SNO RAMSES 2025

DUST GROWTH IN RAMSES

Coupling coagulation and dust dynamics in RAMSES

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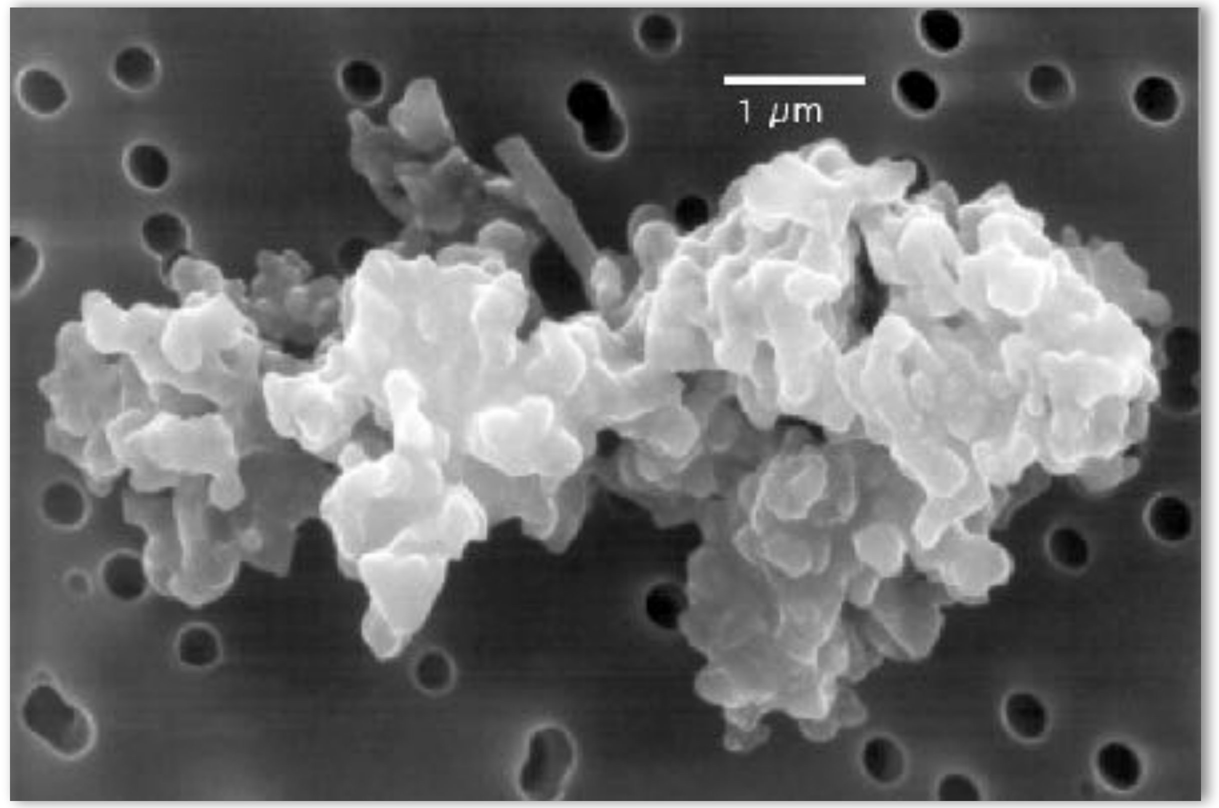
WHAT IS INTERSTELLAR DUST ?

- *Solid particles made of carbon, silicates, iron …*
- *1 % of the mass*
- *Distribution in the diffuse ISM (MRN, Mathis et al., 1977)*

$$\frac{\mathrm{d}n(s)}{\mathrm{d}s} \propto s^{-3.5}; s \in [5, 250] \ \ \mathrm{nm}$$



Interplanetary dust grain (Jessberger et al., 2001)

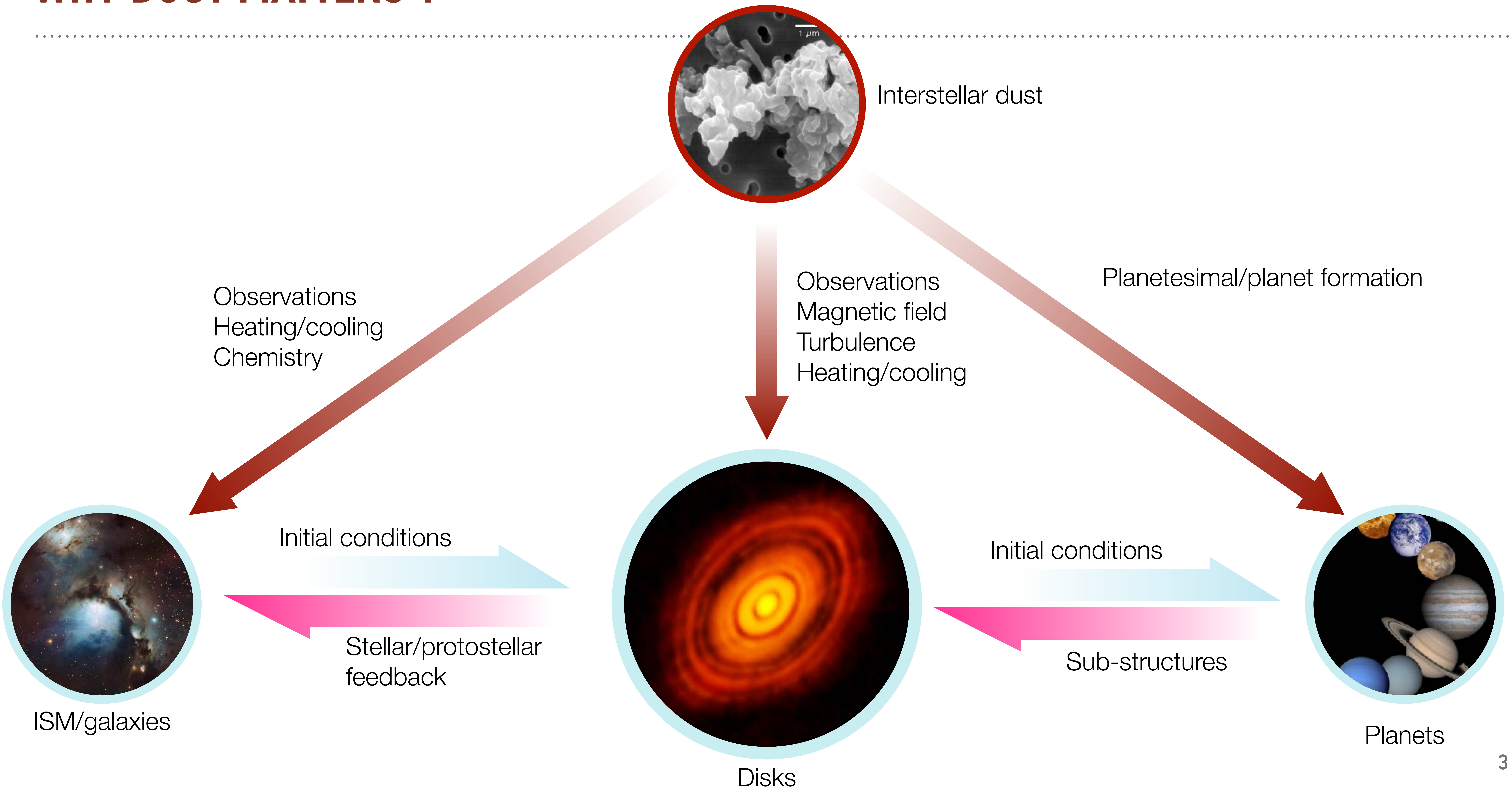
- *Larger grains in denser regions ?*

  1-10 microns in dense cores (Pagani et al., 2010)

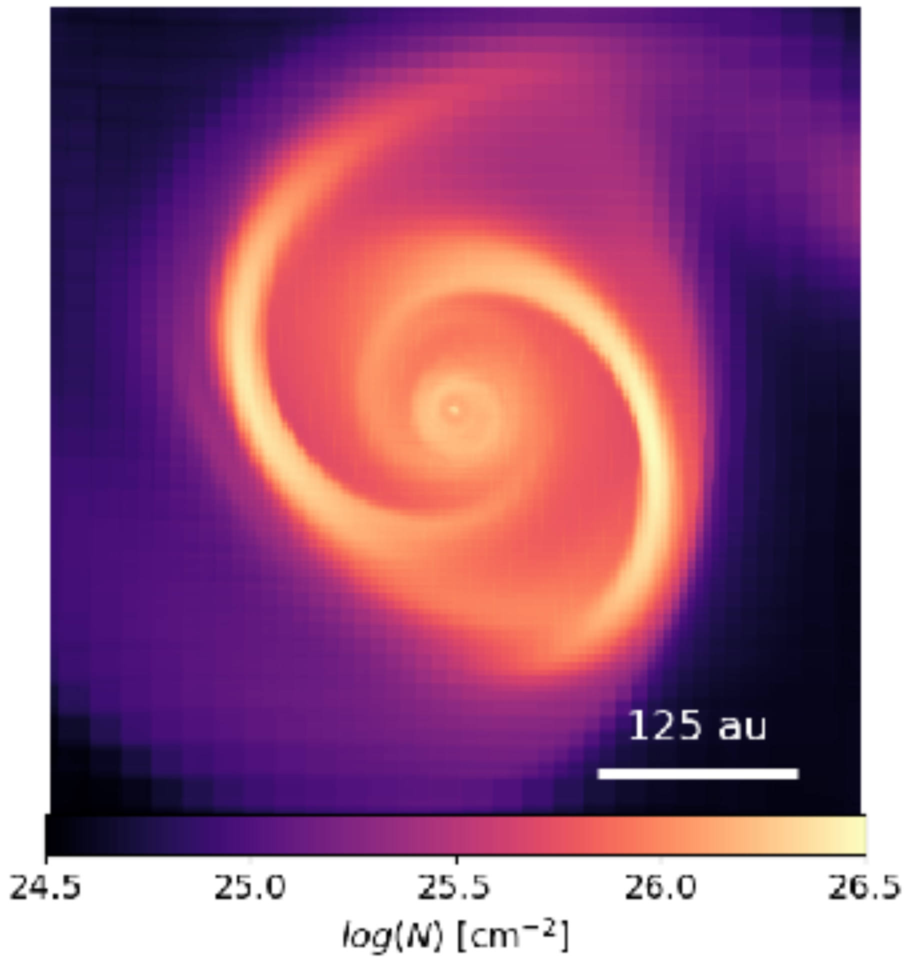
  10-100 microns around protostars (Kataoka et al., 2015; Sadavoy et al., 2018a, b, 2019; Galametz et al., 2019)

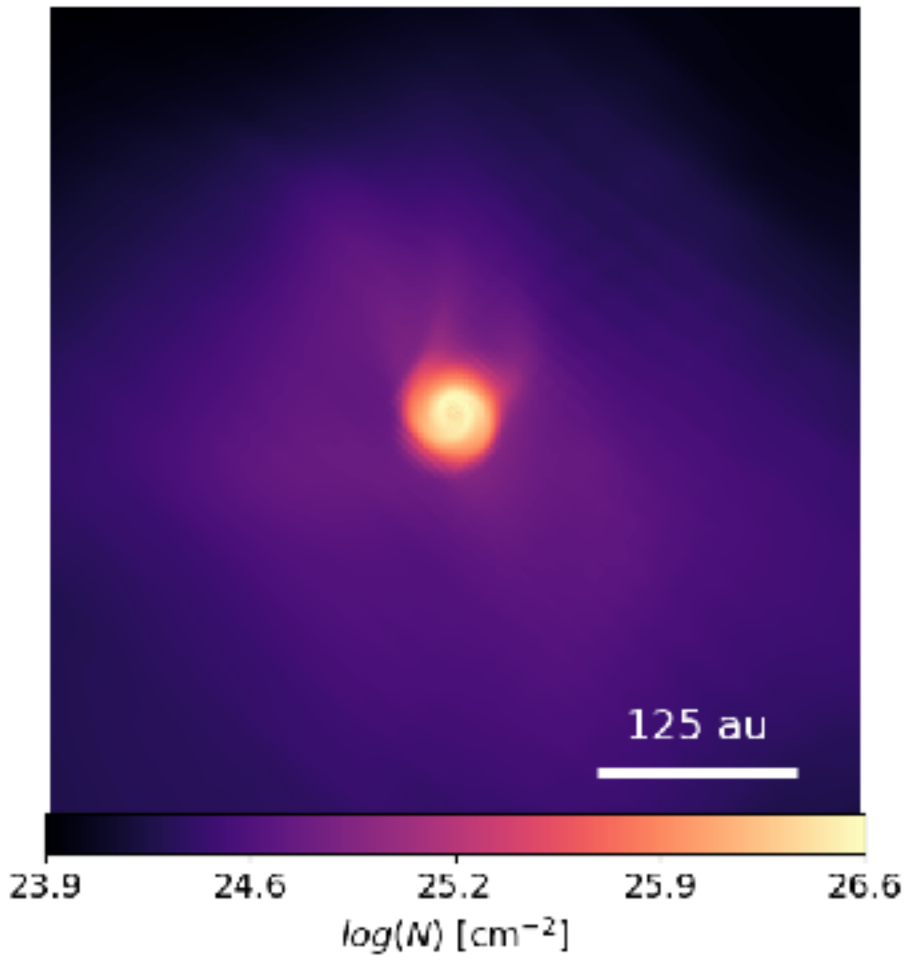
  1-10 mm in protoplanetary disks

WHY DUST MATTERS ?



WHY STUDYING THE DUST SIZE DISTRIBUTION DURING THE COLLAPSE ?





Large disks — Angular momentum

Mediation by the charged particles
(**Dust**, ions & electrons):
Non-ideal MHD

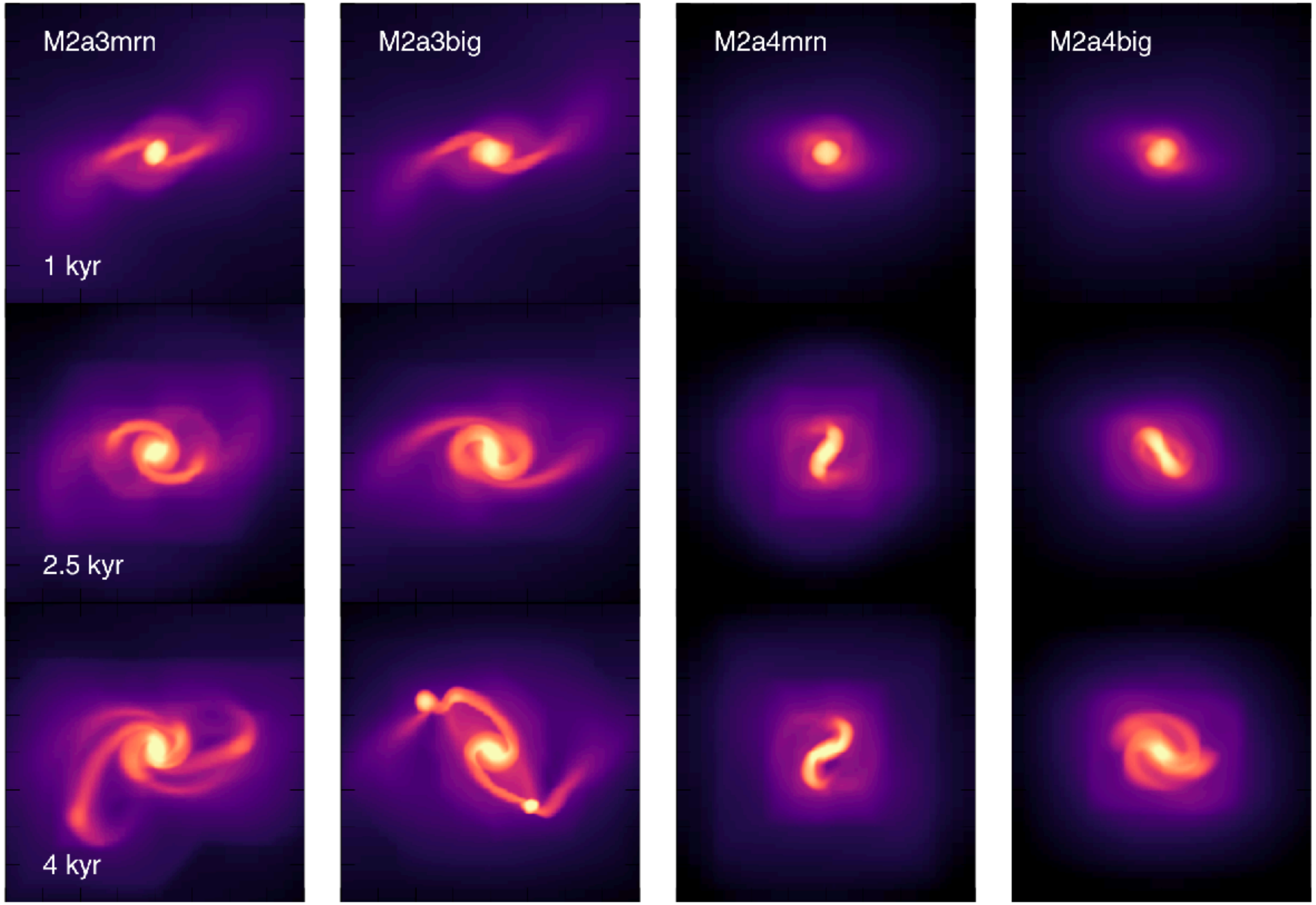
Small disk — Magnetic braking

Large grains

Magnetic conductivity

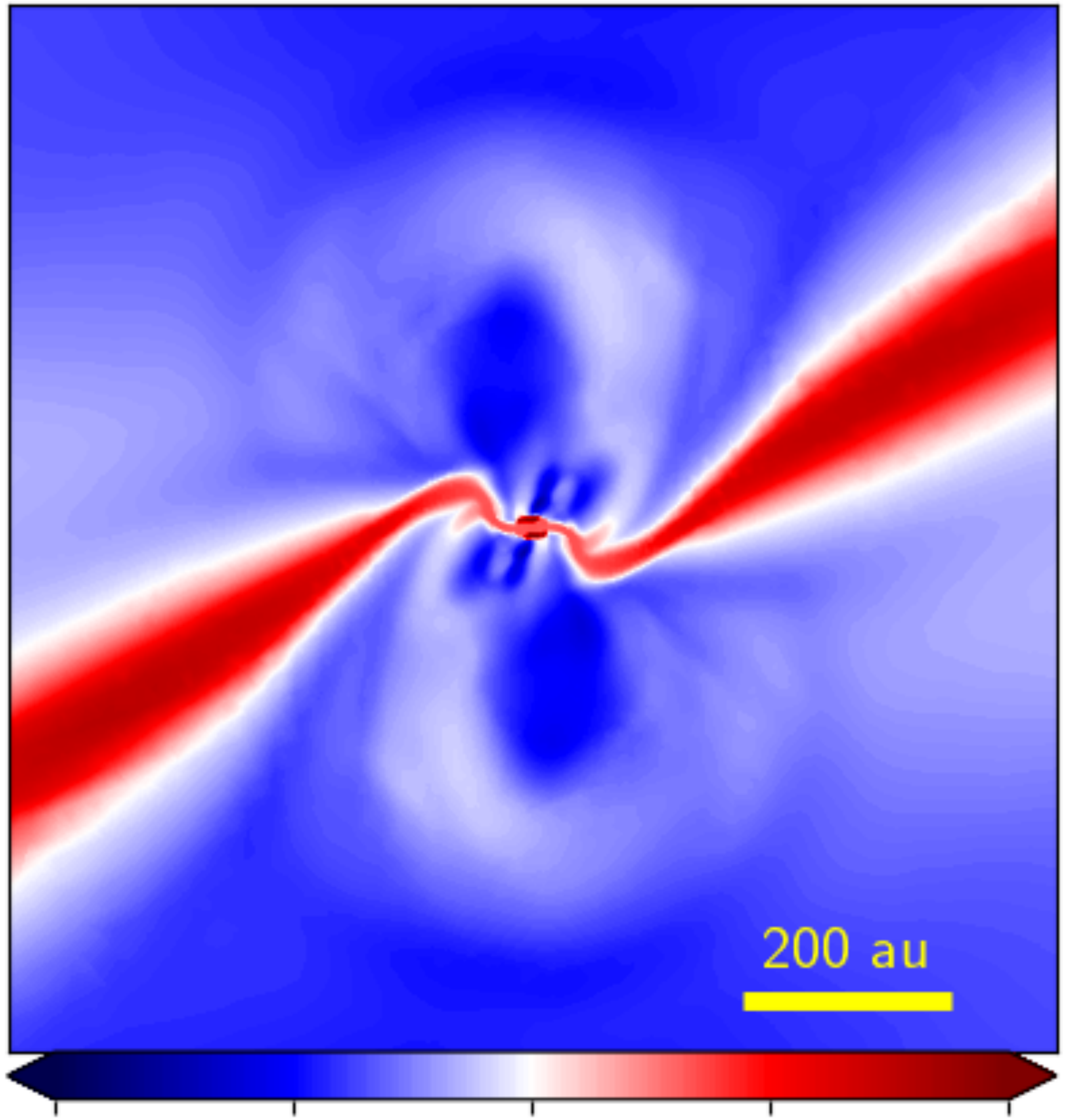
Small grains

WHY STUDYING THE DUST SIZE DISTRIBUTION DURING THE COLLAPSE ?



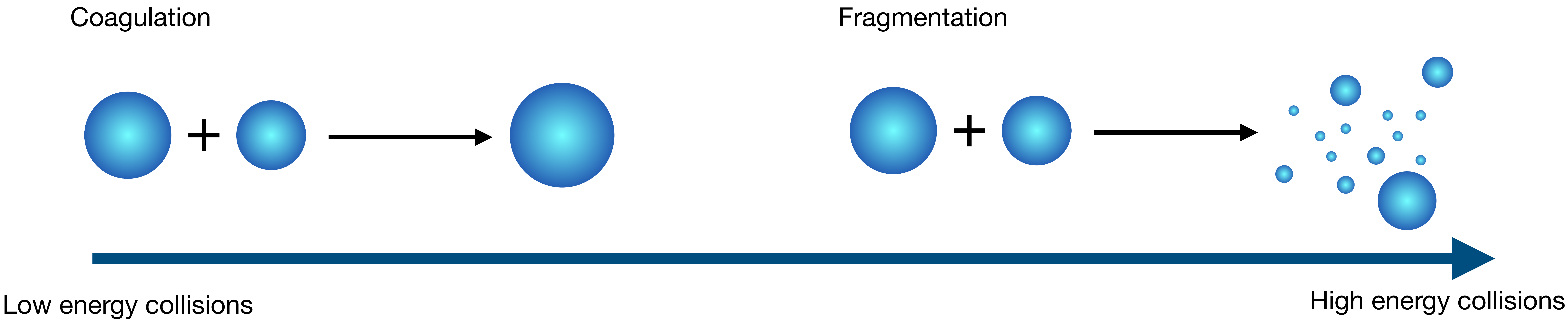
Marchand et al. 2019

WHY STUDYING THE DUST SIZE DISTRIBUTION DURING THE COLLAPSE ?



Lebreuilly et al. 2020

COAGULATION/FRAGMENTATION: BASIC PRINCIPLE



In reality :

bouncing, gas-grain erosion, grain-grain erosion, grain restructuration, mass transfer… (see e.g. Gütter et al. 2010)

DUST DYNAMICS : CASE OF THE FULL MULTIFLUID

See Gabriel talk for the multifluid implementation

$$\frac{\partial \rho_g}{\partial t} + \nabla \cdot \rho_g \vec{v}_g = 0$$

$$\frac{\partial \rho_g \vec{v}_g}{\partial t} + \nabla (\rho_g \vec{v}_g \otimes \vec{v}_g + P_g \mathbb{I}) = \rho_g \vec{f} + \frac{\rho_d}{t_s} \overrightarrow{\Delta v}$$

Gas

$$\frac{\partial \rho_d}{\partial t} + \nabla \cdot \rho_d \vec{v}_d = 0$$

$$\frac{\partial \rho_d \vec{v}_d}{\partial t} + \nabla \rho_d \vec{v}_d \otimes \vec{v}_d = \rho_d \vec{f} - \frac{\rho_d}{t_s} \overrightarrow{\Delta v}$$

Dust

Drag force : t_s is the stopping time

See Saffman 1962

DUST DYNAMICS : TERMINAL VELOCITY APPROXIMATION IN THE MONOFLUID FORMALISM

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\right] = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[P_{\mathrm{g}}\mathbb{I} + \rho(\mathbf{v} \otimes \mathbf{v})\right] = \rho \mathbf{f}$$

$$\frac{\partial \rho_{\mathrm{d}k}}{\partial t} + \nabla \cdot \left[\rho_{\mathrm{d}k}\left(\mathbf{v} + \frac{T_{\mathrm{s},k} \nabla P_{\mathrm{g}}}{\rho}\right)\right] = 0$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P_{\mathrm{g}})\mathbf{v}\right] = \nabla \cdot \left[\frac{\mathcal{E}\mathcal{T}_{\mathrm{s}}}{1 - \mathcal{E}} \frac{\nabla P_{\mathrm{g}}}{\rho} \frac{P_{\mathrm{g}}}{\gamma - 1}\right]$$

$$\rho \equiv \sum_k \rho_{d,k} + \rho_g$$

$$\mathbf{v} \equiv \frac{\sum_k \rho_{d,k}\mathbf{v}_{\mathbf{d},\mathbf{k}} + \rho_{\mathbf{g}}\mathbf{v}_{\mathbf{g}}}{\rho}$$

$$T_{\mathrm{s,k}} \equiv \frac{t_{\mathrm{s},k}}{1 - \epsilon_k} - \sum_{l=1}^{\mathcal{N}} \frac{\epsilon_l}{1 - \epsilon_l} t_{\mathrm{s},l}$$

$$\mathcal{T}_{\mathrm{s}} \equiv \frac{1}{\mathcal{E}} \sum_{l=1}^{\mathcal{N}} \epsilon_l T_{\mathrm{s},l}\, ; \mathcal{E} \equiv \sum_{l=1}^{\mathcal{N}} \epsilon_l$$

See Laibe & Price 2014a,b,c; Lebreuilly et al. 2019

TERMINAL VELOCITY SOLVER OF RAMSES

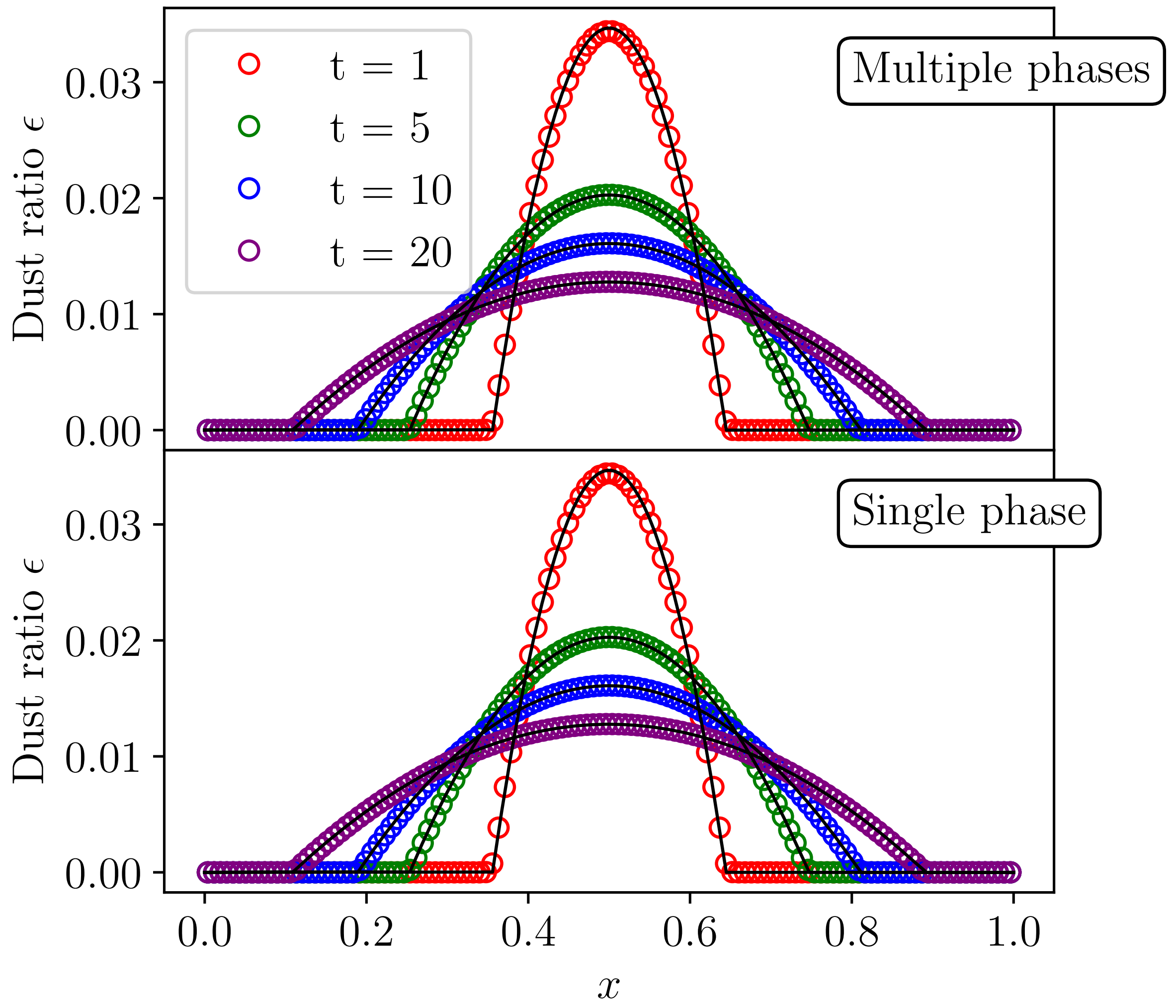
Advantage :

- *Very good for small grains*
- *1 equation per dust species*

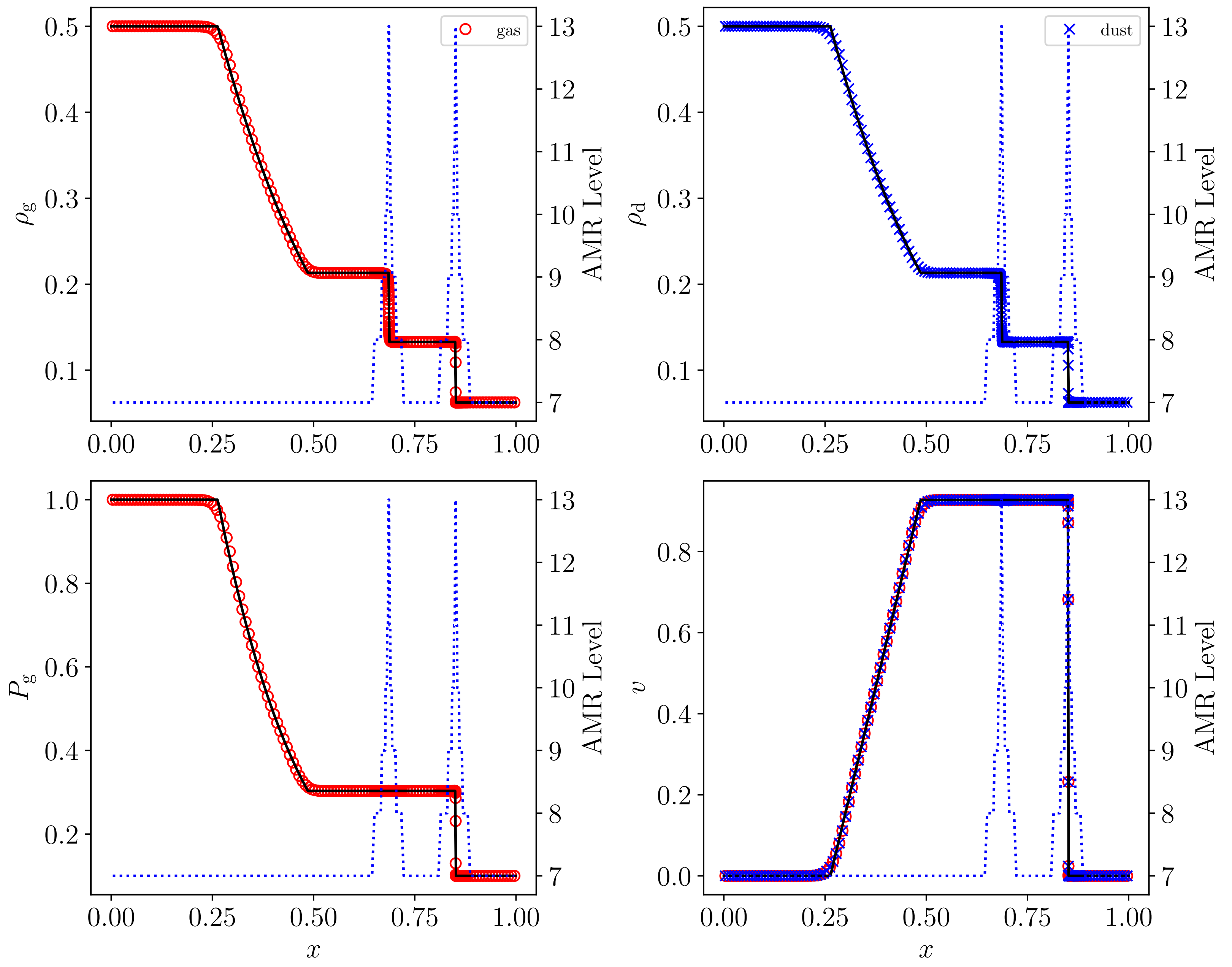
Drawback:

- *Bad for large grains*

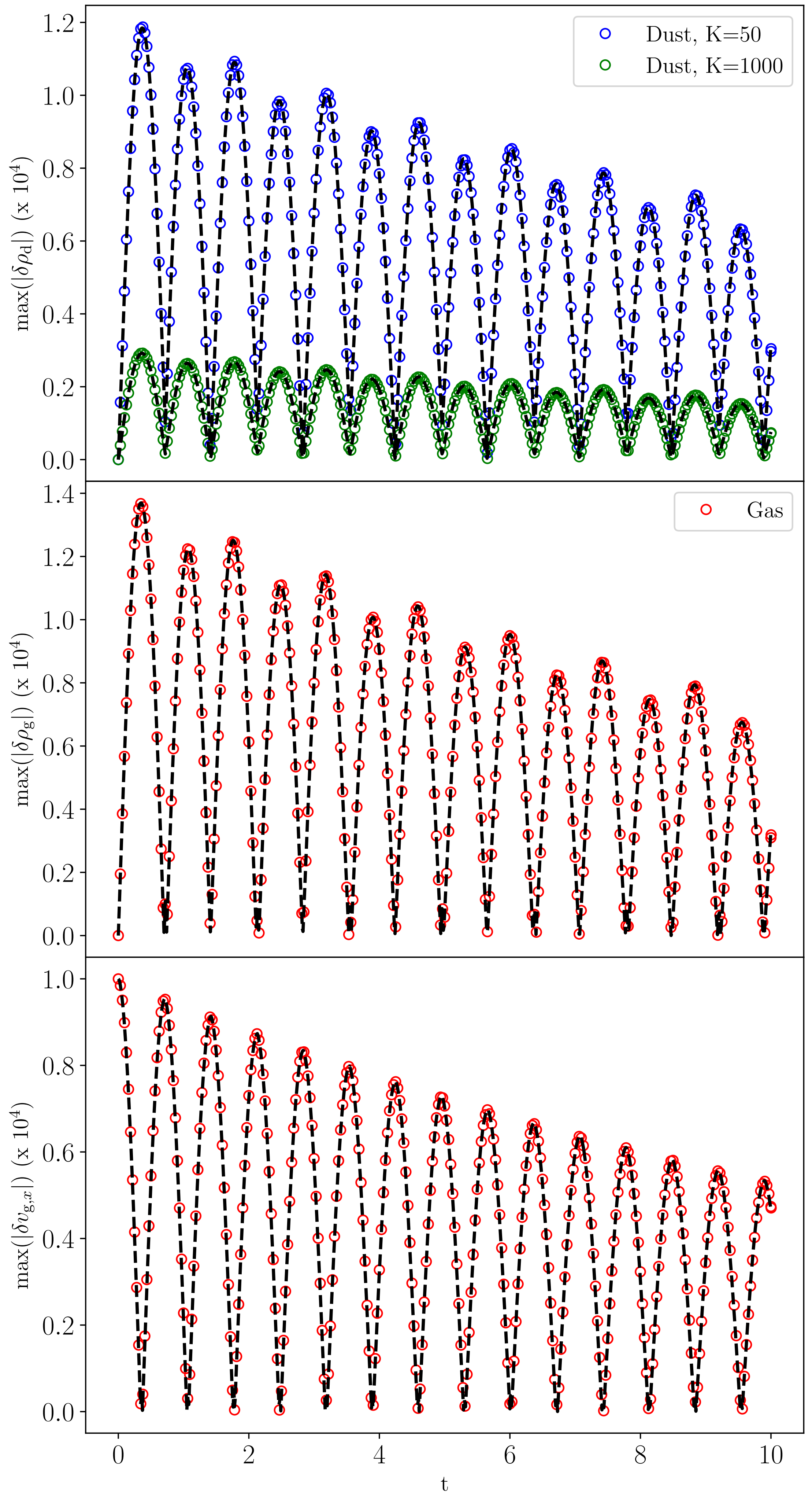
Diffusion (DUSTYDIFFUSE)



Shock (DUSTYSHOCK)



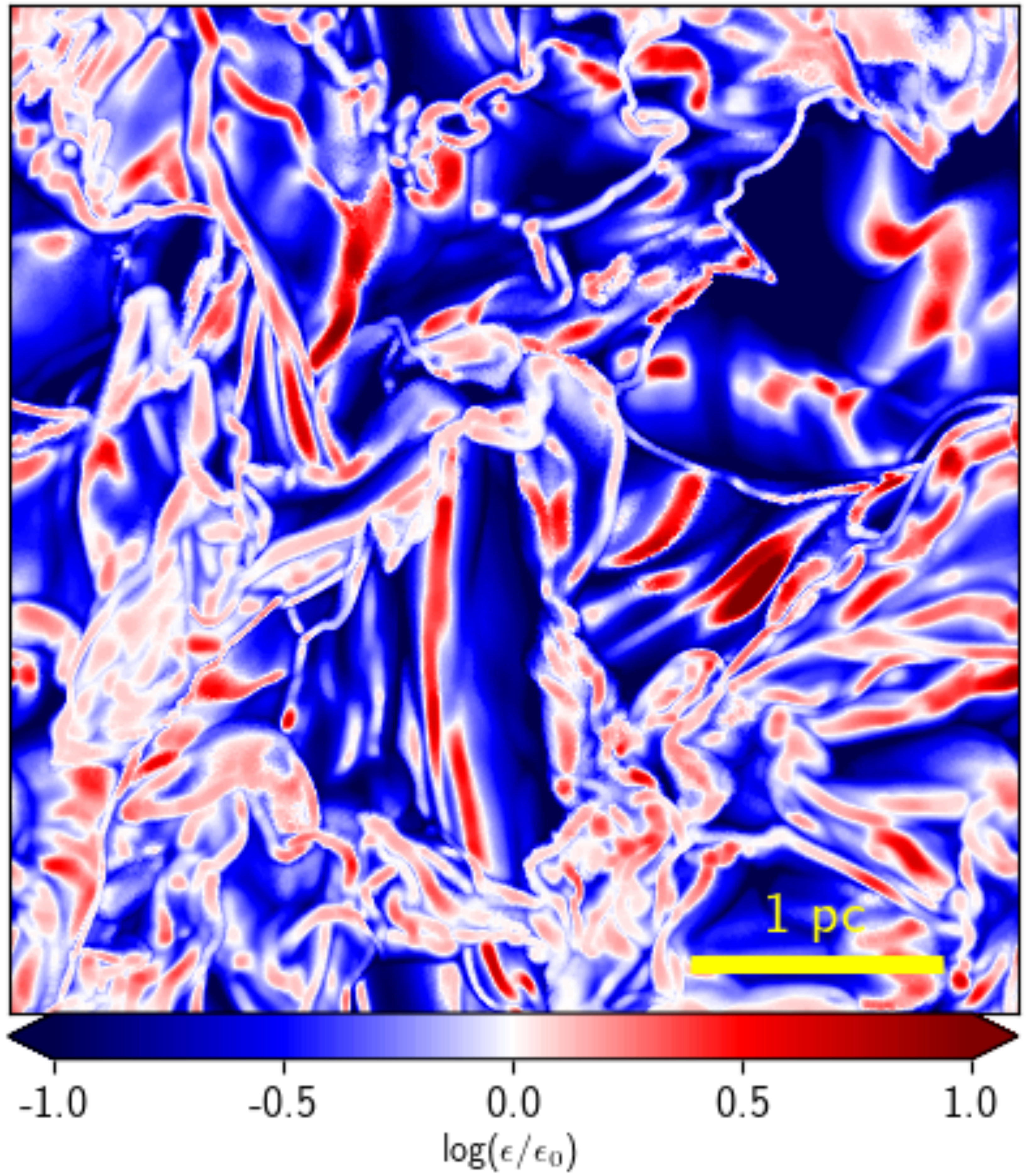
Damping of sound wave in a gas-dust mixture (DUSTYWAVE)

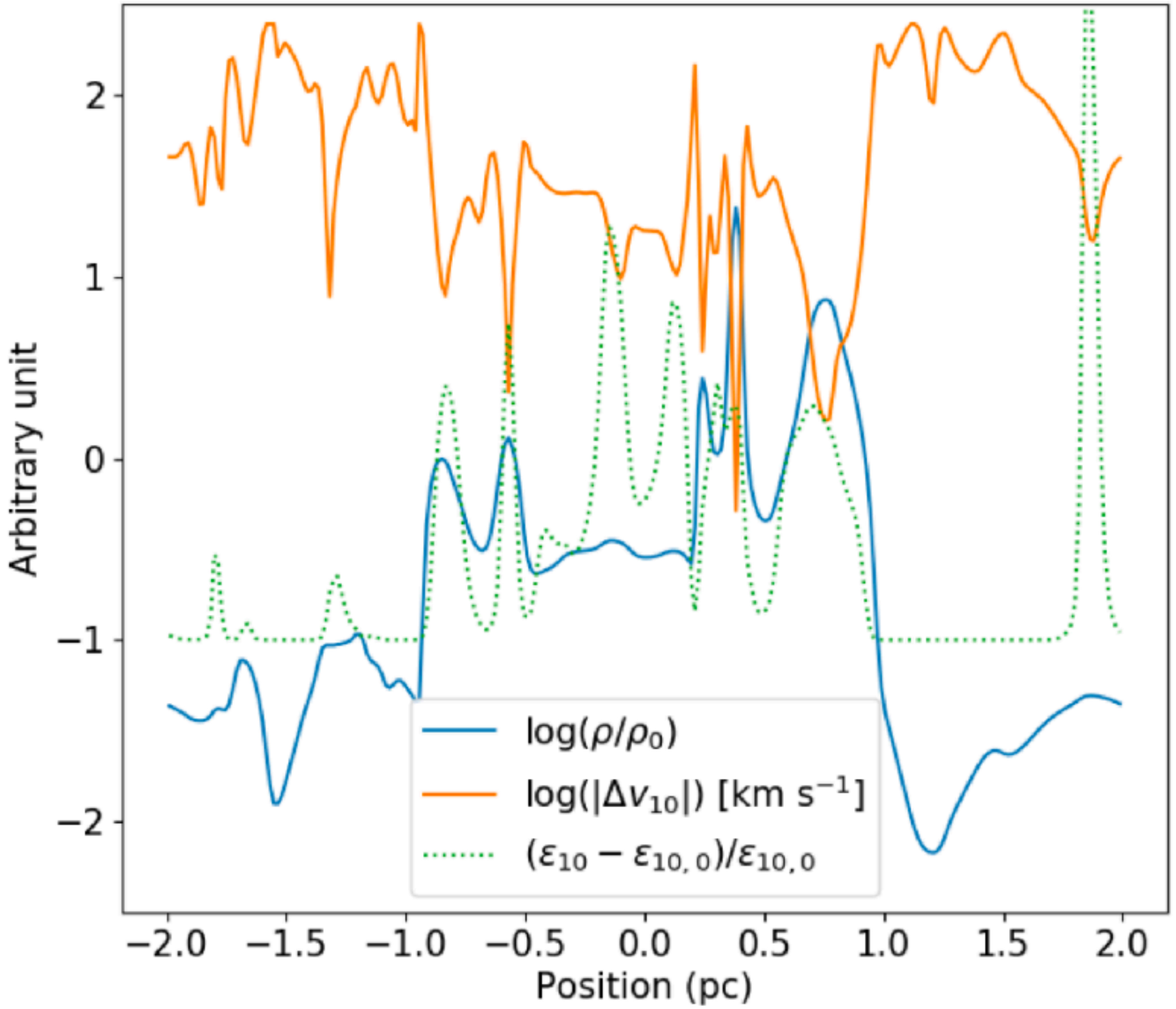


Lebreuilly et al. 2019

IS THE DUST-TO-GAS RATIO CONSTANT IN MOLECULAR CLOUDS ?

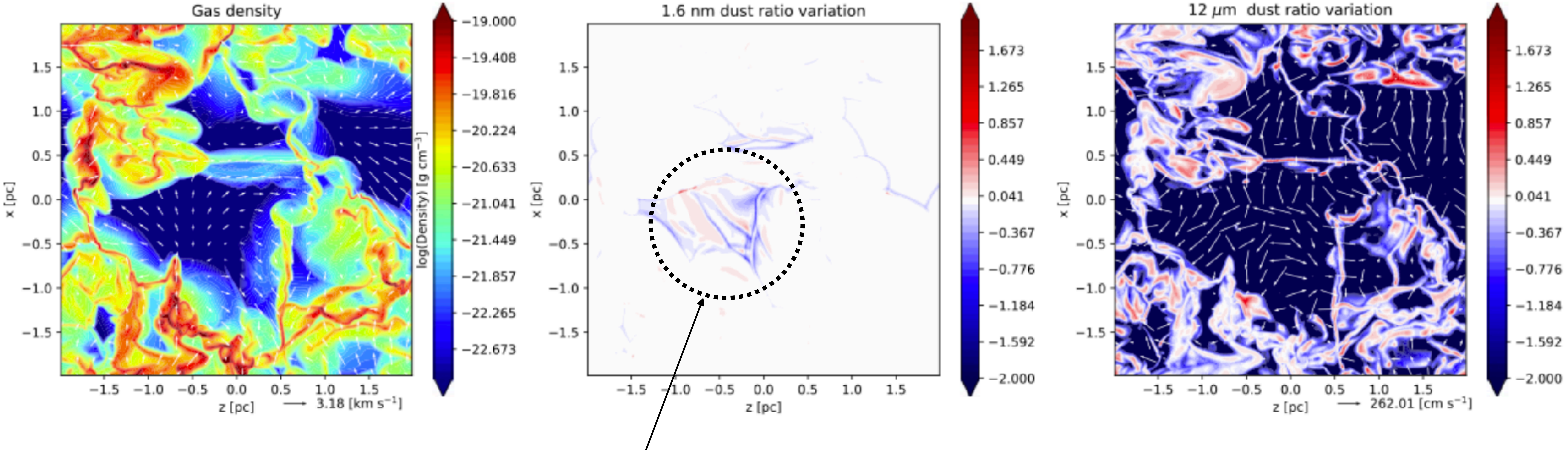
Dust grains of size ~ 10 microns decouple efficiently in turbulent GMCs-like environments (Commerçon et al. 2023)





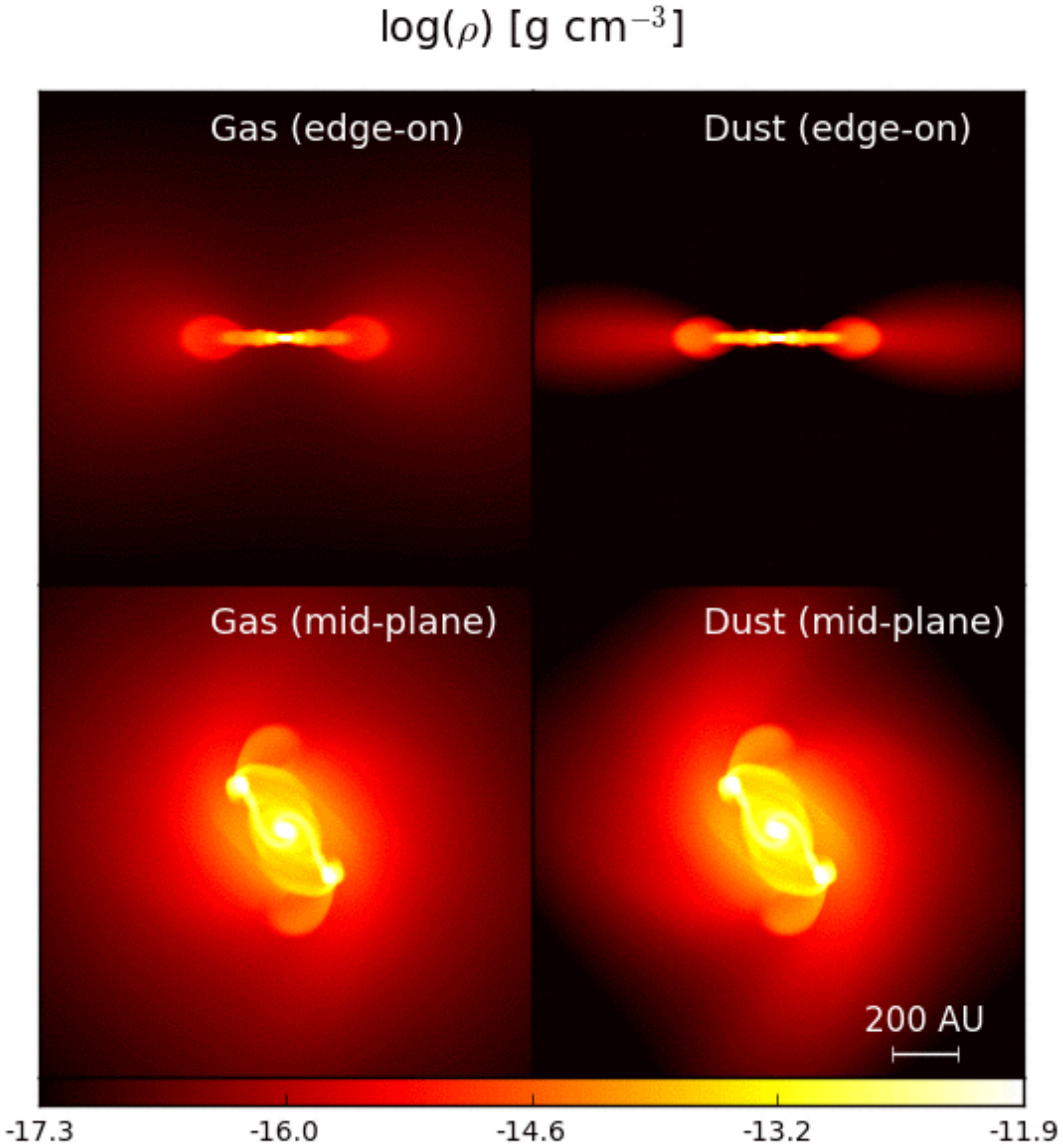
IS THE DUST-TO-GAS RATIO CONSTANT IN MOLECULAR CLOUDS ?

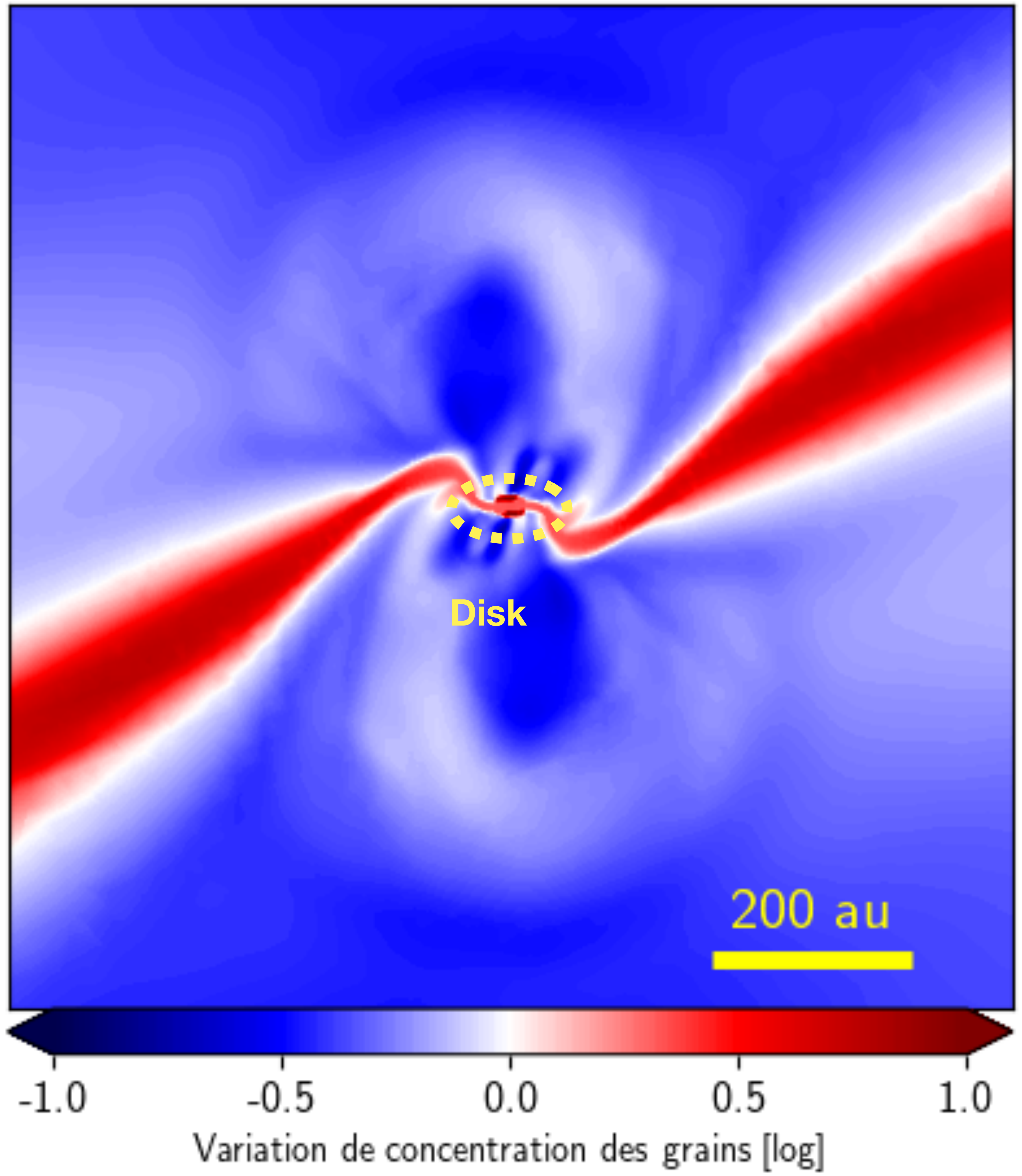
Smaller grains are very well coupled to the gas



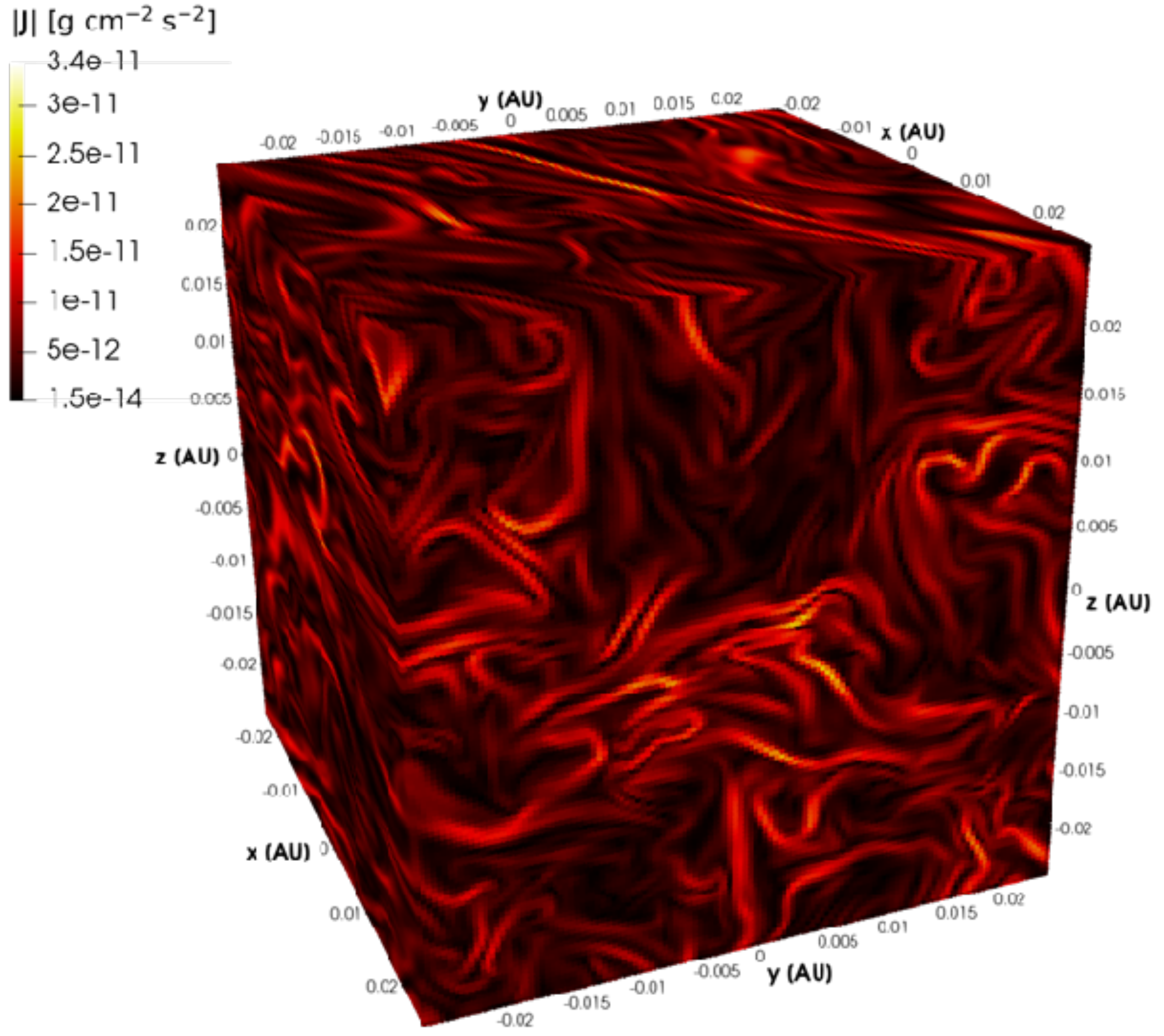
Variations only when density is negligible

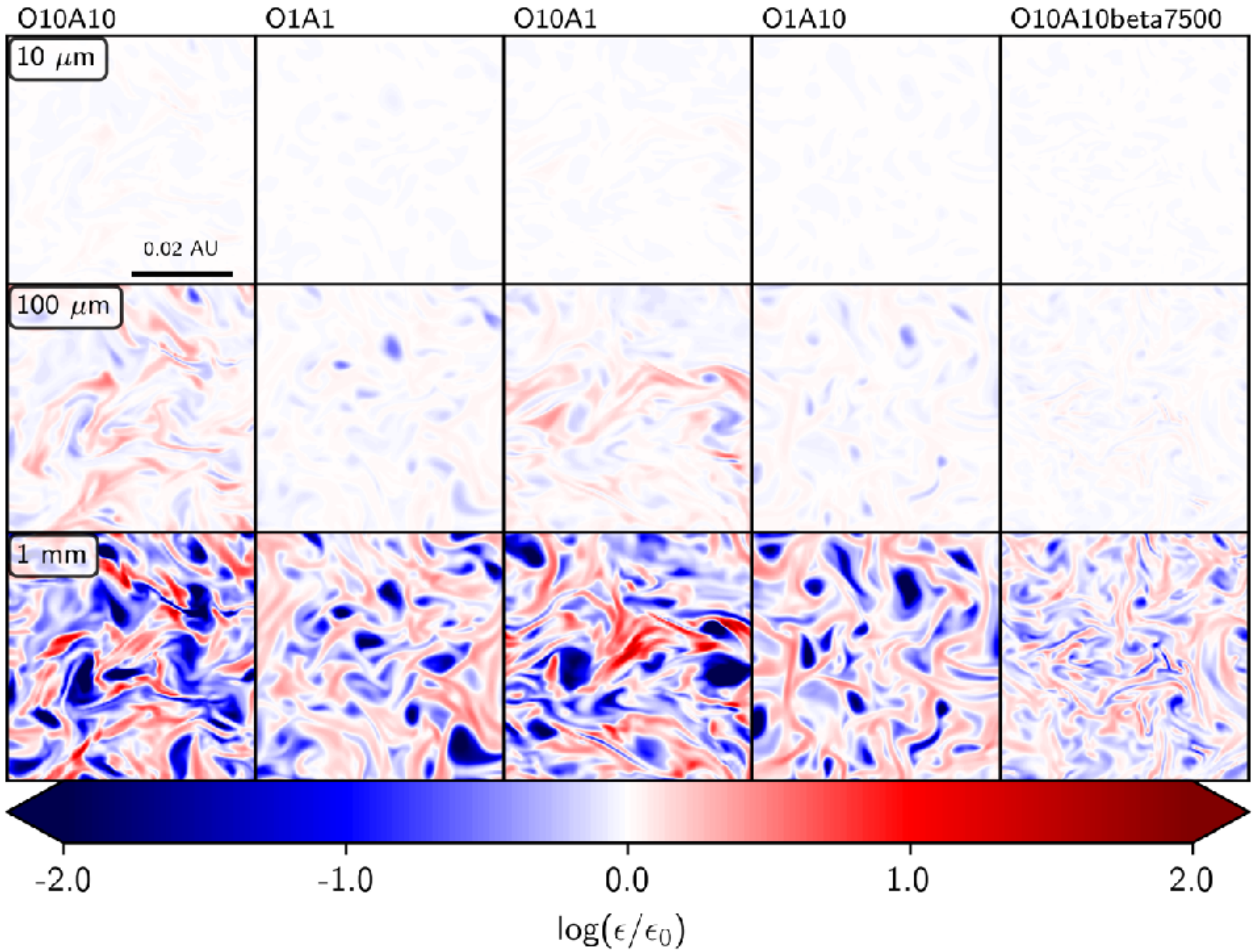
ARE PROTOPLANETARY DISKS BORN DUST RICH ? (Lebreuilly et al. 2020)





CAN CURRENT-SHEETS DRIVE DUST-TO-GAS RATIO VARIATIONS ? (Lebreuilly et al. 2023b)





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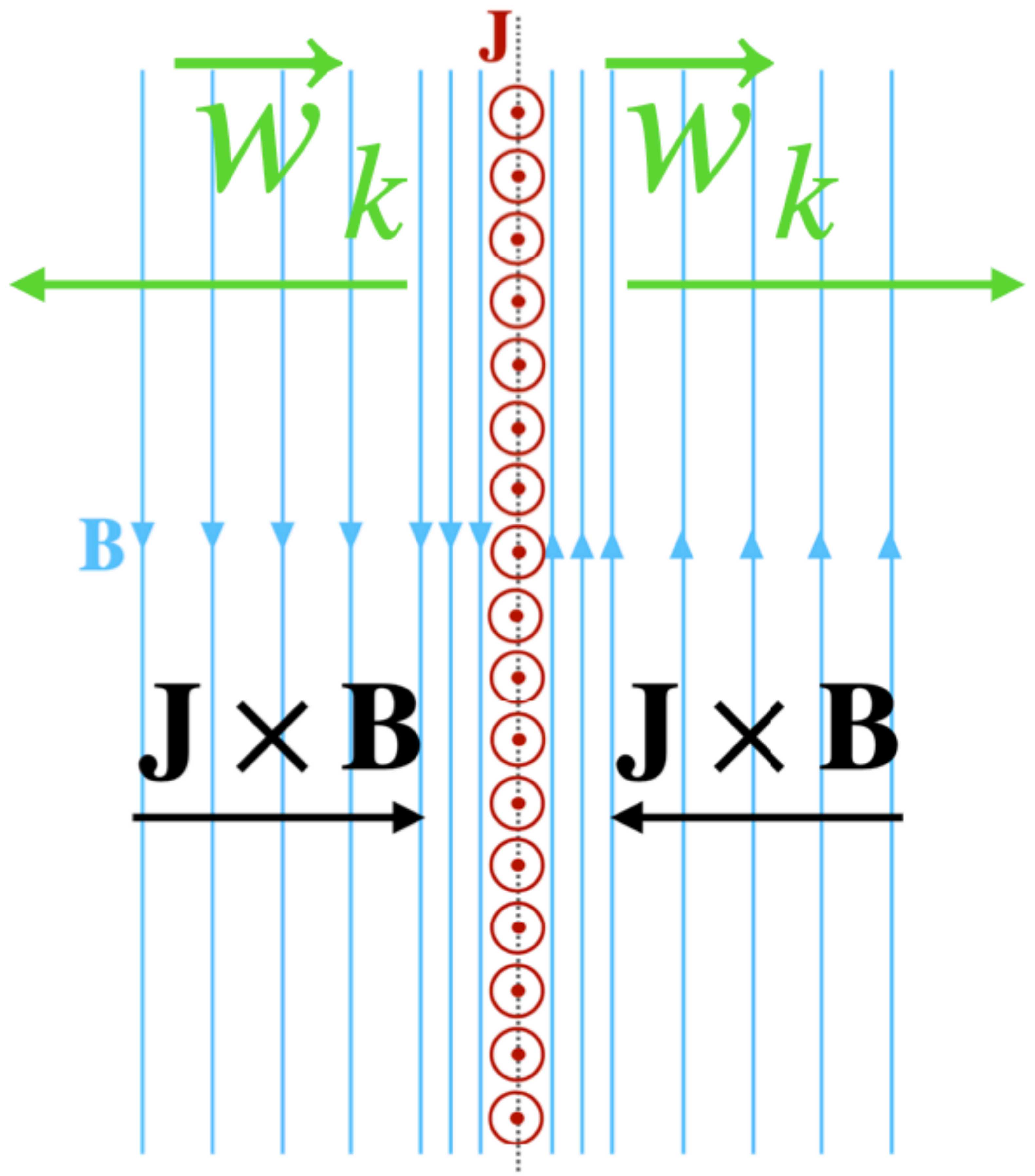
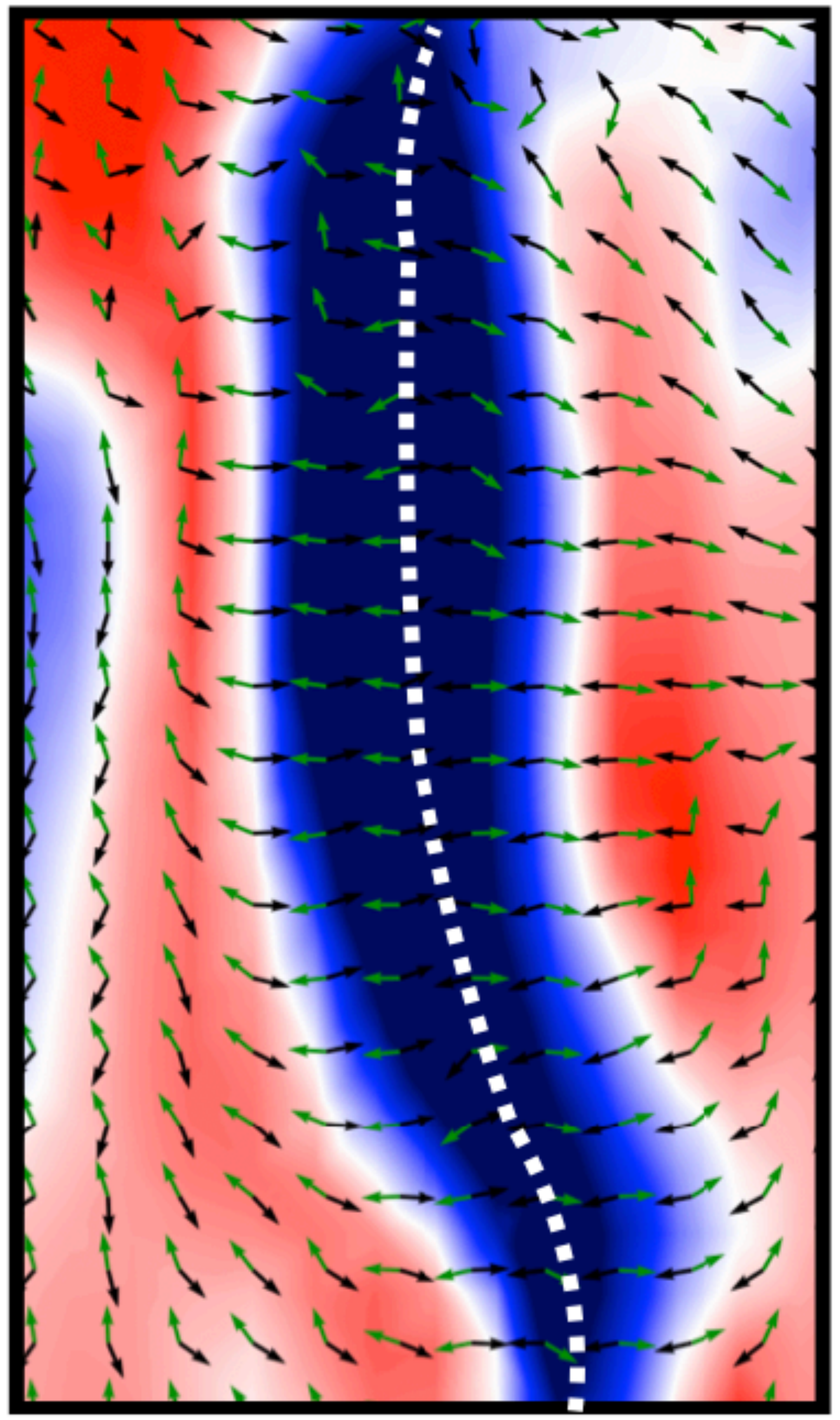




$$\Delta\vec{v} \equiv t_{s,k}\frac{\nabla P_n - \vec{J}\times\vec{B}}{\rho}$$

DUST COAGULATION IN THE MONODISPERSE APPROACH

Lebreuilly et al. in prep

Gas dynamics

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla \cdot \left[\rho \vec{v}\right] = 0, \\ \dfrac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot \left[\rho \vec{v}\vec{v} + P\mathbb{I}\right] = \rho \vec{g} + \sum_j \dfrac{\rho_j}{t_{\mathrm{s,j}}}(\vec{v}_j - \vec{v}), \end{cases}$$

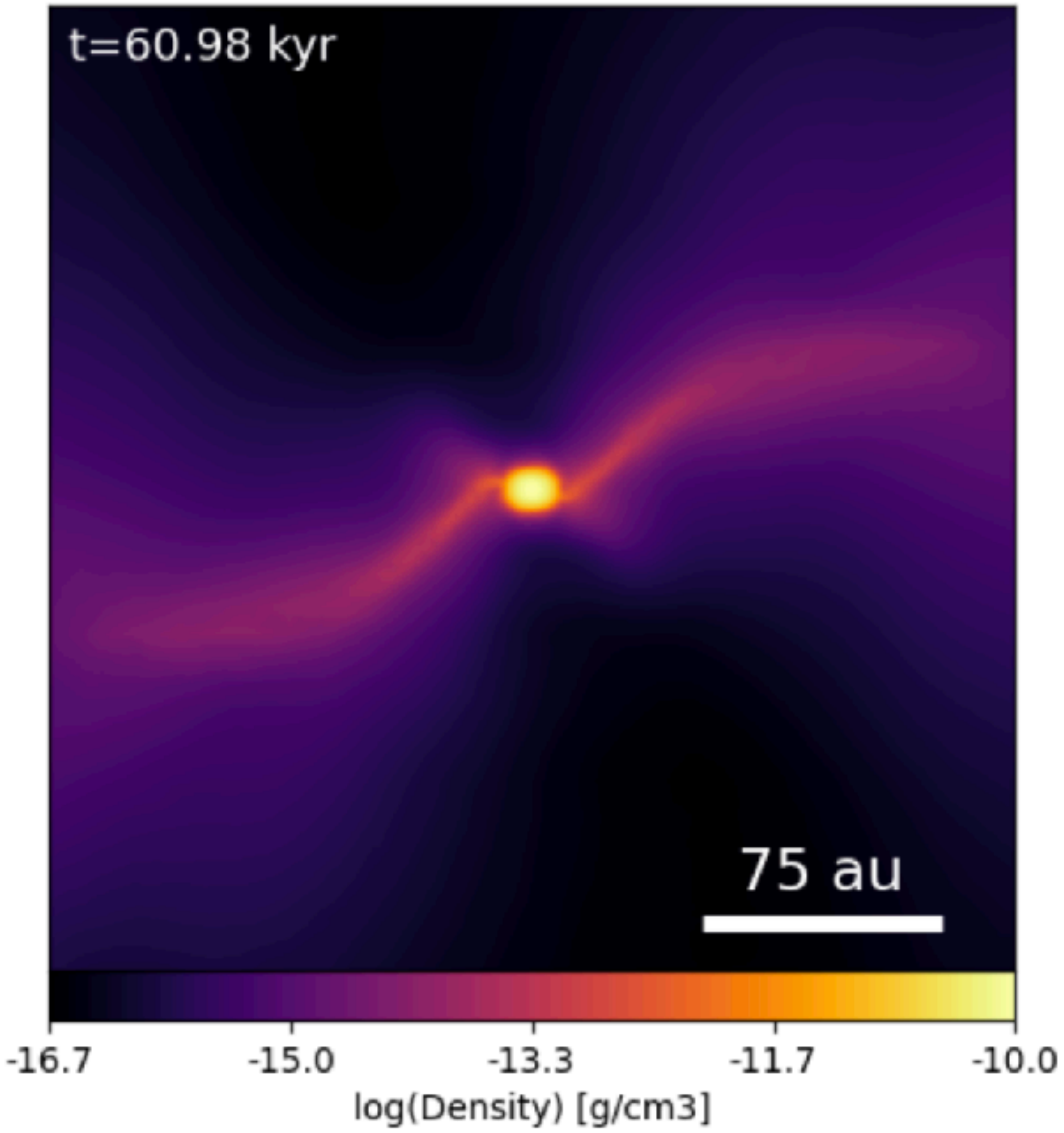
Dust dynamics

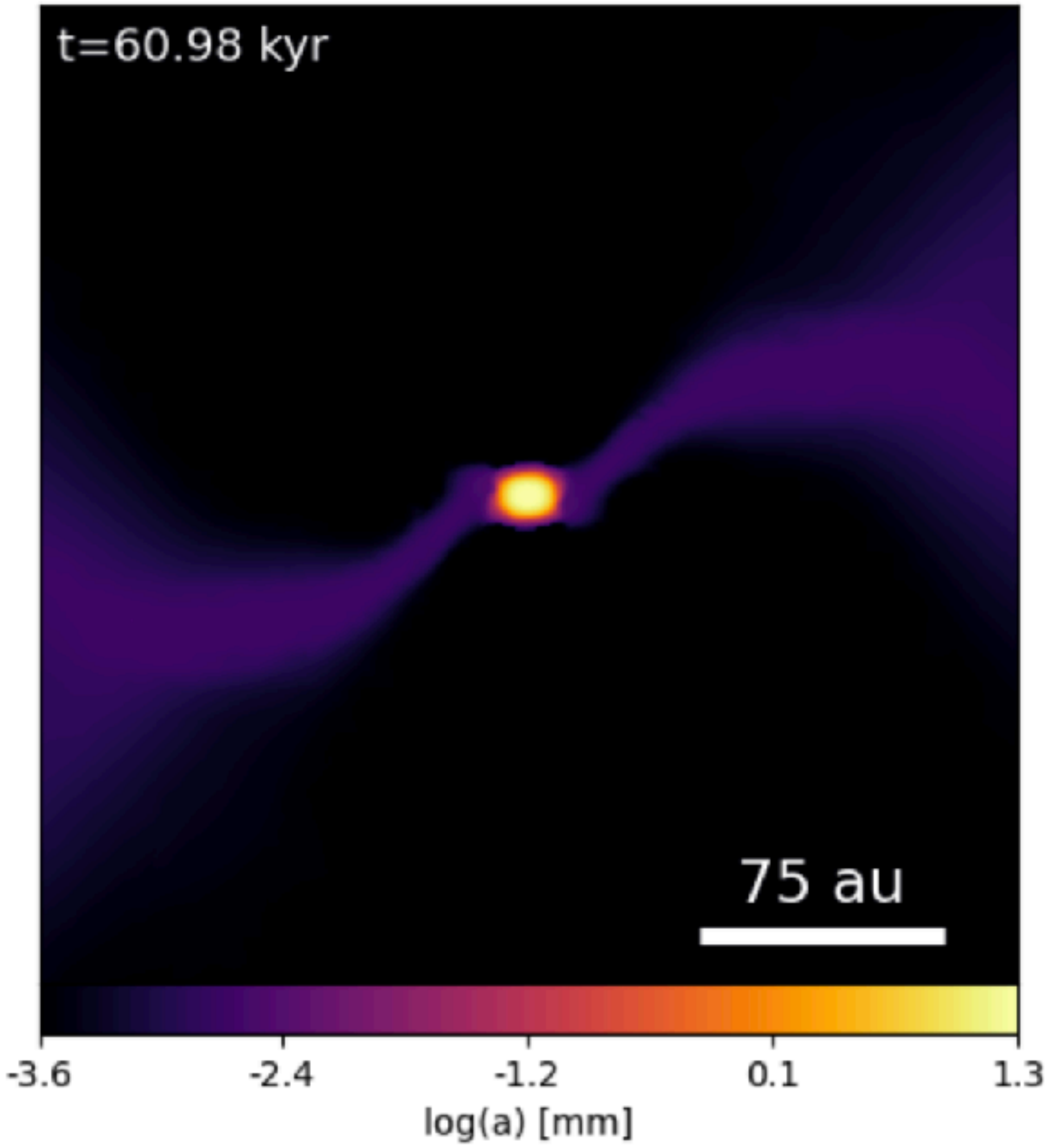
(for a single k)

$$\begin{cases} \dfrac{\partial \rho_k \vec{v_k}}{\partial t} + \nabla \cdot \left[\rho_k \vec{v}_k \vec{v}_k\right] = \rho_k \vec{g} - \dfrac{\rho_k}{t_{\mathrm{s,k}}}(\vec{v}_k - \vec{v}) \\ \dfrac{\partial \rho_k}{\partial t} + \nabla \cdot \left[\rho_k \vec{v_k}\right] = 0 \\ \dfrac{\partial \rho_k s_k}{\partial t} + \nabla \cdot \left[\rho_k \vec{v_k} s_k\right] = A_{\mathrm{coag/frag}} \dfrac{\rho_k s_k}{3\ t_{\mathrm{coag},k}} \end{cases}$$

MONODISPERSE IMPLEMENTATION IN RAMSES

Lebreuilly et al. in prep

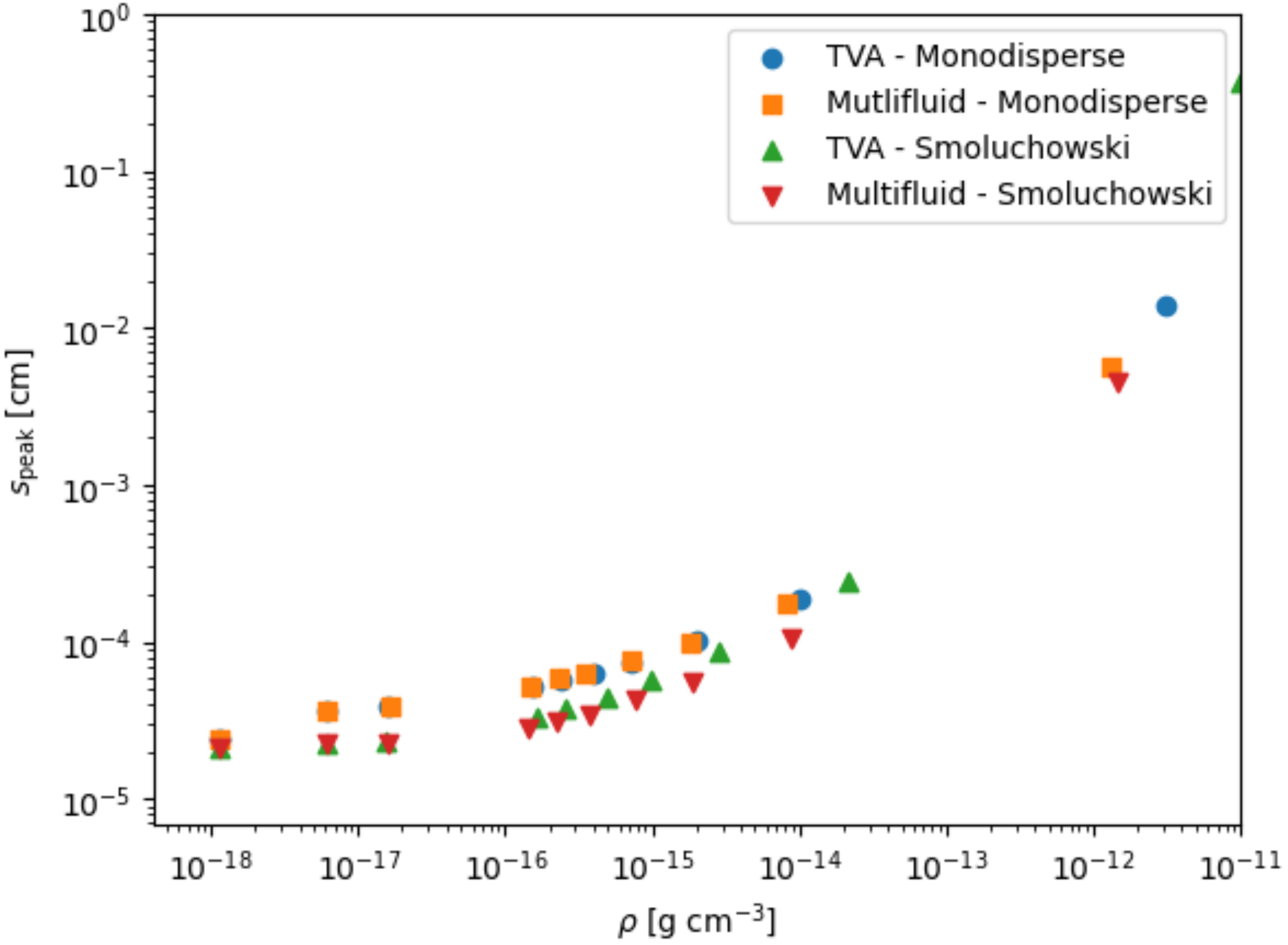




HOW DO ALL METHODS COMPARE TOGETHER

Lebreuilly et al. in prep

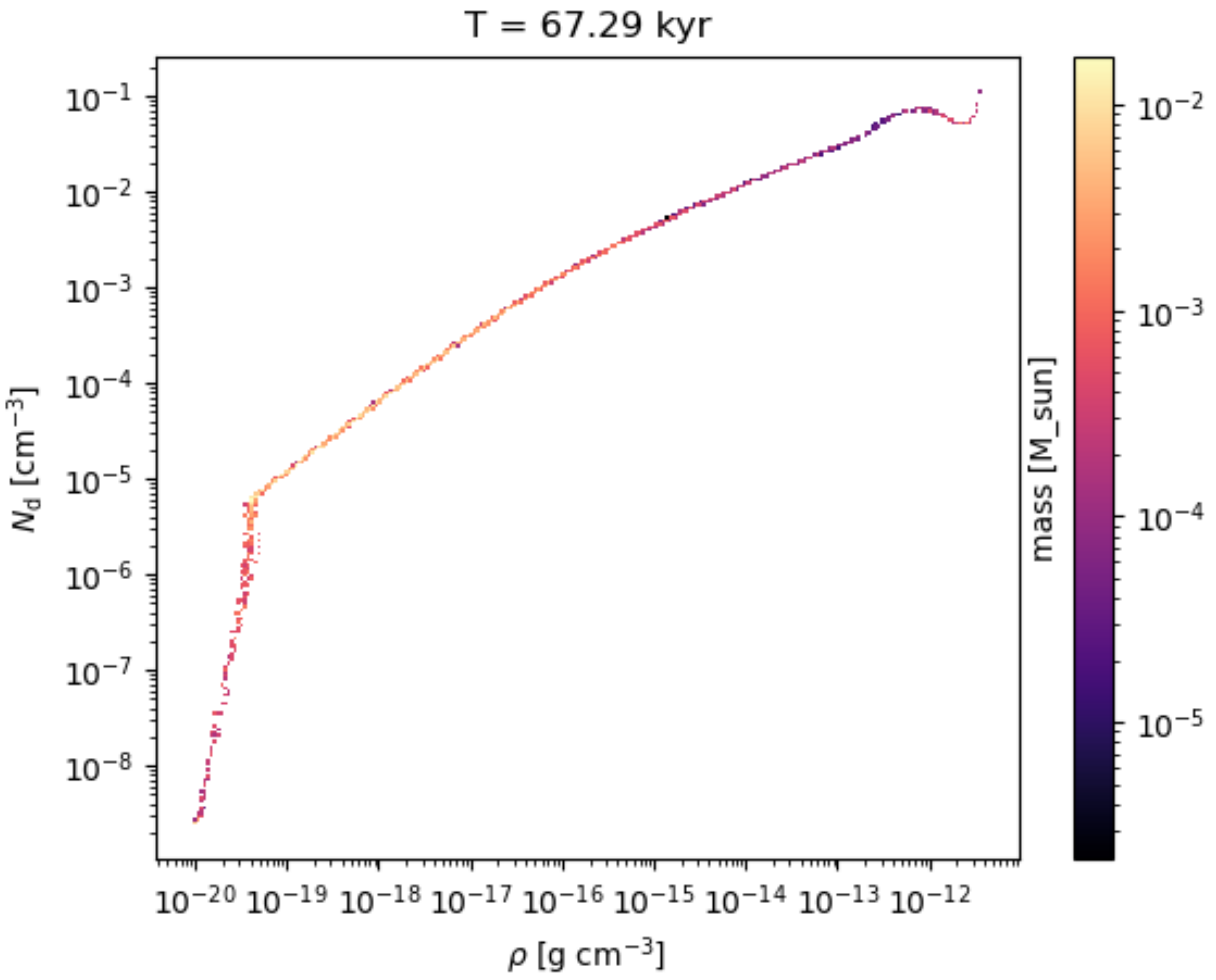
See Maxime’s talk for Smoluchowski



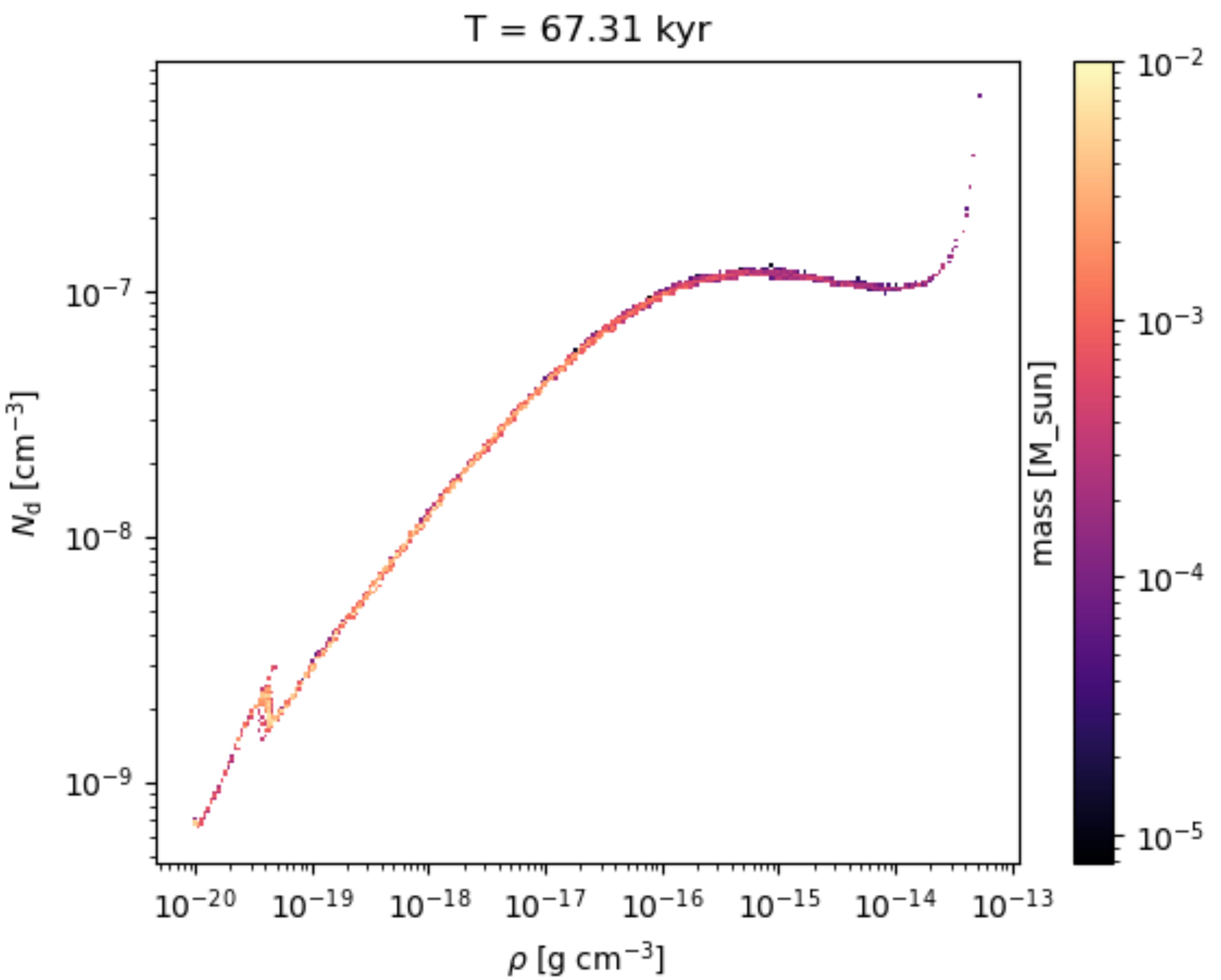
THE ISSUE WITH THE MONODISPERSE APPROACH: ABUNDANCES

See Maxime’s talk for Smoluchowski (COALA)

COALA

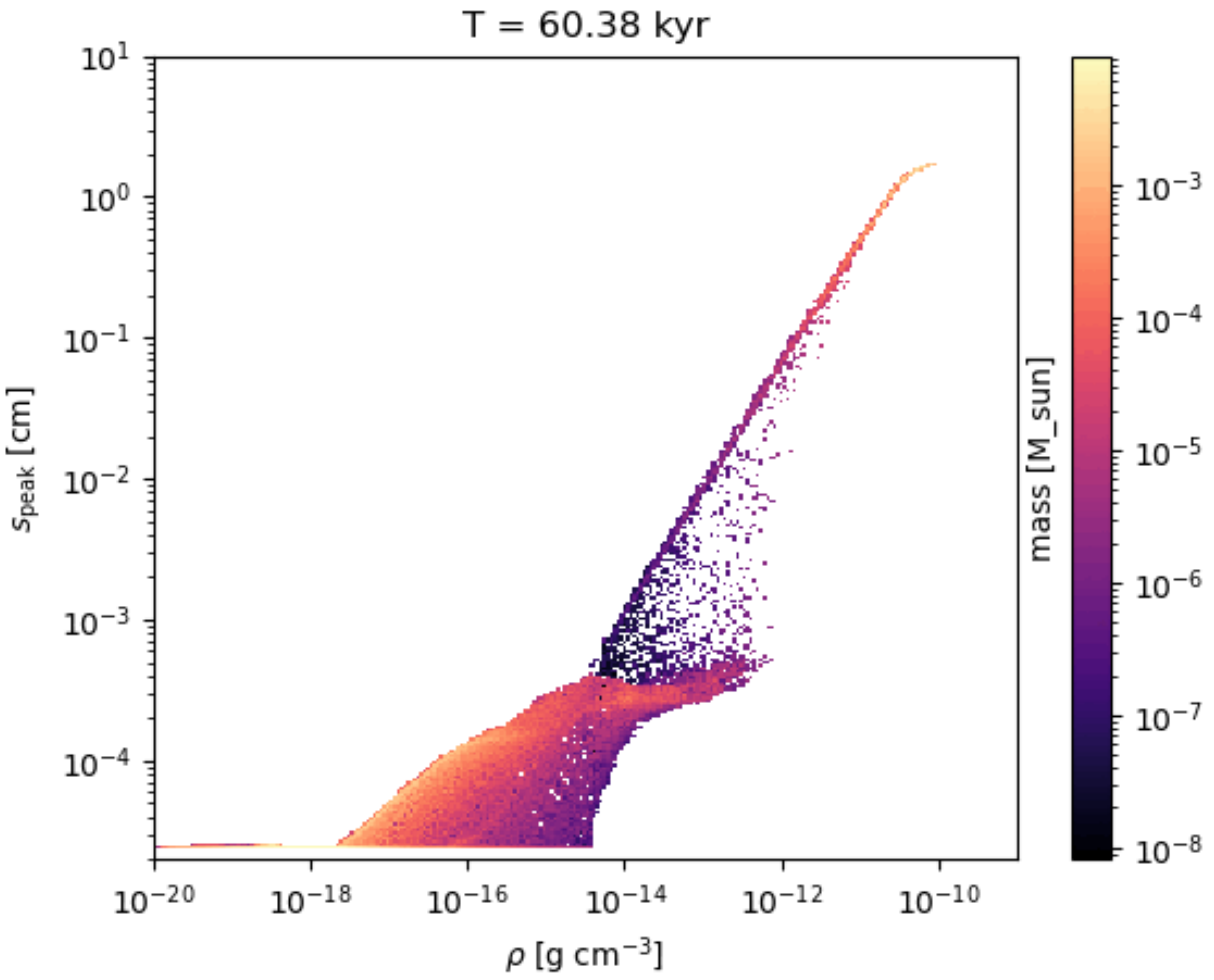


MONO

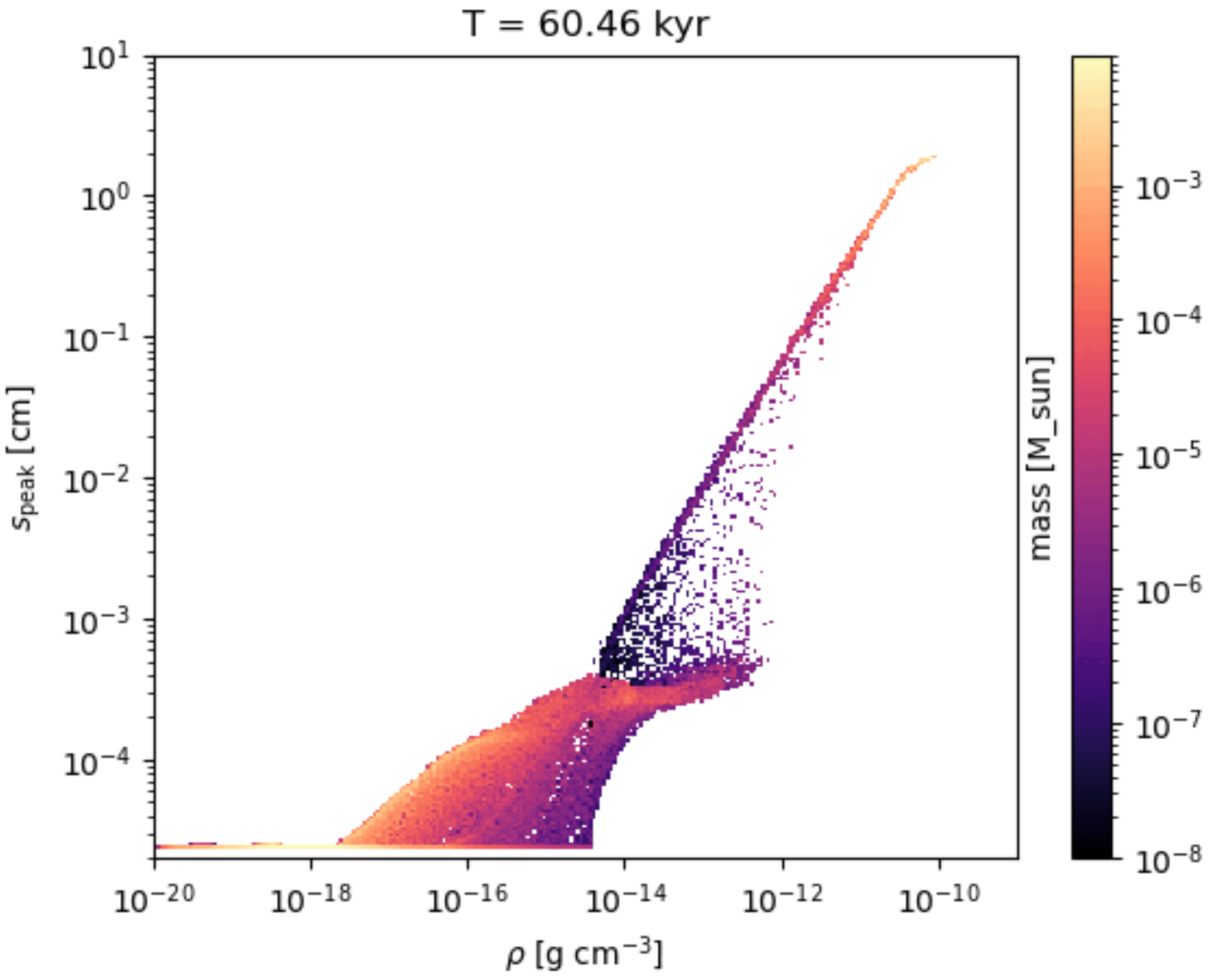


A MODEL WITH B FIELD AND ROTATION – TIME EVOLUTION OF SIZE

Terminal velocity approx.



Multifluid



CONCLUSIONS

- We have implemented a monofluid solver for small grain in RAMSES
- It's fast, efficient, works for multiple dust species
- The solver was used in various astrophysics contexts namely:
  - Protostellar collapses
  - Molecular clouds
  - Protoplanetary disks
- We now extend our methods:
  - Dust growth in the monodisperse approach
  - Full dust growth : see Maxime's talk
  - Full multifluid : see Gabriel's talk