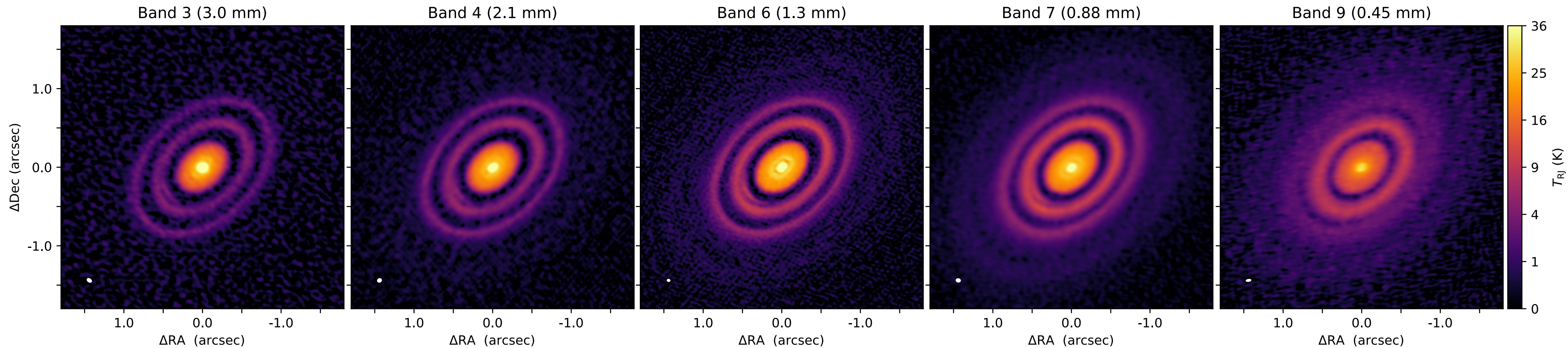


Dust Properties in the HD 163296 Disk

from High-Resolution Multi-wavelength Observations Including ALMA Band 9 (0.45 mm)



Kiyoaki Doi

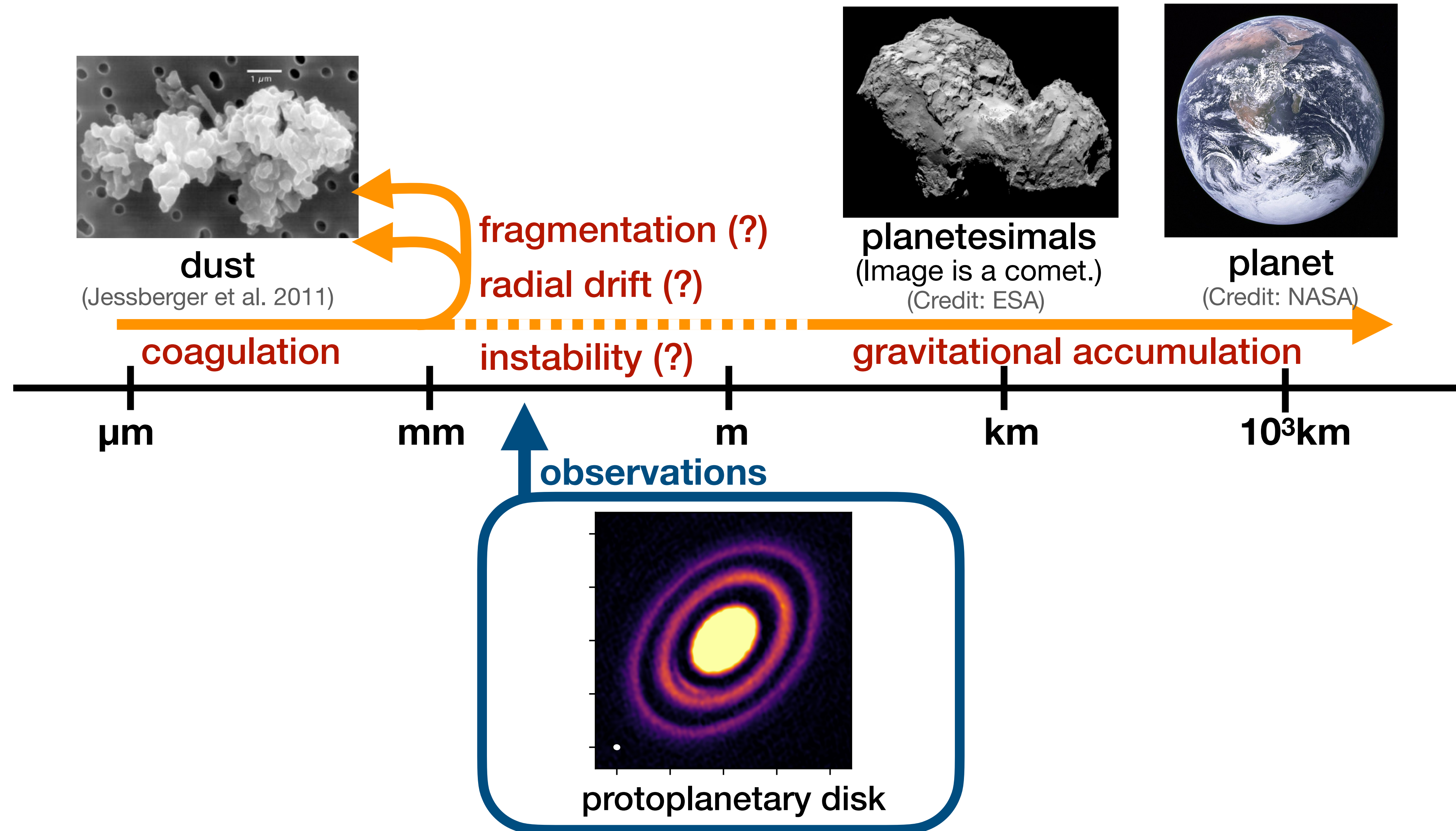
Max Planck Institute for Astronomy, PSF (PFE?) Postdoc

with Myriam Benisty (MPIA), Akimasa Kataoka (NAOJ),

Haochang Jiang (MPIA), Francesco Zagaria (MPIA), Hanyu Baobab Liu (NSYSU), Carsten Dominik (Univ. of Amsterdam), Ryo Tazaki (UTokyo),
Takahiro Ueda (NAOJ), Tomohiro Yoshida (NAOJ), Takashi Tsukakoshi (Ashikaga U.), Yoshihide Yamato (UTokyo), Ryuta Orihara (UTokyo)

Introduction

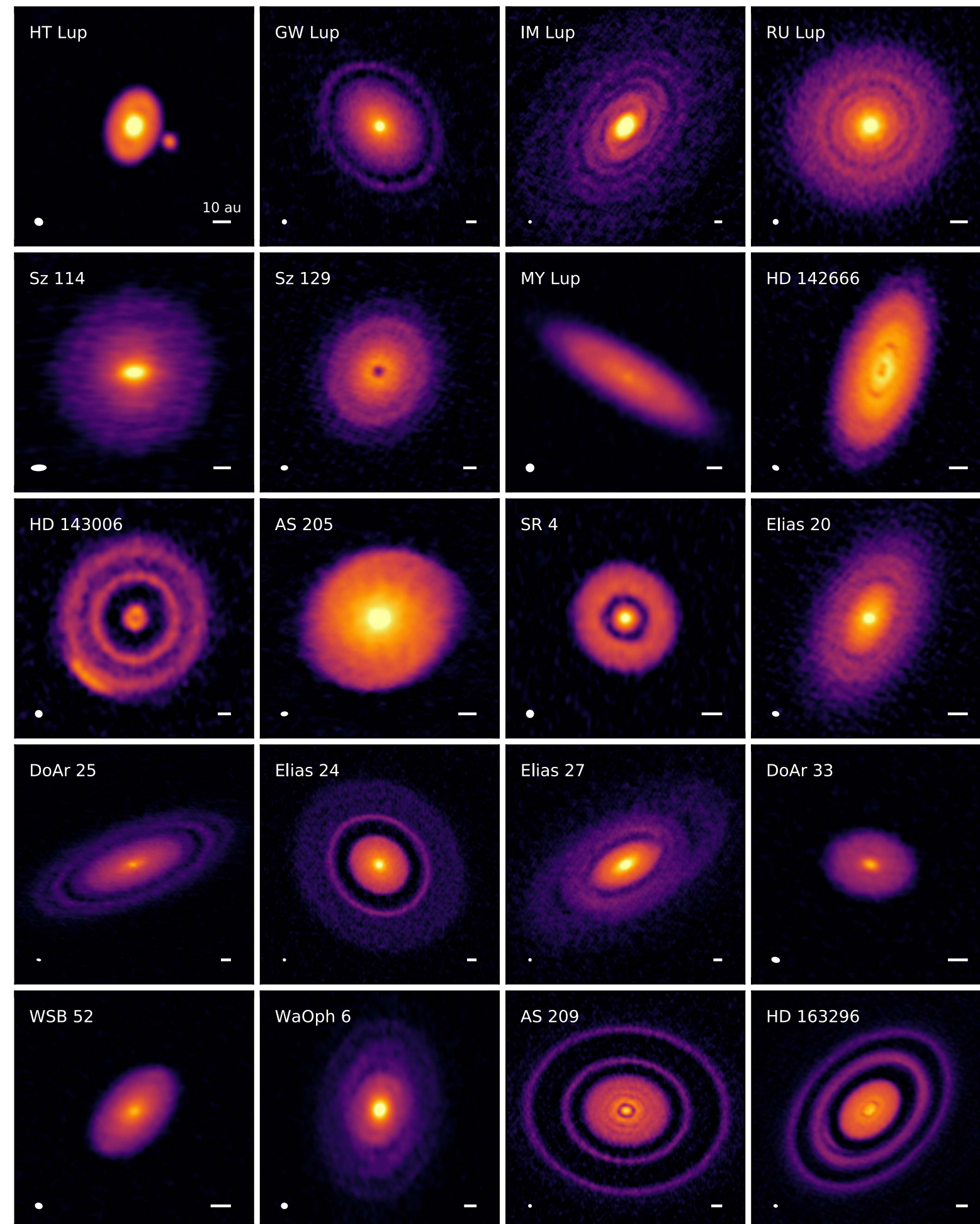
Planet Formation Process



Introduction

Recent Observations

ALMA millimeter continuum images
(thermal emission from dust grains)



(Andrews et al. 2018)

Key Findings

- Millimeter: spatial distribution of dust grains (rings, asymmetries, spirals, ...)
- Infrared: detection of planets (in PDS 70 and WISPIT2)

Challenges

- characterization of **dust properties**
 - dust size
 - dust surface density
 - dust temperature

Method

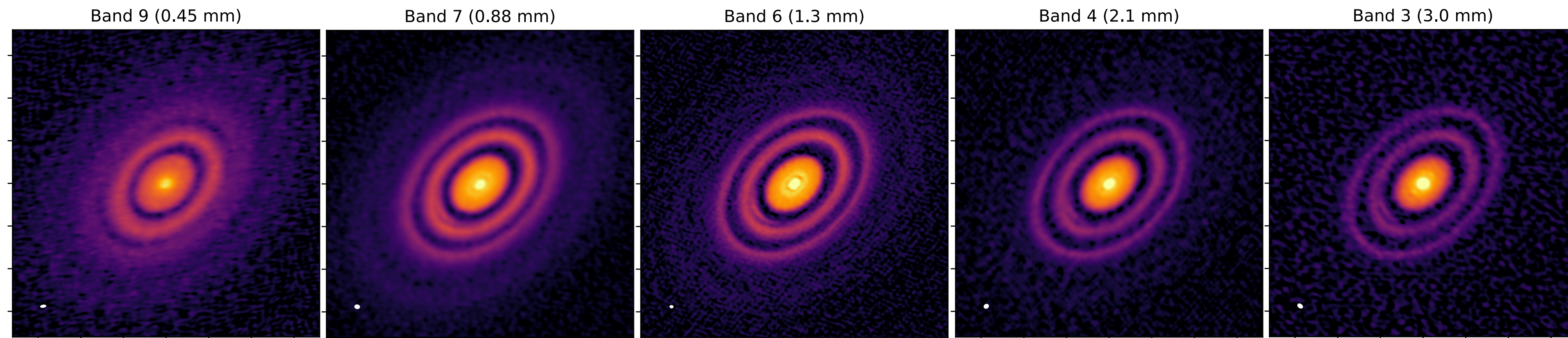
Multi-frequency observations (e.g., Sierra et al. 2021, 2024, Zagaria et al. 2025)

Intensity

$$- I = B(T) \times (1 - \exp(-\tau)) = B(T) \times (1 - \exp(\kappa_{\text{abs}}(a_{\text{dust}})\Sigma_{\text{dust}})) + (\text{scattering})$$

Free parameters:

- **dust temperature** T
- **dust surface density** Σ_{dust}
- dust opacity, depending on **dust size** (distribution): $\kappa(a)$

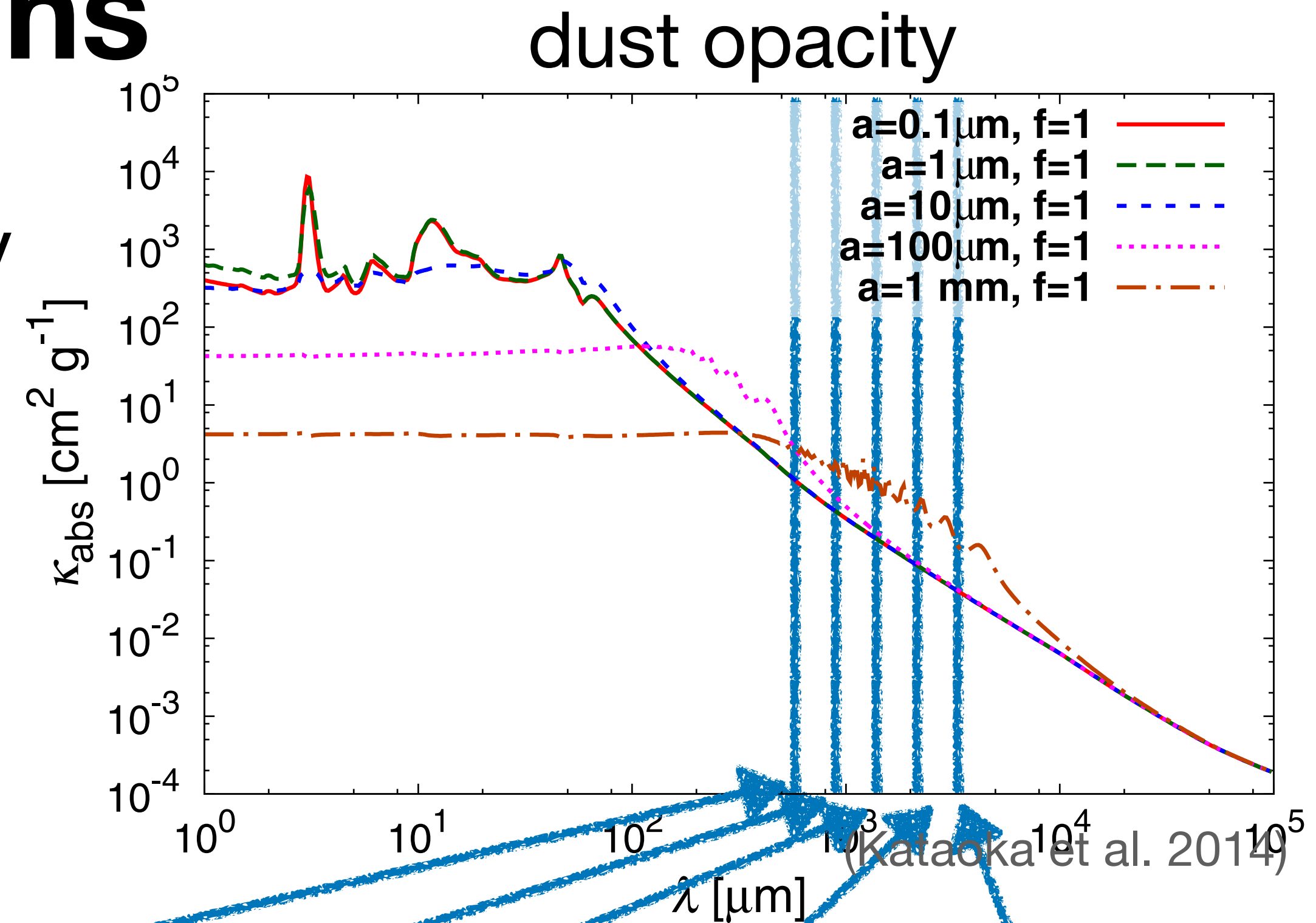


Method

Multi-frequency observations

The wavelength dependence of dust opacity reflects dust properties (size, composition).

→ We can constrain the dust properties from multi-wavelength observations.



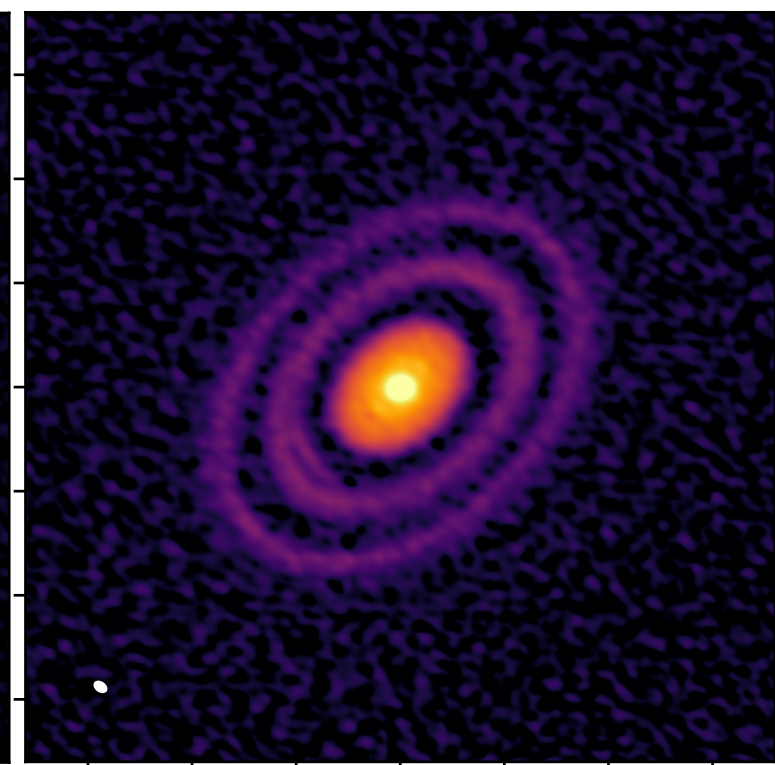
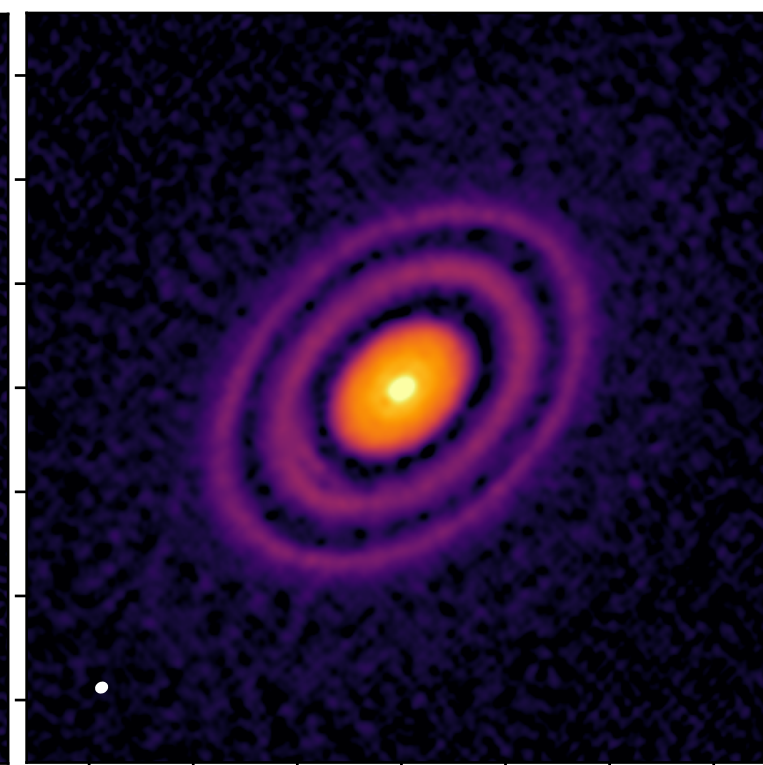
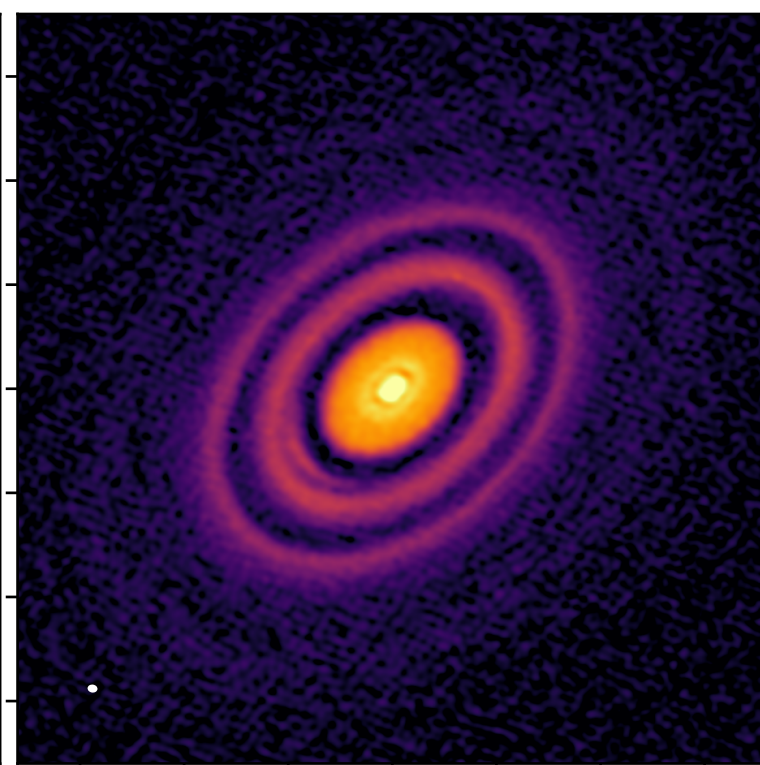
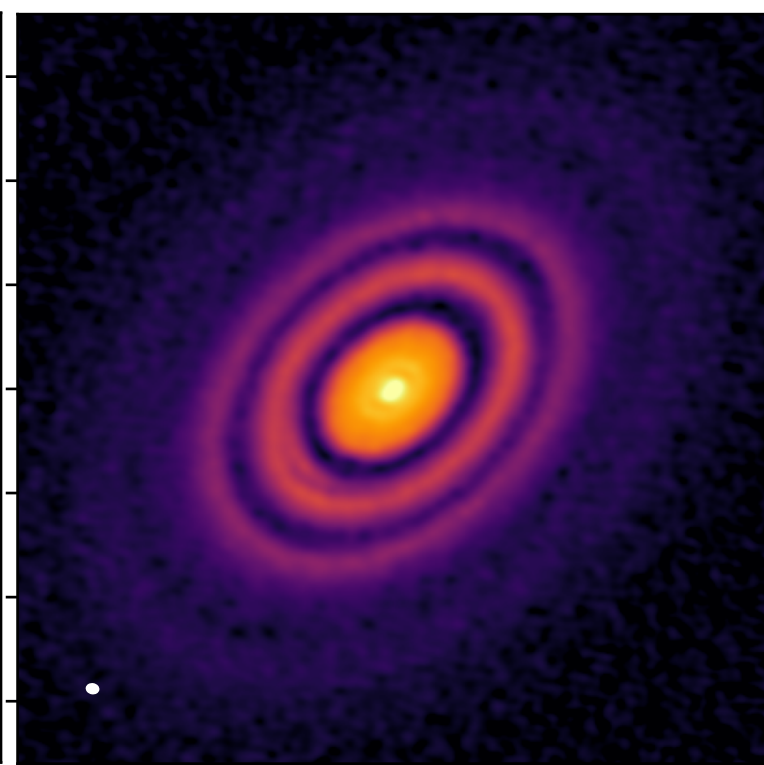
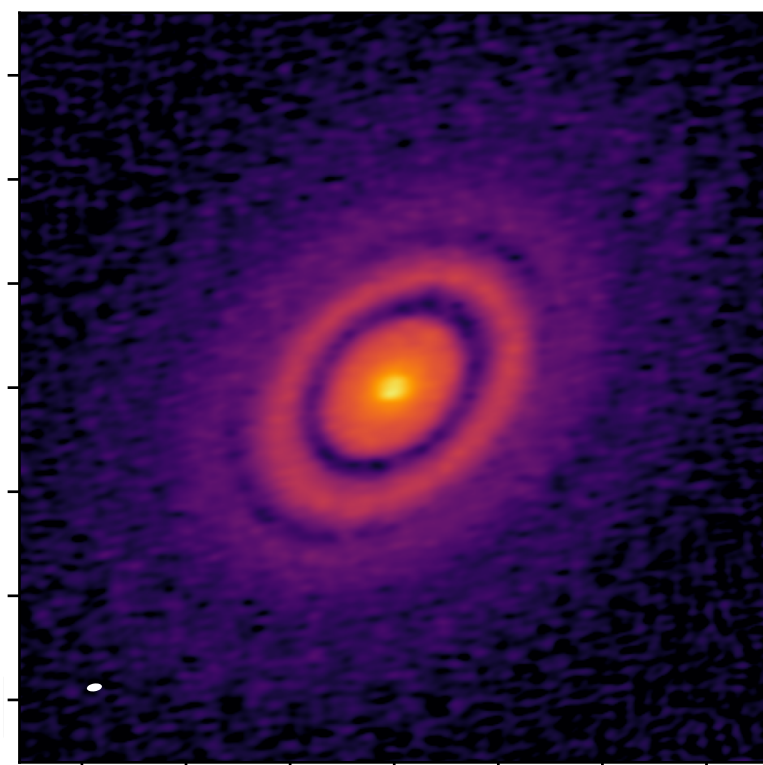
Band 9 (0.45 mm)

Band 7 (0.88 mm)

Band 6 (1.3 mm)

Band 4 (2.1 mm)

Band 3 (3.0 mm)



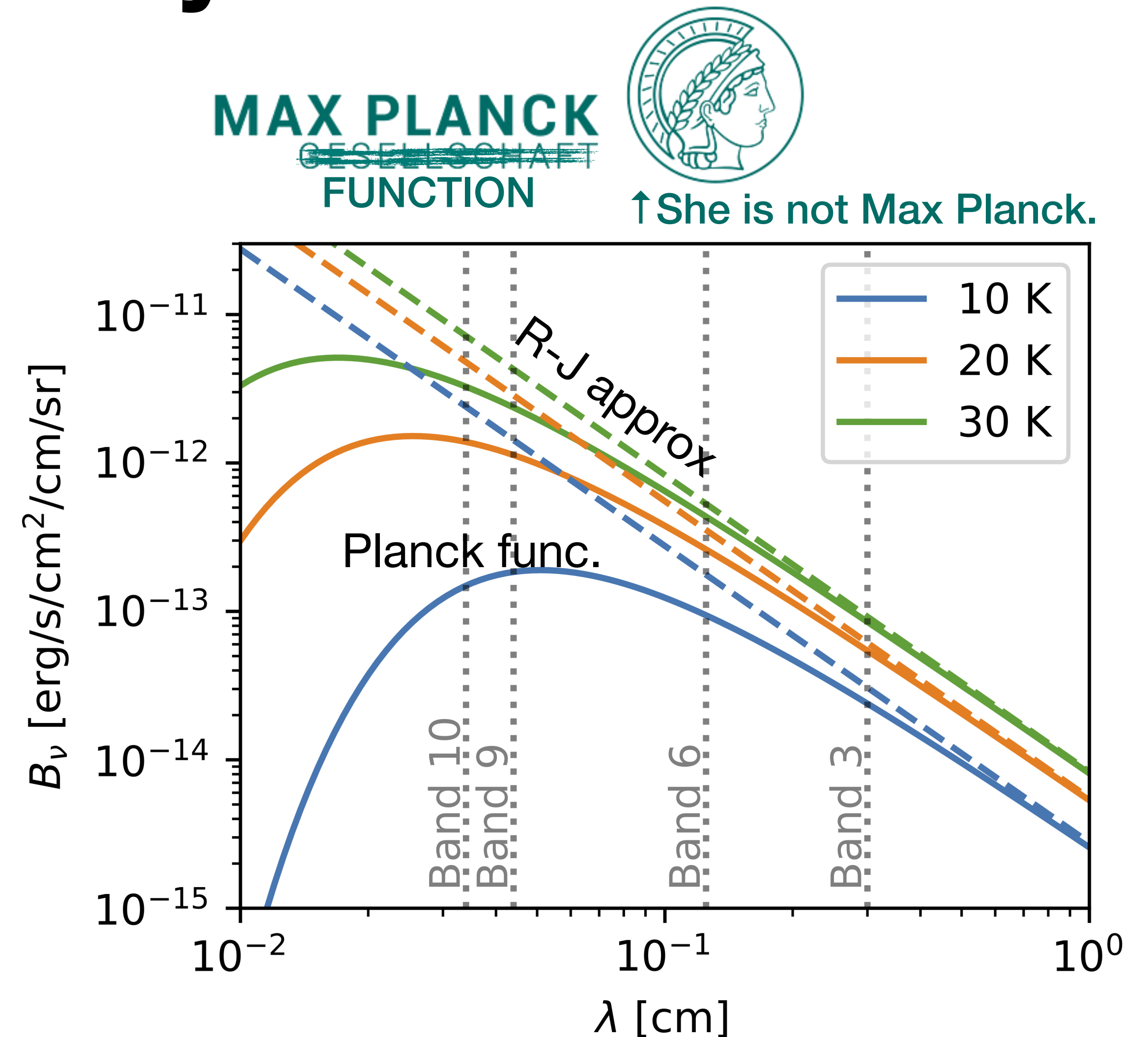
Method

The need for high-frequency observations

$$I = B(T) \times (1 - \exp(-\tau))$$

Free parameters:

- dust **temperature** T
- dust surface density Σ_{dust}
- dust size (distribution) $\kappa(a)$



Band 9 (0.45 mm) observations are sensitive to the dust temperature.

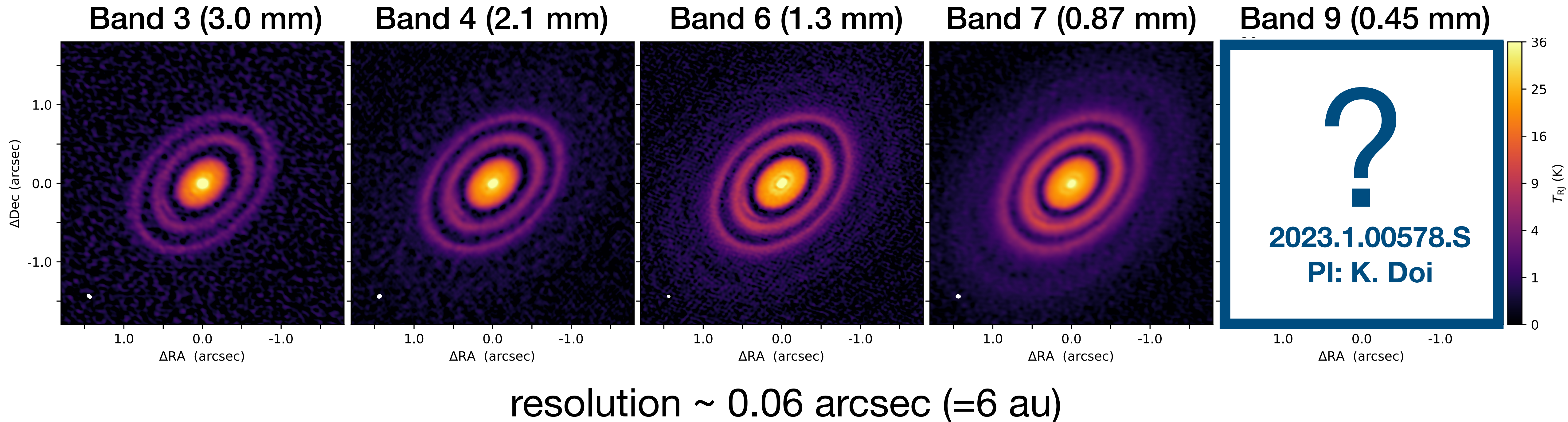
Observations

Proposed observations

High-frequency observations: to break the degeneracy between temperature and optical depth

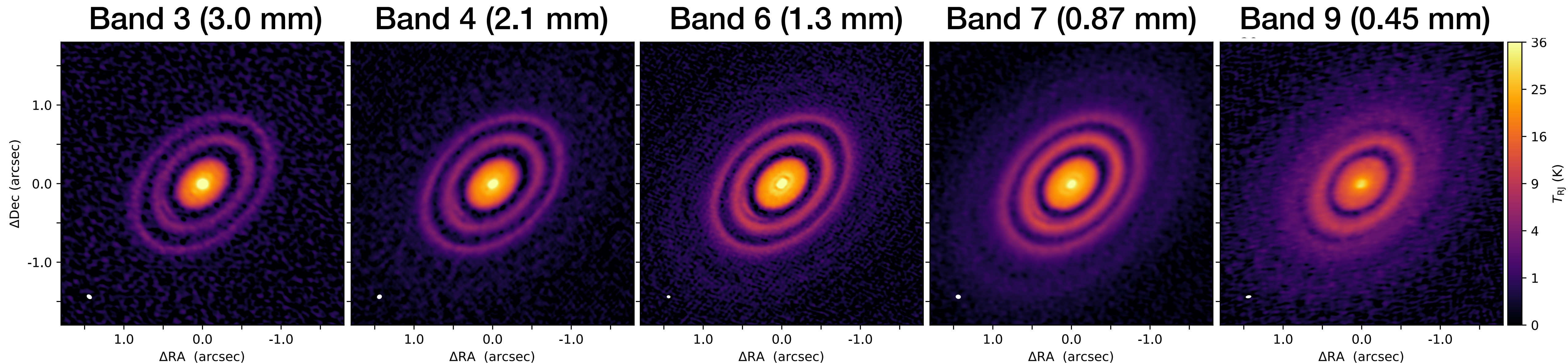
High-resolution observations: to resolve the disk structure

(not to average the emission from different dust properties)



Results

High-resolution images



resolution ~ 0.06 arcsec (=6 au)

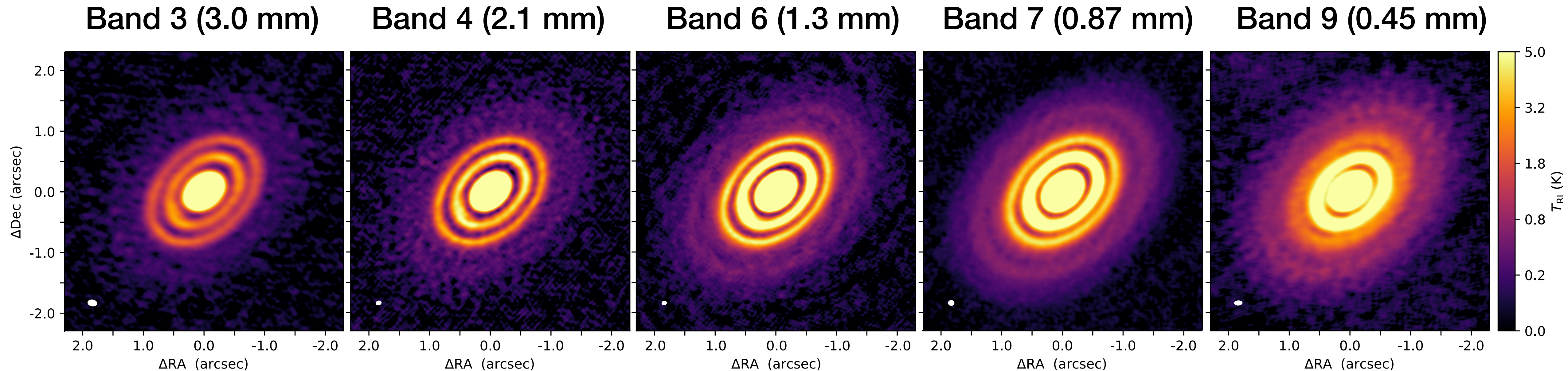
2023.1.00578.S

PI: K. Doi

Central disk + double rings are clearly seen in all wavelengths.

Results

Low-resolution images



resolution ~ 0.1 arcsec (=10 au)

2023.1.00578.S

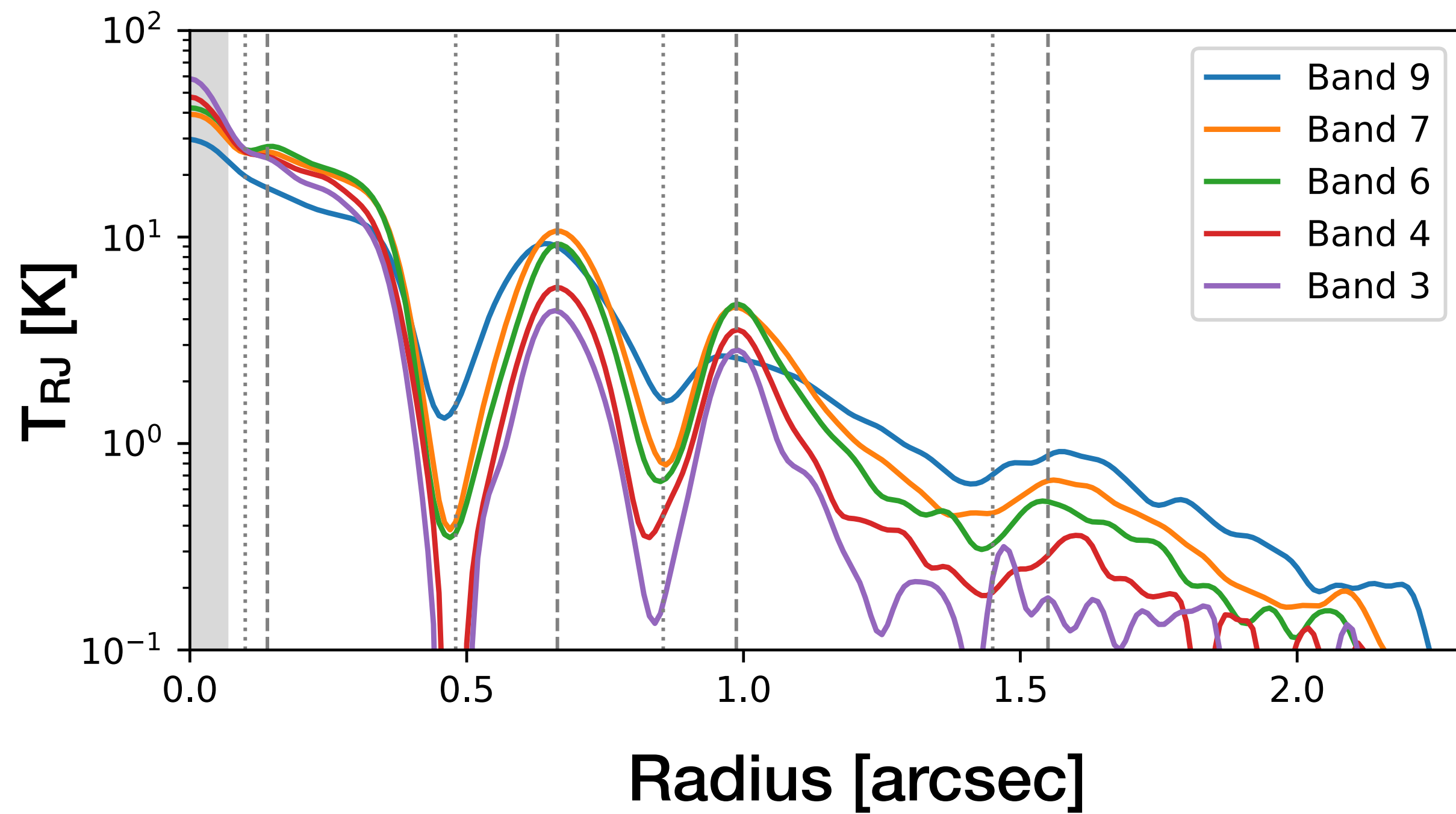
PI: K. Doi

The outer extended emission is brighter at shorter wavelengths.

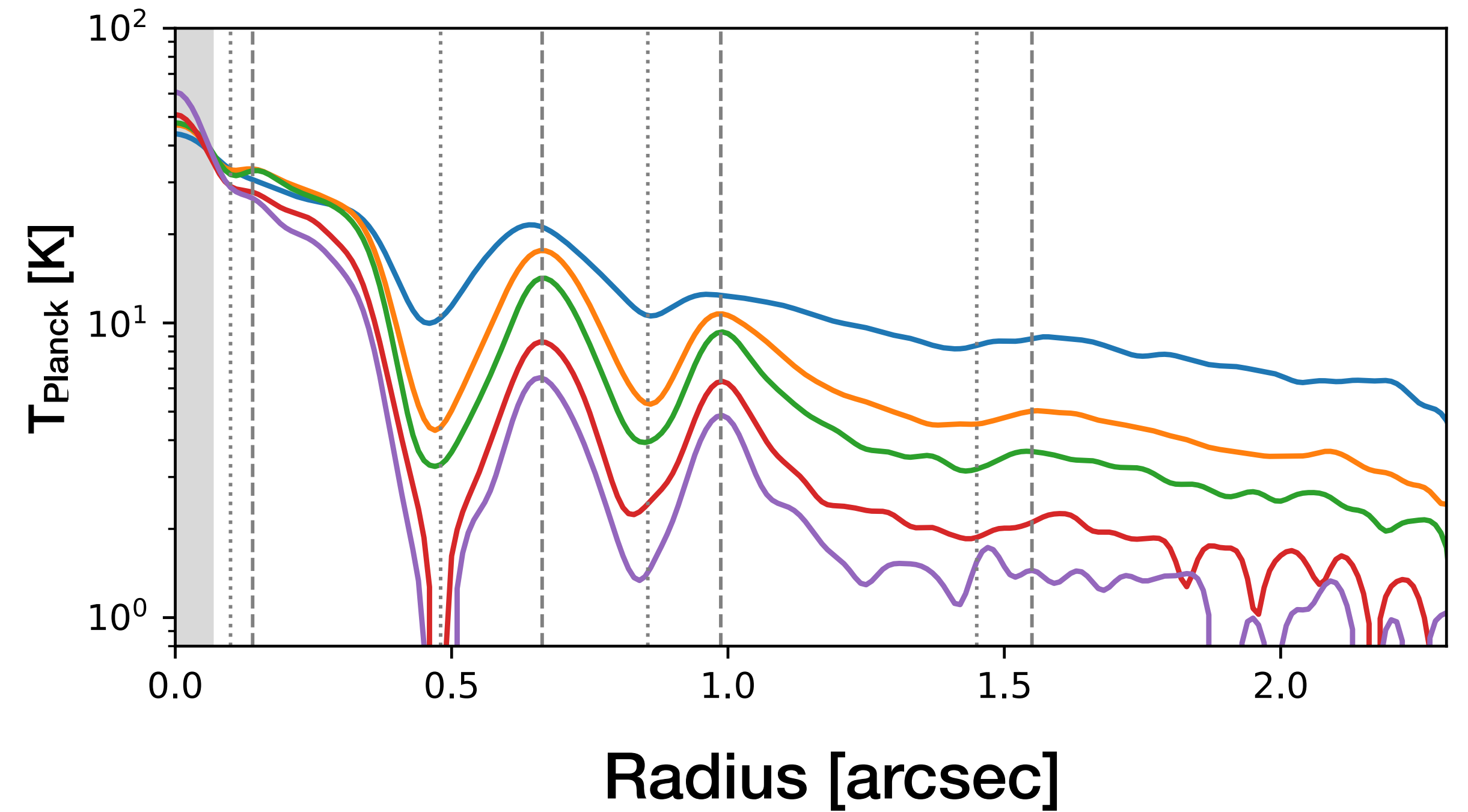
Results

Radial Profiles

Rayleigh–Jeans Conversion



Full Planck Conversion



- The rings appear wider and the gap appears shallower at shorter wavelength.
- The outer ring ($r=1.0''$) is dark in B9.

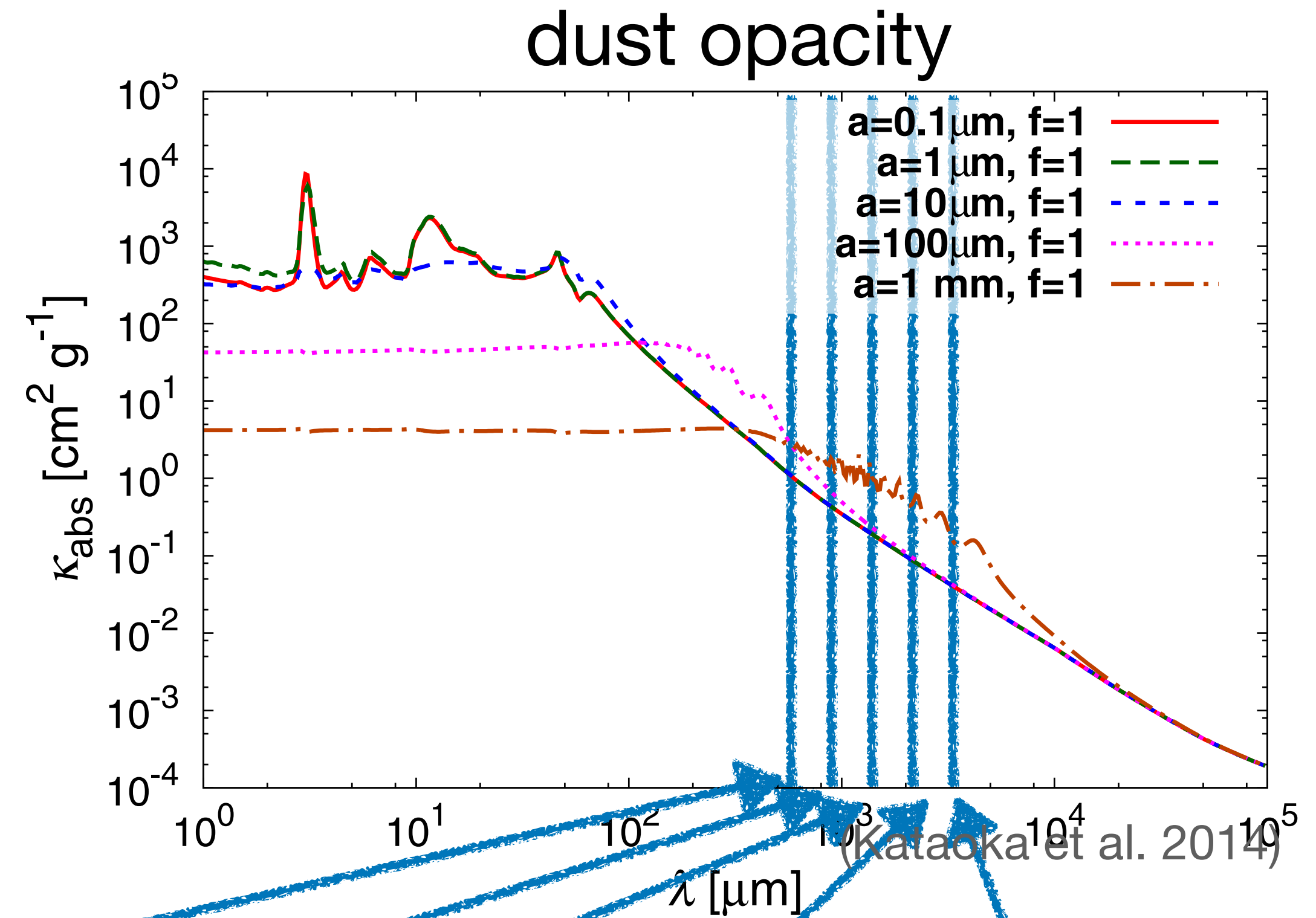
Method

Spectral Fitting

$$I = B(T) \times (1 - \exp(-\tau))$$

Free parameters:

- dust **temperature** T
- dust surface density Σ_{dust}
- dust size (distribution) $\kappa(a)$



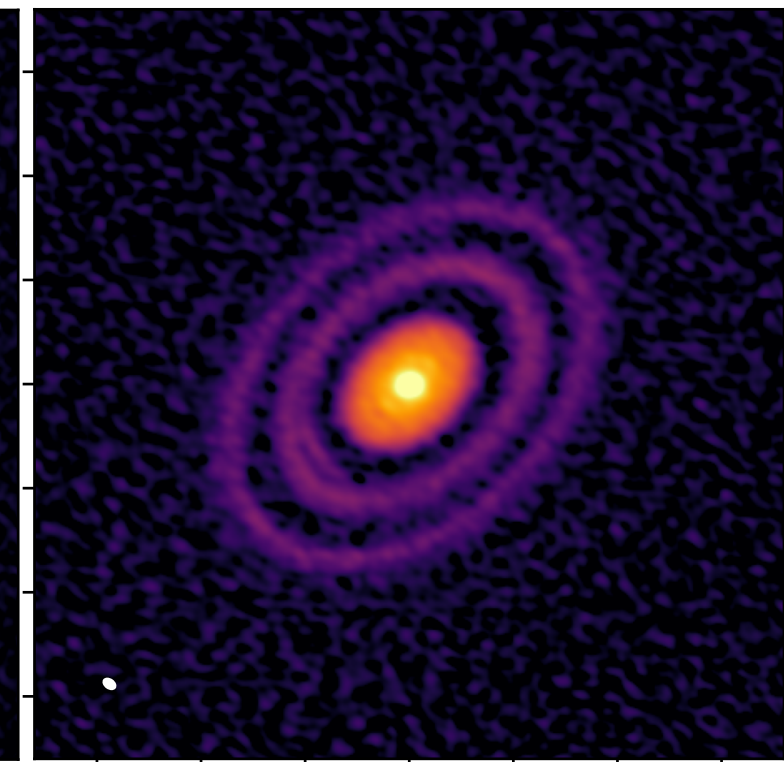
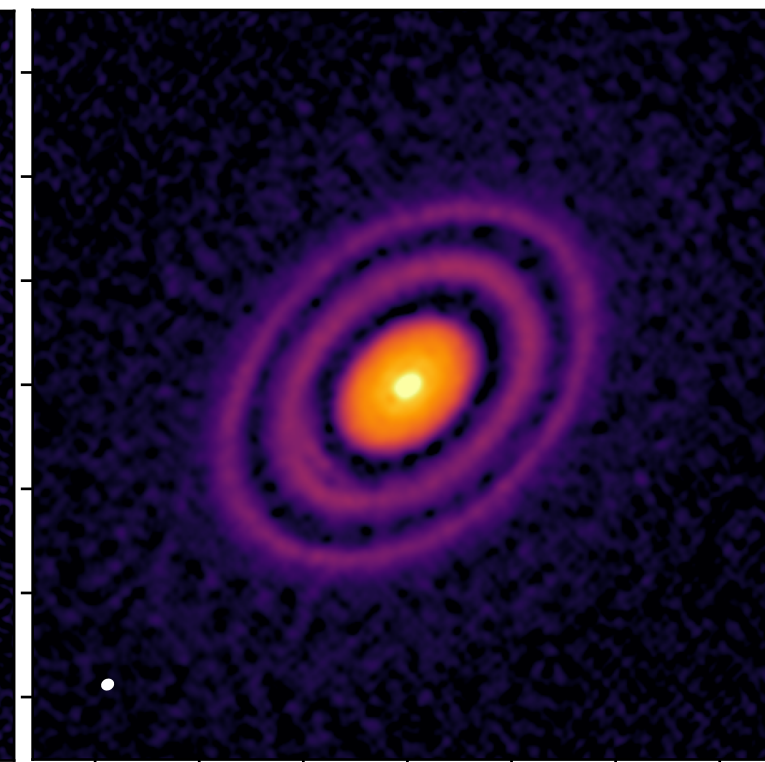
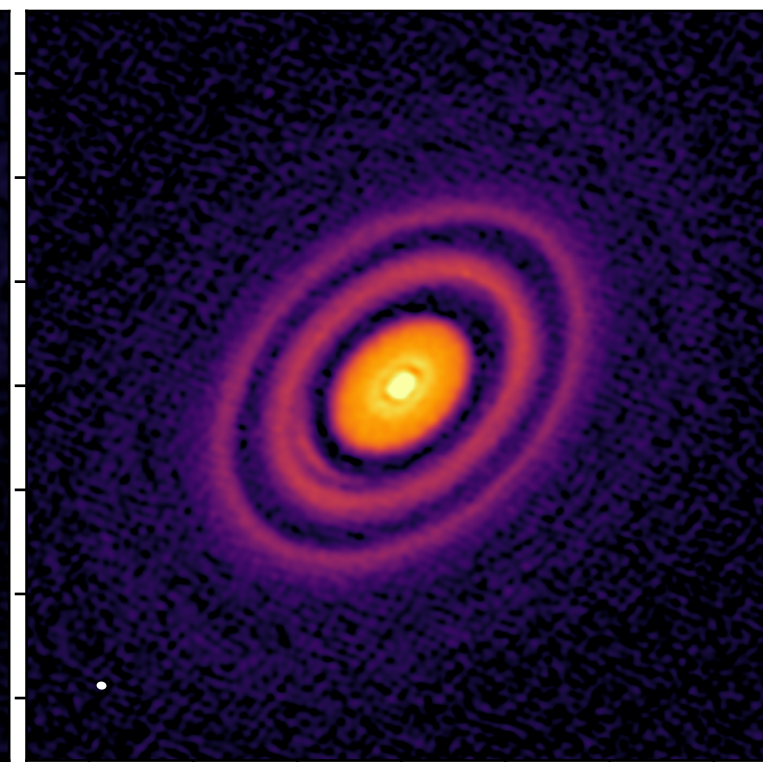
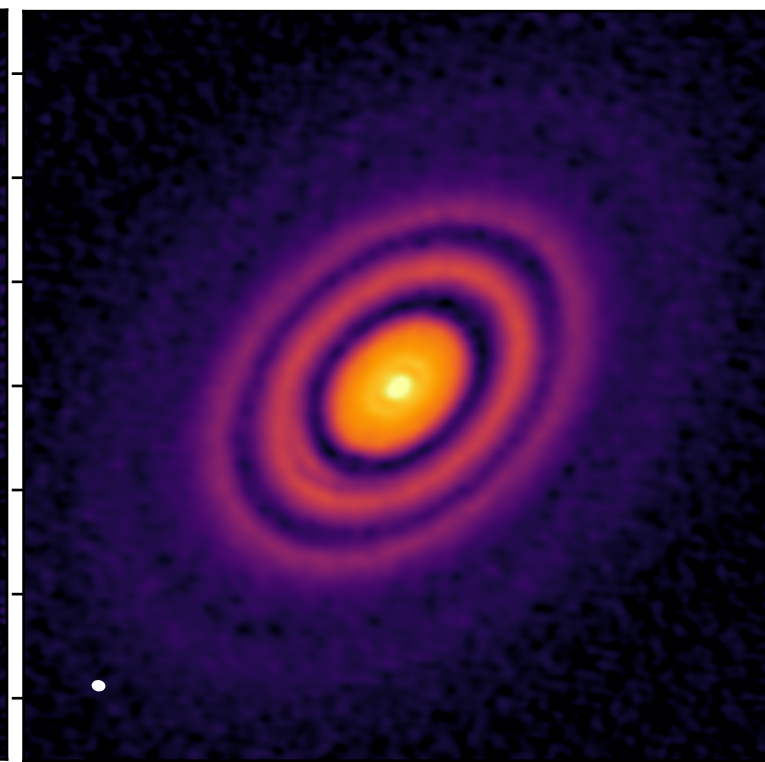
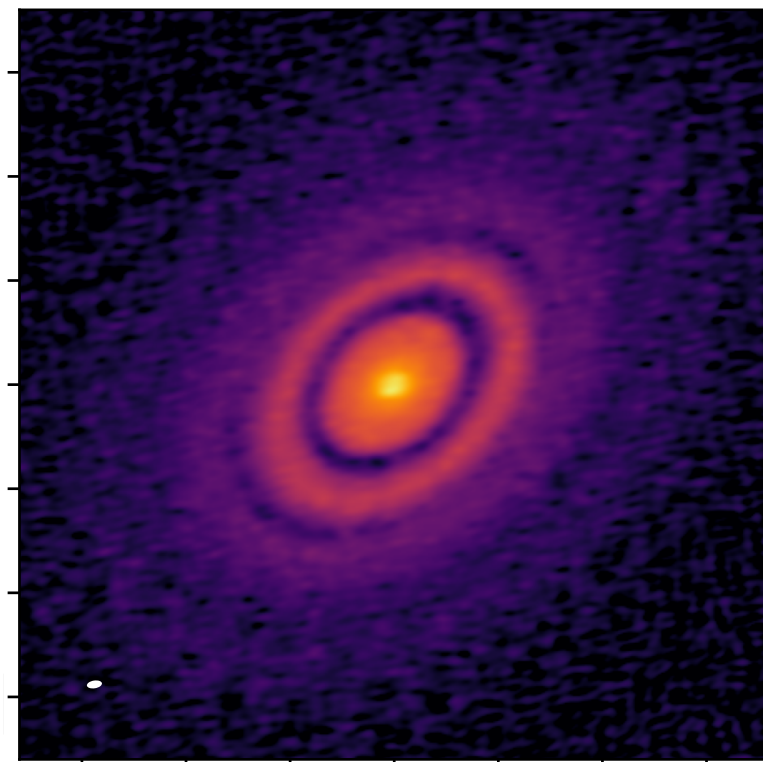
Band 9 (0.45 mm)

Band 7 (0.88 mm)

Band 6 (1.3 mm)

Band 4 (2.1 mm)

Band 3 (3.0 mm)



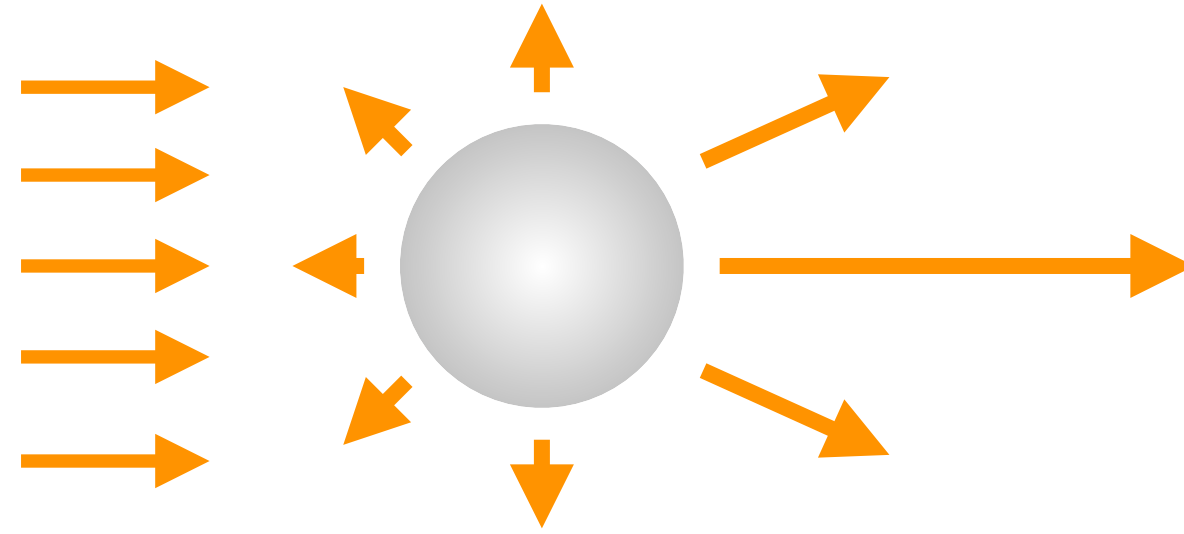
Results

Dust model: composition and porosity

Dust composition:

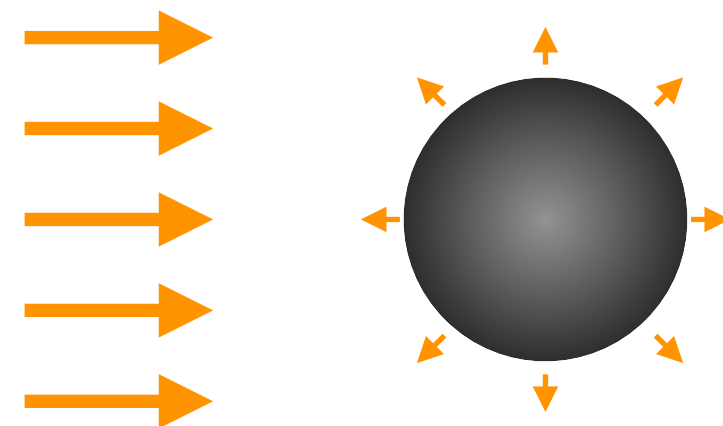
(water + silicates + troilite + carbonaceous material)

- containing **refractory organics**
for carbonaceous material



higher albedo, smaller opacity

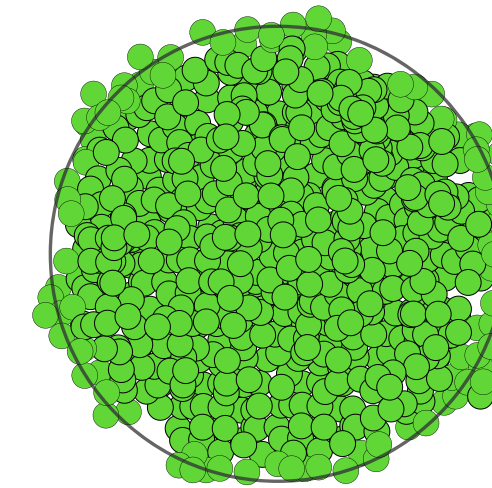
- containing **amorphous carbon**
for carbonaceous material



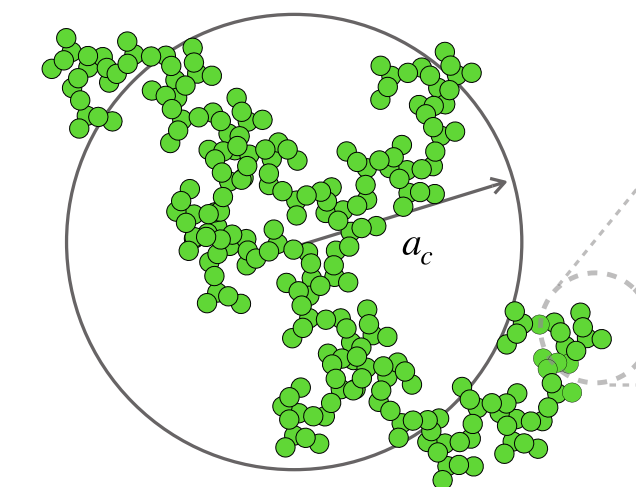
lower albedo, larger opacity

Dust porosity:

- **compact** ($p=0.0$)



- **porous** ($p=0.9$)



We compare 4 models (2 compositions x 2 porosities).

Results

Dust composition and porosity

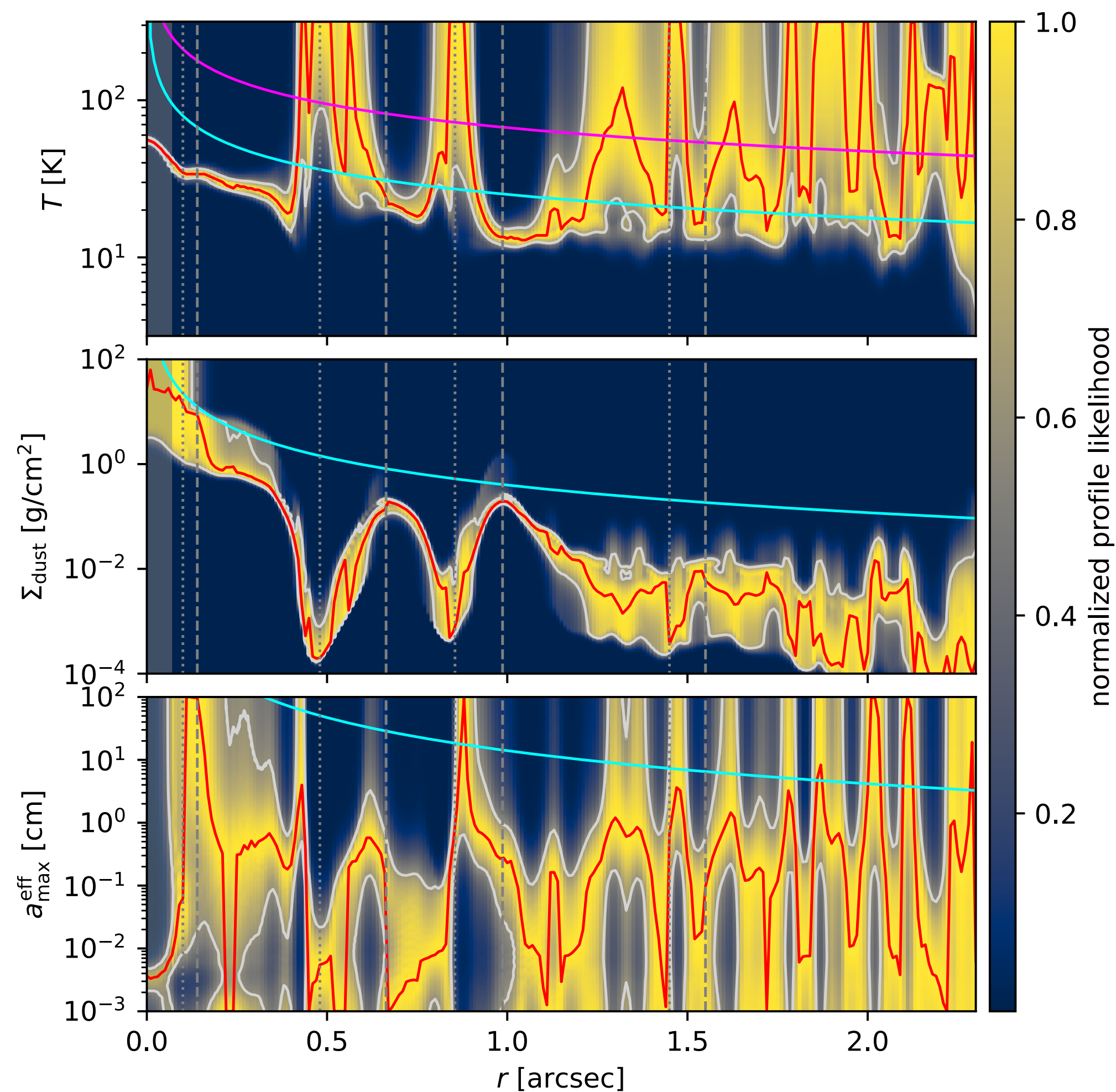
	composition (carbonaceous material)	
	refractory organics (Pollack et al. 1994, Henning and Stognienko 1996)	amorphous carbon (Zubko et al. 1996)
porosity	compact high dust mass: dust-to-gas mass ratio is too high	very small dust size: inconsistent with dust settling (Doi & Kataoka 2021)
	porous high dust mass: gravitationally unstable	preferred

The fitting results, together with some physical requirements, favor **porous grains containing amorphous carbon.**

Results

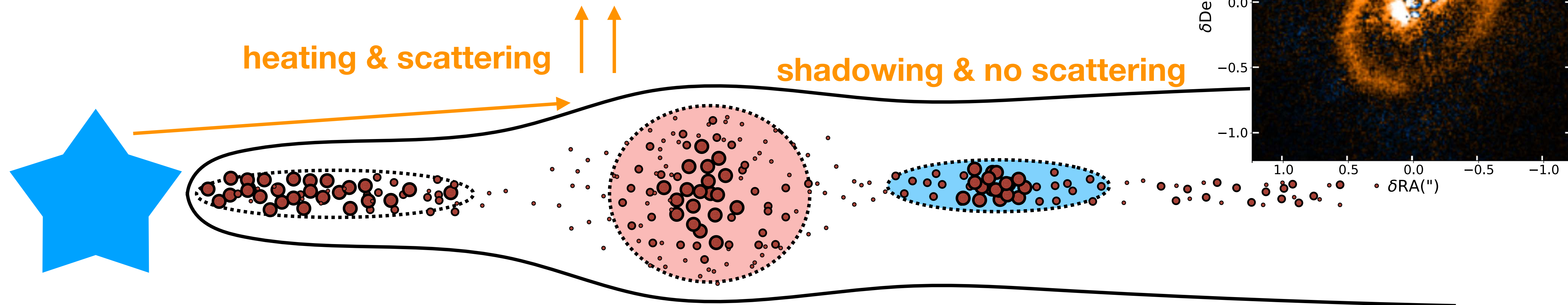
Dust surface density, size, and temperature

Incl. amorphous carbon & porous model (preferred model)



- The outer ring ($r=1.0''$) is cold (~ 13 K)
- The ring gap structures corresponds to the density peaks and gaps.
- The dust size is loosely constrained.

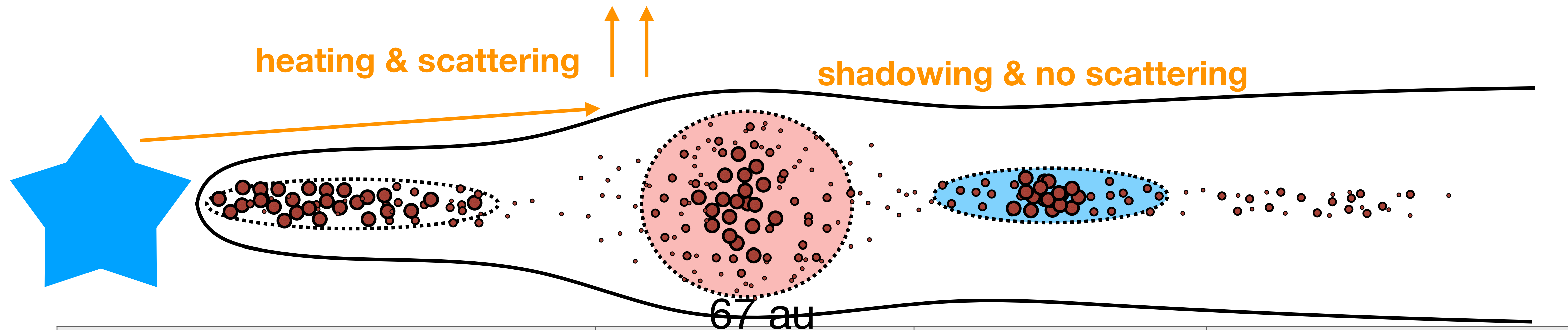
Disk model: thermal structure



	inner ring	outer ring	extended emission
temperature	hot	cold	not well constrained
dust vertical structure	puffed-up	settled	not well constrained
infrared image	bright ring	not visible	not visible

These features are consistent with shadowing by the inner ring.

Disk model: dust mass



	inner ring	outer ring	extended emission
temperature	hot	cold	not well constrained
dust vertical structure	puffed up	settled	not well constrained
infrared image	bright ring	not visible	not visible
dust mass	$35.3^{+11.4}_{-12.2} M_{\text{earth}}$	$63.4^{+32.3}_{-14.7} M_{\text{earth}}$	$10.0^{+28.6}_{-5.8} M_{\text{earth}}$

All structures have sufficient mass to form Earth-mass planets.

Future Plan 1

Low-frequency high-resolution observations

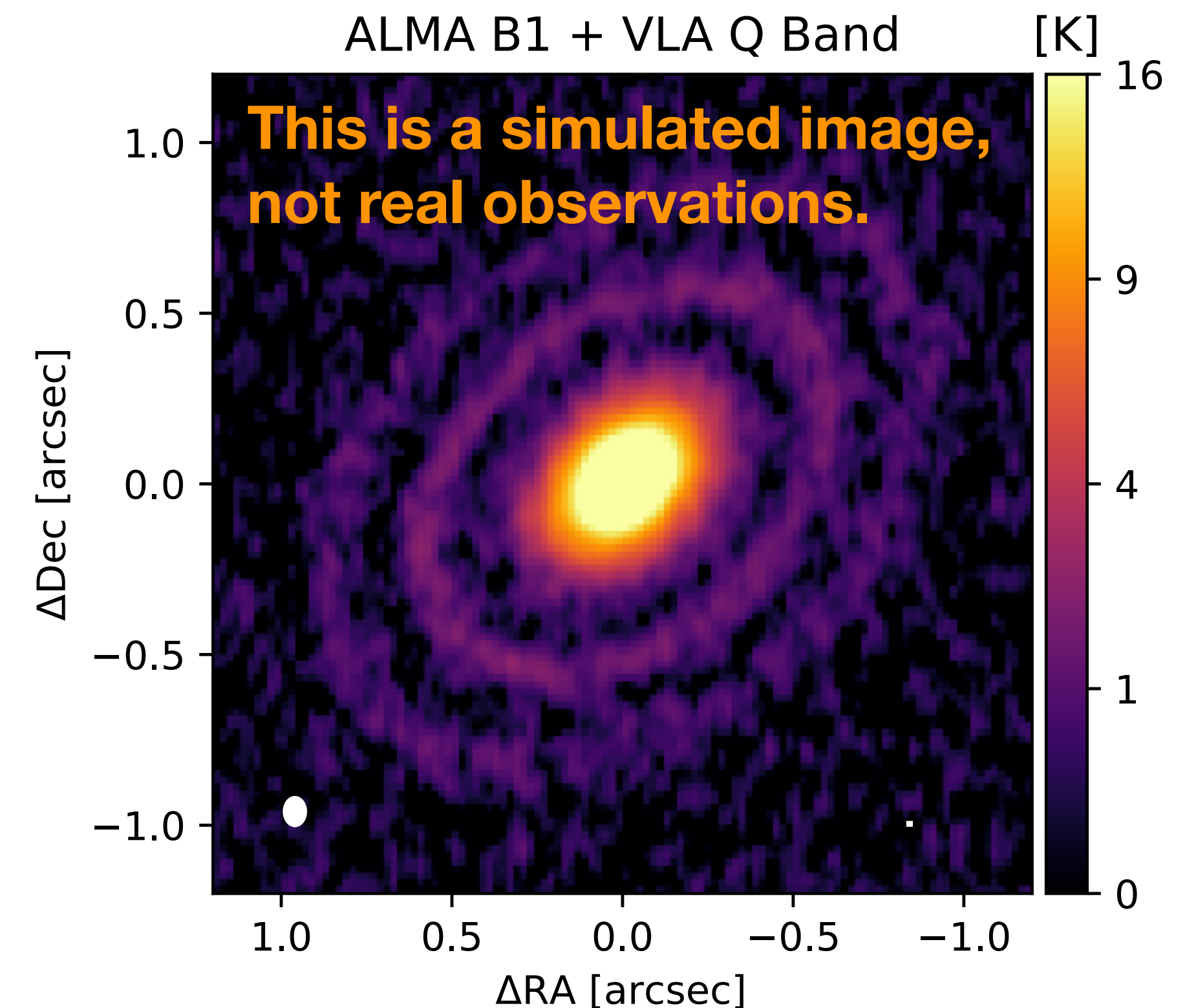
The dust size is not well constrained.

→ Longer wavelength observations are needed.

Future observations:

Combined imaging of ALMA Band 1 + VLA Q Band

- ALMA can achieve higher sensitivity & better image fidelity
- VLA can achieve higher resolution (up to 36 km baseline)



ALMA 2022.A.00035.S, Observatory Proj.

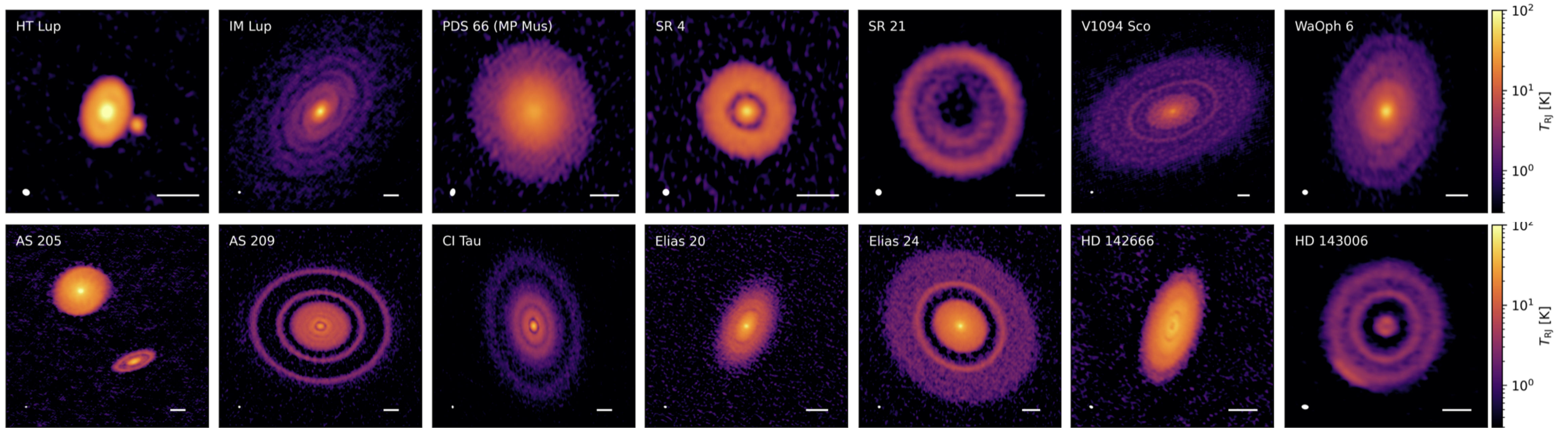
ALMA 2024.1.00351.S, PI: K. Doi

VLA 26A-466, PI: K. Doi

Future Plan 2

High-resolution B9 survey

- High-resolution observations for 14 disks with archival high-resolution B3 and B6 observations



Accepted in Cycle 12

2025.1.00115.S, PI: K. Doi

Summary

Background & Aim

- The dust size and surface density distributions in disks are key quantities for understanding dust growth, accumulation, and planetesimal formation.

Method

- Multi-wavelength SED fitting is key to constraining these parameters.
 - **Including high-frequency ALMA Band 9/10 observations is essential** to constrain dust properties together with the dust temperature.

Results & discussions

- Combining our new Band 9 observations with archival Band 3, 4, 6, and 7 data for the HD 163296 disk, we find:
 - The inferred dust temperature shows **a local dip in the outer ring**, suggesting **shadowing by the inner ring**.
 - The central disk, the two major rings, and the outer extended emission each contain **enough dust mass to form Earth-mass planets**.
 - The preferred dust model is **porous grains containing amorphous carbon**.

**High-resolution, multi-wavelength observations can reveal dust properties in detail,
revealing the planet formation process.**