DUST EVOLUTION IN PROTOSTELLAR COLLAPSE

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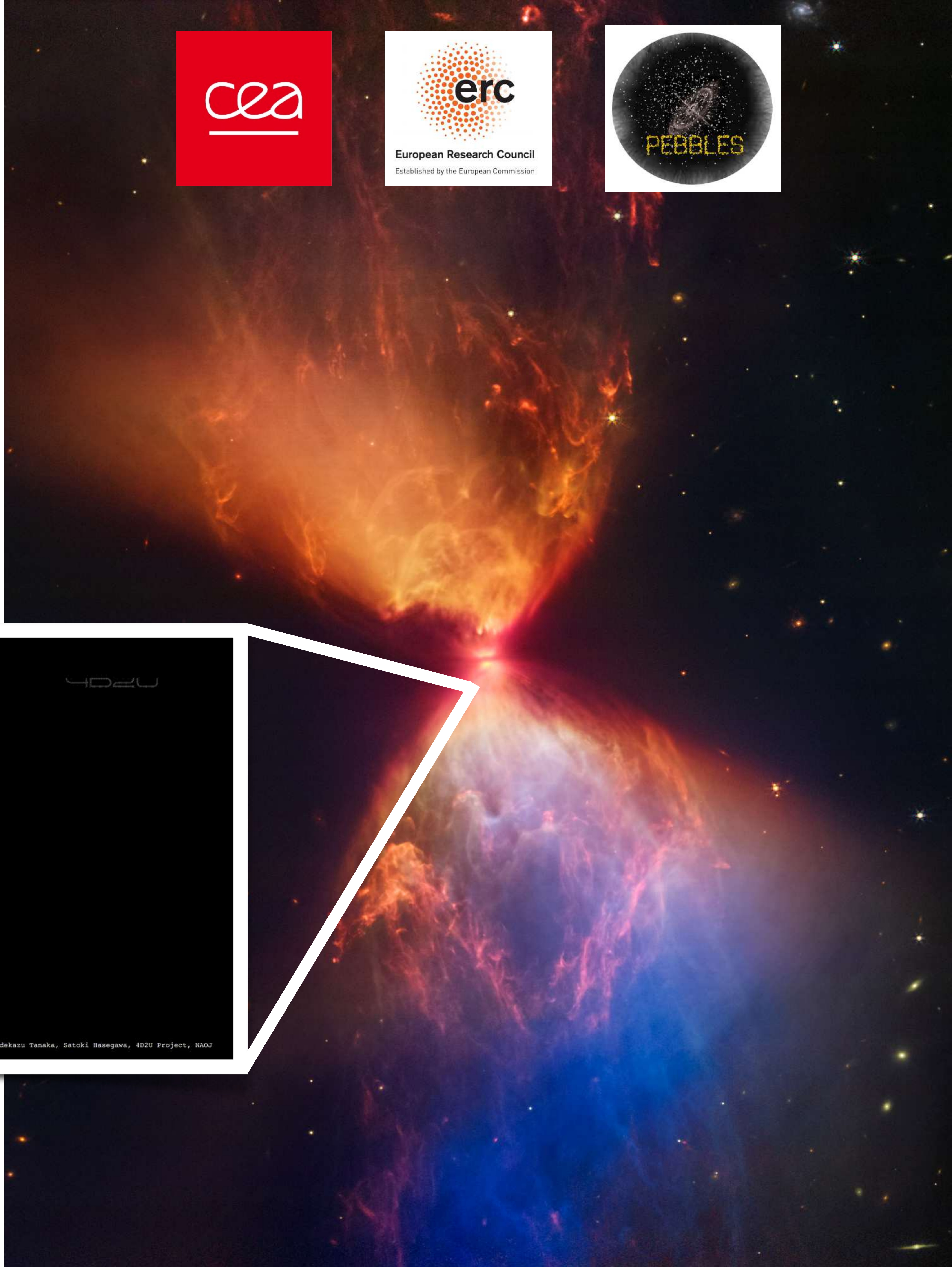
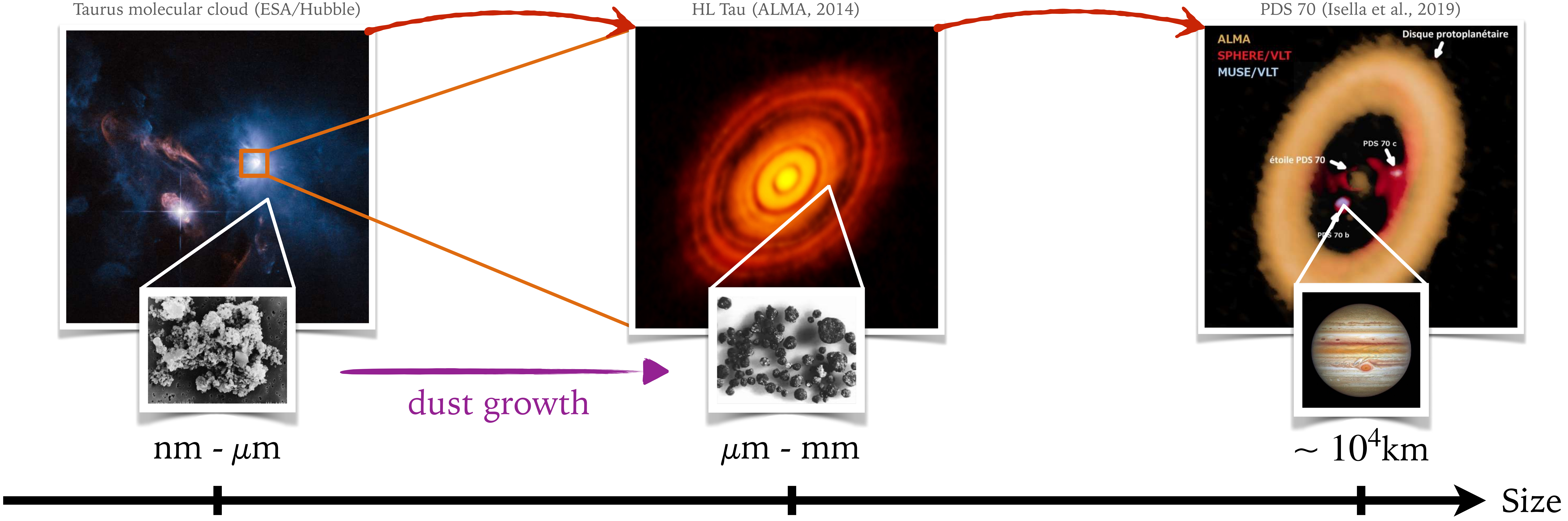
Wada et al. 2018



2nd European Phantom code family users workshop
2025/06/05, Grenoble

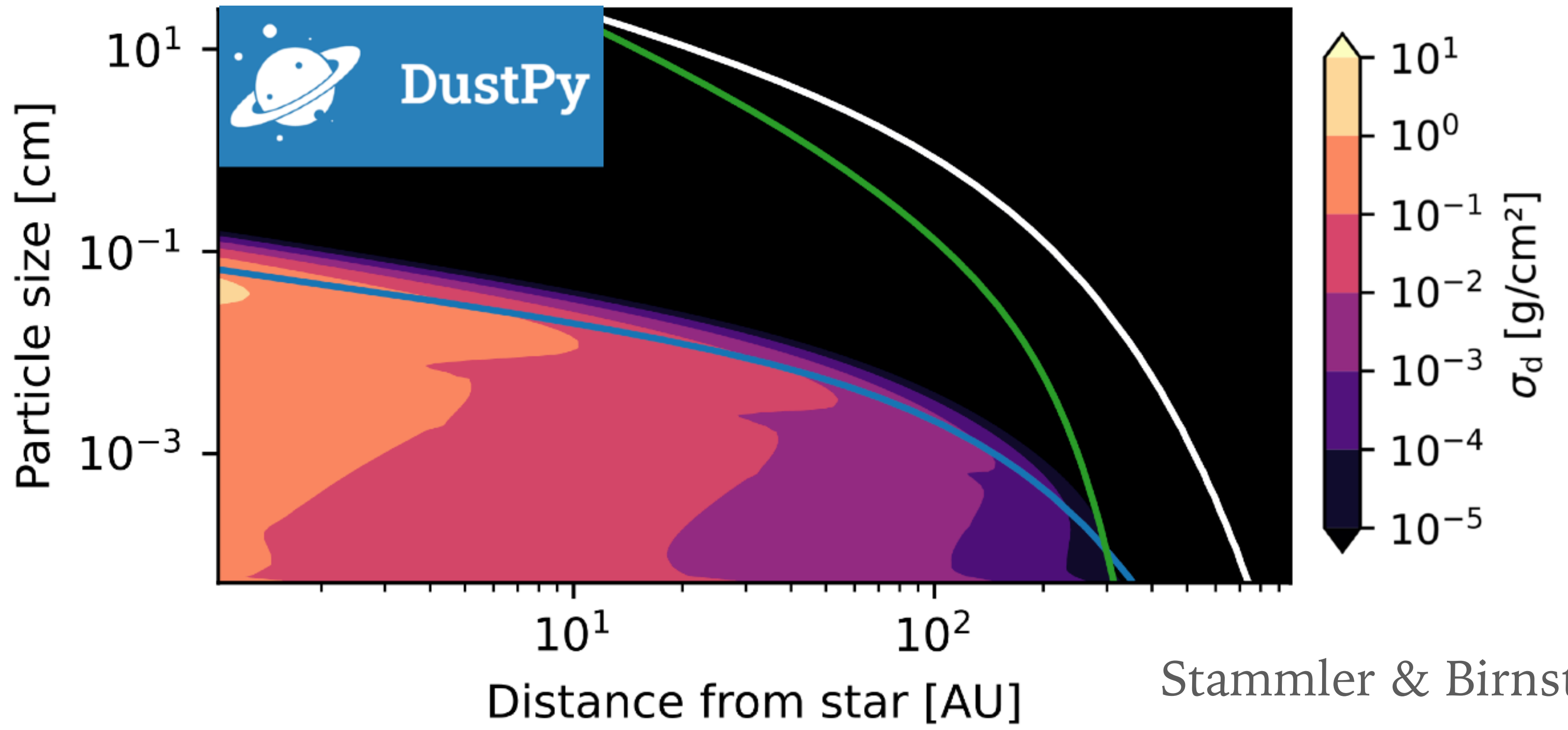
Planets form in less than a few million years



Dust growth is an efficient process !

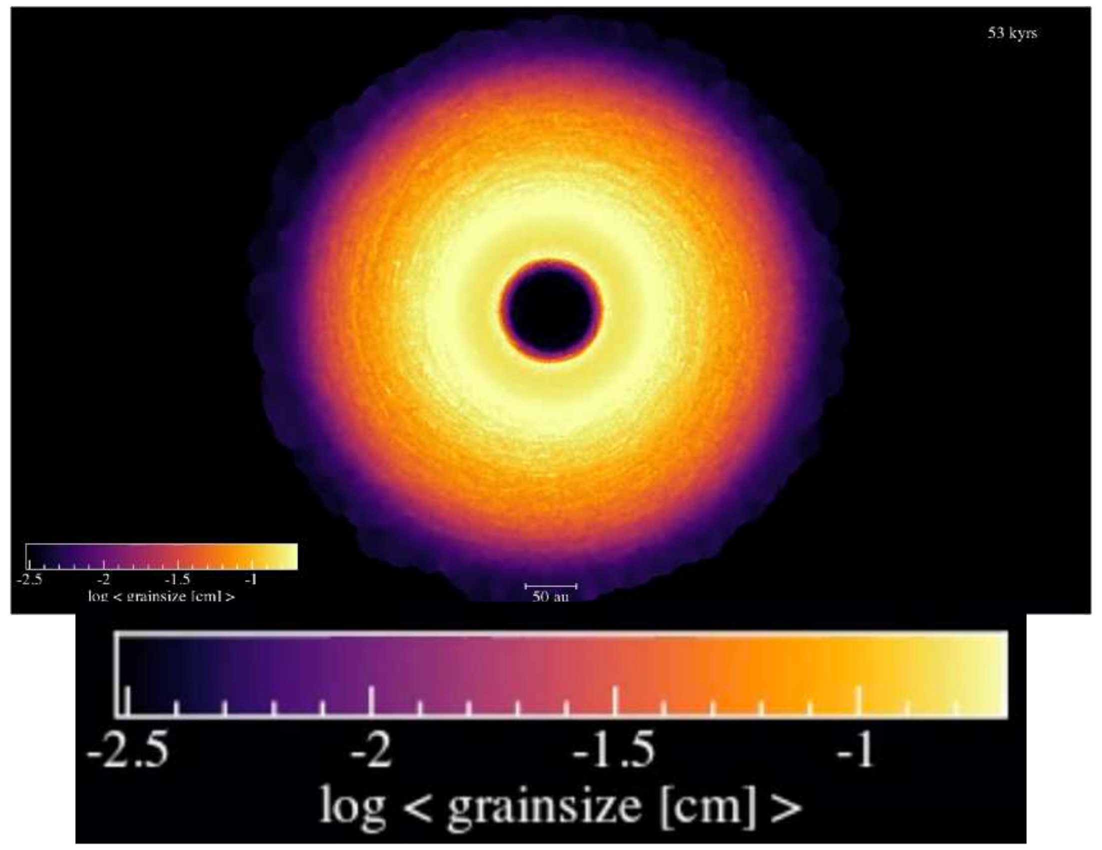
3D SIMULATIONS WITH DUST COAGULATION/FRAGMENTATION

discs

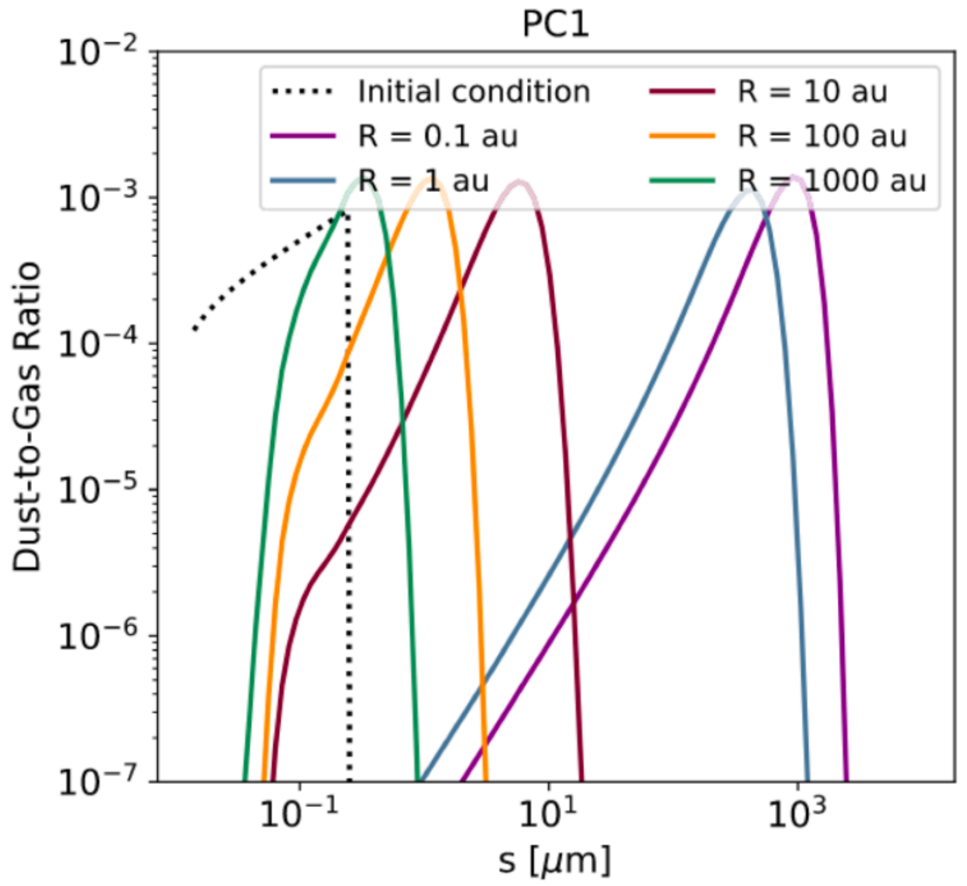


Stammler & Birnstiel, 2022

Vericel et al., 2021

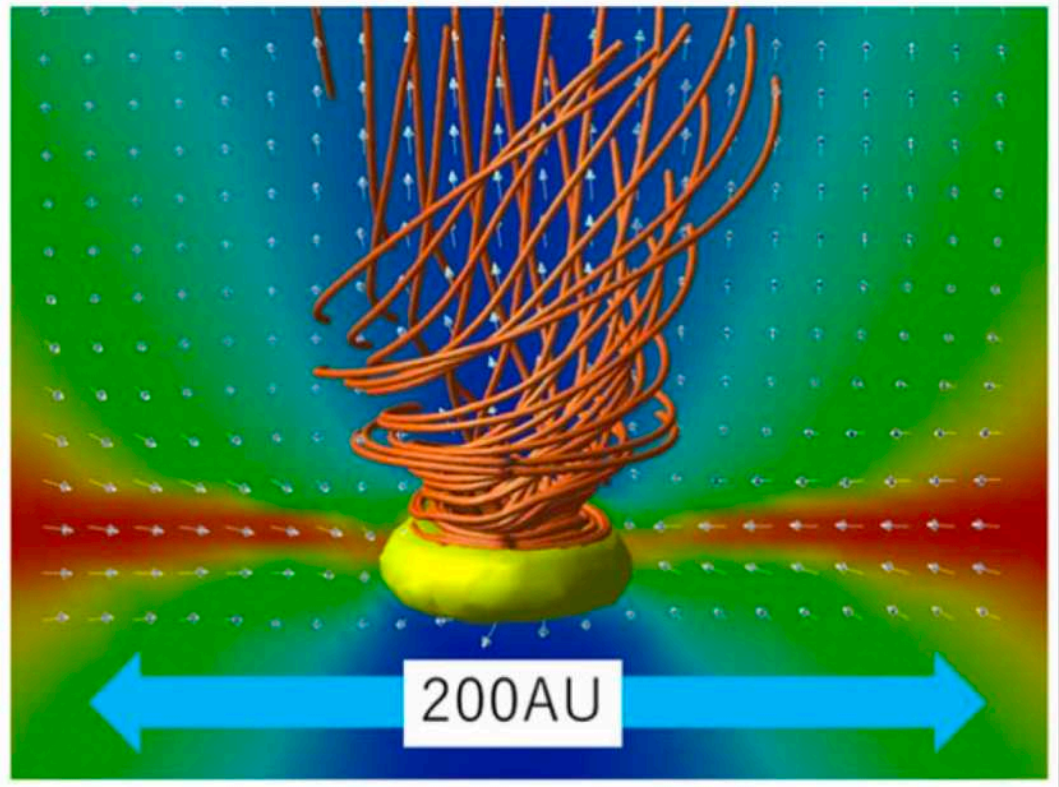


protostellar collapses



Lebreuilly et al., 2023

Tsukamoto et al., 2021



gas and dust dynamic in 1D

single dust size approximation

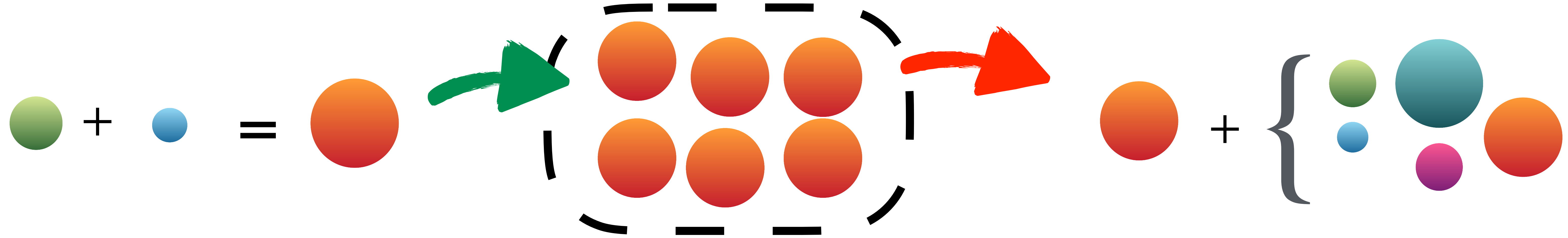
dust size distribution ⟷ gas and dust dynamic in 3D

Marian Smoluchowski
(1872-1917)

m, m': masses

n : number density of particles per mass unit

K: collision kernel



$$\frac{\partial n(m,t)}{\partial t} = \underbrace{\frac{1}{2}\int_0^m K(m', m-m')n(m',t)n(m-m',t)dm'}_{\text{gain}} - \underbrace{n(m,t)\int_0^\infty K(m,m')n(m',t)dm'}_{\text{loss}}$$

Non-linear integro-differential equation !!! 😱

In astrophysics: $K(m_1, m_2) = \sigma(m_1, m_2)\Delta v(m_1, m_2)$ → need numerical solutions

Requirements

- 3 orders of magnitude in size (1μm - 1mm) ⇔ 9 orders in mass
- mass range discretization → 20 mass bins (low numerical cost)

Discontinuous Galerkin scheme

conservative form (Tanaka et al., 1996)

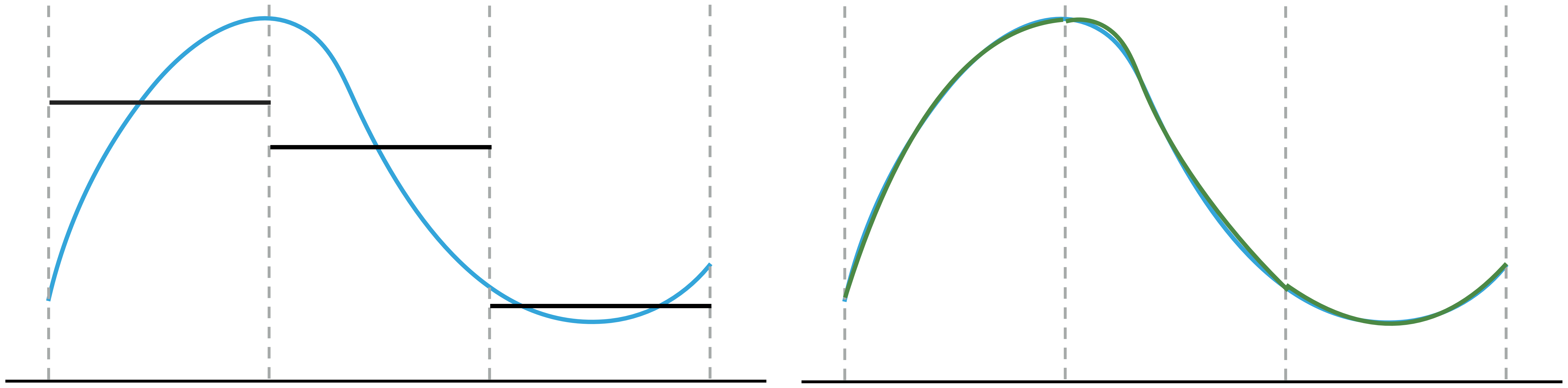
Liu et al., 2019
Lombart & Laibe, 2021

$$\begin{cases} \dfrac{\partial g(m,t)}{\partial t} + \dfrac{\partial F_{\mathrm{coag}}[g](m,t)}{\partial m} = 0 \\ F_{\mathrm{coag}}[g](m,t) = \displaystyle\int_0^m \int_{m-m_1}^{\infty} \frac{K(m_1,m_2)}{m_2} g(m_1,t) g(m_2,t) \mathrm{d}m_2 \mathrm{d}m_1 \end{cases}$$

COALA

COAgulation with Lightning fast Algorithm

constant | polynomials

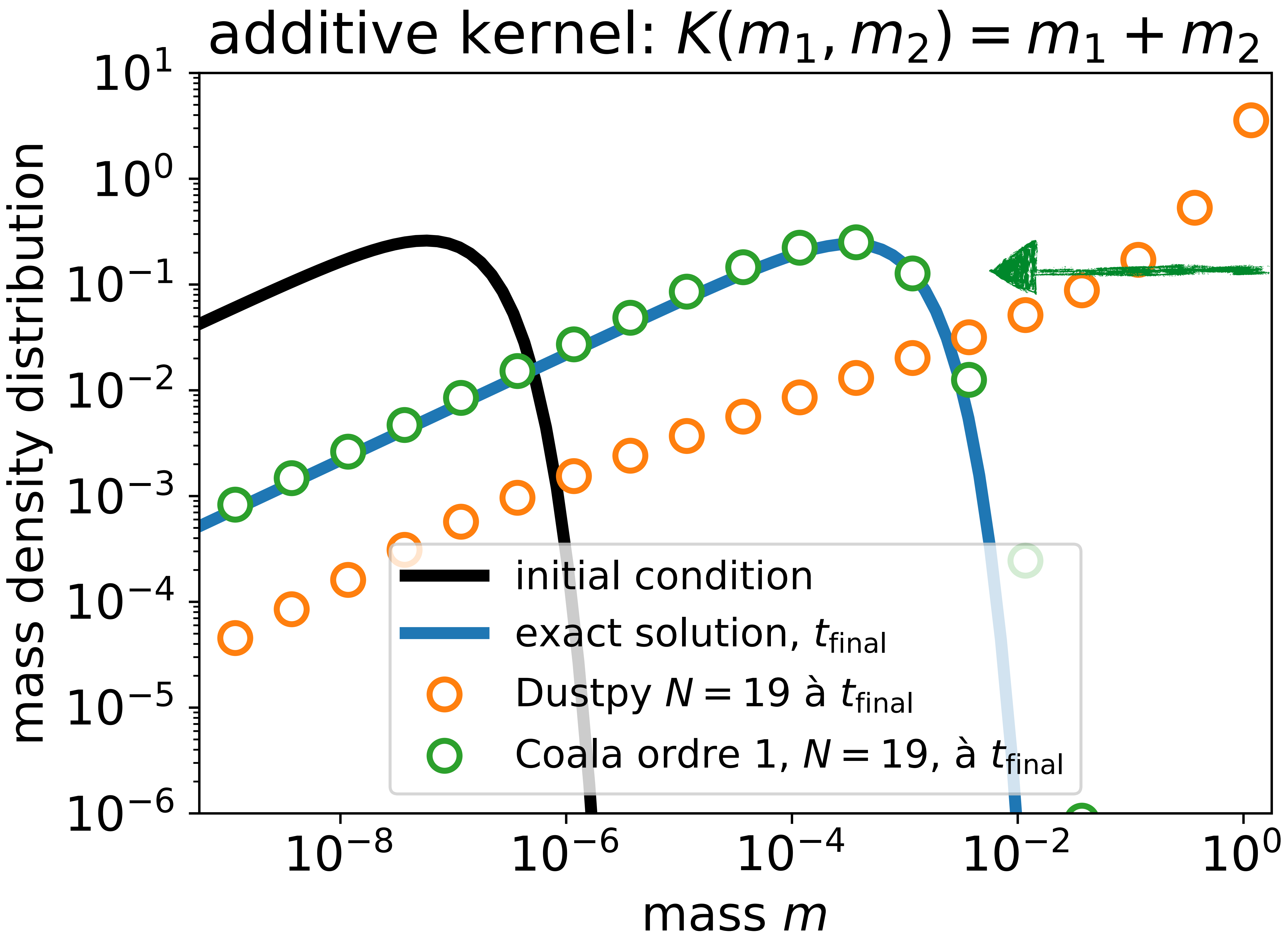


Before | Now

→high accuracy
→few number of mass bins

BENCHMARK COALA

Lombart & Laibe (2021), Laibe & Lombart (2022)



(linear piecewise approximation)

COALA

vs

DustPy

Requirements

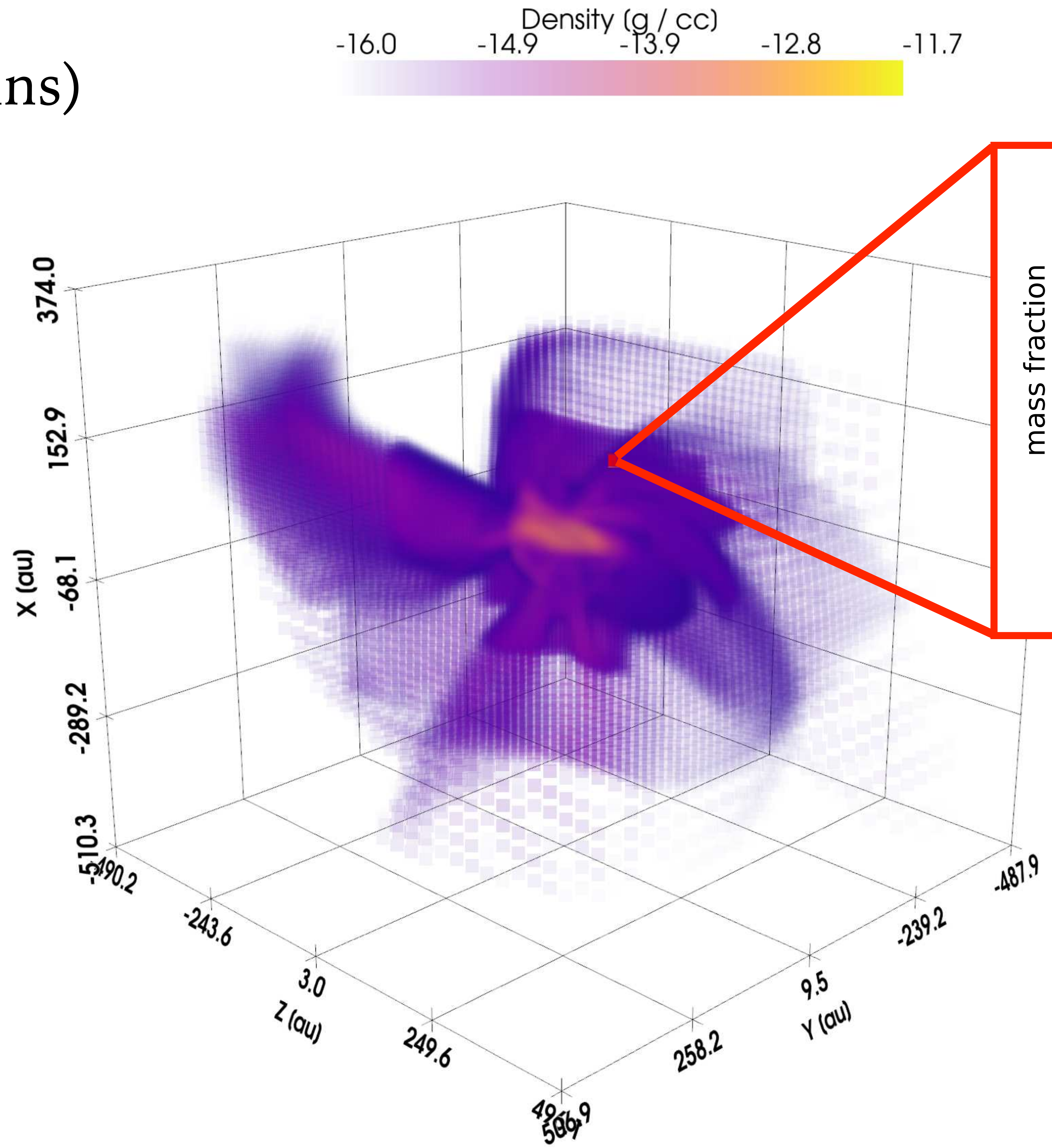
- 9 orders of magnitude in mass
- 10-20 dust size bins

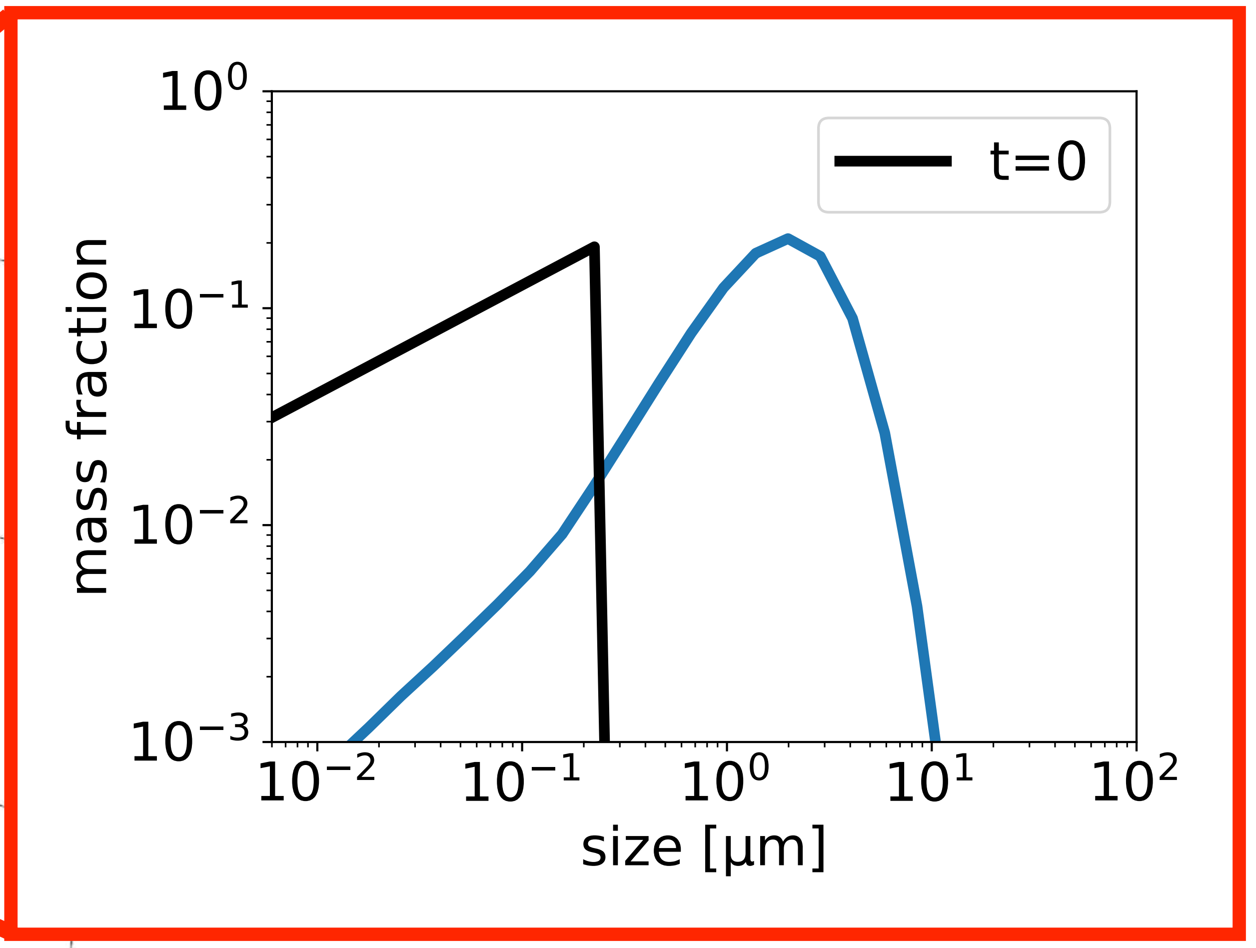
3D simulations with polydisperse coagulation

DUST GROWTH IN PROTOSTELLAR COLLAPSE

Lombart et al., 2025a (in prep)

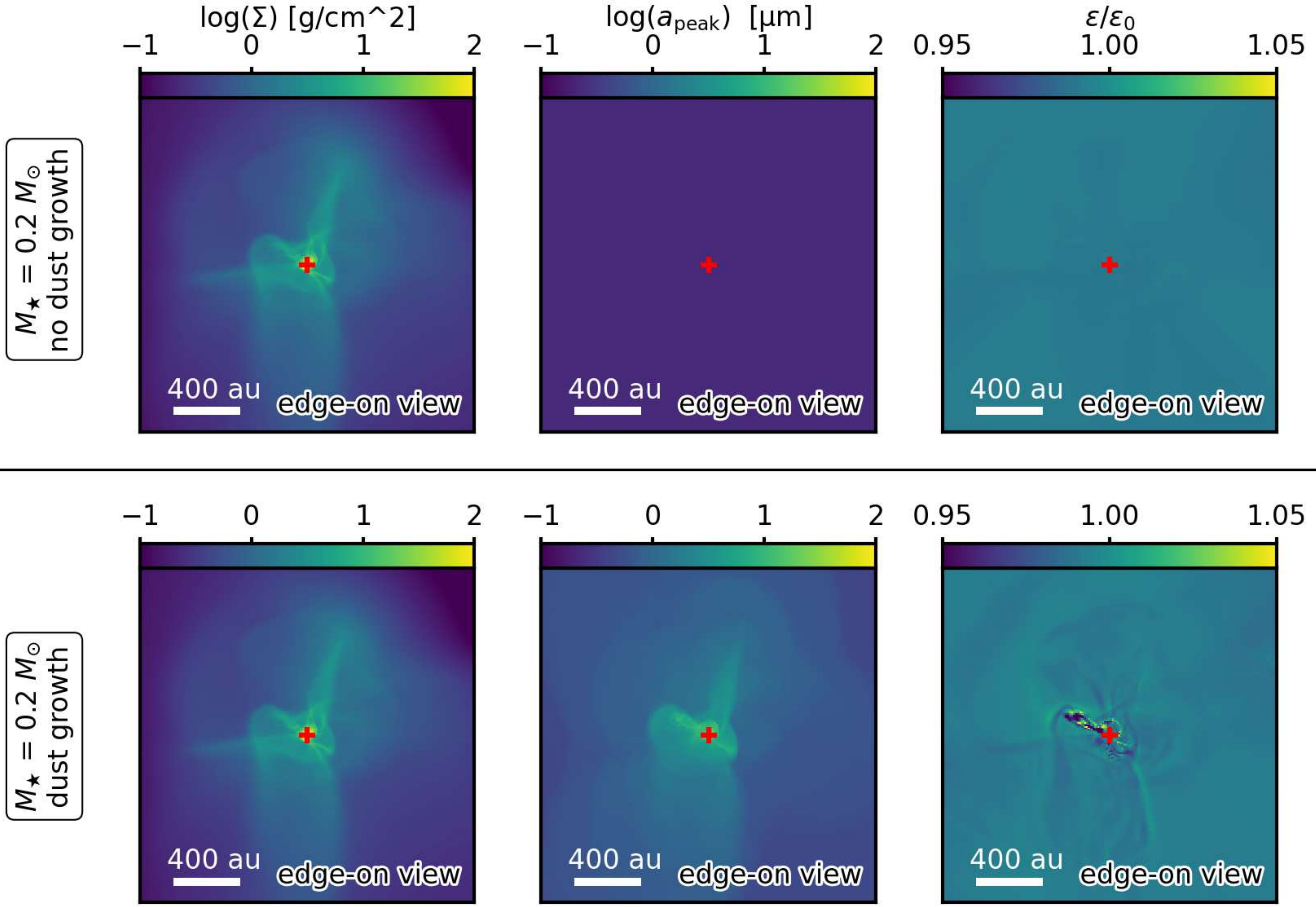
RAMSES (AMR)
gas & dust (40 bins)





DUST GROWTH IN PROTOSTELLAR COLLAPSE

Lombart et al., 2025a (in prep)



188-270 nm

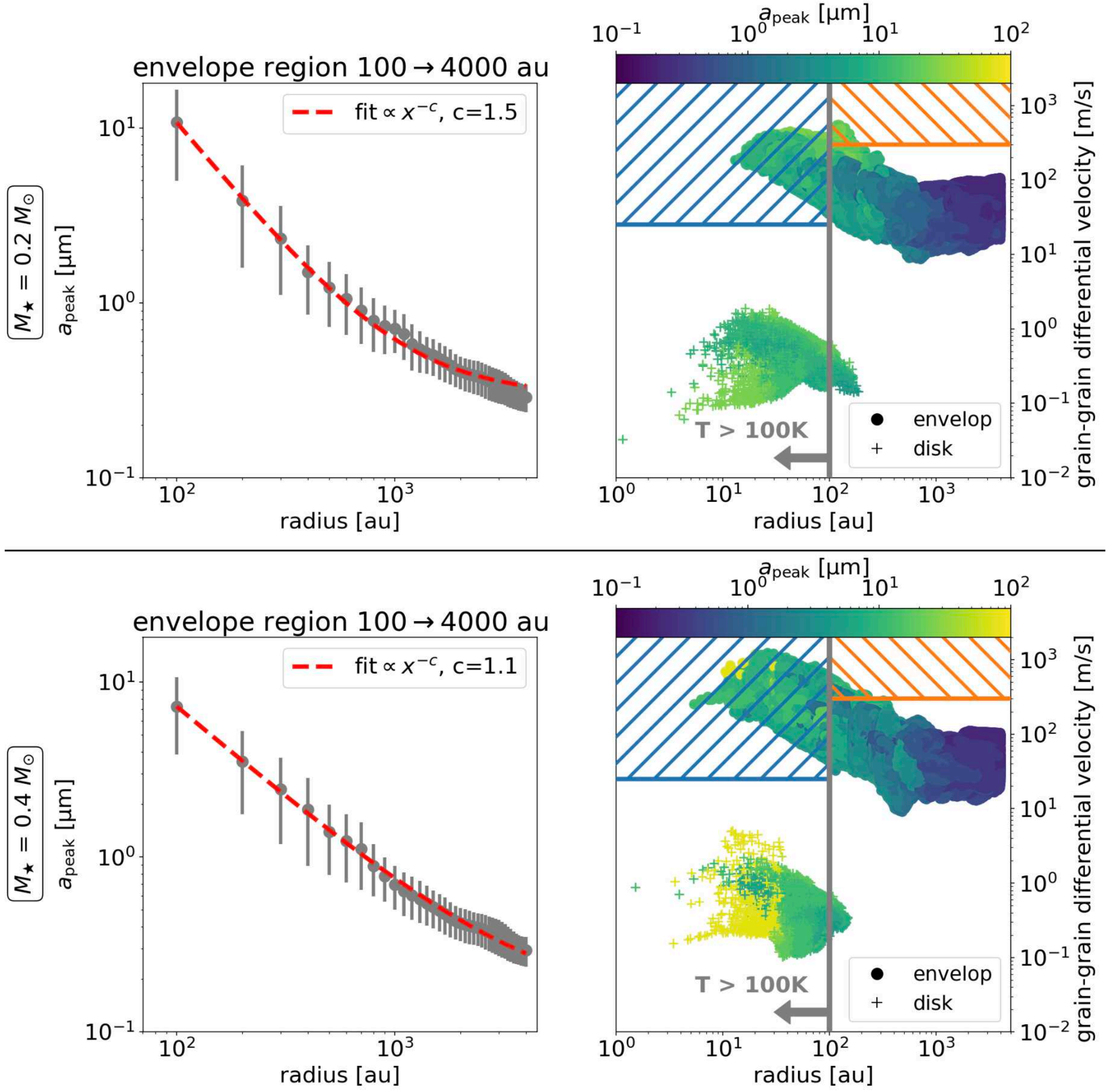
~ 20 % of total dust mass

188-270 nm

~ 12 % of total dust mass

DUST GROWTH IN PROTOSTELLAR COLLAPSE

Lombart et al., 2025a (in prep)



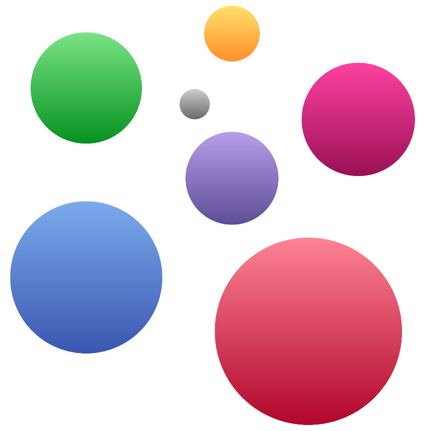
Fragmentation velocity threshold (Ormel et al., 2009)

Silicate grains: ~ 20 m/s

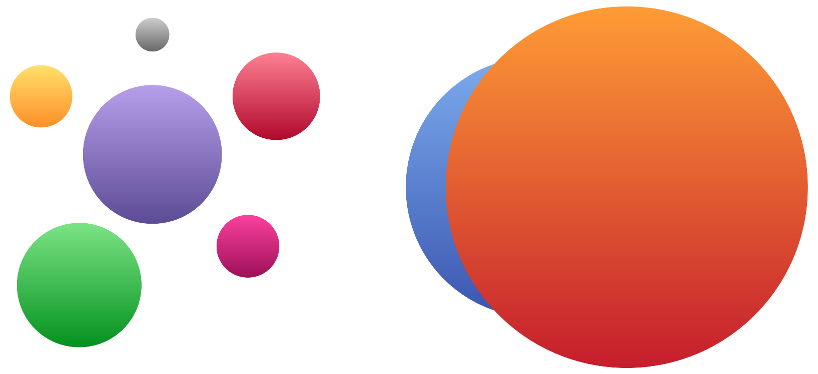
Ice coated grains: ~ 300 m/s

DUST FRAGMENTATION MODEL

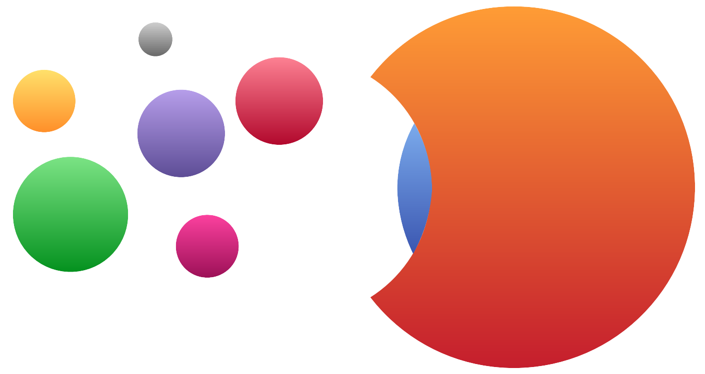
Destructive fragmentation



Mass transfer



Mass transfer + cratering



$$\frac{\partial n(m,t)}{\partial t} = \frac{1}{2}\int_0^\infty\int_0^\infty K(m_1,m_2)\underline{b(m,m_1,m_2)}n(m_1,t)n(m_2,t)\mathrm{d}m_1\mathrm{d}m_2 - n(m,t)\int_0^\infty K(m,m_1)n(m_1,t)\mathrm{d}m_1$$

mass distribution of fragments

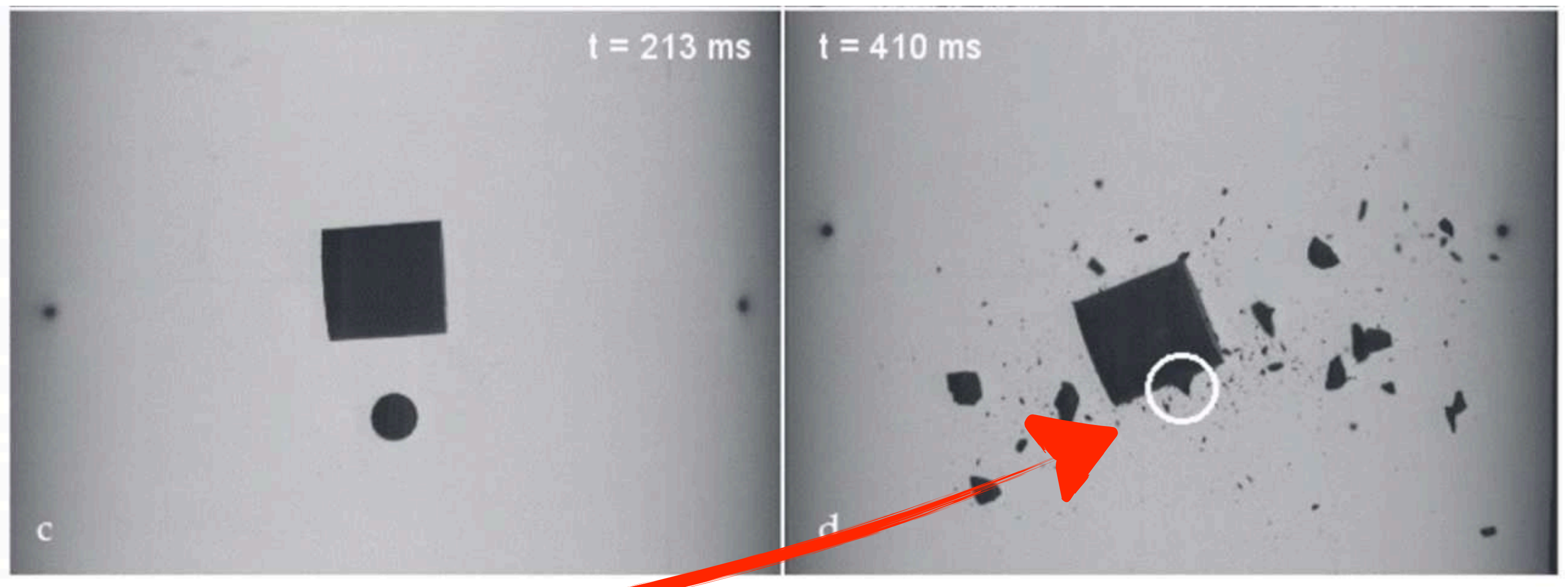
Safronov, 1972; Jones et al., 1996; Suttner et al., 2001; Blum, 2006; Hirashita et al., 2009; Rafikov et al., 2020

Conservative form (Lombart et al. 2024):

$$F[g](m,t) = \frac{1}{2}\int_0^m\int_0^\infty\int_0^\infty \mathbf{1}_{m_1+m_2\geq m}\frac{m_\mathrm{f}}{m_1 m_2}b(m_\mathrm{f},m_1,m_2)K(m_1,m_2)g(m_1,t)g(m_2,t)\mathrm{d}m_2\mathrm{d}m_1\mathrm{d}m_\mathrm{f}$$

$$-\int_0^m\int_{m-m_1}^\infty \frac{K(m_1,m_2)}{m_2}g(m_1,t)g(m_2,t)\mathrm{d}m_2\mathrm{d}m_1$$

Bukhari Syed et al. 2017



Benchmark for fragmentation

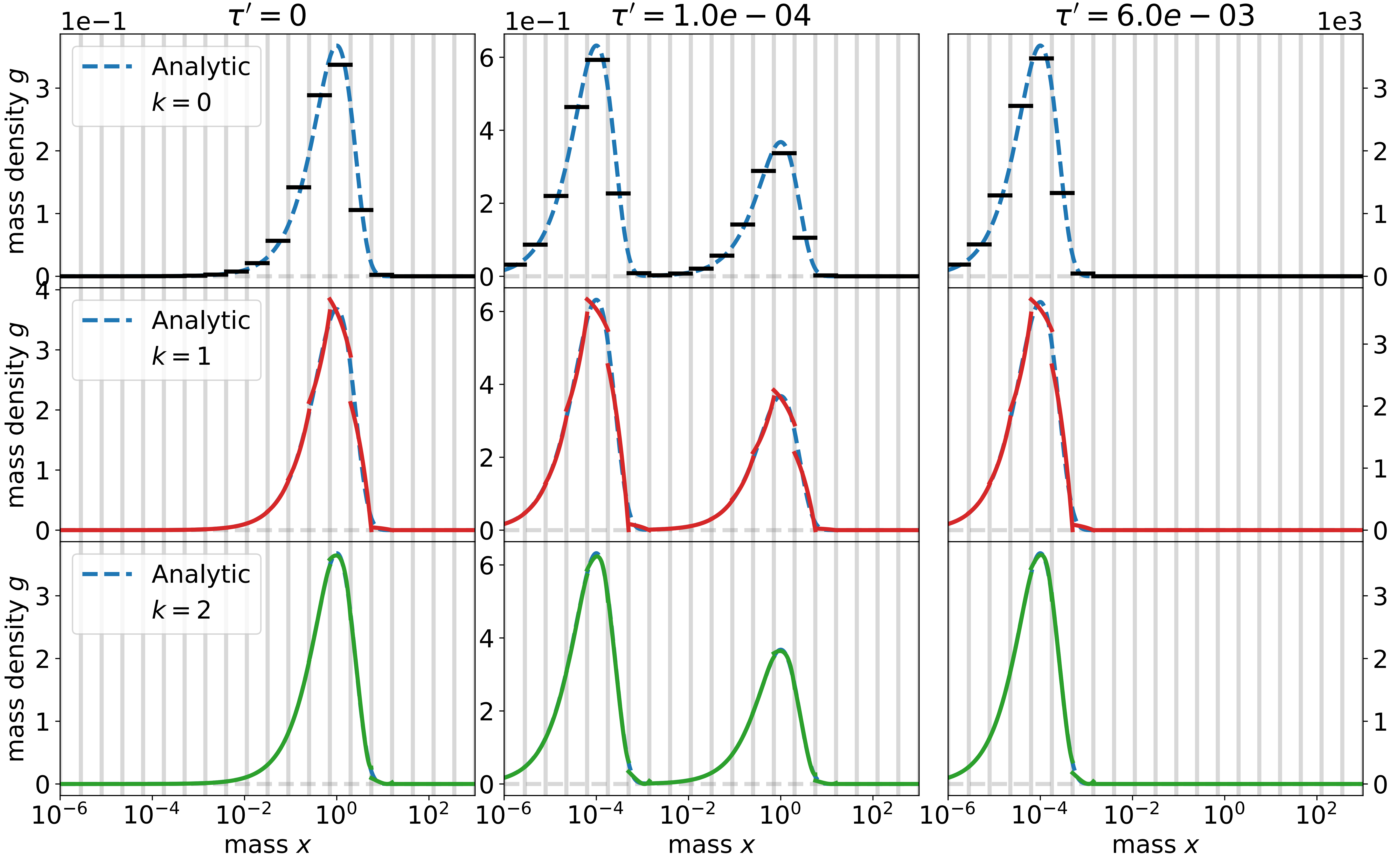
Feingold et al., 1988

$K(u, v) = 1$

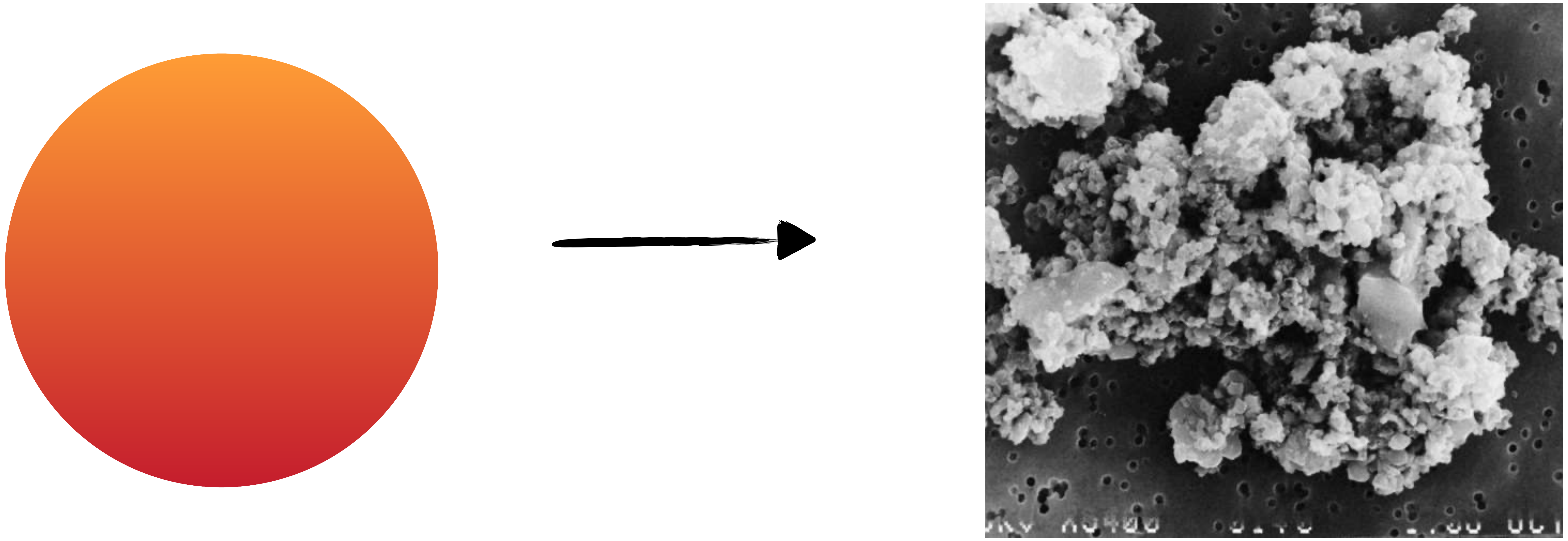
$b(w, u, v) = \gamma^2 (u + v) e^{-\gamma w}$

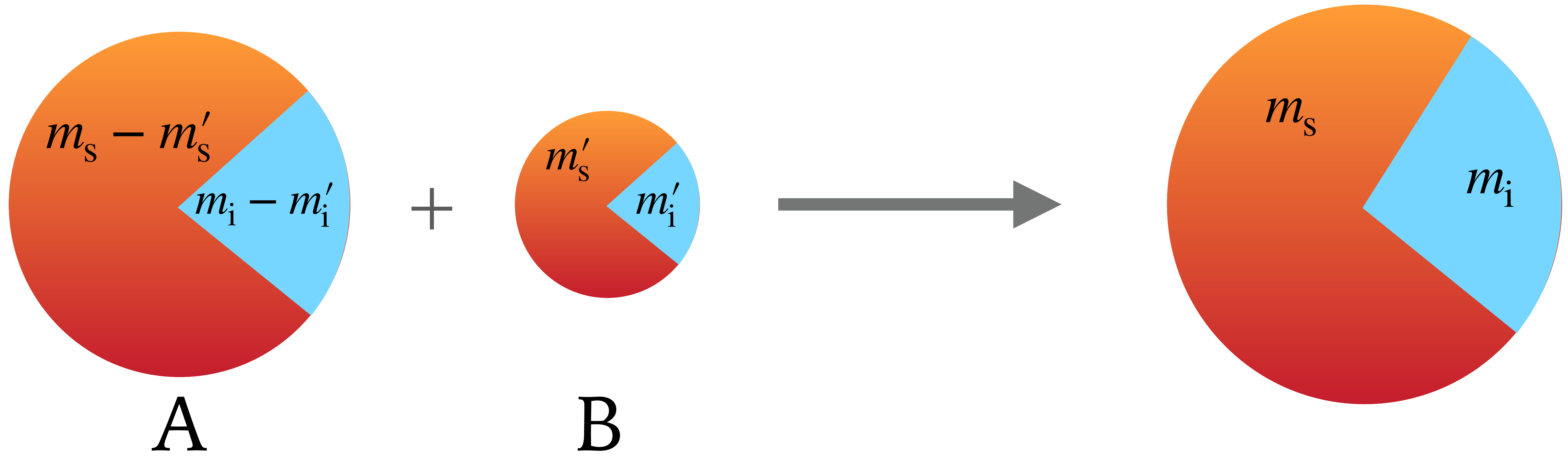
3D simulations with polydisperse general non-linear fragmentation

Lombart et al. 2024



Growth and fragmentation of multi-component dust aggregates





Need 2D Smoluchowski coagulation equation

$$\frac{\partial n(m_s, m_i, t)}{\partial t} = \frac{1}{2}\int_0^{m_s}\int_0^{m_i} K(m_s - m_s', m_s', m_i - m_i', m_i') n(m_s', m_i', t) n(m_s - m_s', m_i - m_i', t) \mathrm{d}m_s' \mathrm{d}m_i' - \int_0^{\infty}\int_0^{\infty} K(m_s, m_s', m_i, m_i') n(m_s, m_i, t) n(m_s', m_i', t) \mathrm{d}m_s' \mathrm{d}m_i'$$

$$K(m_s - m_s', m_s', m_i - m_i', m_i') = P_{\mathrm{stick}}(m_s, m_s', m_i, m_i') \sigma \Delta v$$

Sticking probability

$$P_{\mathrm{stick}}(m_s, m_s', m_i, m_i') = \epsilon_{s-s} \frac{m_{s,A}}{m_A} \frac{m_{s,B}}{m_B} + \epsilon_{s-i} \left(\frac{m_{s,A}}{m_A} \frac{m_{i,A}}{m_A} + \frac{m_{s,B}}{m_B} \frac{m_{i,B}}{m_B} \right) + \epsilon_{i-i} \frac{m_{i,A}}{m_A} \frac{m_{i,B}}{m_B}$$

Sticking efficiency of s-s collision

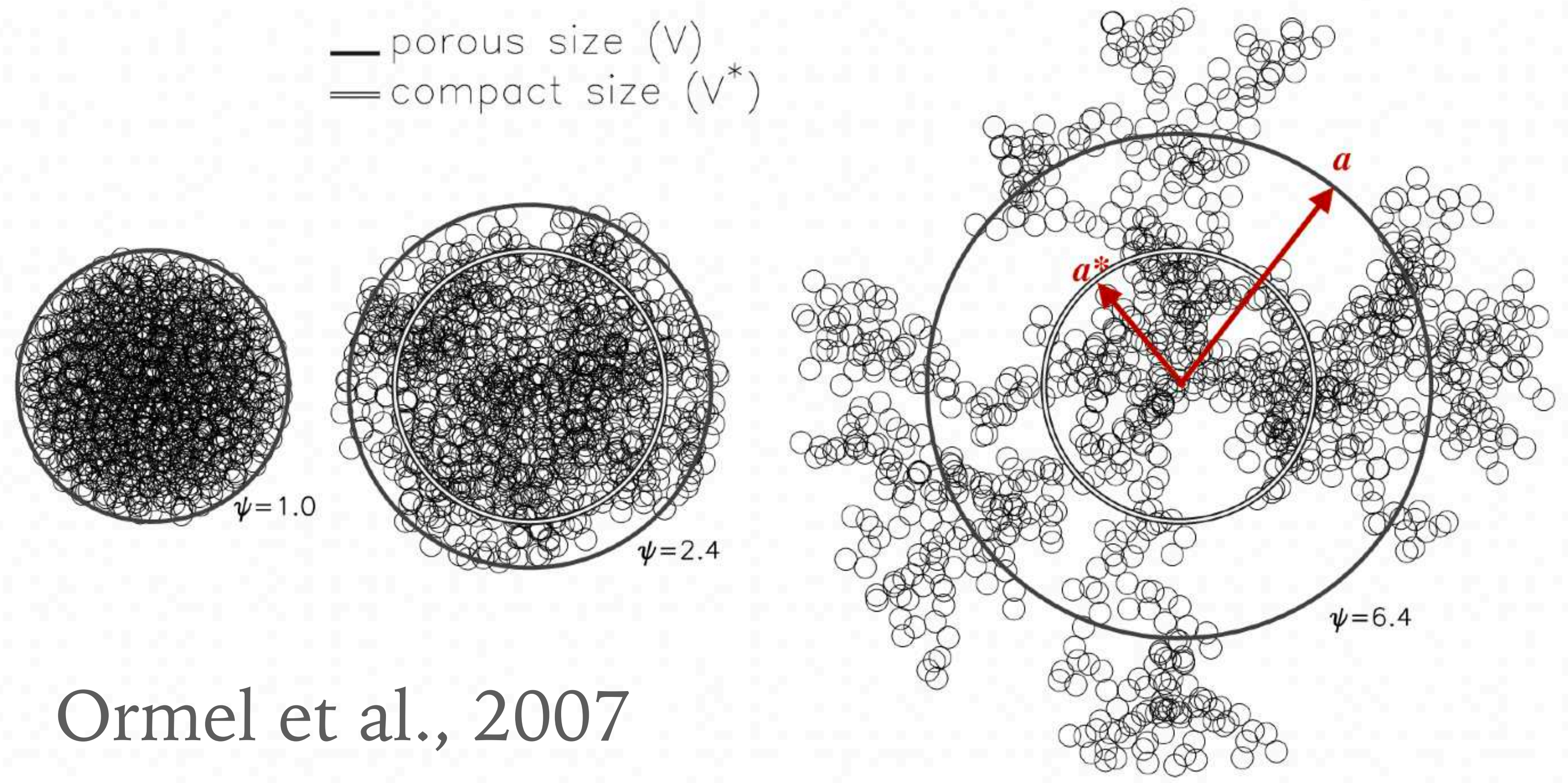
Sticking efficiency of s-i collision

Sticking efficiency of i-i collision

Need data from lab experiments

Laurenzi+2002; Vale+2005; Alexopoulos+2009

Dust aggregate is defined by its mass m and porosity $\psi = \frac{V}{V*}$



Ormel et al., 2007

Need 2D Smoluchowski coagulation equation

$$\frac{\partial n(m,\psi_m,\tau)}{\partial t} = \frac{1}{2}\int_0^m \int_{\psi_{\min}}^{\psi_{\max}} \int_{\psi_{\min}}^{\psi_{\max}} K(m-m_1,\psi_{m-m_1};m_1,\psi_{m_1})n(m_1,\psi_{m_1},t)n(m-m_1,\psi_{m-m_1},t)\delta(\psi_m - \Gamma(m-m_1,\psi_{m-m_1};m_1,\psi_{m_1}))\mathrm{d}\psi_{m-m_1}\mathrm{d}\psi_{m_1}\mathrm{d}m_1$$

$$-n(m,\psi_m,t)\int_0^\infty \int_{\psi_{\min}}^{\psi_{\max}} K(m,\psi_m;m_1,\psi_{m_1})n(m_1,\psi_{m_1},t)\mathrm{d}\psi_{m_1}\mathrm{d}m_1$$

$\Gamma(m-m_1,\psi_{m-m_1};m_1,\psi_{m_1}) \rightarrow$ determine the porosity of the resulting aggregate

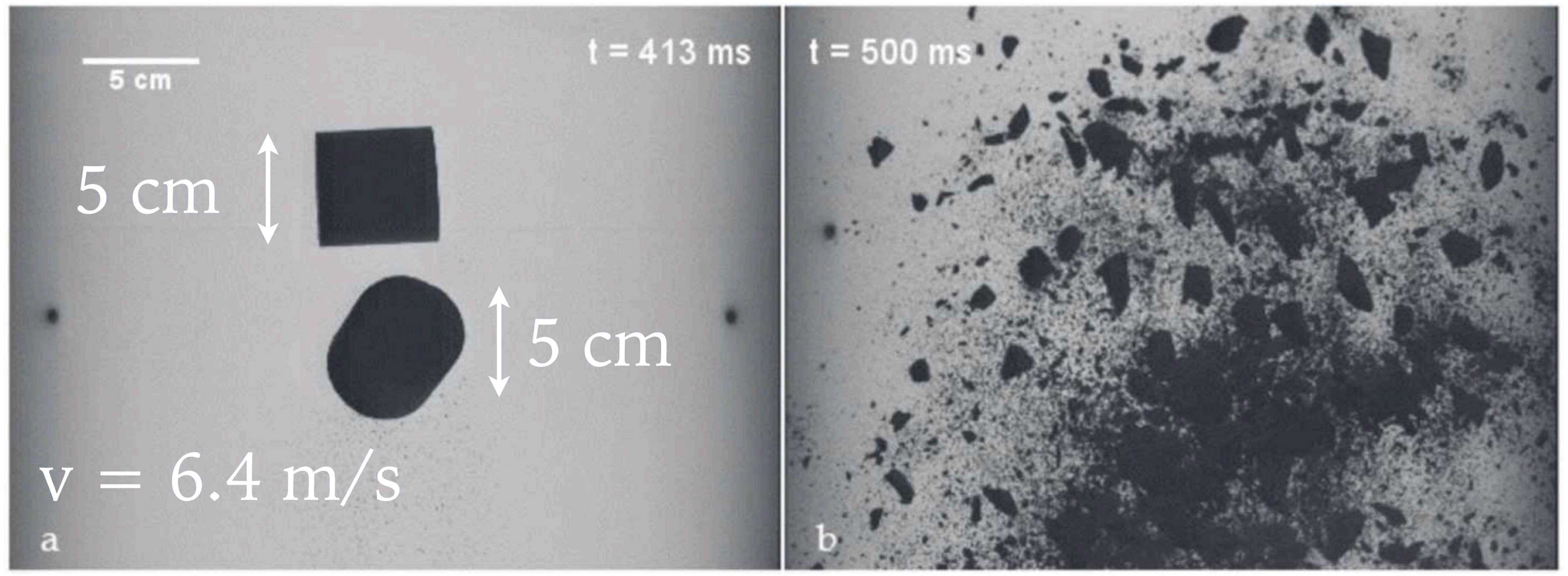
Blum, 2006; Ormel et al., 2007; Okuzumi et al., 2009; Hirashita et al., 2021

Multi-component dust:

→ how to model the composition of fragments ?

Dust aggregates:

→ how to model the mass and porosity of the fragments ?

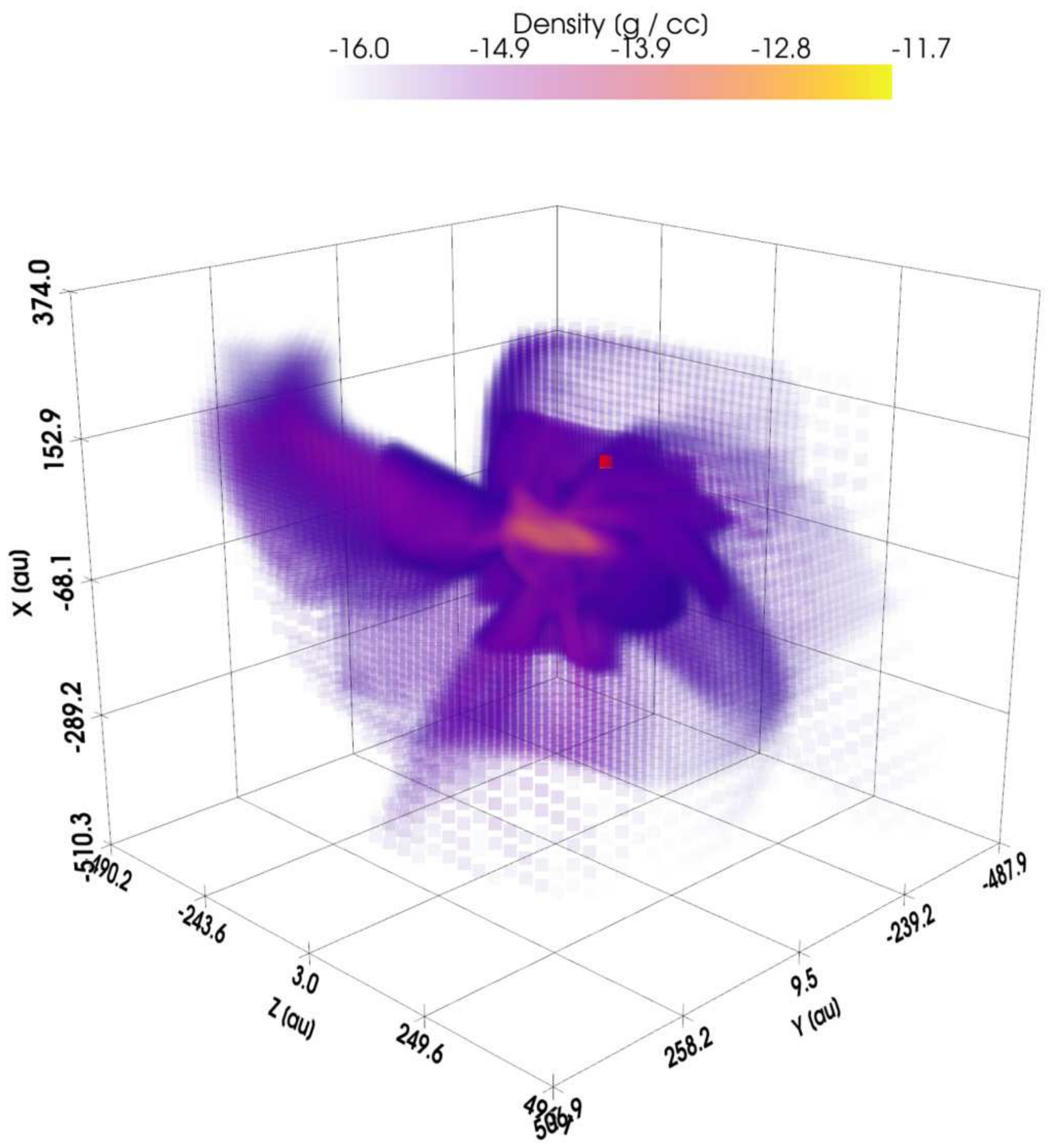


Need data from lab experiments

Blum, 2006; Ormel et al., 2007; Okuzumi et al., 2009; Hirashita et al., 2021; Hasegawa et al., 2022

WORKING PLAN

RAMSES + COALA



PHANTOM

Realistic dust optical properties

Radiative transfer code

Realistic synthetic observations

TAKE HOME MESSAGES

- The **coagulation** and **fragmentation** processes are modeled by **Smoluchowski-like equations**.

- **3D simulations with polydisperse dust coagulation/fragmentation**
  - 9 orders of magnitude in mass (1μm - 1mm)
  - Few number of bins $\sim$ 20
  - Good accuracy

- Coagulation/fragmentation of **dust aggregates** can be modeled by **2D extension** (mass and porosity).

- Coagulation/fragmentation of **multicomponent dust** can be modeled by **2D extension.**

- Realistic synthetic observations by combining simulations, radiative transfer with realistic dust optical properties