Revealing dust disk substructures from multi-wavelength continuum emission

Anibal Sierra
Posdoctoral Researcher at
Departamento de Astronomía
Universidad de Chile

October 2020

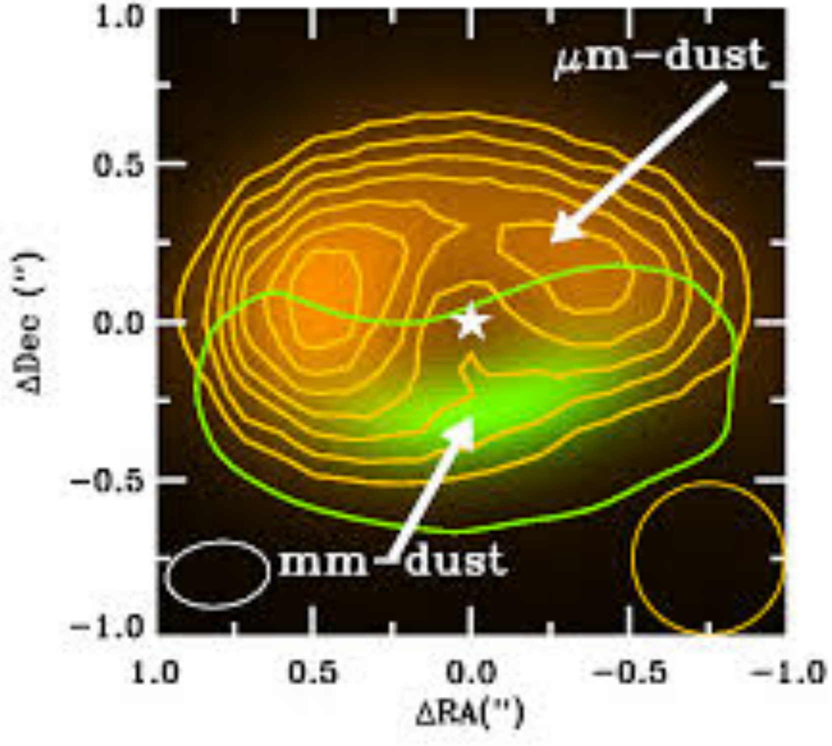
Dust continuum morphologies: rings, vortices, spiral arms

Dust properties?

DSHARP 2018

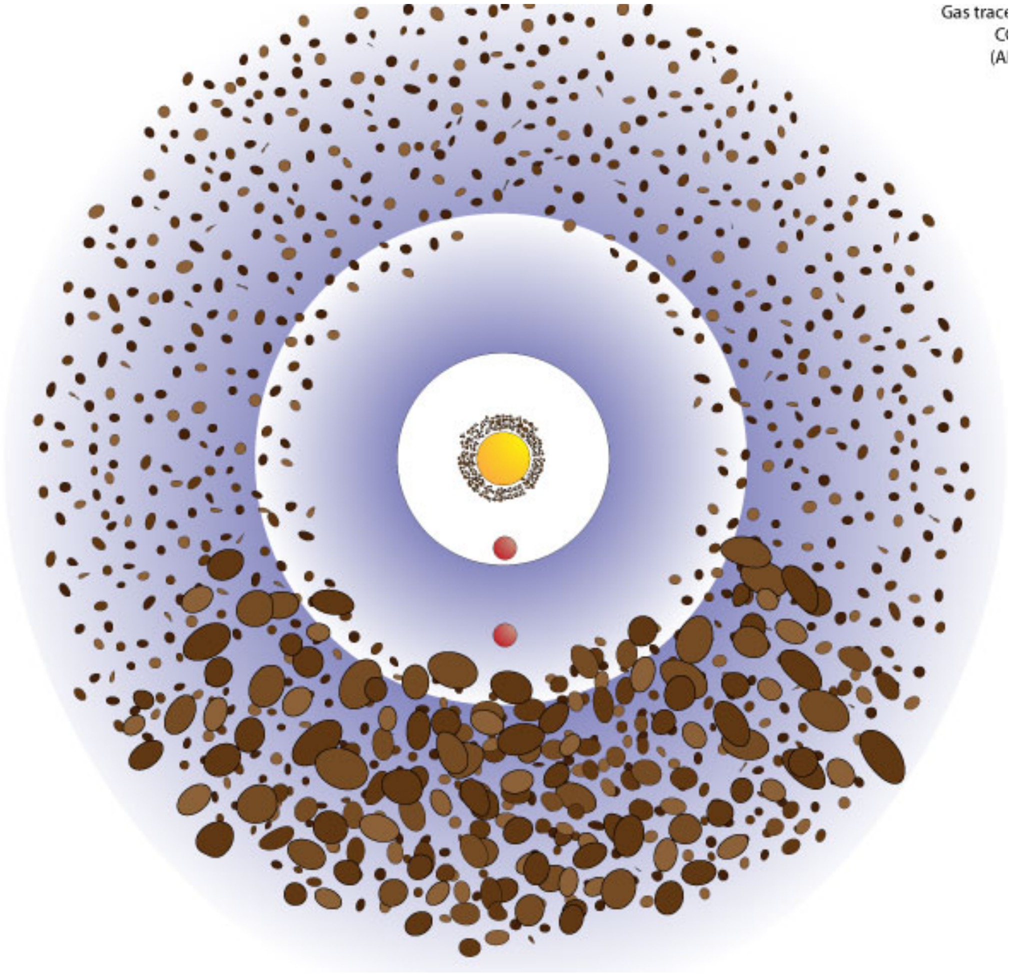
Disks structures: Physical properties

VLT Observation
(18.7 micrometers)



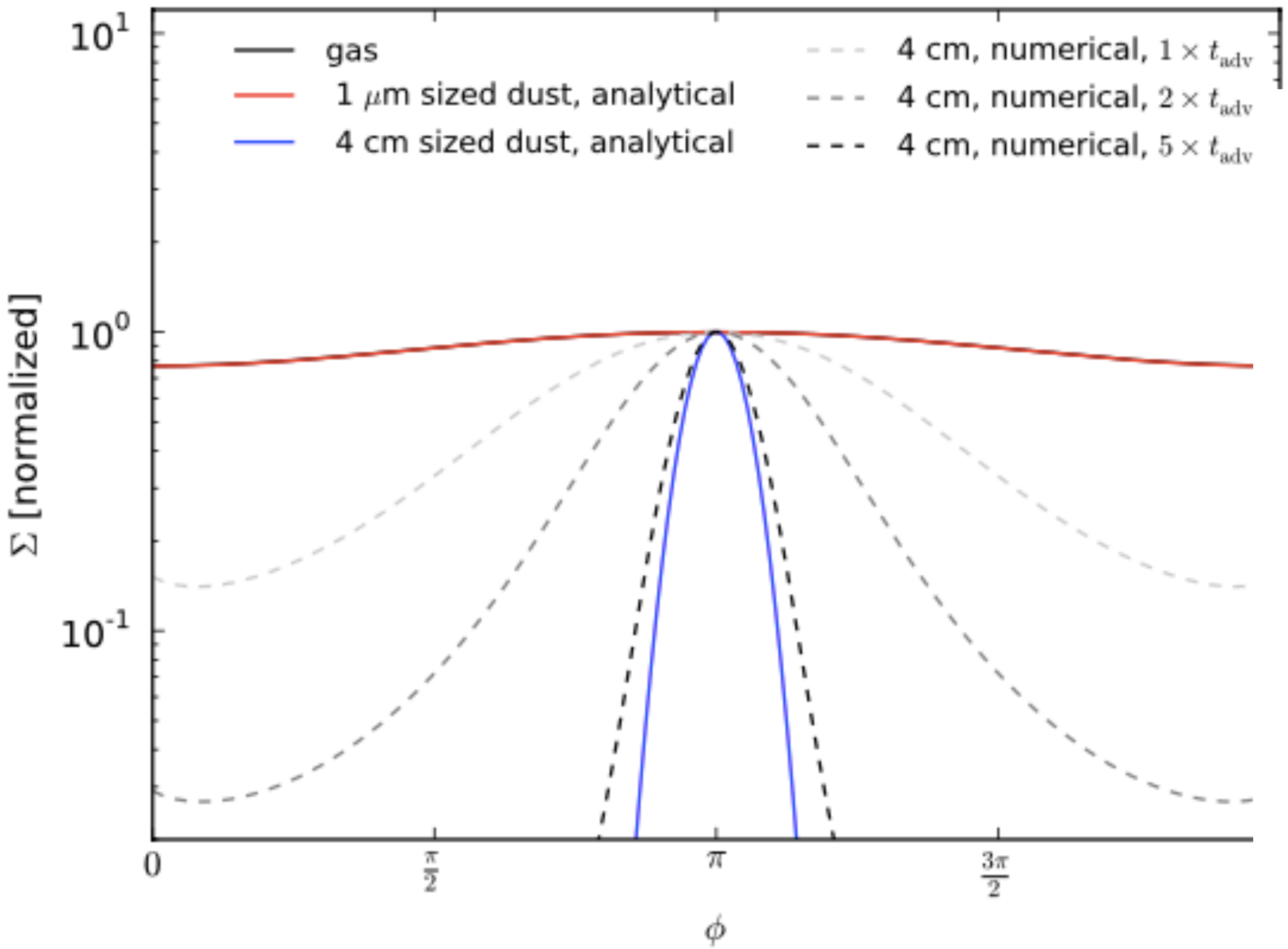
ALMA Observation
(0.44 millimeter)

Dust differential
trapping



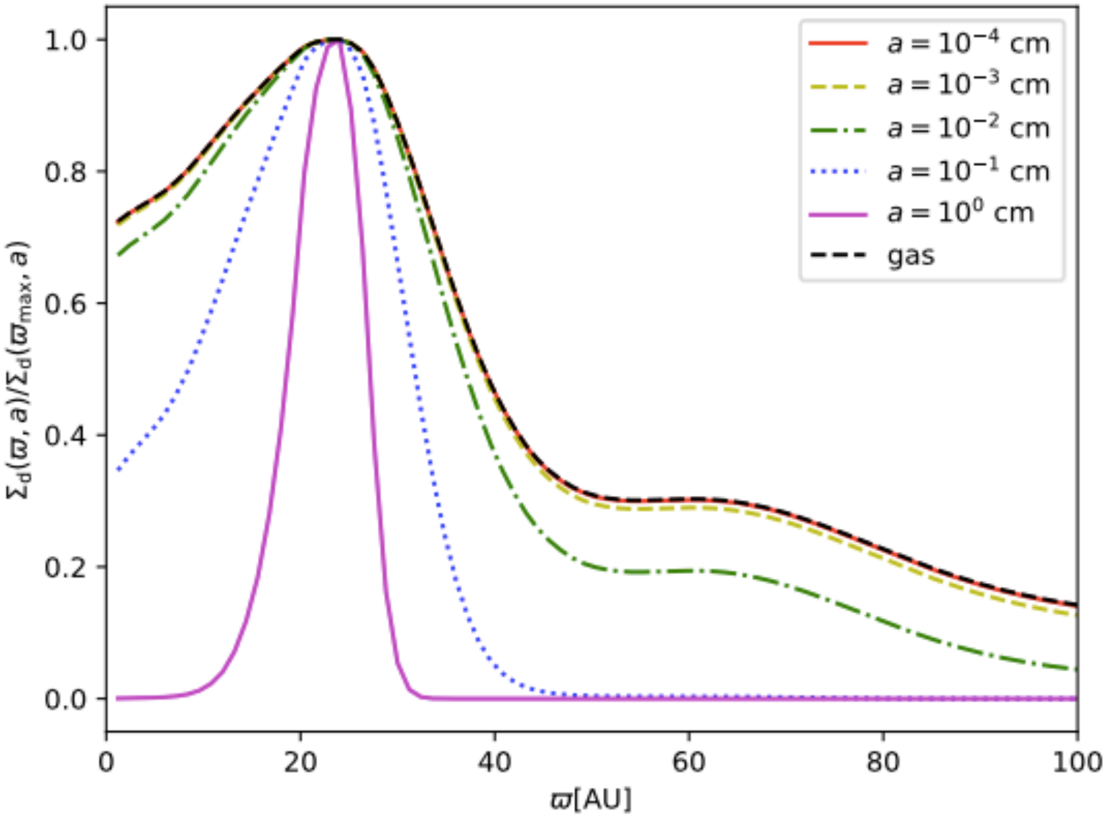
Oph IRS 48 disk: Van der Marel et al. 2013

Disks structures: Physical properties



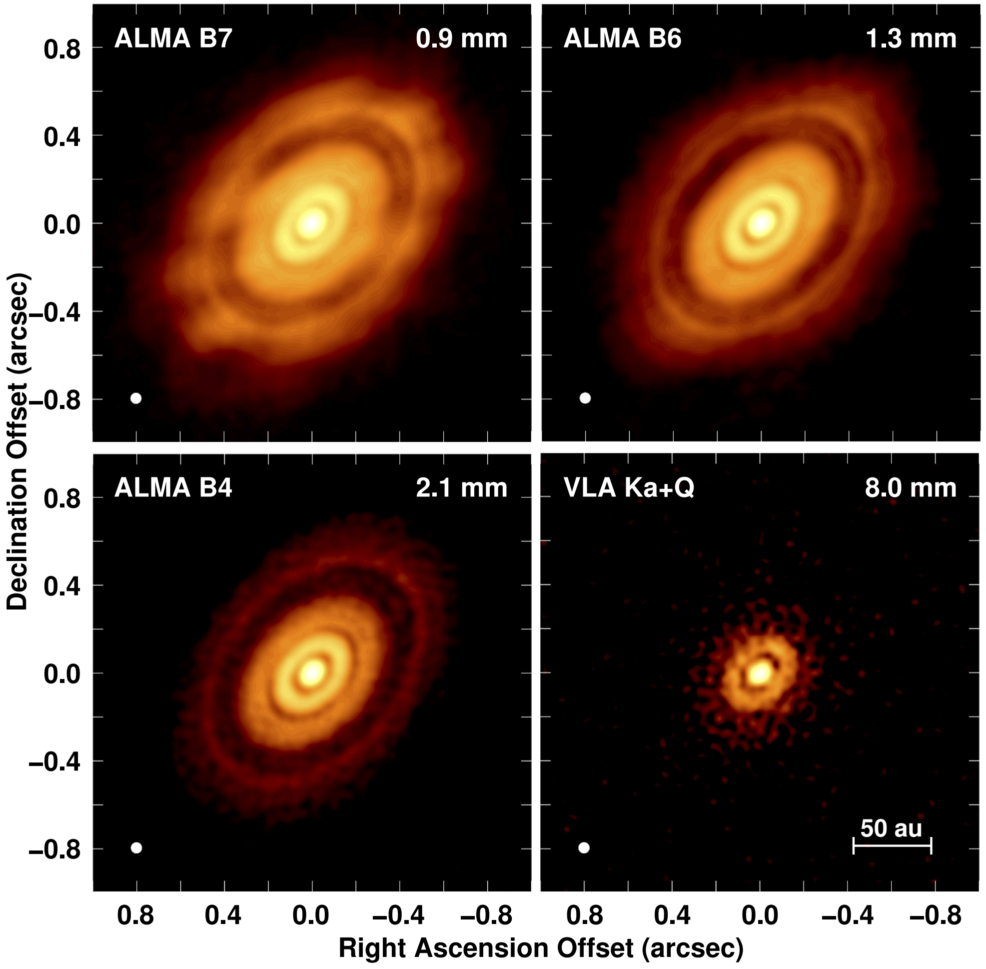
Azimutal dust differential trapping (Birnstiel et al. 2013)

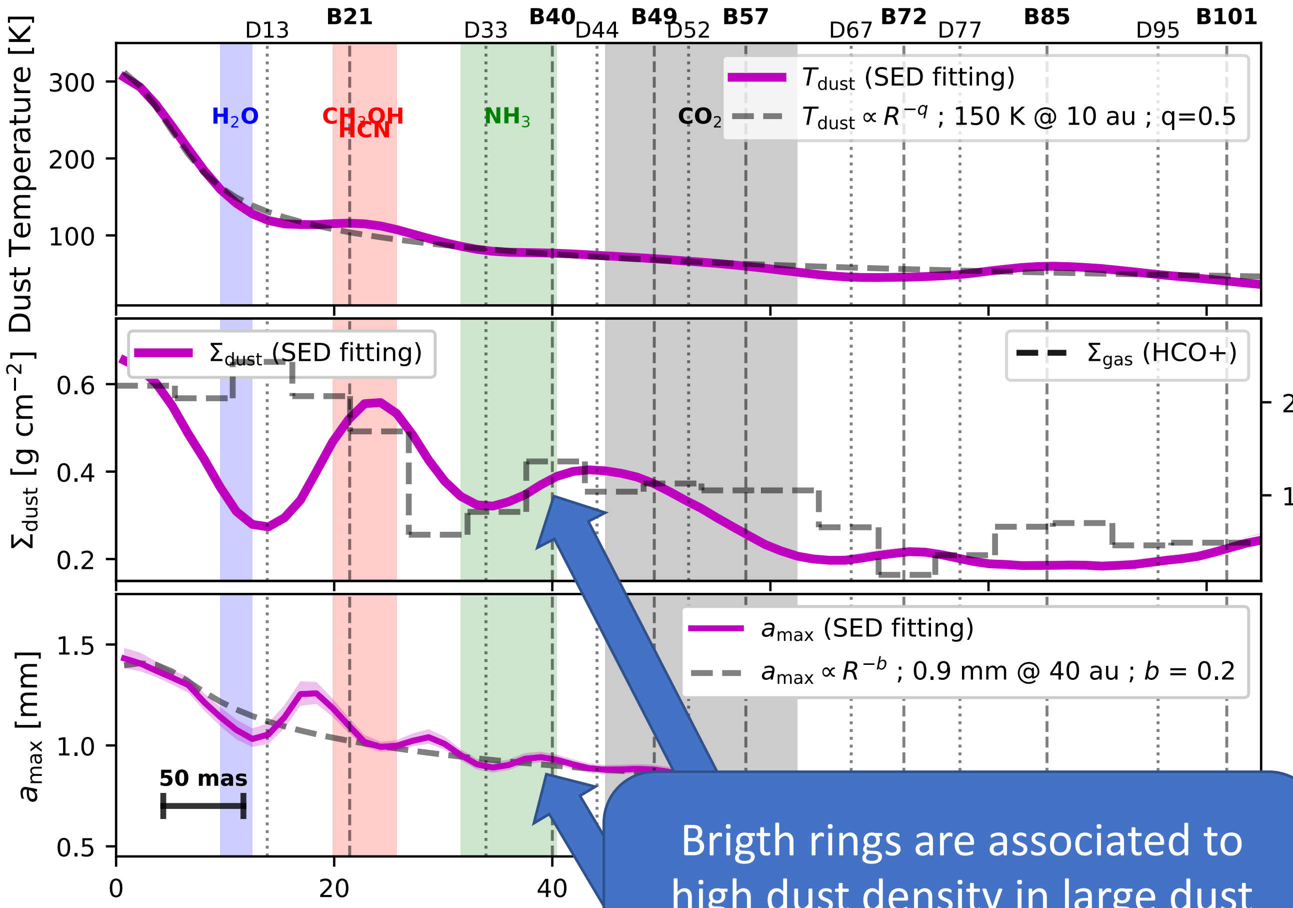
Different wavelengths trace different grain sizes $a \sim \lambda/2\pi$, one can test dust trapping models from observations.



Radial dust differential trapping (Sierra et al. 2019)

Observations --> Physical properties



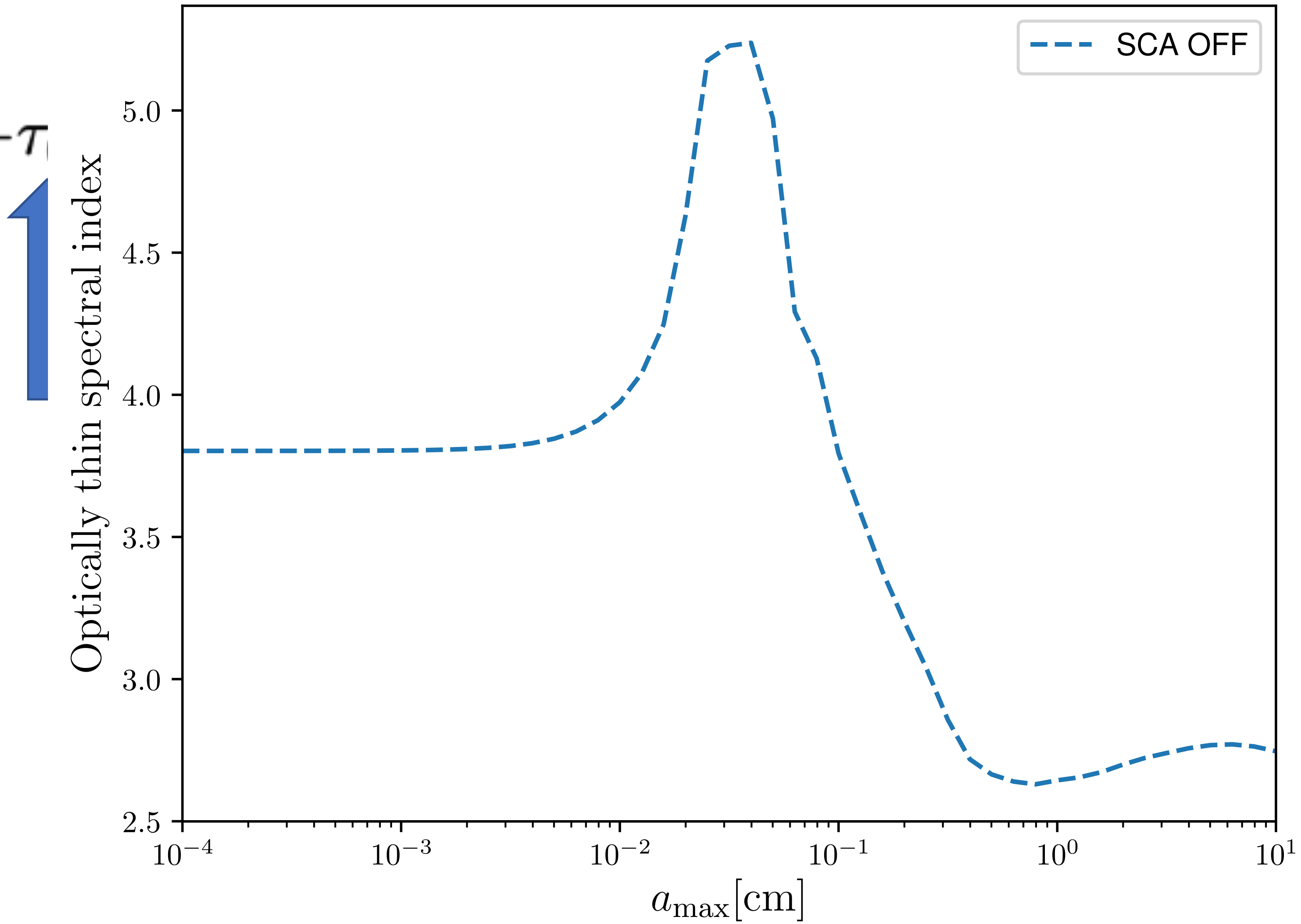


Brigth rings are associated to high dust density in large dust grains (as expected from dust trapping models).

HL Tau disk: Carrasco-Gonzalez et al. 2019

Disks structures: Radiative Transfer model

$$I_\nu = B_\nu(T_\mathrm{d})[1 - \exp(-\tau$$



In the Rayleigh-Jeans regime and optically thin disks:

$$I_\nu \propto \nu^{2+\beta}$$

Disks structures: Radiative Transfer model

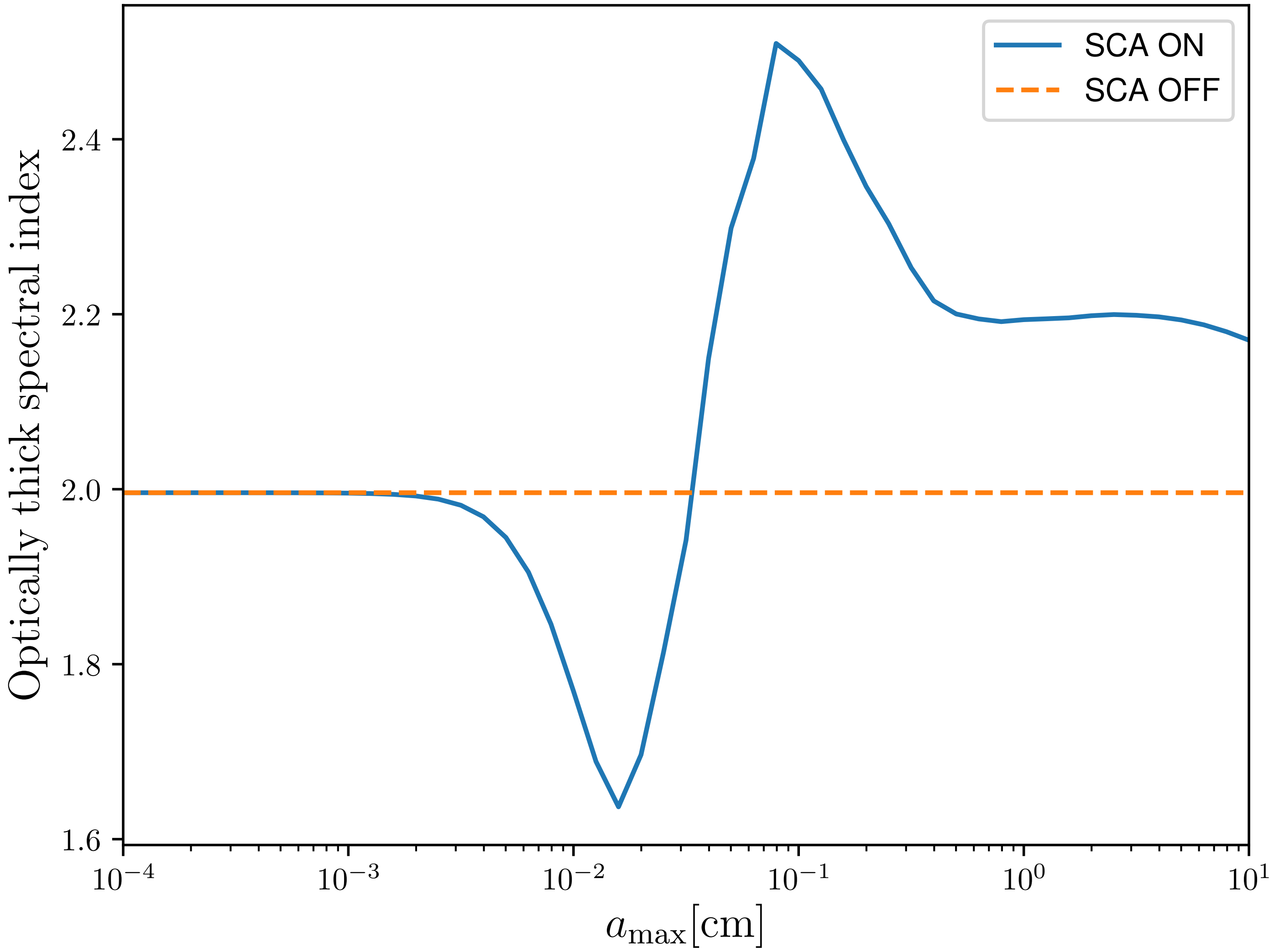
Scattering is important, and can increase the op
Lizano 2020).

$$I_\nu^{\rm sca} = B_\nu(T_{\rm d}) \left[1 - \exp\left(-\frac{\tau}{1 - \ldots}\right.\right.$$

Sierra et al. 2019

Spectral index for optically thick emission (non-scattering model)

$$I_\nu \propto \nu^2$$



Data and Goals

Disks:

AS 209
GM Aur
HD 163296
IM Lup
MWC 480

Observations:

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

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

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

Determine:

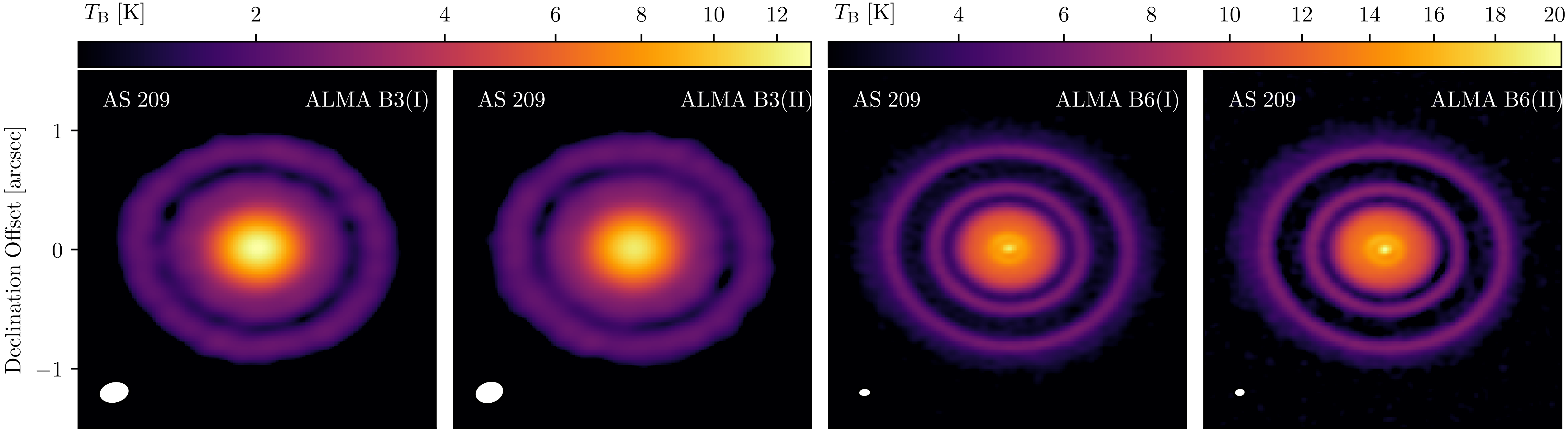
- Dust surface density profiles
- Dust maximum grain size profiles
- Optical depth profiles

Estimate:

- Toomre parameter
- Stokes number

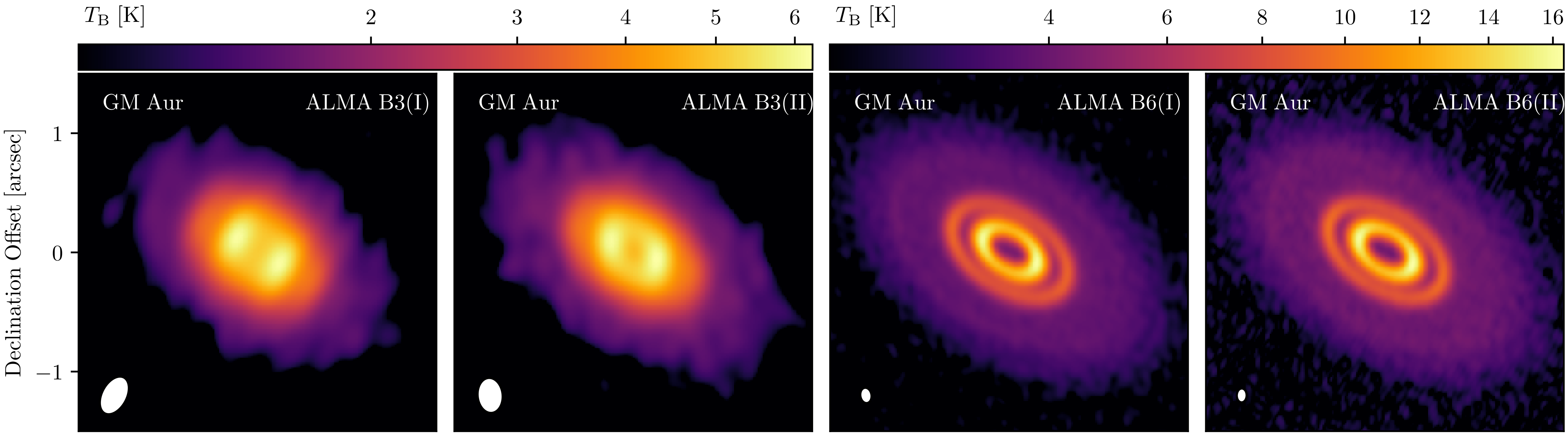
AS 209

1 Myr old T Tauri star



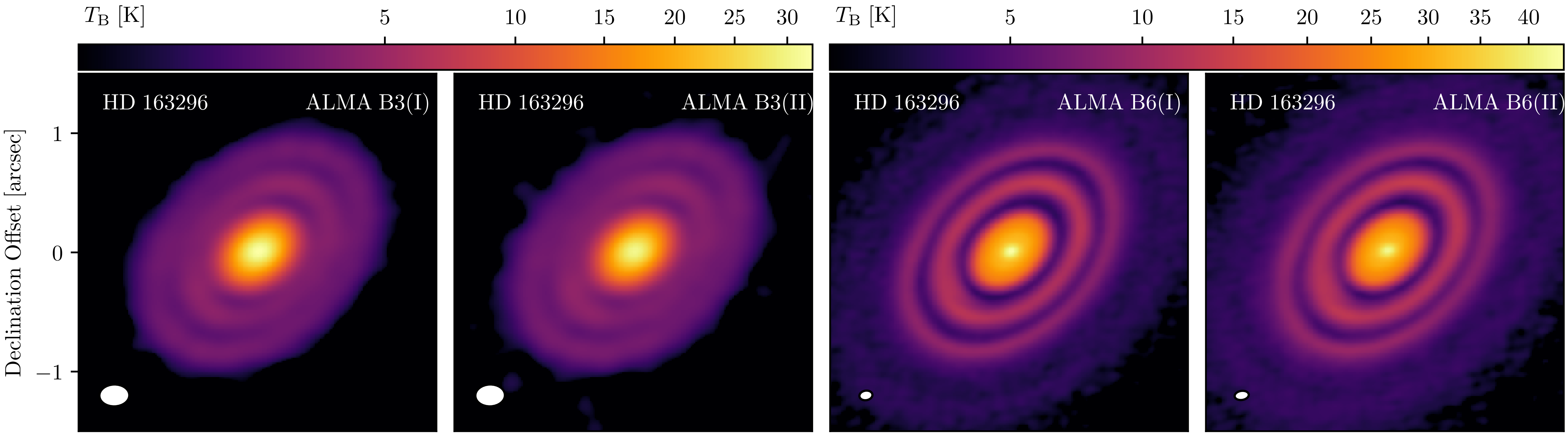
GM Aur

2.5 Myr old T Tauri star



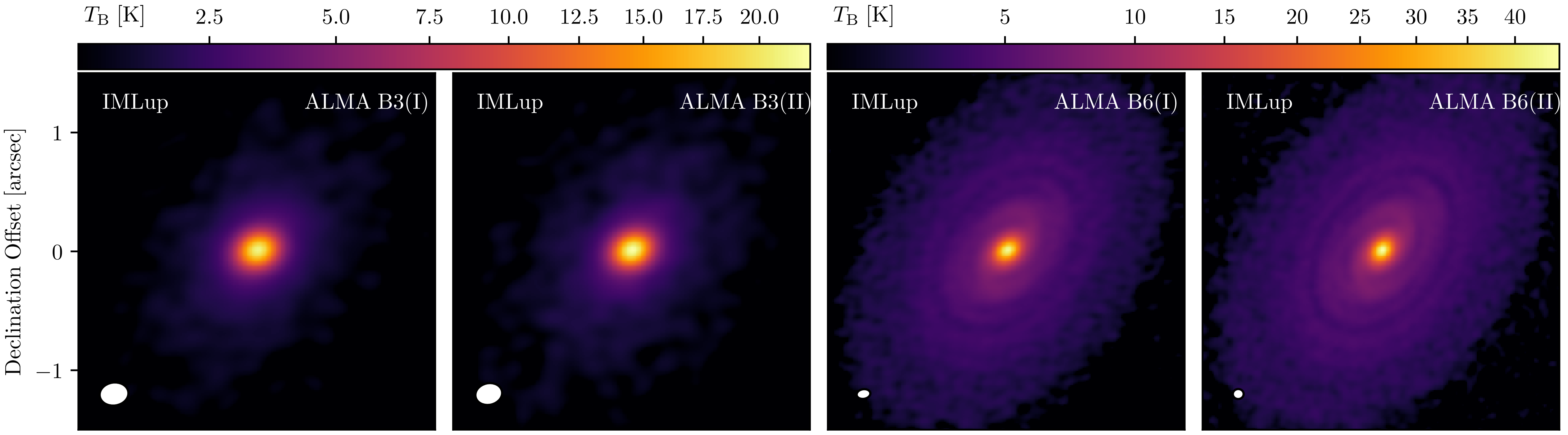
HD 163296

12.5 Myr old Herbig Ae star



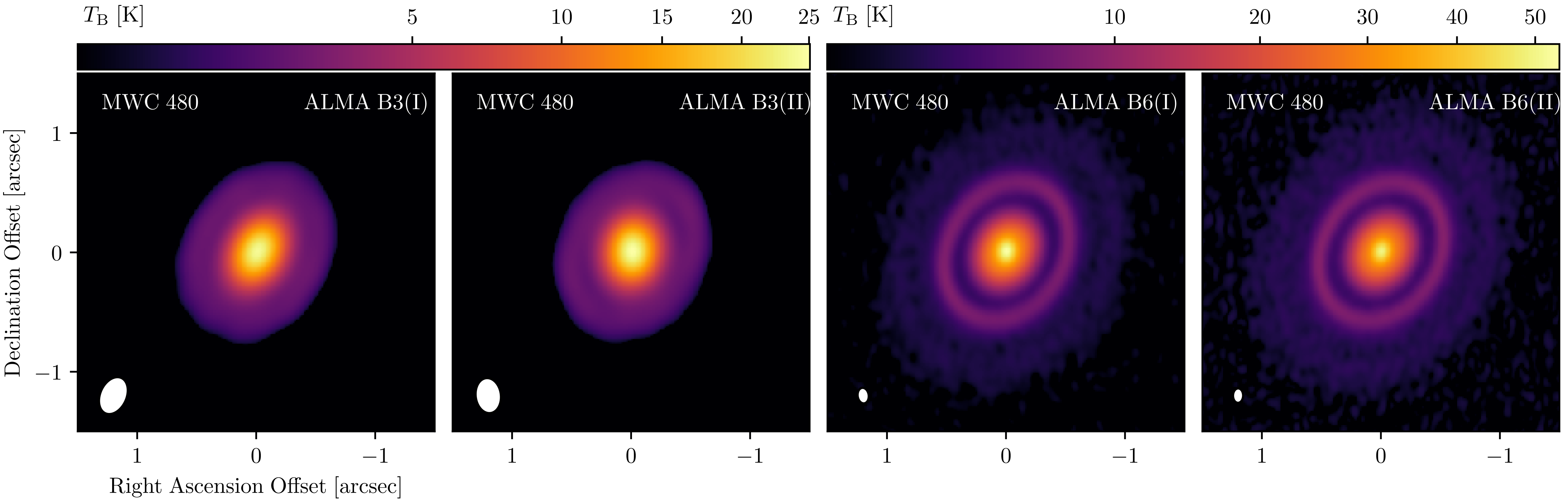
IM Lup

0.5 Myr old T Tauri star



MWC 480

7 Myr old Herbig Ae star



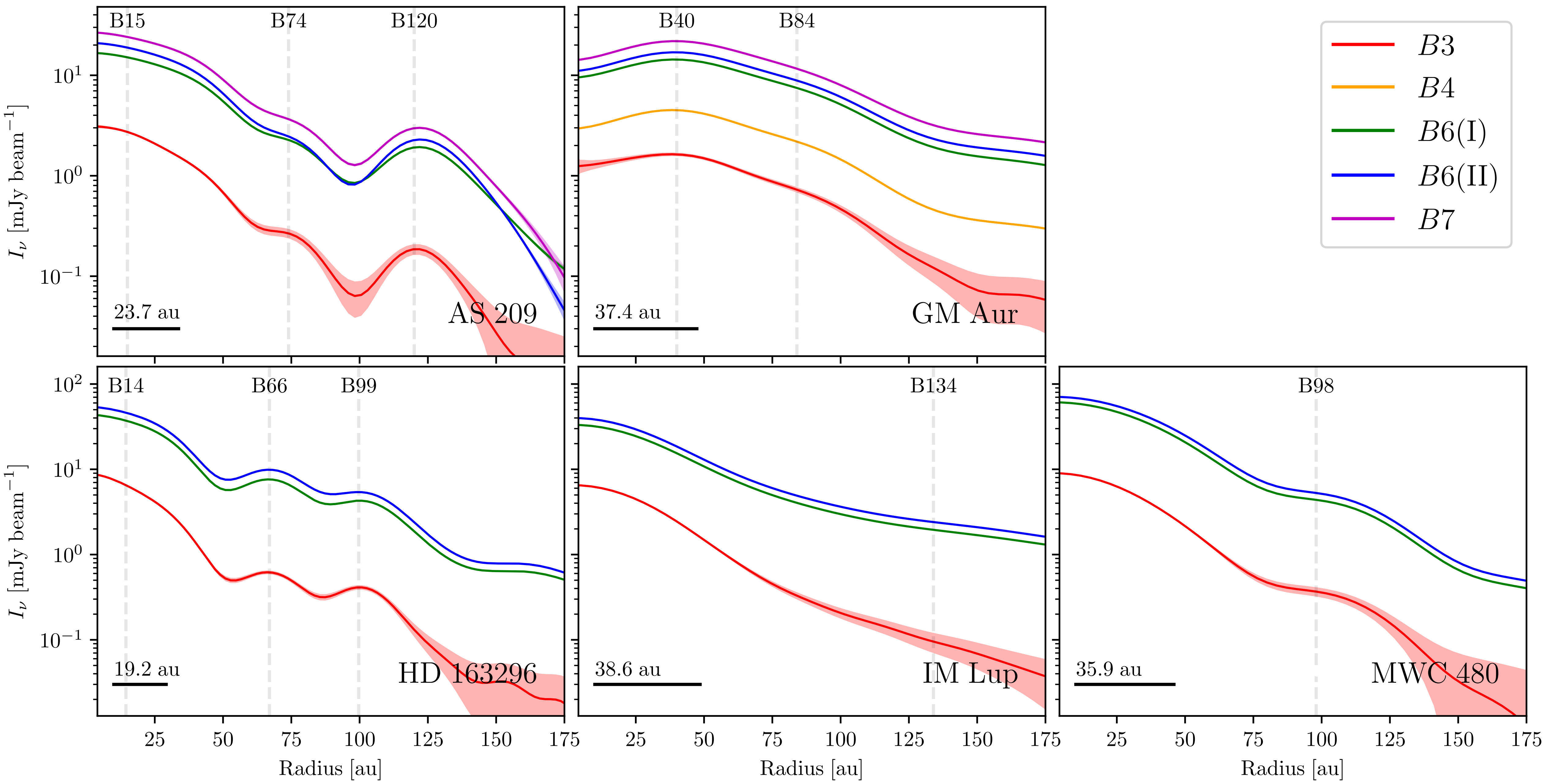
Azimutally averaged profiles

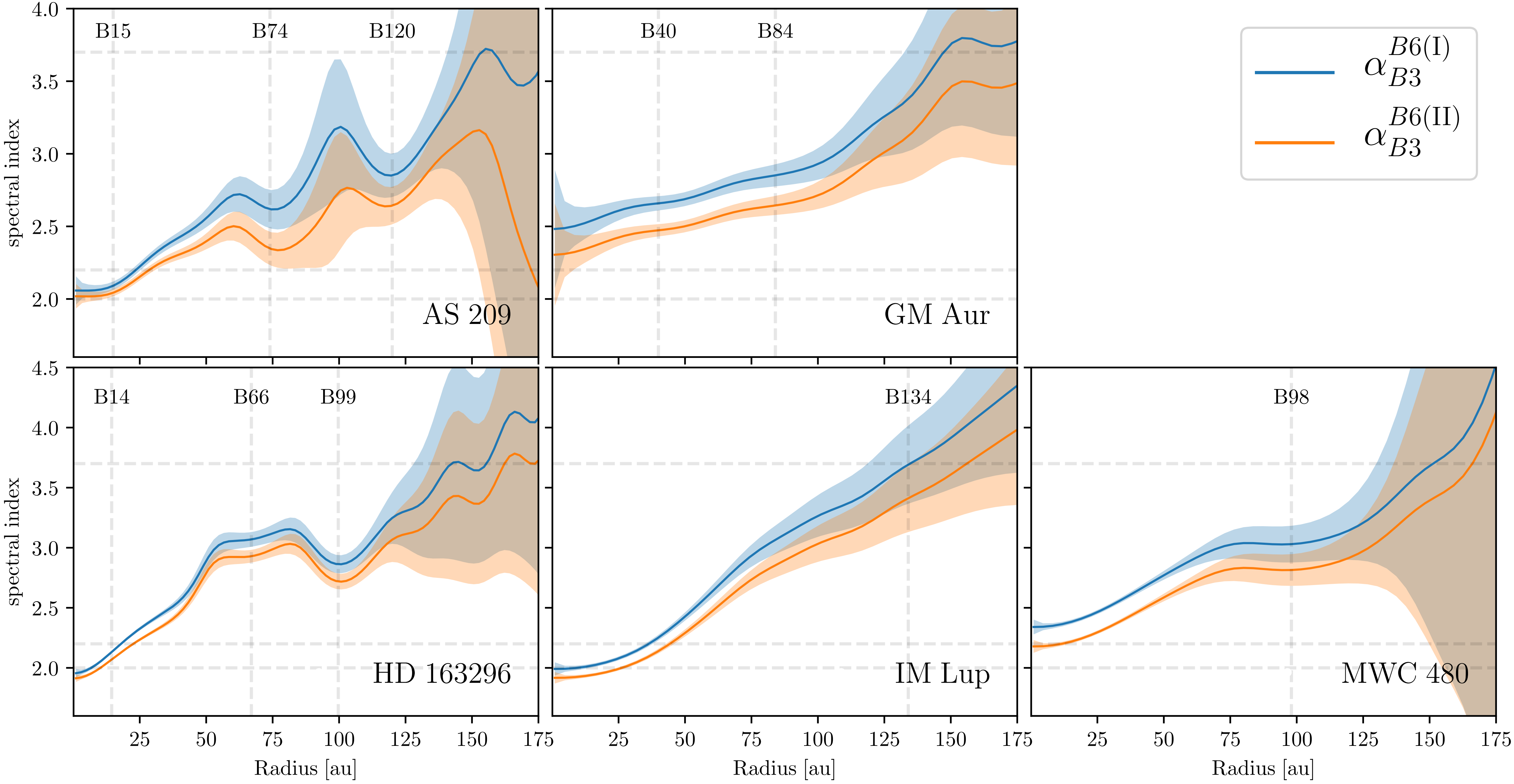
B3(I): 93 GHz
B3(II): 106 GHz
B6(I): 226 GHz
B6(II): 257 GHz

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


B15
B74
B120
AS 209
23.7 au
B40
B84
GM Aur
37.4 au
B3
B4
B6(I)
B6(II)
B7
B14
B66
B99
HD 163296
19.2 au
B134
IM Lup
38.6 au
B98
MWC 480
35.9 au
I_ν [mJy beam^{-1}]
Radius [au]



AS 209
B15
B74
B120
GM Aur
B40
B84
HD 163296
B14
B66
B99
IM Lup
B134
MWC 480
B98
spectral index
Radius [au]
$\alpha_{B3}^{B6(I)}$
$\alpha_{B3}^{B6(II)}$

Methodology

- Fit the SED at each radius using the available wavelengths.
- We use the dust opacity properties from the DSHARP project.
- The midplane dust temperature is given by the thermo-chemical models from Zhang et al. (2020) in prep.

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

Methodology

- Explore a large parameter space

  $(10\ \mu m < a_{max} < 10\ cm$ $10^{-3} < \Sigma_d [g/cm^2] < 10^1$),

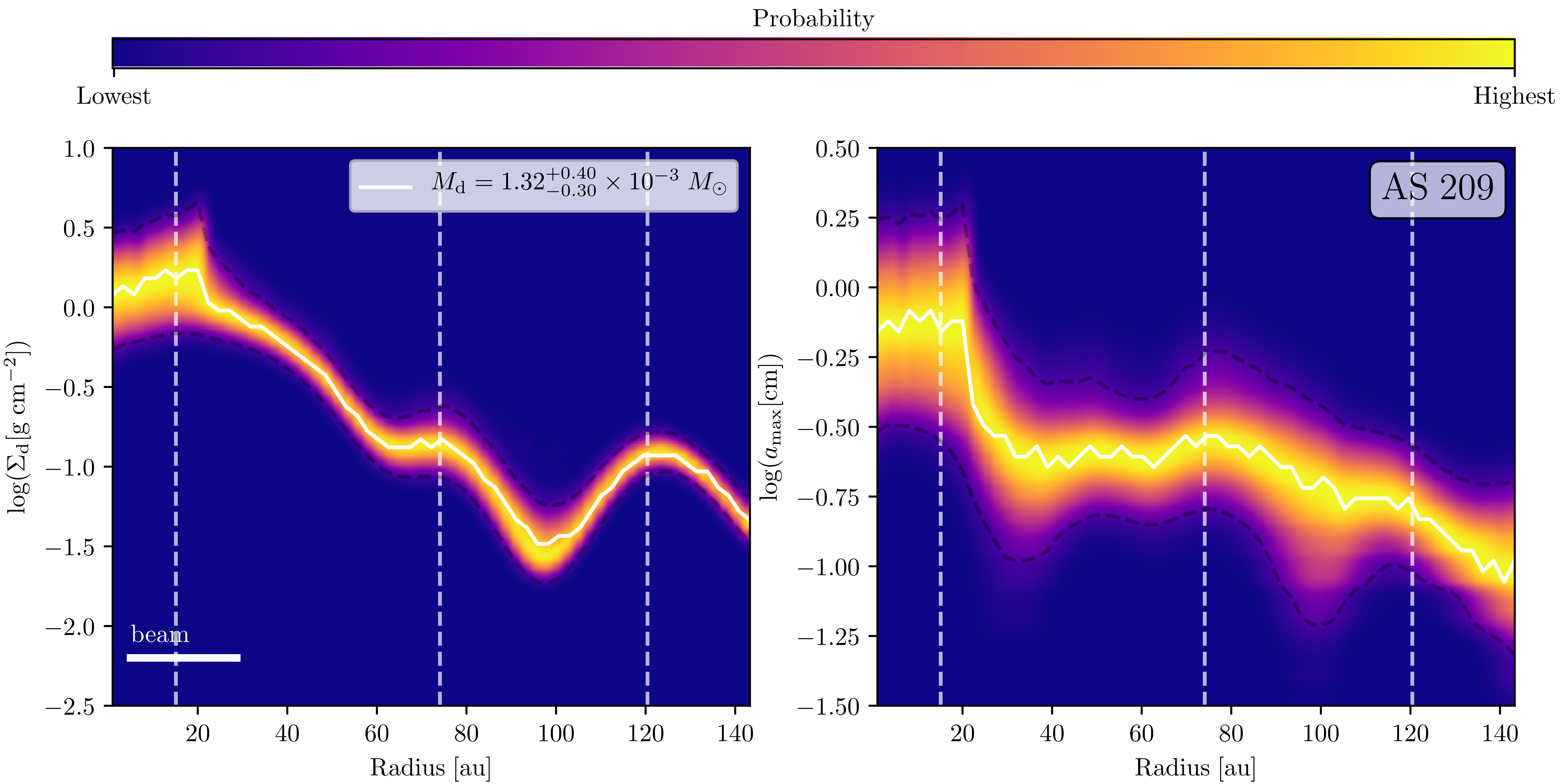
  and obtain the best set of parameters that simultaneously fit the intensity at different wavelengths.

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

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

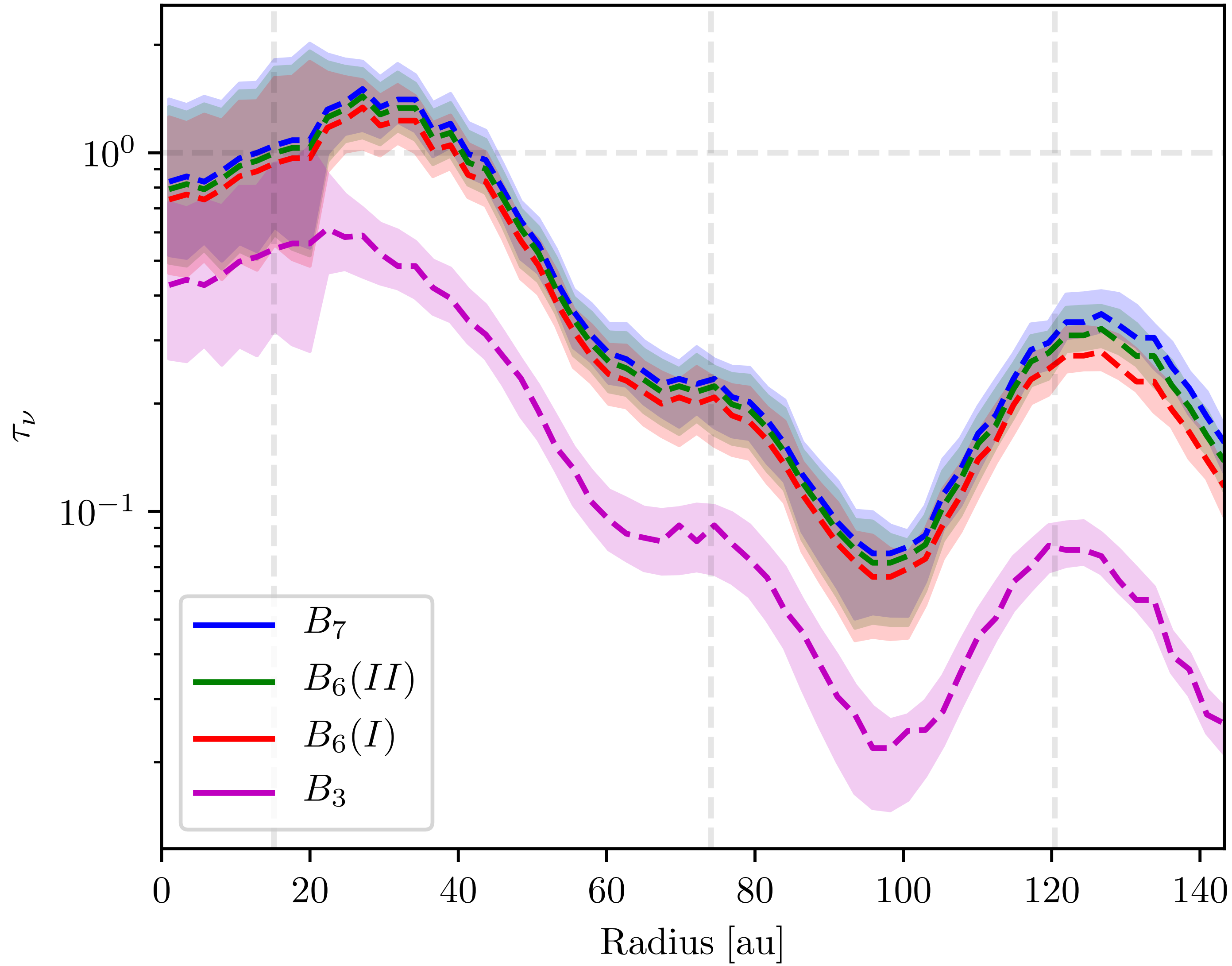
The non-scattering case

AS 209

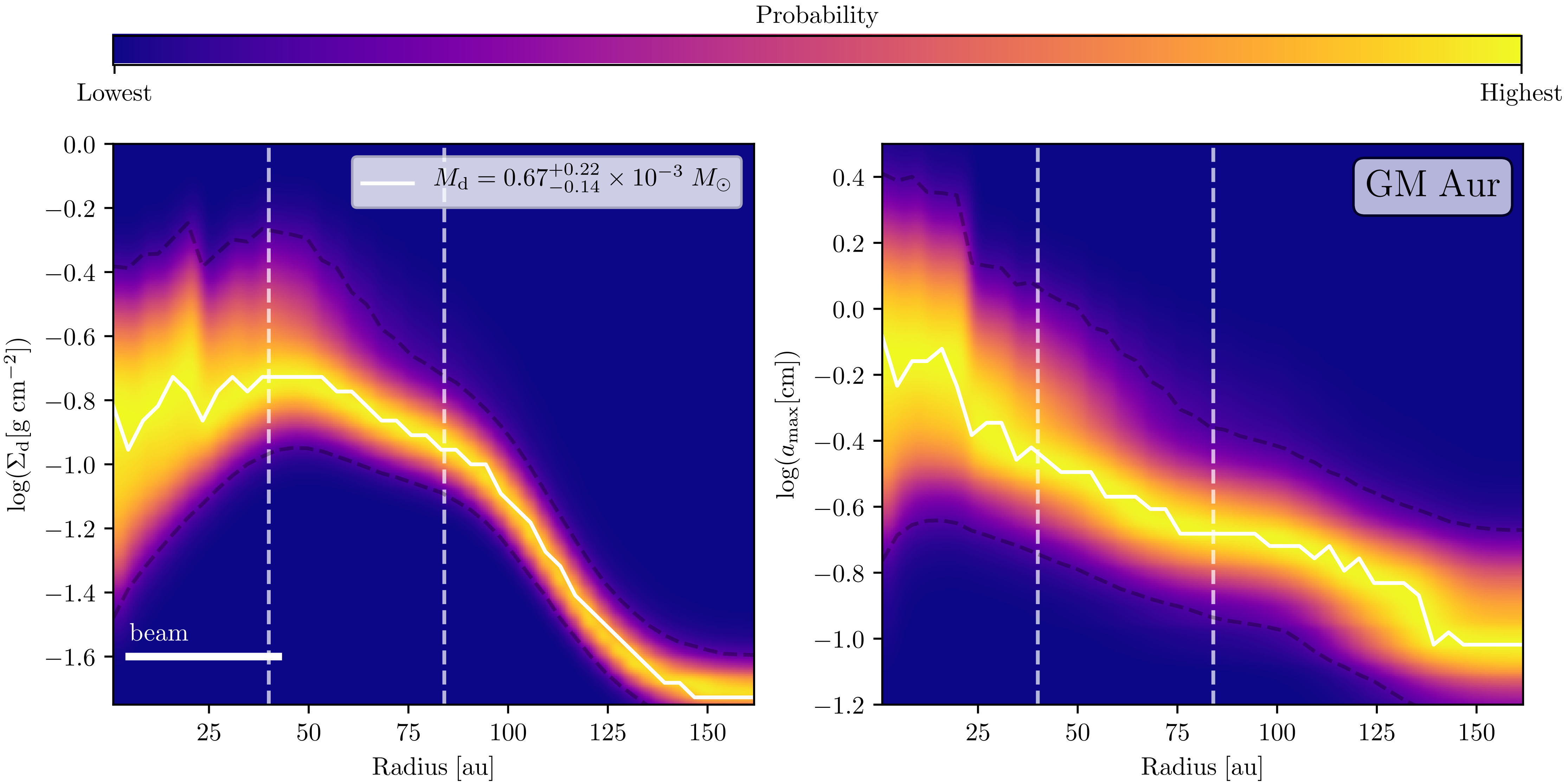


Probability
Lowest
Highest
$M_d = 1.32^{+0.40}_{-0.30} \times 10^{-3}\ M_\odot$
beam
AS 209
log(Σ_d[g cm^{-2}])
log(a_{max}[cm])
Radius [au]
Radius [au]

AS 209

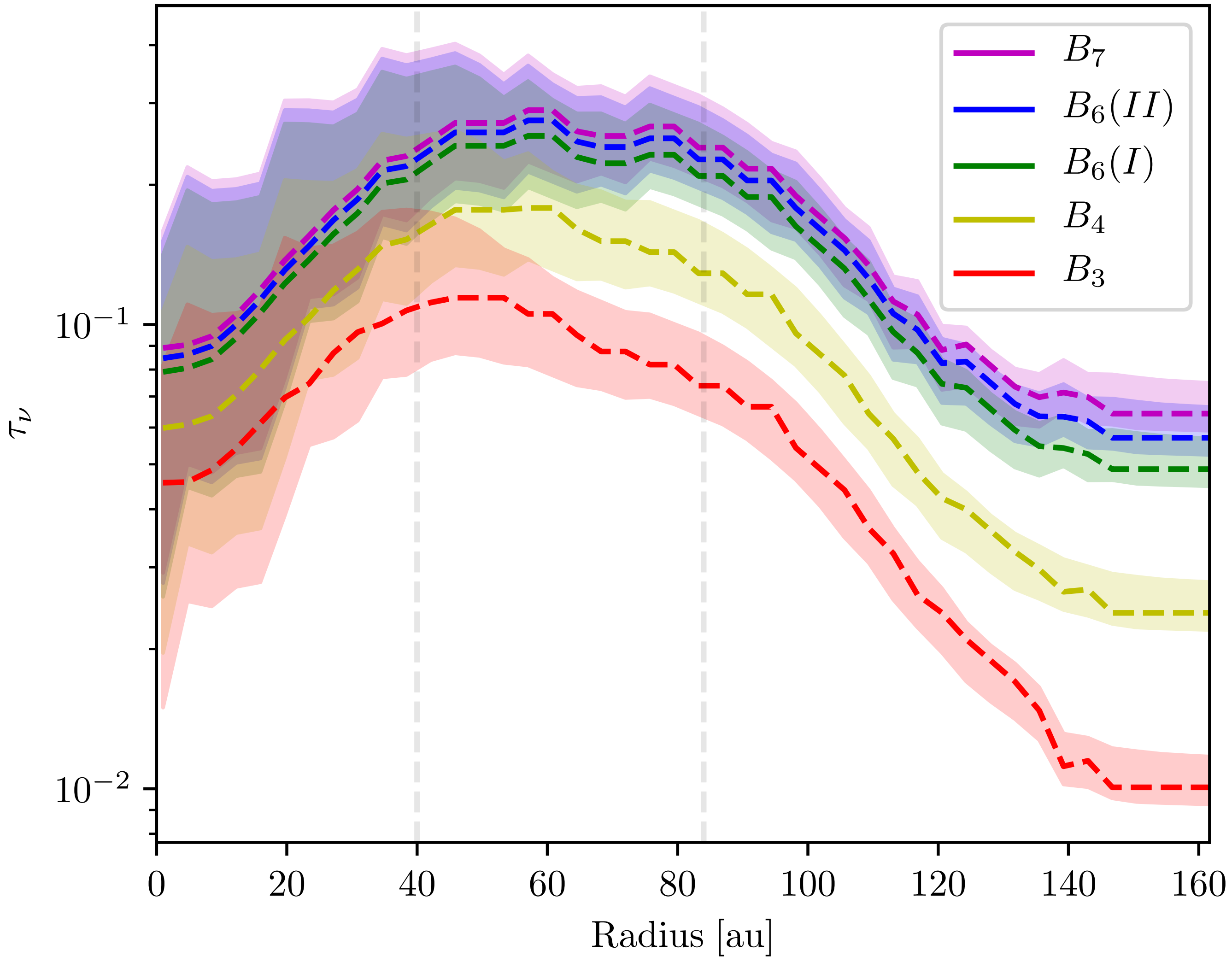


GM Aur



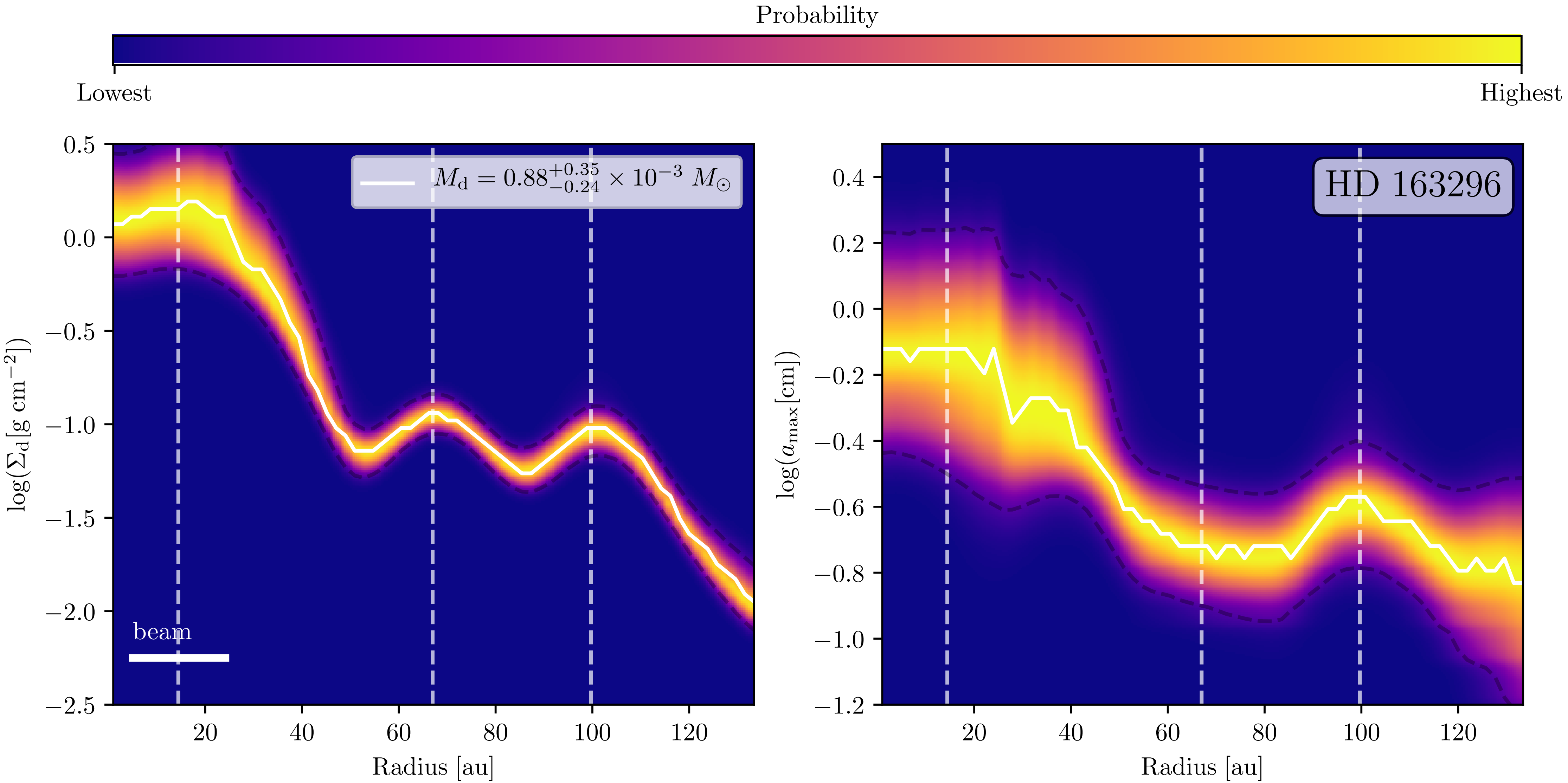
Probability
Lowest
Highest
$M_d = 0.67^{+0.22}_{-0.14} \times 10^{-3}\ M_\odot$
beam
$\log(\Sigma_d[\mathrm{g\ cm^{-2}}])$
Radius [au]
GM Aur
$\log(a_{max}[\mathrm{cm}])$
Radius [au]

GM Aur



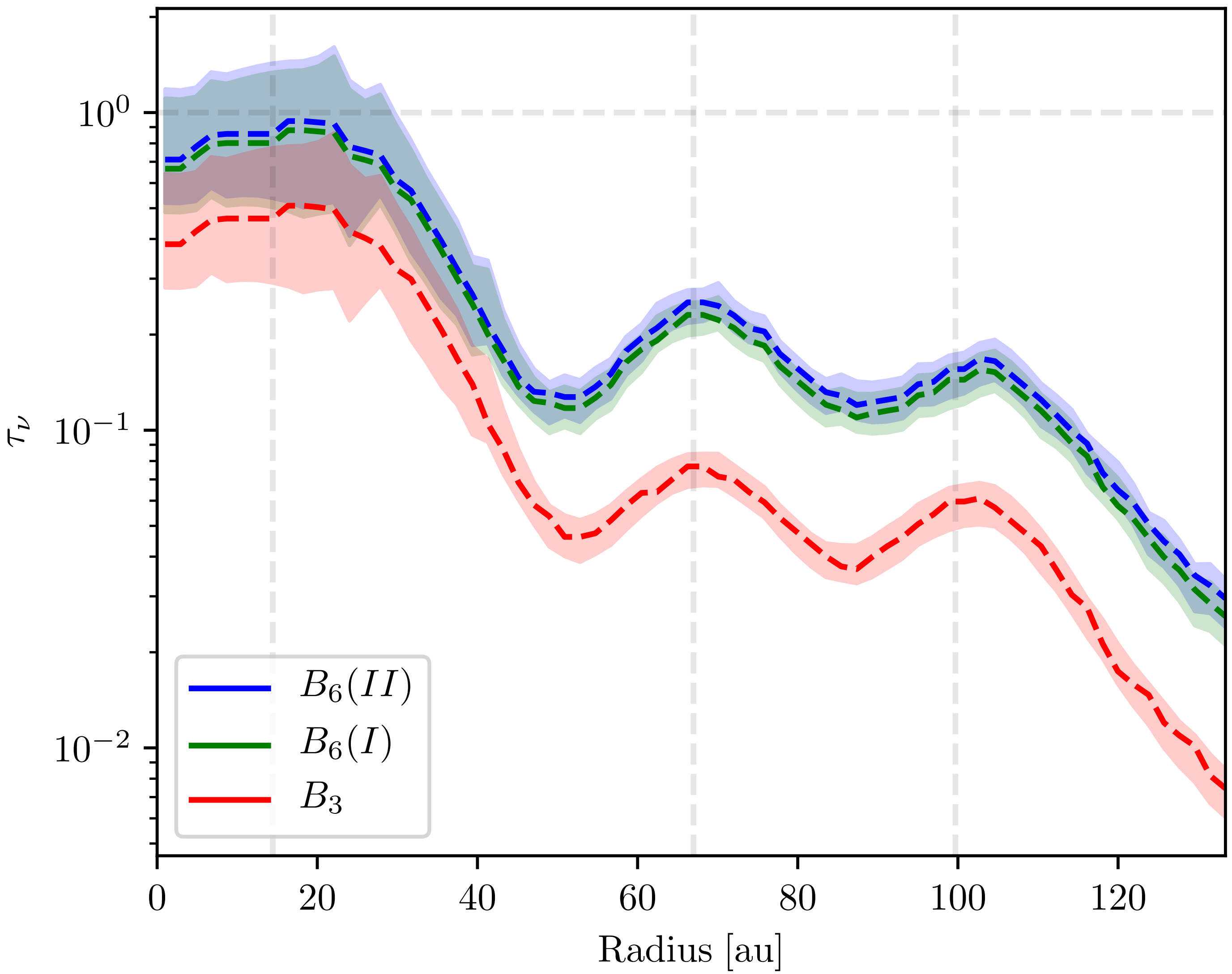
B_7
$B_6(II)$
$B_6(I)$
B_4
B_3
τ_ν
10^{-1}
10^{-2}
0
20
40
60
80
100
120
140
160
Radius [au]

HD 163296

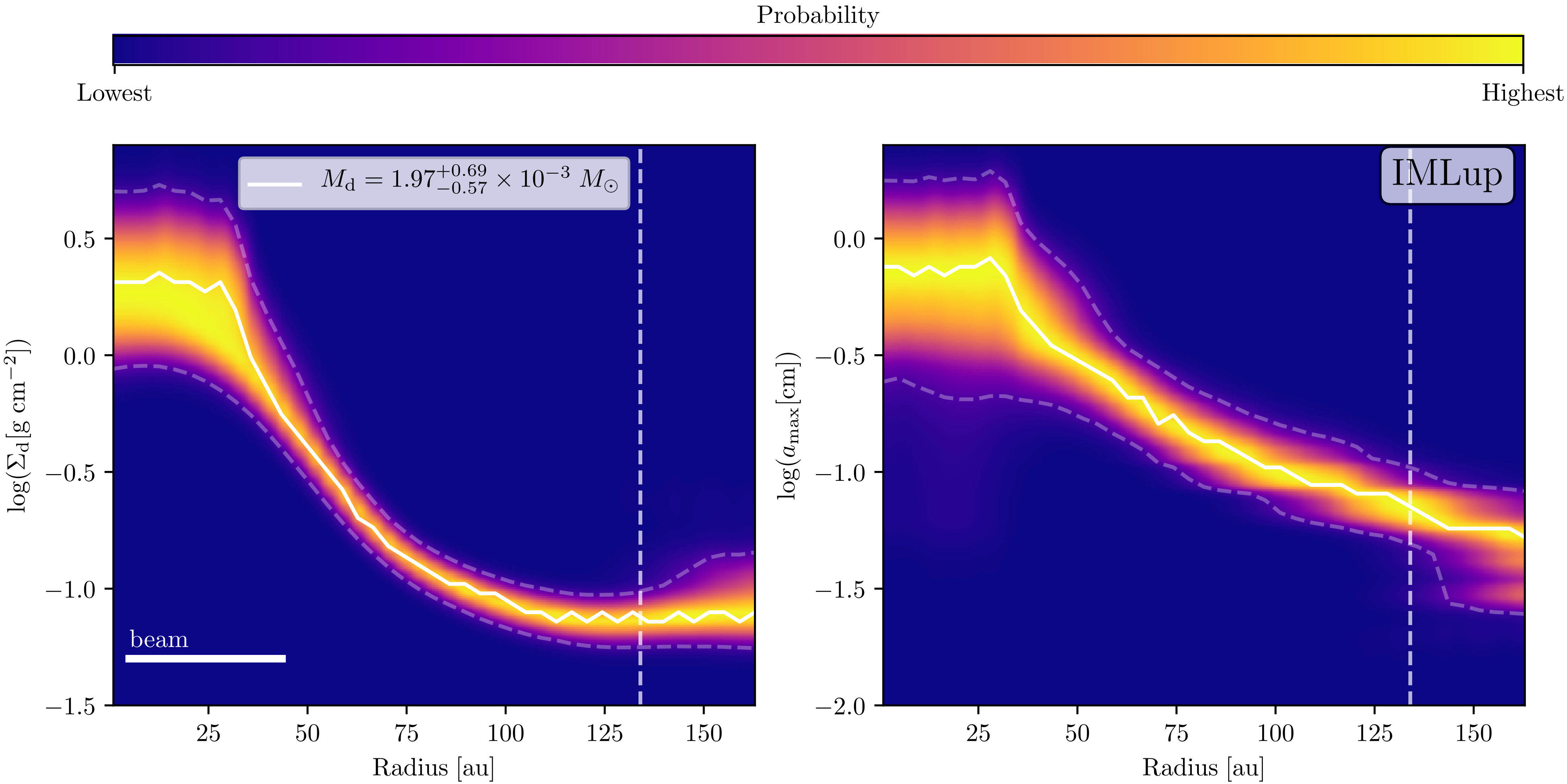


Probability
Lowest
Highest
$M_d = 0.88^{+0.35}_{-0.24} \times 10^{-3}\ M_\odot$
beam
$\log(\Sigma_d[\mathrm{g\ cm^{-2}}])$
Radius [au]
HD 163296
$\log(a_{max}[\mathrm{cm}])$
Radius [au]

HD 163296

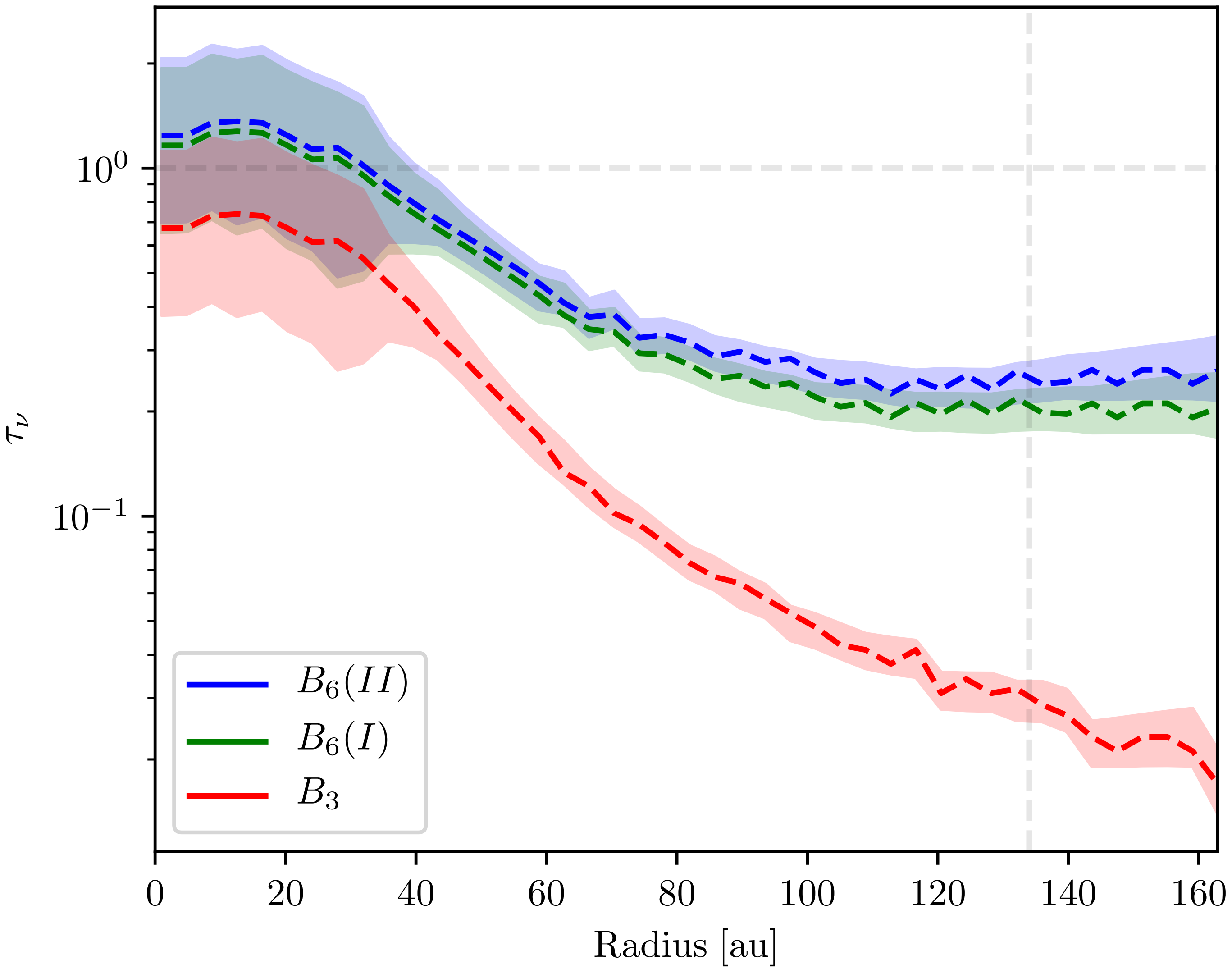


IM Lup

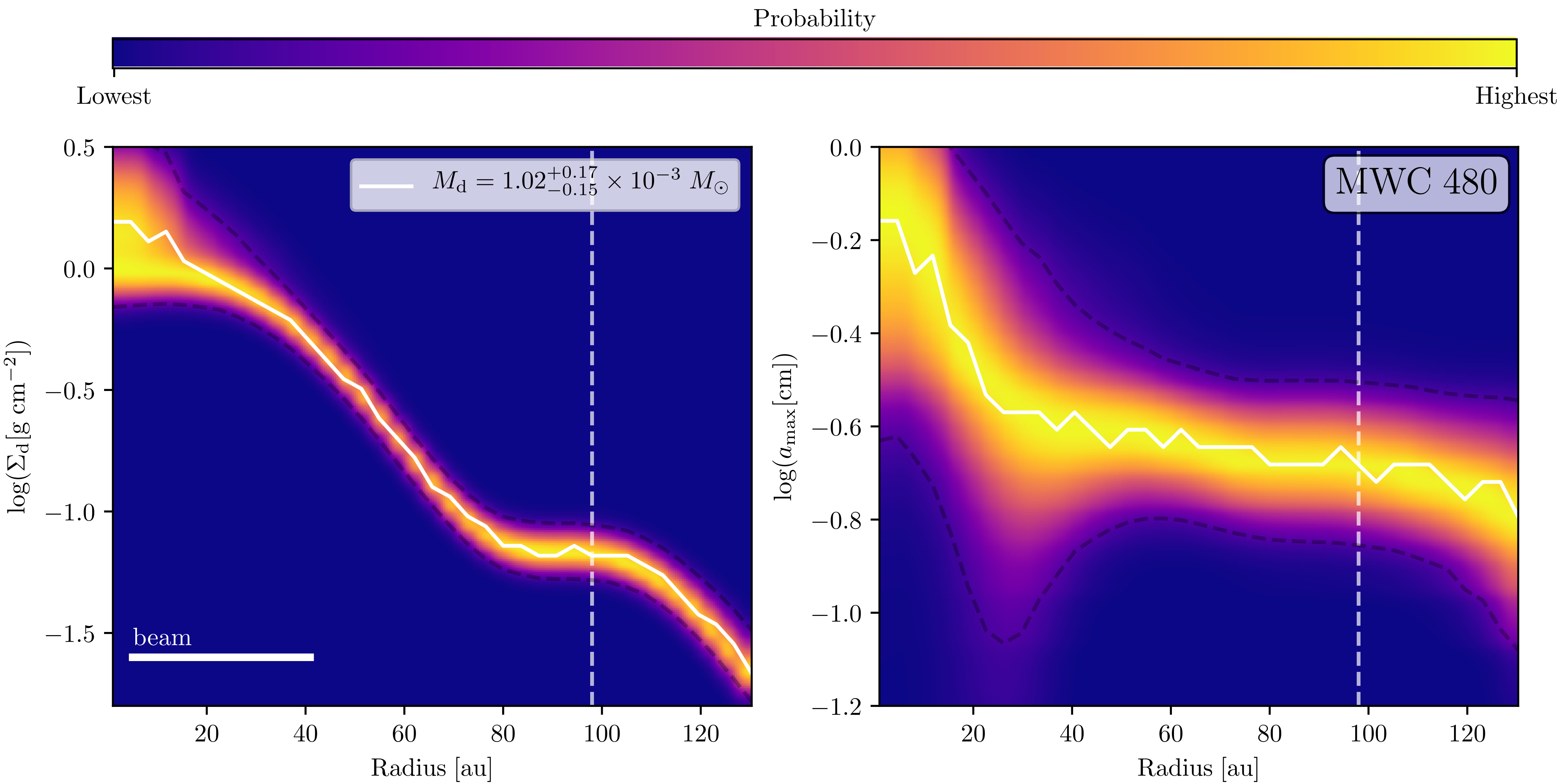


Probability
Lowest
Highest
$M_{\rm d} = 1.97^{+0.69}_{-0.57} \times 10^{-3}\ M_\odot$
beam
$\log(\Sigma_{\rm d}[{\rm g\ cm^{-2}}])$
Radius [au]
IMLup
$\log(a_{\rm max}[{\rm cm}])$
Radius [au]

IM Lup

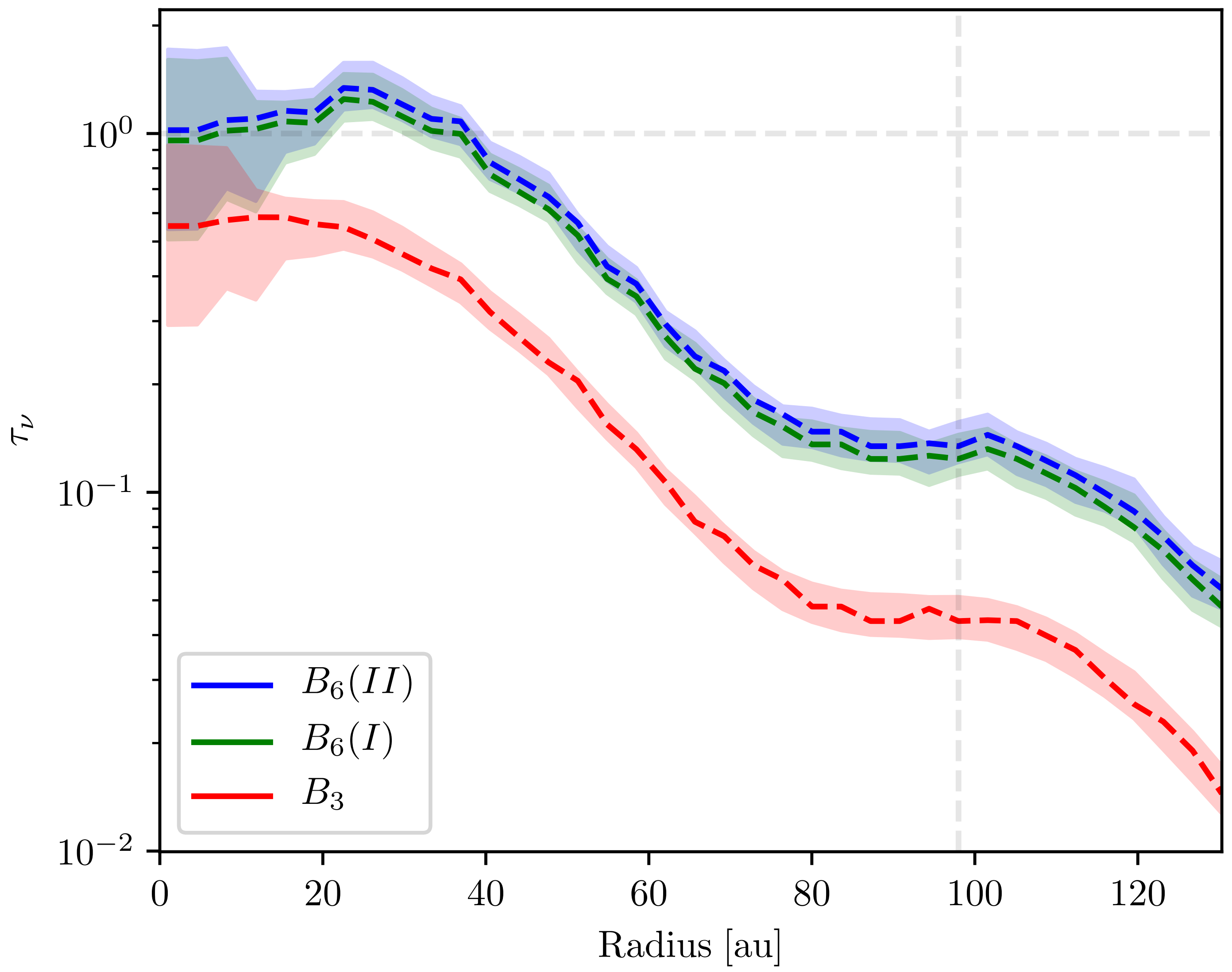


MWC 480

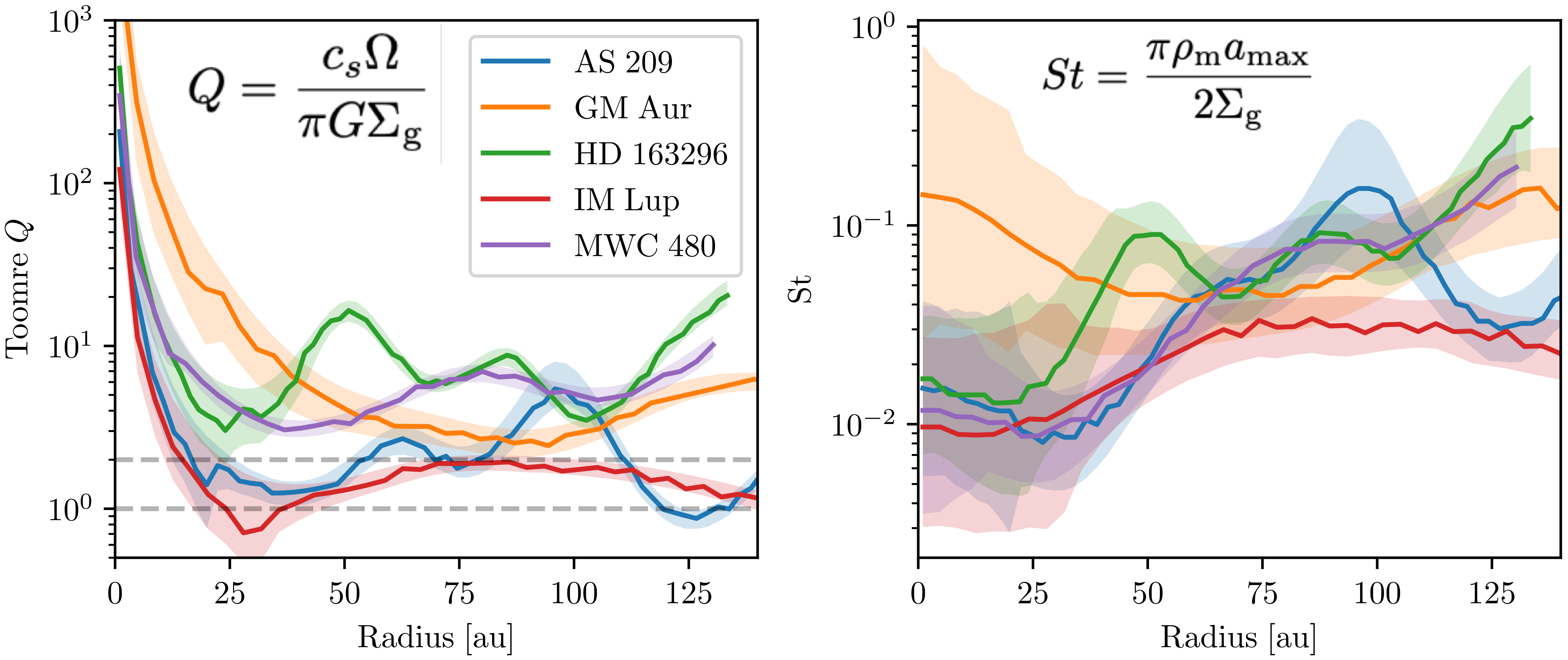


Probability
Lowest
Highest
$M_d = 1.02^{+0.17}_{-0.15} \times 10^{-3}\ M_\odot$
beam
log(Σd[g cm−2])
Radius [au]
MWC 480
log(amax[cm])
Radius [au]

MWC 480

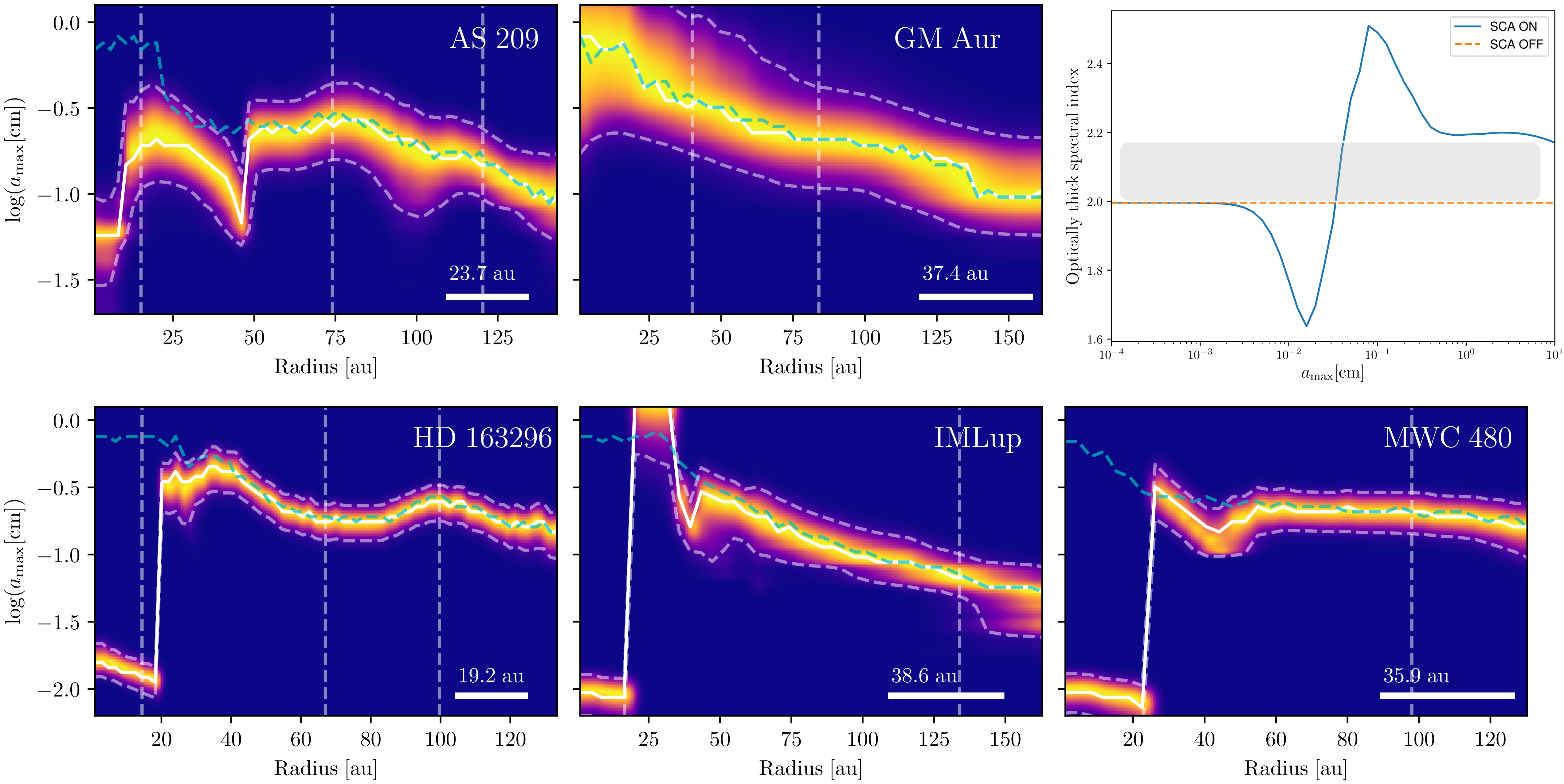


Toomre parameter and Stokes number

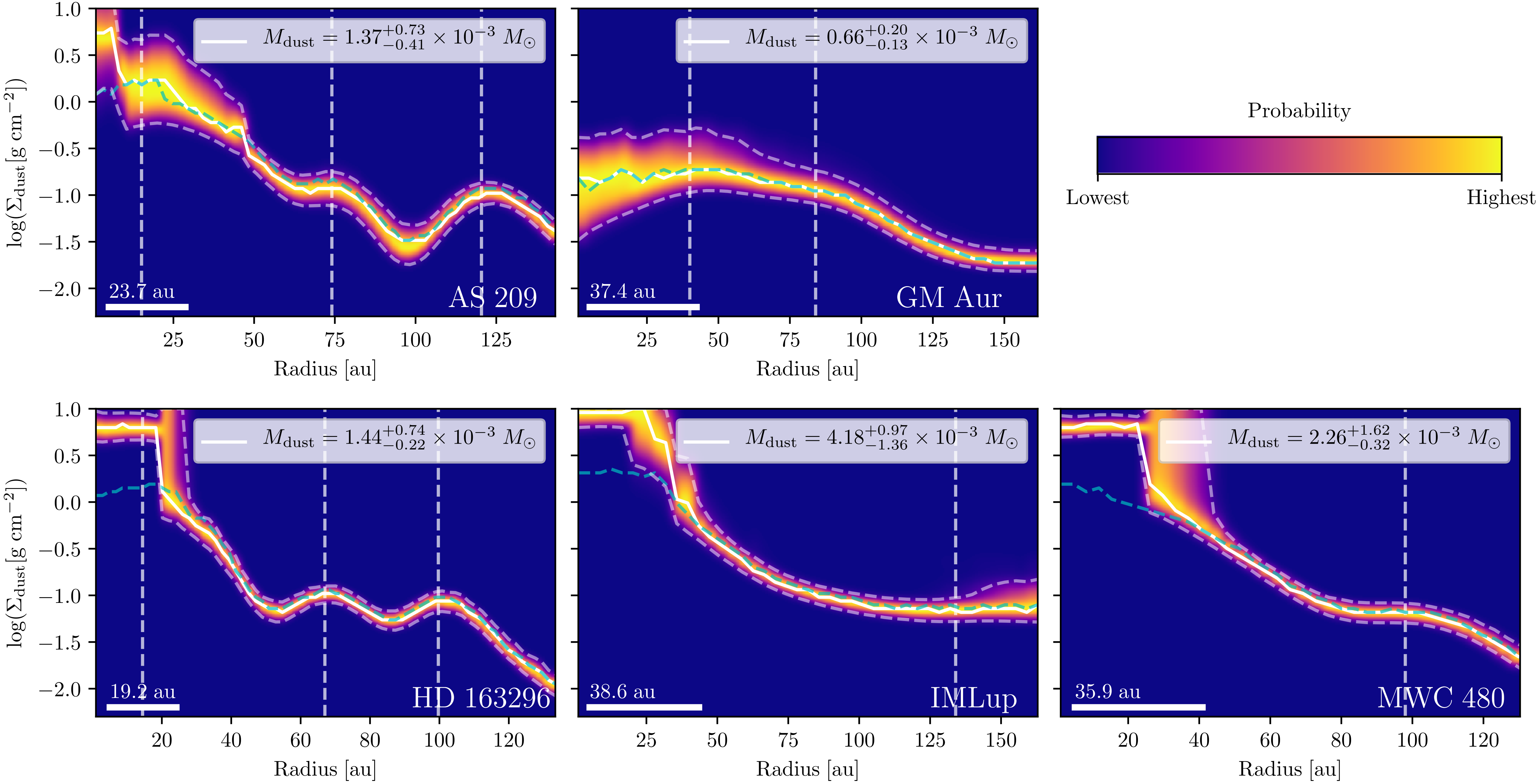


The scattering case

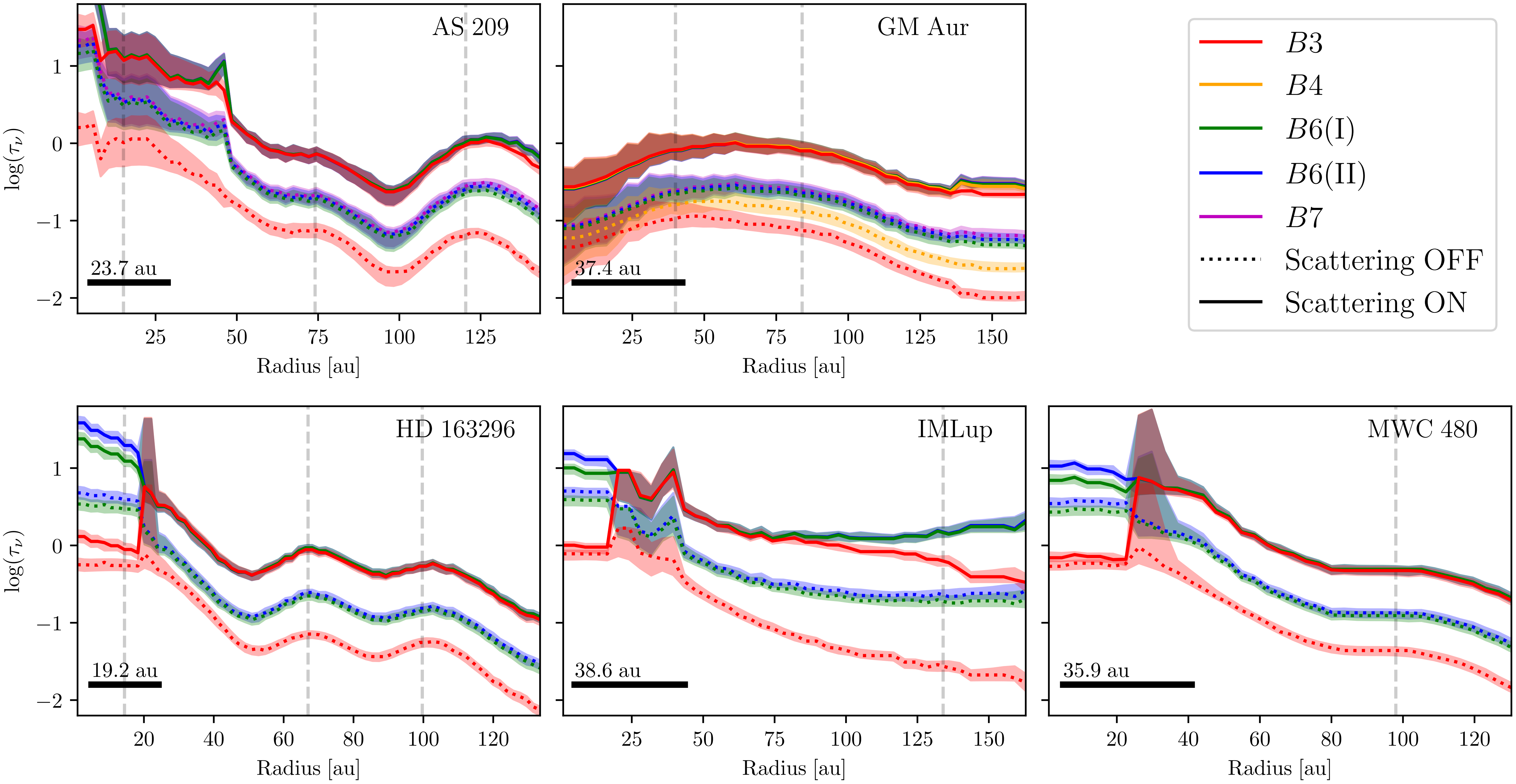
The scattering case



The scattering case



The scattering case



Main Conclusions

- Millimeter grain sizes are found in the disks around AS209, GM Aur, HD 163296, IM Lup, and MWC 480.
  The grain size radial profiles have a negative slope from the inner disk to the outer disk with local maxima at the bright ring of each disk.

- The dust surface densities also decreases with the disk radius, with local maxima at the ring positions. Then, both the dust mass and grain size are enhanced within the rings, consistent with dust trapping models.

Main Conclusions

- Some hundred grain sizes are need to fit the SED in the inner disks if scattering is taken into account, where the spectral indices are between ~2.0 and ~2.2.

  Scattering increases the optical depths by one order of magnitude, due to the albedo of millimeter grains is large at mm wavelenghts.

- Our results strenghten the idea that IM Lup is gravitationally unstable, as our estimated Toomre Q parameter is smaller than 2 for ~> 15 au.