Pebble formation by ice condensation

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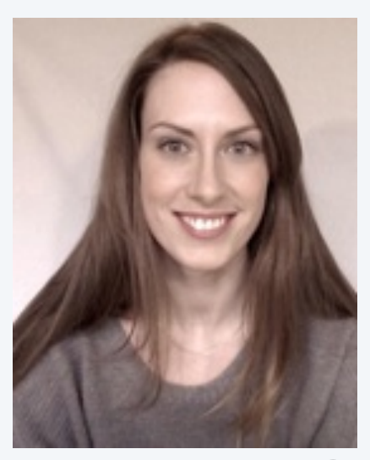

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Problem

Particle growth to pebbles (cm-dm sized particles) is not yet fully understood. Coagulation is efficient only up to mm-sized particles as larger particles tend to fragment or bounce as they collide, instead of stick [1]. The formation of pebbles needs to be explained for at least two reasons:

1) Pebbles are observed in protoplanetary discs [2].
2) Pebbles are crucial in order to explain growth to planetesimals and planets, either via further coagulation [3], or by clumping in streaming instabilities [4], vortices [5] or pressure bumps [6], followed by gravitational collapse.

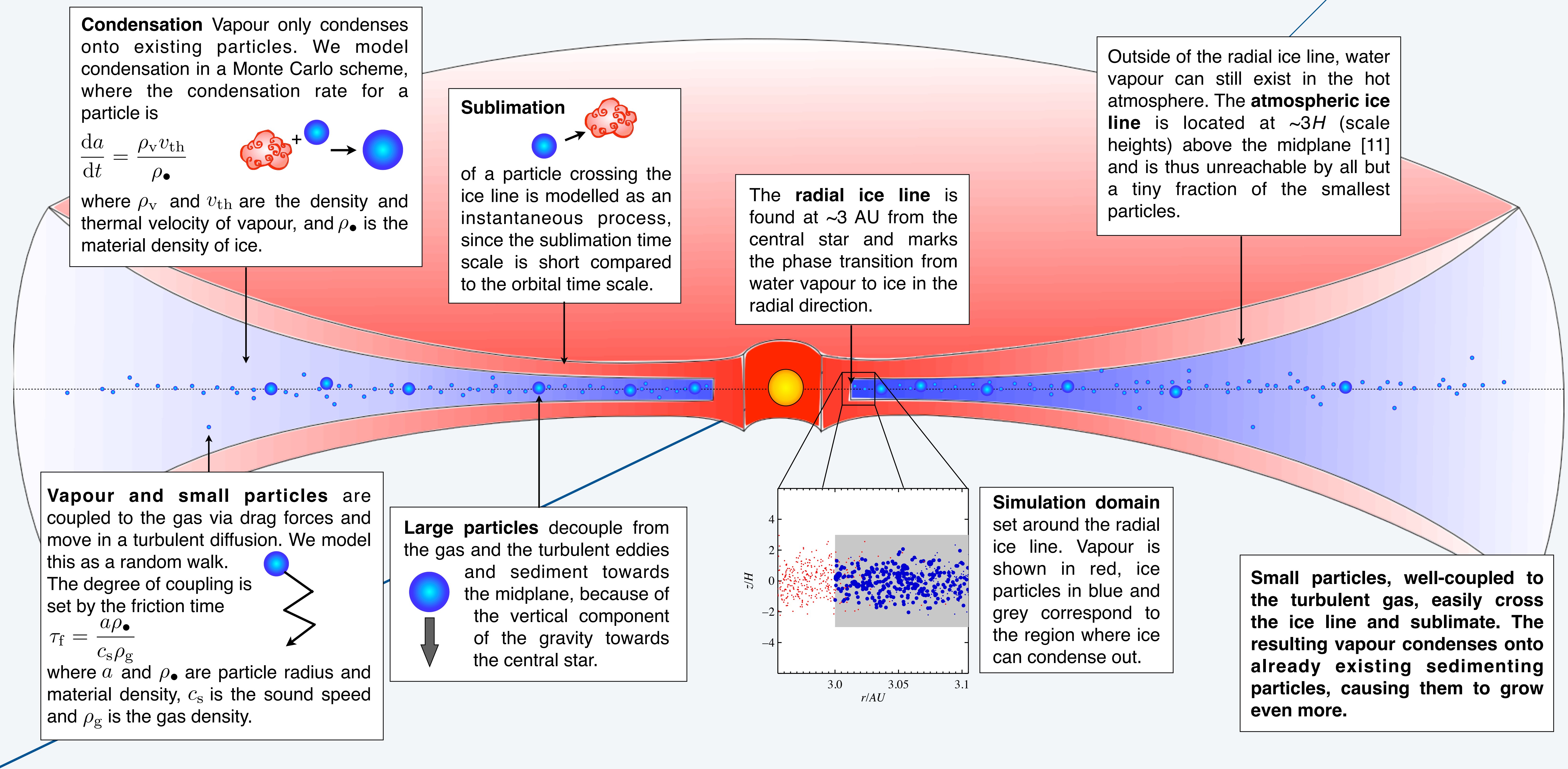
Solution

We investigate particle growth in protoplanetary discs via **ice condensation close to the water ice line** at ~3 AU [7]. Outside of ice lines the solid density is enhanced as material condense out [8]. Particles in these regions can therefore grow to large sizes via condensation of vapour. Additionally, ice is stickier than rock, so collisions between ice-ice and ice-rock particles are less destructive than similar ones involving only rocky particles [9]. **Close to ice lines particles can therefore grow both by condensation and by collisions involving sticky ice particles.**

Model

We have developed an idealized condensation model where we include condensation/sublimation and detailed particle dynamics resulting from turbulent diffusion, differential sedimentation and radial drift towards the central star. Rocky ice nuclei and collisions between particles are ignored.

The figure below is cartoon of a protoplanetary disc, highlighting the most important physical mechanisms in the model. For details, see Ros & Johansen, 2013 [10].



Condensation Vapour only condenses onto existing particles. We model condensation in a Monte Carlo scheme, where the condensation rate for a particle is

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{\rho_\mathrm{v} v_\mathrm{th}}{\rho_\bullet}$$

where ρ_v and v_th are the density and thermal velocity of vapour, and $\rho_\bullet$ is the material density of ice.

Sublimation of a particle crossing the ice line is modelled as an instantaneous process, since the sublimation time scale is short compared to the orbital time scale.

The **radial ice line** is found at ~3 AU from the central star and marks the phase transition from water vapour to ice in the radial direction.

Outside of the radial ice line, water vapour can still exist in the hot atmosphere. The **atmospheric ice line** is located at ~3*H* (scale heights) above the midplane [11] and is thus unreachable by all but a tiny fraction of the smallest particles.

Vapour and small particles are coupled to the gas via drag forces and move in a turbulent diffusion. We model this as a random walk.
The degree of coupling is set by the friction time

$$\tau_\mathrm{f} = \frac{a\rho_\bullet}{c_\mathrm{s}\rho_\mathrm{g}}$$

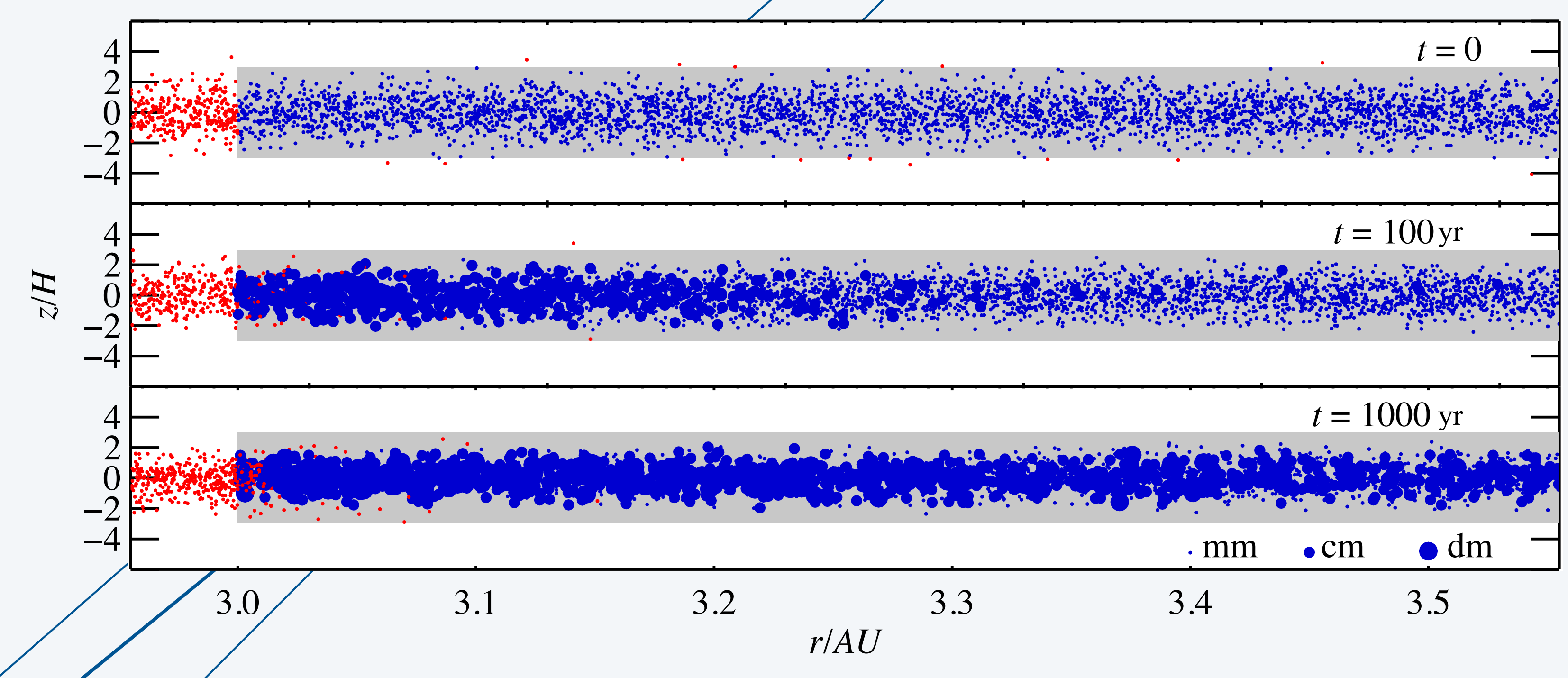
where a and $\rho_\bullet$ are particle radius and material density, c_s is the sound speed and ρ_g is the gas density.

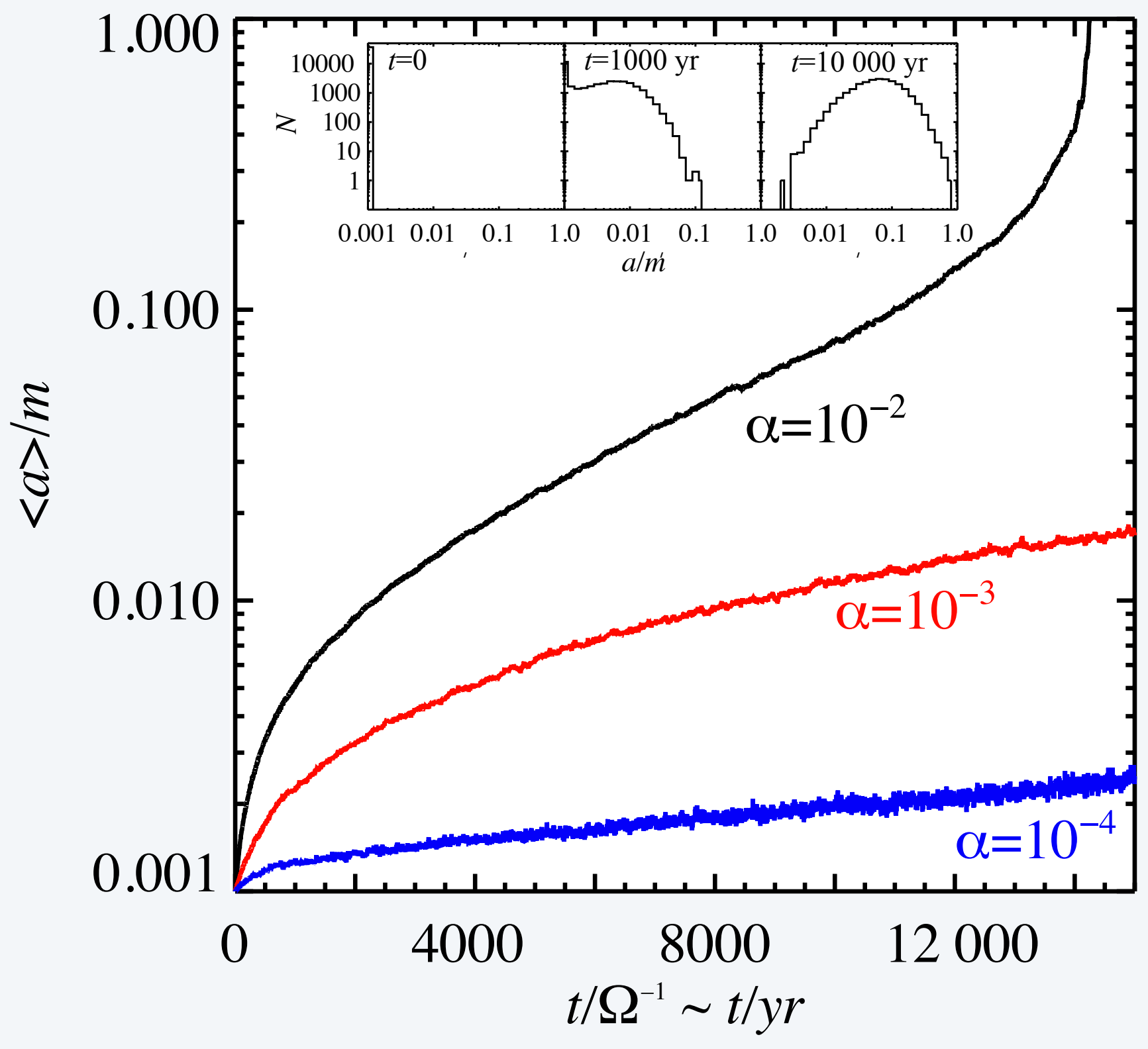
Large particles decouple from the gas and the turbulent eddies and sediment towards the midplane, because of the vertical component of the gravity towards the central star.

Simulation domain set around the radial ice line. Vapour is shown in red, ice particles in blue and grey correspond to the region where ice can condense out.

Small particles, well-coupled to the turbulent gas, easily cross the ice line and sublimate. The resulting vapour condenses onto already existing sedimenting particles, causing them to grow even more.

Results





Left: Ice particles (blue) grow and sediment to the midplane as vapour (red) condenses onto them. The condensation region is shown in grey. Growth occurs preferentially at the radial ice line, with only a small contribution from the atmospheric ice line.

Right: Mean ice particle size as a function of time. The colours denote different turbulent strengths, with black corresponding to a turbulent disc and blue to a dead zone. The inlay picture shows the size distribution of ice particles for $\alpha = 10^{-2}$.

Conclusions

1) In this ideal condensation model **particles grow from dust to large pebbles on a timescale of ~10 000 years**.
2) **Most of the growth takes place at the radial ice line**, whereas the atmospheric ice line contributes to growth of less than a millimetre.
3) **Radial mixing due to turbulent diffusion plays an important role** - large particles are formed close to the ice line, but are radially transported throughout the simulation domain.
4) The resulting particles are large enough to **explain observed pebbles** and to **enable further growth into planetesimals and planets**.

Future

The next step is to develop a **non-ideal condensation model**, where we will include **rocky particles**, functioning as ice nuclei, and **collisions between particles**. Including ice nuclei leads to a less efficient growth, whereas collisions between particles have the potential to enhance growth by sweep-up of small rock and ice particles.

We also plan to extend our model to the **CO ice line**, located farther out in the disc.

References

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