CRAL

CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

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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

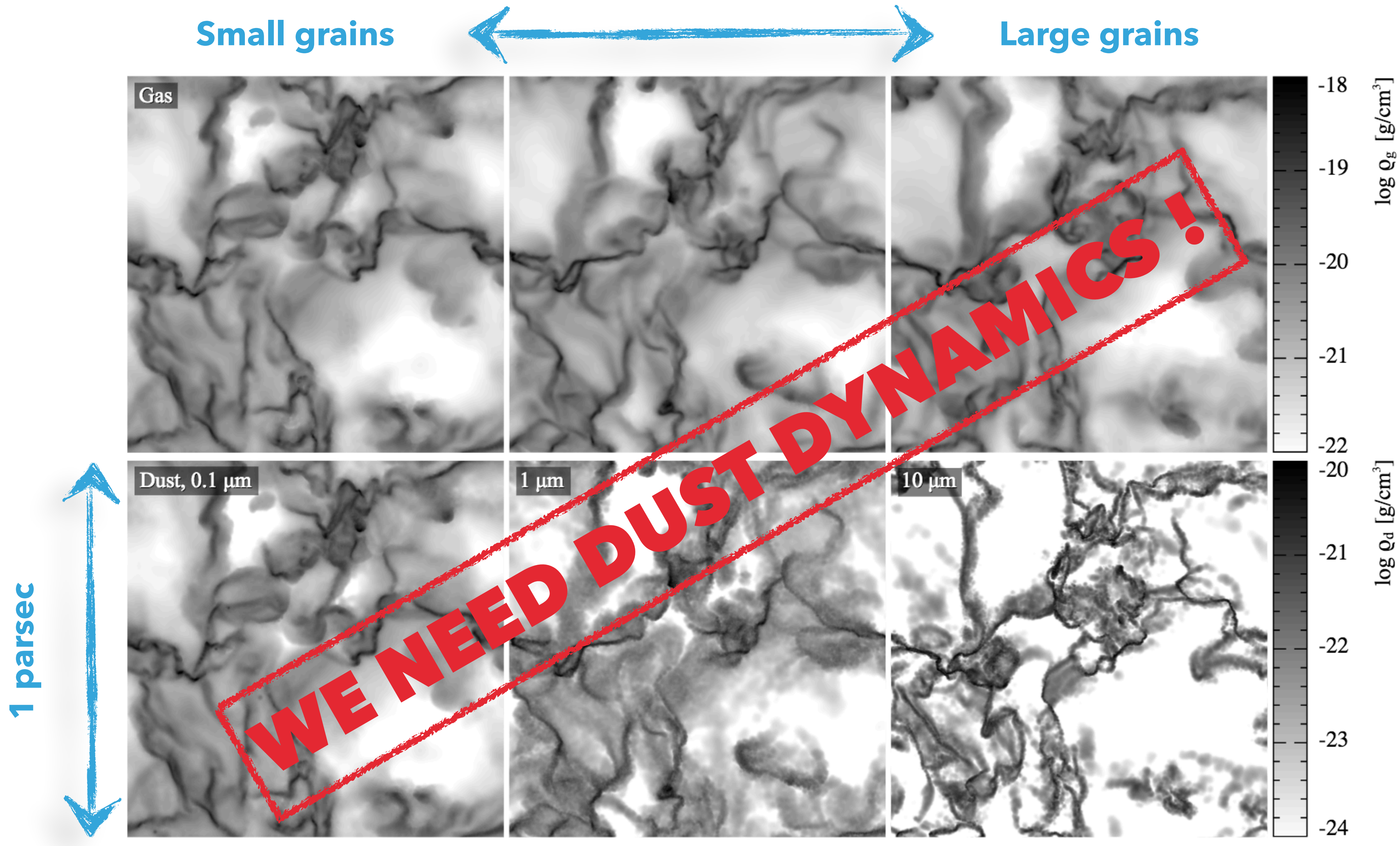
- Continuum (Herschel, Spitzer, JWST, ALMA, SPHERE)
- Polarisation (ALMA, Planck,…)

Dust plays a role in

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

INTRODUCTION: DUST IN SIMULATIONS

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



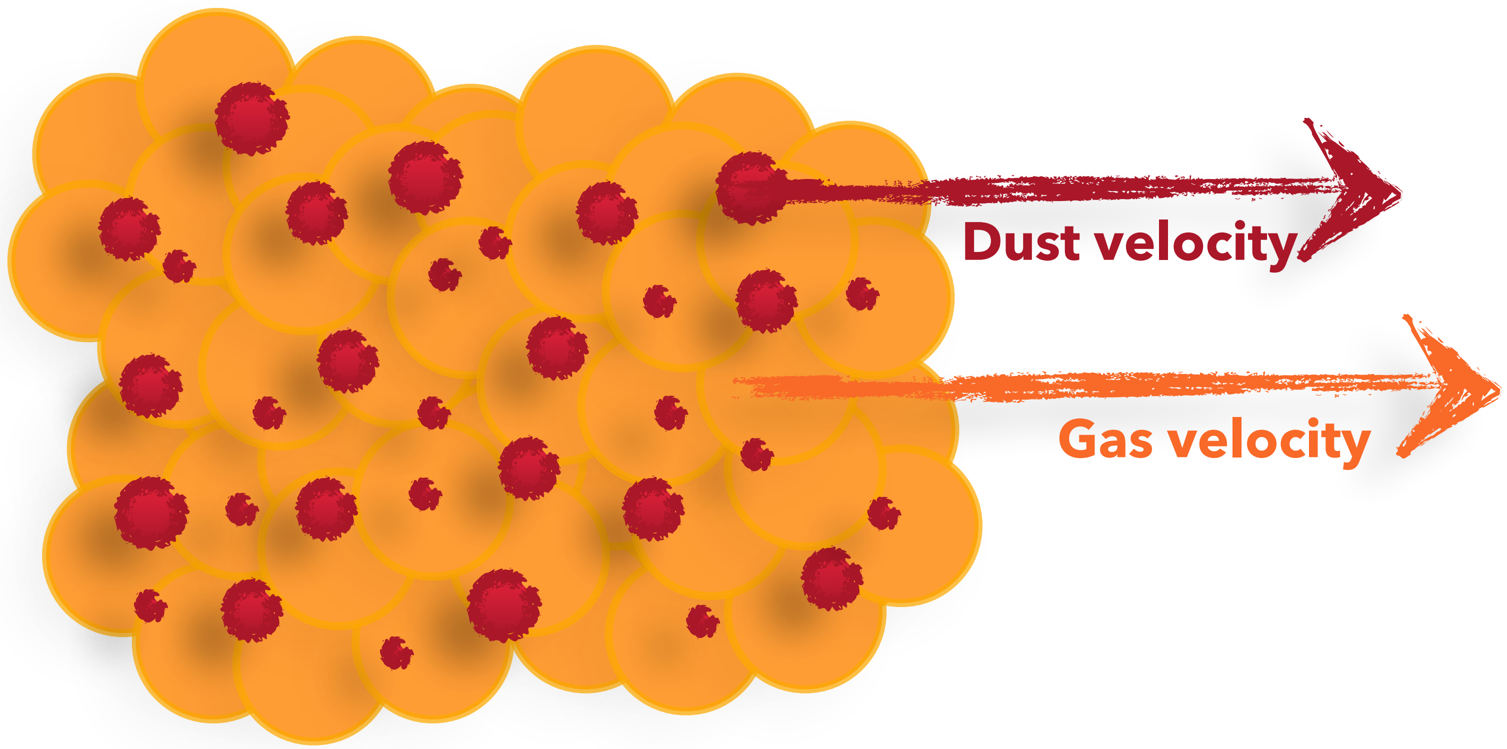
Large grains get trapped in high density regions !

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: A GAS AND DUST MONOFLUID

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

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

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[P_{\mathrm{g}} \mathbb{I} + \rho (\mathbf{v} \otimes \mathbf{v}) \right] = 0,$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P_{\mathrm{g}}) \mathbf{v} \right] = 0,$$

$$\frac{\partial \rho \epsilon_k}{\partial t} + \nabla \cdot [\rho \epsilon_k \mathbf{v}] = -\nabla \cdot \boxed{\left[\epsilon_k T_{\mathrm{s},k} \nabla P_{\mathrm{g}} \right]}, \forall k \in [0, \mathcal{N}]$$

$$\mathbf{w_k} \equiv \frac{T_{\mathrm{s},k} \nabla P_{\mathrm{g}}}{\rho}$$

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

- **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

UMUSCL scheme

Dust diffusion step

UPWIND and predictor-corrector

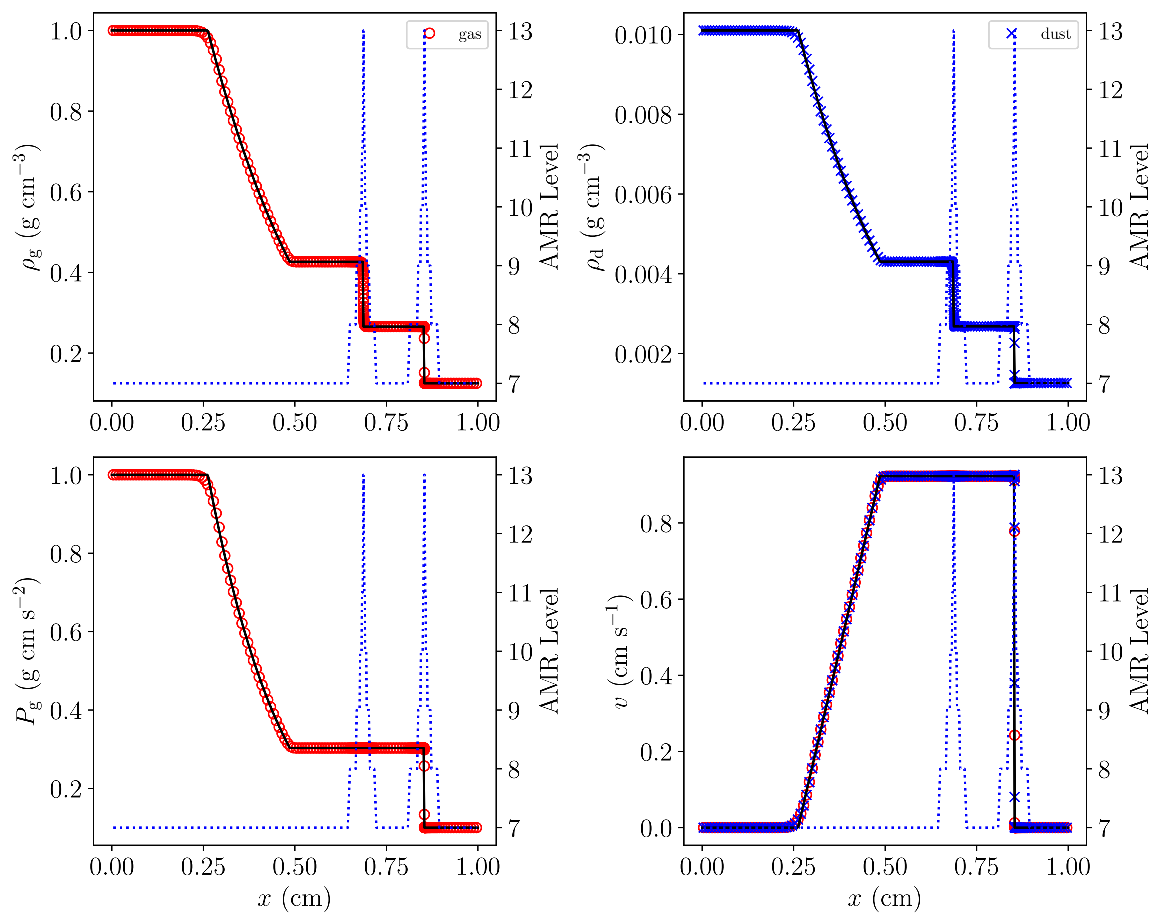
- **Godunov Scheme**

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

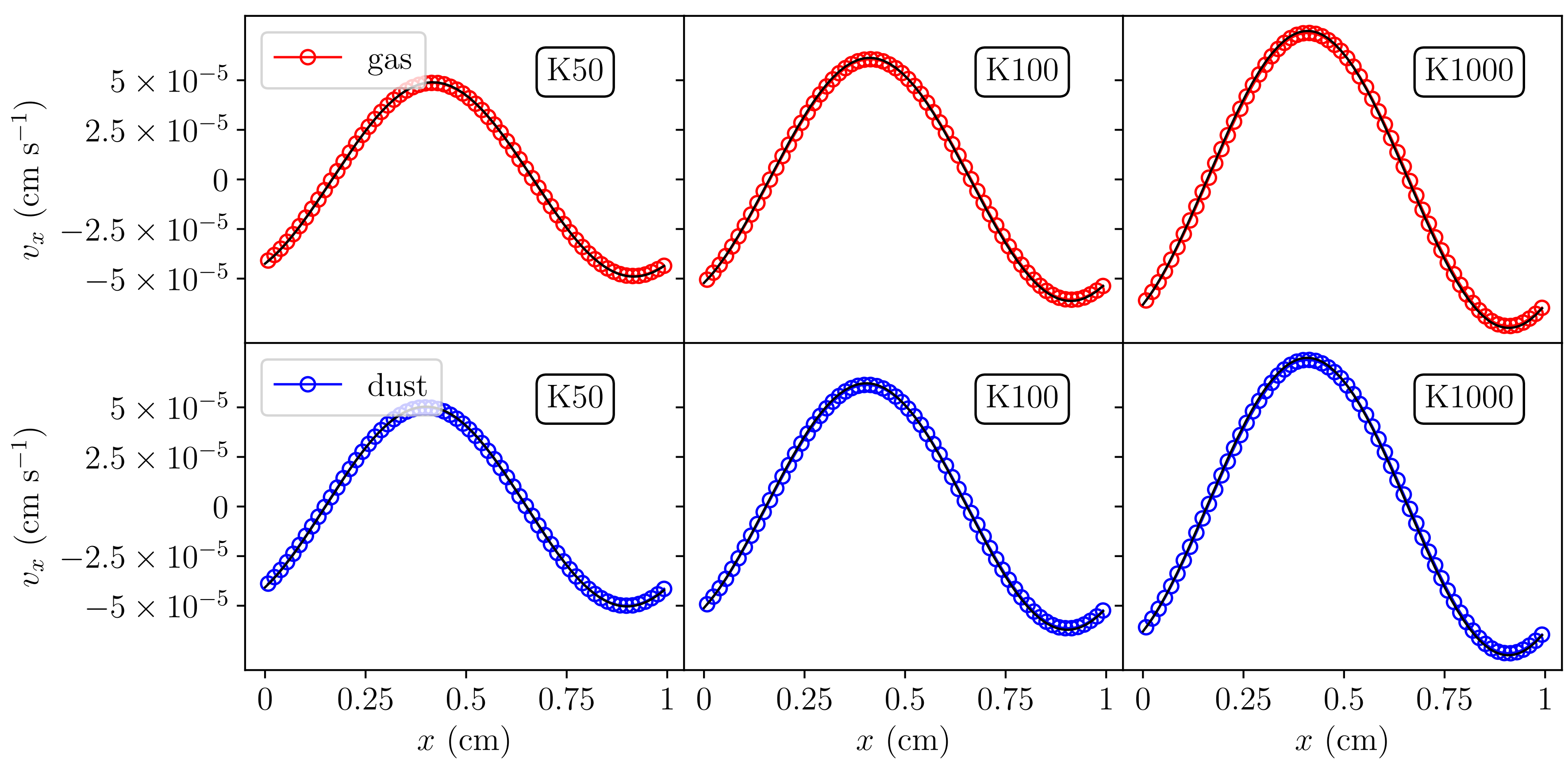
- **Works on AMR grid!**

TESTS: DUSTYSHOCKS AND DUSTYWAVES

Dustyshock



Dustywave



APPLICATION: ROTATING COLLAPSE WITH MULTIPLE SPECIES

Initial conditions : **(Boss and Bodenheimer, 1979)**

Uniform sphere

Solid body rotation

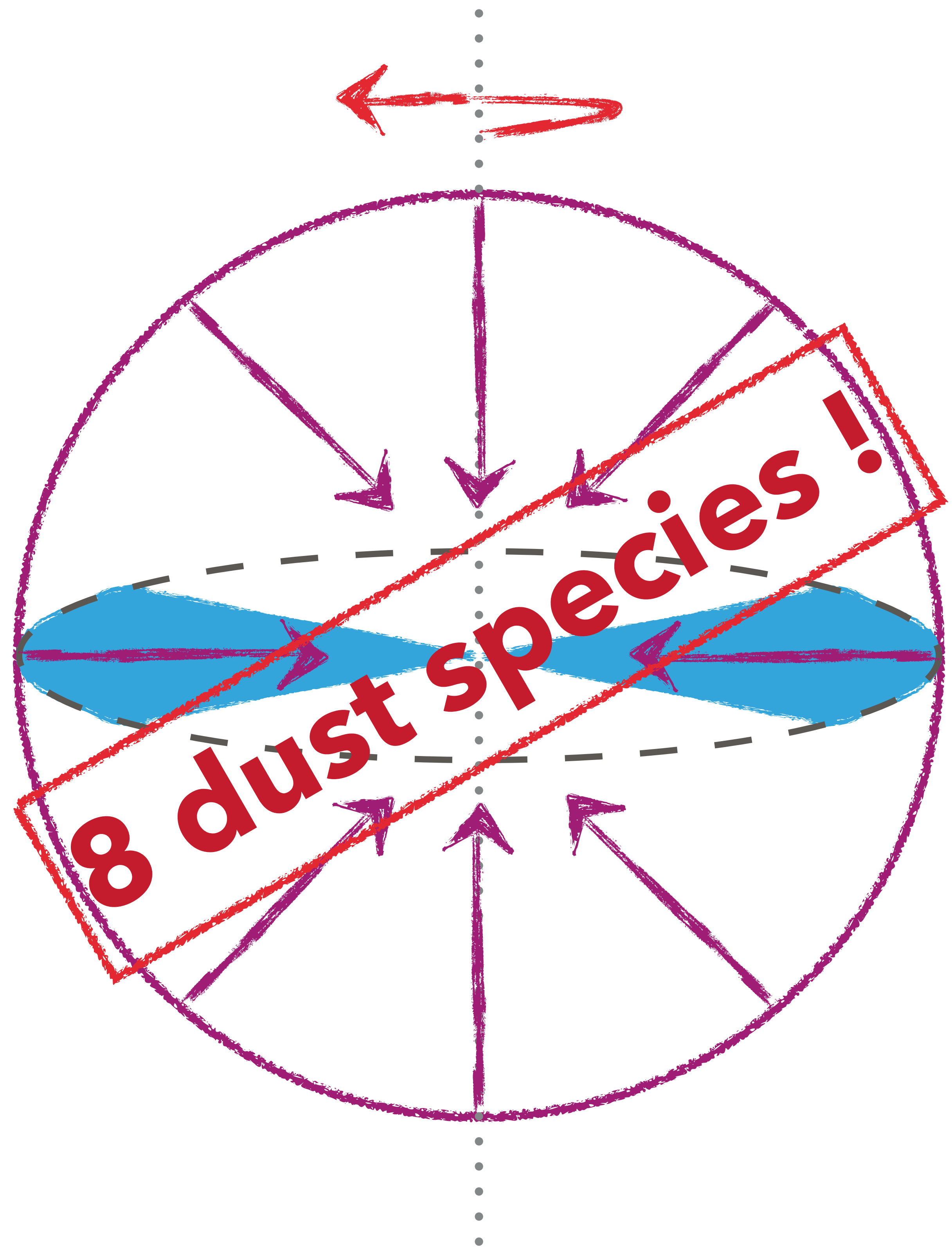
Azimuthal density perturbation

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

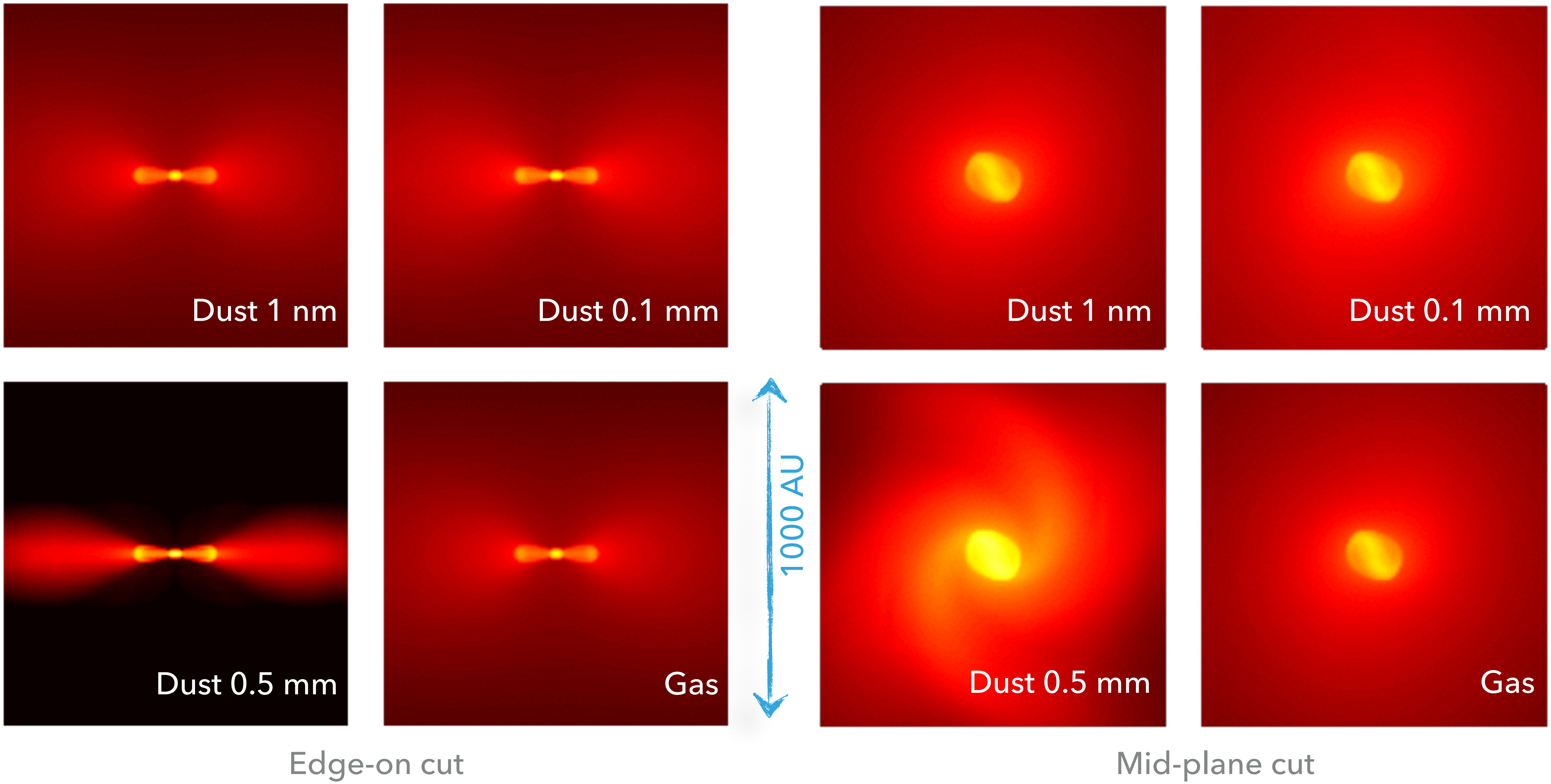
Thermal to gravitational energy ratio : 0.65

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



(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.

CONCLUSION

HPC for dummies

- What about a course about HPC on next Astrosim?
- Can we imagine a few computing hours on national clusters for young researchers? For example, to develop our tools.