Dynamical Instabilities in the Aid of Planet Formation in Circumstellar Disks

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XRP – 2018

Computational Facilities

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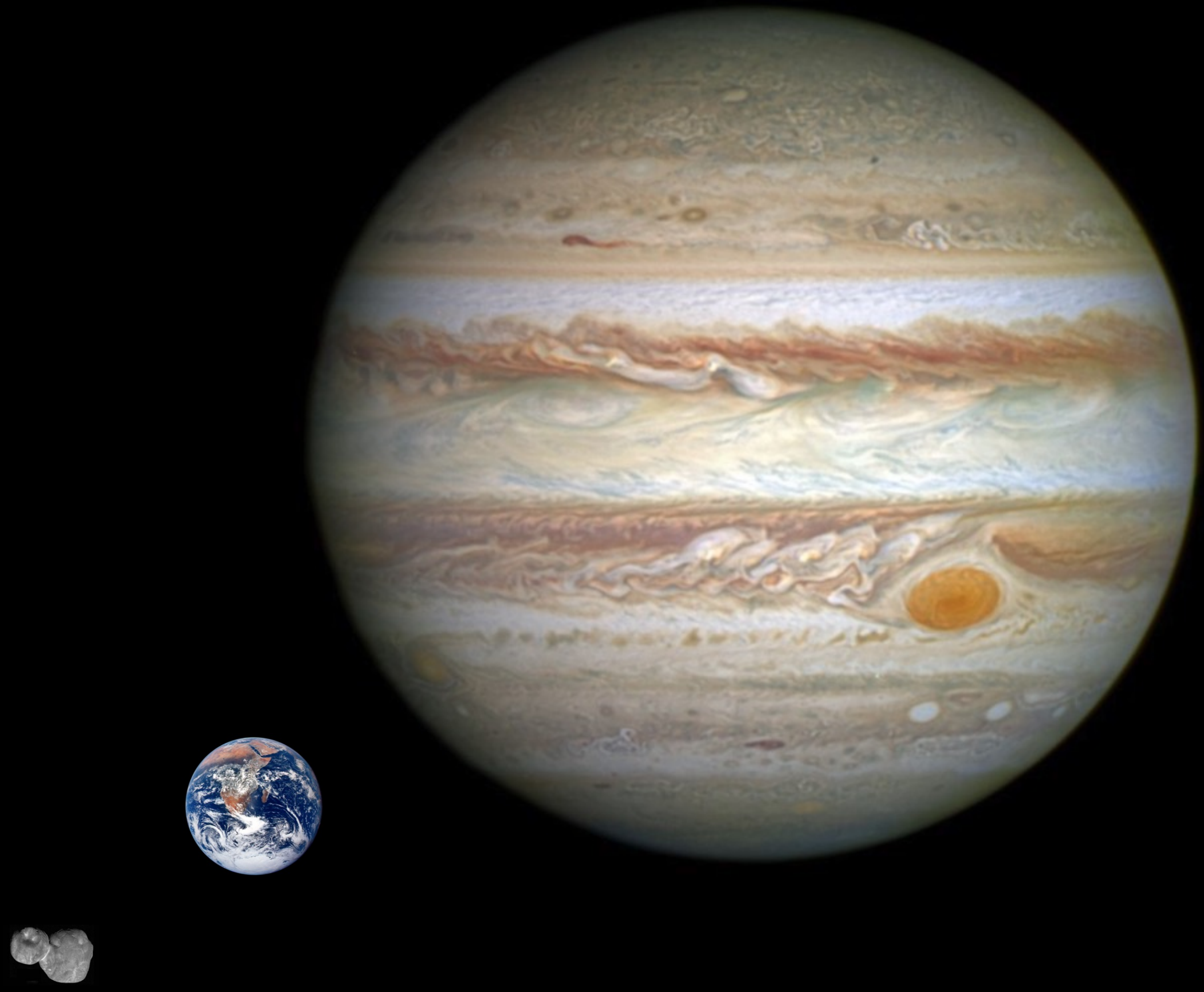
Outline

- Planet Formation
- Disk Instabilities
- Disk observations

Planet Formation



Circumstellar/Protoplanetary Disks

PP disk fact sheet

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

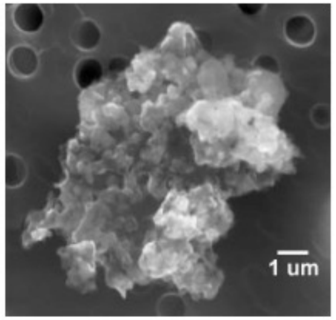
Temperature: 10-1000 K

Scale: 0.1-100AU

Mass: $10^{-3} – 10^{-1}$ M_{sun}

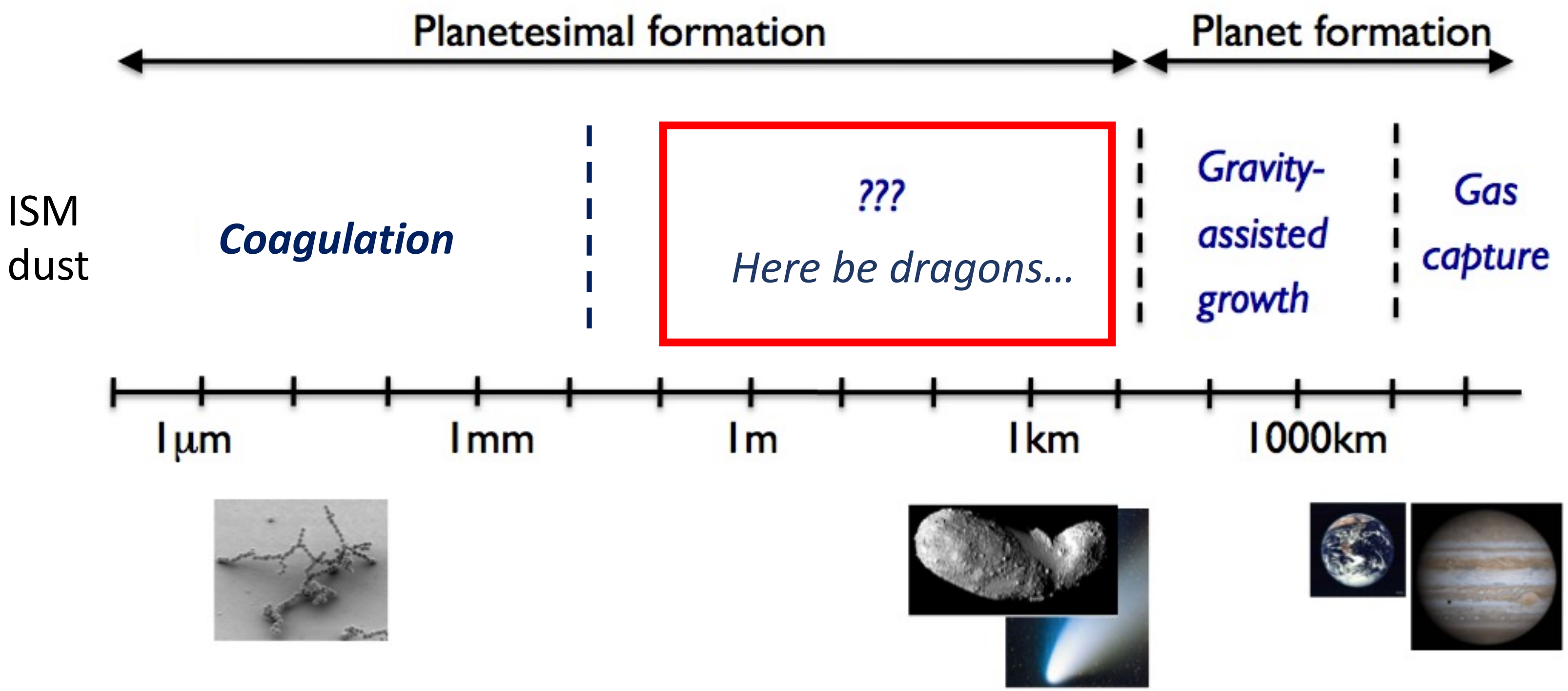
Planet Formation

"Planets form in disks of gas and dust"

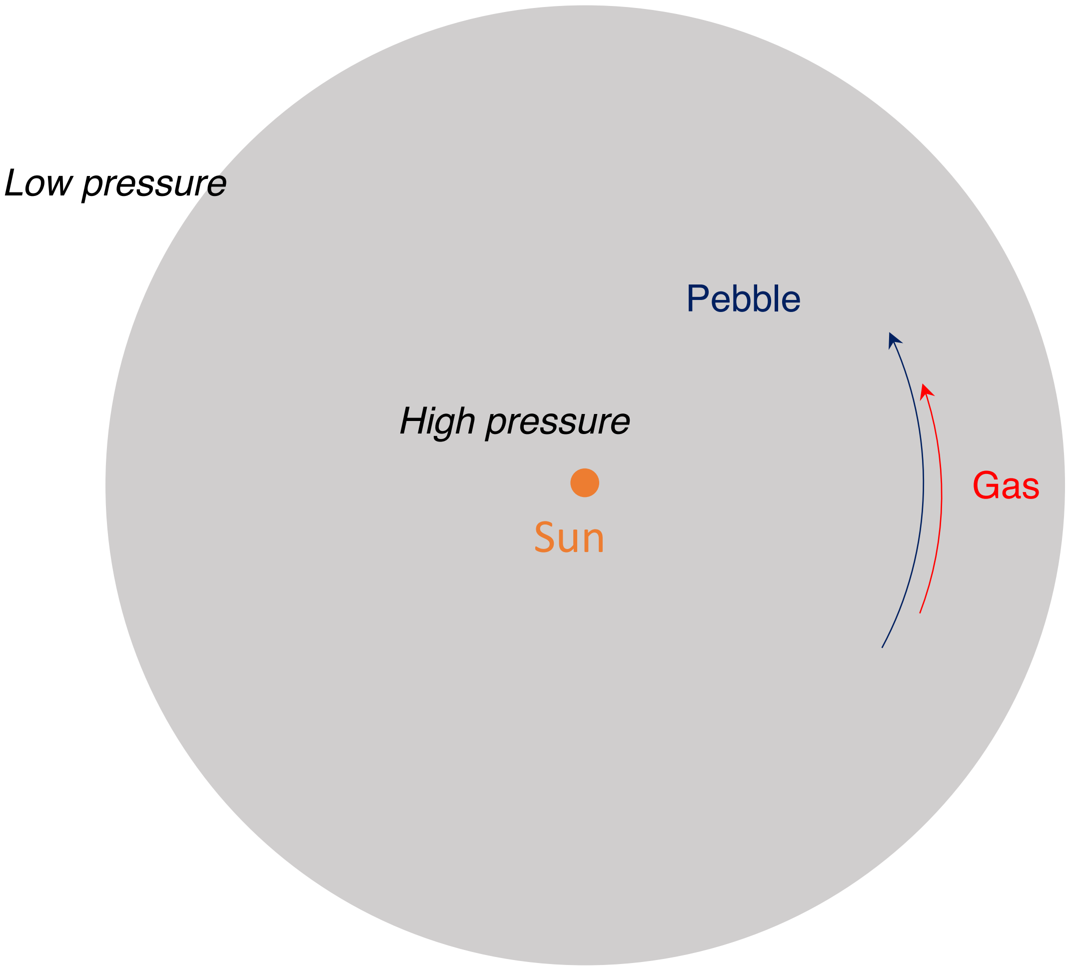


A miracle happens

Dust evolution



Headwind and Dust Drift

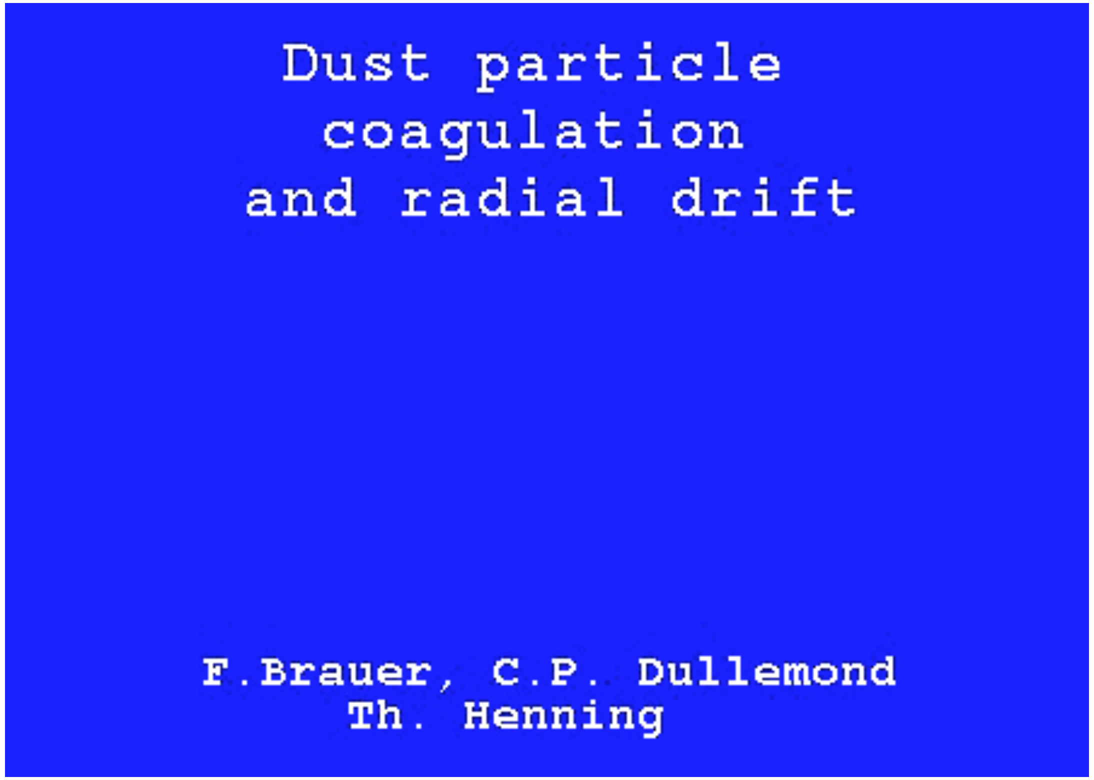


The gas has some pressure support (sub-Keplerian).

The pebbles do not feel gas pressure (Keplerian).

Dust coagulation and drift

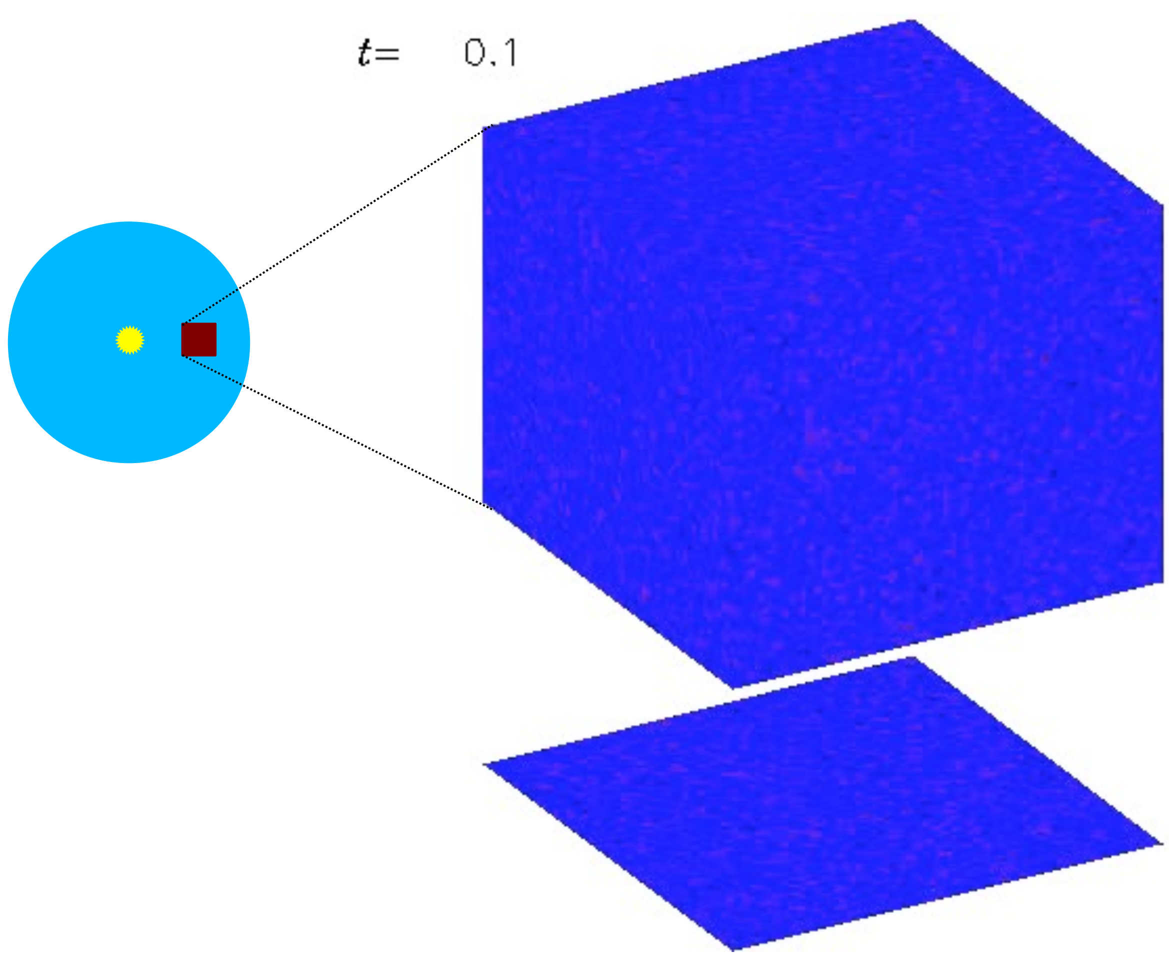
- Grains grow and start drifting inward (white line is the line of maximum drift)
- If that was the whole picture, planets should not exist, as all dust is lost to the star
- Either planets form very fast, or something must be at work to retain the dust

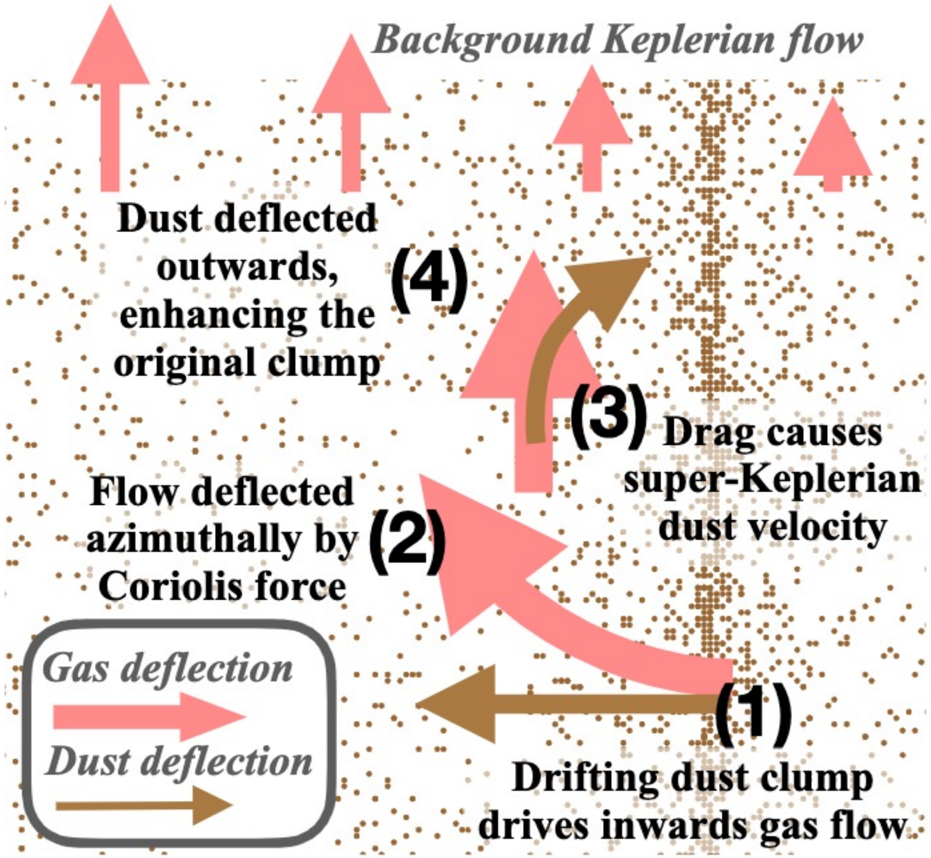


Brauer et al. (2008)

Streaming Instability

The dust drift is hydrodynamically unstable

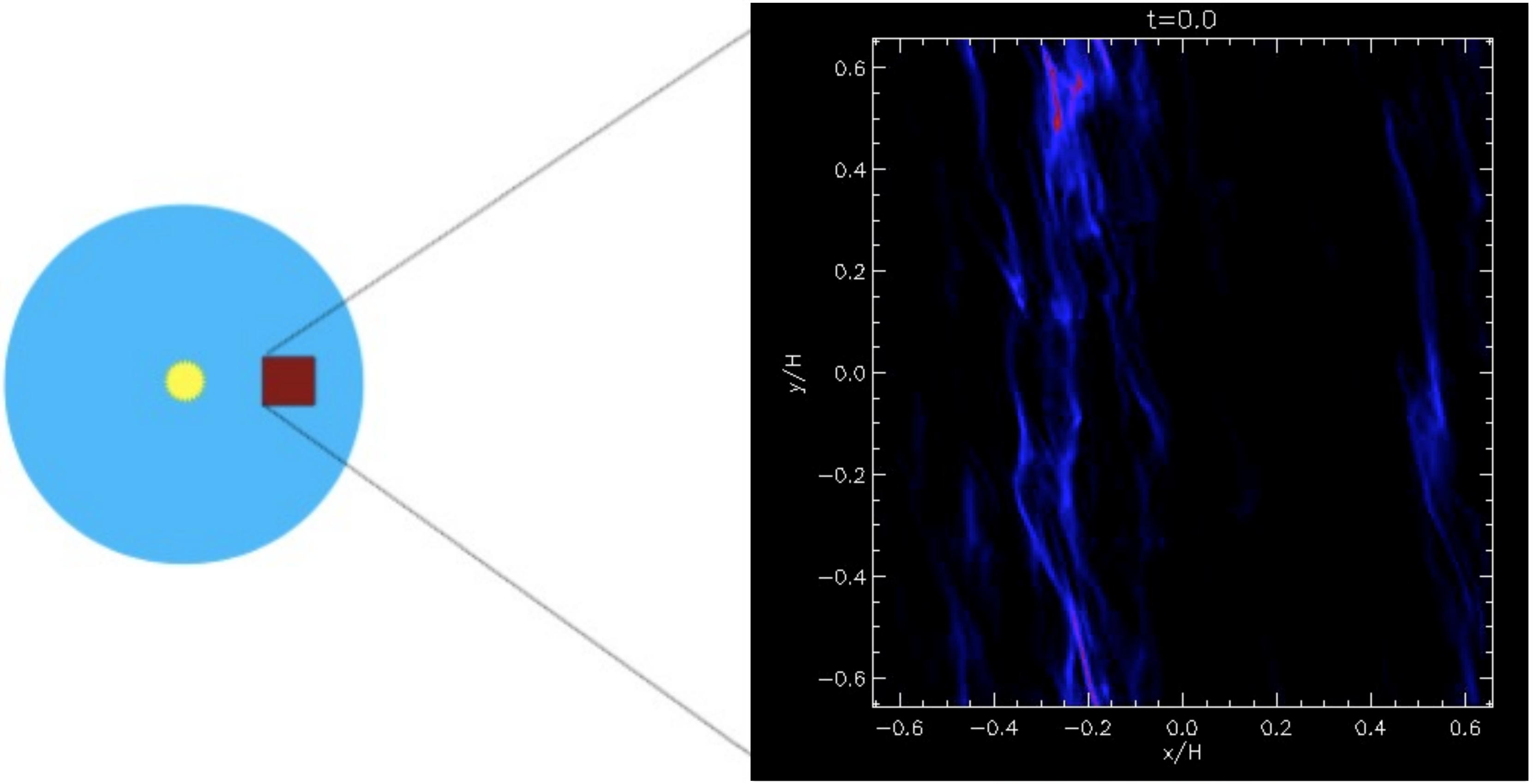




Lesur et al. (2022)

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

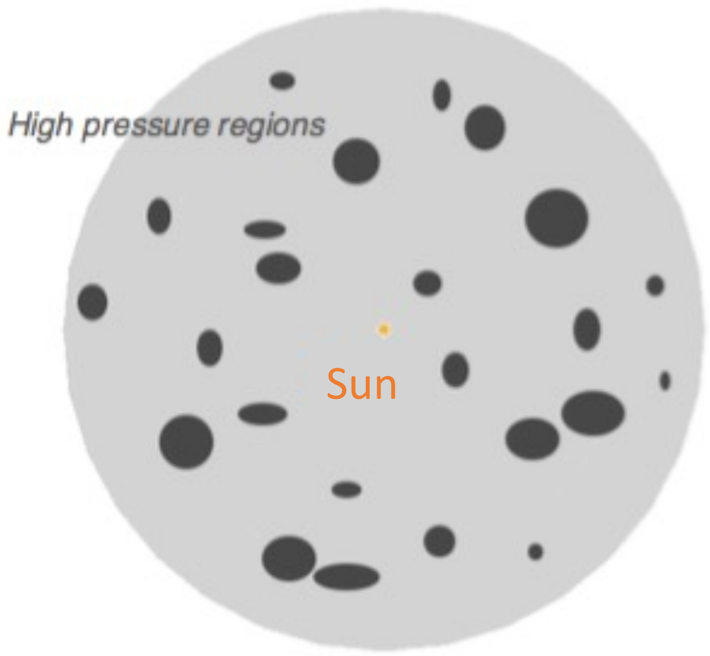
Gravitational collapse into planetesimals

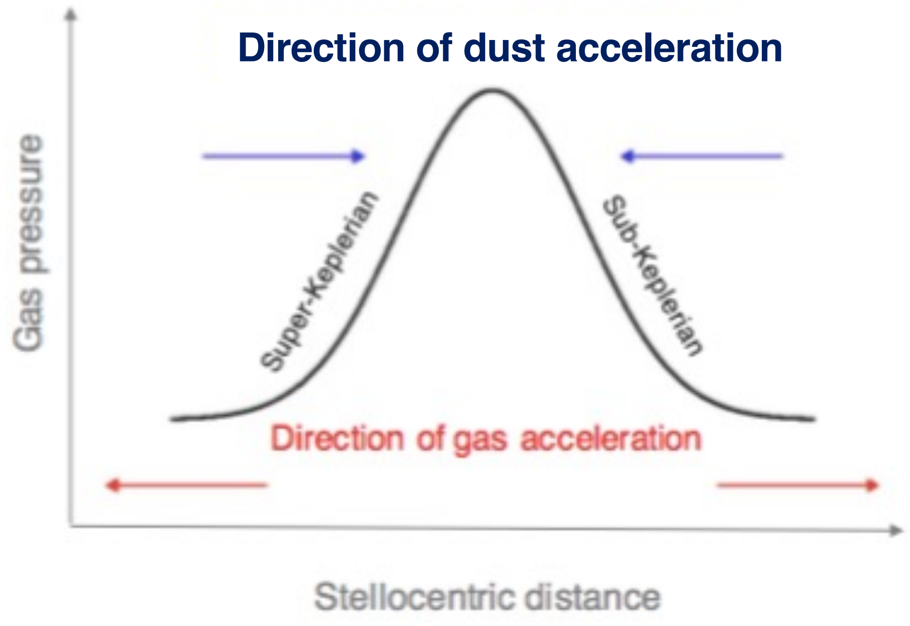


Johansen et al. (2007)

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

Turbulence

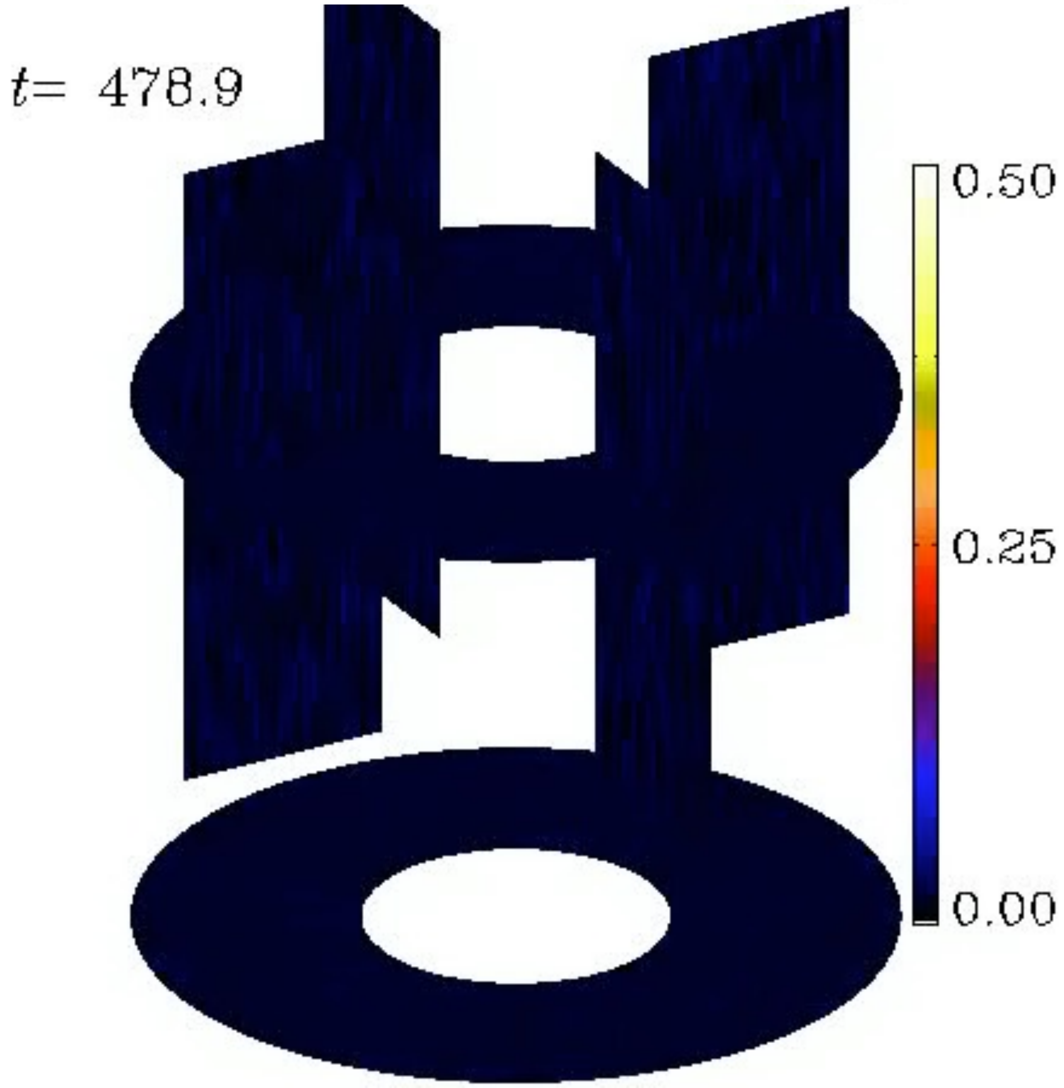




- Grains more toward high pressure
- High pressure regions behave like excellent dust traps
- Turbulence is a way to generate numerous transient high pressure regions

Turbulence concentrates solids mechanically in pressure maxima

- MRI-active disk.
- Grains more toward high pressure
- High pressure regions behave like excellent dust traps
- Turbulence is a way to generate numerous transient high pressure regions
- Bright areas are saturated with dust grains

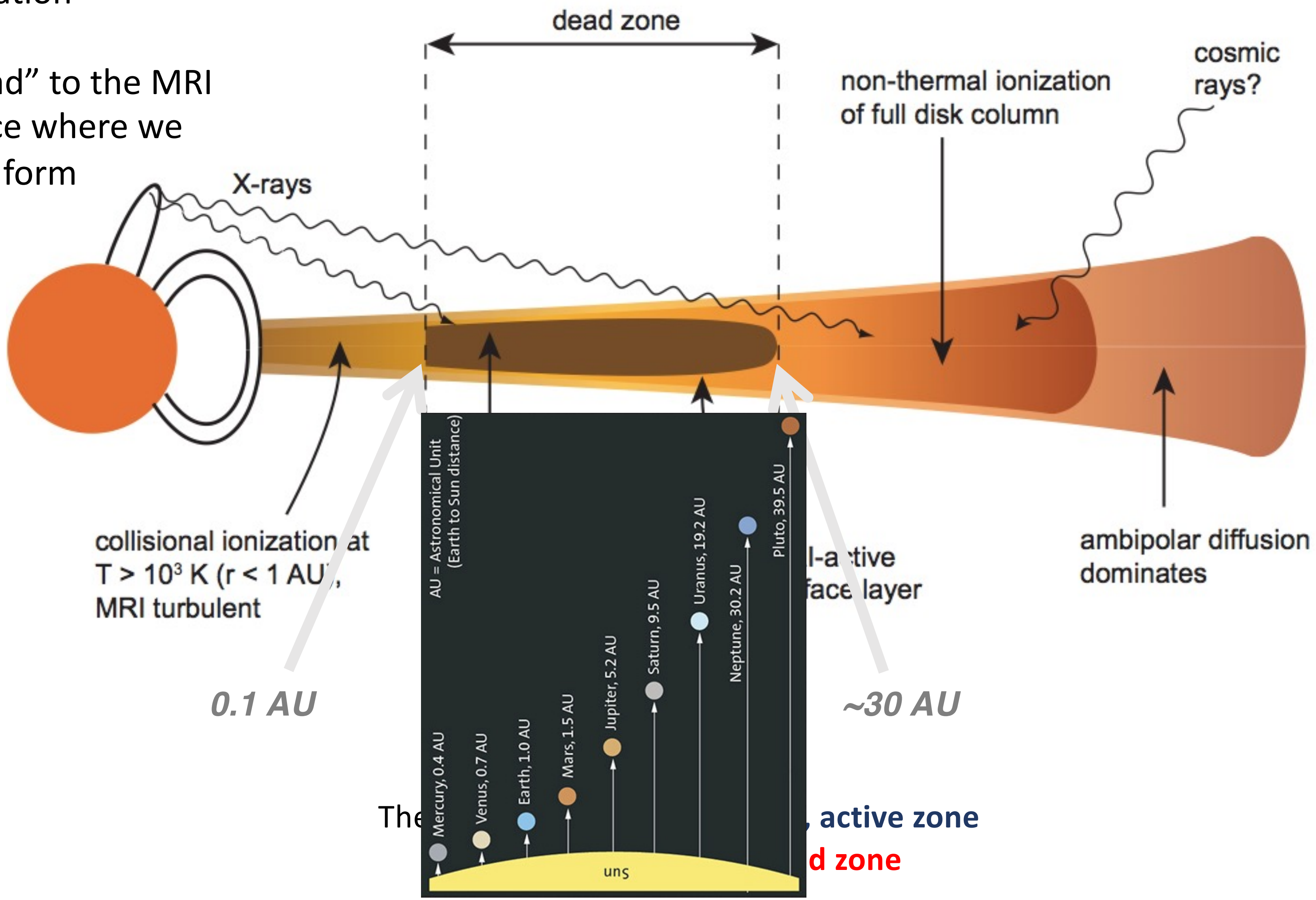


Lyra et al. (2008a)

- MRI is problematic in protoplanetary disks because
  - These disks are cold
  - Lack of ionization

- Huge swaths “dead” to the MRI
- No MRI turbulence where we expect planets to form

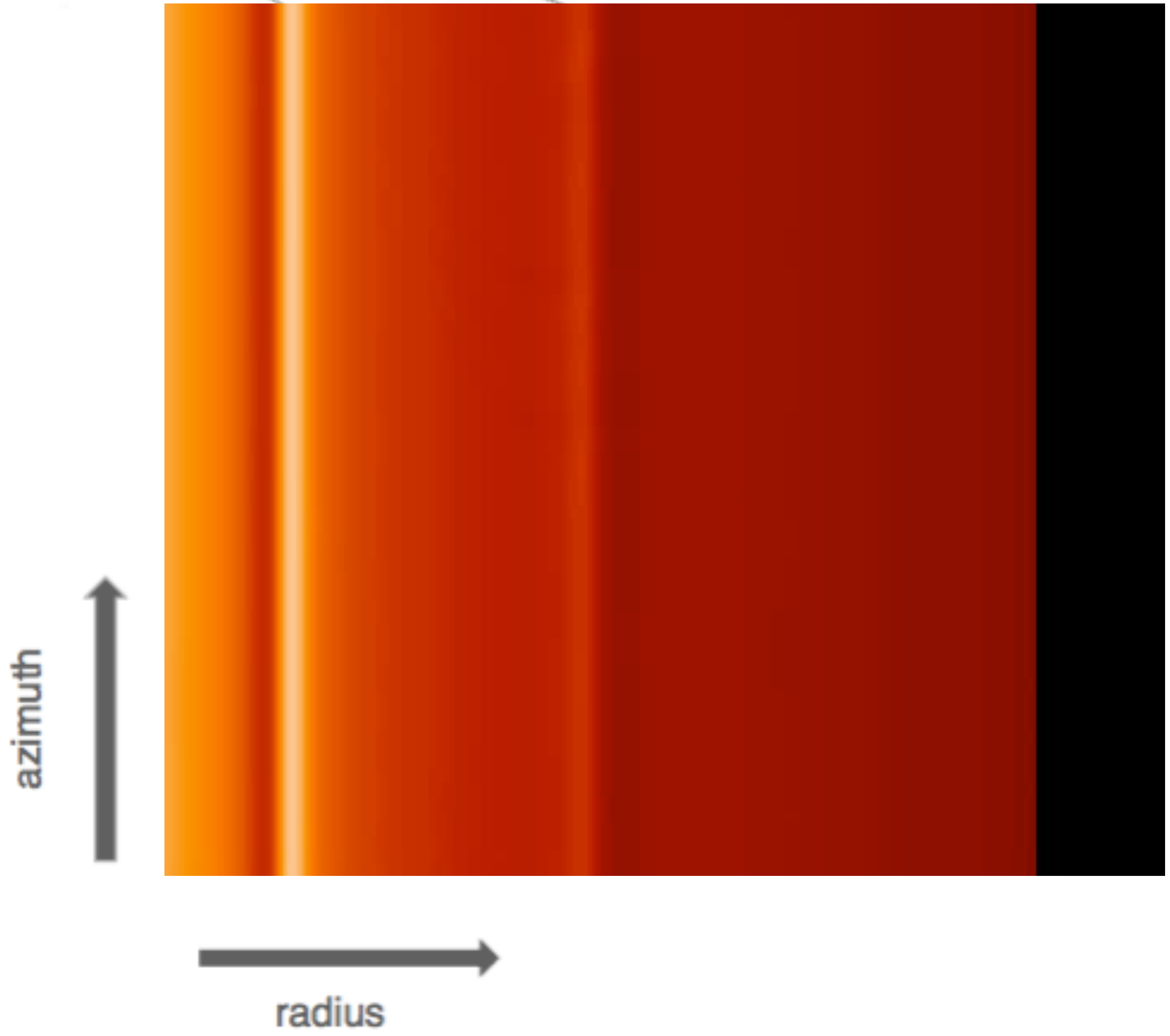
Dead zones



The **, active zone**

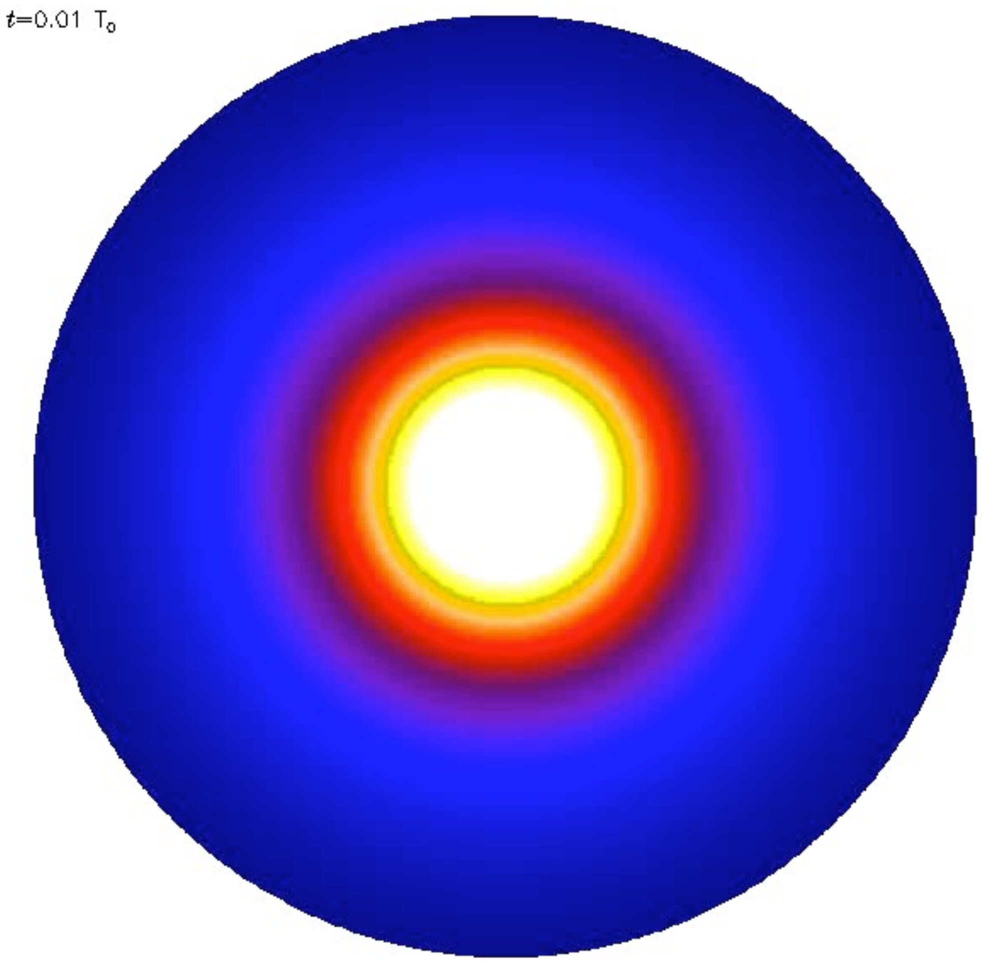
d zone

A simple dead zone model



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



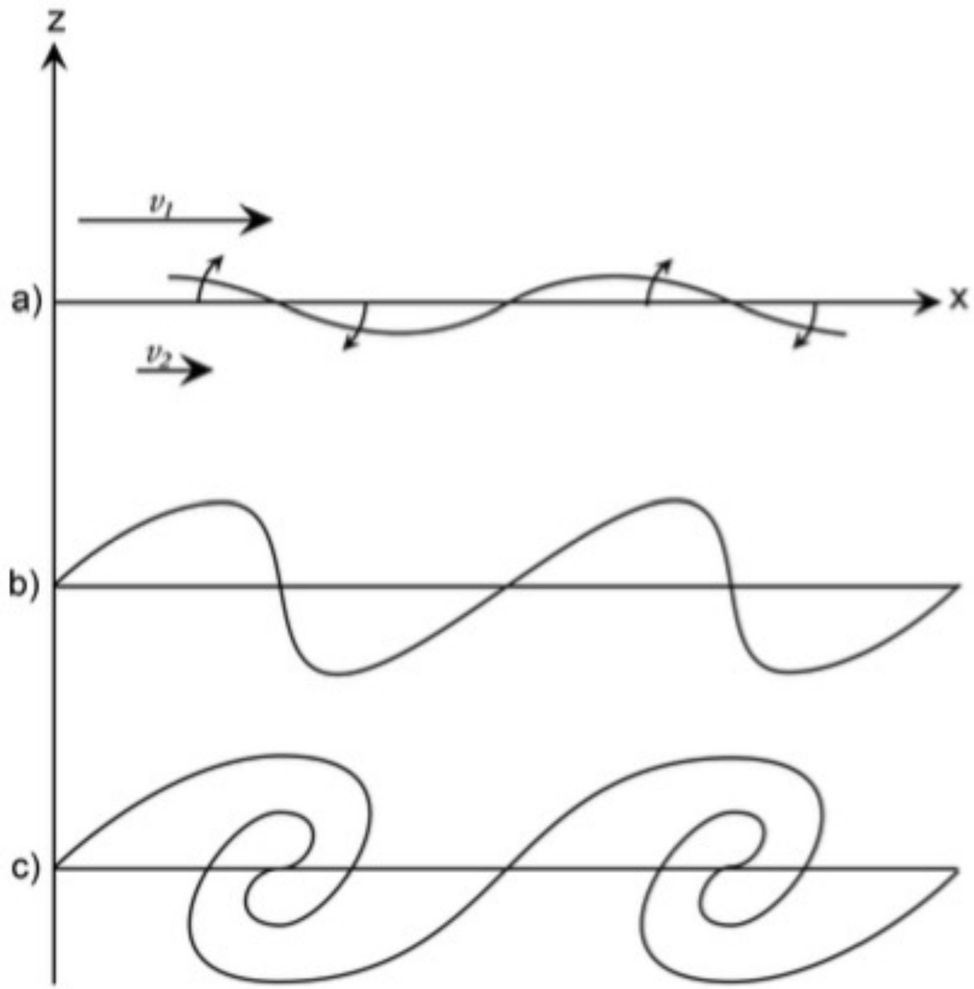
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

- The boundary between the MRI-active and MRI-dead zones is a location or vortex formation via Rossby wave instability

- The Rossby wave instability is a form of the Kelvin-Helmholtz instability

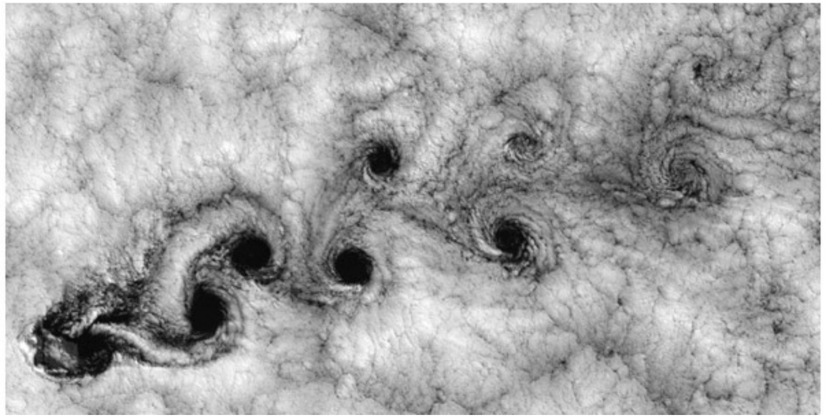
Rossby wave instability
(Kelvin-Helmholtz Instability in rotating disks)



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

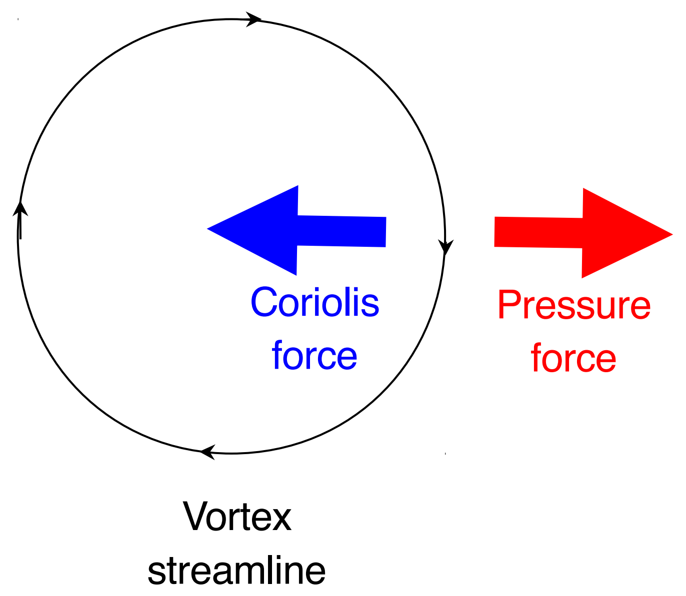
Vortices – an ubiquitous fluid mechanics phenomenon

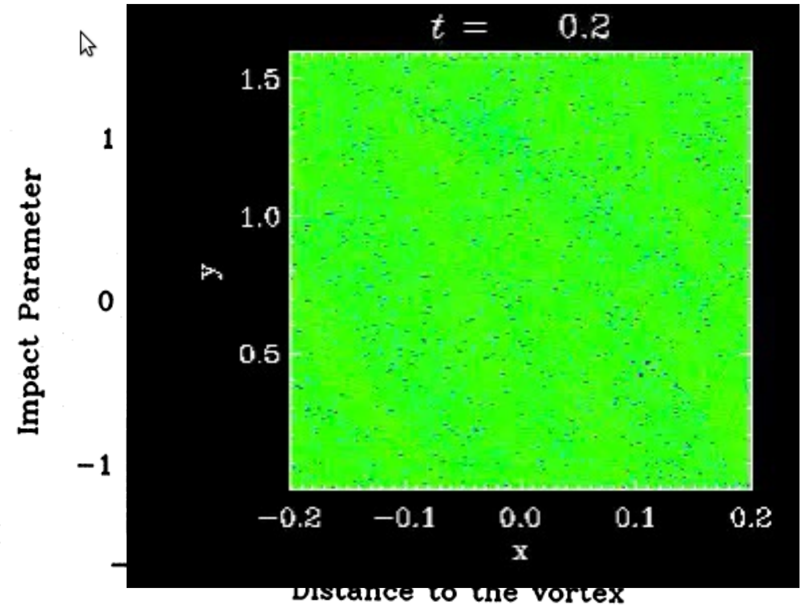
Von Kármán *vortex street*



Vortex Trapping

Geostrophic balance:





Barge & Sommeria (1995)

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

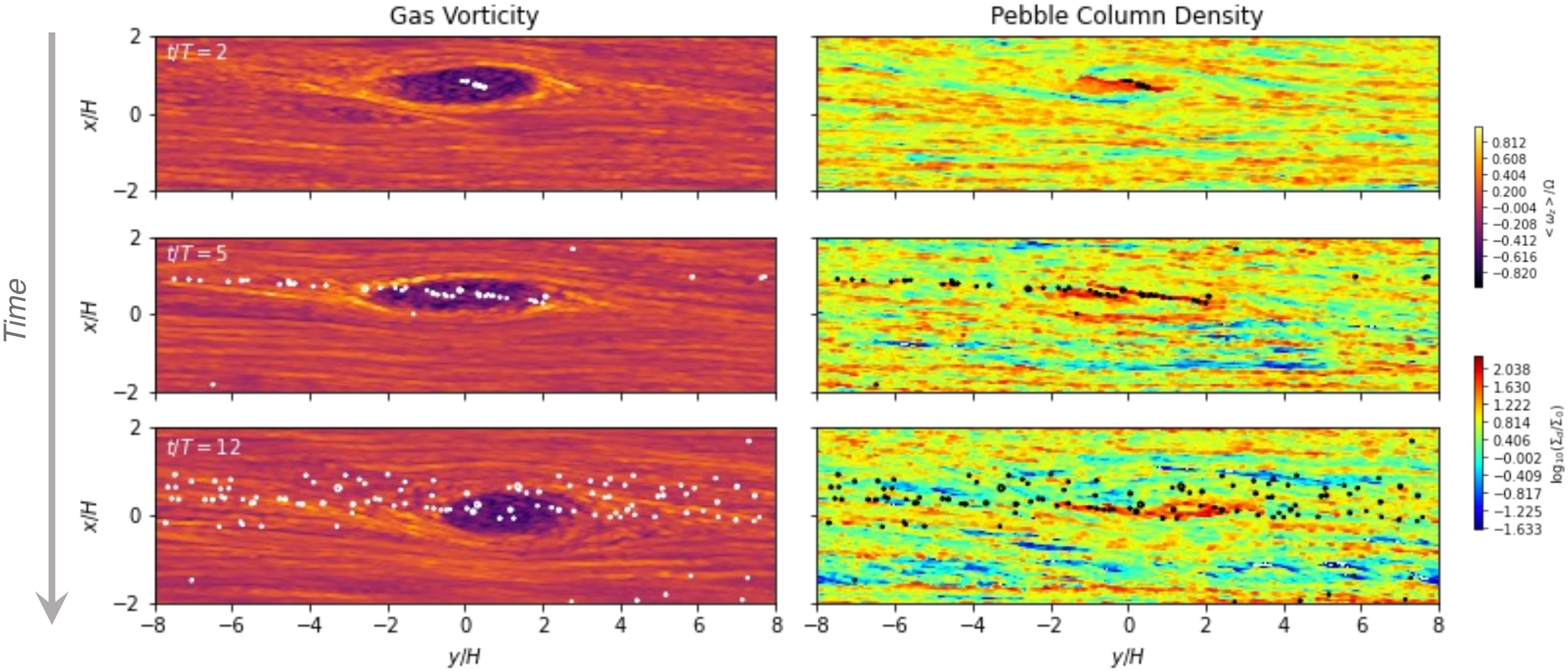
Aid to planet formation

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

Speeds up planet formation enormously

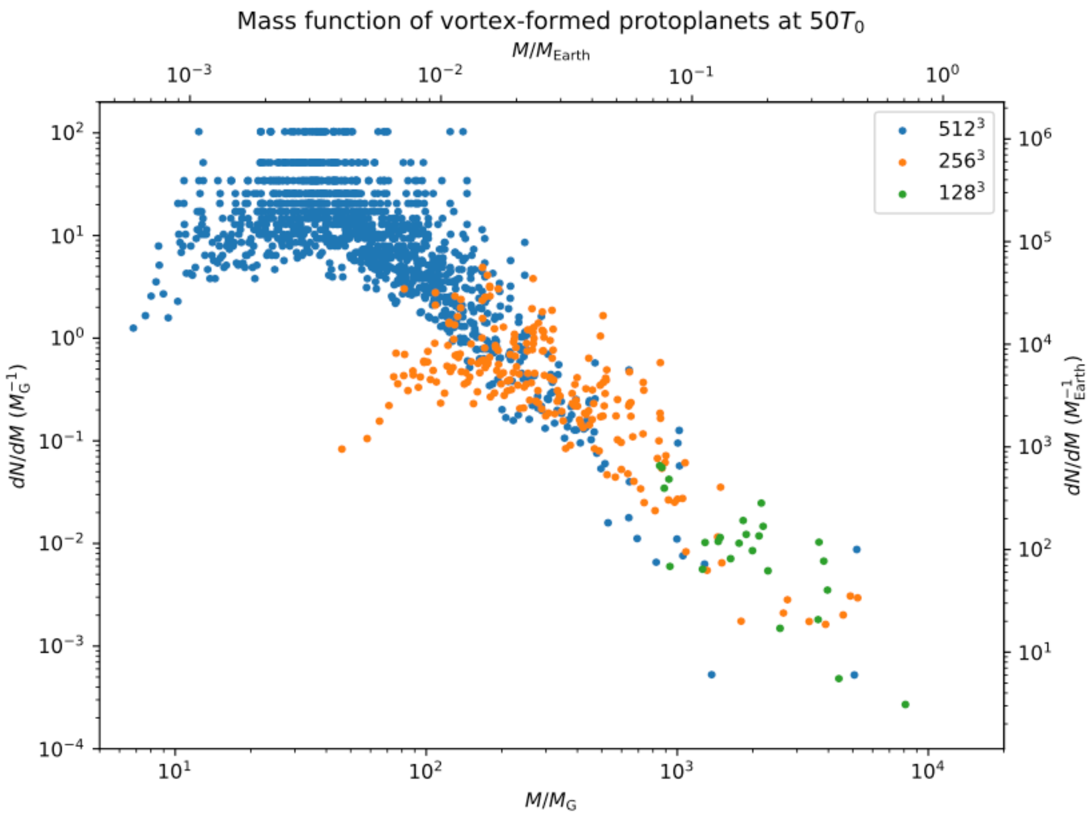
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012, 2021)

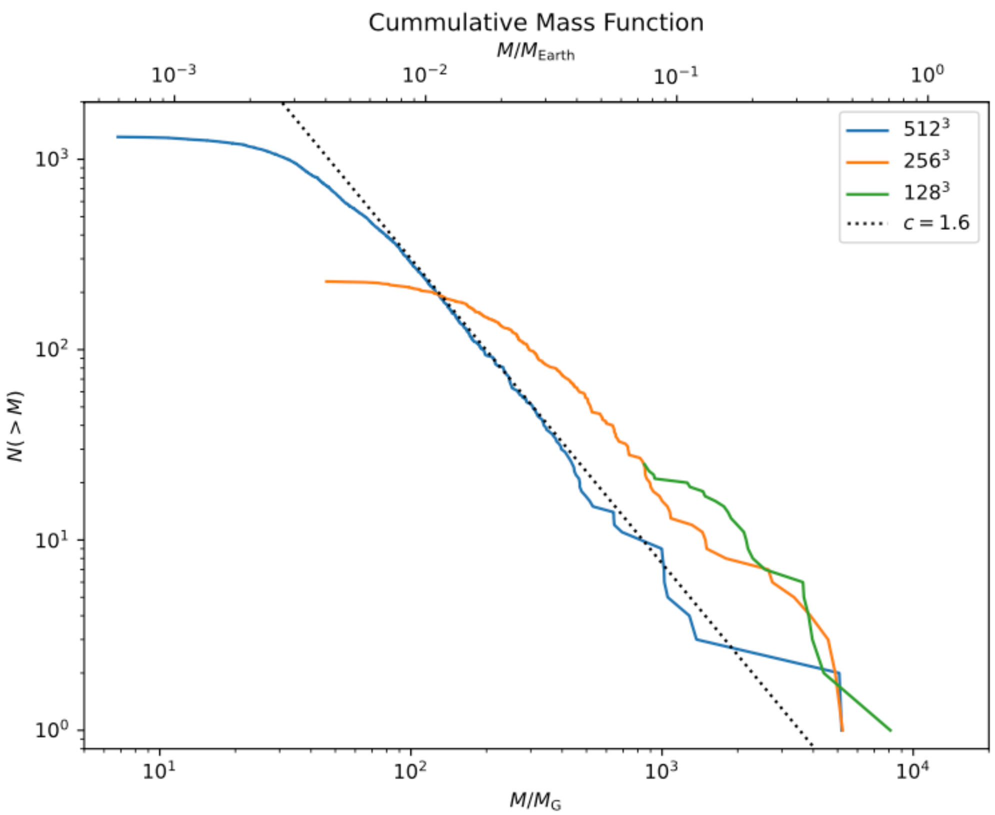
Vortex Trapping



Lyra et al. (in prep)

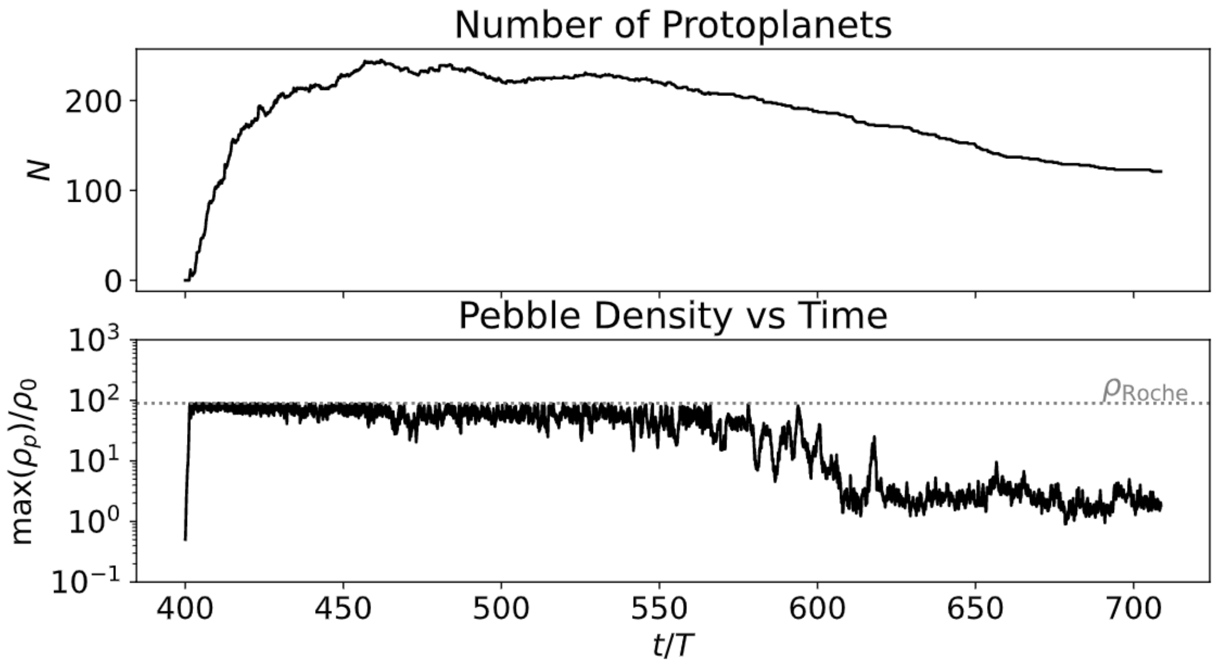
Vortex Trapping – Initial Mass Function

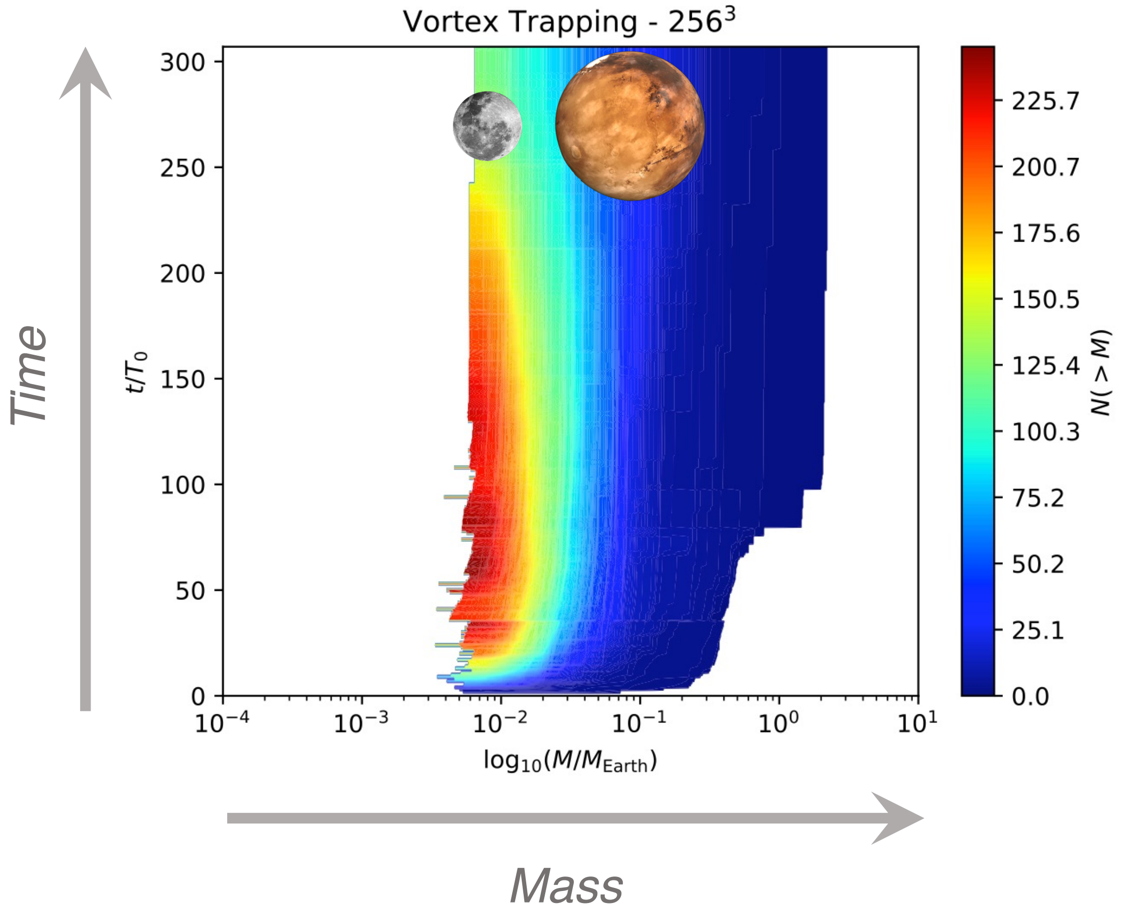




Lyra et al. (in prep)

Initial Mass Function – Convergence



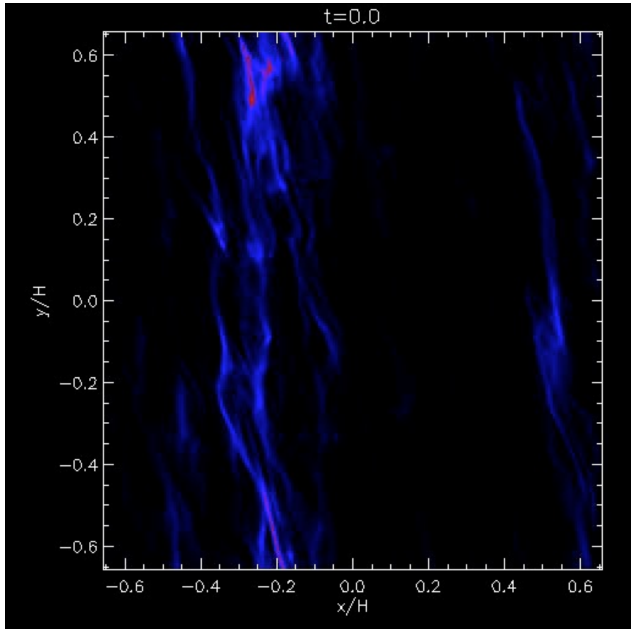


Lyra et al. (in prep)

Take home message

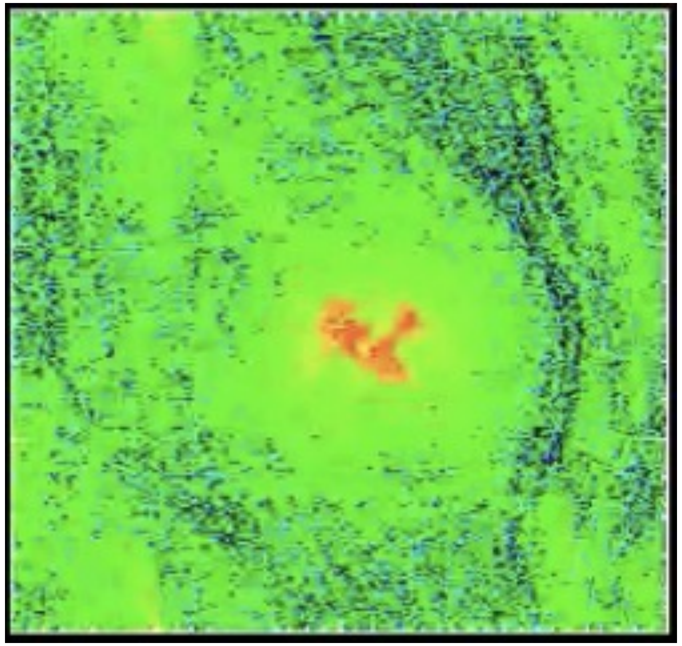
- Two routes for planet formation

Streaming Instability



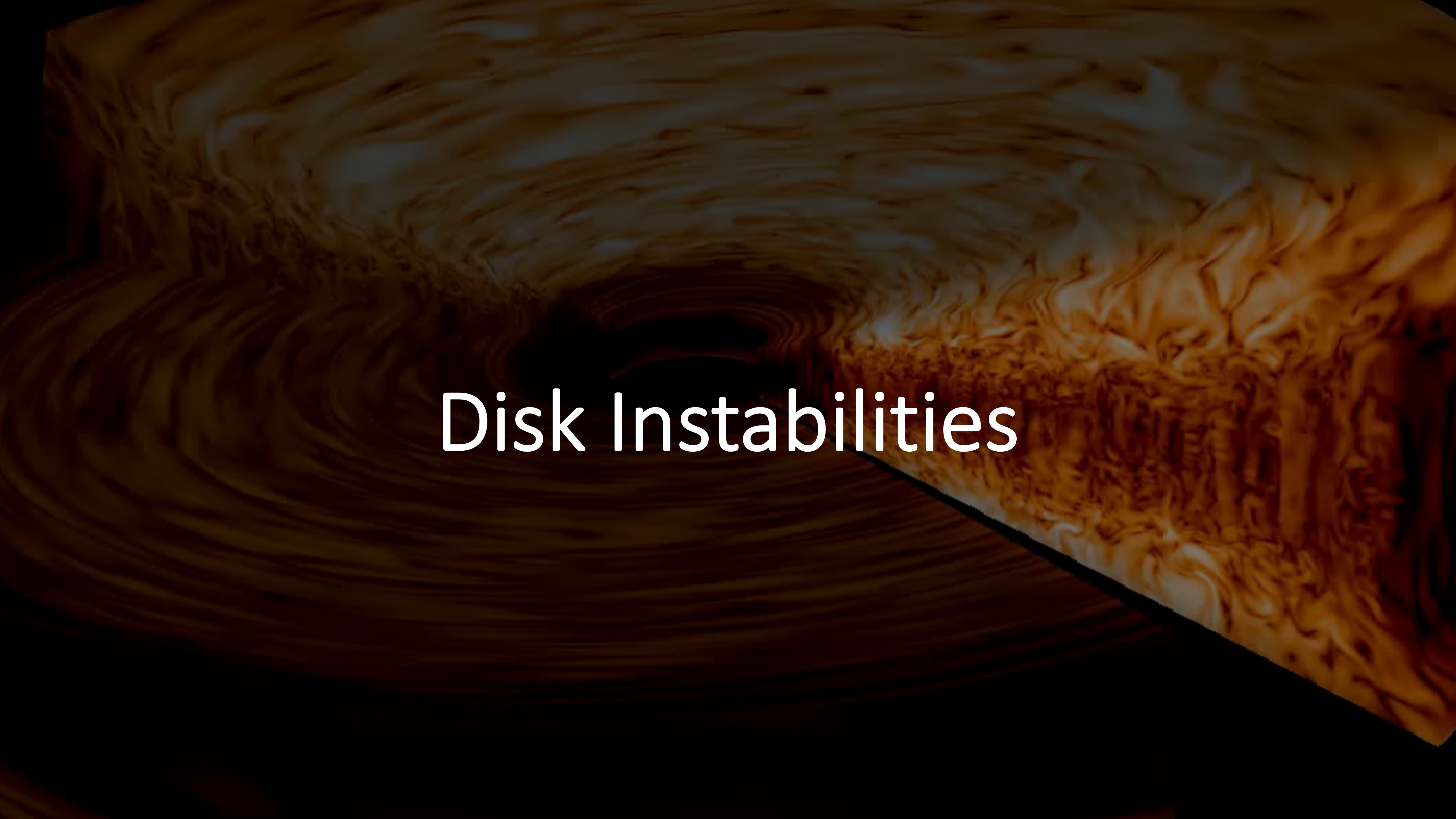
Johansen+ 07

Vortex Trapping



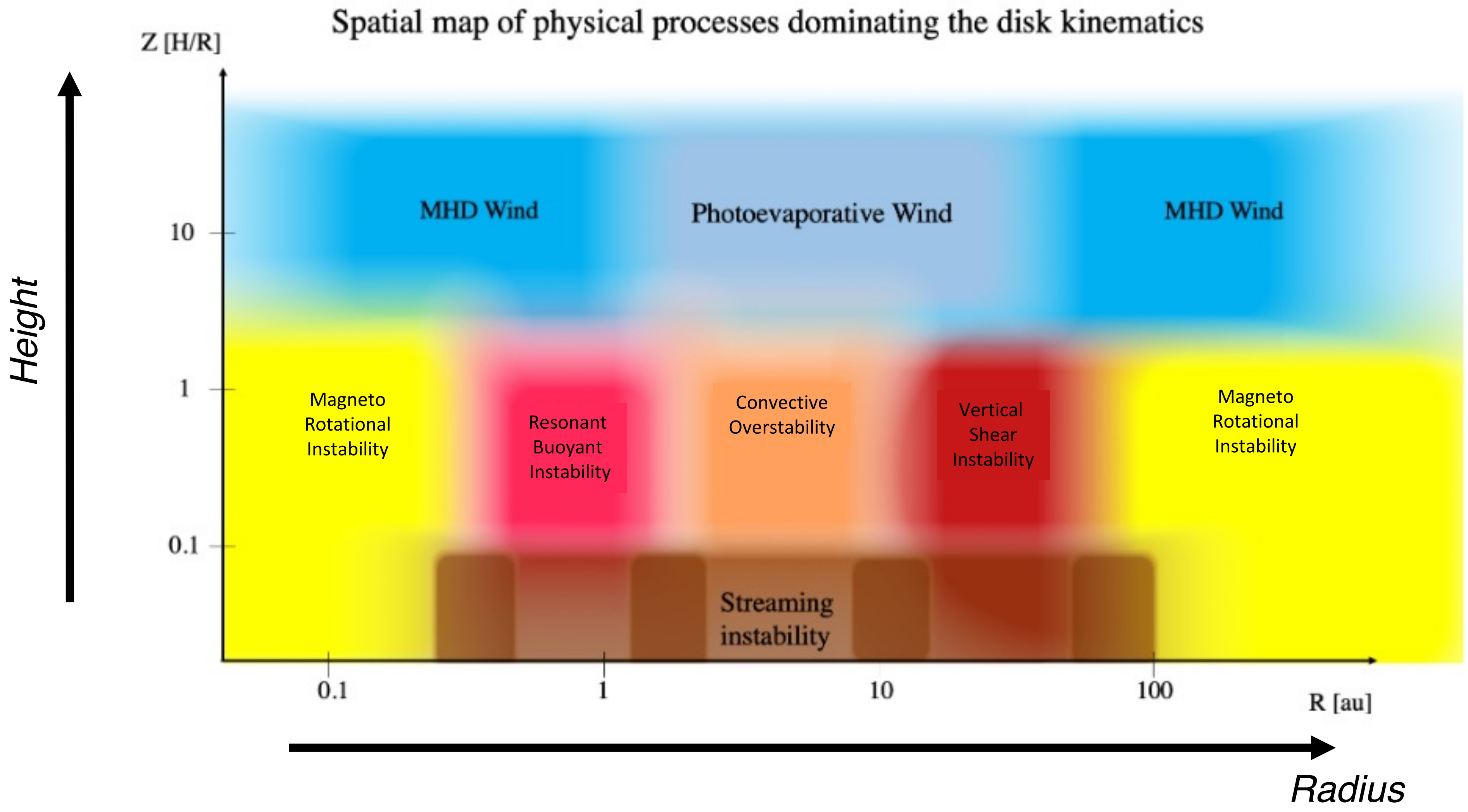
Lyra+08,18 Raettig+Lyra 12,15,21

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



Disk Instabilities

Instability Map

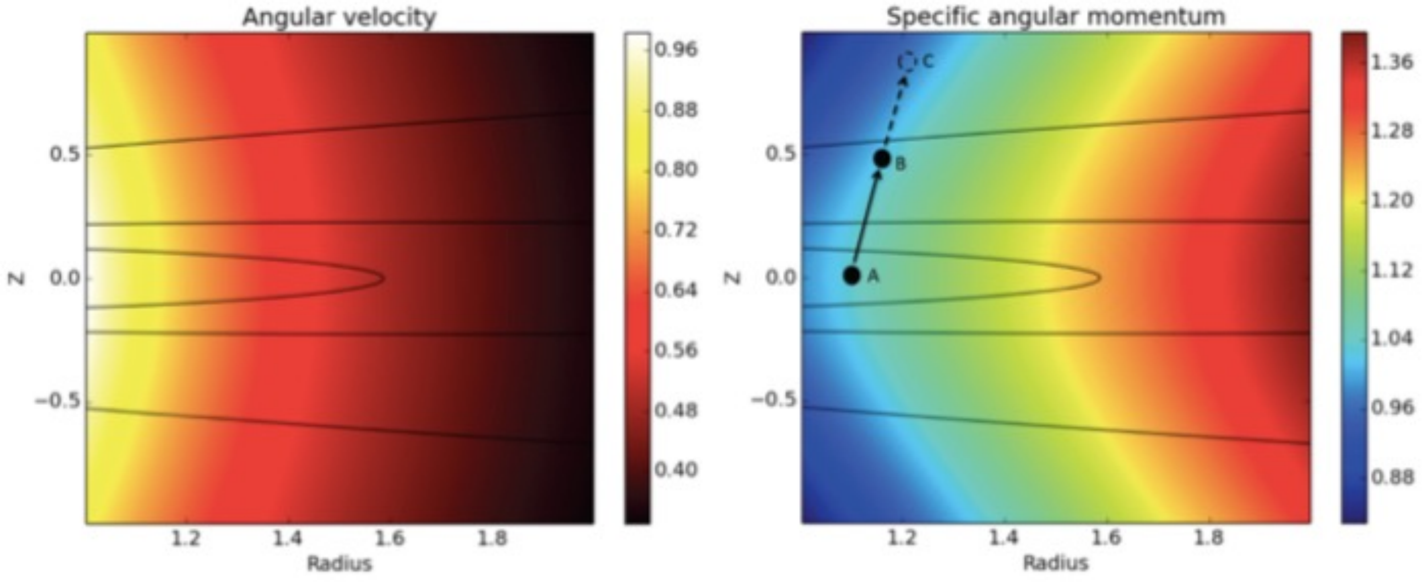


Lesur et al. (2022)

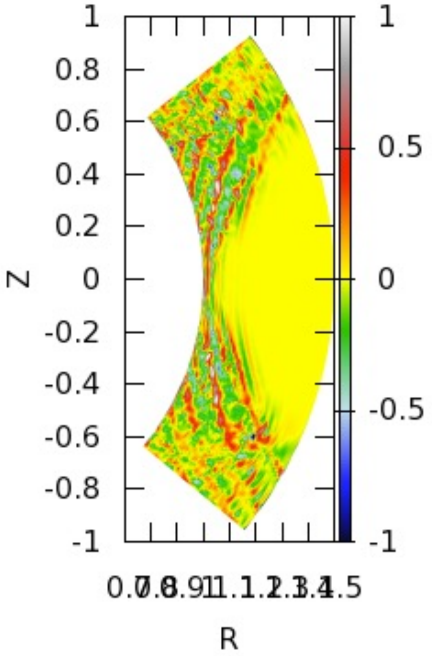
Vertical shear instability

Angular velocity not constant in cylinders: unstable

Buoyancy stabilizes. The most unstable mode is isothermal.

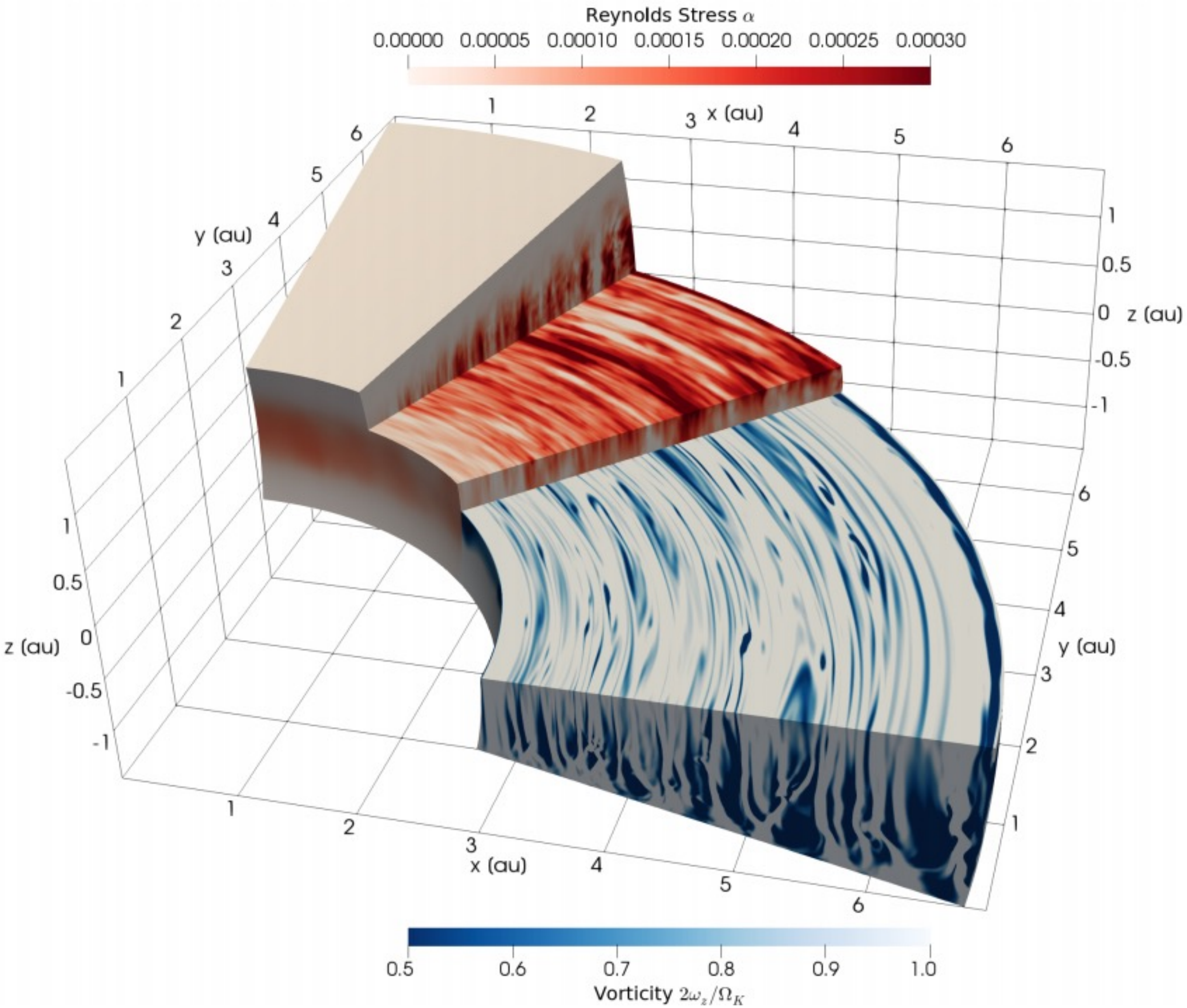


Fromang & Lesur (2017)



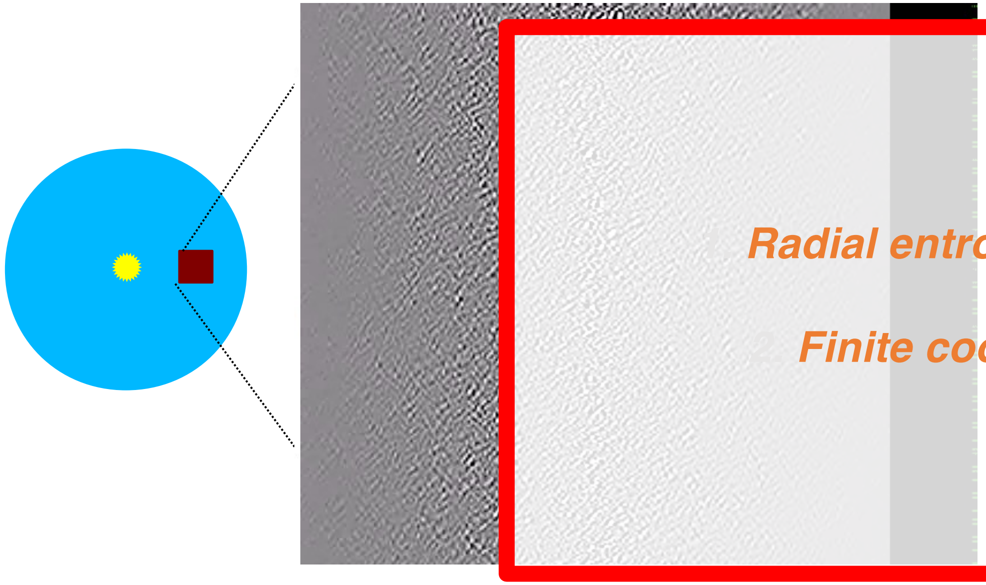
Nelson et al. (2013)

Vertical shear instability



Pfeil & Klahr (2020)

Convective Overstability

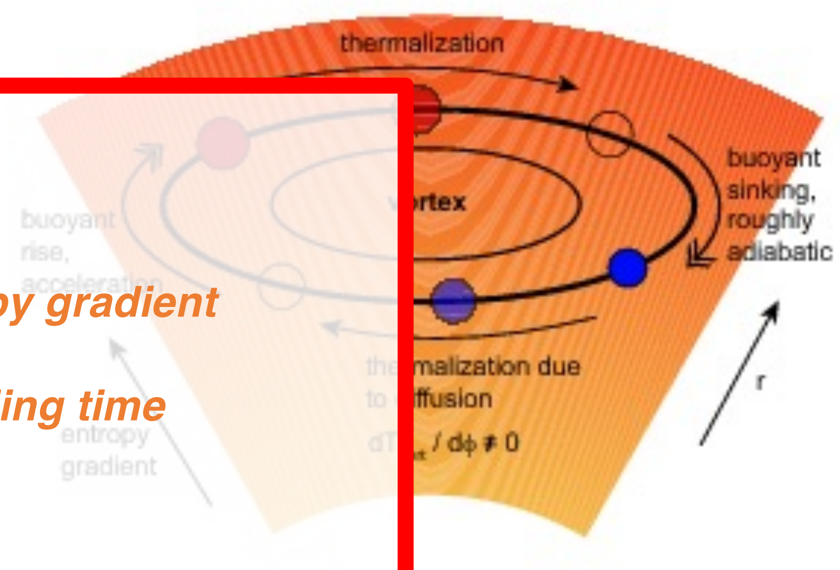


Radial entropy gradient

Finite cooling time

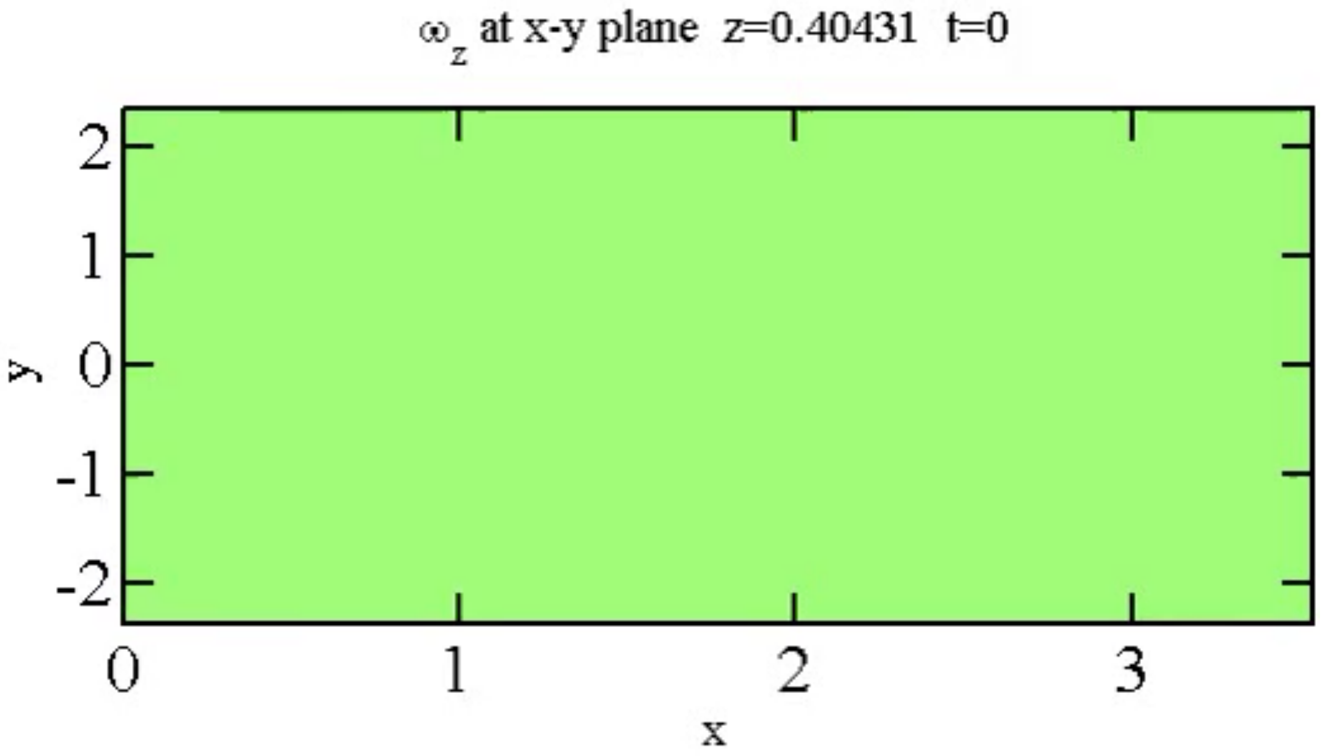
Lesur & Papaloizou (2010)
Lyra & Klahr (2011)
Klahr & Hubbard (2014)
Lyra (2014)
Latter (2016)
Volponi (2016)
Reed & Latter (2021)
Raettig et al. (2021)

Sketch of the
Convective Overstability



Armitage (2010)

Resonant Buoyant Instability (née Zombie Vortex Instability)

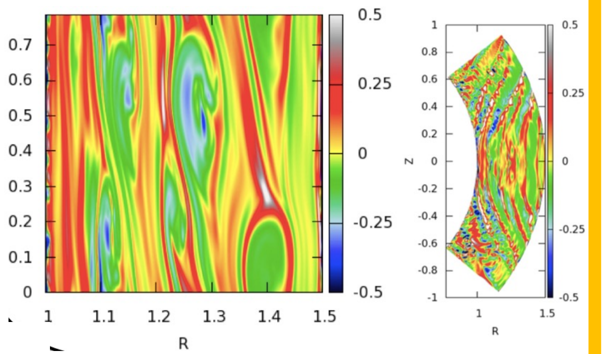


Cascade of baroclinic critical layers

Marcus et al. (2015, 2016), Barranco et al. (2018)

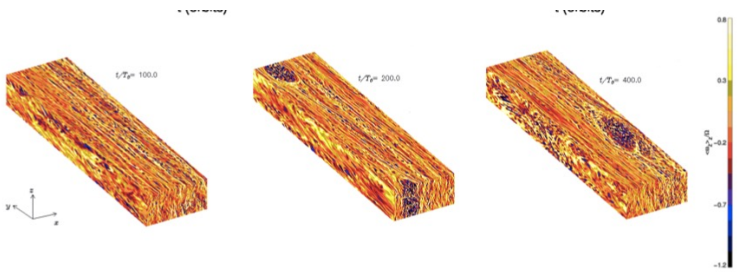
Hydrodynamical Instabilities

Vertical Shear Instability



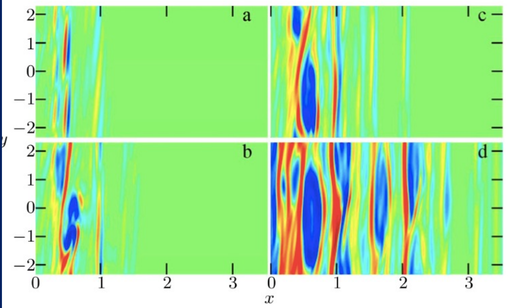
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

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

Fast cooling times
(More isothermal)

$\kappa < 1$ cm^2/g

Cooling time ~ dynamical time

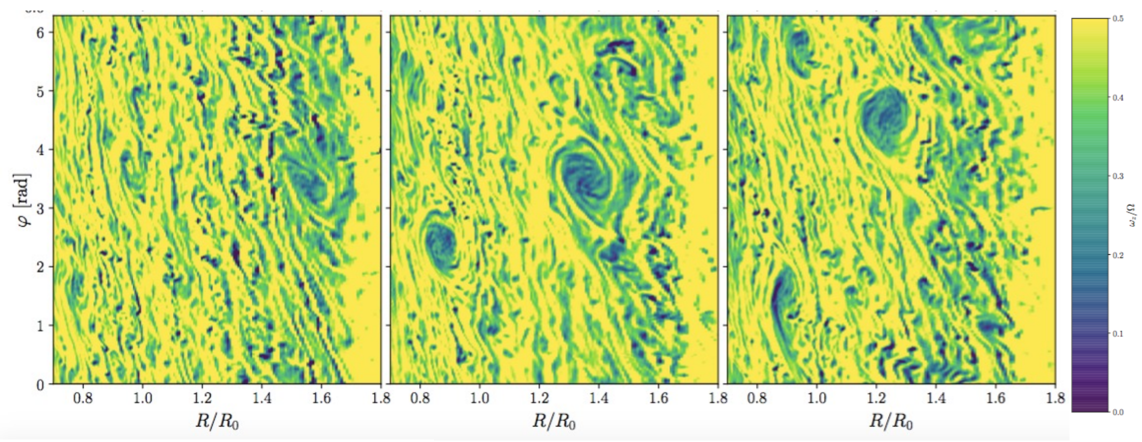
$\kappa \sim 1$–50 cm^2/g

Long cooling times
(More adiabatic)

$\kappa > 50$ cm^2/g

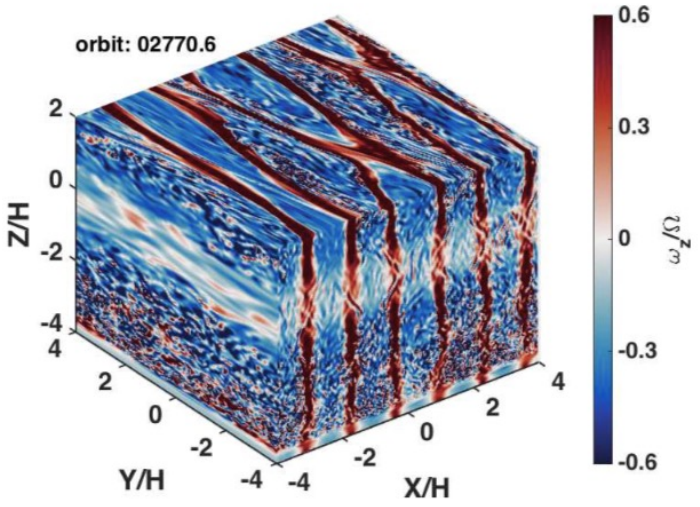
Opacity

Take-home message



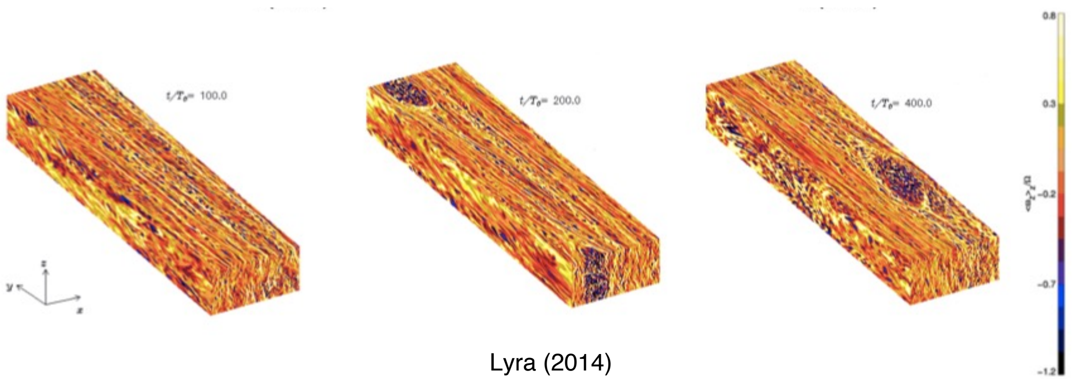
Manger & Klahr (2018)

Vertical Shear Instability
saturates into
vortices



Barranco et al. (2018)

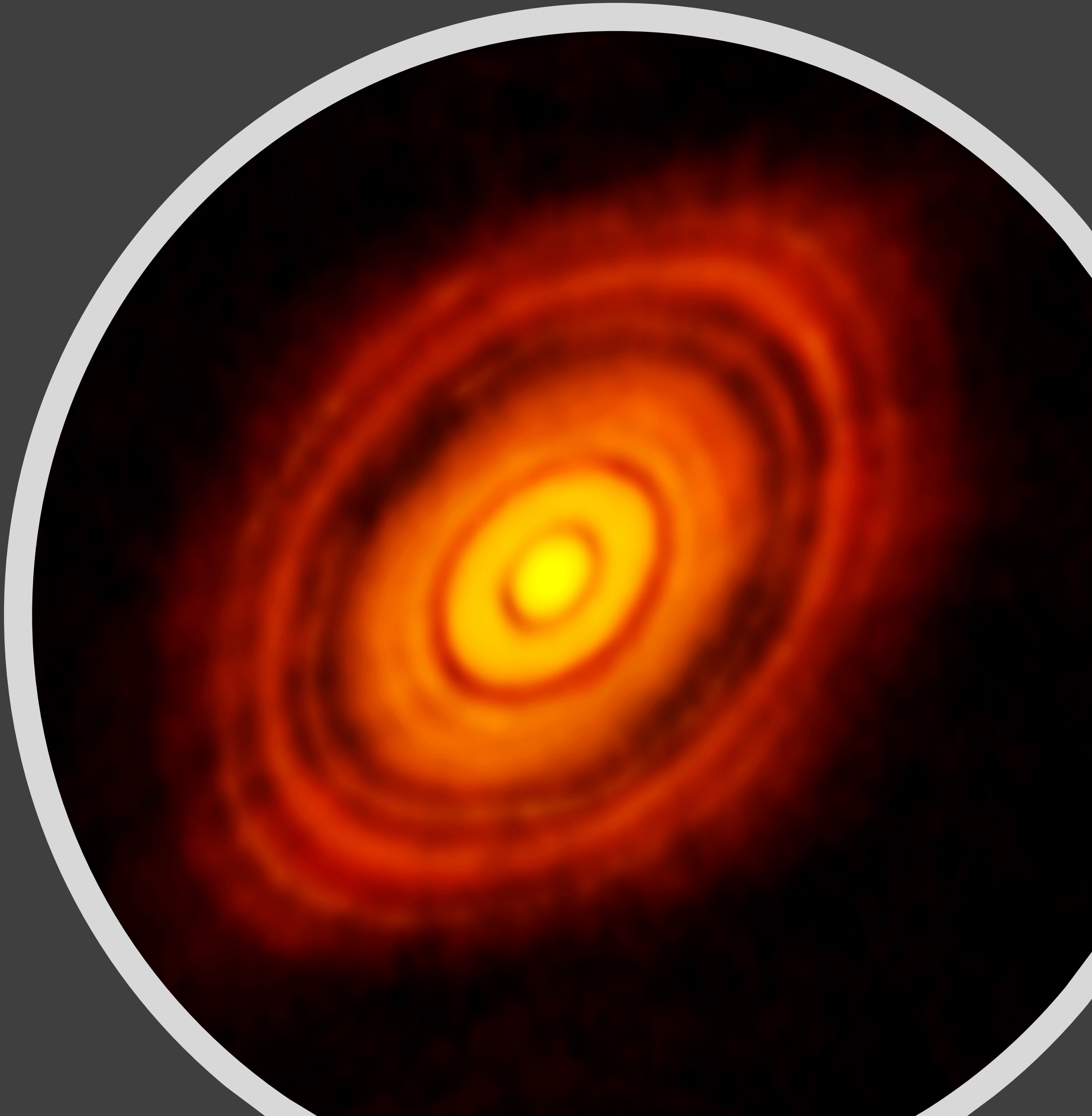
Resonant Buoyant Instability
saturates into
vortices



Lyra (2014)

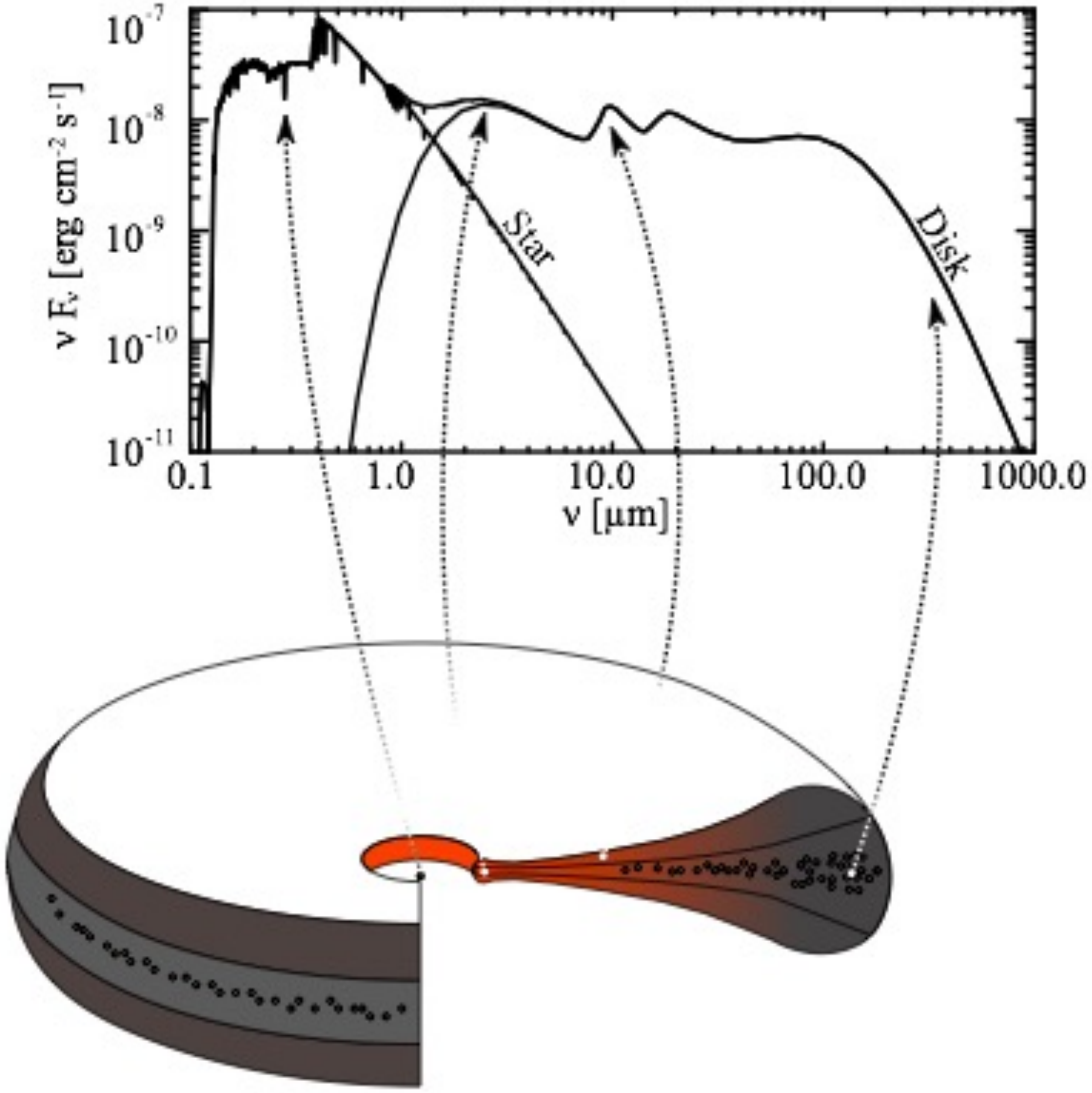
Convective Overstability
saturates into
vortices

Disk Observations



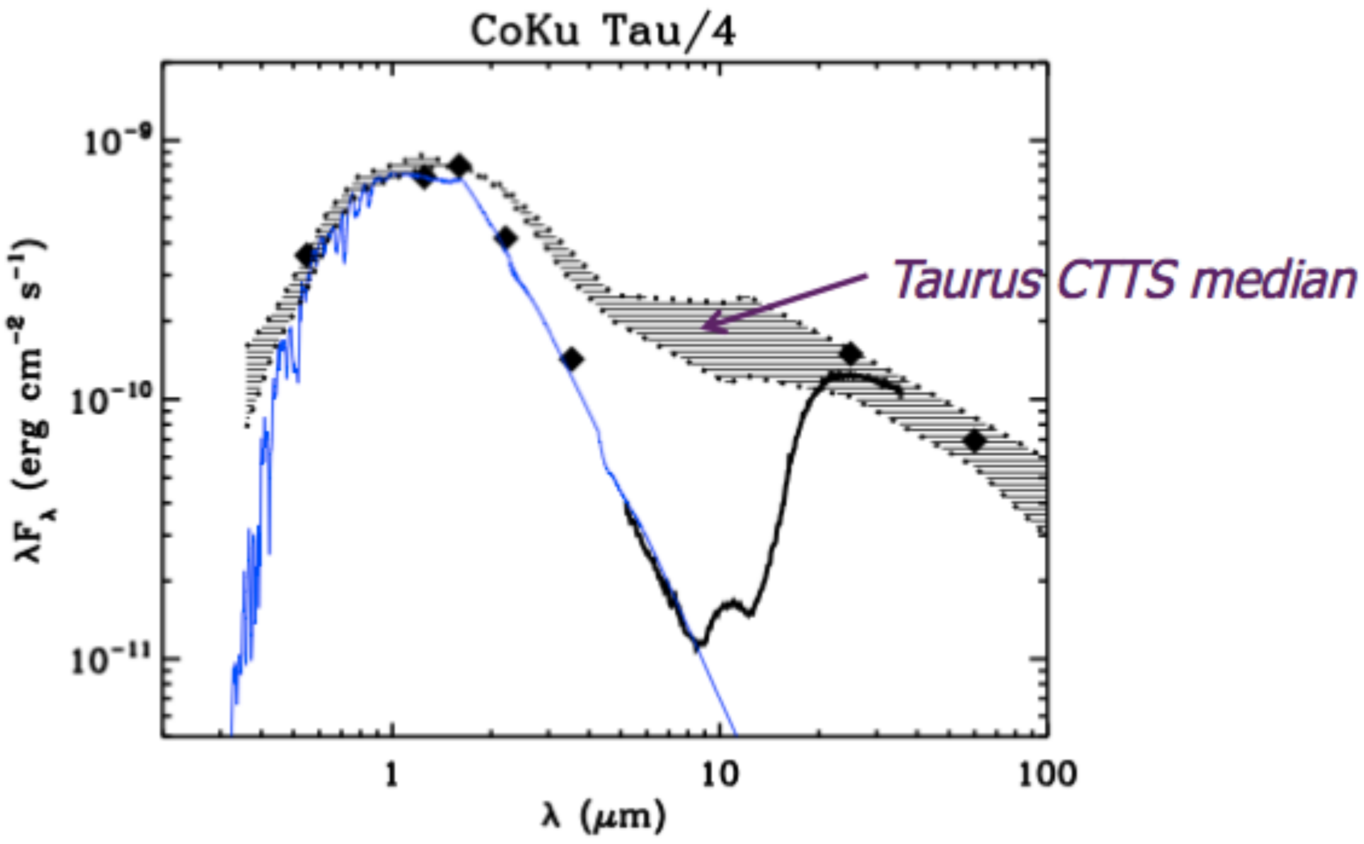
Disk spectra

- Stellar Blackbody
- Dust infrared excess (optically thick)
- Optically thin Rayleigh-Jeans tail in mm.

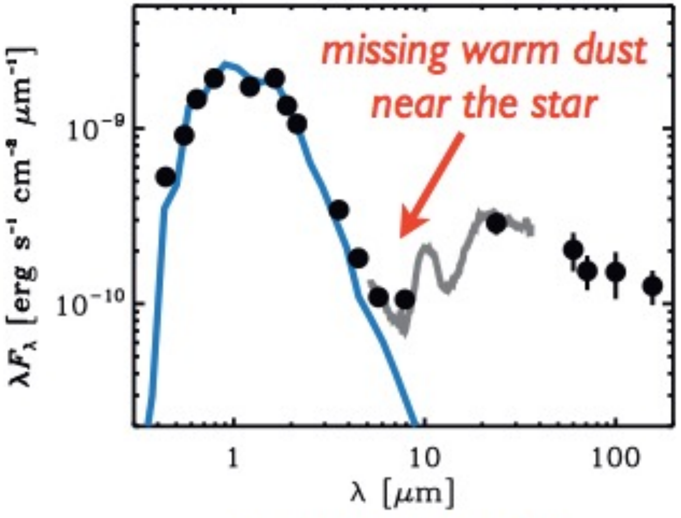


A class of disks with missing hot dust.

- CTTS: Classic T-Tauri star
- ”Transition” disks are disks with missing hot dust.
- The original interpretation is that they could be related to disk evolution, “transitioning” from gas-rich to gas-poor from the inside out.



Disks with missing hot dust.



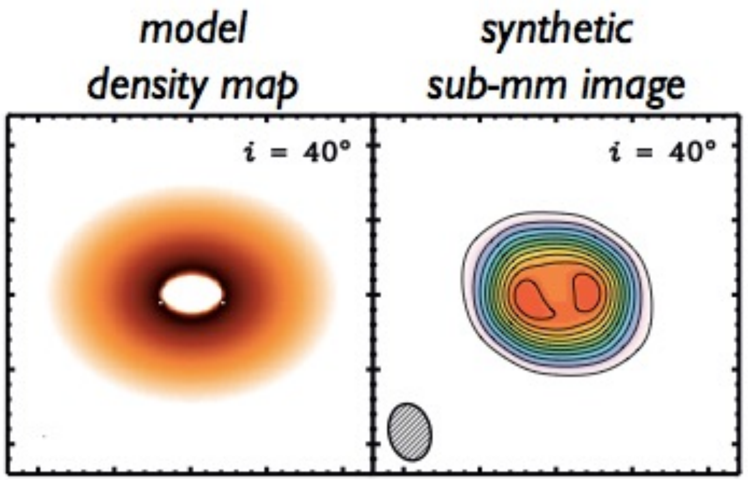
[e.g., Furlan et al. 2009]

"These objects represent...disks whose inner regions are relatively devoid of distributed matter, although the outer regions still contain substantial amounts of dust."

[Strom et al. 1989]

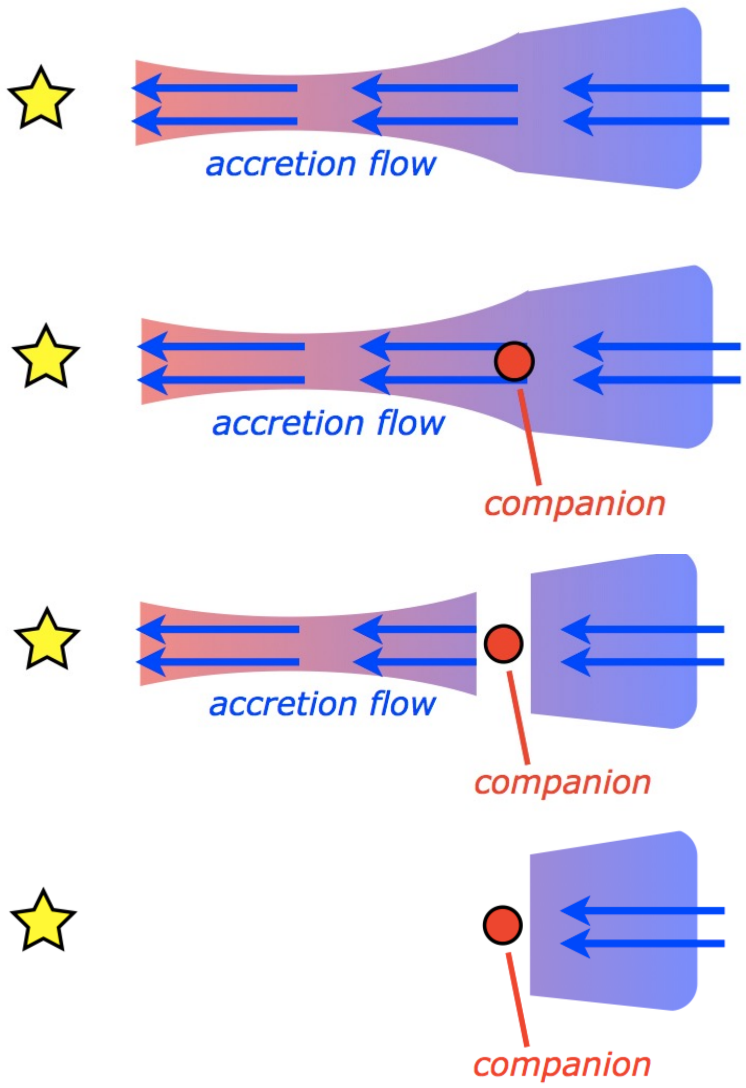
what I mean:

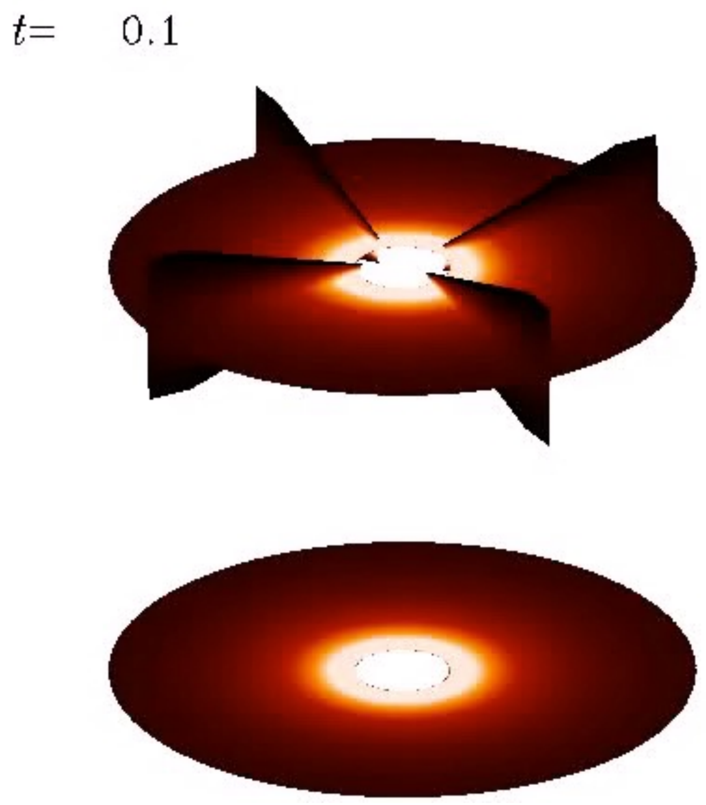
a disk with a large reduction in optical depth near the star (i.e., a "cavity" or "hole")



Planetary companion

- Yet, planets could be another possibility for the missing hot dust.
- A companion carves a gap, isolating the outer disk from the inner disk, which then accretes onto the star



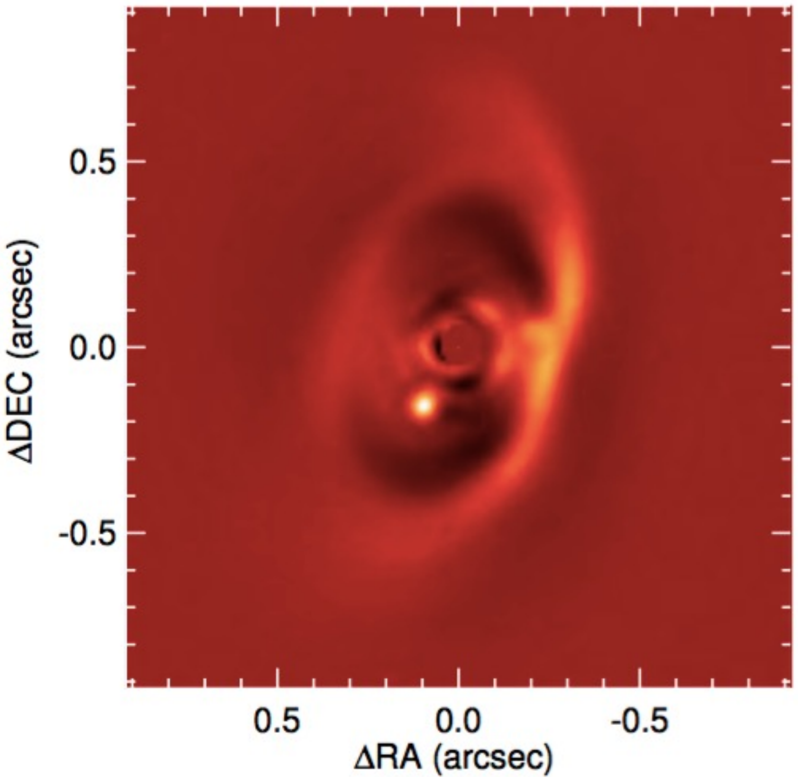


(Lyra 2009)

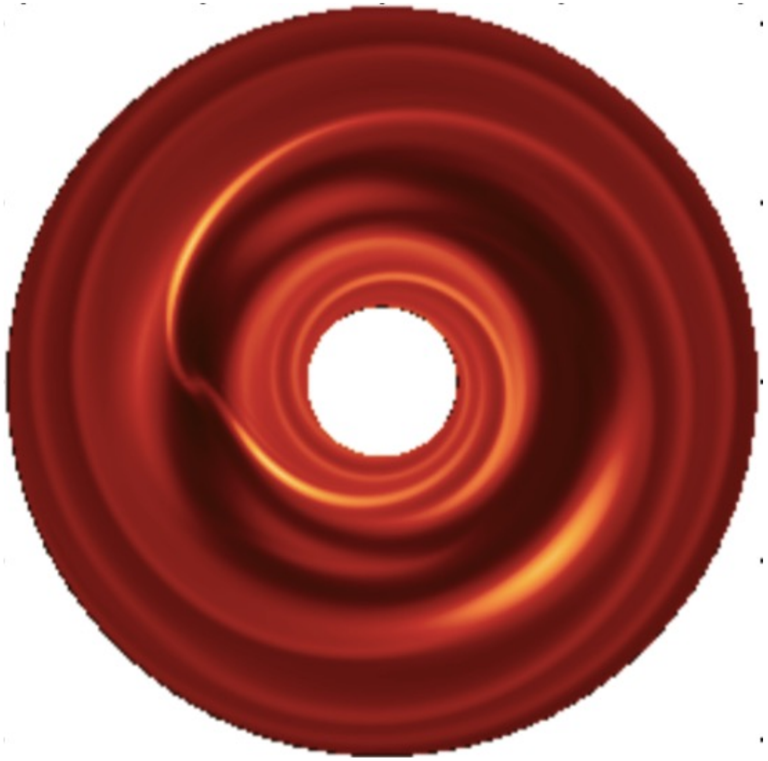
These cavities may be the telltale signature of forming planets

- Hydrodynamical models have predicted that the result of disk-planet interaction should be: gaps, spirals, and vortices.
- These are starting to be seen in ALMA images of protoplanetary disks.
- In a few cases, the young luminous planets has been identified (PDS70).

PDS 70 and PDS 70b



(Muller et al. 2018)



(Lyra et al. 2009b)

A way to directly study planet-disk interaction

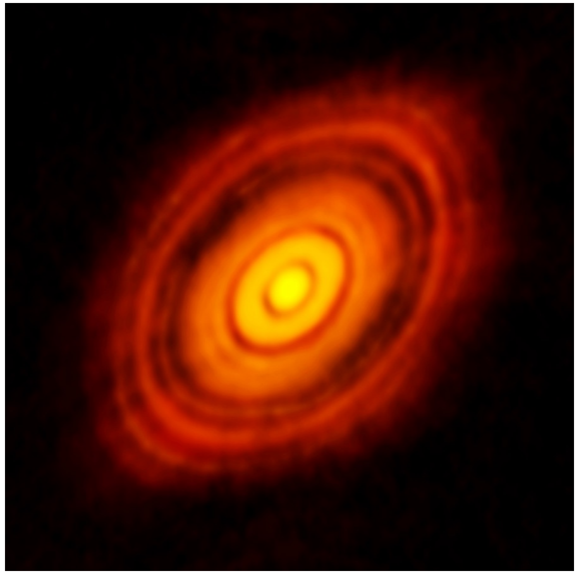
Planet-disk interaction: gaps, spirals, and vortices.

- Hydrodynamical models have predicted that the result of disk-planet interaction should be:
    - Gaps (rings),
    - Spirals, and
    - vortices.

(Lyra et al. 2009b)

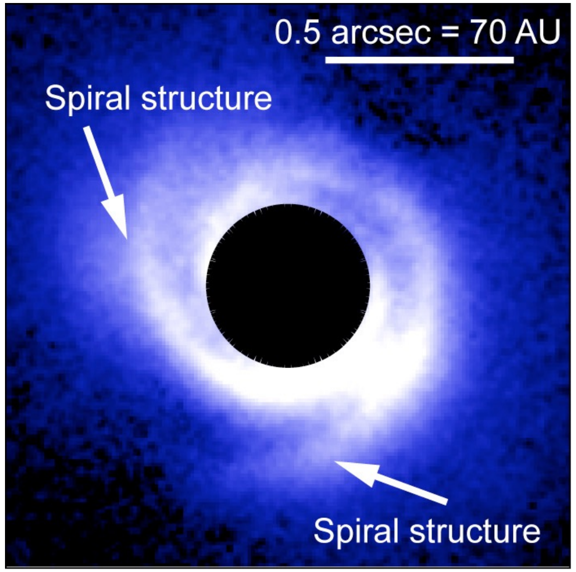
Observational evidence: gaps, spirals, and vortices

HL Tau



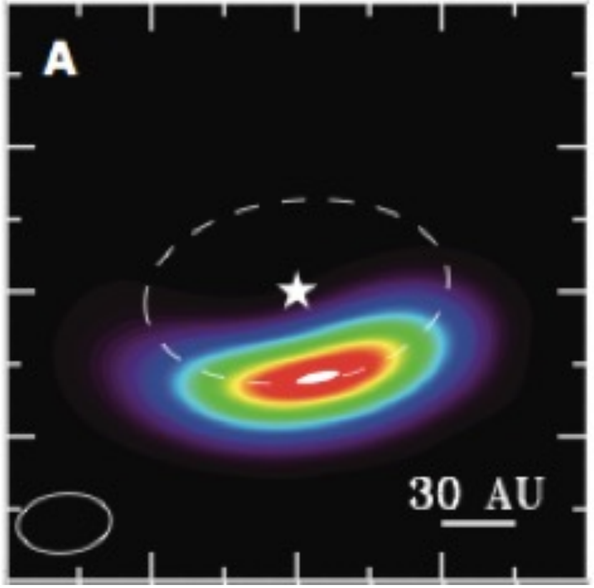
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

Oph IRS 48



van der Marel et al. (2013)

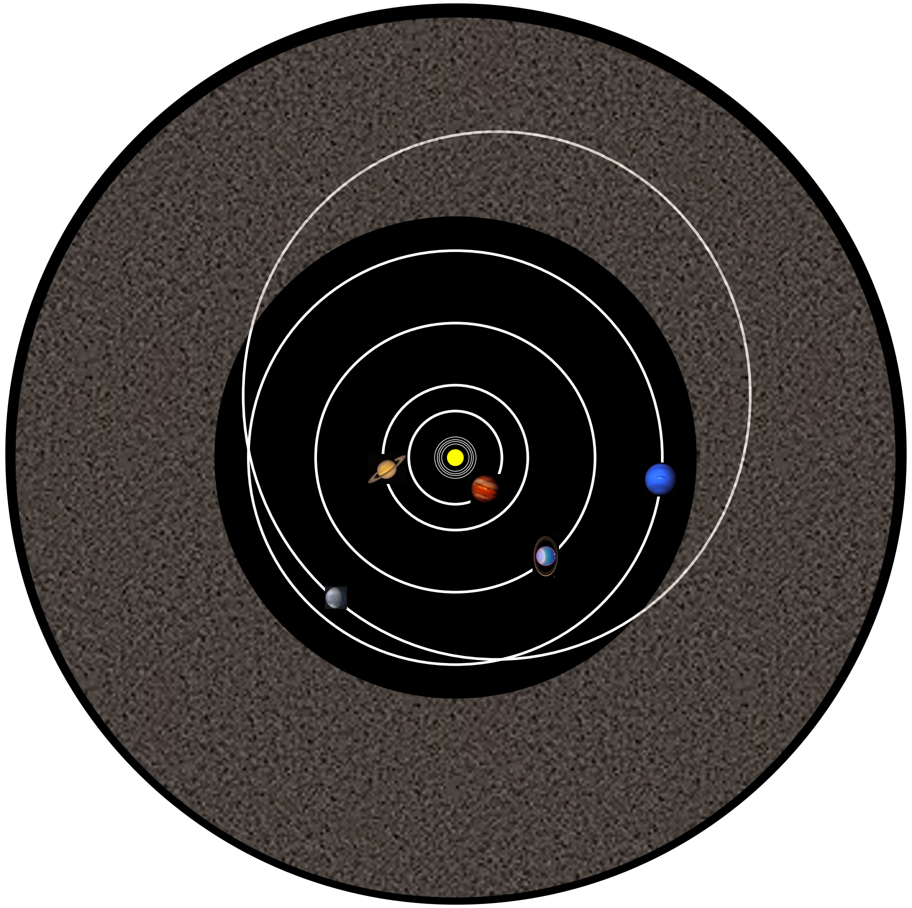
- Disk observations have seen exactly the structured predicted by hydrodynamical models of disk-planet interactions. Although
    - Not in the same disk
    - The planets themselves are elusive (small dim source)

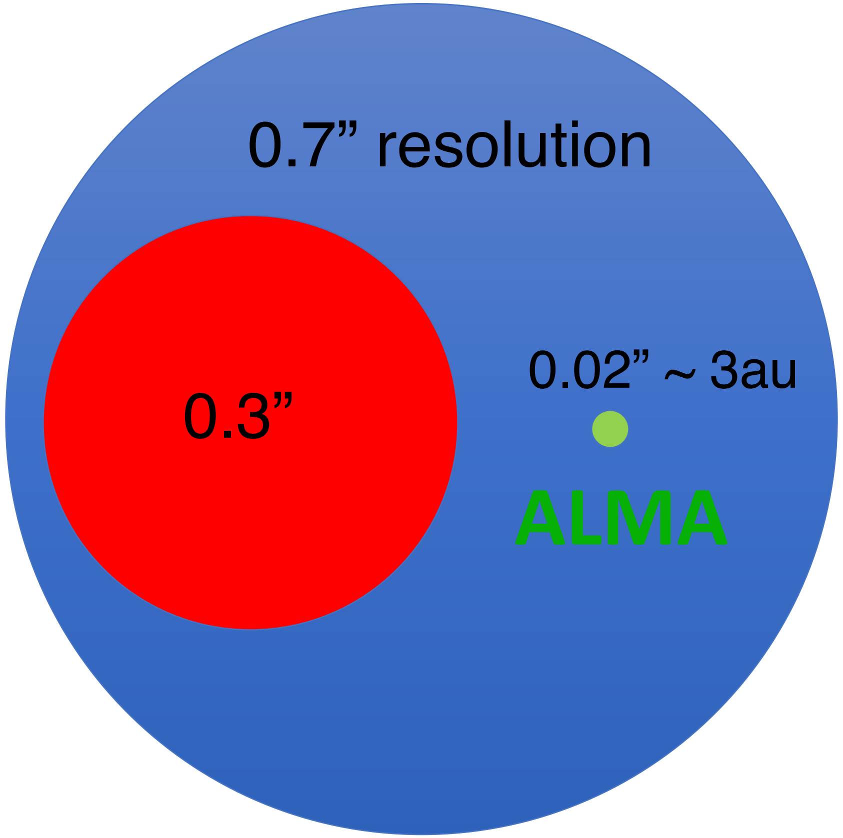
- The lack of planet confirmation leaves room for other interpretation.

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

The ALMA Re~~v~~solution

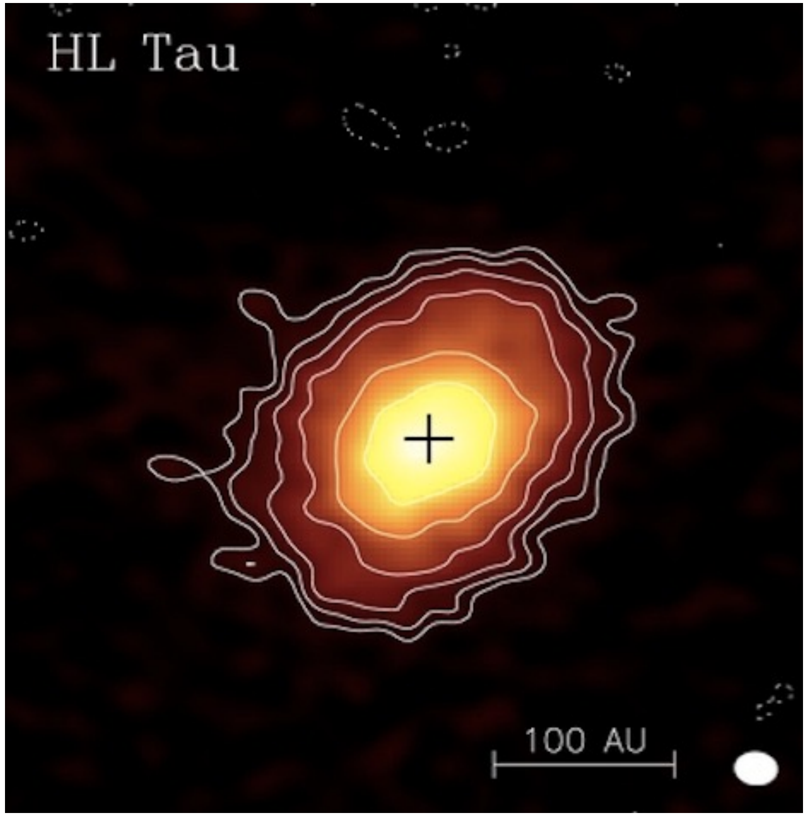
At 140 pc

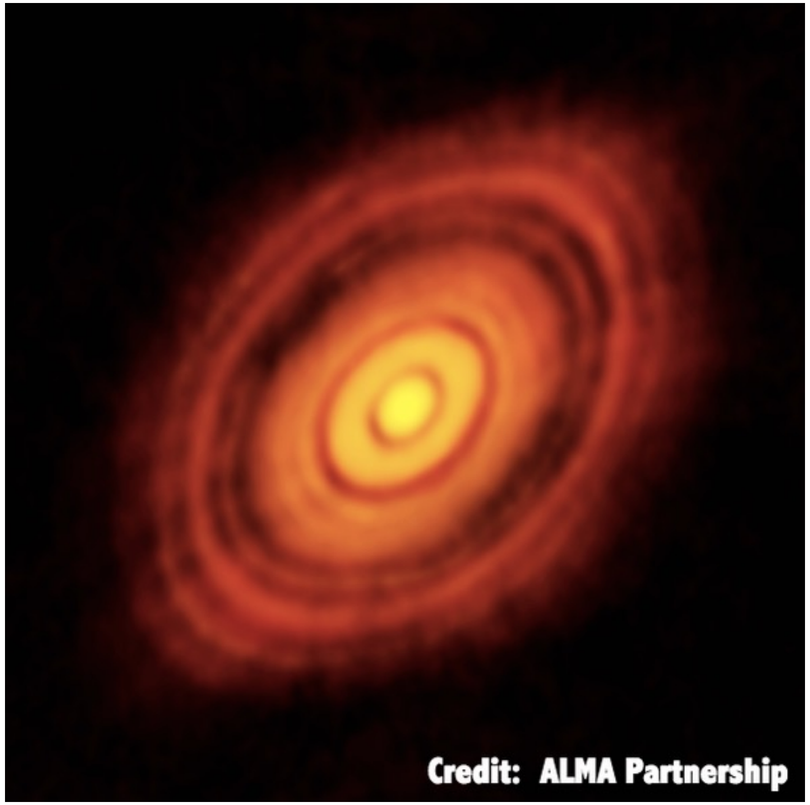




Before ALMA

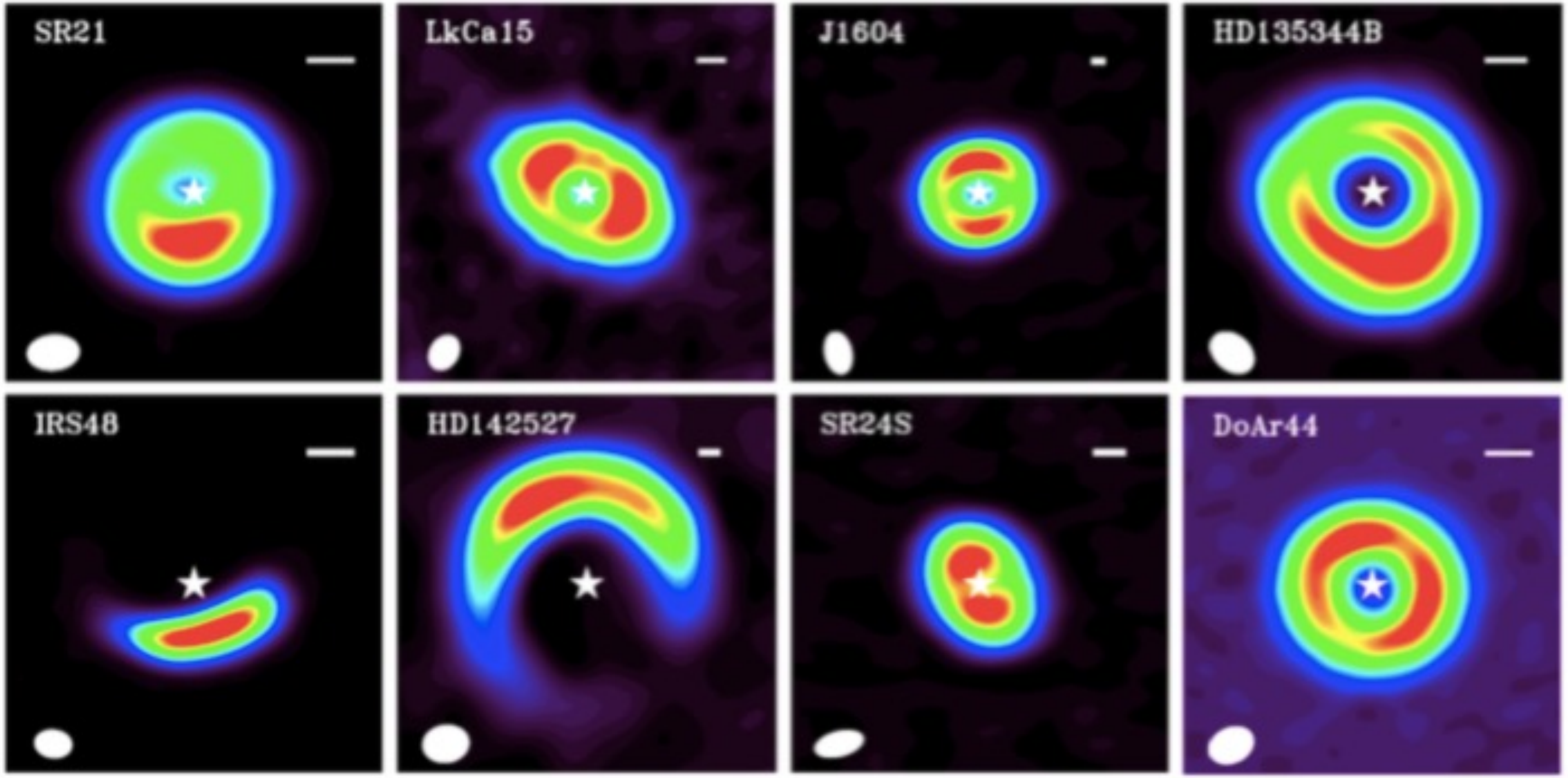
ALMA



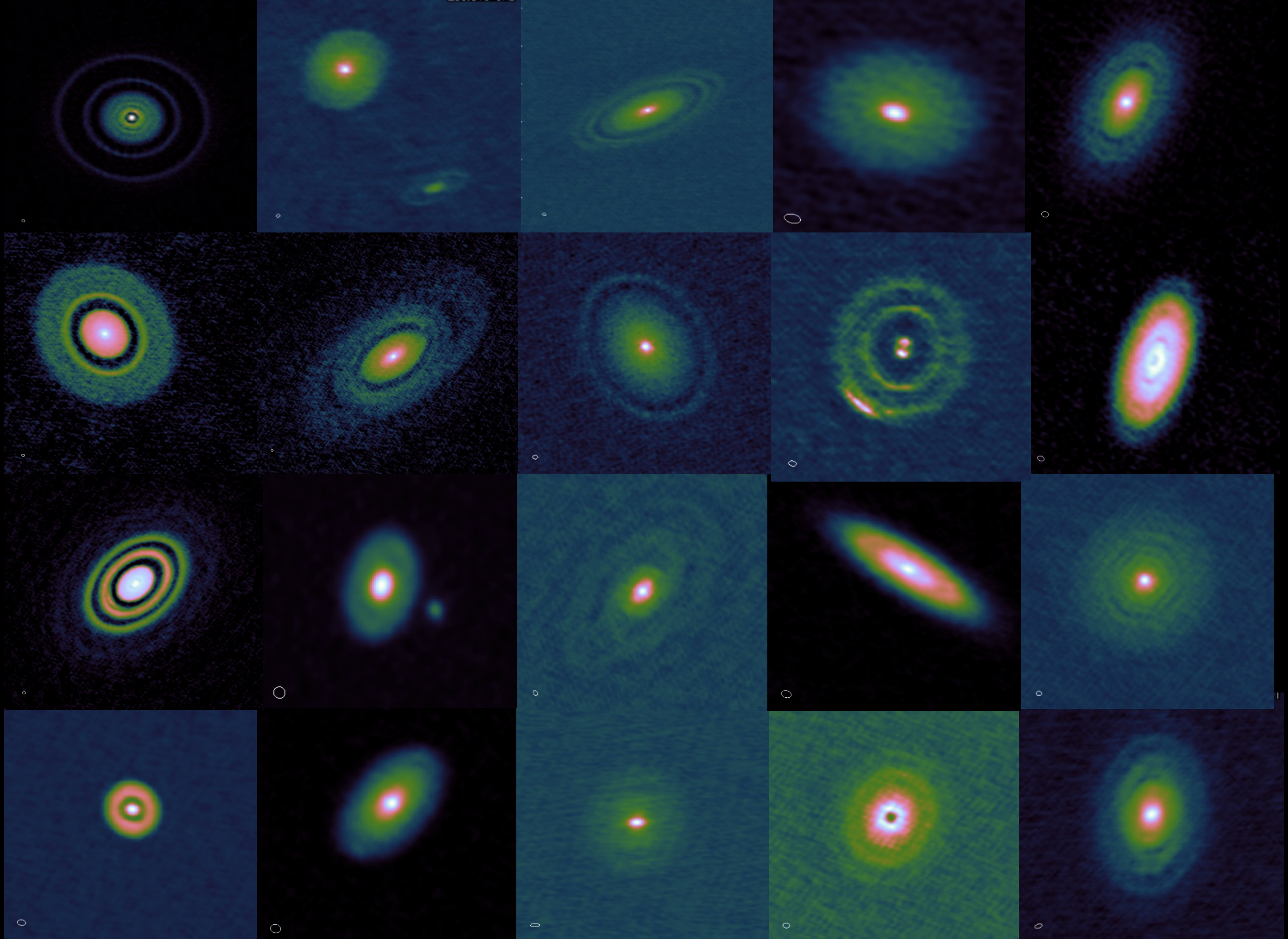


Dust traps in disks: ALMA Cycle 0 (2012)

What ALMA could do back then



What ALMA can do now.
DSHARP survey.



Oph IRS 48

A Major Asymmetric Dust Trap in a Transition Disk

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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

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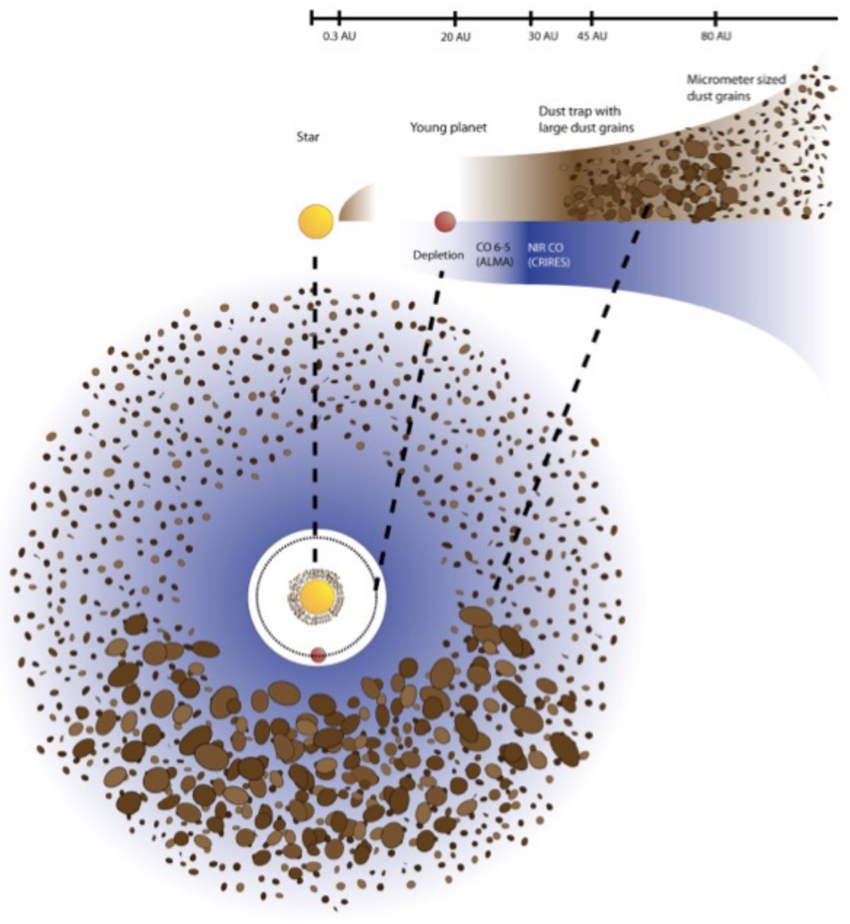
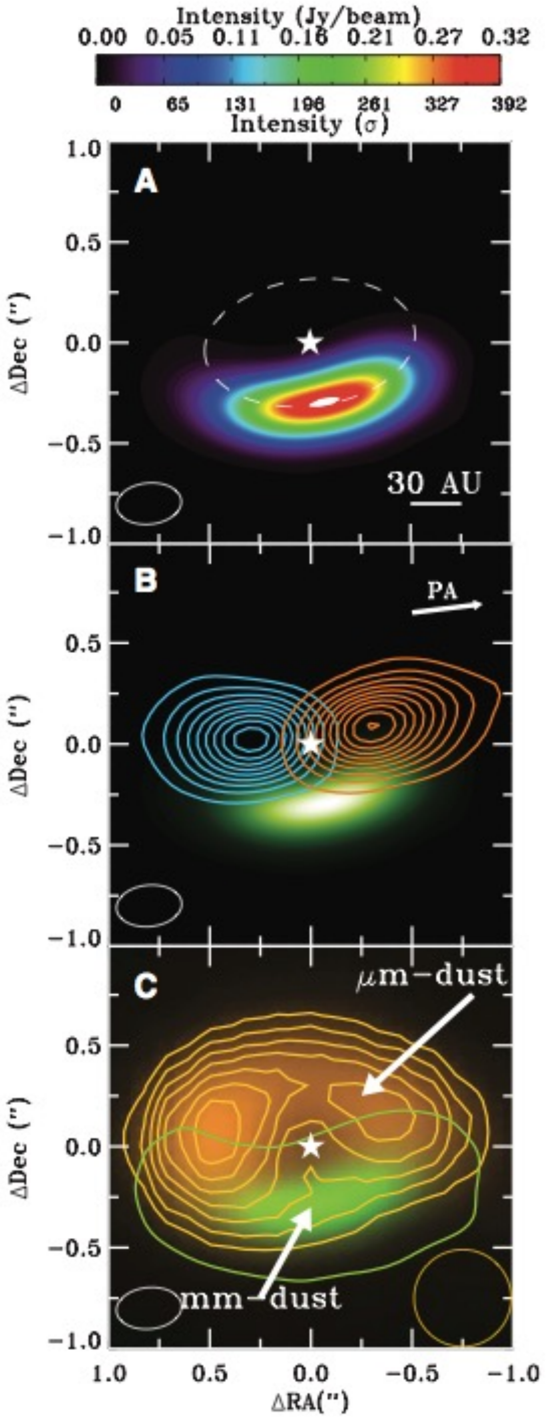
van der Marel+ ‘13

A huge vortex observed with ALMA

The Oph IRS 48 “comet formation factory”



van der Marel+. ‘13

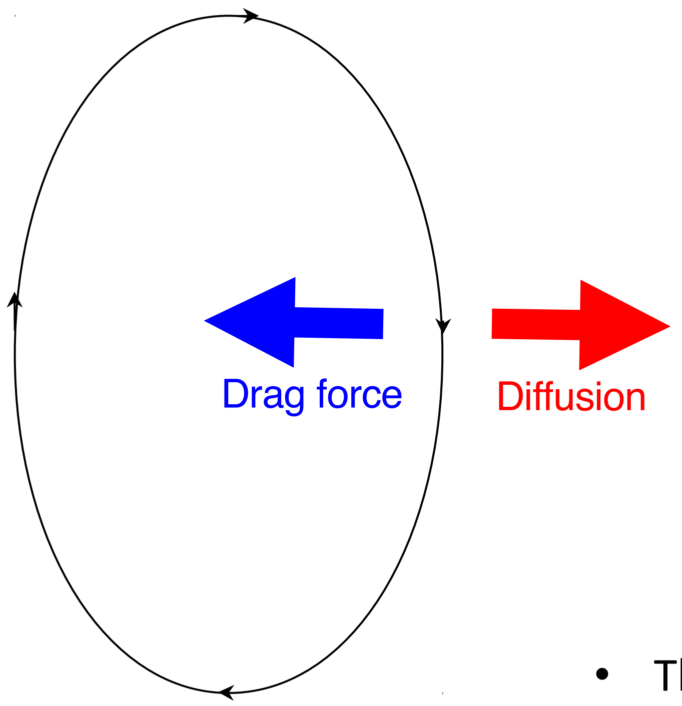


asymmetric
mm dust
at 63 AU

Gas detection:
Keplerian rotation

Micron-sized
dust follows gas

Drag-Diffusion Equilibrium



Trapped particle

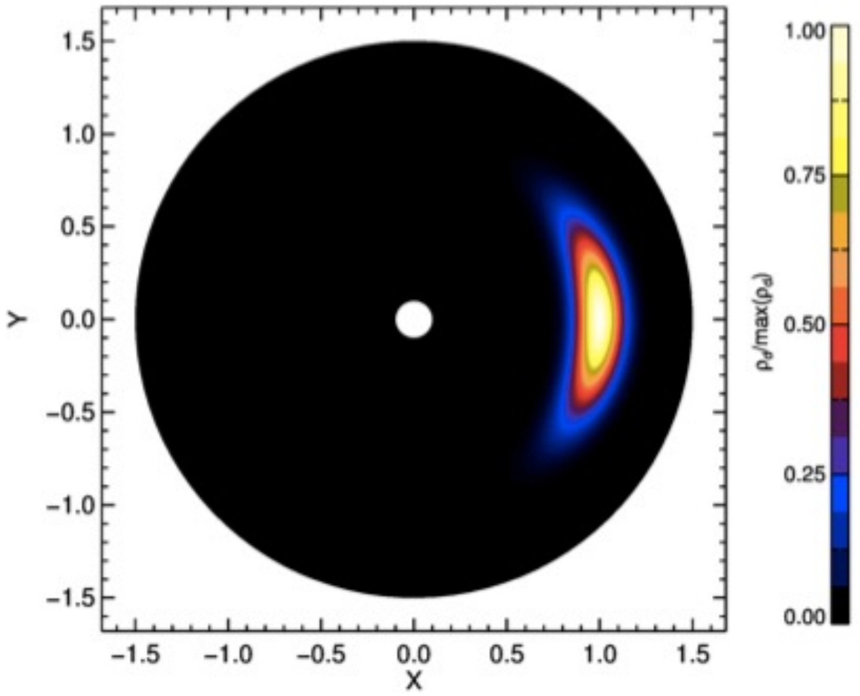
Dust continuity equation

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

- The trapped dust is in a steady state between
  - The drag, pushing it into the vortex and,
  - Turbulent diffusion, kicking it out

- We can solve for the steady state distribution analytically by solving the dust continuity equation.

Analytical Solution for dust in Drag-Diffusion Equilibrium



Solution for

H/r=0.1 χ=4 *S*=1

Steady-state solution

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

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(χ) = model-dependent scale function

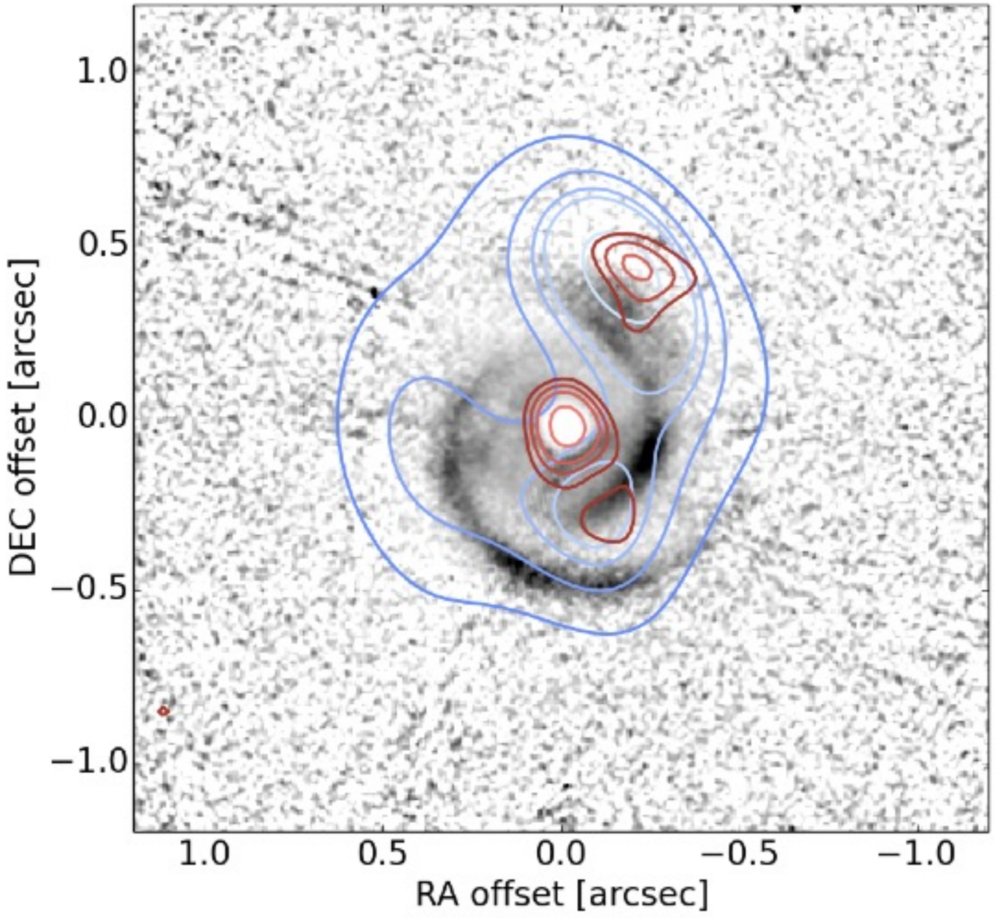
Disk Tomography
SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

ALMA (~ mm)

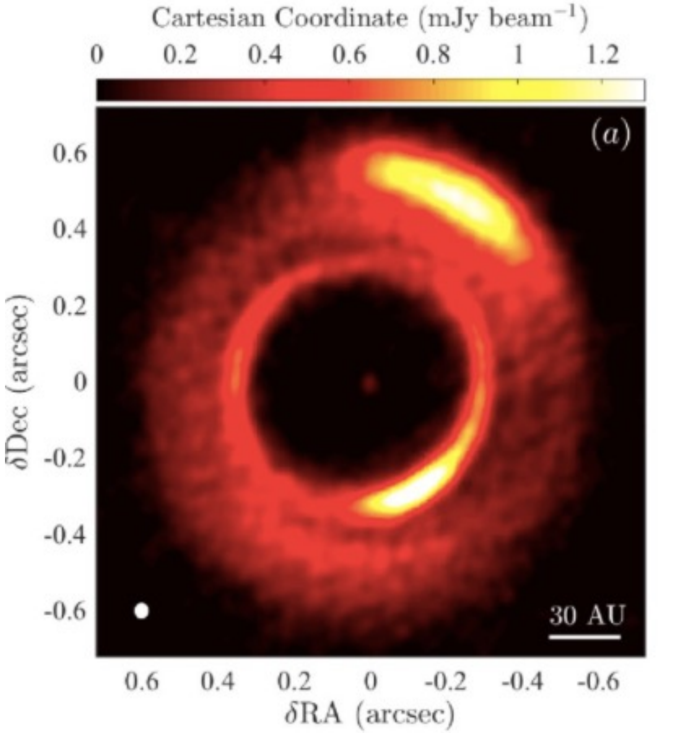
VLA (cm-m)

- Verify the solution by checking it against observations in different wavelengths.
- Infrared stops at the surface of the disk.
- Sub-mm and radio trace the bigger dust, that is settled to midplane and trapped in vortices



Marino+Lyra '15

ALMA

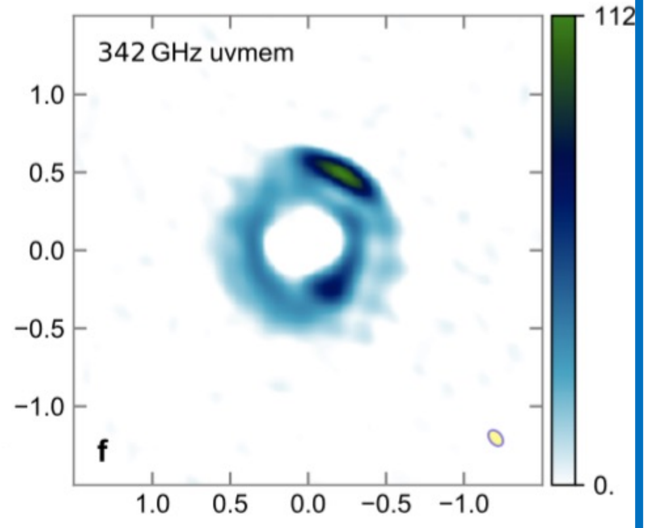


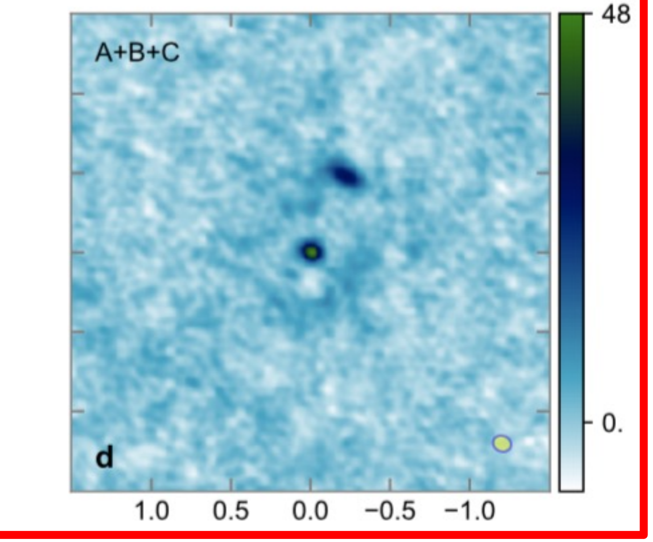
Dong+ '18

Pebble trapping

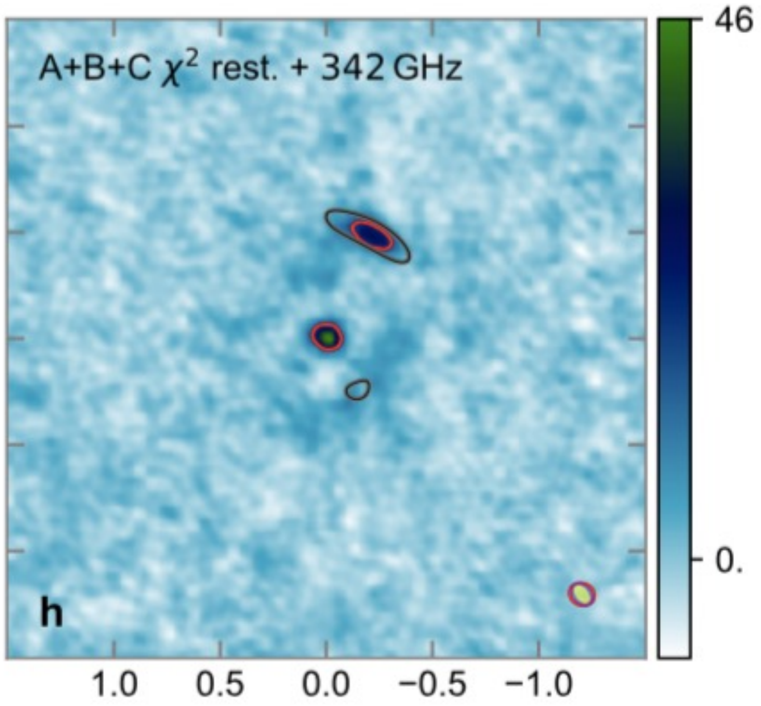
- ALMA traces mm grains
- VLA traces cm grains

- Observations of MWC 758 in ALMA and VLA show that mm-grains are in a more spatially extended than cm-grains.





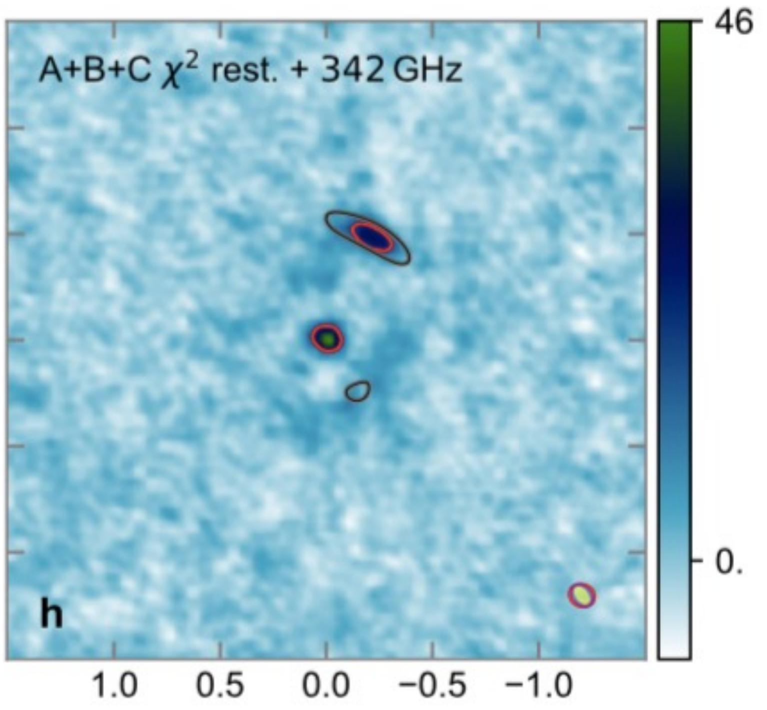
Overlay



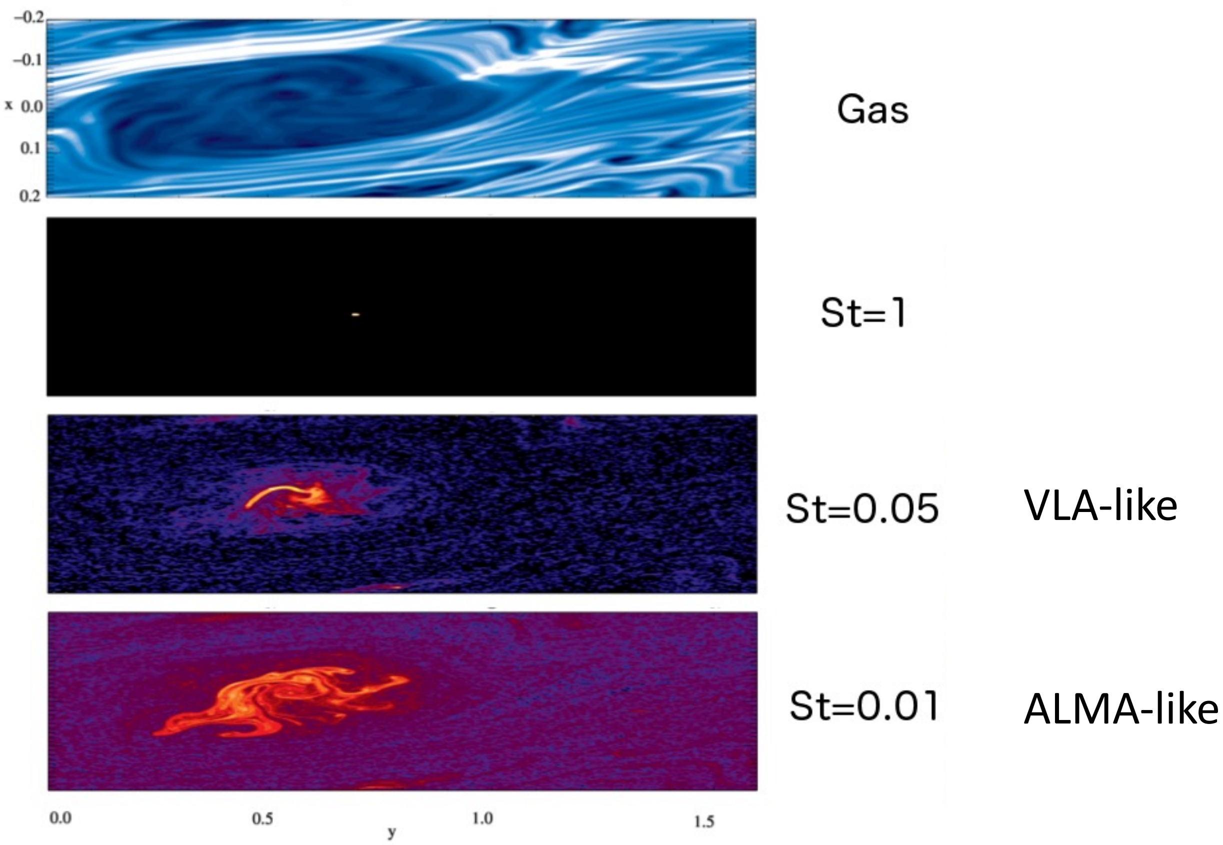
Casassus+Lyra '19

Model vs Observation

- Compatible with theoretical expectations:
- Bigger trains less prone to diffusion



Casassus+Lyra '19



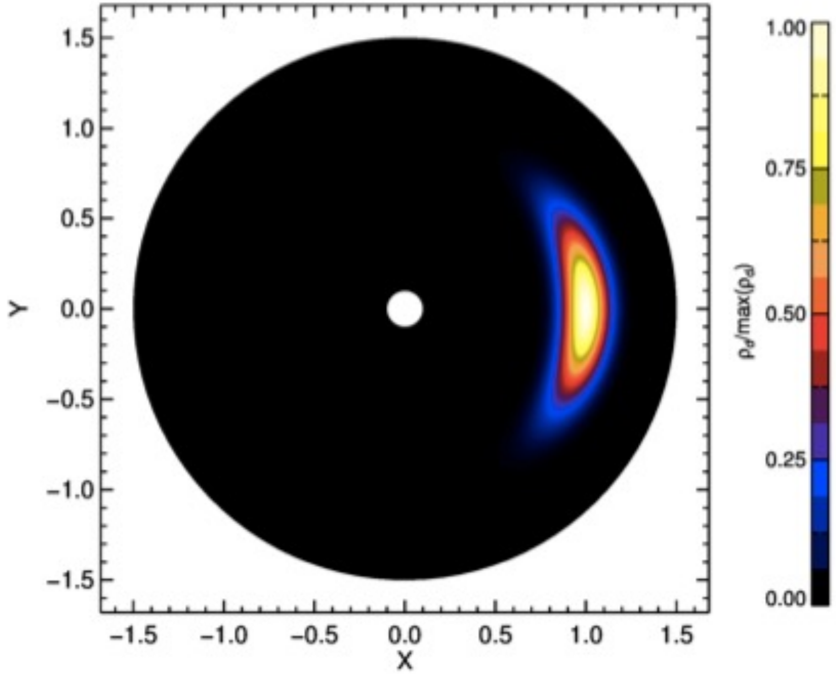
Raettig+Lyra '15

Take home message

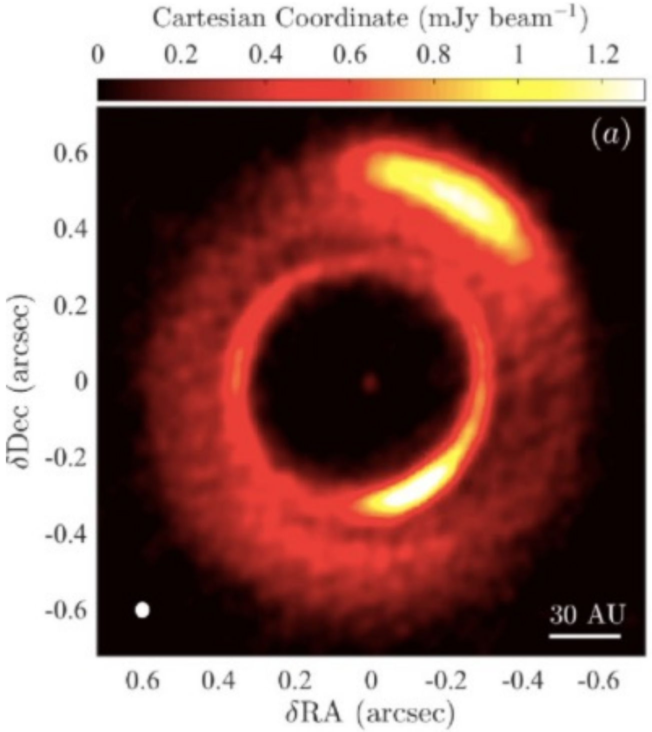
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations

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

Lyra-Lin solution



Observed Disk



The future

After 10 years of ALMA…

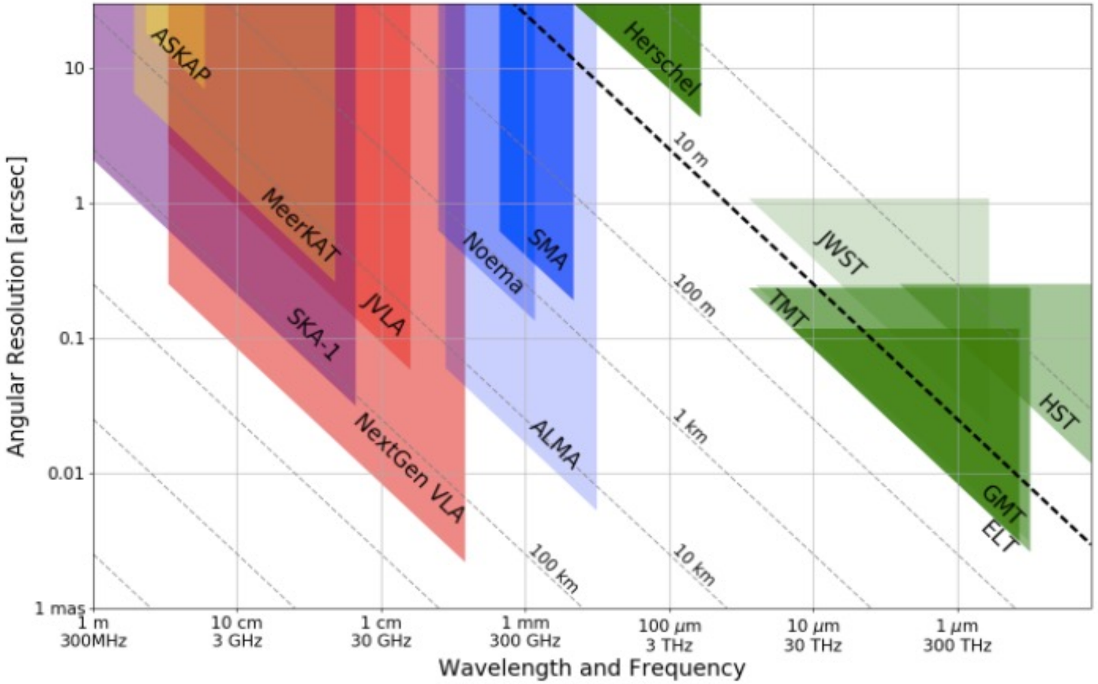
Nearly all nearby disks observed at <0.1” (< 20-30AU) show substructures.

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

Slide from: Luca Ricci

Next Generation Very Large Array (ngVLA)

- JWST is exciting, but for planet-formation the holy grail is resolution.
- ngVLA will afford resolution approaching 1 mas.



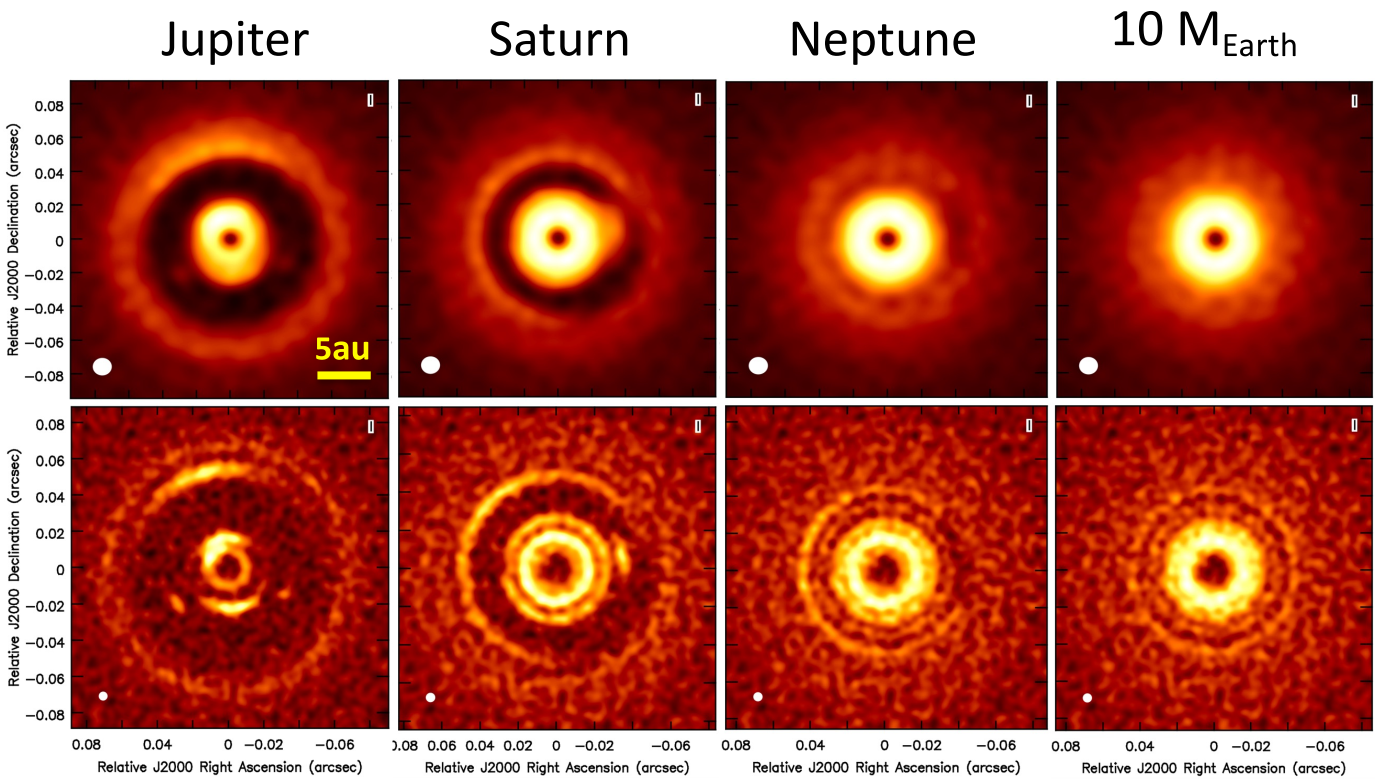
Slide from: Luca Ricci

Planets at 5AU

ALMA @ 0.87mm

ngVLA @ 3mm

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



Ricci et al. 2018

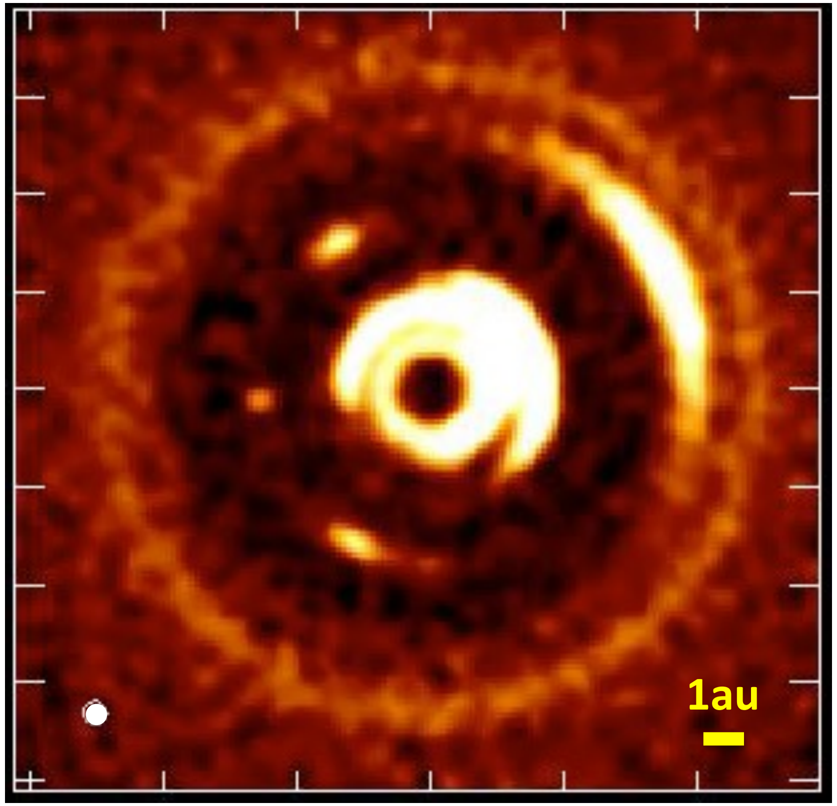
ngVLA identifies gaps/substructures down to ~5-10 M_{Earth}

Slide from: Luca Ricci

ngVLA: Proper motions

- ngVLA simulated observation of a Jupiter-like planet at 5AU, 140 pc away
- The resolution will allow to look for inner planets, with orbital periods short enough that we can follow their orbital motion.

Jupiter at 5 AU



Slide from: Luca Ricci

Conclusions

- Two routes for planet formation (streaming instability and vortices, complementary)
- Does turbulence help (concentration at large scales) or hinder (diffusion at small scales)?

- Three dynamical instabilities in the Ohmic dead zone

    - Different regimes of opacity, operate in different regions
    - Saturate into vortices

  - Dust trapped in drag-diffusion equilibrium explains the observations

- **Issues**:
  - Are the dynamical instabilities (chiefly the Vertical Shear Instability) responsible for the observed crescents?
  - Overlap between instabilities unclear
  - Global model of Convective Overstability needed
  - Relevance of Resonant Buoyant Instability (“zombie vortex”) unclear/unlikely.
  - Planet formation properties / Synergy with streaming instability

	ZVI	COV	VSI
Global model	✗	✗	✓
Vertical Stratification	✓	✗	✓
Boundaries with other instabilities	✗	✗	✗
Interaction with dust	✗	✓	✓
Observational Validation/Rule out	✗	✗	✗
Planet Forming Properties	✗	✗	✗