Dynamical Instabilities in the Aid of Planet Formation in Circumstellar Disks

Wladimir Lyra

New Mexico State University

Funding

AAG – 2020, 2021

EW - 2021
TCAN – 2020
NFDAP – 2019
XRP – 2018

Computational Facilities

Harvard CfA - Institute for Theory and Computation, Oct 13th, 2022

The TCAN-2020 Planet Formation Collaboration

PI

Wladimir Lyra – *New Mexico State University*

Co-Is

Andrew Youdin – *University of Arizona*

Jake Simon – *Iowa State University*

Chao-Chin Yang – *University of Nevada, Las Vegas (now University of Alabama)*

Orkan Umurhan – *NASA Ames*

Postdocs

Debanjan Sengupta (NMSU)

Leonardo Krapp (UA)

Daniel Carrera (ISU)

Graduate Students

NMSU - Daniel Godines, Victoria de Cun, Manuel Cañas.

ISU – Jeonghoon Lim, David Rea, Abigail Davenport

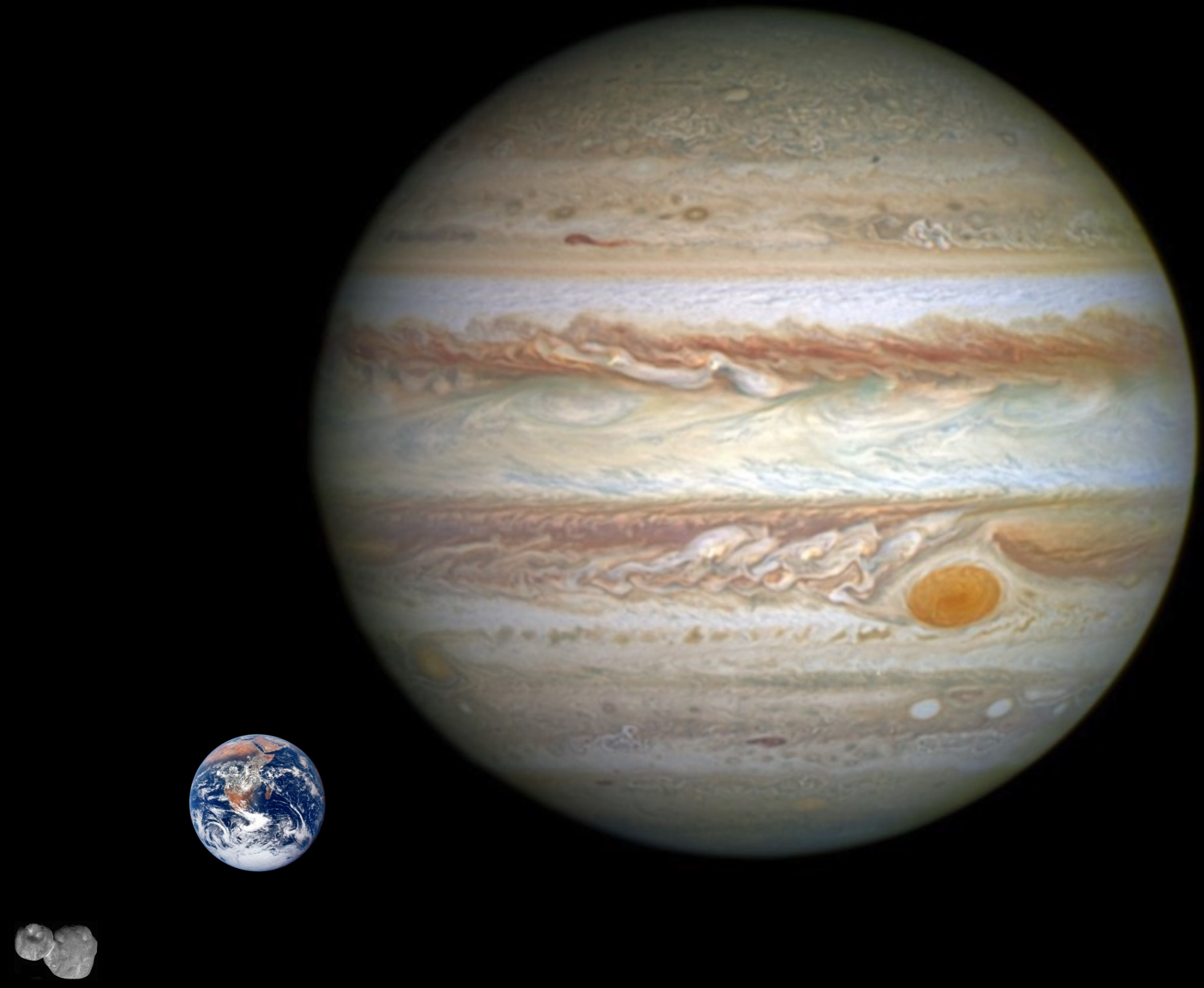
UNLV – Alex Mohov, Stanley Baronett

UA – Eonho Chang

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})

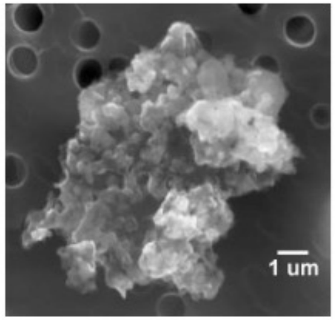
Temperature: 10-1000 K

Scale: 0.1-100AU

Mass: $10^{-3} – 10^{-1}$ M_{sun}

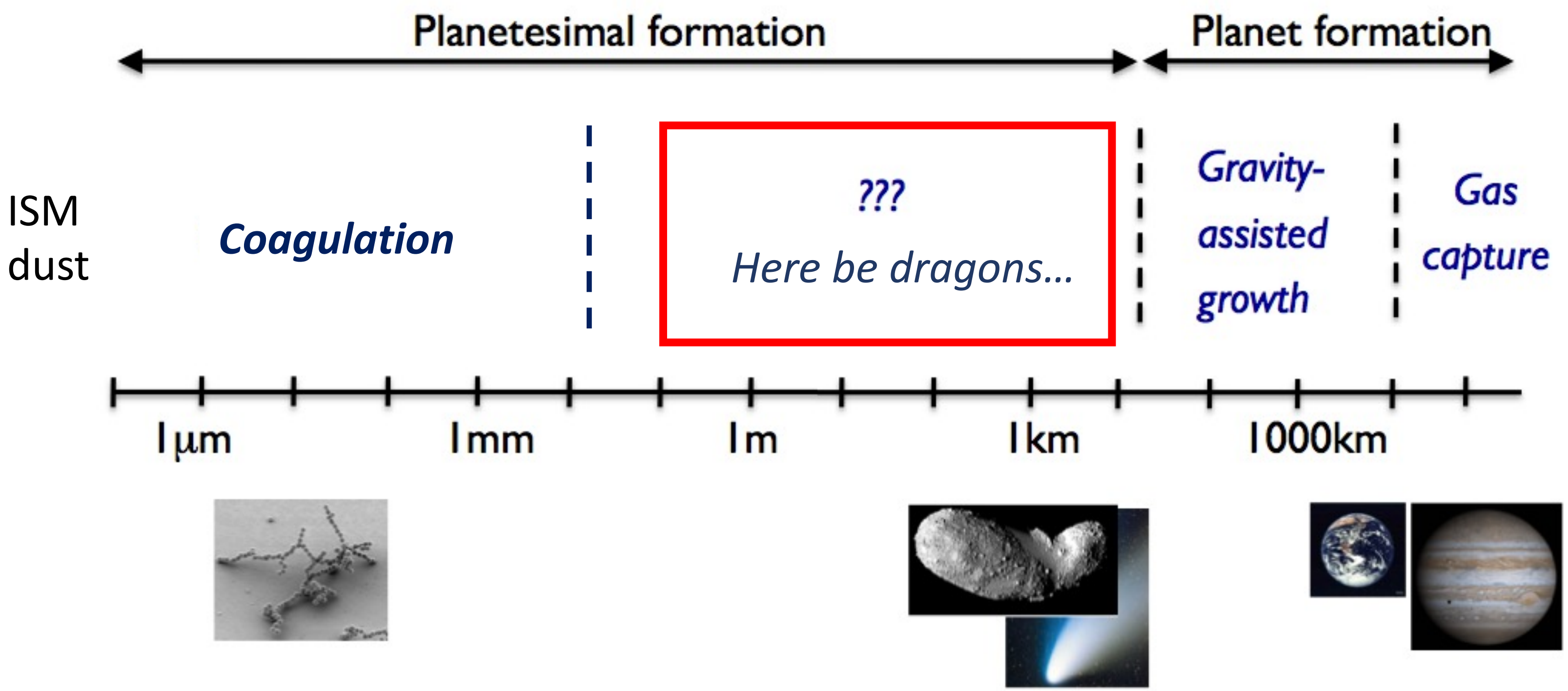
Planet Formation

"Planets form in disks of gas and dust"

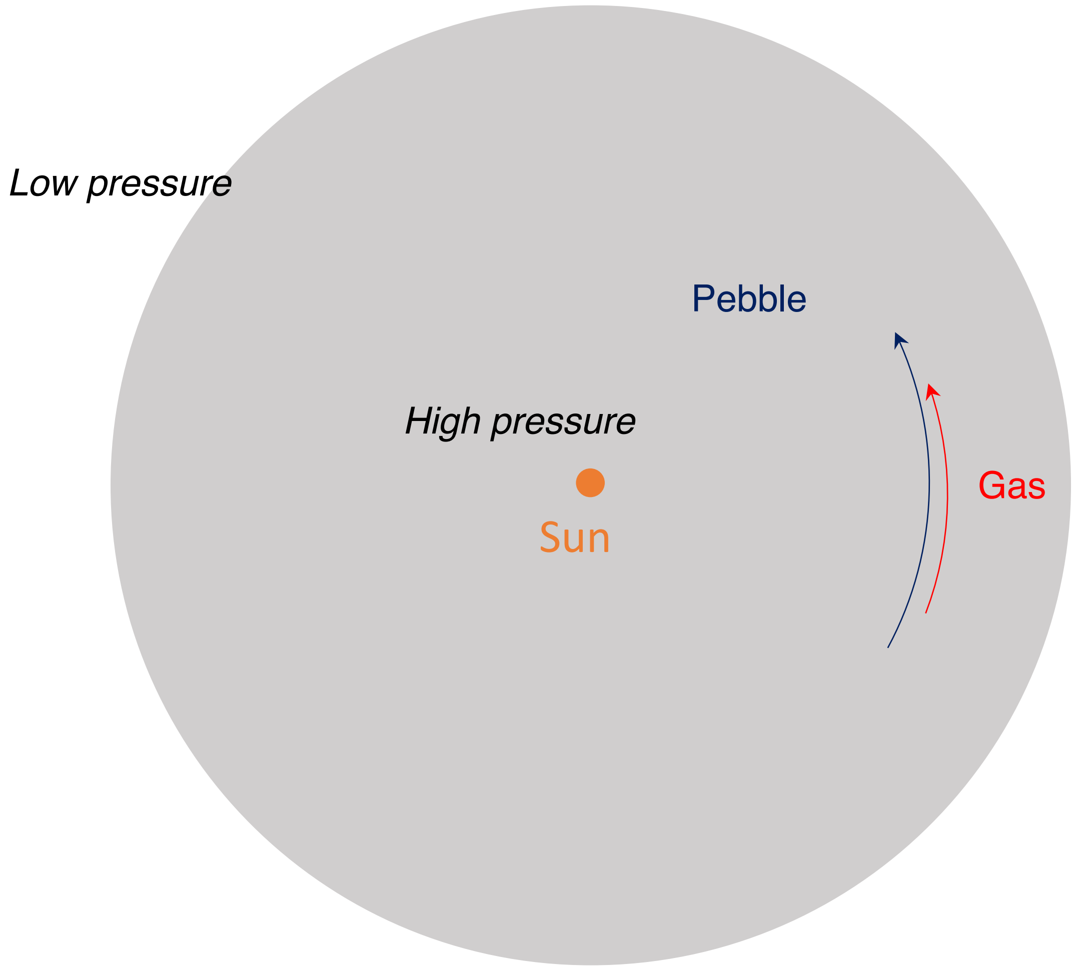


A miracle happens →

Dust evolution



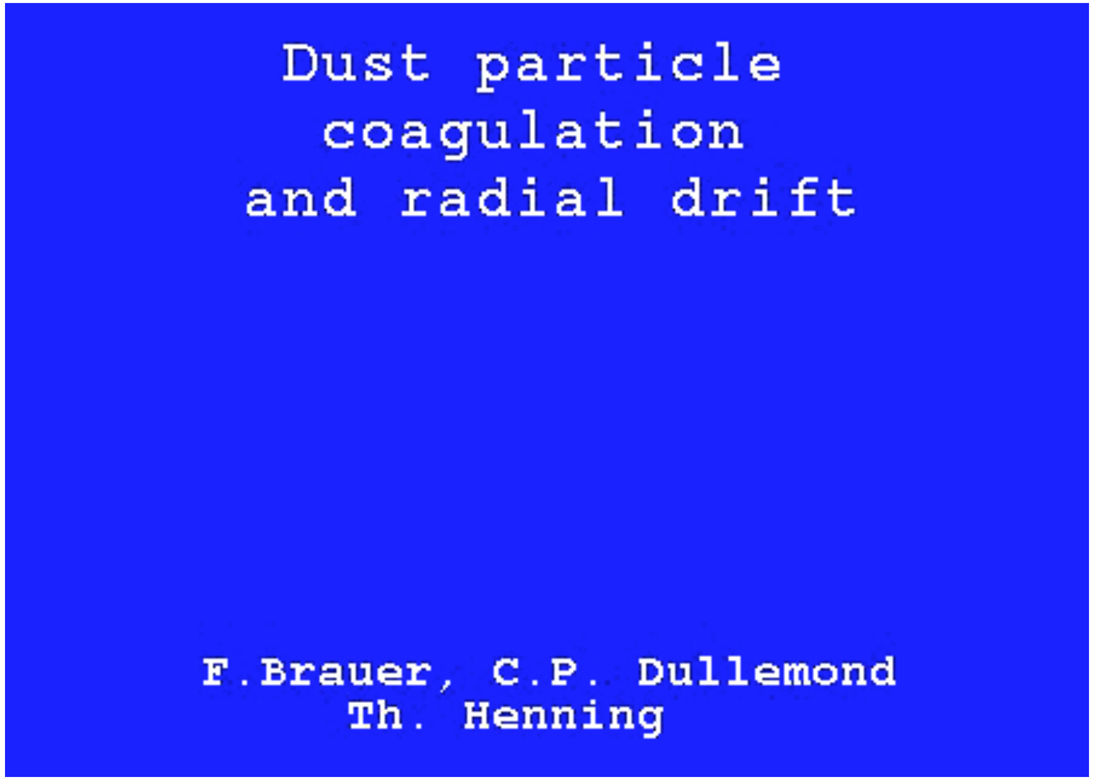
Headwind and Dust Drift



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

The pebbles do not feel gas pressure (Keplerian).

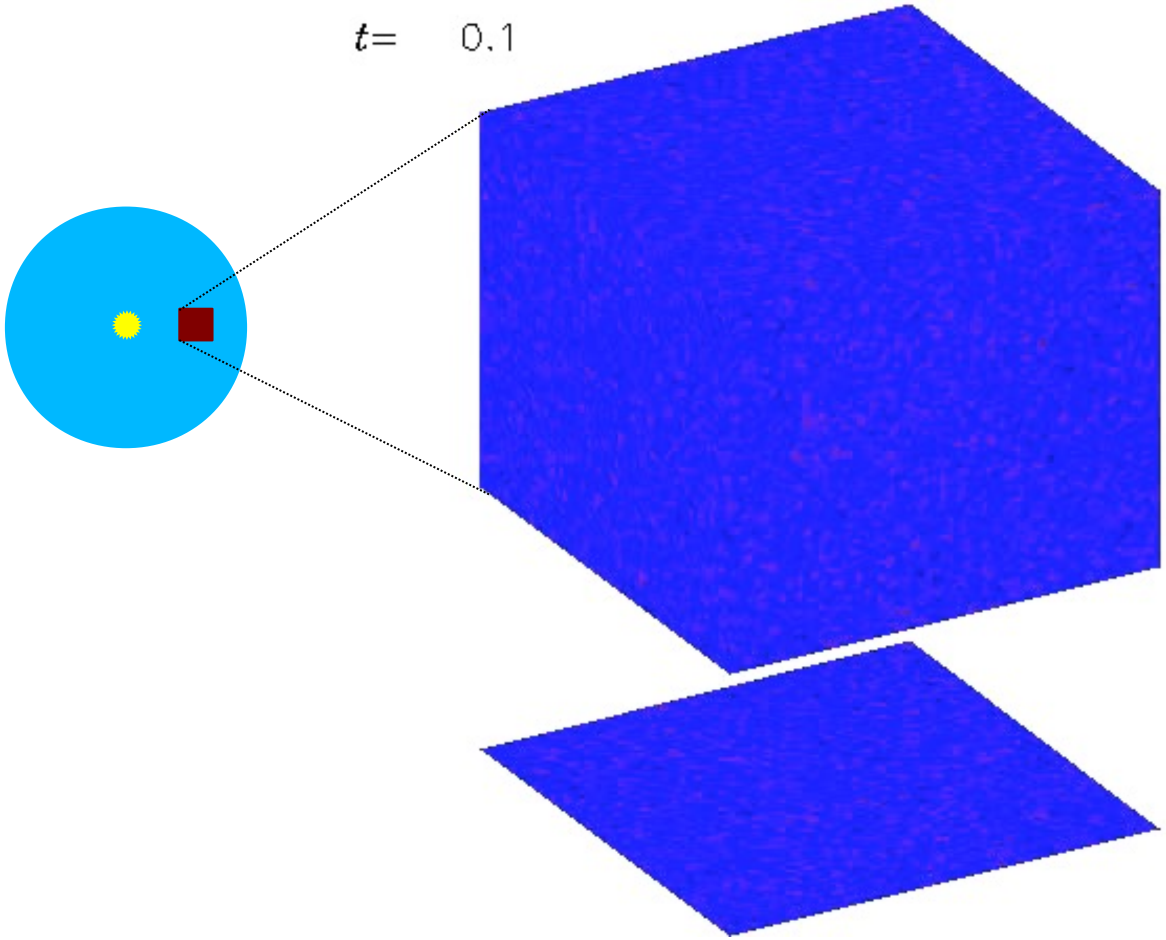
Dust coagulation and drift

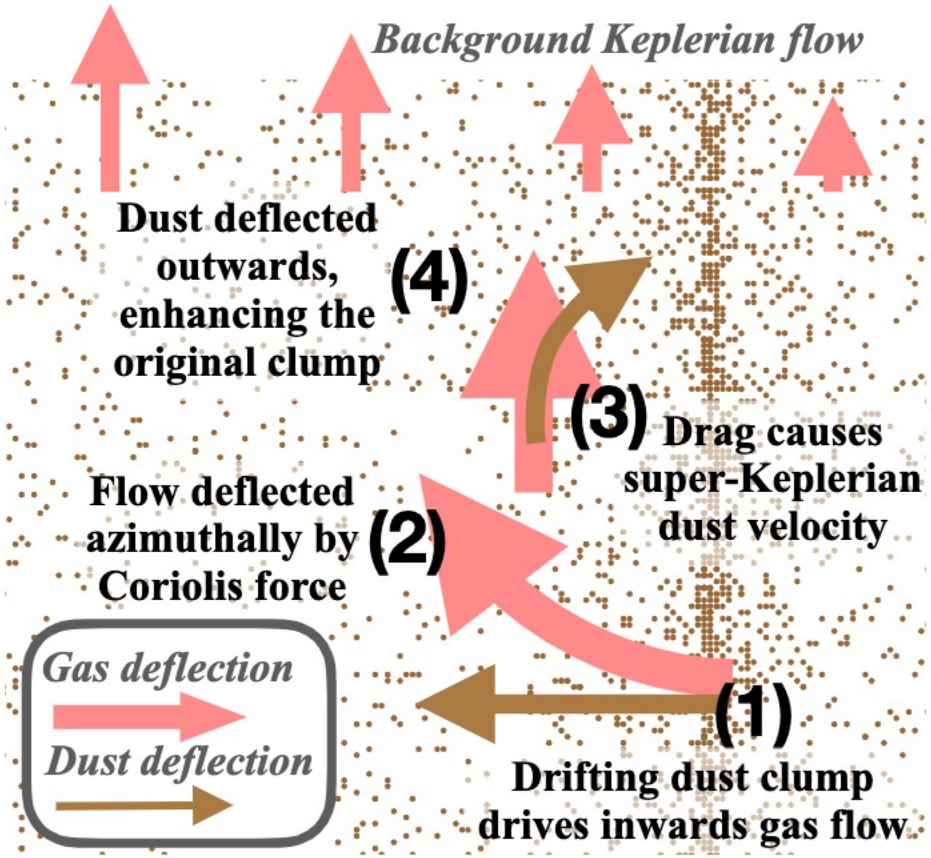


Brauer et al. (2008)

Streaming Instability

The dust drift is hydrodynamically unstable

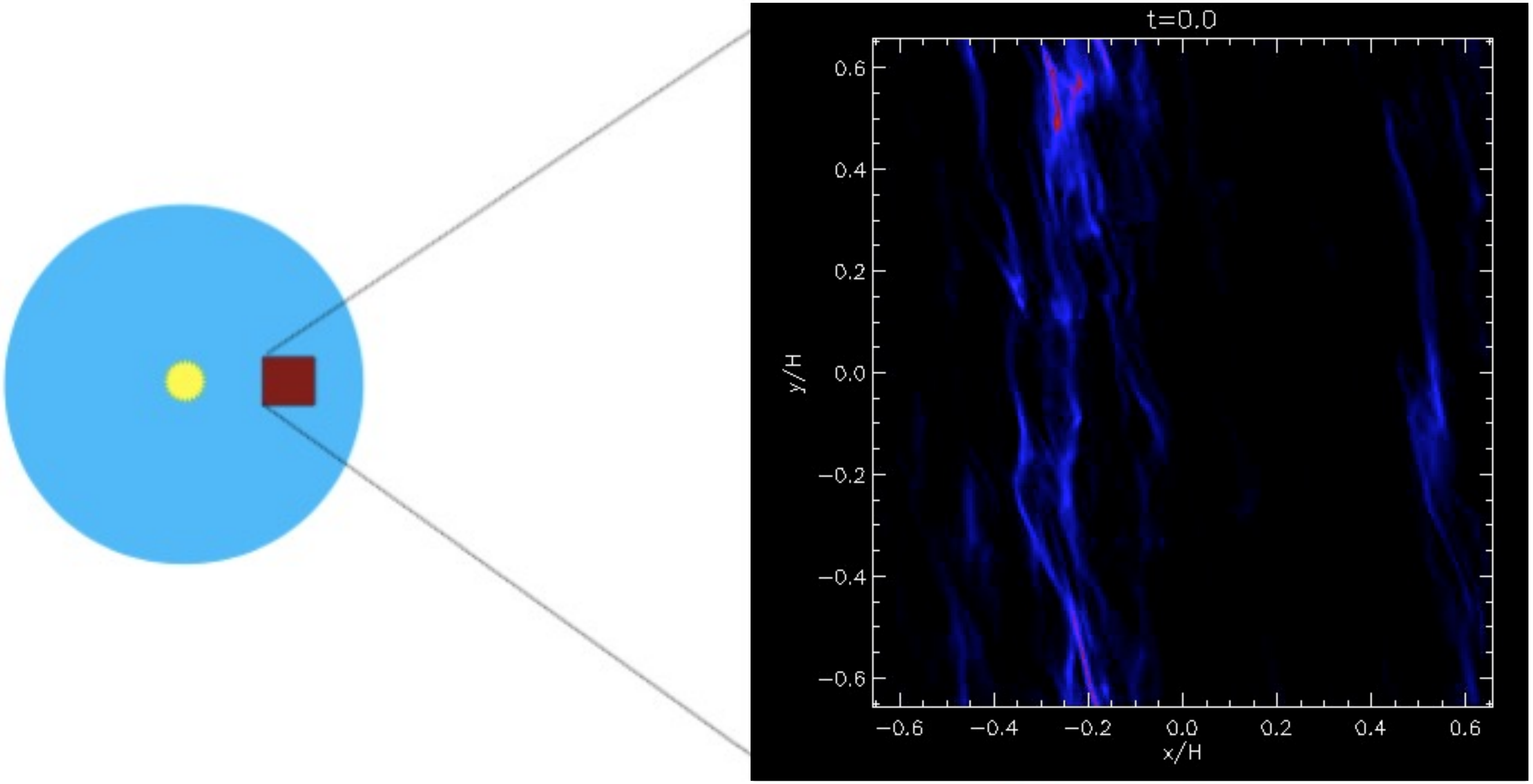




Lesur et al. (2022)

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

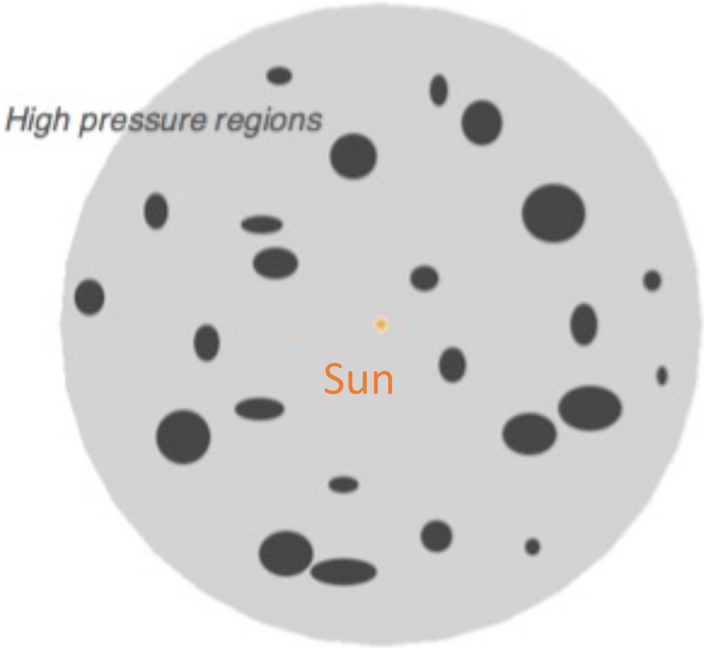
Gravitational collapse into planetesimals

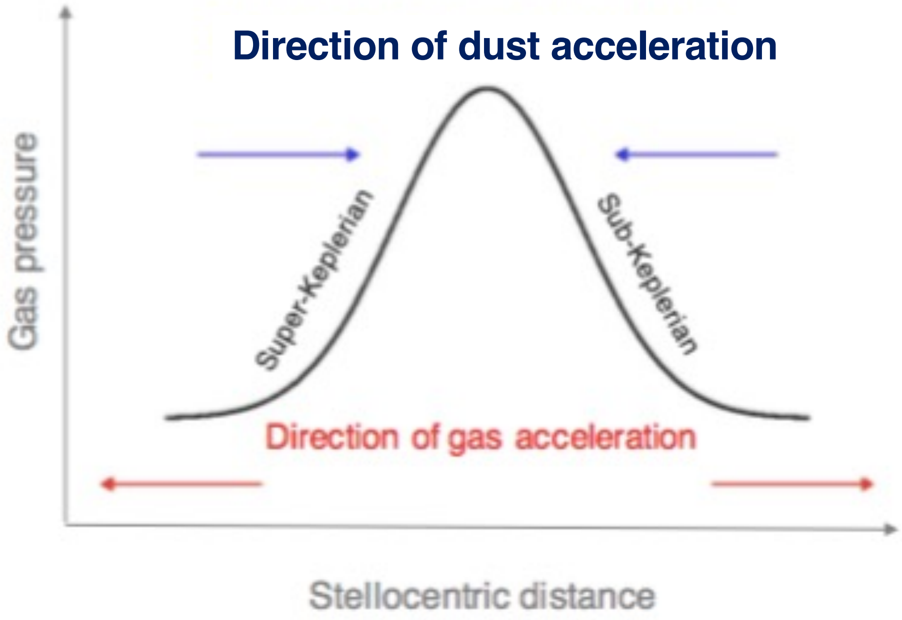


Johansen et al. (2007)

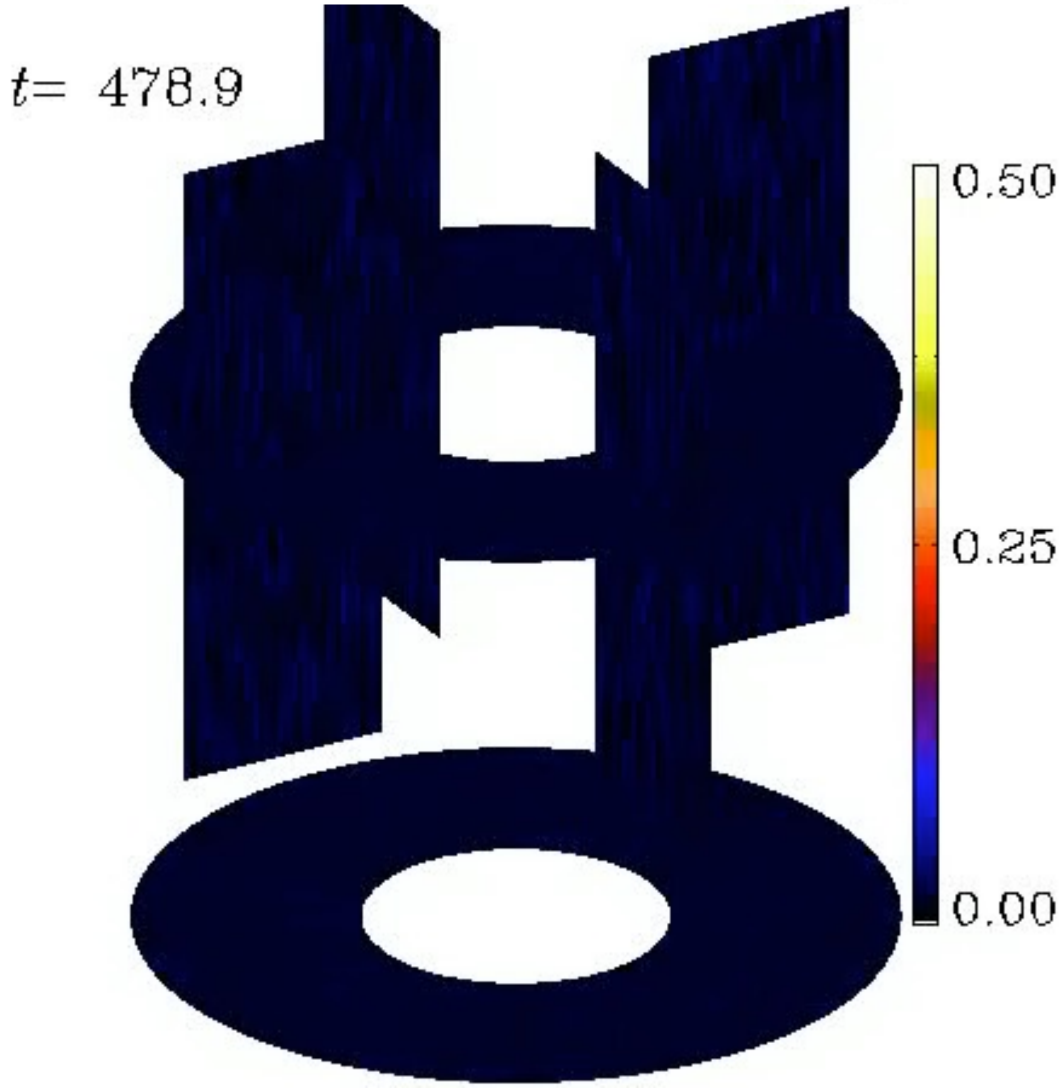
Turbulence and Accretion in 3D Global MHD Simulations of Stratified Protoplanetary Disk

Turbulence


High pressure regions
Sun

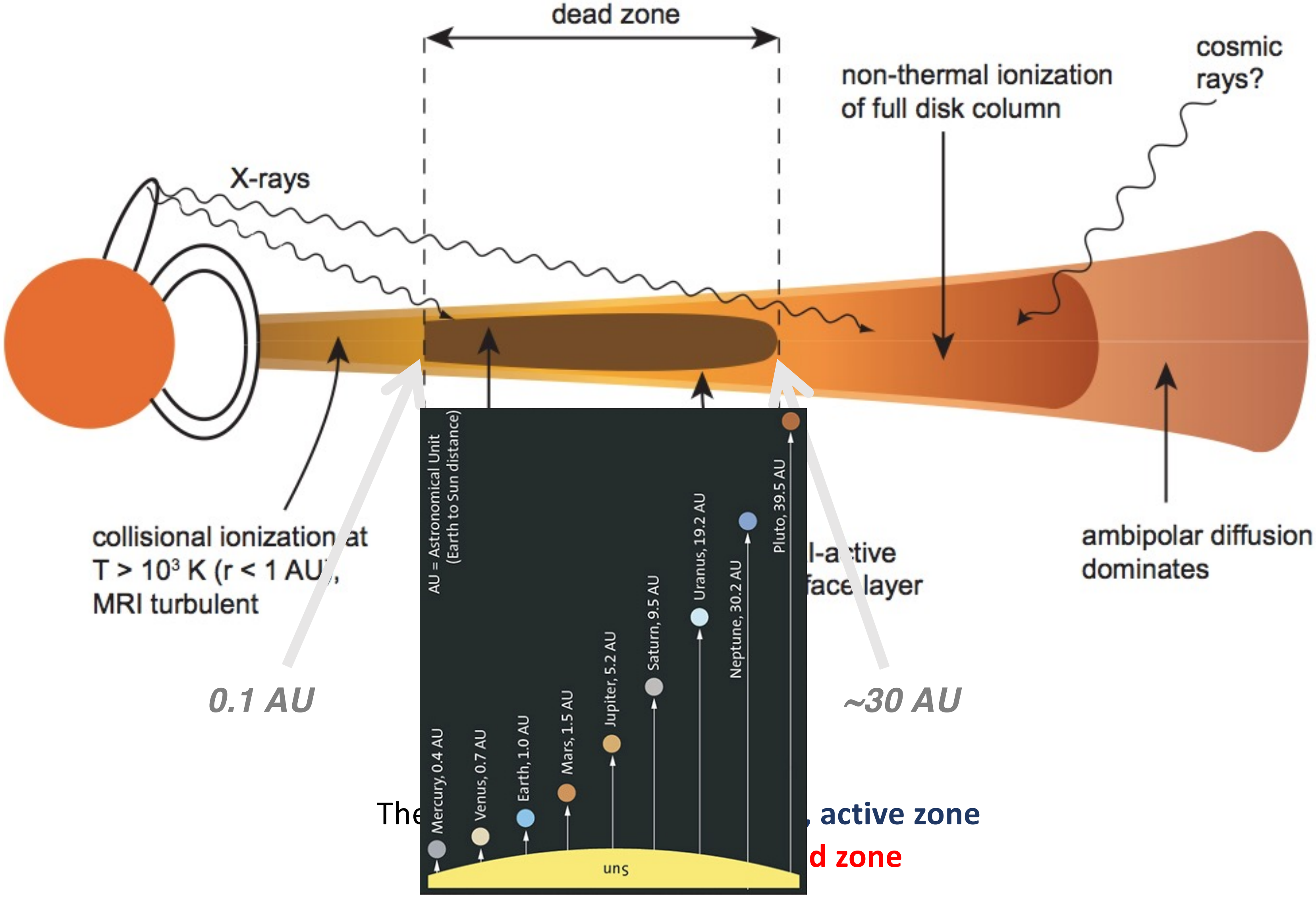

Direction of dust acceleration
Gas pressure
Super-Keplerian
Sub-Keplerian
Direction of gas acceleration
Stellocentric distance

Turbulence concentrates solids mechanically in pressure maxima



Lyra et al. (2008a)

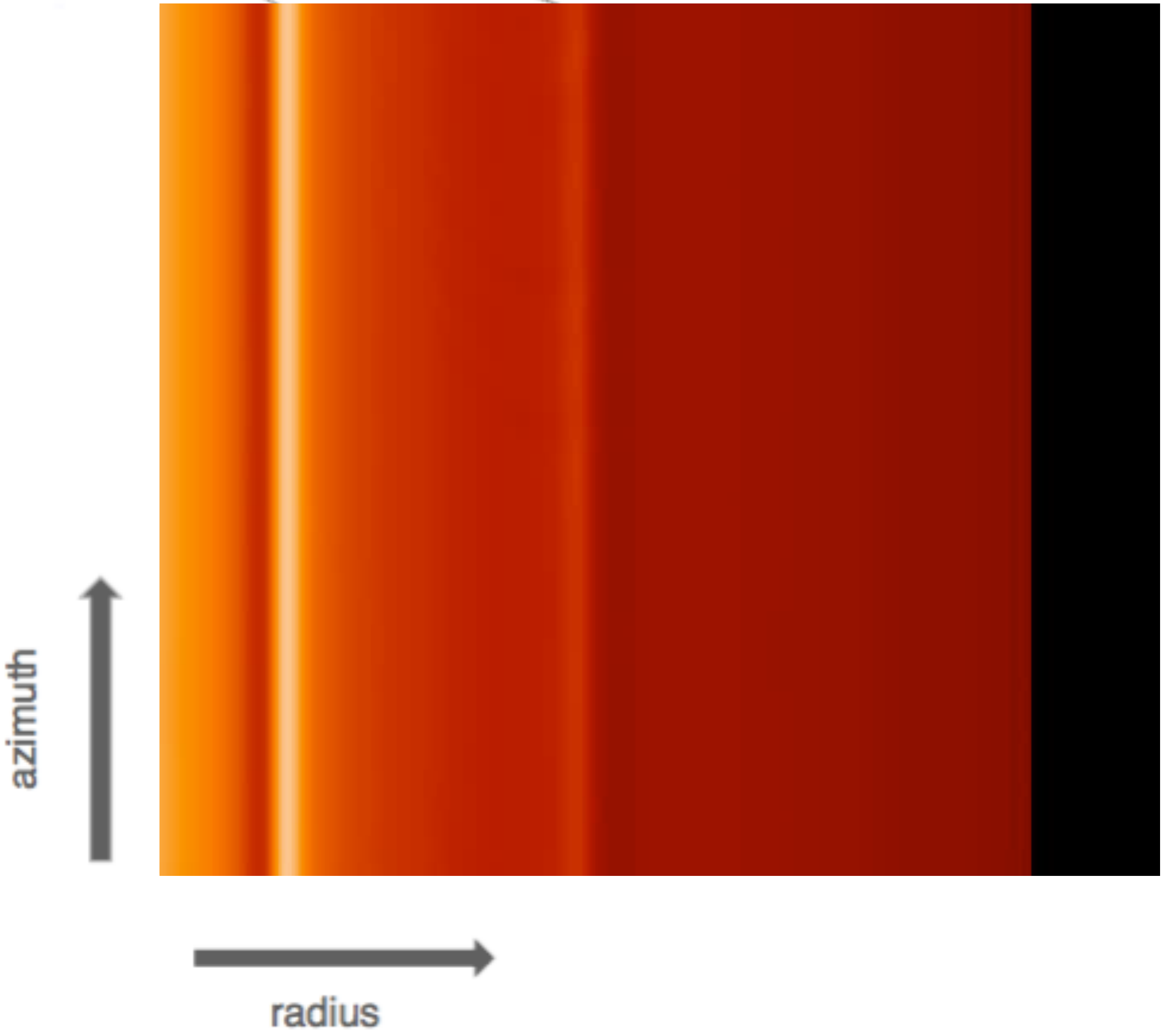
Dead zones



The … , **active zone**

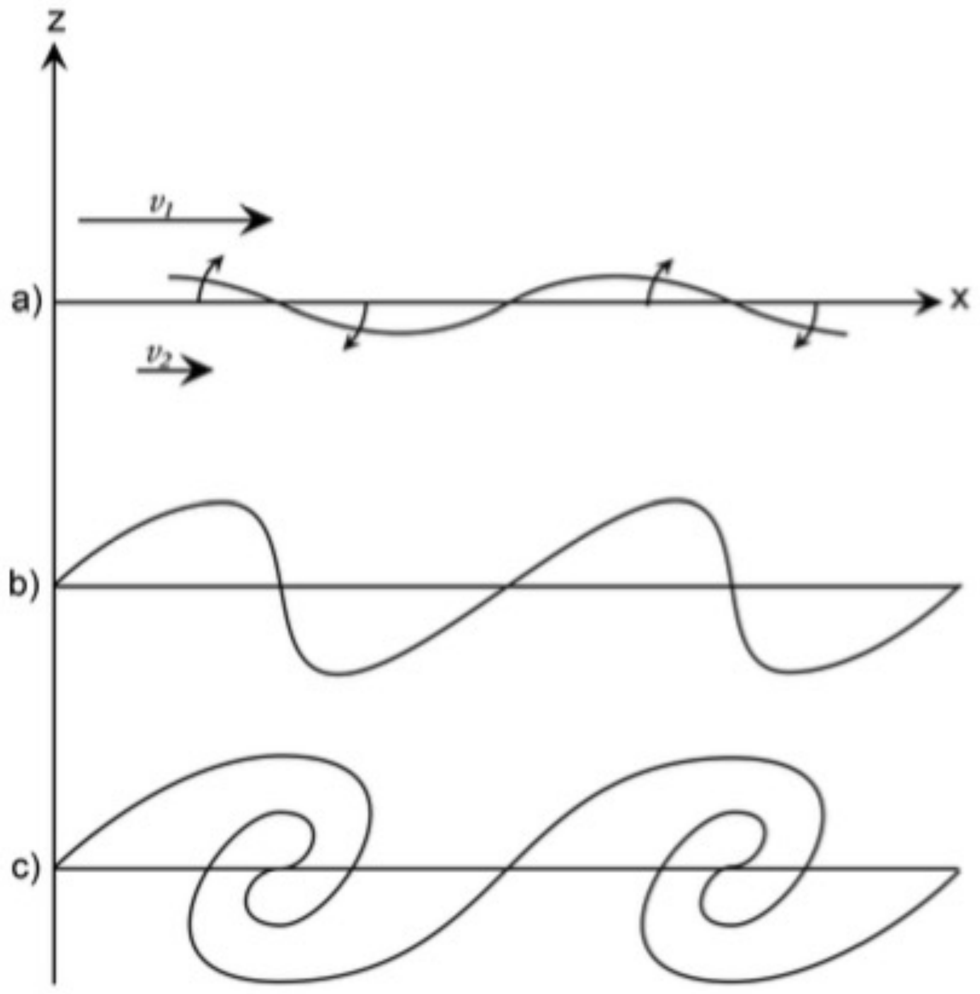
… **d zone**

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).

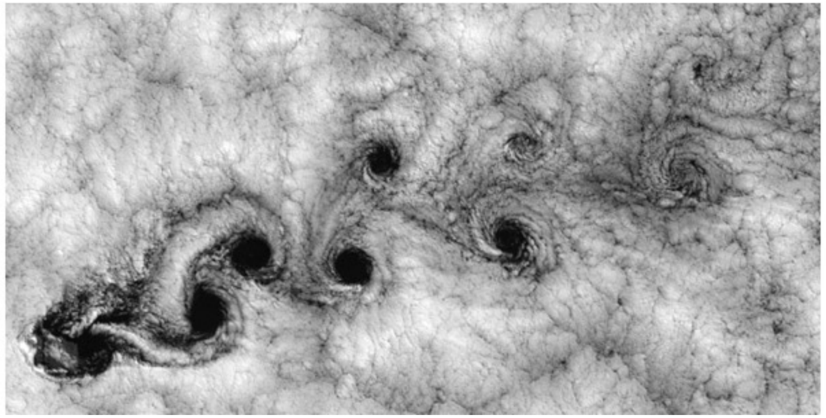
Rossby wave instability
(Kelvin-Helmholtz Instability in rotating disks)



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

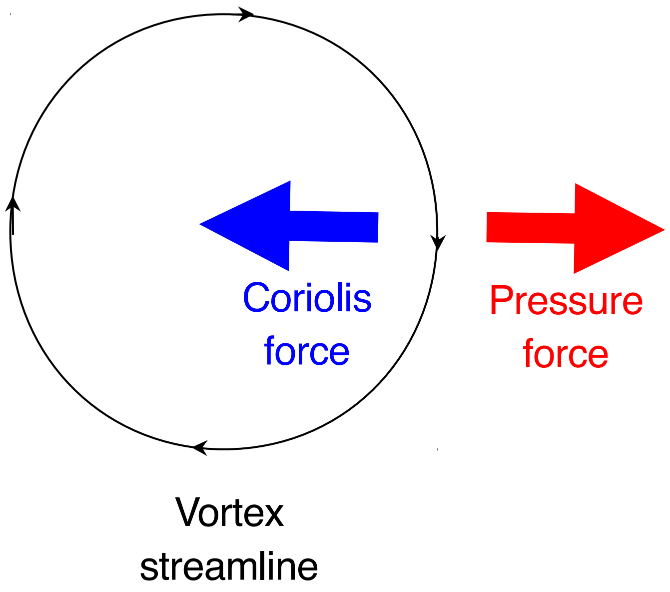
Vortices – an ubiquitous fluid mechanics phenomenon

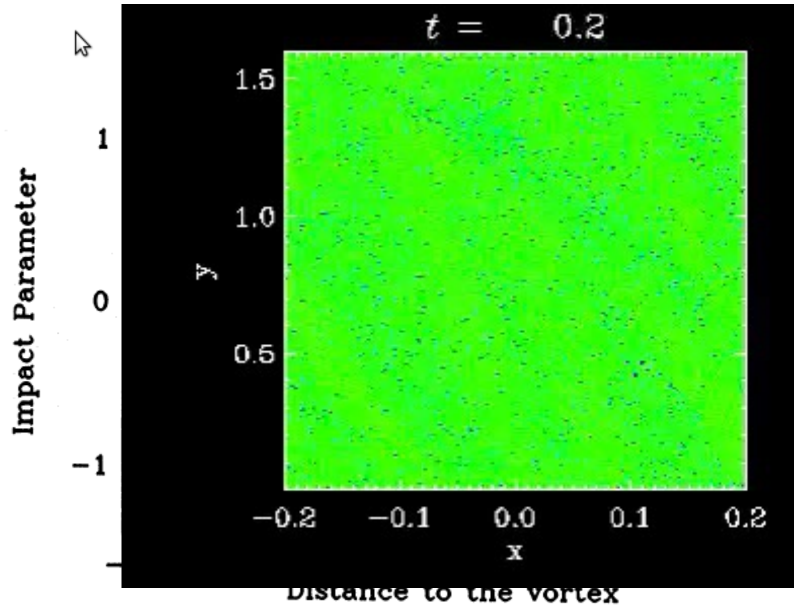
Von Kármán *vortex street*



Vortex Trapping

Geostrophic balance:





Barge & Sommeria (1995)

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

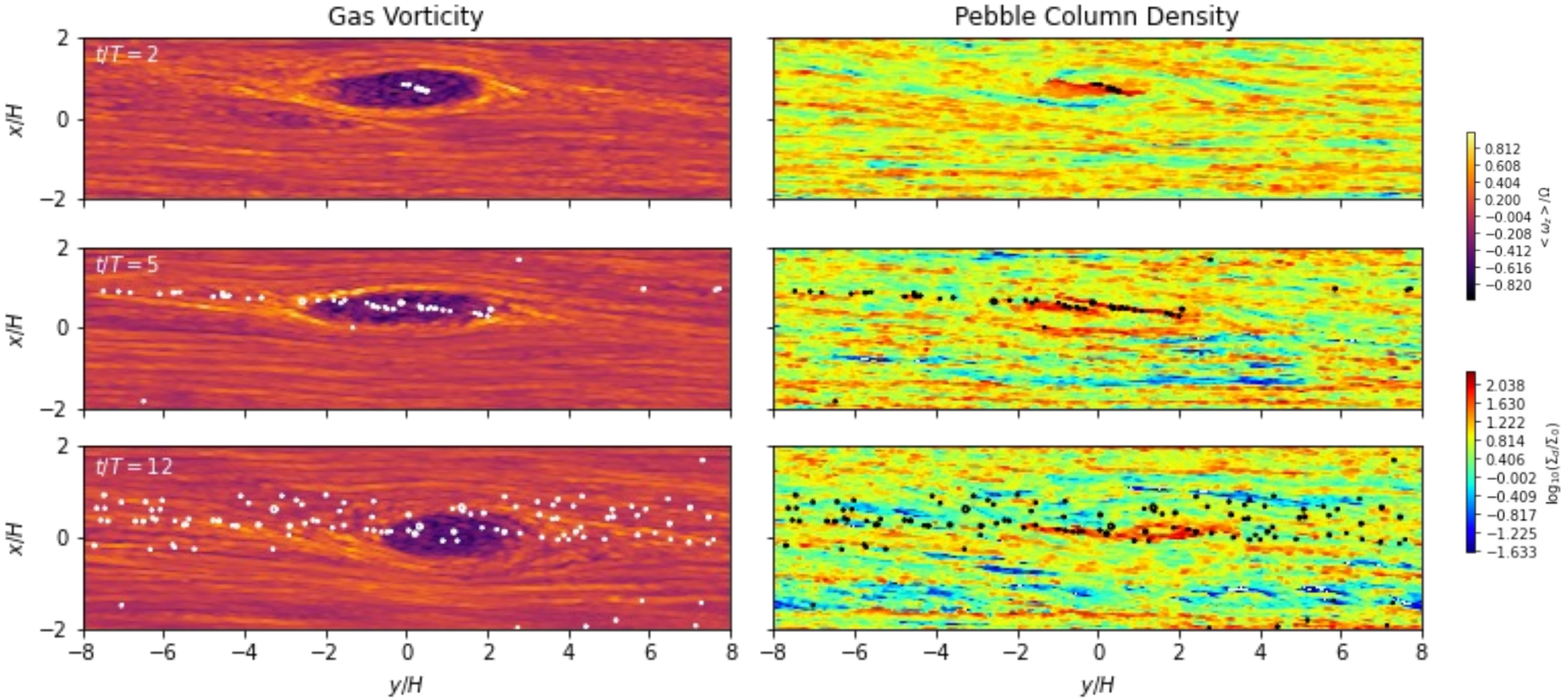
Aid to planet formation

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

Speeds up planet formation enormously

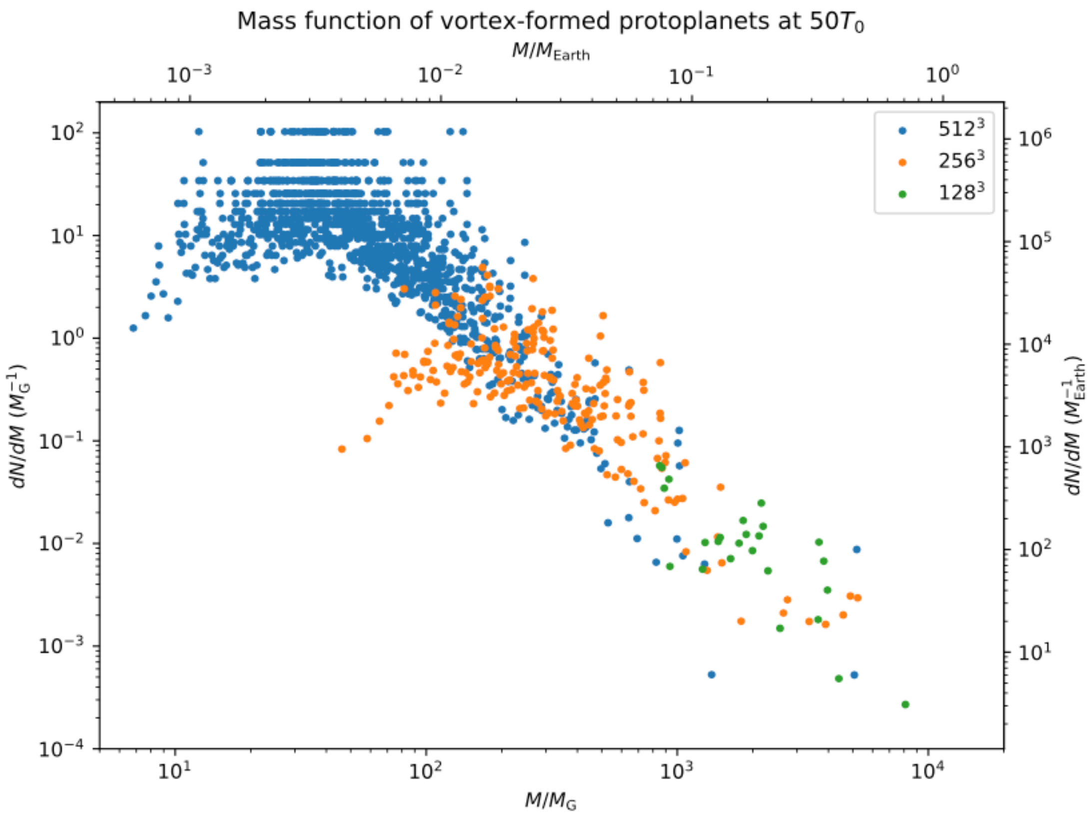
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012, 2021)

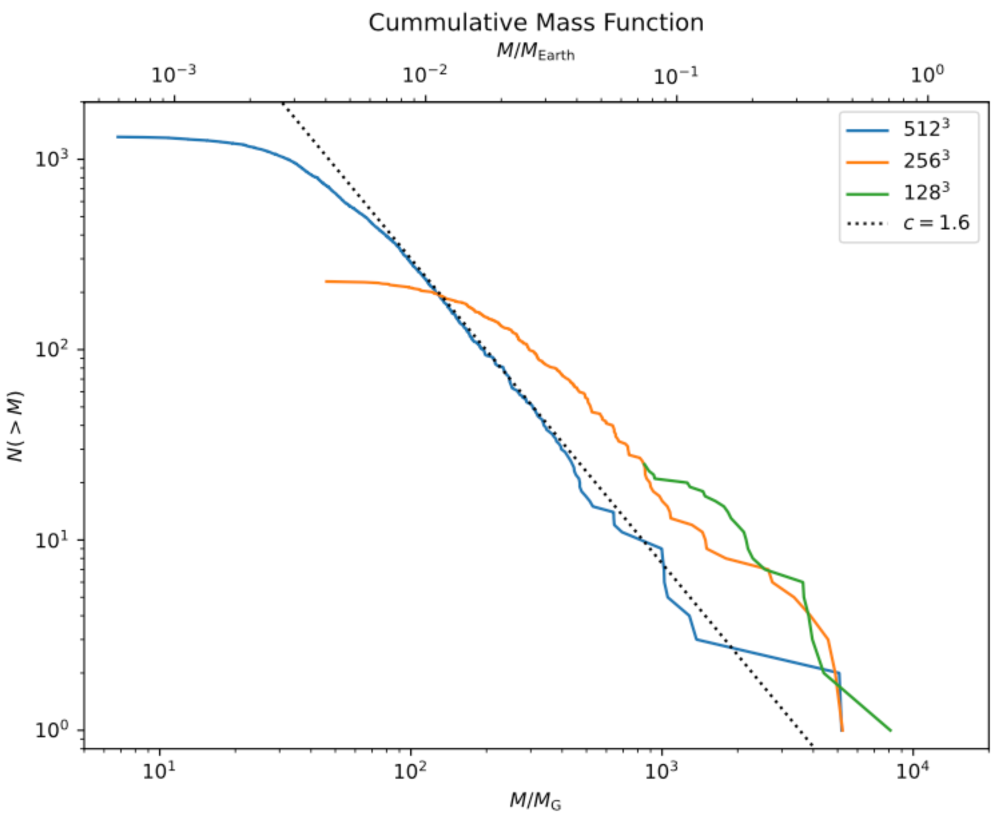
Vortex Trapping



Lyra et al. (in prep)

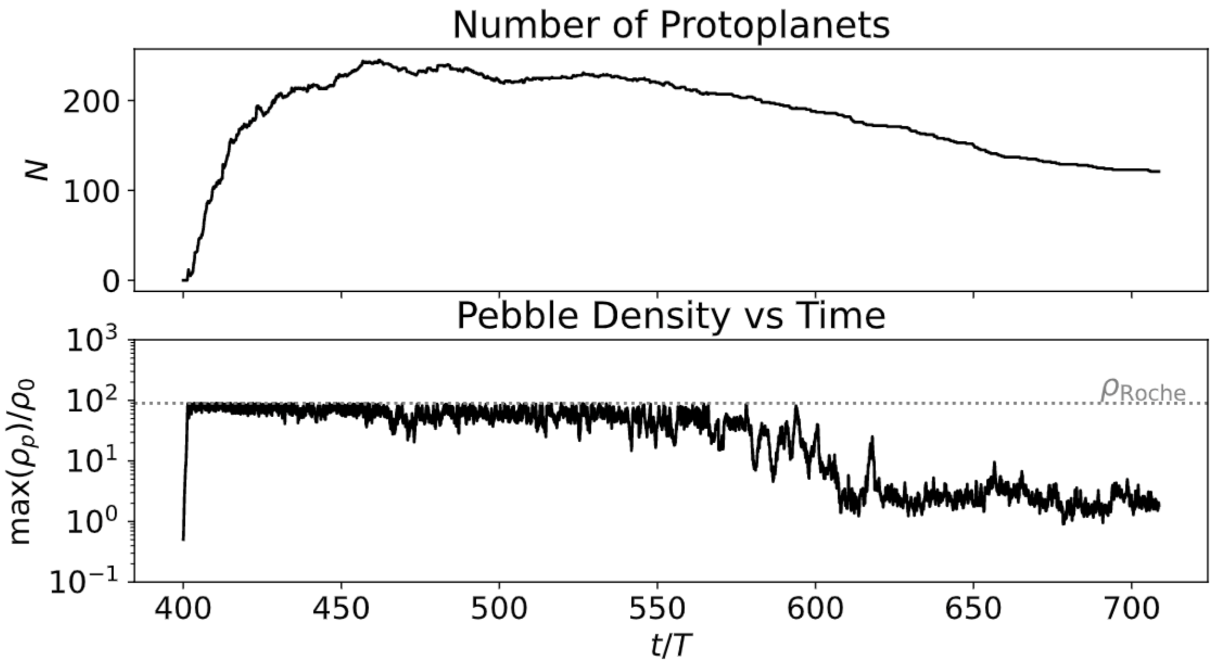
Vortex Trapping – Initial Mass Function

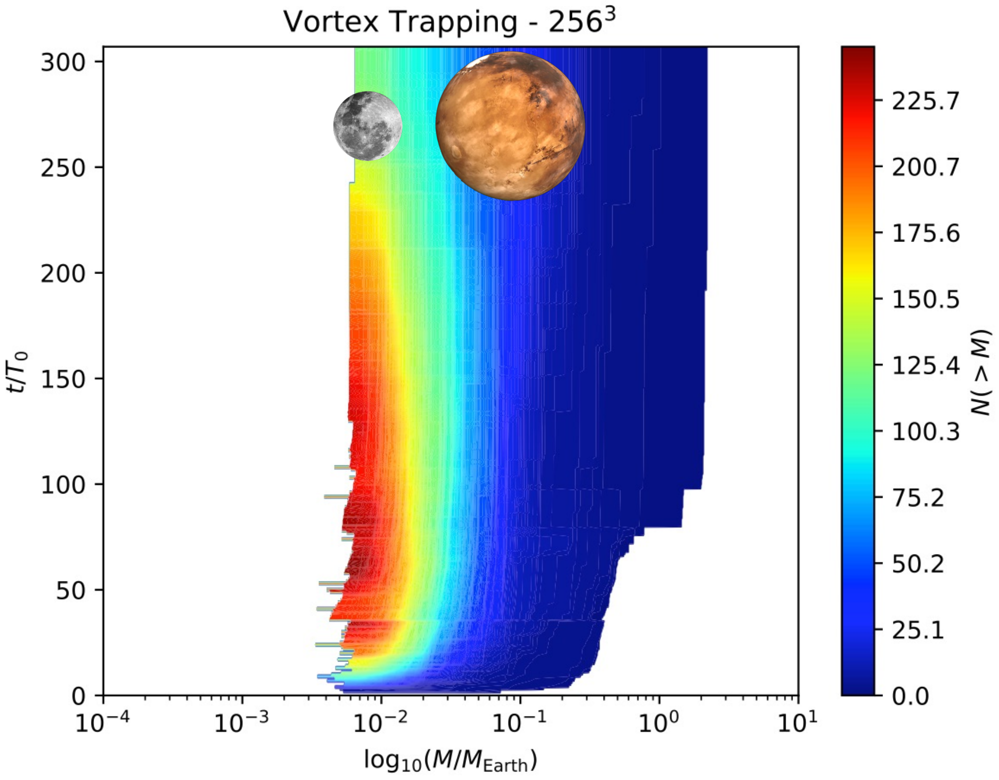




Lyra et al. (in prep)

Initial Mass Function – Convergence



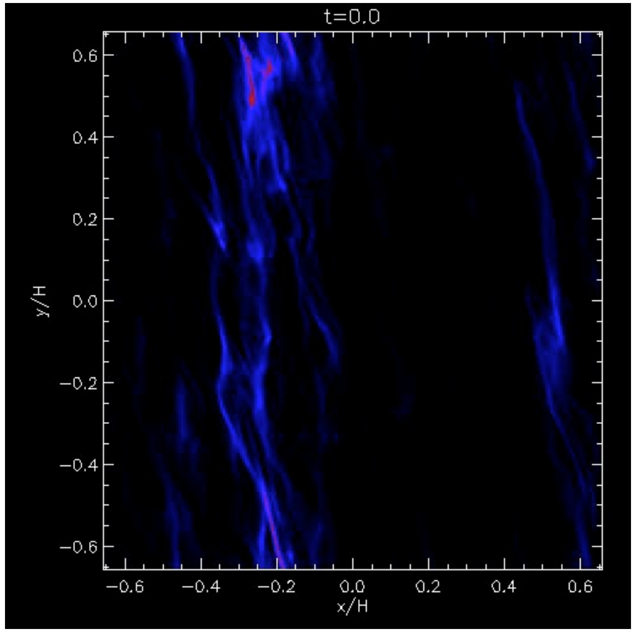


Lyra et al. (in prep)

Take home message

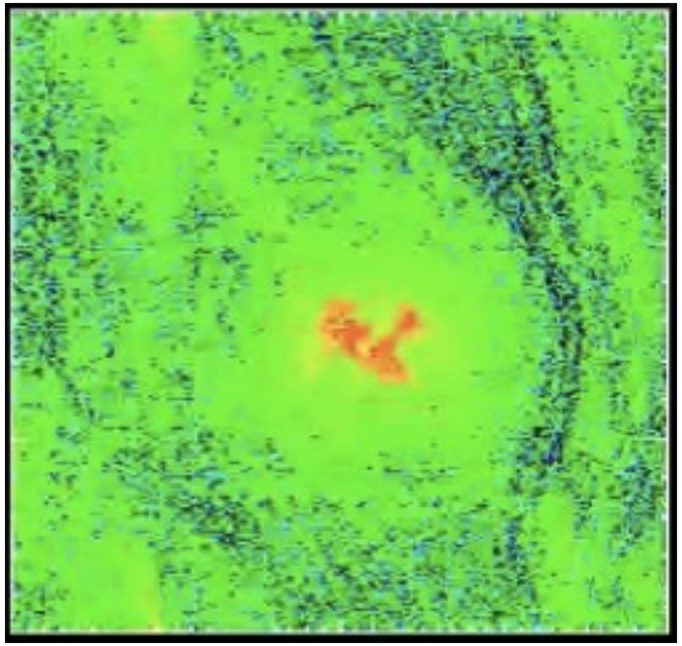
- Two routes for planet formation

Streaming Instability



Johansen+ 07

Vortex Trapping

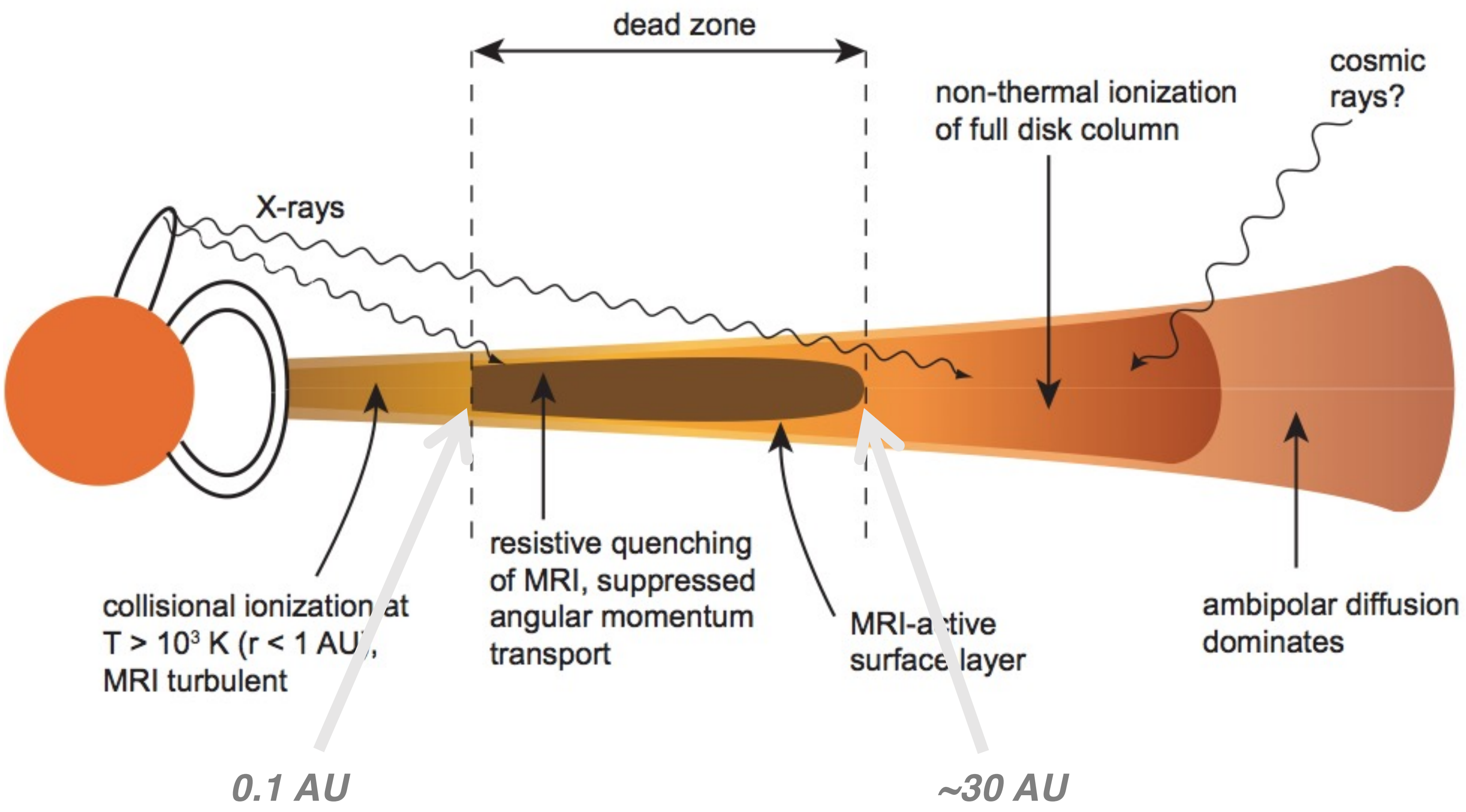


Lyra+08,18 Raettig+Lyra 12,15,21

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

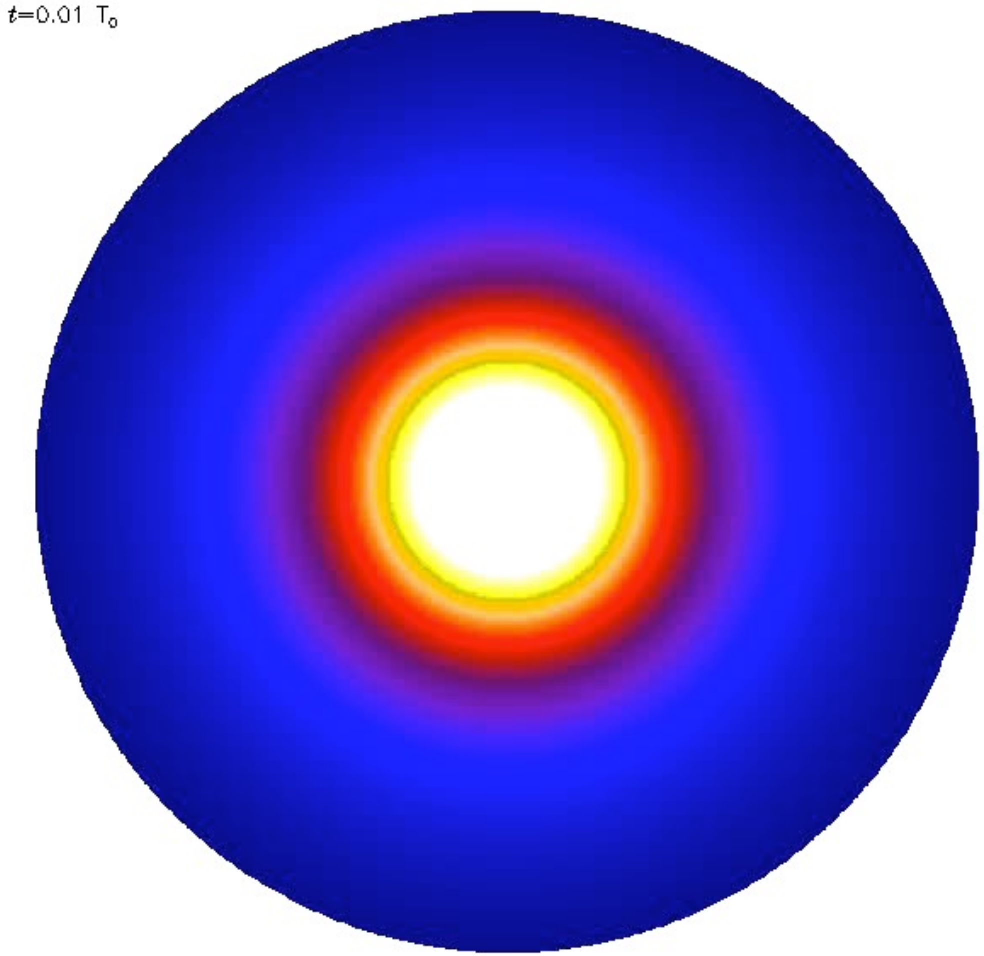
Disk Instabilities

Dead zones



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

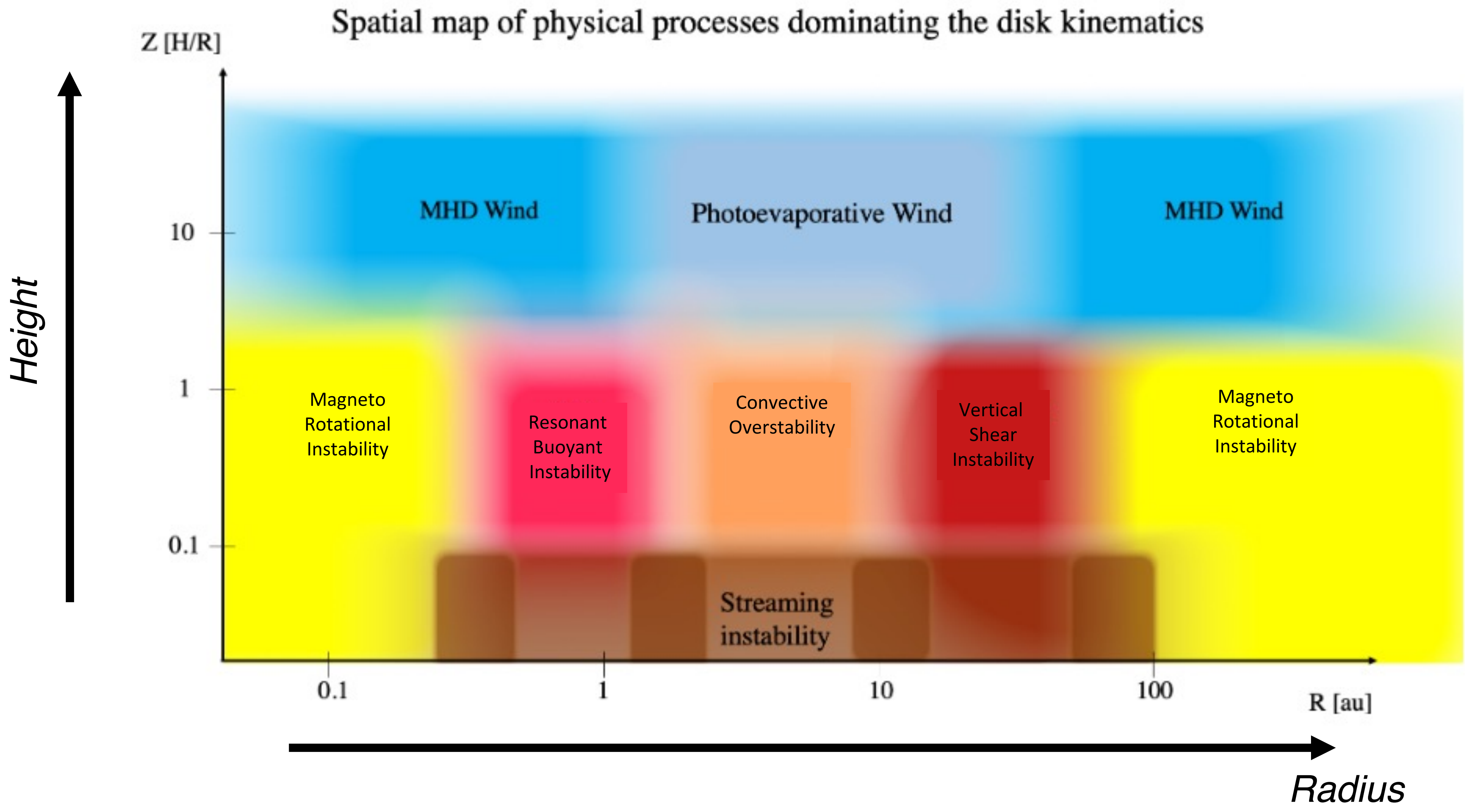
Inner (0.1 AU) active/dead zone boundary



Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Instability Map

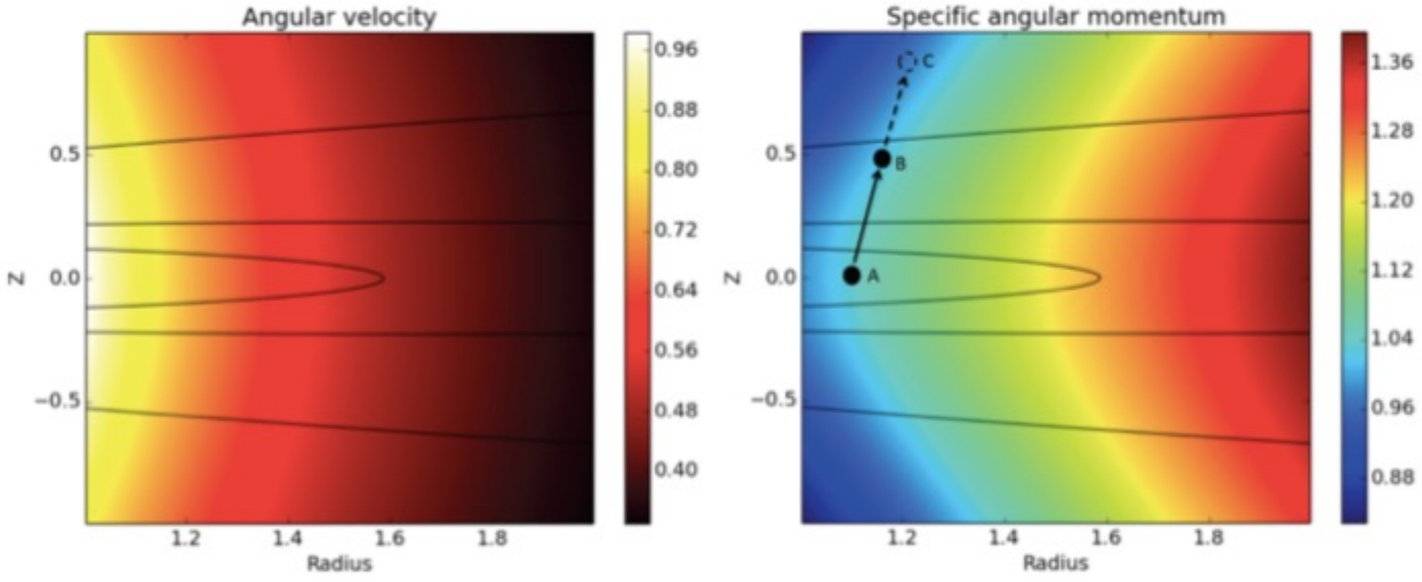


Lesur et al. (2022)

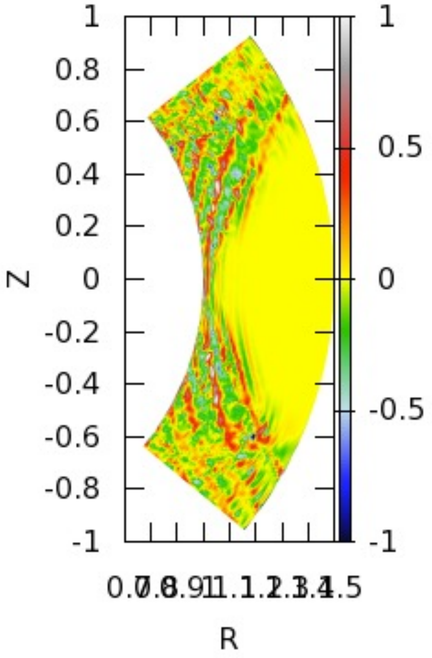
Vertical shear instability

Angular velocity not constant in cylinders: unstable

Buoyancy stabilizes. The most unstable mode is isothermal.

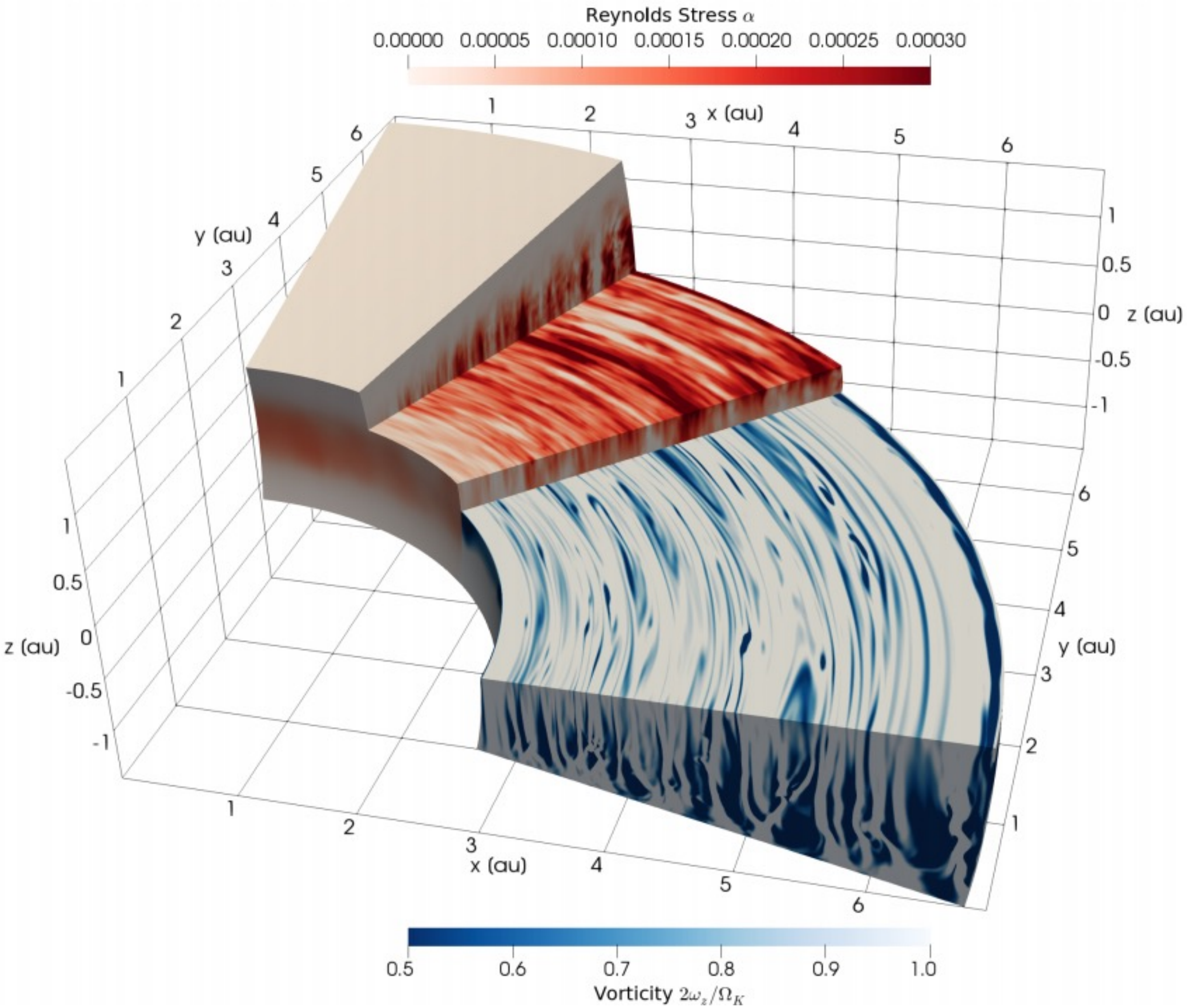


Fromang & Lesur (2017)



Nelson et al. (2013)

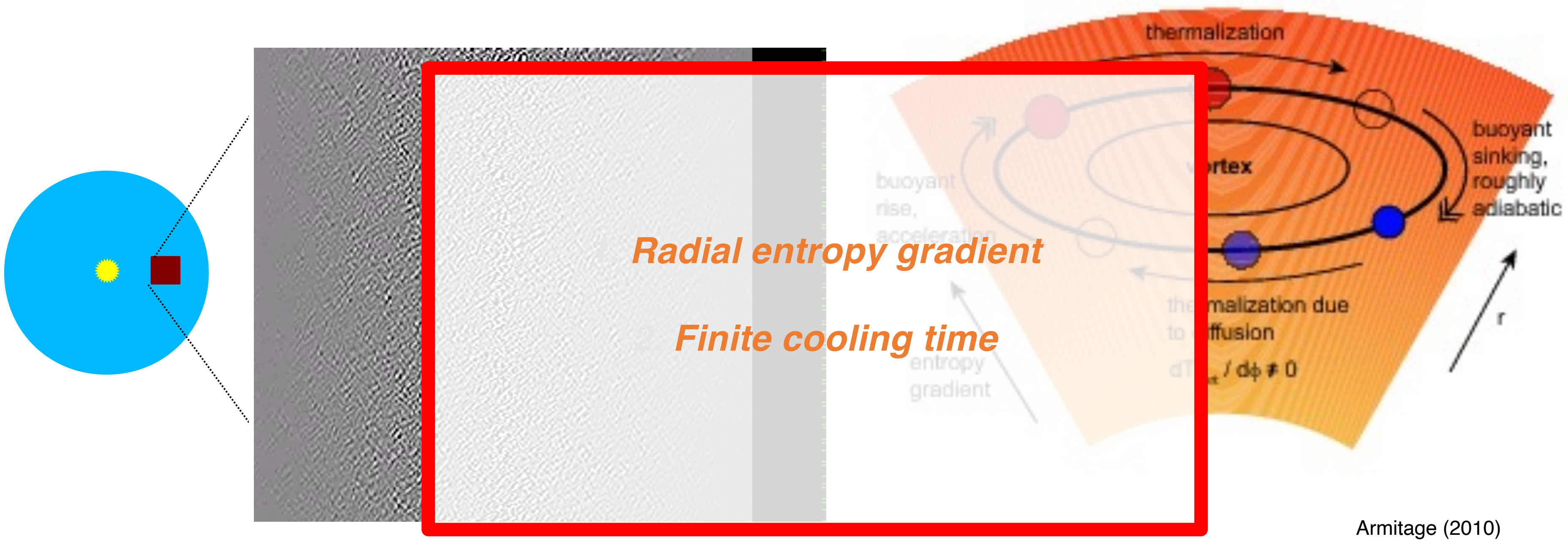
Vertical shear instability



Pfeil & Klahr (2020)

Convective Overstability

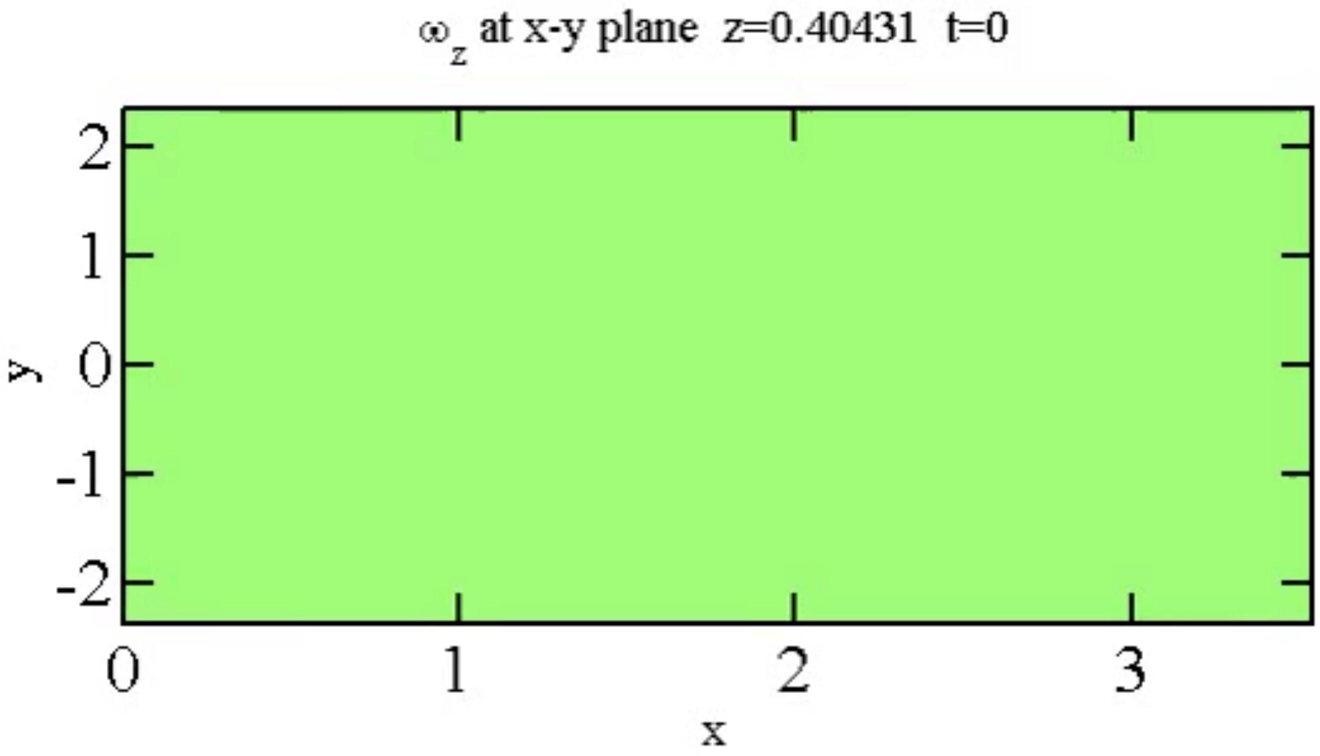
Sketch of the
Convective Overstability



Armitage (2010)

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

Resonant Buoyant Instability (Zombie Vortex Instability)

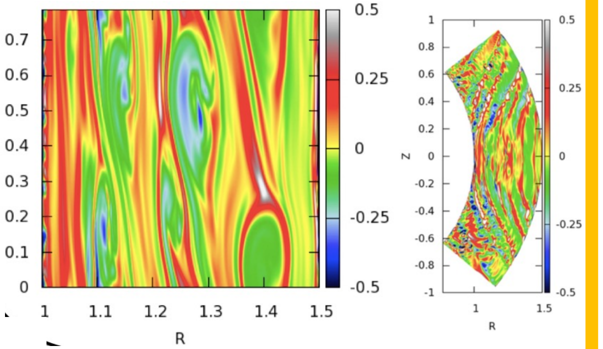


Cascade of baroclinic critical layers

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

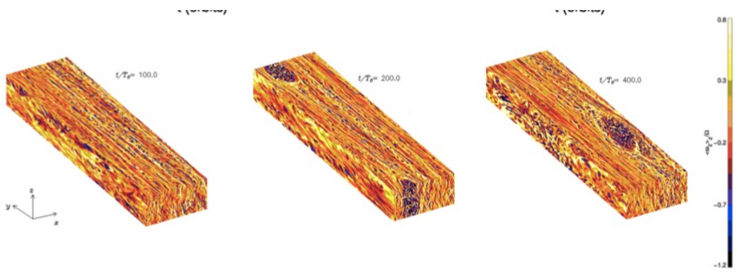
Hydrodynamical Instabilities

Vertical Shear Instability



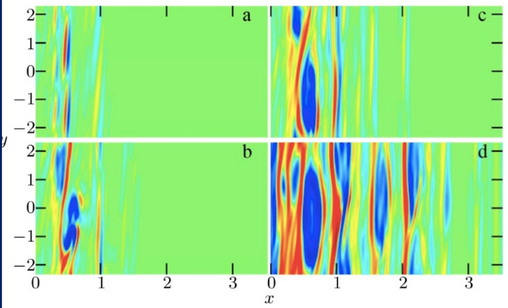
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

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

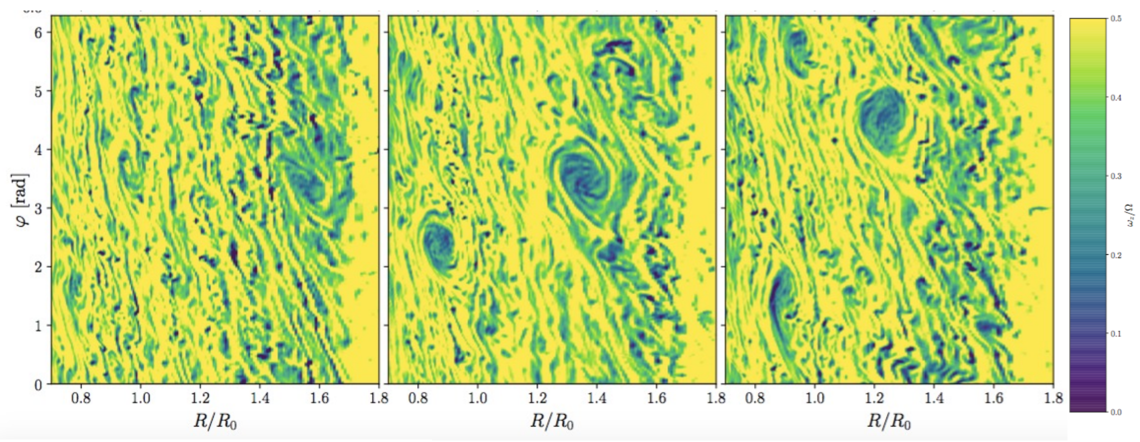
$\Omega\tau \ll 1$
($\kappa < 1$ cm^2/g)

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

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

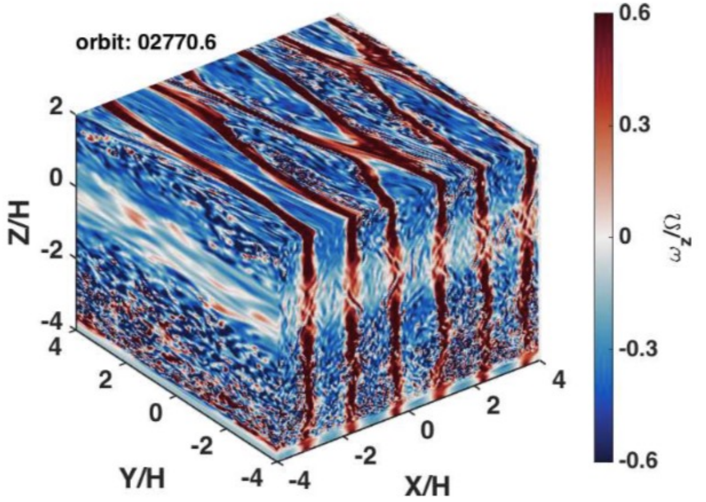
Opacity

Take-home message



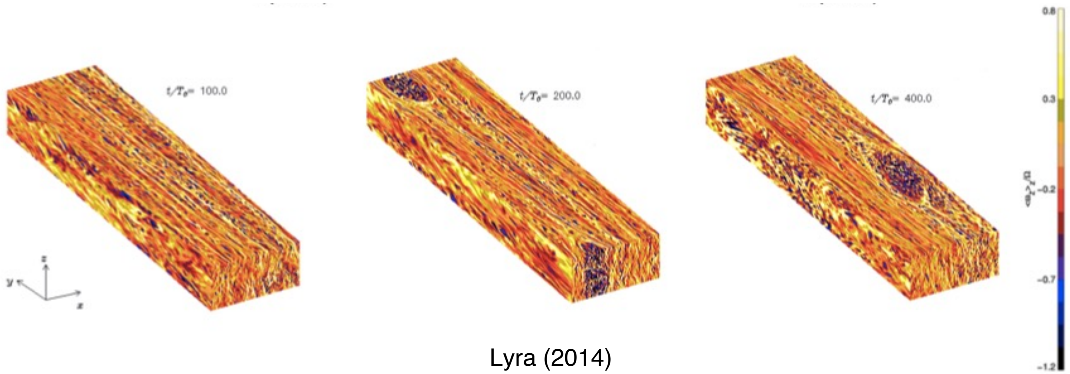
Manger & Klahr (2018)

Vertical Shear Instability
saturates into
vortices



Barranco et al. (2018)

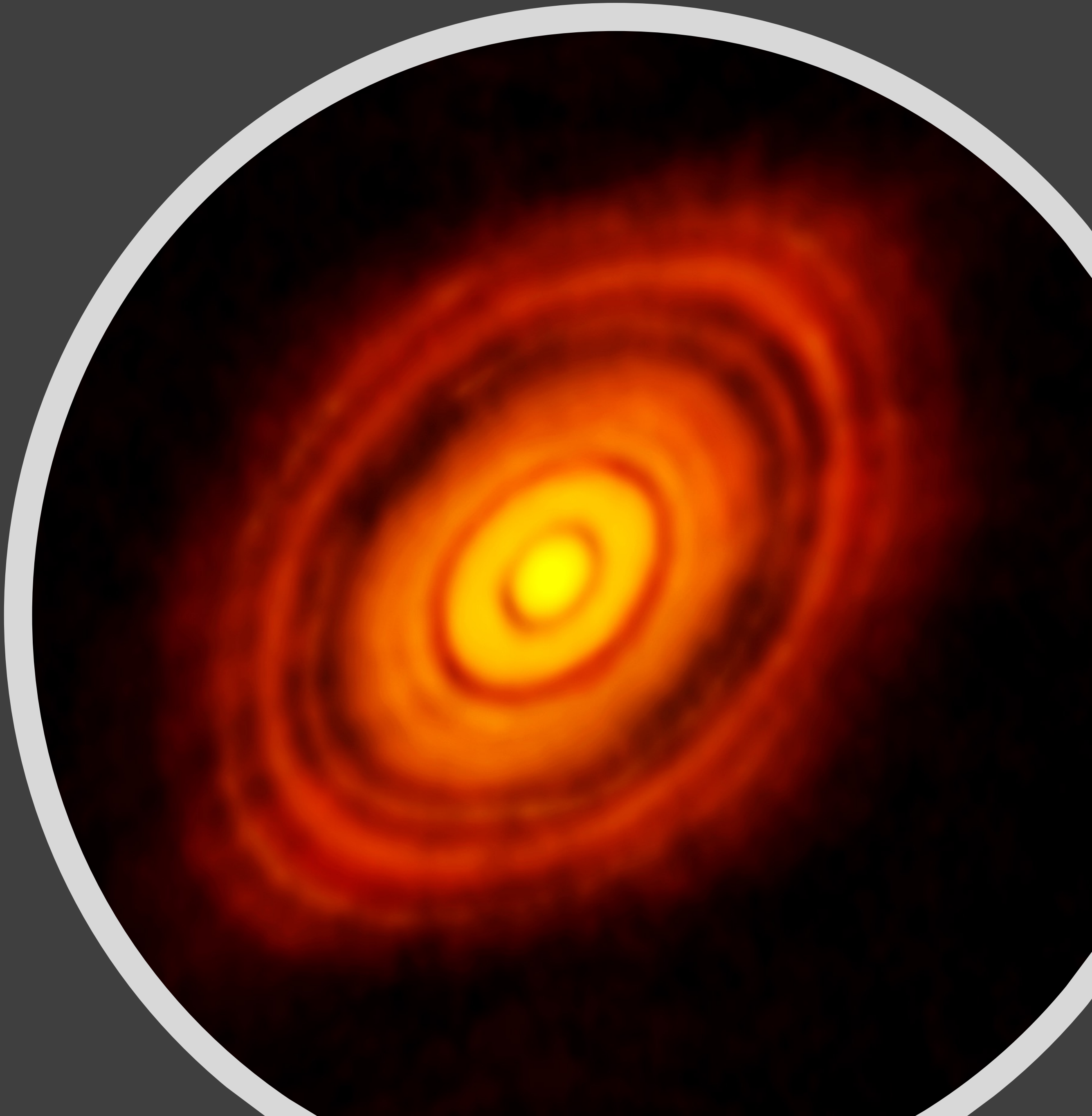
Zombie Vortex Instability
saturates into
vortices

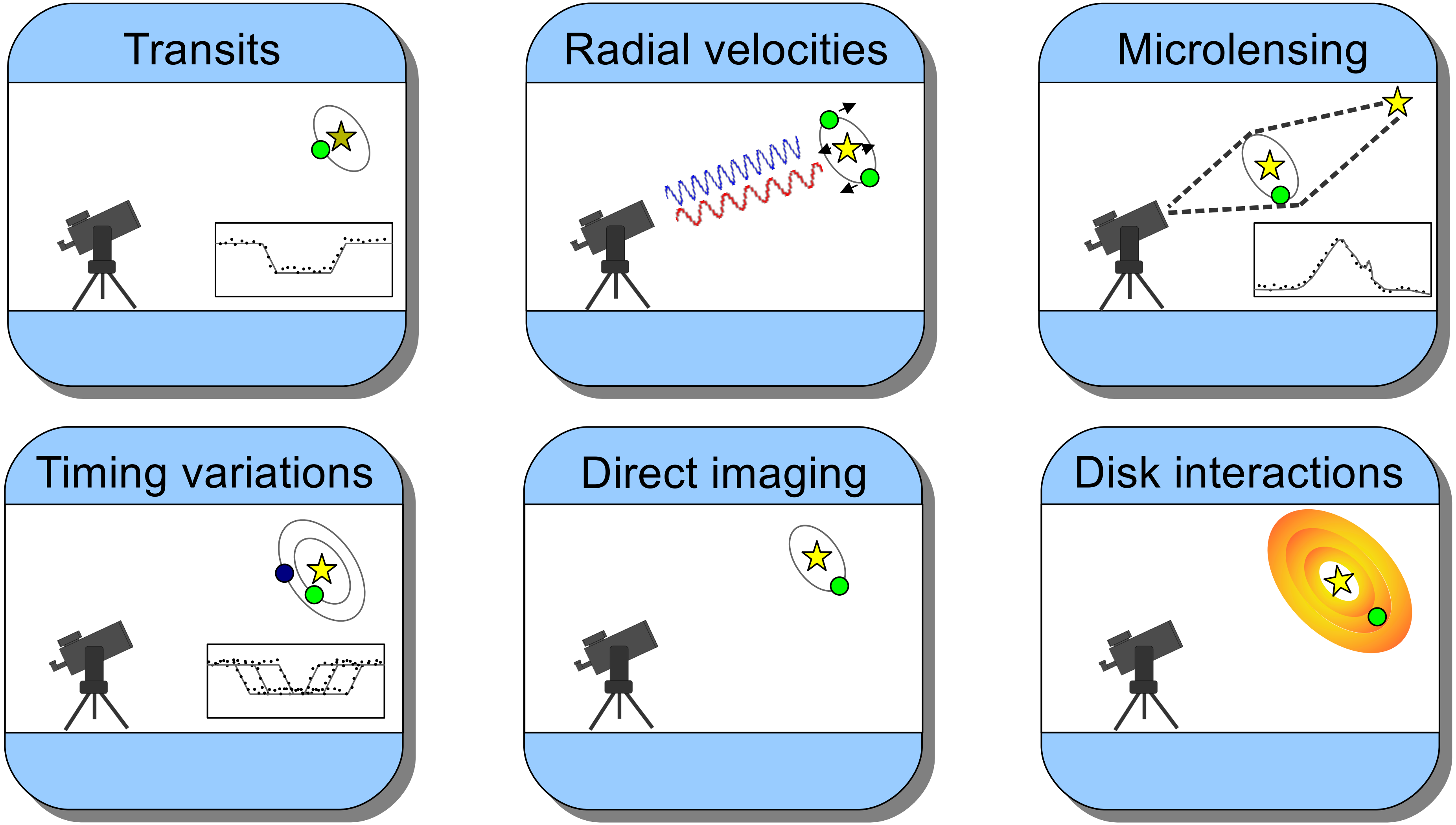


Lyra (2014)

Convective Overstability
saturates into
vortices

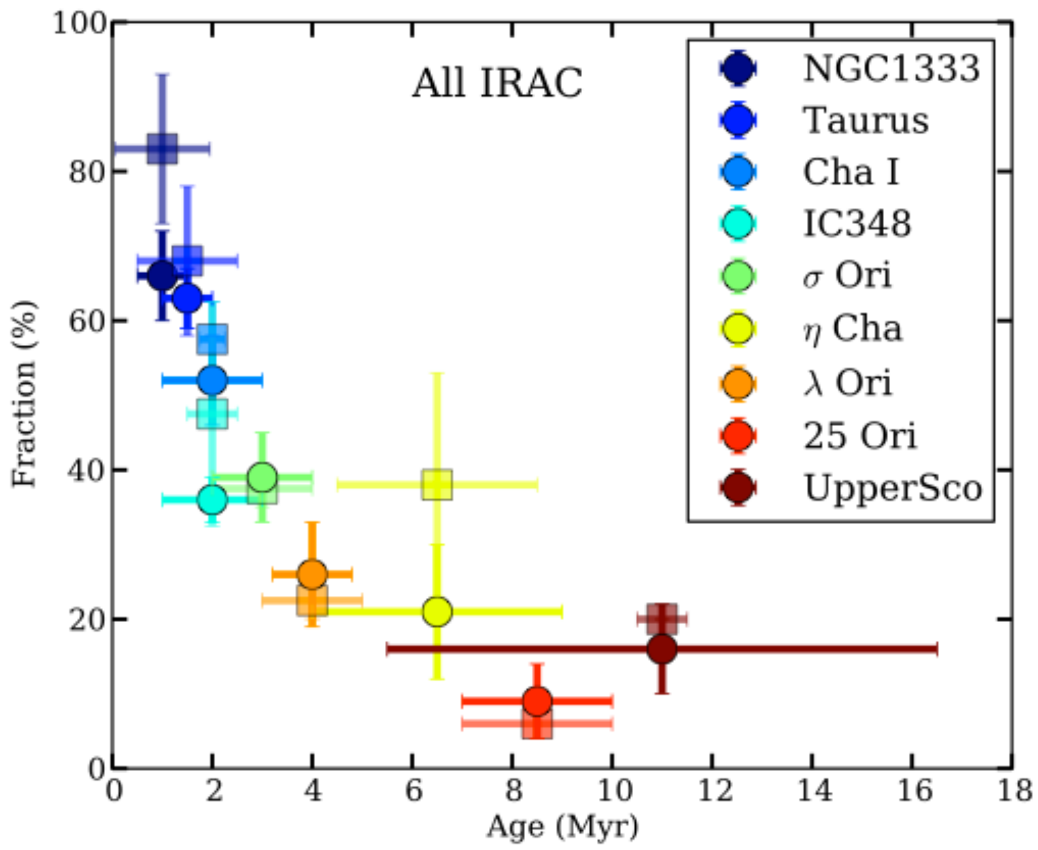
Disk Observations





Slide by A. Richert

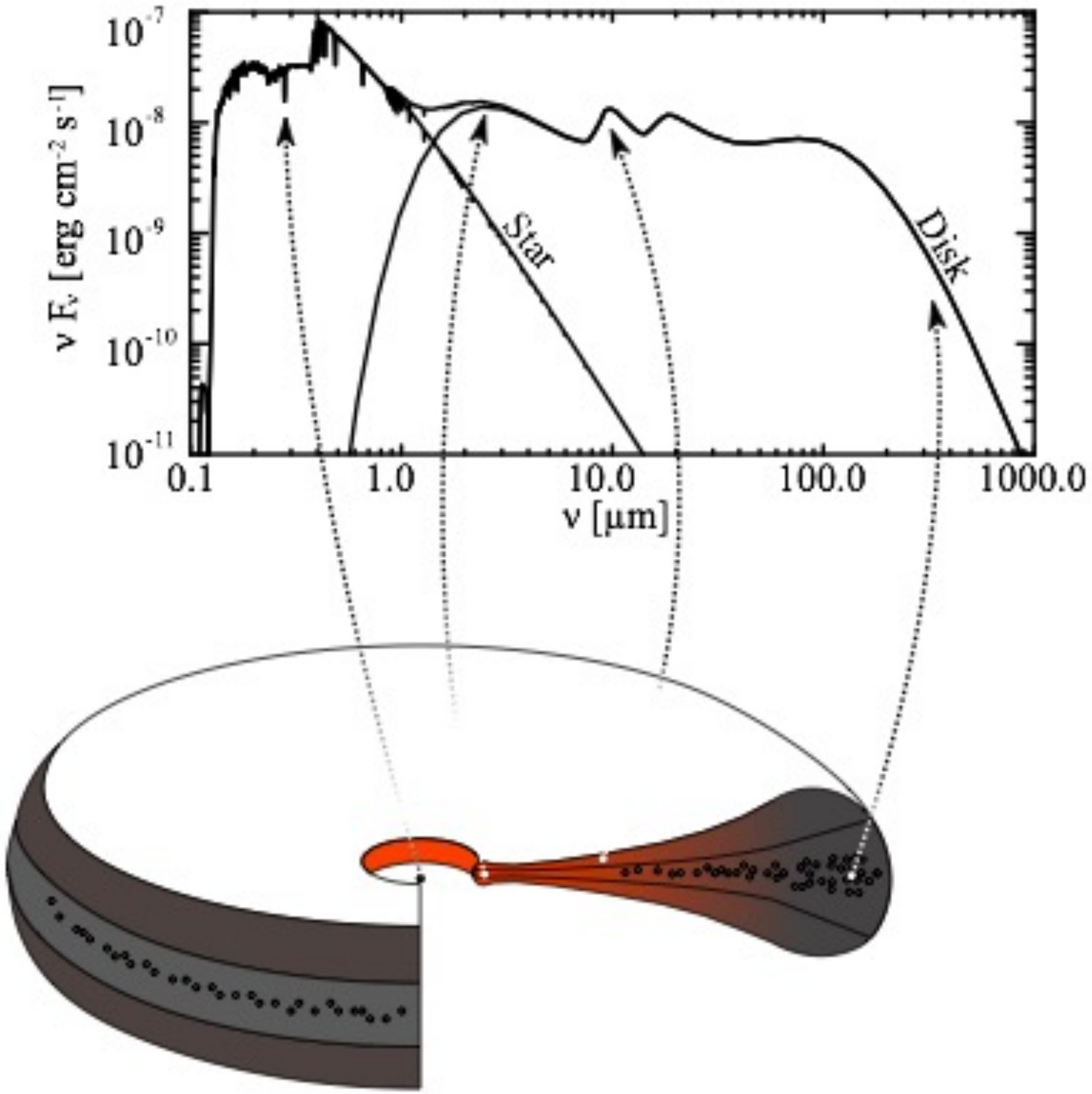
Disk lifetime



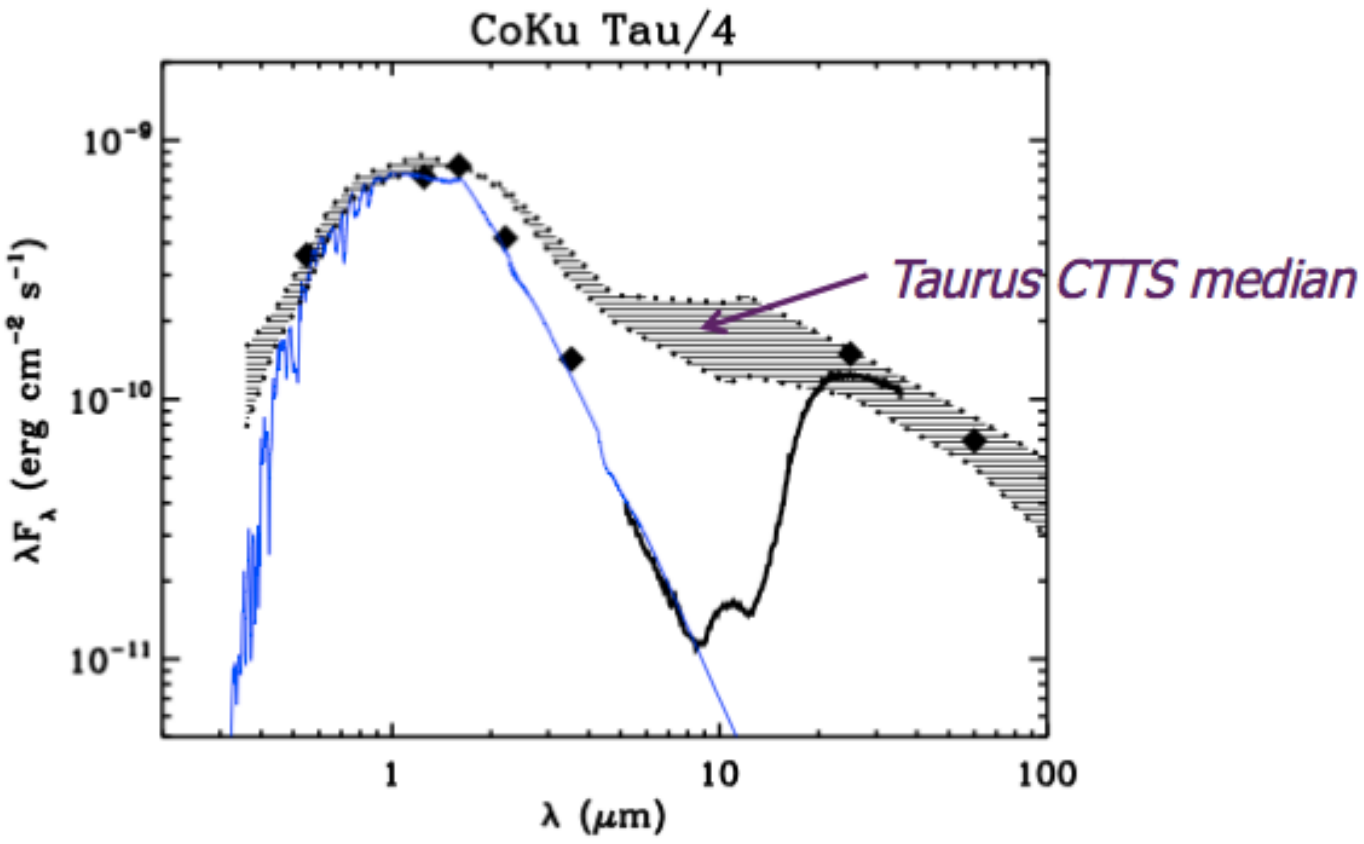
(Ribas et al. 2014)

Disks dissipate within ~10 Myr
Mass accretion rates ~ 10^{-8} $M_{\odot}$ yr^{-1}

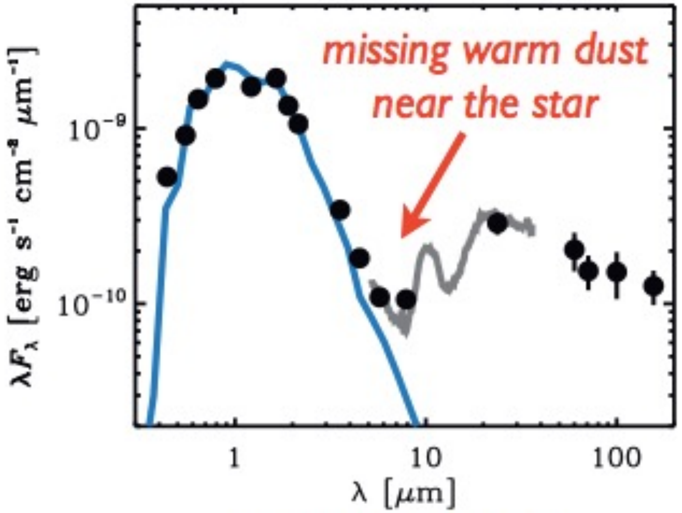
Disk spectra



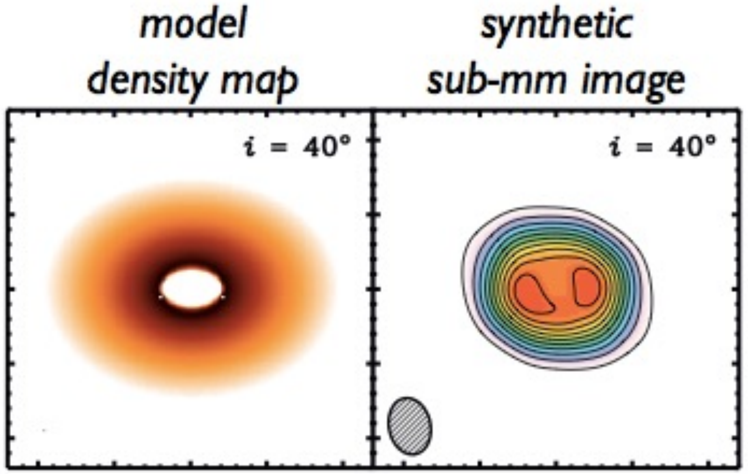
A class of disks with missing hot dust.



Disks with missing hot dust.

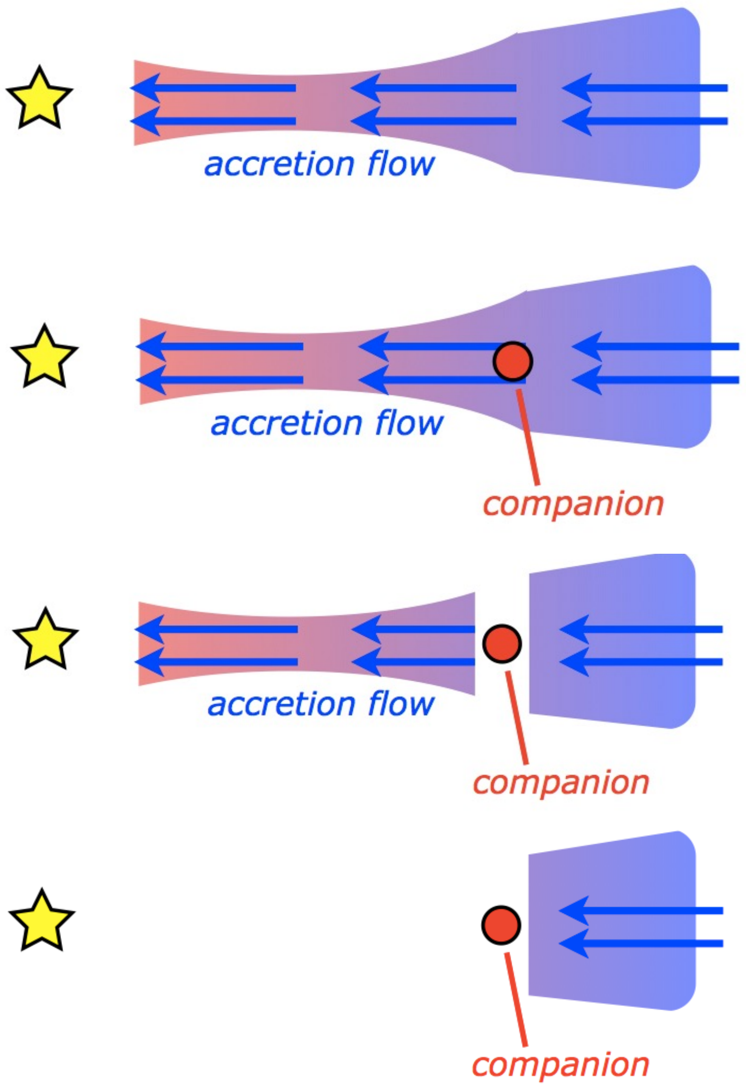


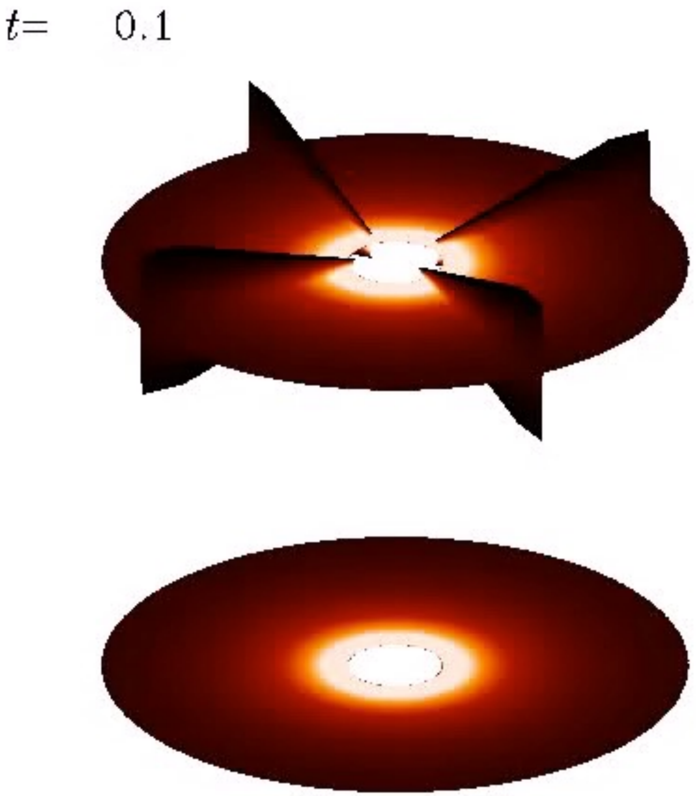
[e.g., Furlan et al. 2009]



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

Planetary companion

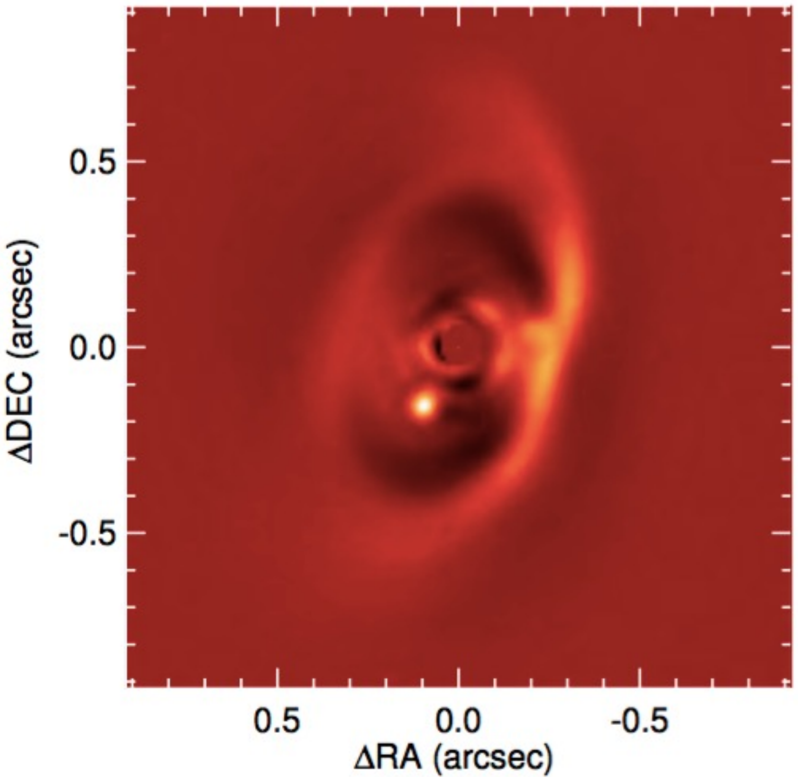




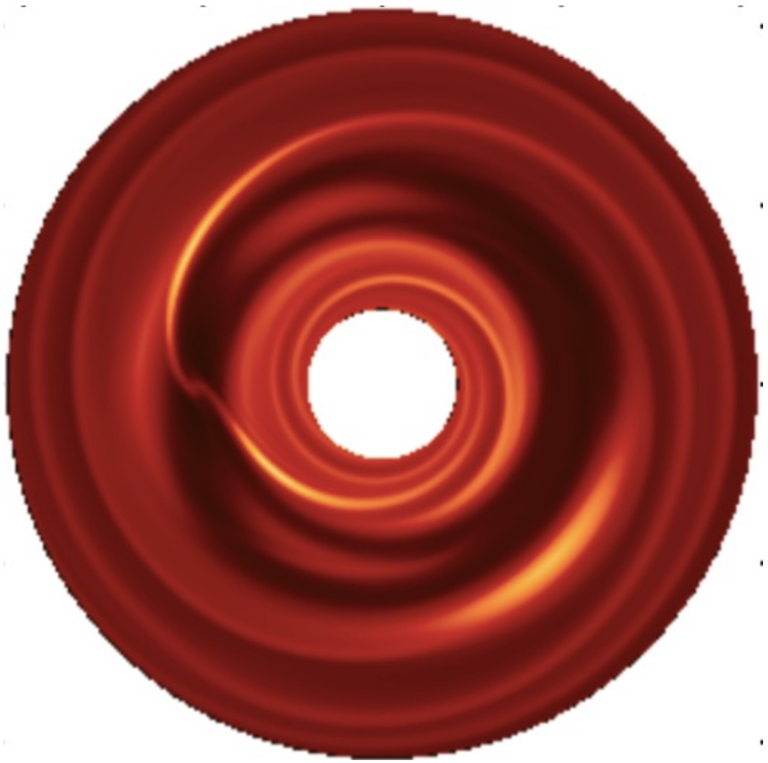
(Lyra 2009)

These cavities may be the telltale signature of forming planets

PDS 70 and PDS 70b



(Muller et al. 2018)



(Lyra et al. 2009b)

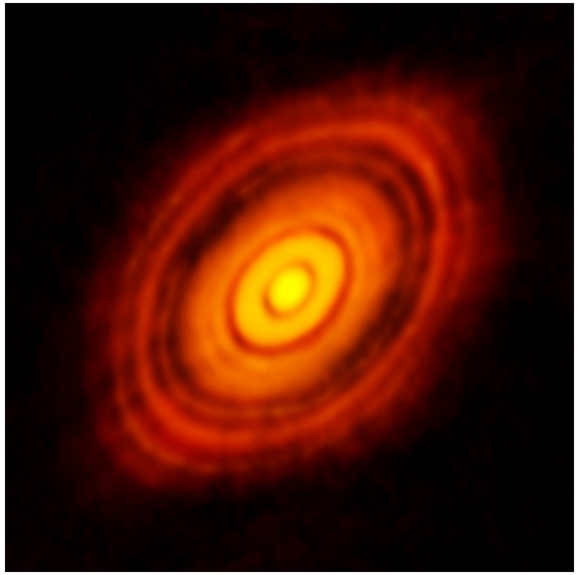
A way to directly study planet-disk interaction

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

(Lyra et al. 2009b)

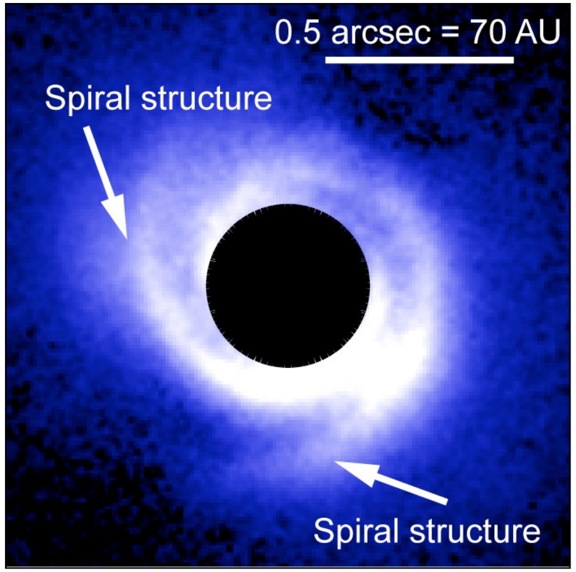
Observational evidence: gaps, spirals, and vortices

HL Tau



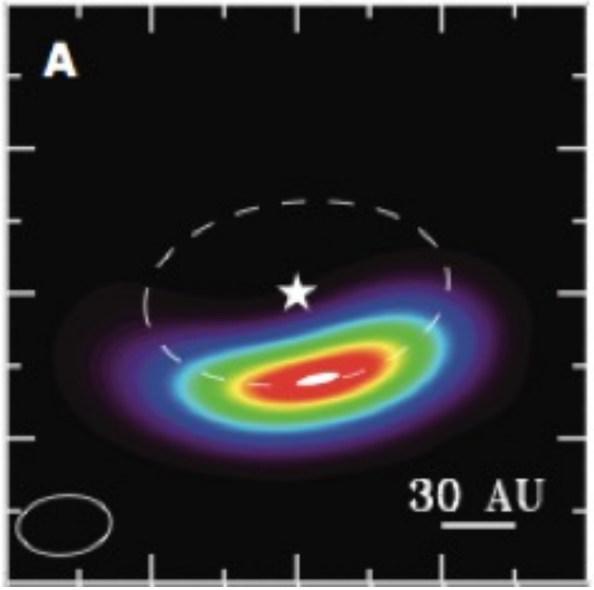
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

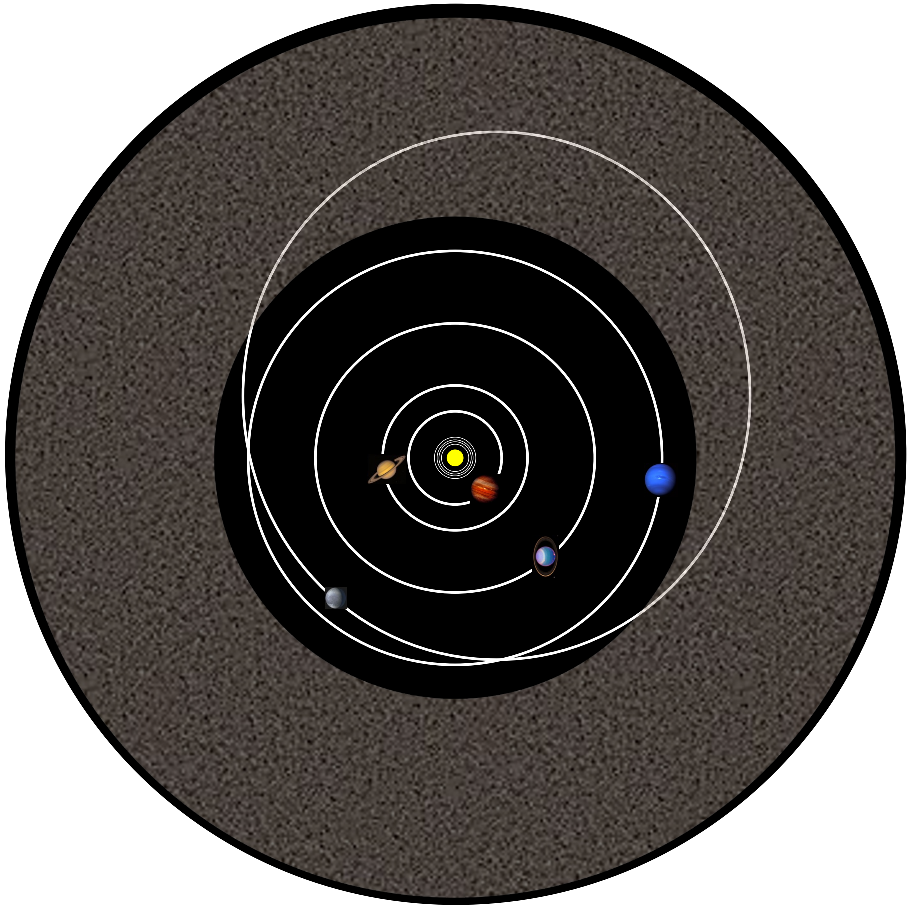
Oph IRS 48

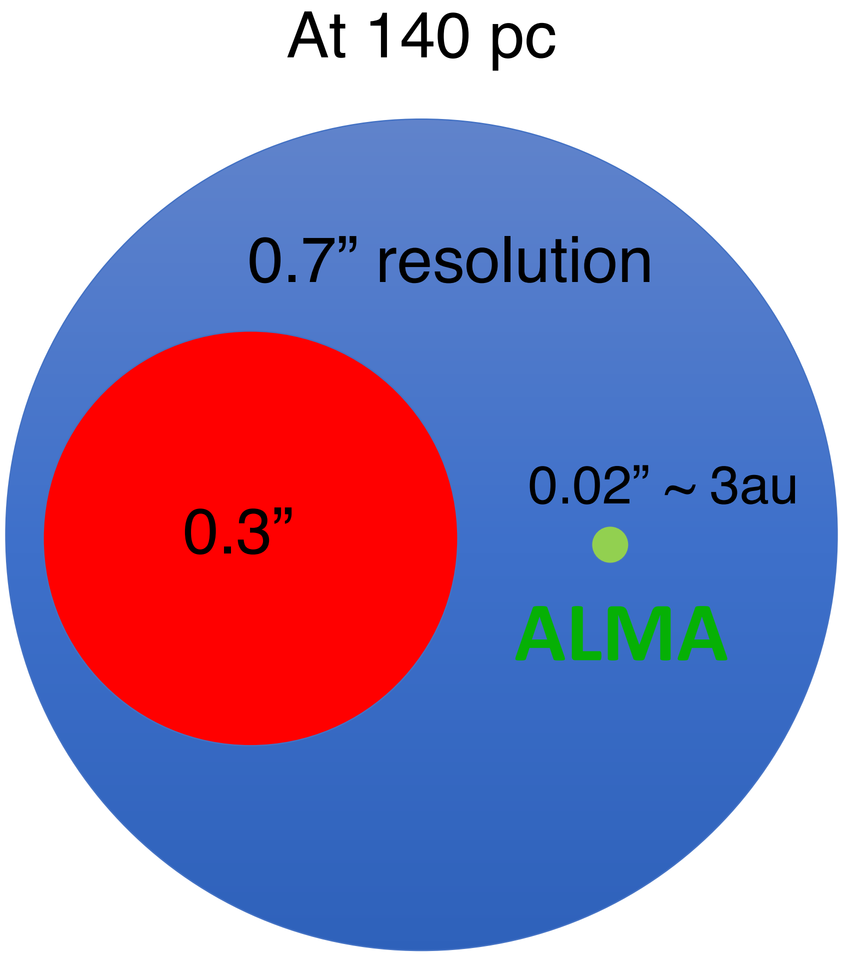


van der Marel et al. (2013)

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

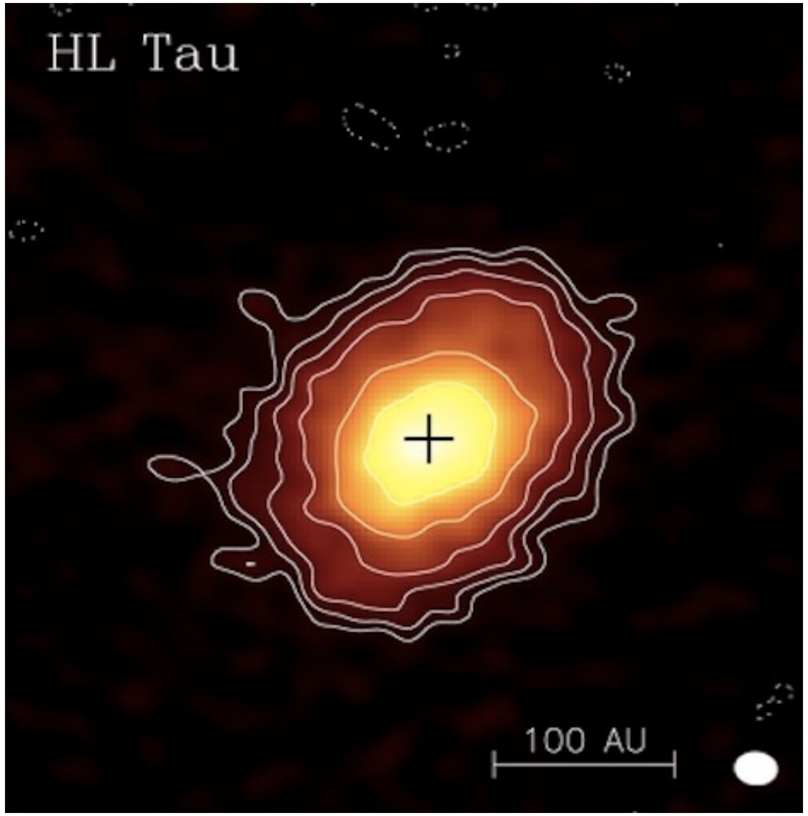
The ALMA ReSolution

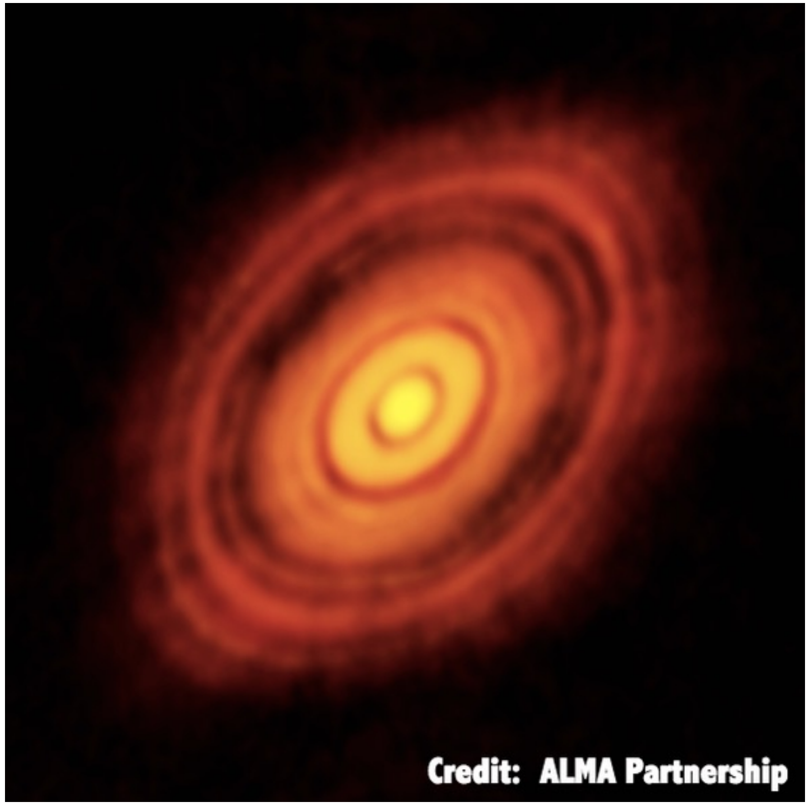




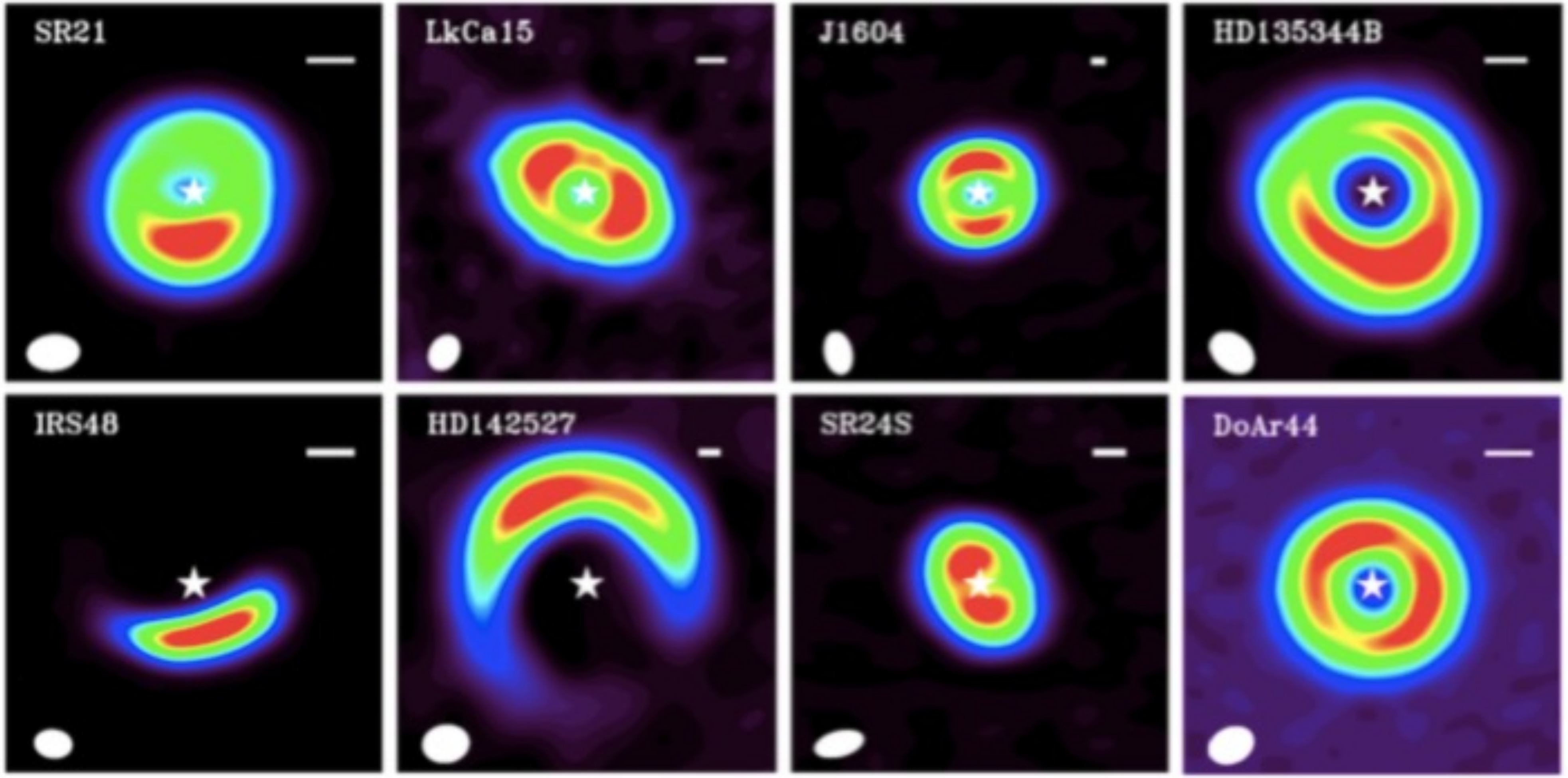
Before ALMA

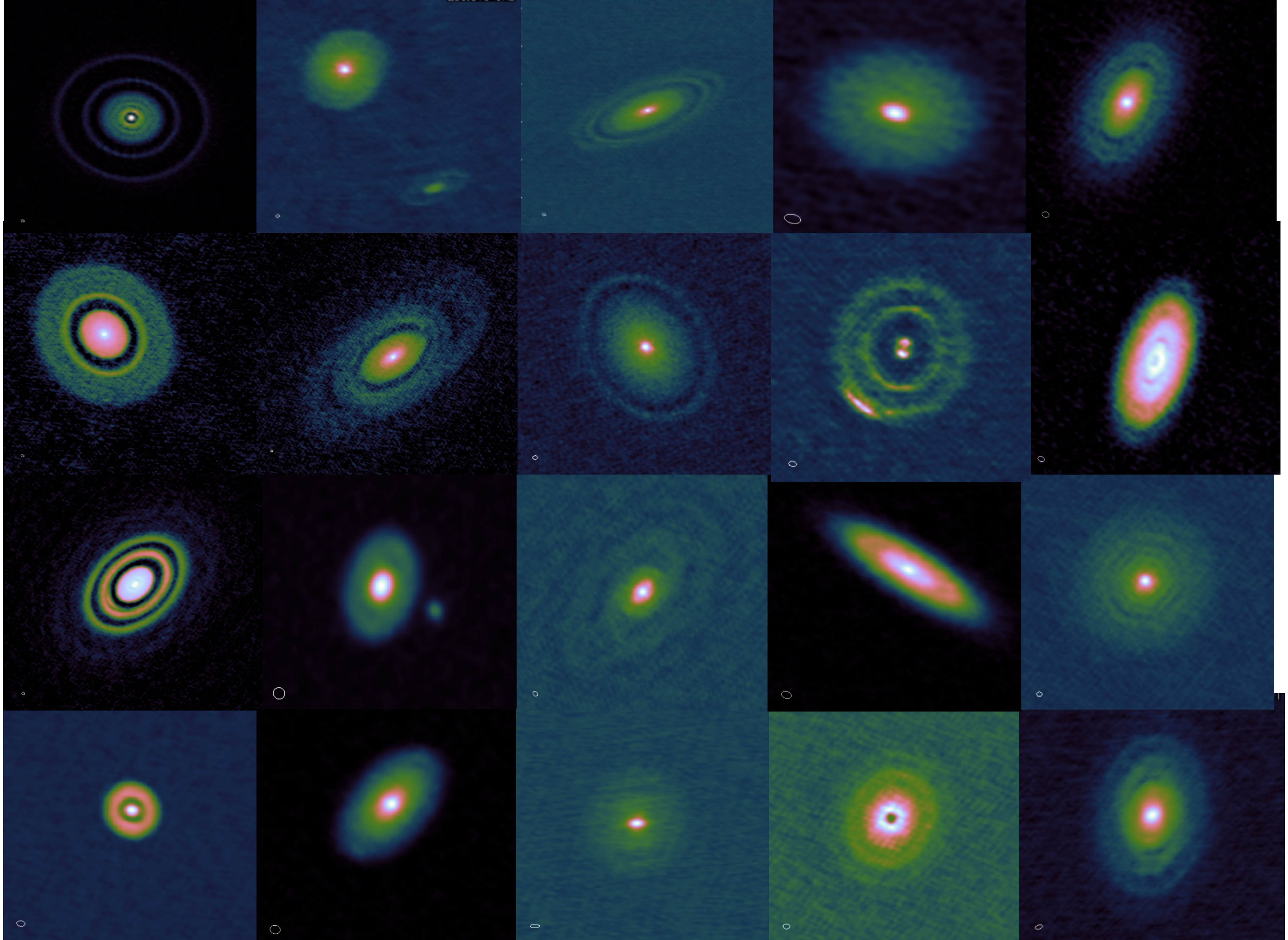
ALMA





Dust traps in disks: ALMA Cycle 0 (2012)





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

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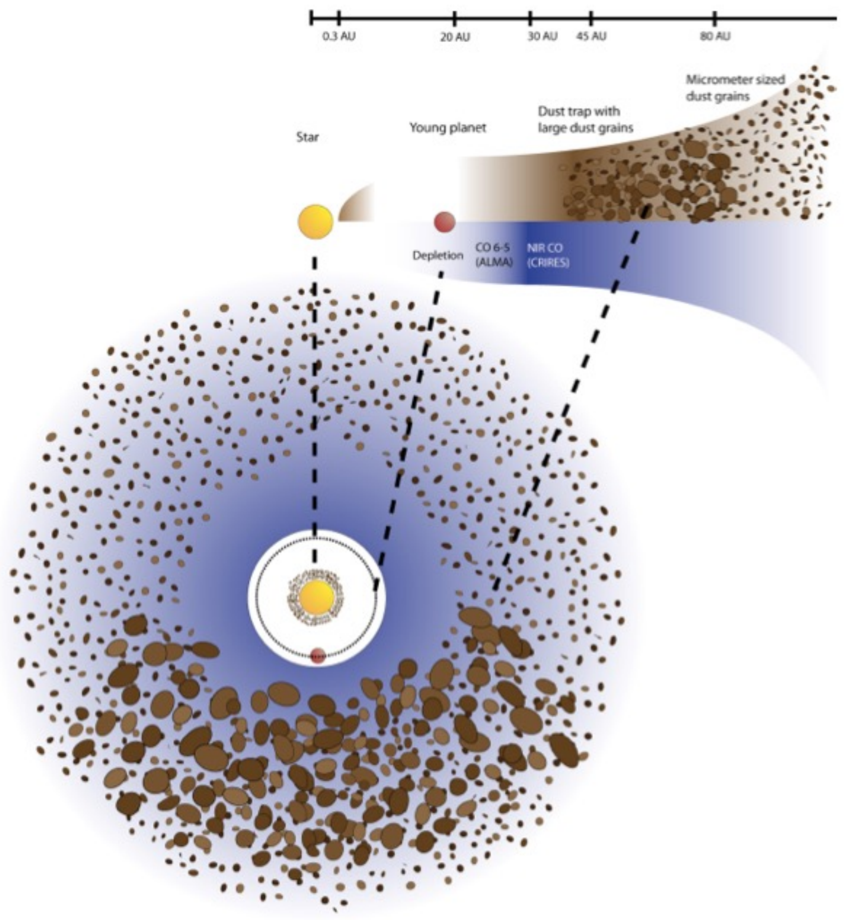
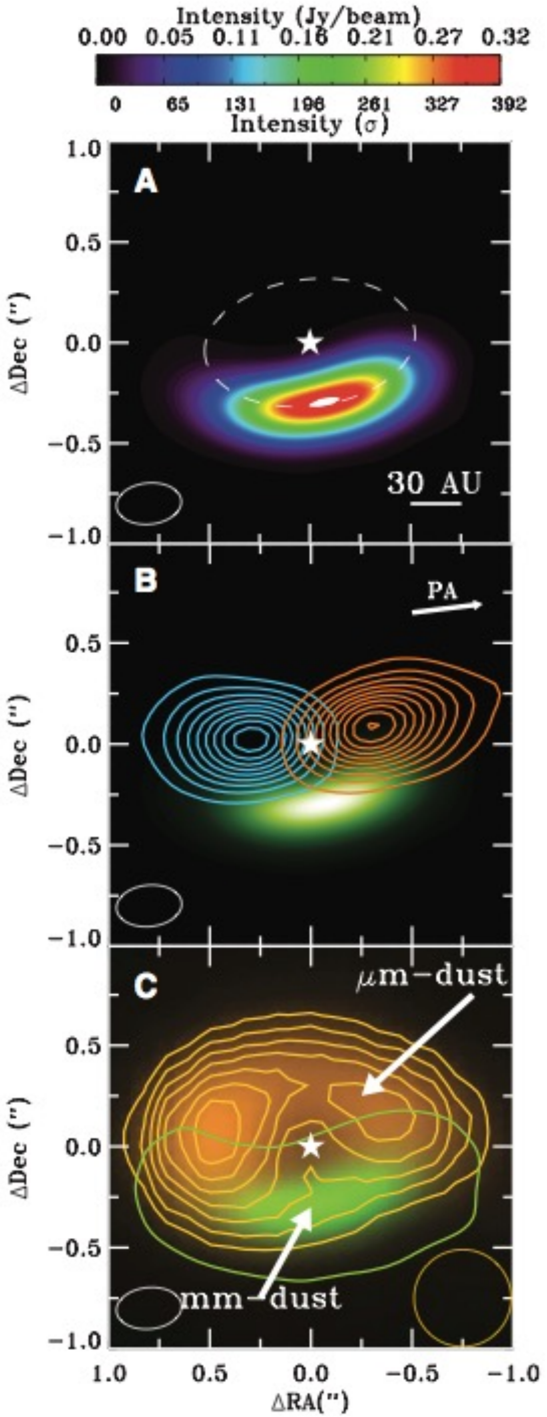
van der Marel+ ‘13

A huge vortex observed with ALMA

The Oph IRS 48 "comet formation factory"



van der Marel+. '13

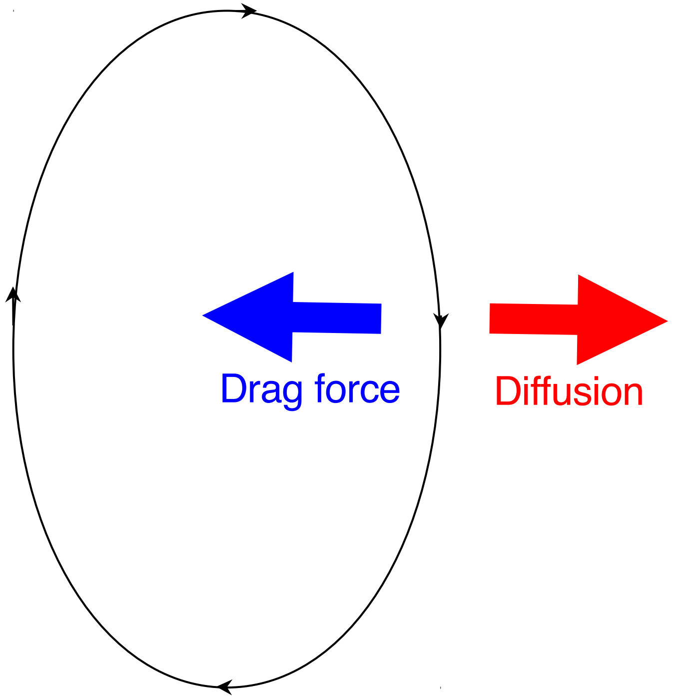


asymmetric mm dust at 63 AU

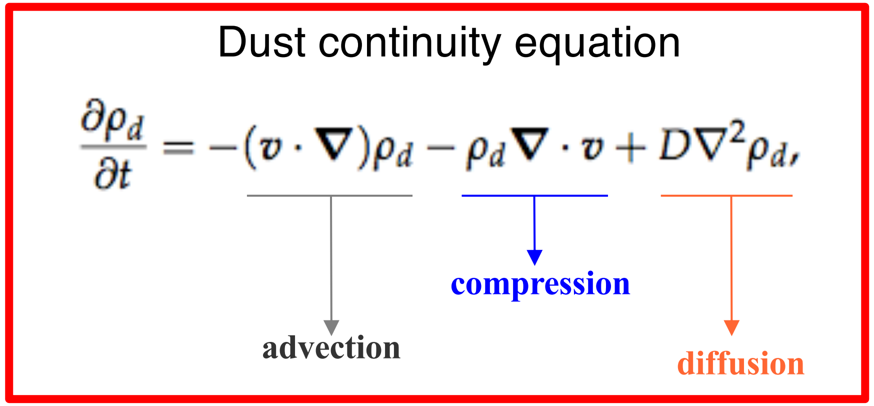
Gas detection: Keplerian rotation

Micron-sized dust follows gas

Drag-Diffusion Equilibrium

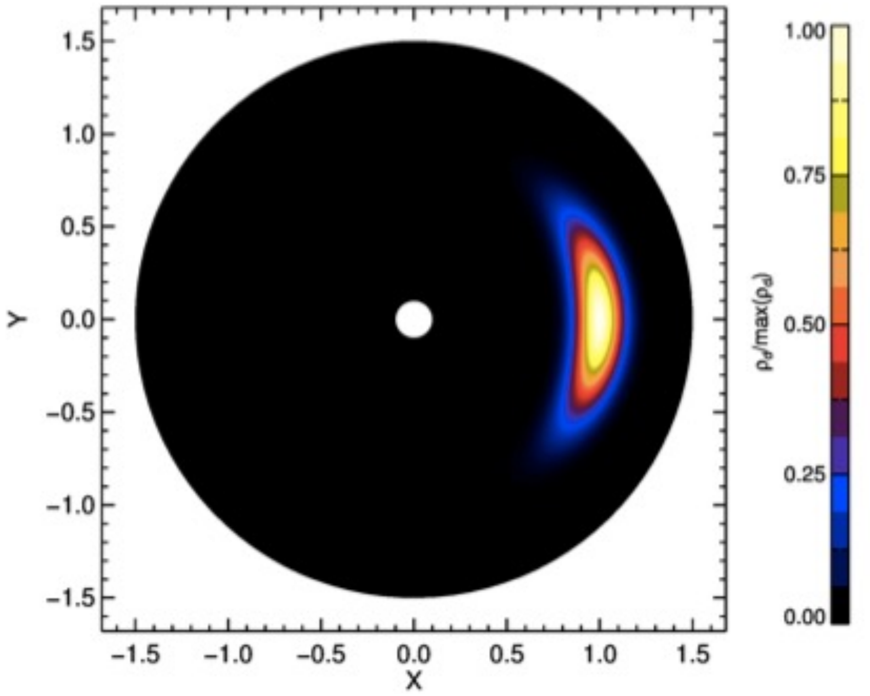


Trapped particle



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

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

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

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

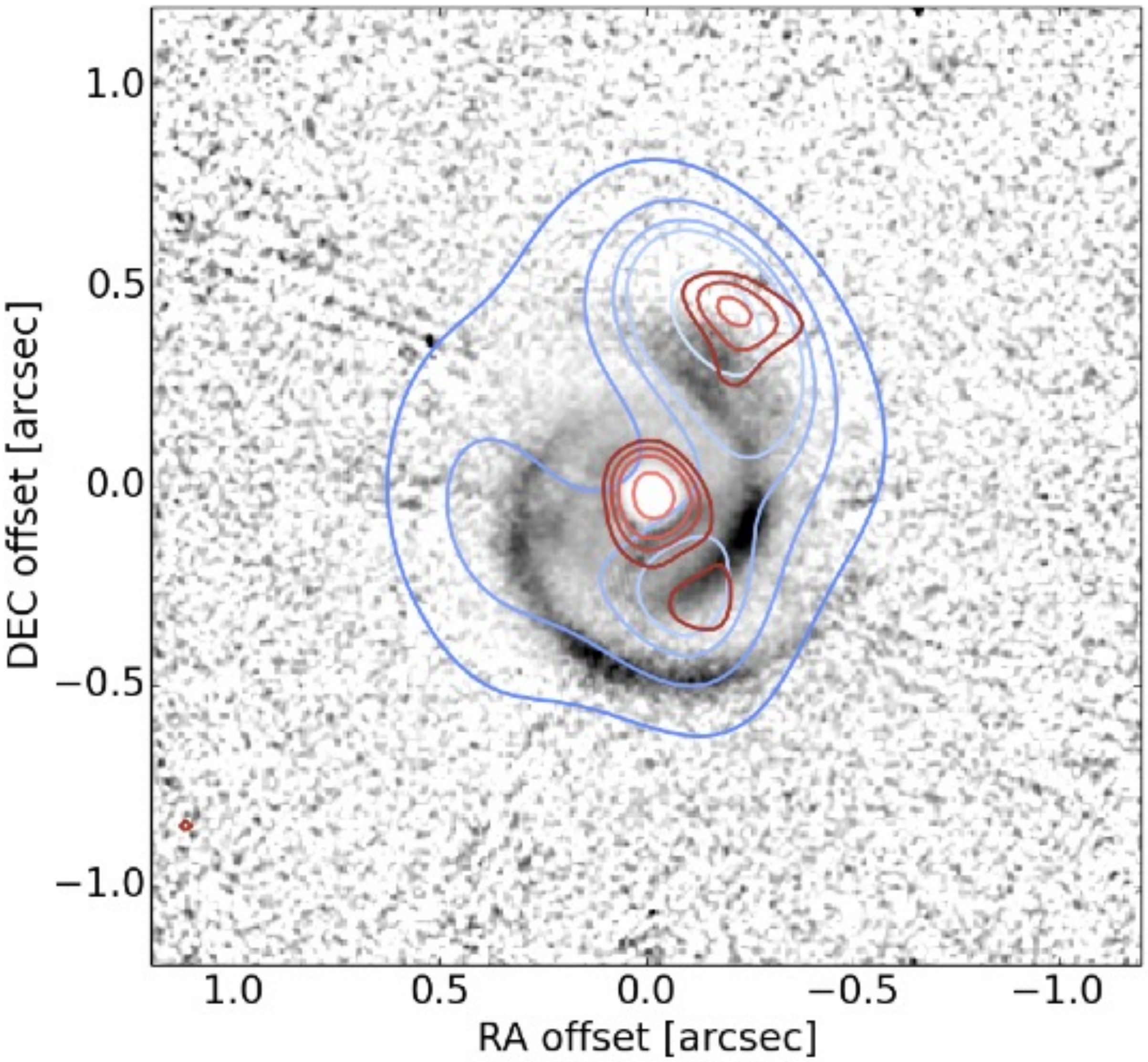
a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
f(χ) = model-dependent scale function

Disk Tomography
SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

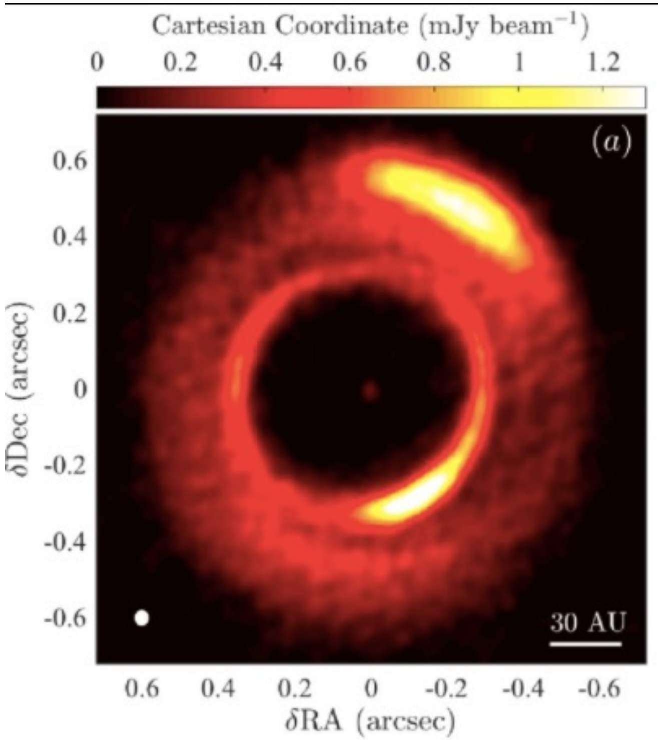
ALMA (~ mm)

VLA (cm-m)



Marino+Lyra '15

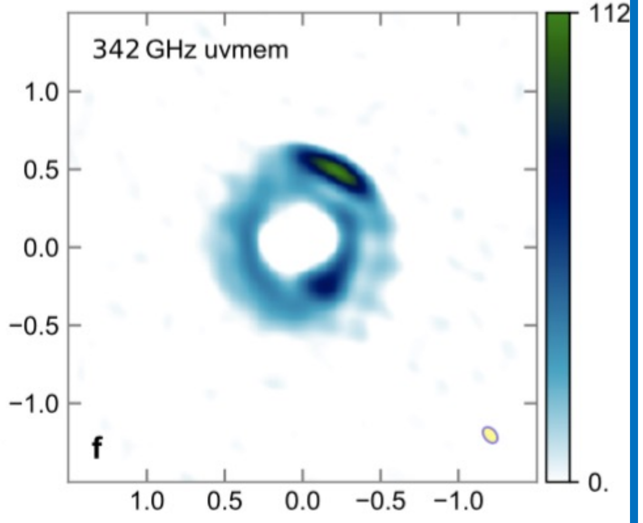
ALMA



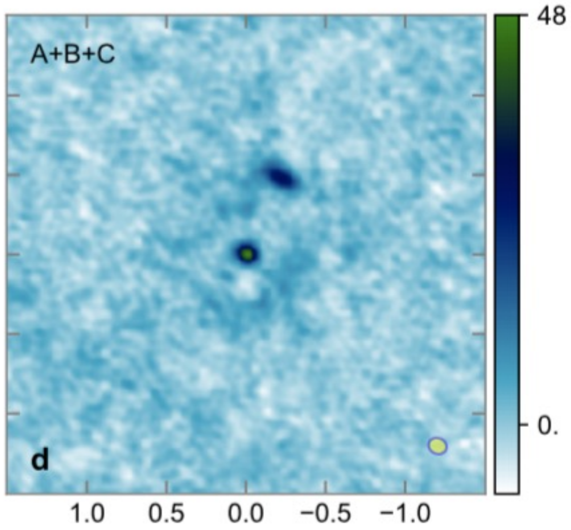
Dong+ '18

Pebble trapping

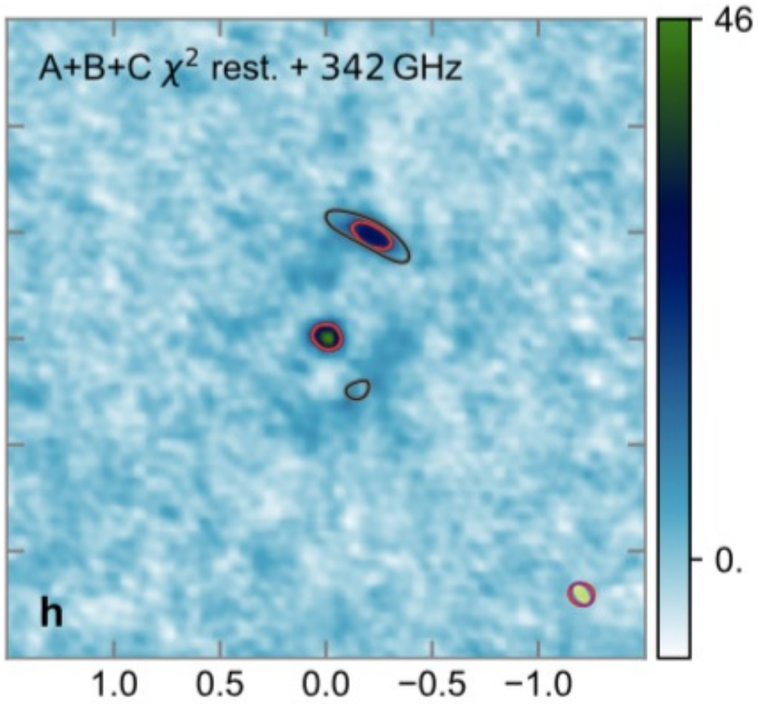
ALMA (mm)



VLA (cm-m)

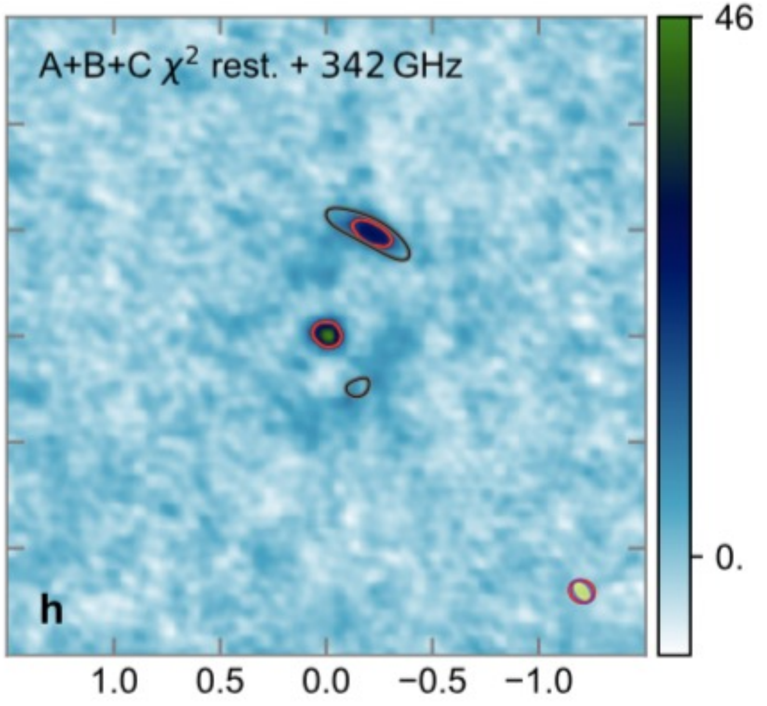


Overlay

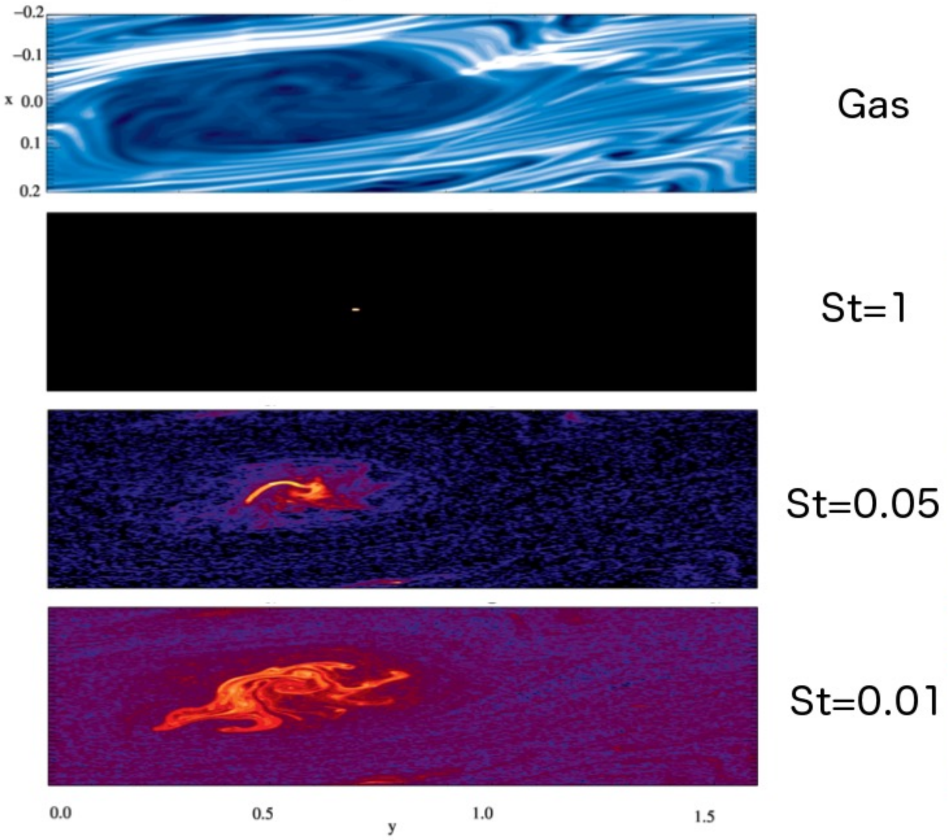


Casassus+Lyra ’19

Model vs Observation



Casassus+Lyra '19



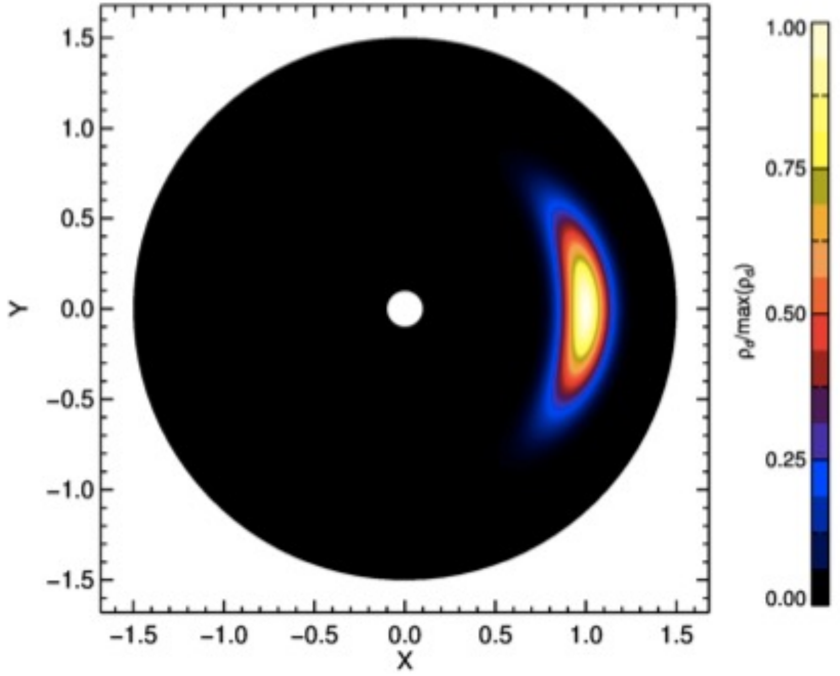
Raettig+Lyra '15

Take home message

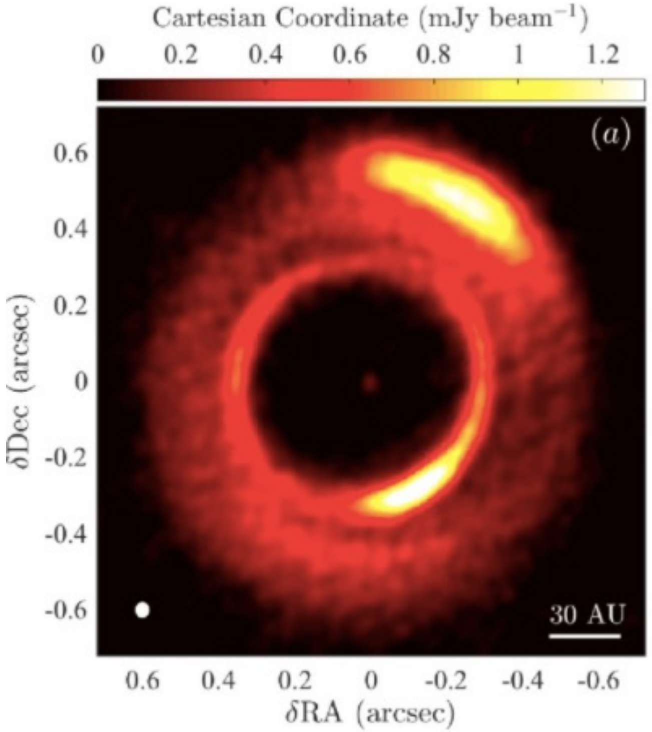
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations

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

Lyra-Lin solution



Observed Disk



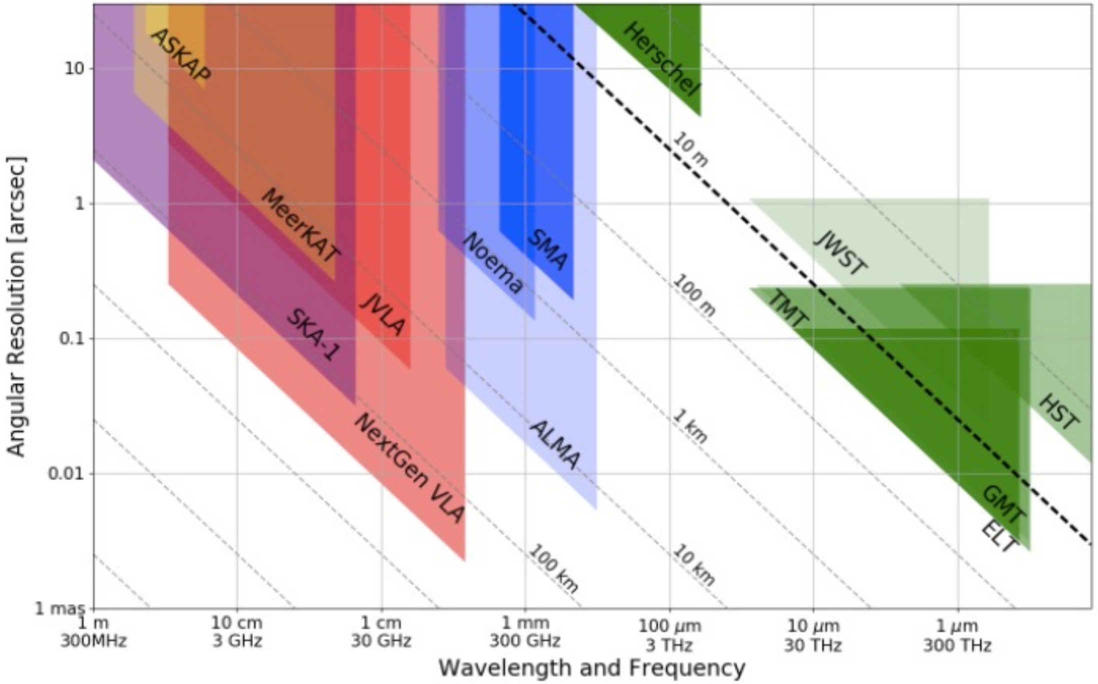
The future

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

Next Generation Very Large Array (ngVLA)



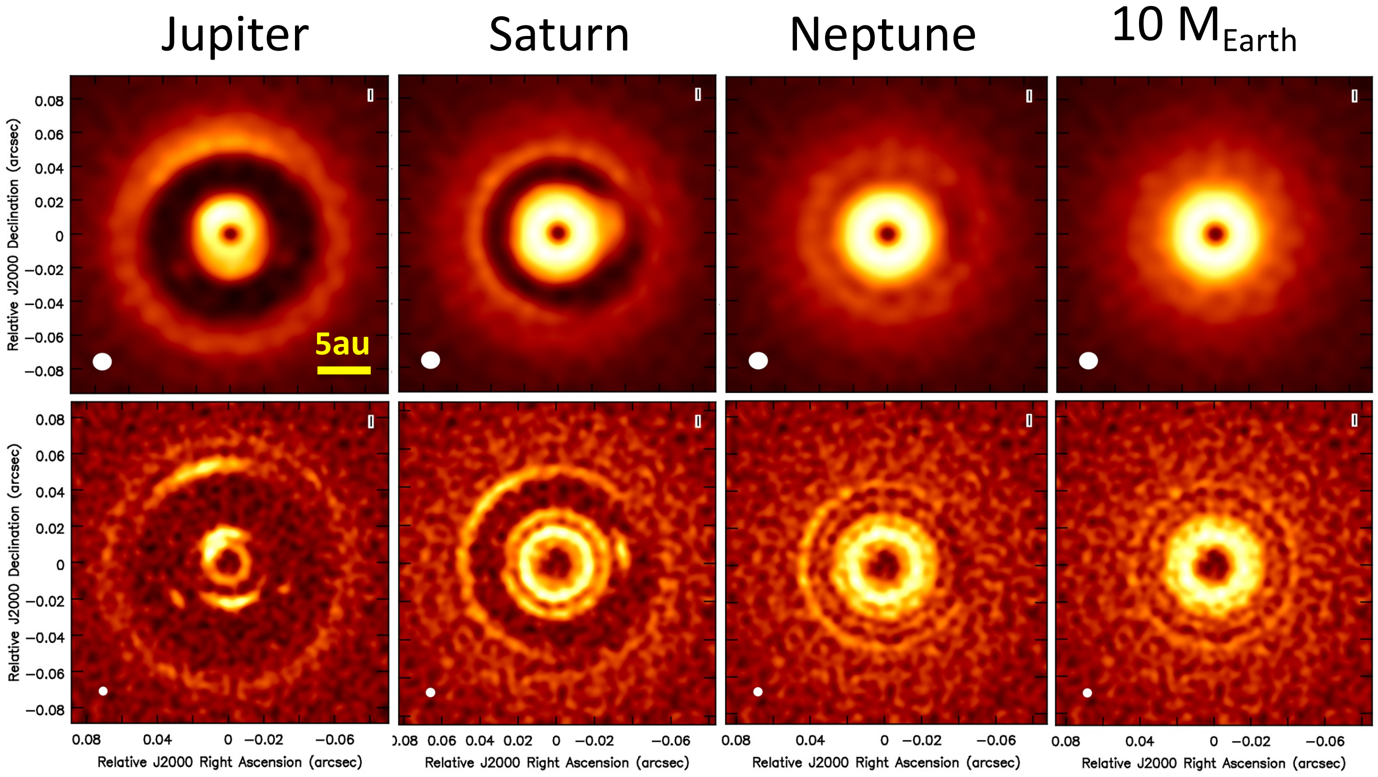
NRAO

Planets at 5AU

ALMA @ 0.87mm

ngVLA @ 3mm

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

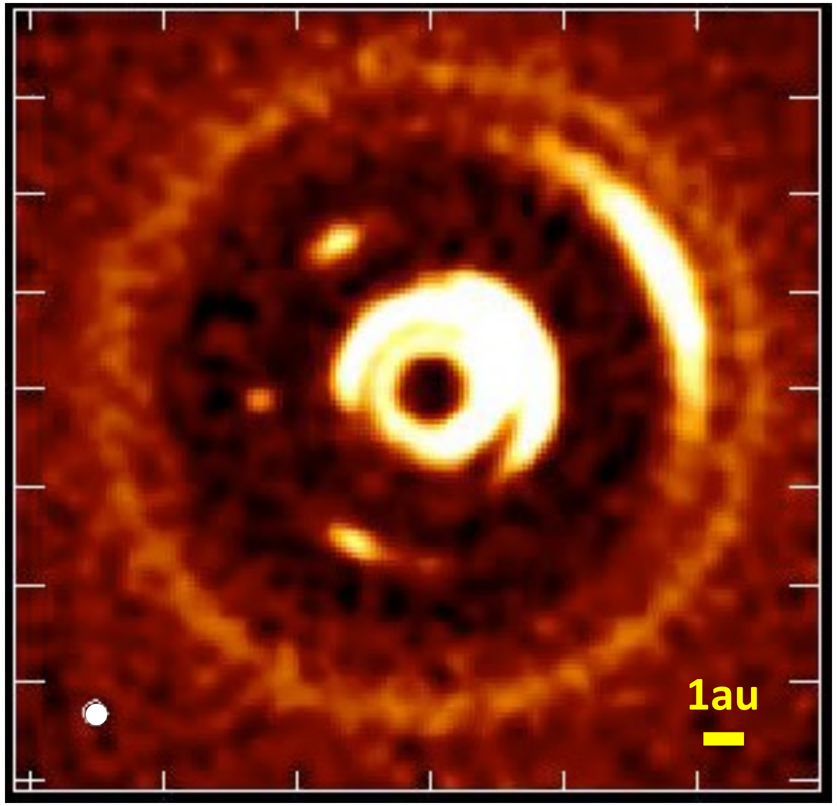


Ricci et al. 2018

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

ngVLA: Proper motions

Jupiter at 5 AU



Conclusions

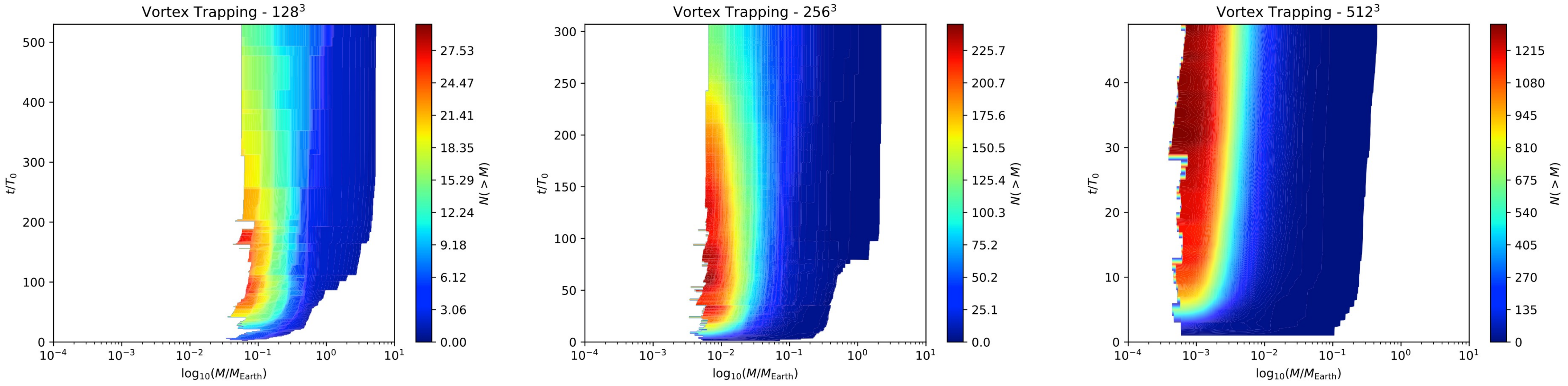
- Two routes for planet formation (streaming instability and vortices, complementary)
- Does turbulence help (concentration at large scales) or hinder (diffusion at small scales)?

- 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	✗	✗	✗

Convergence



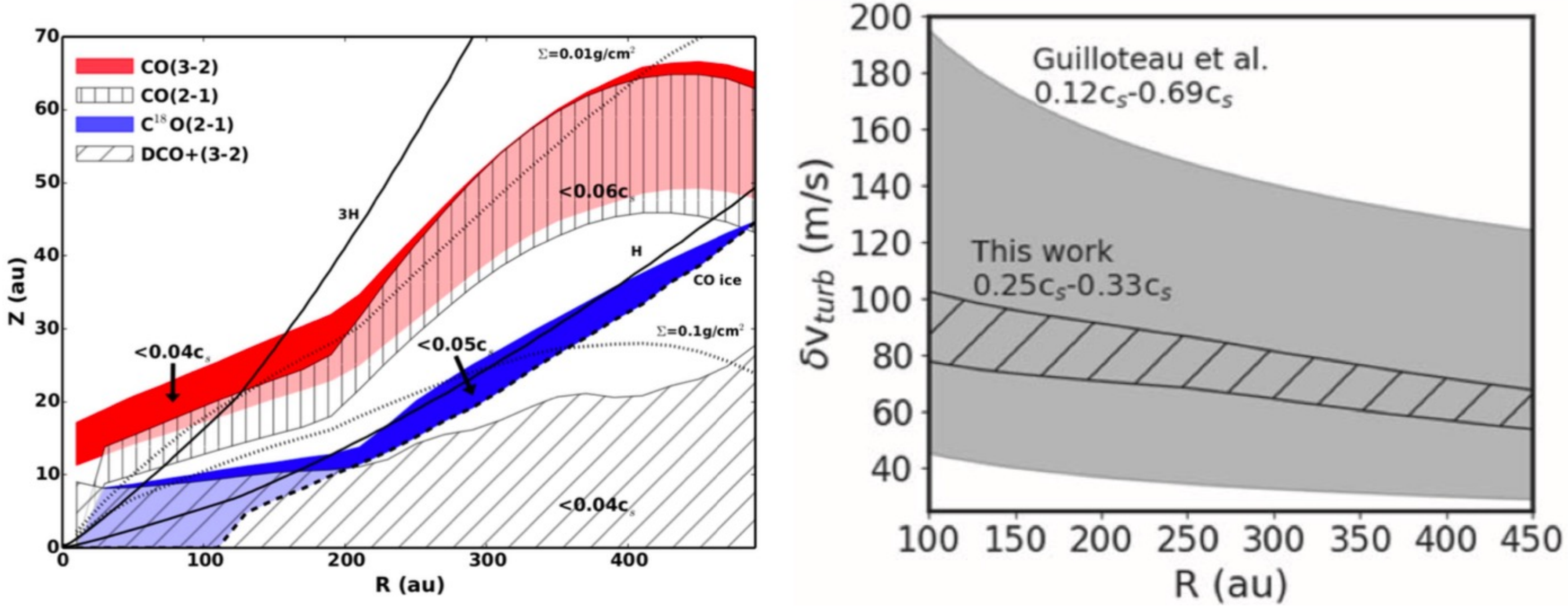
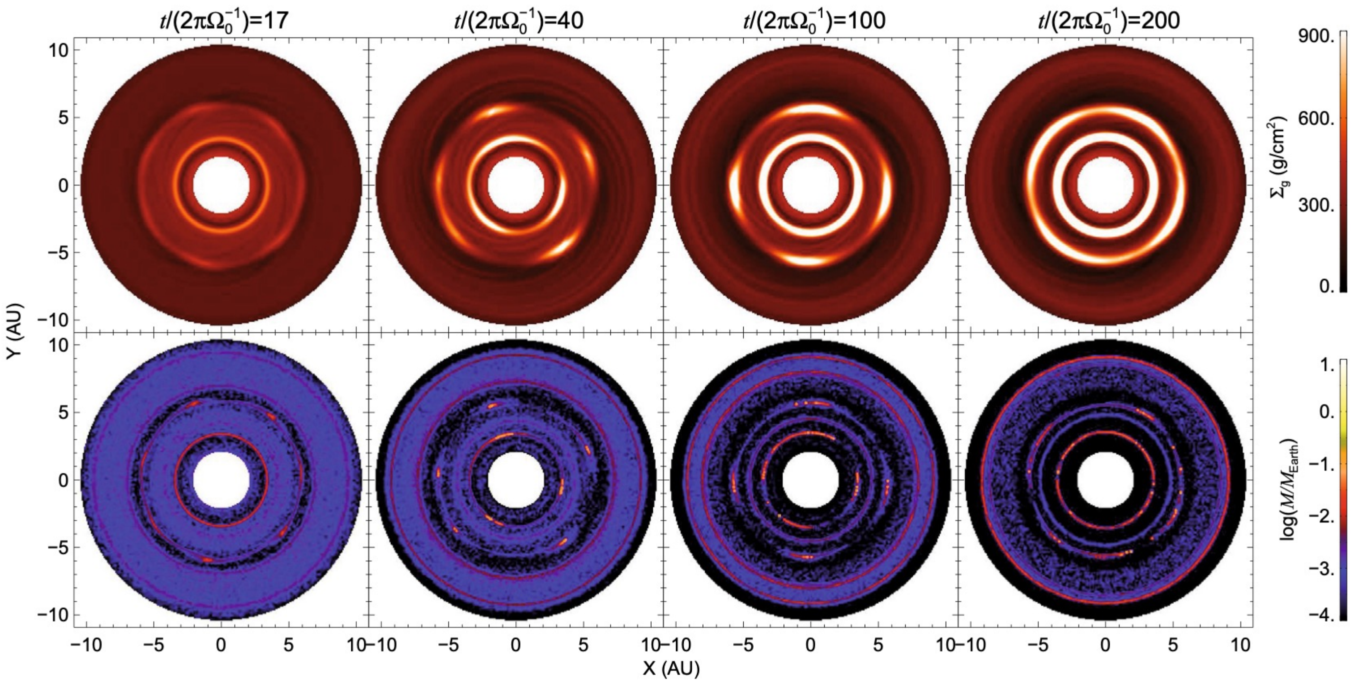
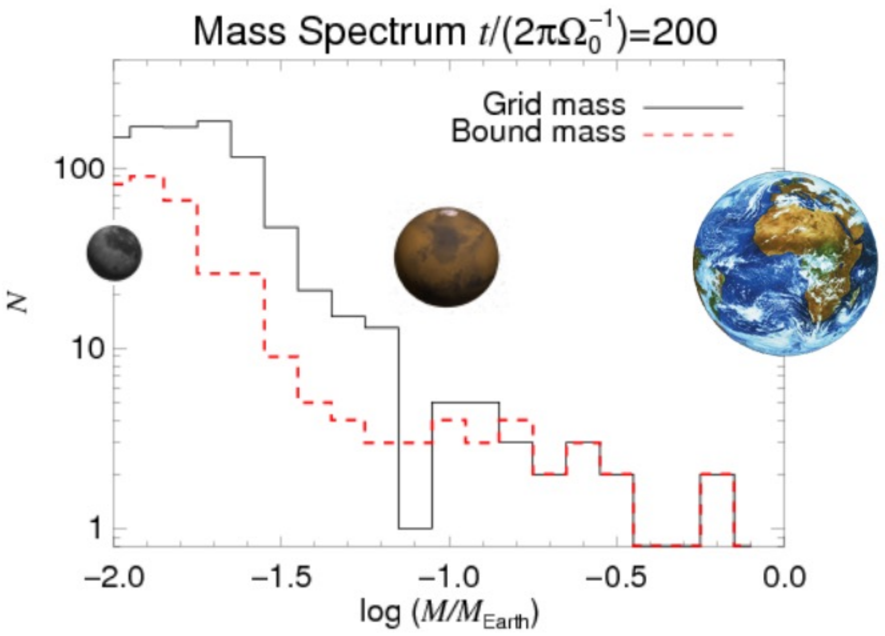


Fig. 7.— *Left:* Upper limits to turbulent velocities in HD 163296 as a function of radius R and mid-plane height z. The colors denote the species from which there is a majority of emission; the CO transitions are at large z whereas $C^{18}O$ and DCO+ are from lower in the disk. Also included on the plot are lines of constant Σ, H and $3H$ (H being the gas scale height) and where CO is ice. In this source, turbulence is at most a few percent of the sound speed. From Flaherty et al. (2017). *Right:* The turbulent velocity as a function of radius as measured from CO emission in DM Tau (hashed lines), compared to the results from previous work using CS (Guilloteau et al. 2012; grey shaded region). As opposed to HD 163296, DM Tau exhibits strong turbulence, consistent with theoretical predictions Flaherty et al. (2020).

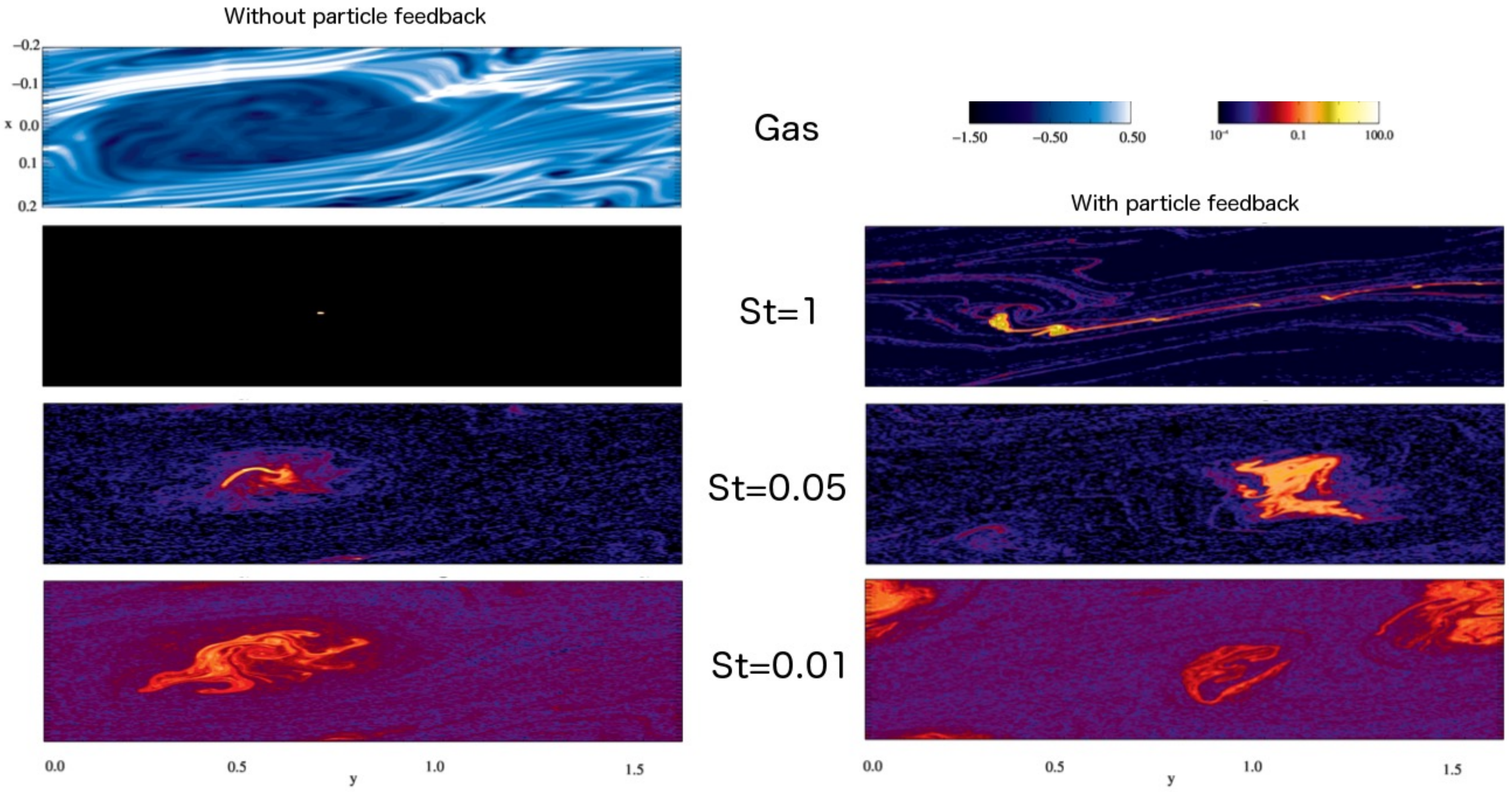
Vortices and Planet Formation





Lyra et al. (2008)

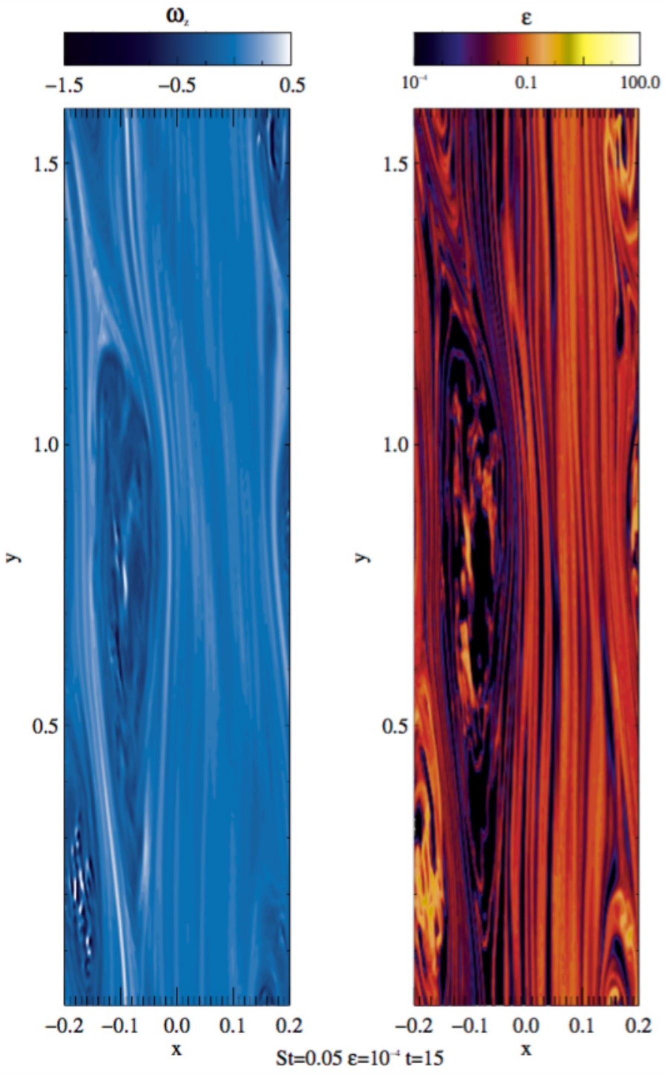
Pebble trapping in vortices in LOCAL models



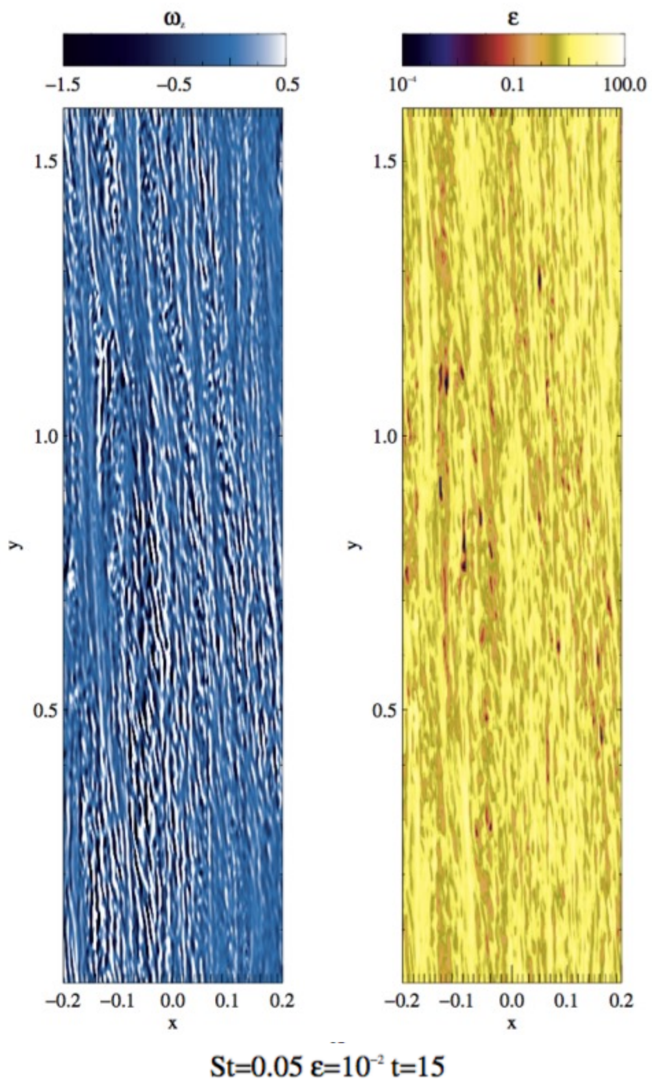
Raettig et al (2015)

Vortex destruction at high dust load?

Dust to gas ratio 10^{-4}

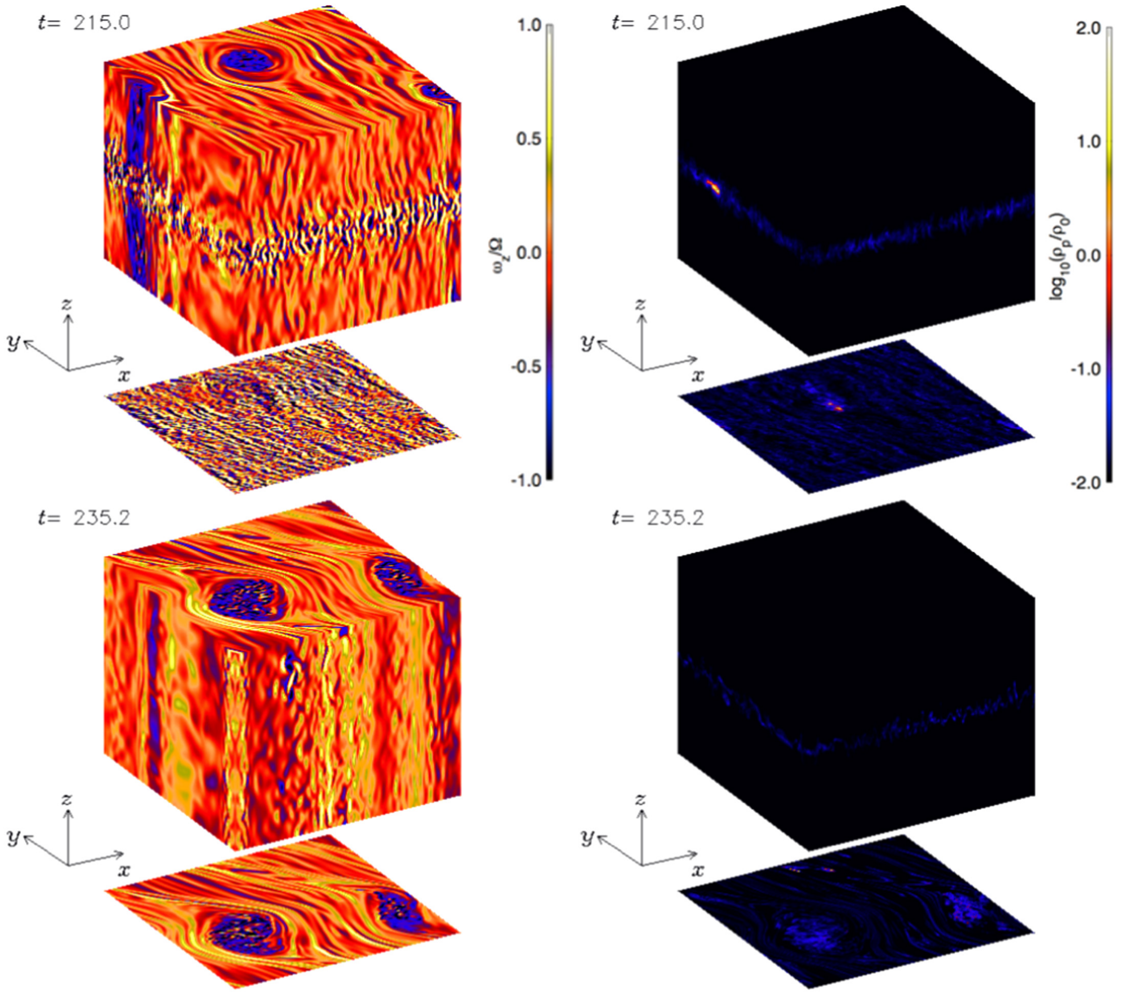


Dust to gas ratio 10^{-2}



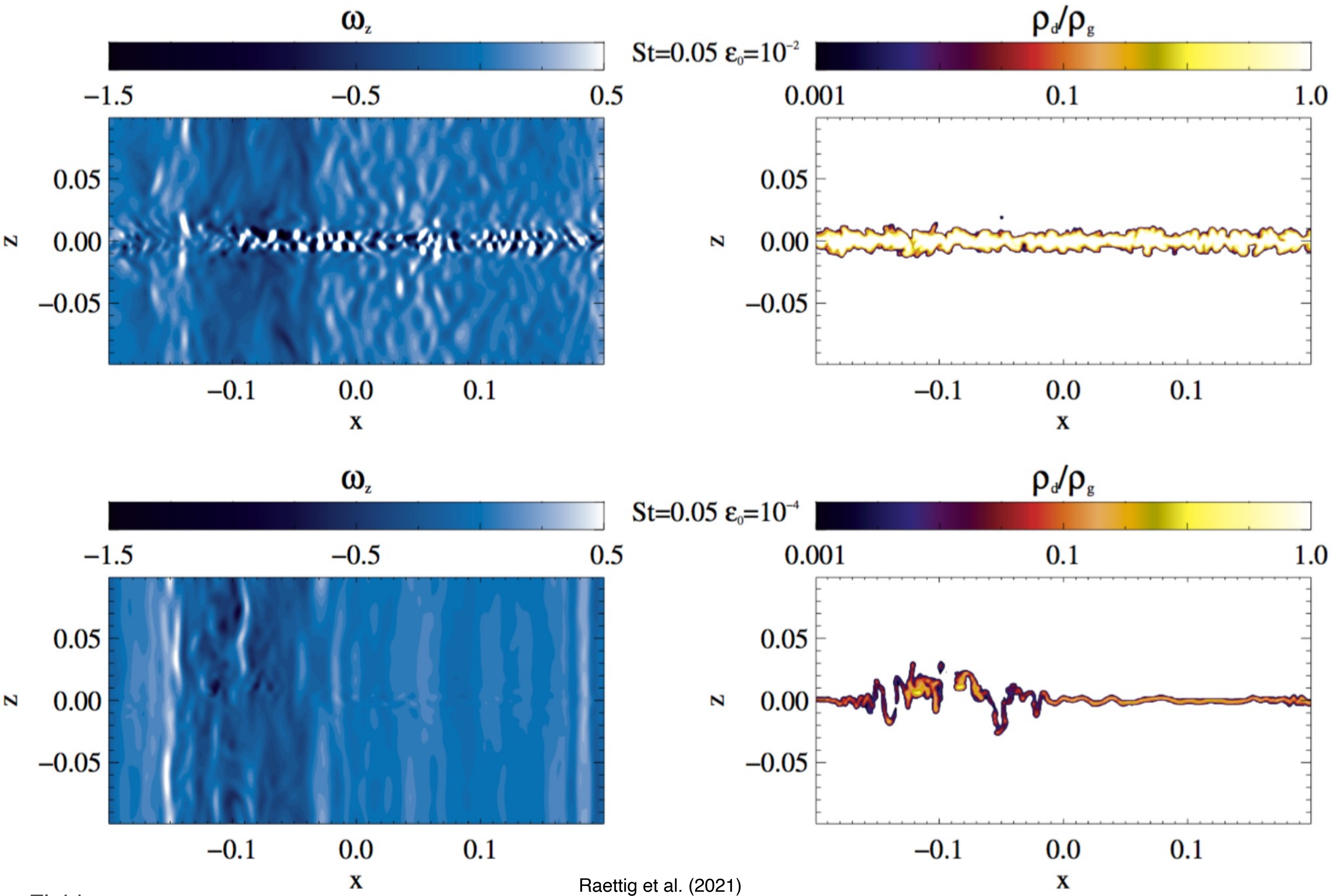
Raettig et al (2015)

Pebble trapping does not destroy vortices



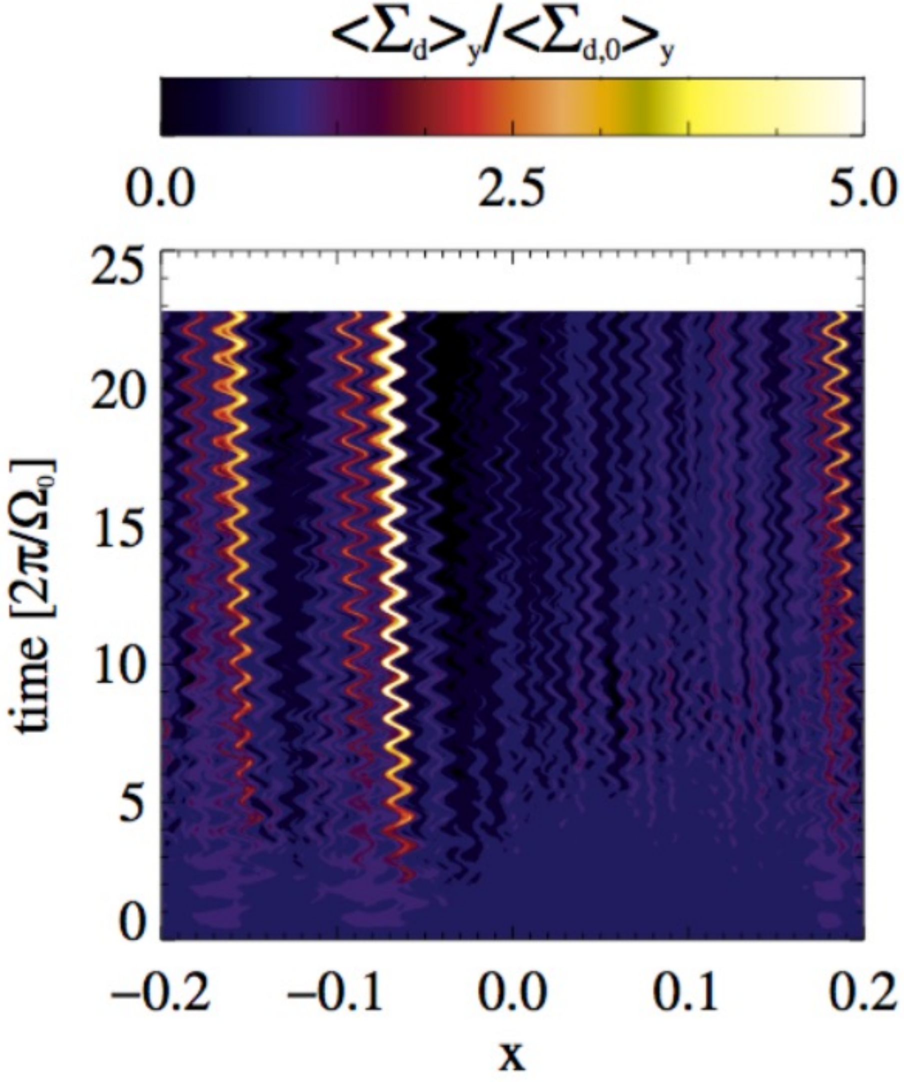
Lyra et al. (2018)

Vortex column disrupted only around the midplane



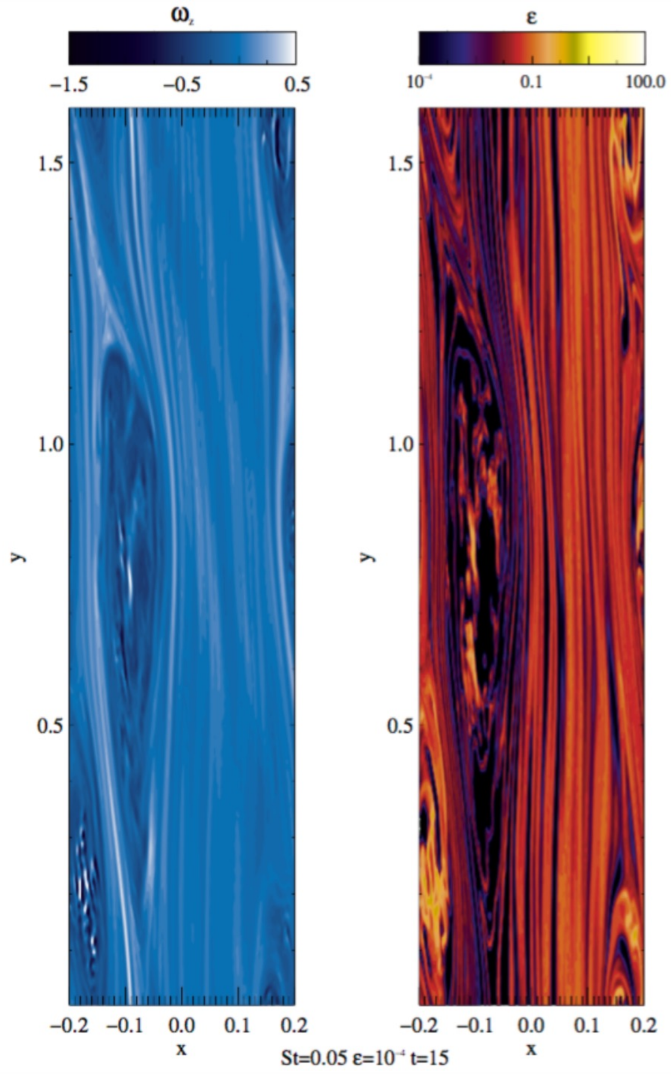
Raettig et al. (2021)

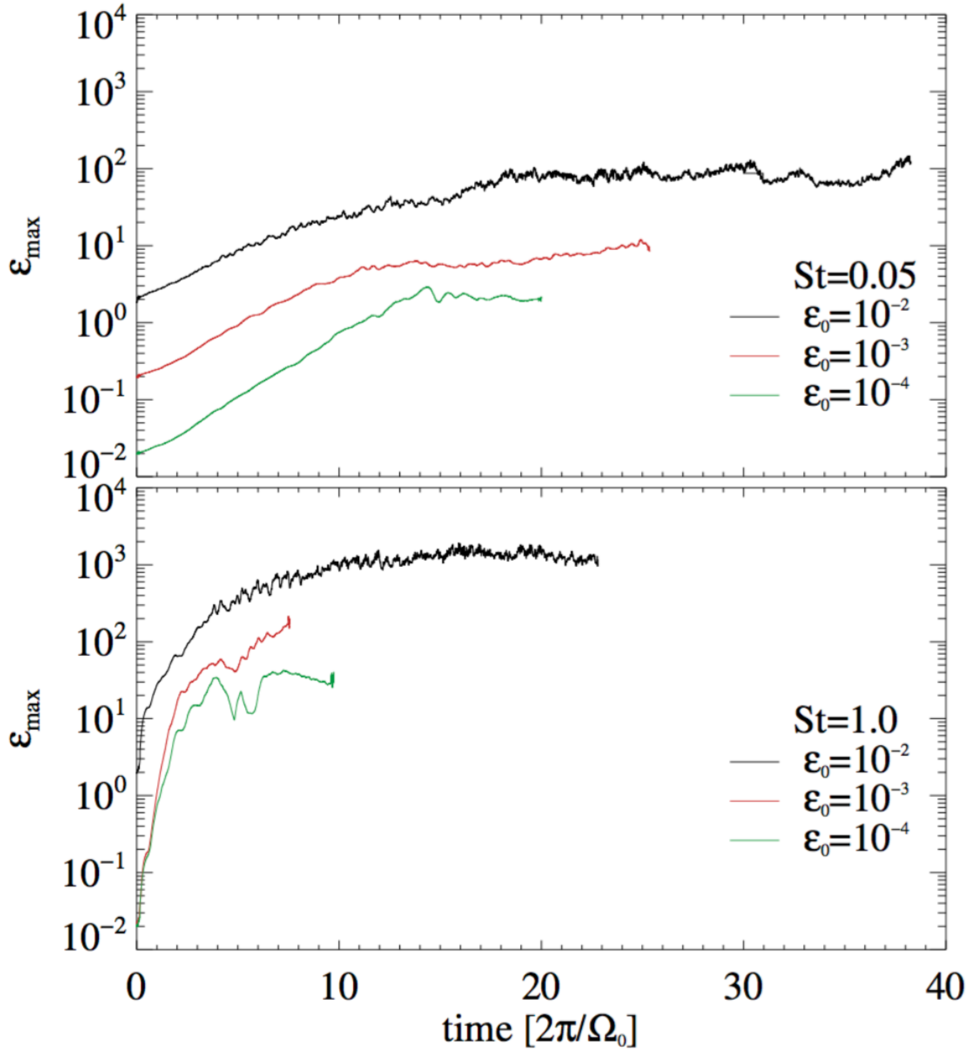
Pebble drift: follows vortex



Raettig et al. (2021)

Pebble trapping in 3D vortices





Raettig et al. (2021)