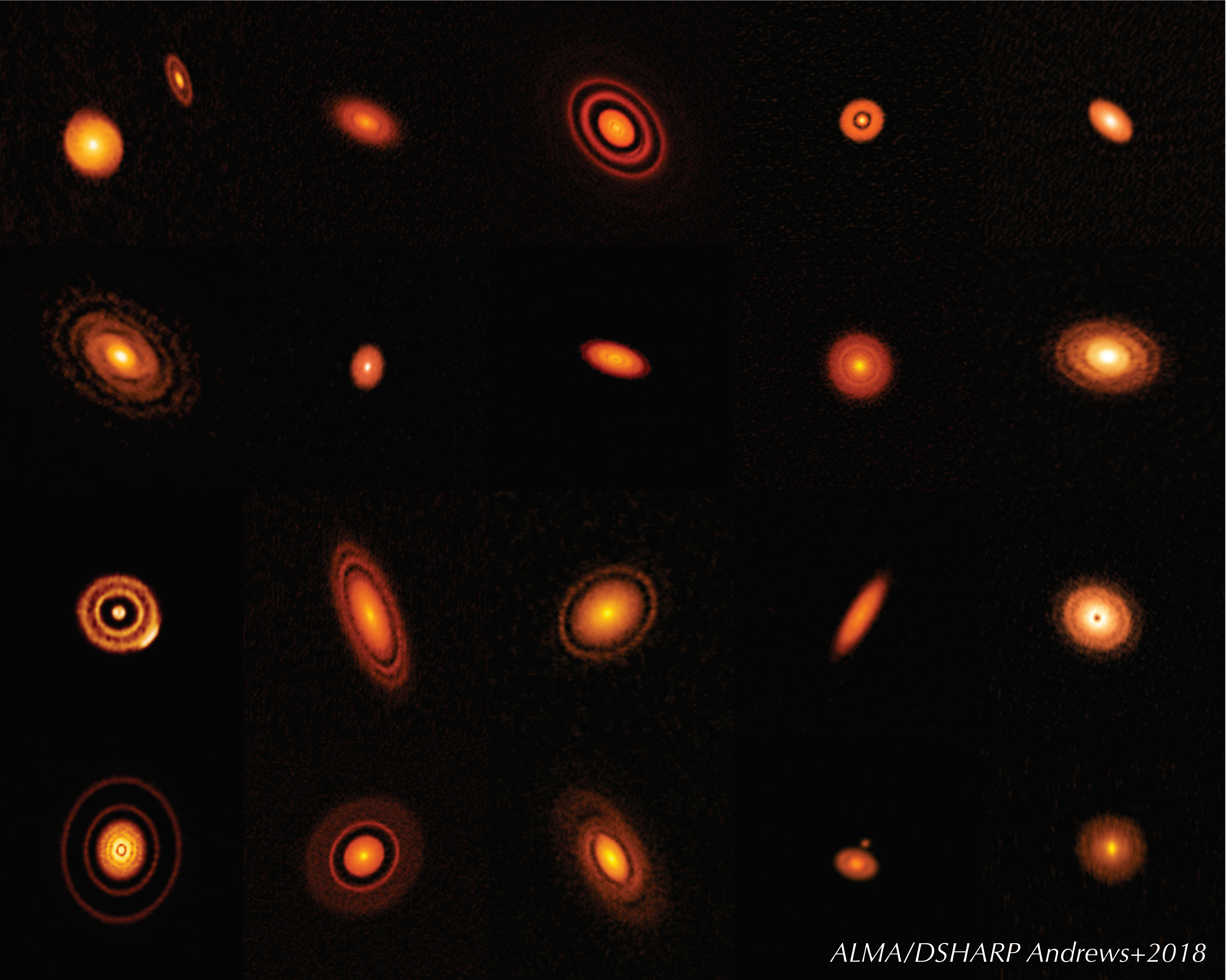
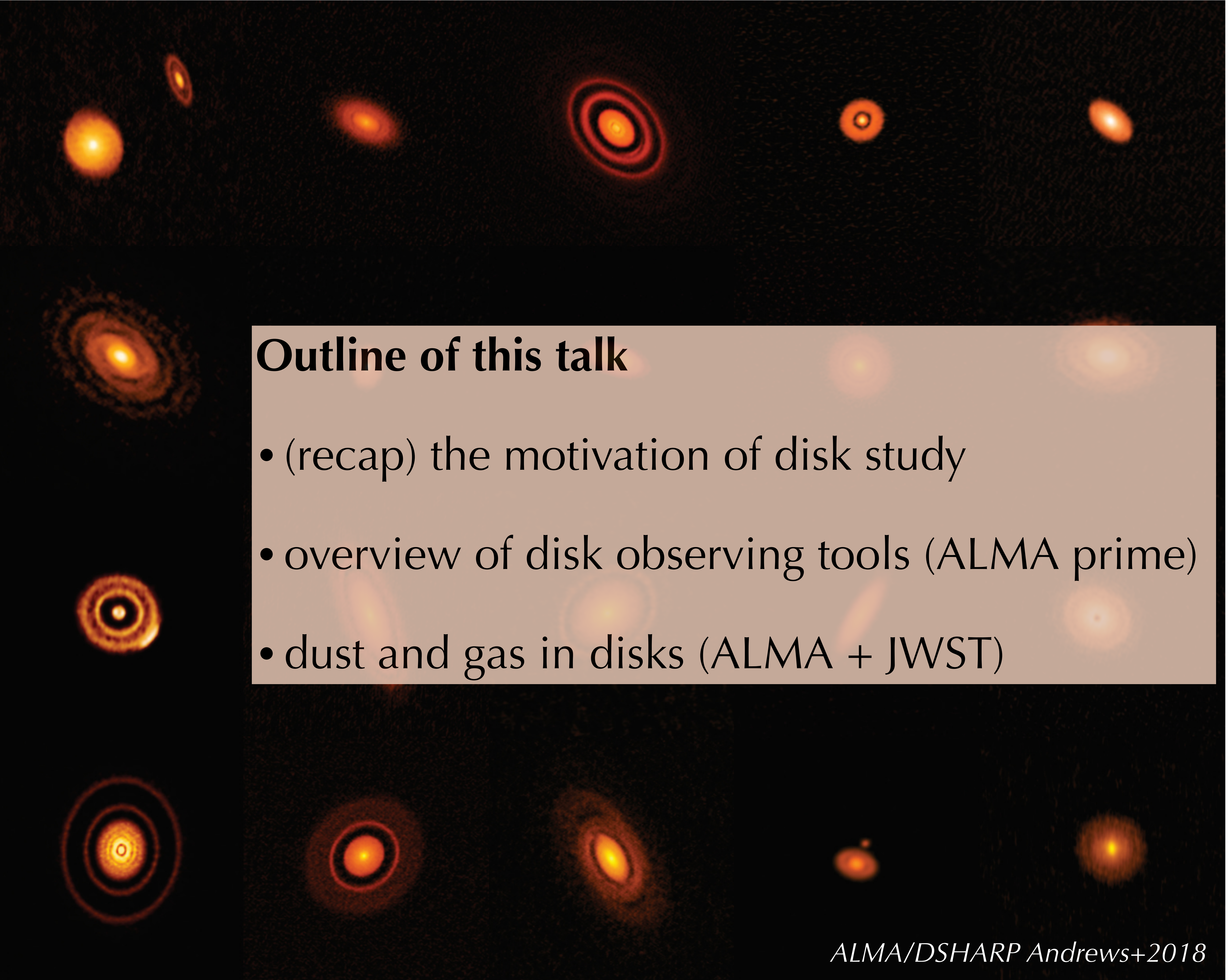


Disk Observations II

Feng Long (龙凤)
University of Arizona

2024 Summer School



ALMA/DSHARP Andrews+2018

Outline of this talk

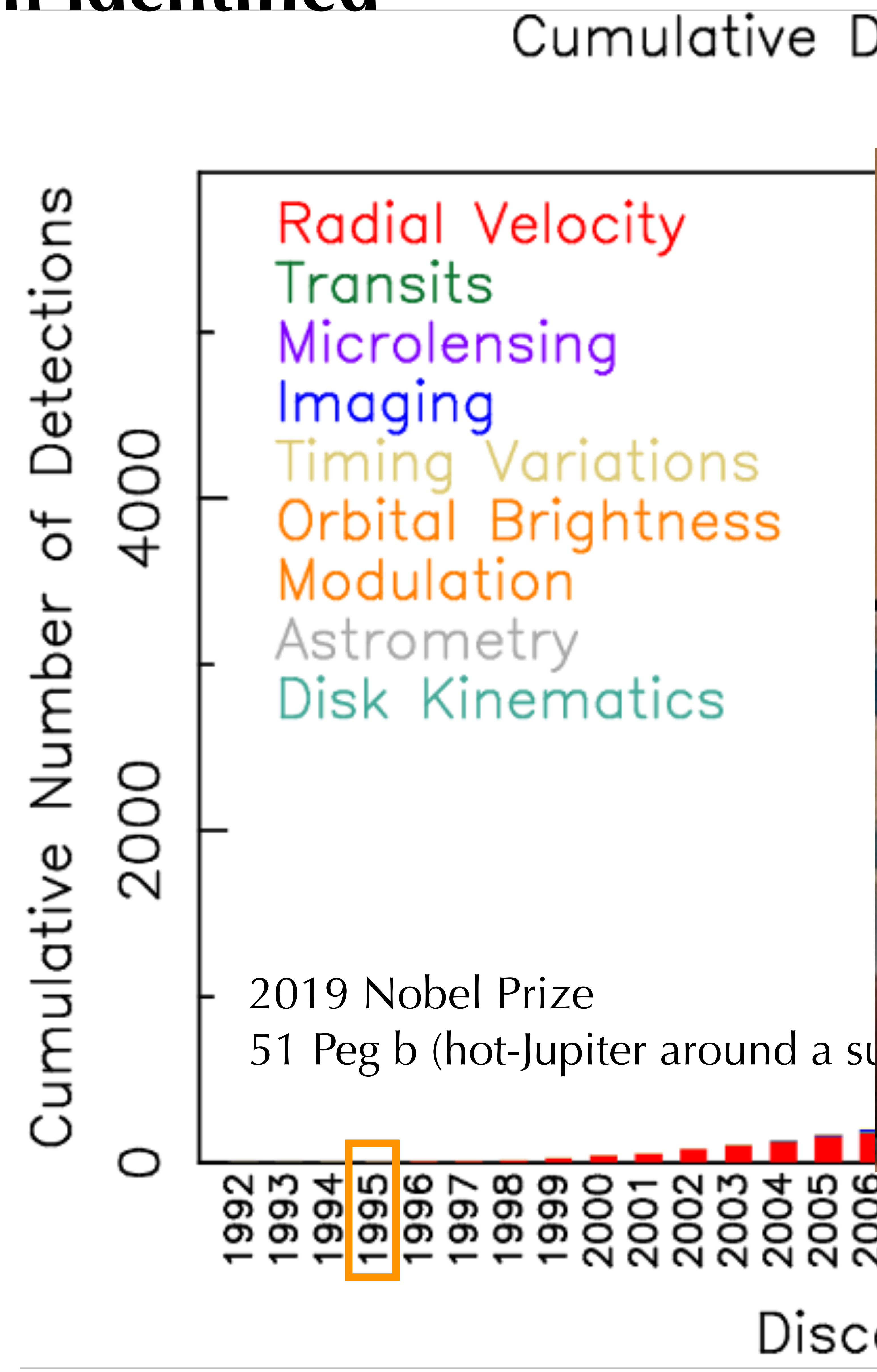
- (recap) the motivation of disk study
- overview of disk observing tools (ALMA prime)
- dust and gas in disks (ALMA + JWST)

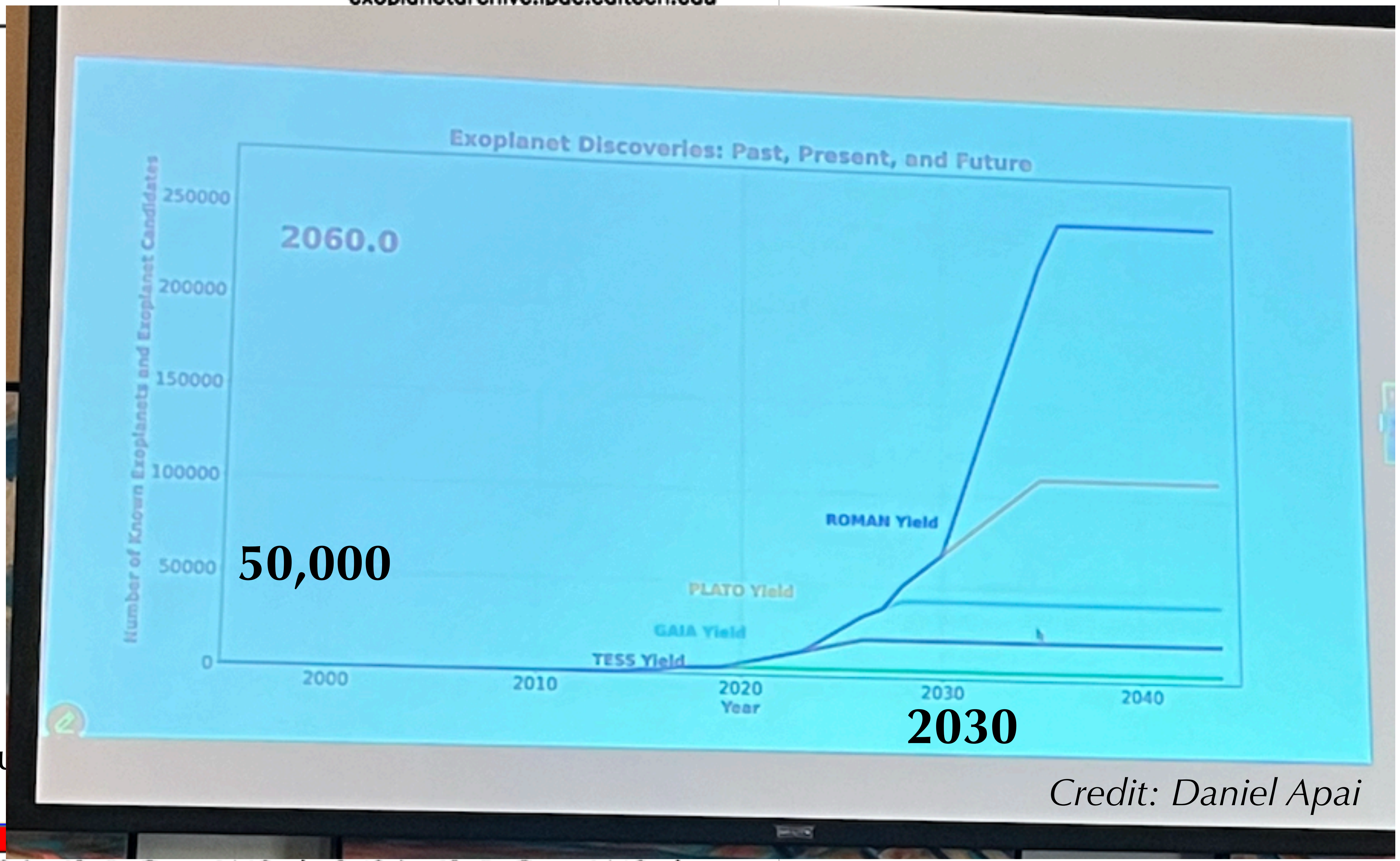
Disk Observations II

Feng Long (龙凤)
University of Arizona

2024 Summer School

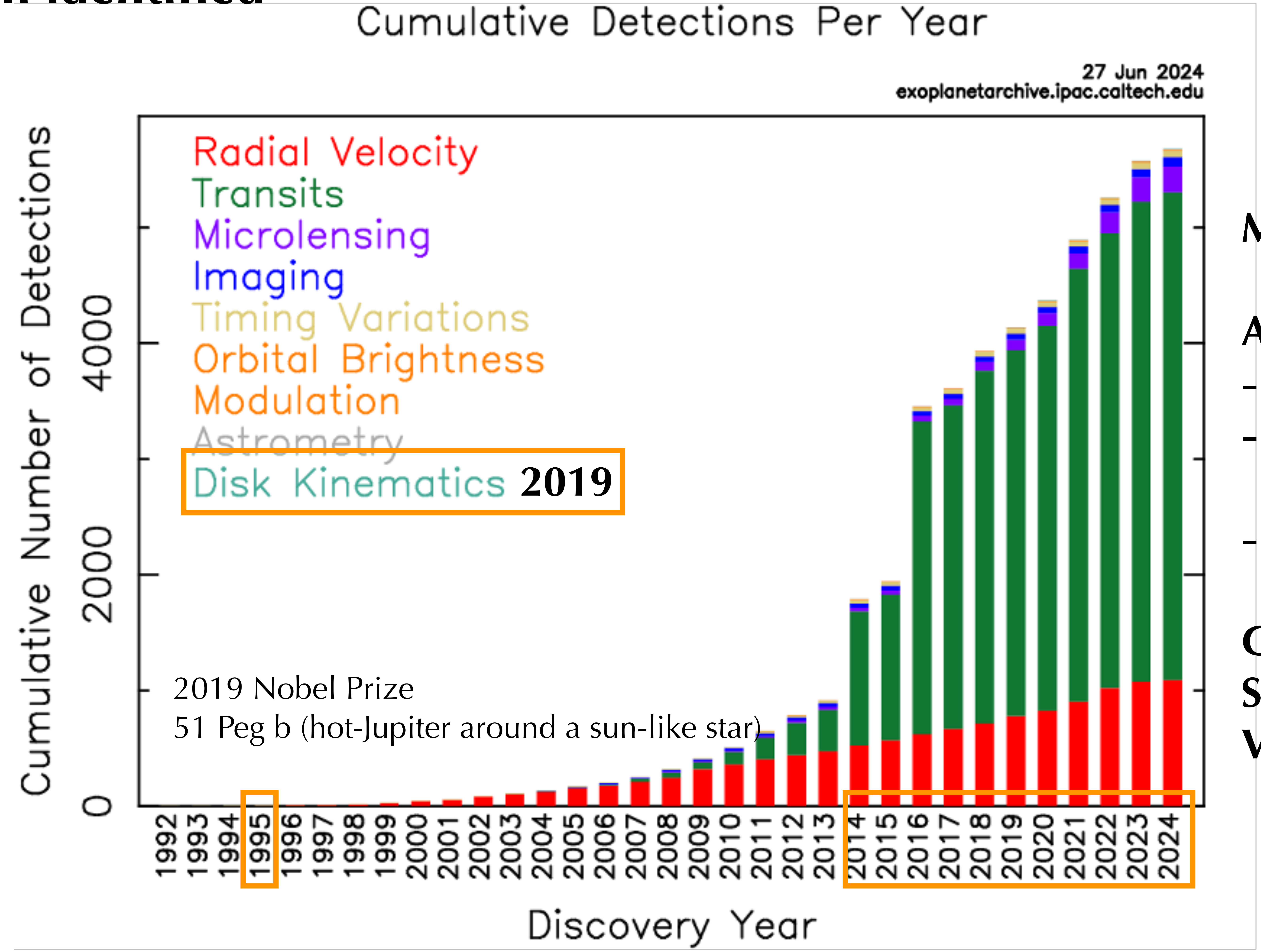
Today, >5000 exoplanets have been identified





Credit: Daniel Apai

Today, >5000 exoplanets have been identified



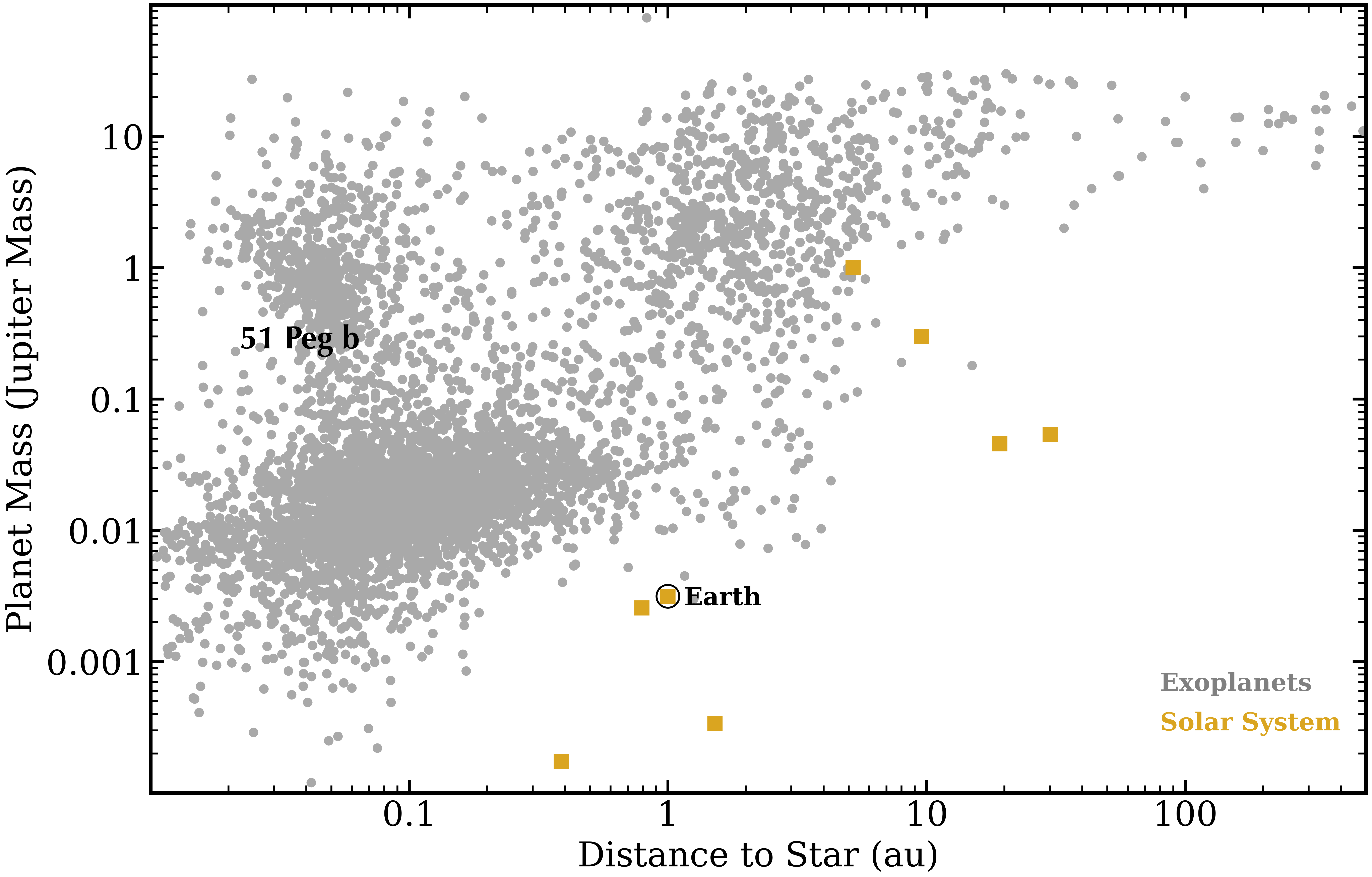
Major facilities for disks

ALMA:

- 2011, Cycle1
- 2015, long-baseline operation
- 2030, wide-band upgrade

Gemini/GPI: 2013, Nov
Subaru/SCExAO: 2014, Jan
VLT/SPEHRE: 2014, May

Rich diversity in planetary systems



To understand the planet formation process and the diverse properties of planetary systems, we need to know well the planet formation environment:

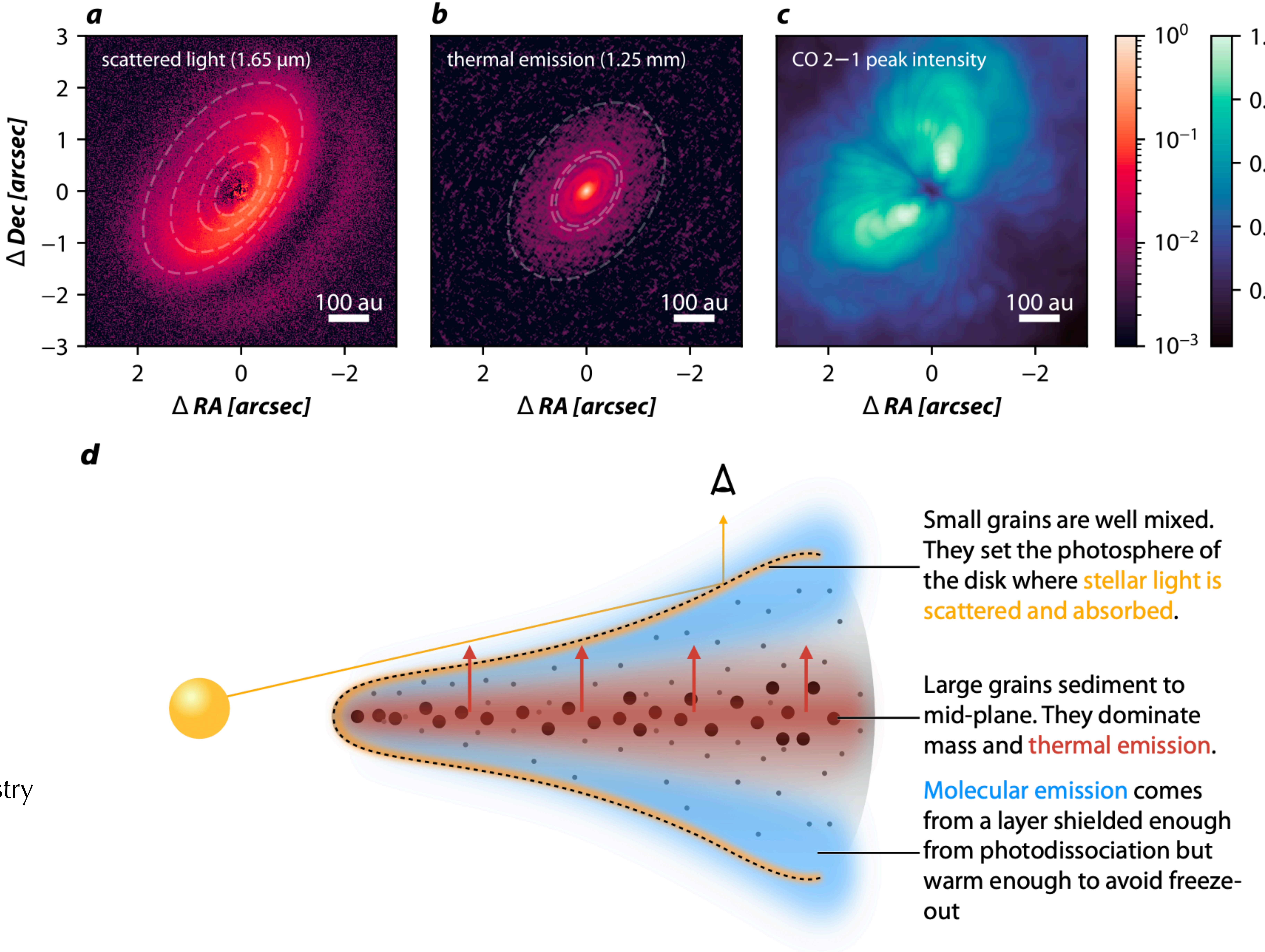
protoplanetary disks

Overview of protoplanetary disk: dust + gas

stellar accretion
planet formation
disk wind/outflow

Henning & Semenov 2013 review

different wavelengths trace different disk area



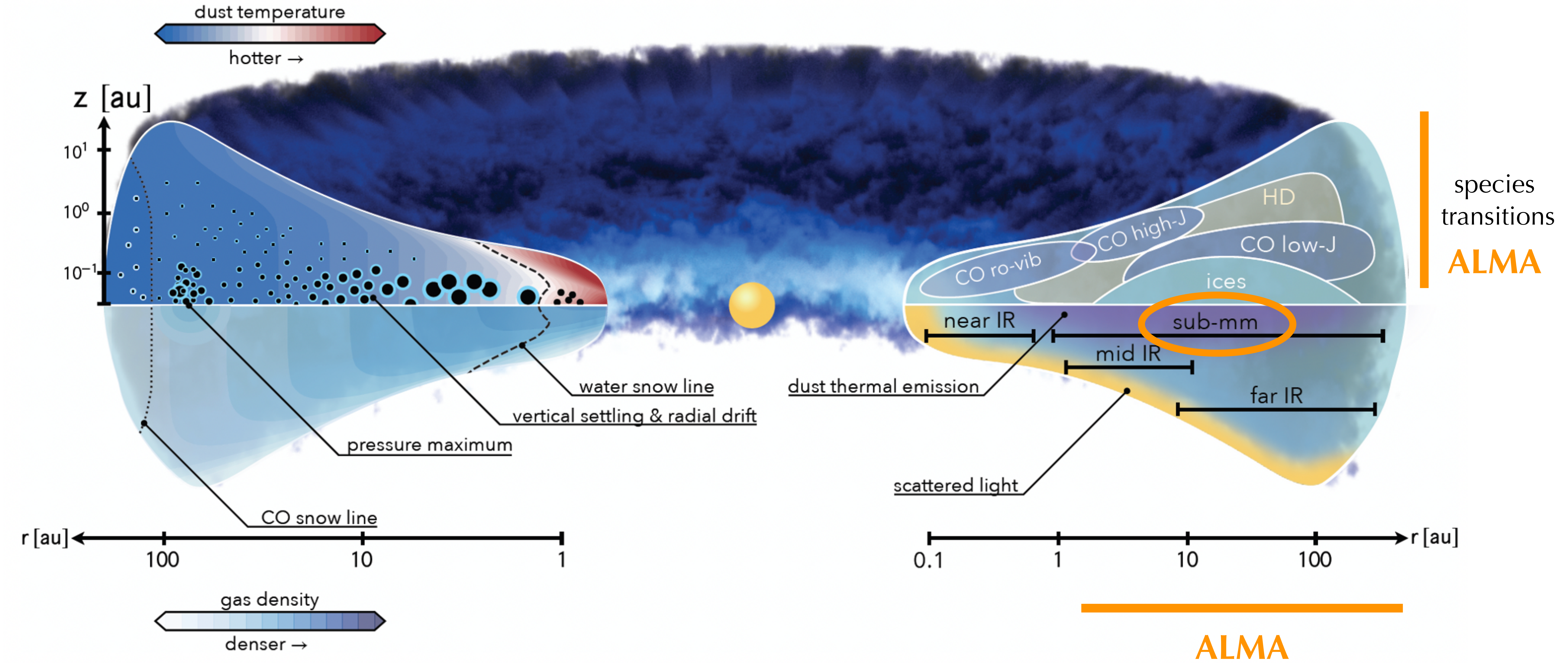
different tracers probe different disk properties

- mass, size, structure
- temperature, density, chemistry
- …

Birnstiel 2023 ARA&A

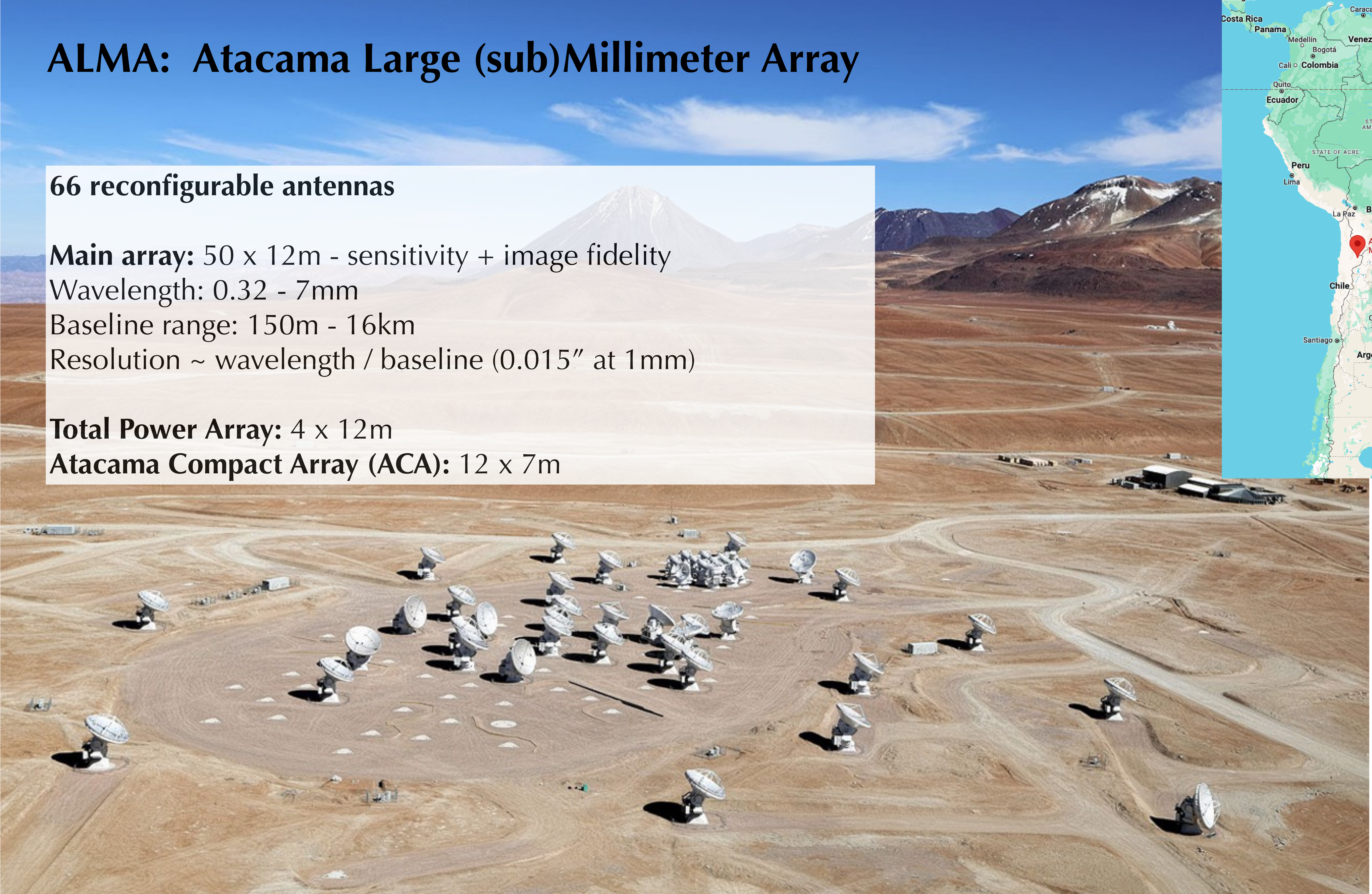
protoplanetary disk scales
10s-100s AU in radius

0.07-0.7 arcsec if d=140pc



Miotello+2023 PPVII review

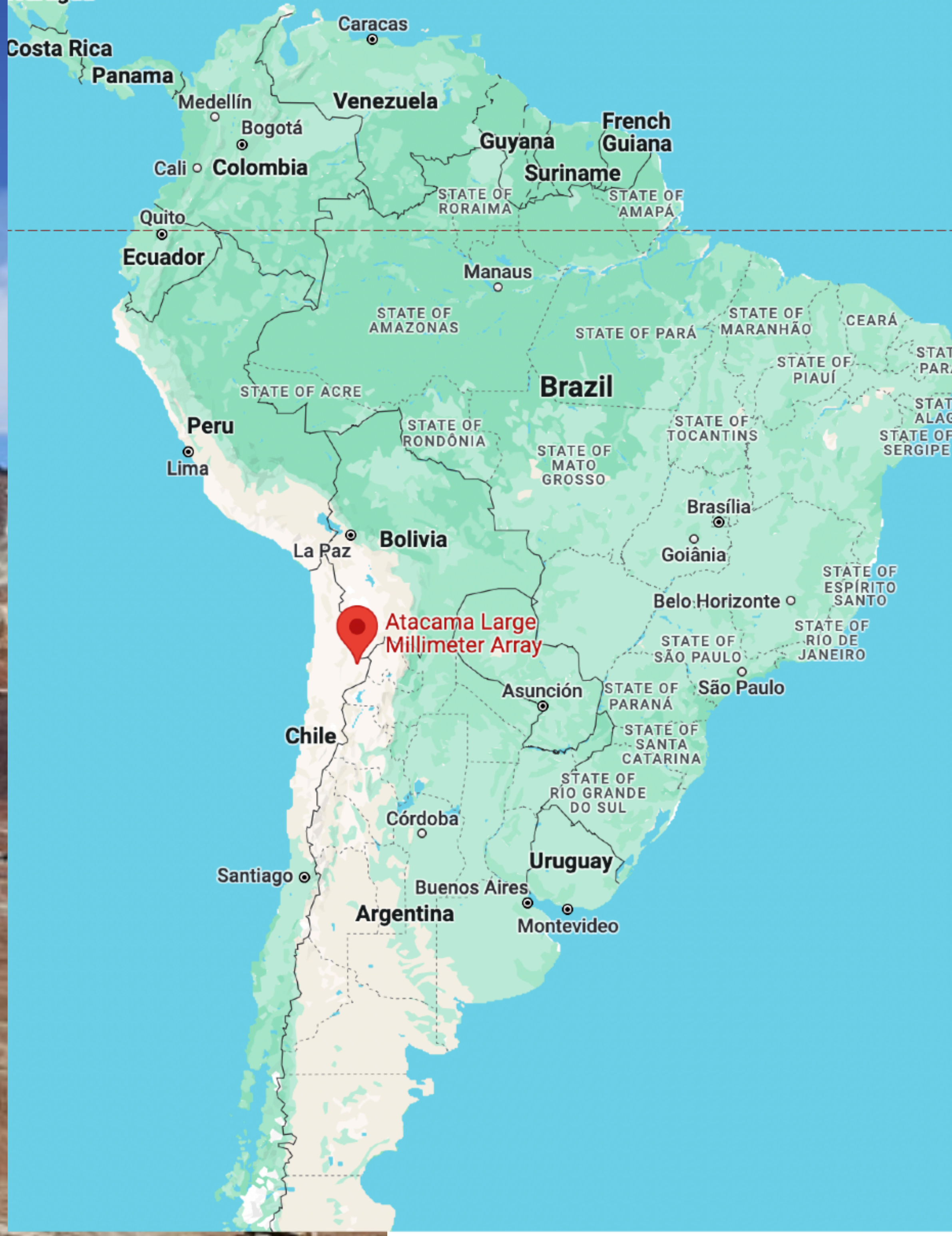
ALMA: Atacama Large (sub)Millimeter Array



66 reconfigurable antennas

Main array: 50 x 12m - sensitivity + image fidelity
Wavelength: 0.32 - 7mm
Baseline range: 150m - 16km
Resolution ~ wavelength / baseline (0.015″ at 1mm)

Total Power Array: 4 x 12m
Atacama Compact Array (ACA): 12 x 7m



5000m
Atacama desert
in Chile

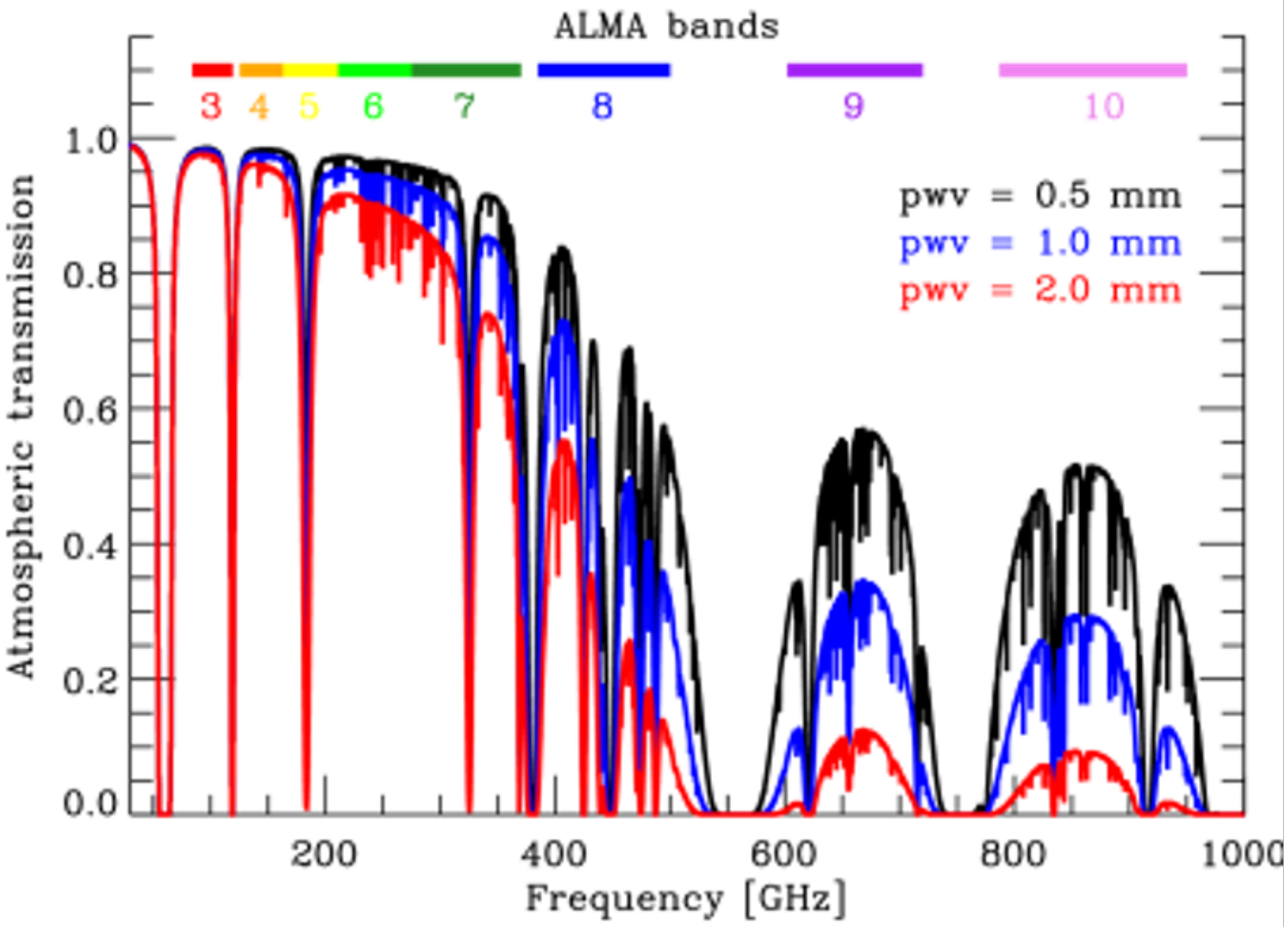
ALMA observations touches the cold universe

Three types of observations

- **continuum** imaging, up to 7.5GHz bandwidth
- **Spectral line** imaging, high velocity resolution of ~30 m/s
- **Polarization** mapping (full Stokes parameters of I, Q, U, V)

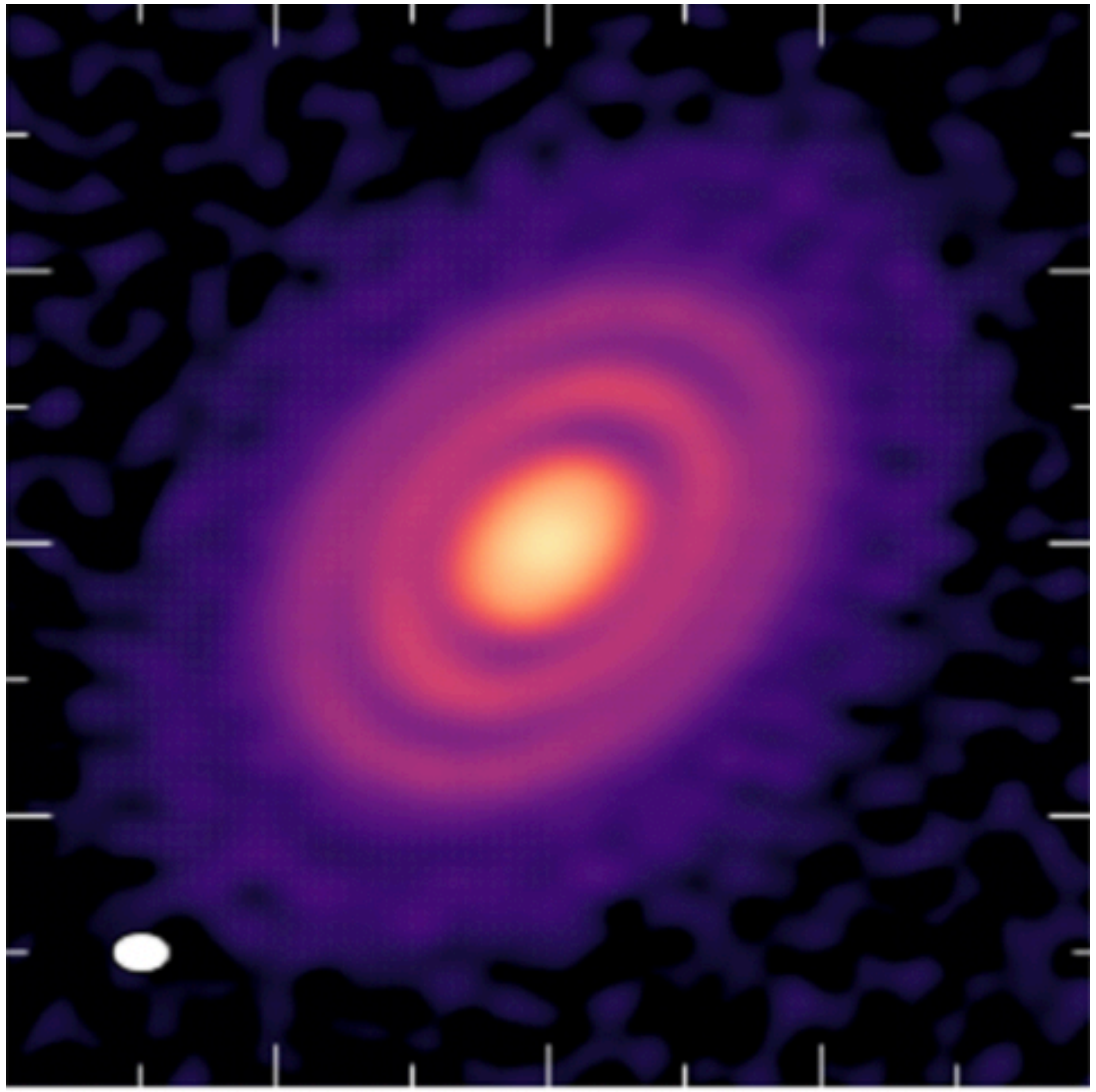
Sub/mm observations need dry weather

This is why it has to sit in the desert!



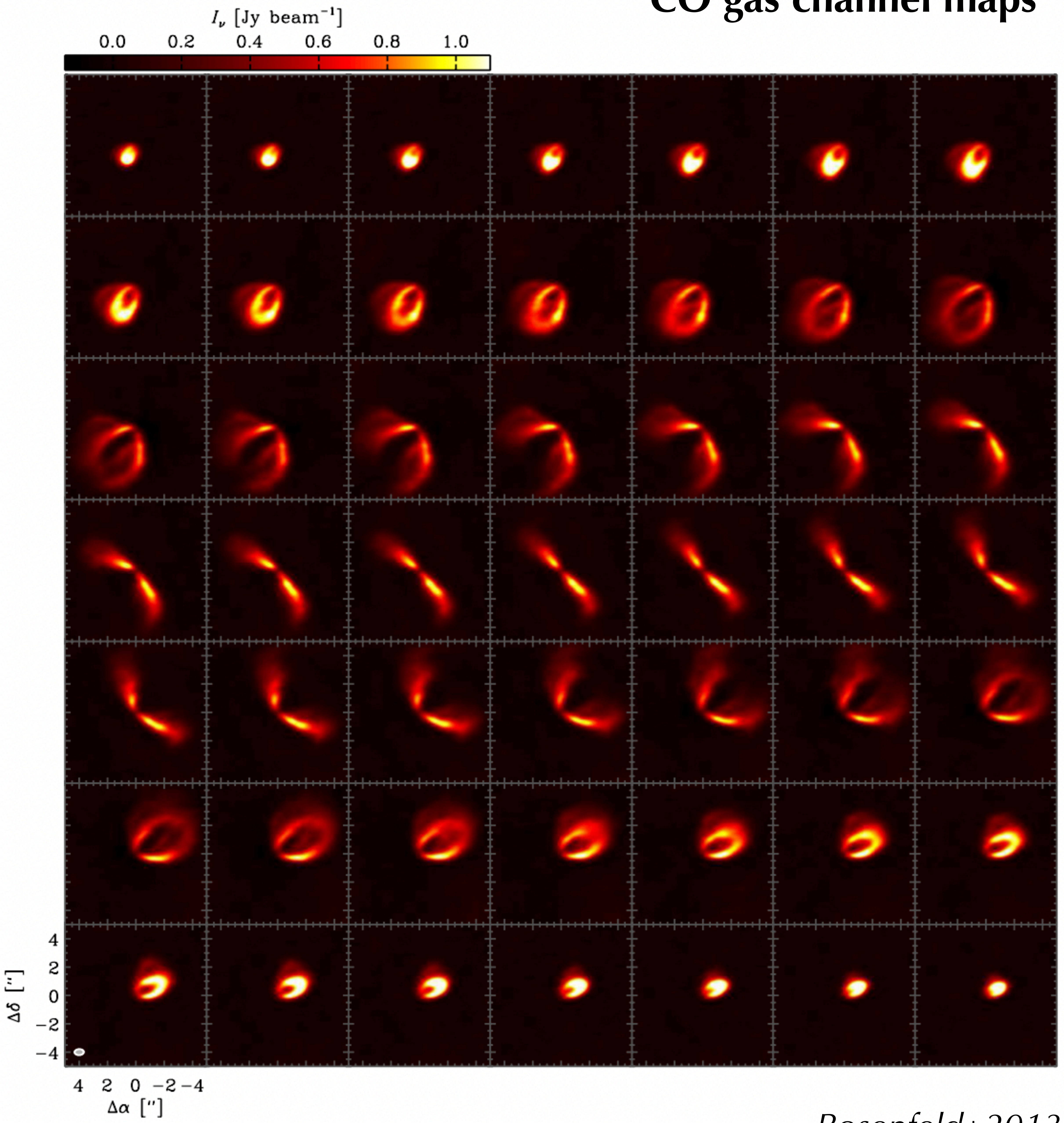
ALMA observation products

mm continuum image



Isella+2016

CO gas channel maps



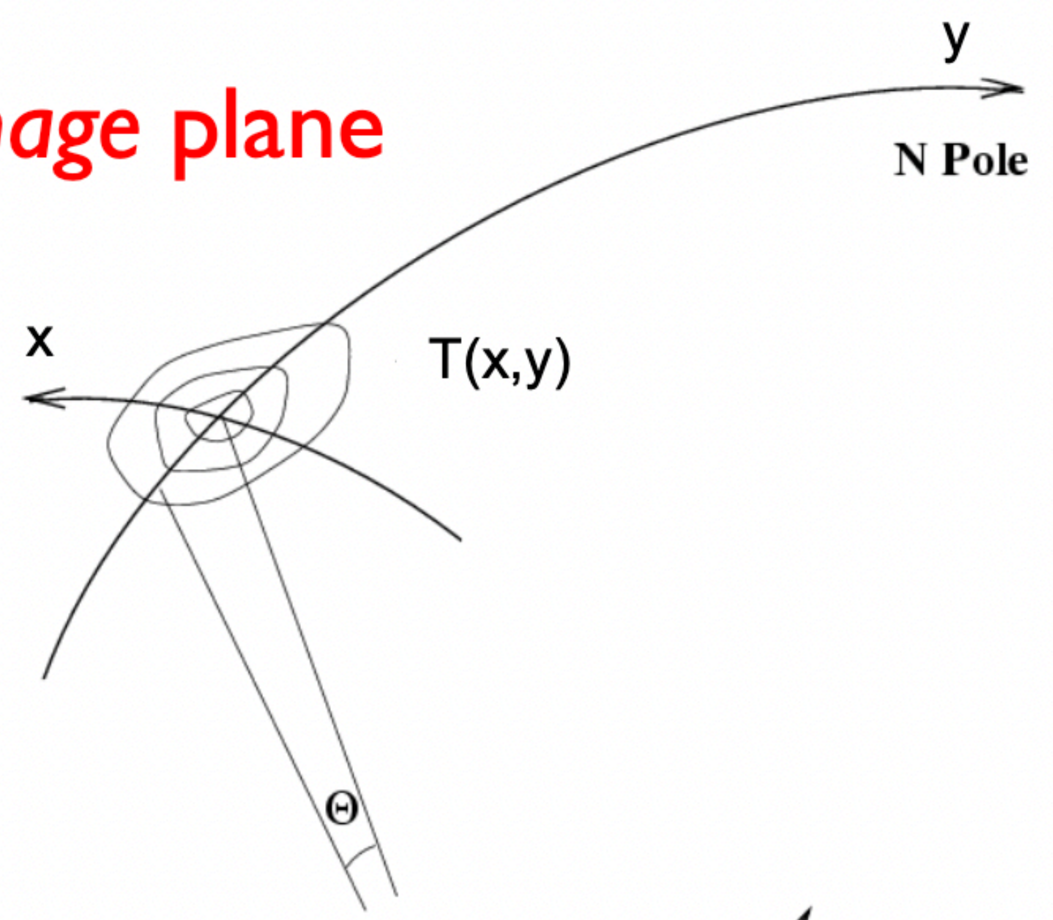
Rosenfeld+2013

From Sky Brightness to Visibility

1. An interferometer measures the interference pattern observed by pairs of apertures
2. The interference pattern is directly related to the source brightness. In particular, for small fields of view, the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)

(van Cittert-Zernike theorem)

image plane



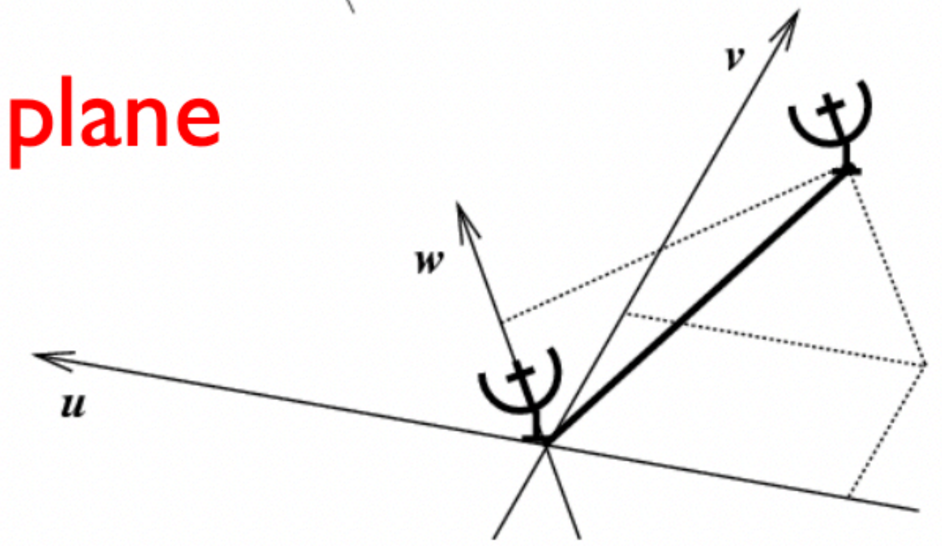
Fourier space/domain

$$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dxdy$$

$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} dudv$$

Image space/domain

uv plane



NRAO

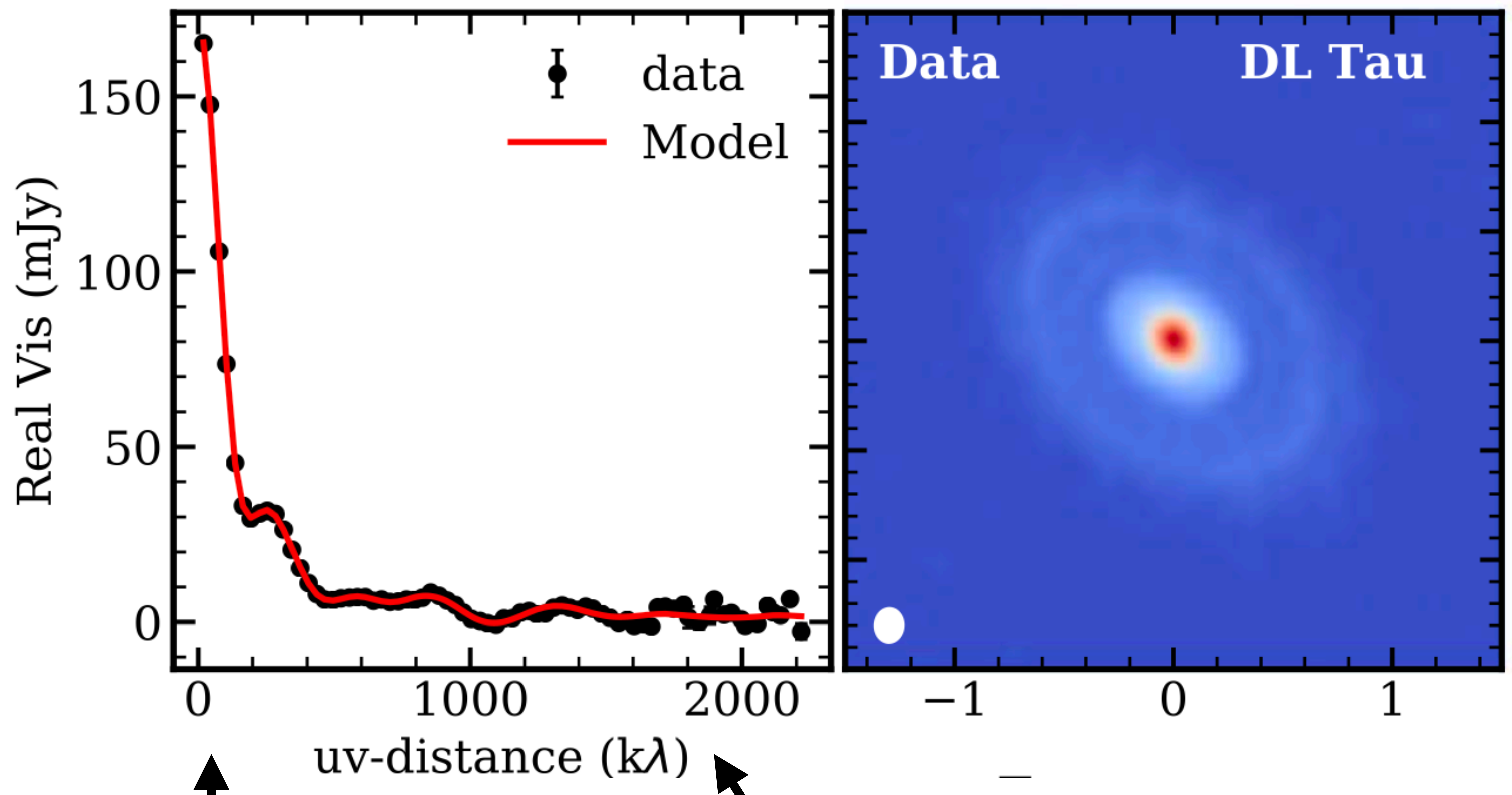
How interferometer (ALMA) works?

Small uv-distance: **short baseline** (measure **extended** emission)

Long uv-distance: **long baseline** (measure **small-scale** emission)

Visibility visualization

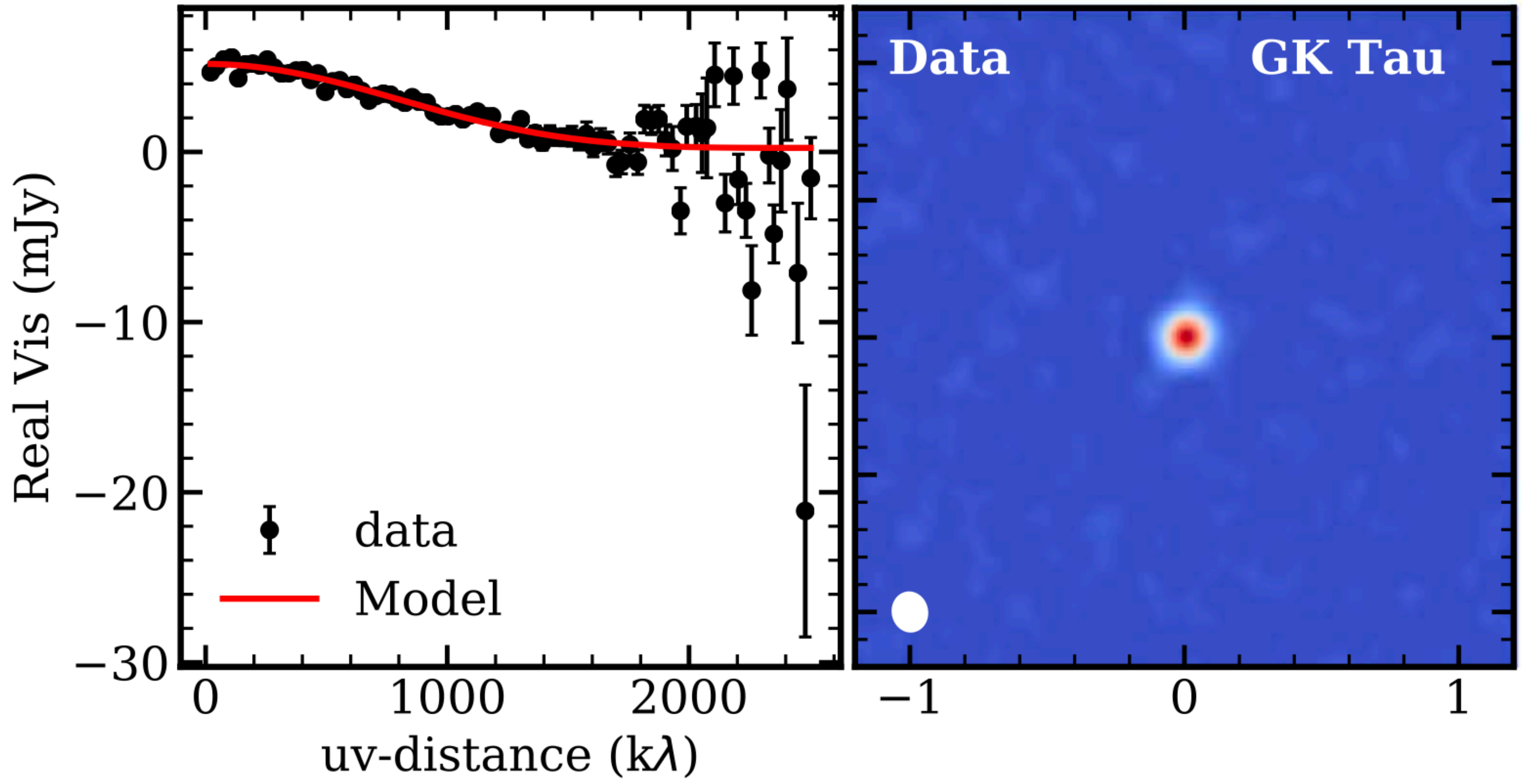
Well-resolved

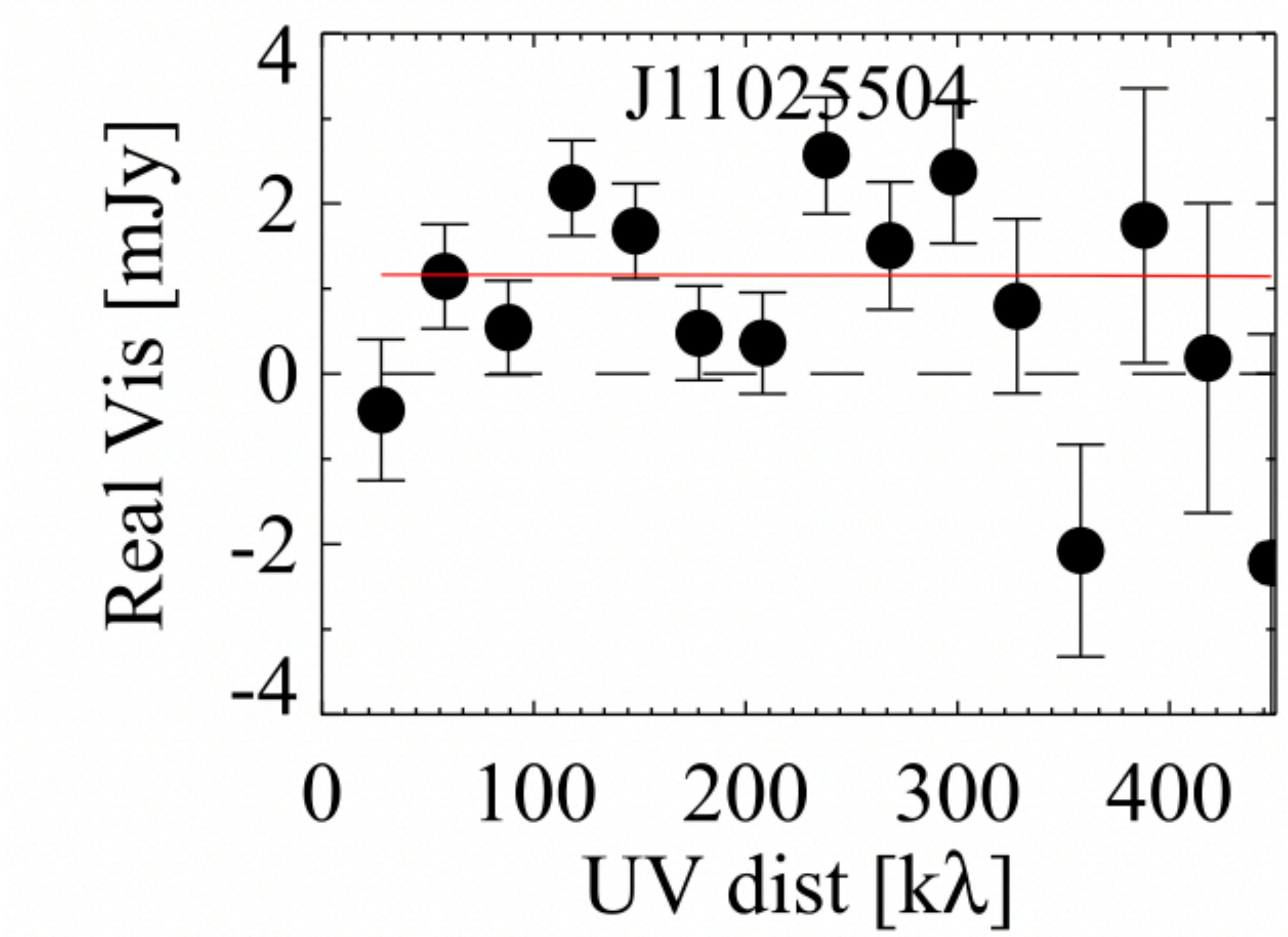


Small uv-distance measures extended emission, captures most disk emission

large uv-distance measures small-scale feature, with low amplitude

marginally-resolved

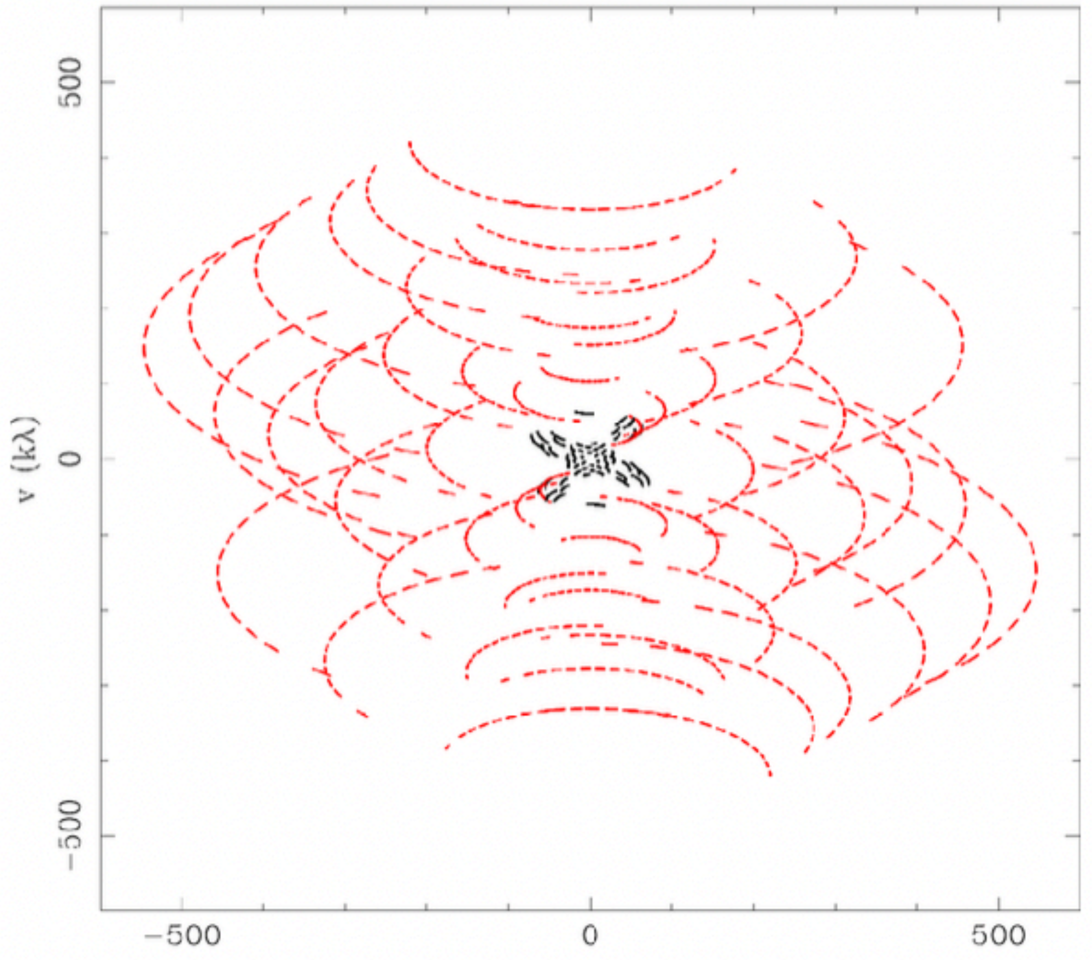




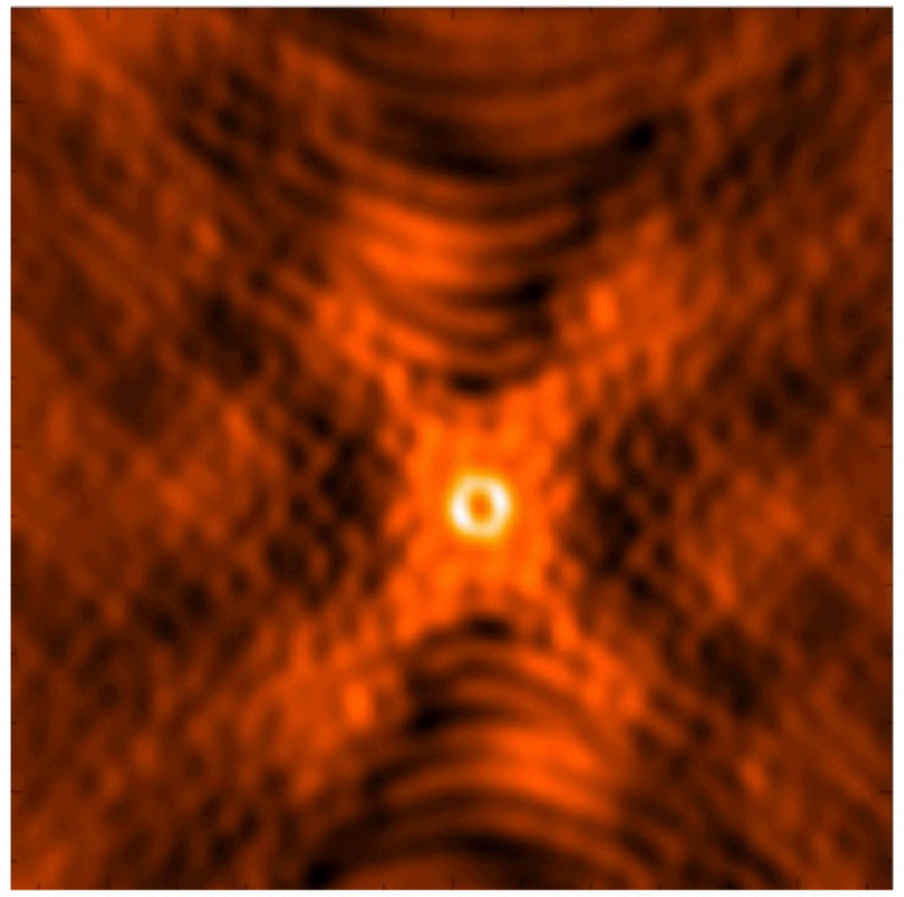
unresolved point source

The observed (AKA dirty) image is the true image convolved with the PSF.

B(u,v)
(sampled visibilities)



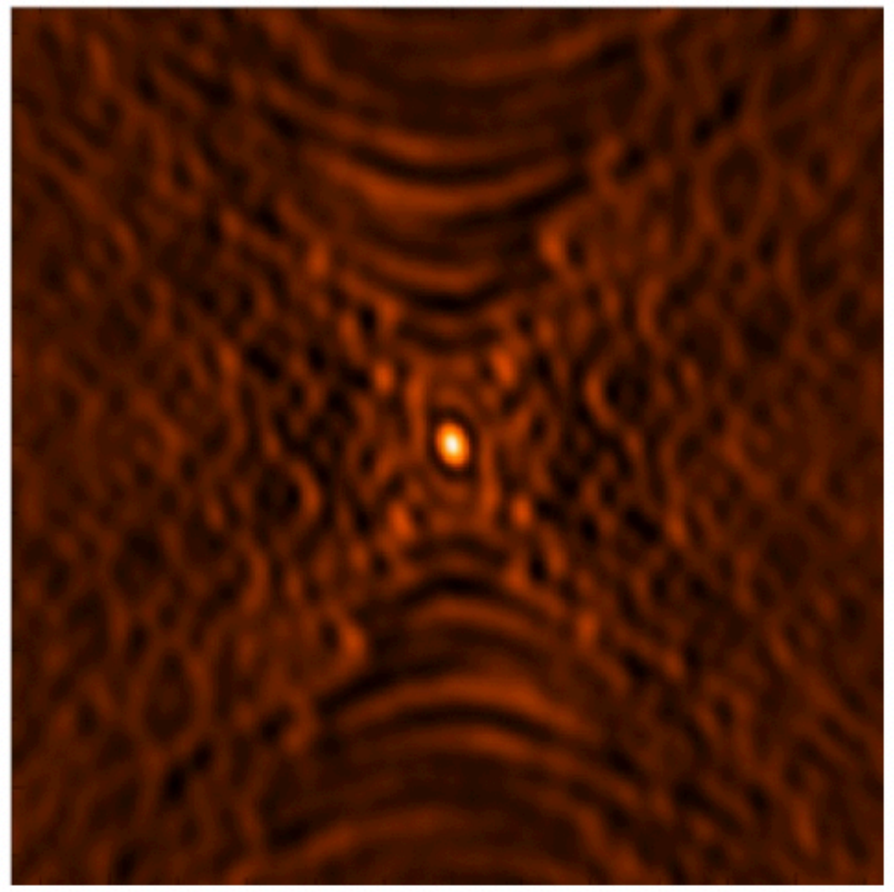
⇌ (Fourier Transform)



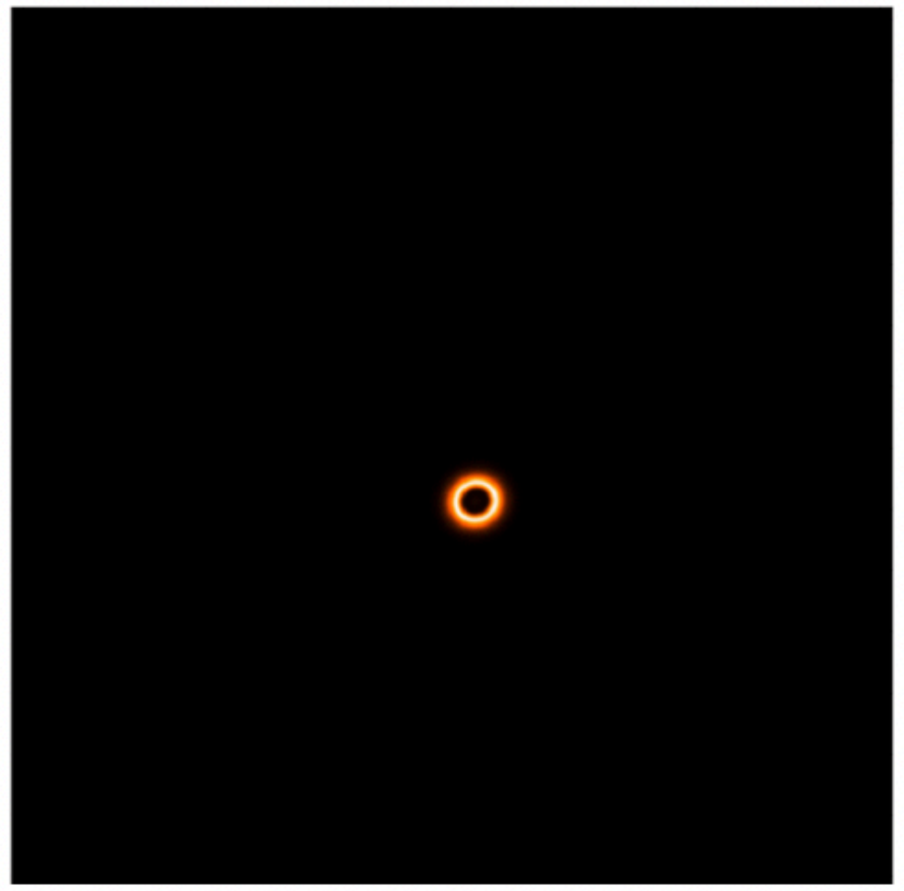
TD(x,y)
(dirty image)

↑

b(x,y)
(dirty beam or psf)



⊗ Convolve



T(x,y)
(True sky brightness)

- Fourier transform of sampled visibilities creates a **dirty image** - the convolution product of true sky brightness and the point spread function (PSF, 'dirty beam')
- We need to **deconvolve** the PSF from the dirty image to reconstruct the source image ('**clean**')
- The final 'cleaned' image is the convolution of sky brightness model and 'cleaned' beam

How to set up ALMA observations to obtain mm fluxes for a typical disk?

ALMA sensitivity calculator

$$\sigma_S = \frac{w_r\, 2\, k\, T_{\rm sys}}{\eta_q \eta_c A_{\rm eff}\,(1 - f_s)\sqrt{N(N-1)\, n_p\, \Delta\nu\, t_{\rm int}}}$$

Common Parameters

- **Declination**: 22:00:00.00
- **Polarisation**: Dual
- **Observing Frequency**: 345 GHz
- **Observing Band**: ALMA_RB_07
- **Bandwidth per Polarization**: 7.500000 GHz
- **Water Vapour**: Automatic Choice / Manual Choice
- **Column Density**: 0.913mm (3rd Octile)
- **Trx, tau, Tsky**: 72 K, 0.158, 50.207 K
- **Tsys**: 174.775 K

Individual Parameters

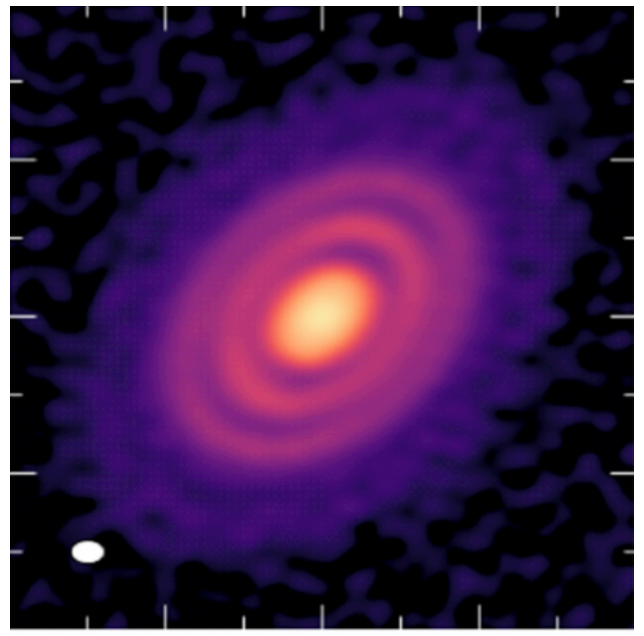
	12 m Array	7 m Array	Total Power Array
Number of Antennas	43	10	3
Resolution	0.3 arcsec	0 arcsec	9.5 arcsec
Sensitivity (rms)	0.2 mJy	2.4826852653365648 mJy	4.85010668201959 mJy
Equivalent to	22.828 mK	Unknown K	0.174 mK
Integration Time	72.61167 s	74.32935 s	60.32737 s

- **Integration Time Unit Option**: Automatic
- **Sensitivity Unit Option**: Automatic

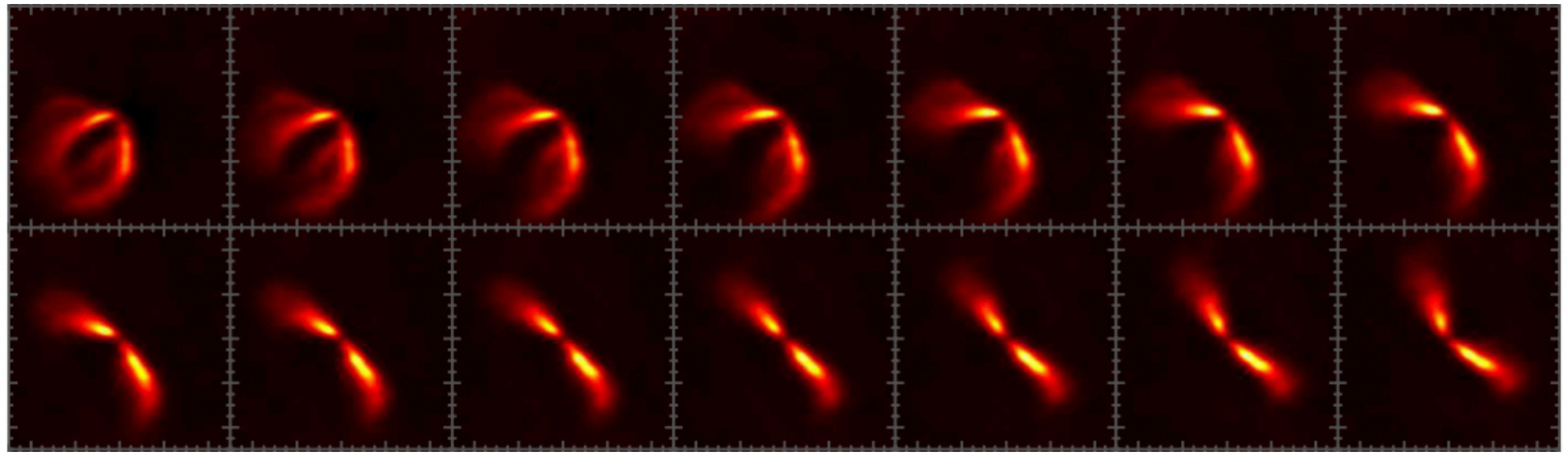
Calculate Integration Time | Calculate Sensitivity

How to set up ALMA observations to obtain mm fluxes for a typical disk?

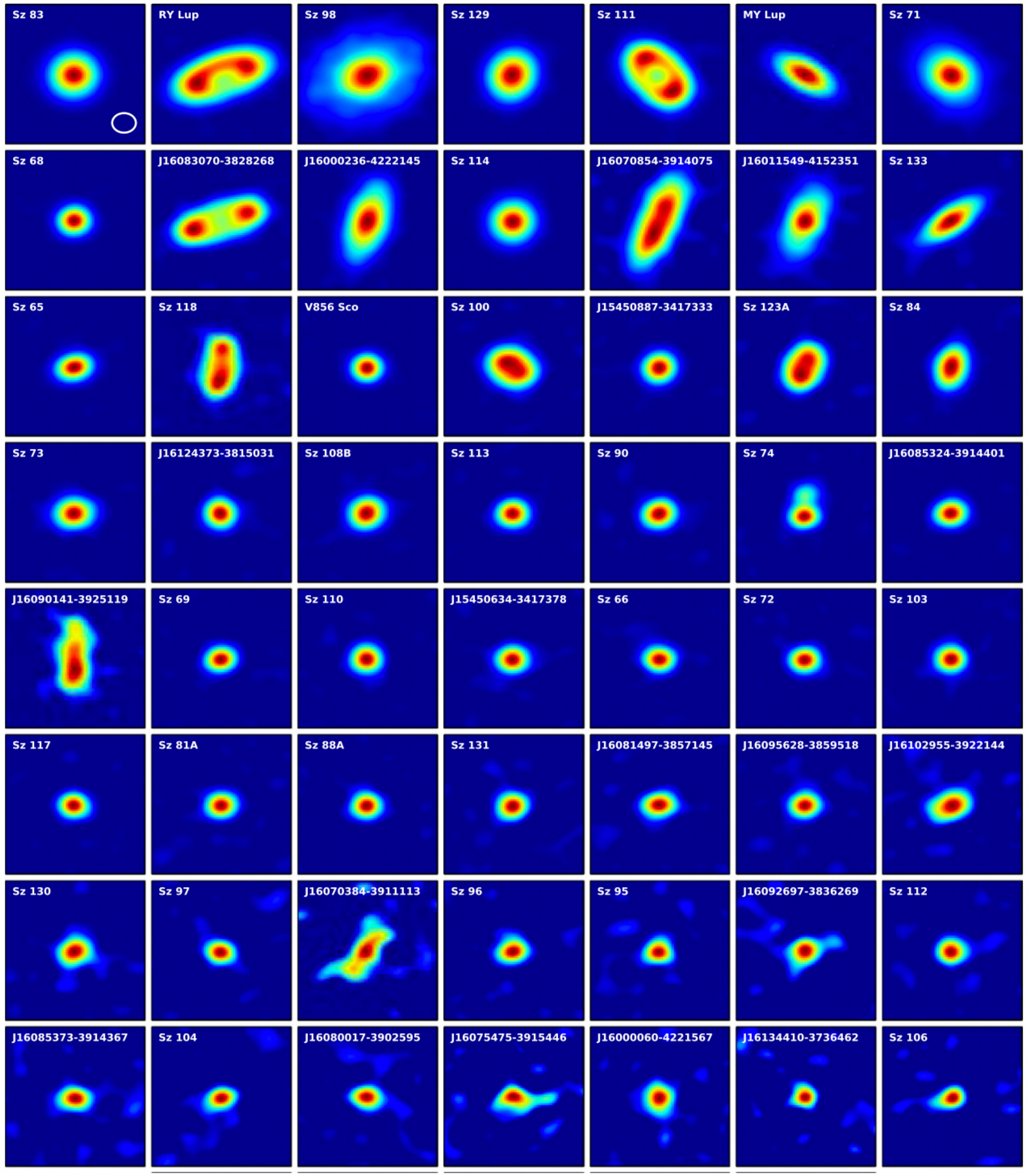
How to set up ALMA observations to map the disk structure?



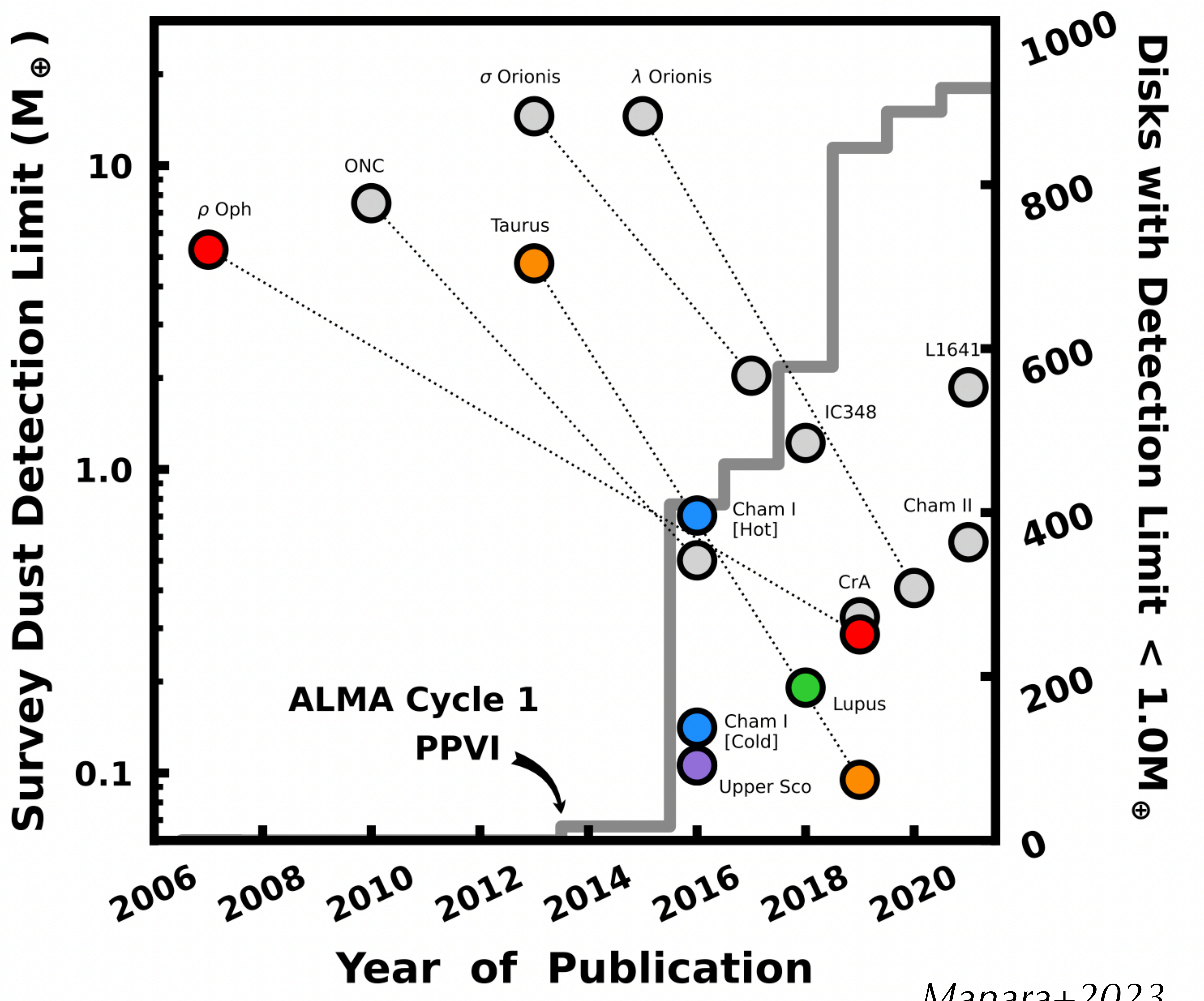
How to set up ALMA observations to get gas line information?



ALMA opens up statistical study of fundamental disk properties



Ansdell+2016

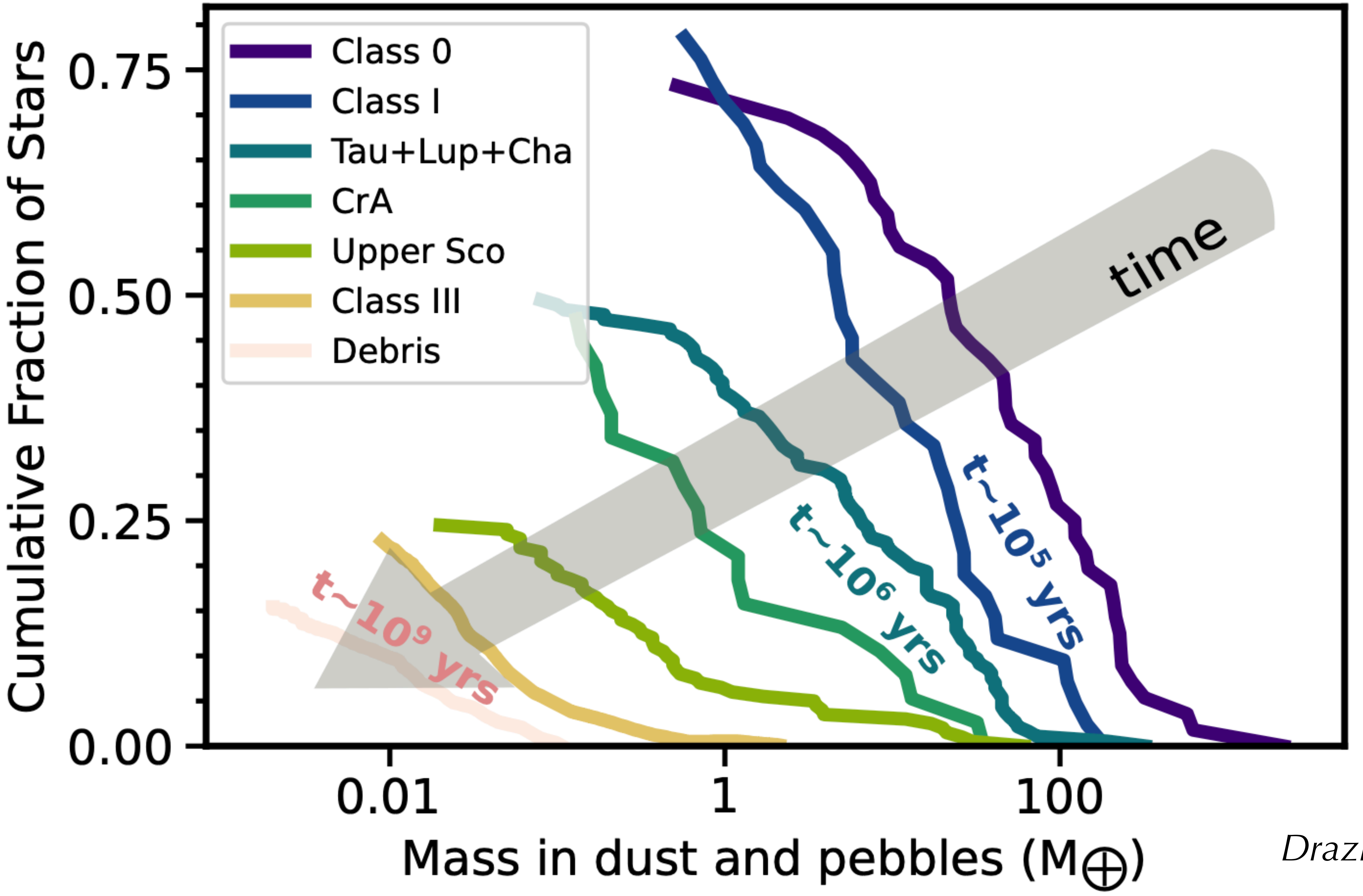


Manara+2023, PPVII review

dust mass in disks

Is the remaining disk material sufficient to form planets?

$$M_d = \frac{d^2 F_\nu}{\kappa_\nu B_\nu(T_c)}$$



Drazkowska+2023 PPVI Chapter

dust mass in disks

Scaling relation with stellar mass

$$M_d = \frac{d^2 F_\nu}{\kappa_\nu B_\nu(T_c)}$$

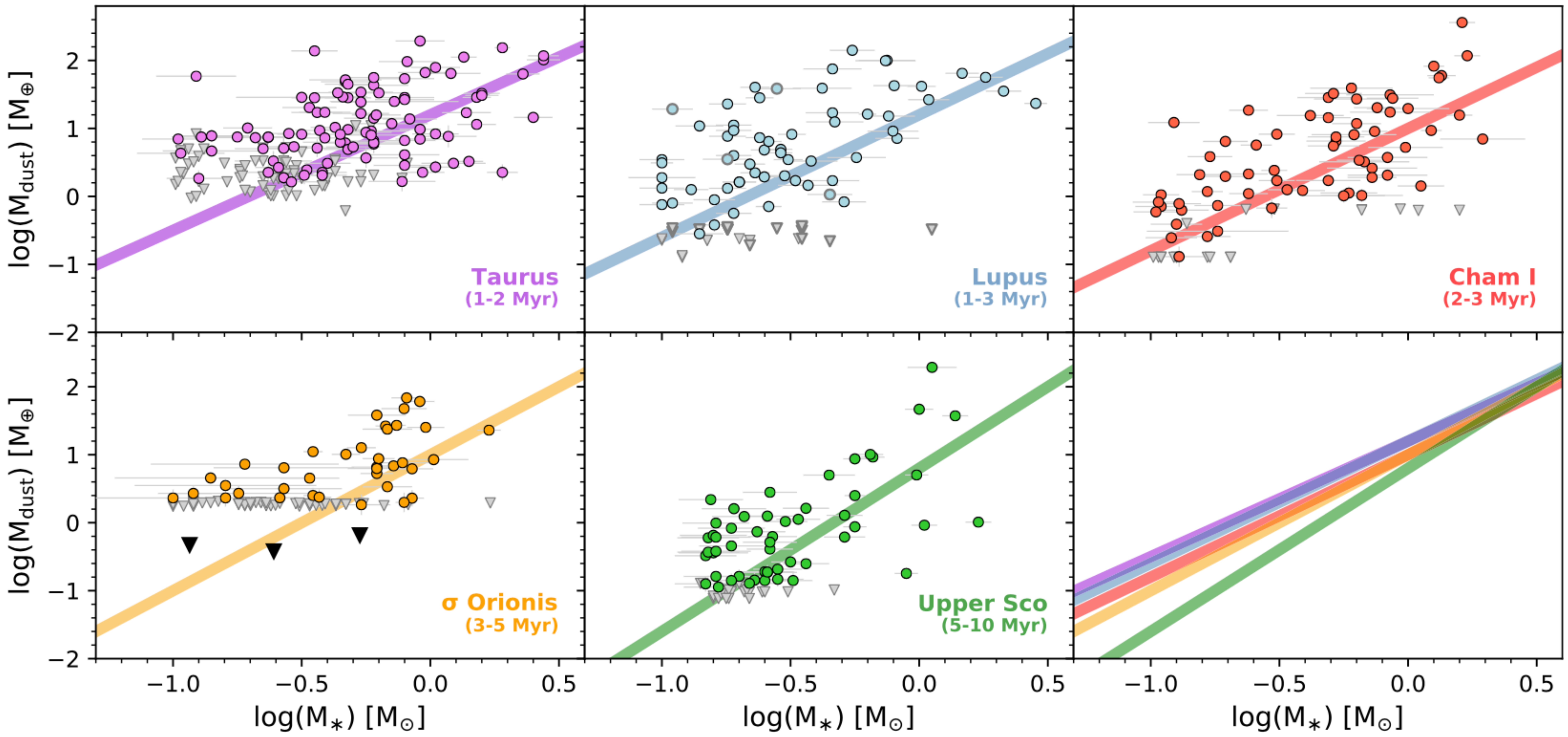


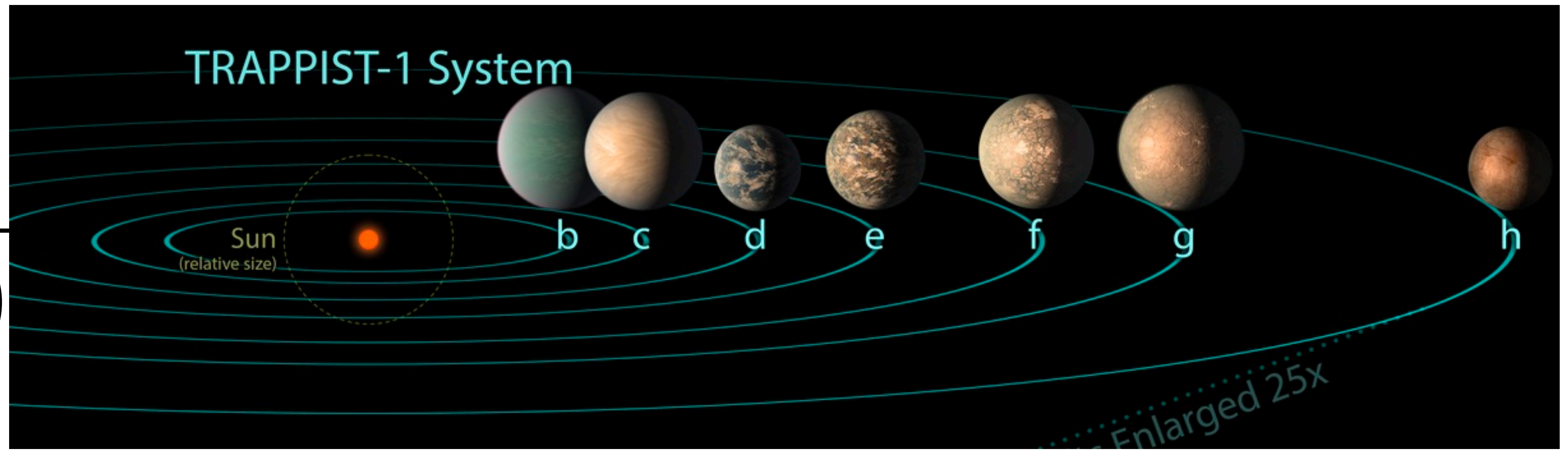
Figure from Ansdell et al. 2017

Using results by Andrews+2013, Ansdell+2016/2017, Pascucci+2016, Barenfeld+2016

dust mass in disks

Scaling relation with stellar mass

$$M_d = \frac{d^2 F_\nu}{\kappa_\nu B_\nu(T_c)}$$



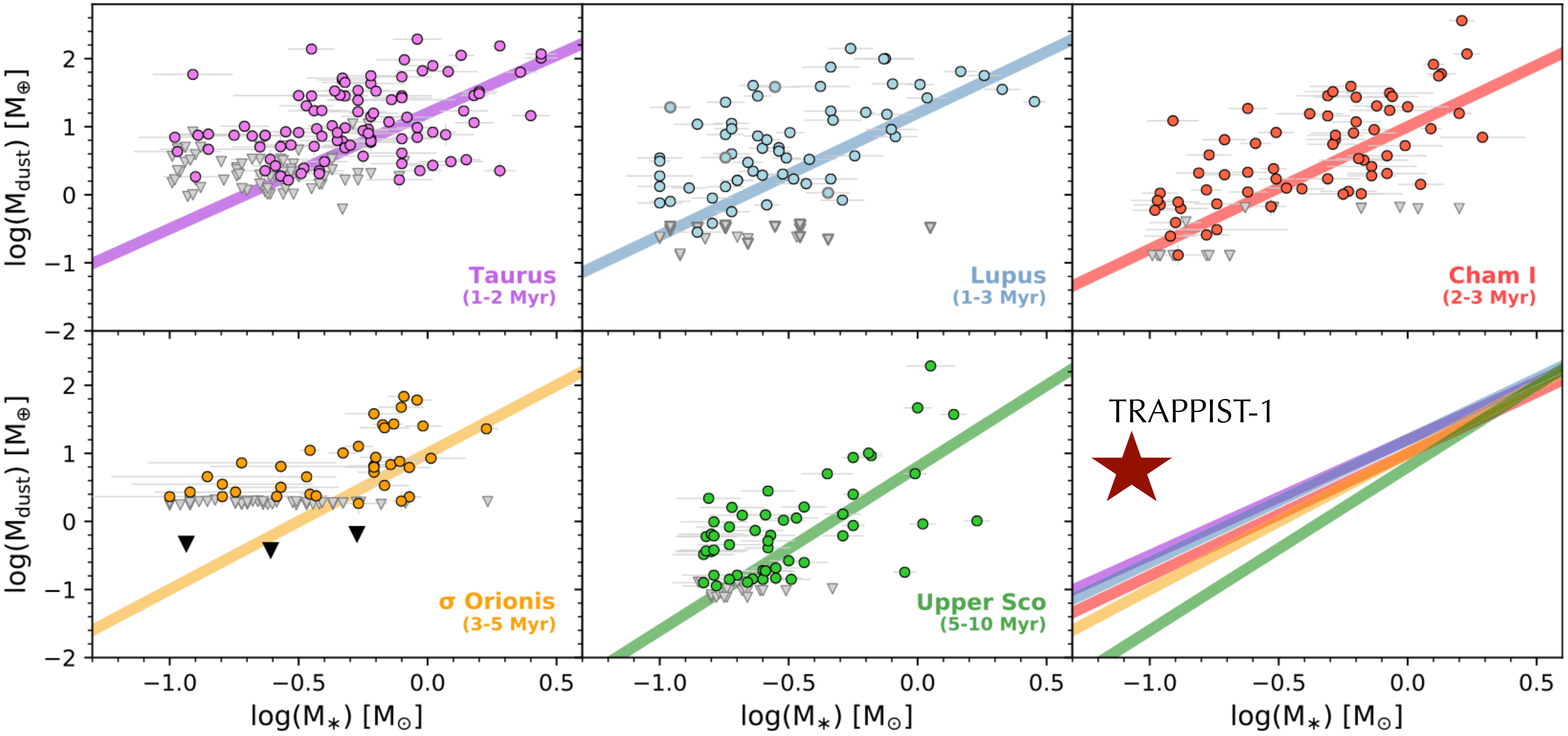
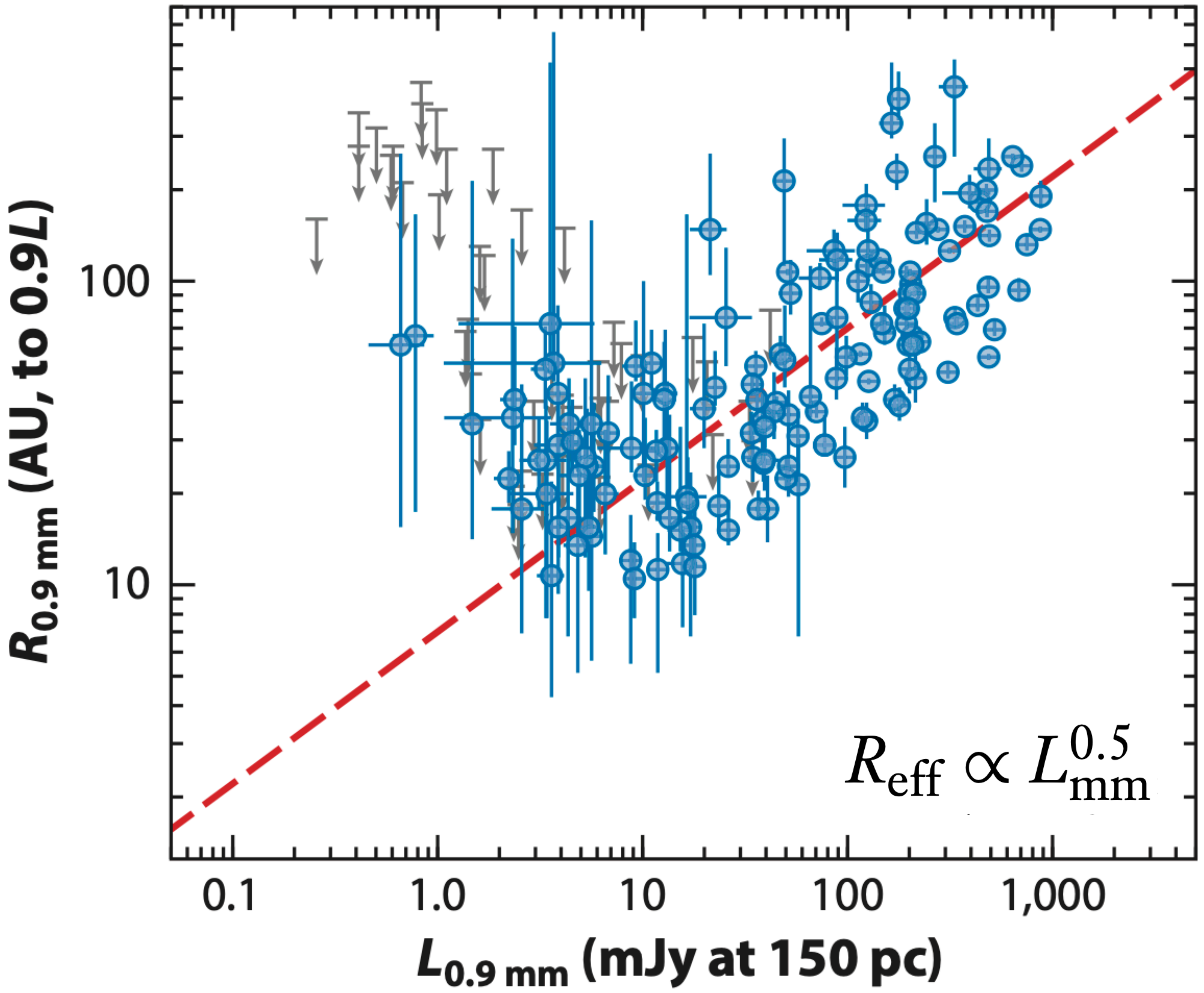


Figure from Ansdell et al. 2017

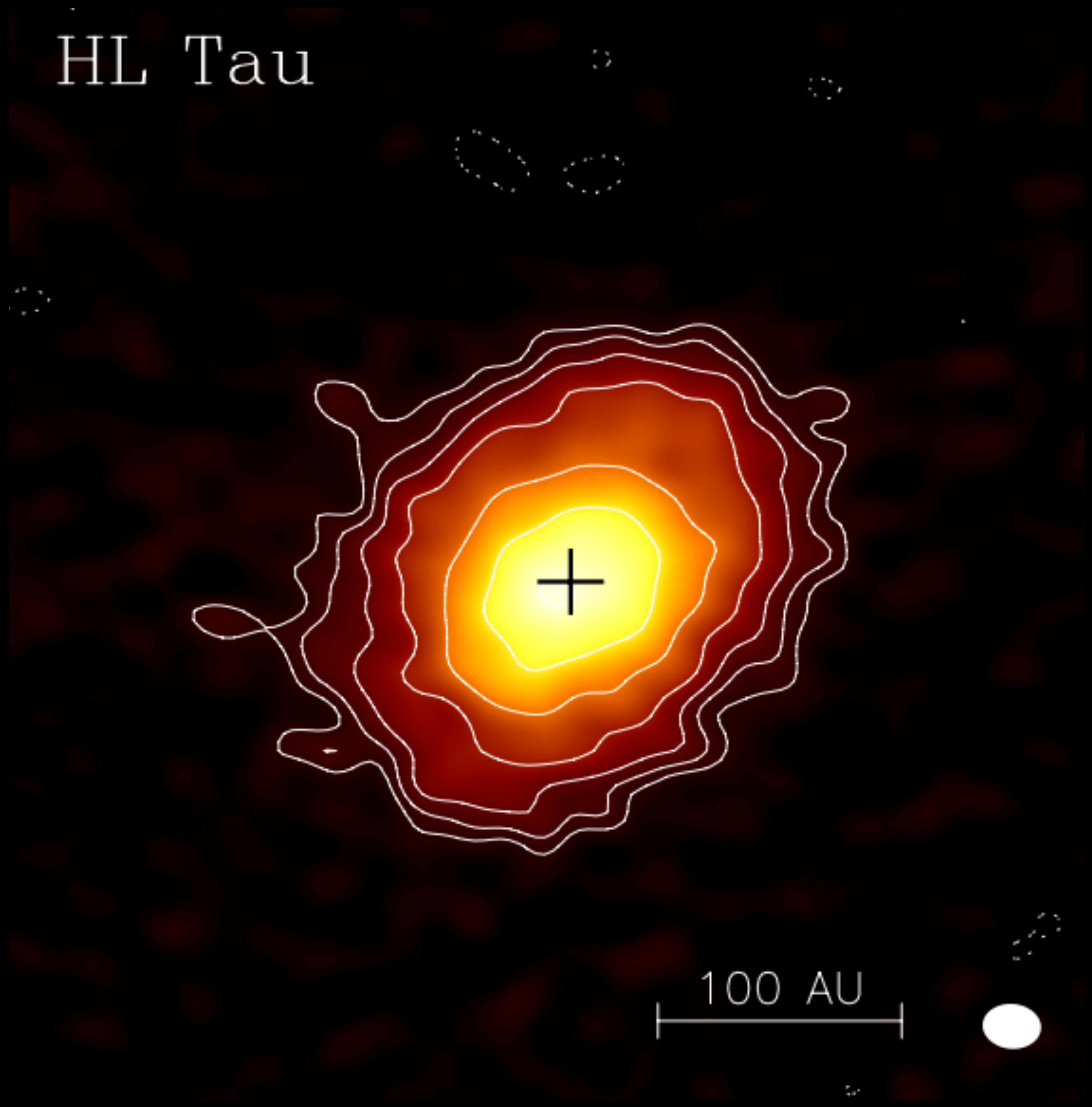
Using results by Andrews+2013, Ansdell+2016/2017, Pascucci+2016, Barenfeld+2016

dust disk size

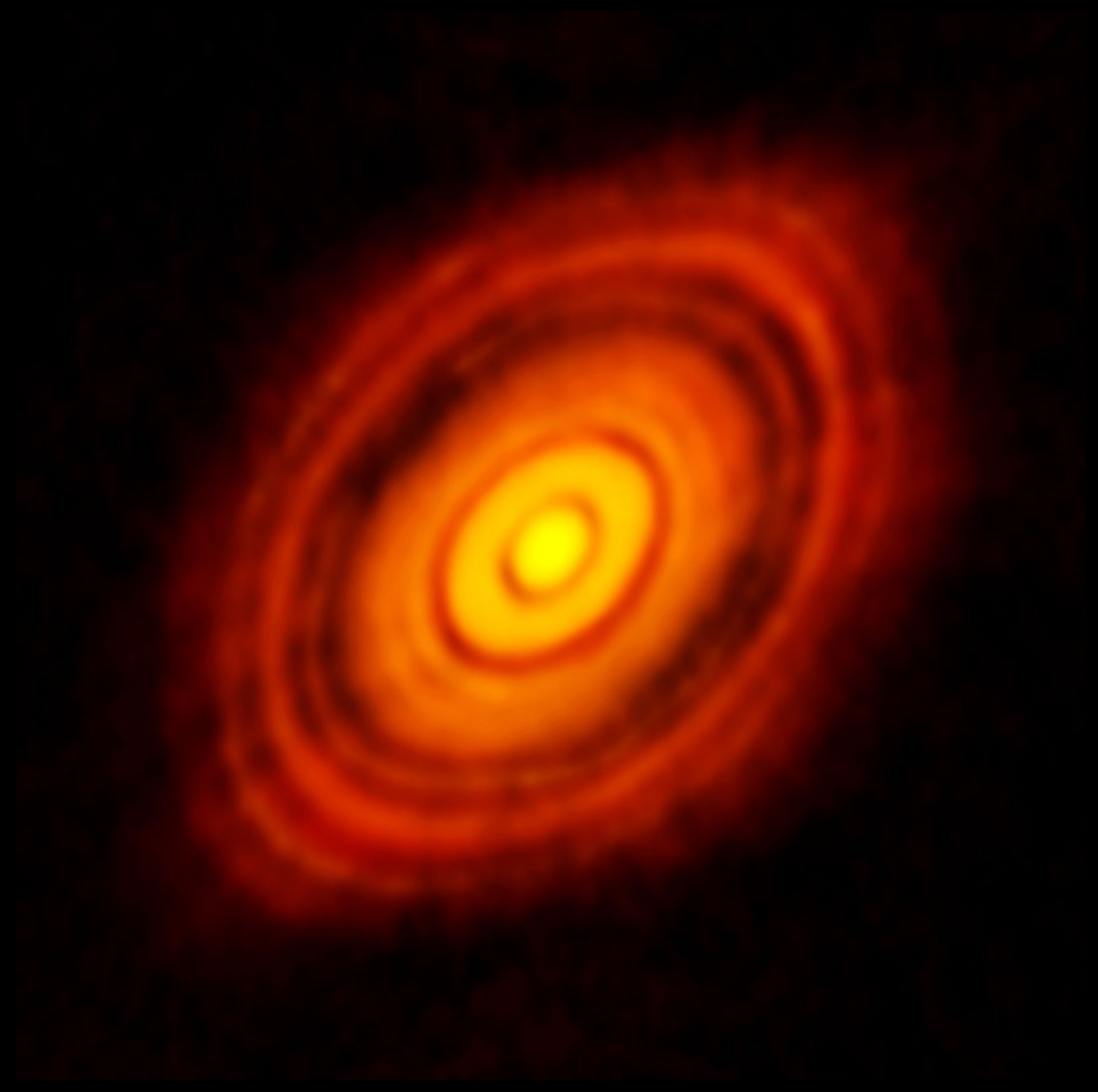


Andrews 2020, ARA&A

The ALMA revolution of disk structure



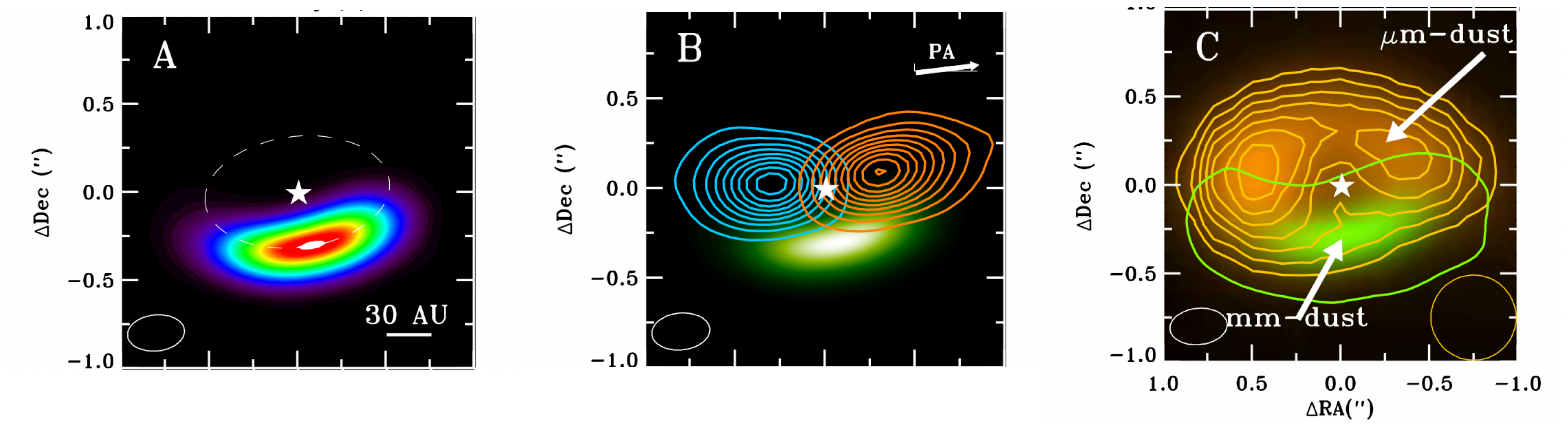
CARMA 0.17″x0.13″
Kwon+2011



ALMA 0.03″
ALMAPartership+2015

Dust “trap” in IRS 48

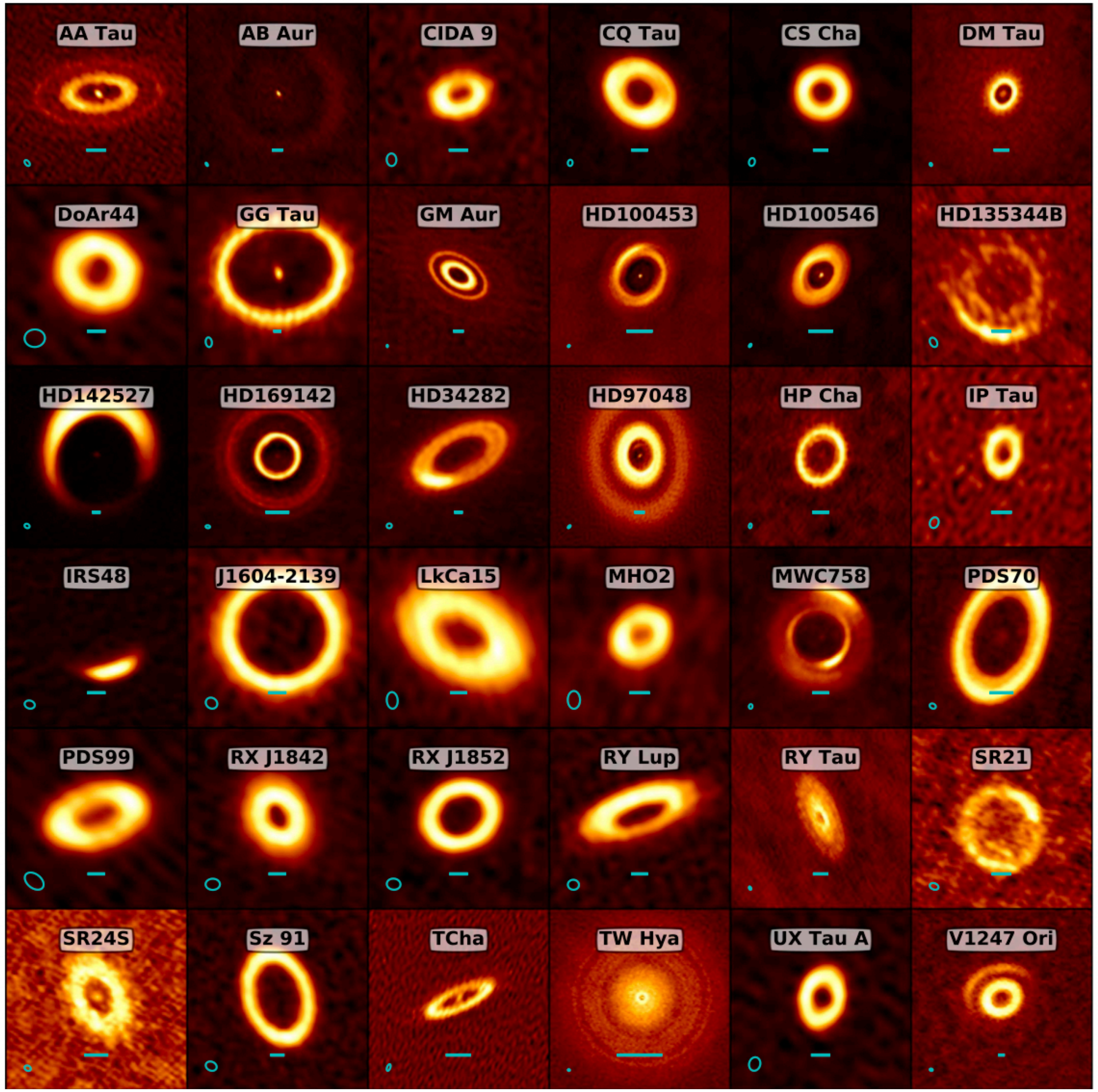
Large mm dust | **CO gas** | **Small micron grains**



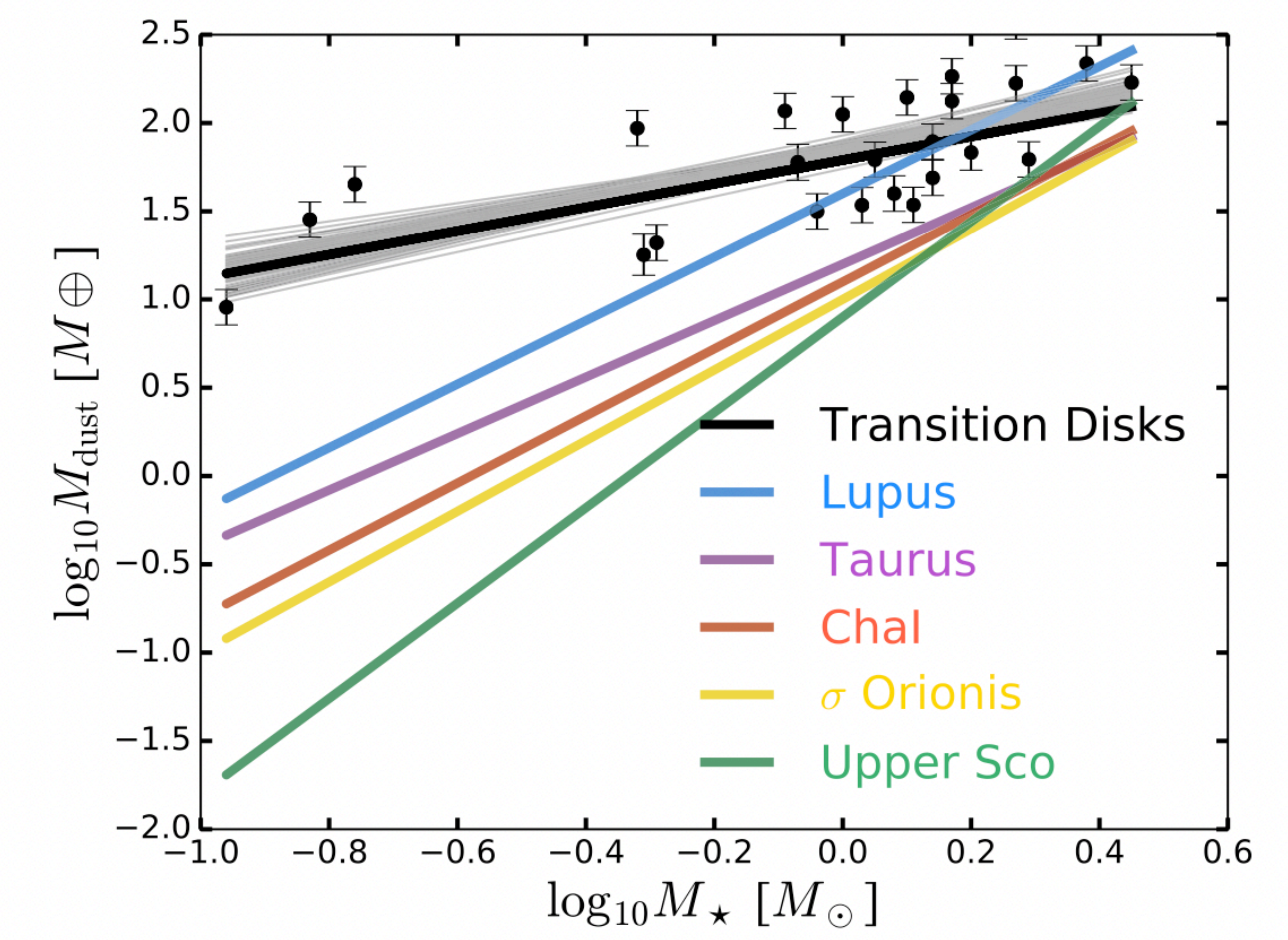
Planet induced vortex?

van der Marel+2013

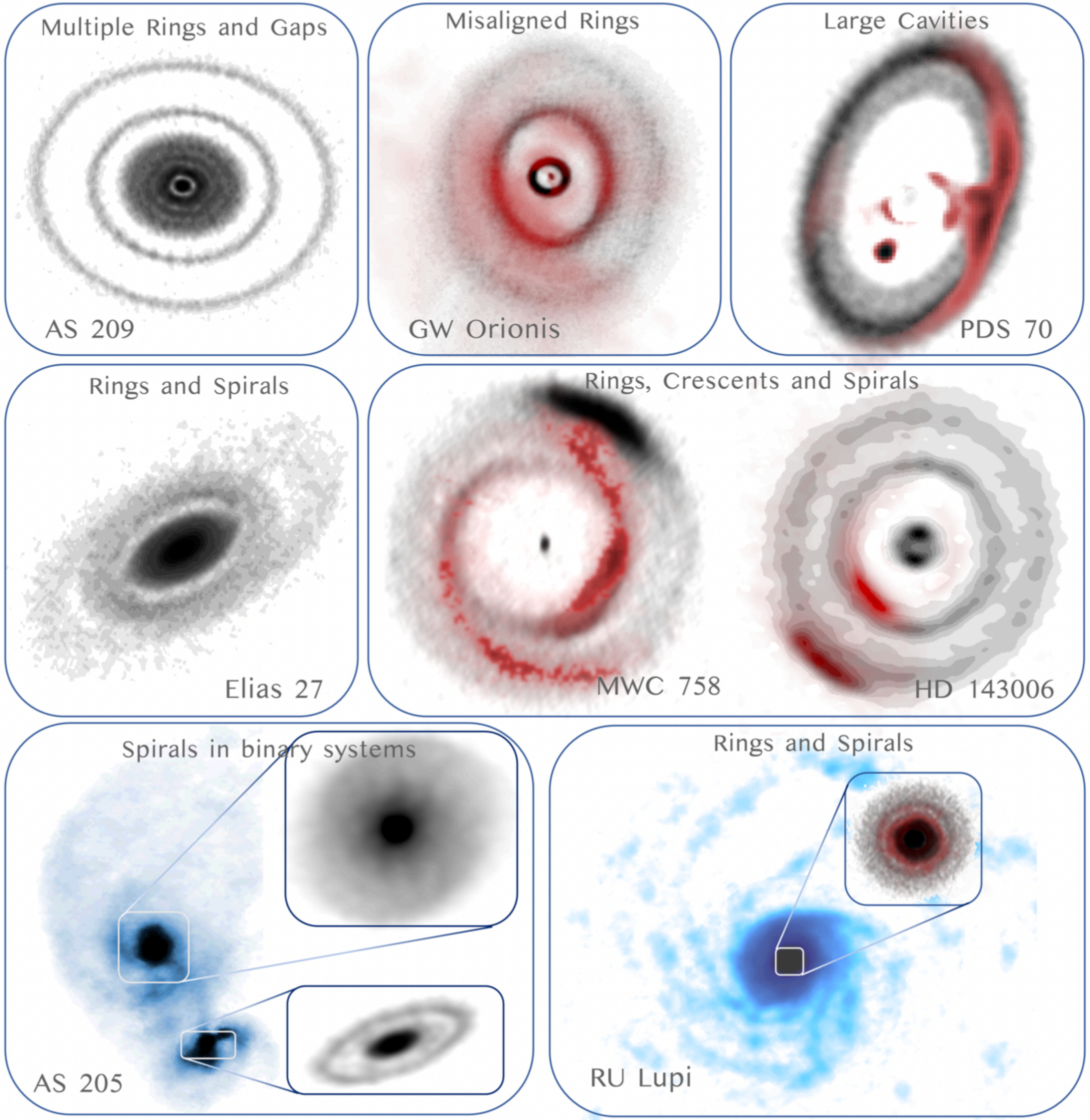
Disks with large inner cavity (transition disks)



Francis & van der Marel 2020



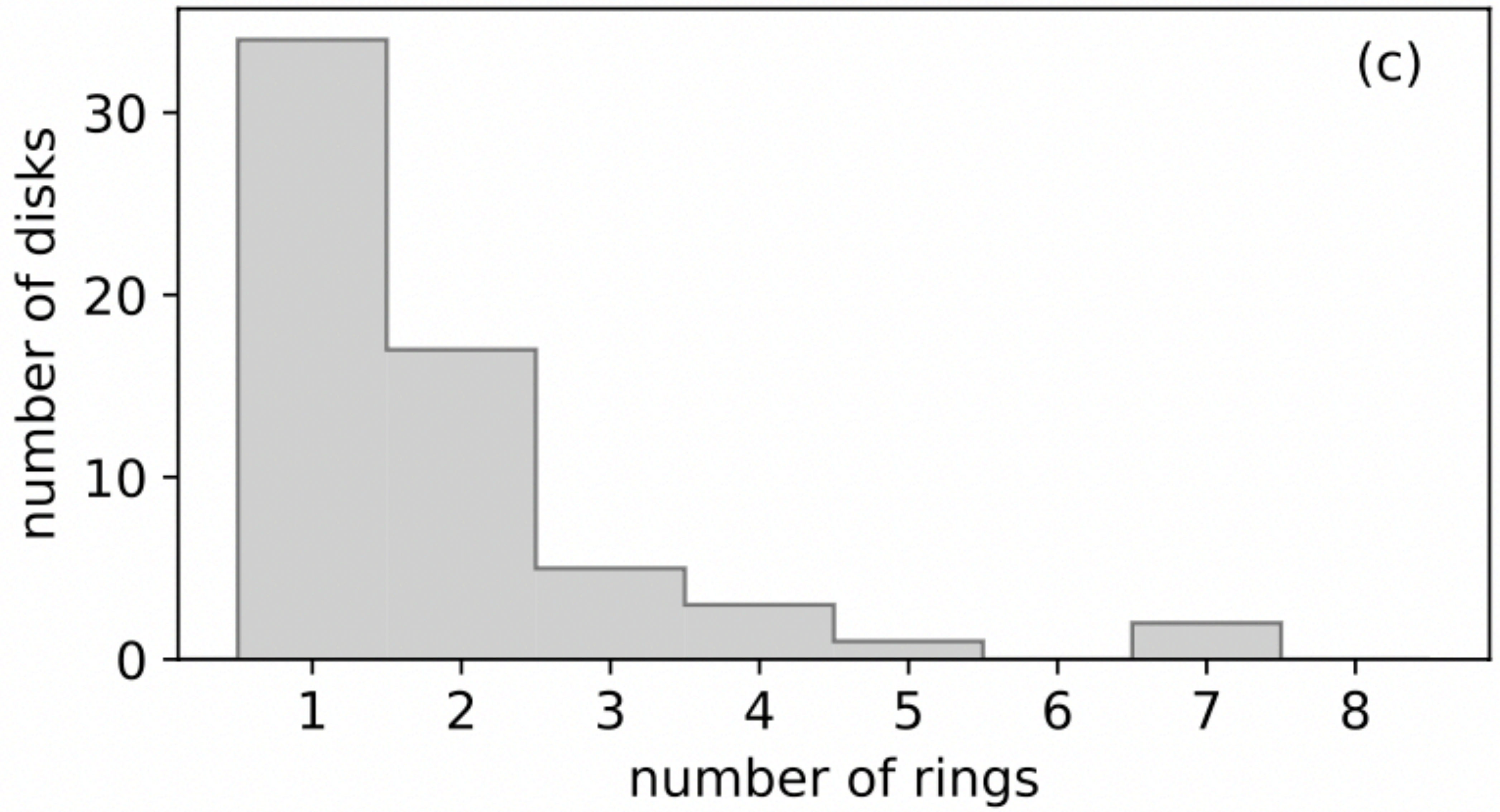
Pinilla+2018

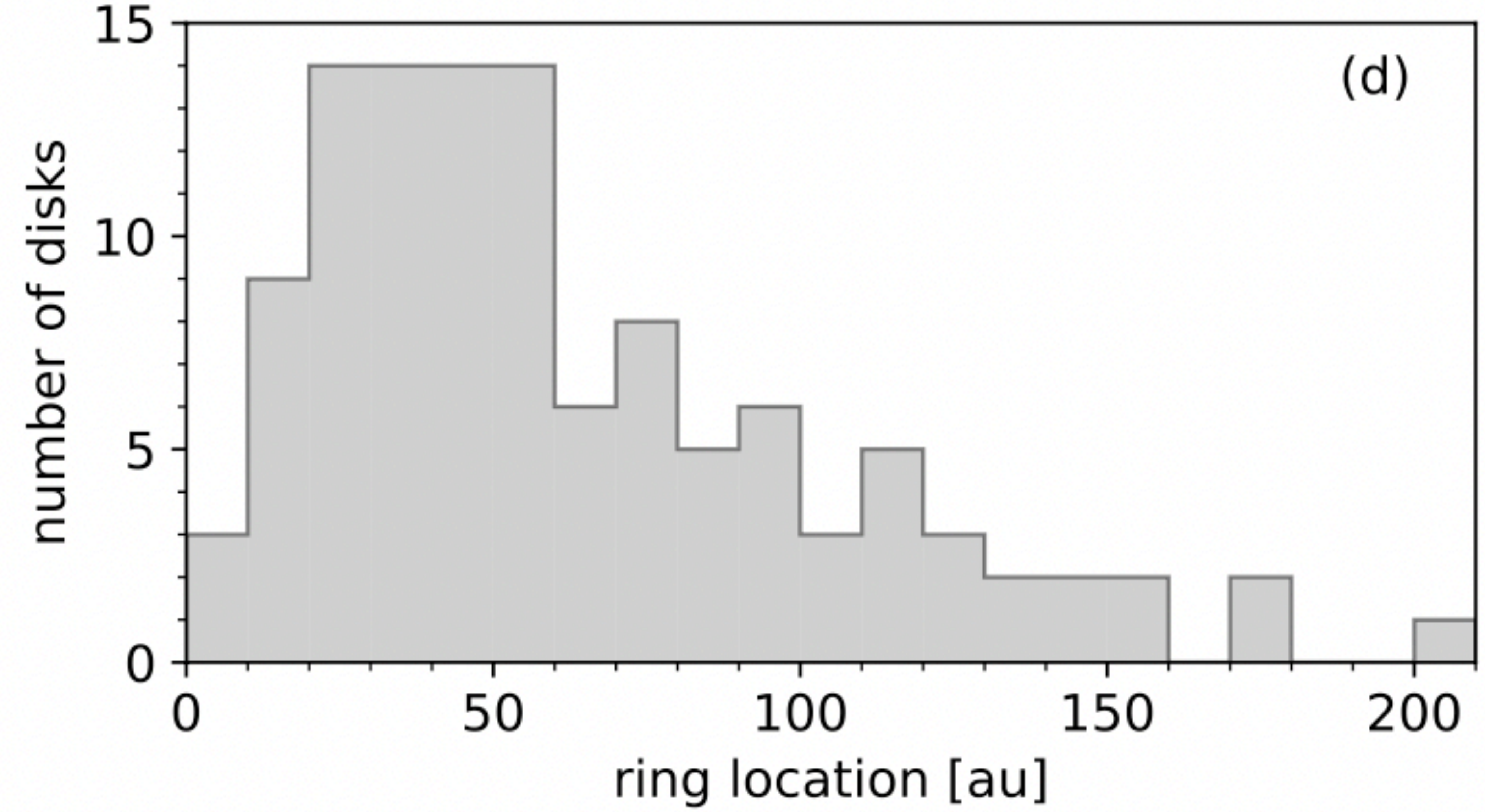


A variety of morphological features observed in disks

Axisymmetric gaps and rings are the most common.

Bae+2023, PPVII review

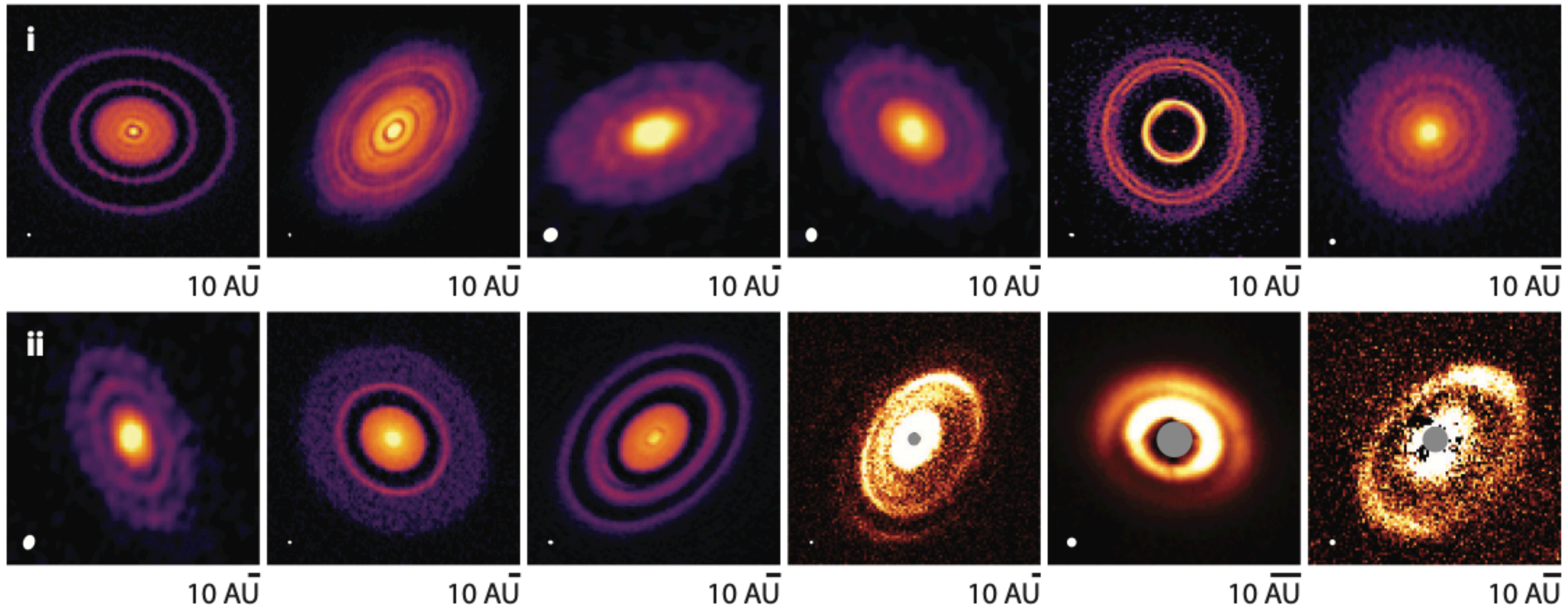




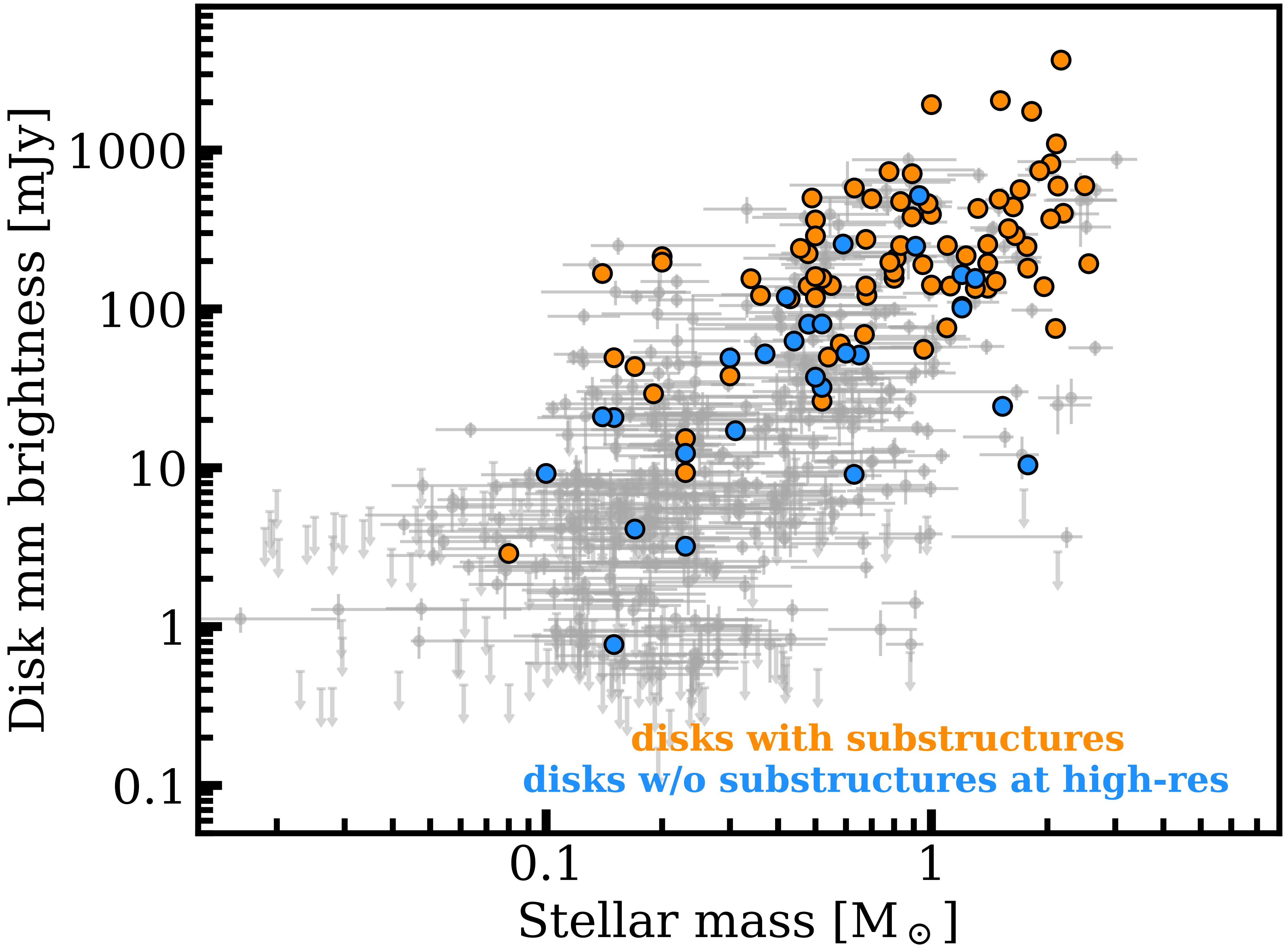
Axisymmetric gaps and rings are the most common.

- Varying numbers of rings
- Found in all disk radii

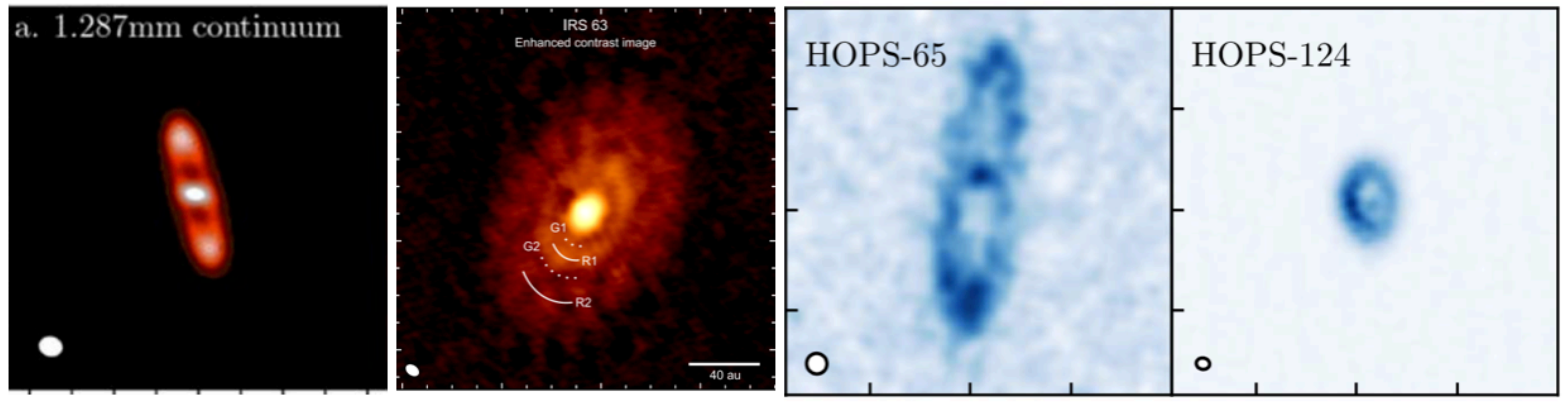
b Rings–gaps



Disk substructures are likely formed early and ubiquitous!

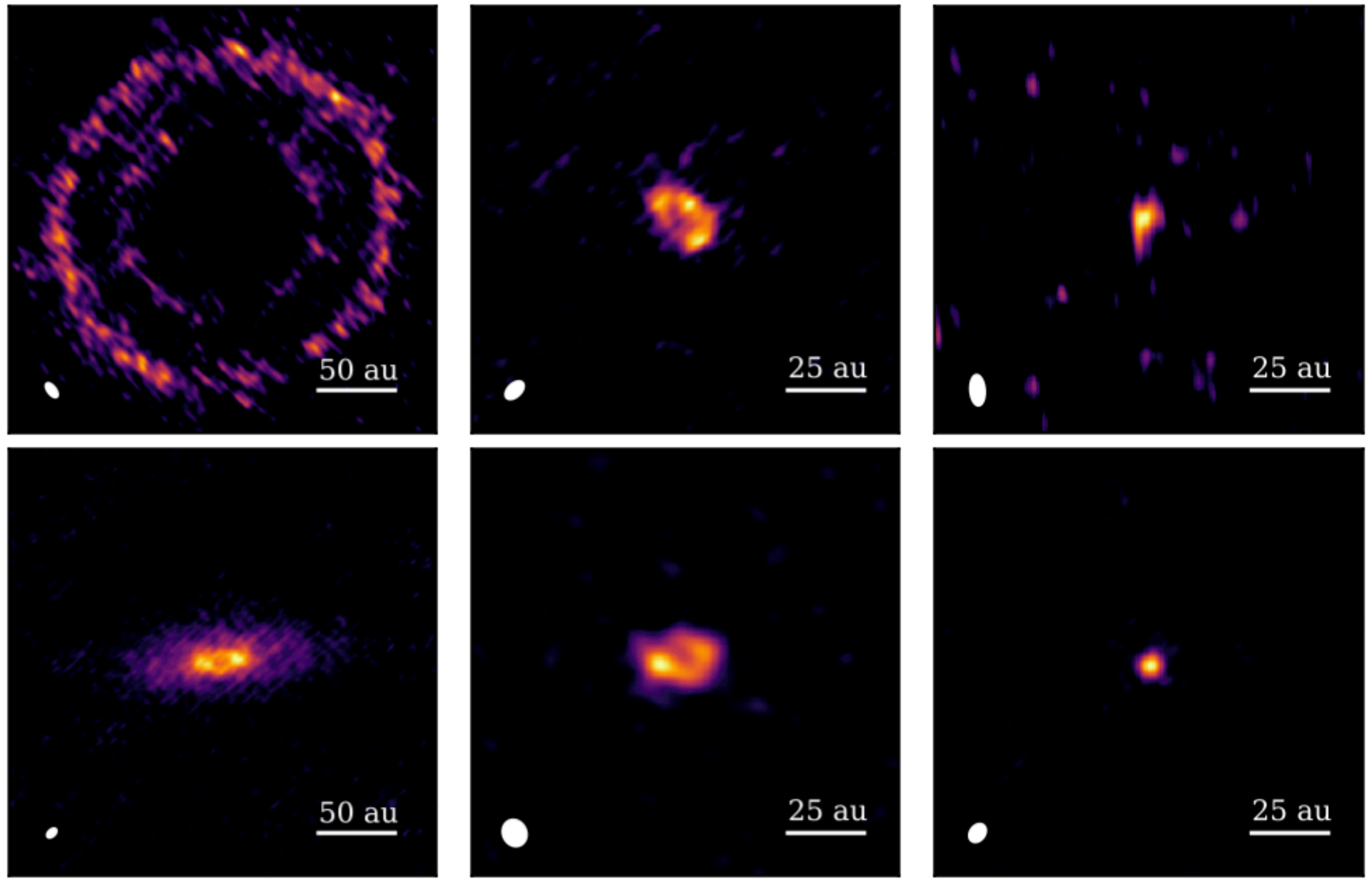


detections in protostellar disks (<1 Myr)



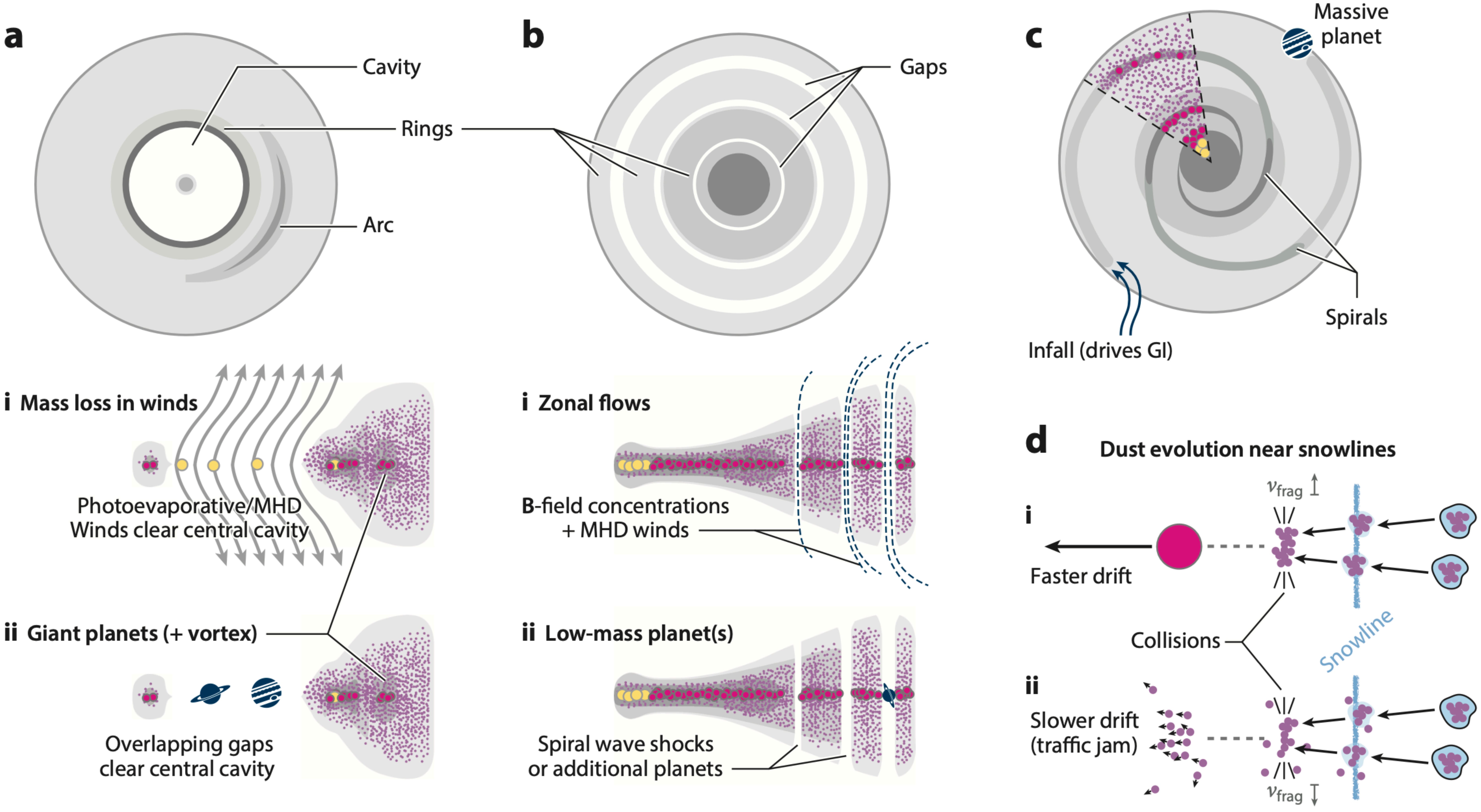
Alves+2020, Segura-Cox+2020

detections in disks around low-mass stars



Shi, Long, Herczeg+2024

The origin of disk substructures



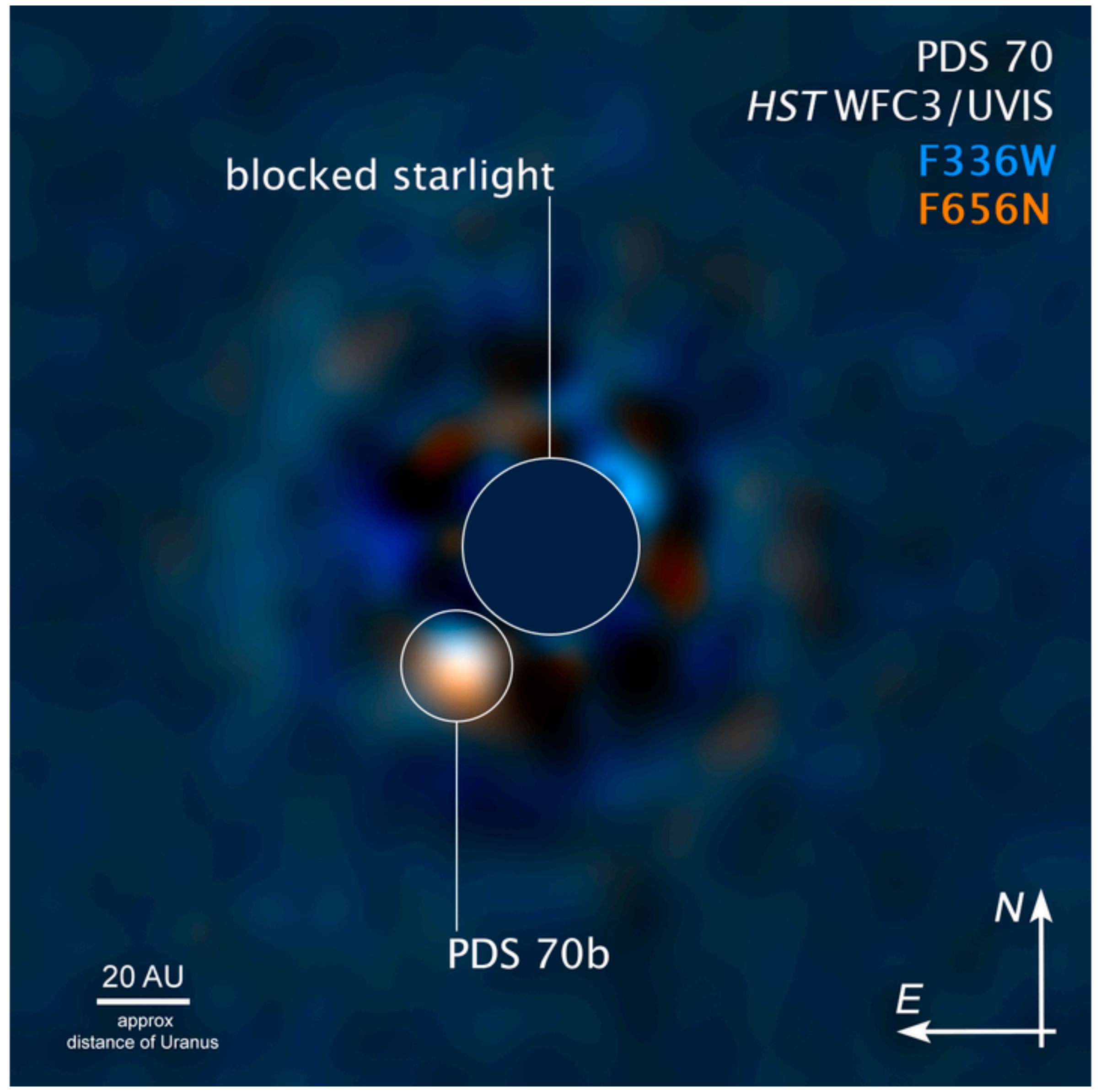
Many different approaches but hard to distinguish!

- MHD physics occurs on small scales, usually not detectable
- Grain growth assessment is often impeded by high optical depth
- Chemistry is often uncertain
- Planets are always obscured from our view!

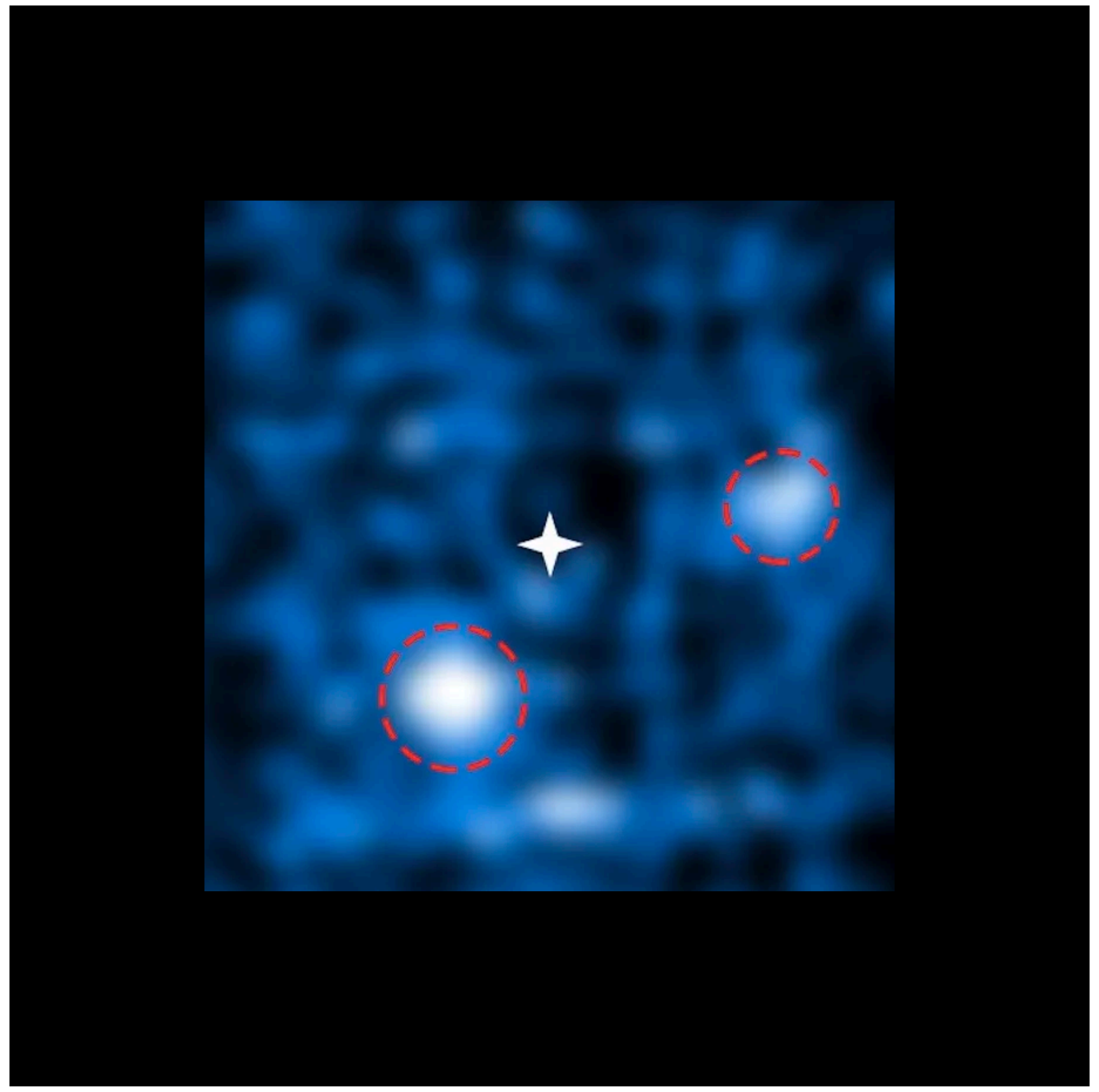
The ALMA search of young planets - dust

Two young accreting giant planets
in the PDS 70 (~5 Myr) disk cavity

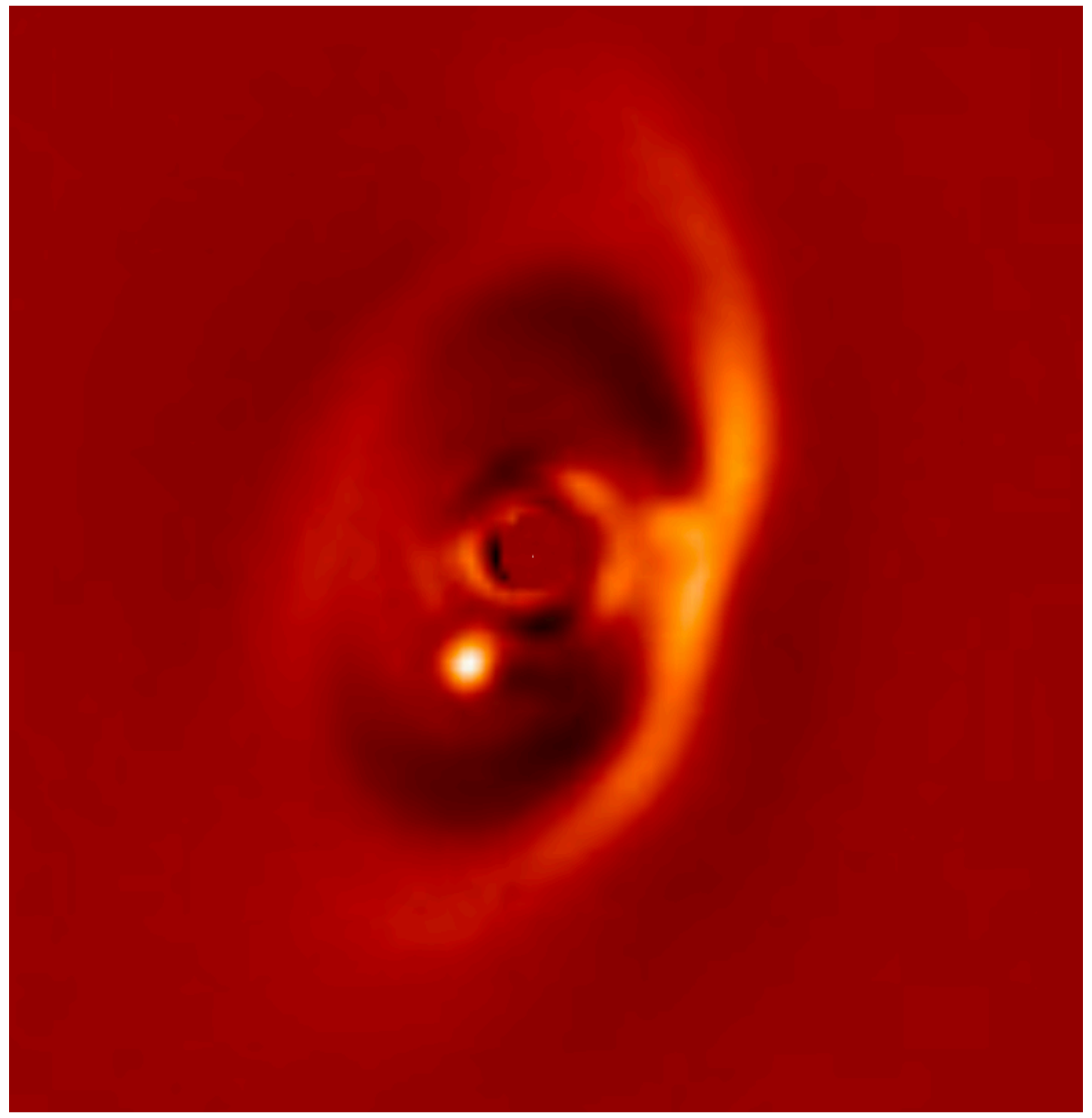
Circumplanetary Disks (CPD)



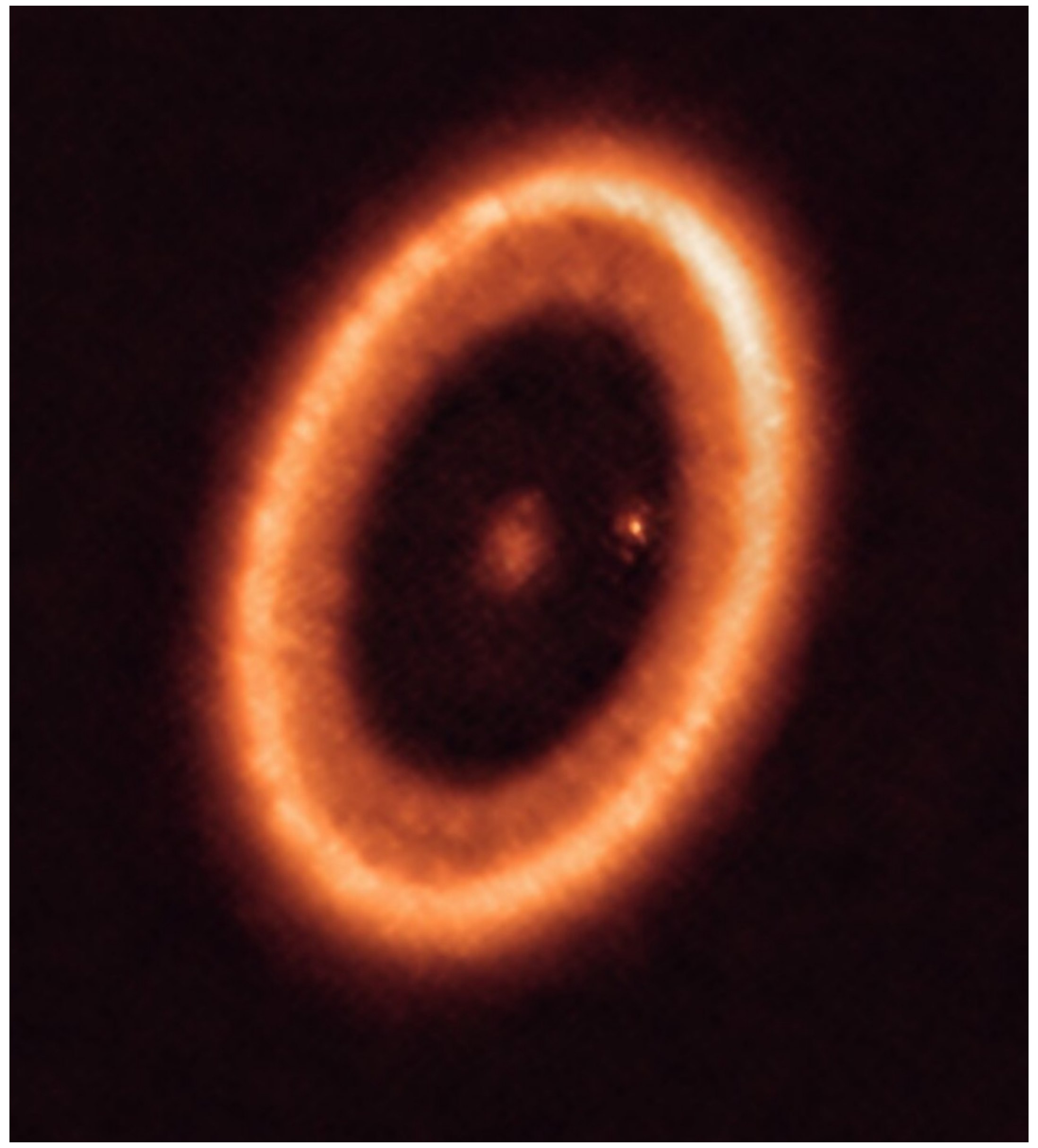
HST - UV+optical
Zhou+2021



VLT/MUSE - optical
Haffert+2019



VLT/SPHERE - infrared
Keppler+2018

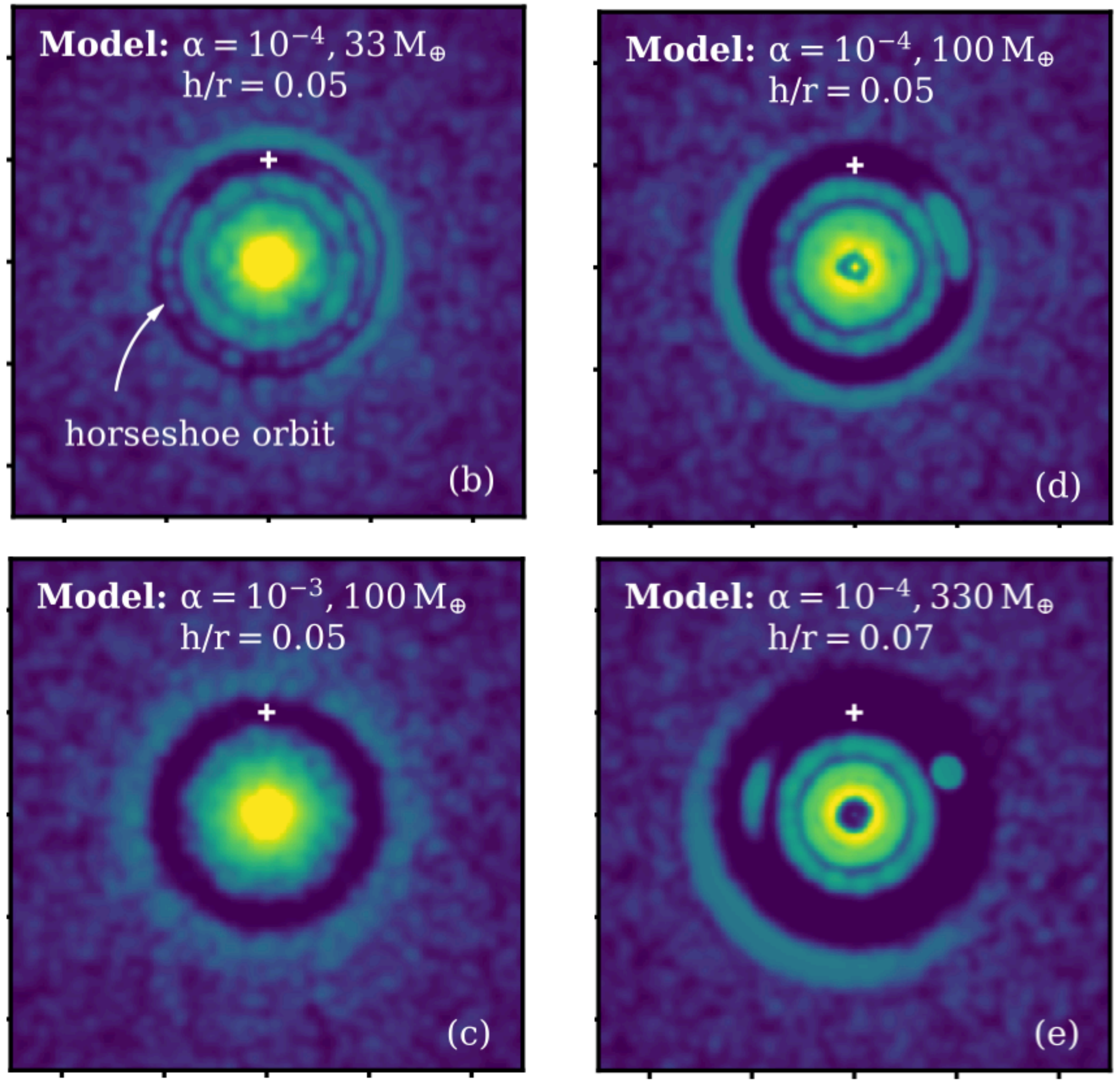


ALMA - mm
Benisty+2021

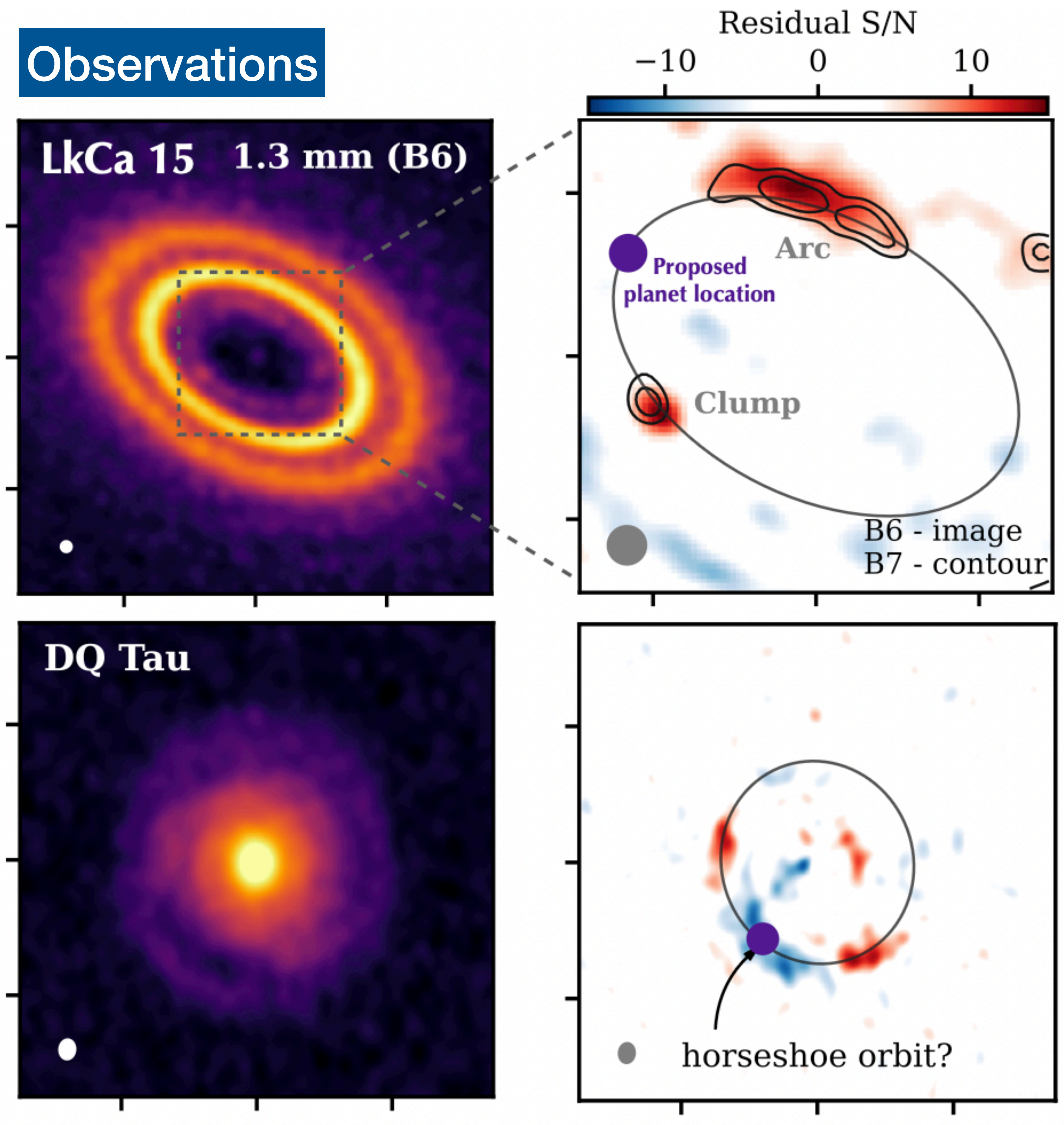
The ALMA search of young planets - dust

Models

Planet **horseshoe orbit** in dust
with dust accumulation in *L4* and *L5*

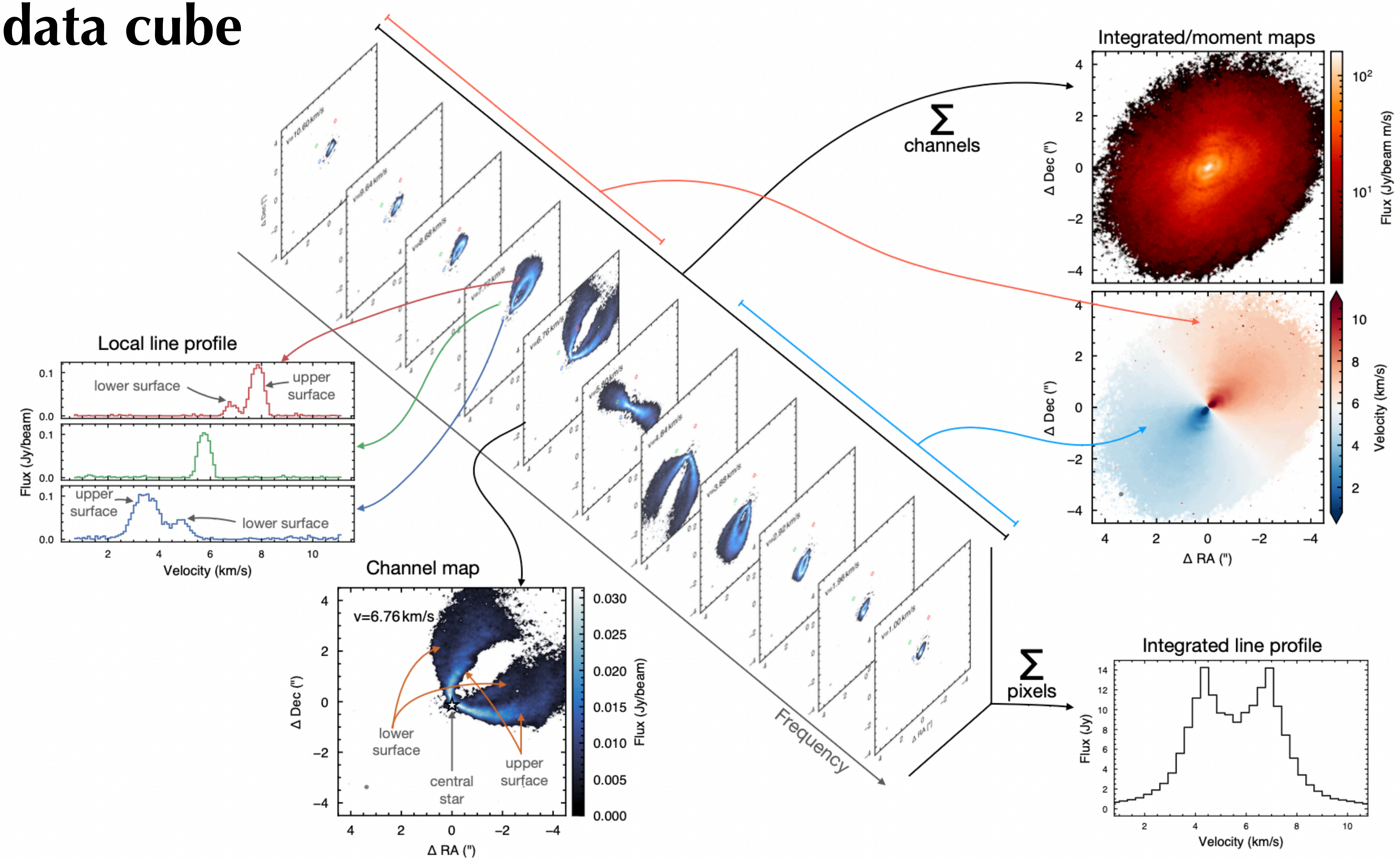


Observations



Long+2020, in prep

The multiple ways to view a line data cube



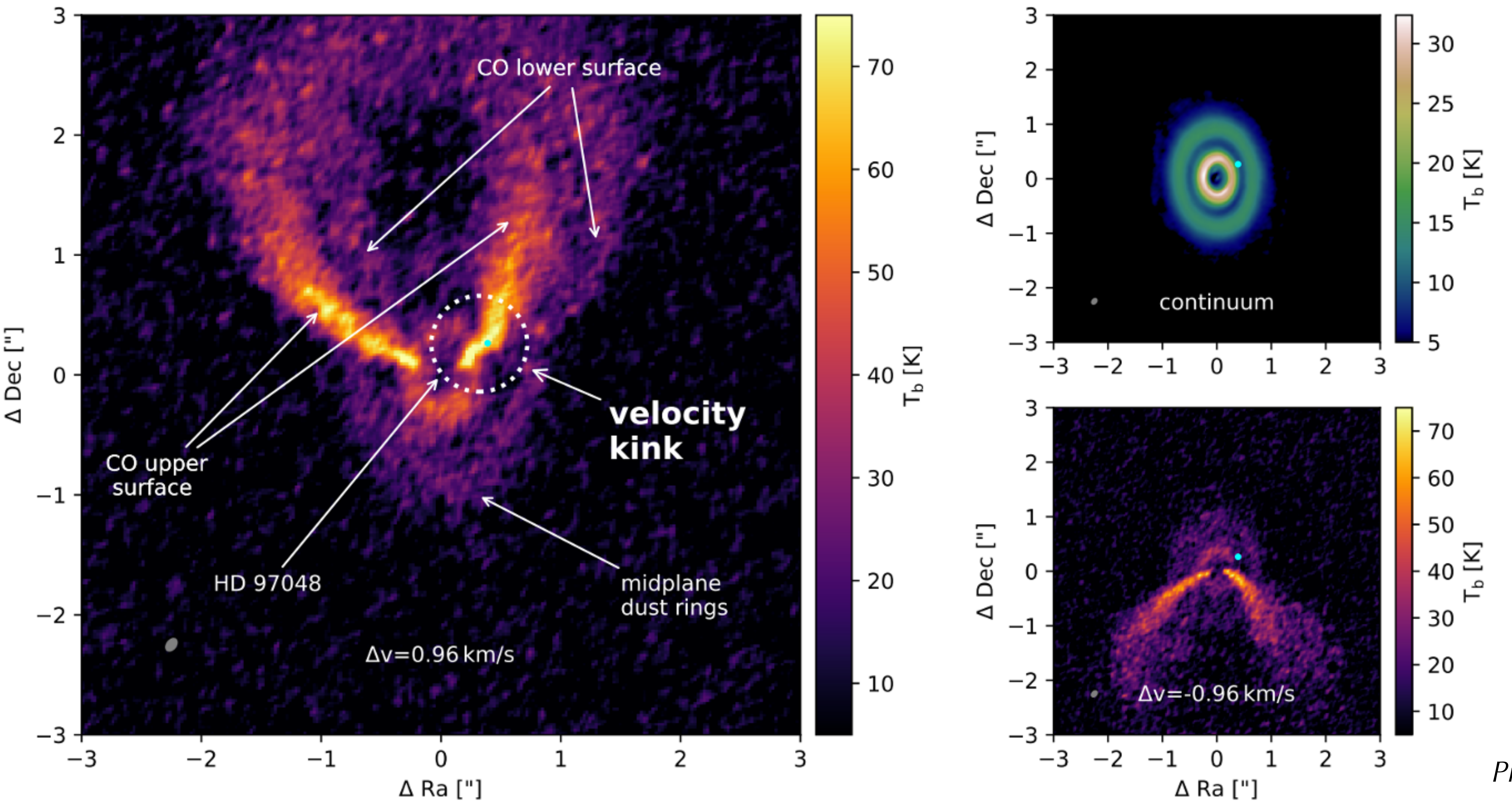
$$M_0 = \sum_i^N I_i \, \Delta v_{\rm chan},$$

$$M_1 = \frac{\sum_i^N I_i v_i}{\sum_i^N I_i}$$

Pinte+2023
PPVII review

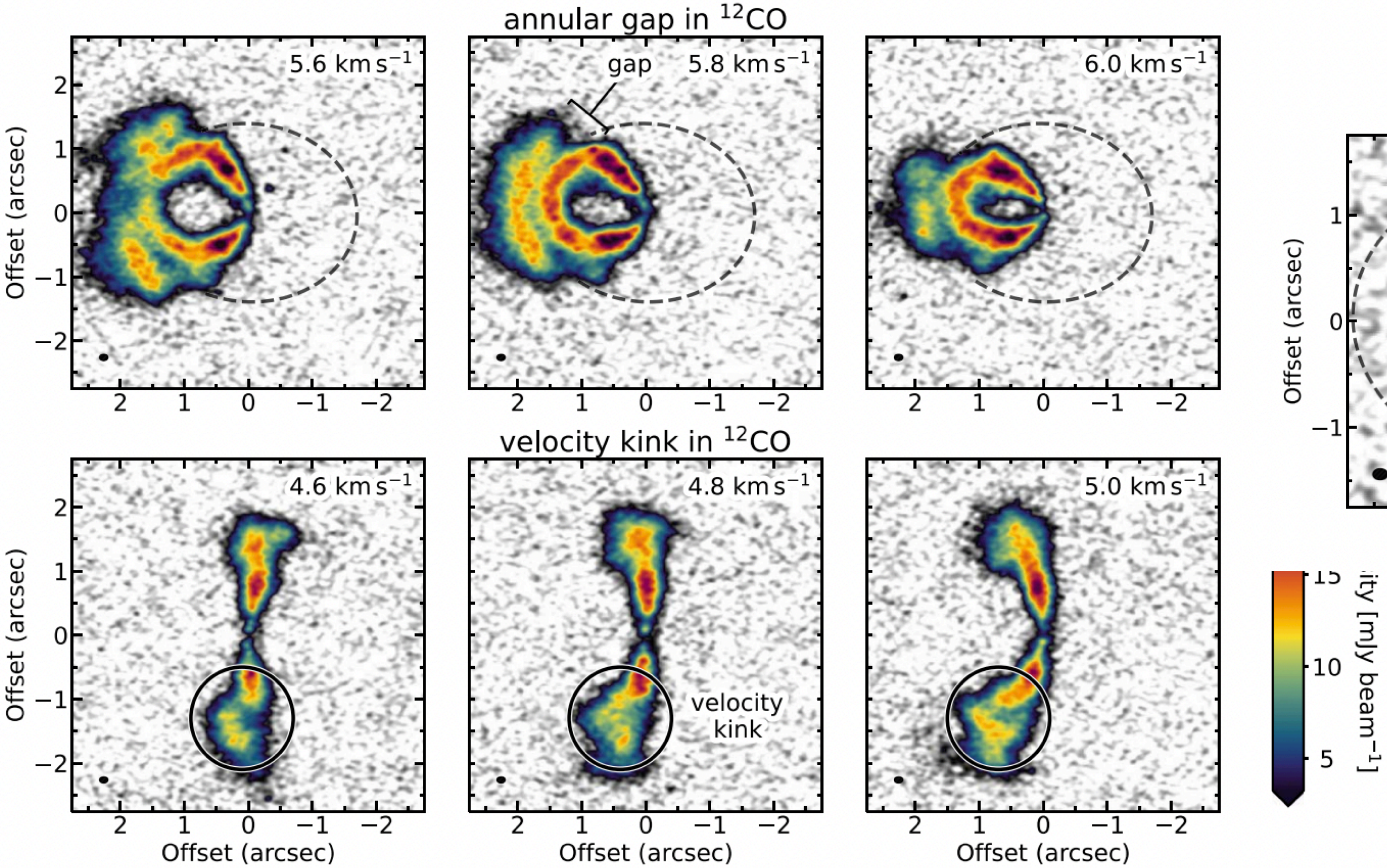
The ALMA search of young planets - gas kinematics

velocity kink in CO channel maps
Location consistent with dust gap



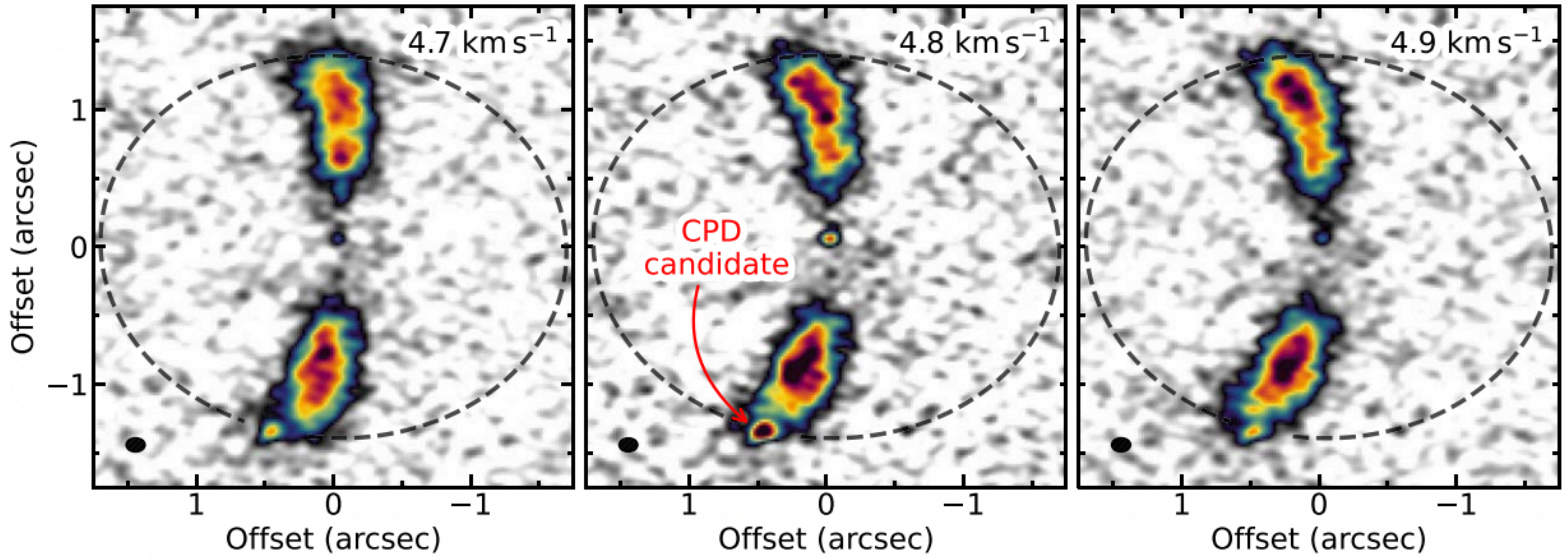
Pinte+2019

The ALMA search of young planets - gas kinematics (CPD)

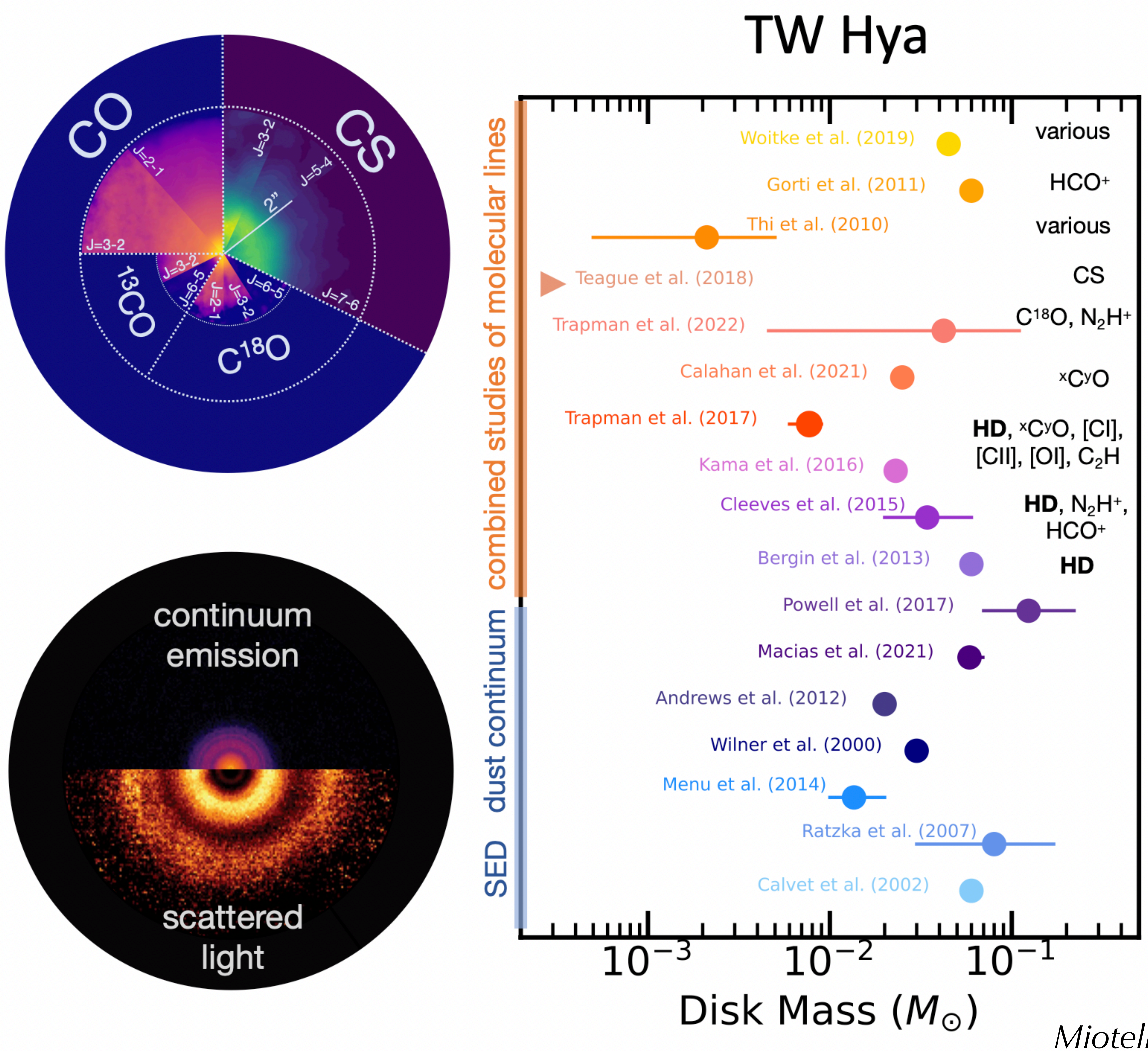


12CO kink feature at larger distance

Point source in 13CO emission along within the dust gap



Bae+2022



What can we use line data for?

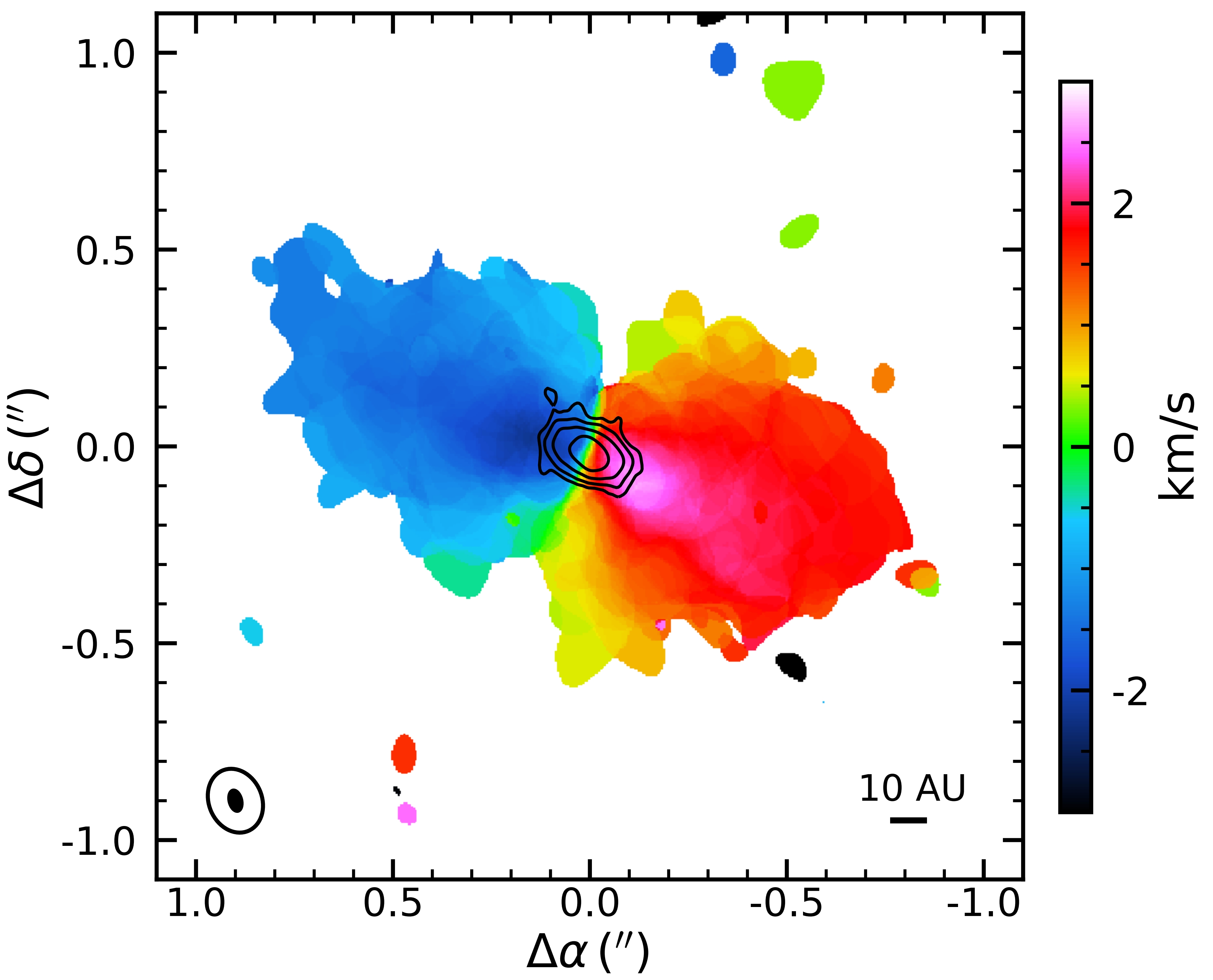
Total gas mass from integrated line fluxes

Miotello+2023 PPVII review

What can we use line data for?

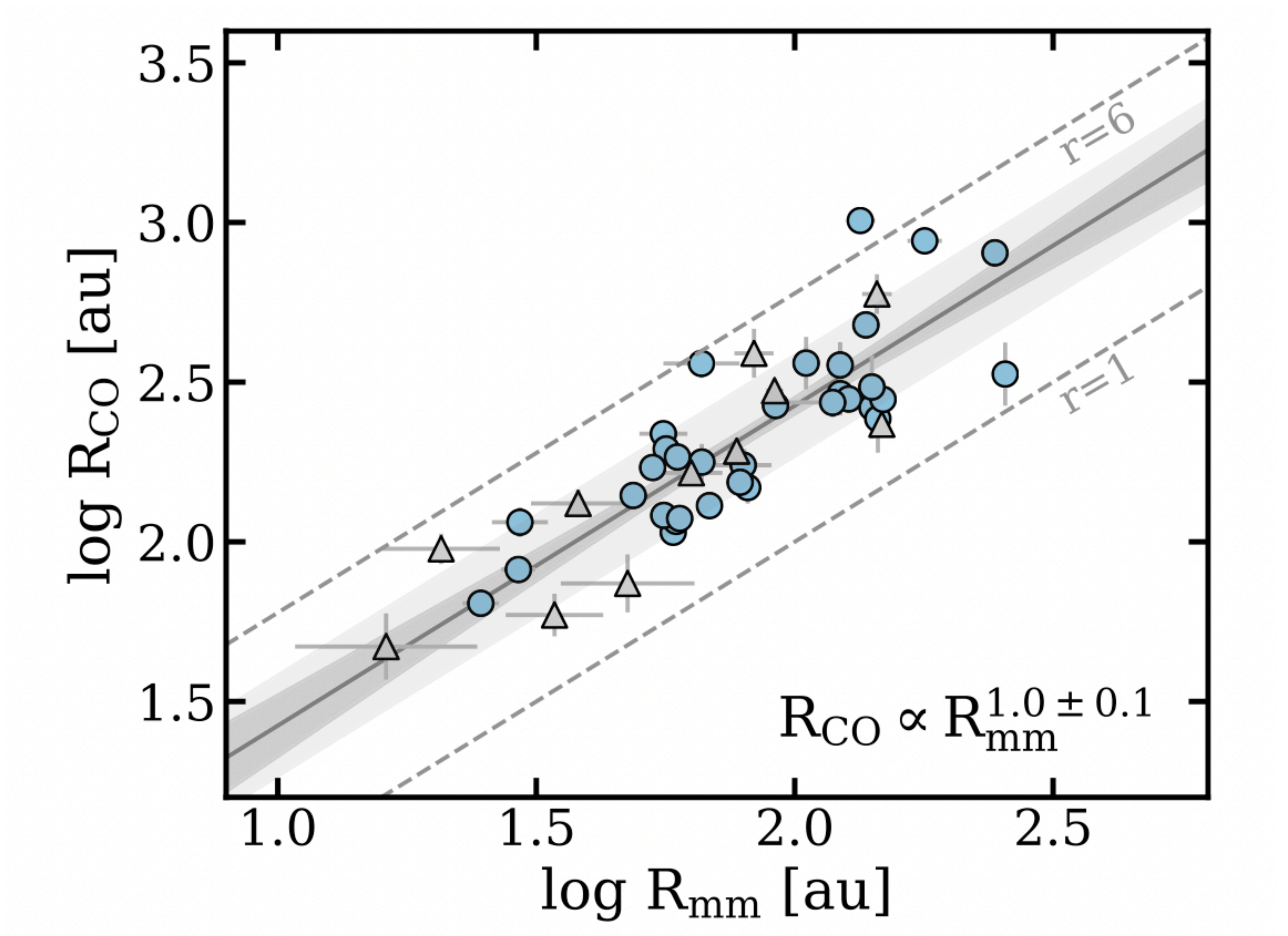
Measuring gas disk size
(Key quantity of disk evolution)

extended gas distribution in a small dust disk:
efficient radial drift for CX Tau?



Contour: mm-continuum emission
Color: CO emission

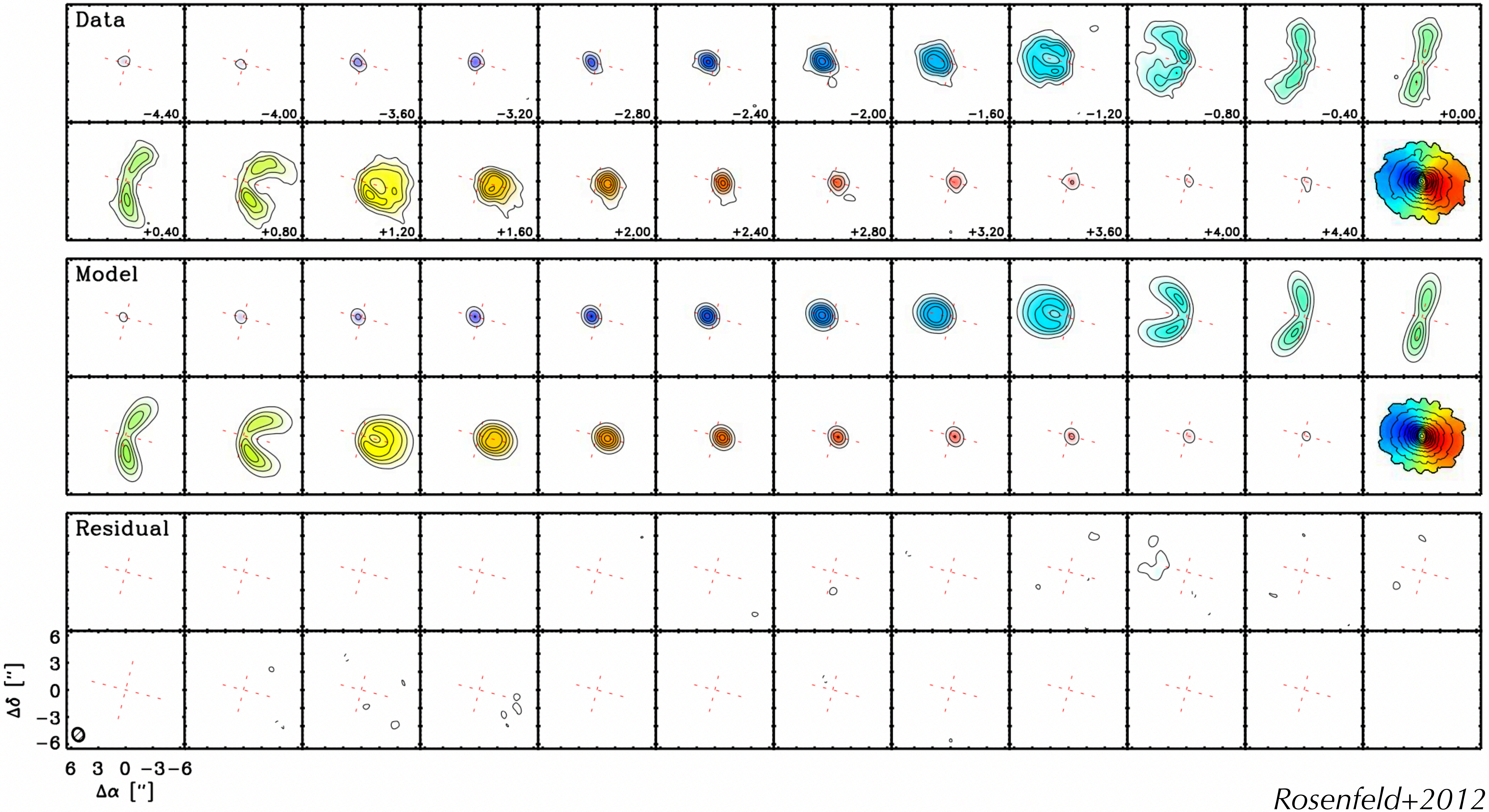
Facchini+2019



Long+2022

What can we use line data for?

Measuring stellar mass using the near-Keplerian rotation of the disk gas

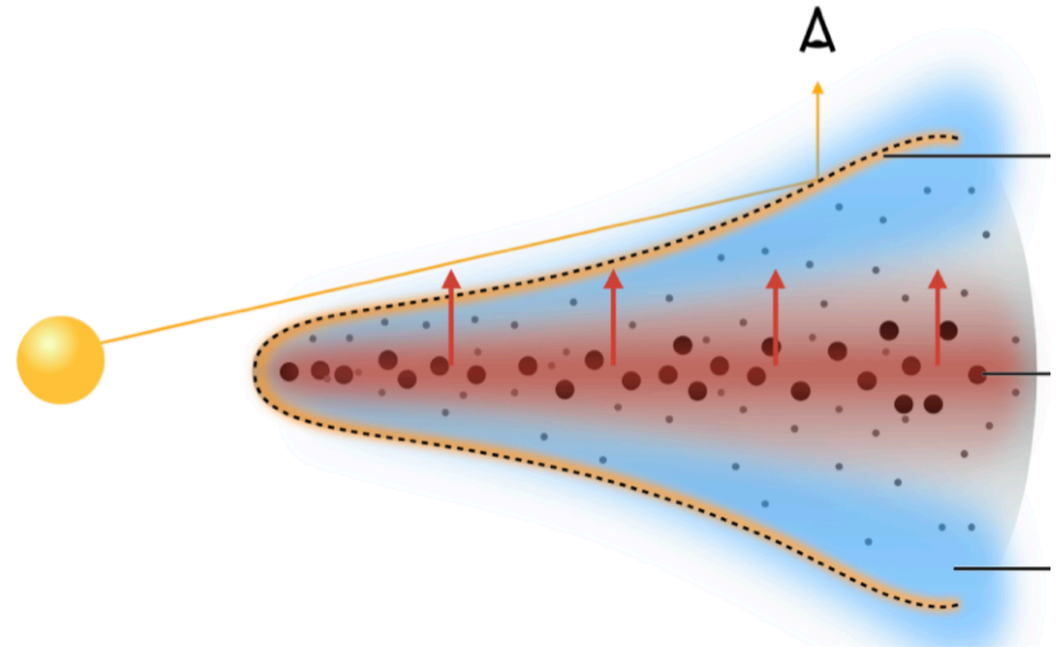


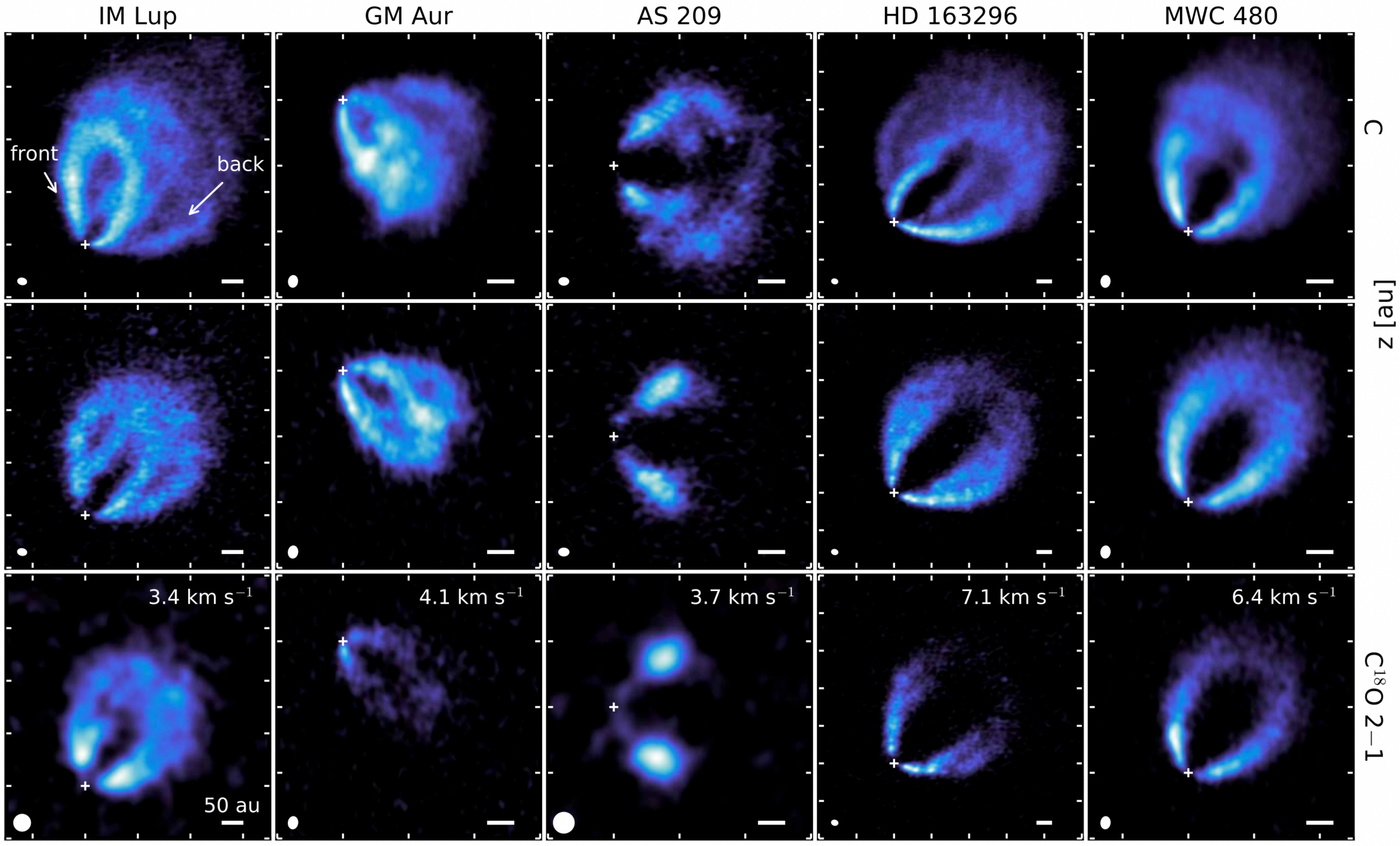
* degeneracy with disk inclination and distance

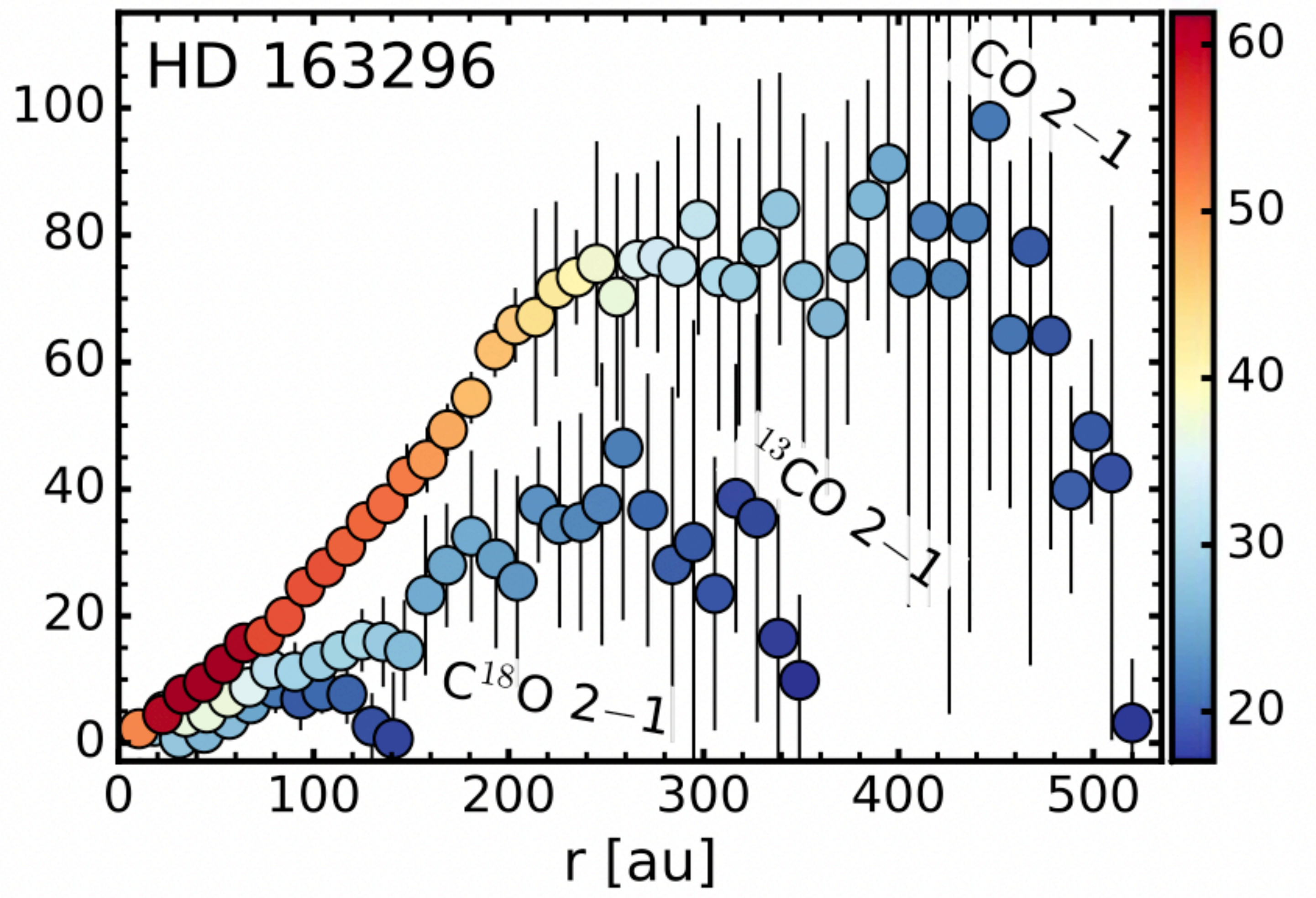
Rosenfeld+2012

What can we use line data for?

Map disk vertical structure and 2D temperature structure



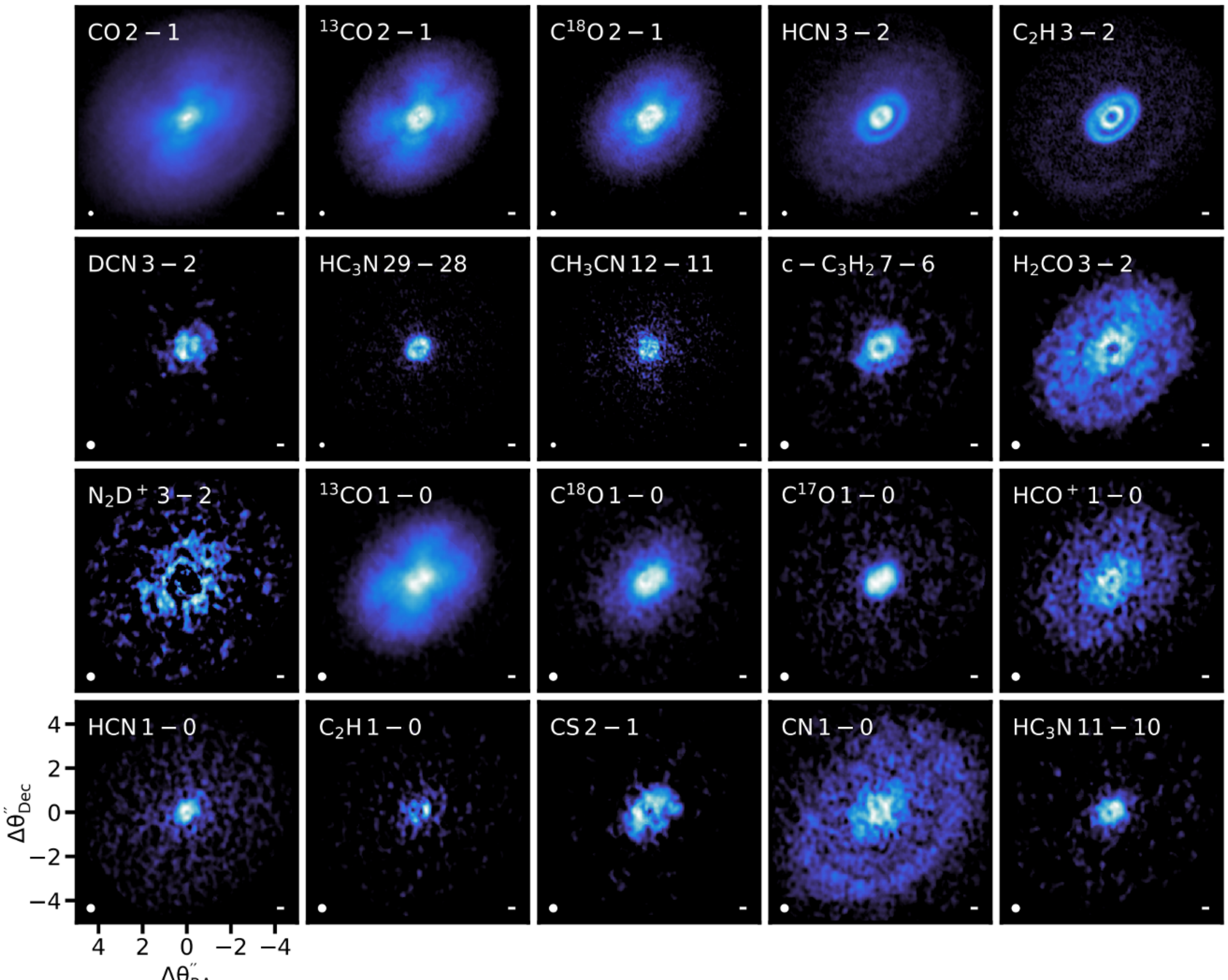




Optically thick lines indicate disk temperature

Lines with different optical depth trace different disk layers

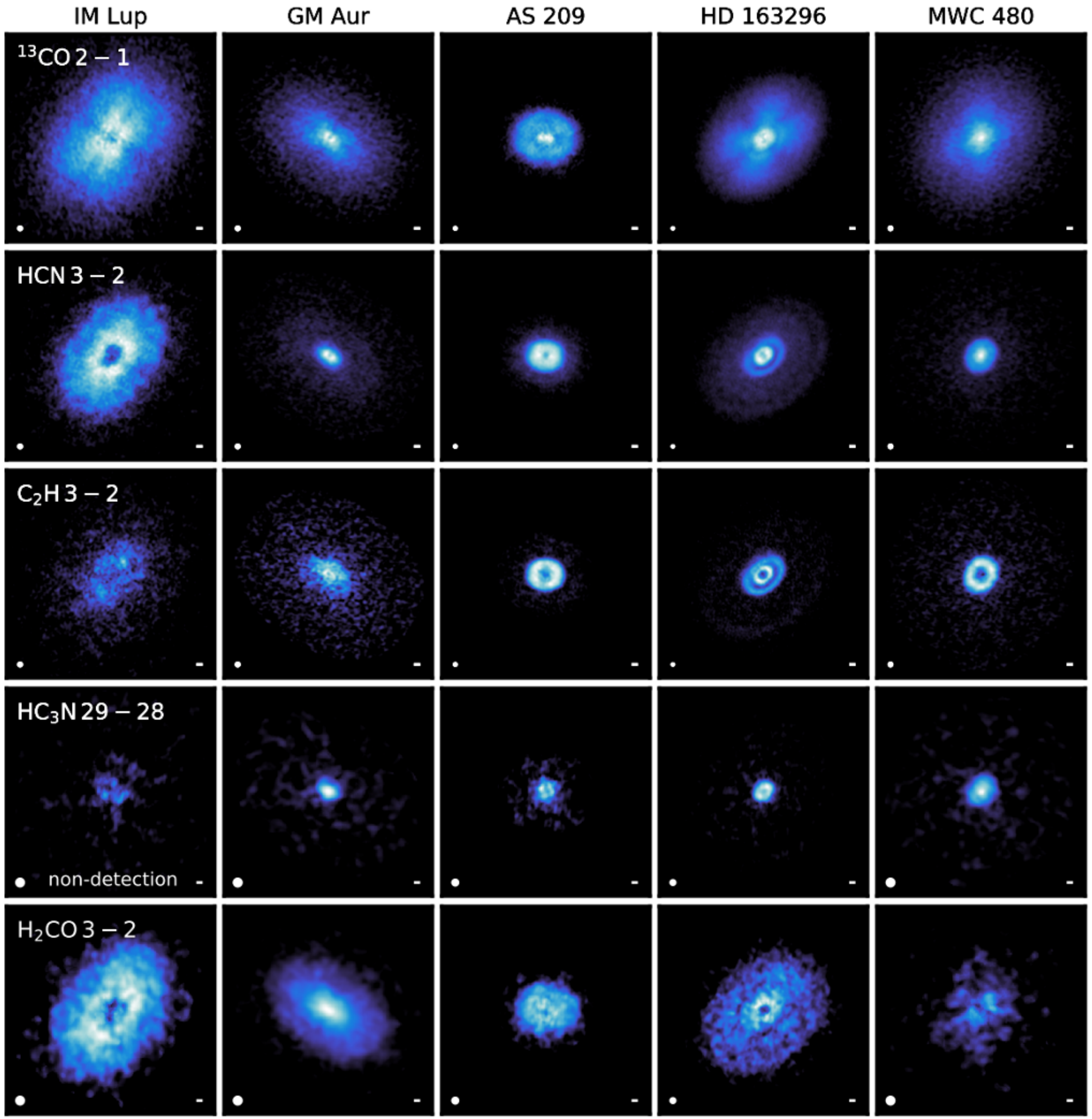
Laws+2021



The disk chemical diversity

The distribution of multiple species/transitions in one disk!

(MAPS: Oberg+2021)



The disk chemical diversity

Gas emission from five disks

Diverse morphology for a single species in different disks
(related to e.g., UV field? dust structure)

(MAPS: Oberg+2021)