Evolution of Circumstellar Disks and Planet Formation

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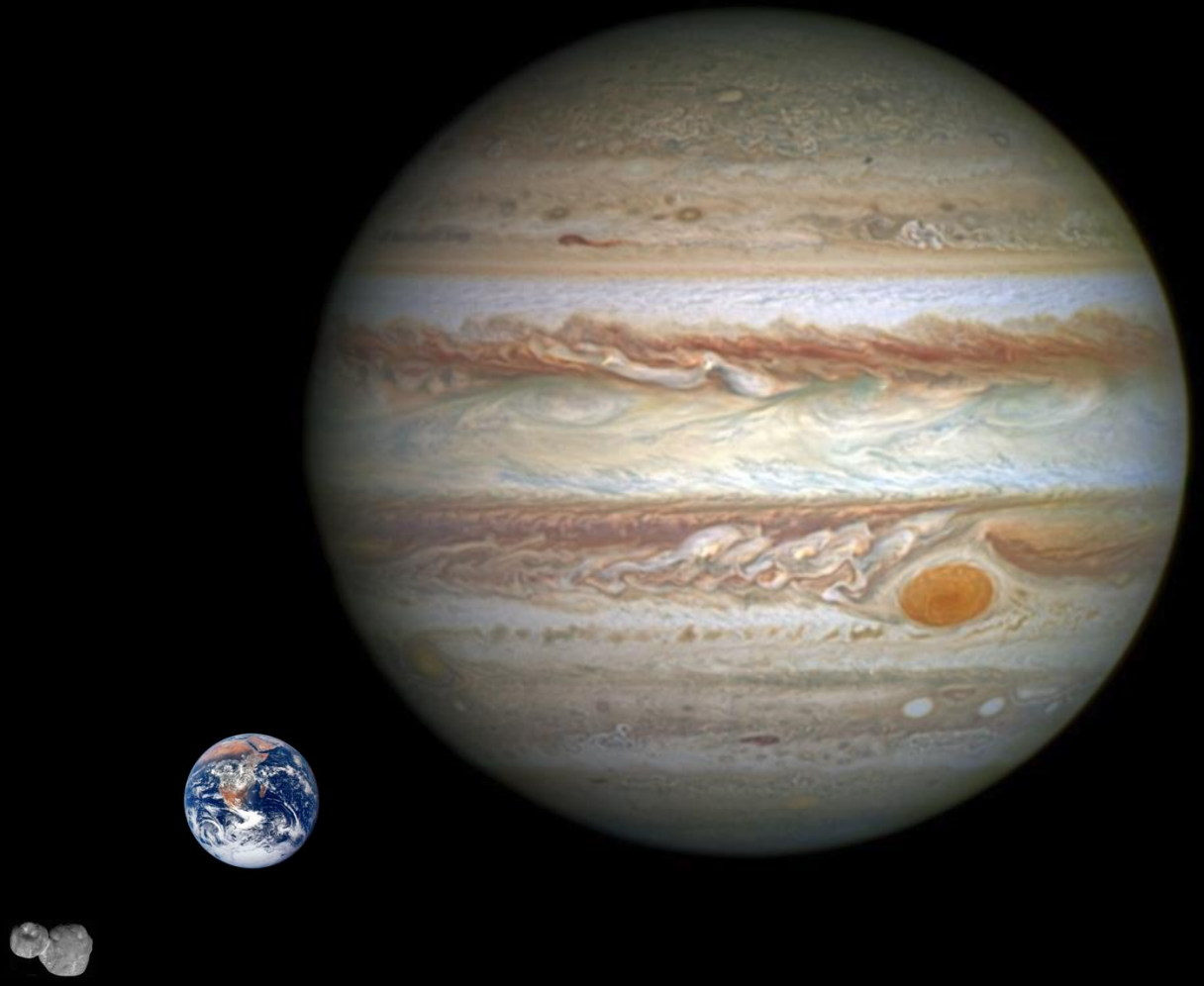
Las Cruces NM, USA

TIFR Mumbai – Oct 7th, 2025

Outline

- Planet Formation
- Disk observations
- Disk Instabilities

Planet Formation



Circumstellar/Protoplanetary Disks

PP disk fact sheet

Density: 10^{13} – 10^{15} cm^{-3}
(Air: 10^{21} cm^{-3})

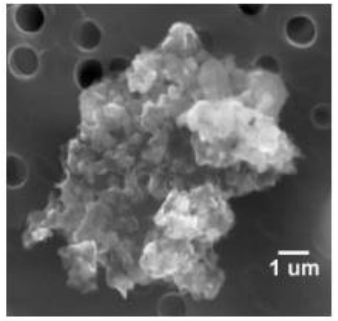
Temperature: 10-1000 K

Scale: 0.1-100AU

Mass: 10^{-3} – 10^{-1} M_{sun}

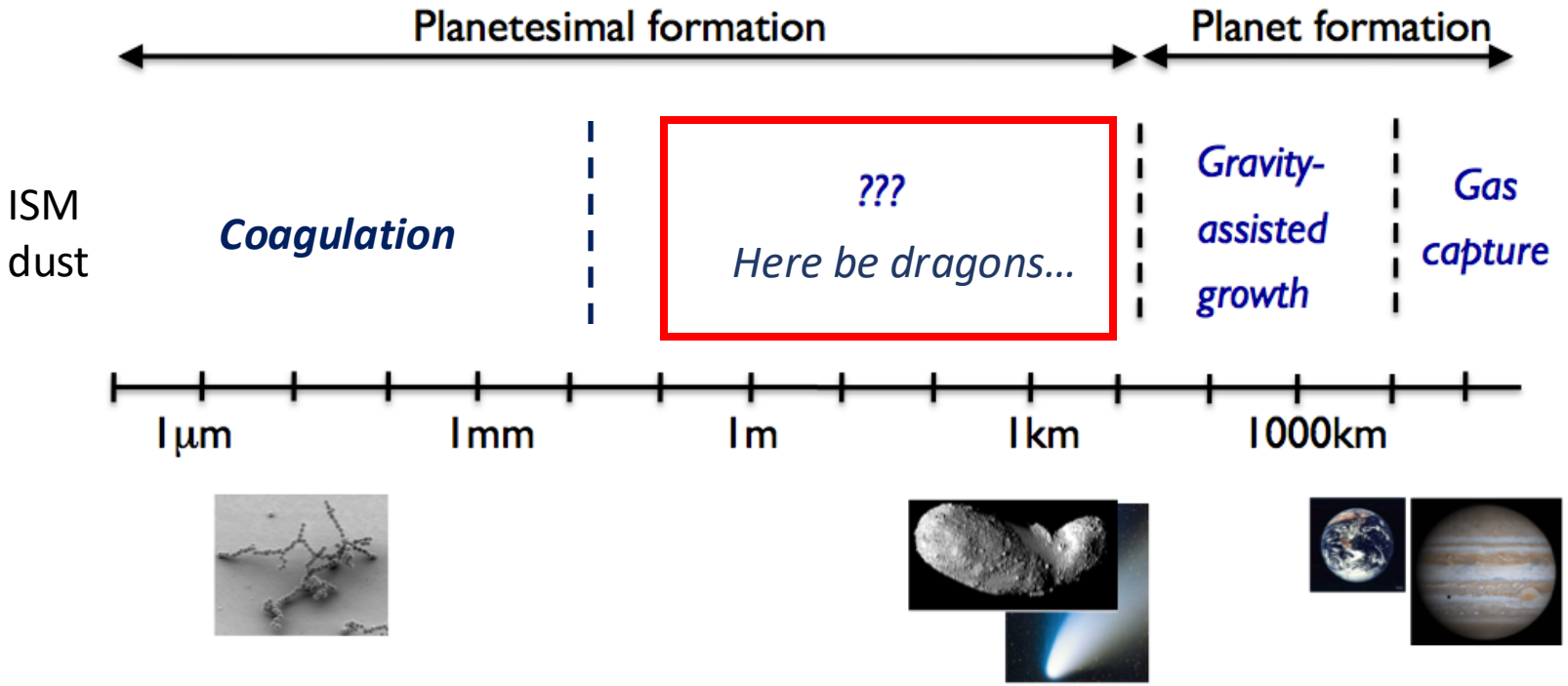
Planet Formation

"Planets form in disks of gas and dust"

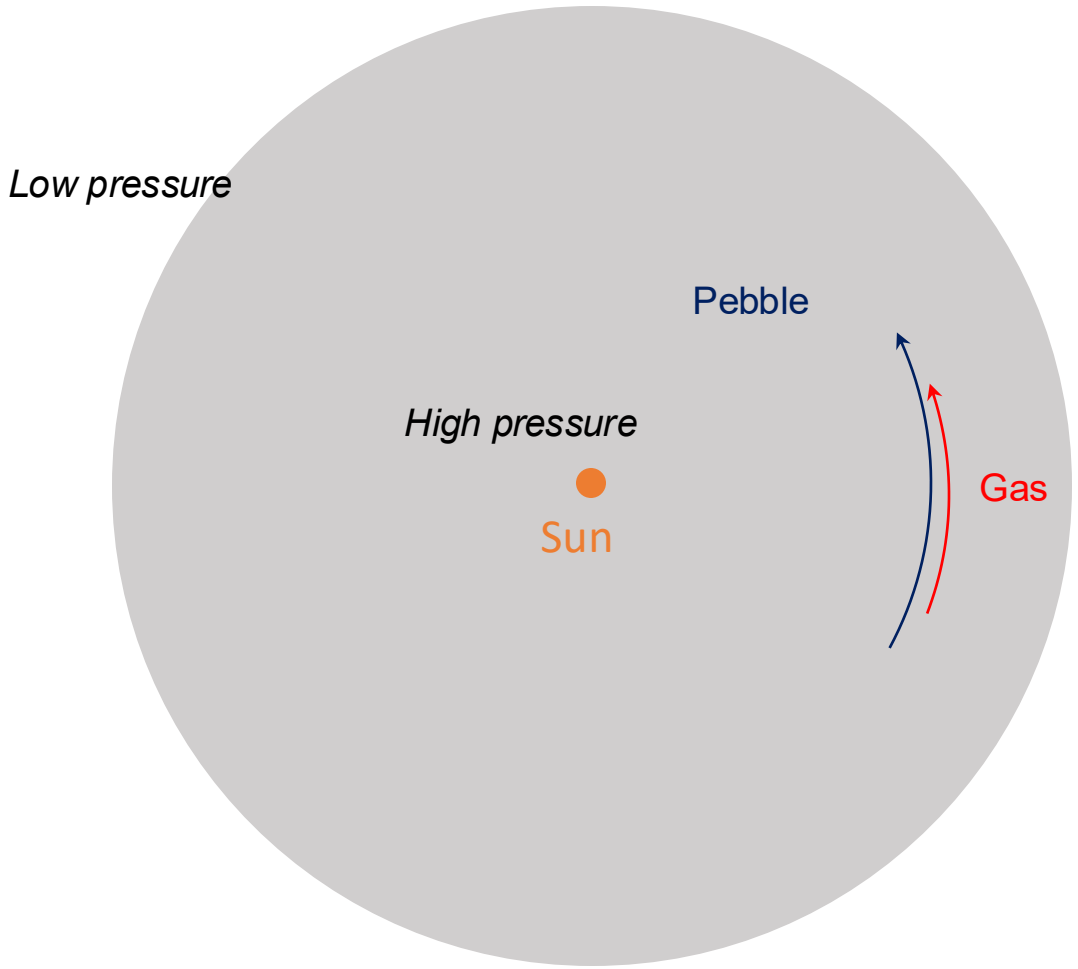


A miracle happens

Dust evolution



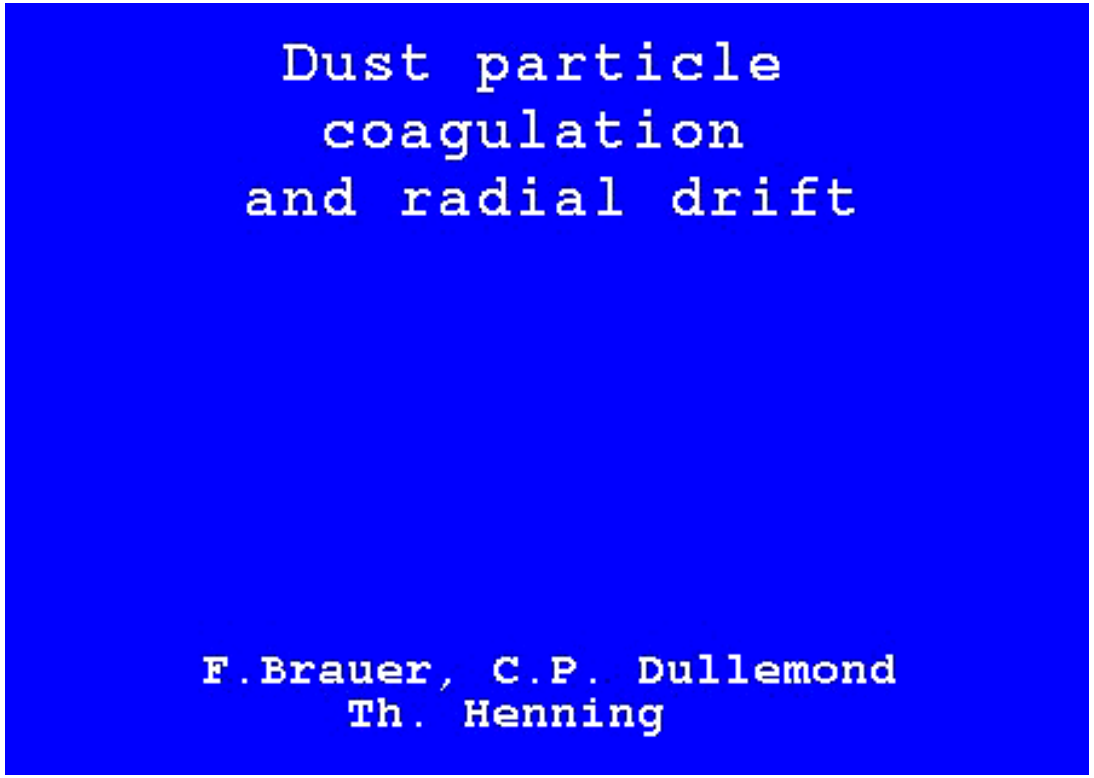
Headwind and Dust Drift



The gas has some pressure support (sub-Keplerian).

The pebbles do not feel gas pressure (Keplerian).

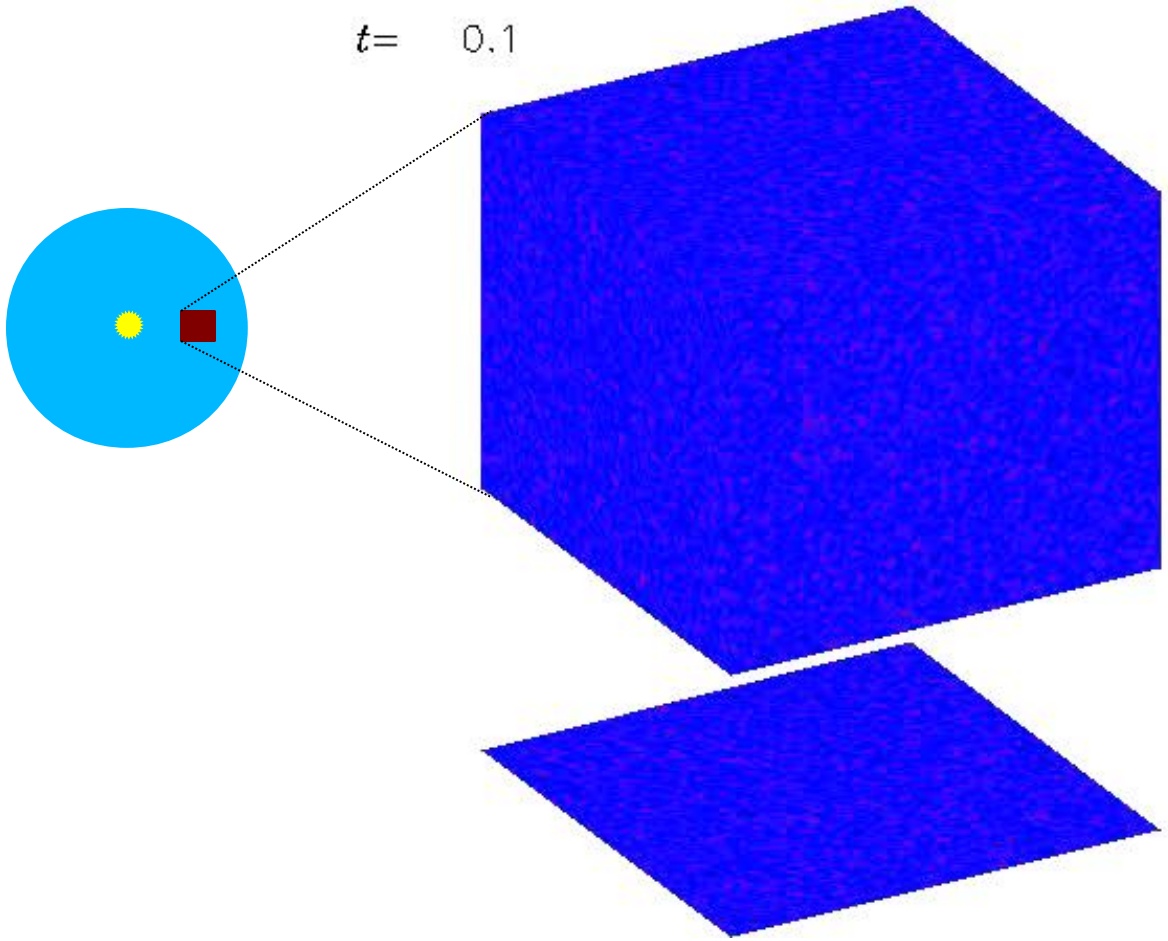
Dust coagulation and drift

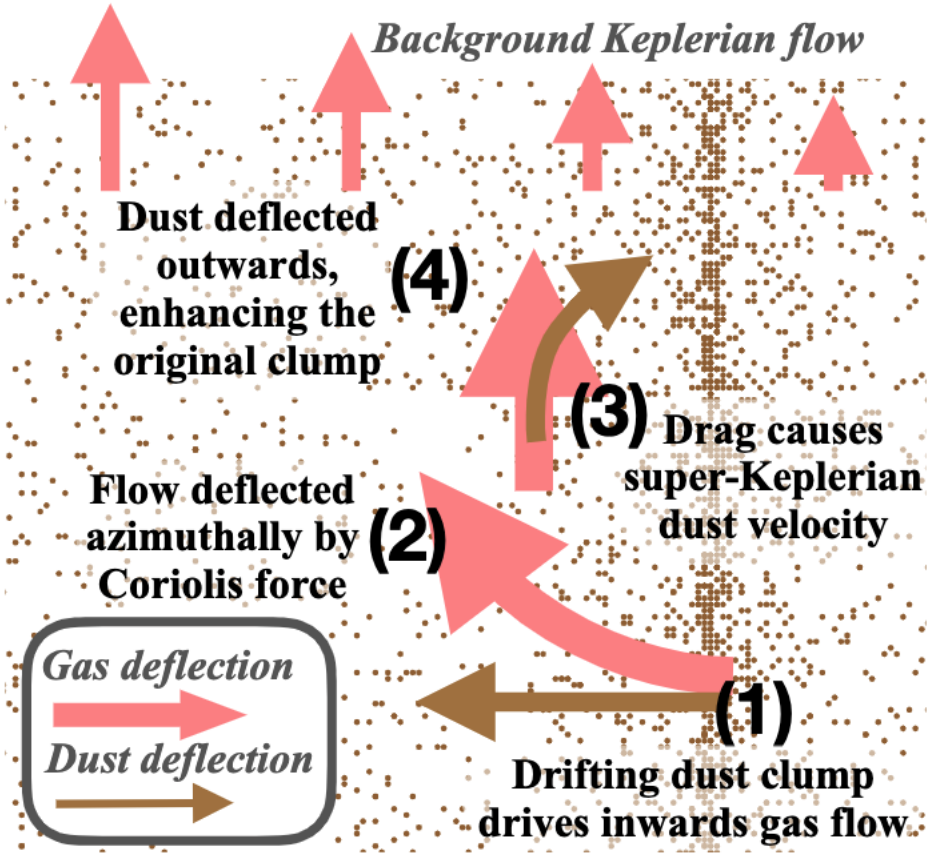


Brauer et al. (2008)

Streaming Instability

The dust drift is hydrodynamically unstable

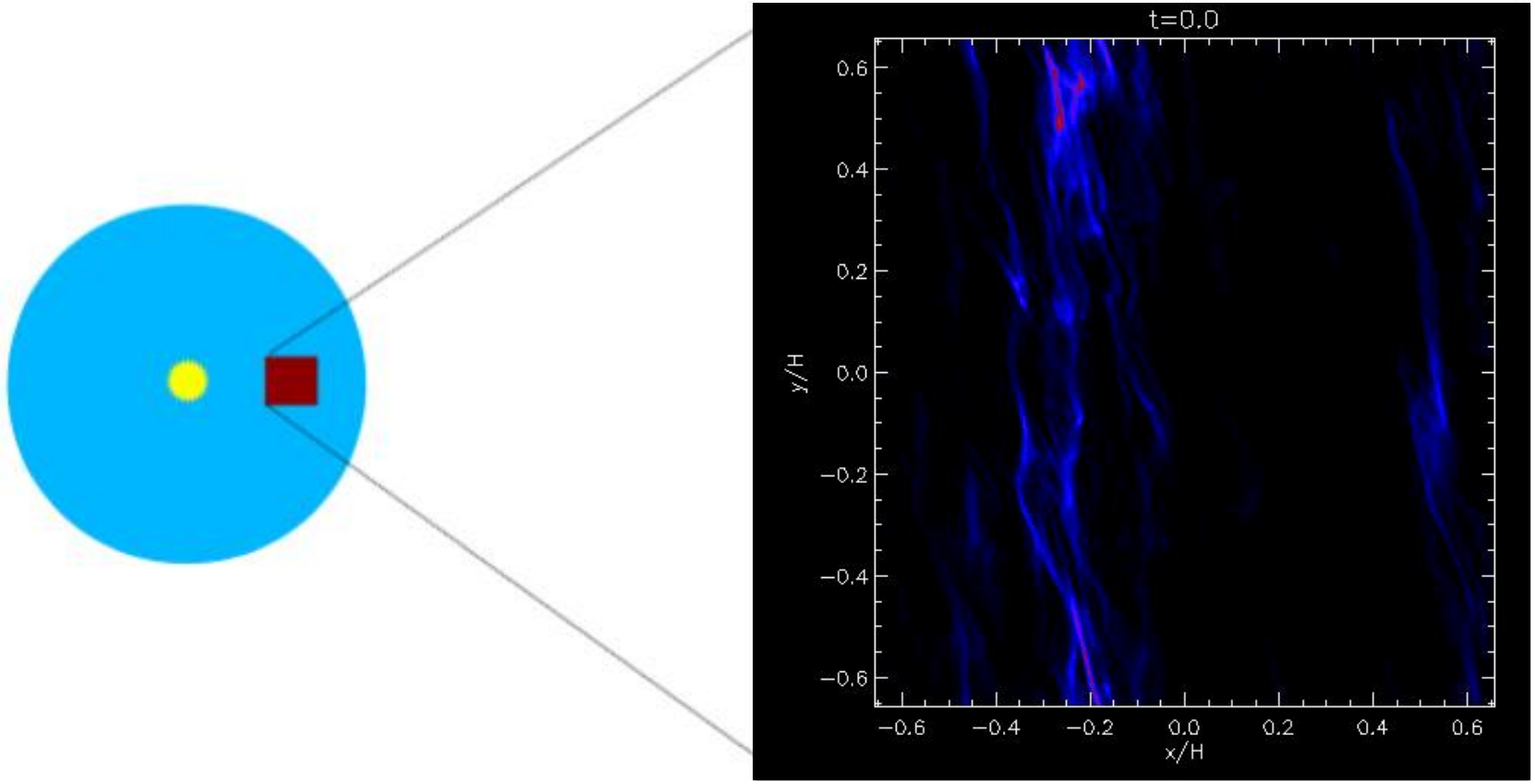




Lesur et al. (2023)

Youdin & Goodman ‘05, Johansen & Youdin ‘07, Youdin & Johansen+ ‘07, Kowalik+ ’13, Lyra & Kuchner ‘13, Schreiber+ ‘18, Klahr & Schreiber ’20, Simon+ ‘16, ‘17, Carrera+ ‘15, ‘17, ‘20, Gole+ ’20, Li+ ‘18, ‘19, Abod+ ’19, Nesvorny+ ’19, Canas+ ‘24

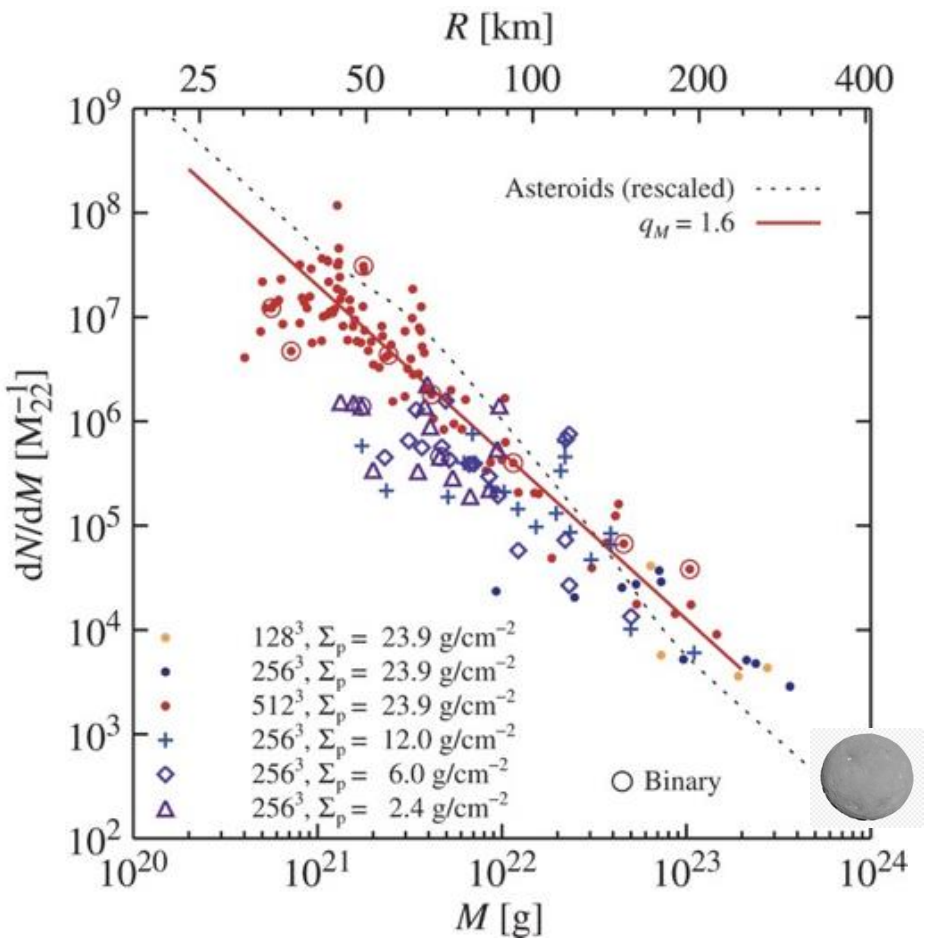
Gravitational collapse into planetesimals

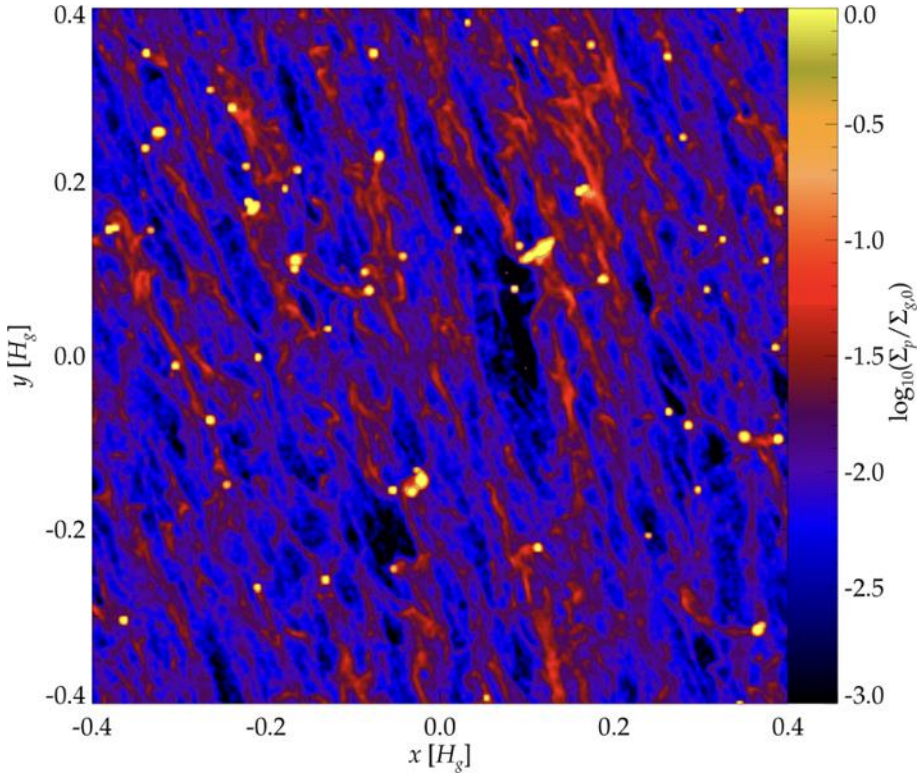


Johansen et al. (2007)

How can we verify the streaming instability hypothesis?

Planetesimal Formation

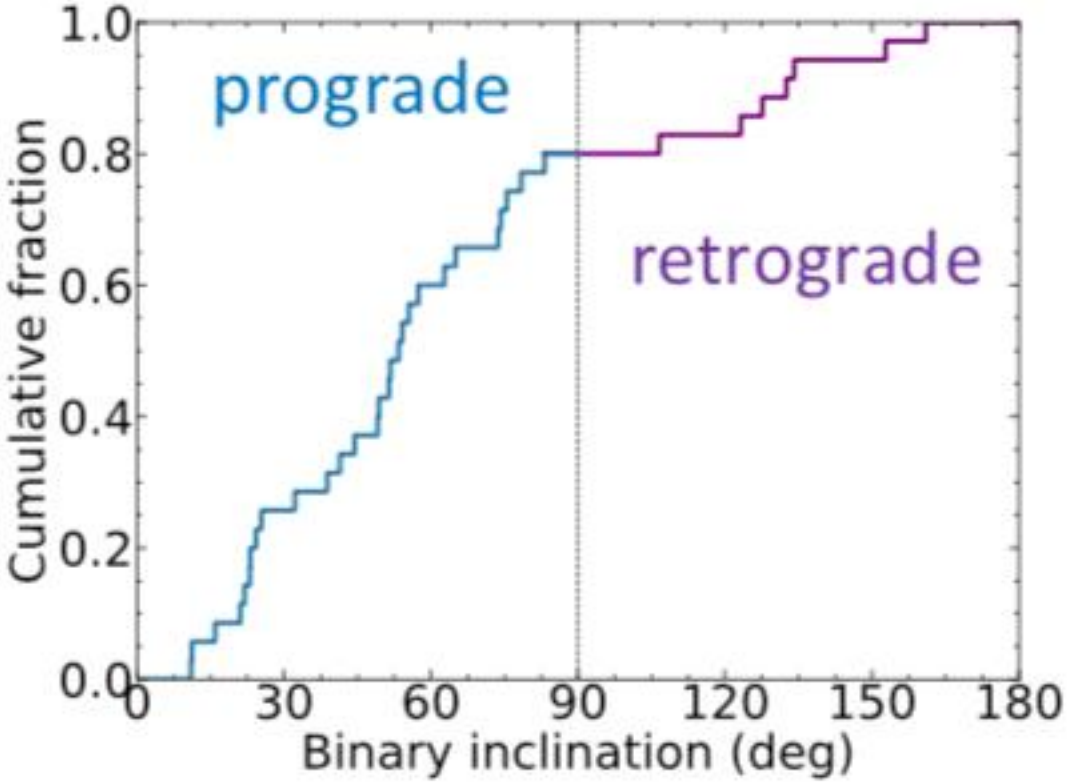


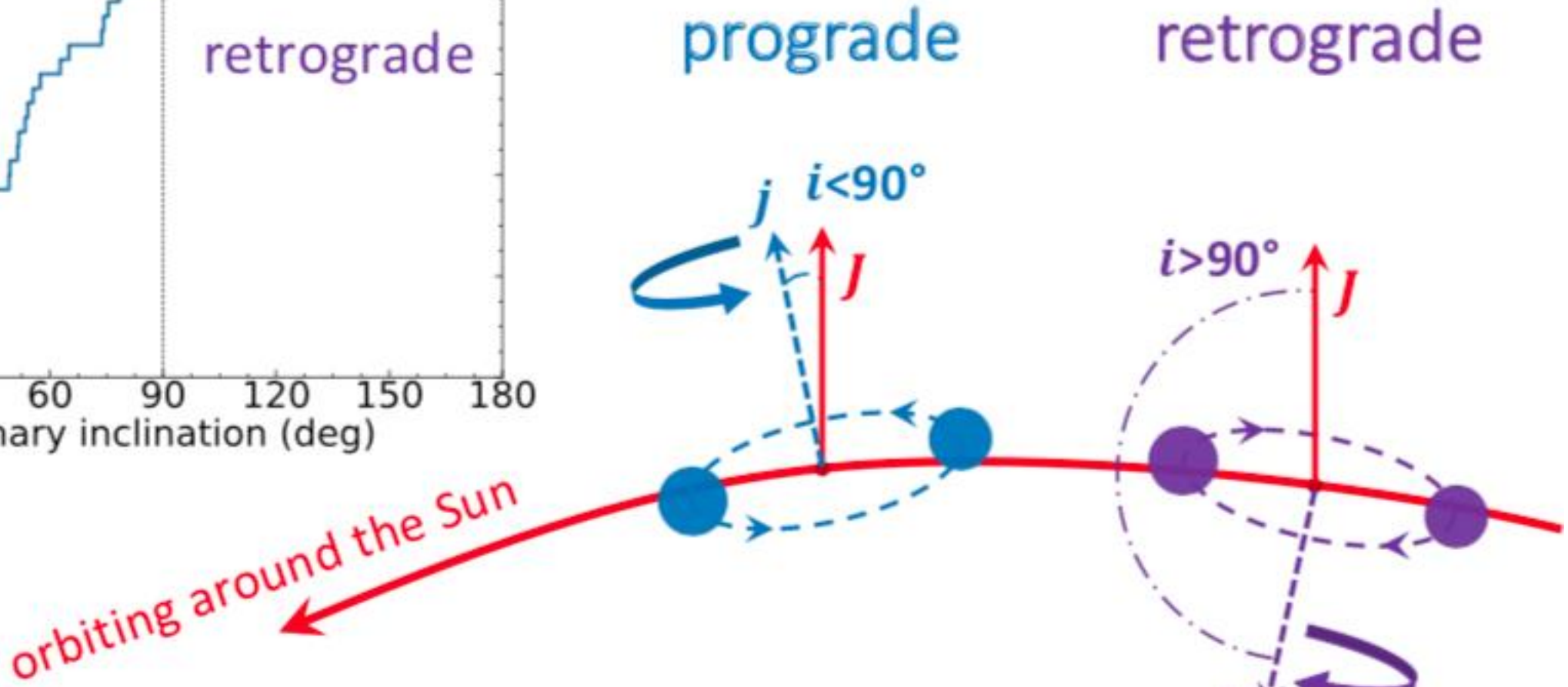


Initial mass function consistent with mass distribution of asteroid belt. Slope 1.6

Yang & Johansen (2014); Schäfer et al. (2017)

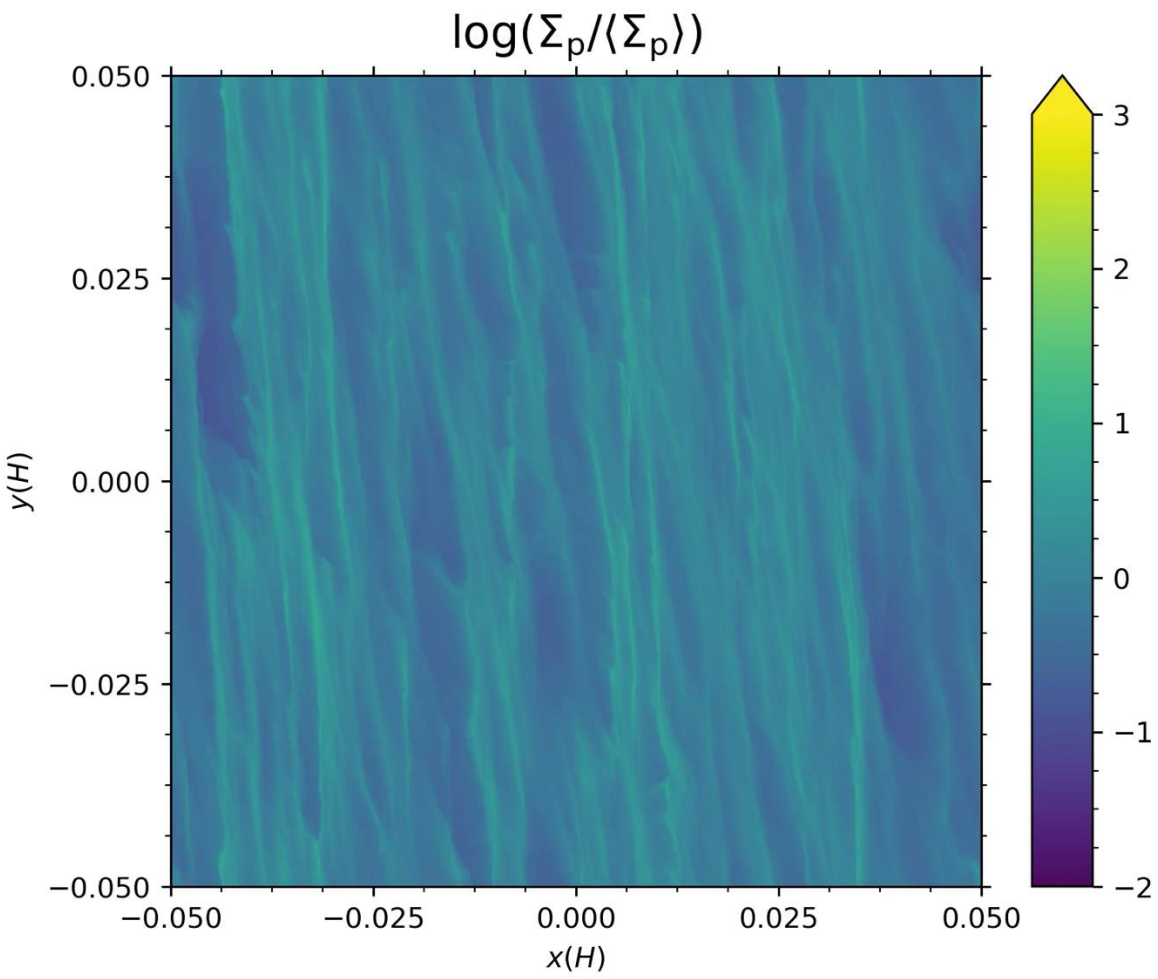
Kuiper Belt Object: Preference for Prograde

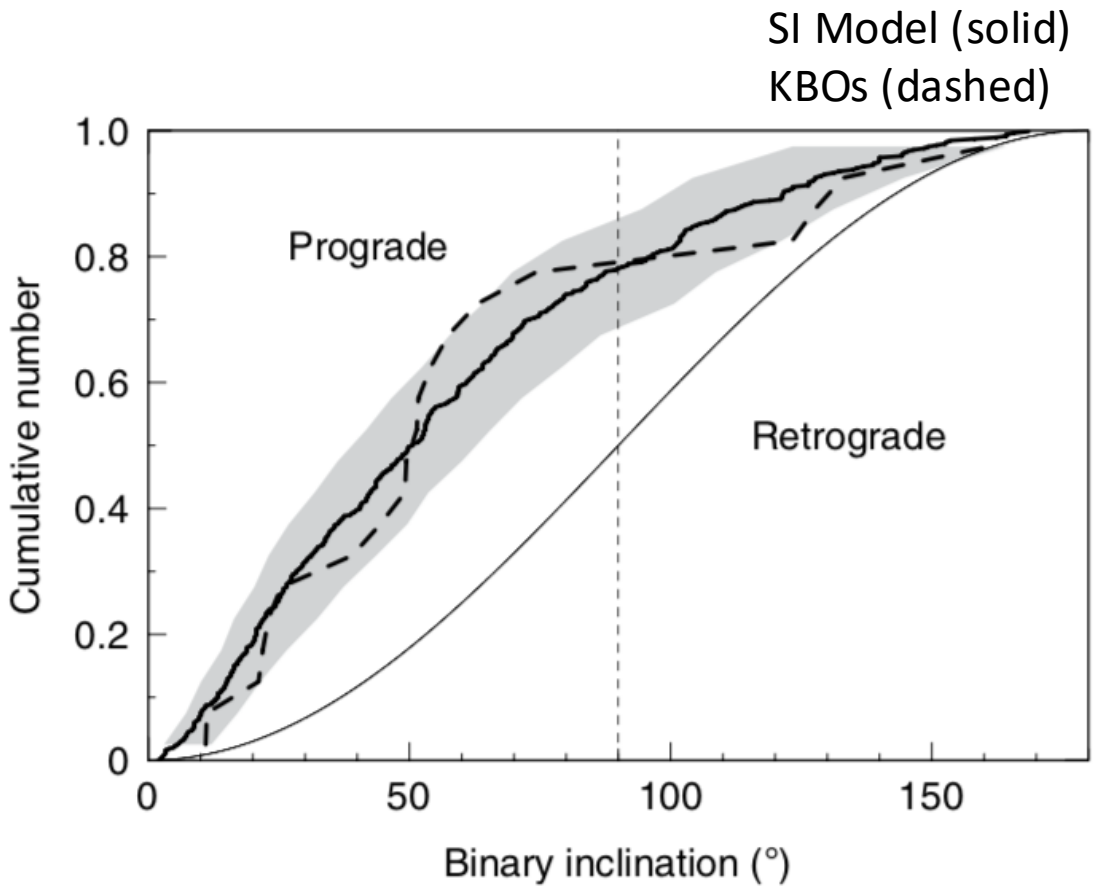




Grundy+2019

Counting binaries: Preference for Prograde (~80%)

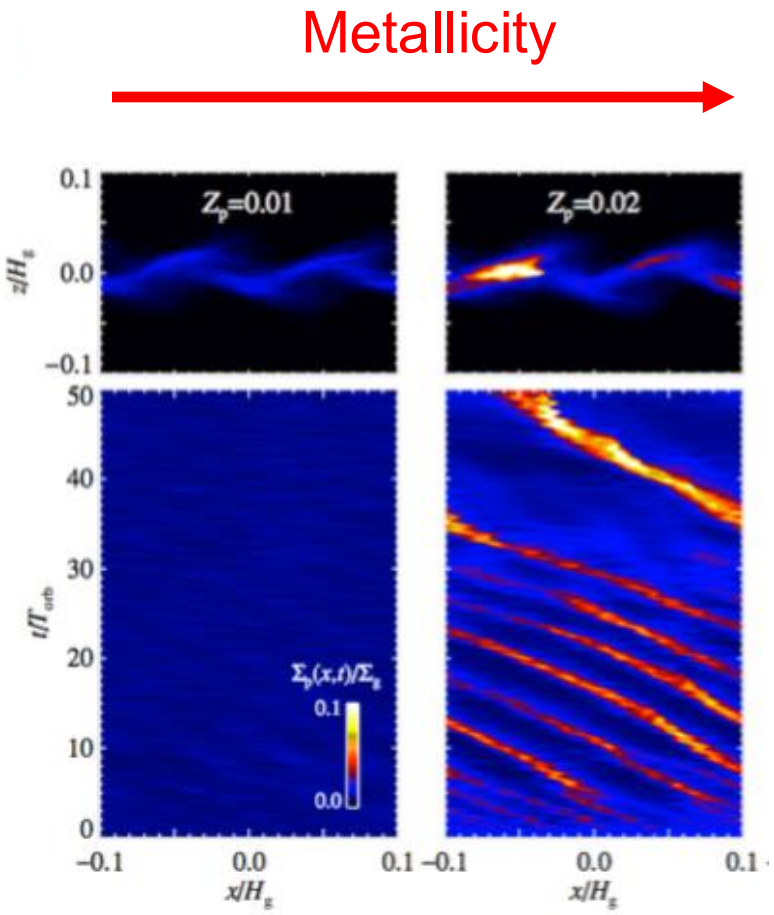




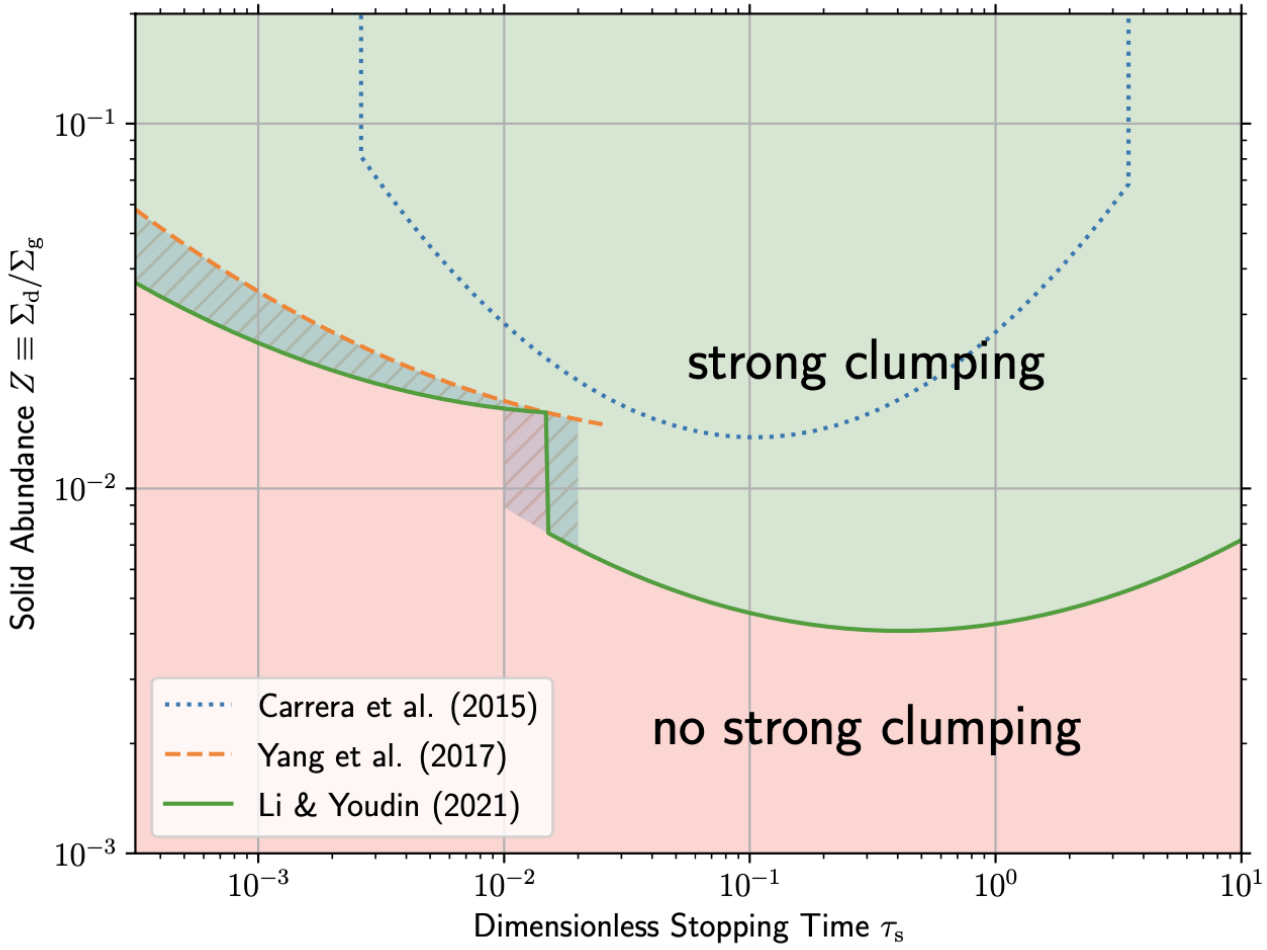
Nesvorny+'19

W. Lyra

Metallicity threshold?

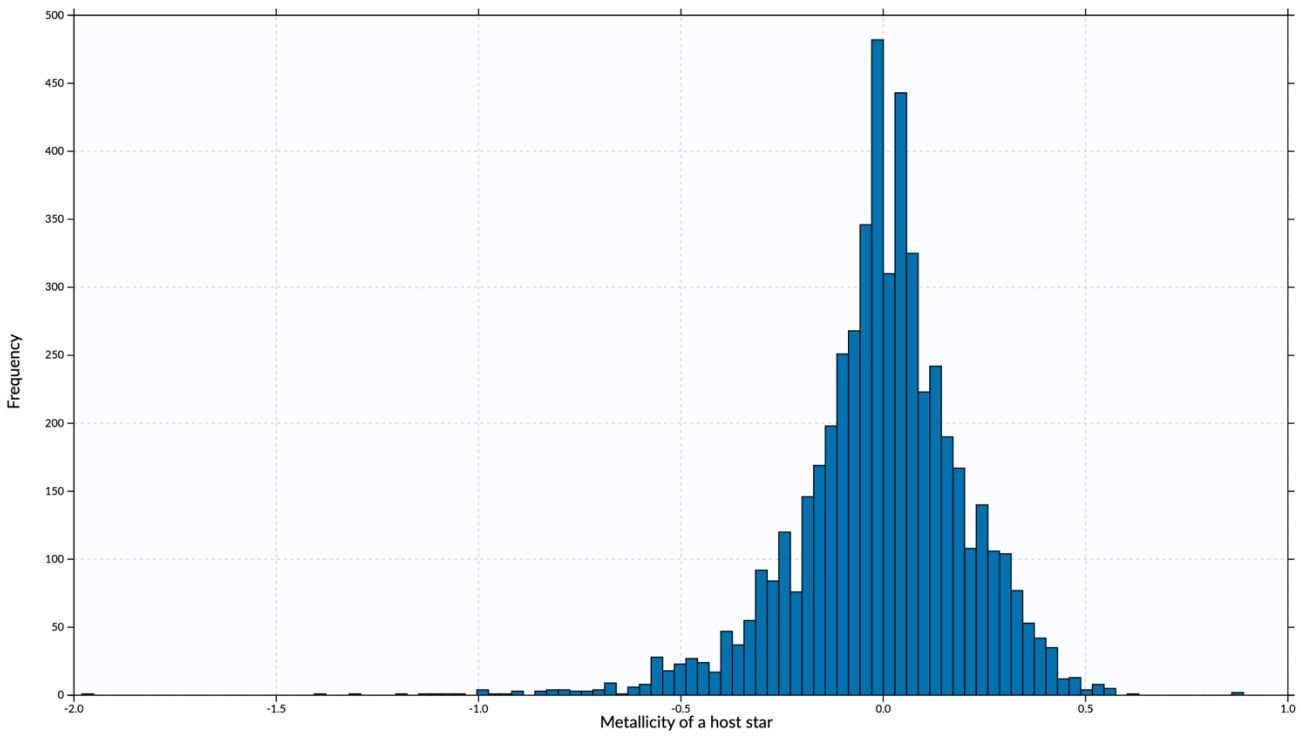


Johansen et al. (2011)



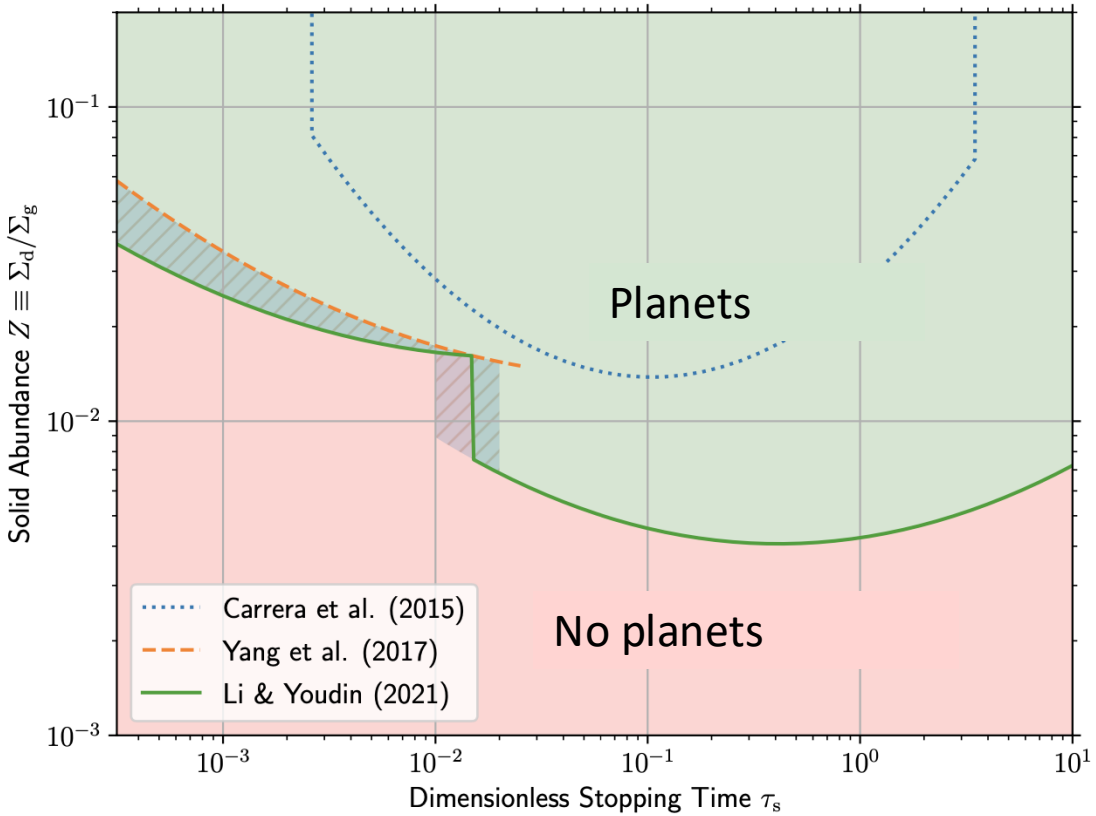
Lesur et al. 2023

Metallicity threshold?

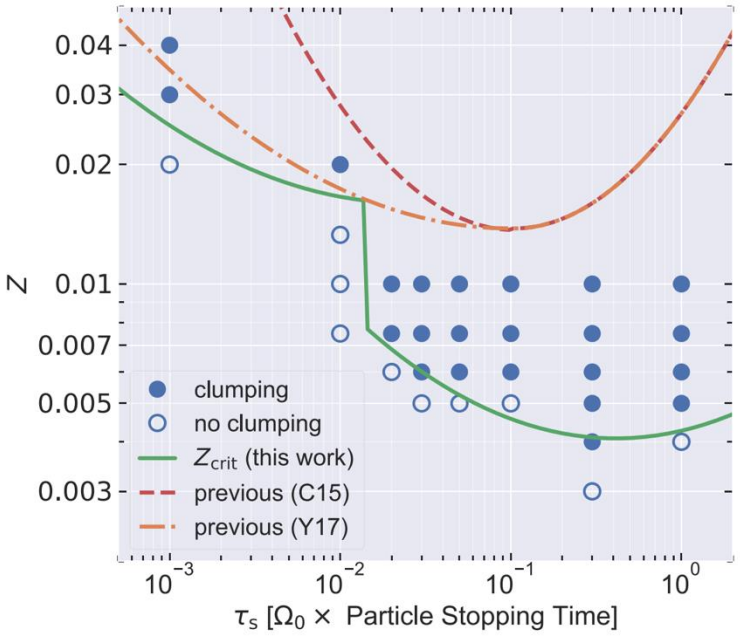


[Fe/H]

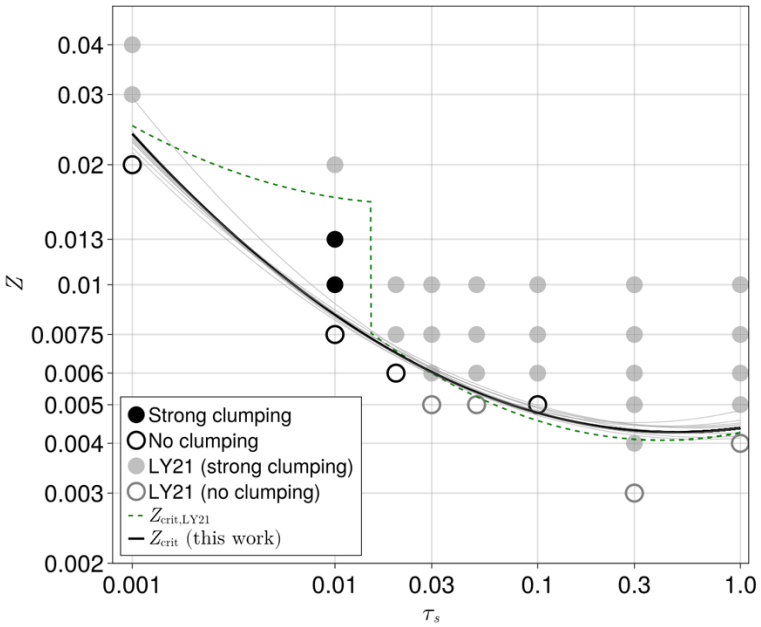
$Z = Z_\odot \, 10^{[Fe/H]}$



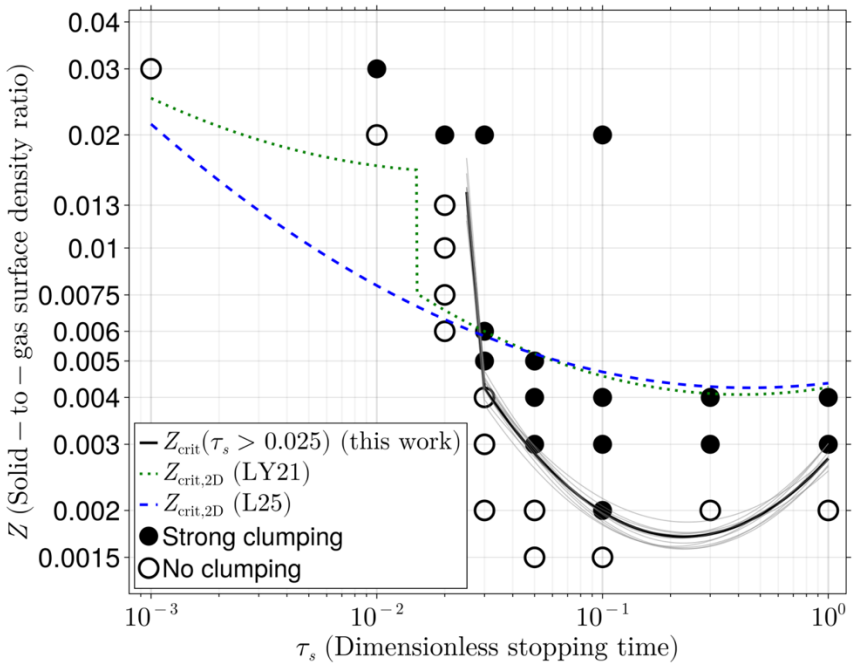
Clumping Threshold Problem



Li & Youdin 2021



Lim(+Lyra) et al. 2024



Lim(+Lyra) et al. 2025

Numerics? Are the codes agreeing?

Draft version September 29, 2025
Typeset using LaTeX **twocolumn** style in AASTeX7.0.1

Streaming Instability Code Comparison

Stanley A. Baronett [1,2,*] Wladimir Lyra [3] Hossam Aly [4] Olivia Brouillette [3] Victoria I. De Cun [3]
Mario Flock [5] Pinghui Huang (黄平辉) [6,7] Leonardo Krapp [8] Geoffroy Lesur [9]
Shengtai Li (李胜台) [10] Jeonghoon Lim (임정훈) [11] Sijme-Jan Paardekooper [4] Jacob B. Simon [11]
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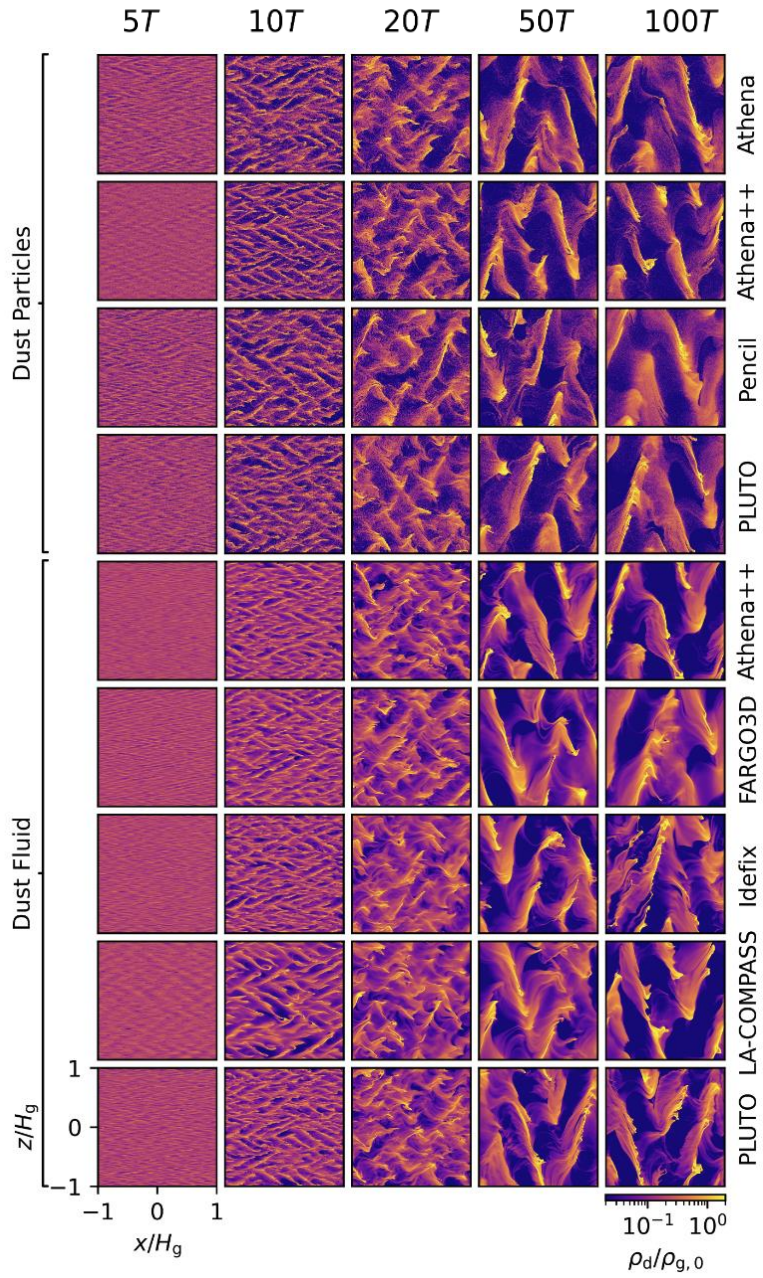
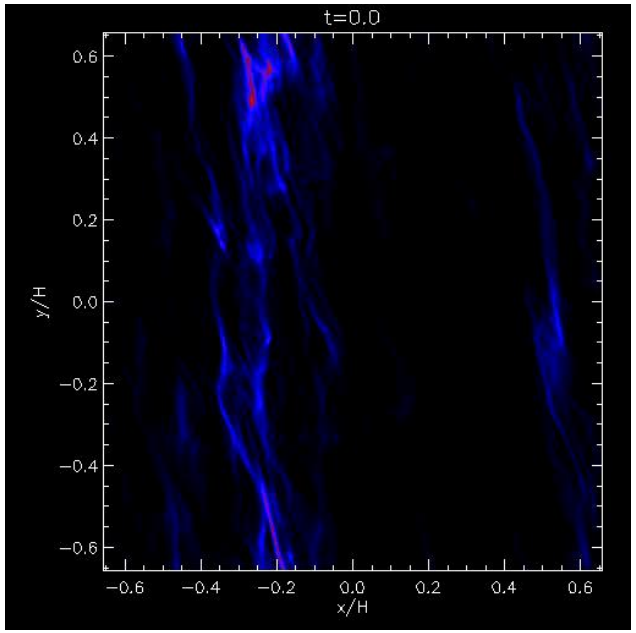


Baronett & Lyra +, in prep

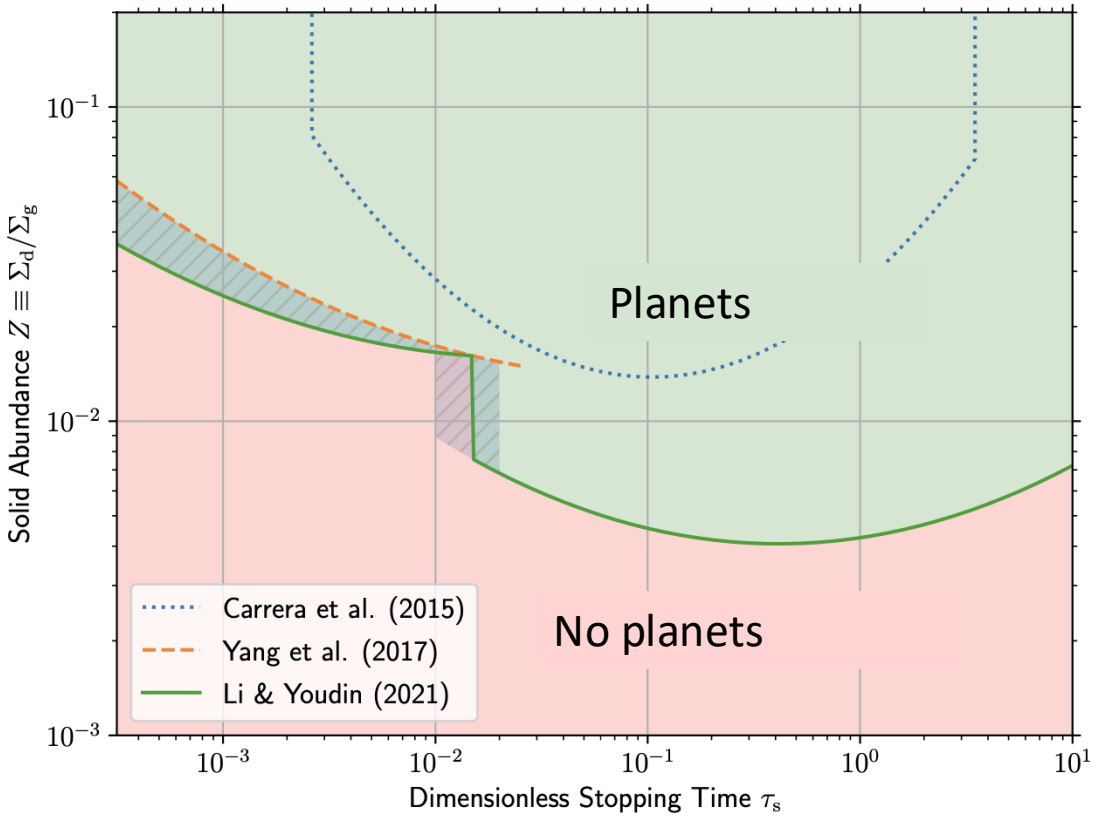
Take home message

- Best bet for planetesimal formation, but metallicity problem

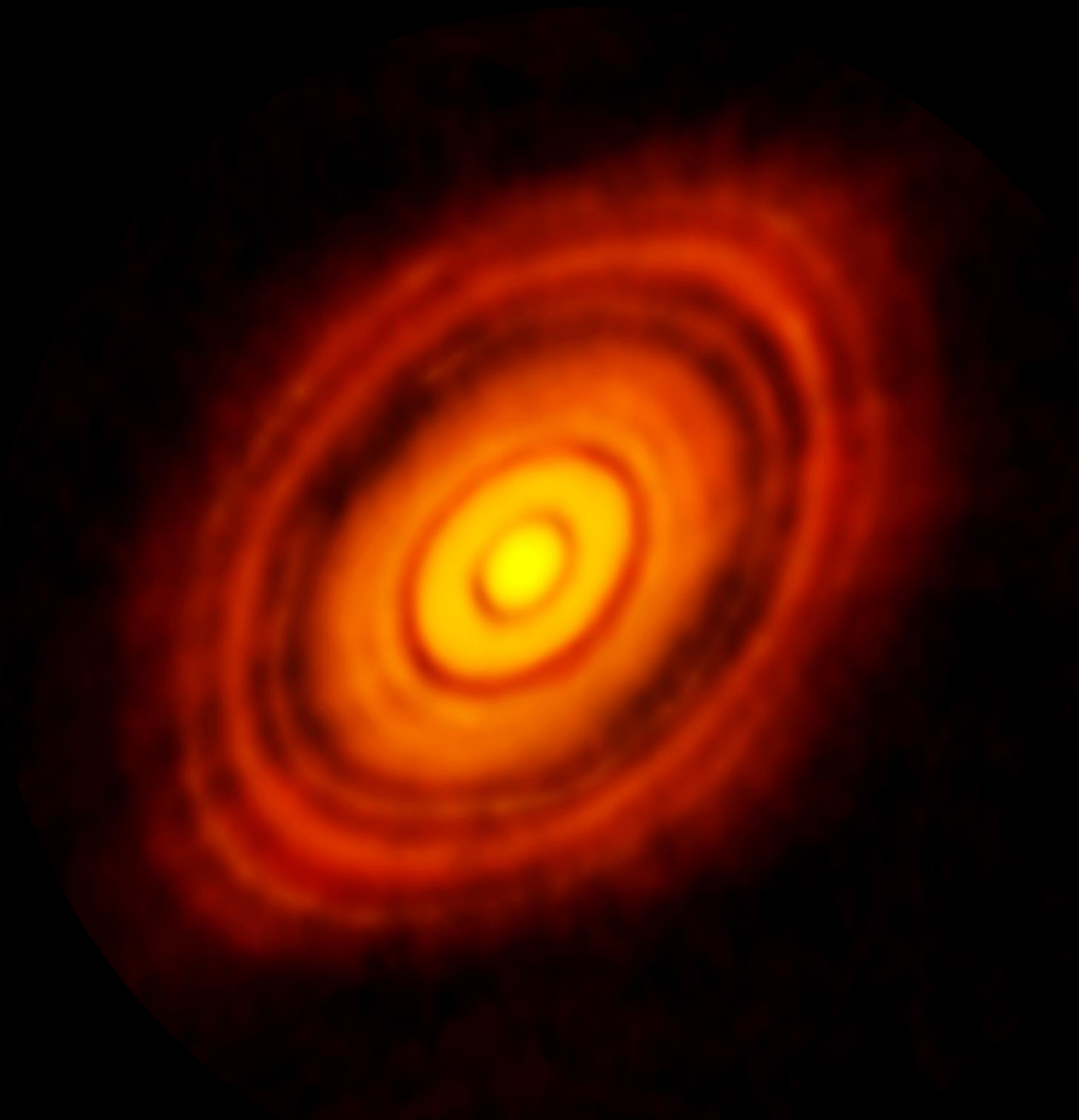
Streaming Instability



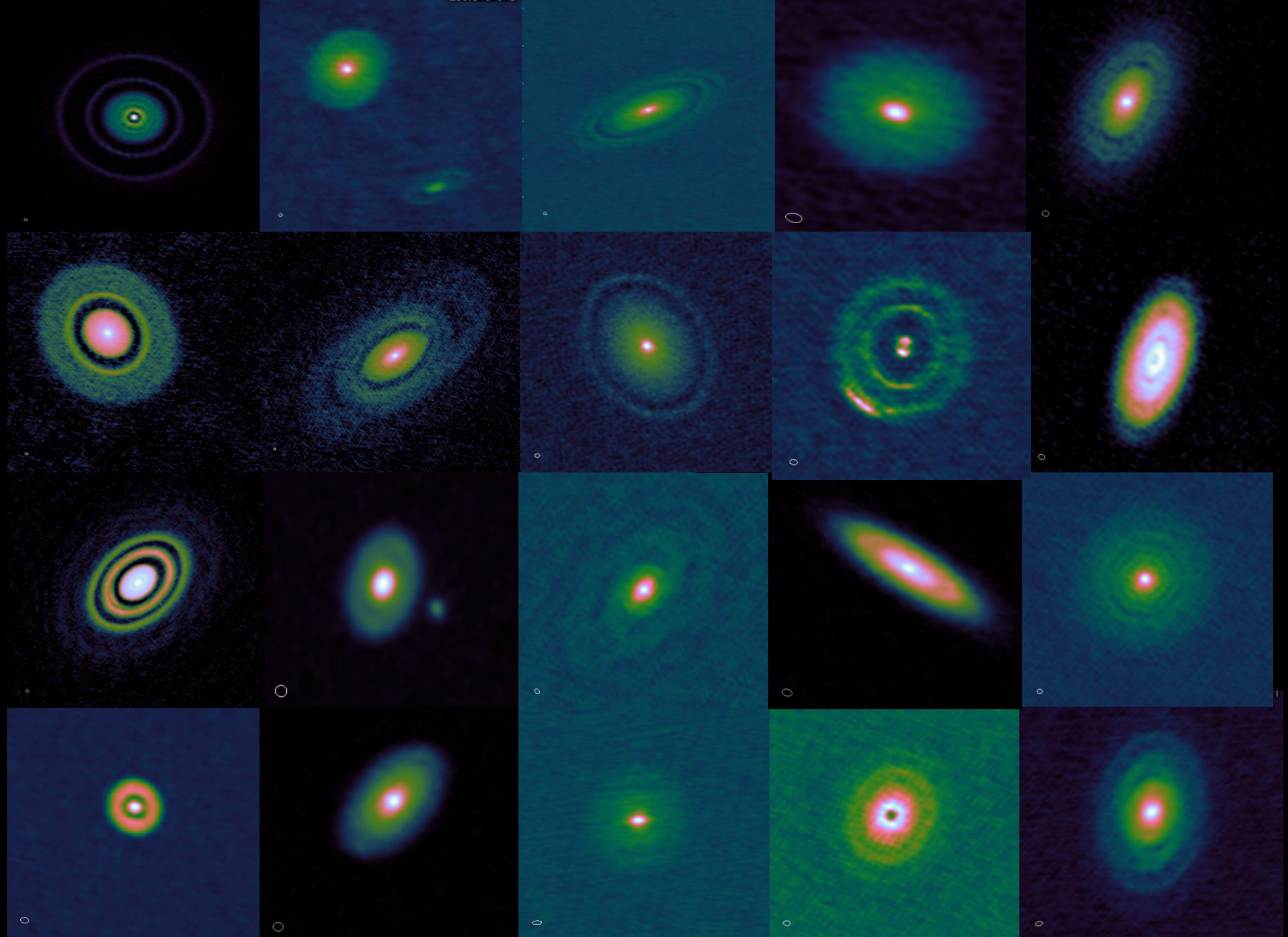
Youdin & Goodman 2005, Johansen+ 07



Disk Observations



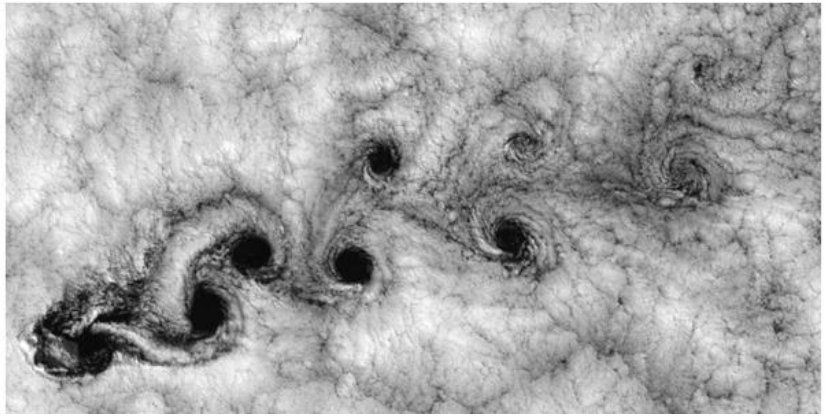
The Atacama Large (sub-)Millimeter Array (ALMA)



MWC 758

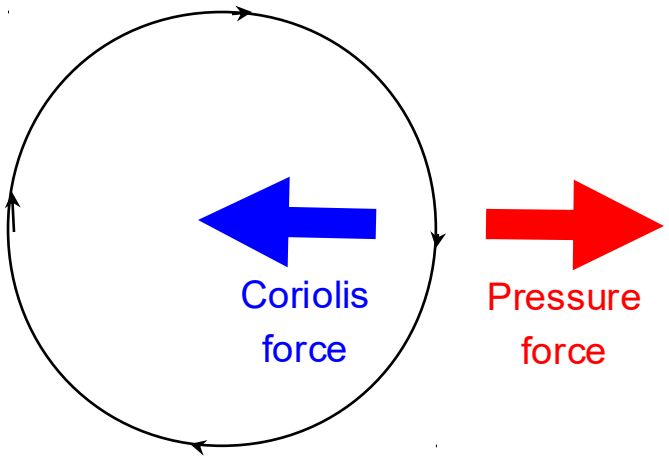
Vortices – an ubiquitous fluid mechanics phenomenon

Von Kármán *vortex street*

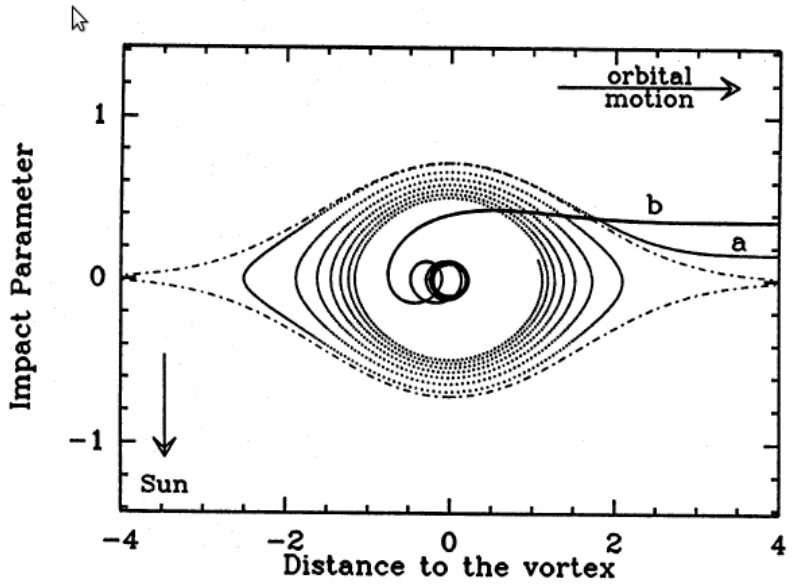


Vortex Trapping

Geostrophic balance:



Vortex
streamline



Barge & Sommeria (1995)

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

Aid to planet formation

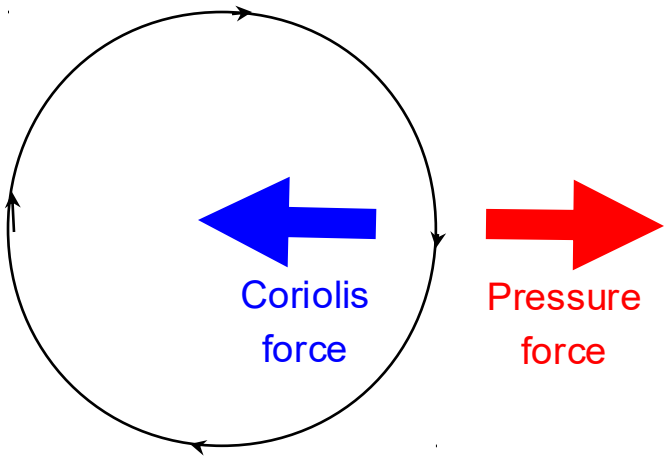
(Barge & Sommeria 1995, Tanga et al. 1996, Adams et al. 1996)

Speeds up planet formation enormously

(Lyra et al. 2008b, 2009ab, Raettig et al. 2021, Lyra et al. 2024)

Vortex Trapping

Geostrophic balance:



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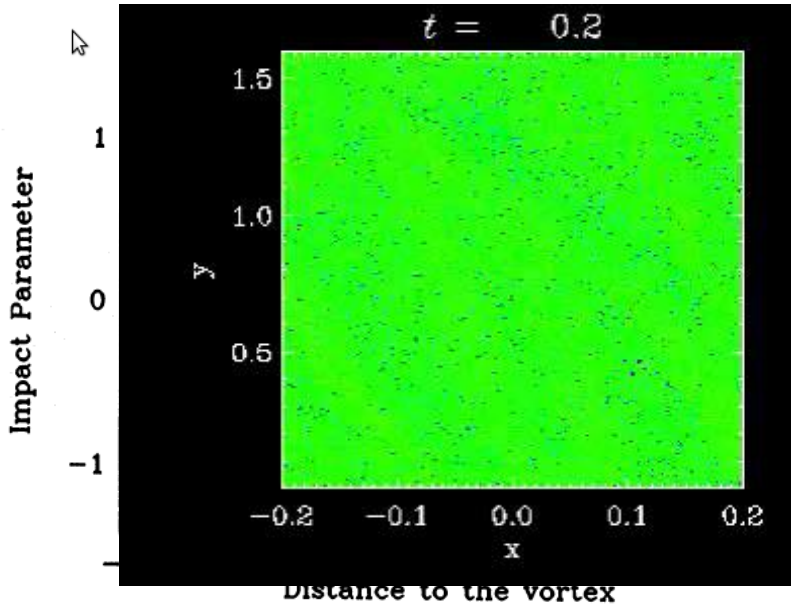
streamline



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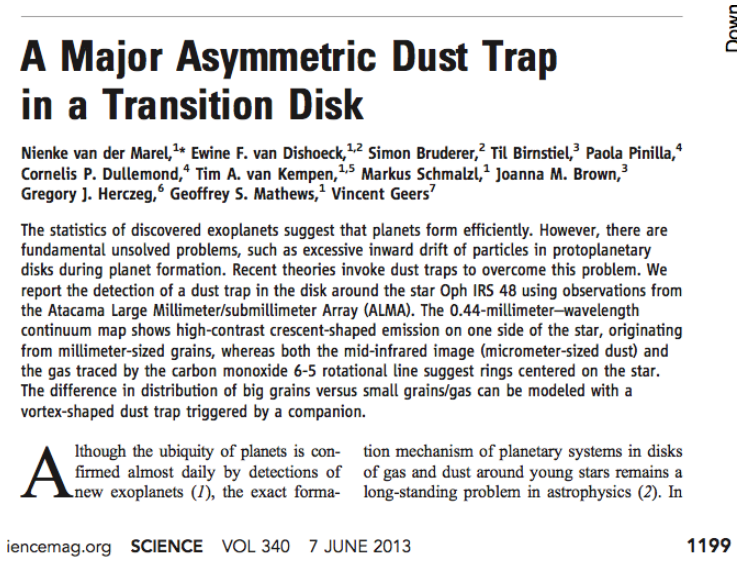
Oph IRS 48



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]

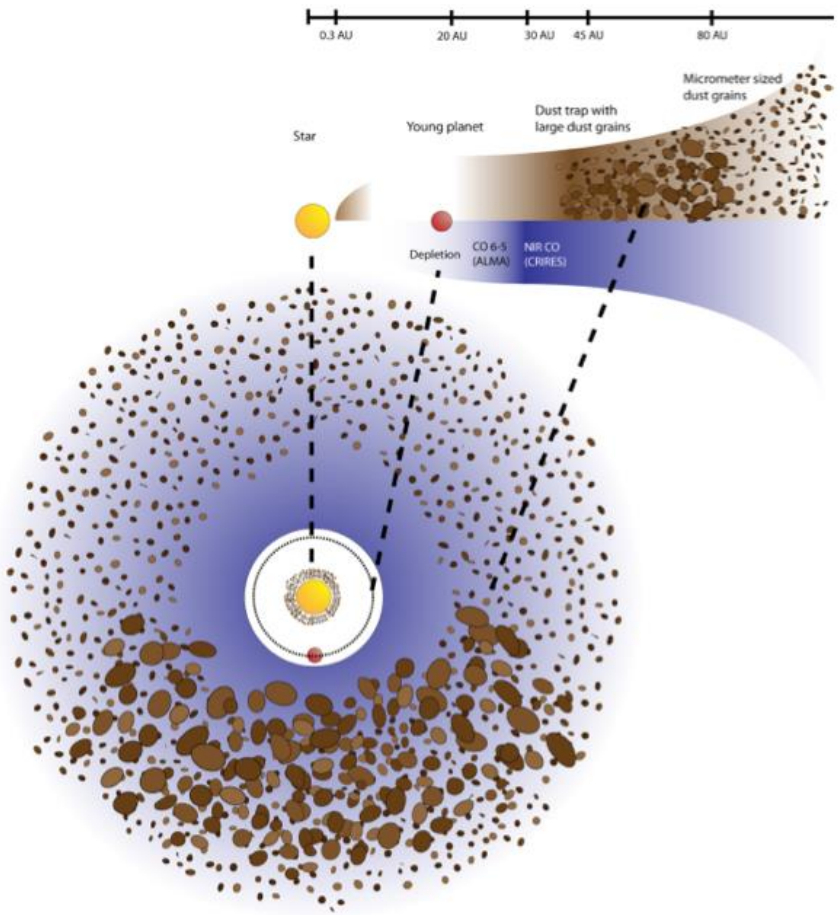
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection 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

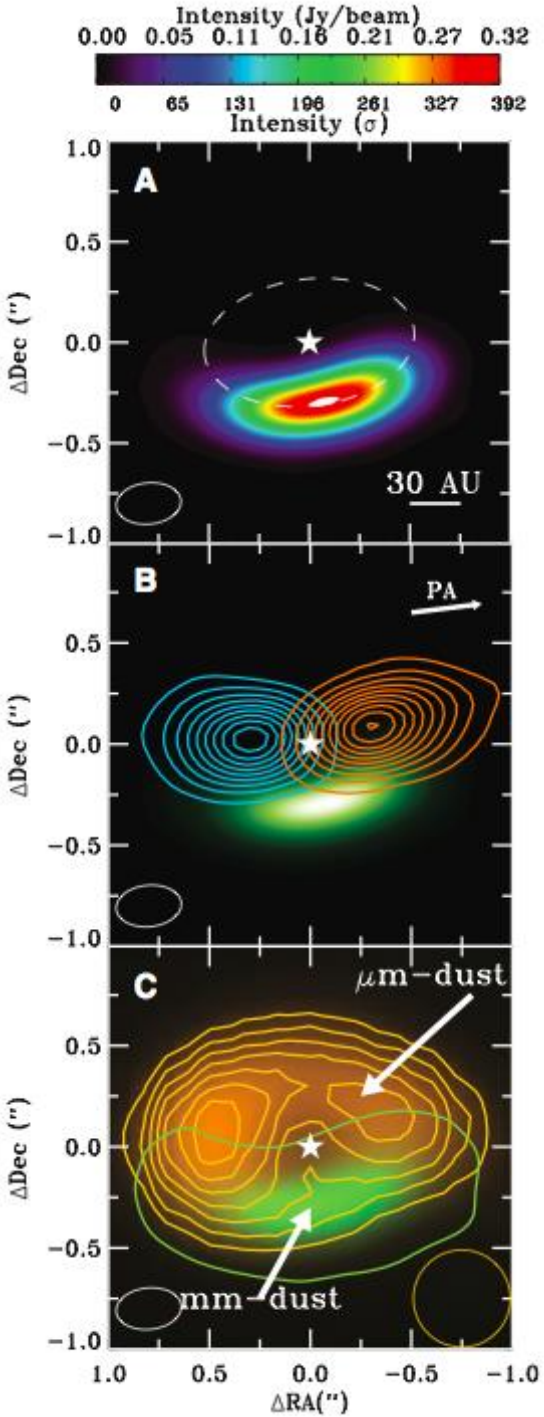
van der Marel+ ‘13

A huge vortex observed with ALMA

Oph IRS 48



van der Marel+. '13

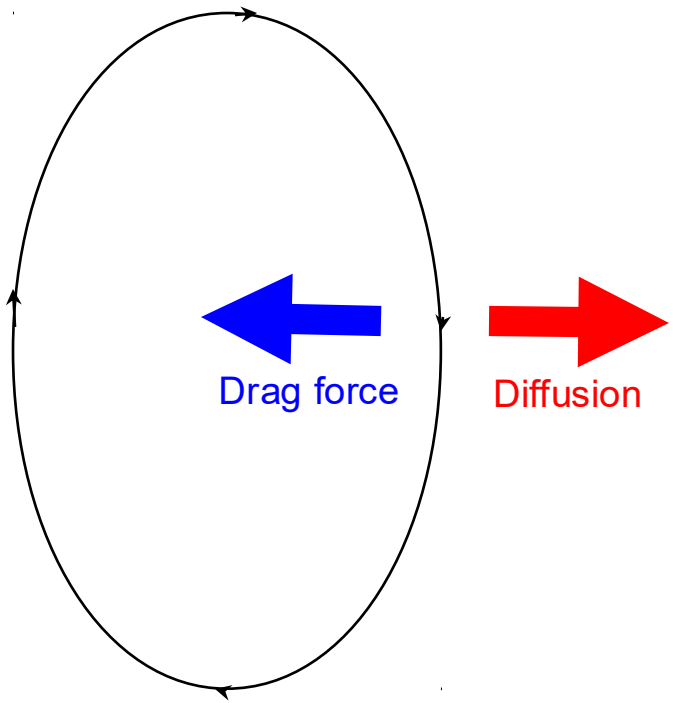


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

Drag-Diffusion Equilibrium

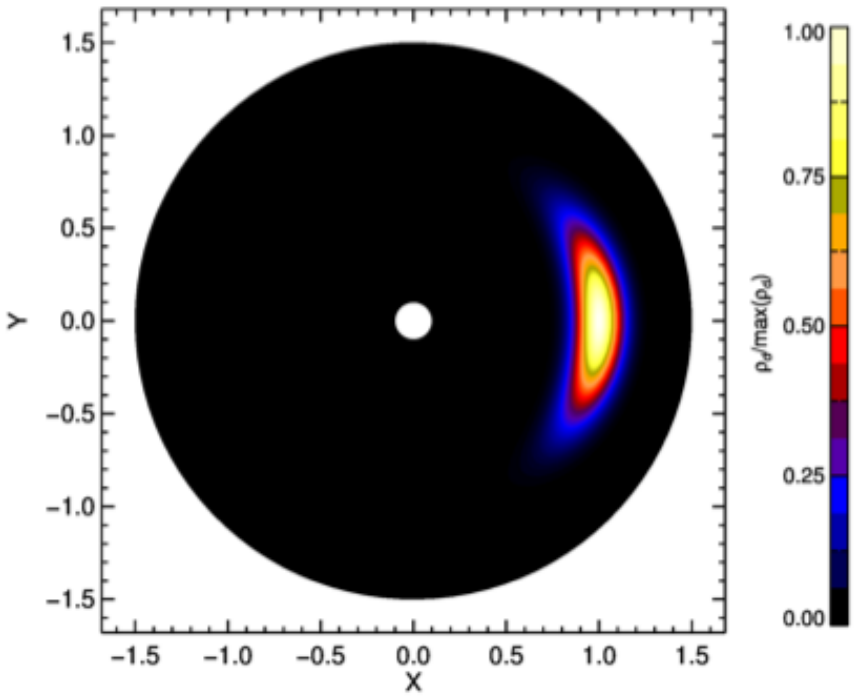


Trapped particle

Dust continuity equation

$$\frac{\partial \rho_d}{\partial t} = \underbrace{-(\boldsymbol{v}\cdot\boldsymbol{\nabla})\rho_d}_{\text{advection}} \underbrace{-\rho_d \boldsymbol{\nabla}\cdot\boldsymbol{v}}_{\text{compression}} + \underbrace{D\nabla^2\rho_d}_{\text{diffusion}},$$

Analytical Solution for dust in Drag-Diffusion Equilibrium



Solution for

H/r=0.1 χ*=4* *S*=1

Steady-state solution

$$\rho_d(a,z) = \varepsilon\rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin '13

$$S = \frac{St}{\delta}$$

$$\delta = v_{\rm rms}^2 / c_s^2,$$

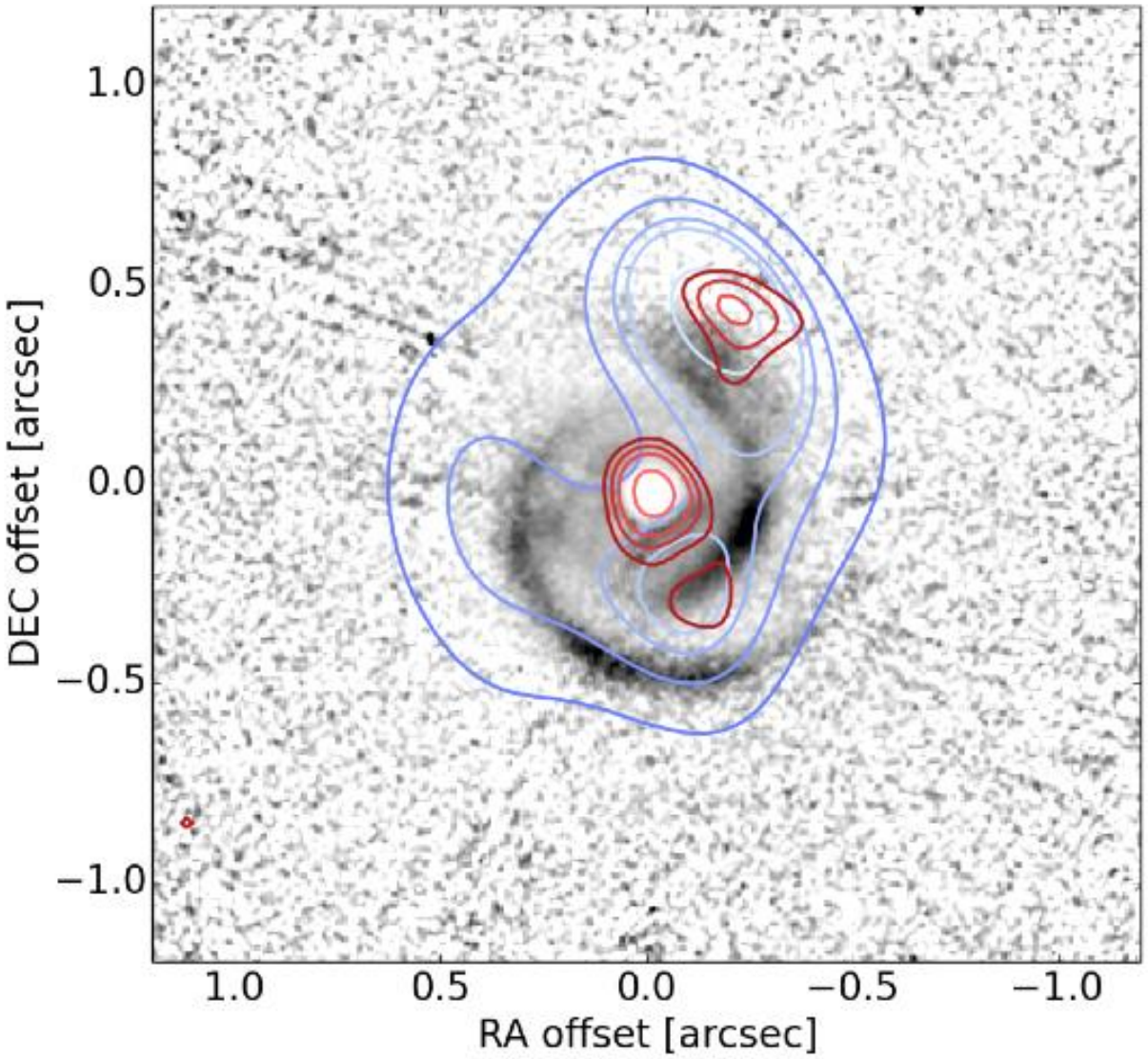
a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

Disk Tomography
SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

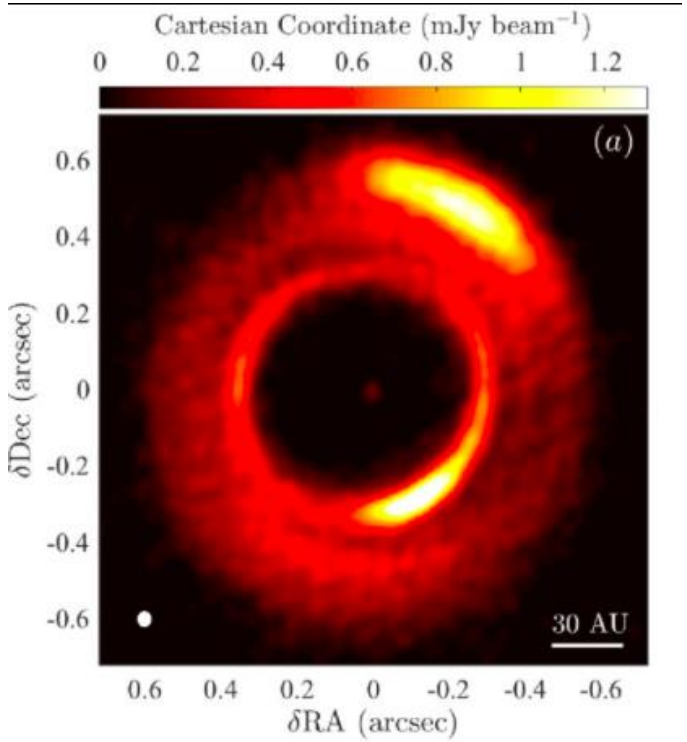
ALMA (~ mm)

VLA (cm-m)



Marino+Lyra '15

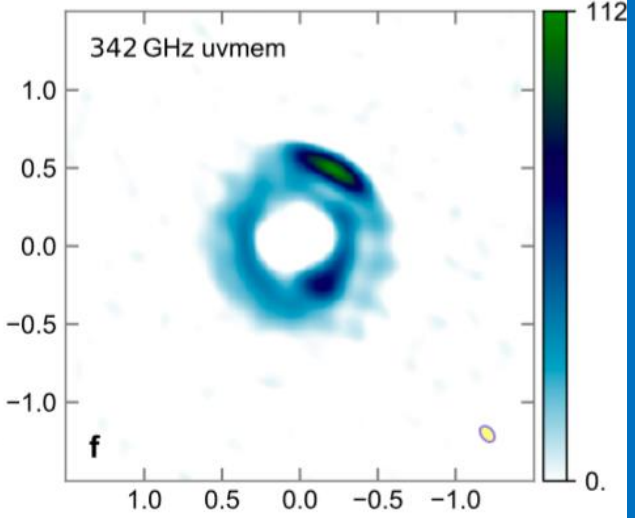
ALMA



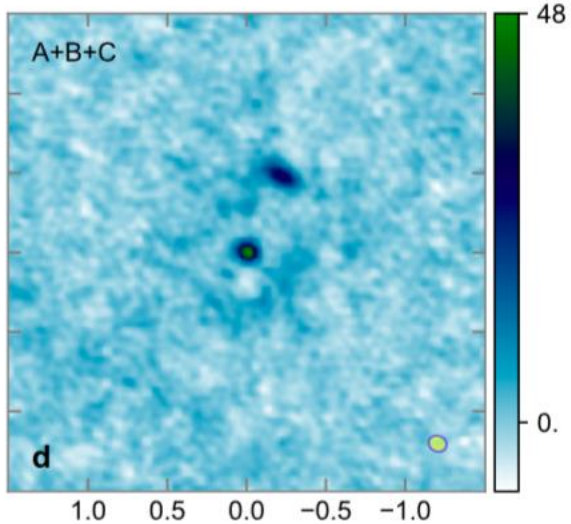
Dong+ '18

Pebble trapping

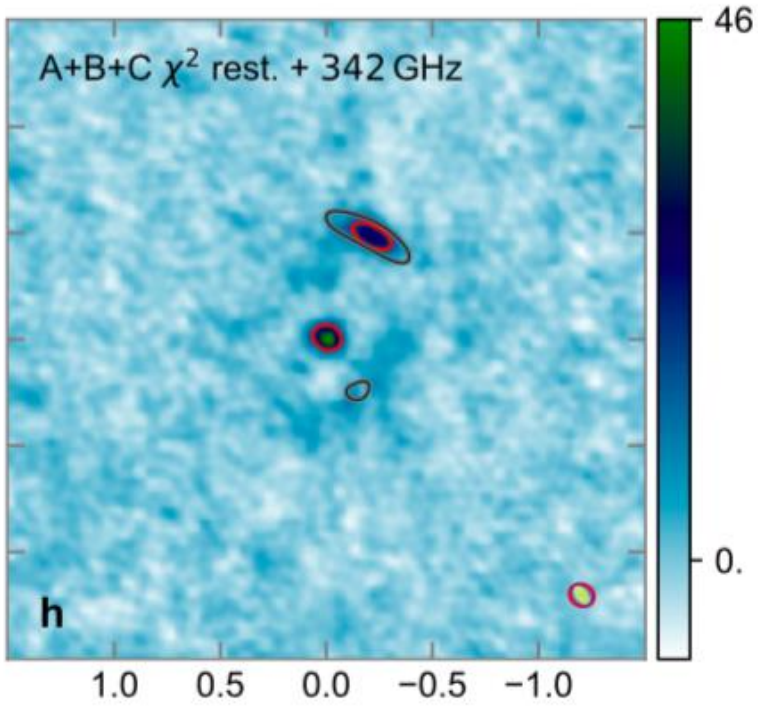
ALMA (mm)



VLA (cm-m)

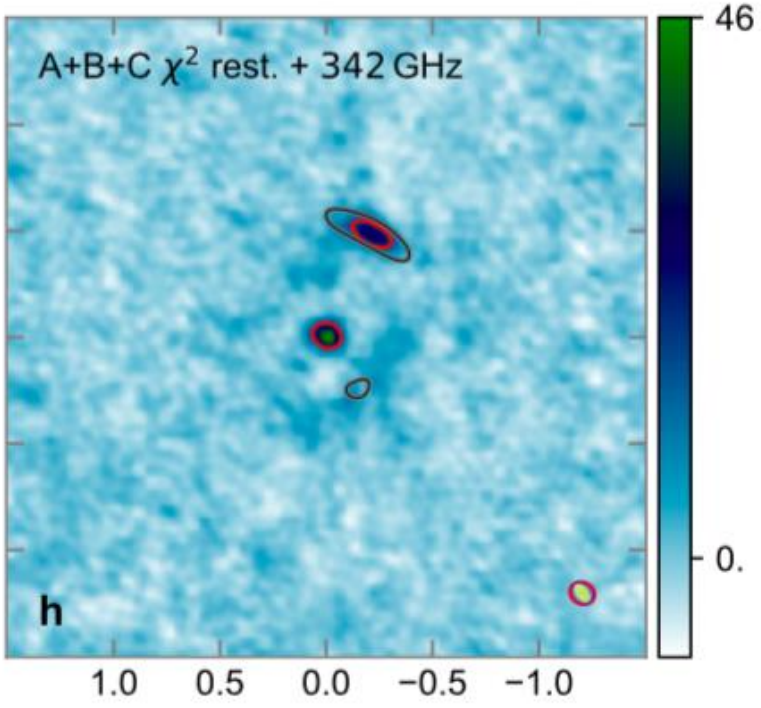


Overlay

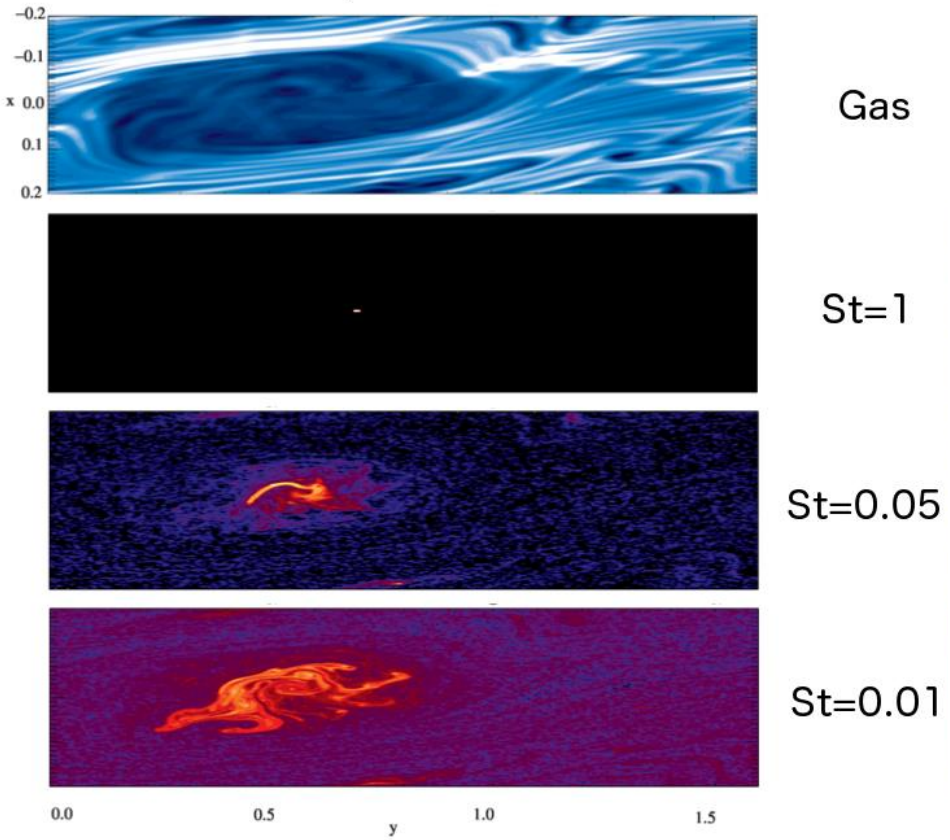


Casassus+Lyra ’19

Model vs Observation



Casassus+Lyra '19



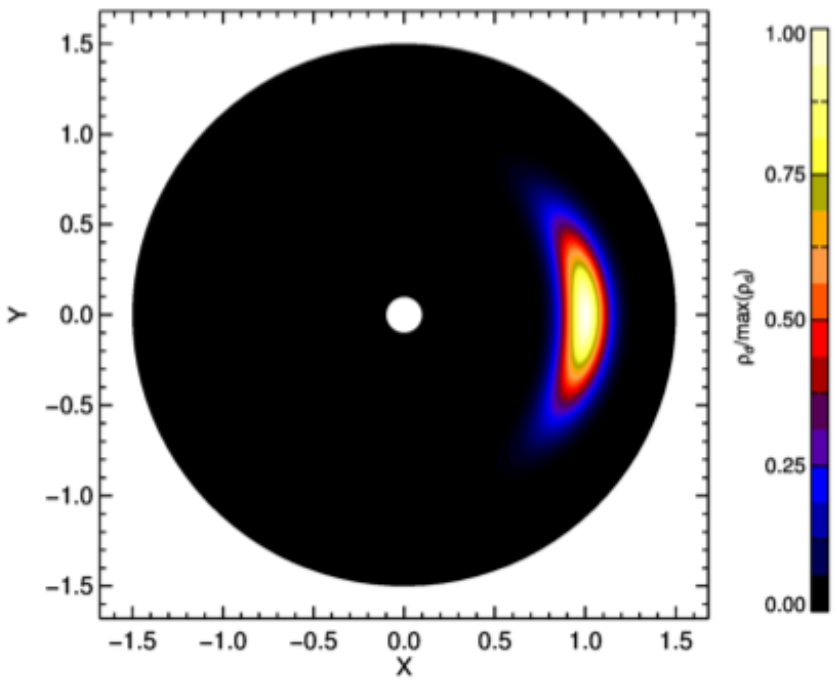
Raettig+Lyra '15

Take home message

- Vortex-trapped dust in drag-diffusion equilibrium explains the observations

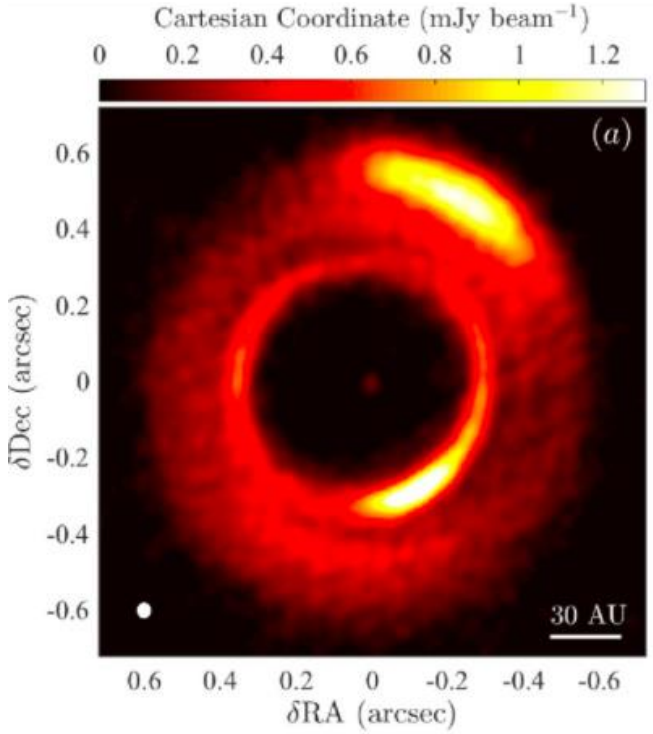
$$\rho_d(a,z) = \varepsilon\rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1)\right\}$$

Lyra-Lin solution



Lyra & Lin (2013)

Observed Disk

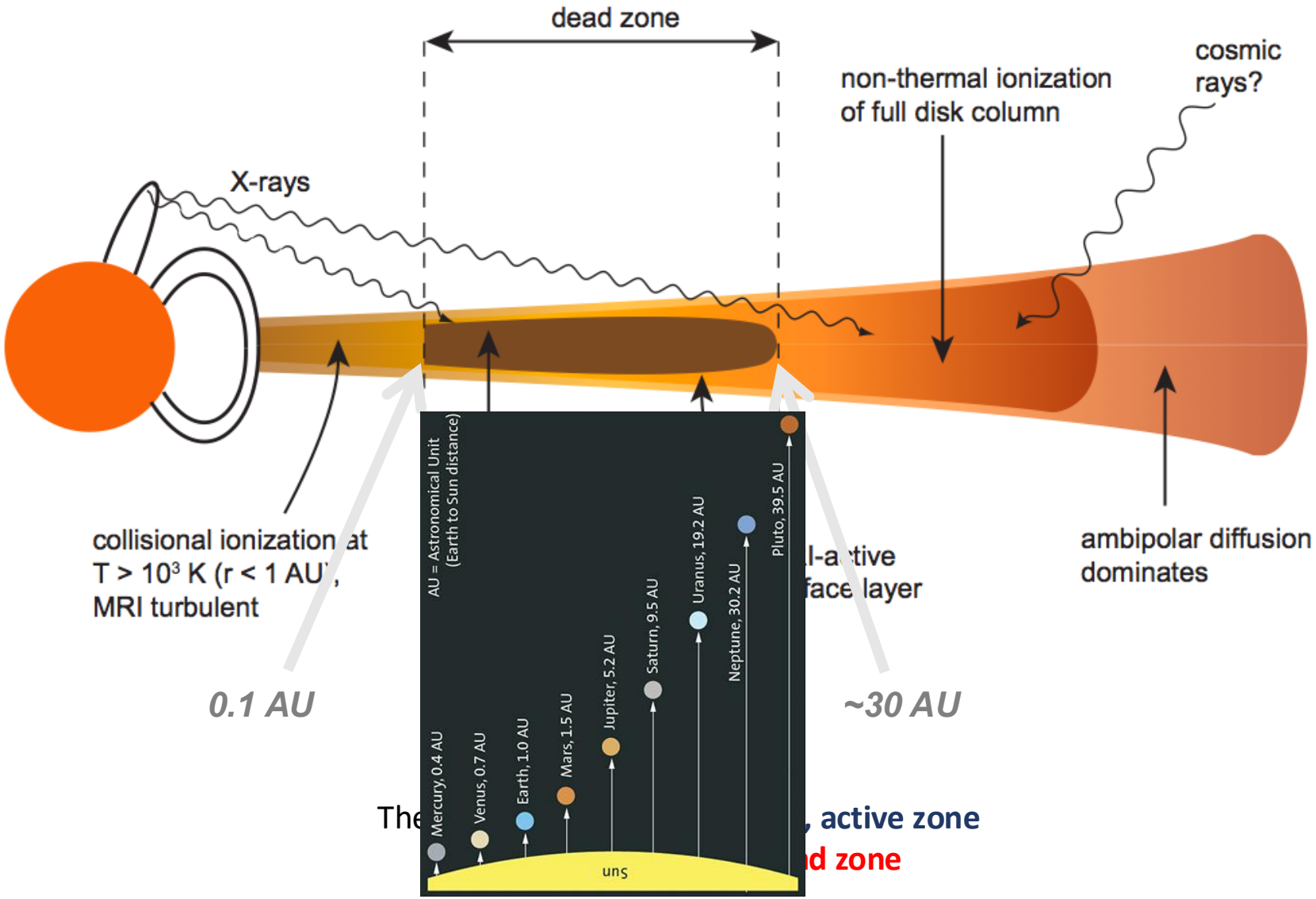


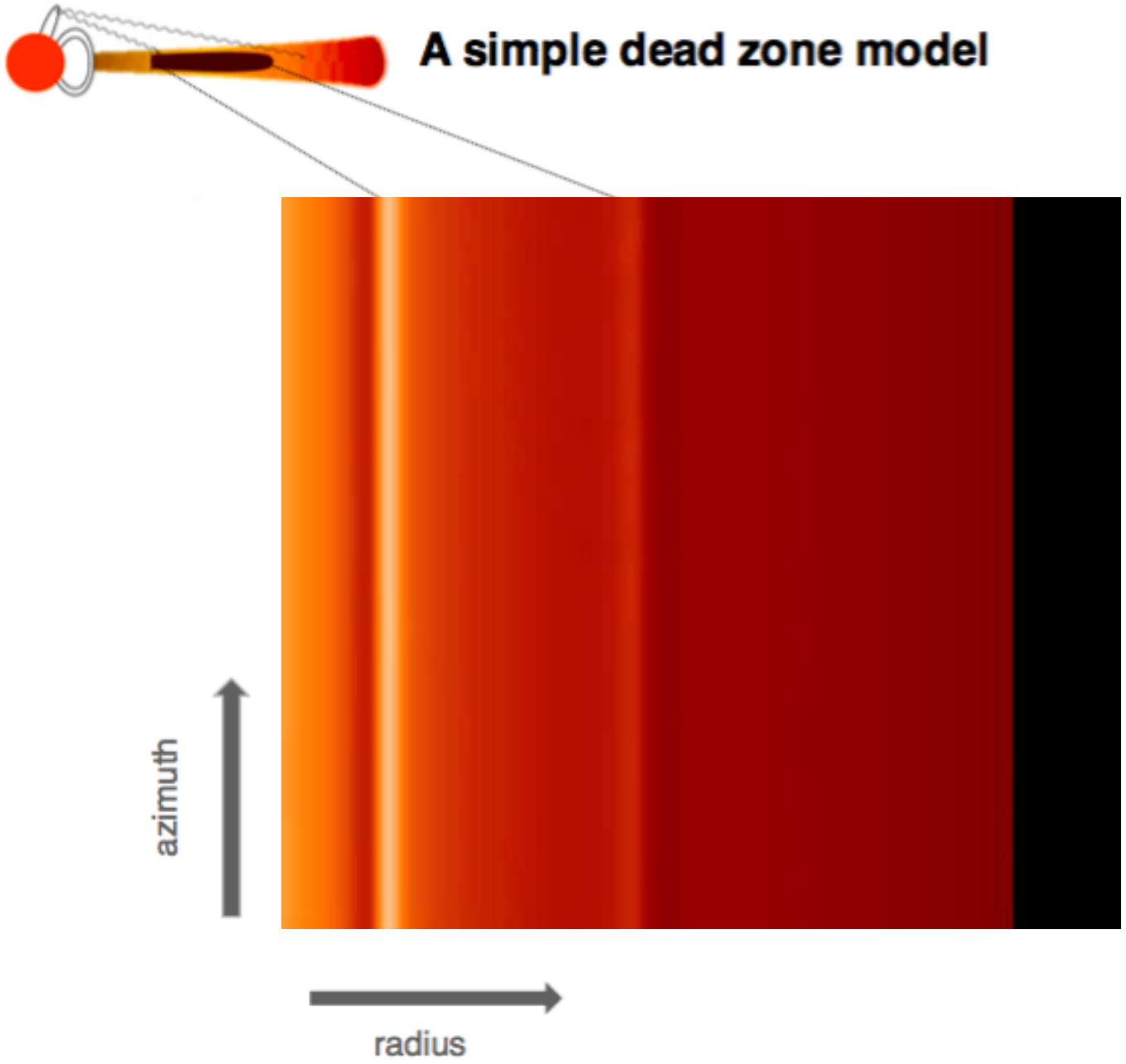
Dong et al. (2018)

Cyclogenesis - Disk Instabilities

Turbulence and Accretion in 3D Global MHD Simulations of Stratified Protoplanetary Disk

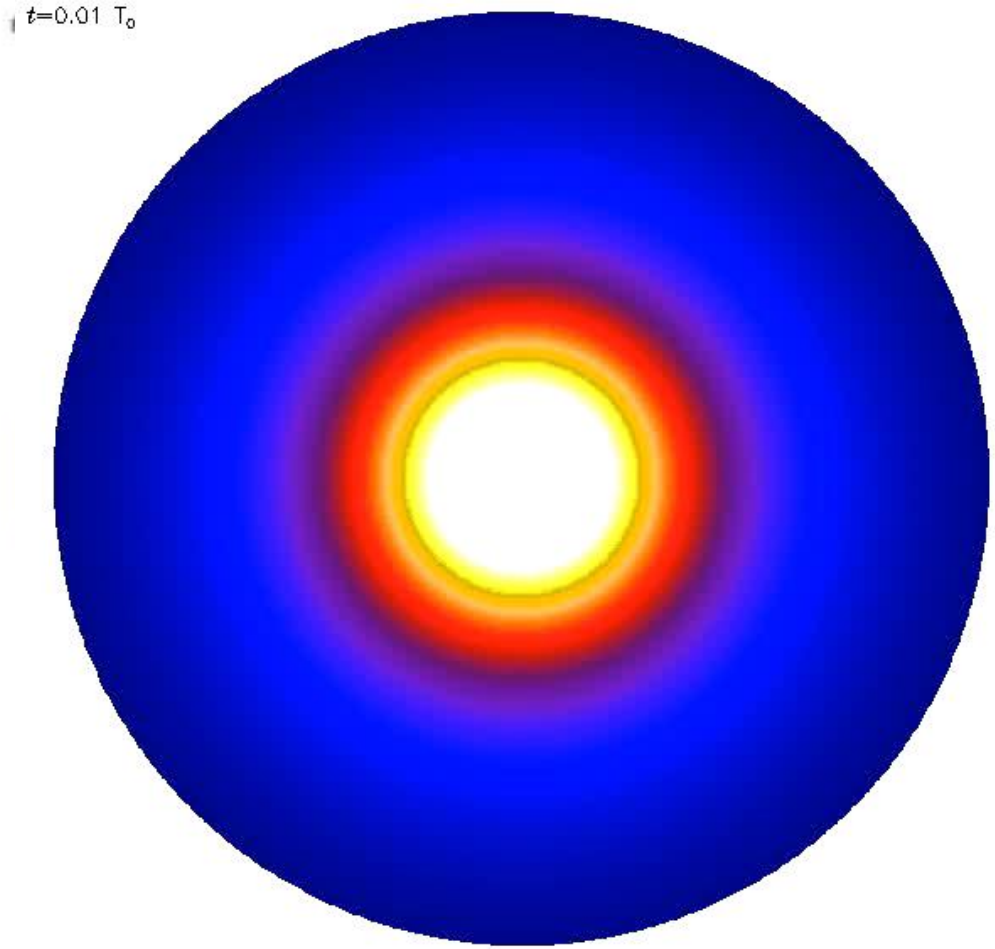
Dead zones


dead zone
non-thermal ionization
of full disk column
cosmic
rays?
X-rays
collisional ionization at
T > 10³ K (r < 1 AU),
MRI turbulent
ambipolar diffusion
dominates
0.1 AU
~30 AU
AU = Astronomical Unit
(Earth to Sun distance)
Mercury, 0.4 AU
Venus, 0.7 AU
Earth, 1.0 AU
Mars, 1.5 AU
Jupiter, 5.2 AU
Saturn, 9.5 AU
Uranus, 19.2 AU
Neptune, 30.2 AU
Pluto, 39.5 AU
Sun
active zone



Lyra et al. (2008b, 2009a);
After Lovelace & Hohlfeld 1978, Toomre 1981, Papaloizou & Pringle (1984), Hawley (1987), Lovelace et al (1999), Li et al. (2000), Varniere & Tagger (2005).

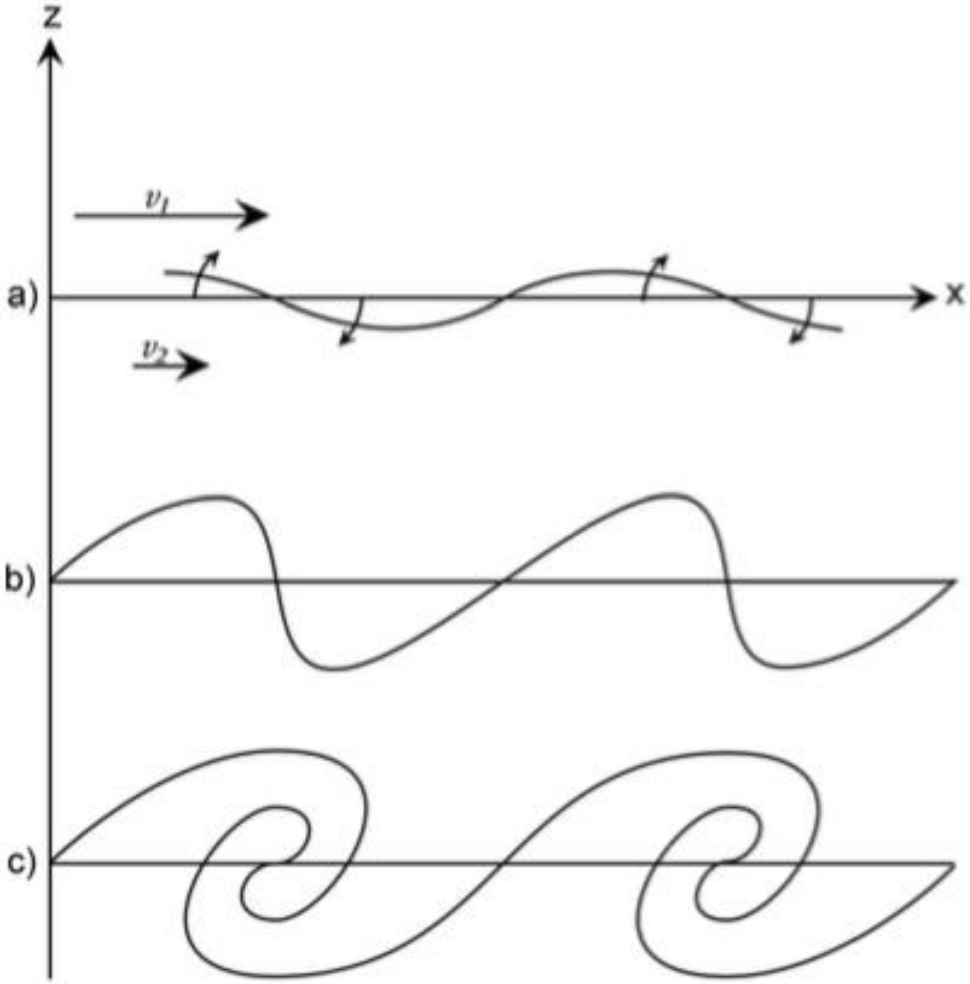
Inner (0.1 AU) active/dead zone boundary



Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Rossby wave instability
(Kelvin-Helmholtz Instability in rotating disks)

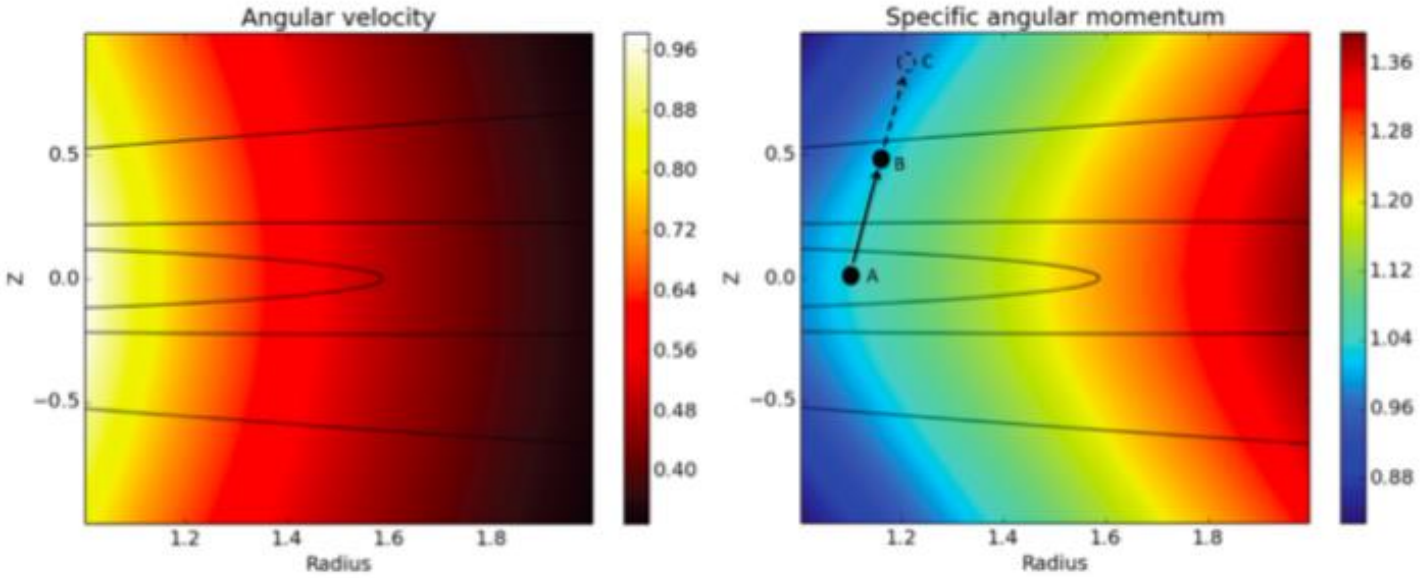


Lovelace & Hohlfeld 1978, Toomre 1981, Papaloizou & Pringle (1984), Hawley (1987), Lovelace et al (1999), Li et al. (2000), Varniere & Tagger (2005), Cheng & Youdin (2023).

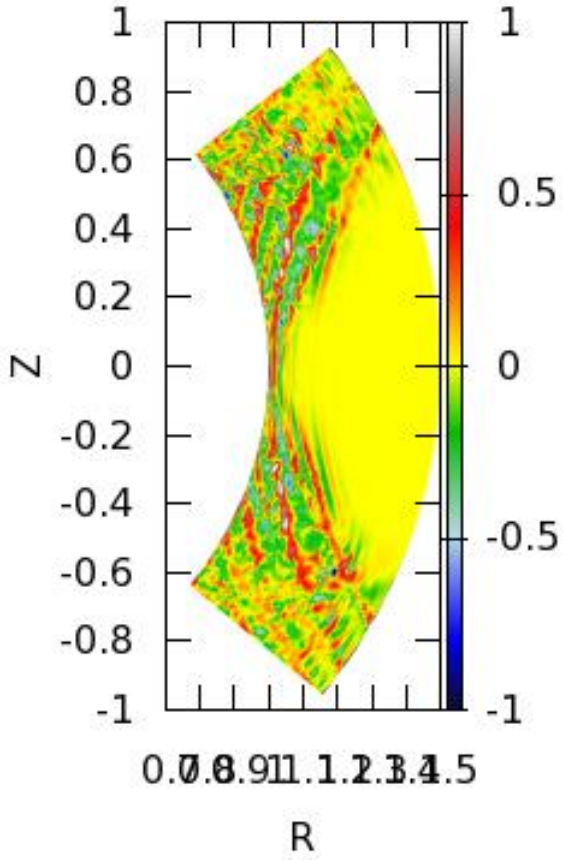
Vertical shear instability

Angular velocity not constant in cylinders: unstable

Buoyancy stabilizes. The most unstable mode is isothermal.

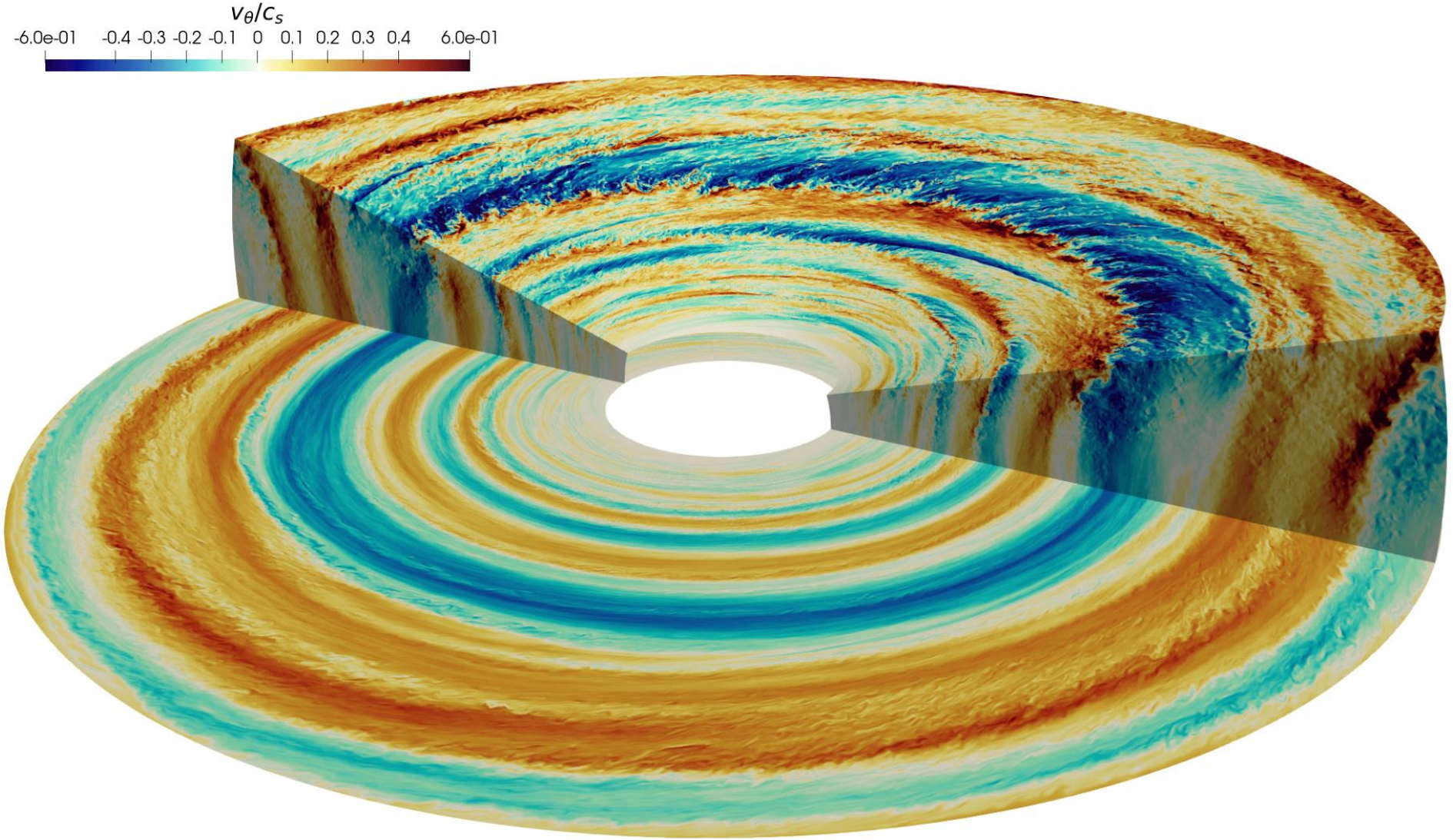


Fromang & Lesur (2017)



Nelson et al. (2013)

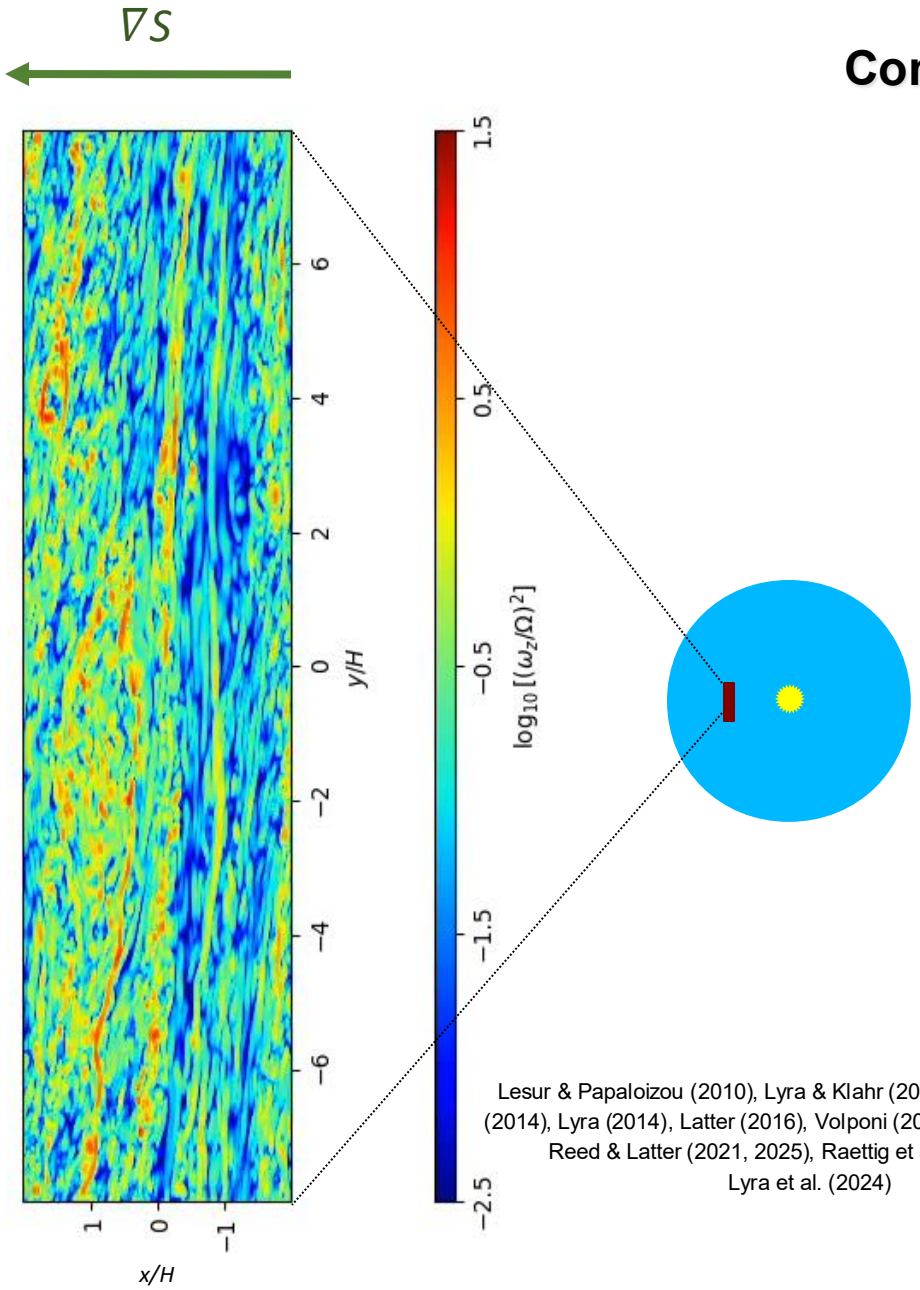
Vertical shear instability



Resolution 3872 x 2000 x 12544
Run on 4096 GPUs

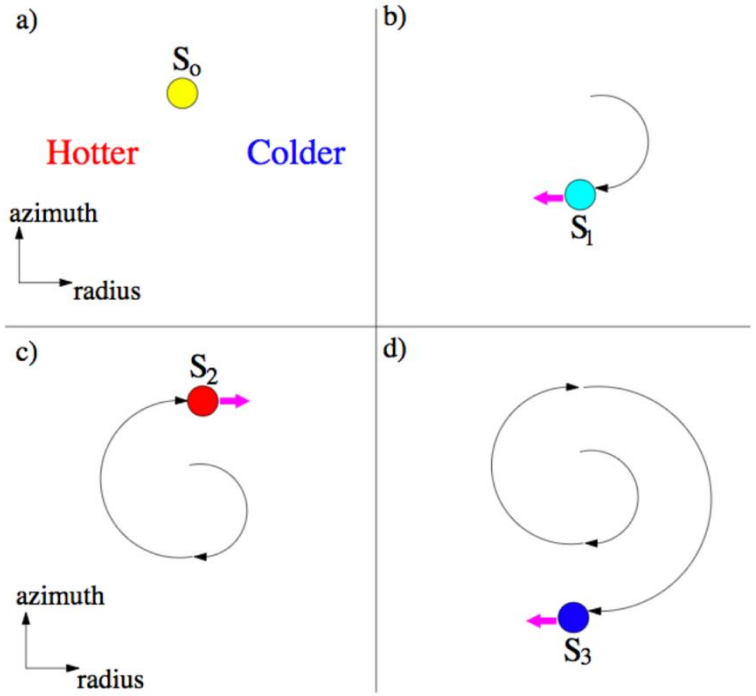
Lesur et al (2025)

Convective Overstability



Lesur & Papaloizou (2010), Lyra & Klahr (2011), Klahr & Hubbard (2014), Lyra (2014), Latter (2016), Volponi (2016), Lyra et al. (2018), Reed & Latter (2021, 2025), Raettig et al. (2015, 2021) Lyra et al. (2024)

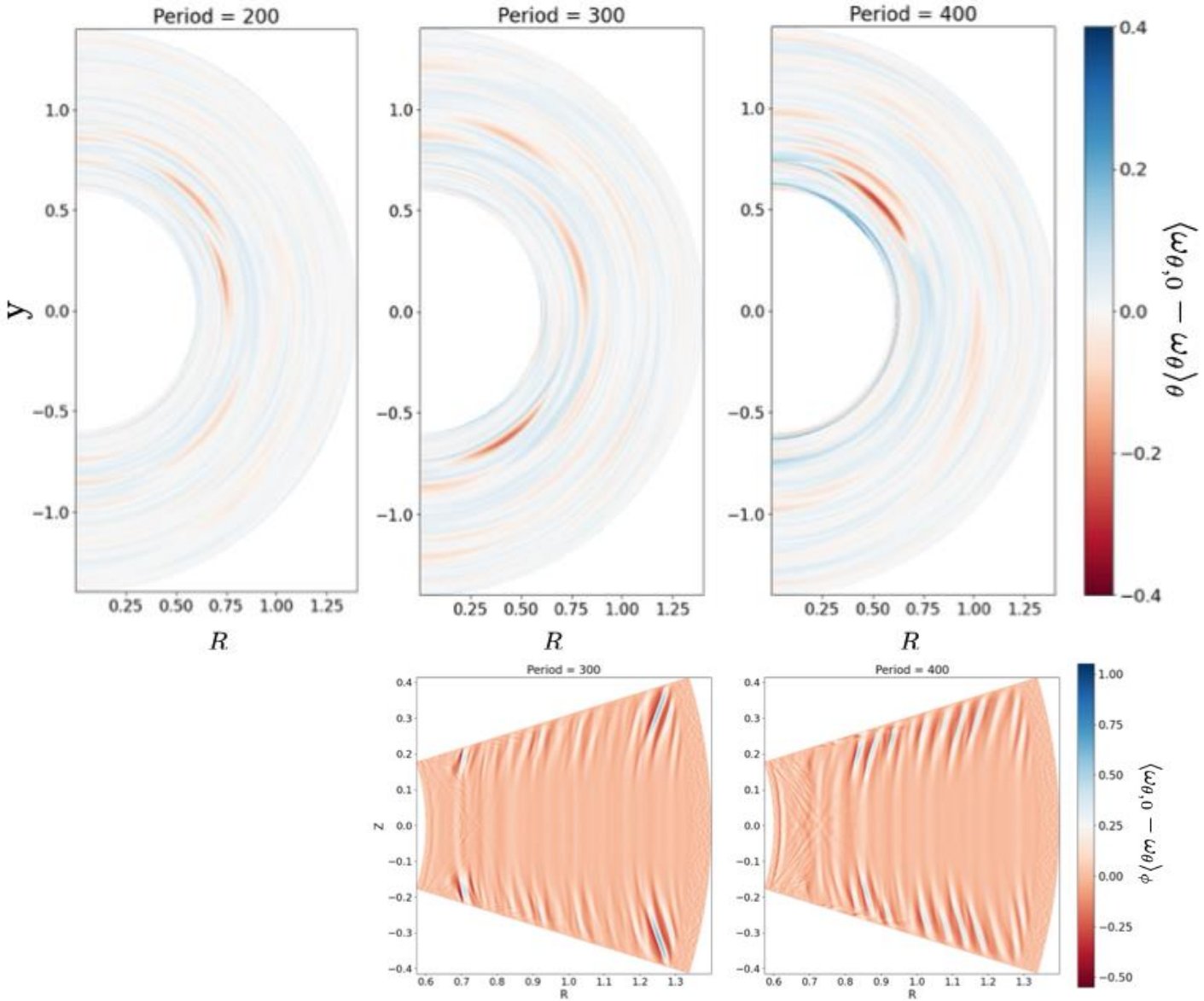
Sketch of the Convective Overstability



Latter (2016)

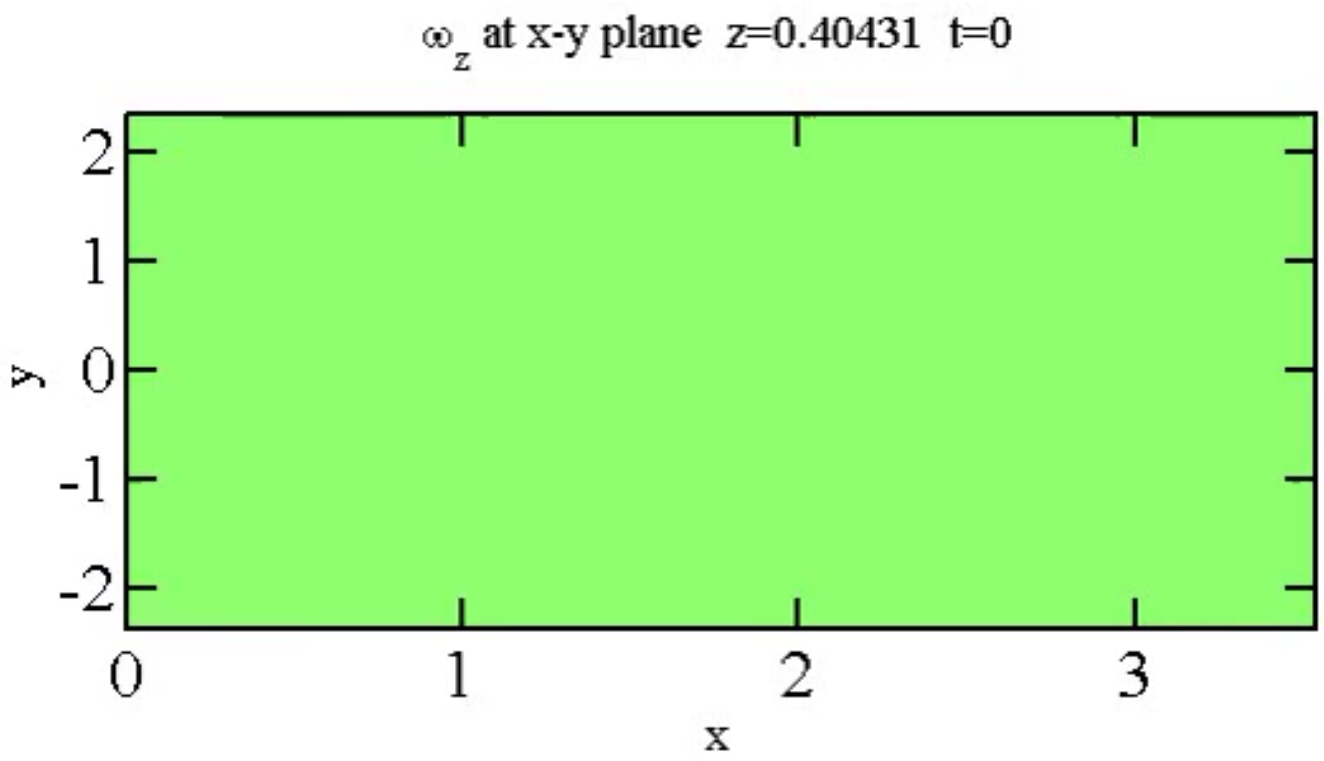
Convective Overstability

Global 3D Model
with vertical stratification



Sengupta & Lyra (in prep)

Resonant Buoyant Instability (née Zombie Vortex Instability)

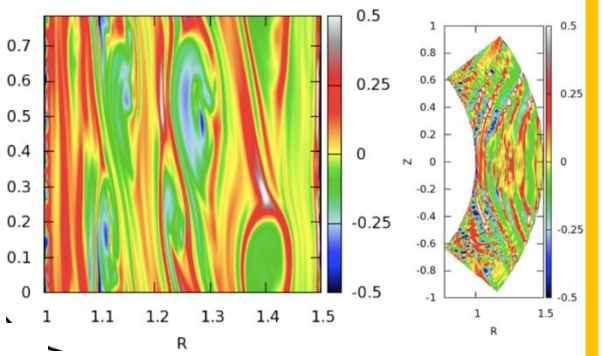


Cascade of baroclinic critical layers

Marcus et al. (2015, 2016), Barranco et al. (2018), Lyra et al. (in prep)

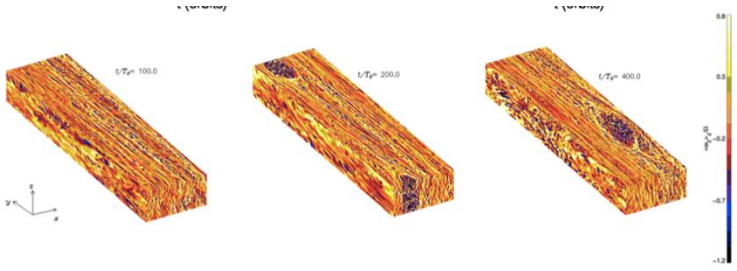
Hydrodynamical Instabilities

Vertical Shear Instability



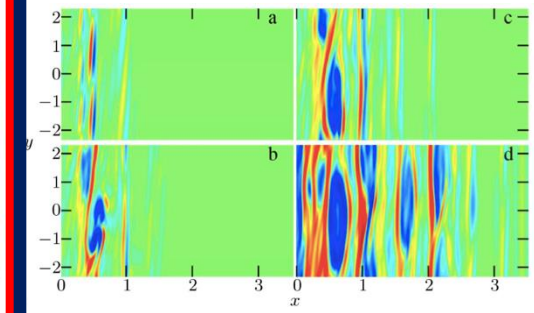
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



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

Resonant Buoyant Instability



Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al. 2016, Lesur & Latter 2016

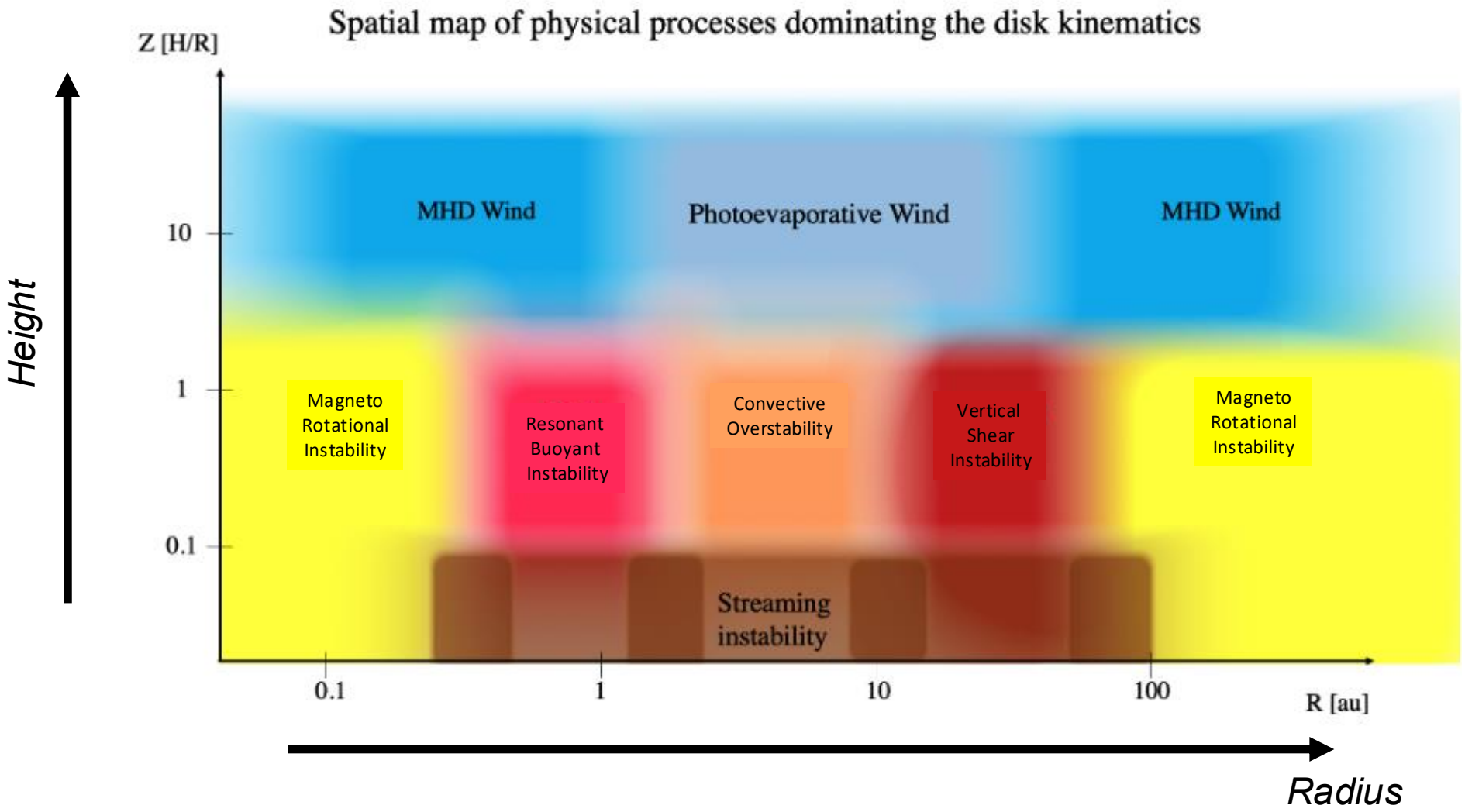
$\Omega\tau \ll 1$
($\kappa < 1$ cm^2/g)

$\Omega\tau \sim 1$
($\kappa \sim 1$–50 cm^2/g)

$\Omega\tau \gg 1$
($\kappa > 50$ cm^2/g)

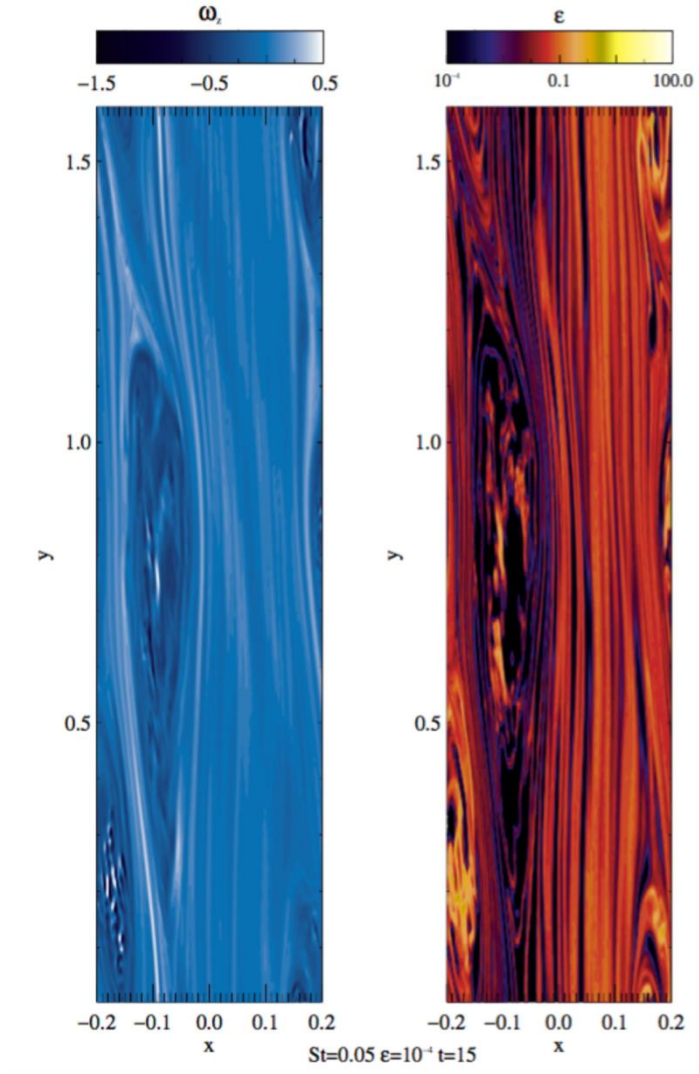
Opacity

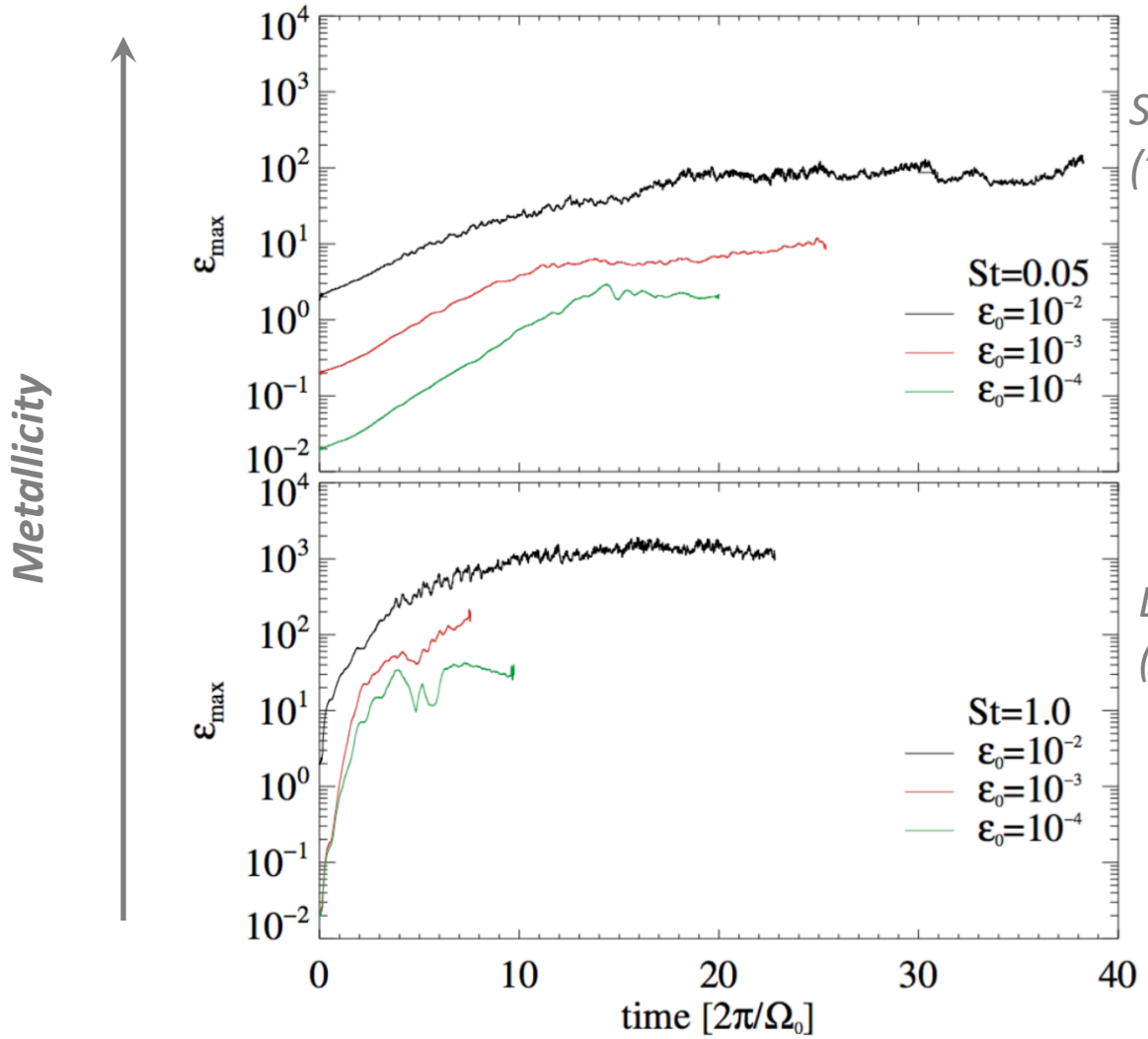
Instability Map



Lyra & Umurhan (2019) Lesur et al. (2023)

Pebble trapping in 3D vortices



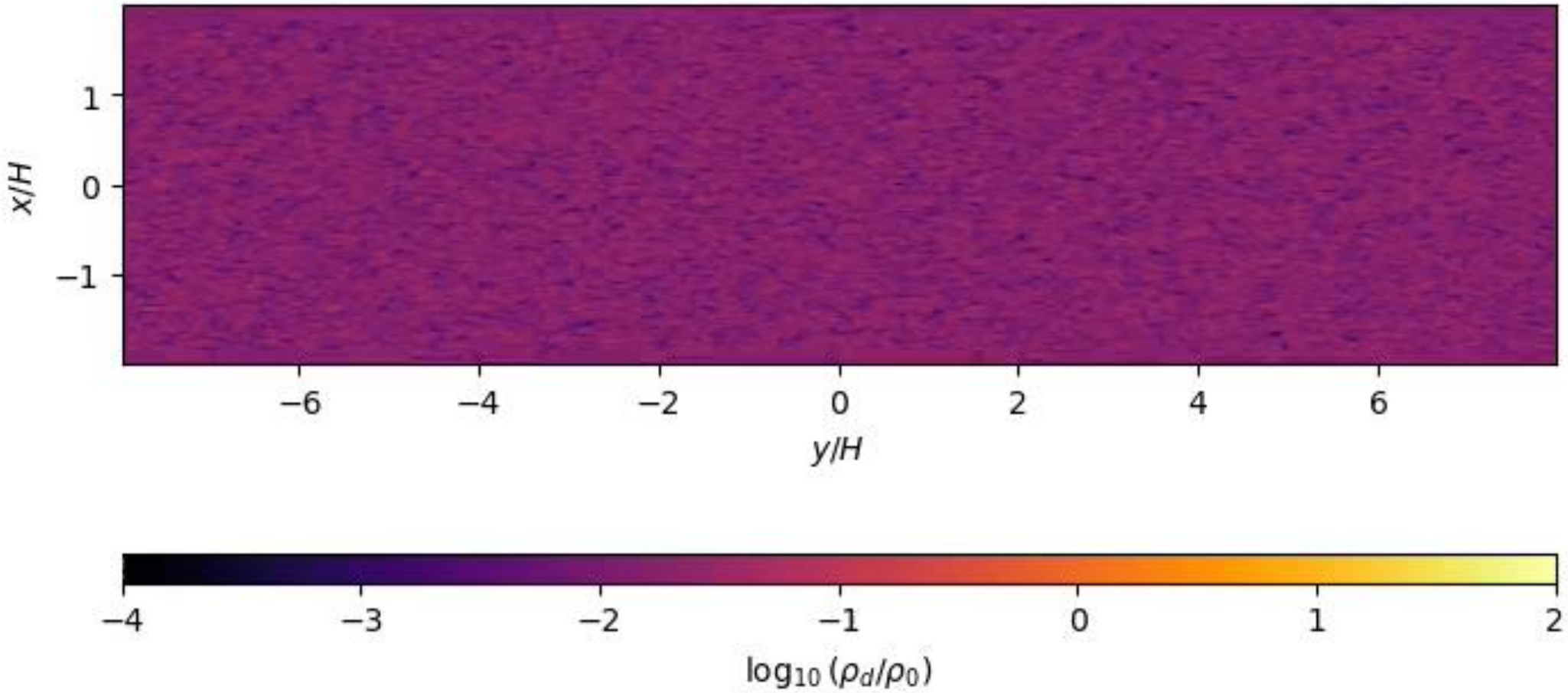


Small grains ("pebbles")

Large grains ("boulders")

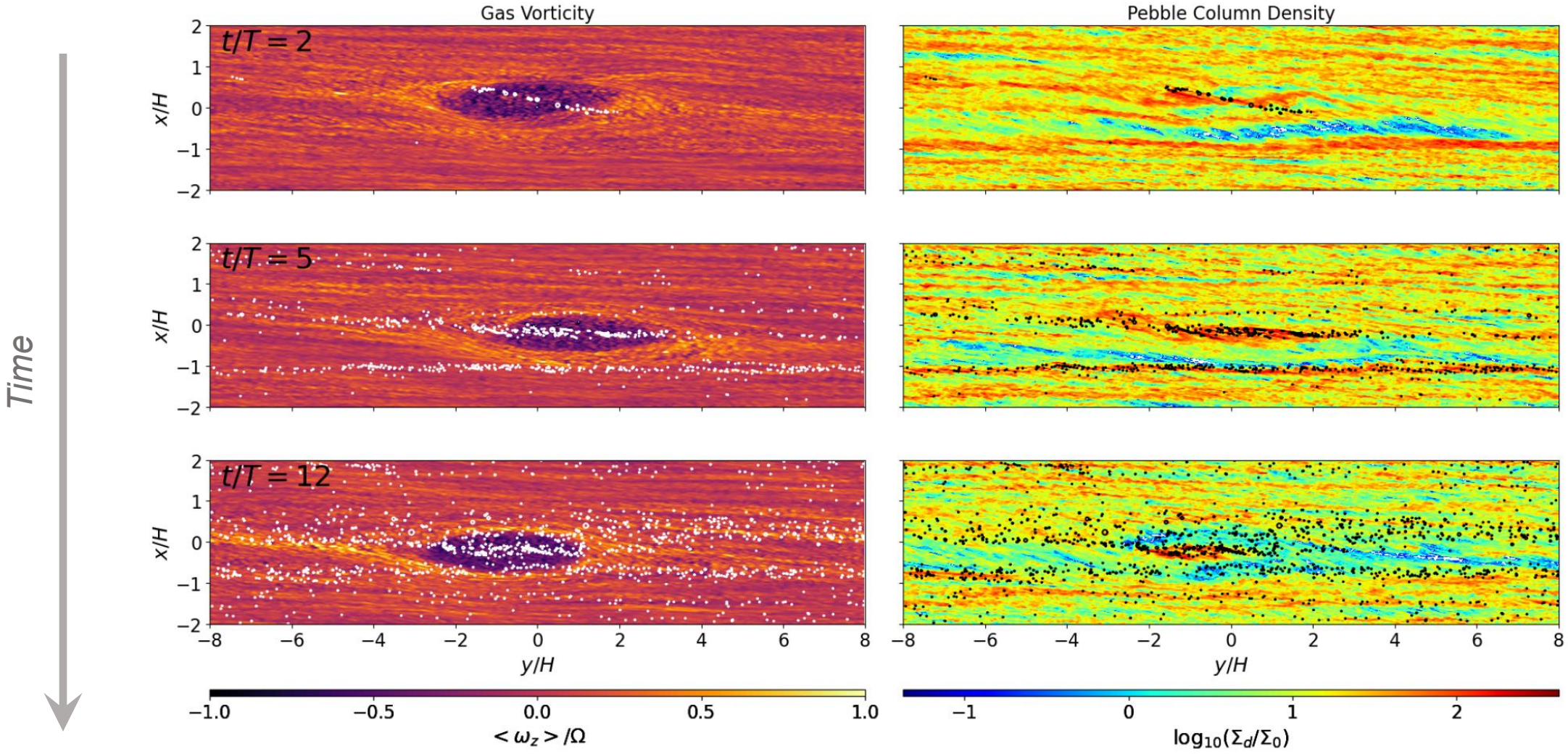
Raettig et al. (2021)

Gravitational Collapse



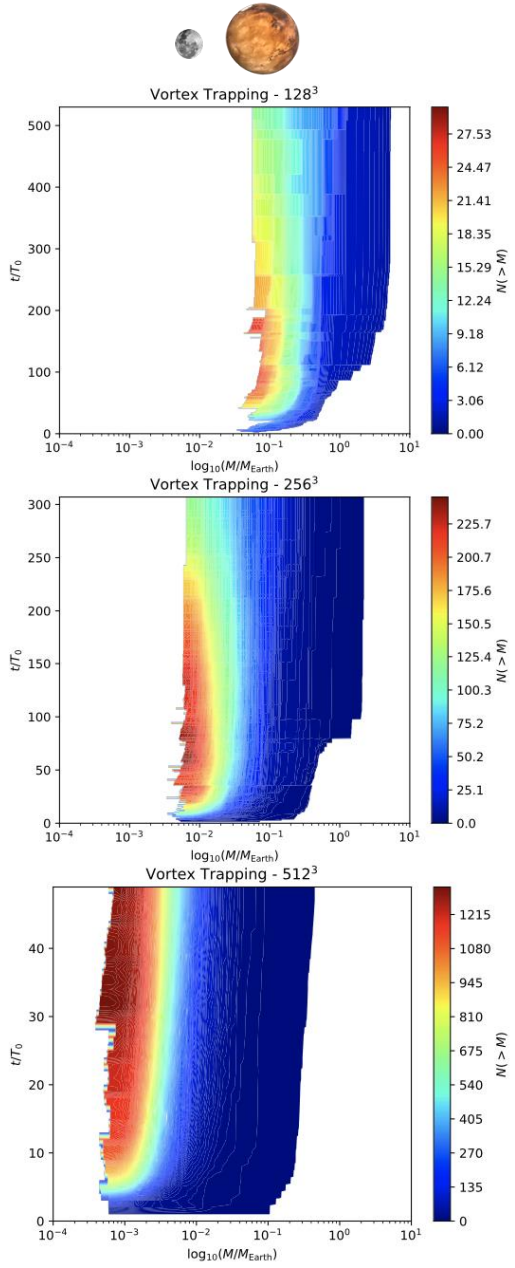
Lyra et al. (2024)

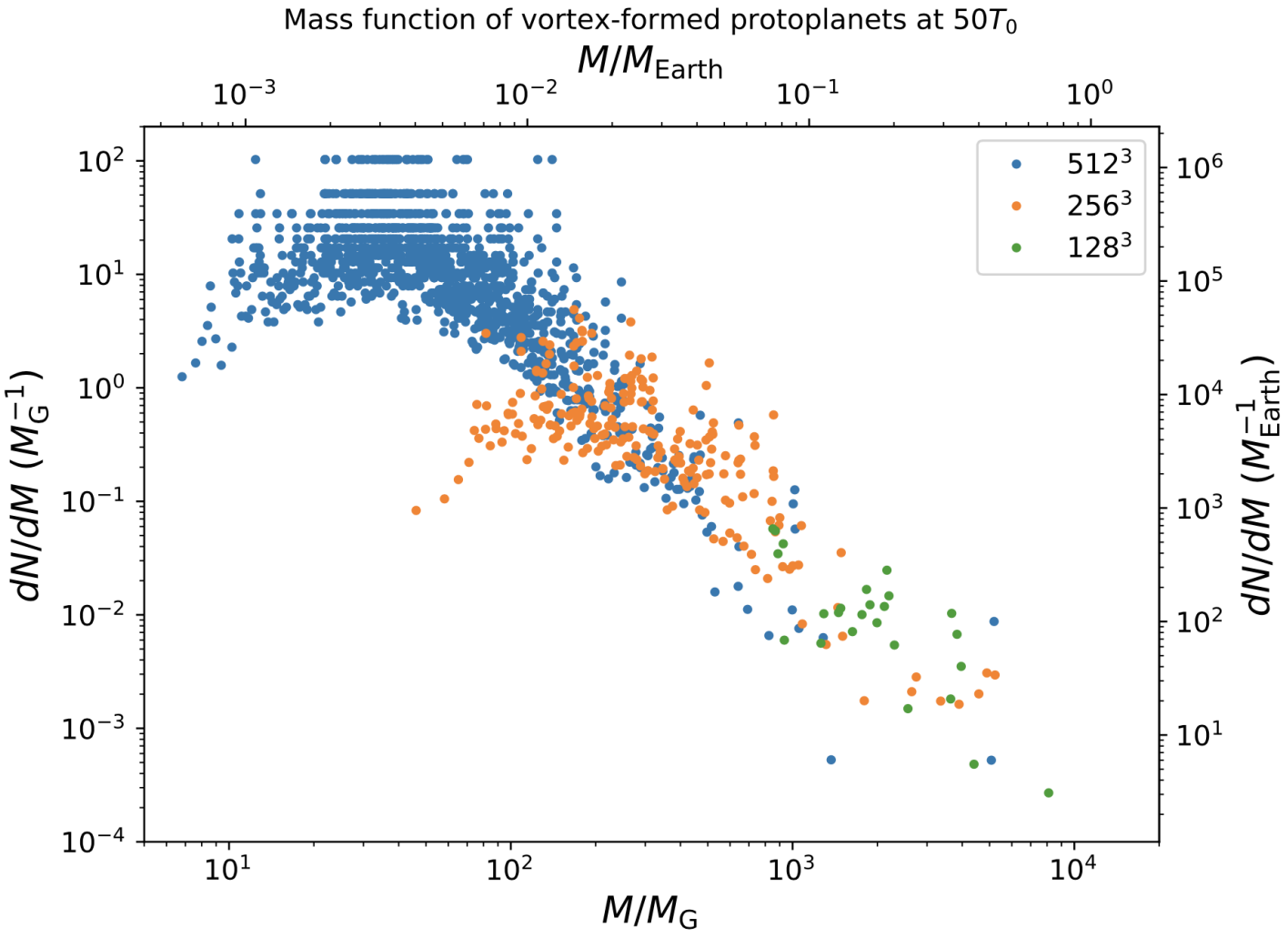
Gravitational Collapse



Lyra et al. (2024)

Convergence (or lack thereof)



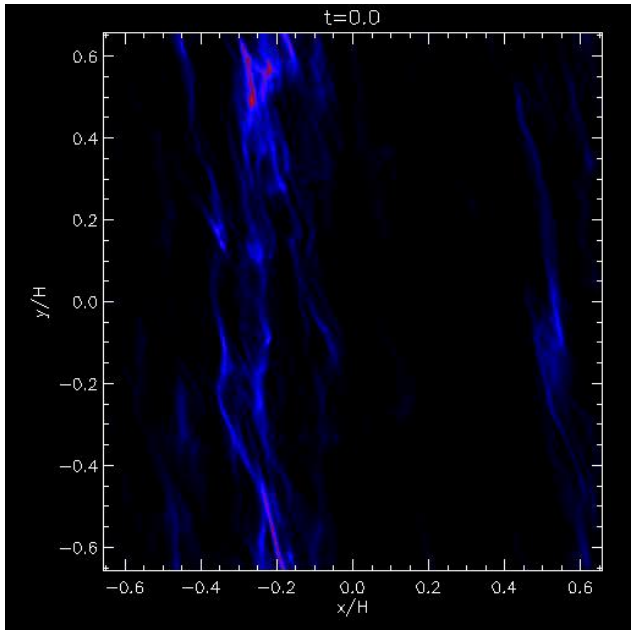


Lyra et al. (2024)

Take home message

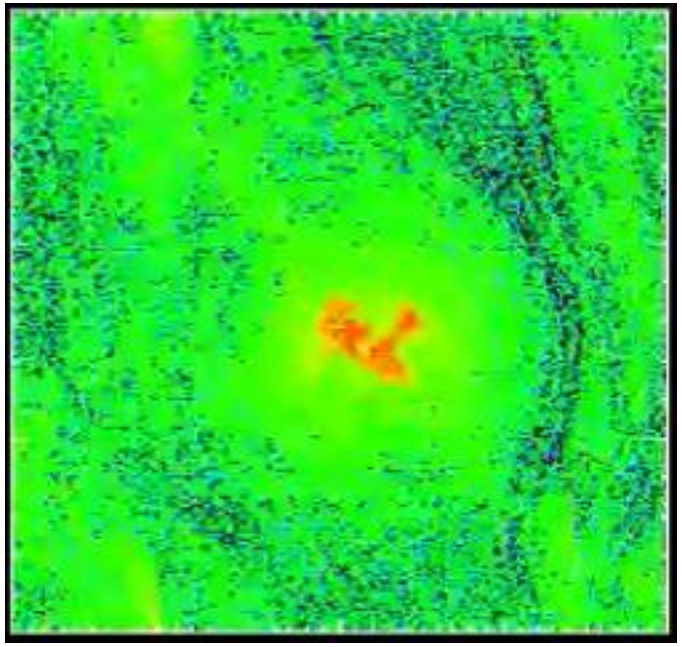
- Two routes for planet formation

Streaming Instability



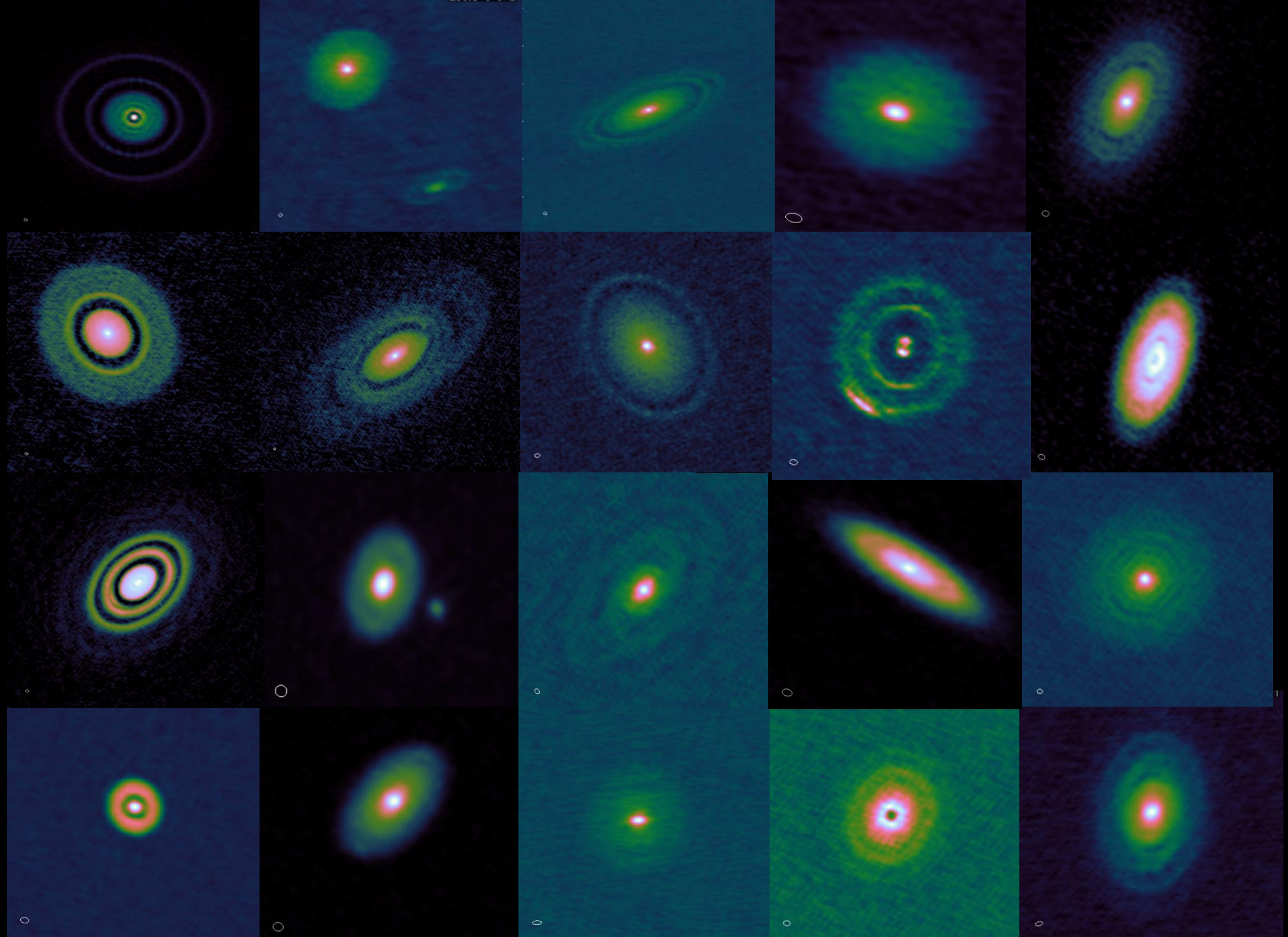
Johansen+ 07

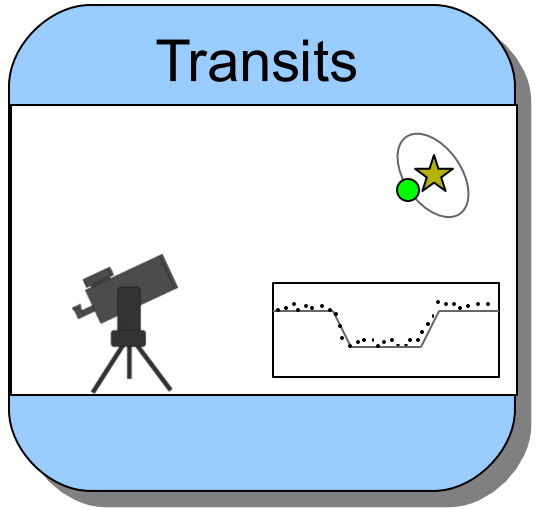
Vortex Trapping

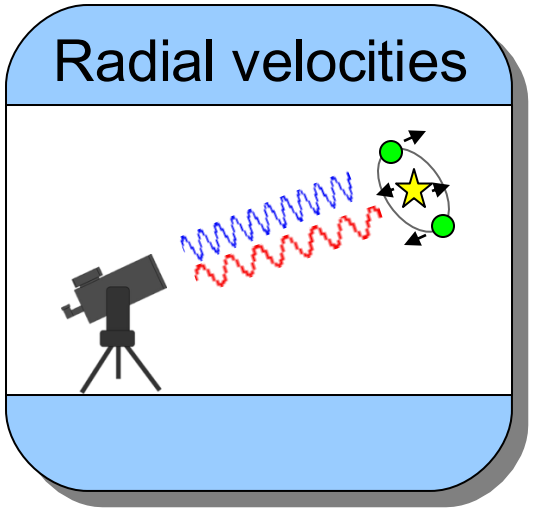


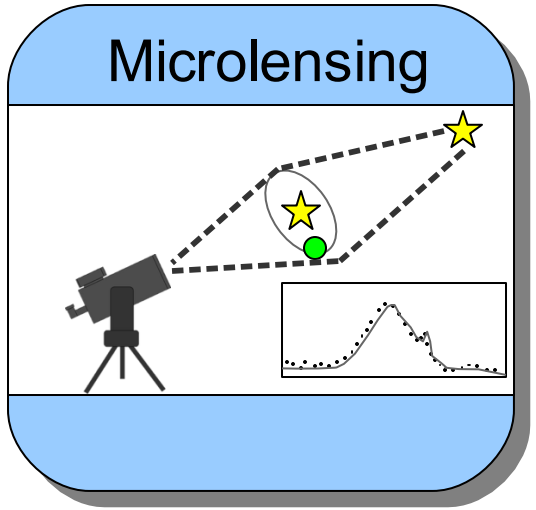
Lyra+08,18 Raettig+Lyra 12,15,21

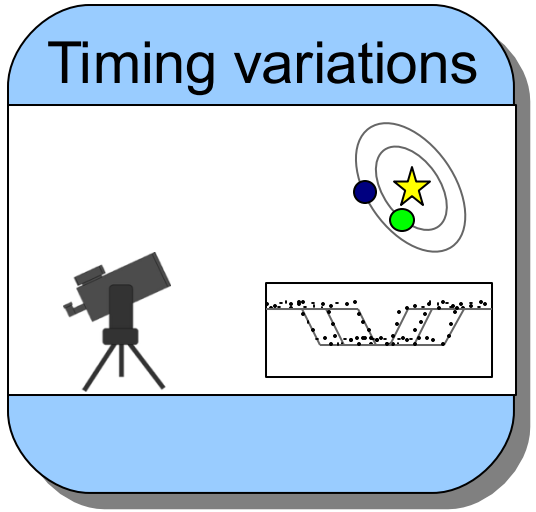
- Planet formation and turbulence.
  - Does turbulence help (concentration at large scales) or hinder (diffusion at small scales)?

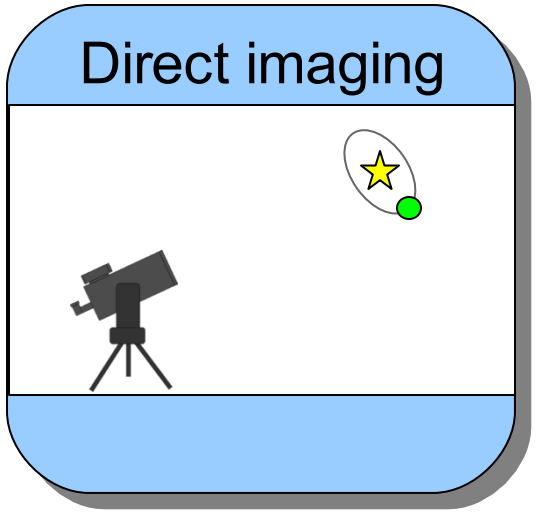


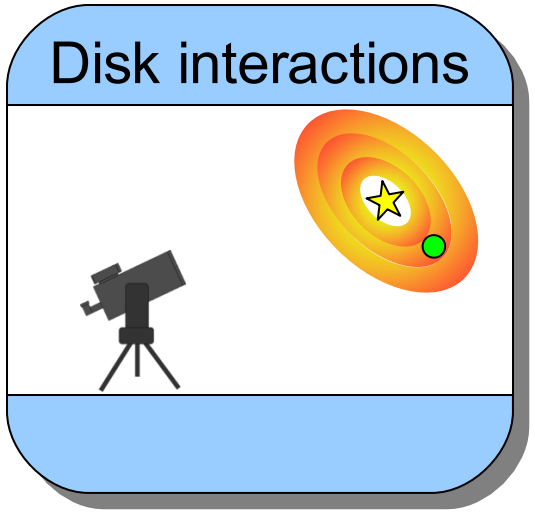






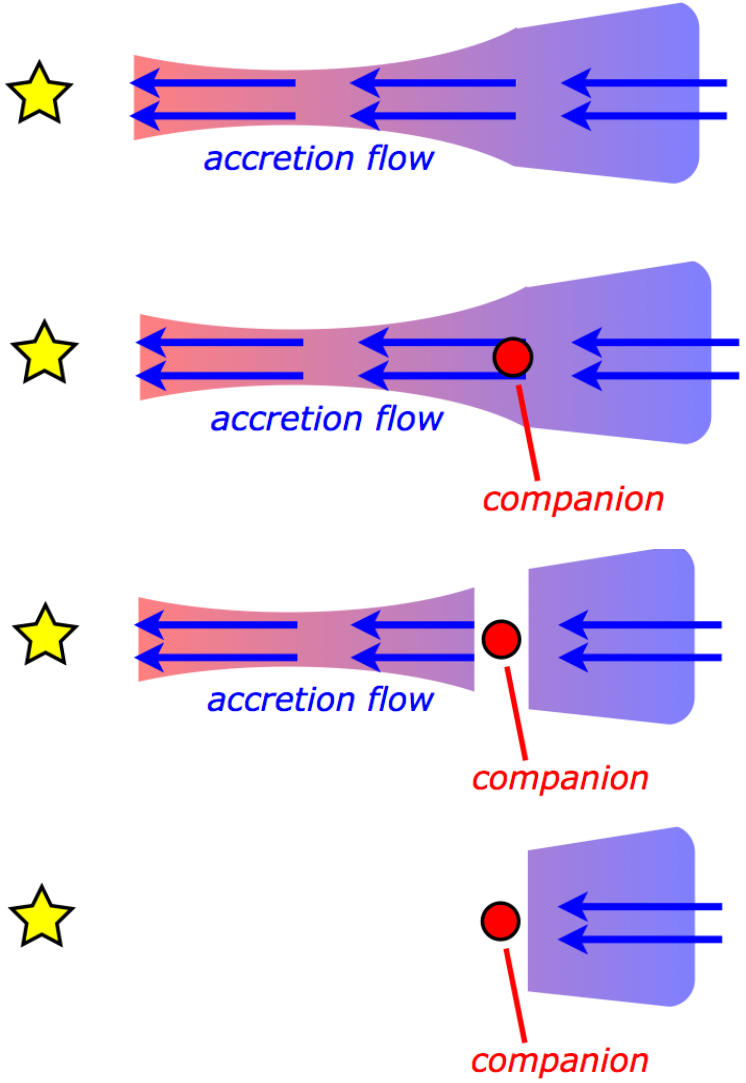


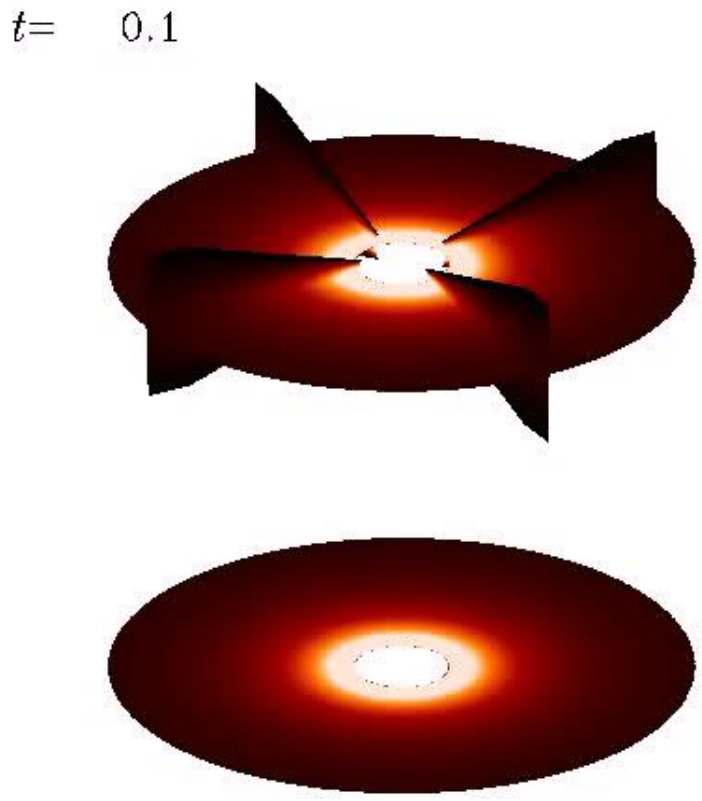




Slide by A. Richert

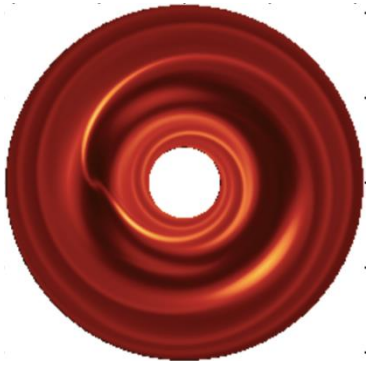
Planetary companion





(Lyra 2009)

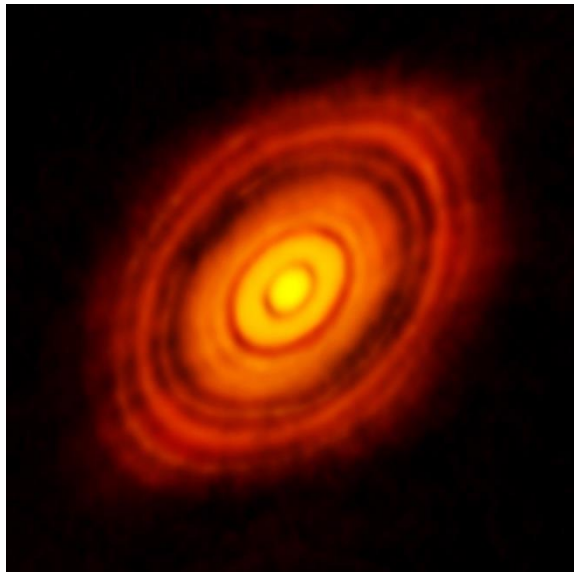
Planet-disk interaction: gaps, spirals, and vortices.



(Lyra et al. 2009b)

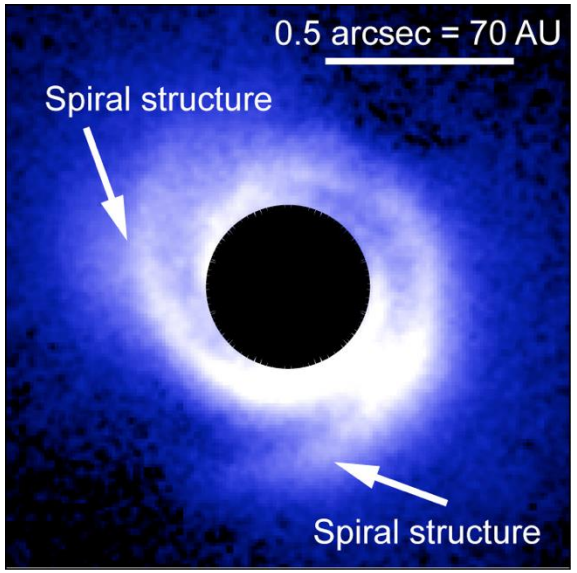
Observational evidence: gaps, spirals, and vortices

HL Tau



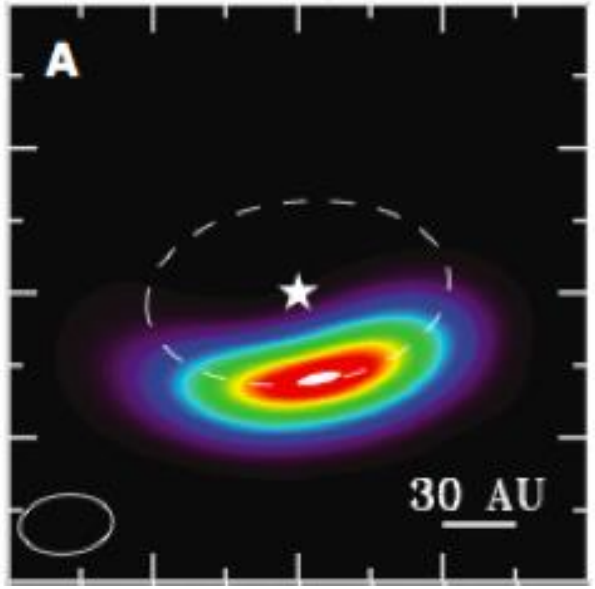
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

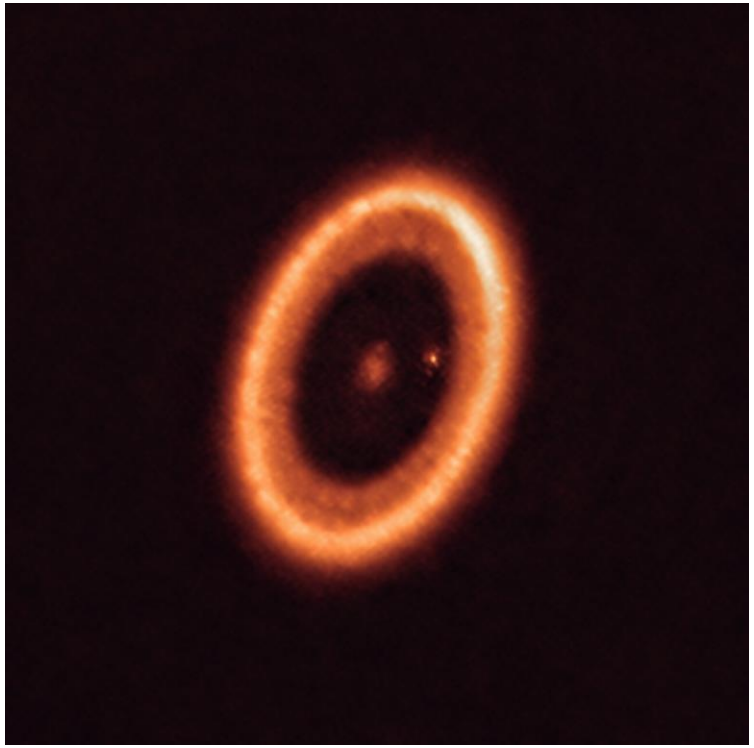
Oph IRS 48



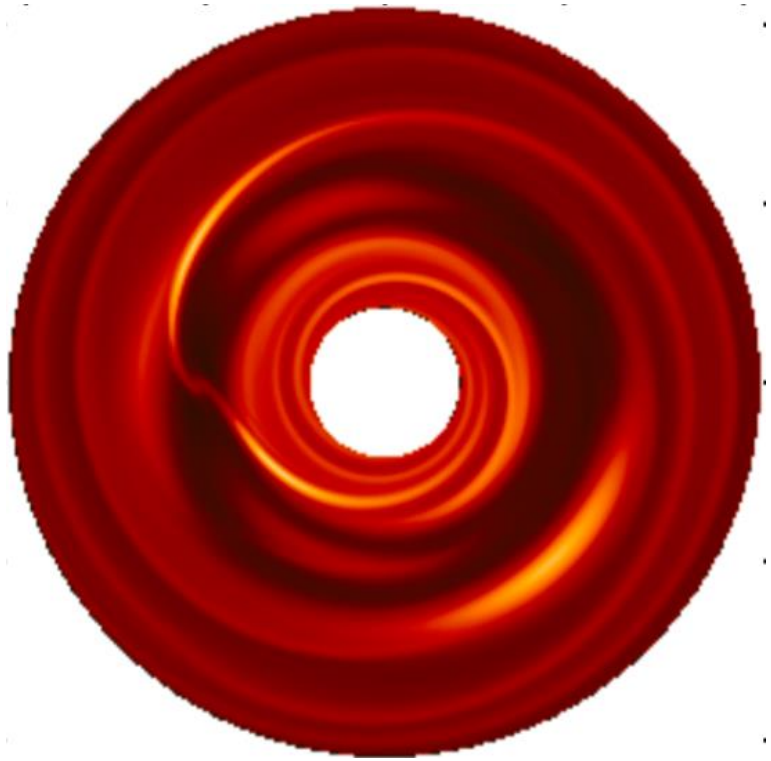
van der Marel et al. (2013)

These rings and cavities may be the telltale signature of forming planets

PDS 70 and PDS 70b



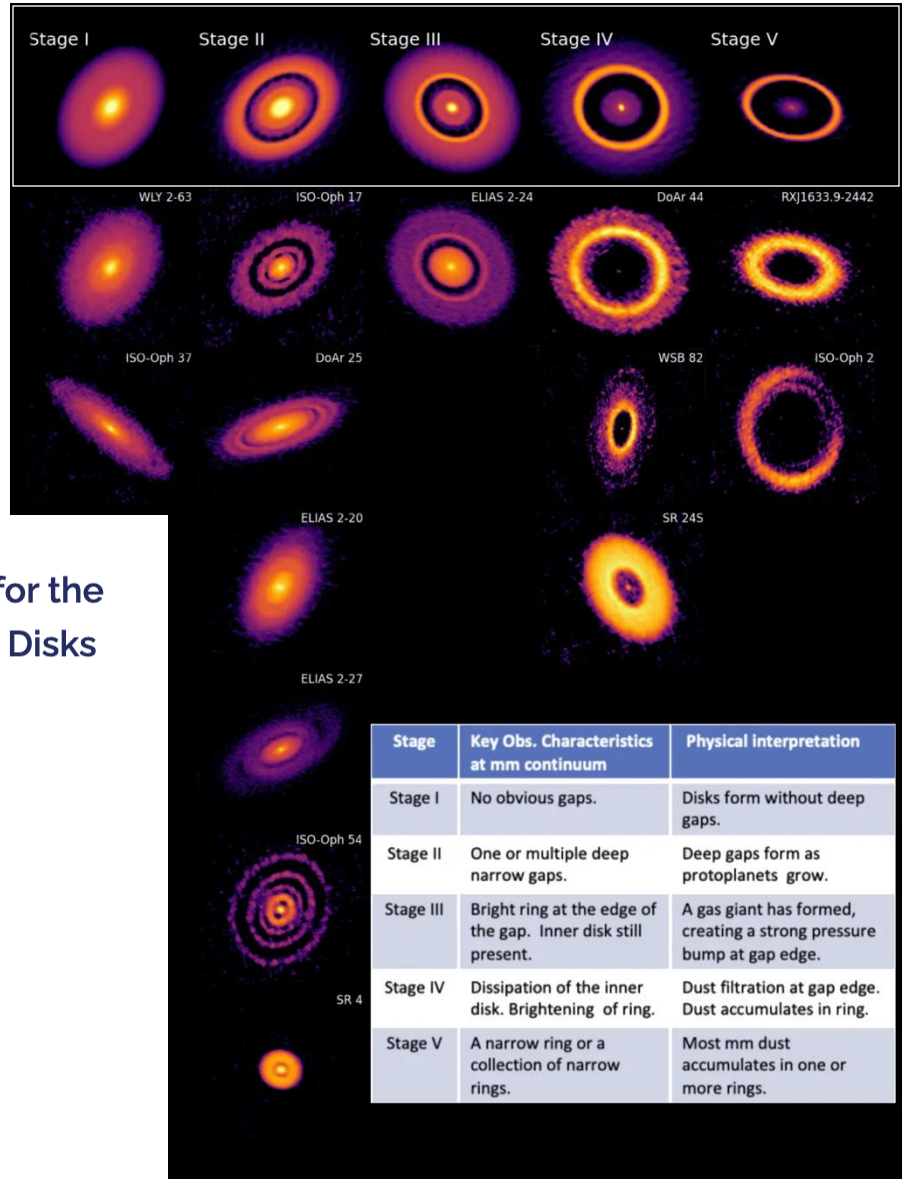
Keppler et al. (2018); Isella et al. (2019); Benisty et al. (2021)
Balsalobre-Ruza et al. (2023)



(Lyra et al. 2009b)

A way to directly study planet-disk interaction

Time series of planet formation?



Stage	Key Obs. Characteristics at mm continuum	Physical interpretation
Stage I	No obvious gaps.	Disks form without deep gaps.
Stage II	One or multiple deep narrow gaps.	Deep gaps form as protoplanets grow.
Stage III	Bright ring at the edge of the gap. Inner disk still present.	A gas giant has formed, creating a strong pressure bump at gap edge.
Stage IV	Dissipation of the inner disk. Brightening of ring.	Dust filtration at gap edge. Dust accumulates in ring.
Stage V	A narrow ring or a collection of narrow rings.	Most mm dust accumulates in one or more rings.

Press Releases

ALMA Inspires New Models for the Evolution of Planet-Forming Disks

6 May, 2025 / Read time: **7 minutes**

Orcajo et al. (2025)

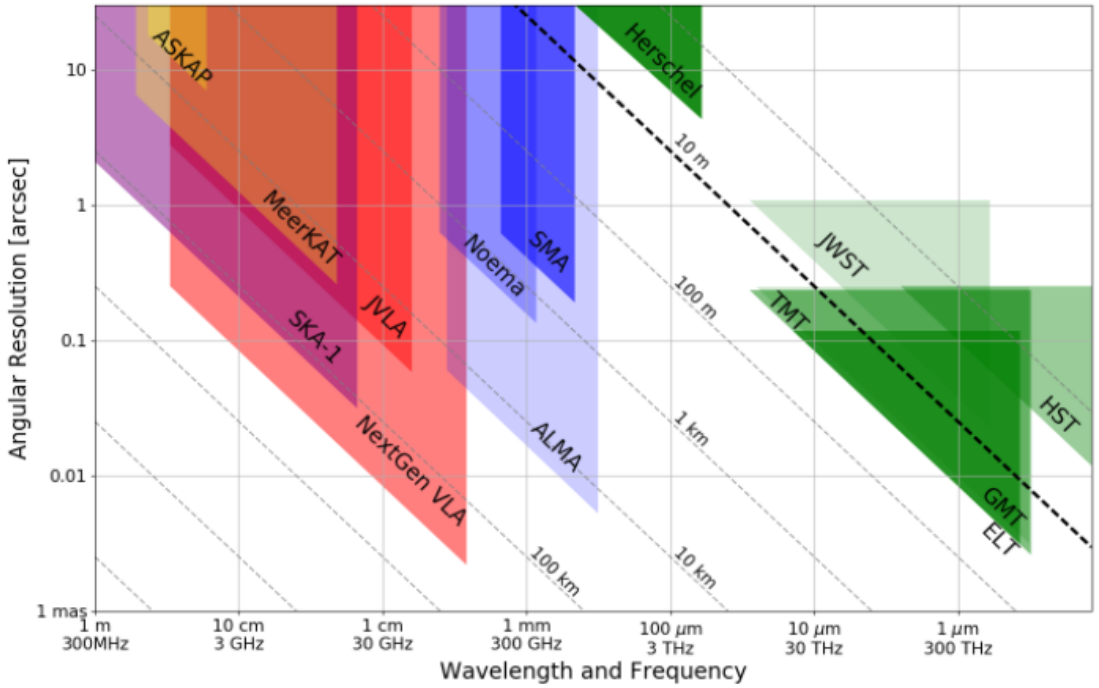
The future

After nearly 15 years of ALMA…

Nearly all nearby disks observed at <0.1” (< 20-30AU) show substructures.

3 main types of substructures
- Crescent-shaped
- Spiral arms
- Rings/Gaps

Next Generation Very Large Array (ngVLA)

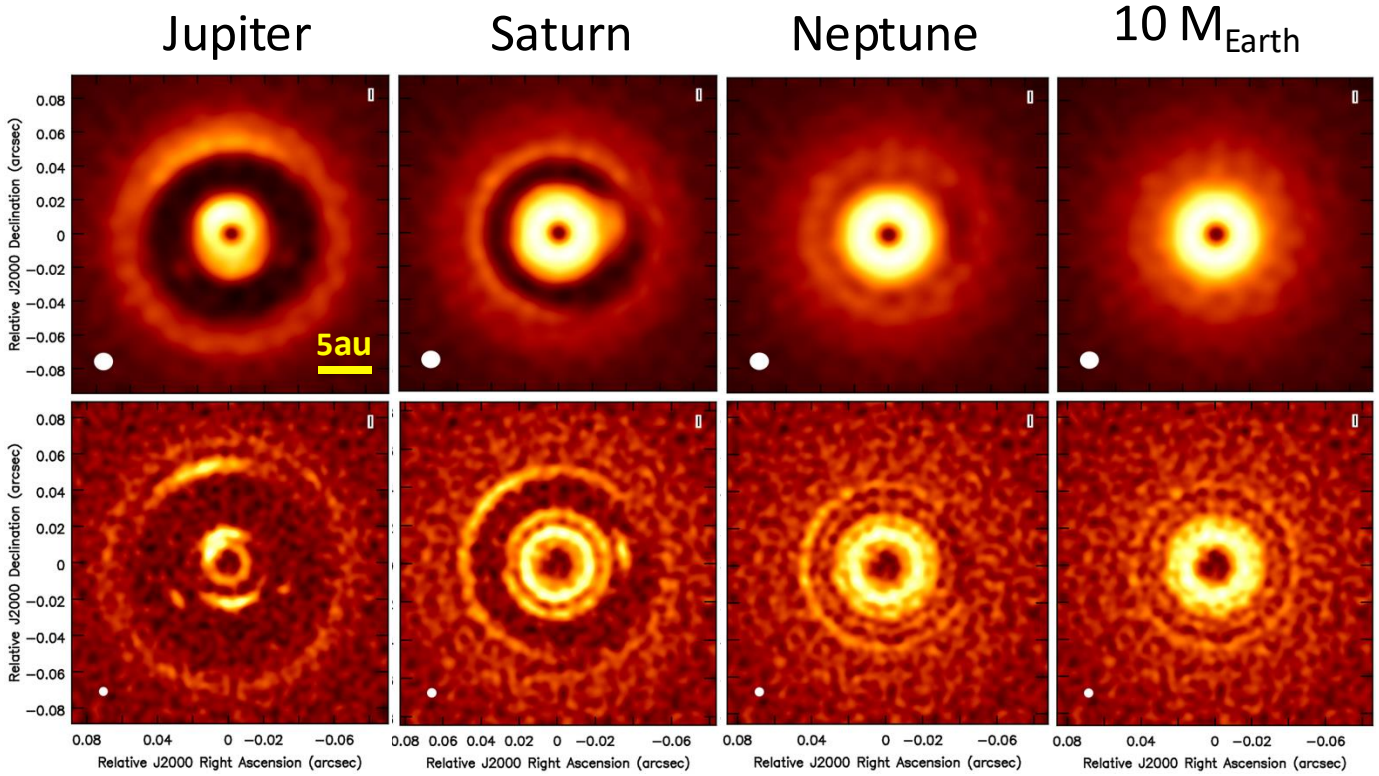


Planets at 5AU

ALMA @ 0.87mm

ngVLA @ 3mm

5 mas = 0.7 AU
rms = 5×10^{-7} Jy/beam

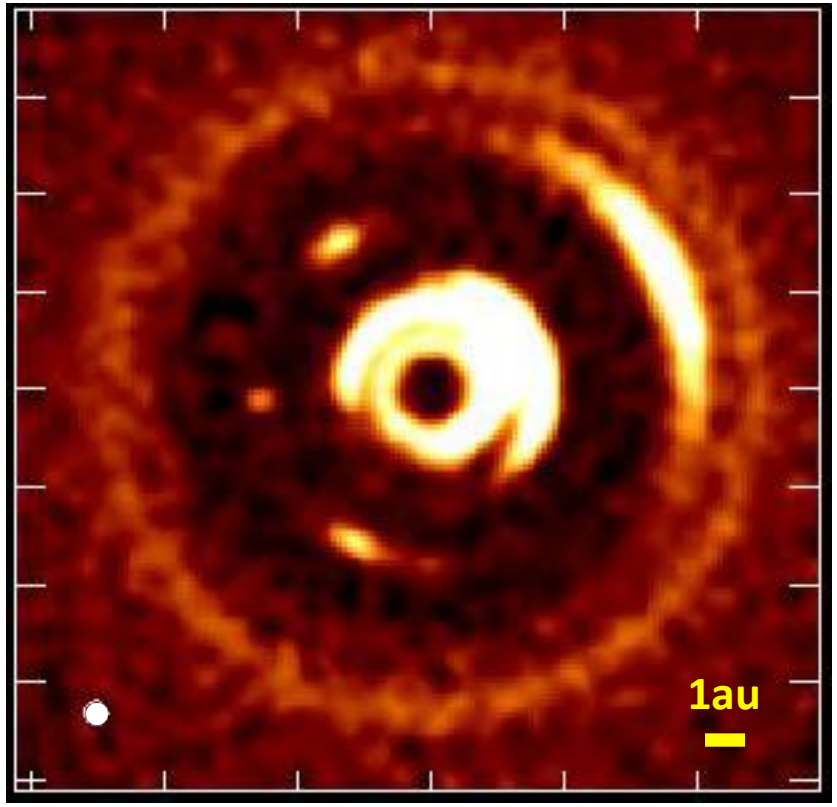


Ricci et al. 2018

ngVLA identifies gaps/substructures down to ~5-10 M_{Earth}

ngVLA: Proper motions

Jupiter at 5 AU



Ricci et al. 2018