Evolution of Circumstellar Disks and Planet Formation

Wladimir Lyra

New Mexico State University

Current Funding

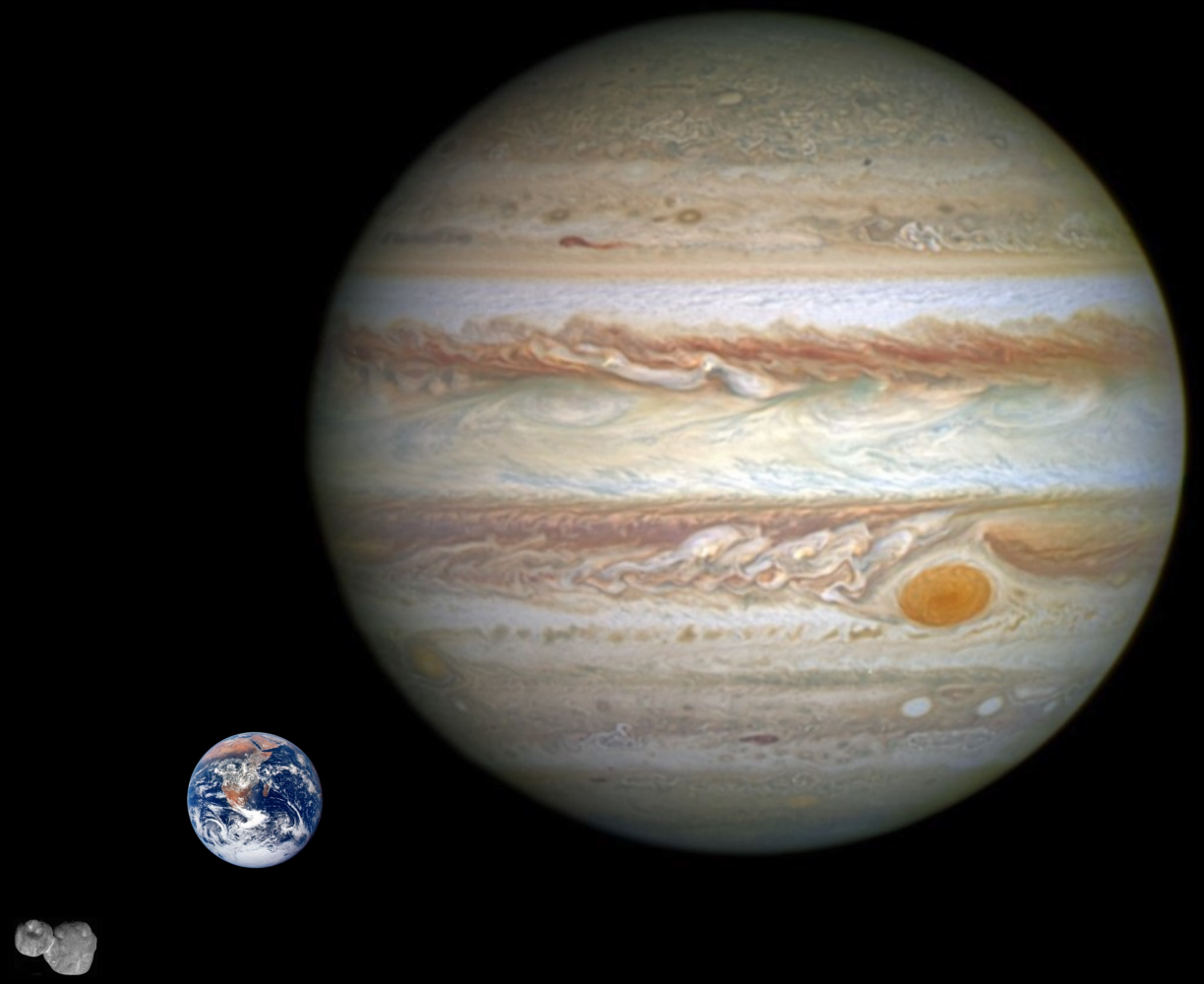
AAG – 2020, 2021

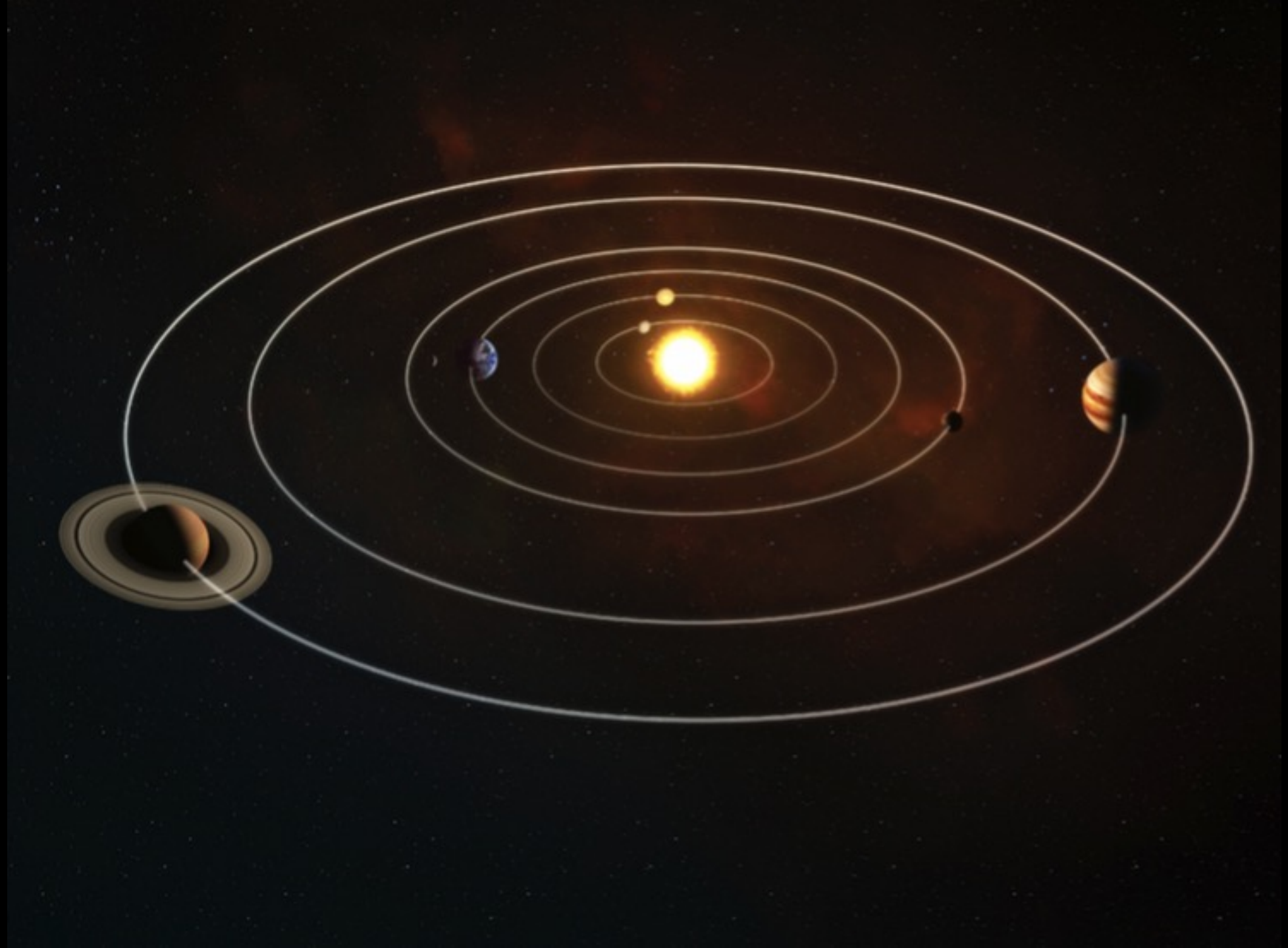
XRP - 2023
EW – 2021, 2022, 2023
TCAN – 2020

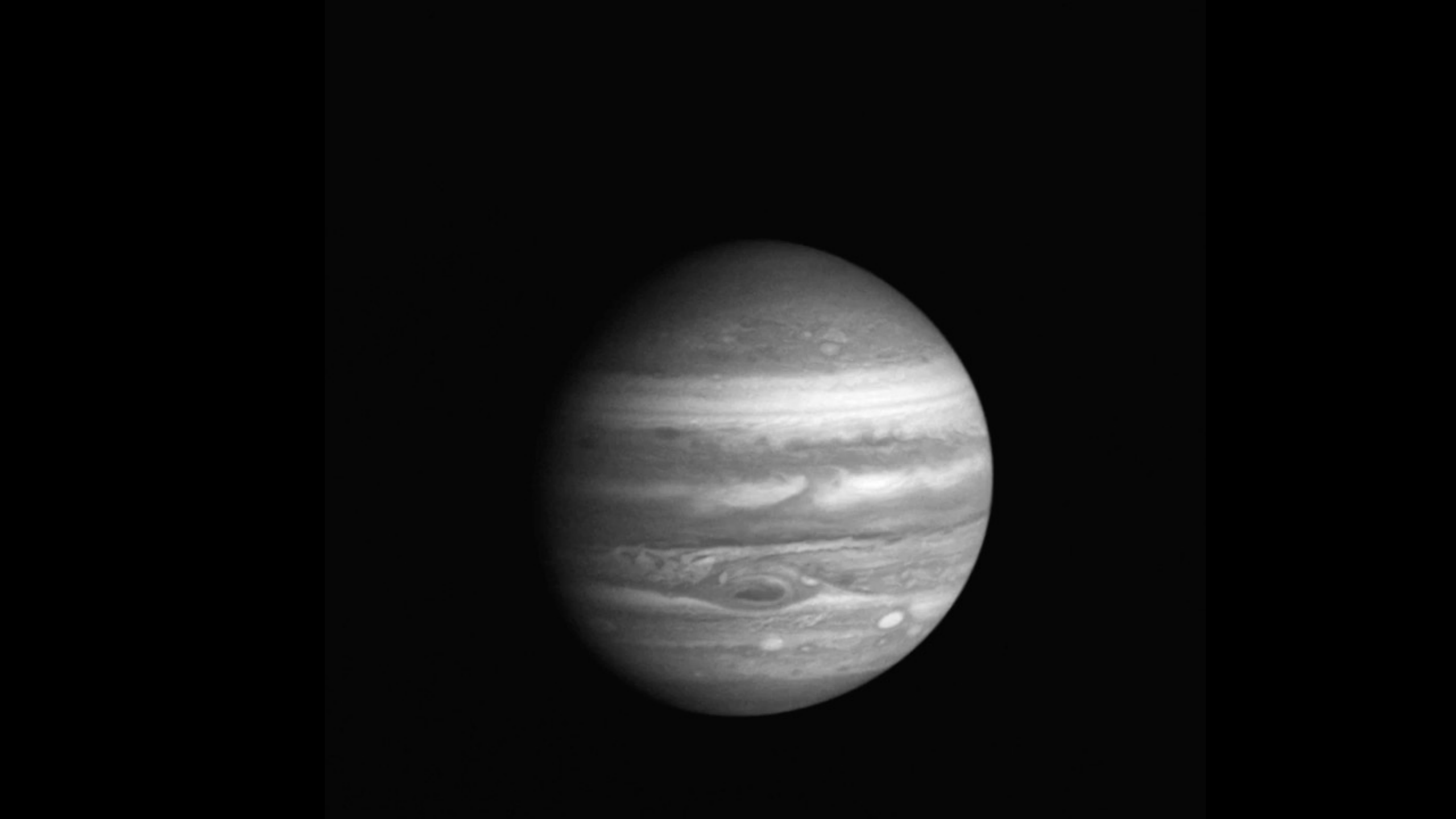
Computational Facilities

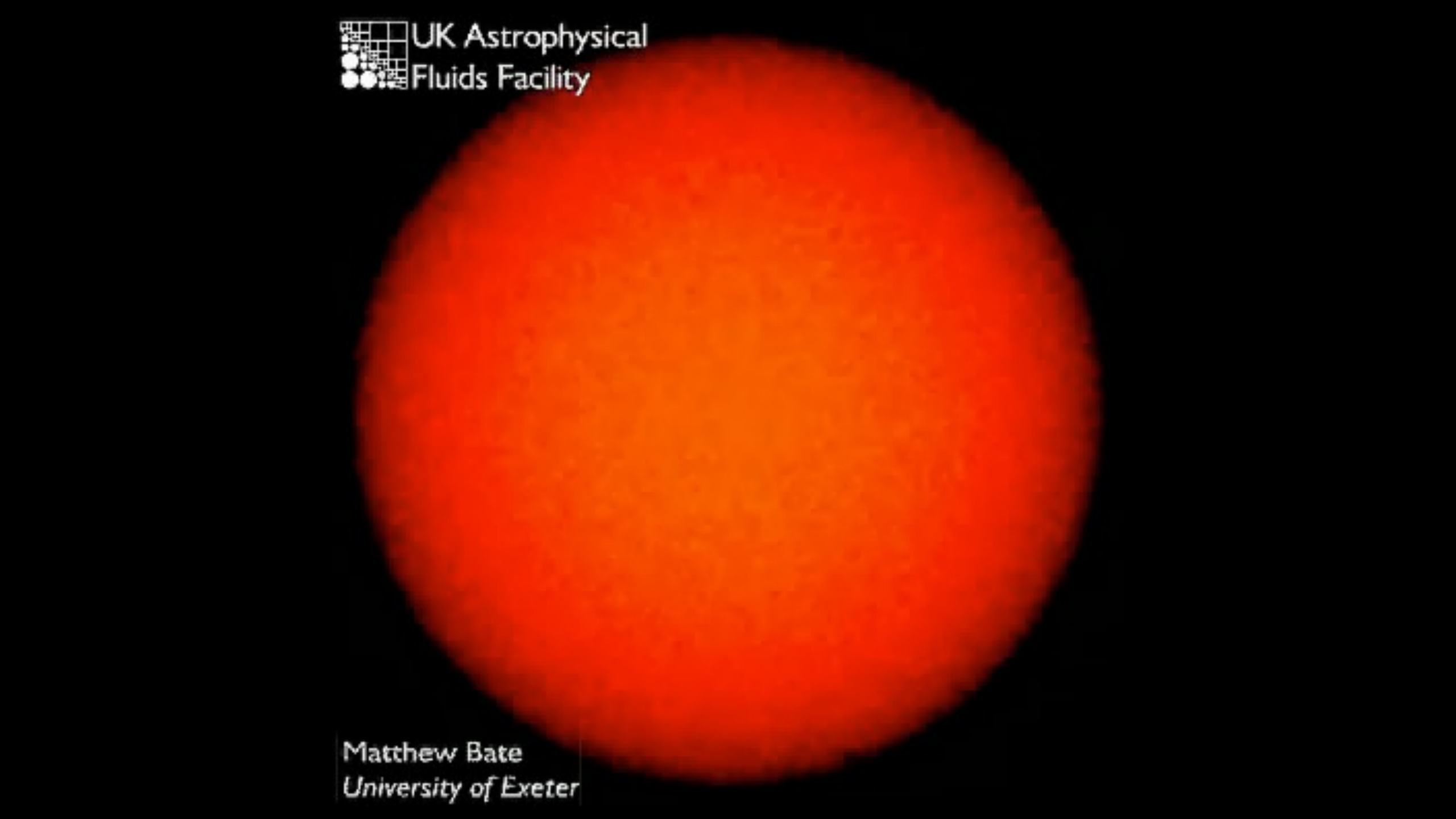
University of New Mexico - Feb 9th, 2024

Planet Formation

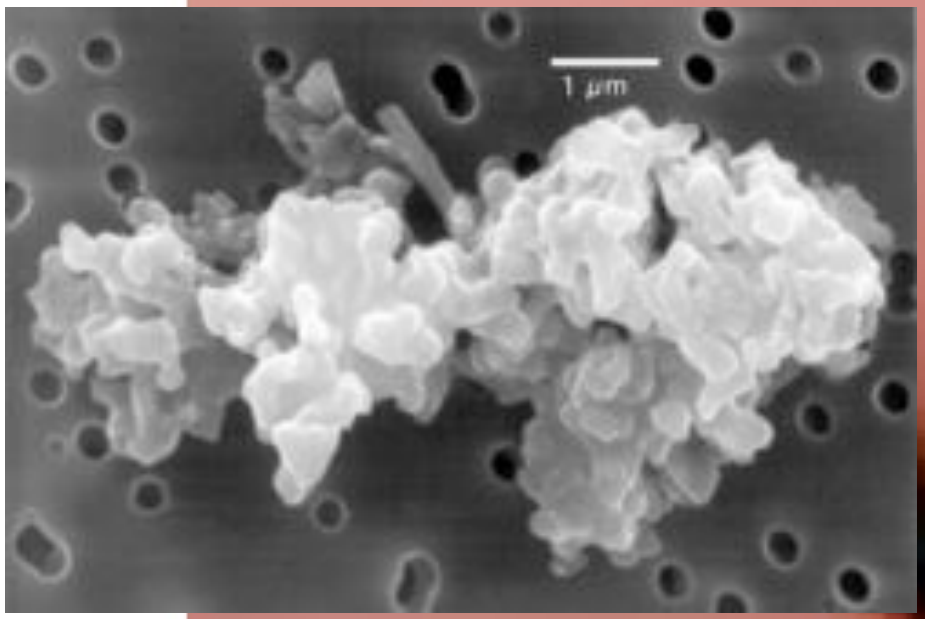







UK Astrophysical
Fluids Facility
Matthew Bate
University of Exeter


Betelgeuse
Bellatrix
Orion's Belt
Orion Nebula
Rigel
Saiph


1 µm

Circumstellar/Protoplanetary Disks

PP disk fact sheet

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

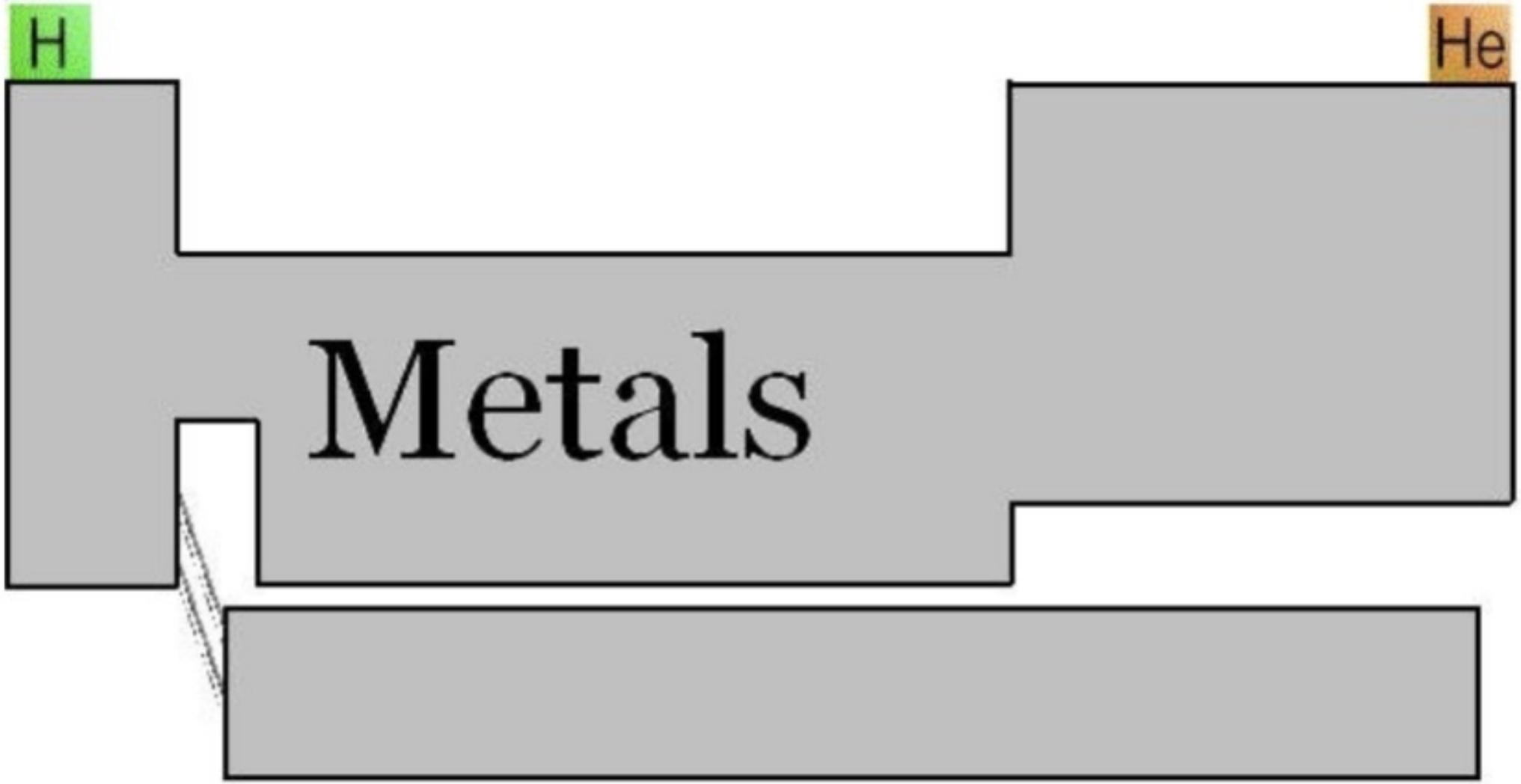
Temperature: 10-1000 K

Scale: 0.1-100AU

Mass: $10^{-3} – 10^{-1}$ M_{sun}

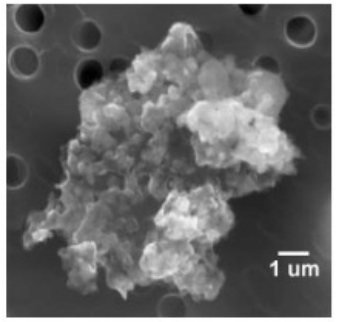
Composition: 5:2 H_2-He mixture. 1% metals.

The Astronomer's Periodic Table



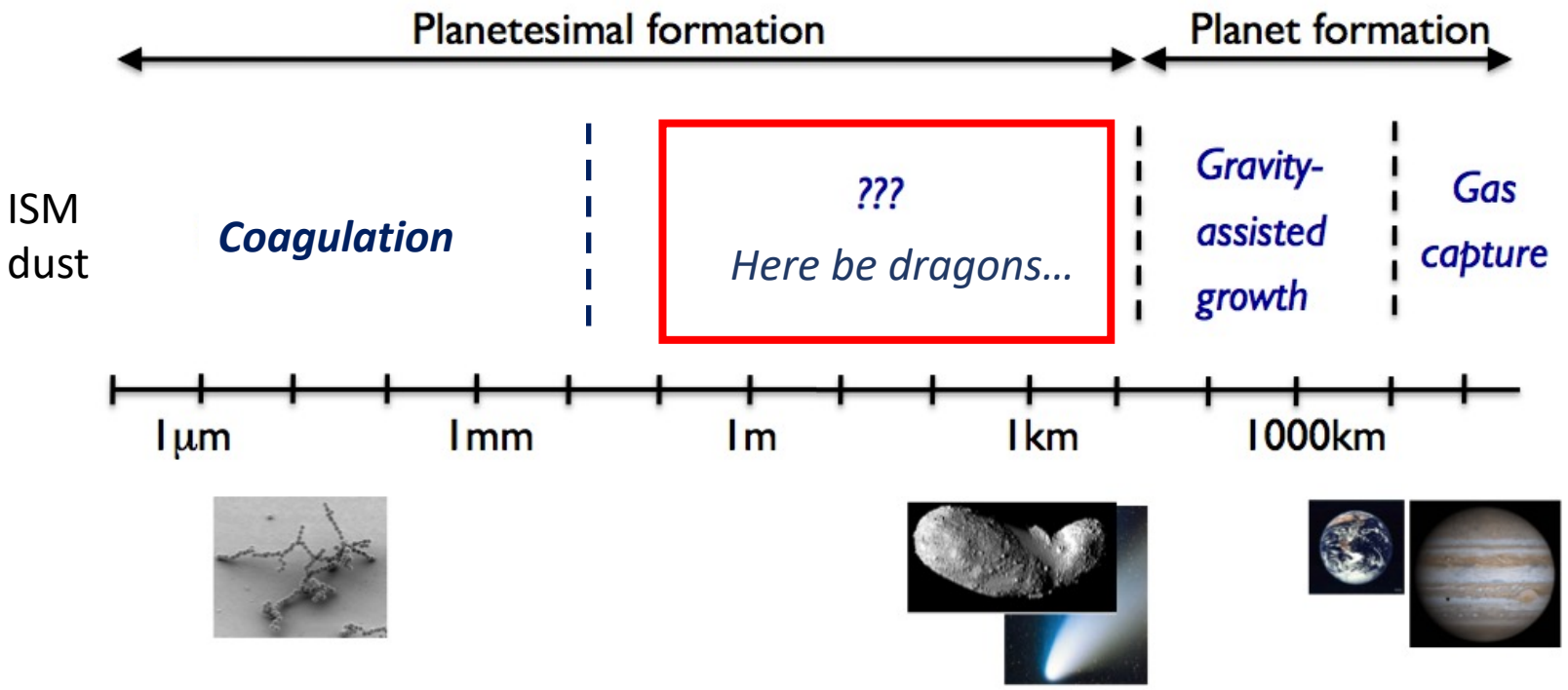
Planet Formation

“Planets form in disks of gas and dust”

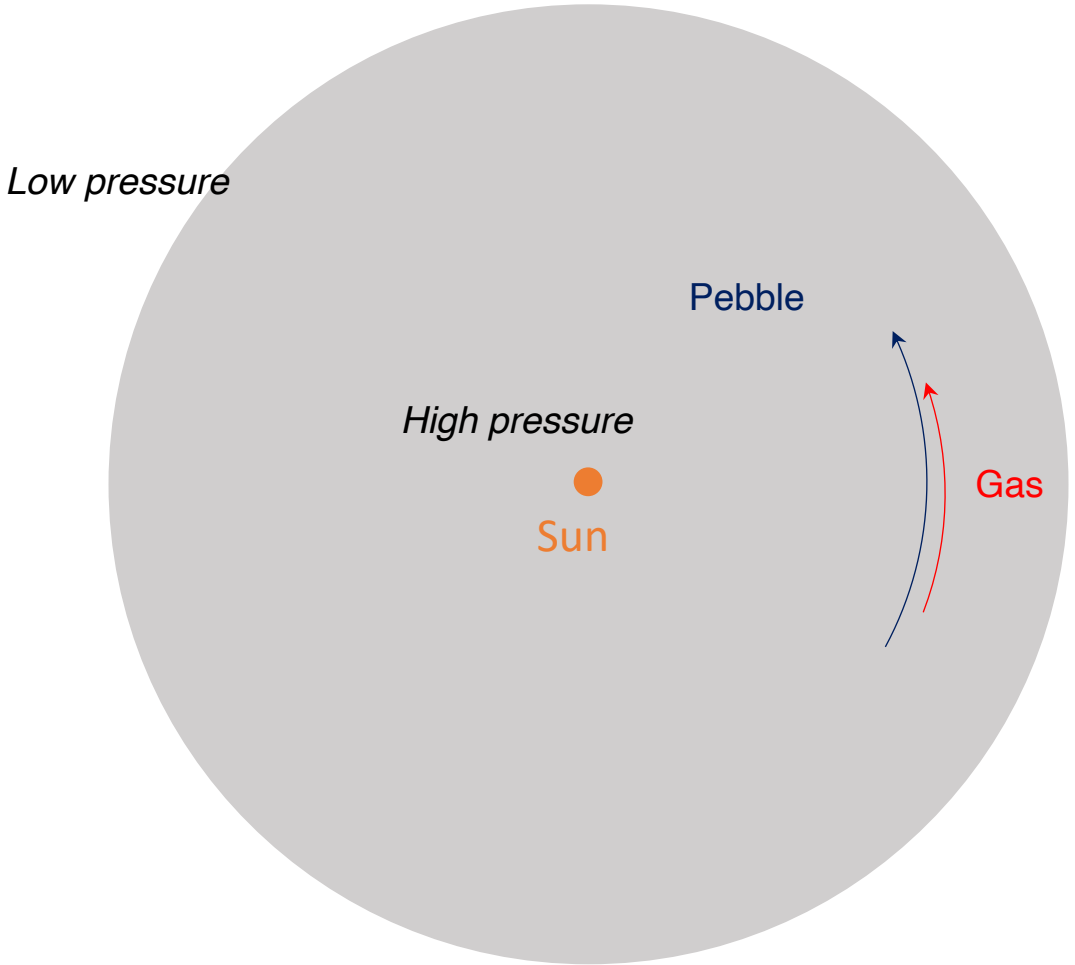


A miracle happens

Dust evolution



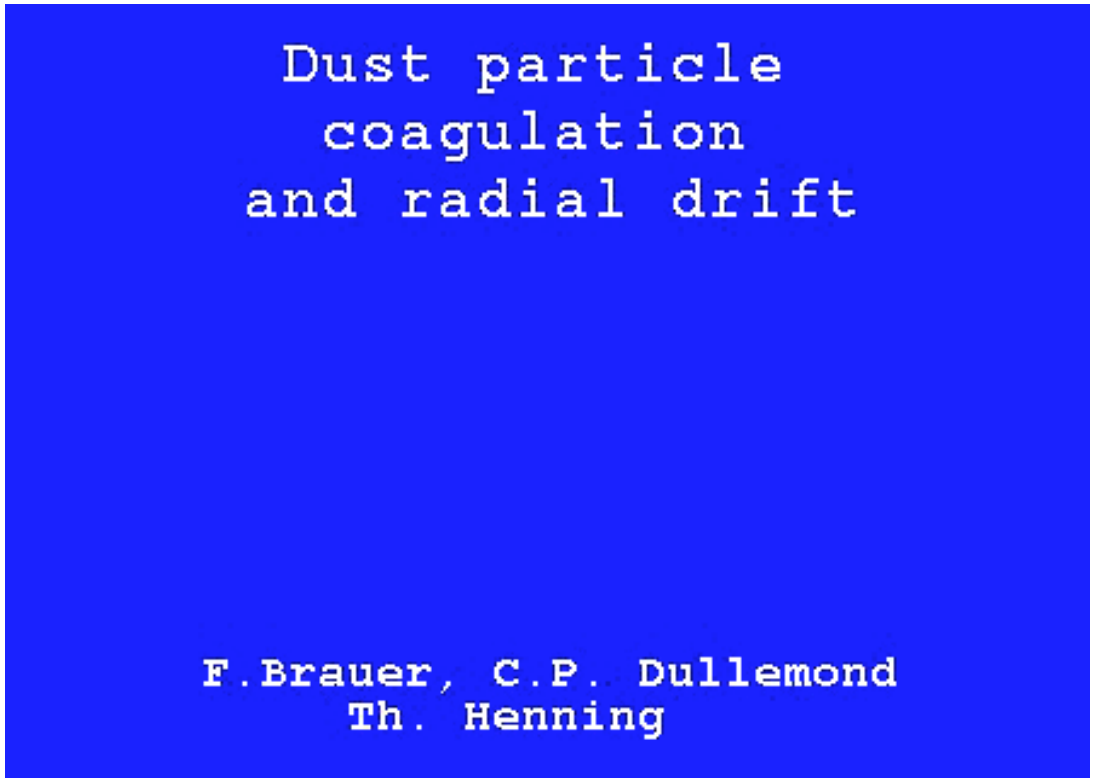
Headwind and Dust Drift



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

The pebbles do not feel gas pressure (Keplerian).

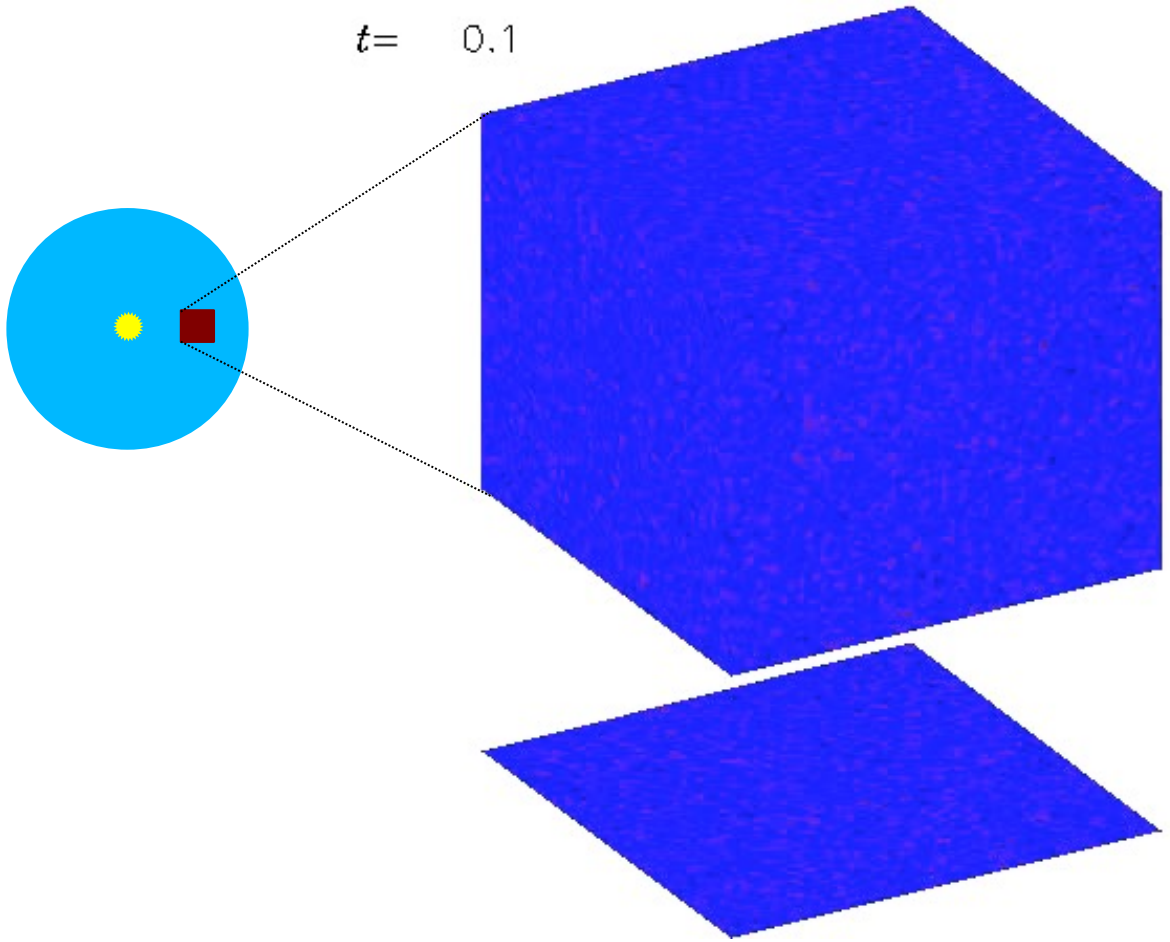
Dust coagulation and drift

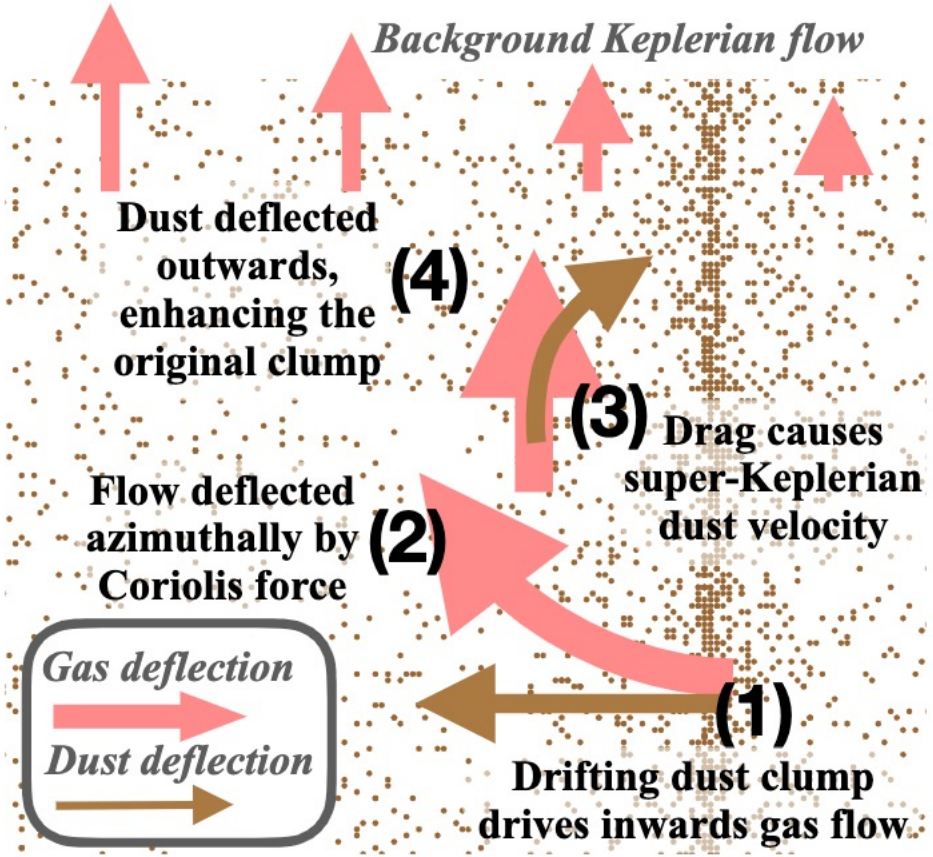


Brauer et al. (2008)

Streaming Instability

The dust drift is hydrodynamically unstable

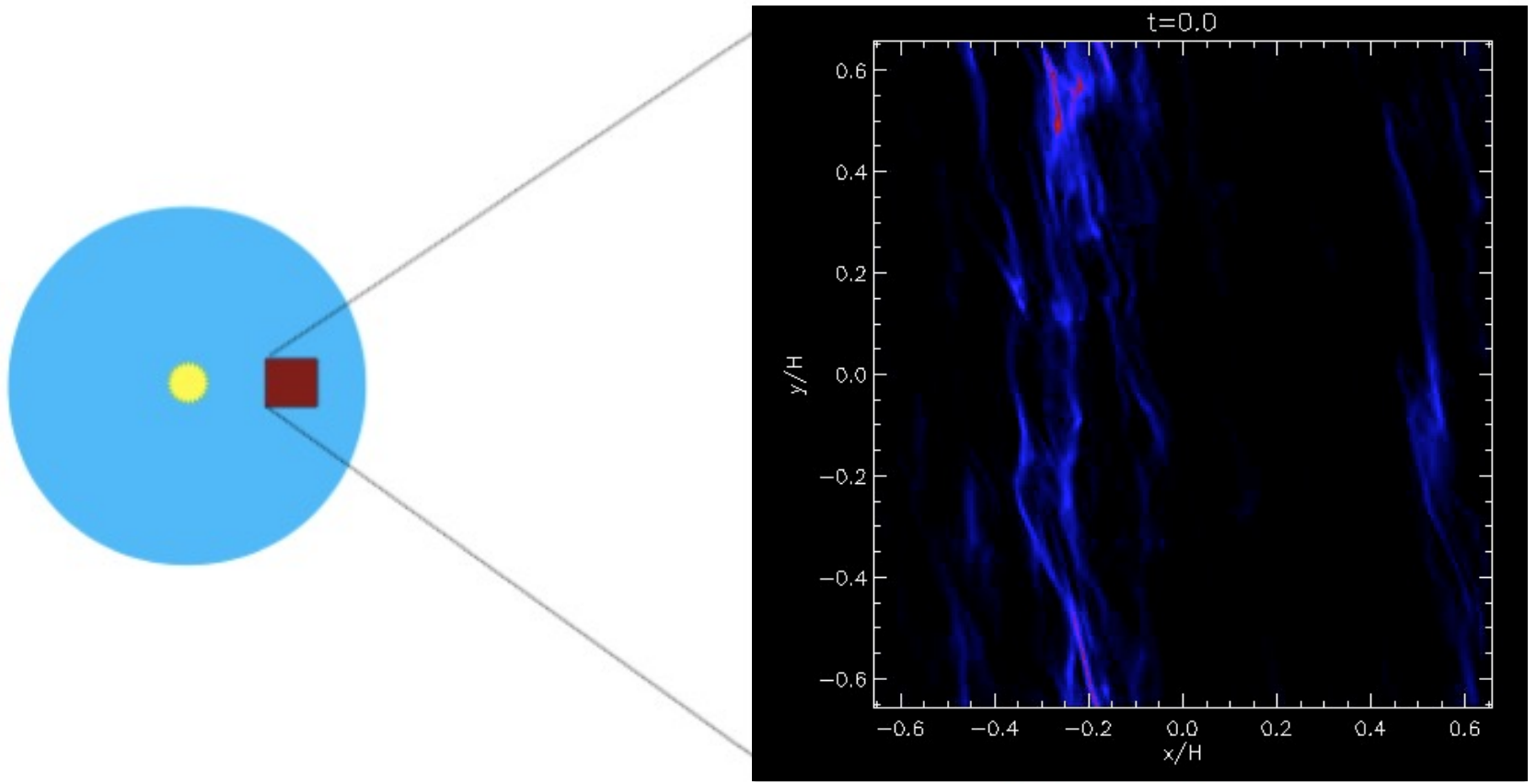




Lesur et al. (2022)

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

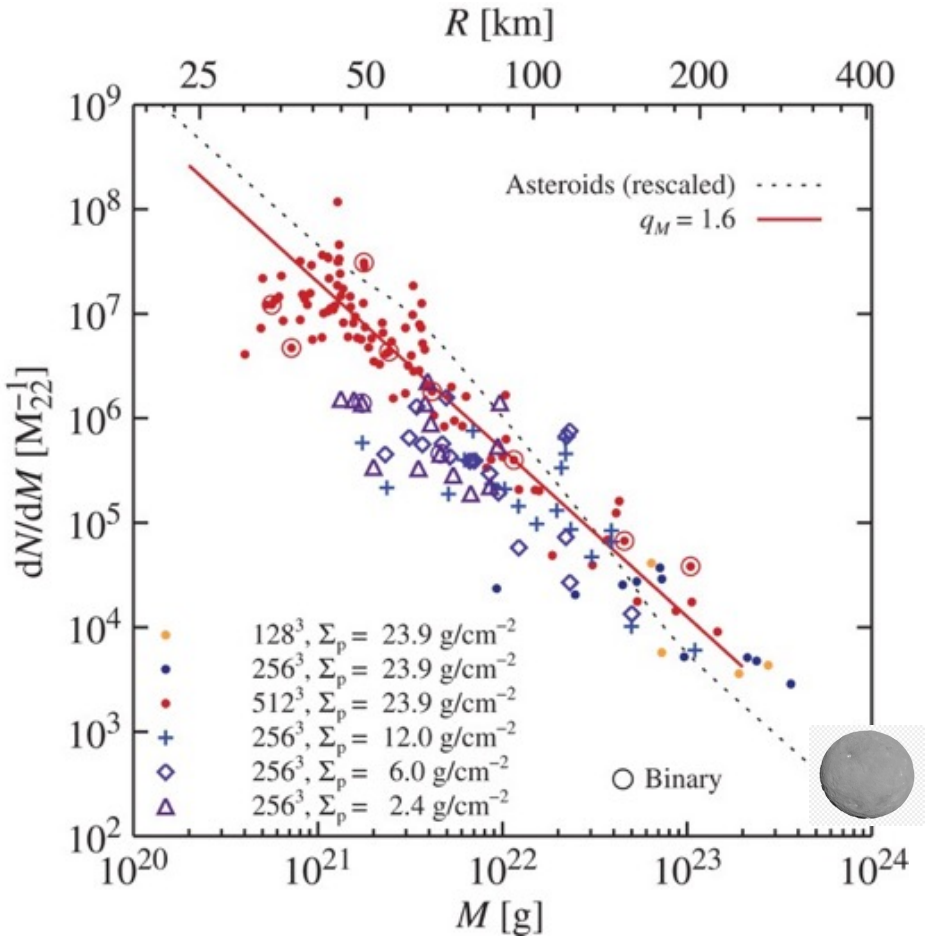
Gravitational collapse into planetesimals

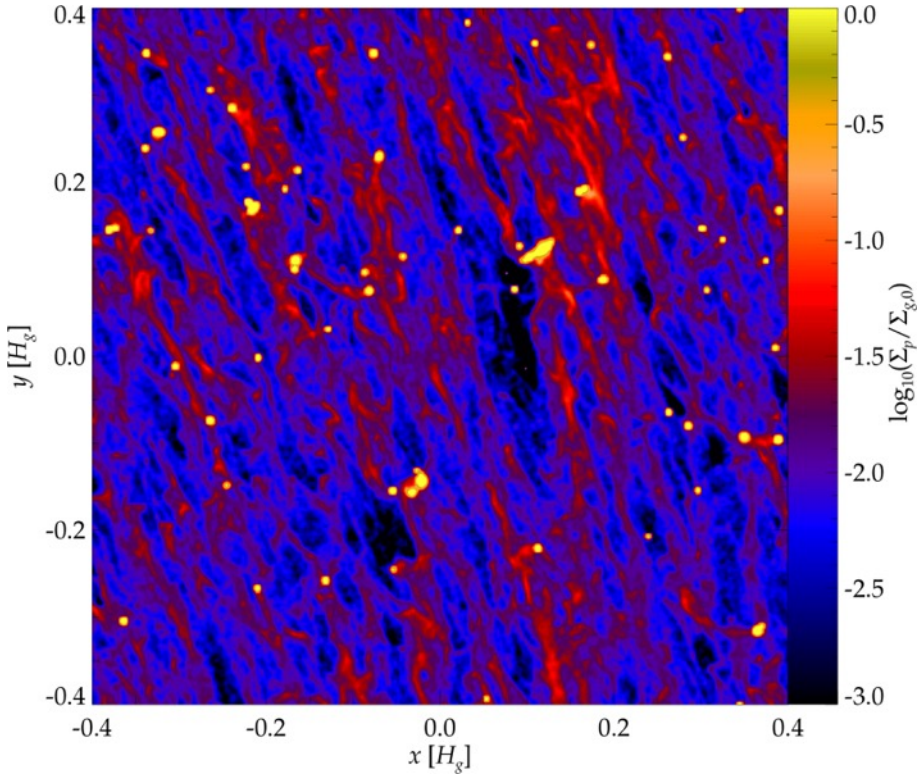


Johansen et al. (2007)

How can we verify the streaming instability hypothesis?

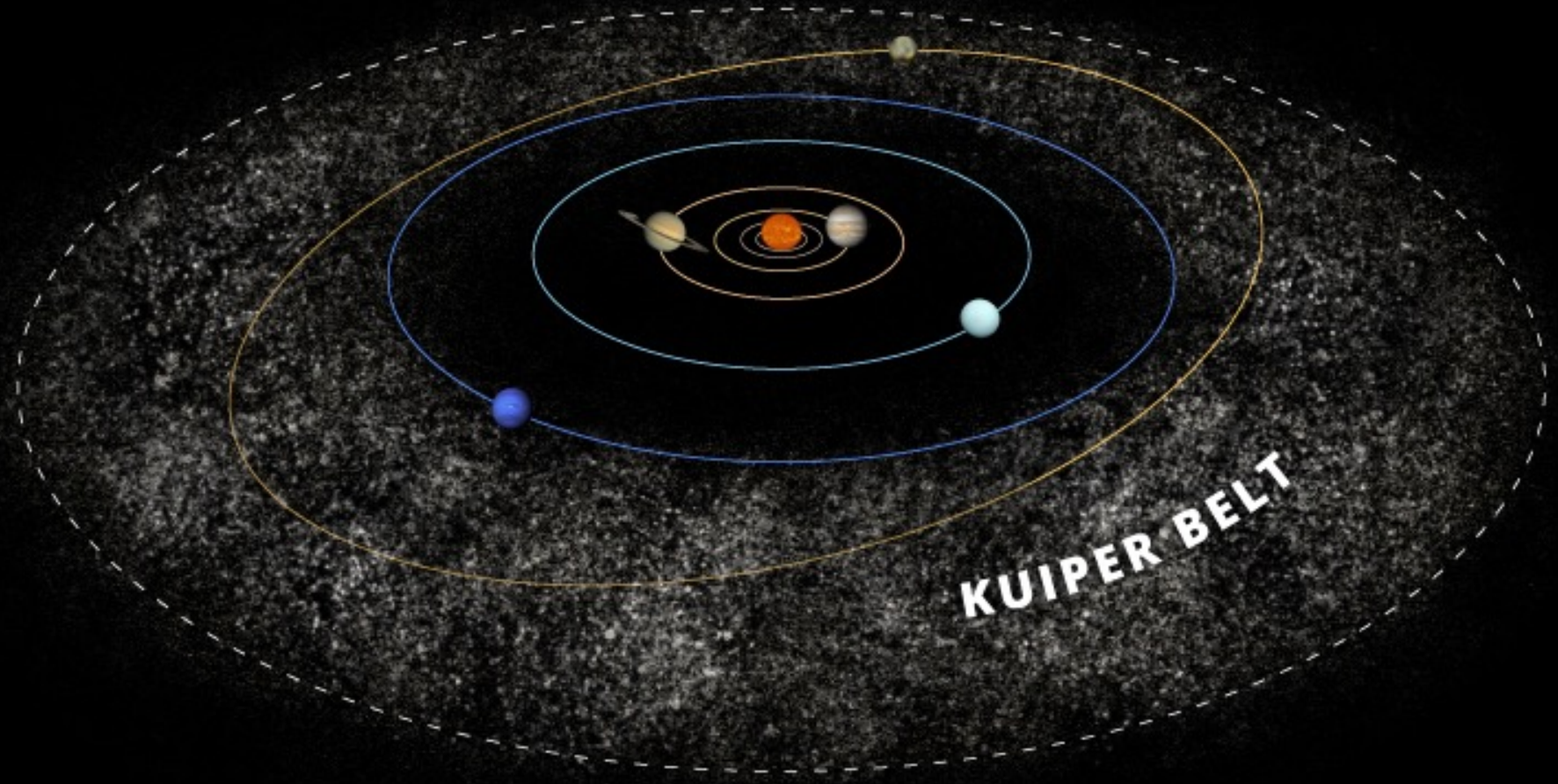
Planetesimal Formation





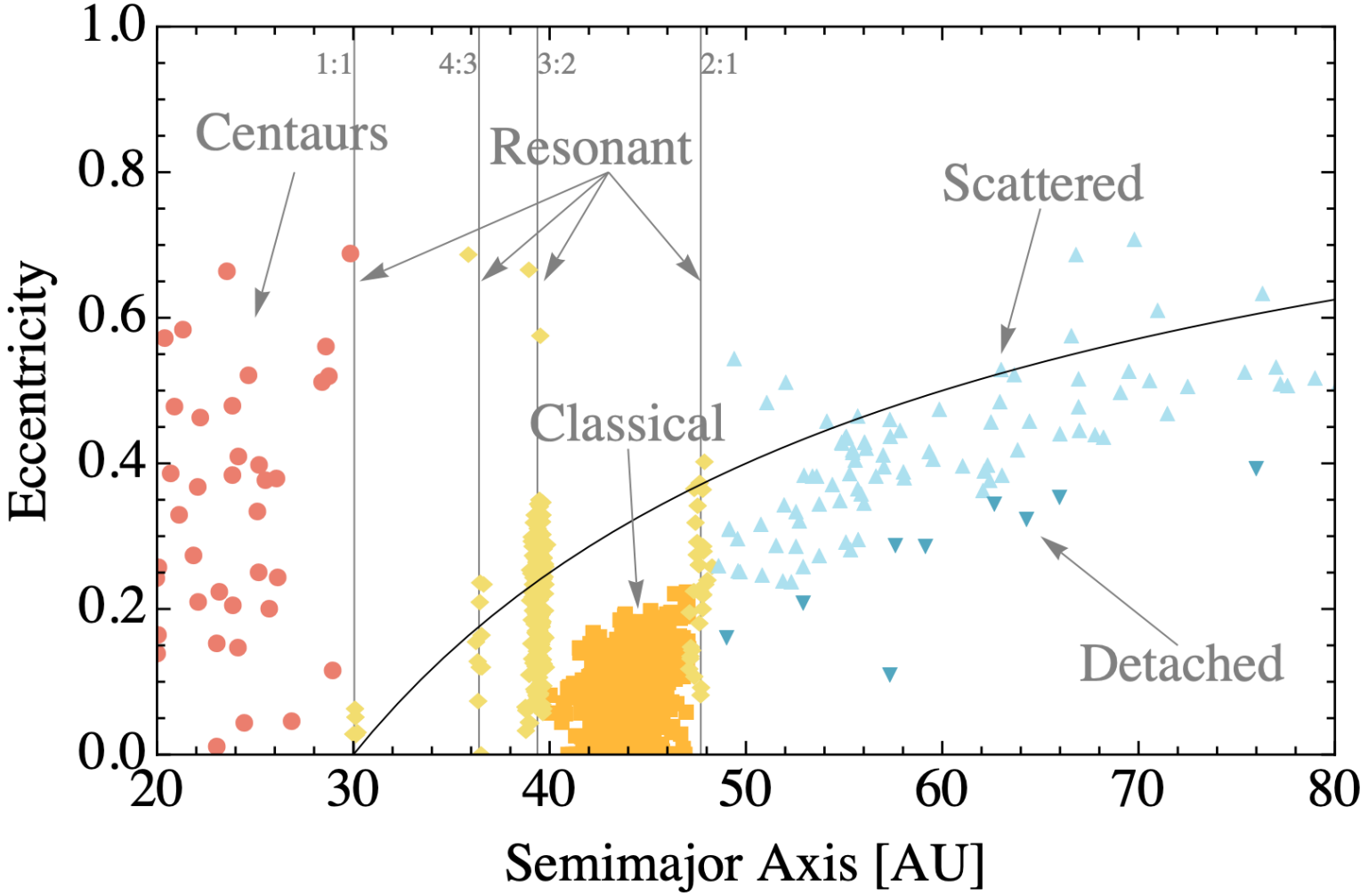
Initial mass function consistent with mass distribution of asteroid belt. Slope 1.6

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



Space Facts / Laurine Moreau

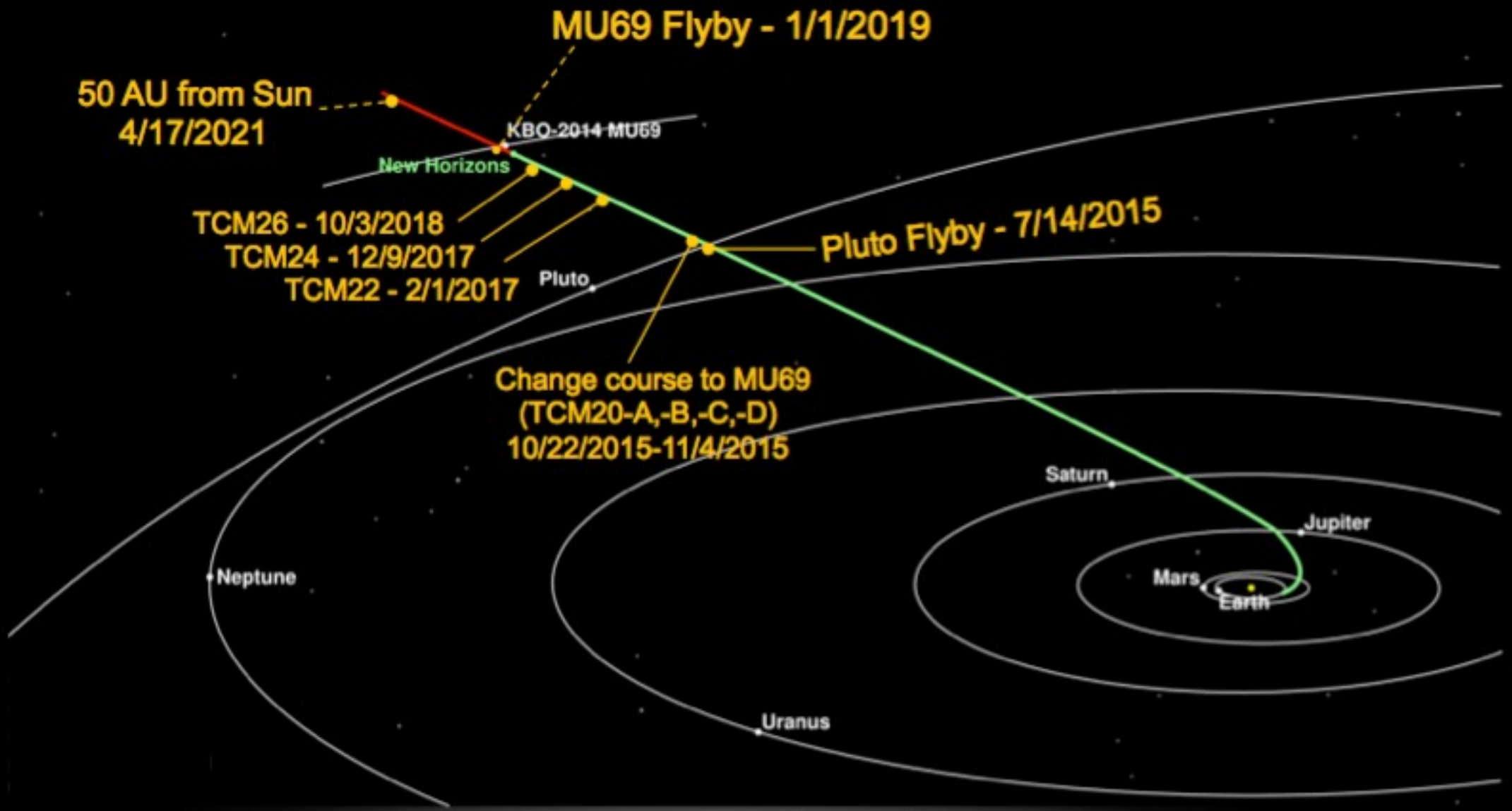
Structure of the Kuiper Belt



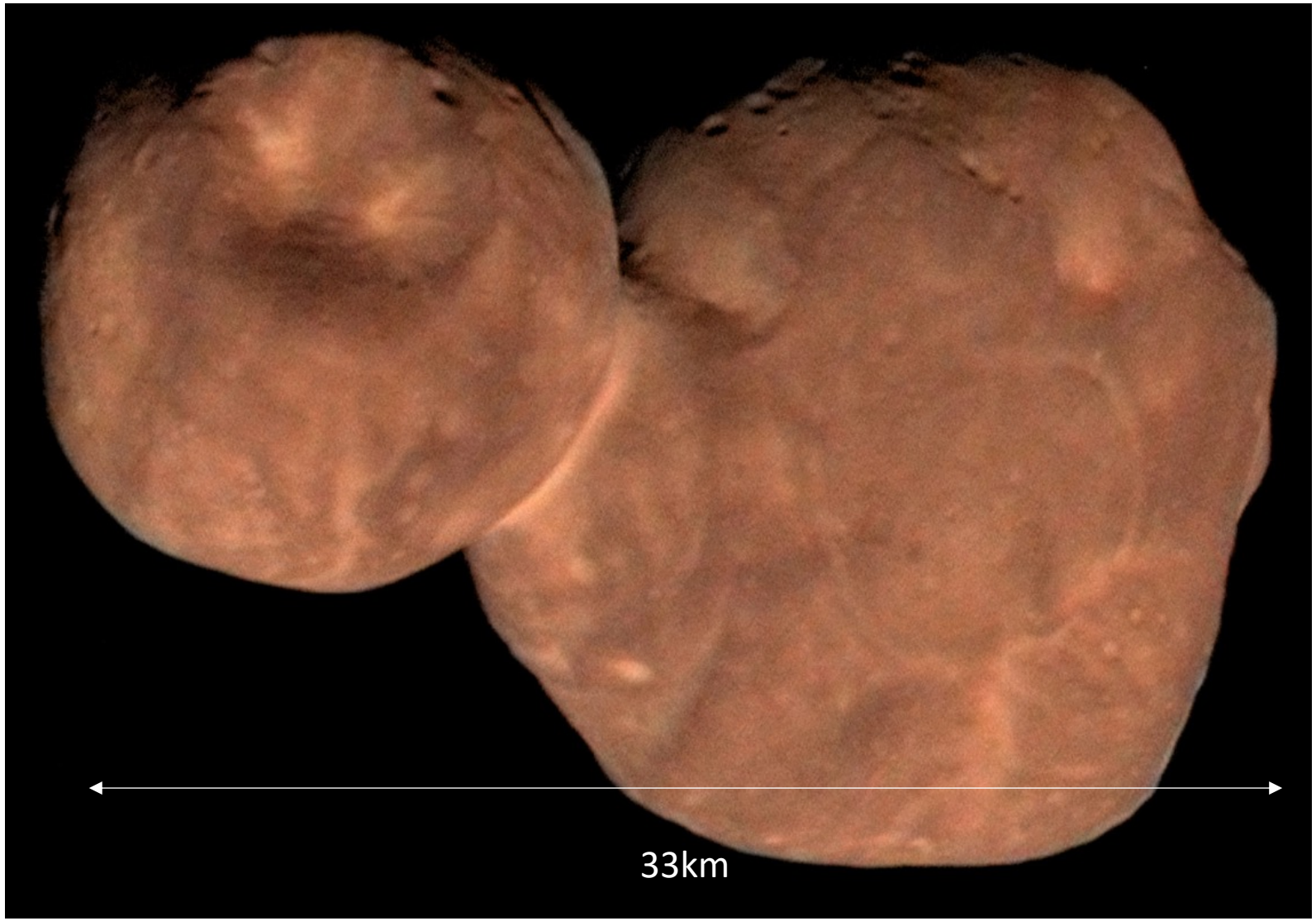
Classicals: Presumably pristine planetesimals

Gladman+ ‘08, Lacerda ‘09, Batygin+ ’10

New Horizons Trajectory

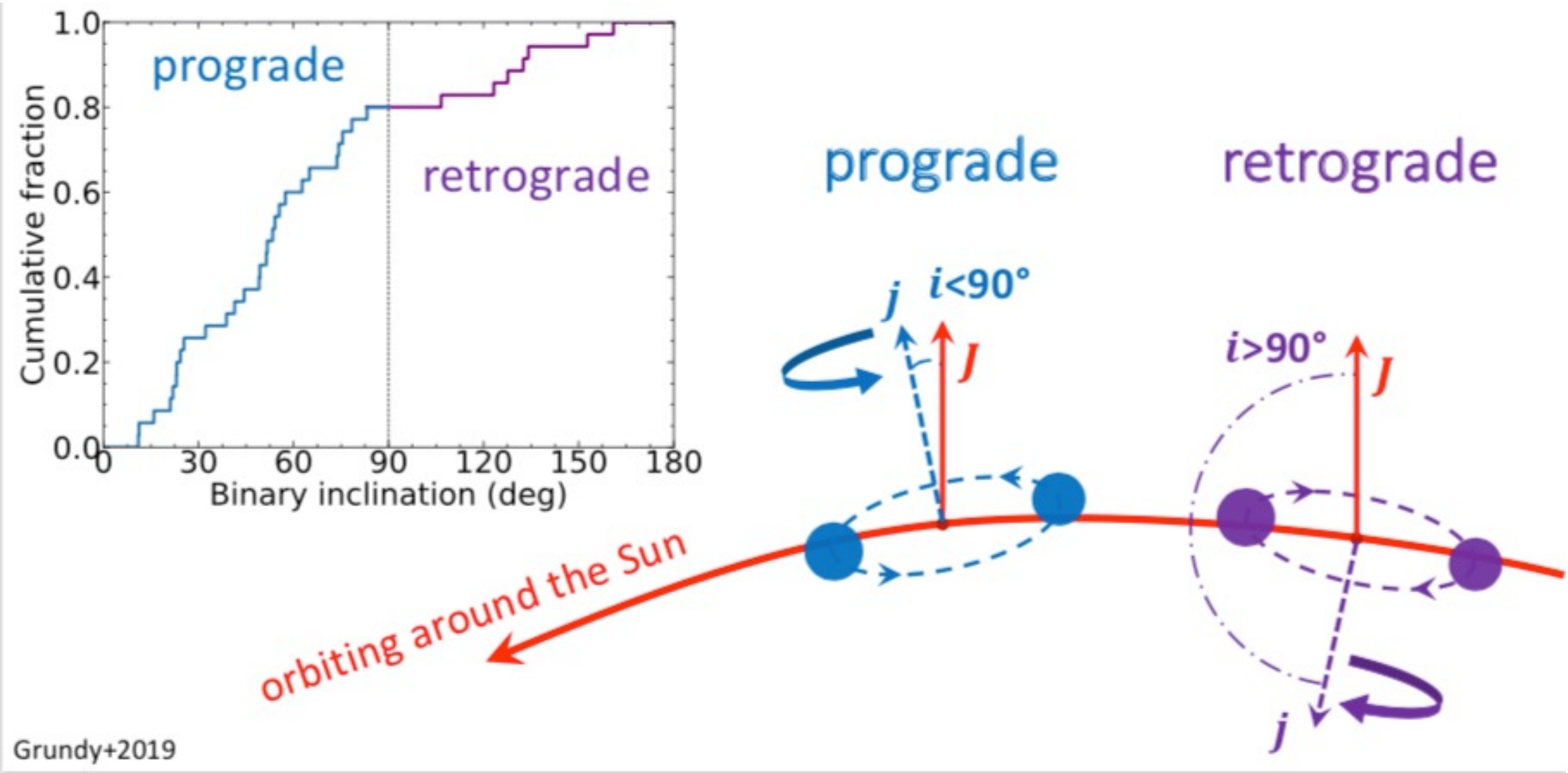


Arrokoth (MU_{69})



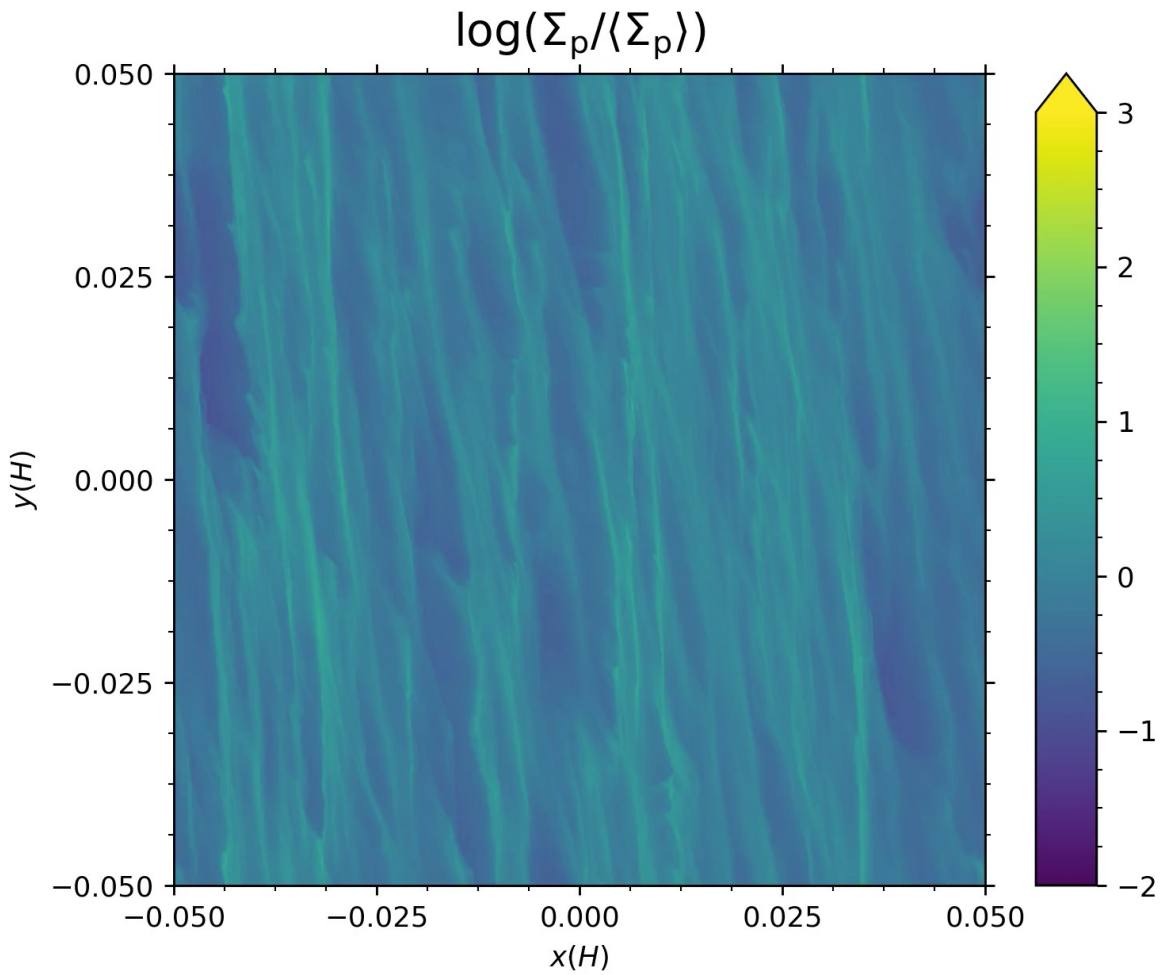
New Horizons Flyby, Jan 2019

Classical KBOs: Preference for Prograde

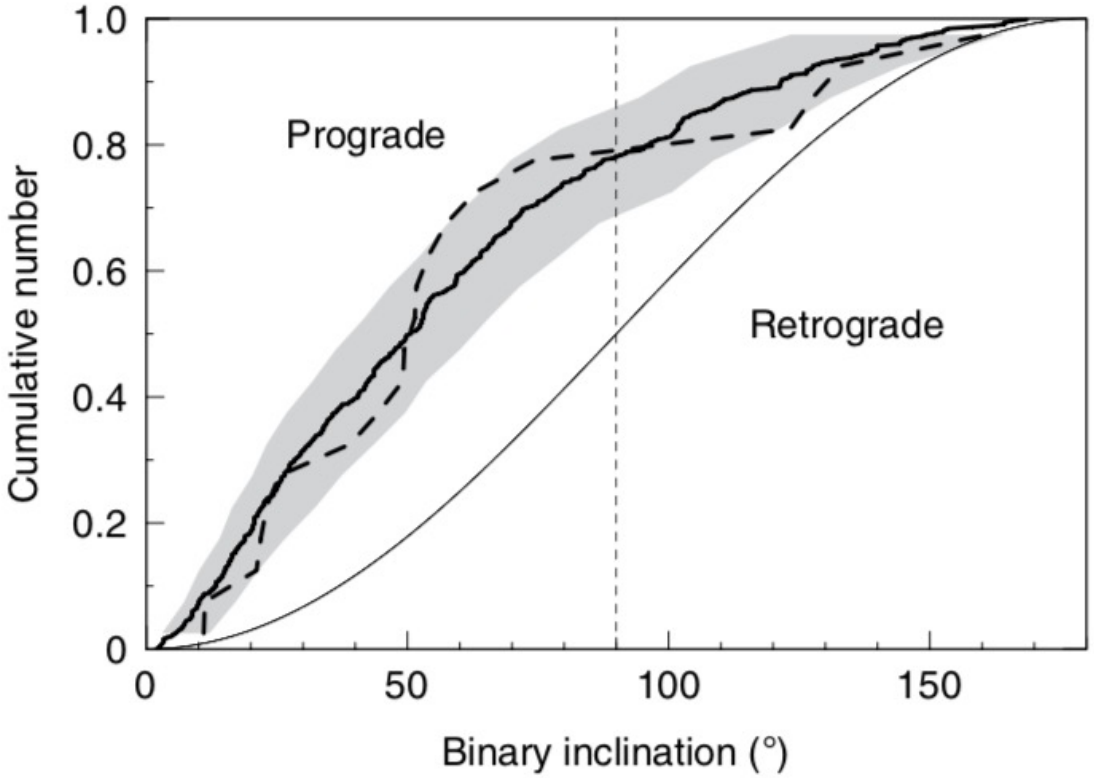


Grundy+2019

Counting binaries: Preference for Prograde (~80%)

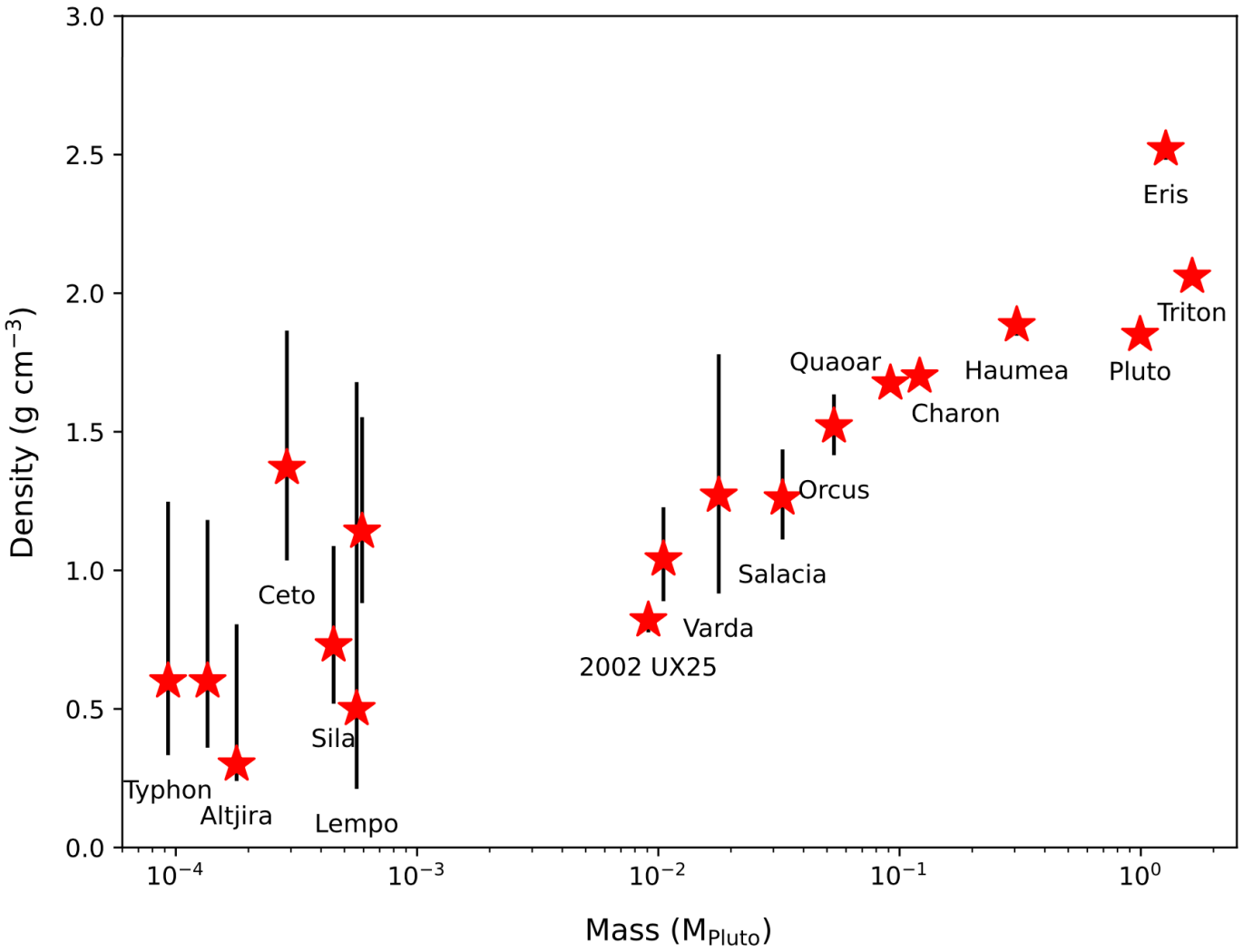


SI Model (solid)
KBOs (dashed)

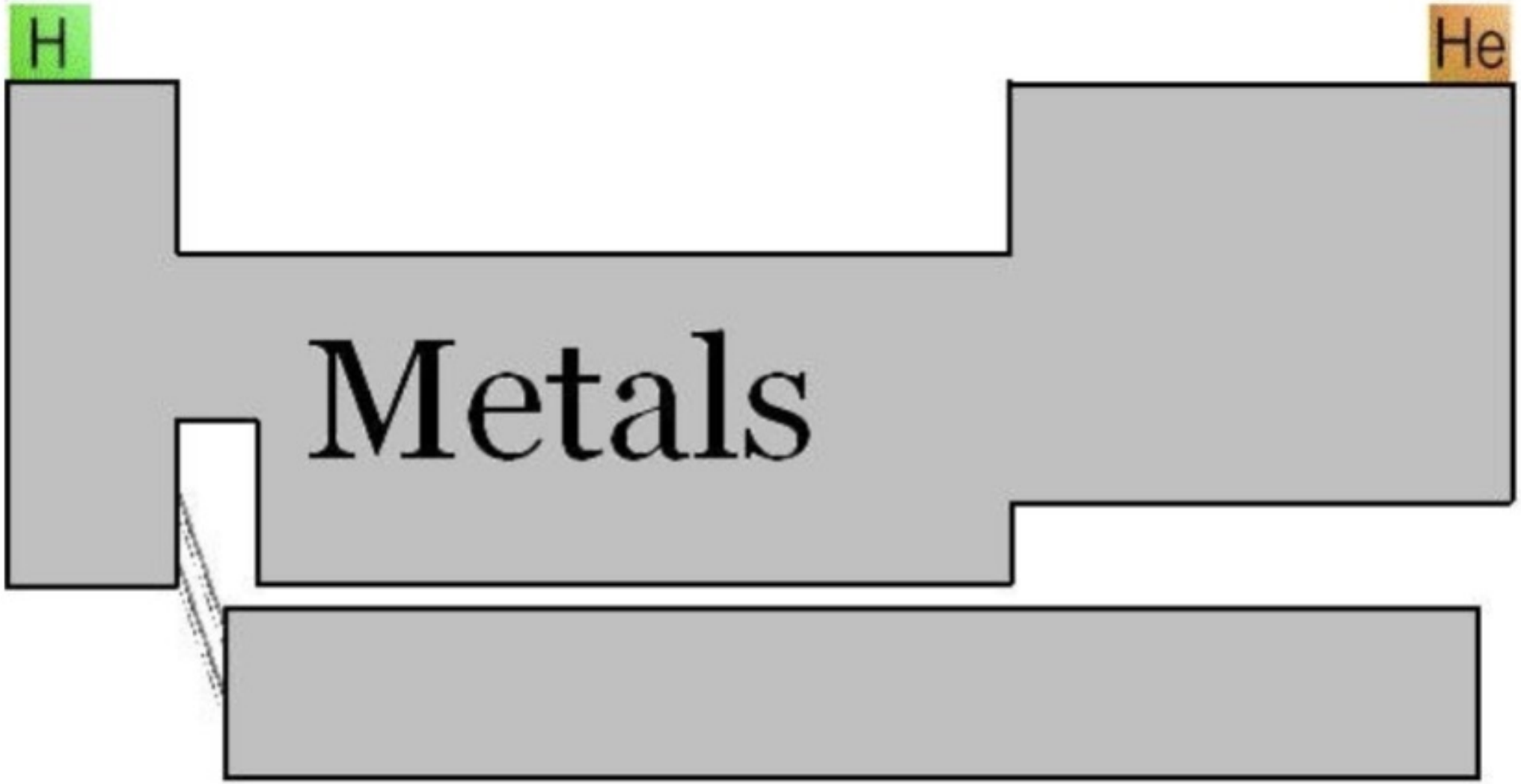


Nesvorny+'19, model by Rixin Li

The density dichotomy of Kuiper Belt objects



The Astronomer's Periodic Table



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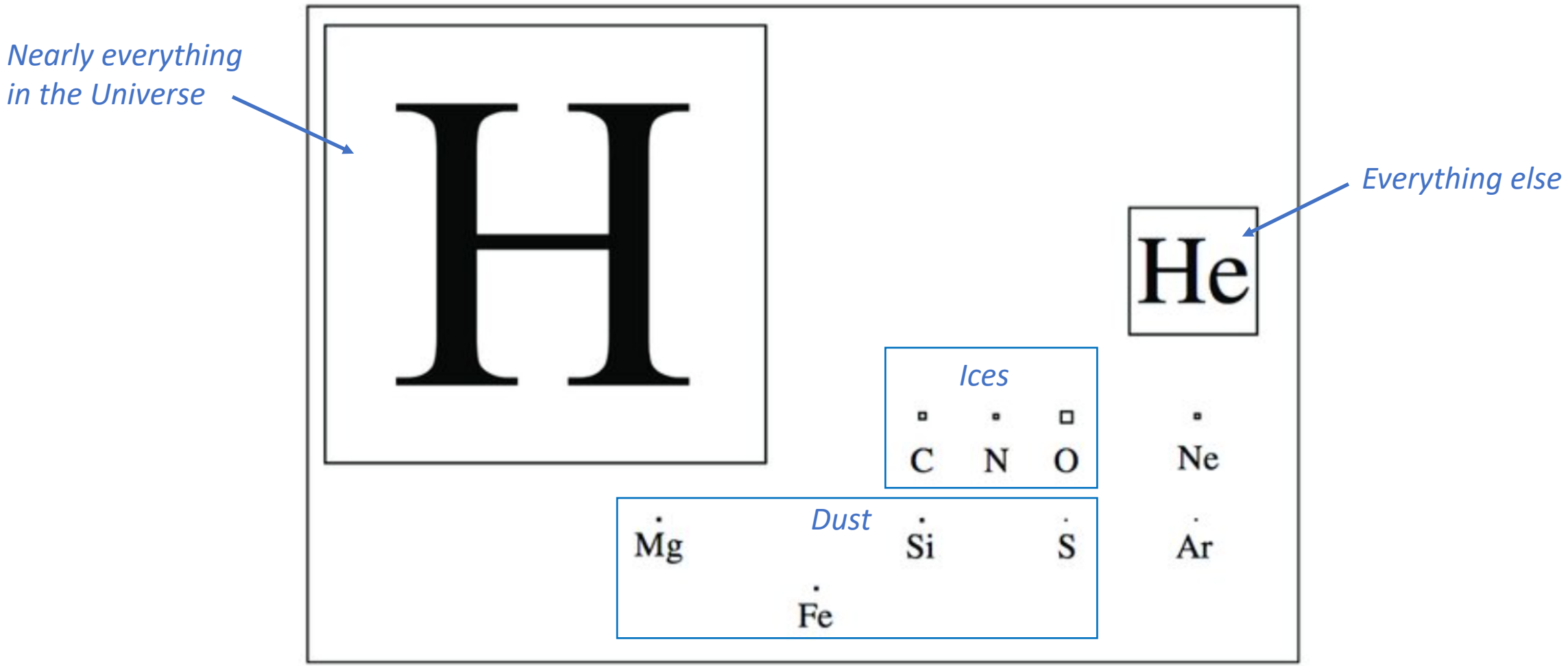
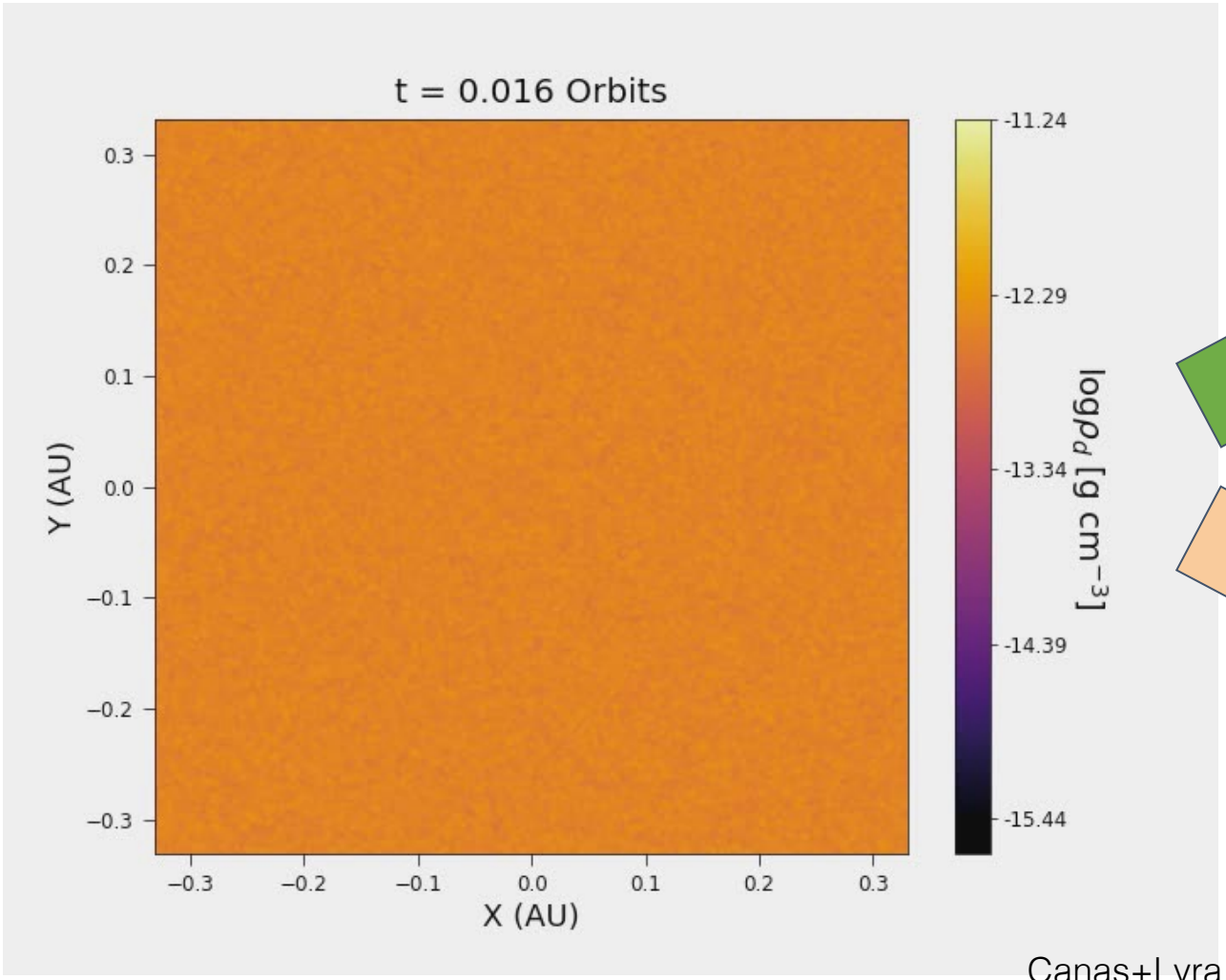
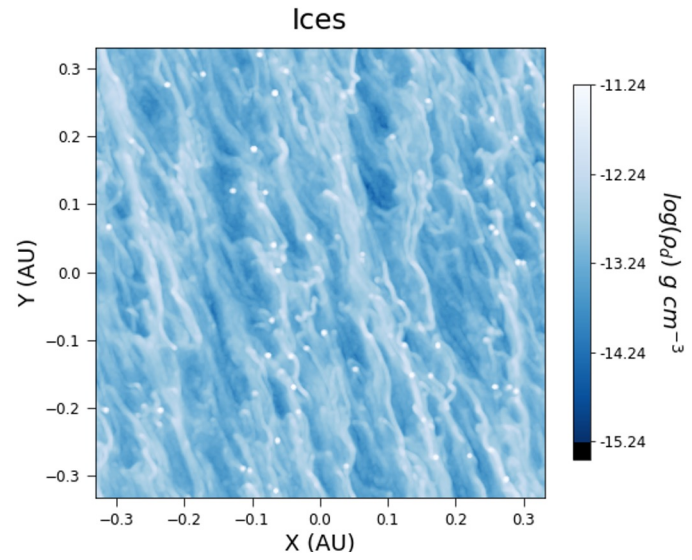
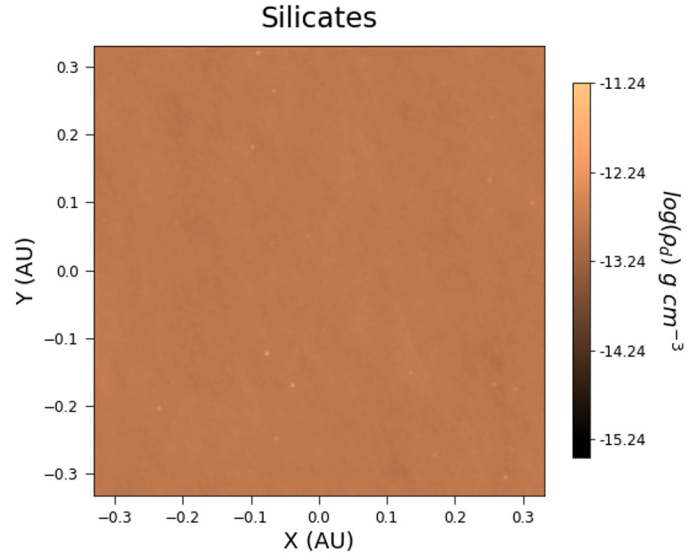


Split into icy and silicate pebbles

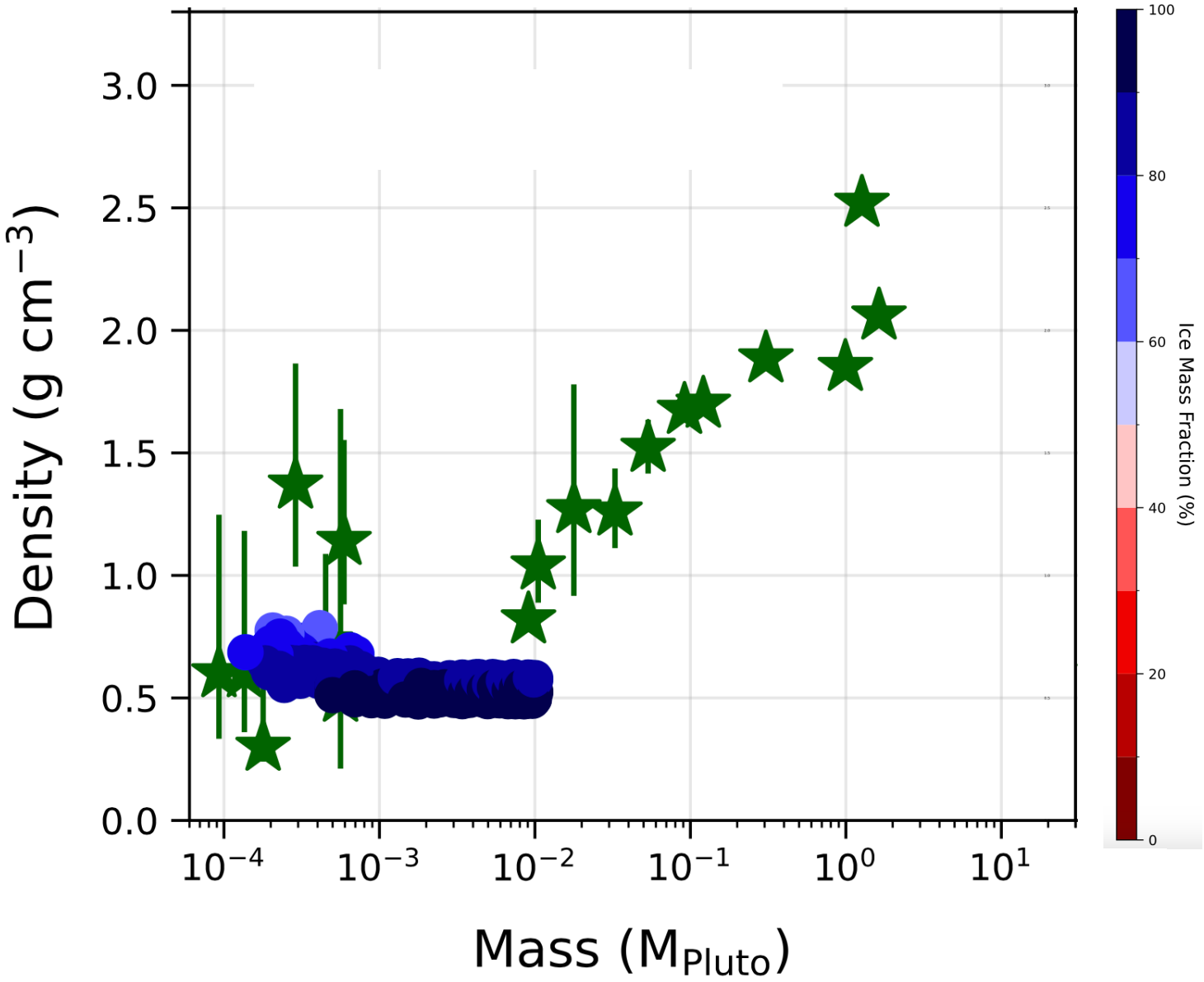






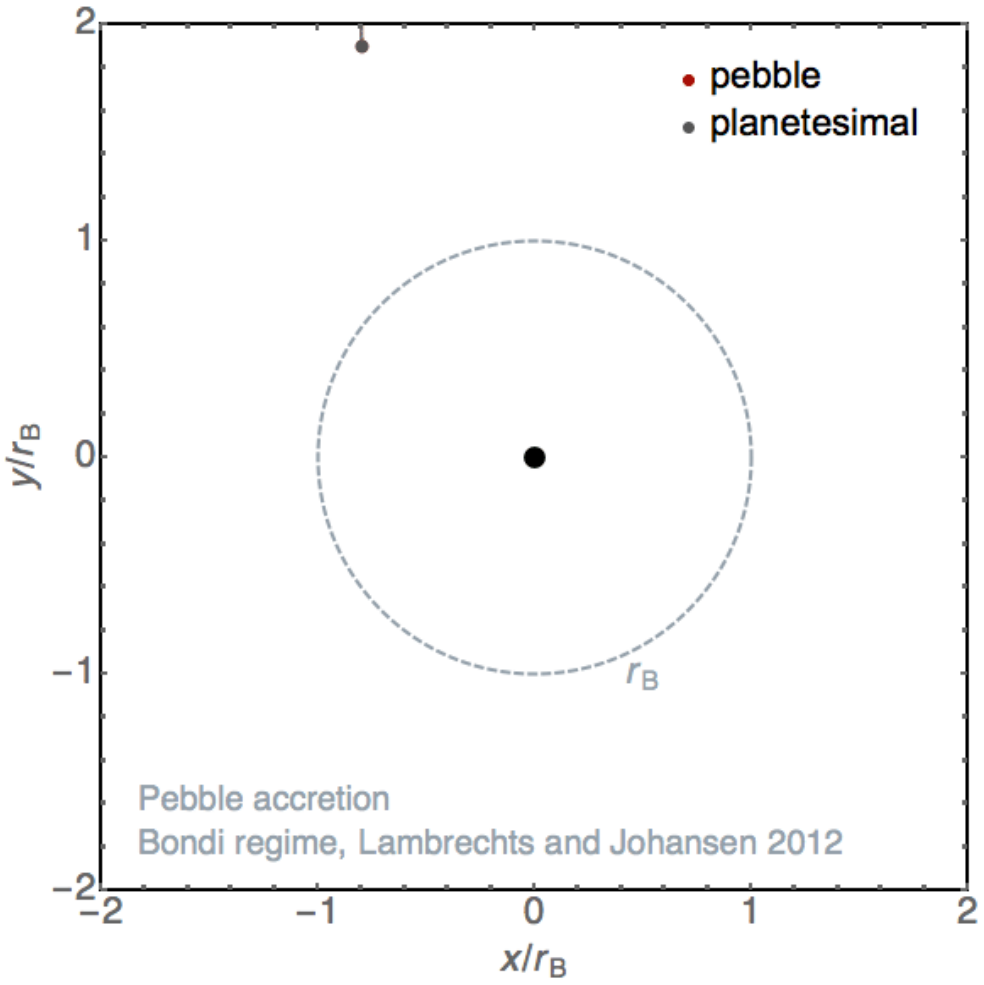
Canas+Lyra et al. 2024

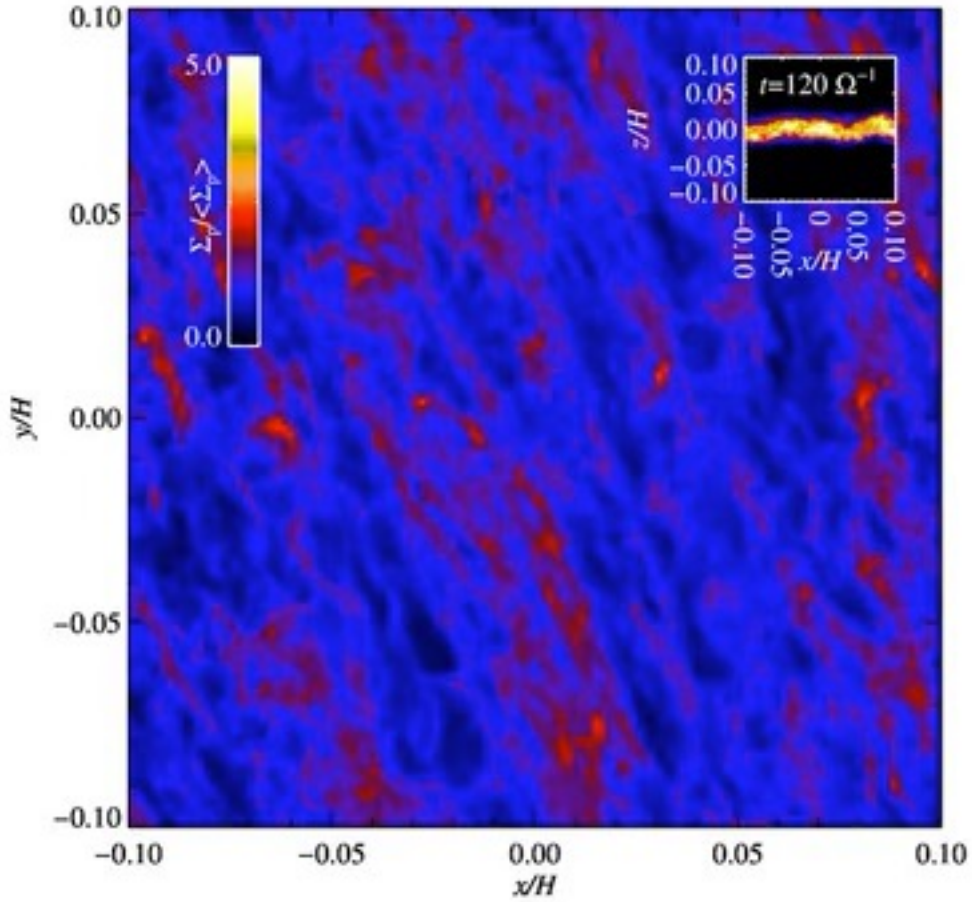
The first planetesimals are icy



Canas+Lyra et al. 2024

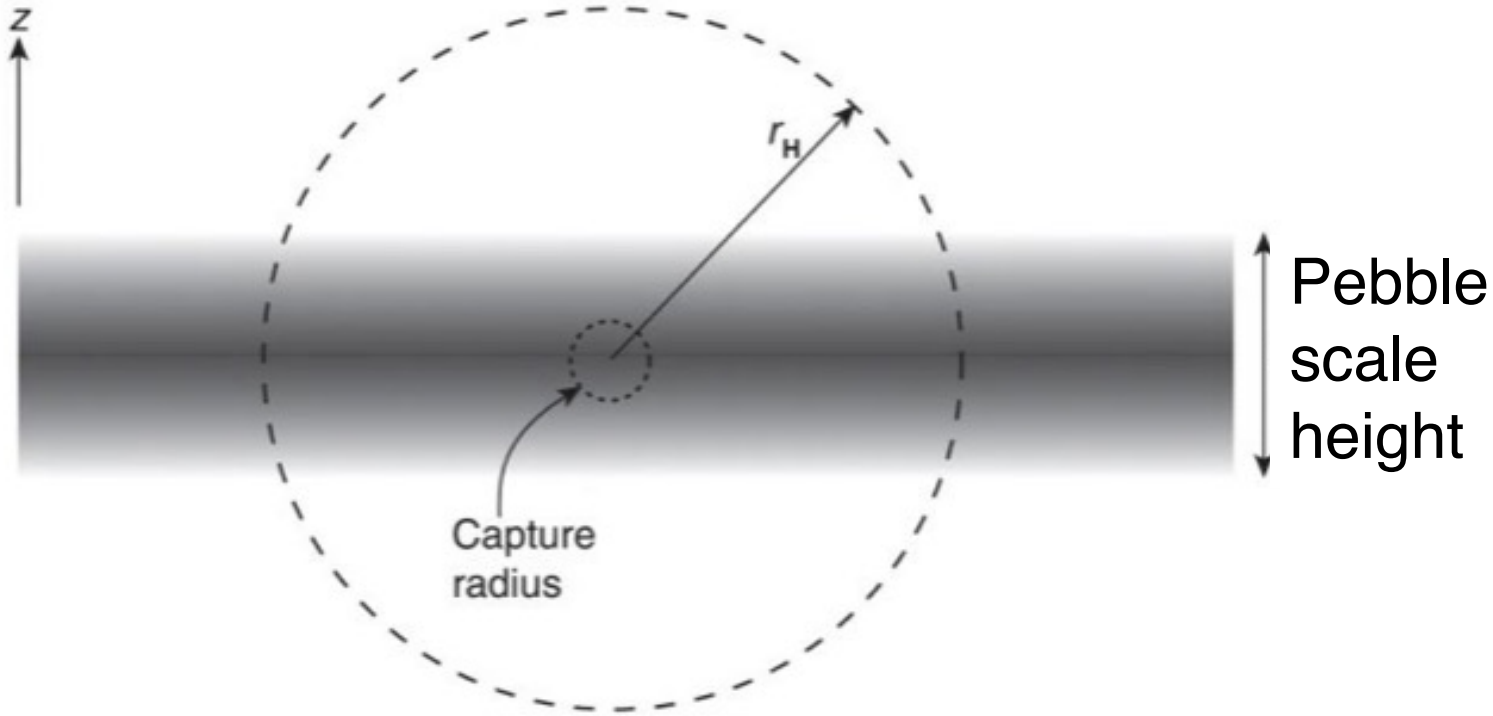
Pebble Accretion



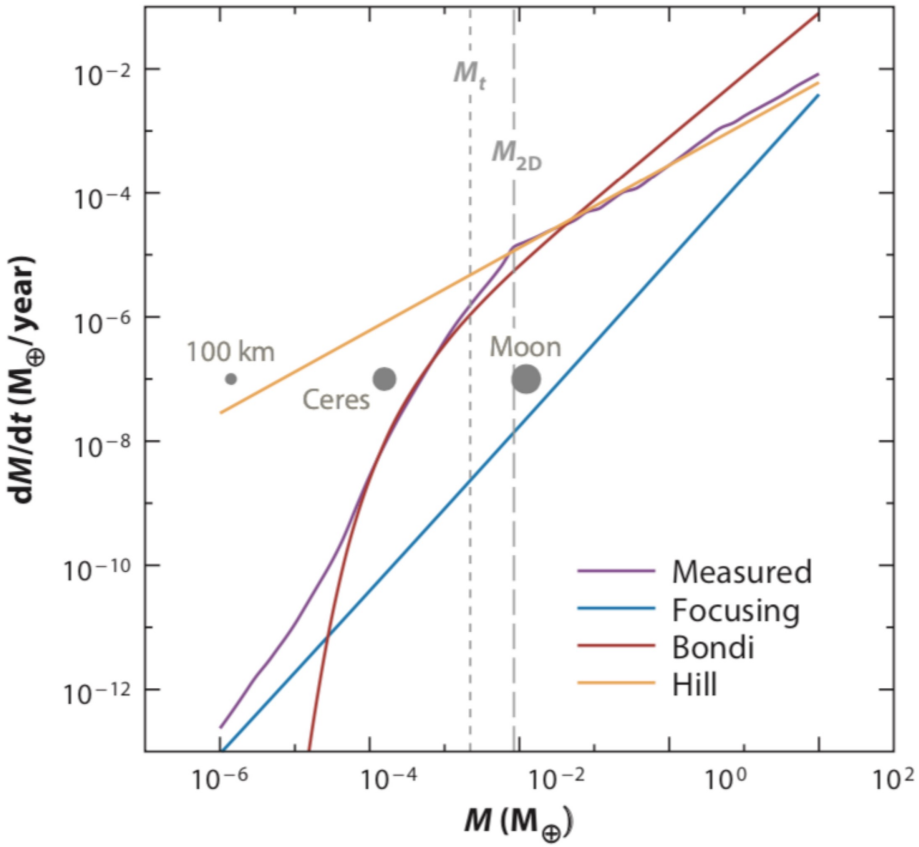


Lyra+ ‘08, ’09, ’23, Ormel & Klahr ‘10, Lambrechts & Johansen ’12
See Johansen & Lambrechts ‘17 for a review

Pebble Accretion: Bondi regime and Hill regime

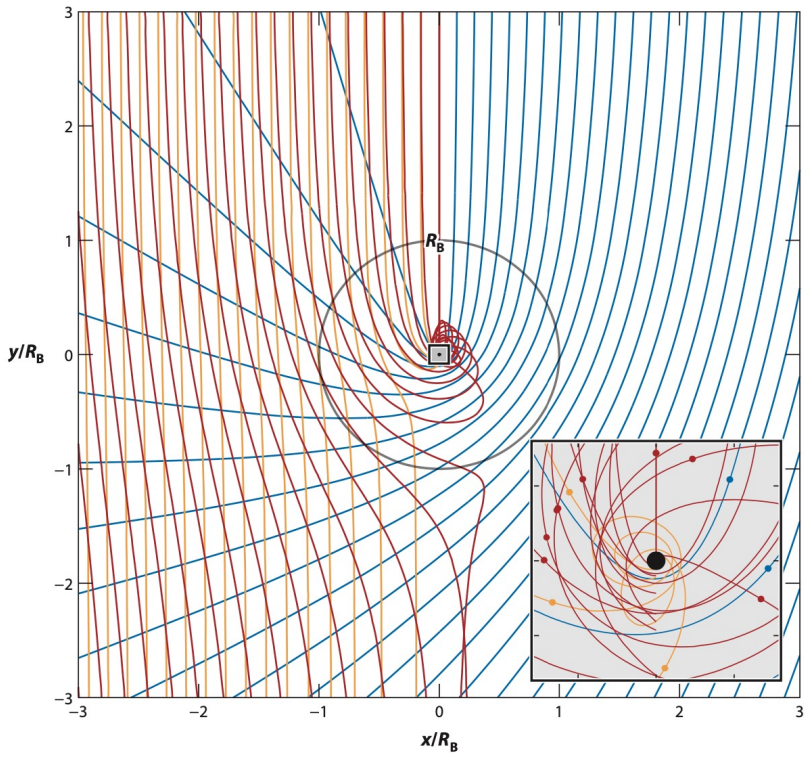


Mass Accretion rates



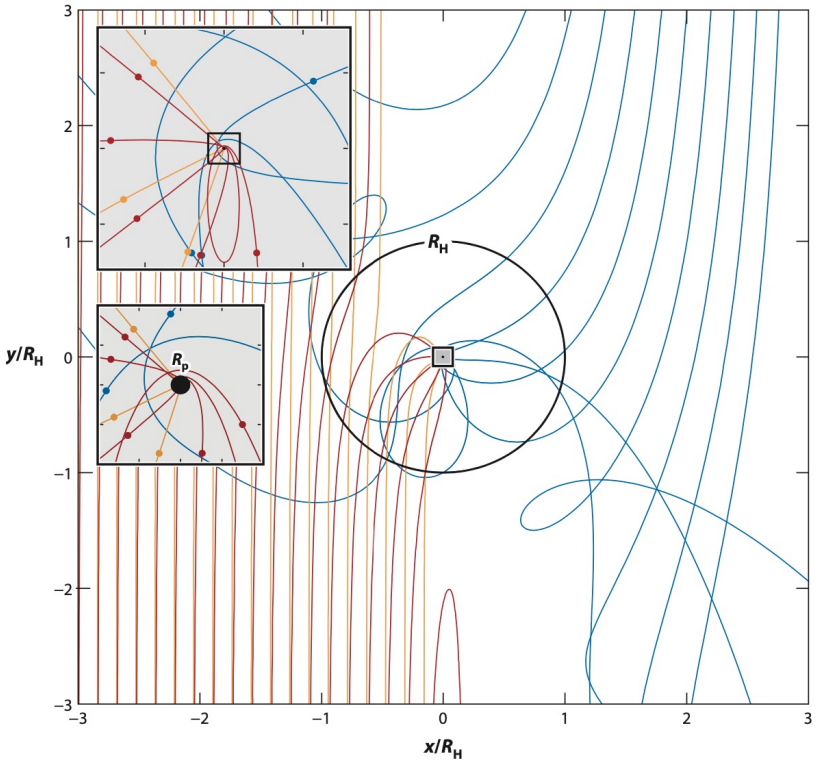
Pebble Accretion: Bondi regime and Hill regime

Bondi Regime



Best accreted
Drag time = Bondi Time

Hill Regime



Best accreted
Drag time ~ Orbital Time

Analytical theory of polydisperse (multi-species) pebble accretion

Monodisperse (single species)

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

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

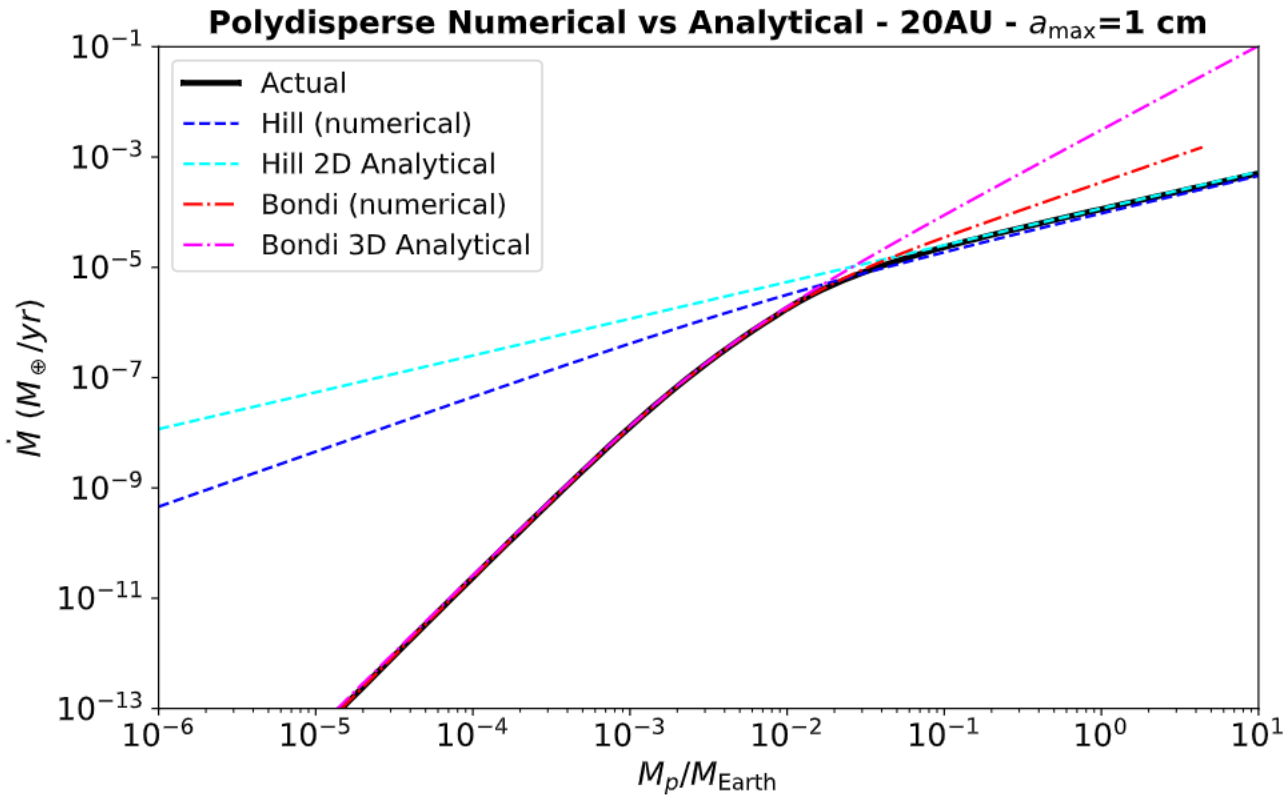
Lambrechts & Johansen (2012)

Polydisperse (multiple species)

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

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

Lyra et al. (2023)



Lyra et al. 2023

Bondi (Low-Mass regime) is 1-2 orders of magnitude more efficient than monodisperse

Monodisperse (single species)

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

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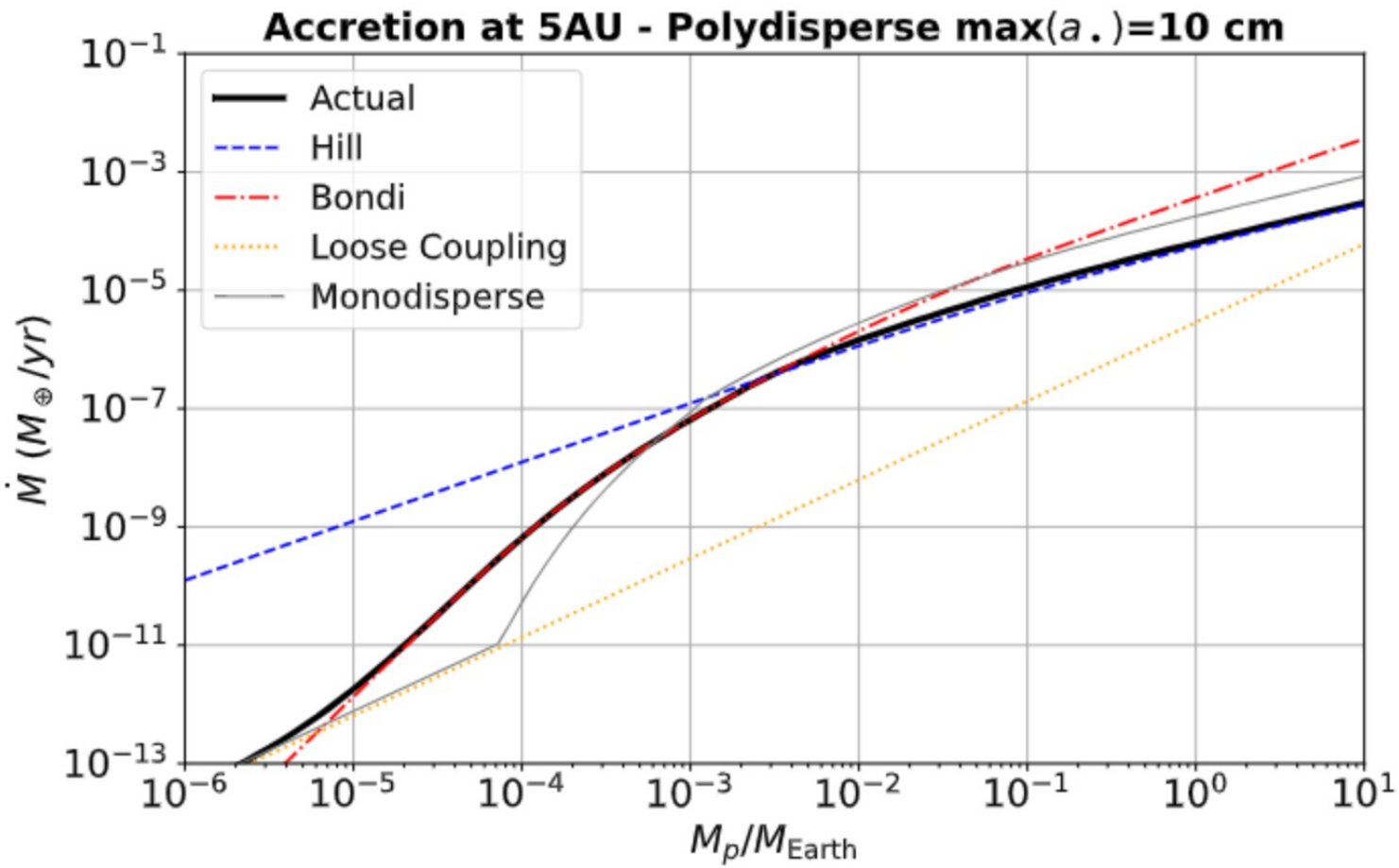
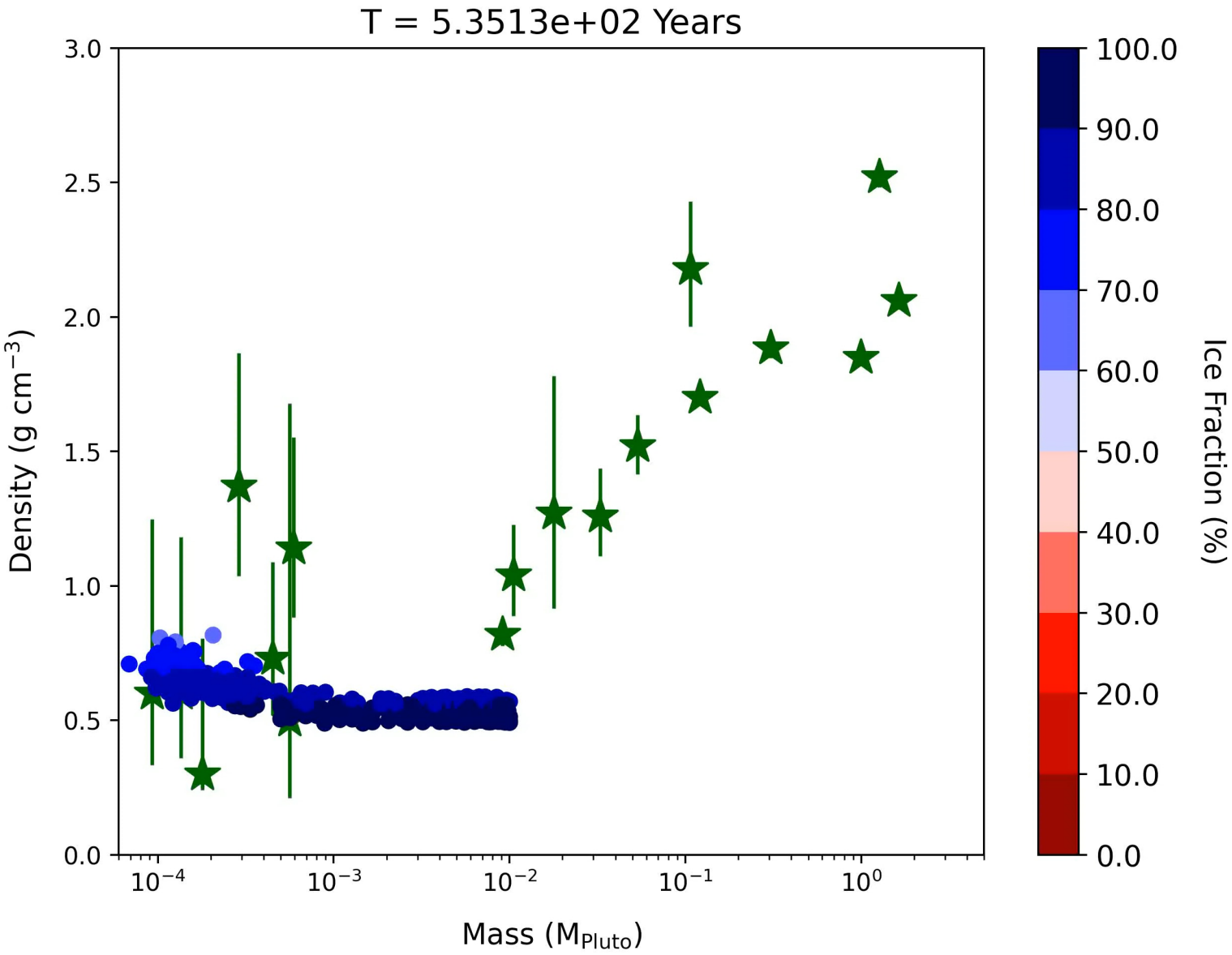
Lyra et al. (2023)



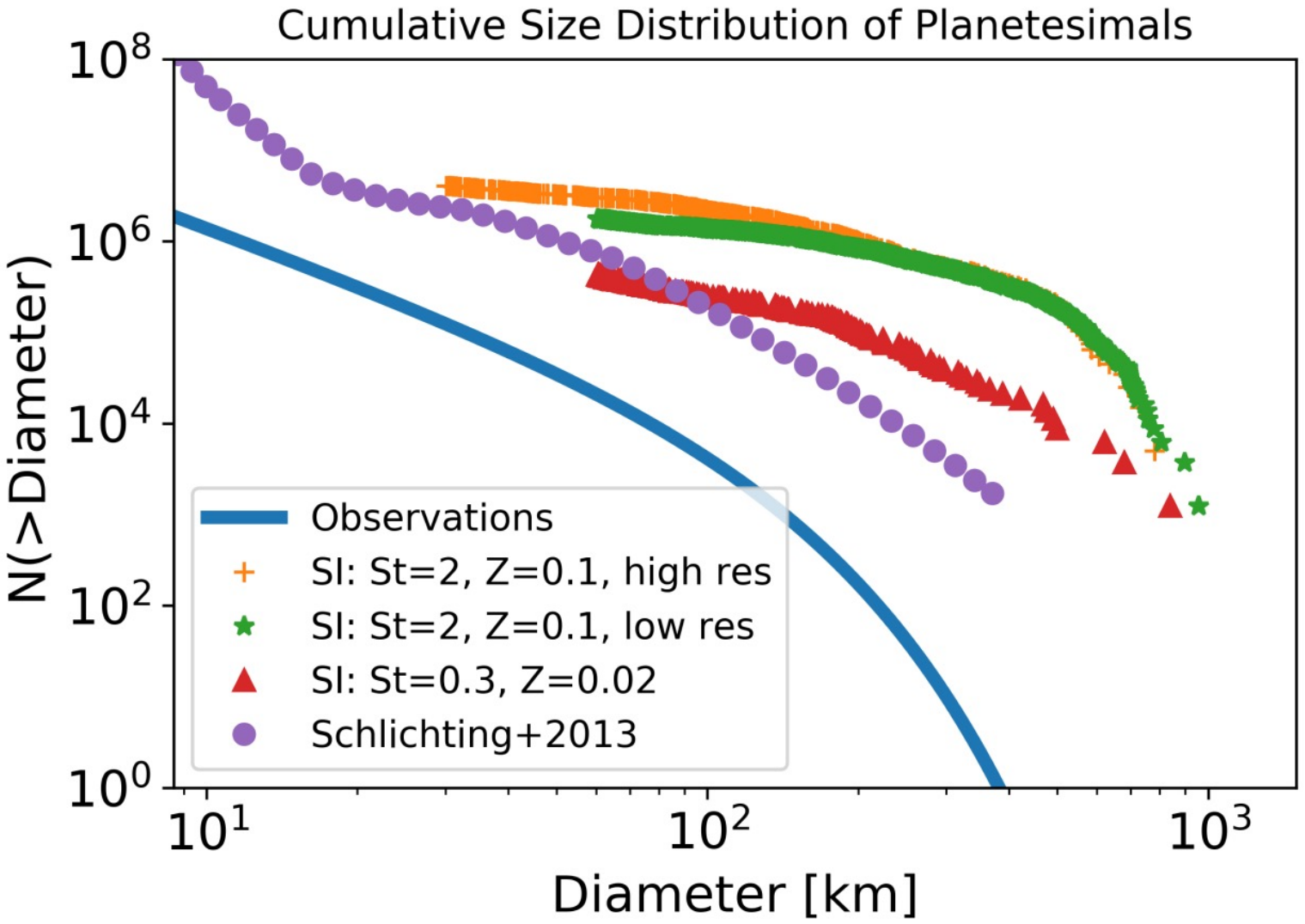
Lyra et al. 2023

Growing Pluto by silicate pebble accretion



Canas+Lyra et al. 2024

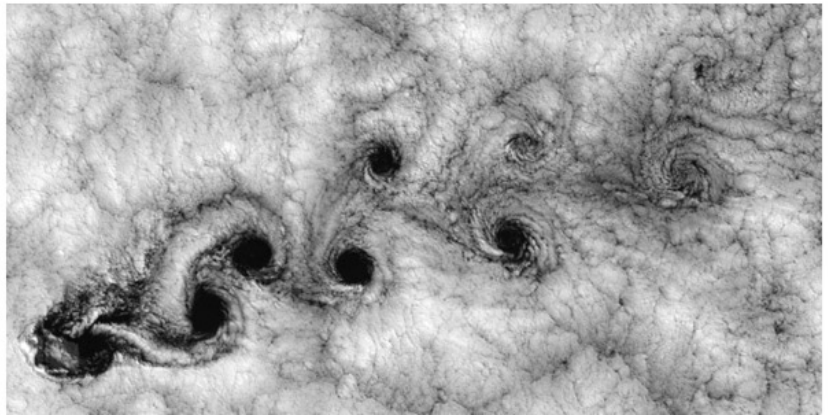
Problem: wrong number density



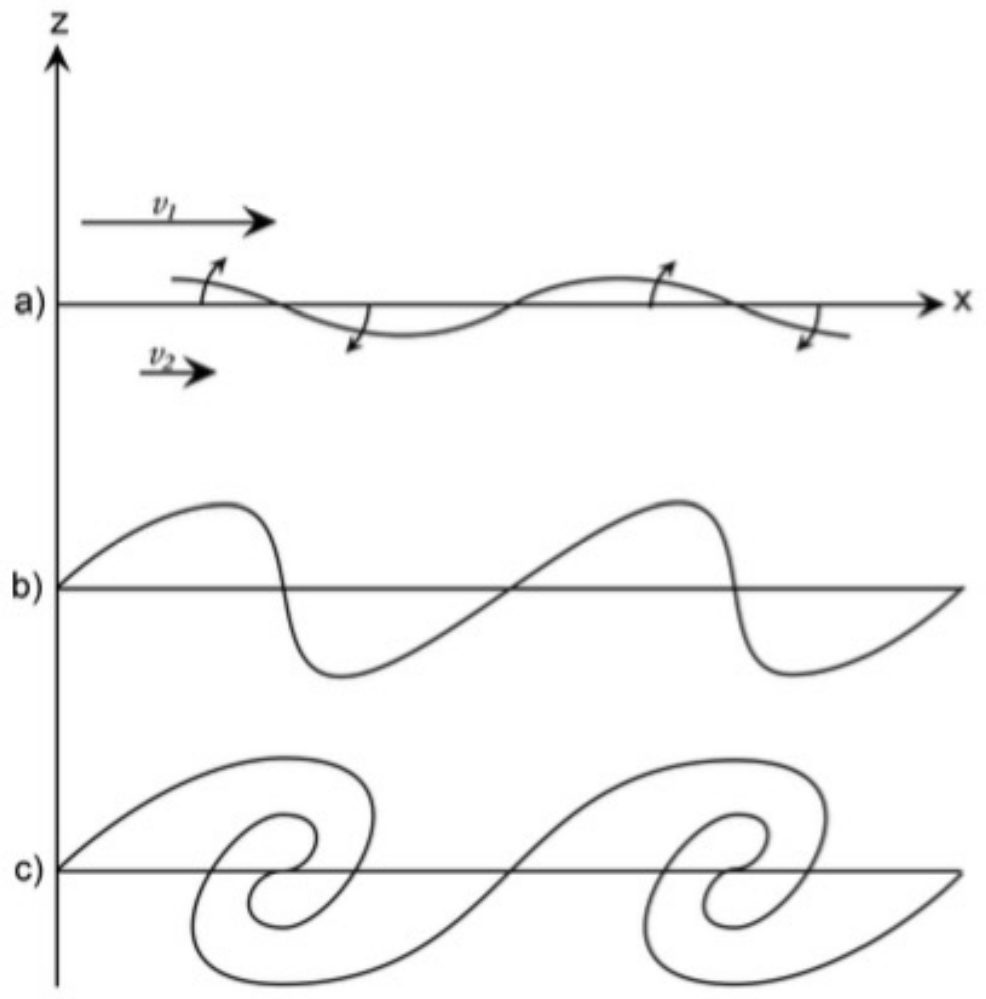
Simon et al. 2023

Vortices – an ubiquitous fluid mechanics phenomenon

Von Kármán *vortex street*

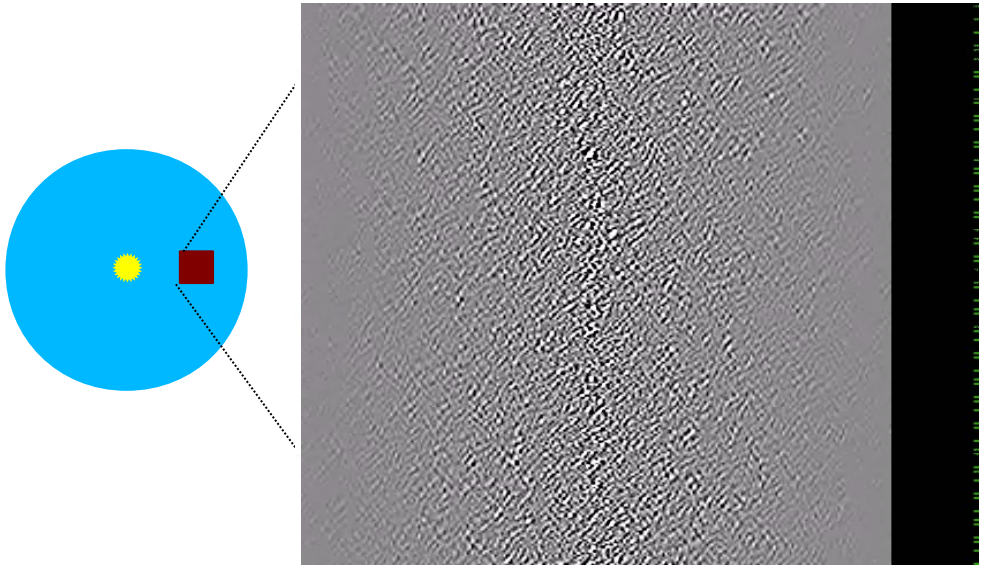


Kelvin-Helmholtz Instability



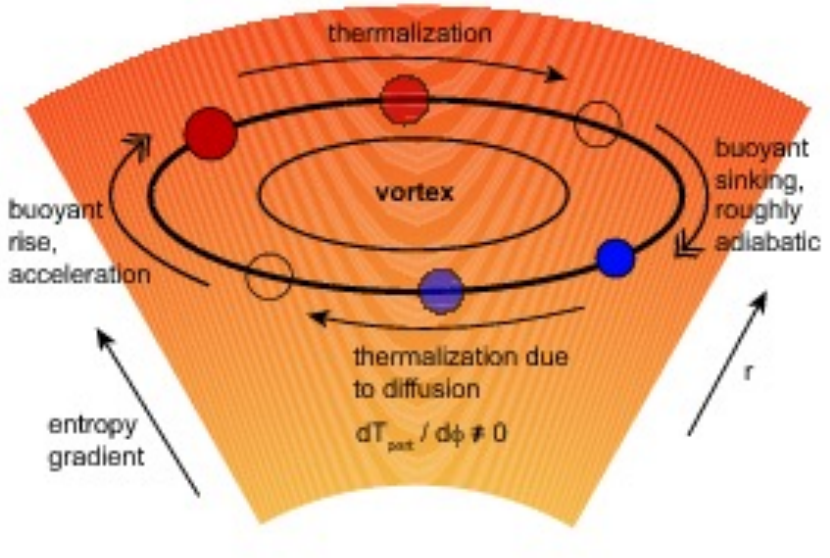
Lovelace & Hohlfeld 1978, Toomre 1981, Papaloizou & Pringle (1984), Hawley (1987), Lovelace et al (1999), Li et al. (2000), Varniere & Tagger (2005), Cheng & Youdin (2023).

Convection



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

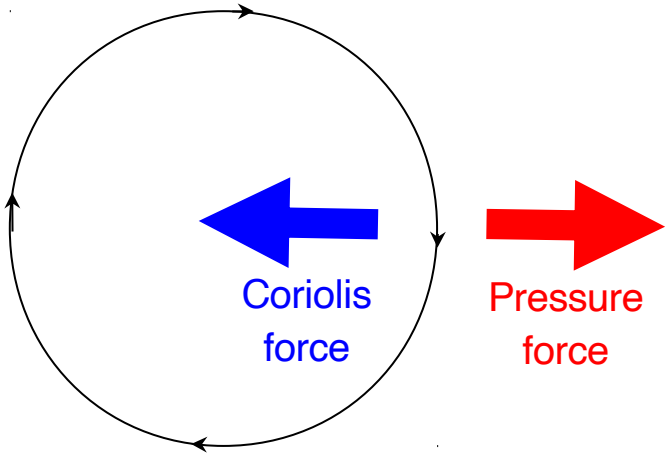
Sketch of the
Convective Instability



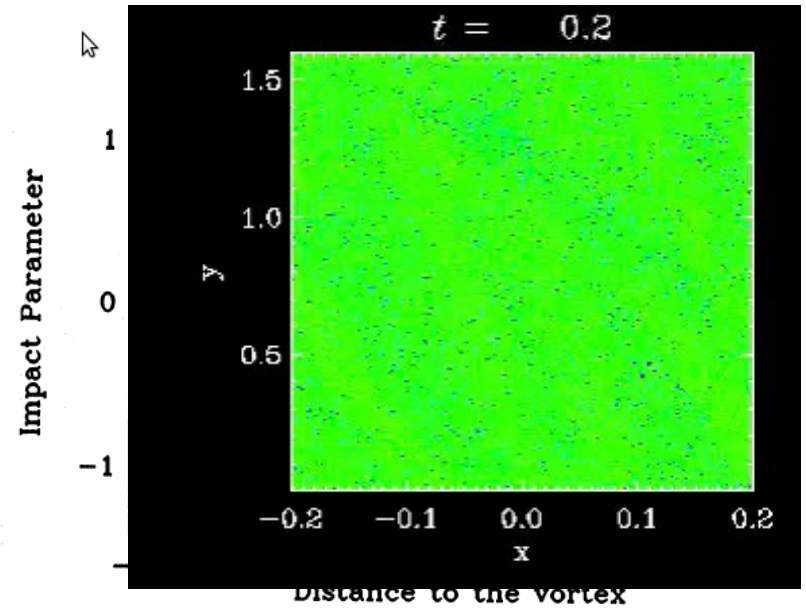
Armitage (2010)

Vortex Trapping

Geostrophic balance:



Vortex
streamline



Barge & Sommeria (1995)

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

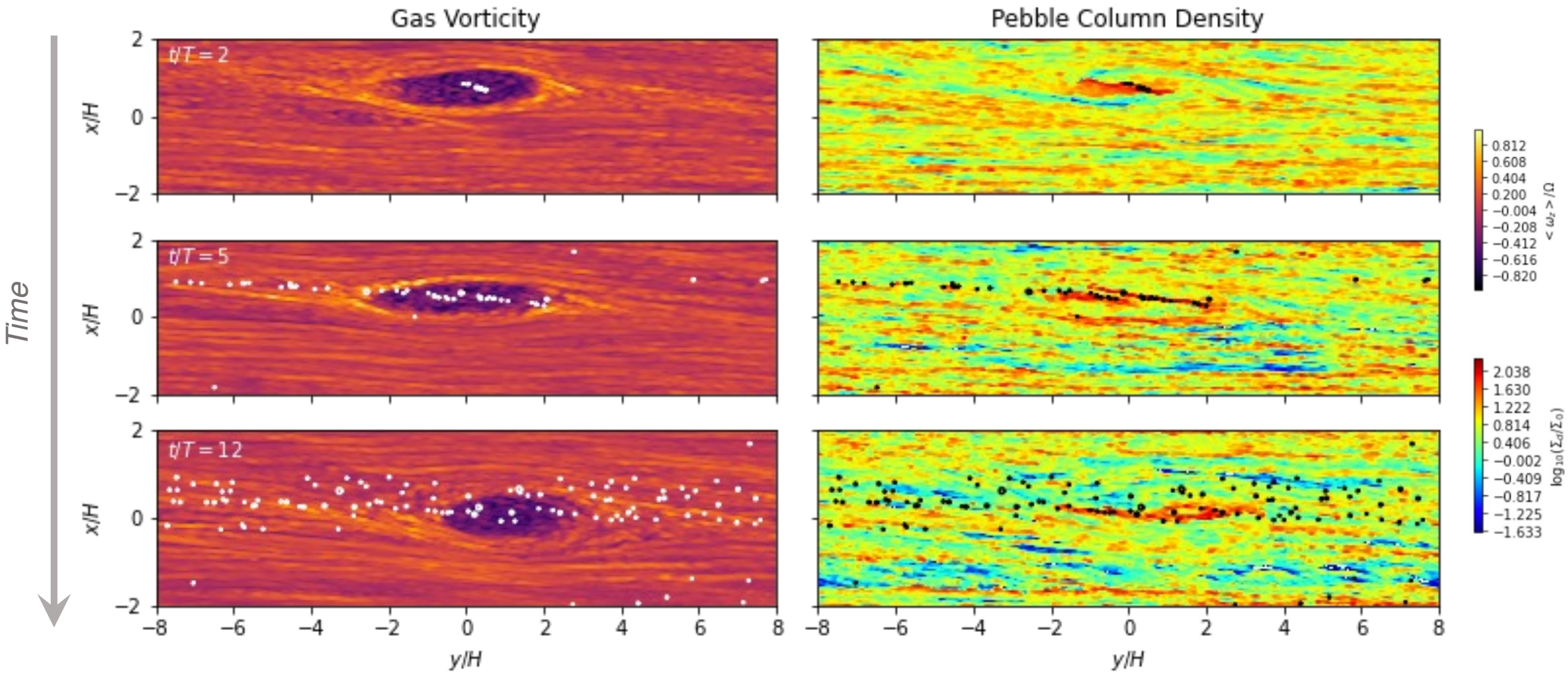
Aid to planet formation

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

Speeds up planet formation enormously

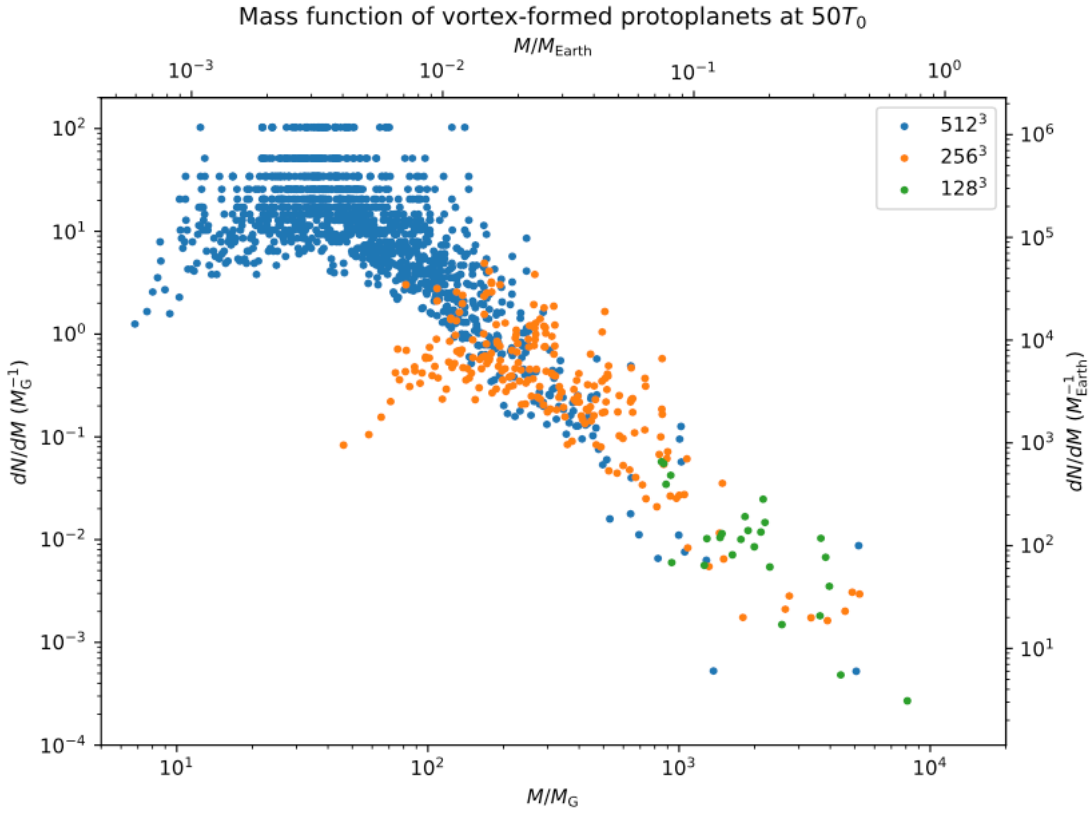
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012, 2021)

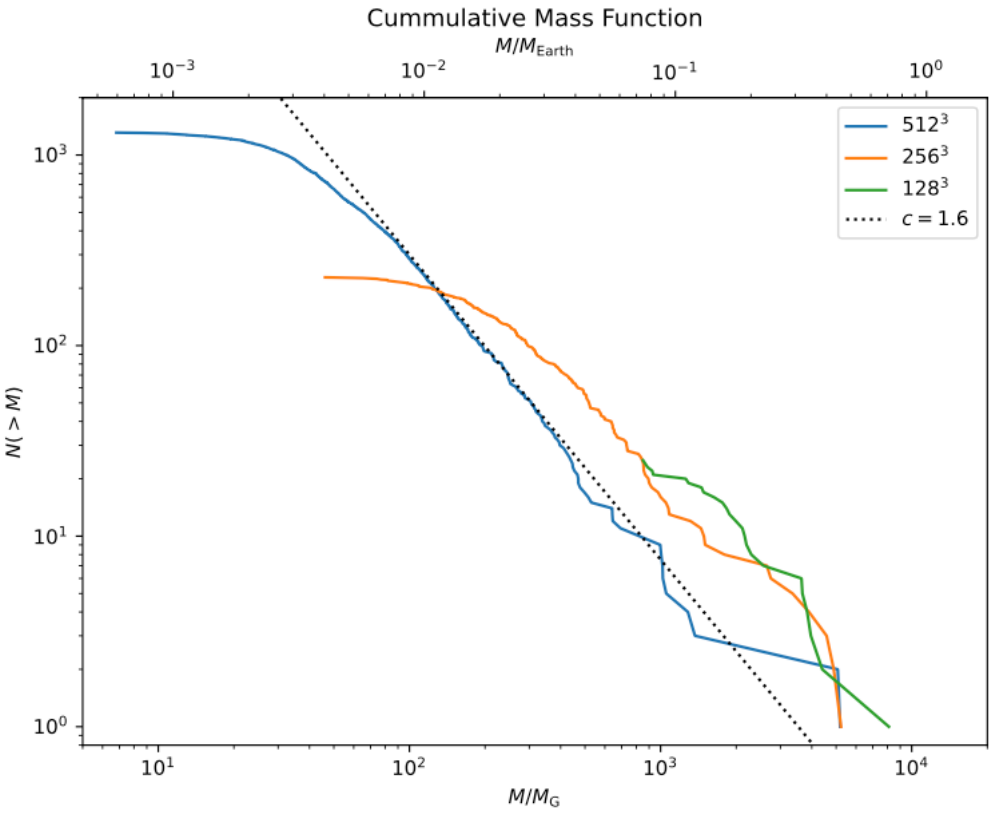
Vortex Trapping



Lyra et al. (in prep)

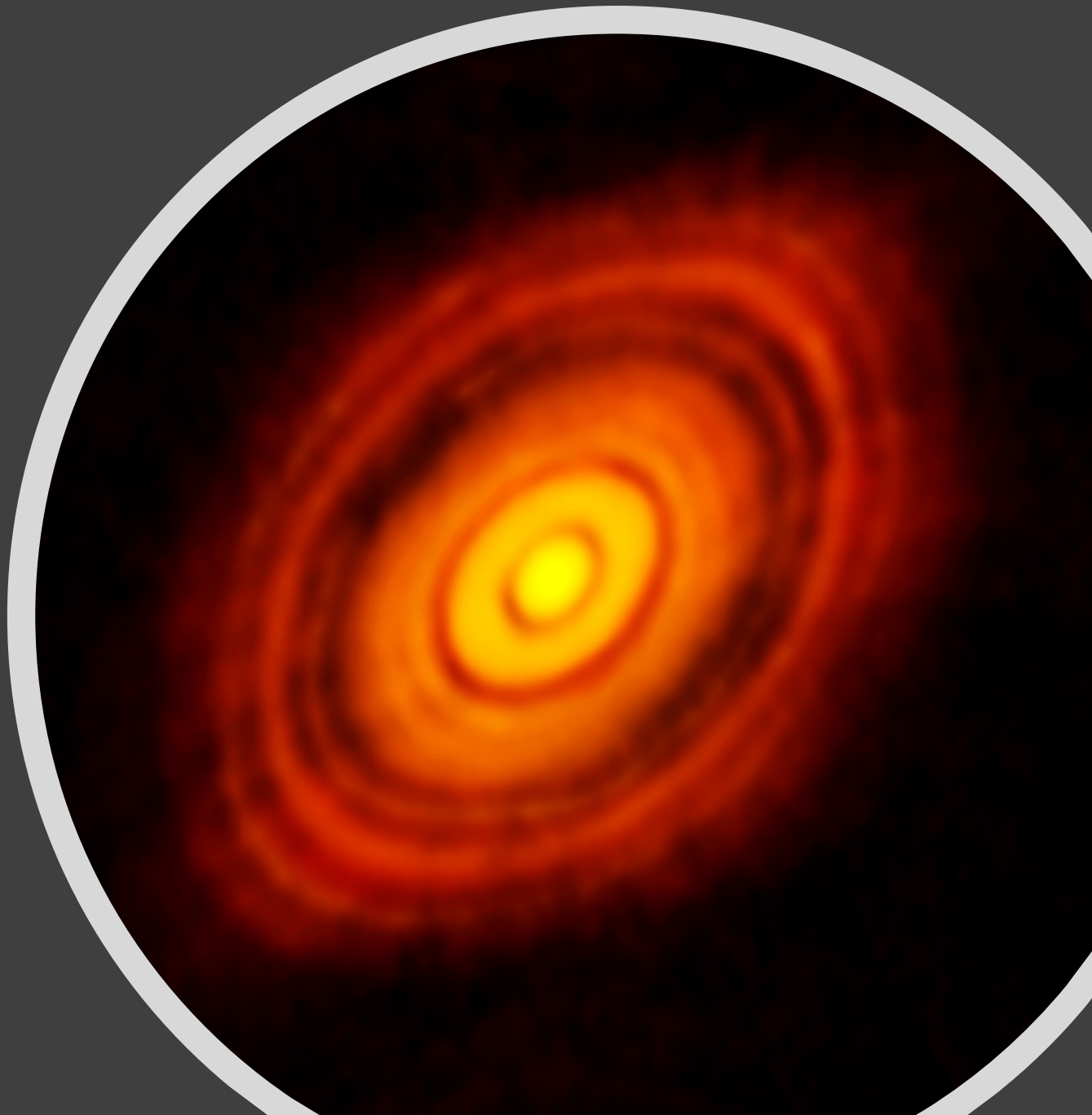
Vortex Trapping – Initial Mass Function

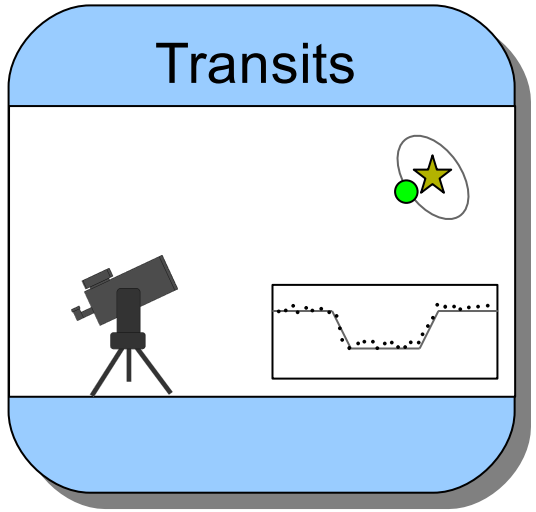


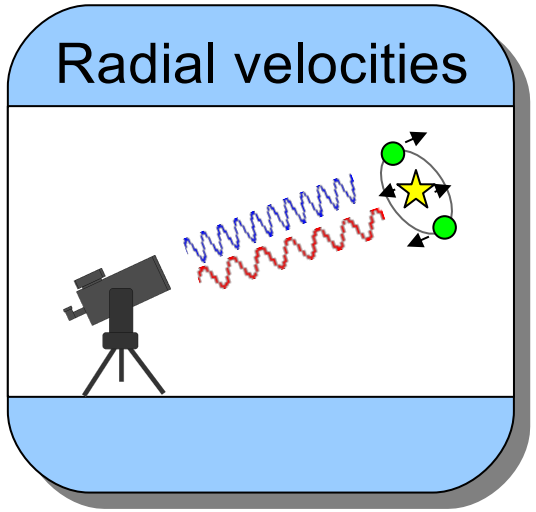


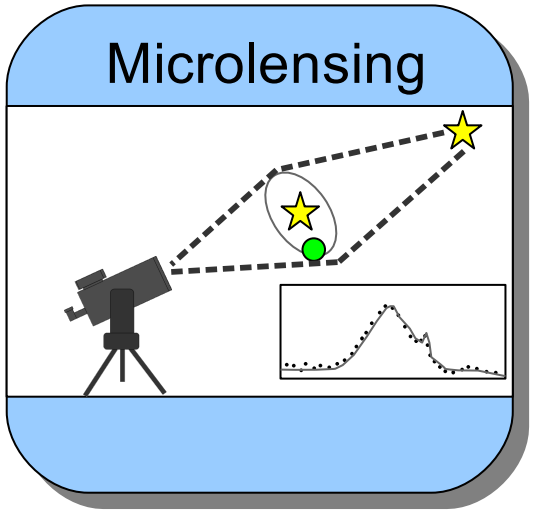
Lyra et al. (in prep)

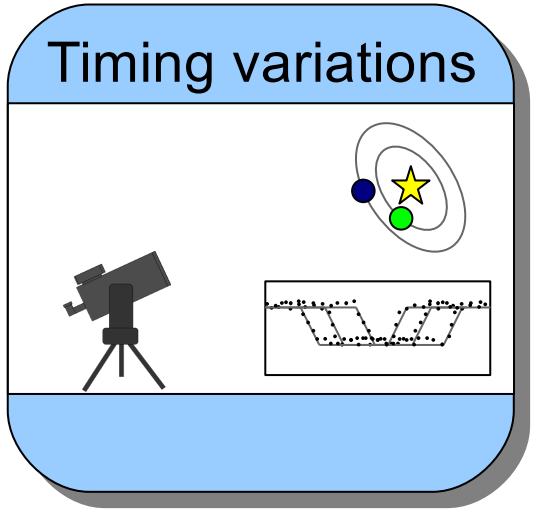
Disk Observations

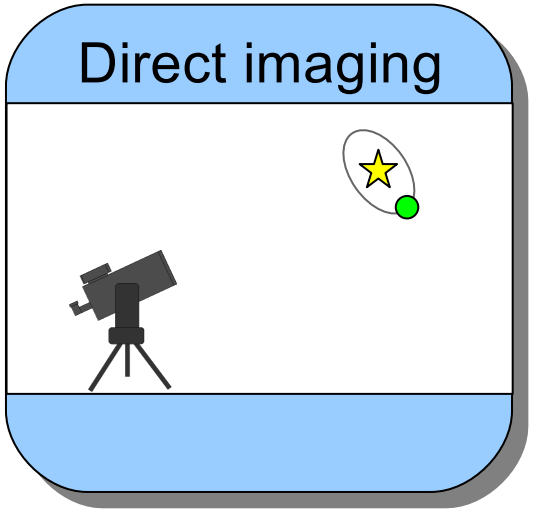


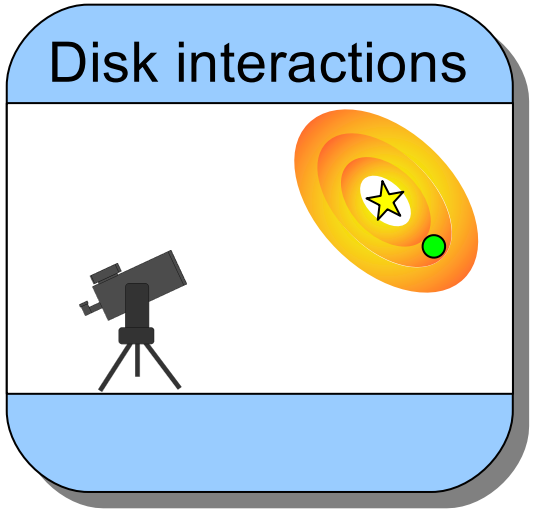






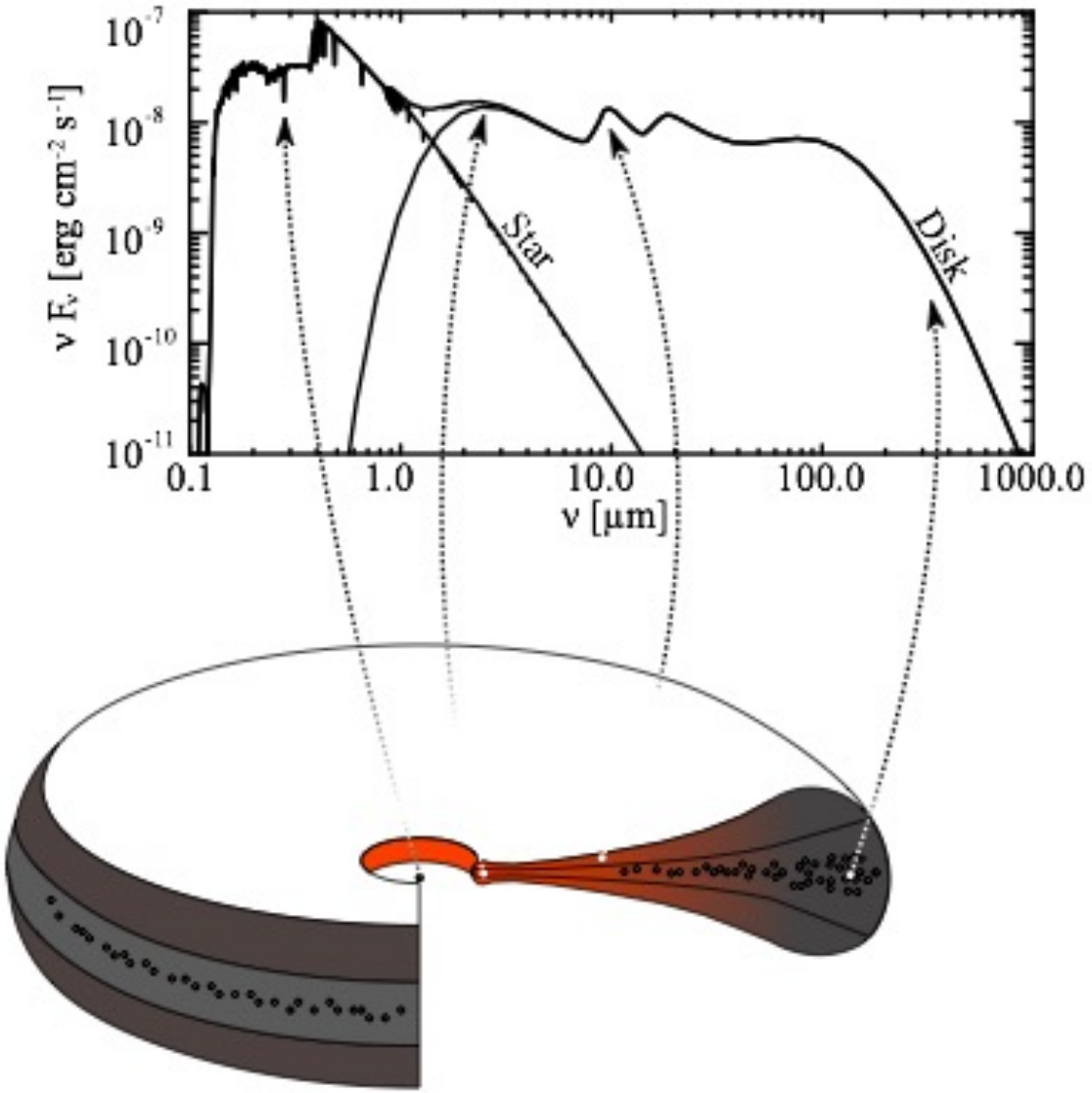




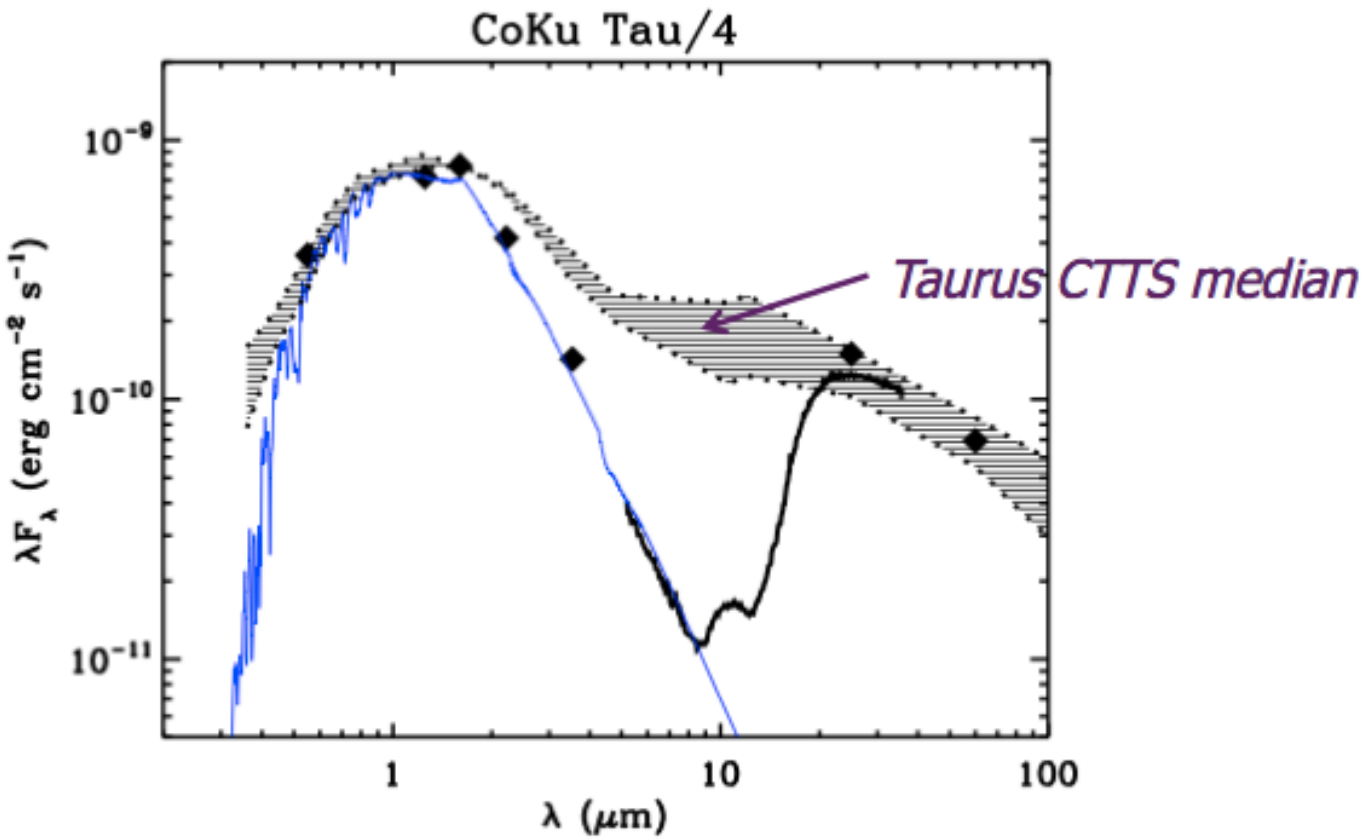


Slide by A. Richert

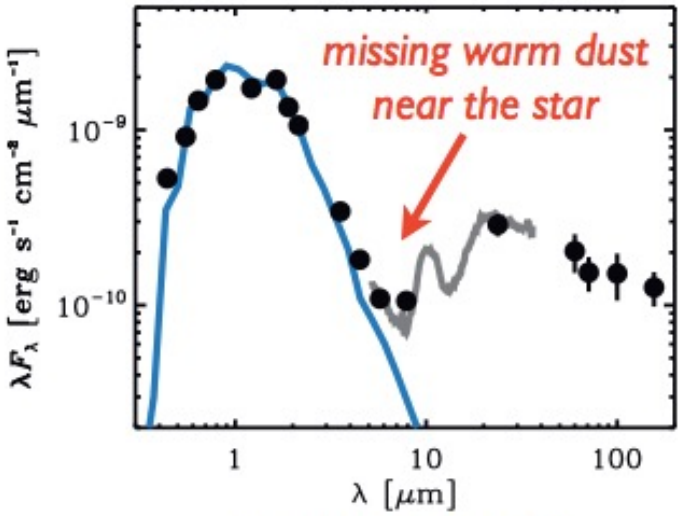
Disk spectra



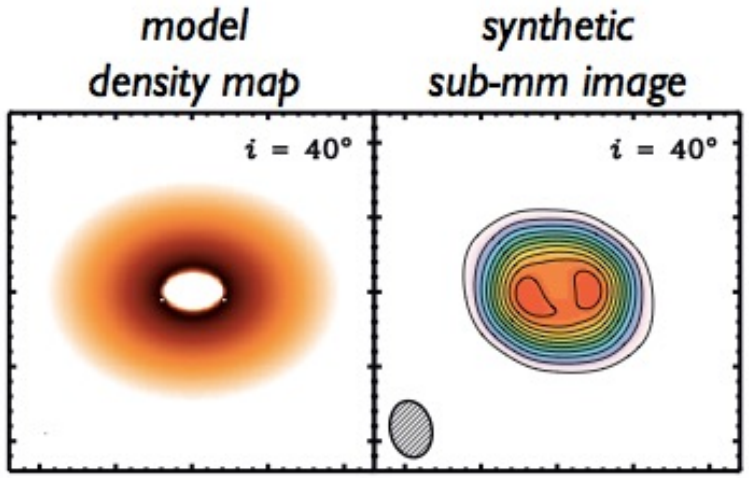
A class of disks with missing hot dust.



Disks with missing hot dust.

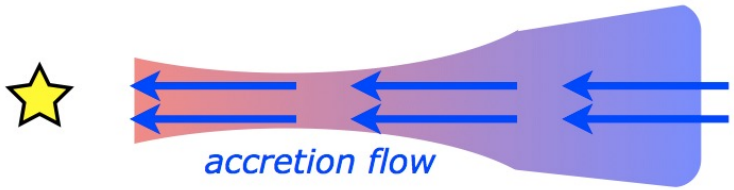


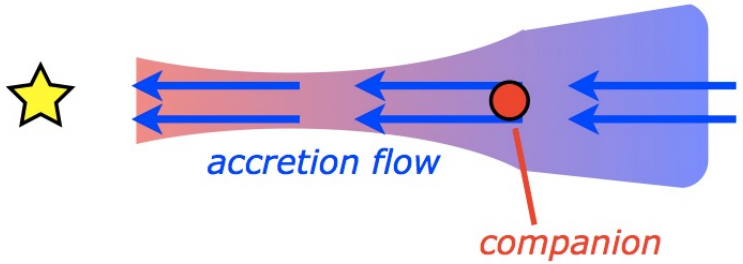
[e.g., Furlan et al. 2009]

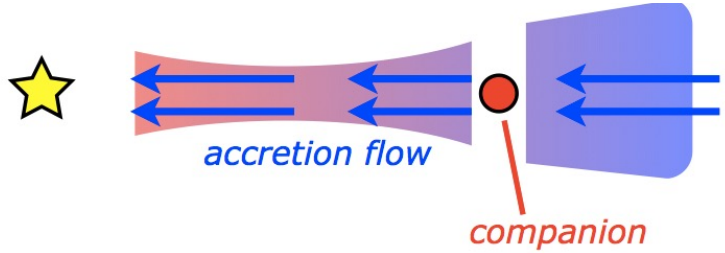


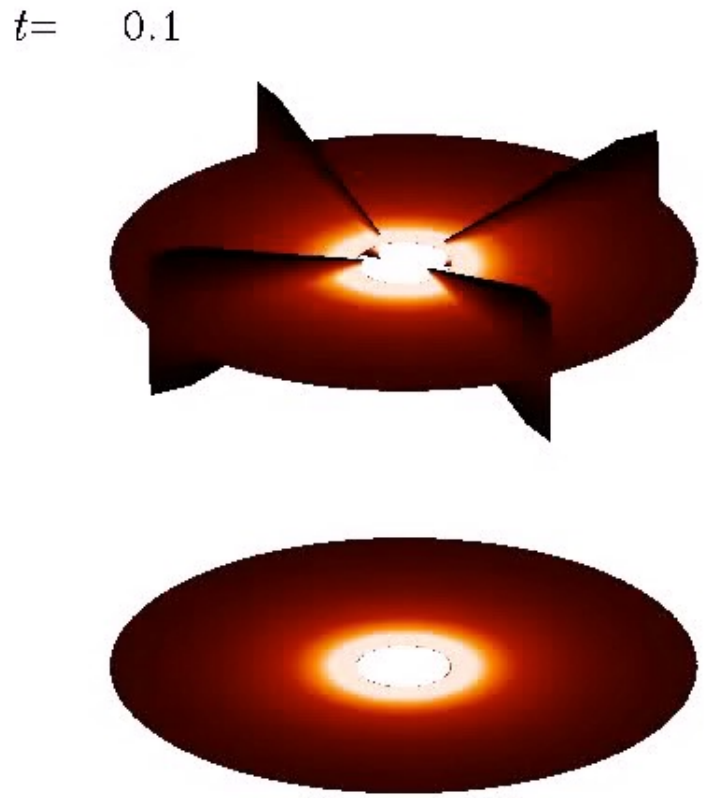
a disk with a large reduction
in optical depth near the star
(i.e., a "cavity" or "hole")

Planetary companion





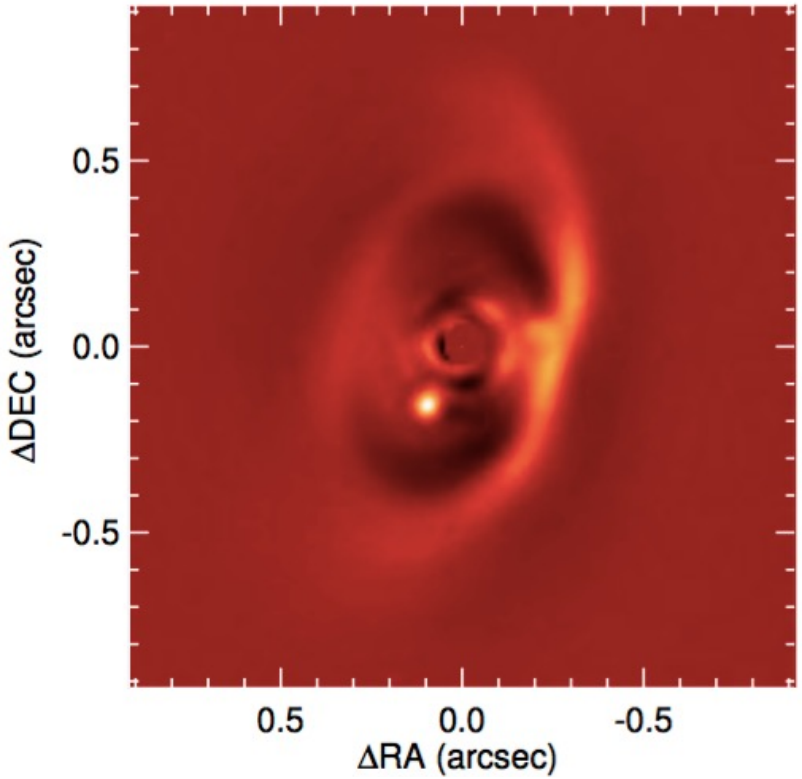




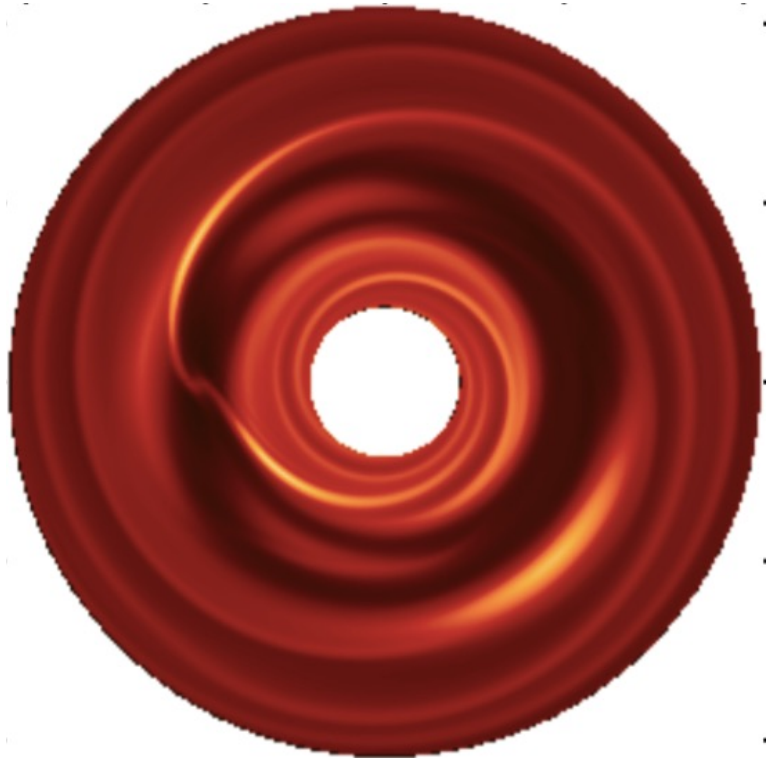
(Lyra 2009)

These cavities may be the telltale signature of forming planets

PDS 70 and PDS 70b



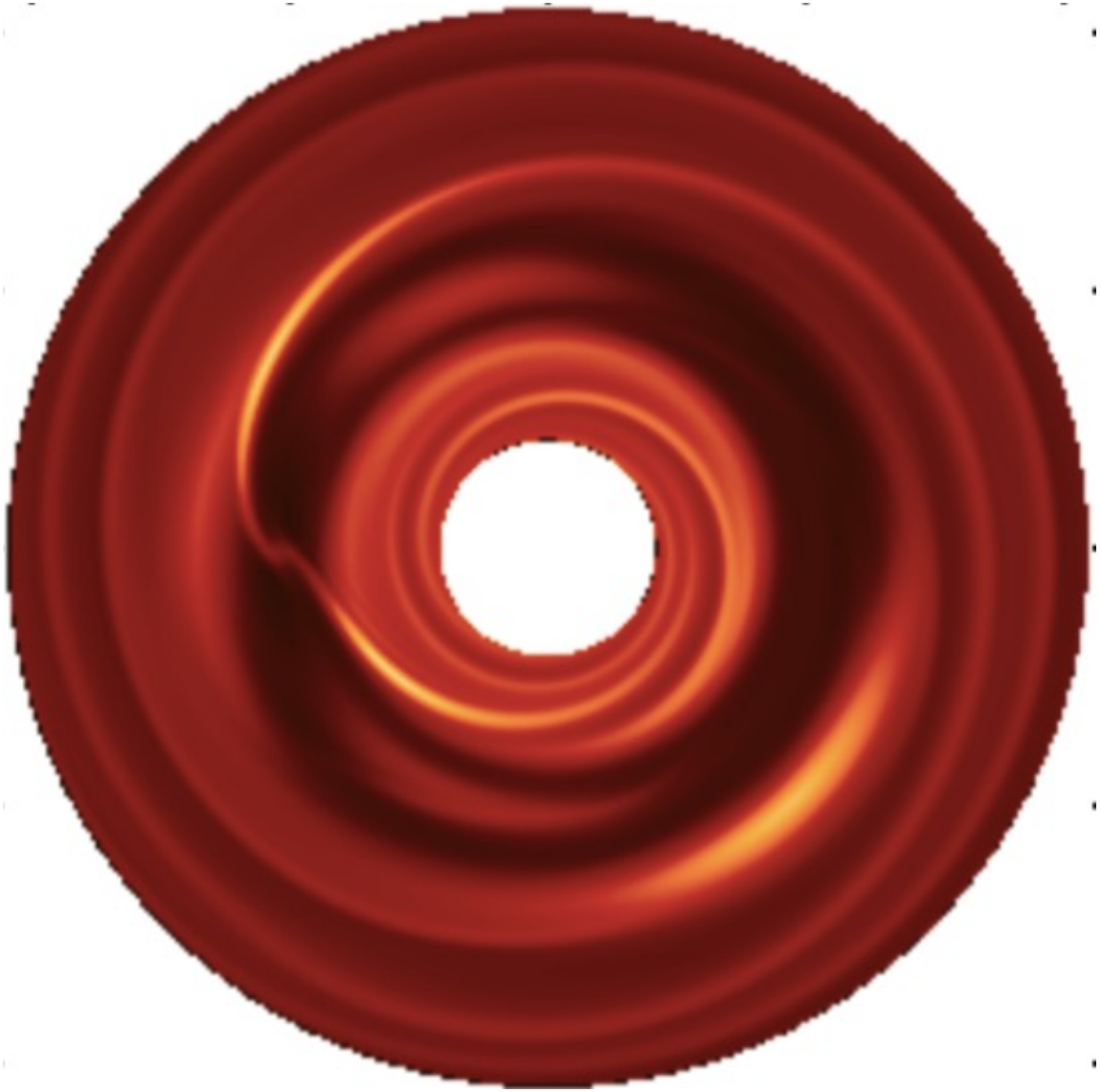
(Muller et al. 2018)



(Lyra et al. 2009b)

A way to directly study planet-disk interaction

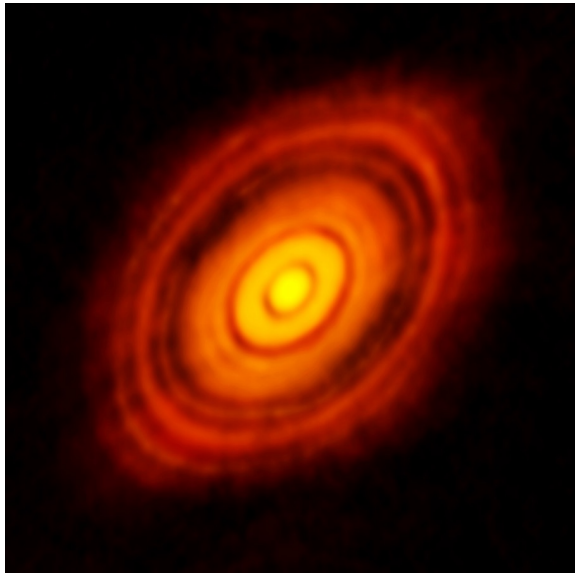
Planet-disk interaction: gaps, spirals, and vortices.



(Lyra et al. 2009b)

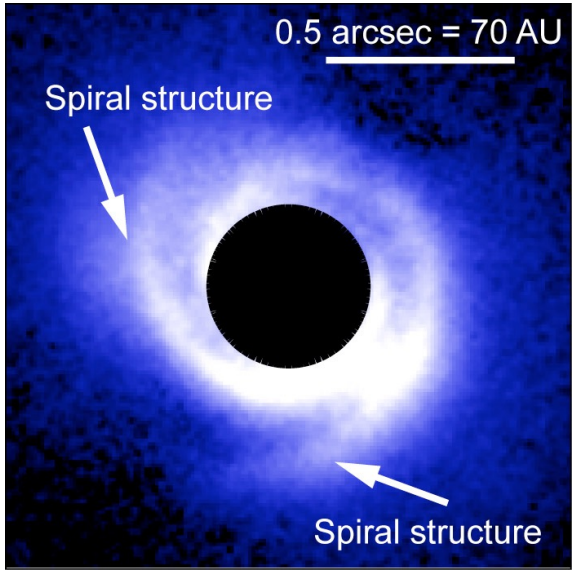
Observational evidence: gaps, spirals, and vortices

HL Tau



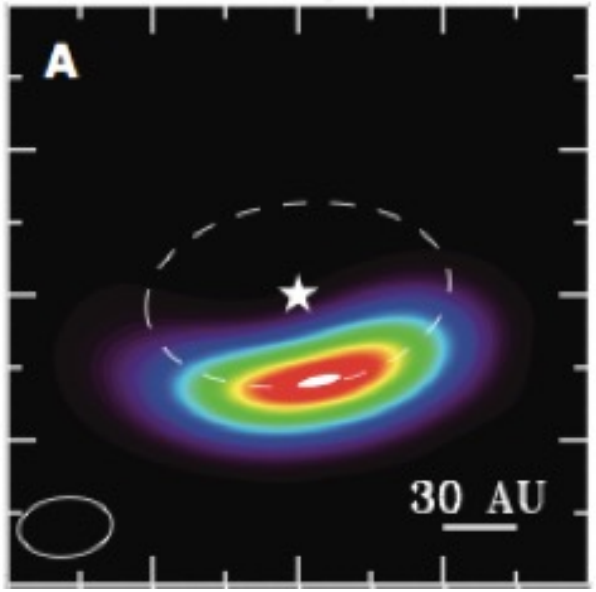
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

Oph IRS 48

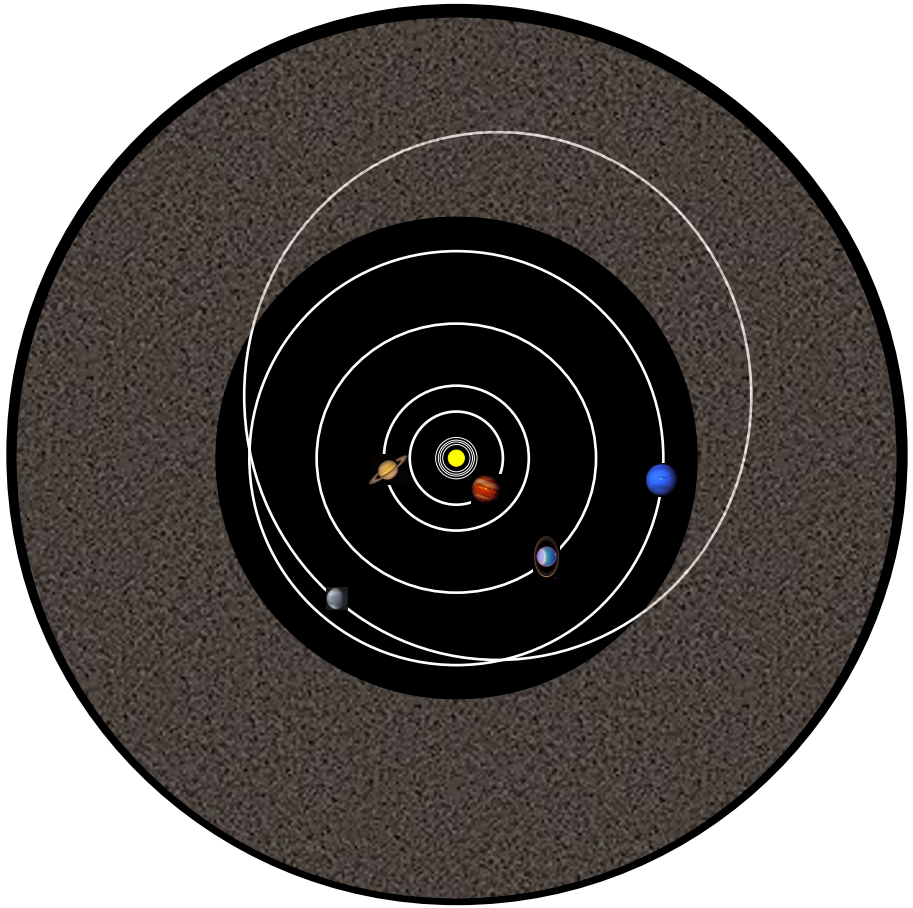


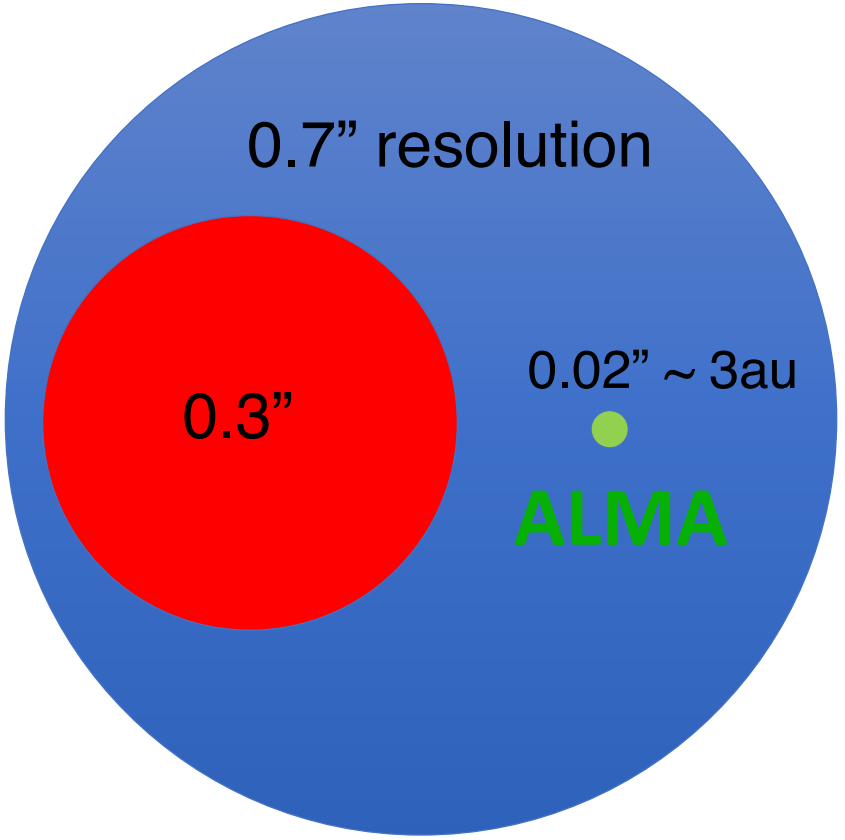
van der Marel et al. (2013)

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

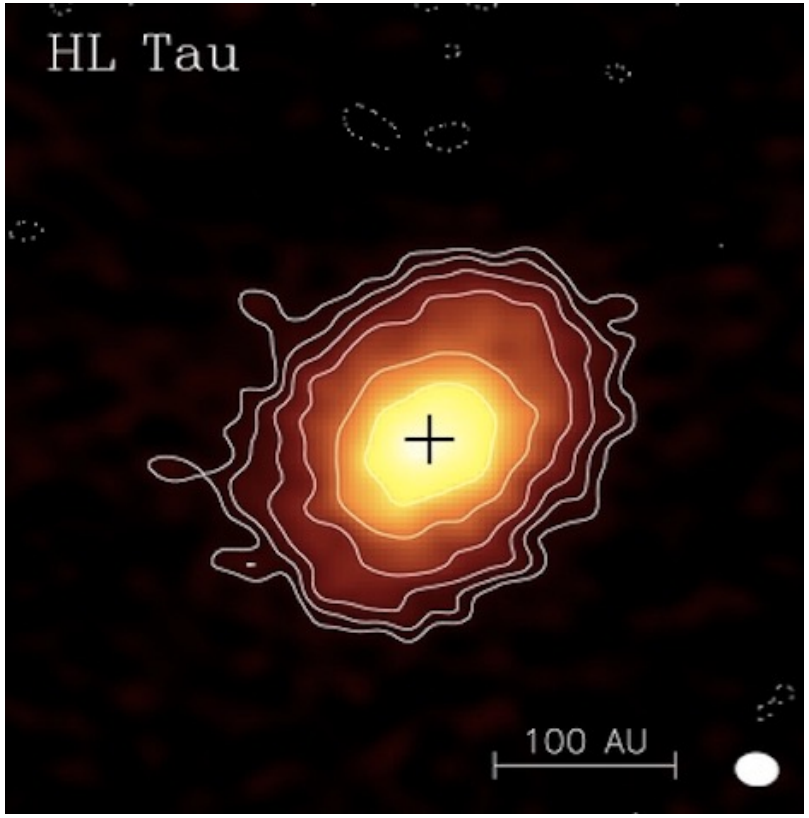
The Very Large Array (VLA)

The ALMA Revolution

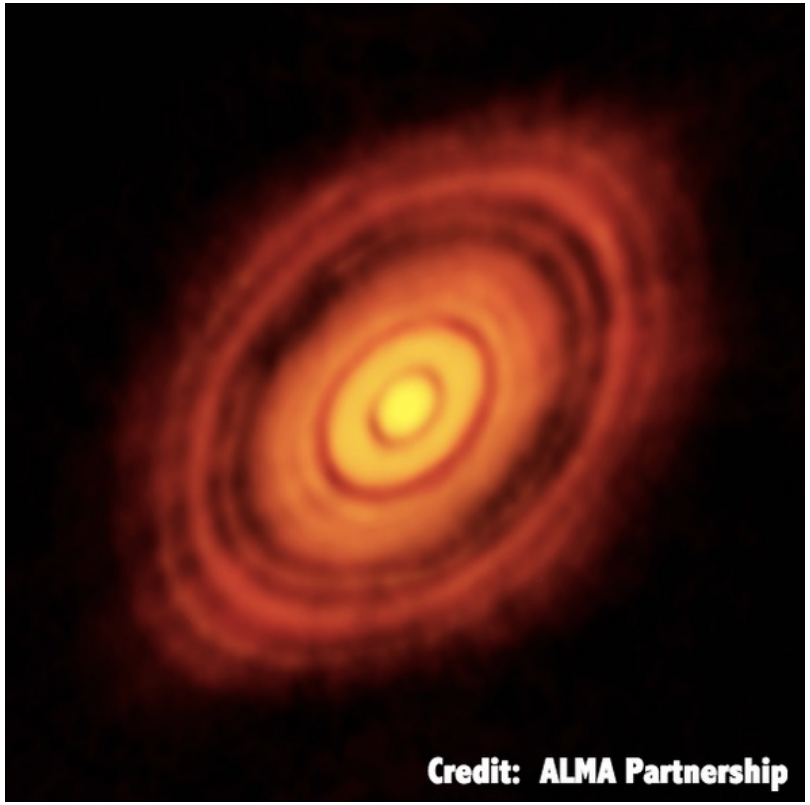




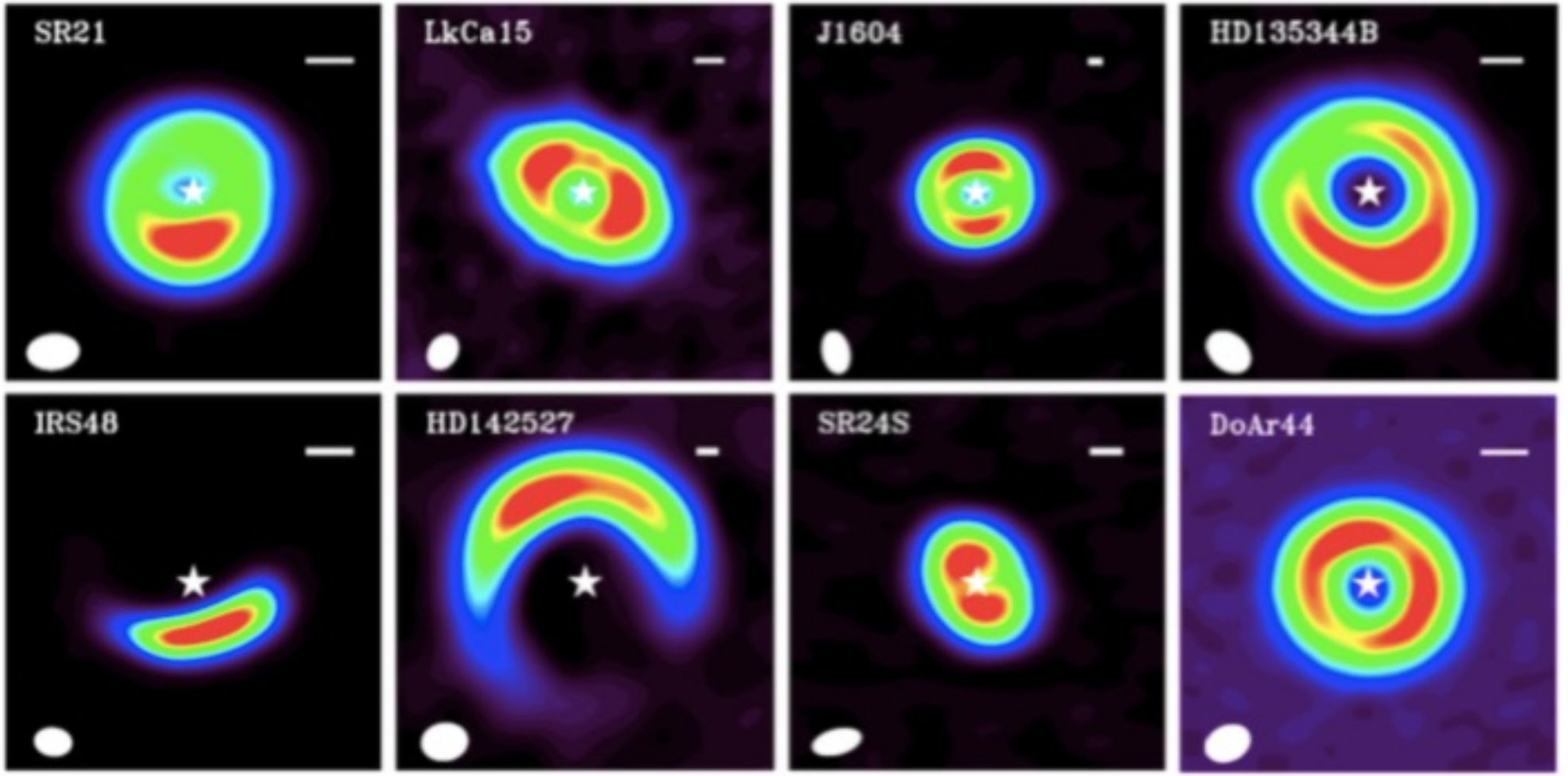
Before ALMA

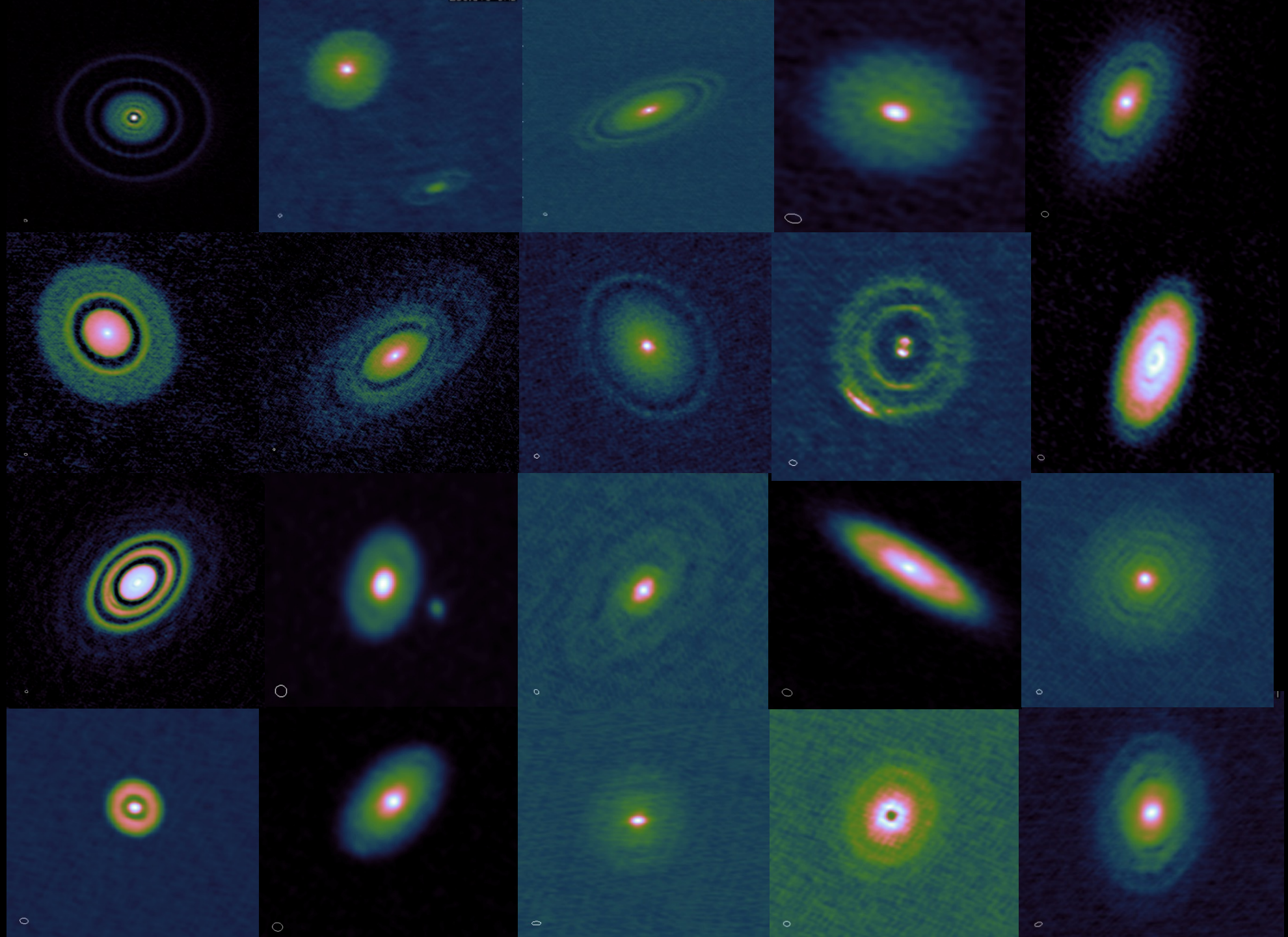


ALMA



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]

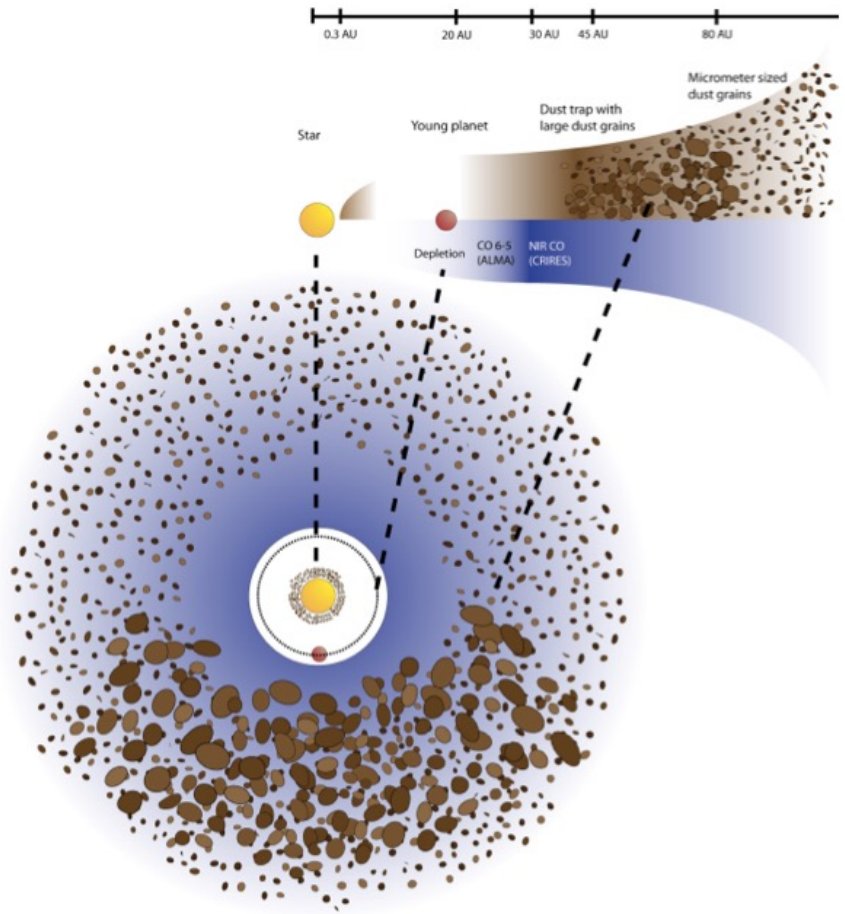
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection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

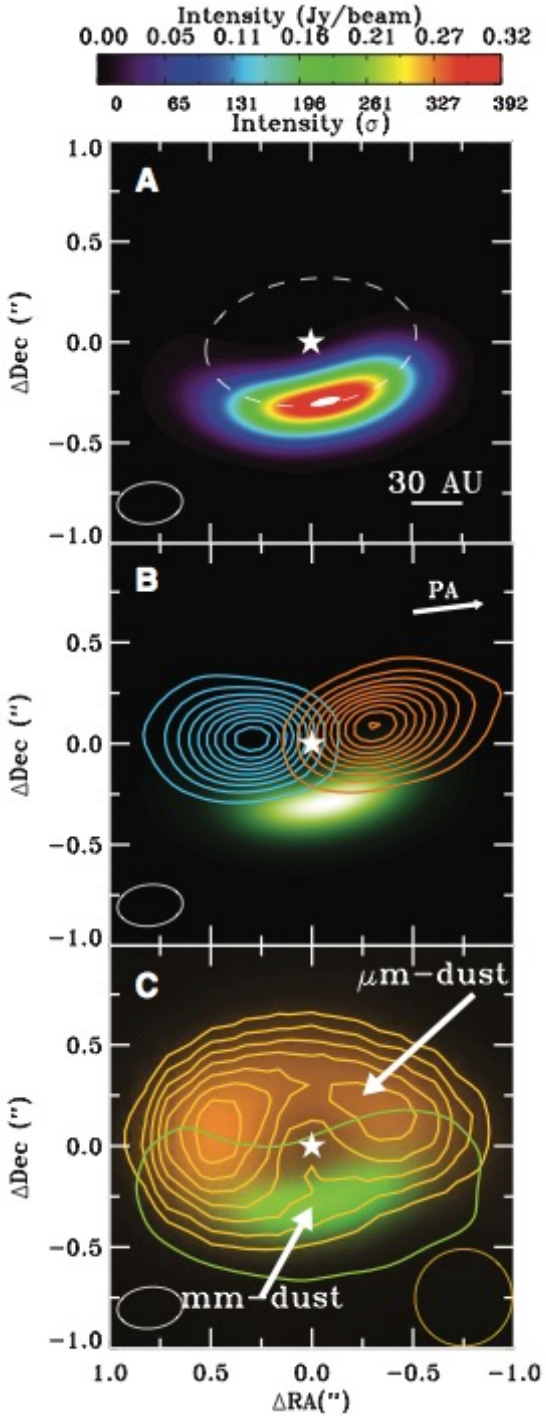
van der Marel+ ‘13

A huge vortex observed with ALMA

The Oph IRS 48 "comet formation factory"



van der Marel+. '13

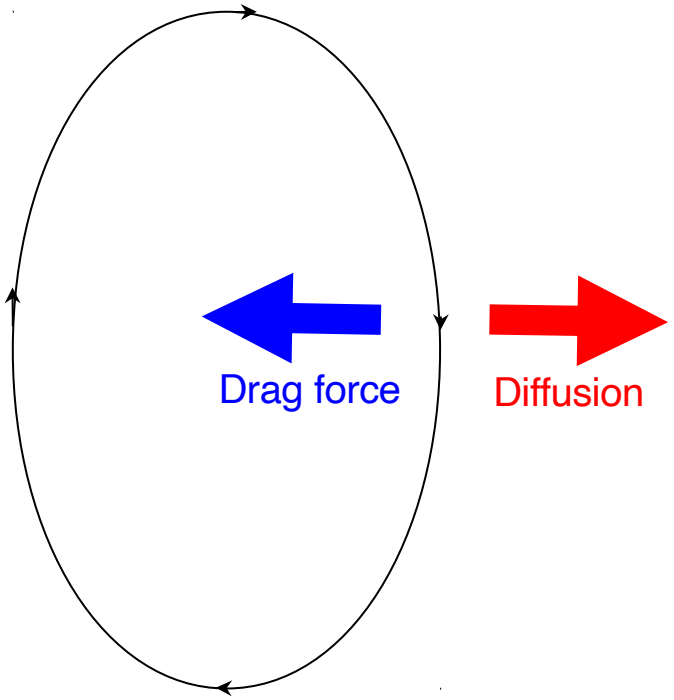


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

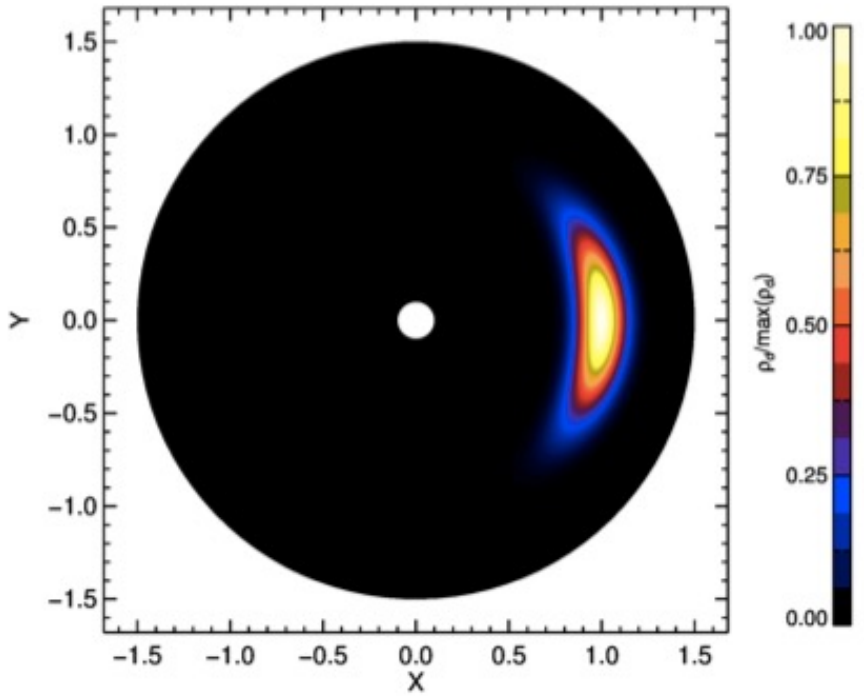
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v}\cdot\boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla}\cdot\boldsymbol{v} + D\nabla^2\rho_d,$$

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

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

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

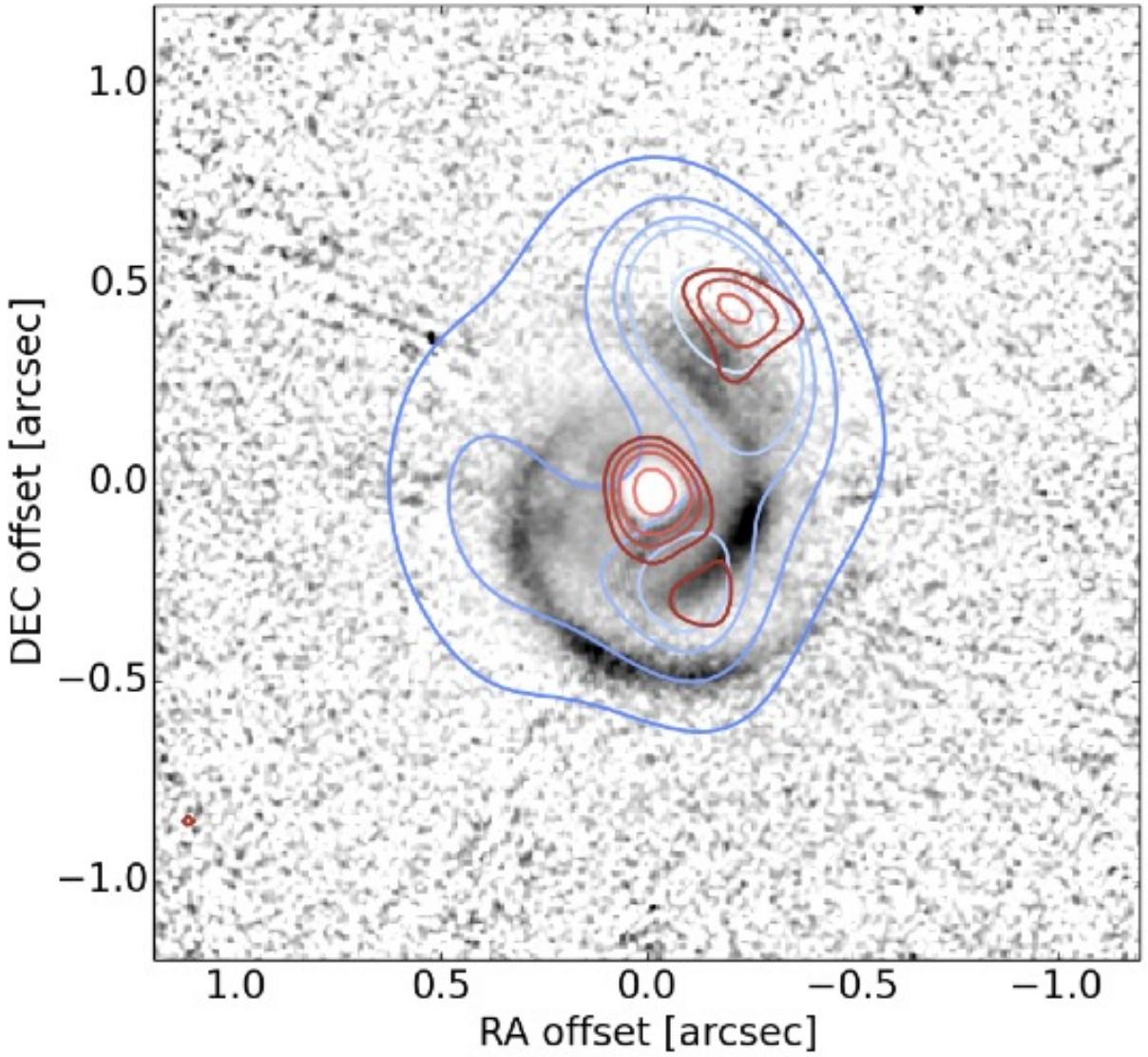
a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

Disk Tomography
SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

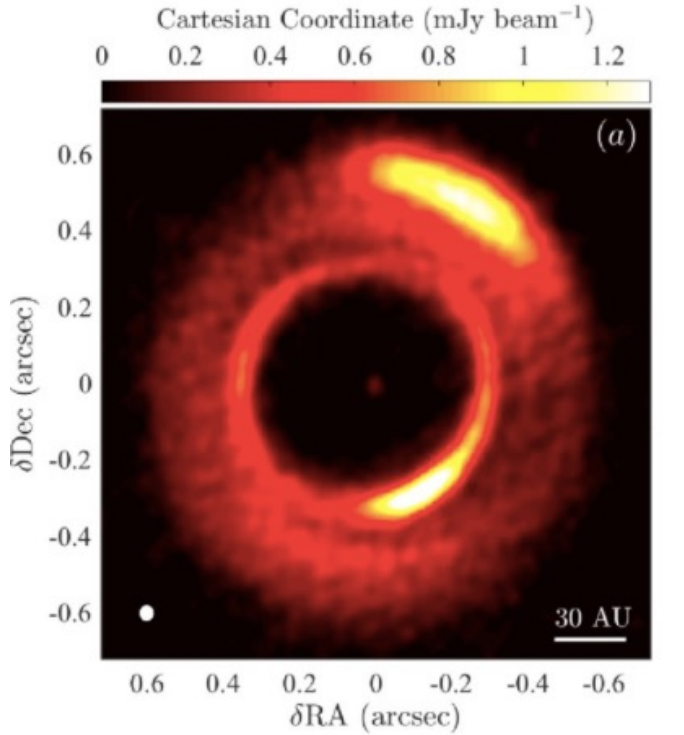
ALMA (~ mm)

VLA (cm-m)



Marino+Lyra ’15

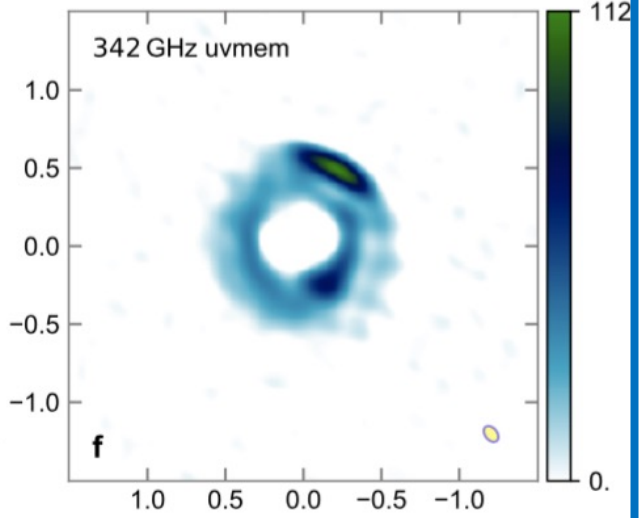
ALMA



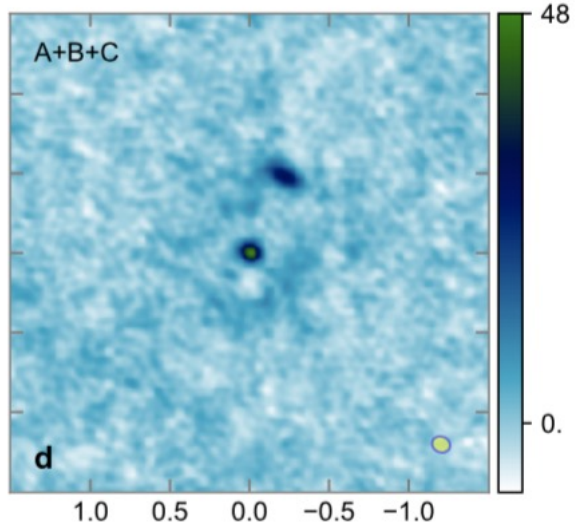
Dong+ ‘18

Pebble trapping

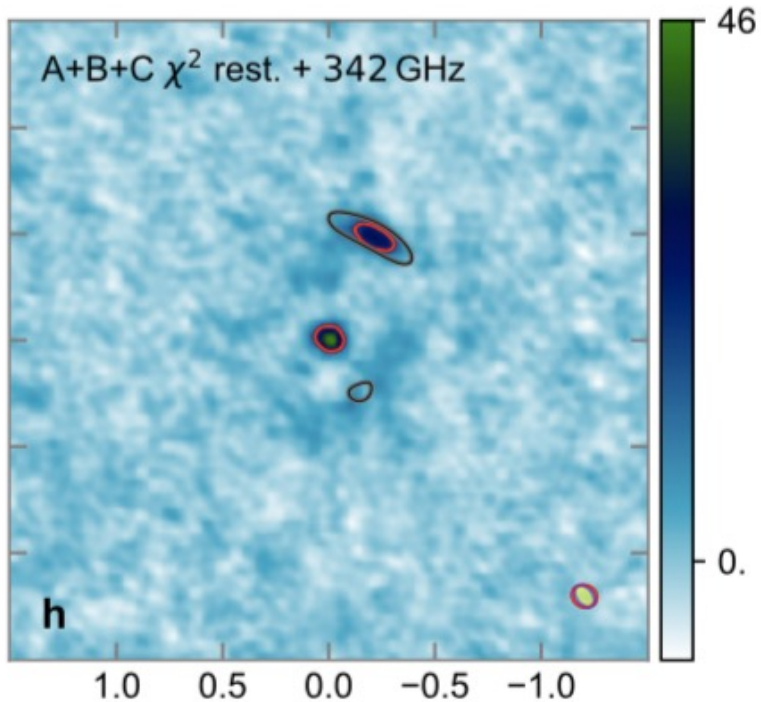
ALMA (mm)



VLA (cm-m)

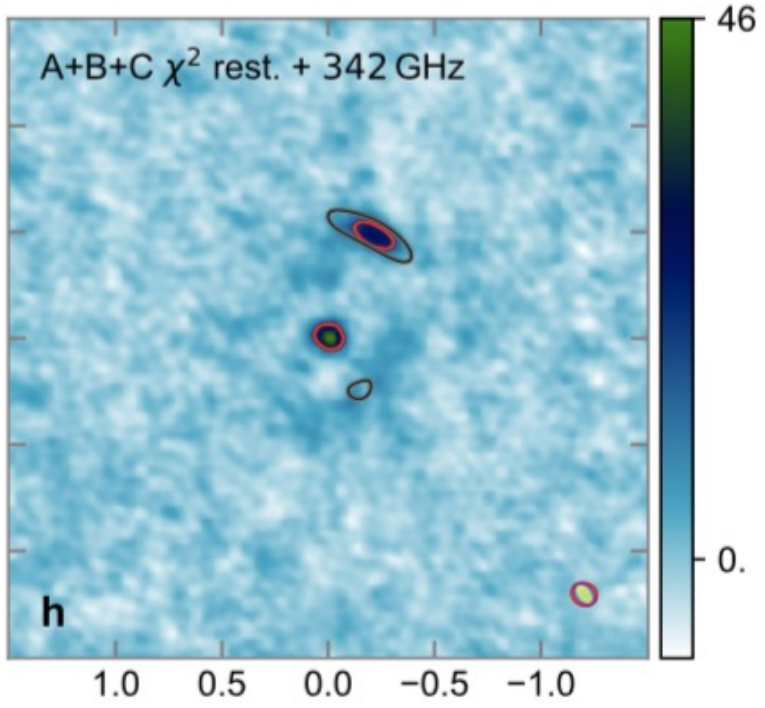


Overlay

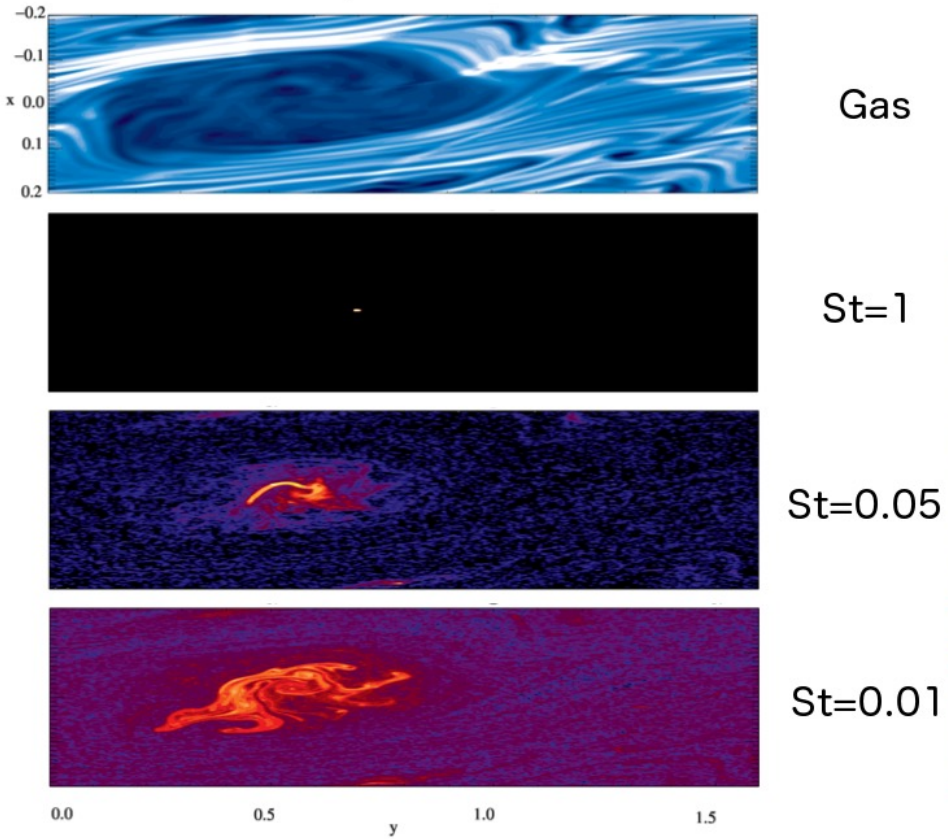


Casassus+Lyra ’19

Model vs Observation



Casassus+Lyra ‘19

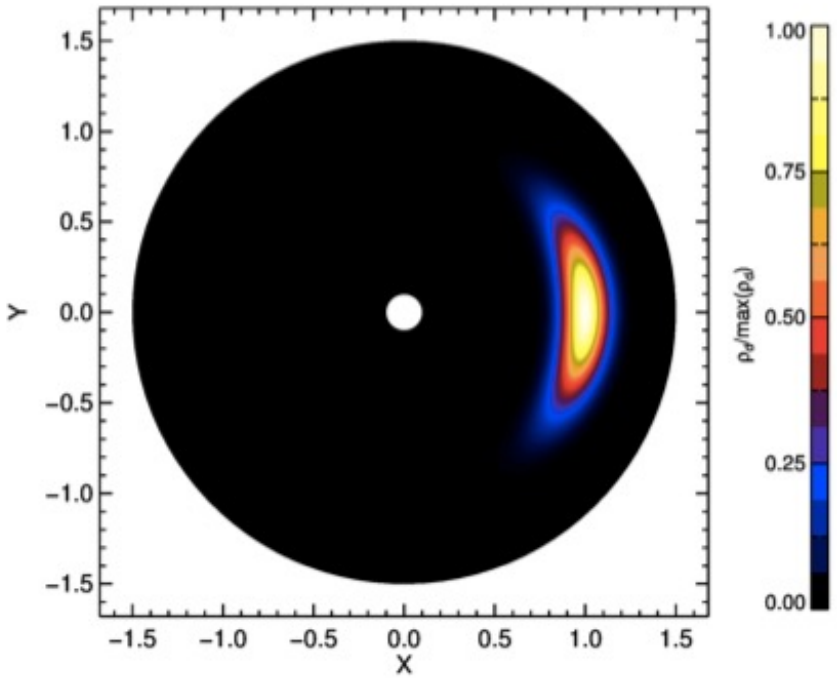


Raettig+Lyra ‘15

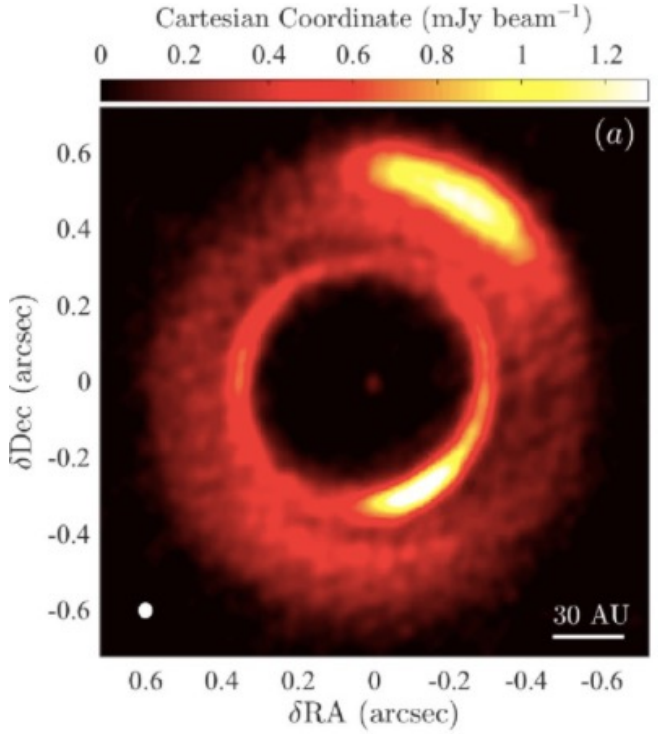
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations

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

Lyra-Lin solution



Observed Disk



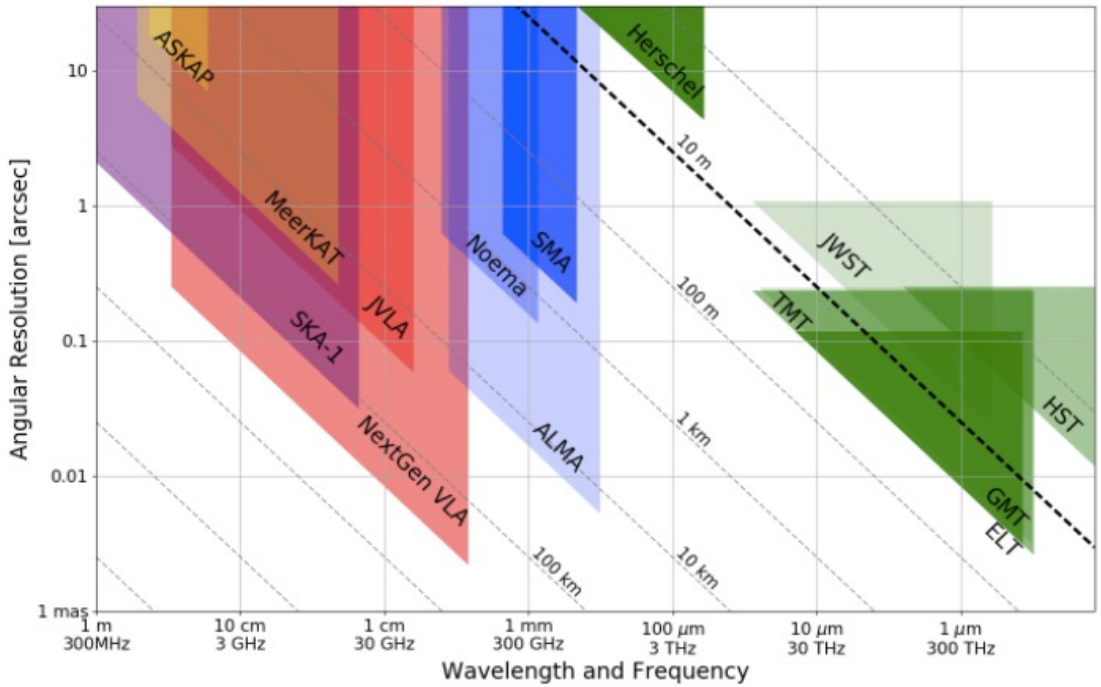
The future

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)

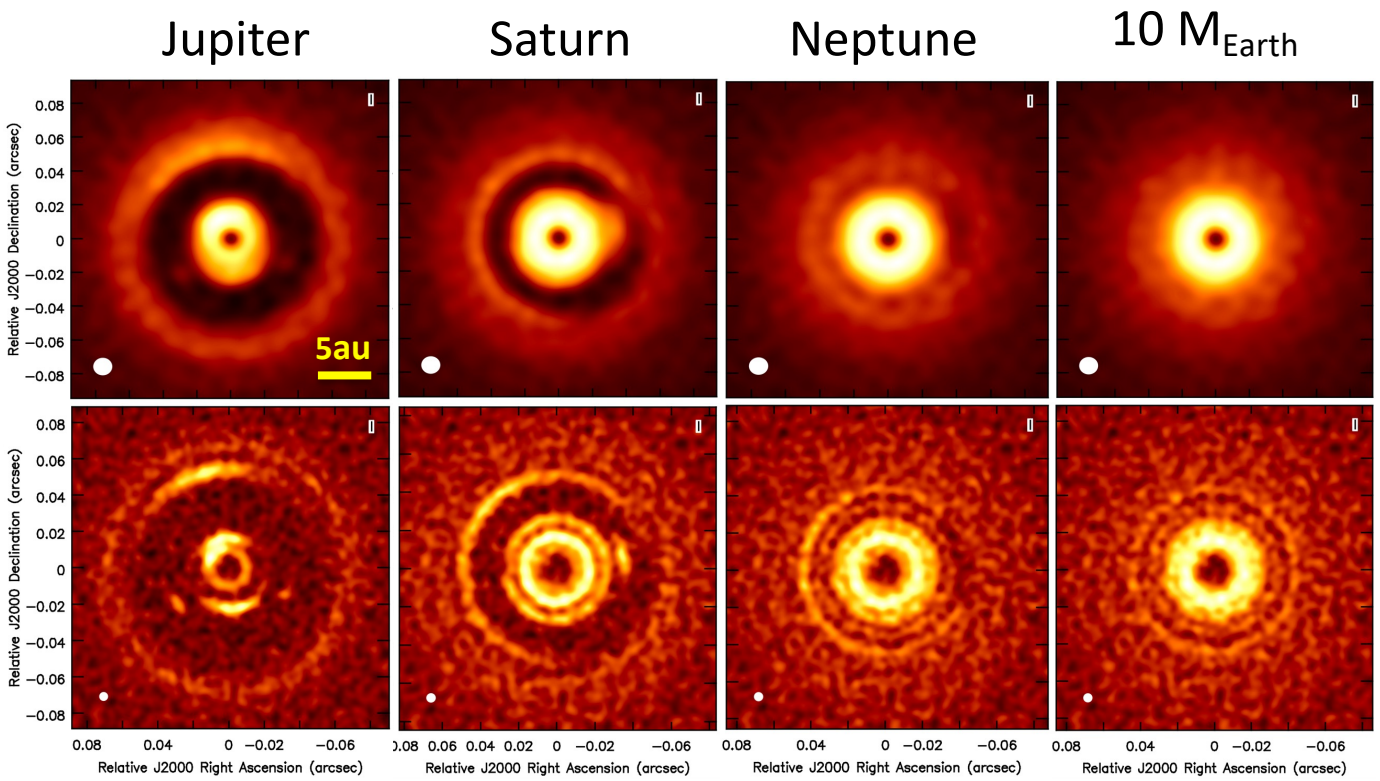


Planets at 5AU

ALMA @ 0.87mm

ngVLA @ 3mm

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

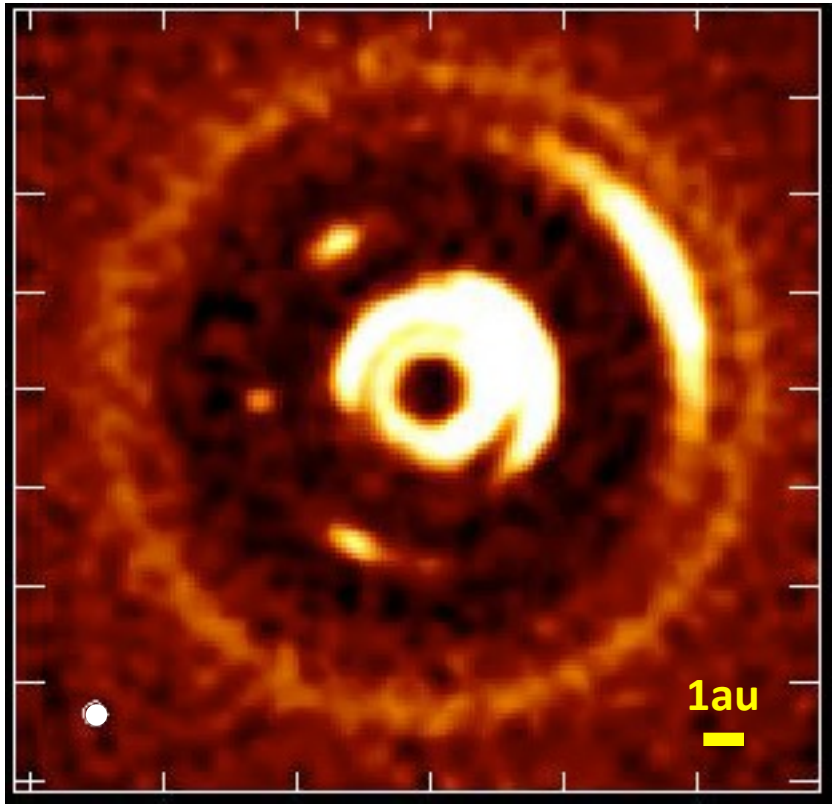


Ricci et al. 2018

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
  - Vortex trapping

- 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

- “Crescents” seen in observations of disks
  - Properties match those of vortices
  - Vortex-trapped dust in drag-diffusion equilibrium explains the observations

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