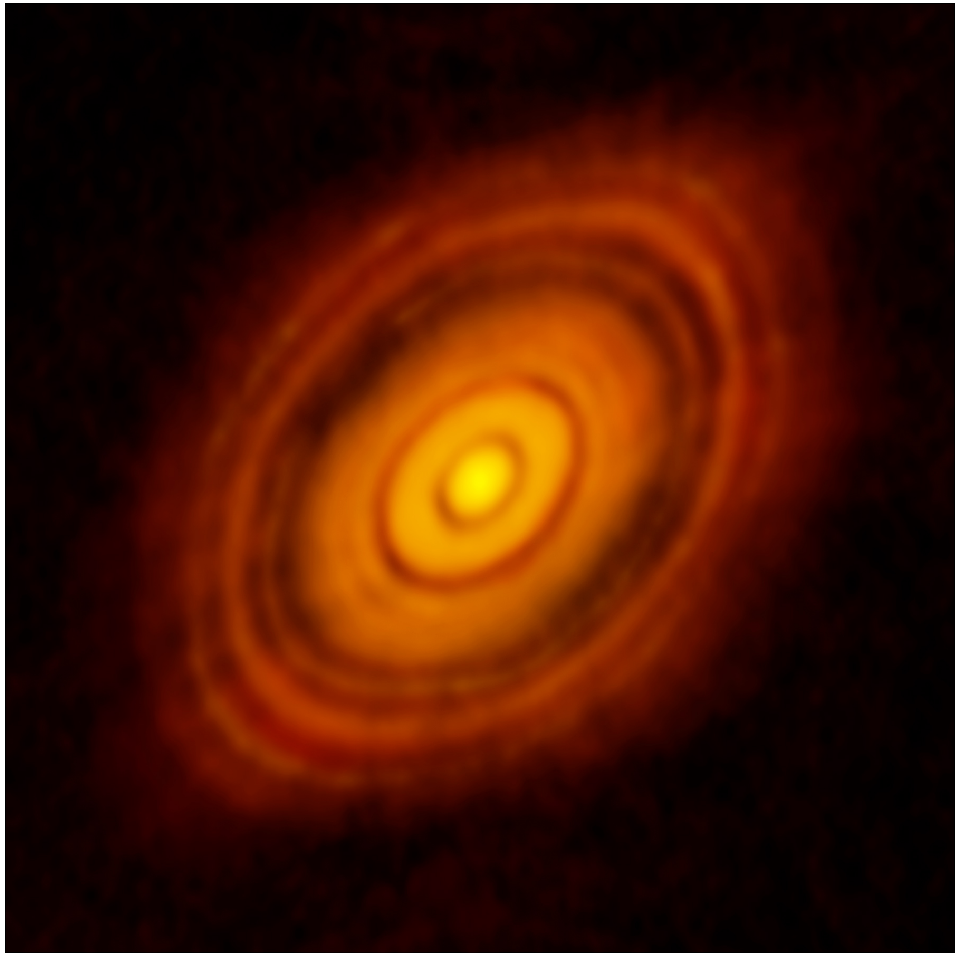
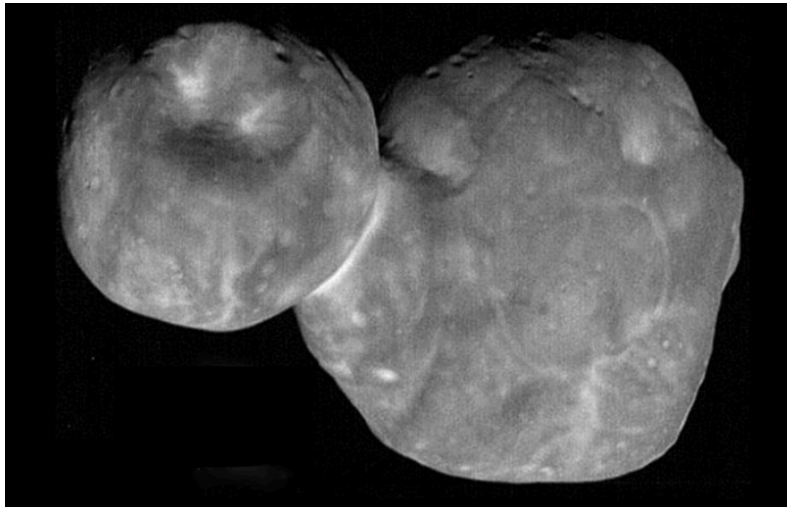
Class 18 – Apr 7th, 2020

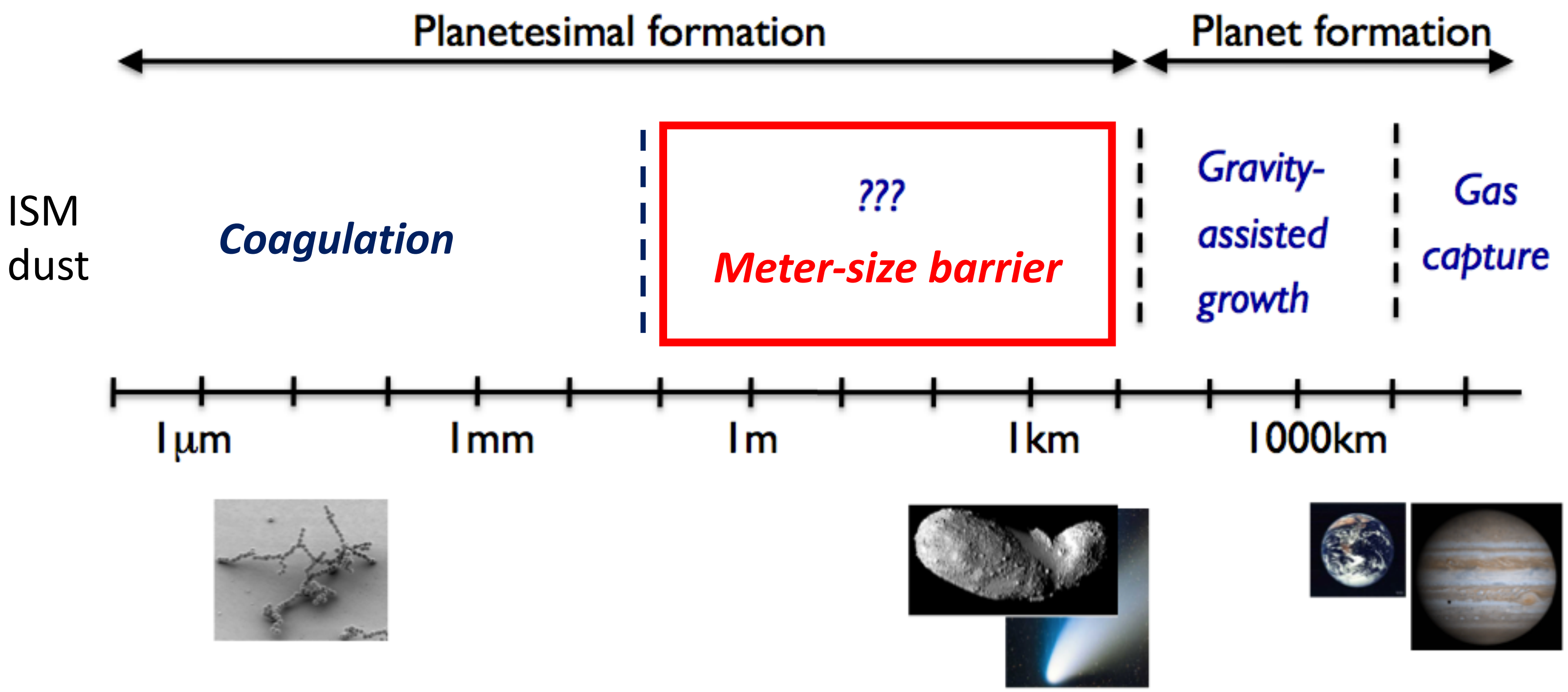
Planetesimal Formation



How?

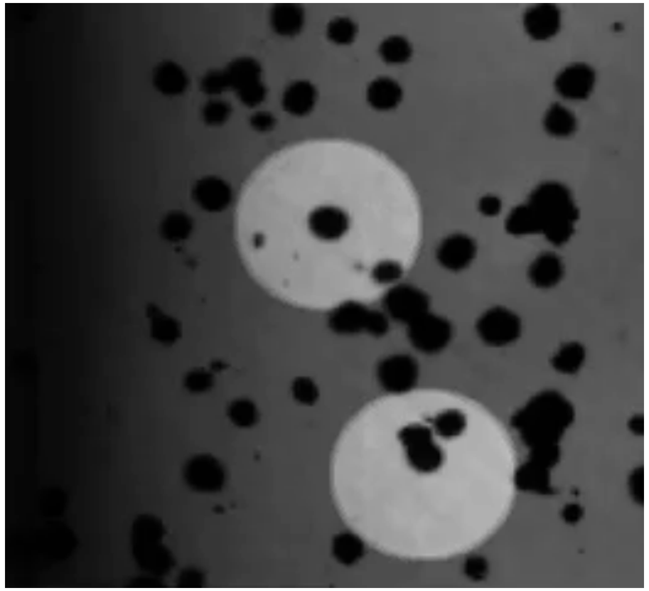


Dust evolution – Barriers to Growth

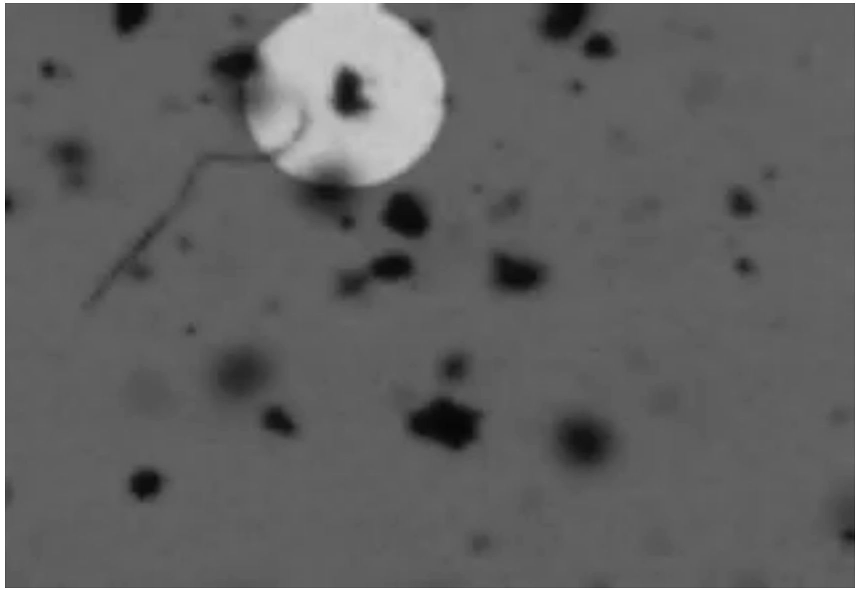


Grain collision outcomes

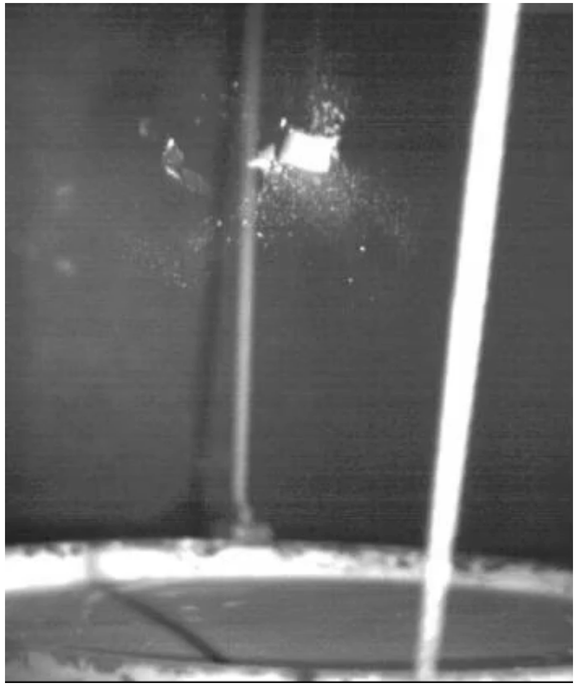
Bouncing



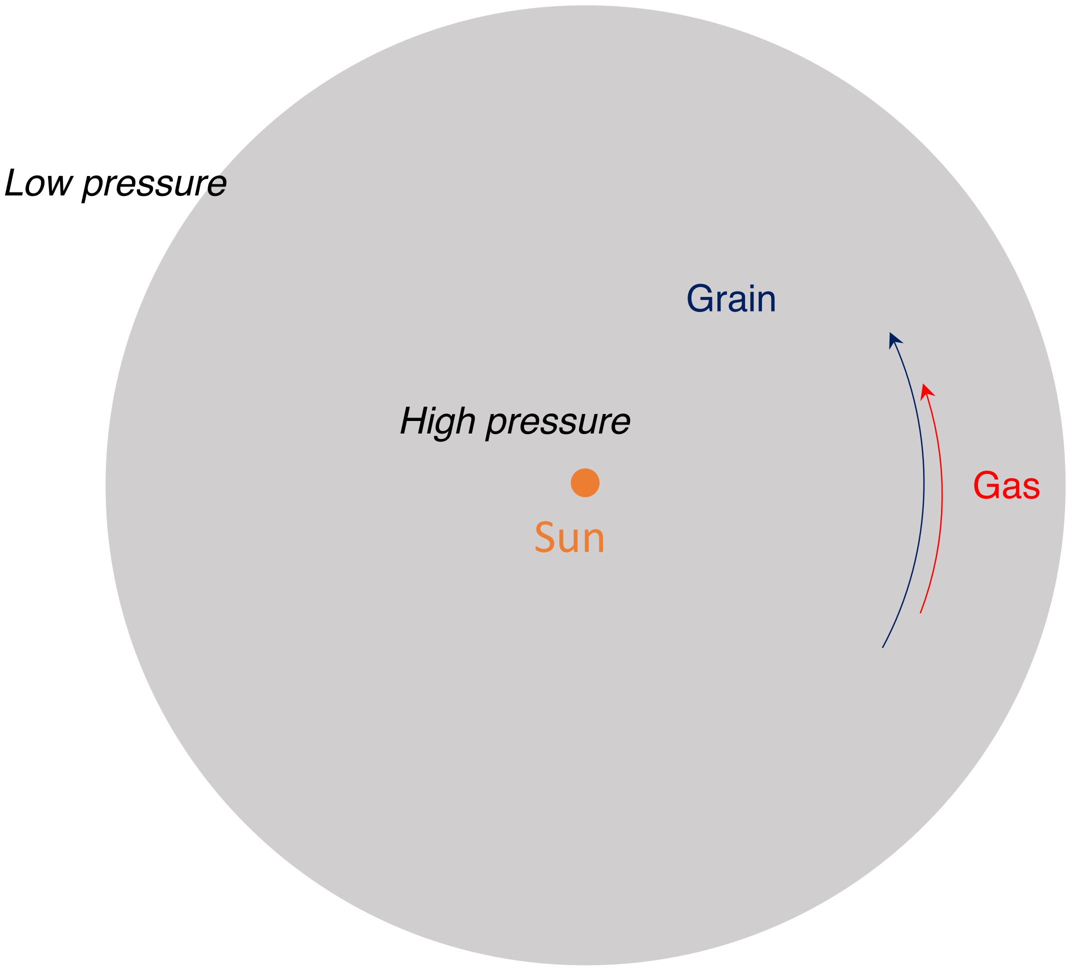
Sticking



Fragmentation



Drift barrier

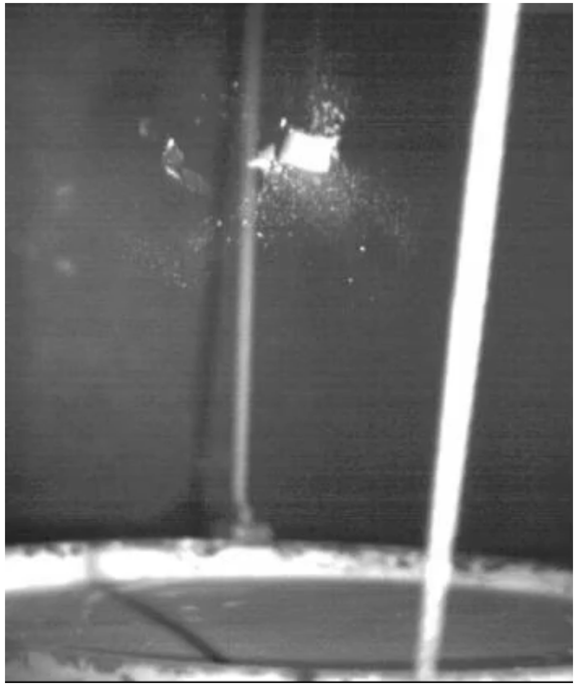


The gas has some pressure support.

The grains have none.

Meter-size barrier

Fragmentation barrier



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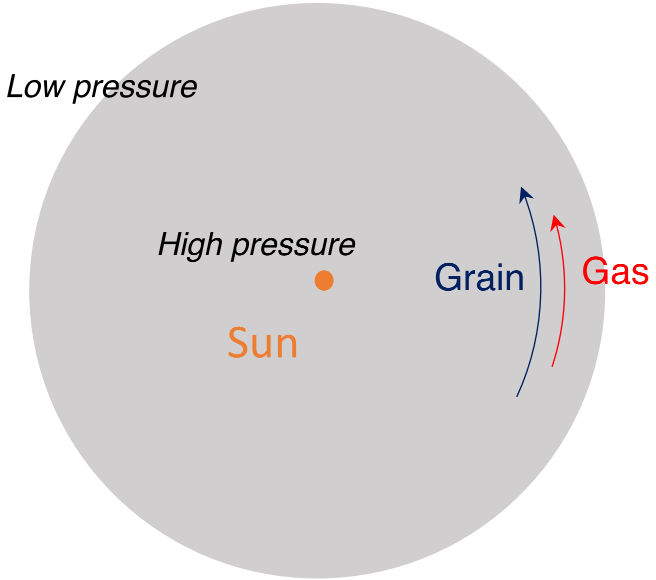
Drift barrier



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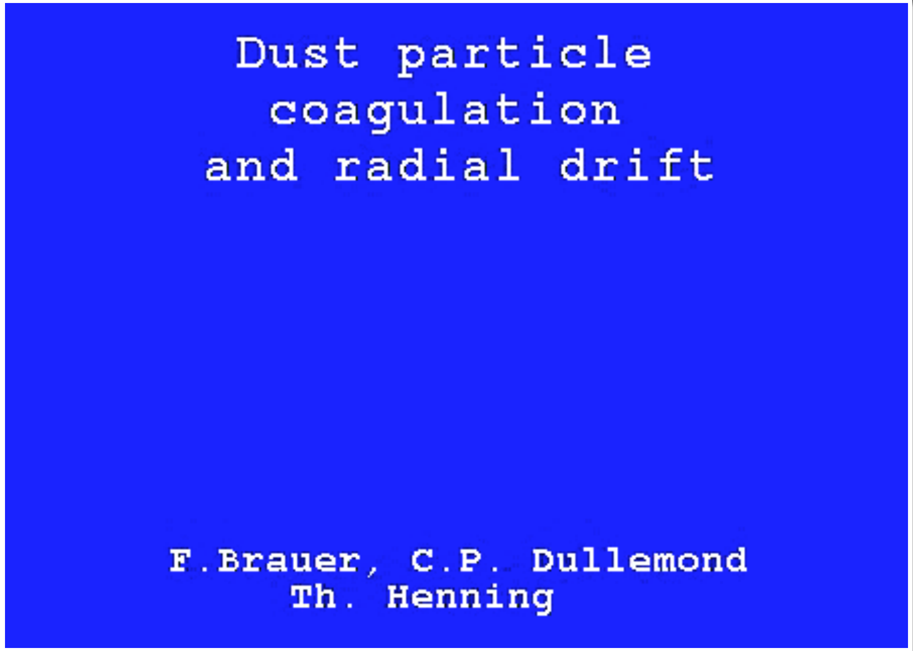
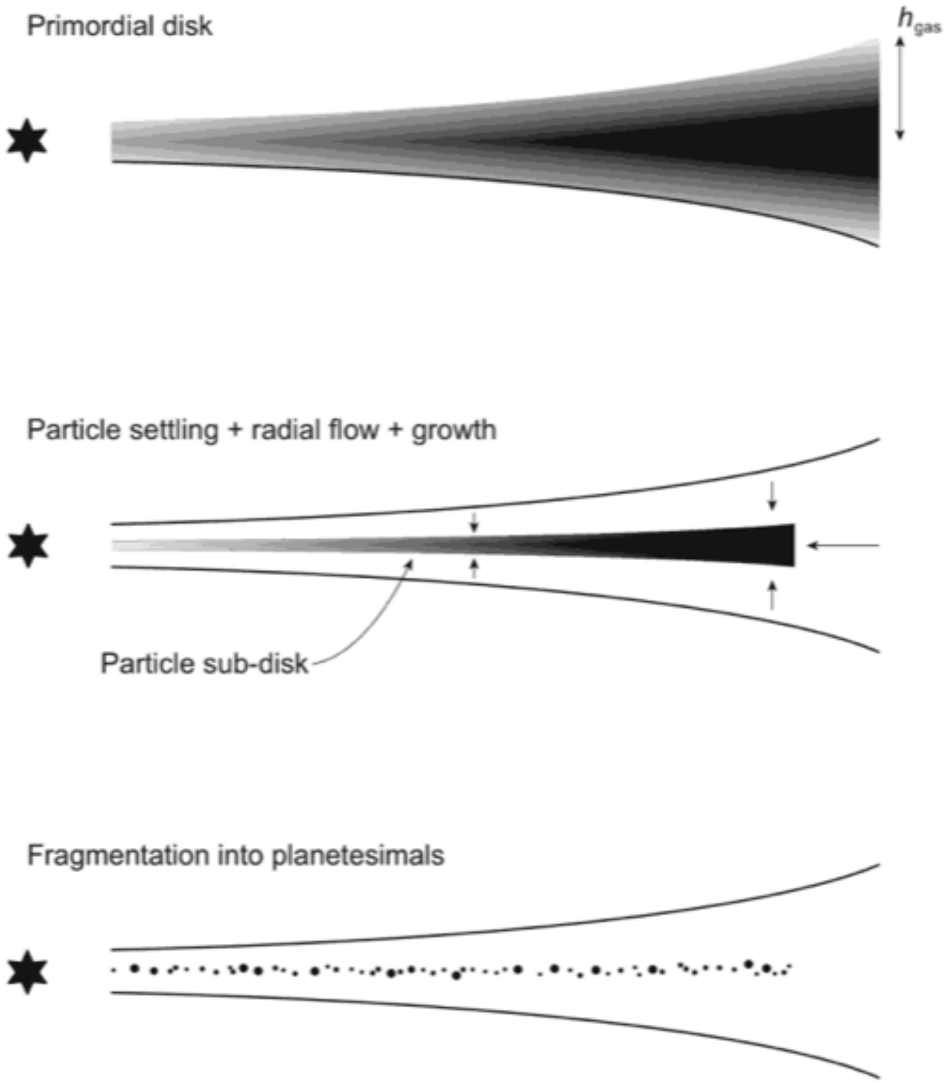
Meter-size barrier

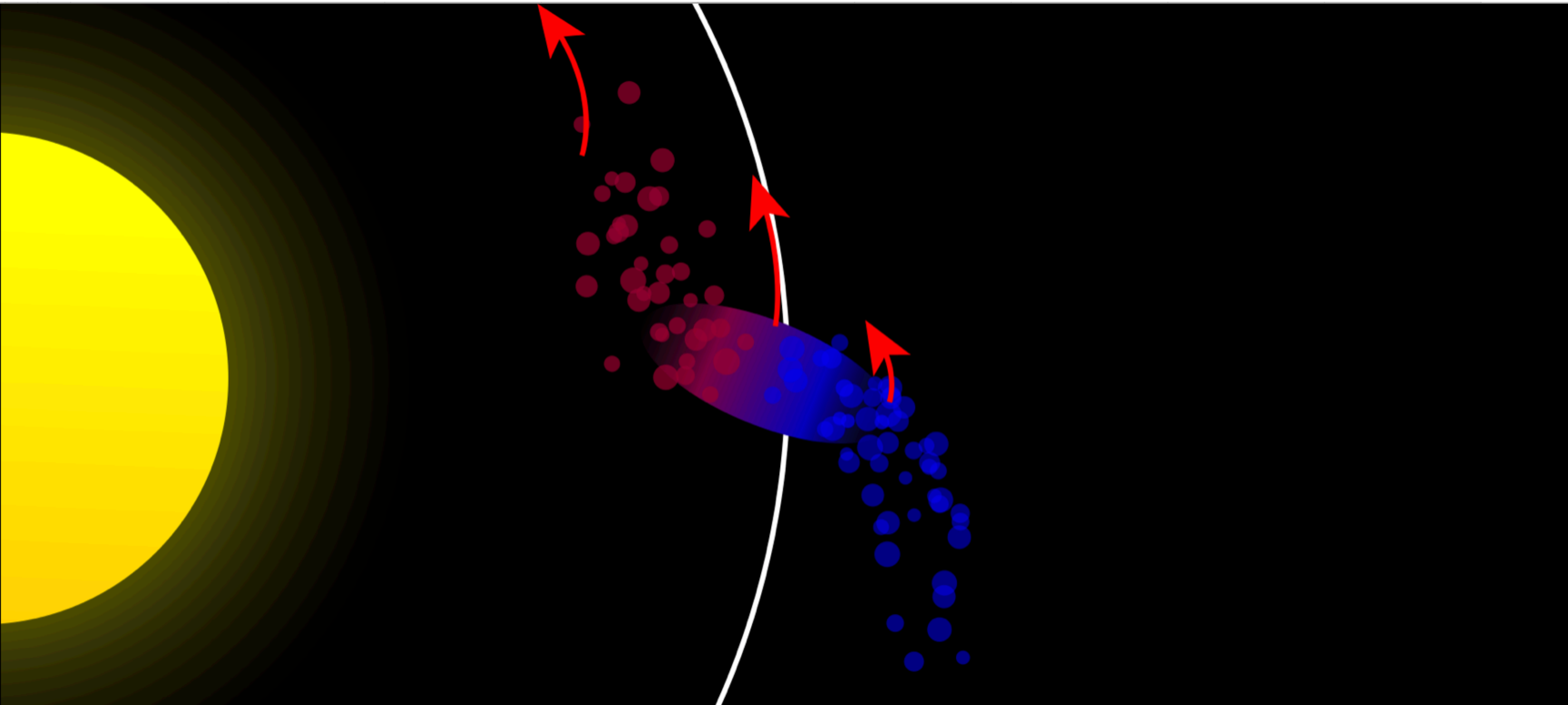


The Goldreich-Ward scenario

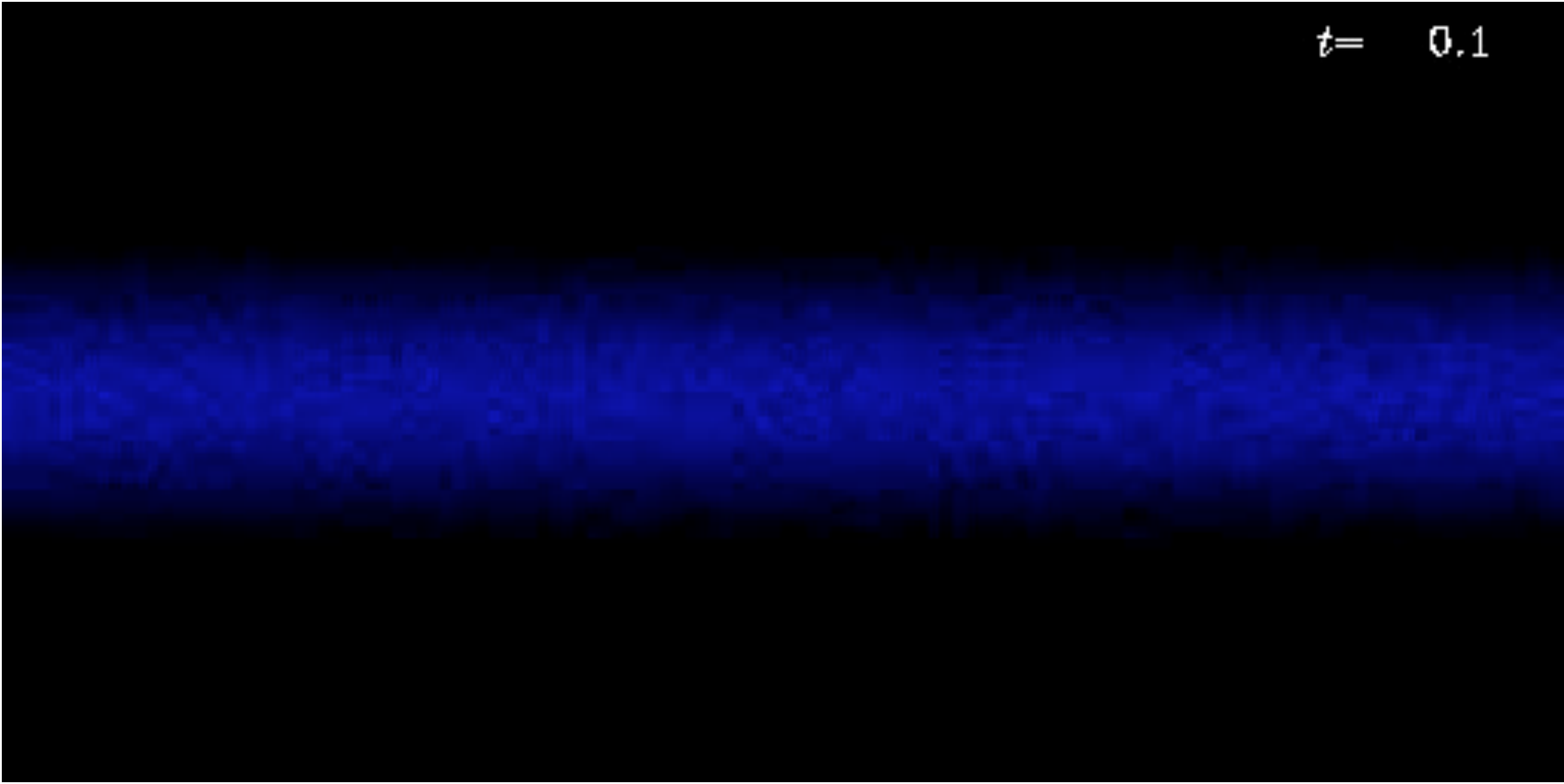


Roche Limit

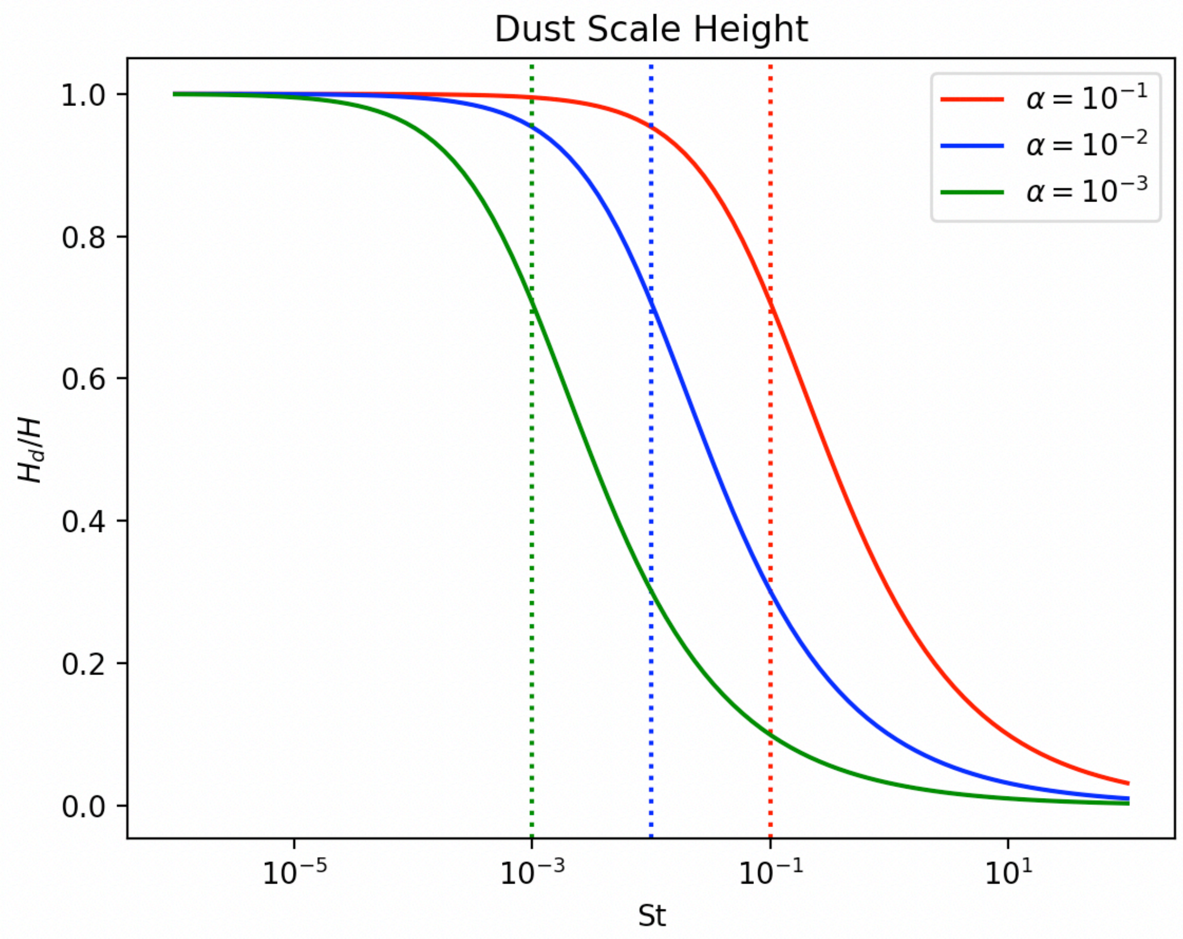
Solar tide *vs* selfgravity




A trillion planetesimals


t= 0.1

Dust: Diffusion-supported



Dust: Diffusion-supported

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The dust subdisk in the protoplanetary nebula.

Show affiliations

Dubrulle, B.; Morfill, G.; Sterzik, M.

We present a self-consistent computation of the structure of the dust subdisk in the protoplanetary nebula. The main physical processes governing the dynamics of the dust disk are reviewed. A (nonlinear) vertical diffusion equation for the transport of dust particles is derived. It is based on a competition between sedimentation processes due to gravity and diffusion due to turbulence. The vertical structure of the subdisk is computed by solving numerically the diffusion equation. The influence of both the particle size and the strength of the turbulence is studied. Large particles are found to settle down toward their equilibrium distribution in a turbulent diffusive time scale. Small particles remain mixed throughout the whole gas disk. Simple analytical estimates of the dust scale height are given. They are found to agree closely with the exact numerical solutions. The implications of our results for cosmochemistry and the structure of the solar nebula are discussed.

Publication: Icarus, Volume 114, Issue 2, p. 237-246.

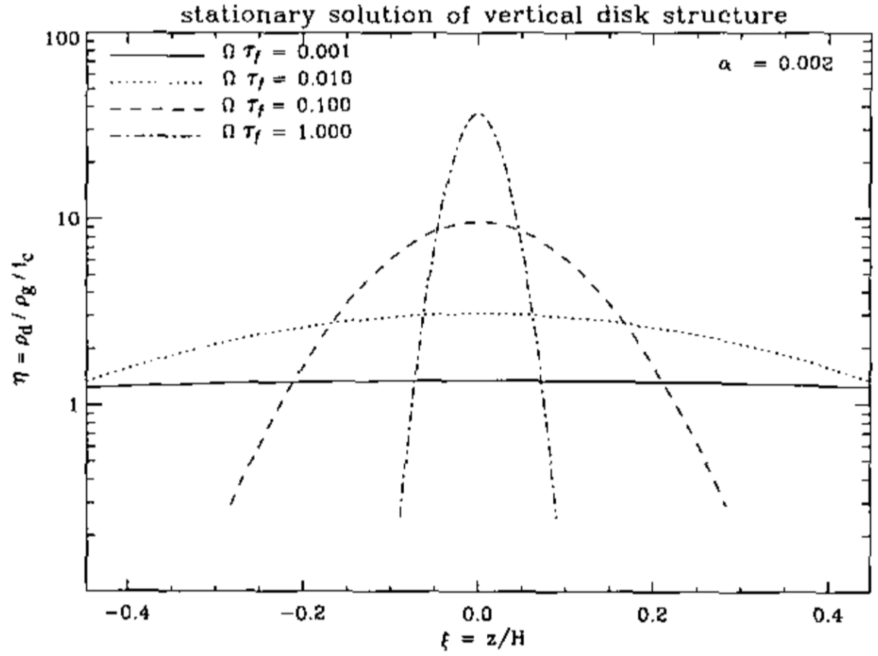
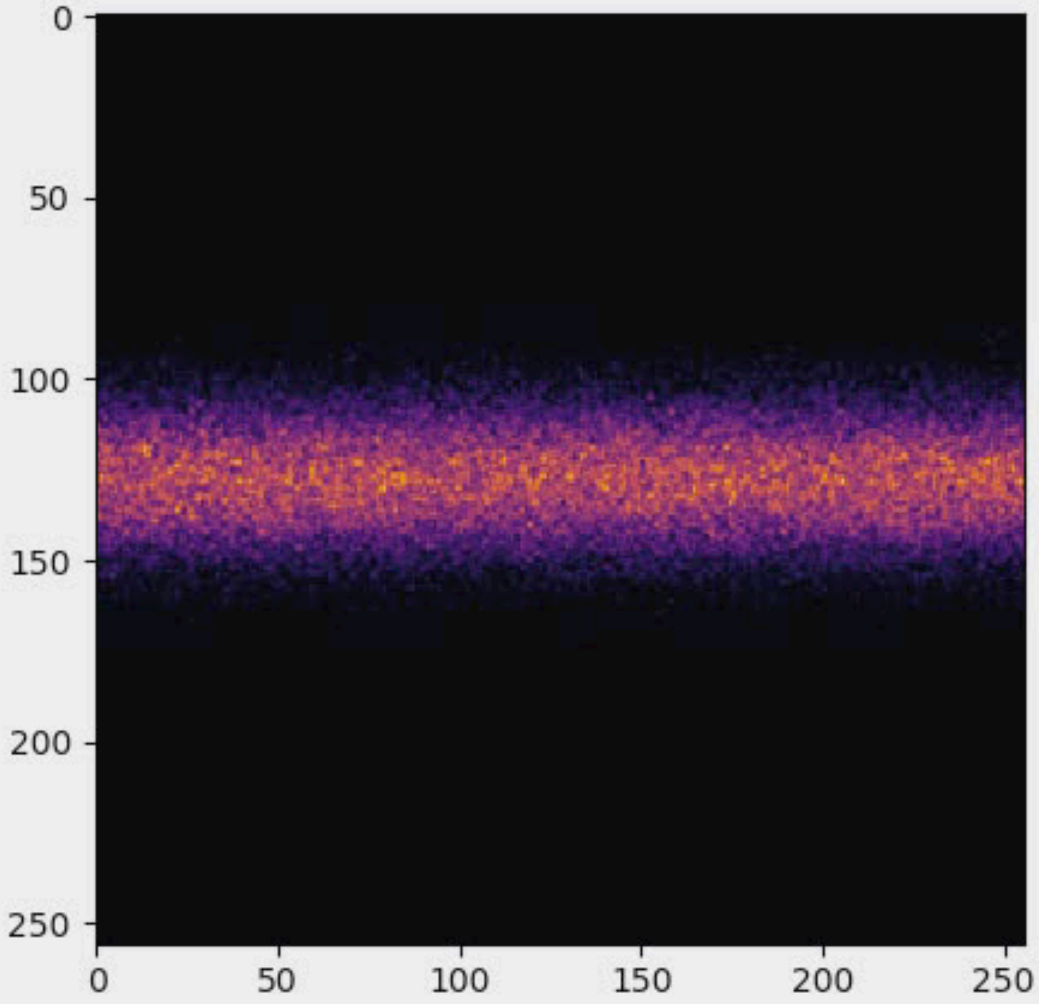


FIG. 3. The stationary solutions of the vertical disk structure for $\Omega\tau_f = 0.001, 0.01, 0.1, 1$, and $\alpha = 0.002$.

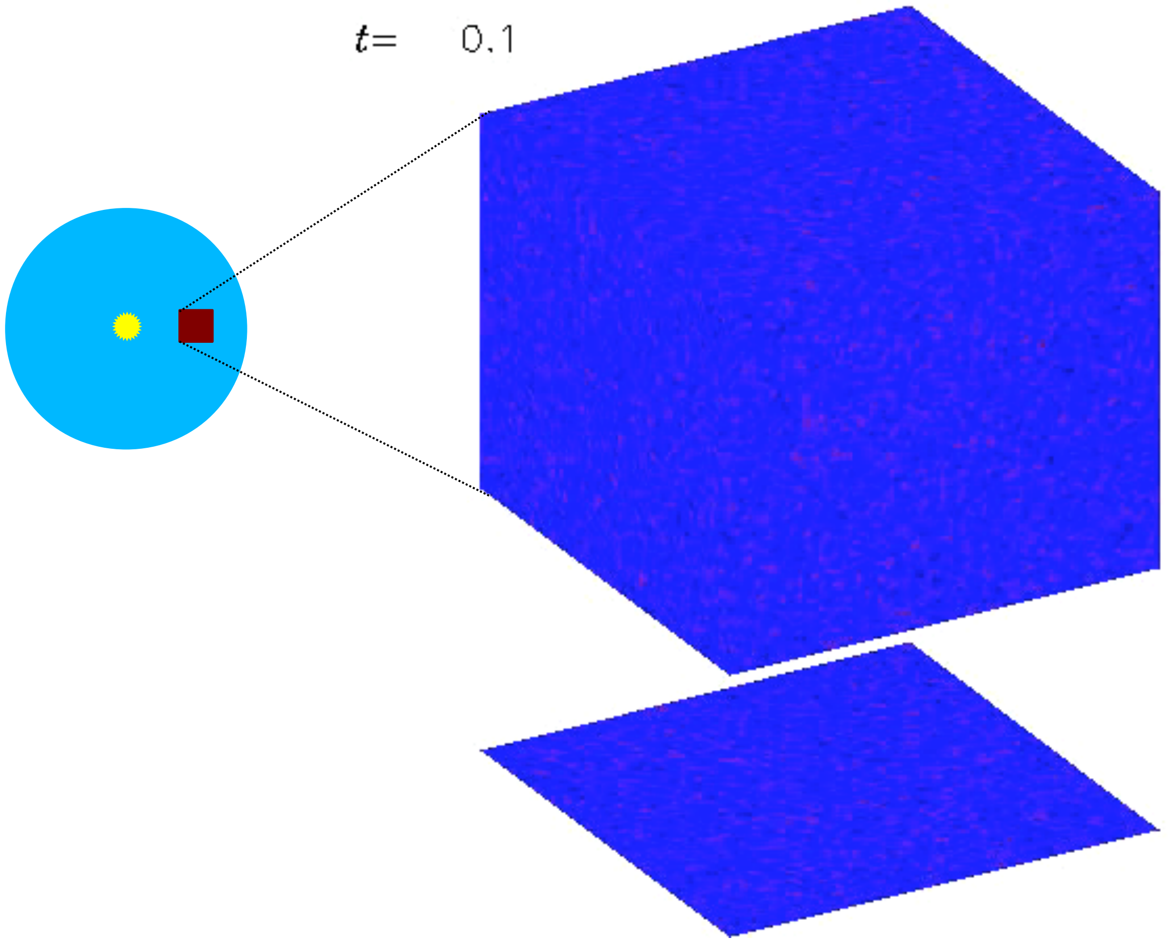
Two-species sedimentation



Canas et al. in prep

Streaming Instability

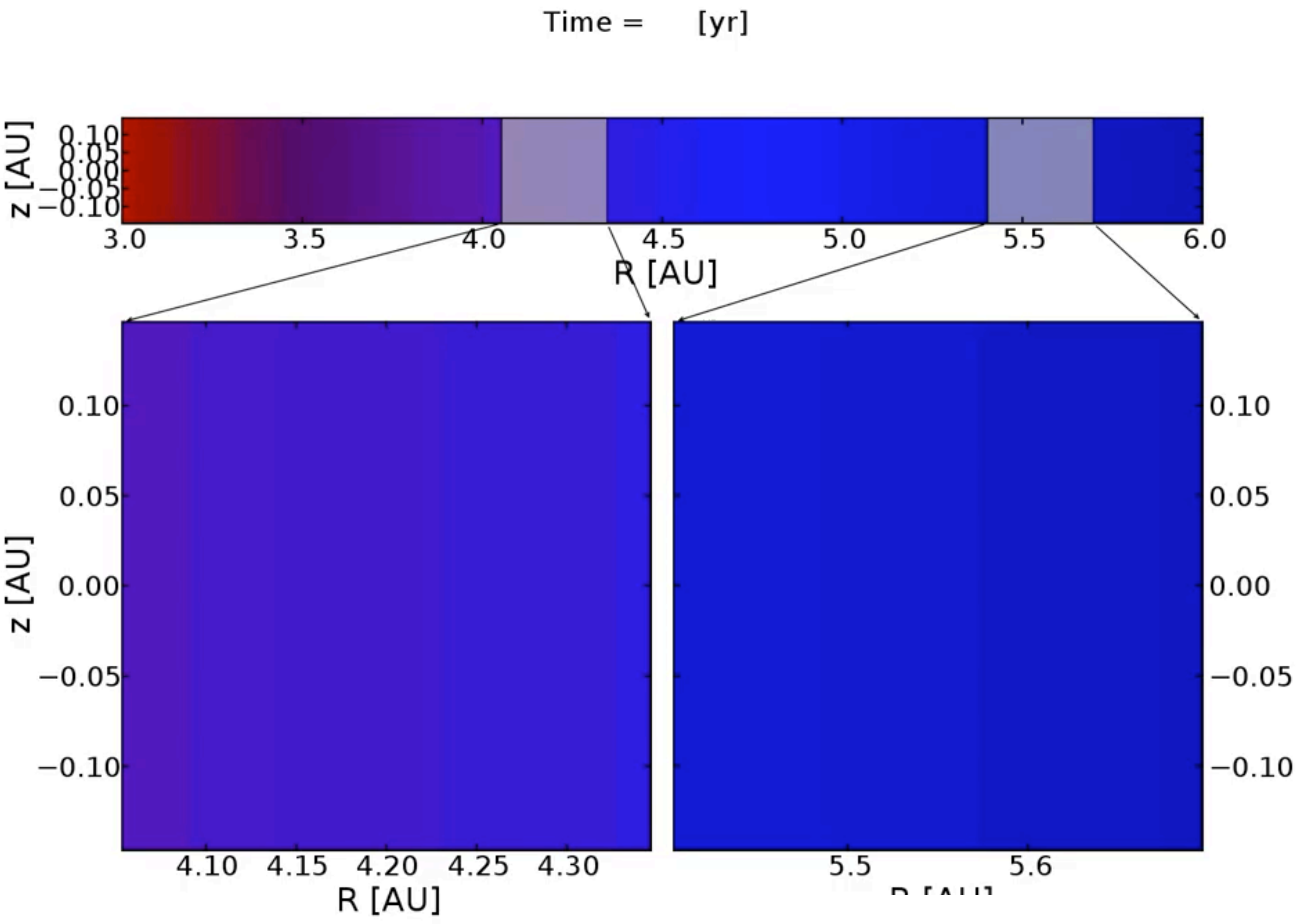
The dust drift is hydrodynamically unstable



Youdin & Goodman ‘05,
Johansen & Youdin ‘07,
Youdin & Johansen ‘07

Streaming Instability

The dust drift is hydrodynamically unstable



Kowalik+ '13

The Nakagawa-Sekiya-Hayashi solution for dust drift

ICARUS 67, 375–390 (1986)

Settling and Growth of Dust Particles in a Laminar Phase of a Low-Mass Solar Nebula

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Geophysical Institute, Faculty of Science, University of Tokyo, Tokyo 113, Japan

MINORU SEKIYA
Department of Physics, Faculty of Science, Kyoto University, Kyoto 606, Japan

AND

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Momoyama Yogoro-cho 1, Fushimi-ku, Kyoto 612, Japan

Received September 6, 1985; revised April 7, 1986

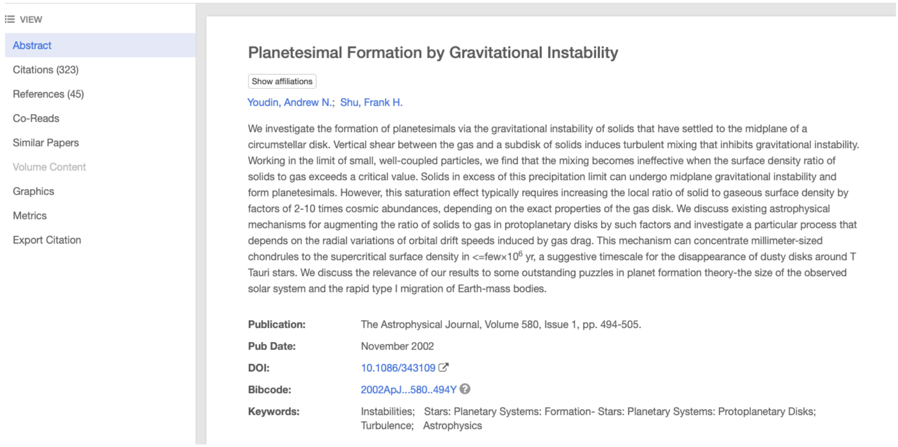
$$
\begin{aligned}
v_r &= -\left(\frac{1}{1+\varepsilon}\right)\frac{2\mathrm{St}}{1+\mathrm{St}^2}\eta u_k \\
u_r &= \left(\frac{\varepsilon}{1+\varepsilon}\right)\frac{2\mathrm{St}}{1+\mathrm{St}^2}\eta u_k \\
&= -\varepsilon v_r
\end{aligned}
$$

Dust drifts inward

Gas is pushed outward

Streaming Instability

The dust drift is hydrodynamically unstable



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Planetesimal Formation by Gravitational Instability

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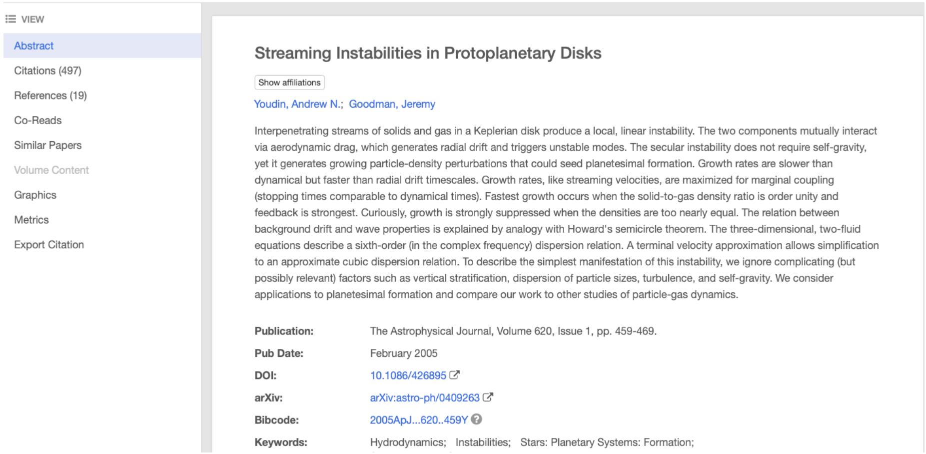
Youdin, Andrew N.; Shu, Frank H.

We investigate the formation of planetesimals via the gravitational instability of solids that have settled to the midplane of a circumstellar disk. Vertical shear between the gas and a subdisk of solids induces turbulent mixing that inhibits gravitational instability. Working in the limit of small, well-coupled particles, we find that the mixing becomes ineffective when the surface density ratio of solids to gas exceeds a critical value. Solids in excess of this precipitation limit can undergo midplane gravitational instability and form planetesimals. However, this saturation effect typically requires increasing the local ratio of solid to gaseous surface density by factors of 2-10 times cosmic abundances, depending on the exact properties of the gas disk. We discuss existing astrophysical mechanisms for augmenting the ratio of solids to gas in protoplanetary disks by such factors and investigate a particular process that depends on the radial variations of orbital drift speeds induced by gas drag. This mechanism can concentrate millimeter-sized chondrules to the supercritical surface density in <=few×10^6 yr, a suggestive timescale for the disappearance of dusty disks around T Tauri stars. We discuss the relevance of our results to some outstanding puzzles in planet formation theory-the size of the observed solar system and the rapid type I migration of Earth-mass bodies.

Publication: The Astrophysical Journal, Volume 580, Issue 1, pp. 494-505.
Pub Date: November 2002
DOI: 10.1086/343109
Bibcode: 2002ApJ...580..494Y
Keywords: Instabilities; Stars: Planetary Systems: Formation- Stars: Planetary Systems: Protoplanetary Disks; Turbulence; Astrophysics



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Streaming Instabilities in Protoplanetary Disks

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Youdin, Andrew N.; Goodman, Jeremy

Interpenetrating streams of solids and gas in a Keplerian disk produce a local, linear instability. The two components mutually interact via aerodynamic drag, which generates radial drift and triggers unstable modes. The secular instability does not require self-gravity, yet it generates growing particle-density perturbations that could seed planetesimal formation. Growth rates are slower than dynamical but faster than radial drift timescales. Growth rates, like streaming velocities, are maximized for marginal coupling (stopping times comparable to dynamical times). Fastest growth occurs when the solid-to-gas density ratio is order unity and feedback is strongest. Curiously, growth is strongly suppressed when the densities are too nearly equal. The relation between background drift and wave properties is explained by analogy with Howard's semicircle theorem. The three-dimensional, two-fluid equations describe a sixth-order (in the complex frequency) dispersion relation. A terminal velocity approximation allows simplification to an approximate cubic dispersion relation. To describe the simplest manifestation of this instability, we ignore complicating (but possibly relevant) factors such as vertical stratification, dispersion of particle sizes, turbulence, and self-gravity. We consider applications to planetesimal formation and compare our work to other studies of particle-gas dynamics.

Publication: The Astrophysical Journal, Volume 620, Issue 1, pp. 459-469.
Pub Date: February 2005
DOI: 10.1086/426895
arXiv: arXiv:astro-ph/0409263
Bibcode: 2005ApJ...620..459Y
Keywords: Hydrodynamics; Instabilities; Stars: Planetary Systems: Formation;

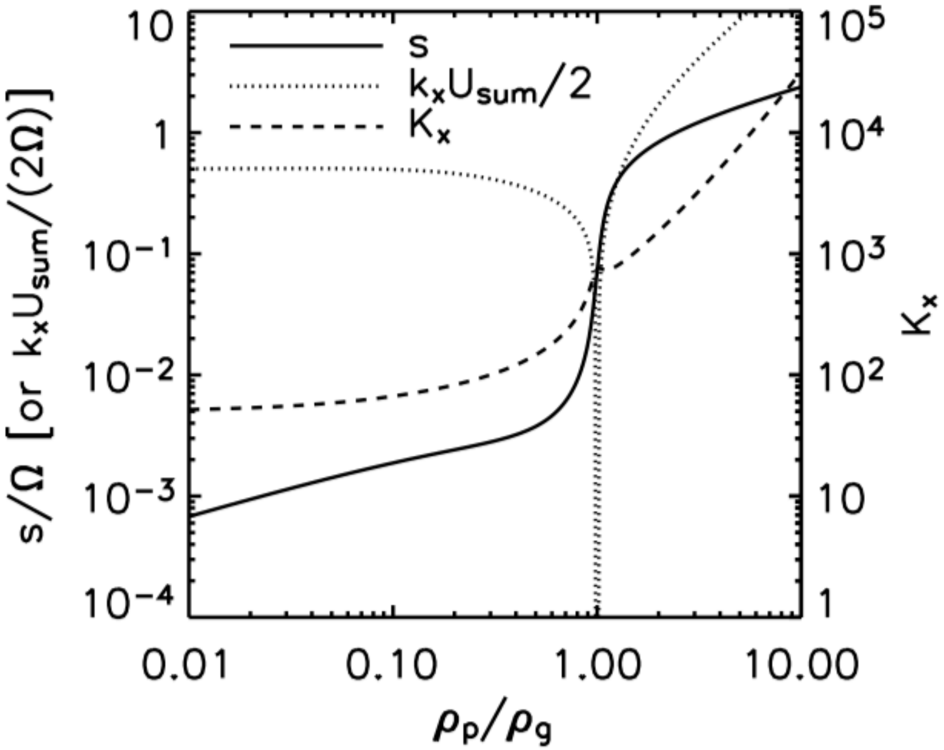
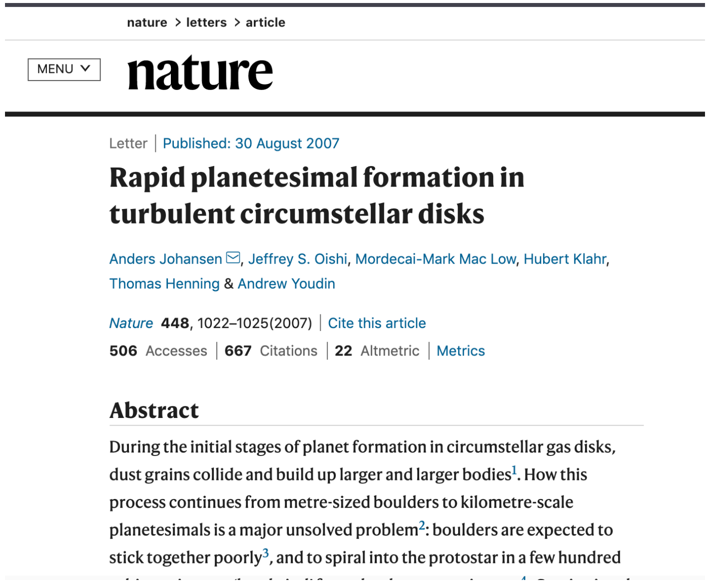


FIG. 3.—Maximum growth rates (*solid line*) and fastest growing radial wavenumber (*dashed line*) vs. solid-to-gas density ratio for $\tau_s = 0.01$ in the limit $K_z \gg K_x$. The growth rates are below the upper limit implied by the semicircle theorem (*dotted lines*), except for a narrow region near equal densities.

Gravitational collapse into planetesimals



nature > letters > article

MENU

nature

Letter | Published: 30 August 2007

Rapid planetesimal formation in turbulent circumstellar disks

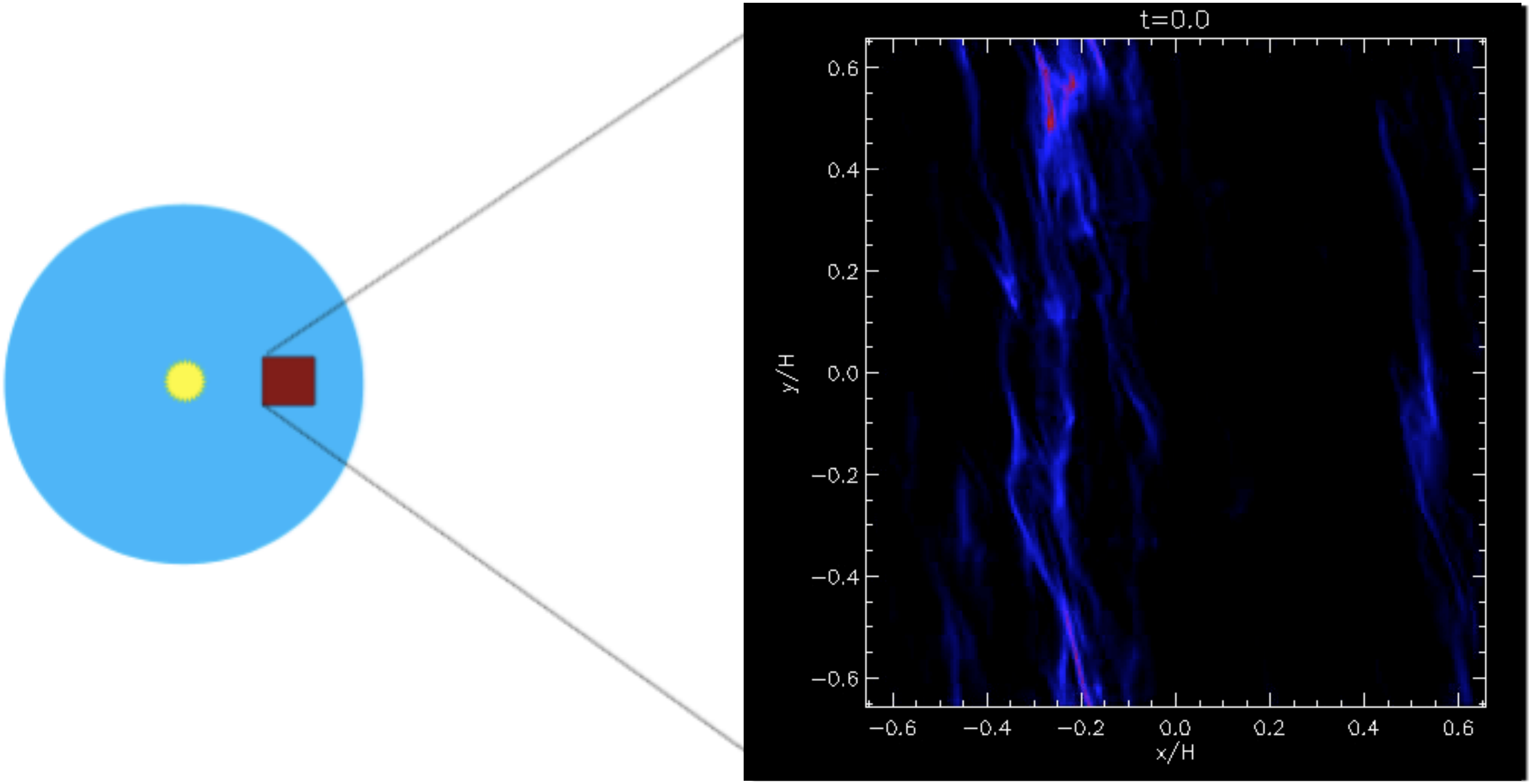
Anders Johansen, Jeffrey S. Oishi, Mordecai-Mark Mac Low, Hubert Klahr, Thomas Henning & Andrew Youdin

Nature **448**, 1022–1025(2007) | Cite this article

506 Accesses | **667** Citations | **22** Altmetric | Metrics

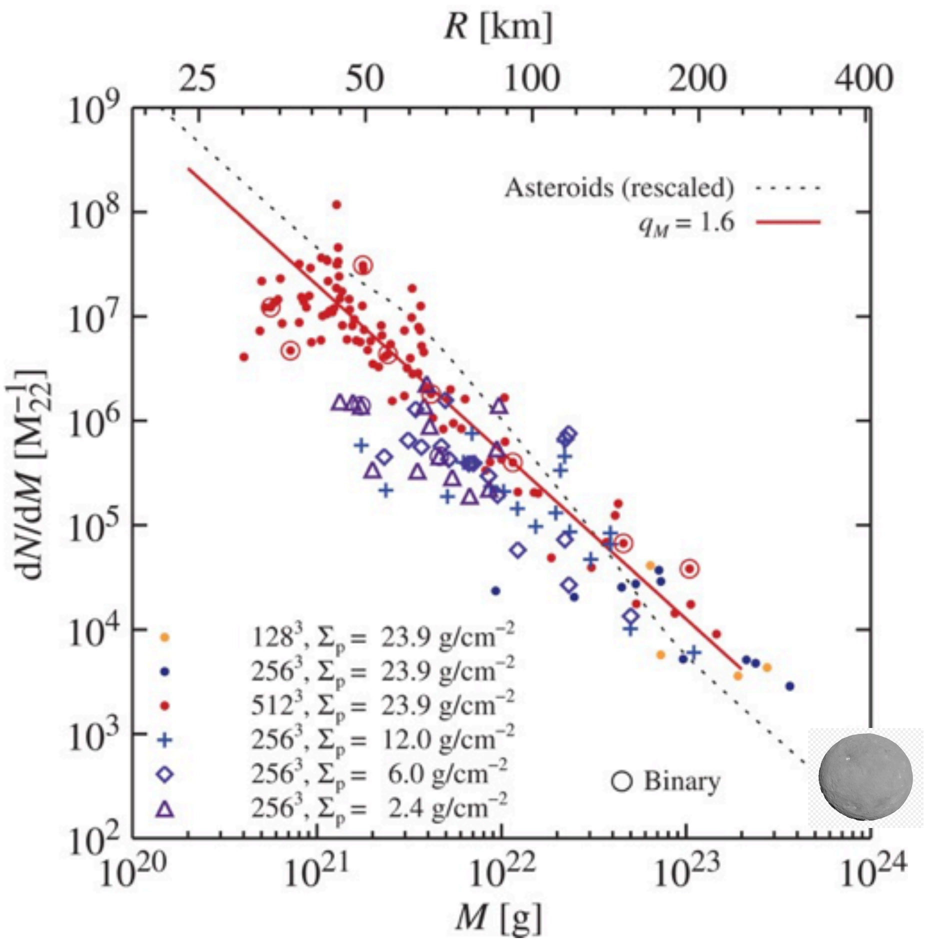
Abstract

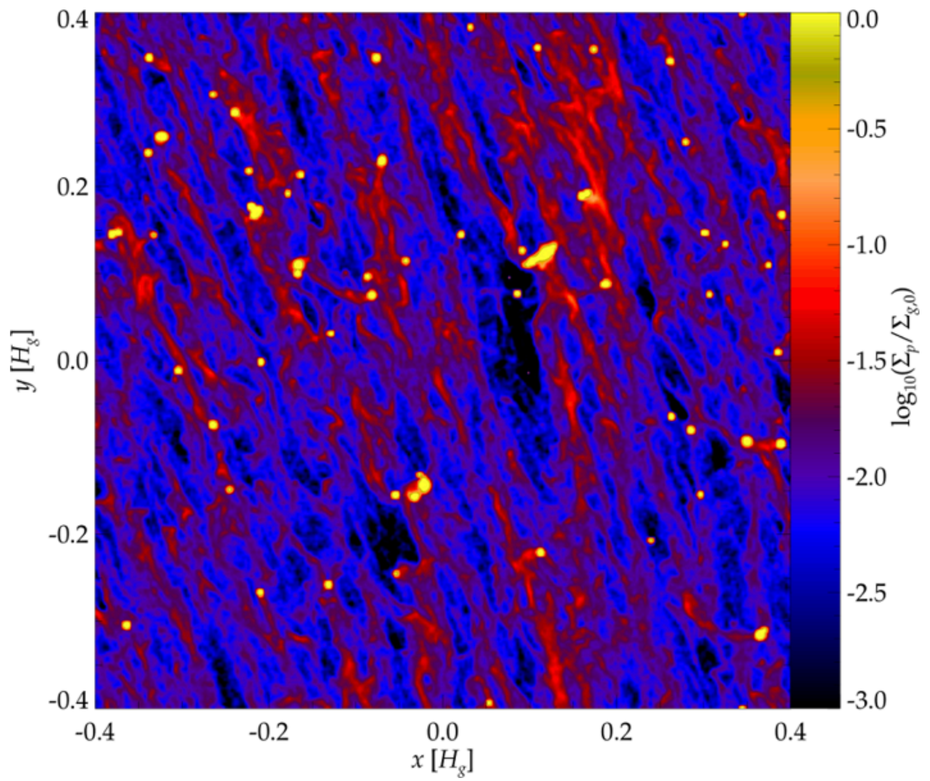
During the initial stages of planet formation in circumstellar gas disks, dust grains collide and build up larger and larger bodies[1]. How this process continues from metre-sized boulders to kilometre-scale planetesimals is a major unsolved problem[2]: boulders are expected to stick together poorly[3], and to spiral into the protostar in a few hundred



Johansen et al. (2007)

Planetesimal Formation



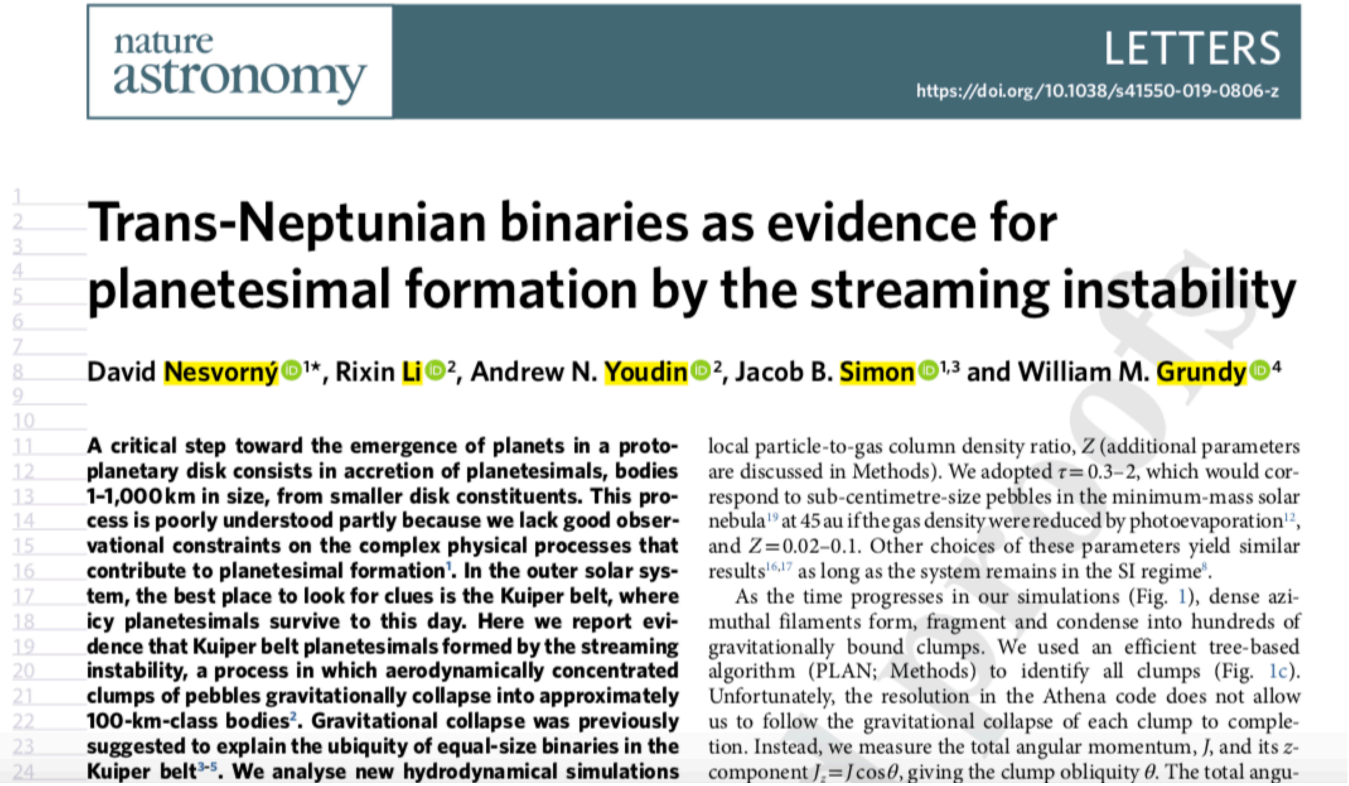


Initial mass function consistent with mass distribution of asteroid belt. Slope 1.6

W. Lyra

Yang & Johansen (2014); Schäfer, Yang, & Johansen (2017)

Planetesimal Formation



nature astronomy

LETTERS

https://doi.org/10.1038/s41550-019-0806-z

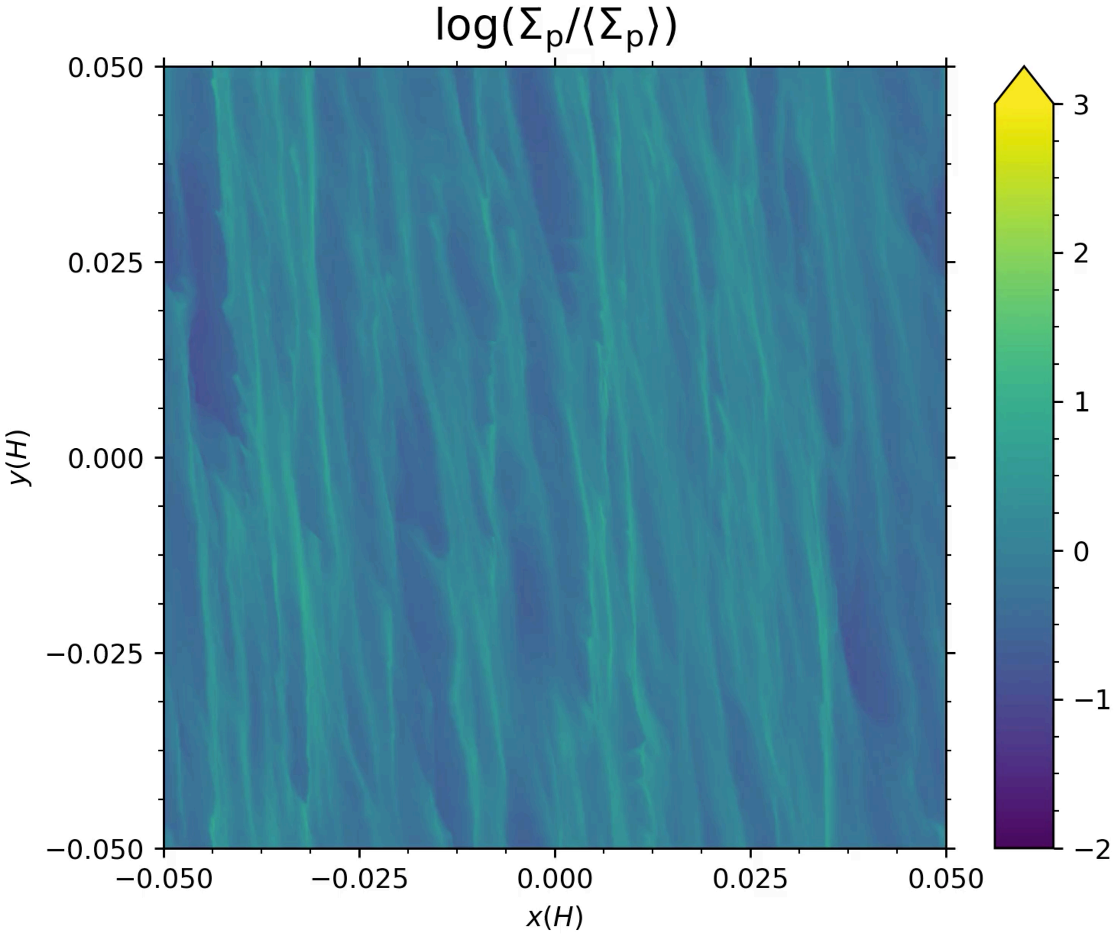
Trans-Neptunian binaries as evidence for planetesimal formation by the streaming instability

David Nesvorný[1*], Rixin Li[2], Andrew N. Youdin[2], Jacob B. Simon[1,3] and William M. Grundy[4]

A critical step toward the emergence of planets in a protoplanetary disk consists in accretion of planetesimals, bodies 1–1,000 km in size, from smaller disk constituents. This process is poorly understood partly because we lack good observational constraints on the complex physical processes that contribute to planetesimal formation[1]. In the outer solar system, the best place to look for clues is the Kuiper belt, where icy planetesimals survive to this day. Here we report evidence that Kuiper belt planetesimals formed by the streaming instability, a process in which aerodynamically concentrated clumps of pebbles gravitationally collapse into approximately 100-km-class bodies[2]. Gravitational collapse was previously suggested to explain the ubiquity of equal-size binaries in the Kuiper belt[3–5]. We analyse new hydrodynamical simulations

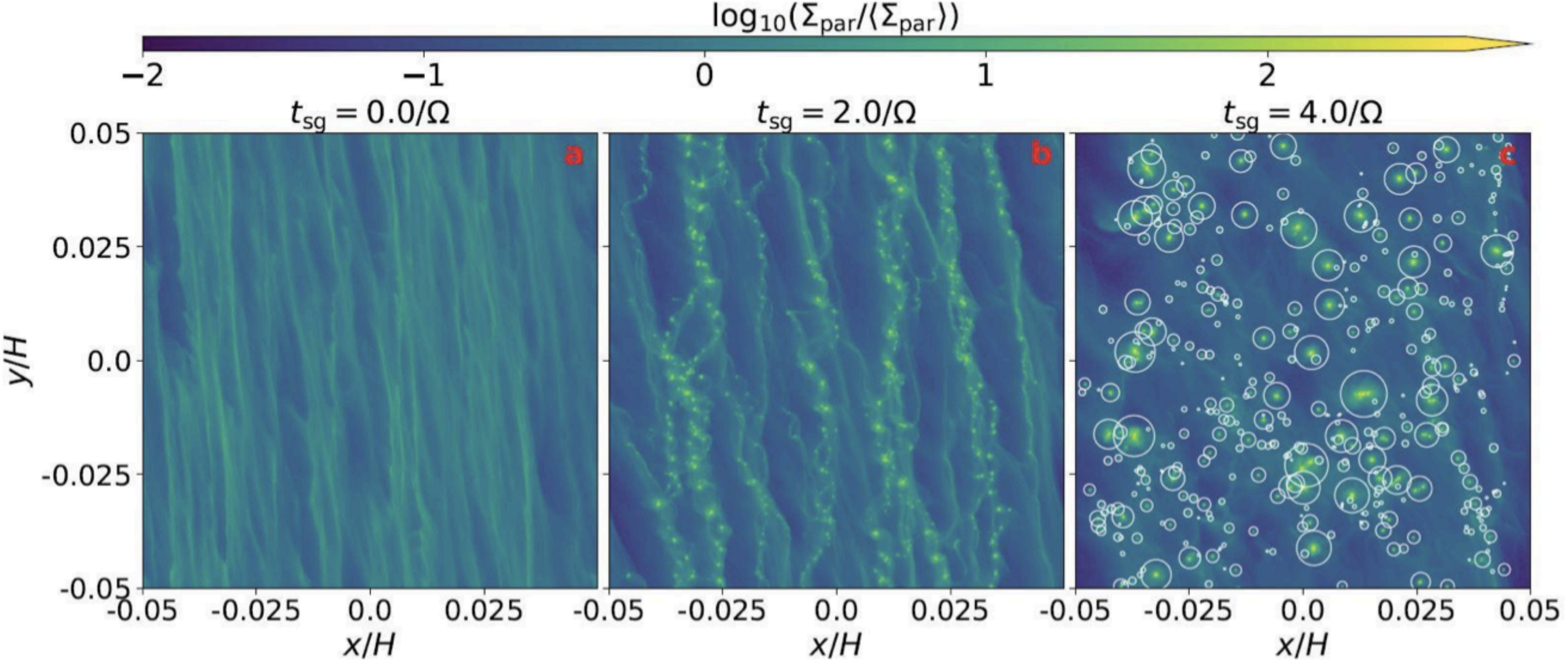
local particle-to-gas column density ratio, Z (additional parameters are discussed in Methods). We adopted $\tau = 0.3$–2, which would correspond to sub-centimetre-size pebbles in the minimum-mass solar nebula[19] at 45 au if the gas density were reduced by photoevaporation[12], and $Z = 0.02$–0.1. Other choices of these parameters yield similar results[16,17] as long as the system remains in the SI regime[8].

As the time progresses in our simulations (Fig. 1), dense azimuthal filaments form, fragment and condense into hundreds of gravitationally bound clumps. We used an efficient tree-based algorithm (PLAN; Methods) to identify all clumps (Fig. 1c). Unfortunately, the resolution in the Athena code does not allow us to follow the gravitational collapse of each clump to completion. Instead, we measure the total angular momentum, J, and its z-component $J_z = J\cos\theta$, giving the clump obliquity θ. The total angu-



Nesvorny+'19, model by Rixin Li

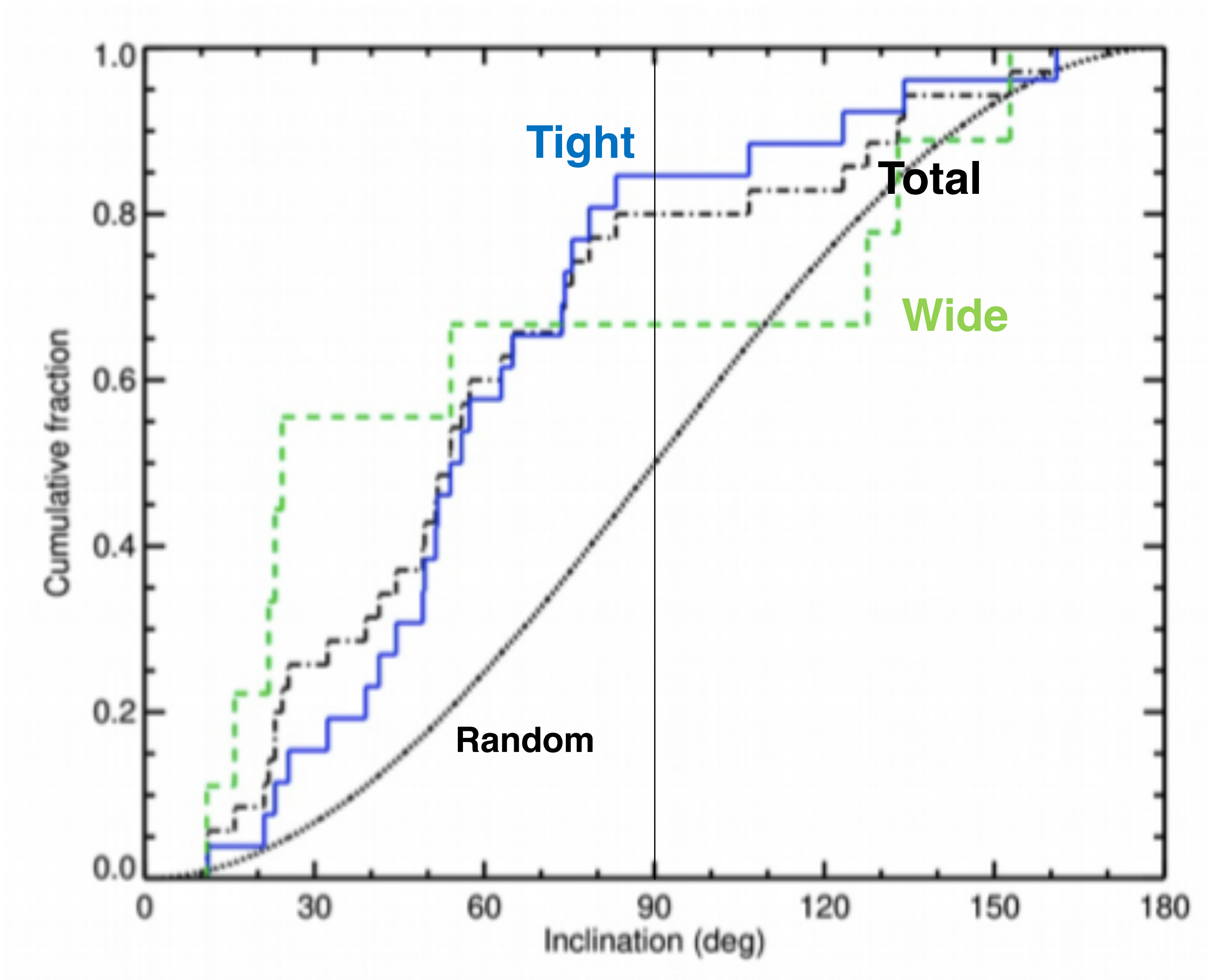
Filaments form and fragment into gravitationally bound clumps



Nesvorny+'19; model by Rixin Li

Angular Momentum: Prograde vs Retrograde distribution of Kuiper Belt objects

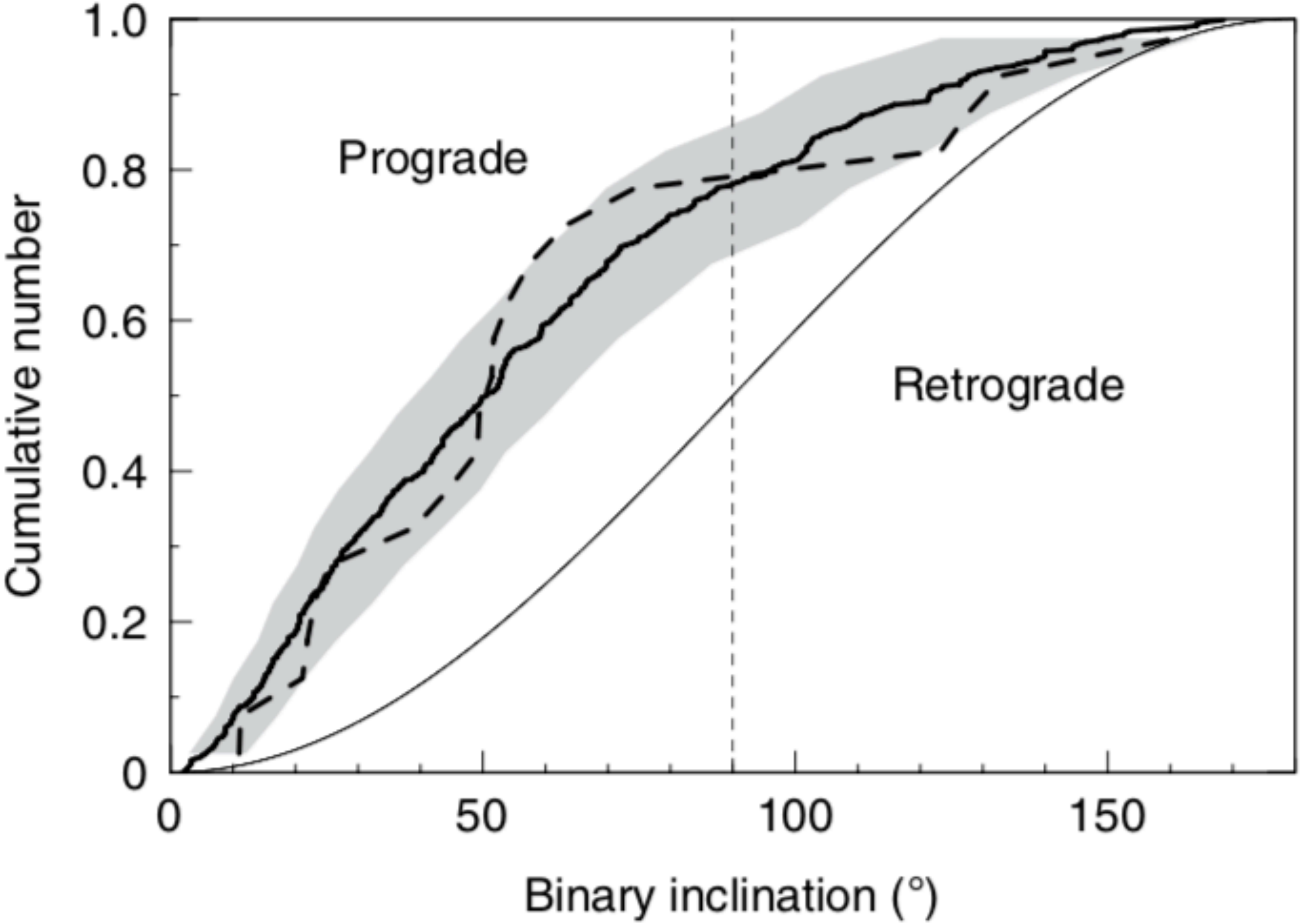
~80% of TNO binaries are prograde



W. Lyra

Grundy+19, Nesvorny+19

Observational evidence: Preference for Prograde (~80%)



SI Model (solid)
KBOs (dashed)

Nesvorny+19