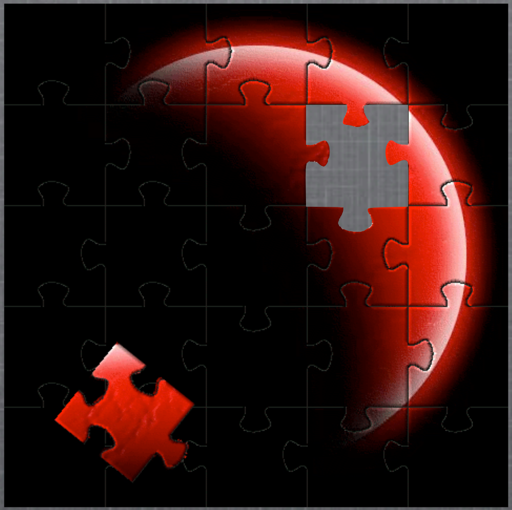
Dust and gas mixtures with one fluid



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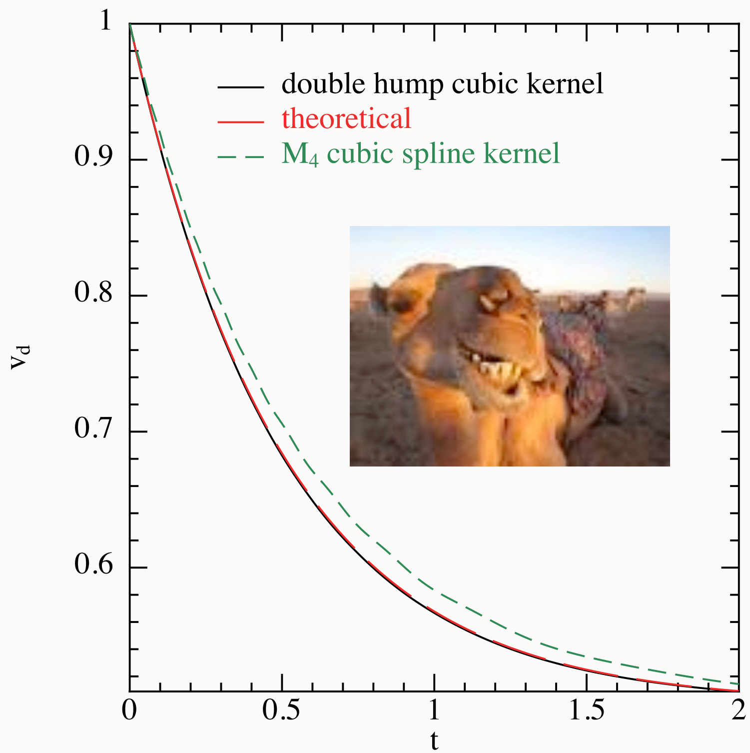
University of St Andrews
MoCA Monash Centre for Astrophysics
European Research Council Established by the European Commission

Once upon a time...

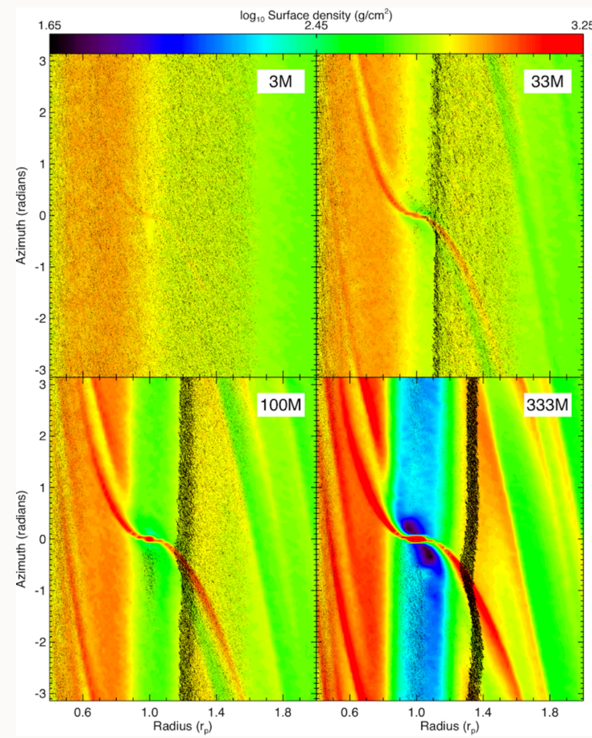
Laibe and Price (2011, 2012 a,b), Ayliffe et al. (2012)

Goals:

- upgrade the old two fluids gas+dust SPH algorithm from Monaghan's (1995)
- implementation in the code PHANTOM



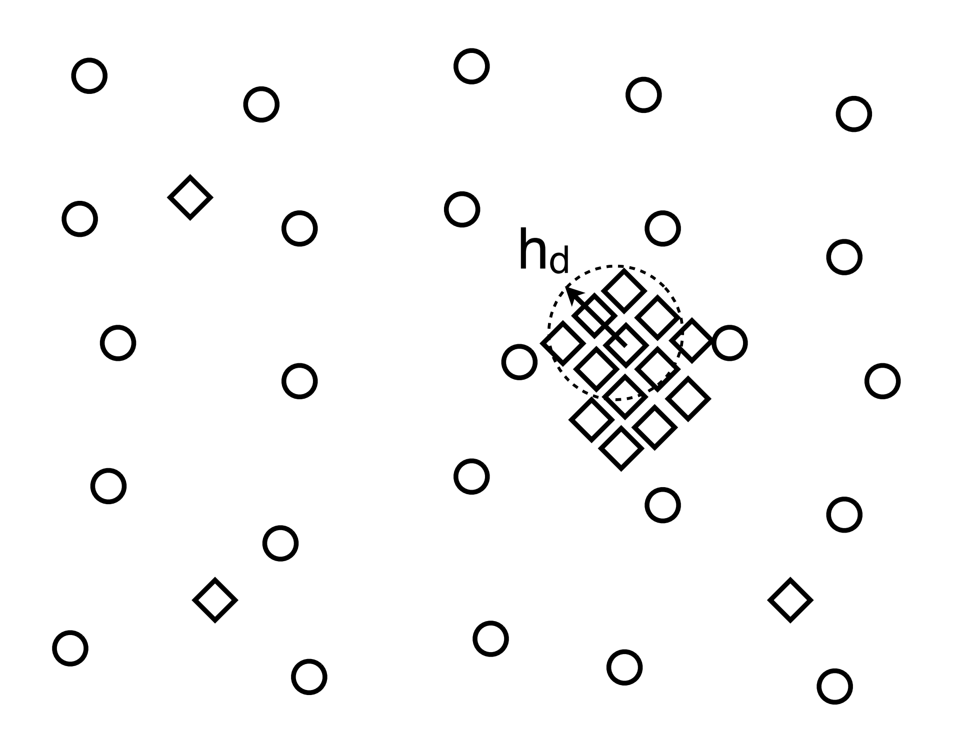
From dust in a 1D box...



..to dust in a 3D disc

Pb 1: beware of artificial clumping !

Planet formation requires dust to concentrate a lot!

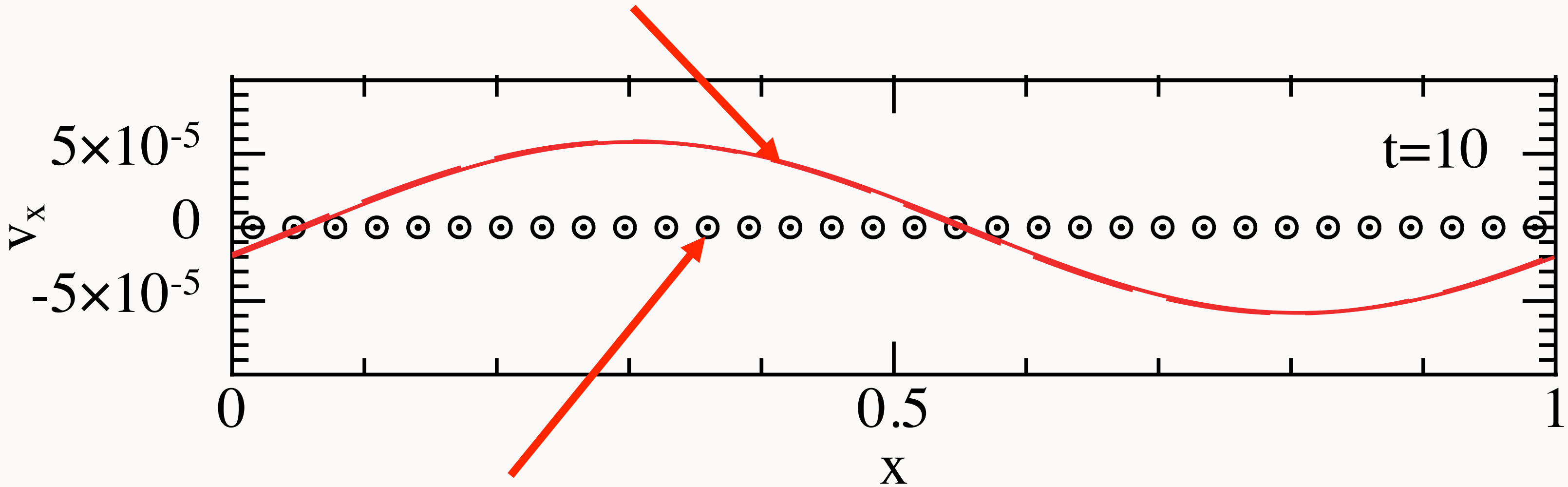


Dust below the gas resolution: artificial aggregates

From Charybe to Scylla...

A sound wave in a mixture with small grains:

Analytics (gas and dust)



Numerics (gas and dust)

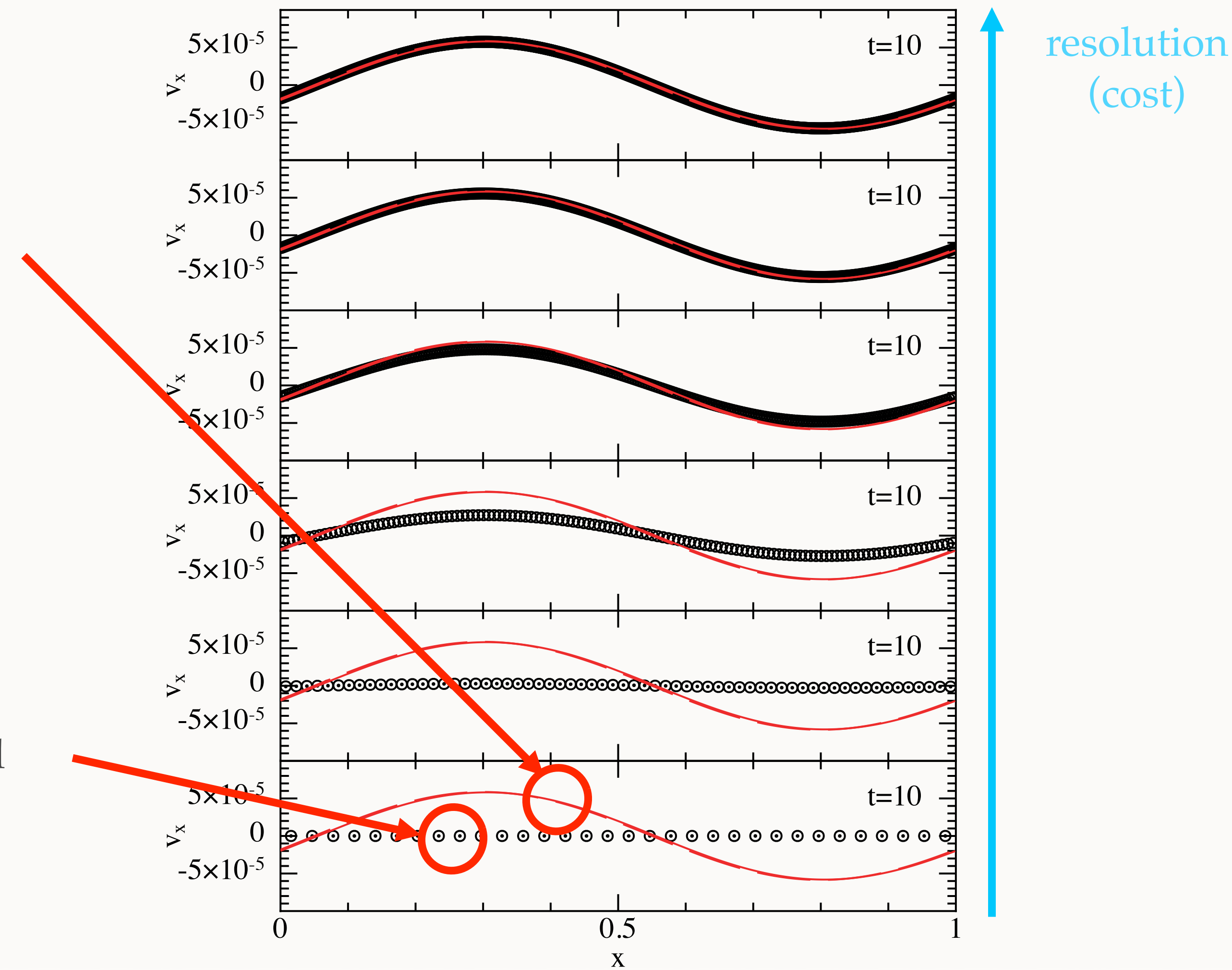
Numerics does not match analytics for small grains !

How to learn physics the hard way

A sound wave in a mixture with small grains:

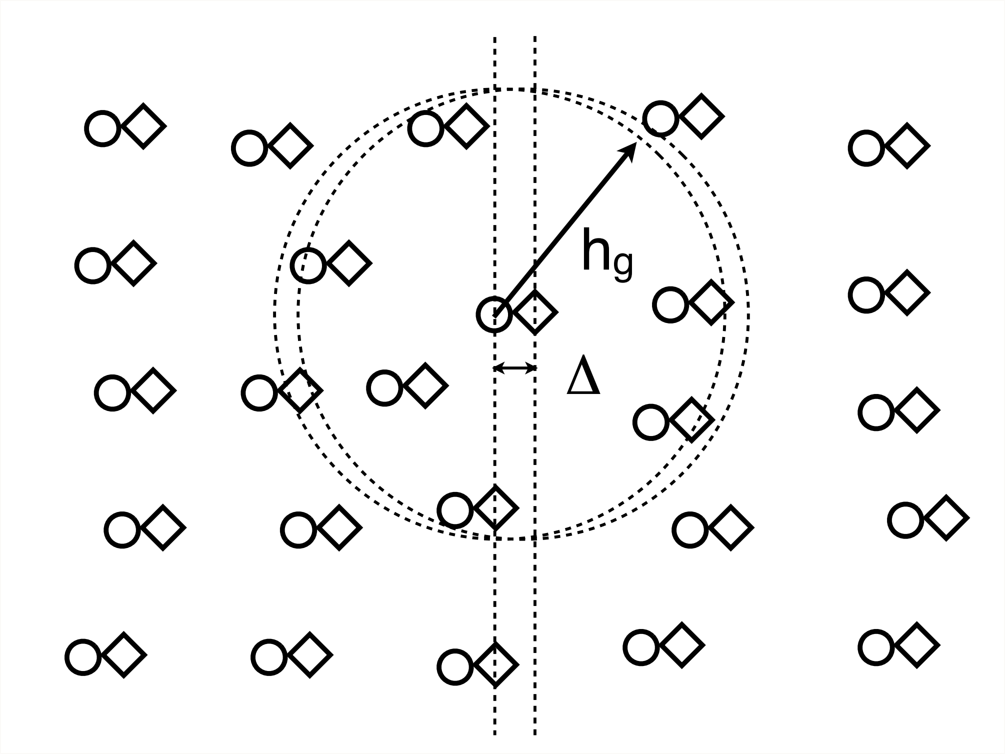
Gas and dust not quite superimposed

Energy hugely over-dissipated



Pb2: spatial resolution criterion for strong drag

The physical spatial dephasing between the phases is not resolved: $h \lesssim c_s t_s$.



Enormous computational cost or massive artificial dissipation of the energy

Deficiency of multifluid algorithms, whatever the numerical method used

The one fluid approach

Dual approach:

Laibe and Price (2014 a,b)

$$\rho \equiv \rho_g + \rho_d \qquad \mathbf{v} \equiv \frac{\rho_g \mathbf{v}_g + \rho_d \mathbf{v}_d}{\rho_g + \rho_d},$$

one fluid...

$$\epsilon = \rho_d / \rho \qquad \Delta\mathbf{v} \equiv \mathbf{v}_d - \mathbf{v}_g$$

...with two phases

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

Total mass conserved

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = -\frac{1}{\rho}\nabla \cdot \left[\epsilon\,(1-\epsilon)\,\rho\Delta\mathbf{v}\right],$$

Composition evolution

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\nabla P_g}{\rho} - \frac{1}{\rho}\nabla \cdot \left[\epsilon\,(1-\epsilon)\,\rho\Delta\mathbf{v}\Delta\mathbf{v}\right] + \mathbf{f},$$

Additional anisotropic pressure

$$\frac{\mathrm{d}\Delta\mathbf{v}}{\mathrm{d}t} = -\frac{\Delta\mathbf{v}}{t_s} + \frac{\nabla P_g}{(1-\epsilon)\,\rho} - (\Delta\mathbf{v}\cdot\nabla)\mathbf{v} + \frac{1}{2}\nabla\left[(2\epsilon - 1)\,\Delta\mathbf{v}^2\right],$$

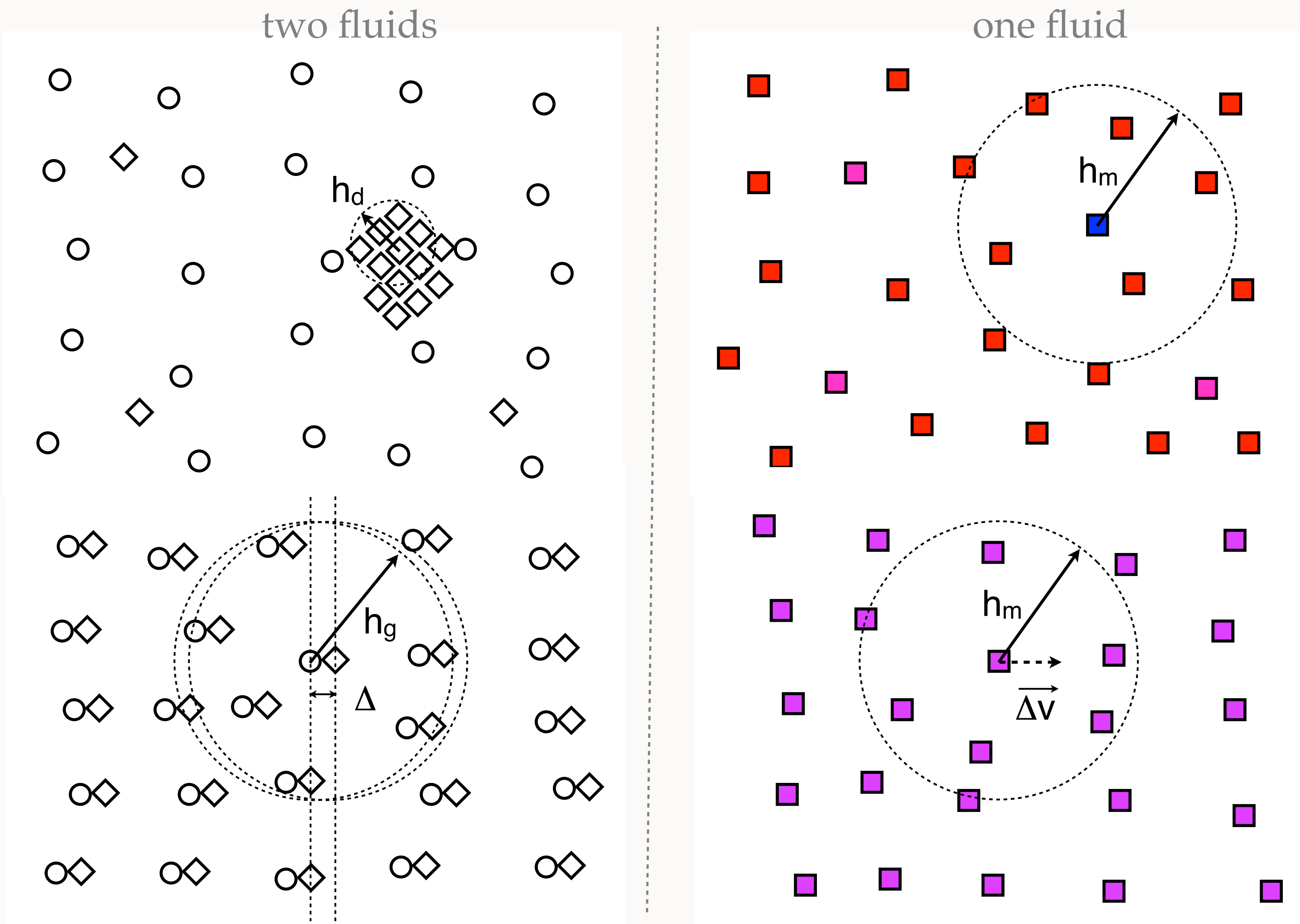
Trivial dissipation term

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P_g}{(1-\epsilon)\,\rho}\nabla\cdot(\mathbf{v} - \epsilon\Delta\mathbf{v}) + \epsilon\,(\Delta\mathbf{v}\cdot\nabla)\,u + \epsilon\frac{\Delta\mathbf{v}^2}{t_s},$$

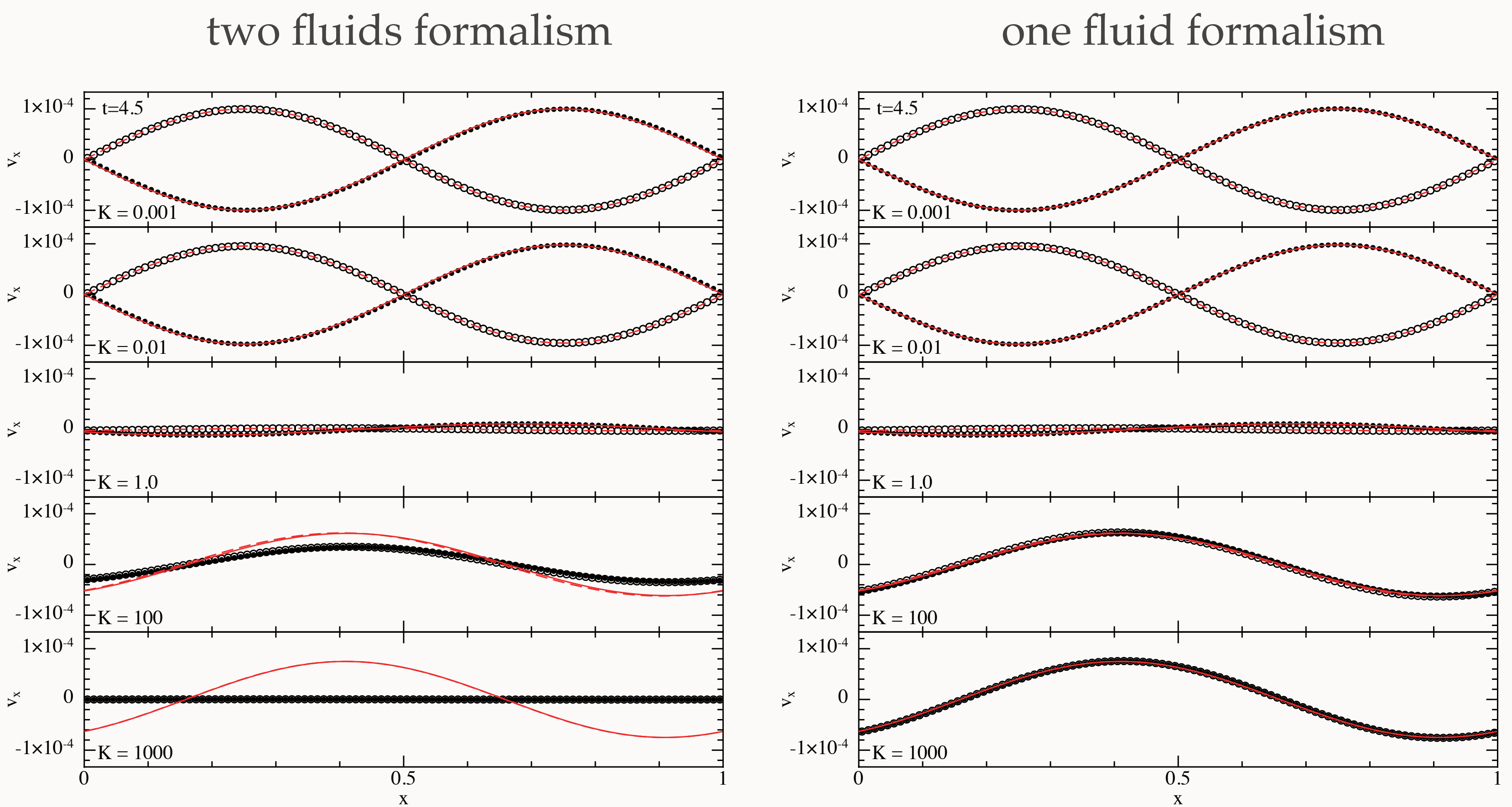
Energy conserved

$$\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\partial}{\partial t} + \mathbf{v}.\nabla$$

Better for planet formation



Sound wave



For a 3D simulation of sub-micronic grains at 1AU:

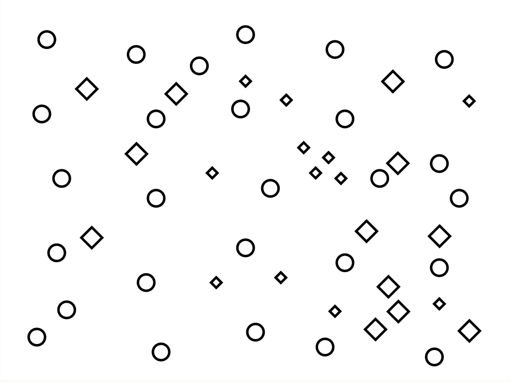
computational time reduced by a factor of... ten billions!

see also Loren-Aguilar and Bate (2014)

New (1): generalisation with any number of dust phases

Laibe and Price (2014 c)

One fluid with one gas phase + N dust phases.



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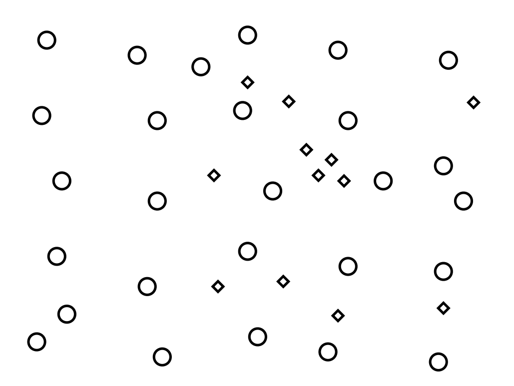

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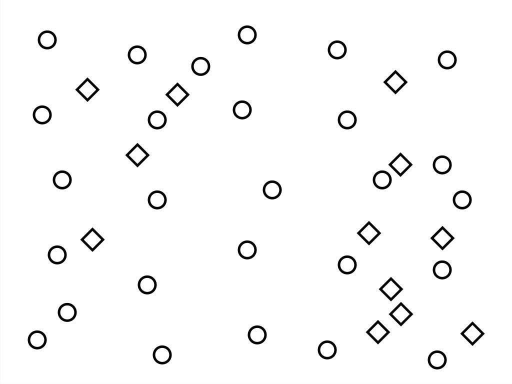
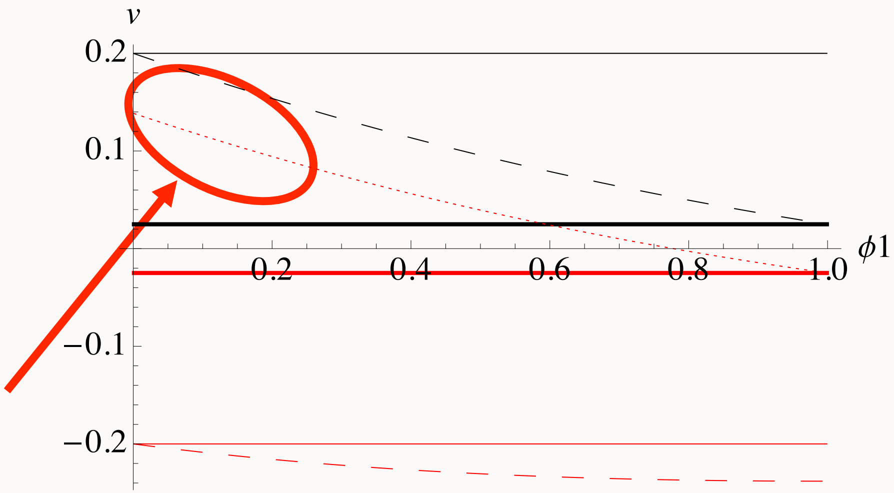
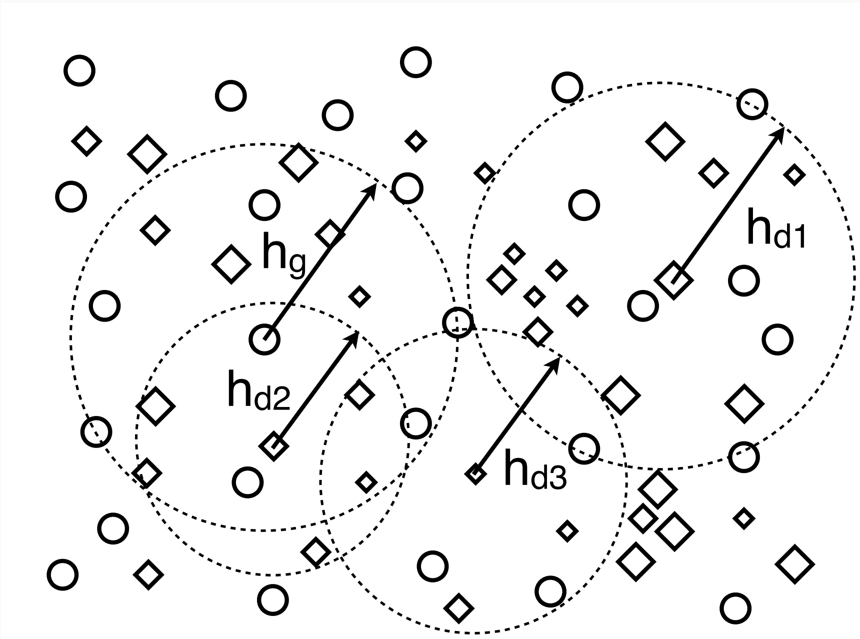


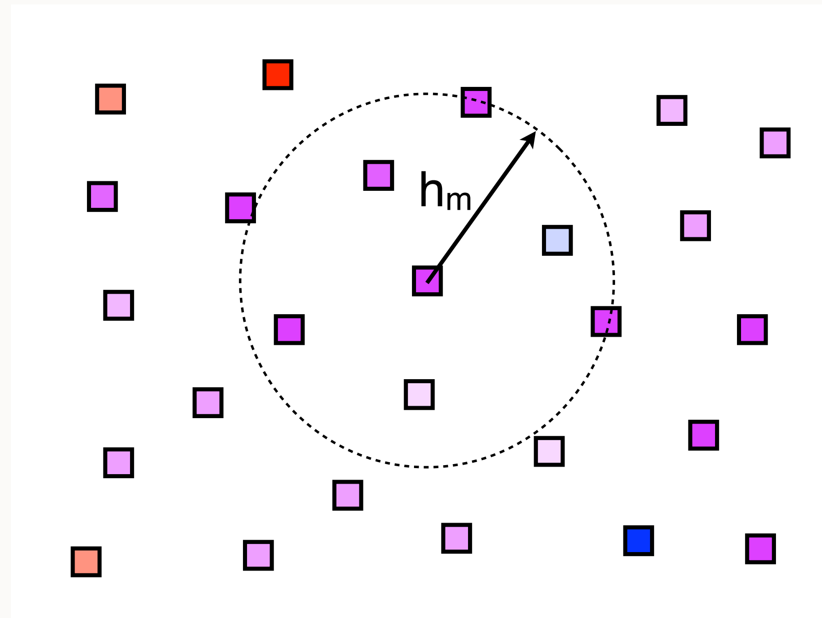
All the dust phases have to be treated simultaneously

Radial-drift with N dust species:
outward migration of large dust grains.



Interest for astrophysical simulations !





1- Ability to treat multiple grains sizes locally

2- Easy to compute the local dust distribution (opacities...)

3- SPH formalism seem to work... to be continued (and growth added)!

New (2): one-fluid as diffusion

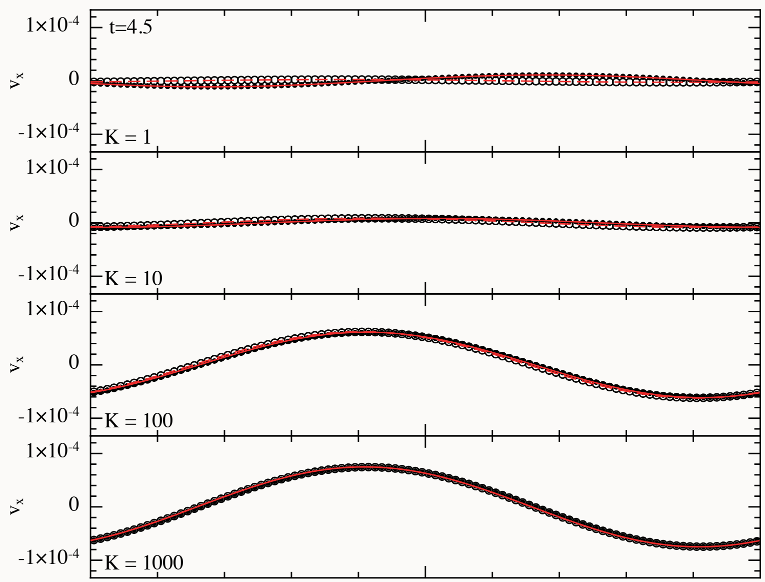
Small grains: the one-fluid terms are replaced by a diffusion-like term

$$\Delta t < t_{\rm s},$$

hard constrain

$$\Delta t < C \left(\frac{\Delta t_{\rm Cour}}{t_{\rm s}} \right)^2 t_{\rm s},$$

soft constrain



Easy and cheap one-fluid formalism

Laibe and Price (in prep.)

With two fluids:

- artificial aggregates when dust concentrates
- huge numerical cost vs energy dissipation for small grains
- issues with grain growth/fragmentation

With one fluid:

- no artefact when dust concentrates
- treats easily small grains
- grains distribution localised for grain growth/fragmentation