Planet-forming disks across wavelength

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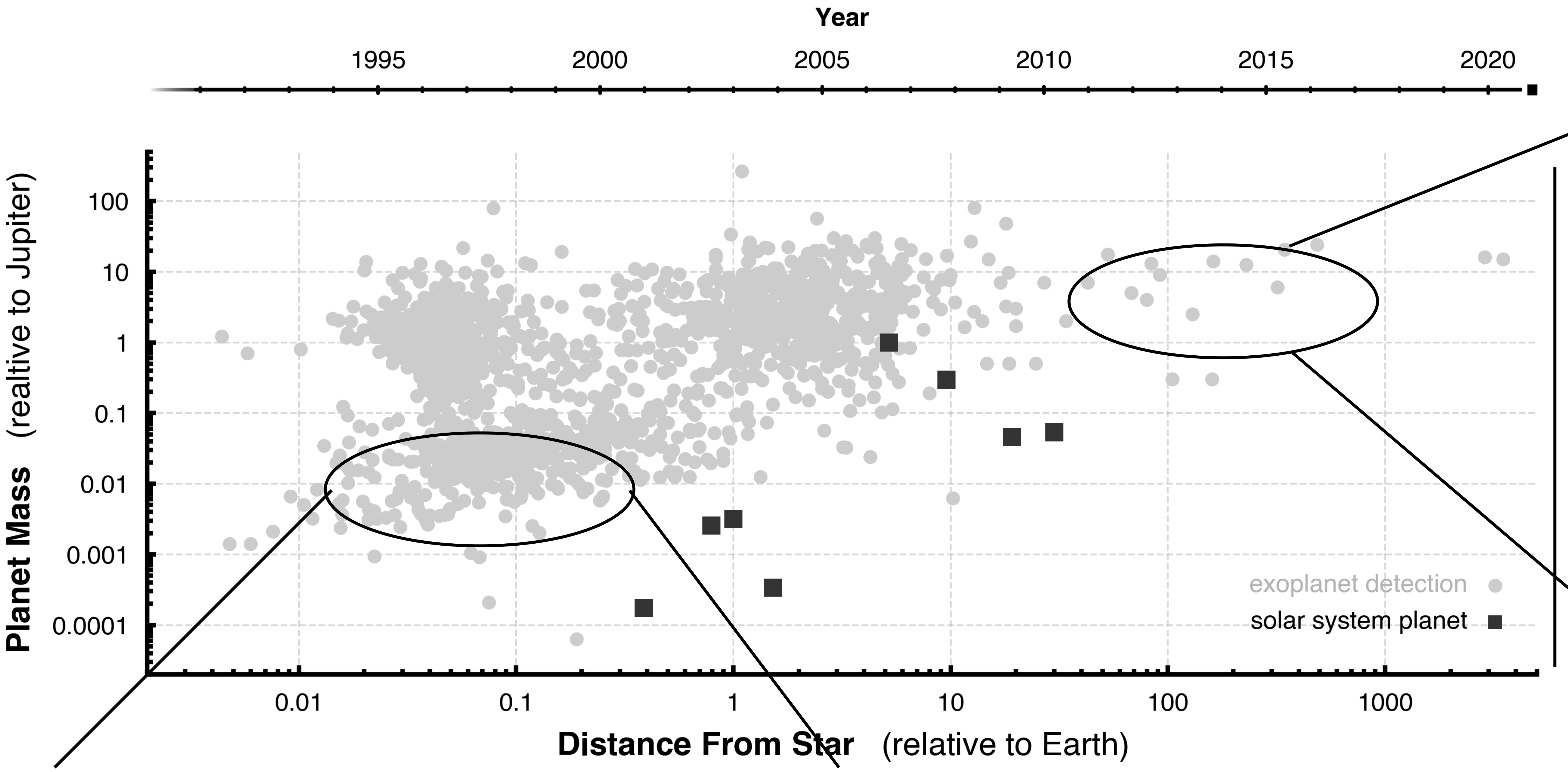
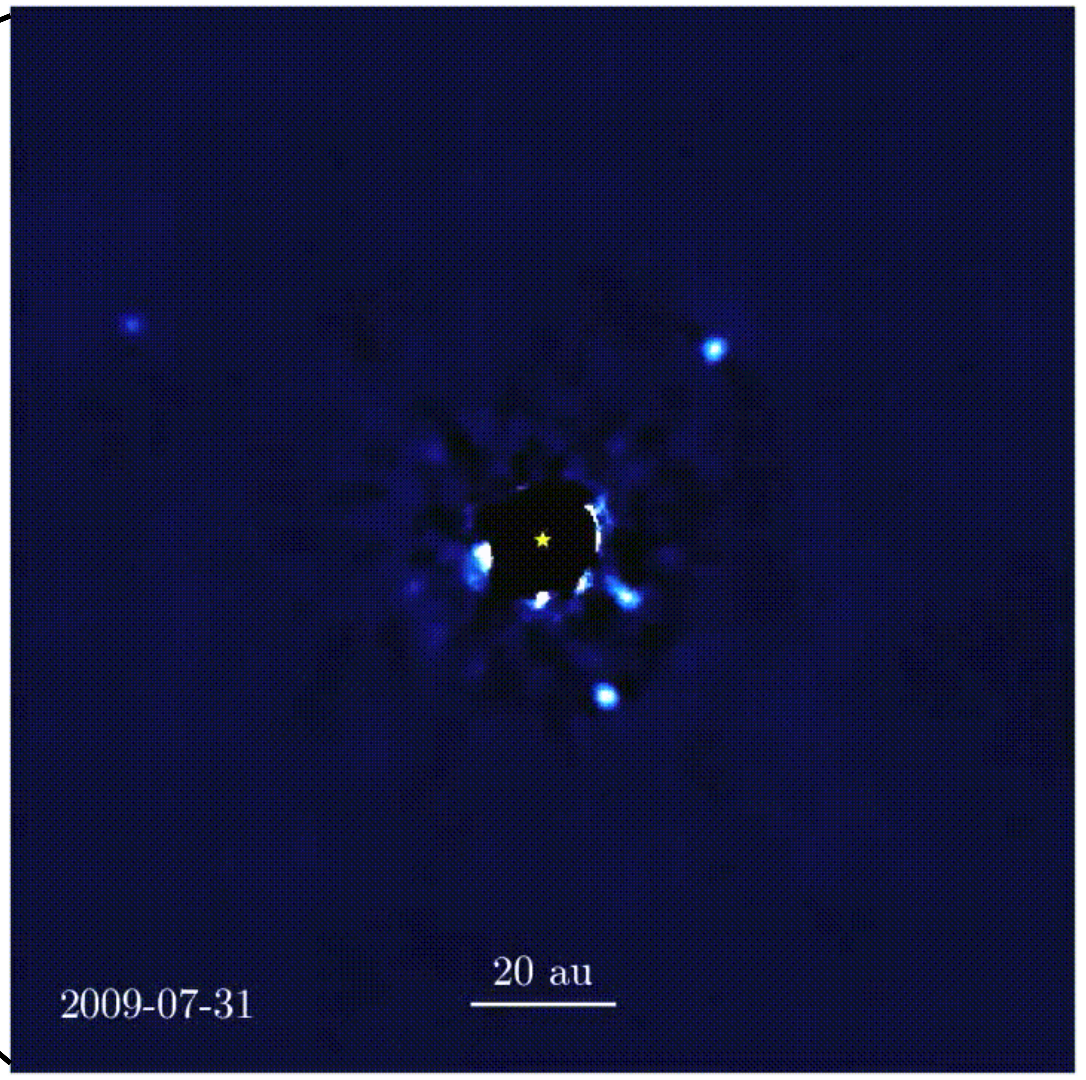
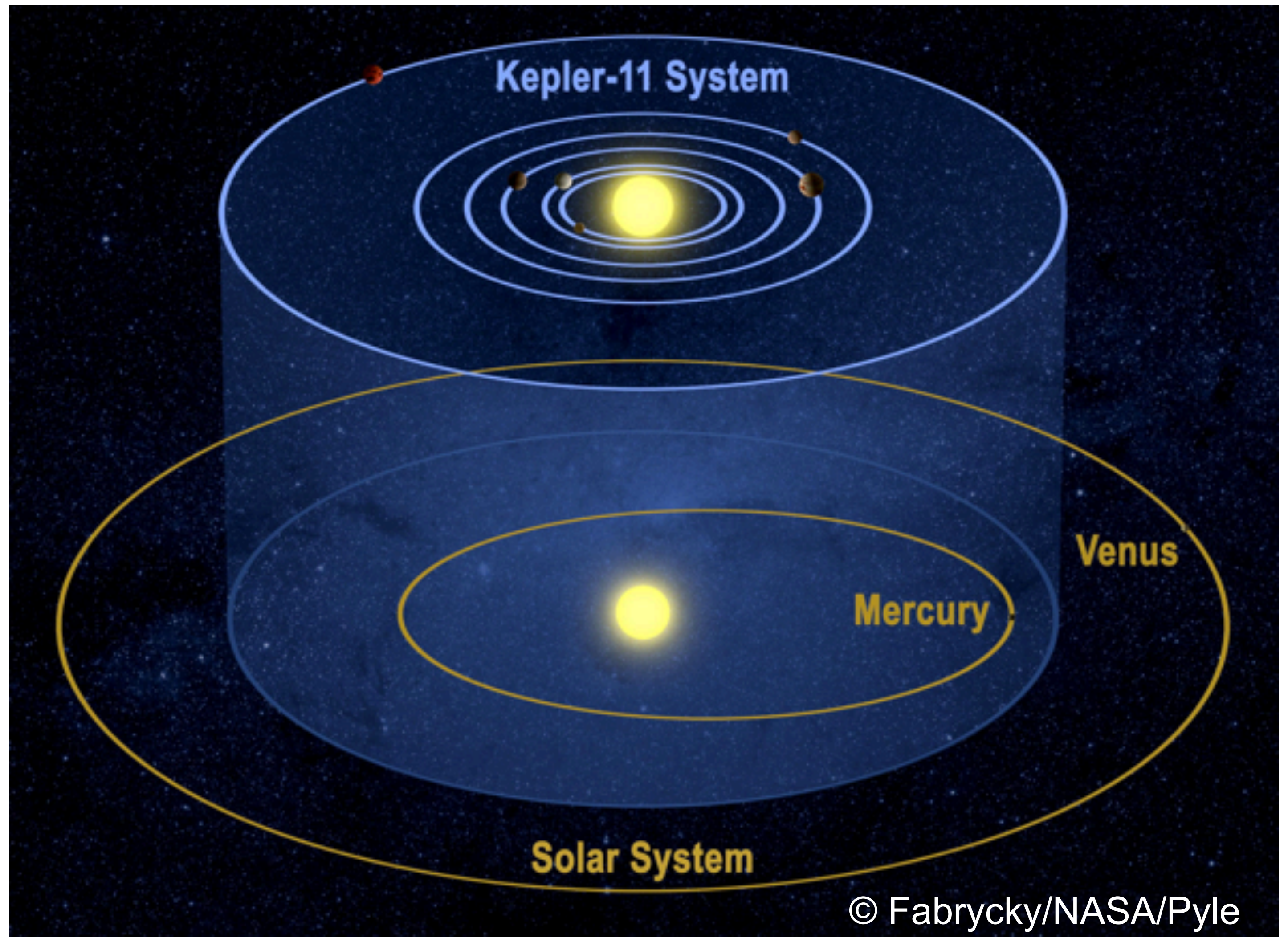
Max Planck Institute for Astronomy

Future Role of FIR-Submm Space Observations - Leiden

Exoplanetary systems are diverse



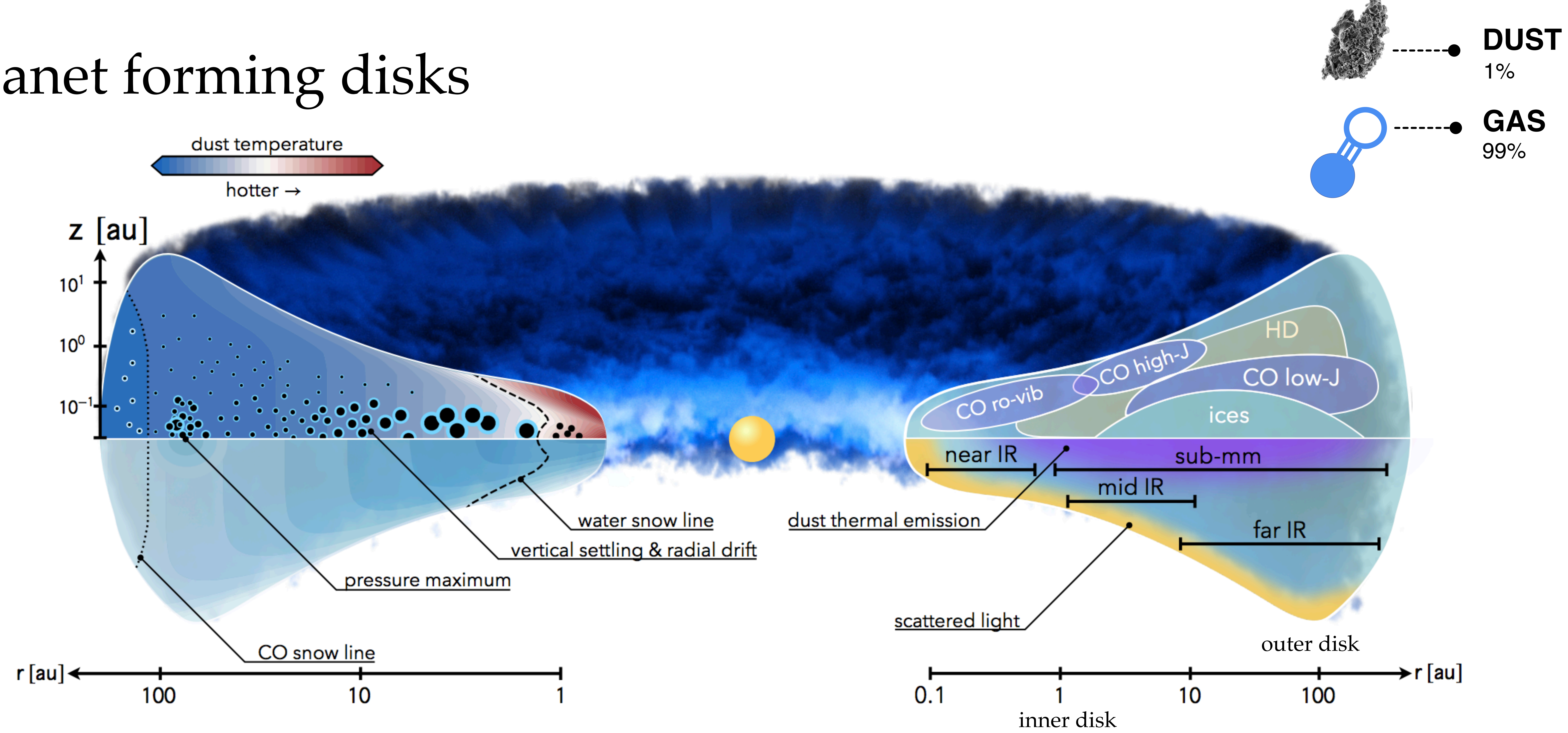




Origin of the diversity?

How much is set at birth?

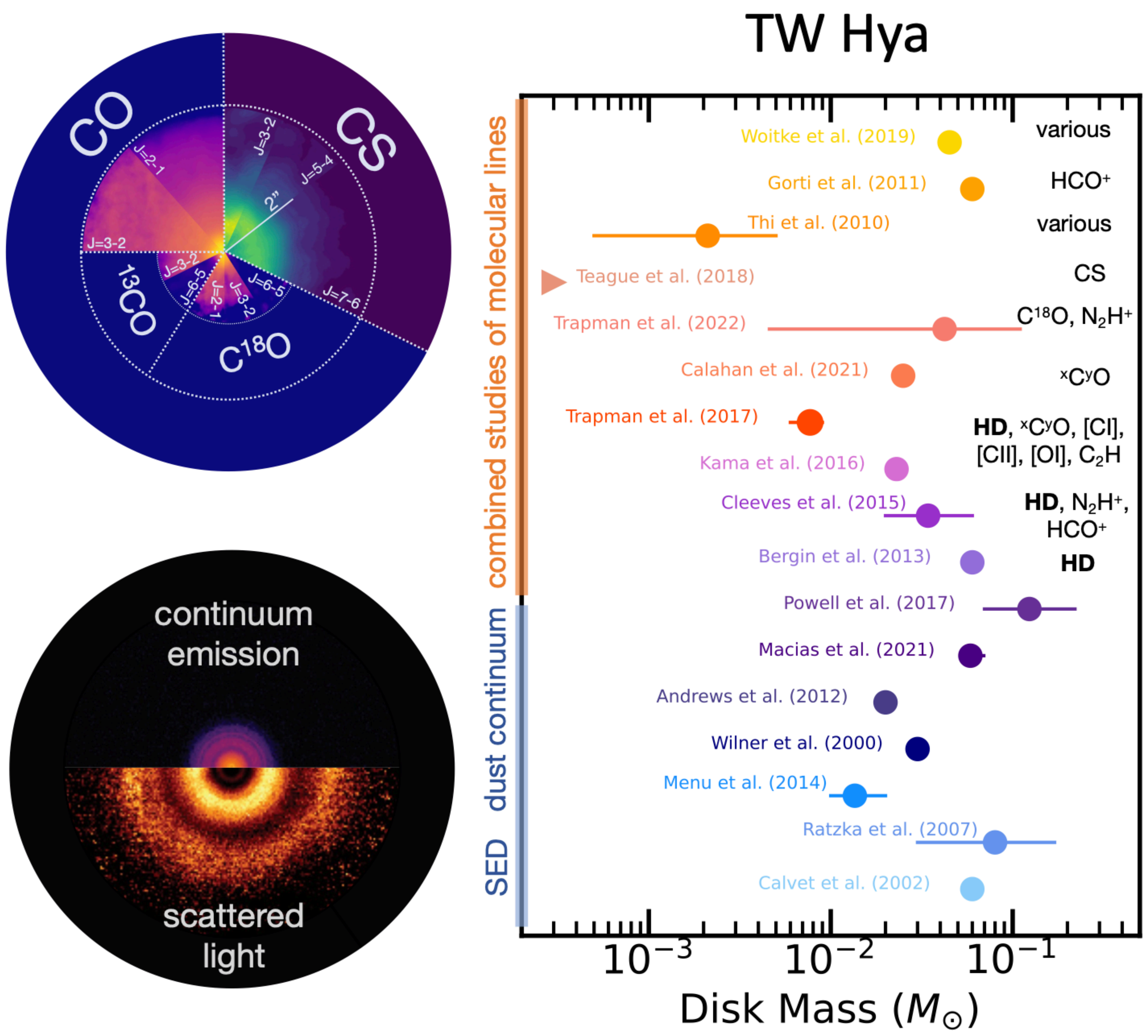
Planet forming disks



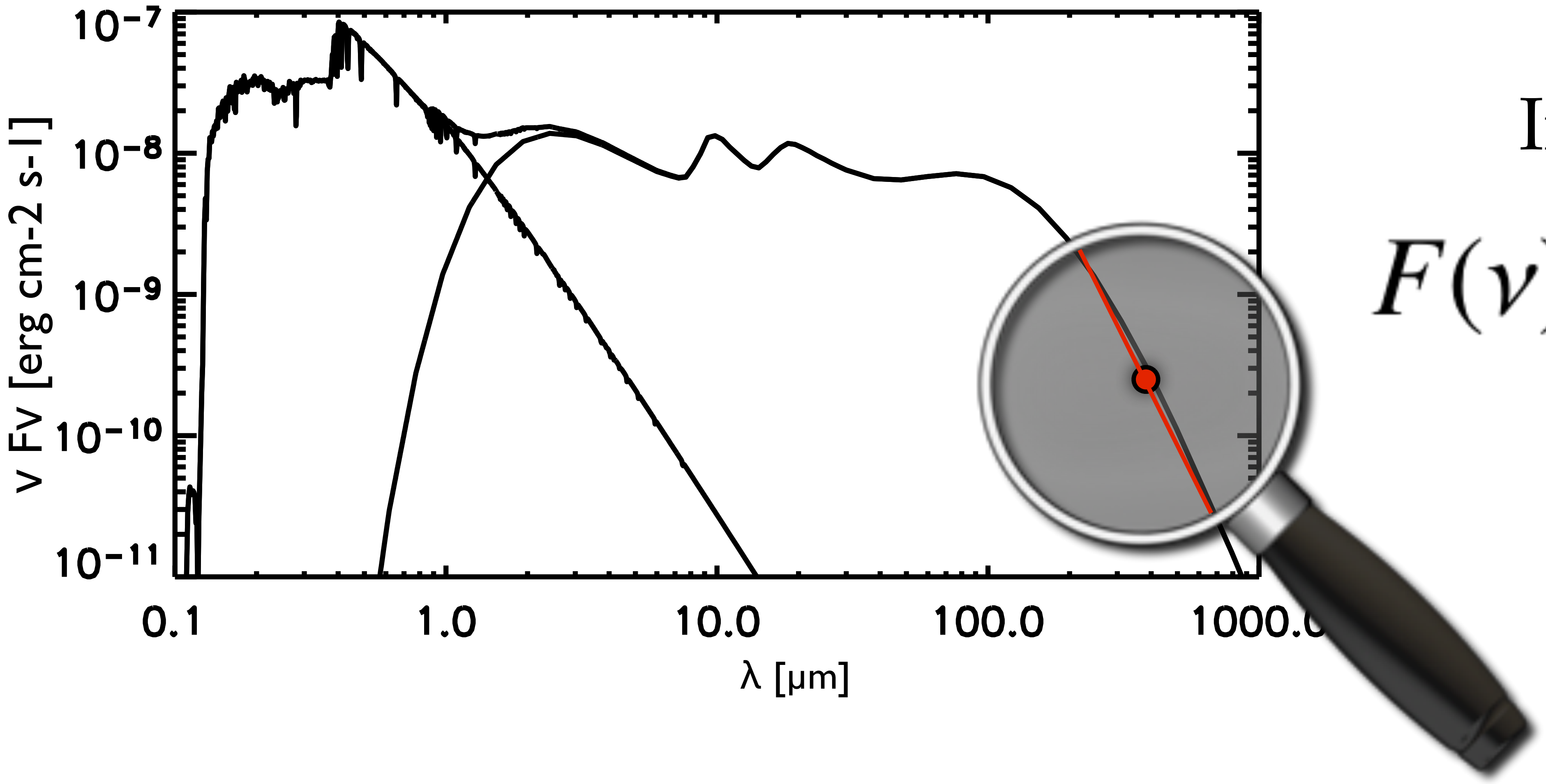
Miotello et al. 2023

Need to probe the disk physical/chemical conditions and disk structure *while* planets are forming

Interlude - Disk mass problem

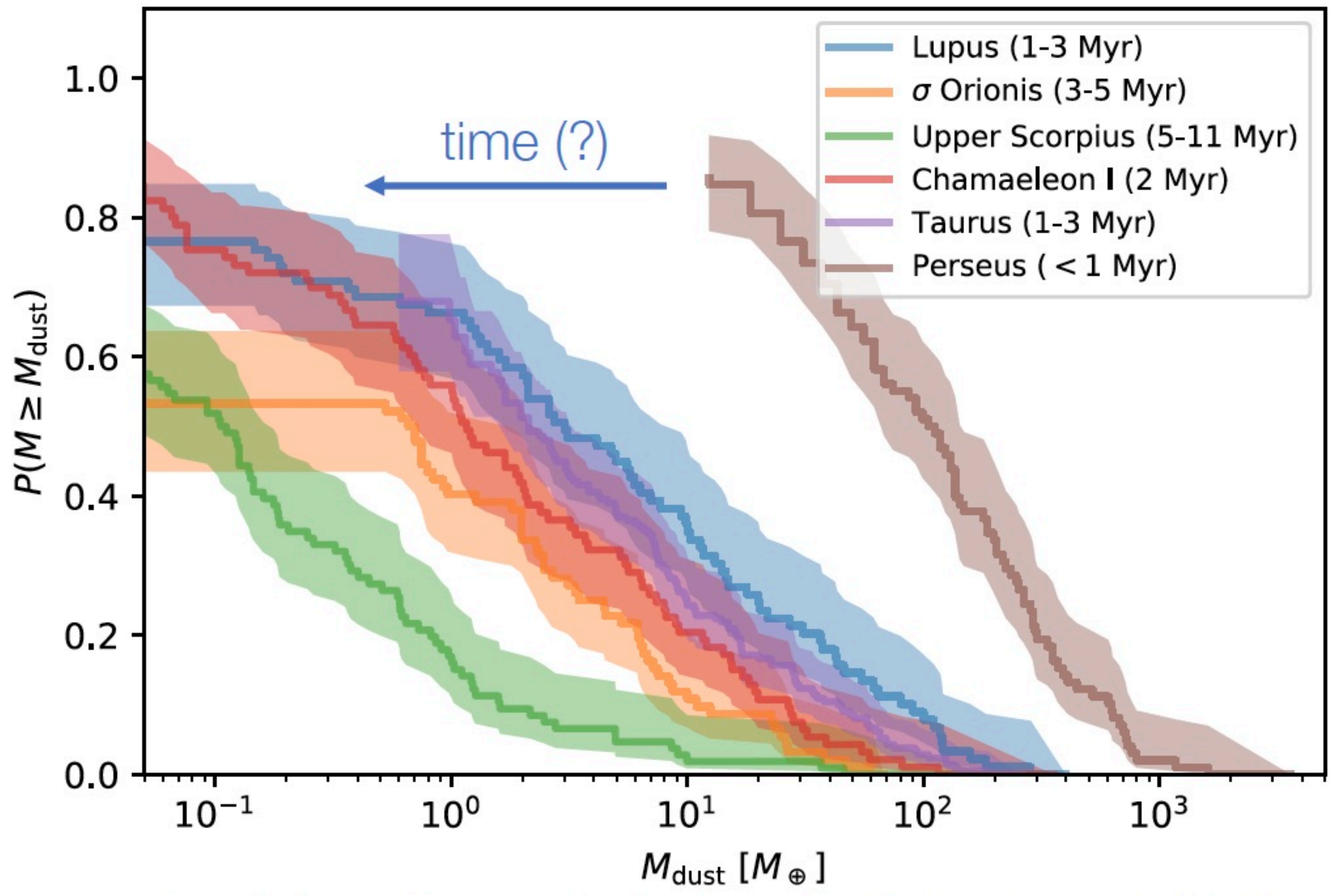


Disk mass problem: dust

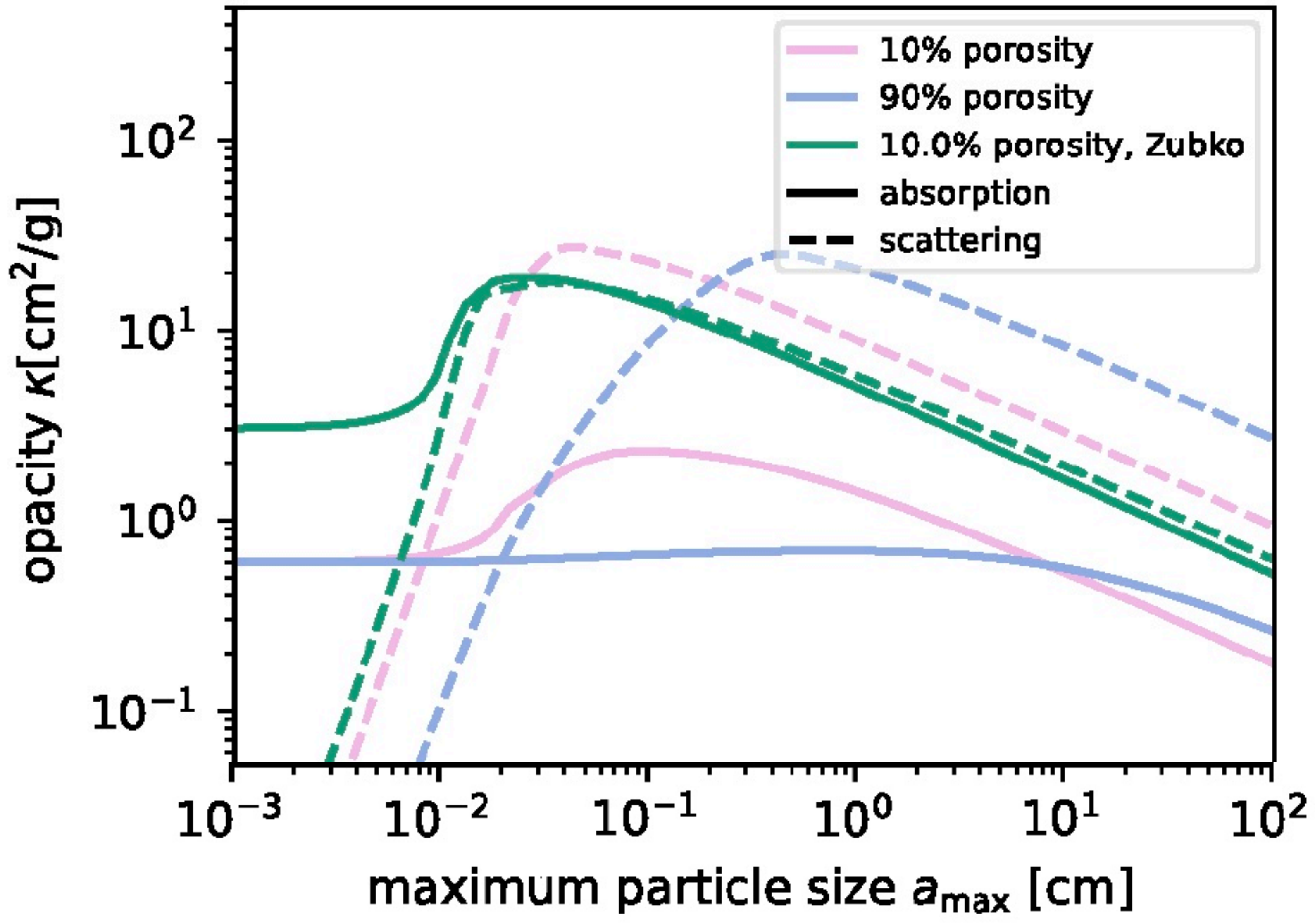


In the optically *thin* regime

$$F(\nu) \propto M_{\rm dust} \cdot B_\nu(T) \cdot \kappa(\nu)$$



Tychionec et al. 2018; Miotello et al. 2023

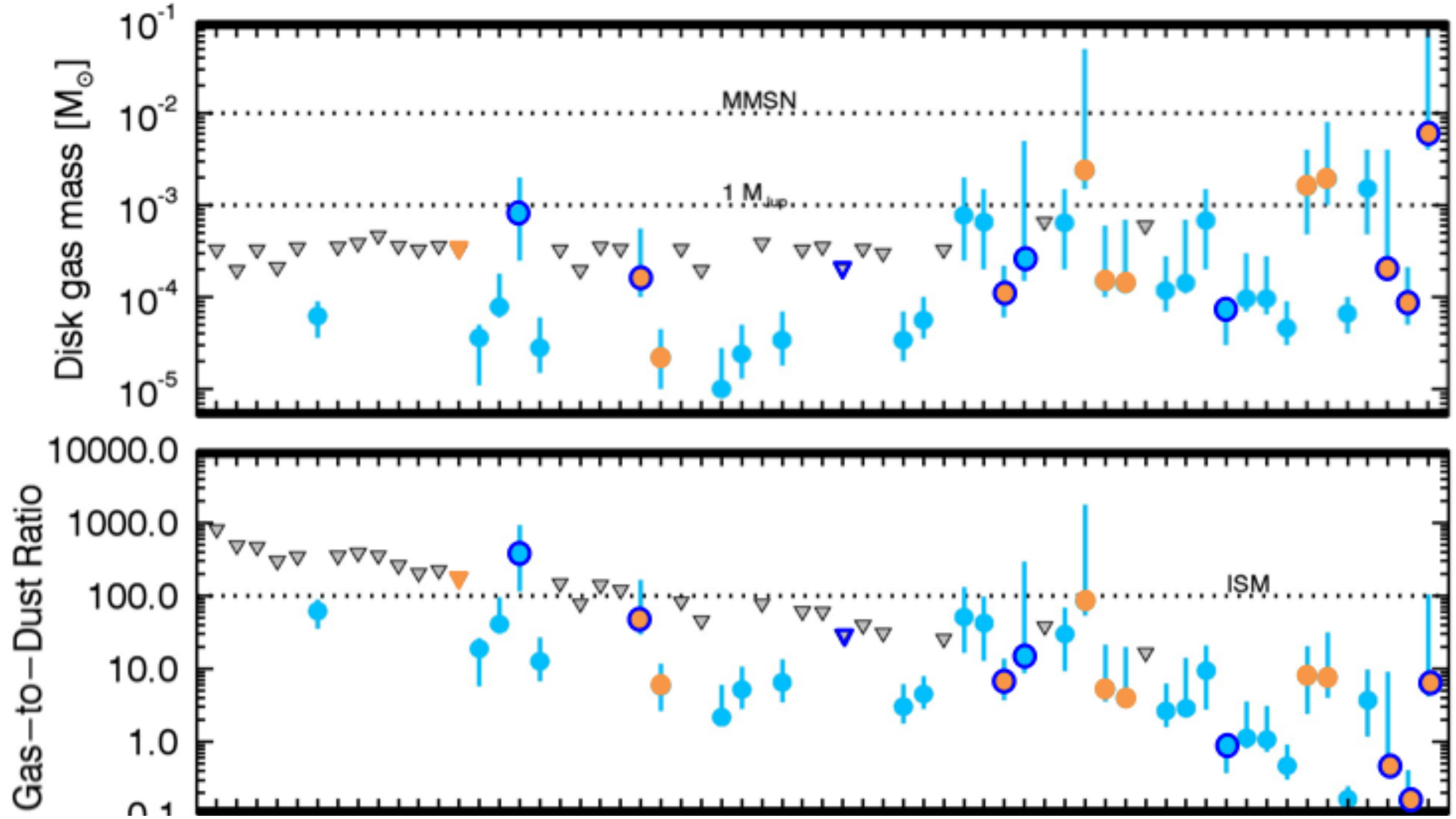


But opacities are unknown!

Disk mass problem: gas

©Miotello

- H_2 has no permanent electric dipole moment
- Use CO optically thin lines to trace the bulk disk mass
- But : can't distinguish disk evolution from chemical evolution (C depletion)



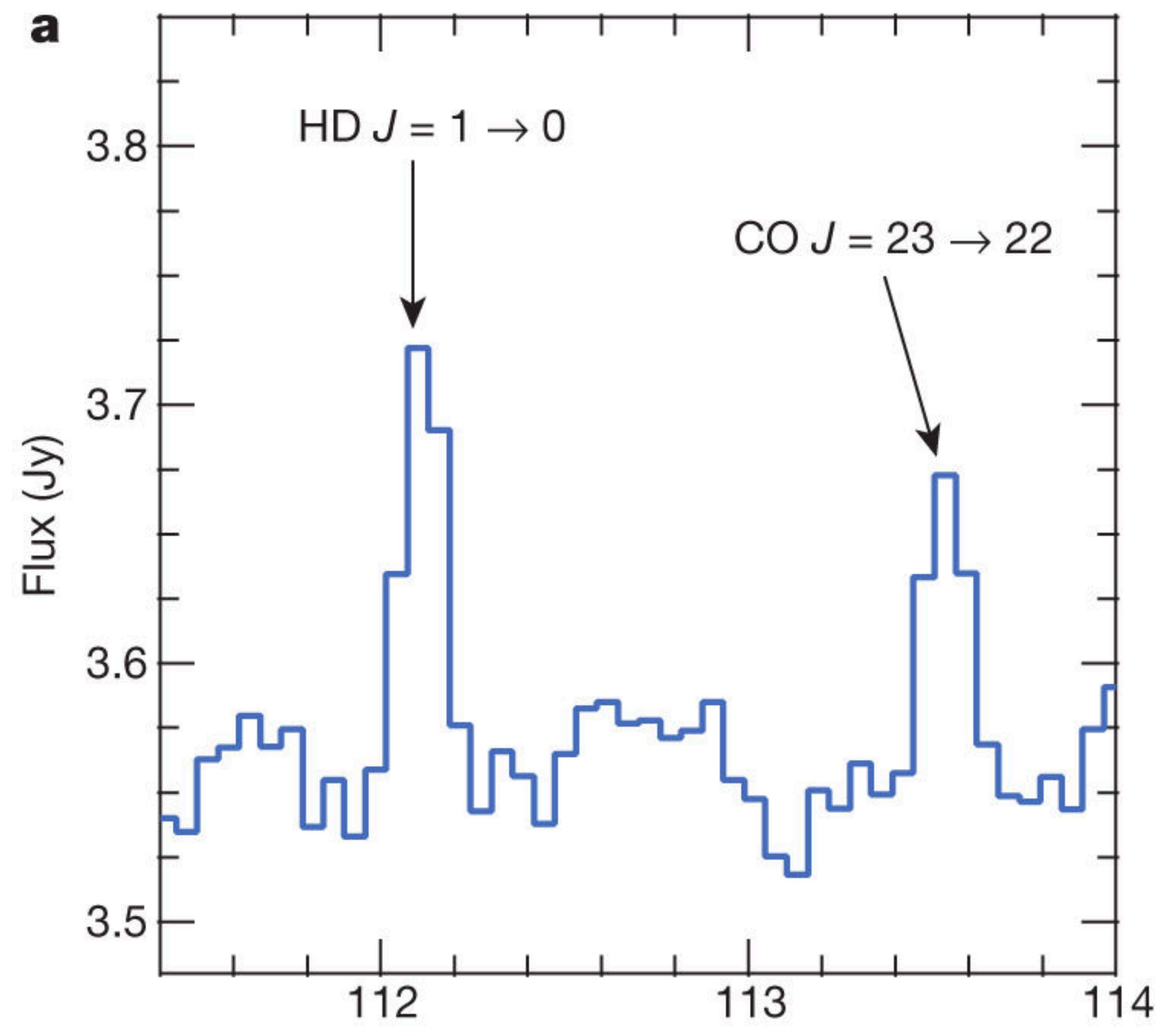
Miotello et al. 2017

Disk mass solution: HD

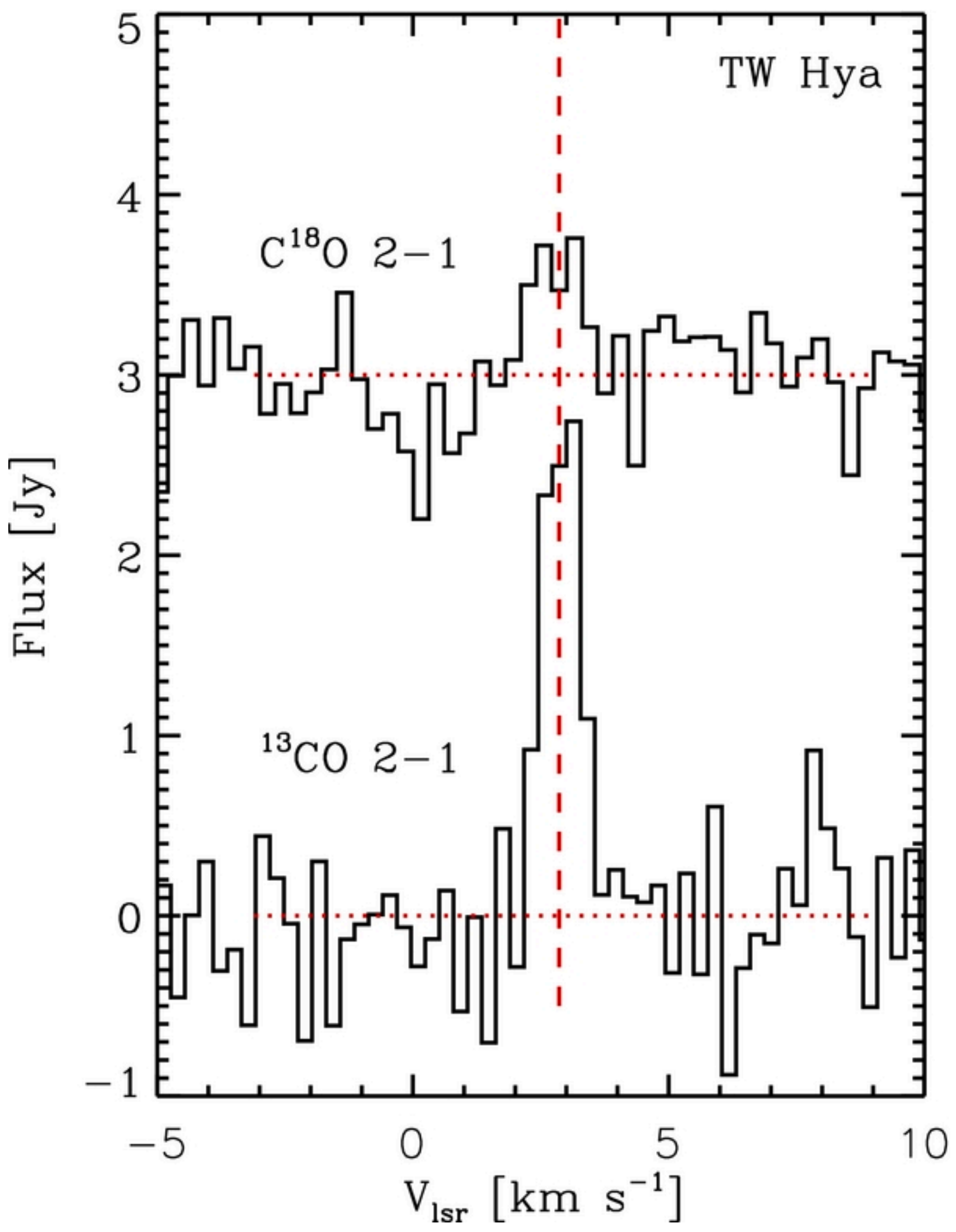
- Less abundance isotopologue of H_2
- Rotational transition detectable in the FIR

$M_{HD} = 100 \times M_{CO}$

Bergin et al., 2013



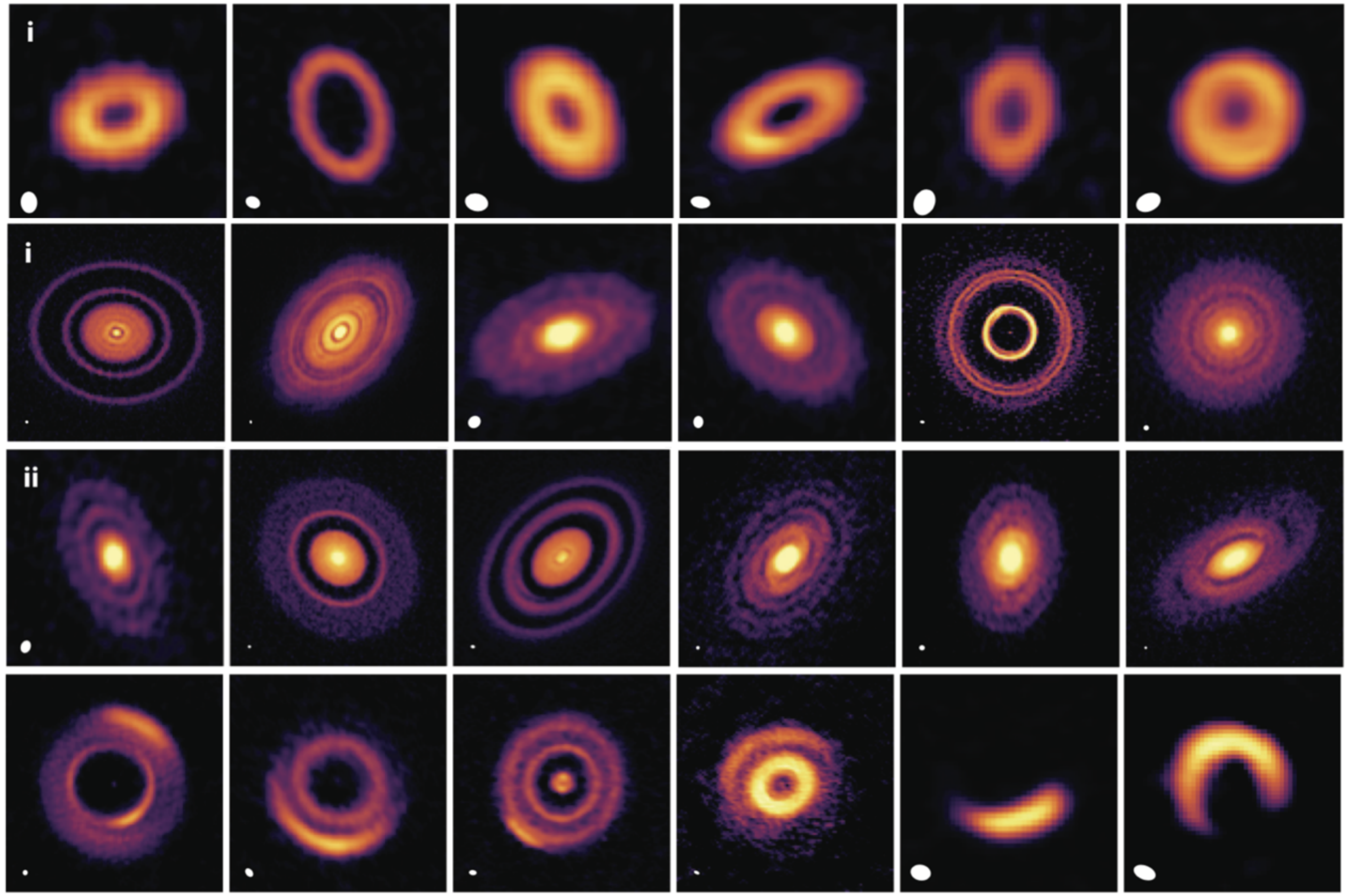
Favre et al., 2013



Only 3 detections so far! We need many more disk mass measurements

Bergin et al. 2013; McClure et al. 2016; Miotello et al. 2023

Substructures (mm grains, midplane)

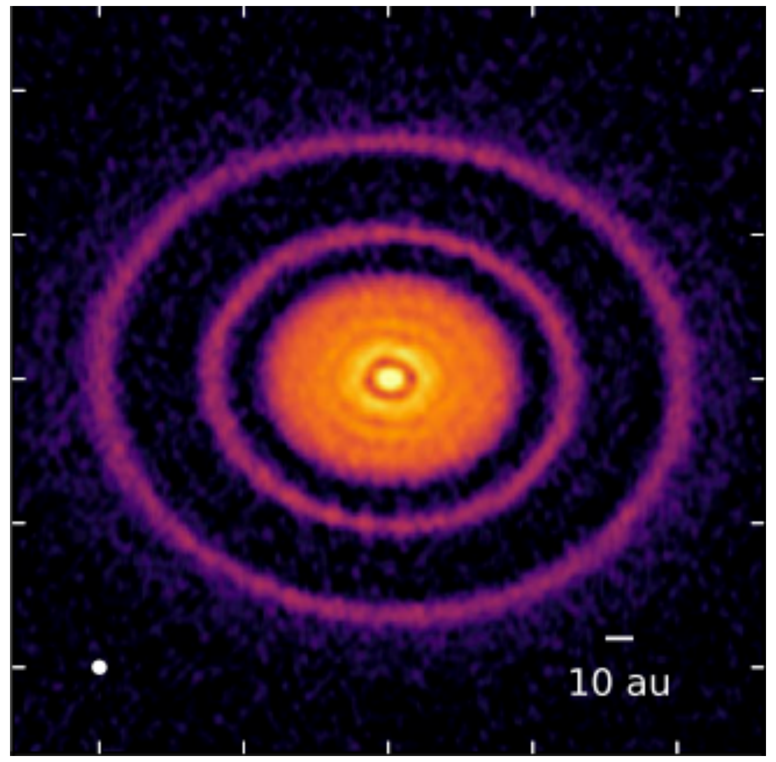


Andrews 2020

Inner cavities, ***gaps/rings***, asymmetries, and spirals are frequently detected in high-resolution mm maps

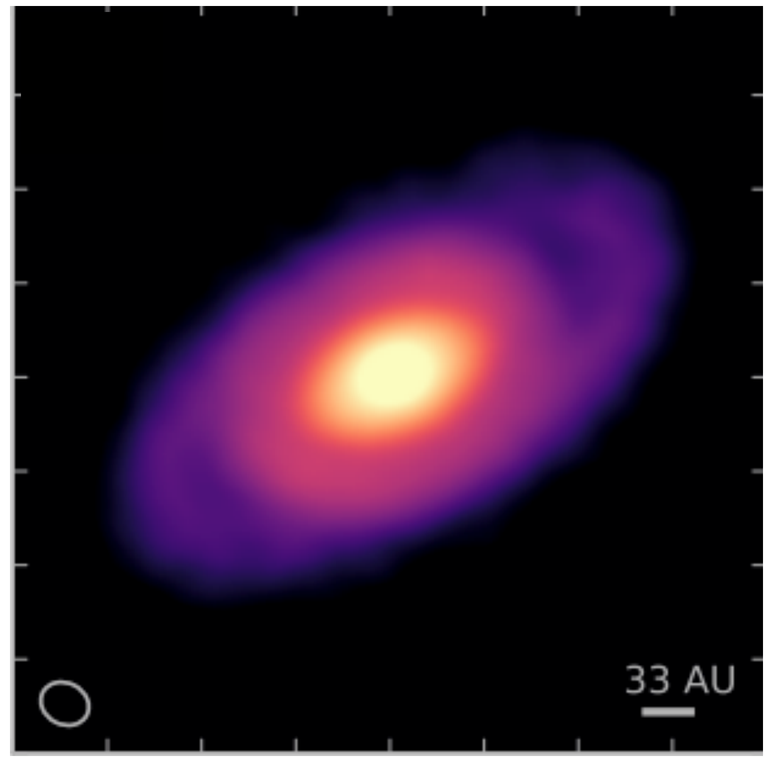
Possible *indirect* signatures of companions

Rings



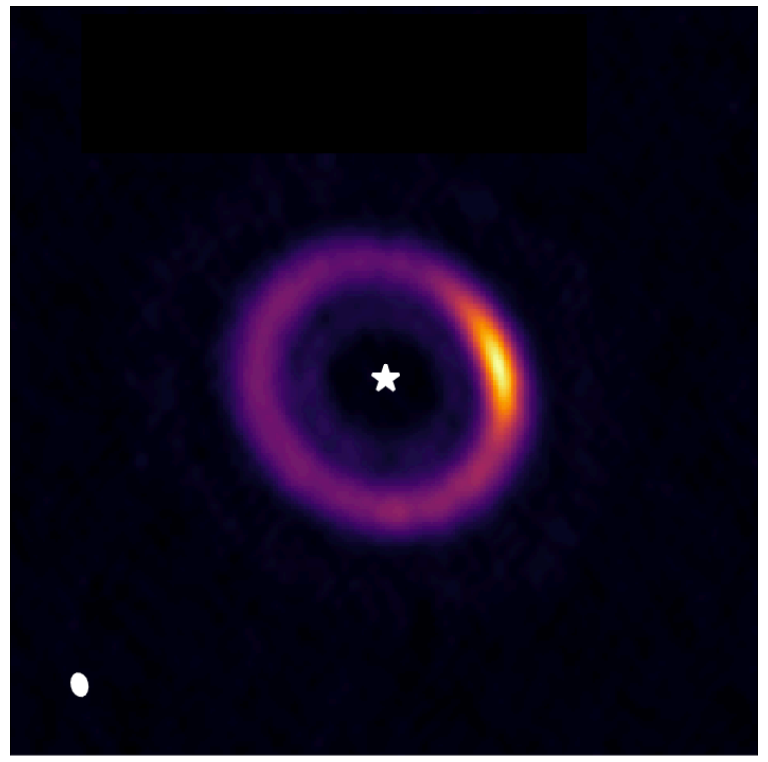
Guzman et al. 2018

Spirals



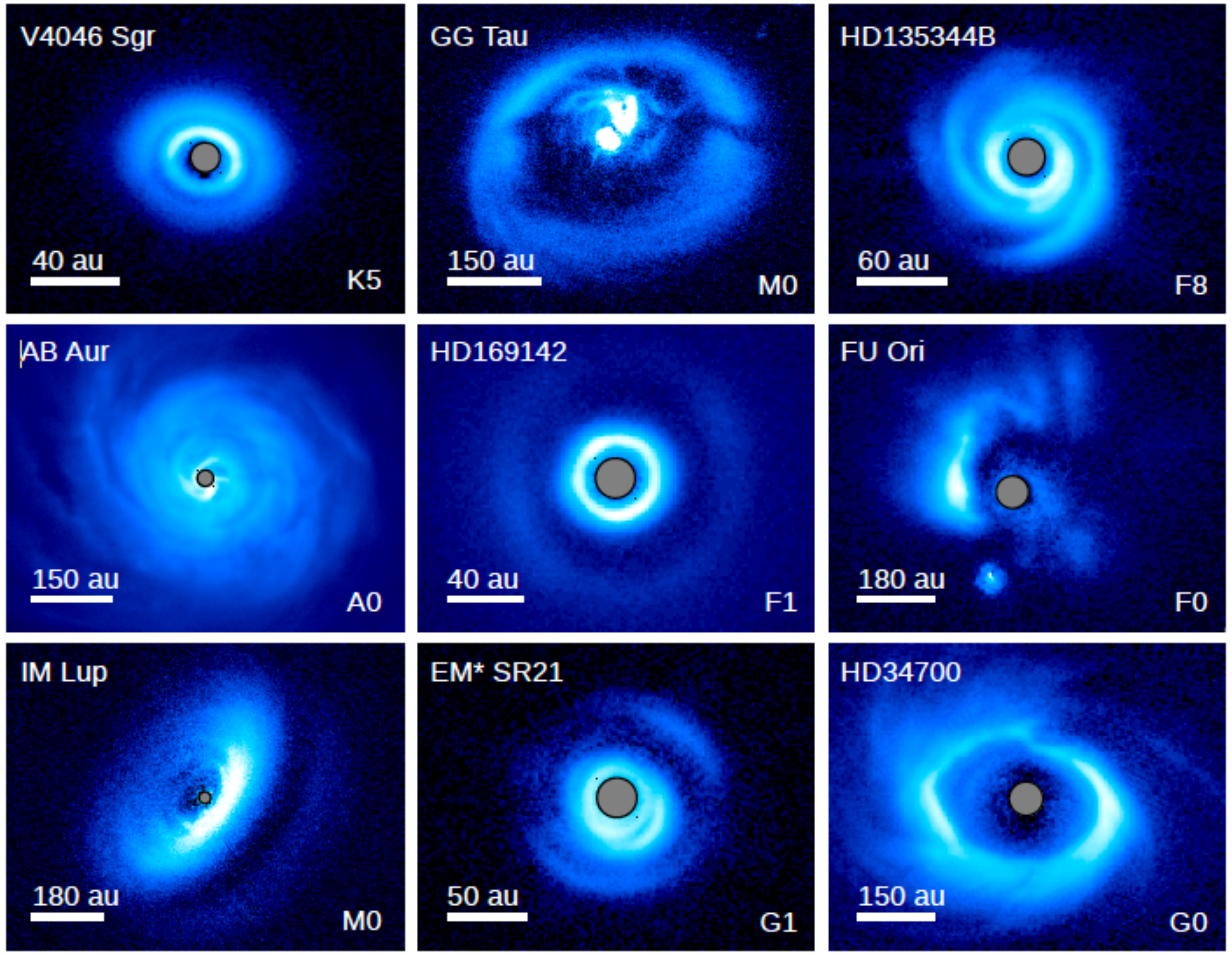
Perez et al. 2016

Asymmetries



Pinilla et al. 2022

Substructures (small dust, surface)

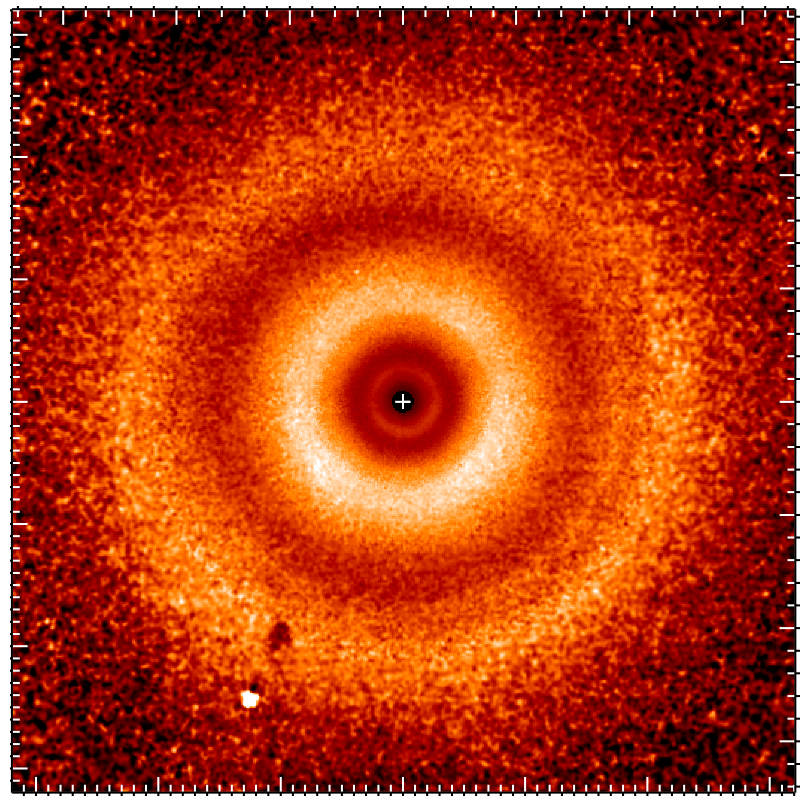


Benisty et al. PPVII

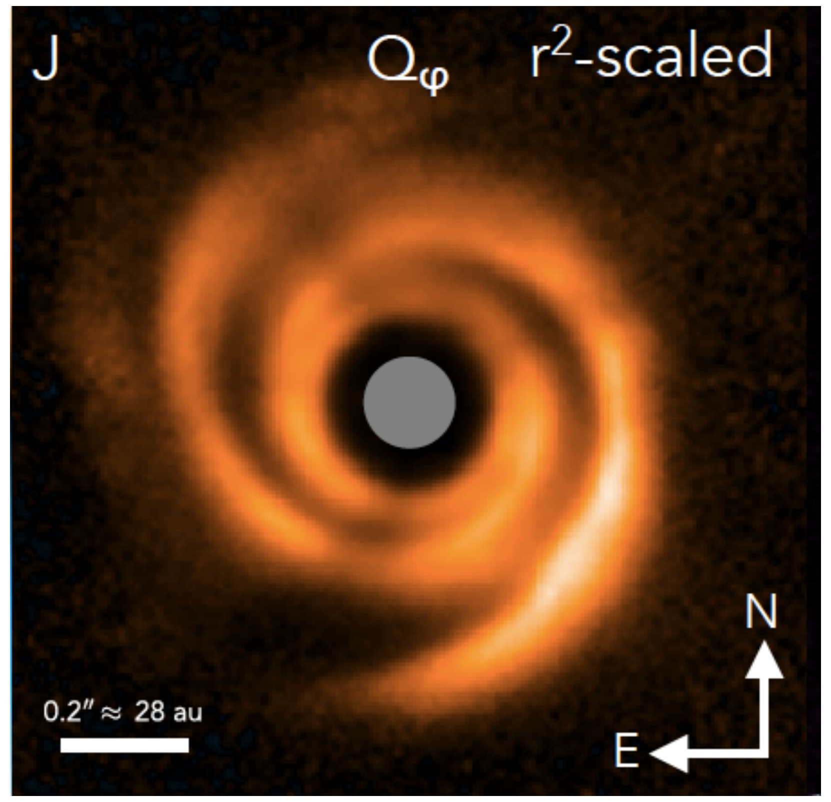
Rings, spirals, asymmetries, shadows are very frequent in scattered light, and **seen at all spectral type in IR-*bright* disks**

Possible *indirect* signatures of companions.

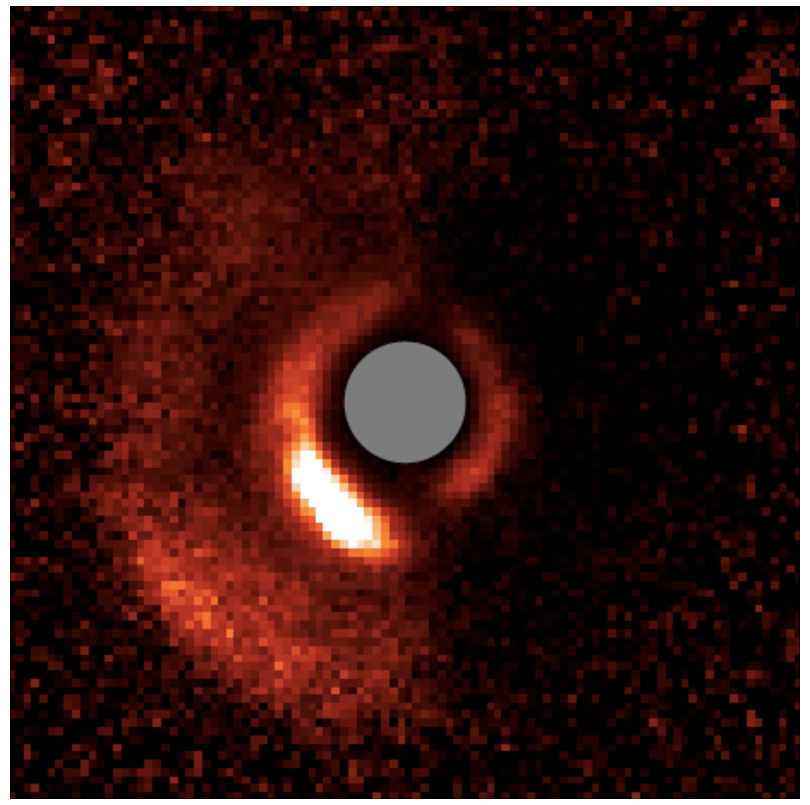
Rings



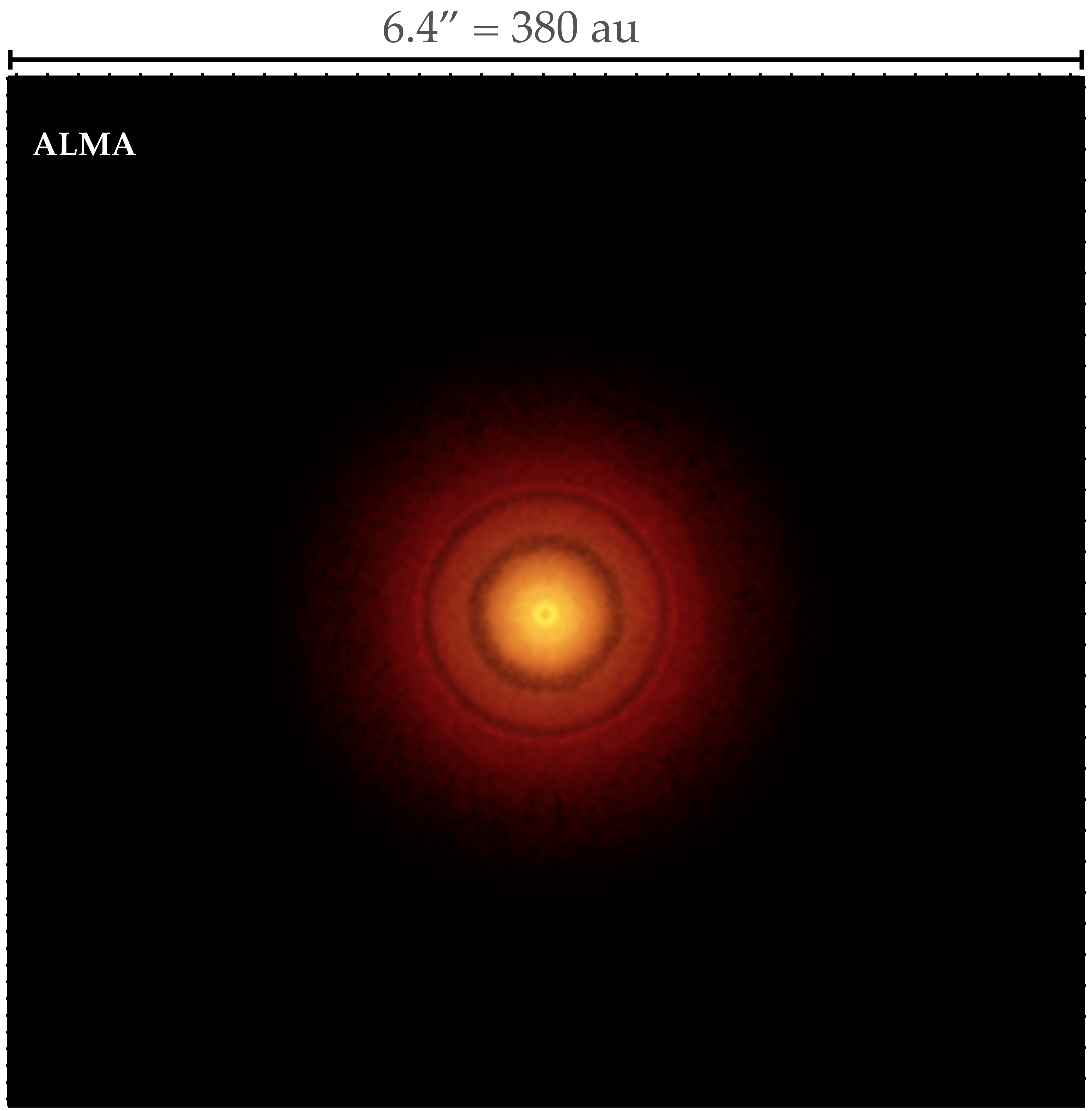
Spirals



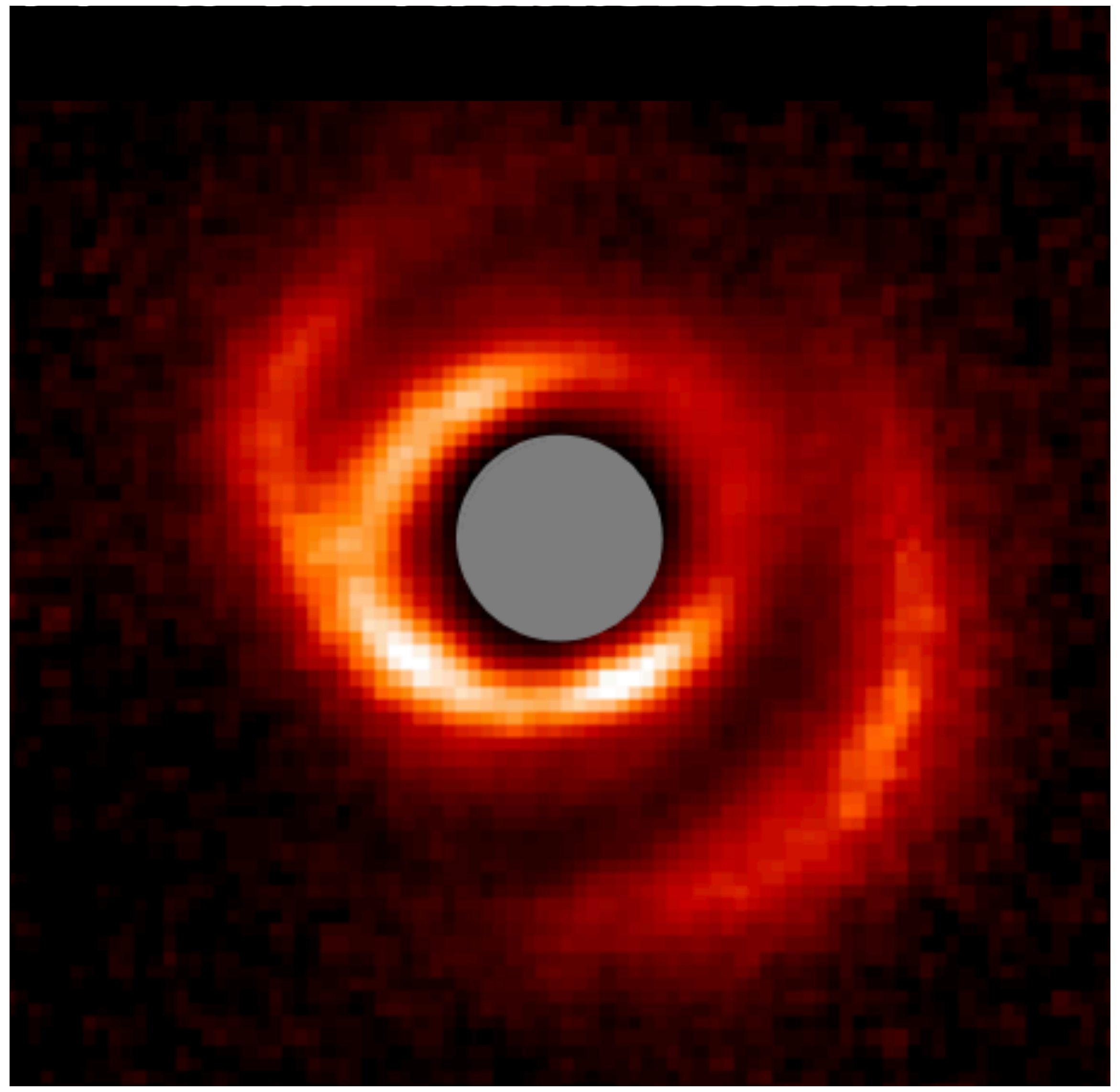
Shadows

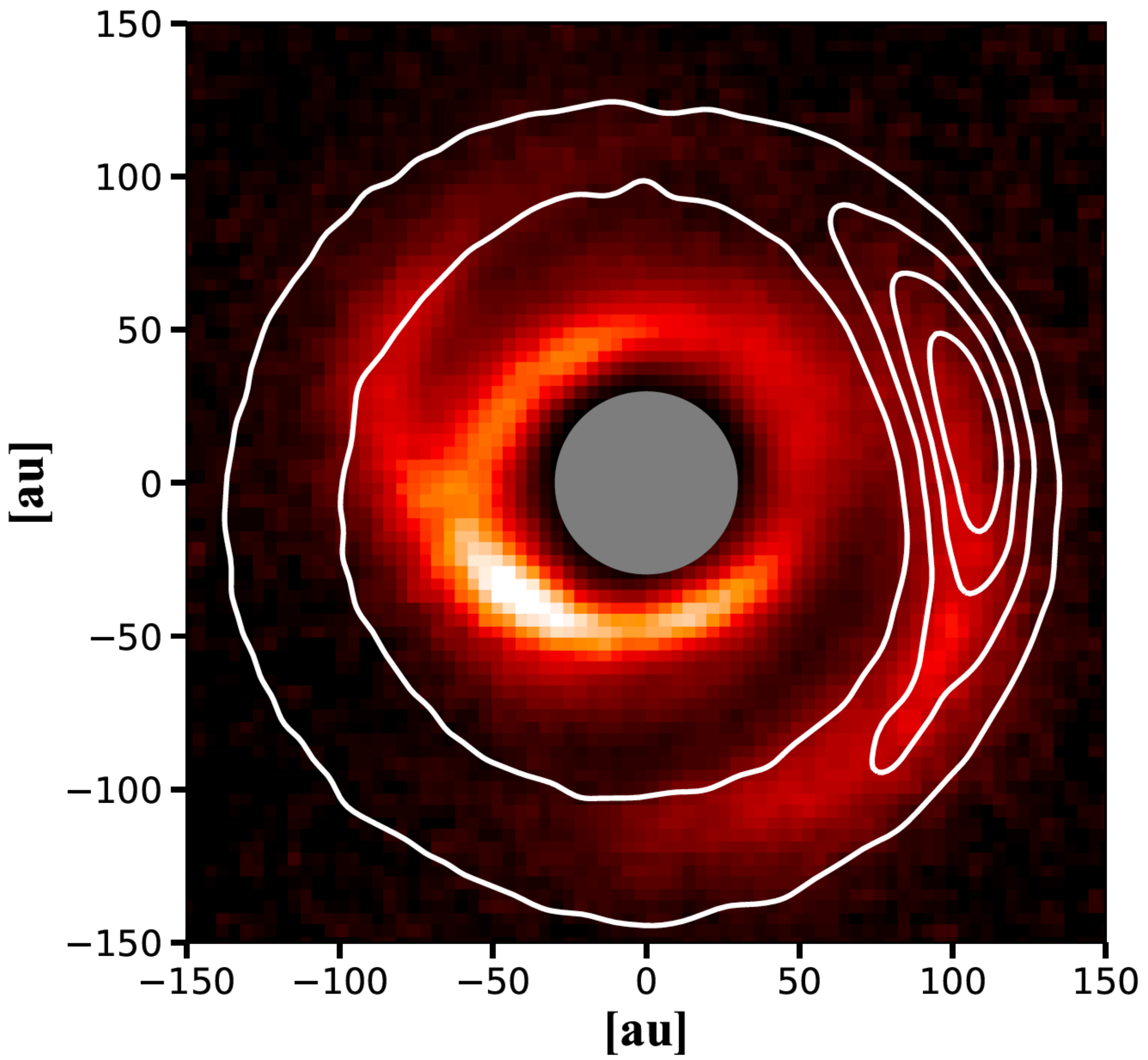


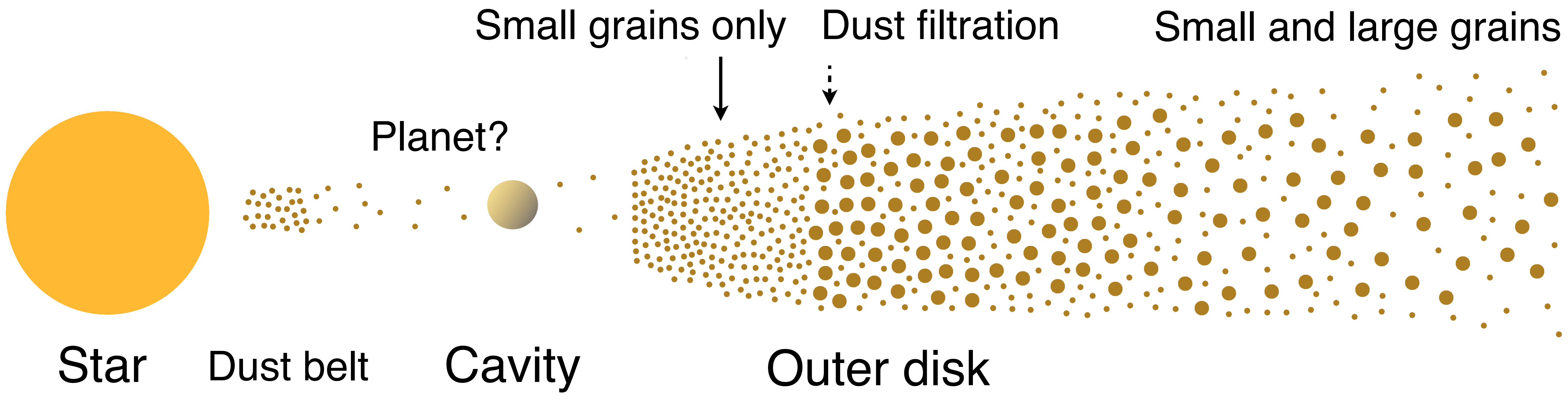
Dust radial drift



van Boekel et al. 2016
Andrews et al. 2016

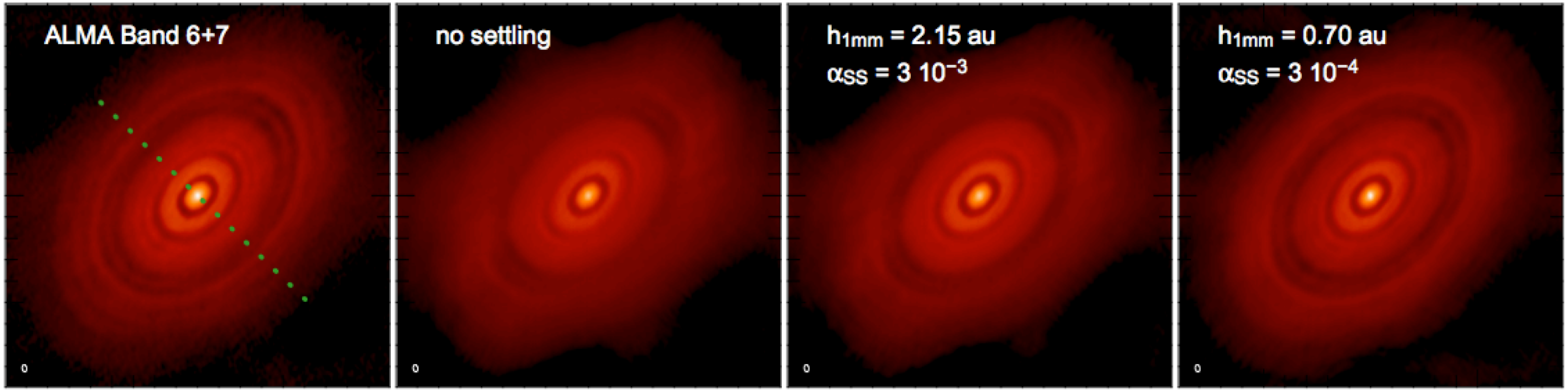




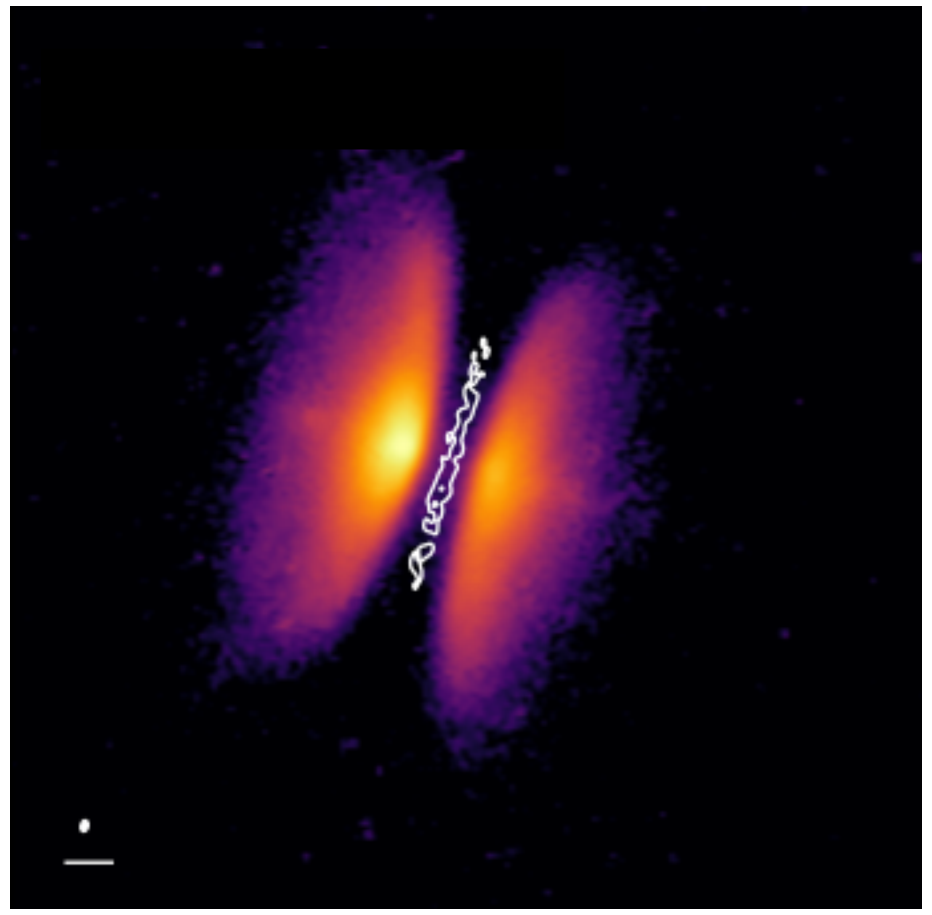


Garufi et al. 2014; Pinilla et al. 2023

Dust settling



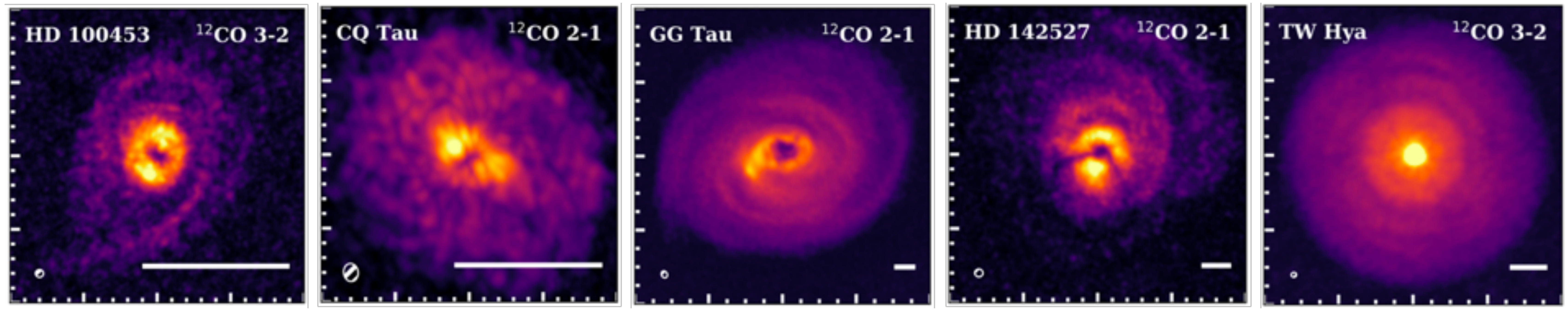
Disks compatible with low α and dust height ~ 1 au @ R=100 au



Pinte et al. 2018

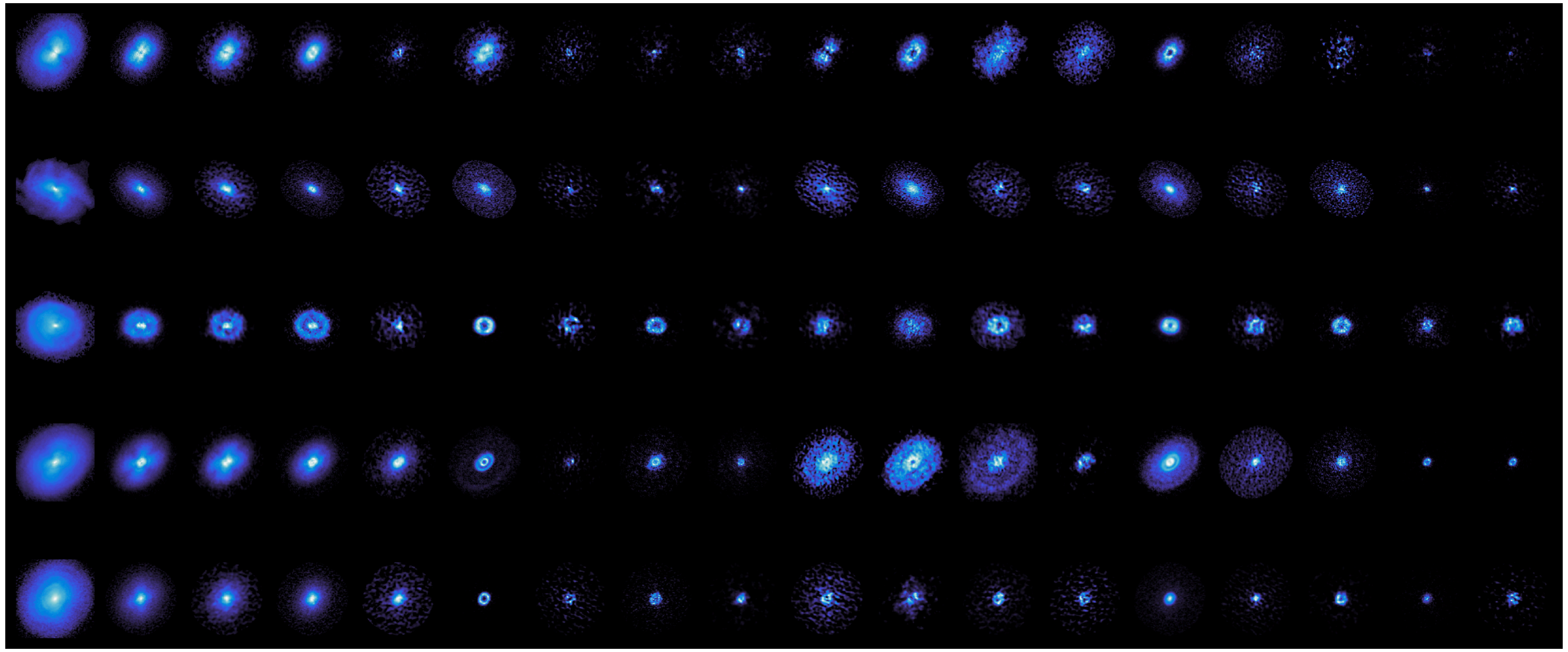
Villenave et al. 2020, 2022

Substructures gas

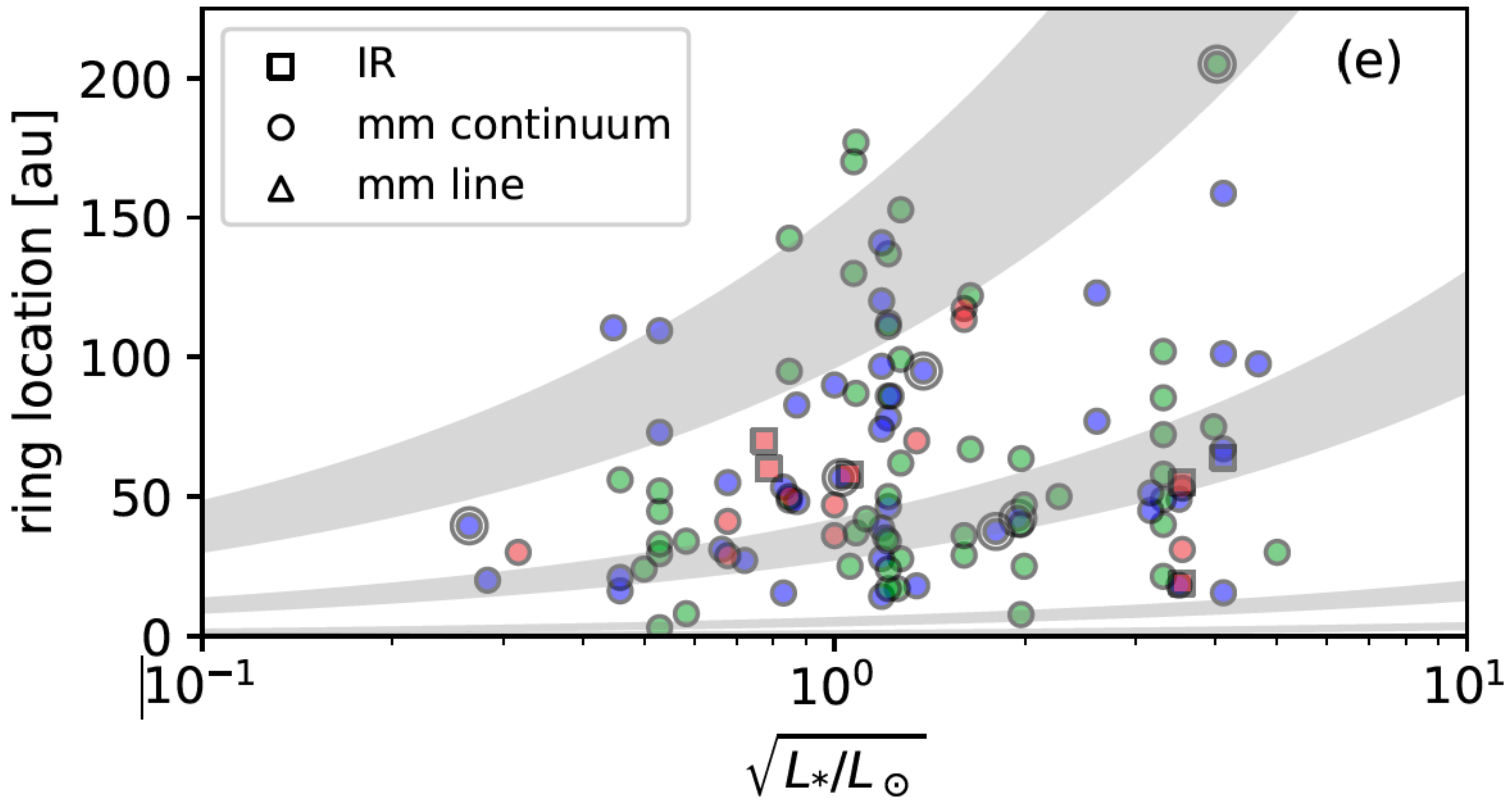


Bohn et al. 2022; Wolfer et al. 2022

Variations in structural and chemical properties



N_2, CO, CO_2, H_2O

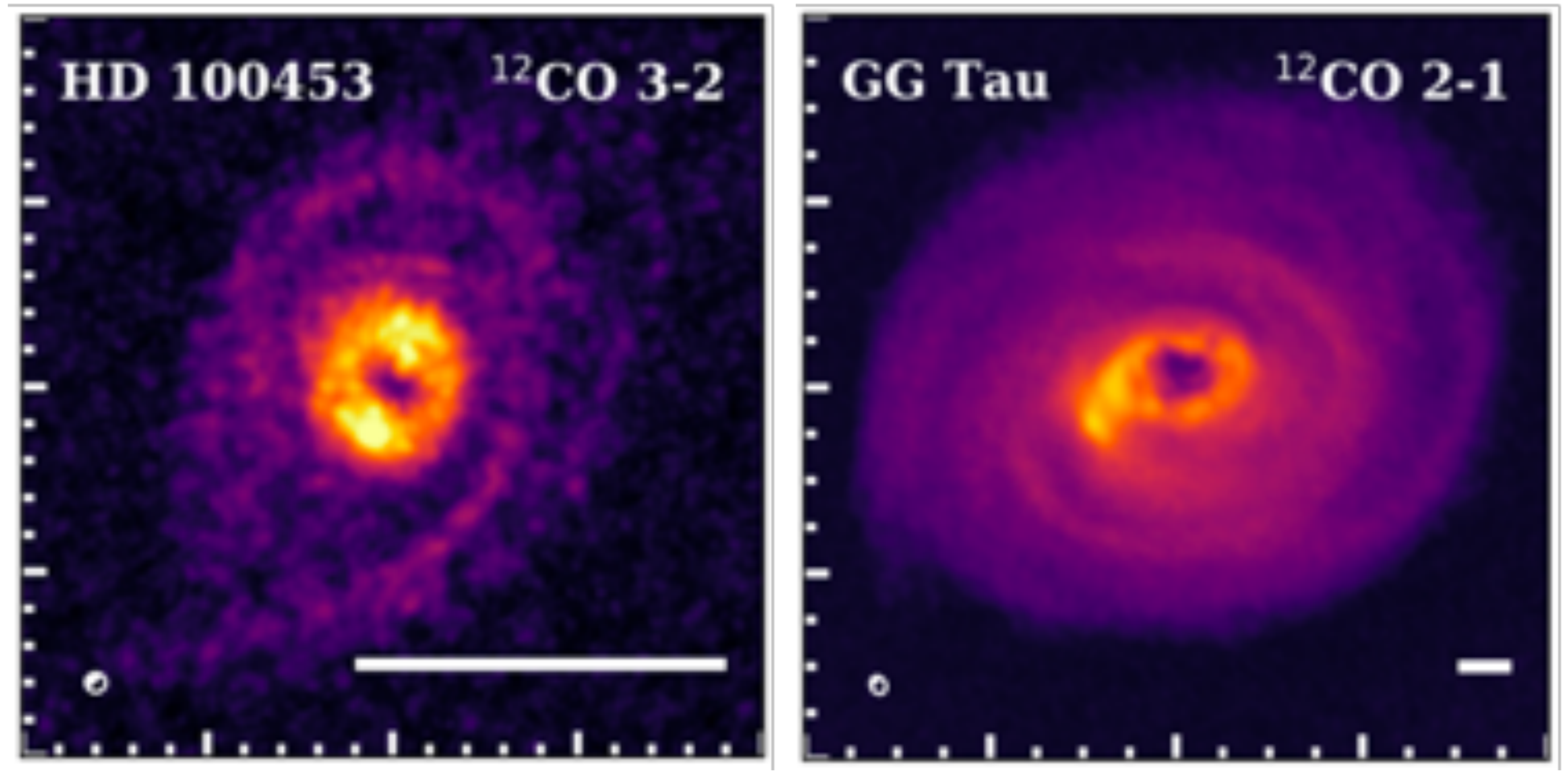


MAPS

Law et al. 2021

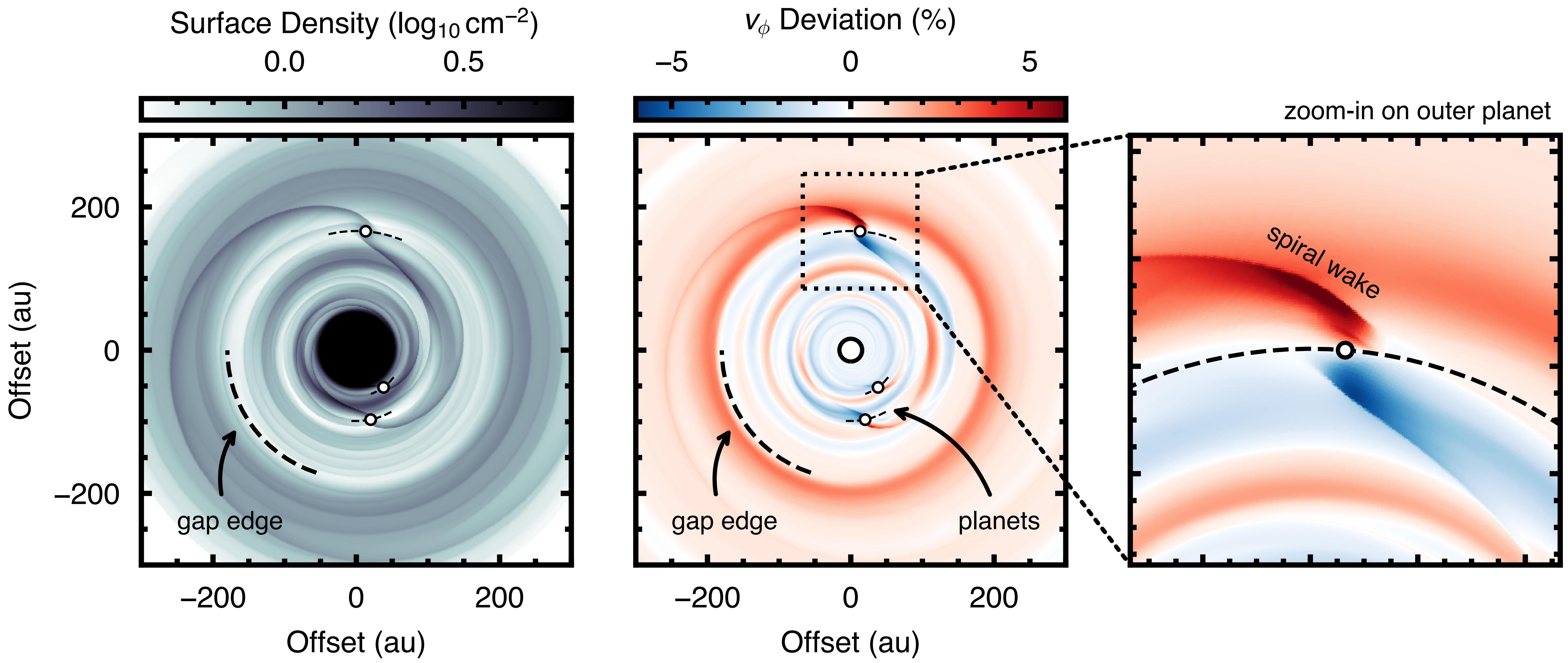
Bae et al. PPVII

Substructures in the gas



Rosotti et al. 2018
Keppler et al. 2020

Deviations in the disk velocity field can constrain the planet properties

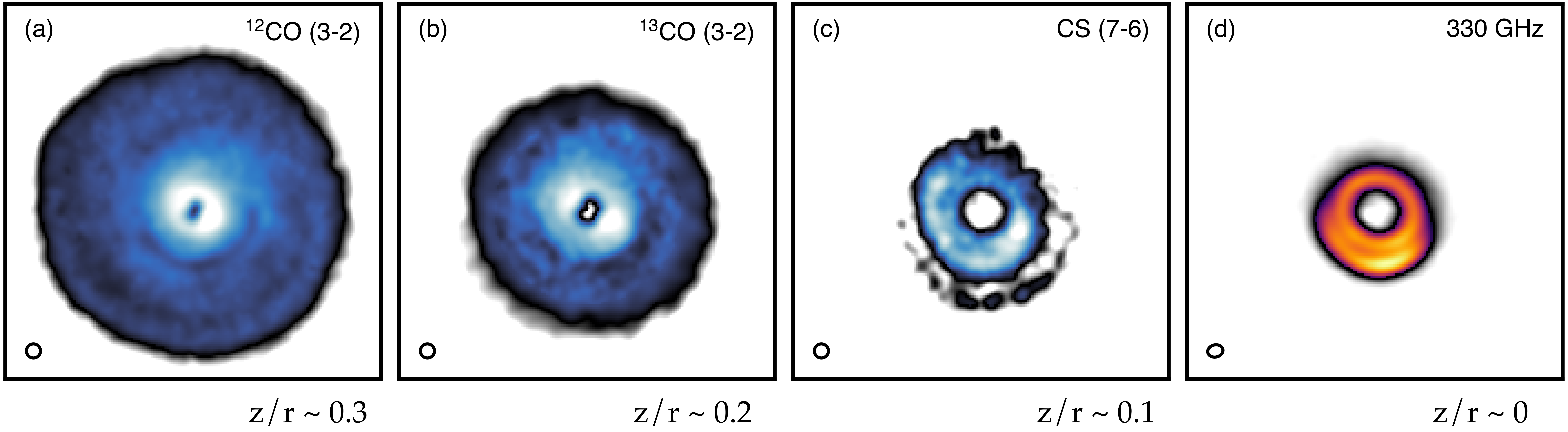


Disk kinematics collaboration 2018

A 180h ALMA Large Program to characterize disk dynamics

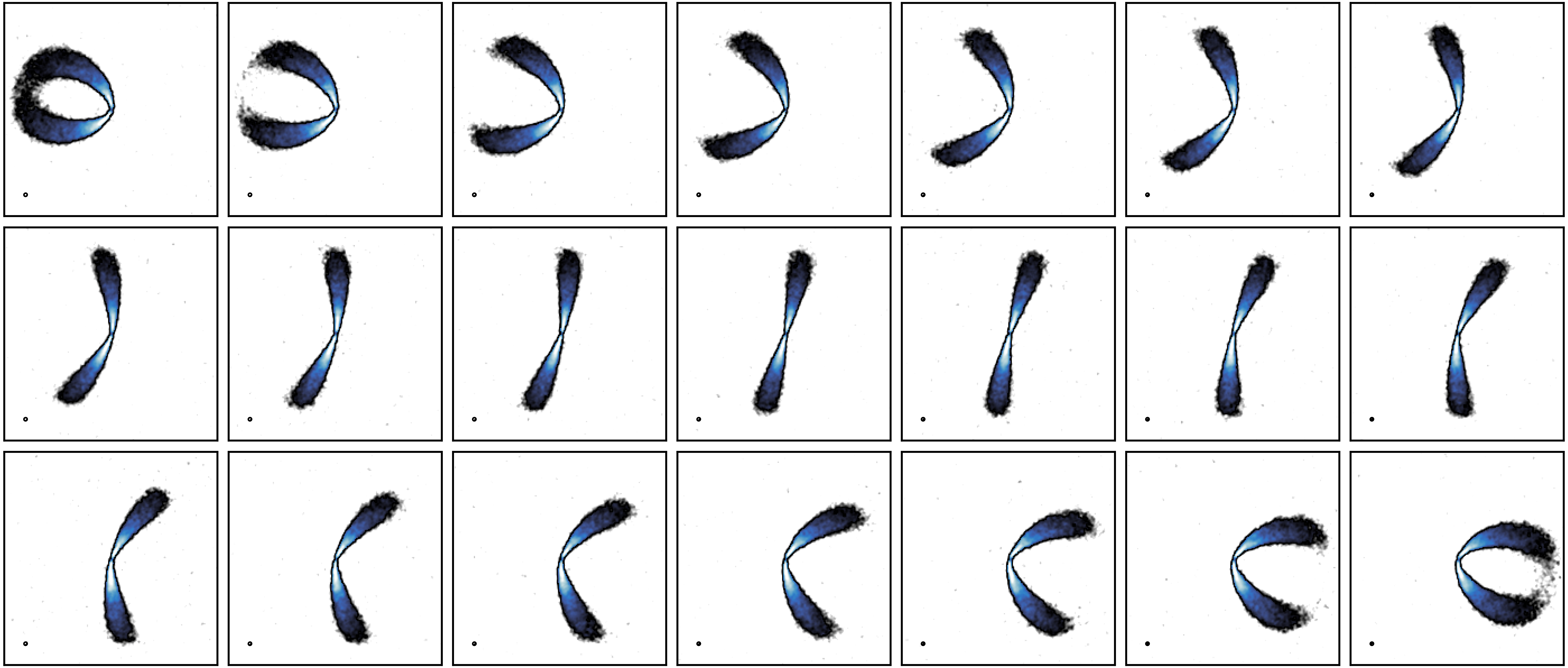
PIs: Teague, Benisty, Facchini, Fukagawa, Pinte

15 disks (28 m/s, 0.1″)



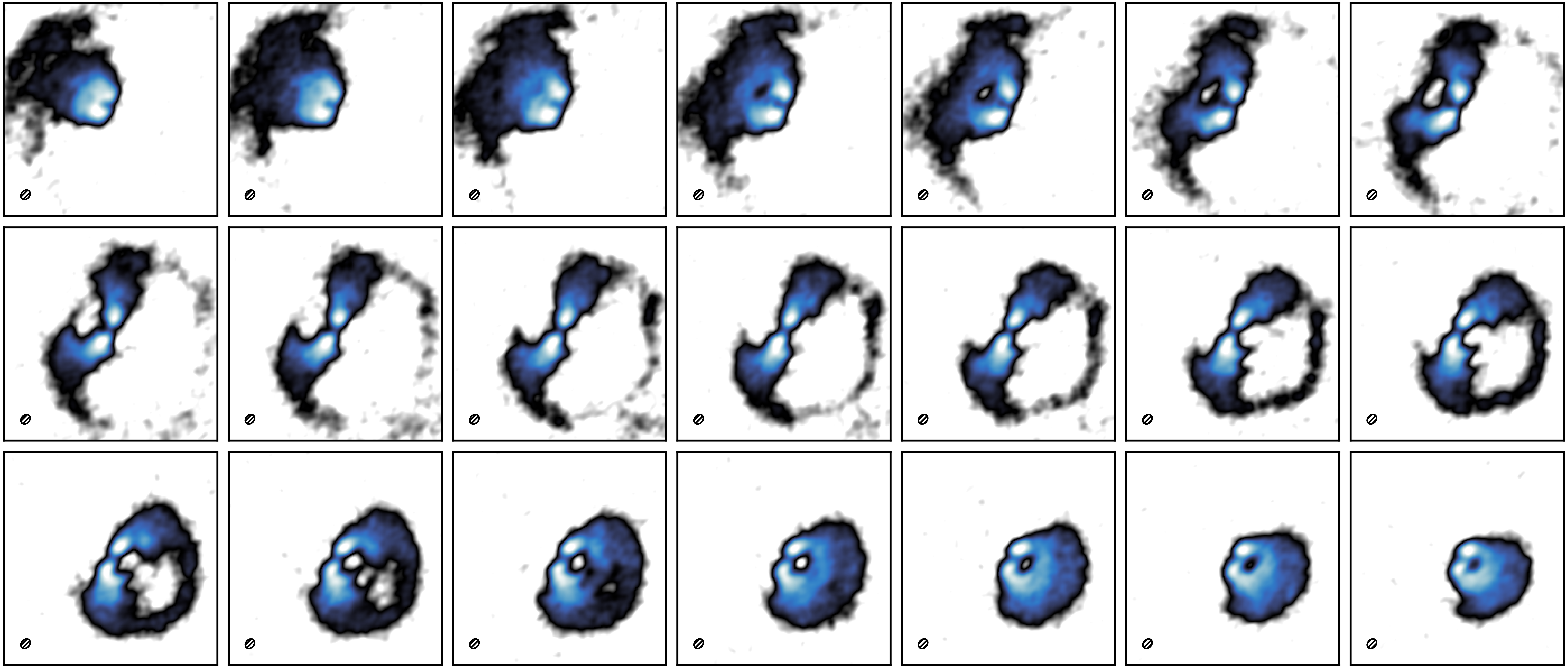
exoALMA collaboration (www.exoalma.com)

Some very well behaving disks…



*Teague et al. (exoALMA I)

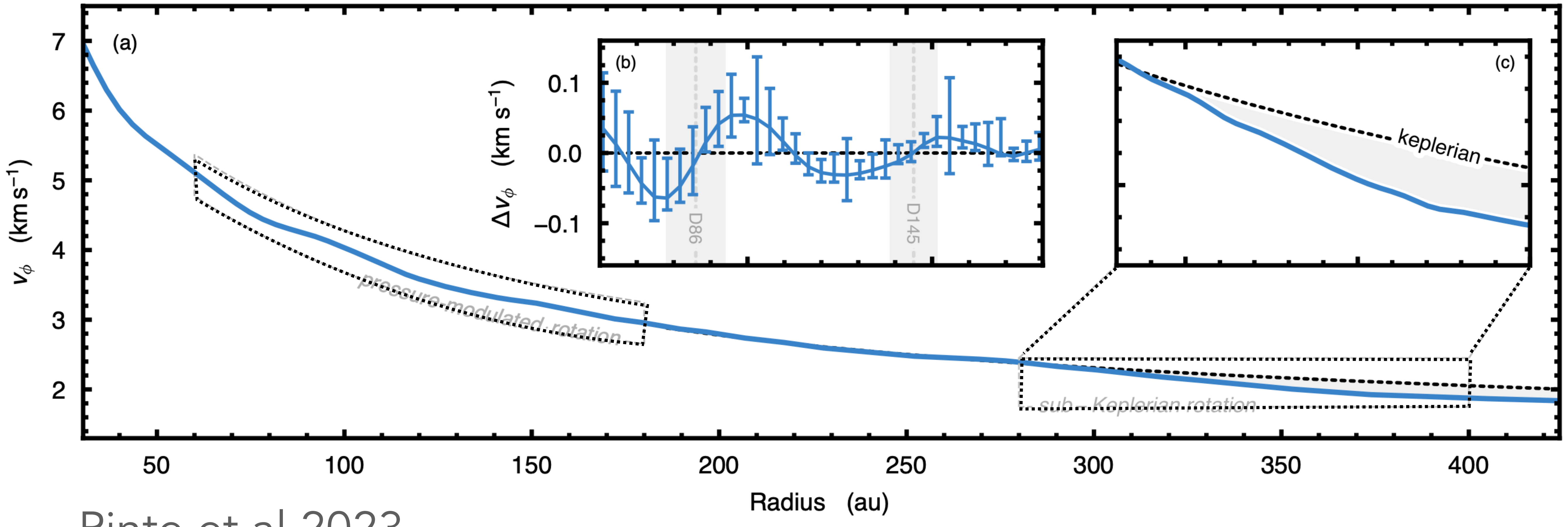
Other are more messy



*Teague et al. (exoALMA I)

Gas kinematics - Methods

I. Rotation curves

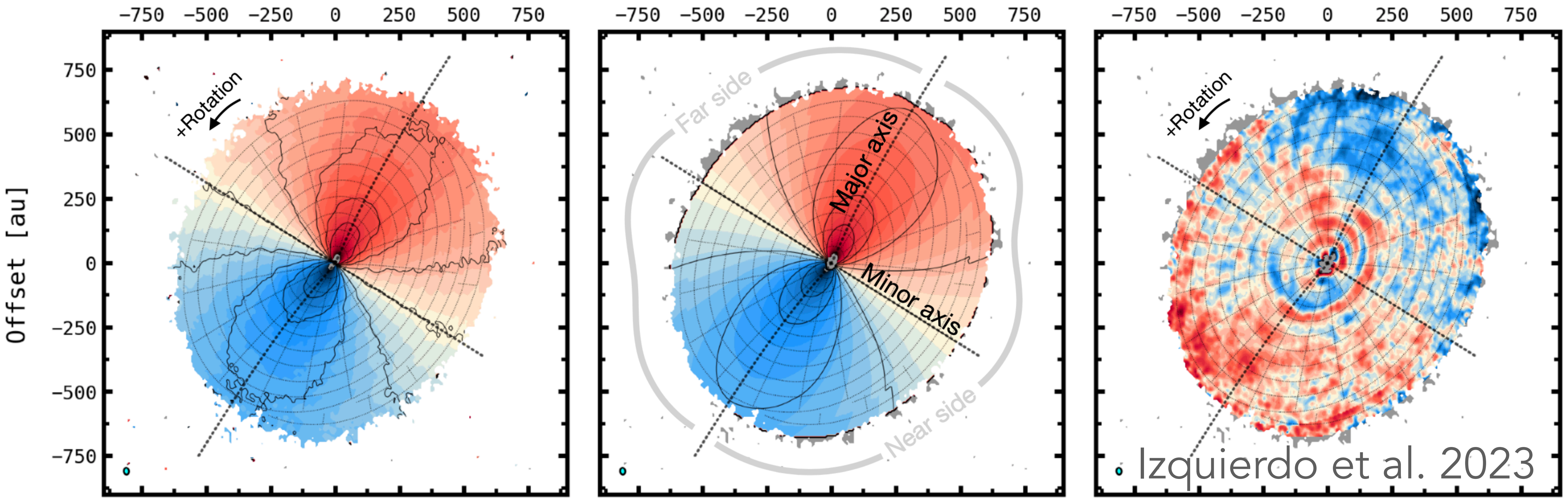


Pinte et al 2023

$$\frac{v^2}{r} = \underbrace{\frac{GM_* r}{(r^2+z^2)^{3/2}}}_{\text{stellar gravity}} + \underbrace{\frac{1}{\rho_{gas}}\frac{\partial P_{gas}}{\partial r}}_{\text{pressure support}} + \underbrace{\frac{\partial \phi_{gas}}{\partial r}}_{\text{self-gravity}}$$

Pressure structure, M_{star}, R_c, M_{disk}

II. Analyse residuals after Keplerian model fit

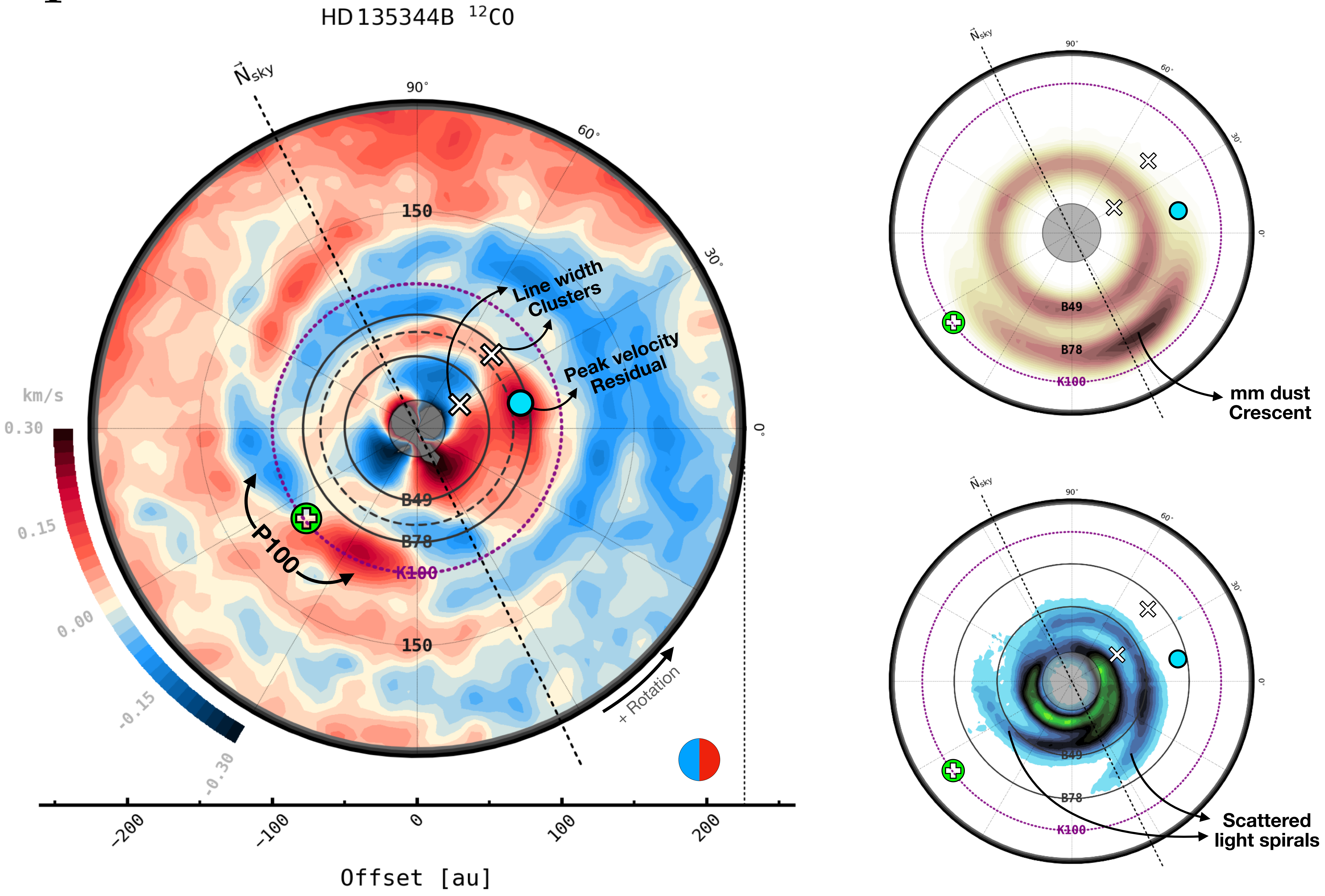


Izquierdo et al. 2023

Planets / companions, instabilities, winds,…

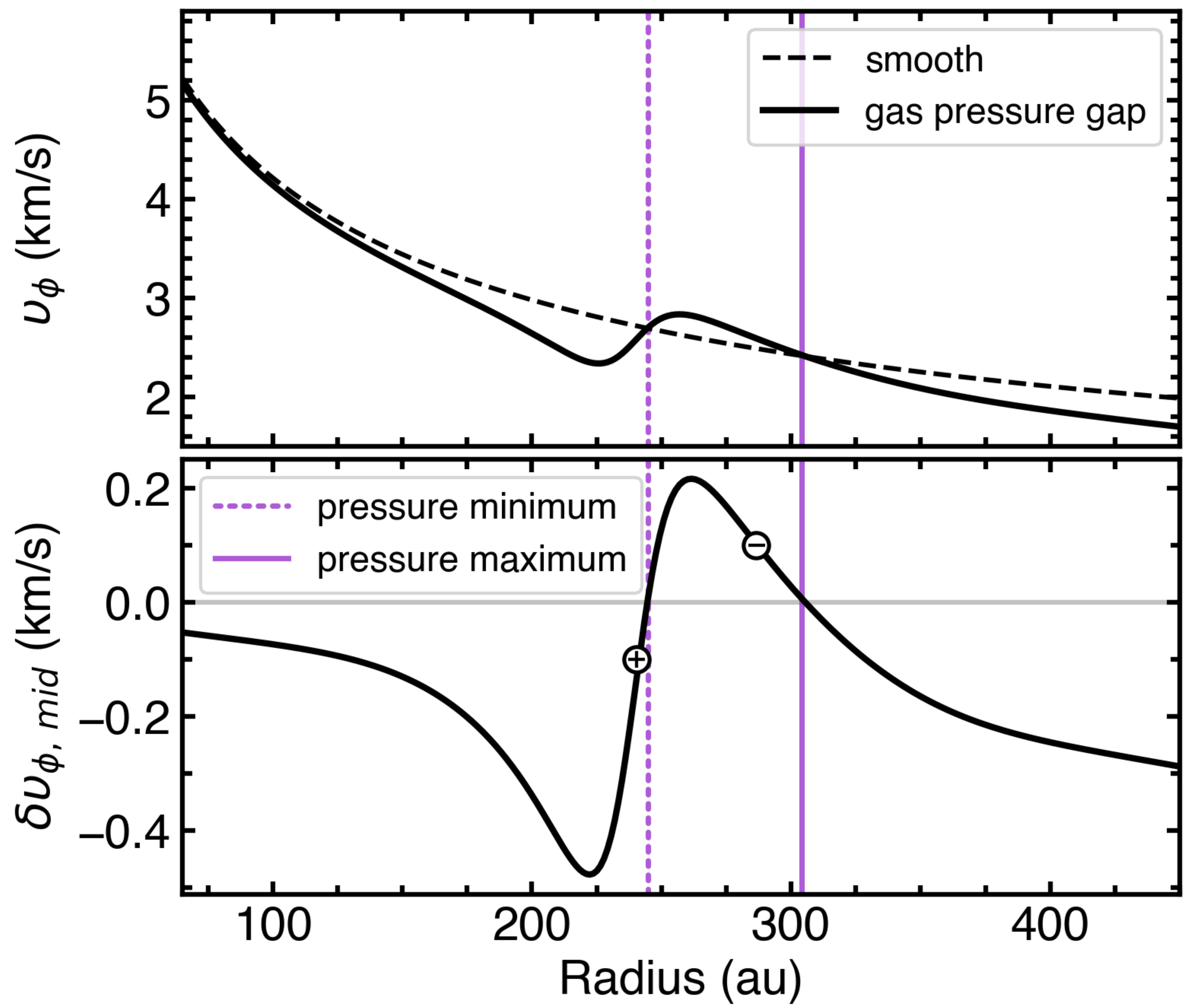
AA Tau
CQ Tau
DM Tau
HD 135344B
HD 143006
HD 34282
J1604
J1615
J1842
J1852
LkCa15
MWC 758
PDS 66
SY Cha
V4046 Sgr
0.4
0.2
0.0
-0.2
-0.4
Δ Centroid Velocity [km s^{-1}]
exoALMA collaboration

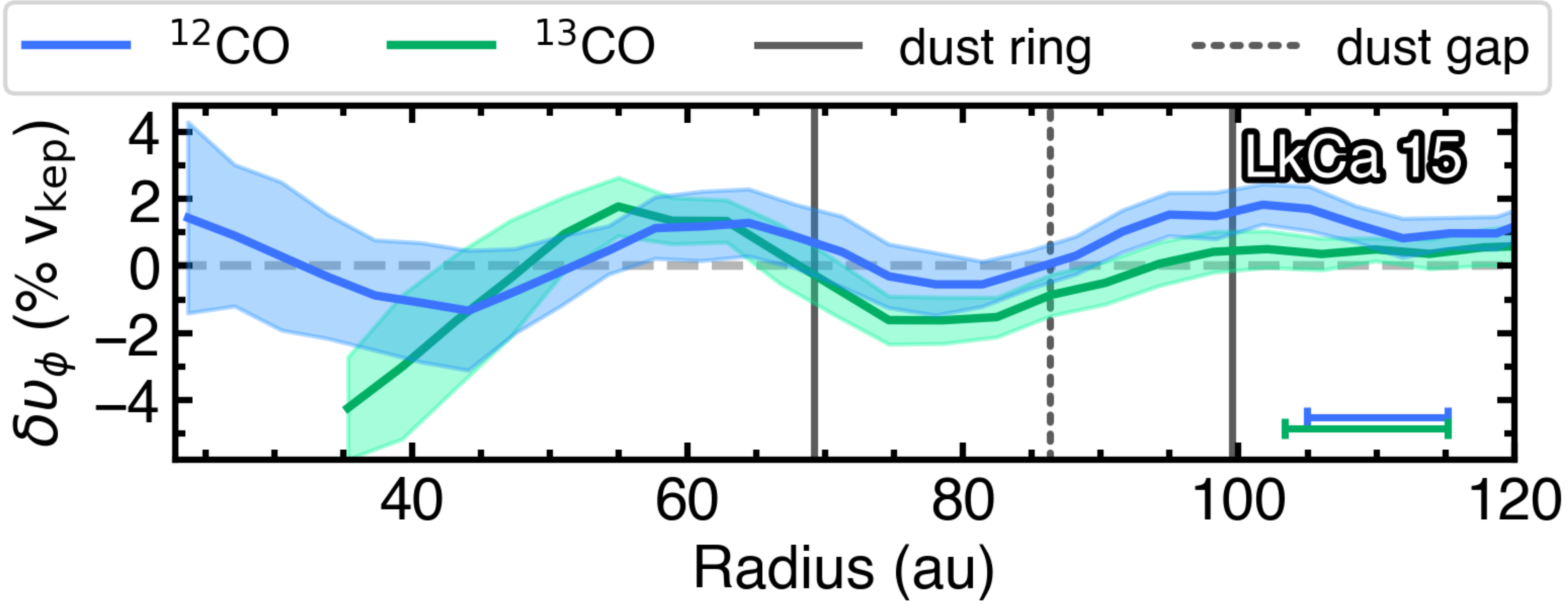
Embedded planets



Izquierdo et al. (exoALMA IV)

Localised pressure variations



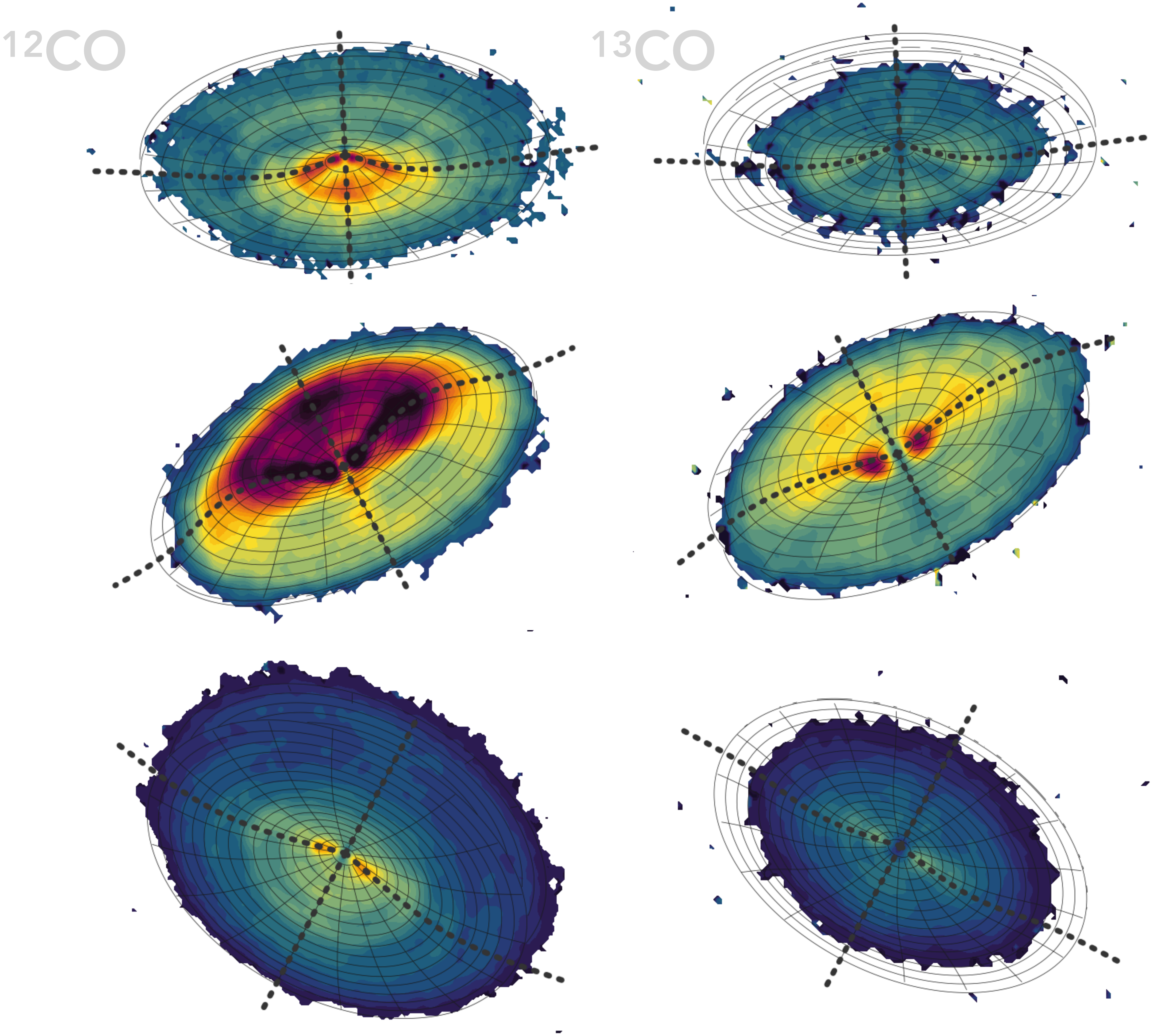


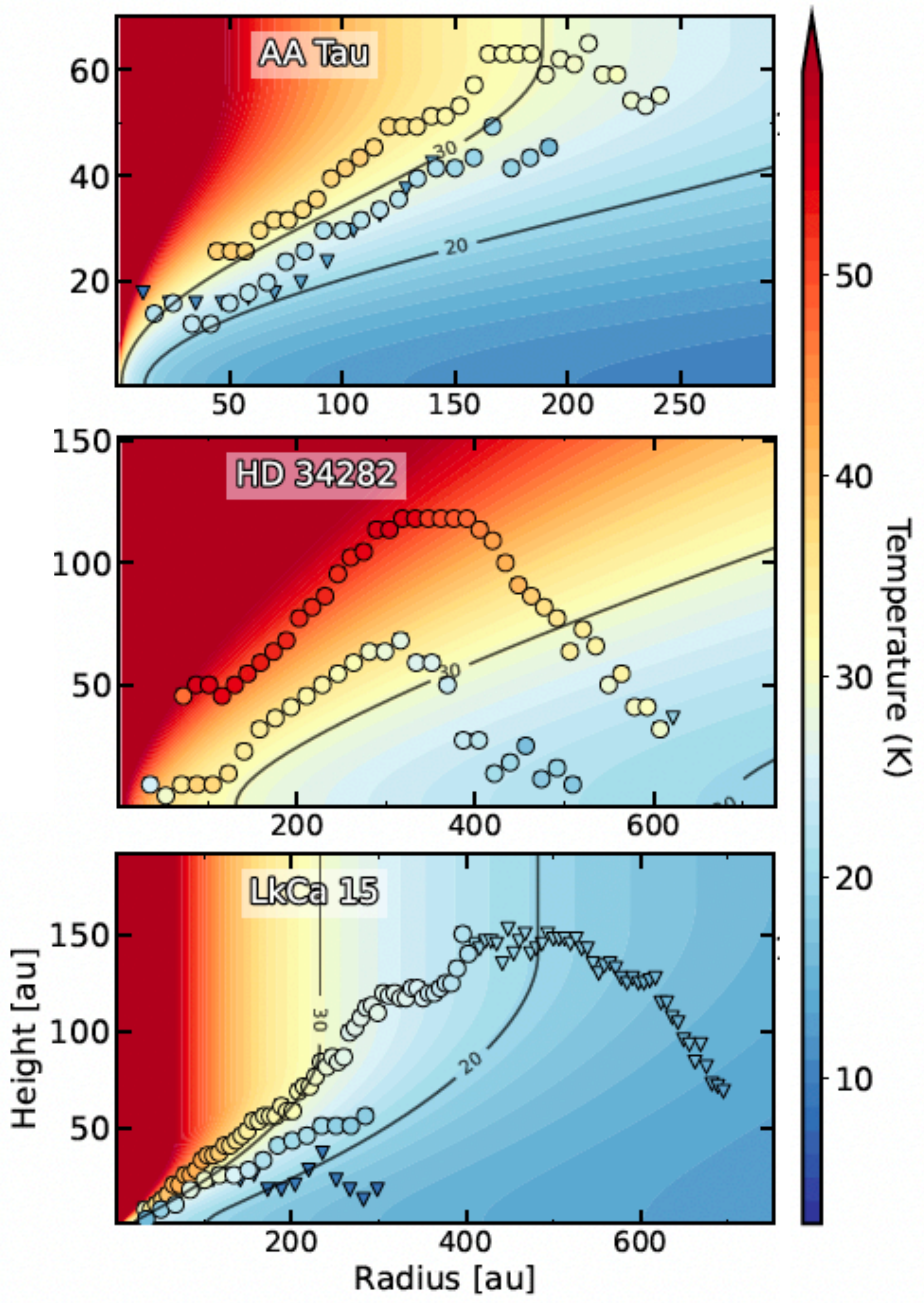
Rotation velocity flows reveal link between pressure modulations and dust substructures.

More than ~75% of the dust rings and gaps are co-located with pressure maxima and minima.

Stadler et al. (exoALMA VI), Curone et al. (exoALMA III)

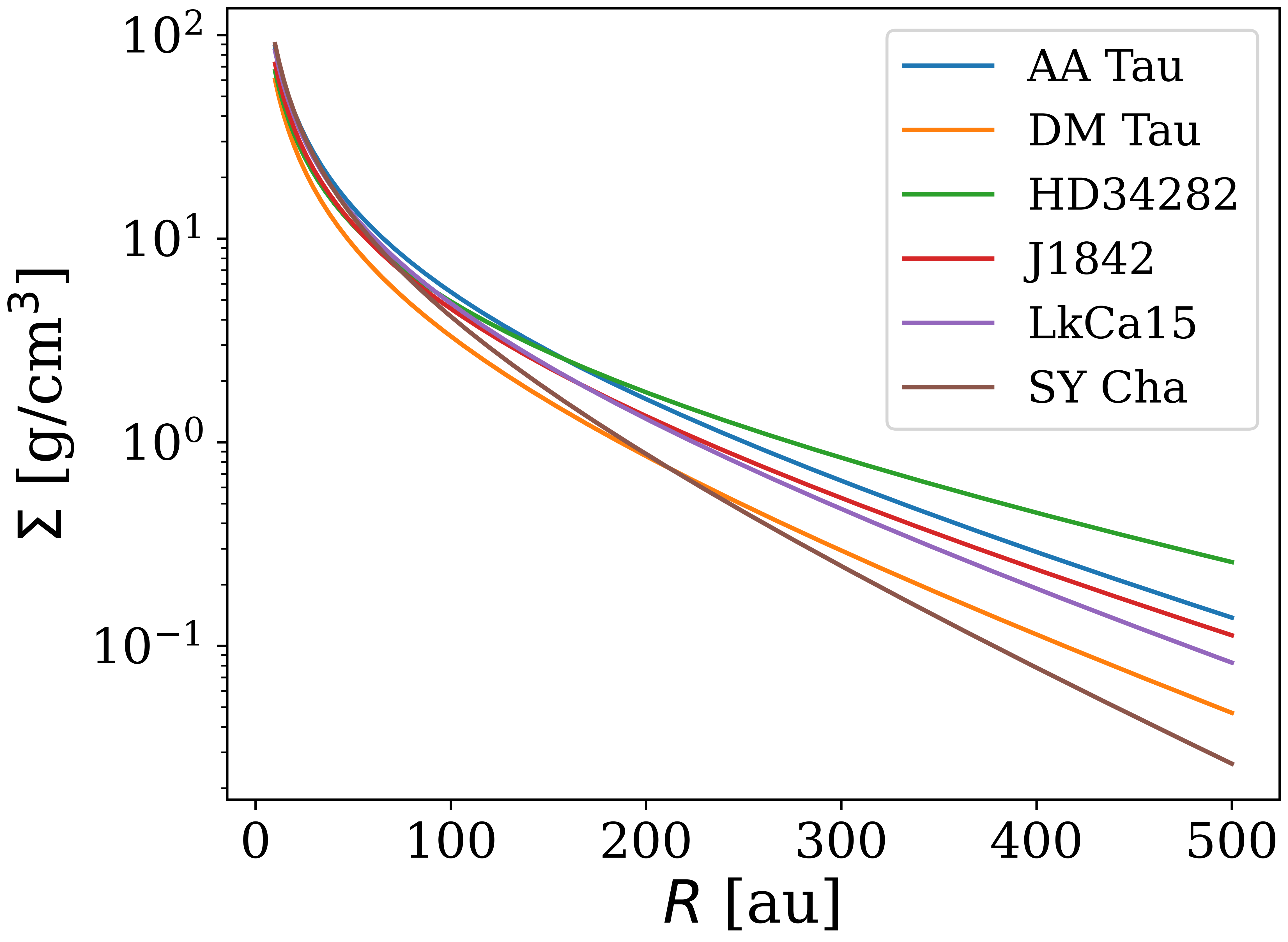
2D temperature structure





Galloway-Sprietsma et al. (exoALMA V)

Disk dynamical masses



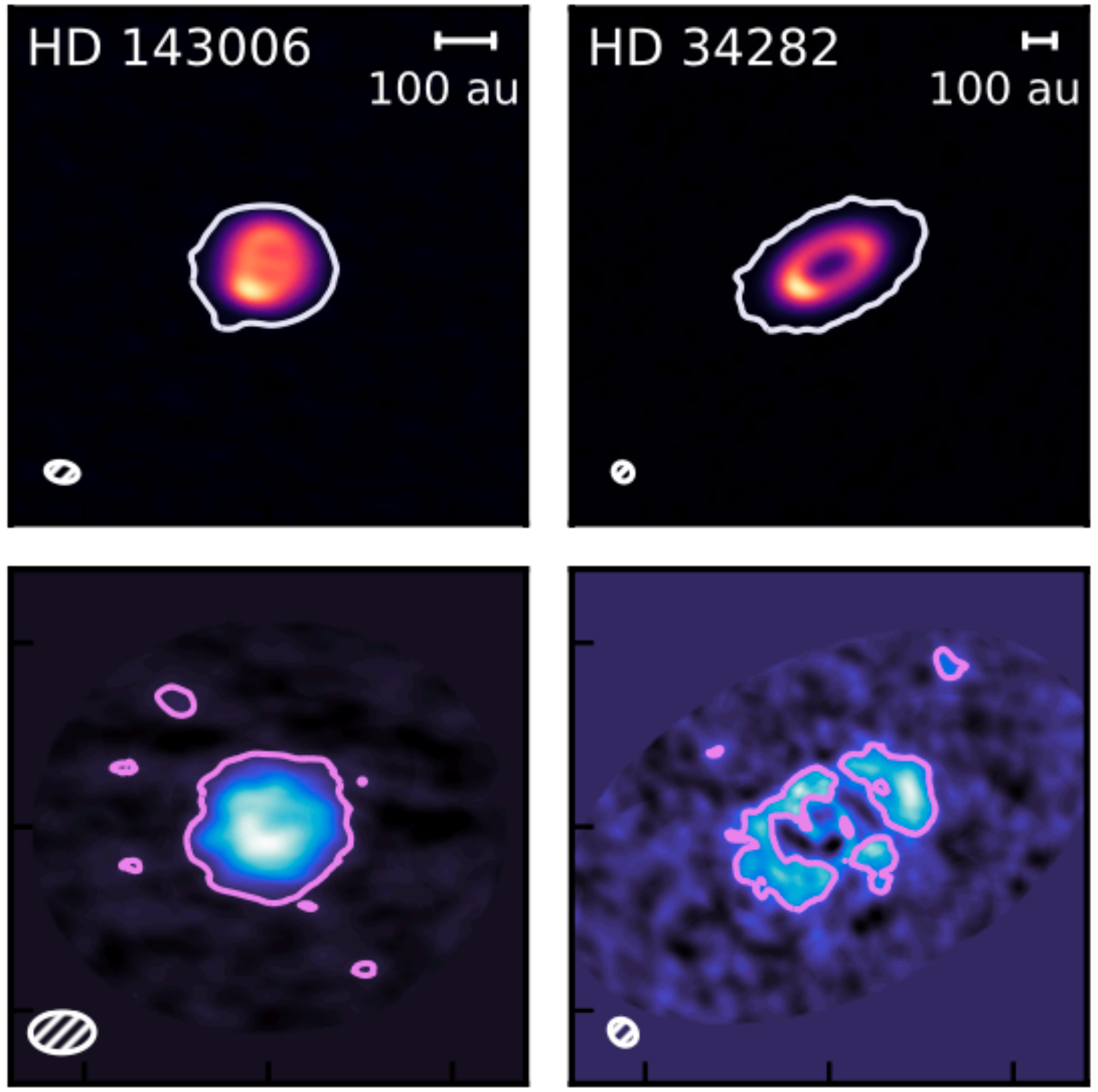
$$\frac{v^2}{r} = \frac{GM_* r}{(r^2+z^2)^{3/2}} + \frac{1}{\rho_{\rm gas}}\frac{\partial P_{\rm gas}}{\partial r} + \frac{\partial \phi_{\rm gas}}{\partial r}$$

Parametric fit of thermally-stratified rotation curves allow to estimate disk masses.

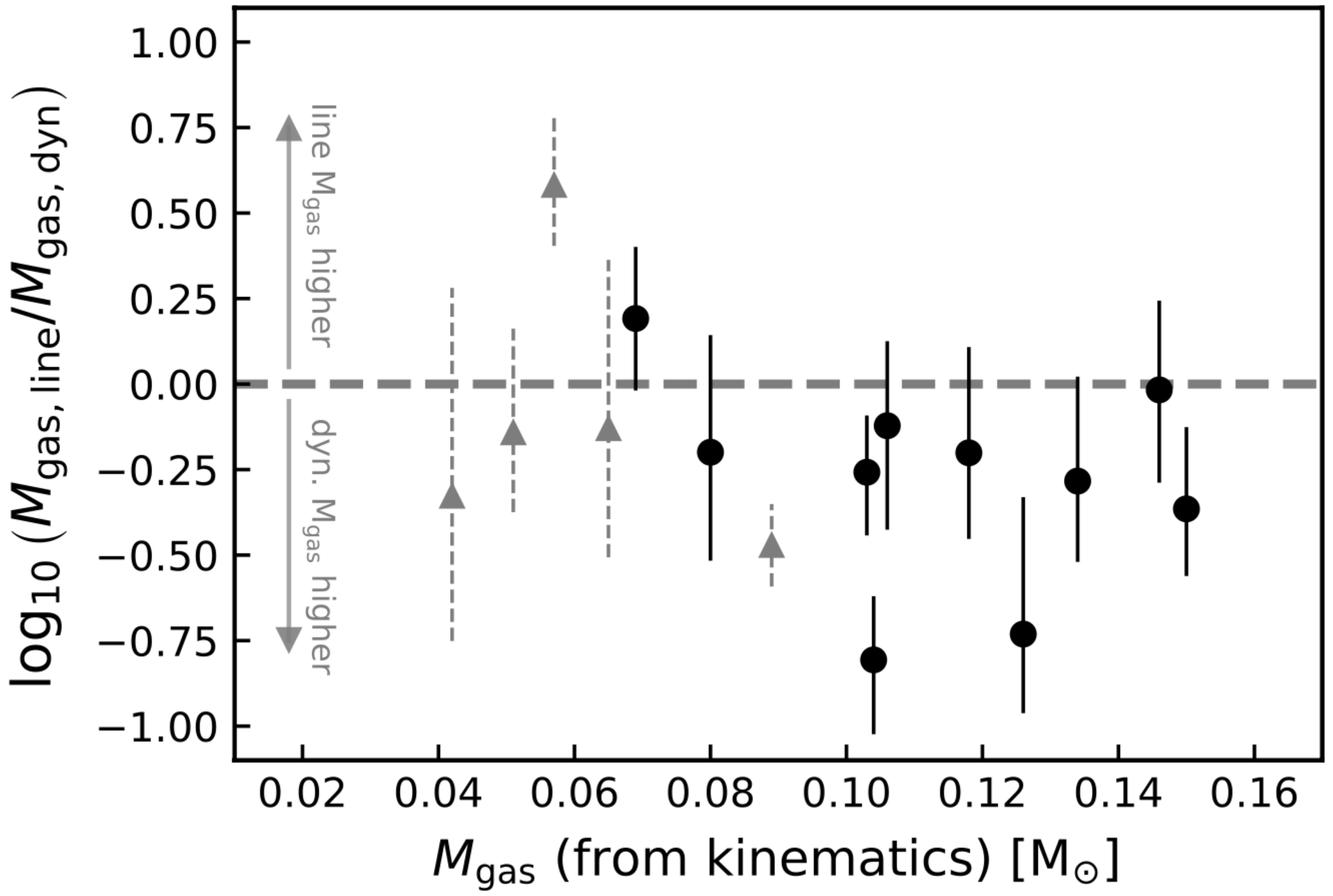
Disks are gravitationally stable.

Longarini et al. (exoALMA XII)

Benchmarking disk gas masses from thermo-chemical models



N_2H^+



Independent methods to measure the gas mass
OK within a factor of 3!

Trapman et al. (exoALMA XIII)

Conclusions

- Disks show extensive substructure in dust and molecular line emission
- Disks show highly complex 3D velocity field
- Subtle kinematical perturbations are indicative of dust trapping
- Dynamical disk masses can be estimated but this can't be scaled to many disks!
- We need statistical disk mass measurements to constrain planet formation