Dust particle growth in evolving protoplanetary disks

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Abstract

Grain growth in circumstellar disks has been investigated by several authors in the context of stationary disks. Our work extends this to disks that are being build up by infall and evolving over several million years. The goal of this work is to better understand the early phases of planet formation.

Disk Model

Infall

We take the Shu-Ulrich infall model as a first order estimate of an inside-out collapsing molecular cloud core. Improved hydrodynamical collapse calculations might be implemented later on.

Gas disk

We model the disk as a one dimensional Shakura-Sunyaev disk,

$$\frac{\partial \Sigma_g}{\partial t} - \frac{1}{R}\frac{\partial}{\partial R}\left[3\sqrt{R}\frac{\partial}{\partial R}\left(\Sigma_g \cdot \nu \cdot \sqrt{R}\right)\right] = \dot{\sigma}_g$$

where Σ_g is the gas surface density and the viscosity ν is taken to be the α-viscosity,

$$\begin{aligned} \nu &= \alpha \cdot c_s \cdot H \\ &= \alpha \cdot \frac{k_b\, T}{\mu} \cdot \sqrt{\frac{R^3}{G \cdot M_\odot}} \end{aligned}$$

The disk equation is solved numerically with an semi-implicit, flux conserving scheme.

Dust disks

The equation determining the evolution of dust is taken from Brauer et al. (2008),

$$\frac{\partial \Sigma_d^i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left\{ r \cdot \left[\Sigma_d^i \cdot v^i - D^i \cdot \frac{\partial}{\partial r}\left(\frac{\Sigma_d^i}{\Sigma_g}\right) \cdot \Sigma_g \right]\right\} = \dot{\sigma}_d^i$$

where Σ_{d^i} is the dust surface density, D^i the dust diffusion coefficient and v^i is the radial drift speed of the dust. v^i has contributions from drag forces (dust is dragged along with the gas) and from radial drift (dust looses angular momentum due to headwind). It is given by

$$v^i = -\frac{2v_n}{St + St^{-1}} + \frac{v_{\mathrm{gas}}}{1 + St^2}$$

where St is the Stokes number (depending on gas surface density and grainsize) and v_n is the maximum drift velocity of the particles. The latter depends on the slope of the gas surface density.
The evolution of the dust strongly depends on the size of the grains. 150 different components with grain sizes from 0.1 μm up to 10 km are being evolved simultaneously.

Evaporation and recondensation

Due to the high temperatures towards the inner edge of the disk, dust particles evaporate. The vaporized dust is treated as a separate layer with Stokes number of zero. If the temperature drops or the vapor moves into a region of lower temperature, it is fed back into the smallest size bin of the dust. It can then again contribute to the coagulation.

Layered Accretion

External irradiation only ionizes a layer of about 100 g/cm². The unionized material cannot couple to the magnetic field and is therefore MRI-inactive. The active surface layer and the inactive mid-plane layer are treated separately. Gravitational instabilities and limit-cycles will be included soon.

Temperature

Irradiation by the central star and viscous heating are taken into account. The mid-plane temperature is being approximated as a sum of optically thick and thin components as derived by Nakamoto et al. (1994).

Grain Growth

Algorithm

The coagulation-fragmentation equation is being solved at every radius during the simulation. The mid-plane densities are being calculated from the surface densities of every grain size taking the different scale heights due to mixing-settling balance into account.
To solve the coagulation-fragmentation equation, we use the implicit algorithm from Brauer et al. (2008).

Relative velocities

The contributions to relative particle velocities are:

- Brownian motion:

$$\Delta v_{\mathrm{B}} = \sqrt{\frac{8\, k\, T\, (m_1 + m_2)}{\pi\, m_1\, m_2}}$$

- Radial drift:

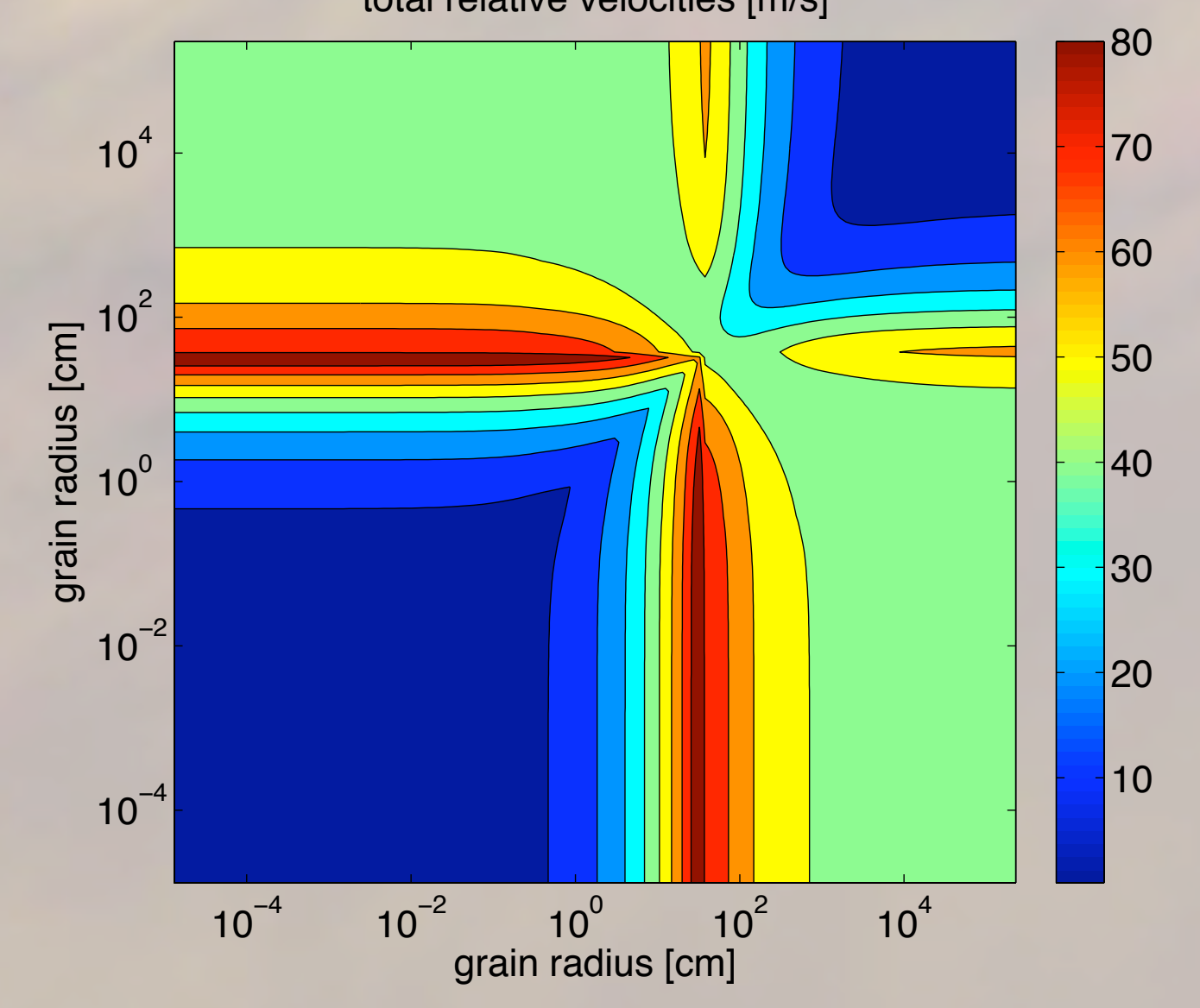
$$\Delta v_{\mathrm{R}} = \left| v_{r,1} - v_{r,2} \right|$$

- Differential settling:

$$\begin{aligned} v_{\mathrm{s},i} &= h_{\mathrm{dust},i} \cdot \Omega_k \cdot \min(St_i, 1) \\ \Delta v_{\mathrm{S}} &= \left| v_{s,1} - v_{s,2} \right| \end{aligned}$$

- Turbulent mixing: see Ormel et al. (2007)

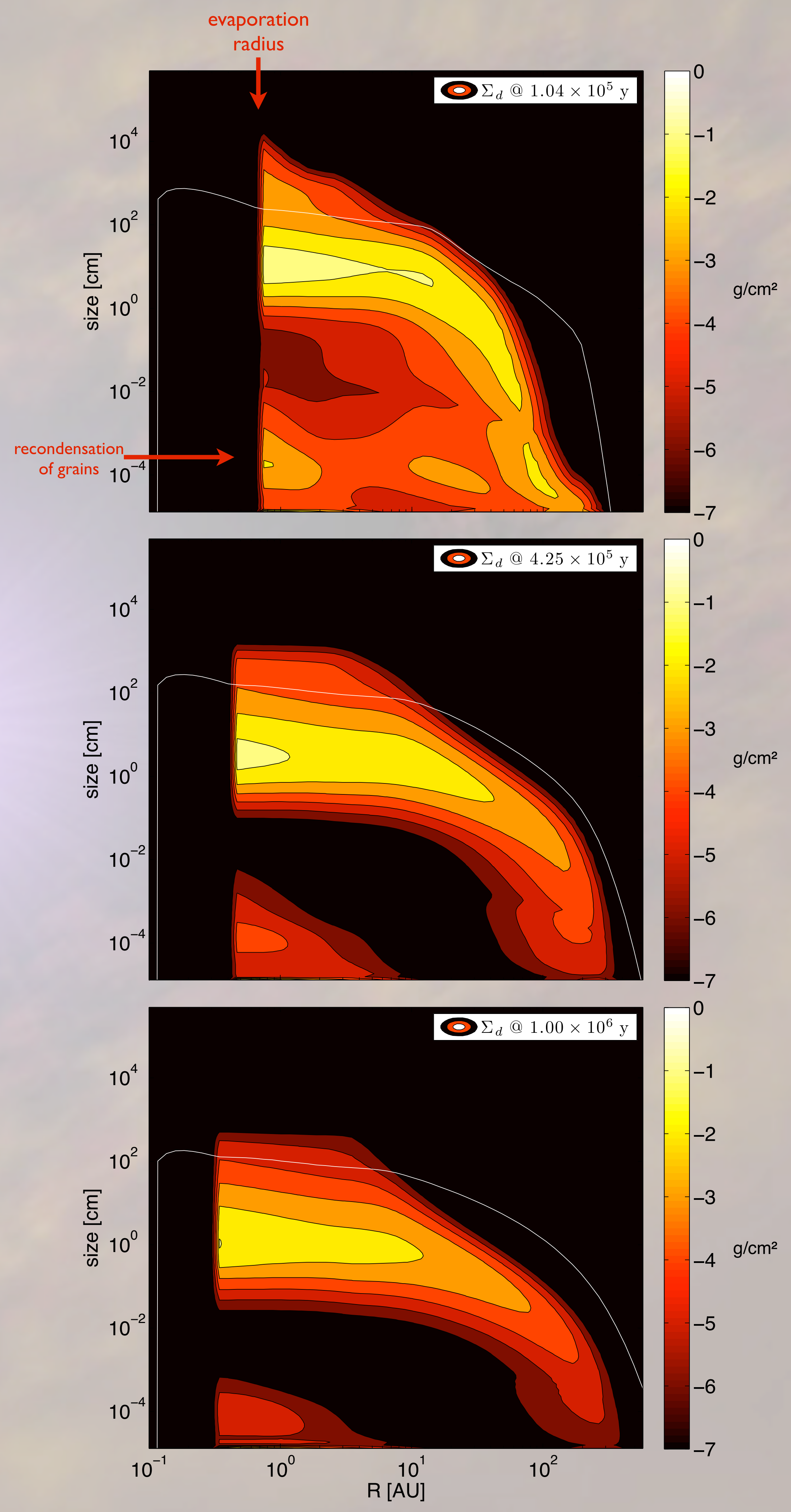
total relative velocities [m/s]

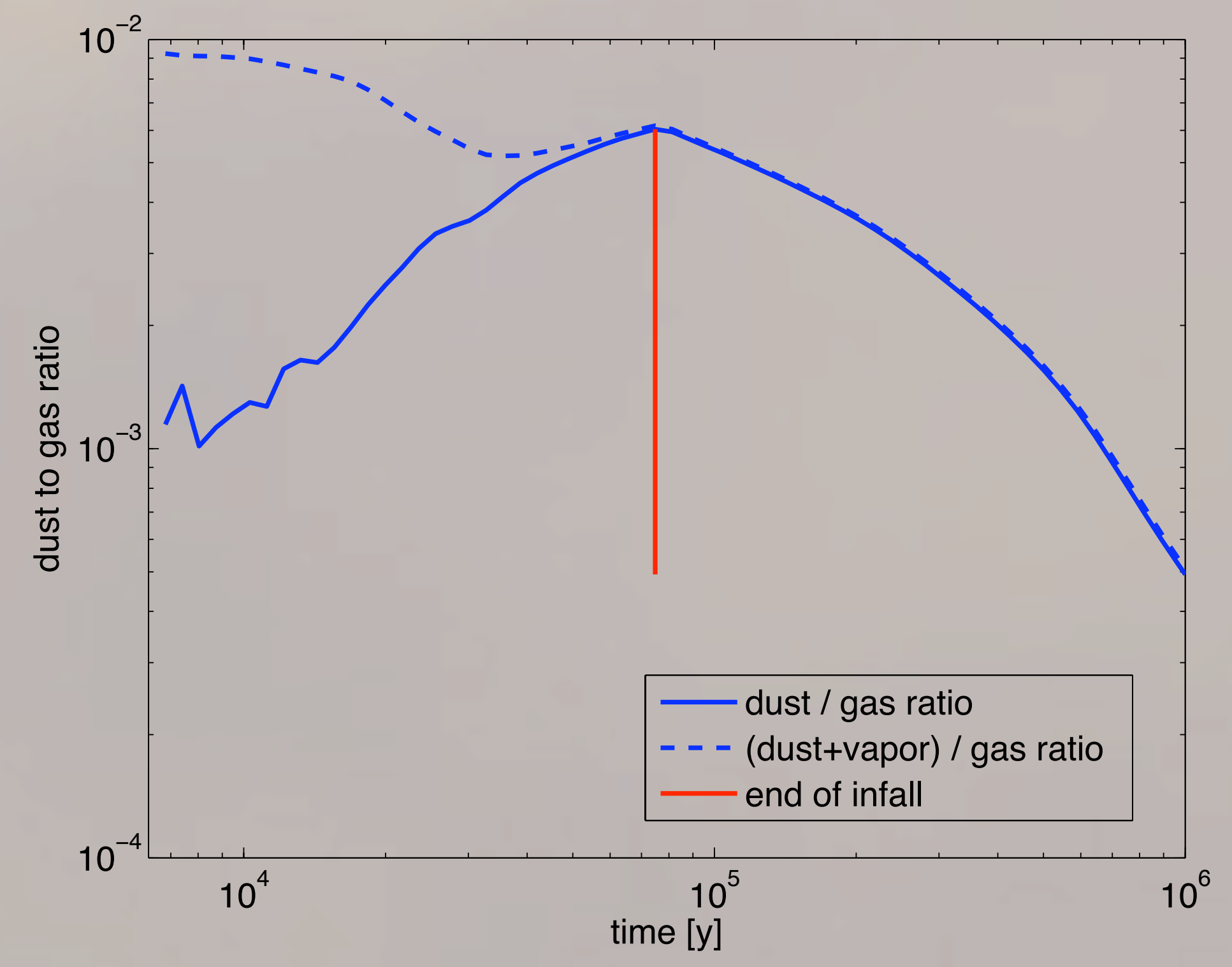


Results

Growth and disk evolution

The following plots show the dust surface density in g/cm² as contour versus radius and grain size. The time of each snapshot is shown in the title. Smaller particles are still present at small radii due to the recondensation of vaporized dust.
The white line denotes particles with Stokes number of unity.

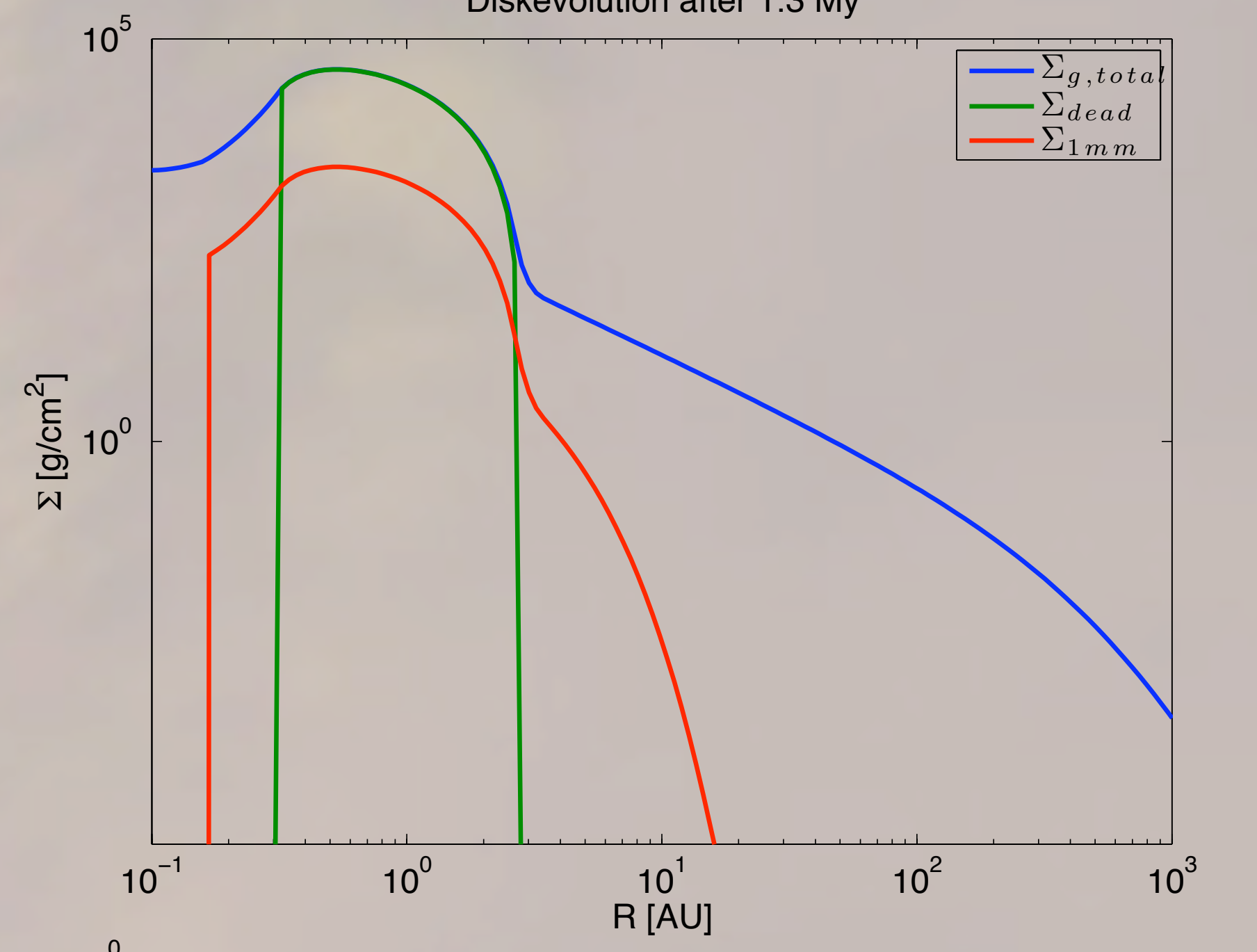


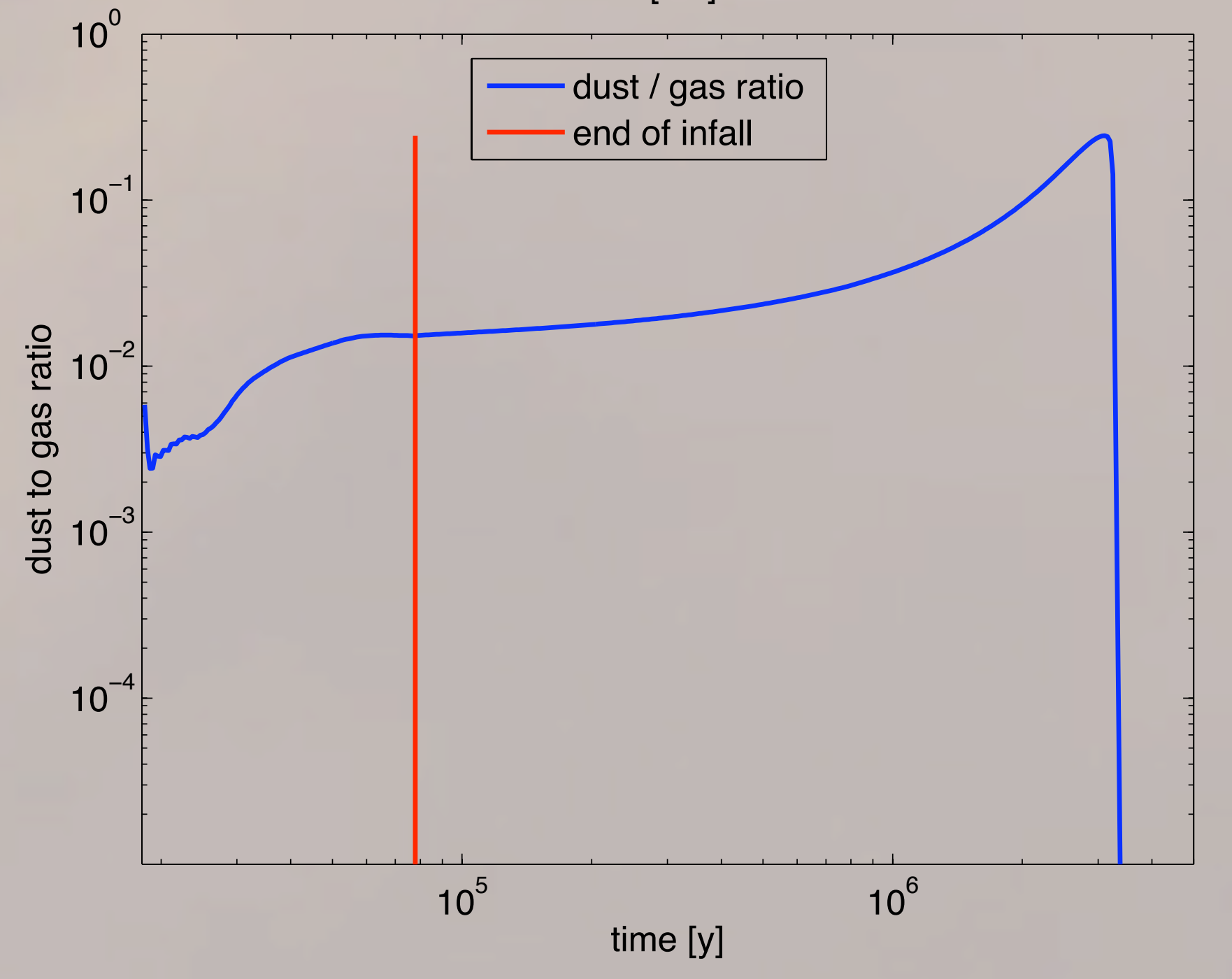


Accumulation of grains in the dead zone

Future work will focus on the evolution and coagulation/fragmentation of dust in dead zones. Preliminary results show that grains can be trapped in the dead zone, where they do not feel the strong accretion flow of the active layer. Additionally, the turbulent velocities are lower in the dead zone. Particles which have grown to a certain size at large radii and start drifting inside will enter the dead zone and stop drifting due to the high gas surface density. This might lead to an accumulation of grains in the dead zone.

Diskevolution after 1.3 My





Conclusions

We present first results of grain growth in a non-stationary circumstellar disks. The model includes the build-up phase of the circumstellar disk, the viscous spreading and accretion. 150 different sizes of grains are evolved simultaneously taking into account the effects of evaporation, recondensation, radial drift and coagulation.
Despite the strong outward movement of the gas, the dust to gas ratio drops strongly as soon as the infall of material has stopped.
Preliminary results of layered accretion show a strong accumulation of grains in the dead zone.

References

Brauer et al., A&A (2008), **480**, *859*

Nakamoto et al., ApJ (1994), **421**, *640*

Ormel et al., A&A (2007), **466**, *413*

Questions?

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Image by Johny Setiawan