POPULATION SYNTHESIS OF STRUCTURED DISKS

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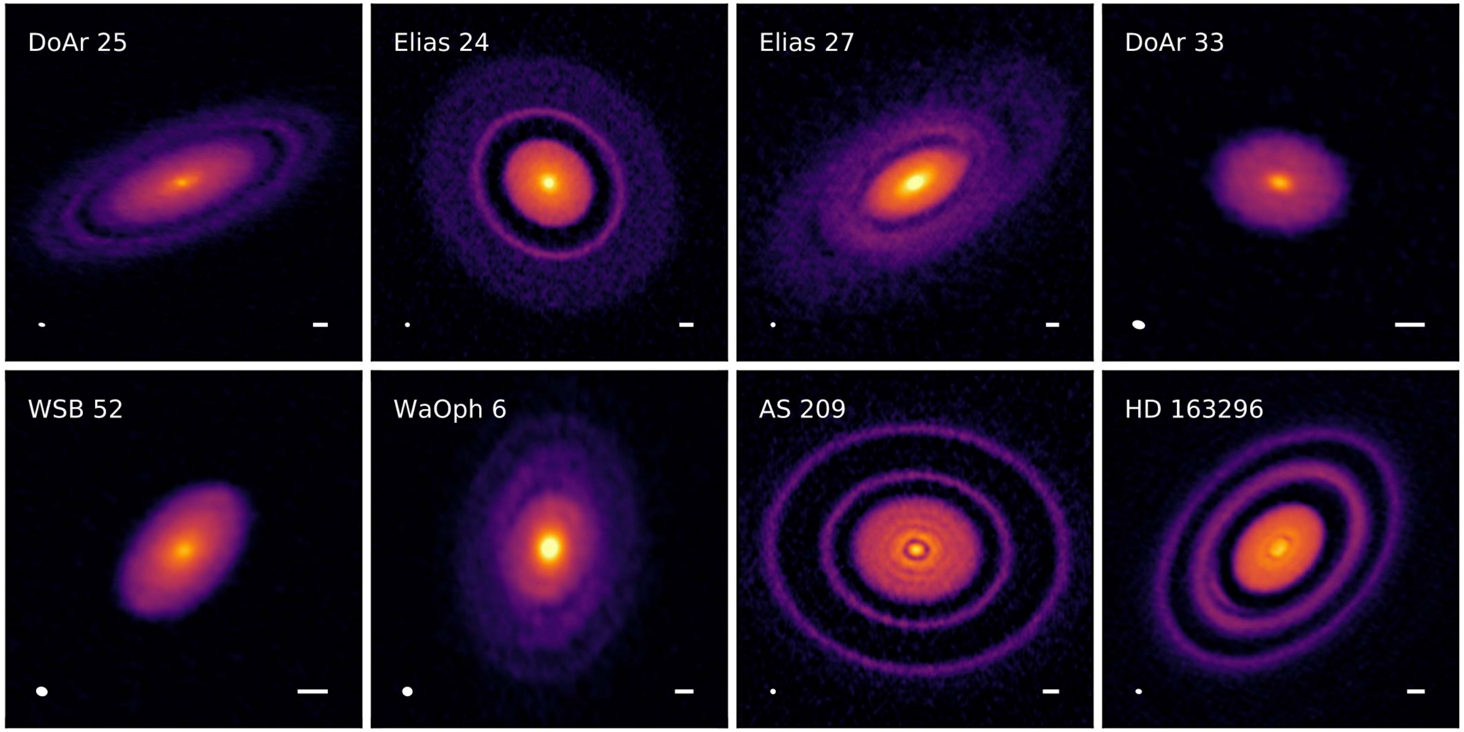
Thomas Pfeil, Sebastian Stammler, Til Birnstiel

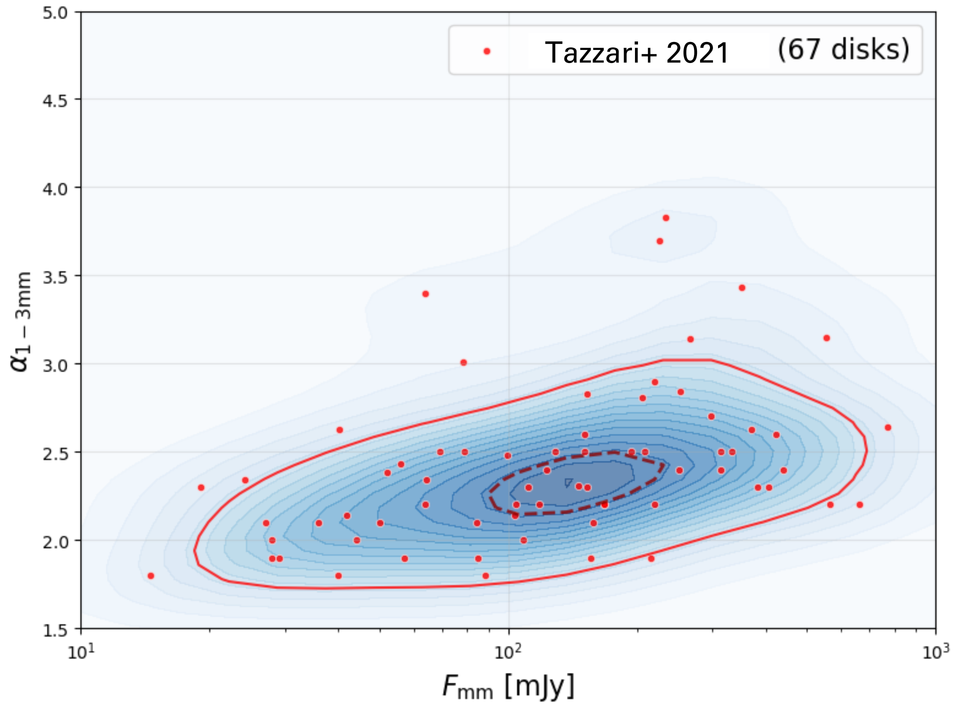
LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

Motivation

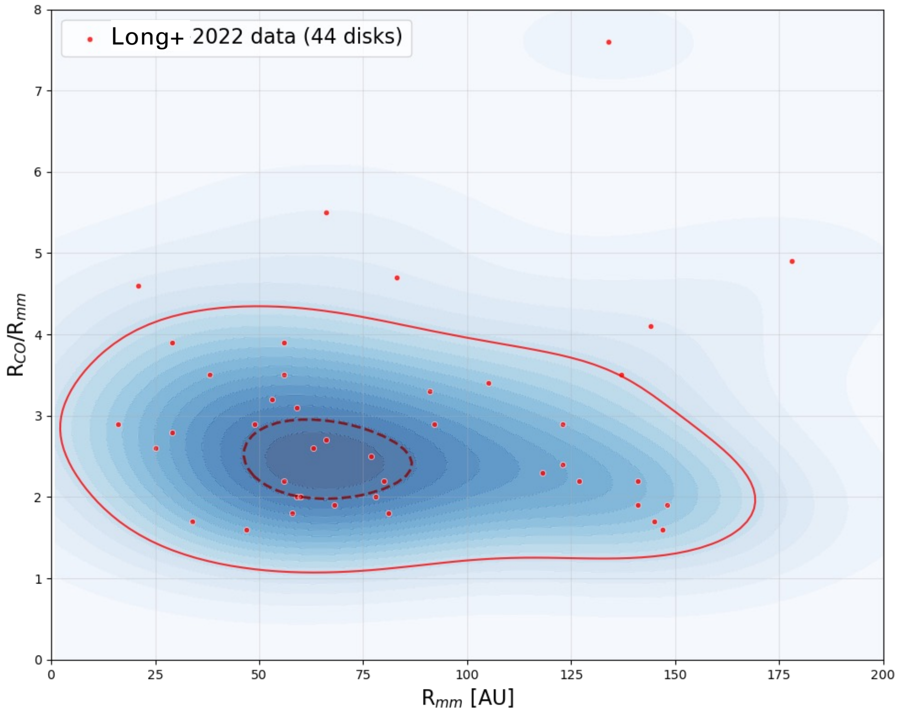


DoAr 25
Elias 24
Elias 27
DoAr 33
WSB 52
WaOph 6
AS 209
HD 163296

Motivation

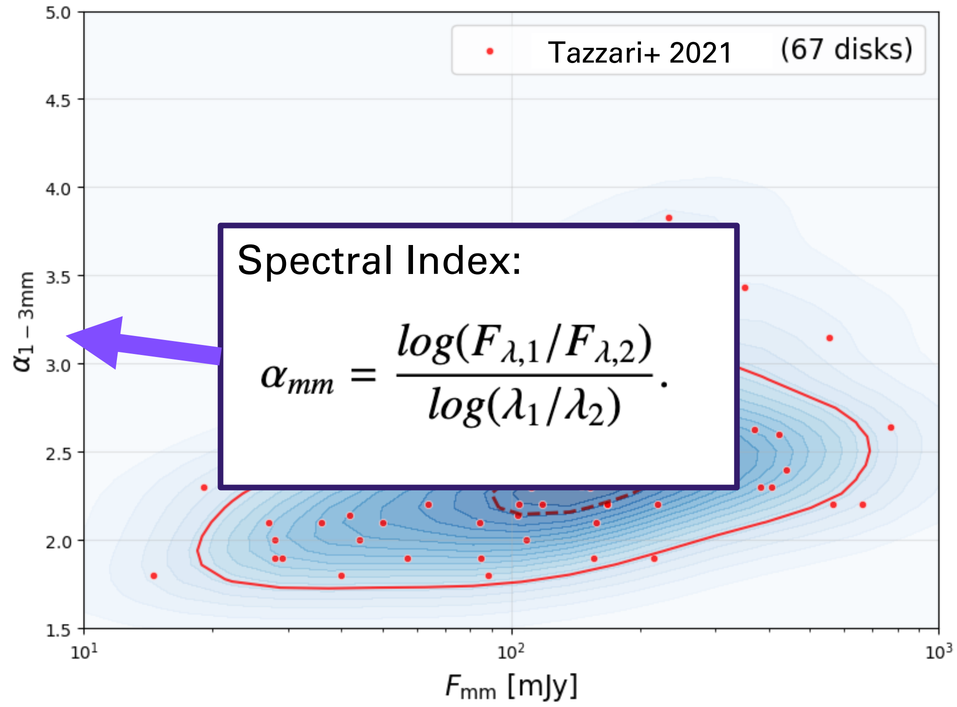


Tazzari+ 2021 (67 disks)
α_{1-3mm}
F_{mm} [mJy]
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
10^1
10^2
10^3

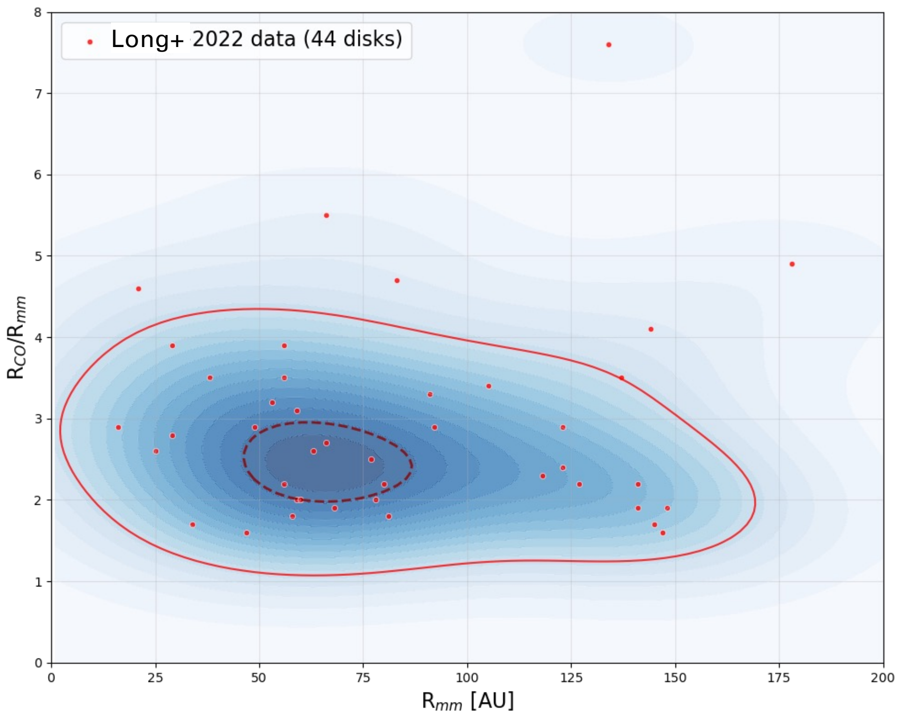


Long+ 2022 data (44 disks)
R_{CO}/R_{mm}
R_{mm} [AU]
0
25
50
75
100
125
150
175
200

Motivation

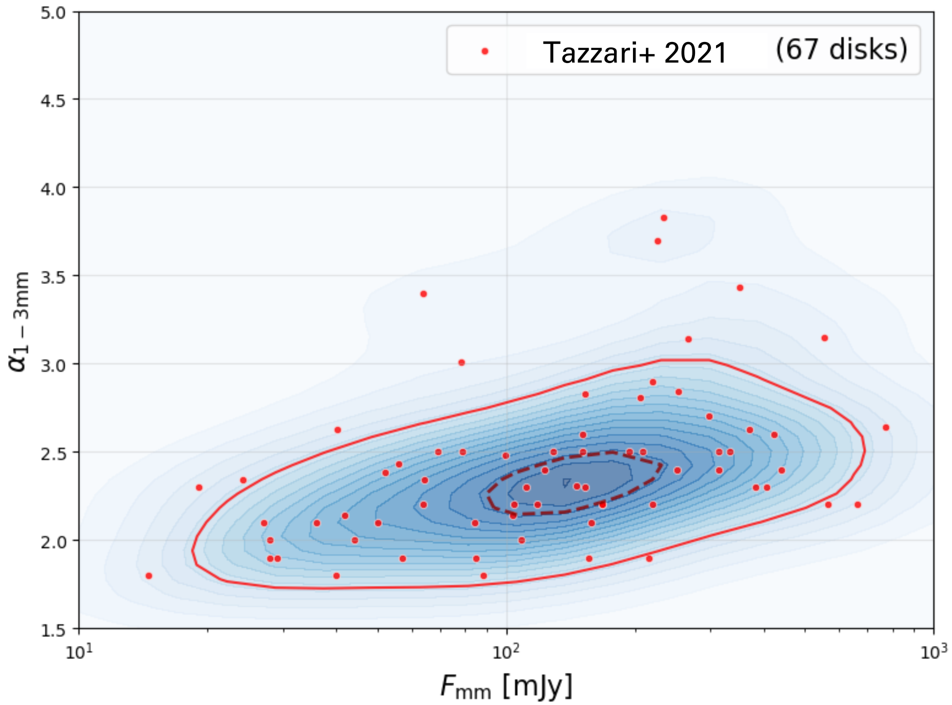


Tazzari+ 2021 (67 disks)
Spectral Index:
$\alpha_{mm} = \frac{log(F_{\lambda,1}/F_{\lambda,2})}{log(\lambda_1/\lambda_2)}.$
α_{1-3mm}
F_{mm} [mJy]

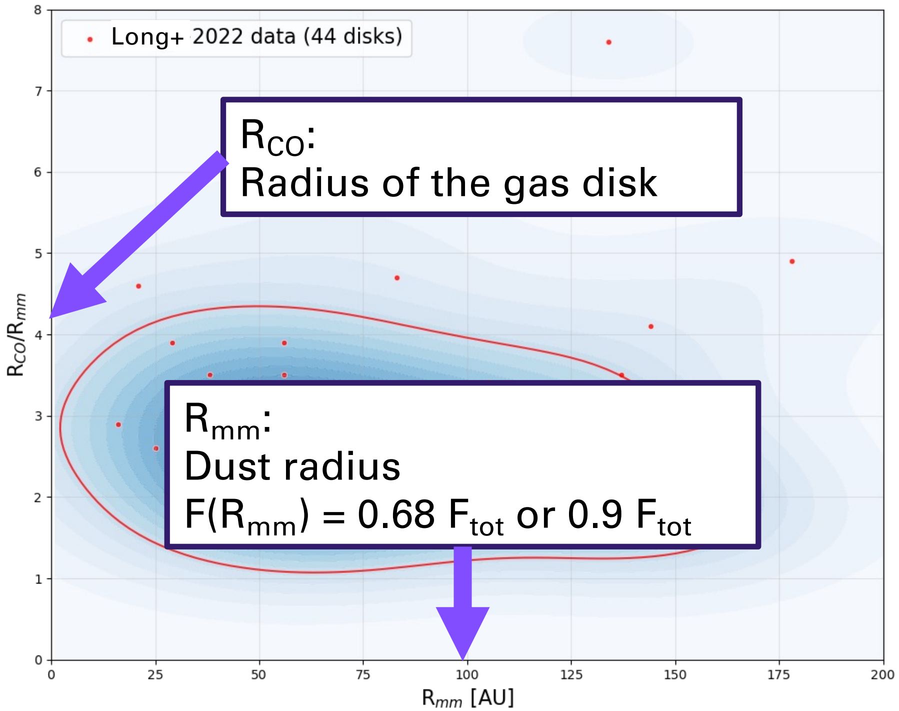


Long+ 2022 data (44 disks)
R_{CO}/R_{mm}
R_{mm} [AU]

Motivation

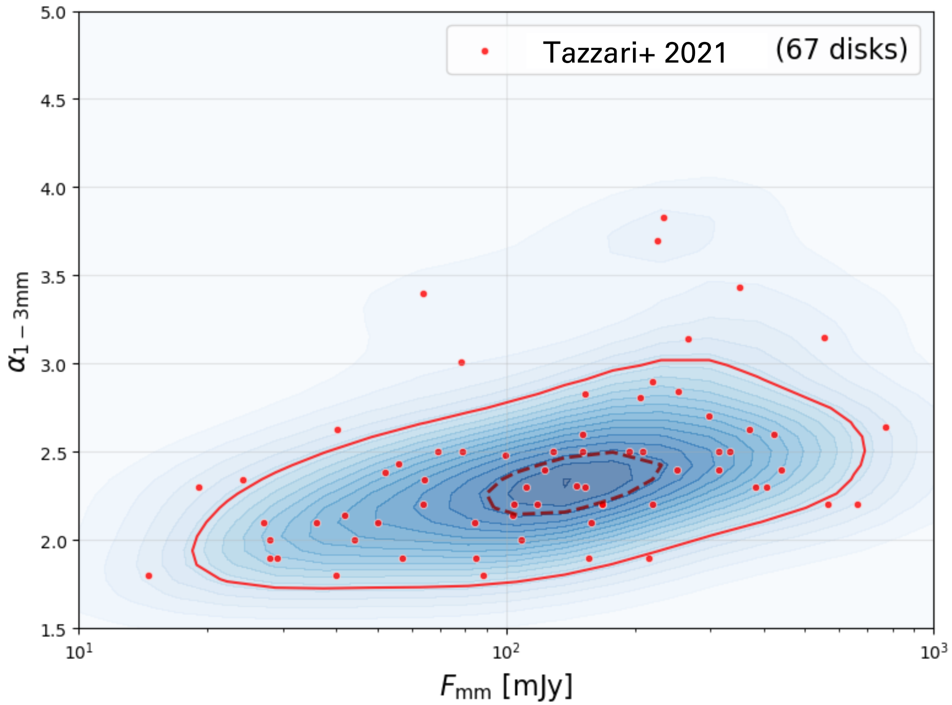


Tazzari+ 2021
(67 disks)
α_{1-3mm}
F_{mm} [mJy]



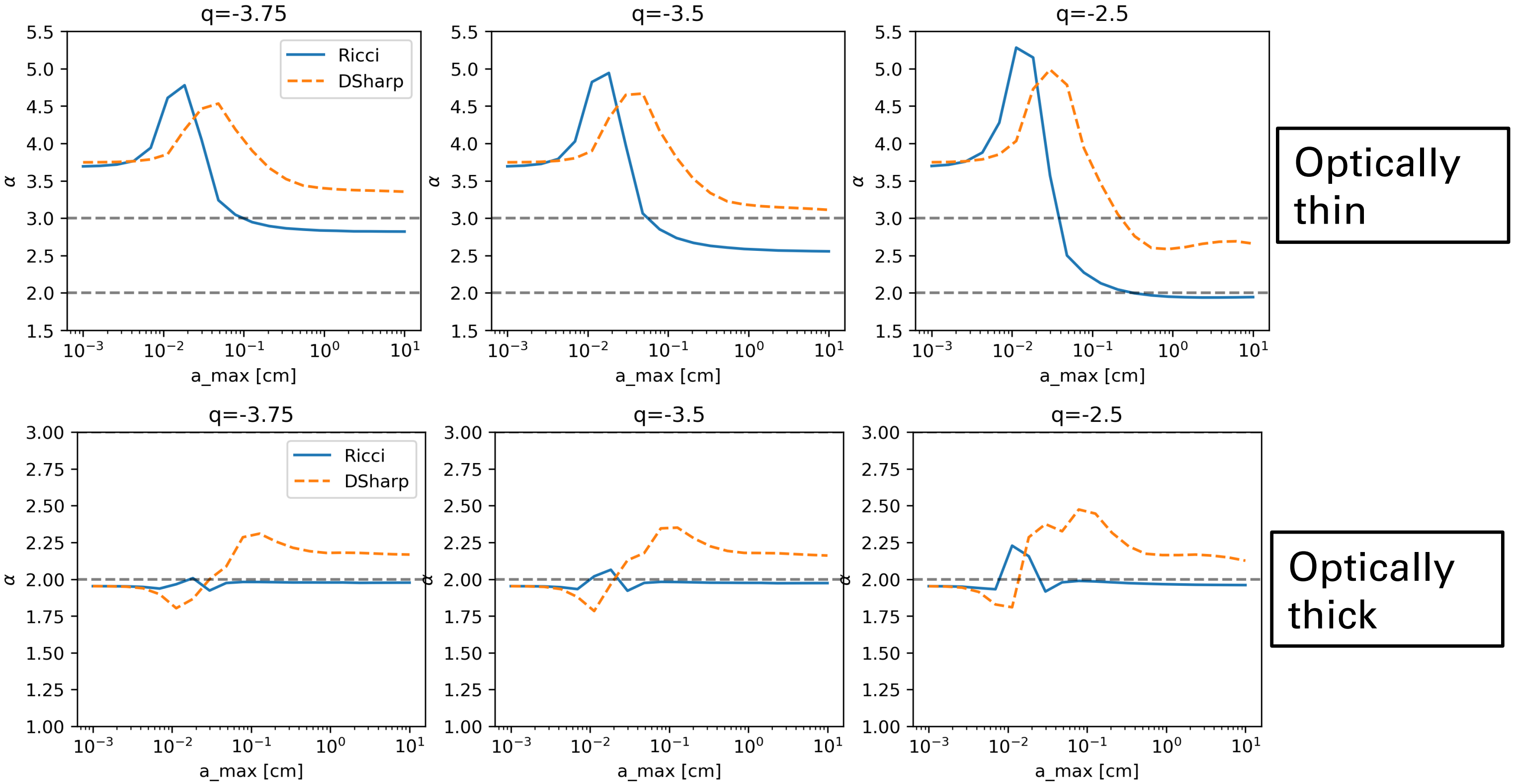
Long+ 2022 data (44 disks)
R_{CO}:
Radius of the gas disk
R_{mm}:
Dust radius
$F(R_{mm}) = 0.68\ F_{tot}$ or $0.9\ F_{tot}$
R_{CO}/R_{mm}
R_{mm} [AU]

Motivation

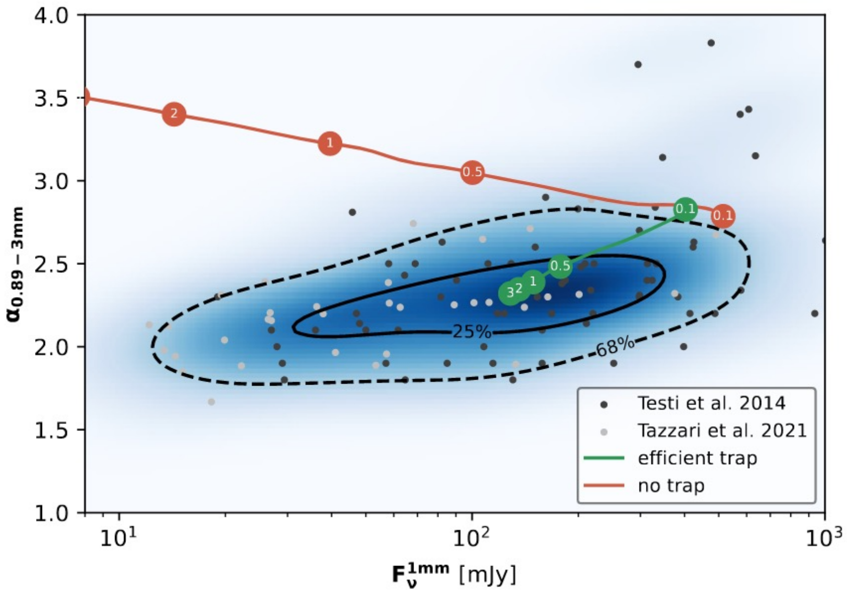


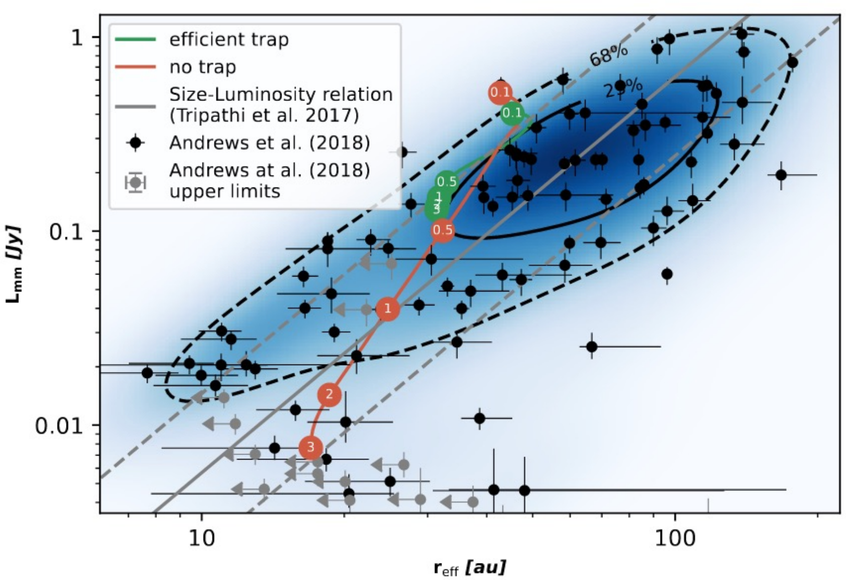
- Taurus and Lupus
- Age: 1-3 Myr
- Hard to quantify observational bias

Spectral index



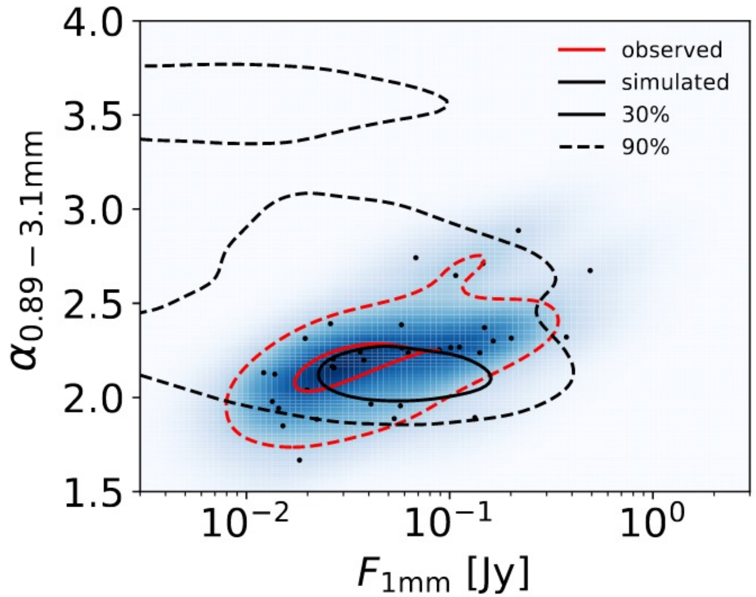
Motivation

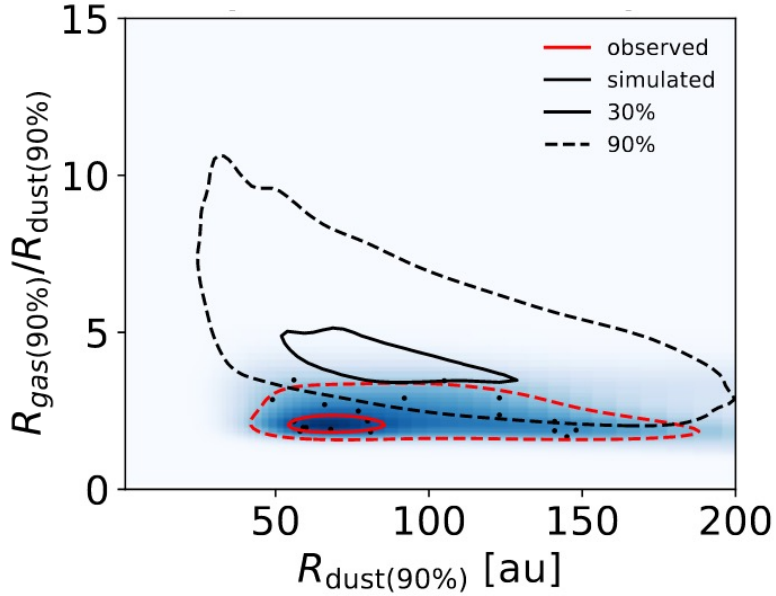




Birnstiel 2024

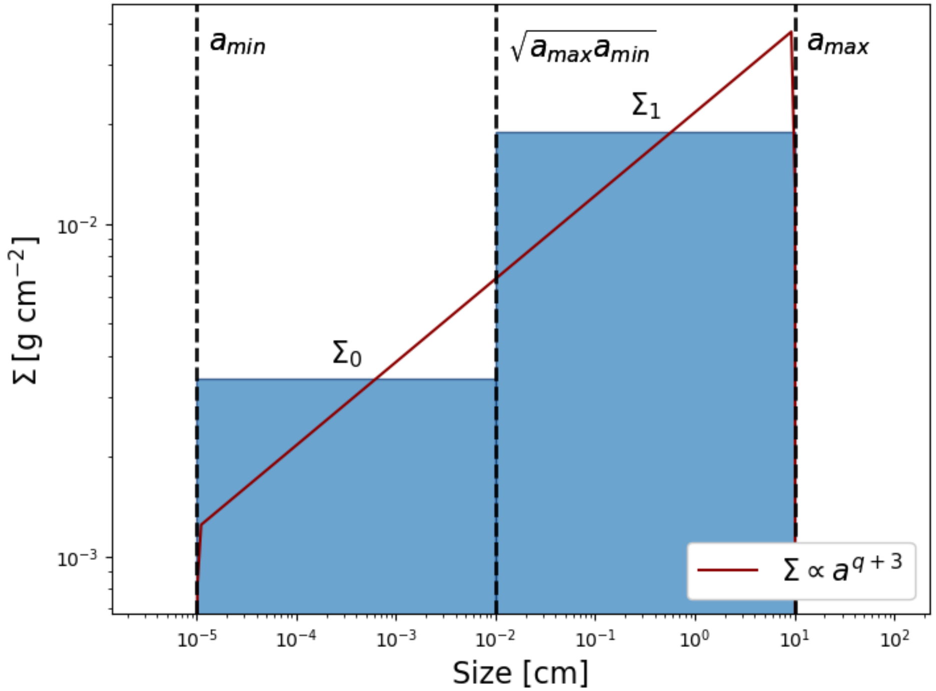
Previous studies





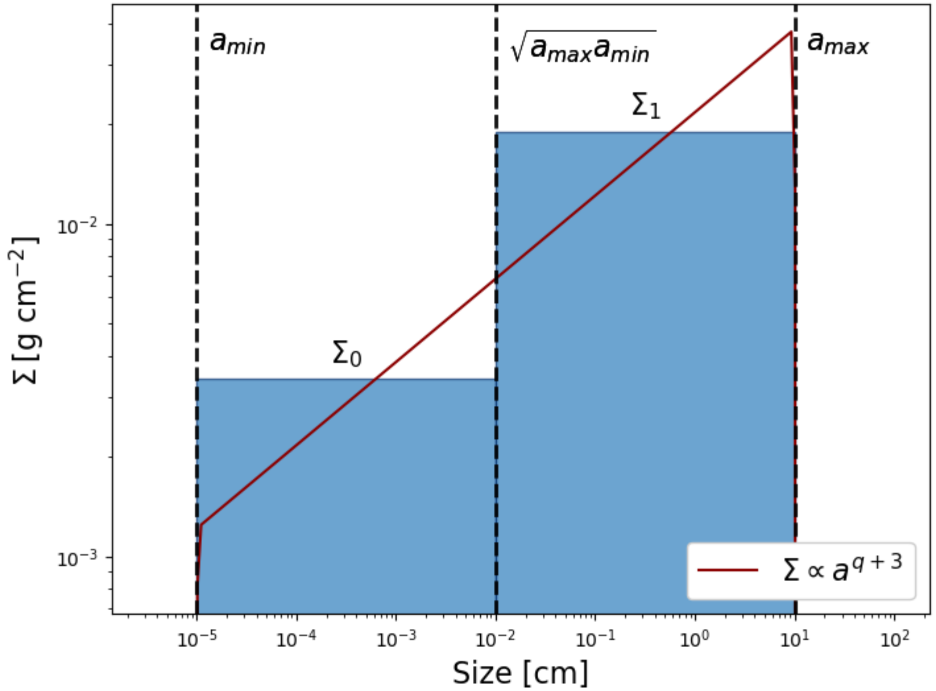
Delussu+ 2025

TriPoDPy



- Two-dust populations
- Size distribution modelled as a **power law**
- **Collisions dictate** the slope (**q**) and maximum size (**a_{max}**)
- Maximum **grain size** radially is **advected**
- Validated with **DustPy** for different M_* and gaps

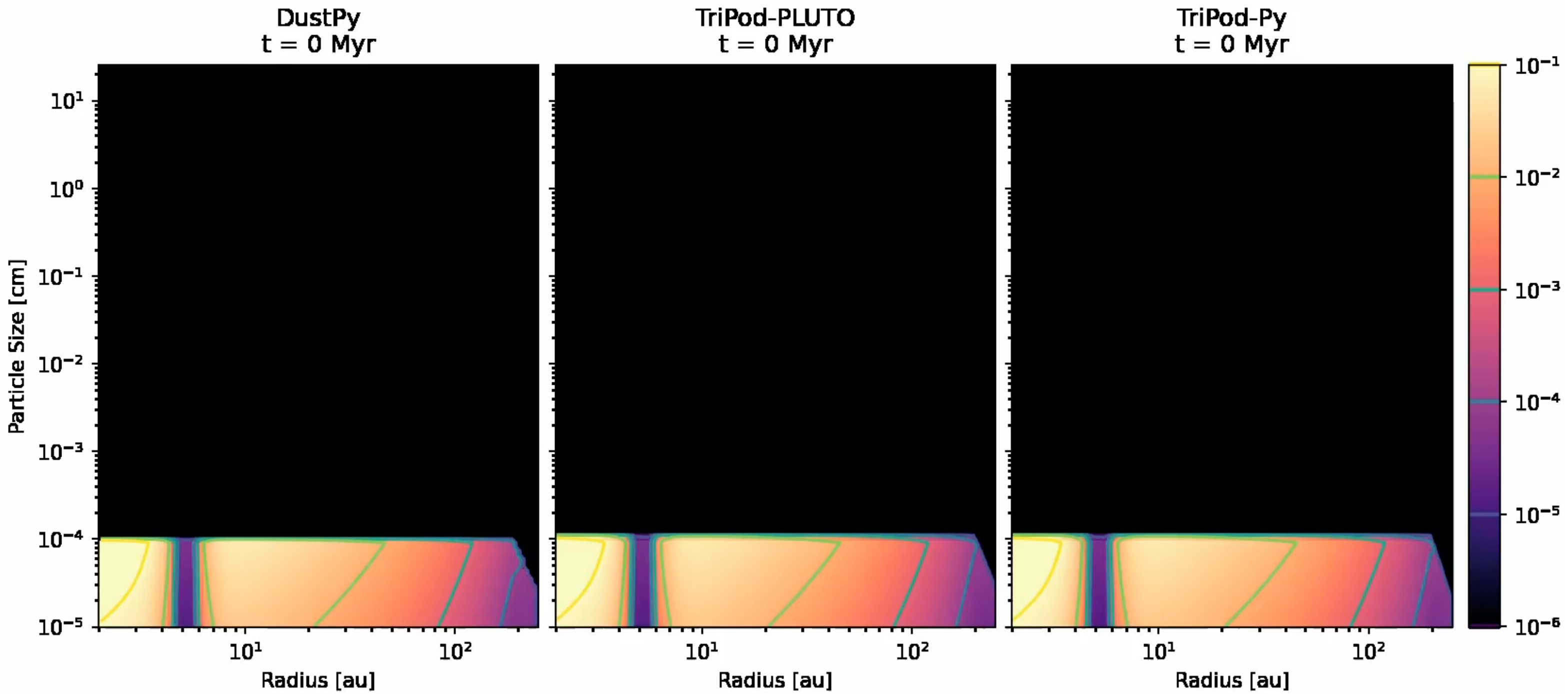
TriPoDPy



https://arxiv.org/abs/2511.20764

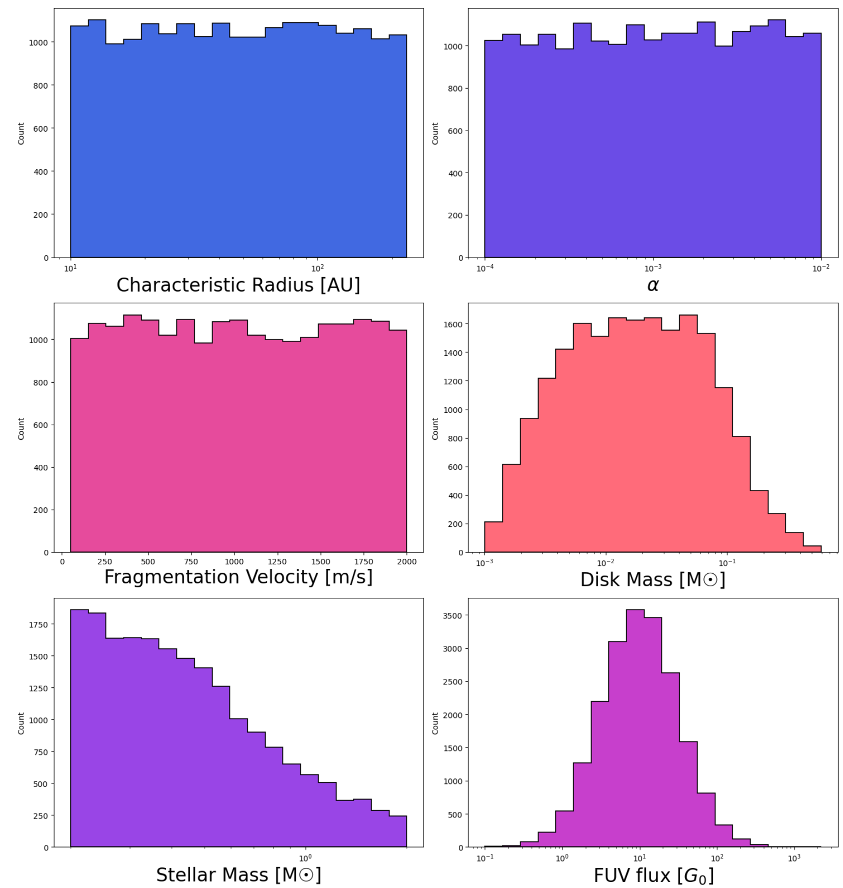
Dust Evolution with TriPoDPy

Pfeil+ 2024

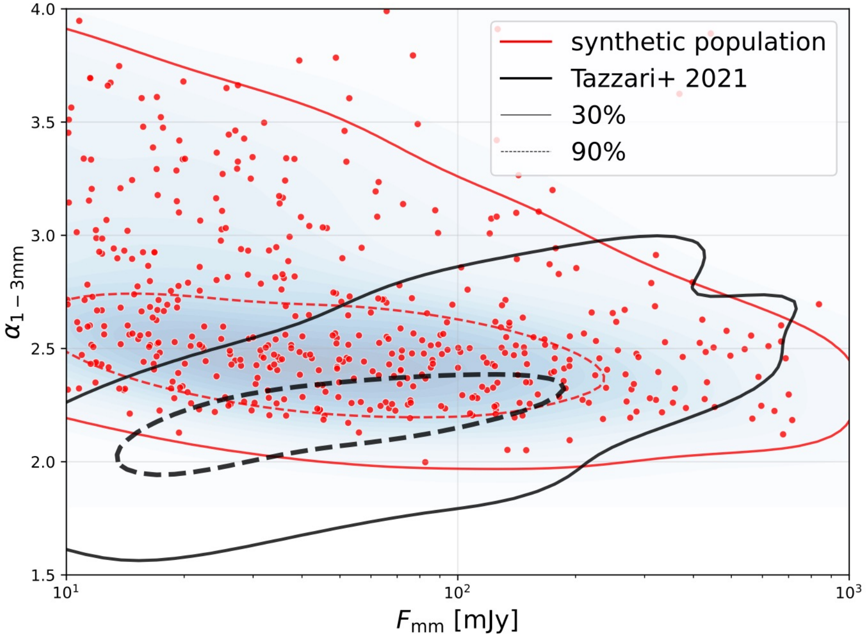


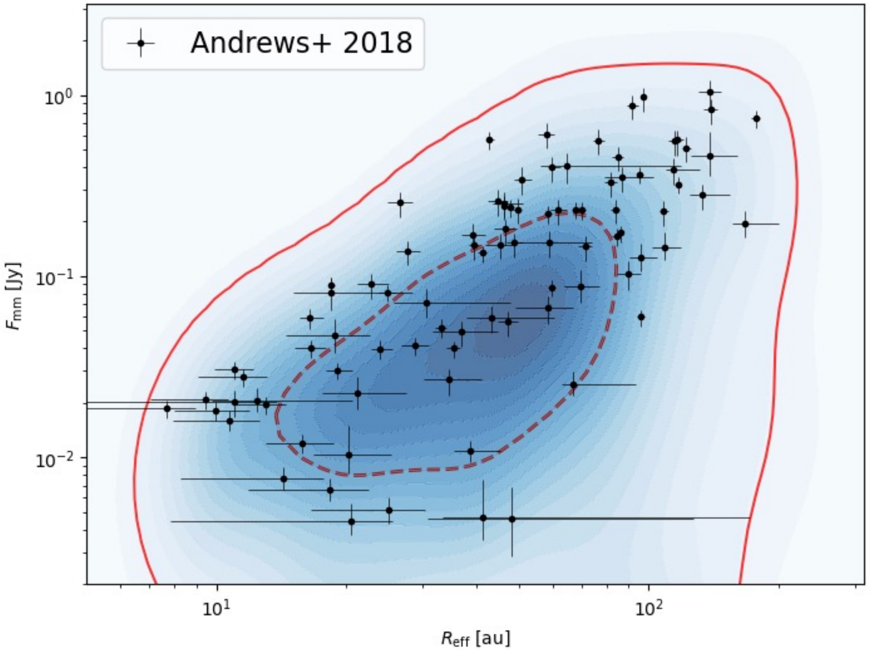
Setup

- gap opening at 0.1 -0.4 Myr
- gap shape via torques:
  M_p: 150 - 1050 $M_\oplus$, Lau 2024
- External photoevaporation:
  Sellek 2020
- Compute observables with
  Miyake scattering solution
  + Ricci Opacities



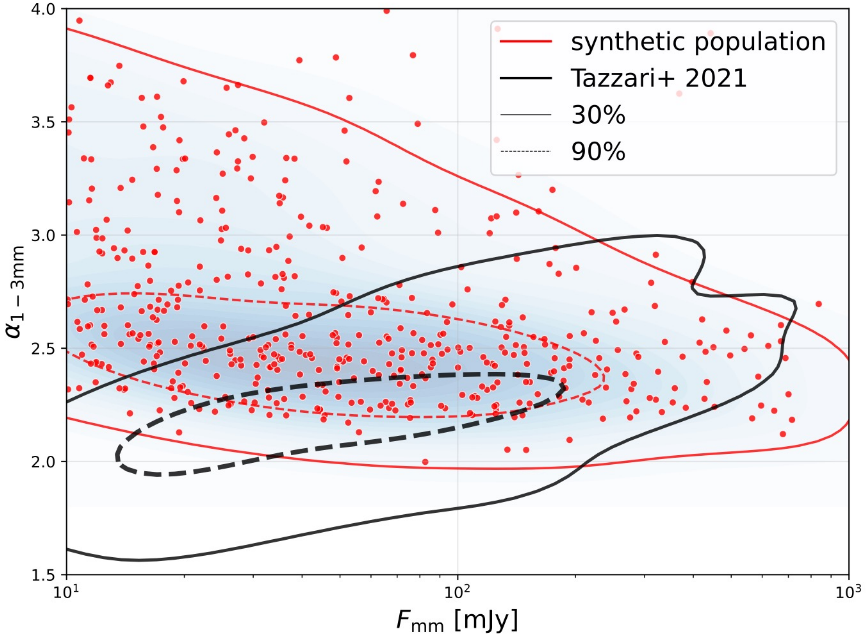
Results

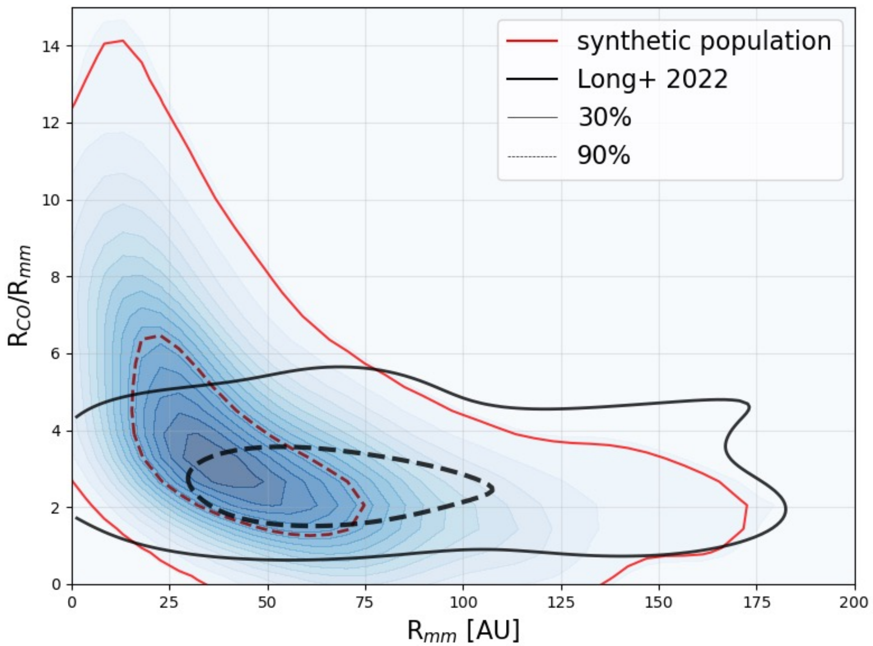




Simulated disks at 1-3 Myr

Results





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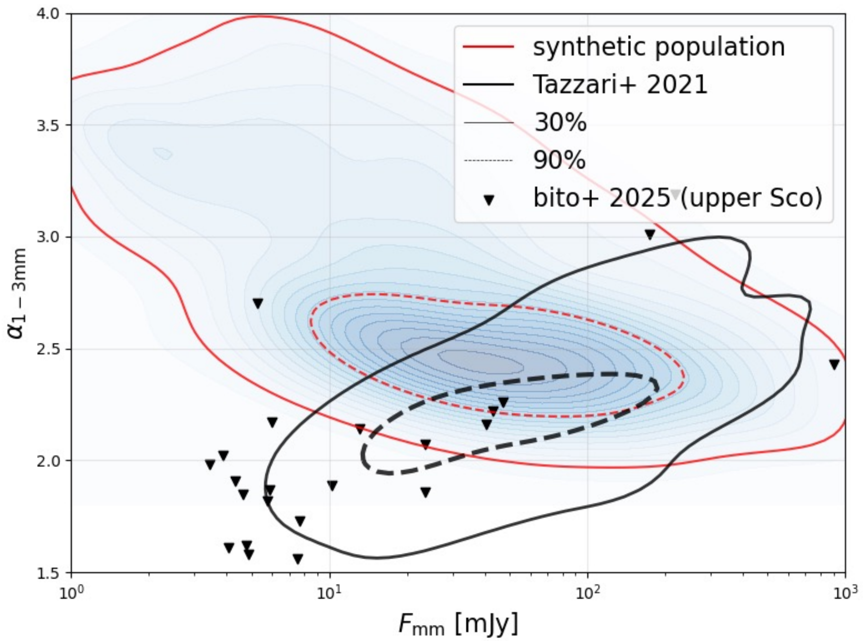
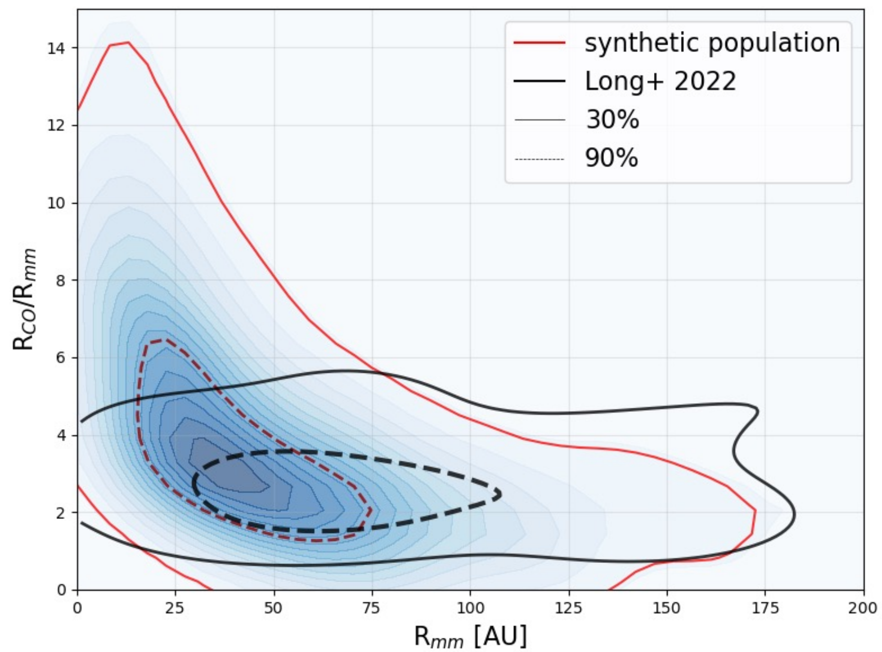
Results



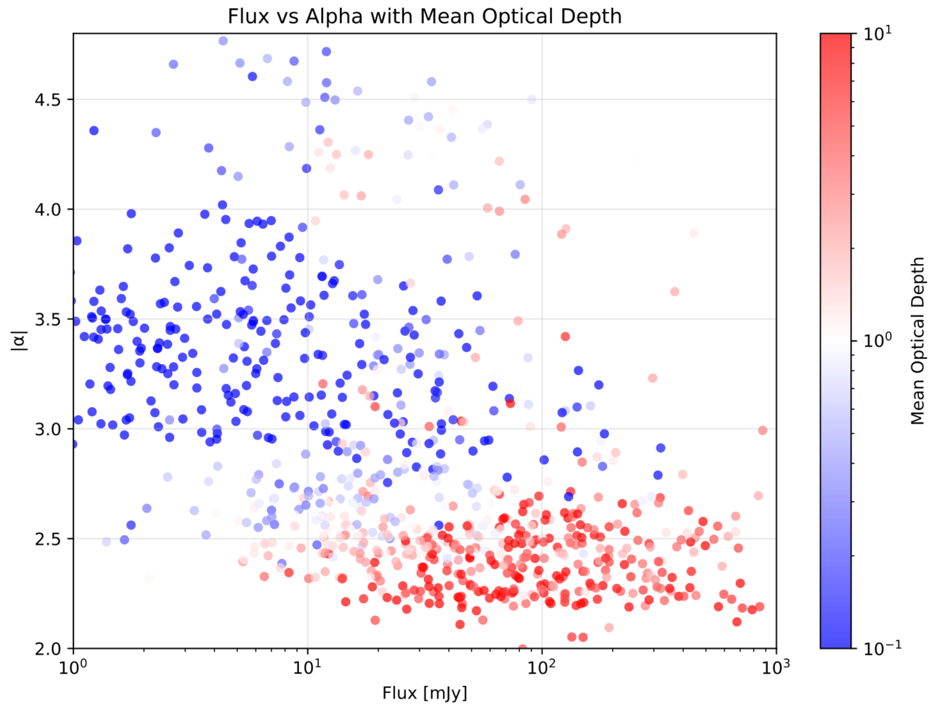
synthetic population
Tazzari+ 2021
30%
90%
bito+ 2025 (upper Sco)
4.0
3.5
3.0
2.5
2.0
1.5
α_{1-3mm}
10^0
10^1
10^2
10^3
F_{mm} [mJy]



synthetic population
Long+ 2022
30%
90%
14
12
10
8
6
4
2
0
R_{CO}/R_{mm}
0
25
50
75
100
125
150
175
200
R_{mm} [AU]

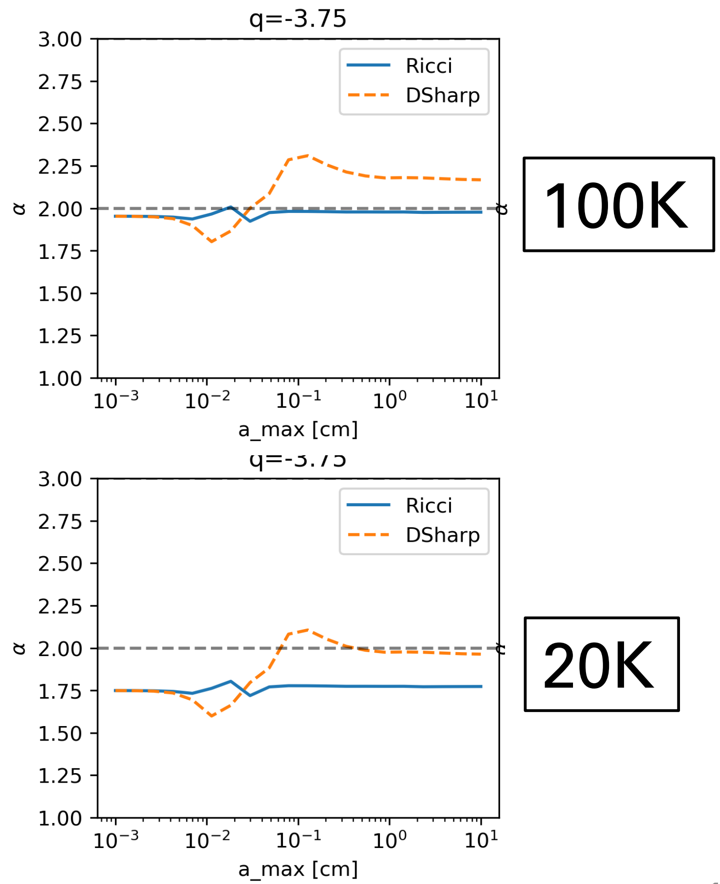
How to get a low spectral index

- Temperatures below Rayleigh-Jeans
- Scattering if the albedo decreases with wavelength
- Free-emission



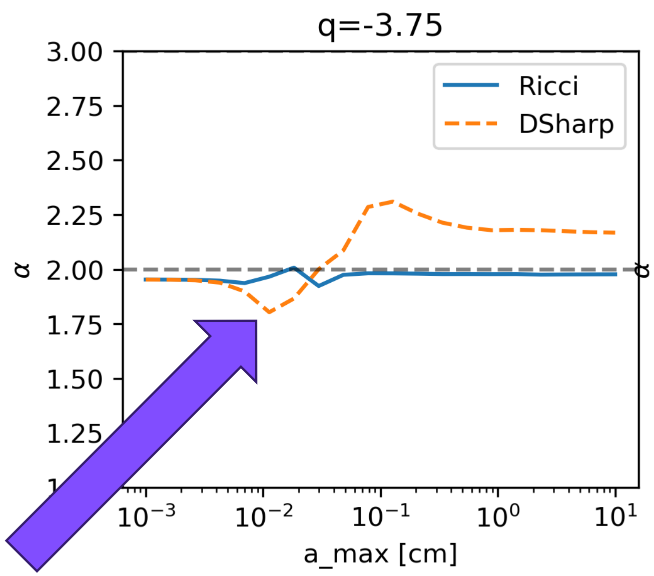
How to get a low spectral index

- **Temperatures below Rayleigh-Jeans**
- Scattering if the albedo decreases with wavelength
- Free-emission



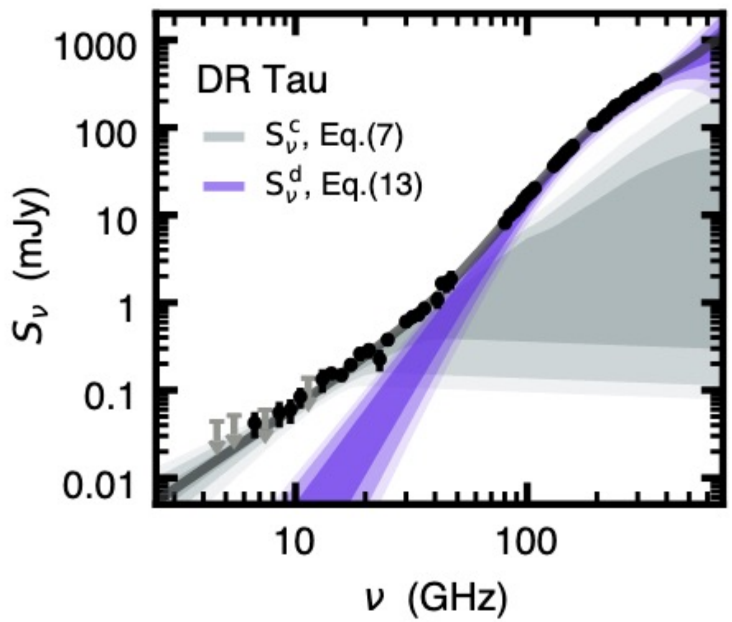
How to get a low spectral index

- Temperatures below Rayleigh-Jeans
- **Scattering if the albedo decreases with wavelength**
- Free-emission



How to get a low spectral index

- Temperatures below Rayleigh-Jeans
- Scattering if the albedo decreases with wavelength
- **Free-emission**



Painter+ 2025

Conclusions

- Simple single trap approach can not explain the observed disks -> low alpha is a problem
- The radius tension is not fully resolved by considering external photoevaporation
- Gaps are leakier than previous models suggested

THANK YOU FOR YOUR ATTENTION

Contact:

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https://github.com/NIcolas-Kaufmann

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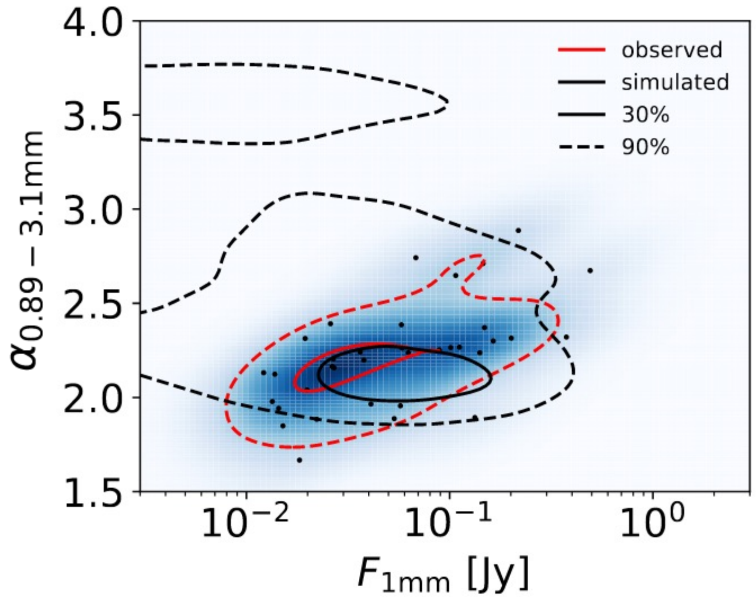
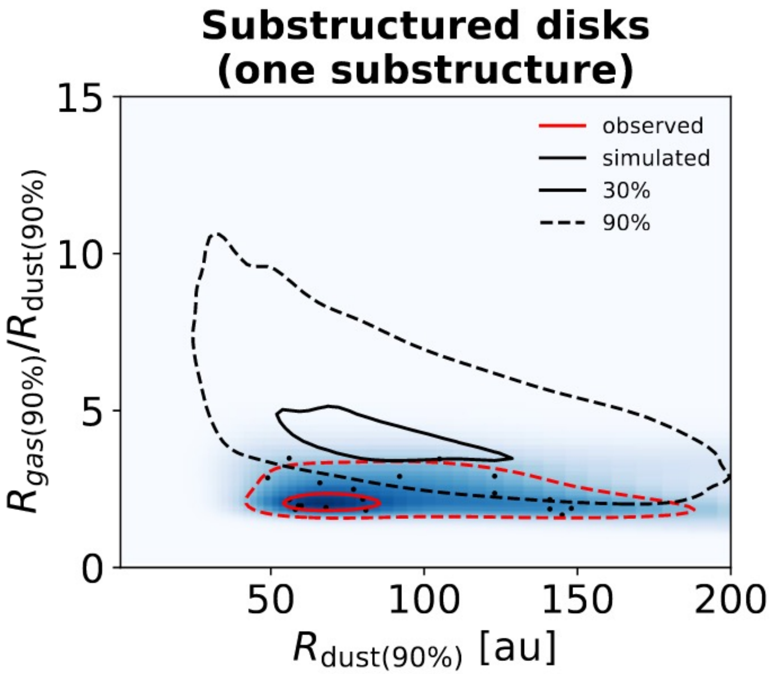
Outlook

- Adding free free contribution
- Longer simulation times to compare with the upper Sco sample
- Explore more physics: MHD winds/internal photoevaporation

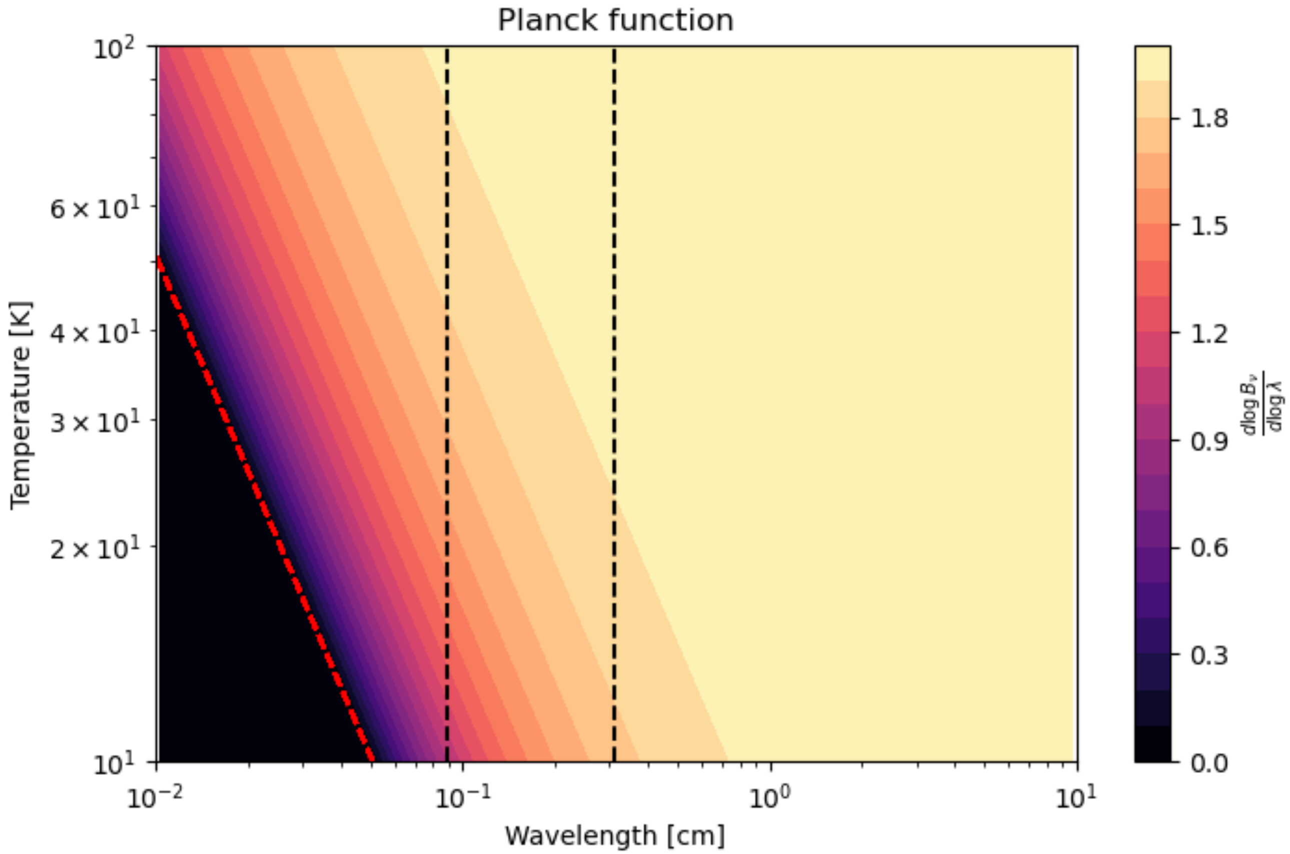
Previous studies





Delussu+ 2025

Rayleigh-Jeans



Setup

Parameter	Description	Range	PDF
α	viscosity parameter	$10^{-4} - 10^{-2}$	log uniform
$M_{\rm disk}$ [$M_\star$]	initial disk mass	$10^{-3} - 10^{-0.5}$	log uniform
$M_\star$ [$M_\odot$]	stellar mass	0.2 – 2.0	Maschberger (2013)
r_c [au]	characteristic radius	10 – 230	log uniform
$v_{\rm frag}$ [cm/s]	fragmentation velocity	50 – 2000	uniform
m_p [$M_\oplus$]	planet mass	150 – 1050	uniform
r_p [r_c]	planet position	0.05 – 1.5	uniform
t_p [Myr]	planet formation time	0.1 – 0.4	uniform
$\mathcal{F}_{\rm FUV}$ [$\log_{10}(G_0)$]	external FUV field	-	$\mathcal{N}(1, 0.5^2)$

Observables

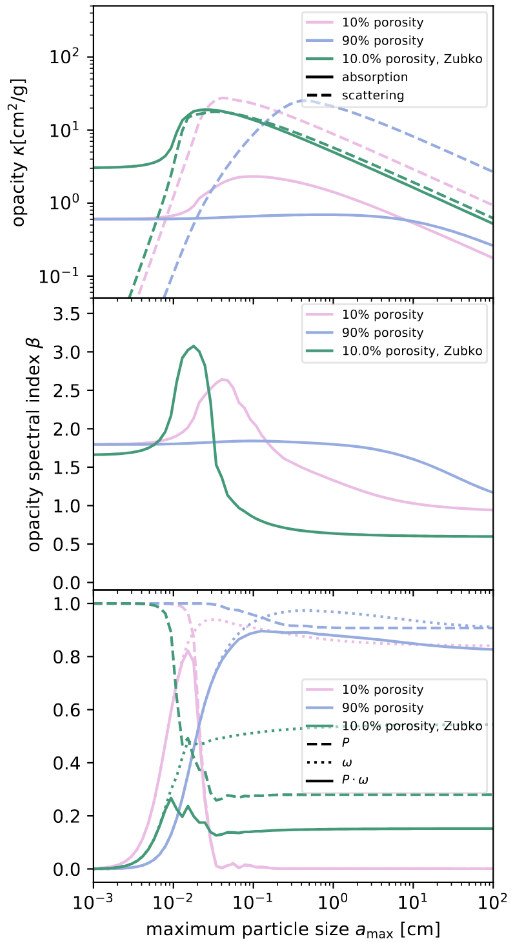
$$I_\nu = B_\nu(1-\exp(-\tau_\nu)) = B_\nu \times \begin{cases} 1 & \text{for } \tau_\nu \gg 1 \\ \tau_\nu & \text{for } \tau_\nu \ll 1, \end{cases}$$

$$\tau_\nu = \Sigma_\mathrm{d}\, \bar{\kappa}_\nu / \cos i,$$

$$\bar{\kappa}_\nu \propto \nu^\beta$$

$$\text{for } \tau_\nu \gg 1 \qquad \alpha_\mathrm{mm} = 2$$

$$\text{for } \tau_\nu \ll 1, \qquad \alpha_\mathrm{mm} = 2 + \beta$$



Slab model

$$\epsilon_\nu^{\mathrm{eff}} = \frac{\kappa_\nu^{\mathrm{abs}}}{\kappa_\nu^{\mathrm{abs}} + \kappa_\nu^{\mathrm{sca,eff}}}.$$

$$\frac{J_\nu(\tau_\nu)}{B_\nu(T_d)} = 1 - b\left(e^{-\sqrt{3\epsilon_\nu^{\mathrm{eff}}}\left(\frac{1}{2}\Delta\tau - \tau_\nu\right)} + e^{-\sqrt{3\epsilon_\nu^{\mathrm{eff}}}\left(\frac{1}{2}\Delta\tau + \tau_\nu\right)}\right)$$

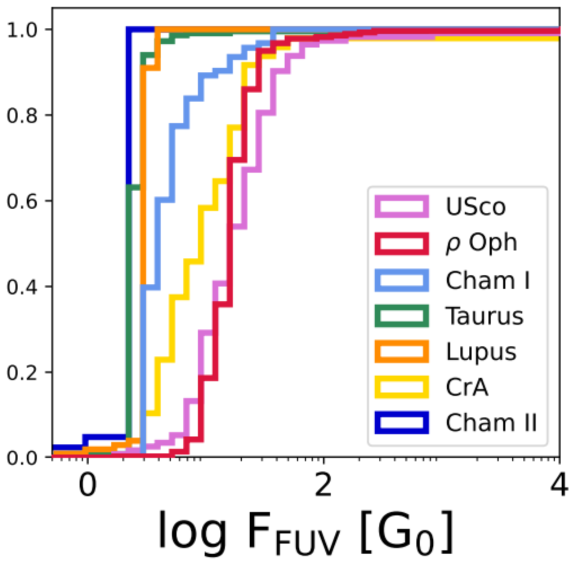
$$b = \left[(1 - \sqrt{\epsilon_\nu^{\mathrm{eff}}})e^{-\sqrt{3\epsilon_\nu^{\mathrm{eff}}}\Delta\tau} + 1 + \sqrt{\epsilon_\nu^{\mathrm{eff}}}\right]^{-1}.$$

$$I_\nu^{\mathrm{out}} \simeq (1 - e^{-\Delta\tau/\mu})S_\nu\left(\left(\frac{1}{2}\Delta\tau - \tau_\nu\right)/\mu = 2/3\right)$$

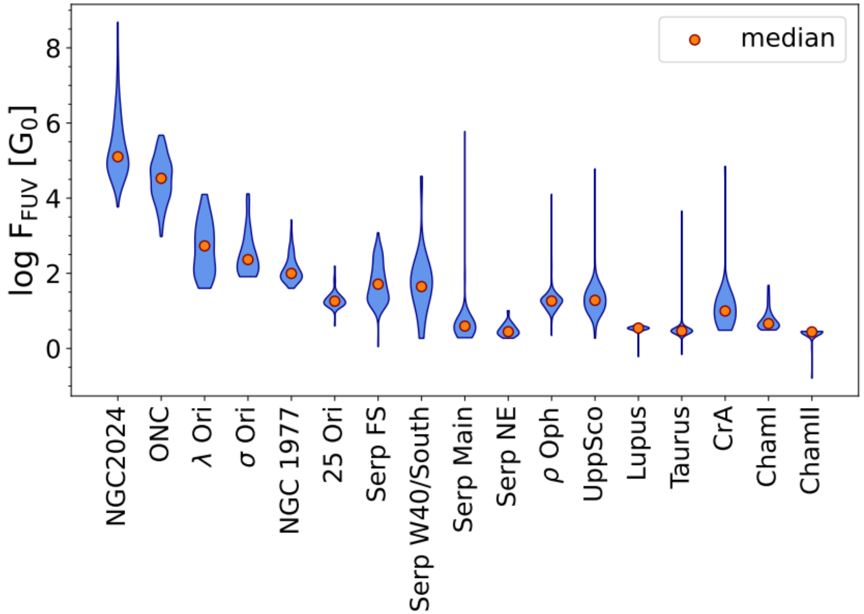
where

$$S_\nu(\tau_\nu) = \epsilon_\nu^{\mathrm{eff}} B_\nu(T_d) + (1 - \epsilon_\nu^{\mathrm{eff}})J_\nu(\tau_\nu)$$

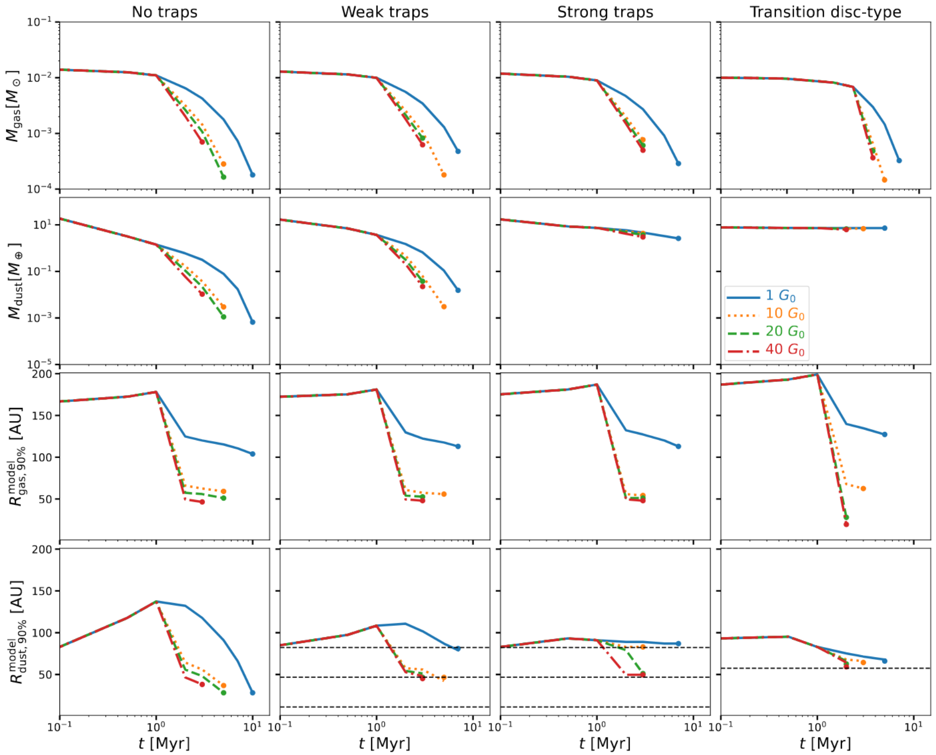
FUV



Anania 2025

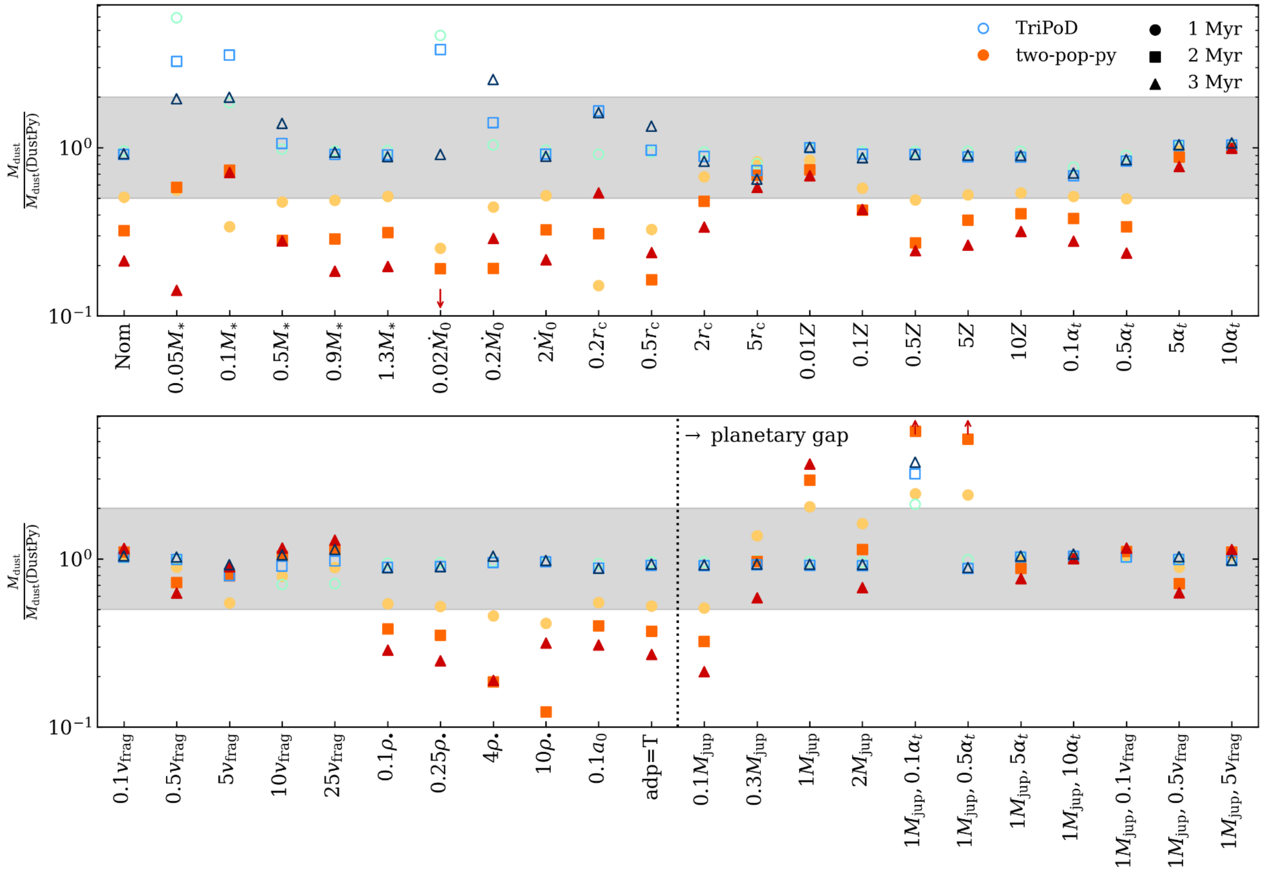


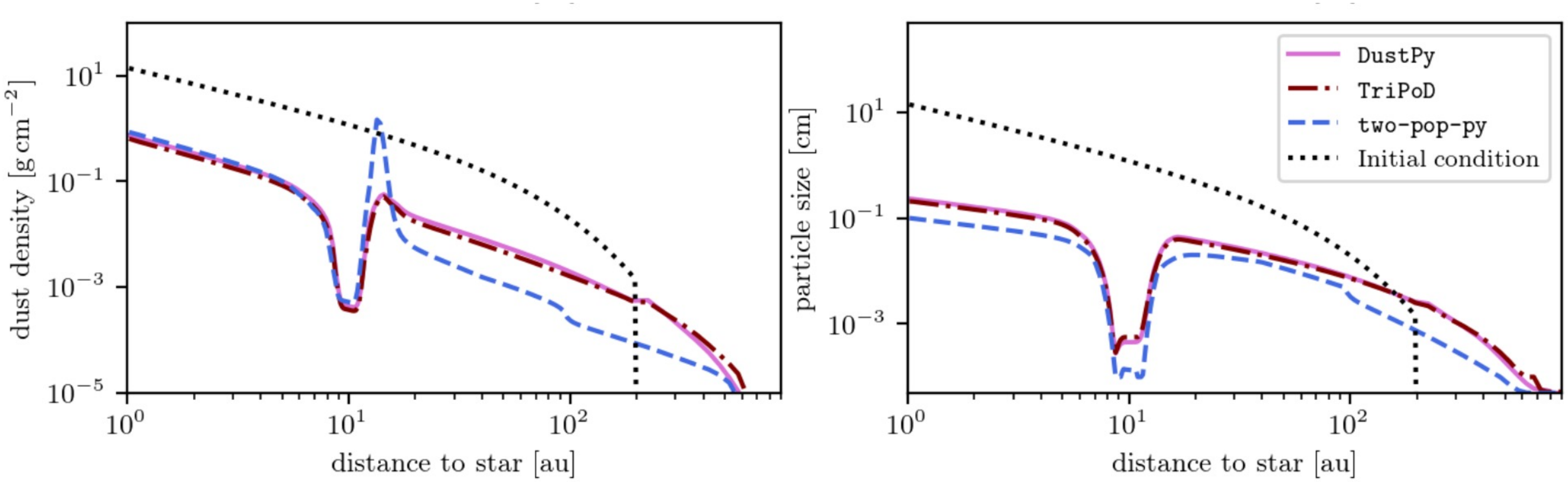
External photo evaporation



M* 0.3

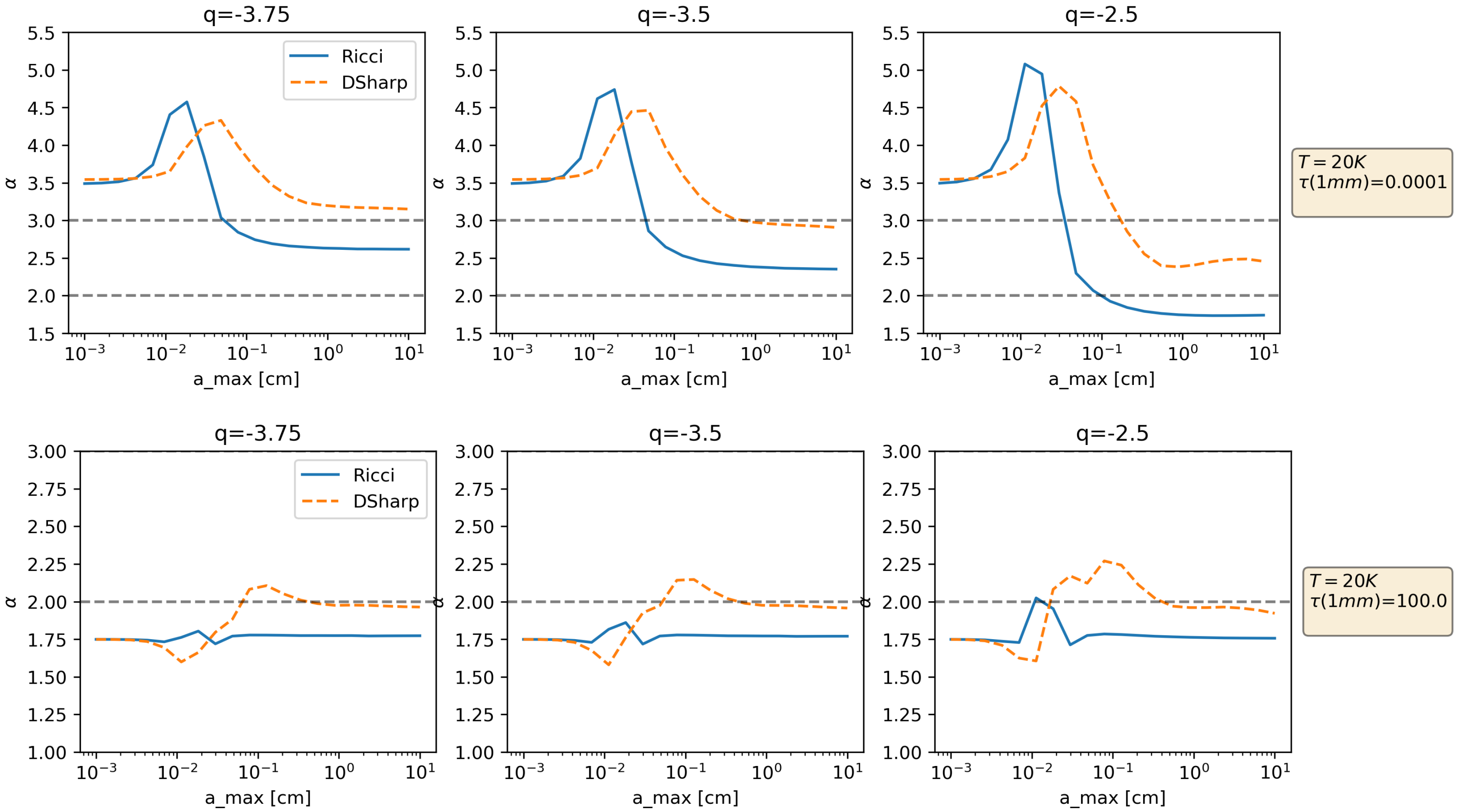
Pinilla+ 2025


TriPoD
two-pop-py
1 Myr
2 Myr
3 Myr
$\frac{M_{\rm dust}}{M_{\rm dust}(\rm DustPy)}$
10^0
10^{-1}
Nom
$0.05M_*$
$0.1M_*$
$0.5M_*$
$0.9M_*$
$1.3M_*$
$0.02\dot{M}_0$
$0.2\dot{M}_0$
$2\dot{M}_0$
$0.2r_c$
$0.5r_c$
$2r_c$
$5r_c$
$0.01Z$
$0.1Z$
$0.5Z$
$5Z$
$10Z$
$0.1\alpha_t$
$0.5\alpha_t$
$5\alpha_t$
$10\alpha_t$
→ planetary gap
$0.1v_{\rm frag}$
$0.5v_{\rm frag}$
$5v_{\rm frag}$
$10v_{\rm frag}$
$25v_{\rm frag}$
$0.1\rho_\bullet$
$0.25\rho_\bullet$
$4\rho_\bullet$
$10\rho_\bullet$
$0.1a_0$
adp=T
$0.1M_{\rm jup}$
$0.3M_{\rm jup}$
$1M_{\rm jup}$
$2M_{\rm jup}$
$1M_{\rm jup}$, $0.1\alpha_t$
$1M_{\rm jup}$, $0.5\alpha_t$
$1M_{\rm jup}$, $5\alpha_t$
$1M_{\rm jup}$, $10\alpha_t$
$1M_{\rm jup}$, $0.1v_{\rm frag}$
$1M_{\rm jup}$, $0.5v_{\rm frag}$
$1M_{\rm jup}$, $5v_{\rm frag}$

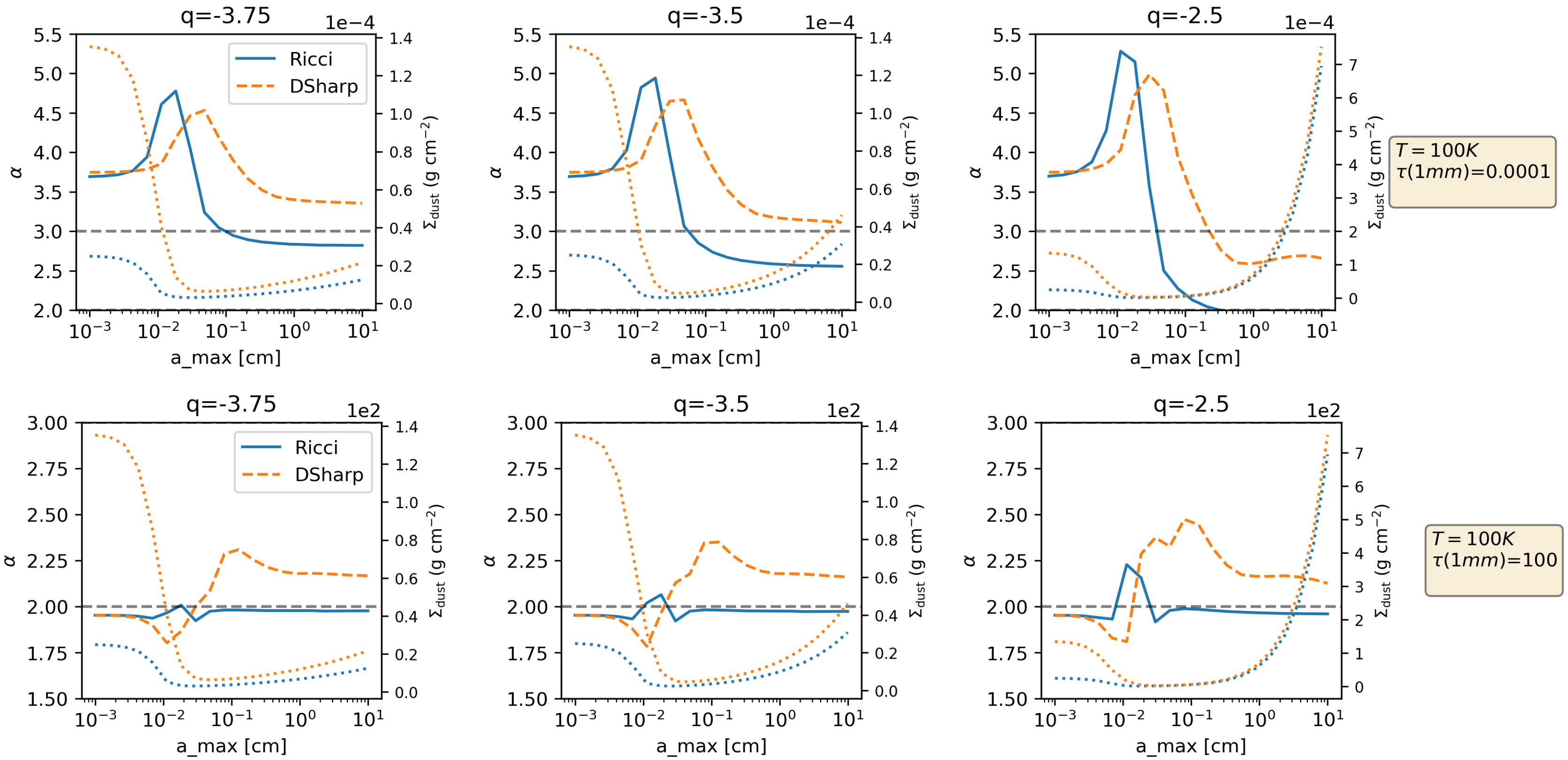


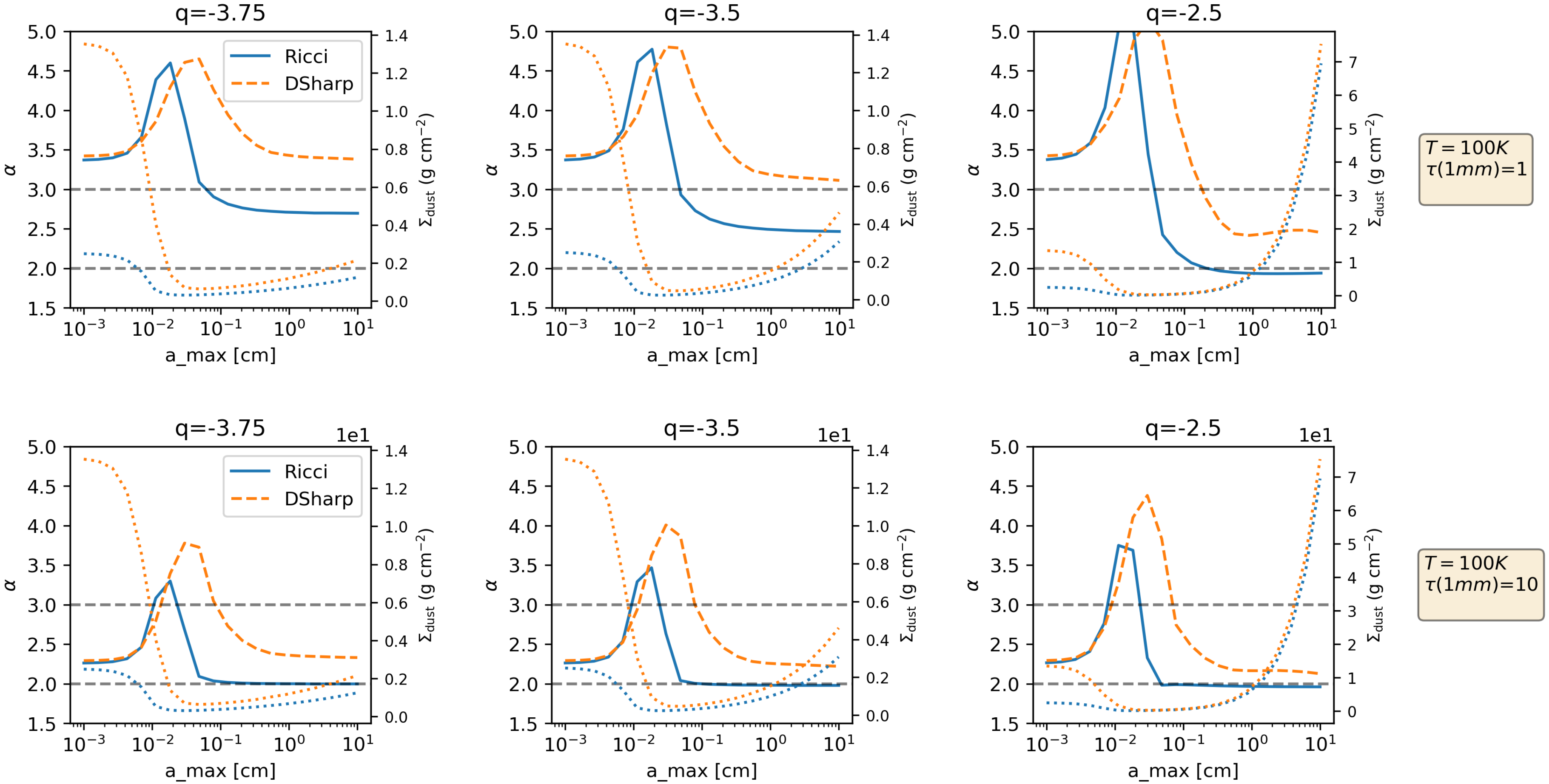
dust density [g cm^{-2}]
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{0}
10^{1}
10^{2}
distance to star [au]
particle size [cm]
10^{1}
10^{-1}
10^{-3}
10^{0}
10^{1}
10^{2}
distance to star [au]
DustPy
TriPoD
two-pop-py
Initial condition

Temperature effect



With Surface Density




q=-3.75
q=-3.5
q=-2.5
Ricci
DSharp
α
a_max [cm]
Σ_dust (g cm^-2)
1e1
T = 100K
τ(1mm)=1
T = 100K
τ(1mm)=10