FROM DUST TO PLANETESIMALS -
HIGH RESOLUTION SIMULATIONS OF PLANET FORMATION PROCESSES

Andreas Schreiber, Karsten Dittrich, Hubert Klahr (2014/15)

BACKGROUND

Planets formation occurs in dusty gas disks within a few million years around young stars and last less than 10 million years.

These disks consist to 98% out of hydrogen and helium. Higher elements have an initial abundance of 10^{-10} kg/m^3 and is thus 13 orders of magnitude lower than the typical density of a planet. Obviously, the planet formation process must be very efficient in concentrating metals locally.

As first step 'dust bunnies' and snow flakes growth within the disk, referred to as dust grains. These grains grow to typically centimeters in size by mutual collisions, but increasing collision velocities prevent further growth. Interestingly, the most abundant species of small solid objects is water ice.

Planets must form out of these small dust grains. Since pure sedimentation to the mid-plane was excluded, we look for different processes to accumulate enough dust to form gravitational bound objects. The most promising candidates are turbulent dust and gas flows.

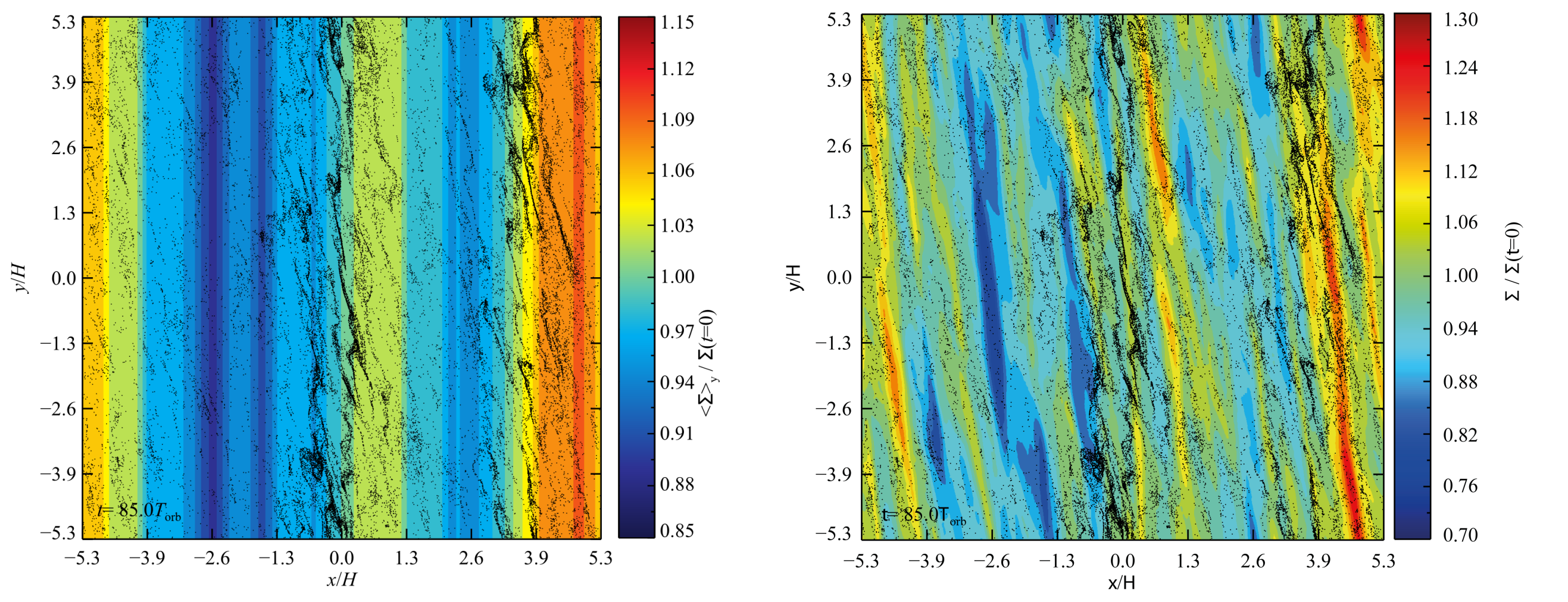

FIG. 1: ZONAL FLOWS

Dust grains concentrate at the inner side of gas pressure maxima, such as zonal flows [2]. These are exited by a weak stellar magnetic field coupling to the disk. The induced transport of momentum separates the orbital gas flow into regions of faster and slower rotation and thus changes the pressure locally (color). Shown is the top view on a shearing box simulation with a million particles. y-Axis shows the azimuthal direction.

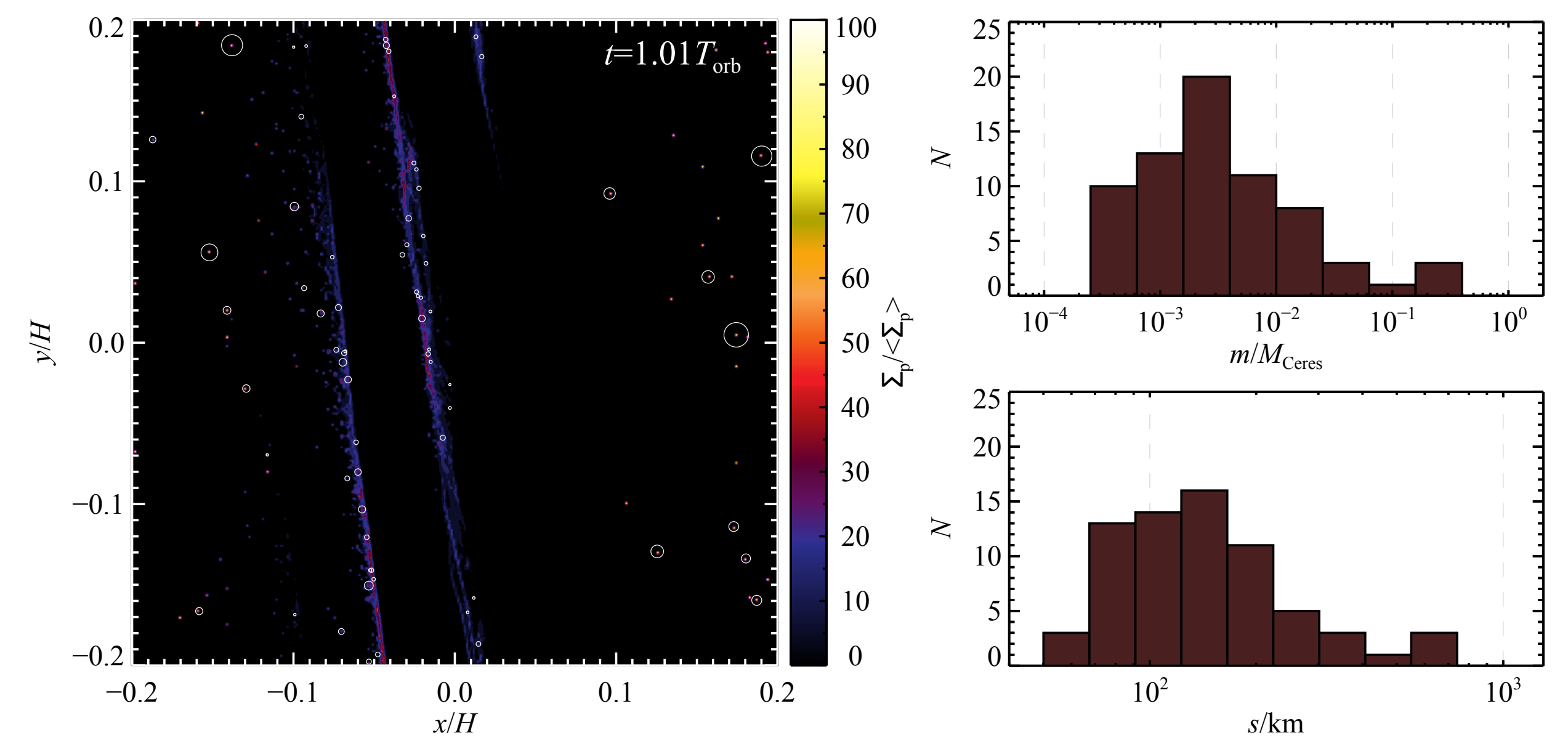

FIG. 2: PLANETESIMAL DISTRIBUTION AFTER COLLAPSE

This simulation snapshot shows all planetesimals which formed out of a particle heap via gravitational collapse. The initial heap had a density higher than Roche density, but due to tidal forces the heap got stretched out to a filament and then partly collapsed into planetesimals. The color indicates the relative dust abundancy. The white circles give the gravitational bound area around a formed planetesimal, called Hill-Sphere. The planetesimal characteristics indicate the typical planetesimal size to be around 100 km and the typical mass to be way below the mass of Ceres.

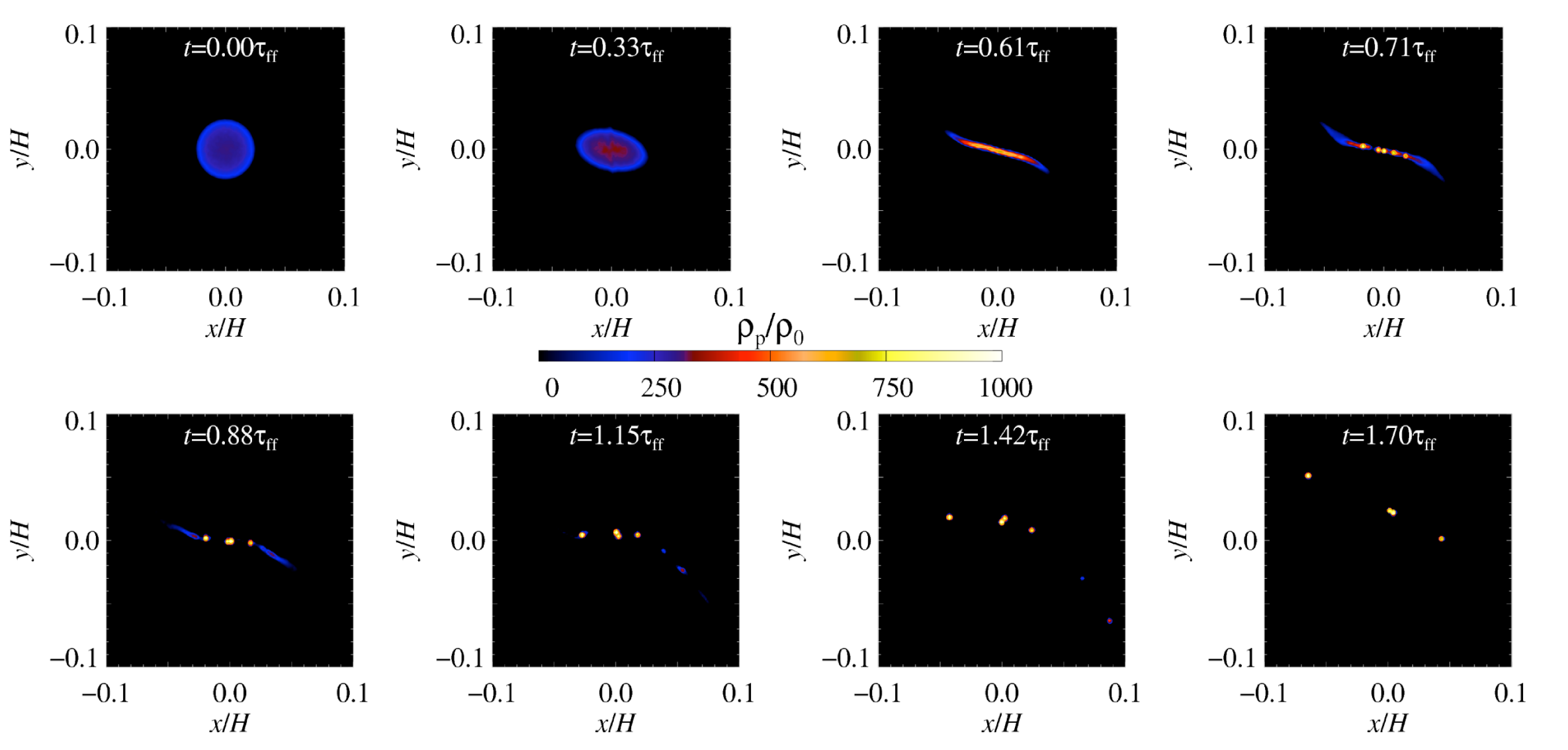

FIG. 3: DUST CLOUD COLLAPSE SIMULATION

This series of snapshots is showing the collapse of a dense spherical particle heap. The colors indicate the relative particle density. The initial spherical cloud gets sheared apart by tidal forces and then collapses into a group of four planetesimals of again around 100 km in size. With such simulations we try to estimate the minimal conditions for planetesimal formation and moreover are a good simulation to test our prediction models on.

PLANETESIMALS AS INTERMEDIATE PLANET BUILDING BRICKS

We know from our solar system that at some stage so called planetesimals must have formed and the entire solar nebula must have been full of those objects. These planetesimals than merged via gravitational growth into terrestrial planets and gas giant cores. Today, leftovers of these planetesimal stage still can be found as asteroids and comets in our solar system. The mechanism of dust grain growth (see BACKGROUND) and the formation of planets out of planetesimals is well understood.

The missing link within the planet formation process is the formation of planetesimals out of dust grains. Till now, no sticking mechanism could be found to overcome the cm-size-barrier. Direct sedimentation to the disk mid plane and gravitational collapse was ruled out too, since at no time the disk was laminar enough to allow a sufficient settling of the grains to the mid plane. Thus, a deeper understanding of the turbulent disk processes is needed to find the criteria for planetesimals formation.

PREDICTION OF PLANETESIMAL GROWTH

In the last years a new model to overcome all barriers was developed. It will give us in near future the ability to make predictions of what sizes and with which rate planetesimals should form at a certain distance from a star *[1]*. Within these models, the planetesimals form via gravitational collapse out of dense dust heaps produced by turbulence, vortices and zonal flows (*Fig. 1*). The occurring turbulence has the property to mix the dust grains on large scales but also concentrates them on small scales. Moreover, induced high dust to gas ratios trigger self-growing streaming instabilities. These instabilities trap even more particles, guaranteeing the heap to survive even longer till its critical density is reached.

STREAMING INSTABILITIES ARE TRAPPING DUST

The gas within a disk not only feels the stellar gravitational force but also an additional force due to increasing gas pressure to the inner side of the disk. Thus, gas moves with a sub-keplerian speed. Dust on the other side does not feel this additional pressure force and tries to move with keplerian speed. The result is a headwind decelerating the dust which leads to an inward drift.

But, if the dust concentration reaches a dust-to-gas ration of $\varepsilon > 1$ the so called streaming instability sets in, see *Fig 4*. In that regime the gas feels a significant back reaction from the dust and gets accelerated to a Keplerian speed. Hence, the dust doesn't feel a headwind anymore and gets trapped in that instability.

If the density within such a heap exceeds the local Roche density, which is the density needed to withstand even tidal forces from the central star, the particle heap will collapse to a 100 km to 1000 km sized planetesimal, see *Fig. 2* and *3*.

SIMULATIONS WITH PENCIL CODE

Our models are derived from magneto-hydro-dynamical simulations we run on Germans biggest supercomputers JUGENE and JUQUEEN with the '*Pencil Code*' [3]. These simulations evolve a small disk patch, so called shearing box, in order to resolve the necessary spatial scales and time scales of planetesimal formation processes. At the same time as we simulate the gas dynamics we also solve for millions of particles embedded in the gas.

The used Pencil Code is a high order finite difference magneto hydro dynamics code with Runga Kutta time-stepping for stability. Dust grains are represented by super particles which are treated as Lagrangian point masses. Self-gravity is solved via a FFT method. Our runs use up to 512^3 grid-cells and 64 Mio. particles [4]. Hence, our code continuously has to solve the Possion equation and applies the resulting forces onto the dust gas mixture.

FUTURE DIRCETIONS

In the future we want to further understand the efficiency of the above mentioned process and derive an initial mass function for planetesimal formation in disks. We further want to understand what the minimal concentrations and dust sizes are, in order to still get converted into planetesimals (*Fig. 3*). Furthermore we are interested in the opportunities of zonal flows and other pressure bumps within the dead zone of a disk. This zone was revitalized in recent studies [5] and it is promising that further investigations will show instabilities in the dead zone capable to trap enough particles for streaming instability to set in and trigger gravitational collapse.

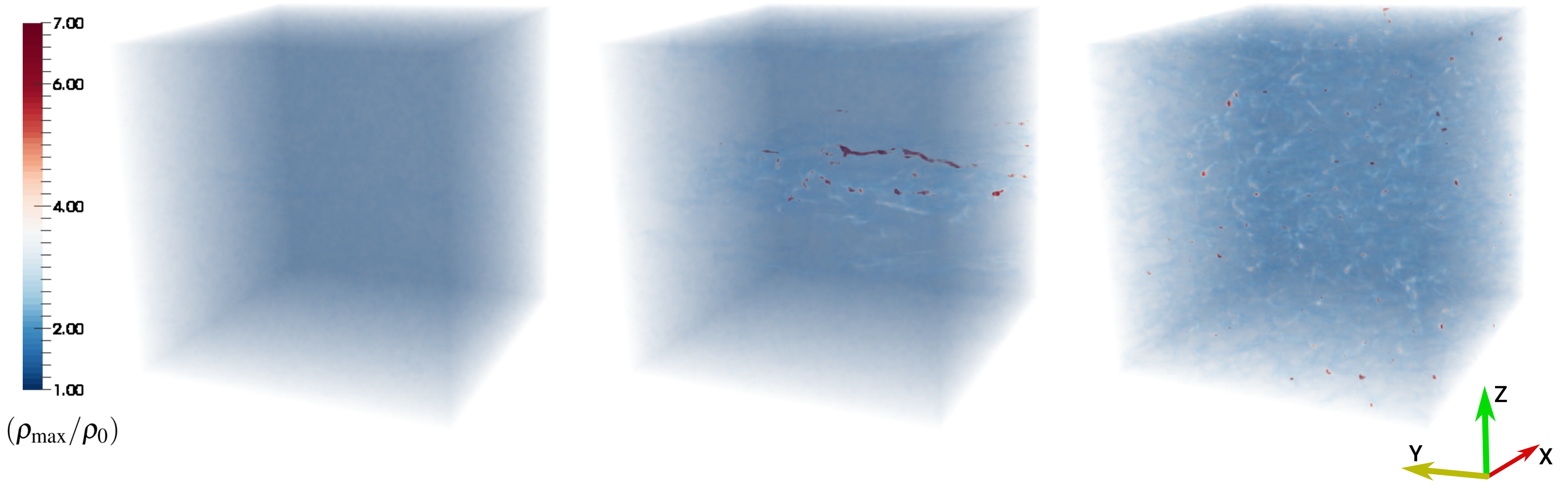

FIG. 4: 3-D STREAMING INSTABILITY SIMULATIONS

Shown is the maximum dust density in terms of initial density $(\rho_{\max}/\rho_0)$ of a streaming instability simulations for three states in time. The box size is L=0.01H, with H the typical disk scale height, and dust to gas radio of ε = 1.The left image shows the initial homogeneous dust distribution. The center image shows the onset of the streaming instability. The total maximum dust density of the whole simulation is reached in this time phase. The starting streaming instability modes are much bigger, compared with the final saturated state modes, shown in the the right image, where small streaming instability modes life in the whole simulation domain.

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MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Astronomie Heidelberg
Max Planck Institute for Astronomy Heidelberg