# PROTOPLANETARY DUST

Til Birnstiel
Ludwig-Maximilians-Universität München

Funded by the European Union
European Research Council
Established by the European Commission

# OUTLINE

From Dust To Planets

Observing Protoplanetary Dust

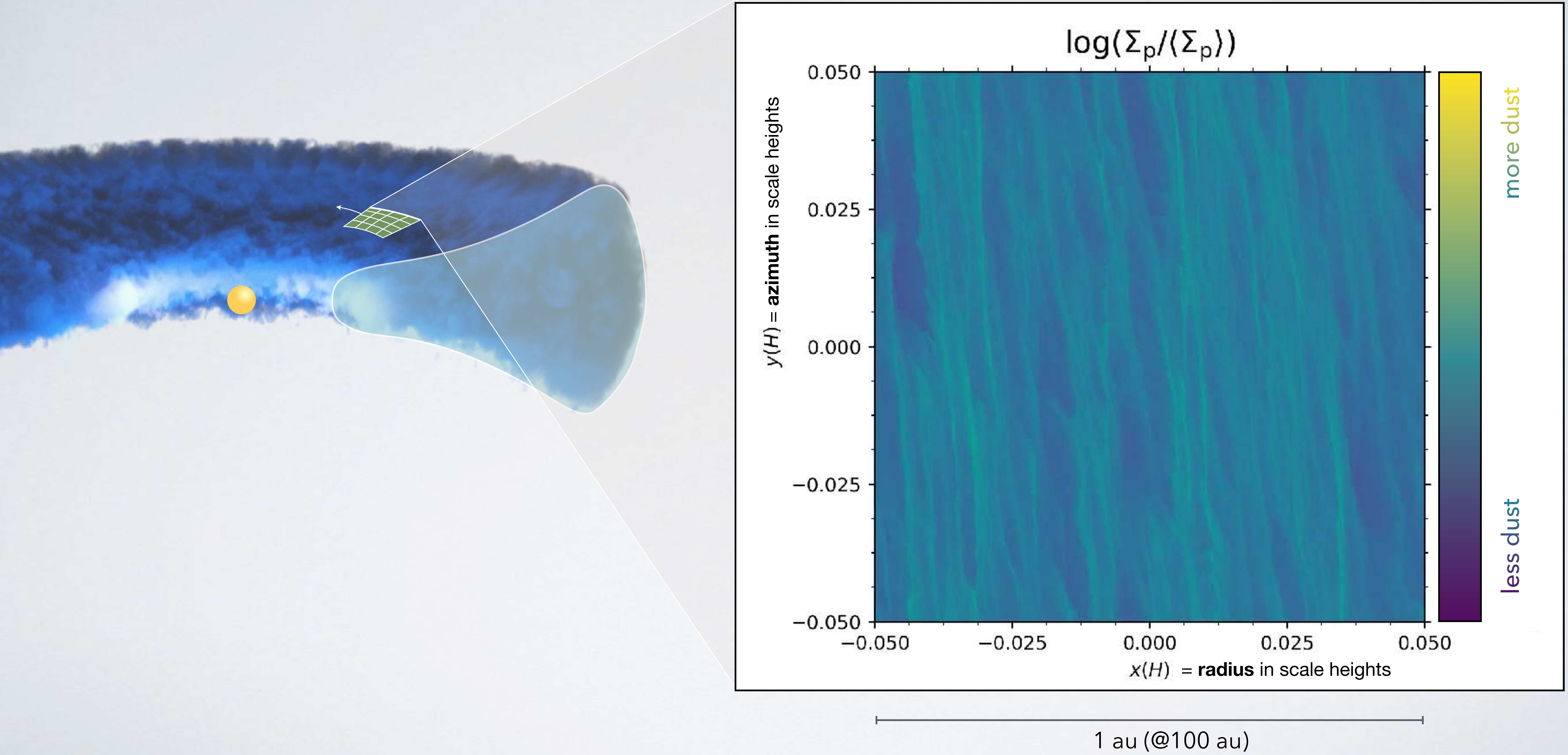
New Paradigms

# 1. From Dust To Planets

# Dust: Crucial Ingredient

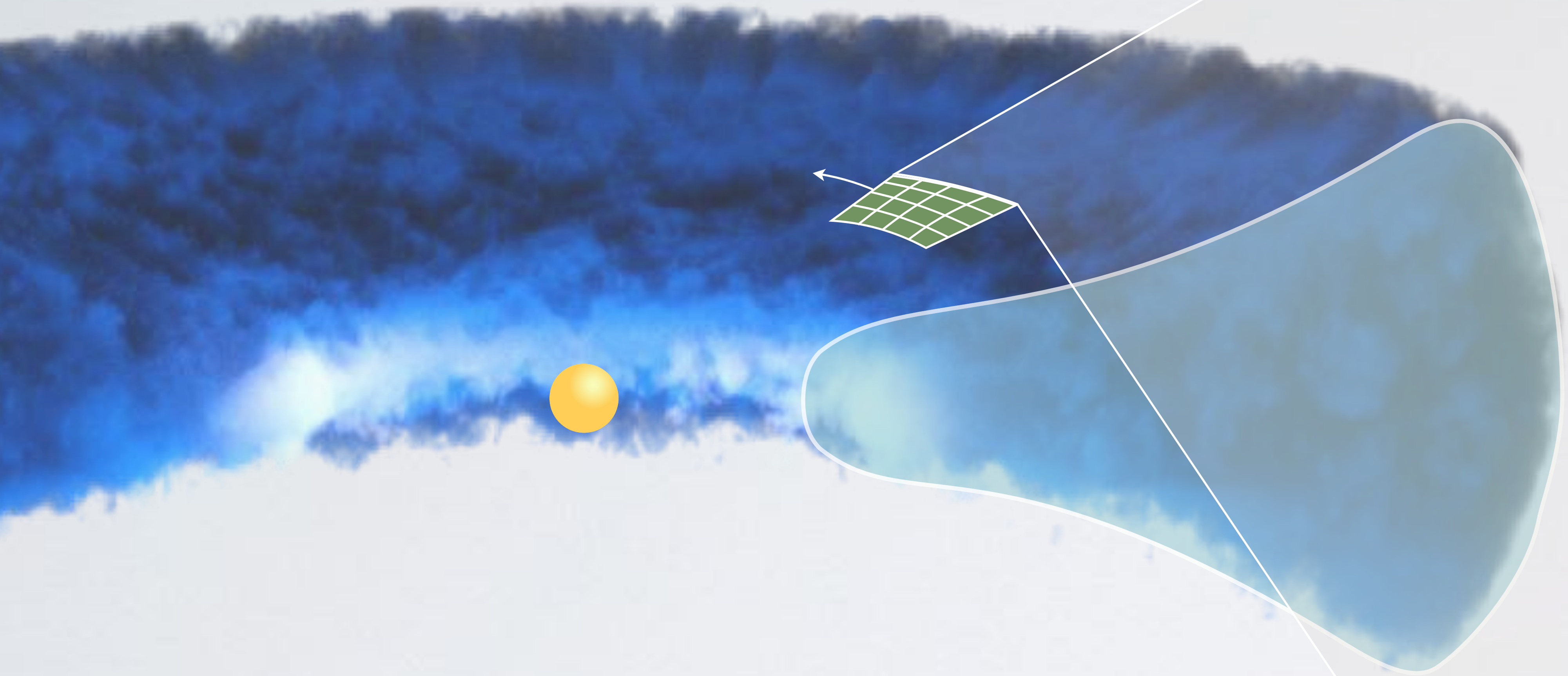

→ see also talk by Jürgen Blum; Reviews: Dust – Birnstiel 2024 (ARA&A), Planet Formation – Drazkowska et al. 2023 (PPVI)

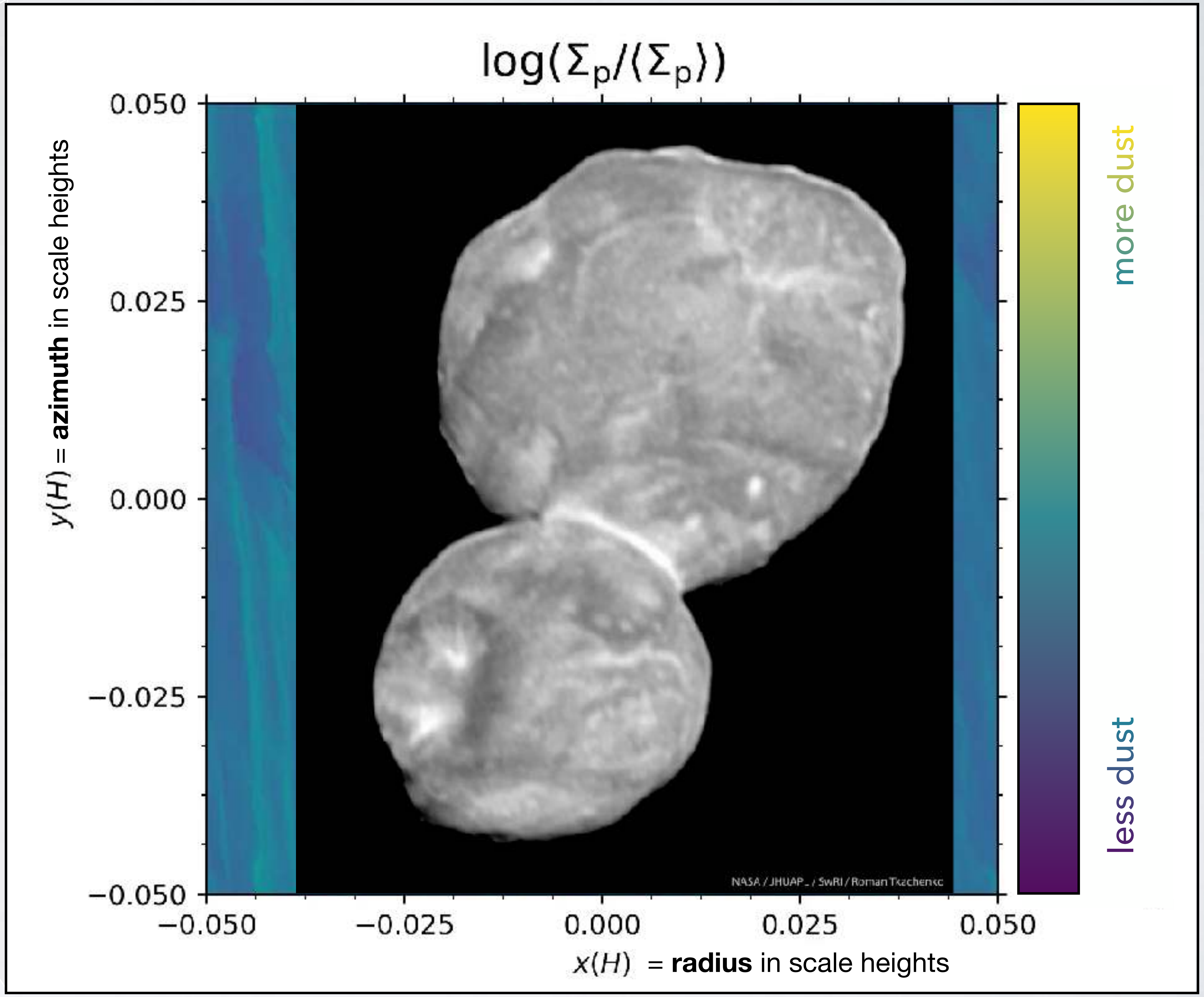
# From Dust To Planetesimal




starting with Youdin & Goodman 2005, Johansen et al. 2007. Here: Nesvorny et al. 2019, Rixin Li

# From Dust To Planetesimal






**Problems:**

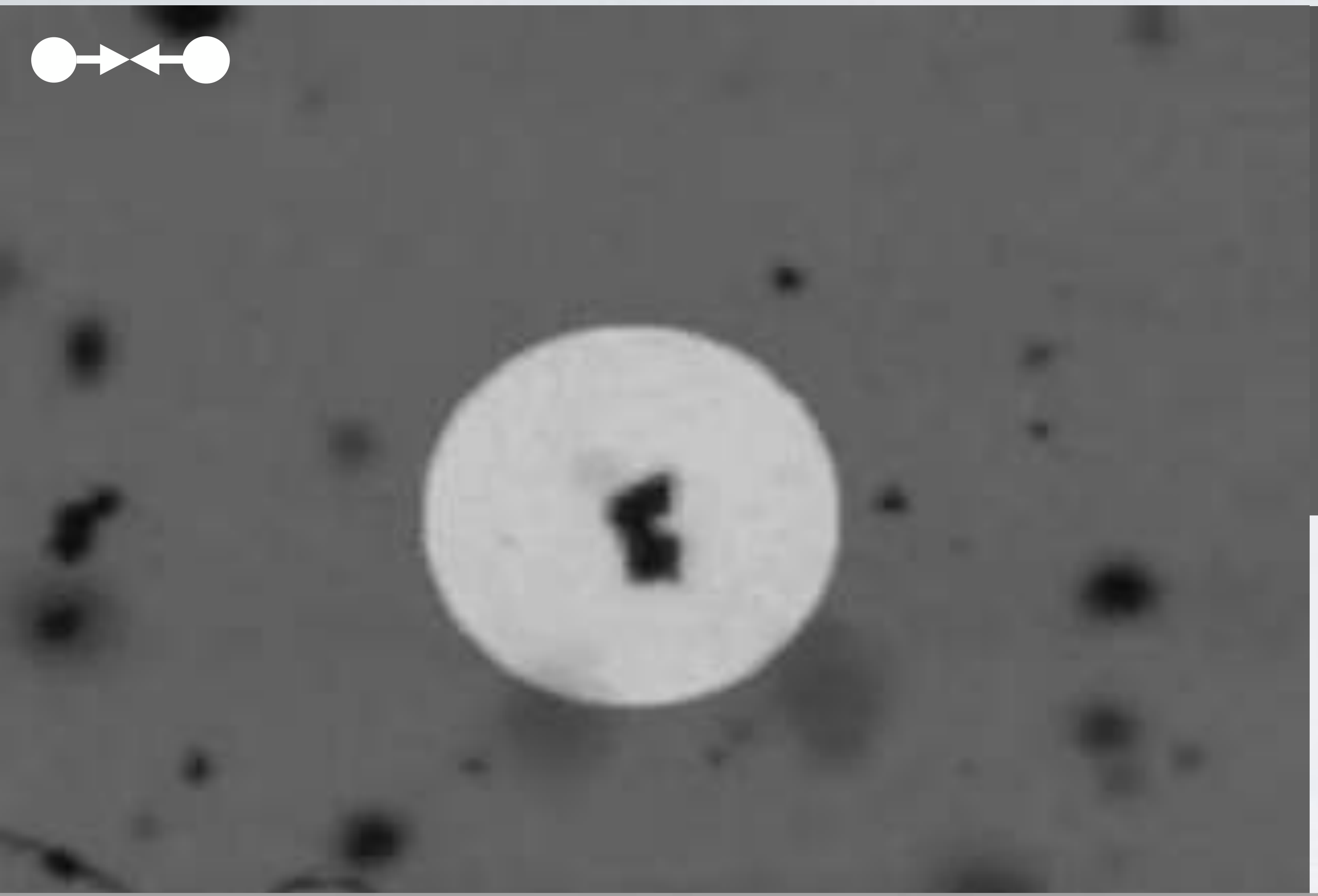
- needs large particles
- needs dust accumulation

1 au (@100 au)

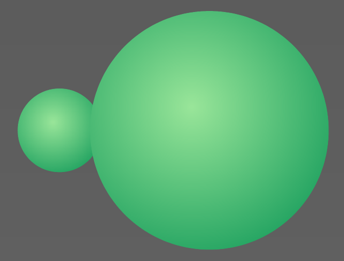
starting with Youdin & Goodman 2005, Johansen et al. 2007. Here: Nesvorny et al. 2019, Rixin Li

# DUST: CRUCIAL INGREDIENT

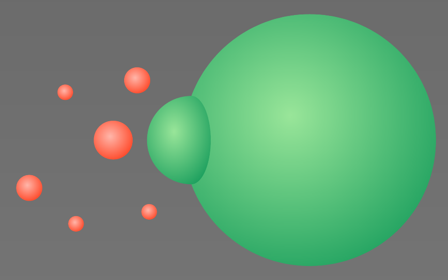
# Ingredient #1: Collisions

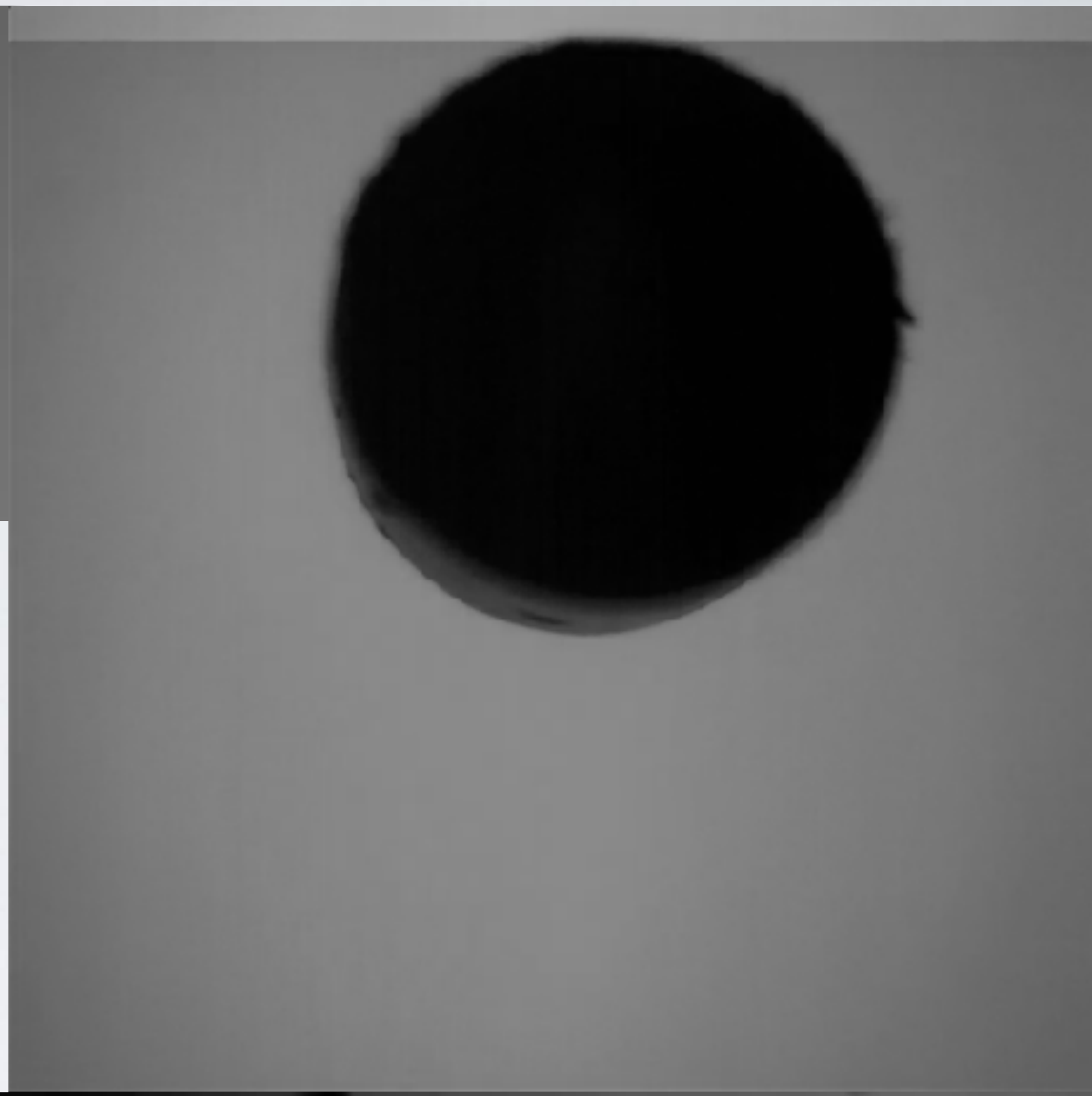


← Sticking

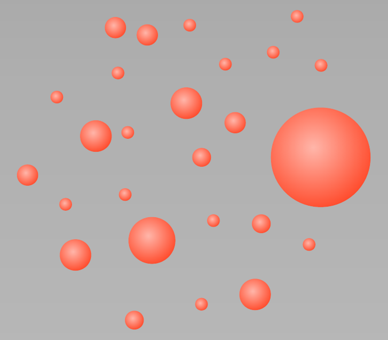


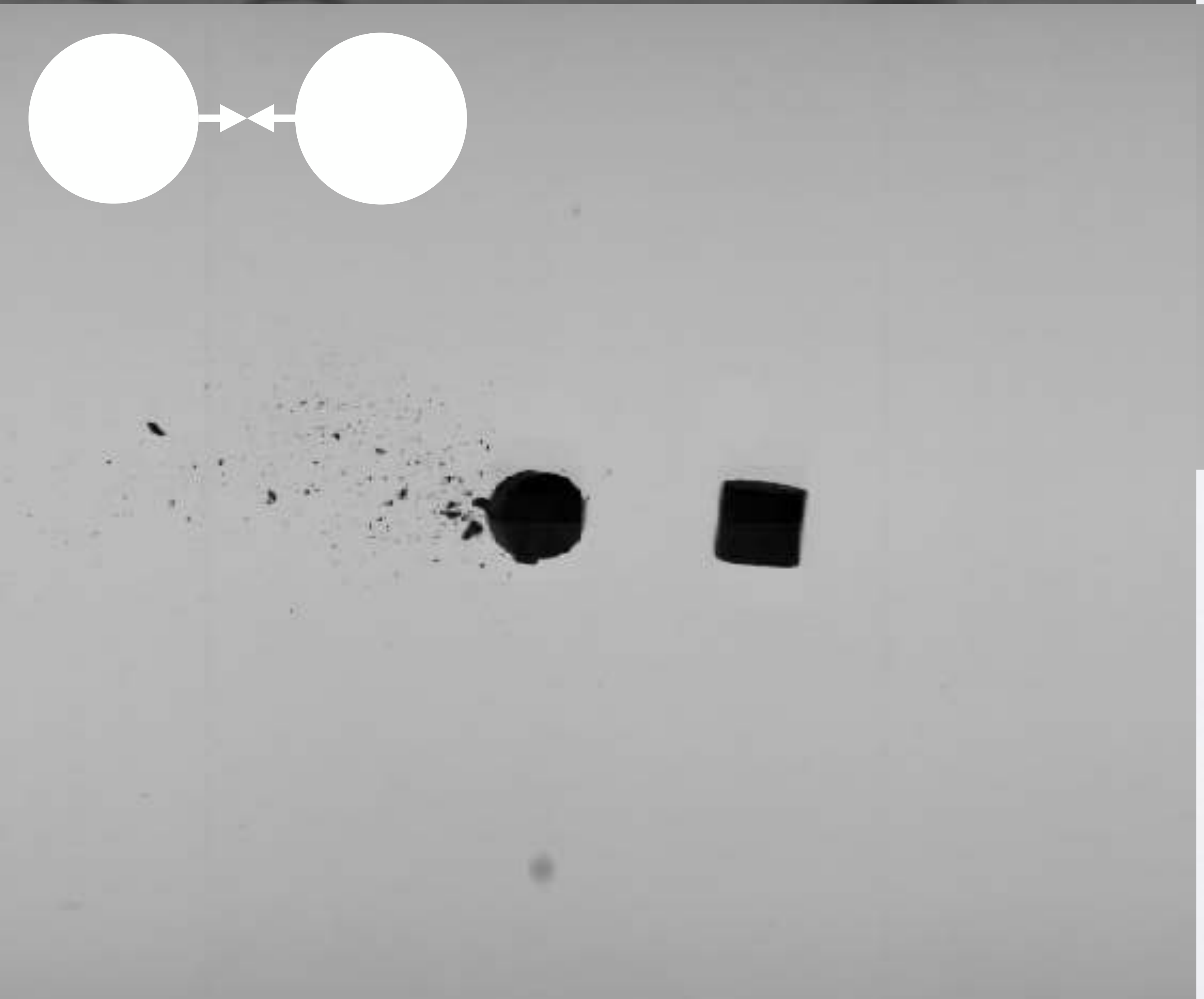
Mass Transfer →



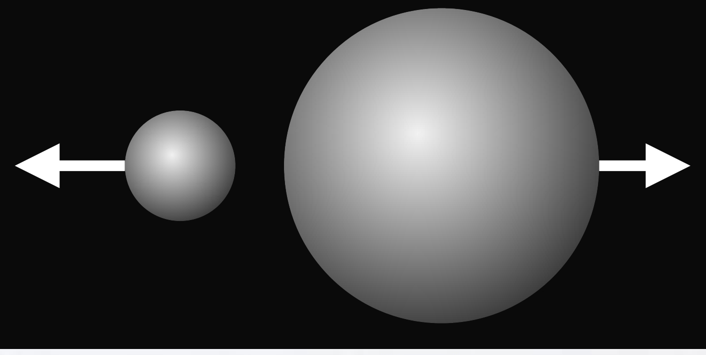


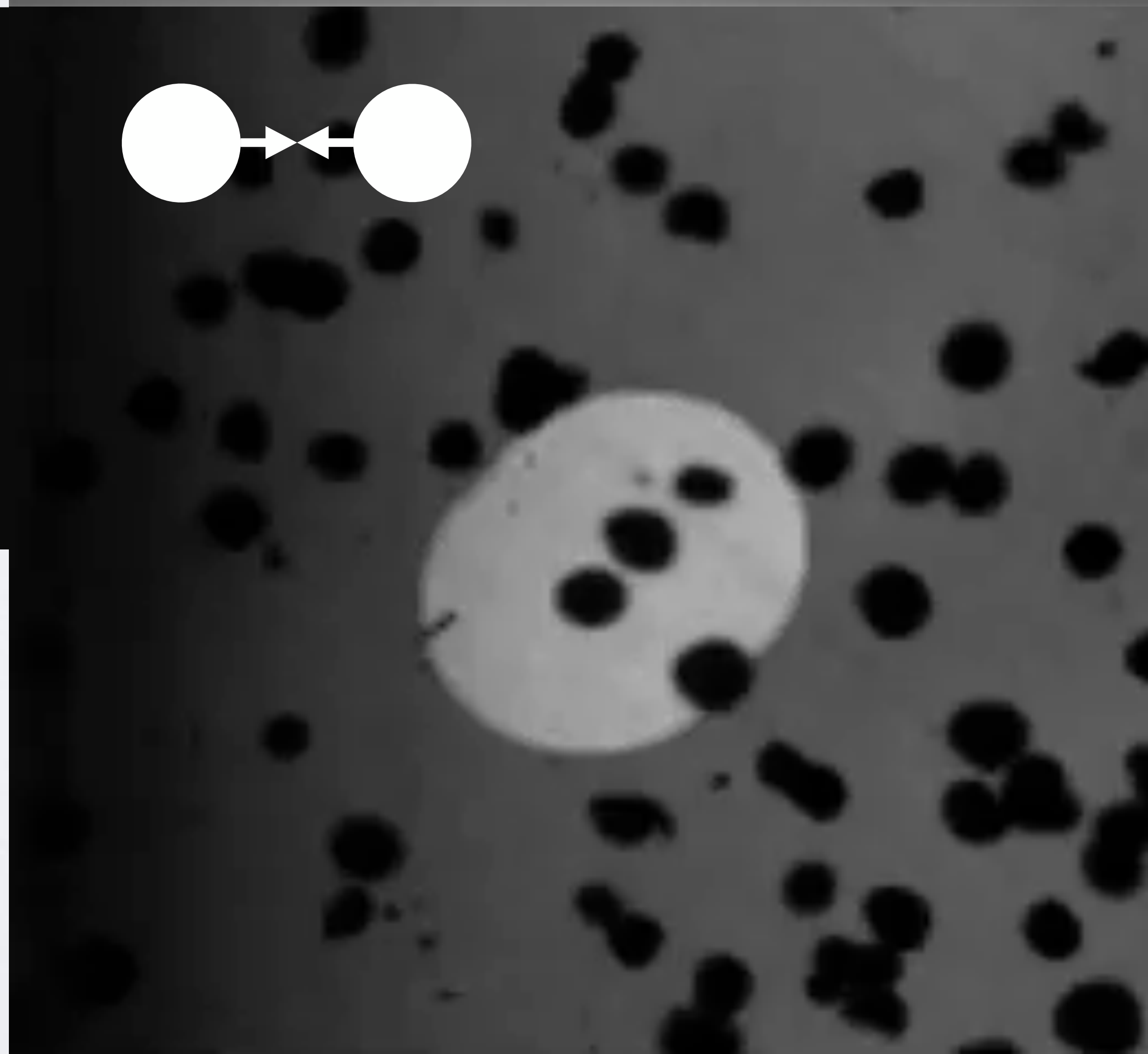
← Fragmentation





Bouncing →





**Macroscopic sizes reached!**

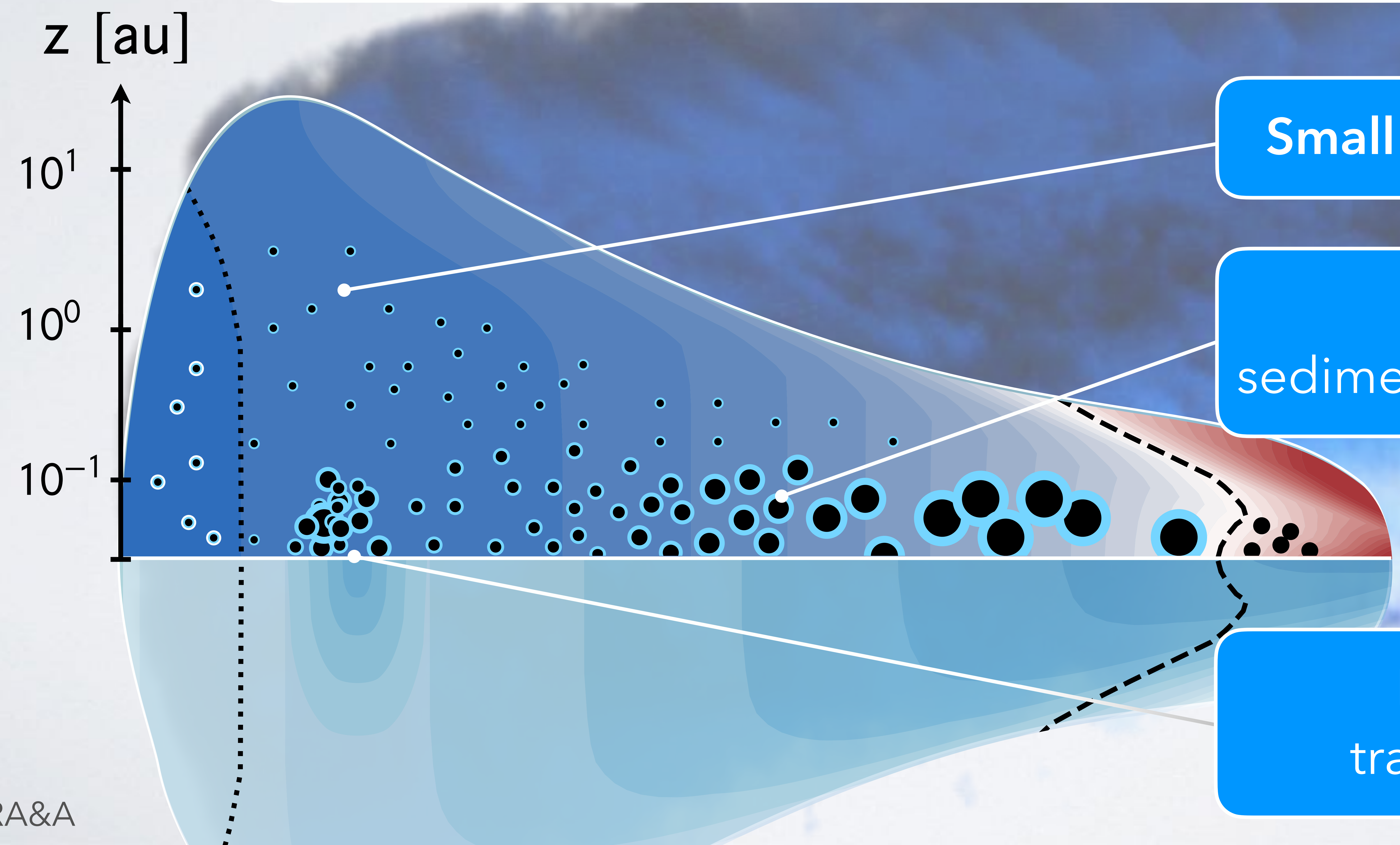
**Sticking → Bouncing/Fragmentation**

© Blum group (e.g. Blum et al. 2014) → **talk by J. Blum**

# Ingredient #2: Dynamics

**Small** particles: well coupled to gas
**Large*** particles: drift to **higher pressure**

* (St>$\alpha$)




**Small particles: well mixed**

**Large** particles:
sediment down & drift inward

**Pressure bump**:
traps large particles

Birnstiel 2024, ARA&A

# DUST: CRUCIAL INGREDIENT

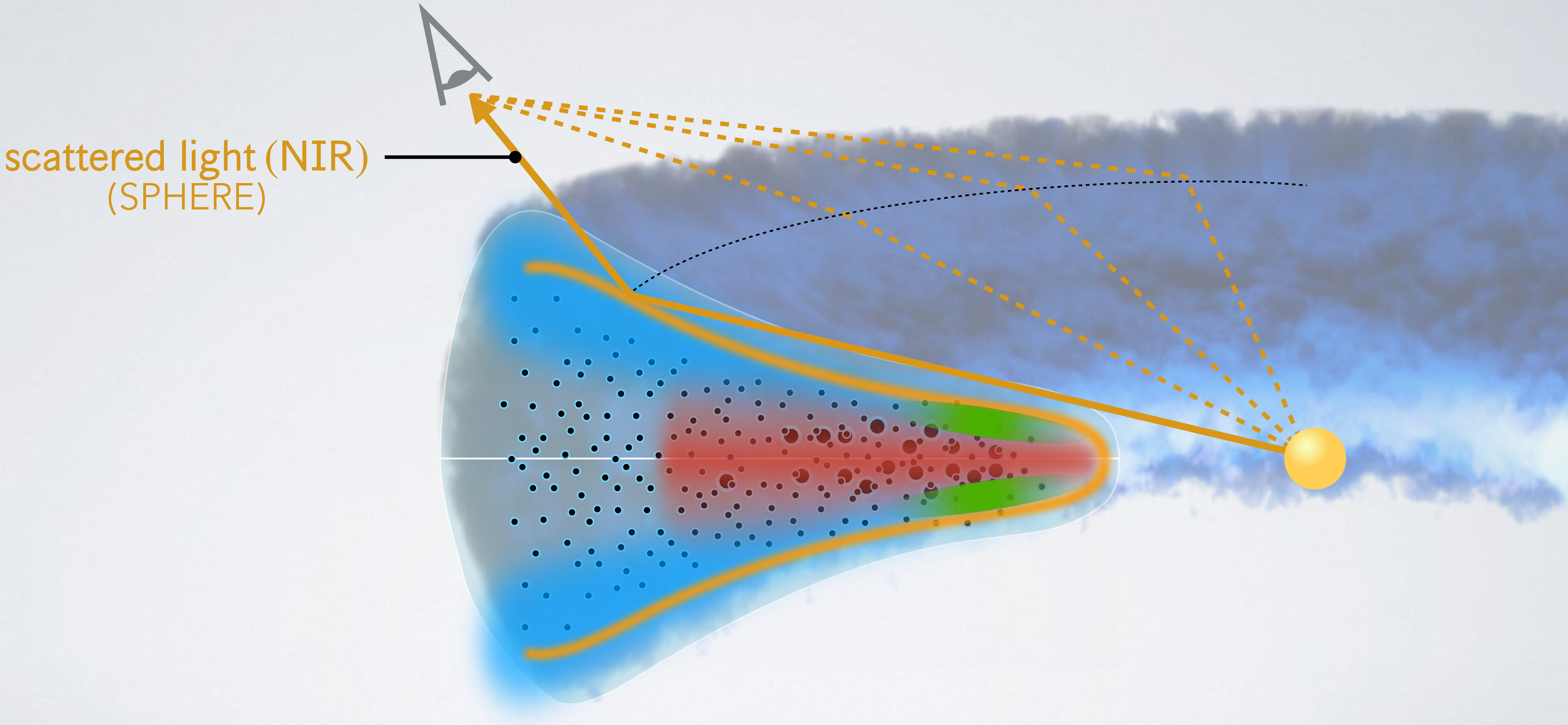

Dust required as **base material**, during **all stages**, and as **tracer**


pebble/ptsl. accretion
streaming instability
Collisional growth

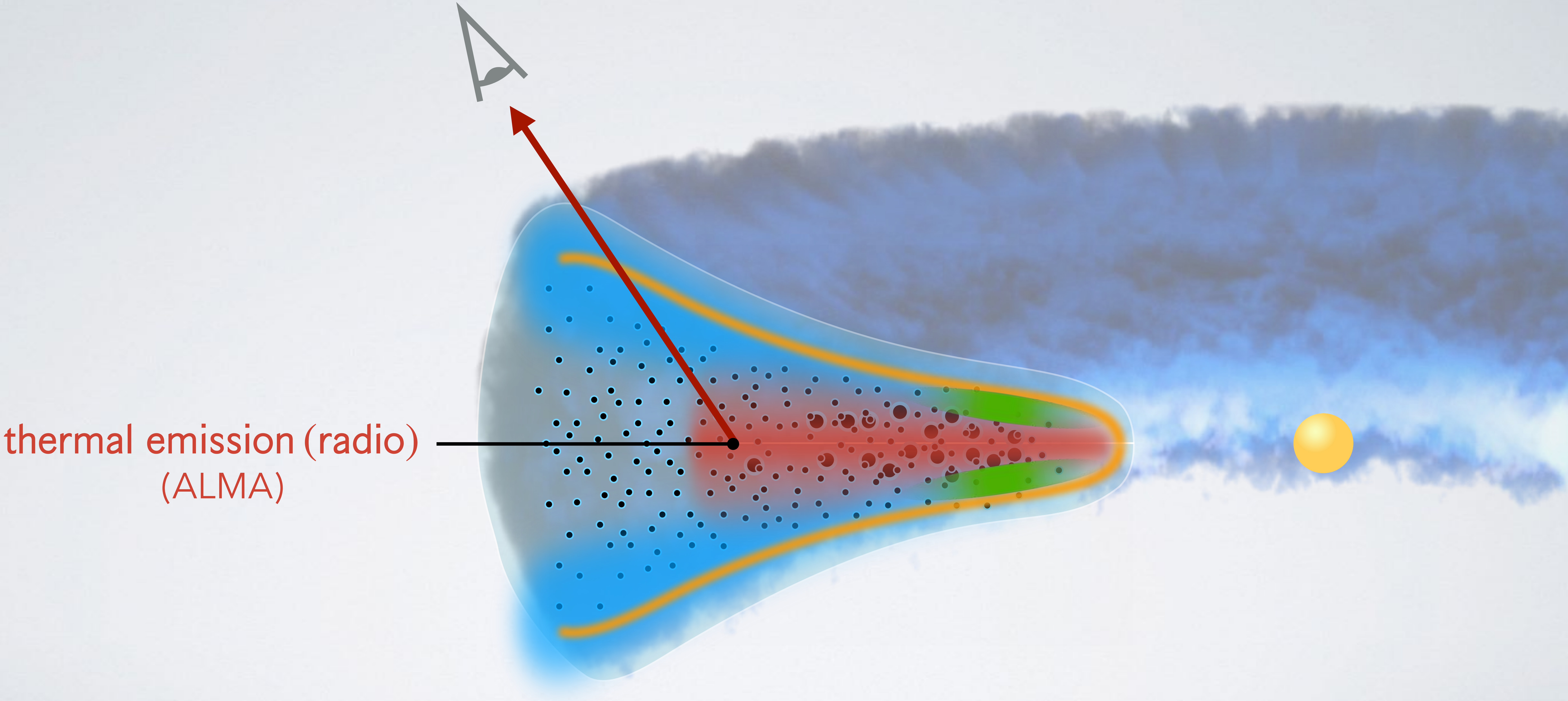
# 2. Observing Protoplanetary Dust

→ talk by Ryo Tazaki

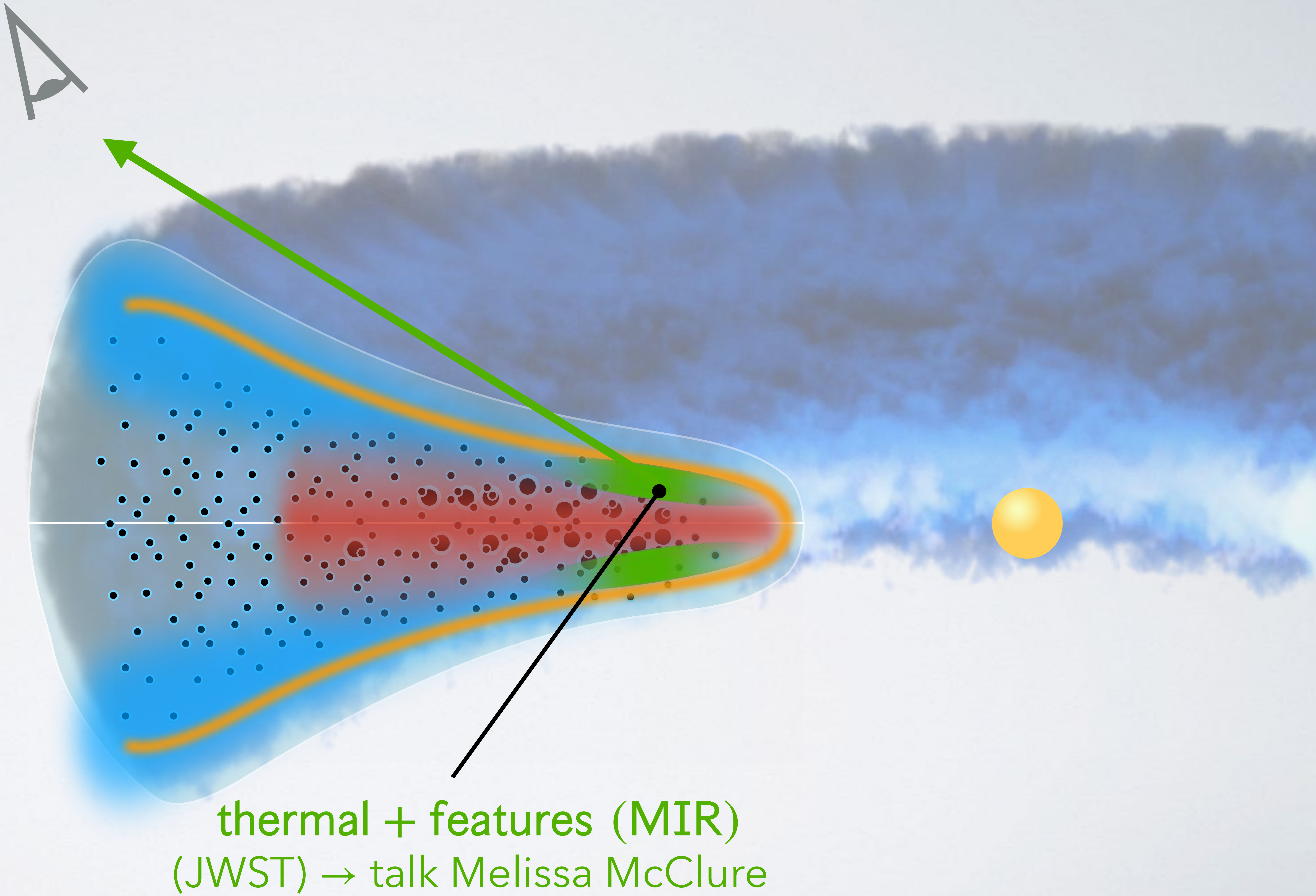
# Observing Protoplanetary Dust



# Observing Protoplanetary Dust



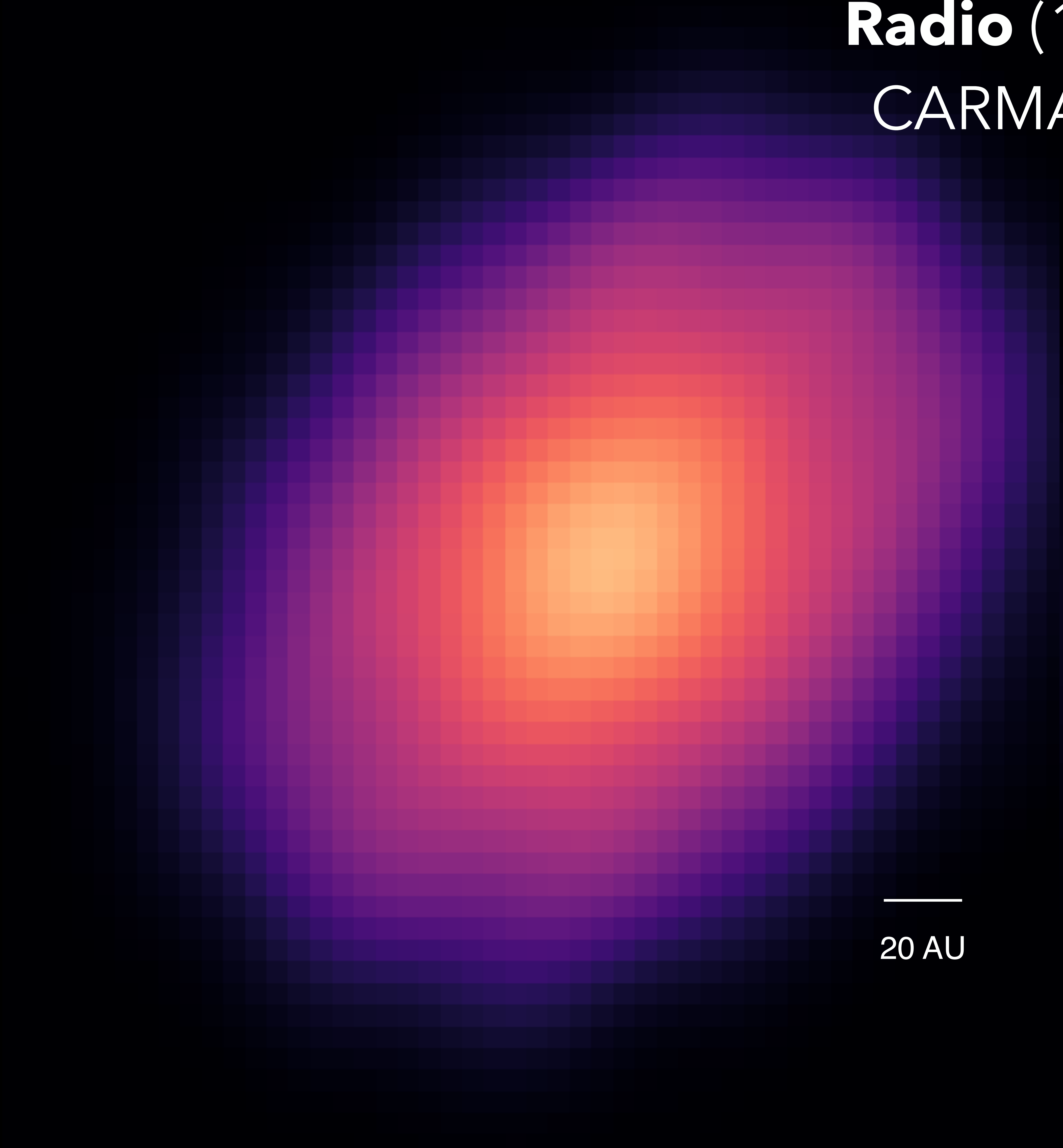
# Observing Protoplanetary Dust

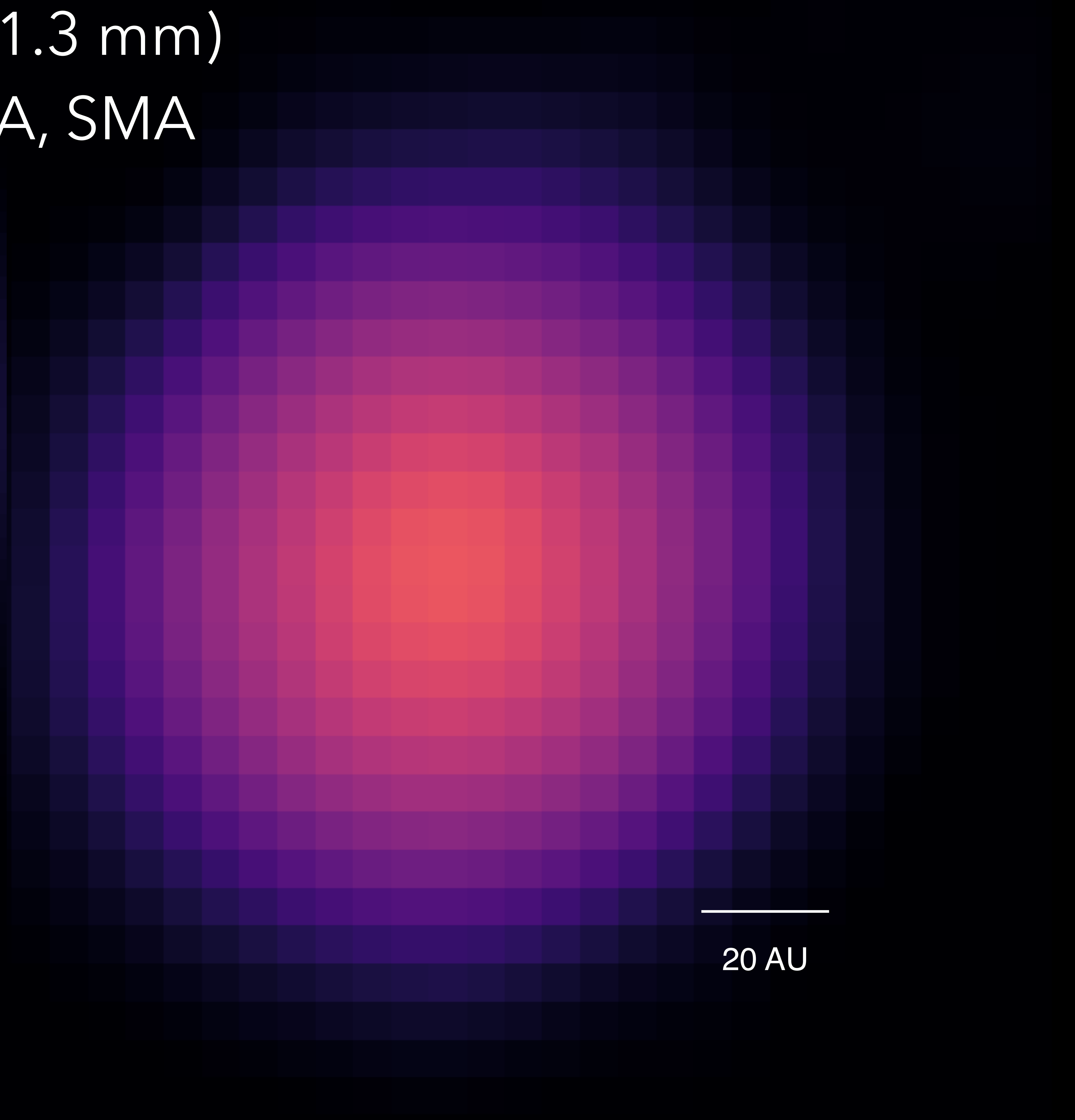


# HIGH RESOLUTION RADIO INTERFEROMETRY

**Radio** (1.3 mm)

CARMA, SMA



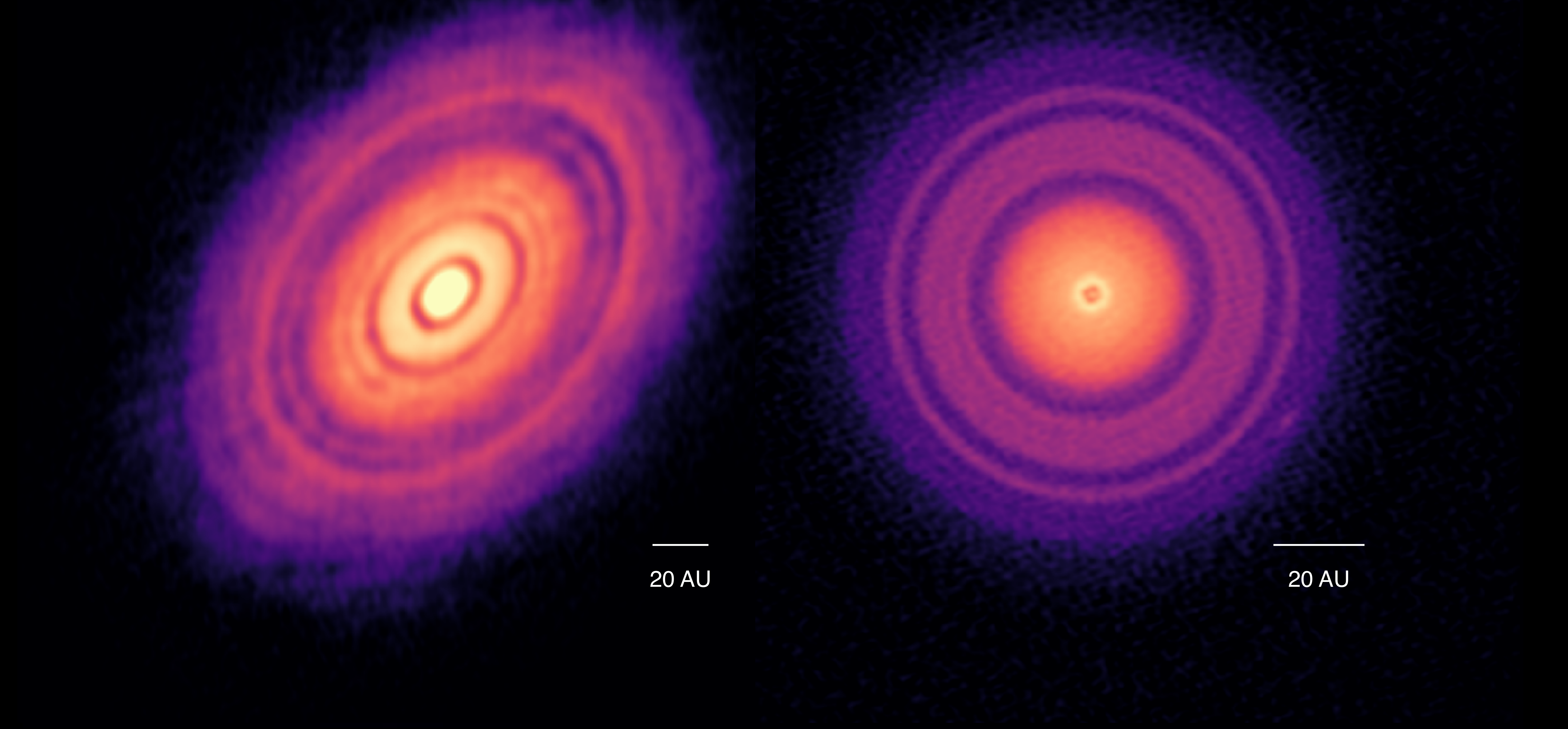




Slide: S. Andrews; Kwon et al. 2011; Andrews et al. 2012

# High Resolution Radio Interferometry

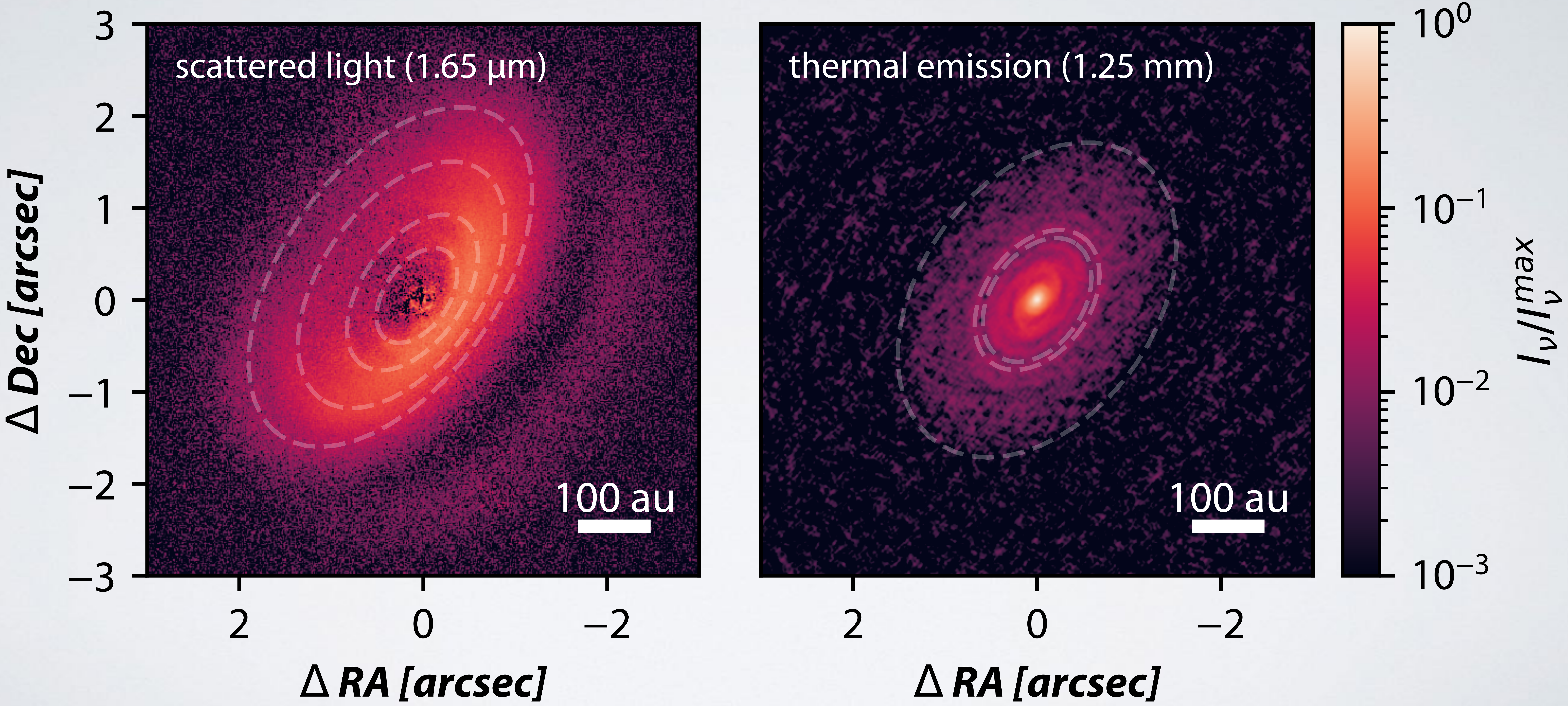
**Radio** (1.3 mm)

ALMA




Slide: S. Andrews; Kwon et al. 2011; Andrews et al. 2012; ALMA Partnership et al. 2015; Andrews et al. 2016

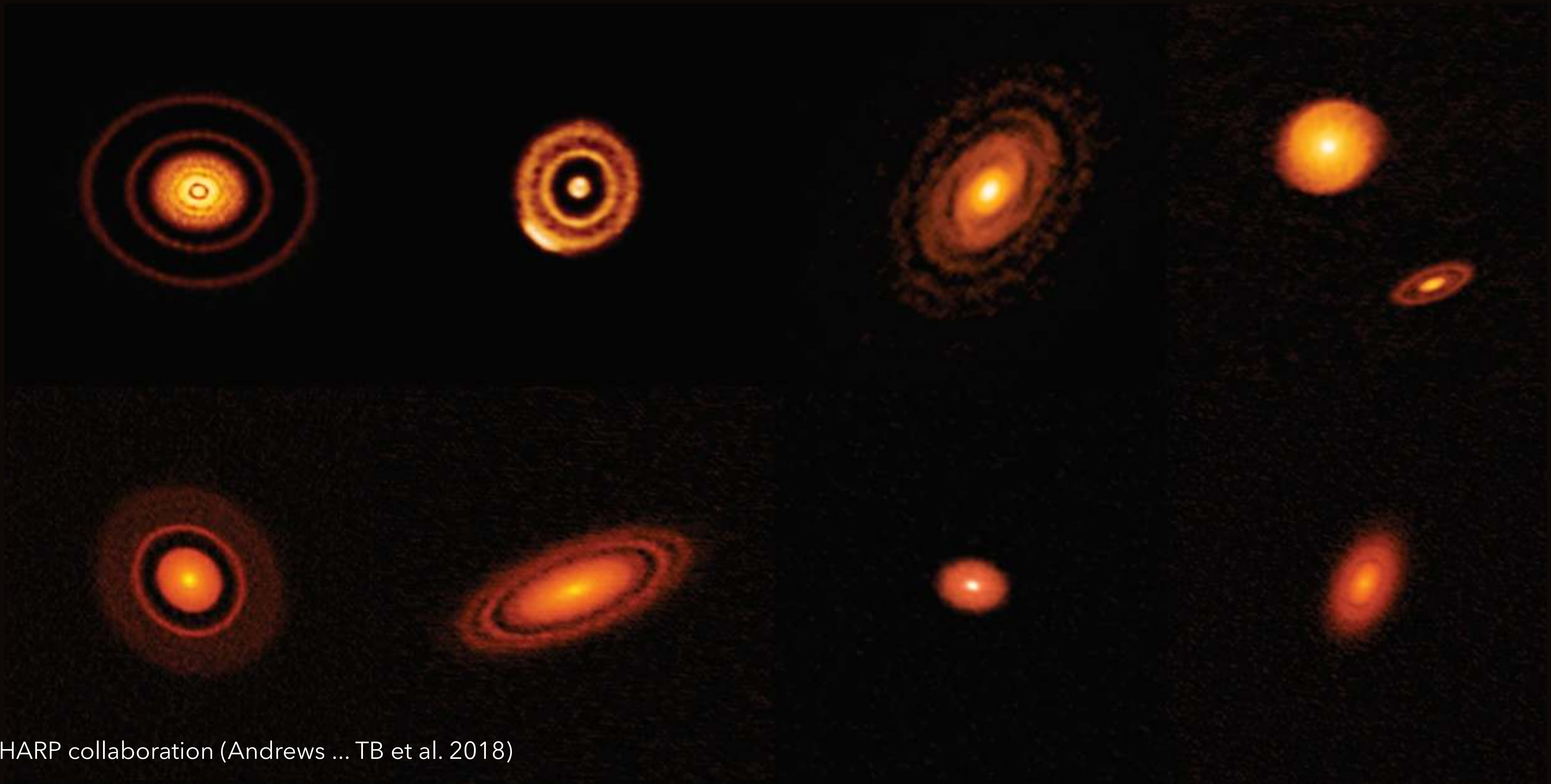
# Observing Protoplanetary Dust




schematic: Birnstiel 2024, data: Avenhaus et al. 2018, Andrews et al. 2018

# 3. New Paradigms

# Obligatory DSHARP Gallery



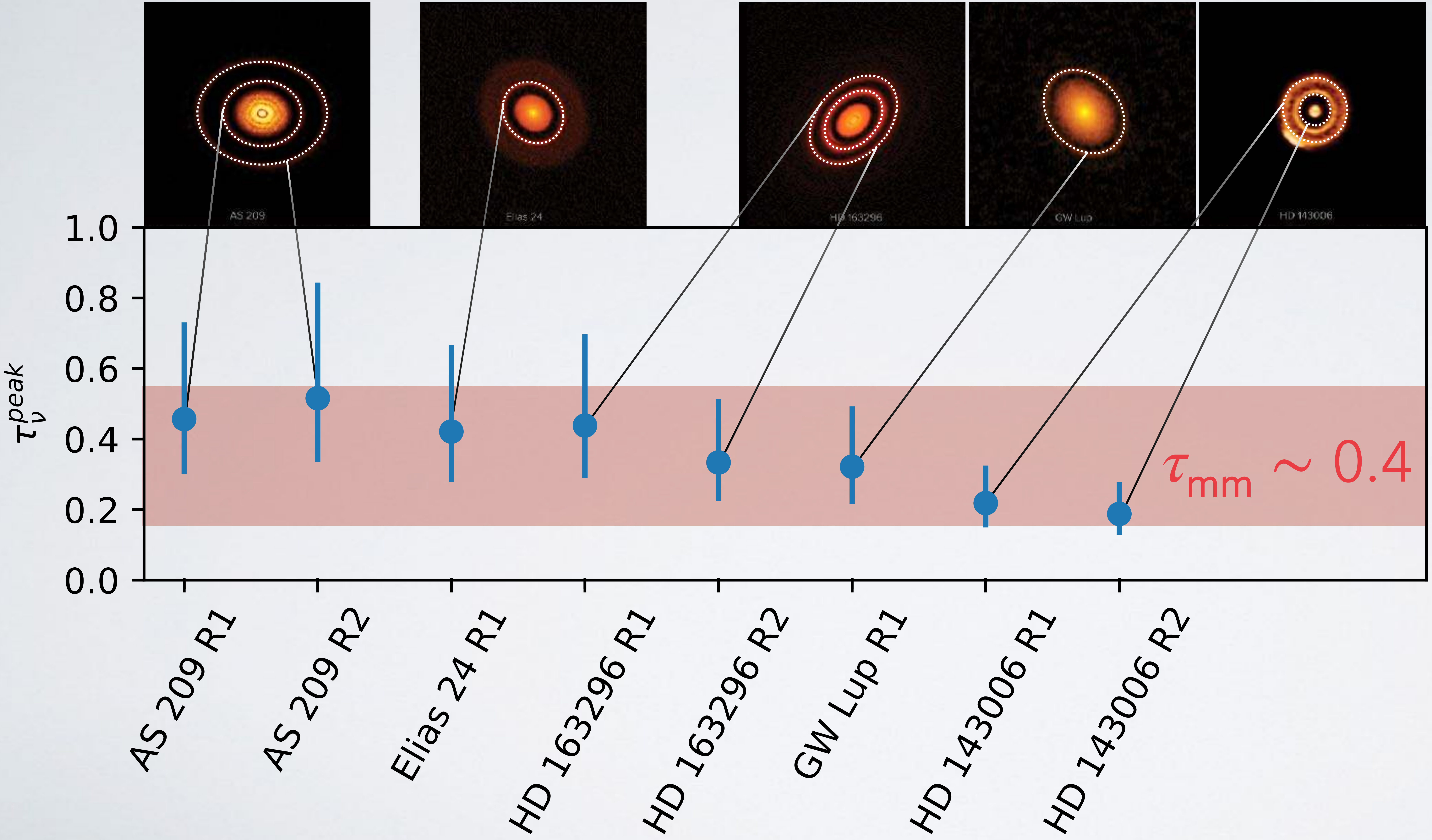
DSHARP collaboration (Andrews ... TB et al. 2018)

# Obligatory DSHARP Gallery

**Substructure in every resolved disk!**

DSHARP collaboration (Andrews ... TB et al. 2018)

# What have we Learned?




Stammler et al. 2019:

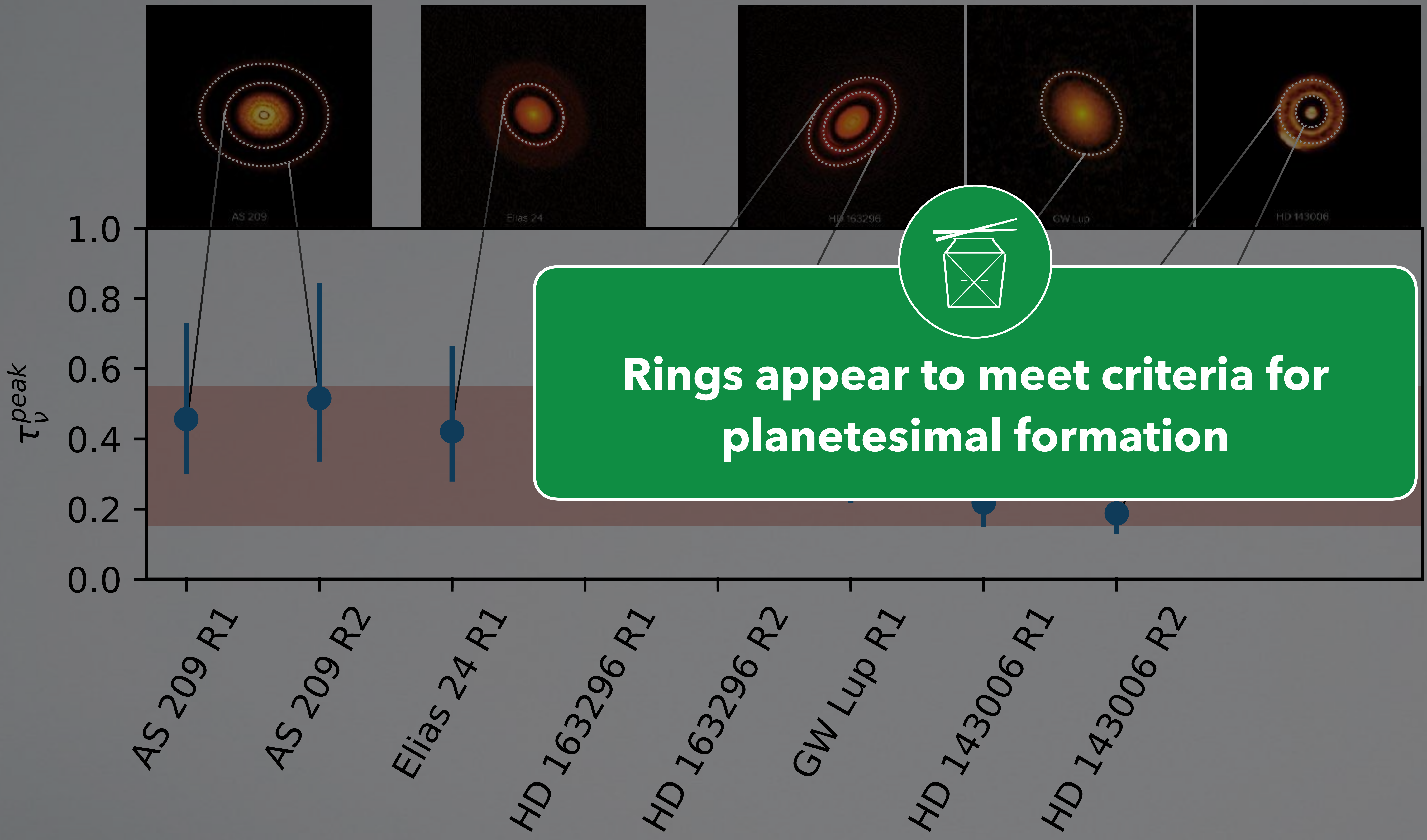
condition to form planetesimals

=

optical depth $\lesssim 1$

Dullemond, TB, & DSHARP collaboration (2018)

# WHAT HAVE WE LEARNED?




**Rings appear to meet criteria for planetesimal formation**

Stammler et al. 2019:

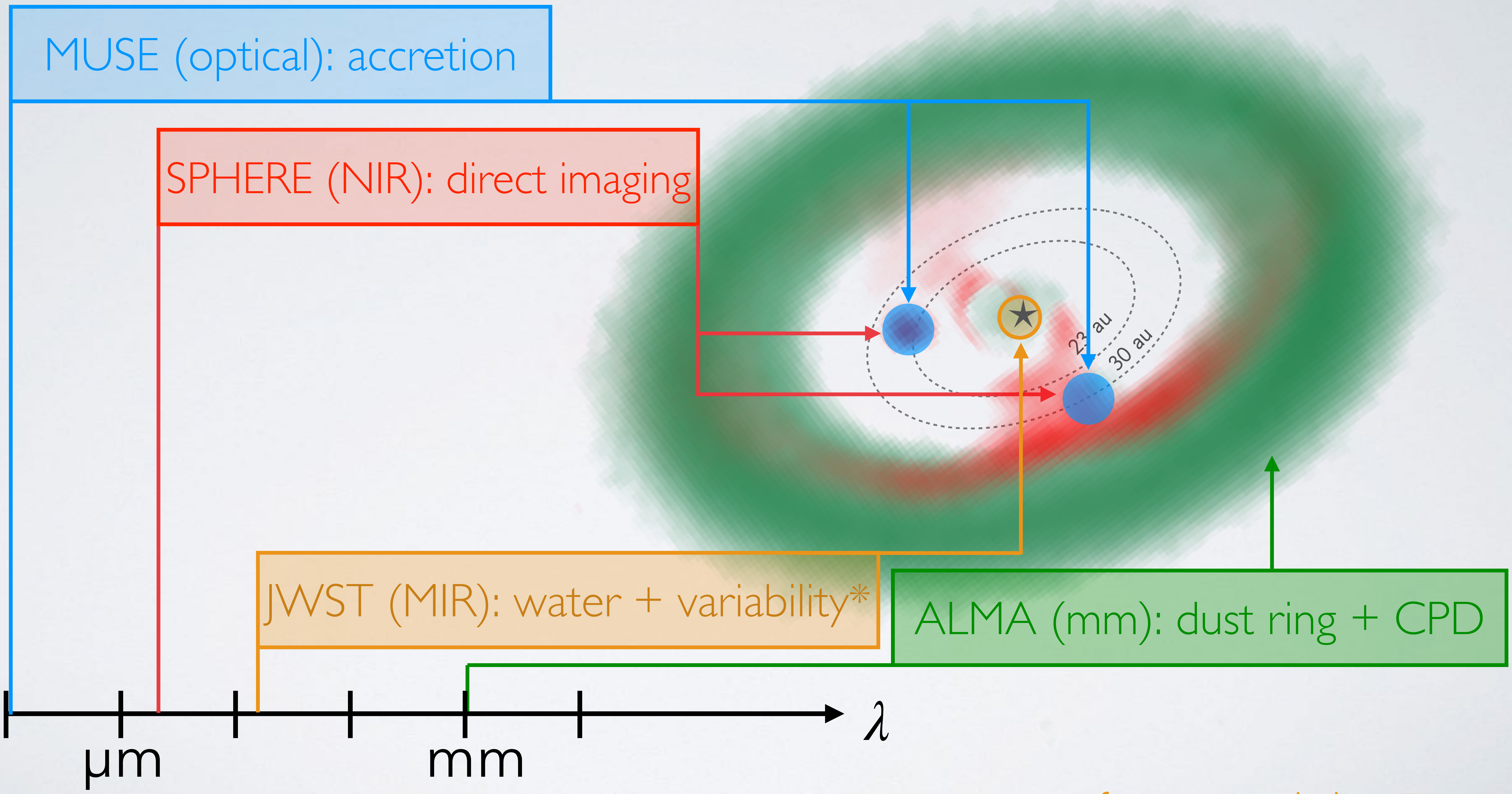
condition to form planetesimals

=

optical depth $\lesssim 1$

Dullemond, TB, & DSHARP collaboration (2018)

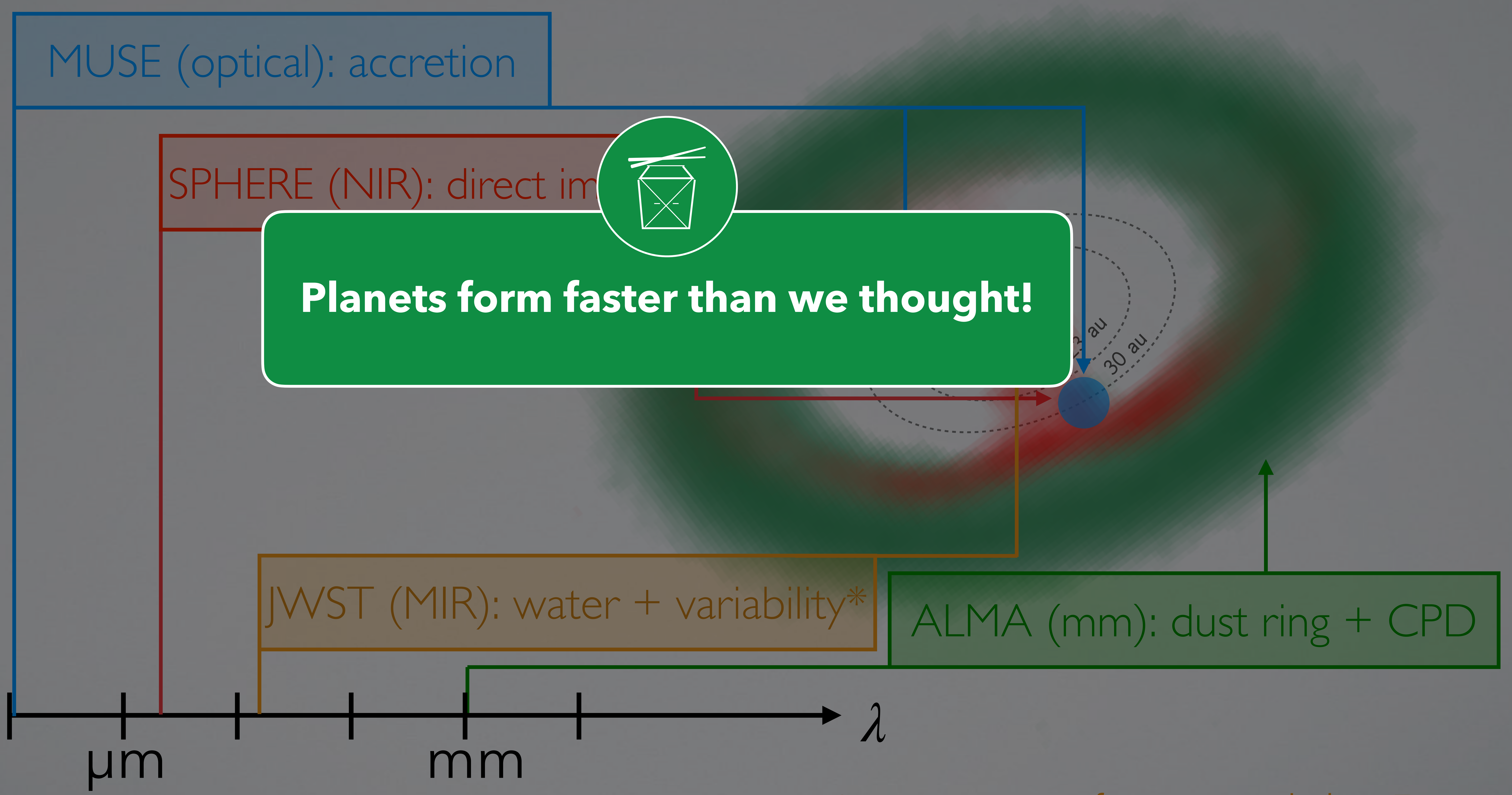
# THE BENCHMARK DISK OF PDS70




*enstatite poor, forsterite rich, low Fe content

Haffert et al. 2019, Keppler et al. 2018, Benisty et al. 2021, Perotti et al. 2024, Jang et al. 2024

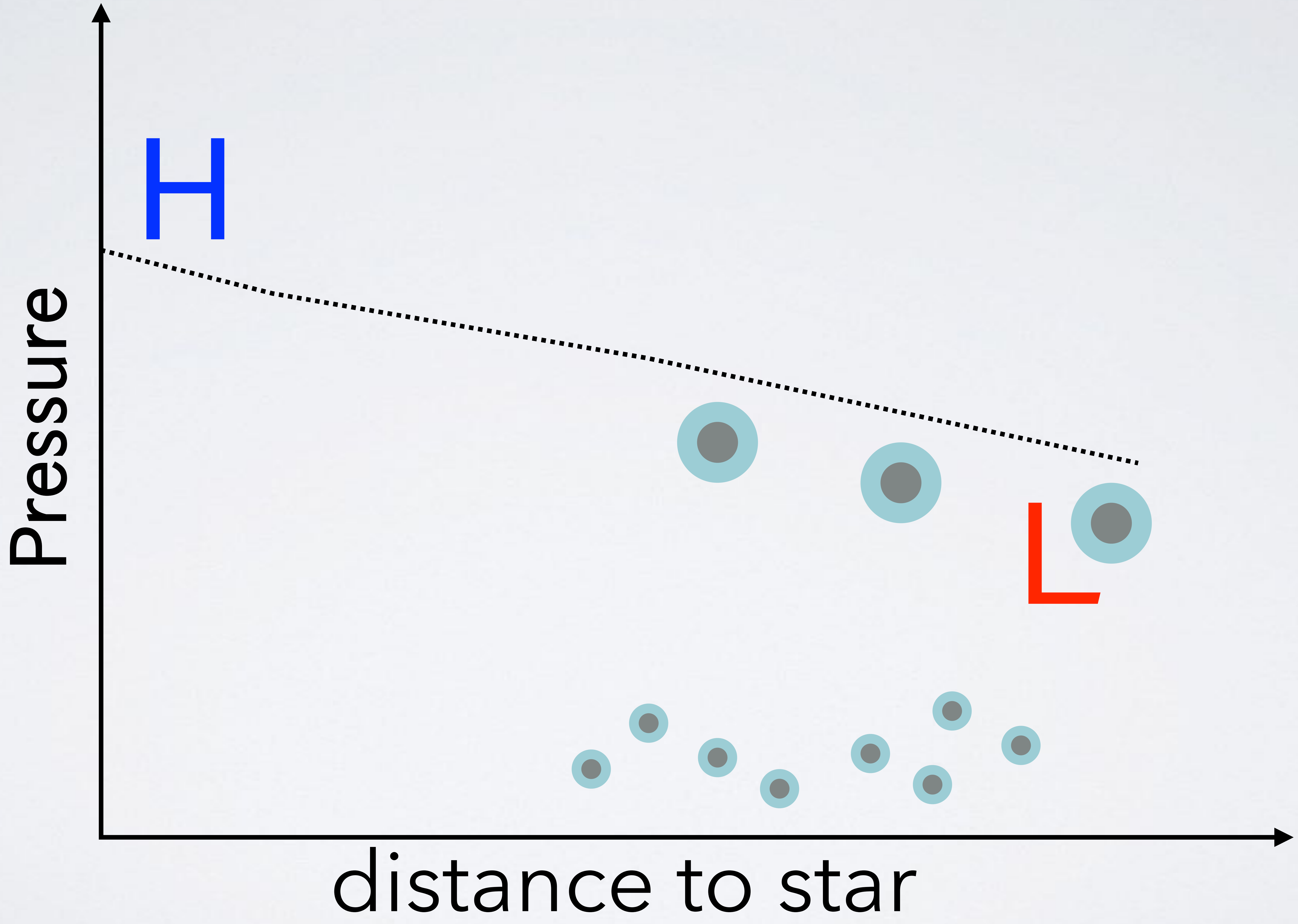
# The Benchmark Disk of PDS70




*enstatite poor, forsterite rich, low Fe content

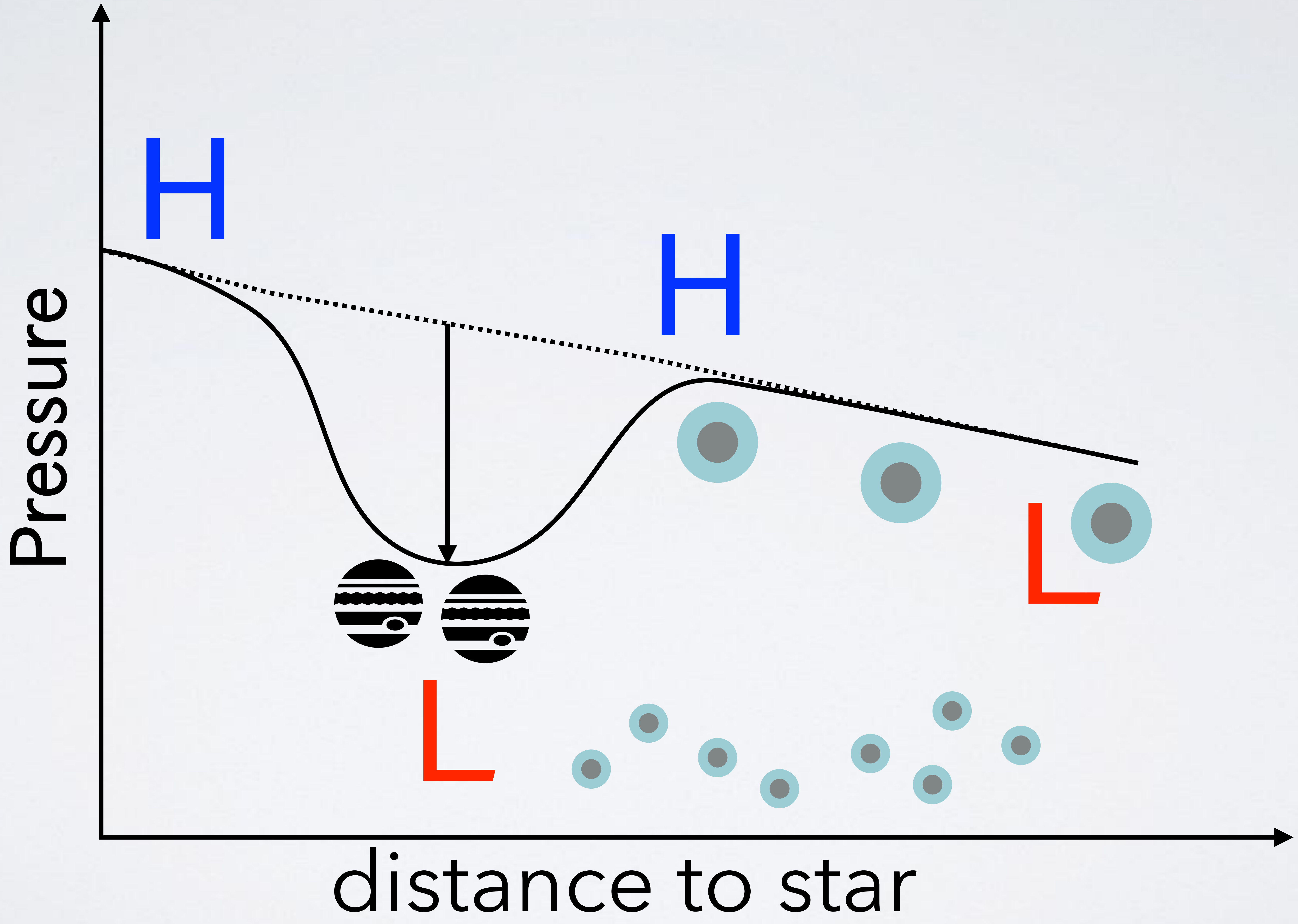
Haffert et al. 2019, Keppler et al. 2018, Benisty et al. 2021, Perotti et al. 2024, Jang et al. 2024

# The Benchmark Disk of PDS70



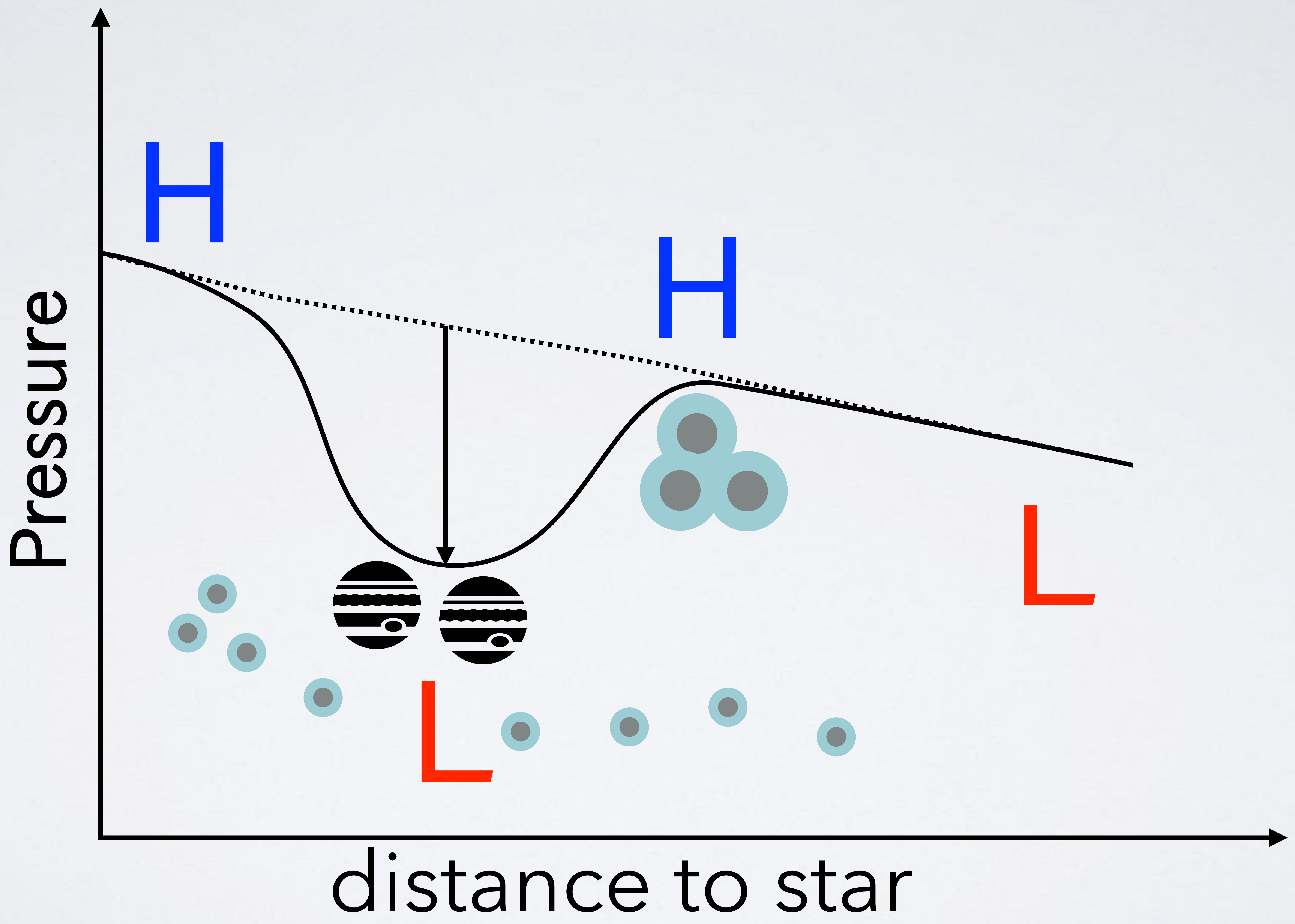

e.g. Stammler et al. 2023, Pinilla et al. 2016, 2024

# The Benchmark Disk of PDS70



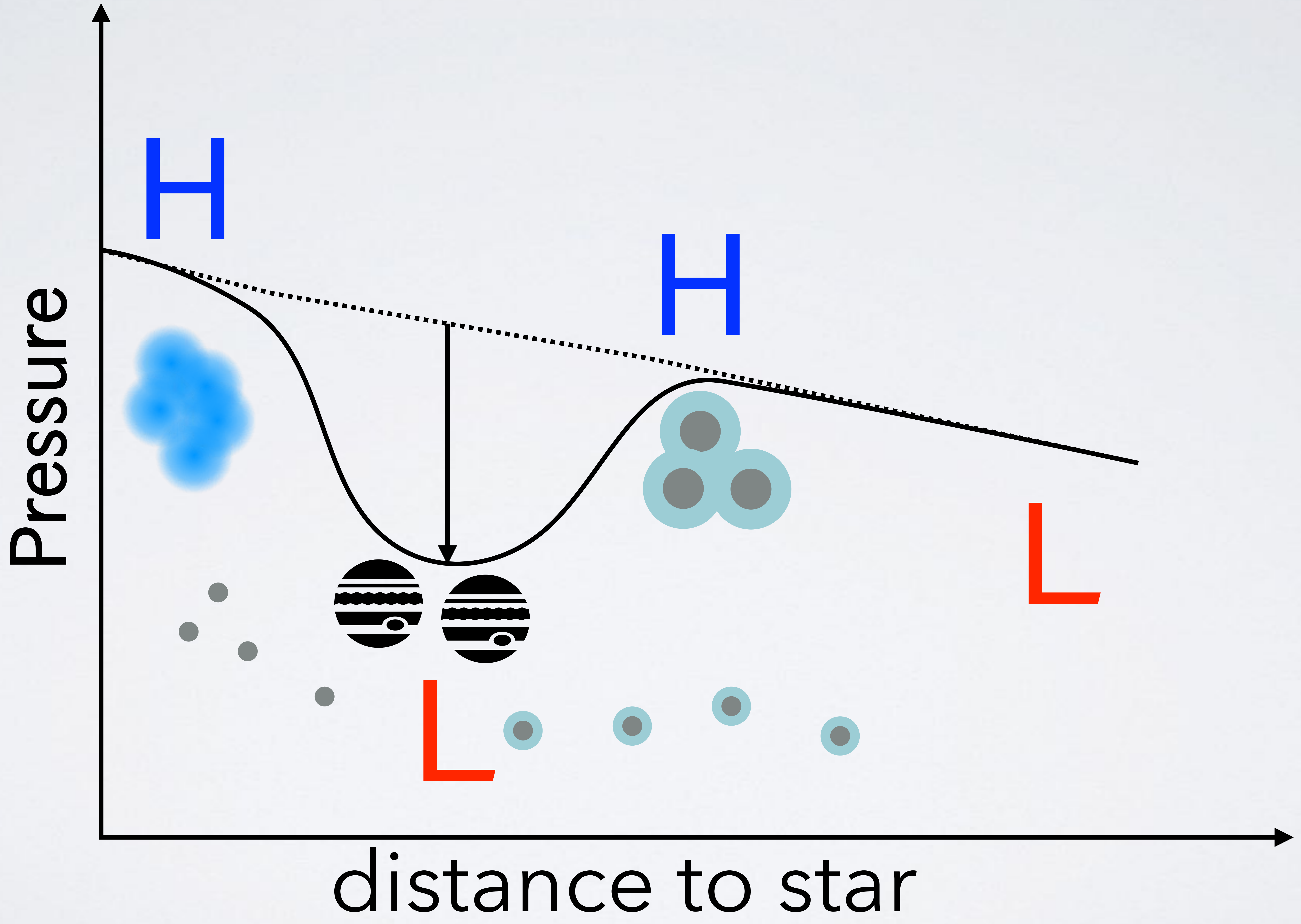

e.g. Stammler et al. 2023, Pinilla et al. 2016, 2024

# The Benchmark Disk of PDS70




e.g. Stammler et al. 2023, Pinilla et al. 2016, 2024

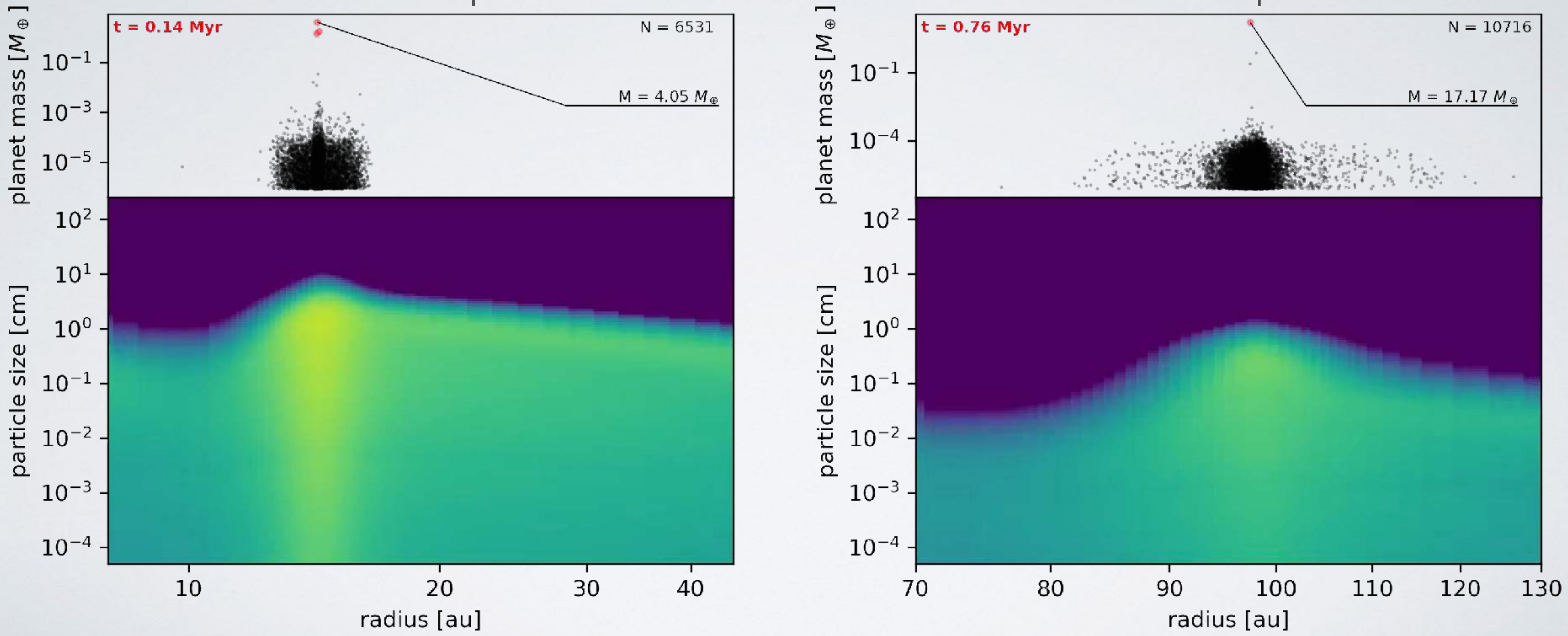
# The Benchmark Disk of PDS70




e.g. Stammler et al. 2023, Pinilla et al. 2016, 2024

# Rapid Formation of Planetary Cores

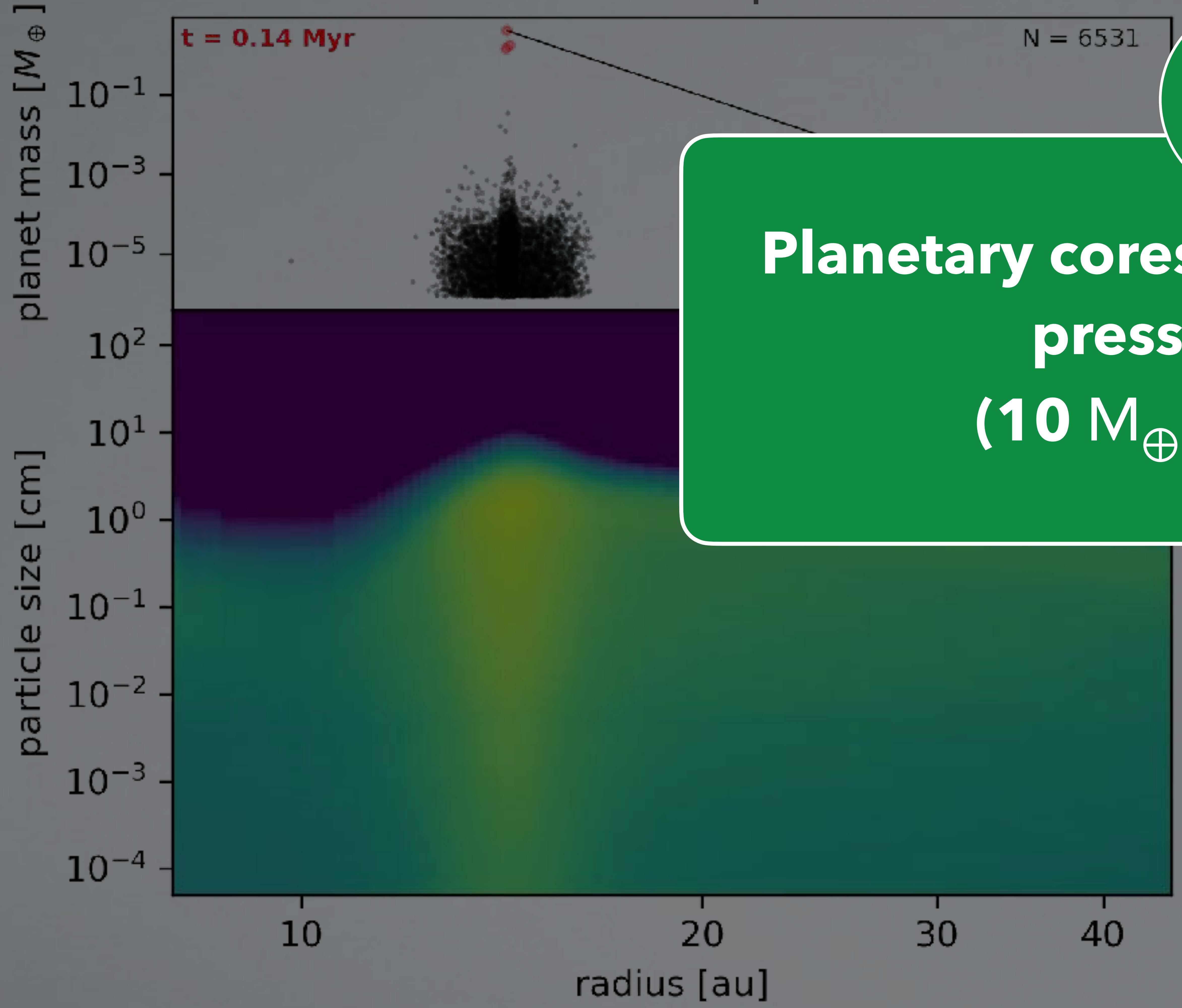
Pressure bump **@ 15 au** Pressure bump **@ 100 au**



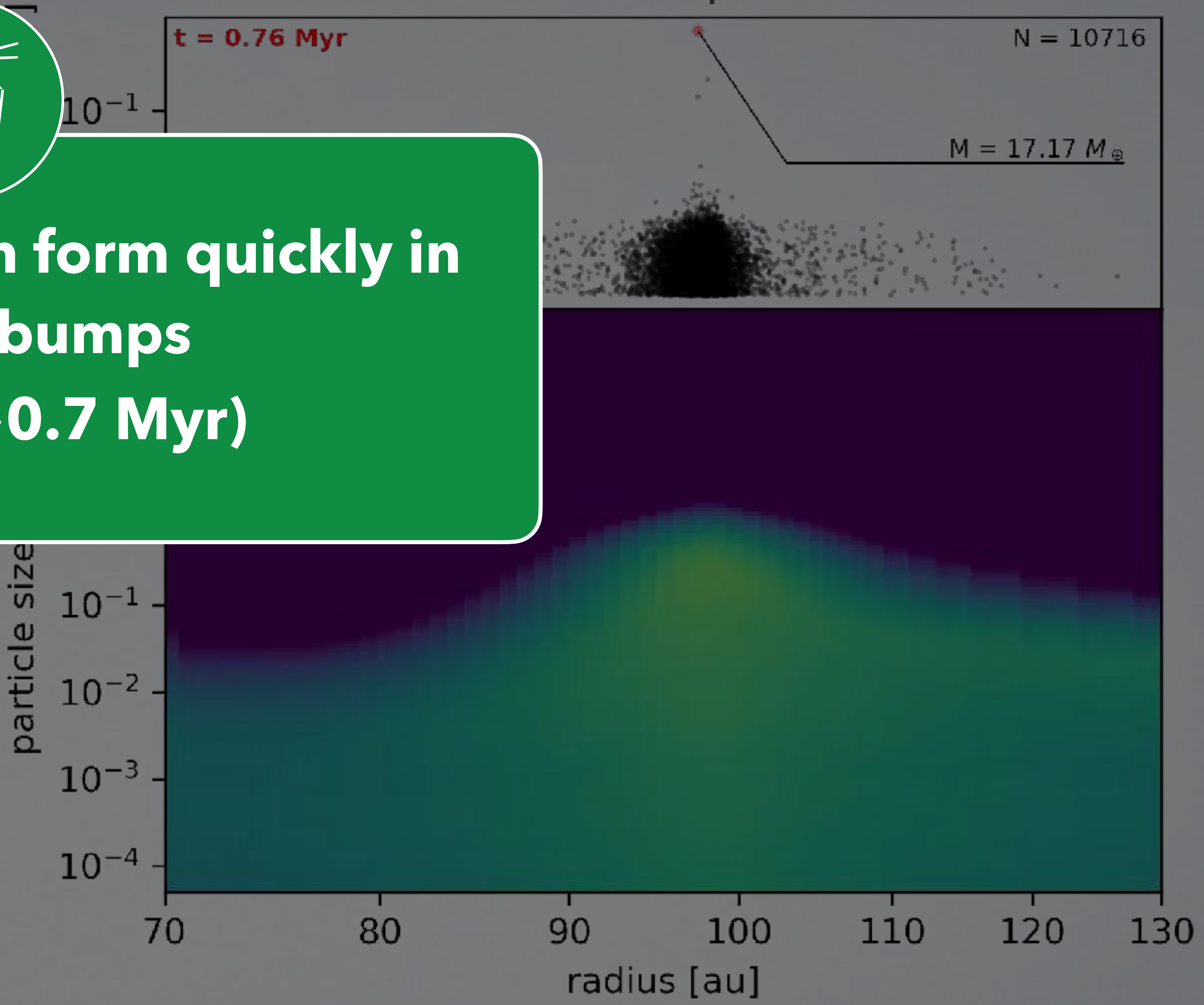

Lau et al. 2022

# Rapid Formation of Planetary Cores

Pressure bump **@ 15 au**




Pressure bump **@ 100 au**



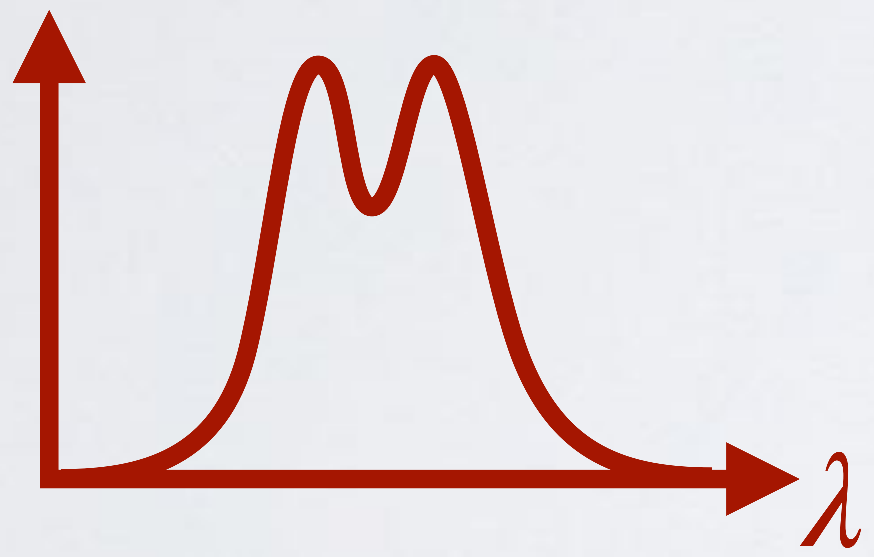

**Planetary cores can form quickly in pressure bumps**
**(10 $M_\oplus$ in ~0.7 Myr)**

Lau et al. 2022

# Vertical Structure & Turbulence

Pinte et al. 2015

# Vertical Structure & Turbulence




Dullemond et al. 2018: dust is radially trapped ($\mathrm{St} \gtrsim \alpha_\mathrm{t}$)

Doi & Kataoka 2021: $\mathrm{St} \gtrsim 1 \ldots 100 \cdot \alpha_\mathrm{t}$

Franceschi et al. 2023: $\alpha_\mathrm{t} \simeq 3 \times 10^{-3}$

Villenave et al. 2025: low turbulence ($\alpha_t < 10^{-3}$)

Tong et al. 2025: $10^{-4} < \alpha_\mathrm{t} < 10^{-3}$

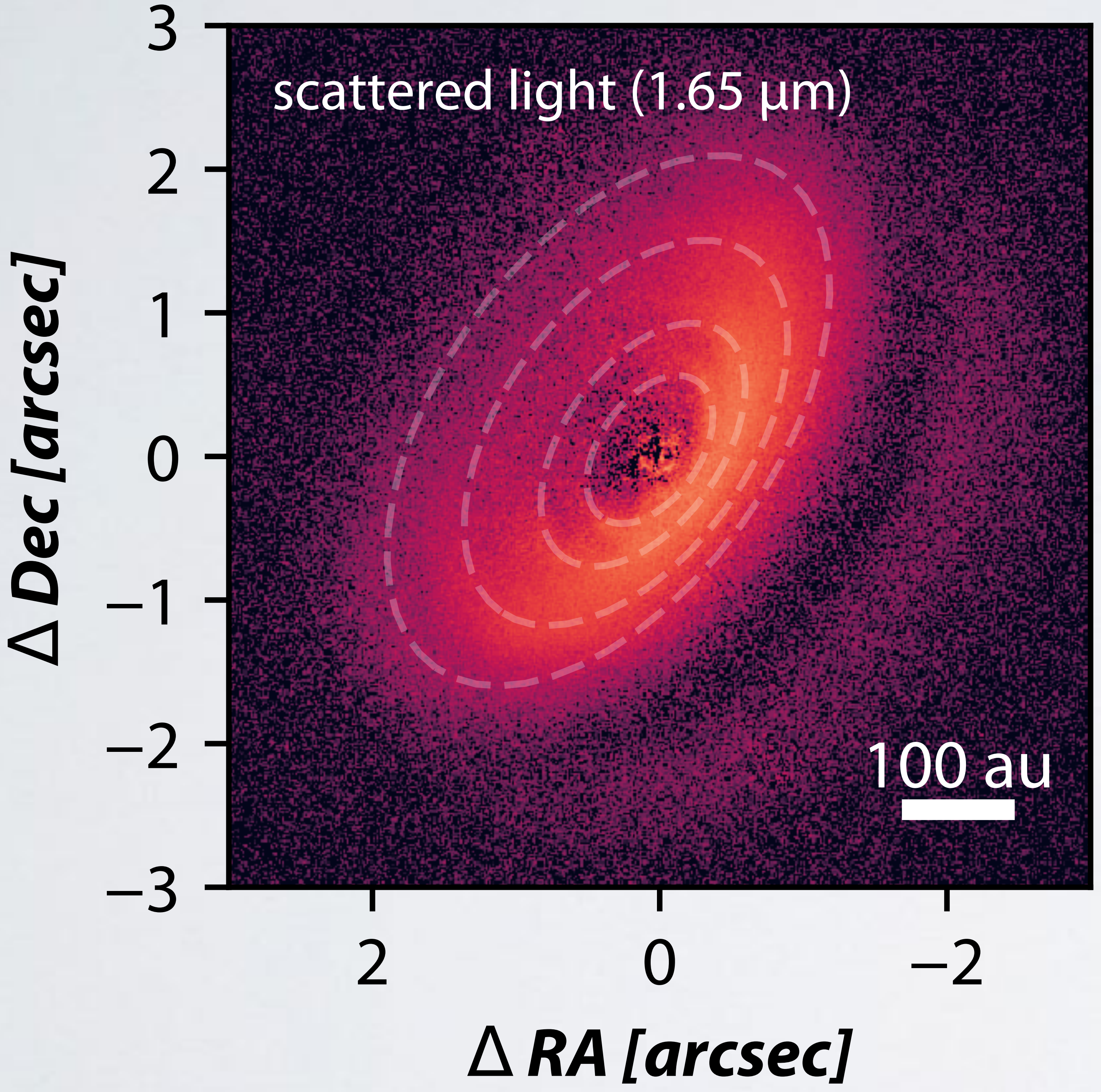
…

Flaherty et al. 2015, 18: $\alpha_\mathrm{t} \simeq \mathrm{few} \times 10^{-3}$

Flaherty et al. 2020, 24: $\alpha_\mathrm{t} \simeq \mathrm{few} \times 10^{-1}$

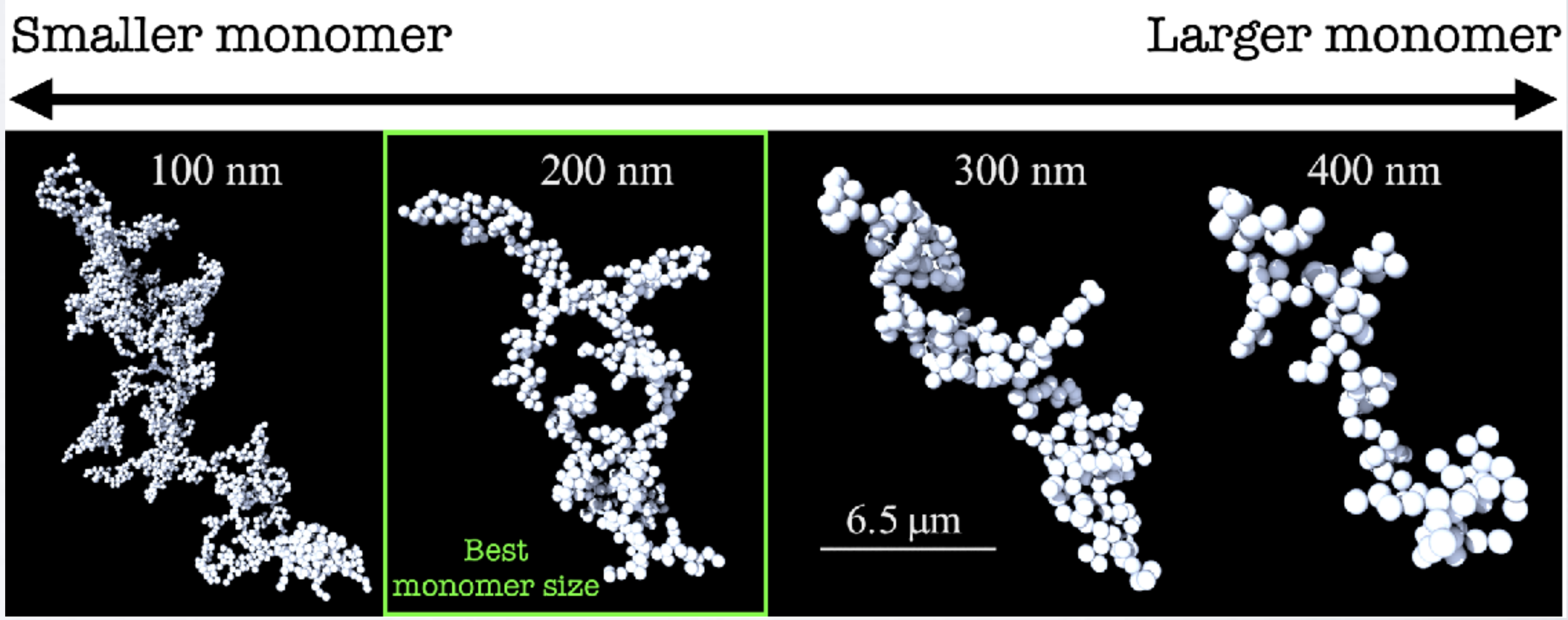
**grains settle & get trapped**
**turbulence is low (except at disk surface)**

# DUST SIZES & POROSITY I: SCATTERED LIGHT




**Surface** of IM Lup: 2 μm fractal grains

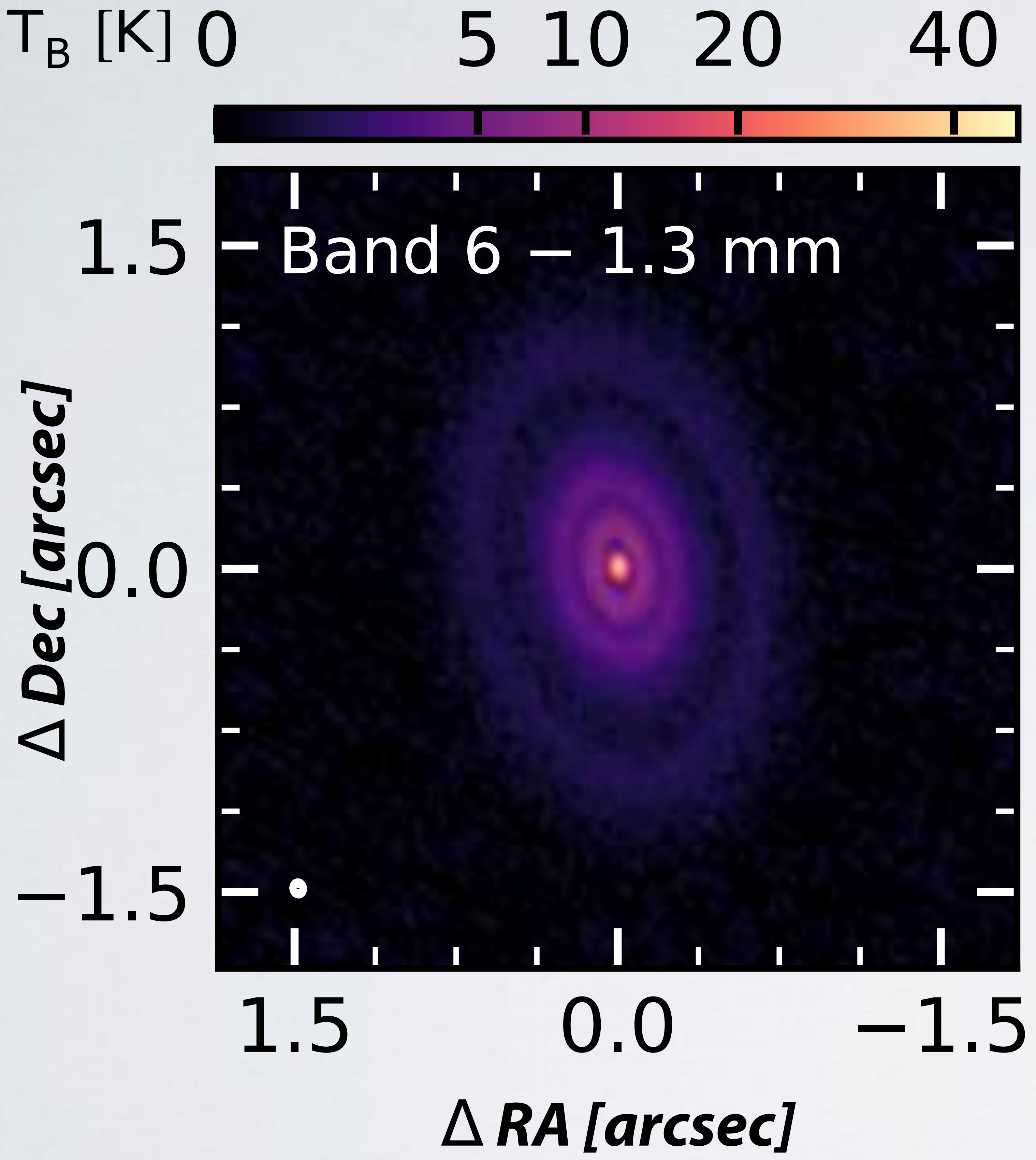
**Many other disks:** non-fractal grains

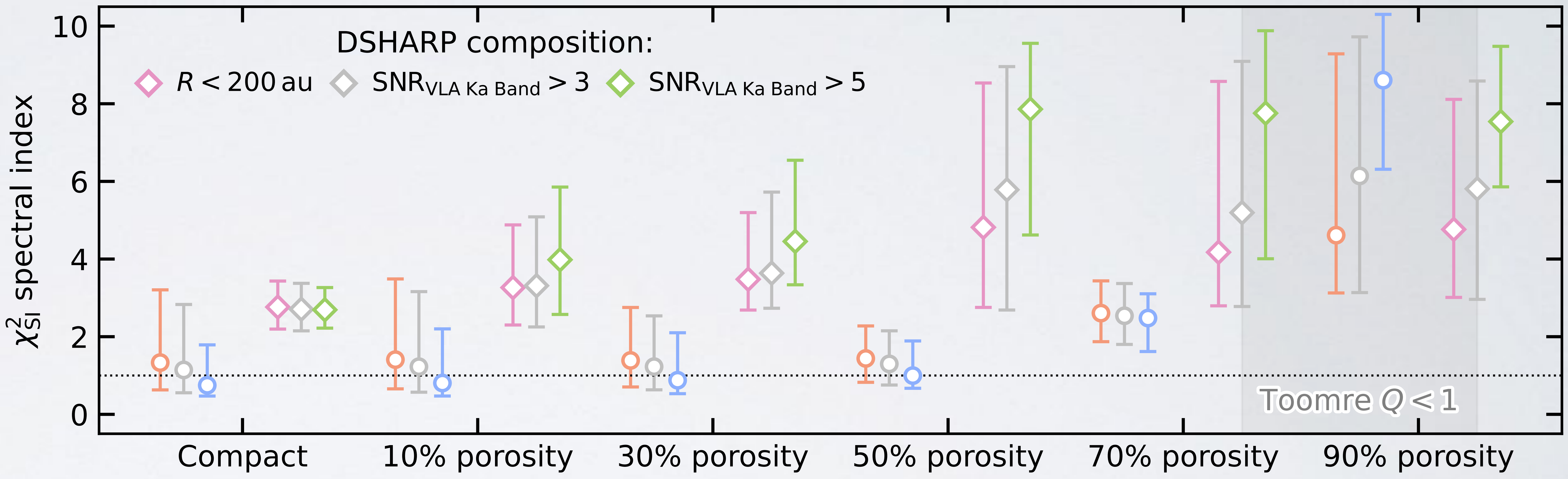



Tazaki et al. 2023, Ginski et al. 2023

# Dust Sizes & Porosity II: Radio-SED

Spectral index in radio-$\lambda$: measures $\beta$ ($\kappa_{abs} \propto \nu^{\beta}$ if optically thin)



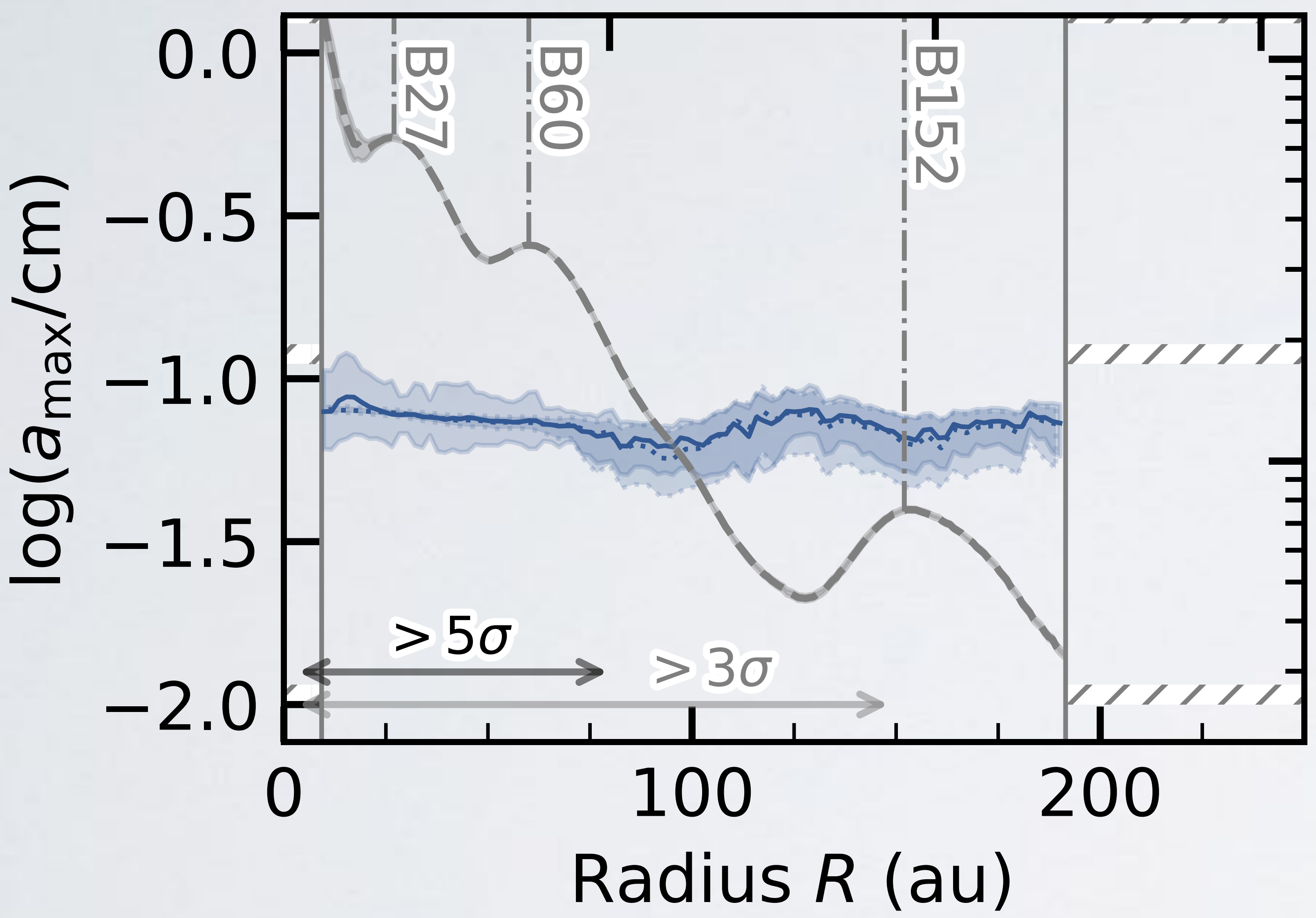



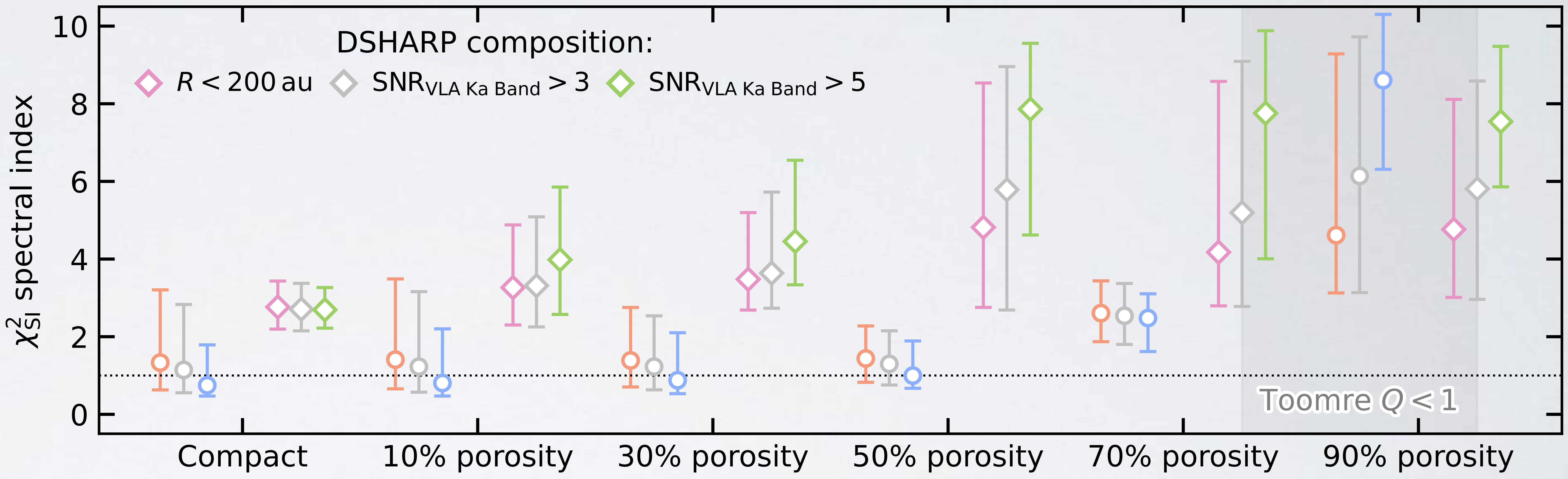

**Radially constant grain size** (~mm) – or limited resolution?

Zagaria et al. 2025, see also Viscardi et al. 2025 → Poster! Other works: include Marcias et al. 2021, Lin et al. 2020, Ueda et al. 2025

# Dust Sizes & Porosity II: Radio-SED

Spectral index in radio-$\lambda$: measures $\beta$ ($\kappa_{abs} \propto \nu^{\beta}$ if optically thin)

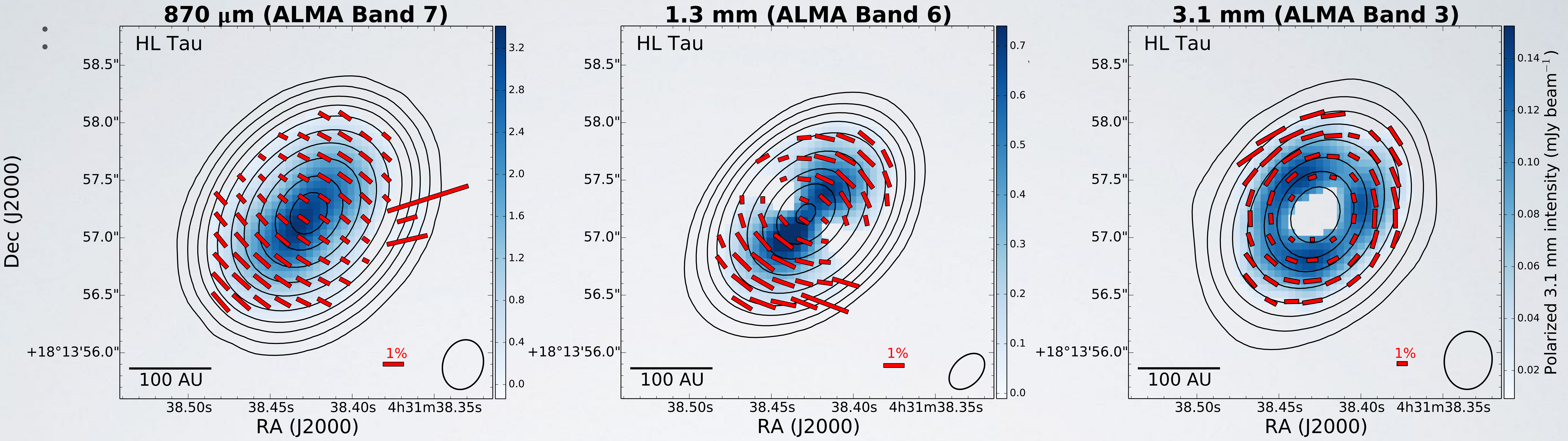



Radially **constant grain size** (~mm) – or limited resolution?

Zagaria et al. 2025, see also Viscardi et al. 2025 → Poster! Other works: include Marcias et al. 2021, Lin et al. 2020, Ueda et al. 2025

# Dust Sizes & Porosity III: Polarization




Grains smaller (~100 μm) and porous → higher dust masses

(complications: high-$\tau$-rings, stratification, different mechanisms mixing and porosity)

image: Stephens et al. 2017; see also Kataoka et al. 2015; Zhang et al. 2023

# Other Topics

:

Carbon depletion in the Solar System

Inner Disk Mineralogy with JWST

Disk Demographics & Population Synthesis

Towards Kuiper Belts and Debris Disks

# SUMMARY

Dust is a crucial ingredient and tracer of all stages of planet formation

Planet forming disks concentrate dust in pressure maxima
those solve several issues of planet formation at once

Amazing observational capabilities open new questions
(variability of spectra, accretion mechanism, porosity)

Measurements of dust properties still mostly disagree in details
but grain of 0.1 – 1 mm likely
porosity still mysterious

LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

European Research Council
Established by the European Commission

# THANKS FOR YOUR ATTENTION!

ORIGINS
Excellence Cluster