Evolution of Circumstellar Disks and Planet Formation

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Current Funding

NSF

AAG – 2020, 2021

NASA

XRP - 2023
EW – 2021, 2022, 2023
TCAN – 2020

Computational Facilities

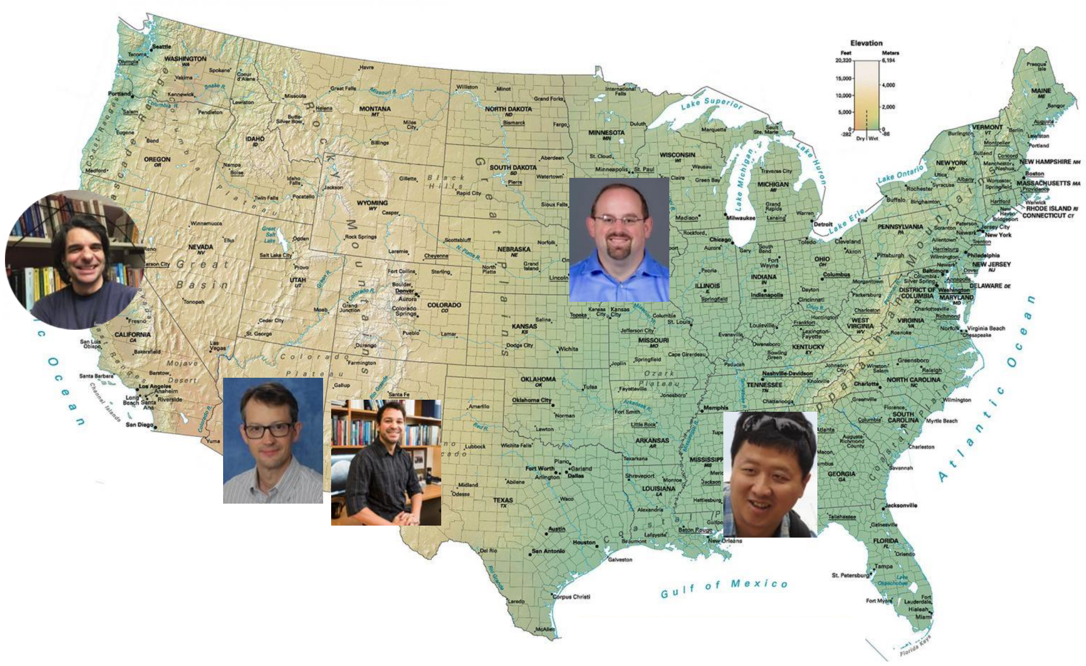
NSF XSEDE

NRAO - Apr 11th, 2024

Outline

- Planet Formation
- Hydrodynamical Instabilities
- Disk observations

TCAN-2020 (Theoretical and Computational Astrophysics Network)
Planet Formation Collaboration



PI

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Orkan Umurhan – *NASA Ames*

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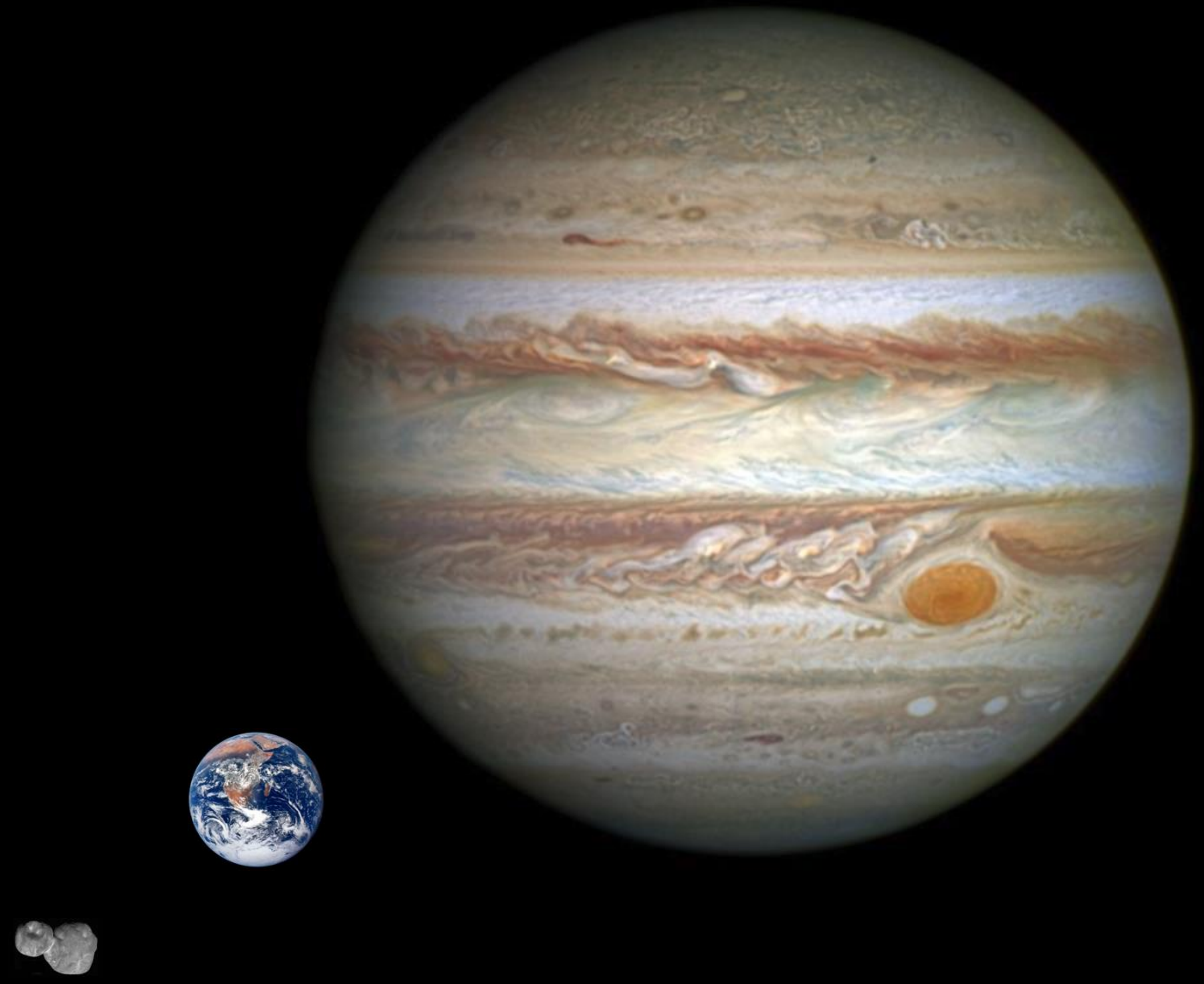
UA – Eonho Chang

Planet Formation



Circumstellar/Protoplanetary Disks

PP disk fact sheet

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

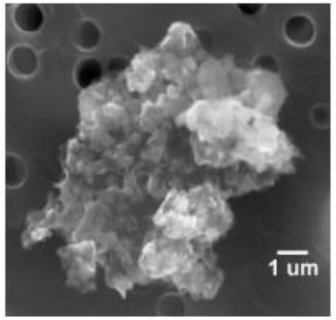
Temperature: 10-1000 K

Scale: 0.1-100AU

Mass: $10^{-3} – 10^{-1}$ M_{sun}

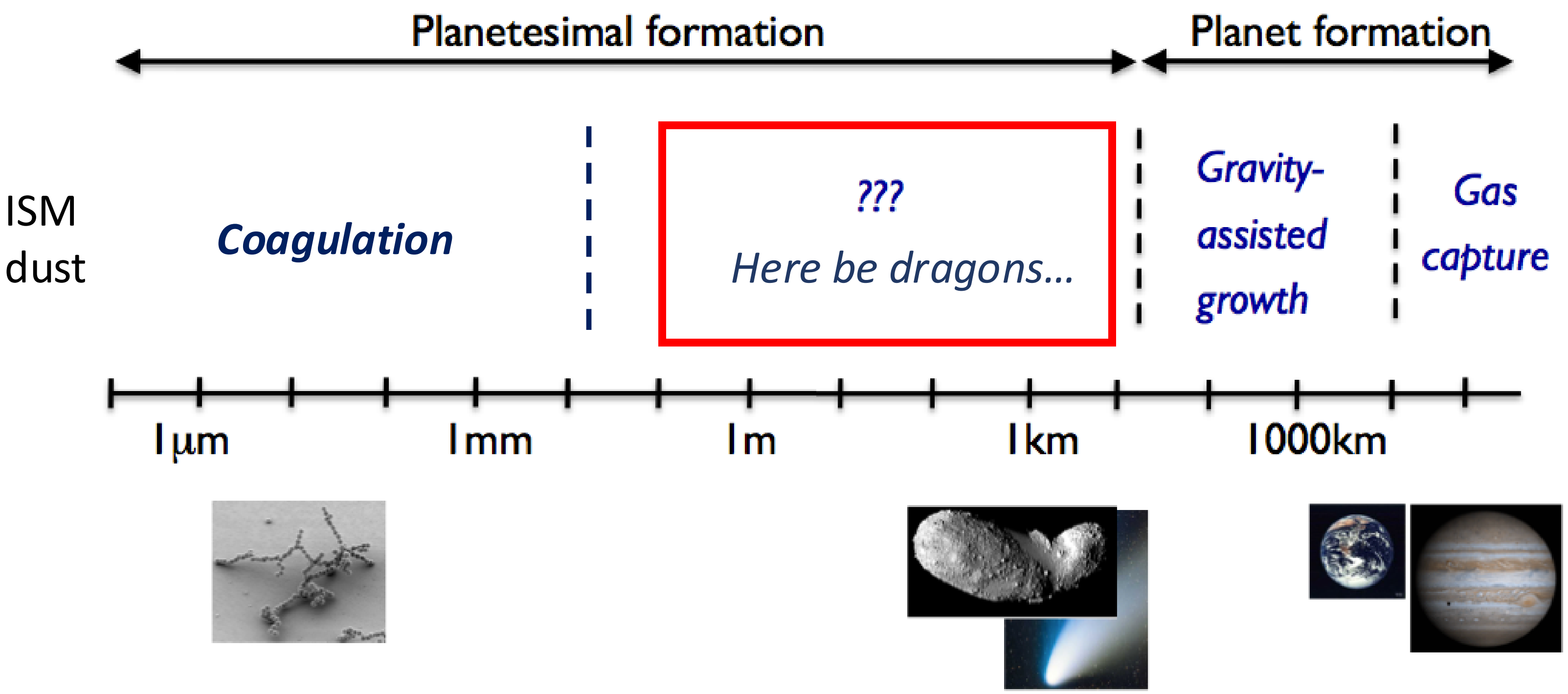
Planet Formation

"Planets form in disks of gas and dust"

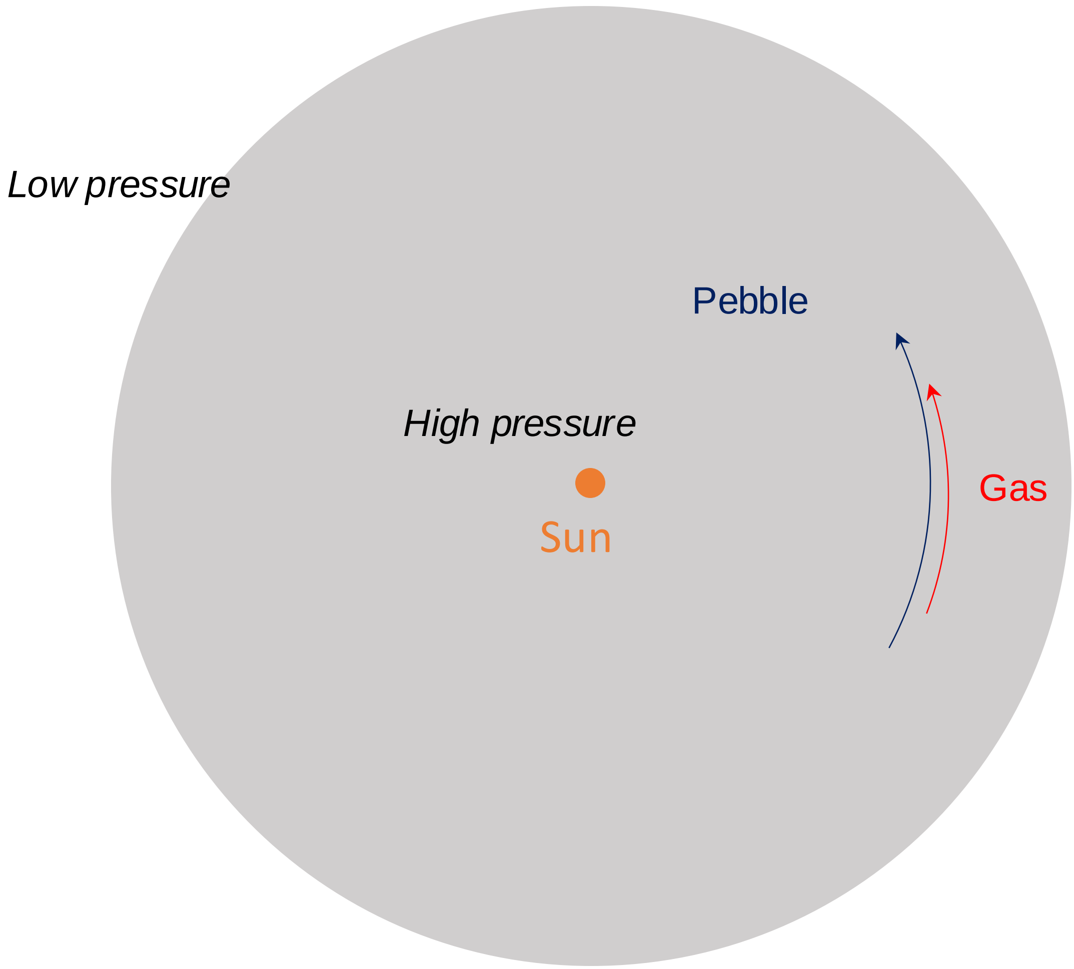


A miracle happens →

Dust evolution



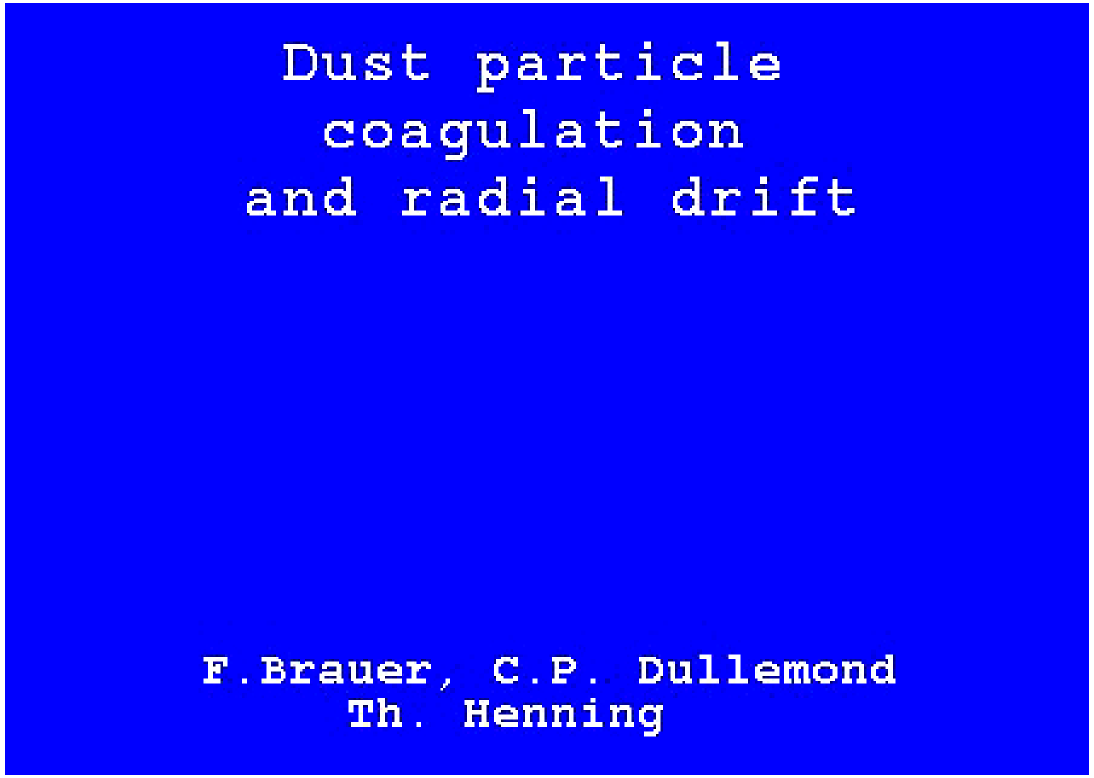
Headwind and Dust Drift



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

The pebbles do not feel gas pressure (Keplerian).

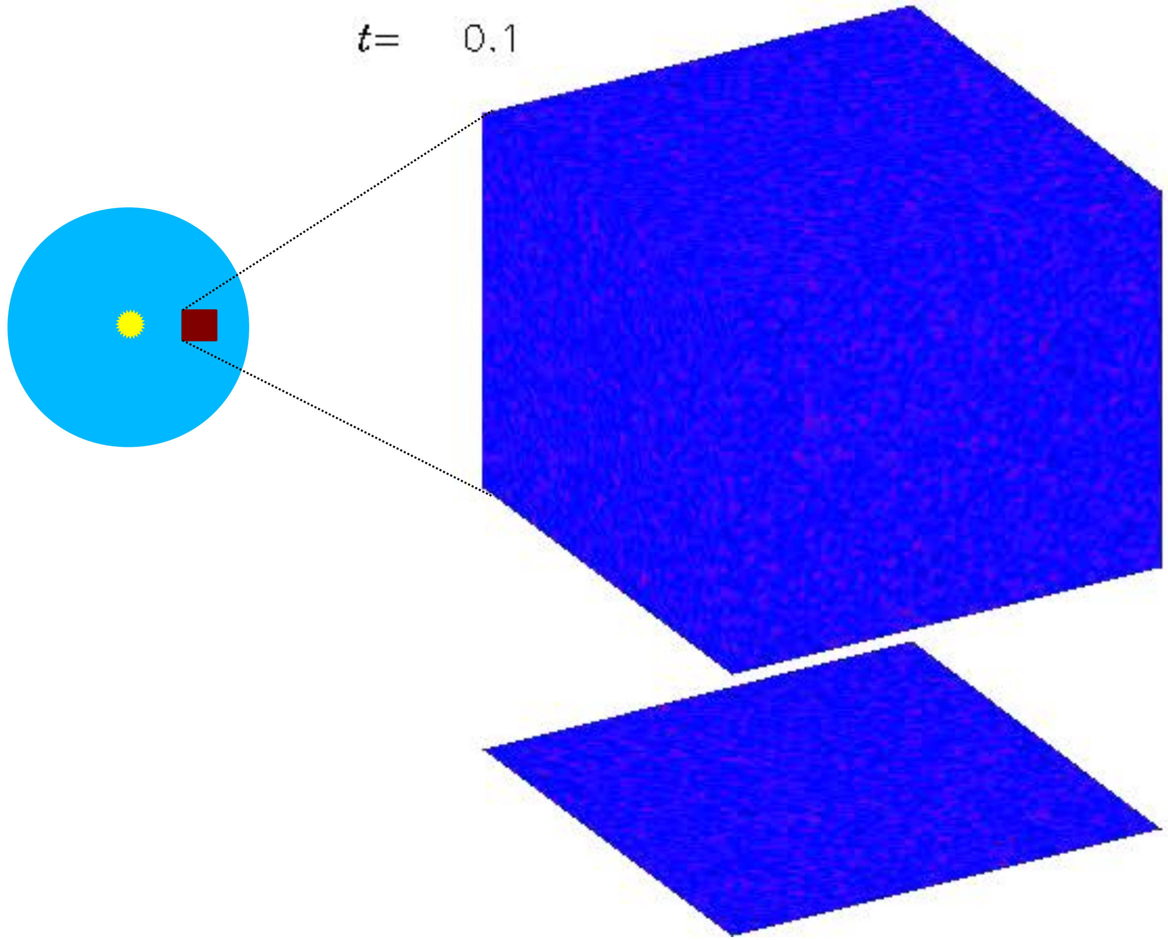
Dust coagulation and drift

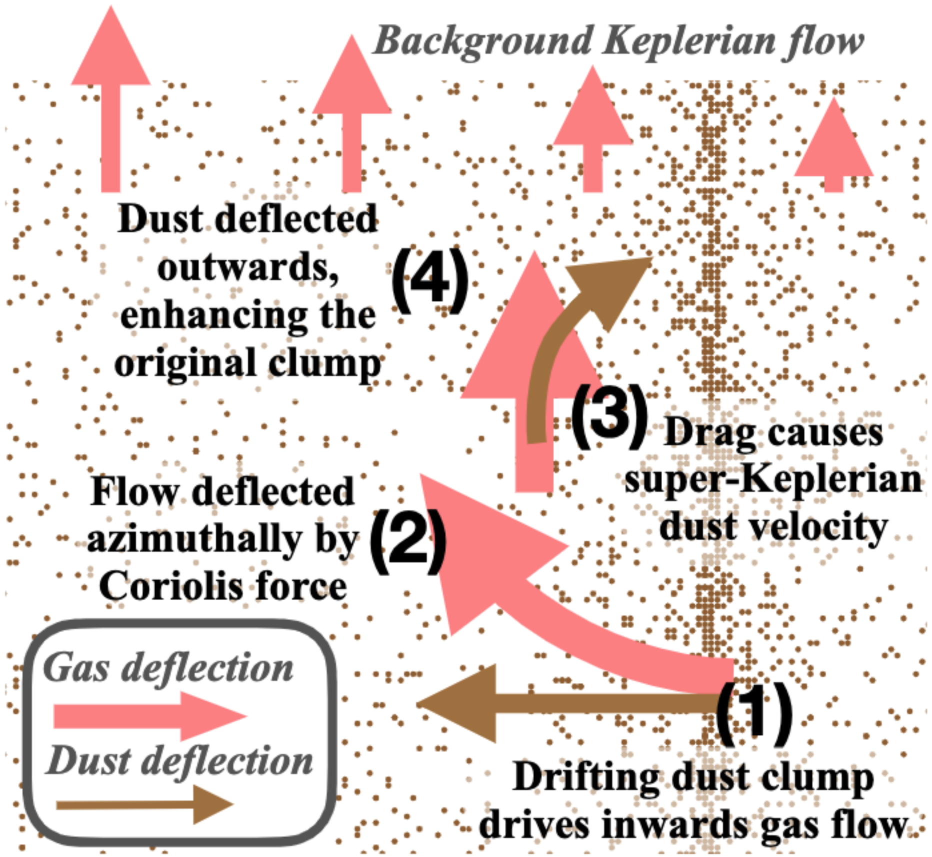


Brauer et al. (2008)

Streaming Instability

The dust drift is hydrodynamically unstable

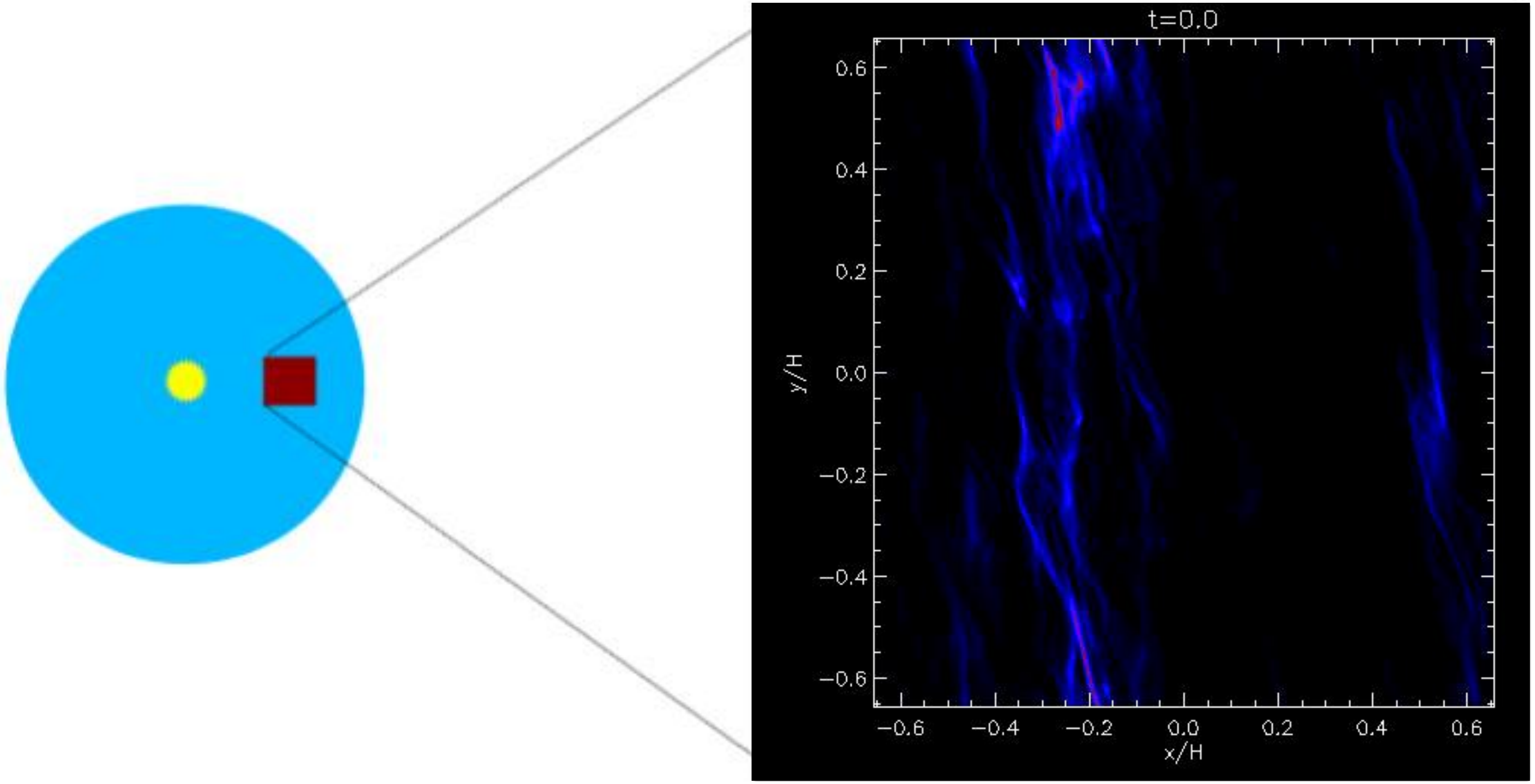




Lesur et al. (2022)

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

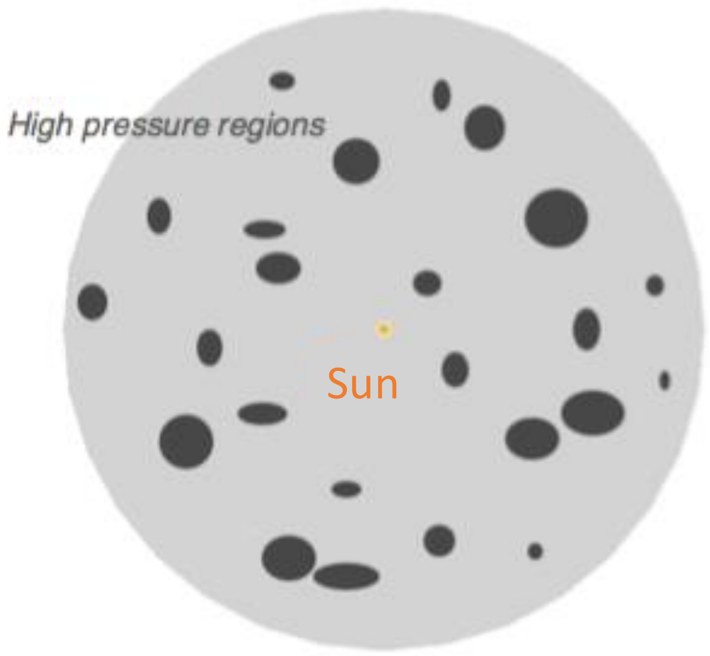
Gravitational collapse into planetesimals

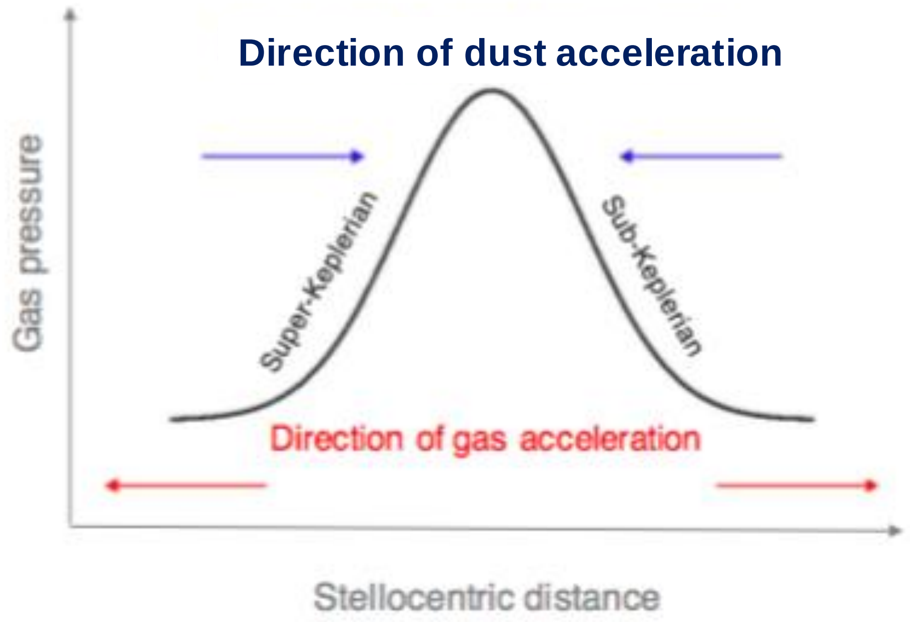


Johansen et al. (2007)

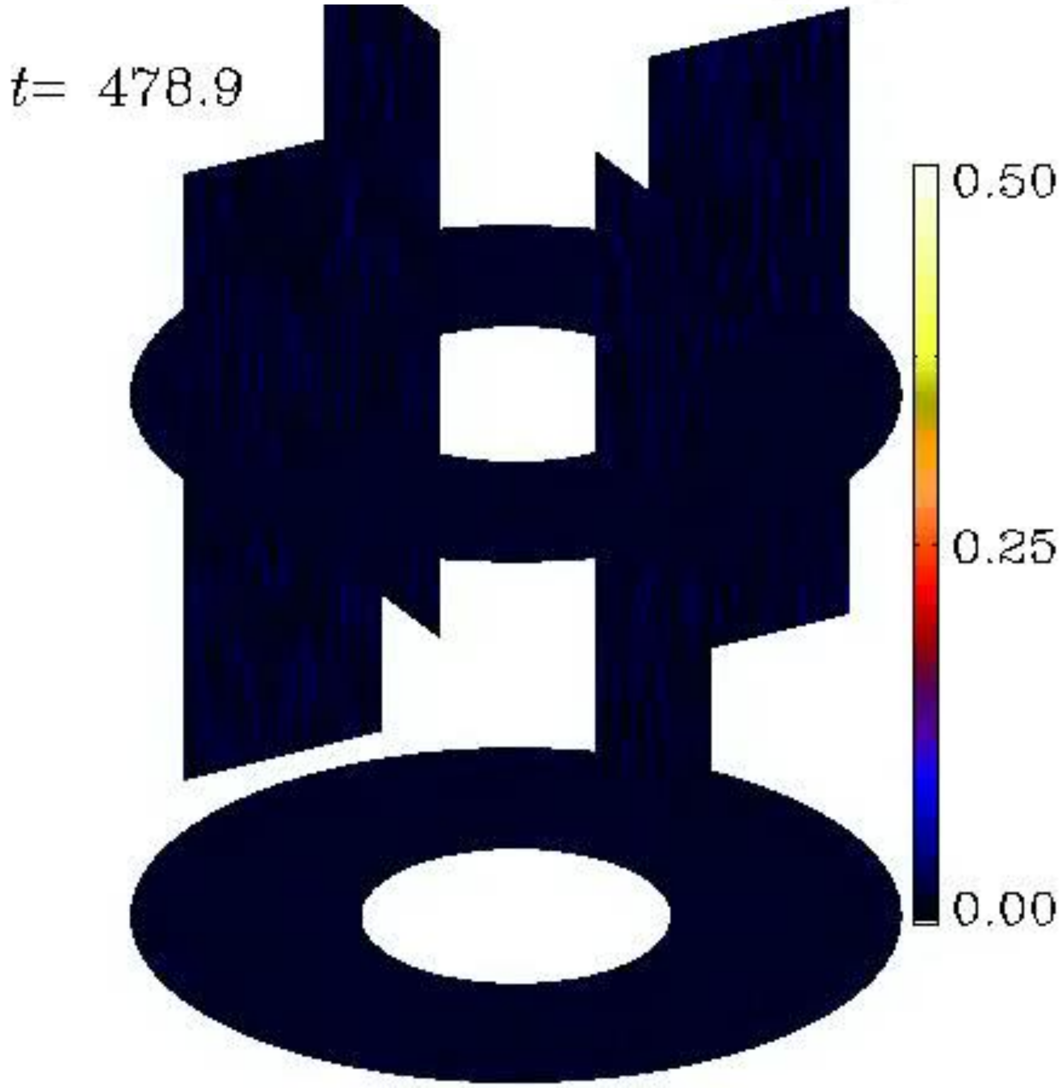
Turbulence and Accretion in 3D Global MHD Simulations of Stratified Protoplanetary Disk

Turbulence


High pressure regions
Sun

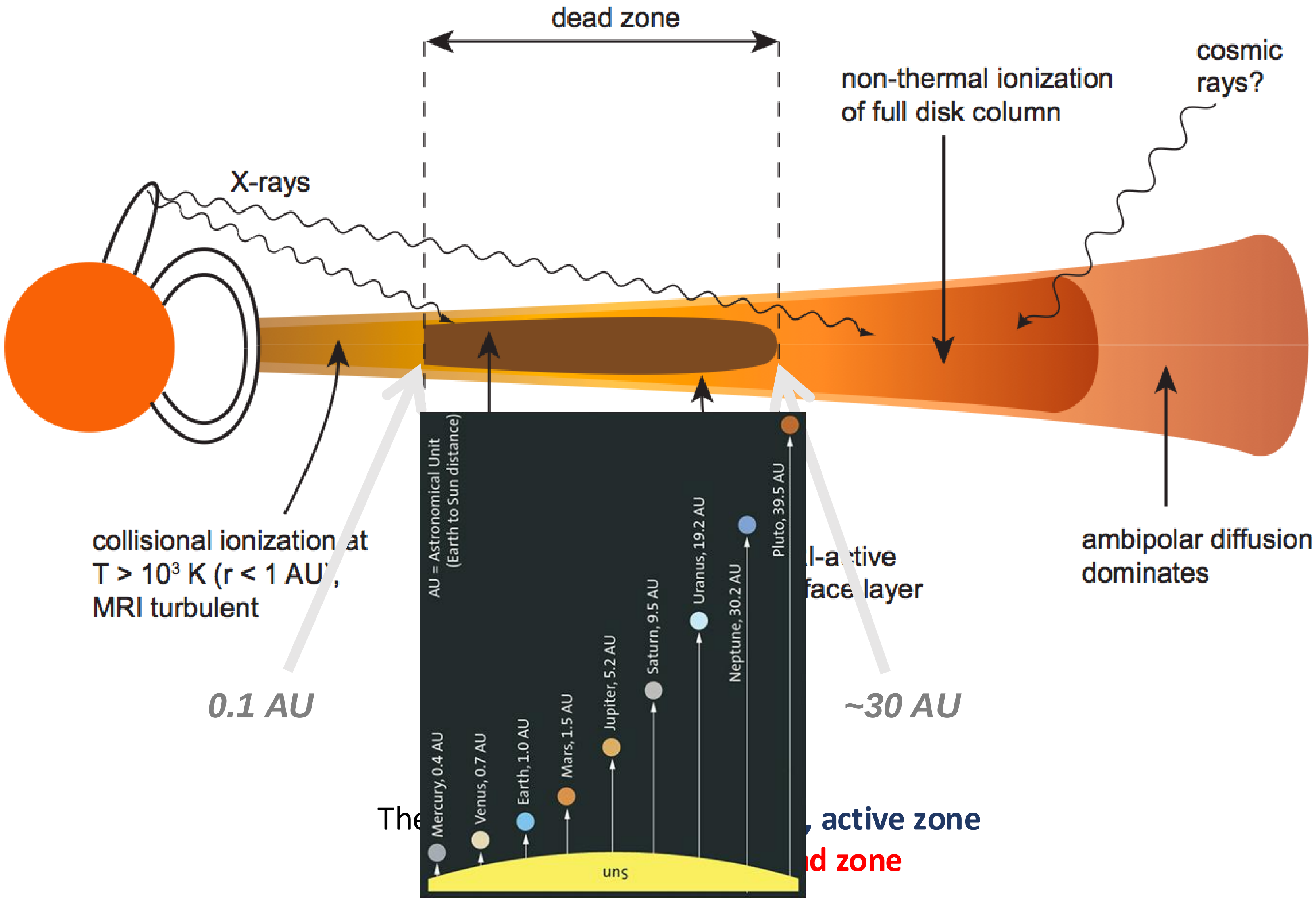

Direction of dust acceleration
Gas pressure
Super-Keplerian
Sub-Keplerian
Direction of gas acceleration
Stellocentric distance

Turbulence concentrates solids mechanically in pressure maxima



Lyra et al. (2008a)

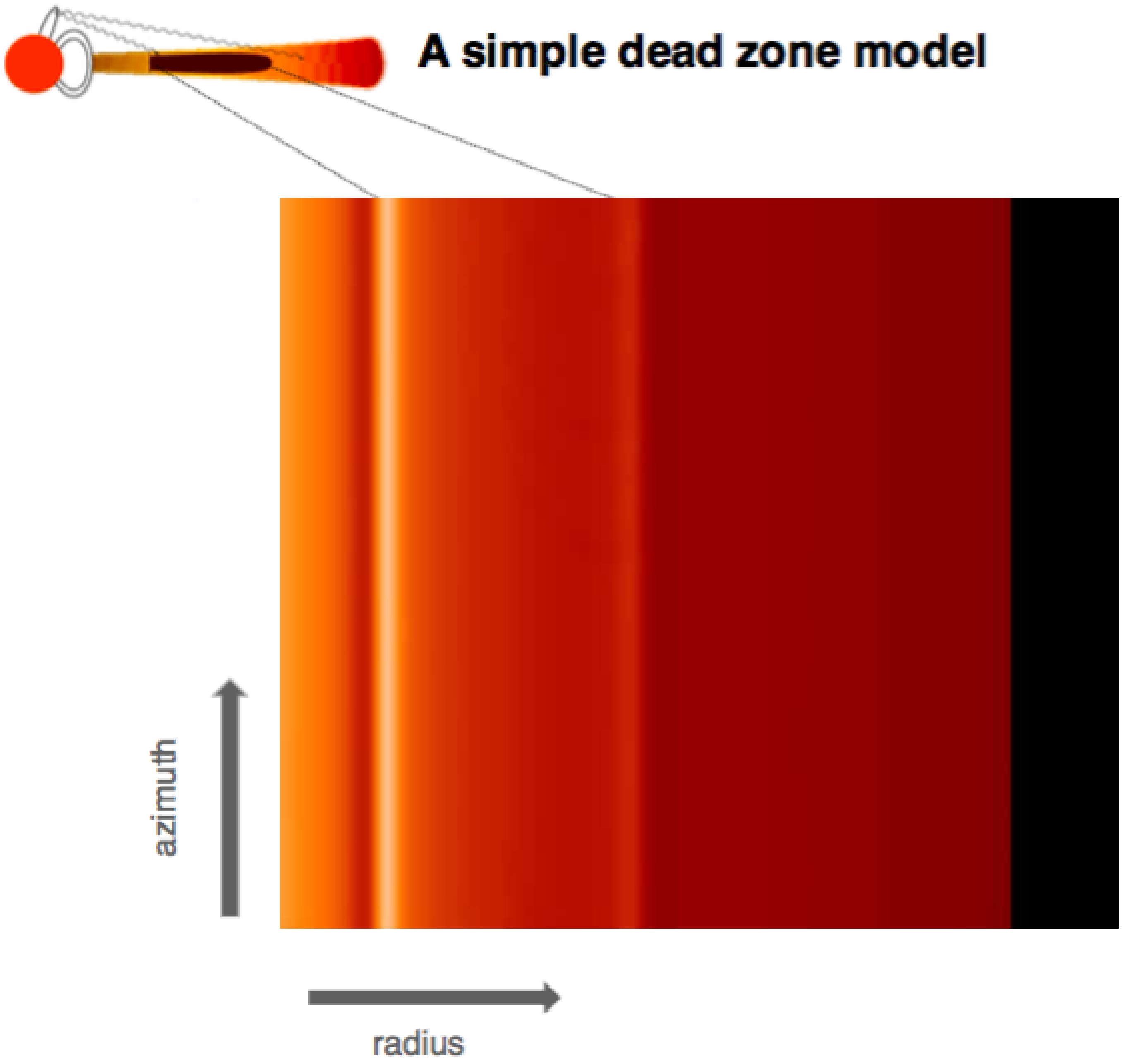
Dead zones



The ... , **active zone**

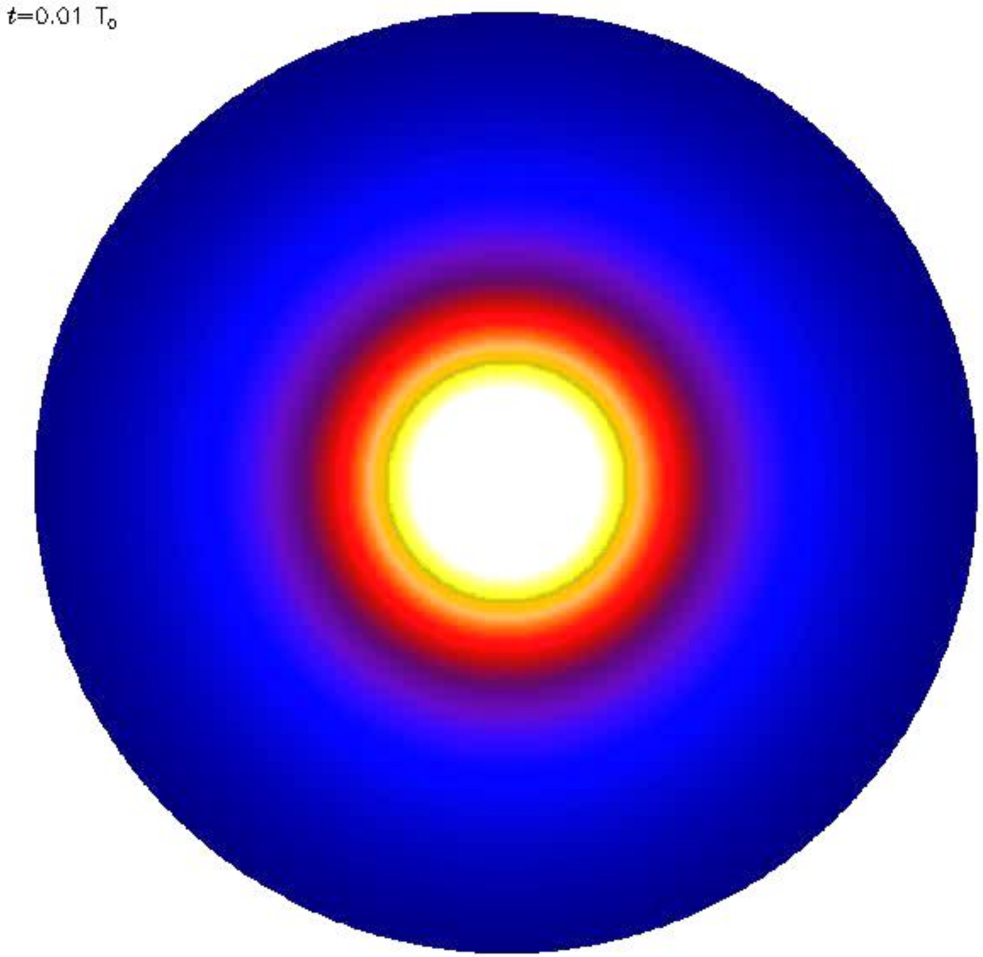
... **d zone**

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).

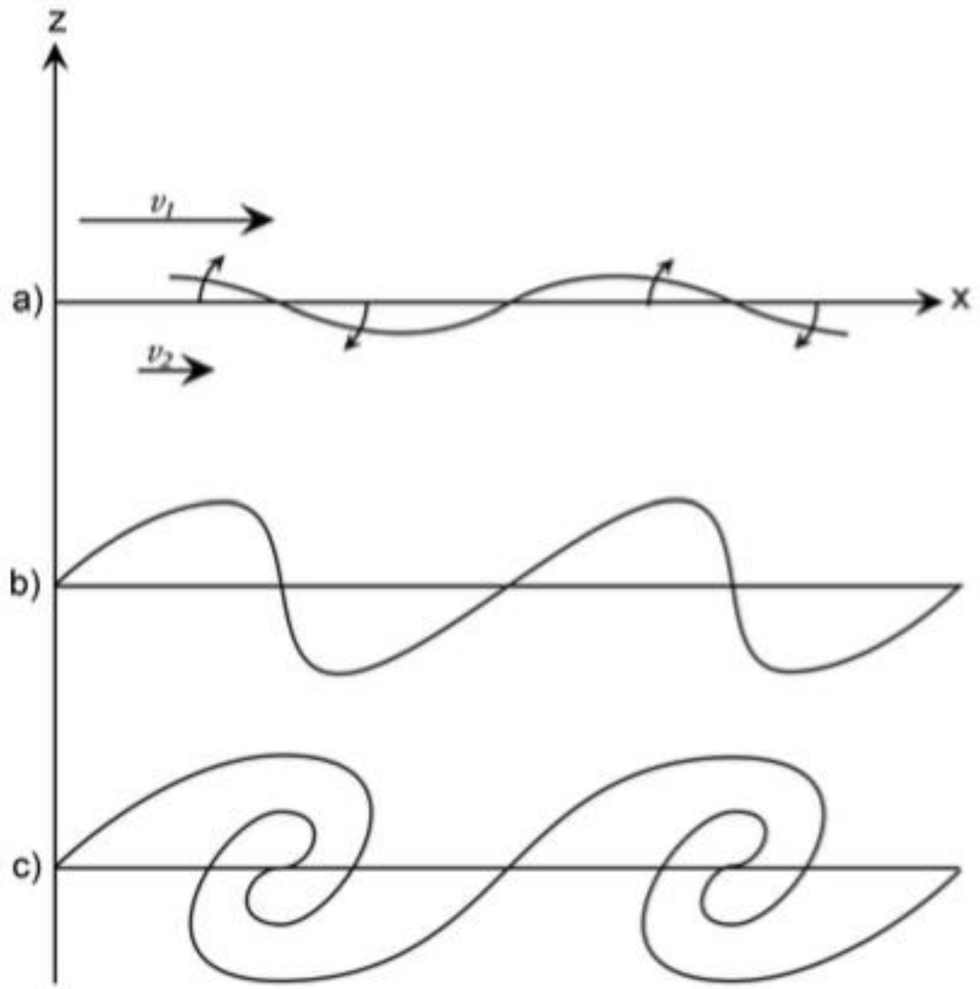
Inner (0.1 AU) active/dead zone boundary



Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

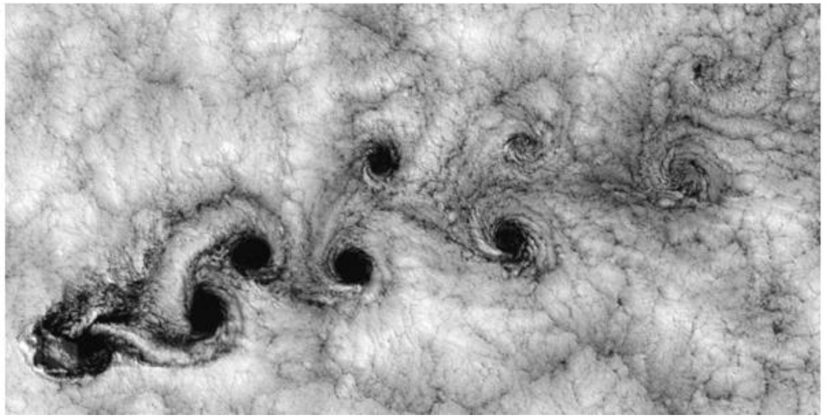
Rossby wave instability
(Kelvin-Helmholtz Instability in rotating disks)



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

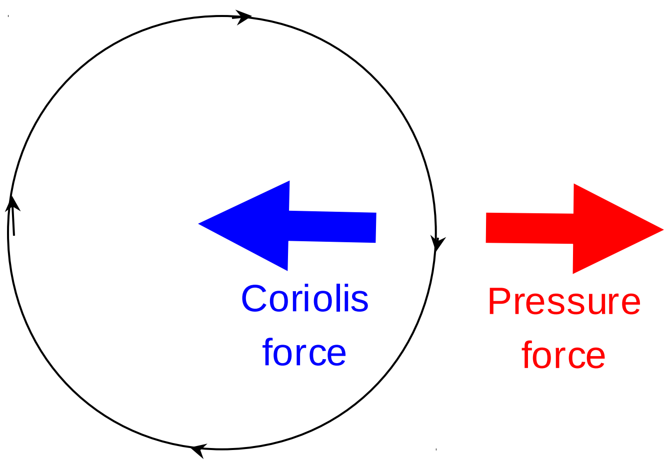
Vortices – an ubiquitous fluid mechanics phenomenon

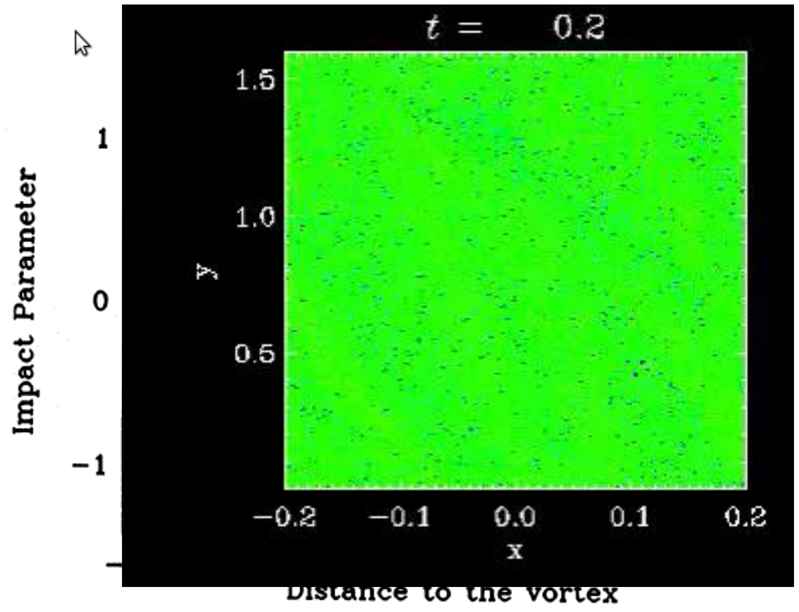
Von Kármán *vortex street*



Vortex Trapping

Geostrophic balance:





Barge & Sommeria (1995)

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

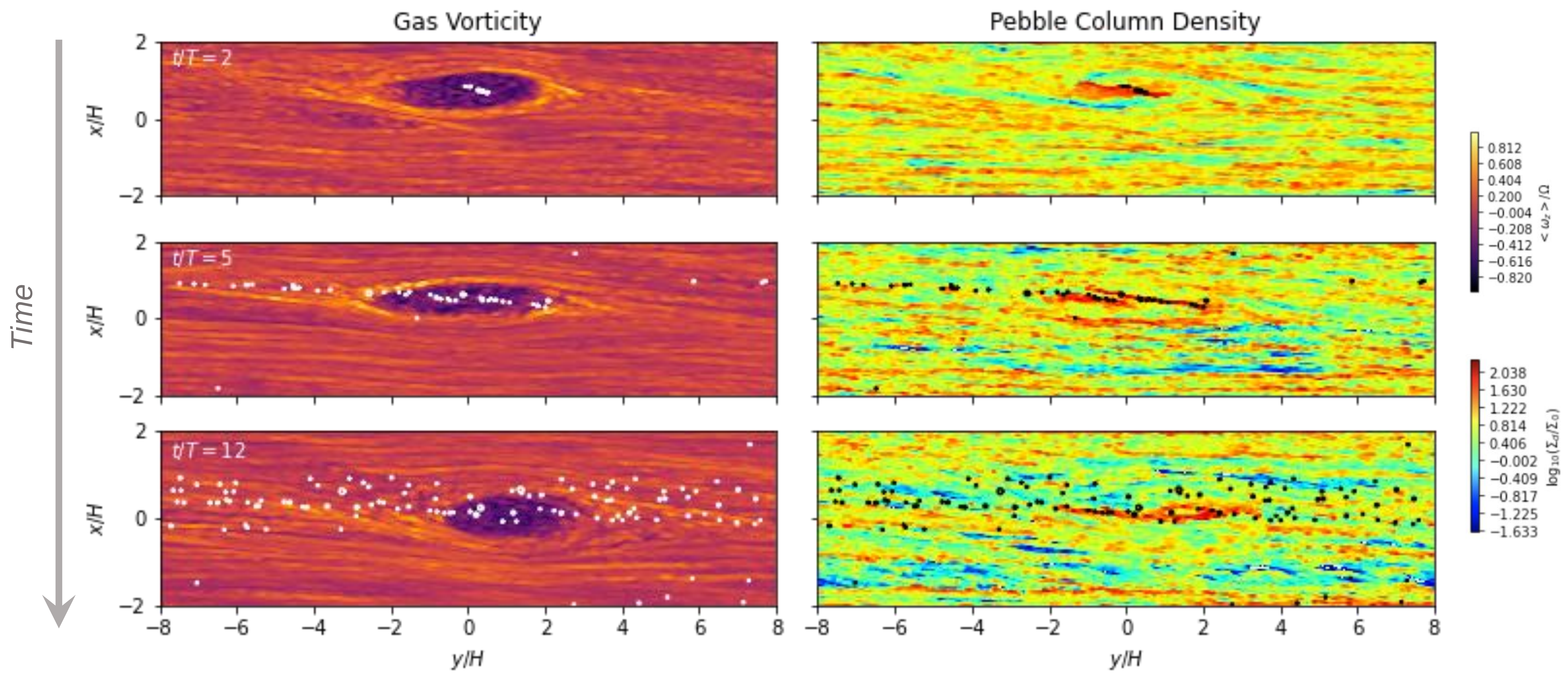
Aid to planet formation

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

Speeds up planet formation enormously

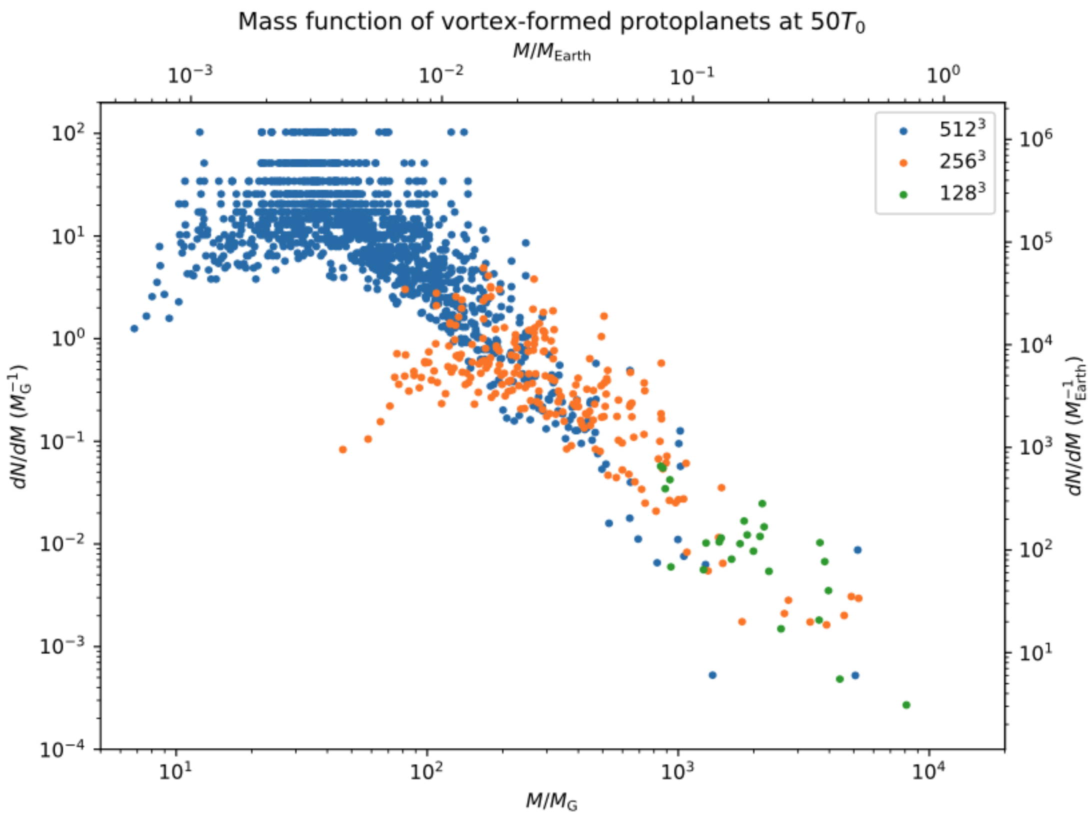
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012, 2021)

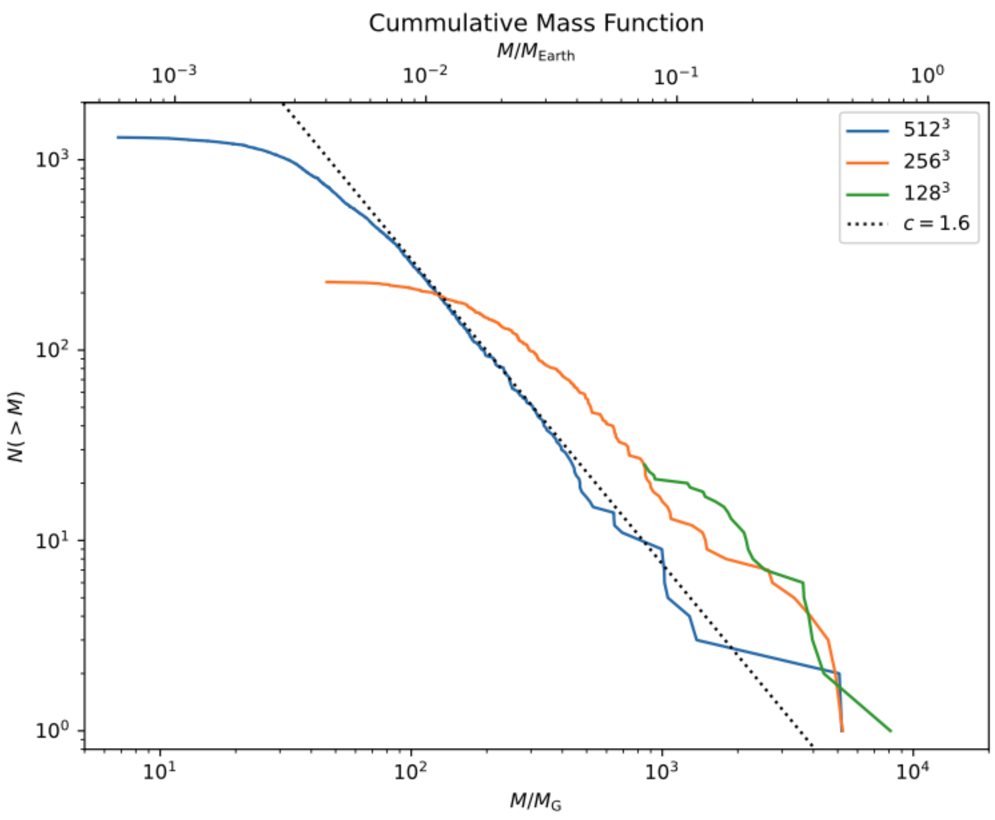
Vortex Trapping



Lyra et al. (submitted)

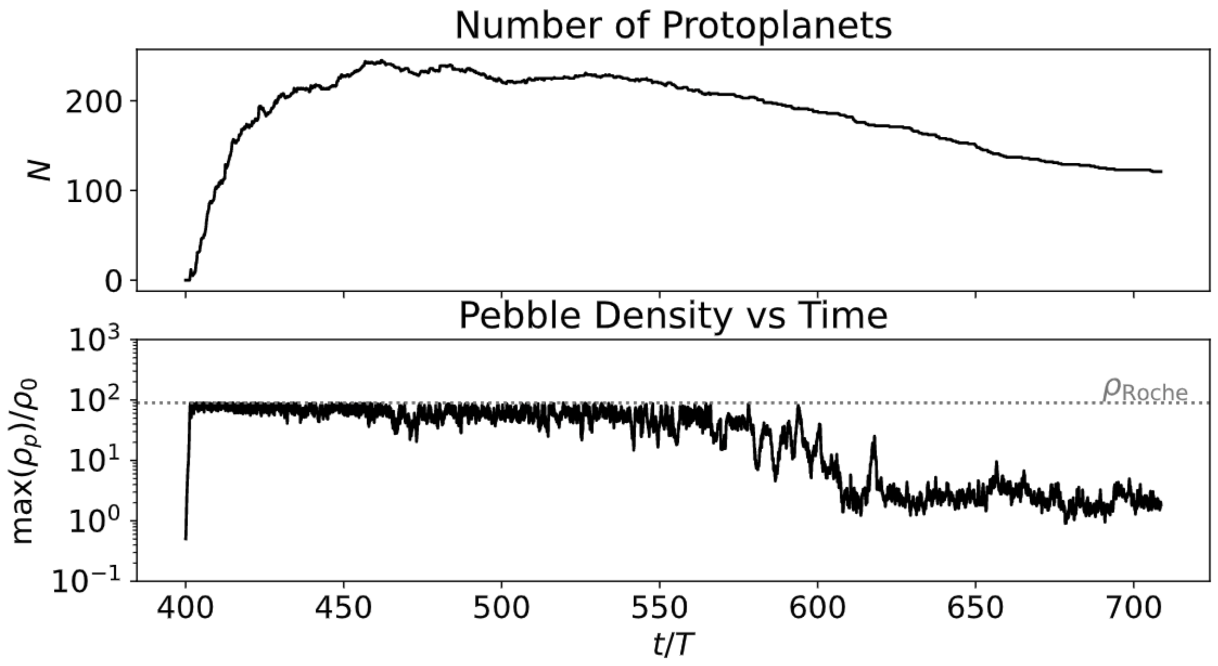
Vortex Trapping – Initial Mass Function

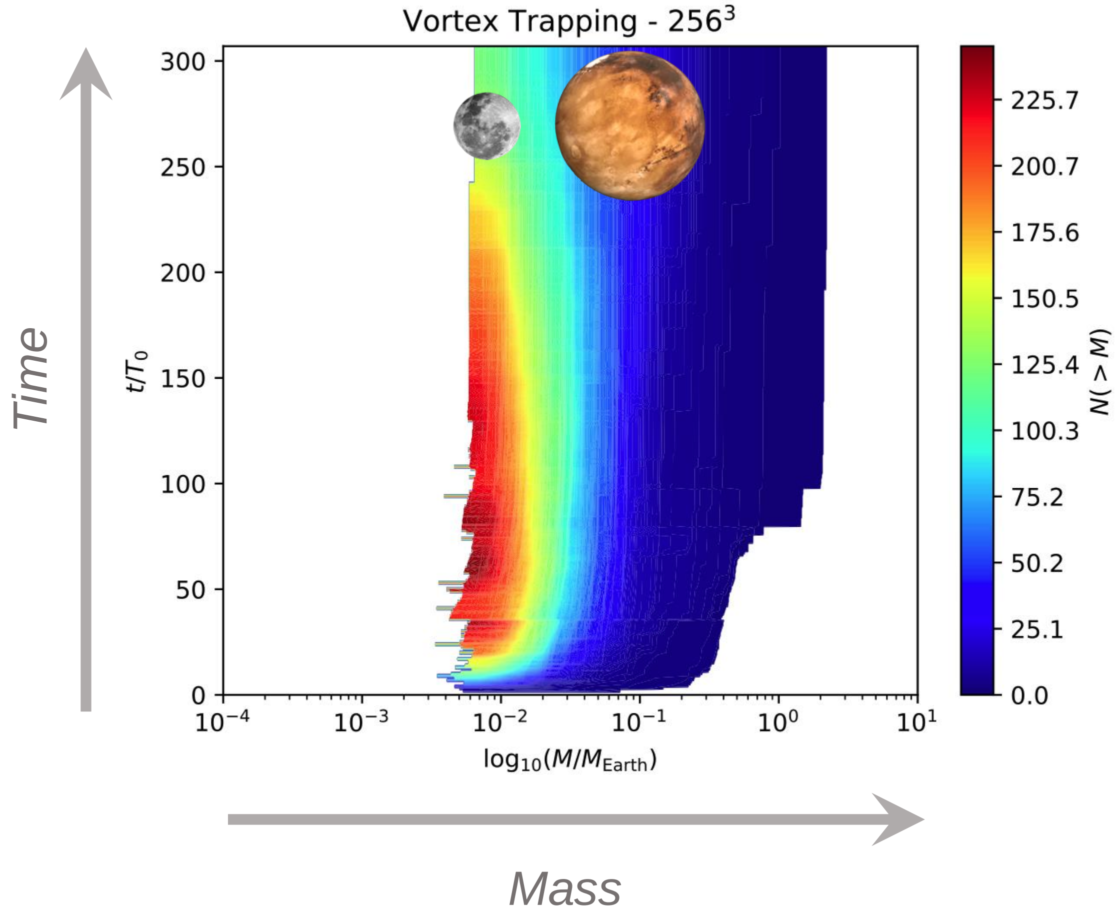




Lyra et al. (submitted)

Initial Mass Function - Convergence



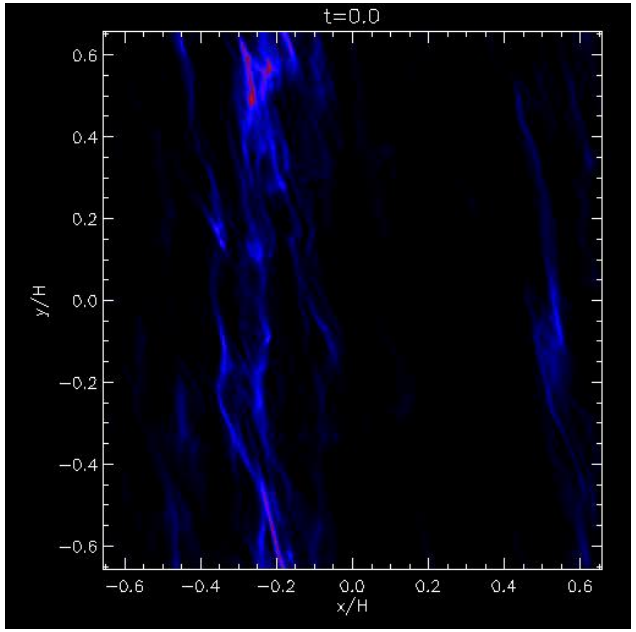


Lyra et al. (submitted)

Take home message

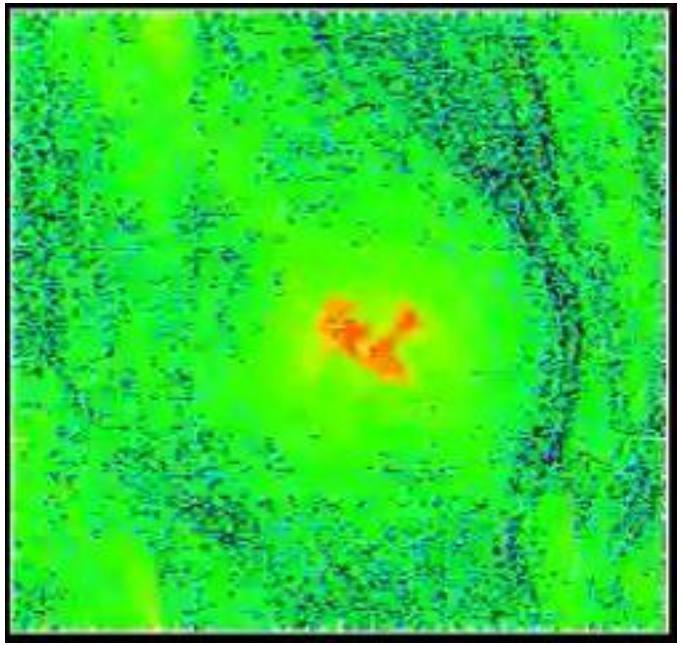
- Two routes for planet formation

Streaming Instability



Johansen+ 07

Vortex Trapping

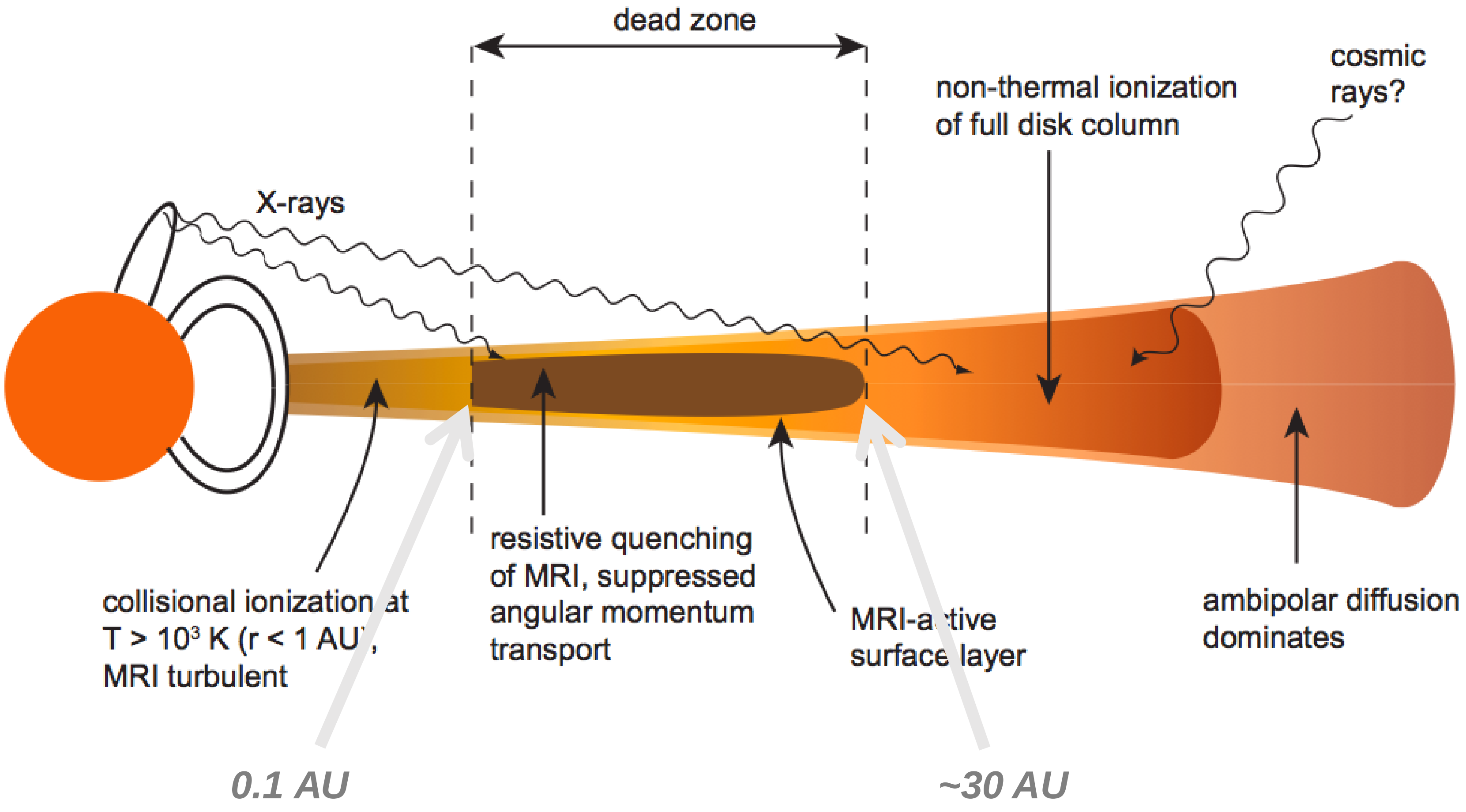


Lyra+08,18 Raettig+Lyra 12,15,21

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

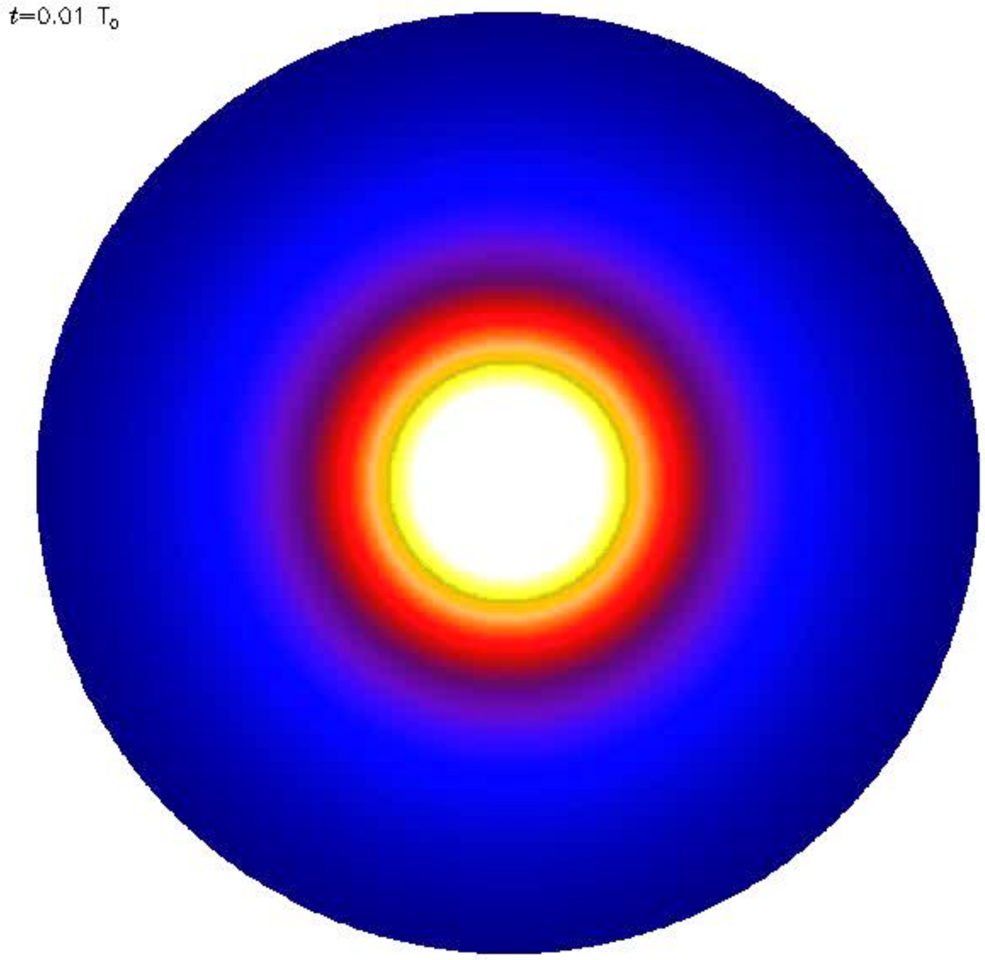
Disk Instabilities

Dead zones



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

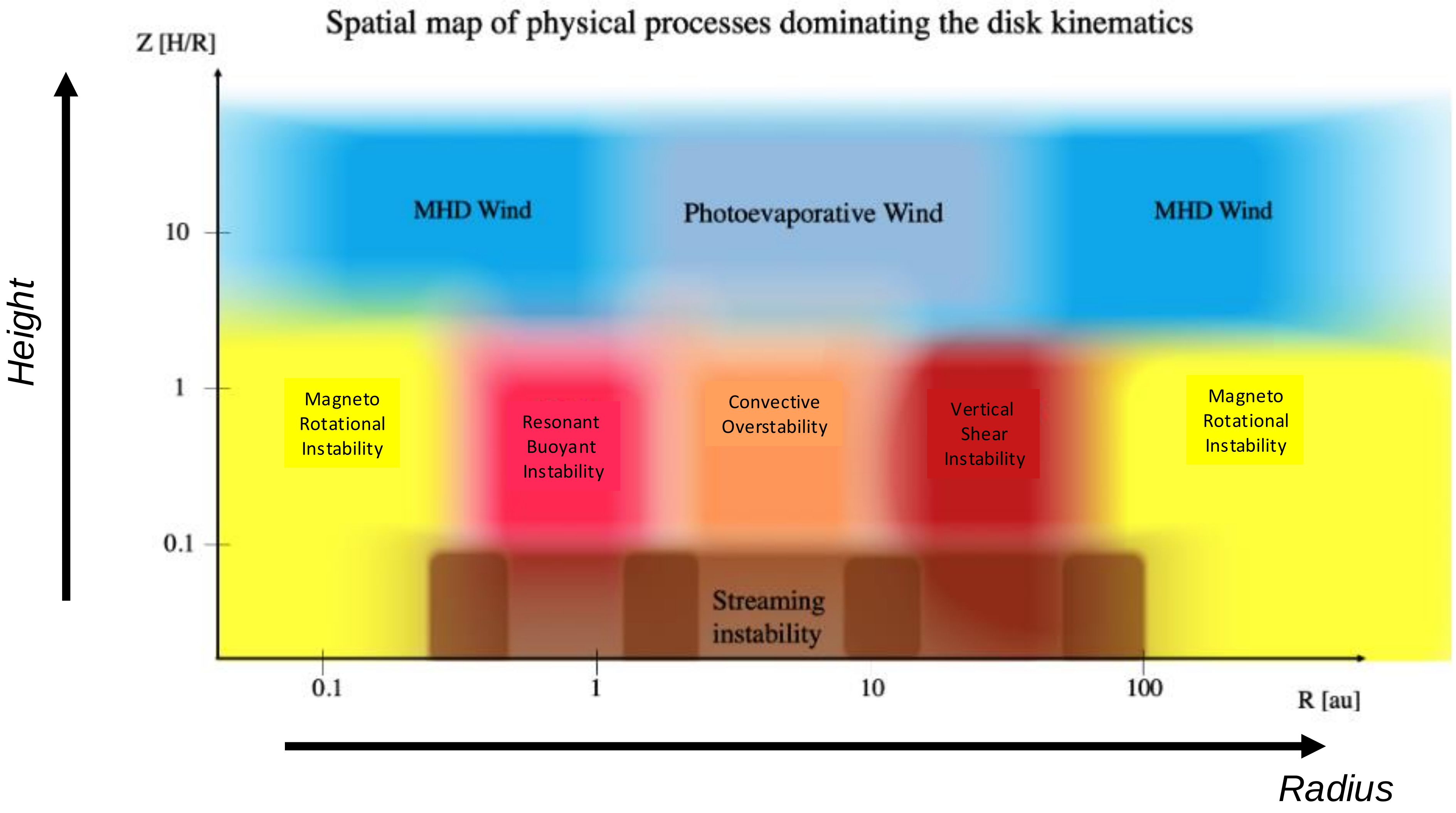
Inner (0.1 AU) active/dead zone boundary



Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Instability Map

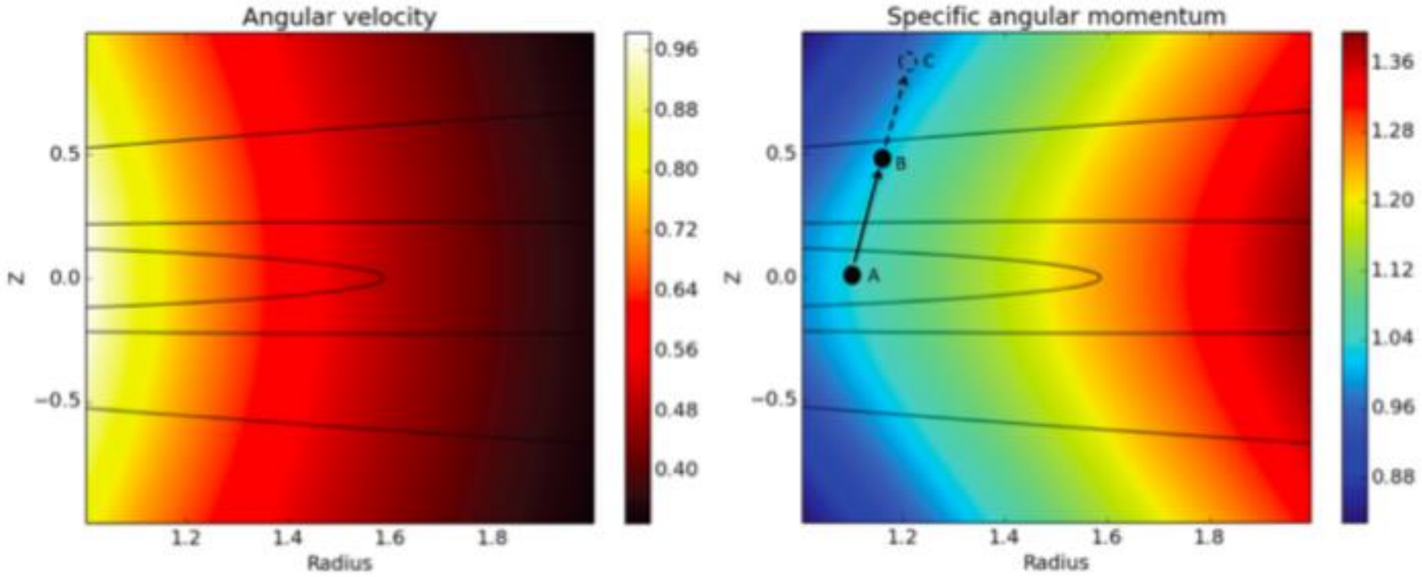


Lesur et al. (2022)

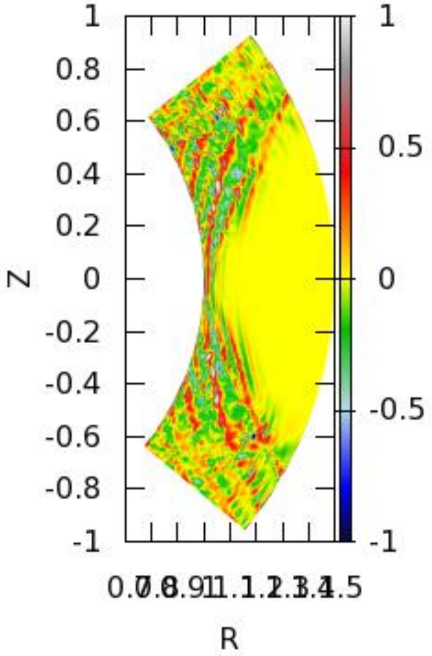
Vertical shear instability

Angular velocity not constant in cylinders: unstable

Buoyancy stabilizes. The most unstable mode is isothermal.

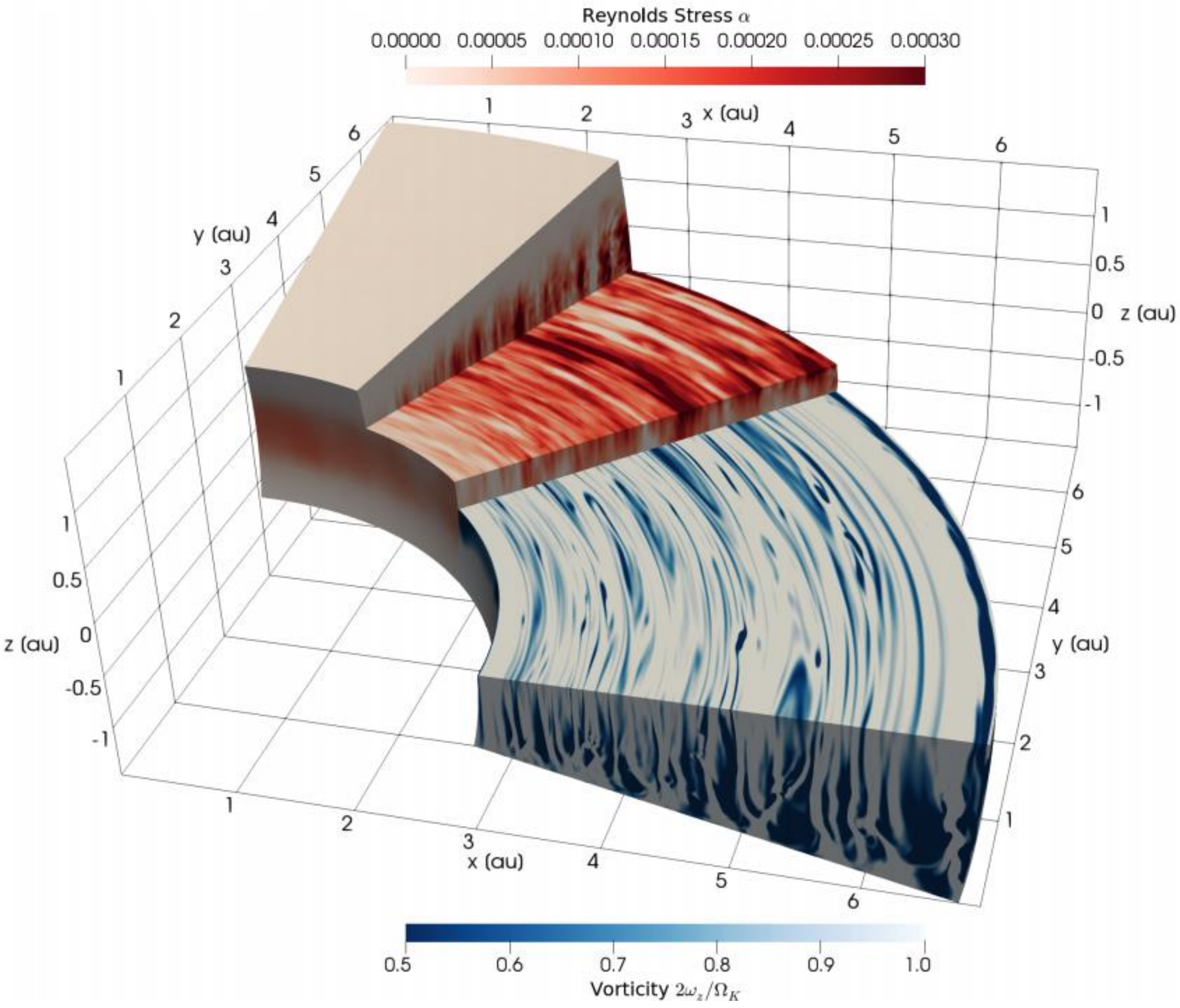


Fromang & Lesur (2017)



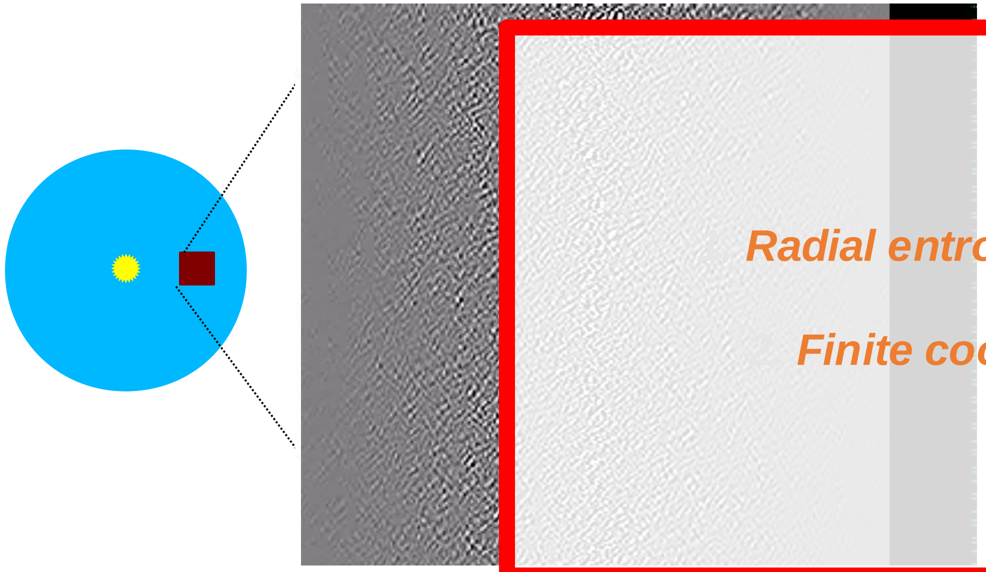
Nelson et al. (2013)

Vertical shear instability



Pfeil & Klahr (2020)

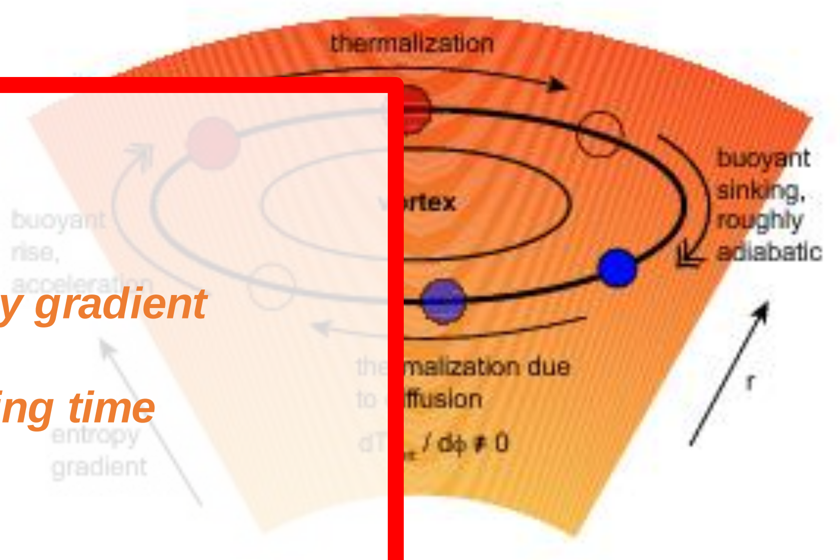
Convective Overstability



Radial entropy gradient

Finite cooling time

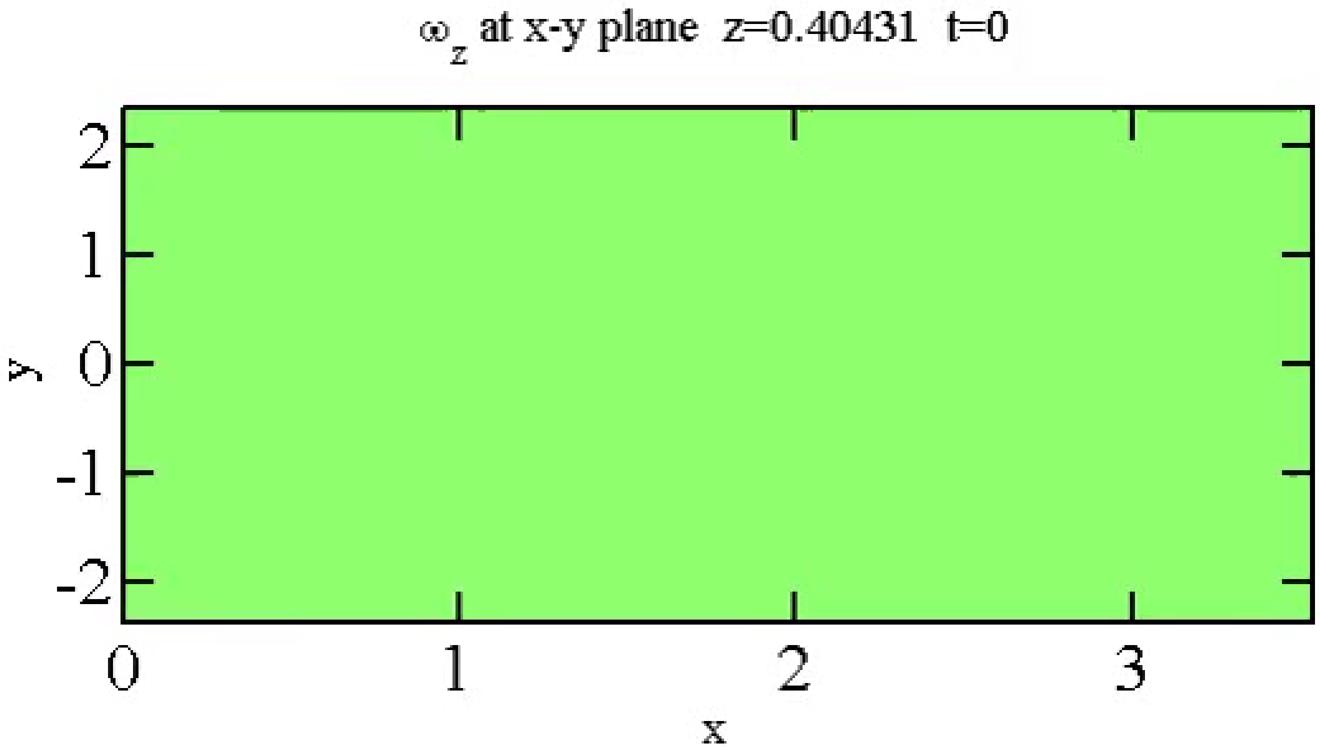
Sketch of the
Convective Overstability



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 (née Zombie Vortex Instability)

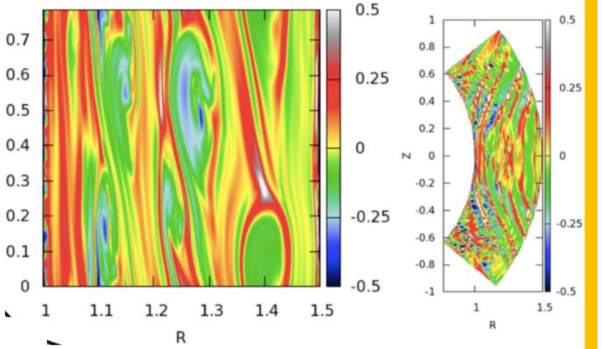


Cascade of baroclinic critical layers

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

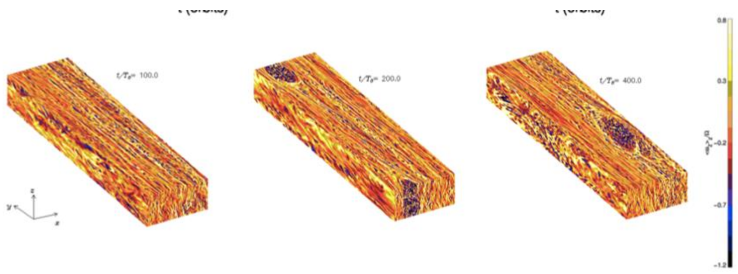
Hydrodynamical Instabilities

Vertical Shear Instability



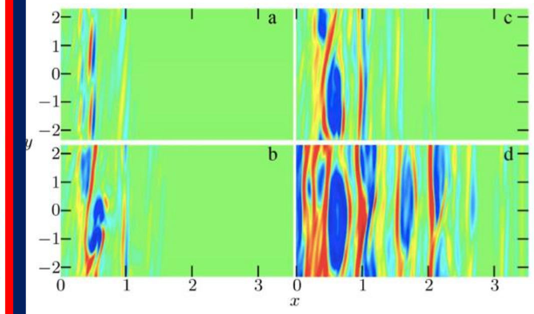
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

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

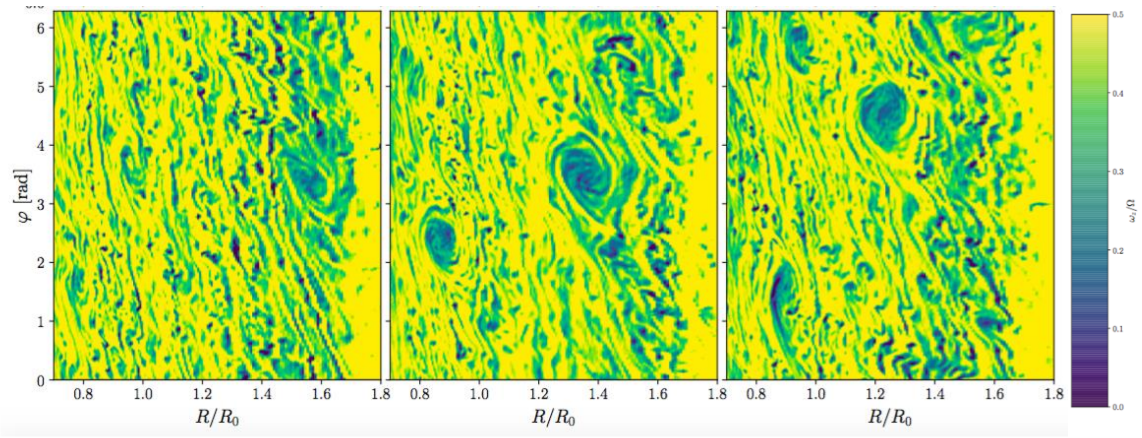
$\Omega\tau \ll 1$
($\kappa < 1$ cm^2/g)

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

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

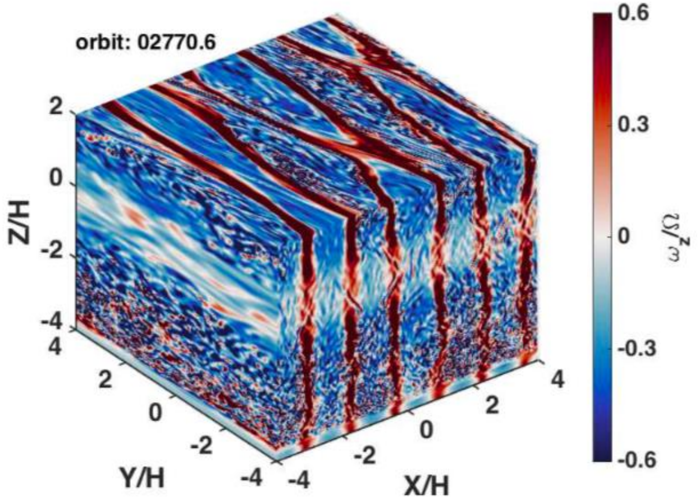
Opacity

Take-home message



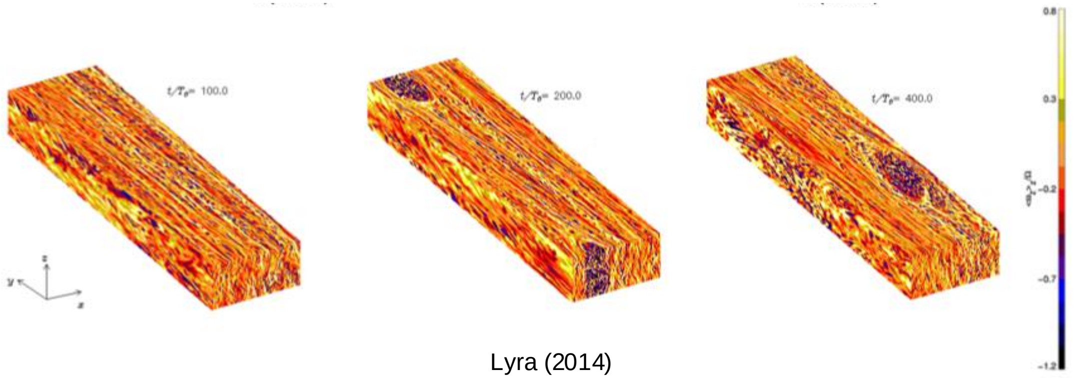
Manger & Klahr (2018)

Vertical Shear Instability
saturates into
vortices



Barranco et al. (2018)

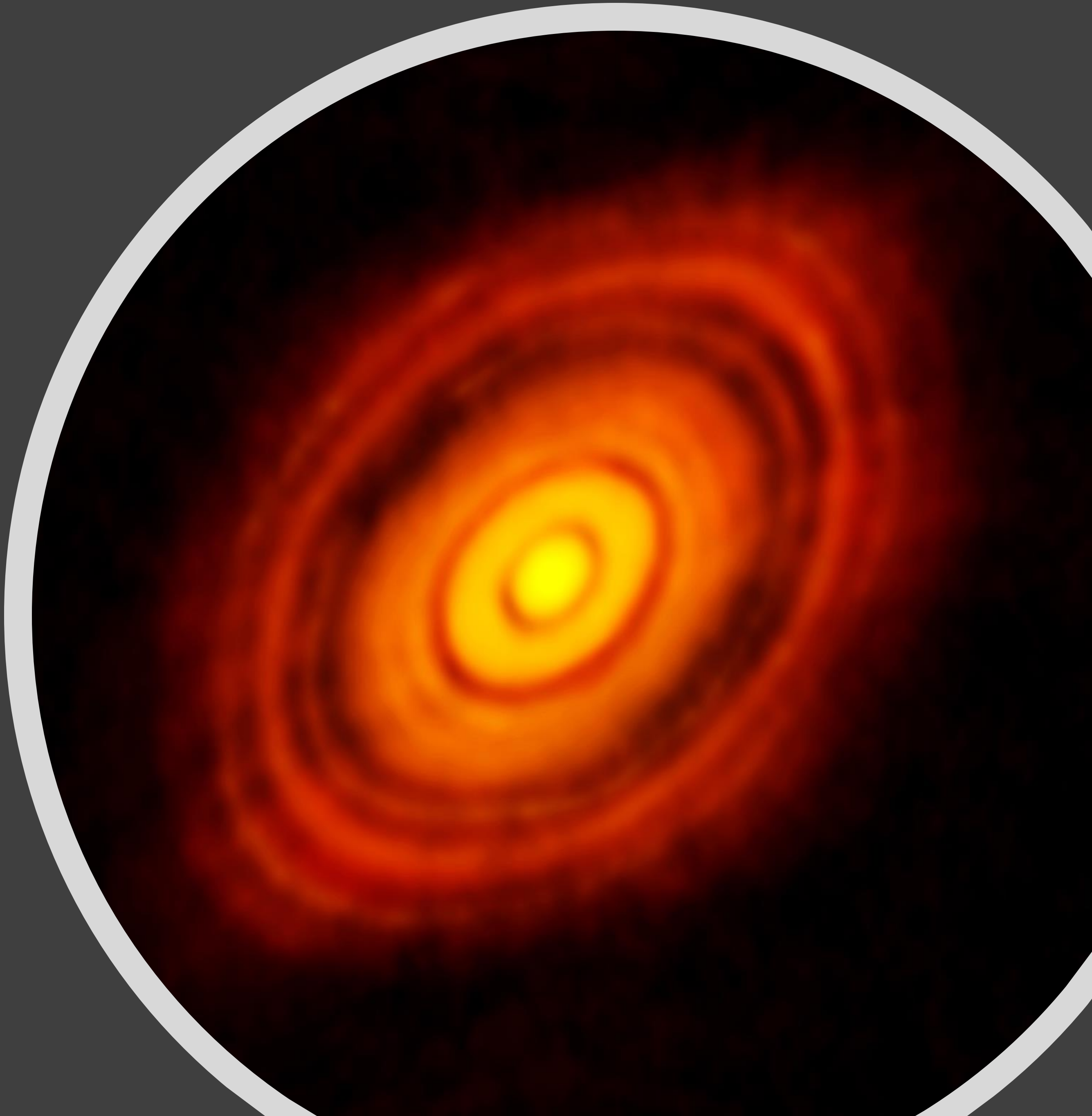
Resonant Buoyant Instability
saturates into
vortices

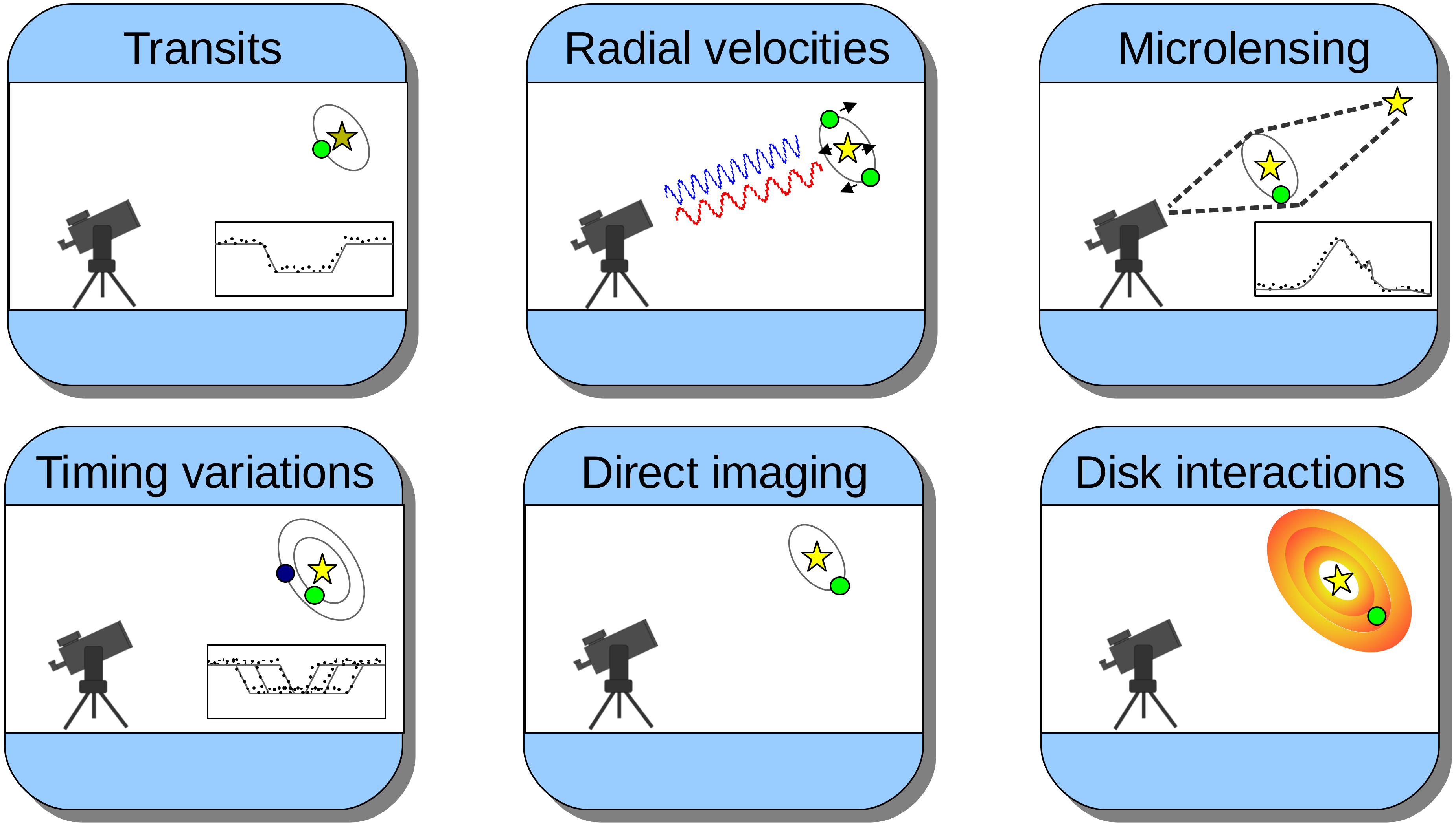


Lyra (2014)

Convective Overstability
saturates into
vortices

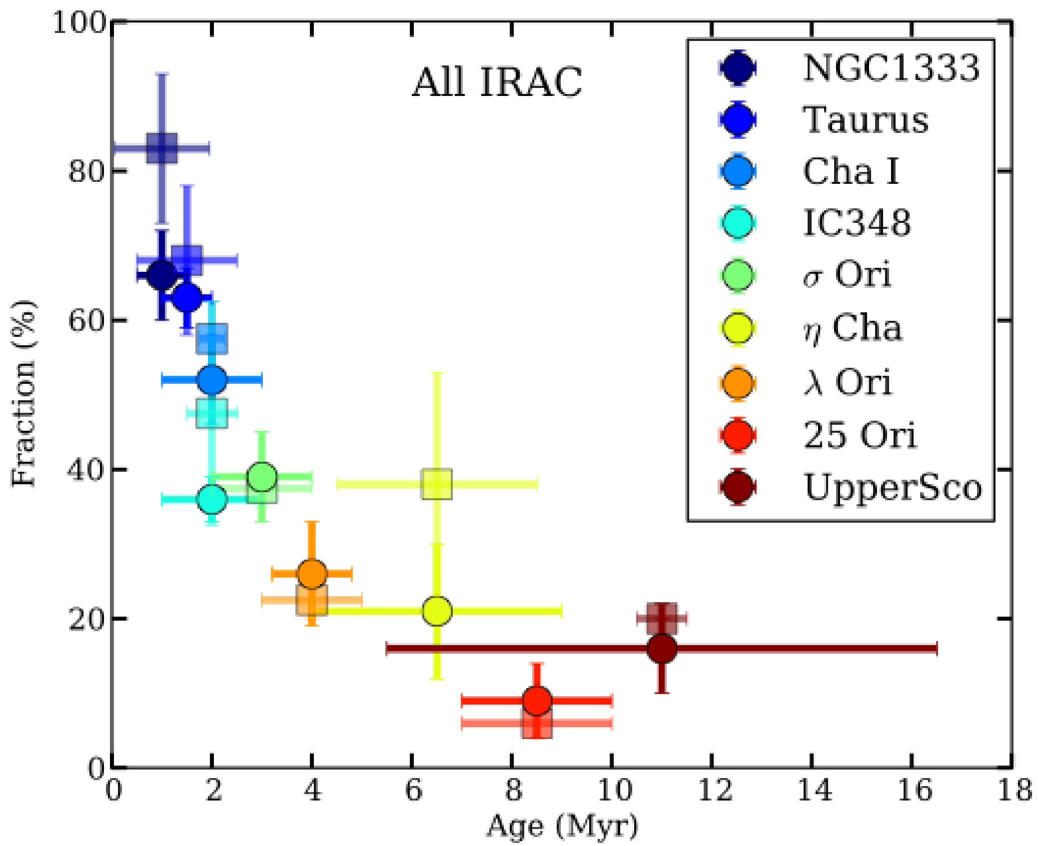
Disk Observations





Slide by A. Richert

Disk lifetime

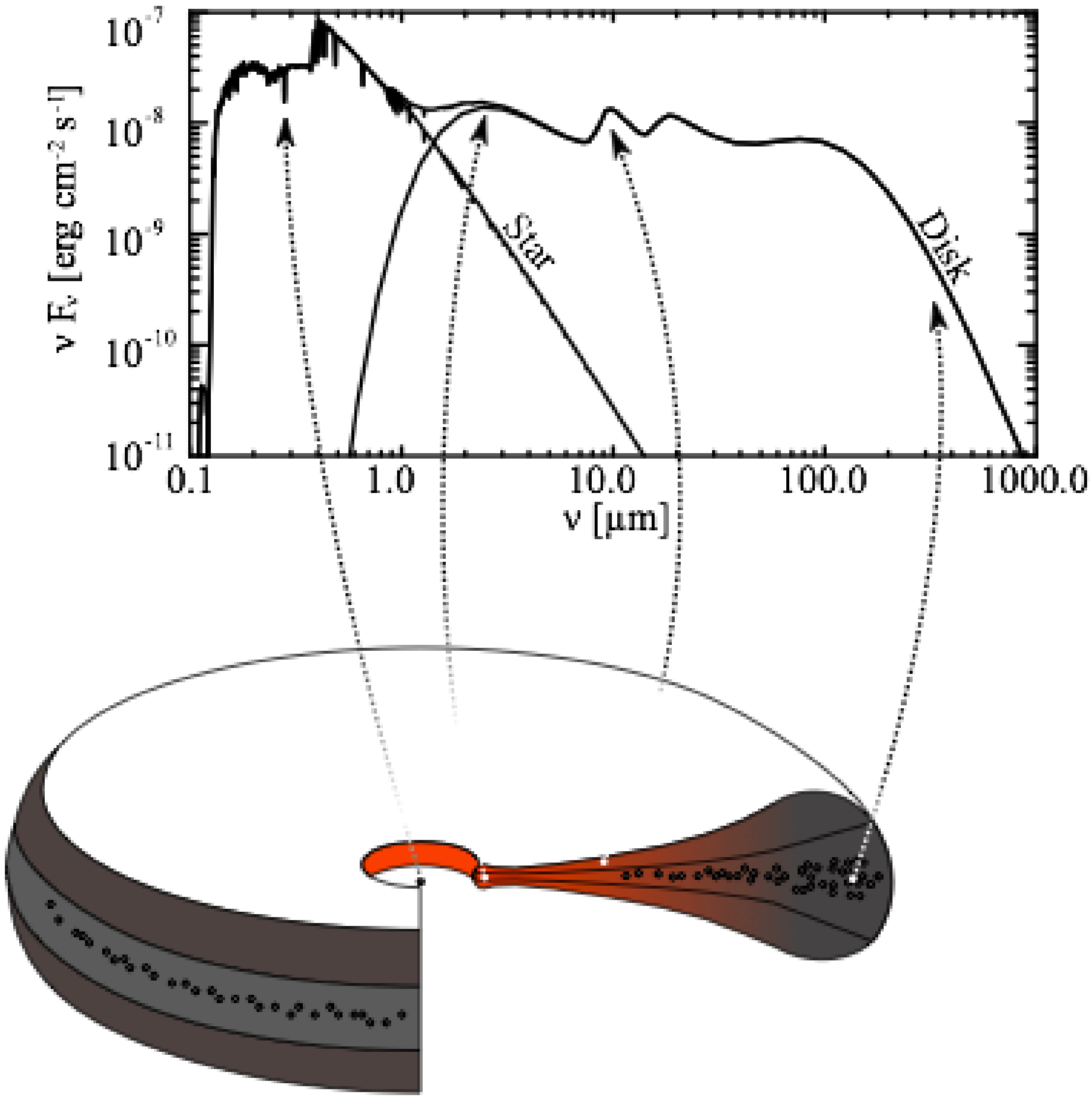


(Ribas et al. 2014)

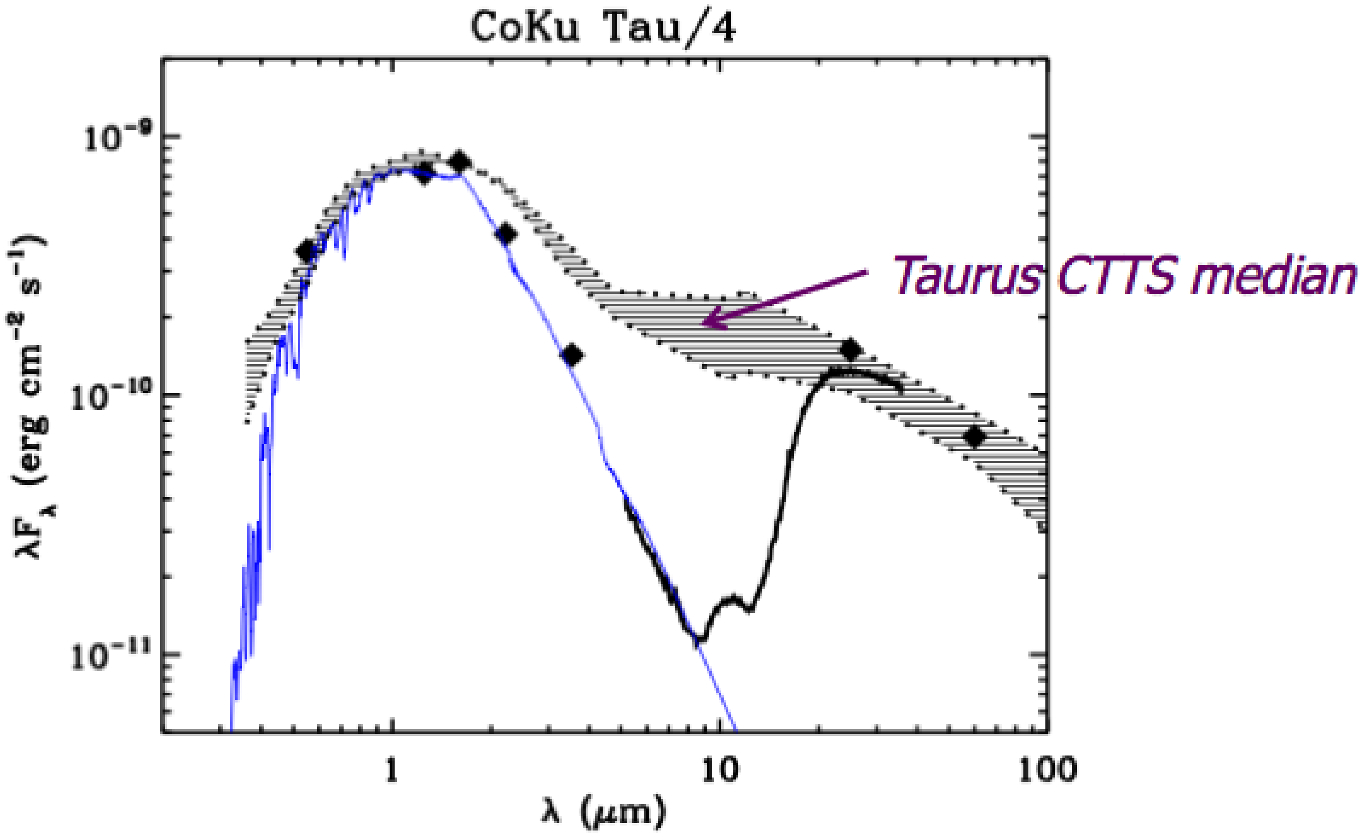
Disks dissipate within ~10 Myr

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

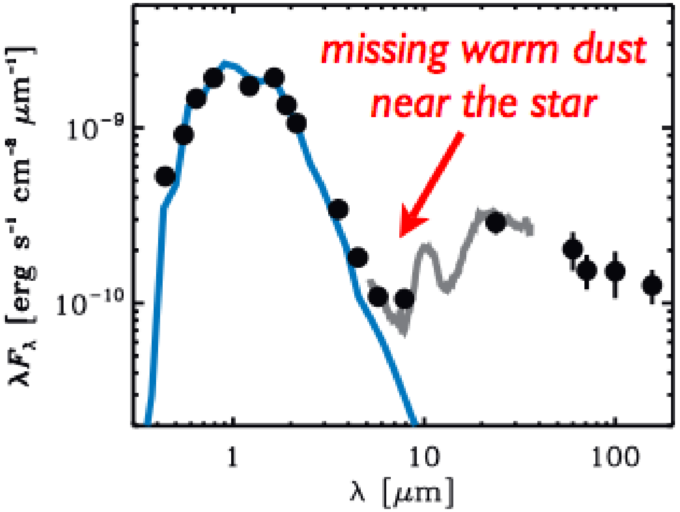
Disk spectra



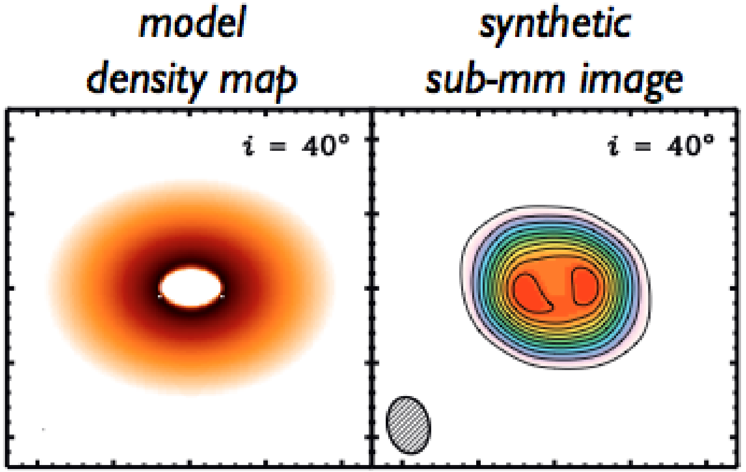
A class of disks with missing hot dust.



Disks with missing hot dust.

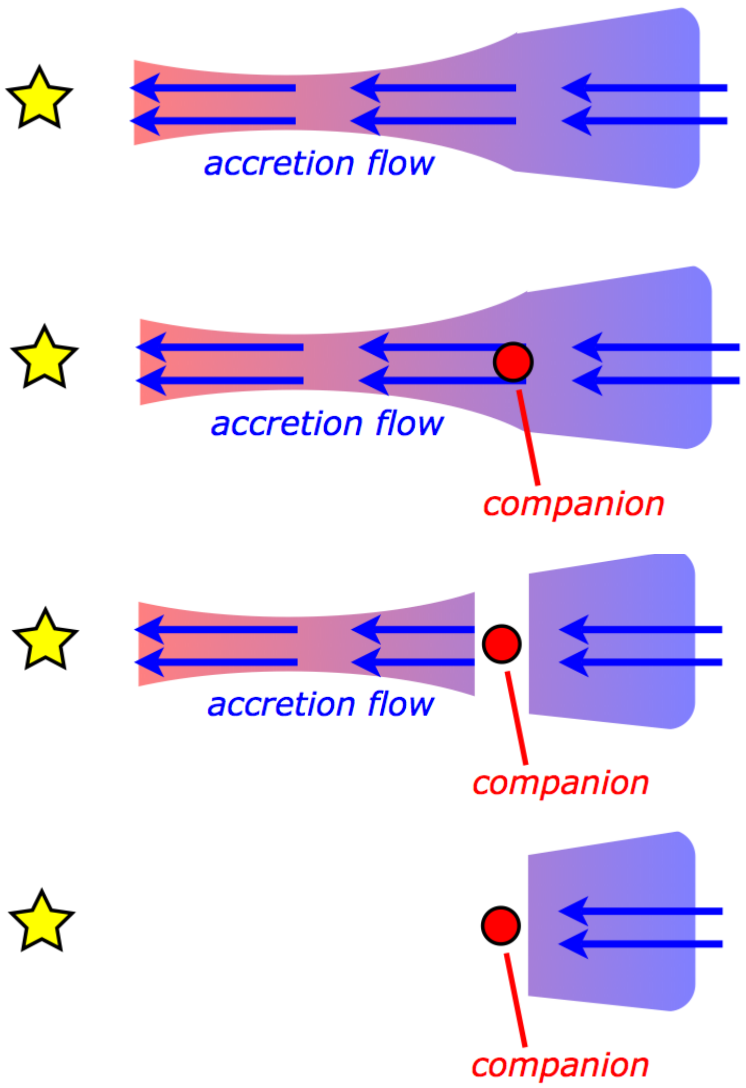


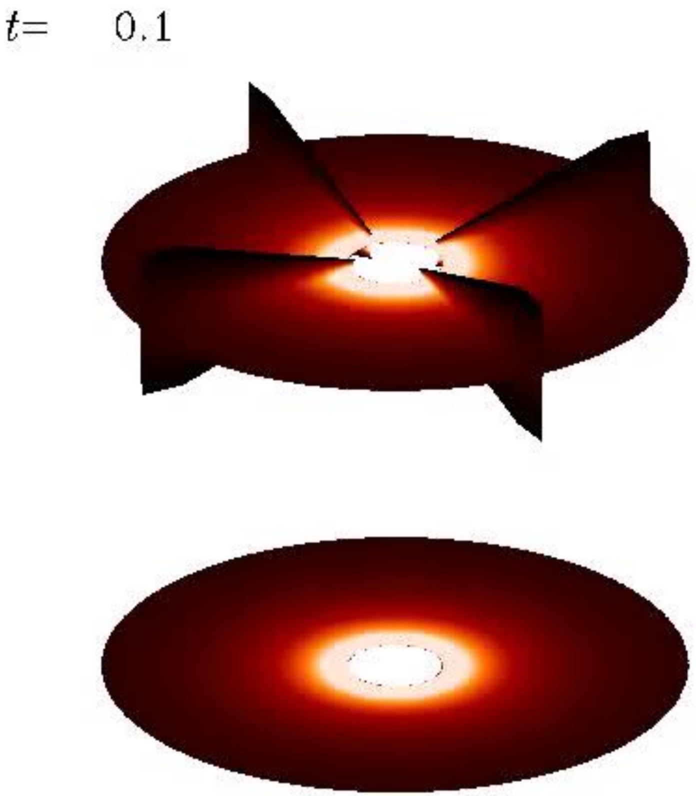
[e.g., Furlan et al. 2009]



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

Planetary companion

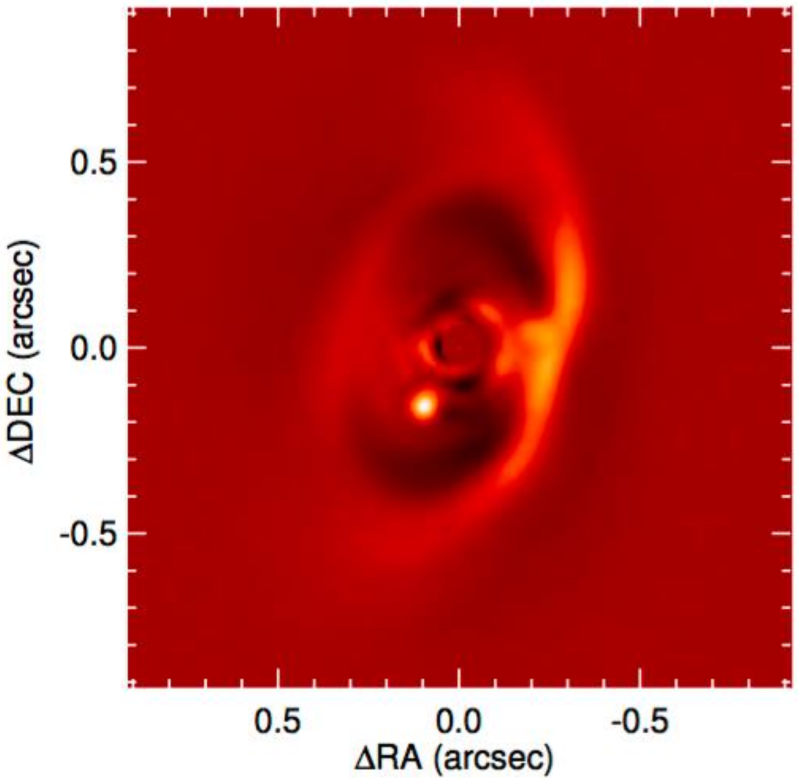




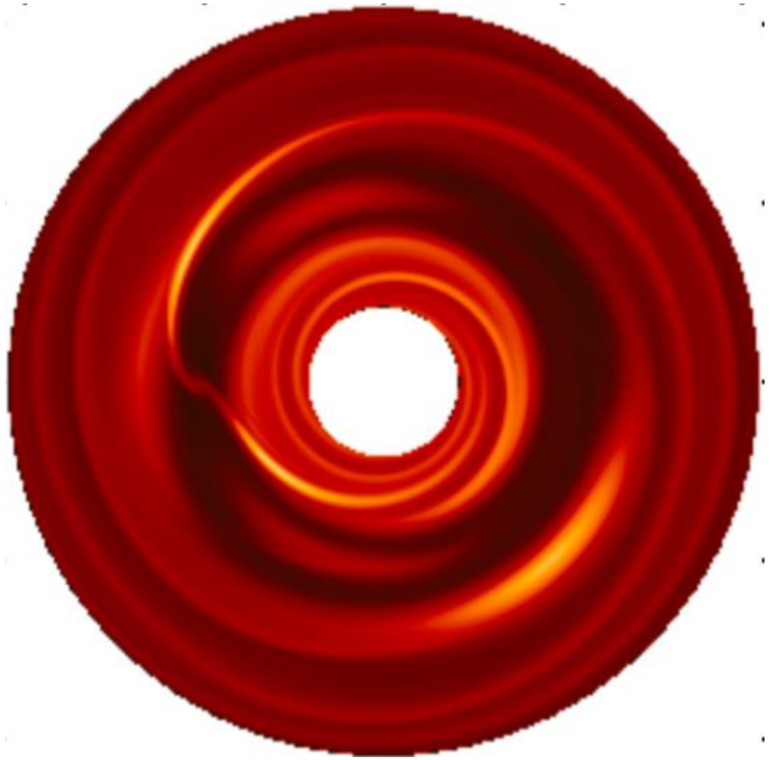
(Lyra 2009)

These cavities may be the telltale signature of forming planets

PDS 70 and PDS 70b



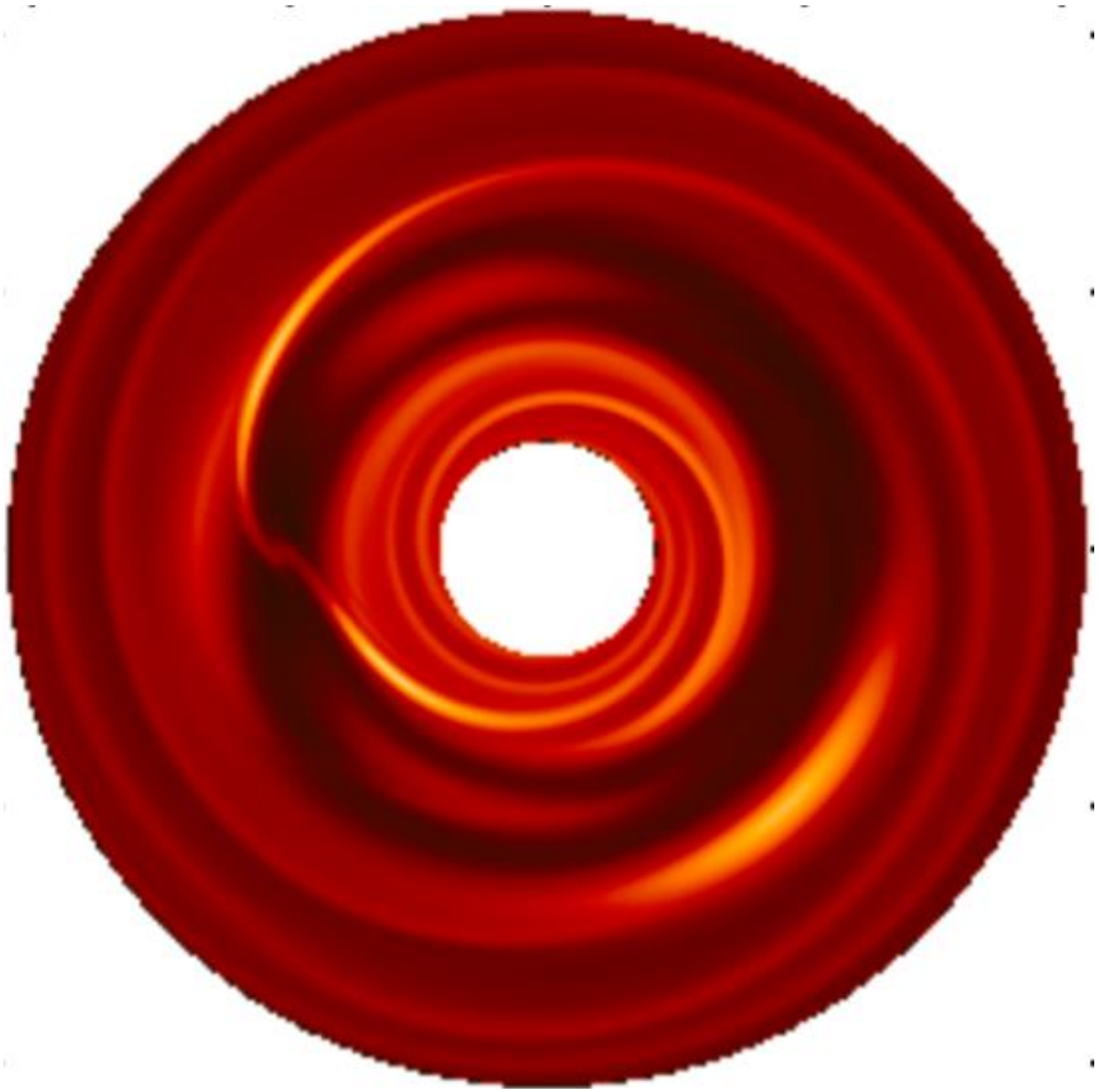
(Muller et al. 2018)



(Lyra et al. 2009b)

A way to directly study planet-disk interaction

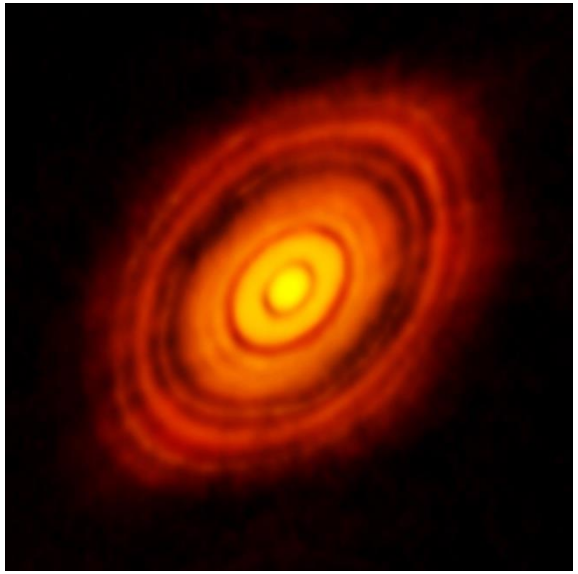
Planet-disk interaction: gaps, spirals, and vortices.



(Lyra et al. 2009b)

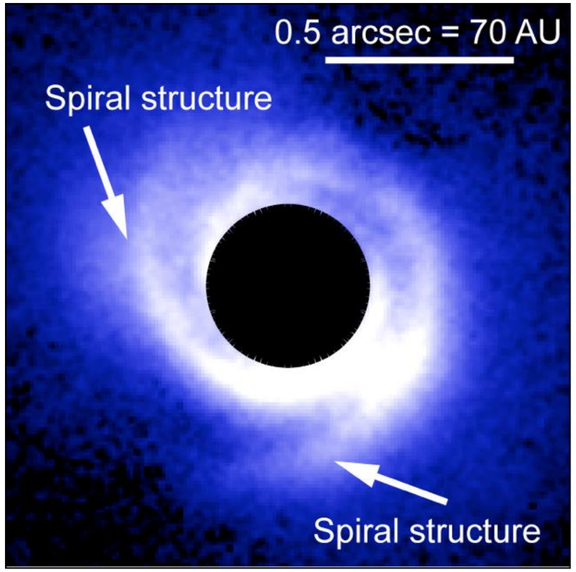
Observational evidence: gaps, spirals, and vortices

HL Tau



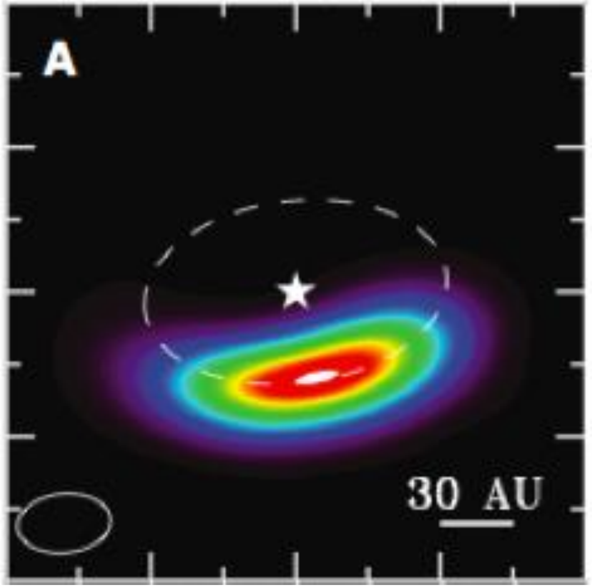
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

Oph IRS 48

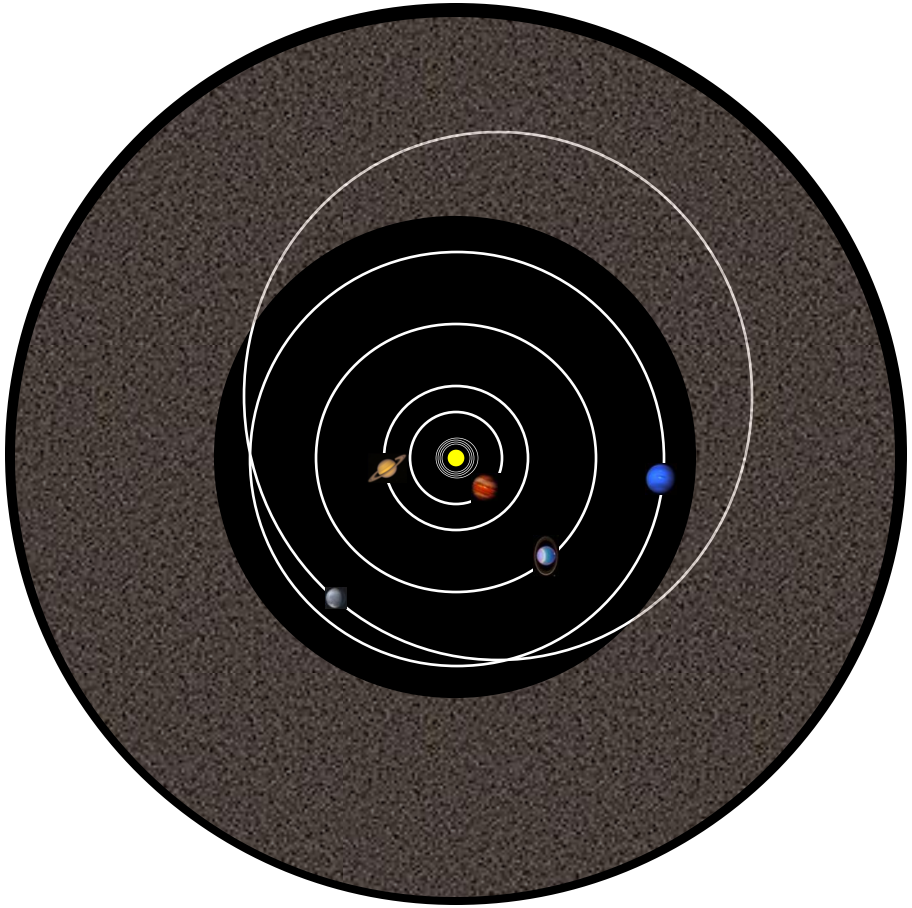


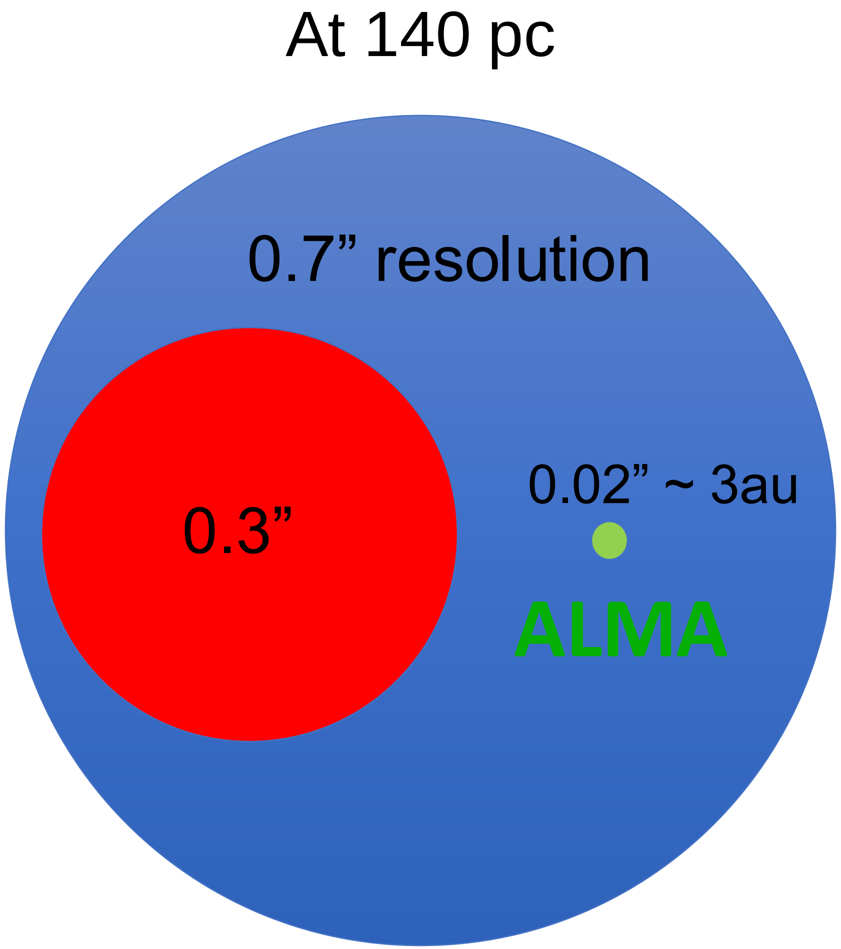
van der Marel et al. (2013)

ALMA

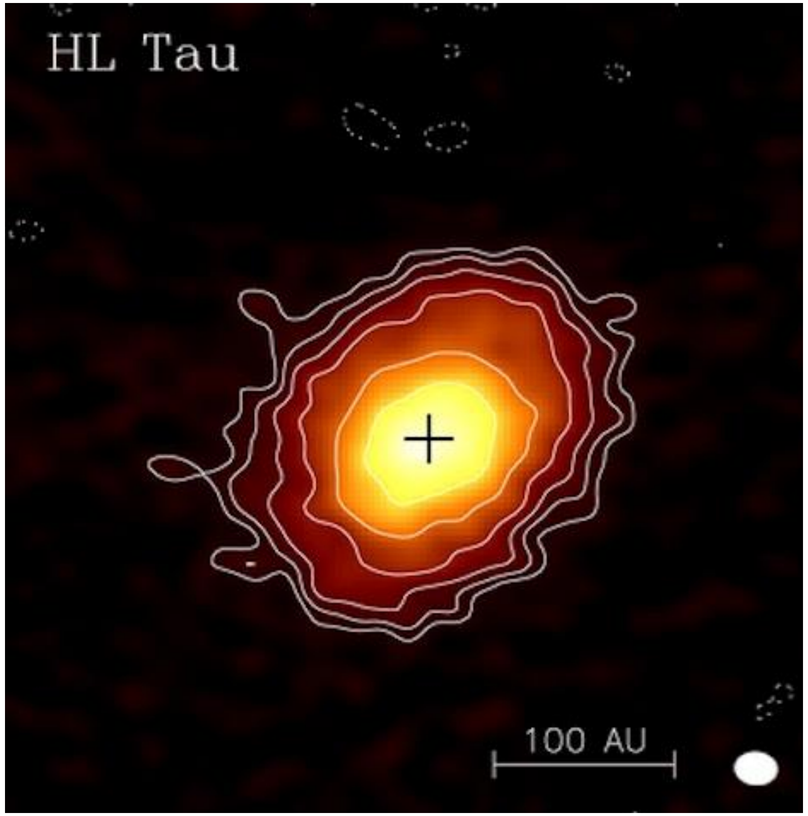
VLA

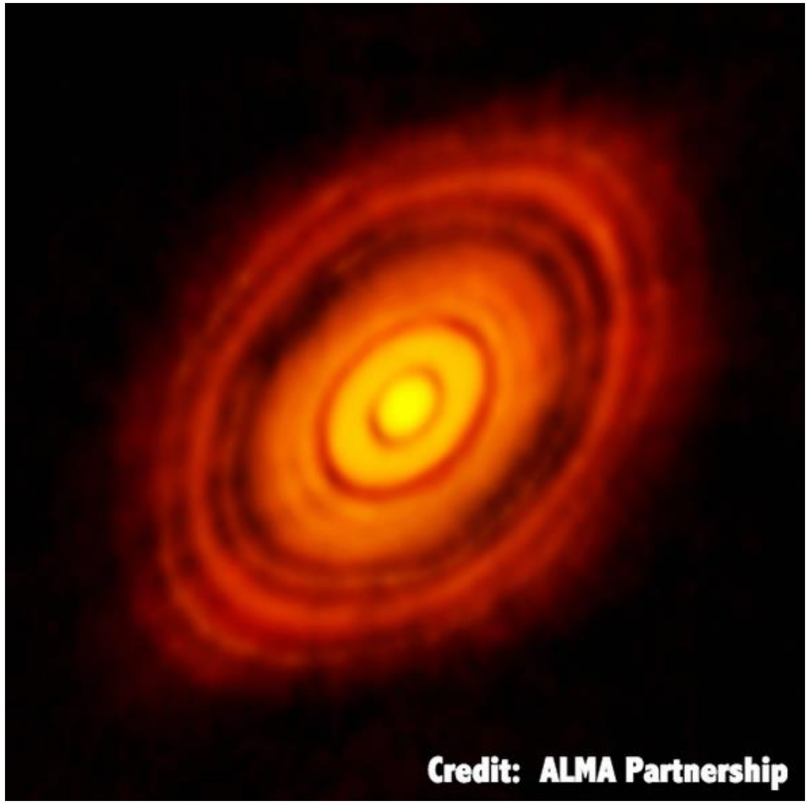
The ALMA Re~~v~~solution



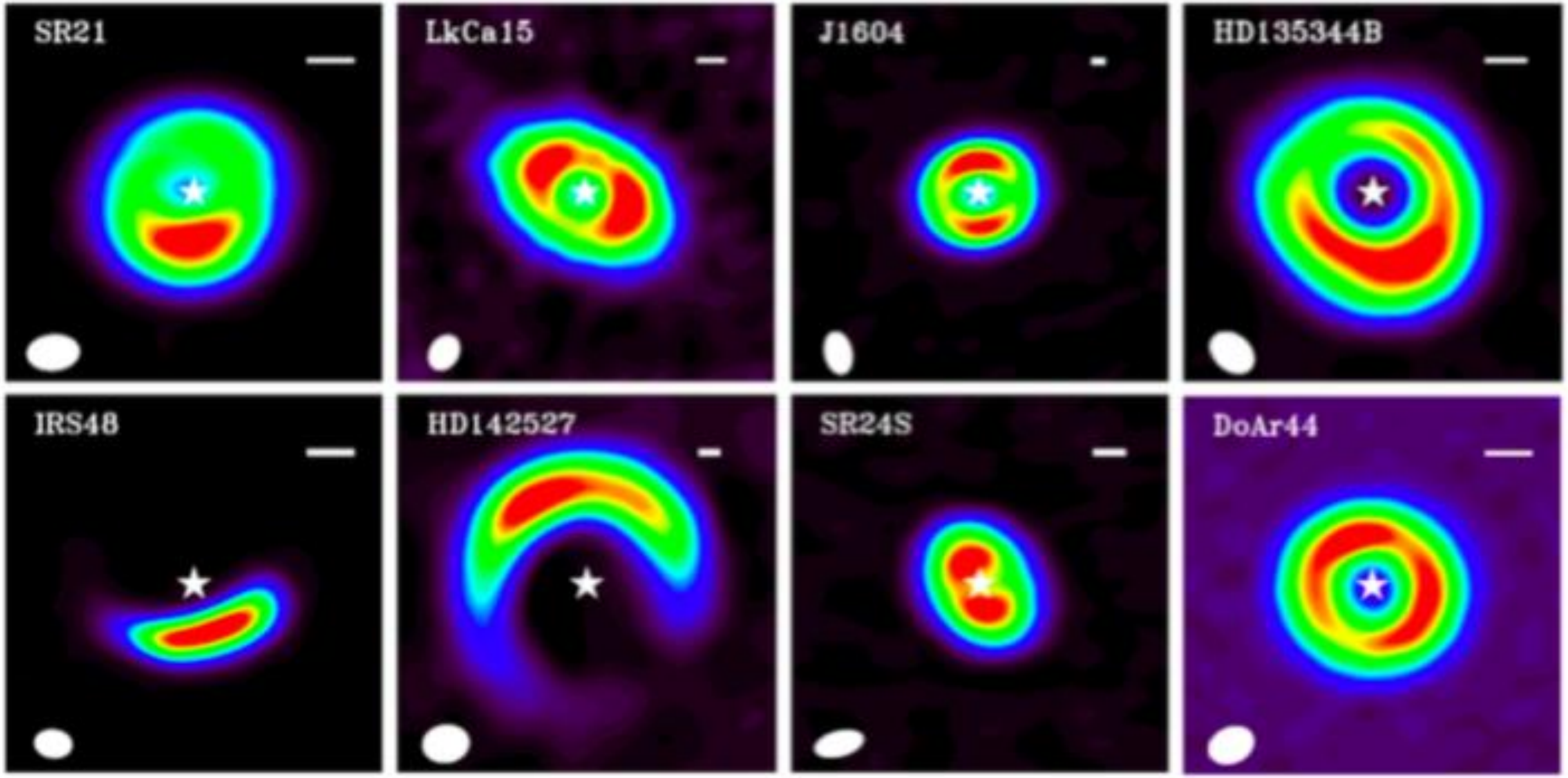


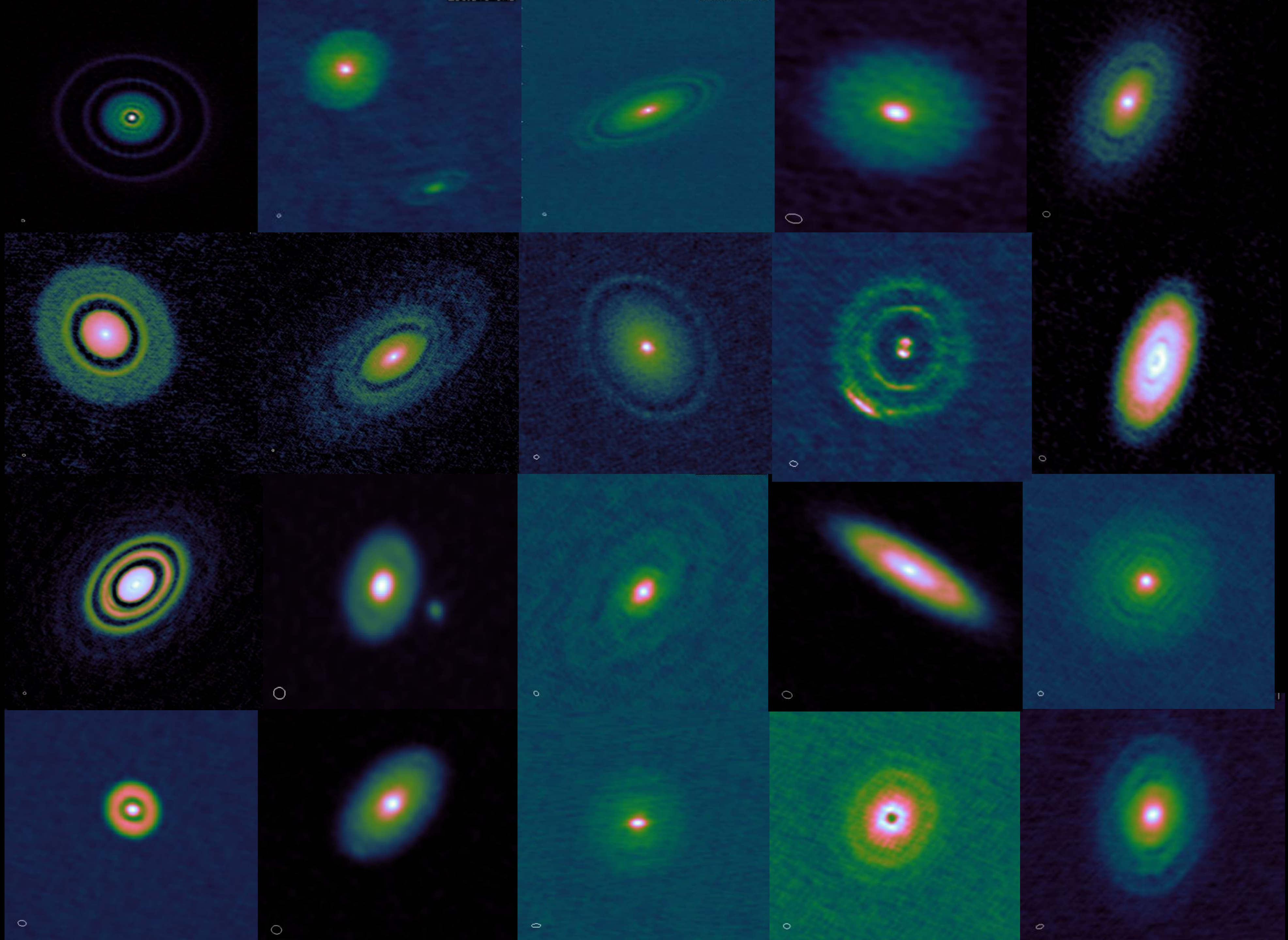
Before ALMA **ALMA**





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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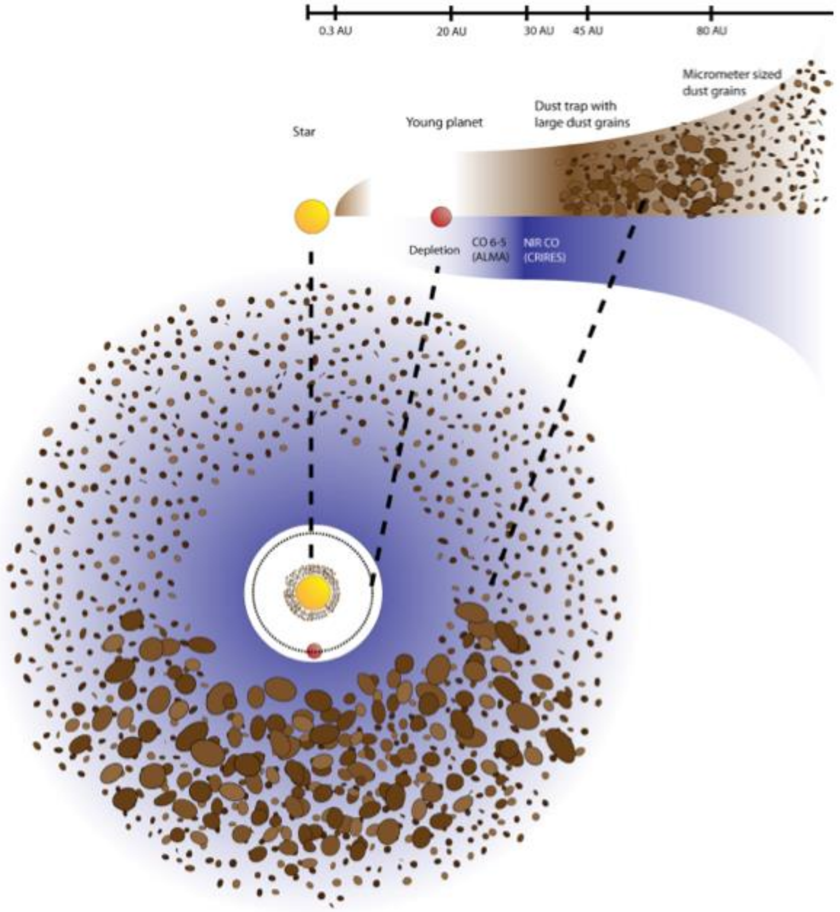
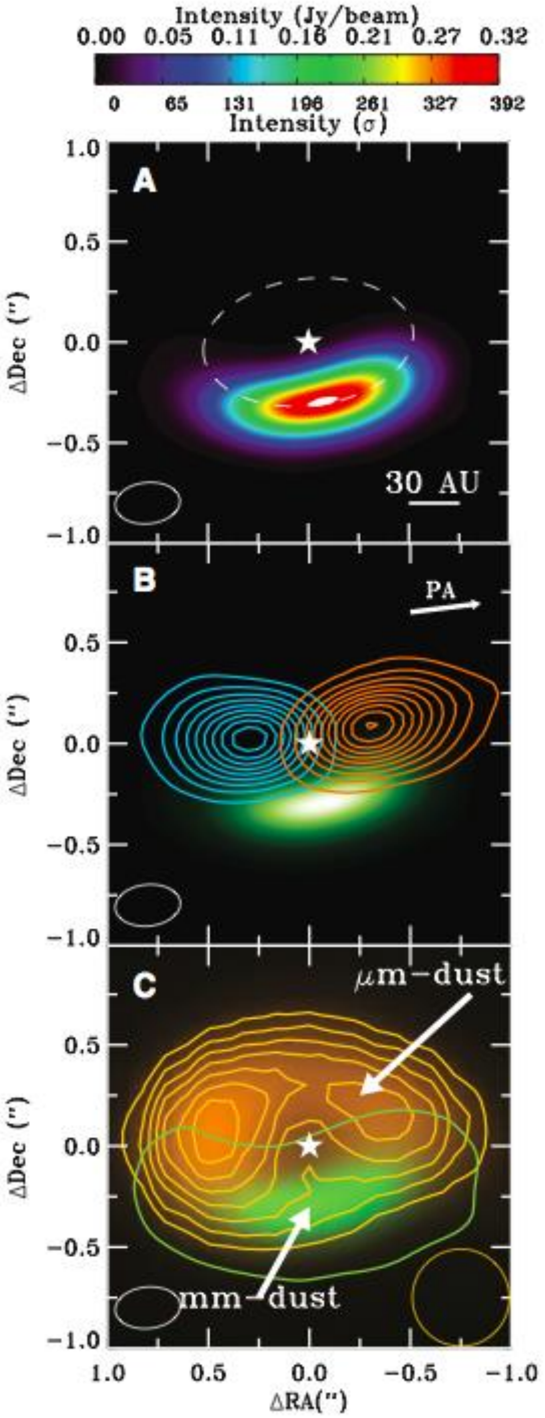
van der Marel+ ‘13

A huge vortex observed with ALMA

The Oph IRS 48 “comet formation factory”



van der Marel+. ‘13

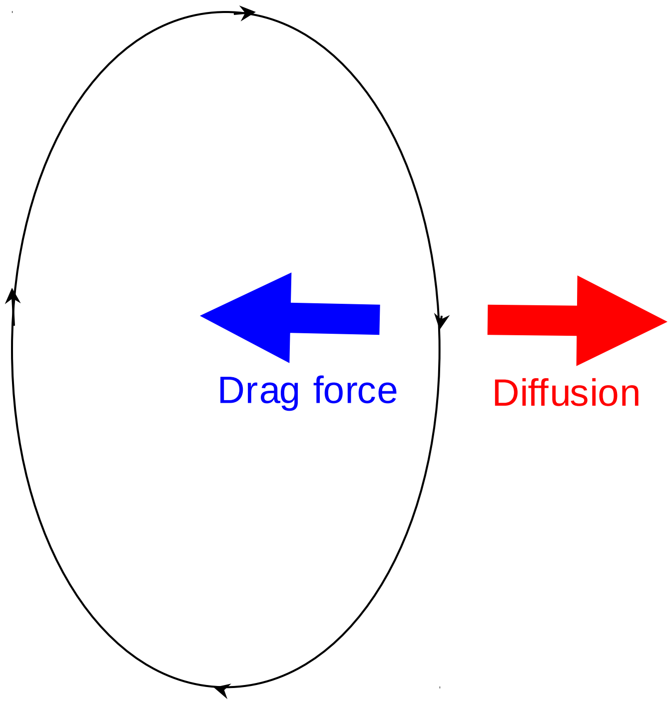


asymmetric
mm dust
at 63 AU

Gas detection:
Keplerian rotation

Micron-sized
dust follows gas

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

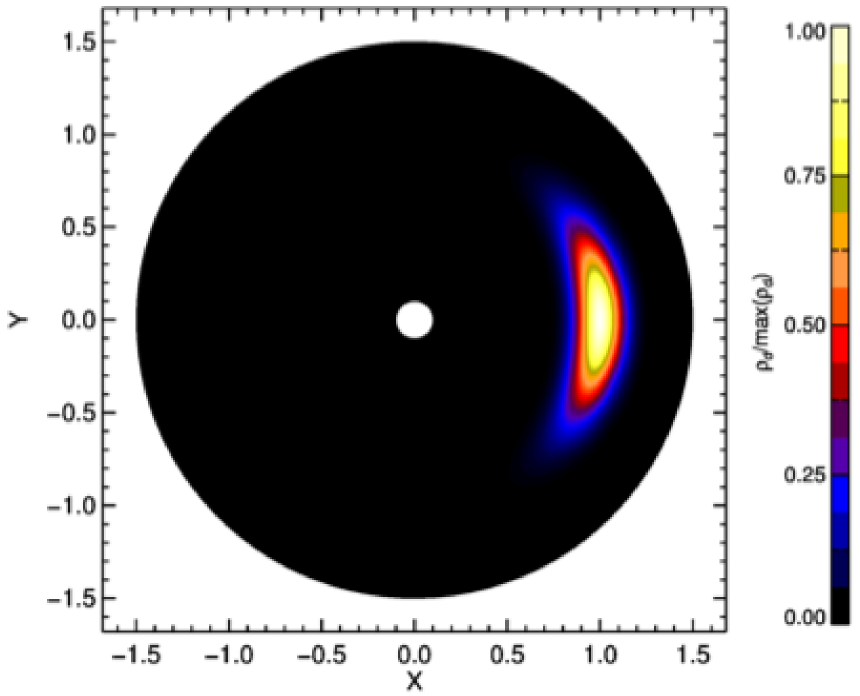
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

advection

compression

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

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

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

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

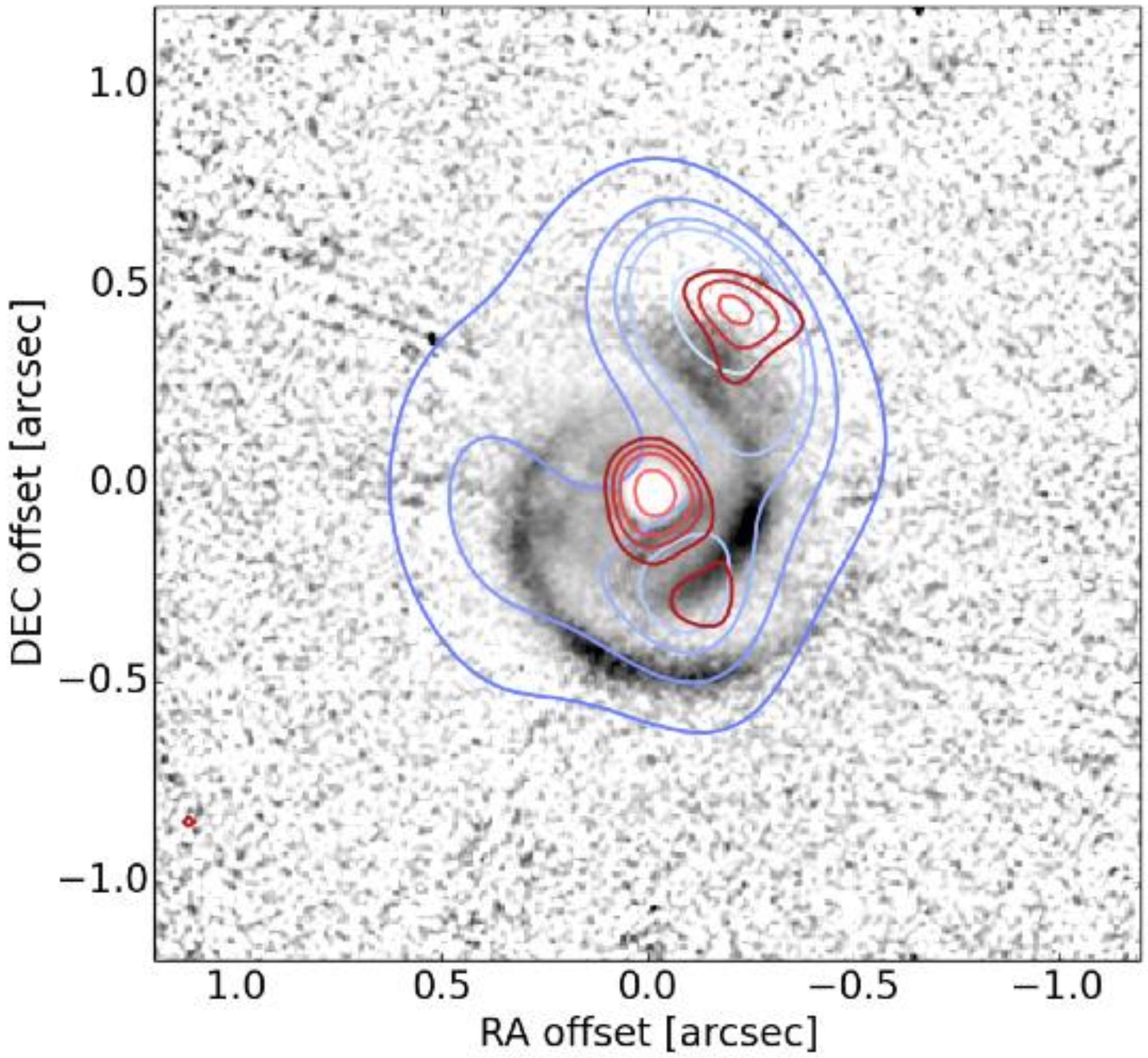
Disk Tomography

SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

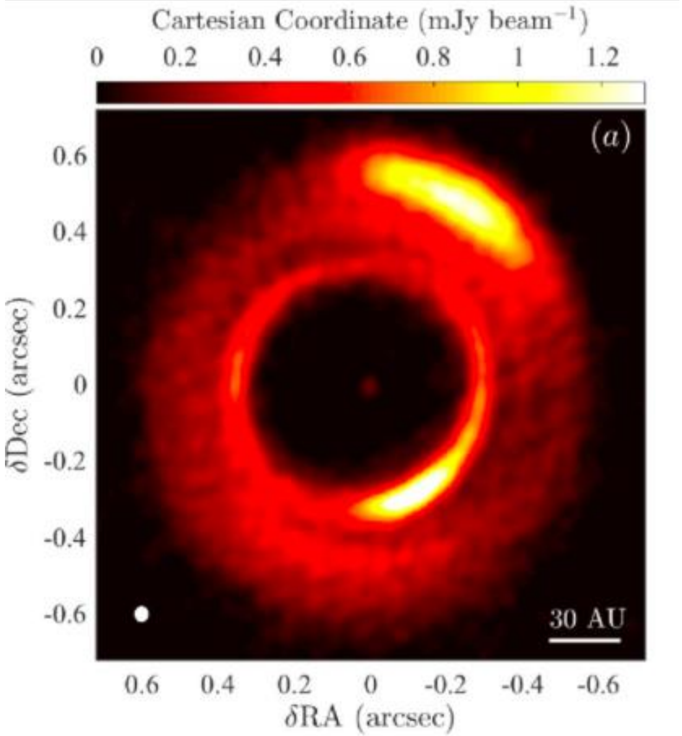
ALMA (~ mm)

VLA (cm-m)



Marino+Lyra '15

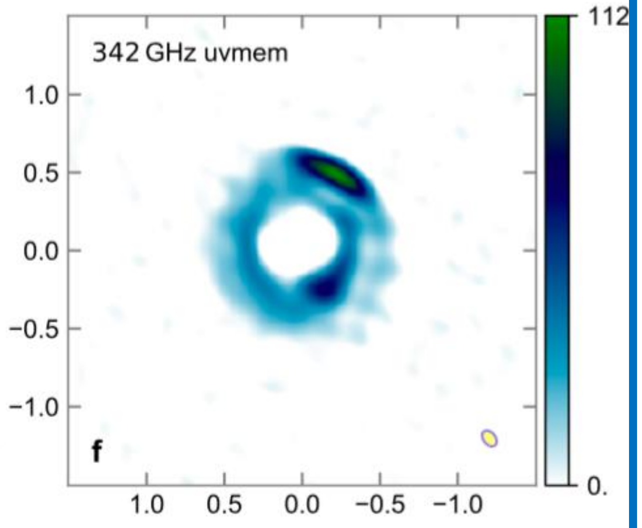
ALMA



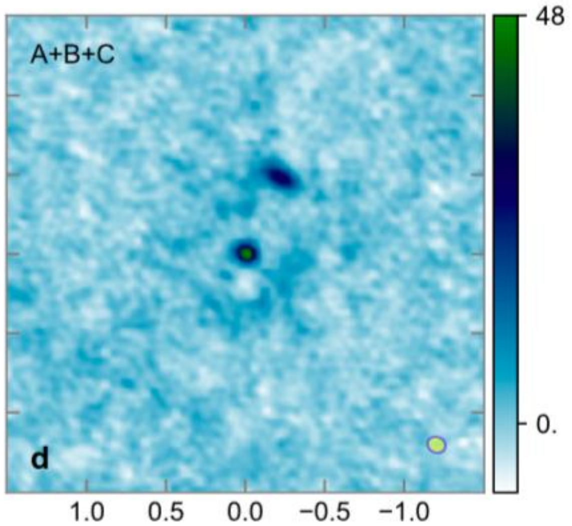
Dong+ '18

Pebble trapping

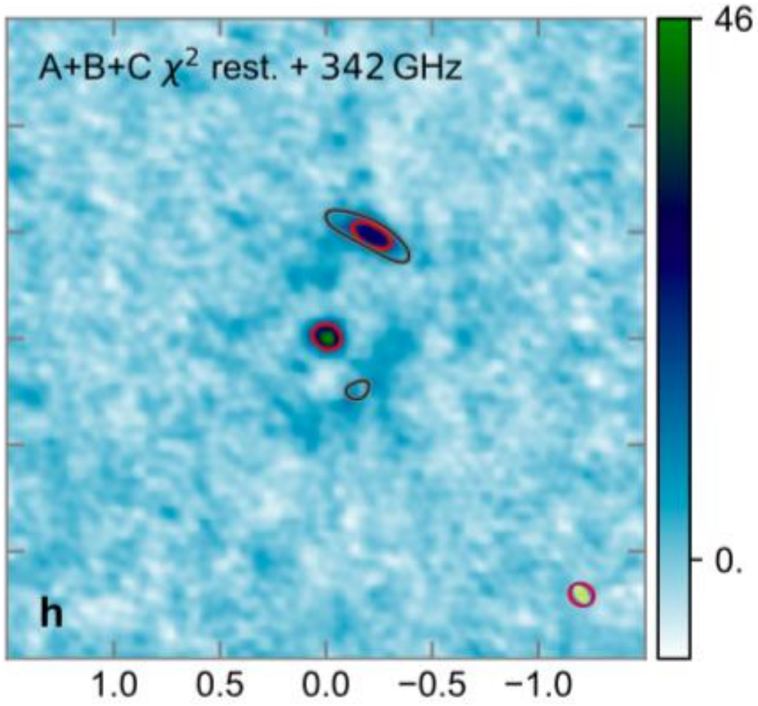
ALMA
(mm)



VLA
(cm-m)

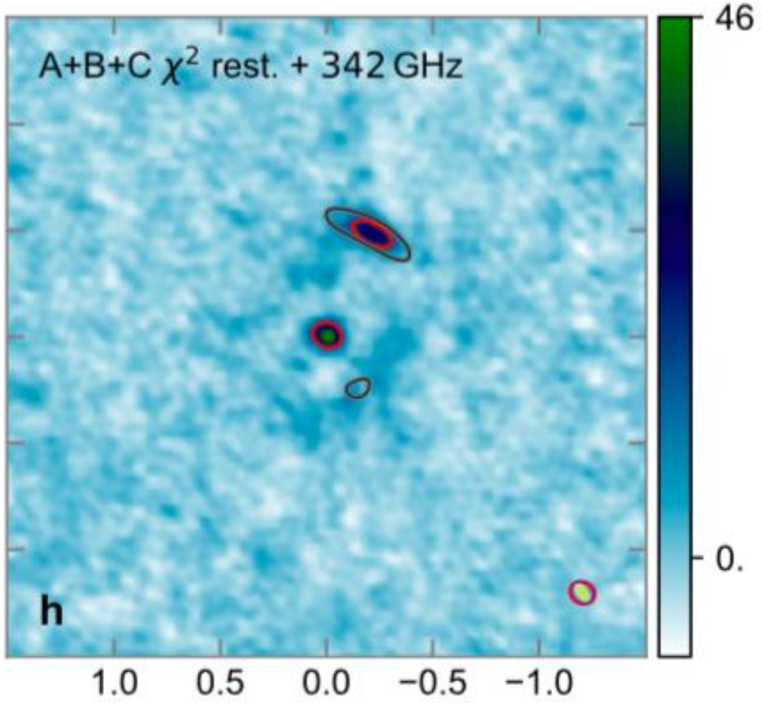


Overlay

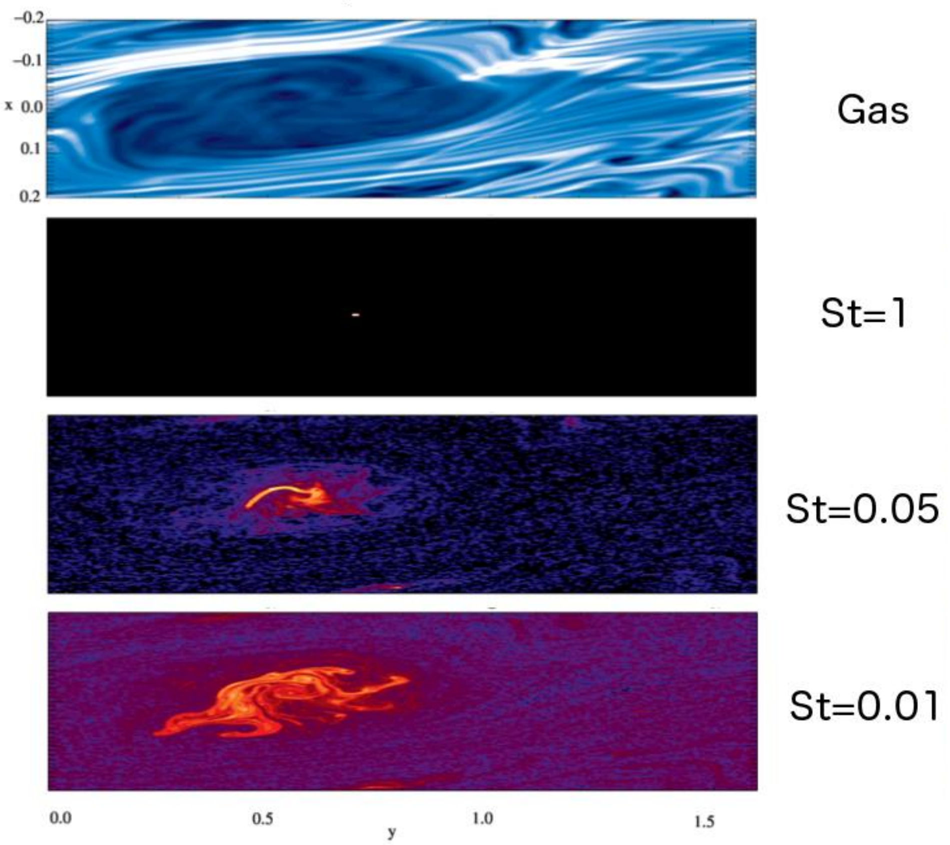


Casassus+Lyra '19

Model vs Observation



Casassus+Lyra '19



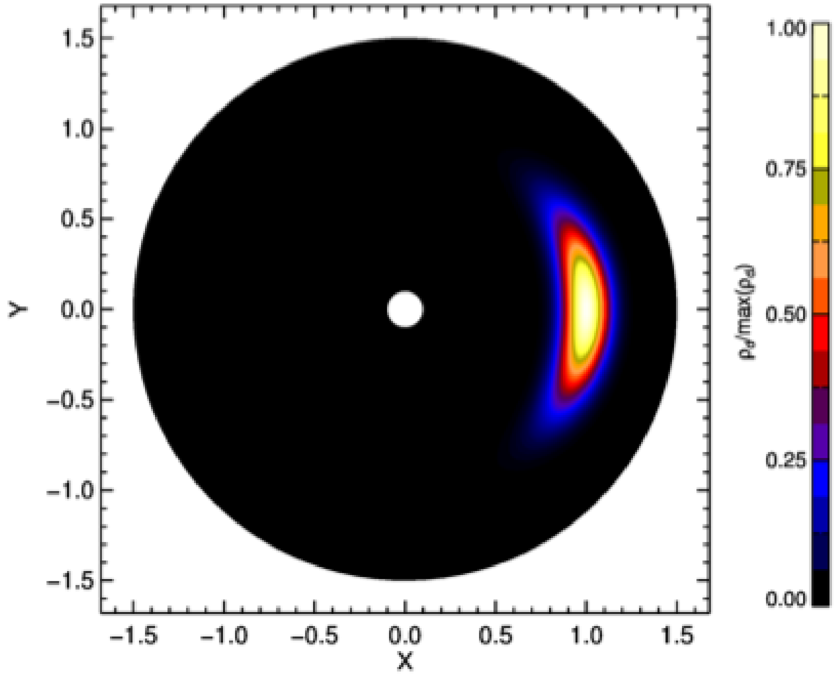
Raettig+Lyra '15

Take home message

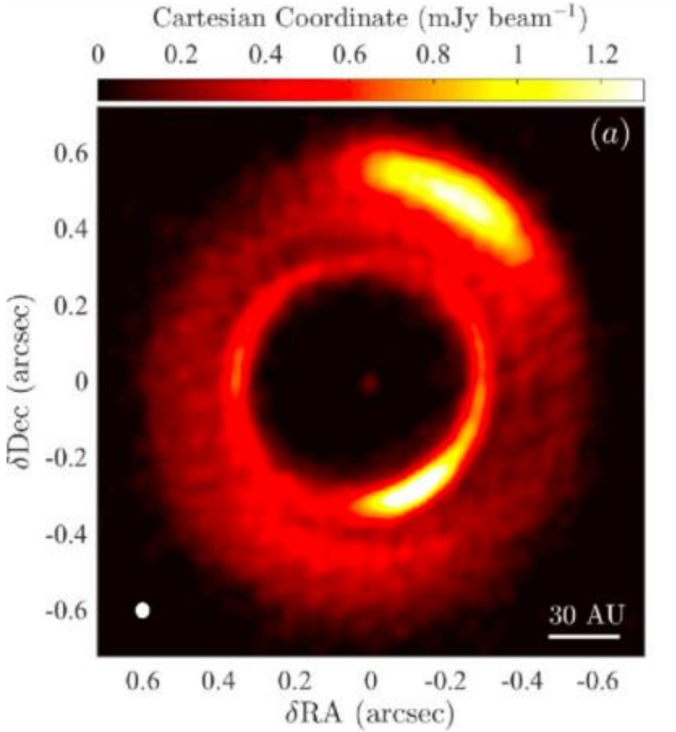
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations

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

Lyra-Lin solution



Observed Disk



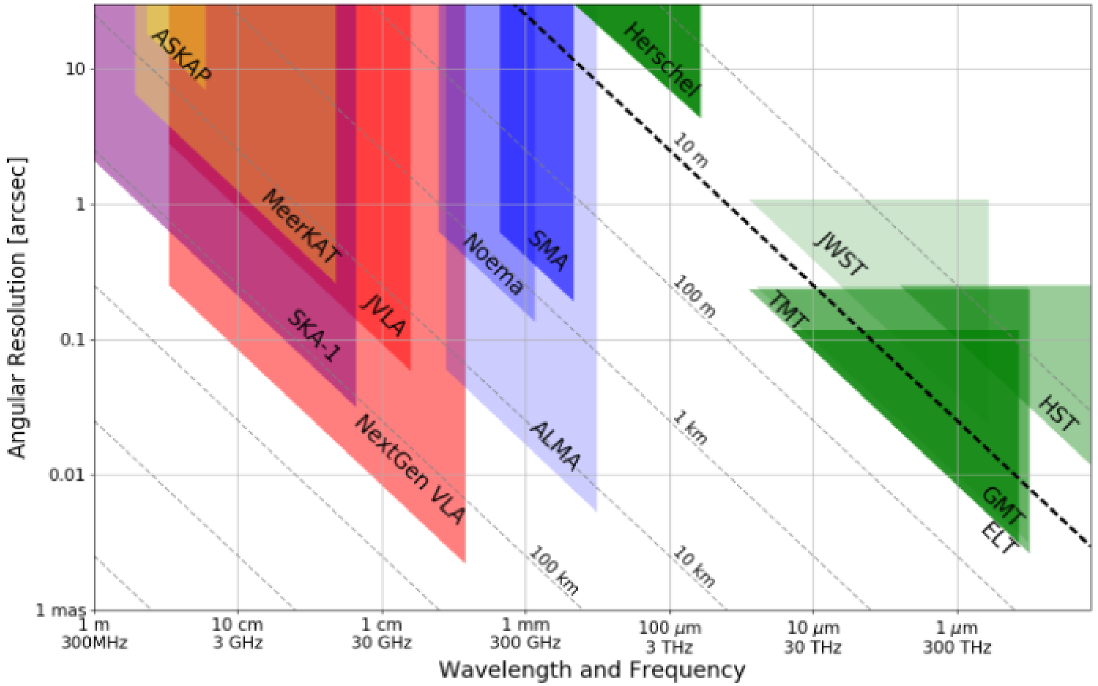
The future

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

ngVLArocks!

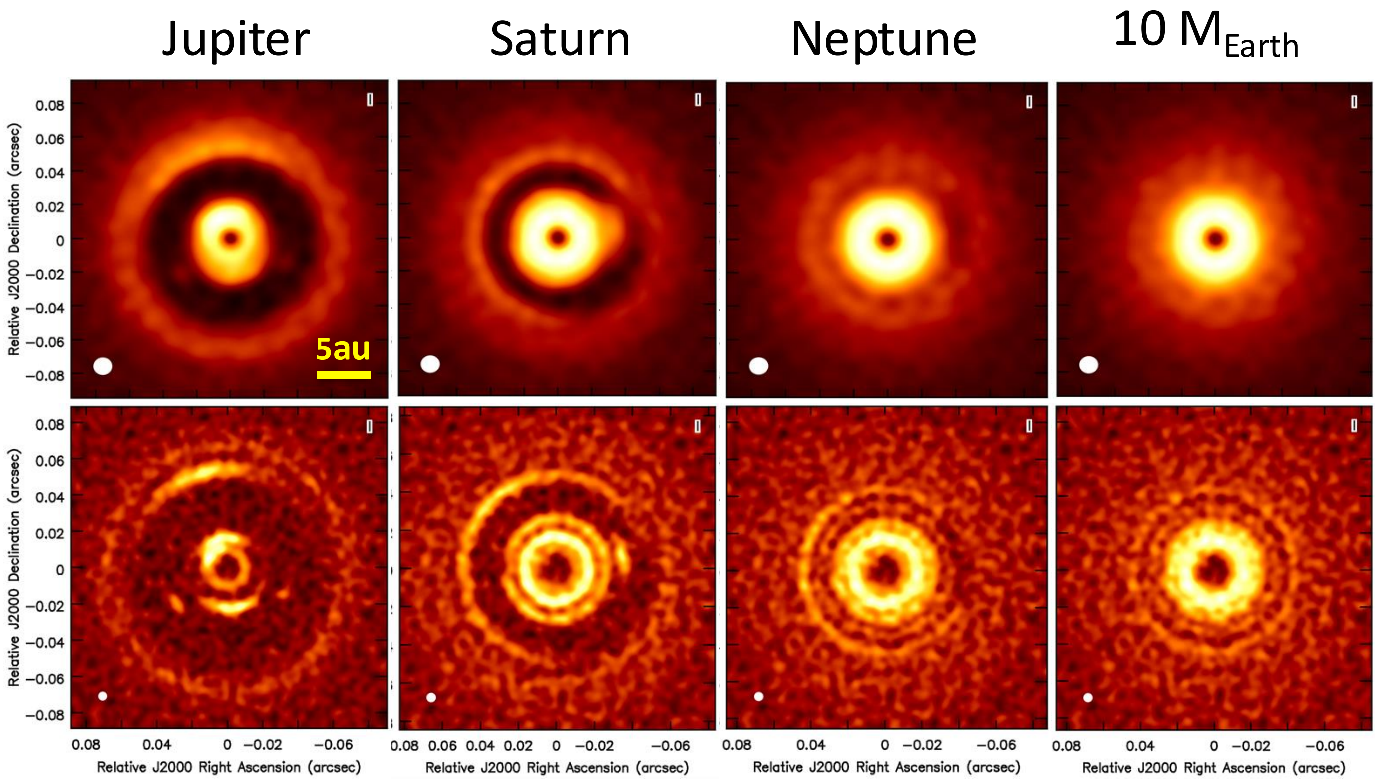

Angular Resolution [arcsec]
10
1
0.1
0.01
1 mas
1 m
300MHz
10 cm
3 GHz
1 cm
30 GHz
1 mm
300 GHz
100 μm
3 THz
10 μm
30 THz
1 μm
300 THz
Wavelength and Frequency
ASKAP
MeerKAT
SKA-1
JVLA
NextGen VLA
Noema
SMA
ALMA
Herschel
JWST
TMT
HST
GMT
ELT
10 m
100 m
1 km
10 km
100 km

Planets at 5AU

ALMA @ 0.87mm

ngVLA @ 3mm

5 mas = 0.7 AU
rms = 5x10^{-7} Jy/beam

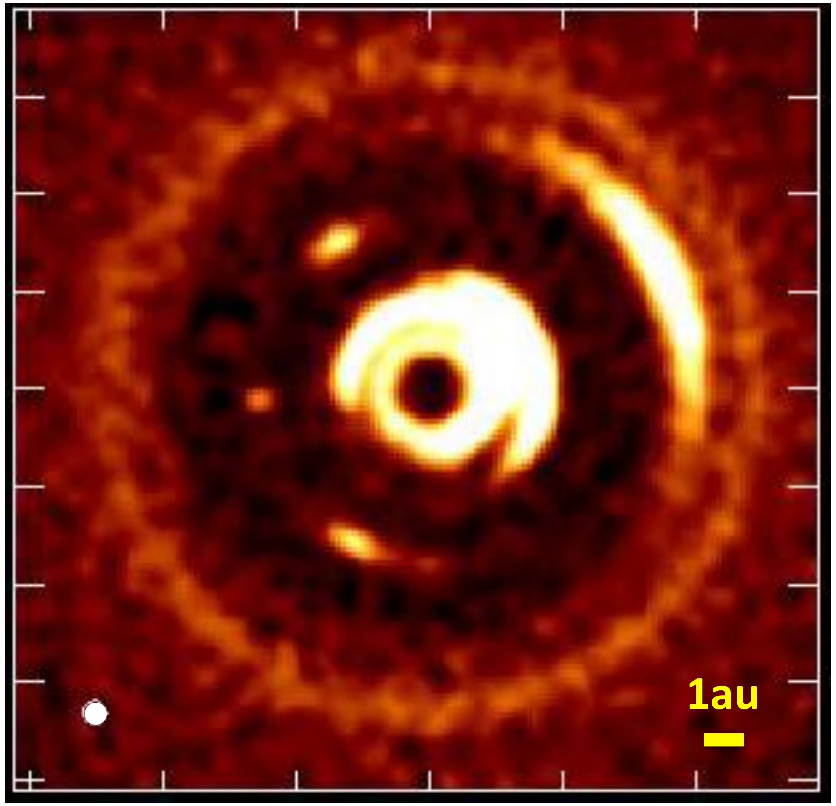


Ricci et al. 2018

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

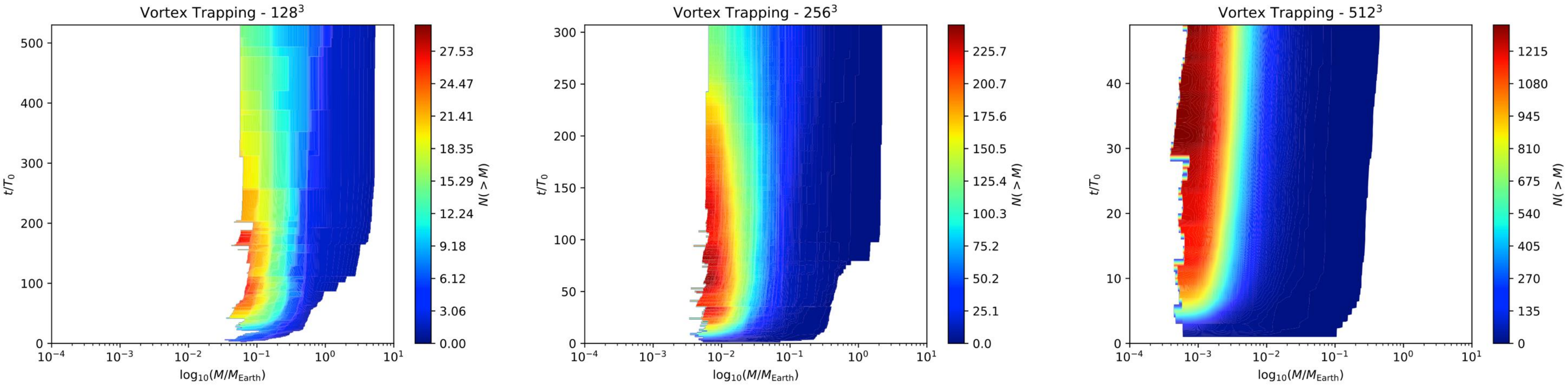
  - Dust trapped in drag-diffusion equilibrium explains the observations

ngVLArocks!

- **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



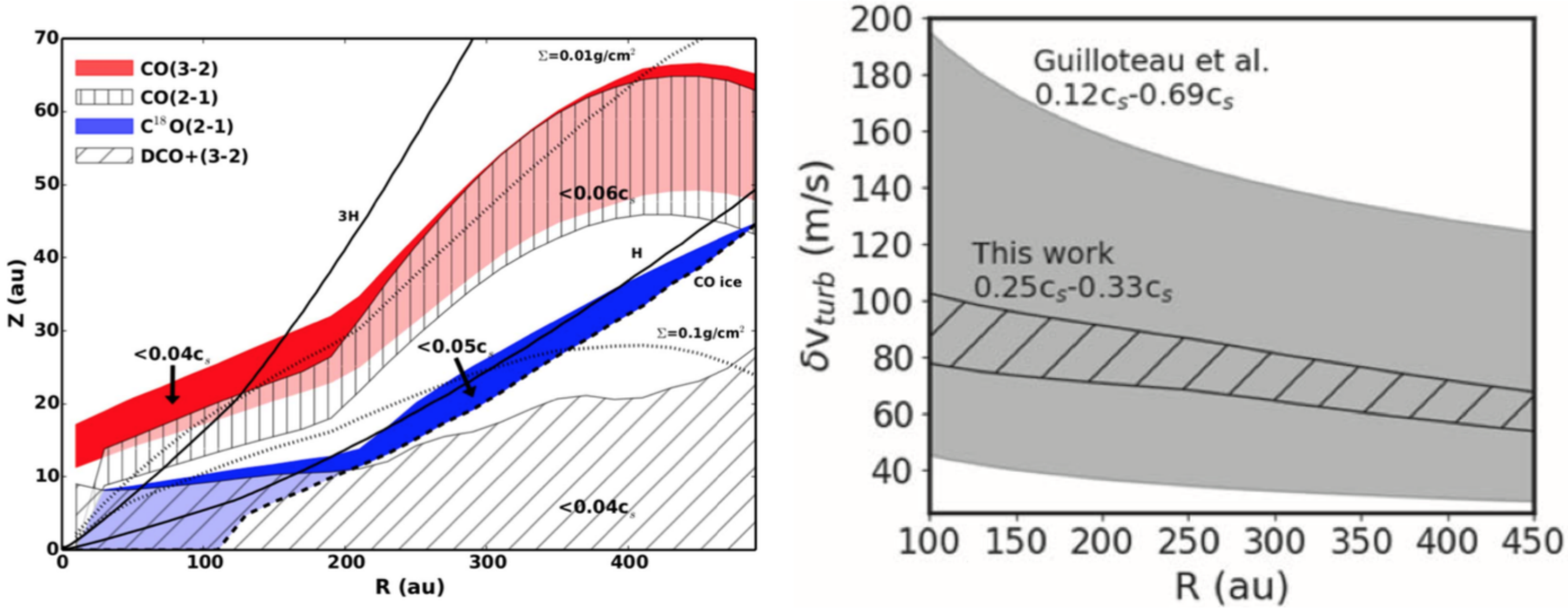
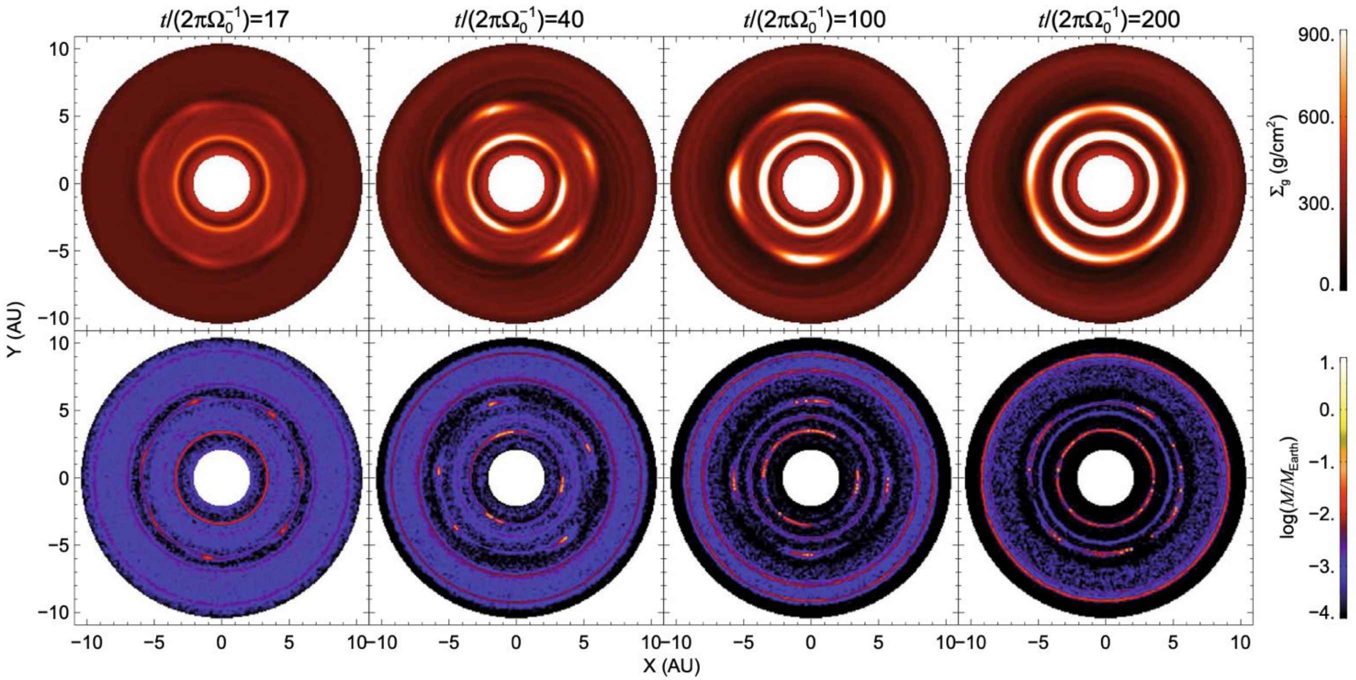
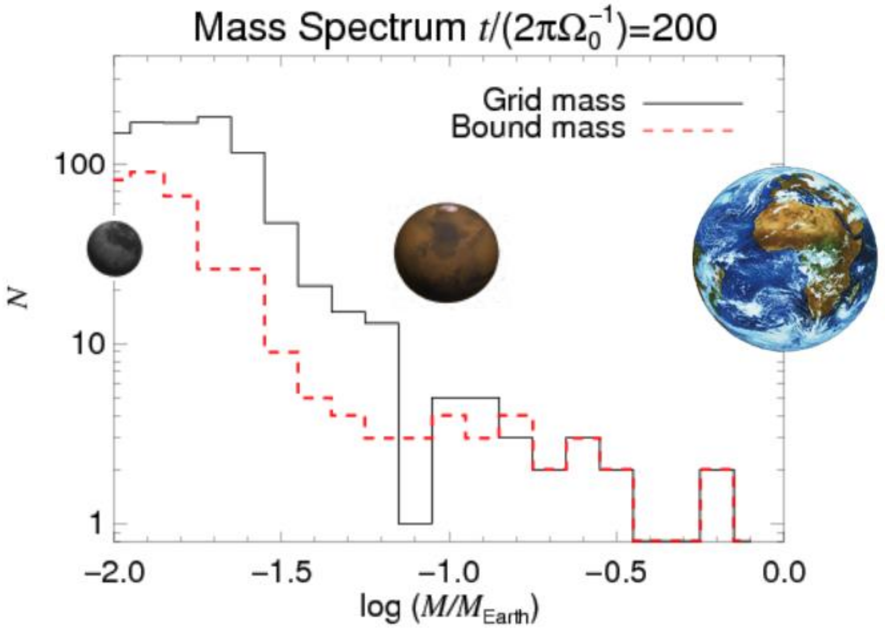


Fig. 7.— *Left:* Upper limits to turbulent velocities in HD 163296 as a function of radius R and mid-plane height z. The colors denote the species from which there is a majority of emission; the CO transitions are at large z whereas $C^{18}O$ and DCO+ are from lower in the disk. Also included on the 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).

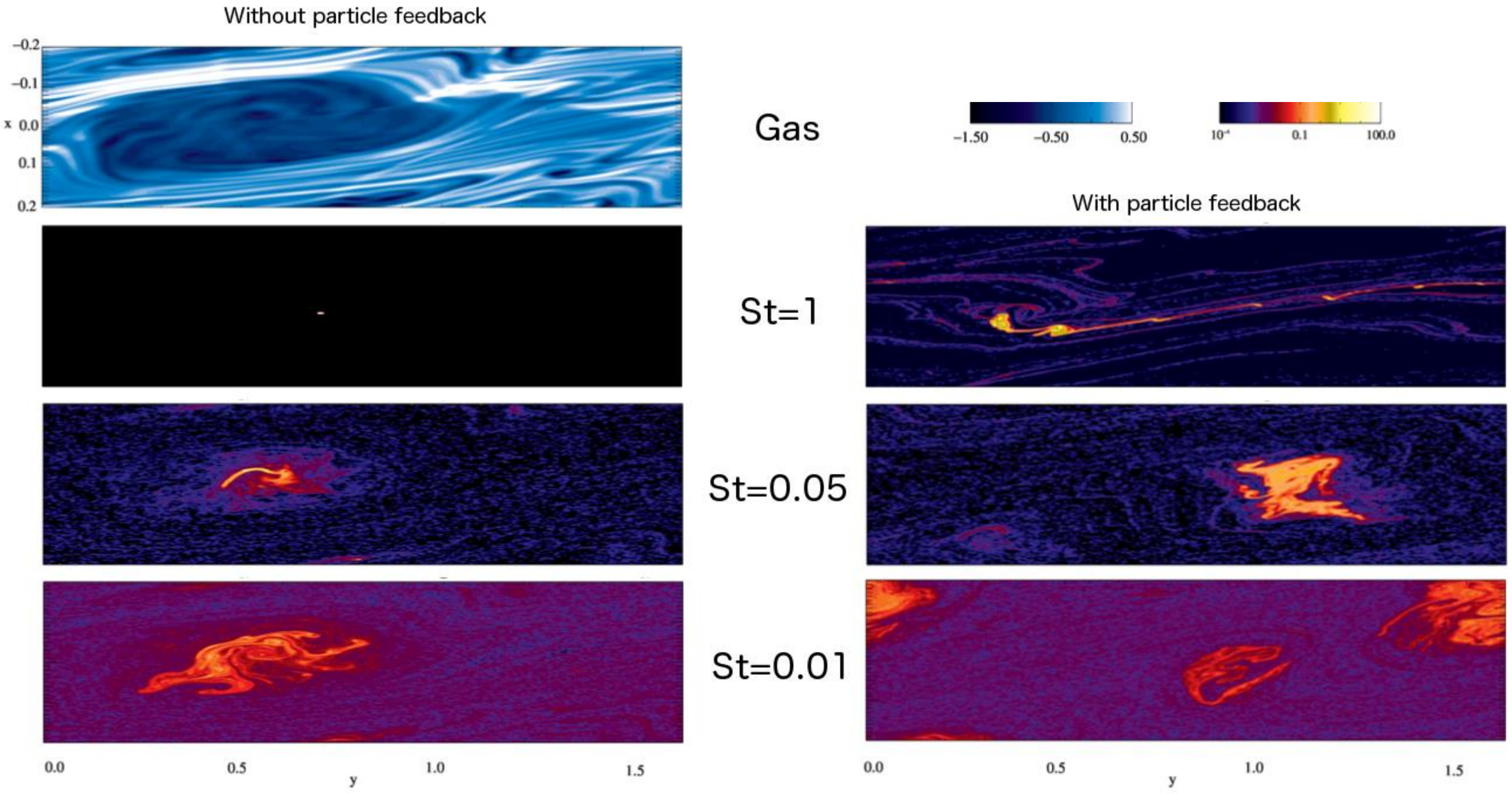
Vortices and Planet Formation





Lyra et al. (2008)

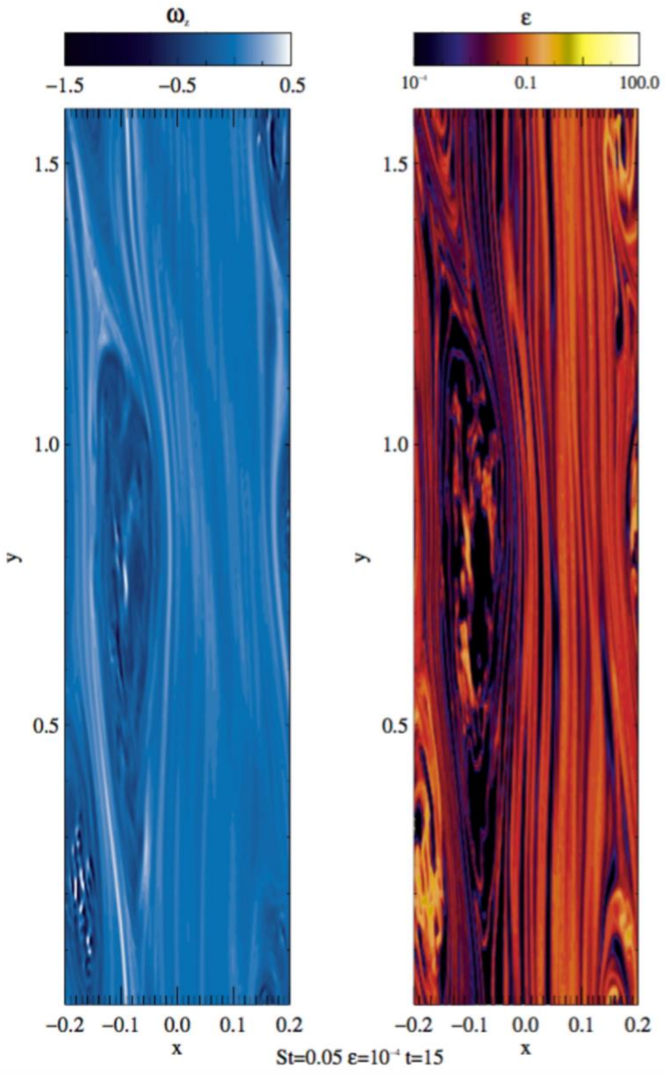
Pebble trapping in vortices in LOCAL models



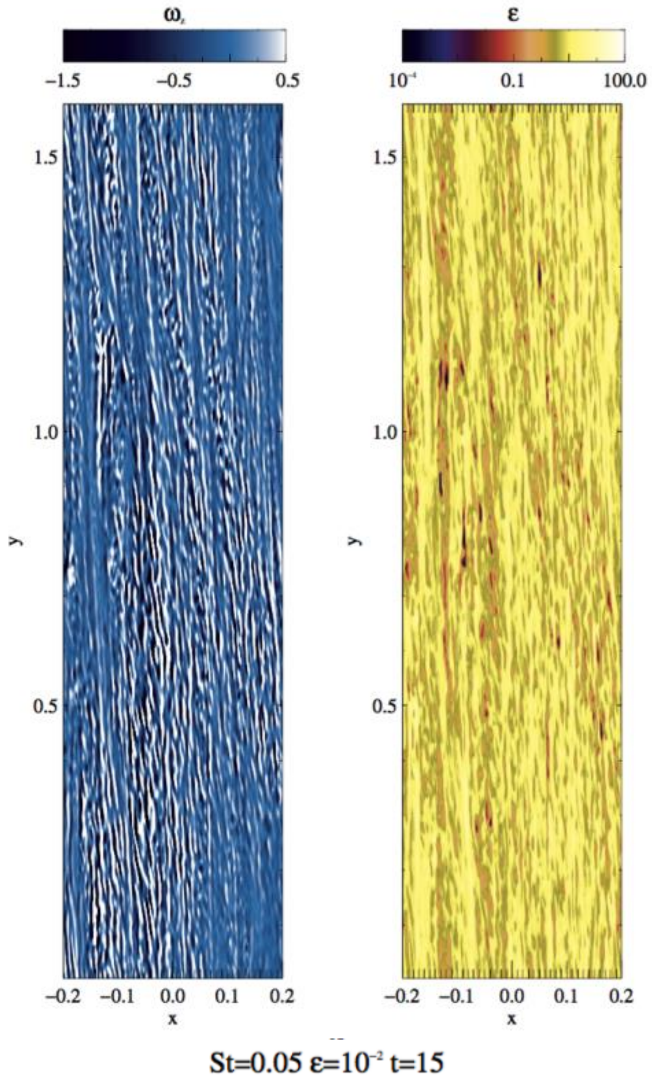
Raettig et al (2015)

Vortex destruction at high dust load?

Dust to gas ratio 10^{-4}

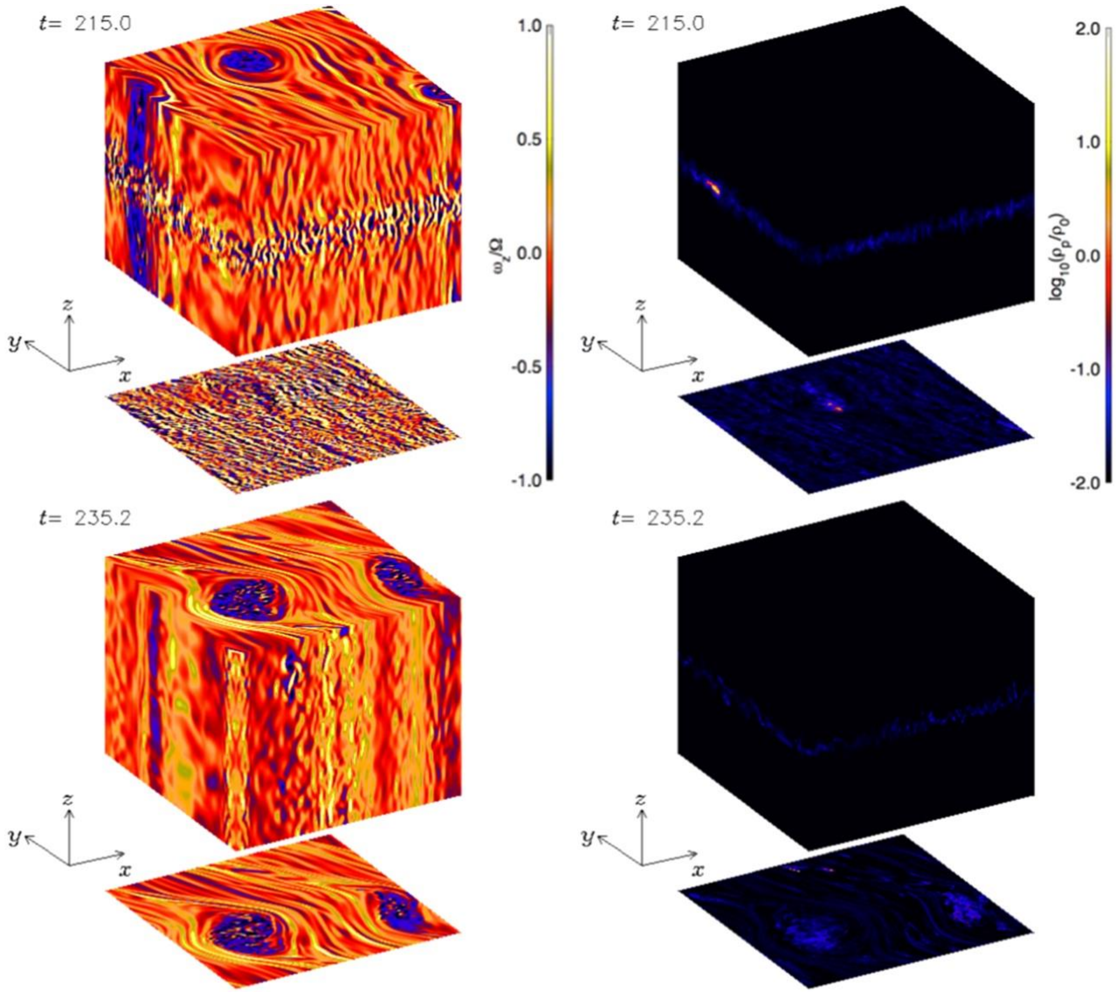


Dust to gas ratio 10^{-2}



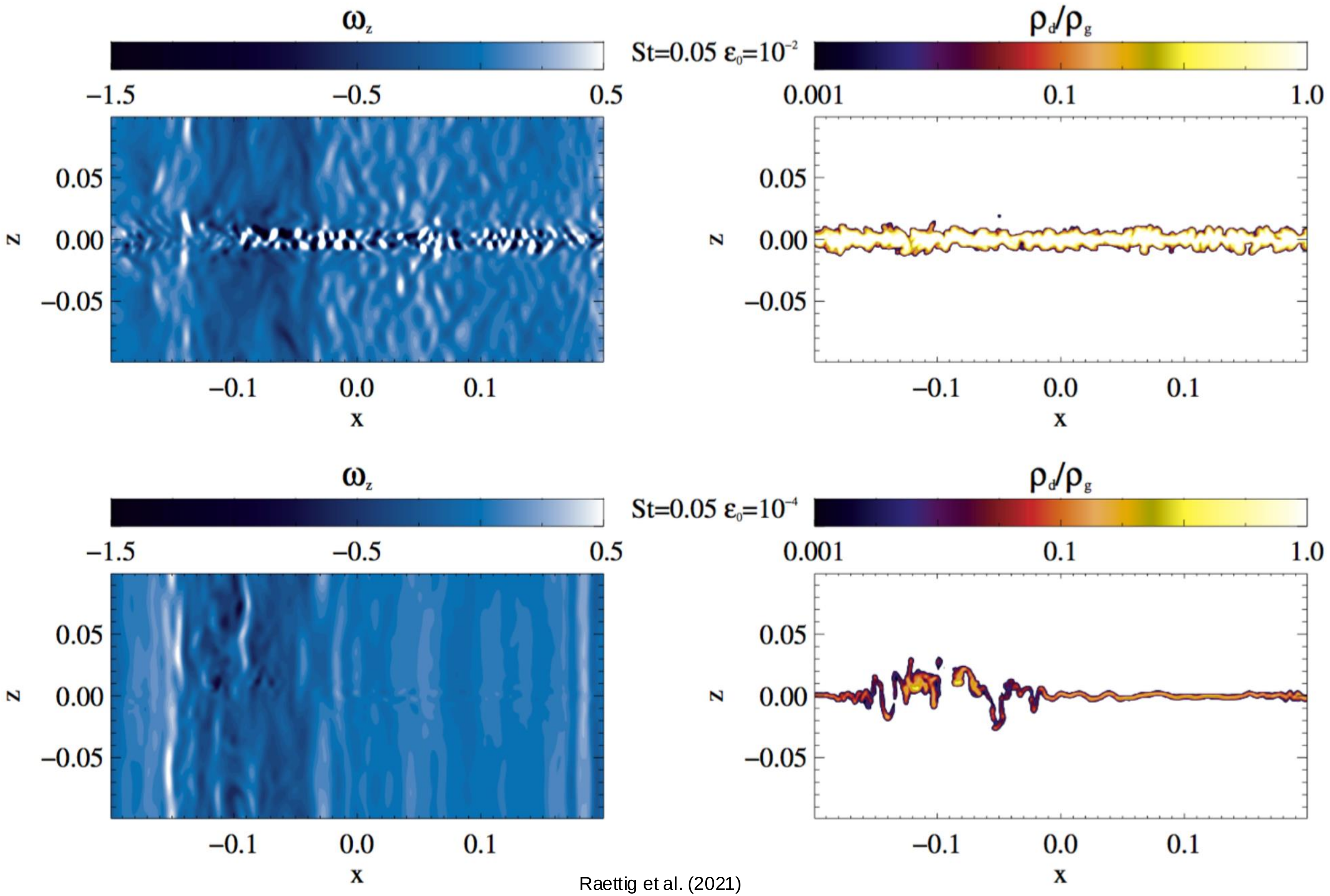
Raettig et al (2015)

Pebble trapping does not destroy vortices



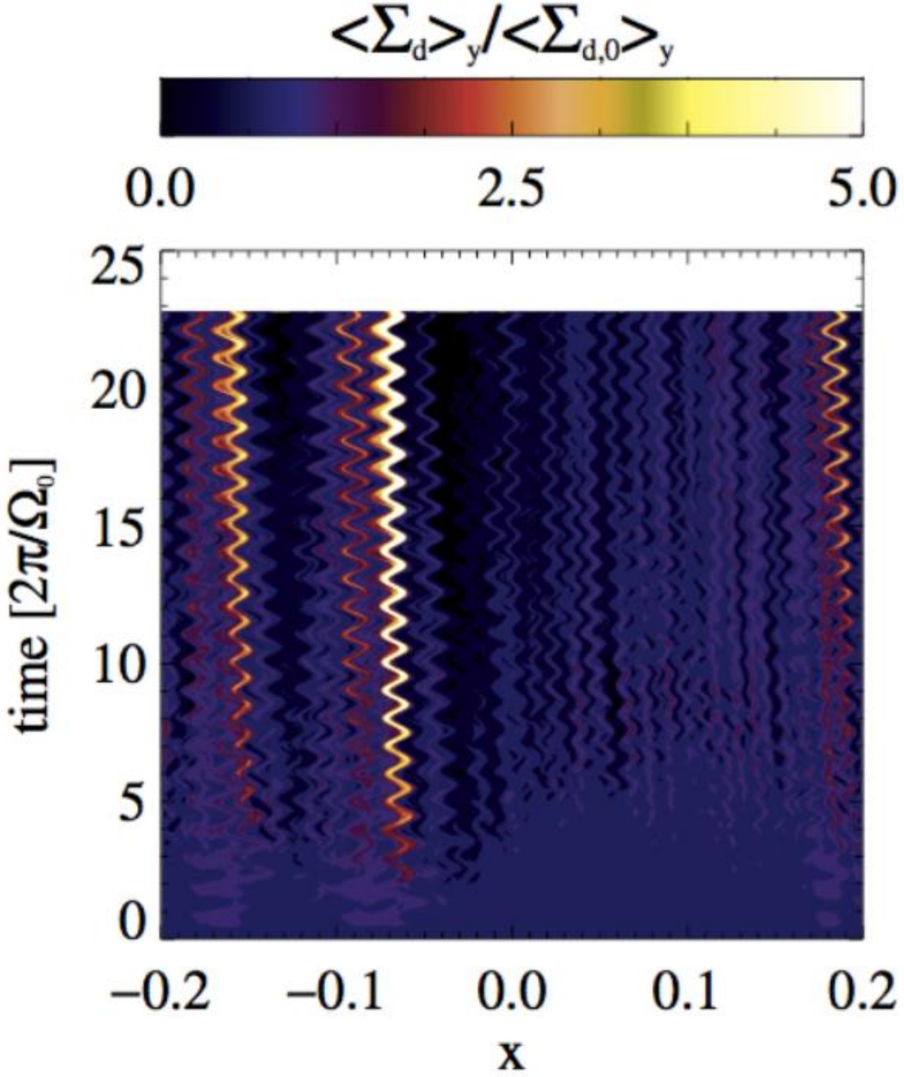
Lyra et al. (2018)

Vortex column disrupted only around the midplane



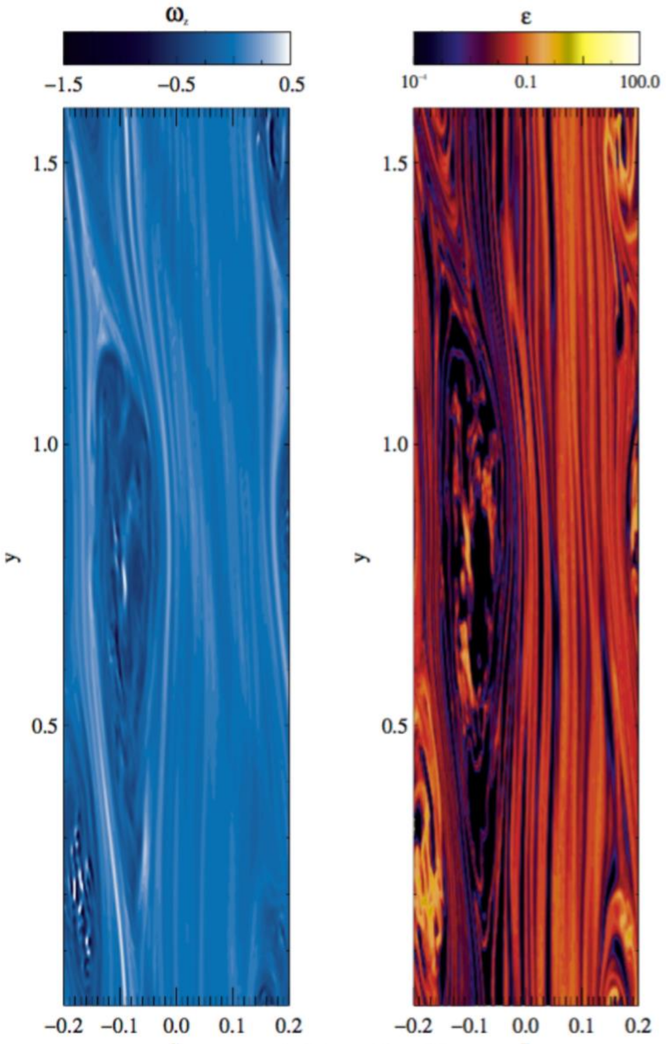
Raettig et al. (2021)

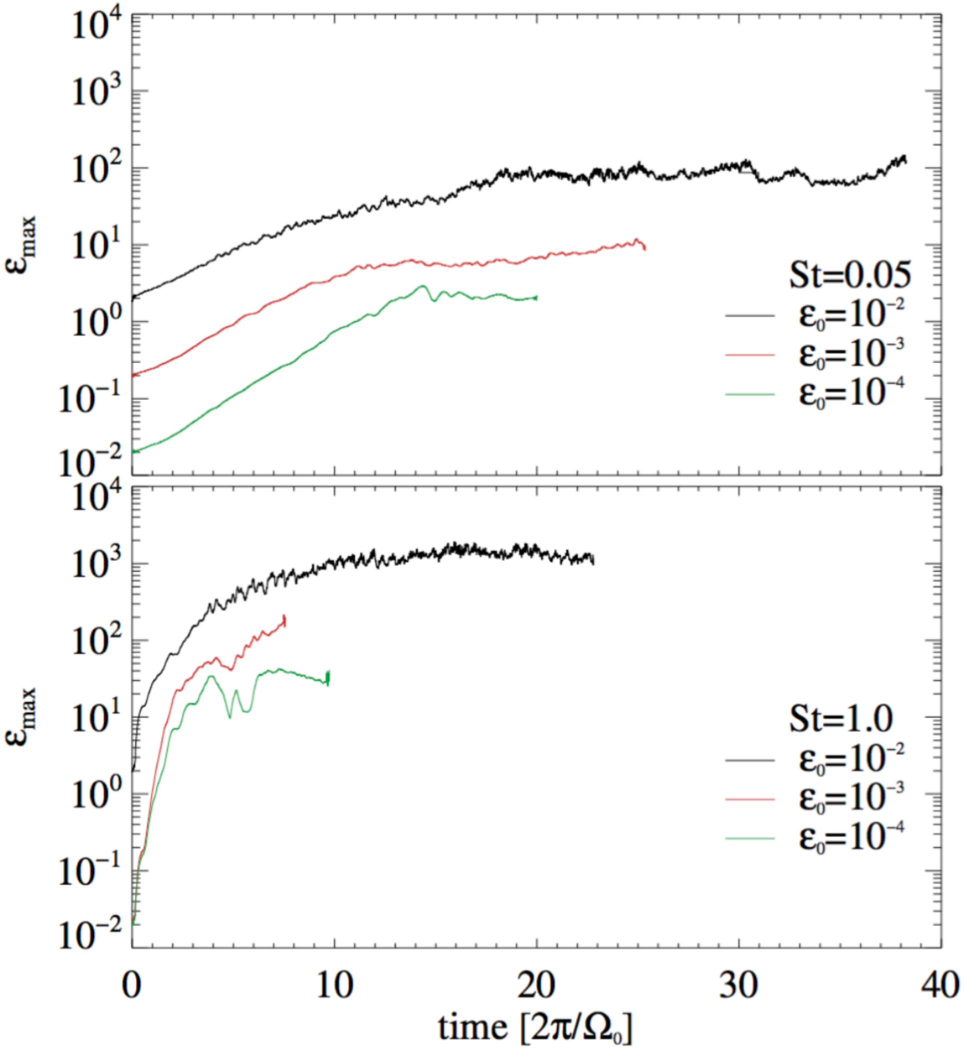
Pebble drift: follows vortex



Raettig et al. (2021)

Pebble trapping in 3D vortices

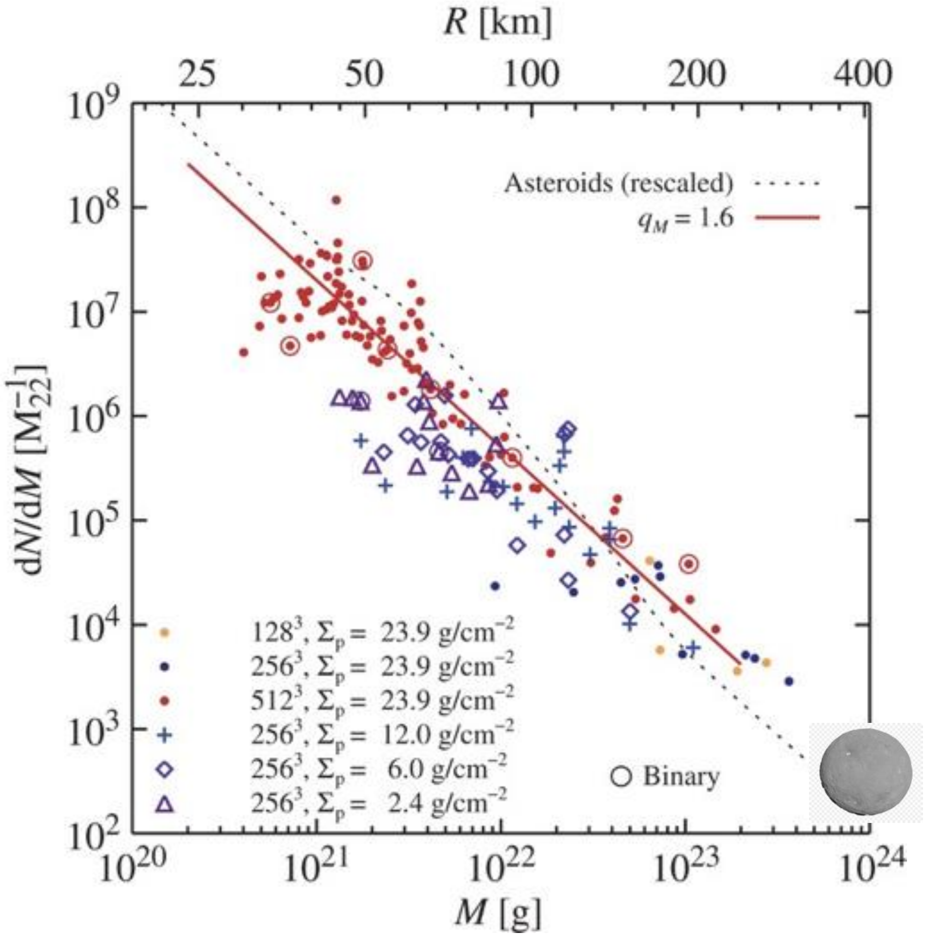


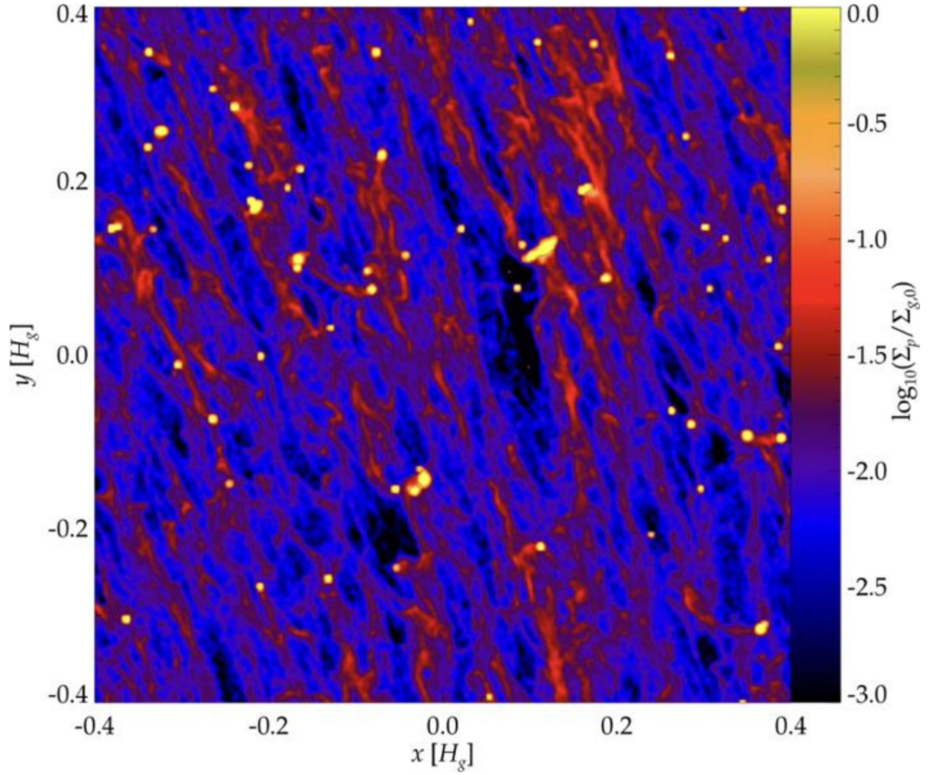


Raettig et al. (2021)

How can we verify the streaming instability hypothesis?

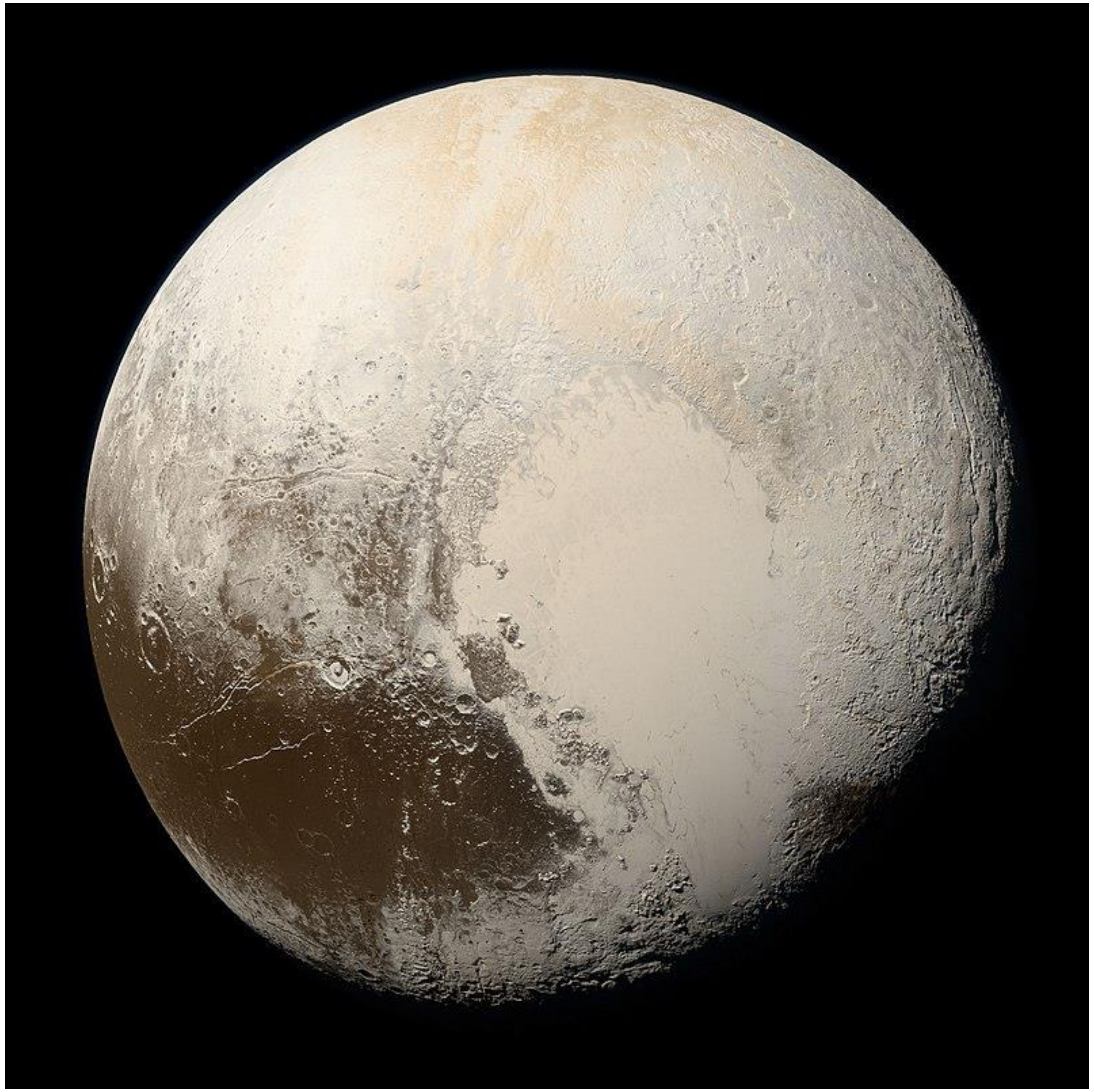
Planetesimal Formation

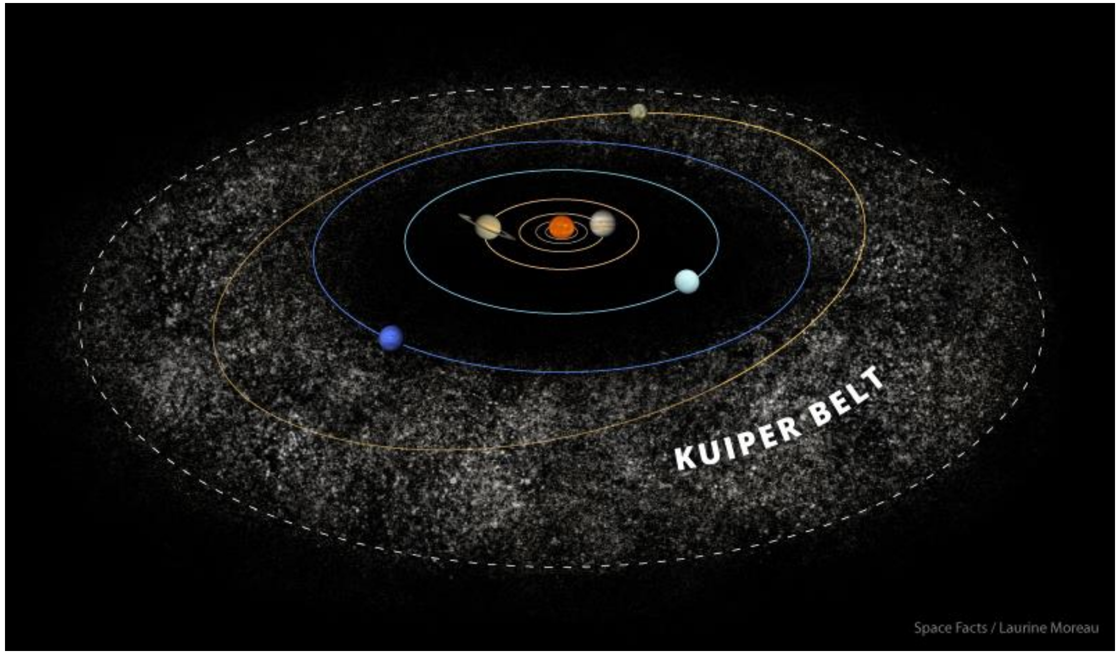




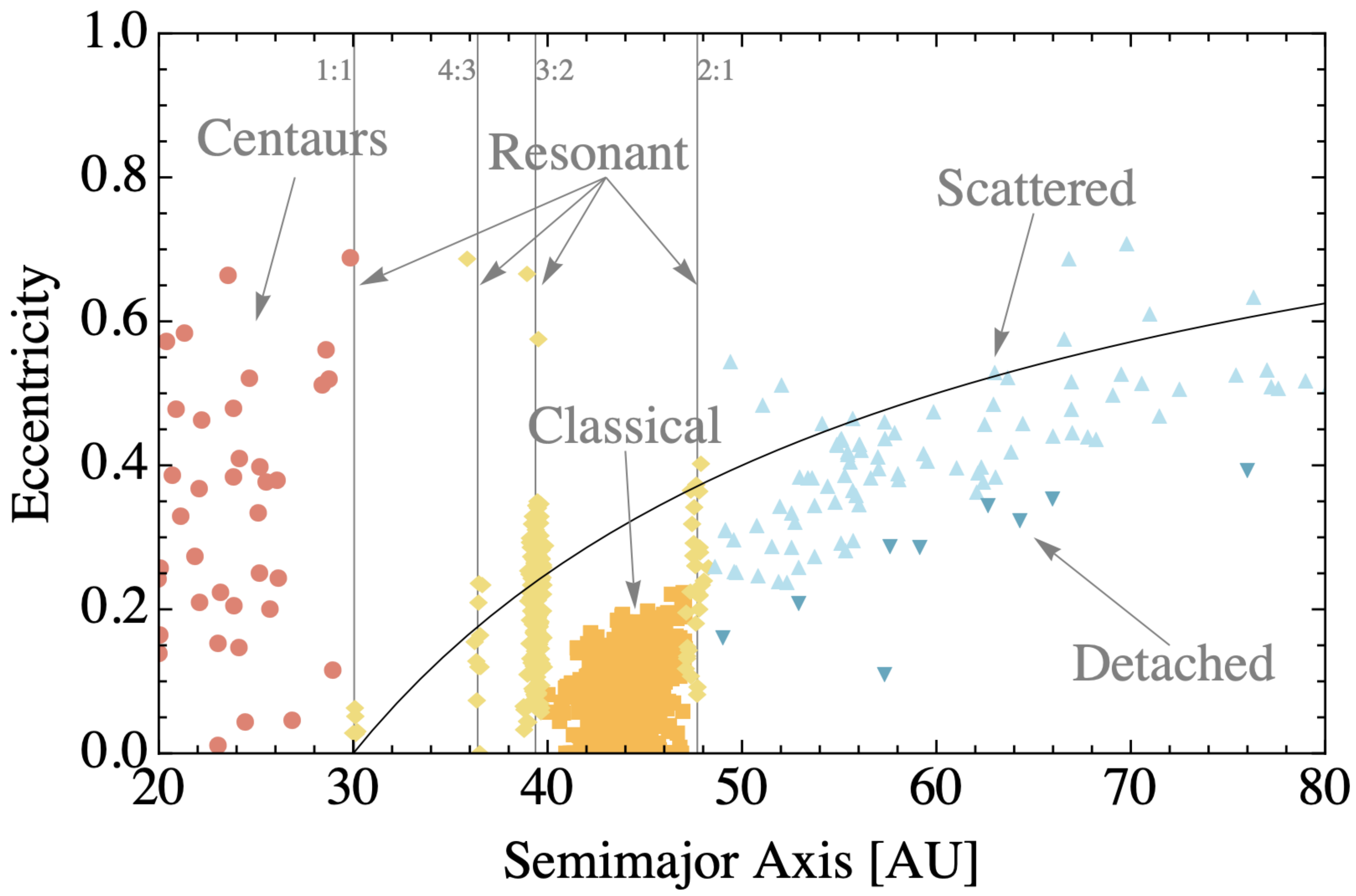
Initial mass function consistent with mass distribution of asteroid belt. Slope 1.6

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



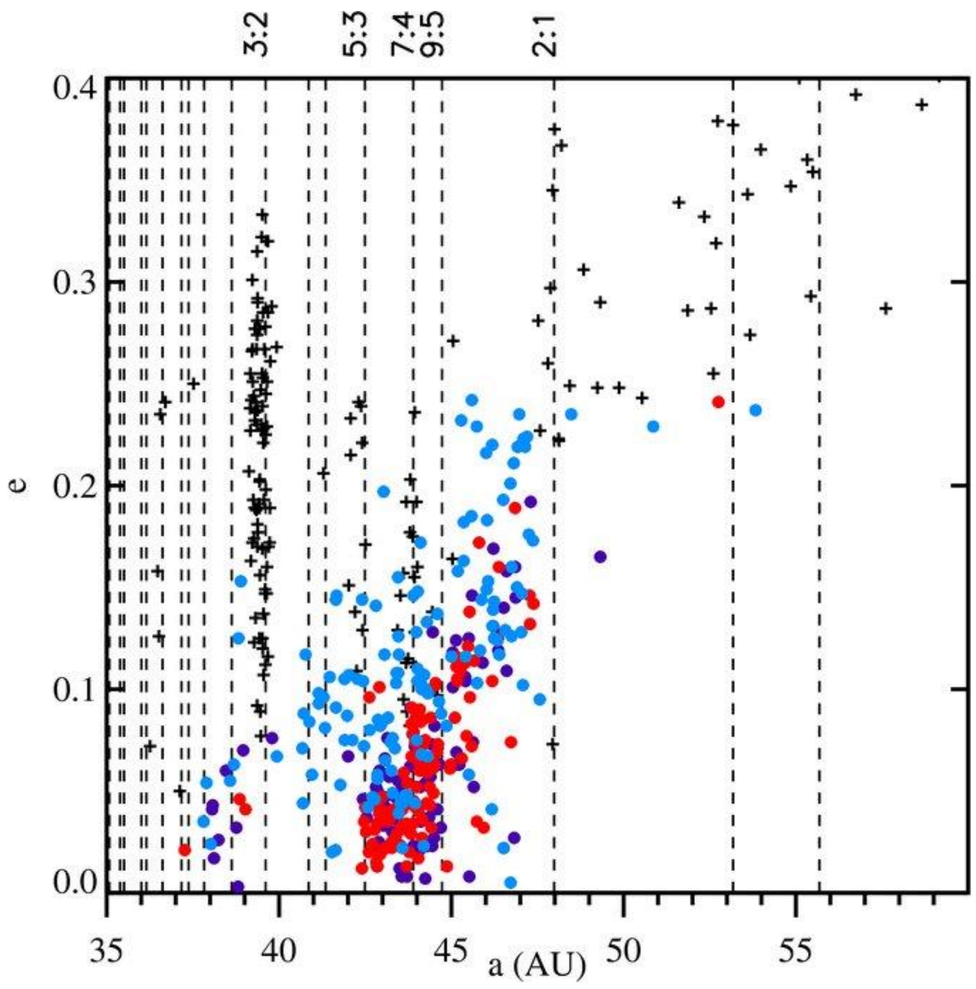

KUIPER BELT
Space Facts / Laurine Moreau

Structure of the Kuiper Belt



Gladman+ ‘08, Lacerda ‘09, Batygin+ ’10, Dawson & Murray-Clay ‘12

Structure of the Kuiper Belt



+ Resonant and Scattered

Cold Classical *i*<2°

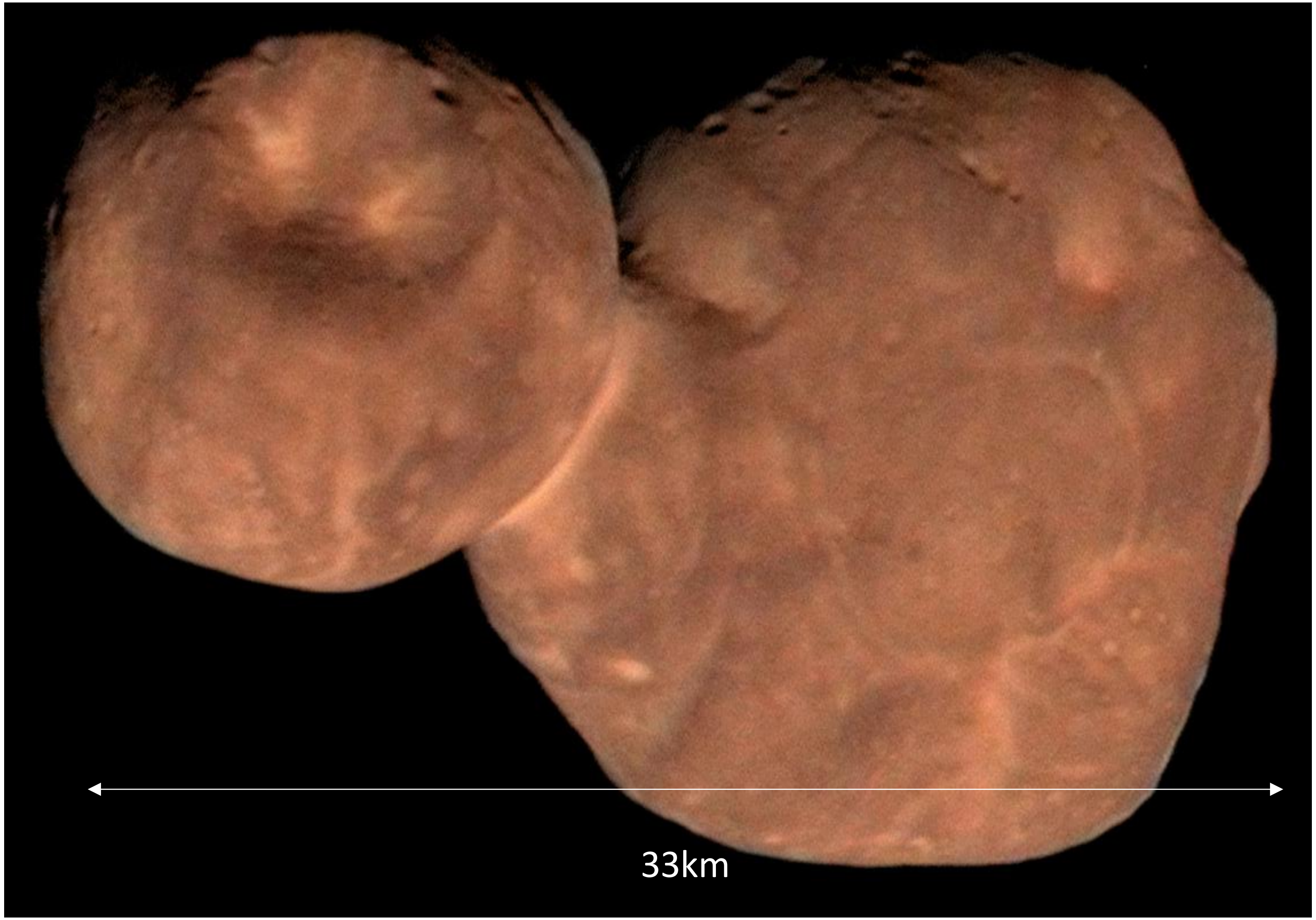
"Ambiguous" 2°<*i*<6°

Hot Classicals i>6°

Cold Classicals: Presumably pristine planetesimals

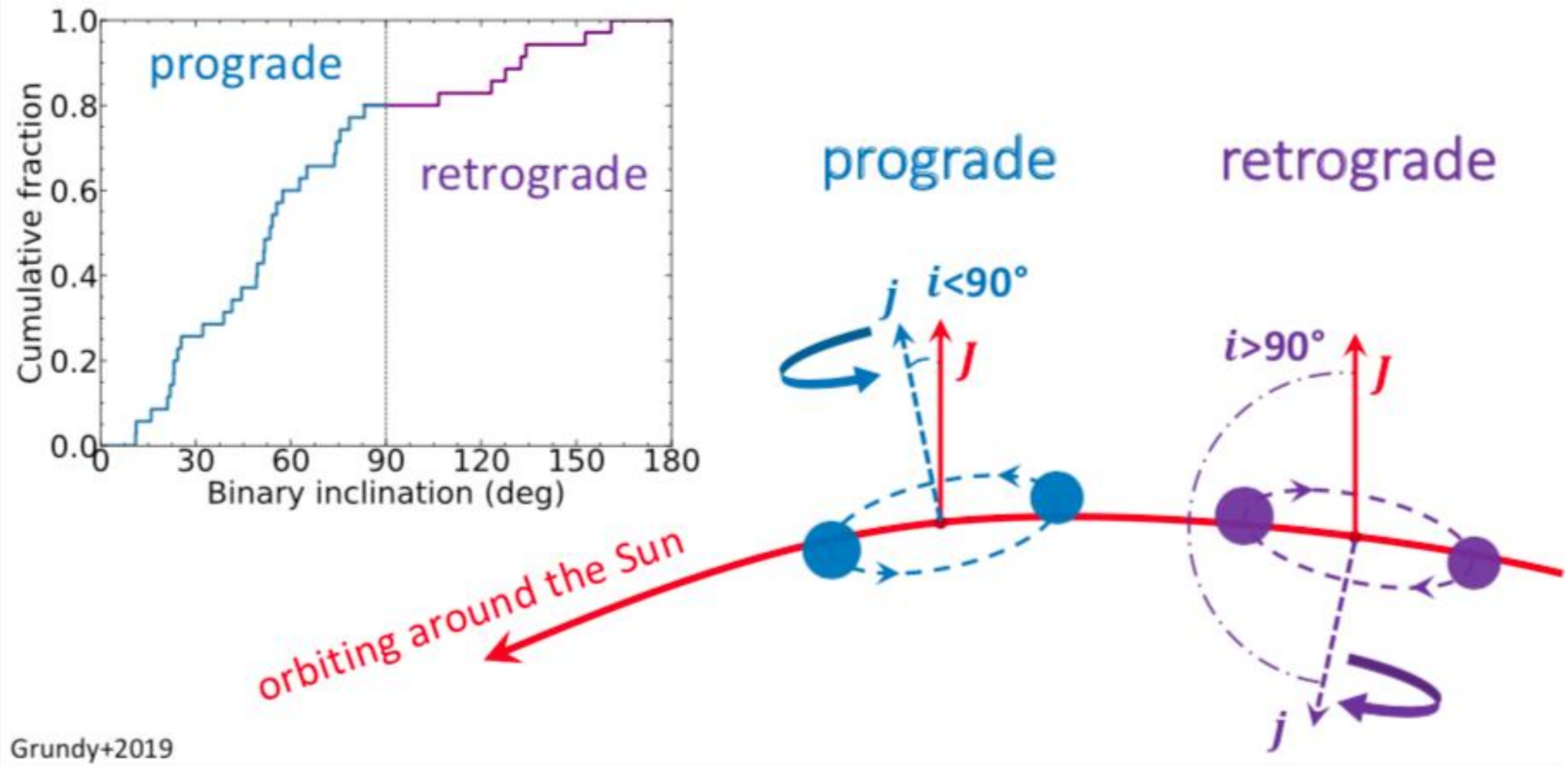
Gladman+ '08, Lacerda '09, Batygin+ '10, Dawson & Murray-Clay '12

Arrokoth (MU_{69})

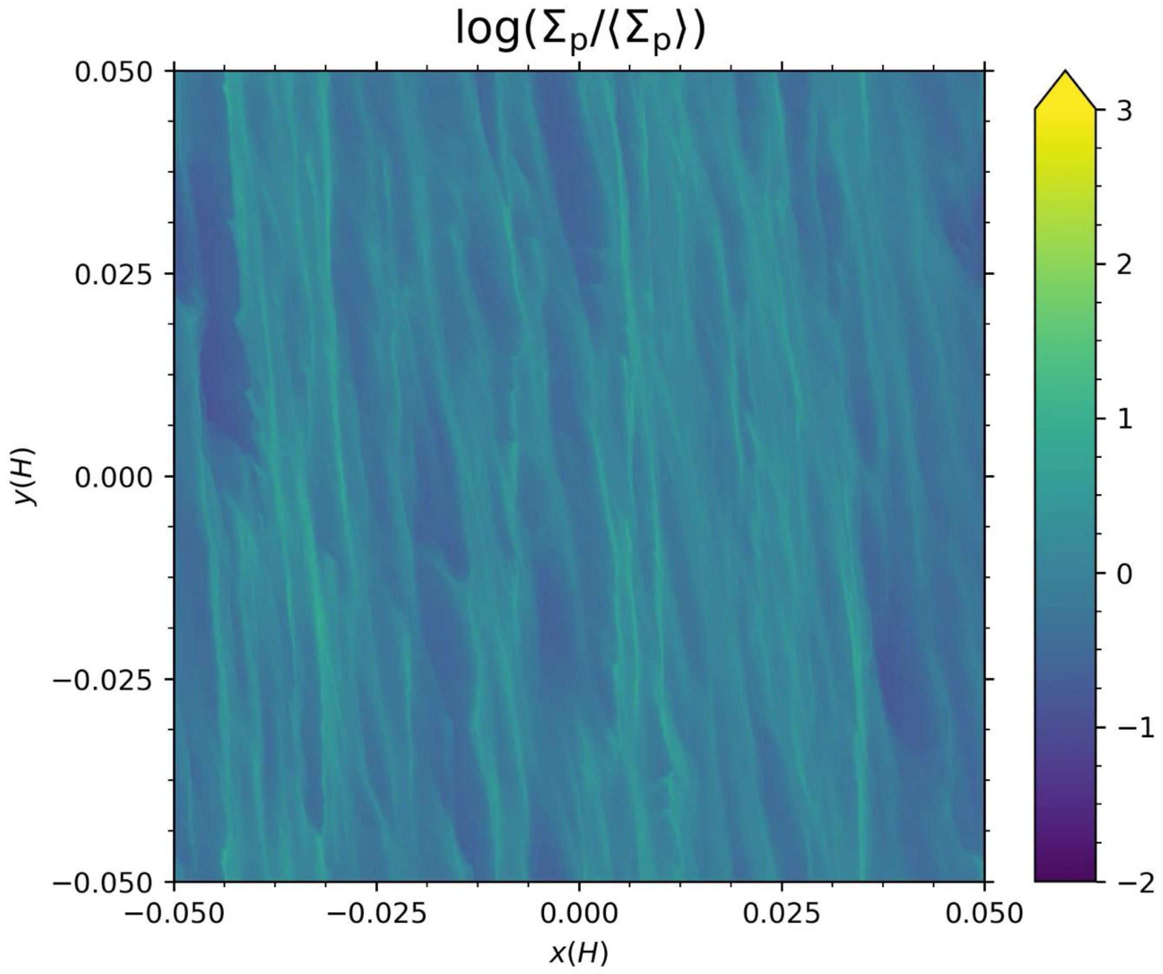


New Horizons Flyby, Jan 2019

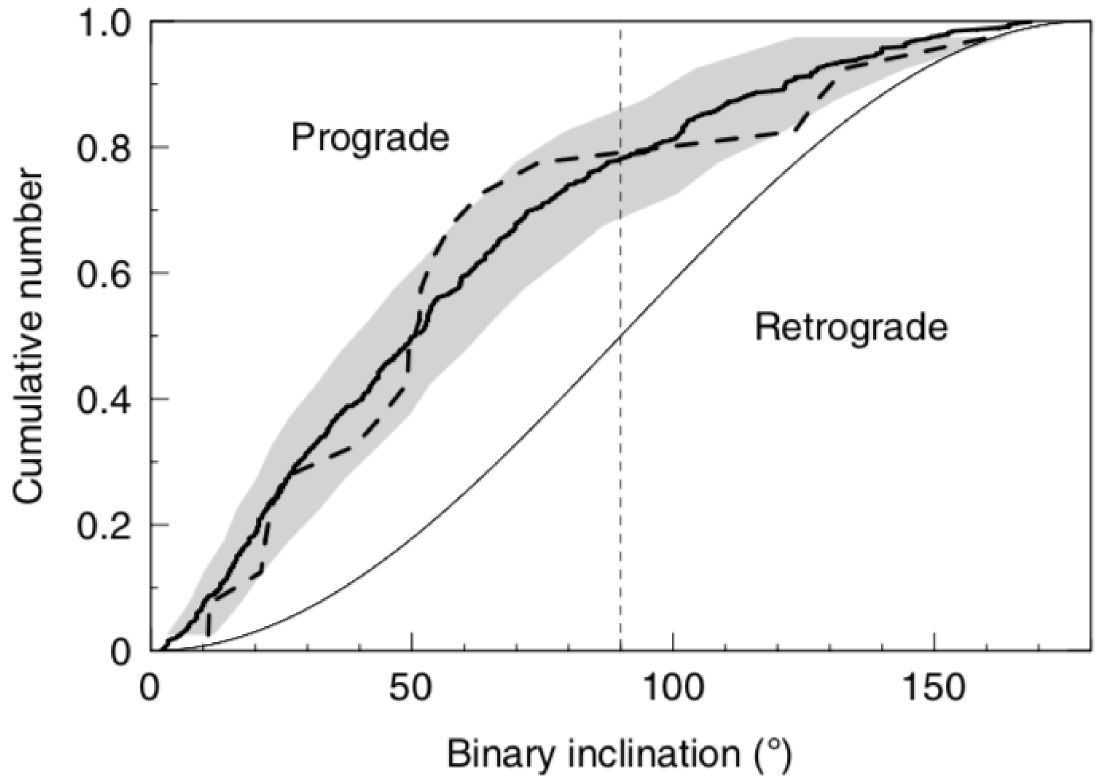
Cold Classical KBOs: Preference for Prograde



Counting binaries: Preference for Prograde (~80%)



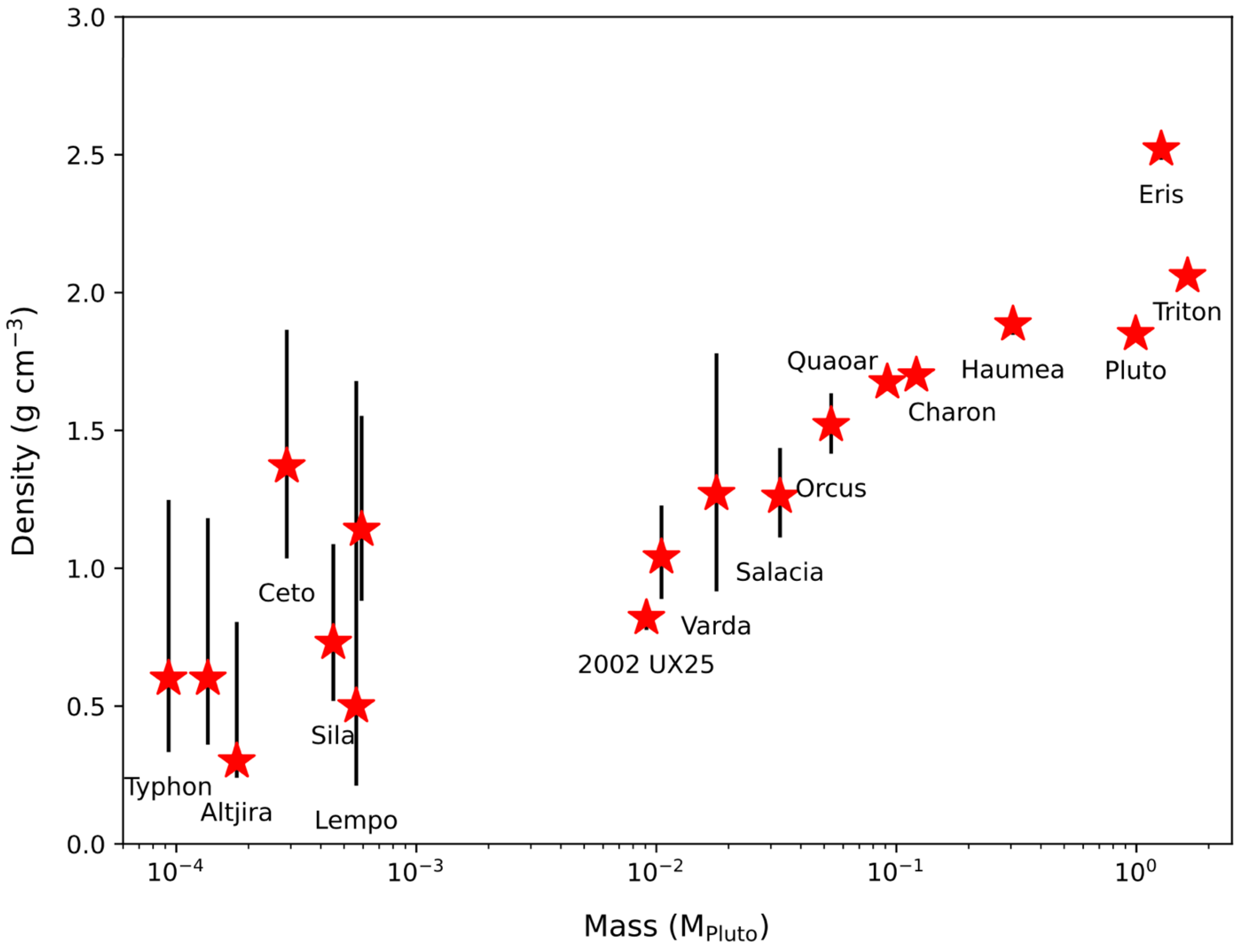
SI Model (solid)
KBOs (dashed)



Nesvorny+'19, model by Rixin Li

W. Lyra

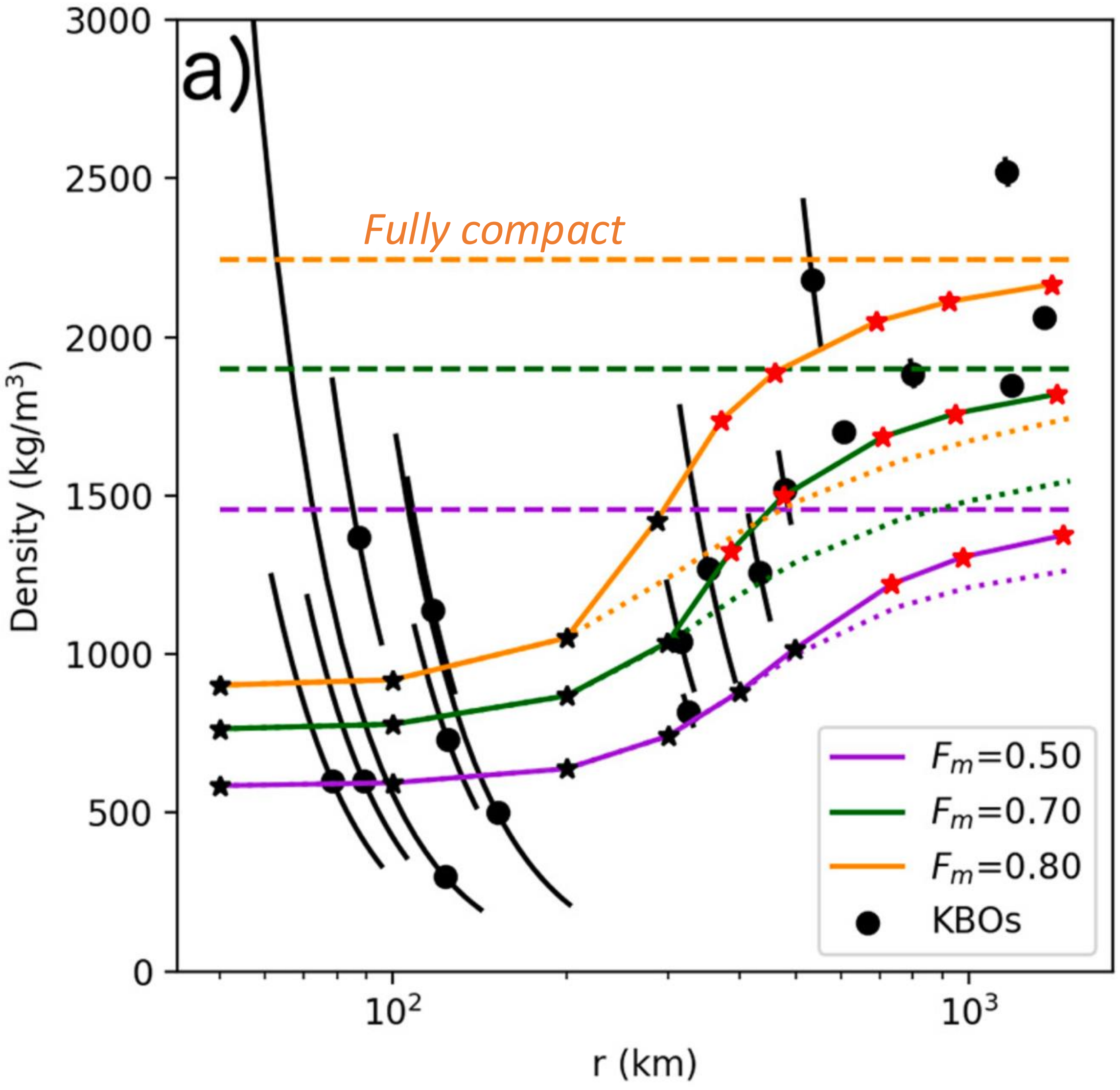
The density dichotomy of Kuiper Belt objects



Canas+Lyra et al. 2024

Possible Solution?

- Assumptions
  - Constant composition at birth and growth
  - Porosity removal by gravitational compaction



Bierson & Nimmo 2019

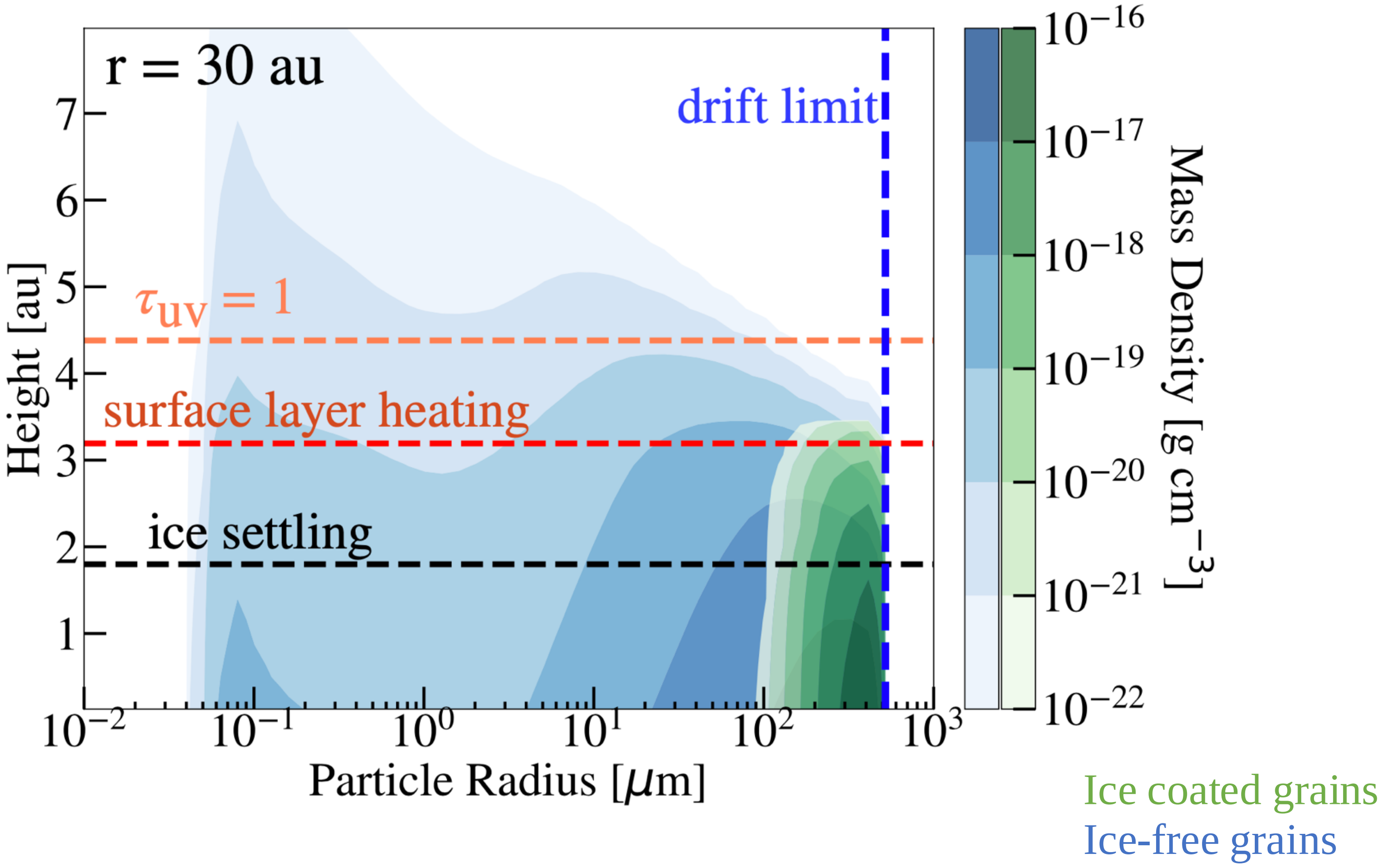
- Problems
  - Low-mass objects need to be unreasonably porous
  - Timing! ^{26}Al would melt if formed within 4 Myr

Abandoning Constant Composition

Heating and UV irradiation remove ice on Myr timescales

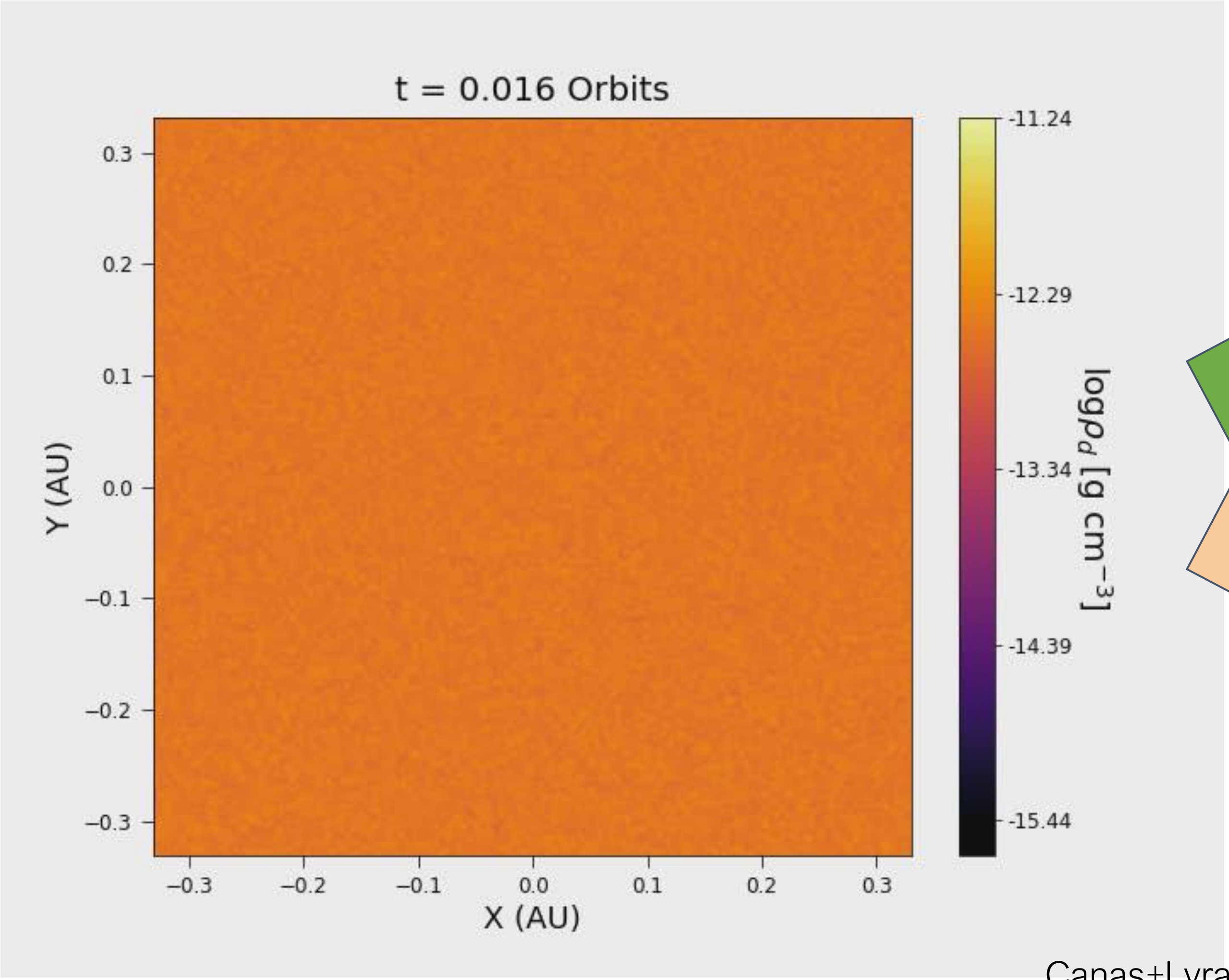
- Small grains lofted in the atmosphere lose ice

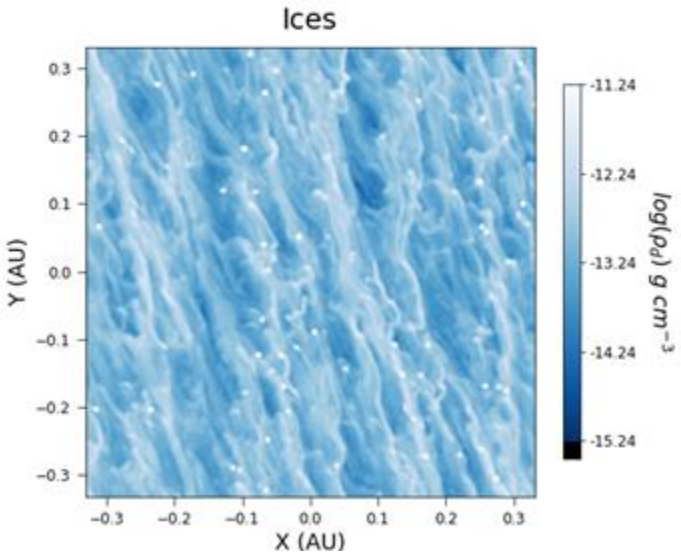
- Big grains are shielded and remain icy.

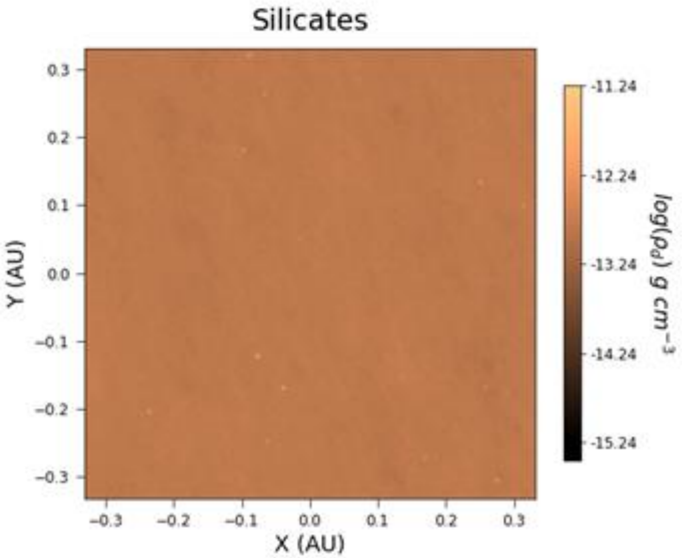


Powell et al. 2022

Split into icy and silicate pebbles

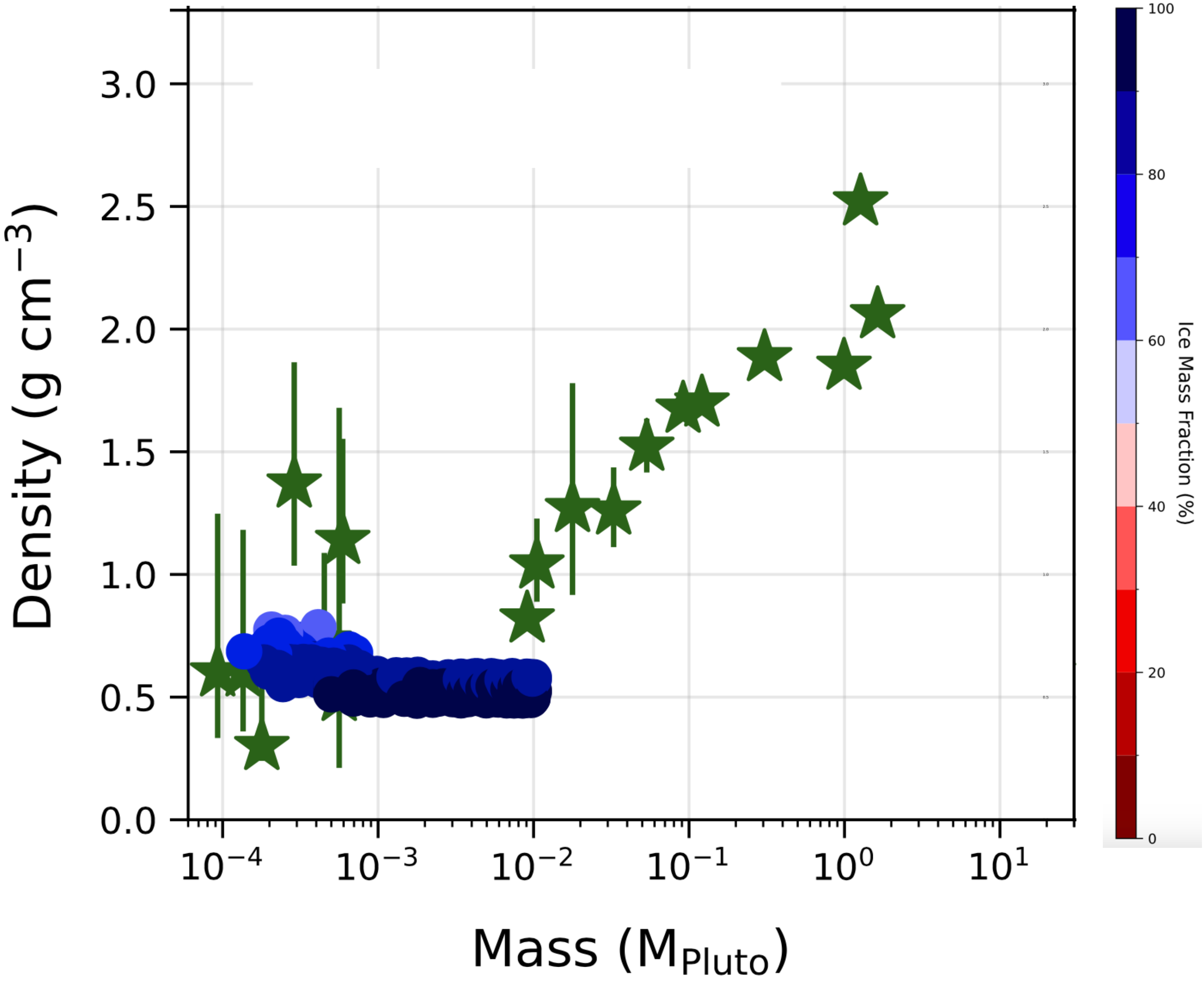






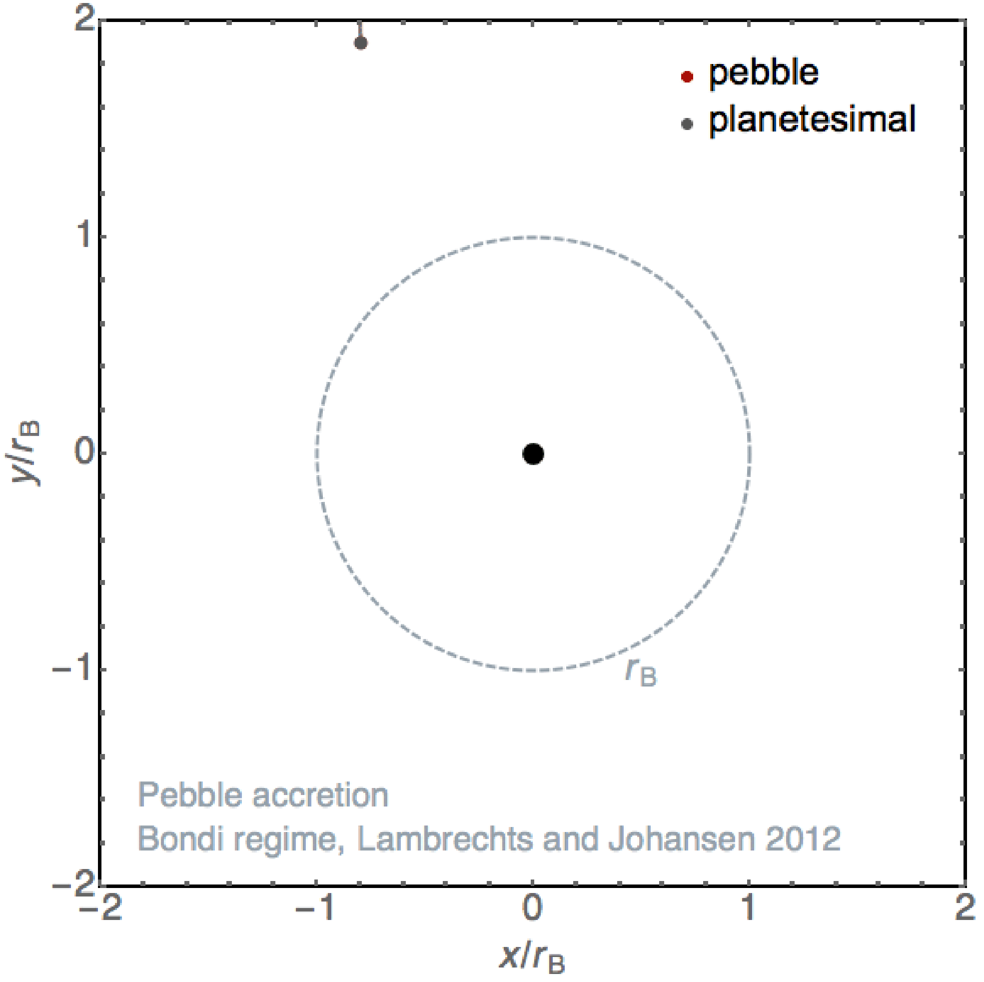
Canas+Lyra et al. 2024

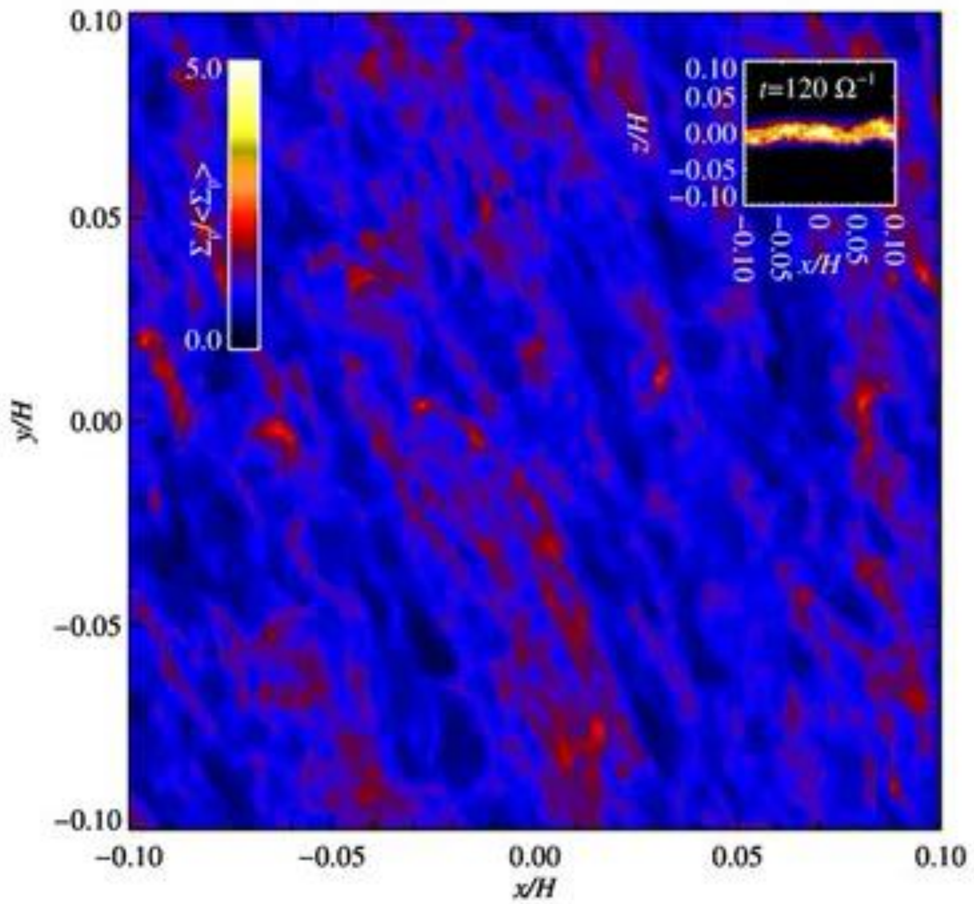
The first planetesimals are icy



Canas+Lyra et al. 2024

Pebble Accretion





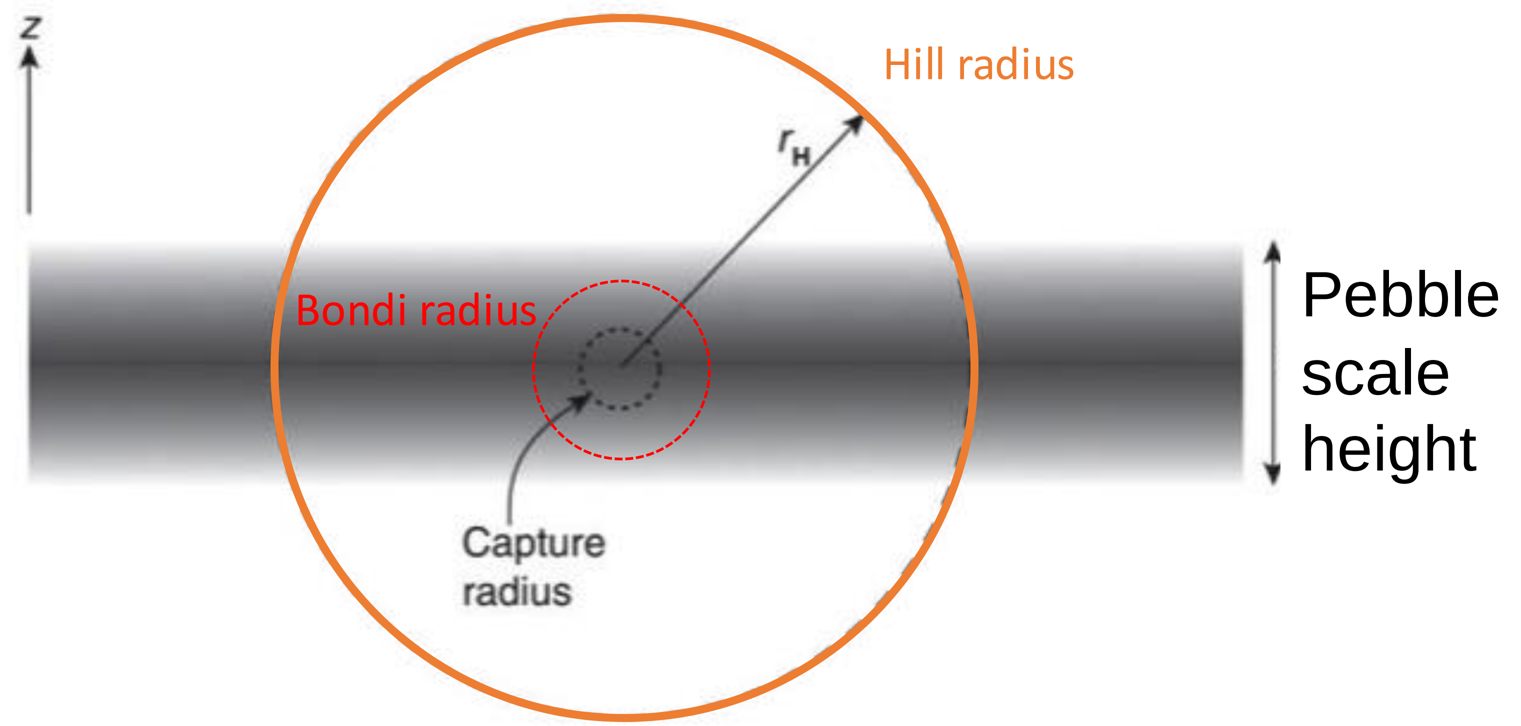
Lyra+ ‘08, ’09, ’23, Ormel & Klahr ‘10, Lambrechts & Johansen ’12
See Johansen & Lambrechts ‘17 for a review

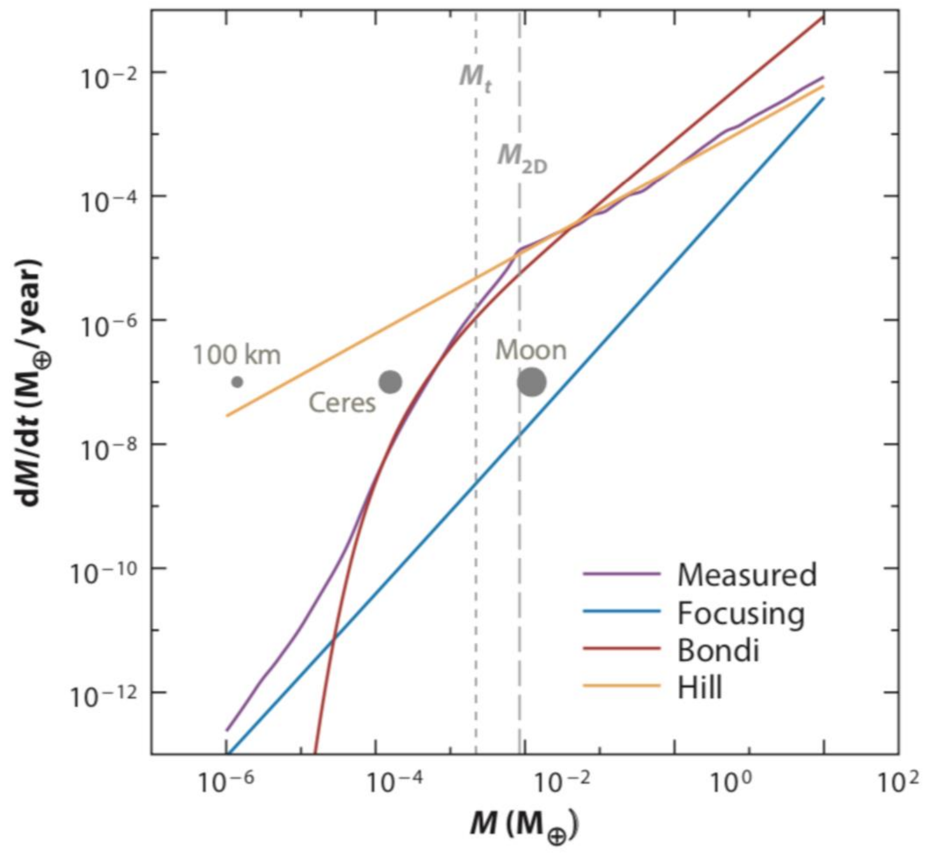
Pebble Accretion: Geometric, Bondi, and Hill regime

$$\xi \equiv \left(\frac{R_{acc}}{2H_d}\right)^2 \qquad \dot{M}_{3D} = \lim_{\xi \to 0} \dot{M} = \pi R_{acc}^2 \rho_{d0} \delta v, \qquad \dot{M}_{2D} = \lim_{\xi \to \infty} \dot{M} = 2R_{acc} \Sigma_d \delta v,$$

Bondi accretion - Bound against thermal (dynamic) kinetic energy
Hill accretion - Bound against stellar tide

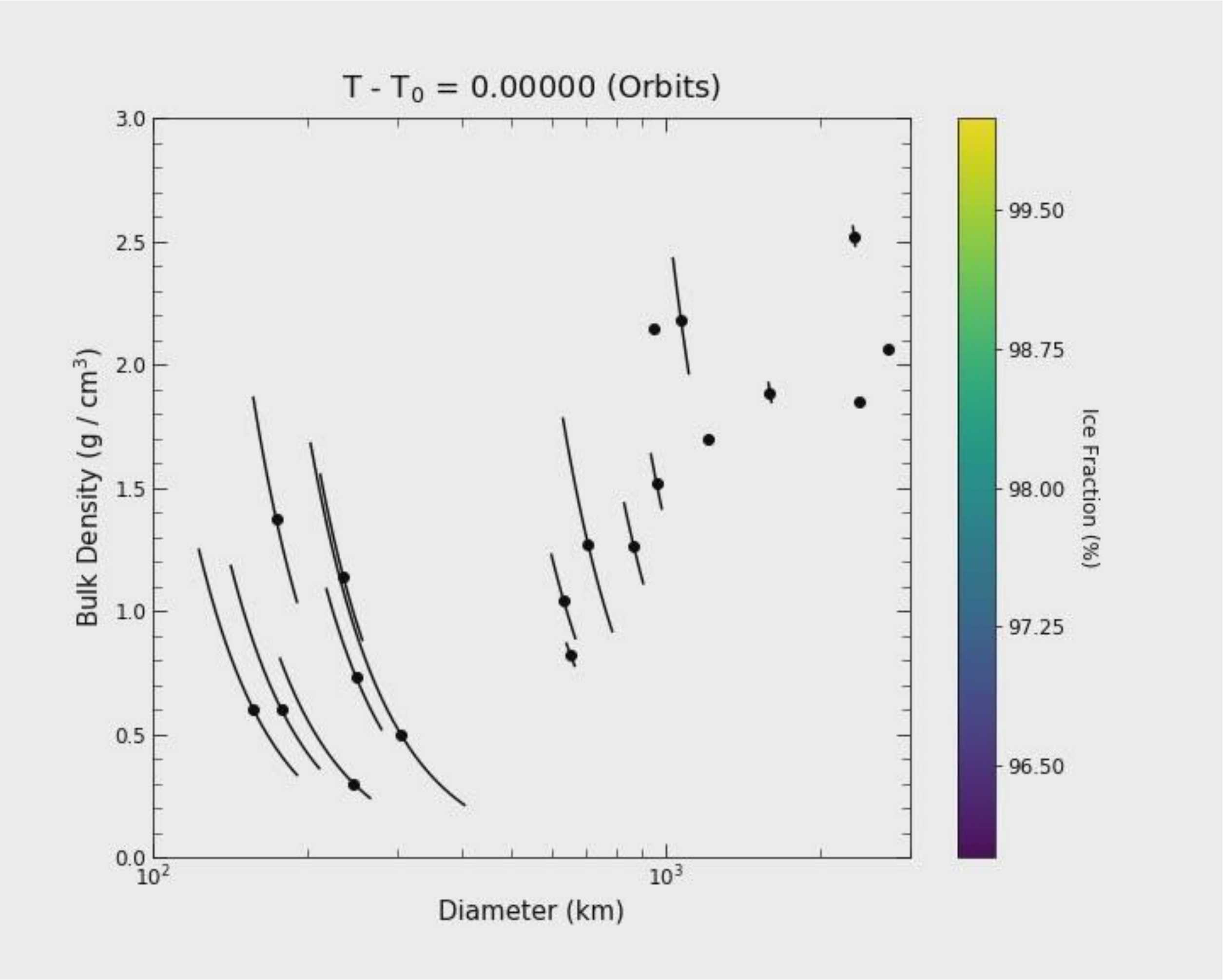
Mass Accretion rates

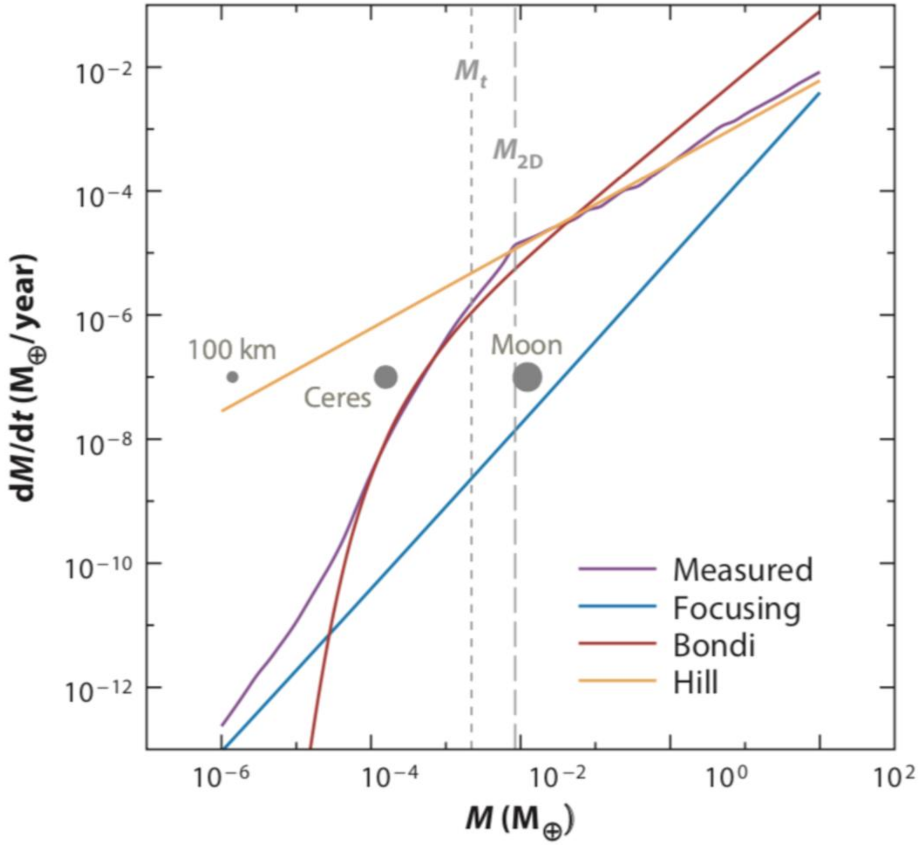




Johansen & Lambrechts '17

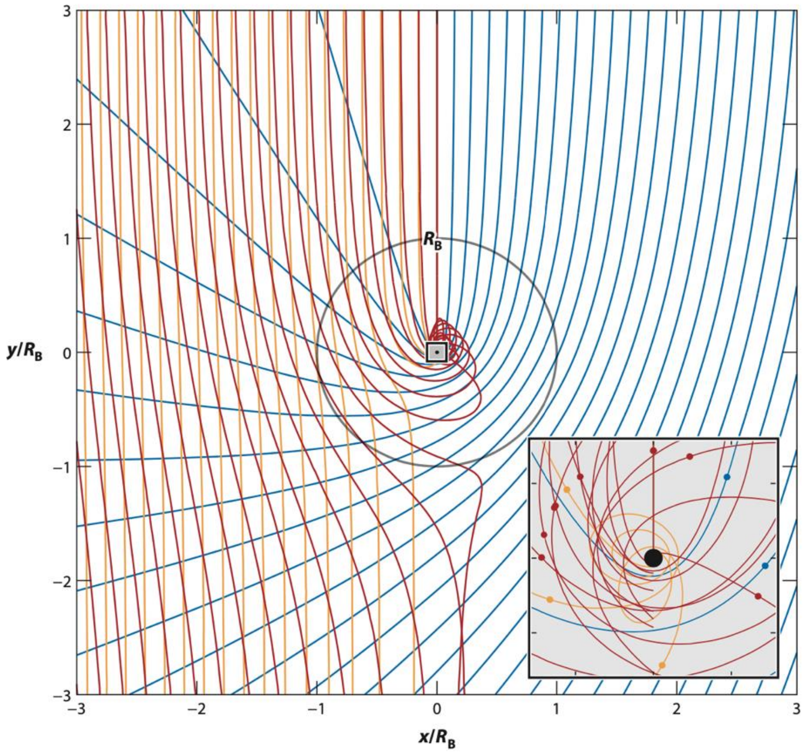
Integrate pebble accretion





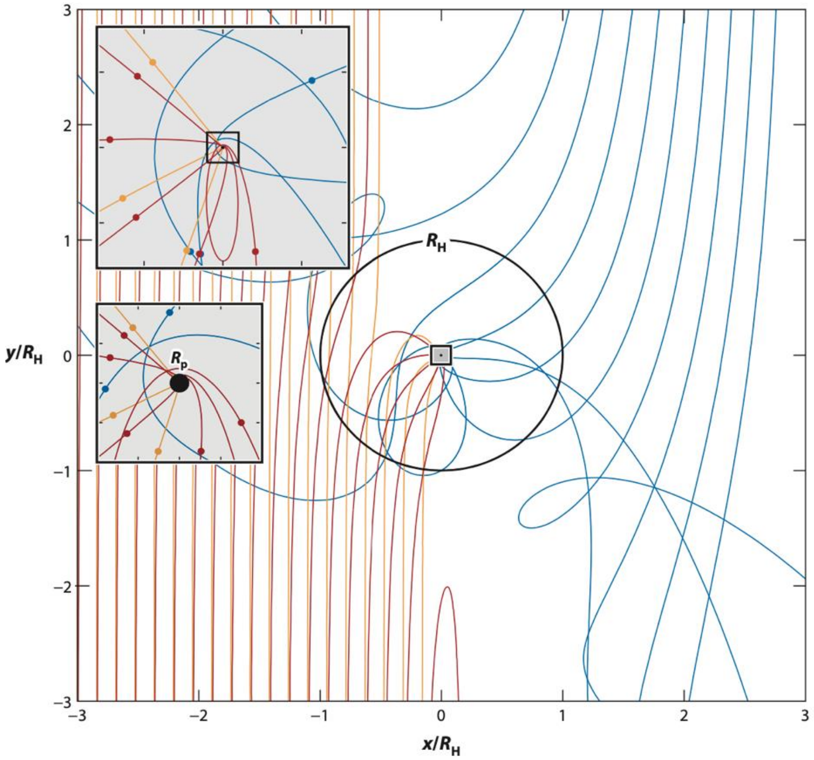
Pebble Accretion: Pebbles of different size accrete differently

Bondi Regime



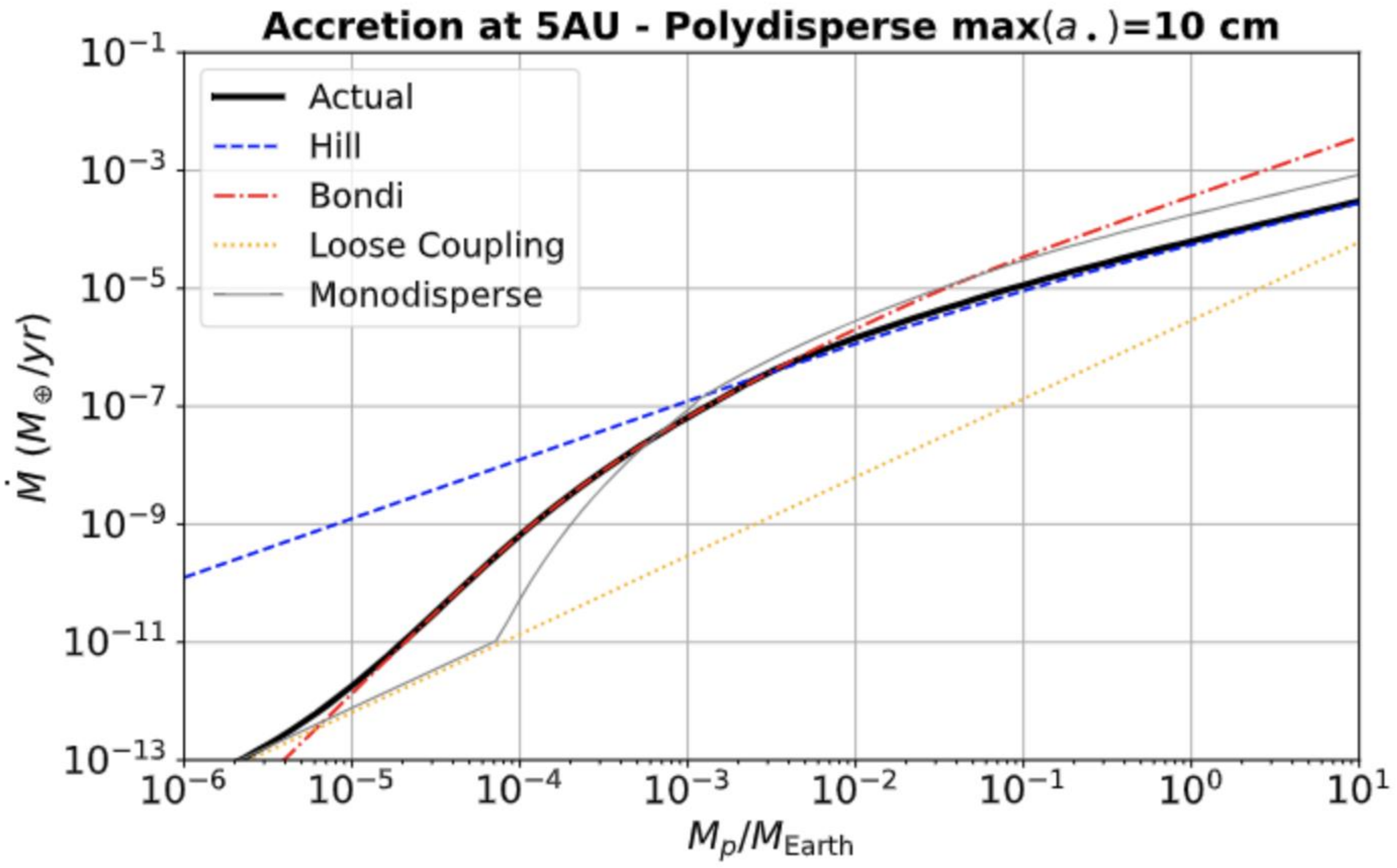
Best accreted
Drag time = Time to cross Bondi sphere

Hill Regime



Best accreted
Drag time ~ Orbital Time

Accretion Rates



Lyra et al. 2023

Analytical theory of polydisperse (multi-species) pebble accretion

Monodisperse (single species)

$$\xi \equiv \left(\frac{R_{\rm acc}}{2H_d}\right)^2$$

$$\dot{M}_{\rm 3D} = \lim_{\xi \to 0} \dot{M} = \pi R_{\rm acc}^2 \rho_{d0} \delta v,$$

$$\dot{M}_{\rm 2D} = \lim_{\xi \to \infty} \dot{M} = 2R_{\rm acc} \Sigma_d \delta v,$$

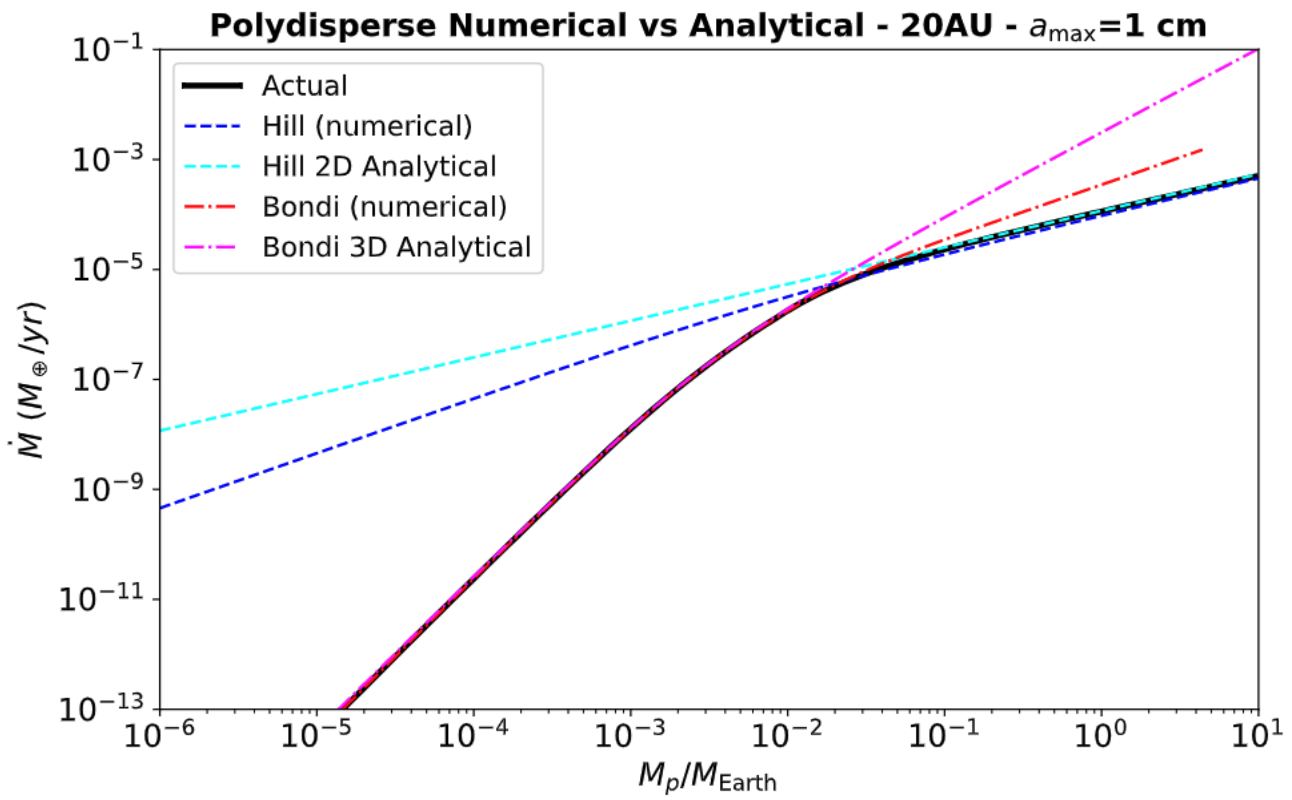
Lambrechts & Johansen (2012)

Polydisperse (multiple species)

$$\dot{M}_{\rm 2D,Hill} = \frac{6(1-p)}{14-5q-3k}\left(\frac{\rm St_{max}}{0.1}\right)^{2/3} \Omega R_H^2 Z \Sigma_g.$$

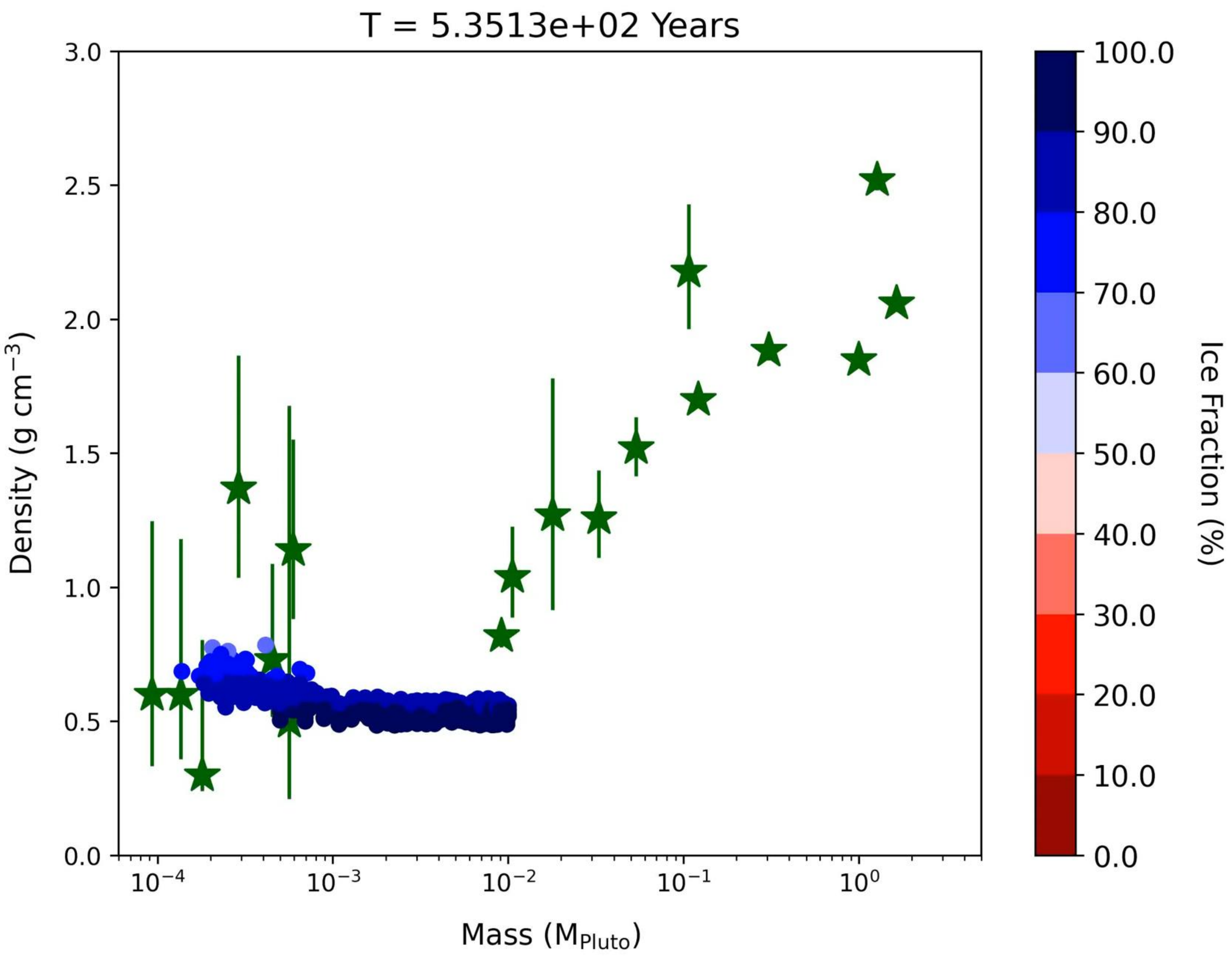
$$\dot{M}_{\rm 3D,Bondi} \approx C_1 \frac{\gamma_l\left(\frac{b_1+1}{s}, j_1 a_{\rm max}^s\right)}{s\, j_1^{(b_1+1)/s}} + C_2 \frac{\gamma_l\left(\frac{b_2+1}{s}, j_2 a_{\rm max}^s\right)}{s\, j_2^{(b_2+1)/s}} + C_3 \frac{\gamma_l\left(\frac{b_3+1}{s}, j_3 a_{\rm max}^s\right)}{s\, j_3^{(b_3+1)/s}} + C_4 \frac{\gamma_l\left(\frac{b_4+1}{s}, j_4 a_{\rm max}^s\right)}{s\, j_4^{(b_4+1)/s}},$$

Lyra et al. (2023)



Lyra et al. 2023

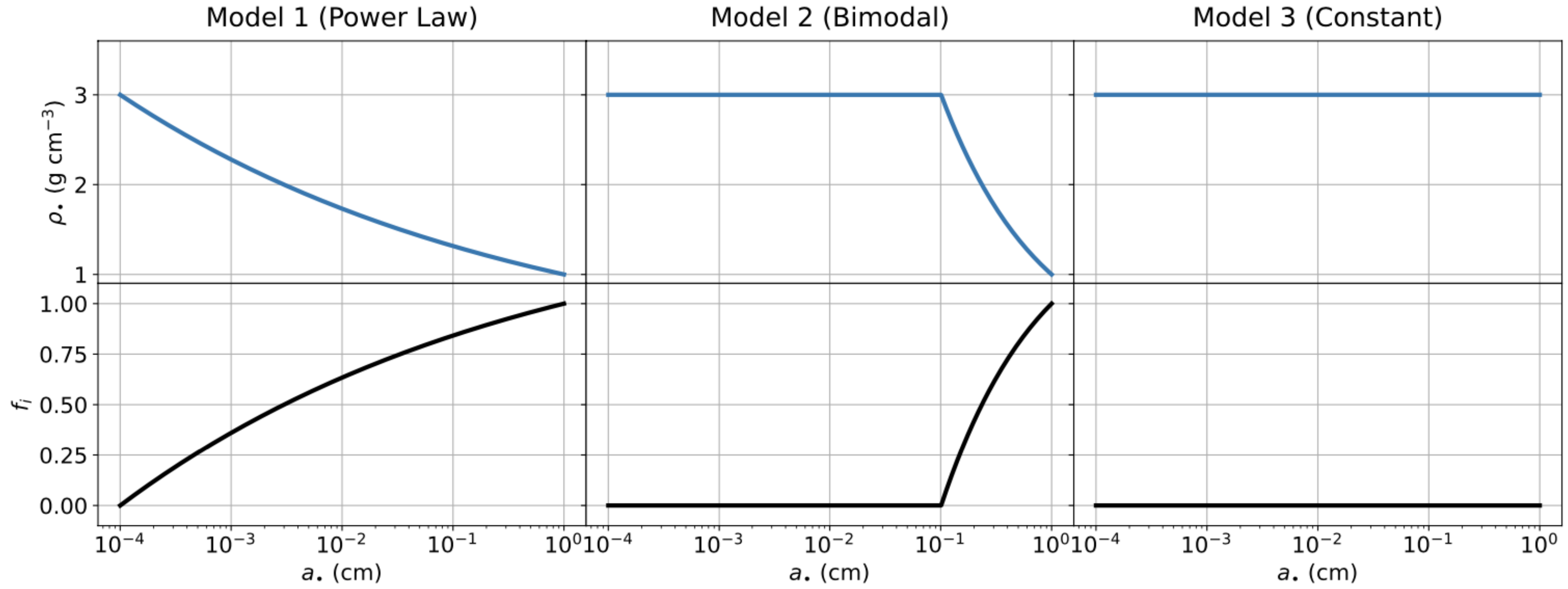
Growing Pluto by silicate pebble accretion



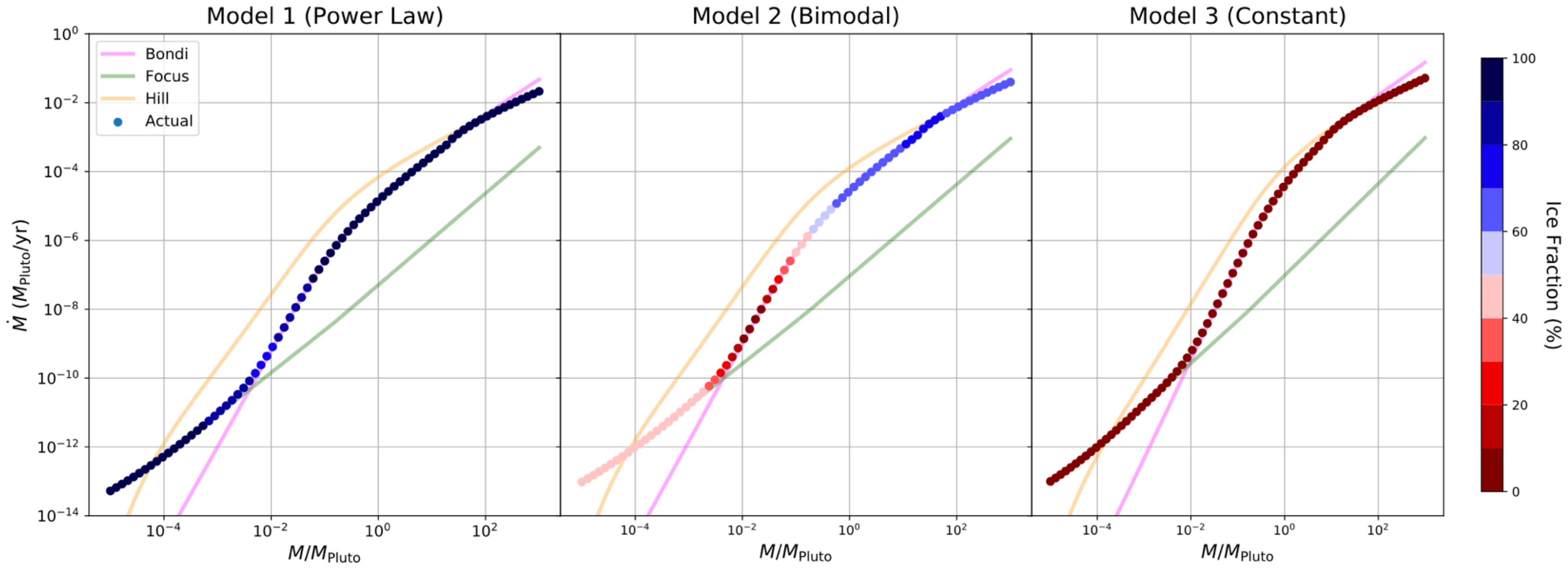
Canas+Lyra et al. 2024

Pebble Density

Ice Fraction

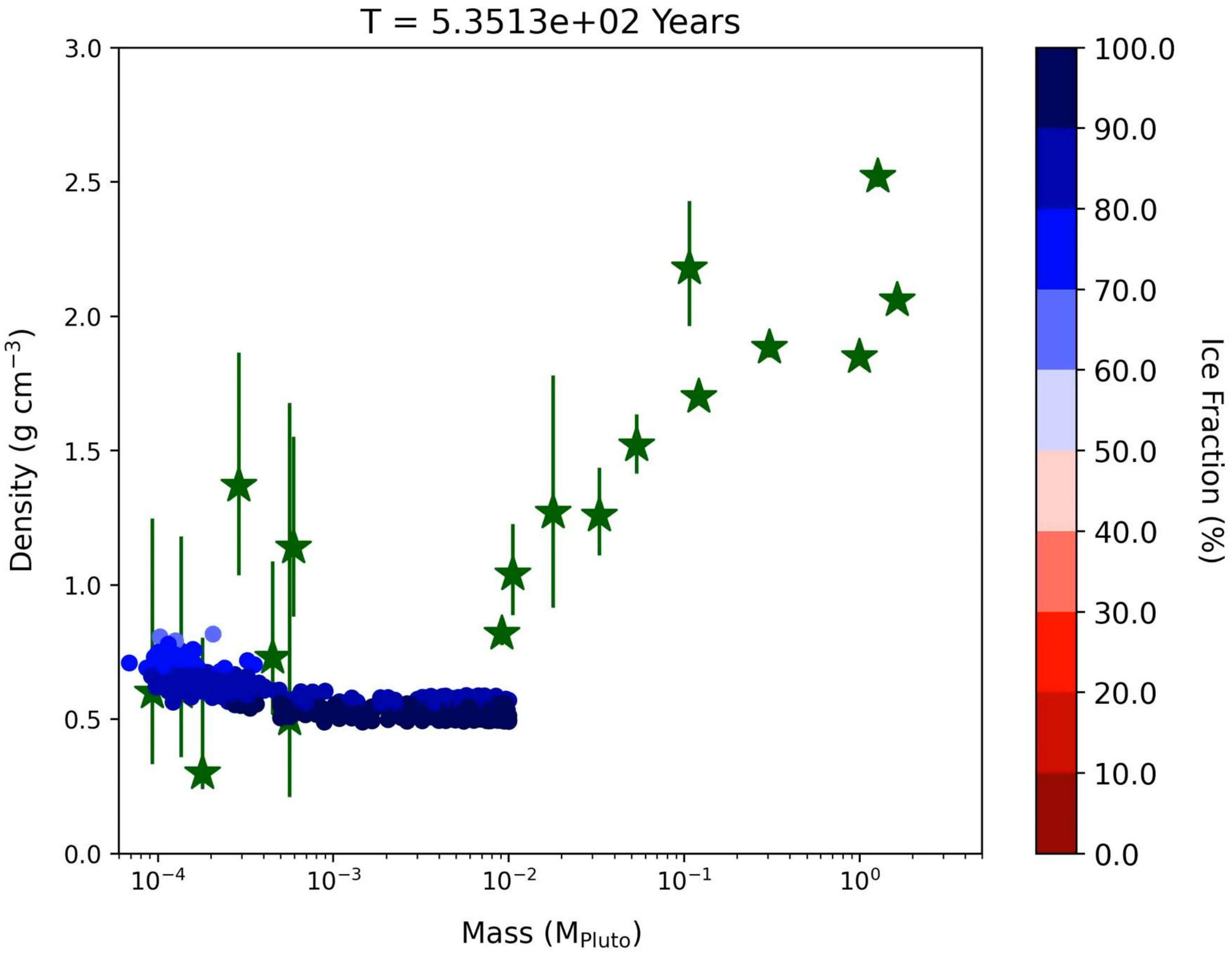


Mass Accretion rate



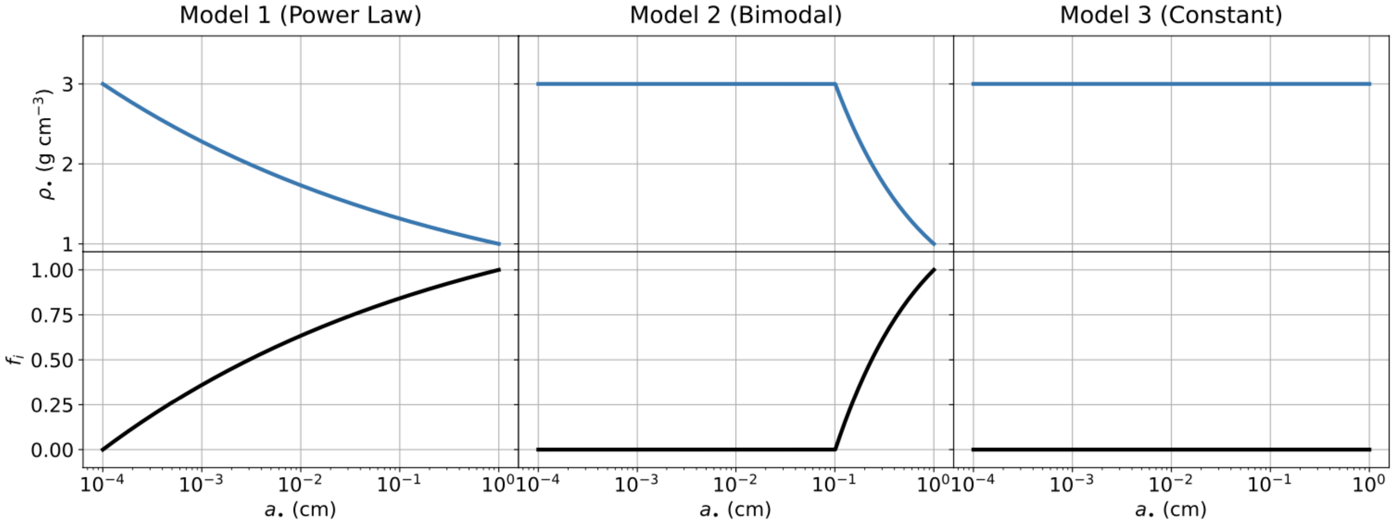
Canas+Lyra et al. 2024

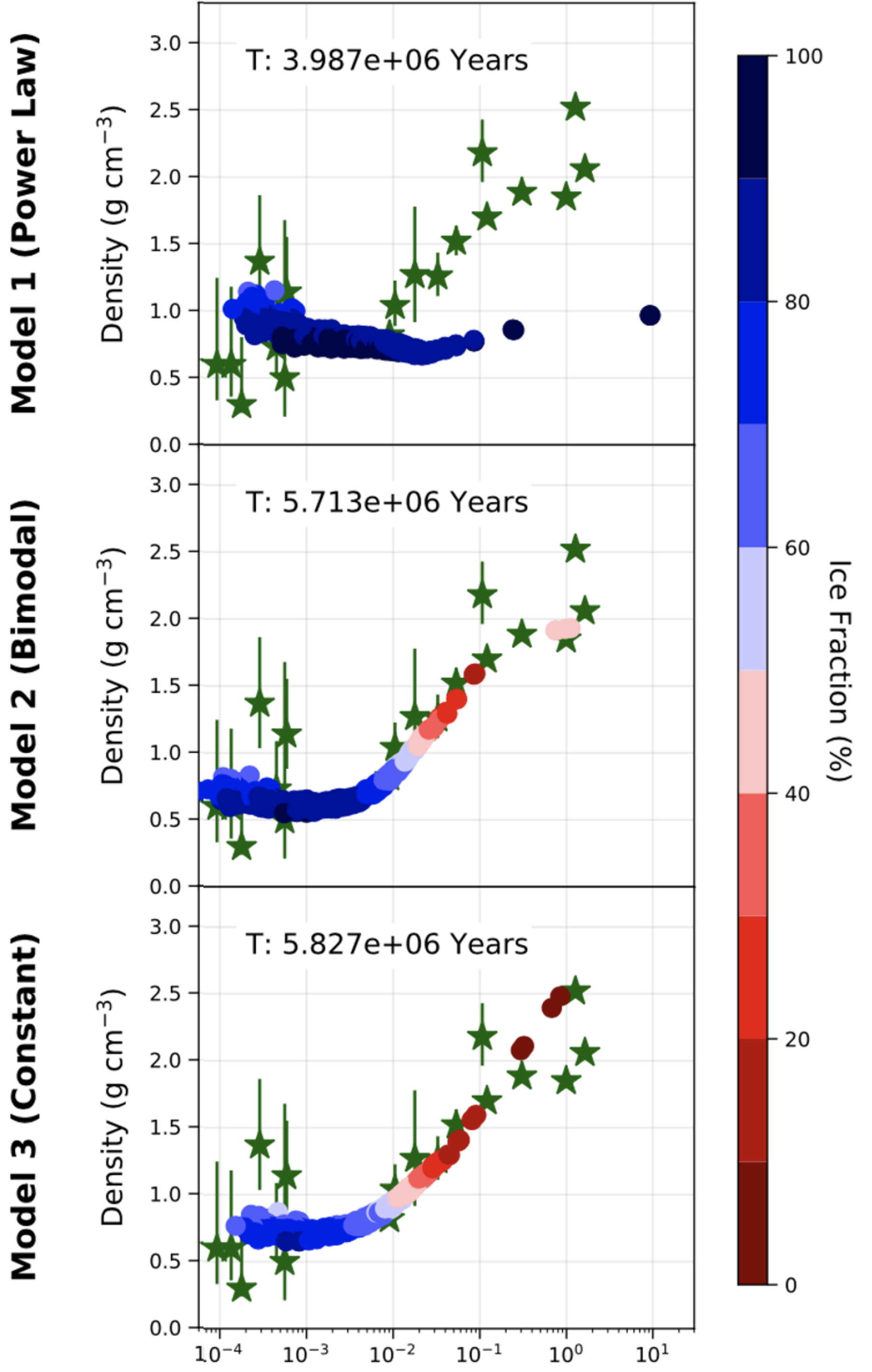
Growing Pluto by silicate pebble accretion



Canas+Lyra et al. 2024

Resulting Densities vs Mass relations





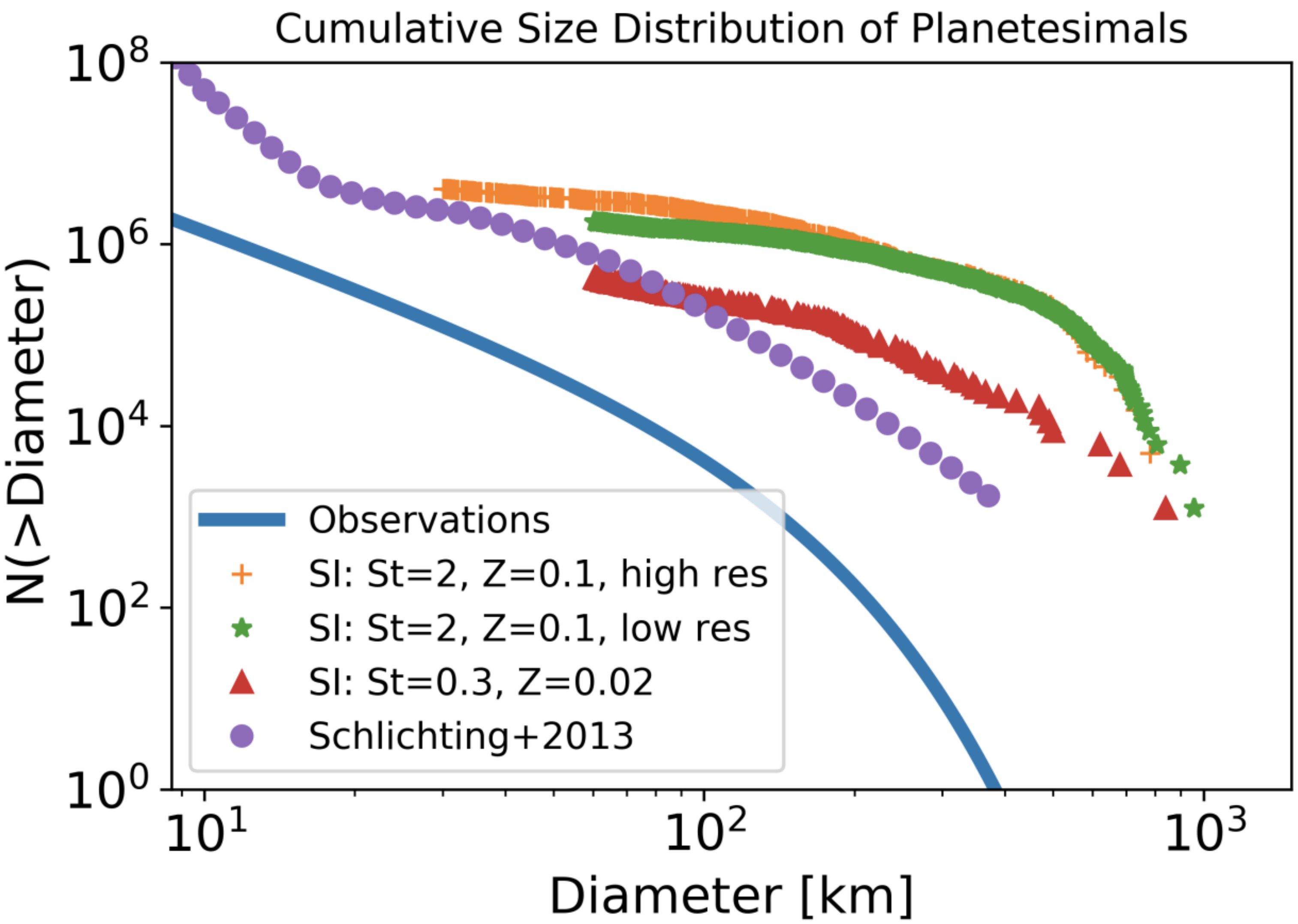
Take-home message

- Streaming Instability fits
  - slope of asteroid belt distribution,
  - prograde-retrograde distribution of Kuiper belt objects
  - Low density of small classical Kuiper belt objects

- Pebble accretion is a very efficient planetary growth mechanism
  - Polydisperse Bondi accretion 1-2 orders of magnitude more efficient than monodisperse
  - Silicate pebble accretion explains densities of high-mass Kuiper belt objects

- Polydisperse Bondi accretion 1-2 orders of magnitude more efficient than monodisperse
  - Best accreted pebbles are those of drag time ~ Bondi time, not the largest ones
  - The largest ones dominate the mass budget, but accrete poorly
- Onset of Bondi accretion 1-2 orders of magnitude lower in mass compared to monodisperse
  - Reaches 100-350km objects within Myr timescales
  - Bondi accretion possible on top of Streaming Instability planetary embryos within disk lifetime
- Analytical solution to
  - Polydisperse 2D Hill and 3D Bondi

Problem: wrong number density



Simon et al. 2023