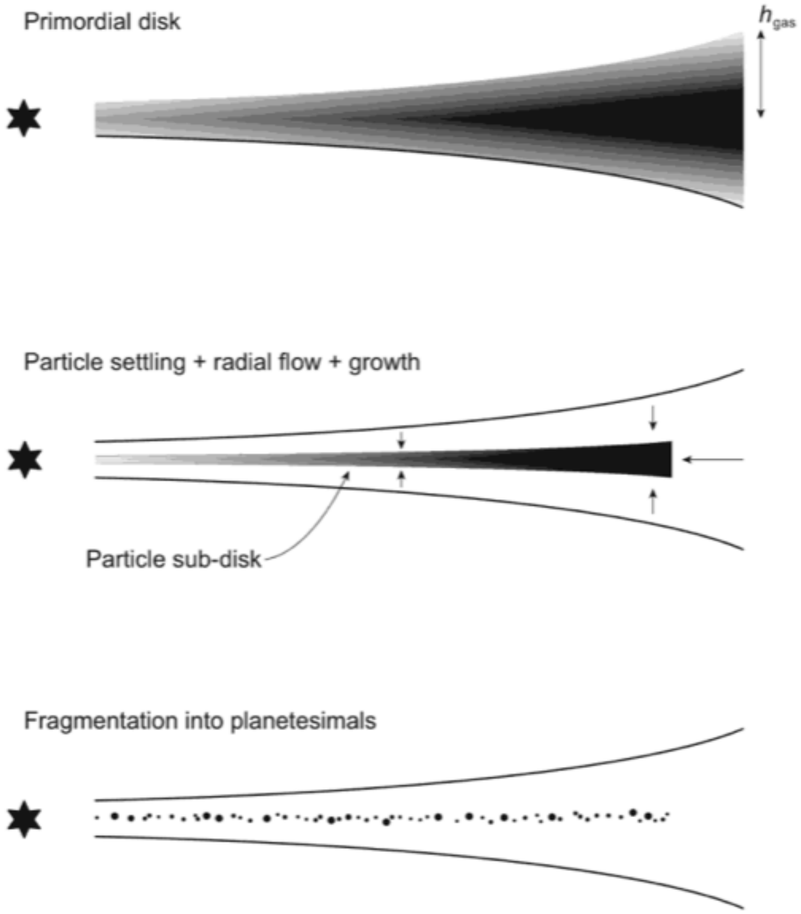
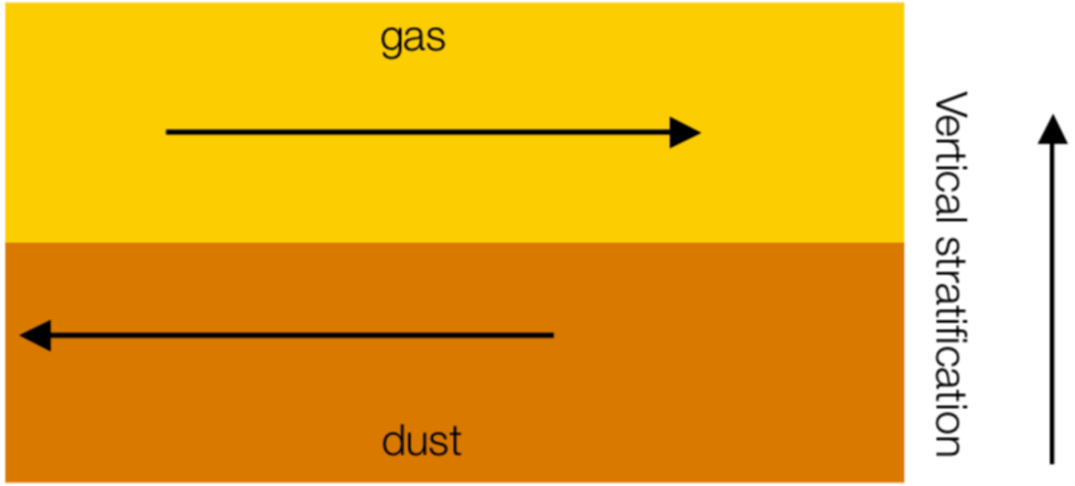
Class 19 – Apr 9th, 2020

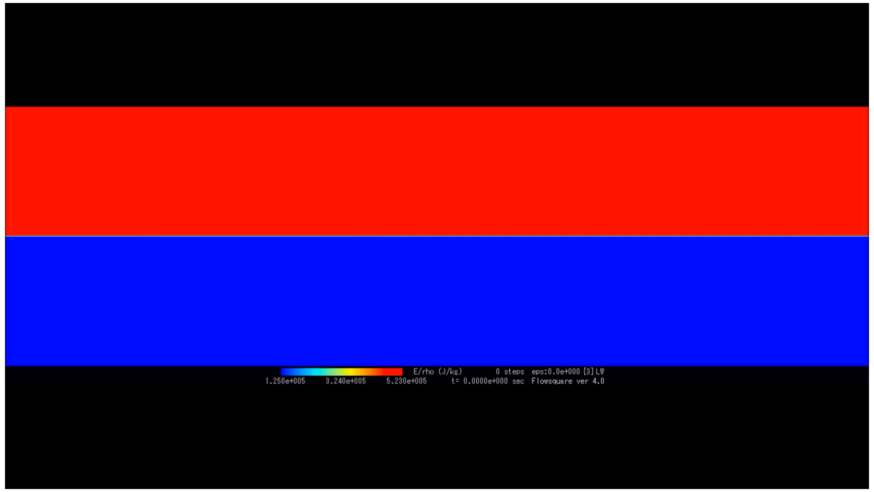
Recap

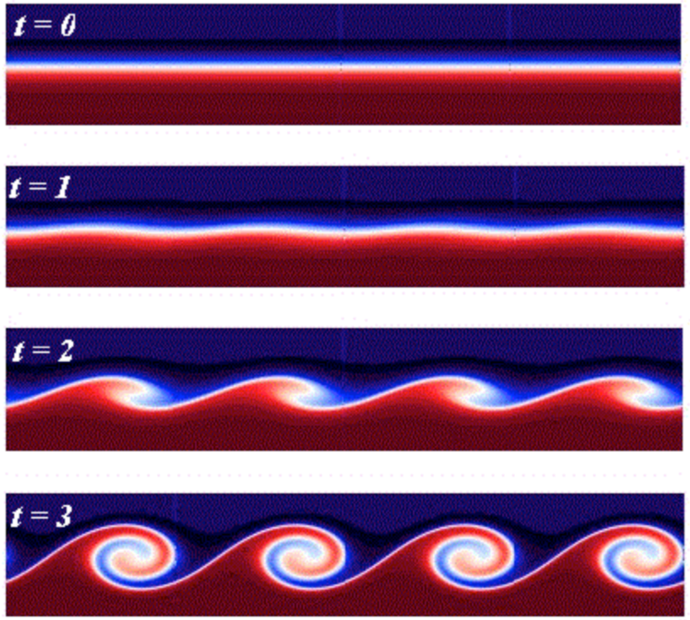
Goldreich-Ward Scenario



Kelvin-Helmholtz instability







Ri = 0.07, Re = 300

Streaming Instability

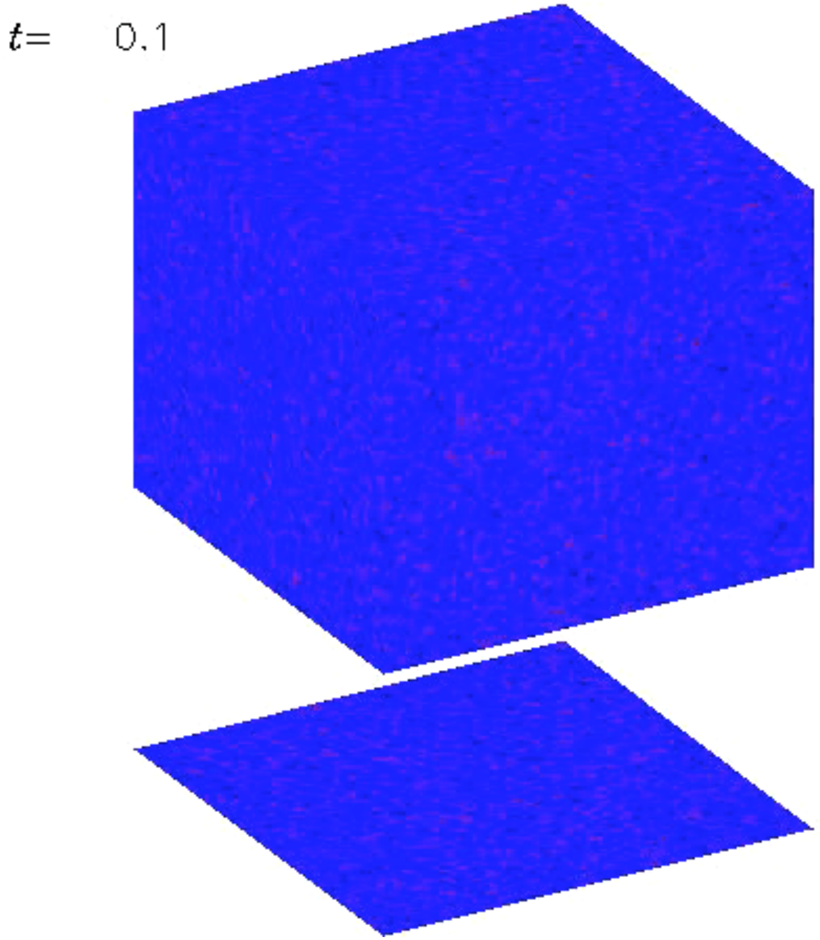
$$v_r = -\left(\frac{1}{1+\varepsilon}\right)\frac{2\mathrm{St}}{1+\mathrm{St}^2}\eta u_k$$

Dust concentrations reduces drift.

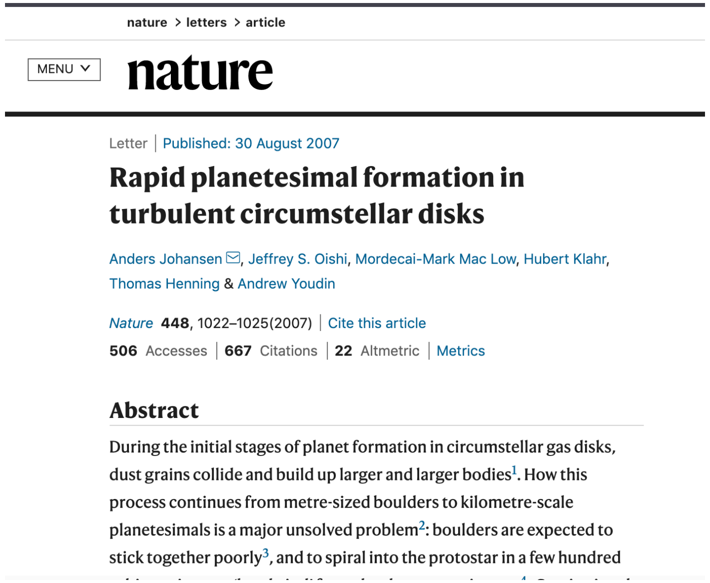
Reduced drift causes dust concentration

Run-away process!

Eventually the particle clumps become self-gravitating, and can collapse to form planetesimals.



Gravitational collapse into planetesimals


nature > letters > article

MENU

nature

Letter | Published: 30 August 2007

Rapid planetesimal formation in turbulent circumstellar disks

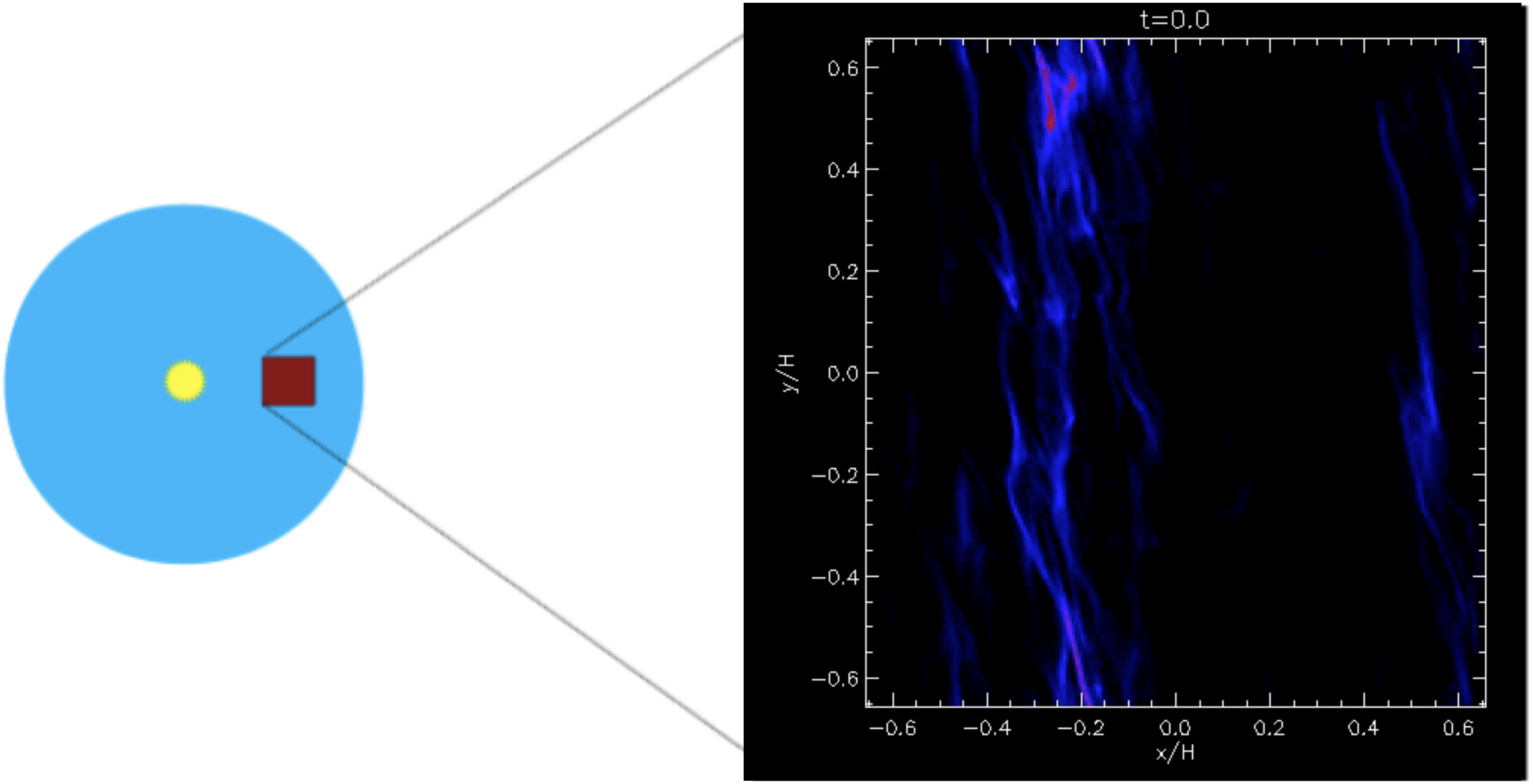
Anders Johansen, Jeffrey S. Oishi, Mordecai-Mark Mac Low, Hubert Klahr, Thomas Henning & Andrew Youdin

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

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

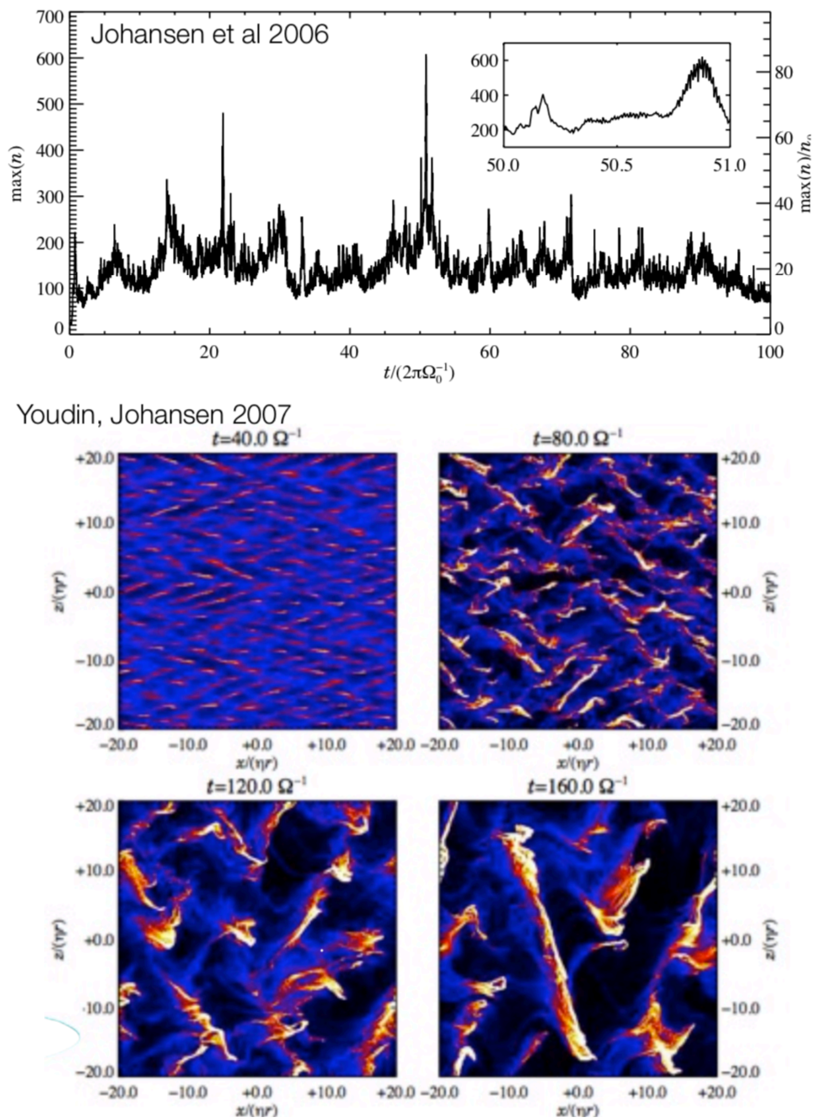
Abstract

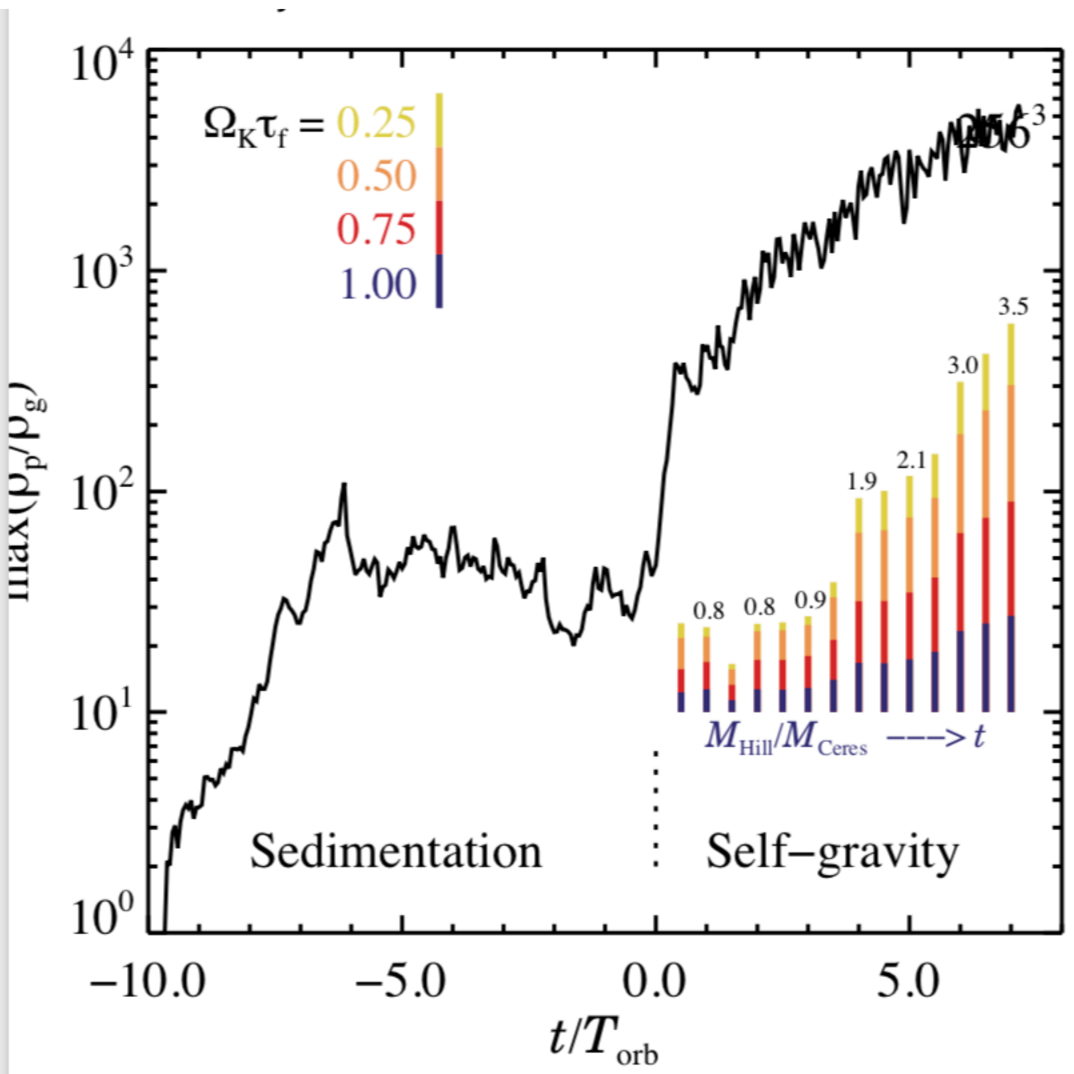
During the initial stages of planet formation in circumstellar gas disks, dust grains collide and build up larger and larger bodies[1]. How this process continues from metre-sized boulders to kilometre-scale planetesimals is a major unsolved problem[2]: boulders are expected to stick together poorly[3],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



Johansen et al. (2007)

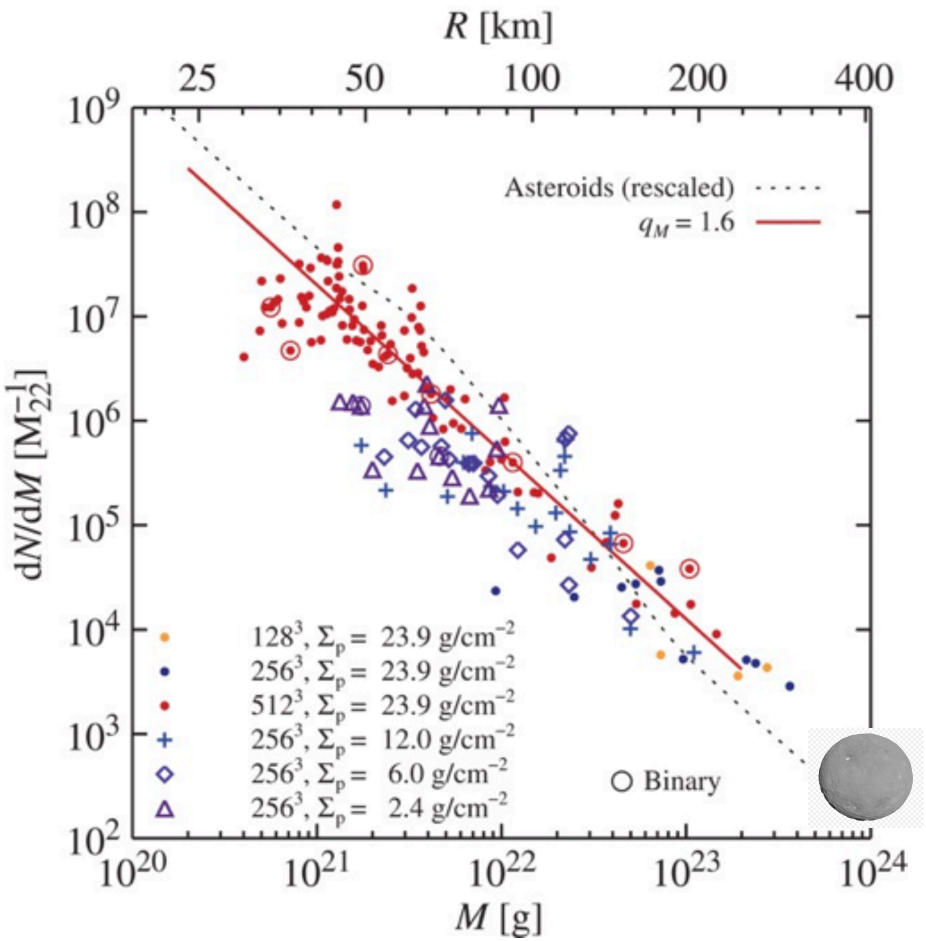
Dust concentration

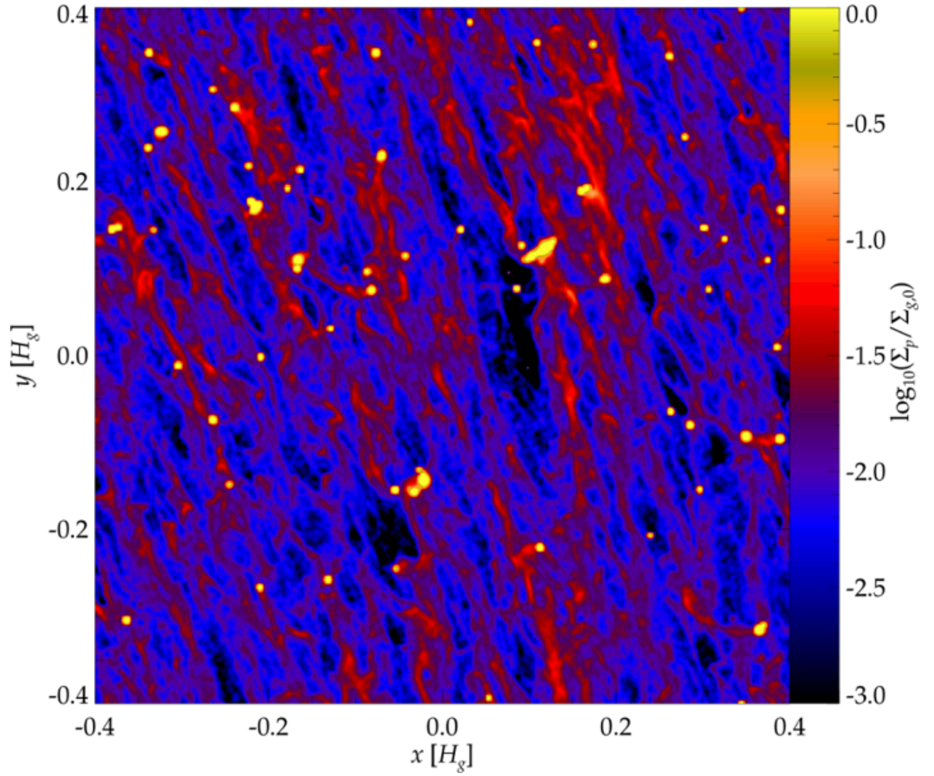




**How can we verify the
streaming instability hypothesis?**

Planetesimal Formation





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

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

Icarus
Volume 204, Issue 2, December 2009, Pages 558-573

Asteroid belt
"Asteroids were born big"

Asteroids were born big

Alessandro Morbidelli [a], William F. Bottke [b], David Nesvorný [b], Harold F. Levison [b]

Show more

https://doi.org/10.1016/j.icarus.2009.07.011

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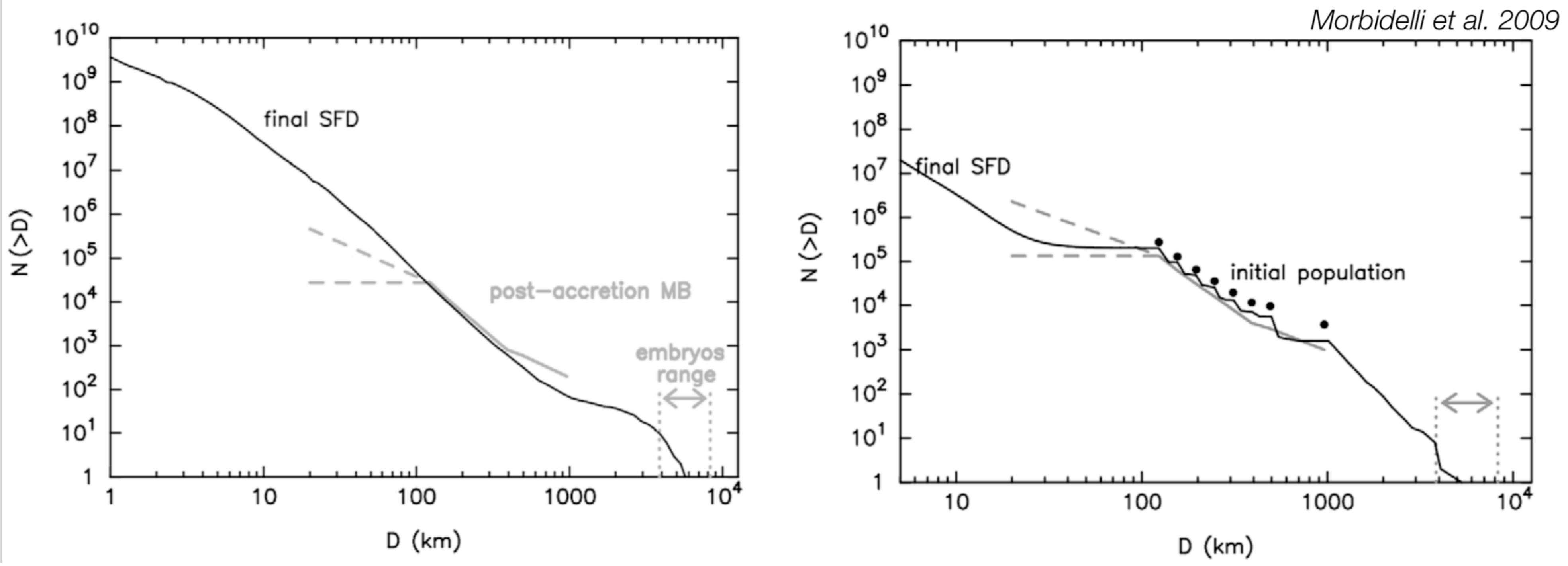
Abstract

How big were the first planetesimals? We attempt to answer this question by conducting coagulation simulations in which the planetesimals grow by mutual collisions and form larger bodies and planetary embryos. The size frequency distribution (SFD) of the initial planetesimals is considered a free parameter in these simulations, and



Planetesimal Formation in the Kuiper belt

nature astronomy

LETTERS

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

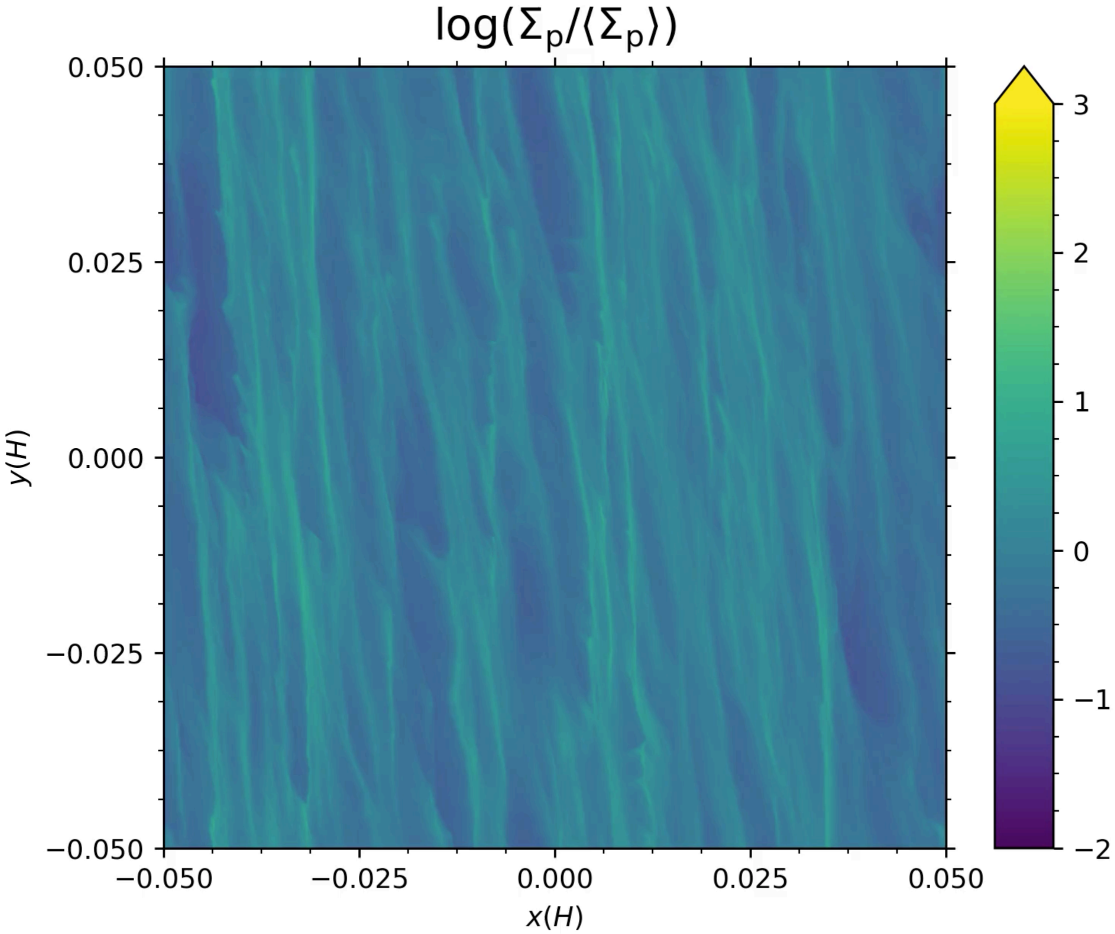
Trans-Neptunian binaries as evidence for planetesimal formation by the streaming instability

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

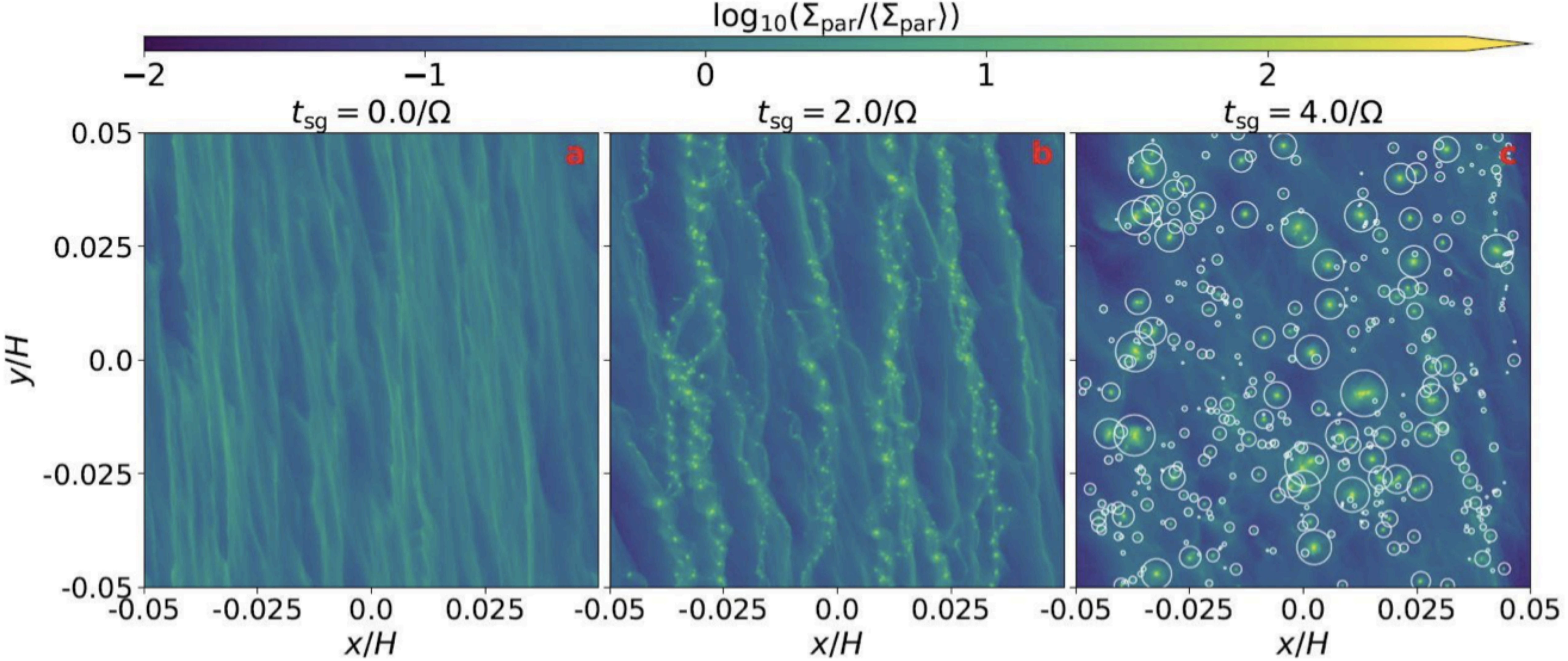
local particle-to-gas column density ratio, Z (additional parameters are discussed in Methods). We adopted $\tau = 0.3$–2, which would correspond to sub-centimetre-size pebbles in the minimum-mass solar nebula[19] at 45 au if the gas density were reduced by photoevaporation[12], and $Z = 0.02$–0.1. Other 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-



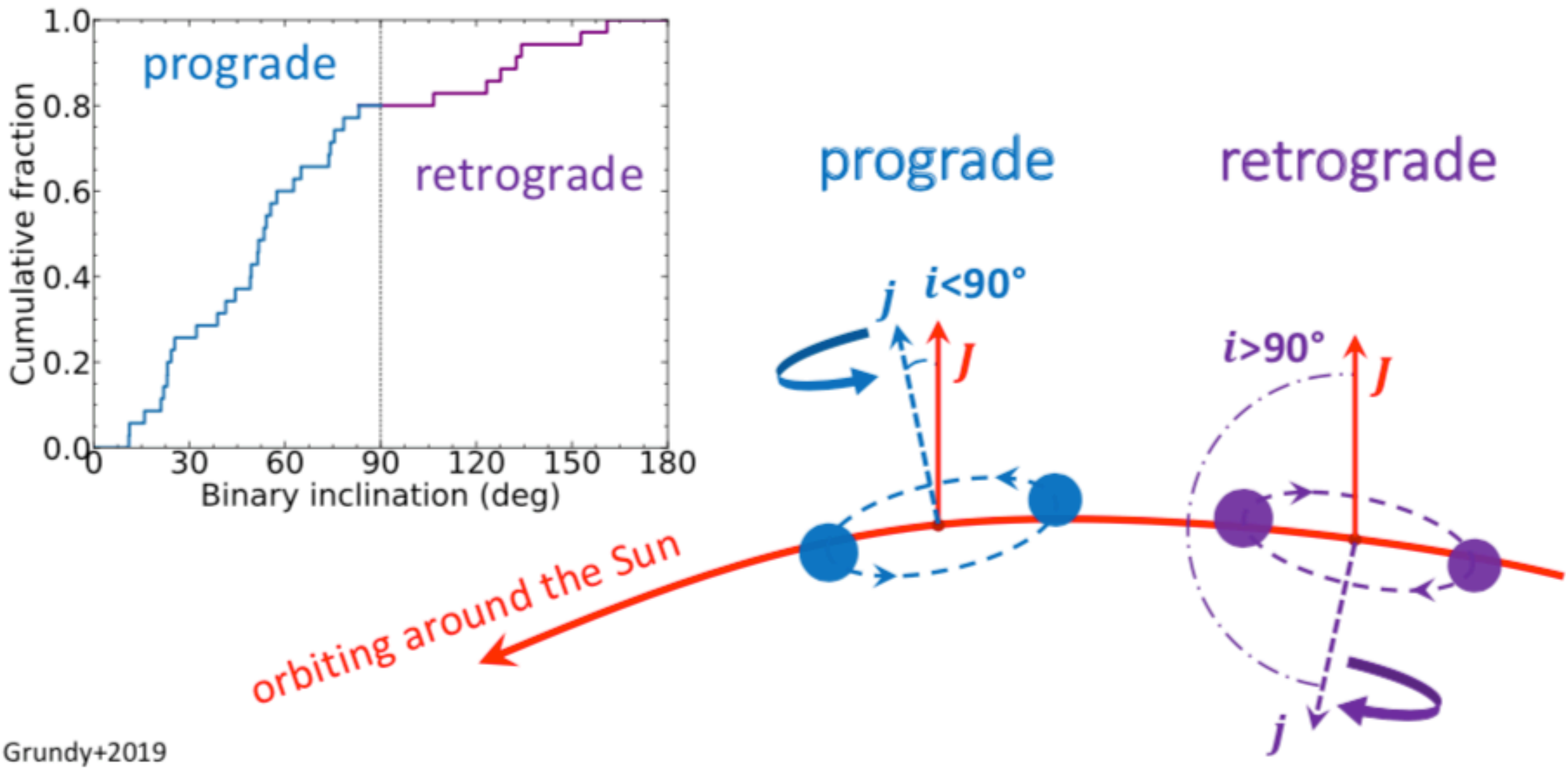
Nesvorny+’19, model by Rixin Li

Filaments form and fragment into gravitationally bound clumps



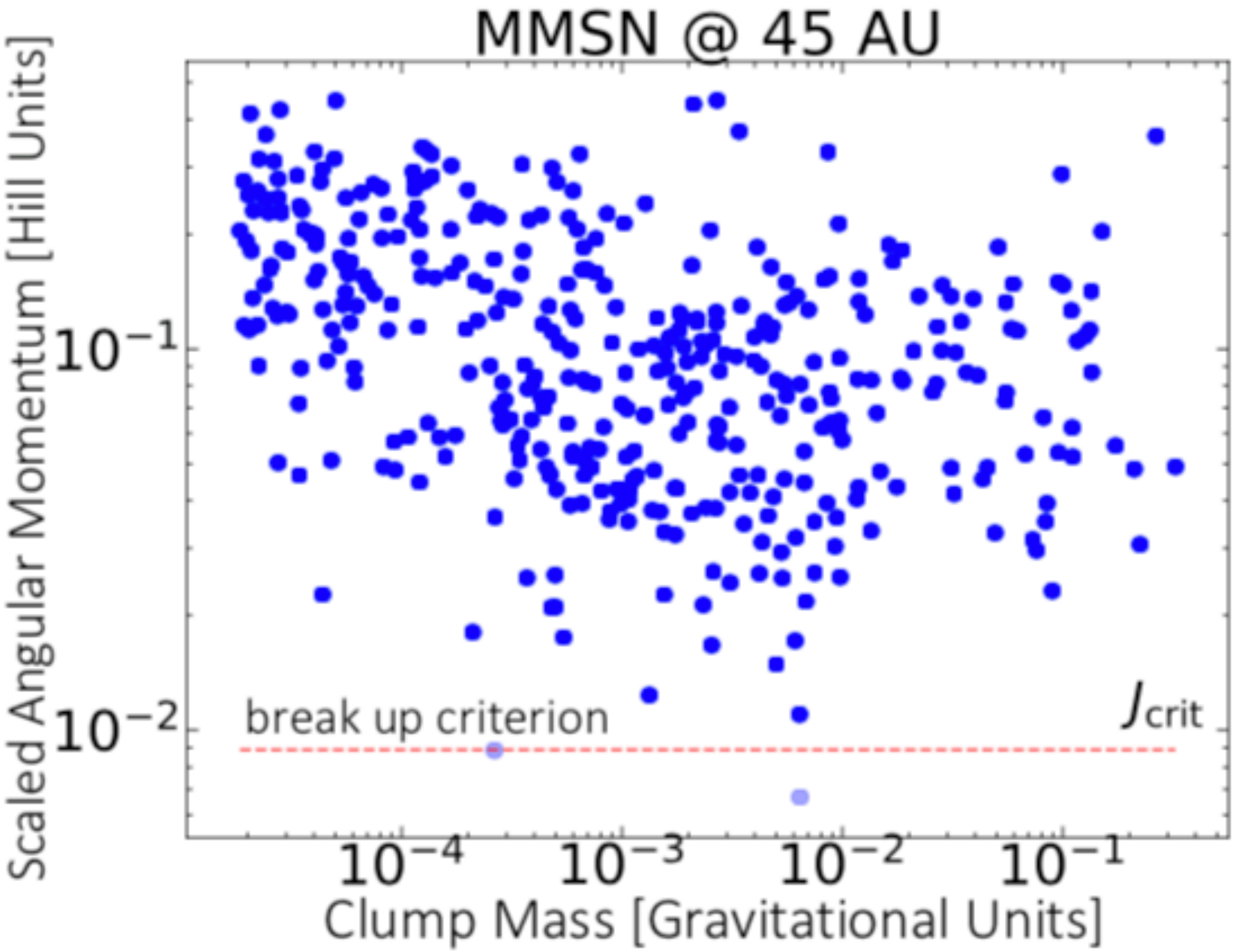
Nesvorny+'19; model by Rixin Li

Preference for Prograde



Grundy+2019

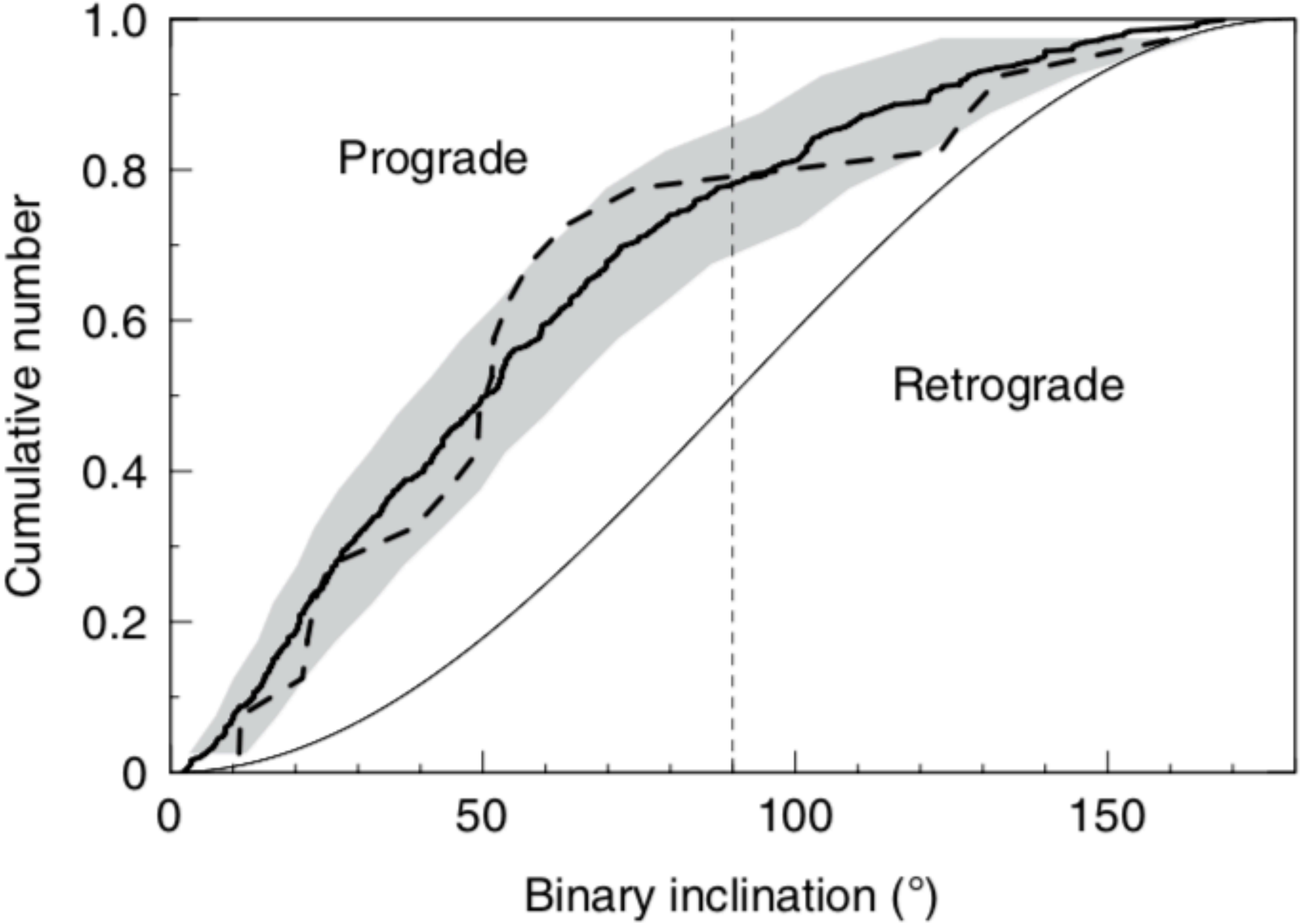
Excess angular momentum



The clumps spin faster than break-up.
Will form binaries.

Li+'19

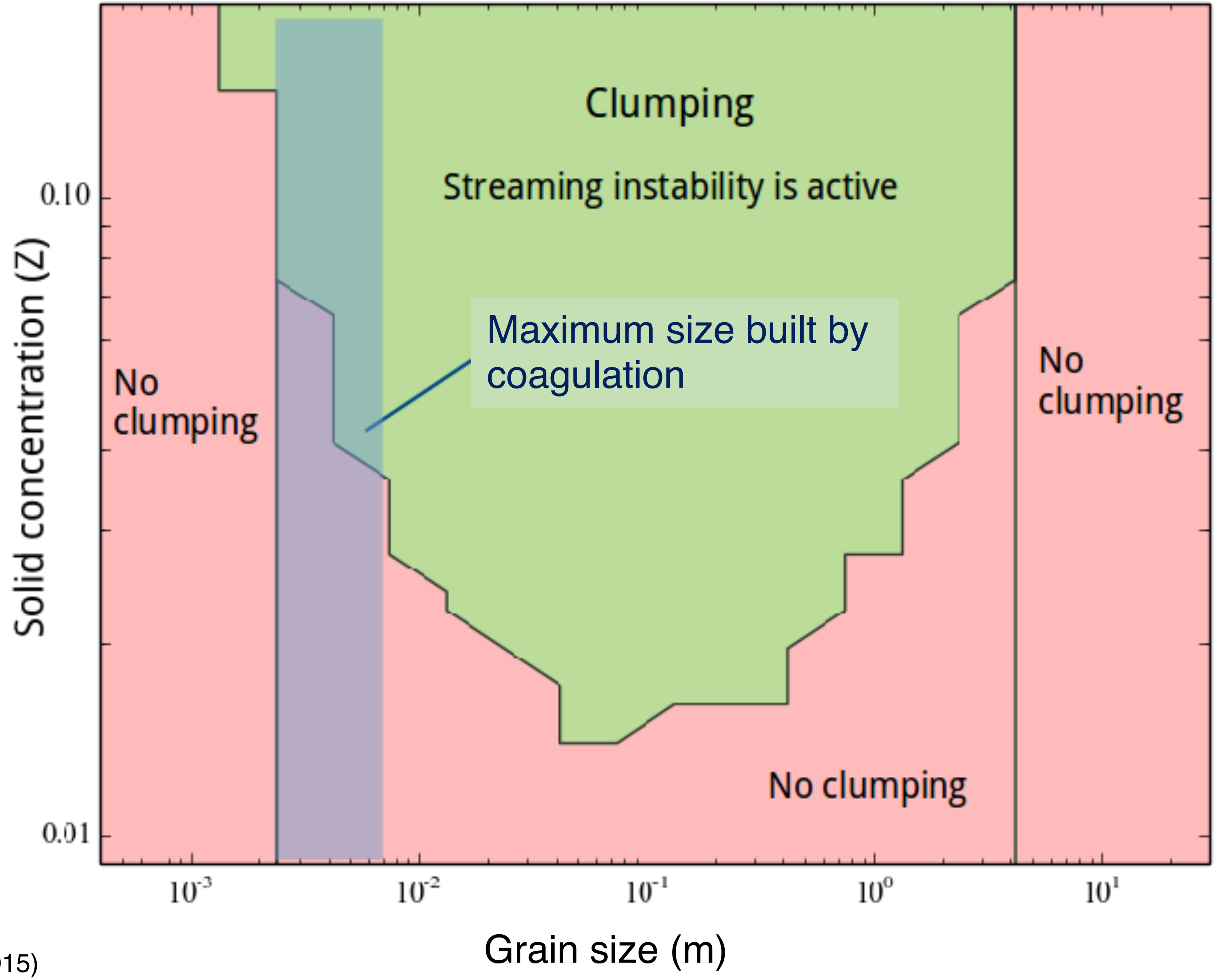
Observational evidence: Preference for Prograde (~80%)



SI Model (solid)
KBOs (dashed)

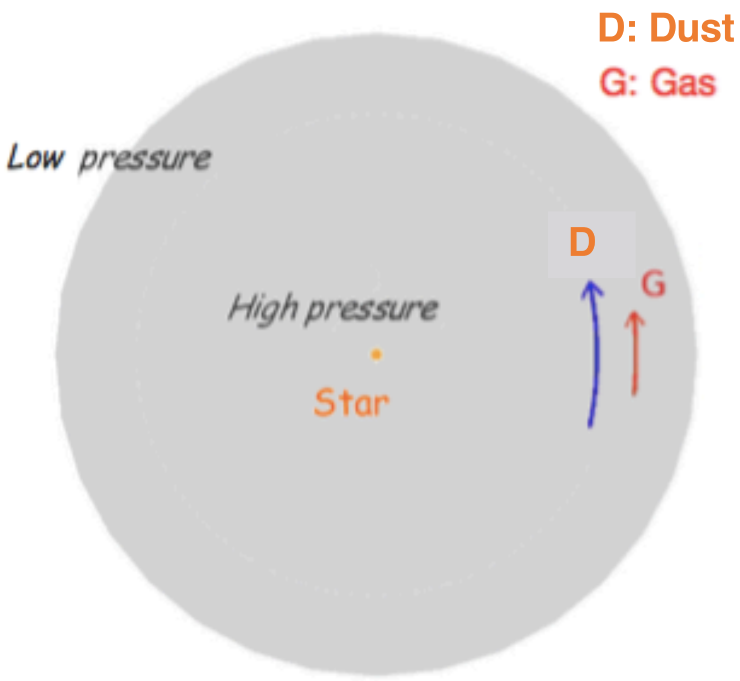
Nesvorny+19

Streaming instability is still a field of active research much still to be learned

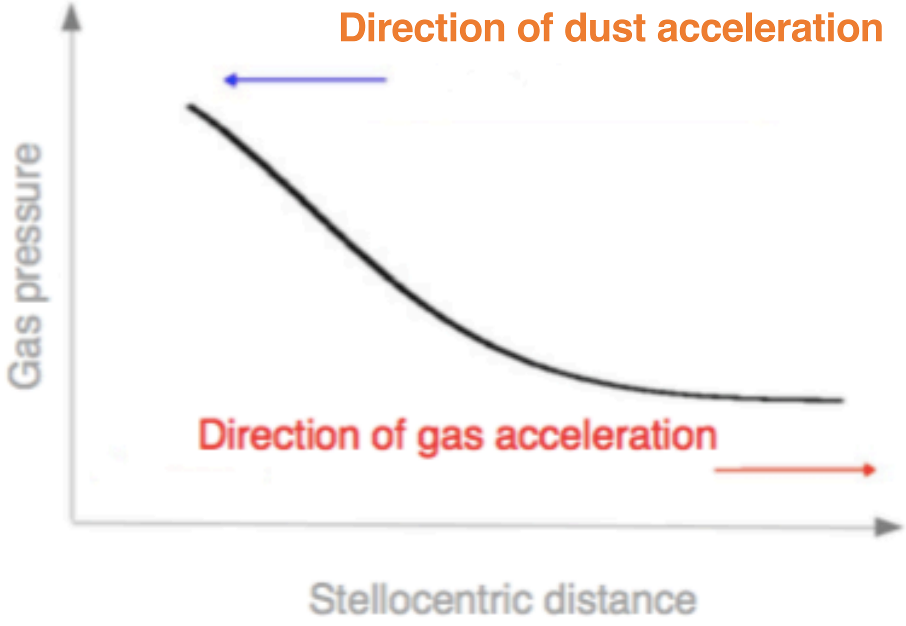


Carrera et al. (2015)

Dust Drift



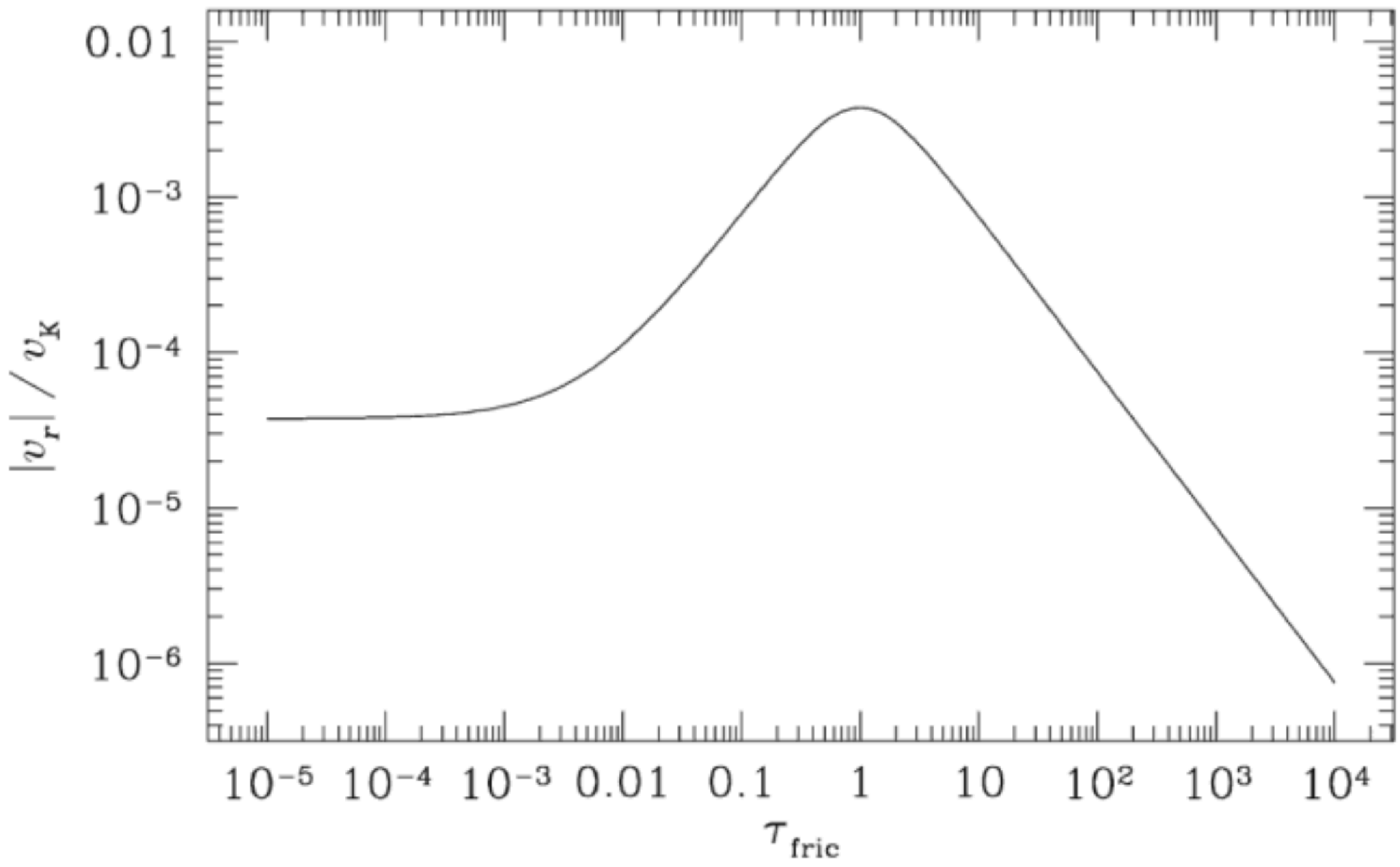
Adapted from Whipple (1972)



The gas has some pressure support.

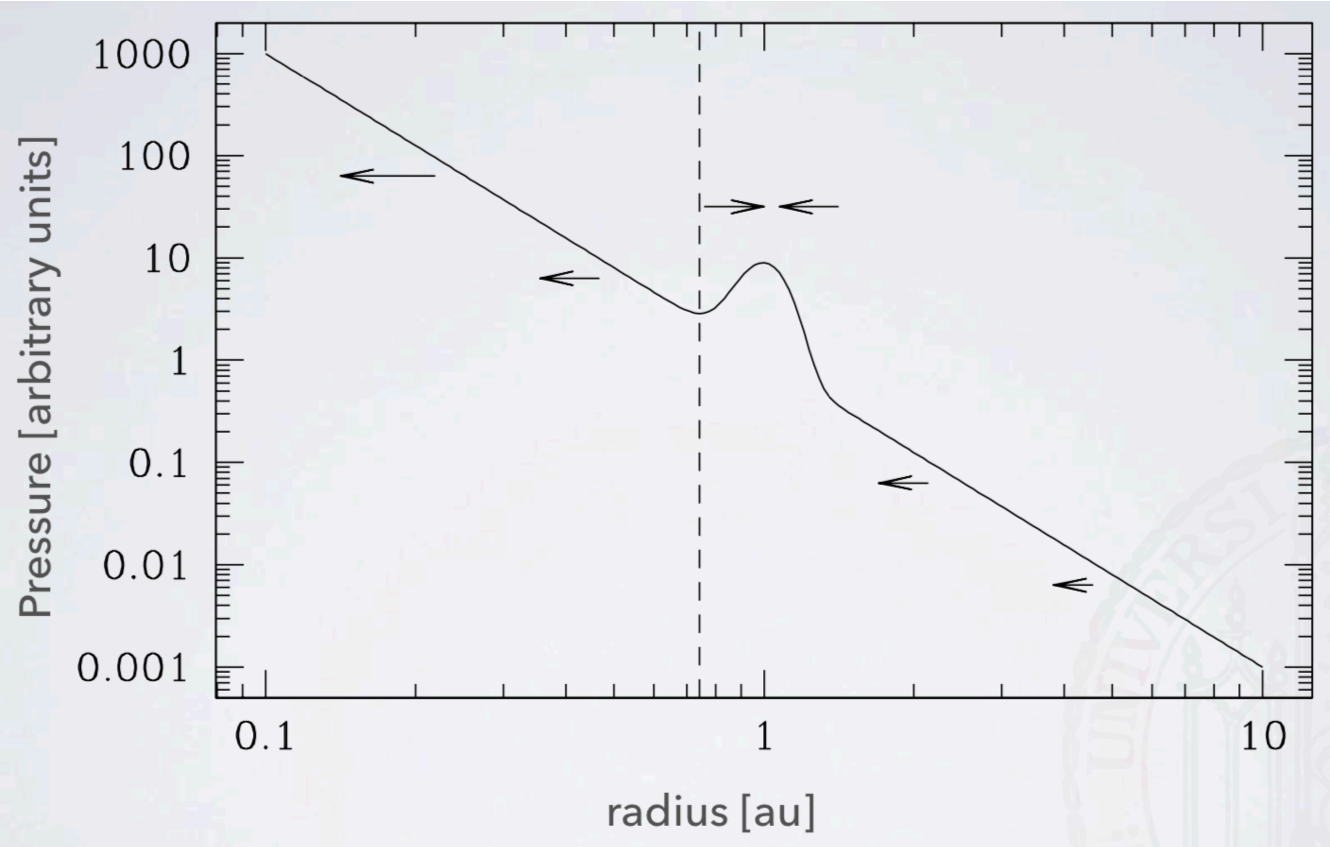
The grains have none.

Radial Drift

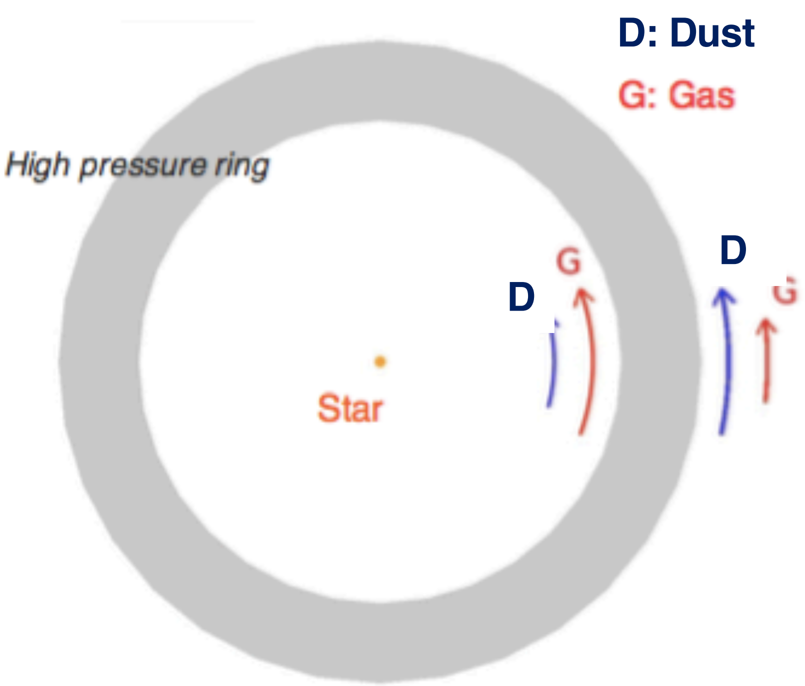


GRAINS MOVE TOWARD PRESSURE MAXIMA

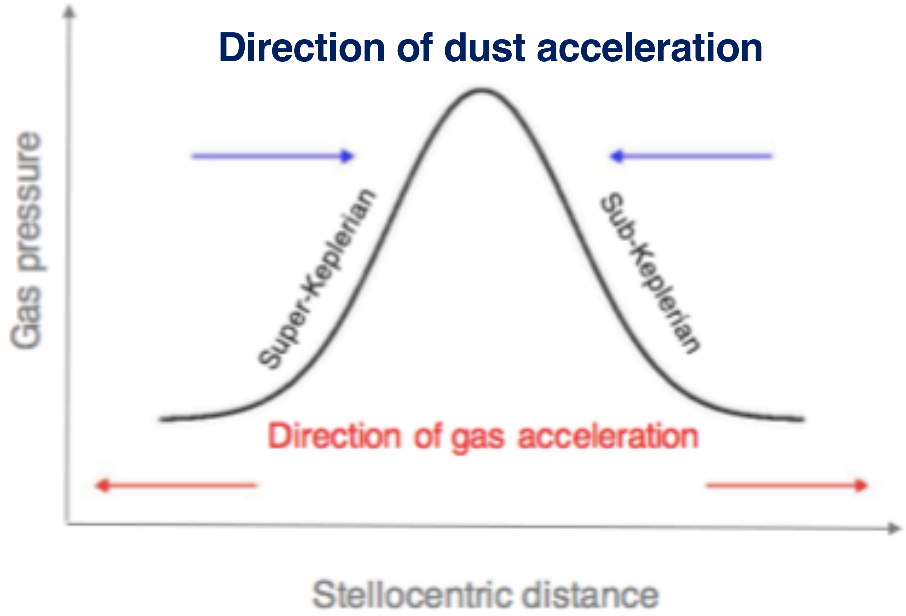
How to stop the drift: Pressure bumps

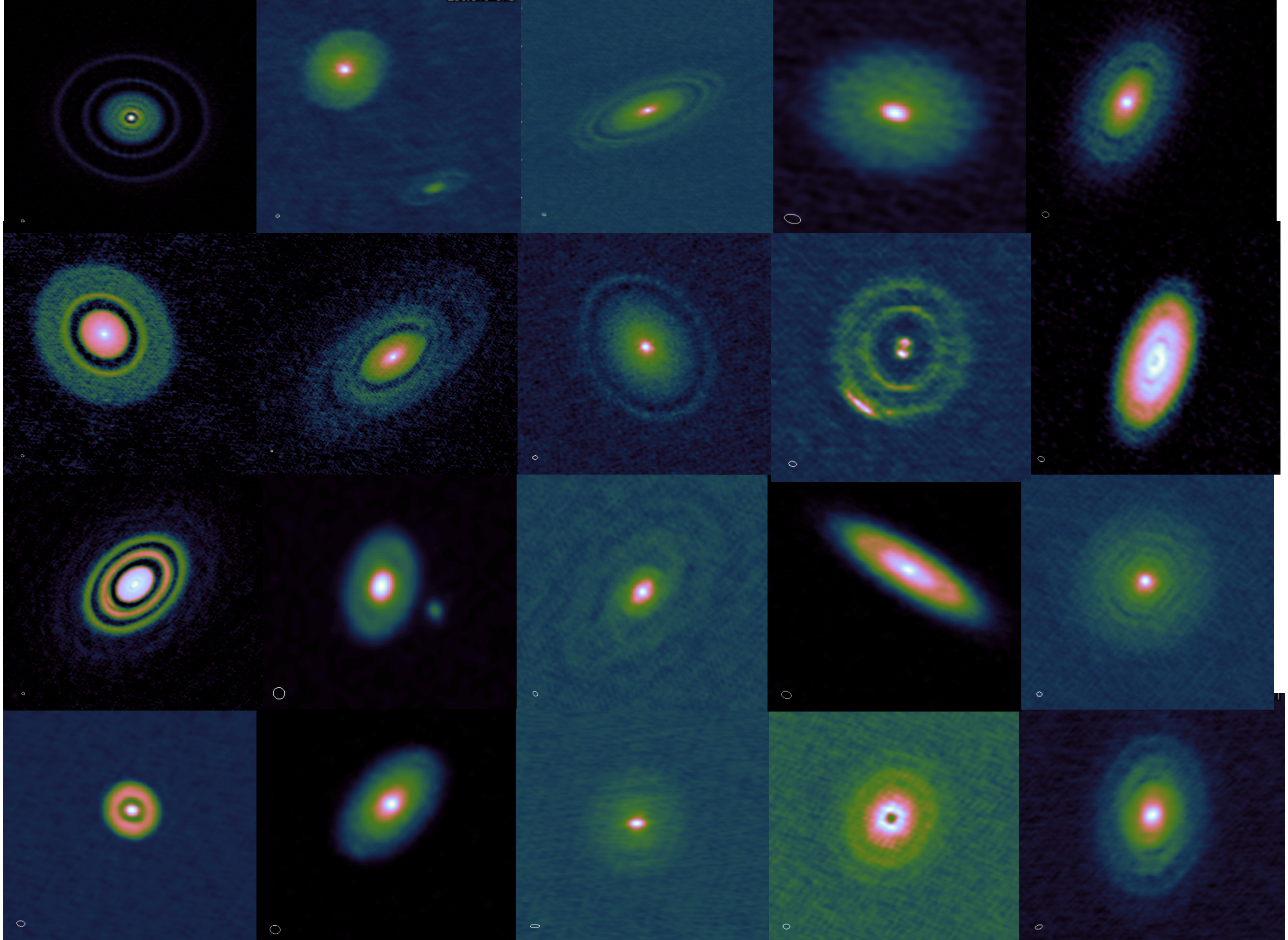


Pressure Trap

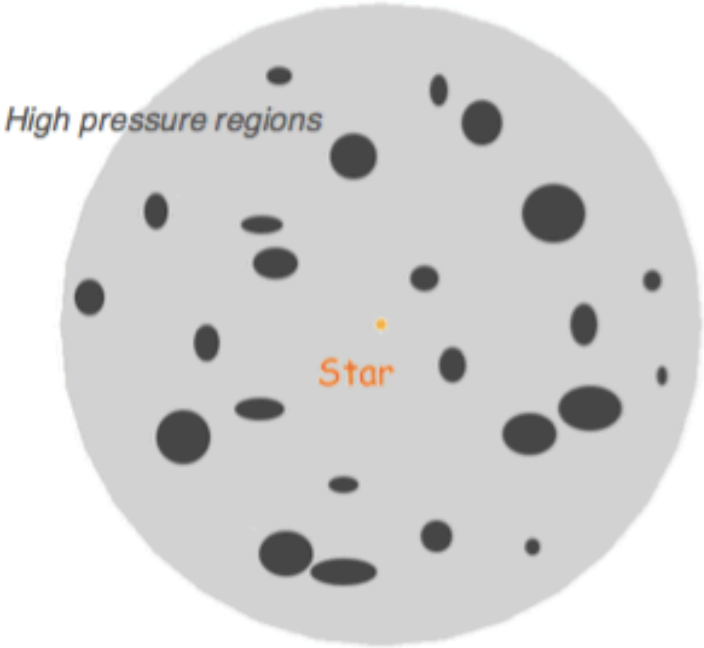


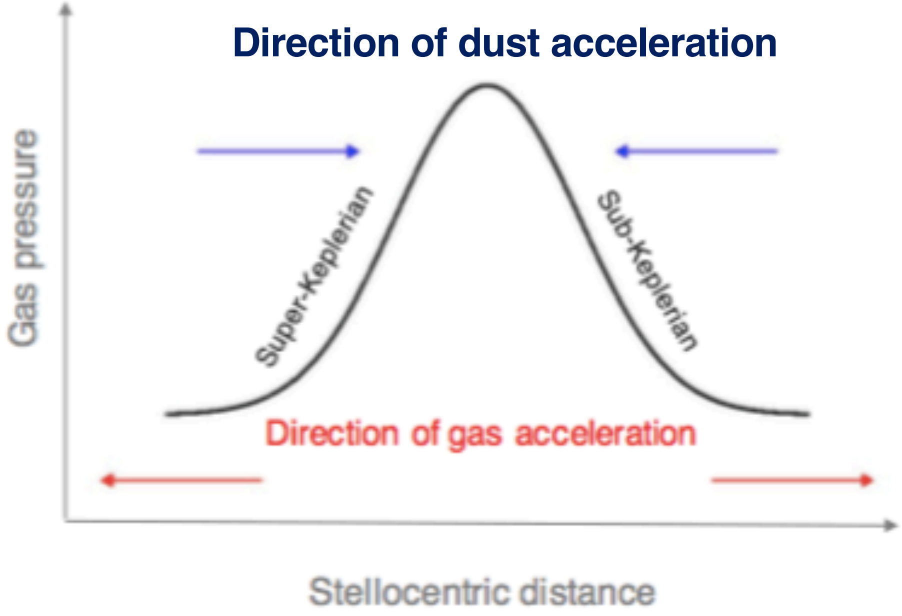
Adapted from Whipple (1972)



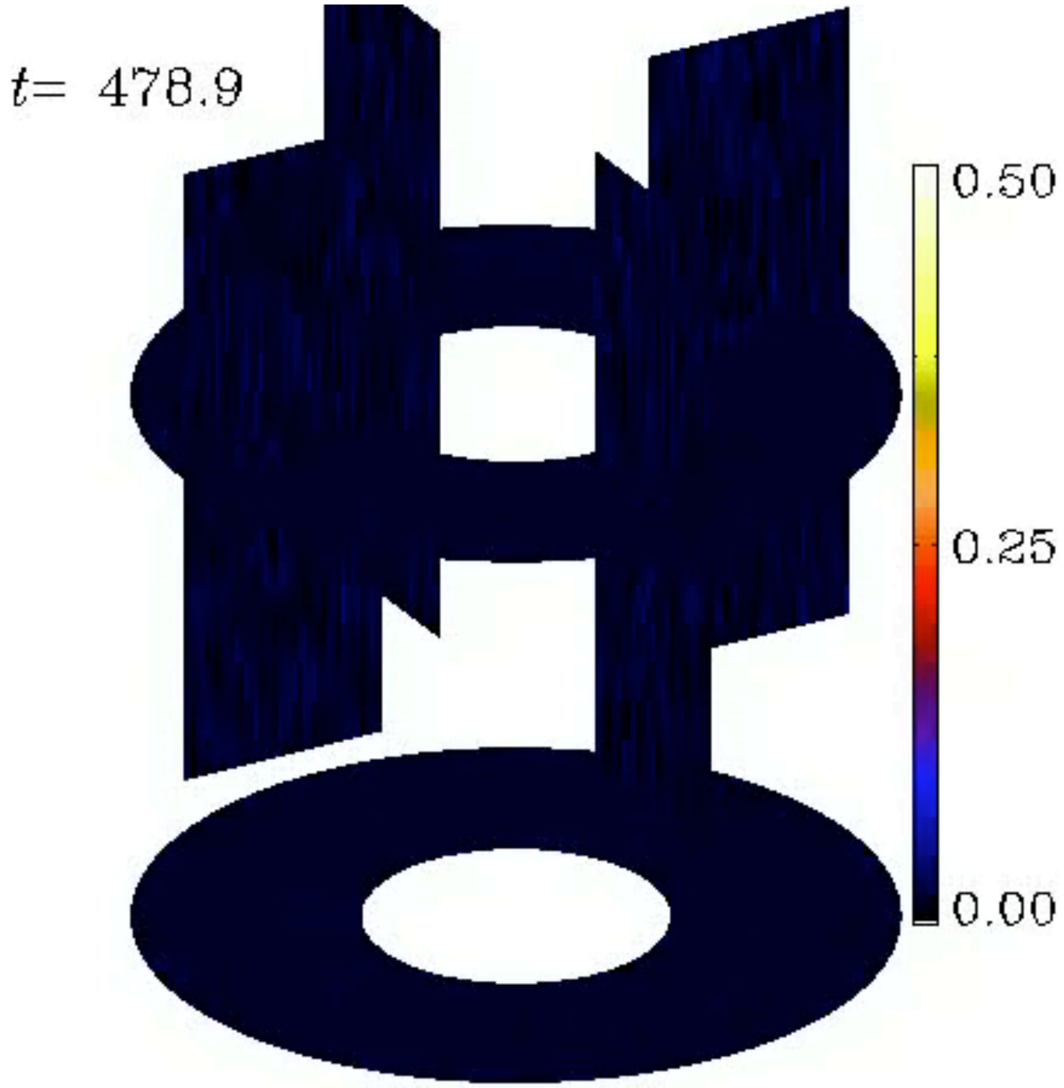


Turbulence


High pressure regions
Star


Direction of dust acceleration
Gas pressure
Super-Keplerian
Sub-Keplerian
Direction of gas acceleration
Stellocentric distance

Turbulence leads to localized short-lived pressure traps



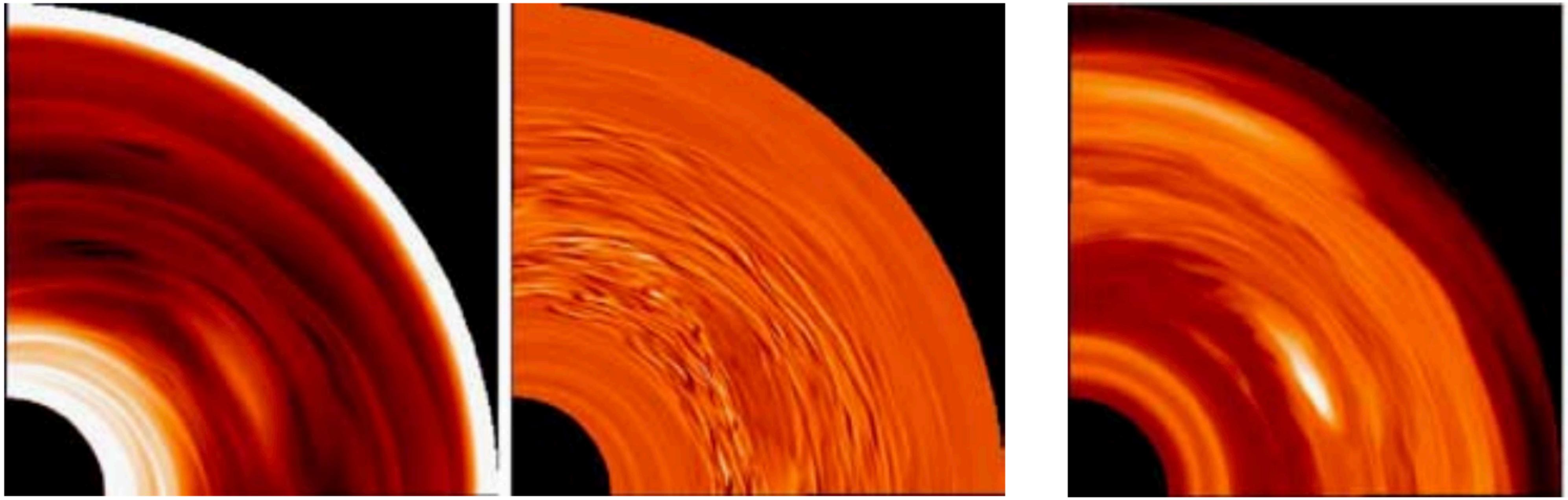
Lyra et al. (2008a)

Vortex Trapping

On the accumulation of solid bodies in global turbulent protoplanetary disc models

Sébastien Fromang★ and Richard P. Nelson
Astronomy Unit, Queen Mary, University of London, Mile End Road, London E1 4NS

Accepted 2005 September 22. Received 2005 September 19; in original form 2005 July 29



Density | Vorticity | Dust to Gas ratio

Vortex trapping

Astron. Astrophys. 295, L1–L4 (1995)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Did planet formation begin inside persistent gaseous vortices?

P. Barge[1] and J. Sommeria[2]

[1] Laboratoire d'Astronomie Spatiale, B.P. 8, F-13376 Marseille cédex 12, France
[2] Ecole Normale Supérieure de Lyon, Laboratoire de Physique, CNRS, 46 Allée d'Italie, F-69364 Lyon cédex 07, France

Received 30 August 1994 / Accepted 3 January 1995

Abstract. We explore here the idea, reminiscent in some respect of Von Weizsäcker's (1944) and Alfvèn's (1976) outmoded cosmogonies, that long-lived vortices in a turbulent protoplanetary nebula can capture large amount of solid particles and initiate the formation of planets. Some puzzling features of the solar system appear as natural consequences of our simple model:

- The captured mass presents a maximum near Jupiter's orbit.

- Outside this optimal orbit, the collected material, mainly composed of low density particles, sinks deeply into the vortices and rapidly collapses into massive bodies at the origin of the solid core of the giant planets.

- Inside this orbit, by contrast, the high density particles are preferentially selected by the vortices and assembled by local gravitational instabilities into planetesimals, massive enough to be released by the vortices and to grow later, in successive collisions, to form the terrestrial planets.

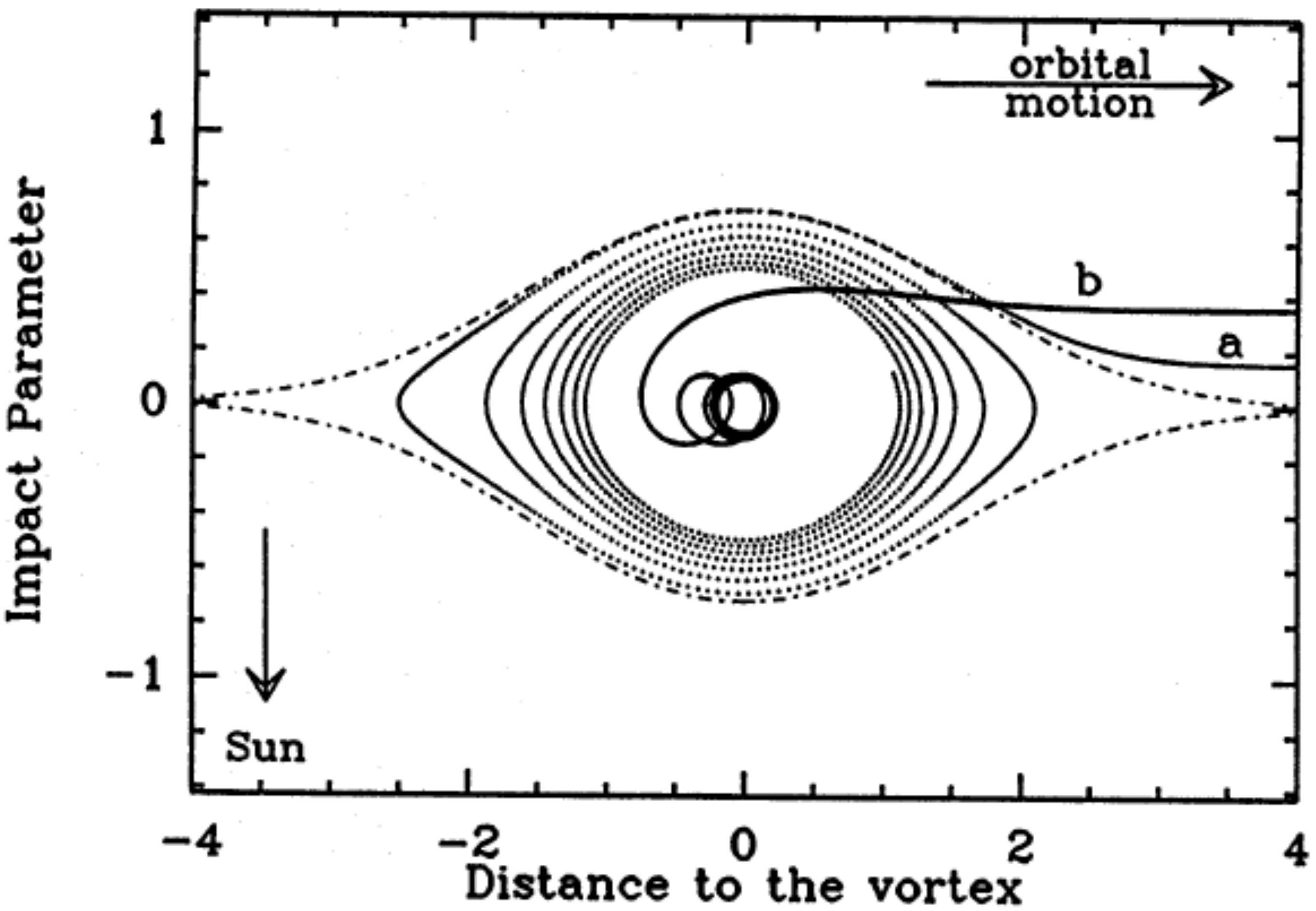
(i) settling of the dust grains toward the mid-plane of the gaseous disk;

(ii) gravitational collapse of the resulting layer of sediment (when dense enough) into numerous kilometer-sized bodies, the so called "planetesimals".

Then, as suggested by the cratering of the present planets, gravitationaly bounded bodies grow by the accumulation of planetesimals in successive collisions; this stage of the planet growth is, indeed, reproduced by a number of dynamical models (Safronov 1969; Barge and Pellat 1991, 1993).

However the above scenario faces two major difficulties.

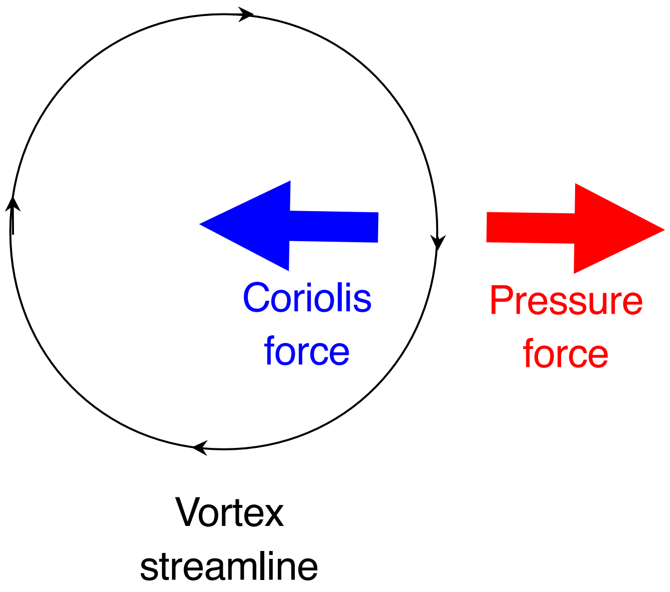
(1) The solid cores of the giant planets must be formed in less than some 10^6 years, in order for the gas to be captured before being swept away (Safronov 1969; Strom *et al.* 1993) during the sun's T-Tauri phase; with a reasonable density of solid material, this is difficult to achieve by planetesimal accumulation (Safronov 1969; Wetherill 1988), especially for the outermost planets.

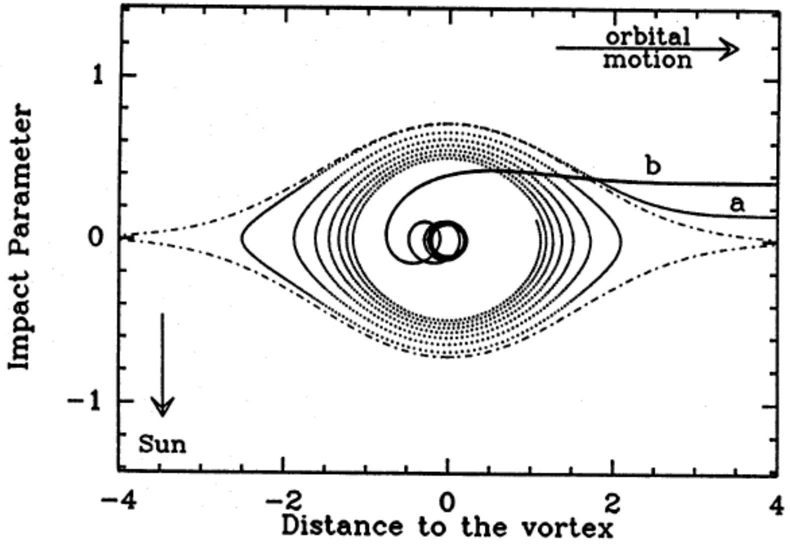


Barge & Sommeria 95

Vortex Trapping

Geostrophic equilibrium:





Barge & Sommeria (1995)

Grains do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation

(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

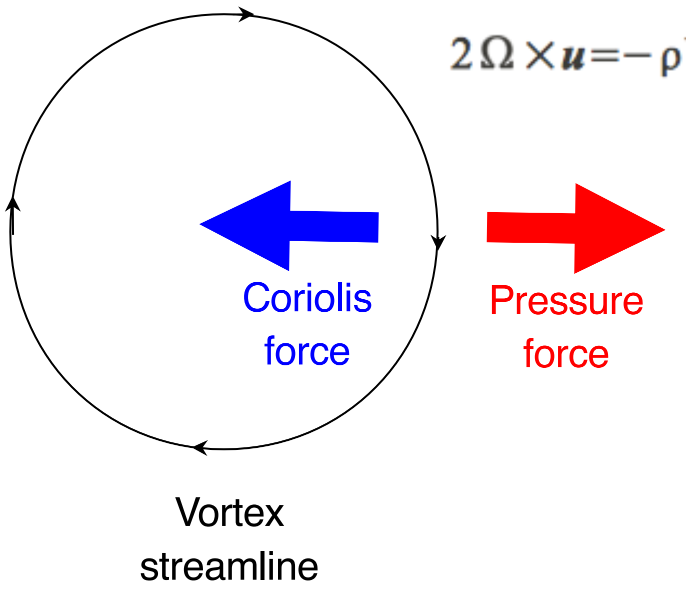
Speeds up planet formation enormously

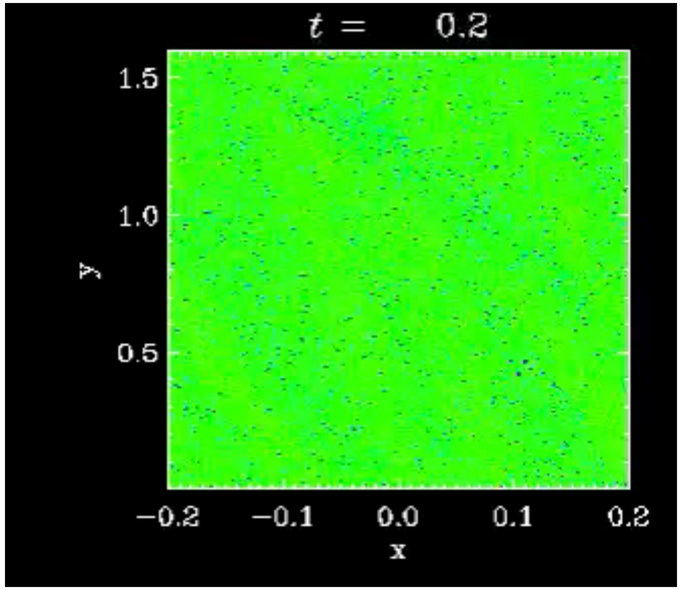
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

Vortex Trapping

Geostrophic balance:

$$2\Omega \times \boldsymbol{u} = -\rho^{-1}\nabla p$$





Raettig, Lyra, & Klahr (2013)

Grains do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation

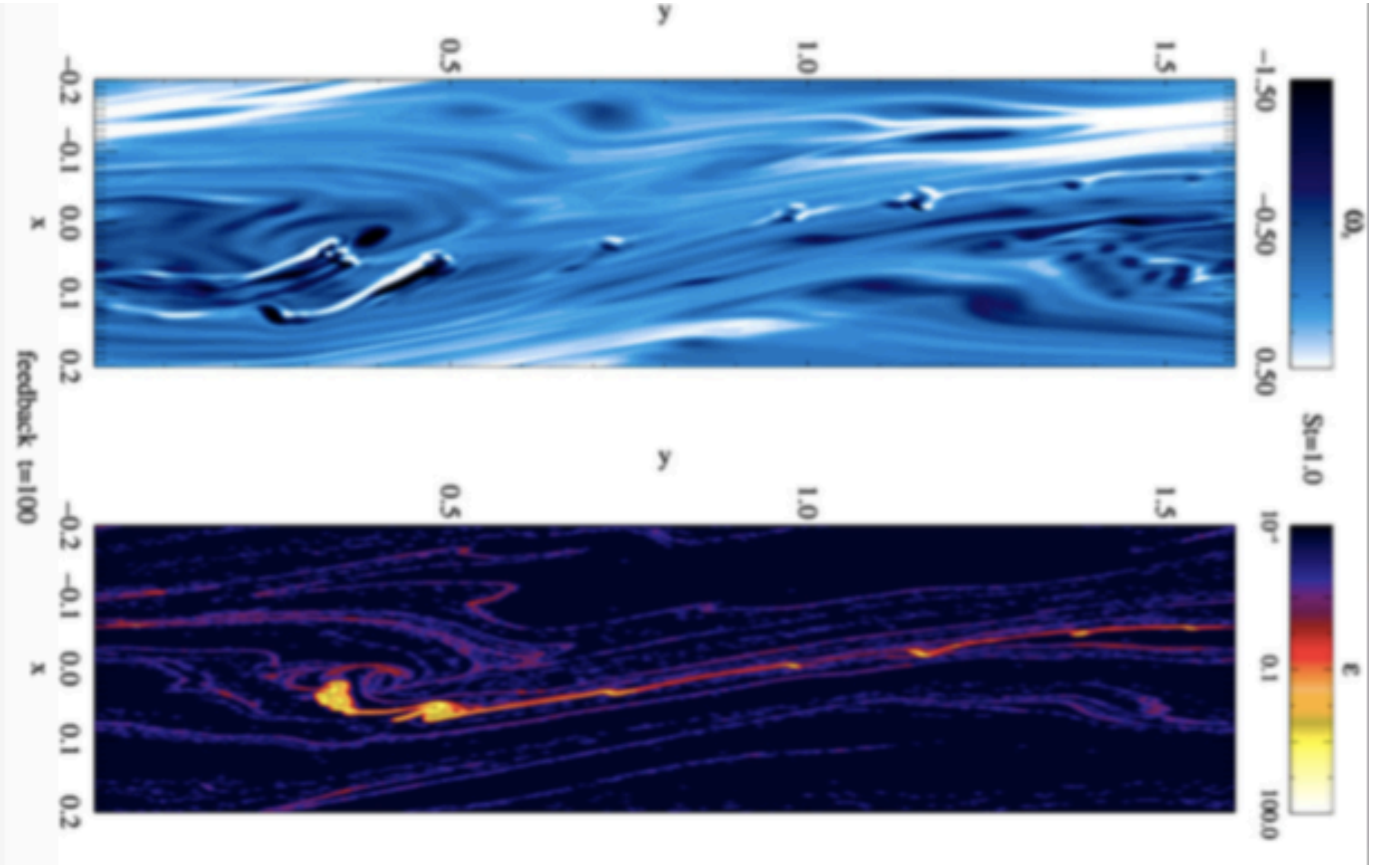
(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

Speed up planet formation enormously

(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

Clumping

Easily reaches dust-to-gas ratio > 1
even for solar (and sub-solar) metallicities.

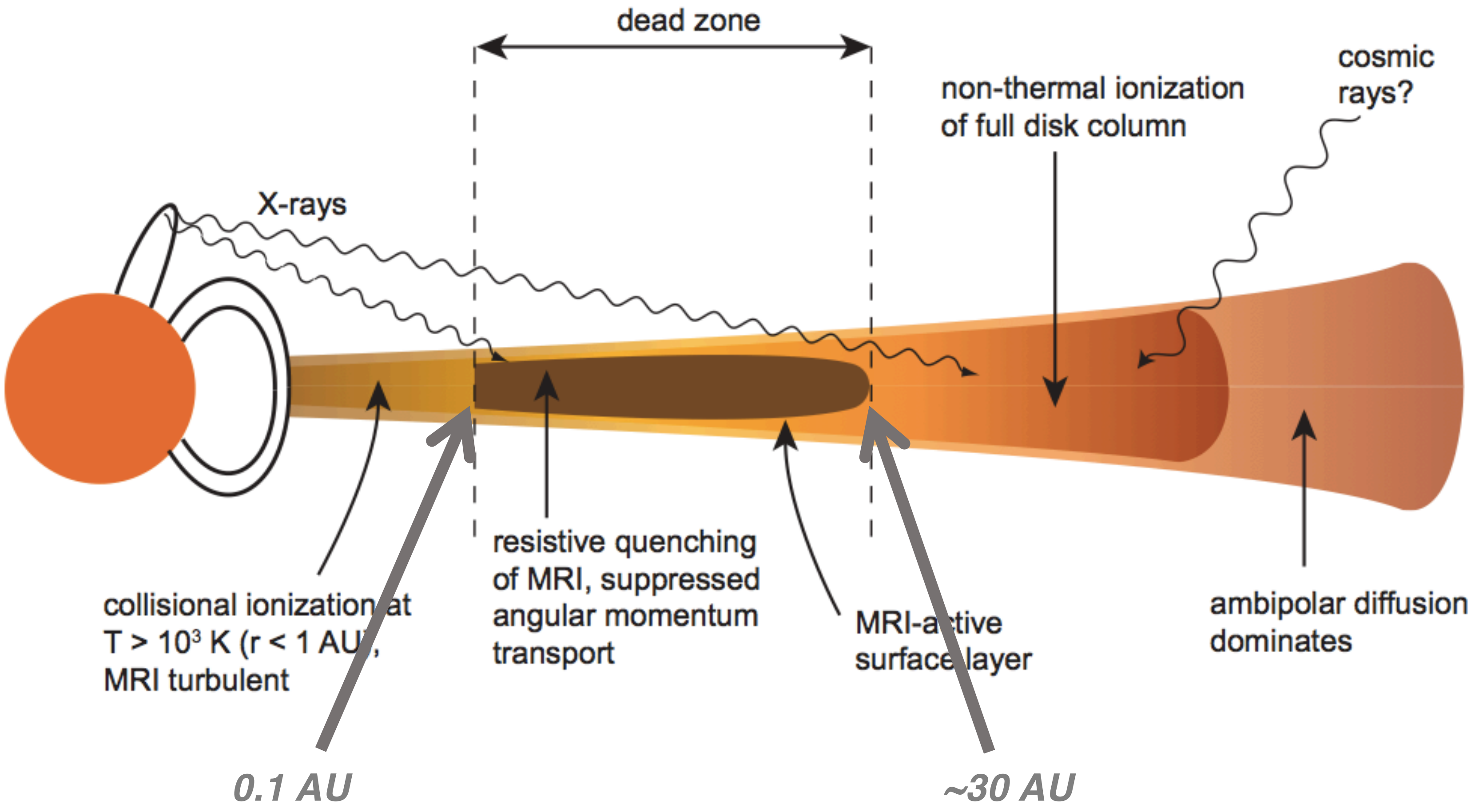


Gas vorticity

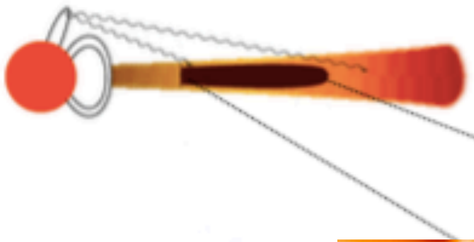
grains-to-gas ratio

Raettig et al. (2015)

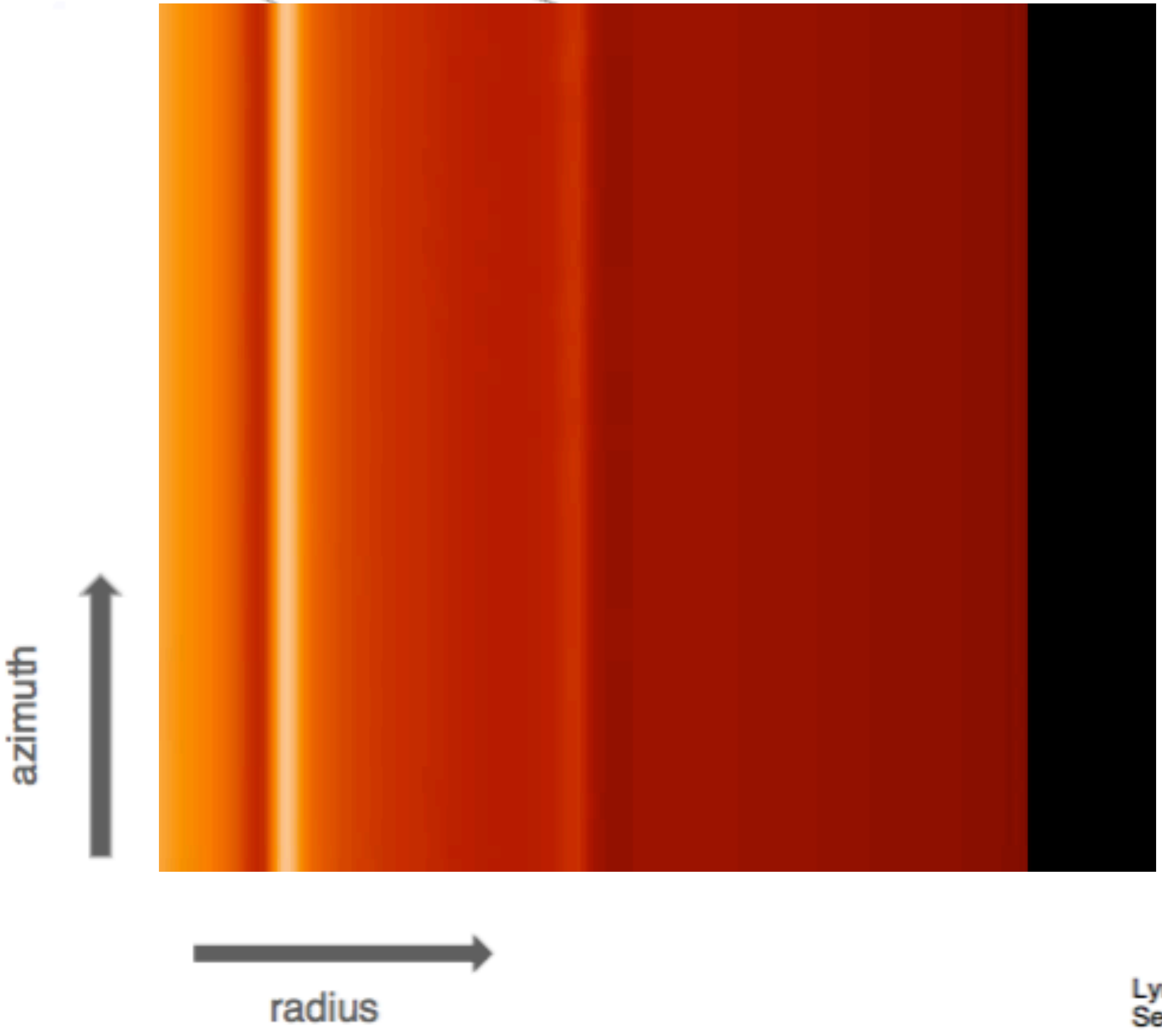
Dead zones



There should be a **magnetized, active zone**
and a **non-magnetic, dead zone**

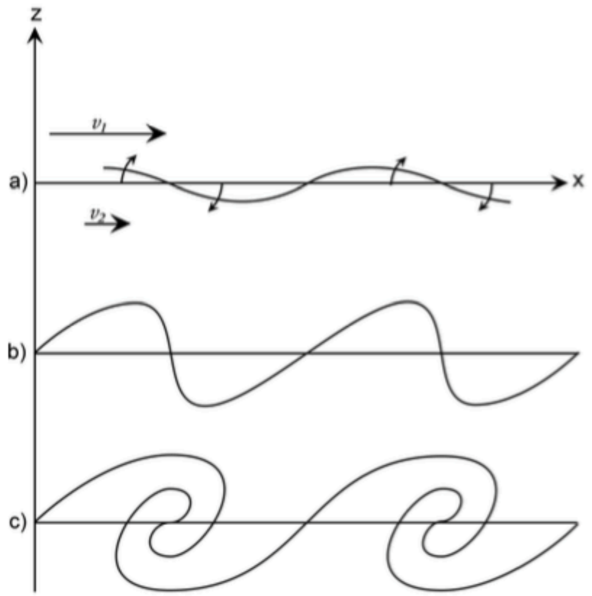


A simple dead zone model



Rossby wave instability

(or… Kelvin-Helmholtz in differentially rotating disks)



Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

Astronomy & Astrophysics

All volumes For authors

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Home

Highlights - Volume 491-3 (December I 2008)

Published on 18 November 2008

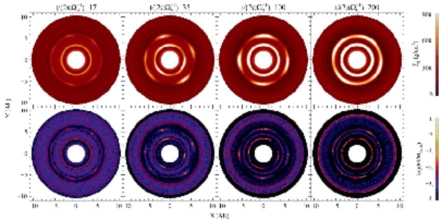
PDF version

HIGHLIGHTS: this week in A&A

Volume 491-3 (December I 2008)

In section 1. Letters

"Embryos grown in the dead zone. Assembling the first protoplanetary cores in low mass self-gravitating circumstellar disks of gas and solids", by W. Lyra et al., A&A 491, p. L41



A particularly difficult phase in planet formation is the growth from meter-size boulders to planetary embryos of the size of our Moon or Mars. These growing objects have been known to drift extremely rapidly in protoplanetary disks, so much so that they would generally fall into the central star in a matter of tens of thousands of years, a very short timescale compared to the million years believed to be necessary to form planets. In this issue, Lyra et al. propose a way out of this by forming planetary embryos in special zones of protoplanetary disks, just at the edge of so-called dead zones. These dead zones would be regions in which disks are passive instead of being turbulent. With hydrodynamical simulations, Lyra et al. show that material accumulating between turbulent and passive regions would be trapped into vortexes to effectively form planetary embryos of Moon- to Mars-mass.

In section 1. Letters

Embryos grown in the dead zone. Assembling the first protoplanetary cores in low mass self-gravitating circumstellar disks of gas and solids

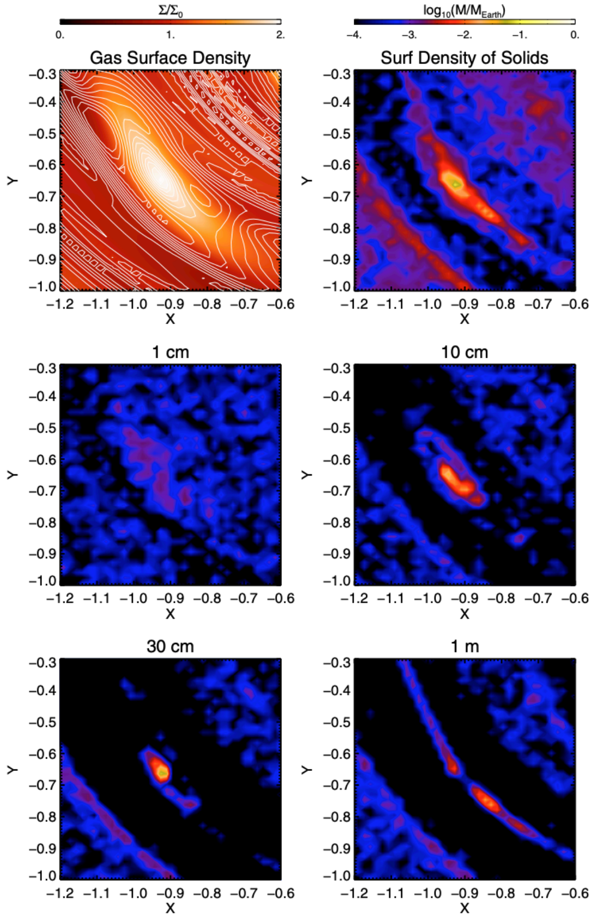
Show affiliations

Lyra, W.; Johansen, A.; Klahr, H.; Piskunov, N.

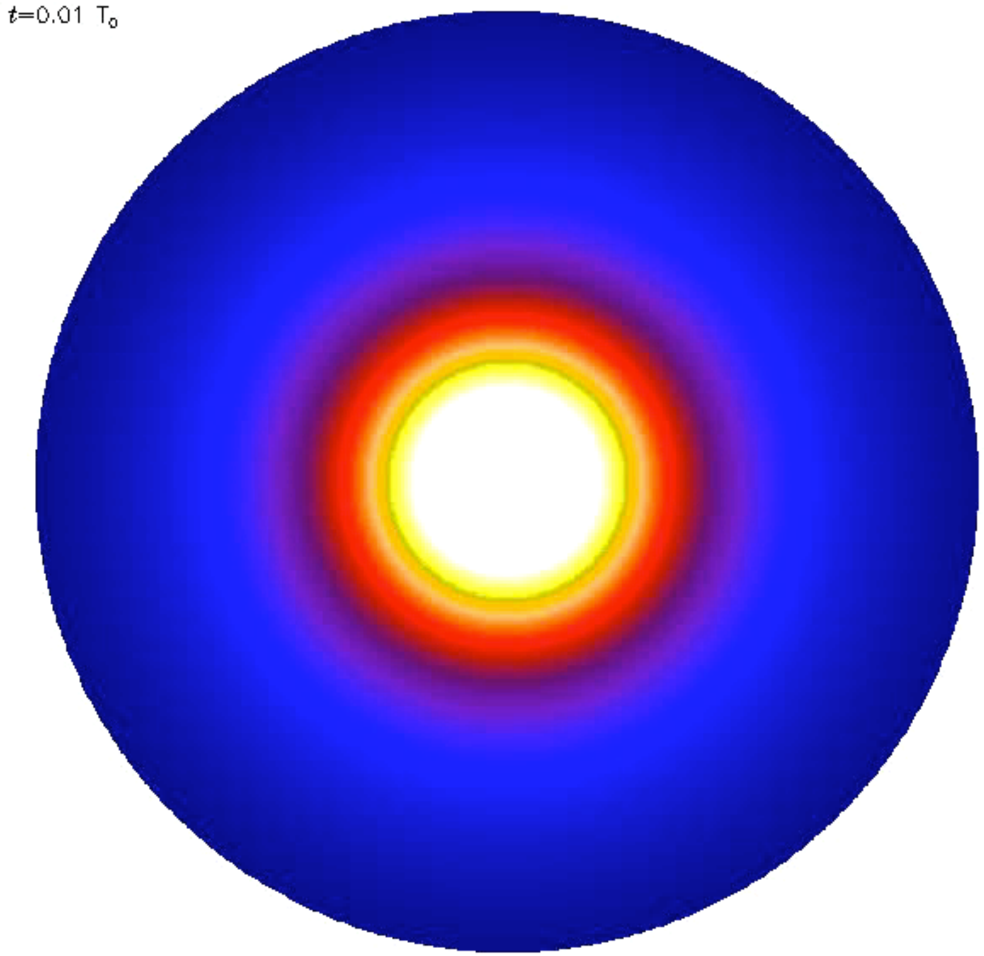
Context: In the borders of the dead zones of protoplanetary disks, the inflow of gas produces a local density maximum that triggers the Rossby wave instability. The vortices that form are efficient in trapping solids.

Aims: We aim to assess the possibility of gravitational collapse of the solids within the Rossby vortices.

Methods: We perform global simulations of the dynamics of gas and solids in a low mass non-magnetized self-gravitating thin protoplanetary disk with the Pencil Code.



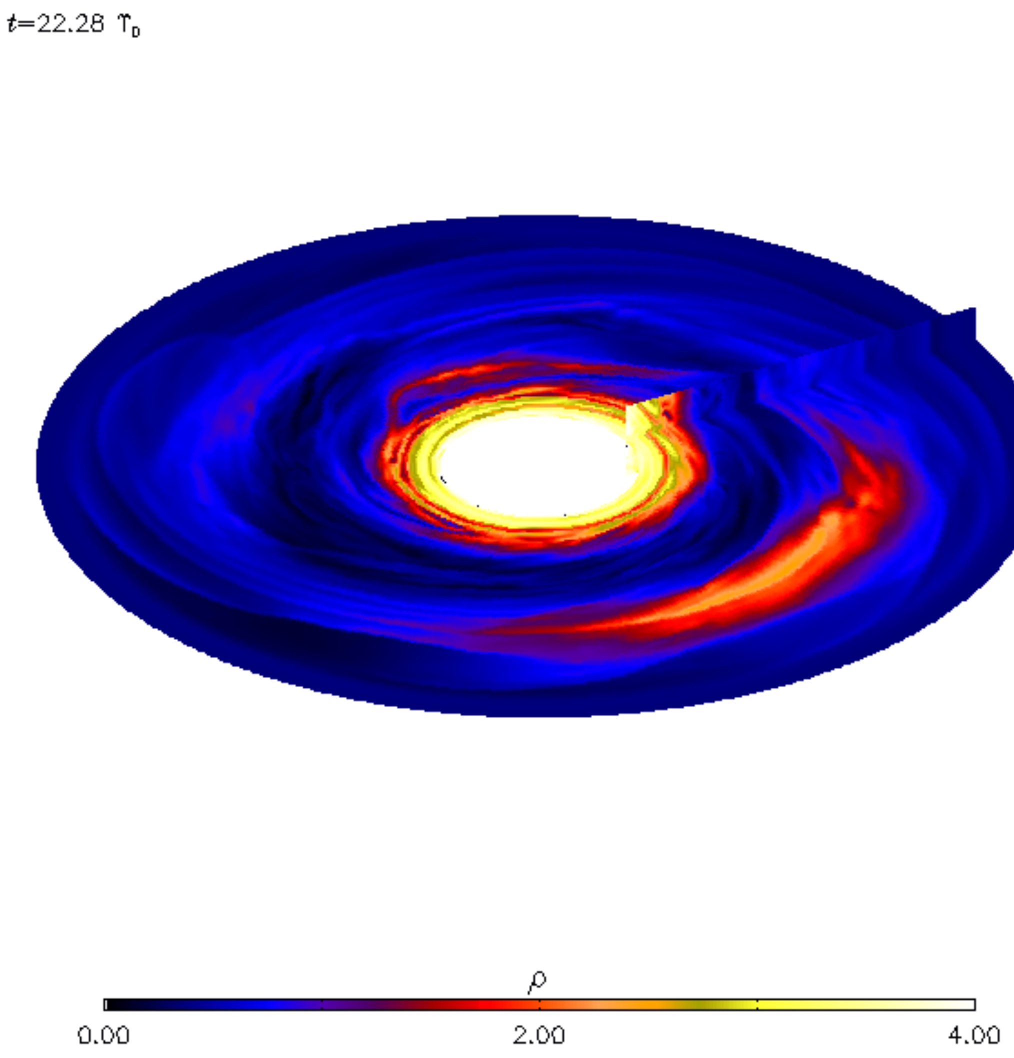
Inner (0.1 AU) active/dead zone boundary

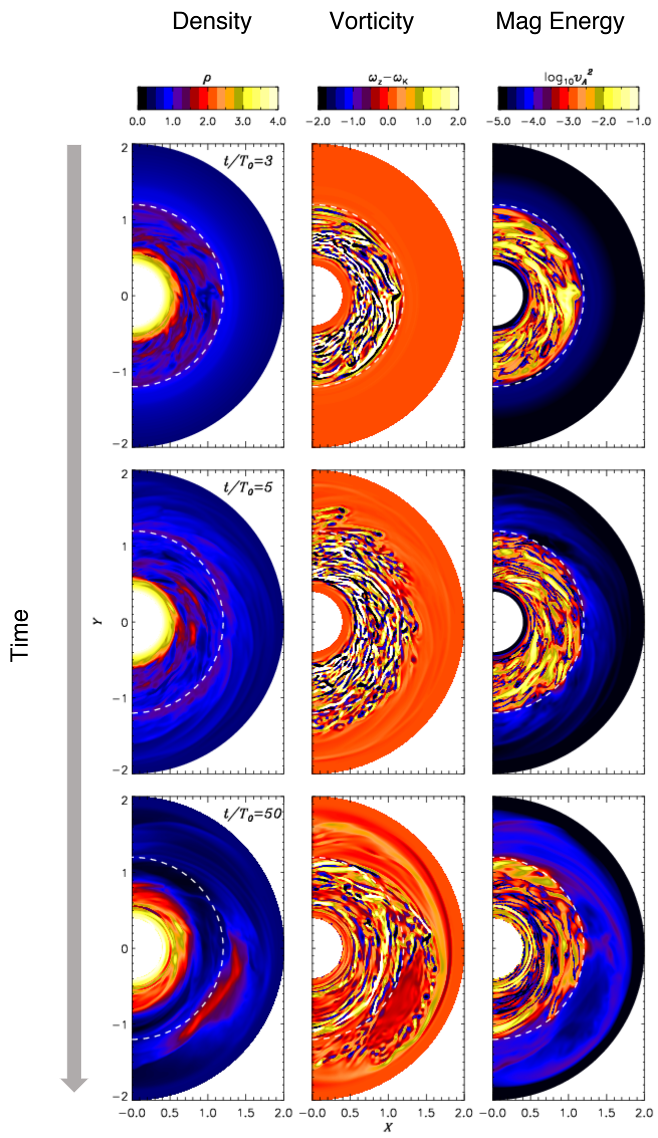


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Active/dead zone boundary

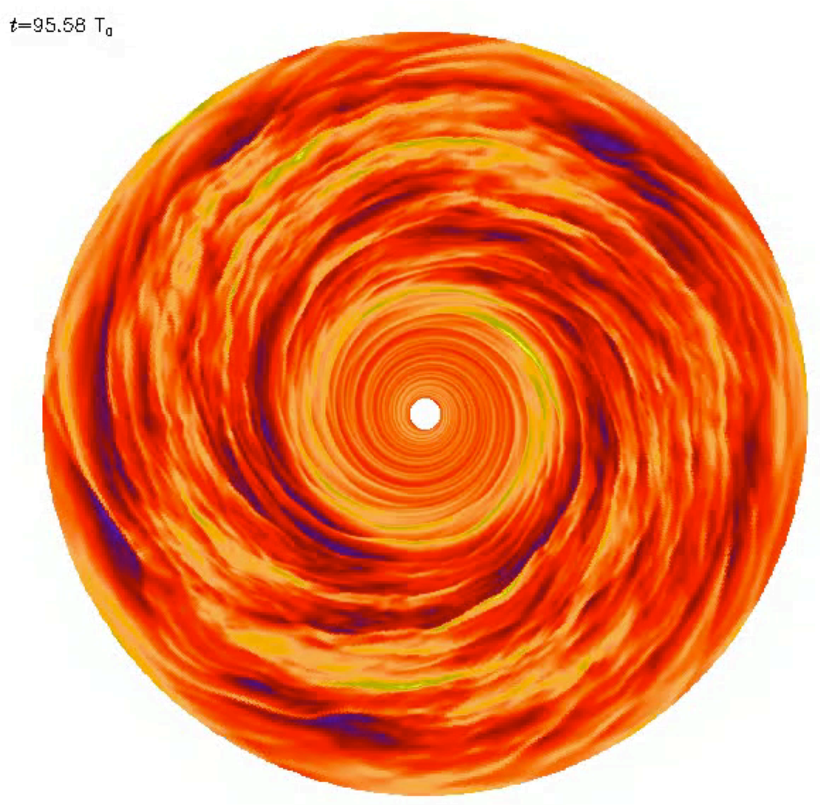


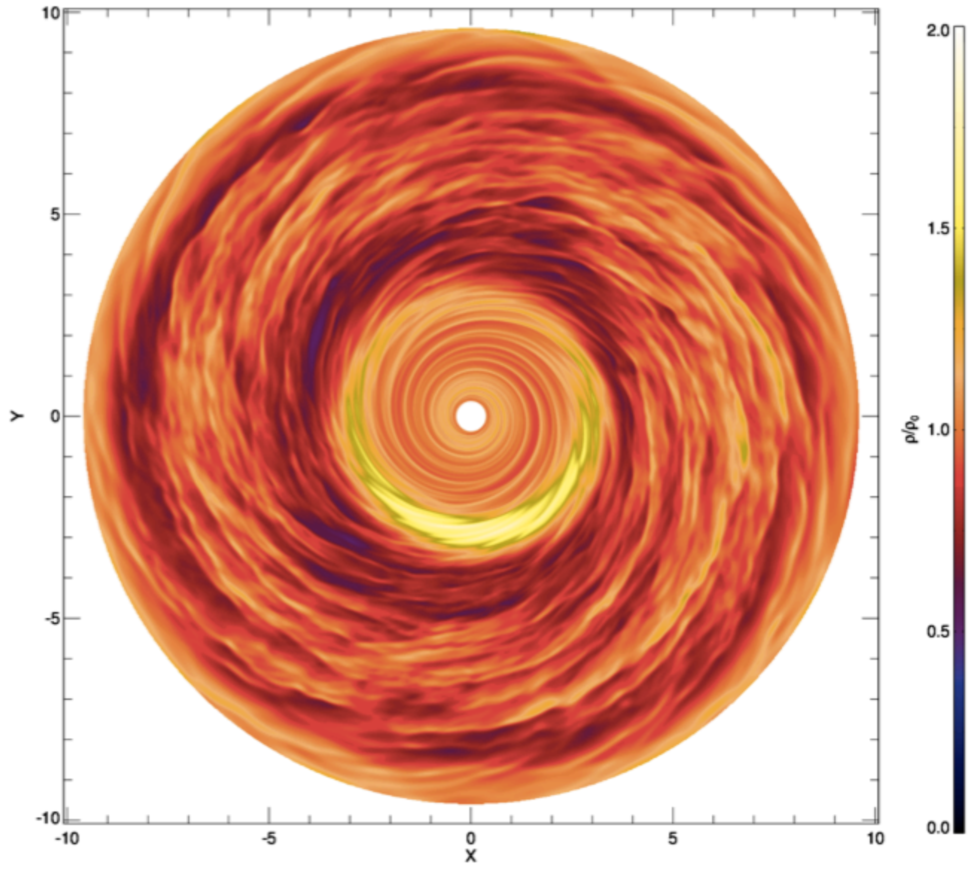


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

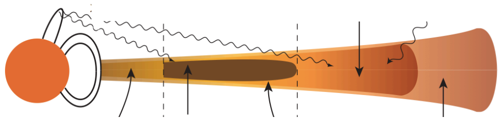
Outer Dead/Active zone transition KHI





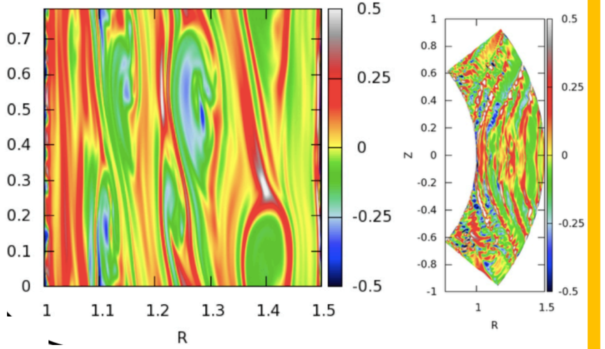
Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)



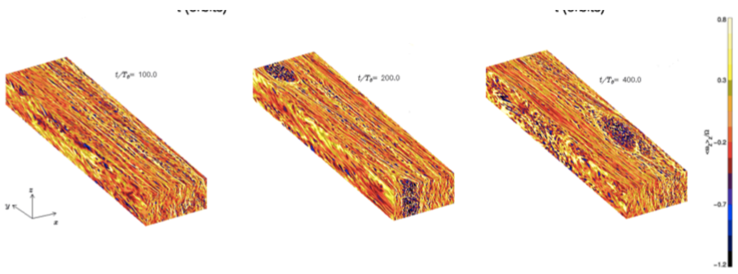
Hydrodynamical Instabilities

Vertical Shear Instability



Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Convective Overstability

The Astrophysical Journal, 789:77 (7pp), 2014 July 1 doi:10.1088/0004-637X/789/1/77

CONVECTIVE OVERSTABILITY IN ACCRETION DISKS: THREE-DIMENSIONAL LINEAR ANALYSIS AND NONLINEAR SATURATION

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ABSTRACT

Recently, Klahr & Hubbard claimed that a hydrodynamical linear overstability exists in protoplanetary disks, powered by buoyancy in the presence of thermal relaxation. We analyze this claim, confirming it through rigorous compressible linear analysis. We model the system numerically, reproducing the linear growth rate for all cases studied. We also study the saturated properties of the overstability in the shearing box, finding that the saturated state produces finite amplitude fluctuations strong enough to trigger the subcritical baroclinic instability (SBI). Saturation leads to a fast burst of enstrophy in the box, and a large-scale vortex develops in the course of the next ≈100 orbits. The amount of angular momentum transport achieved is of the order of $\alpha \approx 10^{-3}$, as in compressible SBI models. For the first time, a self-sustained three-dimensional vortex is produced from linear amplitude perturbation of a quiescent base state.

Key words: hydrodynamics – instabilities – methods: analytical – methods: numerical – planets and satellites: formation – protoplanetary disks

Online-only material: color figures

A&A 527, A138 (2011)
DOI: 10.1051/0004-6361/201015568

Astronomy & Astrophysics

The baroclinic instability in the context of layered accretion

Self-sustained vortices and their magnetic stability in local compressible unstratified models of protoplanetary disks

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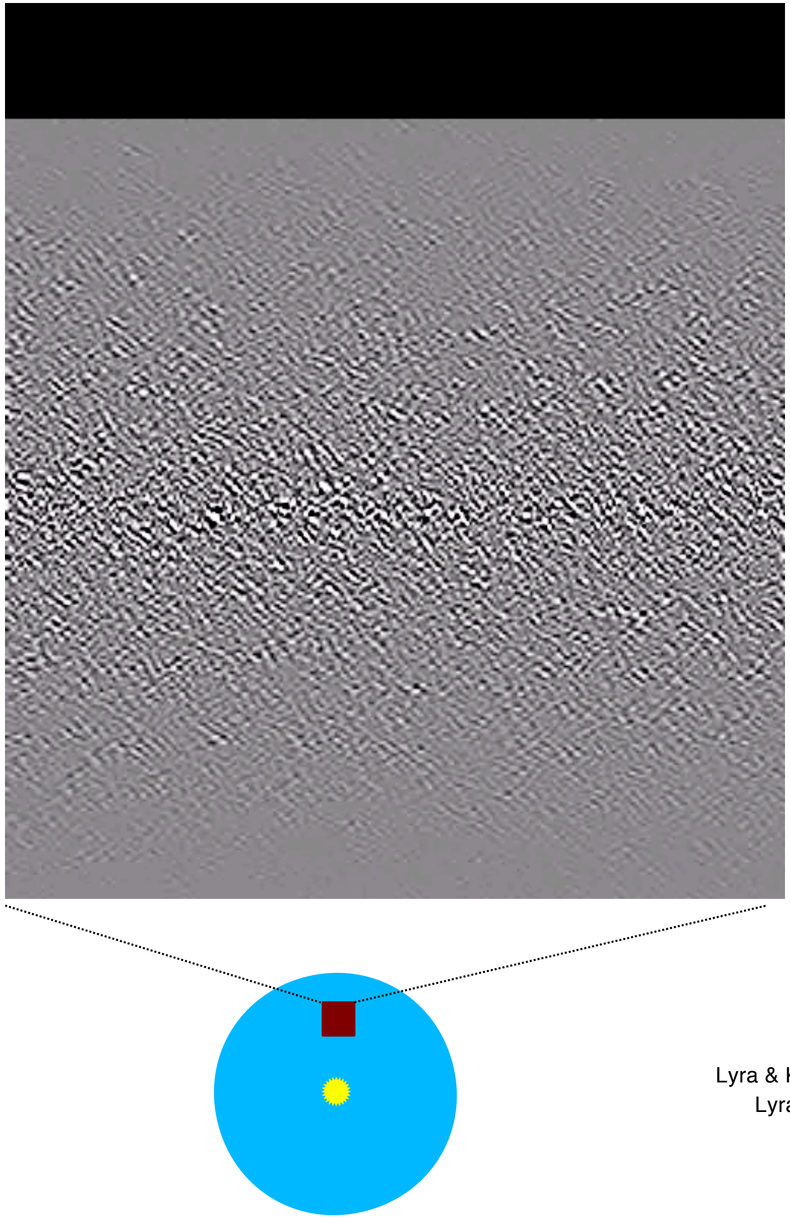
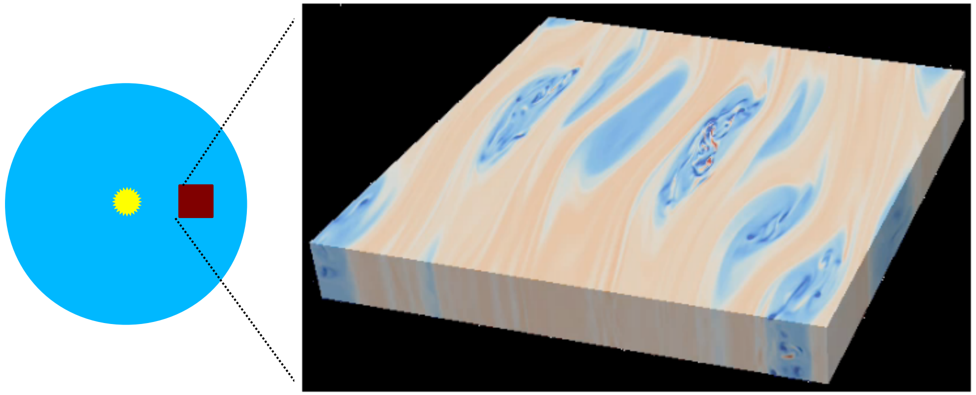
ABSTRACT

Context. Turbulence and angular momentum transport in accretion disks remains a topic of debate. With the realization that dead zones are robust features of protoplanetary disks, the search for hydrodynamical sources of turbulence continues. A possible source is the baroclinic instability (BI), which has been shown to exist in unmagnetized non-barotropic disks.
Aims. We aim to verify the existence of the baroclinic instability in 3D magnetized disks, as well as its interplay with other instabilities, namely the magneto-rotational instability (MRI) and the magneto-elliptical instability.



Lyra & Klahr (2011)
Lyra (2014)

Convective Overstability



Lesur & Papaloizou (2010)

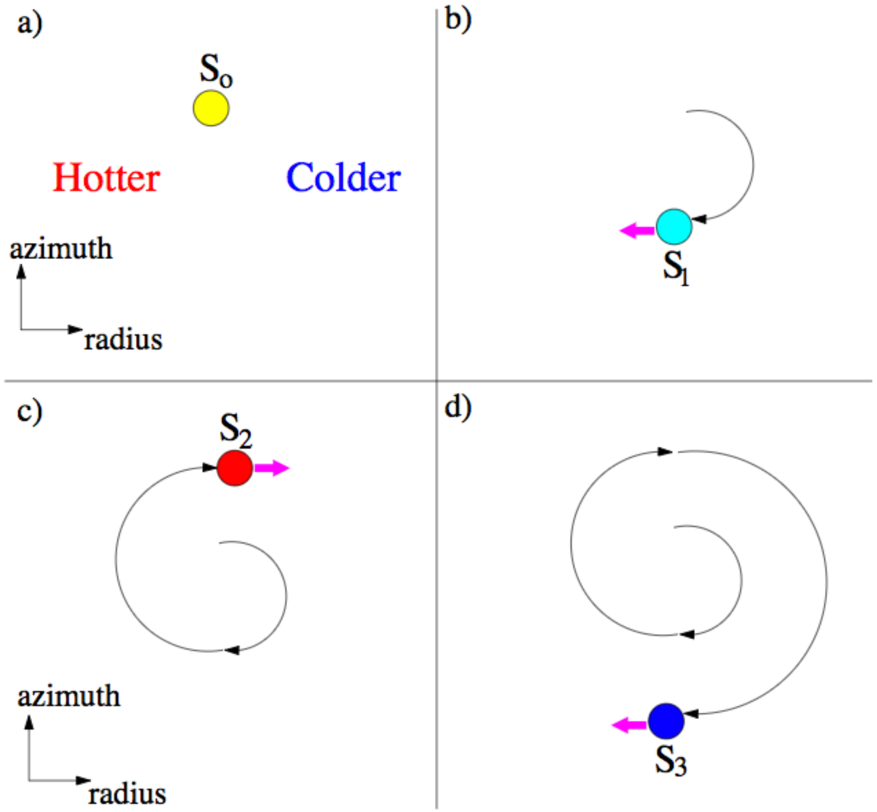


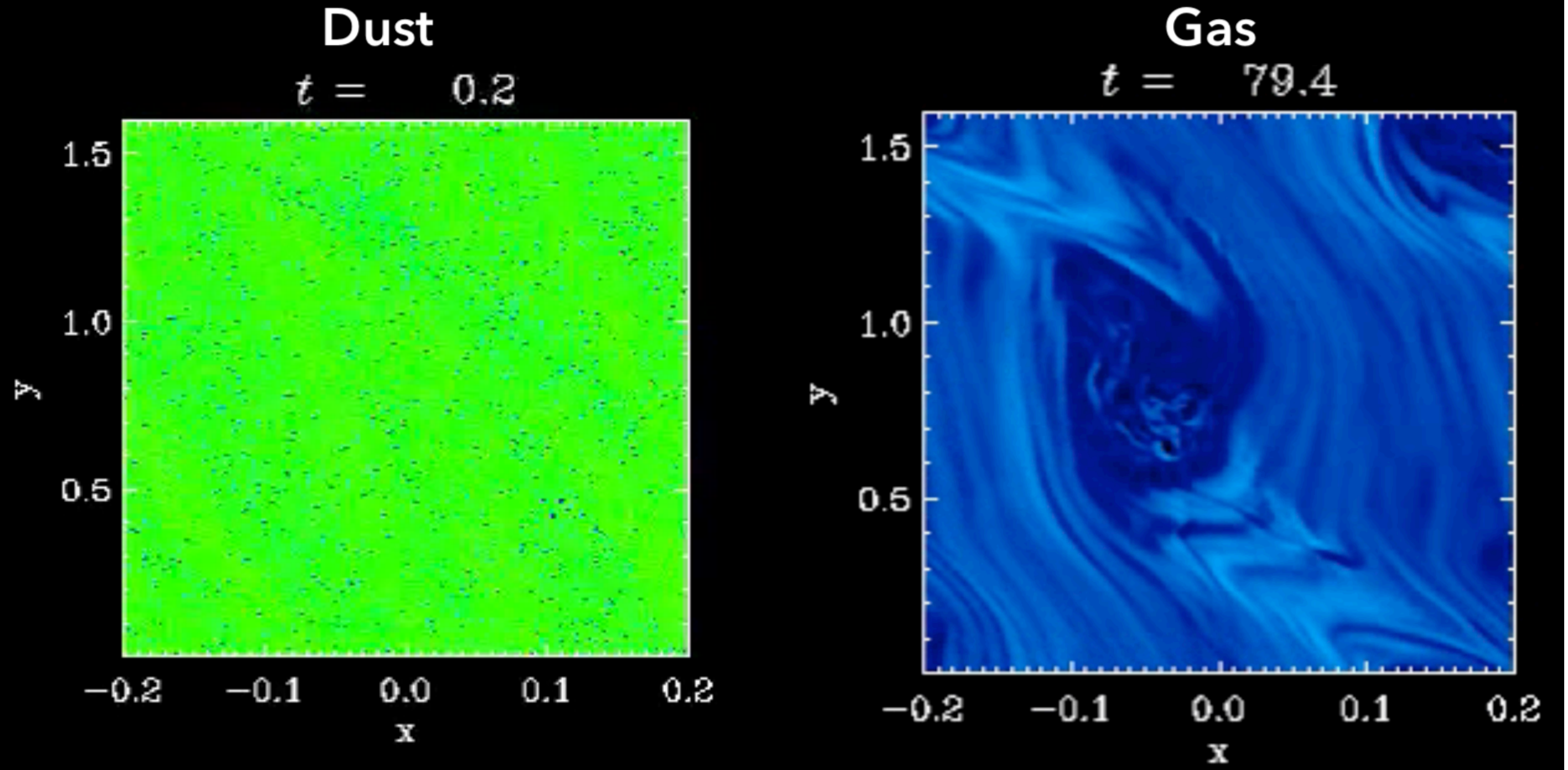
Figure 2. Four panels indicating the convective overstability mechanism. In panel (a) a fluid blob is embedded in a radial entropy gradient. In panel (b) it undergoes half an epicycle and returns to its original radius with a smaller entropy than when it begun $S_1 < S_0$. It hence feels a buoyancy acceleration inwards and the epicycle is amplified. The process occurs in reverse once the epicycle is complete, shown in panel (c), where now $S_2 > S_0$. The oscillations hence grow larger and larger.

Example:

small particles (St=0.01) get trapped in vortex

vortex created by convective overstability

dust piles up, but whether it becomes unstable remains to be shown



Raettig et al., 2013

Vertical shear instability

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **435,** 2610–2632 (2013)
Advance Access publication 2013 September

Linear and non-linear evolution of the vertical shear instability in accretion discs

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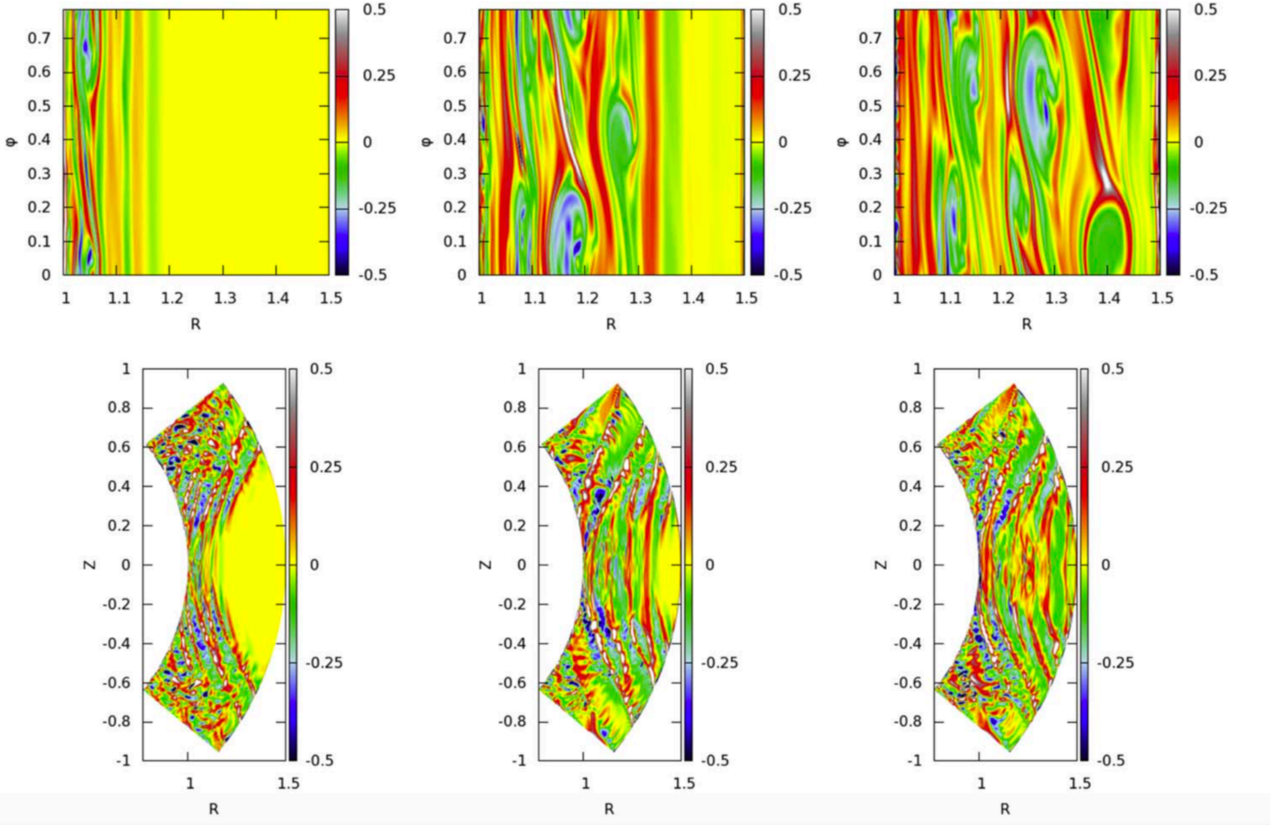
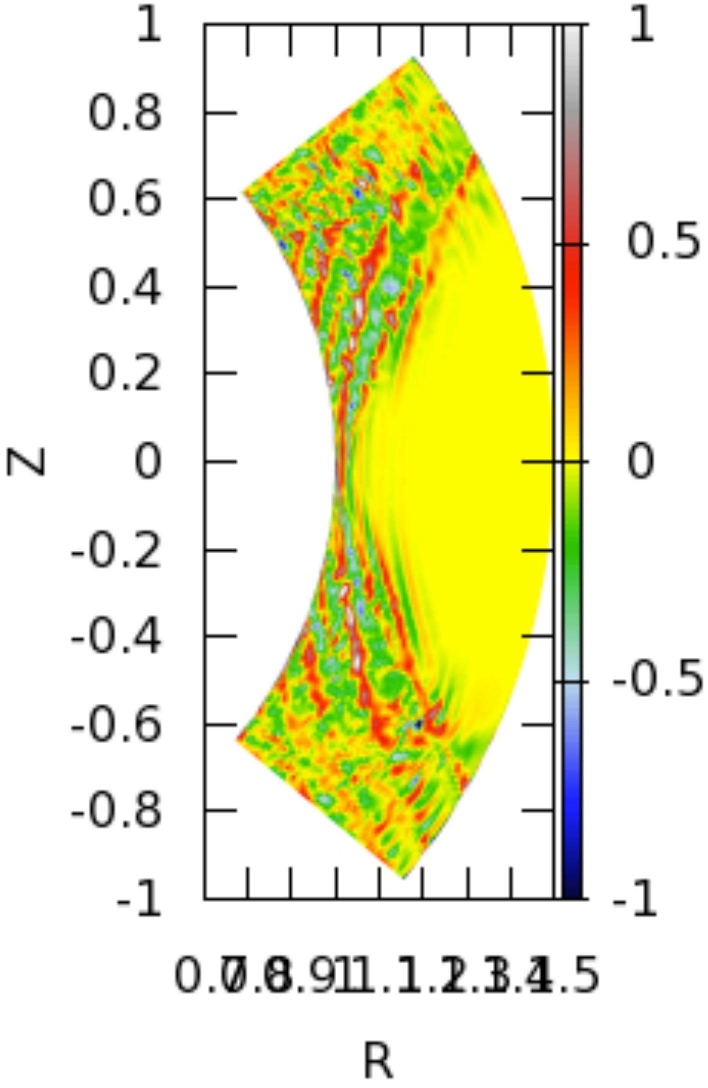
Accepted 2013 August 6. Received 2013 August 6; in original form 2012 September 12

ABSTRACT

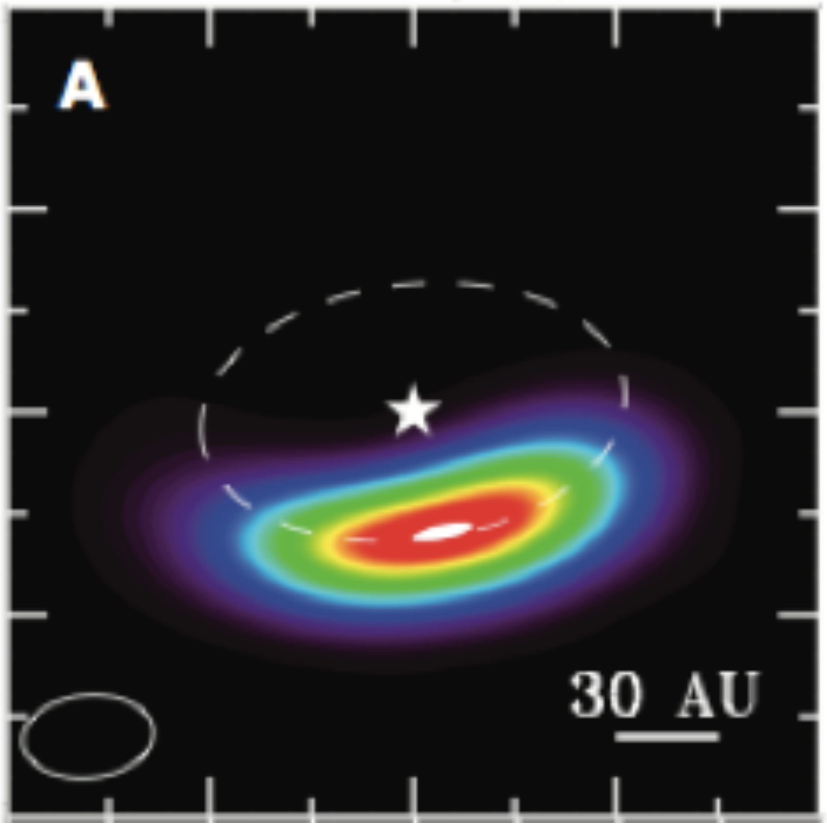




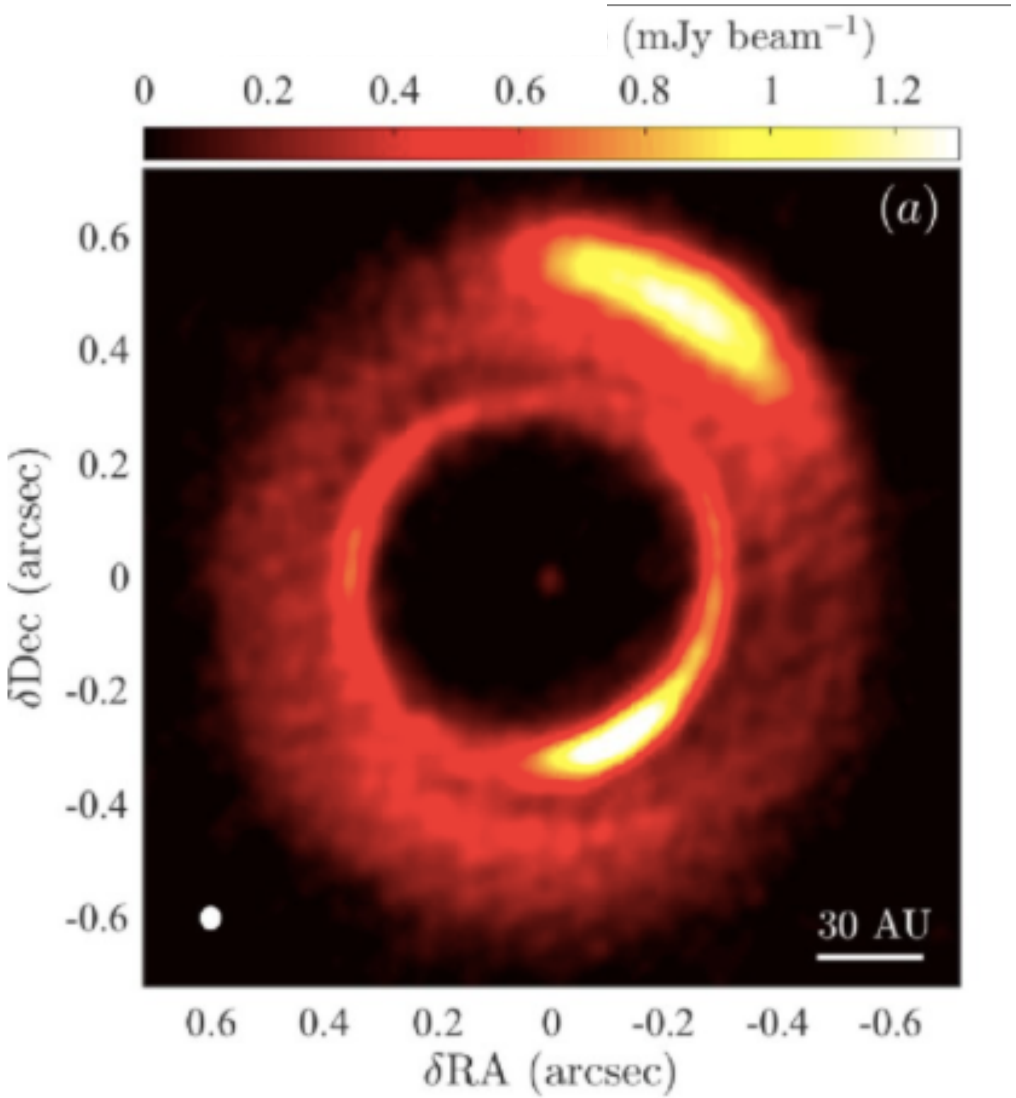
Nelson et al. (2013)

How can we verify
the vortex hypothesis?

Vortices



van der Marel et al. (2013)



Dong+ '18

Oph IRS 48

A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1*] Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]

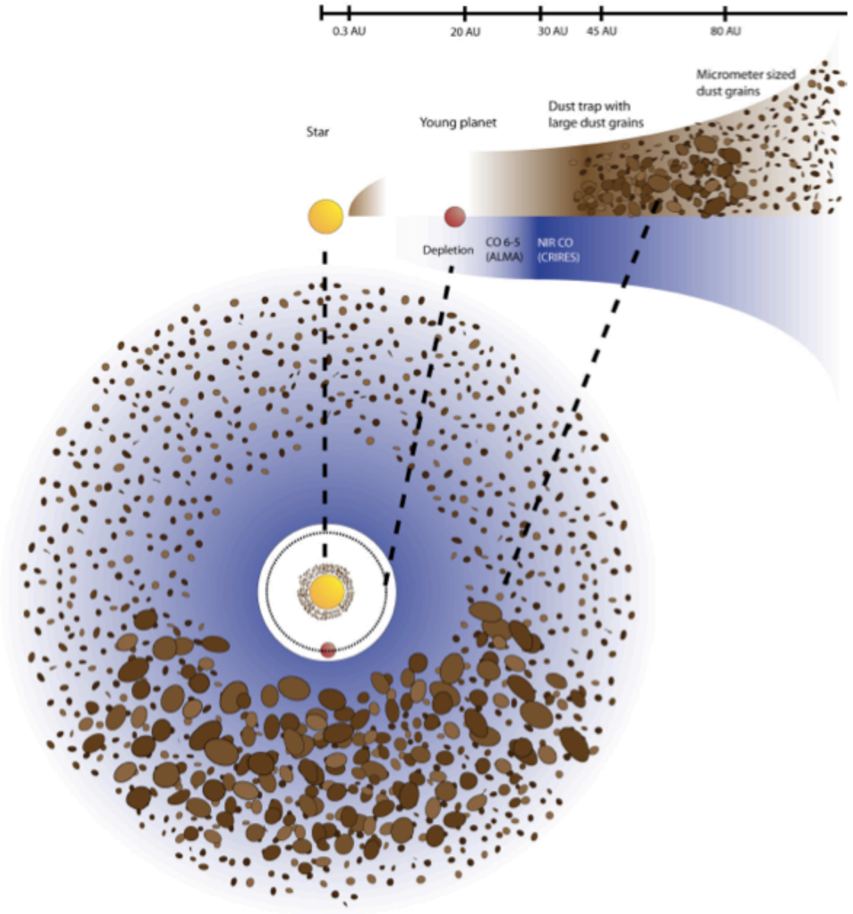
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection of a dust trap in the disk around the star Oph IRS 48 using observations from the Atacama Large Millimeter/submillimeter Array (ALMA). The 0.44-millimeter–wavelength continuum map shows high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains, whereas both the mid-infrared image (micrometer-sized dust) and the gas traced by the carbon monoxide 6-5 rotational line suggest rings centered on the star. The difference in distribution of big grains versus small grains/gas can be modeled with a vortex-shaped dust trap triggered by a companion.

Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

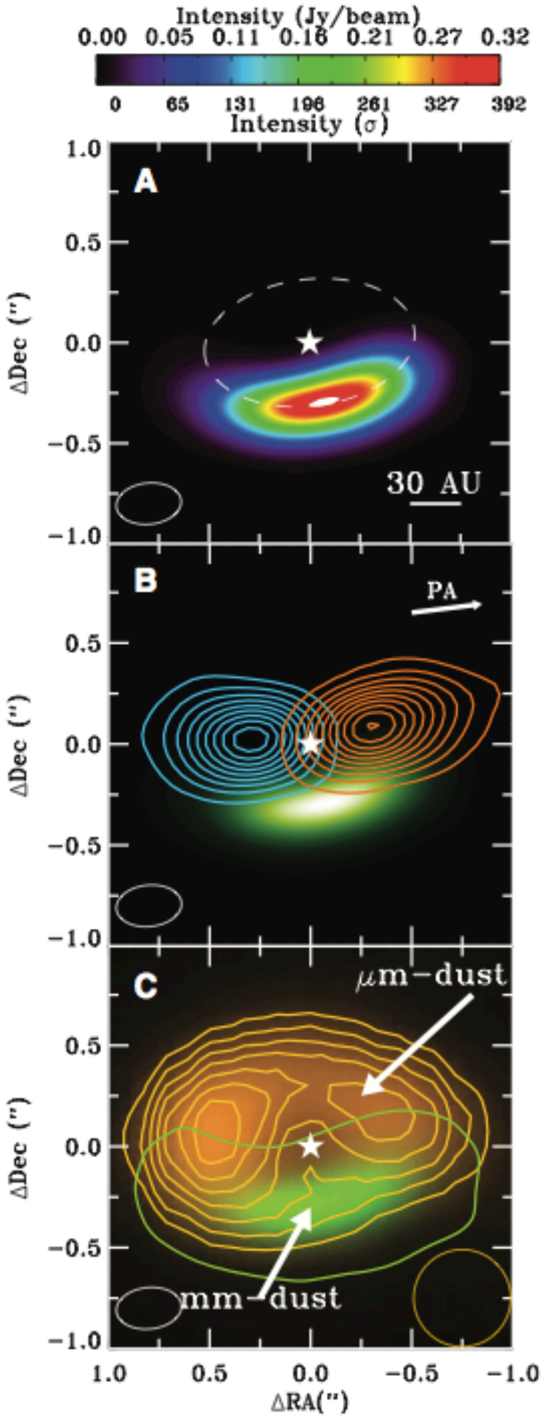
van der Marel+ ‘13

A huge vortex observed with ALMA

The Oph IRS 48 “dust trap”



van der Marel et al. (2013)

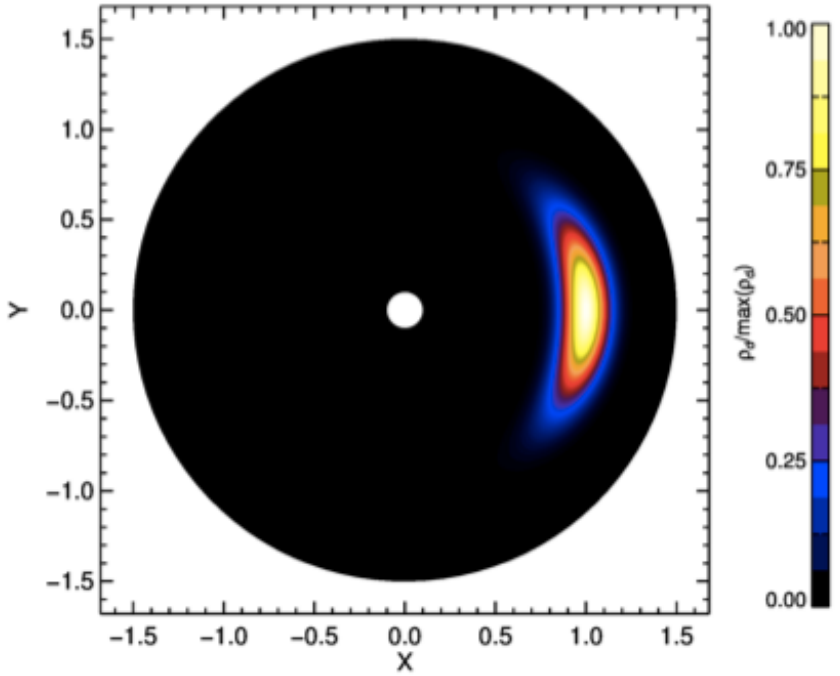


asymmetric mm dust at 63 AU

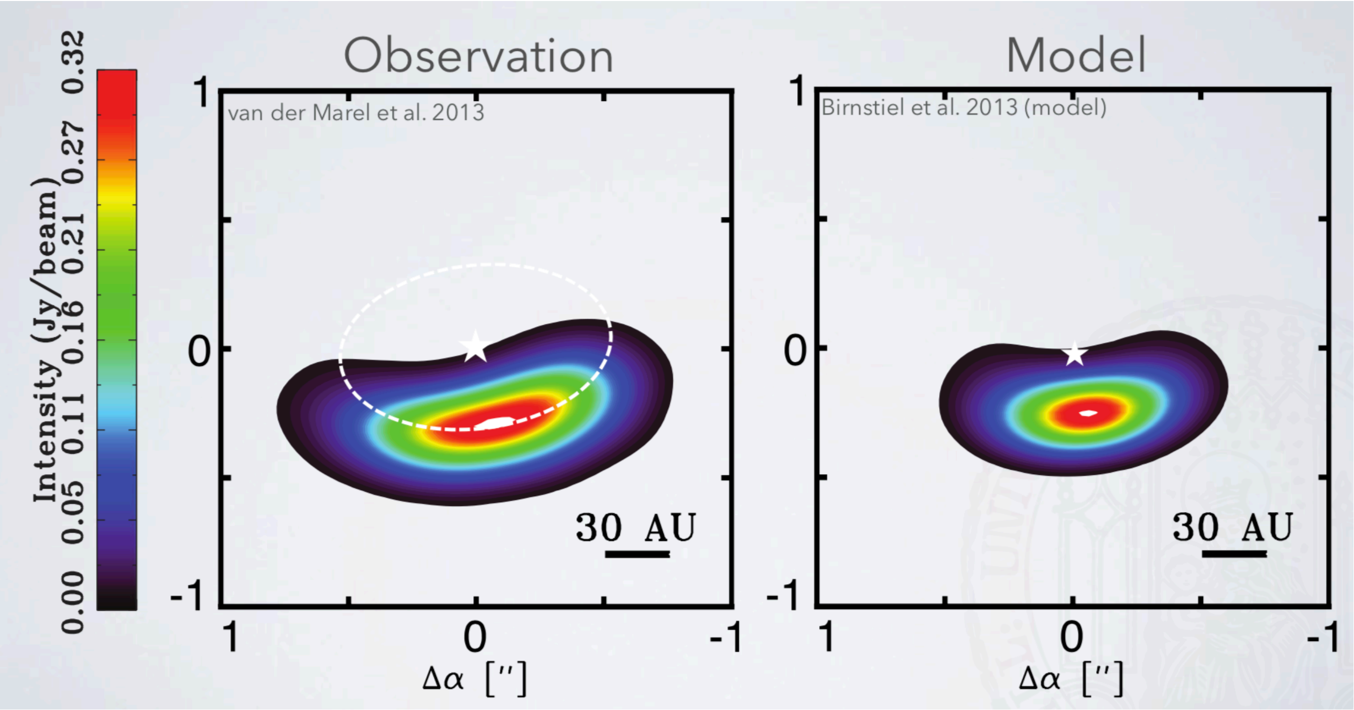
Gas detection: Keplerian rotation

Micron-sized dust follows gas

Oph IRS 48



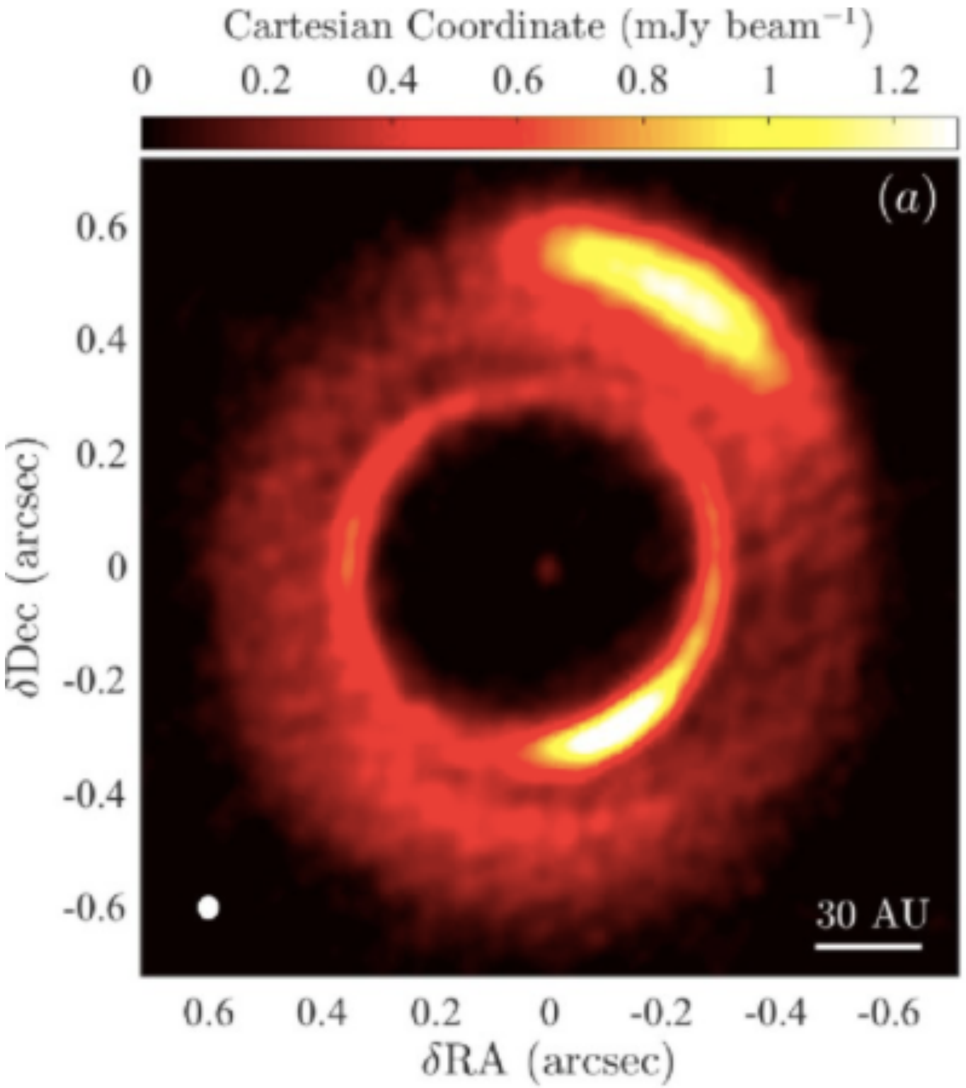
Density of mm grains
(Lyra & Lin 2013)



Observed intensity
(van der Marel et al. 2013)

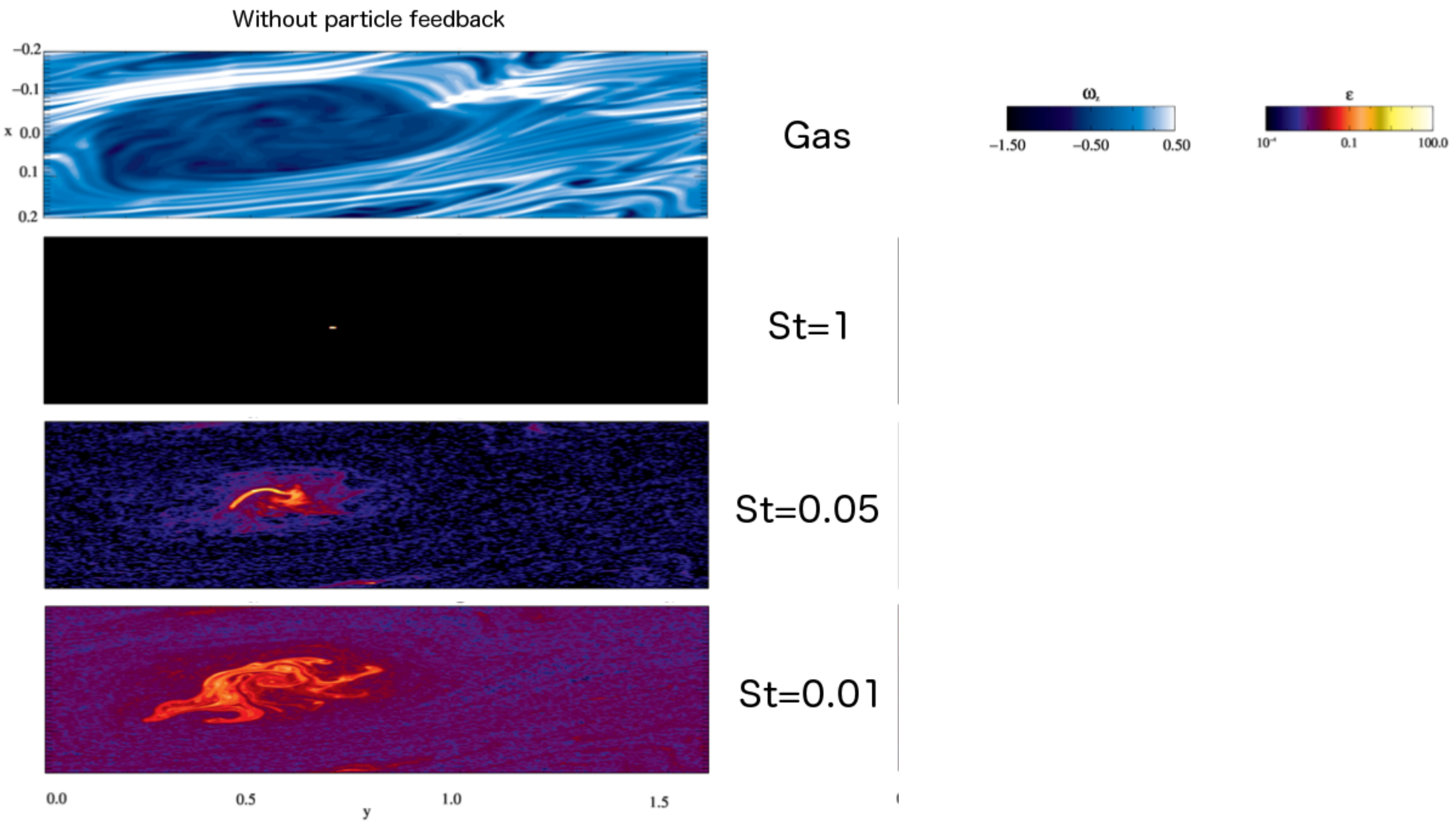
Model intensity
(Birnstiel et al. 2013)

MWC 758



Dong+ '18

Vortex trapping vs grain radius

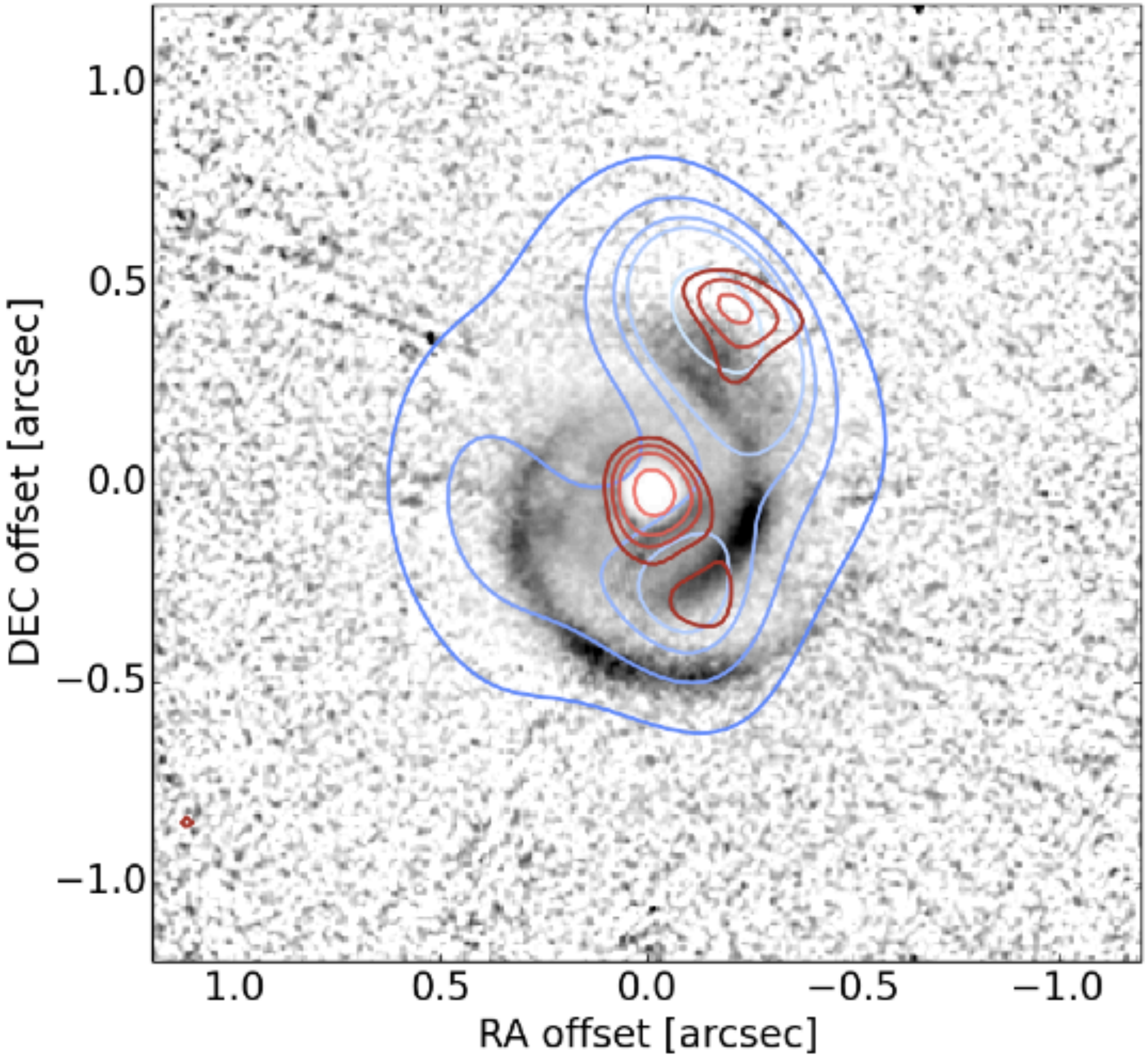


Disk Tomography
SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

ALMA (~ mm)

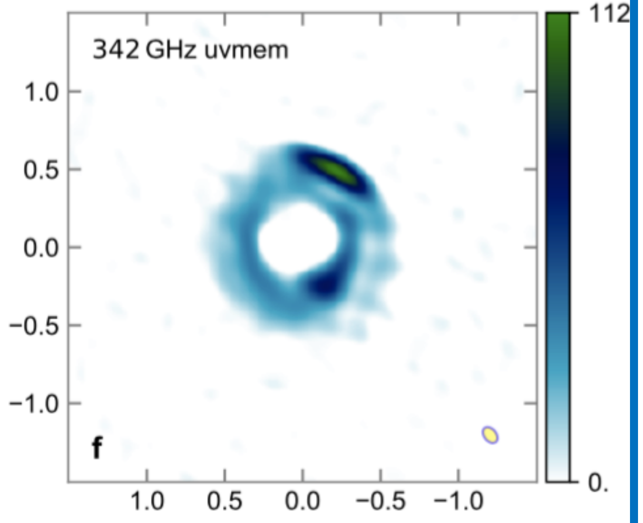
VLA (cm-m)



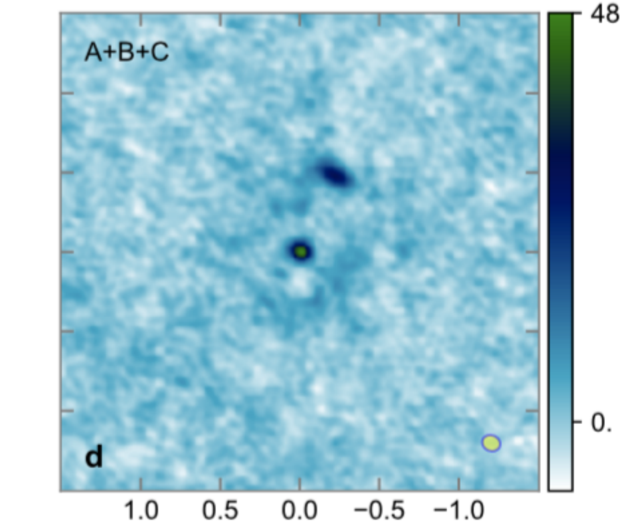
Marino+ ’15

Pebble trapping

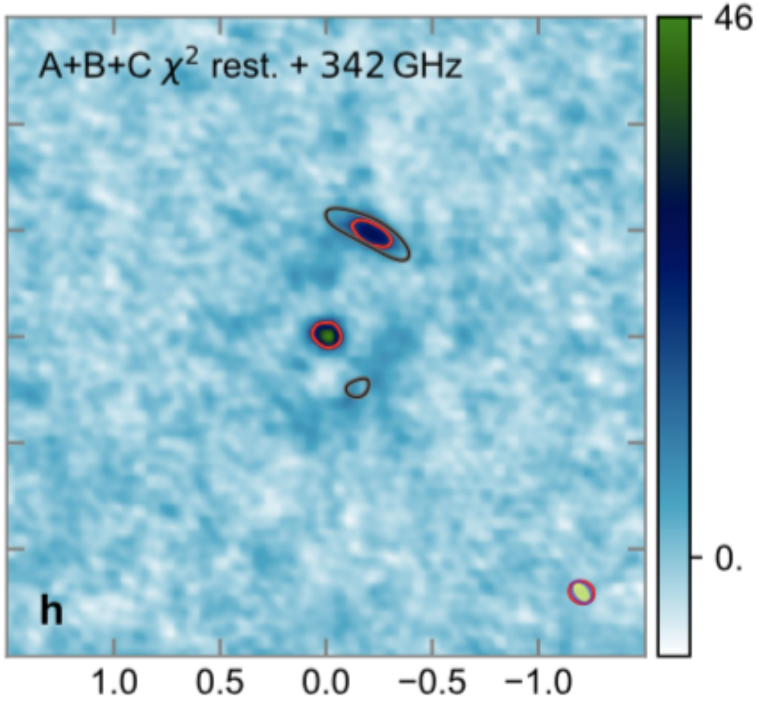
ALMA
(mm)



VLA
(cm-m)

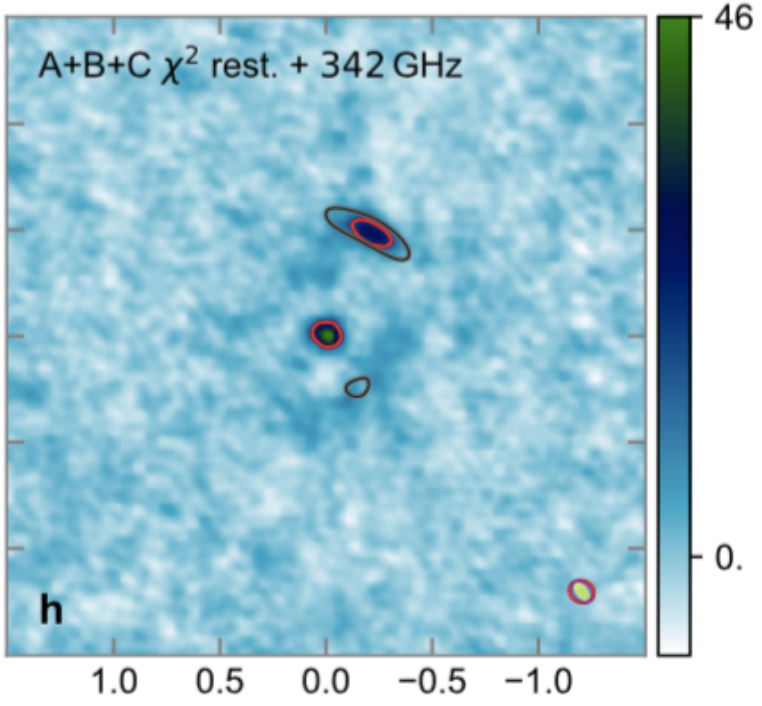


Overlay

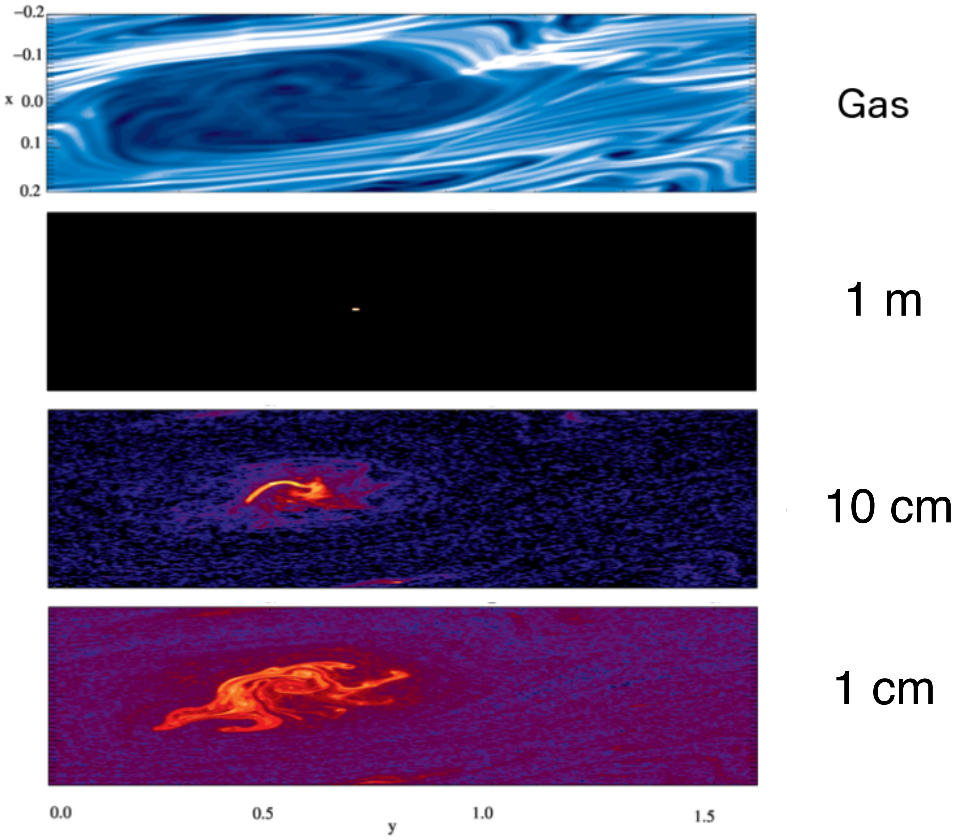


Casassus+ '19

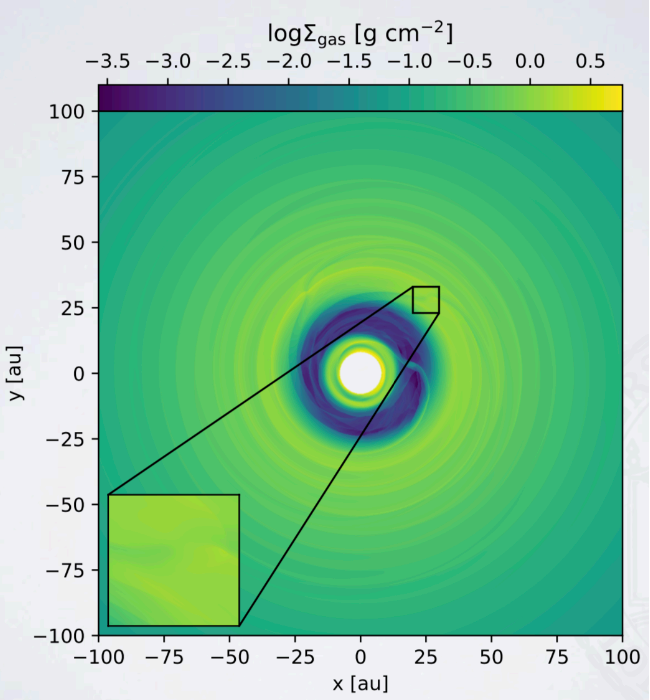
Model vs Observation

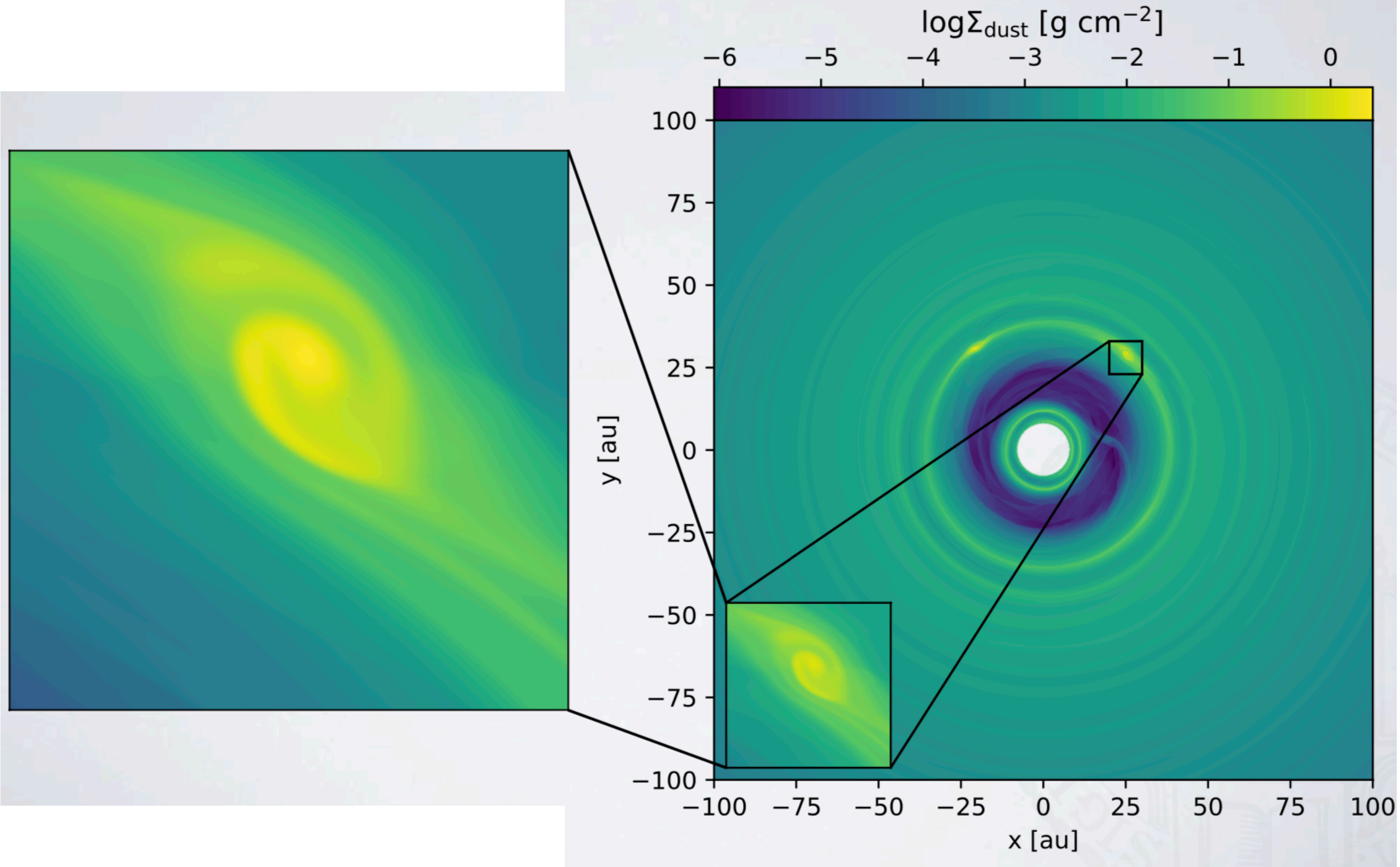


Casassus+Lyra '19



Raettig+Lyra '15


logΣgas [g cm−2]
−3.5 −3.0 −2.5 −2.0 −1.5 −1.0 −0.5 0.0 0.5
y [au]
x [au]


logΣdust [g cm−2]
−6 −5 −4 −3 −2 −1 0
y [au]
x [au]

Growing planetesimals
is hard

Collapsing small dust
is impossible

Growing pebbles
is easy

Collapsing pebbles
is easy
if you have traps

...
Dead Zone Edge
Zonal Flows
Dust Evolution + Convective Overstability = Planetesimals
GSF Instability
Rossby Vortices
...

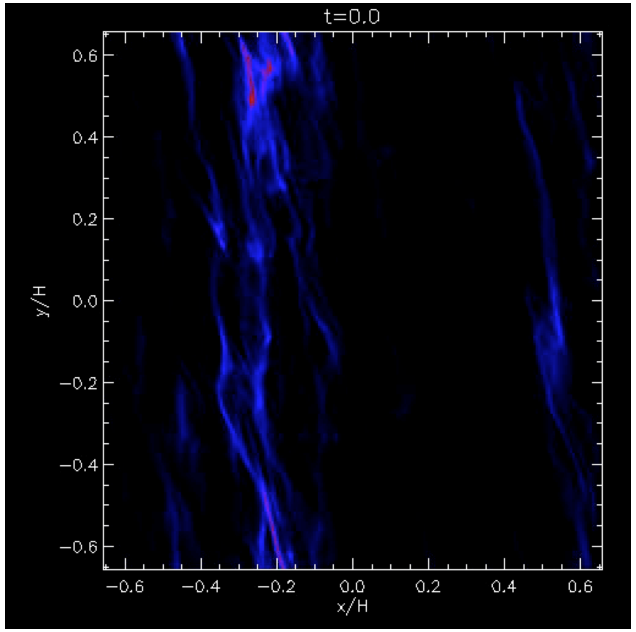
Dust growth to macroscopic sizes easily

Collapse is difficult:
need to accumulate dust and have the right sizes

Drift can be stopped in pressure bumps

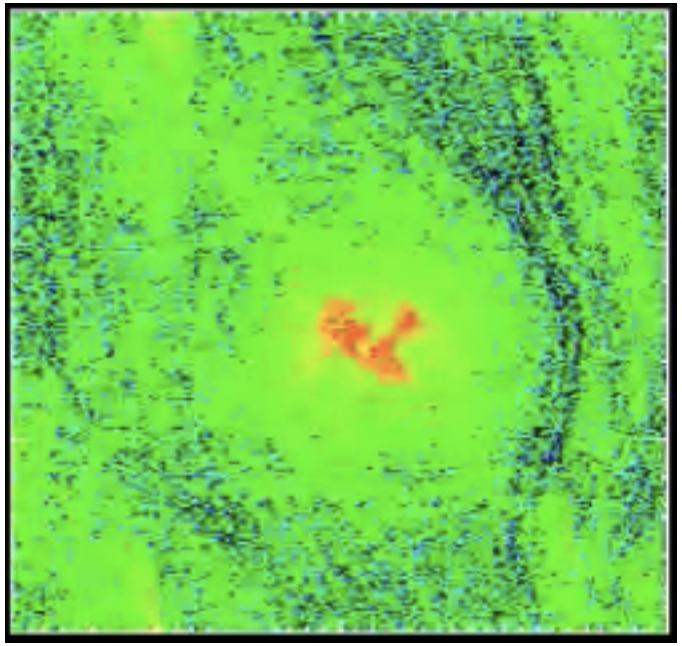
Two routes for planet formation

Streaming Instability



Johansen+ 07

Vortex Trapping



Lyra+08, Raettig+Lyra 12

The Multifaceted Planetesimal Formation Process

Anders Johansen
Lund University

Jürgen Blum
Technische Universität Braunschweig

Hidekazu Tanaka
Hokkaido University

Chris Ormel
University of California, Berkeley

Martin Bizzarro
Copenhagen University

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Uppsala University
Polish Academy of Sciences Space Research Center, Warsaw

Accumulation of dust and ice particles into planetesimals is an important step in the planet formation process. Planetesimals are the seeds of both terrestrial planets and the solid cores of gas and ice giants forming by core accretion. Left-over planetesimals in the form of asteroids, trans-Neptunian objects and comets provide a unique record of the physical conditions in the solar nebula. Debris from planetesimal collisions around other stars signposts that the planetesimal formation process, and hence planet formation, is ubiquitous in the Galaxy. The

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The Initial Conditions for Planet Formation: Turbulence Driven by Hydrodynamical Instabilities in Disks around Young Stars

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Abstract

This review examines recent theoretical developments in our understanding of turbulence in cold, non-magnetically active, planetesimal-forming regions of protoplanetary disks that we refer to throughout as "Ohmic zones." We give a brief background introduction to the subject of disk turbulence followed by a terse pedagogical review of the phenomenology of hydrodynamic turbulence. The equations governing the dynamics of cold astrophysical disks are given and basic flow states are described. We discuss the Solberg–Høiland conditions required for stability, and the three recently identified turbulence-generating mechanisms that are possibly active in protoplanetary disk Ohmic zones: (i) the vertical shear instability, (ii) the convective overstability, and (iii) the zombie vortex instability. We summarize the properties of these processes, identify their limitations, and discuss where and under what conditions these processes are active in protoplanetary disk Ohmic zones.

Key words: turbulence – protoplanetary disks – hydrodynamics – instabilities – accretion – accretion disks – magnetohydrodynamics (MHD)

Online material: color figures

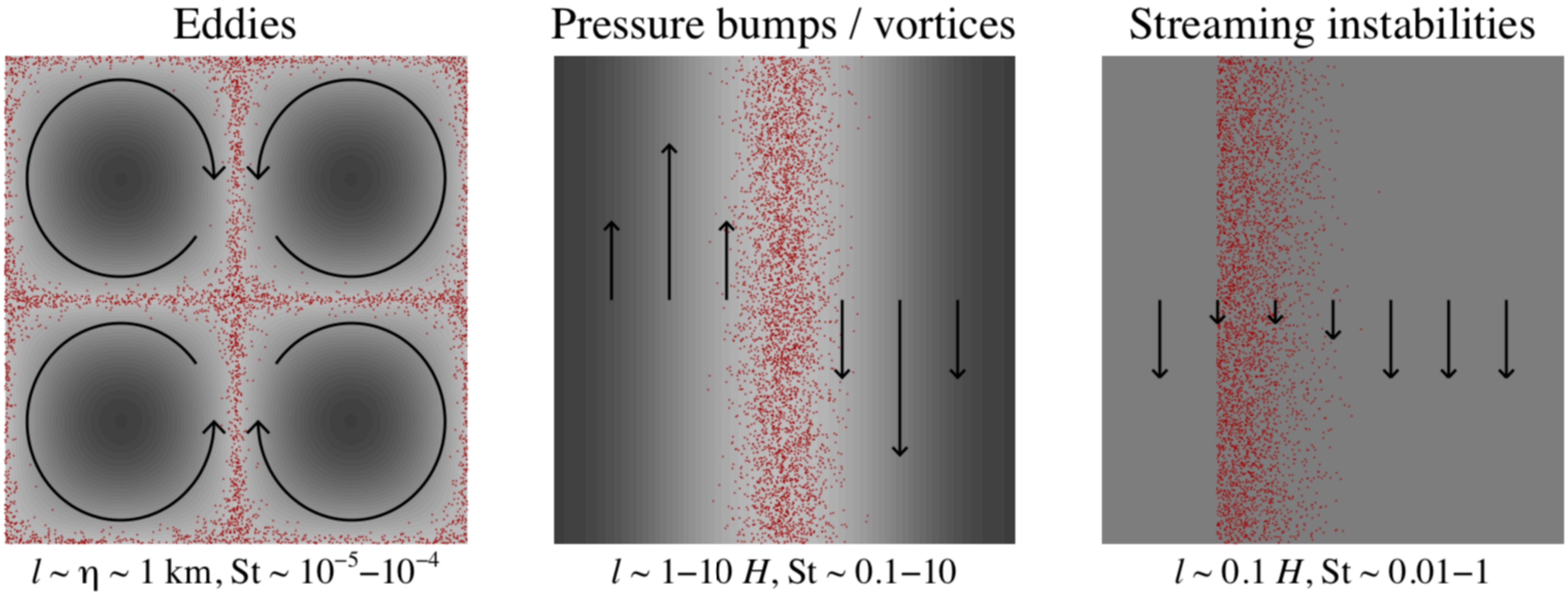

Fig. 6.— The three main ways to concentrate particles in protoplanetary discs. Left panel: turbulent eddies near the smallest scales of the turbulence, η, expel tiny particles to high-pressure regions between the eddies. Middle panel: the zonal flow associated with large-scale pressure bumps and vortices, of sizes from one scale height up to the global scale of the disc, trap particles of Stokes number from 0.1 to 10. Right panel: streaming instabilities on intermediate scales trap particles of Stokes number from 0.01 to 1 by accelerating the pressure-supported gas to near the Keplerian speed, which slows down the radial drift of particles in the concentration region.

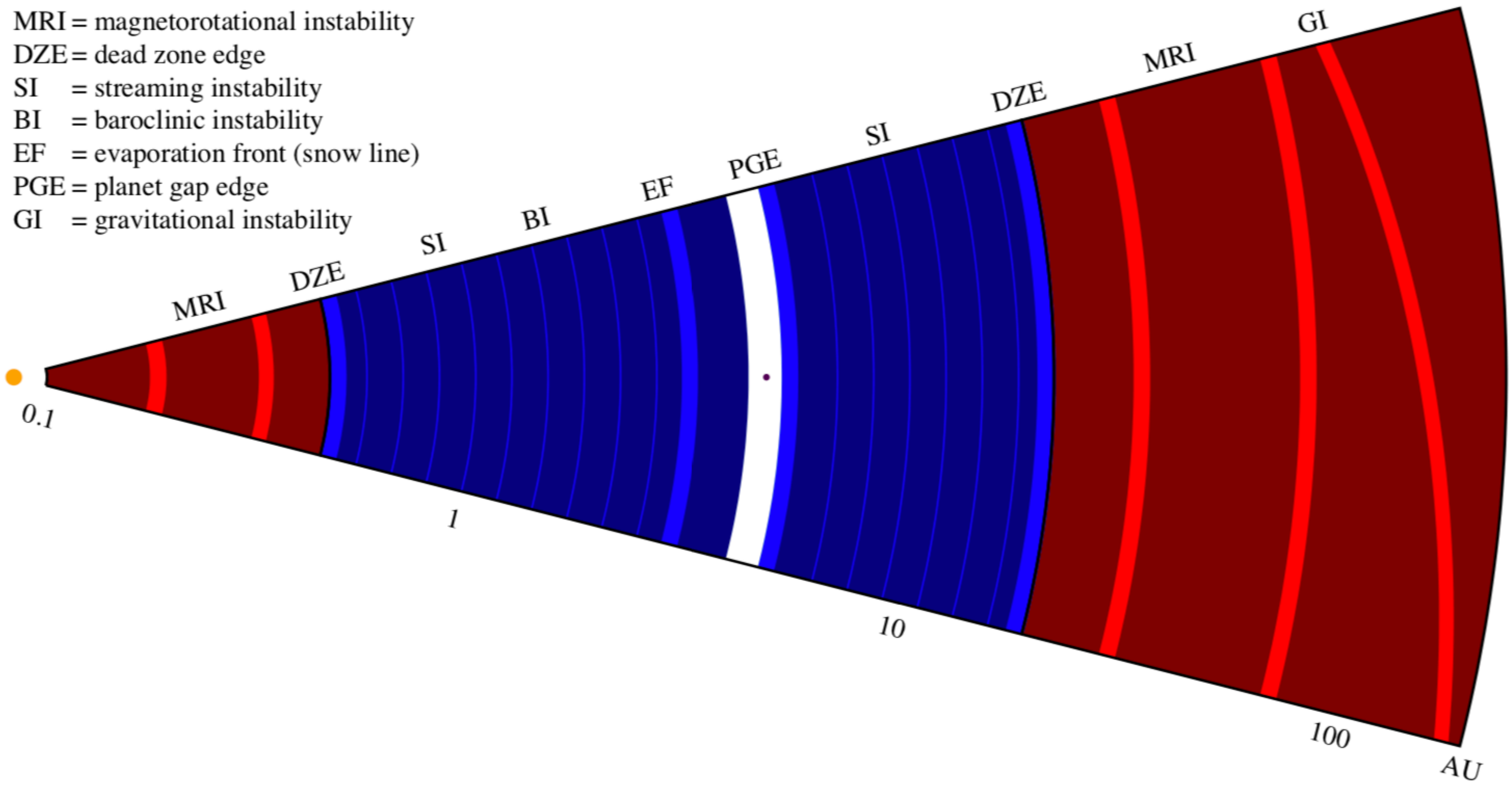

Fig. 7.— Sketch of the particle concentration regions in a wedge of a protoplanetary disc seen from above. Regions where the magnetorotational instability is expected to operate are marked with red, while the extent of the dead zone in a nominal protoplanetary disc model is marked with blue. The particle trapping mechanisms are described in the main text.