INFLUENCE OF GROWTH ON DUST SETTLING AND MIGRATION IN PROTOPLANETARY DISCS

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ABSTRACT:

CONTEXT:
- To form meter-sized pre-planetesimals in protoplanetary discs, dust aggregates have to decouple from the gas at a distance far enough from the central star so that they are not accreted.
- Dust grains are affected by the gas drag, which results in a vertical settling towards the mid-plane, followed by radial migration.

AIMS:
To use a simple grain growth model to study how growth affects the dynamics in order to determine the dust distribution in observed discs.

METHOD:
- We implement a constant growth rate into a gas+dust hydrodynamics (SPH) code and vary the growth rate to study the resulting effects on the dust distribution.
- The growth rate allows us to determine the relative importance between friction and growth.

RESULTS:
We show that depending on the growth rate, a range of dust distribution can result. For large enough growth rates, grains can decouple from the gas before being accreted onto the central star, thus contributing as planetary building blocks.

GAS-DUST DYNAMICS:

Gas-dust interactions:
- **Sub-keplerian** gas velocity due to the pressure gradient, **keplerian** grain velocity.
- There exists a **differential velocity** between gas and dust ⟶ **DRAG FORCE**.
- Dust **settles** in the mid-plane and **migrates** in the inner region of the disc.

Dust behaviour:
- **Small grains** (s < 100 µm): grains are **strongly coupled** to the gas and evolve in the same way.
- **Intermediate sizes** (1 mm < s < 10 cm): friction has an **important effect** on dust dynamics. We introduce a characteristic size for which migration and settling processes are optimized: s_{opt}.
- **Large grains** (s > 1 m): grains are **weakly coupled** to the gas and evolve on nearly keplerian orbits.

SPH SIMULATIONS – DISC MODEL:

System:
- $M_{star} = 1\, M_{sun}$.
- $M_{disk} = 0.02\, M_{sun}$ comprising 1% of dust (ρ_d=1 g.cm^{-3}) by mass.
- The disc extends from 20 AU to 400 AU.
- The disc is vertically isothermal.
- Initial temperature and surface density profiles: $\Sigma \propto r^{-p}$ and $T \propto r^{-q}$ with p=3/2, q=3/4.

Code (Barrière-Fouchet et al. 2005):
- 3D SPH code, α_{SS} =0.01.
- two-fluid (gas and dust).

Initial state:
- 200,000 gas particles in a near-equilibrium disc that relaxes to a stationary disc in approximately 8,000 years. Once the disc is relaxed, we add dust particles superimposed on the gas particles.
- Dust initial size: s_0 = 10 µm.
- We let the disc evolve over 10^5 years.

CONSTANT GRAIN GROWTH MODEL:

A. THEORY

Dust dynamics (subscripts *d* for dust and *g* for gas):
Depends on two competing forces:
- the gravity due to the central star,
- the drag force due to the differential velocity between gas and dust.

Equation of motion in the *(r, θ, z)* plane:

$$\begin{cases} \dfrac{\mathrm{d}v_r}{\mathrm{d}t} - \dfrac{v_\theta^2}{r} + \dfrac{(v_r - v_{gr})}{t_s} + \dfrac{GMr}{(z^2+r^2)^{3/2}} = 0 \\ \dfrac{\mathrm{d}v_\theta}{\mathrm{d}t} + \dfrac{v_r v_\theta}{r} + \dfrac{v_\theta - v_{g\theta}}{t_s} = 0 \\ \dfrac{\mathrm{d}v_z}{\mathrm{d}t} + \dfrac{(v_z - v_{gz})}{t_s} + \dfrac{GMr}{(z^2+r^2)^{3/2}} = 0 \end{cases}$$

Dimensionless parameters:

$$S = \frac{s}{s_{\mathrm{opt}}} \qquad T = \frac{t}{t_K} \qquad \text{with} \qquad s_{\mathrm{opt}} = \frac{\rho_g\, c_s}{\Omega_K\, \rho_d}$$

The growth rate:

$$\frac{dS}{dT} = \frac{ds/dt}{s_{\mathrm{opt}}/t_K} = \gamma \text{ and } S = S_0 + \gamma . T$$

- Stopping time (t_s): represents the time necessary for dust to attain the gas velocity. It depends on the size of the grain s(t) which evolves in time (growth).
- Characteristic size (s_{opt}): which optimizes the migration process. It follows the same evolution as the surface density.
- Densities ρ_i: subscript *i*={*g*,*d*}. Gas local density, dust intrinsic density.
- Local gas sound speed c_s.
- Orbital frequency $\Omega_K = t_K^{-1}$.

We assume constant growth for grains:
γ=constant>0

The value of the constant grain growth rate gives the relative importance between the two major phenomena driving grain evolution: growth and friction.

- If **γ » 1**: growth dominates grain dynamics (t_s»t_k).
- If **γ « 1**: friction dominates grain dynamics (t_k»t_s), and migration or settling dominates the motion depending on values of γ.
- If **γ = 1**: both processes have the same importance.

We ran 3D SPH simulations with different values for γ and study the dust behaviour in the disc. Results from these simulations are presented in figures 1, 2 and 3.

B. RADIAL AND VERTICAL DISTRIBUTIONS (Figure 1)

The gas (resp. dust) distribution in the *(r,z)* plane is shown by black (resp. light blue) dots. Varying the value of γ we conclude that:

- **Small growth rate**: grains are strongly coupled to the gas and evolve in the same way. They are distributed in a large part of the disc and experience little settling or radial drift.
- **Intermediate growth rate**: grains reaching intermediate sizes settle efficiently and are concentrated in the mid-plane. Particles experience a radial drift but are not depleted if coming from the outer part of the disc.
- **Large growth rate**: grains decouple from the gas early in the disc lifetime. They are distributed in the entire disc as they were initially.

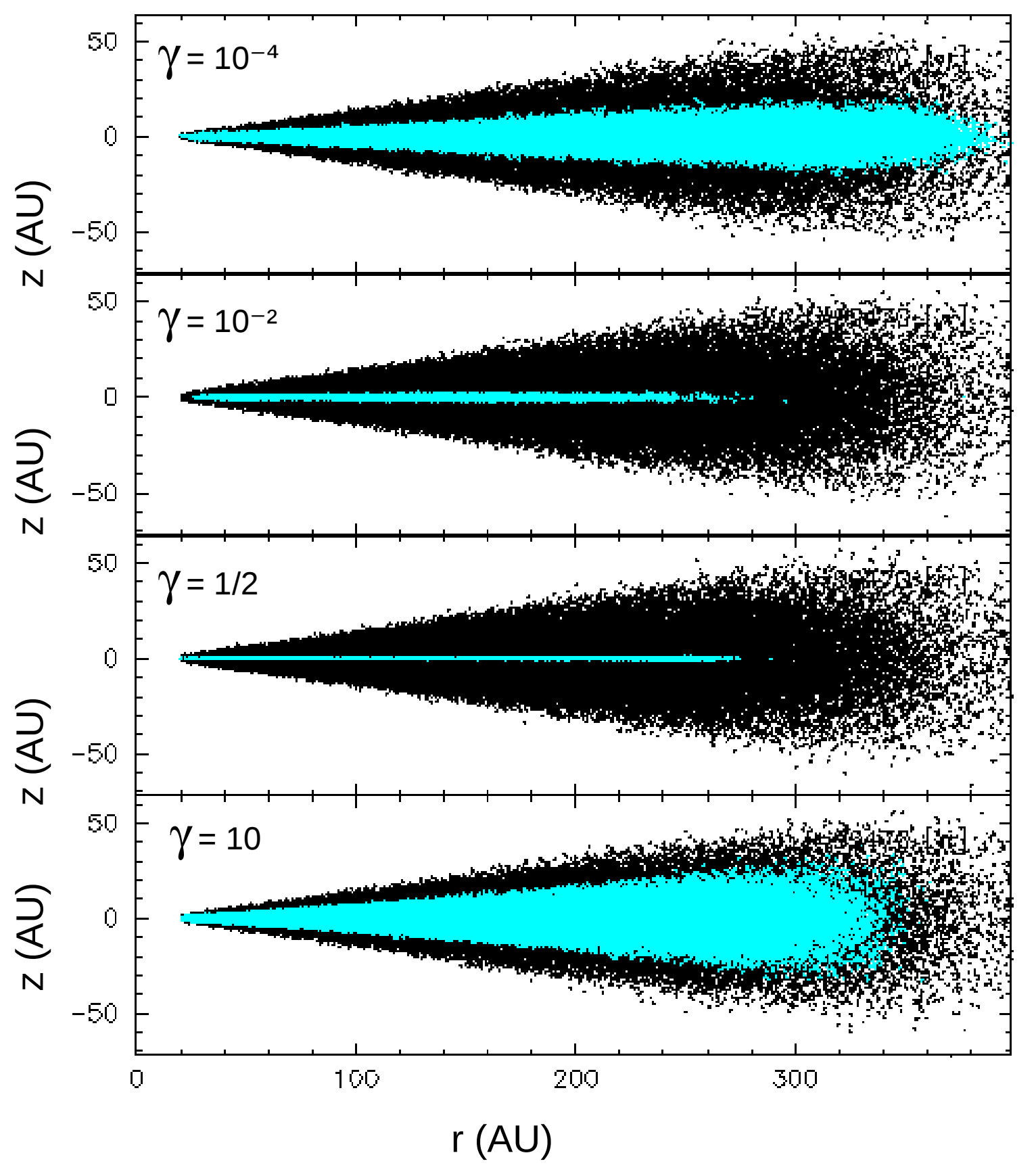

Fig.1: Radial distribution in an edge-on view of the disc obtained with our SPH code after 10^5 years. From top to bottom: γ = 10^{-4}, 10^{-2}, ½ and 10 (blue = dust; black = gas).

C. TRAJECTORIES (Figure 2)

Trajectories of SPH particles in the disc for various values of γ:

- **Small growth rate**: grains are highly coupled to the turbulent gas. Dust trajectories are driven by the gas motion.
- **Intermediate growth rate**: sedimentation and migration in the mid-plane. Grains grow as they fall to the mid-plane. Then, they start their radial drift. If the growth is sufficient, grains can decouple from the gas and evolve in the regime of large grains.
- **Large growth rate**: grains grow quickly and become larger than s_{opt} in less than an orbit. Therefore, particles decouple from the gas and evolve on keplerian orbits. They remain at a quasi-constant radius.

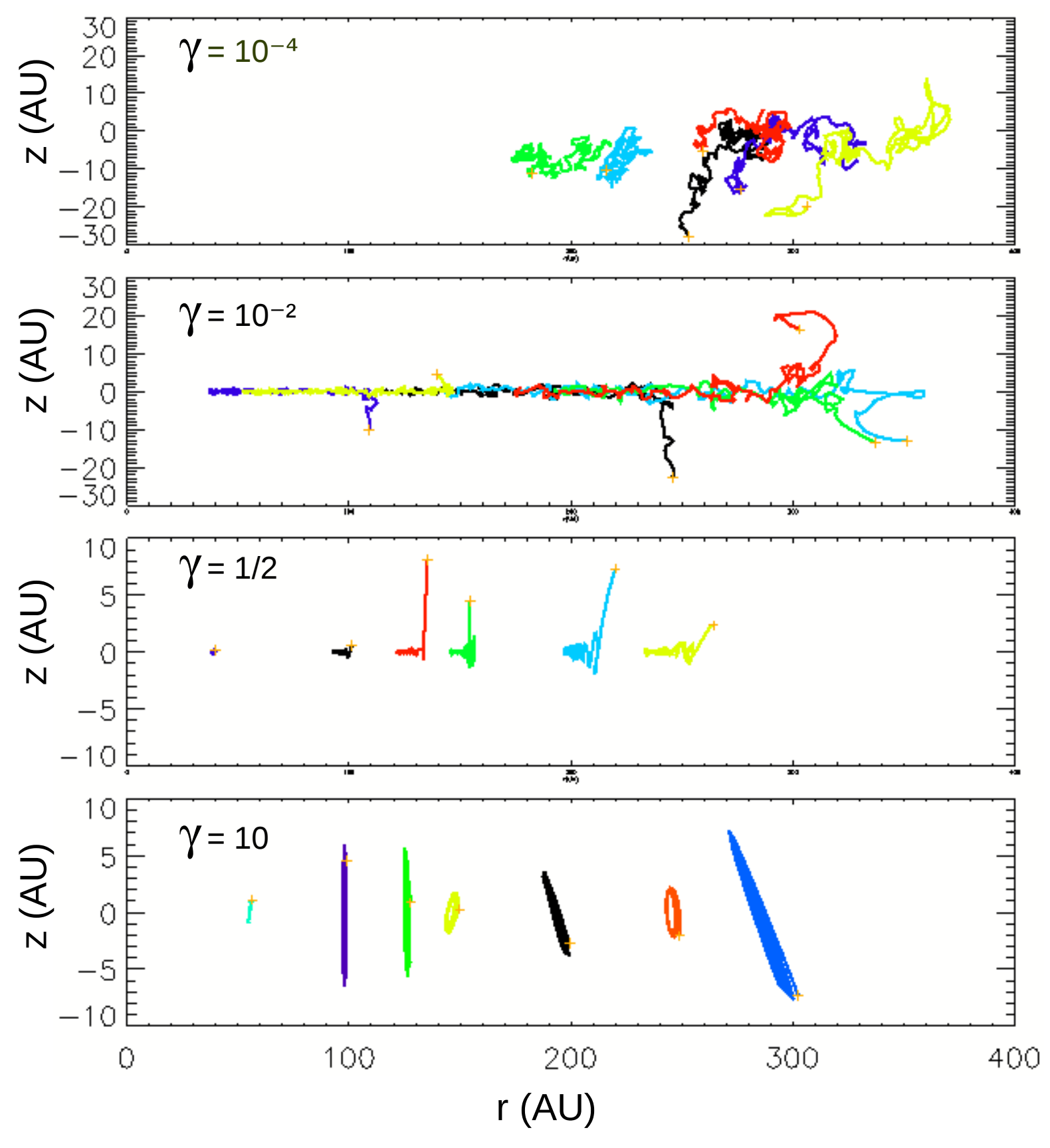

Fig.2: Trajectories in the *(r,z)* plane of individual SPH particles. From top to bottom: γ = 10^{-4}, 10^{-2}, ½ and 10.

D. GRAIN SIZE DISTRIBUTIONS (Figure 3)

- **Small growth rate**: grains dynamics is dominated by drag. Grains do not have time to grow and are acccreted onto the central star.
- **Intermediate growth rate**. As growth is moderately efficient, grains (particularly if they come from outer part of the disc) have time to grow enough to change their regime of migration. Their sizes become larger than s_{opt} therefore grains decouple from the gas and stop their migration. The growth continues while grains stay at the same radius (γ = 10^{-2}).
- **Large growth rate** (γ >1) :Growth is more efficient and grains decouple from the gas therefore they are distributed in the whole disc.

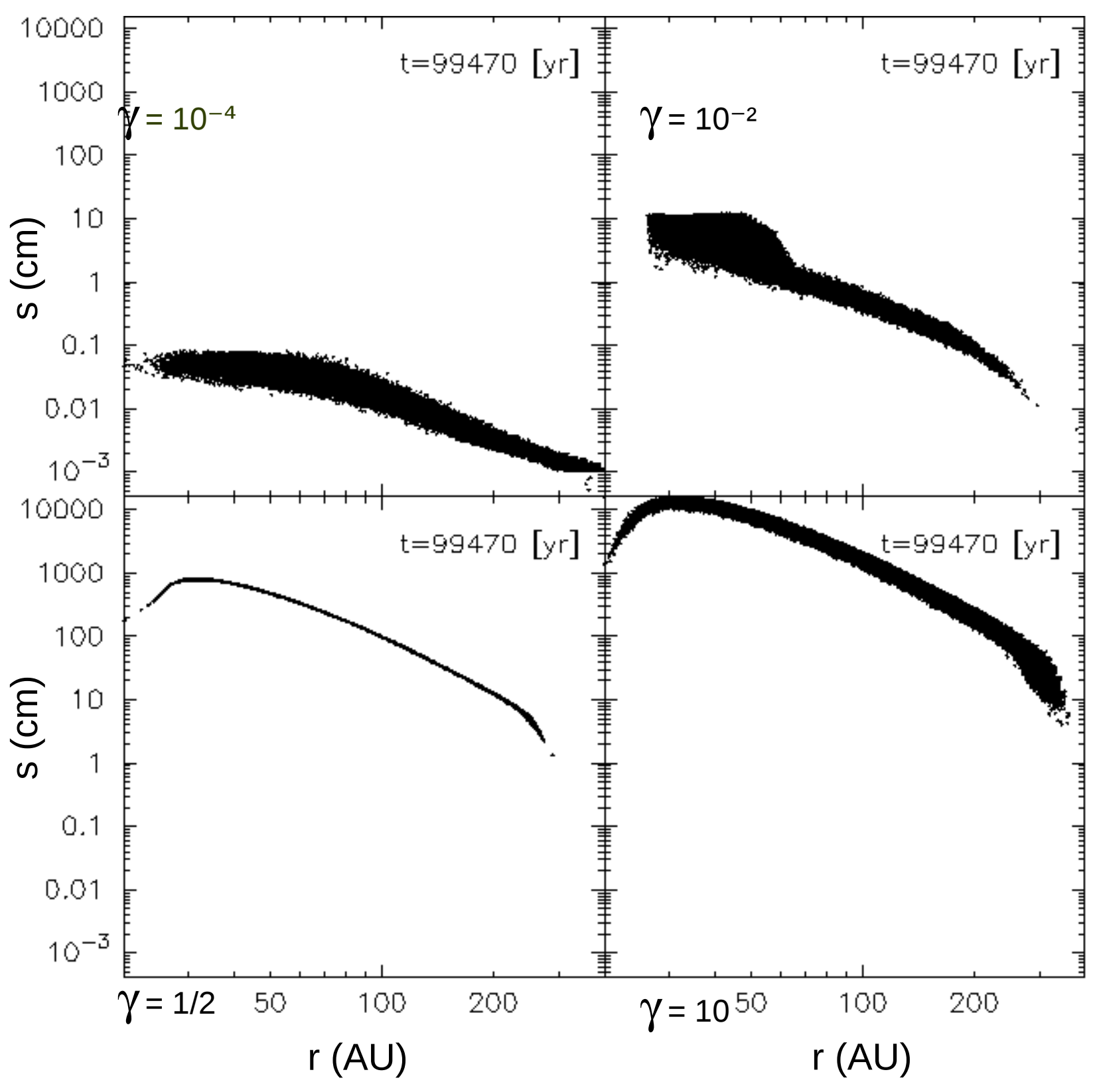

Fig.3: Radial grain size distribution obtained with our SPH code after 10^5 years. From left to right and top to bottom: γ = 10^{-4}, 10^{-2}, ½, 10.

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CONCLUSION:

We consider the case of a constant grain growth rate γ to study the influence of growth on dust dynamics. The analytical study of the grain dynamics is detailed in Laibe et al. (2010a) for non-growing grains and is generalized for the case of growing grains in Laibe et al. (2010b). A constant grain growth rate allows us to determine the relative influence of growth and drag processes. 3D SPH simulations validate the analytical results and the direct numerical integration performed in Laibe et al. (2010b). We distinguish three major behaviours for growing grains.

Small value of γ: dust grains are highly coupled to the turbulent gas and are distributed over the entire disc. The growth is not sufficient to change the regime of evolution. Grains migrate slowly toward the inner part of the disc and can be accreted onto the central star.

Intermediate value of γ: grains grow slowly as they settle to the mid-plane of the disc. Then, they experience a radial drift toward the inner part of the disc. As the growth is moderately efficient, grains can reach larger sizes. Their regime of evolution changes and they can evolve like large grains, decouple from the gas and move on keplerian orbits.

Large value of γ: growth is very efficient and grains do not have the time to feel the gas, decoupling in less than one orbit. They experience little radial drift and are distributed in the whole disc, as they were initially.

This study gives insight on grain size distributions in protoplanetary discs. The constant growth rate model gives an approximation of the physical growth process and underline the fact that we can observe various dust distribution depending on the dust growth rate. An example is the results obtained with γ = 0.01 that are in good approximation with our study of grain growth using the model of Stepinsky & Valageas (1997) (Laibe et al. 2008).

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