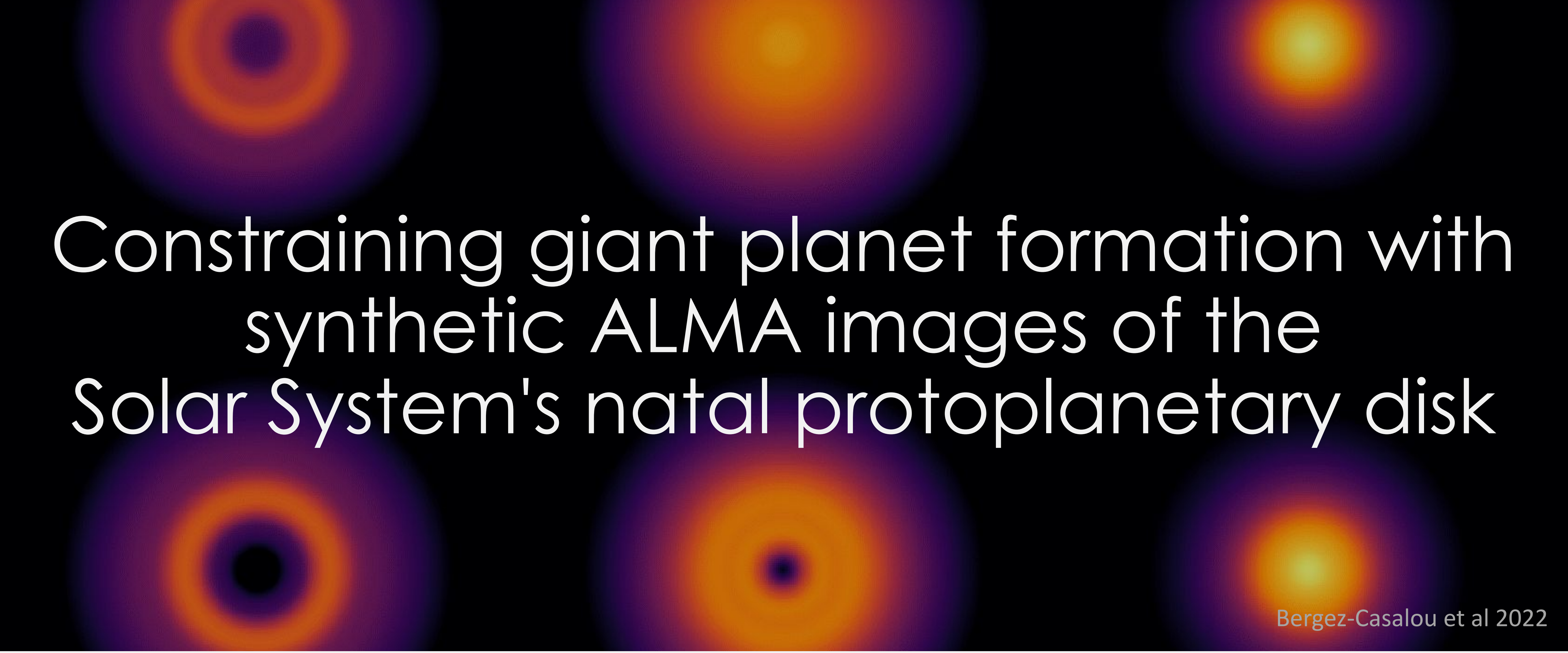
Constraining giant planet formation with synthetic ALMA images of the Solar System's natal protoplanetary disk



Bergez-Casalou et al 2022

Camille Bergez-Casalou   Postdoc at LESIA since Nov. 2022

+ B. Bitsch, N.T. Kurtovic, P. Pinilla

l'Observatoire de Paris | LESIA

Motivations

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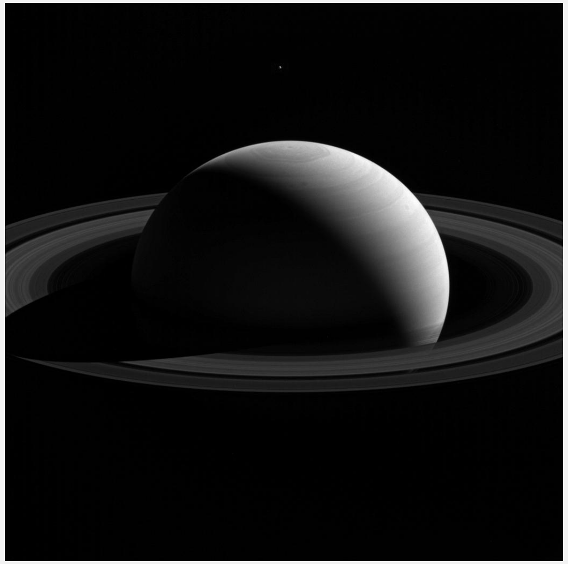
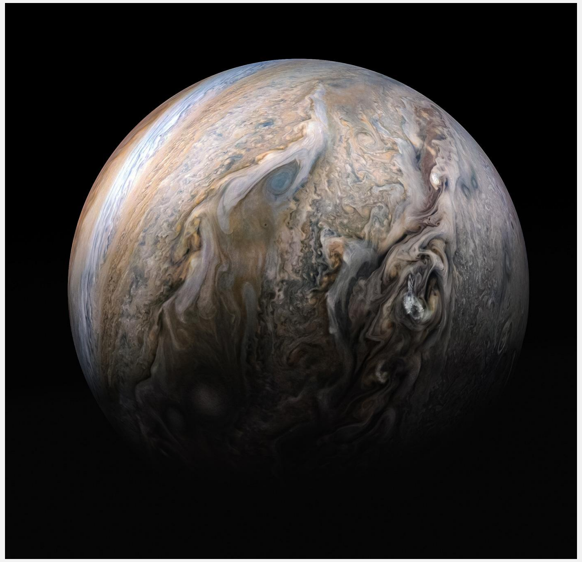


Cassini mission - nasa.gov



Juno mission - nasa.gov

Constraints from the Solar system:

Studies on cosmochemical composition of meteorites:
Kruijer 2017,2020, Morbidelli et al 2020, Raymond & Izidoro 2017b

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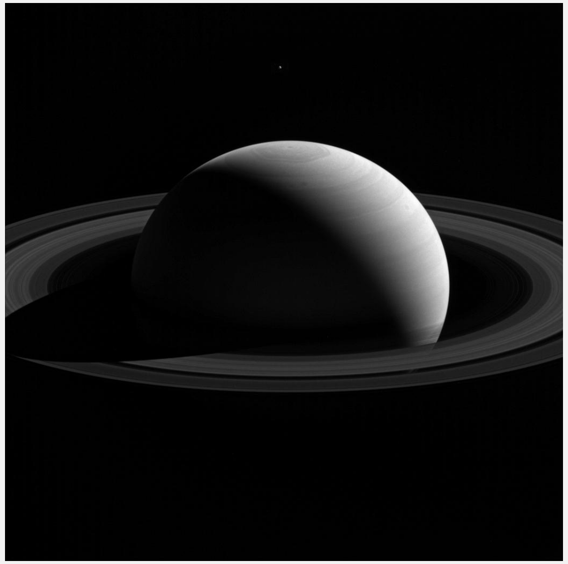

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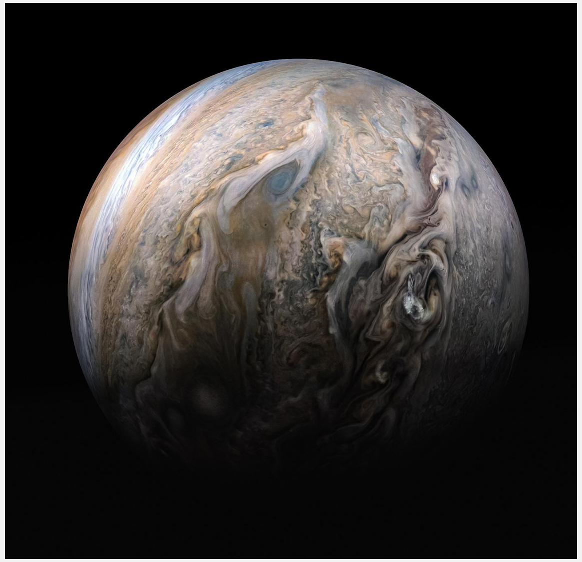

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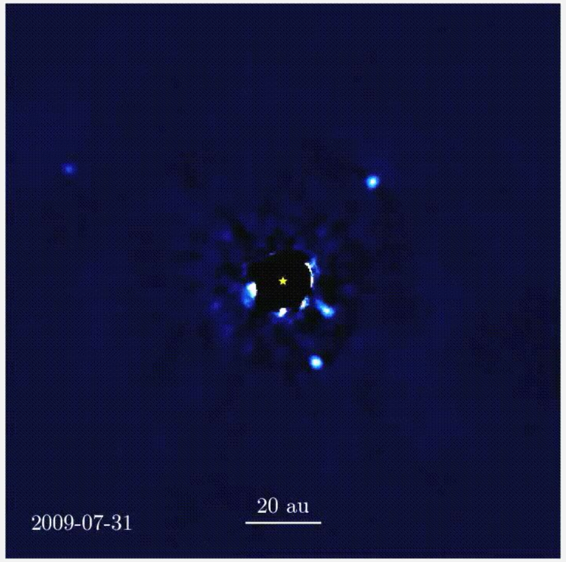
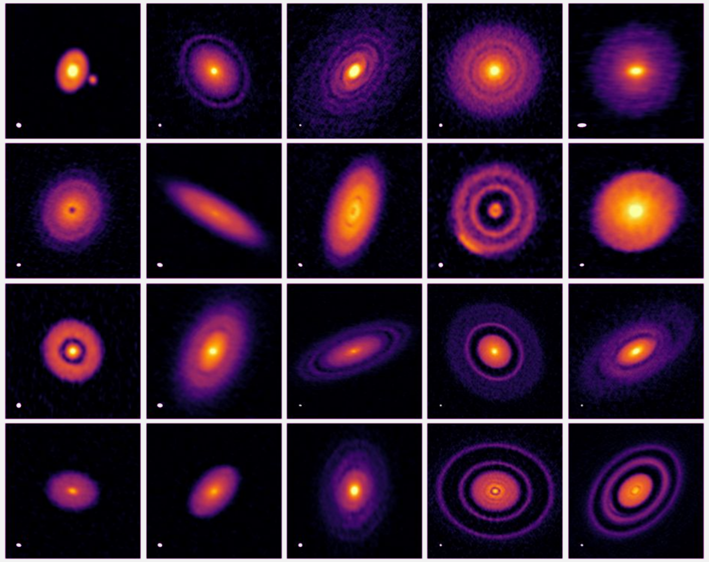


Wang et al 2016



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Derivation of planet characteristics from observations of gaps:
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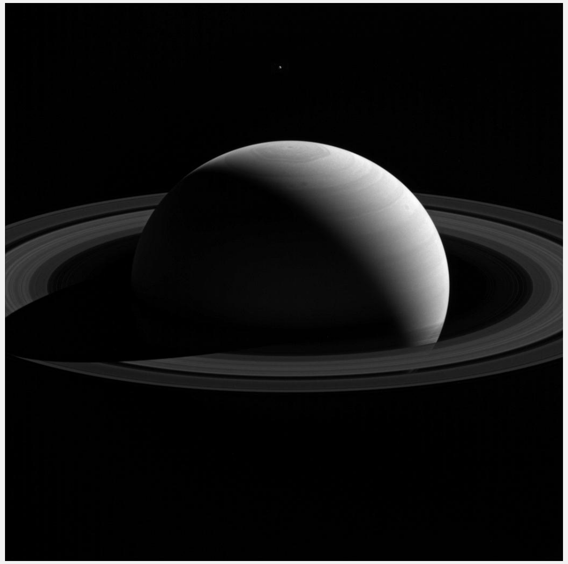
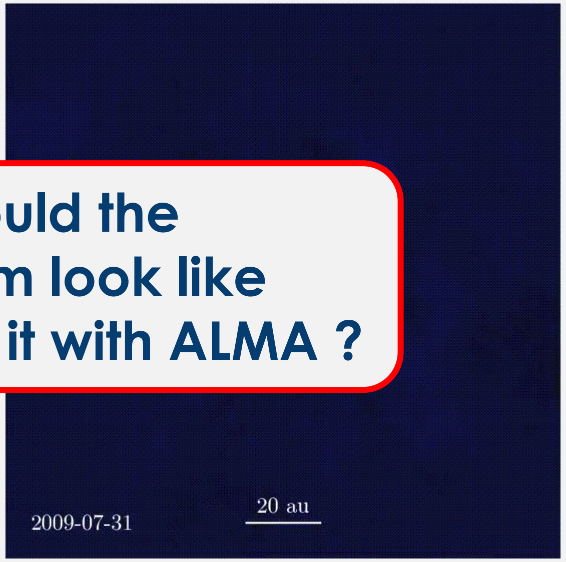


Cassini mission - nasa.gov

Juno mission - nasa.gov

How would the
Solar System look like
if we observed it with ALMA ?



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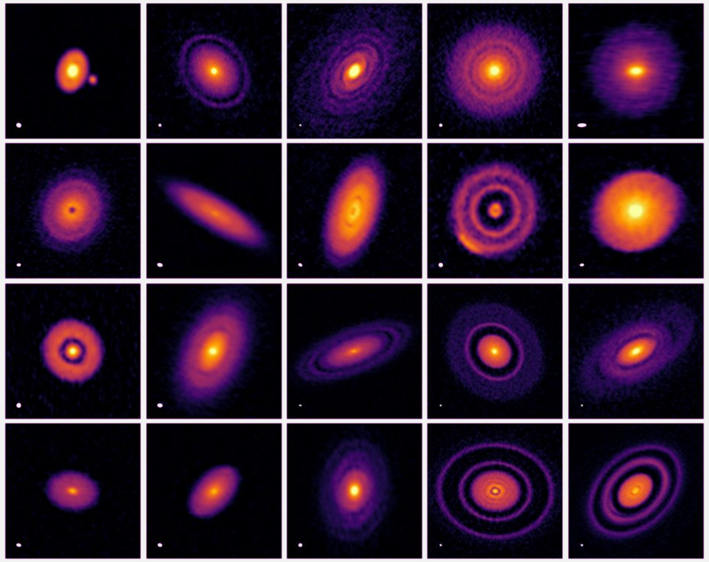

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Numerical set-up

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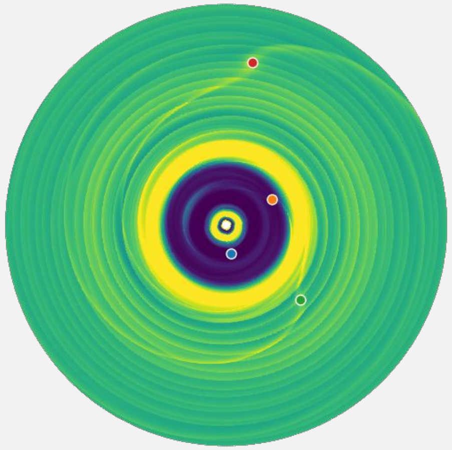
Hydrodynamical Simulation — FARGO2D1D → Dust Evolution — TWOPOPPY → Radiative Transfer + opacities calculations — RADMC3D, OPTOOL → Synthetic Images — RADMC3D

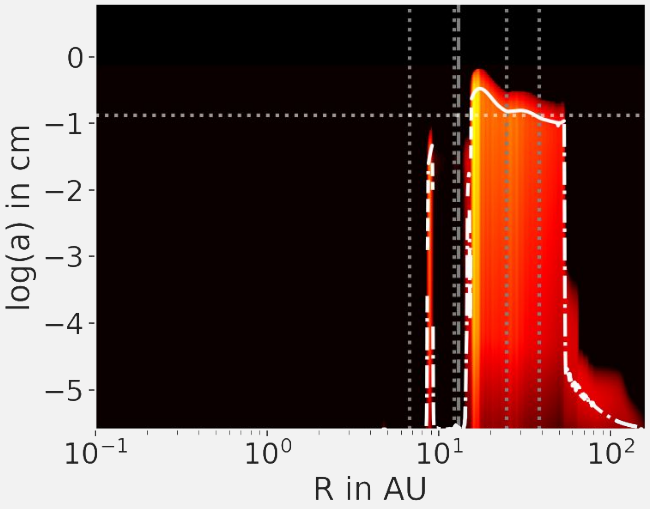
Gas
1D average
Σ_r and v_r

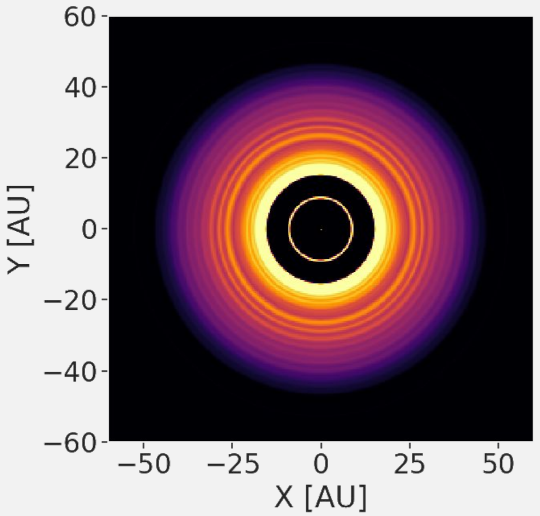
Dust
Size distribution

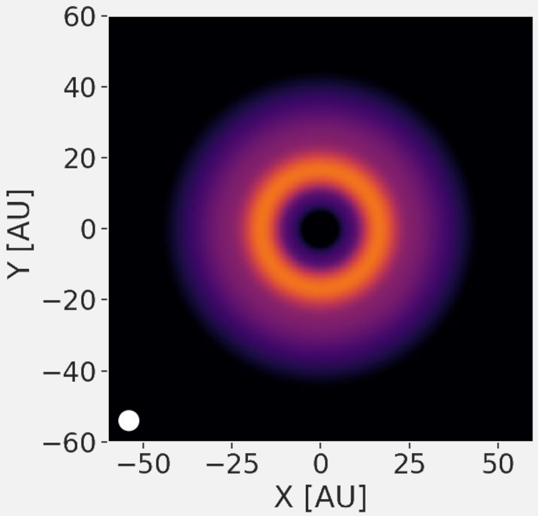
Dust
temperature

Dust emission
+ convolution
with a beam









Explored planetary systems

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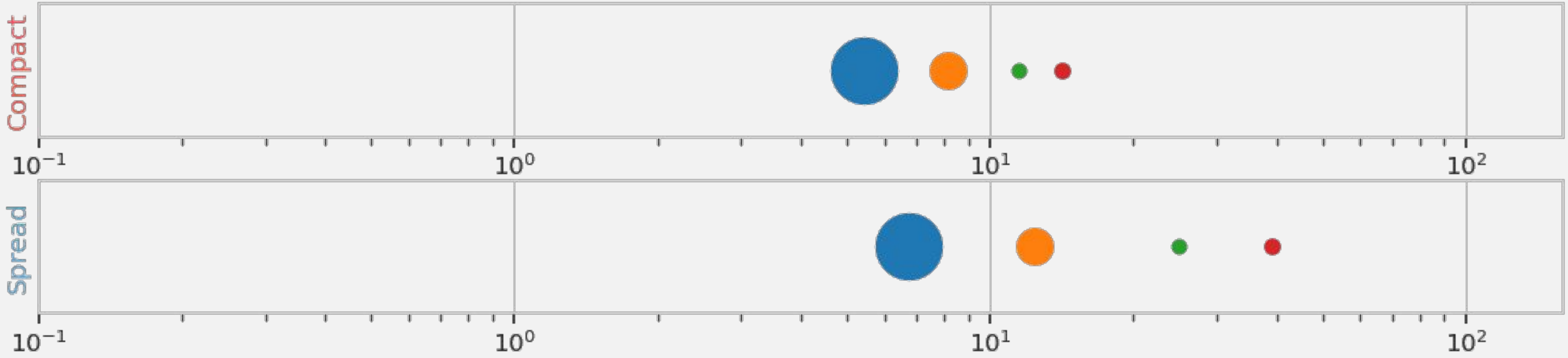
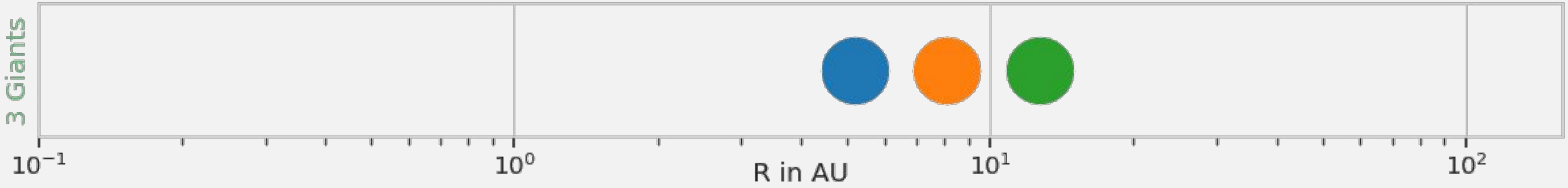
2 Solar System configurations: Compact — Nice instability (Gomes+2005)

Spread — $r_p = 1.3 \times r_{nowadays}$ (migration)



1 Exoplanetary system: 3 Giants Typical scattering process (Bitsch+2020)



Time evolution

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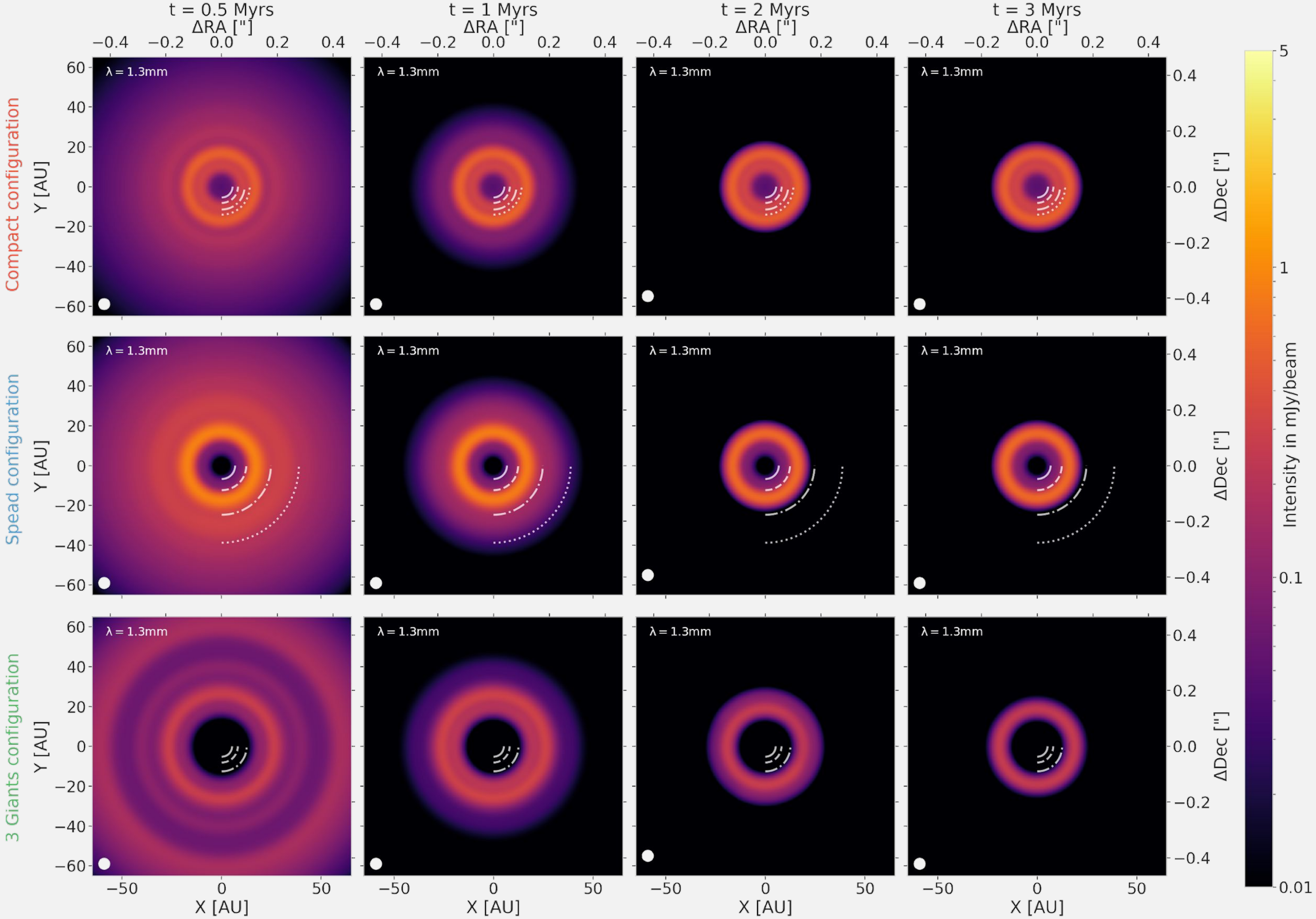
Bergez-Casalou+2022 A&A

Low alpha
Low aspect ratio

In less than 1 Myr,
all the discs appear **small**
(< 60 AU)

Different from the famous
DSHARP images

➡ formation pathway of
giant planets ?



Dust growth

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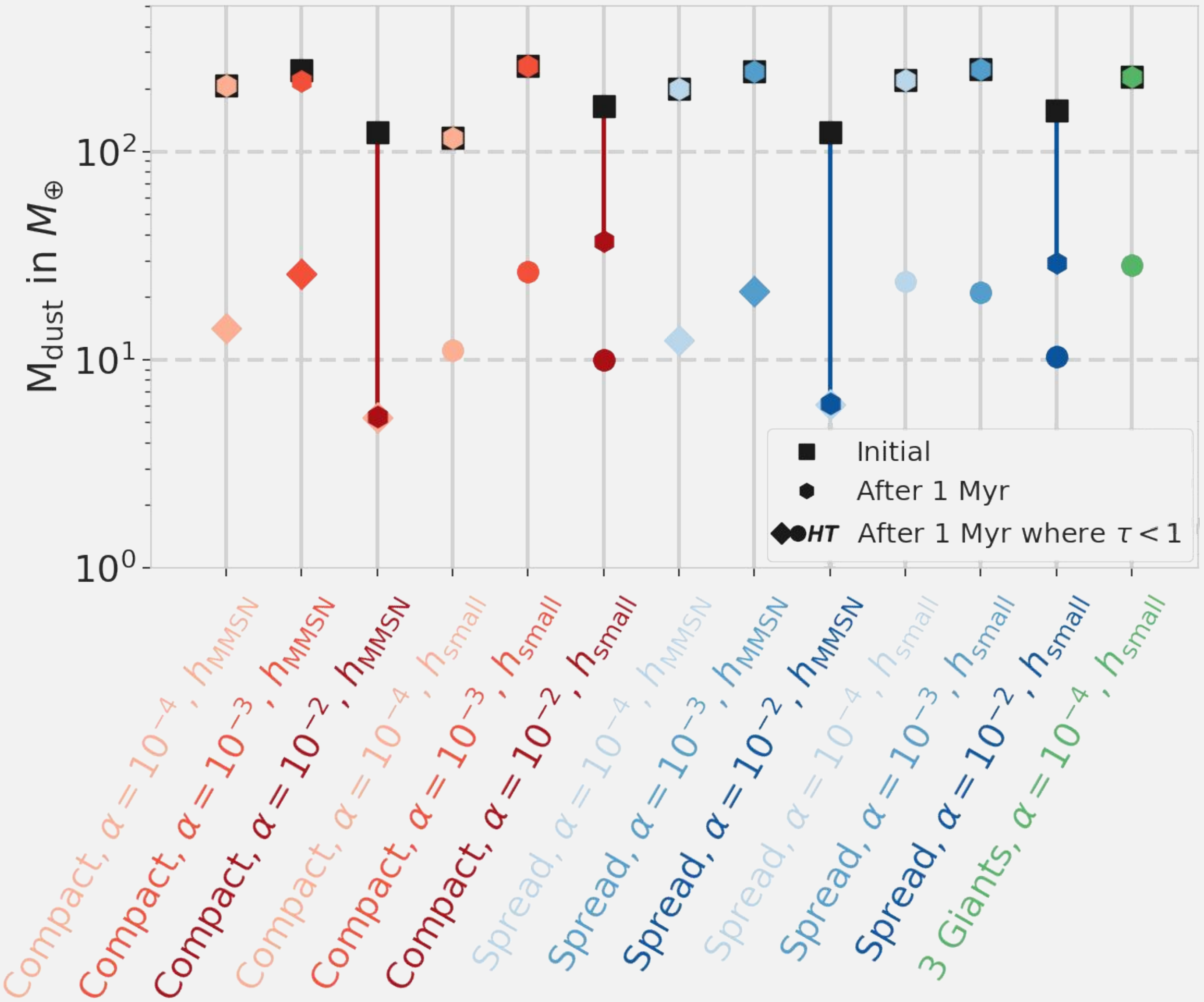
Bergez-Casalou+2022 A&A

Comparison between:

- Initial dust mass
- Total remaining mass after 1 Myr
- Optically thin mass after 1 Myr



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Bergez-Casalou+2022 A&A

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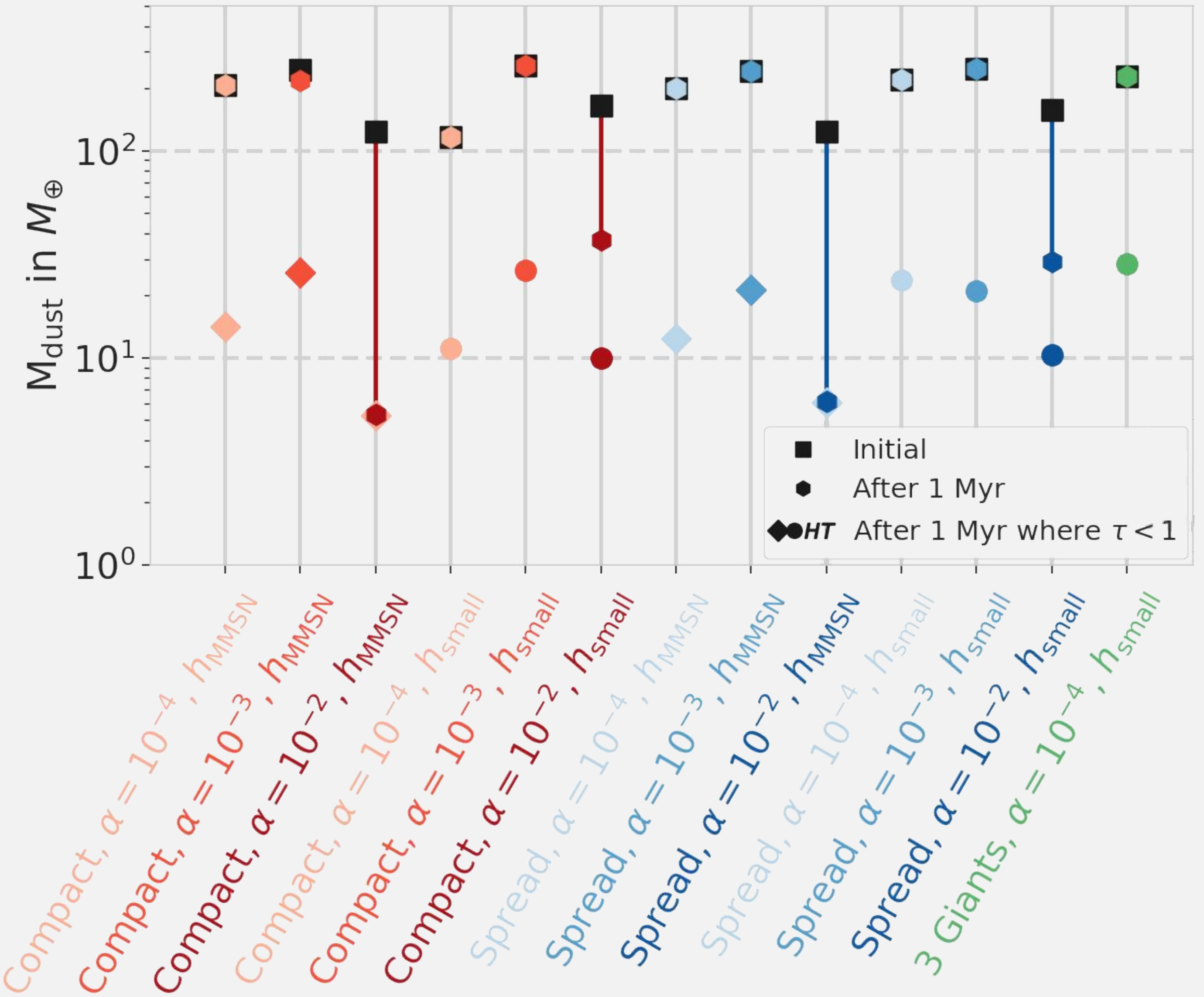

- Depends on whether the dust is trapped by the pressure bumps (depends on alpha)
- In all cases, optically thin dust represents only **10%** of the initial reservoir

Observations

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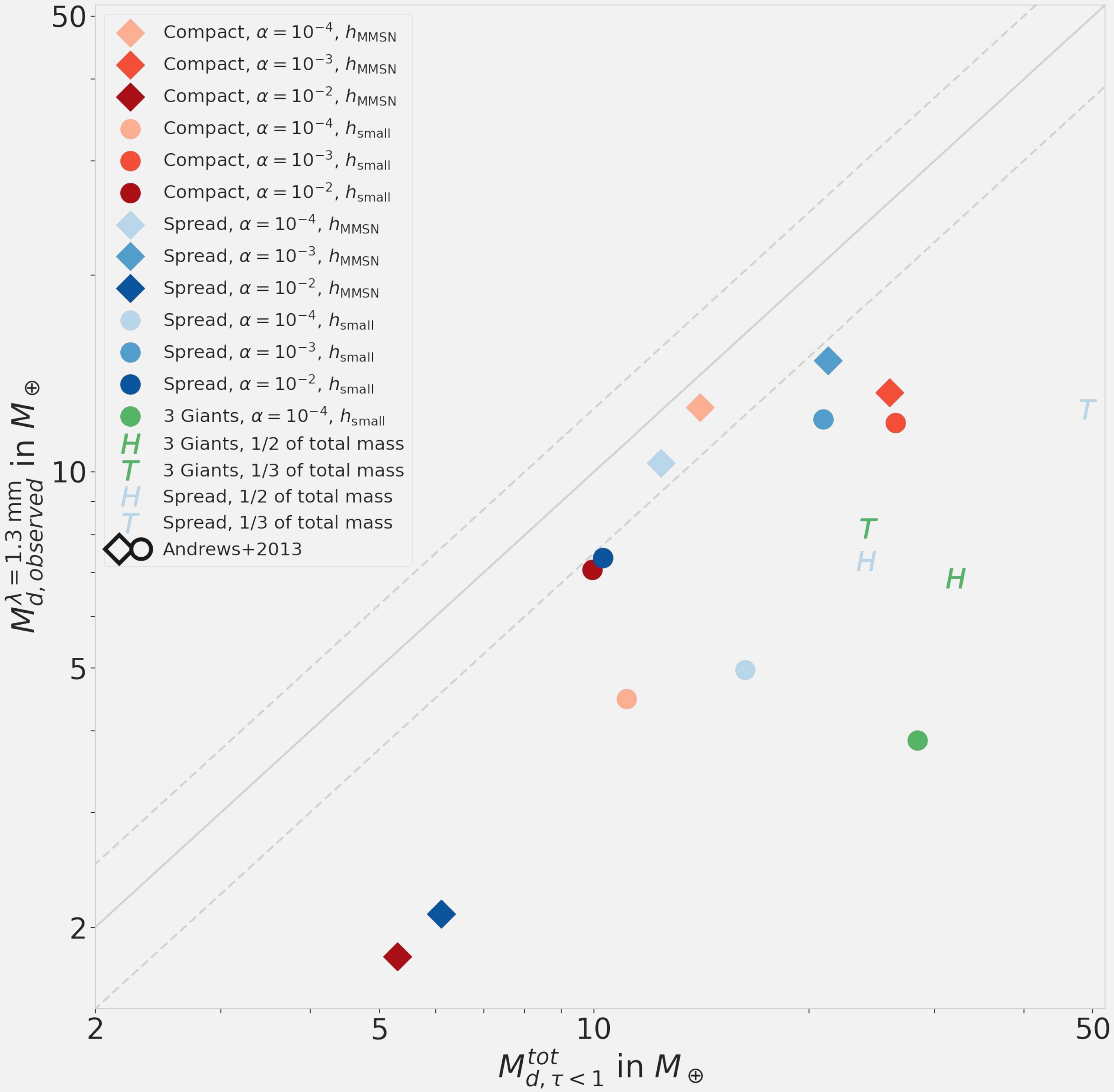
Bergez-Casalou+2022 A&A

Comparison between:

- Mass derived from 1.3mm flux
- Total optically thin mass after 1 Myr

- In theory:
  We know the dust properties, simulated observations **underestimate** the total dust mass



Observations

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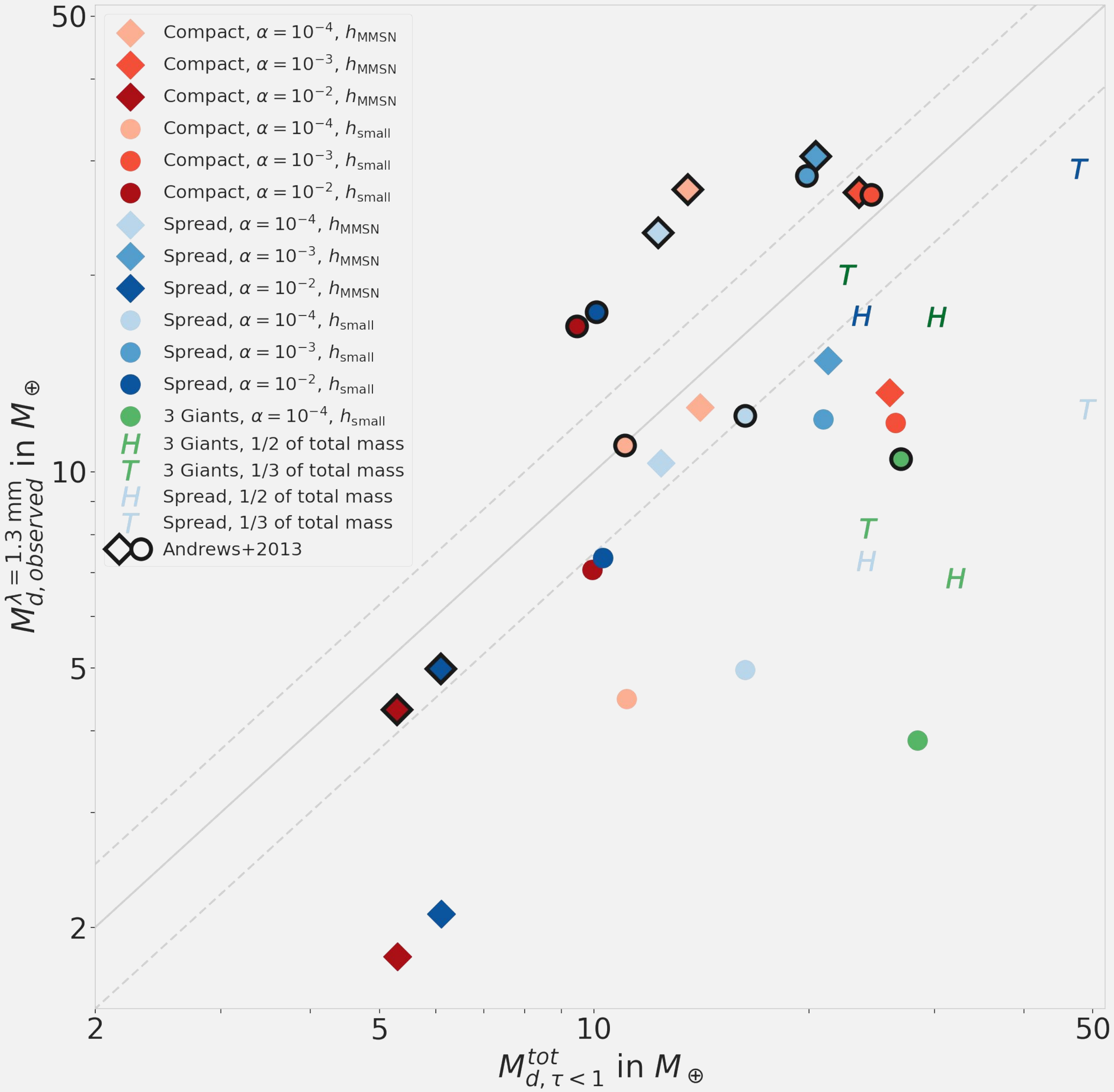
Bergez-Casalou+2022 A&A

Comparison between:

- Mass derived from 1.3mm flux
- Total optically thin mass after 1 Myr

- In theory:
  We know the dust properties, simulated observations **underestimate** the total dust mass

- In observations,
  When assuming the properties as Andrews et al 2013 (opacity and temperature), observations **overestimate** the total dust mass



Take home messages

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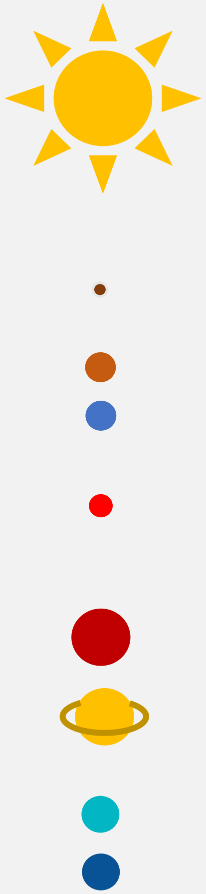
Bergez-Casalou+2022 A&A



- The Solar System's disk was probably **compact** compared to current observed disks
- The presence of giant planets is very efficient at creating **optically thick** dust rings, **hiding the majority of the dust mass**
- The need of an accurate description of the dust properties (**opacity, temperature**) is **primordial** to interpret the observations

Take home messages

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Bergez-Casalou+2022 A&A

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Thank you for your attention !
See you at my poster

My research:
https://www2.mpia-hd.mpg.de/homes/bergez/
Giant planets - Gas accretion - Planet disc interactions

MMSN like aspect ratio

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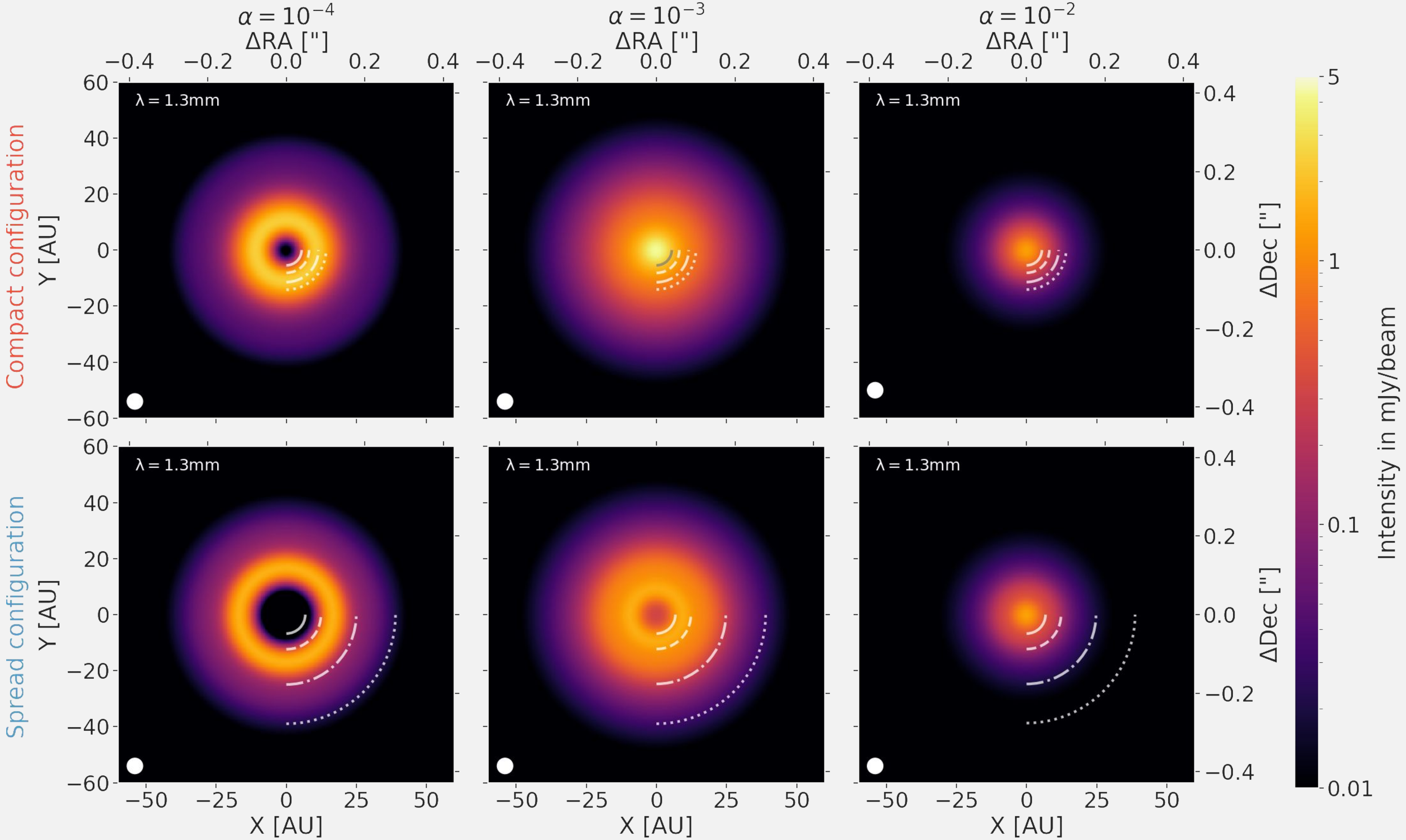
Bergez-Casalou+2021 (in prep)



Gas surface density

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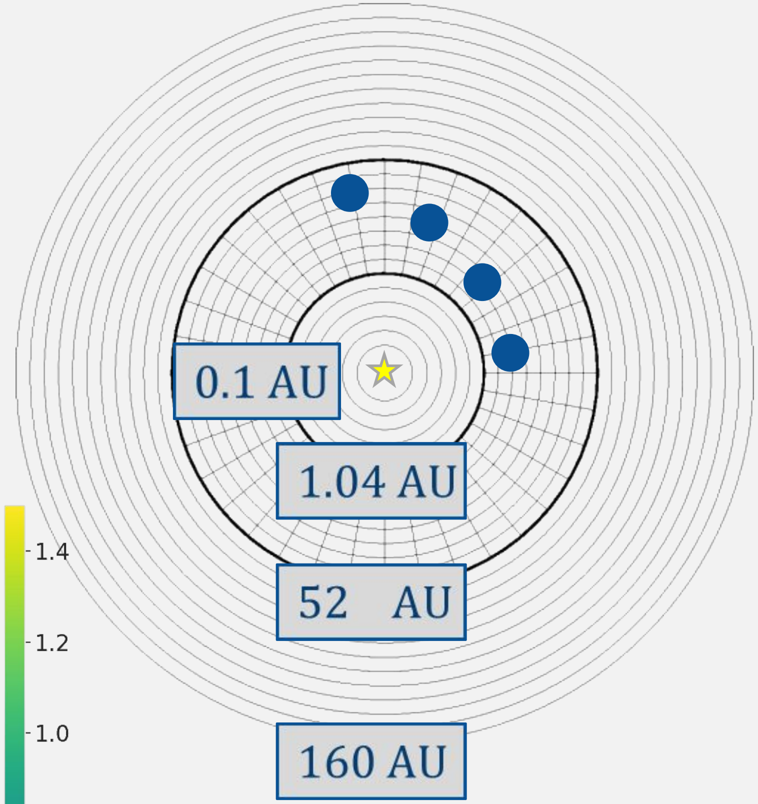
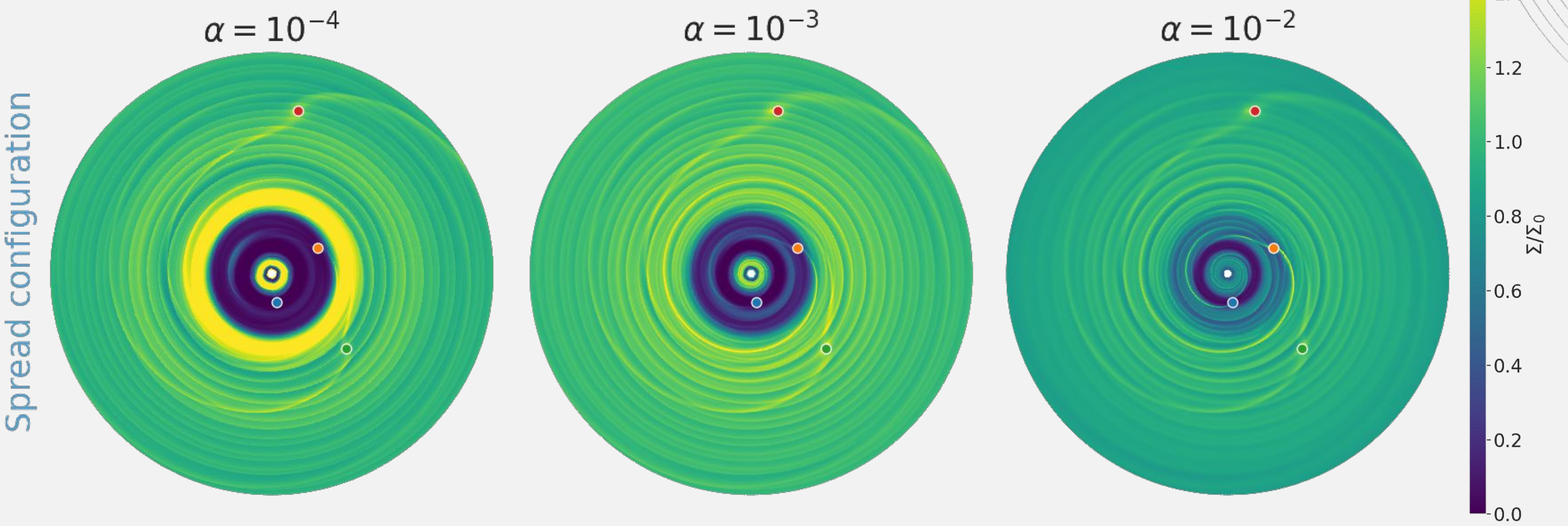
Fargo2D1D: isothermal disc

$$\Sigma(r) = 844\ g/cm^2 \quad \times r_{AU}^{-1}$$

$$h = (0.033; 0.025) \quad \times r_{AU}^{2/7} \qquad \alpha = 10^{-4}; 10^{-3}; 10^{-2}$$

$t = 12\,500\ orbits\ (5.2\ \mathrm{AU})\ + 2\,500\ orbits$ time averaged





Hydro – h MMSN

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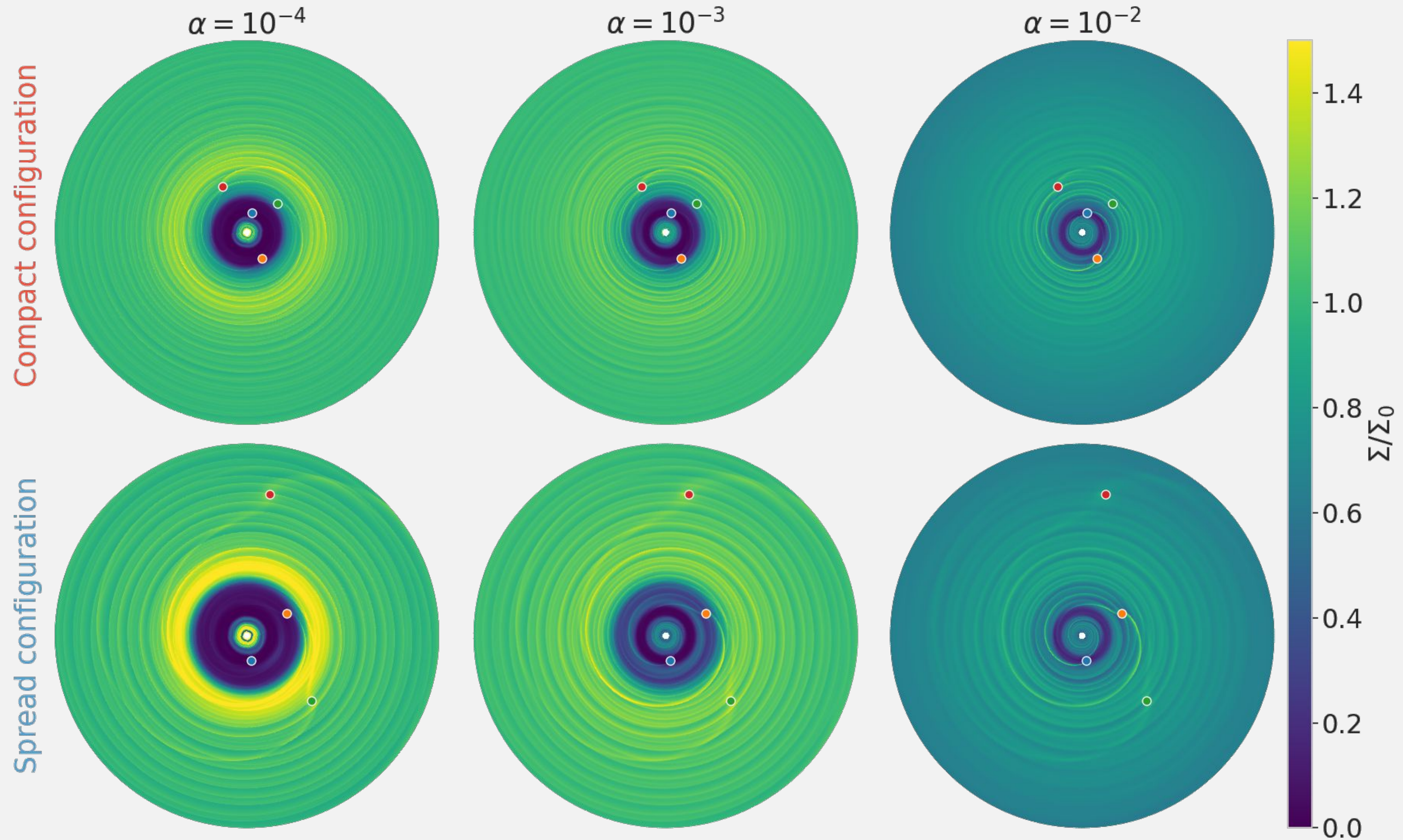
Bergez-Casalou+2021 (in prep)



Hydro – h small

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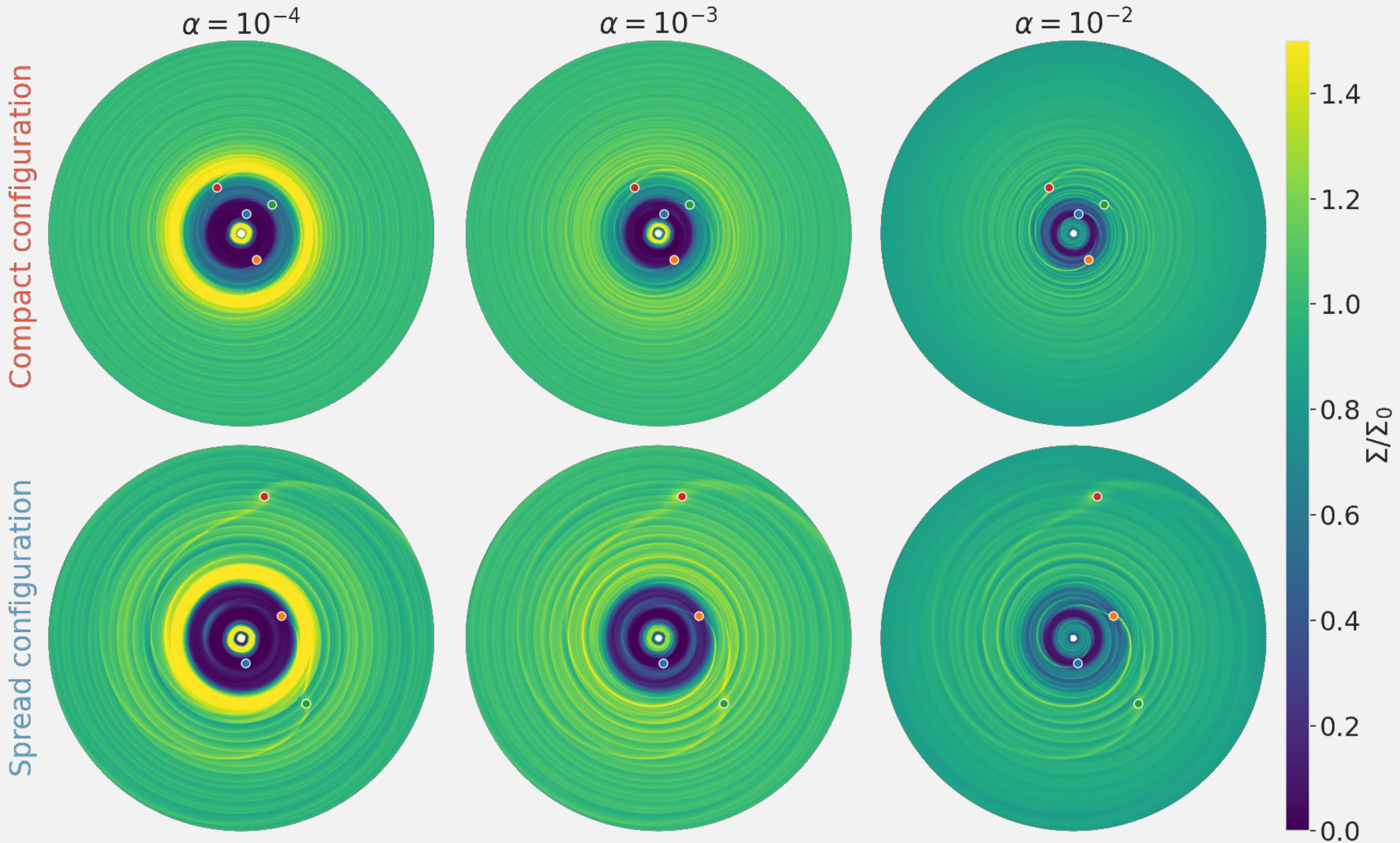
Bergez-Casalou+2021 (in prep)



Dust distribution - h MMSN

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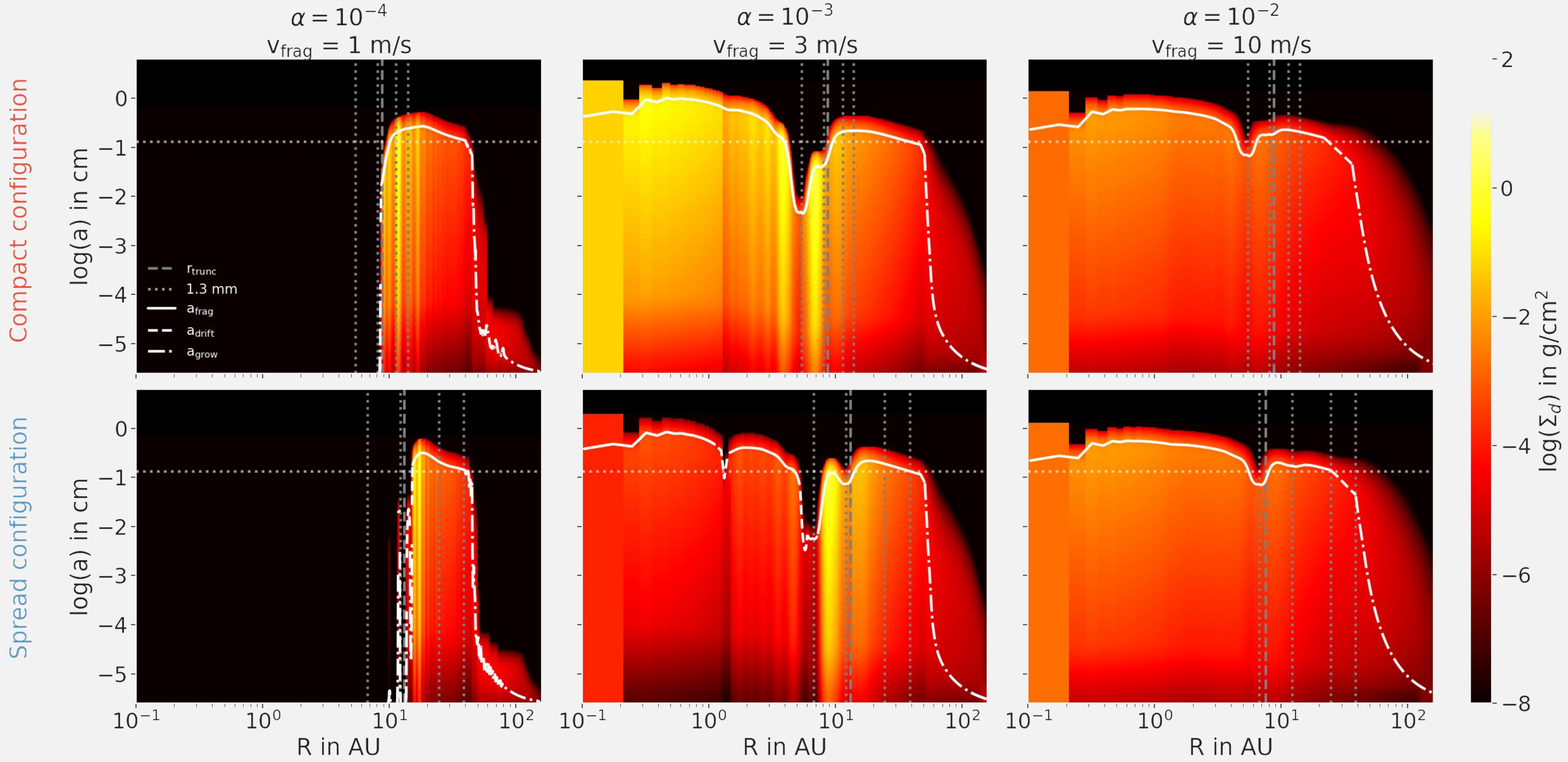
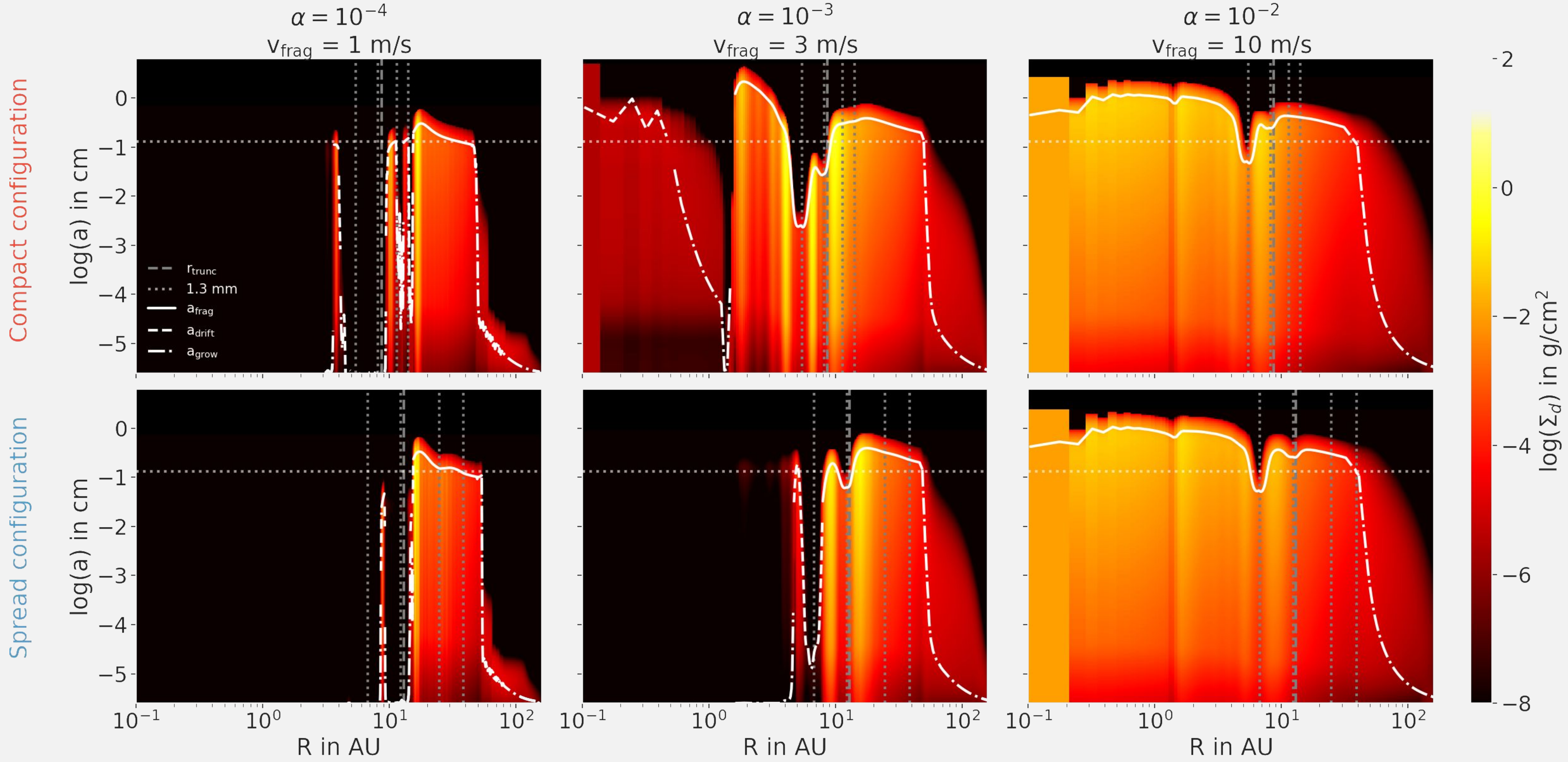
Bergez-Casalou+2021 (in prep)



Dust distribution - h small

bergez@mpia.de

Bergez-Casalou+2021 (in prep)



Gas and Dust setup

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Fargo2D1D: isothermal $r = [0.1; 160]\mathrm{AU}$

$$h = (0.033; 0.025) \times r_{AU}^{2/7}$$

$$\alpha = 10^{-4}; 10^{-3}; 10^{-2}$$

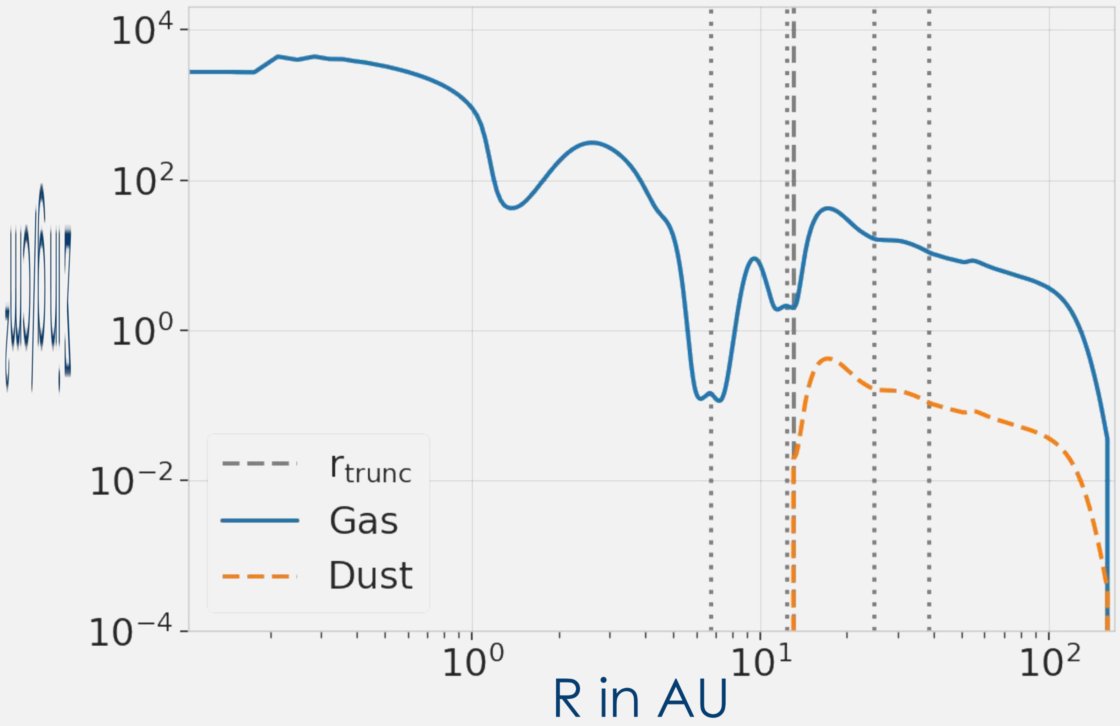
Twopoppy: input = time and azimuthal averaged 1D profiles from Fargo2D1D

To have $s_{max} \geq 1.3mm$:

$$\alpha = 10^{-4} \quad v_{frag} = 1 \quad m/s$$
$$\alpha = 10^{-3} \quad v_{frag} = 3 \quad m/s$$
$$\alpha = 10^{-2} \quad v_{frag} = 10 \, m/s$$

Initial truncation of the inner dust disc:

➡ assume inward drift would clear the inner disc by the time the giant planets formed



Synthetic images

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RADMC3D: input = full dust distribution from Twopoppy

- Assume that the discs are at $d = 140$ pc
- Band 6 ALMA wavelength: $\lambda = 1.3\ mm$
- DSHARP opacities(Birnstiel et al 2018):

Material	Mass Fraction
Refractory organics	0.3966
Astronomical Silicates	0.3291
Water Ice	0.2000
Troilite	0.0743

- Beam sizes studied:

  0.02" x 0.02" (2.8 AU x 2.8 AU)

  0.04" x 0.04" (5.6 AU x 5.6 AU)

  0.1" x 0.1" (14 AU x 14 AU)