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Formation of Asteroid Belts
in Particle-Enriched Regions of Protoplanetary Discs

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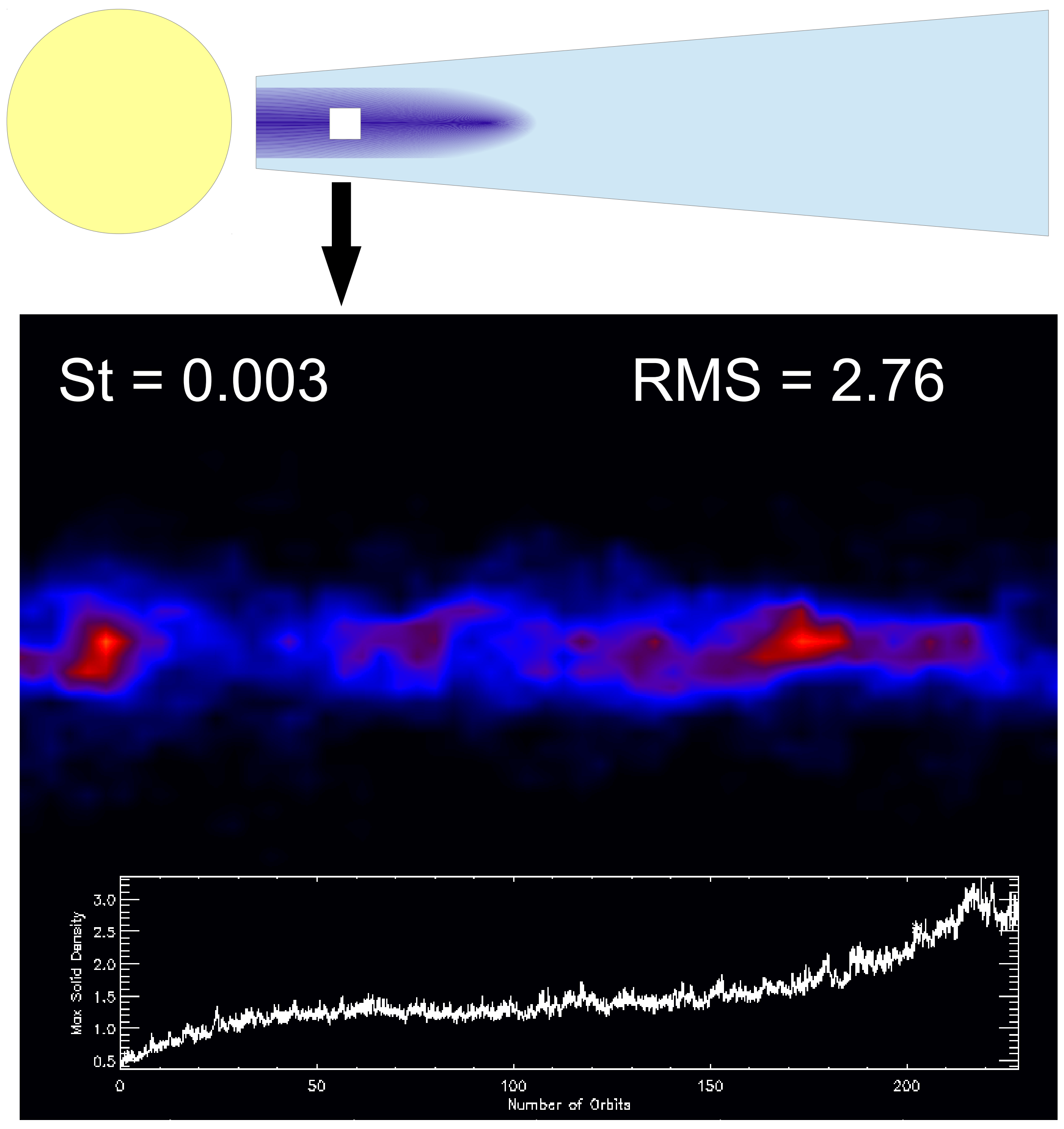

Figure 1: We use the root mean squared particle density (Equation 1) to measure clumping. Particle clumps are easily distinguishable when RMS ~ 2.7 - 2.8

Introduction

There is mounting evidence that the traditional picture of the formation of asteroids must be revised. The size distribution of asteroids is hard to reconcile with a bottom-up formation scenario. Instead, asteroids may form top-down, with large 100-1000 km sized objects forming first by the gravitational collapse of dense clumps of small particles.

In this work, we model the dynamics of small solid particles in particle-enriched regions of protoplanetary discs. We explore whether the streaming instability can continue to be effective for very small particles (Stoke number << 1) and large particles (up to St = 10). We perform shearing box simulations using the Pencil Code in which we gradually remove gas from the inner disk.

Clumping and particle drift

The streaming instability (SI) has two effects that make it interesting for planet formation:

(1) The SI causes **particle clumping**, which can enhance coagulation and may lead directly to gravitational collapse via gravitational instability. In this project we use the *root mean squared* particle density as a measure of clumping:

$$RMS = \frac{\rho_{p,RMS}}{\langle\rho_p\rangle} = \frac{1}{\langle\rho_p\rangle}\sqrt{\frac{1}{N^2}\sum_{x,z}\rho_p^2} \qquad (1)$$

By inspection, we note that clumping is evident at around $\rho_{p,RMS} \sim 2.8\,\langle\rho_p\rangle$ (see Figure 1).

(2) The SI reduces the rate of **radial drift**, so that solids are not lost into the Sun. The rate of radial drift can be estimated directly from the simulation. In this project we select particle concentrations that lead to a radial drift in the order of the disk lifetime.

Results

#1 Chondrule-sized particles (St = 0.0018 or R ~ 1 mm at 2 AU) can form dense clumps inside a pressure bump. Outside a pressure bump, large chondrules (St = 0.0032 or R ~ 1.7 mm at 2 AU) can clump if the mass loading is high enough. Those same large chondrules can clump inside a pressure bump with mass loadings barely higher than solar (Z_{crit} ~ 0.0125).

#2 More generally, we obtain an empirical relation between particle size and the solids-to-gas ratio needed to cause particle clumps and reduce radial drift to the point where these clumps can survive for periods comparable to the disk lifetime.

Future work

One option for future work is to determine the range of collision speeds inside these particle clumps. One can suspect that inside these clumps particle collisions are both common and low-speed.

One can also consider making a more complete simulation that includes both particle coagulation and hydrodynamical effects like the streaming instability. The SI and coagulation may be complementary, where particle growth enhances the SI and in turn the SI produces particle clumps that enhance coagulation.

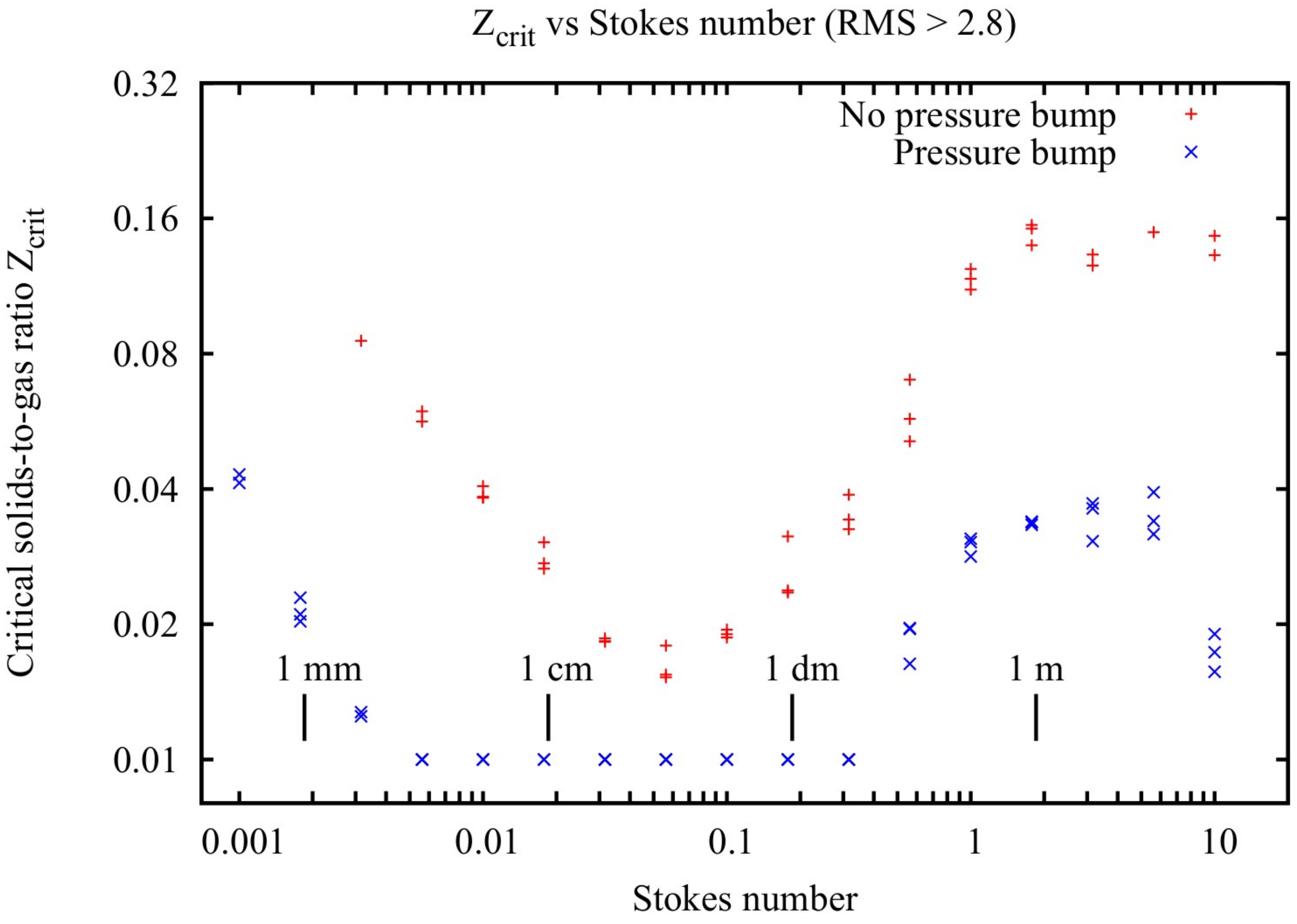

Figure 2: Critical Z value to produce dense clumps and reduce radial drift. Because the simulations start at Z = 0.01 we cannot resolve Z_{crit} values lower than that. But clearly, particles around St ~ 0.06 - 0.3 can clump very easily inside a pressure bump without any need for particle enrichment.

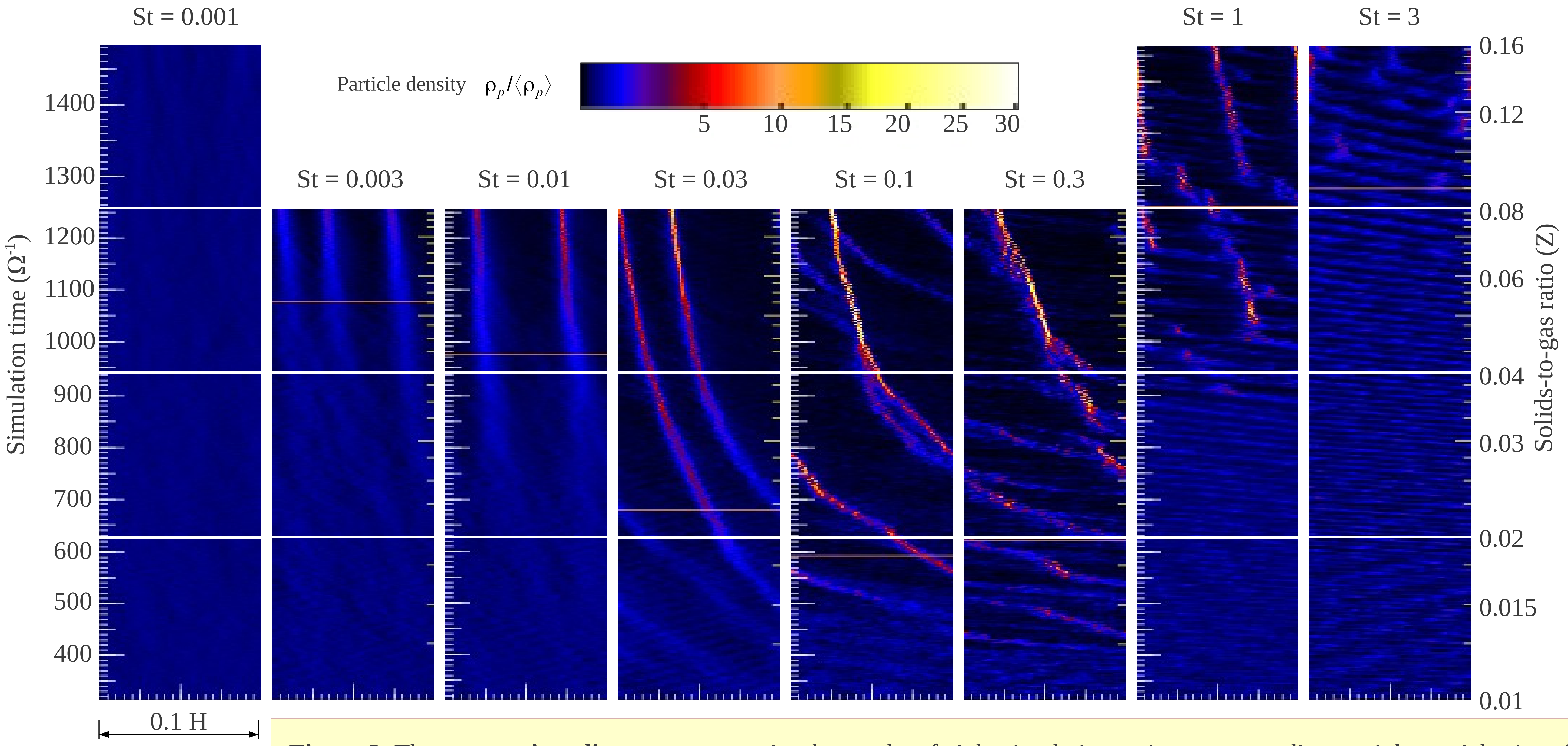

Figure 3: These **spacetime diagrams** summarise the results of eight simulation series corresponding to eight particle sizes (Stokes number from 0.001 to 3). Each series starts with a solids-to-gas ratio of Z = 0.01 which is then increased exponentially over time. The vertical axis corresponds to time (left) or solids-to-gas ratio (right). The colour denotes the particle density. The width of the box is 0.1 scale heights.