

Signatures of Planet Formation in Transition Disks



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New Mexico State University

Funding



AAG – 2020



TCAN – 2020

NFDAP – 2019

XRP – 2018

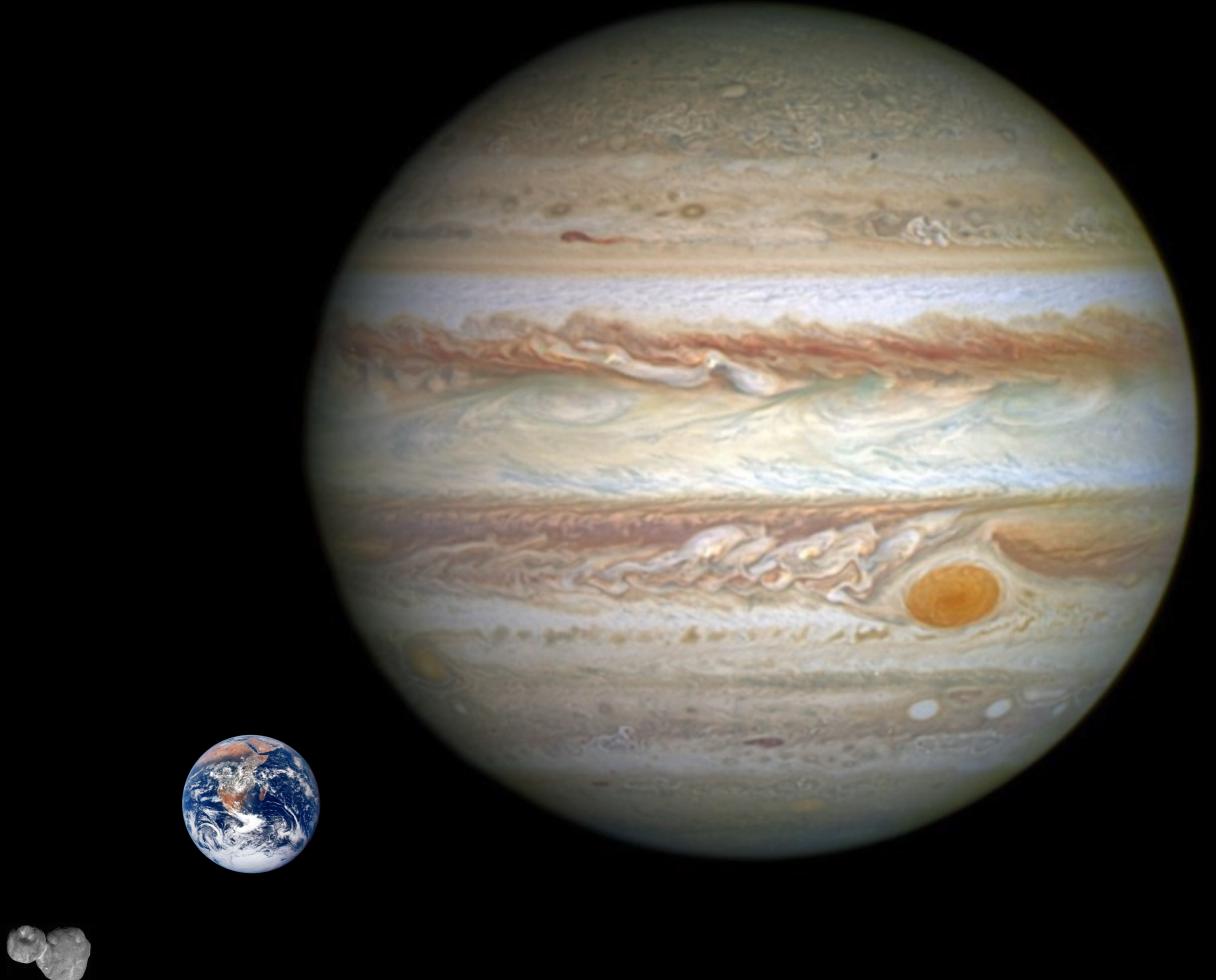
Computational Facilities



Outline

- Planet Formation
- Disk Instabilities
- Disk observations

Part 1. Planet Formation



Circumstellar/Protoplanetary Disks



PP disk fact sheet

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

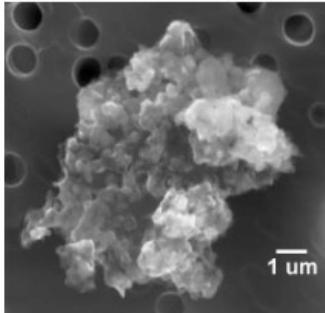
Temperature: 10-1000 K

Scale: 0.1-100AU

Mass: $10^{-3} - 10^{-1} M_{\text{sun}}$

Planet Formation

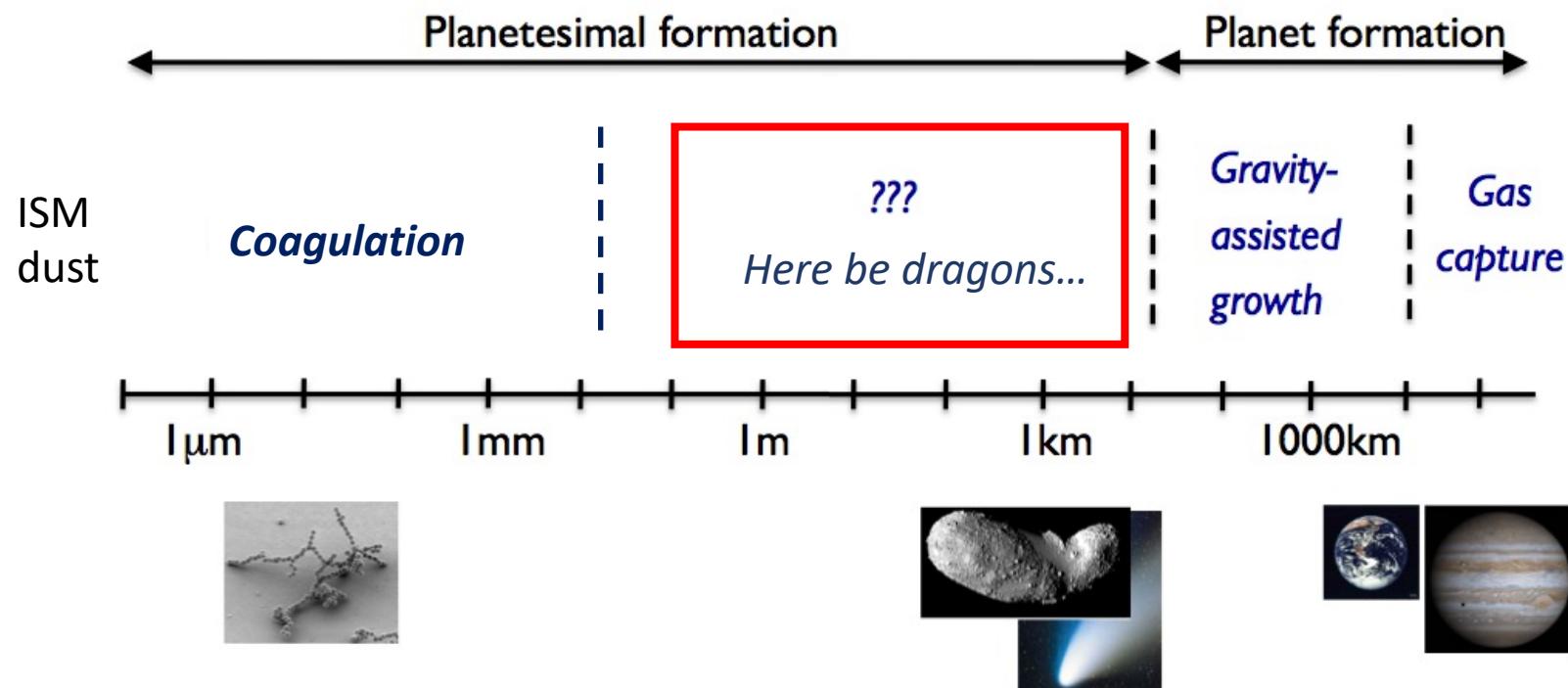
“Planets form in disks of gas and dust”



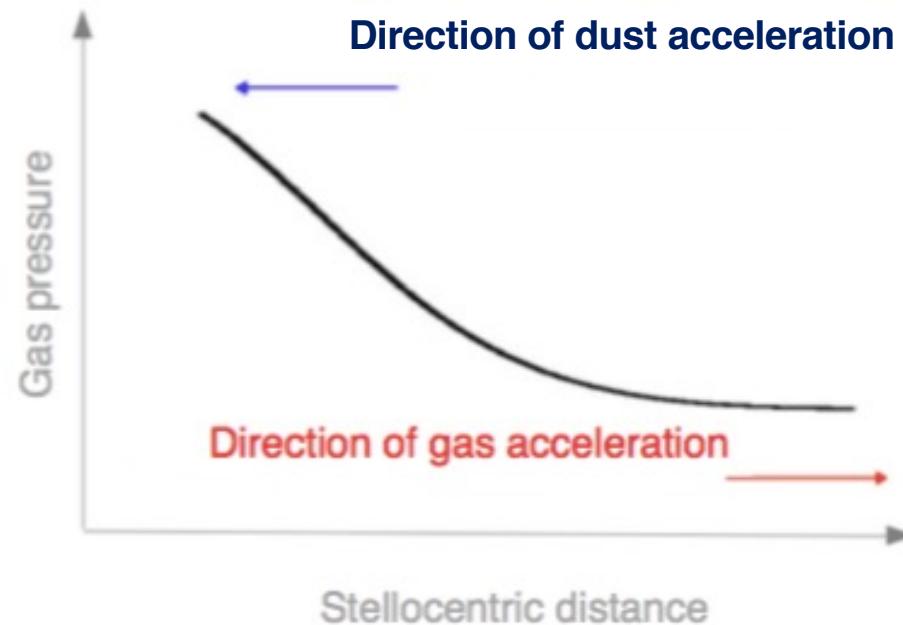
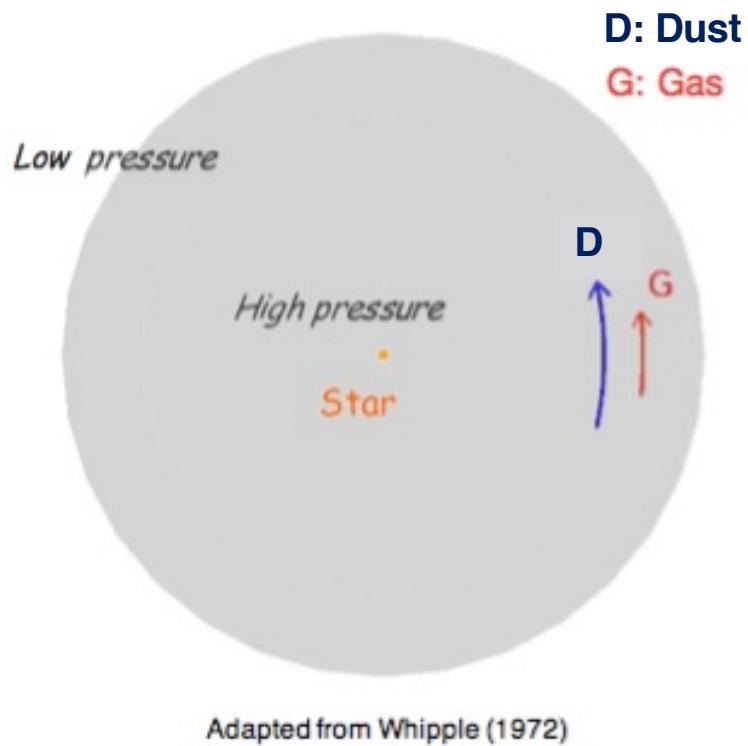
A miracle happens



Dust evolution



Dust Drift



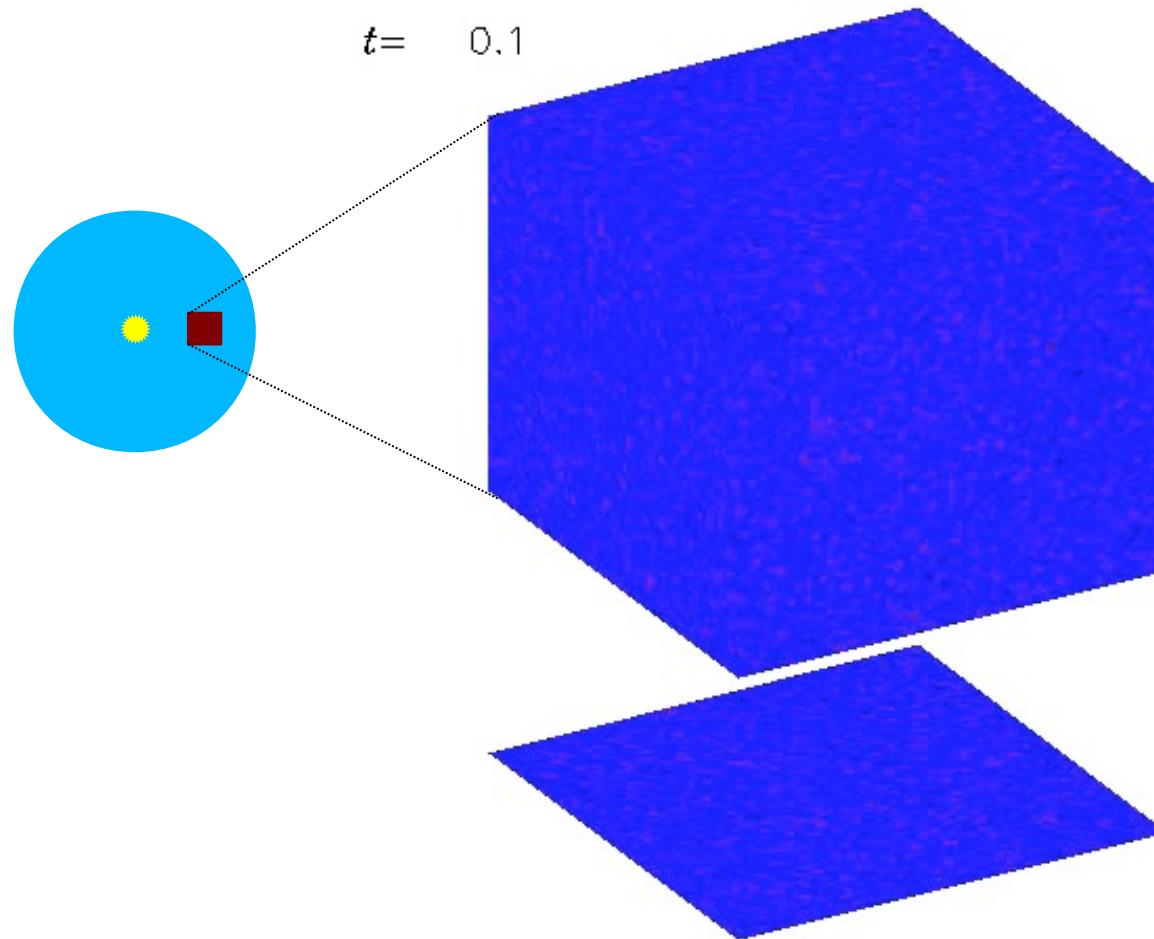
Dust coagulation and drift

Dust particle
coagulation
and radial drift

F. Brauer, C.P. Dullemond
Th. Henning

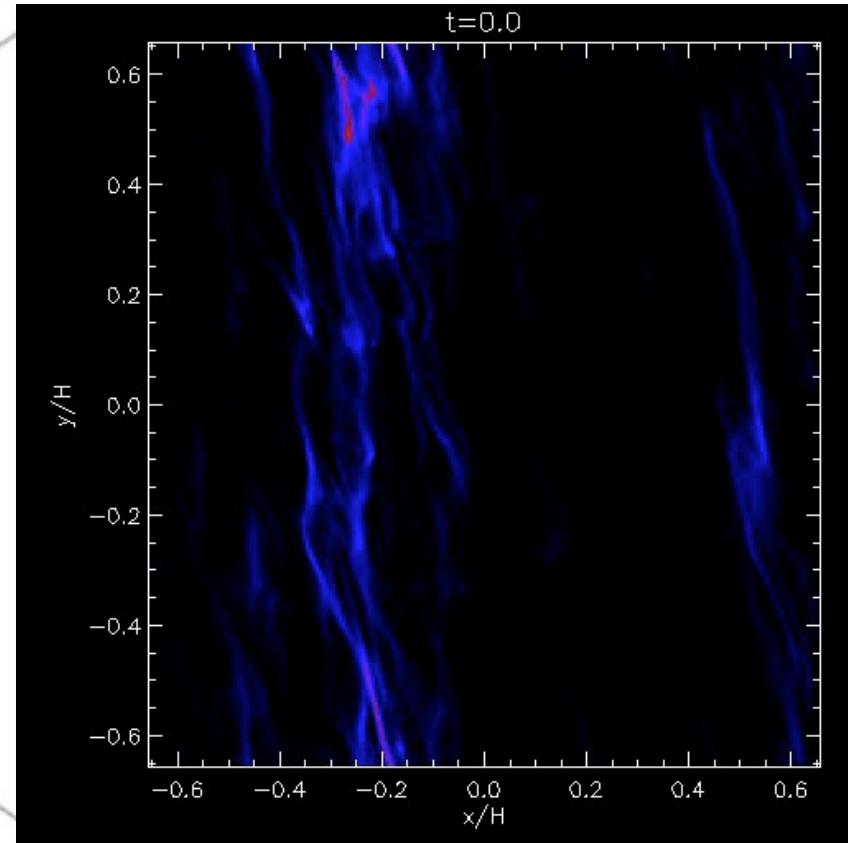
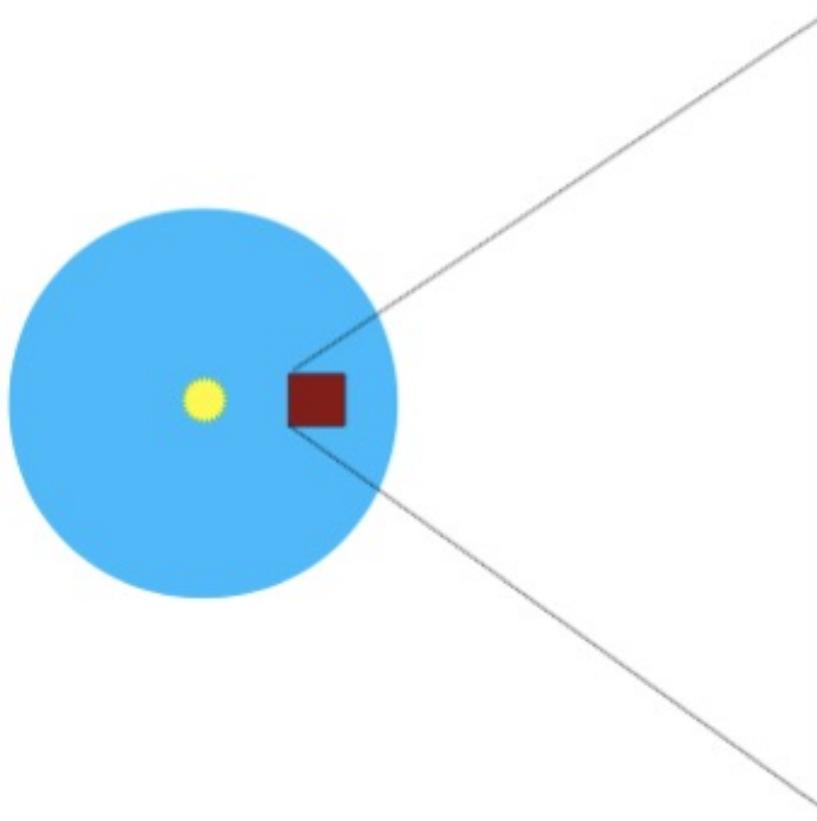
Streaming Instability

The dust drift is hydrodynamically unstable



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, Nesvorný+ '19

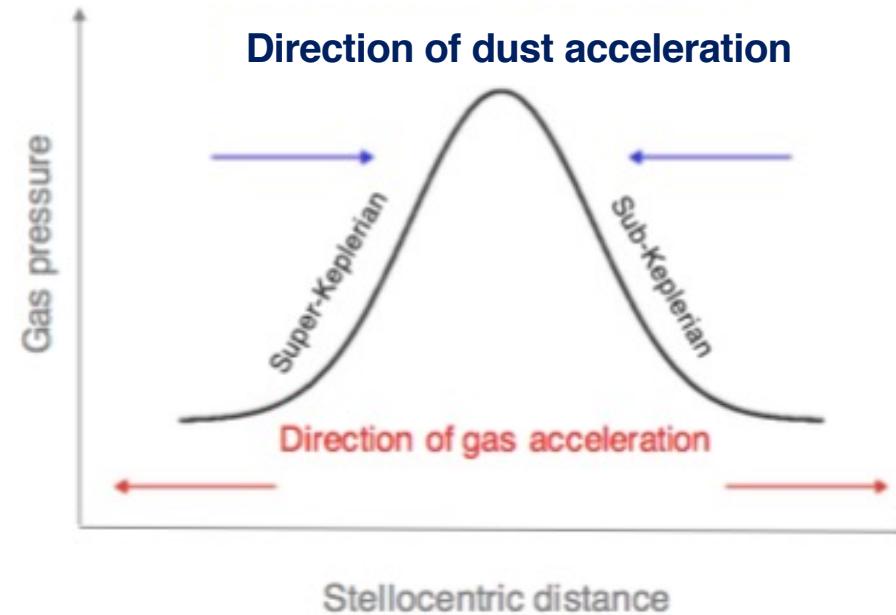
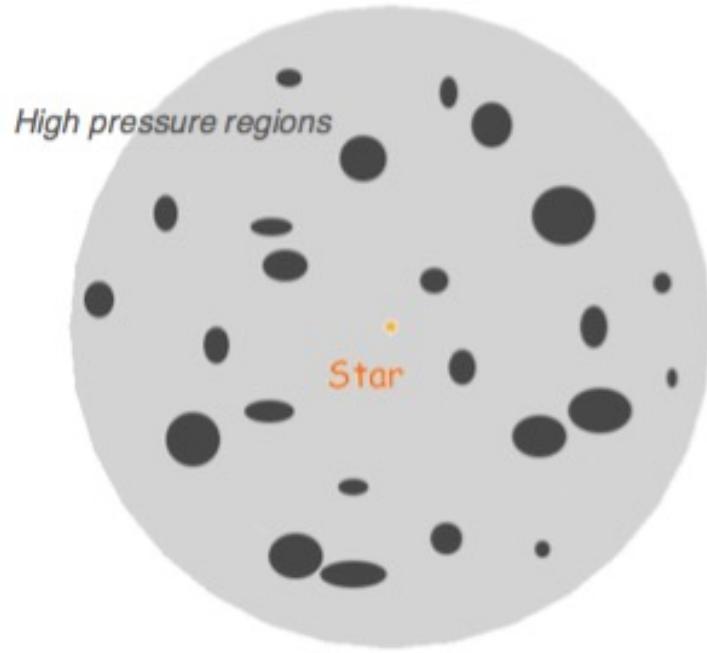
Gravitational collapse into planetesimals



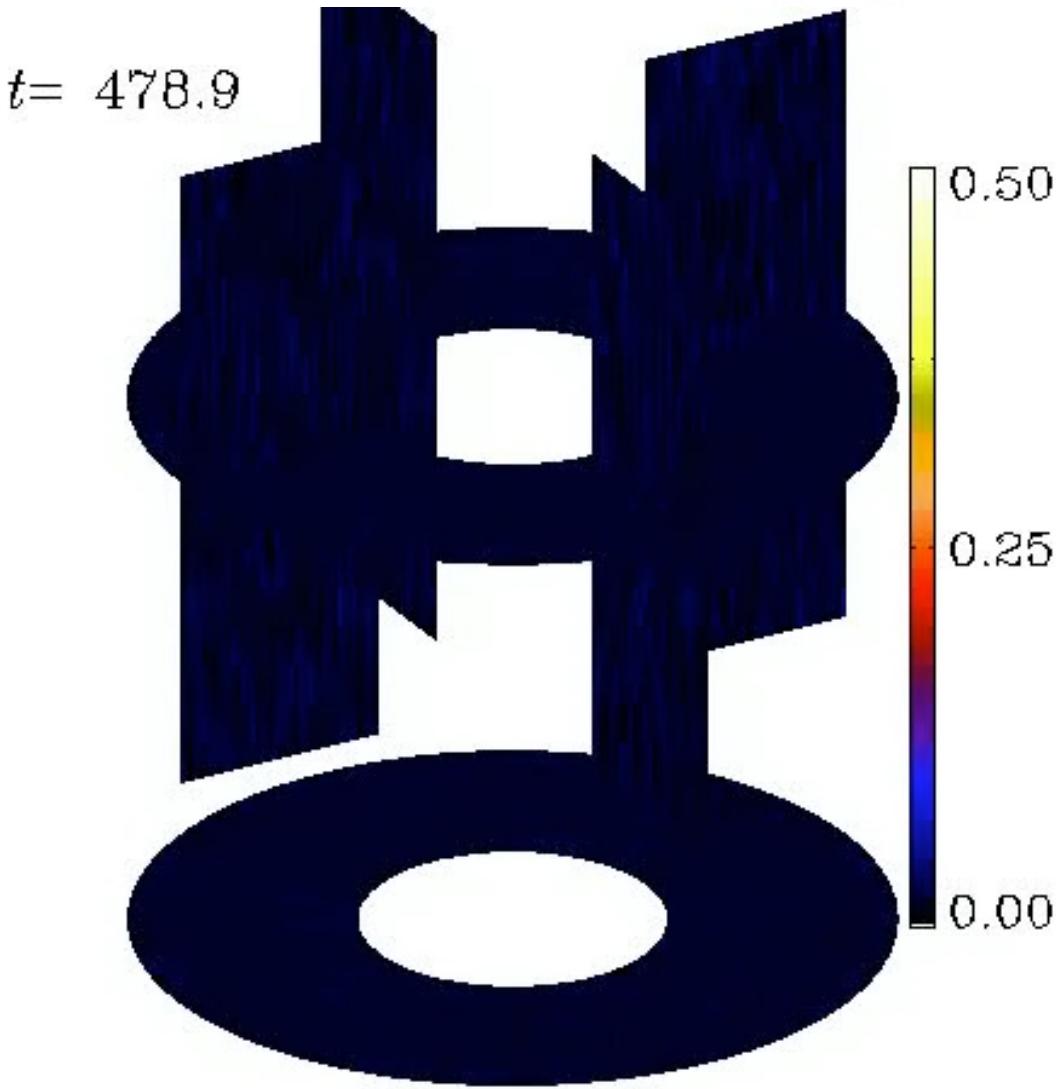
Johansen et al. (2007)

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

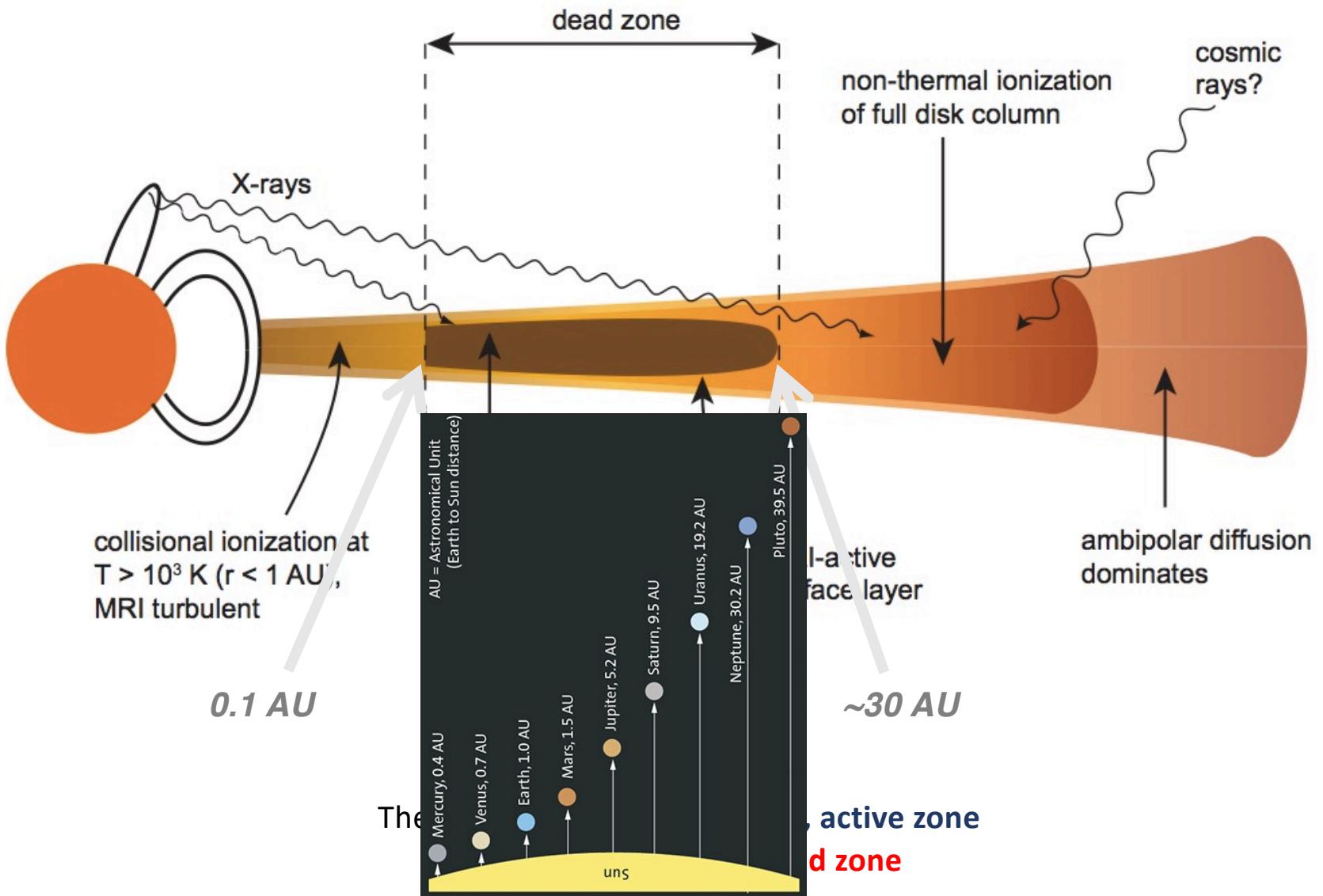
Turbulence



Turbulence concentrates solids mechanically in pressure maxima

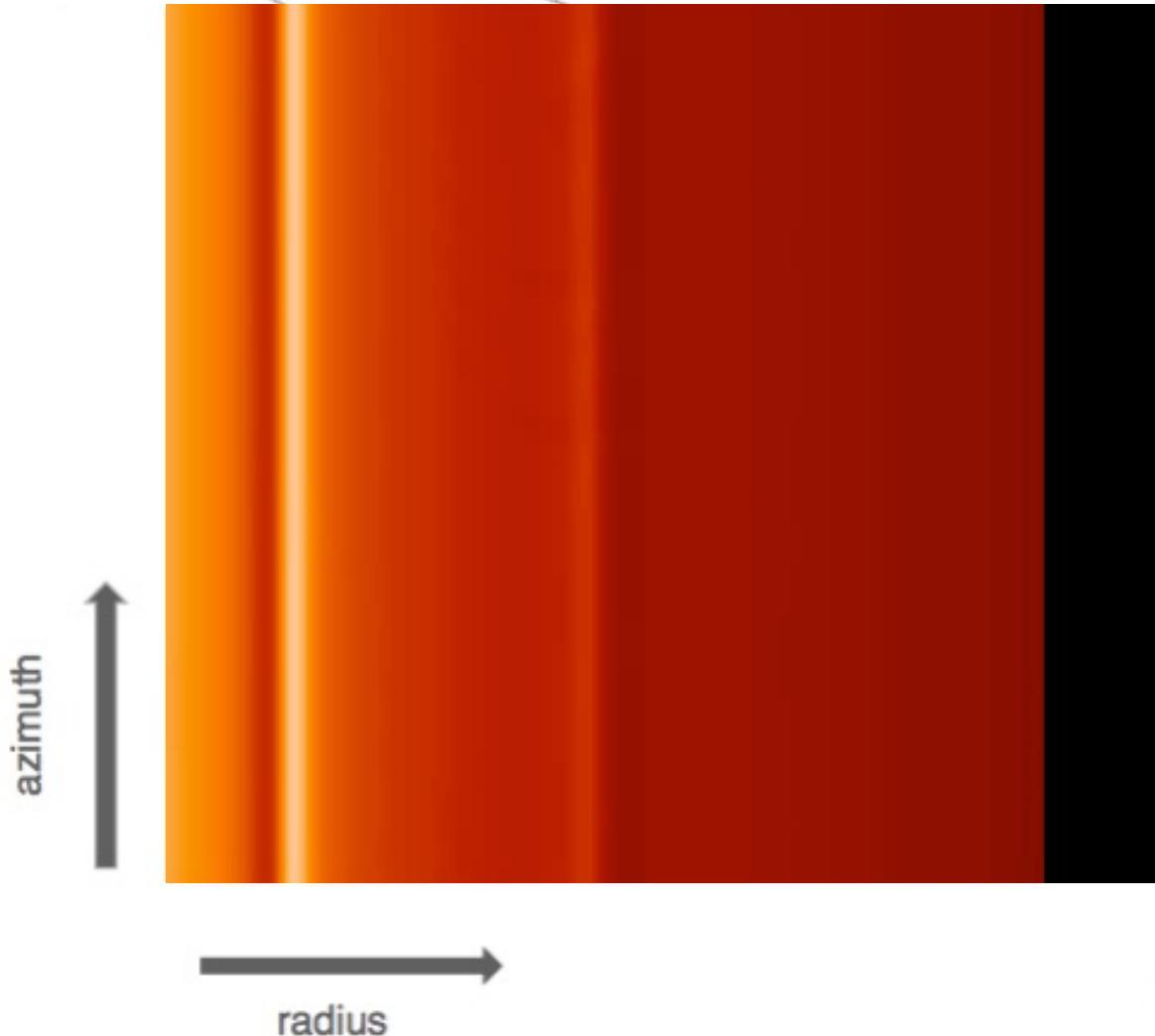


Dead zones



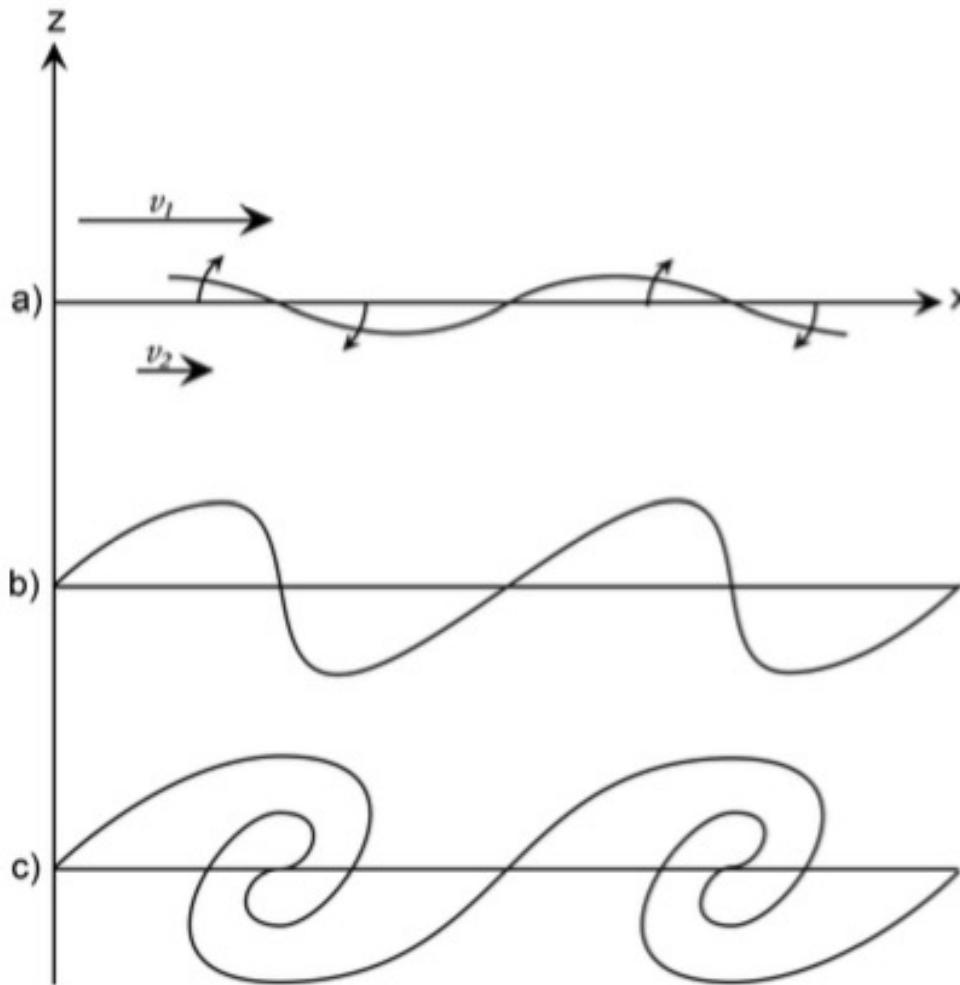


A simple dead zone model



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).

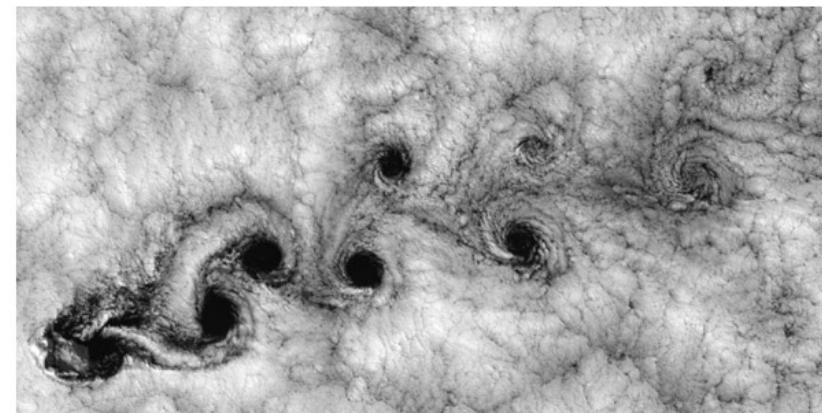
Rossby wave instability (Kelvin-Helmholtz Instability in rotating disks)



Vortices – an ubiquitous fluid mechanics phenomenon

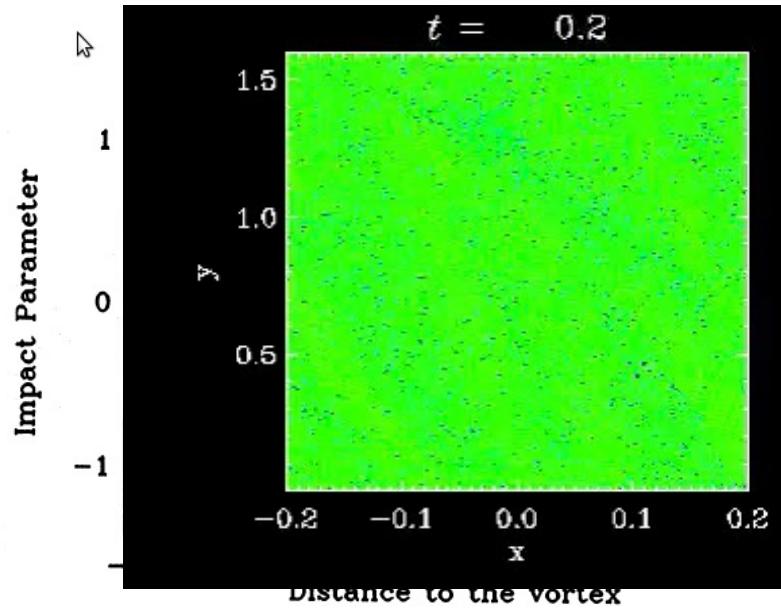
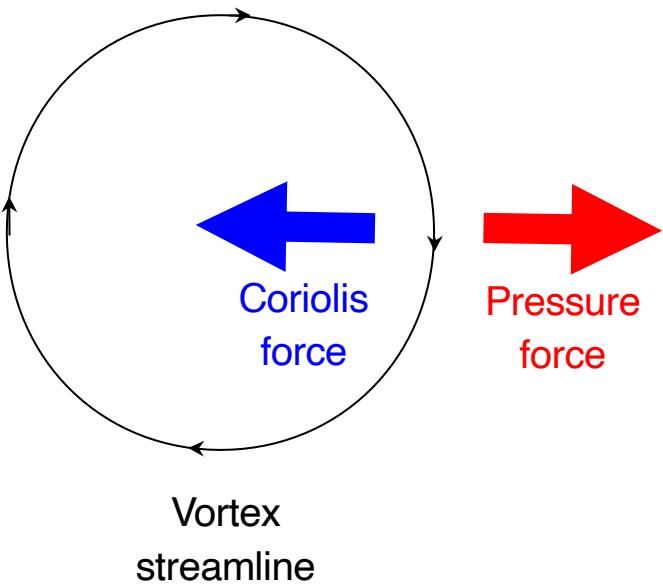


Von Kármán vortex street



Vortex Trapping

Geostrophic balance:



Barge & Sommeria (1995)

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

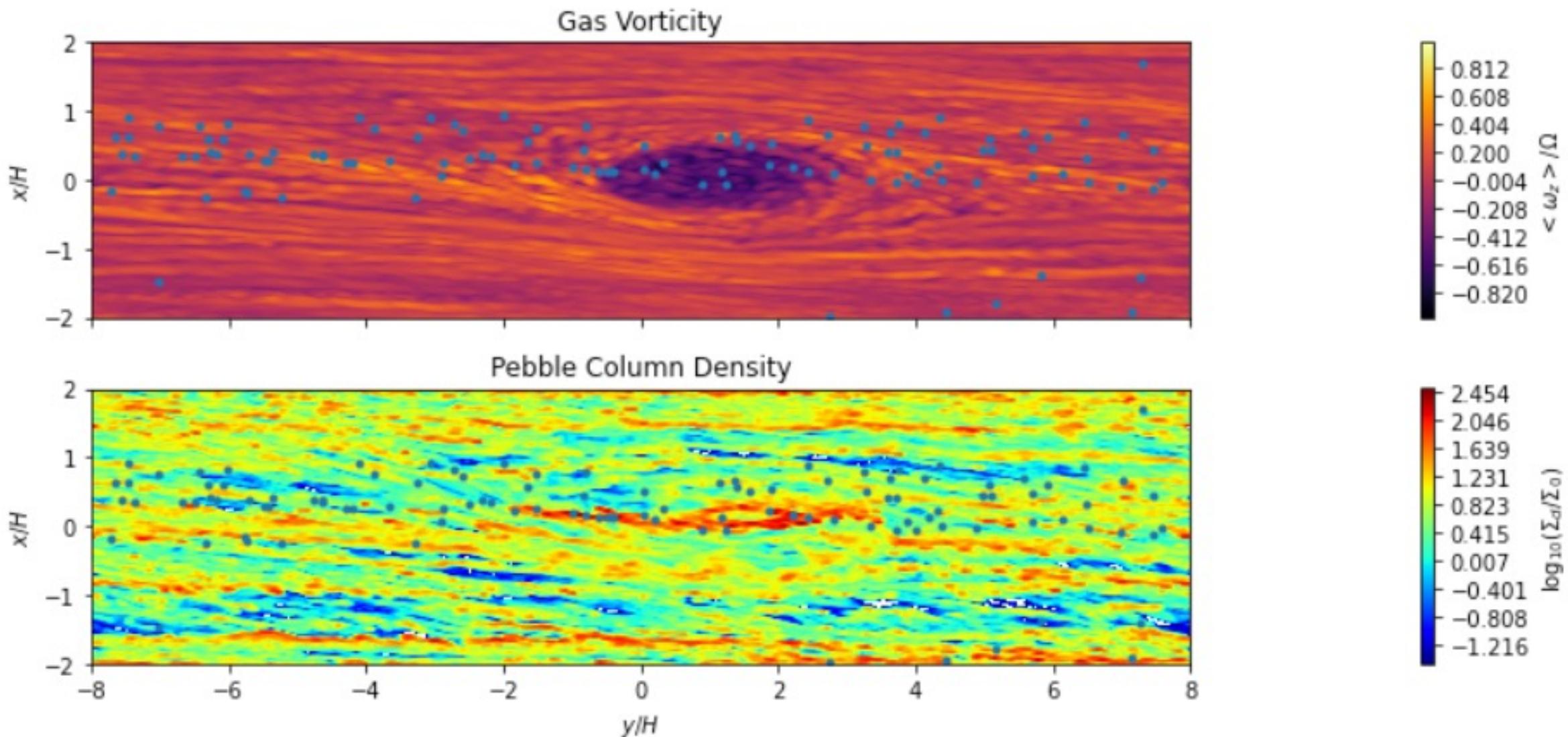
Aid to planet formation

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

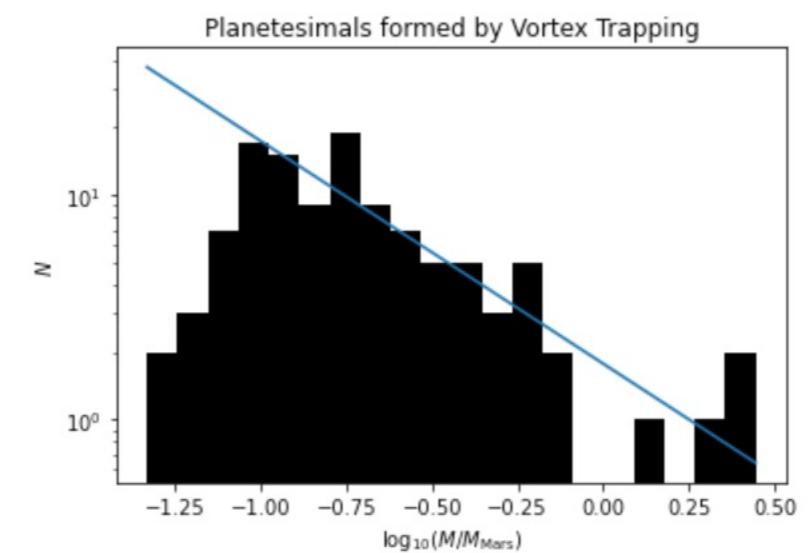
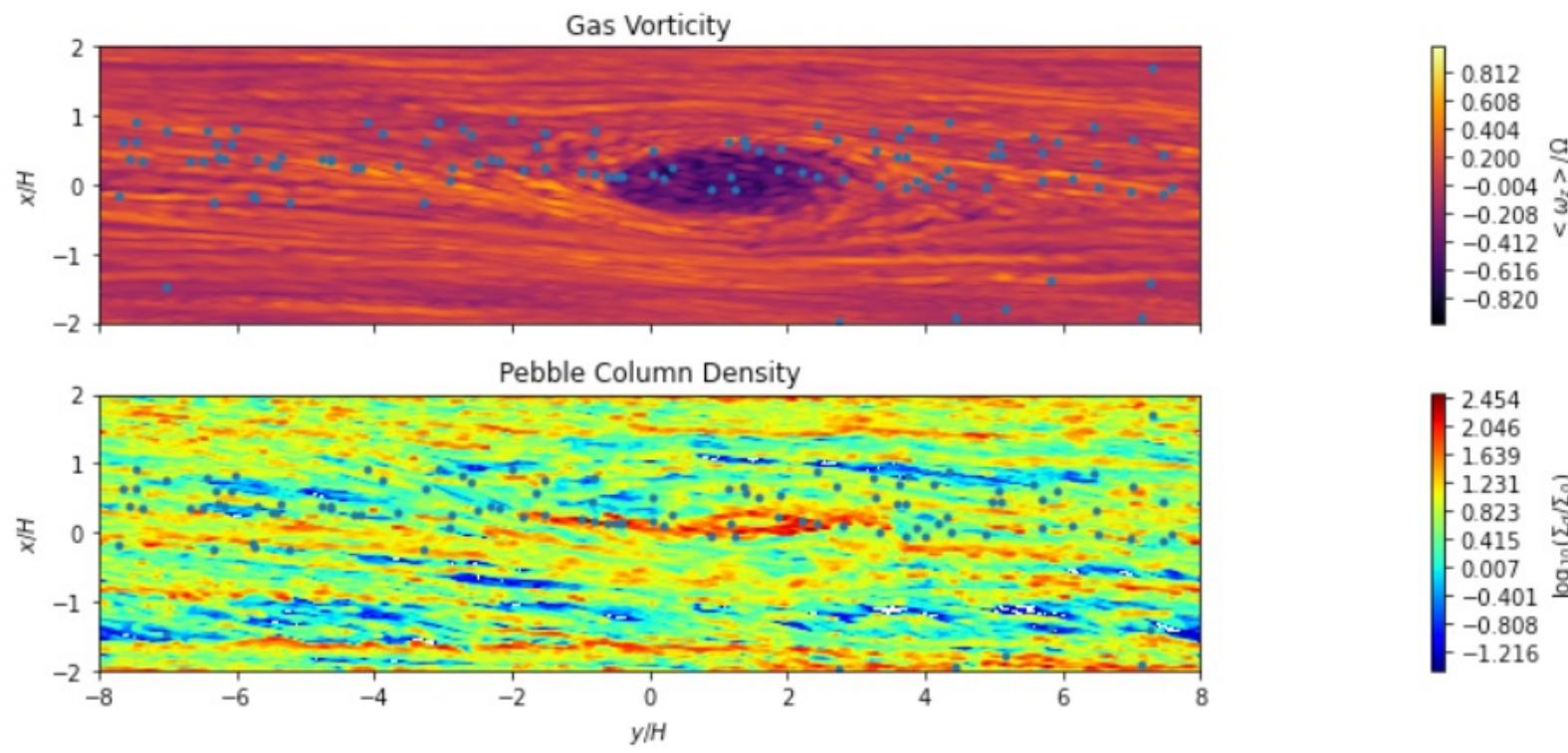
Speeds up planet formation enormously

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

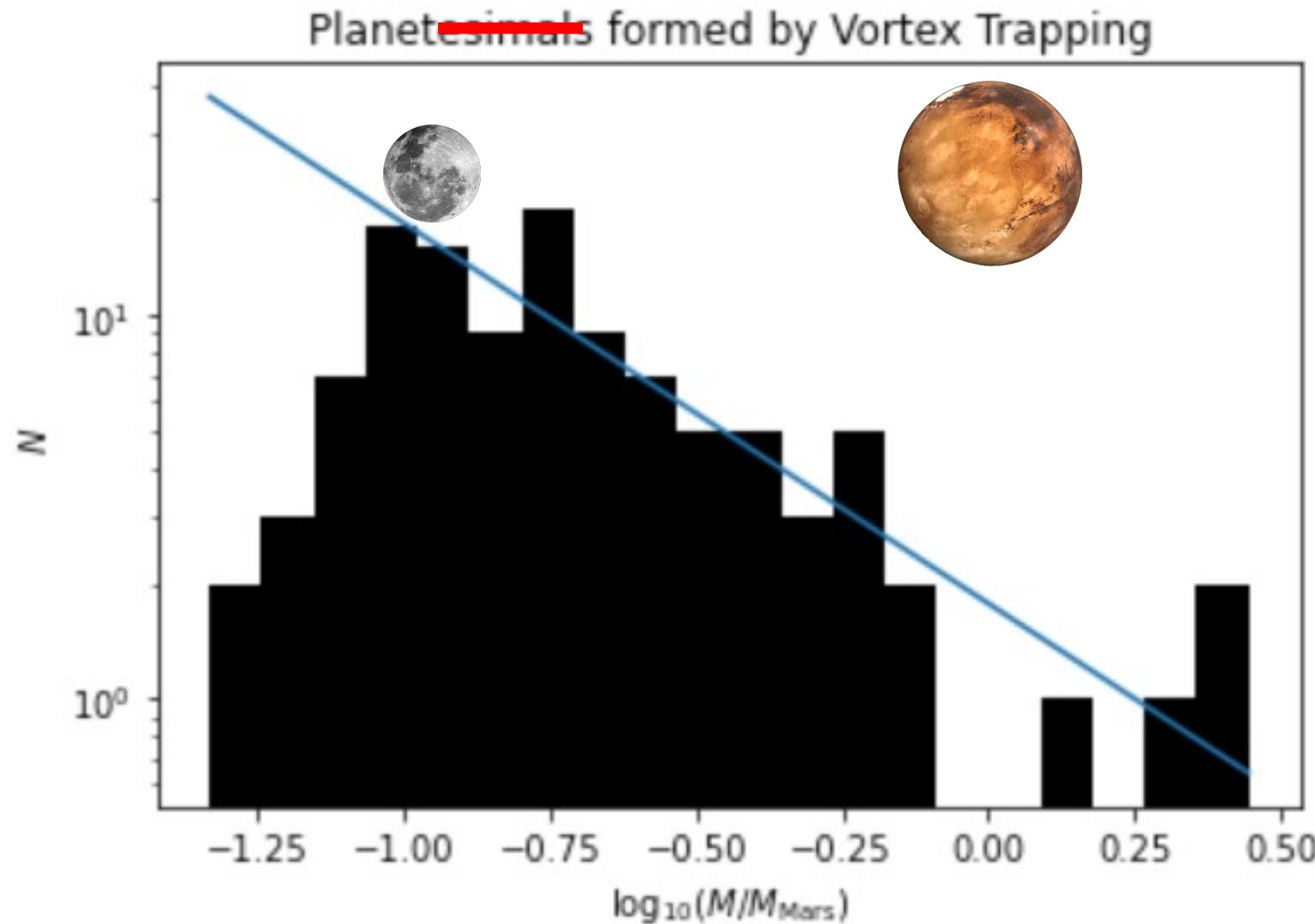
Planetesimal Formation



Planet Formation



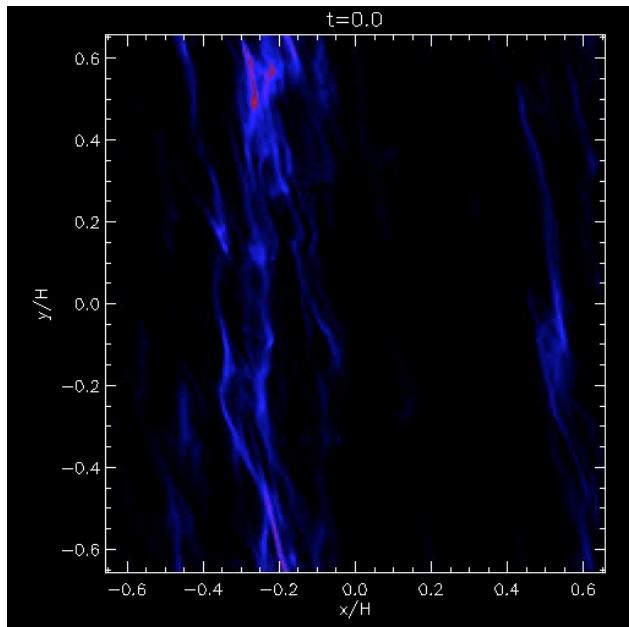
Initial Mass Function



Take home message

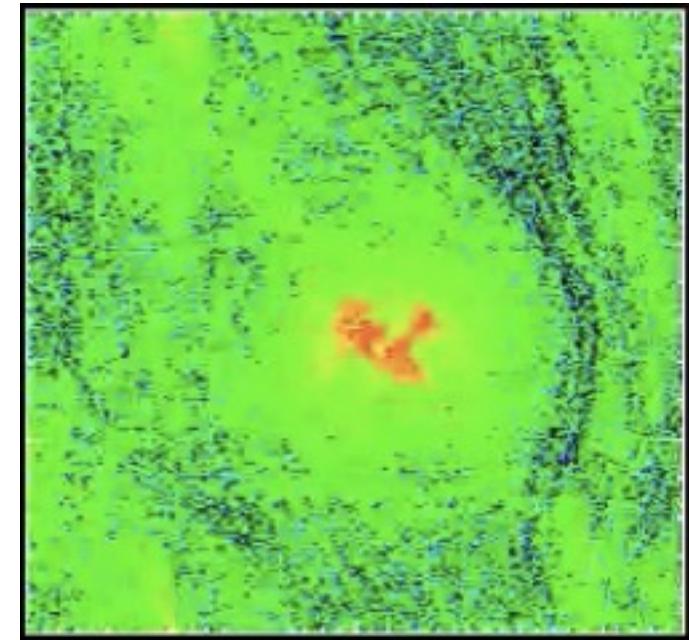
- Two routes for planet formation

Streaming Instability



Johansen+ 07

Vortex Trapping

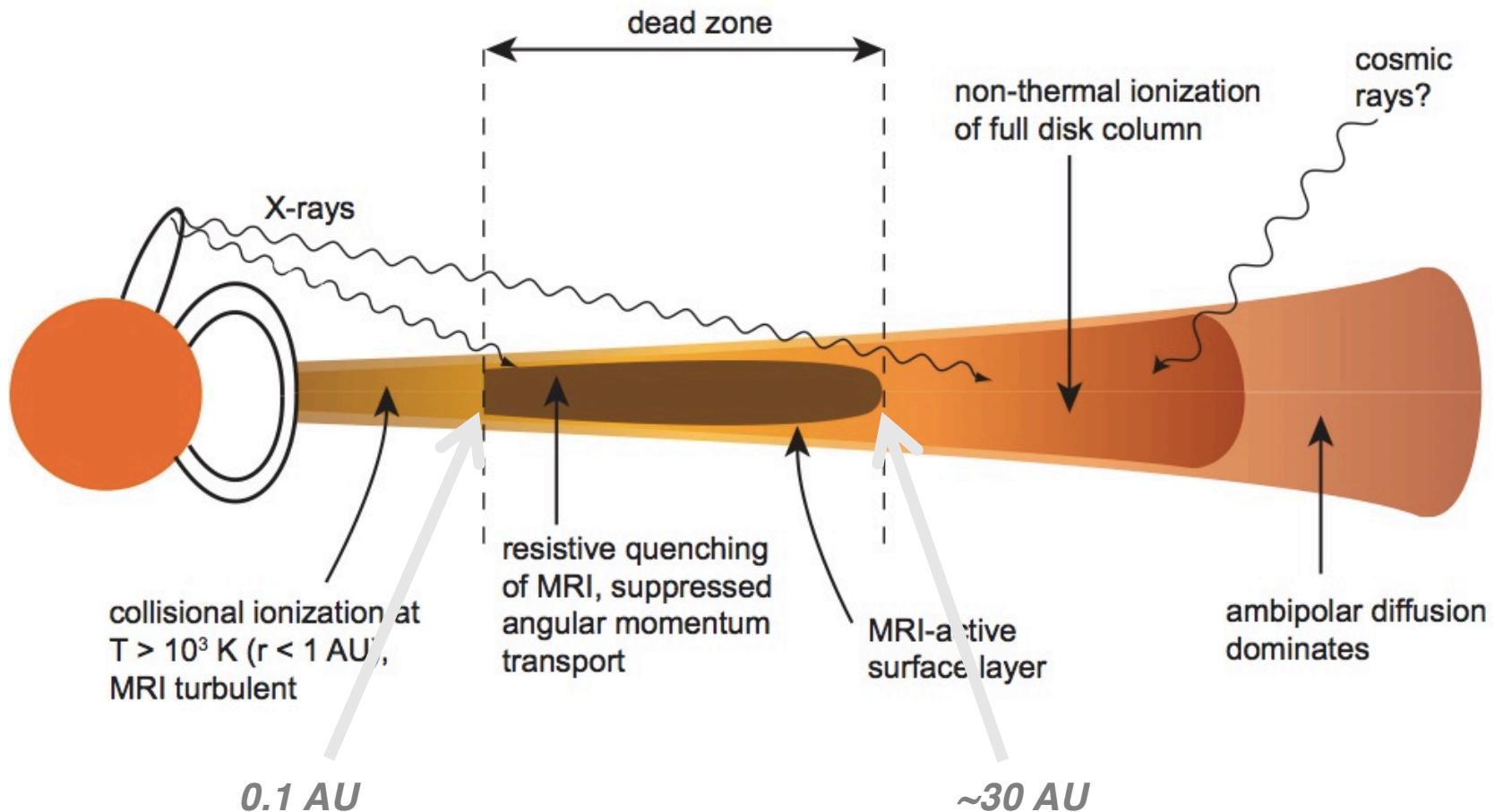


Lyra+08, Raettig+Lyra 12

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

Part 2: Disk Instabilities

Dead zones

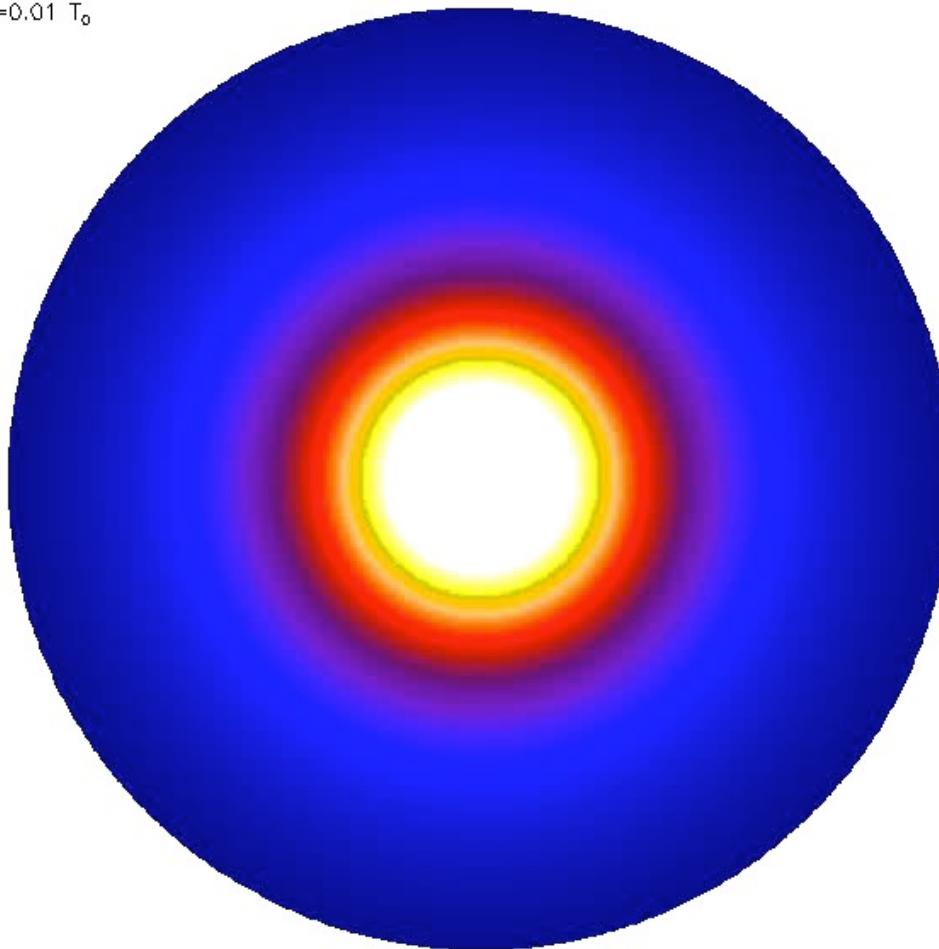


There should be a **magnetized, active zone**
and a **non-magnetic, dead zone**



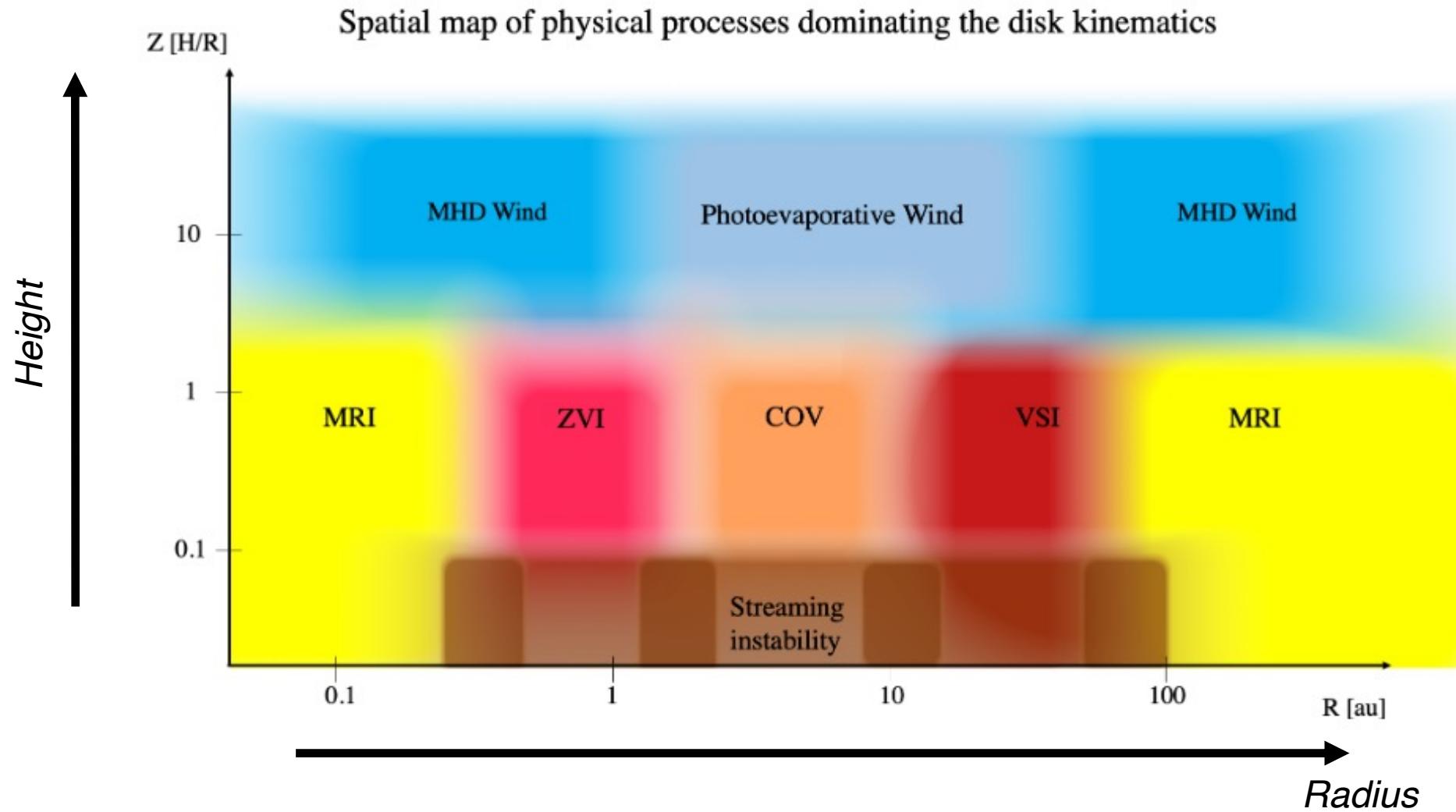
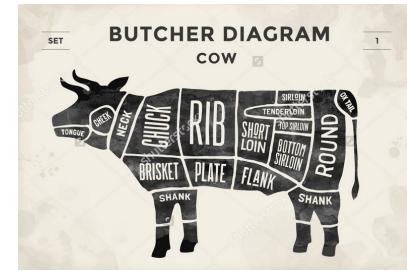
Inner (0.1 AU) active/dead zone boundary

$t=0.01 T_0$



Magnetized inner disk + resistive outer disk
Lyra & Mac Low (2012)

Instability Map

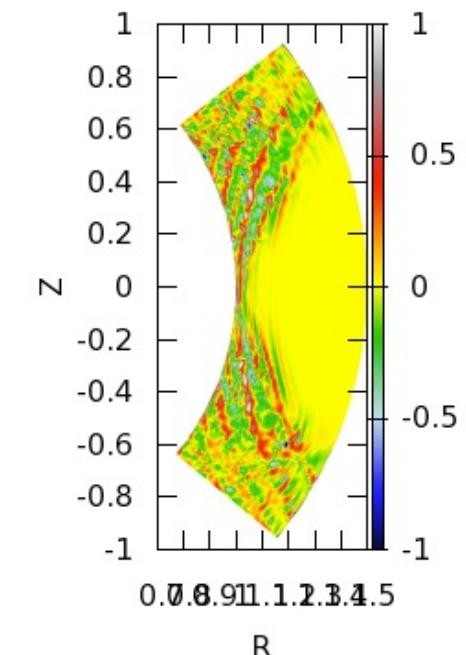
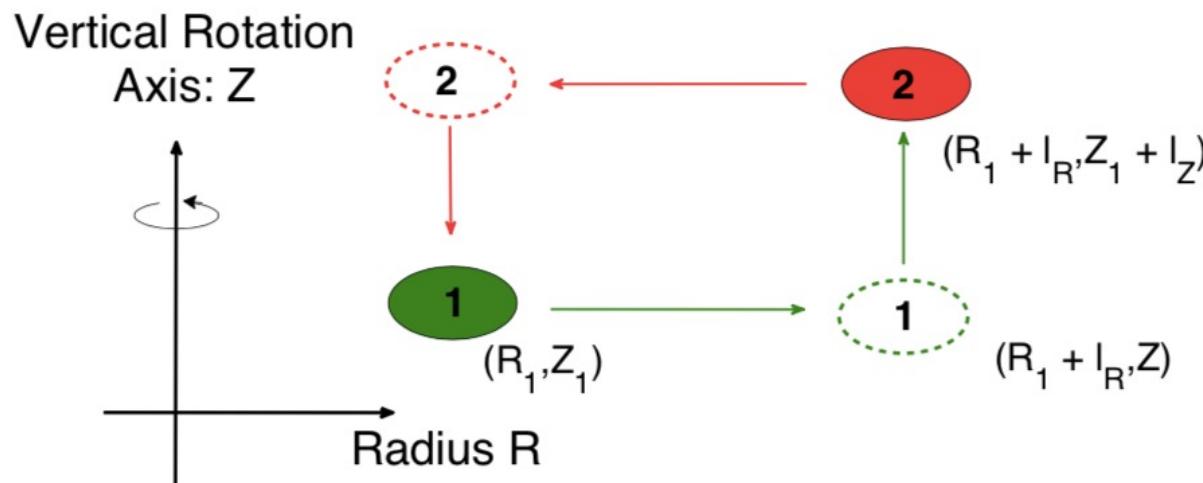
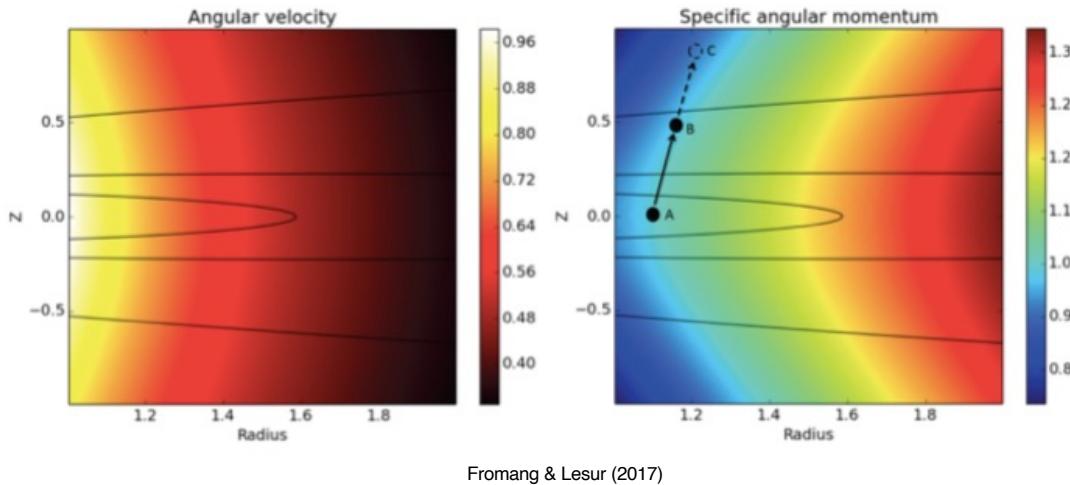


Lesur et al. (2021)

Vertical shear instability

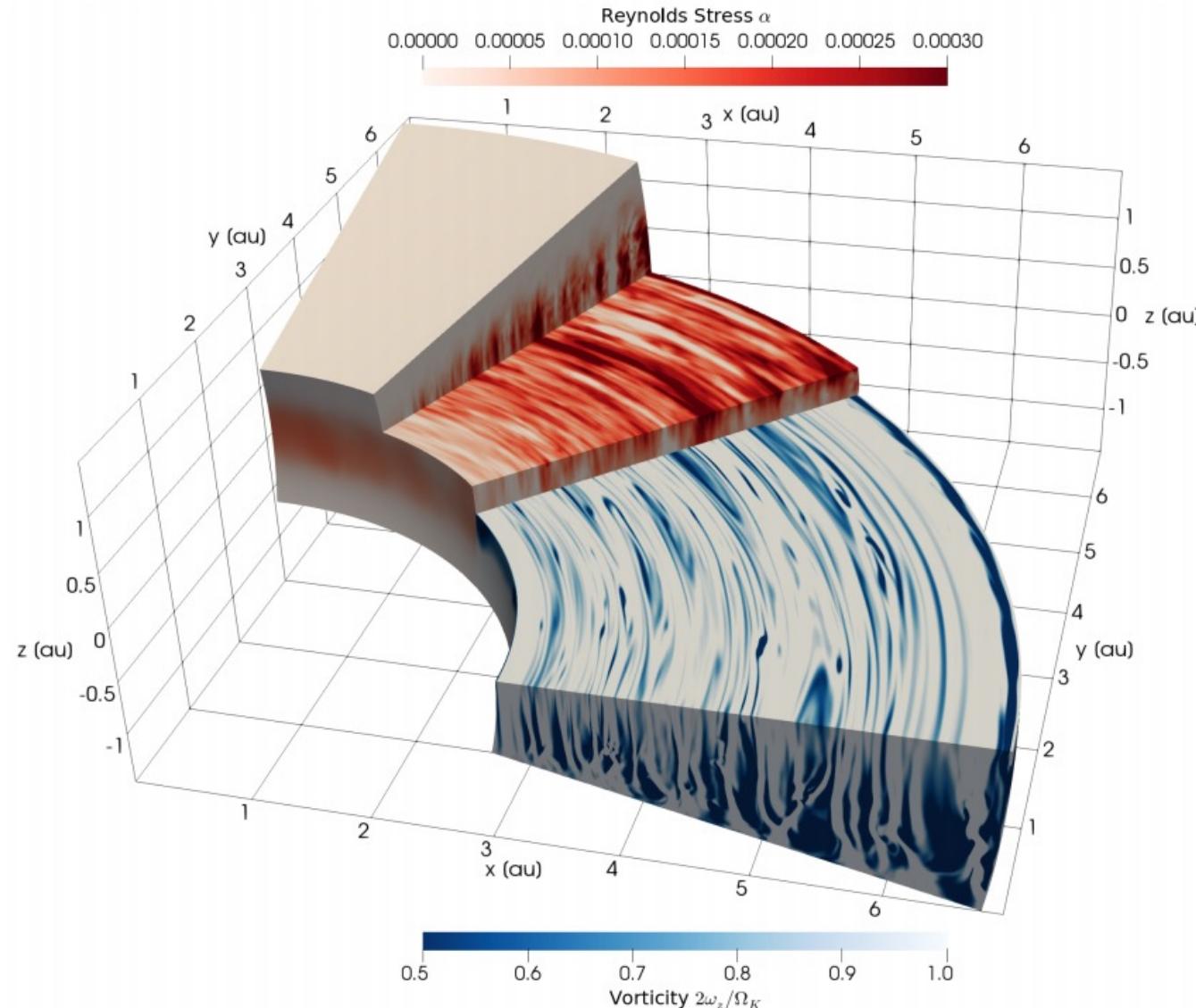
Angular velocity not constant in cylinders: unstable

Buoyancy stabilizes! The most unstable mode is isothermal.



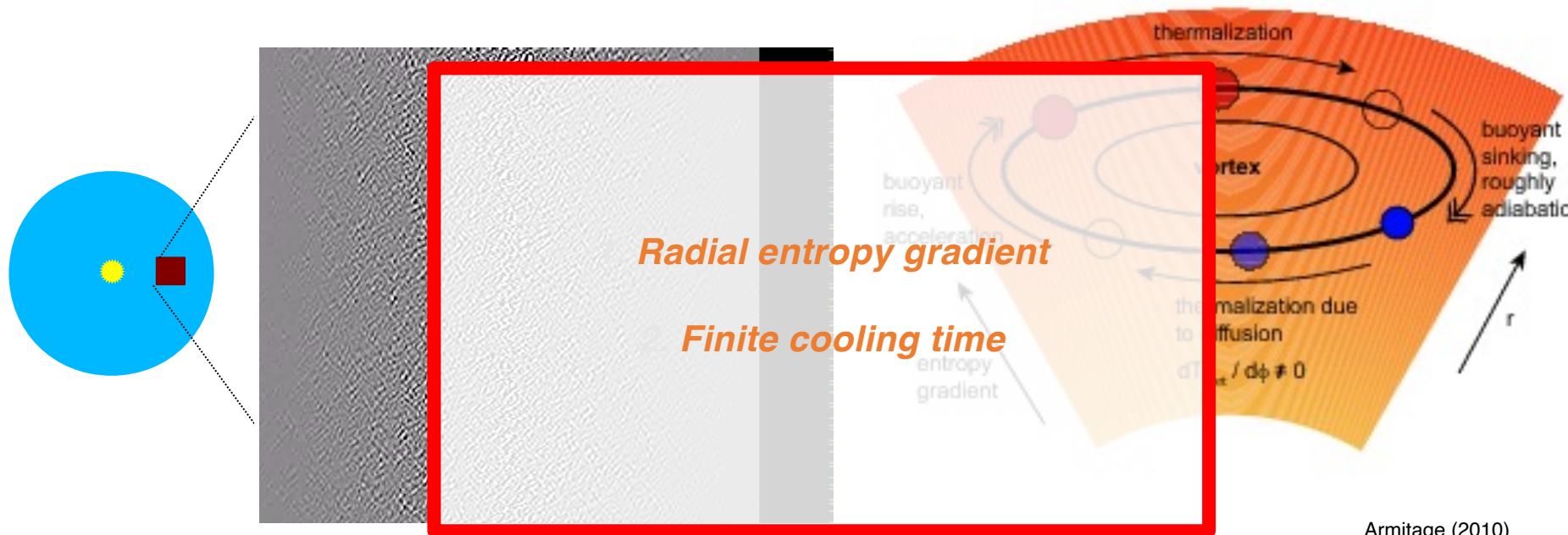
Nelson et al. (2013)

Vertical shear instability



Convective Overstability

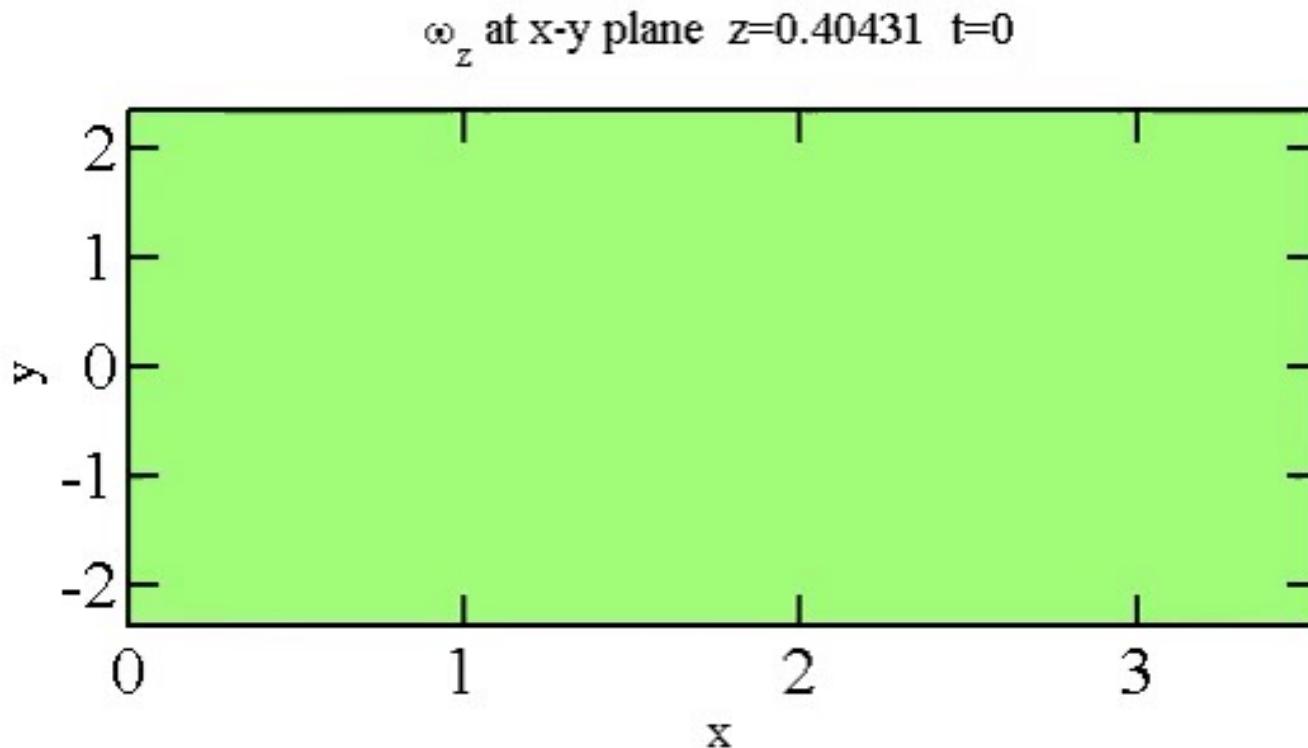
Sketch of the
Convective Overstability



Lesur & Papaloizou (2010)

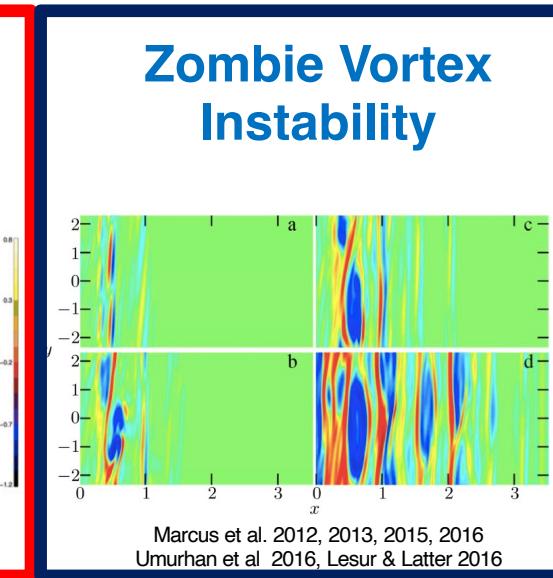
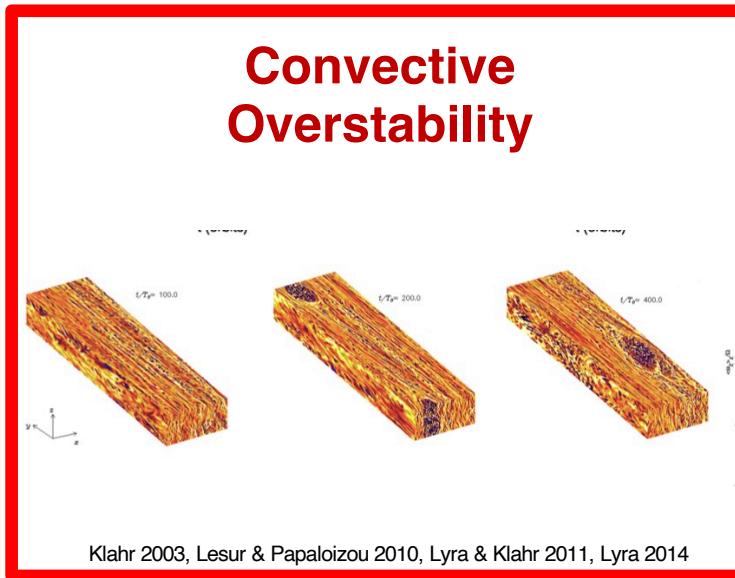
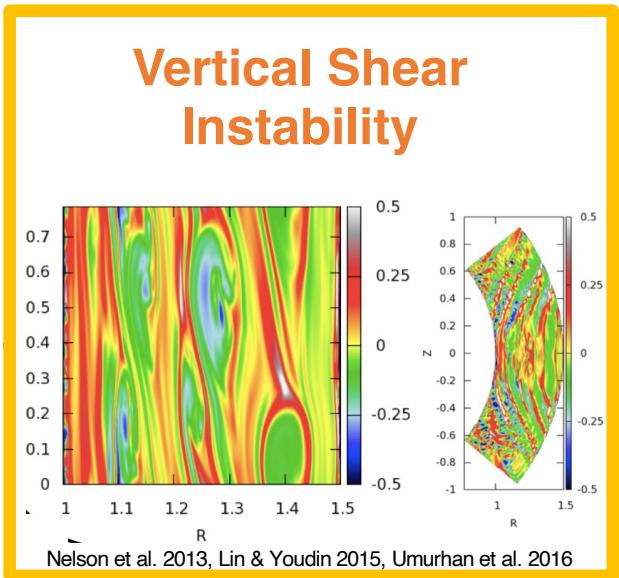
Lyra & Klahr (2011)

Zombie Vortex Instability



Cascade of baroclinic critical layers

Hydrodynamical Instabilities



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

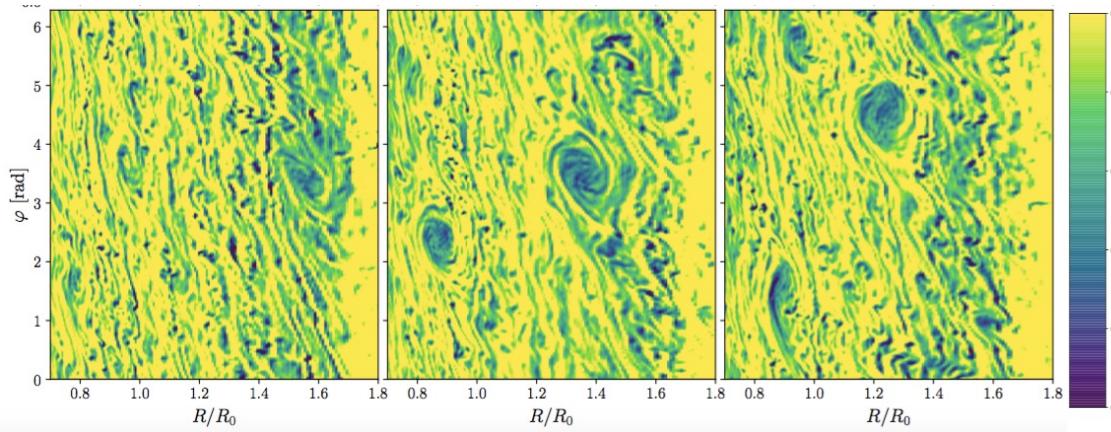
$\Omega\tau \sim 1$
($\kappa \sim 1\text{--}50 \text{ cm}^2/\text{g}$)

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



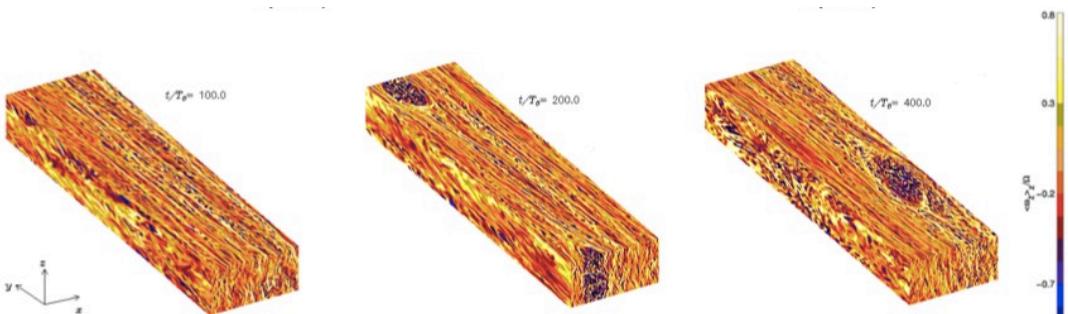
Opacity

Take-home message



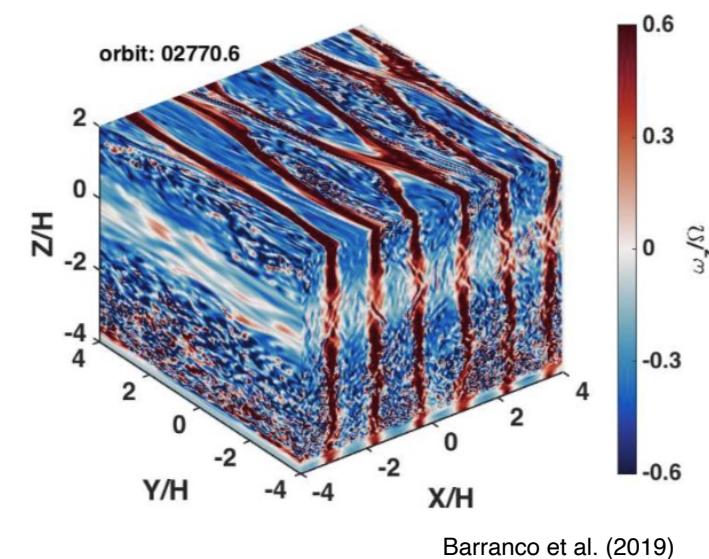
Manger & Klahr (2018)

Vertical Shear Instability
saturates into
vortices



Lyra (2014)

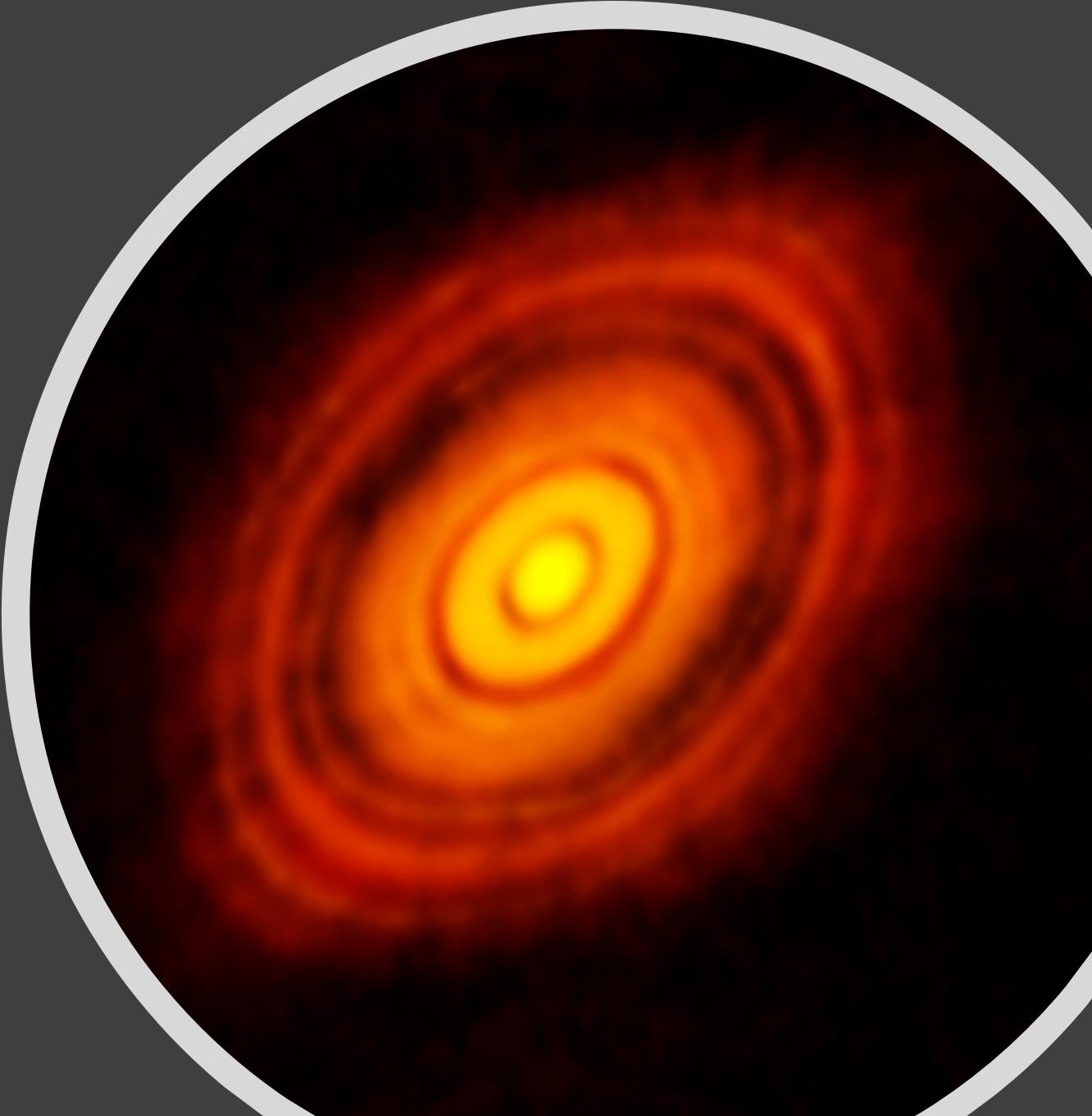
Zombie Vortex Instability
saturates into
vortices



Barranco et al. (2019)

Convective Overinstability
saturates into
vortices

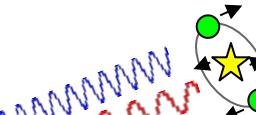
Part 3: Disk Observations



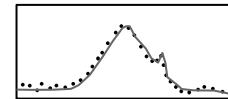
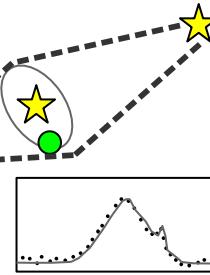
Transits



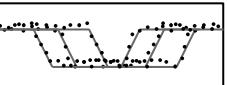
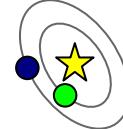
Radial velocities



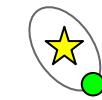
Microlensing



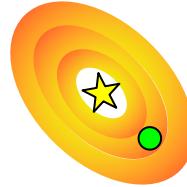
Timing variations



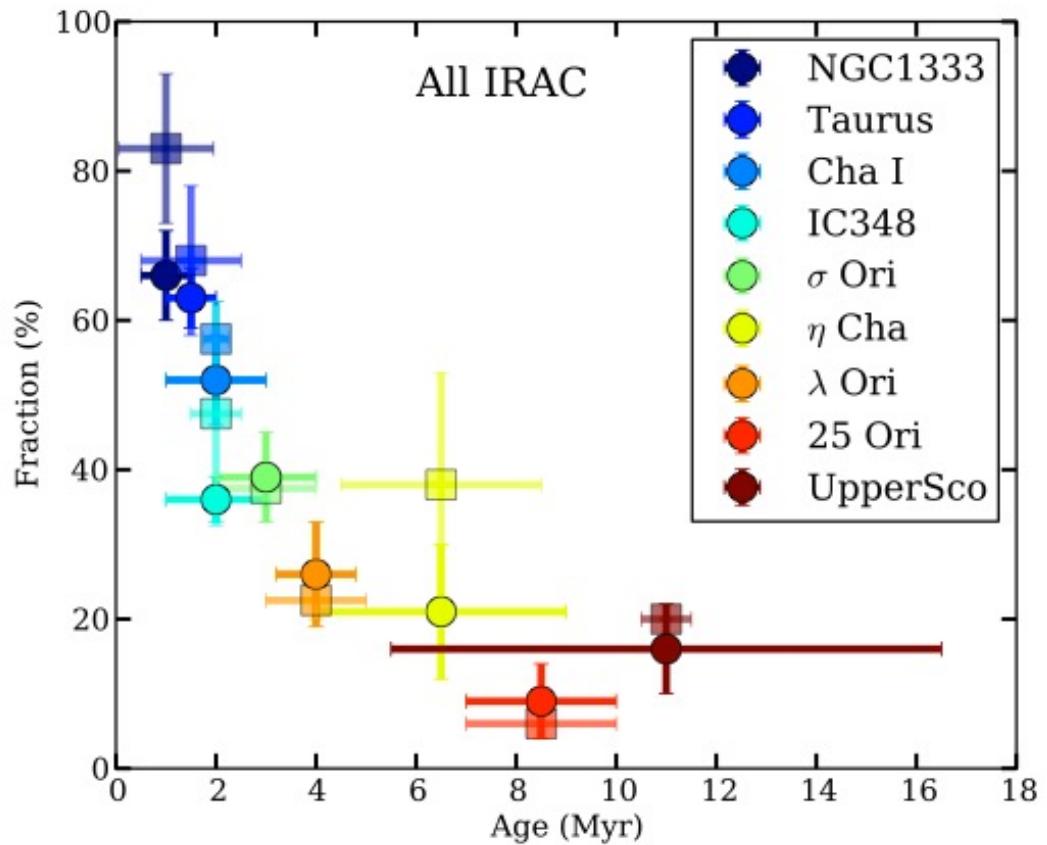
Direct imaging



Disk interactions



Disk lifetime

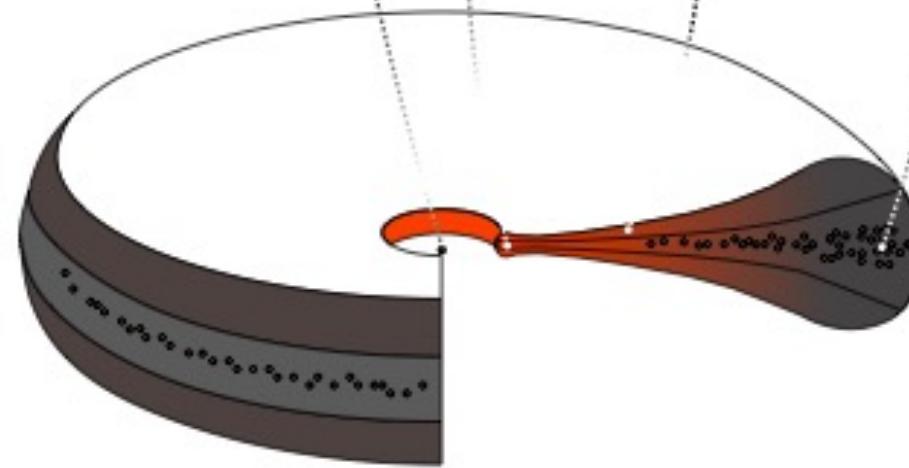
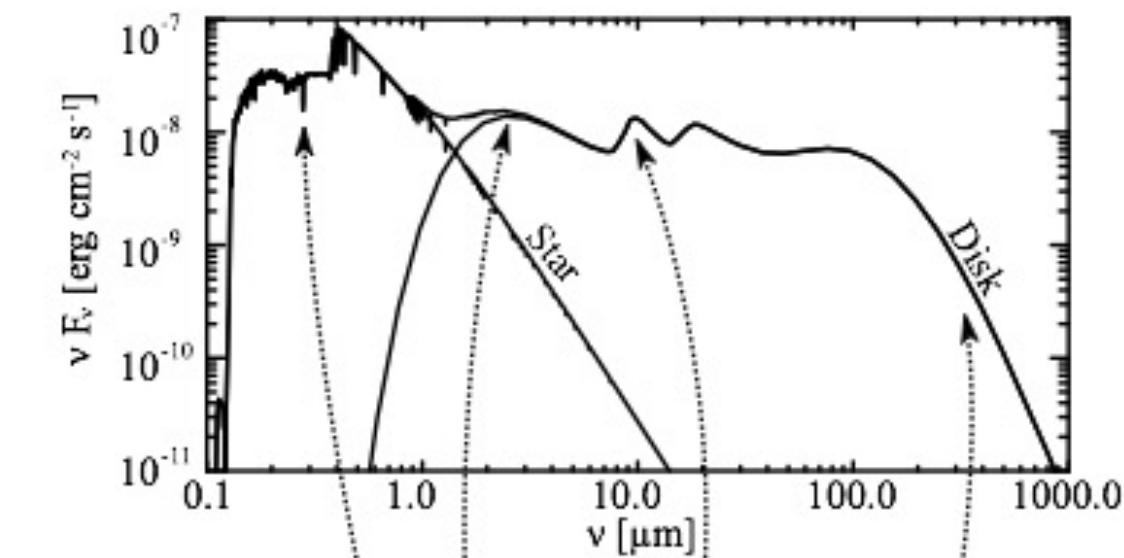


(Ribas et al. 2014)

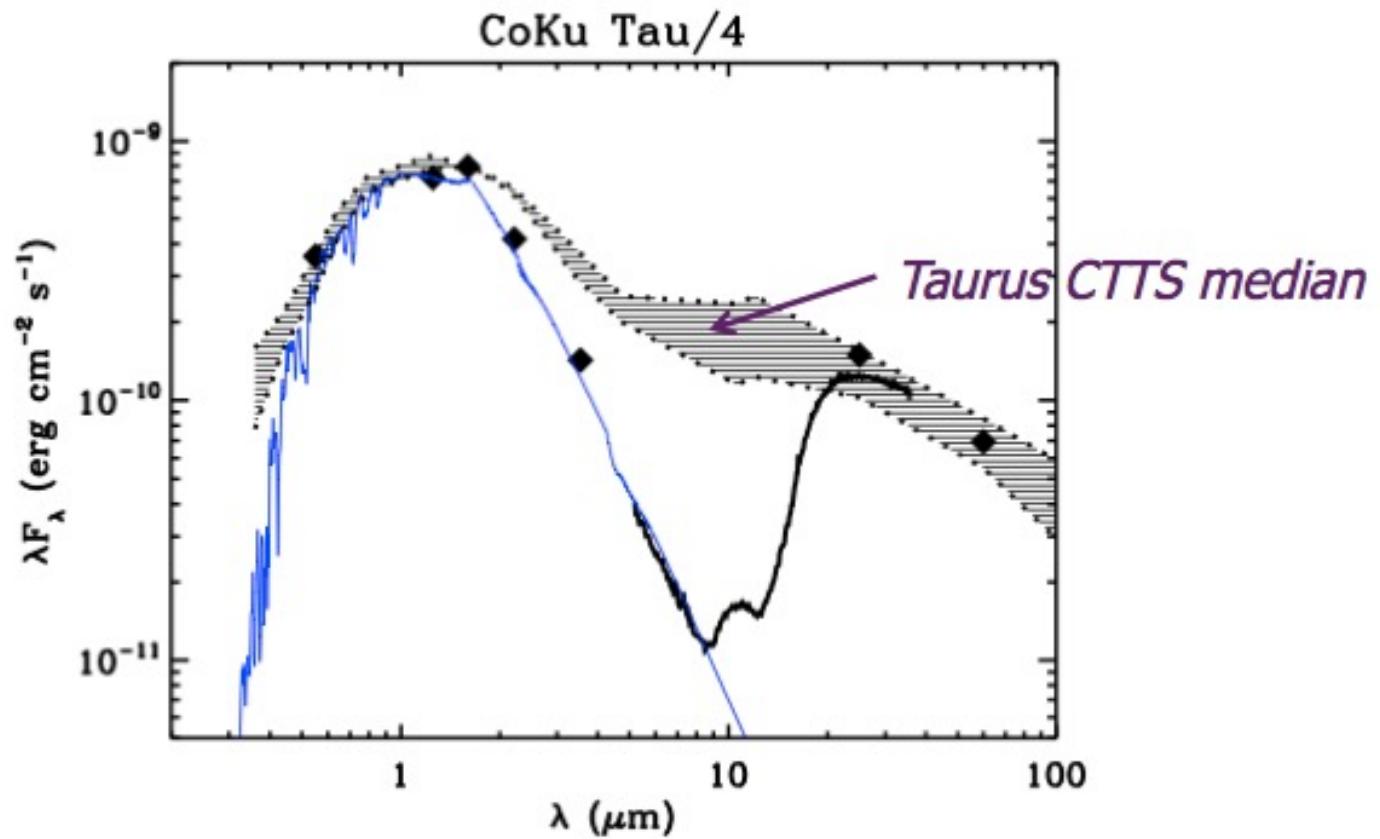


Disks dissipate within ~10Myr

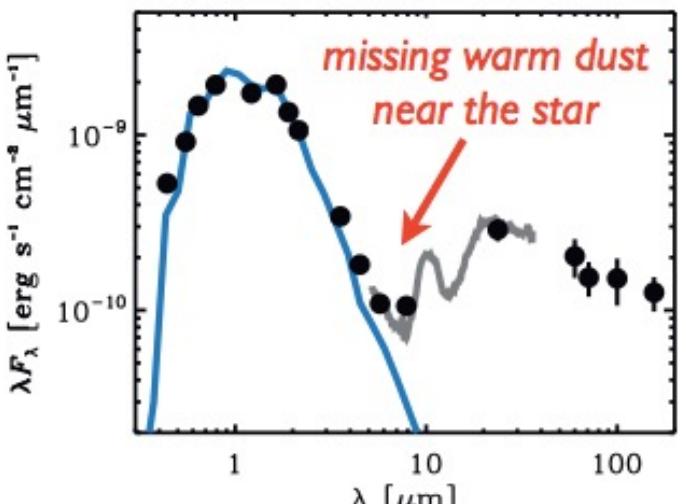
Disk spectra



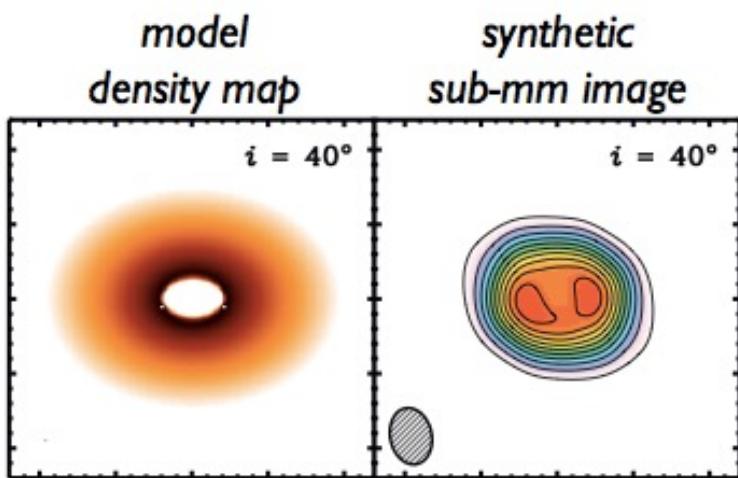
A class of disks with missing hot dust.



Disks with missing hot dust.



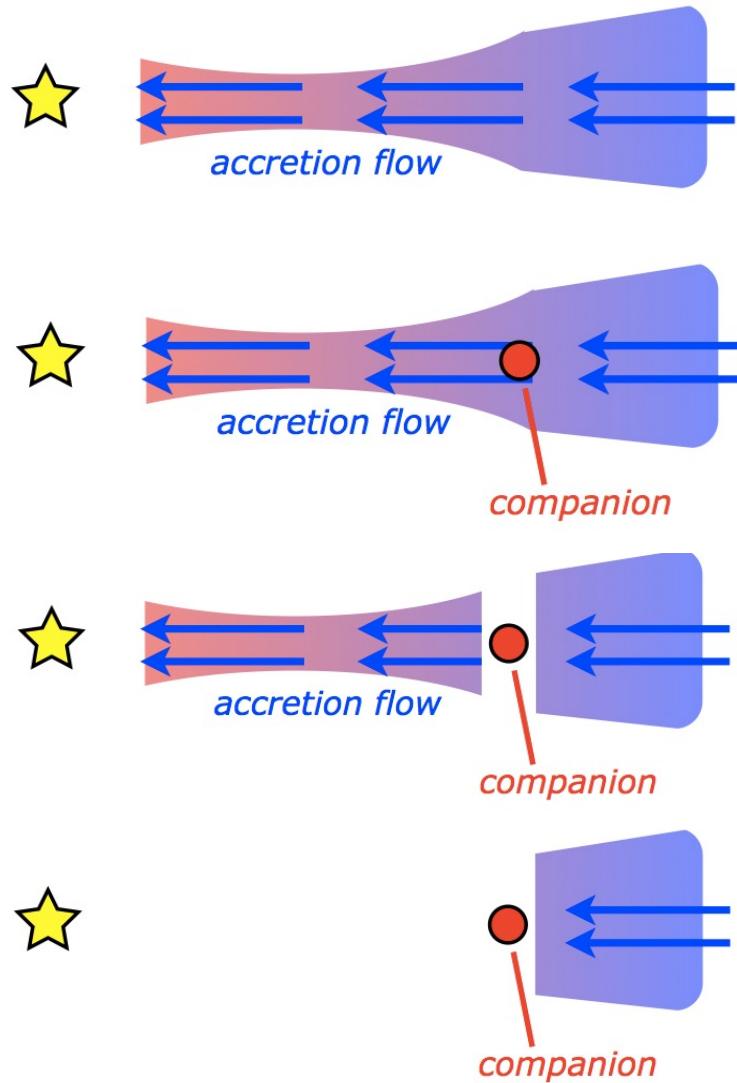
[e.g., Furlan et al. 2009]



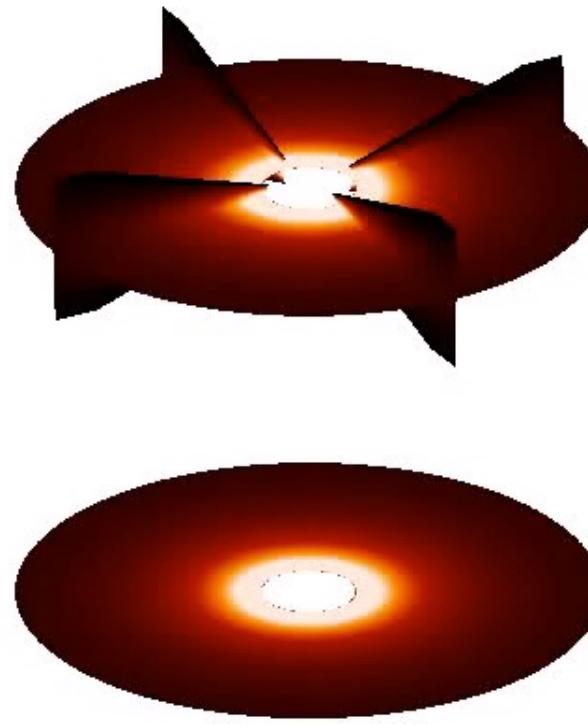
a disk with a large reduction
in optical depth near the star
(i.e., a “cavity” or “hole”)



Planetary companion



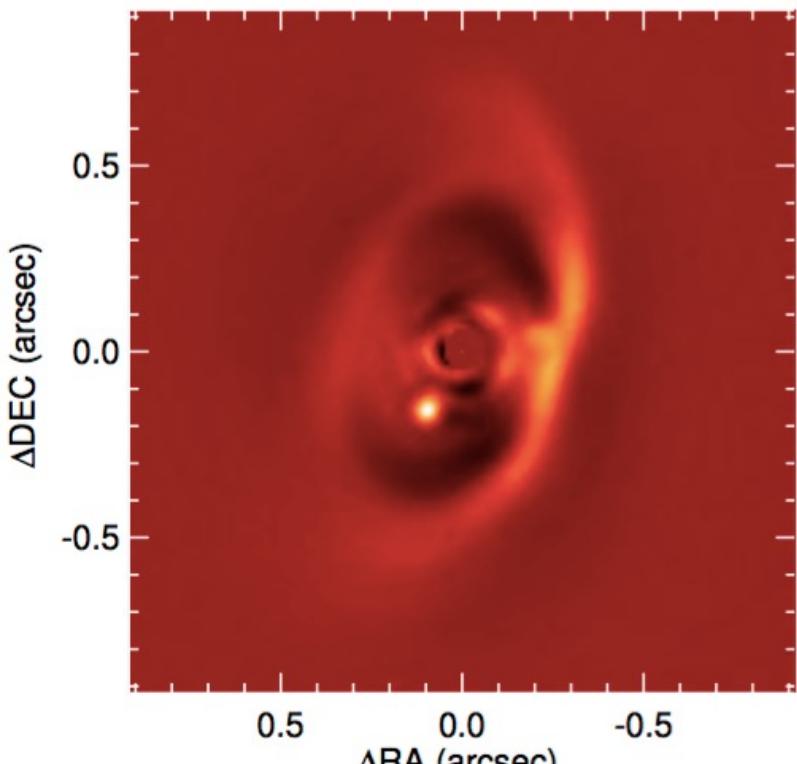
$t = 0.1$



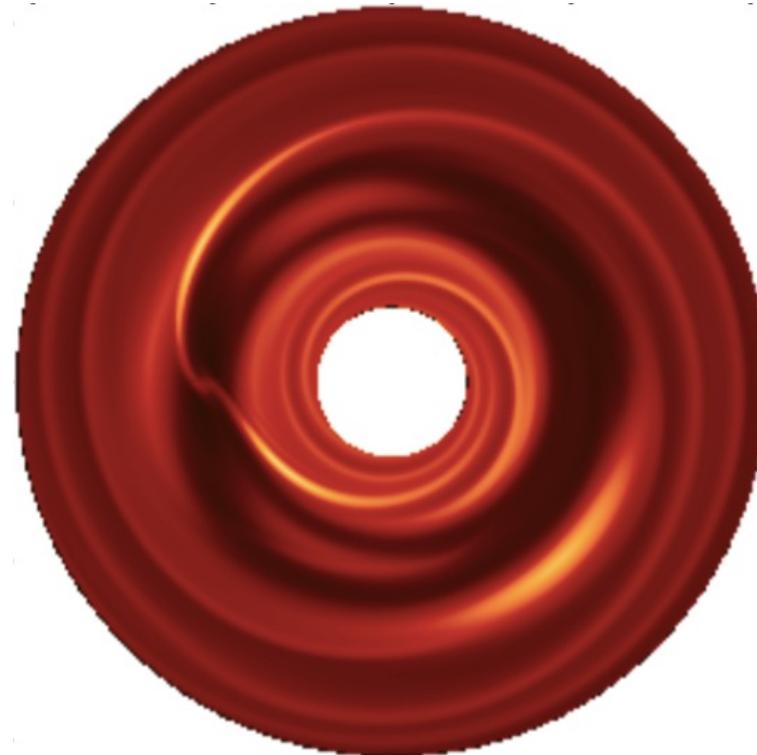
(Lyra 2009)

These cavities may be the telltale signature of forming planets

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.

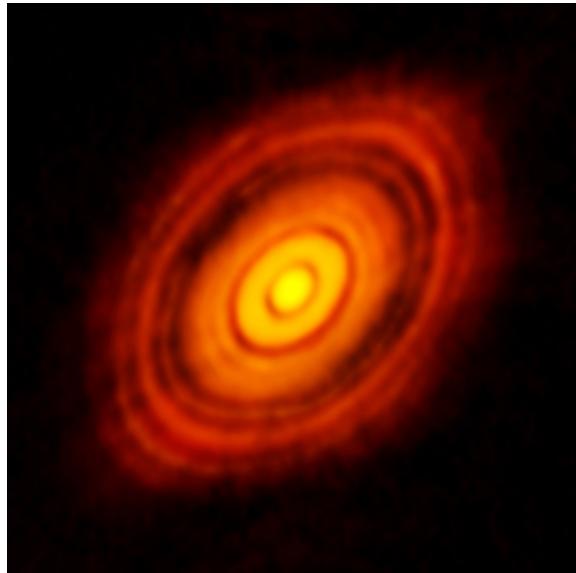


(Lyra et al. 2009b)

41

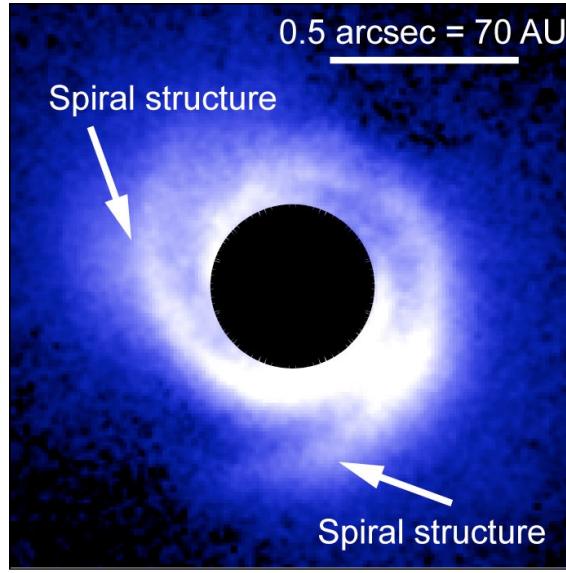
Observational evidence: gaps, spirals, and vortices

HL Tau



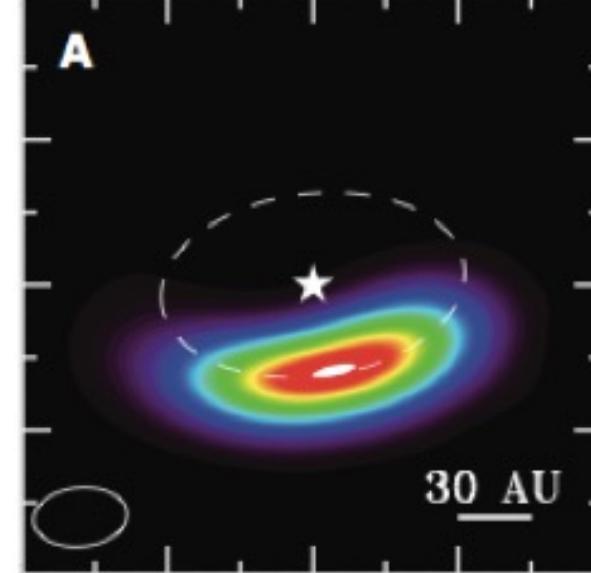
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

Oph IRS 48

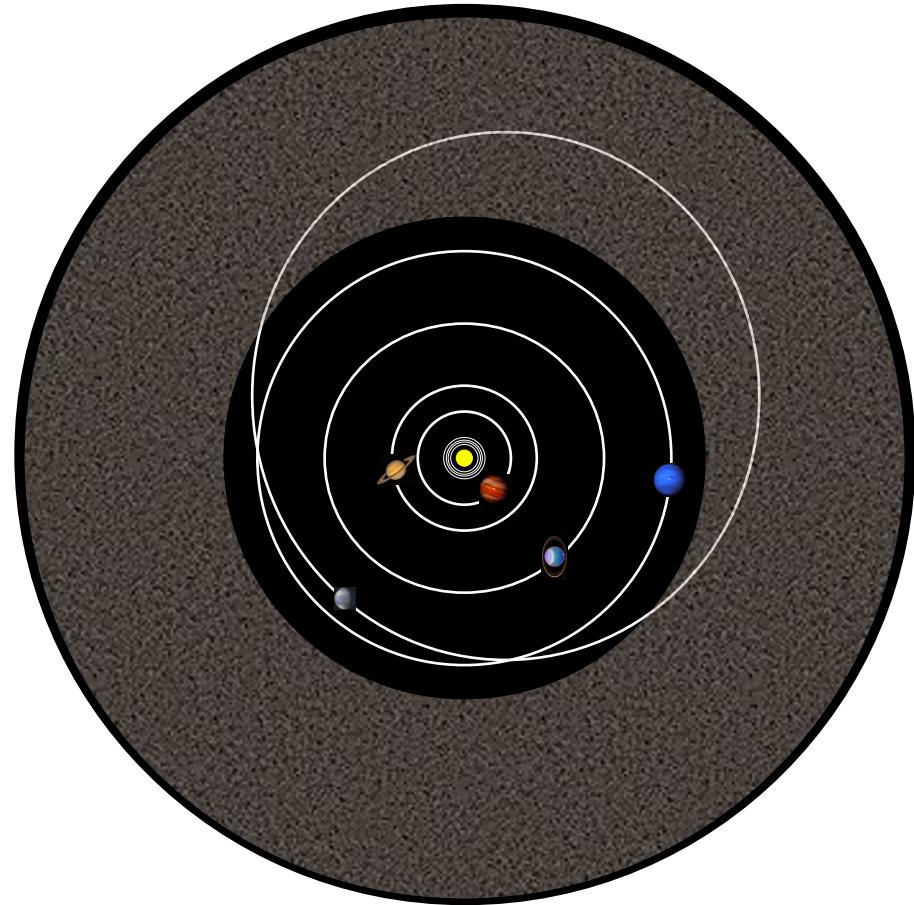


van der Marel et al. (2013)

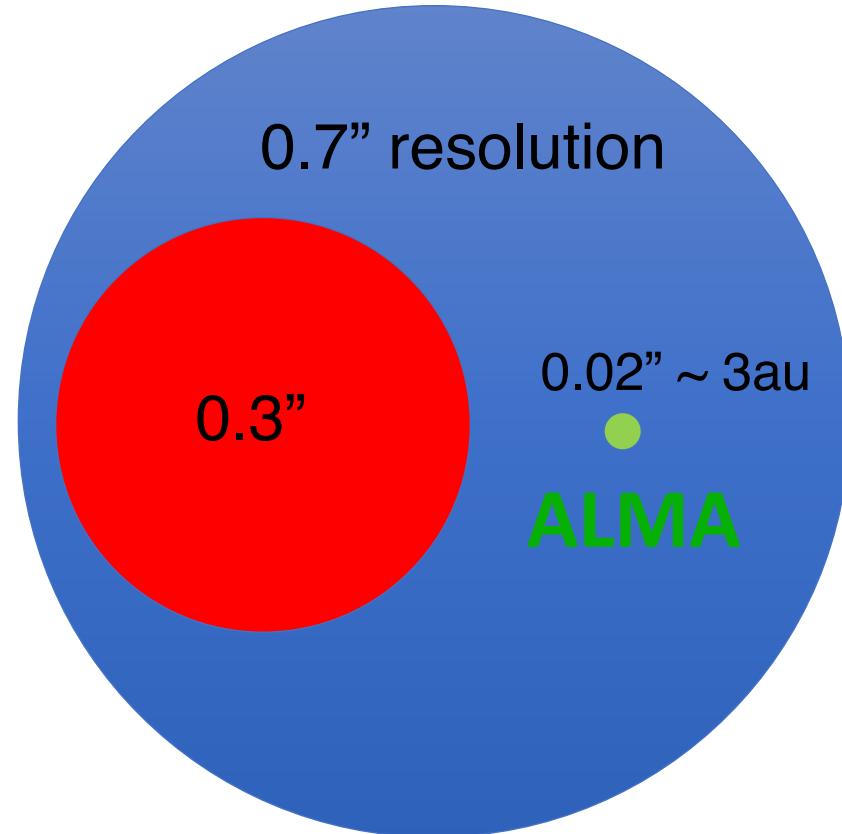
The Atacama Large (sub-)Millimeter Array (ALMA)



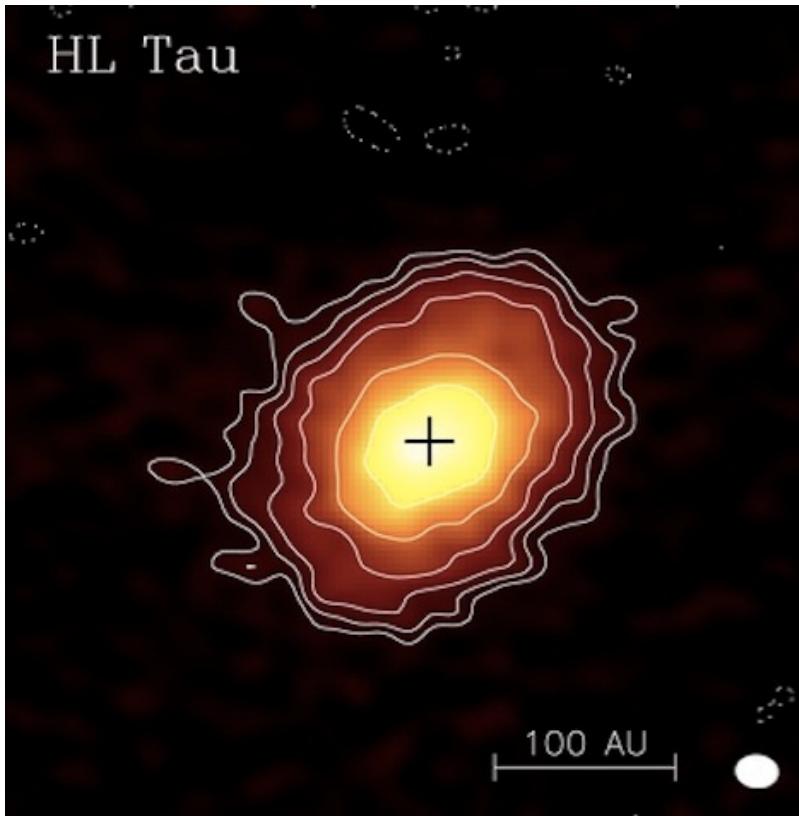
The ALMA ReSolution



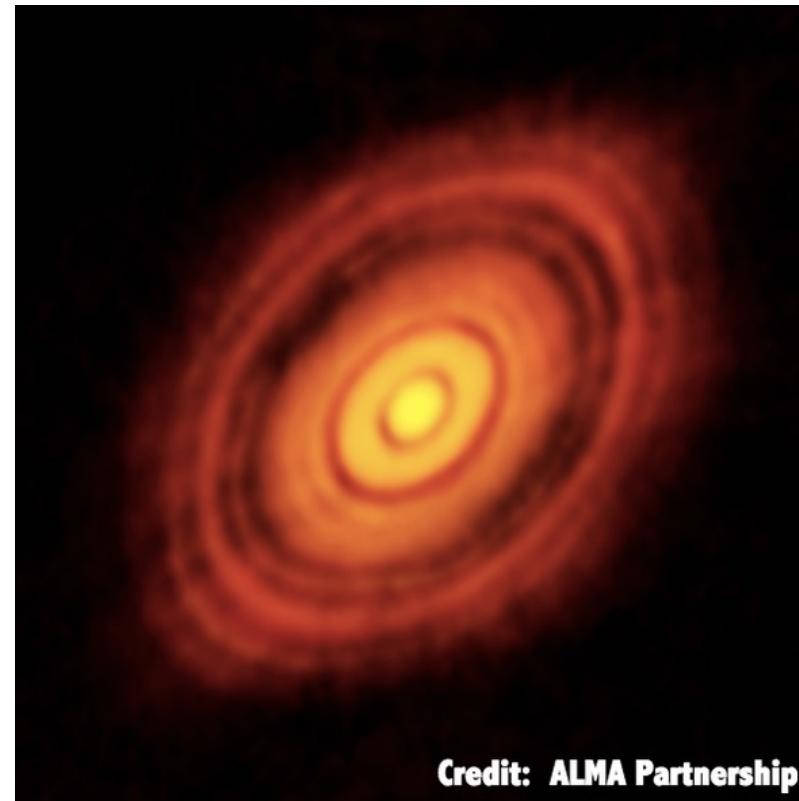
At 140 pc



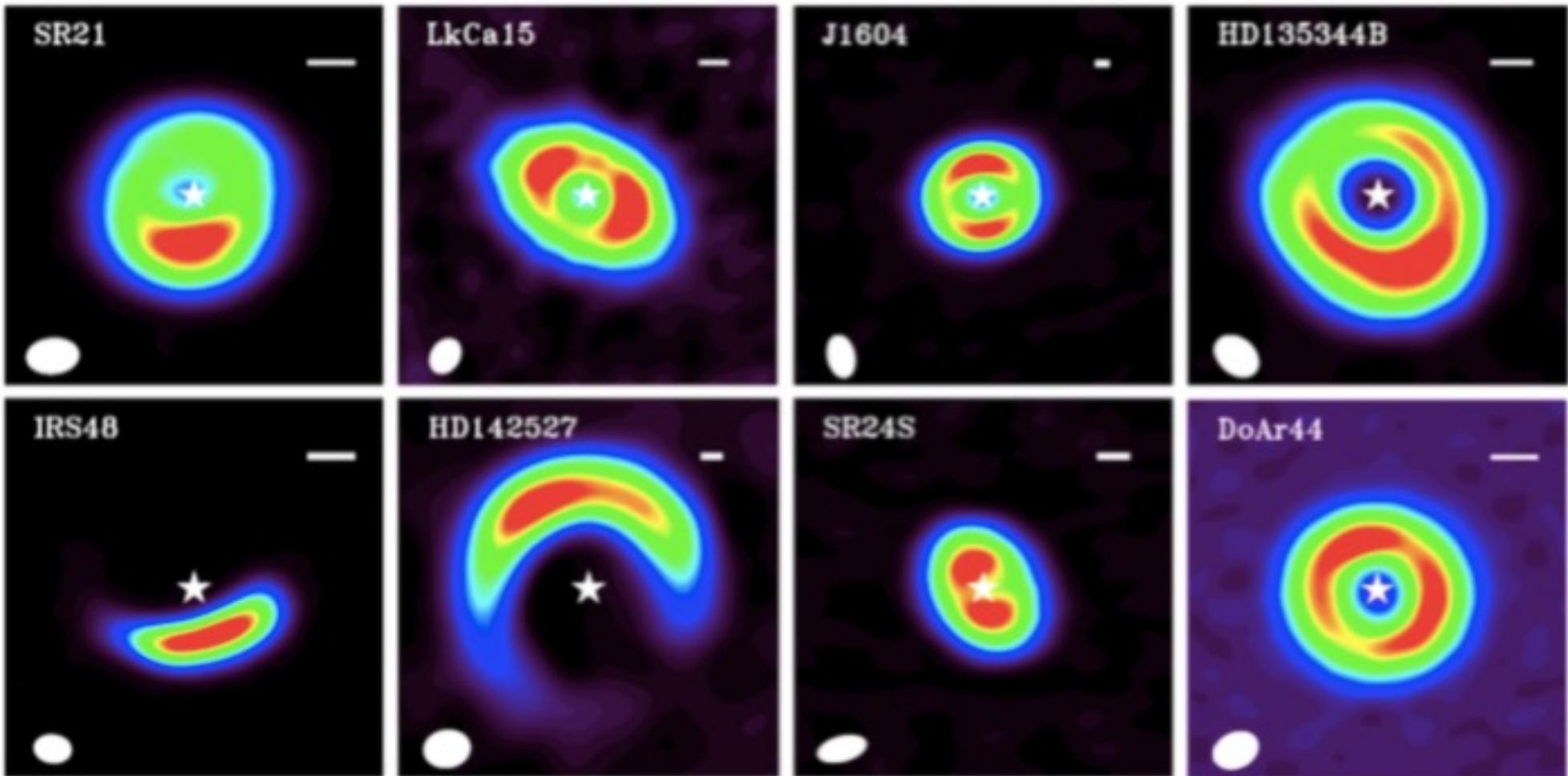
Before ALMA

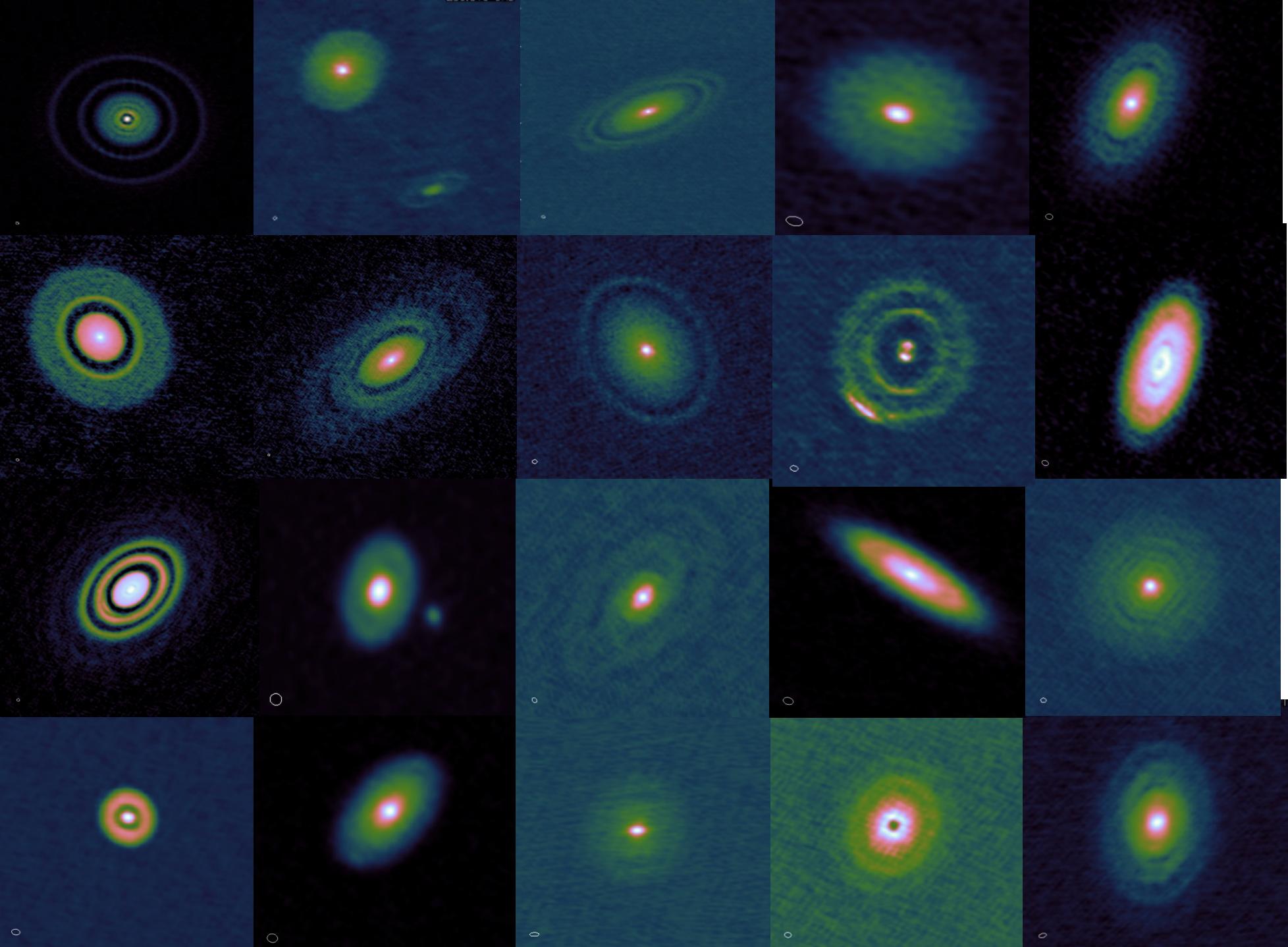


ALMA



Dust traps in disks: ALMA Cycle 0 (2012)





Oph IRS 48



Down

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,³ Vincent Geers⁷

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 forma-

tion mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

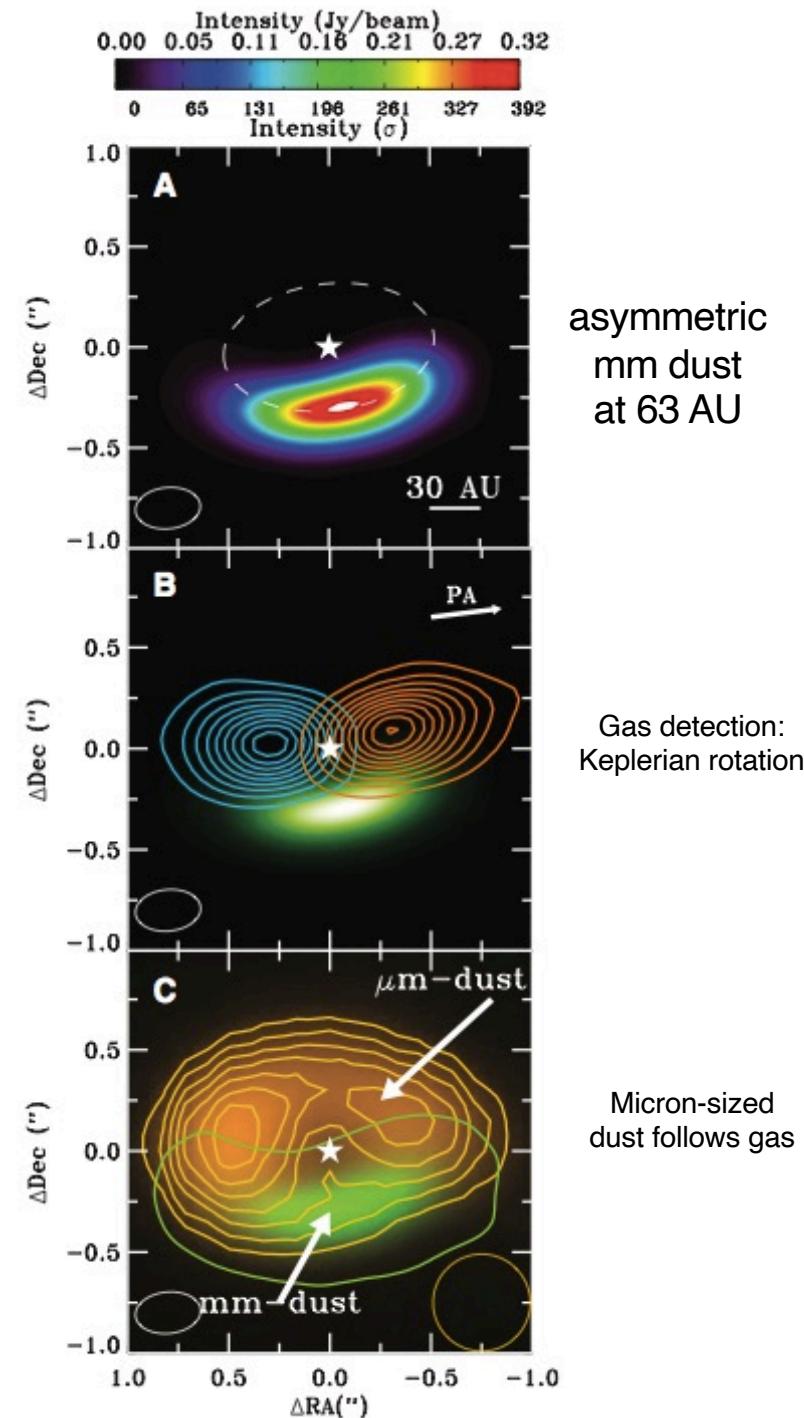
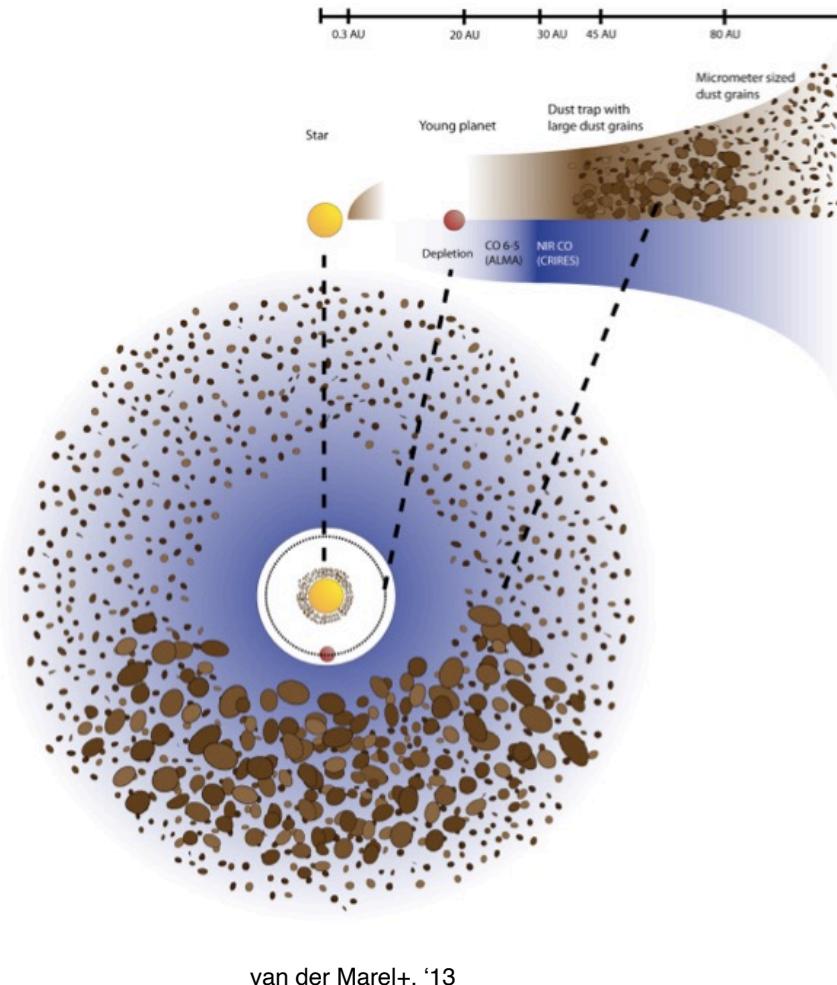
ience.org SCIENCE VOL 340 7 JUNE 2013

1199

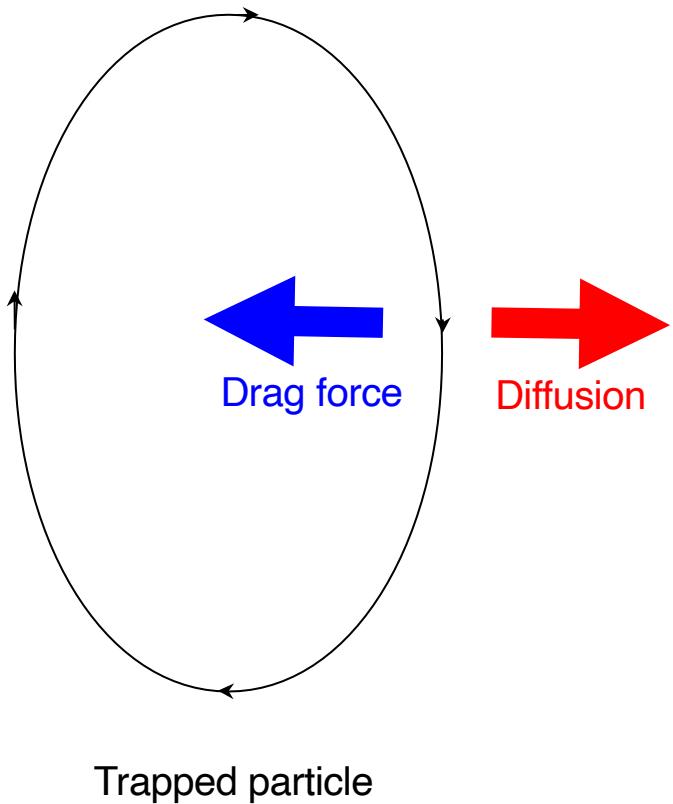
van der Marel+ '13

A huge vortex observed with ALMA

The Oph IRS 48 “comet formation factory”



Drag-Diffusion Equilibrium

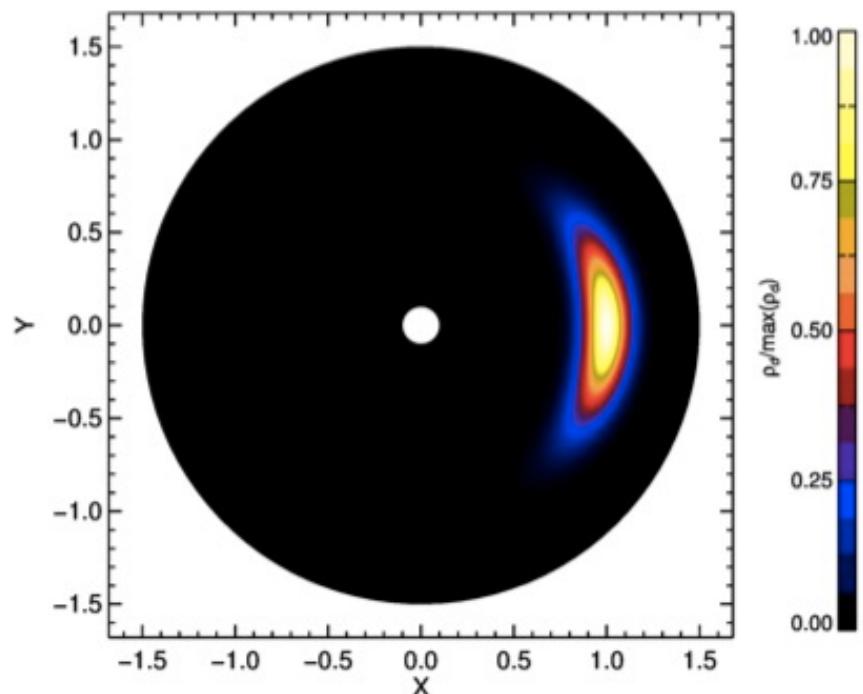


Dust continuity equation

$$\frac{\partial \rho_d}{\partial t} = -(\mathbf{v} \cdot \nabla) \rho_d - \rho_d \nabla \cdot \mathbf{v} + D \nabla^2 \rho_d,$$

advection compression diffusion

Analytical Solution for dust in Drag-Diffusion Equilibrium



Solution for

$$H/r=0.1 \quad \chi=4 \quad S=1$$

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

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

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

- 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

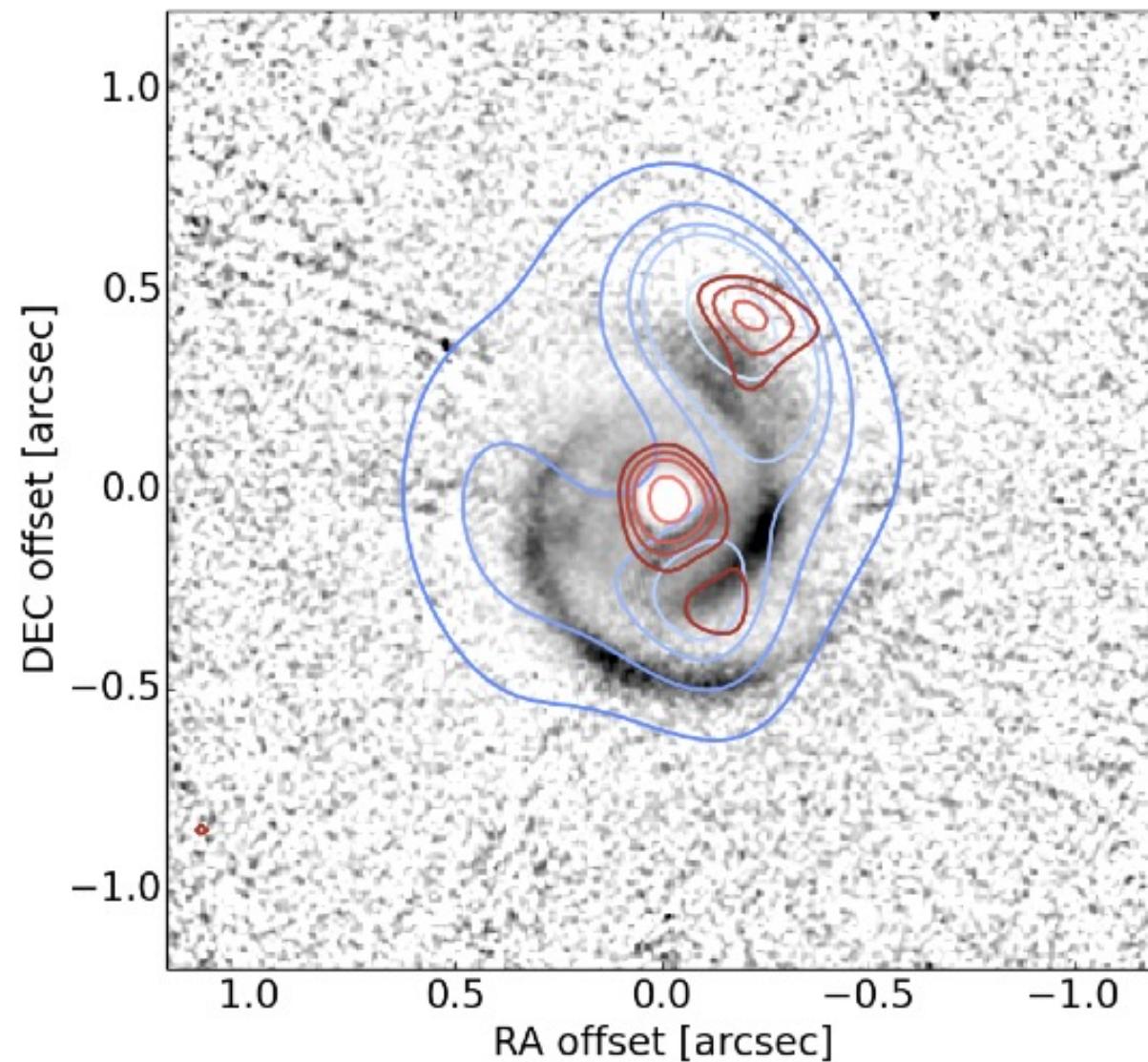
Disk Tomography

SPHERE-ALMA-VLA overlay of MWC 758

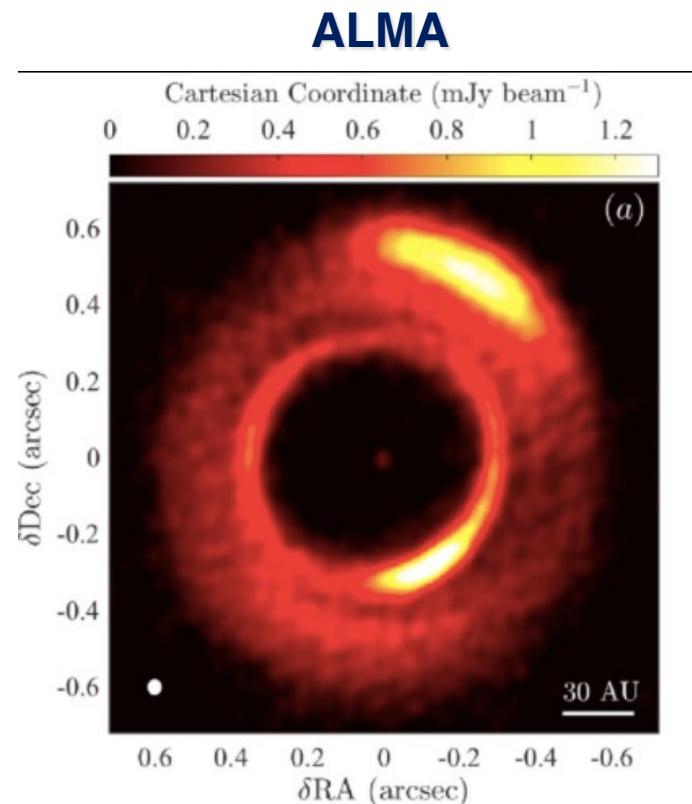
SPHERE (μm)

ALMA ($\sim \text{mm}$)

VLA (cm-m)



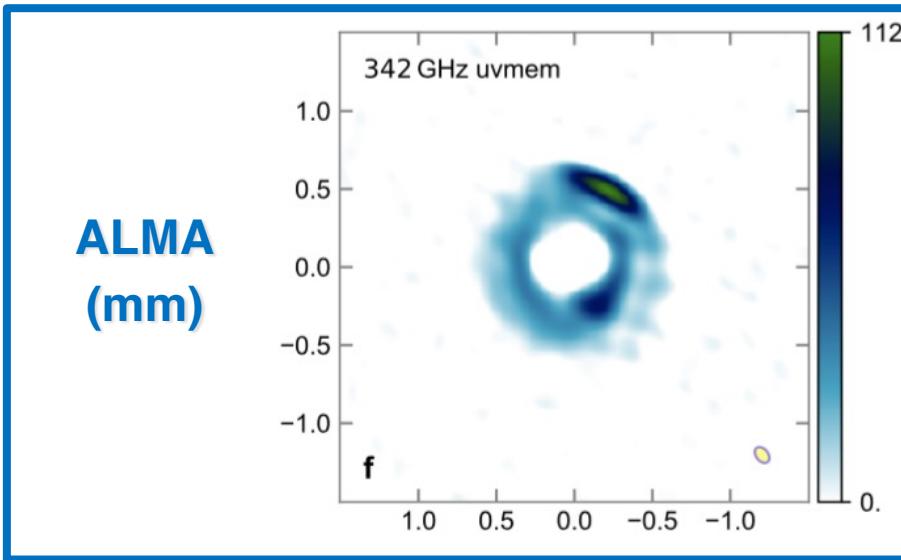
Marino+Lyra '15



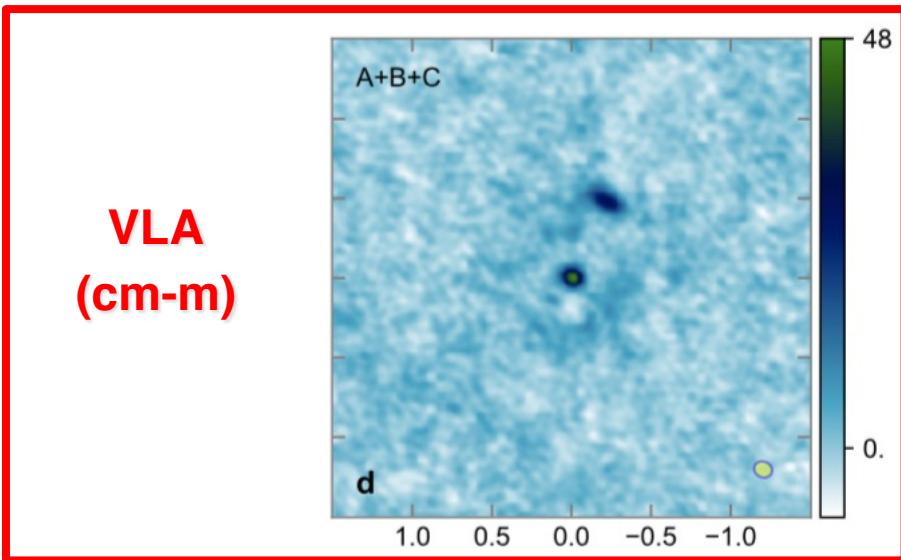
Dong+ '18

Pebble trapping

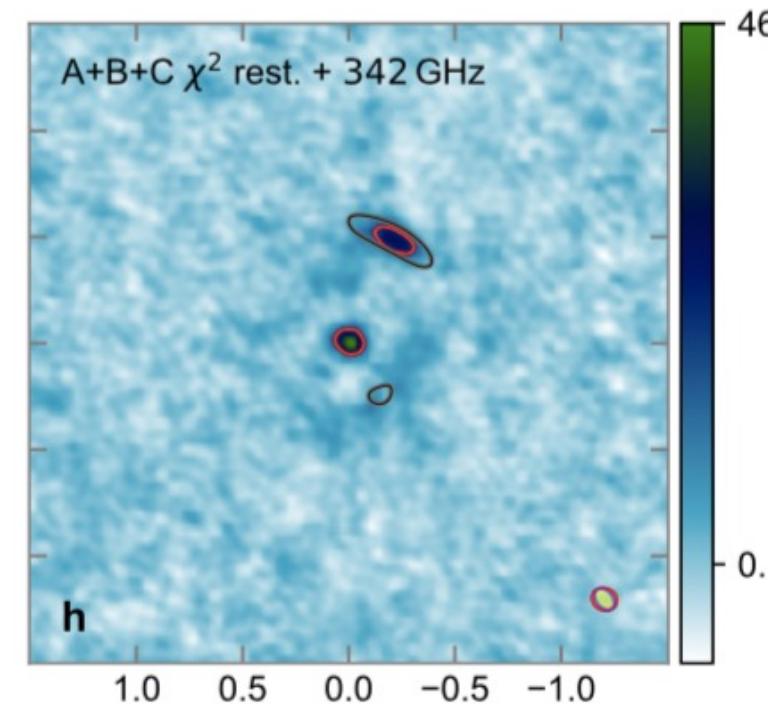
ALMA
(mm)



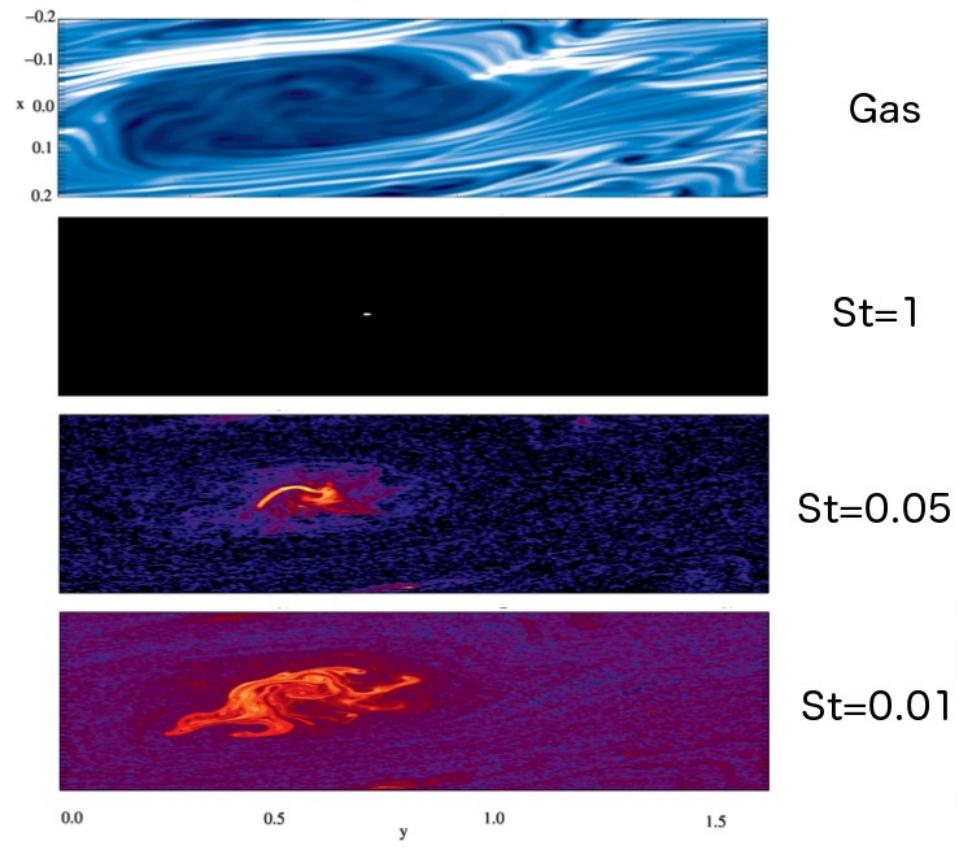
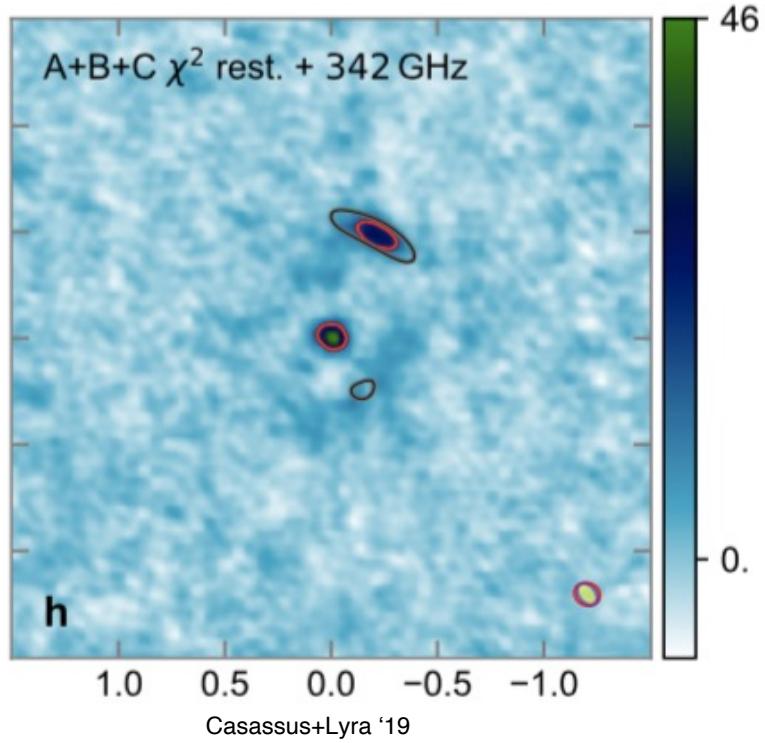
VLA
(cm-m)



Overlay



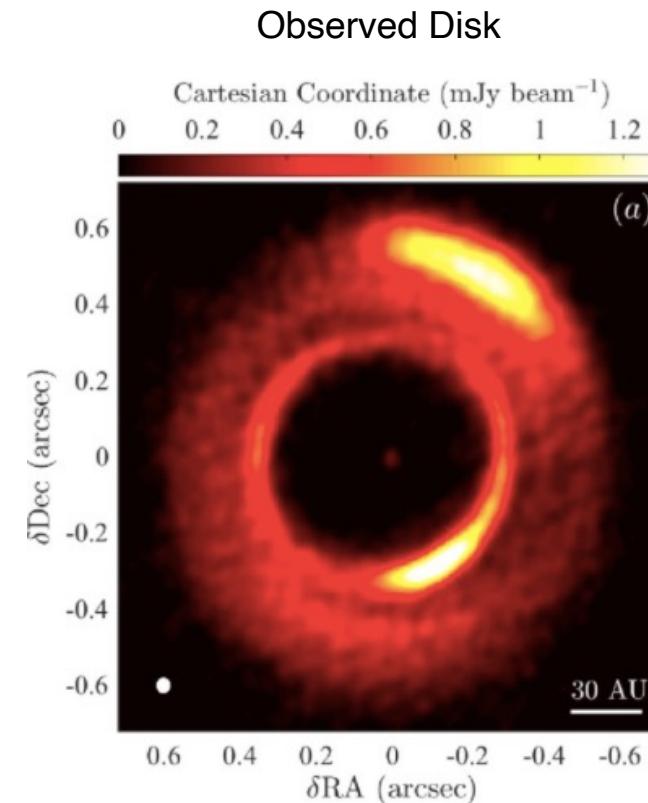
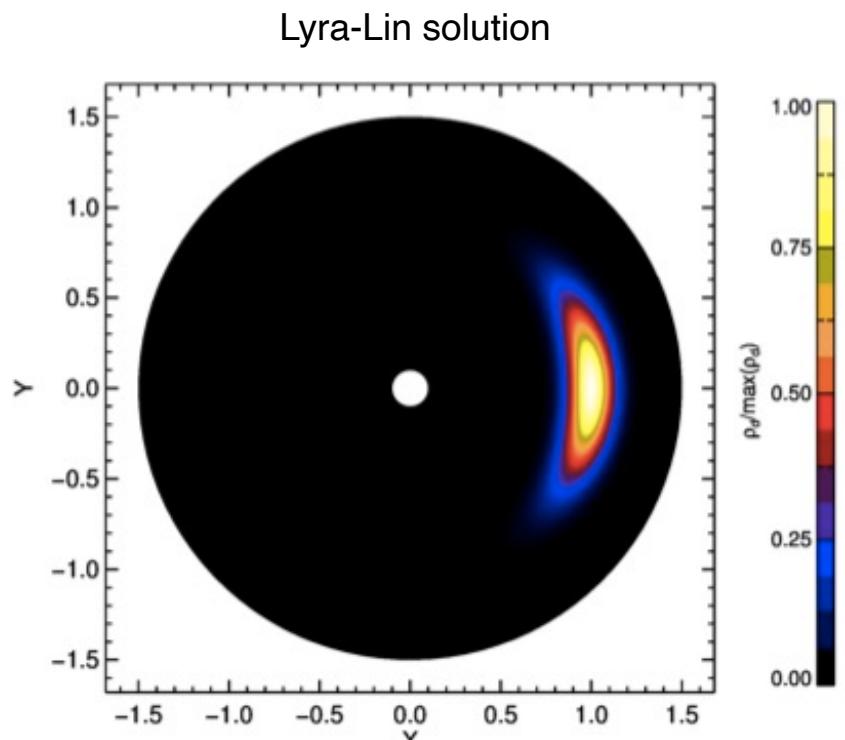
Model vs Observation



Take home message

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

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



The future

After 9 years of ALMA...

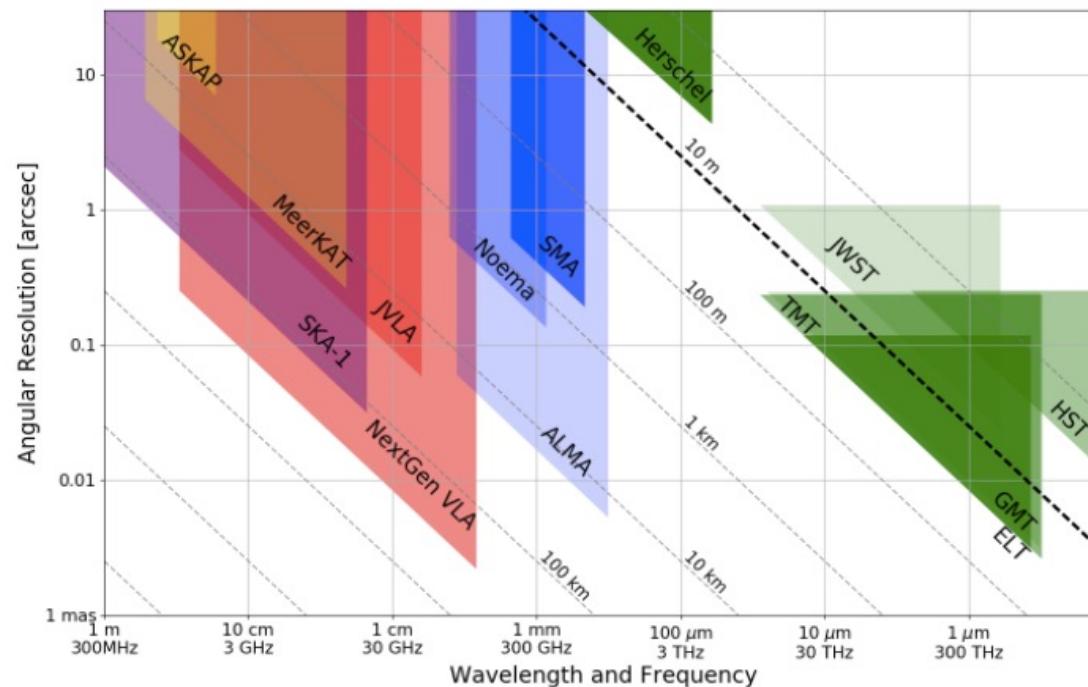
Nearly all nearby disks observed at $<0.1''$ ($< 20\text{-}30\text{AU}$) show substructures.

3 main types of substructures

- Crescent-shaped
- Spiral arms
- Rings/Gaps



Next Generation Very Large Array (ngVLA)

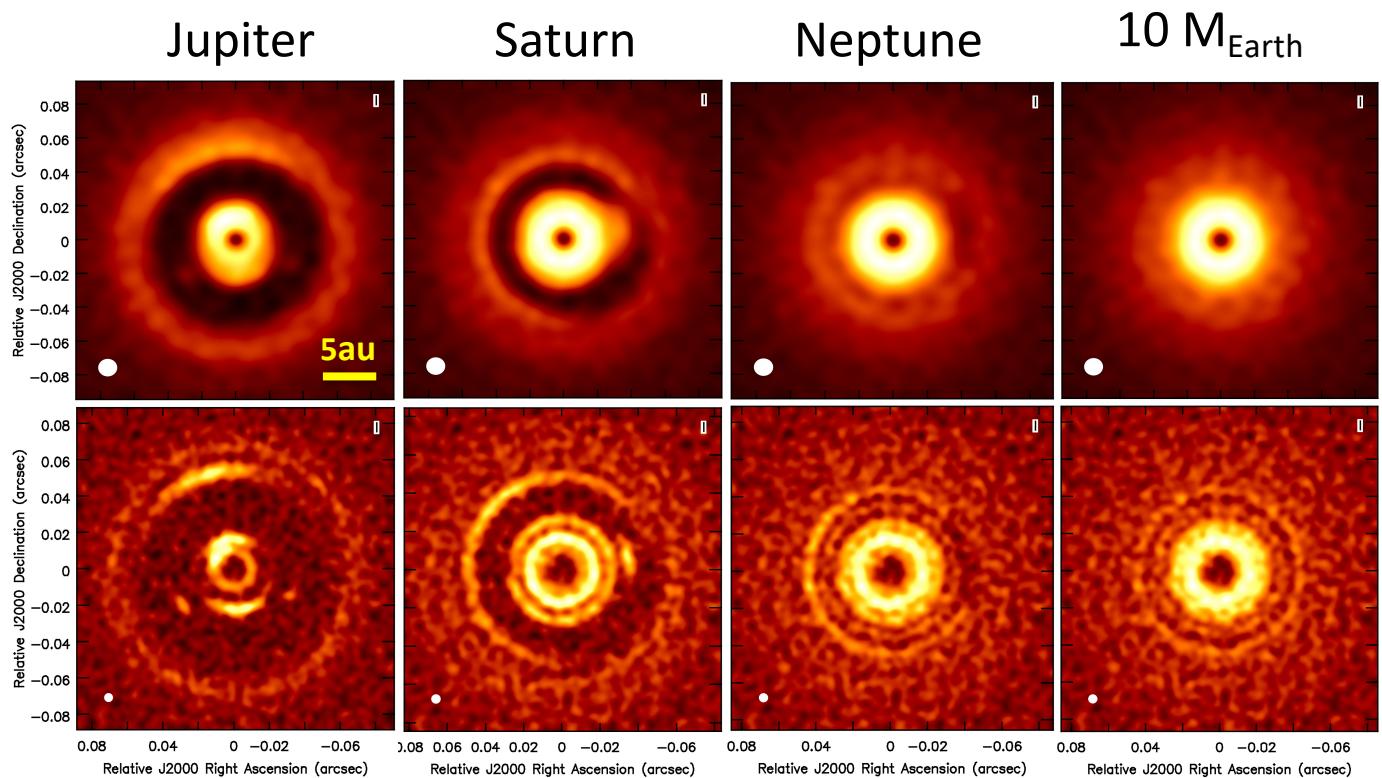


Planets at 5AU

ALMA @ 0.87mm

ngVLA @ 3mm

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

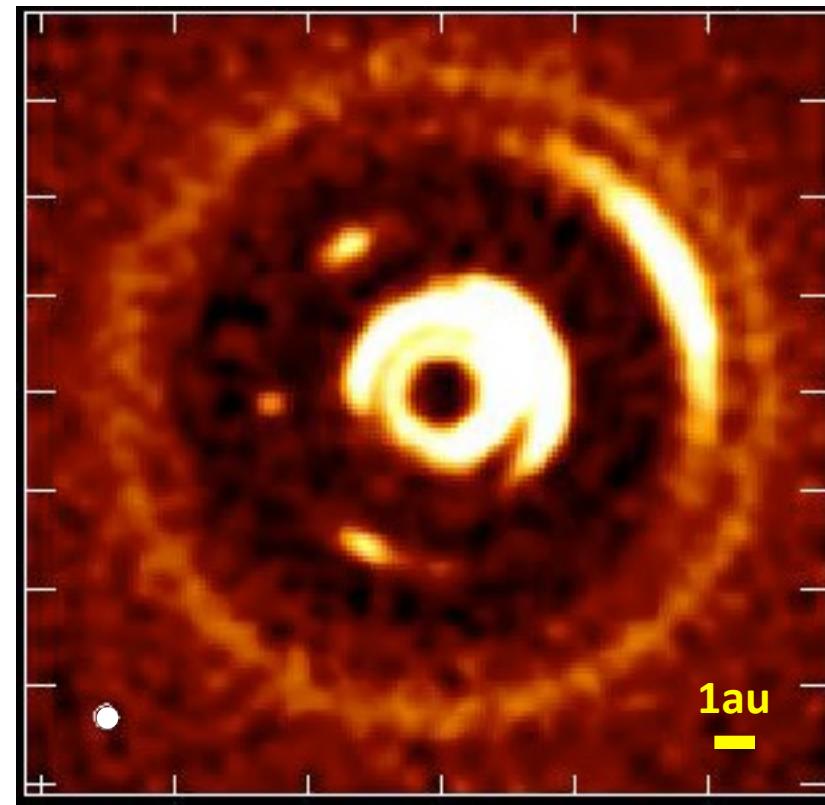


Ricci et al. 2018

ngVLA identifies gaps/substructures down to $\sim 5\text{-}10 M_{\text{Earth}}$

ngVLA: Proper motions

Jupiter at 5 AU



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 Zombie Vortex Instability 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	✗	✗	✗