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GAPS, RINGS, SPIRALS, AND VORTICES: STRUCTURE FORMATION IN PLANET-FORMING DISKS

Garching 22.10.21

A Large Population Study of Protoplanetary Disks

Explaining the Size-Luminosity relation with or without sub-structure

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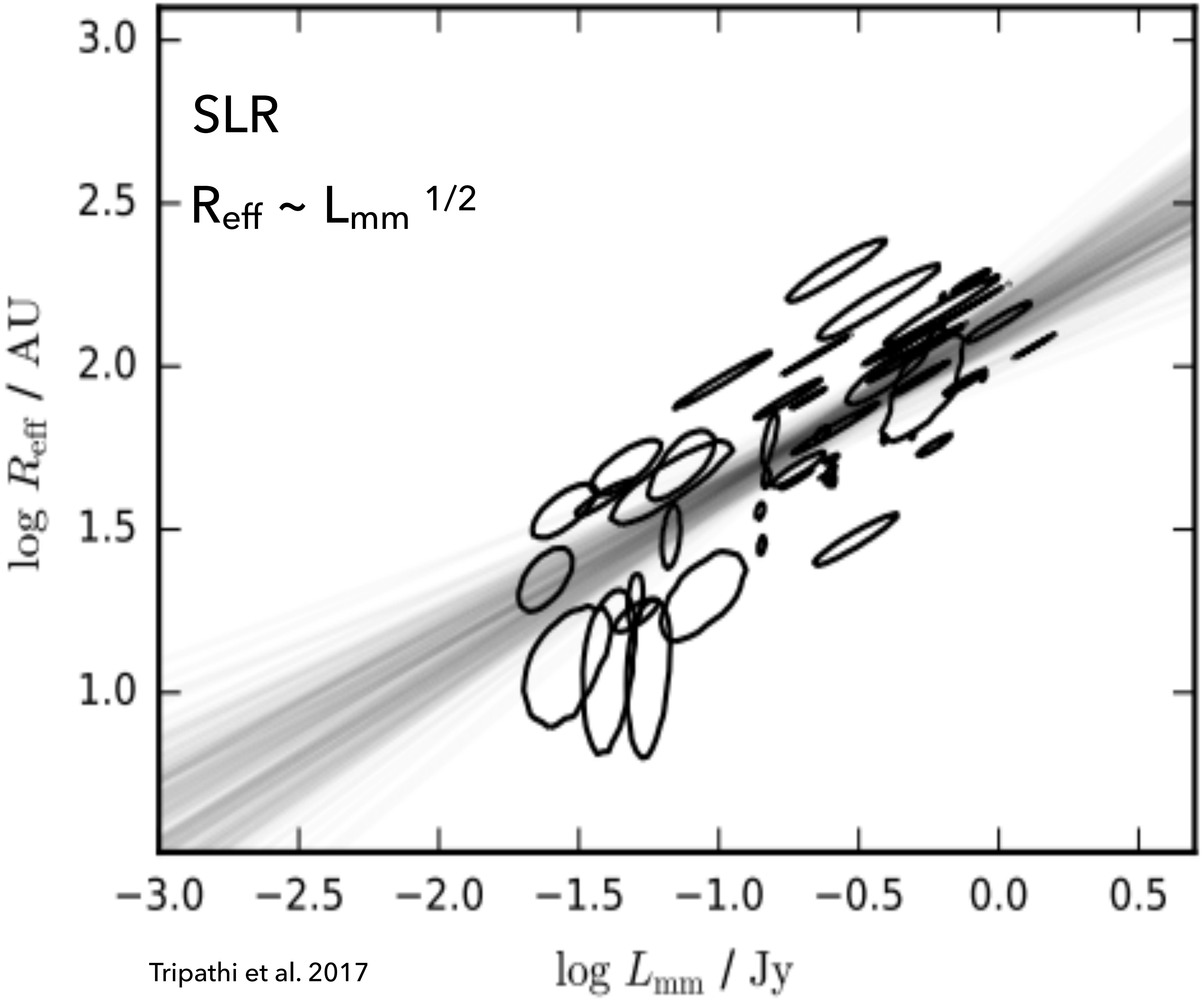
ABSTRACT

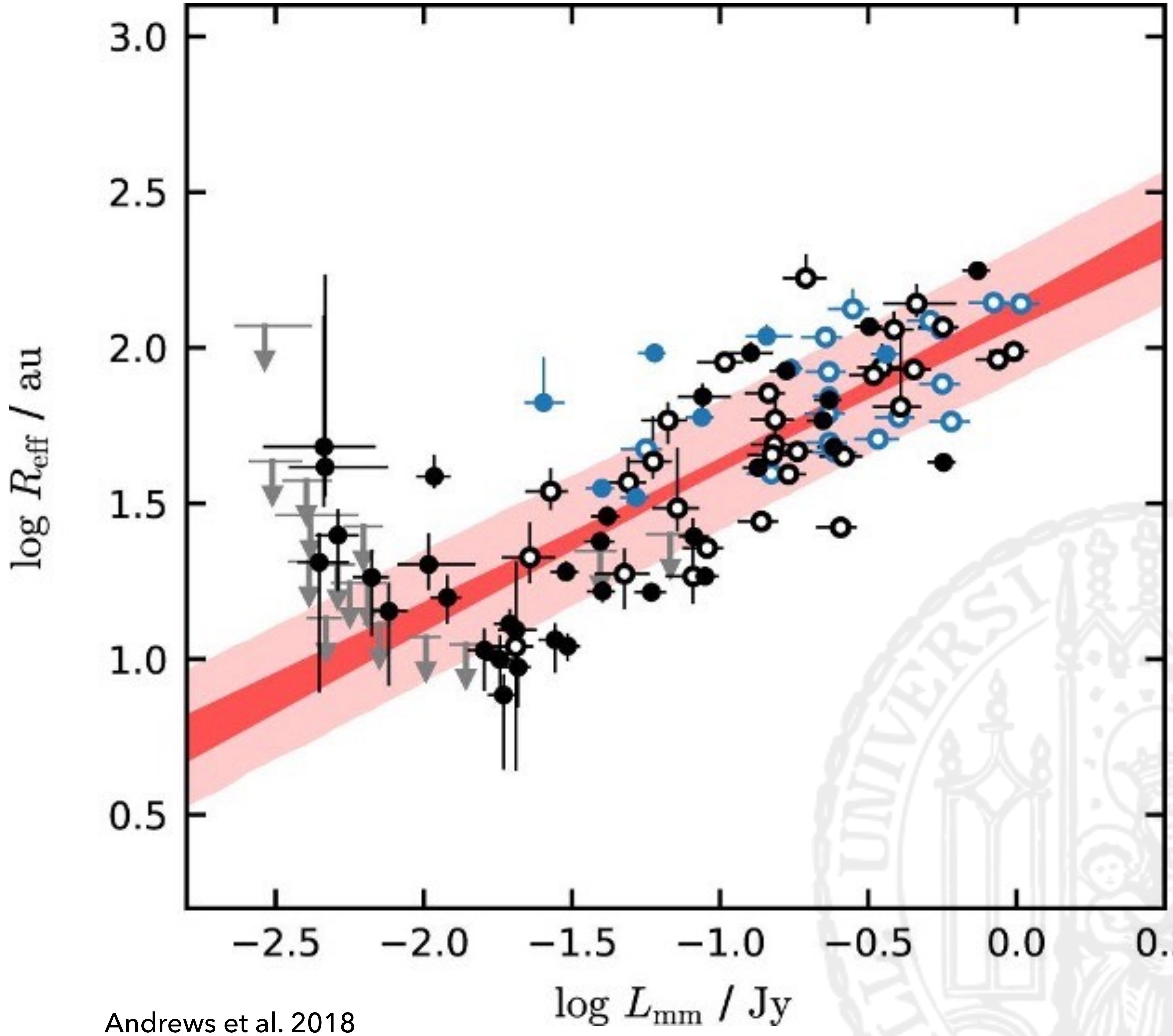
Recent sub-arcsecond resolution surveys of the dust continuum emission from nearby protoplanetary disks showed a strong correlation between the sizes and luminosities of the disks. We aim to explain the origin of the size-luminosity relation (SLR) between the 68% effective radius ($r_{\rm eff}$) of disks with their continuum luminosity ($L_{\rm mm}$), with models of gas and dust evolution in a simple viscous accretion disk and radiative transfer calculations.
We use a large grid of models (10^5 simulations) with and without planetary gaps, varying the initial conditions of the key parameters. We calculate the disk continuum emission and the effective radius for all models as a function of time. By selecting those simulations that continuously follow the SLR, we can derive constraints on the input parameters of the models.
We confirm previous results that models of smooth disks in the radial drift regime are compatible with the observed SLR ($L_{\rm mm} \propto r_{\rm eff}^2$) but only smooth disks cannot be the reality. We show that a larger fraction of disks populates the SLR if planets are present. However they tend to follow a different relation than smooth disks, potentially implying that a mixture of smooth and sub-structured disks are present in the observed sample. We derive a SLR ($L_{\rm mm} \propto r_{\rm eff}^{5/4}$) for disks with strong sub-structure. To be compatible with the SLR, models need to have an initially high disk mass ($\geq 2.5 \cdot 10^{-2} M_\star$) and low turbulence-parameter α values ($\leq 10^{-3}$). Furthermore, we find that the grain composition and porosity drastically affects the evolution of disks on the size-luminosity diagram where relatively compact grains that include amorphous carbon are favoured. Moreover, a uniformly optically thick disk with high albedo (0.9) that follows the SLR cannot be formed from an evolutionary procedure.

Key words. Accretion disks – Planets and satellites: formation – Protoplanetary disks – Circumstellar matter

Motivation

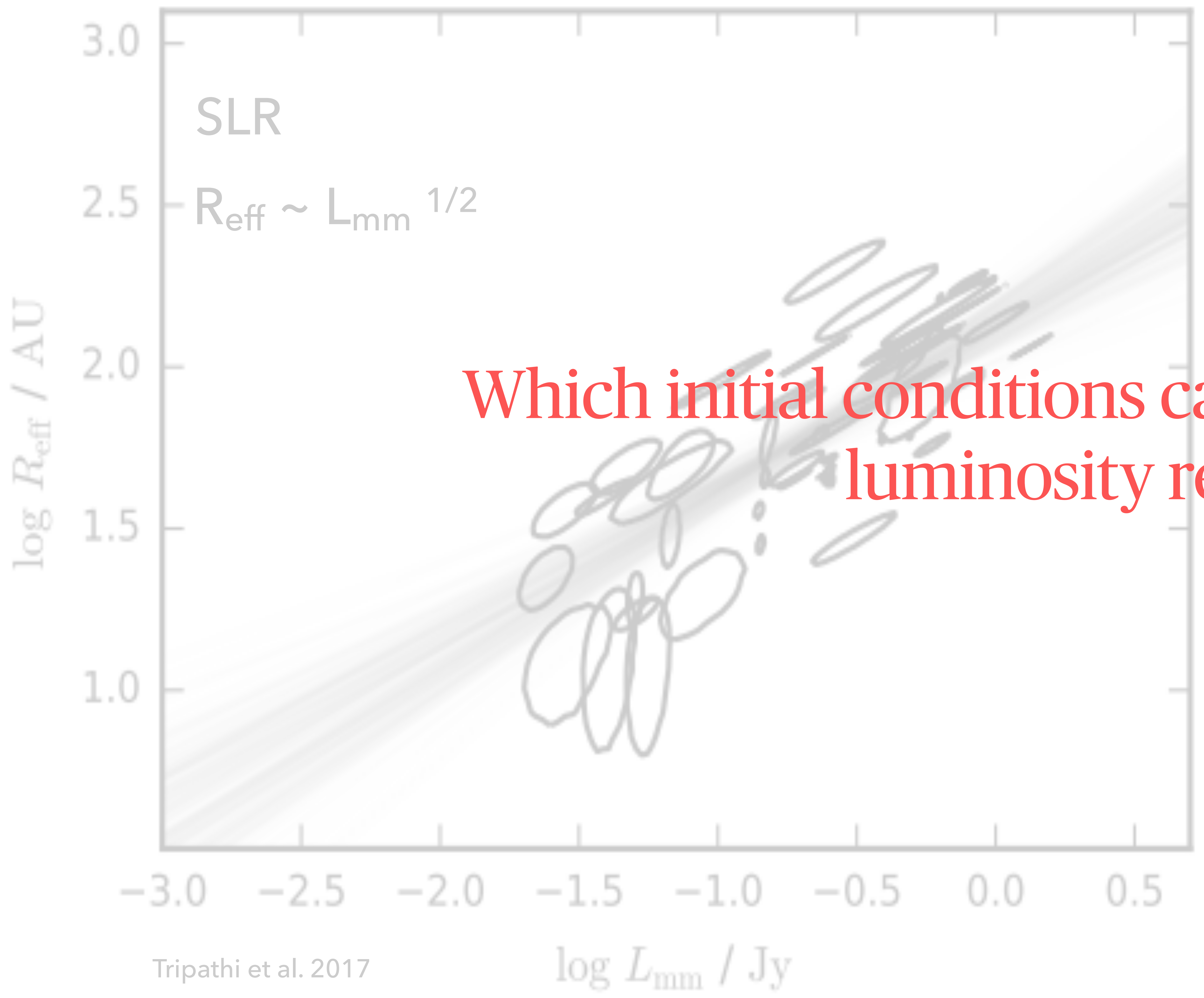


Tripathi et al. 2017

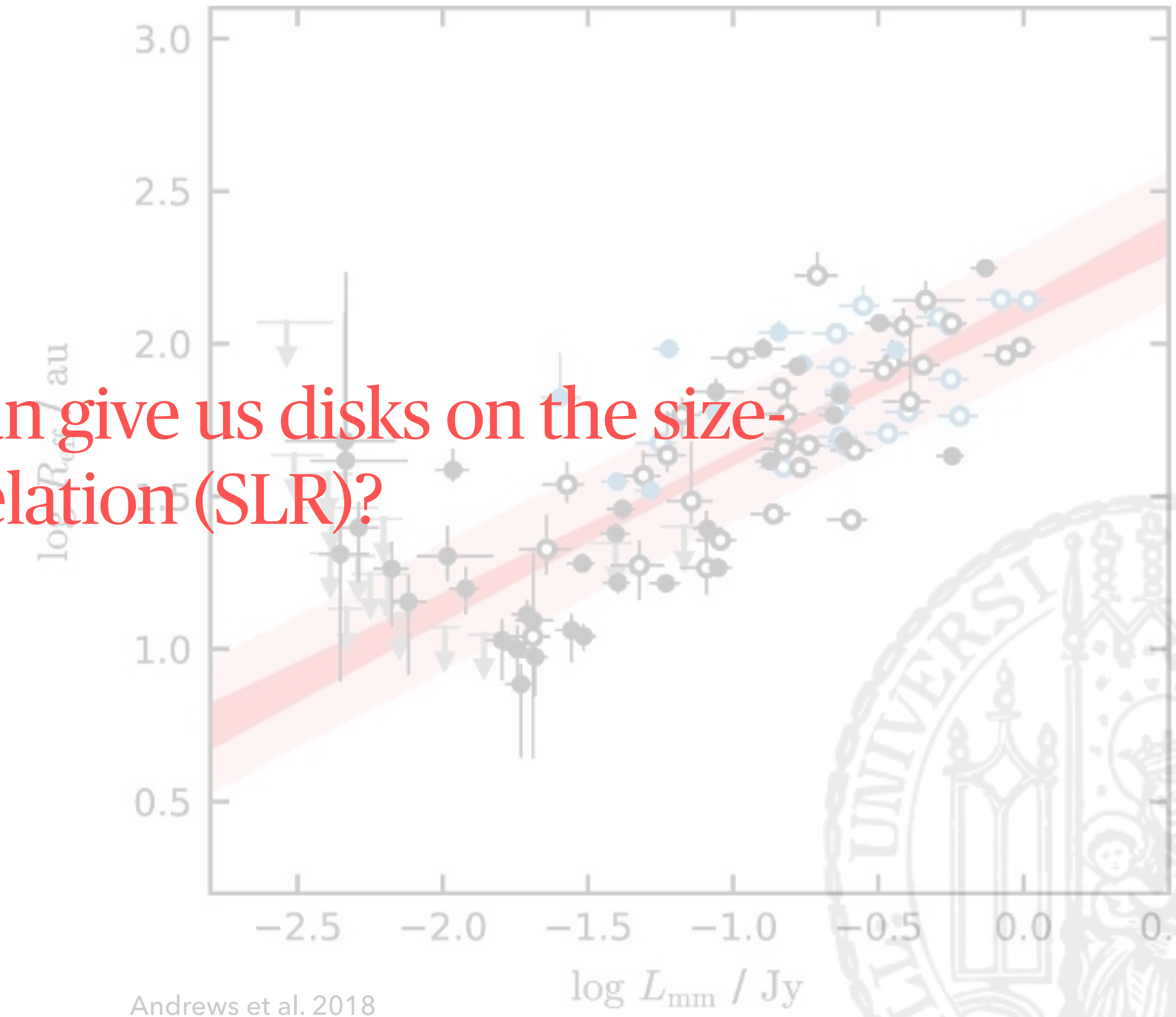


Andrews et al. 2018

Motivation



Tripathi et al. 2017



Andrews et al. 2018

Which initial conditions can give us disks on the size-luminosity relation (SLR)?

Parameter Grid

Parameter	Description	Value-Range
α	viscosity parameter	10^{-4} - 2.5×10^{-2}
M_d [M_*]	initial disk mass	10^{-3} - 2.5×10^{-1}
M_* [$M_\odot$]	stellar mass	0.2 - 2.0
r_c [au]	characteristic radius	10 - 230
v_f [cm/s]	fragmentation velocity	200 - 2000
q Kanagawa et al. 2016	planet/star mass ratio	3×10^{-4}, 10^{-3}, 3×10^{-3}
r_p [r_c]	planet position	1/3, 2/3

Simulations performed with *two-pop-py* model by Birnstiel et al. 2012.

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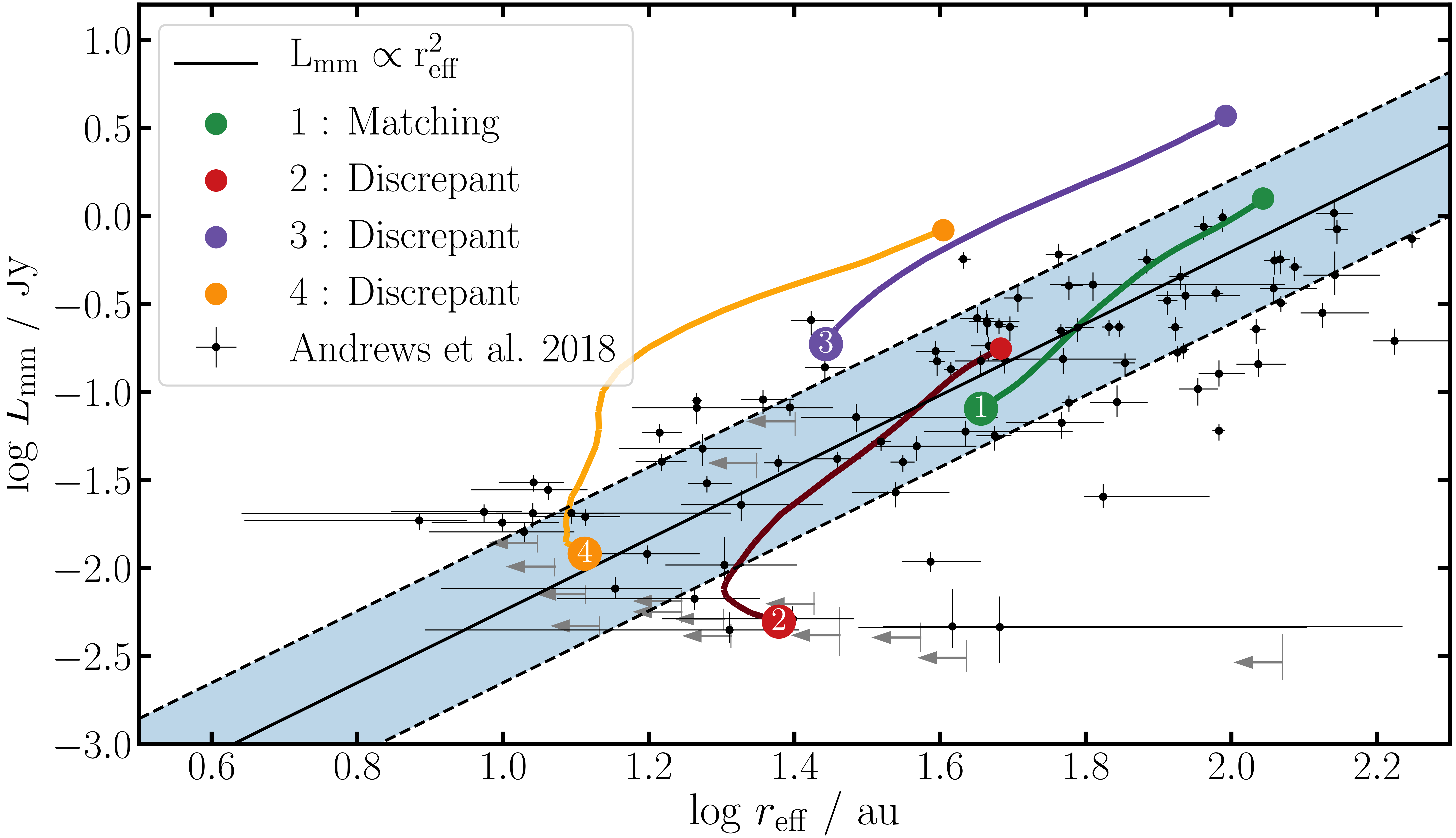
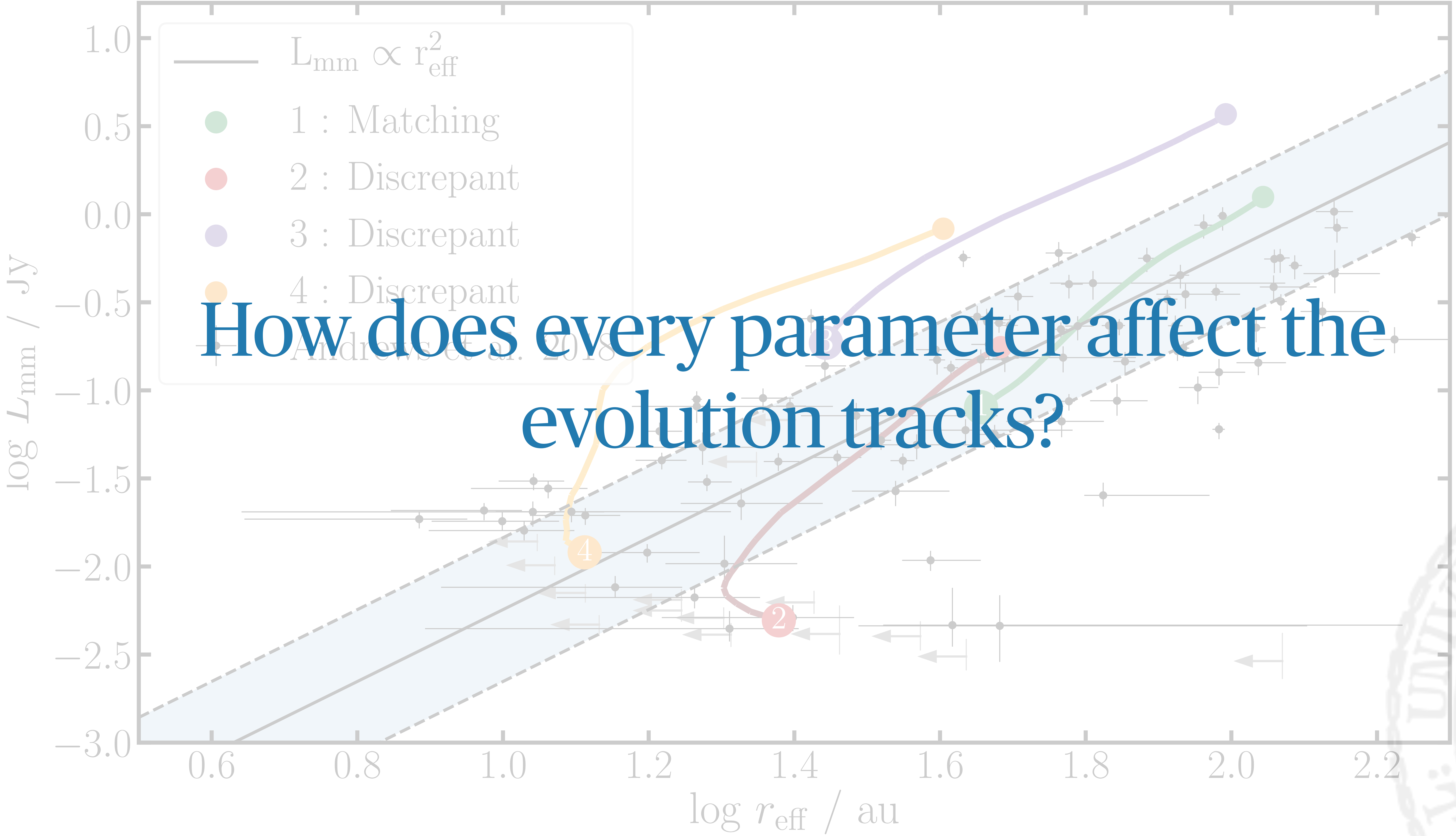
100.000 simulations

Simulations performed with *two-pop-py* model by Birnstiel et al. 2012.

Evolution tracks



Evolution tracks



How does every parameter affect the evolution tracks?

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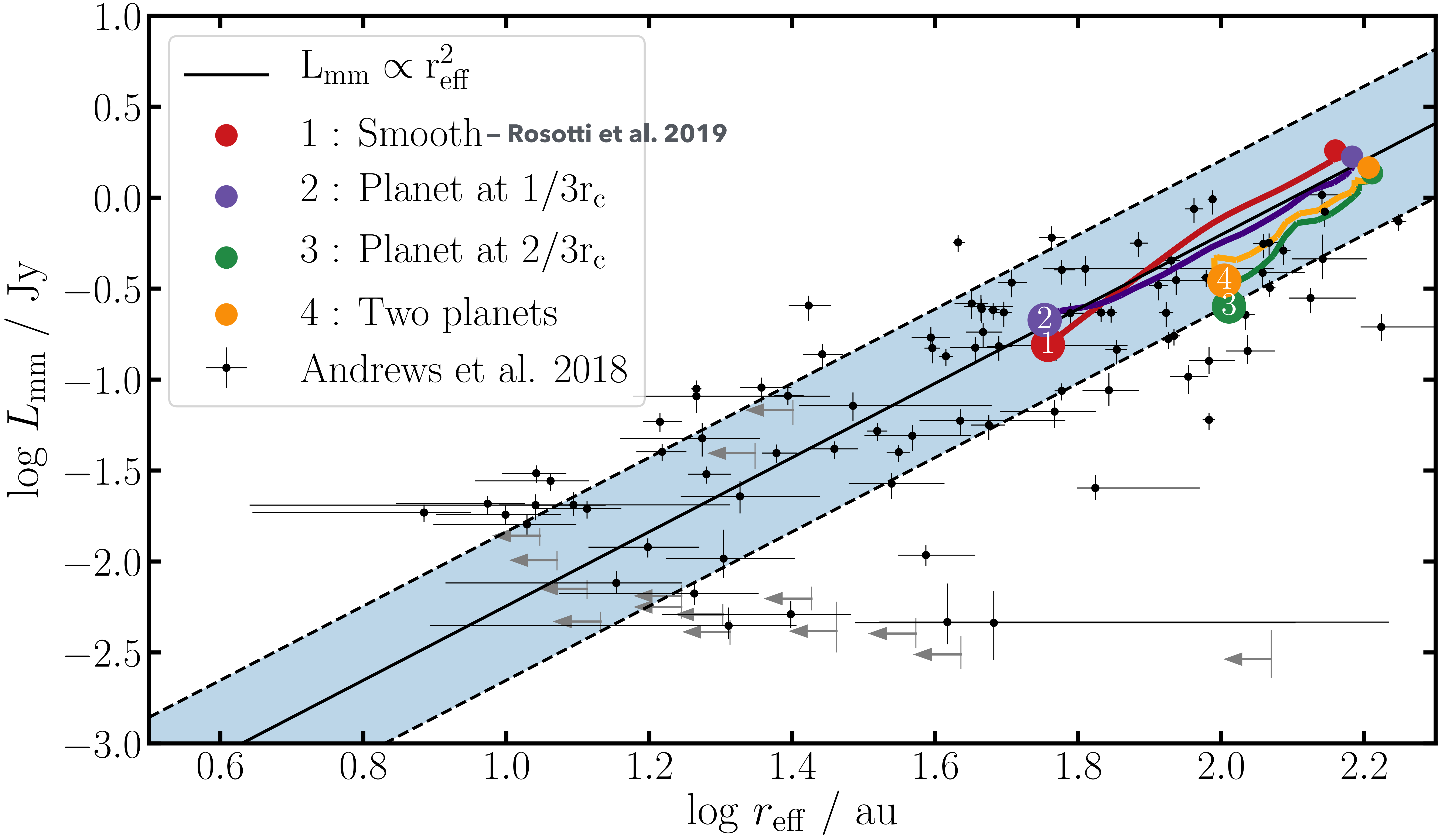
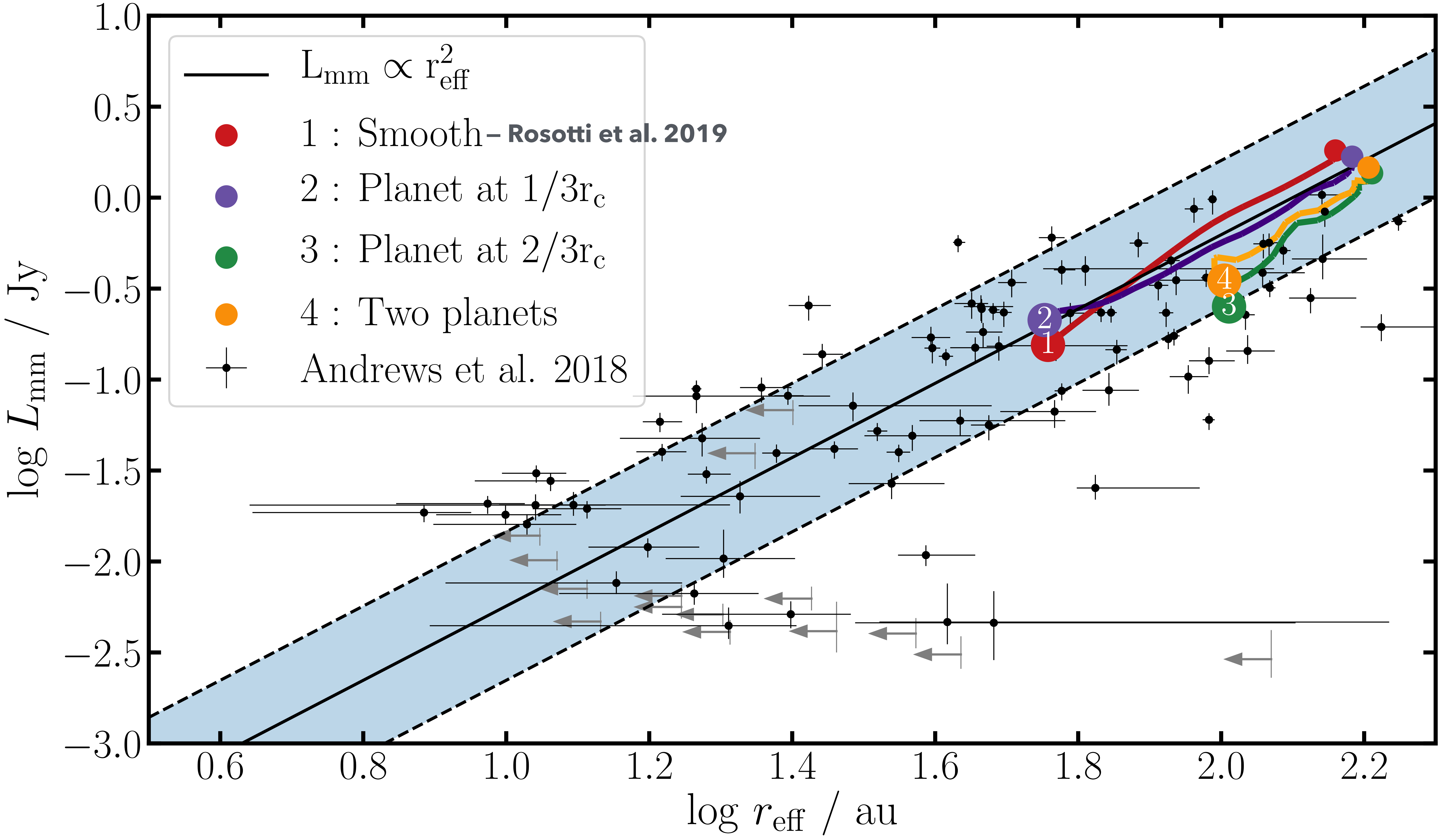
Dependence on the planet position

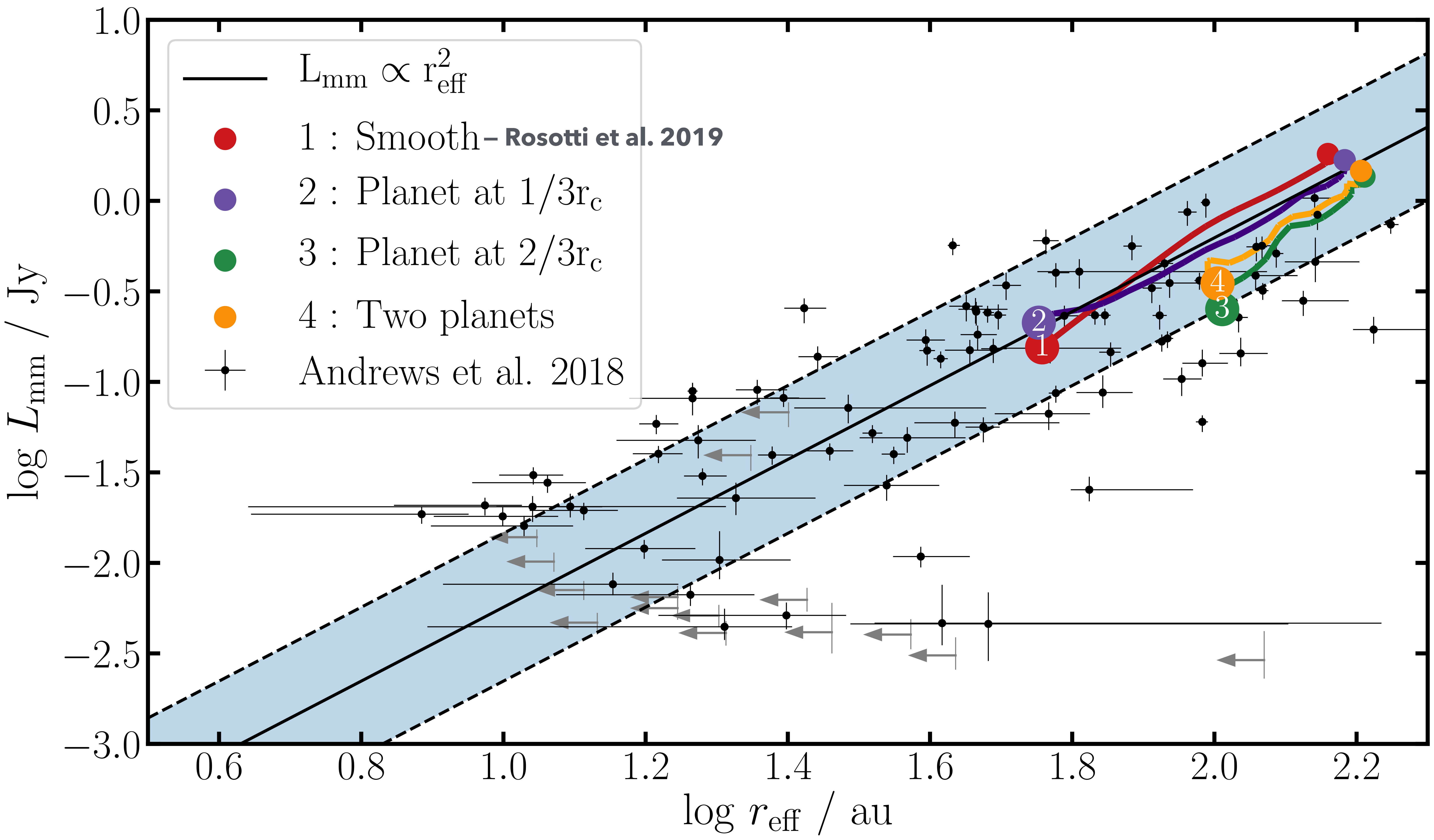


Dependence on the planet position



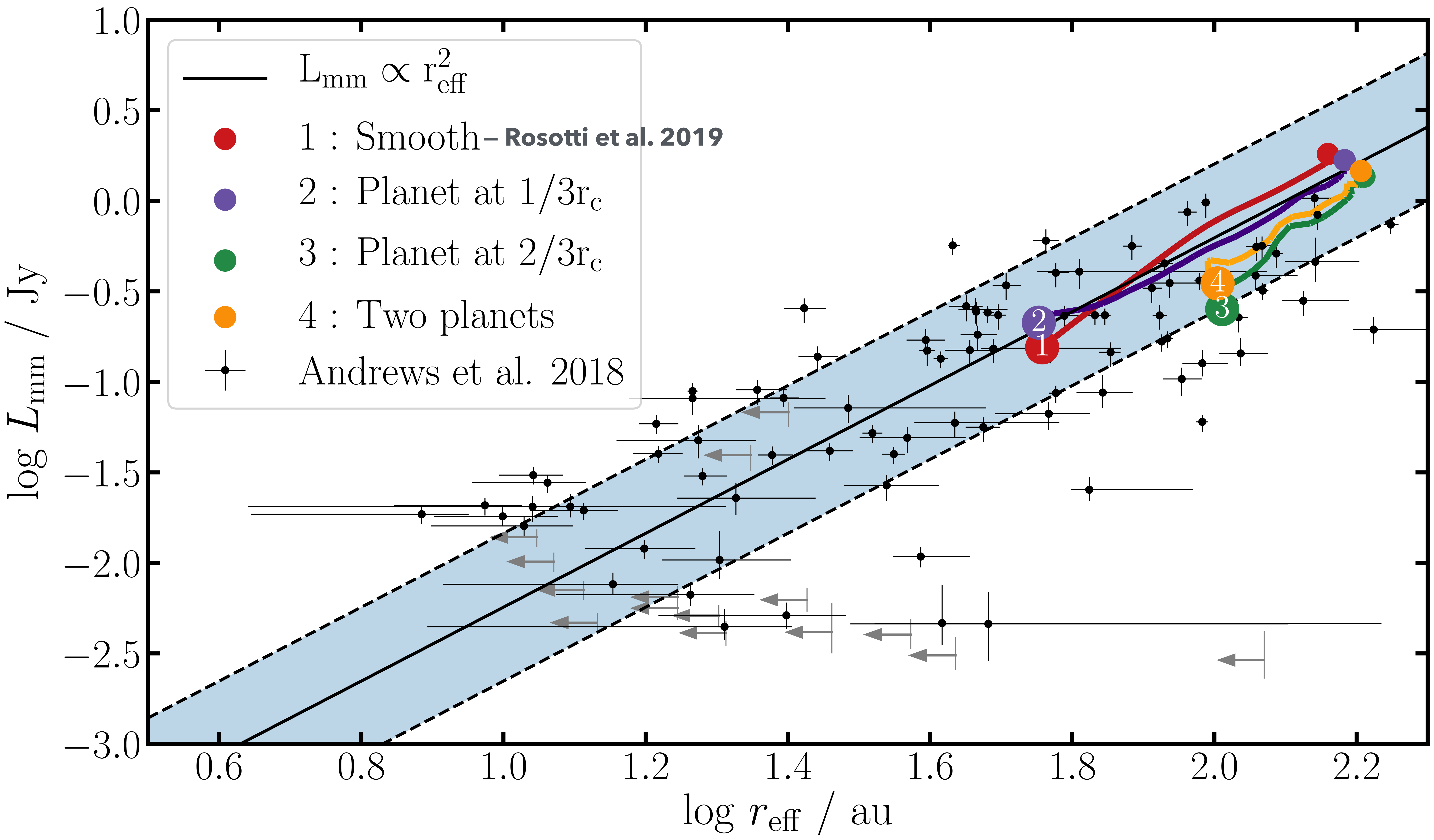
Smooth

Dependence on the planet position



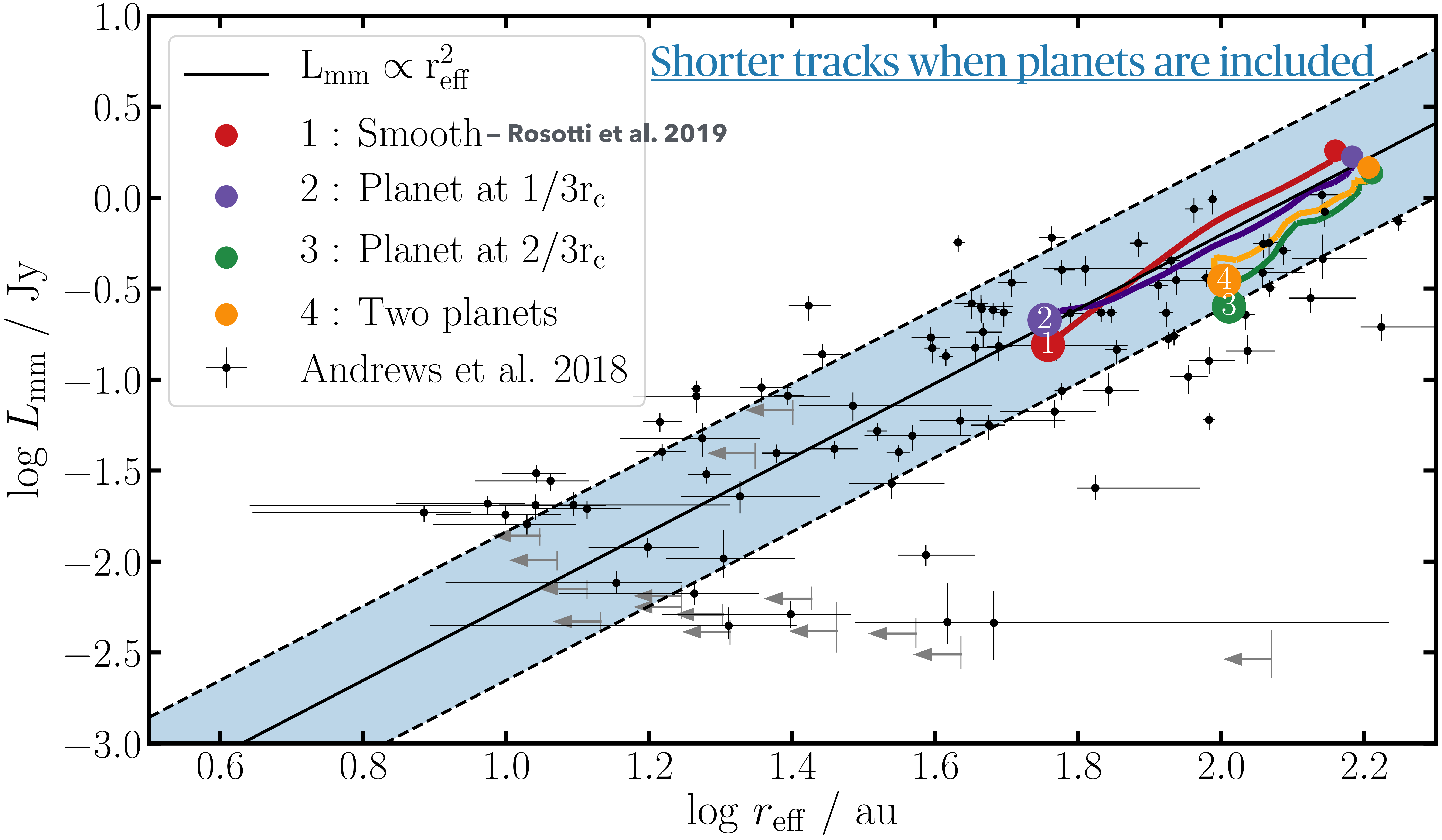
Smooth

Dependence on the planet position



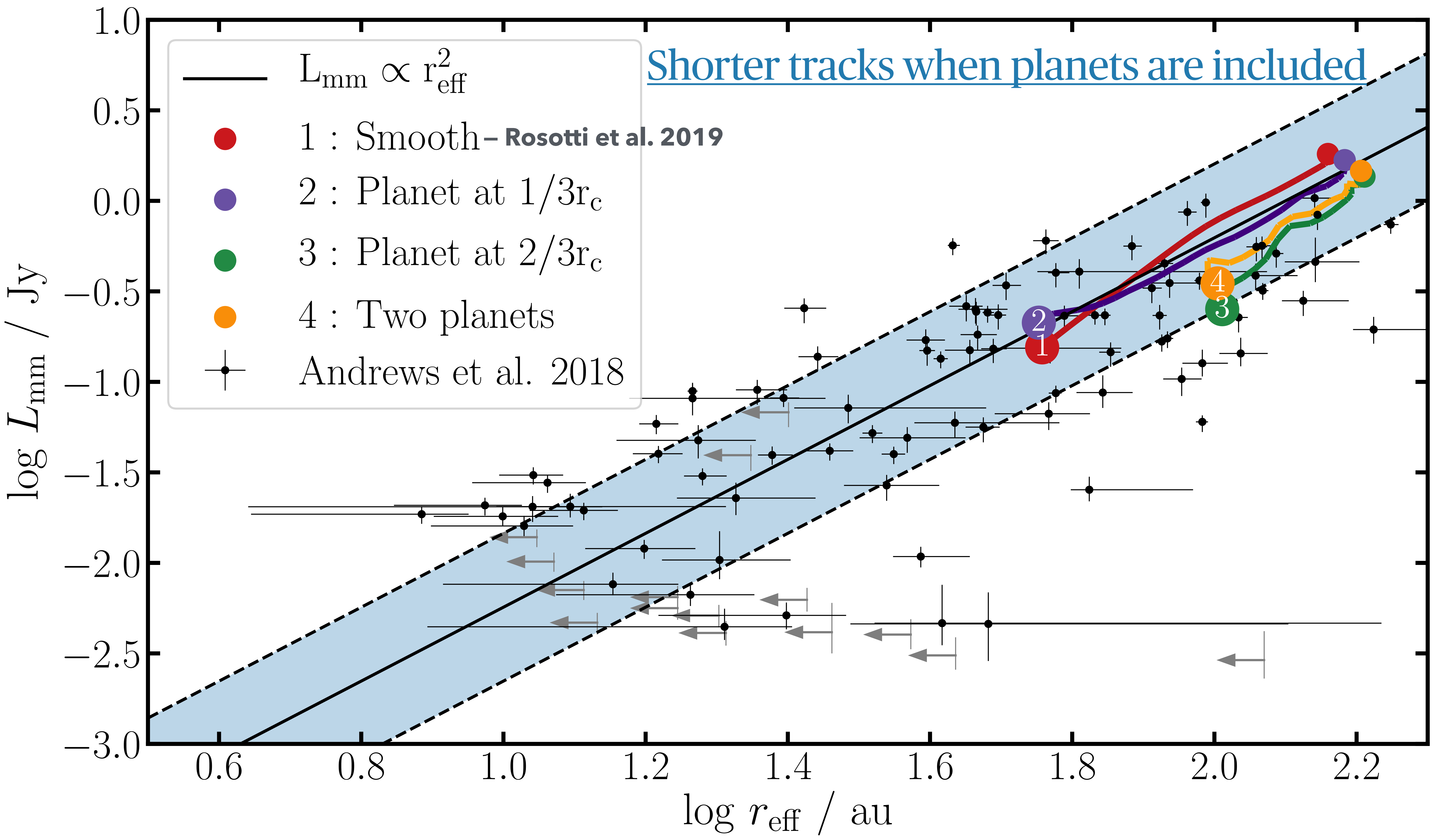
Single planet

Dependence on the planet position



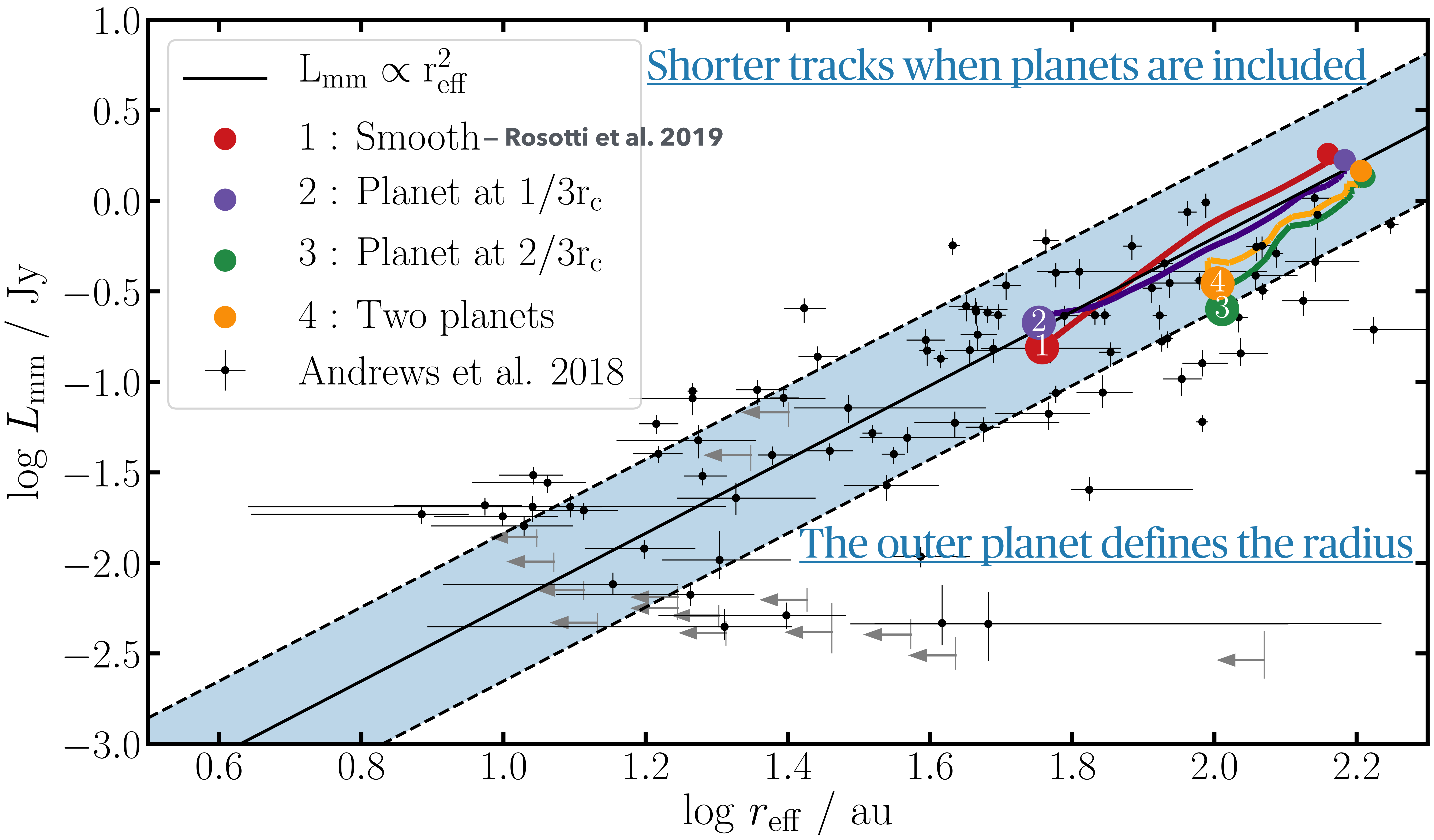
Single planet

Dependence on the planet position



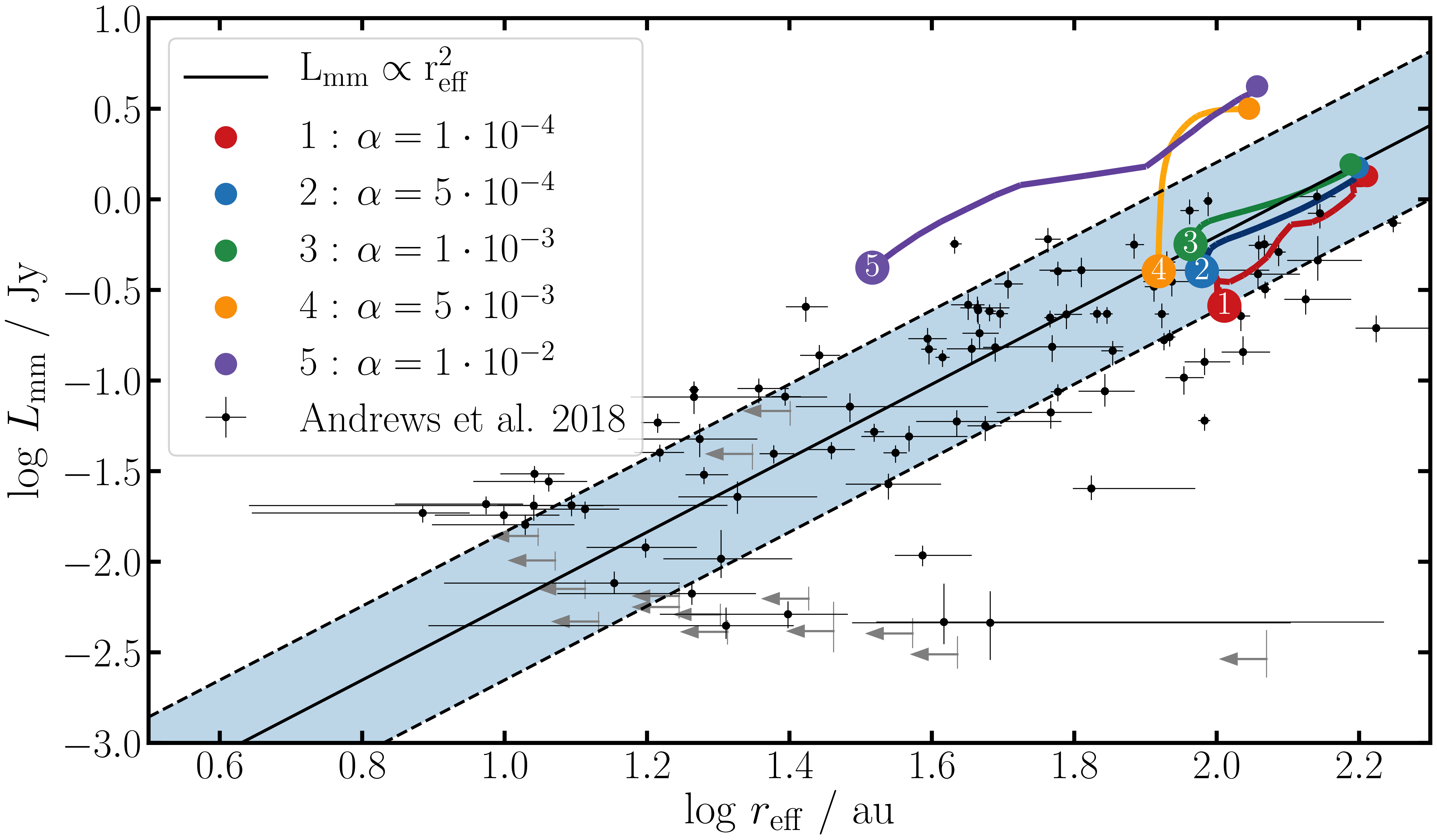
Two planets

Dependence on the planet position

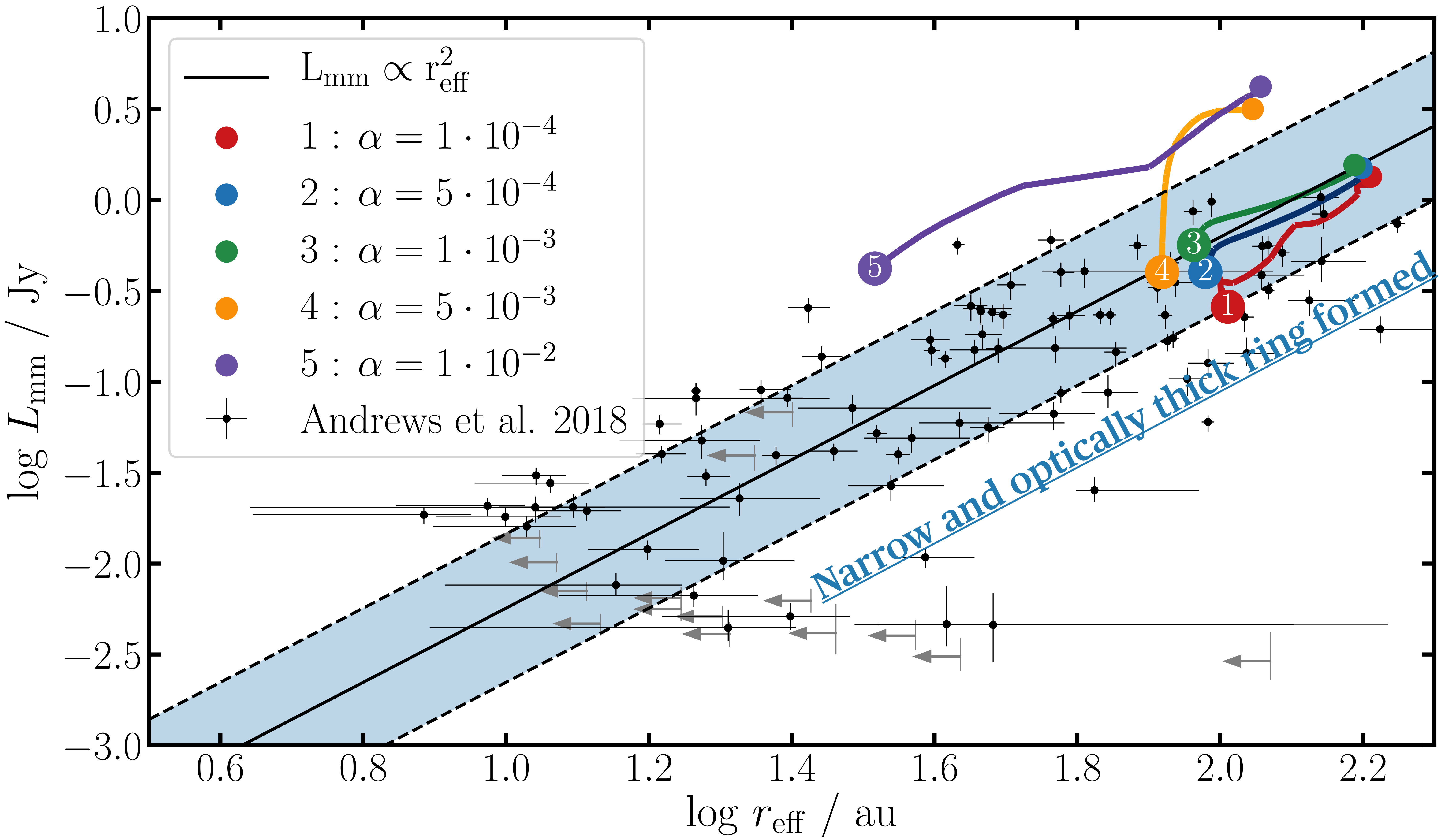


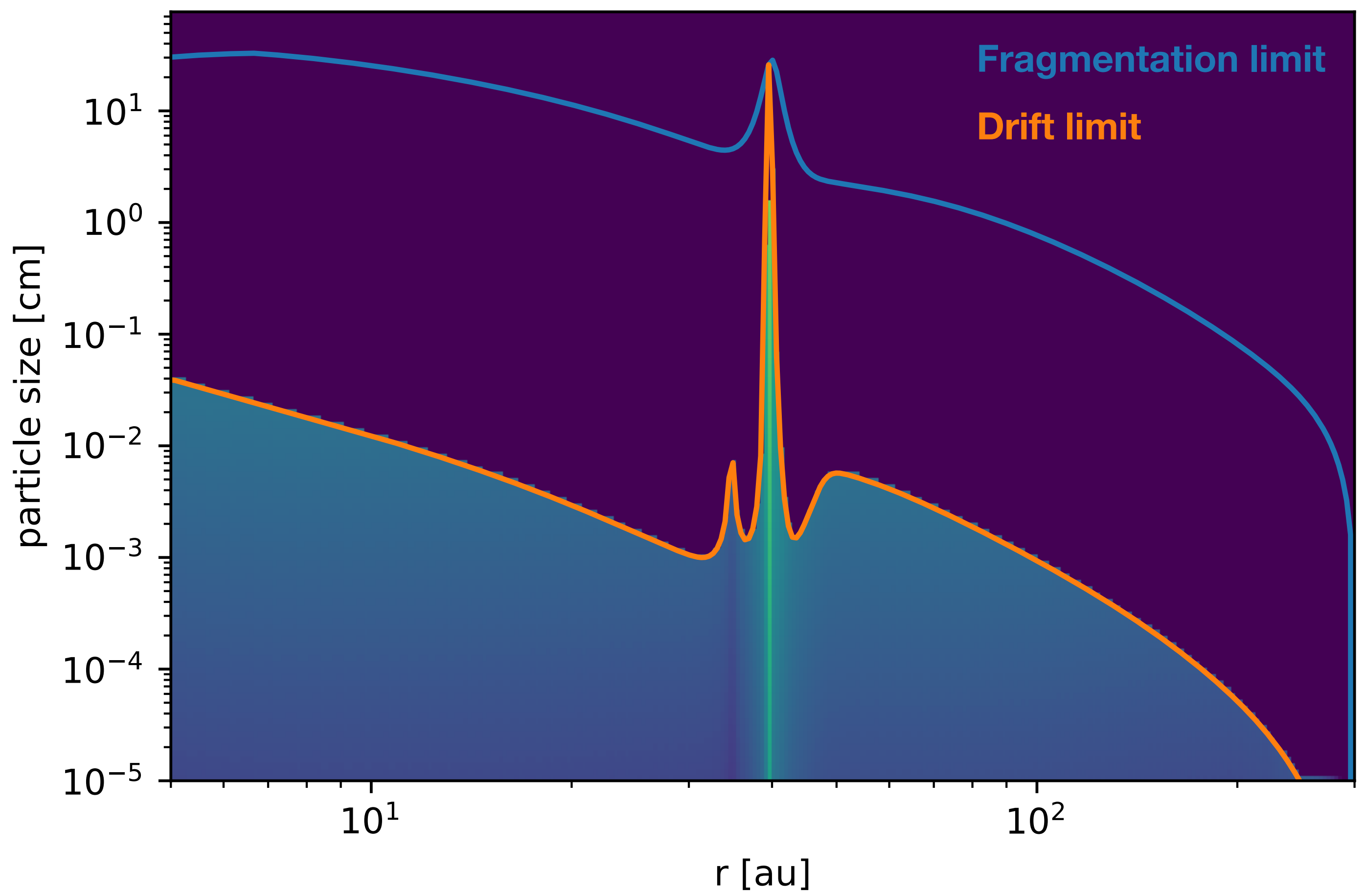
Two planets

Dependence on the α-parameter



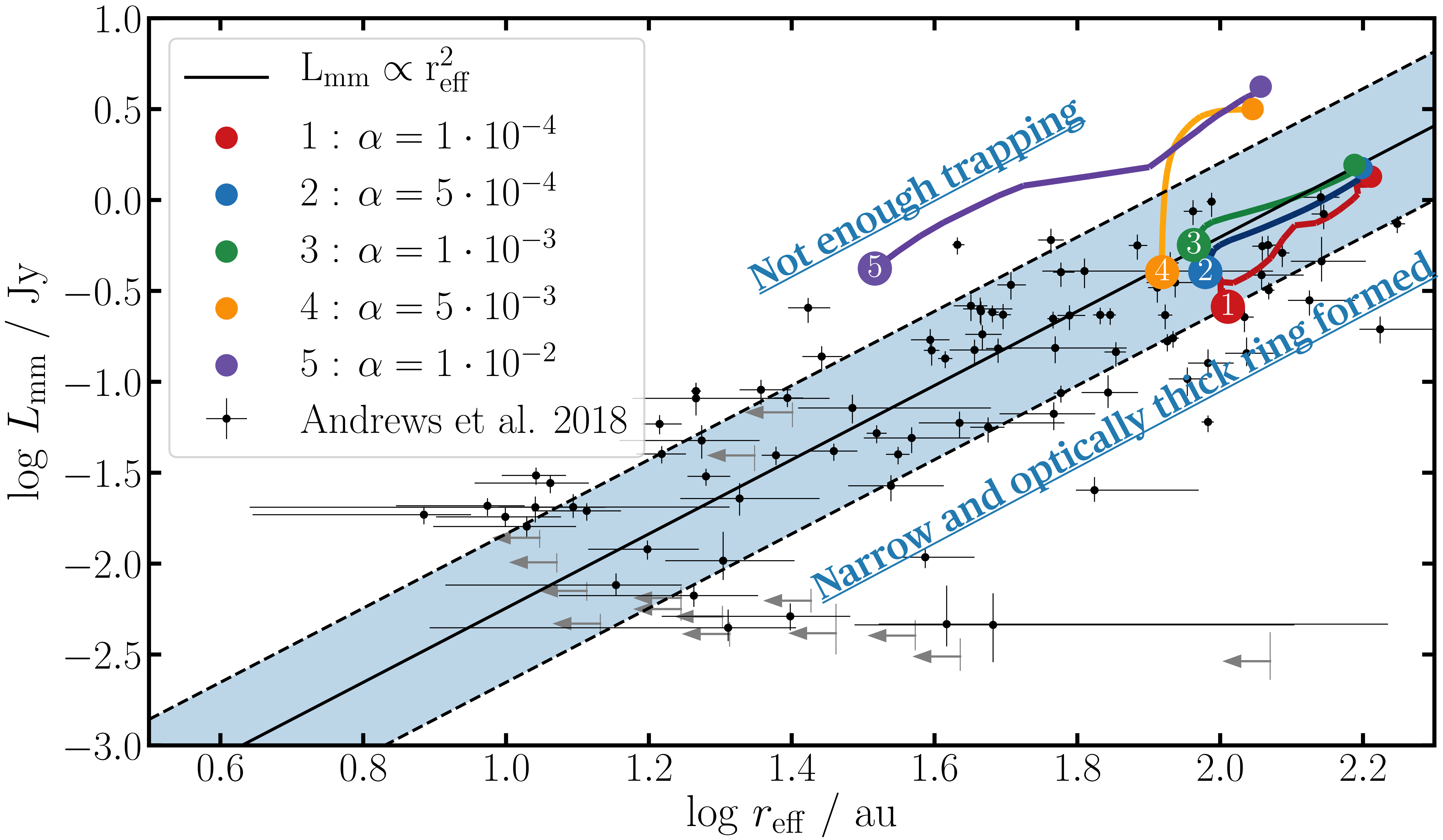
Dependence on the α-parameter

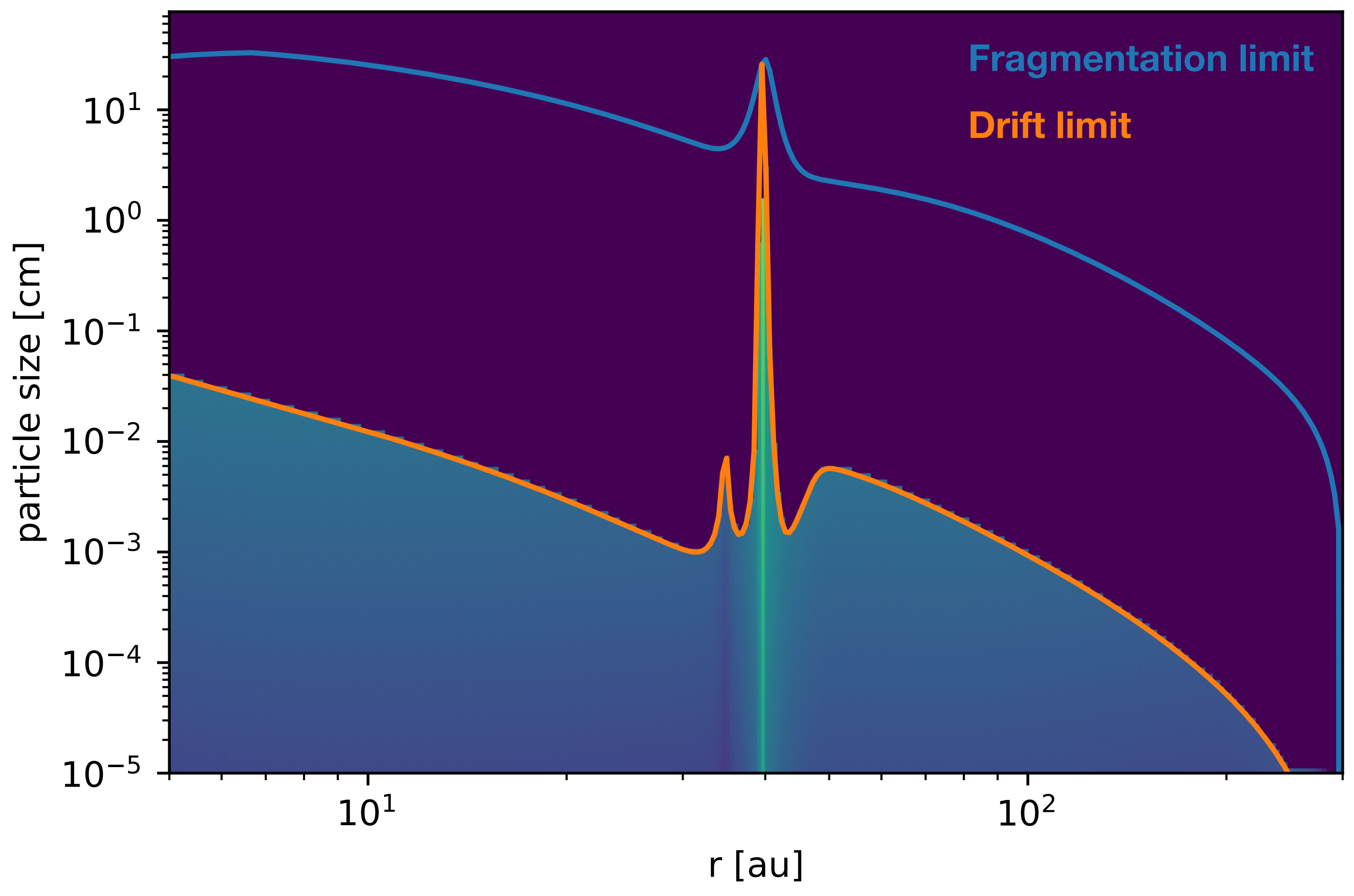




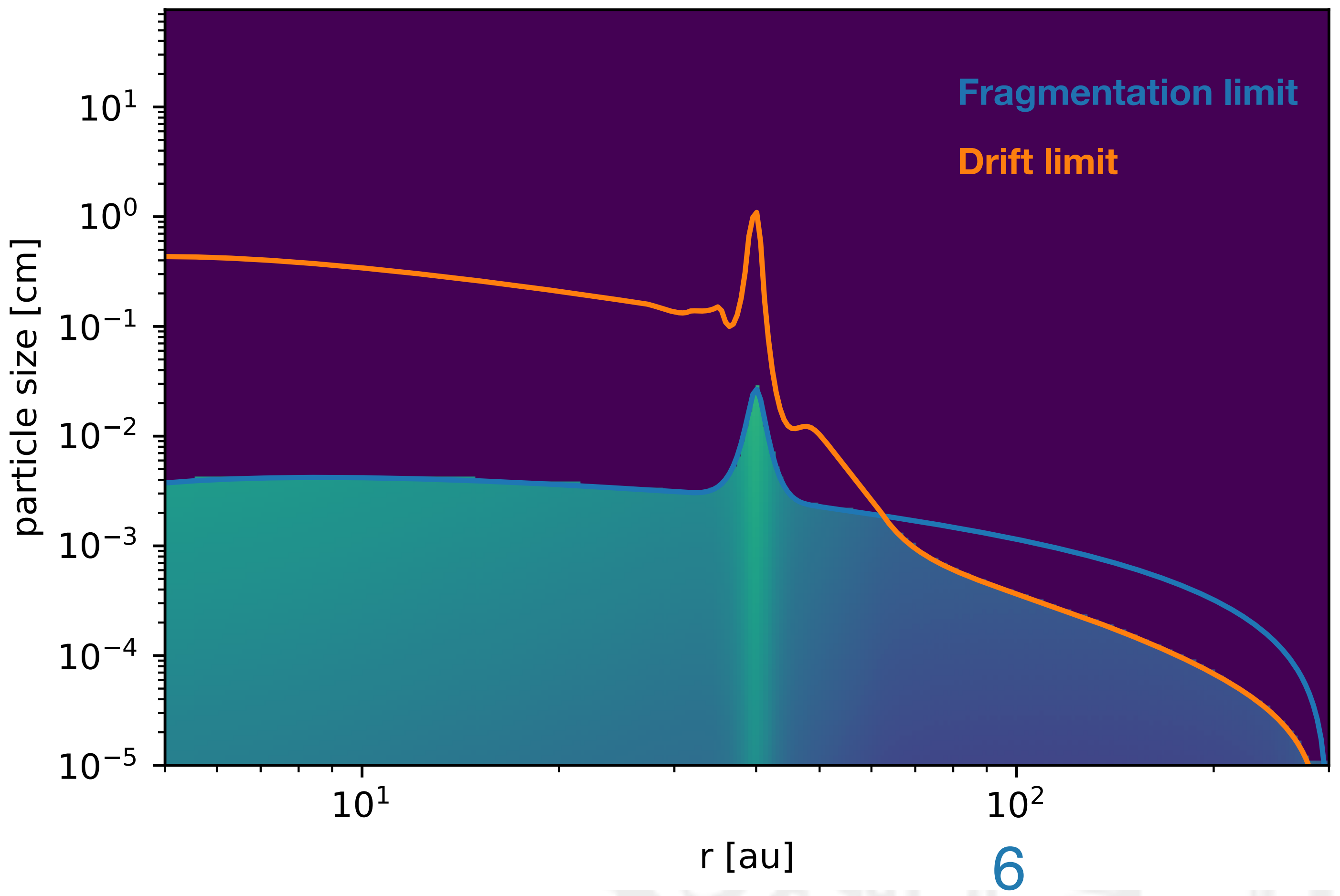
$\alpha = 10^{-4}$

Dependence on the α-parameter



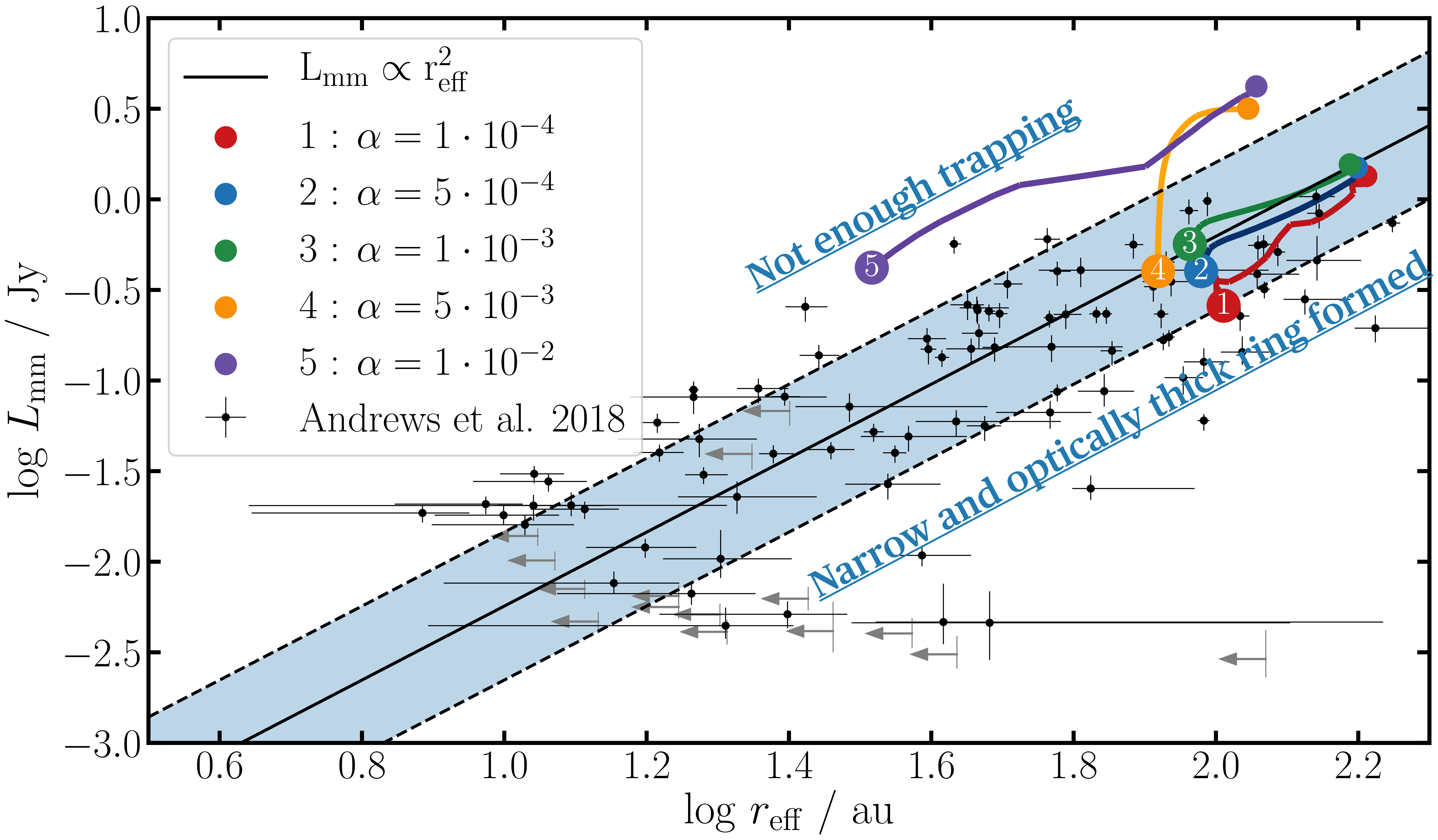


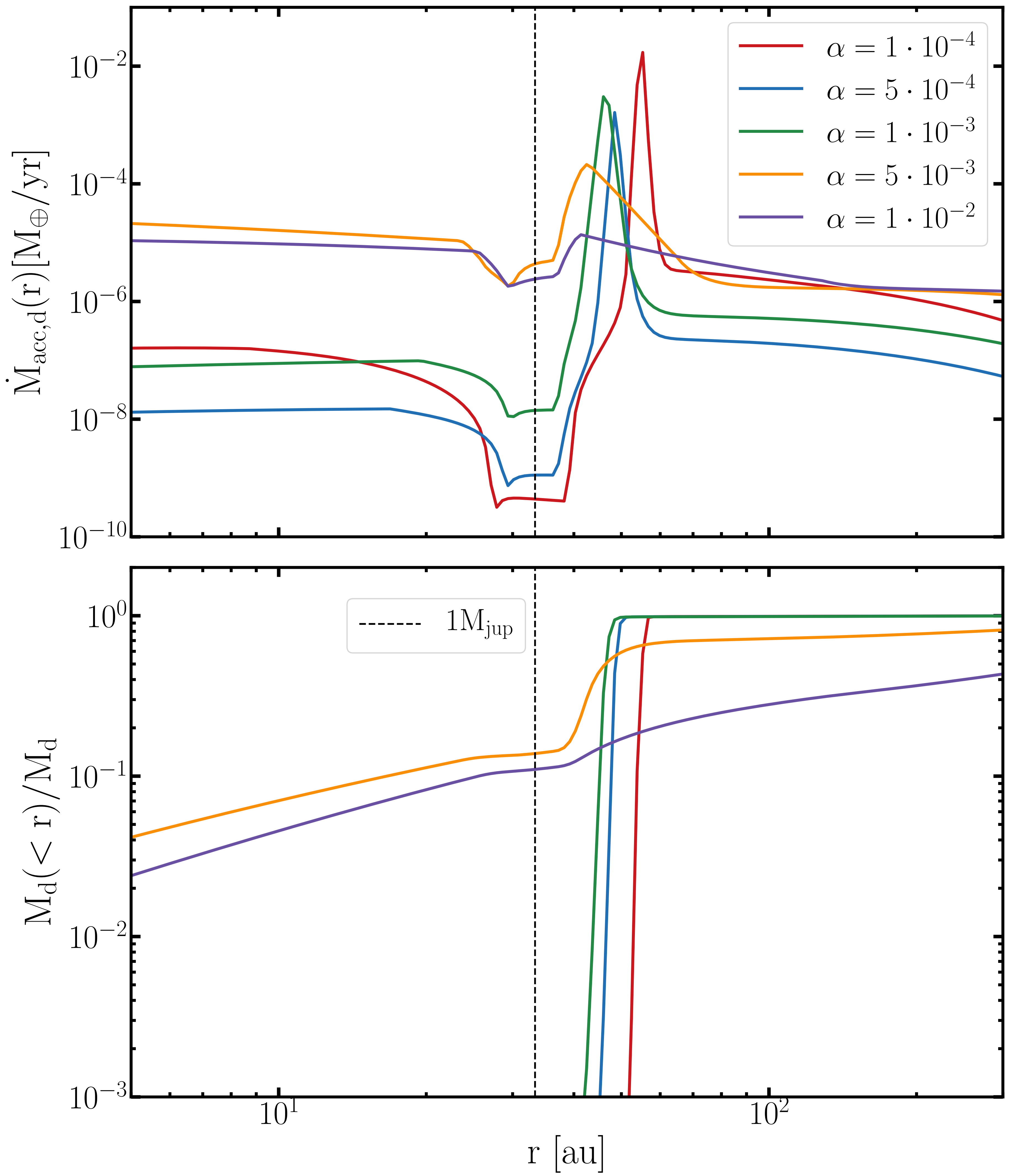
α = 10^{-4}



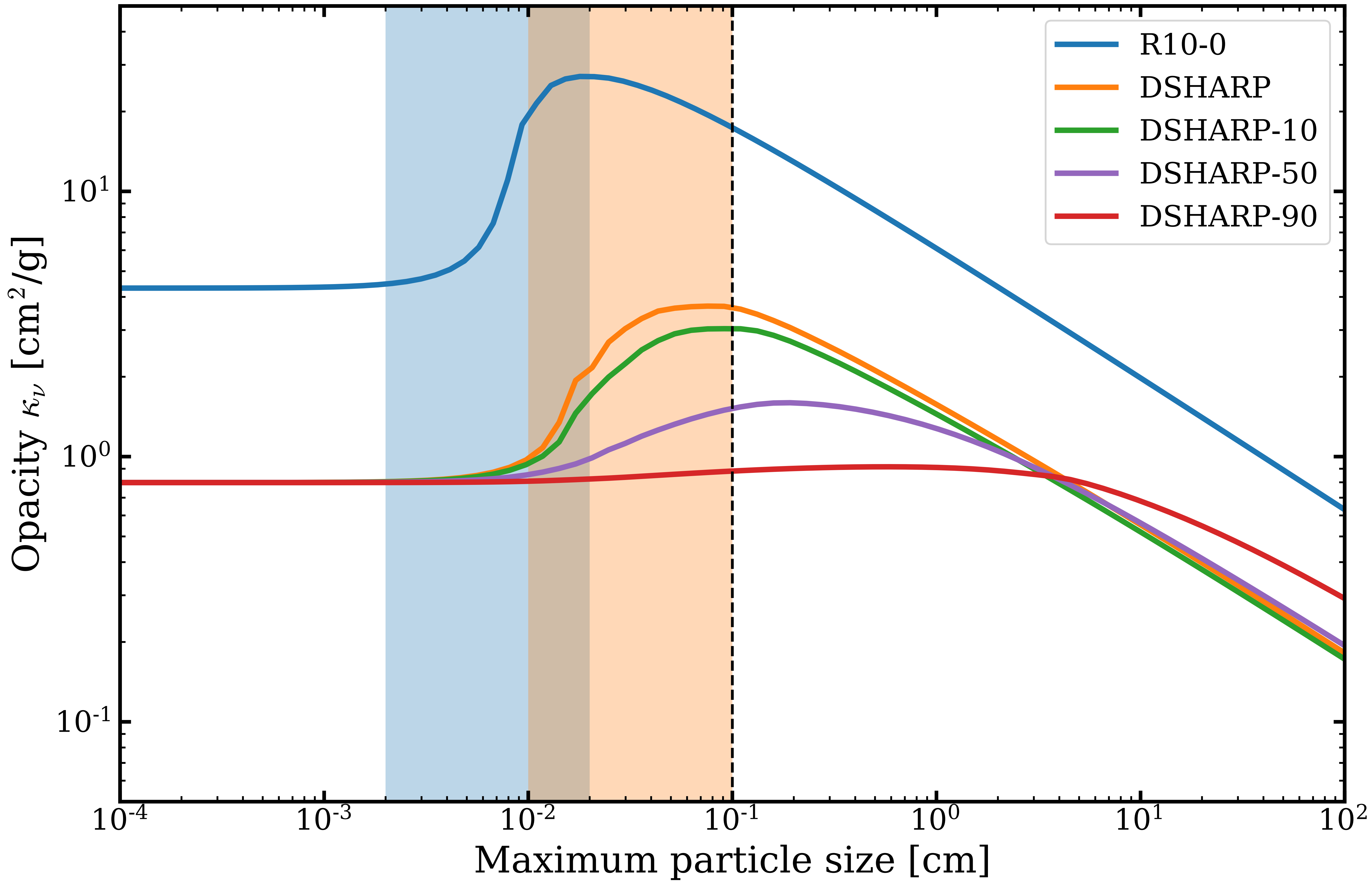
α = 10^{-2}

Dependence on the α-parameter

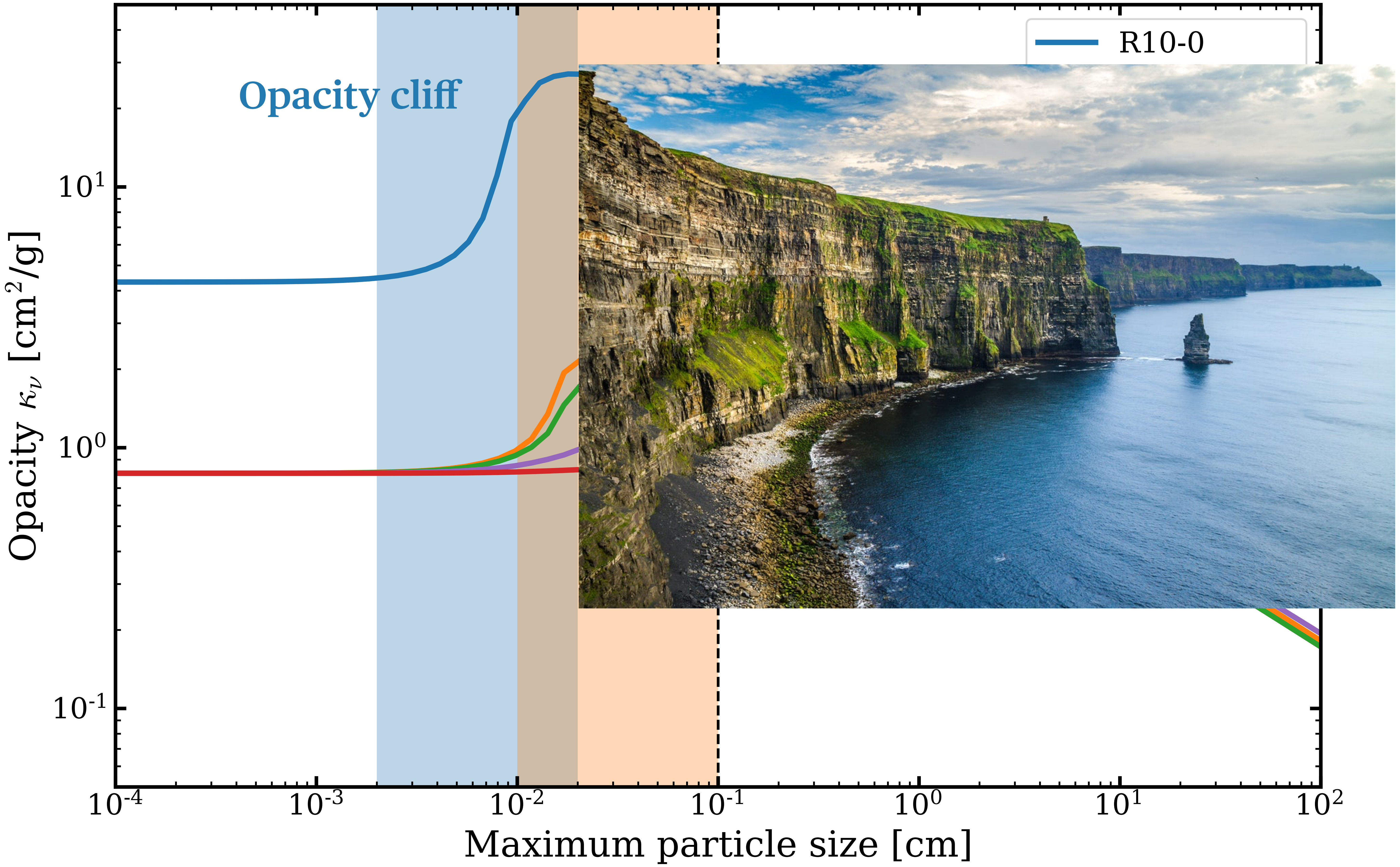




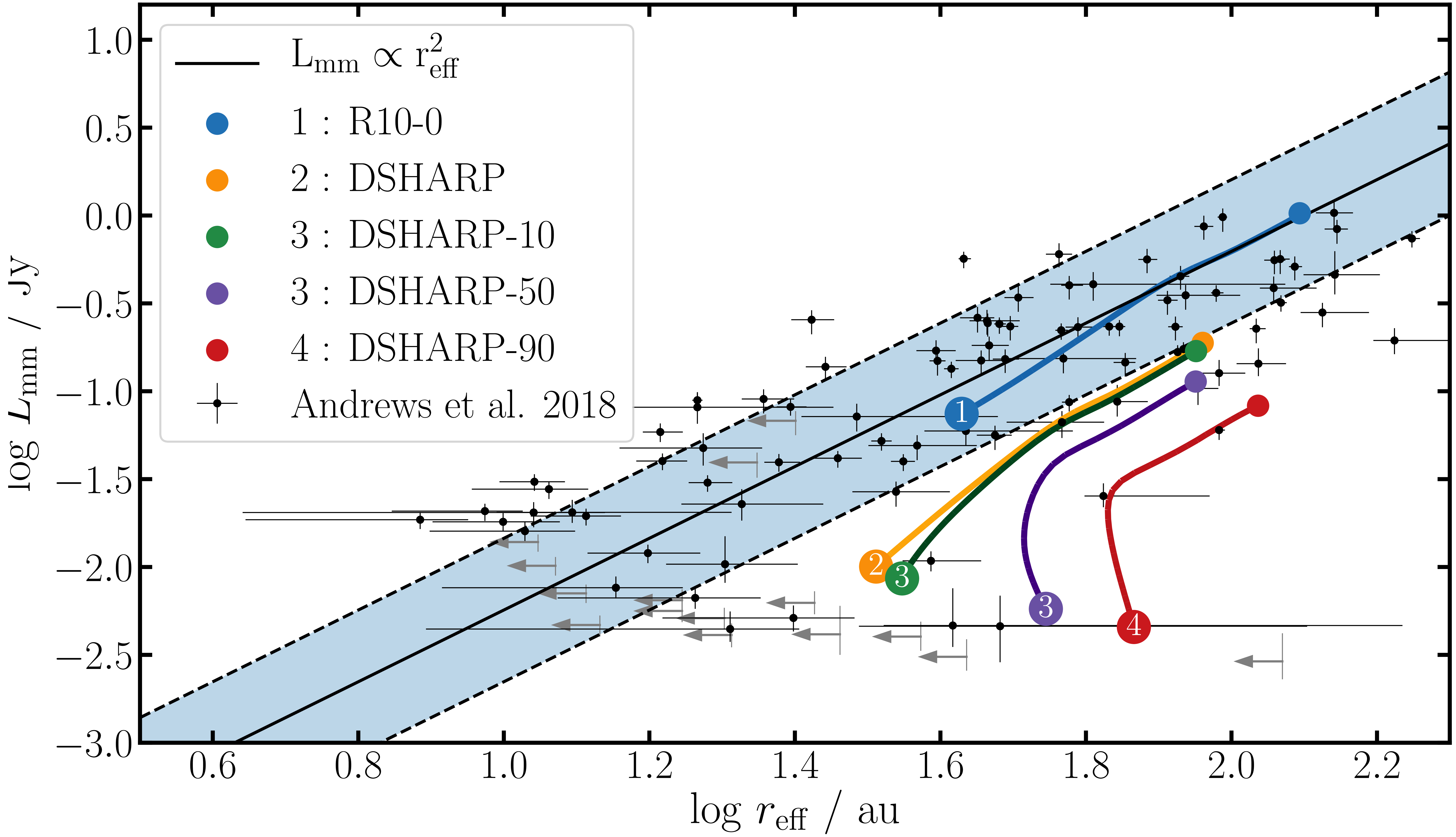
Opacity models



Opacity models



Opacity models



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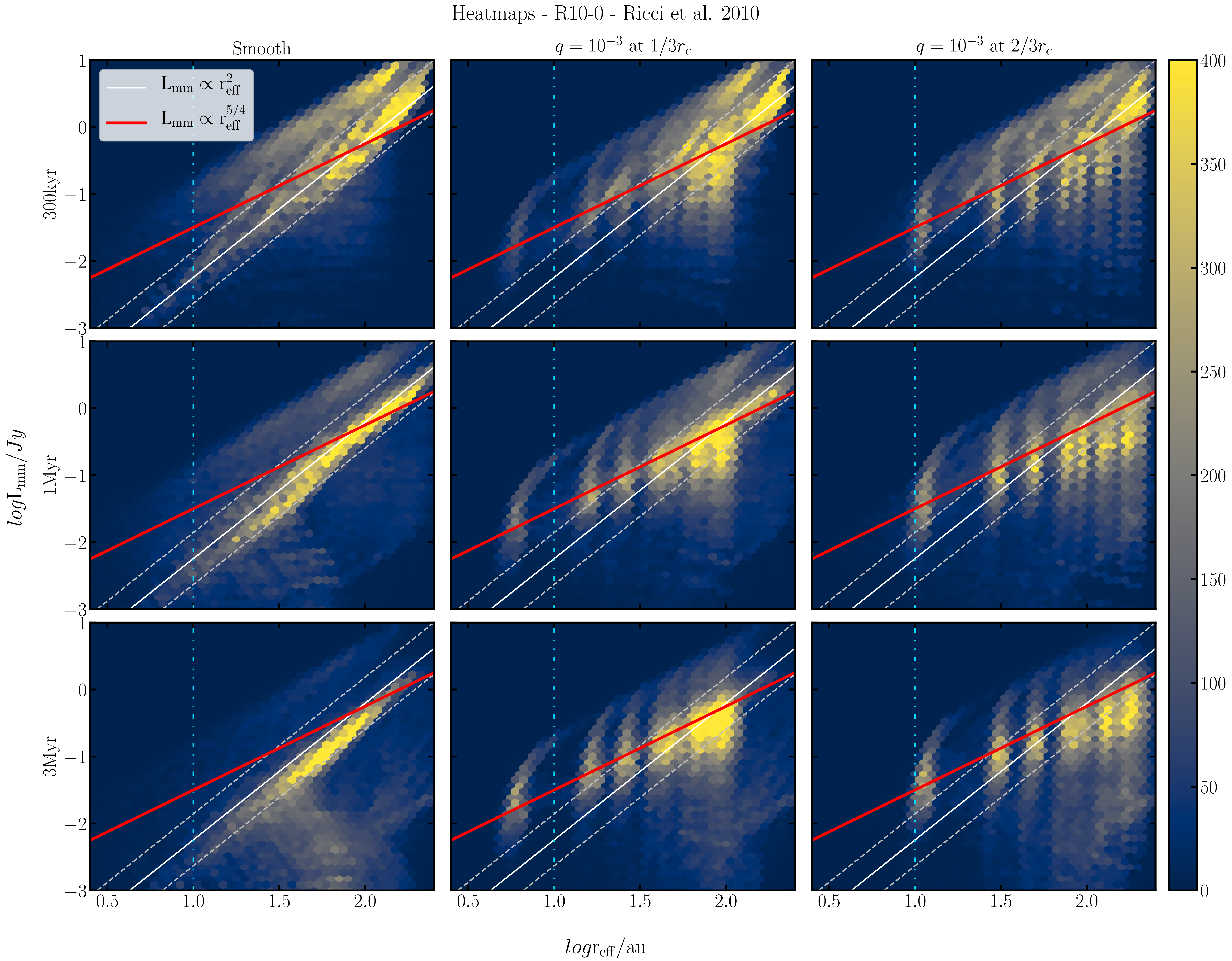
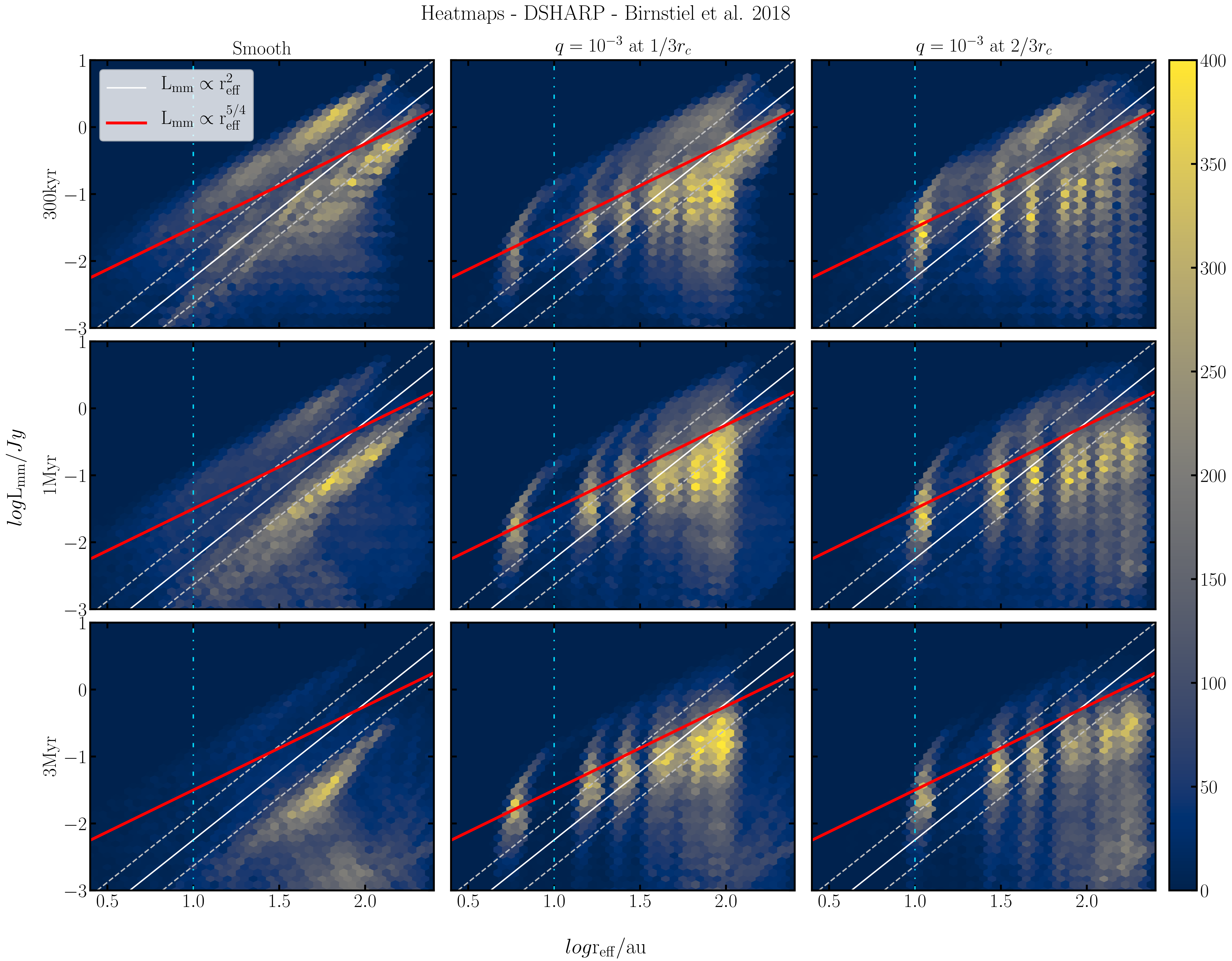
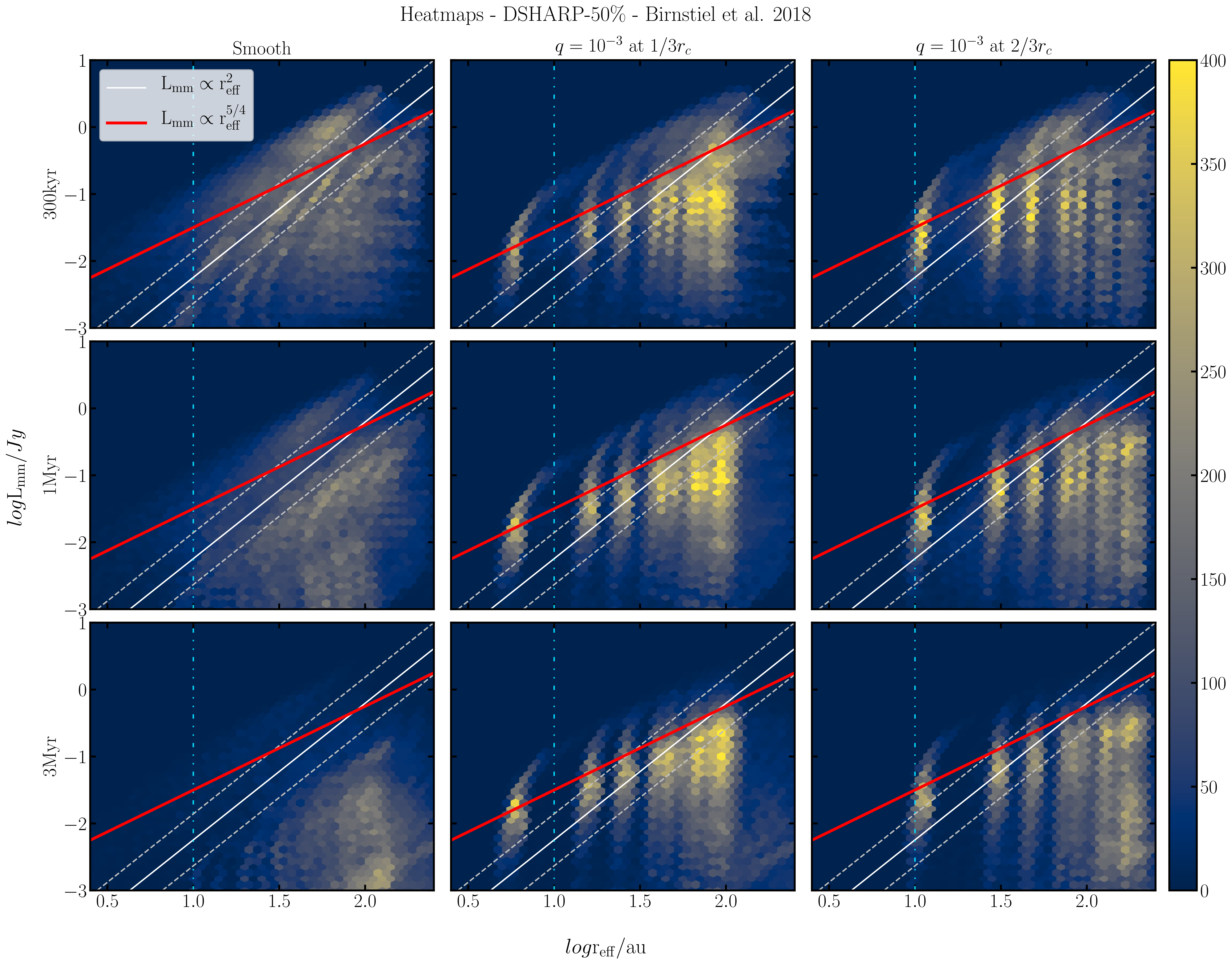
Heatmaps



Heatmaps

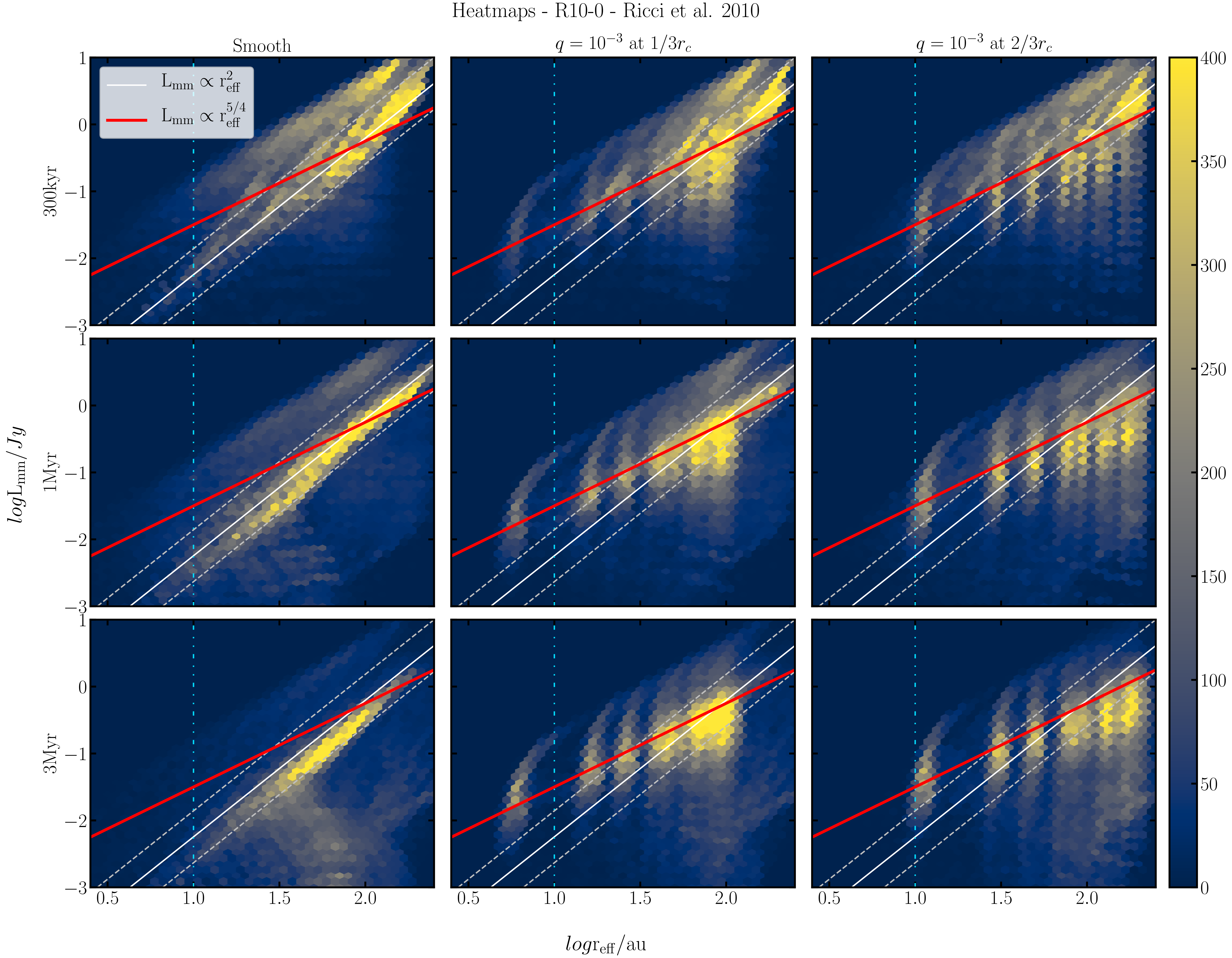

Heatmaps - DSHARP - Birnstiel et al. 2018
Smooth
$q = 10^{-3}$ at $1/3r_c$
$q = 10^{-3}$ at $2/3r_c$
$L_{mm} \propto r_{eff}^2$
$L_{mm} \propto r_{eff}^{5/4}$
300kyr
1Myr
3Myr
$log L_{mm}/Jy$
$log r_{eff}/au$
0.5
1.0
1.5
2.0
1
0
−1
−2
−3
400
350
300
250
200
150
100
50
0

Heatmaps

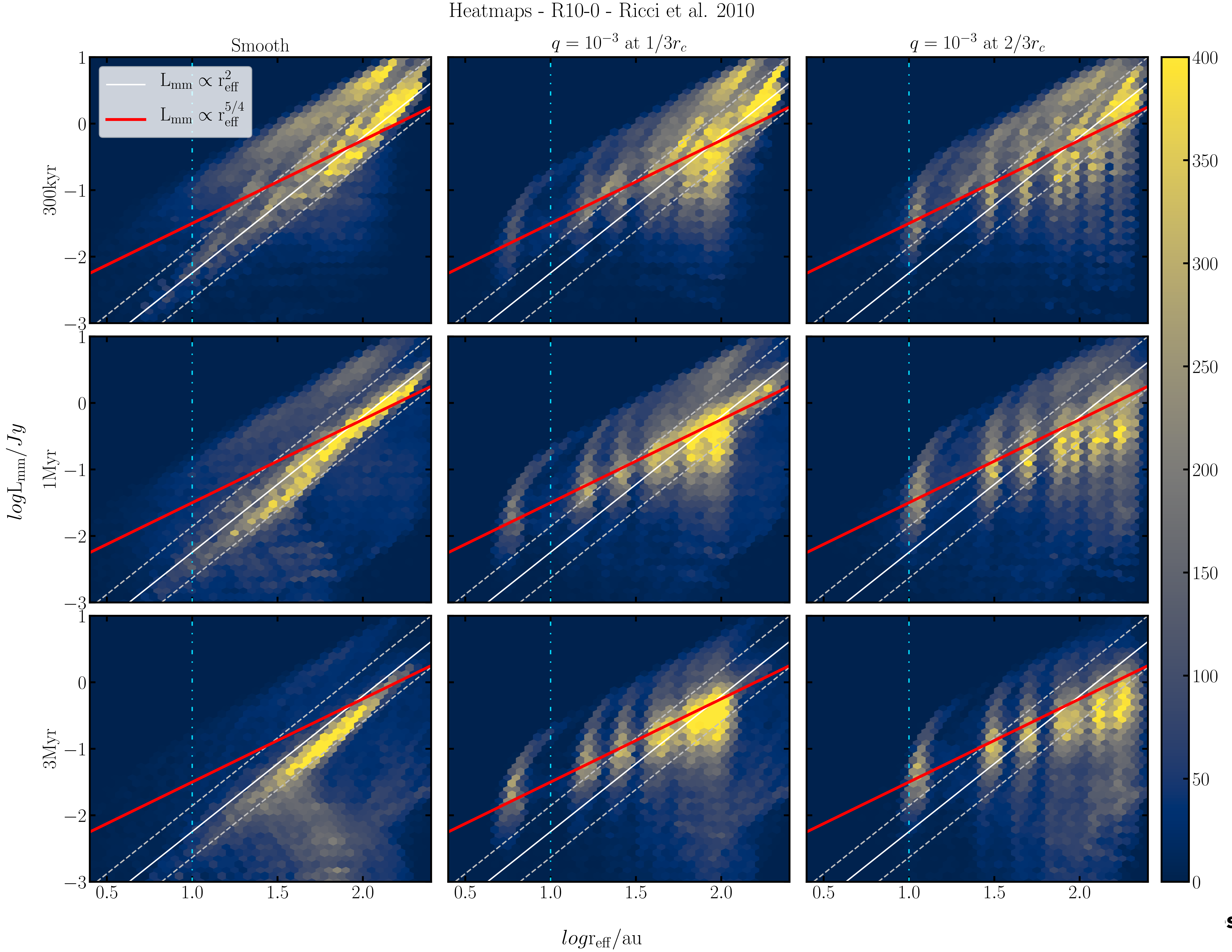


Heatmaps - DSHARP-50% - Birnstiel et al. 2018
Smooth
$q = 10^{-3}$ at $1/3r_c$
$q = 10^{-3}$ at $2/3r_c$
$L_{mm} \propto r_{eff}^2$
$L_{mm} \propto r_{eff}^{5/4}$
300kyr
1Myr
3Myr
$log L_{mm}/Jy$
$log r_{eff}/au$

Heatmaps

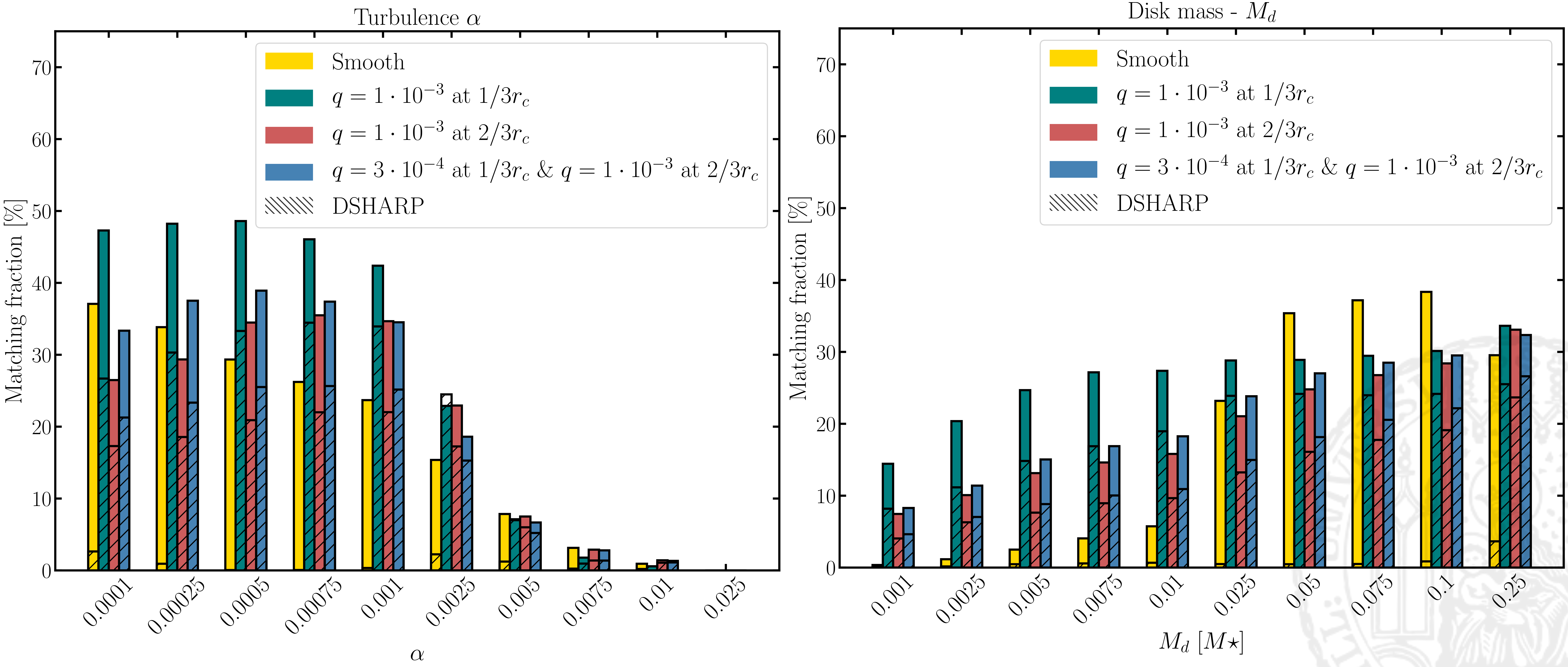

Heatmaps - R10-0 - Ricci et al. 2010
Smooth
$q = 10^{-3}$ at $1/3r_c$
$q = 10^{-3}$ at $2/3r_c$
$\mathrm{L_{mm}} \propto \mathrm{r_{eff}^2}$
$\mathrm{L_{mm}} \propto \mathrm{r_{eff}^{5/4}}$
300kyr
1Myr
3Myr
$log\mathrm{L_{mm}}/Jy$
$log\mathrm{r_{eff}}/\mathrm{au}$
400
350
300
250
200
150
100
50
0

Heatmaps



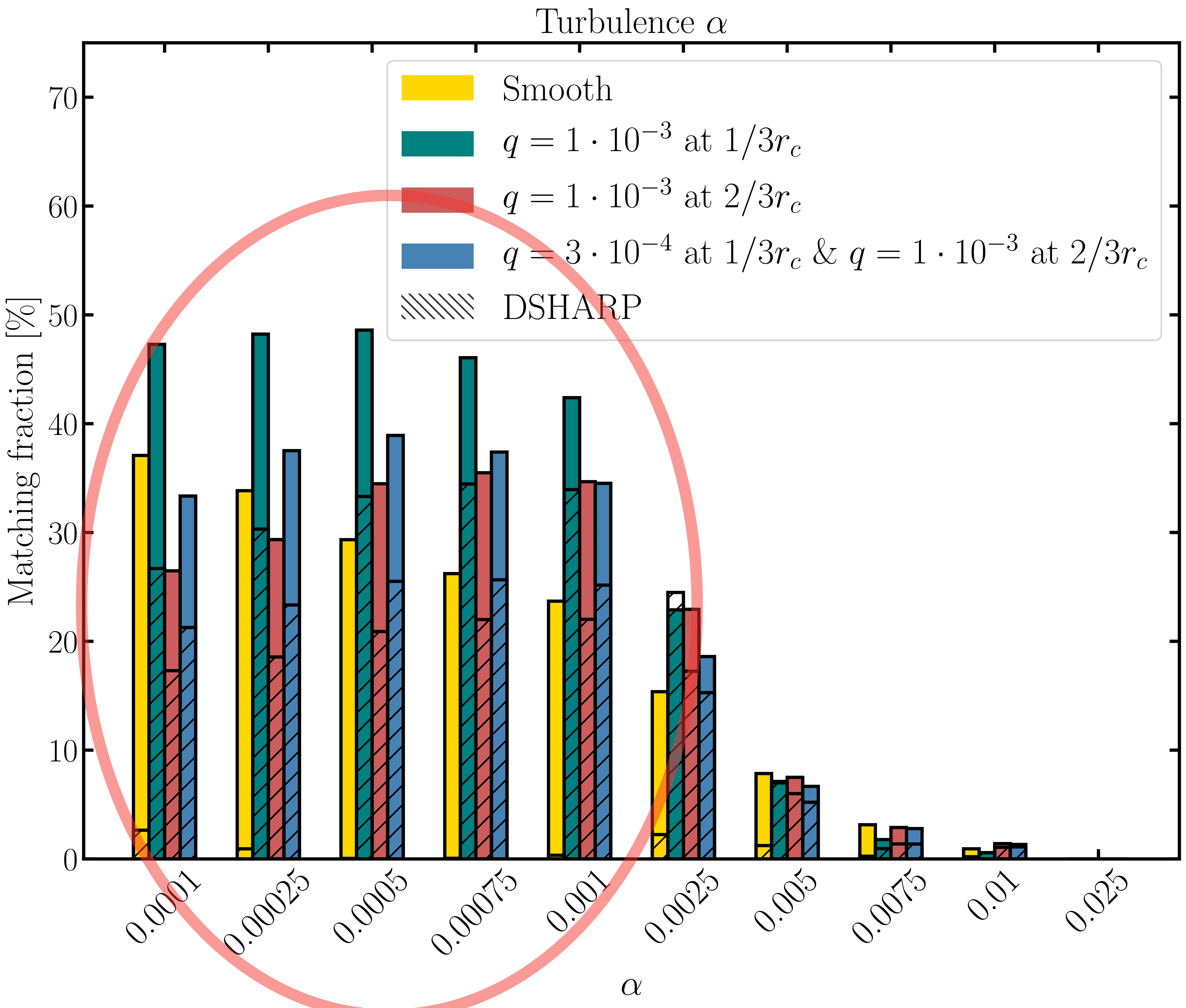
- Disks with strong substructures (i.e. massive planets) follow a different SLR, while smooth disks are more consistent with the SLR in terms of the shape of the relation.
- A bright disk (top right of the SL diagram) is more probable to remain in the SLR if there is a pressure bump formed in the first 1Myr, regardless of the opacity model.

Statistics



Turbulence α
Smooth
$q = 1 \cdot 10^{-3}$ at $1/3 r_c$
$q = 1 \cdot 10^{-3}$ at $2/3 r_c$
$q = 3 \cdot 10^{-4}$ at $1/3 r_c$ & $q = 1 \cdot 10^{-3}$ at $2/3 r_c$
DSHARP
Matching fraction [%]
0 10 20 30 40 50 60 70
0.0001 0.00025 0.0005 0.00075 0.001 0.0025 0.005 0.0075 0.01 0.025
α
Disk mass - M_d
Smooth
$q = 1 \cdot 10^{-3}$ at $1/3 r_c$
$q = 1 \cdot 10^{-3}$ at $2/3 r_c$
$q = 3 \cdot 10^{-4}$ at $1/3 r_c$ & $q = 1 \cdot 10^{-3}$ at $2/3 r_c$
DSHARP
Matching fraction [%]
0 10 20 30 40 50 60 70
0.001 0.0025 0.005 0.0075 0.01 0.025 0.05 0.075 0.1 0.25
M_d [$M\star$]

Statistics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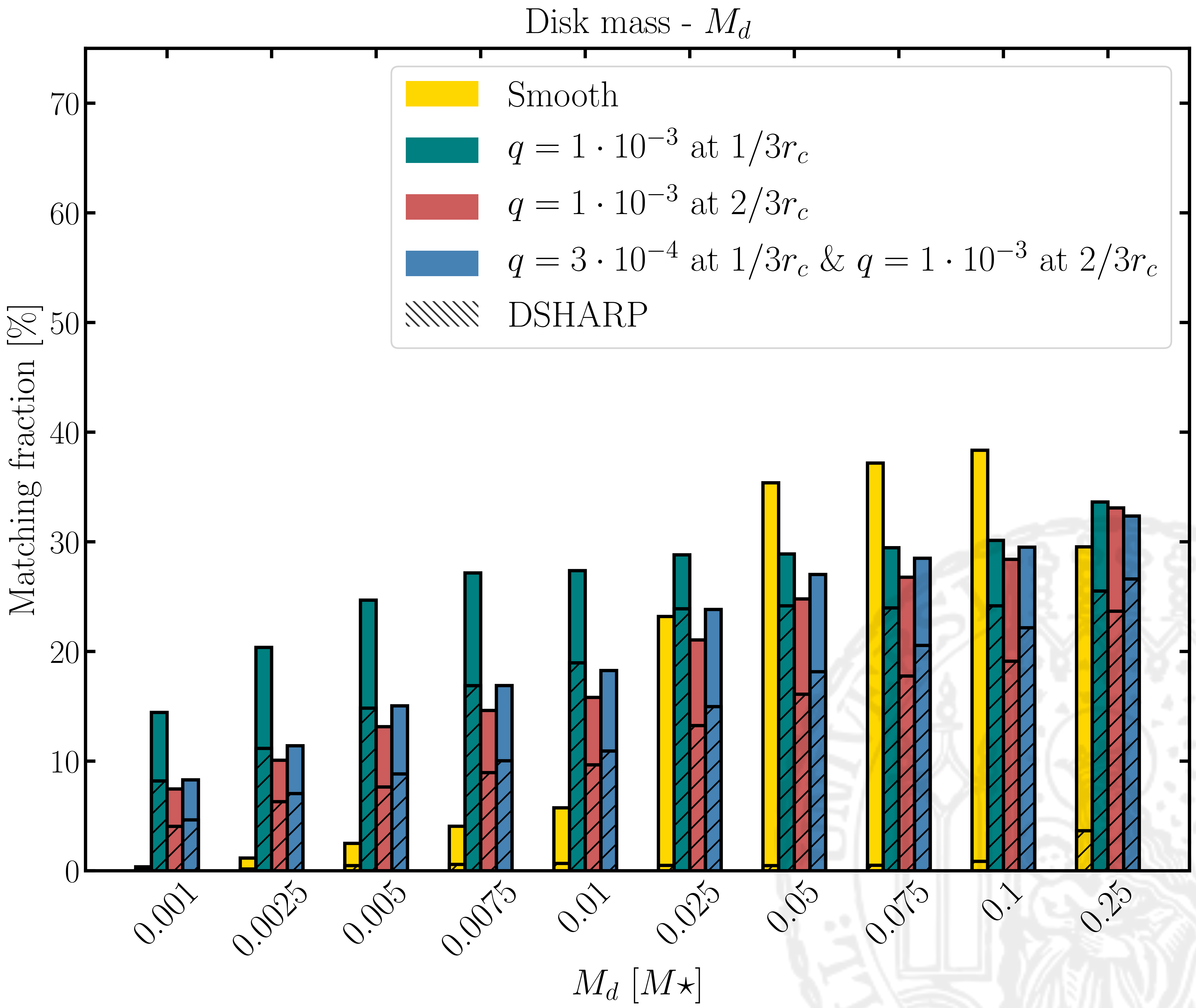
$q = 1 \cdot 10^{-3}$ at $2/3r_c$
$q = 3 \cdot 10^{-4}$ at $1/3r_c$ & $q = 1 \cdot 10^{-3}$ at $2/3r_c$
DSHARP
Matching fraction [%]
0
10
20
30
40
50
60
70
0.0001
0.00025
0.0005
0.00075
0.001
0.0025
0.005
0.0075
0.01
0.025
α


Disk mass - M_d
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$q = 1 \cdot 10^{-3}$ at $2/3r_c$
$q = 3 \cdot 10^{-4}$ at $1/3r_c$ & $q = 1 \cdot 10^{-3}$ at $2/3r_c$
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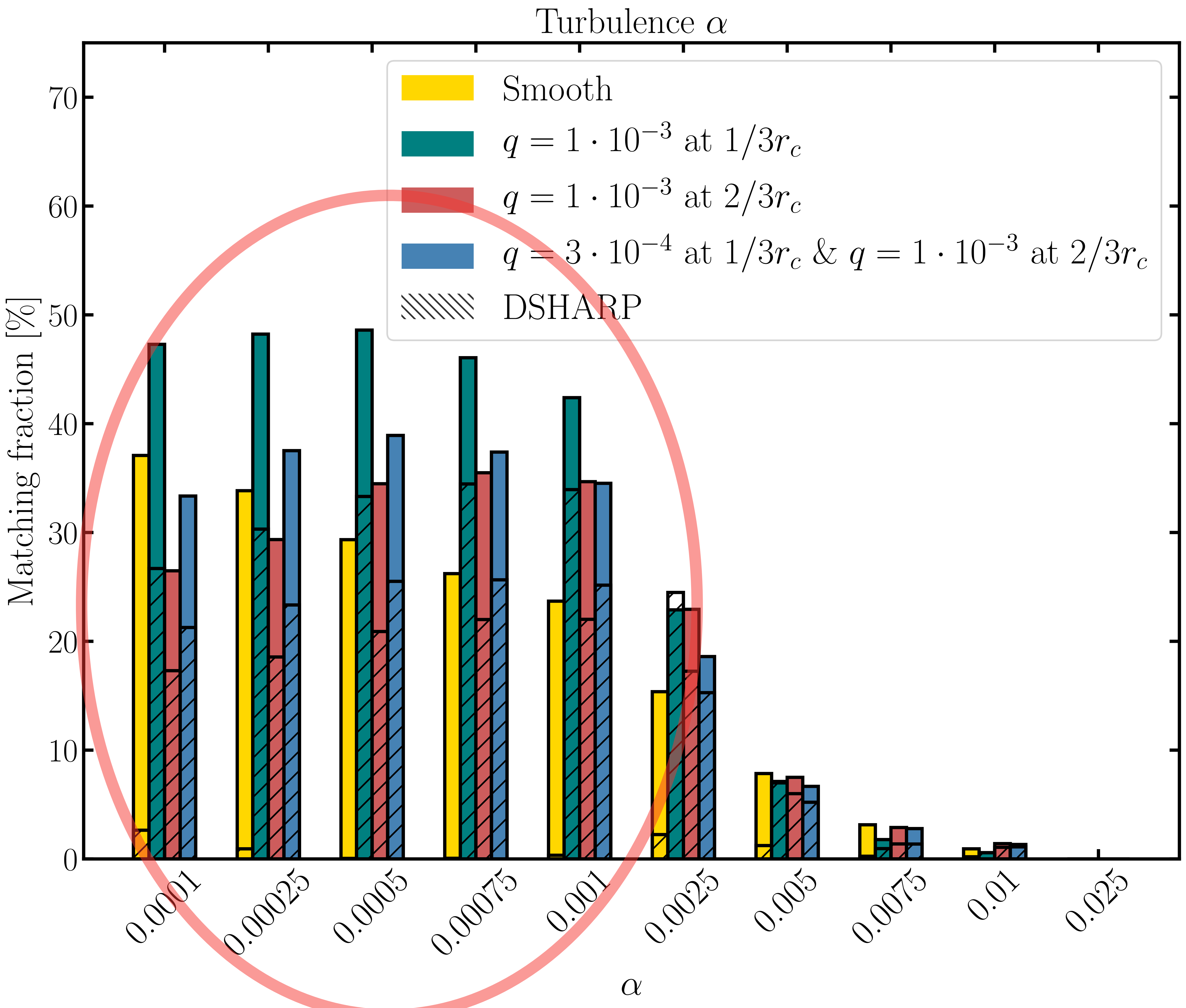
Matching fraction [%]
0
10
20
30
40
50
60
70
0.001
0.0025
0.005
0.0075
0.01
0.025
0.05
0.075
0.1
0.25
M_d [$M\star$]

Statistics



Turbulence α
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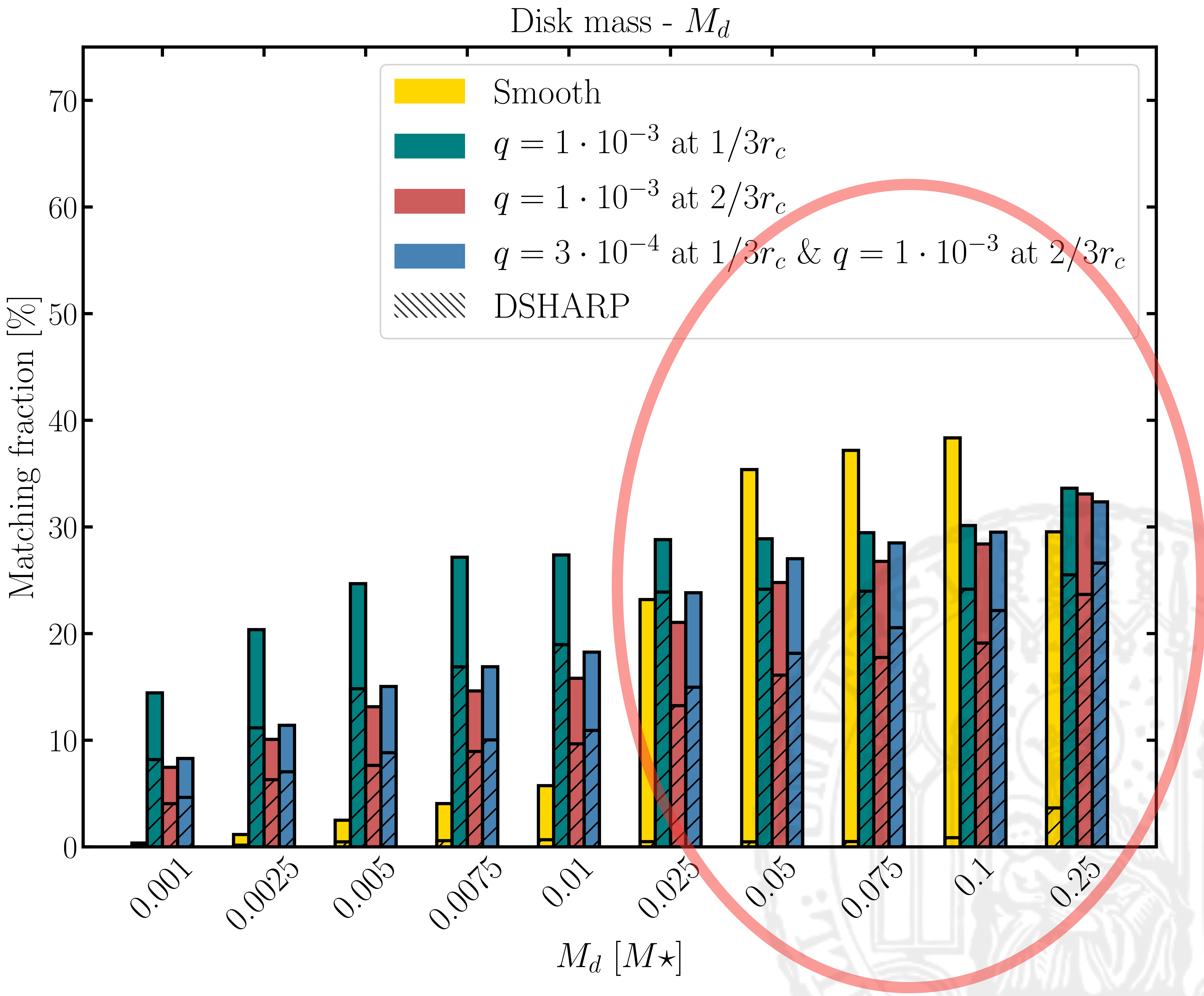
$q = 1 \cdot 10^{-3}$ at $1/3 r_c$
$q = 1 \cdot 10^{-3}$ at $2/3 r_c$
$q = 3 \cdot 10^{-4}$ at $1/3 r_c$ & $q = 1 \cdot 10^{-3}$ at $2/3 r_c$
DSHARP
Matching fraction [%]
0
10
20
30
40
50
60
70
0.0001
0.00025
0.0005
0.00075
0.001
0.0025
0.005
0.0075
0.01
0.025
α



Disk mass - M_d
Smooth
$q = 1 \cdot 10^{-3}$ at $1/3 r_c$
$q = 1 \cdot 10^{-3}$ at $2/3 r_c$
$q = 3 \cdot 10^{-4}$ at $1/3 r_c$ & $q = 1 \cdot 10^{-3}$ at $2/3 r_c$
DSHARP
Matching fraction [%]
0
10
20
30
40
50
60
70
0.001
0.0025
0.005
0.0075
0.01
0.025
0.05
0.075
0.1
0.25
M_d [$M\star$]

Conclusions

- More simulations stay on the SLR when we include planets.

- Disks with strong traps (i.e. massive planets) follow a different SLR than smooth disks. ($L \propto r_{eff}^{2}$ vs $L \propto r_{eff}^{1.25}$)

- Preference towards high initial disk mass (> $2.5\text{x}10^{-2}$)

- Preference towards low α-values (< 10^{-3}).

- If disks are matching or not depends heavily on the opacity model and the grain porosity.