Protoplanetary Disk Rings as Sites for Planetesimal Formation

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Abstract

Axisymmetric dust rings are a ubiquitous feature of young protoplanetary disks. These rings are likely caused by pressure bumps in the gas profile; a small bump can induce a traffic-jam-like pattern in the dust density, while a large bump may halt radial dust drift entirely. The resulting increase in dust concentration may trigger planetesimal formation by the streaming instability (SI), as the SI itself requires some initial concentration of dust. Here we present the first 3D simulations of planetesimal formation in the presence of a pressure bump modeled specifically after those seen by Atacama Large Millimeter/submillimeter Array. We place a pressure bump at the center of a large 3D shearing box, along with an initial solid-to-gas ratio of $Z = 0.01$, and we include both particle back-reaction and particle self-gravity. We consider millimeter-sized and centimeter-sized particles separately. For simulations with centimeter-sized particles, we find that even a small pressure bump leads to the formation of planetesimals via the SI; a pressure bump does *not* need to fully halt radial particle drift for the SI to become efficient. Furthermore, pure gravitational collapse via concentration in pressure bumps (such as would occur at sufficiently high concentrations and without the SI) is not responsible for planetesimal formation. For millimeter-sized particles, we find tentative evidence that planetesimal formation does not occur. If this result is confirmed at higher resolution, it could put strong constraints on where planetesimals can form. Ultimately, our results show that for centimeter-sized particles planetesimal formation in pressure bumps is extremely robust.

Unified Astronomy Thesaurus concepts: Planet formation (1241); Planetesimals (1259); Protoplanetary disks (1300); Planetary system formation (1257)

Resilience of Planetesimal Formation in Weakly-Reinforced Pressure Bumps

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ABSTRACT

The discovery that axisymmetric dust rings are ubiquitous in protoplanetary disks has provoked a flurry of research on the role of pressure bumps in planet formation. Recent high-resolution simulations by our group have shown that even a modest bump can collect enough dust to trigger planetesimal formation by the streaming instability. In this work, we probe the limits of planetesimal formation when the external source of pressure bump reinforcement is extremely weak. We conduct simulations of radially elongated shearing boxes to capture the entire bump, which itself is generated and maintained over some timescale $t_{\rm reinf}$ by a Newtonian relaxation scheme. We find that planetesimal formation is extremely resilient for cm-sized grains. We reduced the strength of reinforcement by up to a factor of 100 and planetesimal formation (i.e., location, number, and initial masses) was essentially unaffected. However, we do find that strong reinforcement causes much faster pebble drift compared to the the standard pebble drift rates. The resulting larger pebble flux enhances the planetesimal growth rate by pebble accretion. We hypothesize that to sustain the bump, our code has to extract angular momentum (the strength of this negative torque depends on $t_{\rm reinf}$), and some of this torque is transferred to the particles, causing them to drift faster for a stronger torque (i.e., smaller $t_{\rm reinf}$). Since any physical process that sustains a pressure bump must do so by torquing the gas, we conjecture that the effect on pebble drift is a real phenomenon, motivating further work with physically realistic sources to generate the bump.

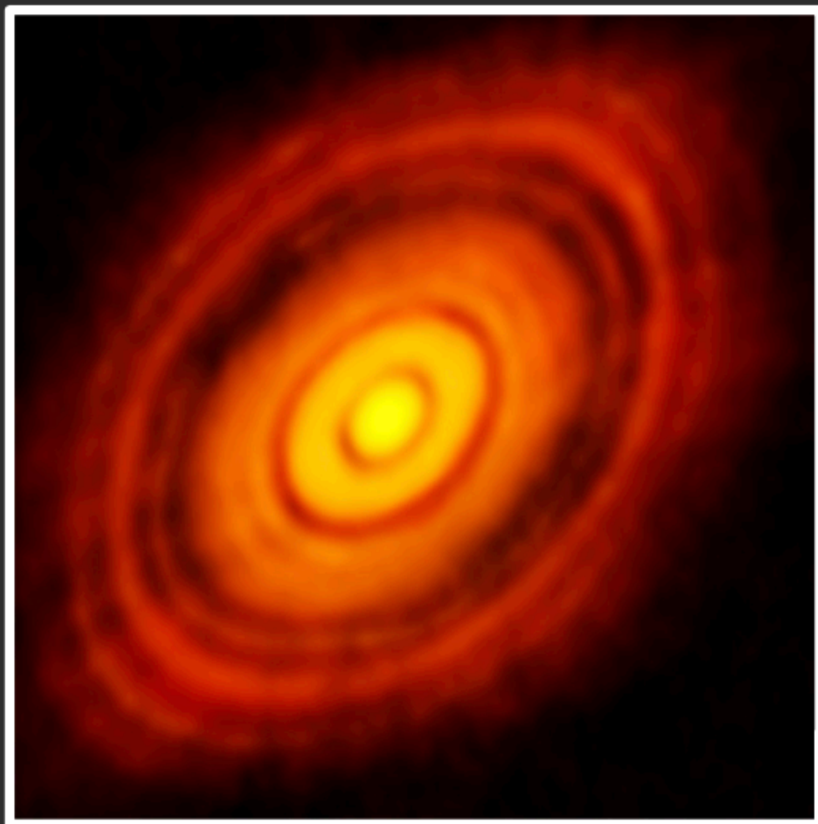
Keywords: accretion disks – protoplanetary disks – planets and satellites: formation

Can The Streaming Instability Ever Form Planetesimals From mm-size Grains?

Daniel Carrera[1] and Jacob B. Simon[1]

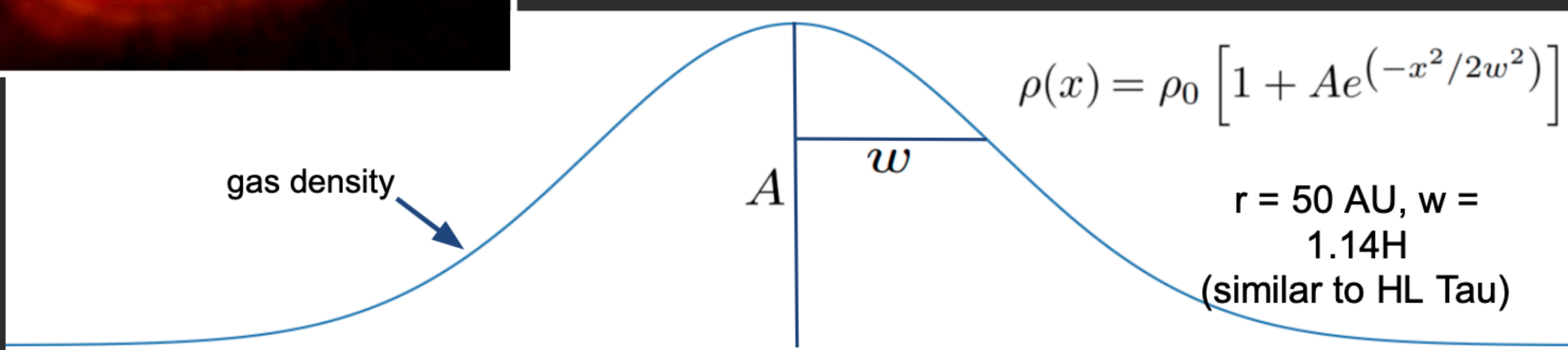
abstract to be written

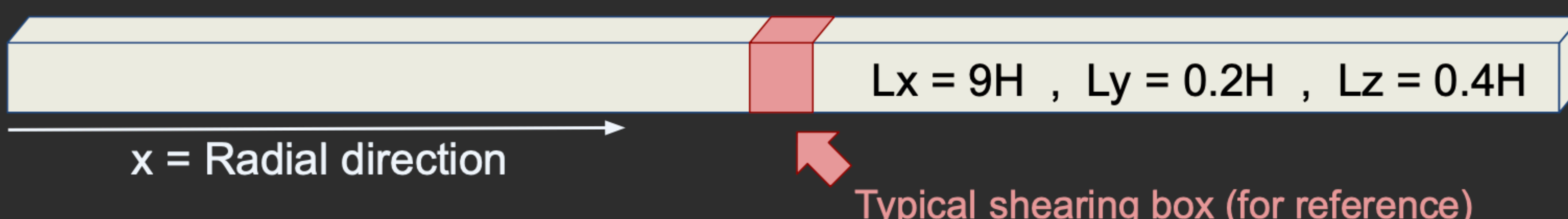
Experiment Setup



- Large 3D simulation box (~40 AU wide)
- Gaussian pressure bump similar to HL Tau
  (r = 50 AU, FWHM = 12 AU)
- Solar-like metallicitiy (Z = 0.01)
- cm size particles

Q: Will the bump trigger the SI?





Carrera, Simon, Kretke, Klahr (2020)

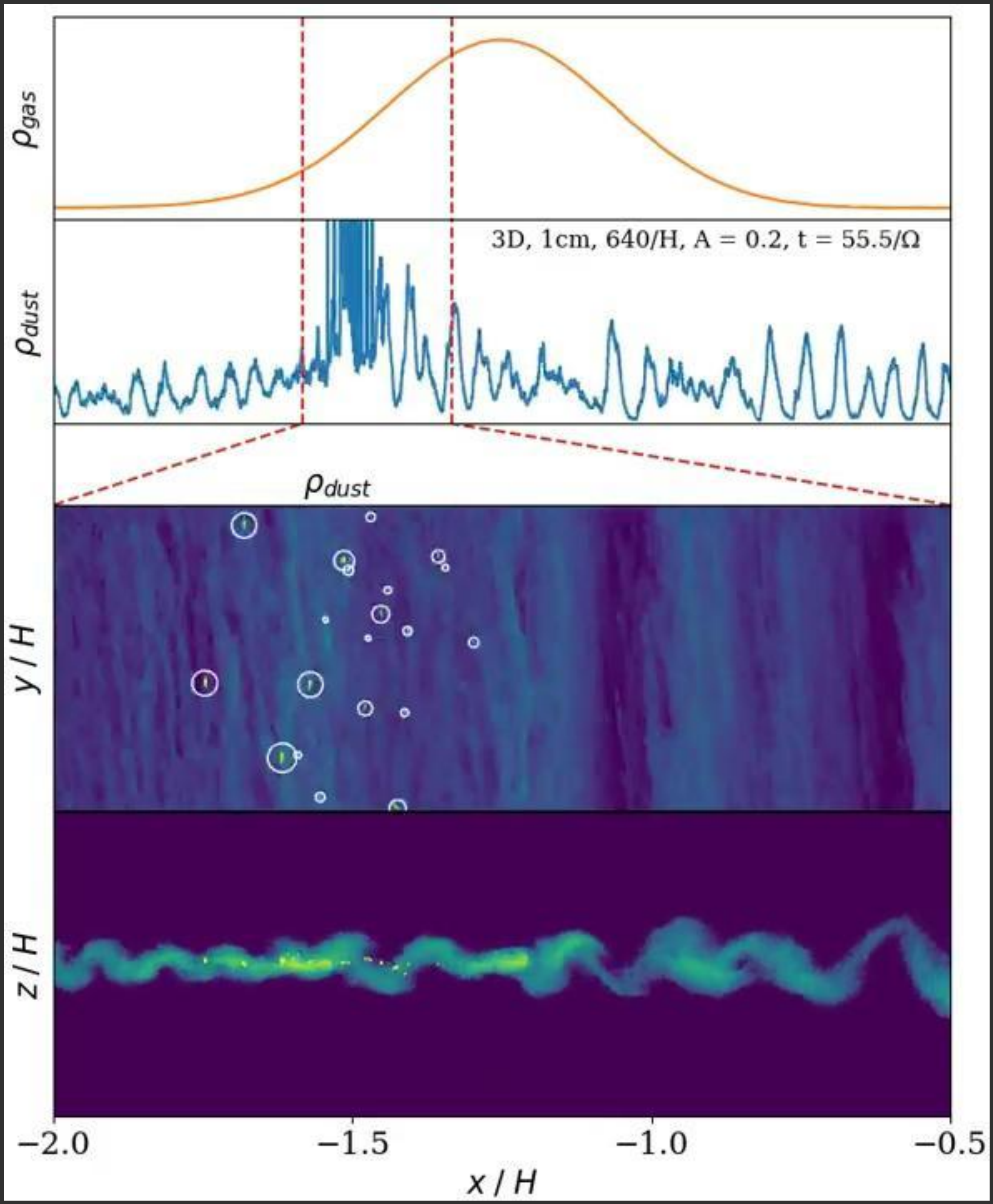
Results:

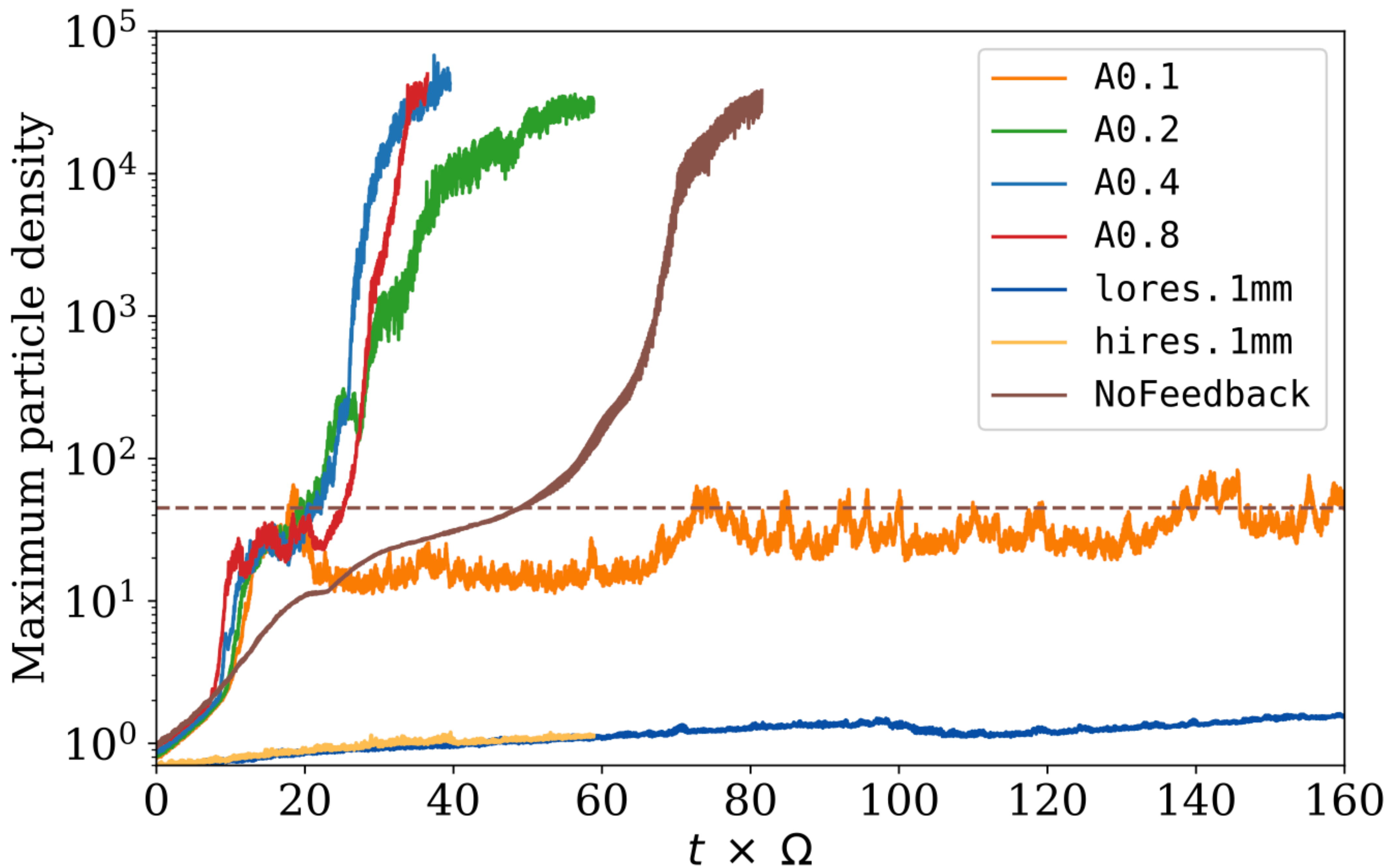
Particles form filaments everywhere

When the filaments pass through the bump they become denser

That overdensity triggers the SI and planetesimal formation.

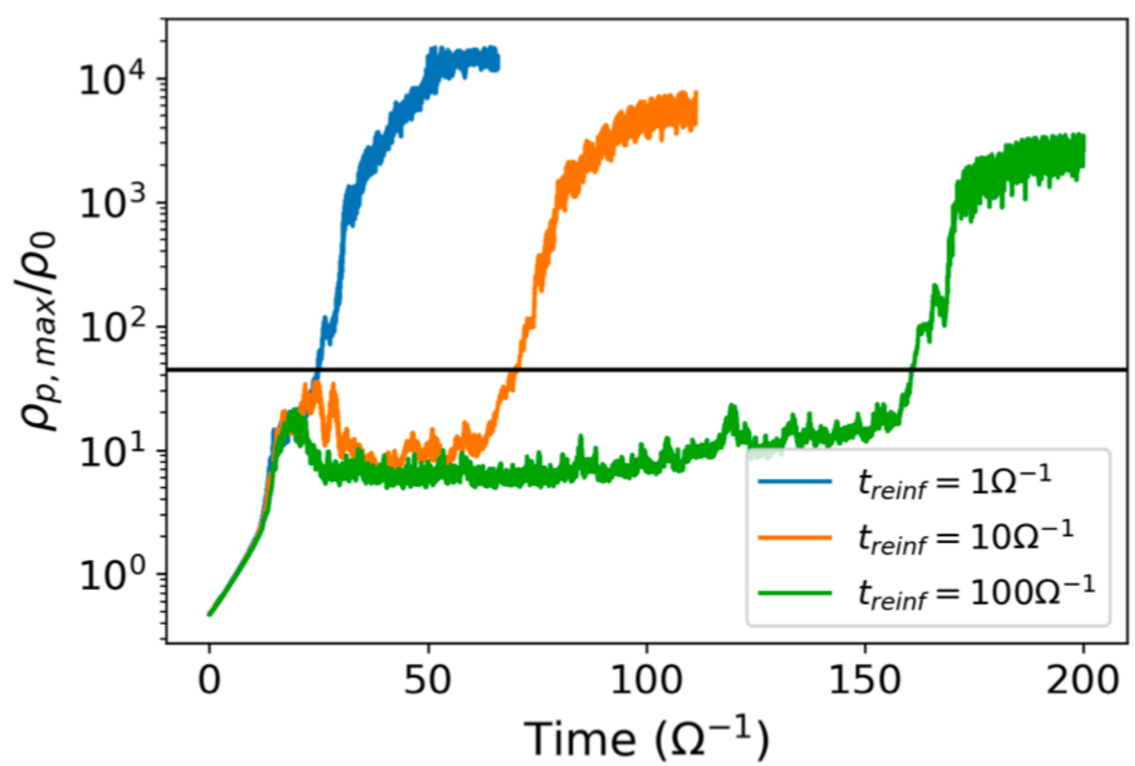
A particle trap is not needed to form planetesimals (for cm-size grains). A small pressure bump works fine.

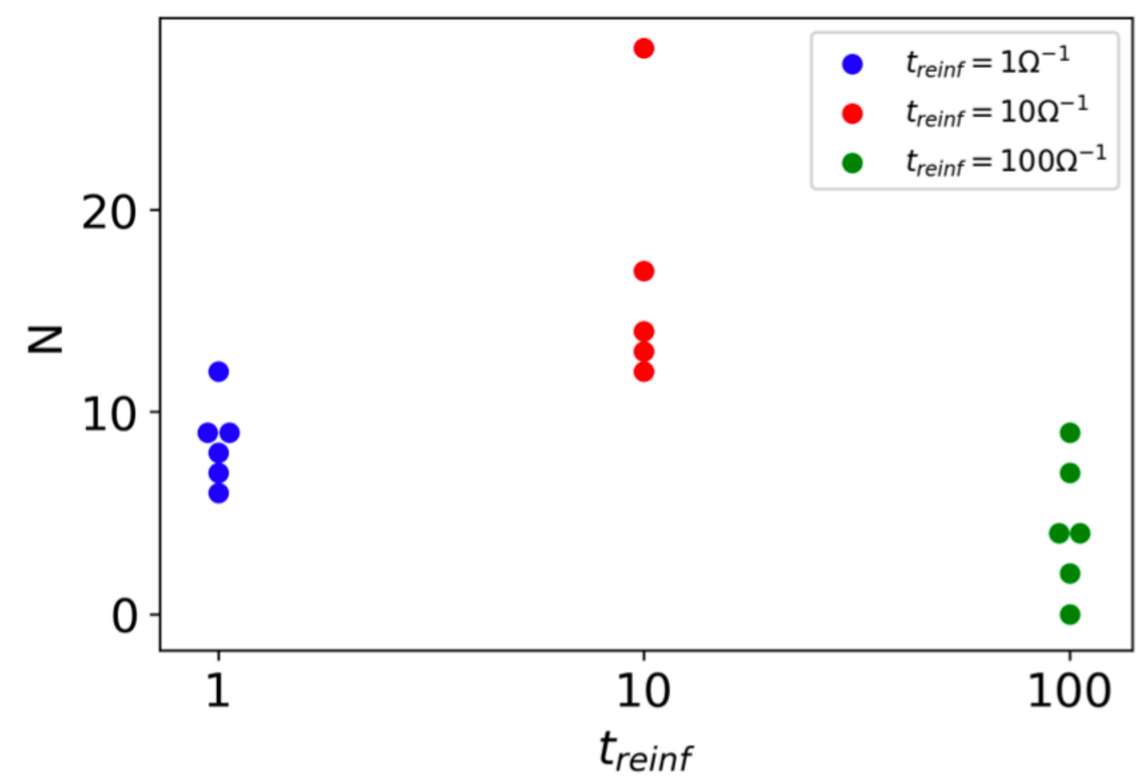




Maximum particle density
$t \times \Omega$
10^0
10^1
10^2
10^3
10^4
10^5
0
20
40
60
80
100
120
140
160
A0.1
A0.2
A0.4
A0.8
lores.1mm
hires.1mm
NoFeedback

$t_{\rm reinf}$ =	$1\Omega^{-1}$	$10\Omega^{-1}$	$100\Omega^{-1}$
$A = 0.20$	✓	✓	✓
$A = 0.15$	✓	✓	✓
$A = 0.10$	✗	✗	✗
$A = 0.05$	✗	✗	✗





Carrera, Simon (2021, in prep)

A = 0.5

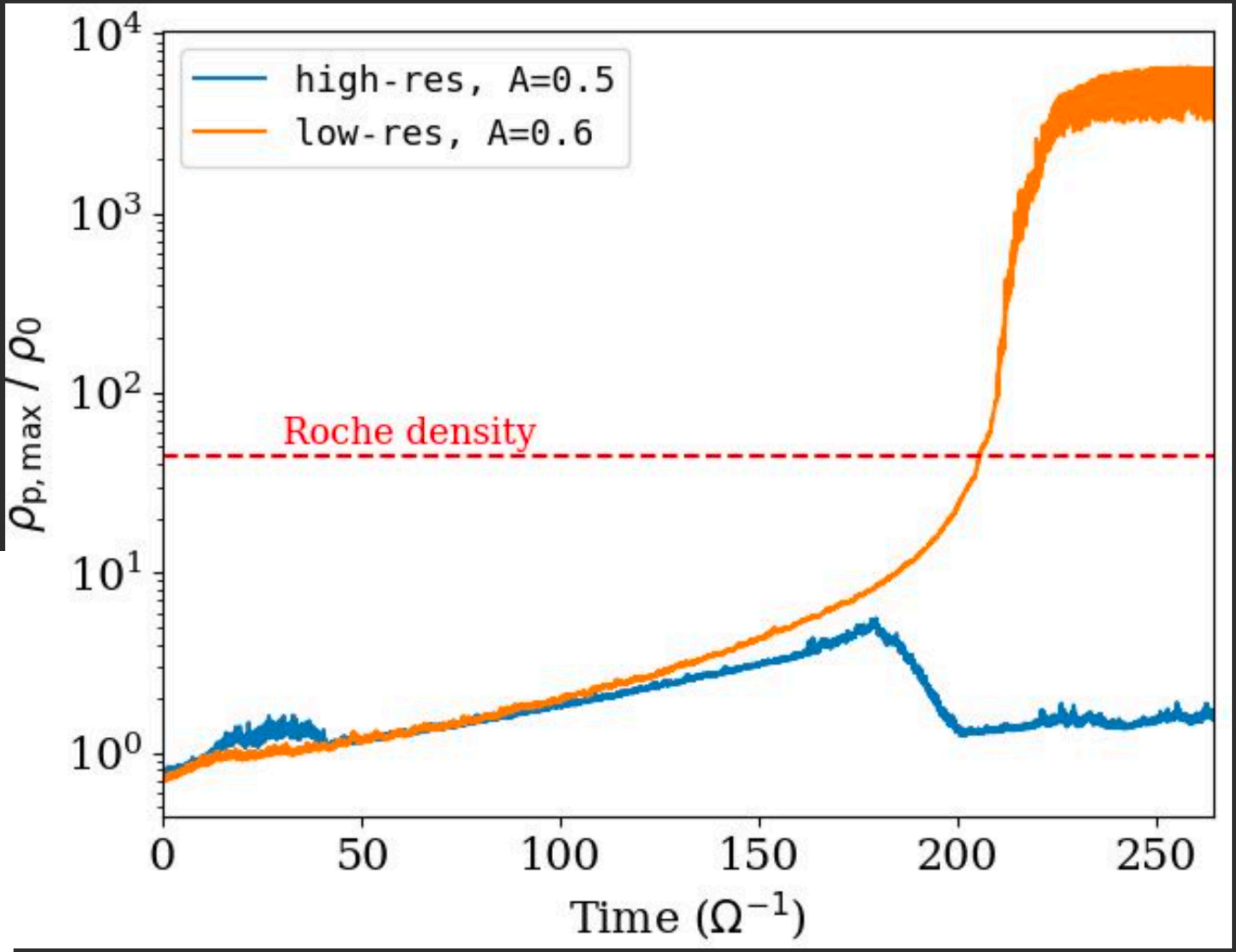
- high-res (1000/H)

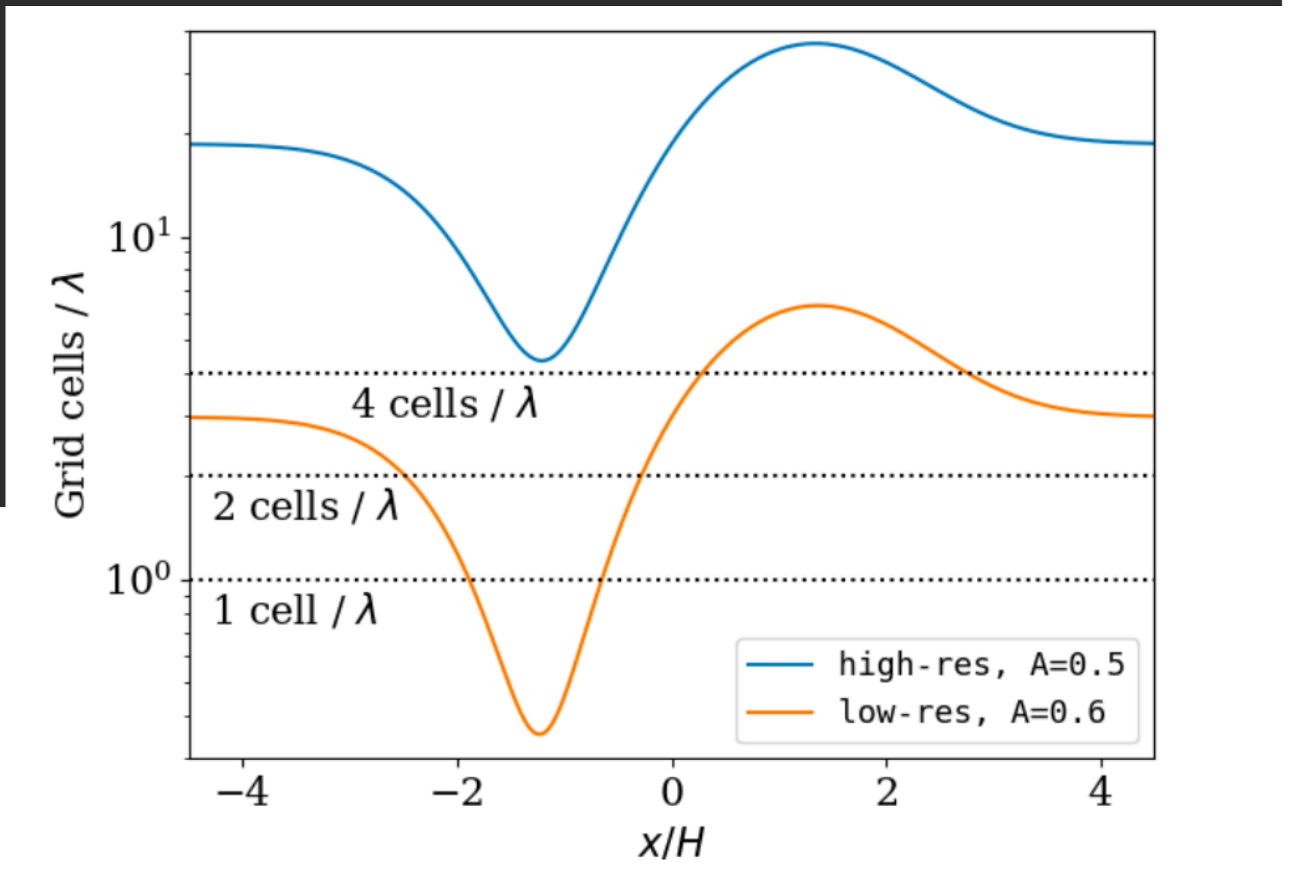
⇒ No planetesimals or strong clumping despite apparently high Z / Π

A = 0.6

- low-res (160/H)

⇒ Planetesimals form by gravitational instability *without the SI*.





Summary: (Key Points)

Paper I & Paper II

cm-size grains:

- Pressure bumps readily trigger planetesimal formation
- Particle trap is not needed; small bump works fine
- No constraint on the source of the bump
- But strong bumps lead to faster planetesimal growth

Paper III

mm-size grains:

- Any pressure bump large enough to form planetesimals by the SI is (probably) large enough to form planetesimals without it

∴ *EITHER,* disks form larger grains
OR the *SI* is not how planetesimals form