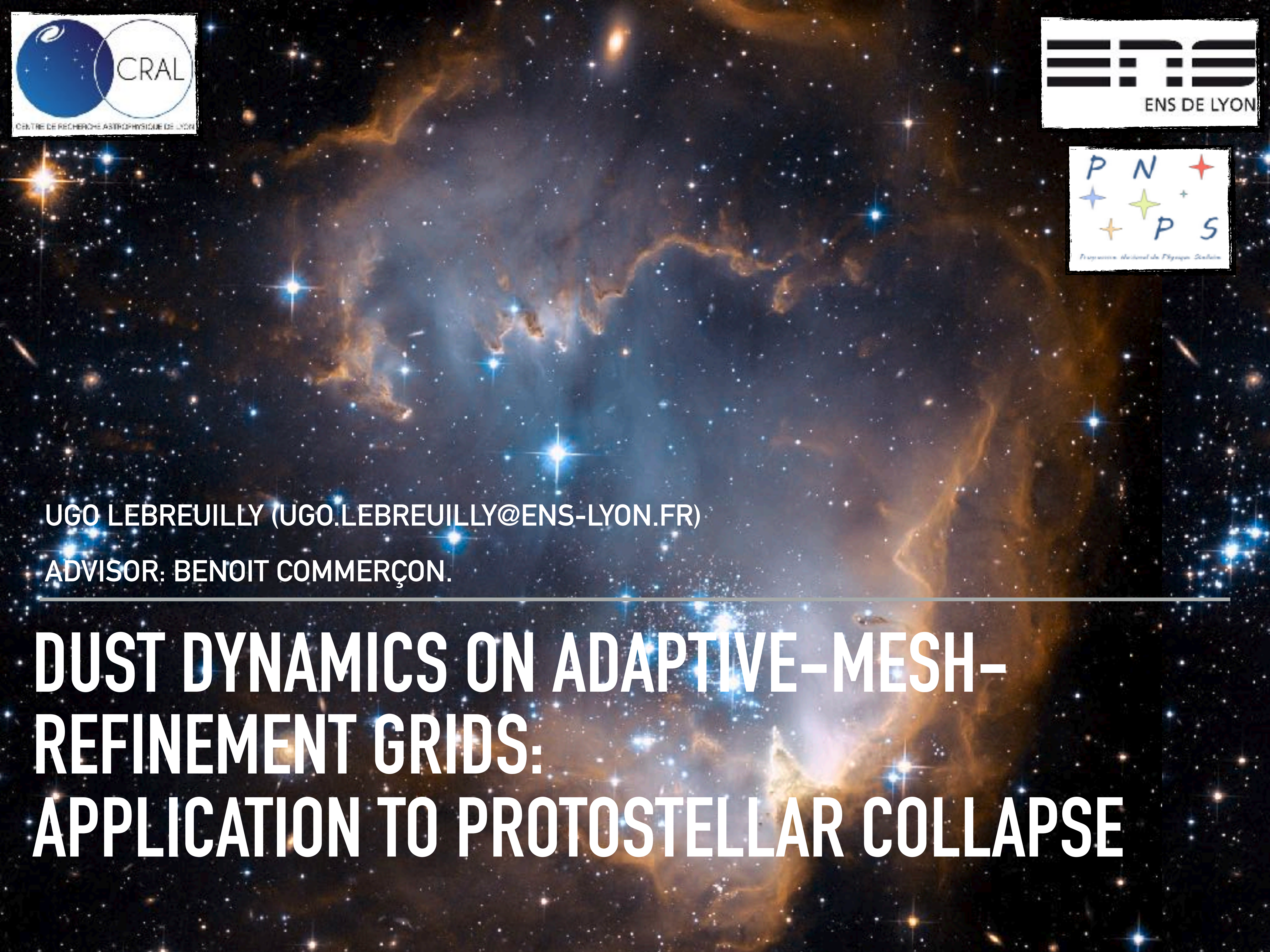


UGO LEBREUILLY (UGO.LEBREUILLY@ENS-LYON.FR)

ADVISOR: BENOIT COMMERÇON.

DUST DYNAMICS ON ADAPTIVE-MESH-REFINEMENT GRIDS: APPLICATION TO PROTOSTELLAR COLLAPSE

INTRODUCTION: DUST IN ASTROPHYSICS

Properties of interstellar dust

- 1% of the mass of the ISM
- Size from nm to micron (or more), MRN distribution : $n(s) \propto s^{-3.5}$ (Matthis et al. 1977)

Observations

- Continuum (Herschel, Spitzer, JWST, ALMA, SPHERE)
- Polarisation (ALMA, Planck,…)

Dust plays a role in

- Gas-grain chemistry
- Planet formation
- Star/disk formation

INTRODUCTION: STATE OF THE ART

In simulations

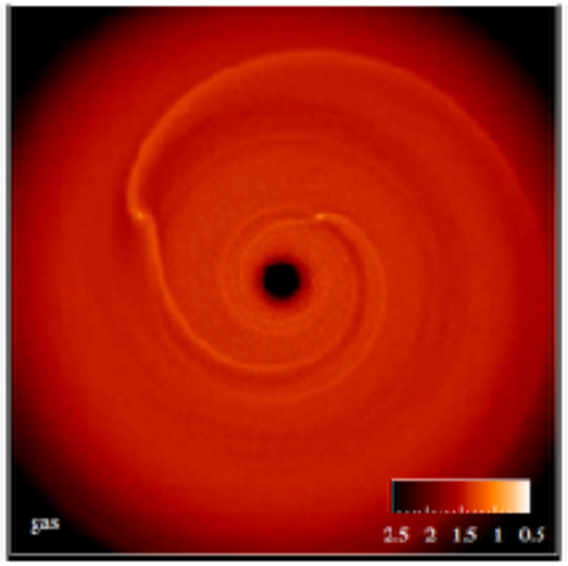
- SPH simulations, e.g. Laibe&Price (2012), Aguilar&Bate(2014)
- Lagrangian particles on grids, e.g. Johanssen (2007), Meheut et al. (2012)
- Eulerian grid codes but for disks, e.g. Lin (2018)

My step

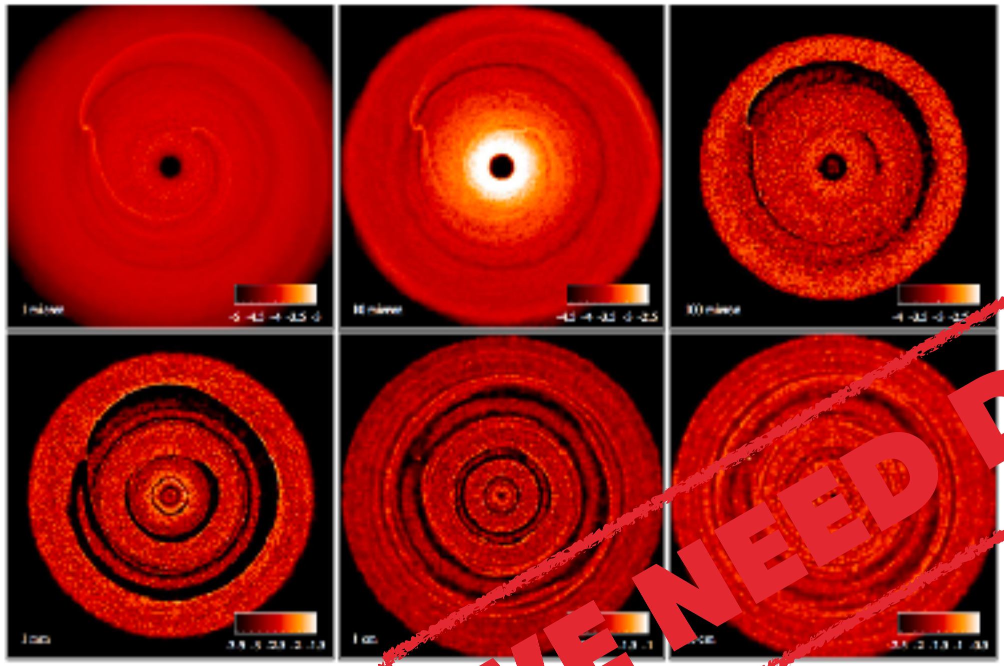
- **Eulerian approach in RAMSES (Lebreuilly et.al, submitted)**

INTRODUCTION: DUST IN SIMULATIONS

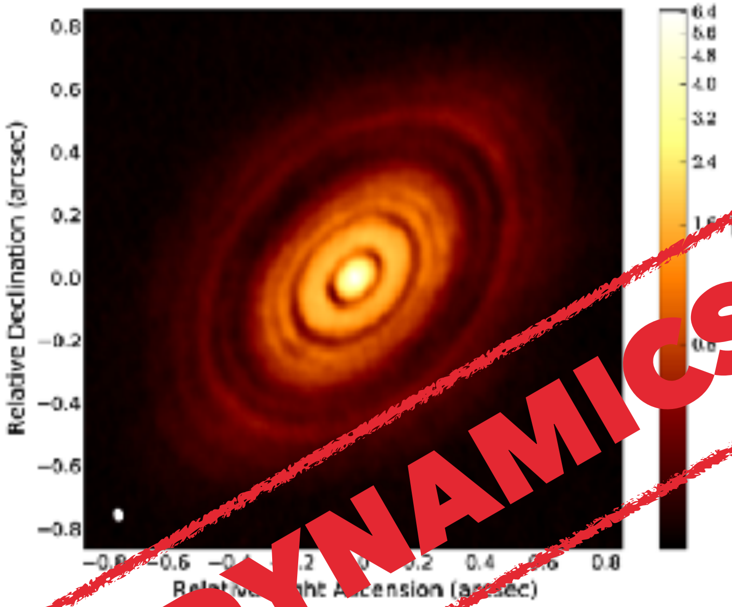
- **Dusty disk with SPH, e.g, HL Tau (Dipierro et al. 2015)**



Simulation (Gas density)

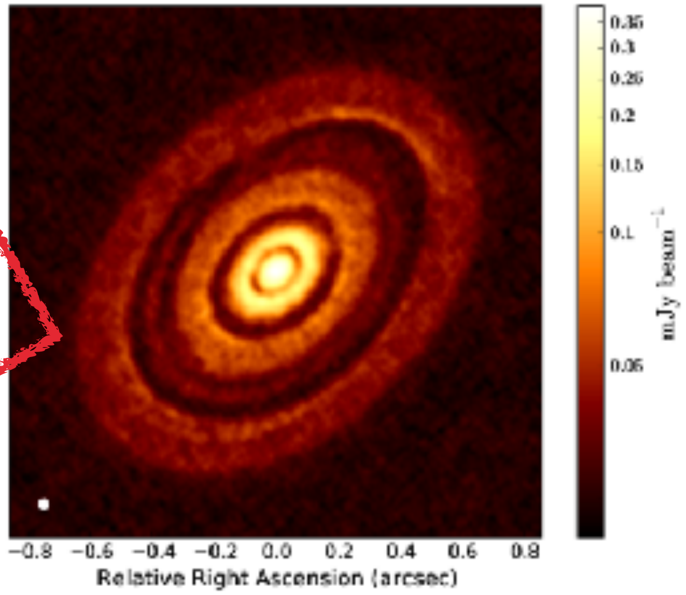


Simulation (Dust densities)



ALMA image

(ALMA partnership 2015)



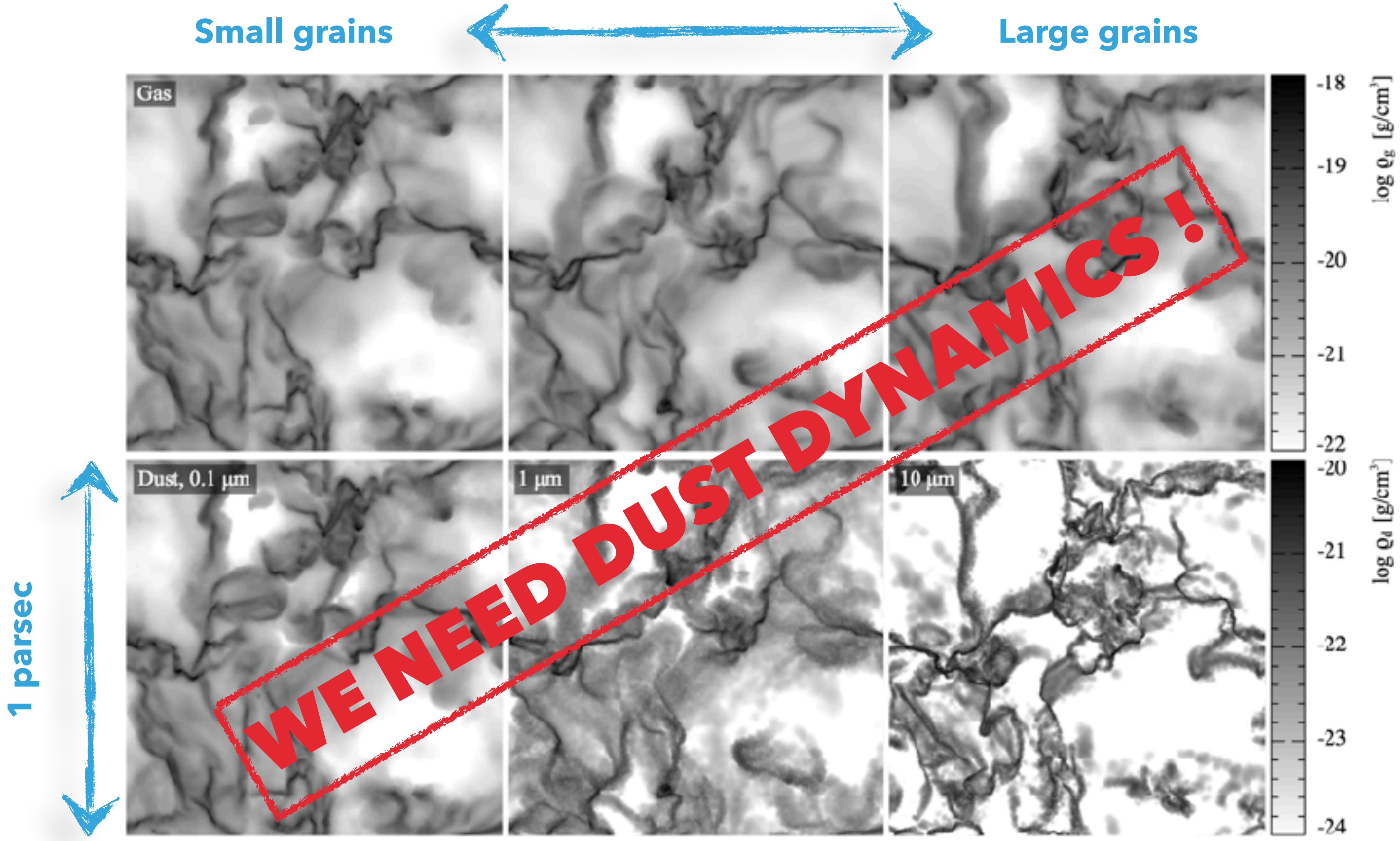
Simulation

(Synthetic observation)

WE NEED DUST DYNAMICS !

INTRODUCTION: DUST IN SIMULATIONS

- **Dynamical sorting in turbulent clouds (Tricco et al. 2017)**



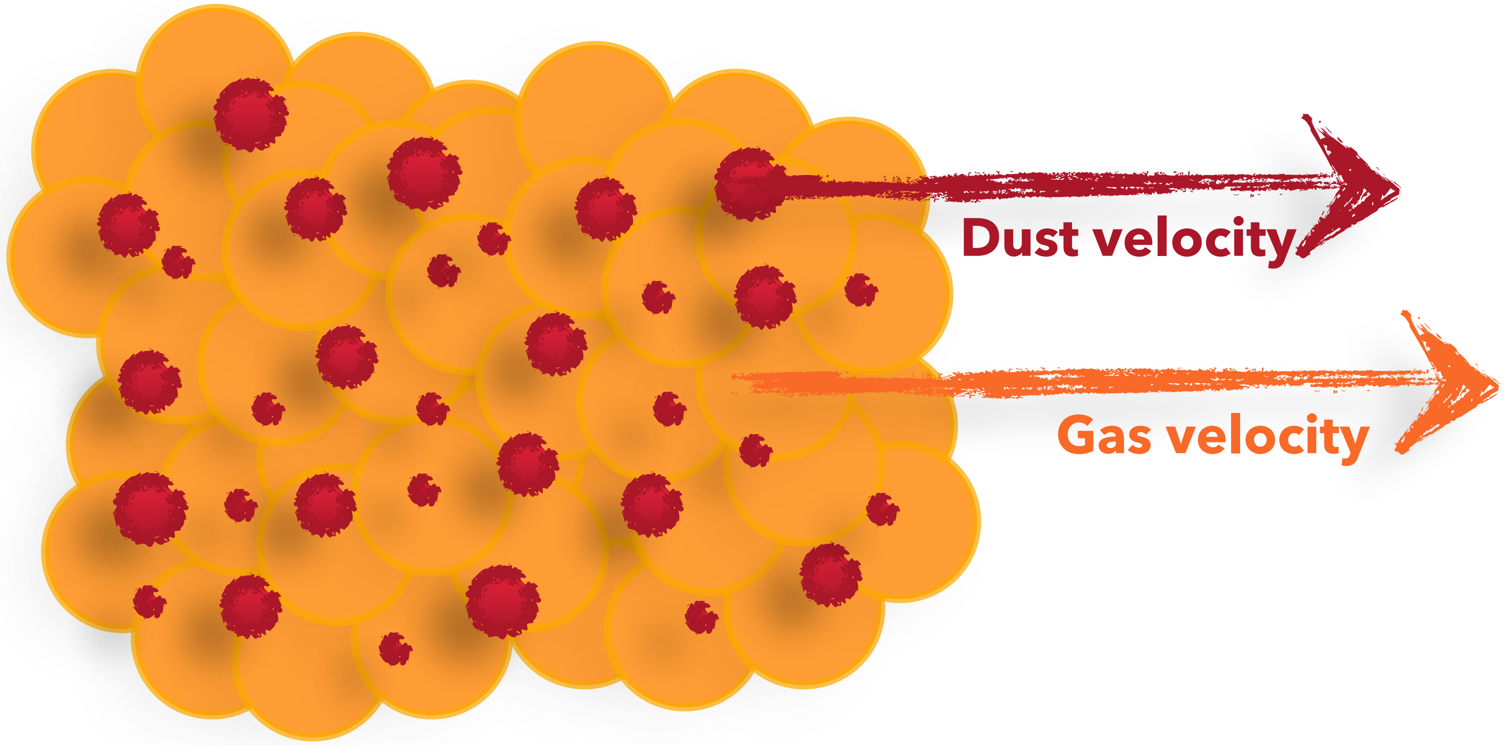
Large grains get trapped in high density regions !

Small grains are trapped everywhere !

METHOD: GAS-GRAIN INTERACTION

Drag force

$$\mathbf{F}_{\mathrm{g/d}} = -\frac{m_{\mathrm{grain}}}{t_{\mathrm{s}}}(\mathbf{v}_{\mathrm{d}} - \mathbf{v}_{\mathrm{g}})$$



Stopping time (Epstein 1924)

$$t_{\mathrm{s}} = \sqrt{\frac{\pi\gamma}{8}}\frac{\rho_{\mathrm{grain}}}{\rho}\frac{s_{\mathrm{grain}}}{c_{\mathrm{s}}}$$

Coupling with the gas (Stokes number)

$$\mathrm{St} \equiv \frac{t_{\mathrm{s}}}{t_{\mathrm{dyn}}}$$

- If St<1, strong coupling
- If St>1, poor coupling

METHOD: (I) DUST AND GAS AS TWO FLUIDS

Bifluid formalism (Saffman 1962)

$$\frac{\mathrm{d}_{\mathrm{g}}\rho_{\mathrm{g}}}{\mathrm{d}t} = -\rho_{\mathrm{g}}(\nabla\cdot\mathbf{v}_{\mathrm{g}}),$$

$$\frac{\mathrm{d}_{\mathrm{d}}\rho_{\mathrm{d}}}{\mathrm{d}t} = -\rho_{\mathrm{d}}(\nabla\cdot\mathbf{v}_{\mathrm{d}}),$$

Two mass conservation equations

$$\rho_{\mathrm{g}}\frac{\mathrm{d}_{\mathrm{g}}\mathbf{v}_{\mathrm{g}}}{\mathrm{d}t} = \rho_{\mathrm{g}}\mathbf{f}_{\mathrm{g}} + \rho_{\mathrm{g}}\mathbf{f} + \frac{\rho_{\mathrm{g}}}{t_{\mathrm{s}}}\mathbf{\Delta v}$$

$$\rho_{\mathrm{d}}\frac{\mathrm{d}_{\mathrm{d}}\mathbf{v}_{\mathrm{d}}}{\mathrm{d}t} = \rho_{\mathrm{d}}\mathbf{f}_{\mathrm{d}} + \rho_{\mathrm{d}}\mathbf{f} - \frac{\rho_{\mathrm{d}}}{t_{\mathrm{s}}}\mathbf{\Delta v}$$

Two momentum conservation equations

Problem : Two resolutions.

Hard to integrate numerically for small grains!

$$\Delta x < c_{\mathrm{s}} t_{\mathrm{s}}$$

METHOD: (II) A GAS AND DUST MONOFLUID

Multiple small dust species monofluid (Laibe and Price 2014c)

$$\mathbf{w_k} \equiv \frac{T_{s,k}\nabla P_g}{\rho}$$

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \mathbf{v}] &= 0, \\
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[P_g \mathbb{I} + \rho(\mathbf{v} \otimes \mathbf{v})\right] &= 0, \\
\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P_g)\mathbf{v}\right] &= 0, \\
\frac{\partial \rho \epsilon_k}{\partial t} + \nabla \cdot [\rho \epsilon_k \mathbf{v}] &= -\nabla \cdot \boxed{\left[\epsilon_k T_{s,k} \nabla P_g\right]}, \forall k \in [0, \mathcal{N}]
\end{aligned}$$

✓ **Approximation for small grains : St <1** ✓

ρ	Total density	ϵ_k	Dust ratio of species k
$\mathbf{v}$	Barycentre velocity		
E	Total energy of the mixture		

METHOD: IMPLEMENTATION IN RAMSES

- **Hyperbolic form**

$$\frac{\partial \mathbb{U}}{\partial t} + \nabla \cdot \mathbb{F}(\mathbb{U}) = 0,$$

- **Gas hydrodynamics**

$$\mathbb{U} \equiv \cancel{\left(\rho_{\mathrm{g}}, \rho \mathbf{v}_{\mathrm{g}}, E_{\mathrm{g}}\right)},$$

$$\mathbb{F}(\mathbb{U}) \equiv \cancel{\left(\rho_{\mathrm{g}} \mathbf{v}_{\mathrm{g}}, \rho_{\mathrm{g}} \mathbf{v}_{\mathrm{g}} \otimes \mathbf{v}_{\mathrm{g}} + P_{\mathrm{g}} \mathbb{I}, \mathbf{v}_{\mathrm{g}}(E_{\mathrm{g}} + P_{\mathrm{g}})\right)},$$

- **Gas and dust hydrodynamics**

$$\mathbb{U} \equiv \left(\rho, \rho \mathbf{v}, E, \rho_{\mathrm{d}.k}\right),$$

$$\mathbb{F}(\mathbb{U}) \equiv \left(\rho \mathbf{v}, \rho \mathbf{v} \otimes \mathbf{v} + P_{\mathrm{g}} \mathbb{I}, \mathbf{v}(E + P_{\mathrm{g}}), \rho_{\mathrm{d},k}(\mathbf{v} + \mathbf{w}_{\mathbf{k}})\right),$$

METHOD: IMPLEMENTATION IN RAMSES

- **Operator splitting**

$$\mathbb{U} \equiv \left(\rho, \rho\mathbf{v}, E, \rho_{\mathrm{d},k}\right),$$

$$\mathbb{F}(\mathbb{U}) \equiv \left(\rho\mathbf{v}, \rho\mathbf{v}\otimes\mathbf{v} + P_{\mathrm{g}}\mathbb{I}, \mathbf{v}(E+P_{\mathrm{g}}), \rho_{\mathrm{d},k}(\mathbf{v} + \mathbf{w_k})\right),$$

Classical Hydro step

Dust diffusion step

UMUSCL scheme

UPWIND and predictor-corrector

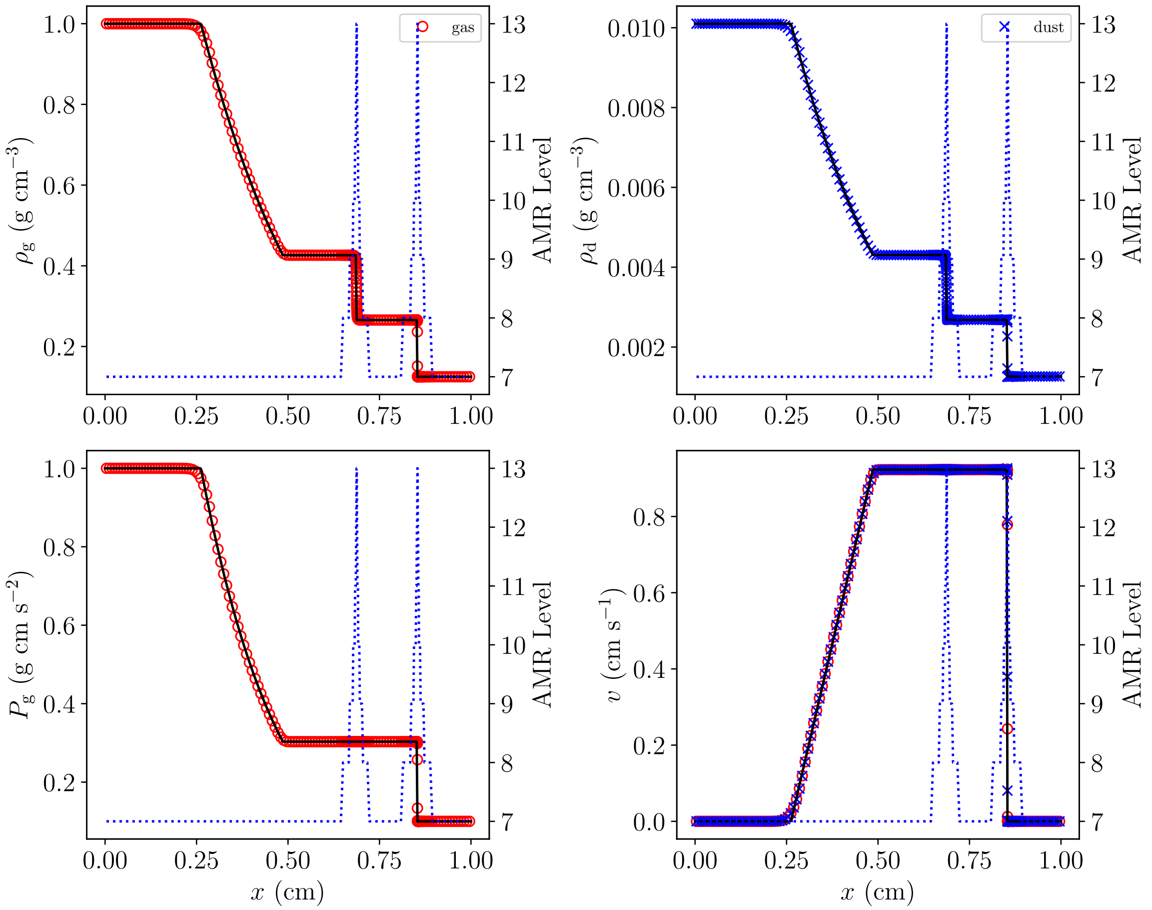
- **Godunov Scheme**

$$\mathbb{U}_i^{n+1} = \mathbb{U}_i^n - \left(\mathbb{F}_{i+1/2}^{n+1/2} - \mathbb{F}_{i-1/2}^{n+1/2}\right)\frac{\Delta t}{\Delta x},$$

- **Works on AMR grid!**

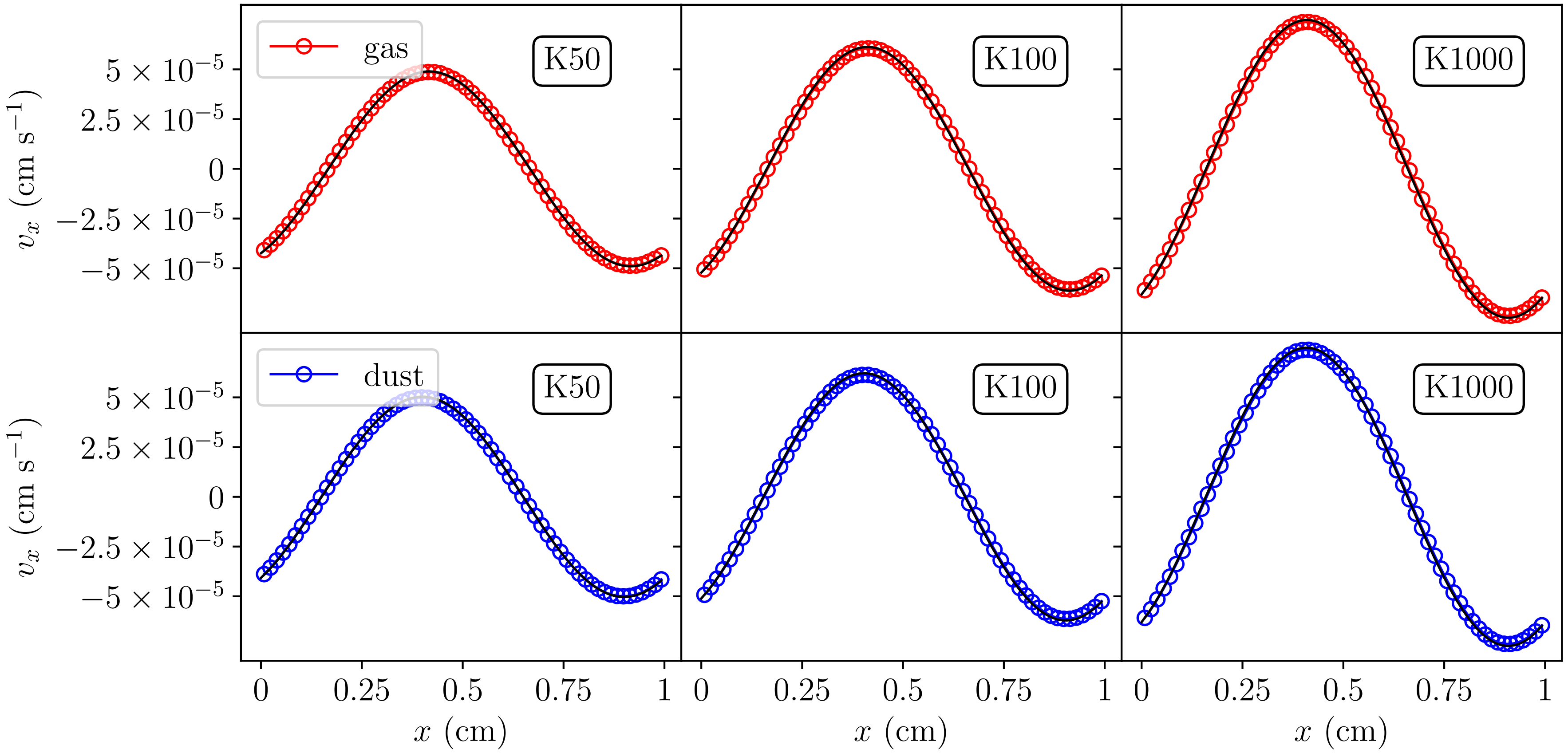
TESTS: DUSTYSHOCKS AND DUSTYWAVES

Dustyshock



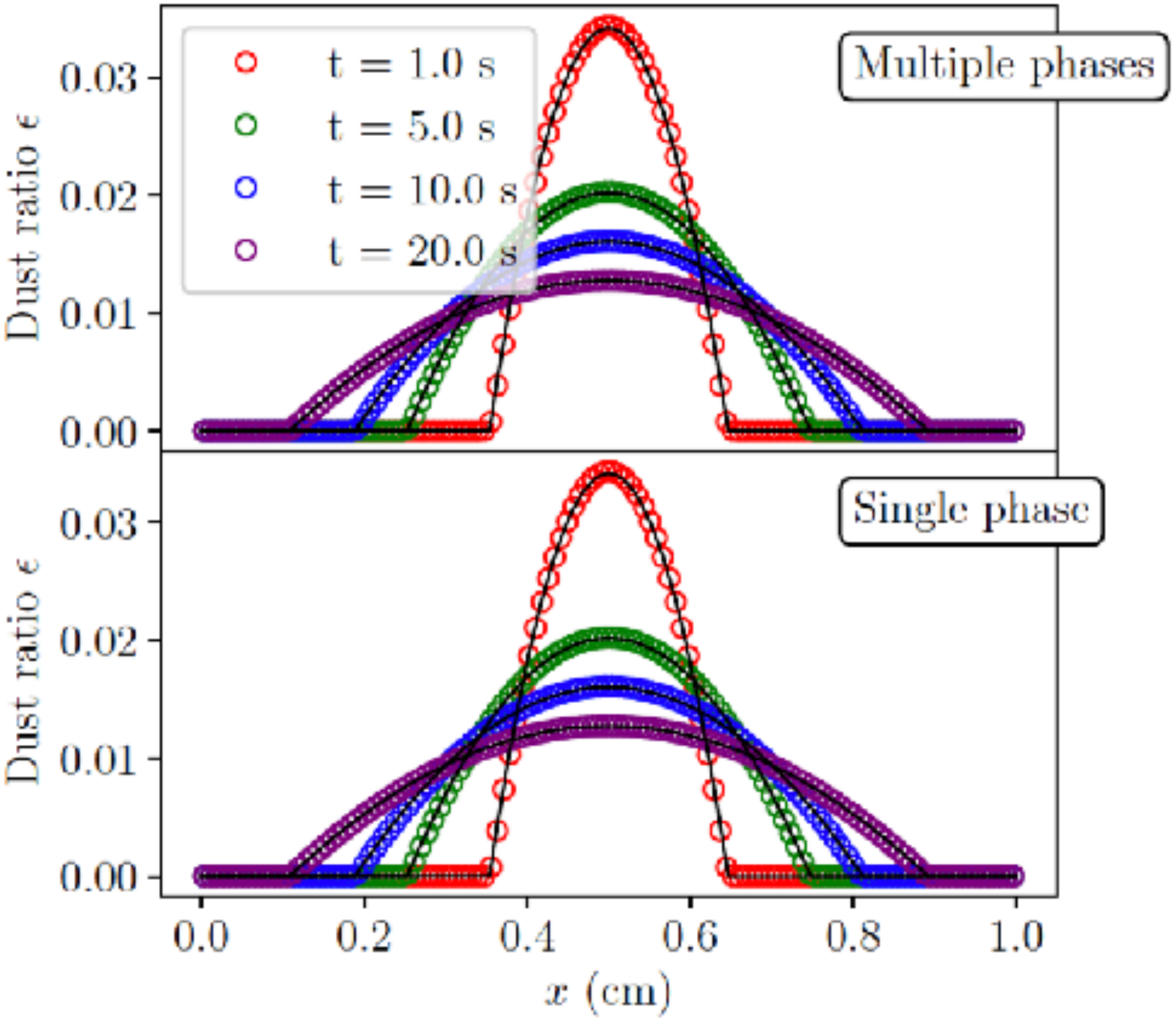
✓

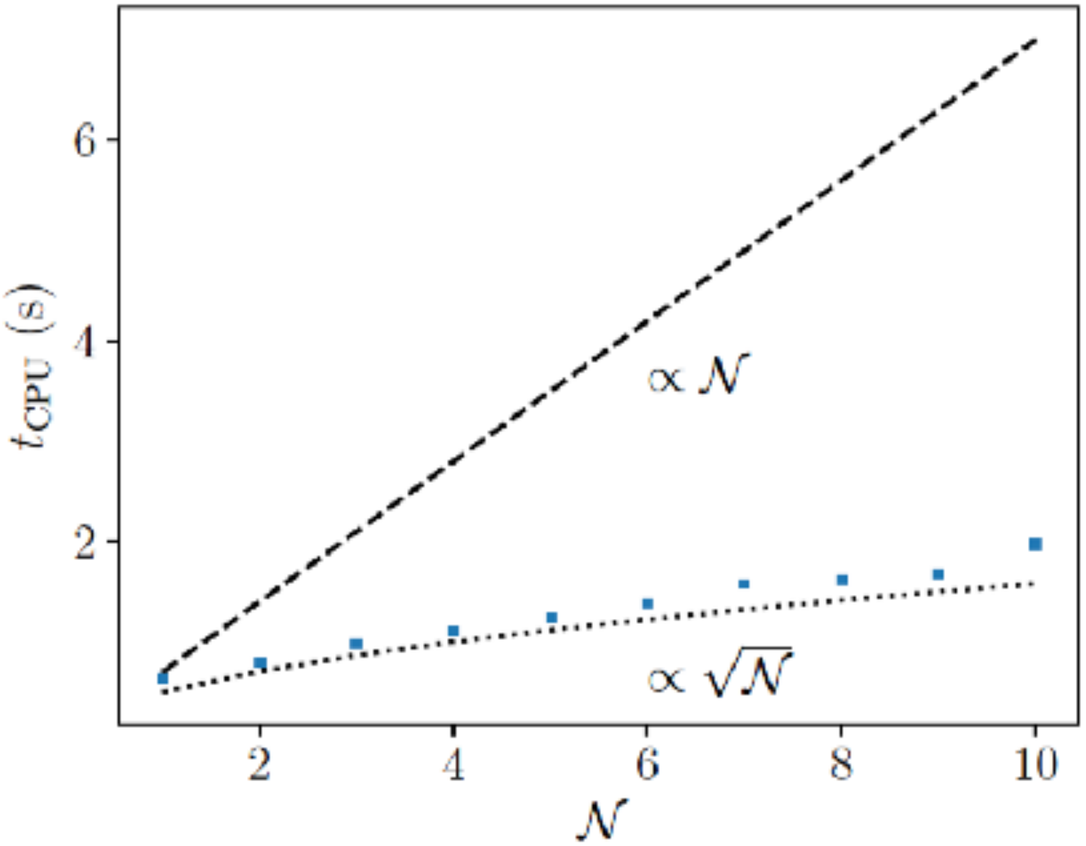
Dustywave



✓

TEST: SIMULTANEOUS TREATMENT OF MULTIPLE SPECIES





Fast !

APPLICATION: ROTATING COLLAPSE WITH MULTIPLE SPECIES

Initial conditions : (Boss and Bodenheimer, 1979)

Uniform sphere

Solid body rotation

Azimuthal density perturbation

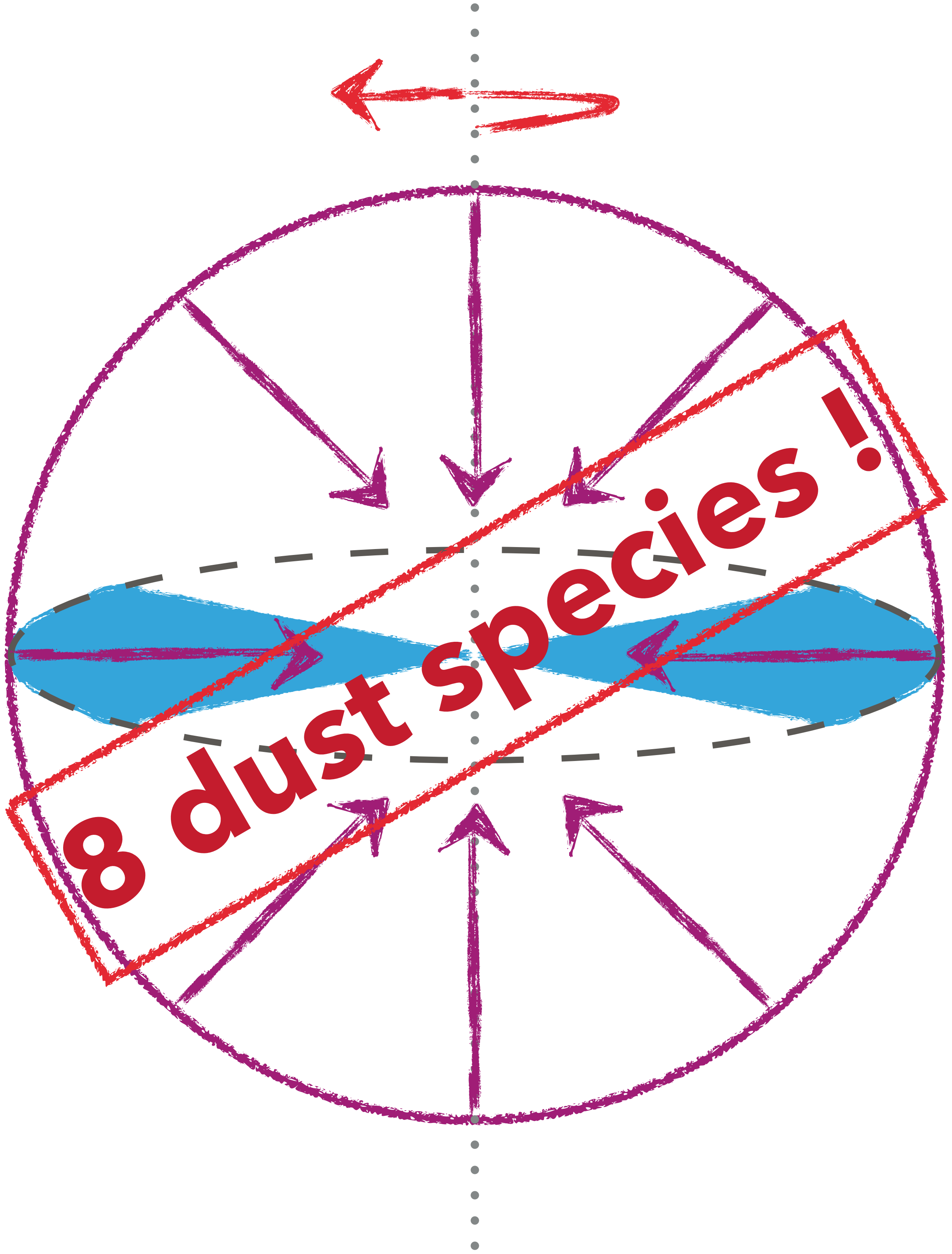
Initial core mass $1 M_{\odot}$, 1 % dust

Thermal to gravitational energy ratio : 0.65

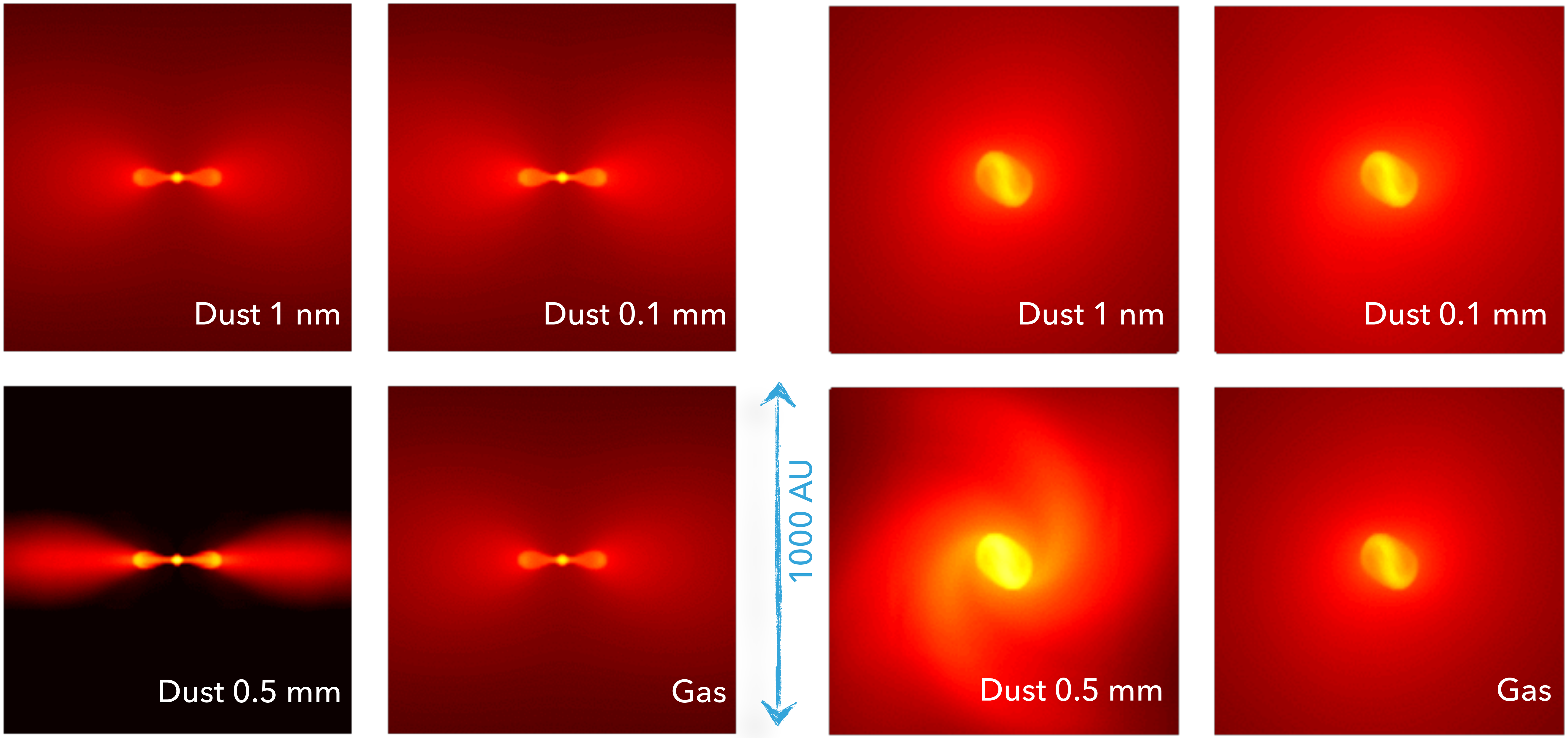
Rotational to gravitational energy ratio : 0.03

Grains from 1 nm to 0.5 mm distributed as

a MRN power law!



APPLICATION: DECOUPLING DURING THE COLLAPSE



Edge-on cut

Mid-plane cut

(Lebreuilly et al., In Prep)

CONCLUSION

Summary

- Dust in RAMSES works!
- Low numerical cost even for multiple species
- Protostellar collapse, dust decouples at 100 micron
- Potential application : turbulent ISM, protostellar collapse, disk evolution