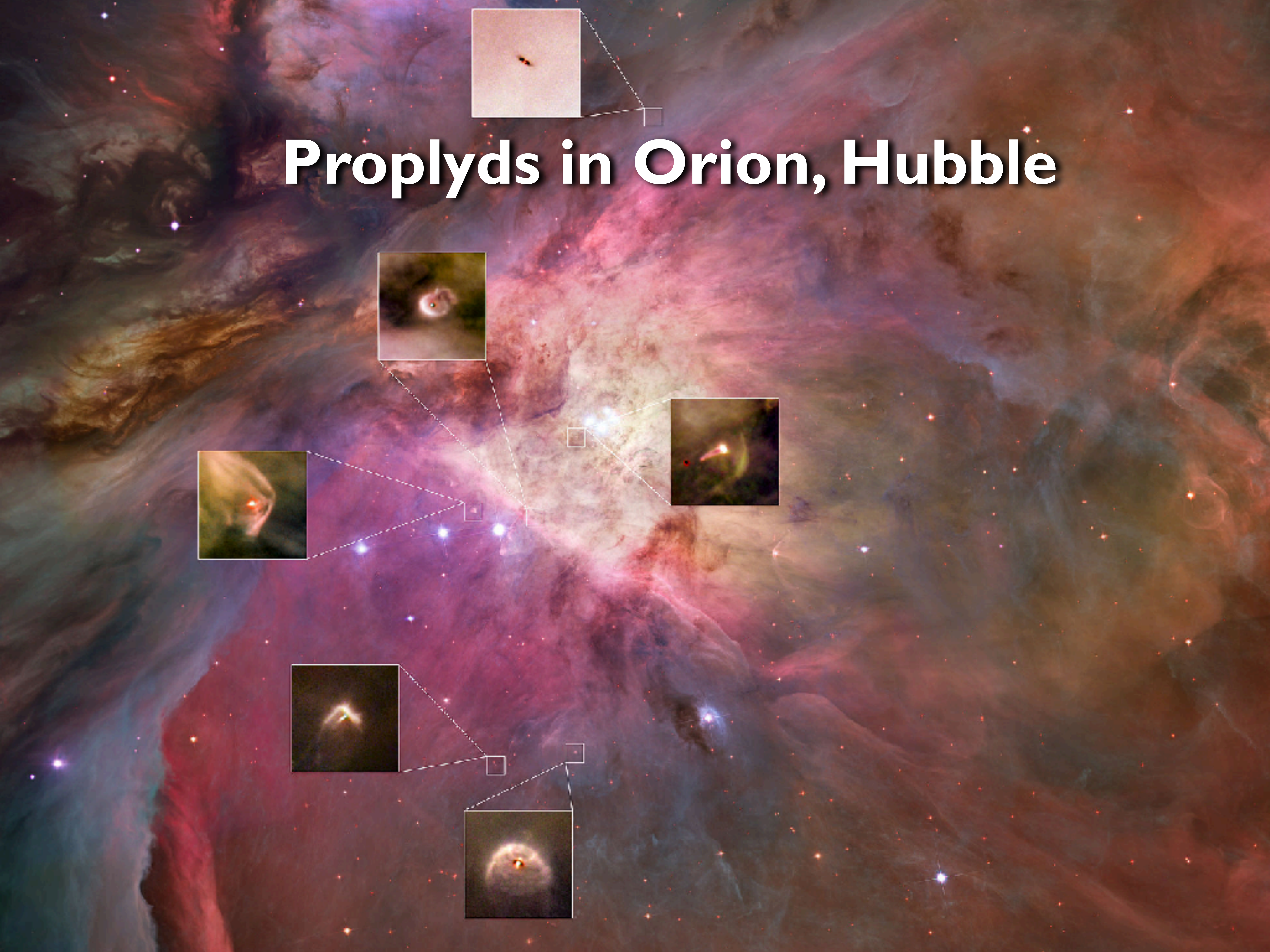
Allgemeine
Naturgeſchichte
und
Theorie des Himmels,
oder
Verſuch
von der Verfaſſung und dem mecha-
niſchen Urſprunge
des ganzen Weltgebäudes

Transformation of a cloud into a disk

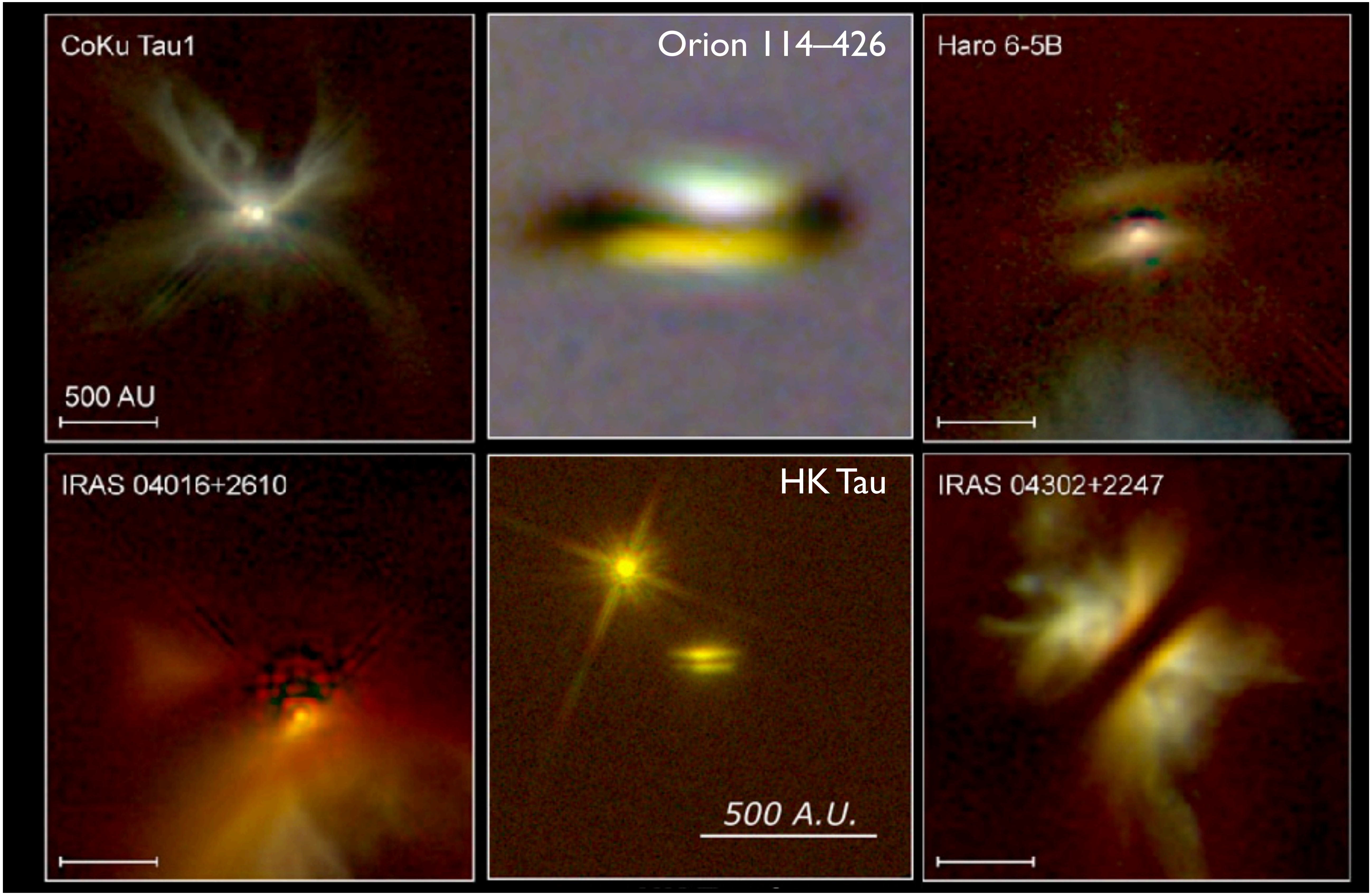


- Rotating dense cloud becomes gravitationally unstable
- Protostar with massive accretion disk, infalling envelope, and outflow
- Young star with planet-forming disk only
- Star with planetary system

Proplyds in Orion, Hubble



Edge-on PPDs: Hubble, near – IR

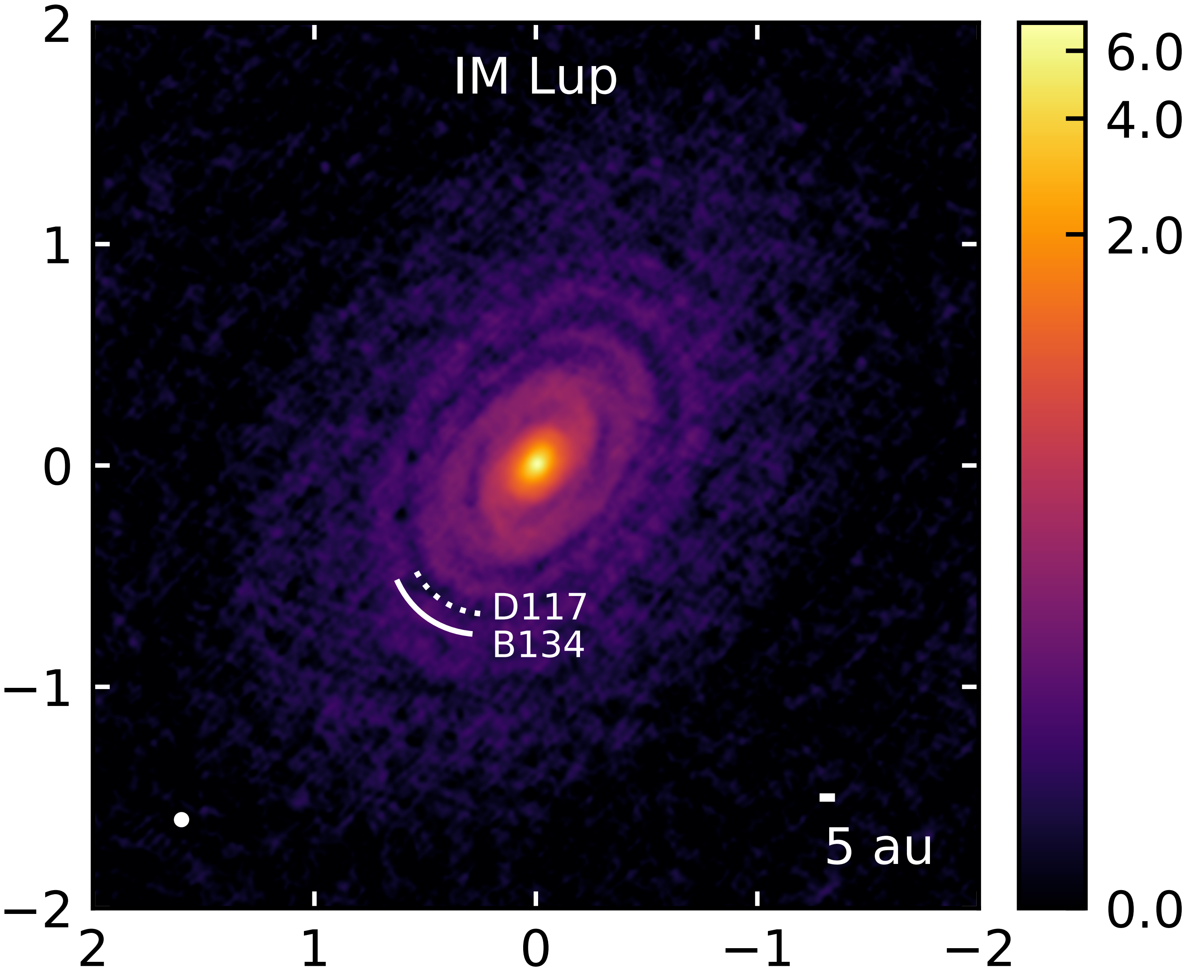


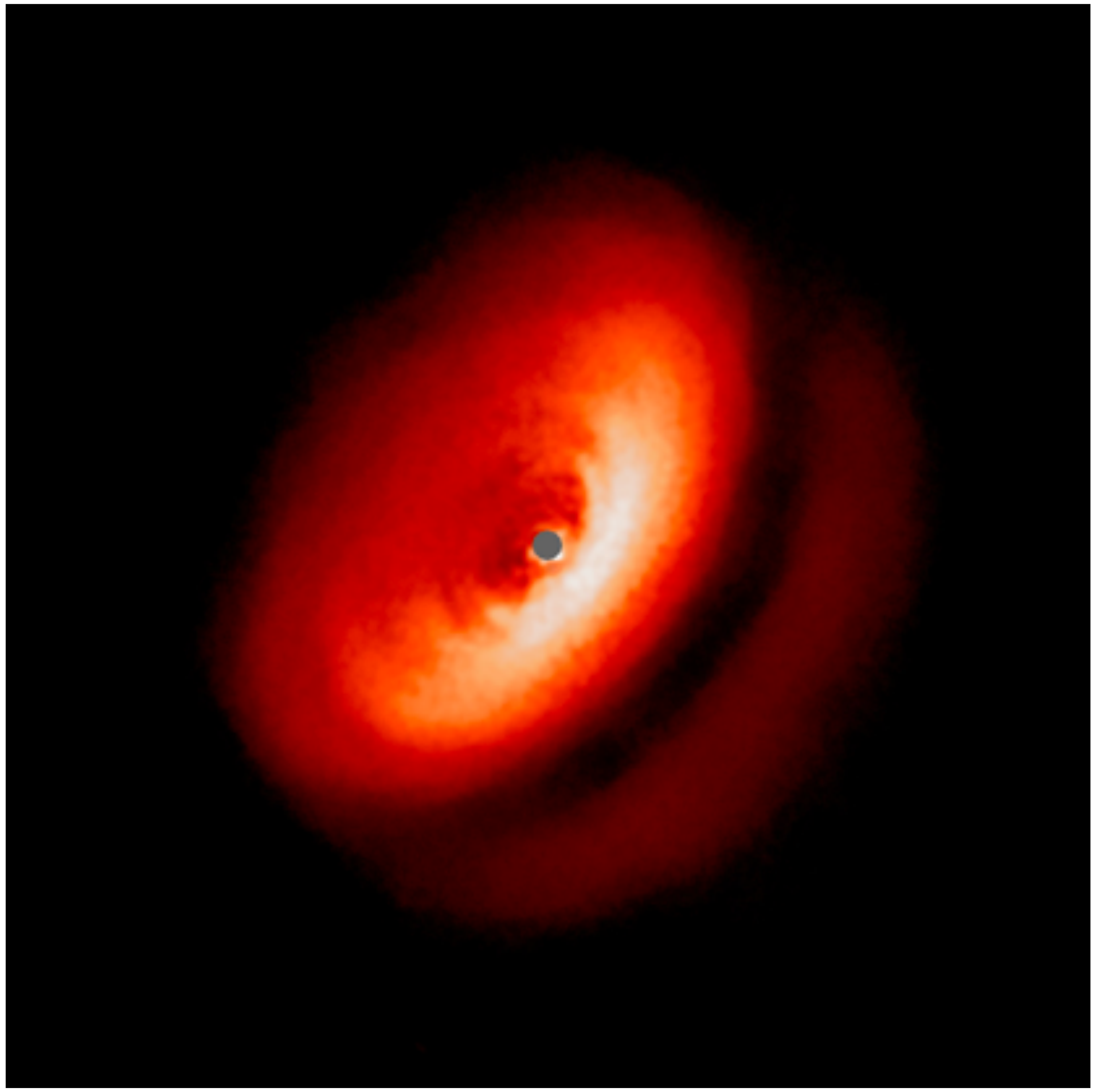
- Dark lane: mm-sized dust (absorption)
- Bright cones: (sub)micron-sized dust (scattering)

Dust distribution: IM Lup

ALMA, radio:
mm dust (emission)

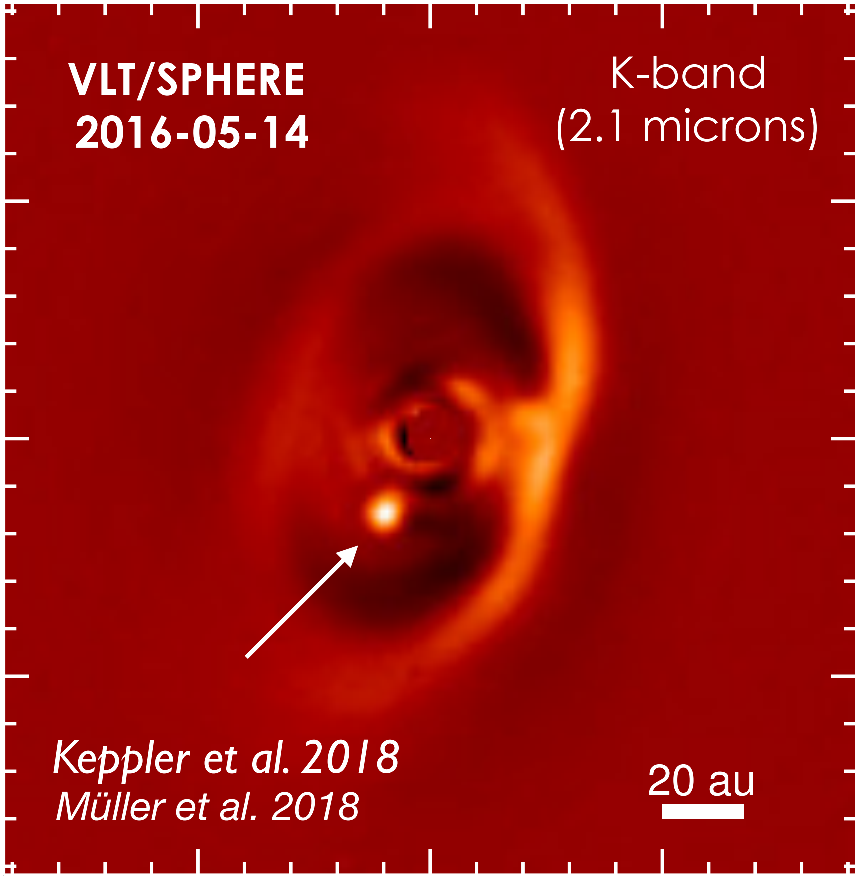
VLT/SPHERE, near–IR:
µm dust (scattering)



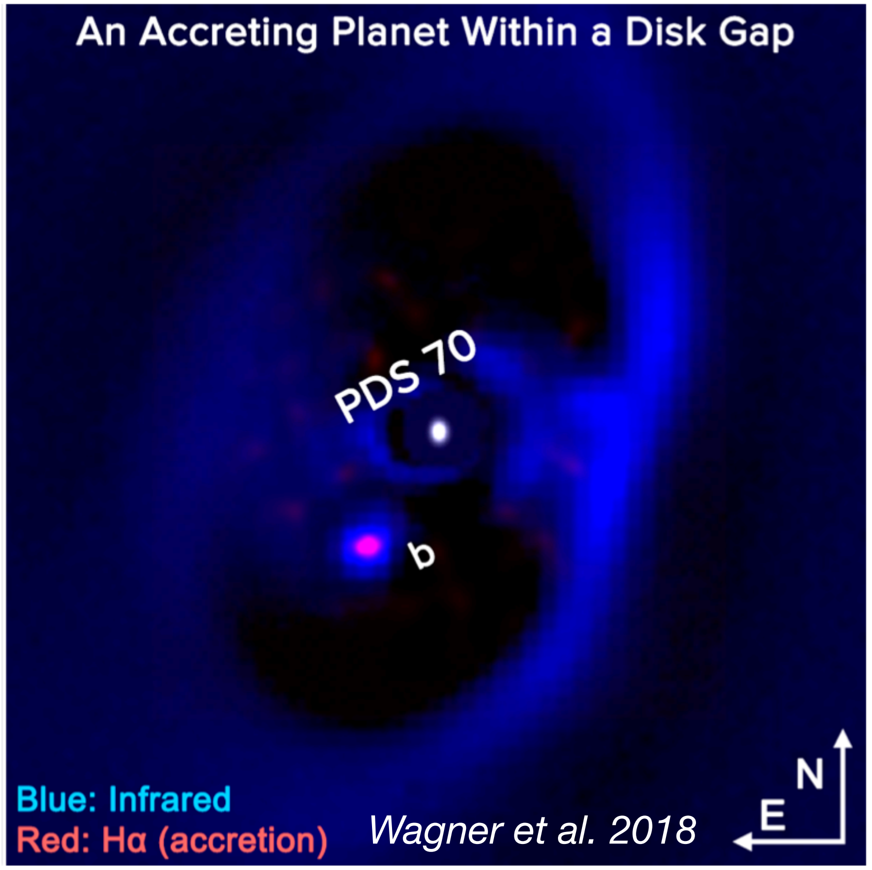


- Large mm-sized dust is in midplane
- Small µm-sized dust is coupled to the gas and vertically extended
- Gaps and rings due to (forming) planets?

Young gas planets in PDS70 disk

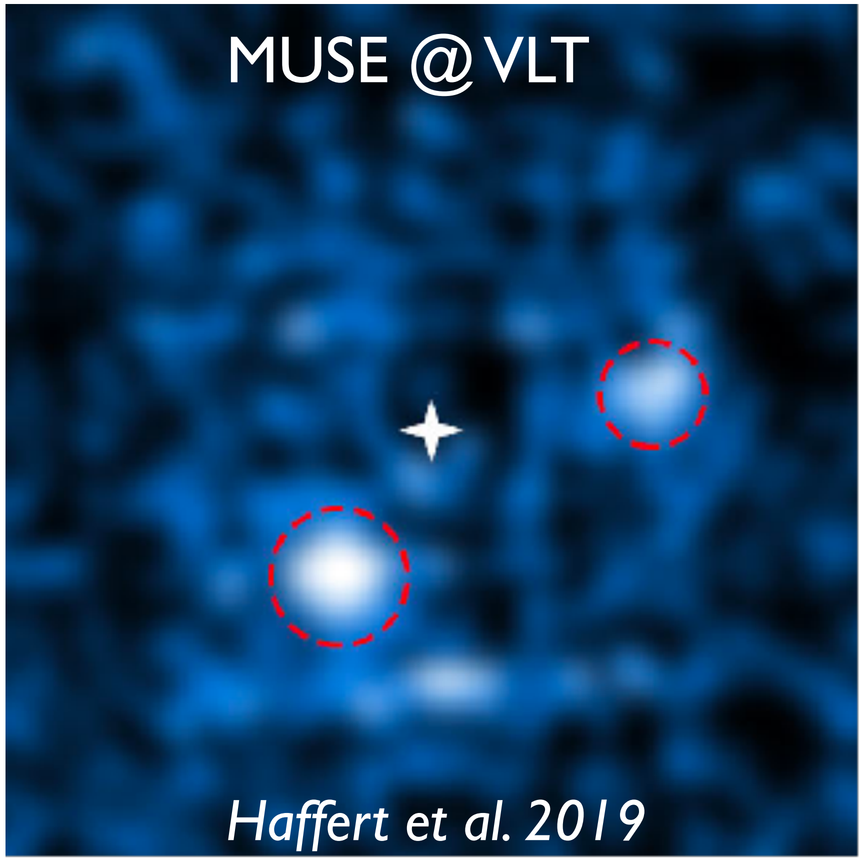


Keppler et al. 2018
Müller et al. 2018



An Accreting Planet Within a Disk Gap

Wagner et al. 2018



Haffert et al. 2019

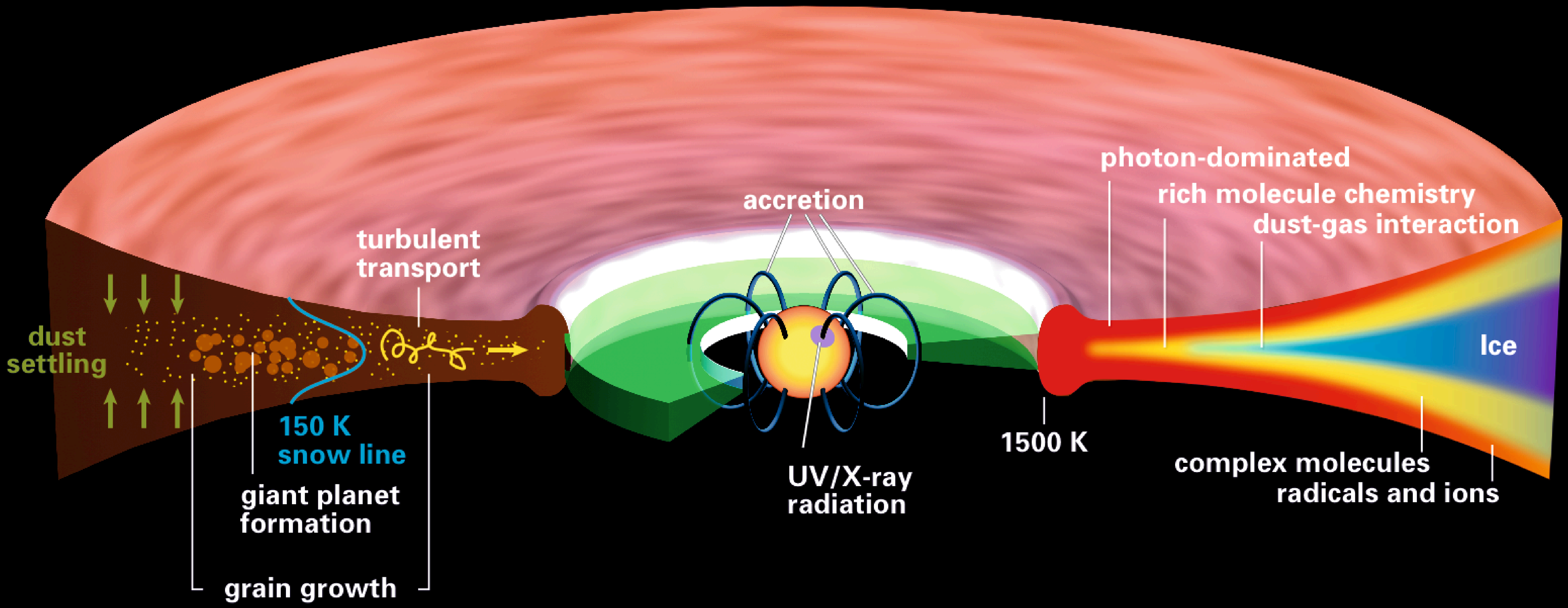
- Sun-like star with a disk (~5–10 Myr old)
- A wide gap between 20 and 40 au
- Two ~2 – 10 M_{Jup} planets at 21.5 and 35.5 au (2:1 resonance)
- Accreting gas from the disk

Disks: basic information

- 99% gas (mainly H_2 and He), 1% dust
- Masses: <0.01 – 0.2 M_{Sun}
- Keplerian rotation: $v_\phi \cong \Omega_K r = \sqrt{\frac{GM_*}{r}}$
- Radii: <10 – 1000 au
- Heights: increase with radius (flaring)
- Accretion rates: $\sim 10^{-9} - 10^{-7}$ M_{star}/year
- Lifetime: ~1 – 10 Myr

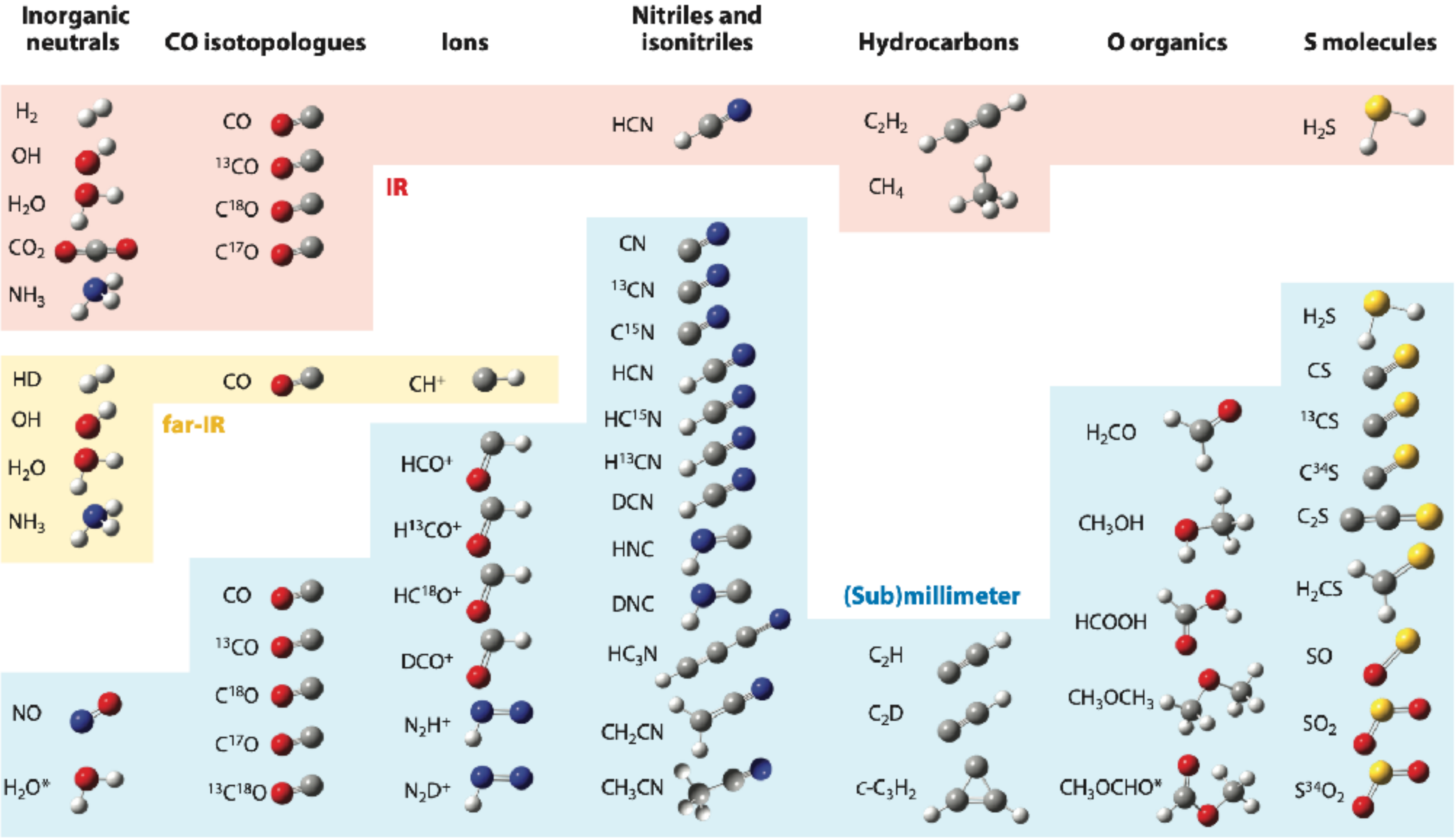
Scheme of a disk structure

Henning & Semenov 2013, Chem. Reviews



- Gradients of T and n_H ⇒ layered chemistry
- Complex dynamics
- Grain evolution & formation of planets

Astrochemistry: ~300 molecules detected in space, only 33 in disks



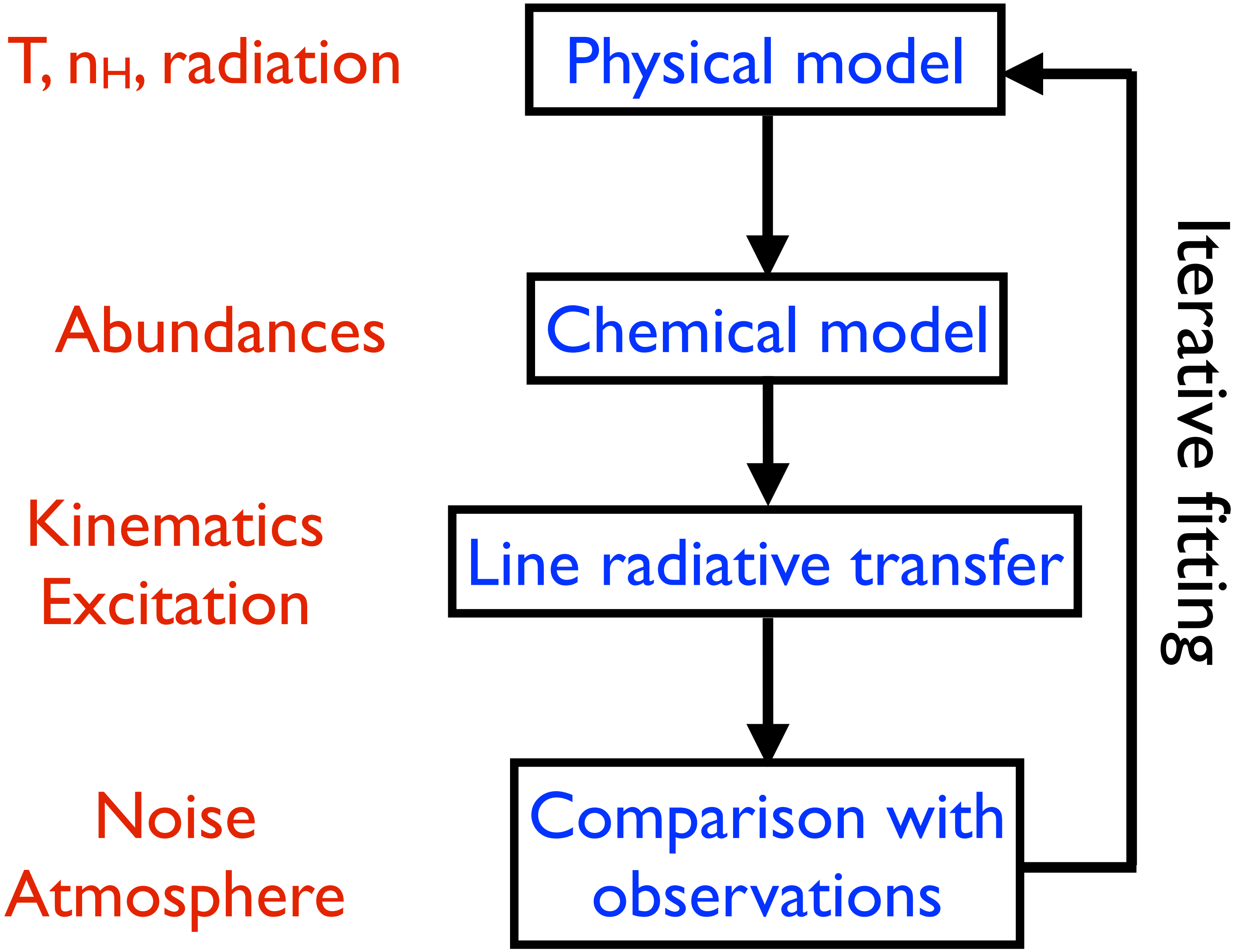
Öberg, Facchini, Anderson (2023)

Molecules as probes of disk physics

Tracer	Quantity
^{12}CO,^{13}CO, $C^{18}O$, $C^{17}O$, $^{13}C^{18}O$, $^{13}C^{17}O$	Temperature, density
HD	Gas mass
HCO^+, N_2H^+,…	Ionization
CN, HCN, HNC, C^+, C_2H, c-C_3H_2	FUV/X-rays
H_2CO, CH_3OH, CH_3CN	Surface processes
^{13}CO, $C^{18}O$, DCO^+, $H^{13}CN$, $C^{15}N$, $C^{34}S$,…	Isotopic fractionation
CS/SO, C_2H/CO,…	C/O ratio

Semenov et al. (2010)

Challenging „obs vs theory“ cycle



T, n_H, radiation

Physical model

Abundances

Chemical model

Kinematics
Excitation

Line radiative transfer

Noise
Atmosphere

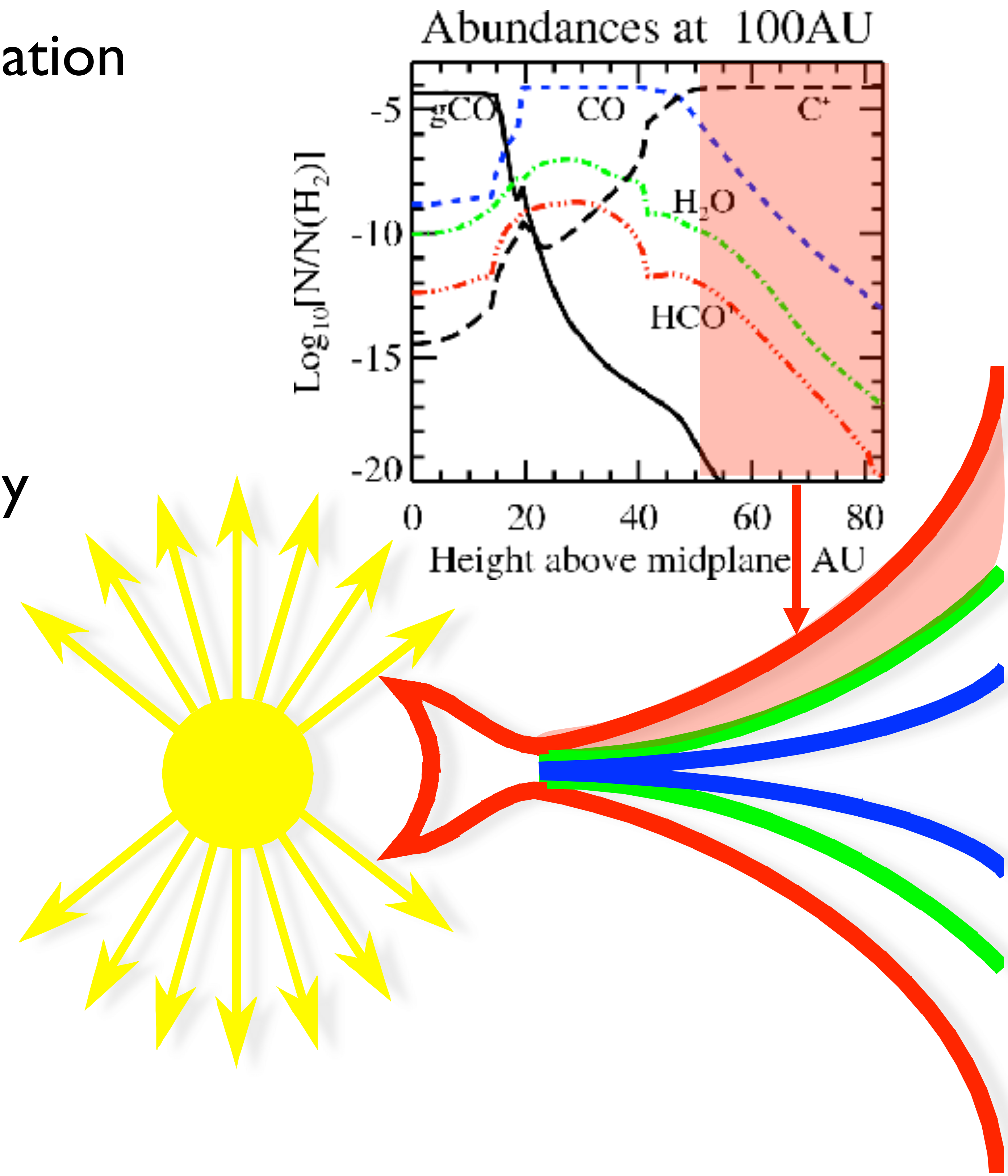
Comparison with observations

Iterative fitting

- Physics: parametrized structure, $T_d = T_g$ (fast)
- Chemistry: parameterized (fast) or full-scale (slowest part)
- Radiative transfer: LTE is often assumed (fast)

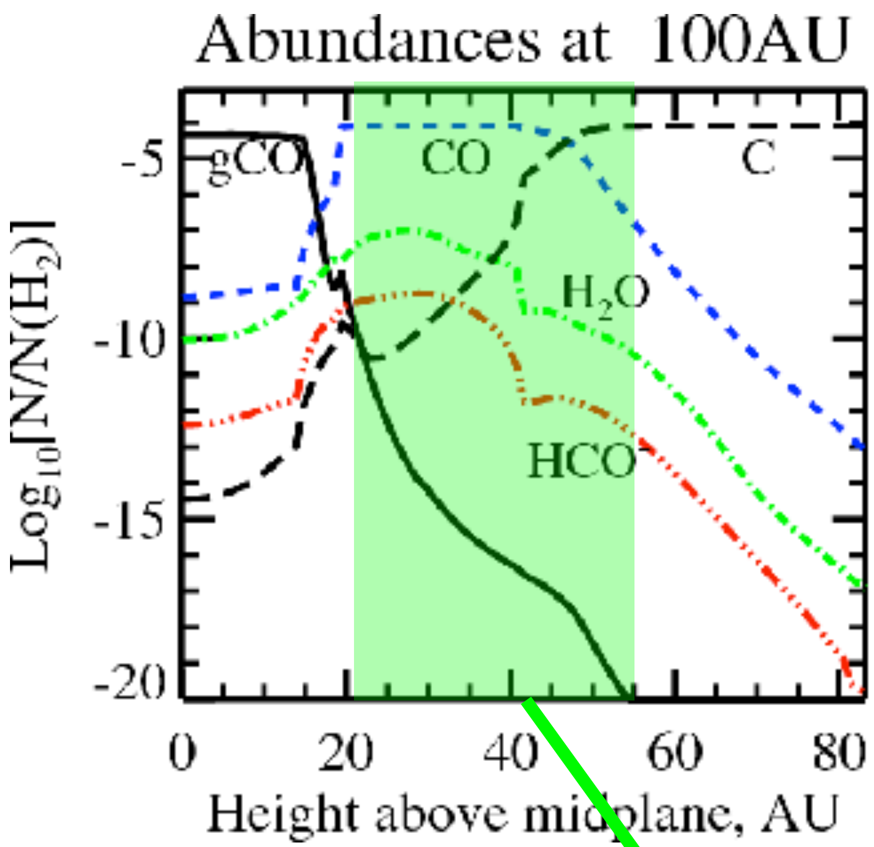
Hot irradiated atmosphere: simple ions and radicals

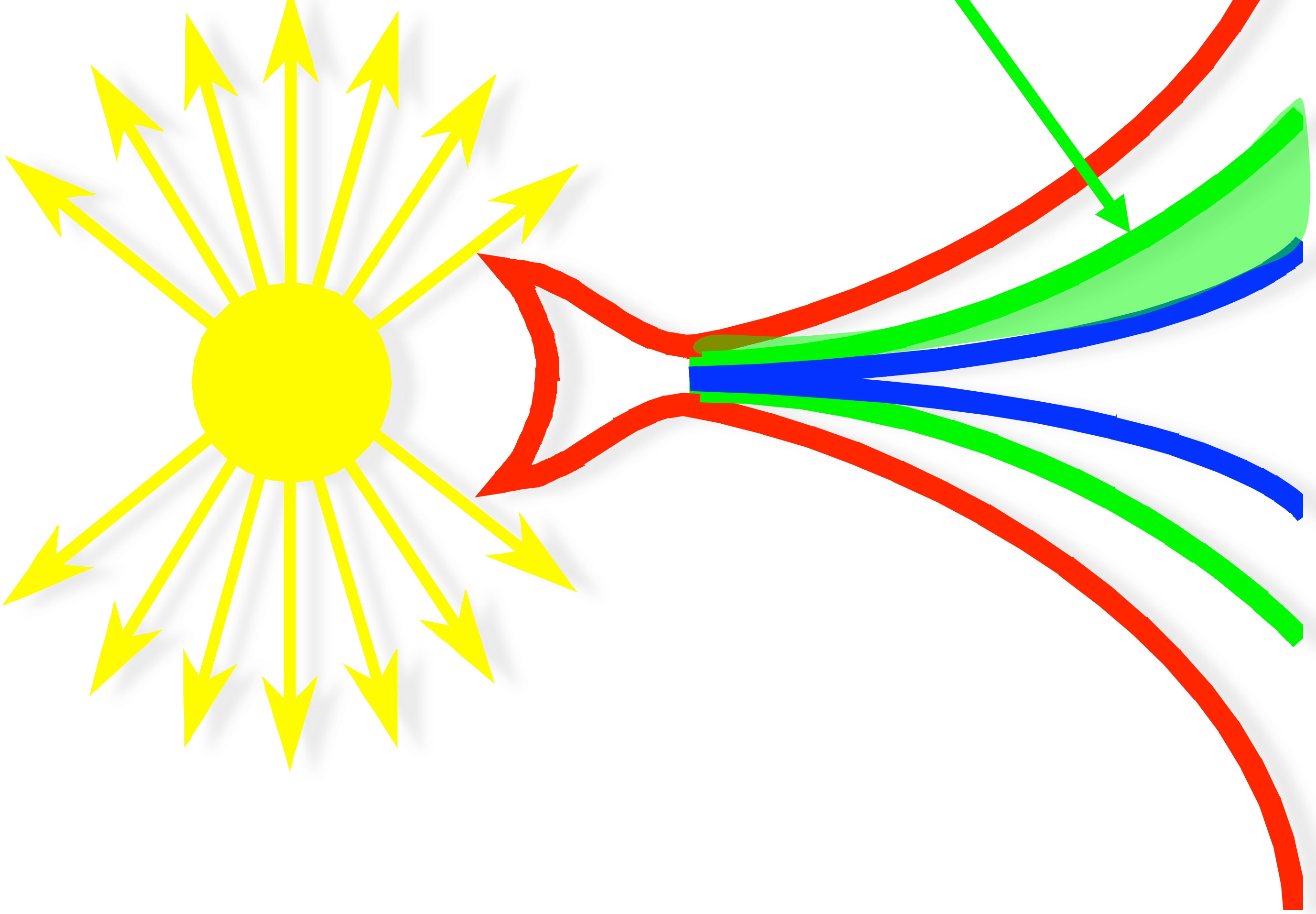
- Intense UV and X-rays radiation
- $n_H < 10^{5\text{-}6}$ cm^{-3}
- T > 100–10 000 K
- High ionization degree
- Limited gas-phase chemistry



Warm intermediate layer: molecules

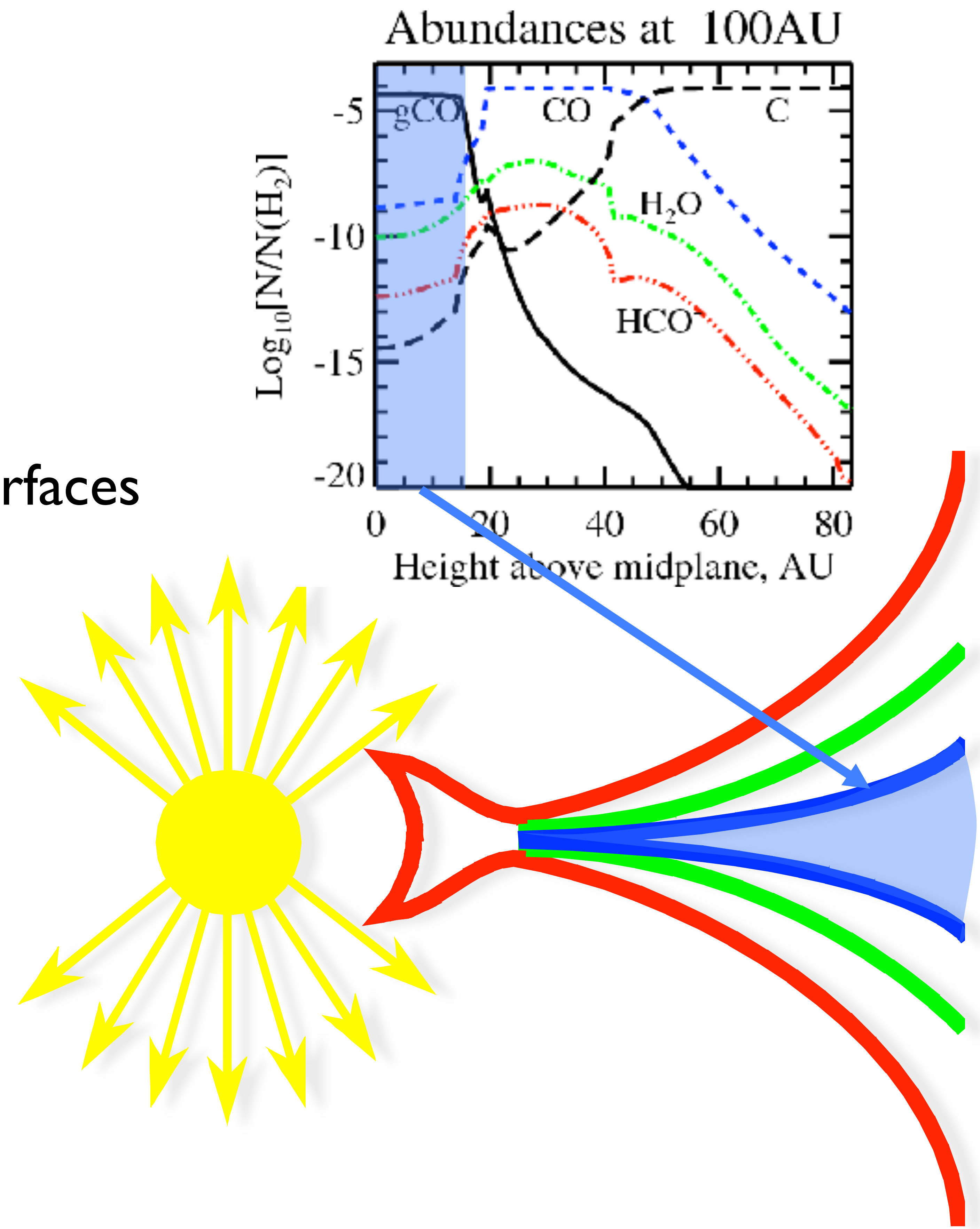
- Partly shielded from UV and X-rays
- $n_H \sim 10^6 - 10^9\ \mathrm{cm^{-3}}$
- T ~ 20 – 500 K
- Rich chemistry
- Molecules are in the gas phase
- Emission lines!





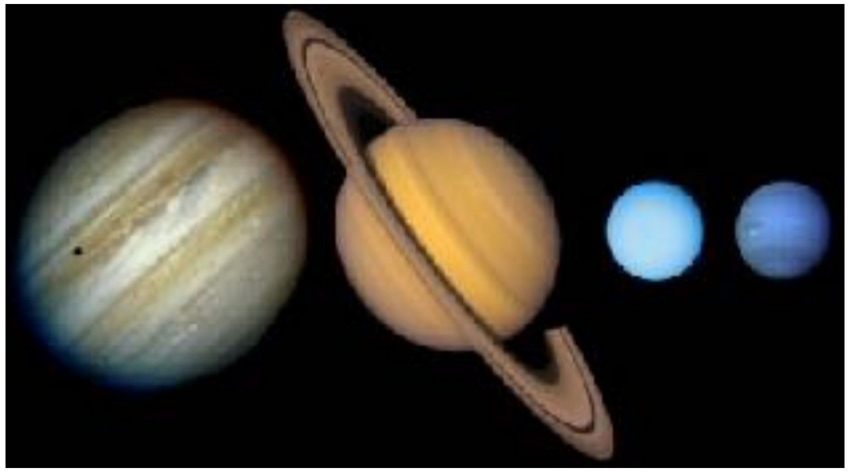
Cold, dense midplane: ices

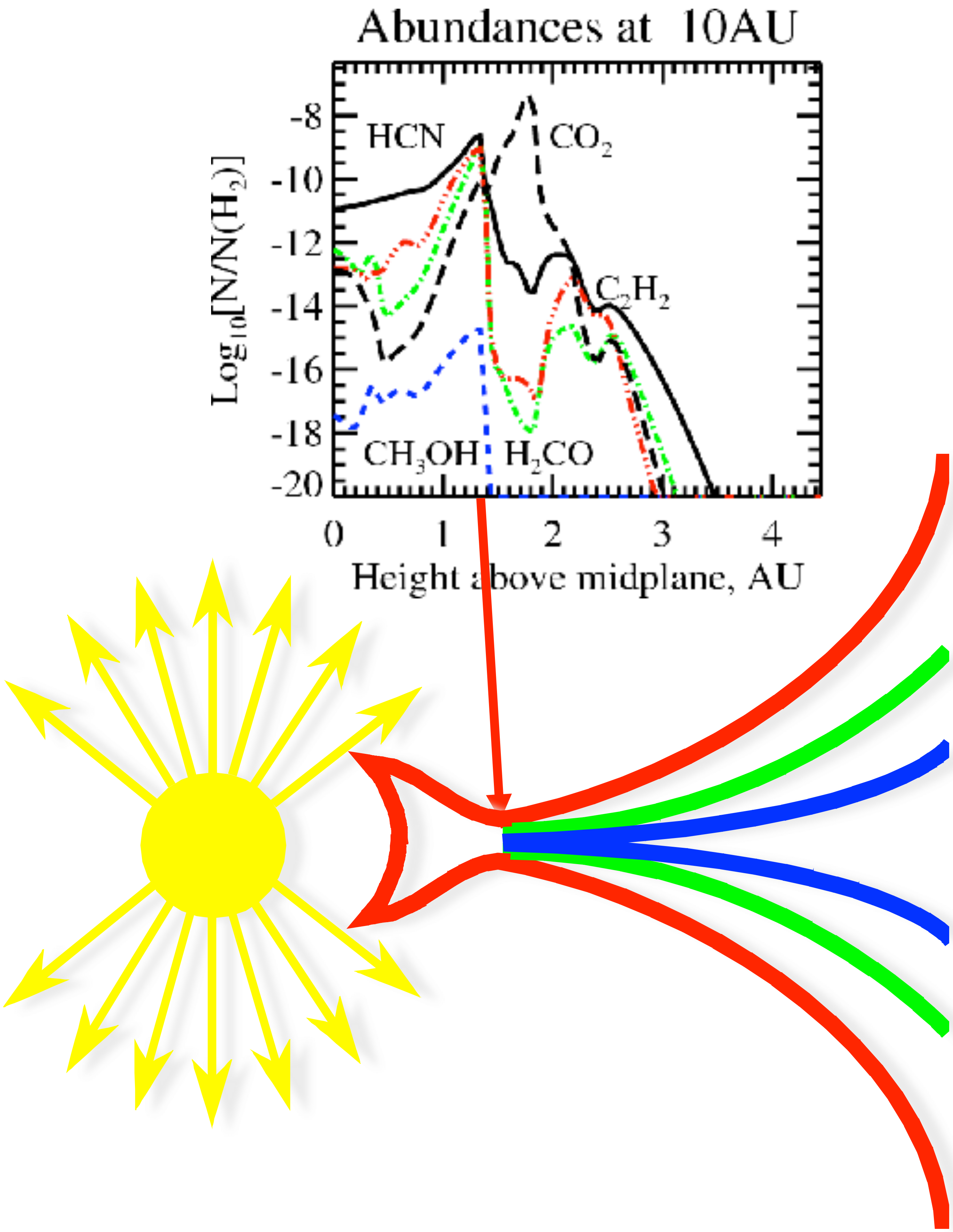
- Only CRPs can penetrate
- $n_H > 10^8$ cm^{-3}
- T < 10–50 K
- Freeze-out, a lot of ices
- Rich chemistry on dust surfaces



Planet-forming inner zone: dynamics

- $n_H > 10^{10}$ cm^{-3}
- T > 50–200 K
- 3-body collisions
- X-ray-driven processes
- No freeze-out
- Grain evolution

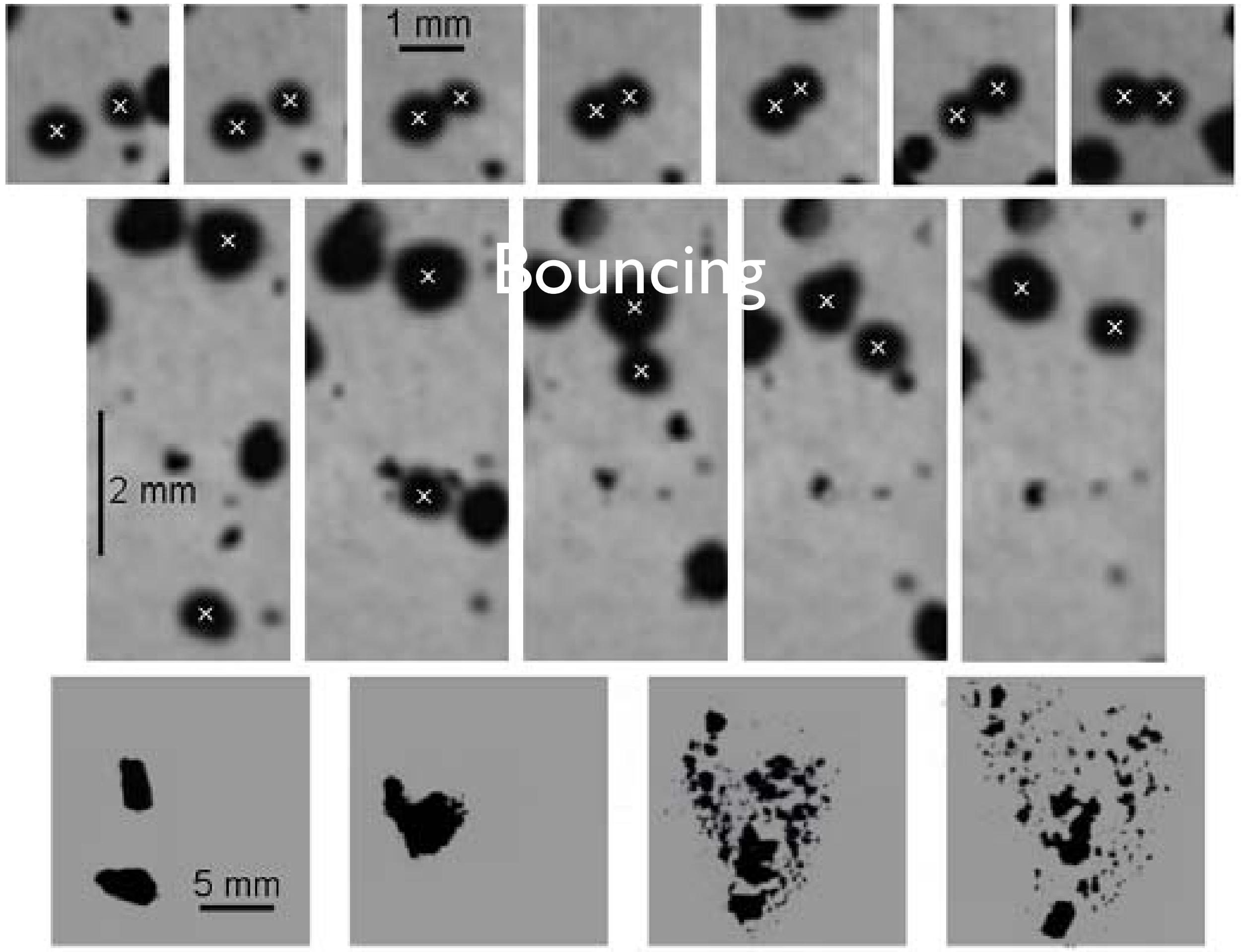




Dust evolution in a nutshell

- Sticking collisions due to Brownian motion (V <10 cm/s)
- Fragmentation at V >10 – 100 m/s
- mm grains rain down (settling)
- mm grains drift inward (head wind)
- Mostly proved by experiments

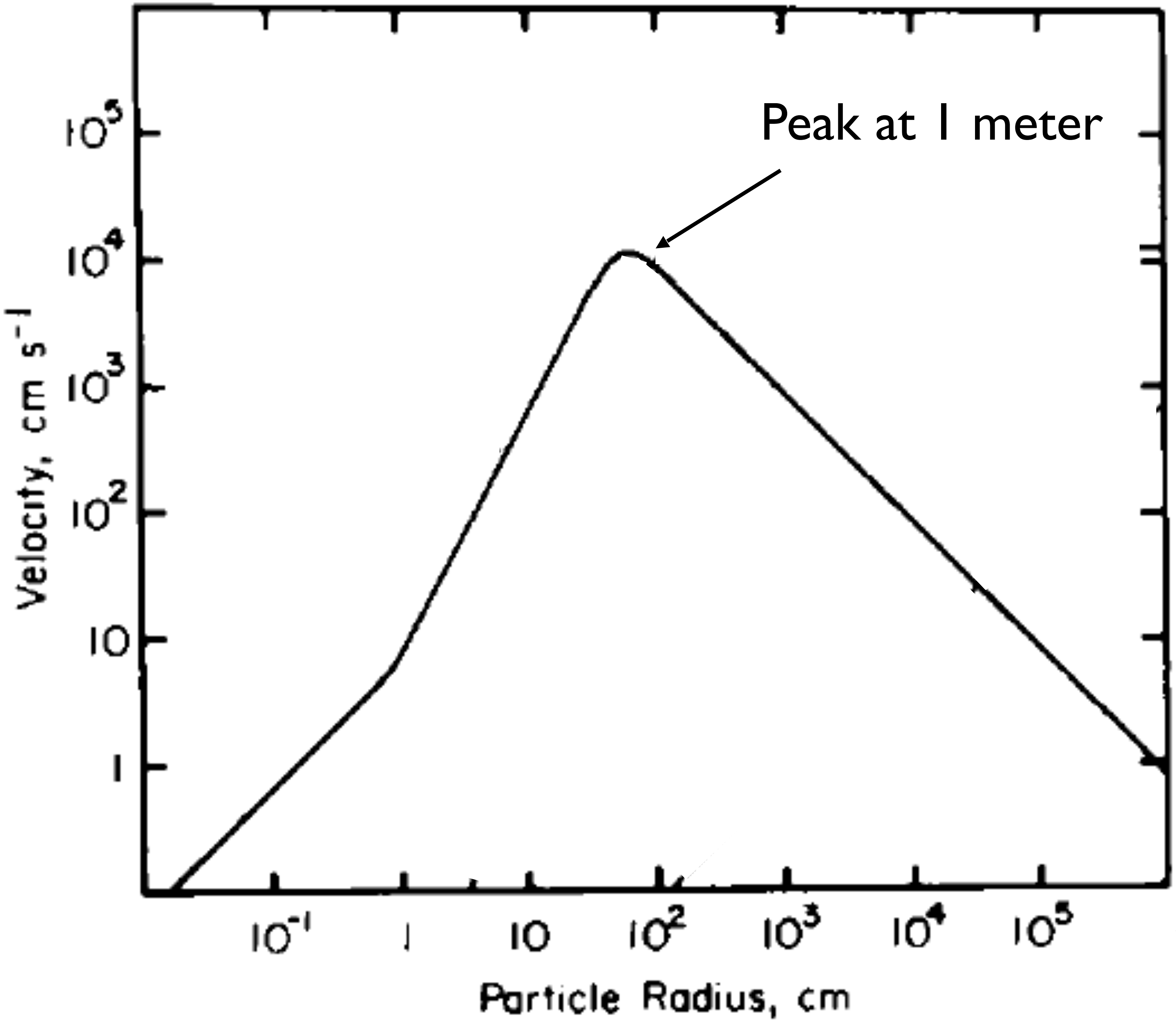
Sticking



Fragmentation

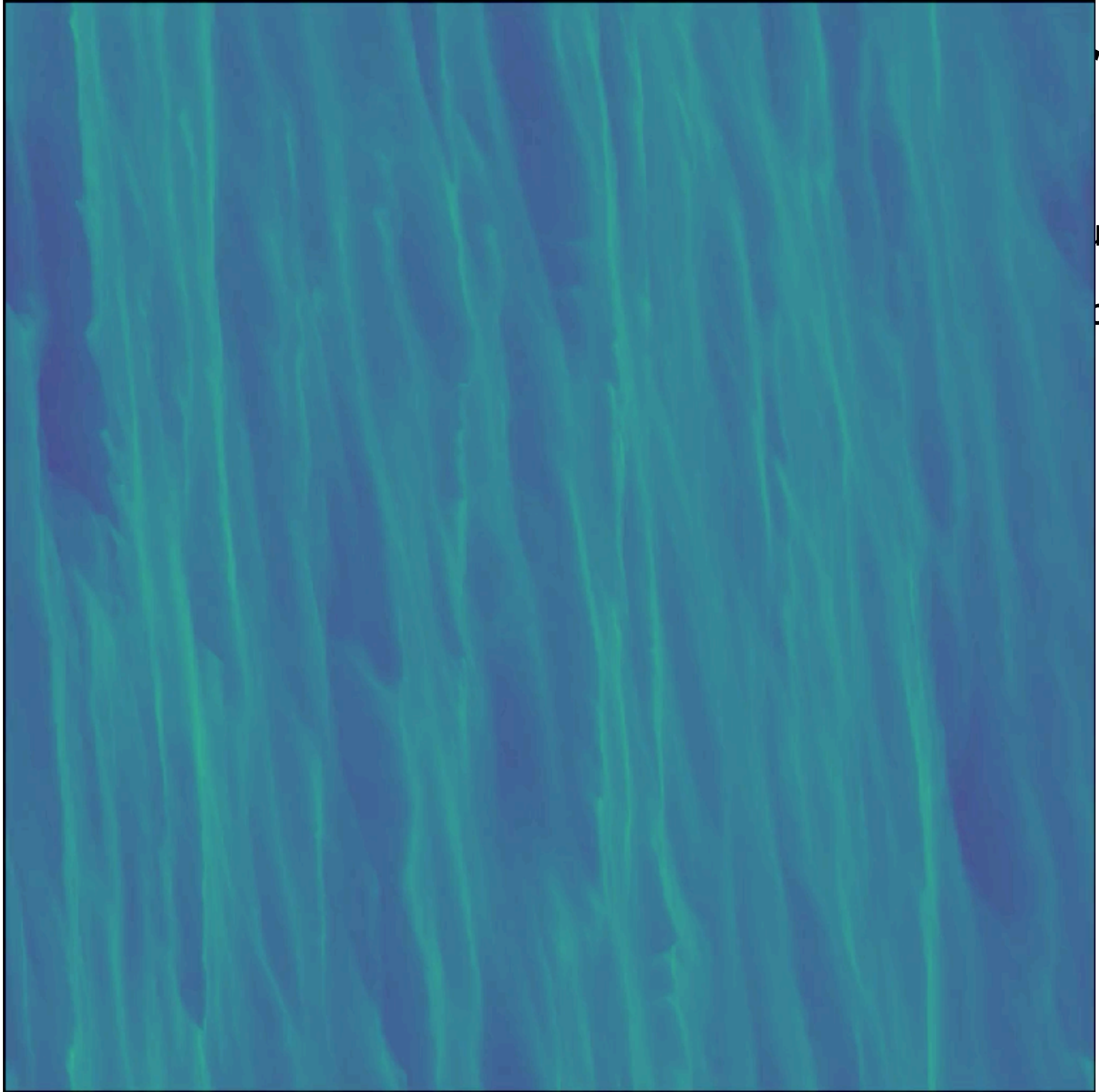
Weidenschilling et al. (1993), Blum (2010)

1m barrier to solid growth



Weidenschilling 1980

- Head wind (rotational velocity difference between gas and dust)
- Meter-sized bodies drift inward within <10^4 years
- How to overcome it? A few mechanisms have been proposed



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bility)

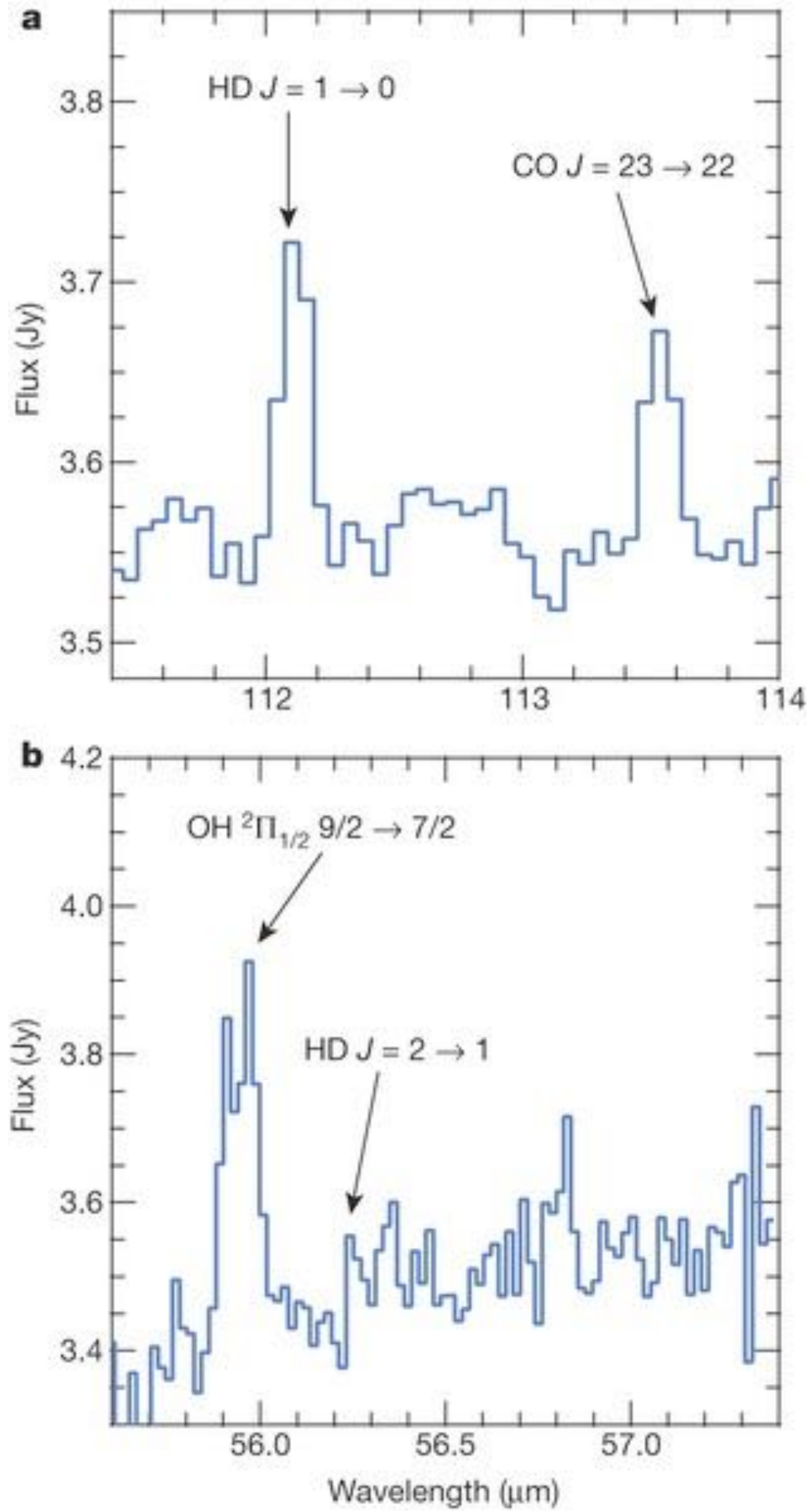
FIR/mm wavelengths are best to study disks

- Sensitive to cold ~10–20 K regions
- Optically thin dust emission: measure of dust mass
- Rotational transitions of many molecules: gas physics, chemistry
- High frequency resolution detectors: R $>10^6$ (up to 20 m/s)
- High angular resolution interferometers: ~1 au at 60 pc

Gas masses via HD: Herschel, FIR

Credit: NASA/JPL

Bergin et al. (2013), Nature 493, 644



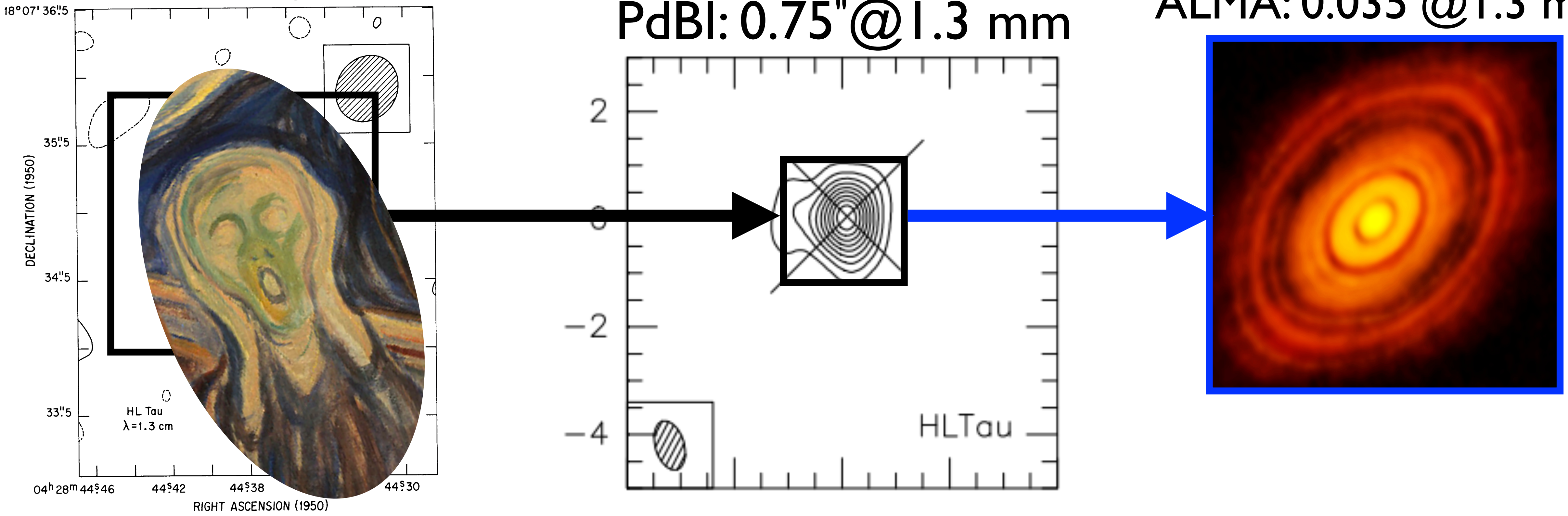
- TW Hya disk: $M_{disk} \sim 0.05\ M_{sun}$
- Enough mass to form a planetary system
- Gas masses have been measured only in 3 disks

Power of radio-interferometry: HL Tau disk

VLA: 0.45"@1.3 cm

PdBI: 0.75"@1.3 mm

ALMA: 0.035"@1.3 mm



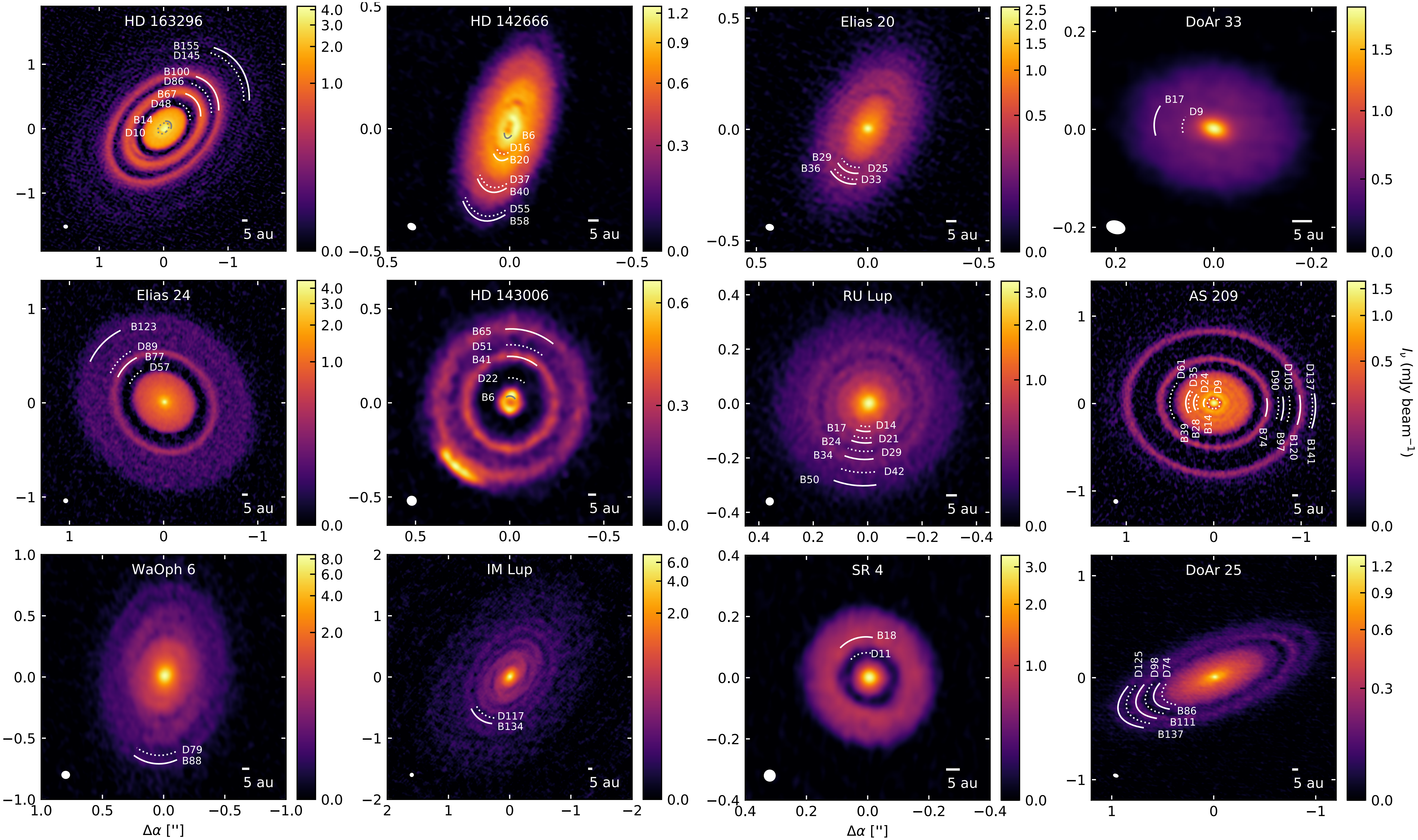
Rodriguez et al. (1992)

Guilloteau et al. (2011)

ALMA Partnership (2015)

- Modern (sub-)mm interferometry:
- Continuum: resolution > 0.02" ⇒ ~1 au (TW Hya) / ~5 au (others)
- Lines: resolution >0.06" ⇒ ~3 au (TW Hya) / ~15 au (others)

ALMA, 0.03″@1.25mm, dust emission (DSHARP data)

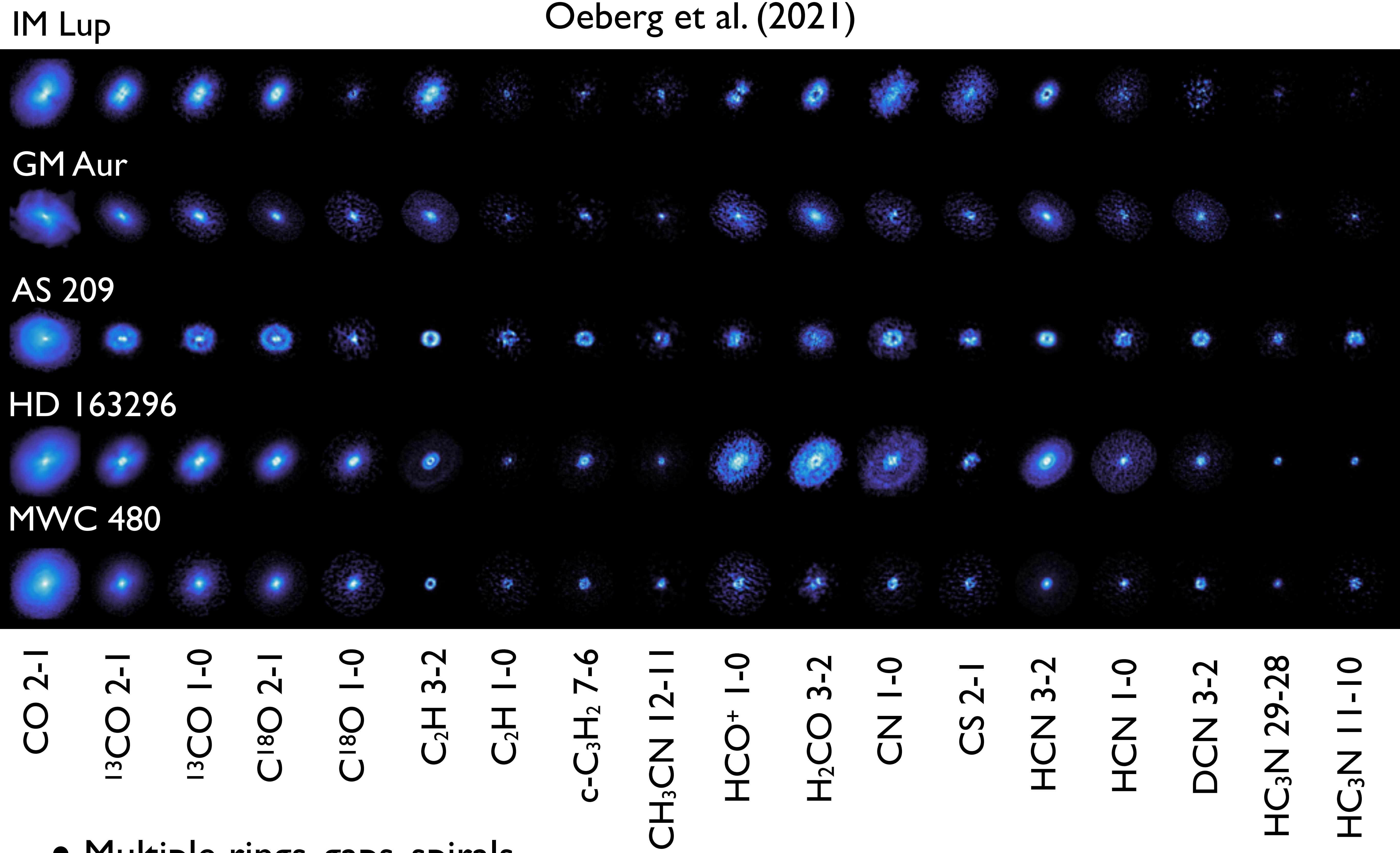


- Concentric gaps and rings in 20 disks, much less spirals or blobs
- Rings consistent with dust trapping in pressure maxima; α <10^{-3}
- No obvious systematics wrt star or disk properties

Andrews et al. 2020

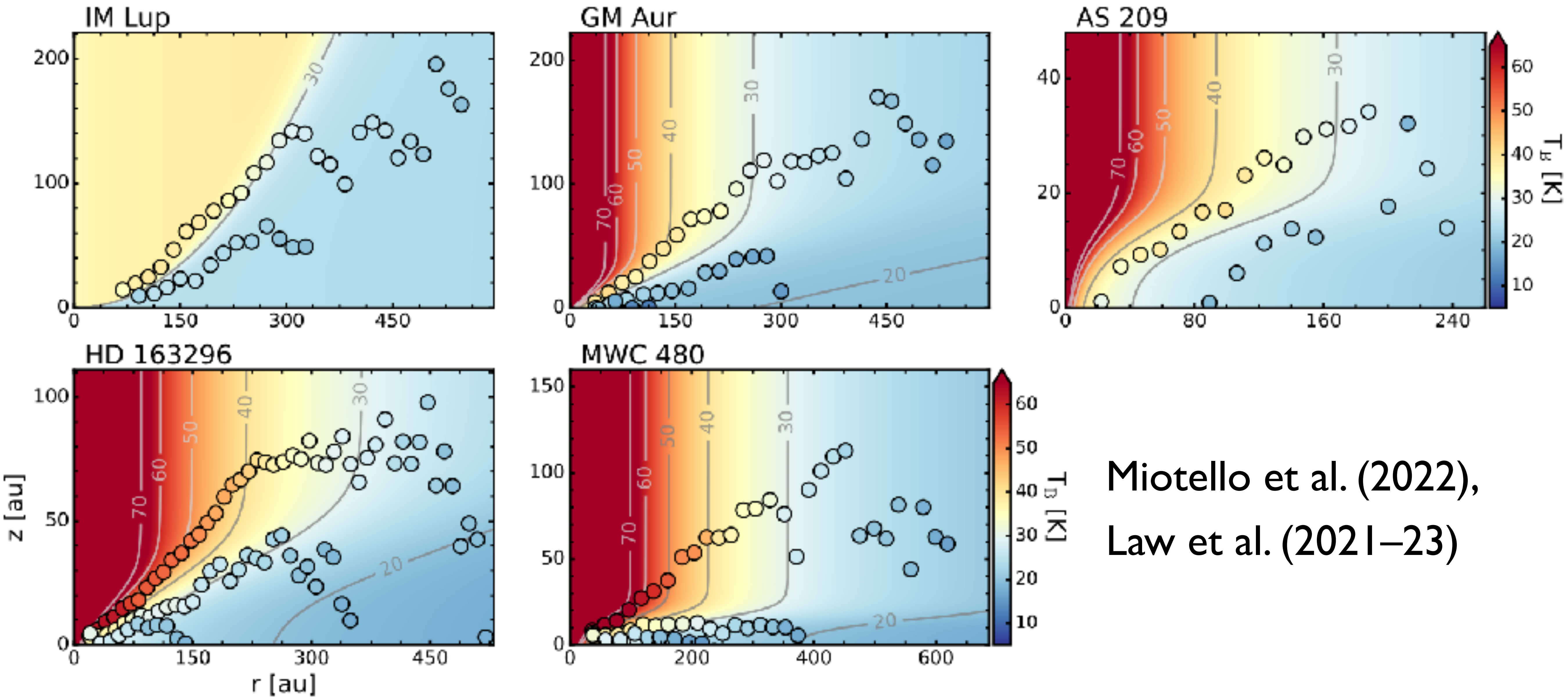
ALMA, line emission at <0.1″ (MAPS data)

Oeberg et al. (2021)



- Multiple rings, gaps, spirals
- Various emission sizes, inner radii, bright inner emission "cores"

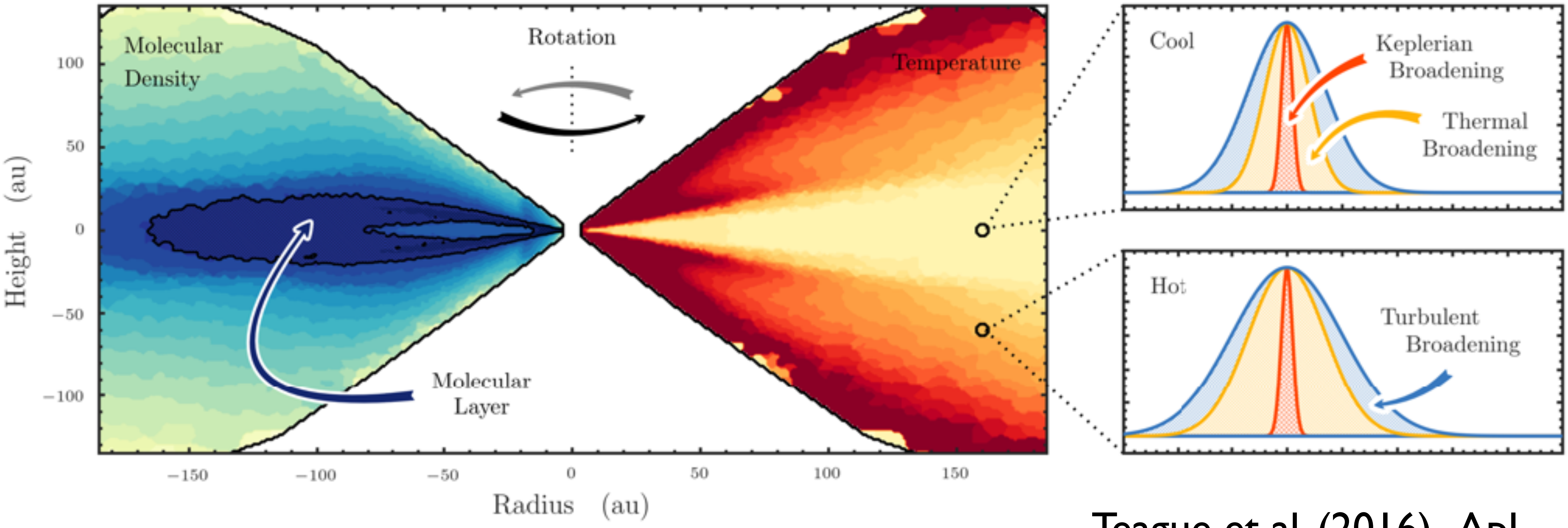
Temperatures from CO lines: ALMA, radio



Miotello et al. (2022),
Law et al. (2021–23)

- Low T ~ 20 – 60 K at r > 100 au
- Temperature decrease with radius and increase with height
- Agreement with radiative transfer models

Gas kinematics in disks

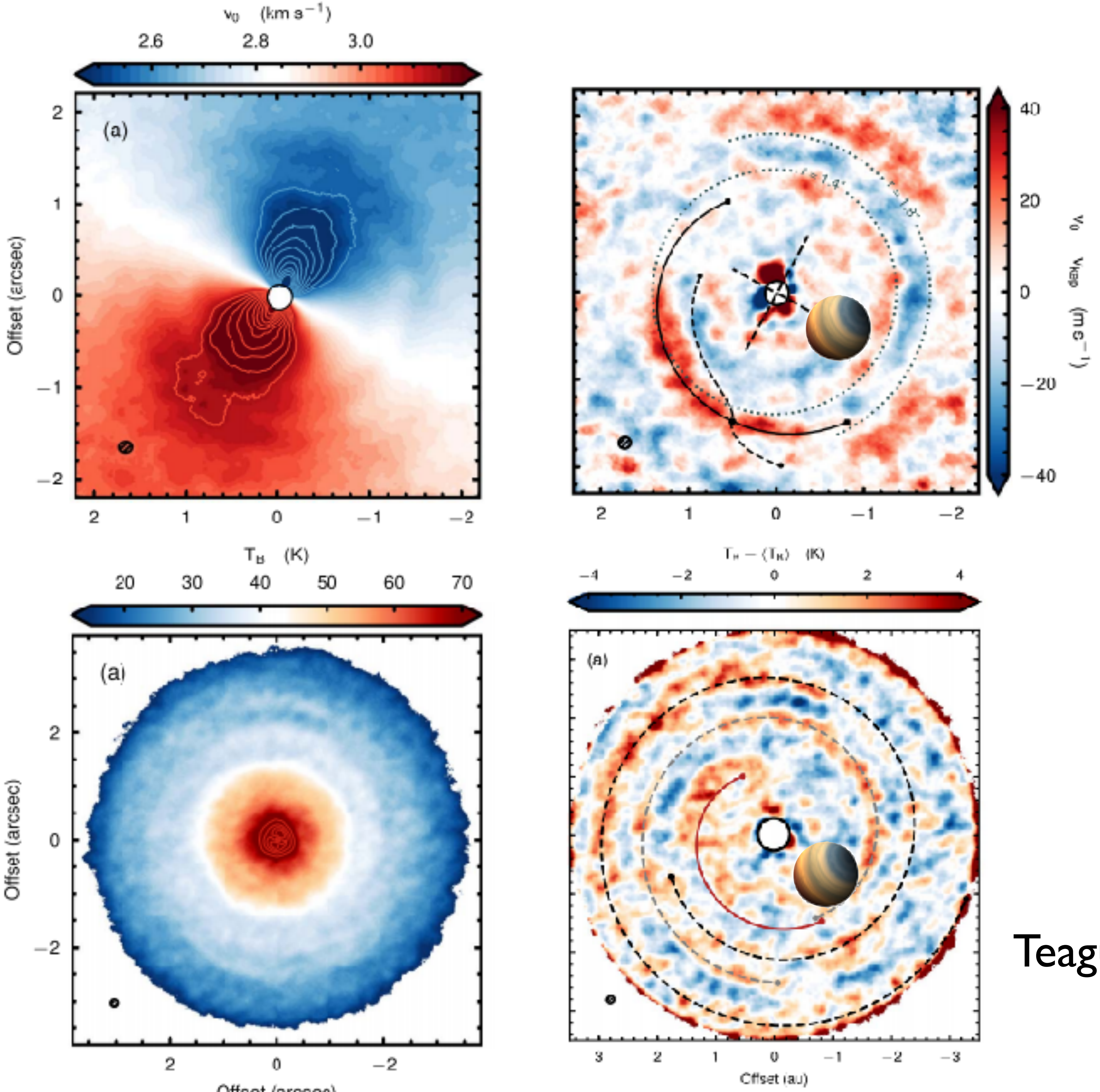


Teague et al. (2016), ApJ

Flaherty et al. (>2016), ApJ

- Keplerian rotation
- Gas temperature
- Local line width: $\Delta V(r) = \sqrt{\dfrac{2kT(r)}{\mu m_H} + \delta V_{\rm tu}(r)^2}$
- Heavy molecules are the best (CS) ⇒ disks are not turbulent!

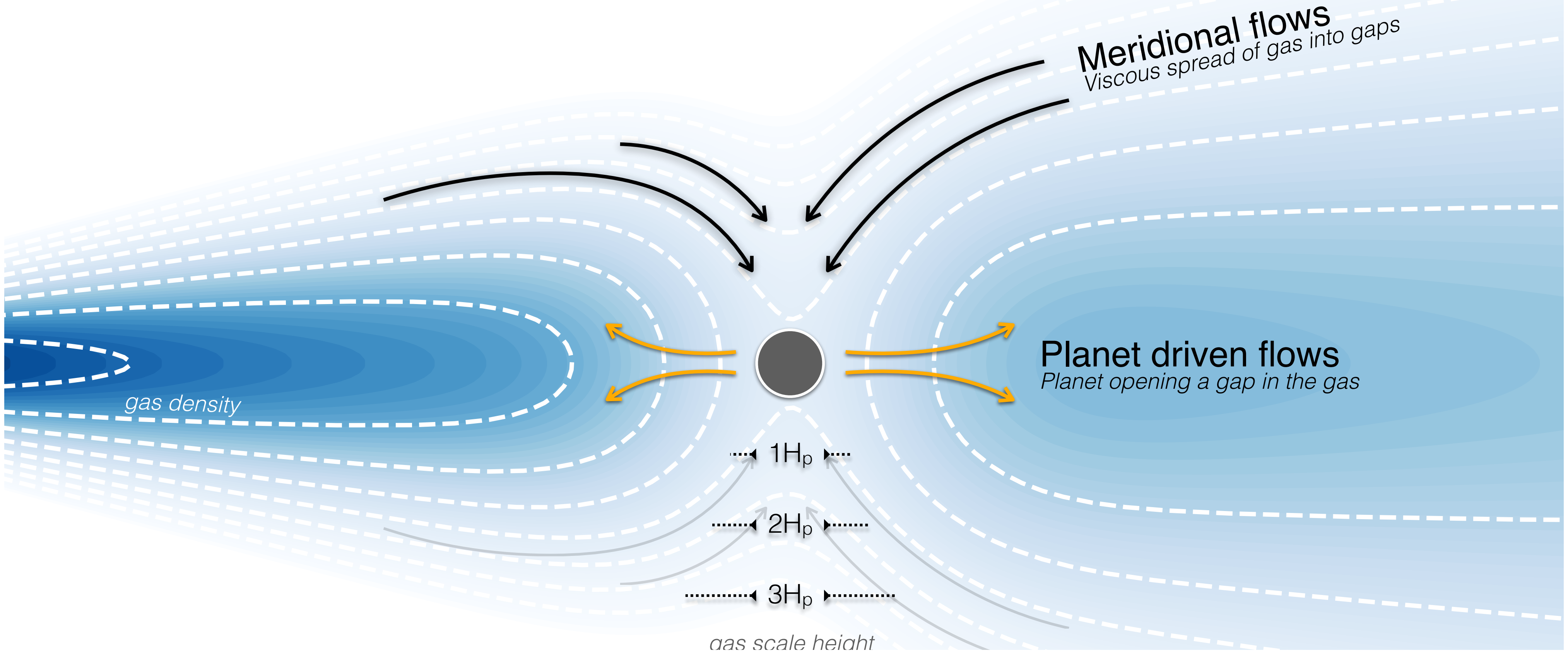
Gas spirals in TW Hya via ^{12}CO

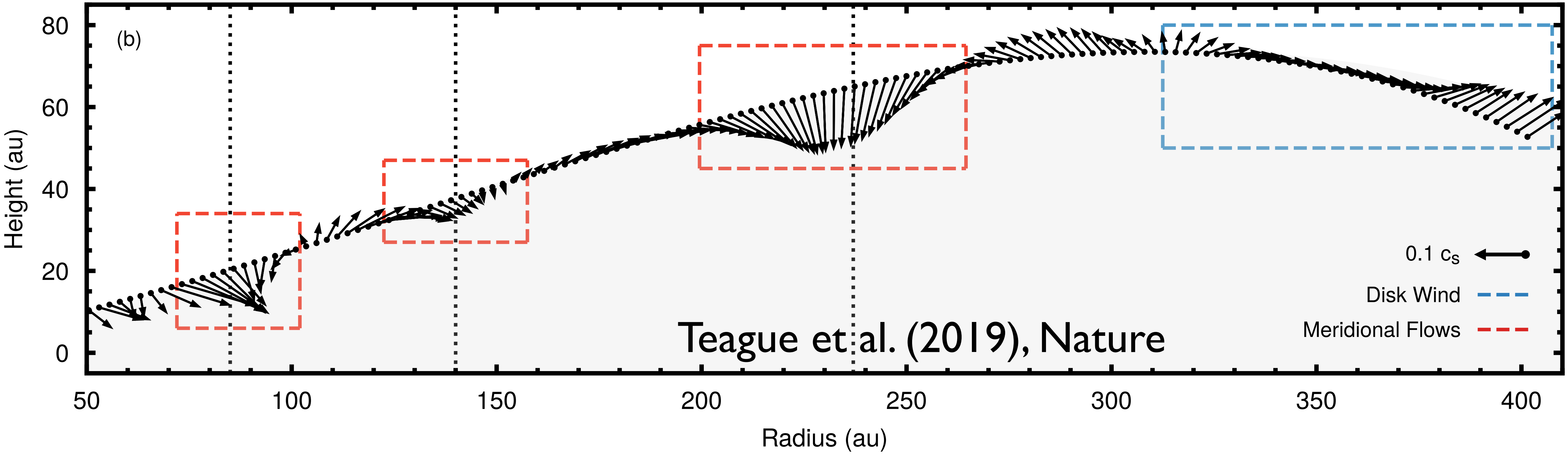


Teague et al. (2019), ApJ

- Archimedean spirals in V and T at >80 au ⇒ planet-disk interactions?

Meridional flows in HD 163296

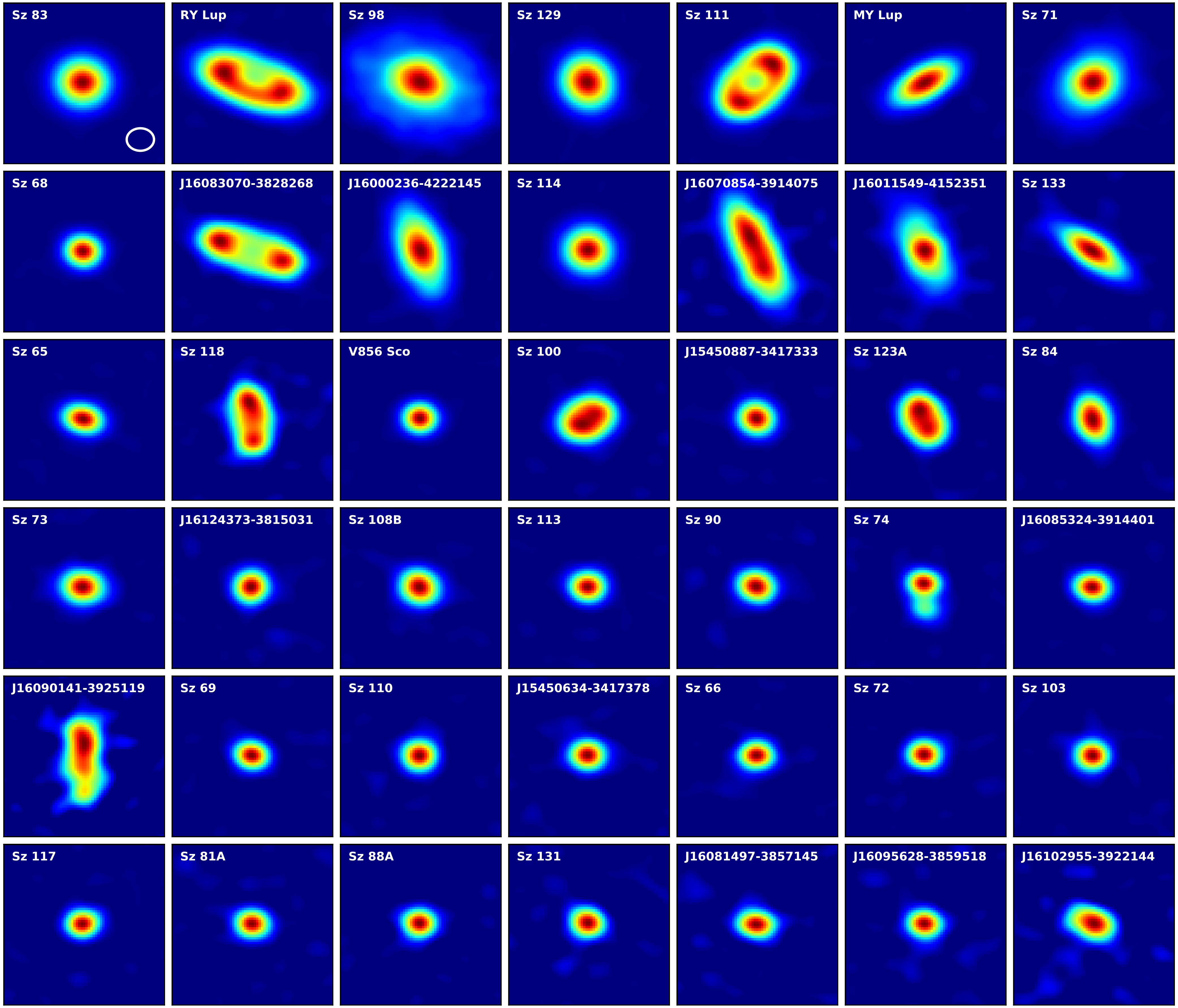




Teague et al. (2019), Nature

- 3 gaps in dust and CO at ~ 90, 140 and 240 au
- ^{12}CO ⇒ accurate T measurement ⇒ $V_z(r)$

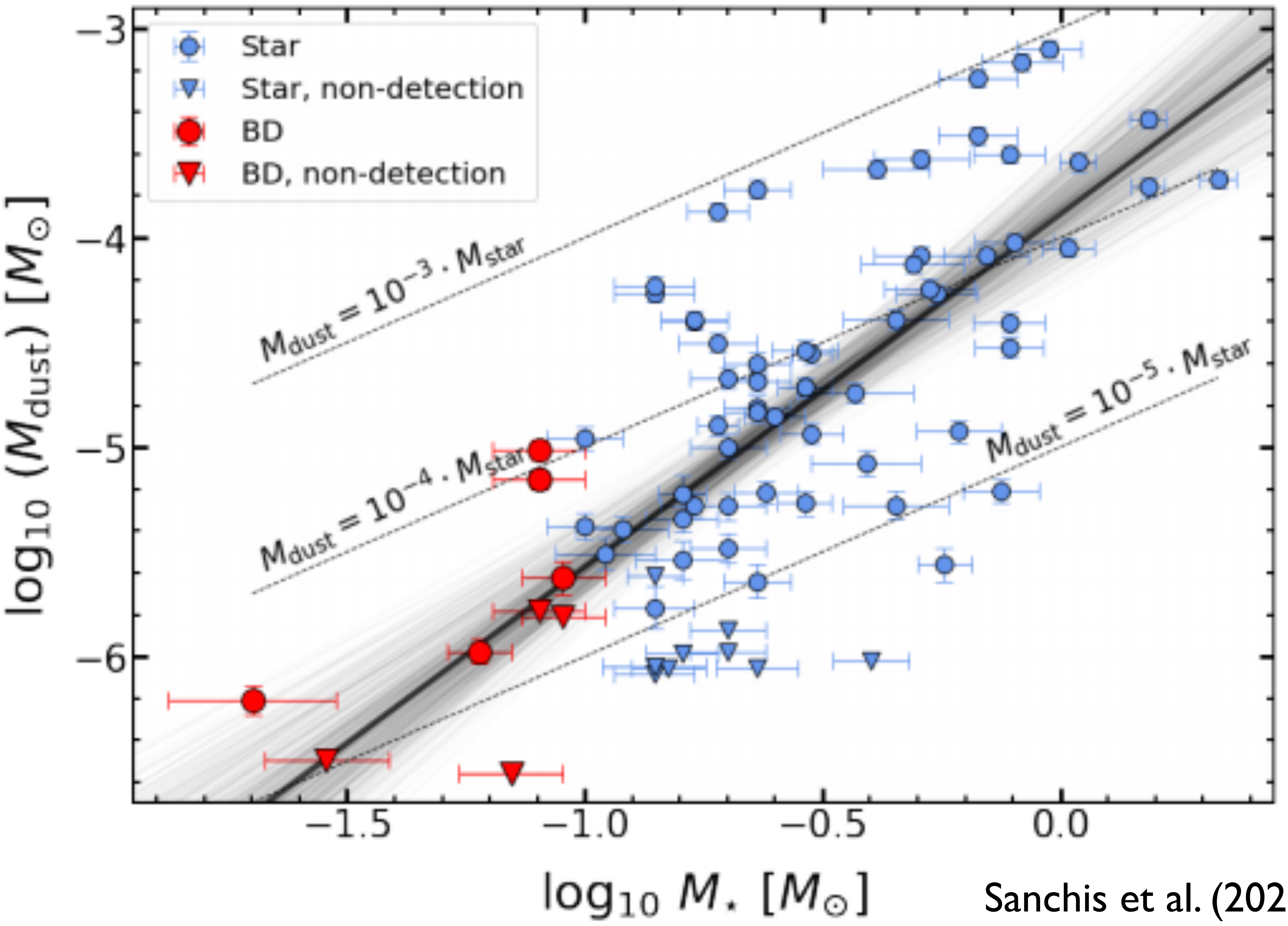
Large disk surveys: Lupus star-forming region



- 89 resolved disks: dust CO emission

Ansdell et al. (2016), ApJ

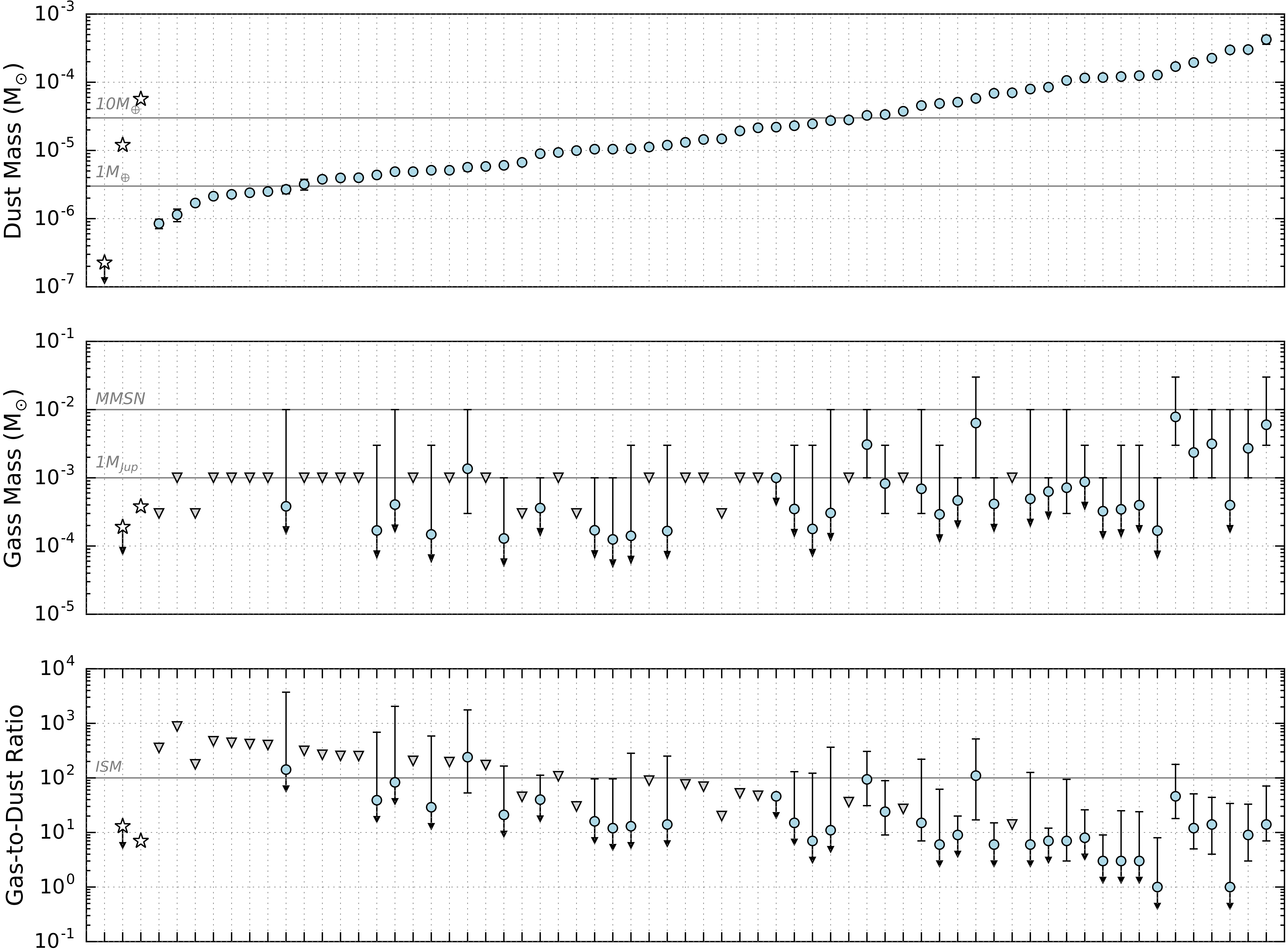
Large disk surveys: Lupus star-forming region



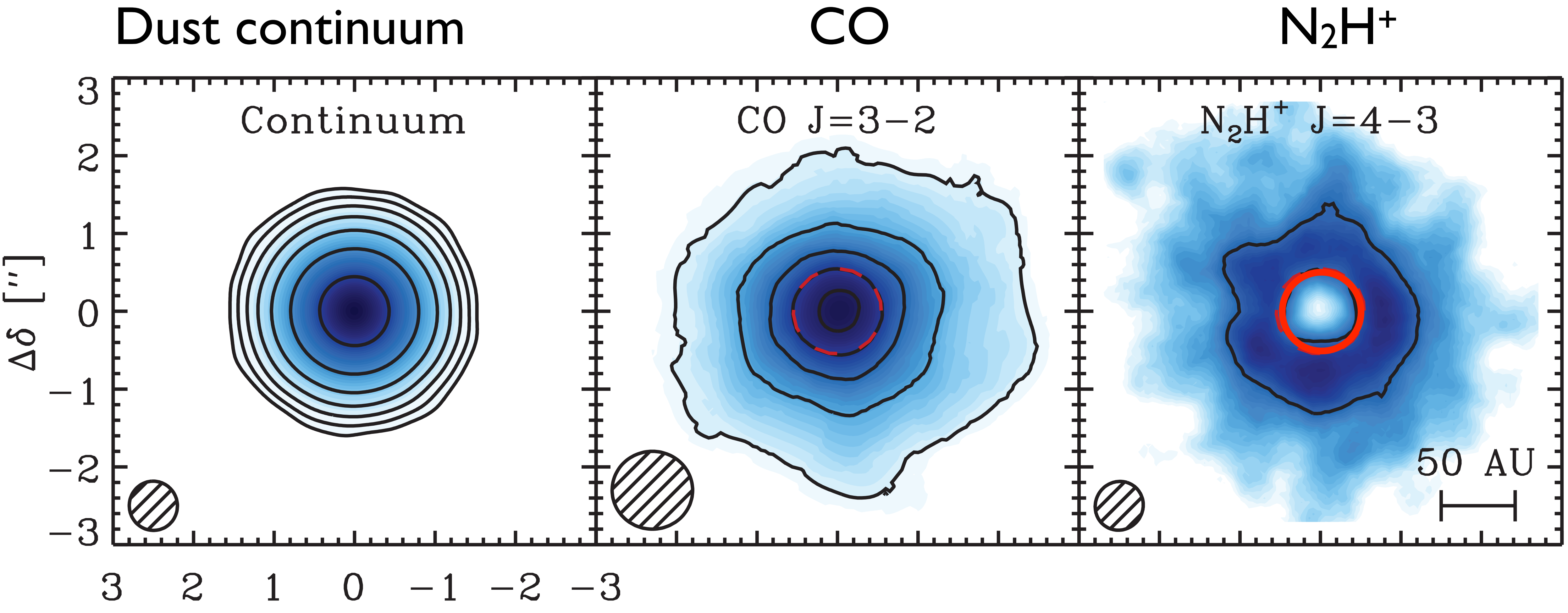
Sanchis et al. (2020), A&A 633

- M_{dust} scales as $[M\star]^{1.73 \pm 0.25}$

Lupus disk survey: dust and gas masses



Resolved chemistry: CO snowline in TW Hya



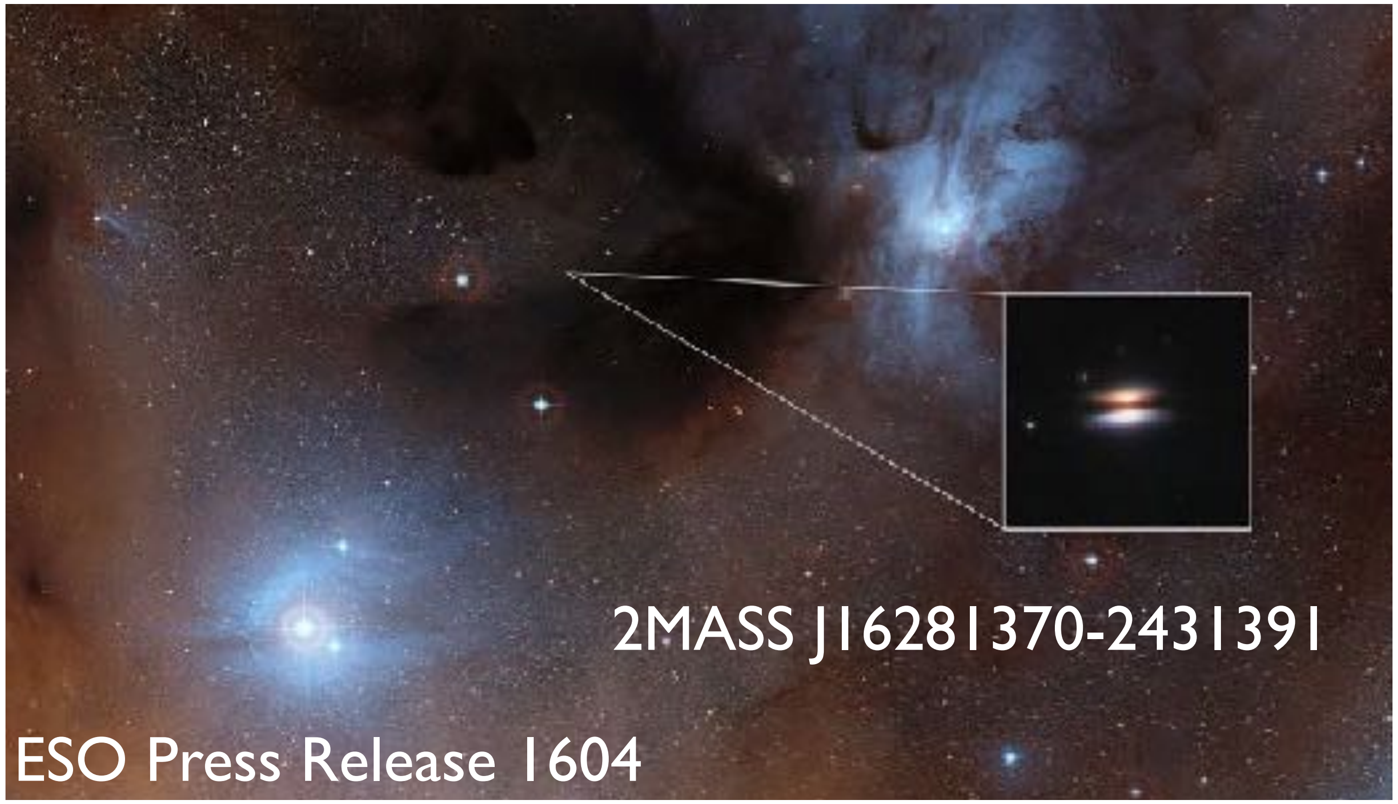
Dust continuum | CO | N_2H^+

- N_2H^+ anti correlates with CO: $N_2H^+ + CO \rightarrow HCO^+ + N_2$

- N_2H^+ ring at r > 30 au, where CO is frozen

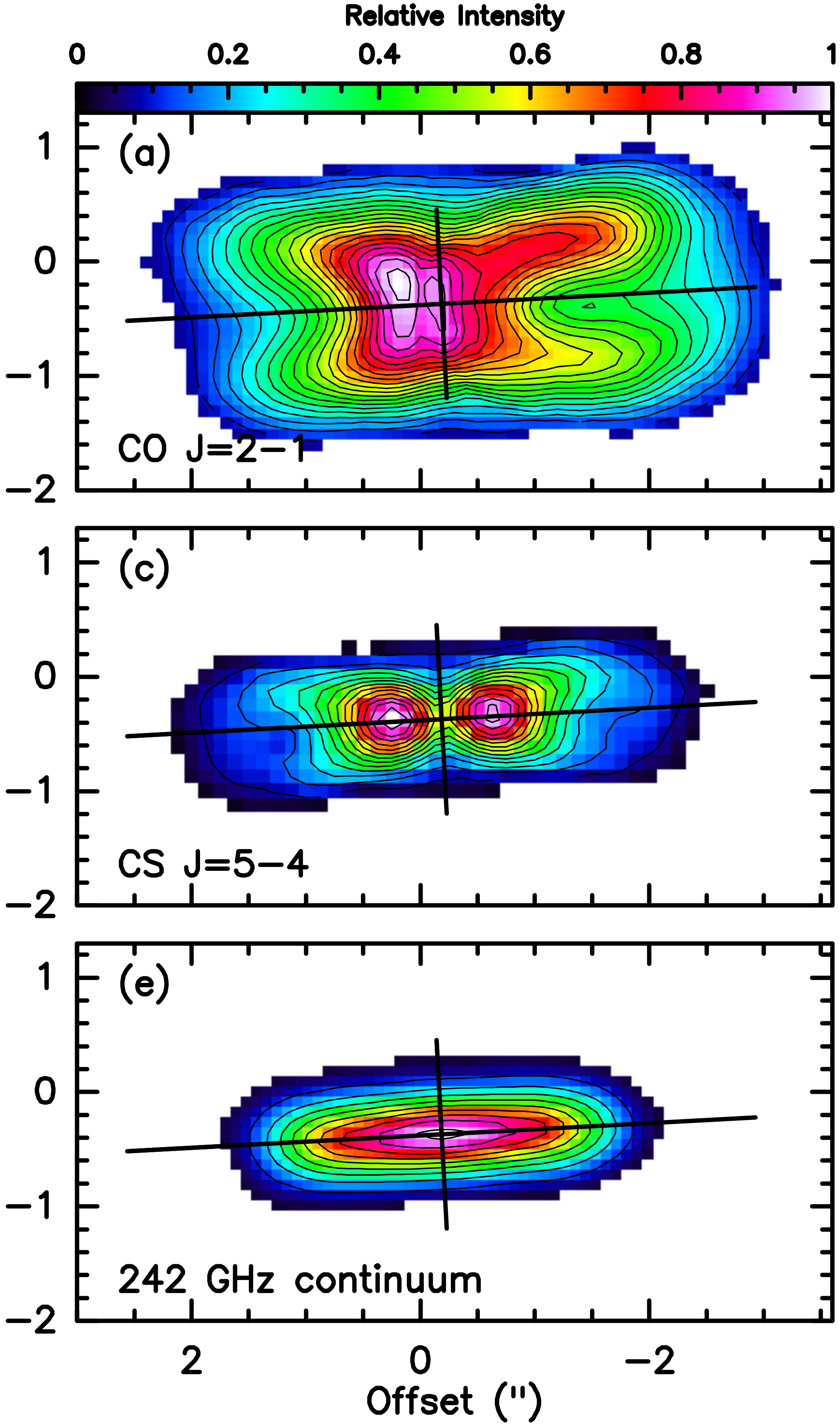
Qi et al. (2013), Science

Edge-on disk: „Flying Saucer“



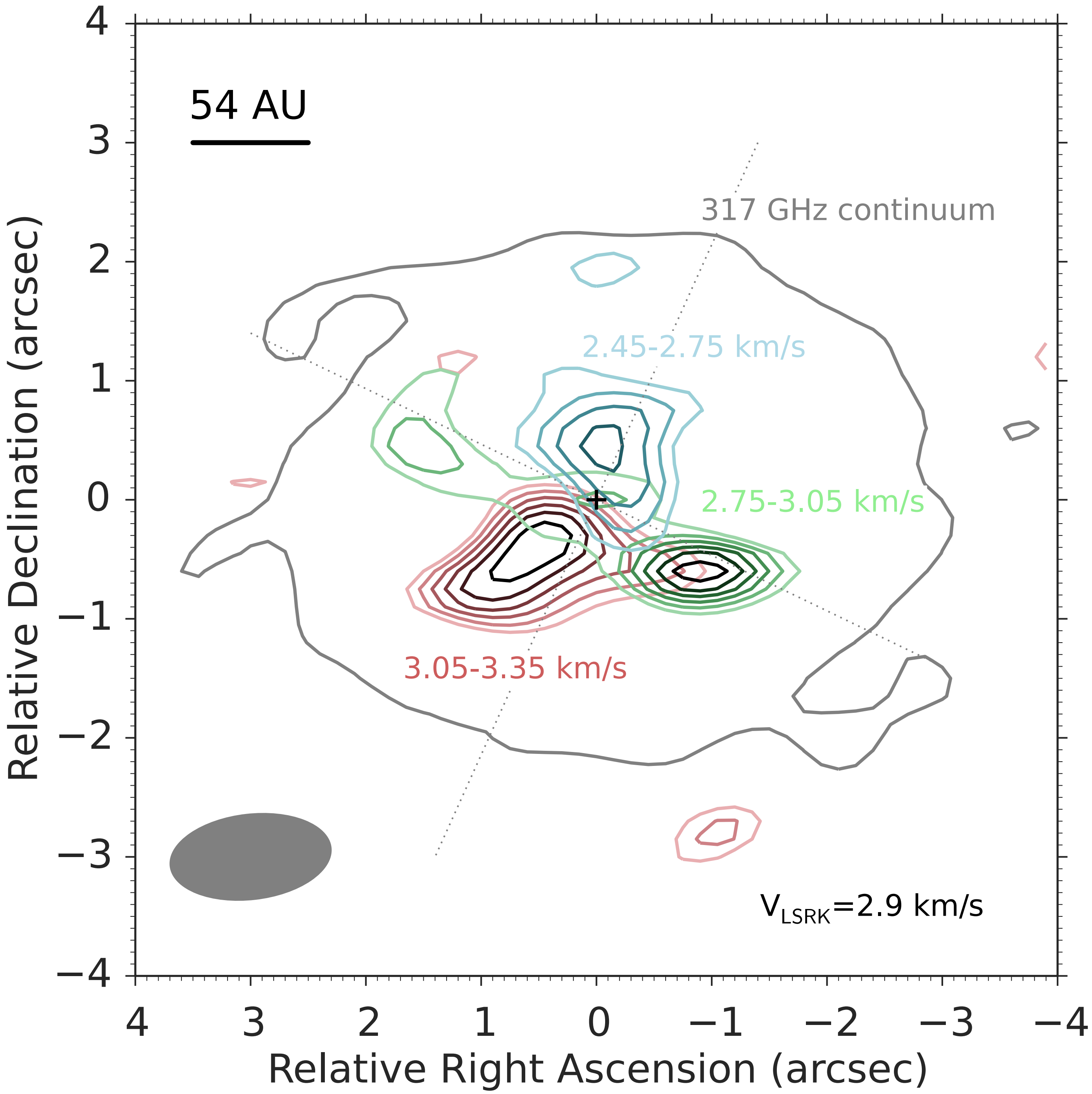
ESO Press Release 1604

- Cold, narrow dust disk: ~ 10 K
- Large, ~1mm grains
- Edge-on + Rotation ⇒ Emission (r,z)
- **Direct image of disk gas structure!**



Dutrey et al. (2017)

Alcoholes: CH_3OH in TW Hya

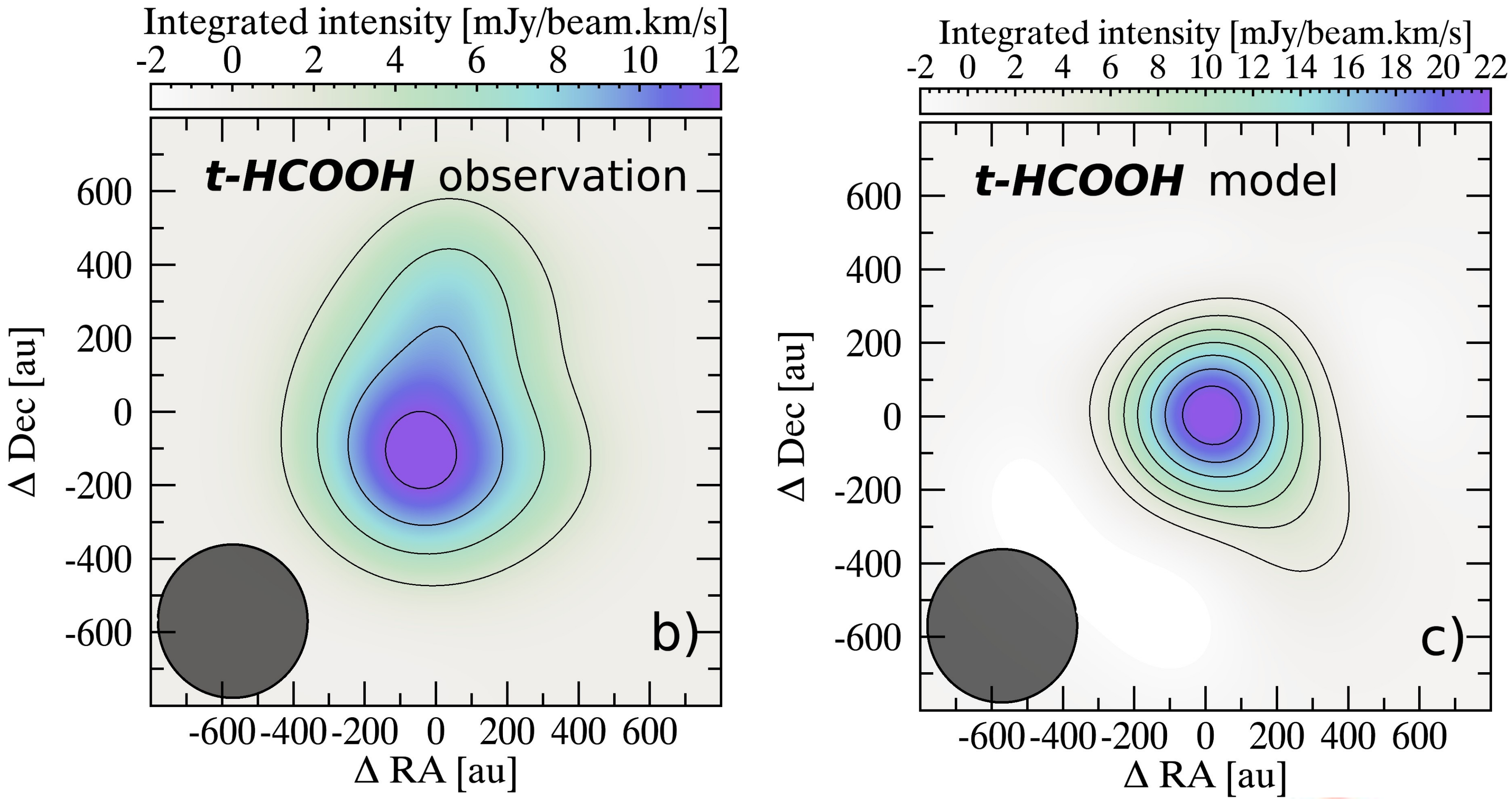


Walsh et al. (2016)

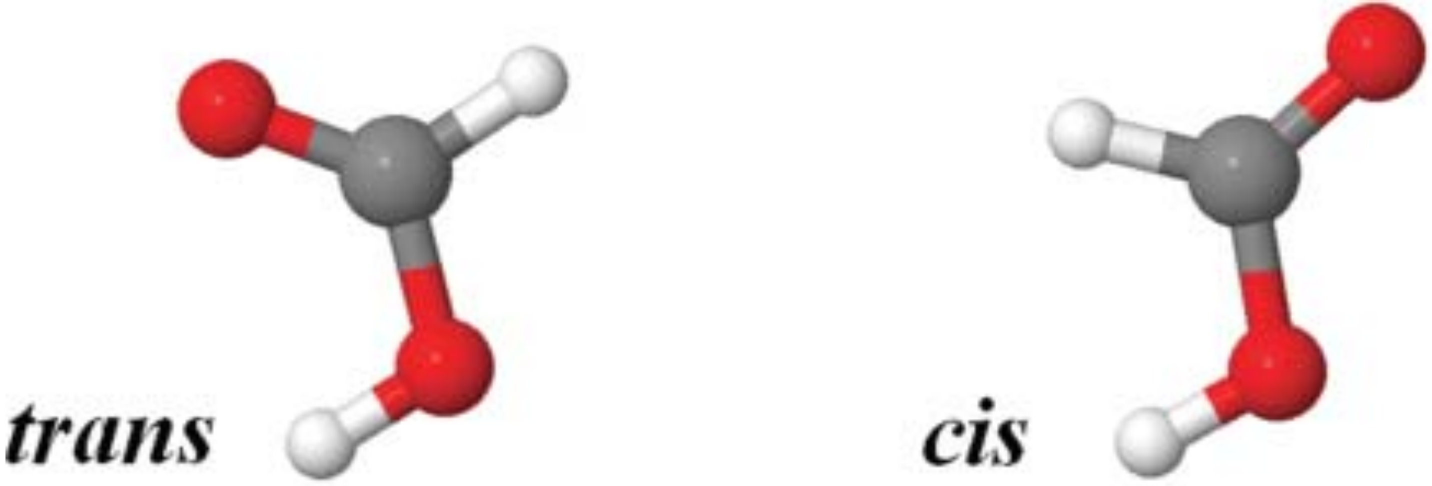
Parfenov et al. (2017)

- Methanol ring that peaks at ~30 au
- Produced by CO surface chemistry

Organic acid: HCOOH in TW Hya

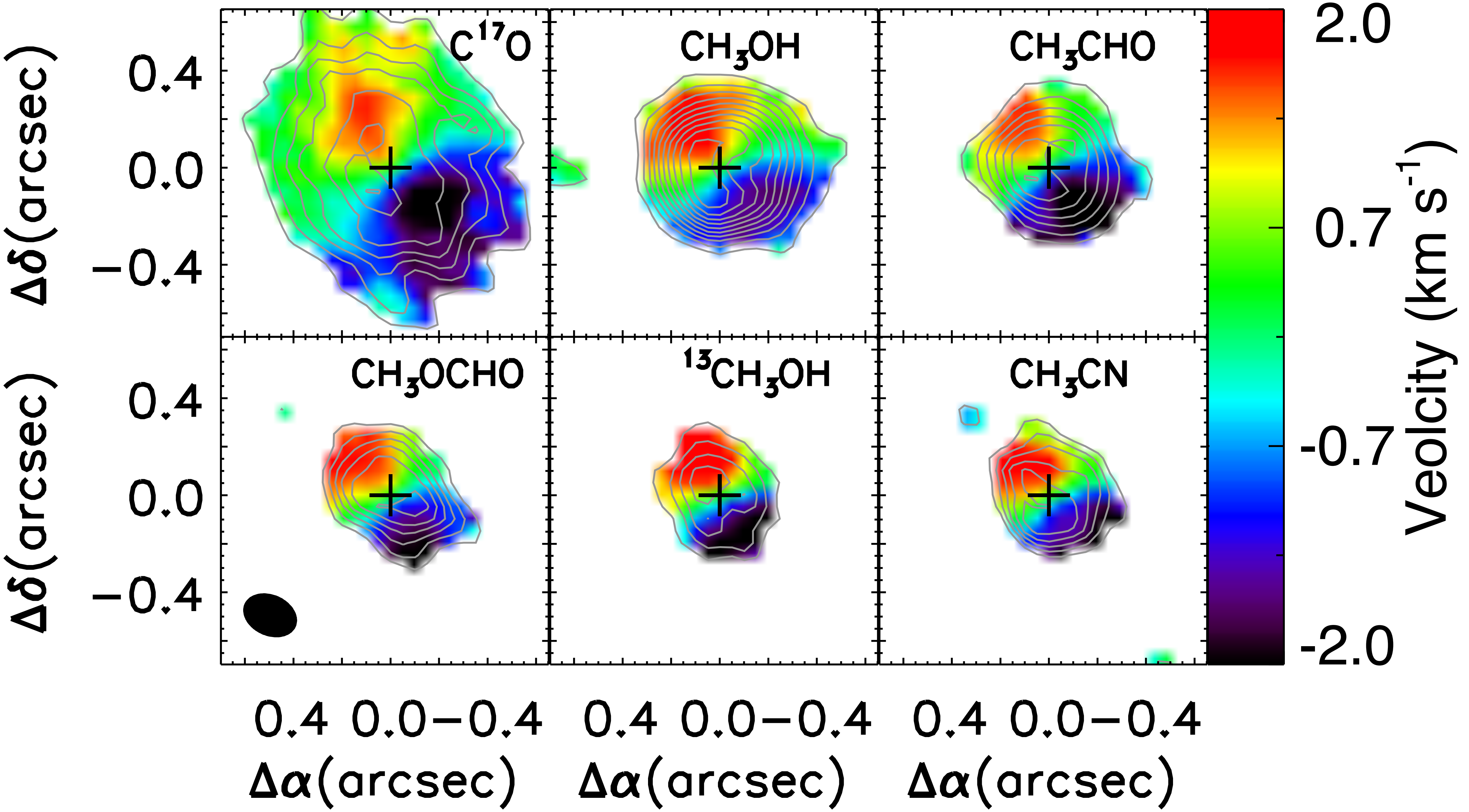


Favre et al. (2018)



- Outer cold disk region
- Produced by CO surface chemistry

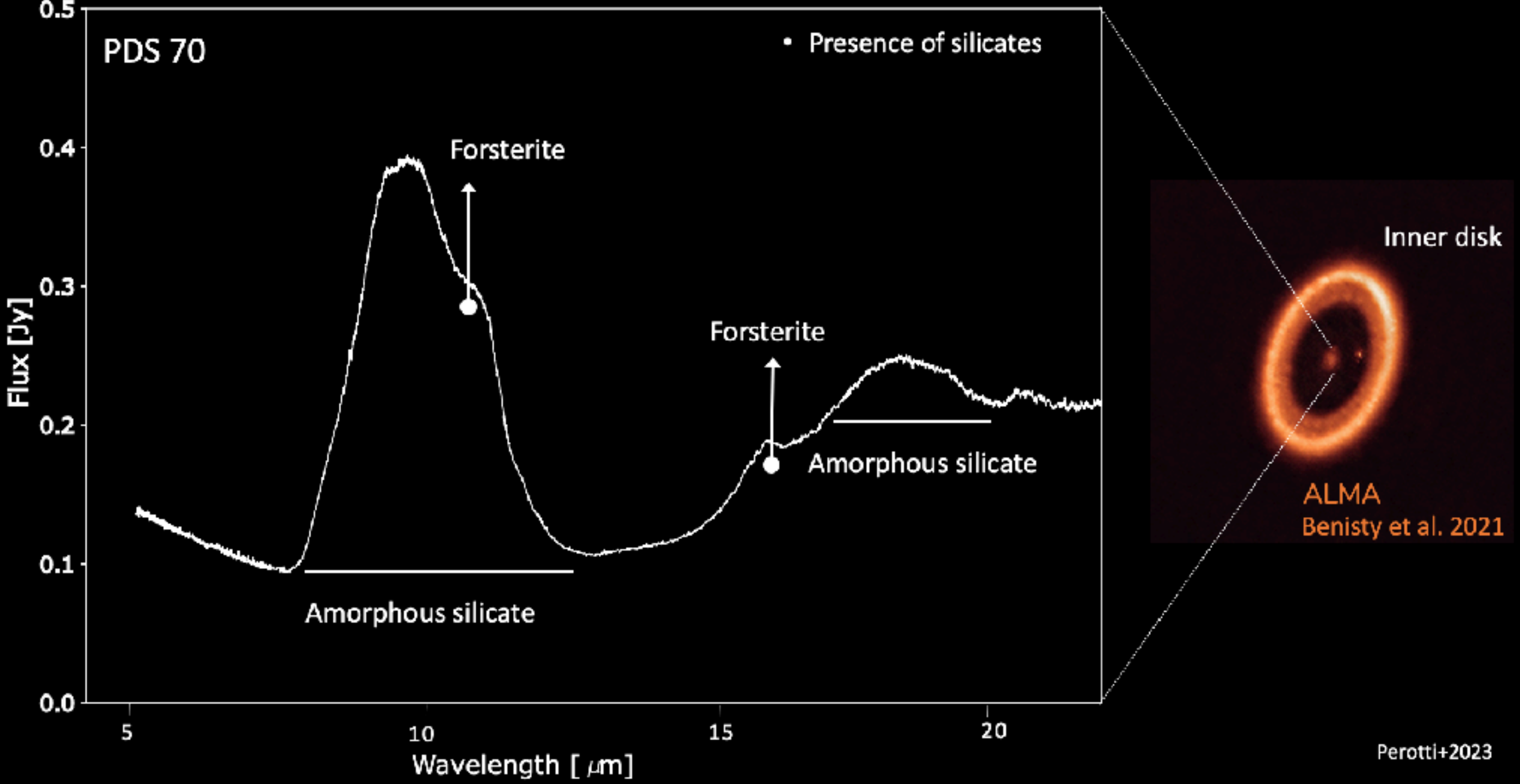
Organics in FU Ori systems: V883 Ori



van t'Hoff et al. (2018), Lee et al. (2019)

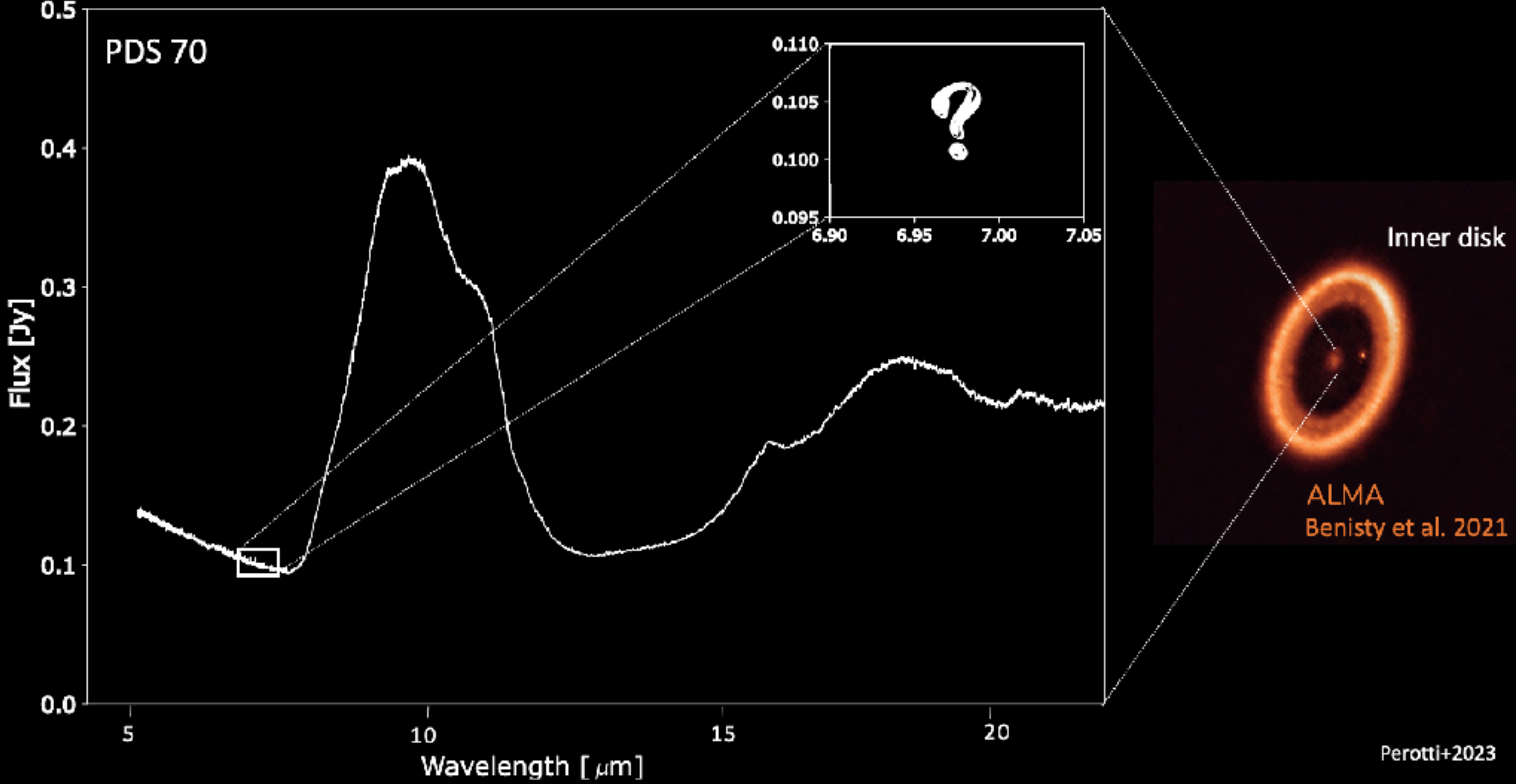
- Methanol, acetone, acetonitrile, acetaldehyde, and methyl formate
- Sublimated ices at the edge of the snowline (T>100 K)

PDS70 system: small, thermally processed dust grains



Perotti+2023

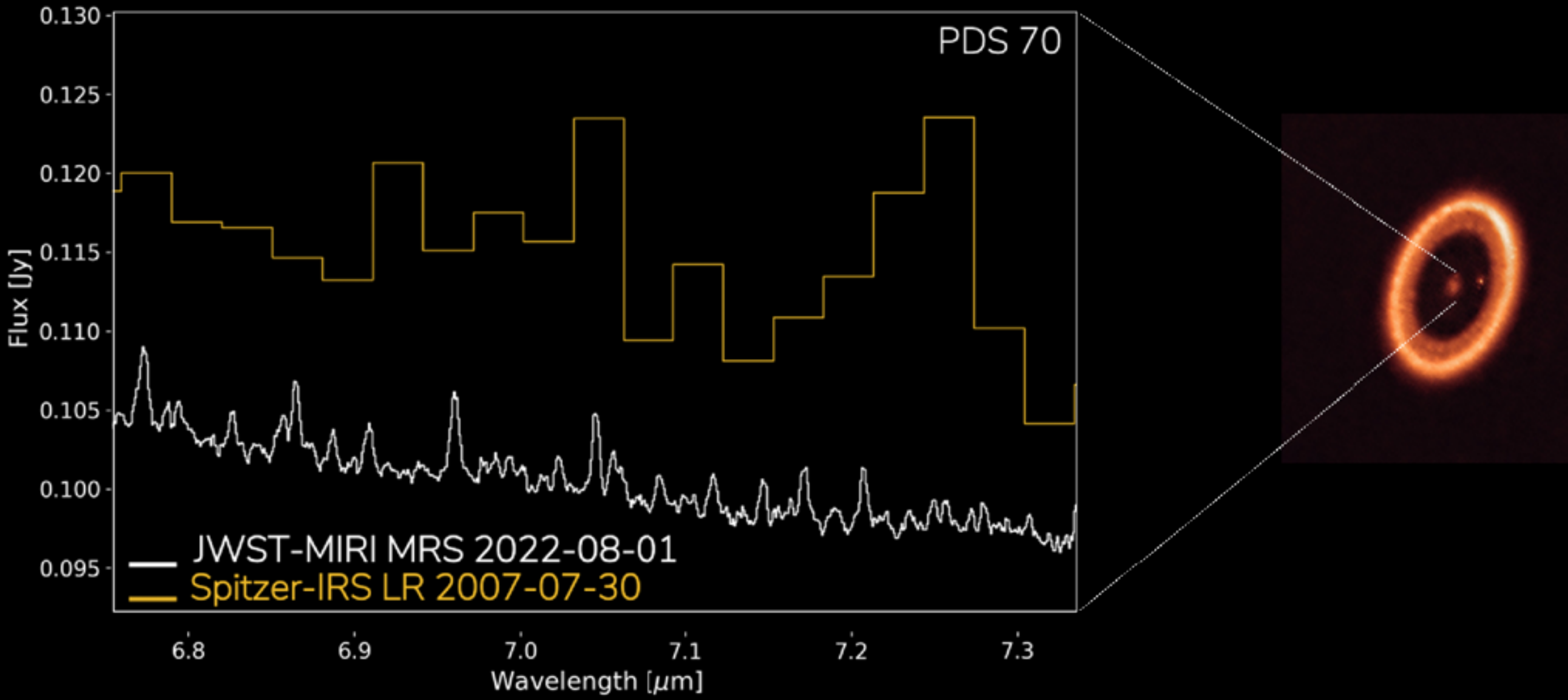
Zooming in…



Perotti+2023

Pre-JWST times

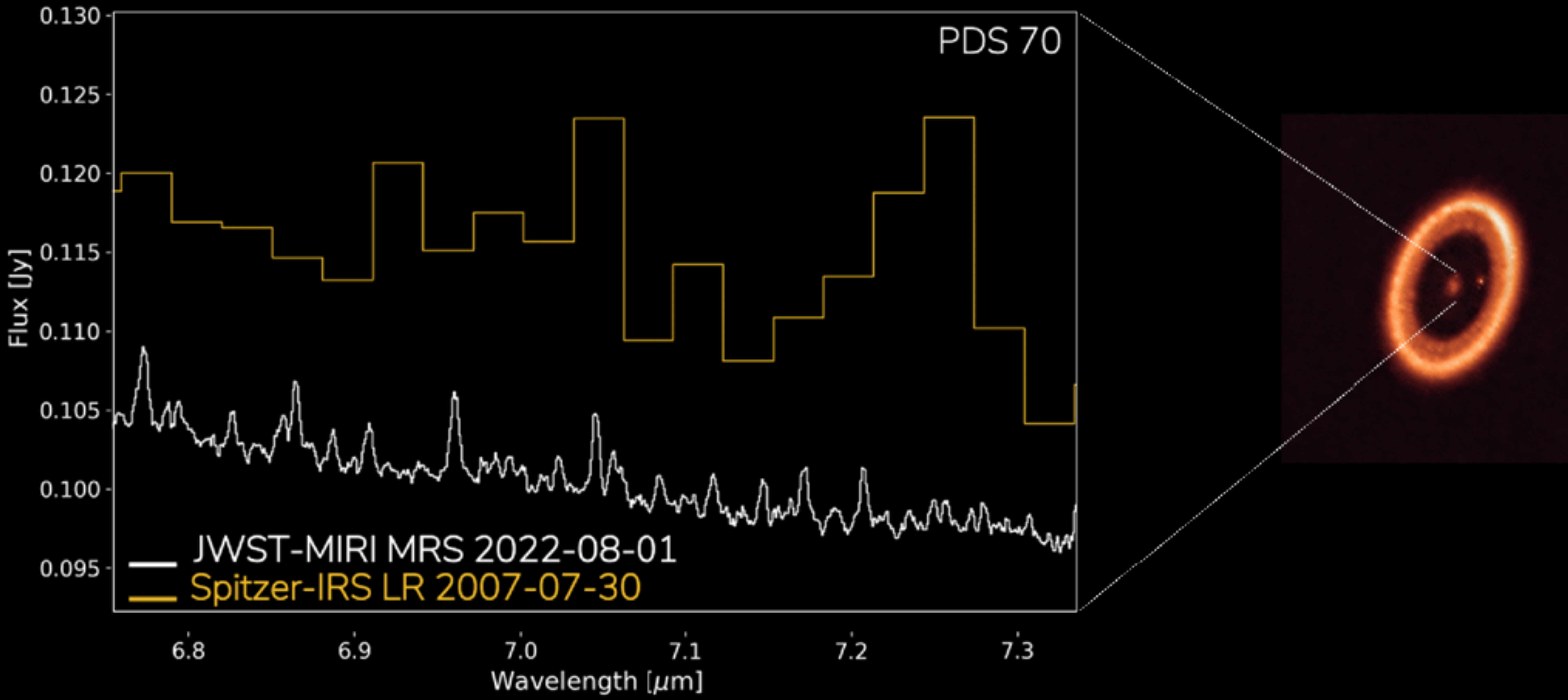
Spitzer: large bandwidth, low spectral resolving power ($R=\lambda/\Delta\lambda$)



Nascent Solar System
5.5 Myr old

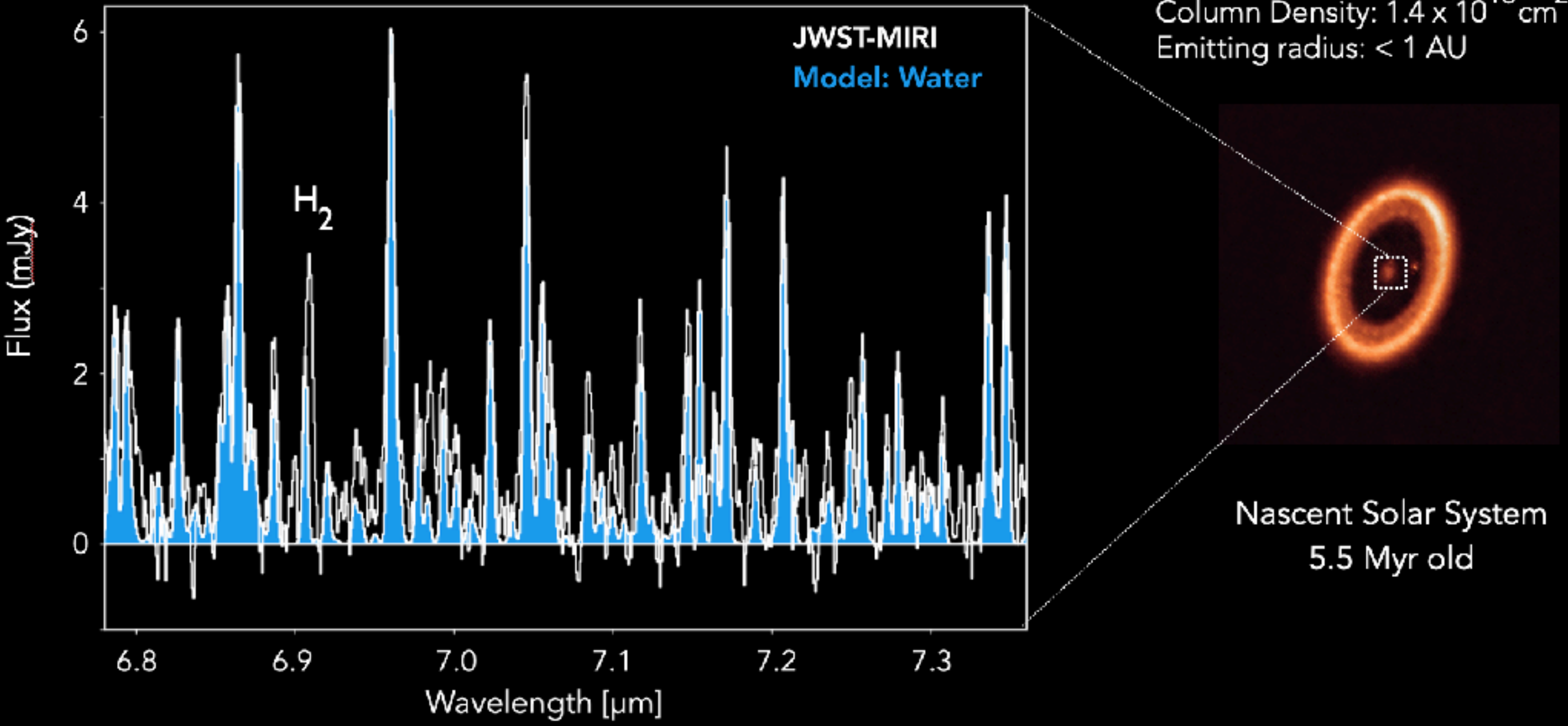
The JWST era

JWST enables high resolution spectroscopy at the birthplace of rocky planets



Nascent Solar System
5.5 Myr old

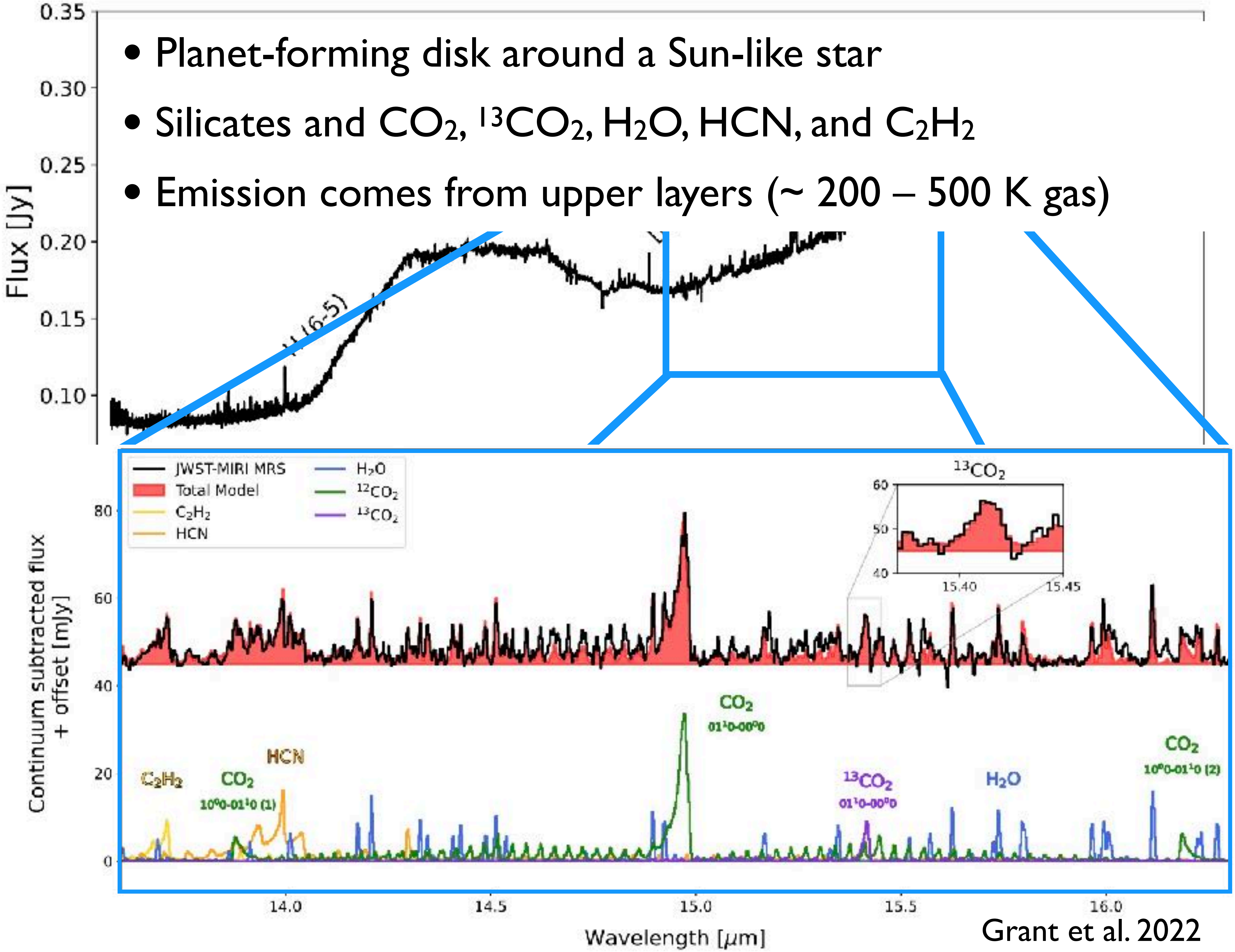
First water detection in a planet-hosting disk



Temperature: 600 K
Column Density: 1.4×10^{18} cm^{-2}
Emitting radius: < 1 AU

Nascent Solar System
5.5 Myr old

JWST: GW Lup



- Planet-forming disk around a Sun-like star
- Silicates and CO_2, $^{13}CO_2$, H_2O, HCN, and C_2H_2
- Emission comes from upper layers (~ 200 – 500 K gas)

Grant et al. 2022

Conclusions

- Planet-forming environments
- Vertical and radial gradients of T and n_H
- Layered chemistry
- Spatially-resolved with radio-interferometers
- Statistically significant surveys of dust and gas emission
- ALMA and JWST are fantastic!

Suggested literature

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- Dutrey, A. et al. (2014), Protostars & Planets VI, 317
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