ASNUM 2025

Dust dynamics during a protostellar collapse: a multifluid method in RAMSES

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- The role of the dust grains in star and planet formation

- Implementation of the multifluid in RAMSES
- Riemann solvers of interacting dust and gas

- Protostellar collapses and turbulence

The multiple roles of the grain dust size distribution in star and planet formation

- Thermodynamics and the chemistry of molecular clouds (for instance, the formation of H2, Gould & Salpeter 1963)
- Opacity of collapsing protostellar cores (Larson, 1969)
- Coupling between the gas and the magnetic field during the protostellar collapse (Marchand et al., 2016)
- Solid content to form planetesimals in protoplanetary disks

A dust-to-gas mass ratio of 1 % means different things depending on the size distribution:

Surface (in smallest grains): opacity, chemistry, drag forces, charging

Mass (in largest grains): inertia, seeds for pebbles

A multifluid approach for interacting gas and dust grains

Gas dynamics

$$\partial_t \rho_g + \nabla(\rho_g \mathbf{V}_g) = 0$$

$$\partial_t \left(\rho_g \mathbf{V}_g\right) + \nabla \left(\rho_g \mathbf{V}_g \mathbf{V}_g + P_g \mathbf{I}\right) = \sum \rho_d \rho_g \gamma_d (\mathbf{V}_d - \mathbf{V}_g)$$

Dust multifluid: a collection of pressureless fluids
that samples a grain size distribution
(or represents multiple dust species)

$$\partial_t \rho_d + \nabla(\rho_d \mathbf{V}_d) = 0$$

$$\partial_t \left(\rho_d \mathbf{V}_d\right) + \nabla \left(\rho_d \mathbf{V}_d \mathbf{V}_d\right) = -\rho_d \rho_g \gamma_d (\mathbf{V}_d - \mathbf{V}_g)$$

grain inertia

drag forces with gas

Multifluid in RAMSES: Verrier et al., 2025

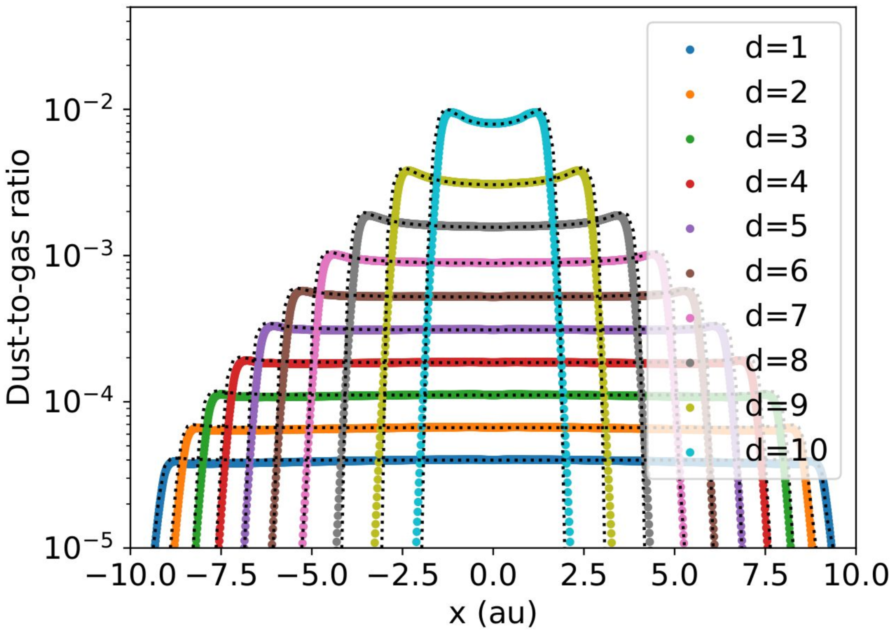
$$
\begin{aligned}
\partial_t \rho_d + \nabla(\rho_d \mathbf{V}_d) &= 0 \\
\partial_t (\rho_d \mathbf{V}_d) + \nabla(\rho_d \mathbf{V}_d \mathbf{V}_d) \quad \text{flux} &= -\rho_d \rho_g \gamma_d (\mathbf{V}_d - \mathbf{V}_g) \quad \text{drag} \\
\partial_t \rho_g + \nabla(\rho_g \mathbf{V}_g) &= 0 \\
\partial_t (\rho_g \mathbf{V}_g) + \nabla(\rho_g \mathbf{V}_g \mathbf{V}_g + P_g \mathbf{I}) &= \sum \rho_d \rho_g \gamma_d (\mathbf{V}_d - \mathbf{V}_g)
\end{aligned}
$$

- **Riemann solvers** in UMUSCL for the multifluid.
  - **Individual** Riemann solvers: Upwind (Huang & Bai, 2022), Local Lax-Friedrichs (LLF).
  - **Common** Riemann solvers*: LLFgd and HLLgd
- **Drag solver :** 1st order implicit (Krapp & Benítez-Llambay, 2020) from FARGO3D
- **Operator splitting:** Fractional steps with 1st order* Lie splitting Drag o Flux
- Validation tests: dustybox, dustywave (scheme order in time and space*), multijeanswave, disk settling, shock, advection of passive scalars (→ grain growth)

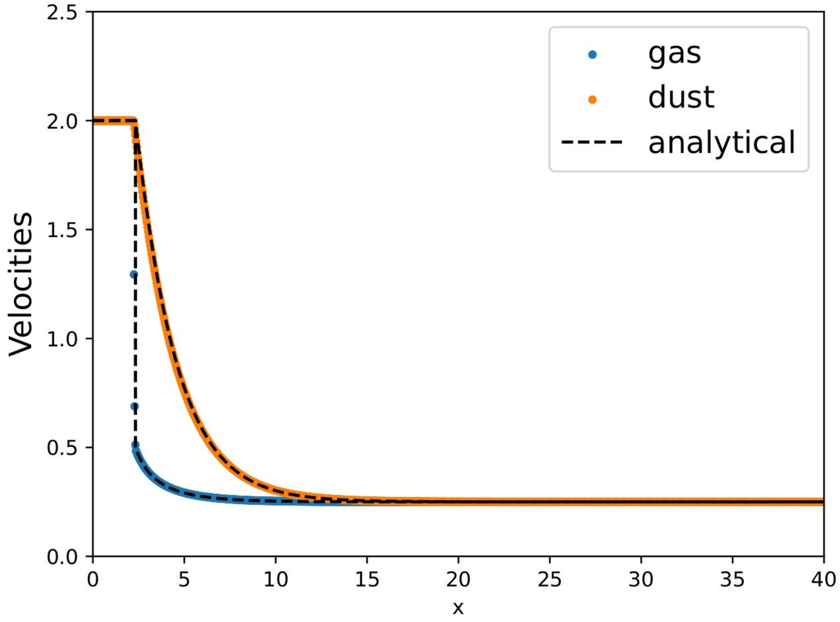
*In the literature, development of high-order drag scheme and splitting scheme: Huang & Bai 2022 for Athena++, Krapp et al., 2024, Sewanou et al., 2025 for Dyablo and Shamrock (see Leodasce Sewanou's talk), Tedeschi-Prades et al., 2025 for Bigpen.

Validation tests

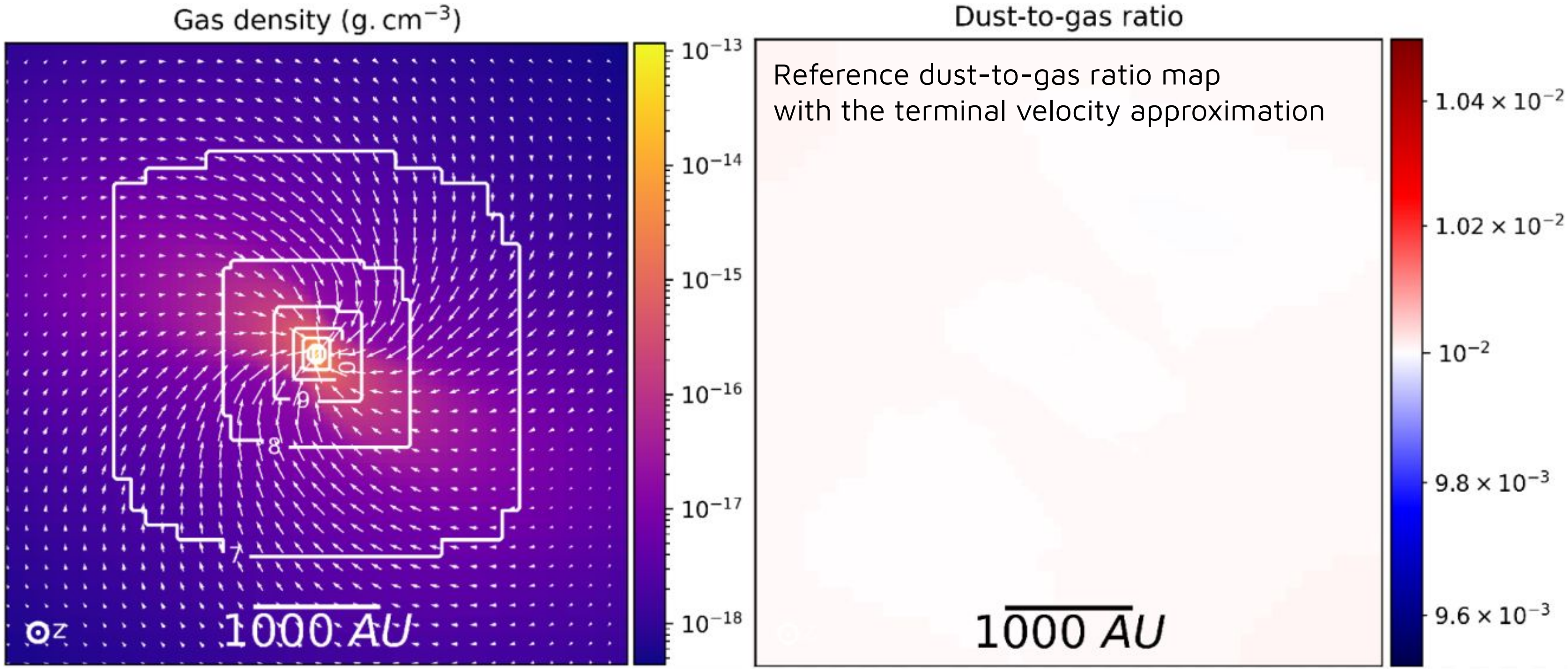
Disk settling for a distribution of 10 dust species (one fluid=one grain size)



Supersonic shock in a gas and dust mixture



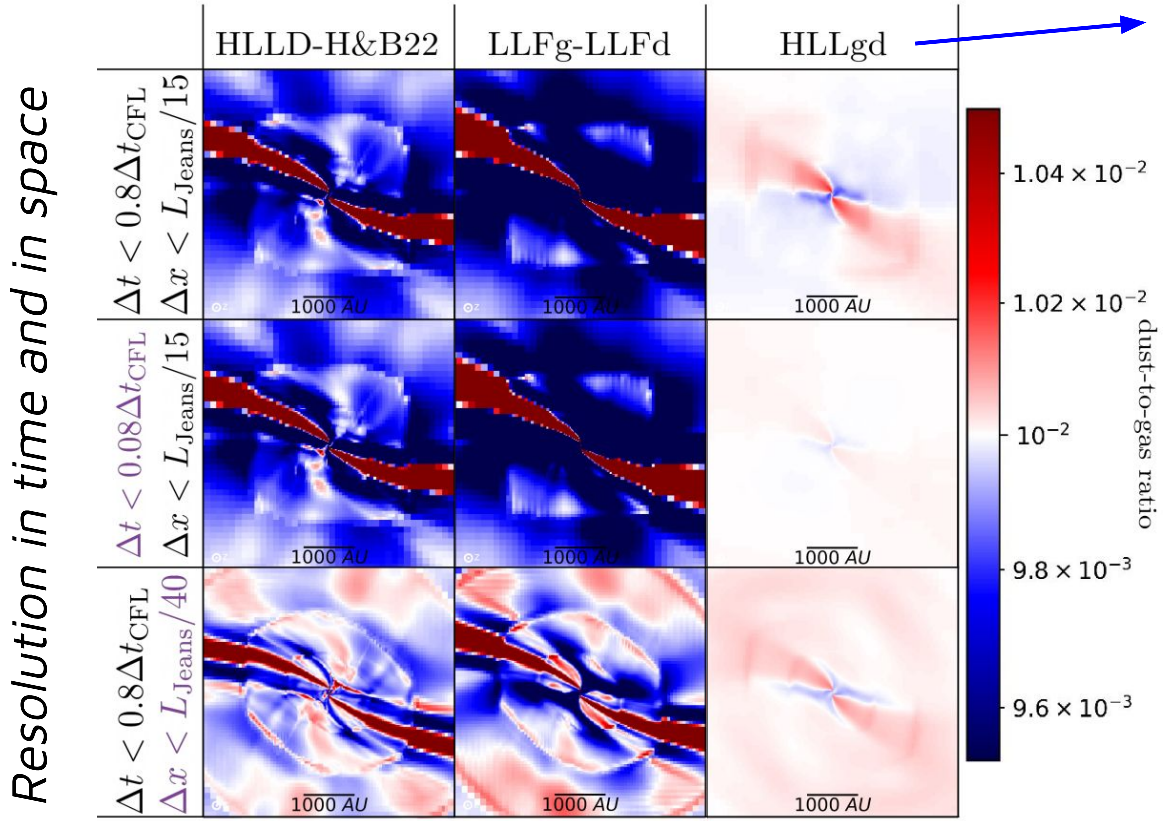
Terminal velocity approximation vs multifluid method
Protostellar collapses with sub-micron grains



→ Sub-micron grains are tightly coupled to the gas, thus dust-to-gas ratio variations are weak

Terminal velocity approximation vs multifluid method
Protostellar collapses with sub-micron grains

Riemann solver for the multifluid



New Riemann solver (Verrier et al, 2025) for which the dust fluid shares the same wave fan as the gas if a kinematic coupling criterion is satisfied (next slides).

The advections of the gas and the dust are unbalanced for individual solvers.

The Riemann solvers may agree if the recoupling length is resolved.

$$\Delta x < c_s t_{s,d} \propto s_{\rm grain}/\rho$$

Importance of the common Riemann solver for the collapse of large grains

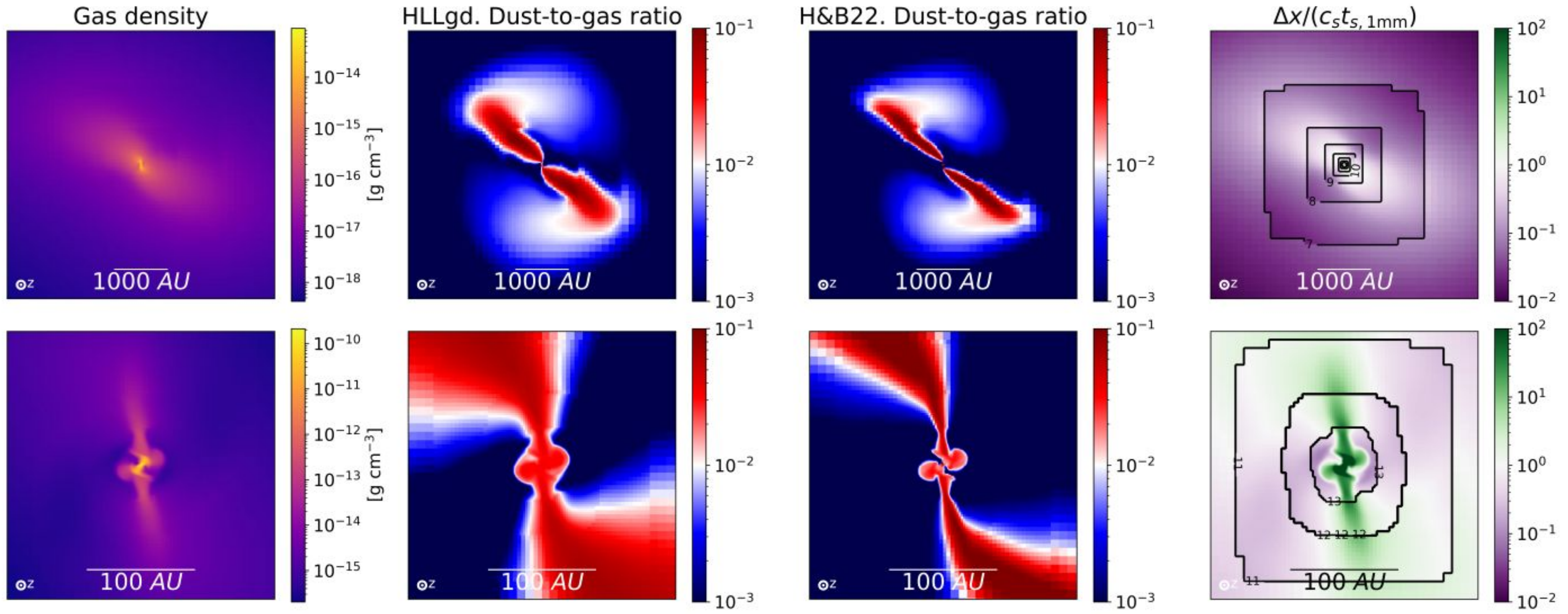
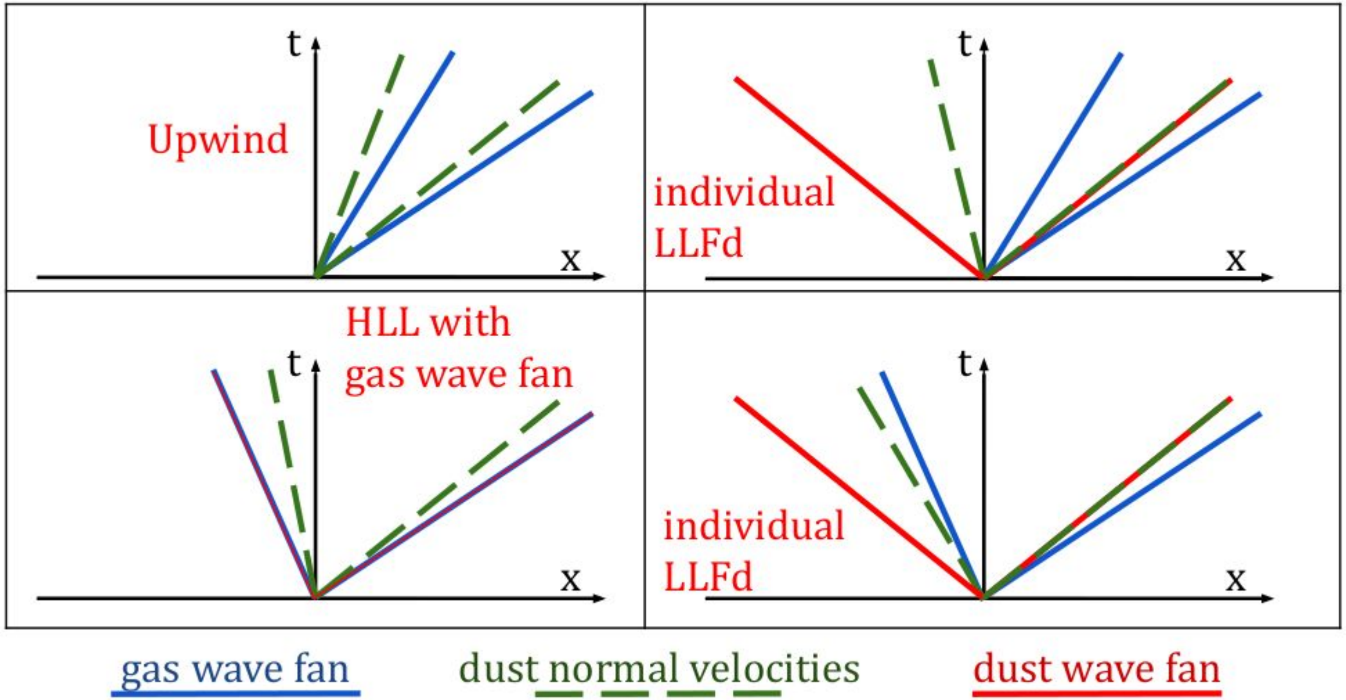


Fig. G.1: Comparison between two Riemann solvers for the dust fluid: HLLgd and H&B22, the solver from Huang & Bai (2022). Gas density map in the first column (HLL solver) at t = 60.6 kyr, dust-to-gas ratio maps from the two Riemann solvers (HLLgd in the second column and H&B22 in the third column), and resolution of the recoupling length expressed as $\Delta x/(c_s t_{s,1\mathrm{mm}})$, with mesh-refinement levels indicated by contours, in the last column. Zoom-in of the collapse region (upper panels) to the disk scale (lower panels). Dust feedback has been deactivated to ease the comparison between the two solvers.

Riemann solver for a dust multifluid coupled to the gas



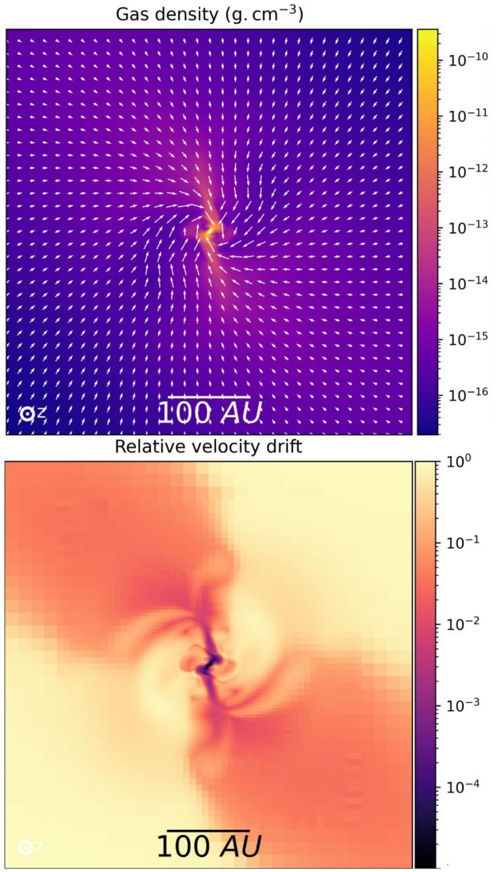
Linear regime (eigenmode identification)

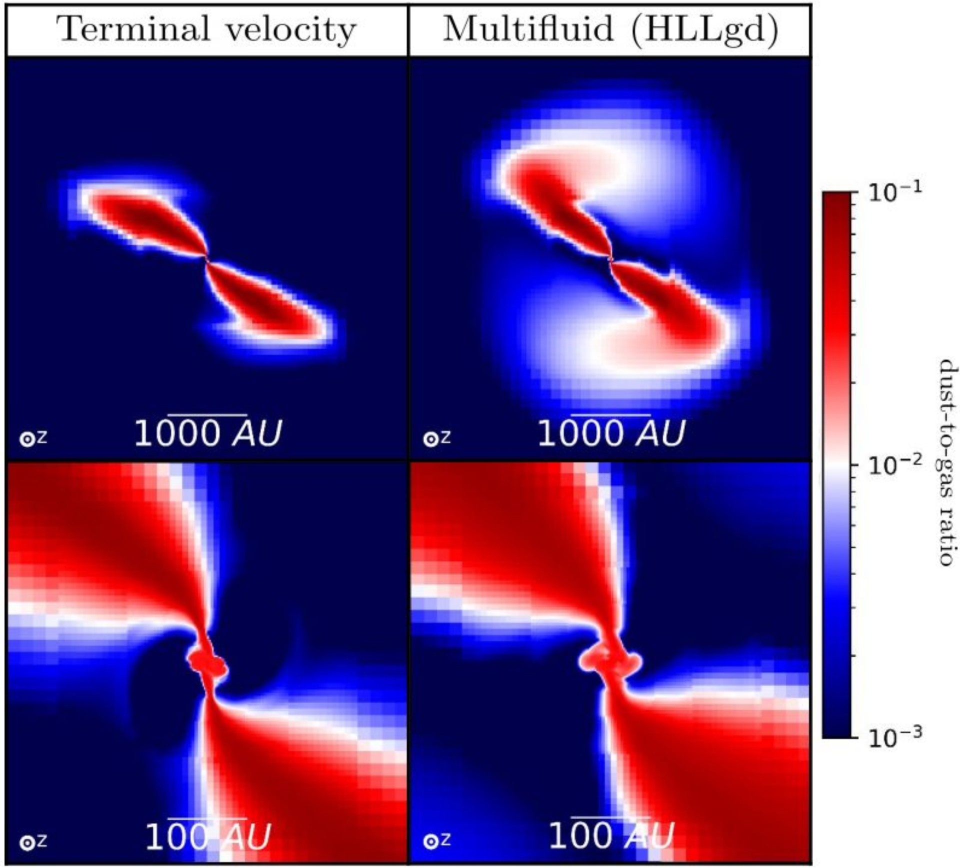
$$\frac{\delta\theta_d}{\theta_d} = \frac{\delta v_d - \delta v_g}{c_\phi},$$

Switch to individual LLF if the dust (velocity) is outside the influence of the gas

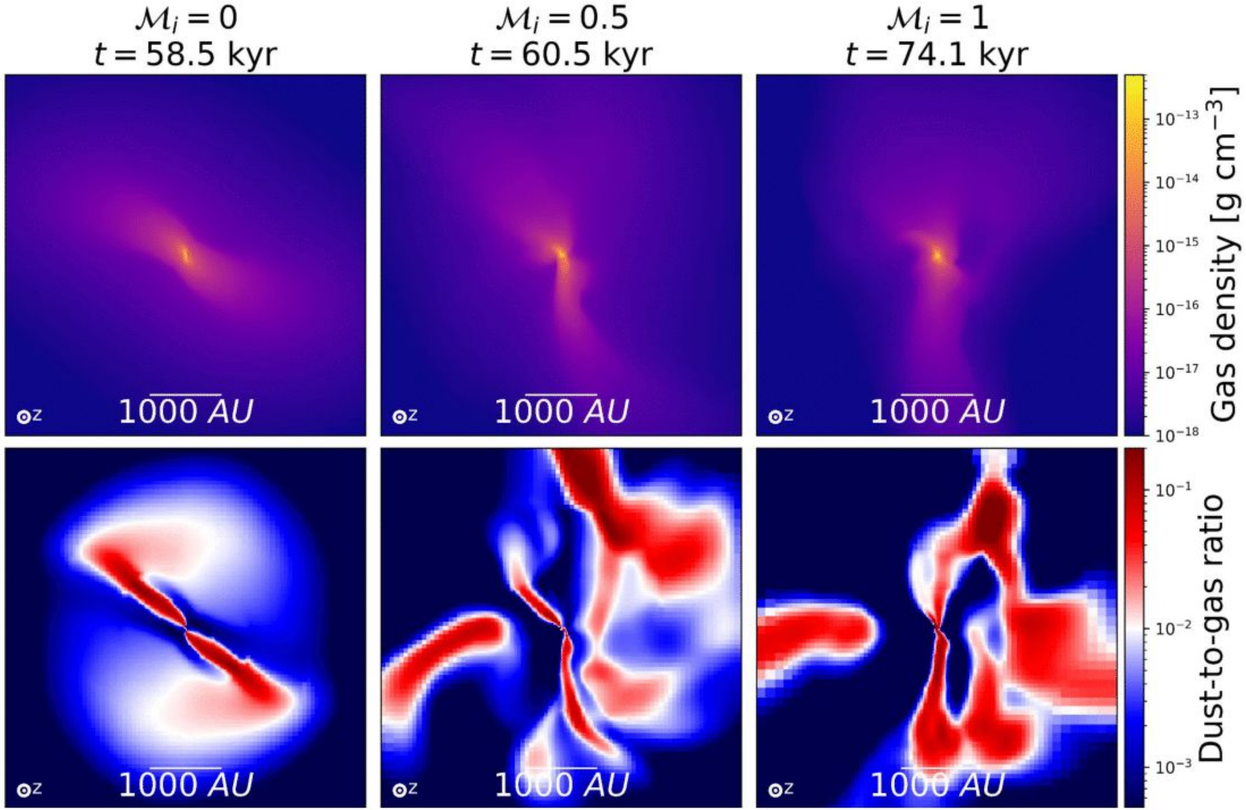
$$|\delta v_d - \delta v_g| > c_\phi$$

Terminal velocity approximation vs multifluid method
Protostellar collapses with millimeter grains



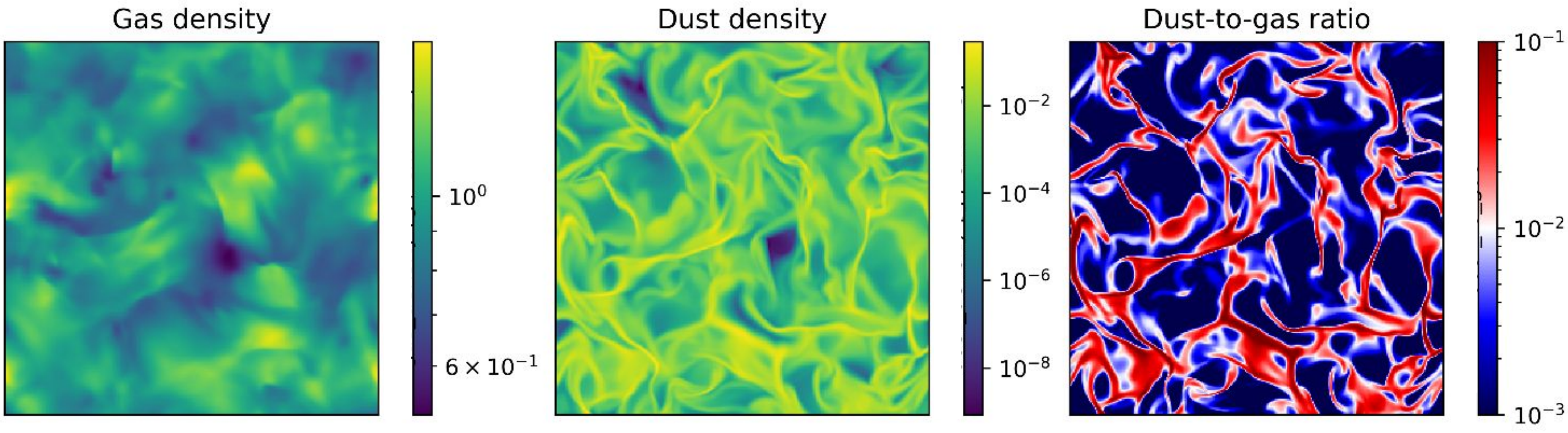


Millimeter grains in a turbulent collapse



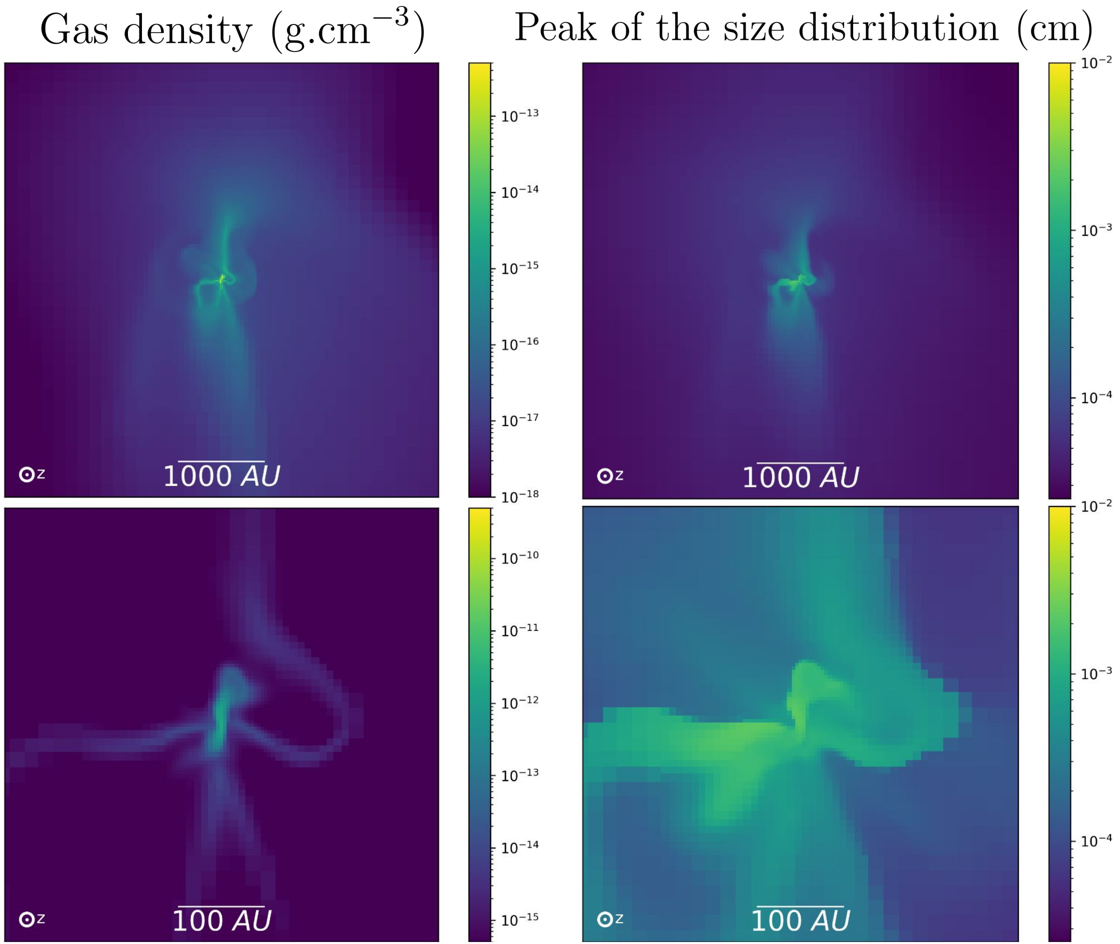
▲ Dust enrichment within the hydrostatic core and in some locations of the envelope increases as a function of the grain size and the level of initial turbulence.
However, the turbulent cascade is highly truncated.

Dust in turbulent boxes



- Probability density function of the dust density as a function of the Stokes number, the turbulent Mach number and the dust-to-gas ratio.
→ subgrid models and conversion fraction into pebbles
- Modification of the properties of the turbulent cascade in the presence of dust.
→ it could modify the collision rates leading to dust growth (Gong et al., 2021).

Evolution of a size distribution in protostellar collapses



MHD (RAMSES AMR code)
+ Dust (terminal velocity)
+ Multi-species growth
(Smoluchowski equation)
in Lombart, Lebreuilly
and Maury (in revision)
see Maxime Lombart's talk

◀ First simulations with the dust multifluid (40 bins).

Conclusions

- Turbulence in protostellar envelopes is a promising mechanism for dust enrichment of large grains prior to the formation of a disk.

- Understanding the fundamental physics of interacting systems is a necessary first step to design multifluid solvers:
  it questions the architecture/modularity of the code despite a operator splitting strategy (hydro o drag).

Perspectives

- Dust coupling with the magnetic field:
  resistivities, chemical network, Lorentz forces
  to study magnetic braking and magnetic dust enrichment