Testing the Streaming Instability: A comparison of planetesimal size distributions between simulation and the Cold Classical Belt

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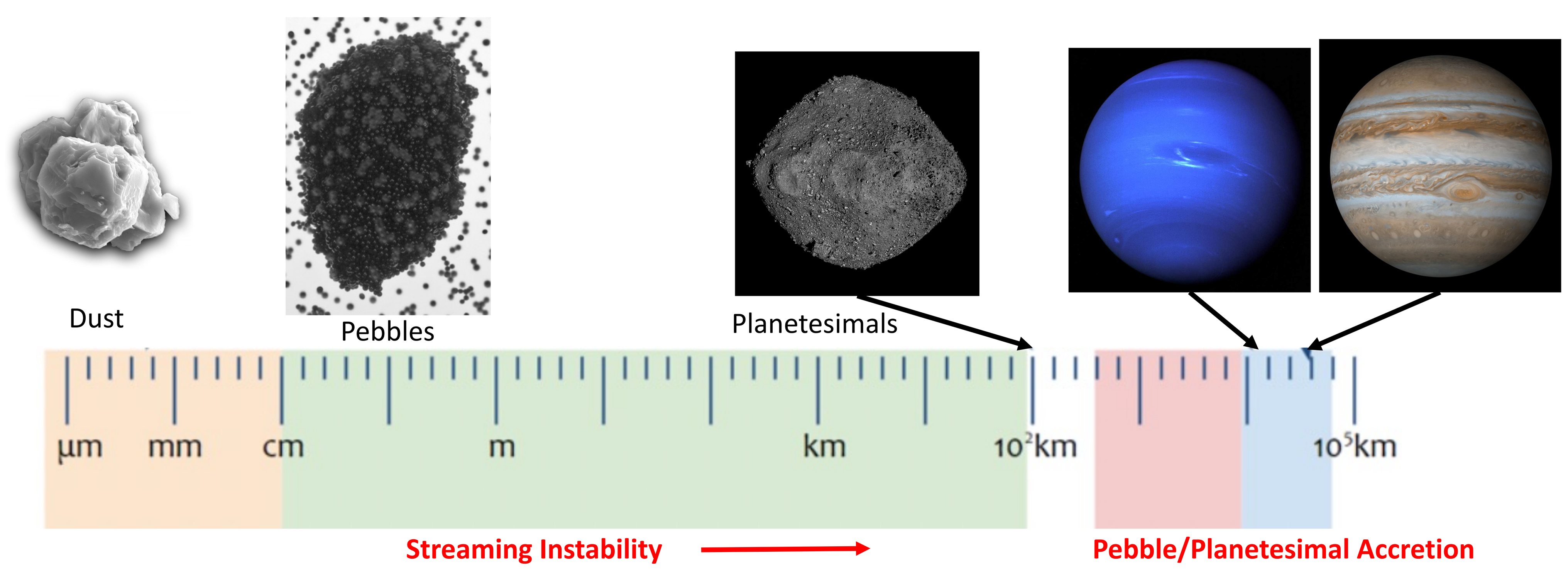
Introduction

Planet formation encompasses a growth of more than 13 orders of magnitudes in size, ranging from mm-sized dust grains to km sized planets. The intermediate stage involves formation of 1km—100km sized building blocks of planets, known as planetesimals. How dust grains grow into planetesimals is one of the largest outstanding questions in planet formation.

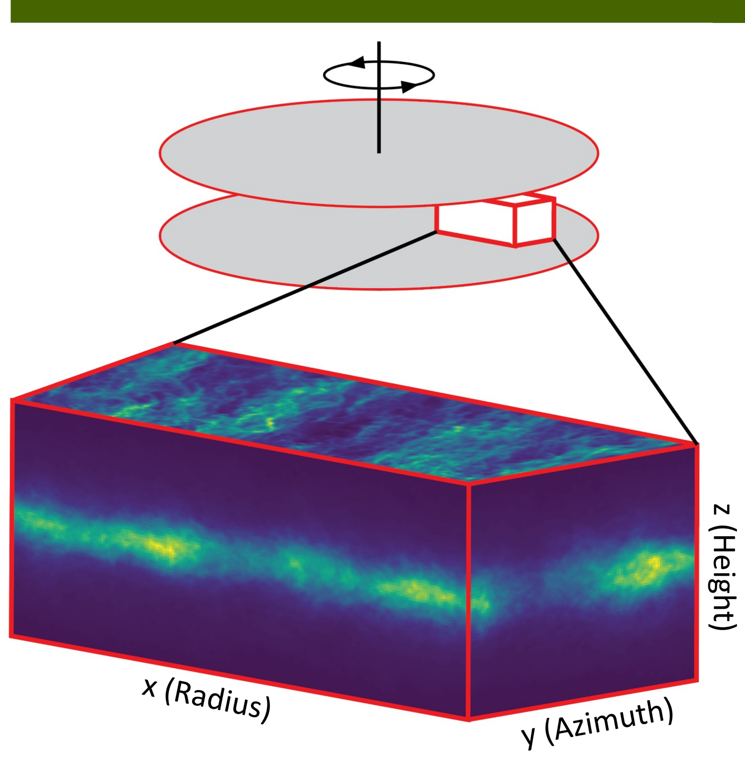
The streaming instability (SI) is one of the most promising mechanisms for planetesimal formation as it provides a robust and rapid path around growth barriers. The SI arises from angular momentum exchange between gas and solid particles via aerodynamic coupling in protoplanetary disks, resulting in sufficiently high particle densities that gravitational collapse ensues, producing planetesimals.



Motivation

- Observation shows exponential taper in the CCB size distribution. Does that taper occur in planetesimal populations from streaming instability simulations?
- What physical parameters for SI simulations bring the planetesimal size distribution closer to observation?

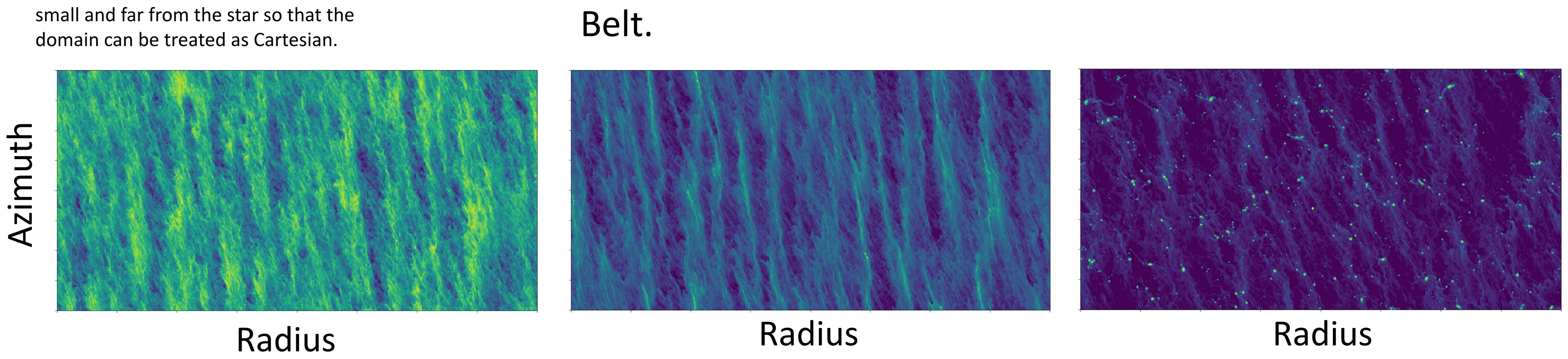
Numerical Methods: Shearing Box



*A co-rotating patch of the disk, sufficiently small and far from the star so that the domain can be treated as Cartesian.

We carry out fully 3D gas+particle hydrodynamic simulations in a shearing box using the *Athena* code. We include self-gravity of particles to form planetesimals. We vary the physical parameters of the gas in the shearing box to investigate how the shape of planetesimal initial mass functions is affected.

By tracking individual particles, gravitationally bound clumps of particles are identified as planetesimals. By tracking from frame to frame, their initial mass at formation can be captured to construct an initial mass function. By ignoring further accretion, these planetesimals should be similar to a pristine, low-collision population such as the Cold Classical Belt.



Result 1: Non -parametric Comparison

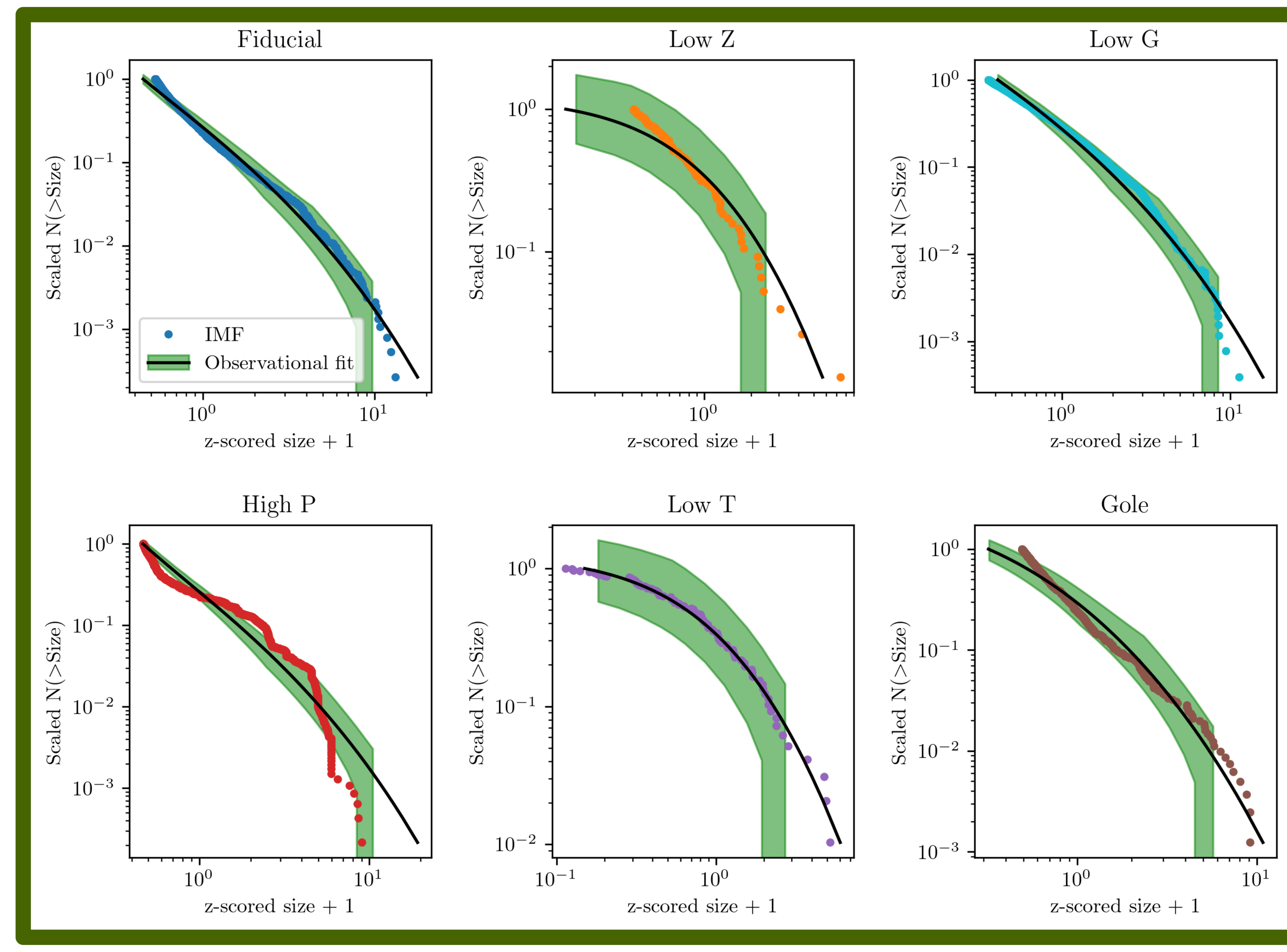


Figure 1. Normalized size distributions from observation (black/green) and simulation (color). Y-axis is scaled by total number in simulation to be between 0-1, x-axis is scaled with the z-score linear transformation.

By subsampling from the observational distributions, we can compare simulation to observation in a normalized space. Simulation and observation samples can be compared via K-S test. High p-values are calculated for the Low G and Low T simulations. This demonstrates that the general shape of the simulation IMFs are similar to observation.

	Objects	OSSOS 1 N/A	OSSOS 2 N/A	DEEP N/A
Fiducial	3762	~ 0	~ 0	~ 0
Low Z	76	0.002	0.002	0.002
Low G	2567	~ 0	**0.265**	0.047
High P	4644	~ 0	~ 0	~ 0
Low T	97	**0.899**	**0.563**	**0.899**
Gole	808	~ 0	~ 0	~ 0

Result 2: Parametric Comparison

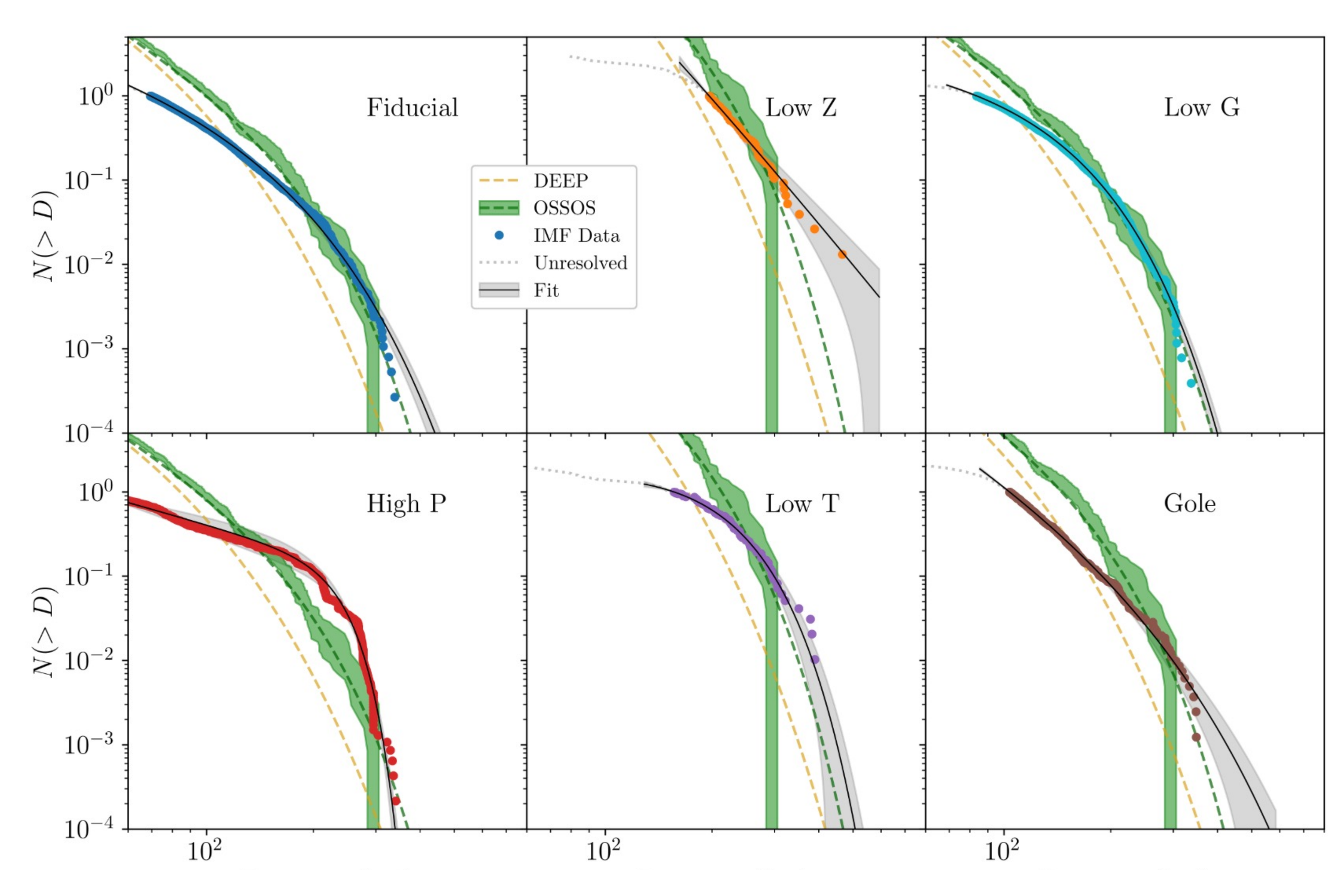


Figure 2 . Size distributions in physical diameter space, unnormalized. Y-axis is scaled by the total number of objects to be between 0-1. Observational distribution models are in dashed lines, and the simulation objects are in color, with their VTPL fits in black/grey with 1 sigma error.

$$N(>M) = c\, M^{-\alpha} \exp\left[-\left(\frac{M}{M_{exp}}\right)^{-\beta}\right]$$

A parametric comparison can be done by assuming a form to the IMF/size distribution. The variably (or exponentially) tapered power law (VTPL) takes the form above. Power law components alpha and beta can be directly compared to observation. This comparison favors the lower α from the DEEP survey, and the tapering power β for the Low Z, Low G, and Low T physical parameters matches the tapering for observation.

Conclusion

- The SI can reproduce a taper in size distribution that is similar to observation.
- Simulation parameters that are more representative of the conditions in the early protosolar disk at the location of the CCKB produce size distributions in stronger agreement with observations.
- Our work represents another critical test of the streaming instability paradigm; preliminary evidence suggests that the streaming instability passes this test.

References
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Link to PDF of poster, supplemental videos, and additional references (github.com)