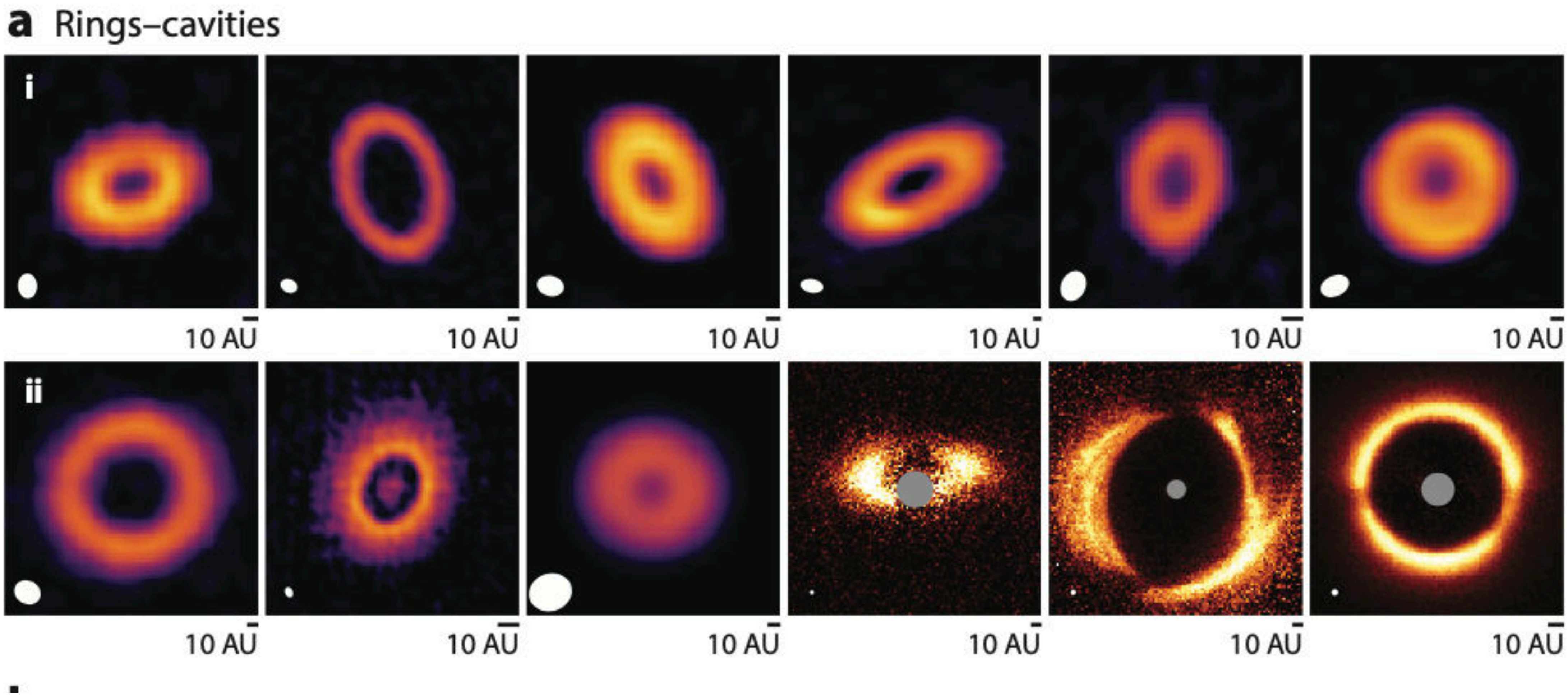
# Grain size substructures inferred from multi-wavelength dust continuum emission at ALMA wavelengths

Anibal Sierra
Posdoc at
Departamento de Astronomía
Universidad de Chile

MIAPP October 2021

# Disk substructures?




Andrews et al. 2020

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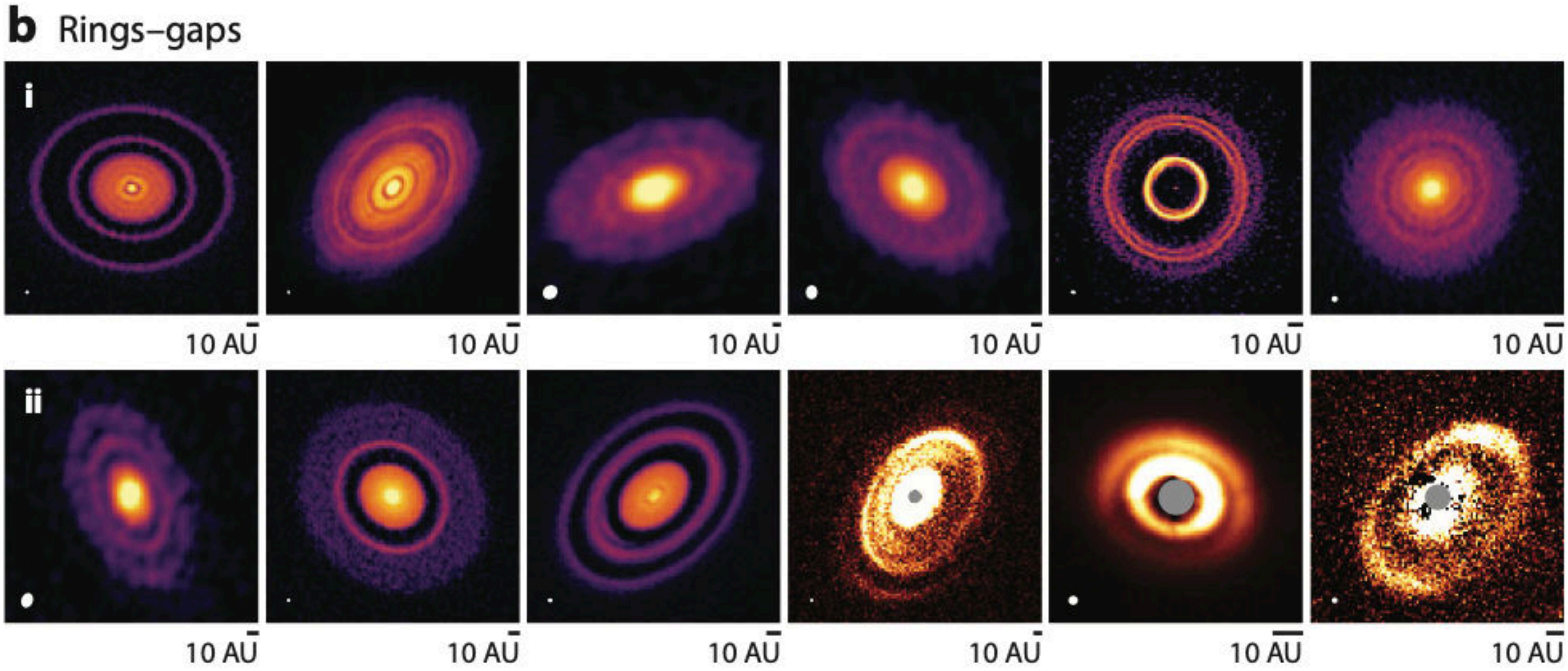


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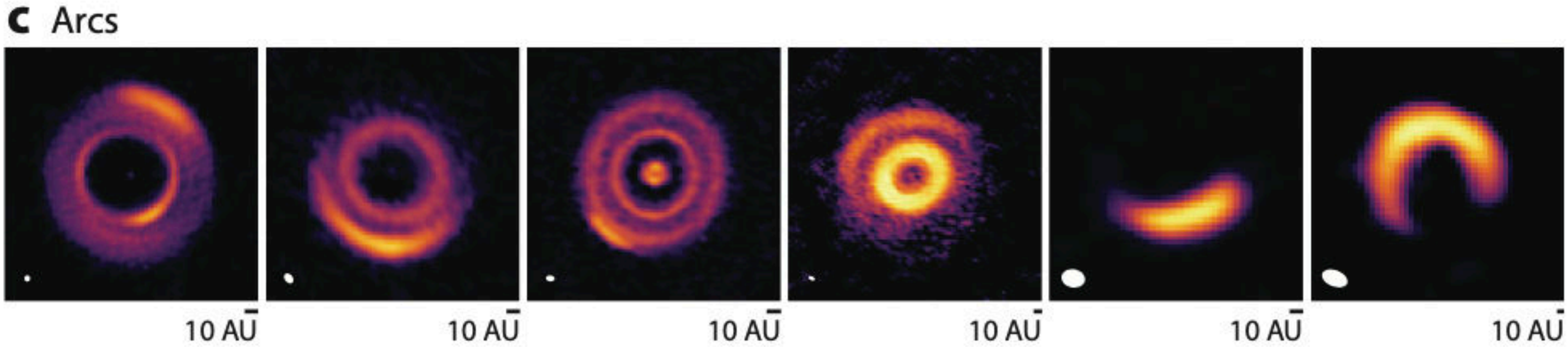


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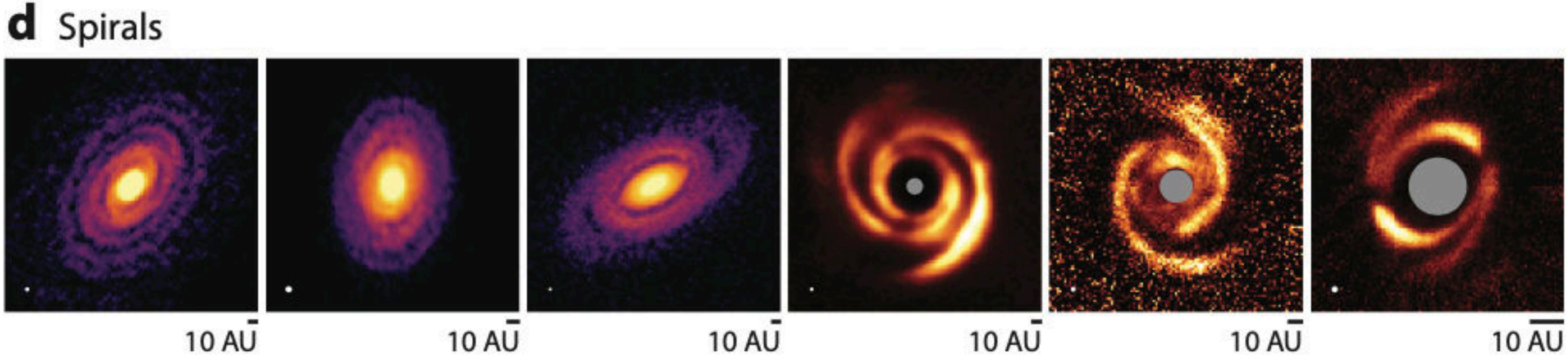
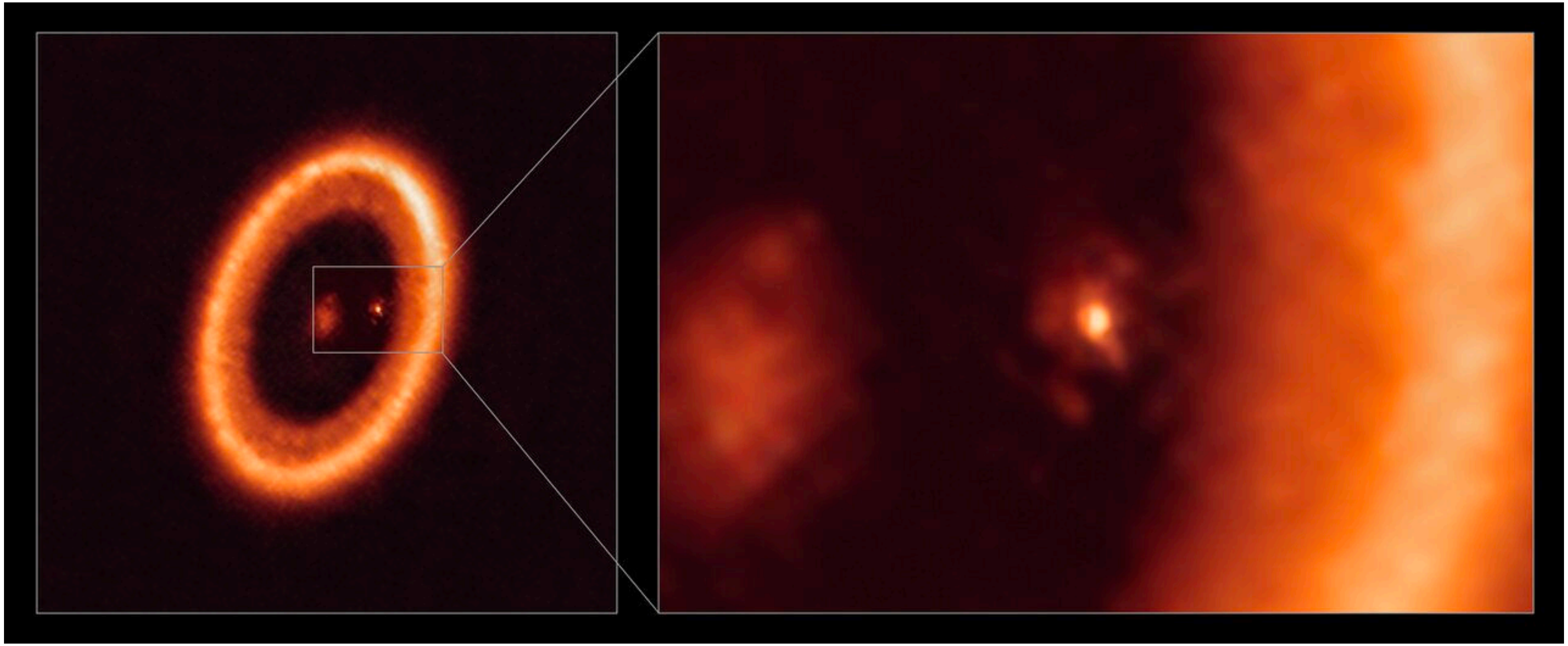



Andrews et al. 2020

# Disk substructures?

Circumplanetary disks



Benisty et al. 2021

# Disk substructures?

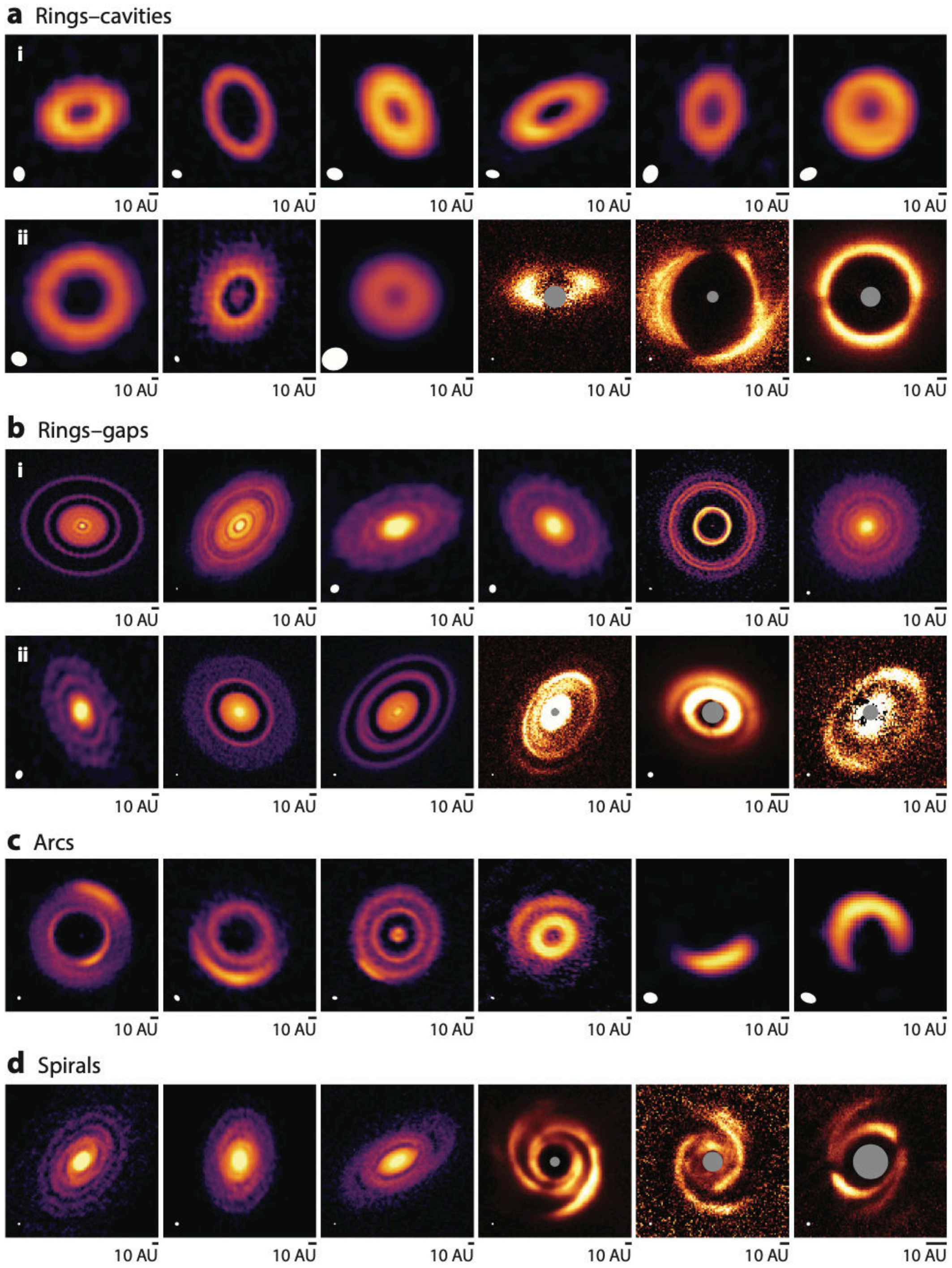
These structures could be triggering planet formation, or they can the the consequence of planet formation.

Substructures —> Dust traps?

Analysis of multi-wavelength dust continuum emission is needed.

Now we are able to test the dust trap models at high angular resolution

Andrews et al. 2020



# Disk substructures - Dust trap

Characteristics:
- A local enhancement of:
  a) the dust surface density
  b) maximum grain size
- The width of the continuum ring decreases with the wavelength

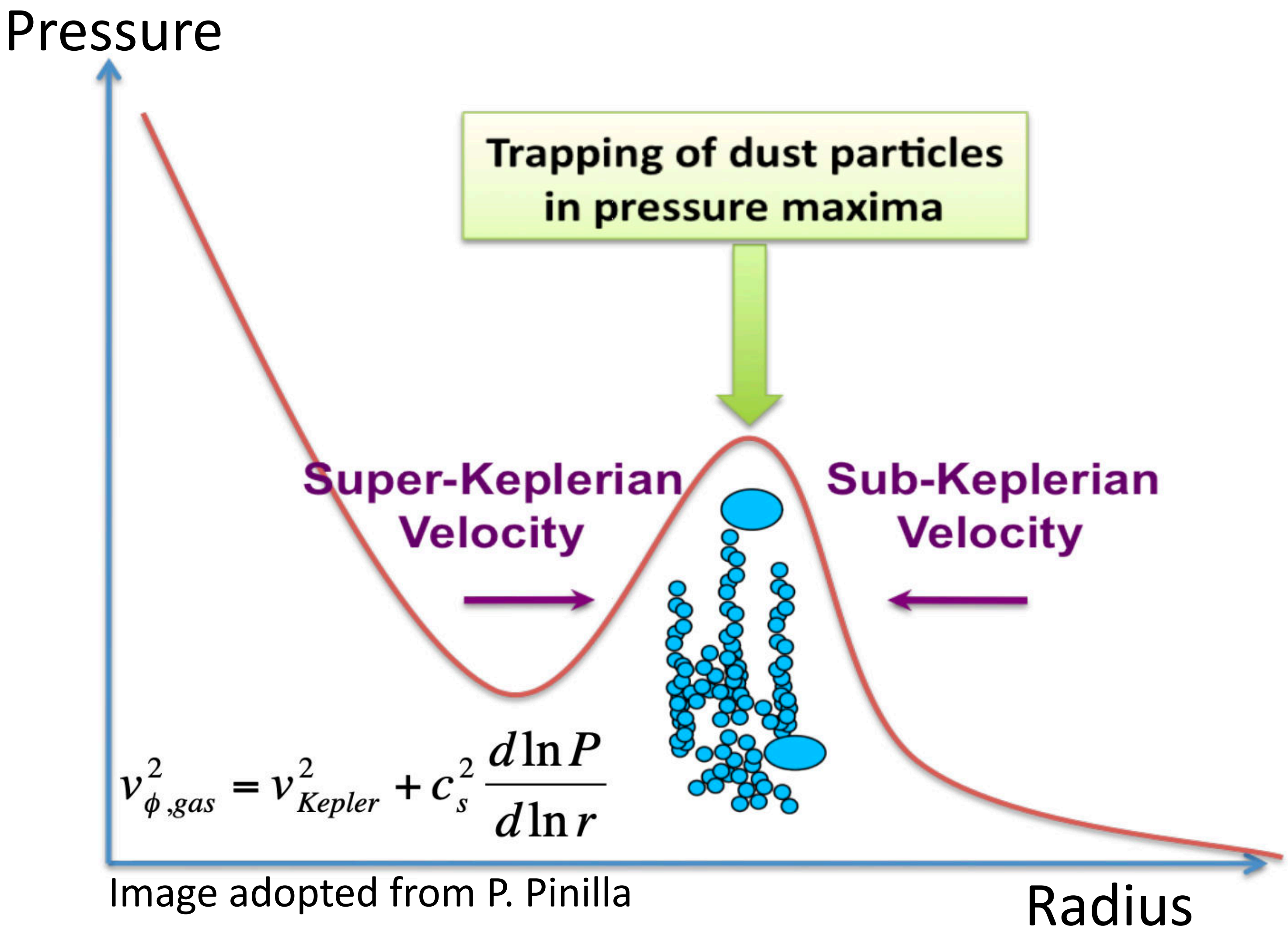


Image adopted from P. Pinilla

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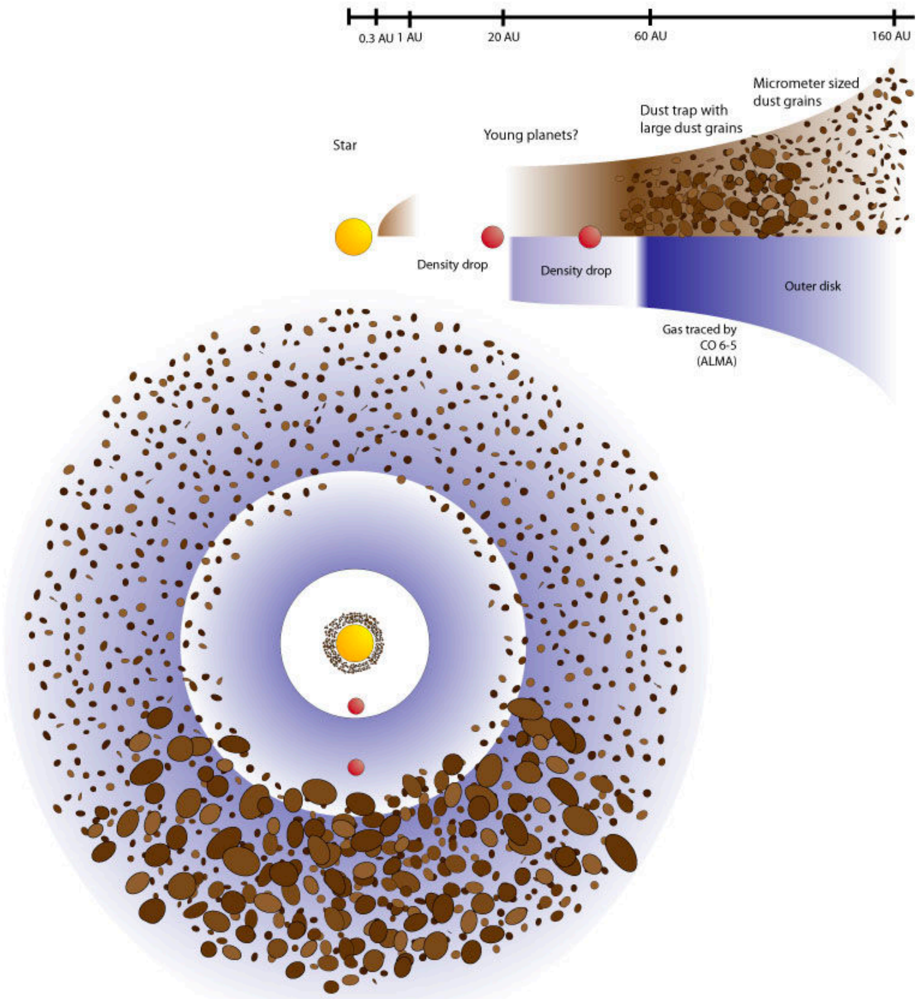



Image: Van der Marel et al. (2013)

# Grain Size

How do we infer grain size?

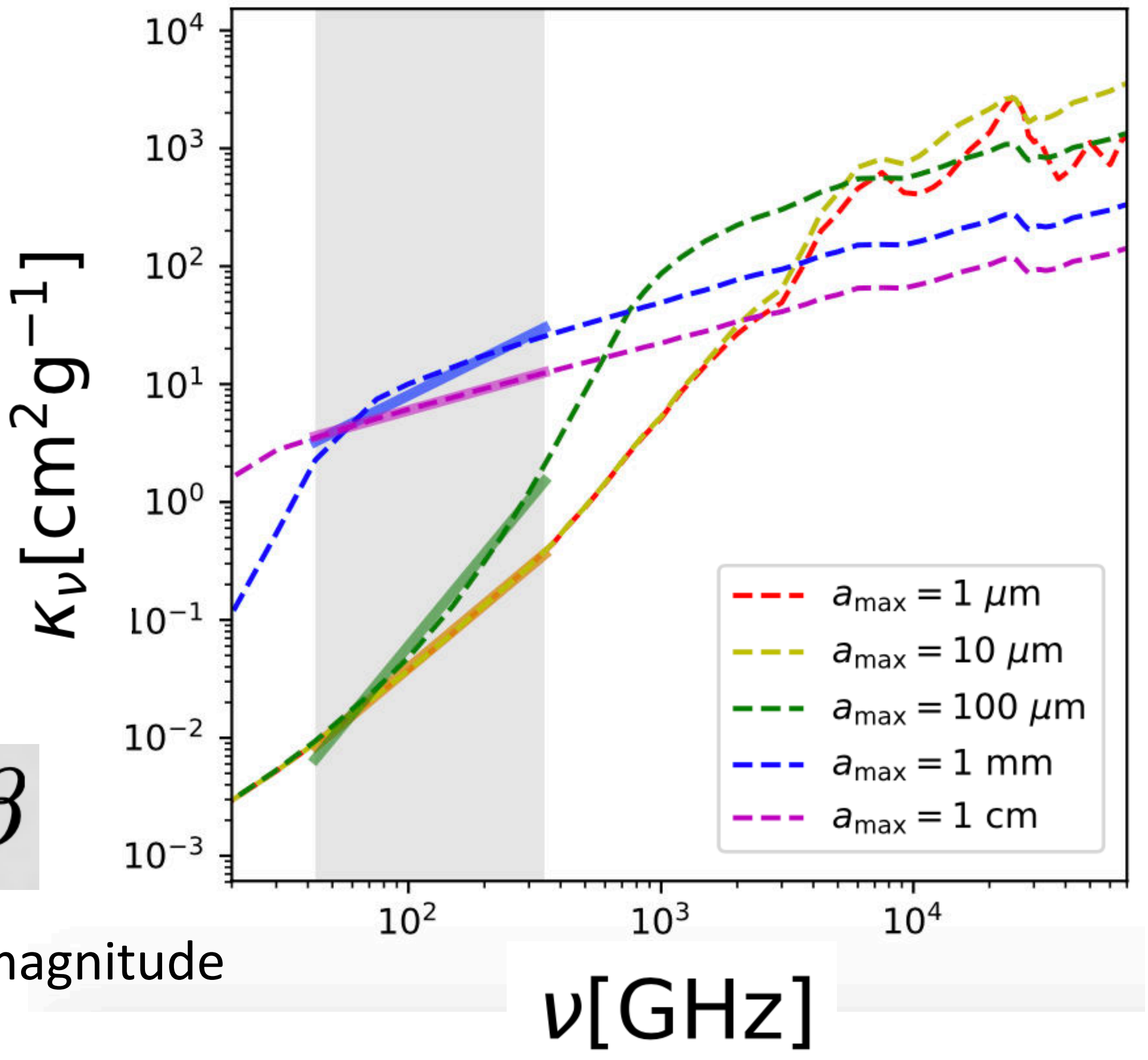
In the optically thin regime:

$$F_\nu \approx \kappa(\nu) M_d B_\nu(T_d) d^{-2}$$

At mm wavelengths:

$$\kappa(\nu) \propto \nu^\beta$$

$$F_\nu \propto \nu^\alpha, \text{with } \alpha = 2 + \beta$$




Grain size can be inferred even if the absolute magnitude of opacity and temperature are unknown.

# Grain Size

How do we infer grain size?

Note that

$$\alpha = \beta + 2$$

is only true when:

- The source function is the Planck function,
- In the Rayleigh-Jeans limit
- In the optically thin regime.

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- It does not apply for cold disks
- The inner disks and bright rings where dust grains accumulate are not optically thin

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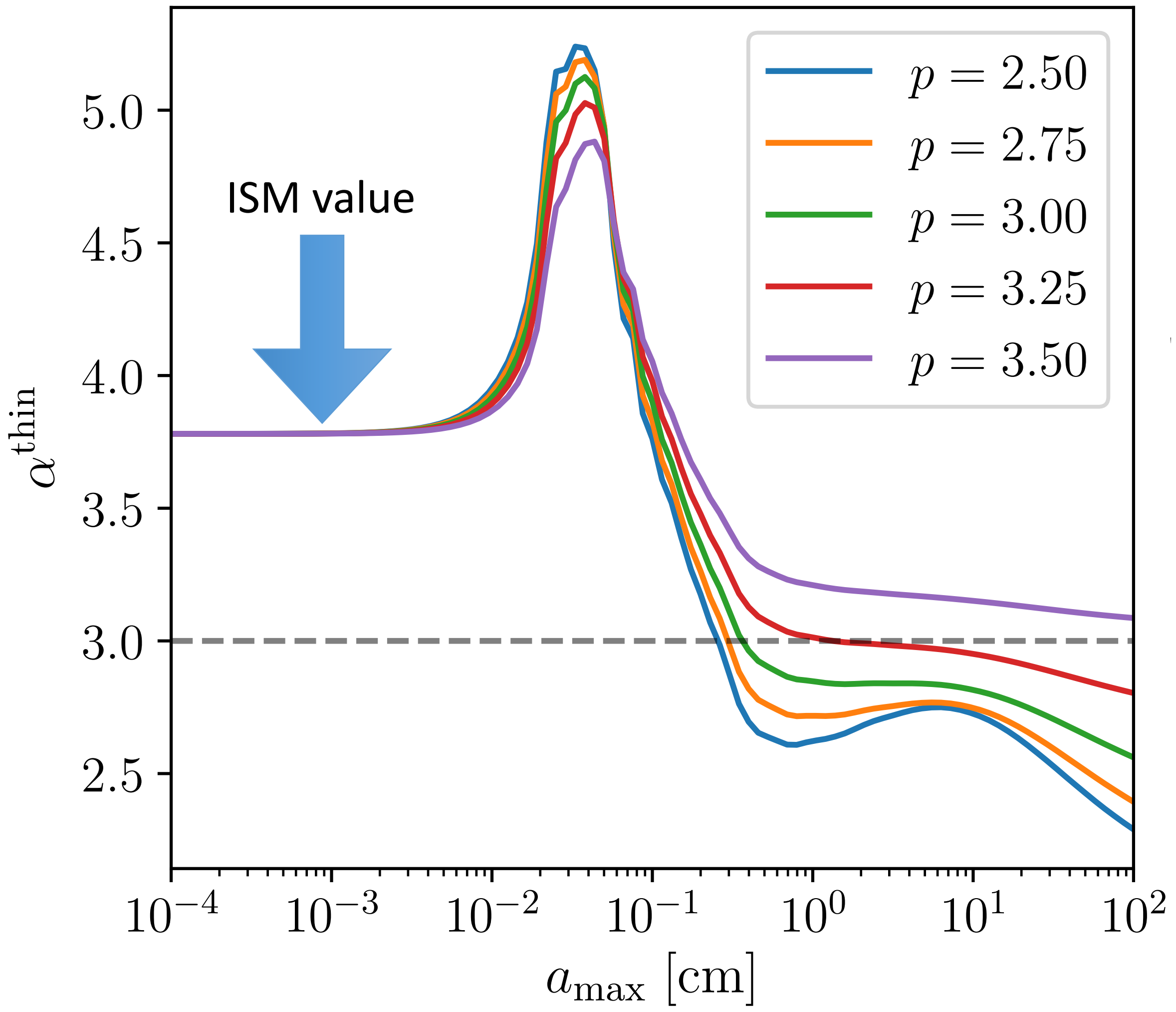

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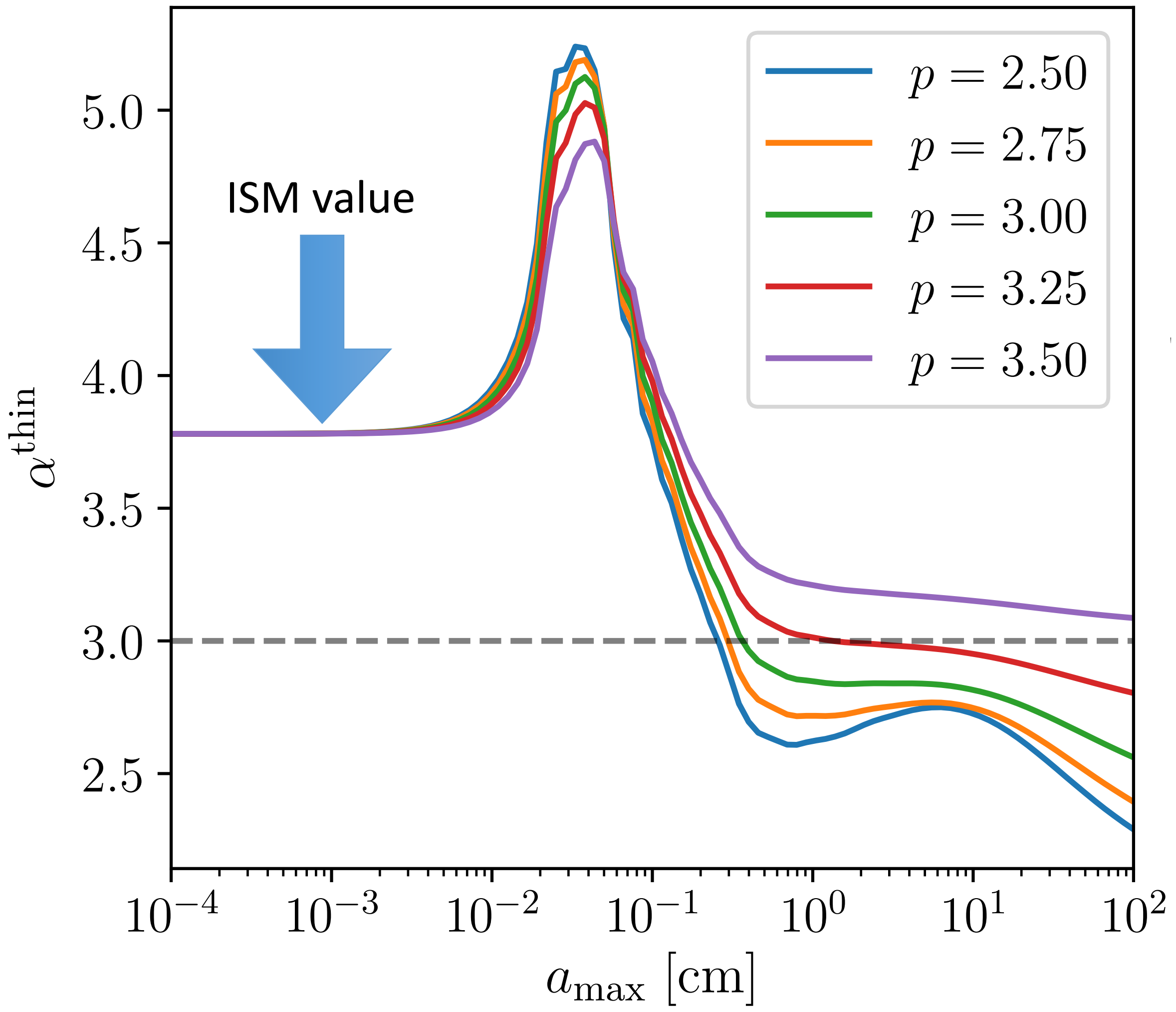


e.g., for 26 bright disk in Lupus

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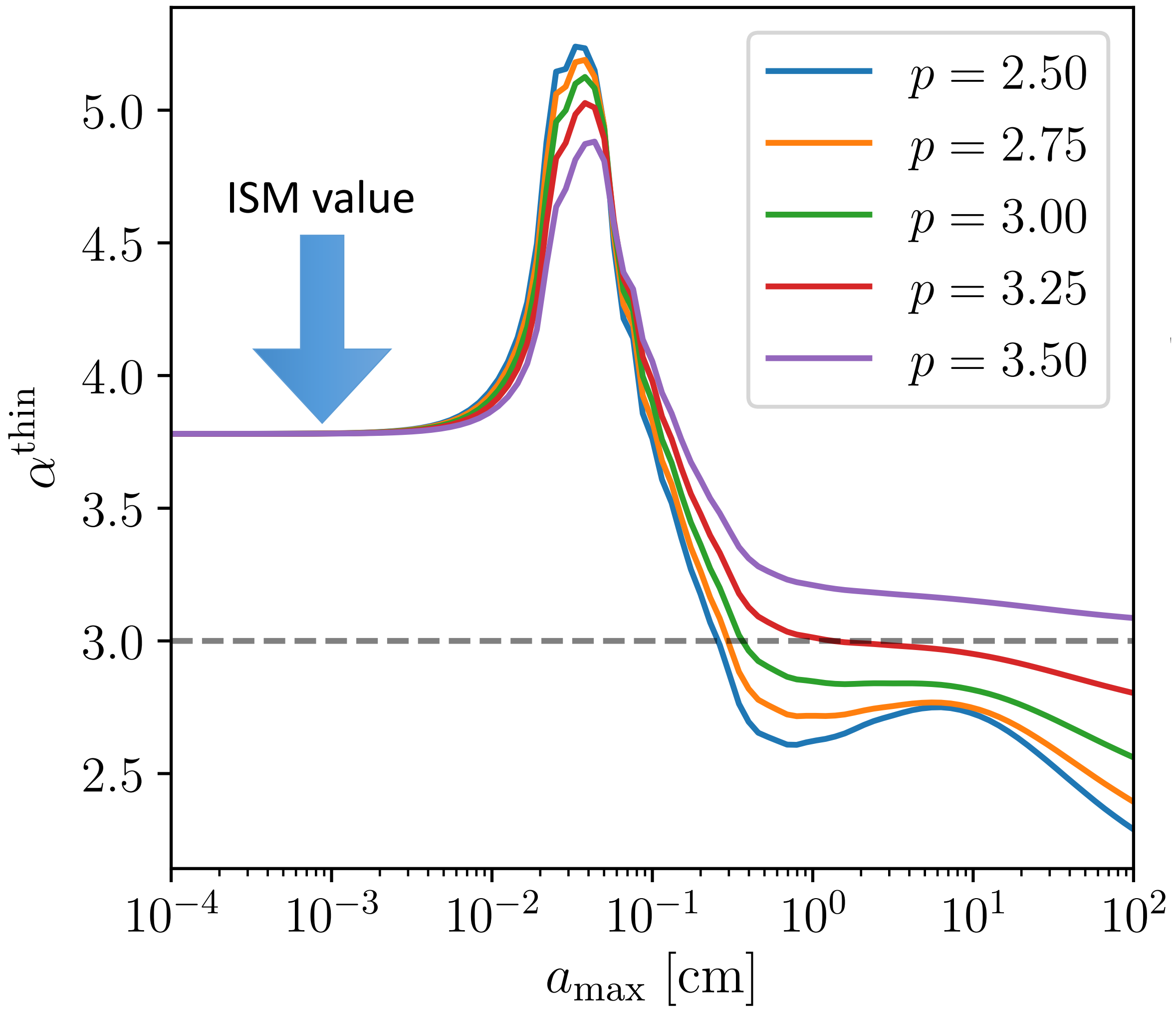


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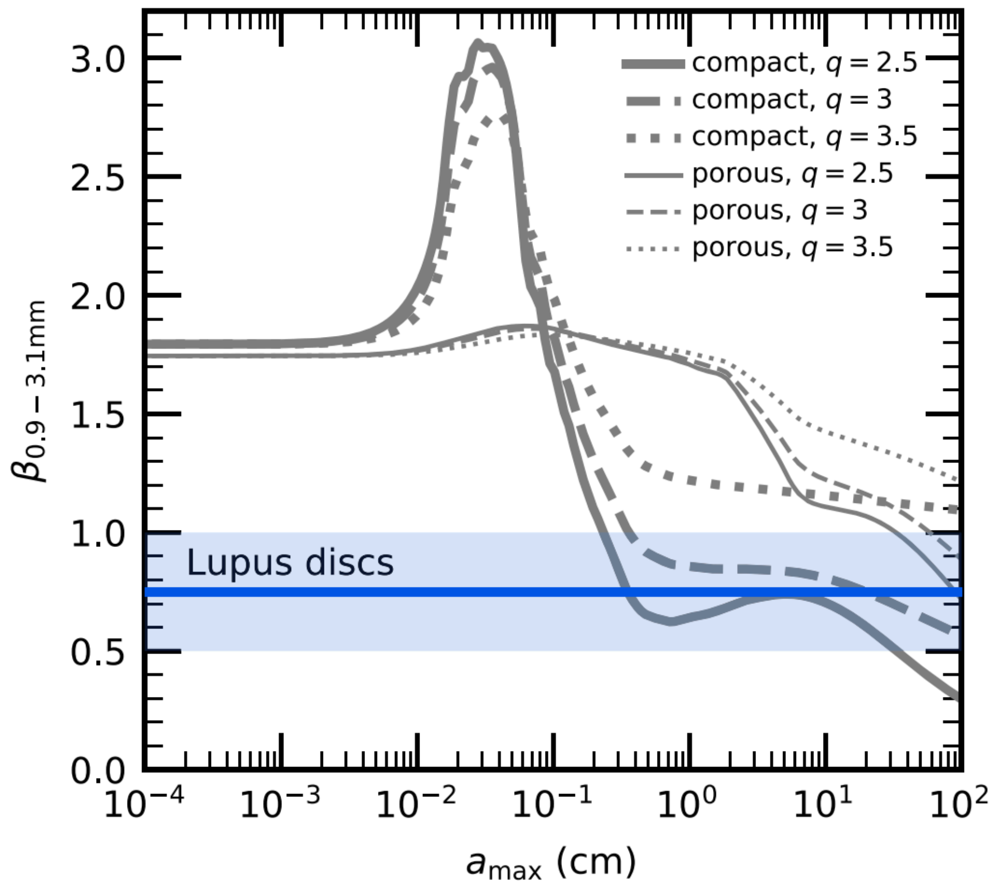

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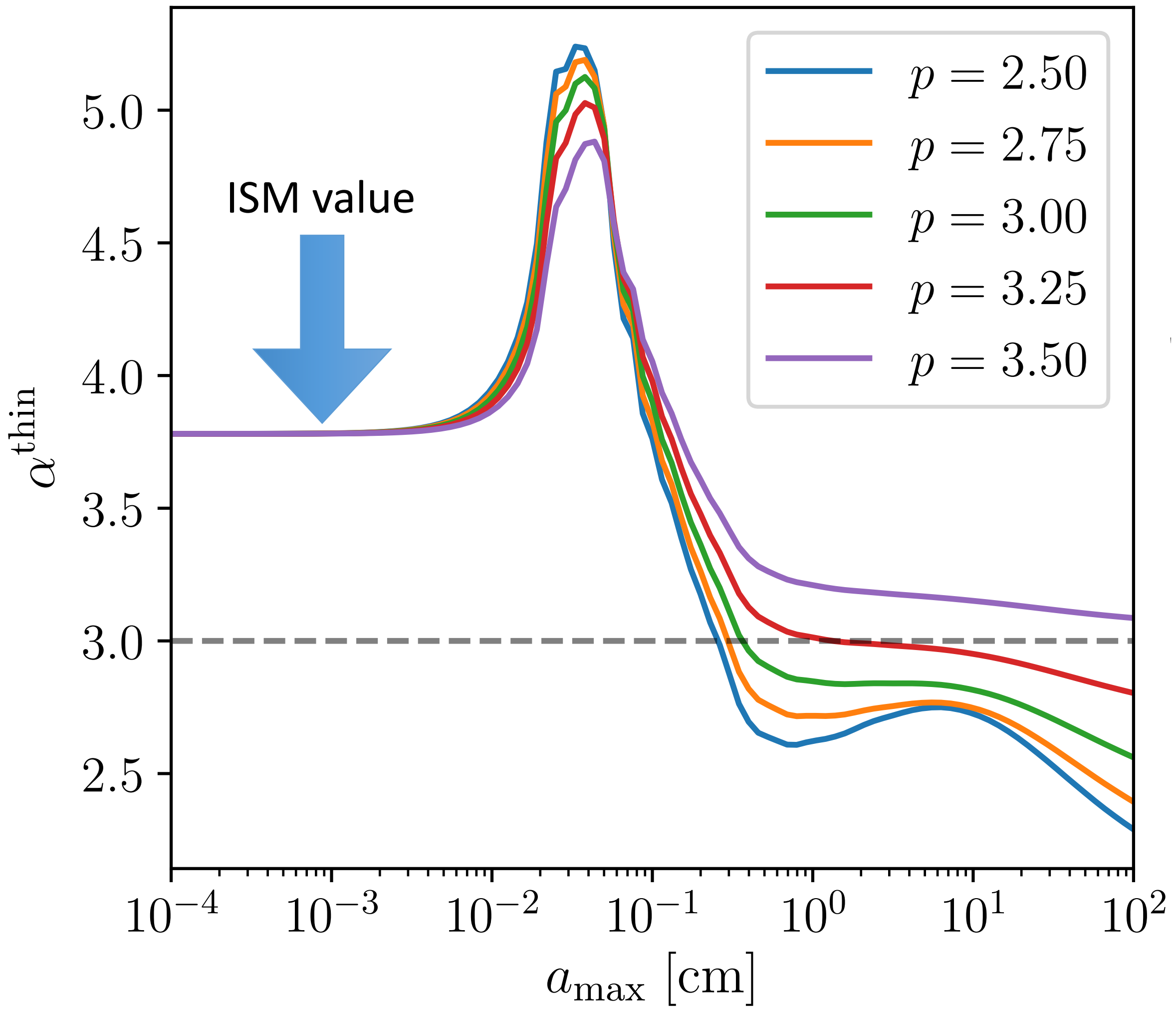


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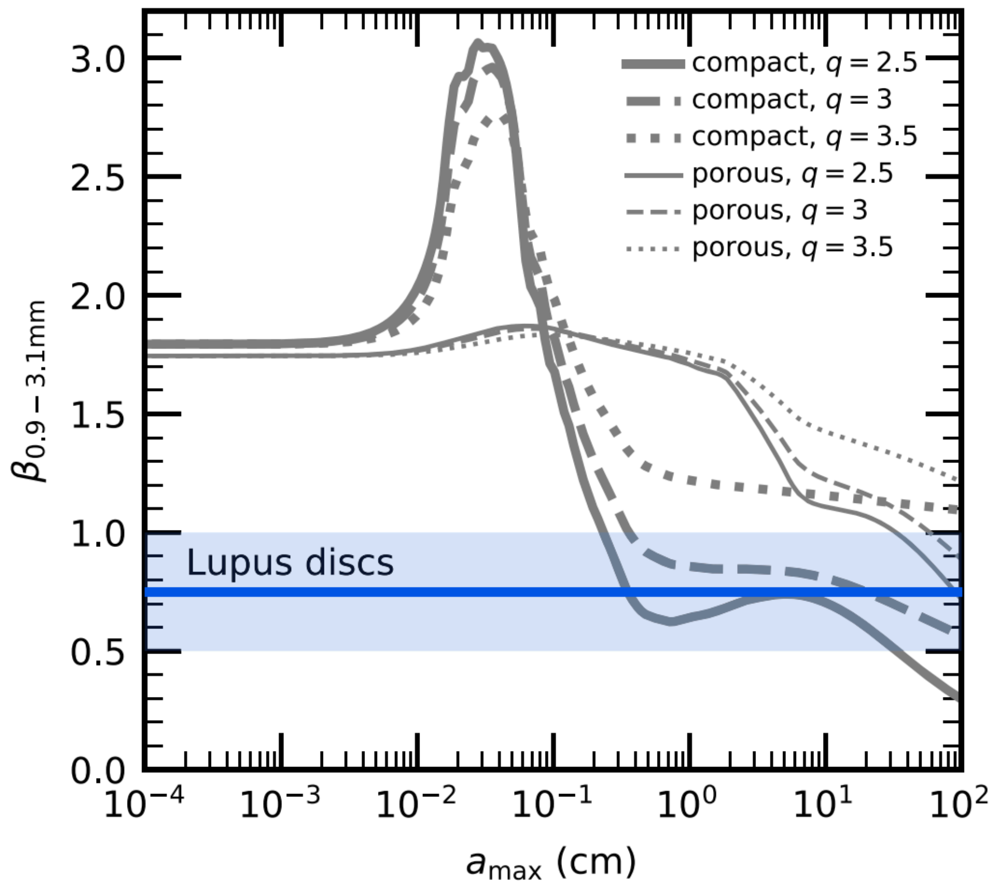
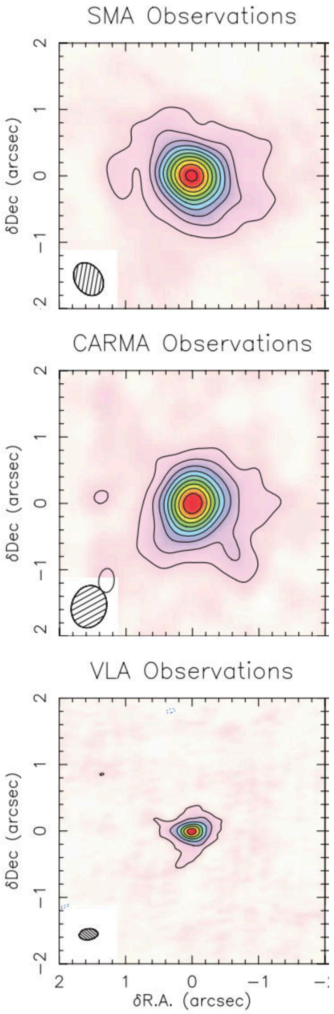
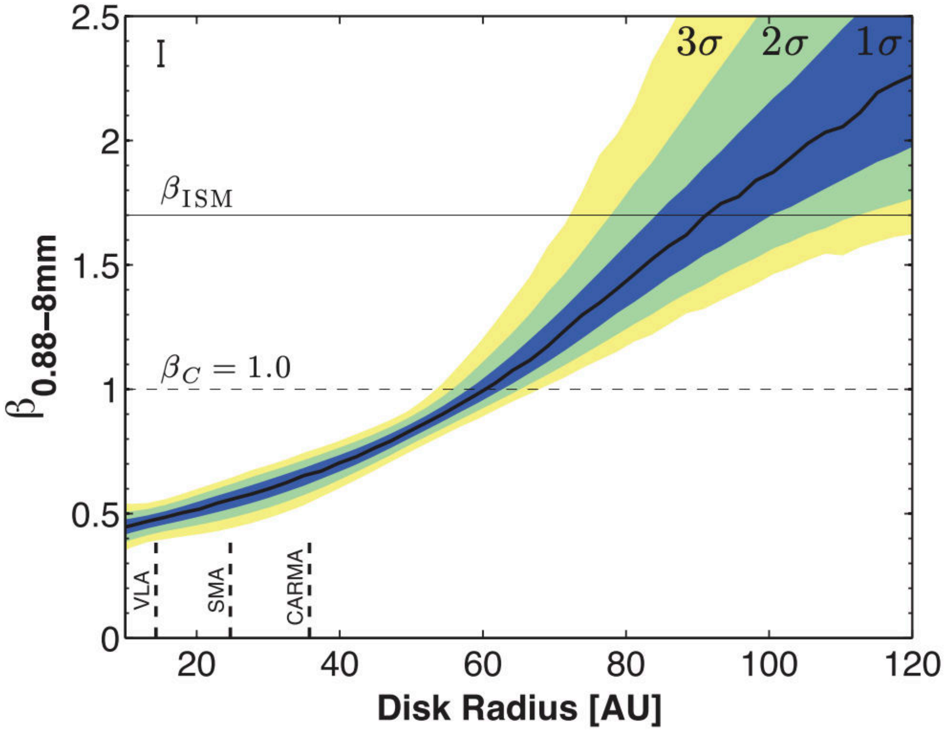


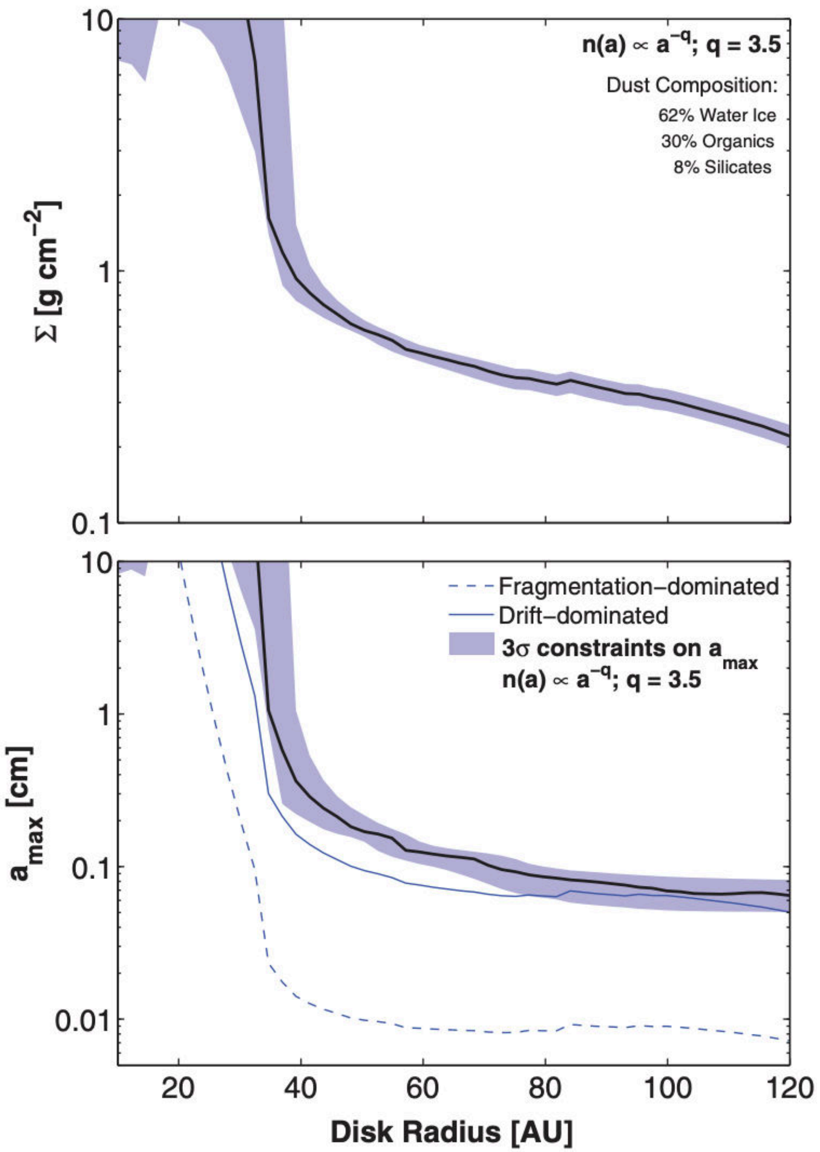

Tazarri et al. 2021

# Grain Size Substructures

AS 209 disk: Pérez et al. 2012

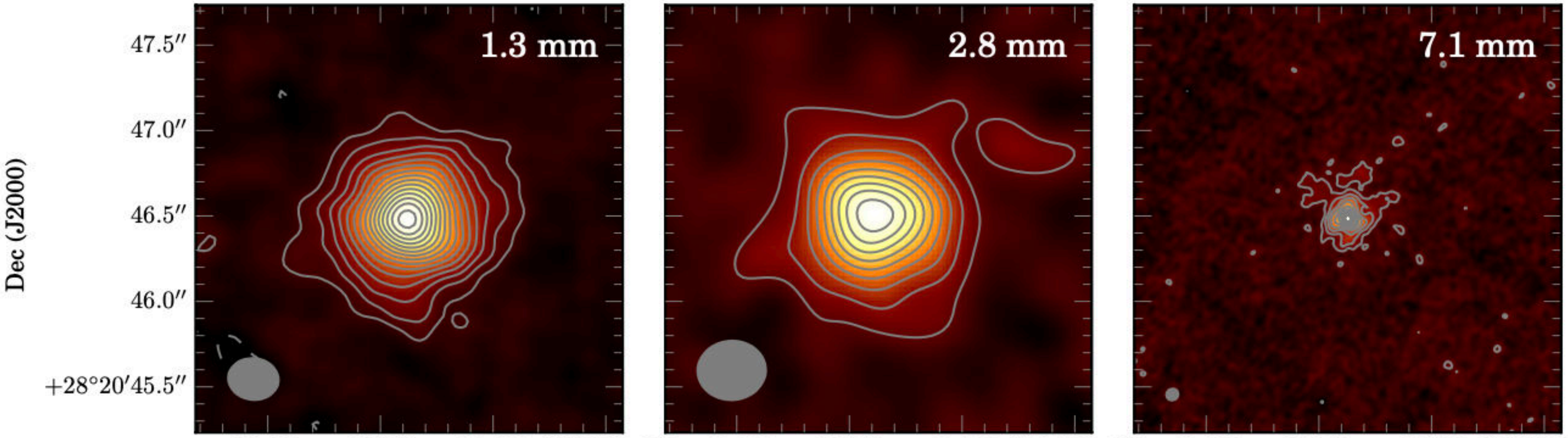


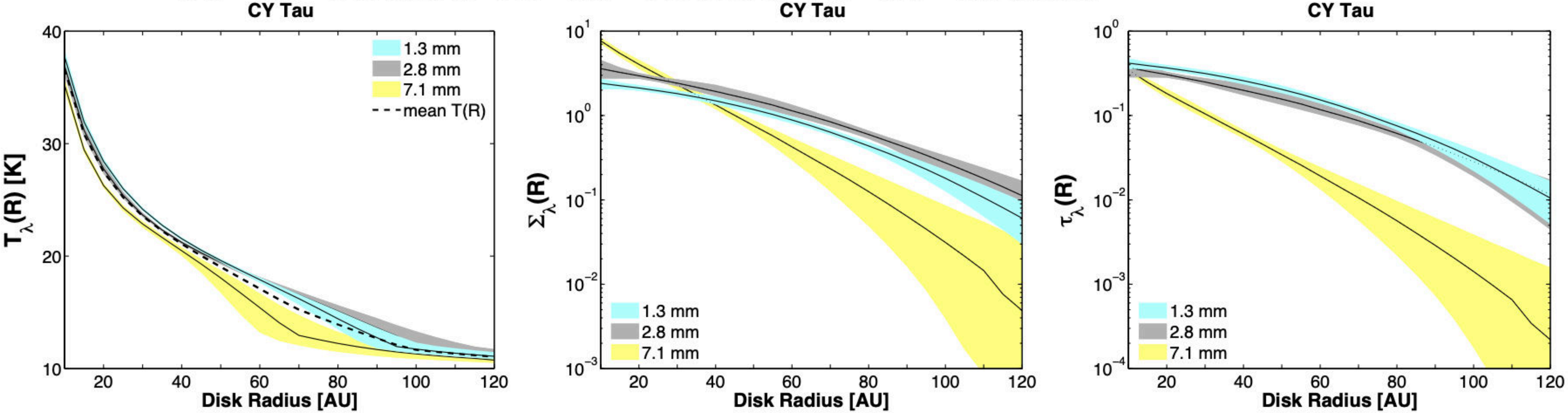



# Grain Size Substructures

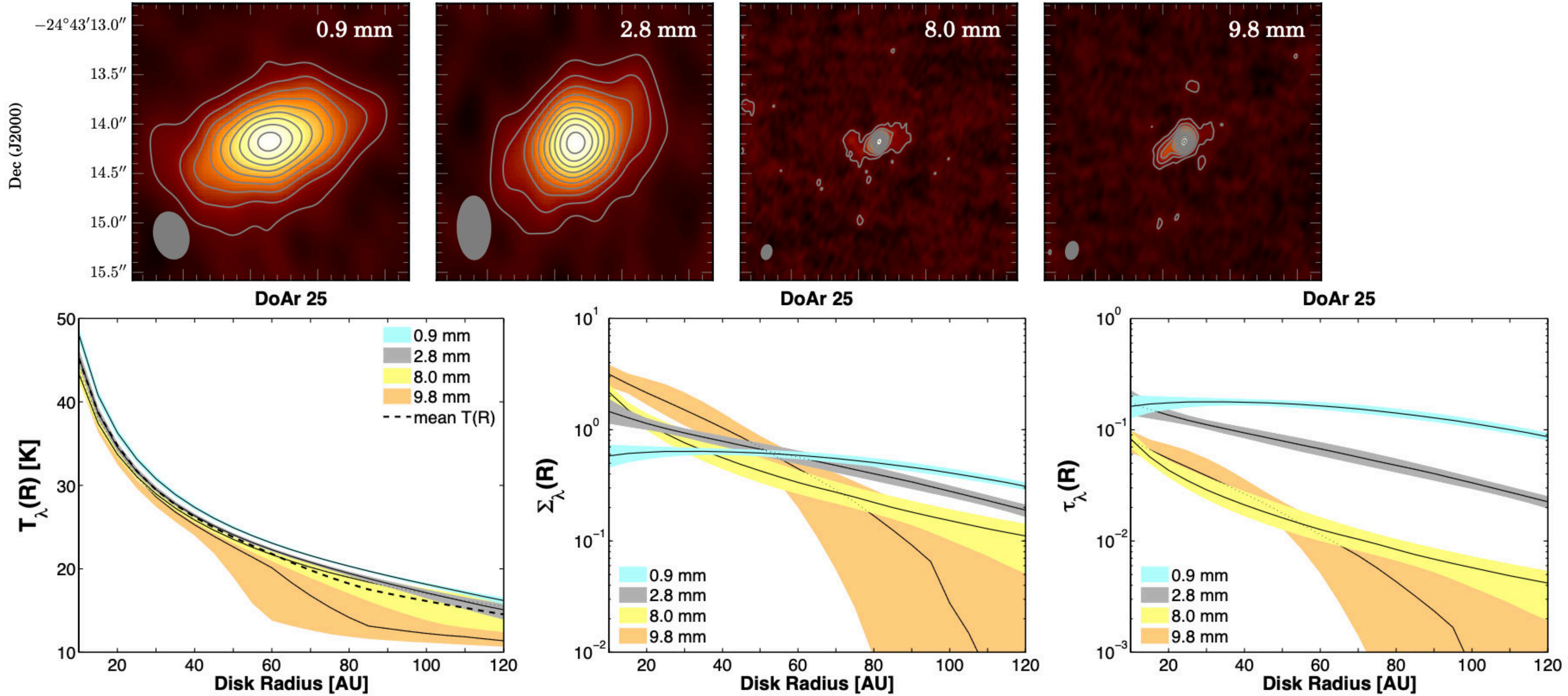
CY Tau disk: Pérez et al. 2015



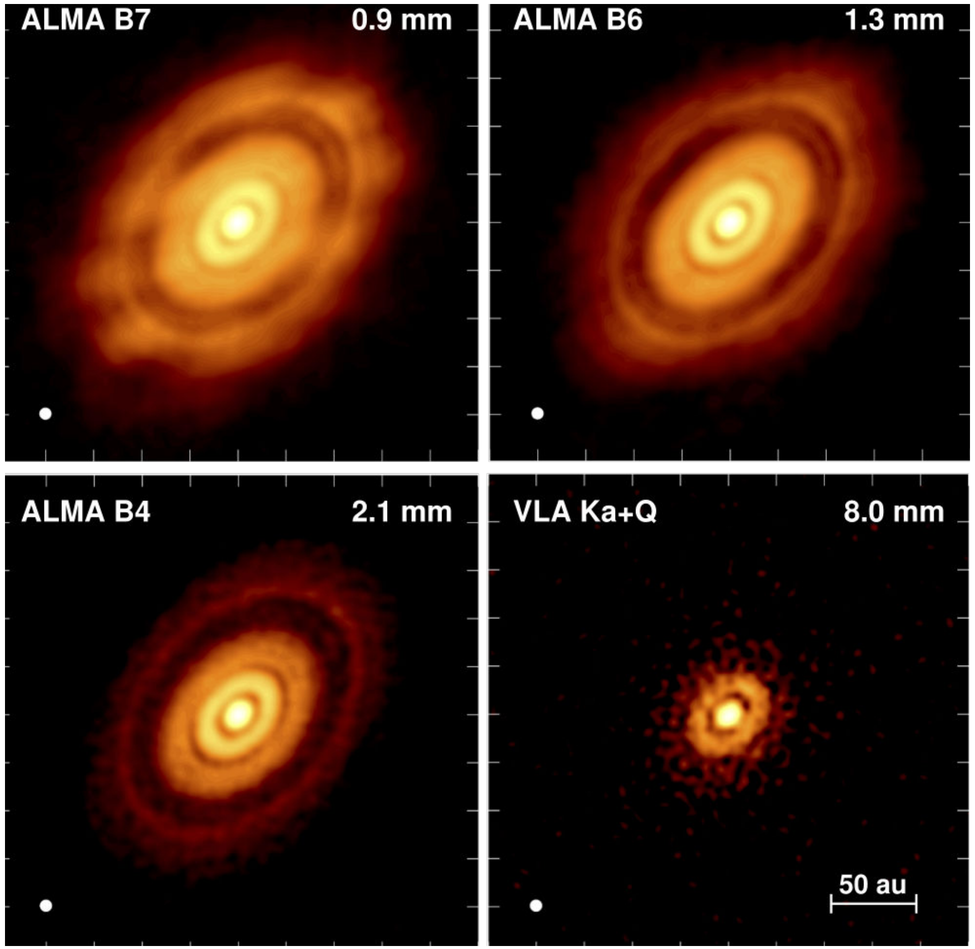
# Grain Size Substructures

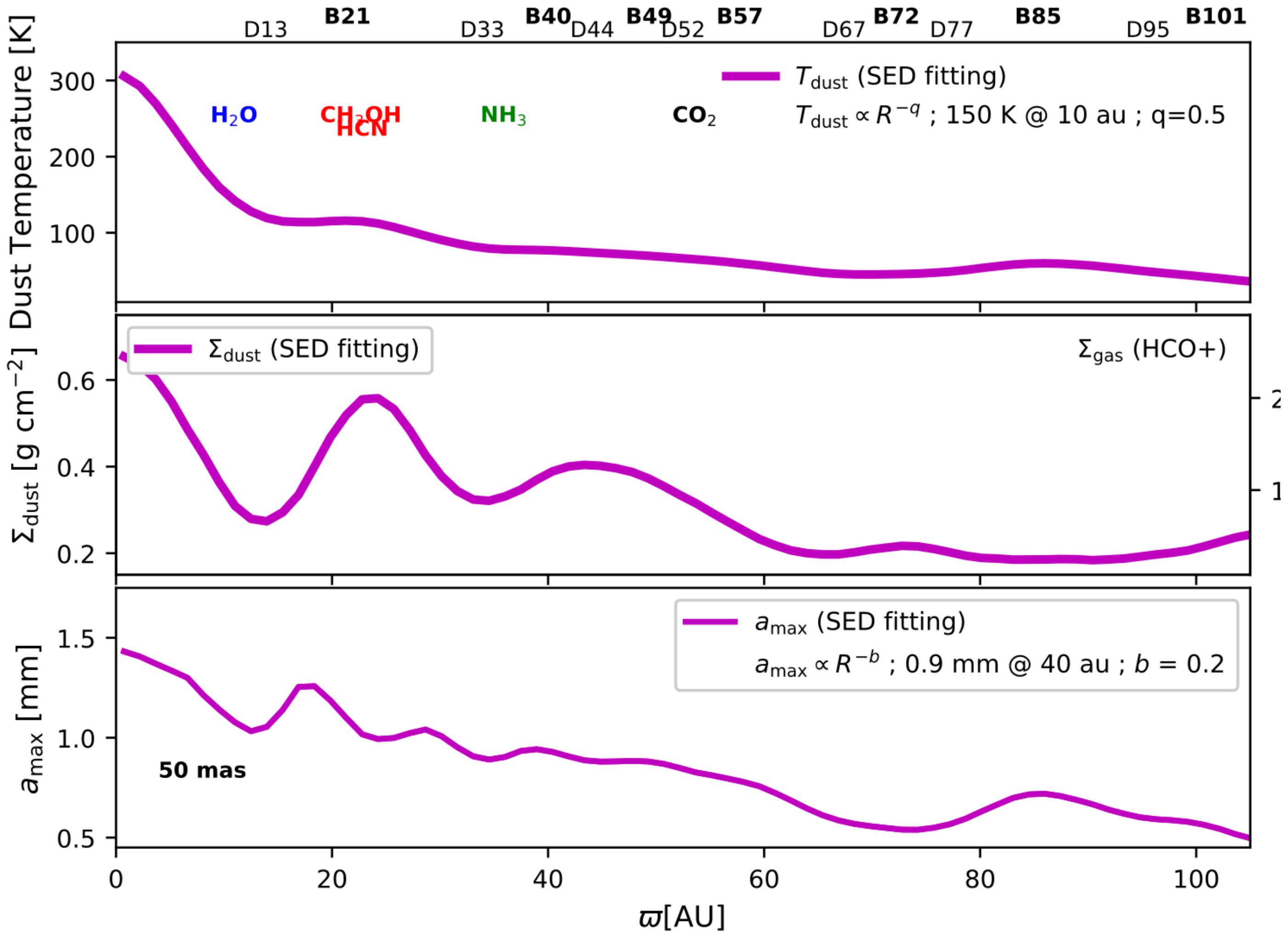
Do Ar 25 disk: Pérez et al. 2015



# Grain Size Substructures

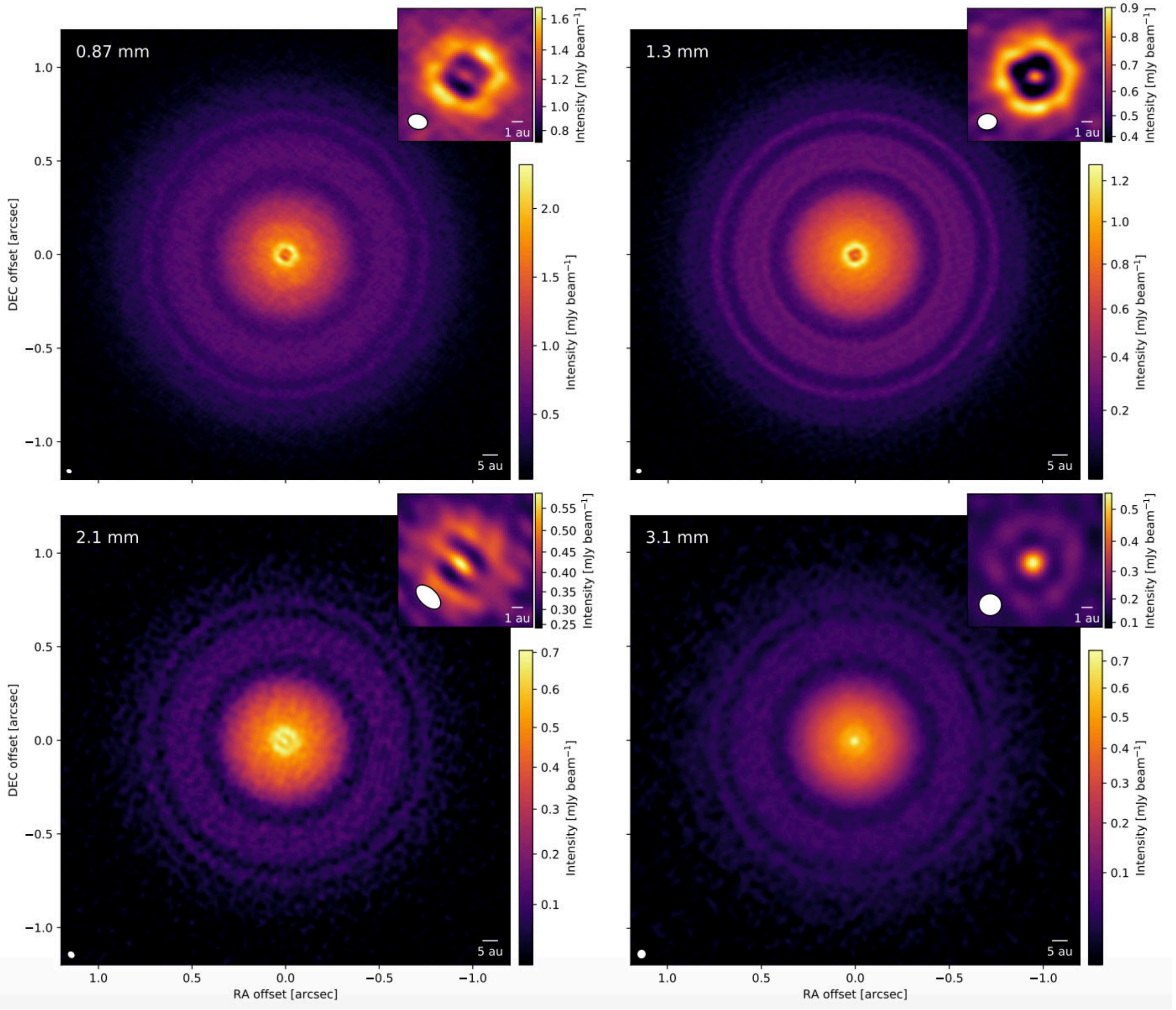
HL Tau disk: Carrasco-Gonzalez et al. 2019



# Grain Size Substructures

TW Hya disk: Macias et al. 2021



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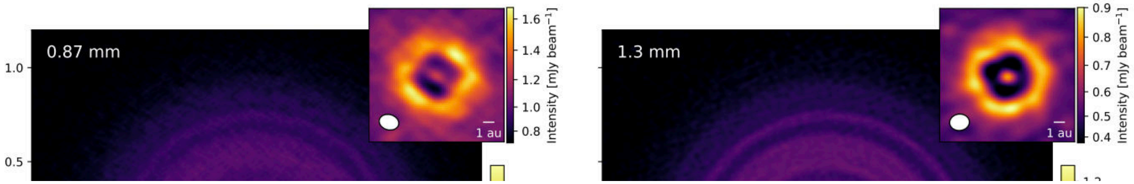
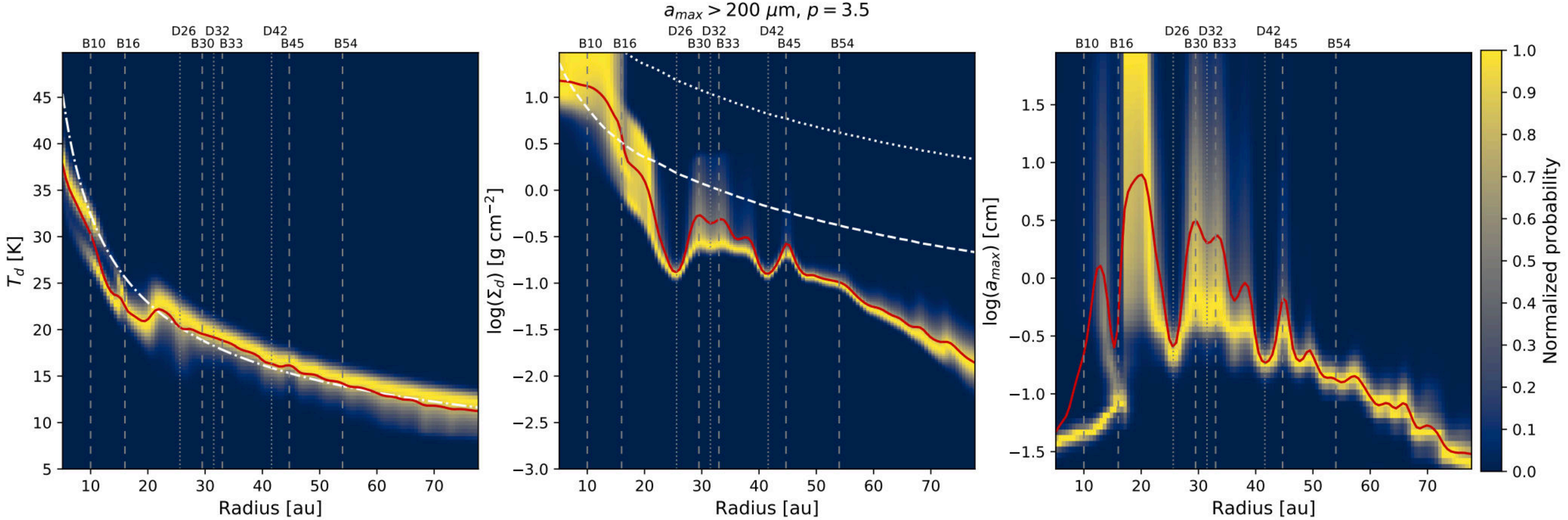


# MAPS Project

The **M**olecules with **A**LMA at **P**lanet-forming **S**cales (MAPS) focuses on study the chemistry of planet formation in scales down to 10 au.

Sources observed:

- IM Lup
- GM Aur
- AS 209
- HD 163296
- MWC 480

The disks in 4 spectral setups, covering ~40 lines from 20 different species.

# MAPS Data and Goals

Disks:

IM Lup
GM Aur
AS 209
HD 163296
MWC 480

Observations:

ALMA B3(I): 93 GHz
ALMA B3(II): 106 GHz
ALMA B6(I): 226 GHz
ALMA B6(II): 257 GHz

**Goals:**
Study the dust physical properties from the dust continuum emission.

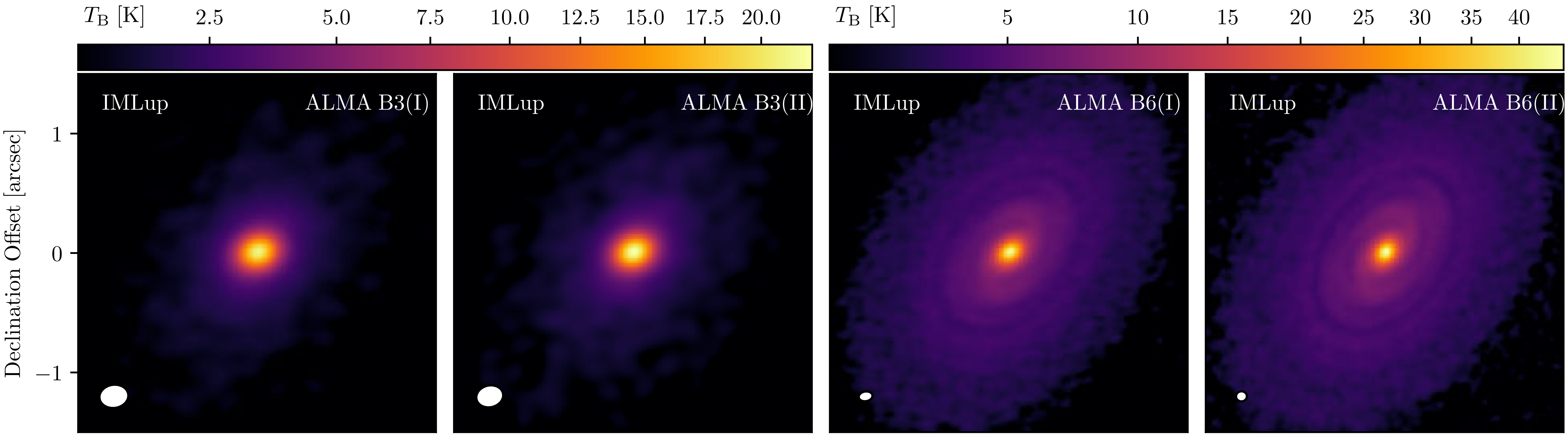
**Determine:**

- Dust surface density profiles
- Dust maximum grain size profiles
- Optical depth profiles
- What is the importance of scattering?

ALMA Large Program "Molecules with ALMA on Planet-forming Scales" (MAPS)

# IM Lup

~1.0 Myr old T Tauri star




ALMA B3(I): 93 GHz

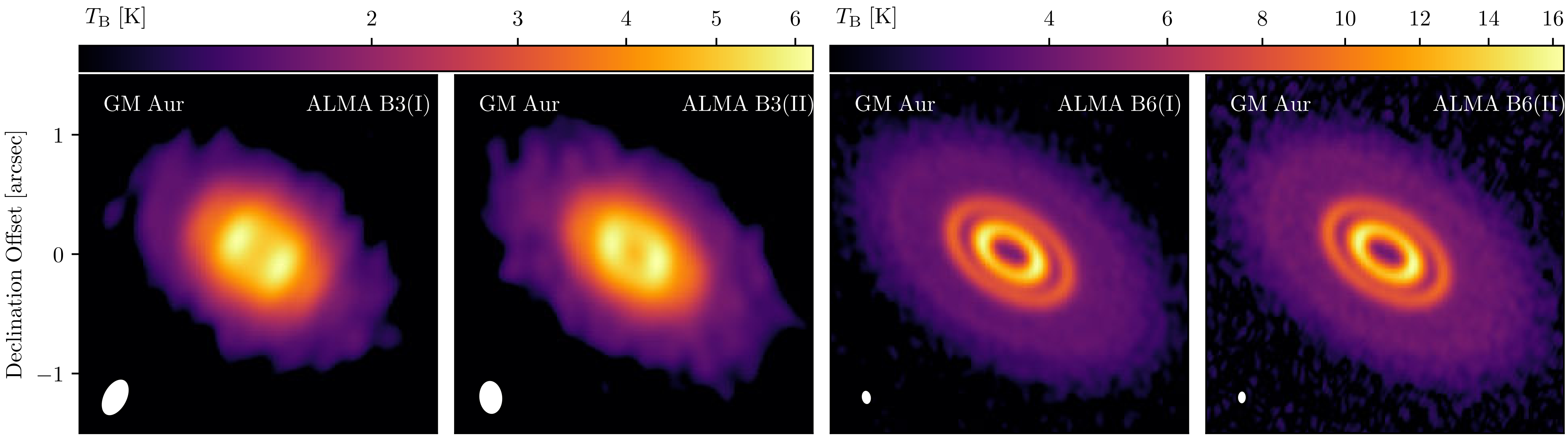
ALMA B3(II): 106 GHz

ALMA B6(I): 226 GHz

ALMA B6(II): 257 GHz

# GM Aur

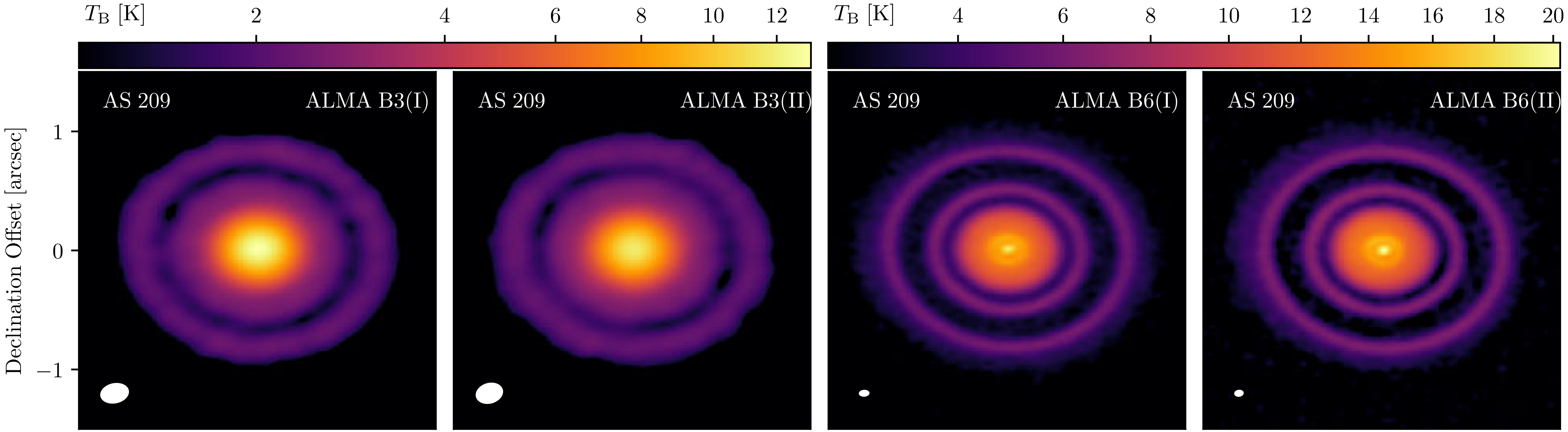
~3-10 Myr old T Tauri star




ALMA B3(I): 93 GHz    ALMA B3(II): 106 GHz    ALMA B6(I): 226 GHz    ALMA B6(II): 257 GHz

# AS 209

~1 Myr old T Tauri star




ALMA B3(I): 93 GHz

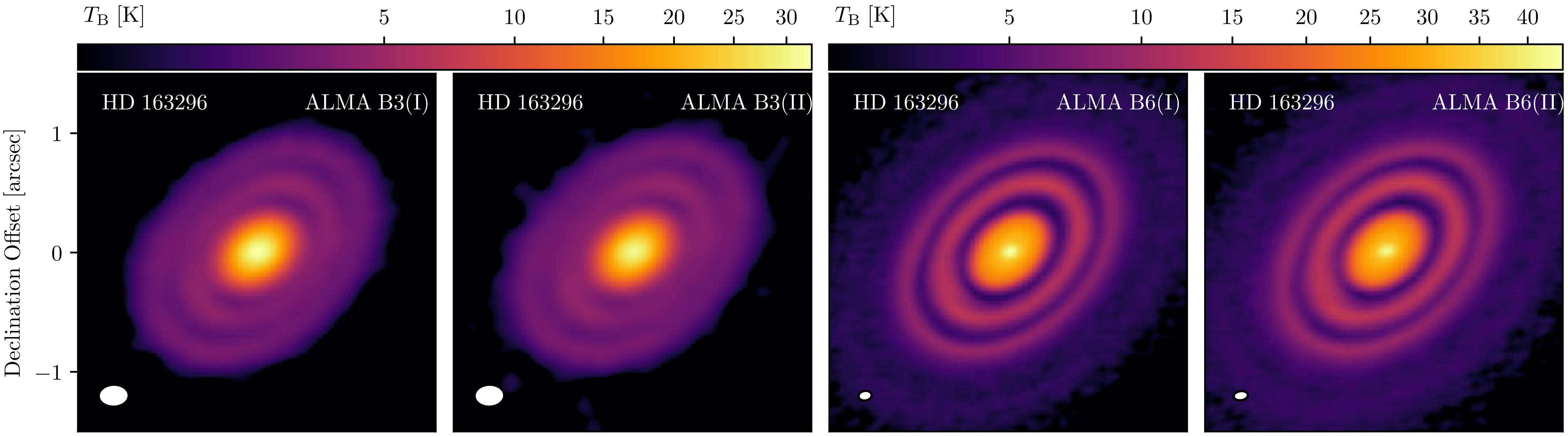
ALMA B3(II): 106 GHz

ALMA B6(I): 226 GHz

ALMA B6(II): 257 GHz

# HD 163296

>6 Myr old Herbig Ae star




ALMA B3(I): 93 GHz

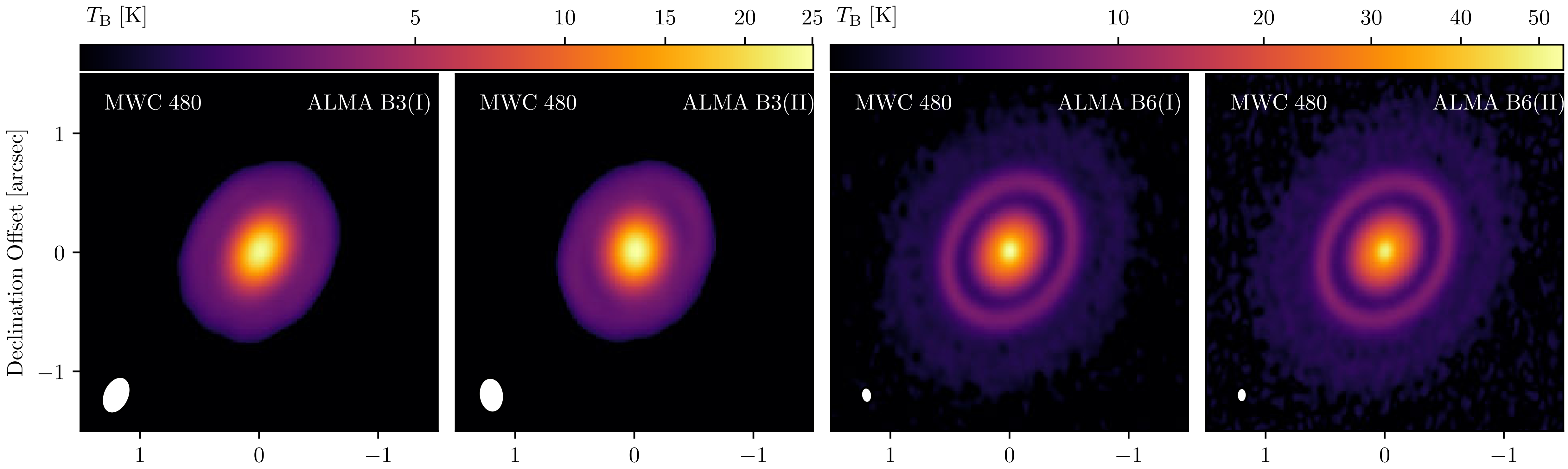
ALMA B3(II): 106 GHz

ALMA B6(I): 226 GHz

ALMA B6(II): 257 GHz

# MWC 480

~7 Myr old Herbig Ae star




ALMA B3(I): 93 GHz

ALMA B3(II): 106 GHz

ALMA B6(I): 226 GHz

ALMA B6(II): 257 GHz

# Azimutally averaged profiles

B3(I): 93 GHz
B3(II): 106 GHz
B6(I): 226 GHz
B6(II): 257 GHz

↔

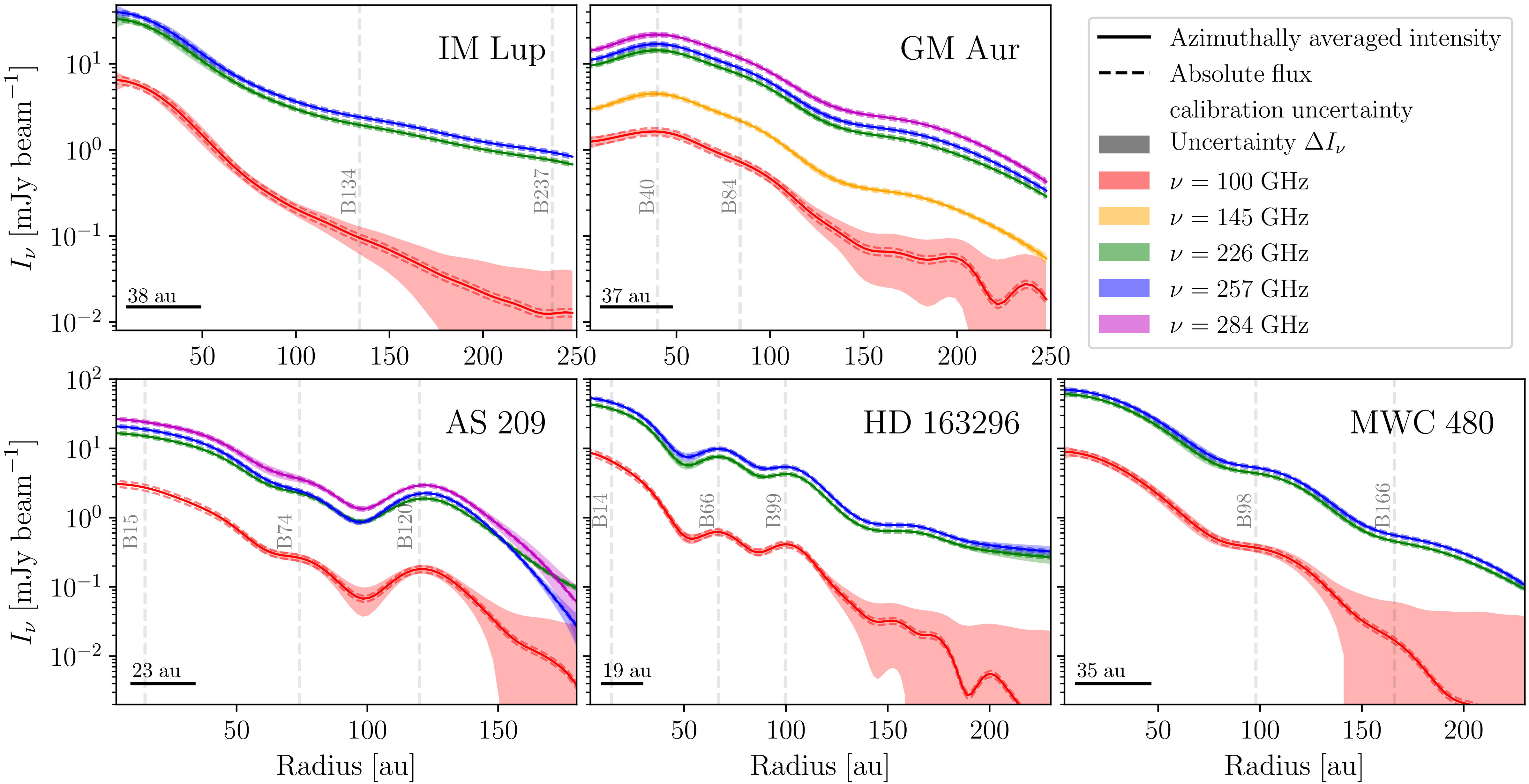
B3: 100 GHz
B6(I): 226 GHz
B6(II): 257 GHz
+ archive data

↔

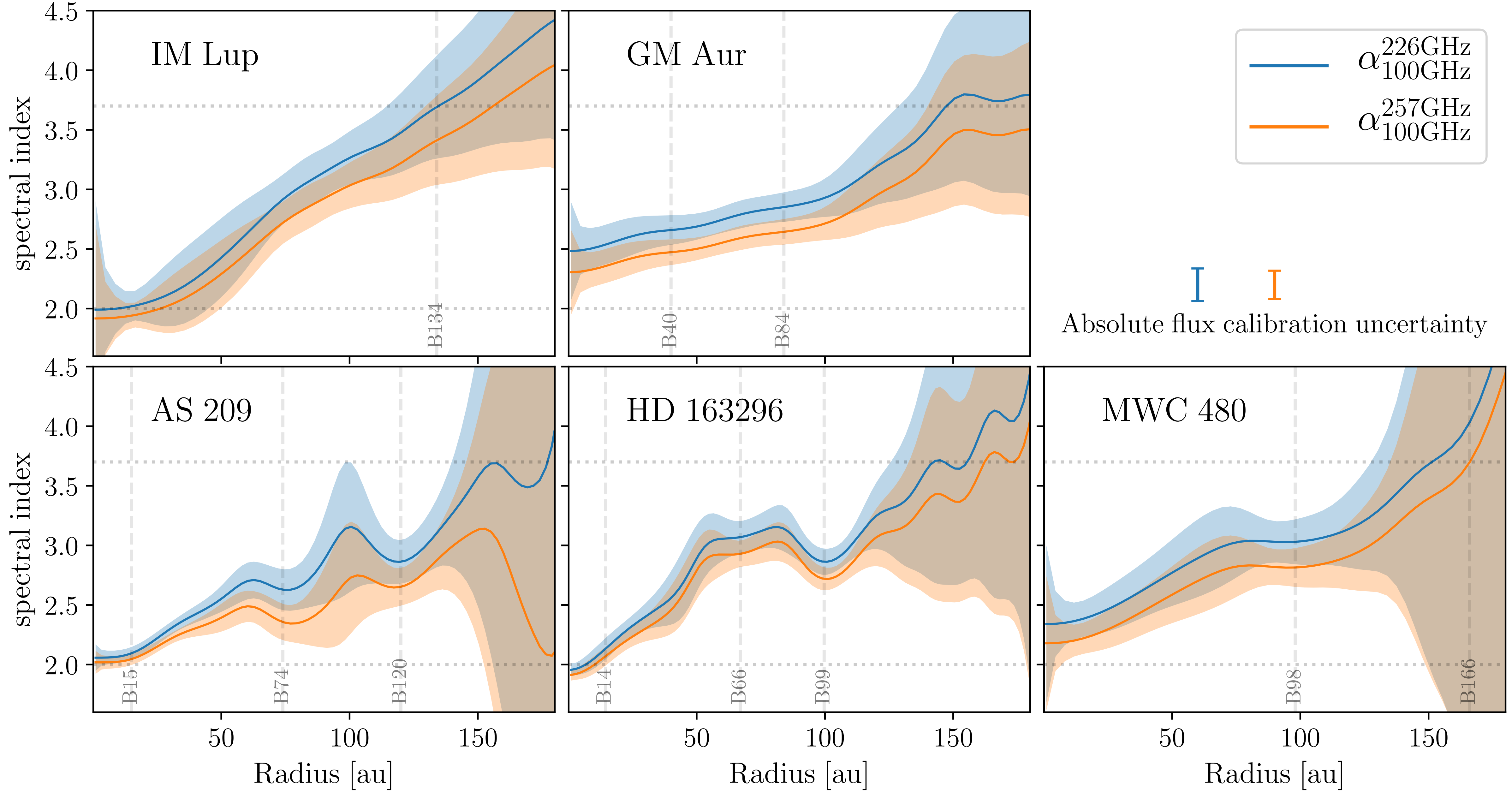
B3 resolution

| Disk | Resolution (mas) |
|---|---|
| AS 209 | 196 |
| GM Aur | 235 |
| HD 163296 | 190 |
| IM Lup | 244 |
| MWC 480 | 222 |

# Azimutally averaged profiles



# Spectral Indices



# Methodology

- Fit the SED at each radius using the available wavelengths.

Non-Scattering Model

$$I_\nu = B_\nu(T_\mathrm{d})[1 - \exp(-\tau_0(\nu/\nu_0)^\beta)].$$

Scattering model

$$I_\nu = B_\nu(T_\mathrm{d})[1 - \exp(-\tau_\nu/\mu) + \omega_\nu F(\tau_\nu, \omega_\nu)]$$

The spectral indices are modified in the optically thick regime.
Sierra & Lizano (2020)

# Methodology

- Fit the SED at each radius using the available wavelengths.
- The free parameters:

  - The maximum grain size $a_{\mathrm{max}}$
  - The dust surface density $\Sigma_{\mathrm{d}} + a_{\mathrm{max}} \rightarrow \tau_{\kappa_{\nu}}$

- The mid-plane dust temperature is given by the thermo-chemical models from MAPS V: Zhang et al. (2021) [Accepted]

# Methodology

- A probability is assigned to each combination of the free parameters by

$$p(I_{\nu_1}, I_{\nu_2}, \ldots, I_{\nu_n} | a_{\max}, \Sigma_{\rm d}) \propto \exp(-\chi^2/2),$$

$$\chi^2 = \sum_n w_{\nu_n} \times \left( \frac{I_{\nu_n} - I_{\nu_n}^{\rm model}}{\epsilon_{\nu_n}} \right)^2,$$

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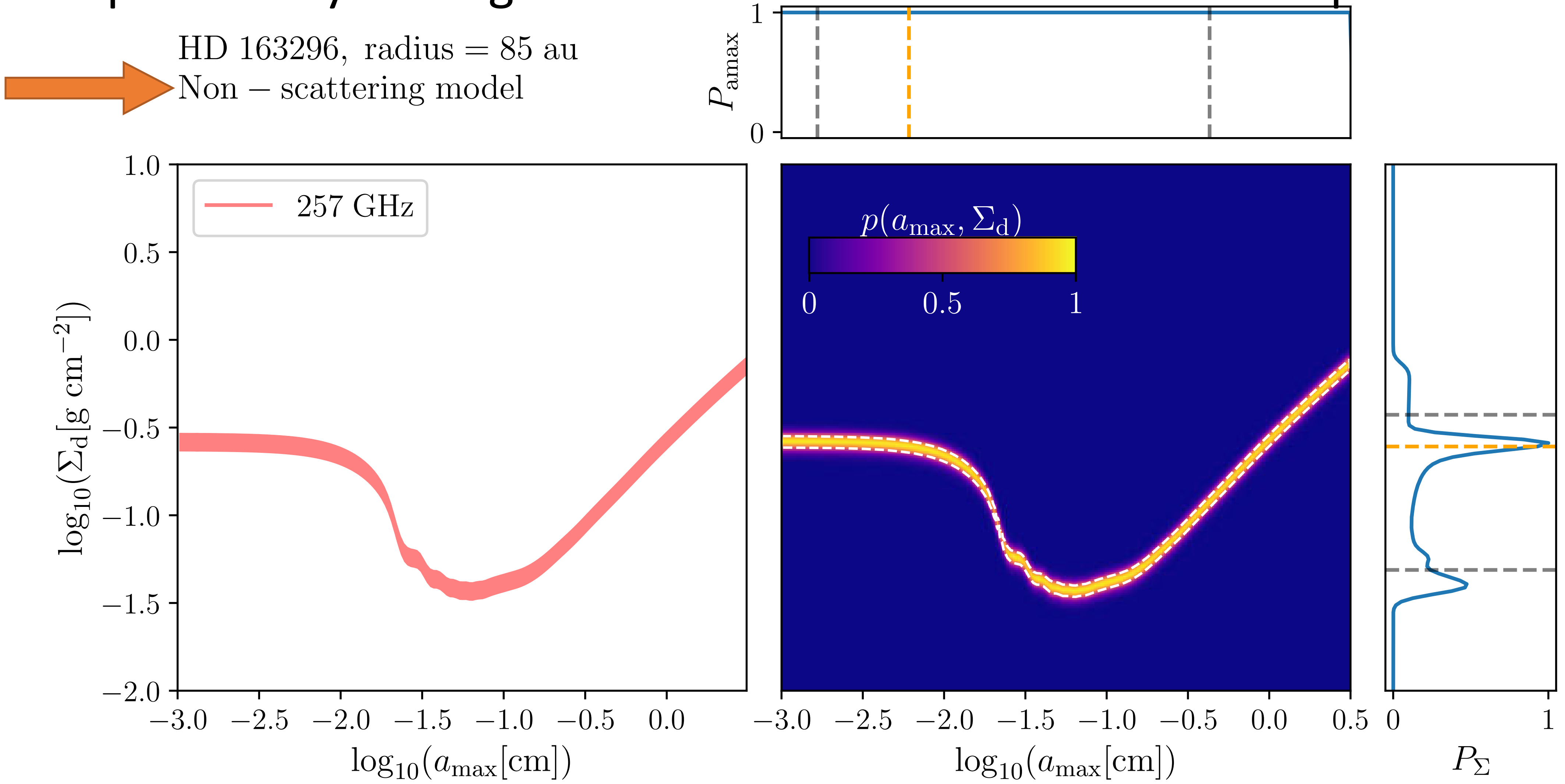

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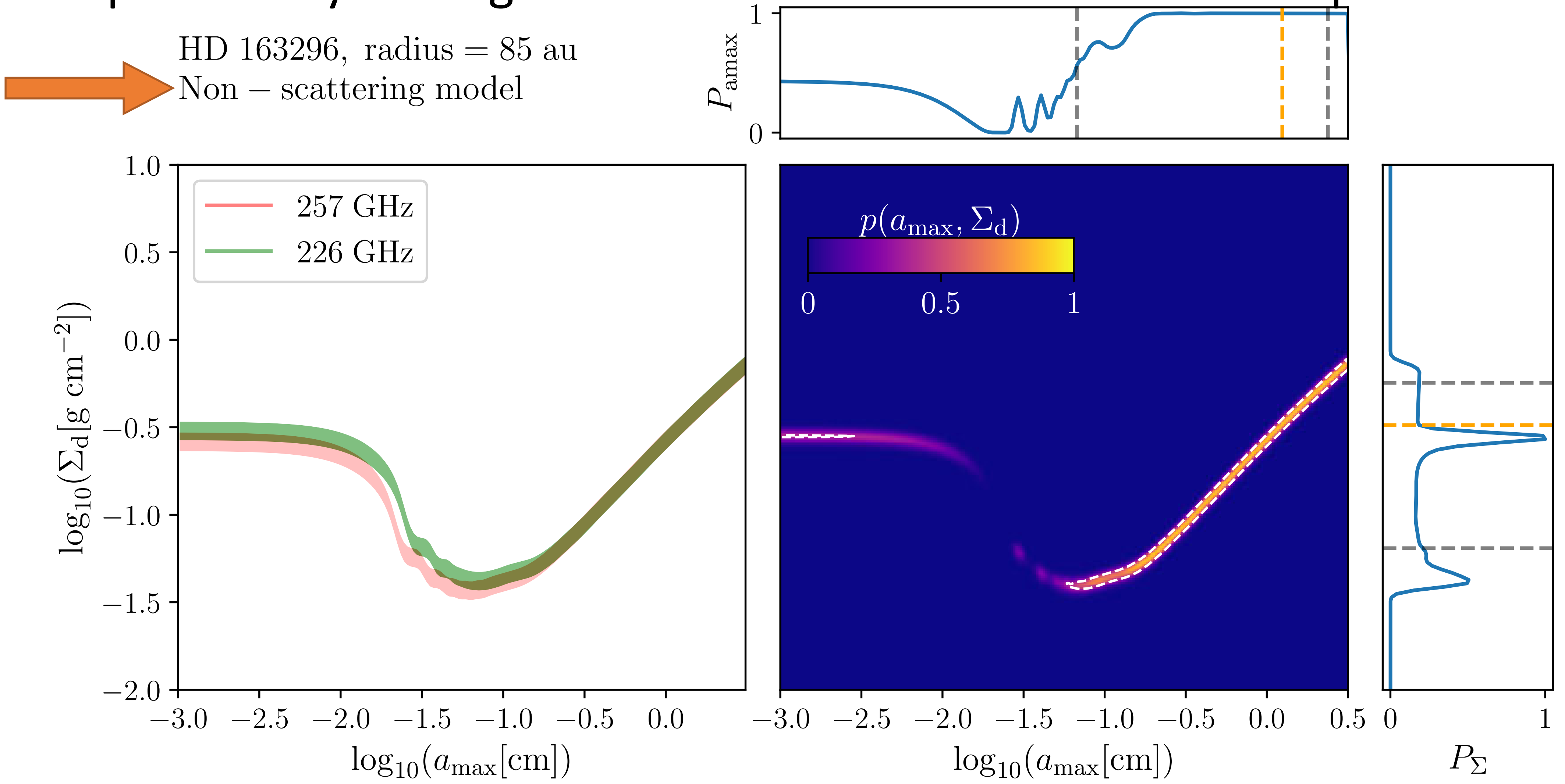

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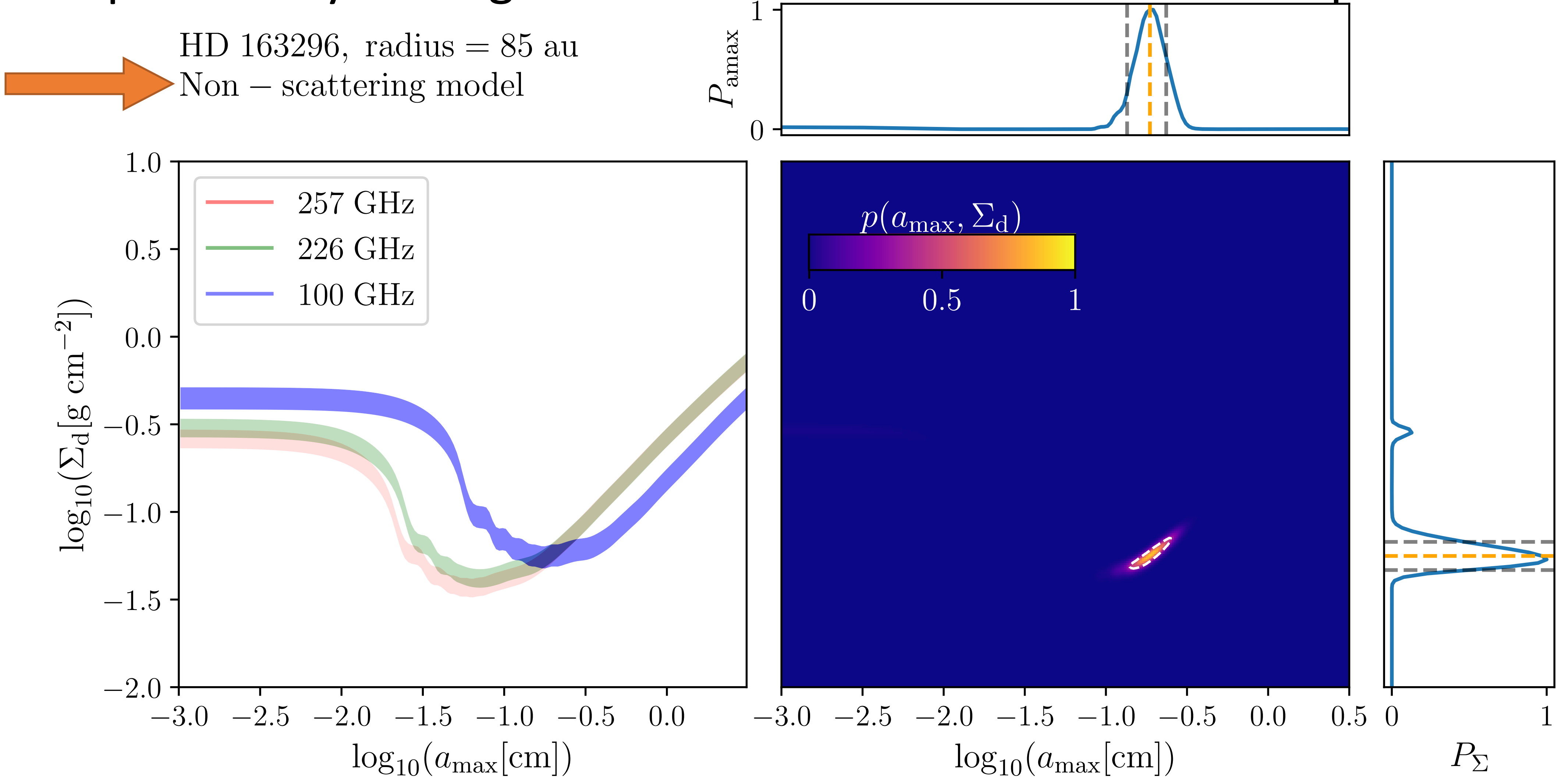

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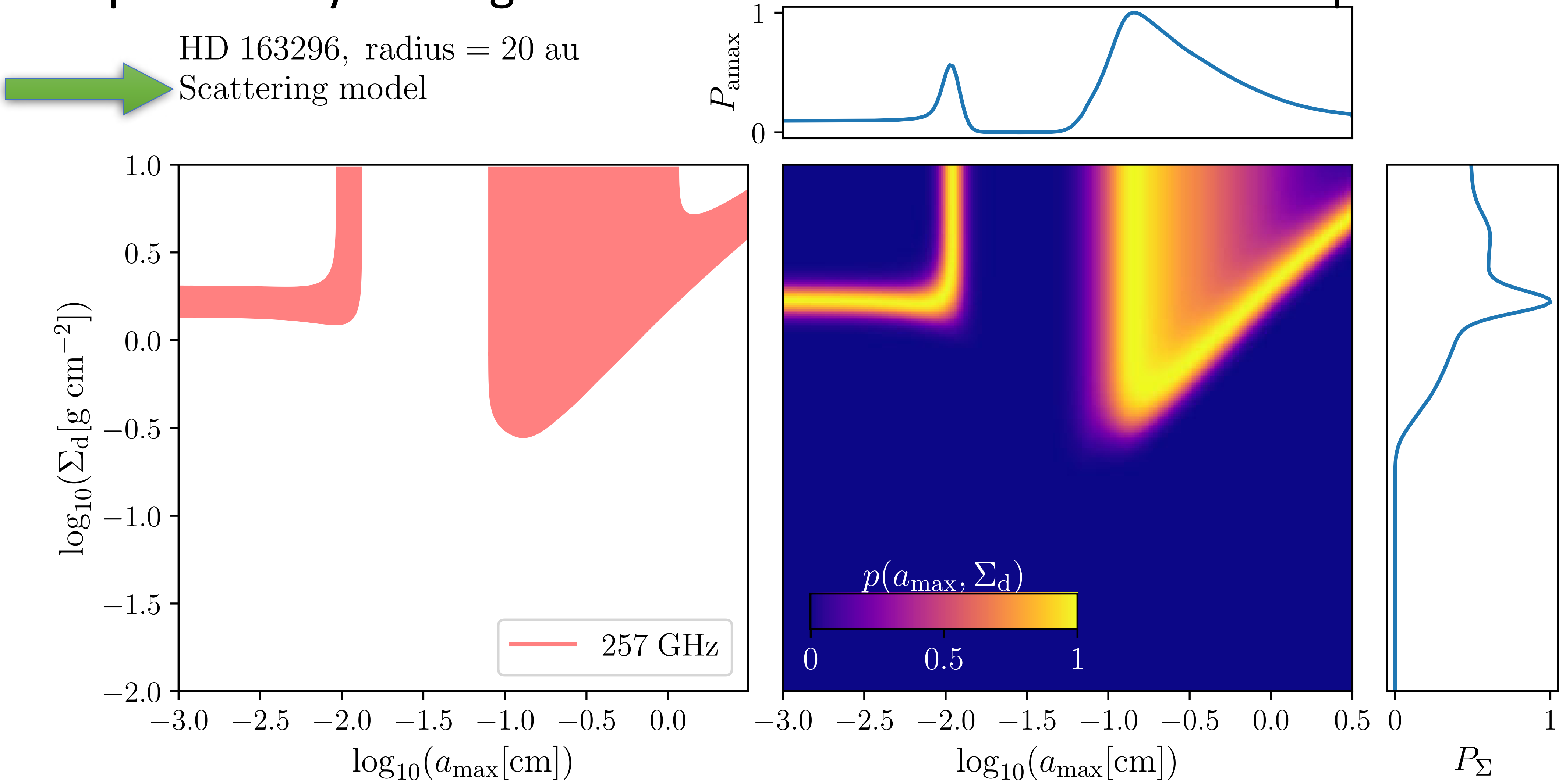

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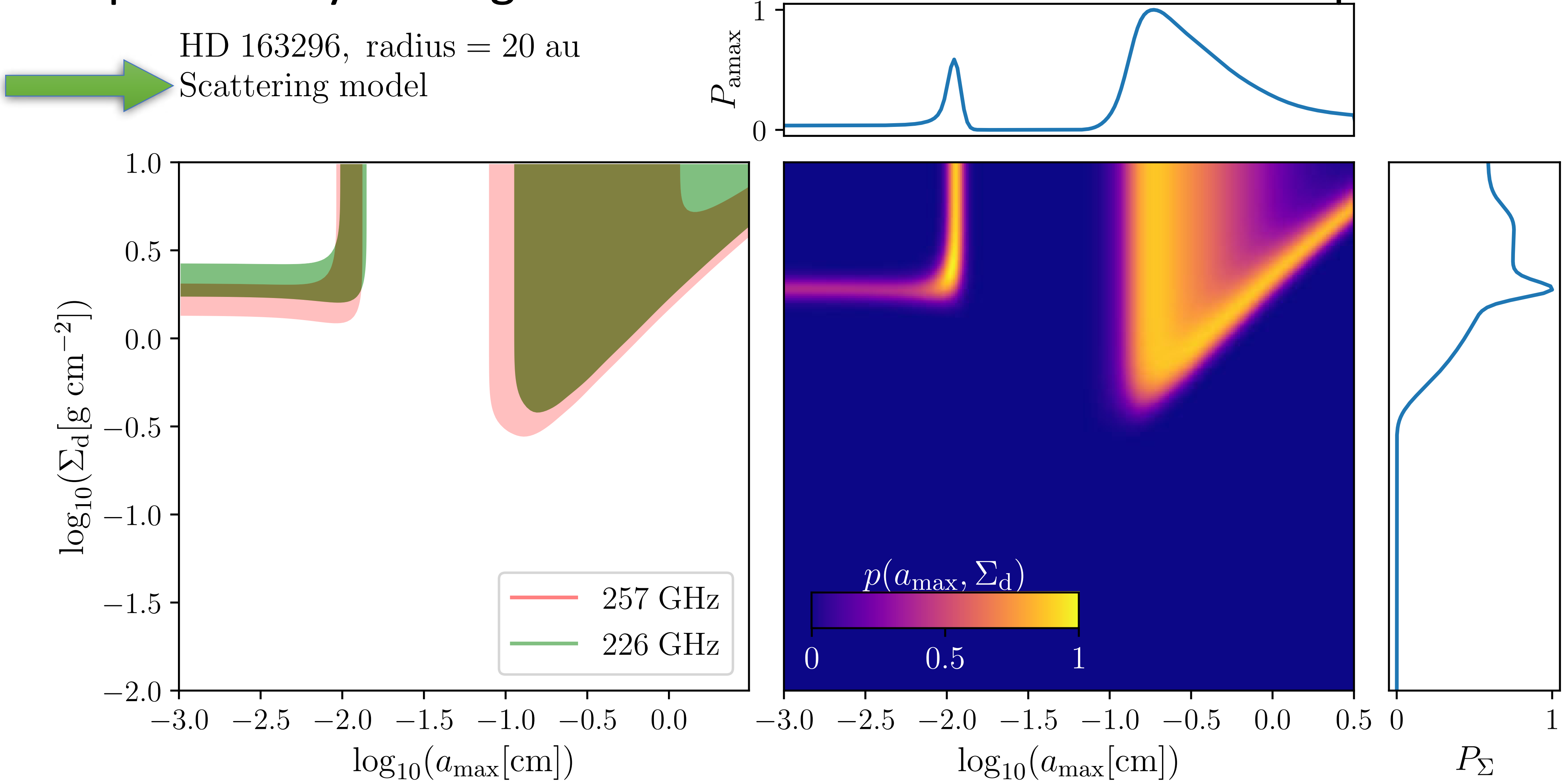

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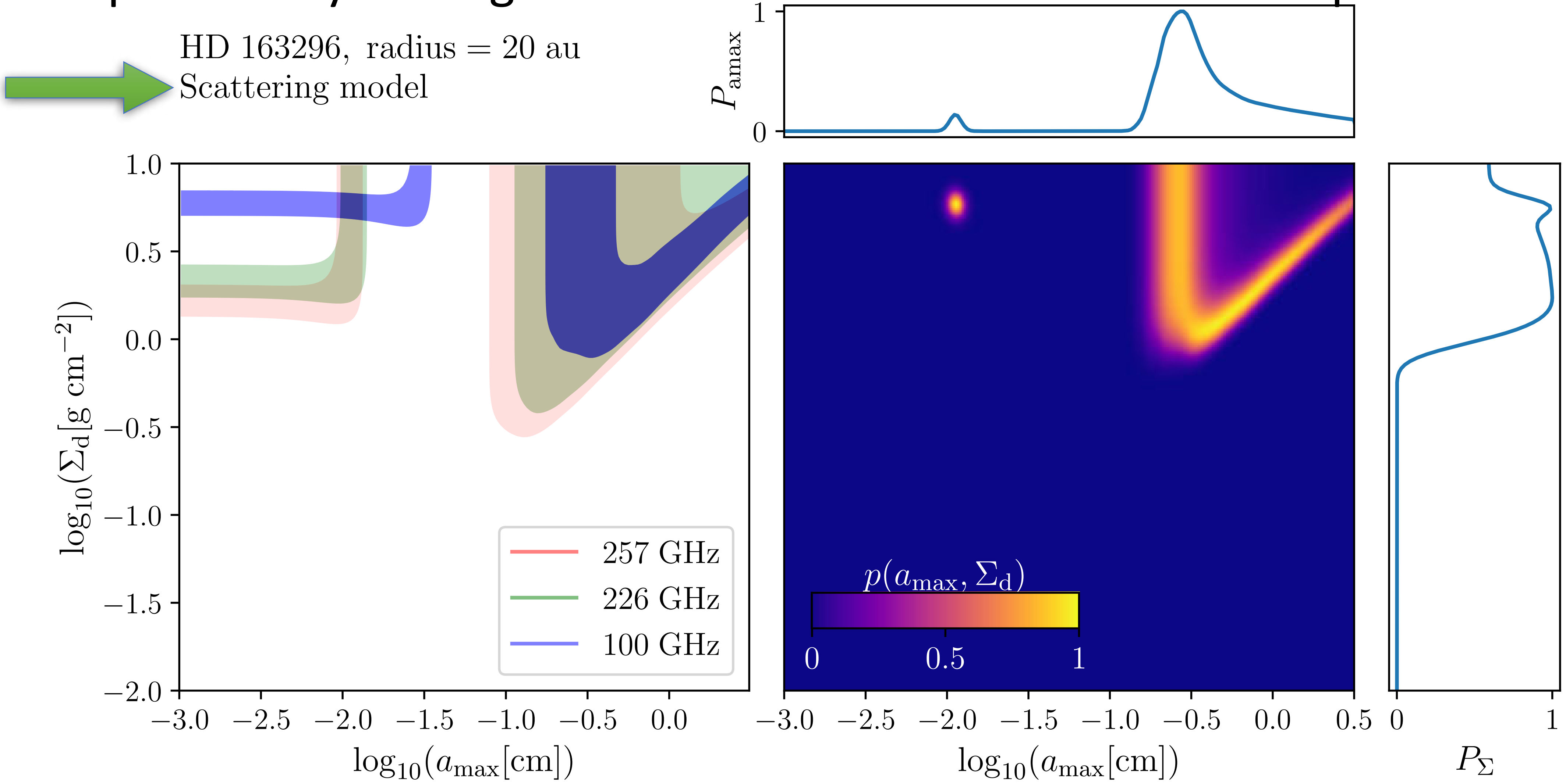

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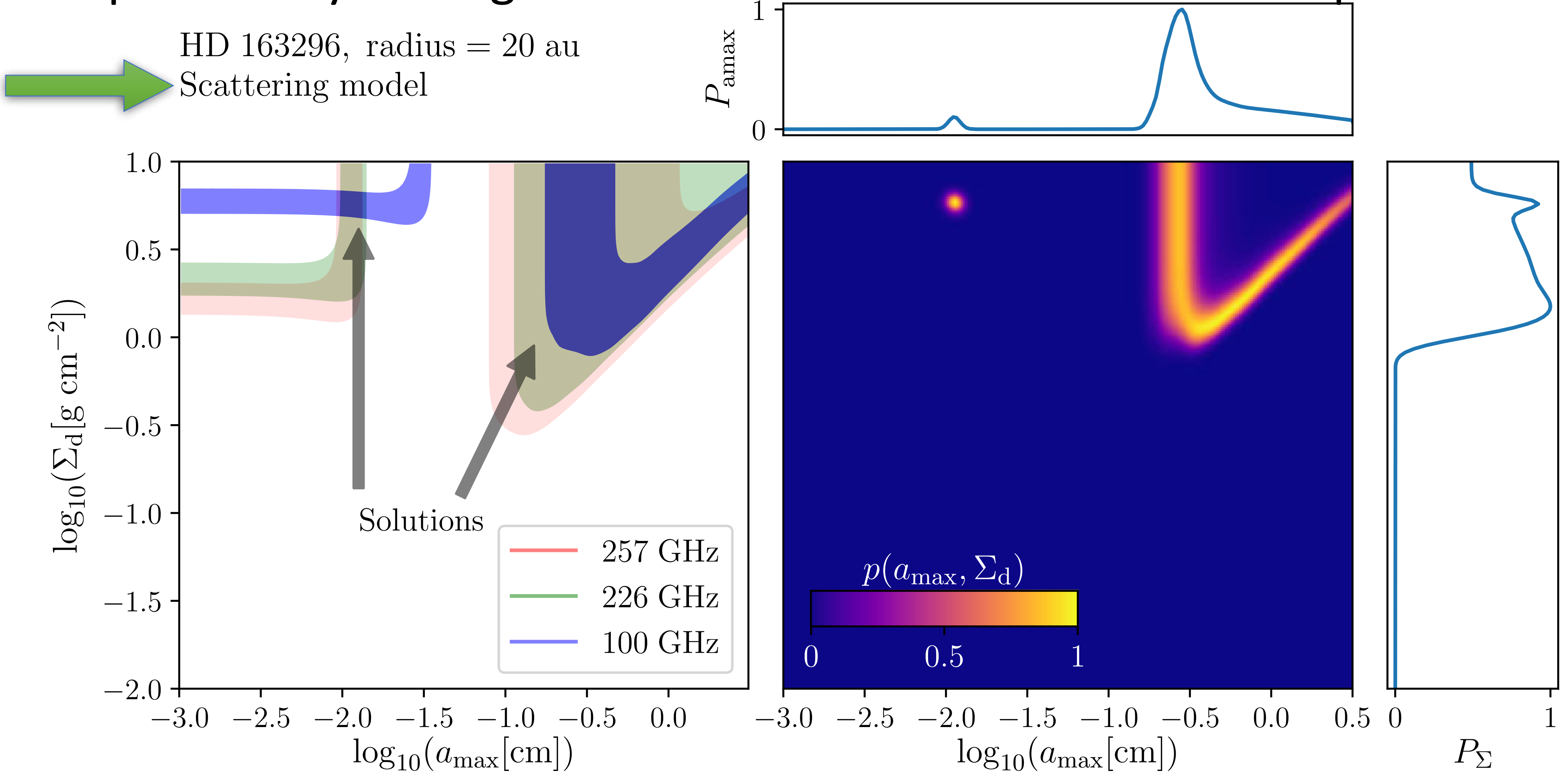
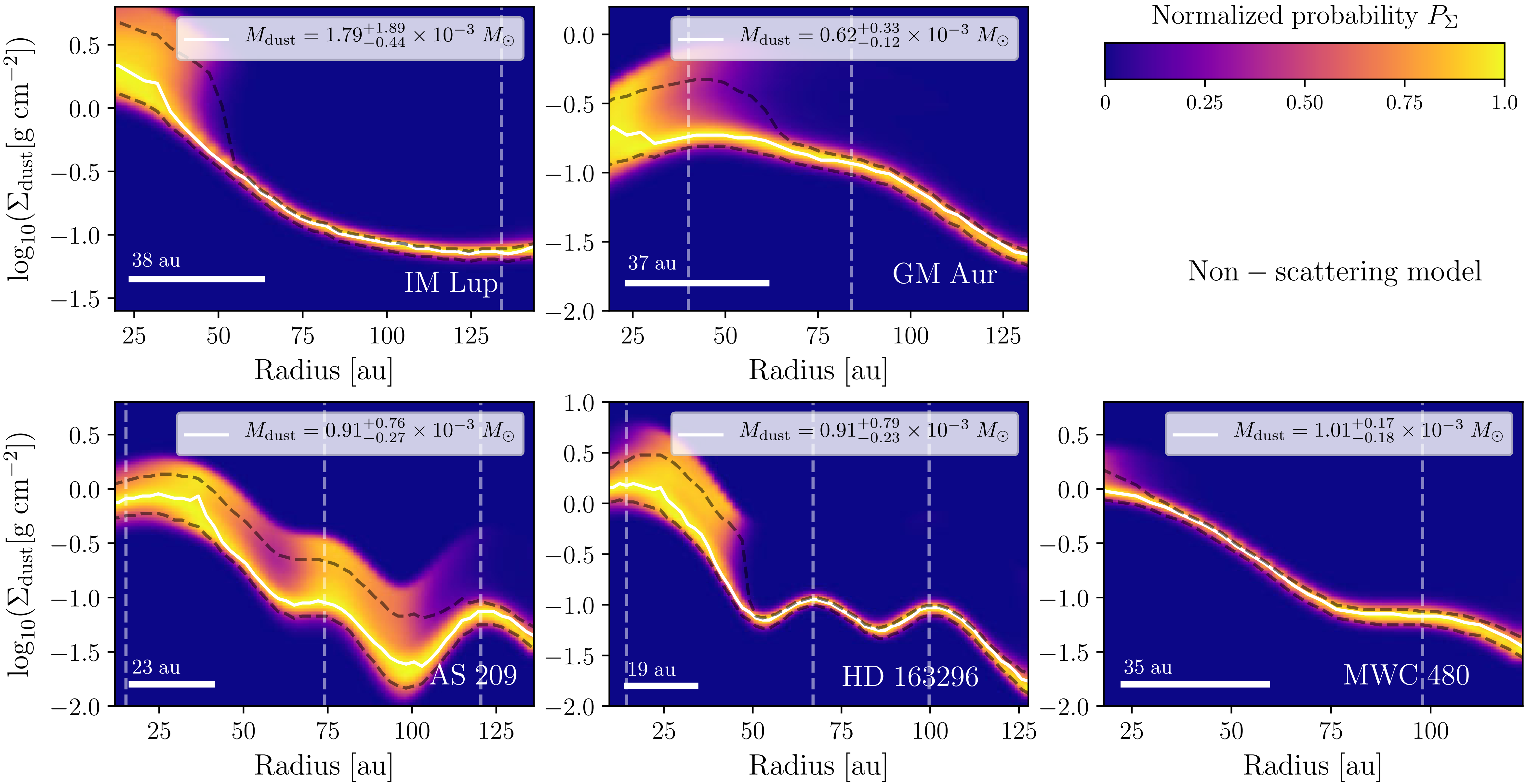


# Results: Non-scattering model



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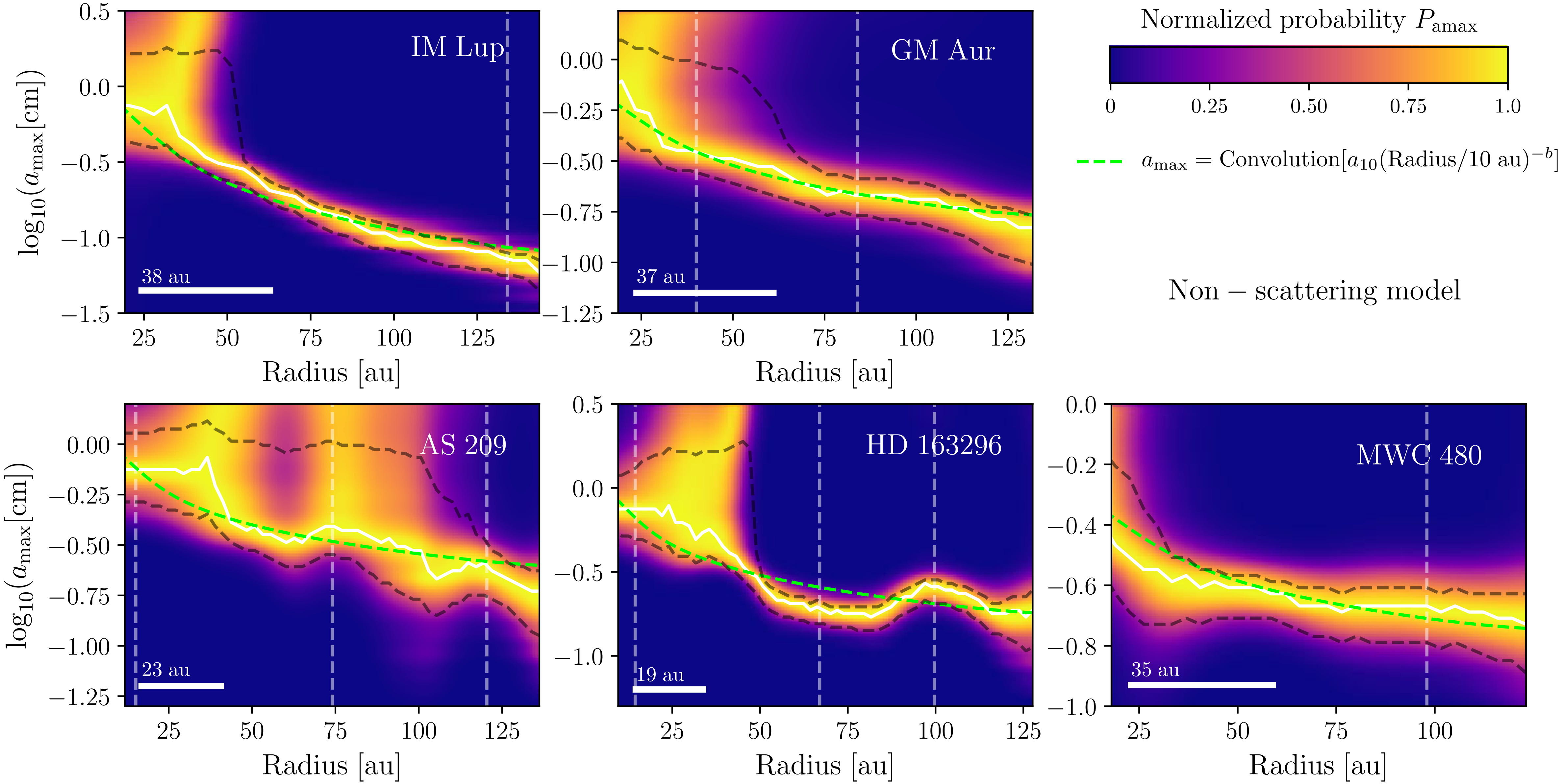

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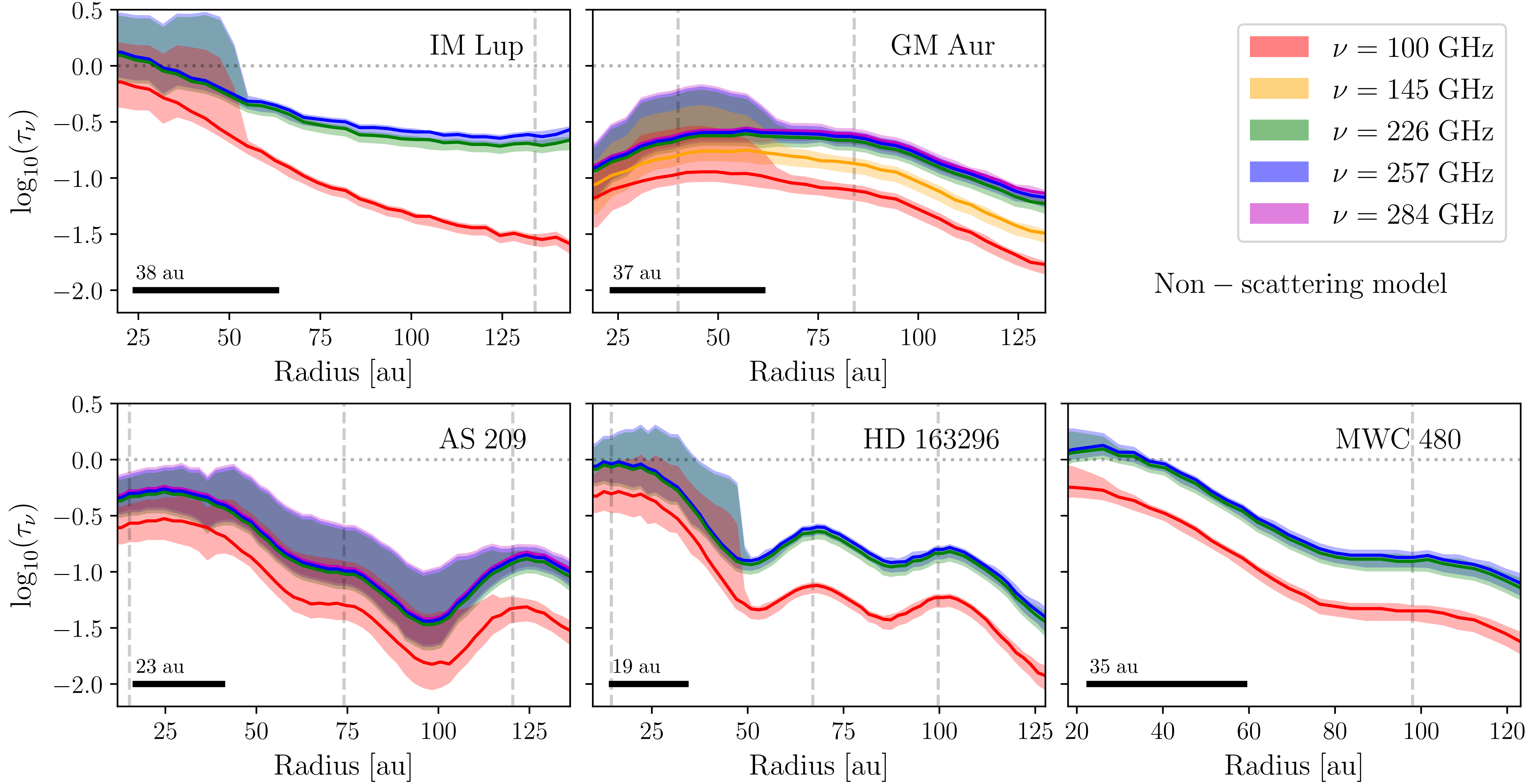

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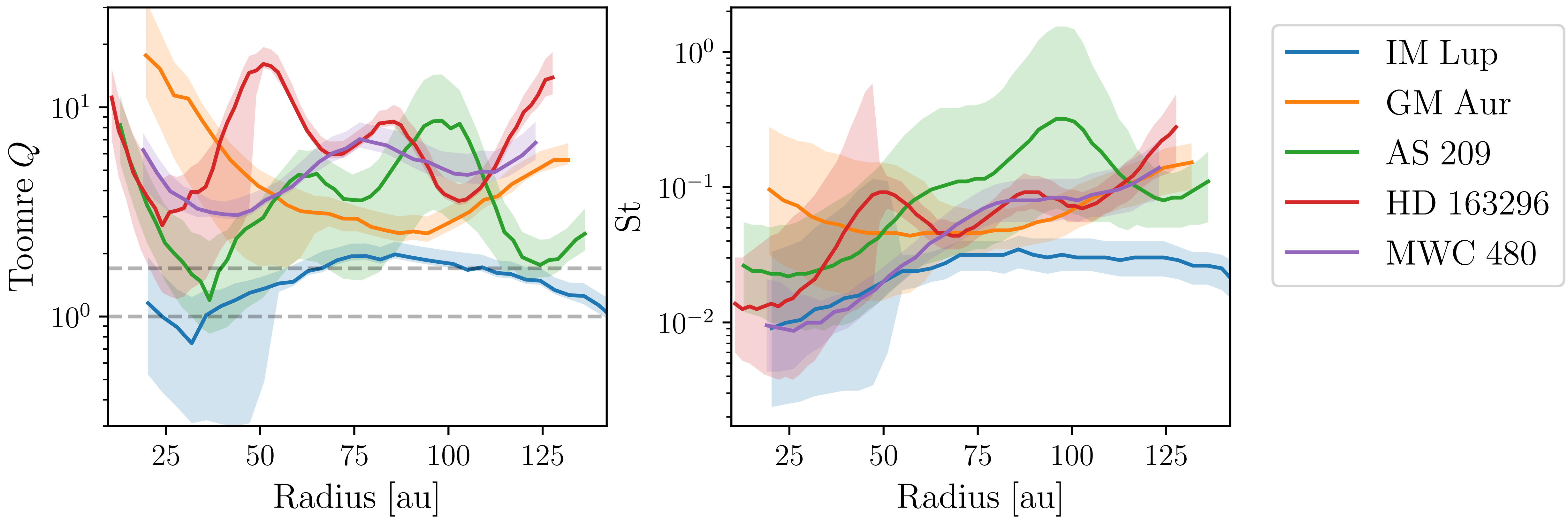


*Gas surface density is assumed 100 times the dust surface density

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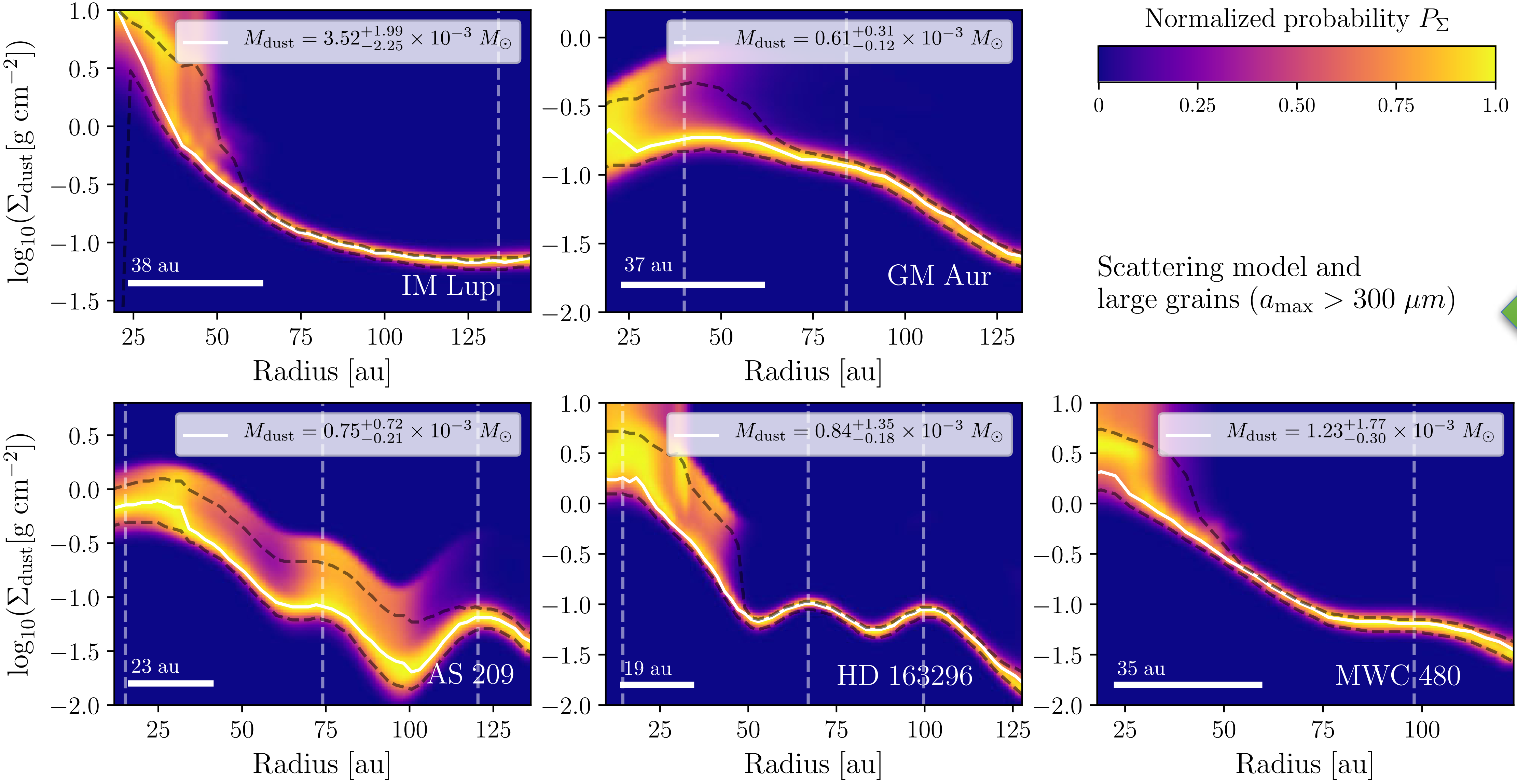


Scattering model and
large grains ($a_{\max} > 300\ \mu m$)

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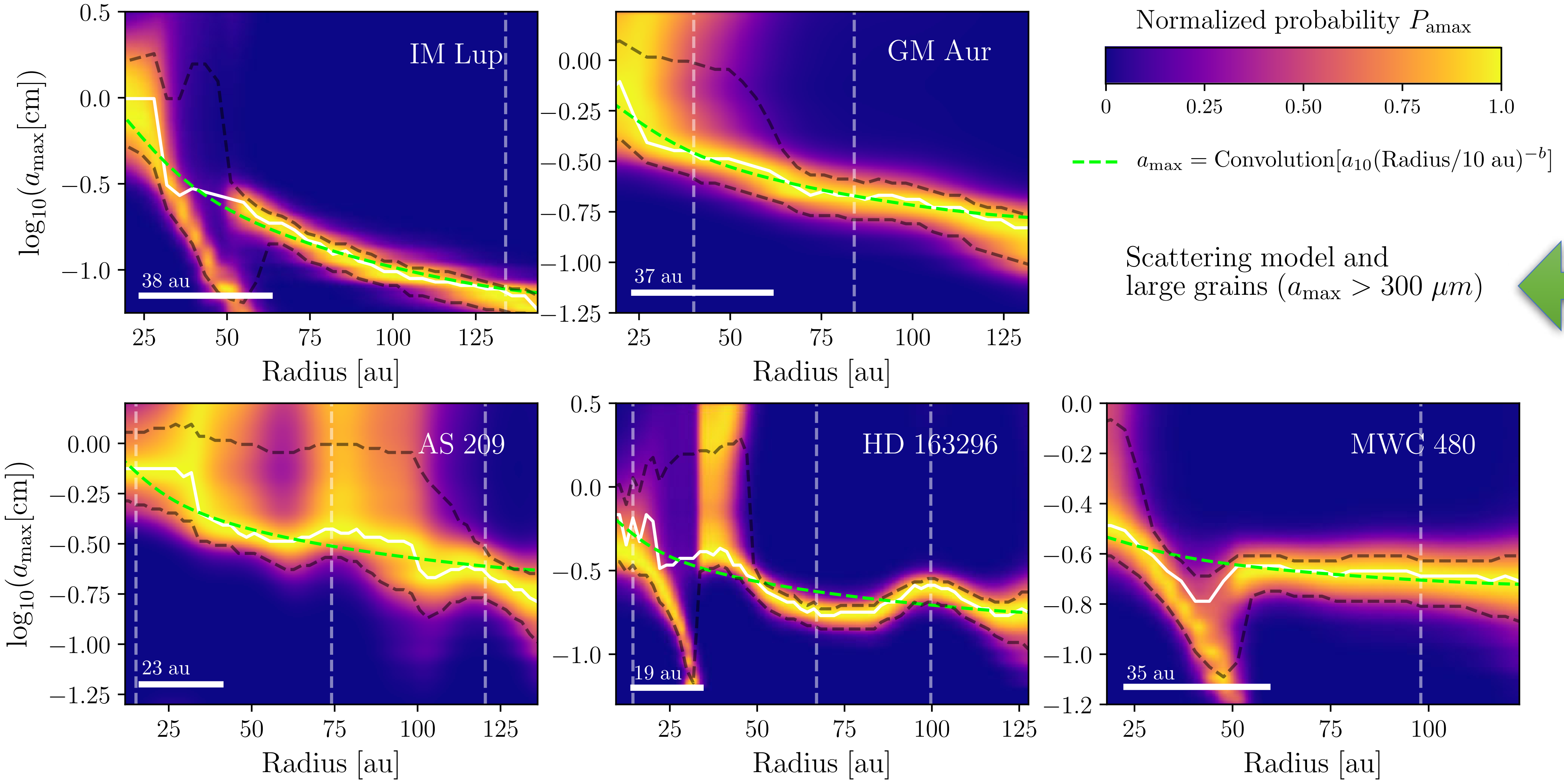


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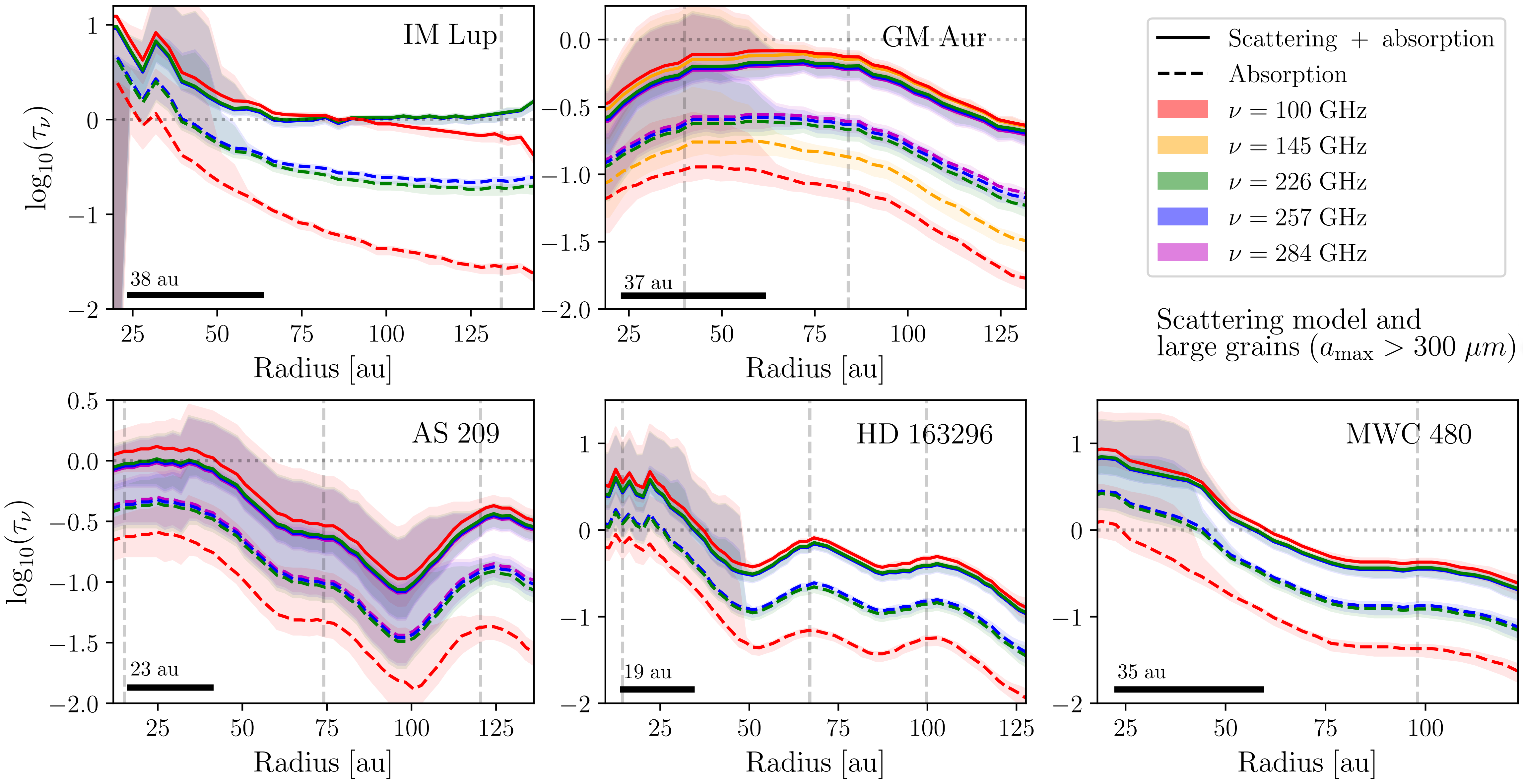
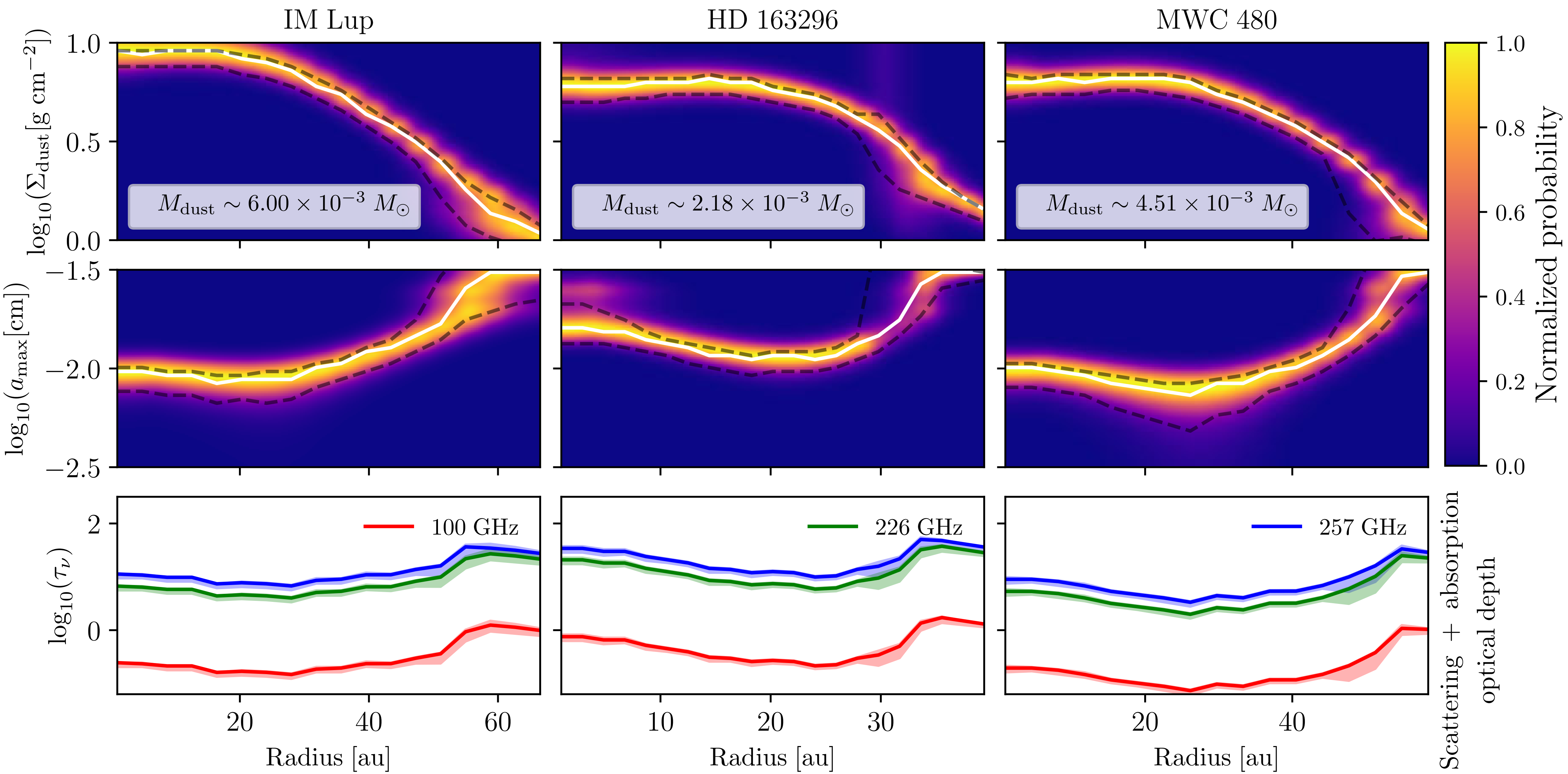



Scattering model and large grains ($a_{\max} > 300\ \mu m$)

# Results: Scattering model [small grains < 300 microns]



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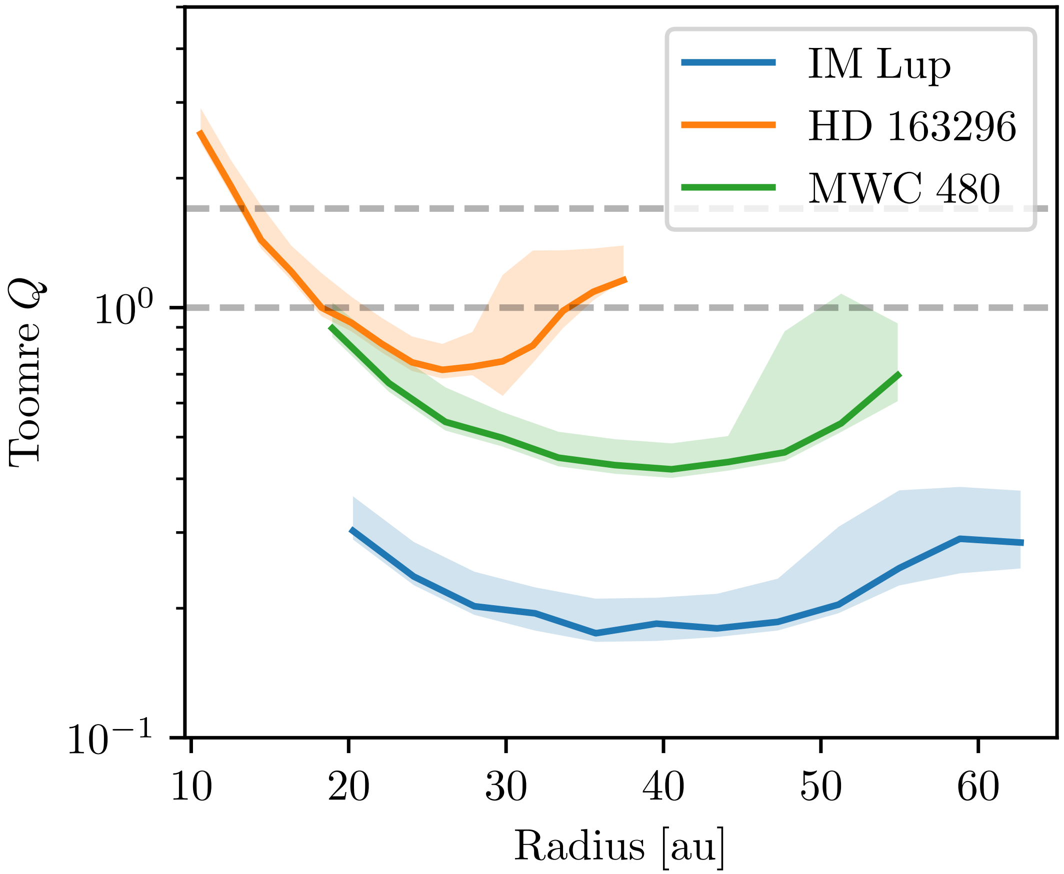


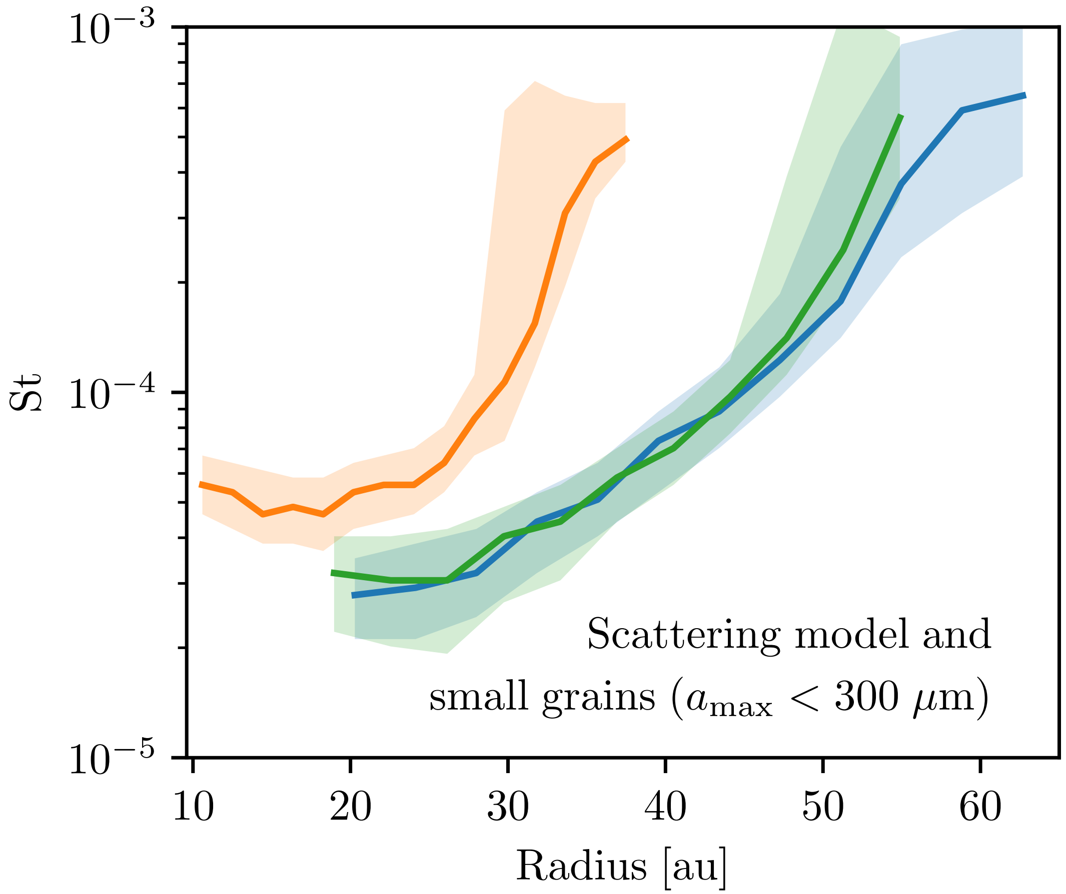


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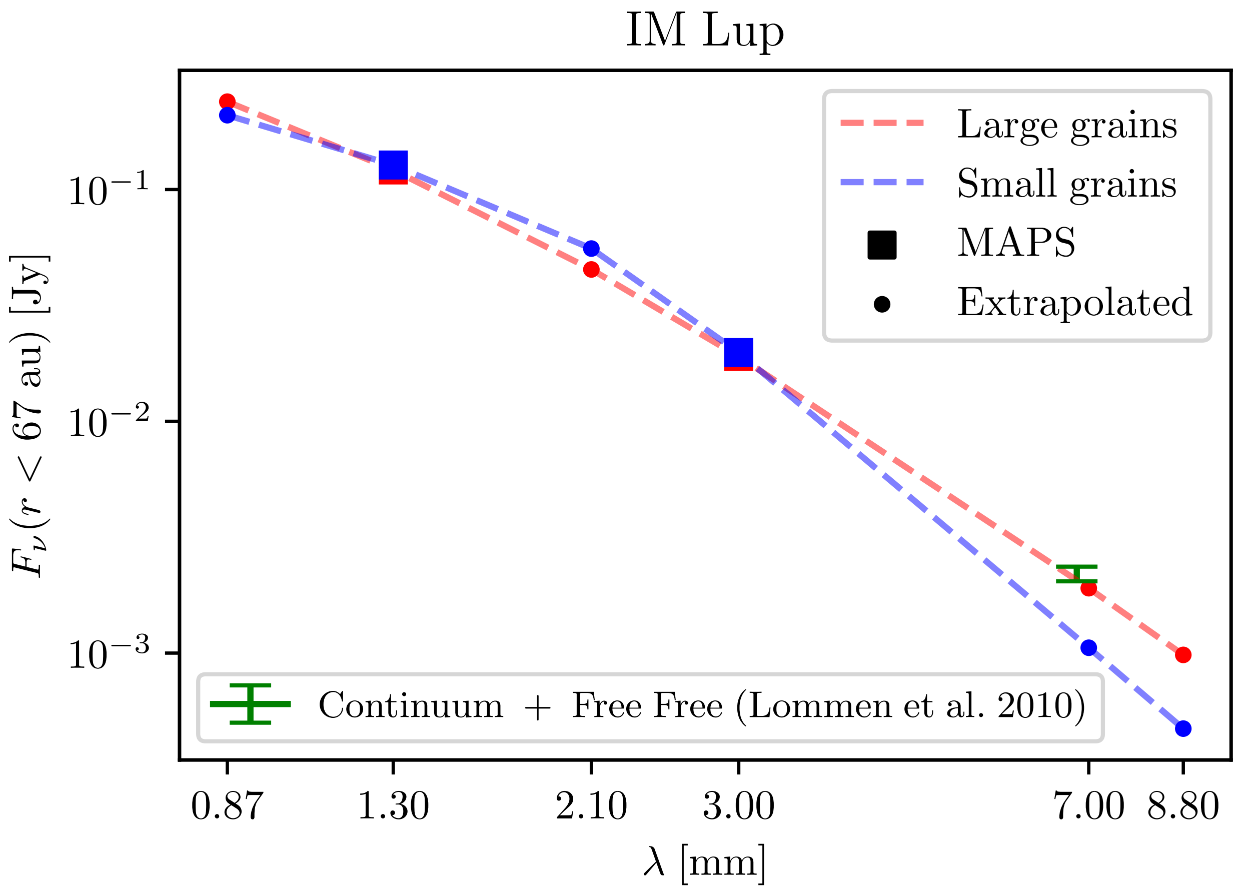
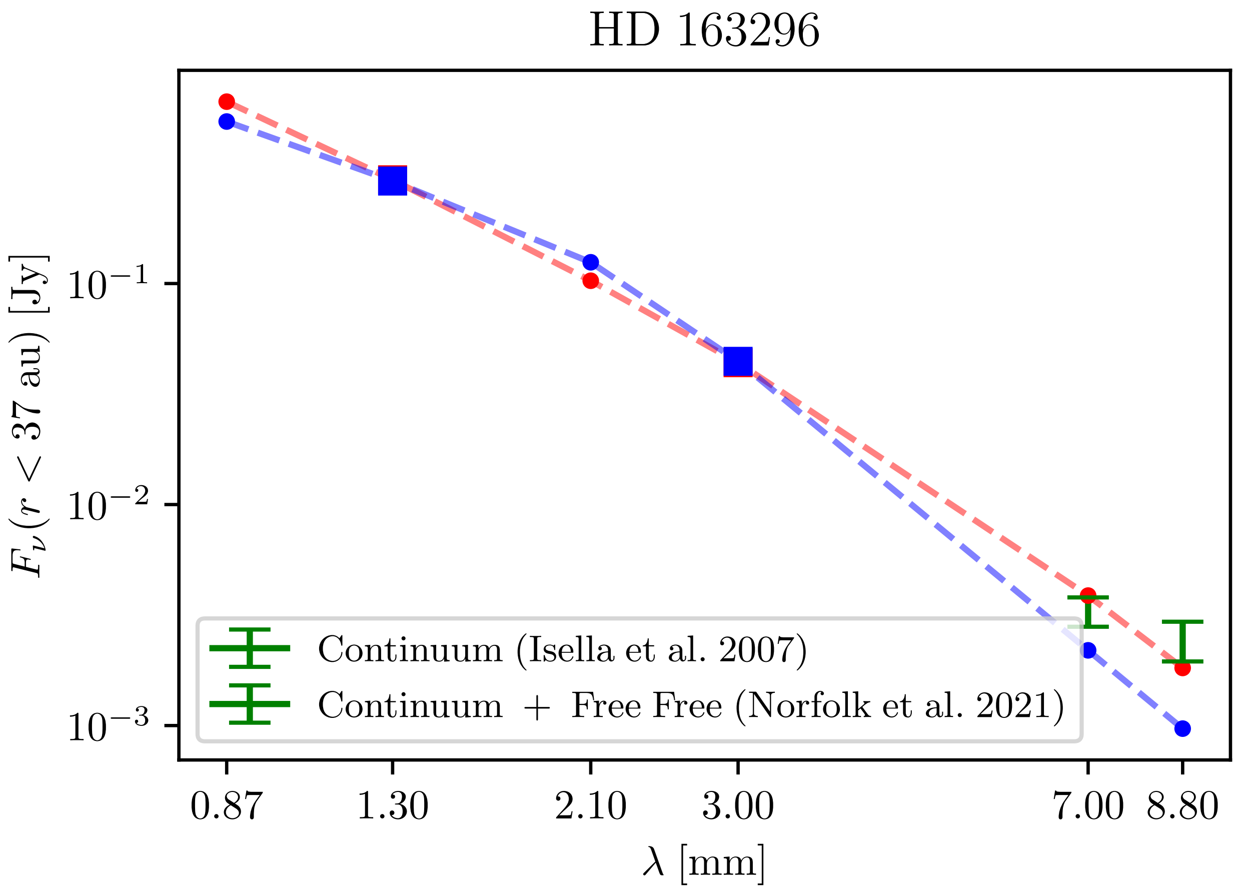
# Results: Scattering model [small grains < 300 microns]

What can we expect from the small and large solutions at 7 mm?



# Main Conclusions

We constrained the dust properties (dust surface density, maximum grain size and dust temperature) for the MAPS disks: IM Lup, GM Aur, AS 209, HD 163296, MWC 480

Non-Scattering Model: → Some mm grain sizes (All the disks) →

Scattering Model: → Some mm grain sizes (All the disks) →

Scattering Model: → ~ hundred micrometer grains in the inner disks (IM Lup, HD 163296, MWC 480)

Dust surface density and maximum grain size have local maxima in most of the bright rings of the disks.

# Main Conclusions

Scattering Model:

Small grain solution requires a large amount of dust (gravitationally unstable disk)

The expected 7 mm flux from the small and large grain solution suggest that the mm grains model is ~ consistent with the observed values.

# Main Conclusions

- Our results strengthen the idea that IM Lup (which presents spiral arms structures) is a gravitationally unstable disk, as our estimated Toomre Q parameter is lower than 2 outside of $\sim$ 15 au.

# Thanks for your attention!