GROWTH OF POROUS AGGREGATES IN PROTOPLANETARY DISCS USING SPH SIMULATIONS

Phantom users workshop
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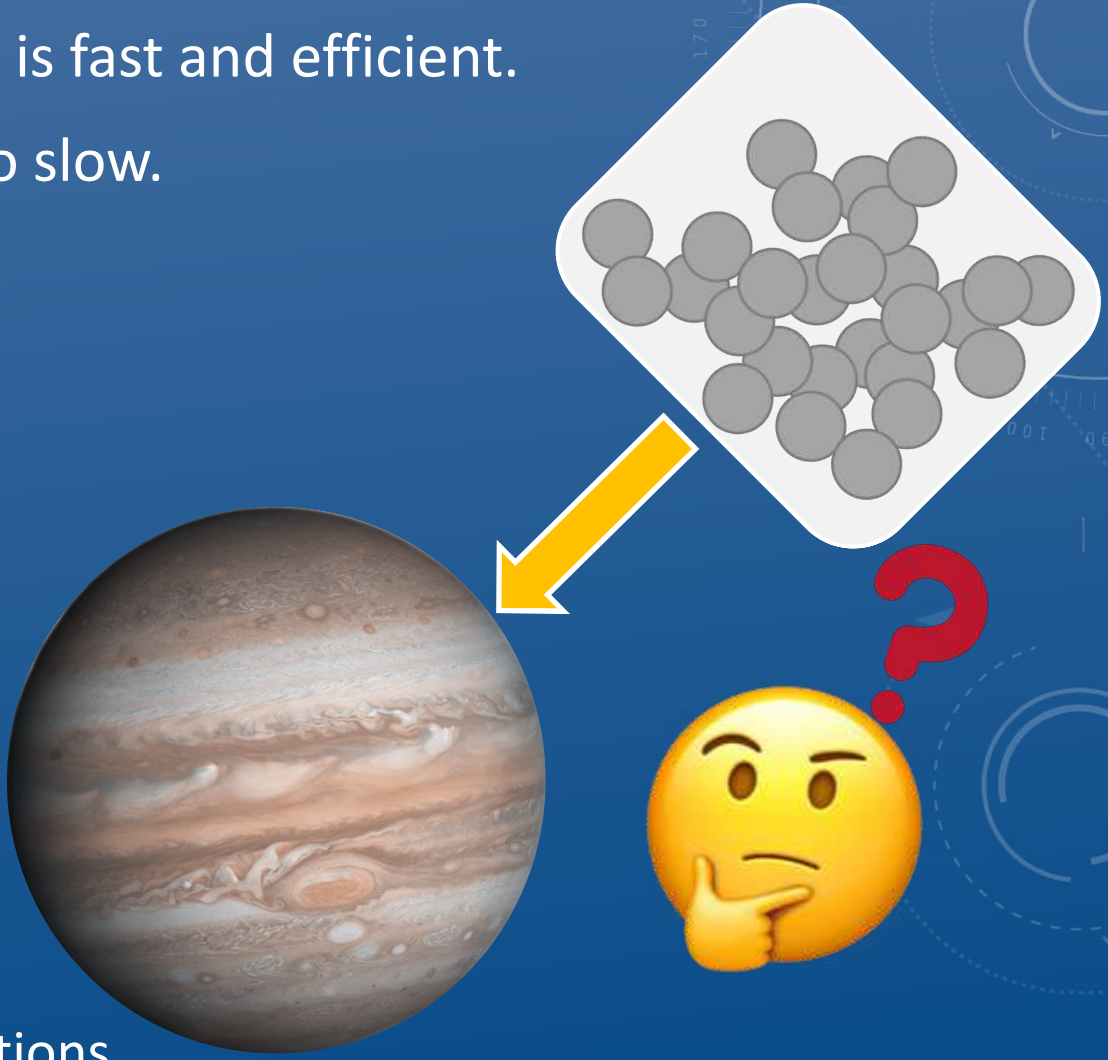
MOTIVATIONS

- According to observations, planet formation is fast and efficient.
- Theoretical formation of planetesimals is too slow.
- Several problems prevent dust growth.

- Multiple solutions have been proposed:
  - Dust traps, vortices, instabilities, etc.
  - Dust porosity.

- Why porosity is important ?
  - Comets and asteroids are porous.
  - Grain growth is faster with porous grains.
  - May explain planetesimal formation/observations



INTRODUCTION TO POROSITY

- Mass is computed using the formula:

$$m = {}^{4\pi}/_{3}\, s^3 \rho_\mathrm{s} \Phi$$

- Φ is the filling factor:

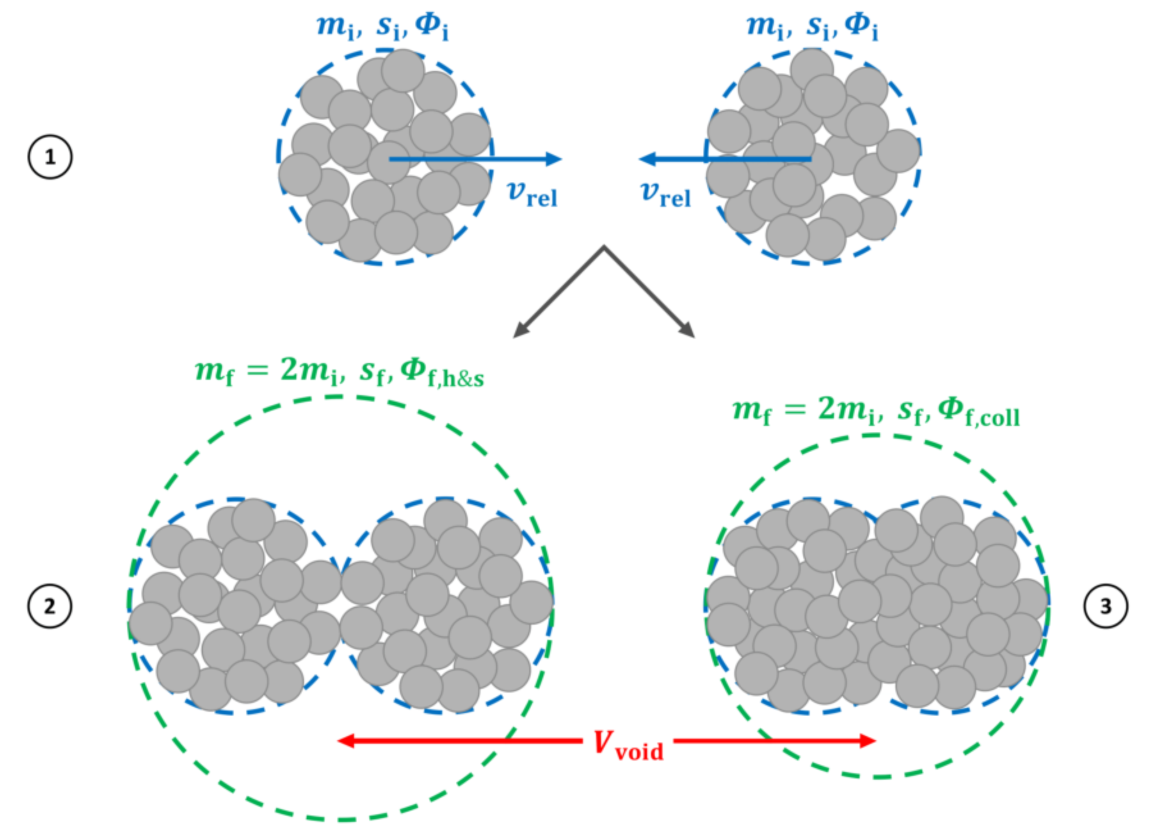
$$\Phi = {}^{V_\mathrm{mat}}/_{V_\mathrm{tot}}$$

- Growth rate (mono-disperse approx.):

$$\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_\mathrm{g} = 4\pi\rho_\mathrm{d} s^2 v_\mathrm{rel}$$

Mass is the natural variable to treat dust growth.

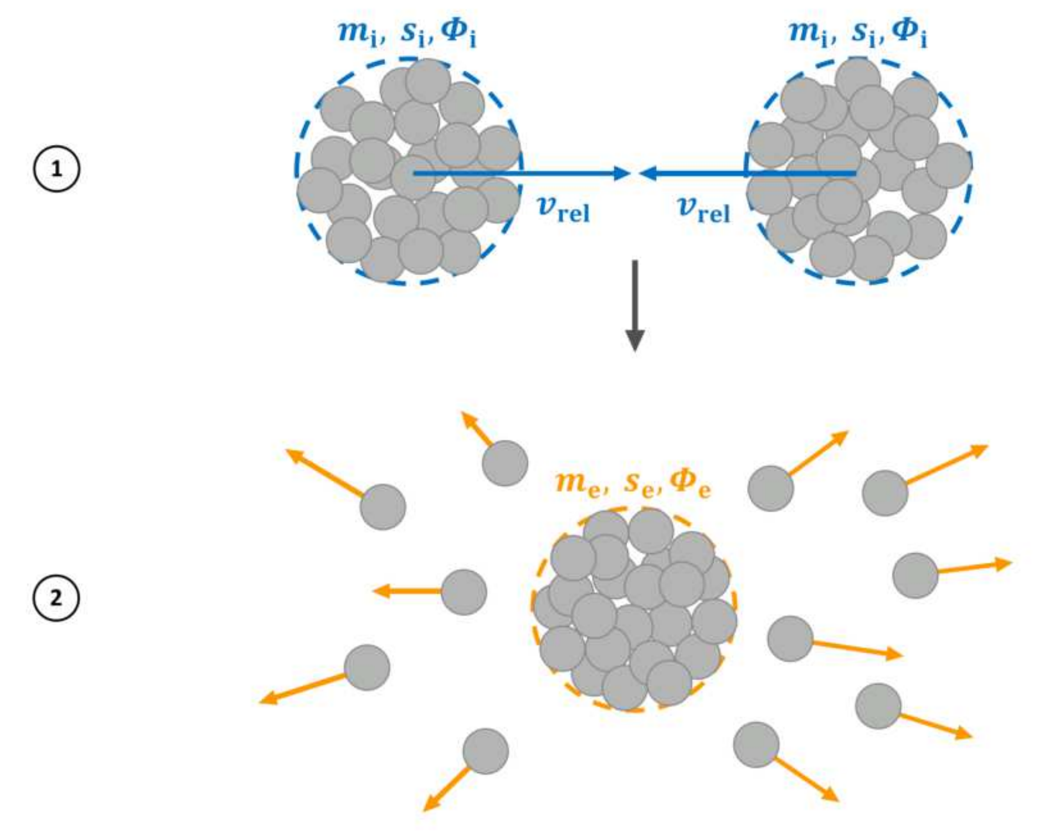
Stepinski & Valageas (1996,1997)



(1): 2 grains of mass m_i collide with a relative velocity v_rel.
(2): In the " hit & stick ", grains simply stick together.
(3): Higher v_rel collision leads to internal restructuring.

Credits: Michoulier

INTRODUCTION TO POROSITY: FRAGMENTATION



(1): 2 grains of mass m_i collide with a high relative velocity v_rel
(2): If fragmentation occurs, the new grain is called the remnant.

If $v_\mathrm{rel} < v_\mathrm{frag}$ → growth

If $v_\mathrm{rel} \geq v_\mathrm{frag}$ → fragmentation

``Smooth fragmentation model''

$$\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_\mathrm{f} = -\frac{v_\mathrm{rel}^2}{v_\mathrm{rel}^2 + v_\mathrm{frag}^2}\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_\mathrm{g}$$

Kobayashi & Tanaka (2010), Garcia (2018)

Credits: Michoulier

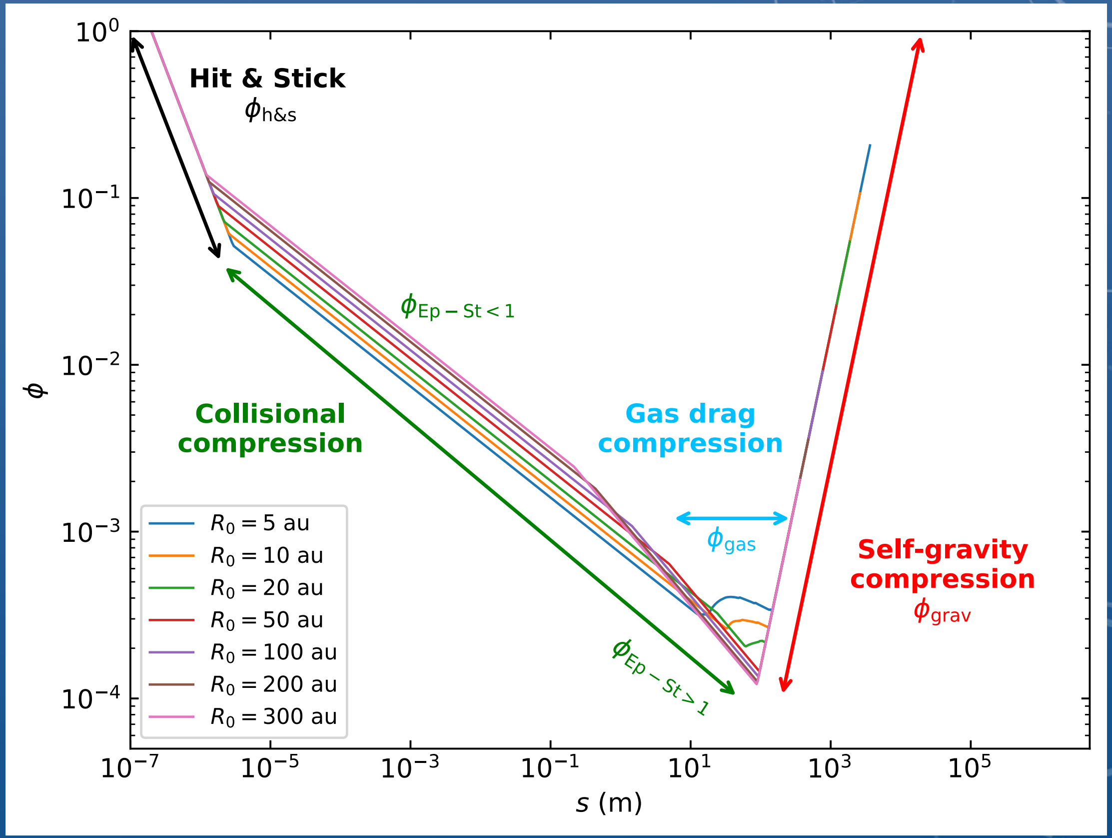
POROSITY EVOLUTION MODEL

The porosity evolution model handles many physical processes:

- Growth
- Bounce
- Fragmentation (+ compaction)
- Disruption

As few as possible new parameters (heavy work on modelling bounce and compaction):

- Monomer size
- Young modulus
- Surface energy
- Force-to-torque efficiency



Expansion/compression regimes during grain growth.

https://github.com/StephaneMichoulier/Pamdeas.git

* Porous Aggregate Model and Dust Evolution in protoplAnetary discS

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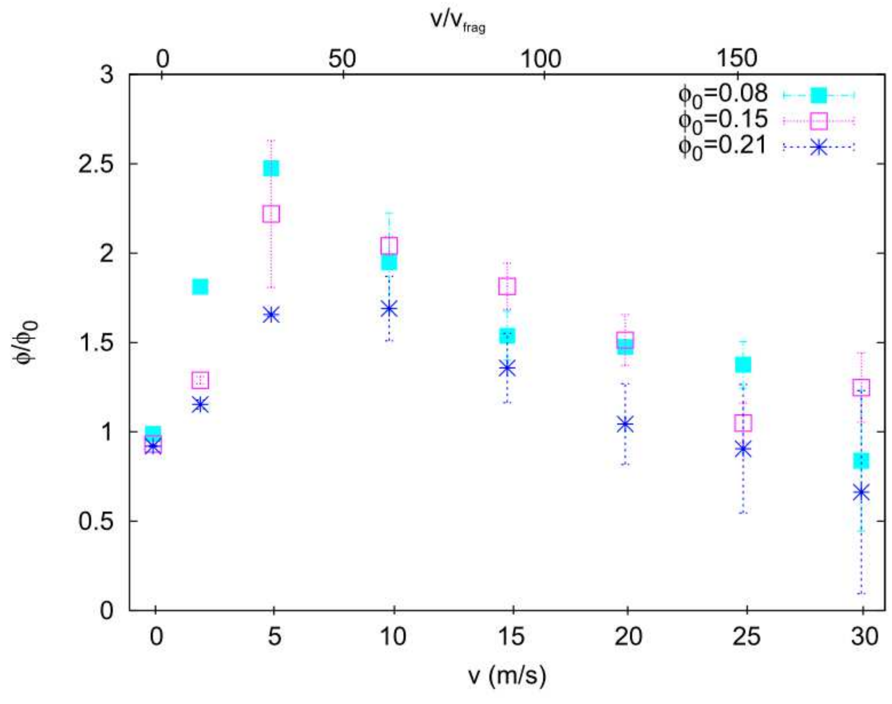
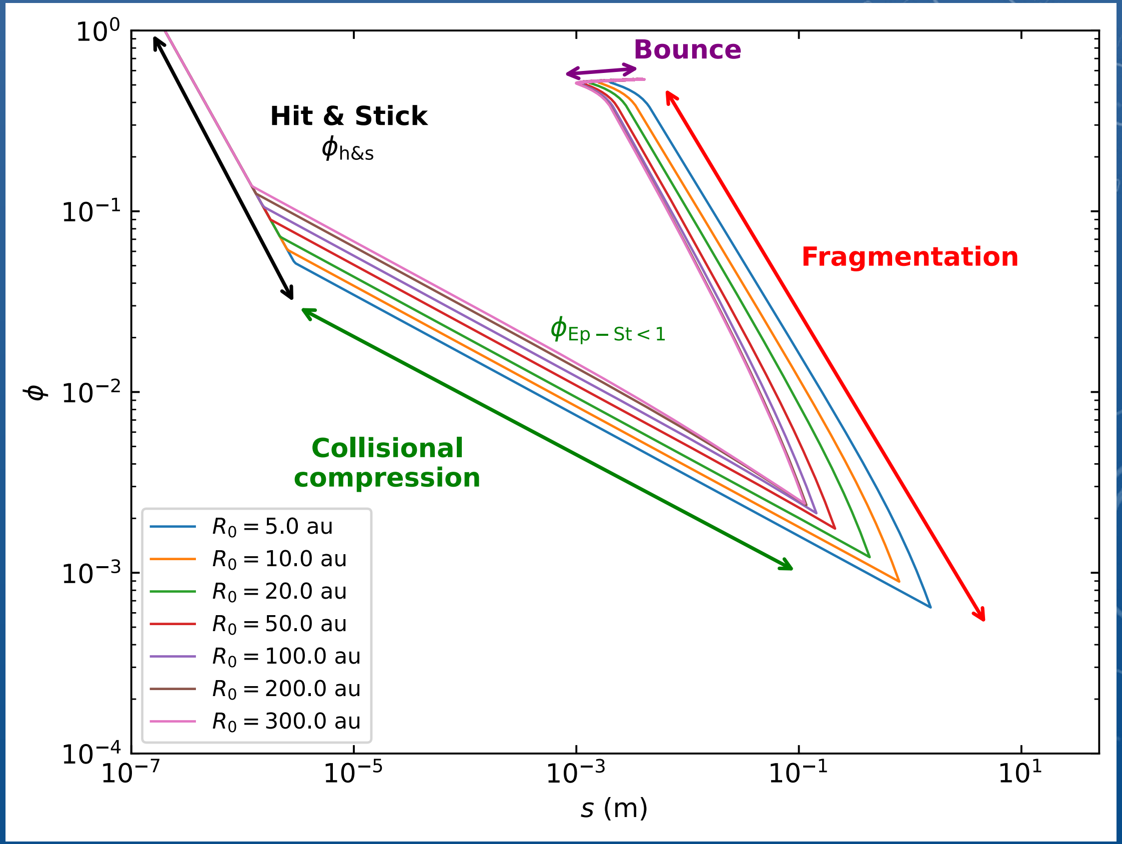
COMPACTION OF AGGREGATES

Fragmentation can compacted grains very efficiently.

→ Can reconcile ϕ deduced by observations from polarization (Kataoka et al. 2016; Tazaki et al. 2019, 2022), comets (Güttler et al. 2019) and theory.



Ringl & Brinda (2012)



Credits: Michoulier

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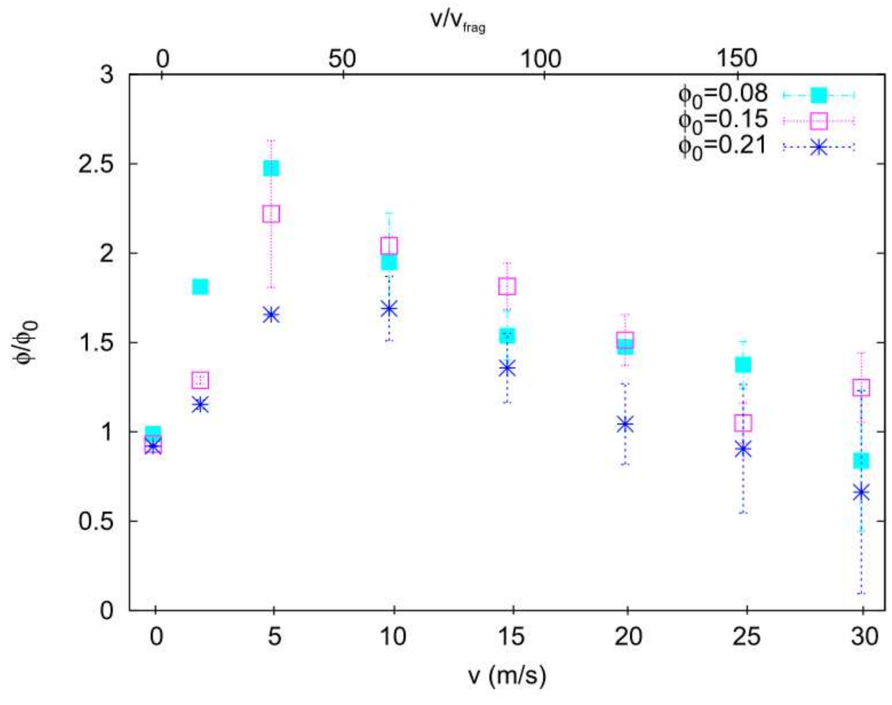

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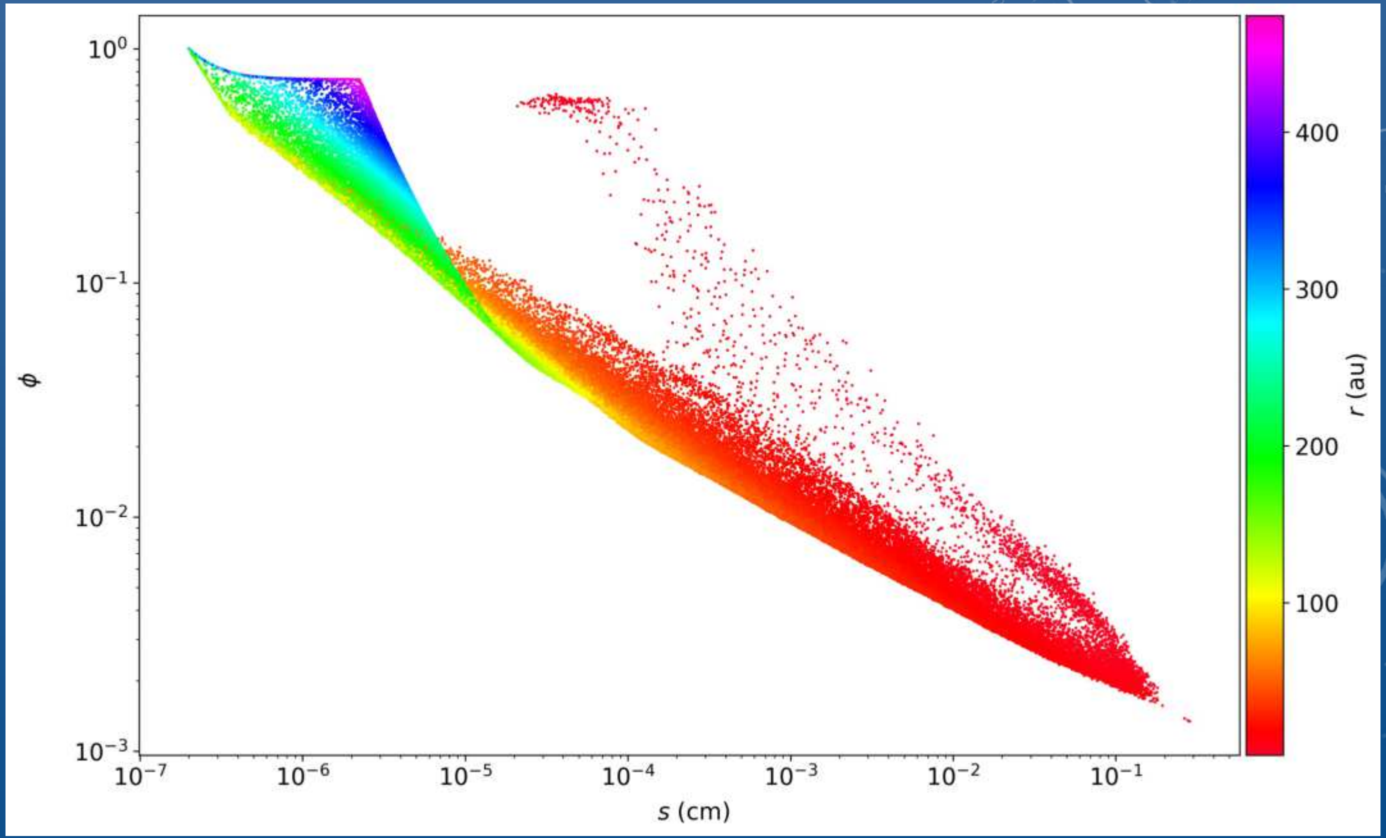

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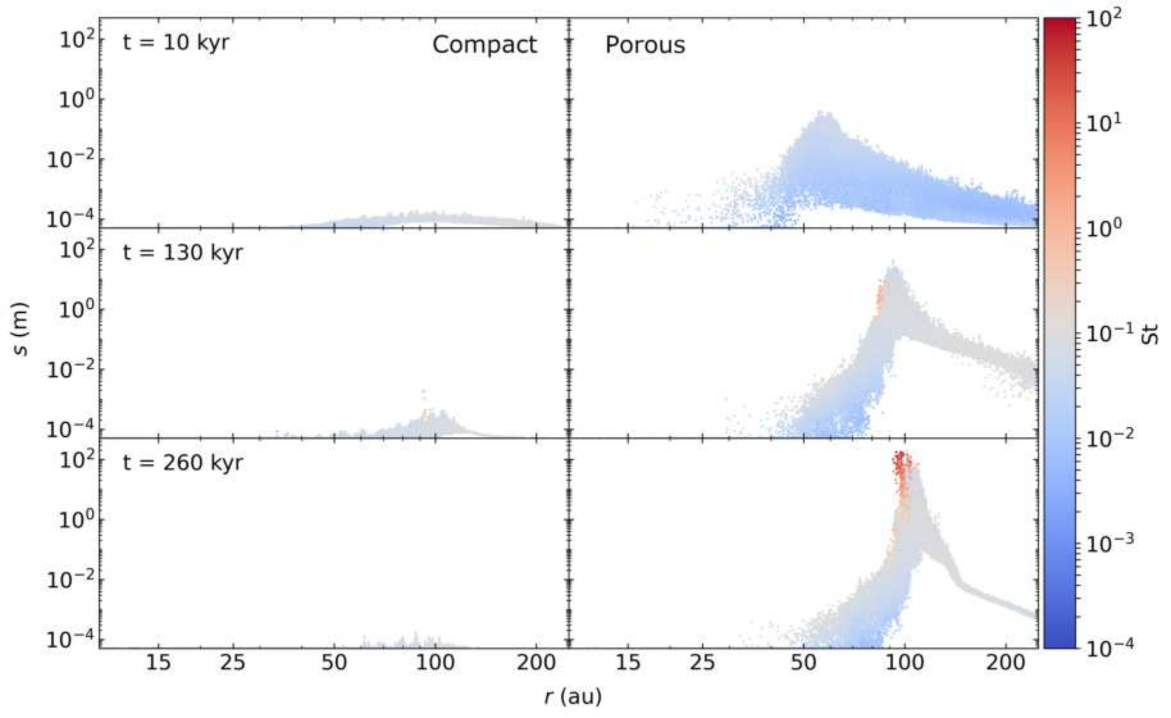
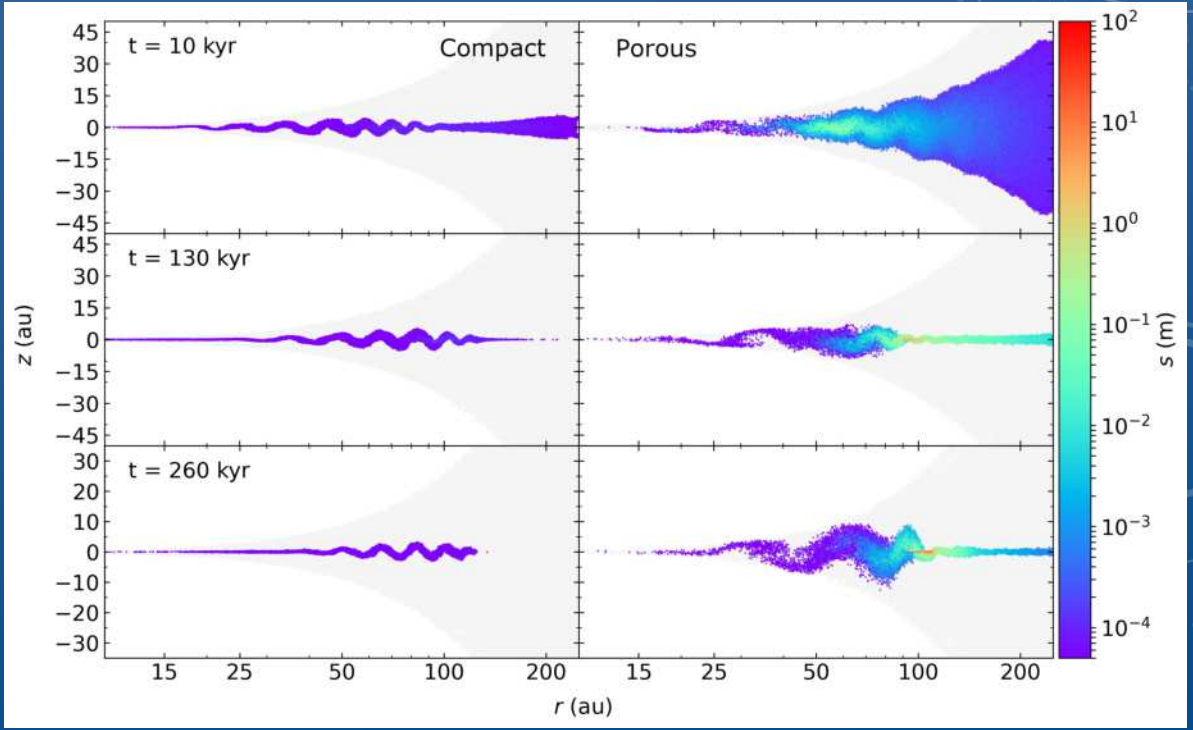
SOME OLD RESULTS… WITH PROBLEMS



- The disc of compact grains is much thinner and settled.
- The most porous aggregates, and thus the larger ones, are close to the midplane.
- The disc of porous dust is not settled in the inner region (baroclinic instability?) due to turbulence and fragmentation, which maintain dust size so that $\mathrm{St} \sim 1$.



- Porous grains are more coupled at the beginning, but totally decouple from the gas near 100 au.
- Aggregates are able to quickly form cm-sized object, and some can grow as large as 100 m.
- A self induced dust trap (Gonzalez et al. 2015) is formed at 100 au, holding the dust in the disc.

1) DEALING WITH SMALL STOPPING TIMES (FRAGMENTATION)

- Current problem when simulating dust growth:
  - Small grains for initial condition: $s \sim 10 - 50\ \mu\mathrm{m}$.
  - Dust porosity lower St by 1-2 order of mag.
  - Dust growth with porosity is very fast (2 fluid needed).
  - Current method impose a minimum grain size.
- We need a method relying on both size and filling factor:
  - New method for porosity impose a minimum St.

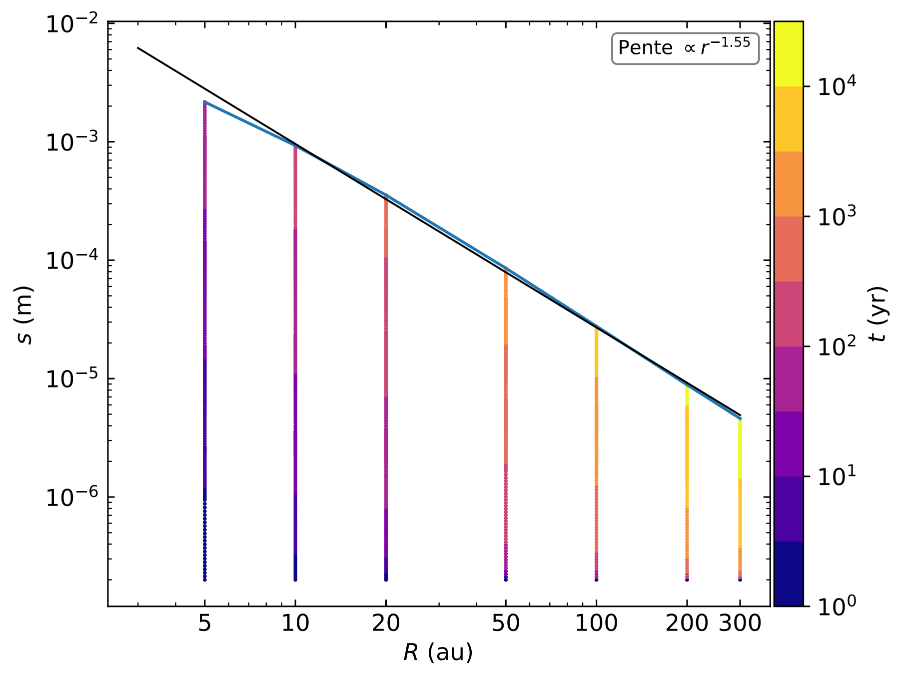
Epstein drag regime

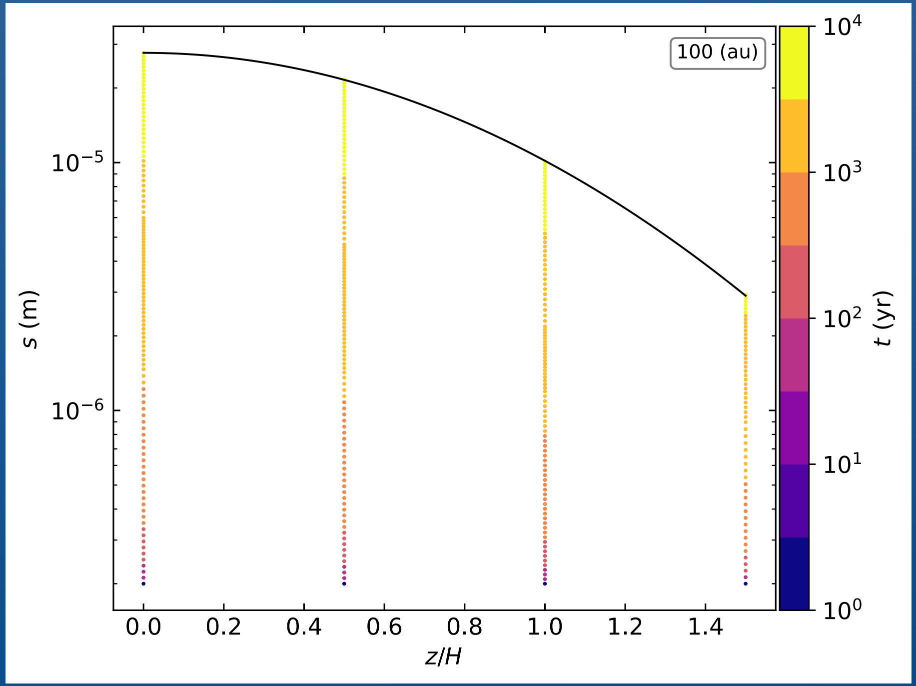
$$\mathrm{St}_{\mathrm{Ep}} = \frac{\rho_s \phi s}{\rho c_g}$$

2) INITIAL CONDITIONS FOR SIMULATIONS

- Current method: all grains start with the same size!
  - Lebreuilly et al. (2020), Bate (2022) shows grain growth during cloud collapse.
  - Porosity depends on location in the disc -> identical grains in the midplane and on the surface not realistic.

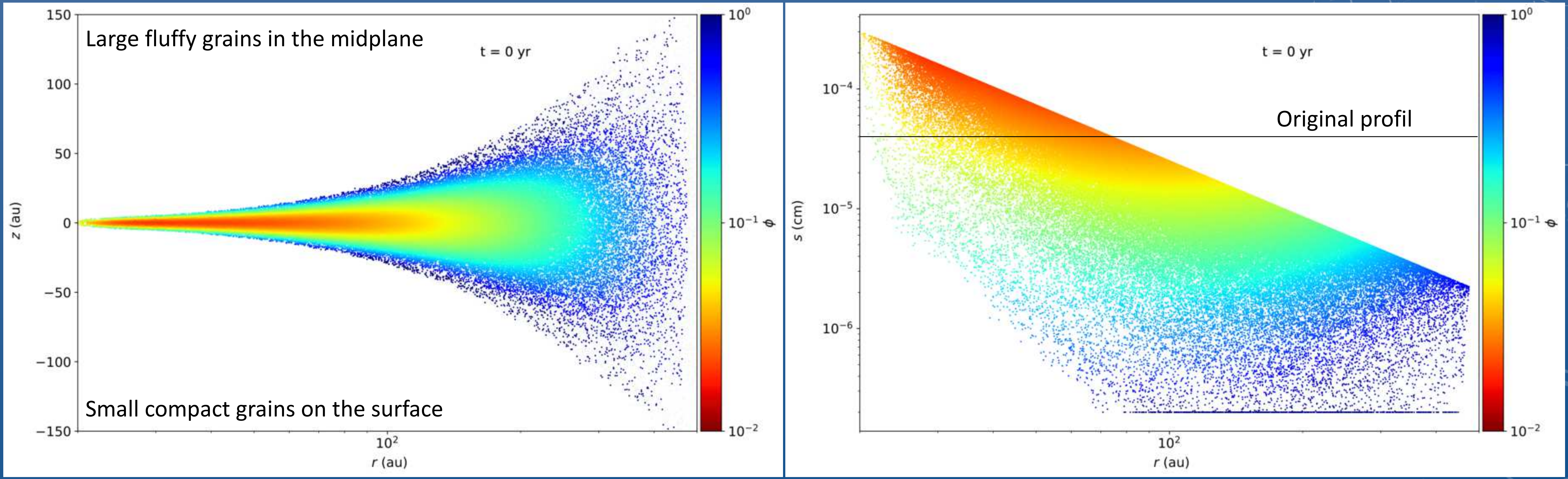
- At early stage, grain size can be approximate by a power law ∝ radius for a given St.
- Grain growth scales with scale height.





Credits: Michoulier

2) INITIAL CONDITIONS FOR SIMULATIONS



Large fluffy grains in the midplane

Small compact grains on the surface

Original profil

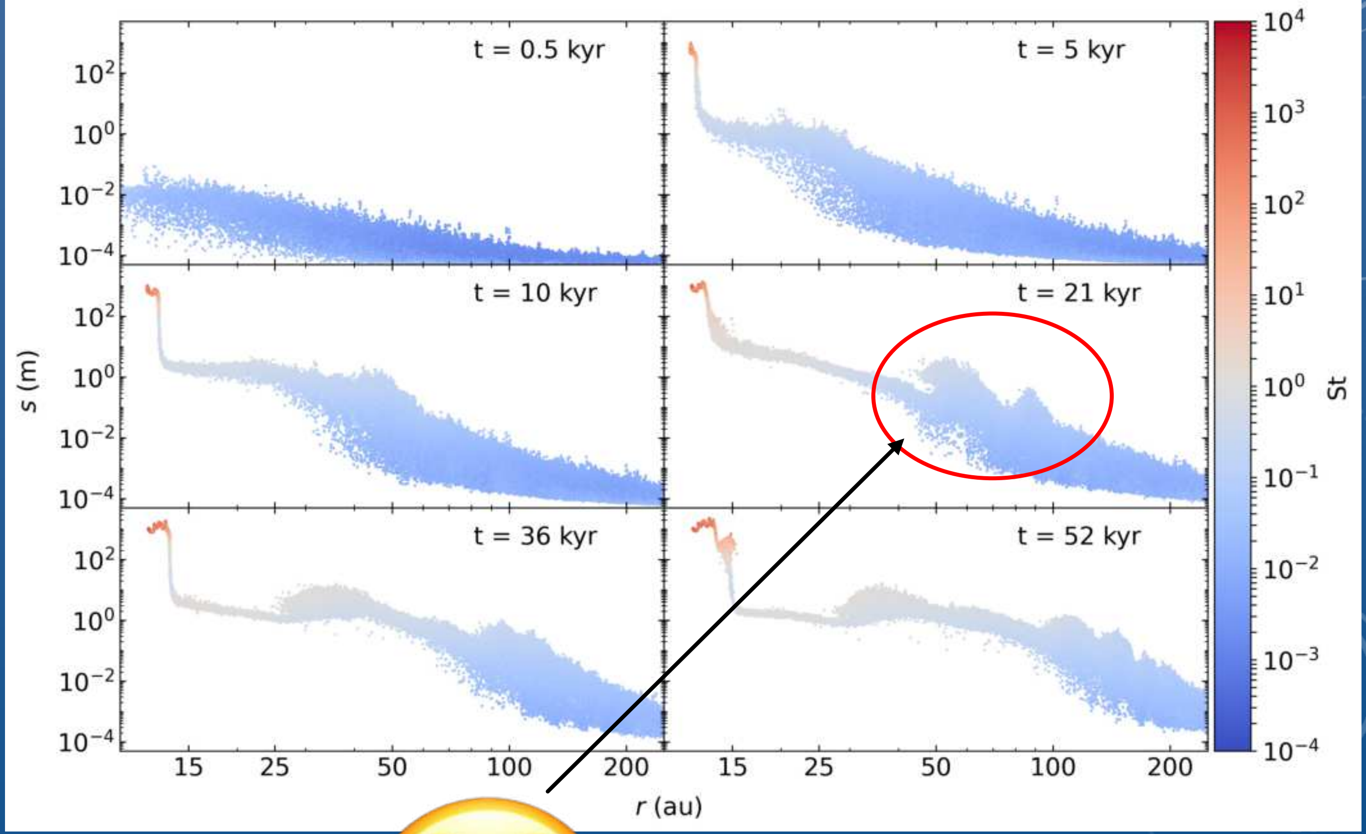
Credits: Michoulier

3) SIMULATIONS WITHOUT ARTEFACTS

- Disc relaxation cause problems with grain growth and porosity (anomalous growth).

- Current method in phantom:
  - Start with gas and dust (2 fluids), and set the outer dust radius to 5/6 of the gas one.

Véricel et al. (2021)

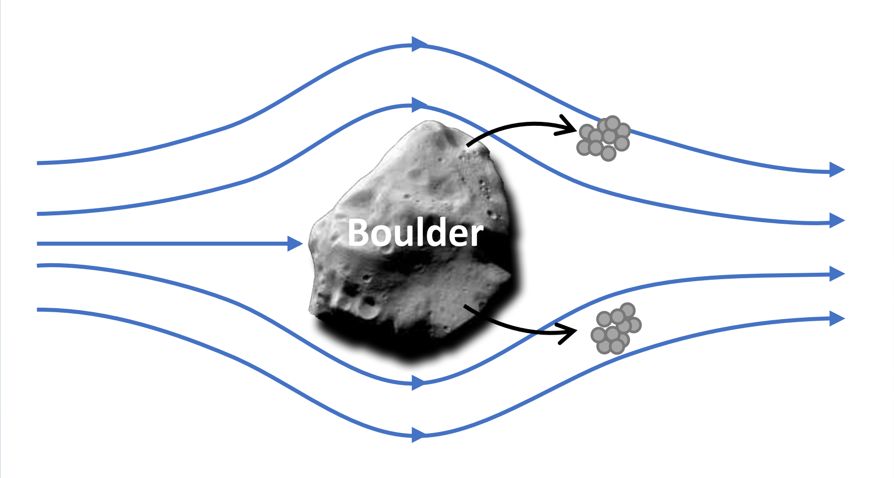


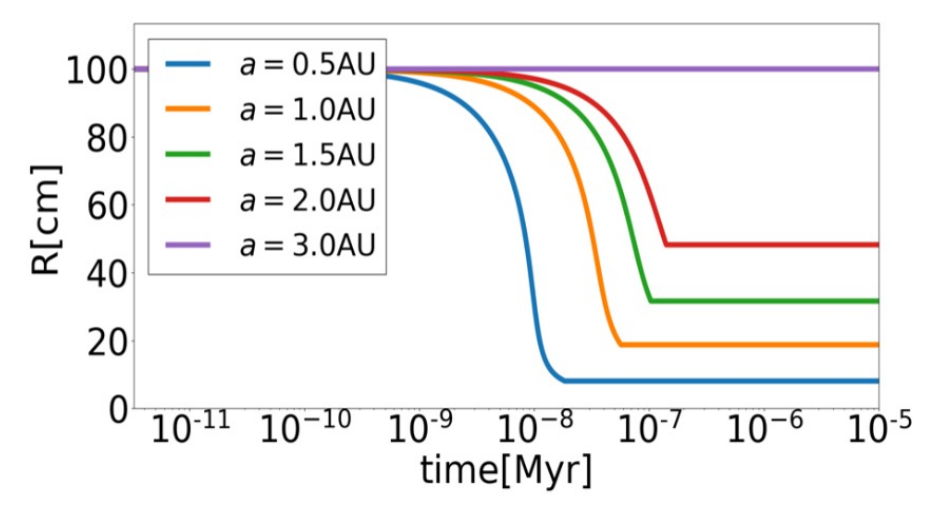
- New (old fashion) method:
  - First run disc without dust to remove relaxation artefacts.
  - add dust in 2 fluids with a growth profile.

Credits: Michoulier

EROSION

- Add another new physical effect to dust growth: aeolian-erosion.
- Erosion modelled as a mass lose rate:
  - $$\left(\frac{\mathrm{dm}}{\mathrm{dt}}\right)_{\mathrm{ero}} = -\rho_{\mathrm{g}}\, \Delta v^3 \,\frac{m_{\mathrm{d}}}{\beta d}\, s$$
- Easy to add in Phantom.





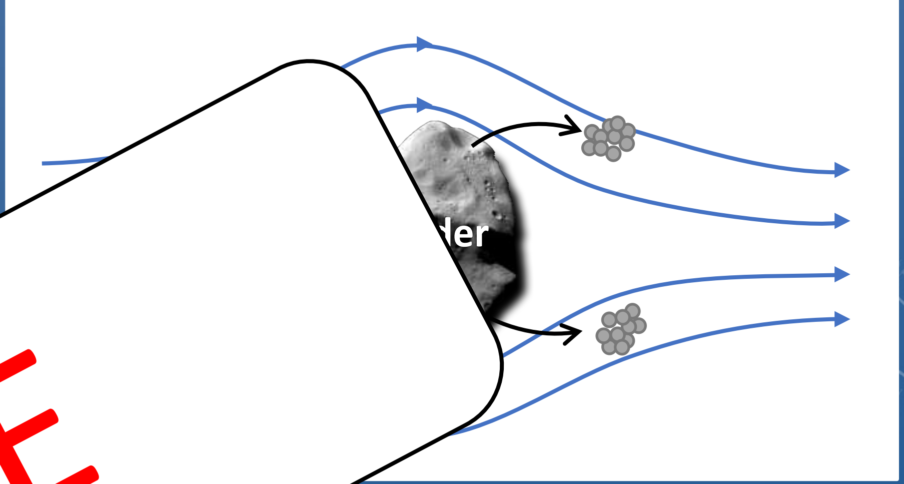
Dependence of the evolution at different distances from the star for objects with a fixed initial radius of 102 cm.

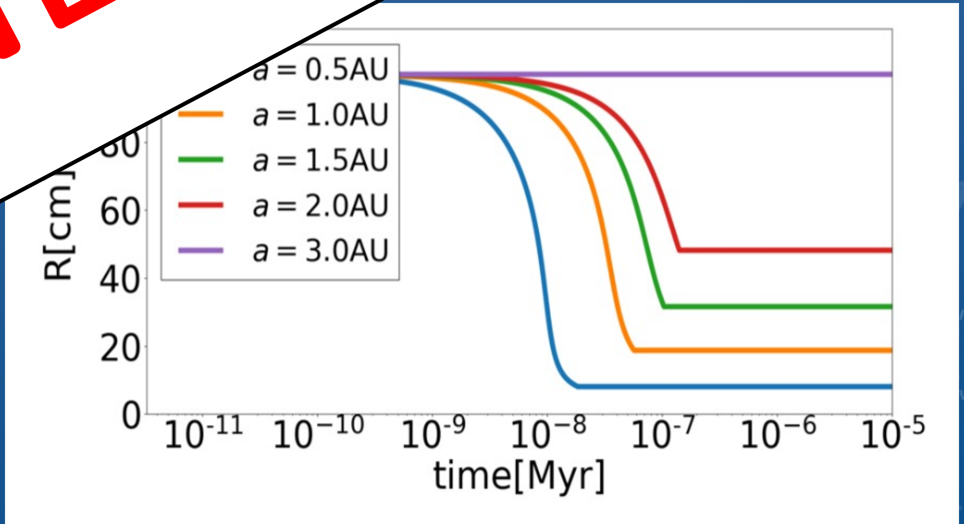
Rozner et al. (2020)

EROSION

- Add another new physical effect to dust growth: aeolian-erosion.
- Erosion modelled as a mass
  - $\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_{\mathrm{ero}} =$
- Easy to add in

DONE



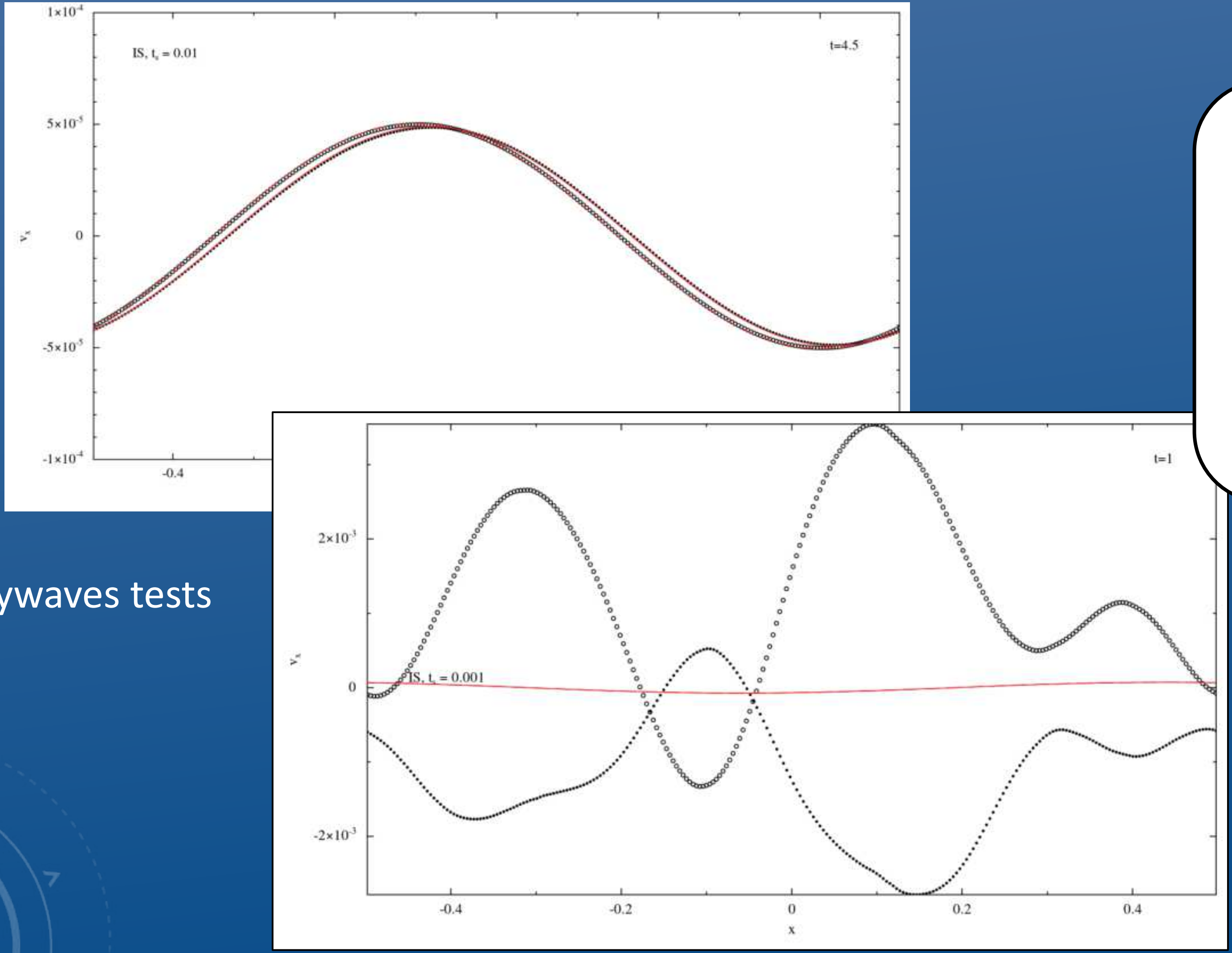


Dependence of the evolution at different distances from the star for objects with a fixed initial radius of 102 cm.

Rozner et al. (2020)

A SOLUTION TO EVERYTHING (4~~2~~)

→ FULLY IMPLICIT DRAG SCHEME!



Dustywaves tests

$$\mathrm{v}_\mathrm{a}^1 = \mathrm{v}_\mathrm{a}^0 - \frac{m_\mathrm{j}\left(\mathrm{v}_\mathrm{aj}.\,\mathrm{r}_\mathrm{aj}^*\right)r_\mathrm{aj}^*}{\left(m_\mathrm{j}+m_\mathrm{a}\right)\left(r_\mathrm{aj}^*\right)^2}\left(1-e^{-\frac{1}{2}\omega\delta t}\right)$$

$$\mathrm{v}_\mathrm{j}^1 = \mathrm{v}_\mathrm{j}^0 - \frac{m_\mathrm{a}\left(\mathrm{v}_\mathrm{aj}.\,\mathrm{r}_\mathrm{aj}^*\right)r_\mathrm{ja}^*}{\left(m_\mathrm{j}+m_\mathrm{a}\right)\left(r_\mathrm{aj}^*\right)^2}\left(1-e^{-\frac{1}{2}\omega\delta t}\right)$$

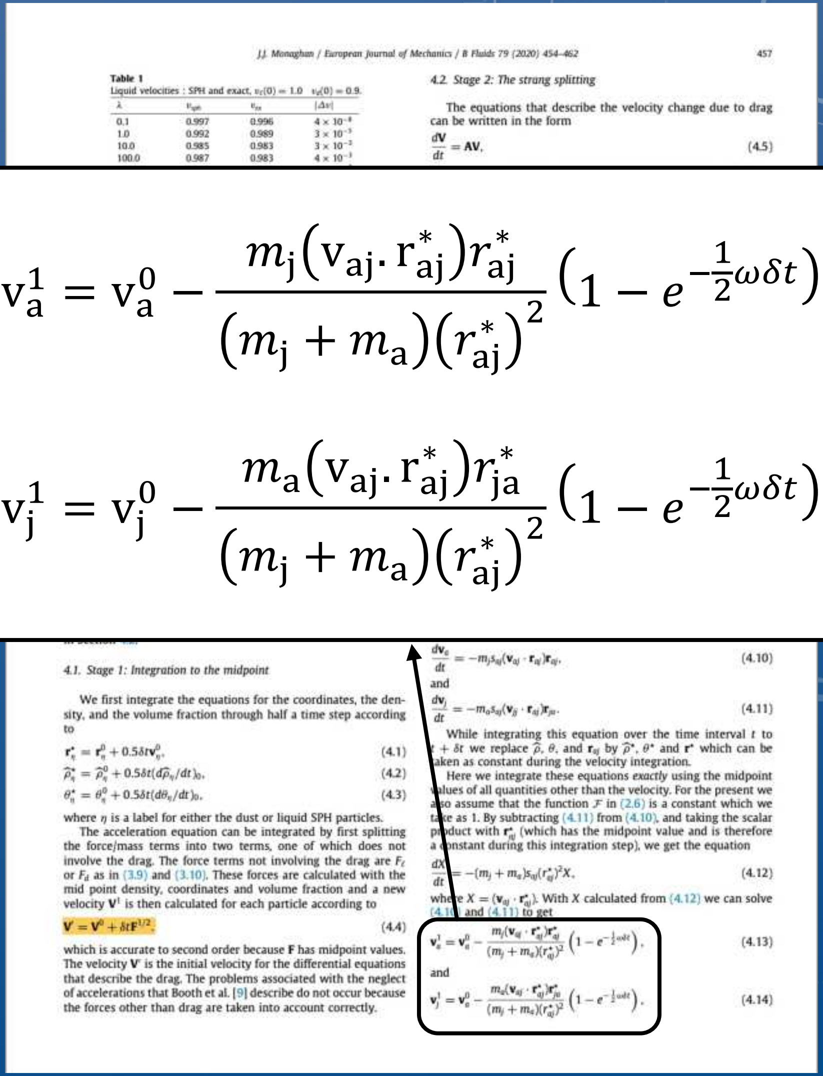


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Table 1
Liquid velocities : SPH and exact, $v_\ell(0) = 1.0$ $v_d(0) = 0.9$.

λ	v_{sph}	v_{ex}	$\lvert\Delta v\rvert$
0.1	0.997	0.996	4×10^{-4}
1.0	0.992	0.989	3×10^{-3}
10.0	0.985	0.983	3×10^{-3}
100.0	0.987	0.983	4×10^{-3}

4.2. Stage 2: The strong splitting

The equations that describe the velocity change due to drag can be written in the form

$$\frac{d\mathbf{V}}{dt} = \mathbf{AV}, \qquad (4.5)$$

4.1. Stage 1: Integration to the midpoint

We first integrate the equations for the coordinates, the density, and the volume fraction through half a time step according to

$$\mathbf{r}_\eta^* = \mathbf{r}_\eta^0 + 0.5\delta t\mathbf{v}_\eta^0, \qquad (4.1)$$

$$\widehat{\rho}_\eta^* = \widehat{\rho}_\eta^0 + 0.5\delta t(d\widehat{\rho}_\eta/dt)_0, \qquad (4.2)$$

$$\theta_\eta^* = \theta_\eta^0 + 0.5\delta t(d\theta_\eta/dt)_0, \qquad (4.3)$$

where η is a label for either the dust or liquid SPH particles.

The acceleration equation can be integrated by first splitting the force/mass terms into two terms, one of which does not involve the drag. The force terms not involving the drag are F_ℓ or F_d as in (3.9) and (3.10). These forces are calculated with the mid point density, coordinates and volume fraction and a new velocity $\mathbf{V}^1$ is then calculated for each particle according to

$$\mathbf{V}' = \mathbf{V}^0 + \delta t\mathbf{F}^{1/2}, \qquad (4.4)$$

which is accurate to second order because $\mathbf{F}$ has midpoint values. The velocity $\mathbf{V}'$ is the initial velocity for the differential equations that describe the drag. The problems associated with the neglect of accelerations that Booth et al. [9] describe do not occur because the forces other than drag are taken into account correctly.

$$\frac{d\mathbf{v}_a}{dt} = -m_j s_{aj}(\mathbf{v}_{aj}\cdot\mathbf{r}_{aj})\mathbf{r}_{aj}, \qquad (4.10)$$

and

$$\frac{d\mathbf{v}_j}{dt} = -m_a s_{aj}(\mathbf{v}_{ji}\cdot\mathbf{r}_{aj})\mathbf{r}_{ja}. \qquad (4.11)$$

While integrating this equation over the time interval t to $t+\delta t$ we replace $\widehat{\rho}$, θ, and $\mathbf{r}_{aj}$ by $\widehat{\rho}^*$, θ^* and $\mathbf{r}^*$ which can be taken as constant during the velocity integration.

Here we integrate these equations *exactly* using the midpoint values of all quantities other than the velocity. For the present we also assume that the function $\mathcal{F}$ in (2.6) is a constant which we take as 1. By subtracting (4.11) from (4.10), and taking the scalar product with $\mathbf{r}_{aj}^*$ (which has the midpoint value and is therefore a constant during this integration step), we get the equation

$$\frac{dX}{dt} = -(m_j+m_a)s_{aj}(r_{aj}^*)^2X, \qquad (4.12)$$

where $X = (\mathbf{v}_{aj}\cdot\mathbf{r}_{aj}^*)$. With X calculated from (4.12) we can solve (4.10) and (4.11) to get

$$\mathbf{v}_a^1 = \mathbf{v}_a^0 - \frac{m_j(\mathbf{v}_{aj}\cdot\mathbf{r}_{aj}^*)\mathbf{r}_{aj}^*}{(m_j+m_a)(r_{aj}^*)^2}\left(1-e^{-\frac{1}{2}\omega\delta t}\right), \qquad (4.13)$$

and

$$\mathbf{v}_j^1 = \mathbf{v}_a^0 - \frac{m_a(\mathbf{v}_{aj}\cdot\mathbf{r}_{aj}^*)\mathbf{r}_{ja}^*}{(m_j+m_a)(r_{aj}^*)^2}\left(1-e^{-\frac{1}{2}\omega\delta t}\right). \qquad (4.14)$$

J.J. Monaghan (2020)

CONCLUSION & PROSPECTS

- New physics in Phantom:
  - Porosity with growth, fragmentation and bounce.
  - Rotational disruption.
  - Dust compaction during fragmentation.
- Find a robust method without numerical artefacts to simulate a gas and porous dust disc
  - Gas disc relaxation first.
  - Add dust with the 2-fluid method with correct initial conditions.
- Determine the thickness of dust midplanes with porous grains.
- Determine if and where the conditions to form planetesimals are fulfilled.
- Explain, if it happens, the rapid formation of planetesimals.

THANKS