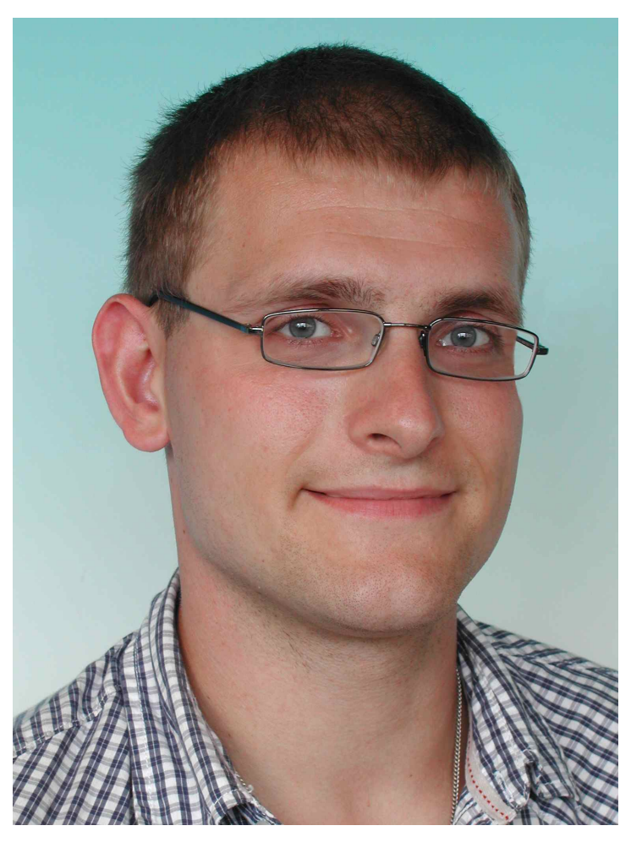

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Planetesimal Formation in Zonal Flows

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Abstract

Recent numerical simulations show long lived sub- and super-Keplerian flows in protoplanetary disks. These so-called zonal flows are found in local as well as global simulations of magneto-rotationally unstable disks. The resulting gas over- and under-densities have a radial size of $\sim$5 local pressure scale heights, and are stable for several tens of orbits. This is the first study about the effects of zonal flows on dust particles. Centimeter sized particles reach a hundred-fold density enhancement without self-gravity.

Numerical simulations in a protoplanetary disk

Experiments [1] and simulations [2] showed that dust growth through sticking is efficient up to centimeter sizes. Sweep-up of small particles by a few big boulders [3] allows growth up to some meter-sized objects [4]. We investigate growth to the kilometer-size regime by performing ideal magneto-hydrodynamic simulations with meter-sized bodies in local shearing boxes of different sizes. We do not include dust back-reaction on the gas. Large-scale magnetic field structures create super-Keplerian flows. Through geostrophic balance gas over-densities develop. These high pressure regions lead to dust trapping, high dust densities, and planetesimal formation.

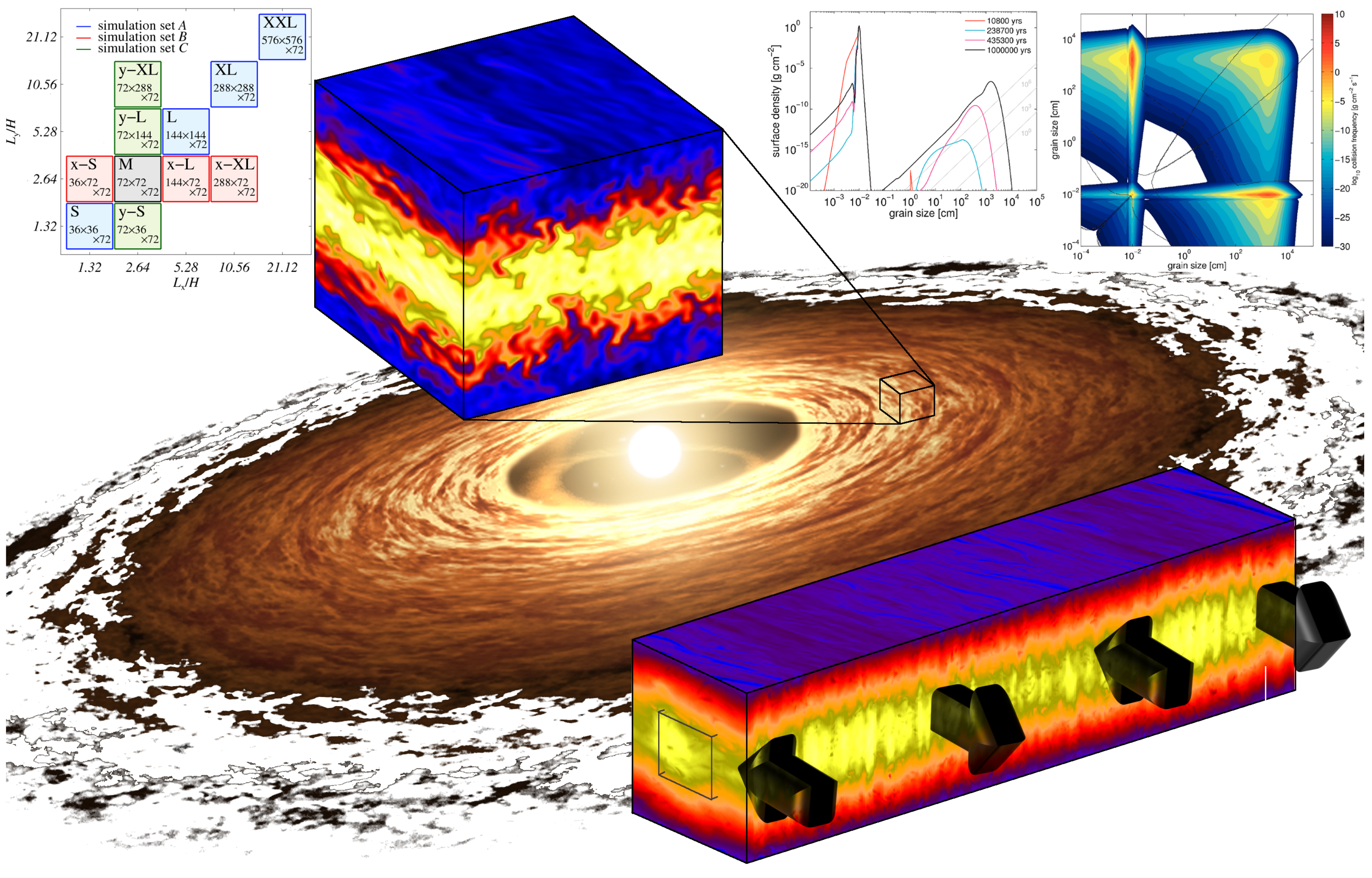
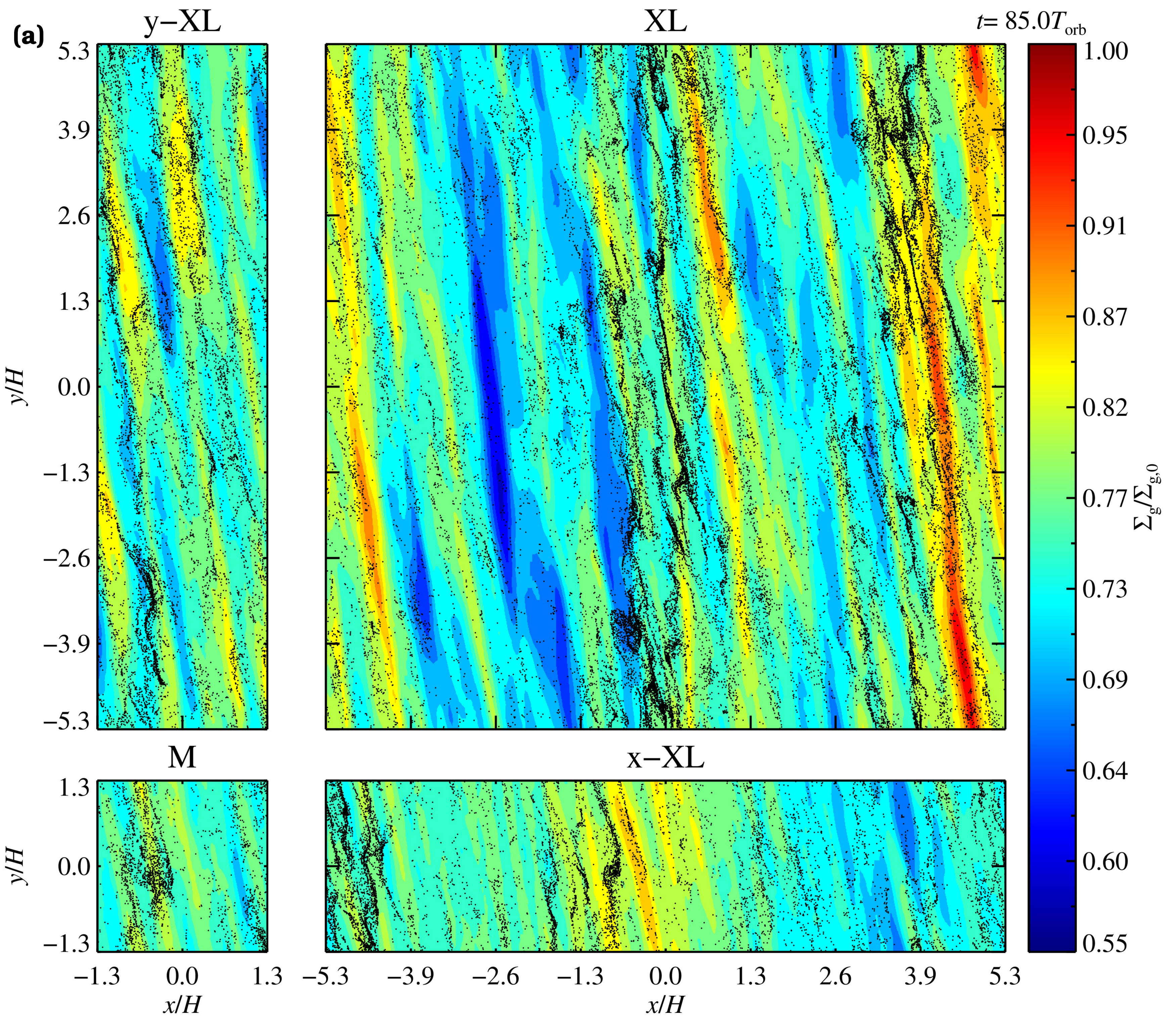
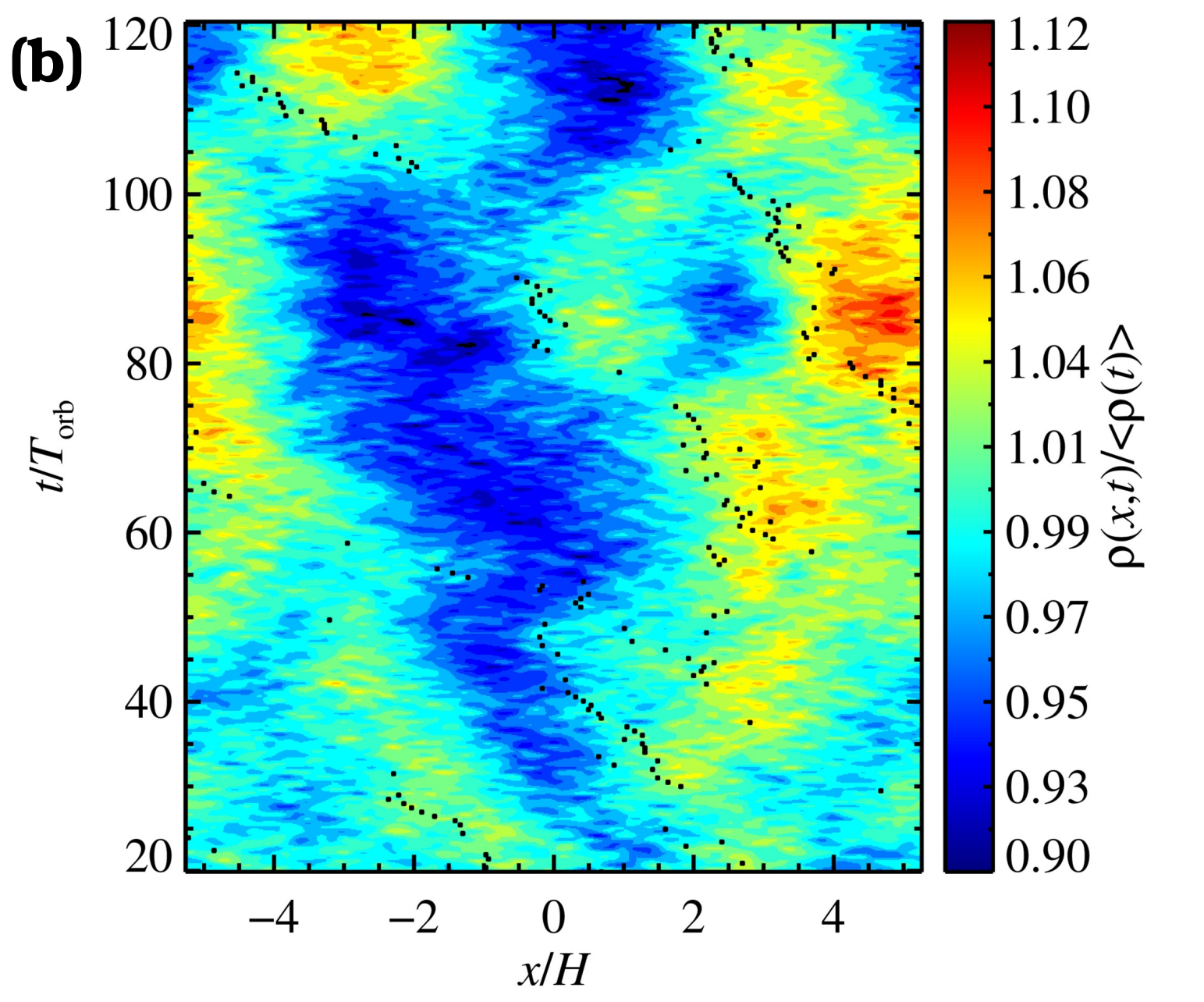


image credit: www.spitzer.caltech.edu, [3], [5], and [6]
boxes show gas density, the arrows indicate the direction of gas flow.

Zonal flows

Numerical simulations in large local shearing boxes of the magnetorotational instability (MRI) show that MRI-turbulence is able to form large-scale gas density concentrations in some regions of a protoplanetary disk [7]. Global simulations [8] confirmed the occurence of long-lived high-pressure regions. At 5AU from the central star, they form an annulus of overdense gas that has a radial size of $\sim$1.25AU and is stable for several hundred years.

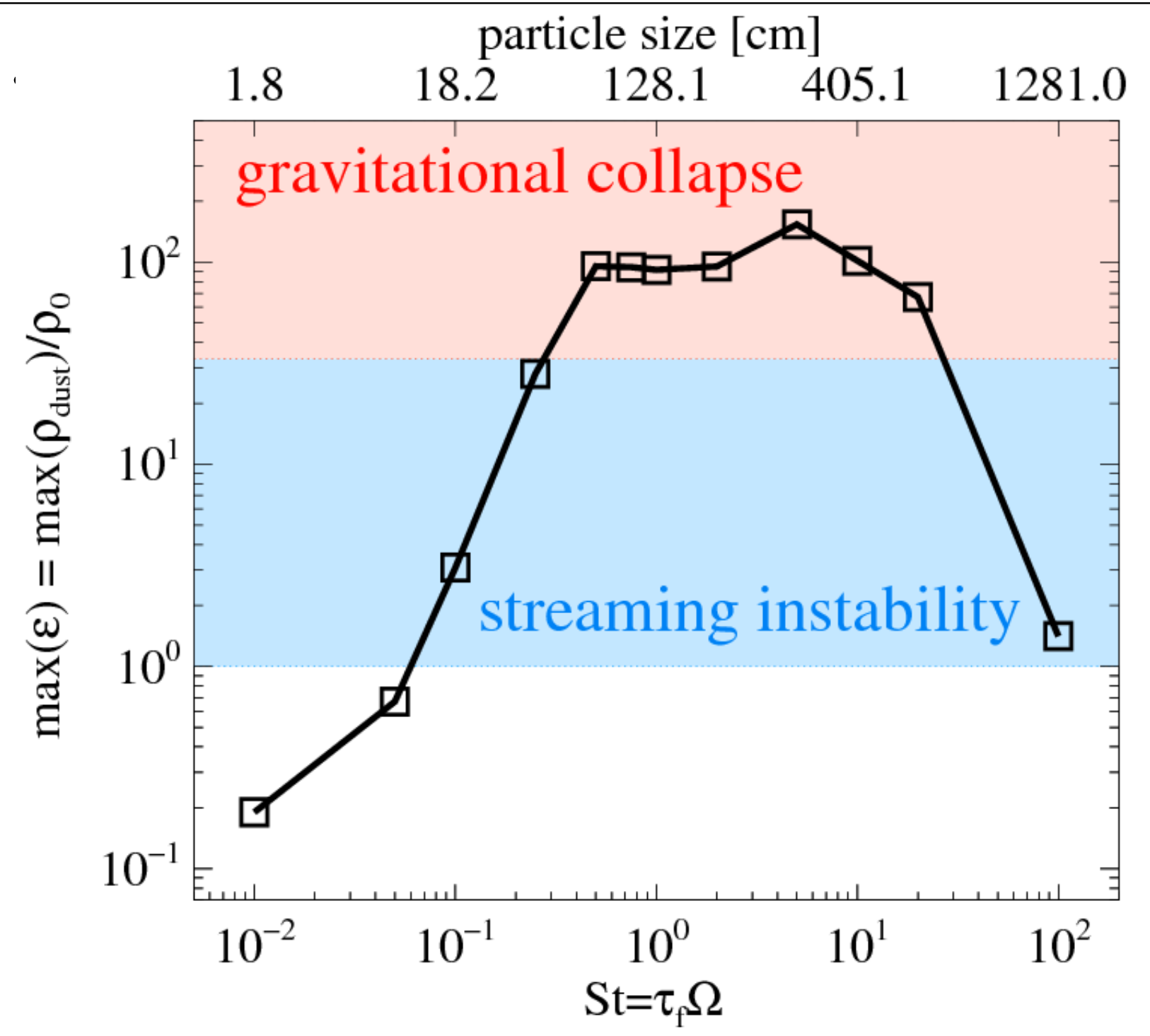




both plots from [6], black dots show particle positions (a) and position of highest dust density (b)

Planetesimal formation

Particles of different sizes respond differently to the gas. Meter-sized boulders (St=1) couple strongest, and therefor form the highest over-densities. Decimeter-sized dust pebbles (St=0.1) can reach a dust-to-gas ratio about unity for the standard overall dust-to-gas ratio of 0.01. They will trigger the streaming instability [9], and further increase the dust density to form planetesimals.



from [6], sizes assume a 3·MMSN at 5AU

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The Figure at the left hand side from [10] gives a time series of the collapse of overdense seeds in the early solar system into gravitationally bound boulder clusters. The column densities of four different sizes of boulders, plotted independently at a time just before self-gravity is turned on, is shown in the top four panels. The time series of total column density of solids, in the radial-azimuthal (x-y) plane of the disk, summed over all particle sizes, is shown in the 9 panels below. The times are given in orbital times after self-gravity is turned on. The insets in each panel show an enlargement of a square region (as indicated in the main panels) centered around the Hill sphere of the most massive cluster in the simulation. The Hill sphere grows in time as the clusters grow in mass by accreting boulders from the turbulent flow.