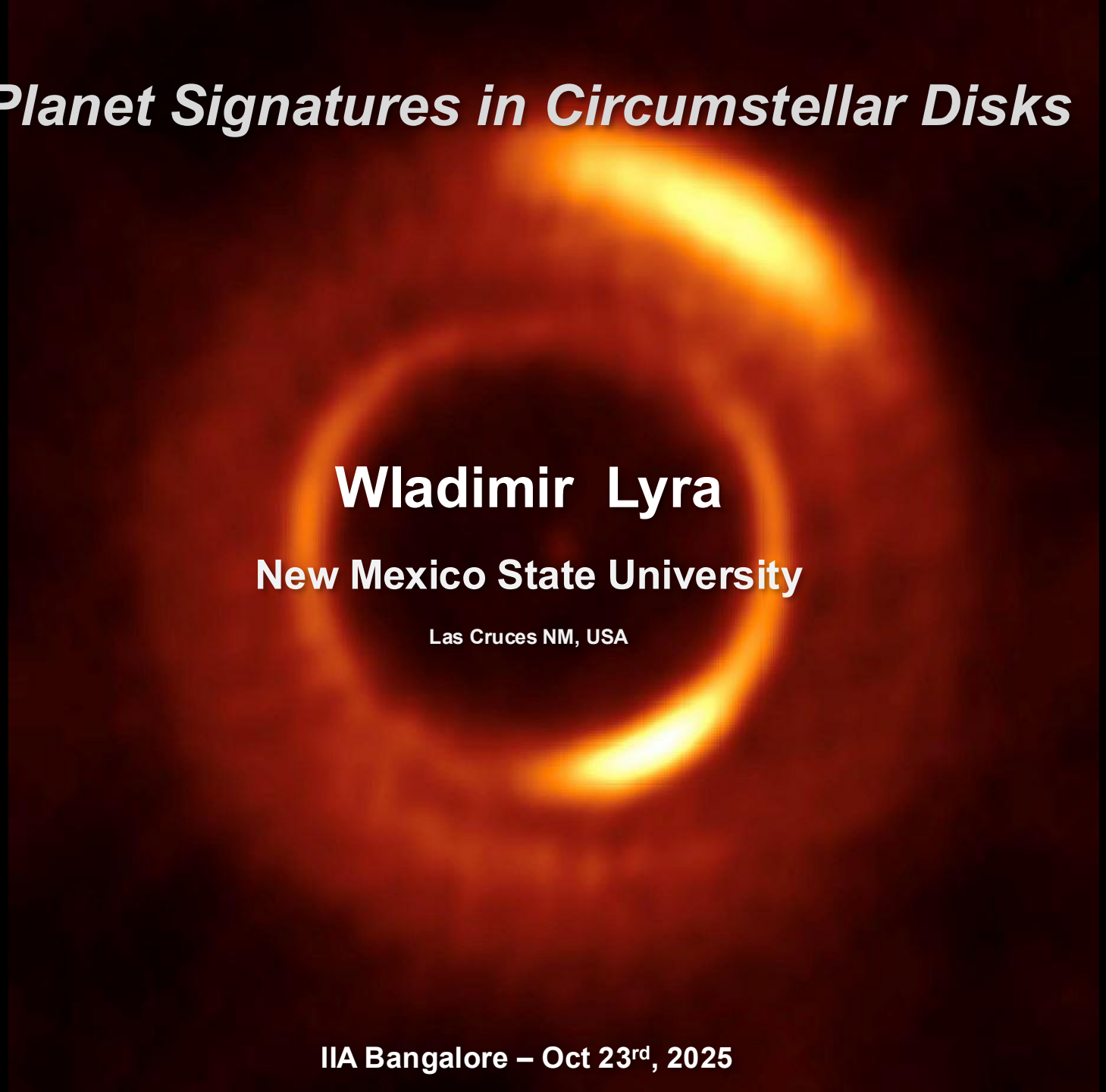
Planet Signatures in Circumstellar Disks



Wladimir Lyra

New Mexico State University

Las Cruces NM, USA

IIA Bangalore – Oct 23rd, 2025

NMSU Circumstellar Disks and Planet Formation Group

Postdoctoral Scholars

Debanjan Sengupta
(2022-)
Dust growth, meteoritics, Turbulence and accretion.

Daniel Carrera
(2024-)
Planetesimal formation, pebble accretion

Graduate Students

Harrison Cook
(2019-)
Black hole mergers
Transients in AGN

Daniel Godines
(2021-)
Observational signatures of streaming instability

Eleanor Serviss
(2024-)
Gravitational Instability

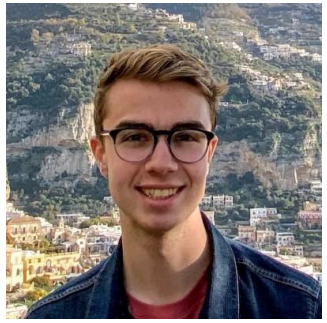
Leopold Hutnik
(2024-)
Pebble Accretion

Olivia Brouillette
(2024-)
Streaming Instability

Alumni

Ali Hyder
(2019-2022)
Jupiter's atmospheric dynamics and geochemistry.

Manuel Cañas
(2019-2023)
Formation of Kuiper belt objects.



Blake Hord
(2016-2017)
Radiative Transfer, Synthetic images

Alex Richert
(2015-2017)
Shock Thermal Instability

Natalie Raettig
(2012-2015)
Cyclogenesis

The PFITS+ Collaboration
(Planet Formation in the Southwest – and beyond)

Co-PIs

Wladimir Lyra – *New Mexico State University*
Andrew Youdin – *University of Arizona*
Jake Simon – *Iowa State University*
Chao-Chin Yang –*University of Alabama*
Orkan Umurhan – *NASA Ames*

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Daniel Carrera (ISU -> NMSU)
Sergei Dyda (U Al)
Tabassum Tanvir (ISU)
Marius Leehman (ISU)

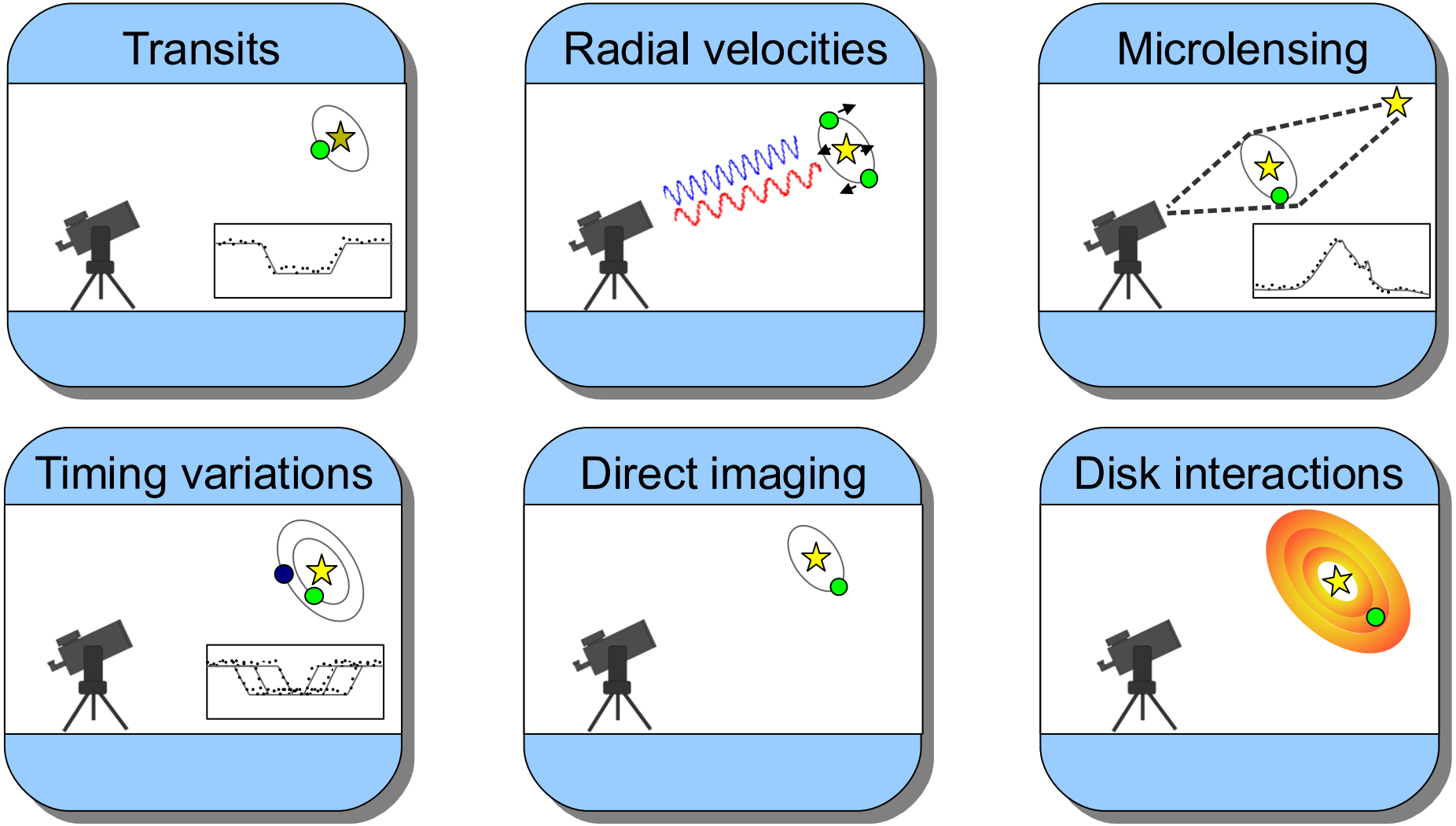
Graduate Students

NMSU - Daniel Godines, Olivia Brouillette,
Eleanor Serviss, Leopold Hutnik
ISU – Jeonghoon (Jay) Lim, David Rea, Weston Hall
UNLV – Stanley Baronett
U Az – Eonho Chang

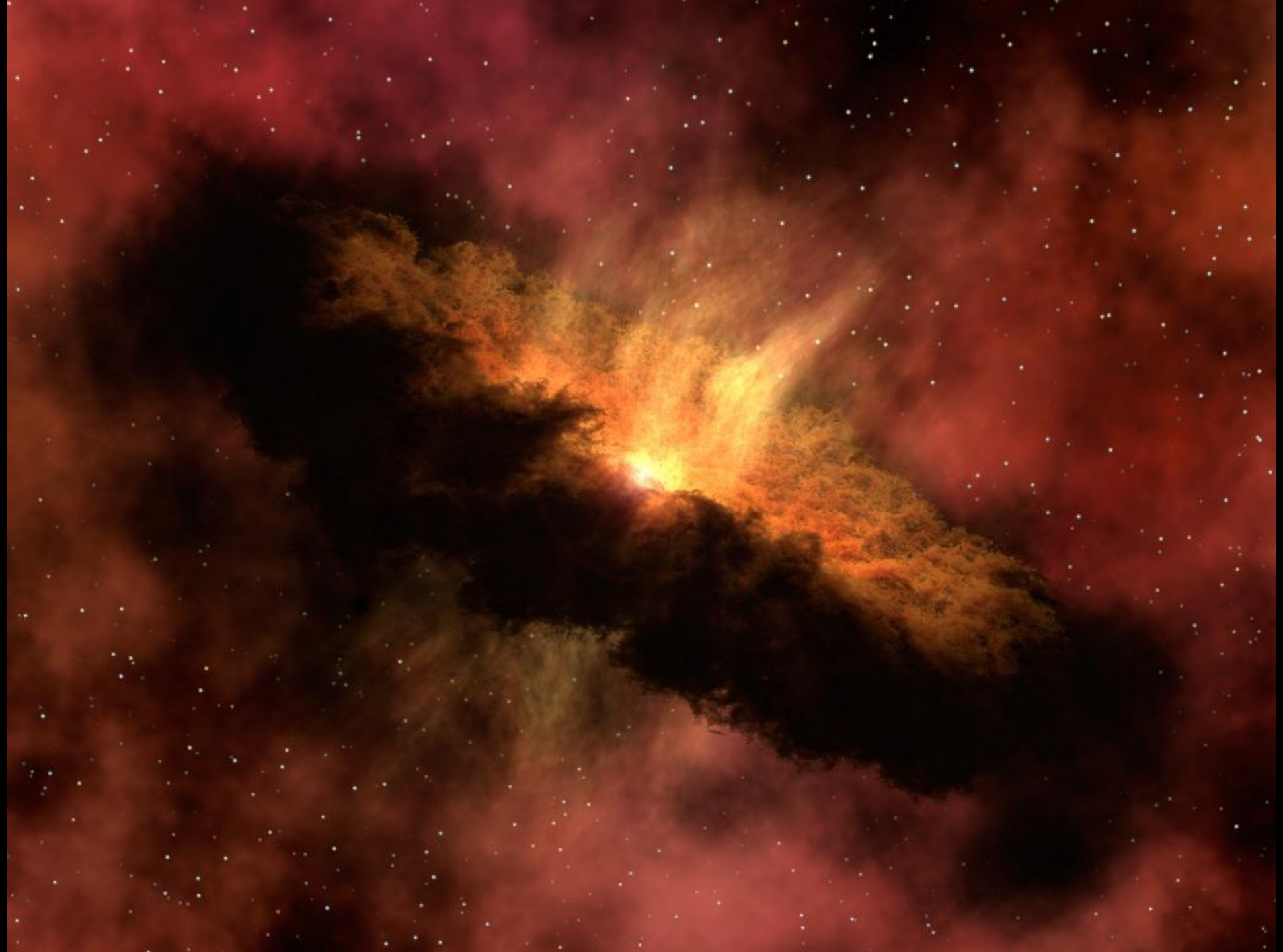
Alumni

Manny Cañas (NMSU), Aleksey Mohov (MSc UNLV),
Leonardo Krapp (UAz -> Chile),

Planet Detection Methods



Credit: A. Richert



Circumstellar/Protoplanetary Disks

PP disk fact sheet

Density: 10^{13} – 10^{15} cm^{-3}
(Air: 10^{19} cm^{-3})

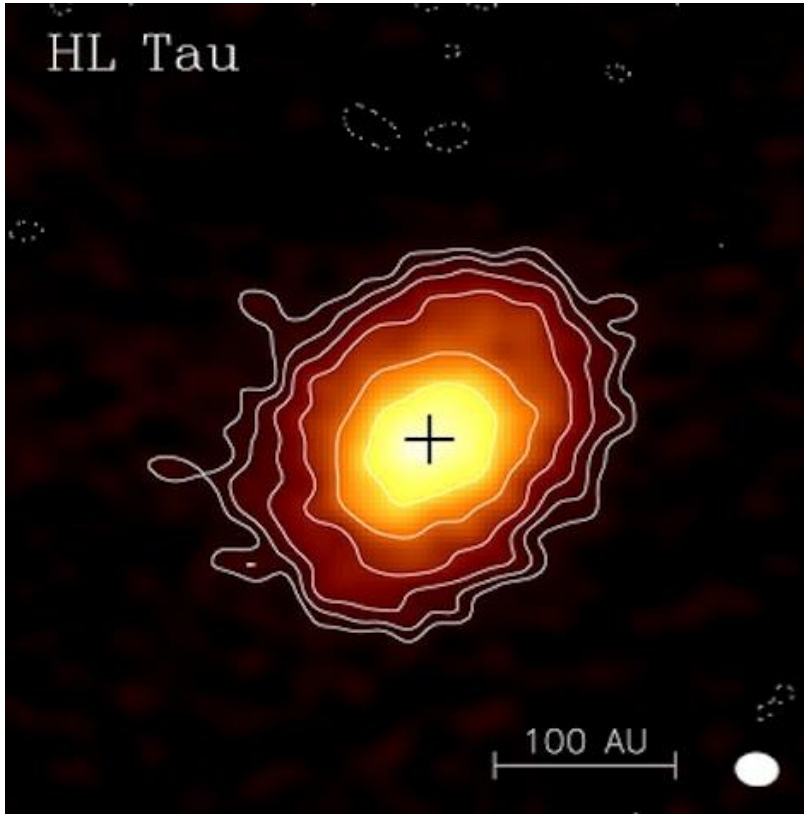
Temperature: 10-1000 K

Scale: 0.1-100AU

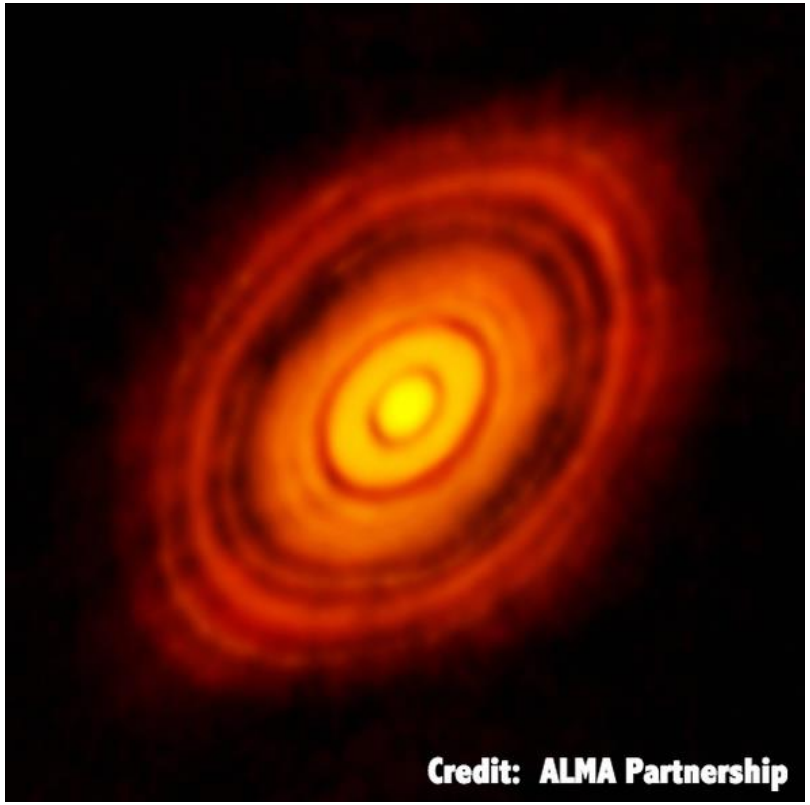
Mass: 10^{-3} – 10^{-1} M_{sun}

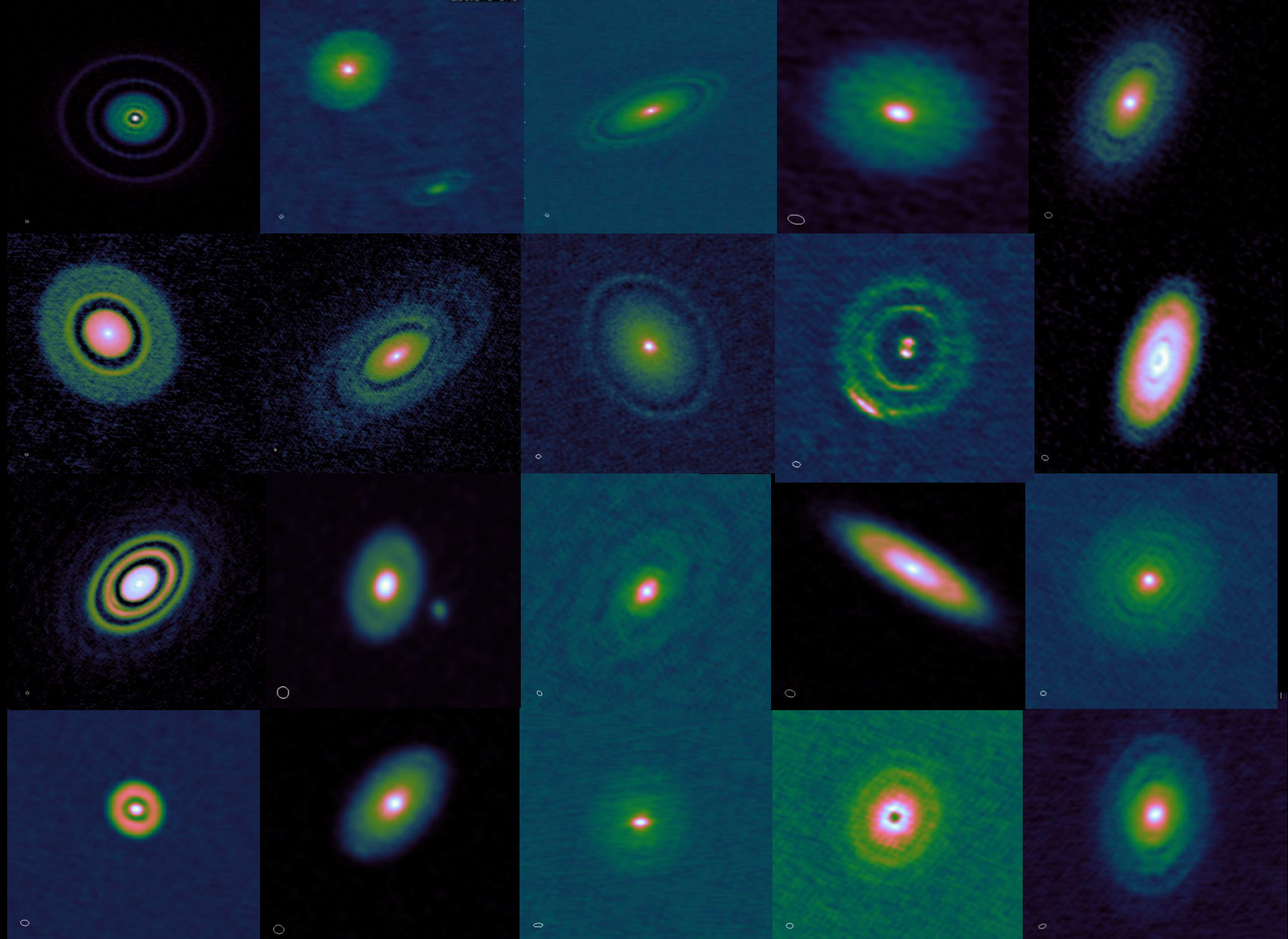
Composition:
5:2 H_2-He mixture.
1% “metals”

Before ALMA

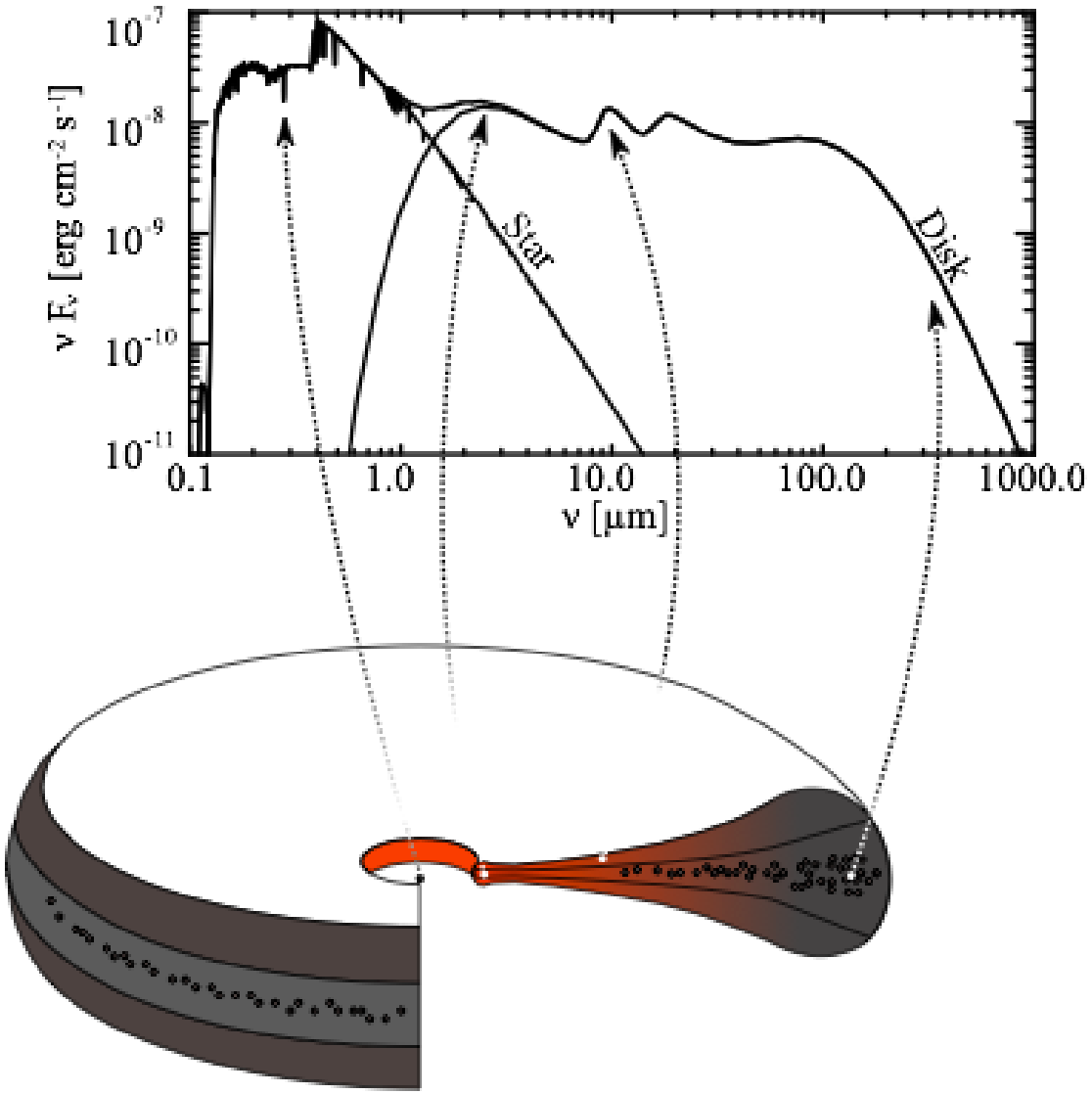


ALMA

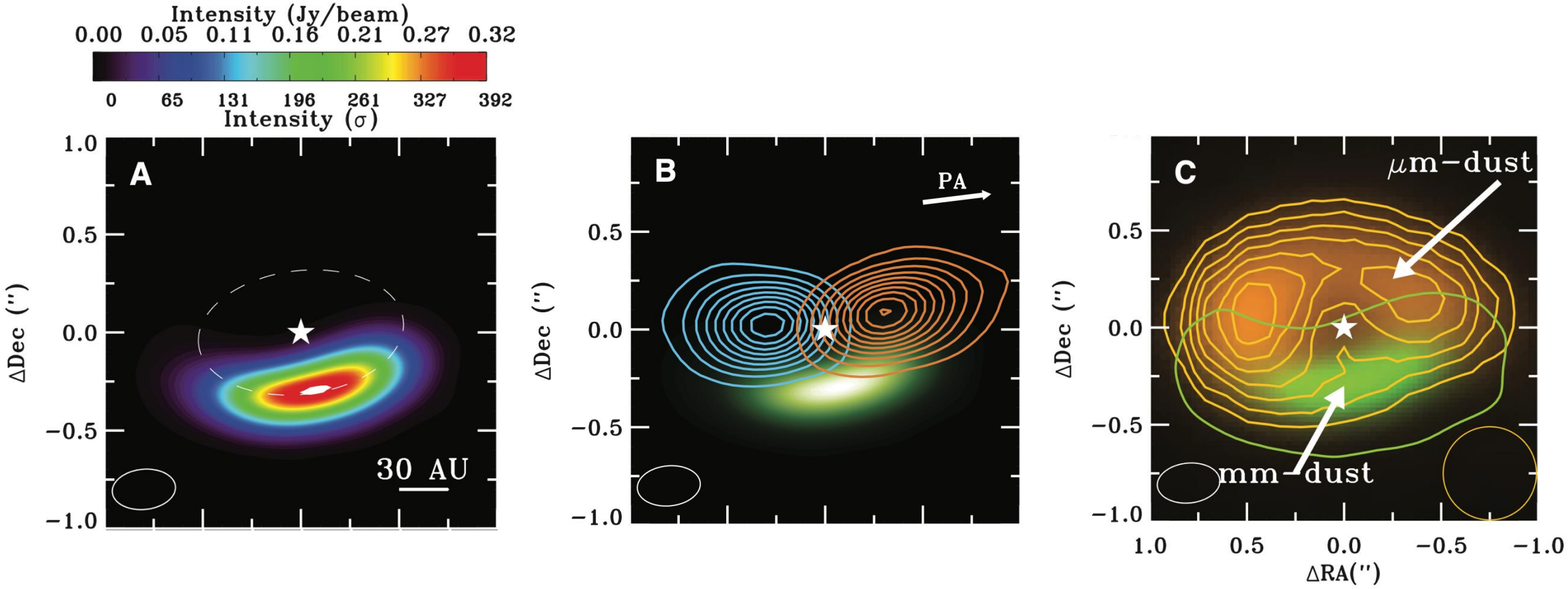




Disk spectra



Oph IRS 48



ALMA:
asymmetric
mm grains (pebbles)
at 63 AU

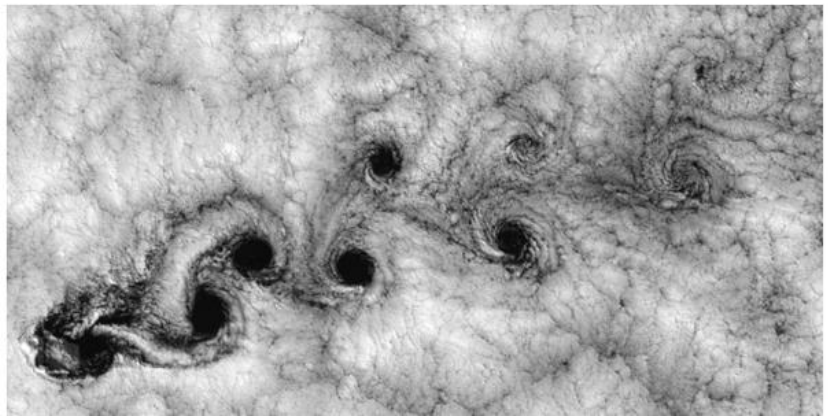
Gas lines:
Keplerian rotation

Infrared: Micron-sized
grains follows gas

van der Marel et al. (2013)

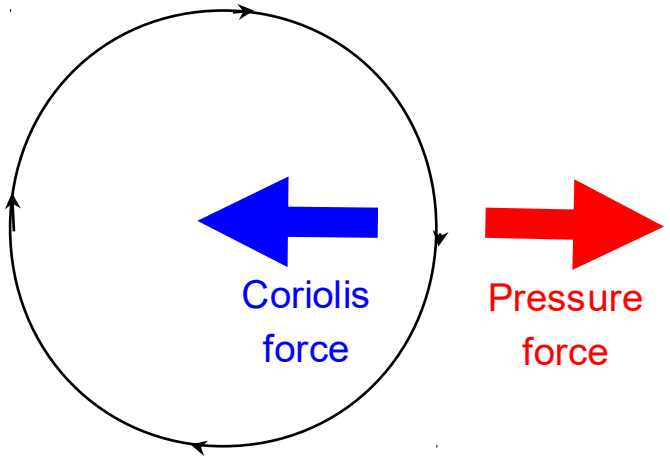
Vortices – an ubiquitous fluid mechanics phenomenon

Von Kármán *vortex street*

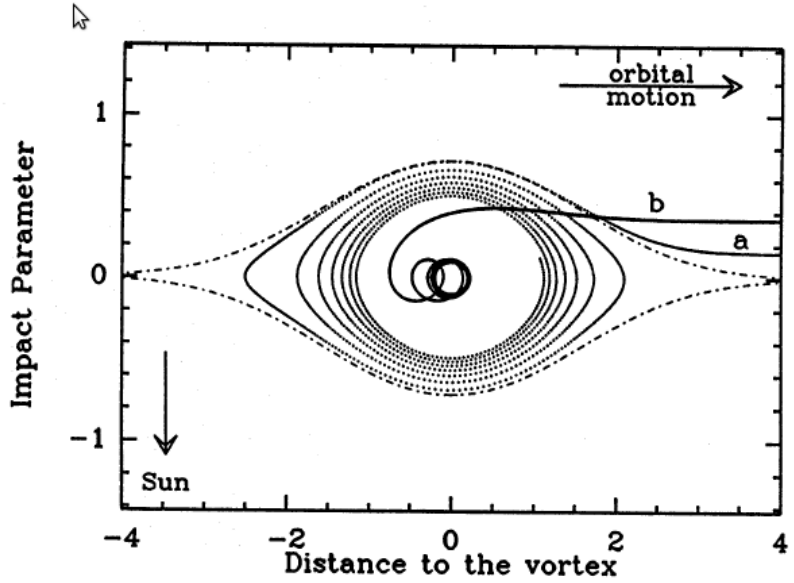


Vortex Trapping

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

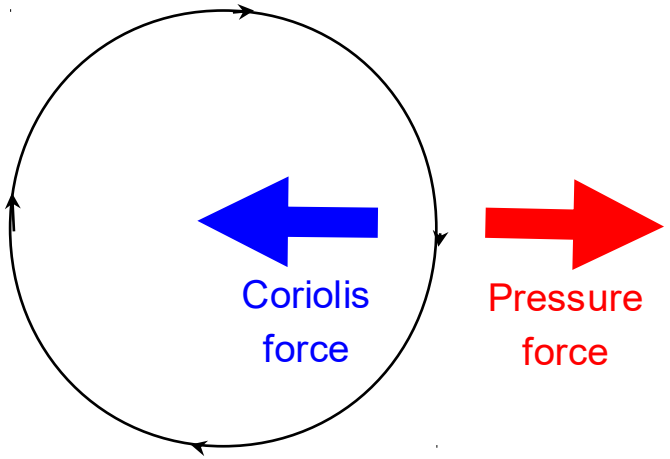
(Barge & Sommeria 1995, Tanga et al. 1996, Adams et al. 1996)

Speeds up planet formation enormously

(Lyra et al. 2008b, 2009ab, Raettig & Lyra + 2021, Lyra et al. 2024)

Vortex Trapping

Geostrophic balance:



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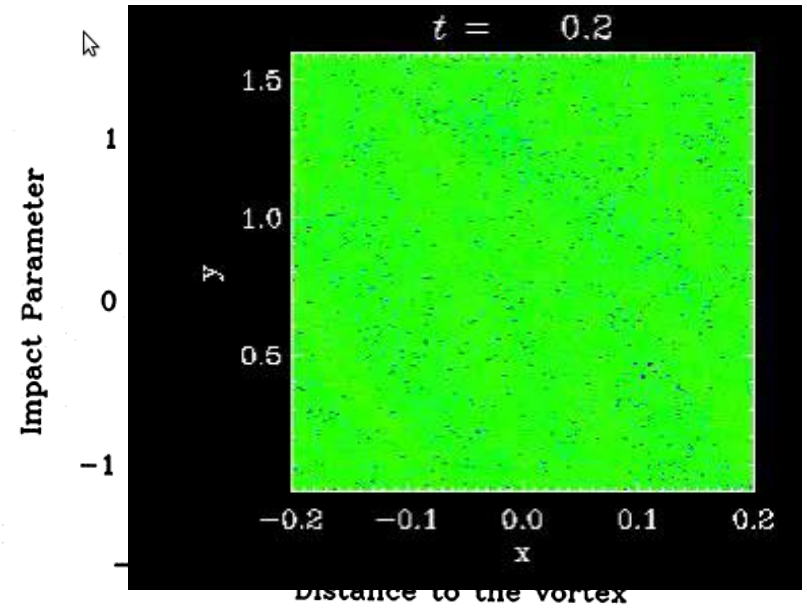

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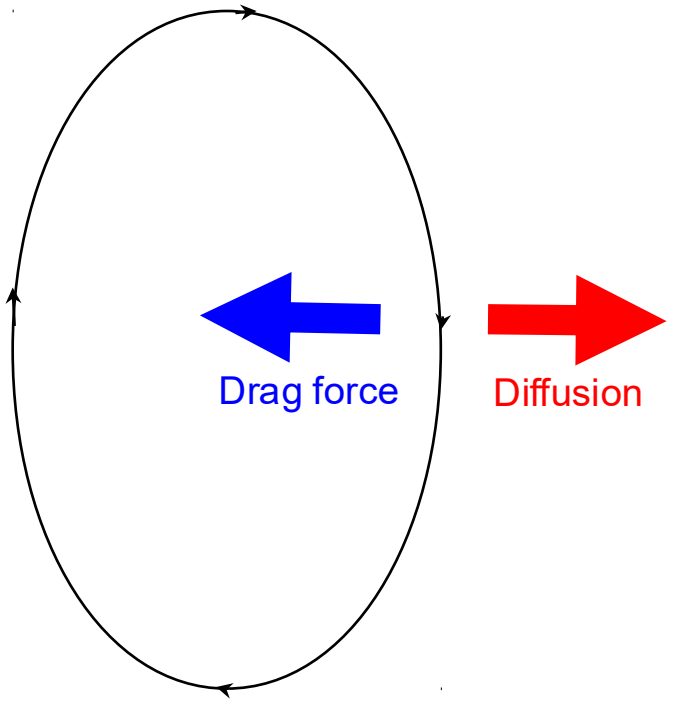
Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

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

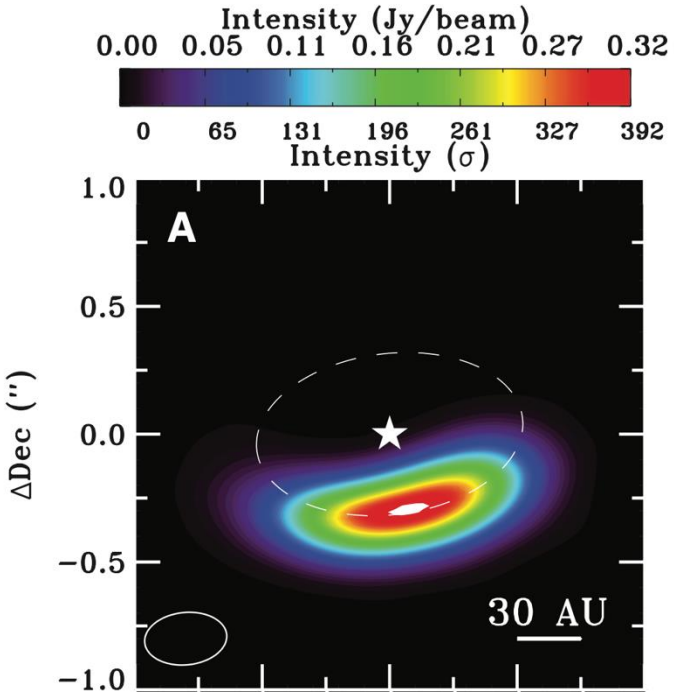
advection

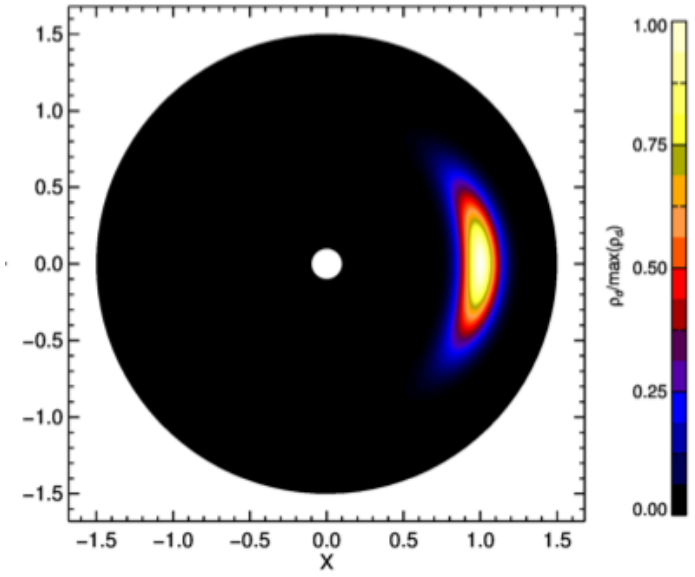
compression

diffusion

Lyra & Lin (2013)

Analytical Solution for dust in Drag-Diffusion Equilibrium





Solution for

H/r=0.1 χ*=4* *S*=1

Steady-state solution

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

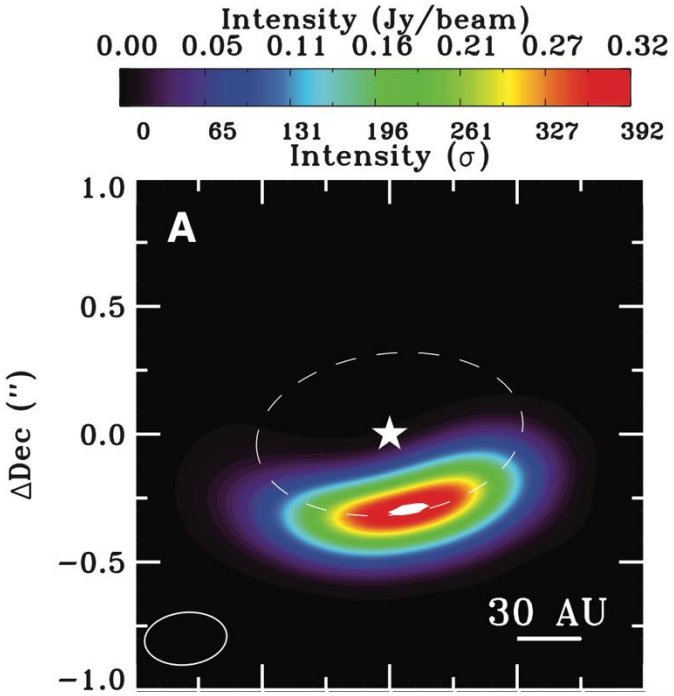
$$S = \frac{St}{\delta}$$

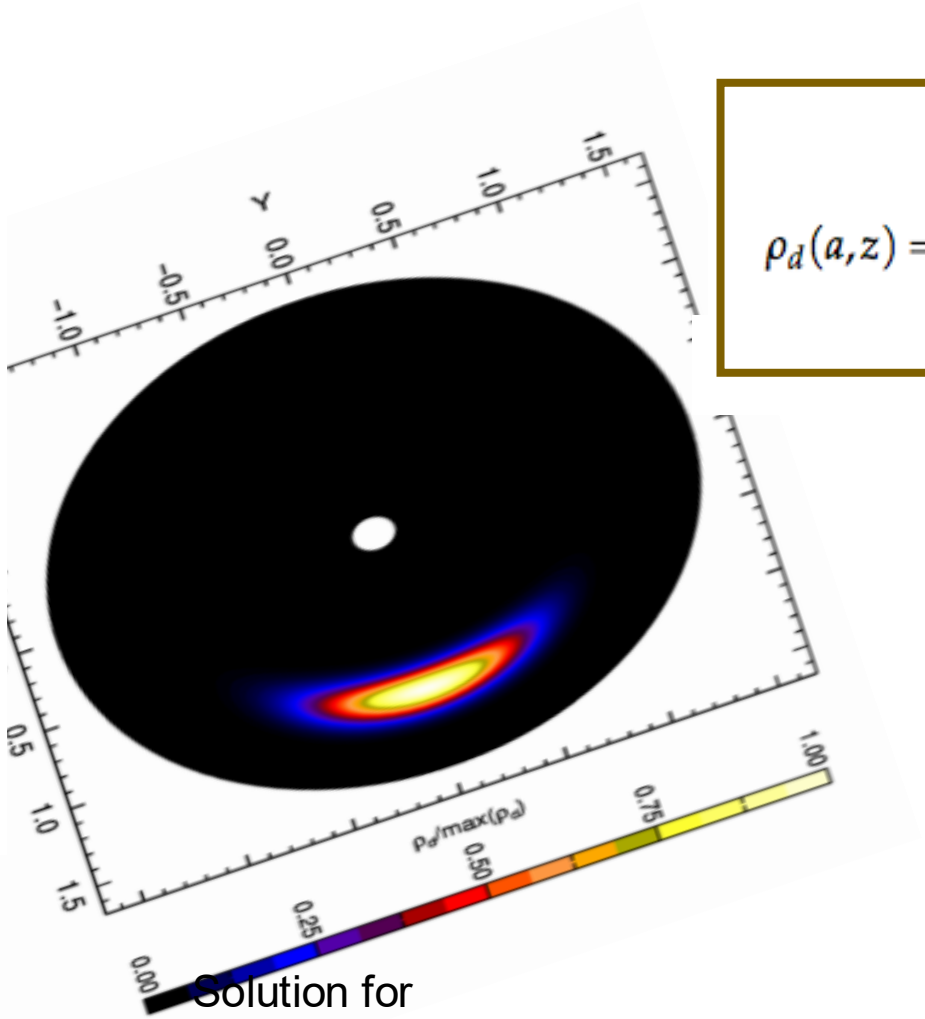
$$\delta = v_{\rm rms}^2 / c_s^2,$$

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

Lyra & Lin (2013)

Analytical Solution for dust in Drag-Diffusion Equilibrium





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Lyra & Lin '13

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

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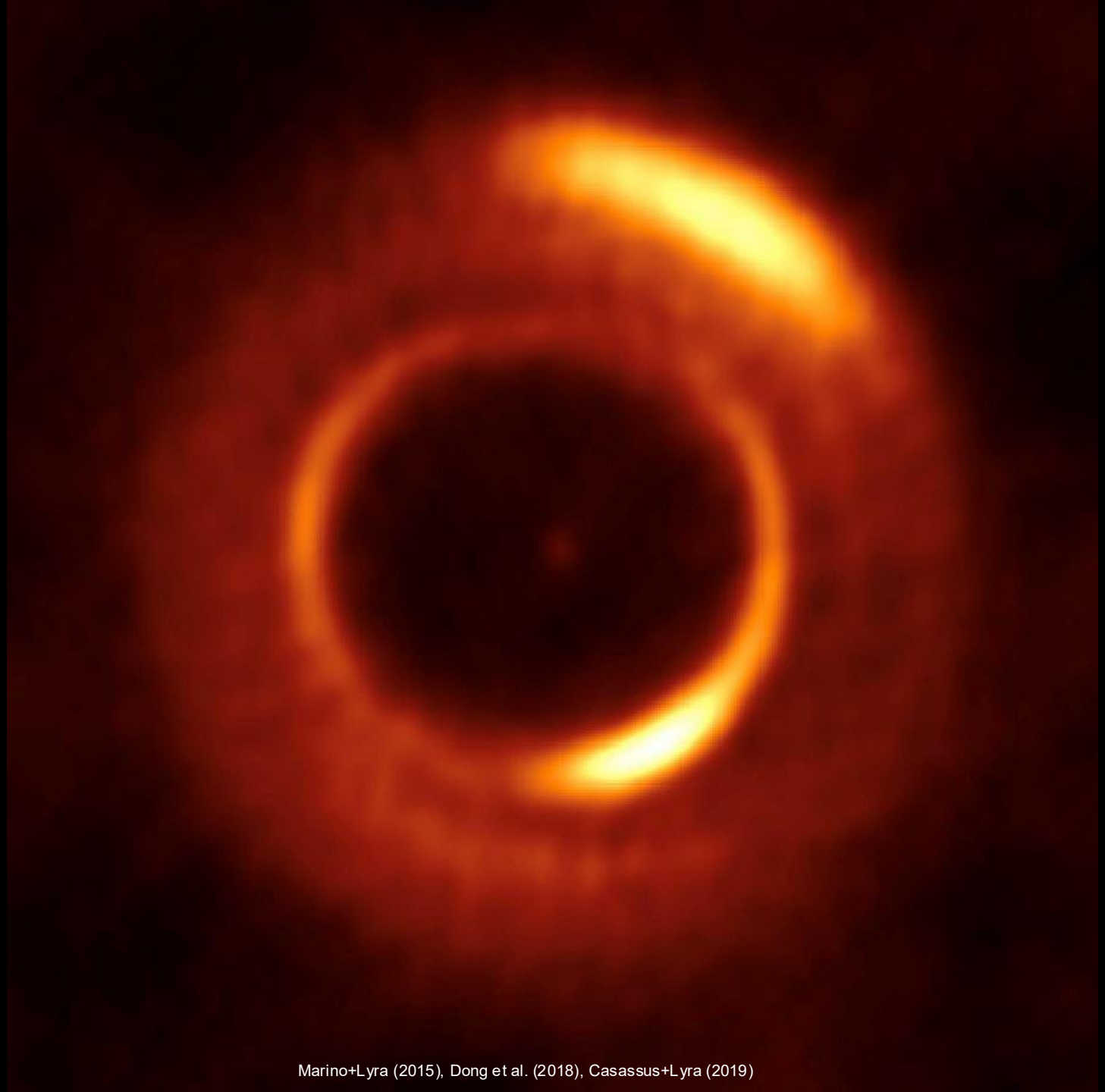
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

Lyra & Lin (2013)

MWC 758



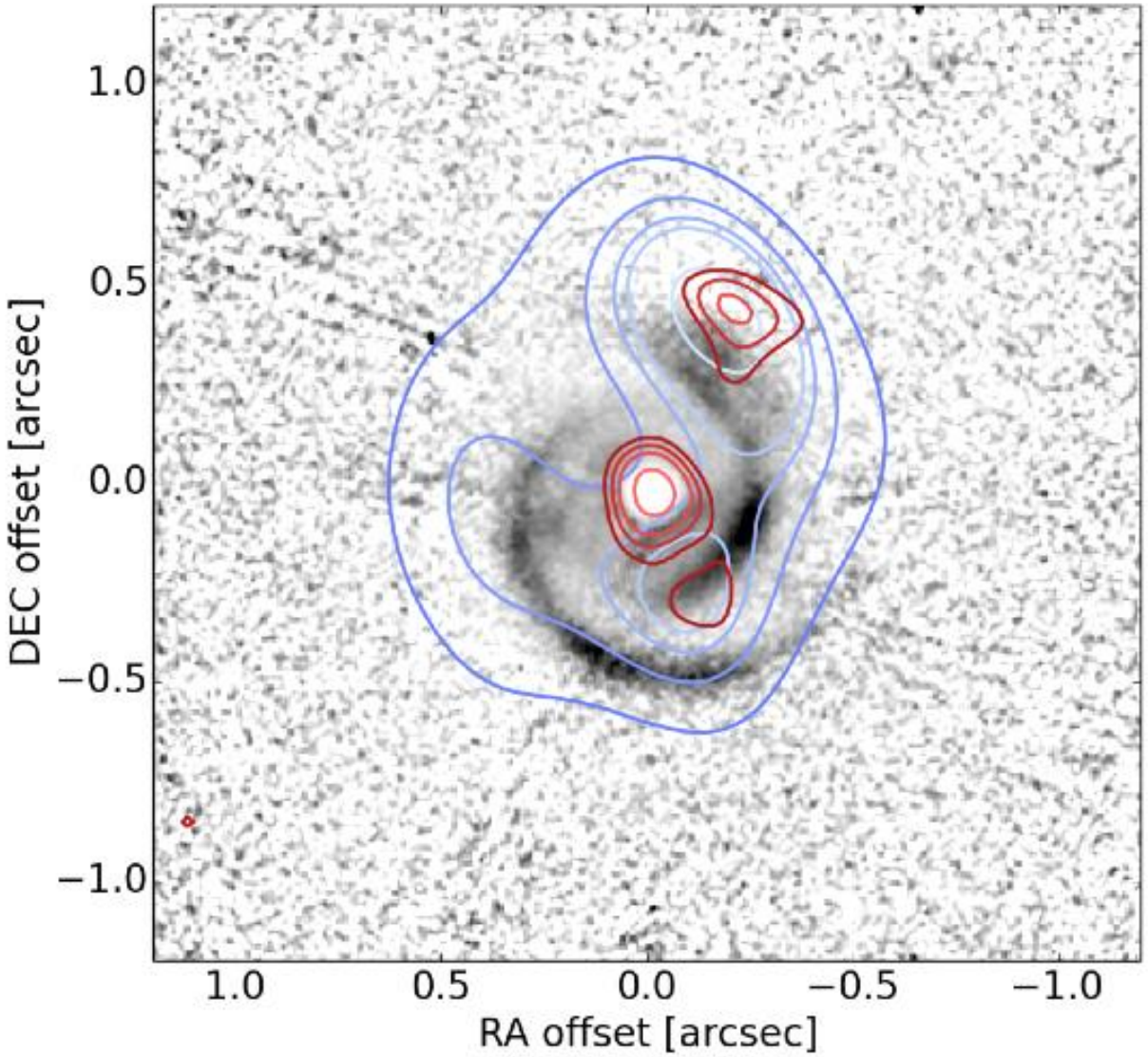
Marino+Lyra (2015), Dong et al. (2018), Casassus+Lyra (2019)

Disk Tomography
SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (~μm)

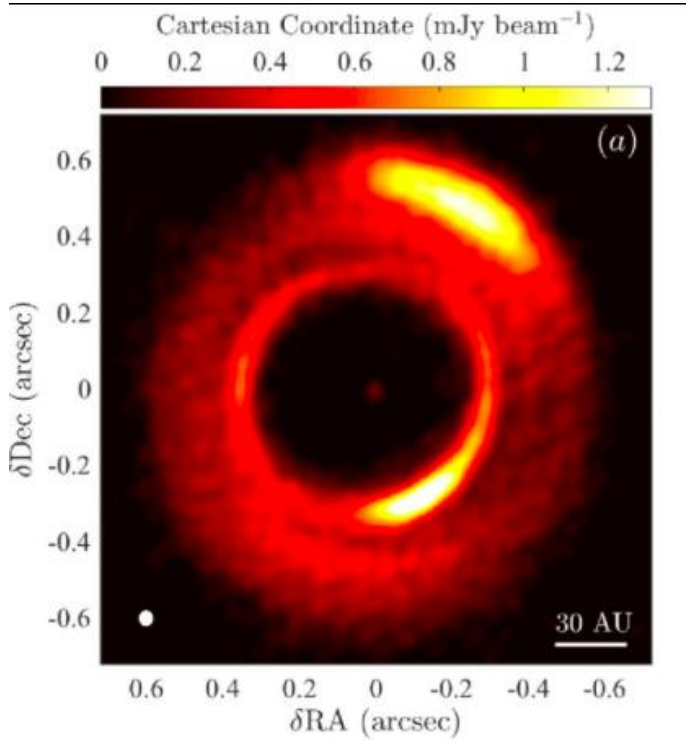
ALMA (~ mm)

VLA (~cm)



Marino+Lyra '15

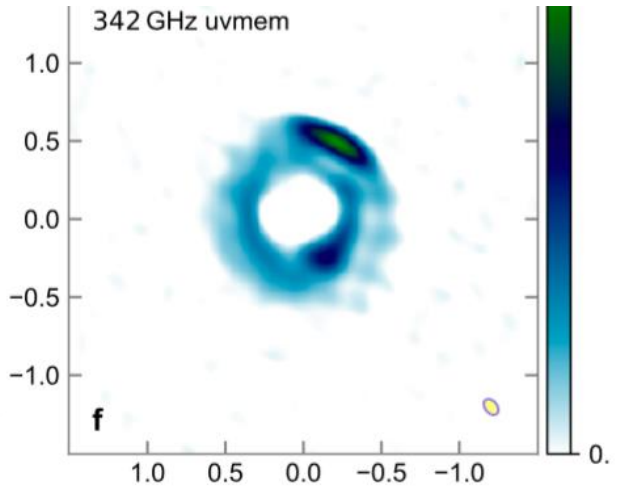
ALMA



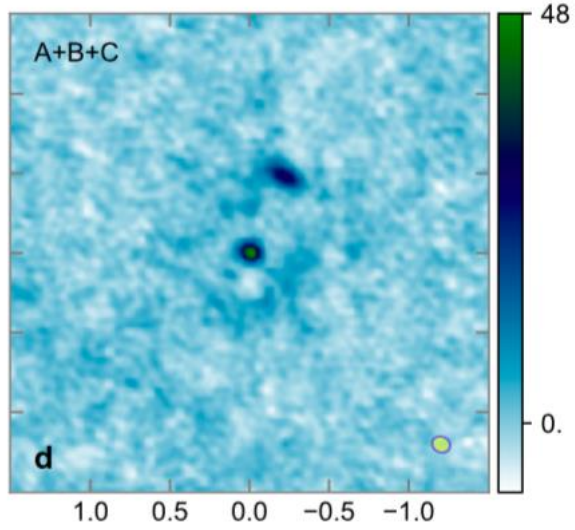
Dong+ '18

Pebble trapping

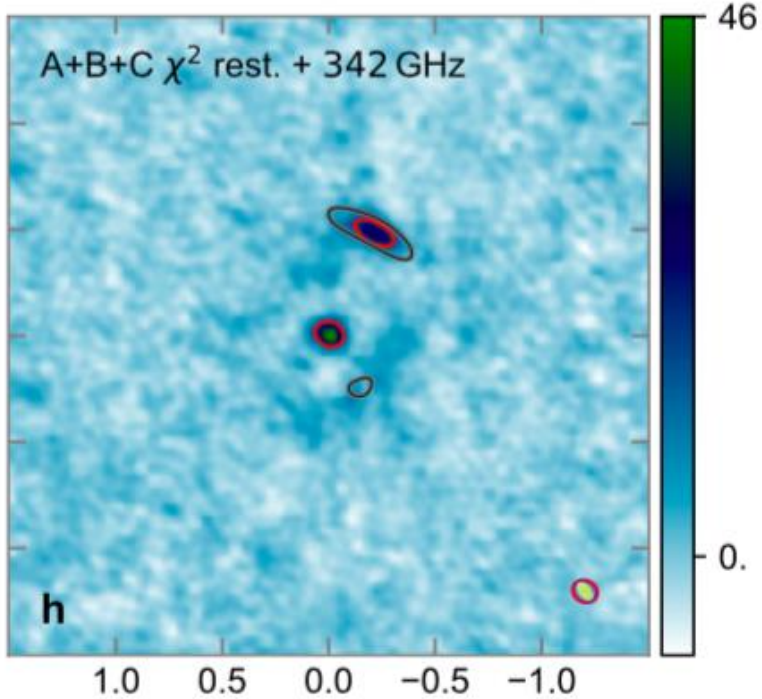
ALMA (mm)



VLA (cm)

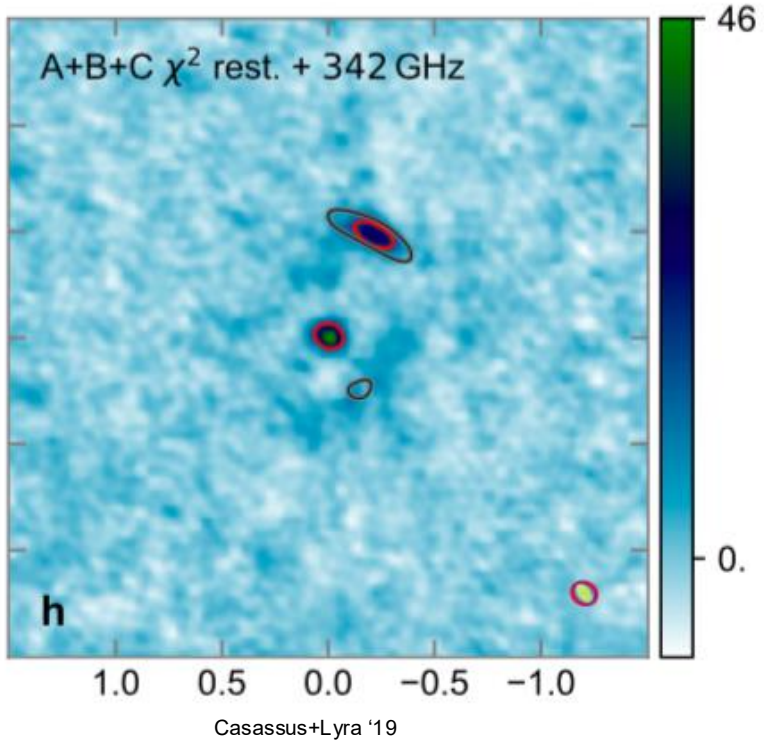


Overlay

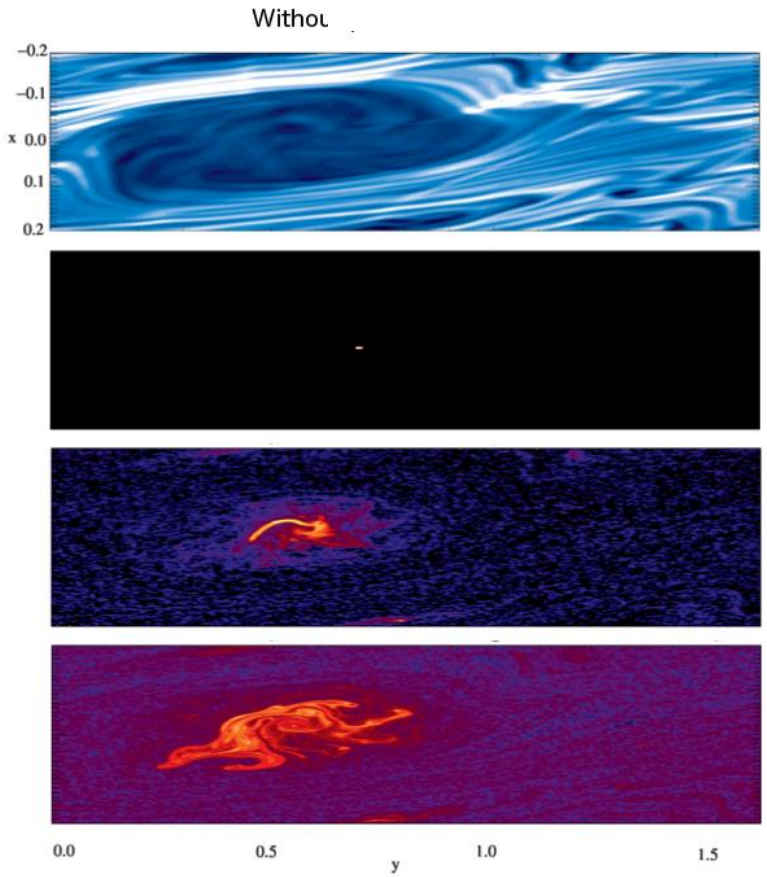


Casassus+Lyra ’19

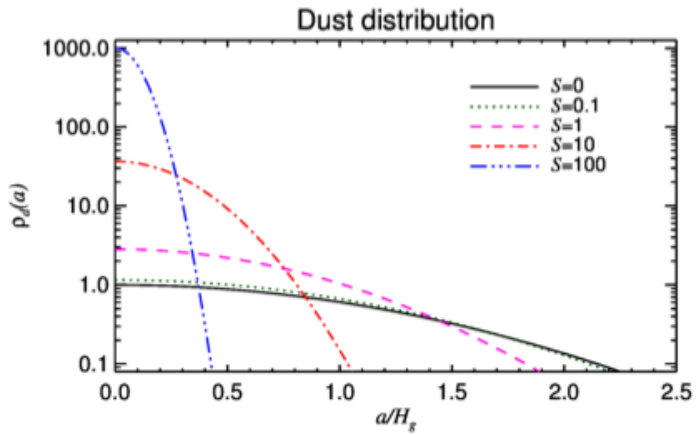
Model vs Observation



Casassus+Lyra '19



Raettig+Lyra '15



Lyra & Lin (2013)

$S = \mathrm{St}/\delta$

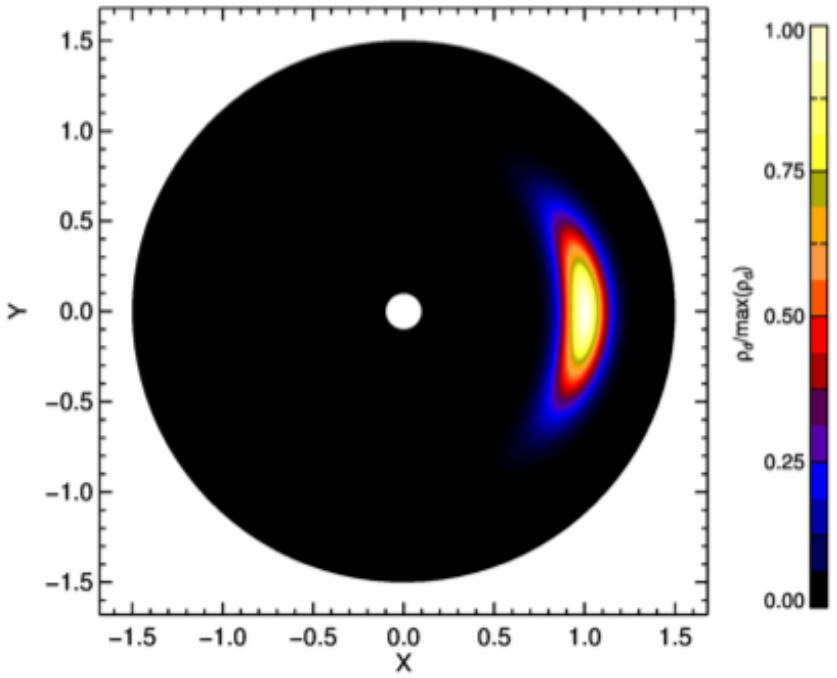
$\delta = v_{\mathrm{rms}}^2 / c_s^2,$

Take home message

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

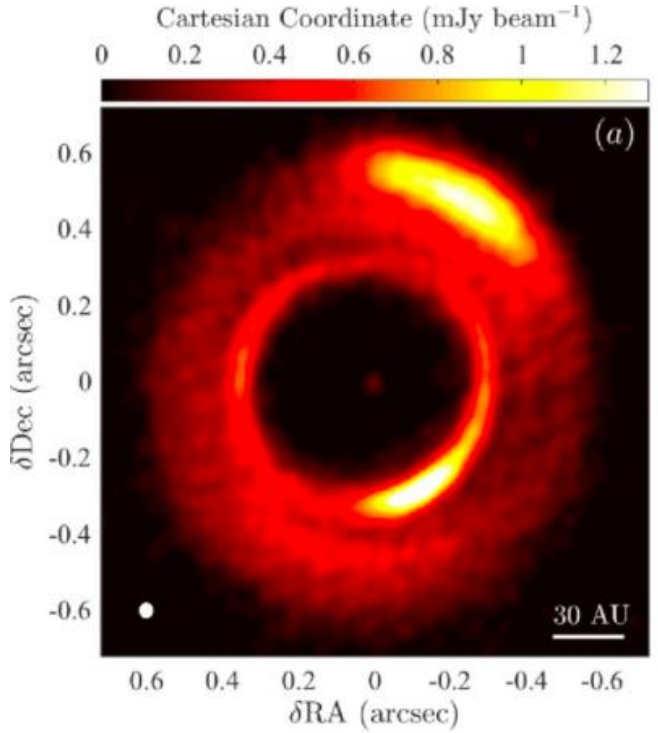
$$\rho_d(a,z) = \varepsilon\rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi)+z^2]}{2H^2}(S+1)\right\}$$

Lyra-Lin solution



Lyra & Lin (2013)

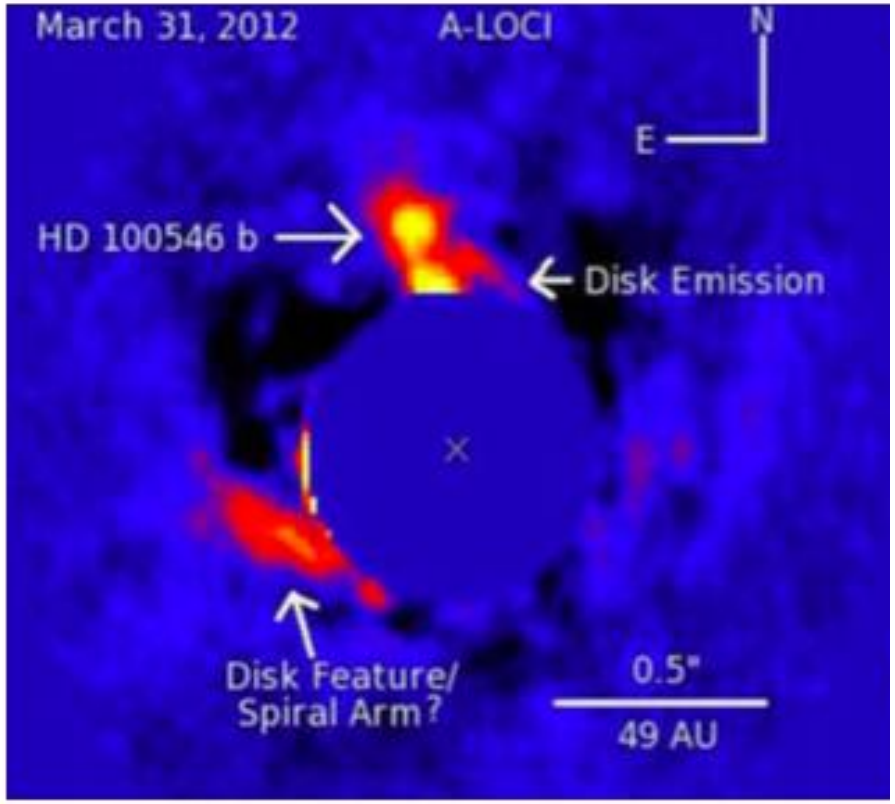
Observed Disk



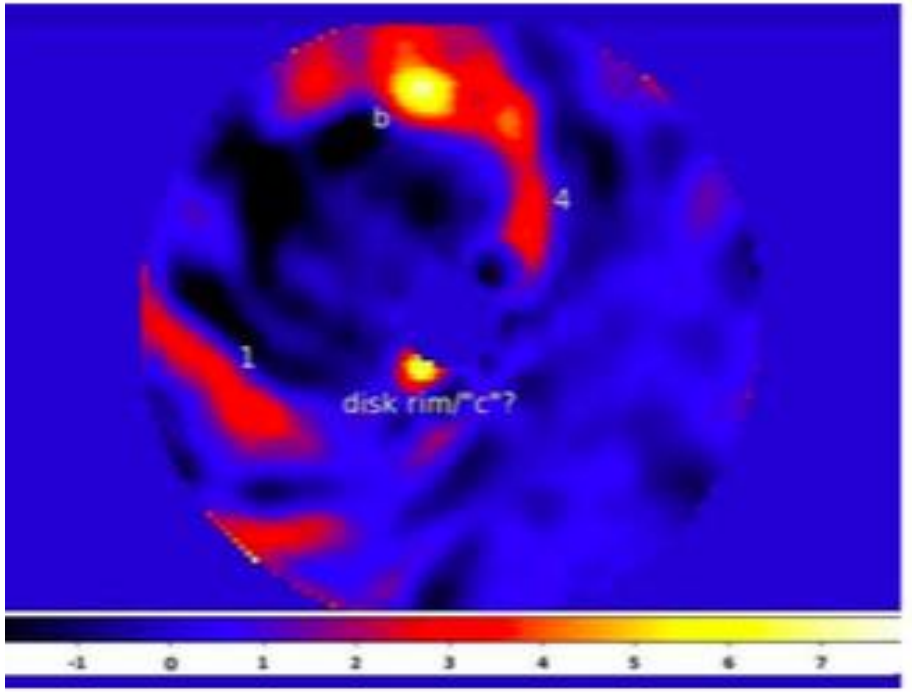
Dong et al. (2018)

KR Muscae (HD 100546)

L band (~3.5 μm)



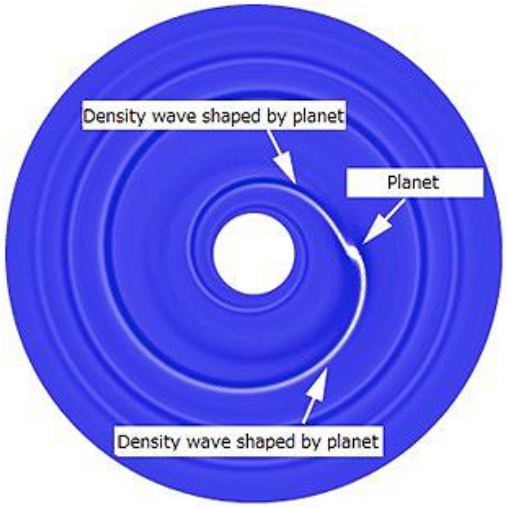
H band (~1.6 μm)



Currie et al. (2014), Currie (2015)

Spiral arm fitting leads to problems

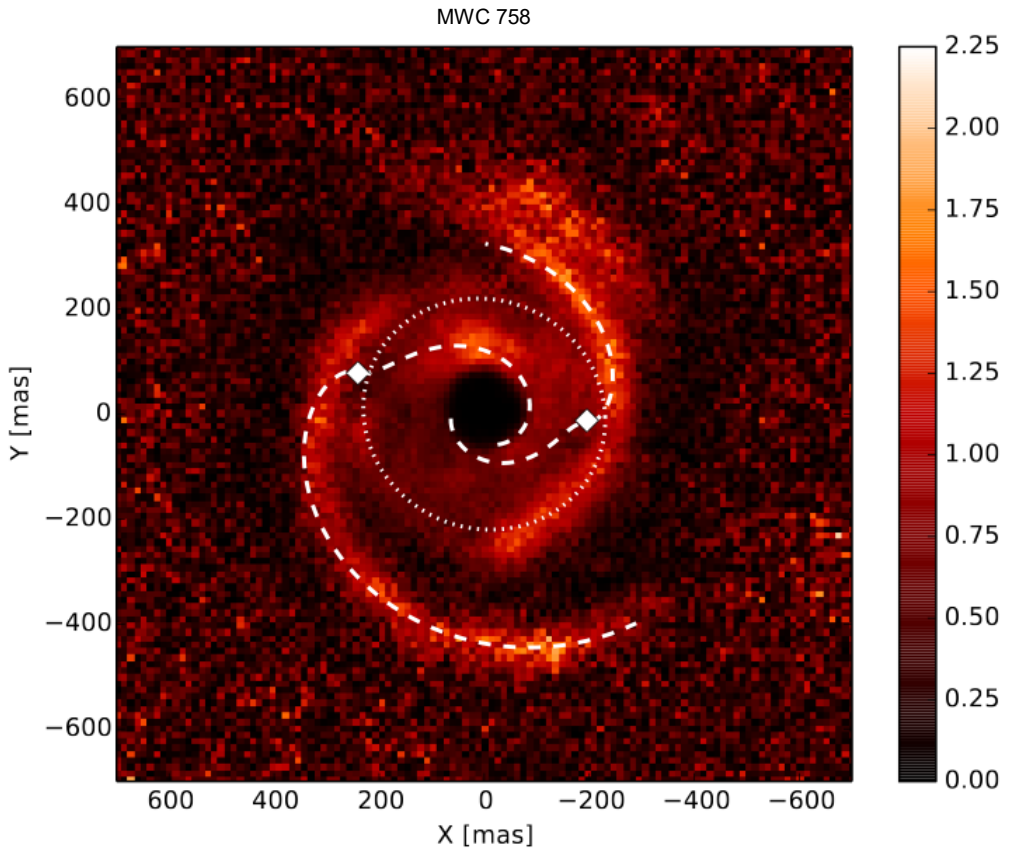
Analytical spiral fit



$$\theta(r) = \theta_c + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c}\right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \left(\frac{r}{r_c}\right)^{-\alpha} \right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \right) \right\},$$

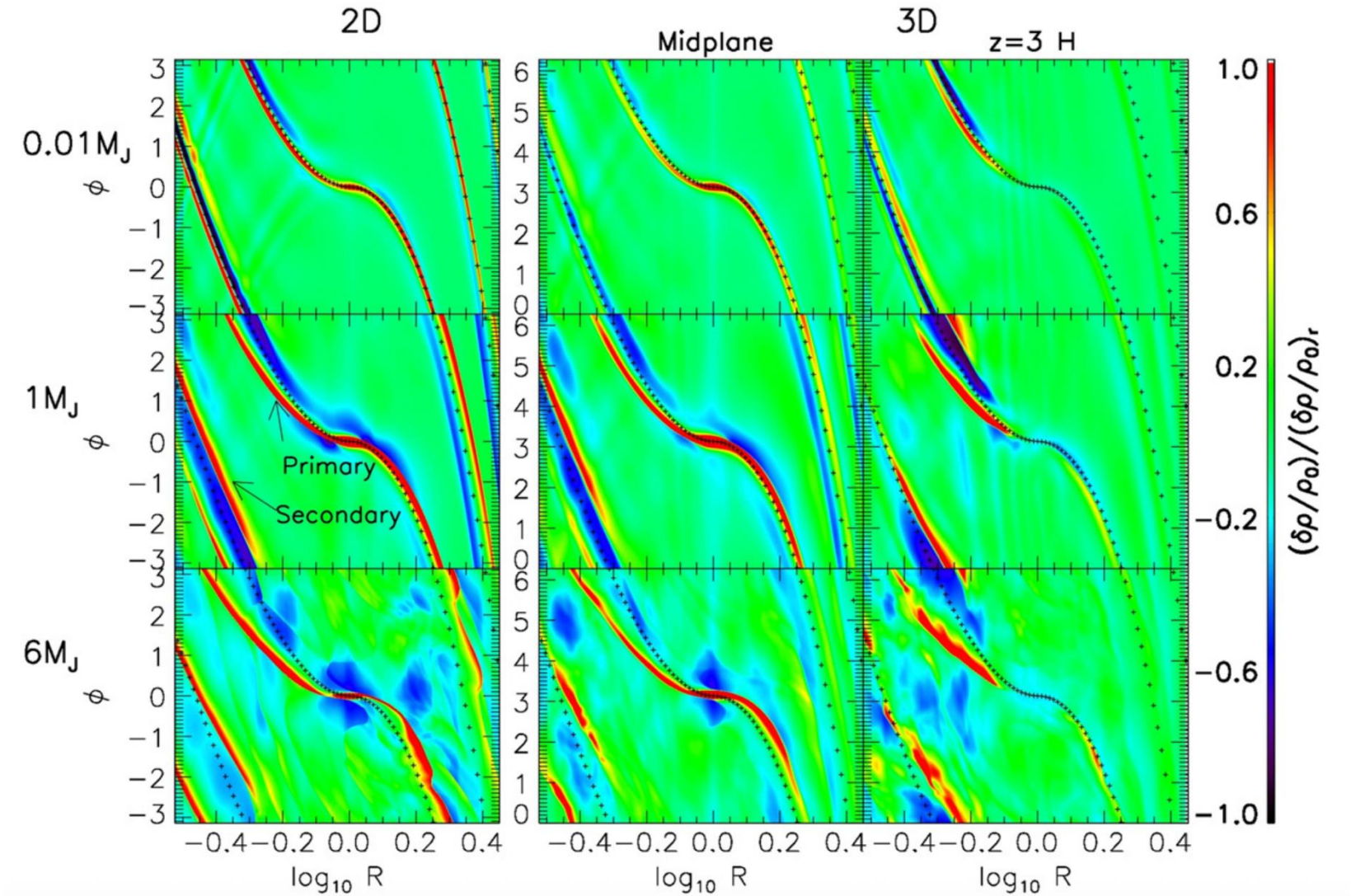
Rafikov (2002)
Muto et al. (2012)

Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



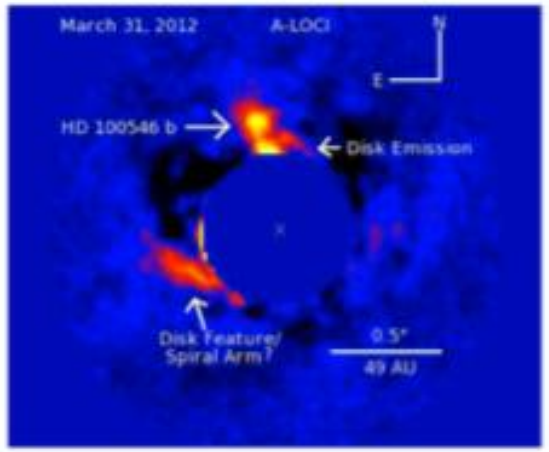
Benisty et al. (2015)

Supersonic wake of high mass planets does not follow the linear prediction

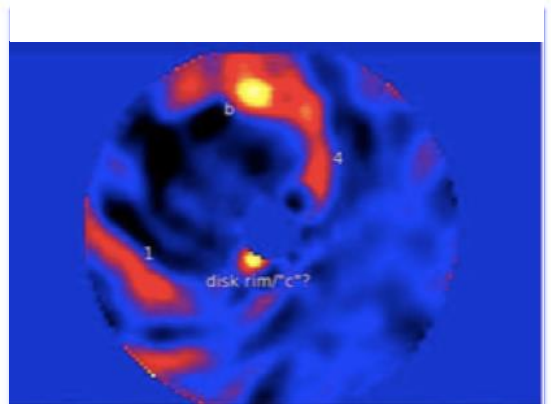


Zhu et al. (2015)

Pinning down the temperature

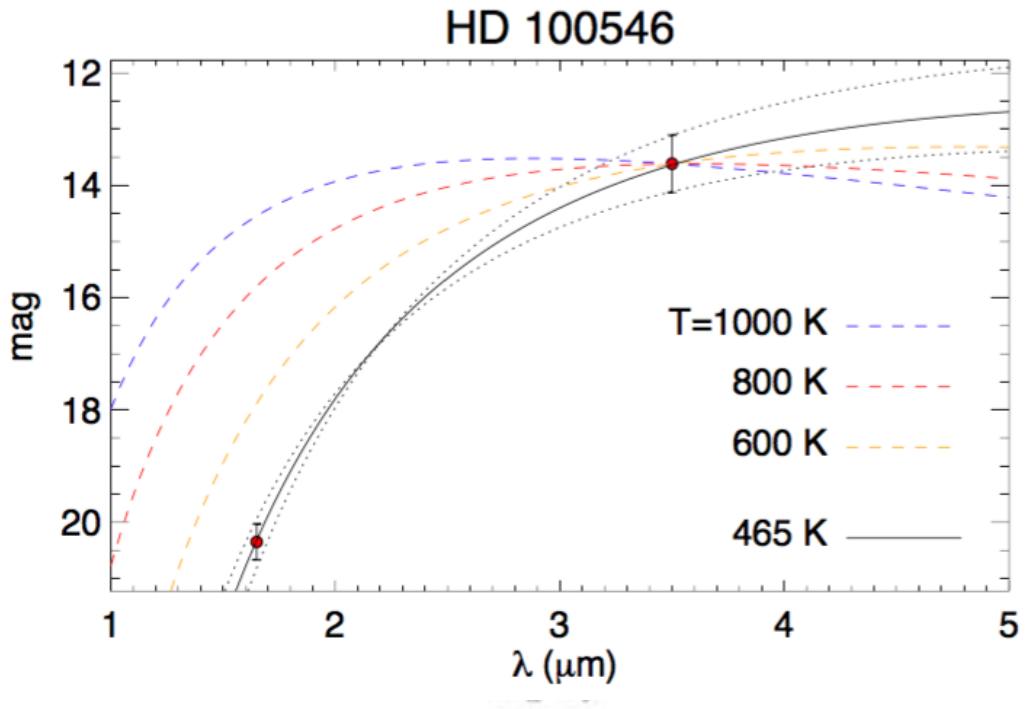


L band



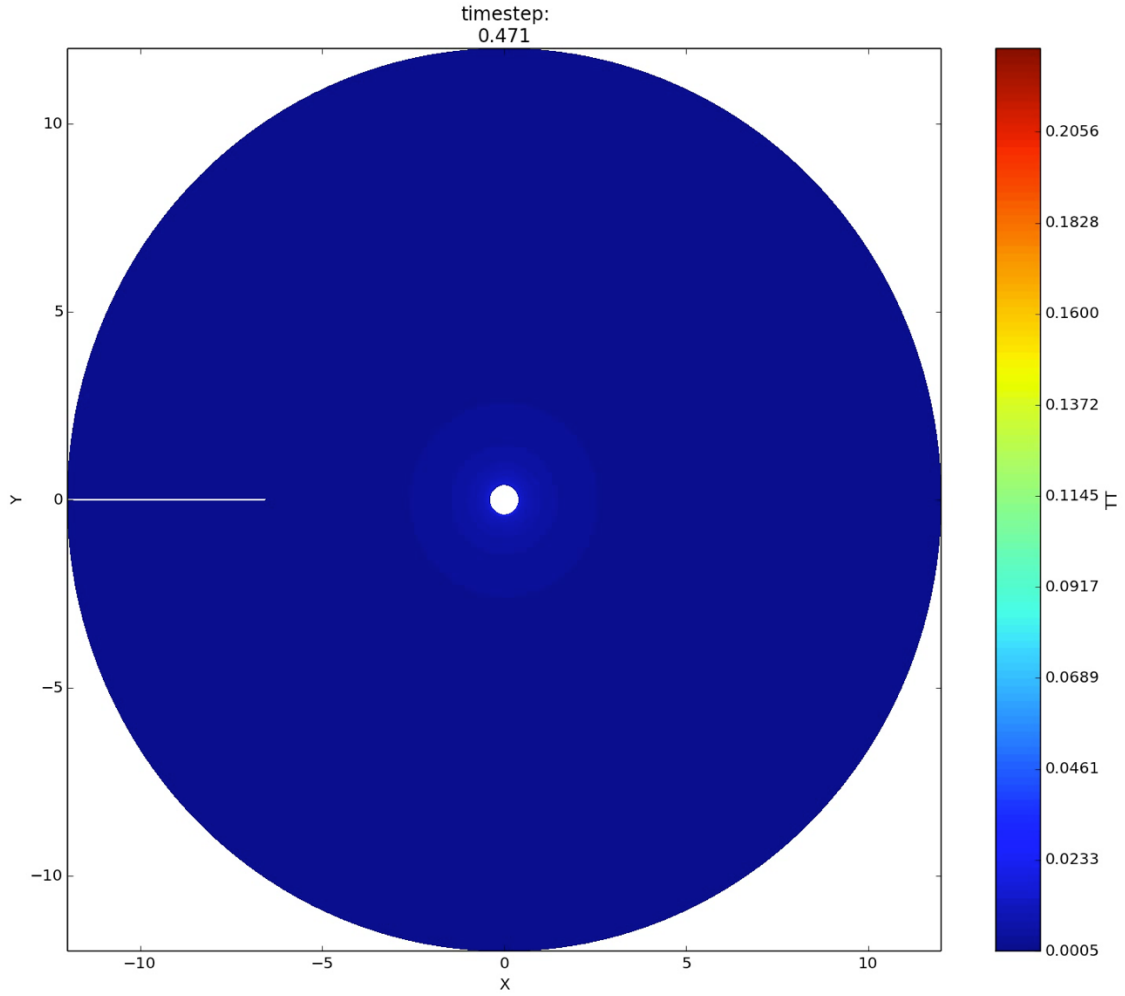
H band

Currie et al. (2014, 2015)



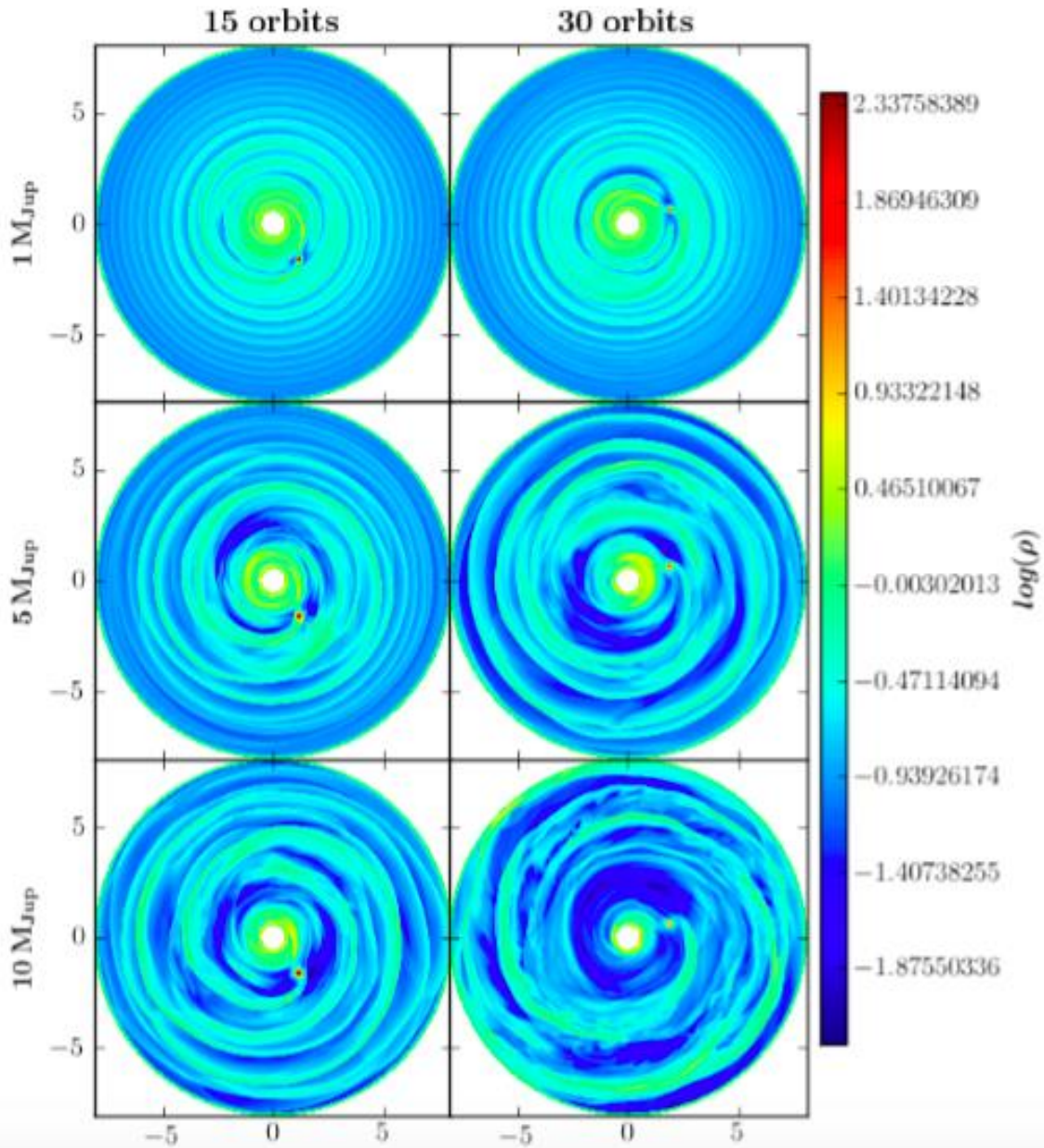
Lyra et al. (2016)

Planet-driven turbulence

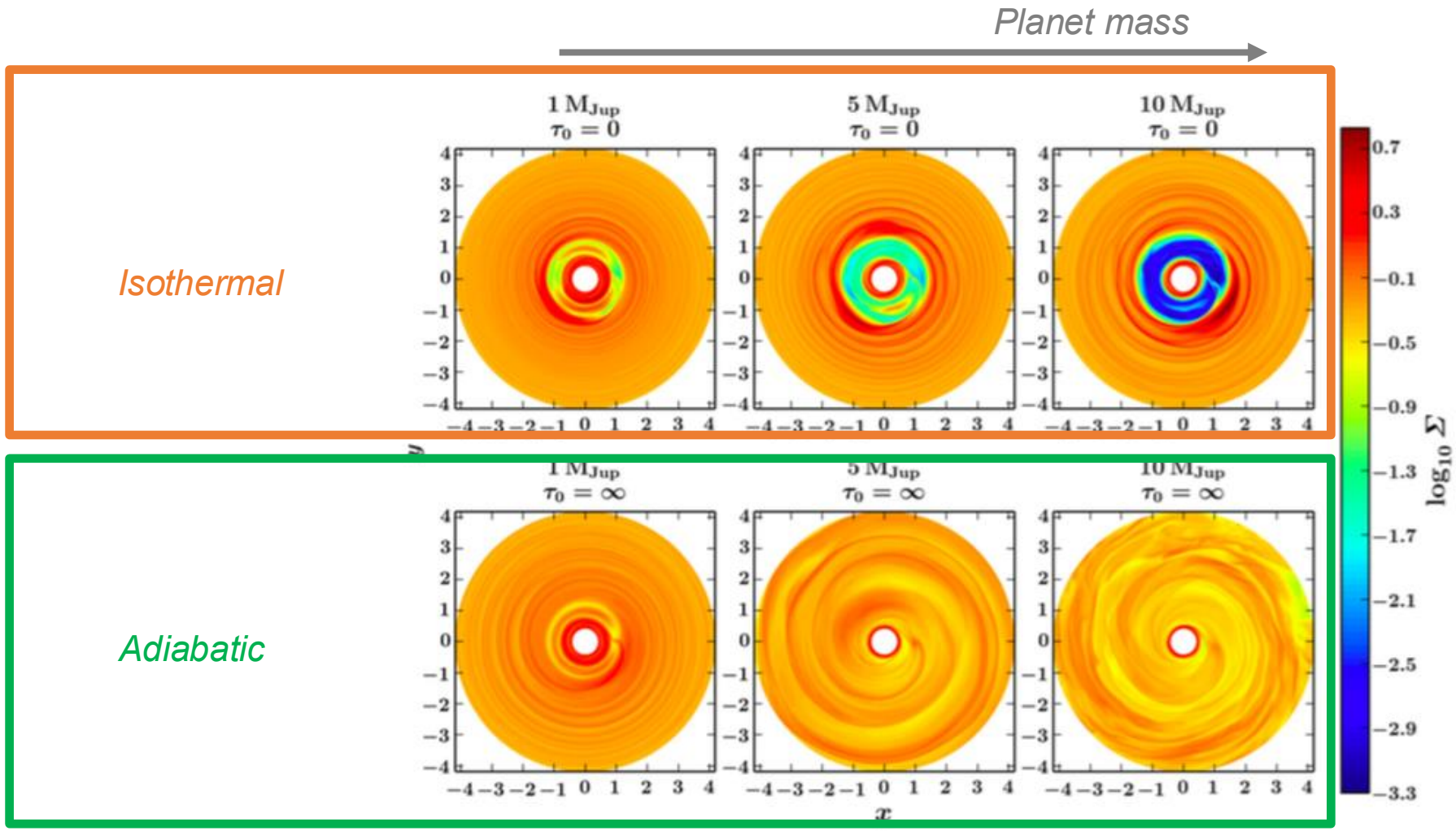


Richert & Lyra + (2015)

Some crazy turbulence showing up at high planet mass….

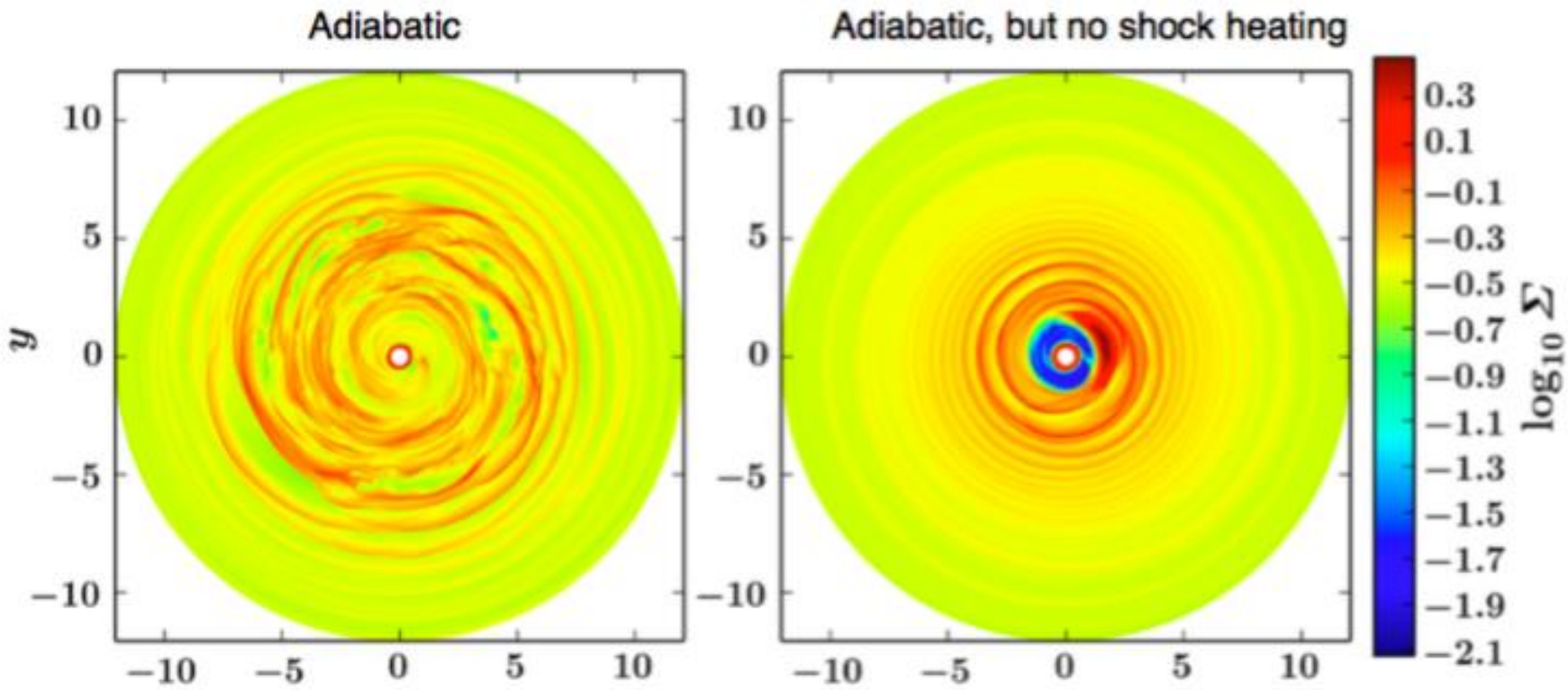


Turbulence in high-mass planets in adiabatic disks



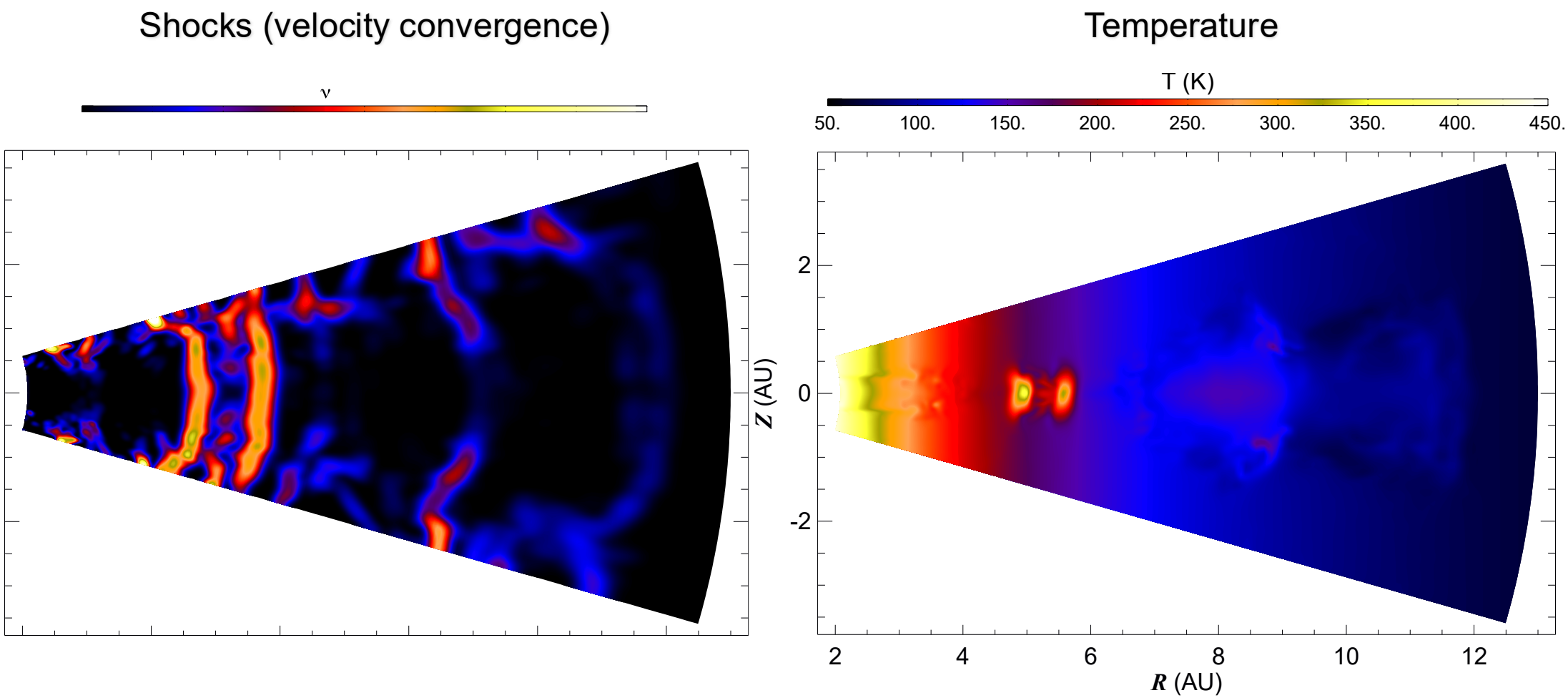
Richert & Lyra + (2015)

The energy source: shock heating!



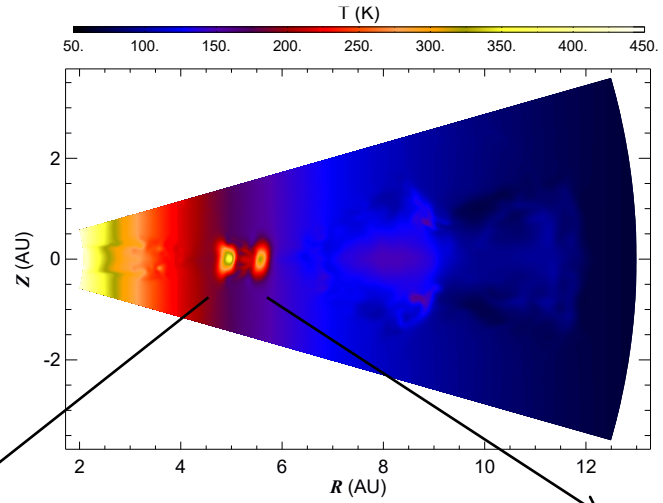
Richert & Lyra + (2015)

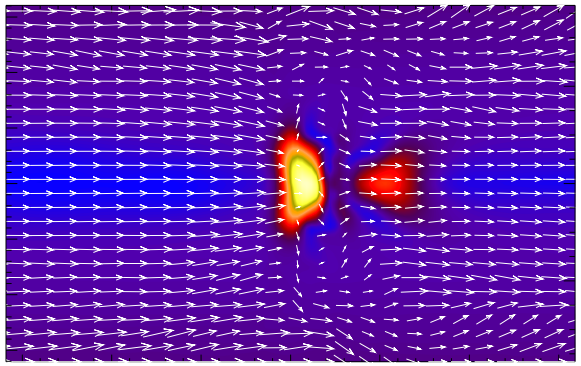
3D: Shock bores



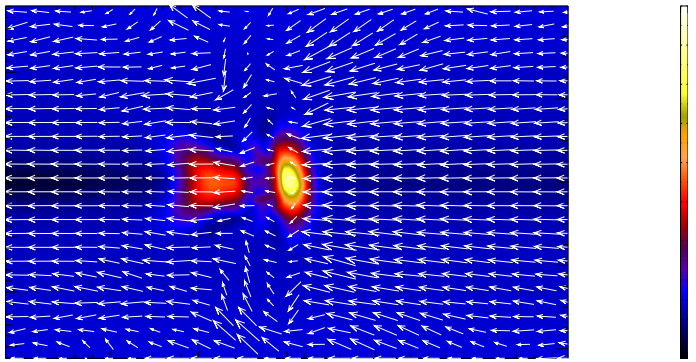
Lyra et al. (2016)

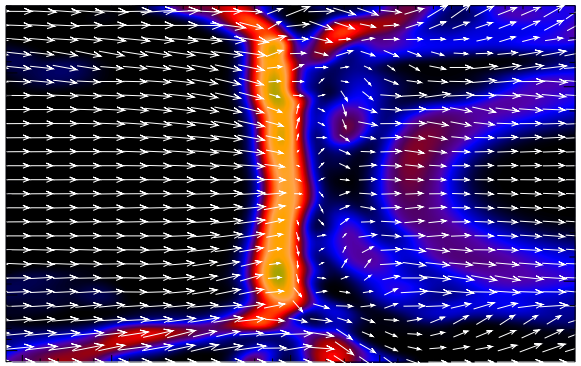
3D shocks: bores and breaking waves



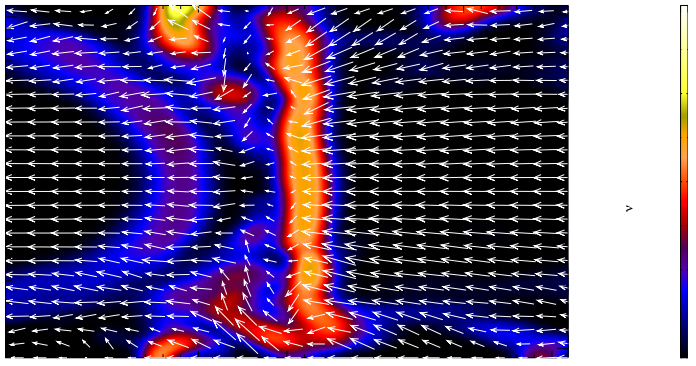


Temperature



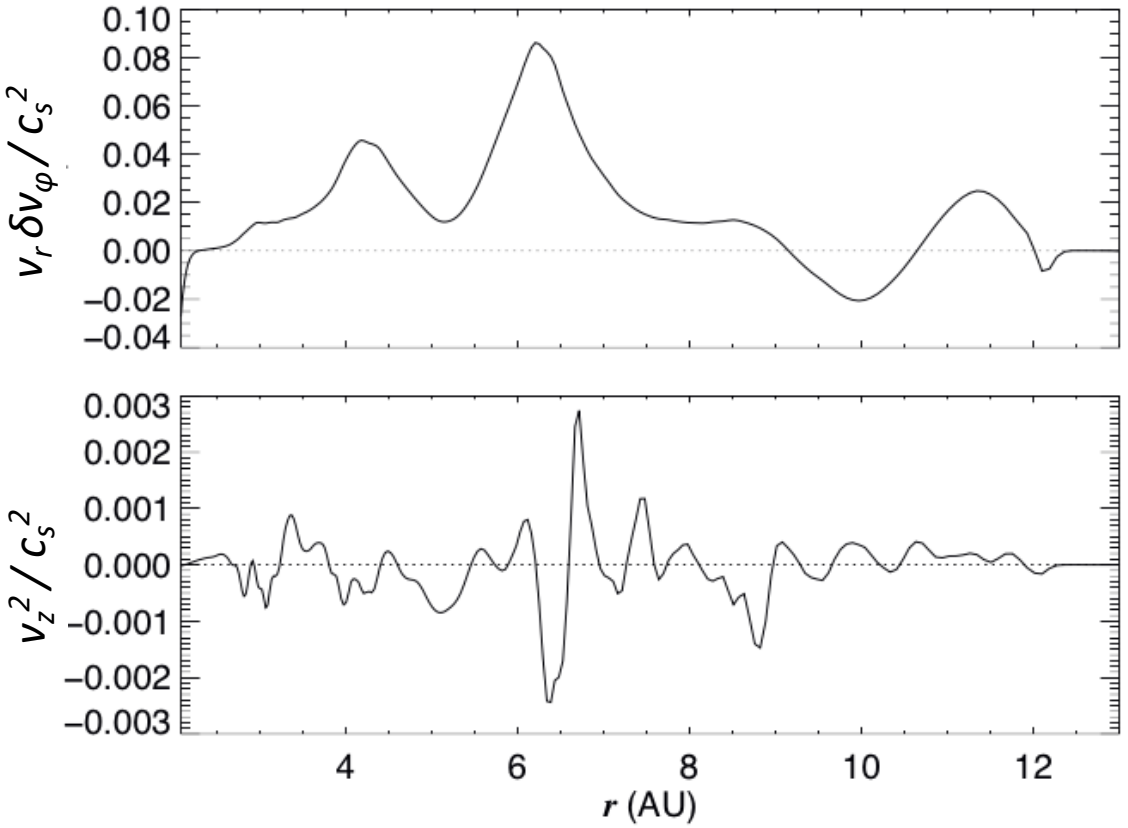


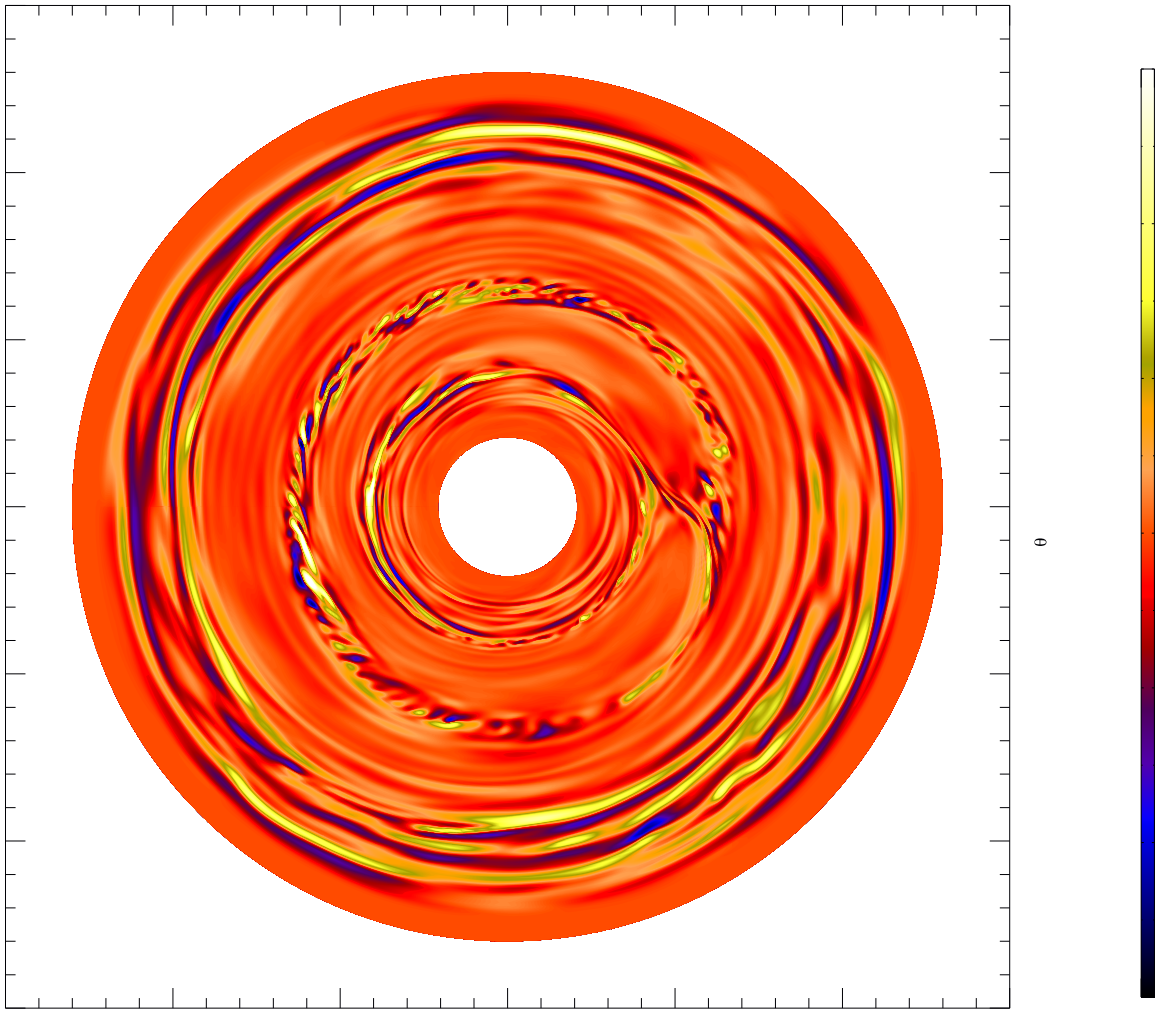
Div u
(shock)



Lyra et al. (2016)

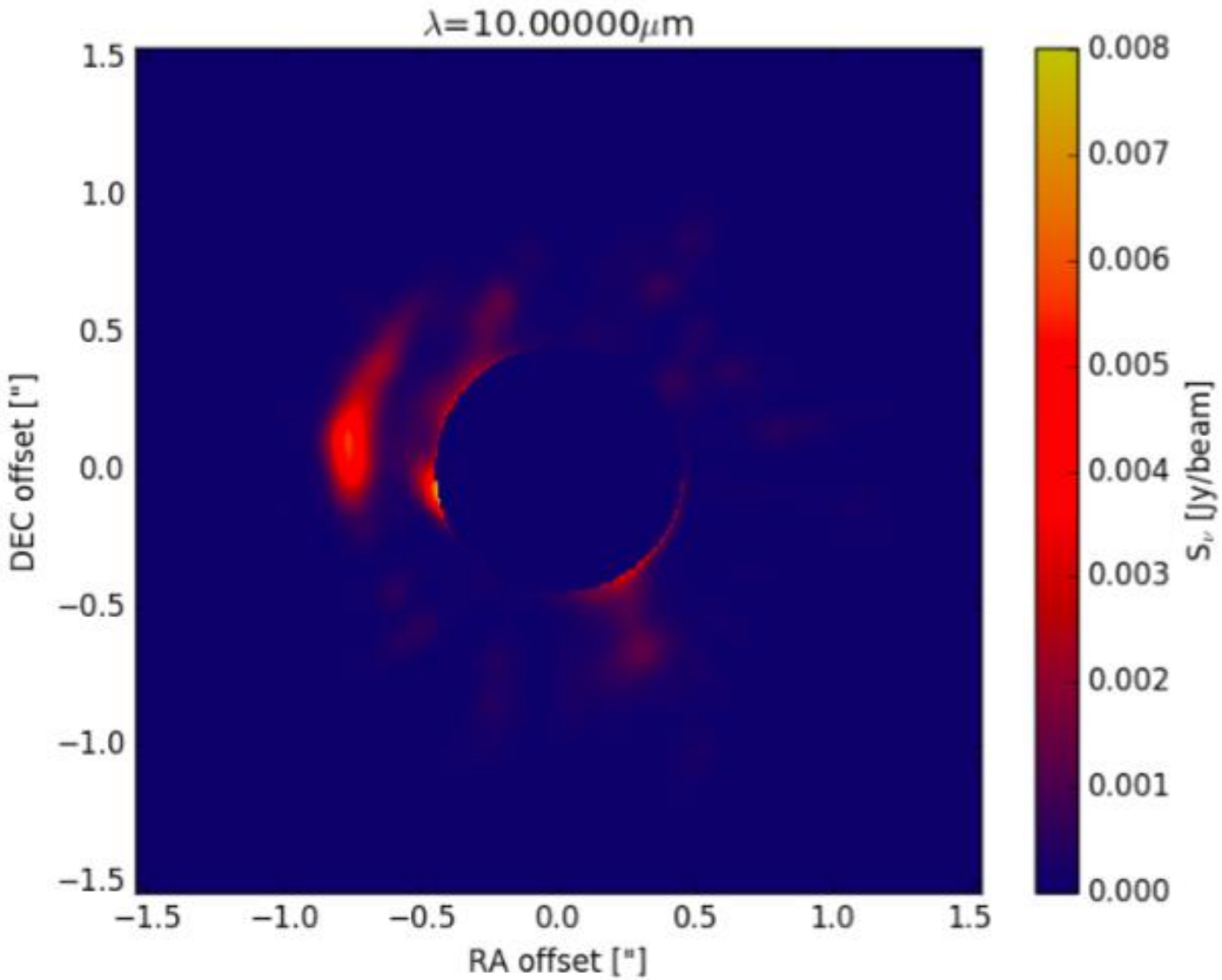
Turbulent surf





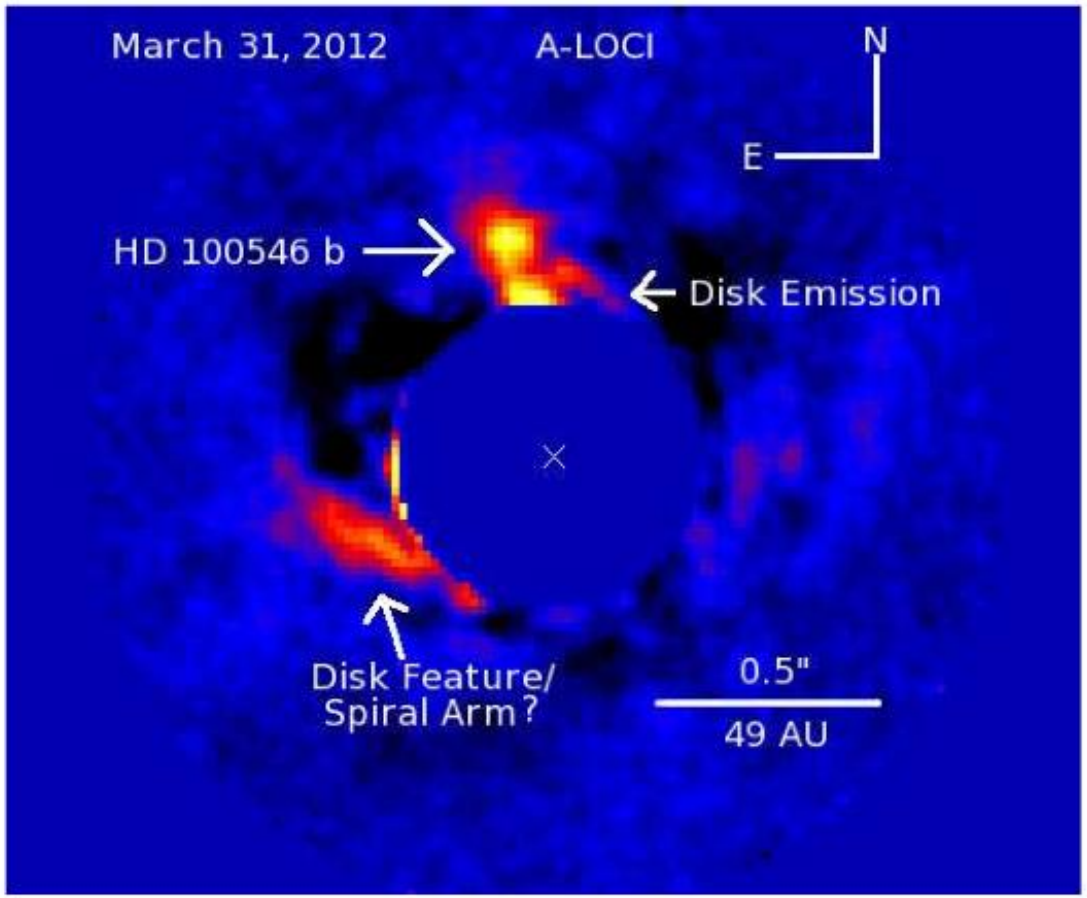
Lyra et al. (2016)

Synthetic image with RADMC3D and shock heating

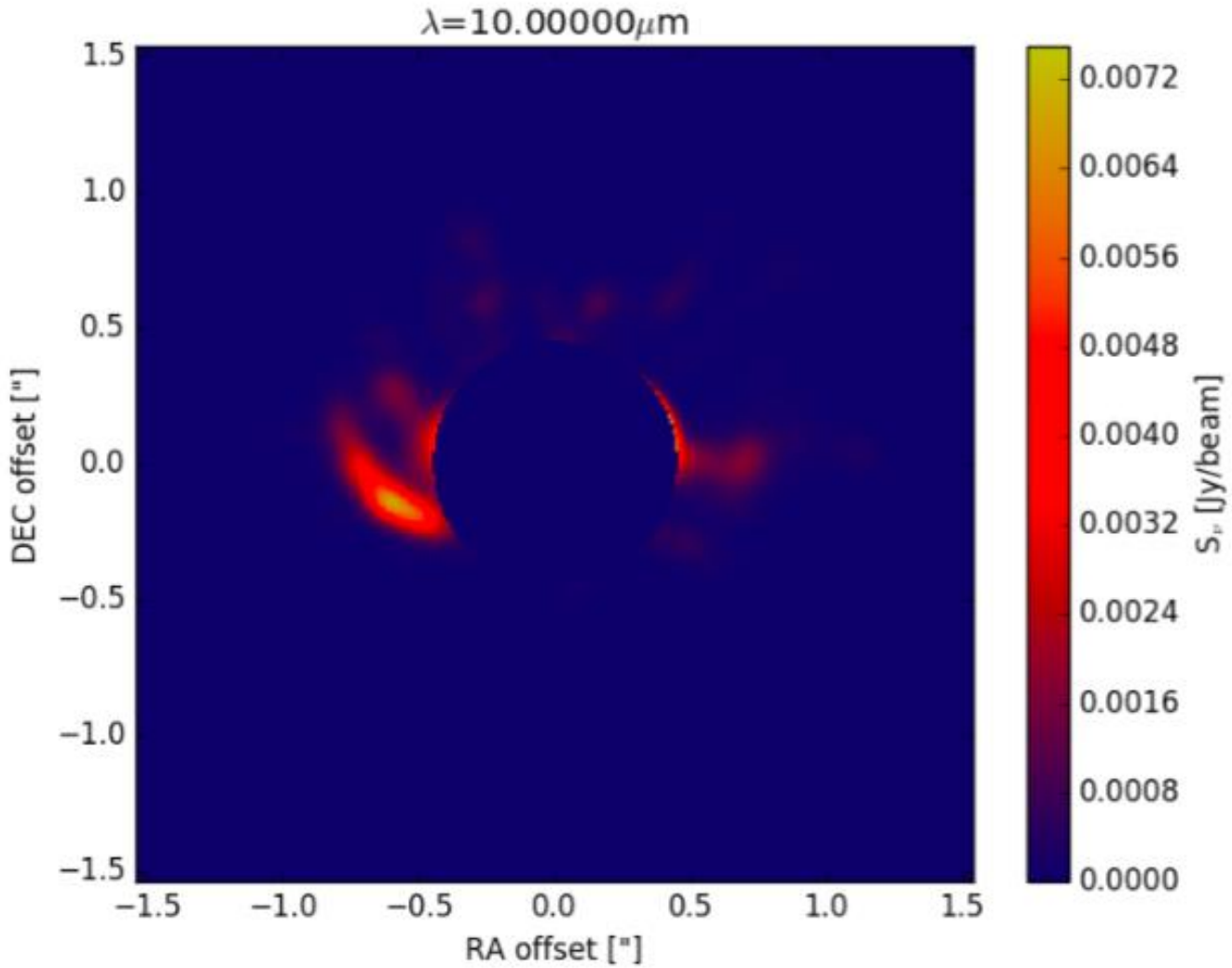


Hord & Lyra + (2017)

Observation vs Synthetic Image

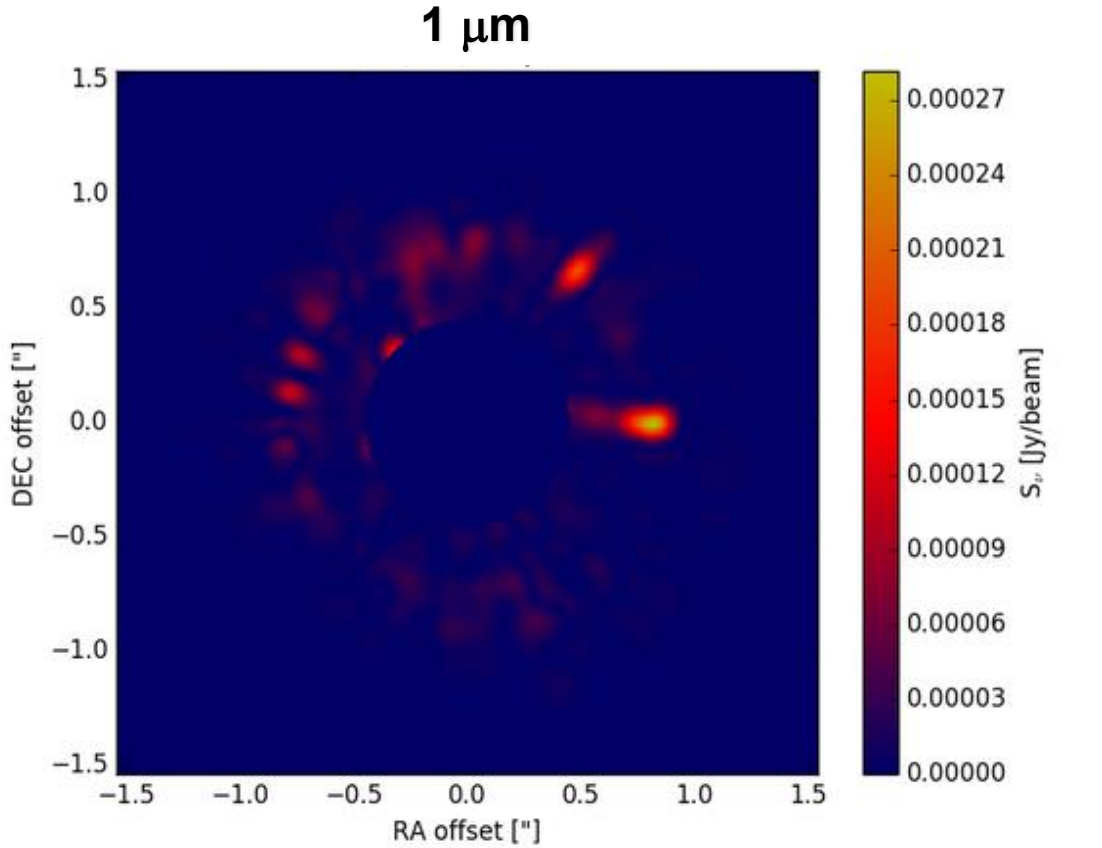


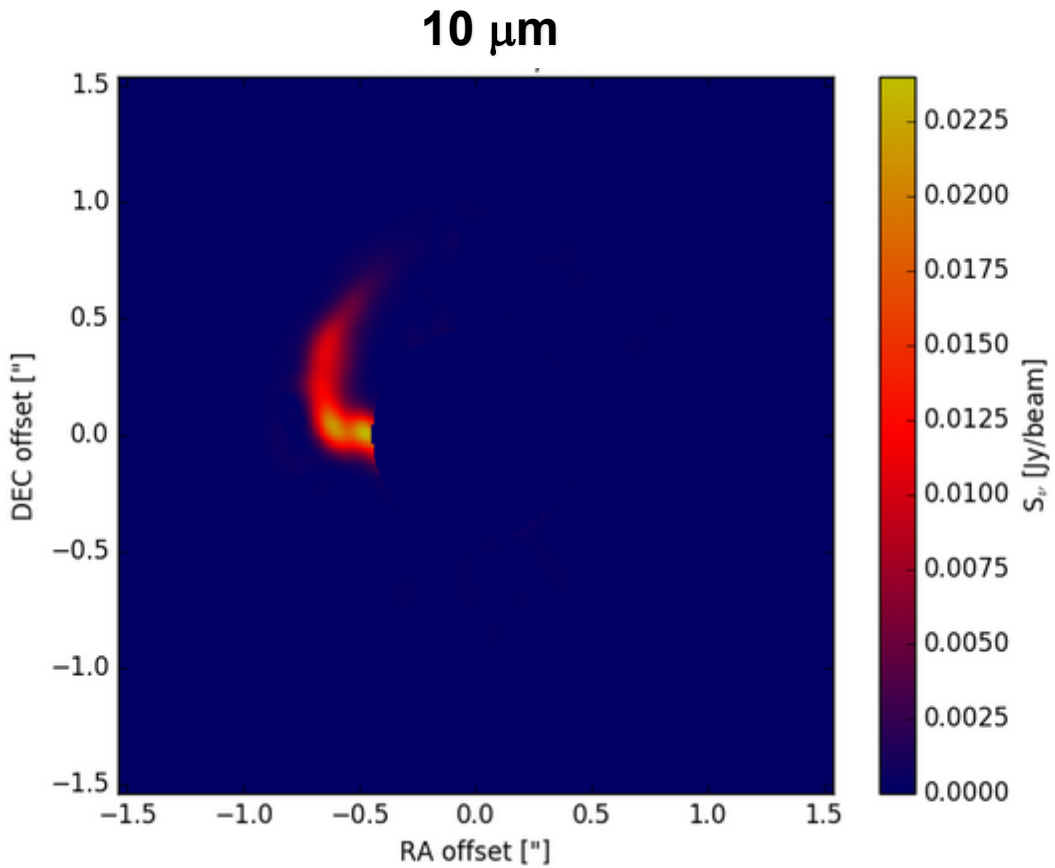
Currie et al. (2015)



Hord & Lyra + (2017)

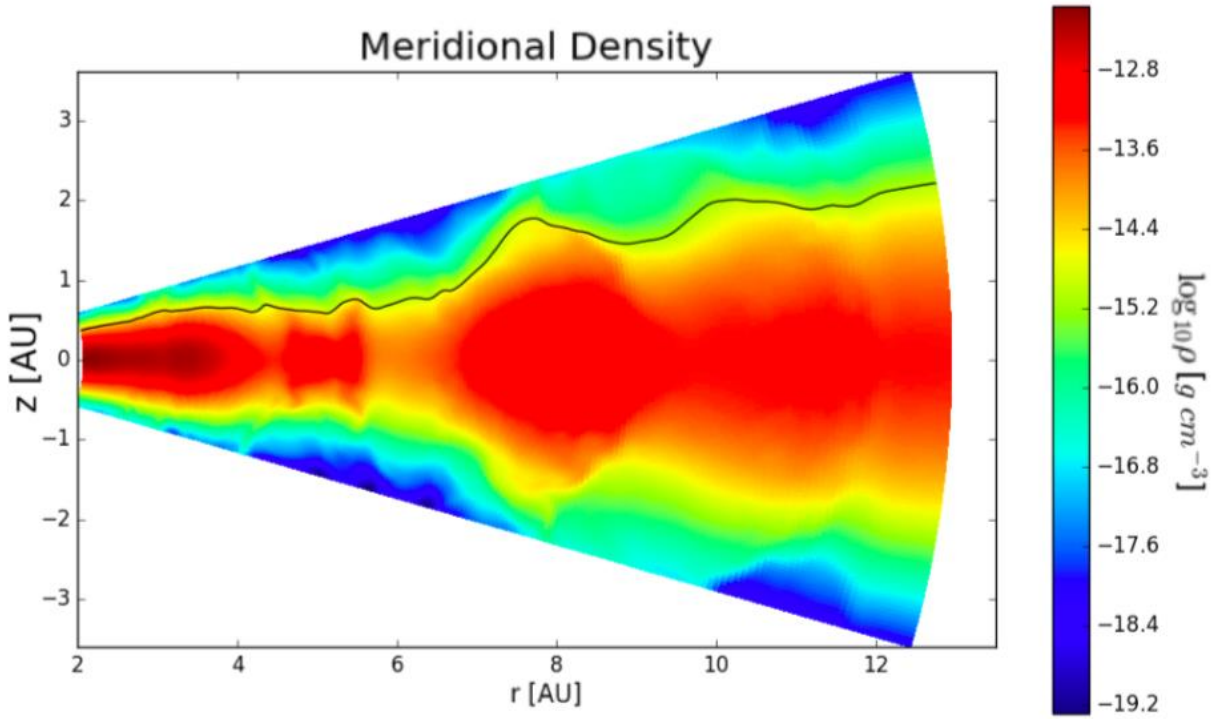
Effect of shocks alone

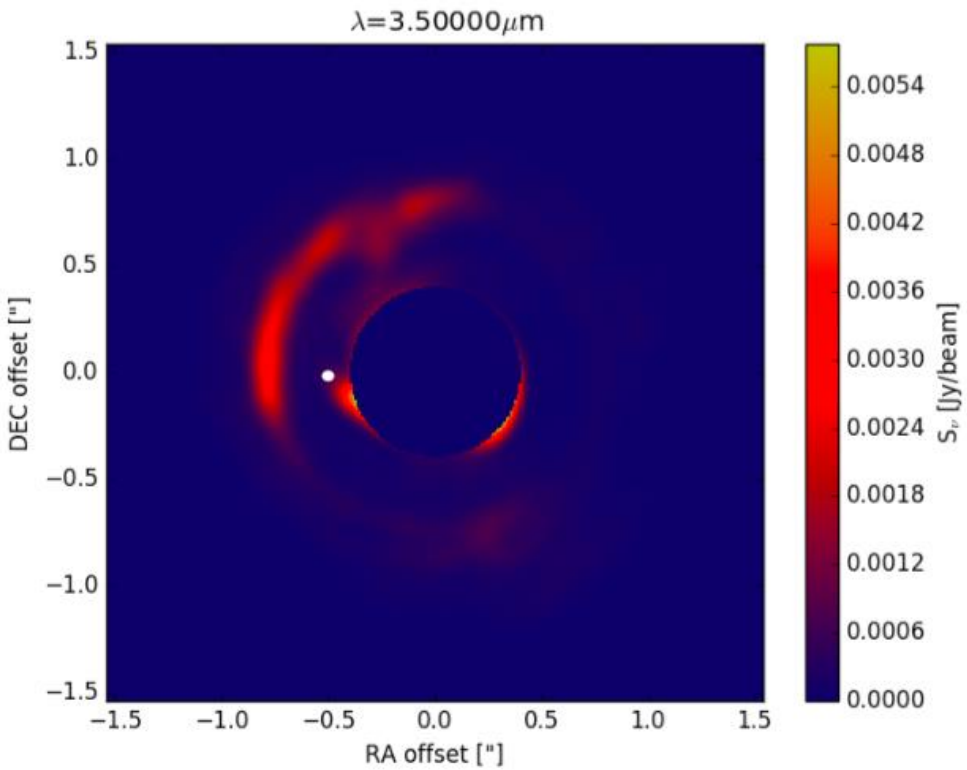




Hord & Lyra + (2017)

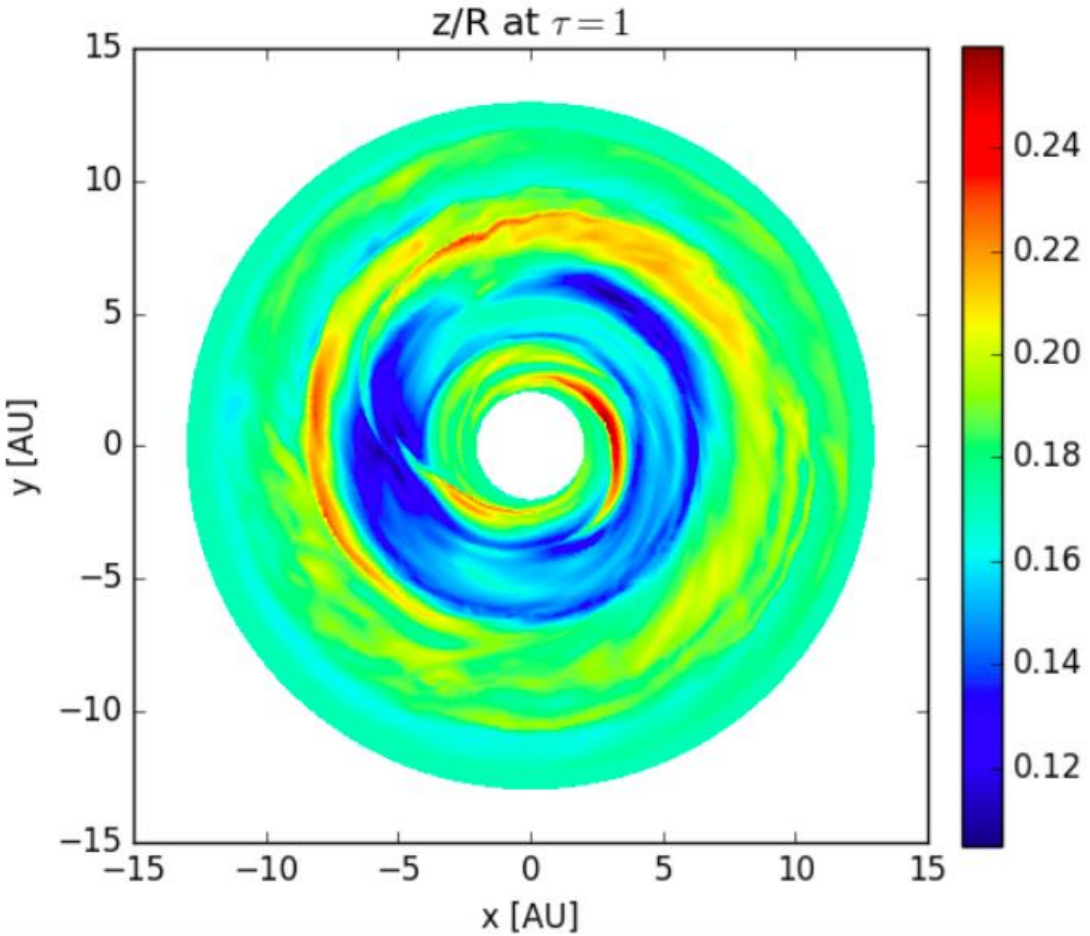
Scattering – A puffed up outer gap

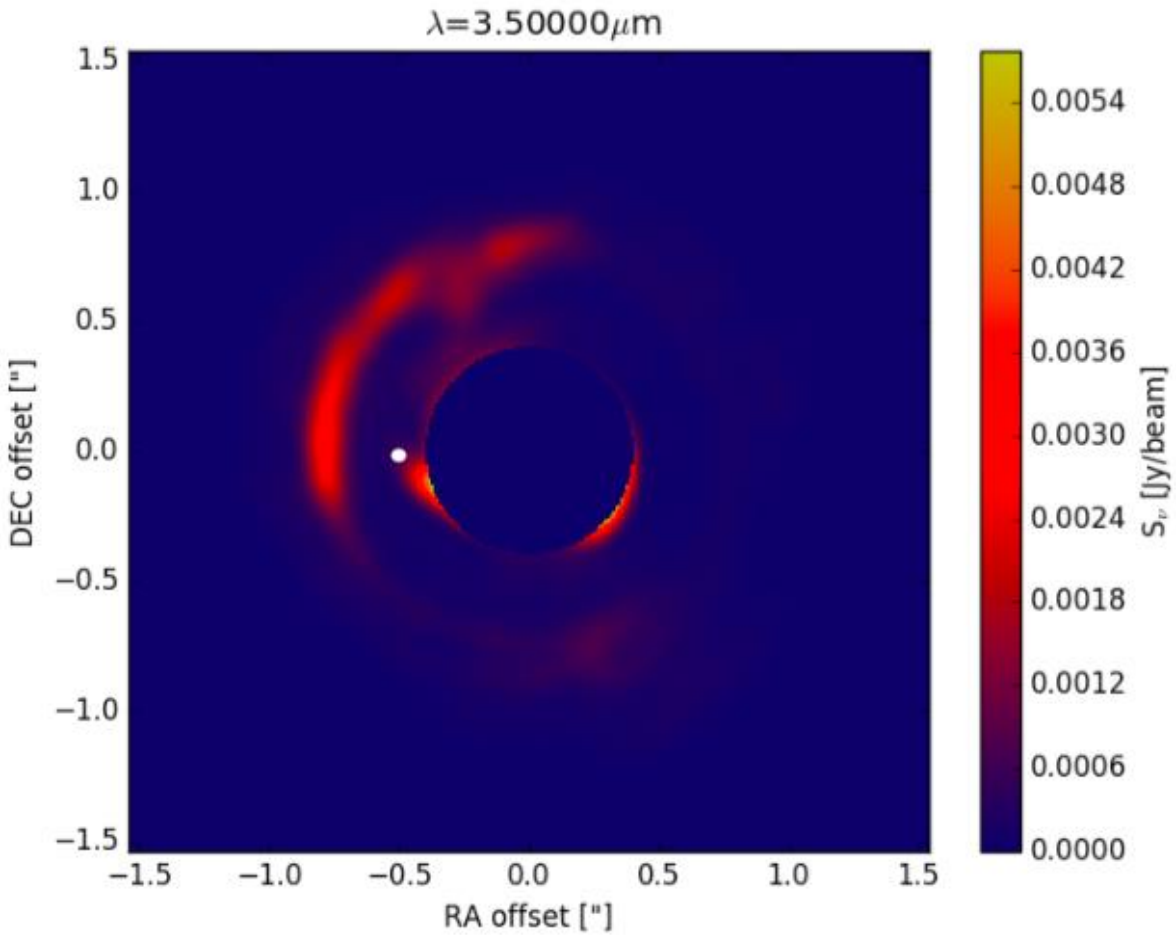




Hord & Lyra + (2017)

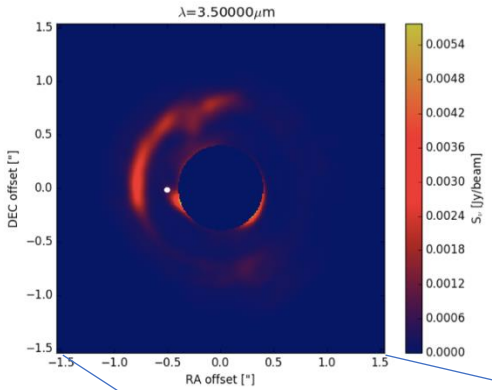
Scattering

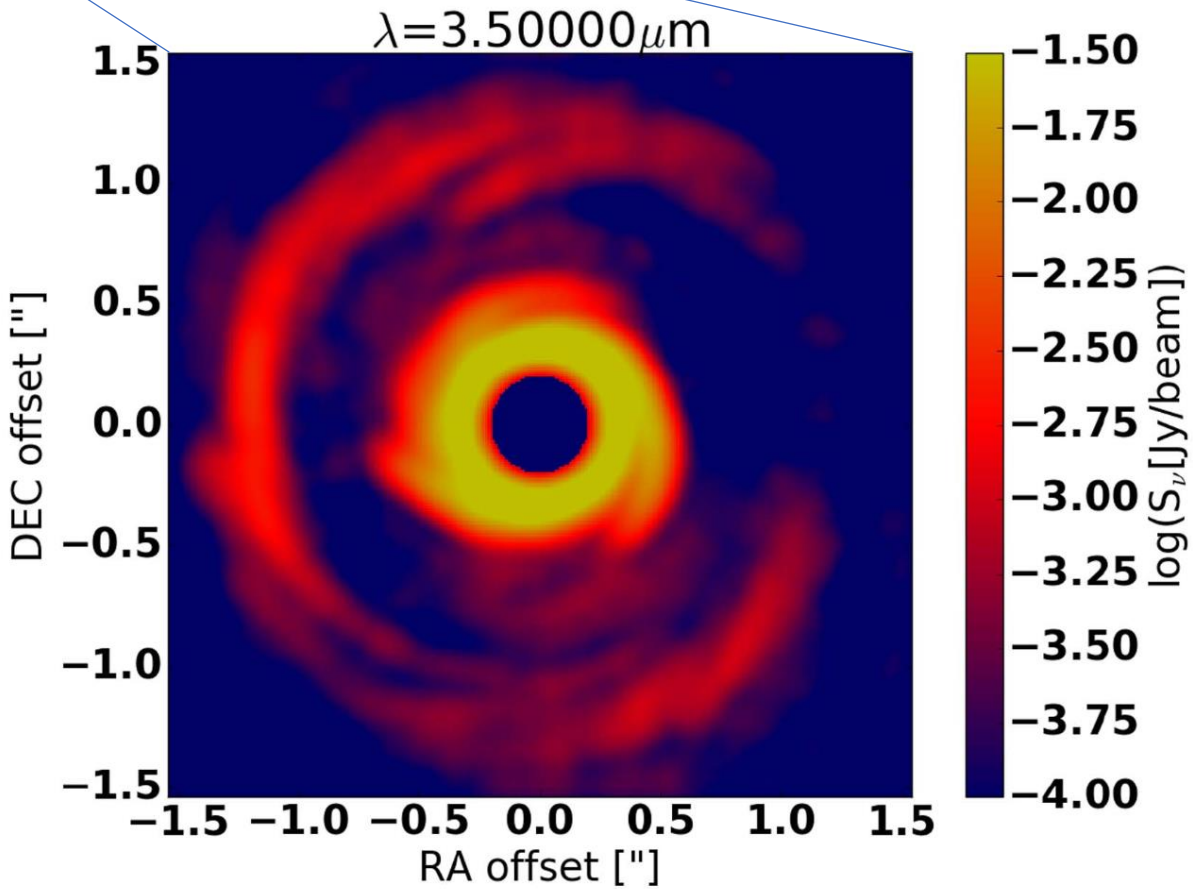


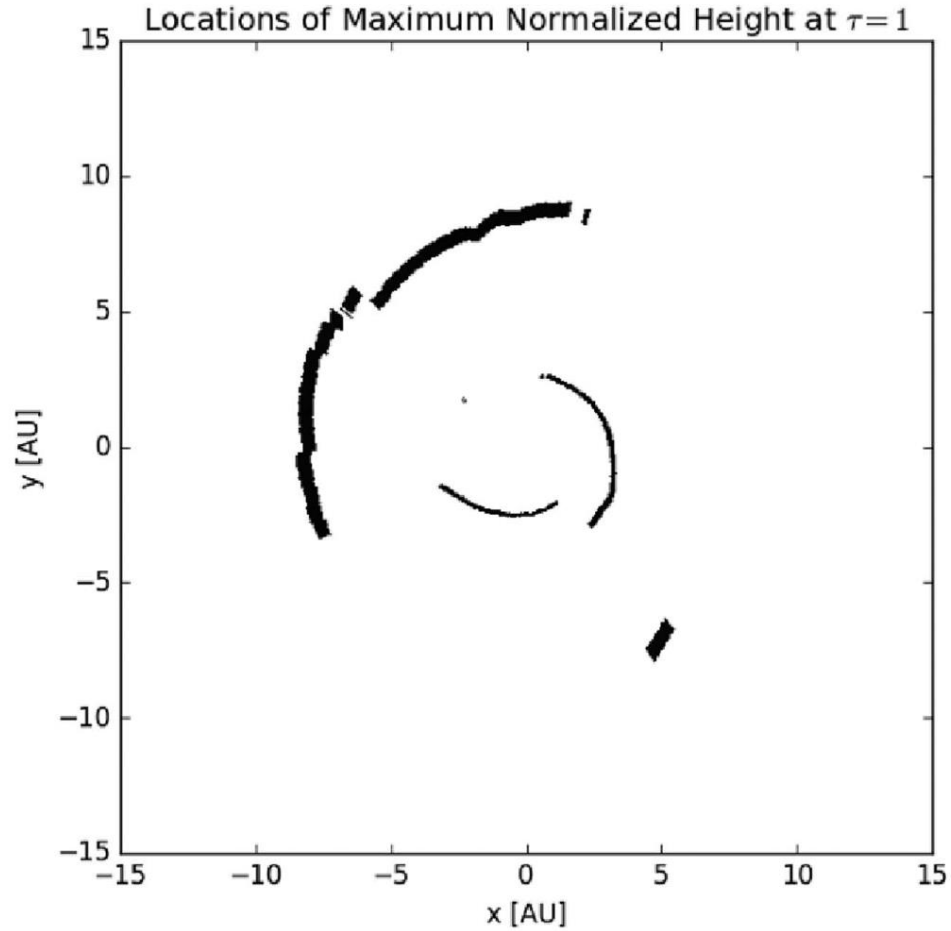


Hord & Lyra + (2017)

Inner disk shadowing







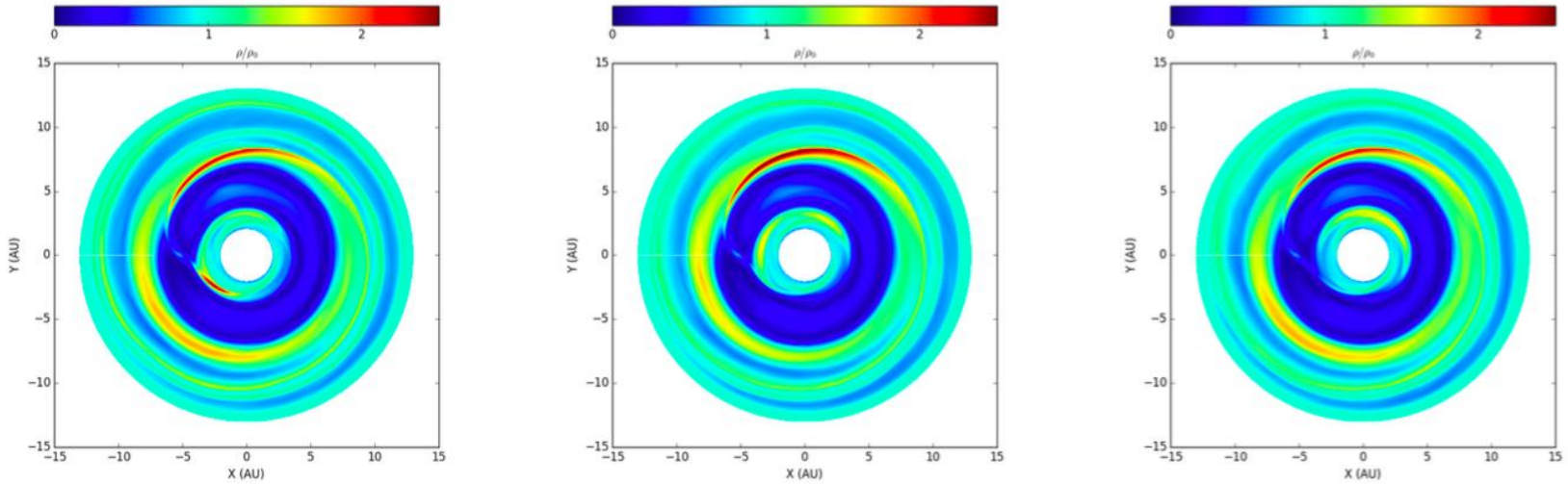
The pattern is stationary

T = 39 orbits

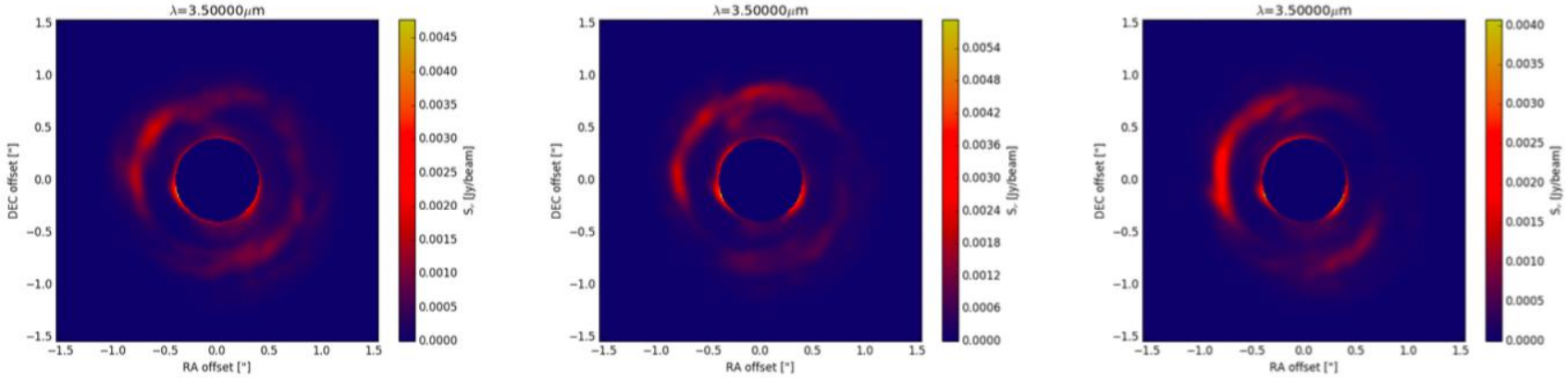
T = 40 orbits

T = 41 orbits

Density



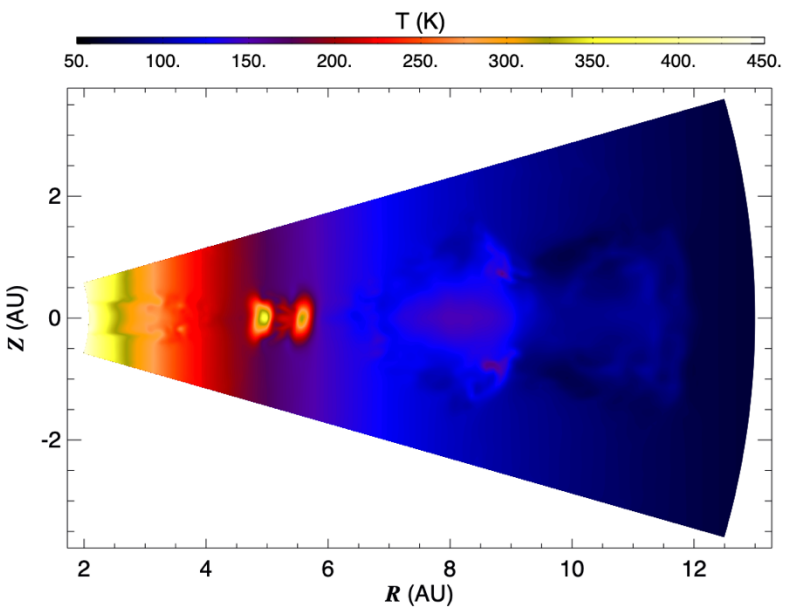
Intensity



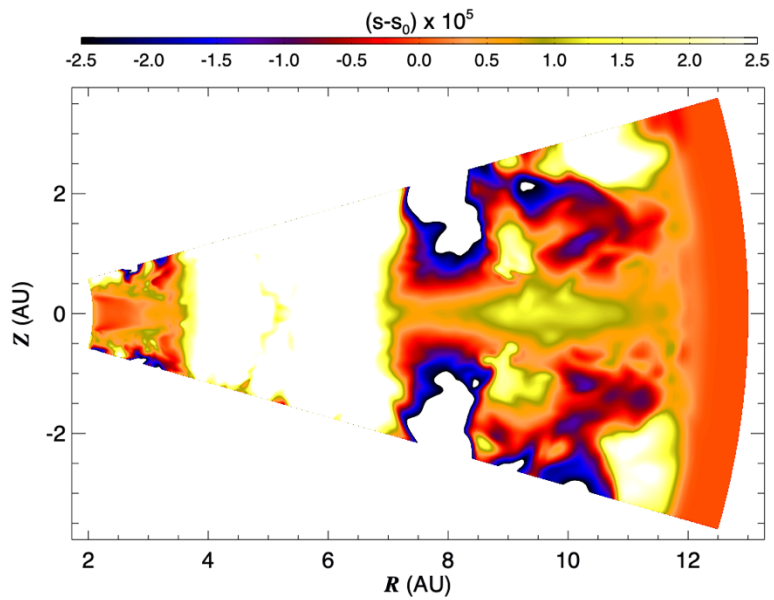
Hord & Lyra + (2017)

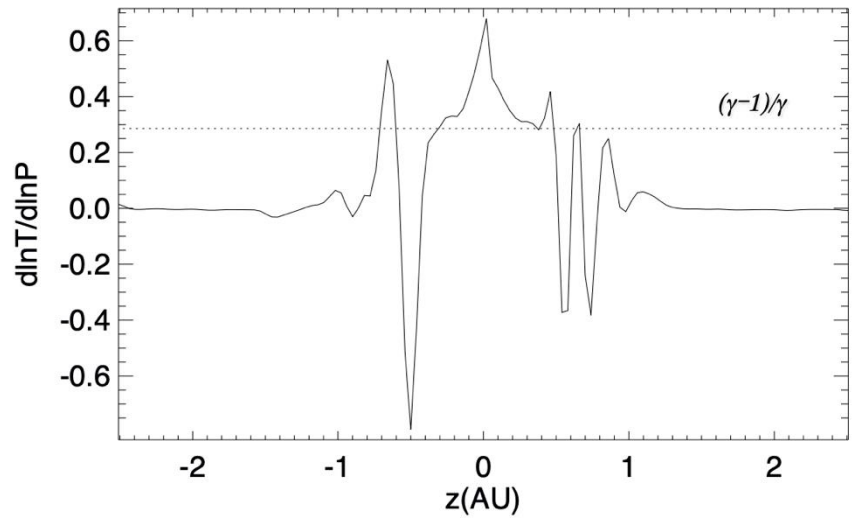
Convection

Temperature



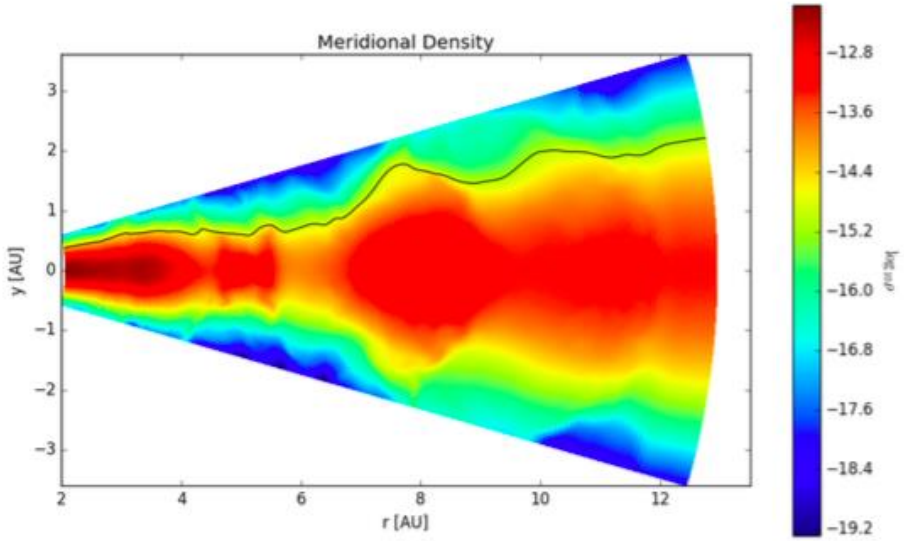
Entropy

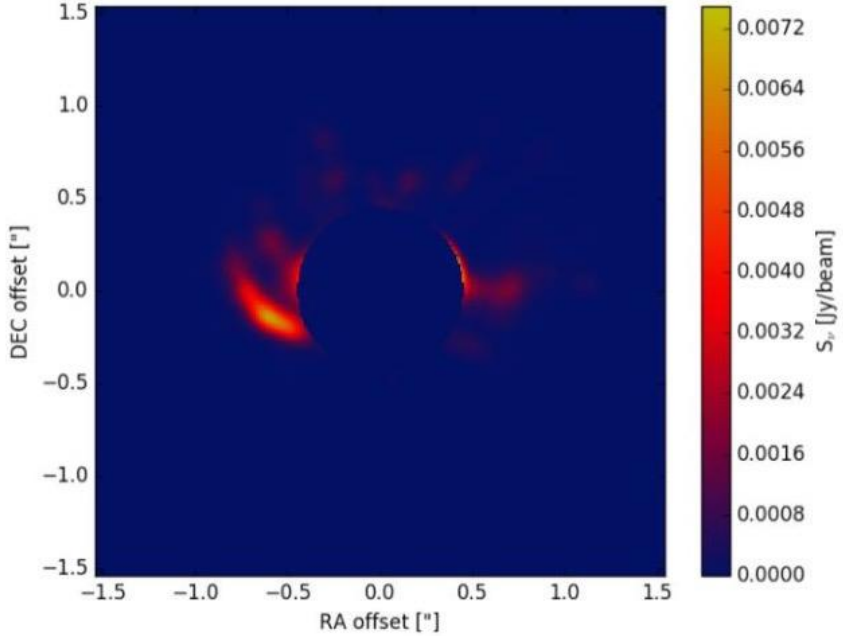


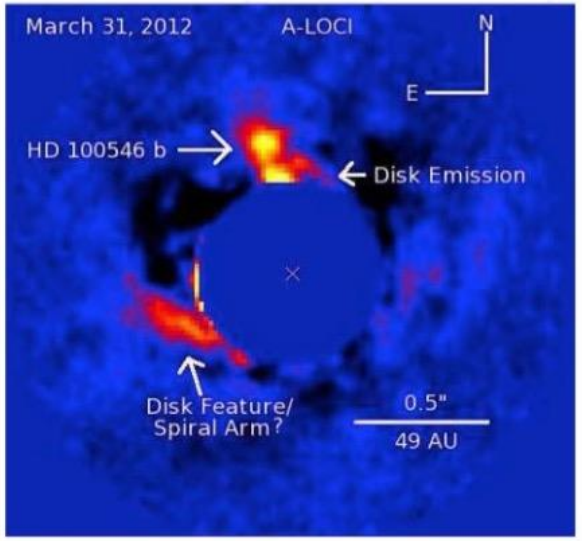


Take Home Message

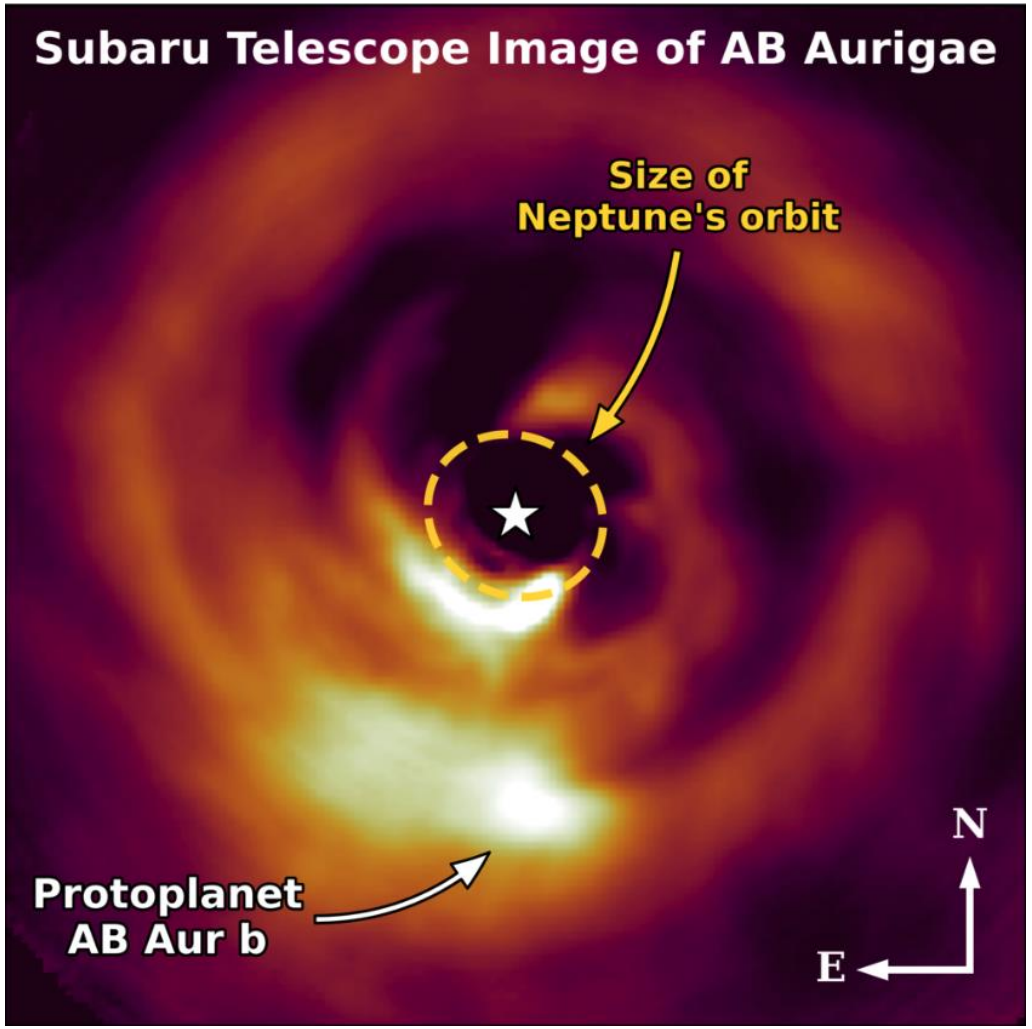
- Planet-induced shocks modify disk structure
- Hot lobes near high-mass planets in high resolution
- Convection puffs up the outer gap – visible in scattered light

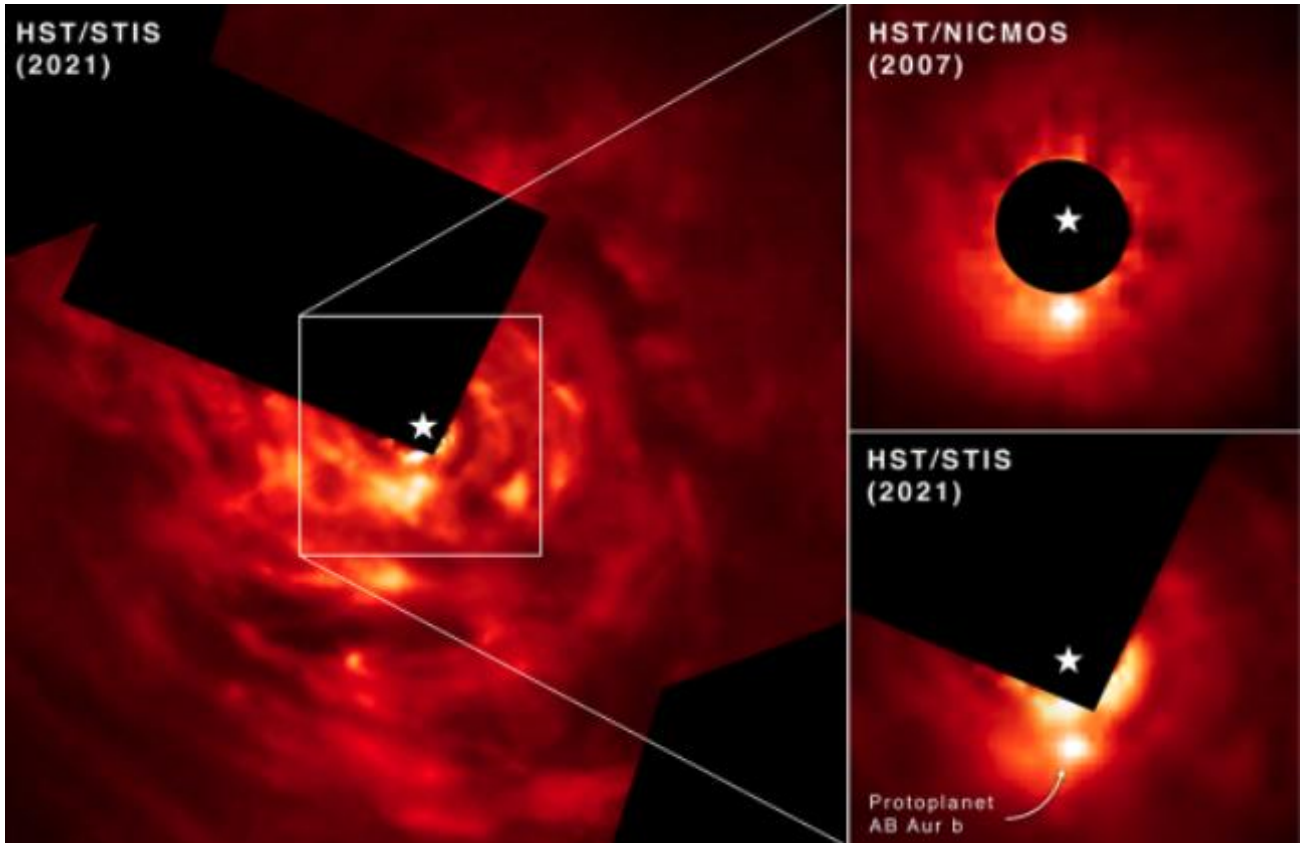






AB Aur

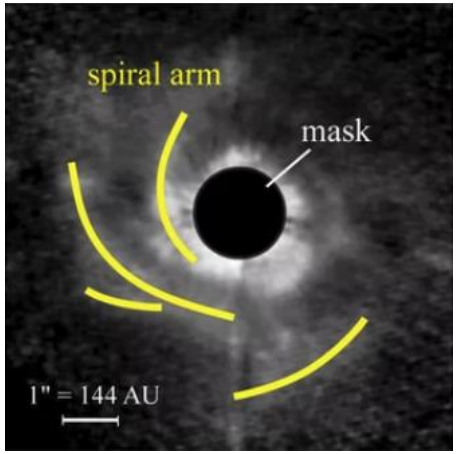




Currie et al (+Lyra) 2022

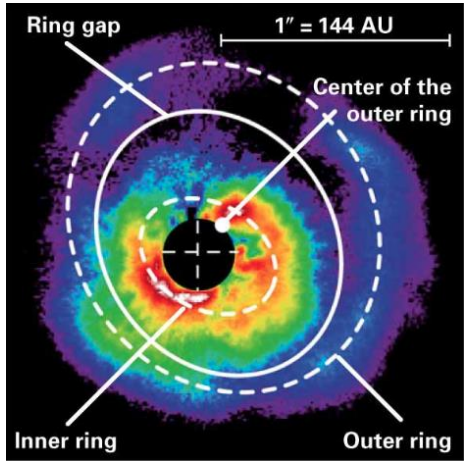
AB Aurigae: Long considered a planet formation laboratory

CIAO+AO36



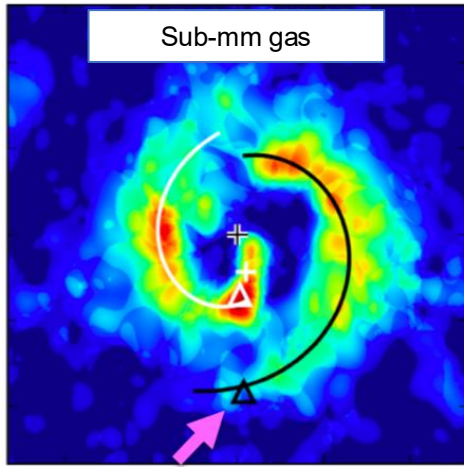
Fukagawa et al. 2004

HiCIAO + AO188



Hashimoto et al. 2011

ALMA

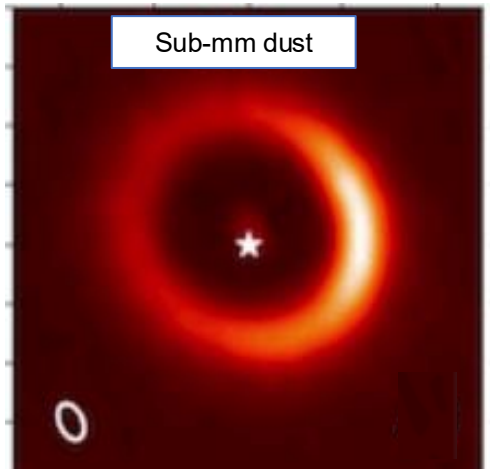


Tang et al. 2017

SPHERE

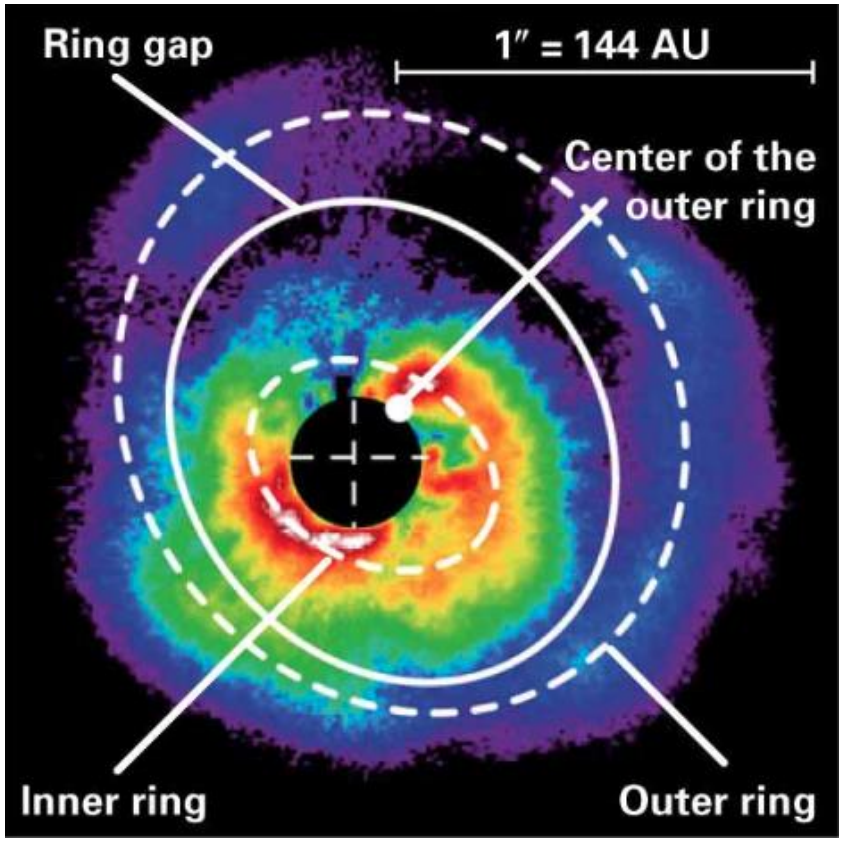
Boccaletti et al. 2020

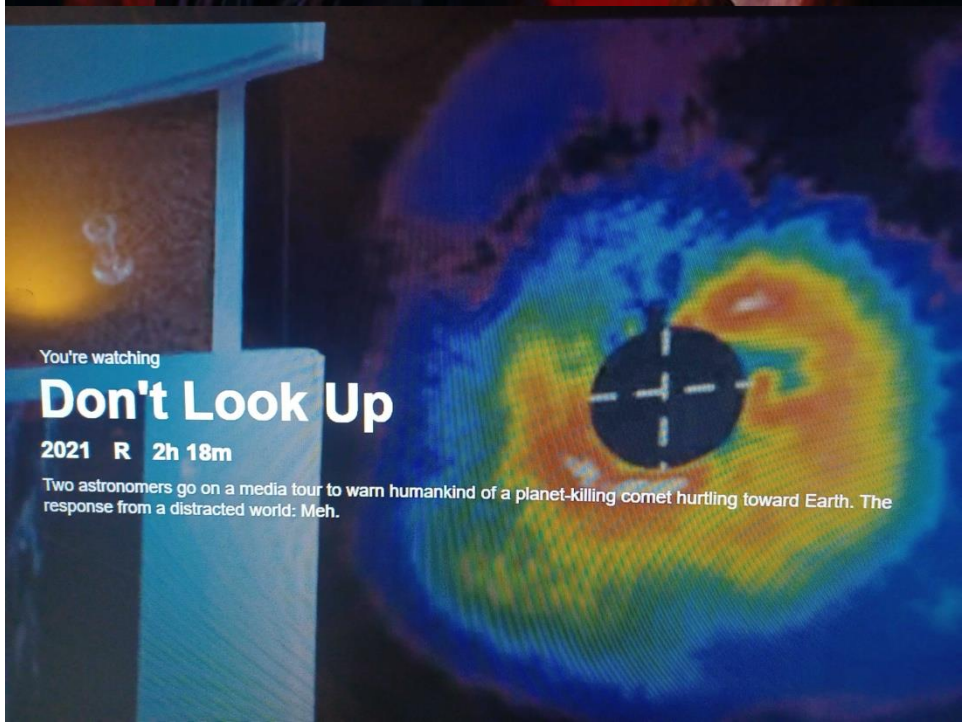
ALMA



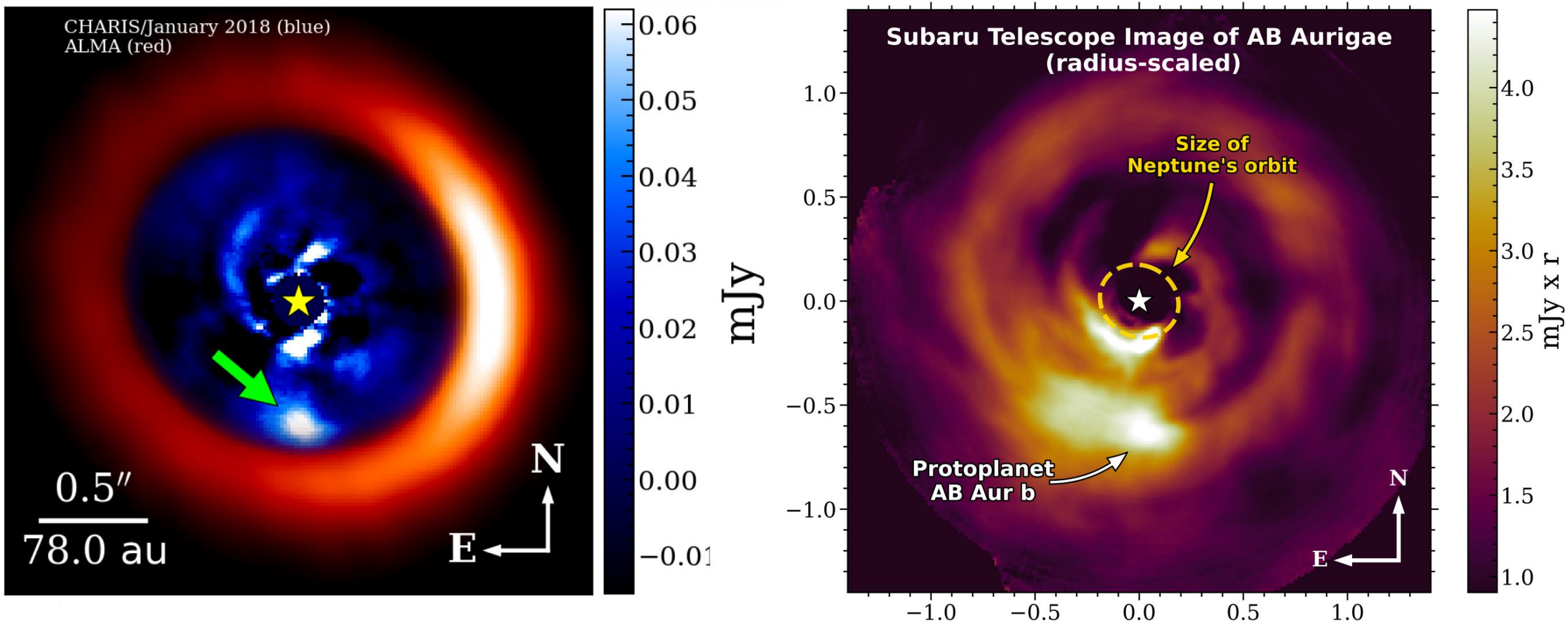
Francis & van der Marel 2020

… with film appearances



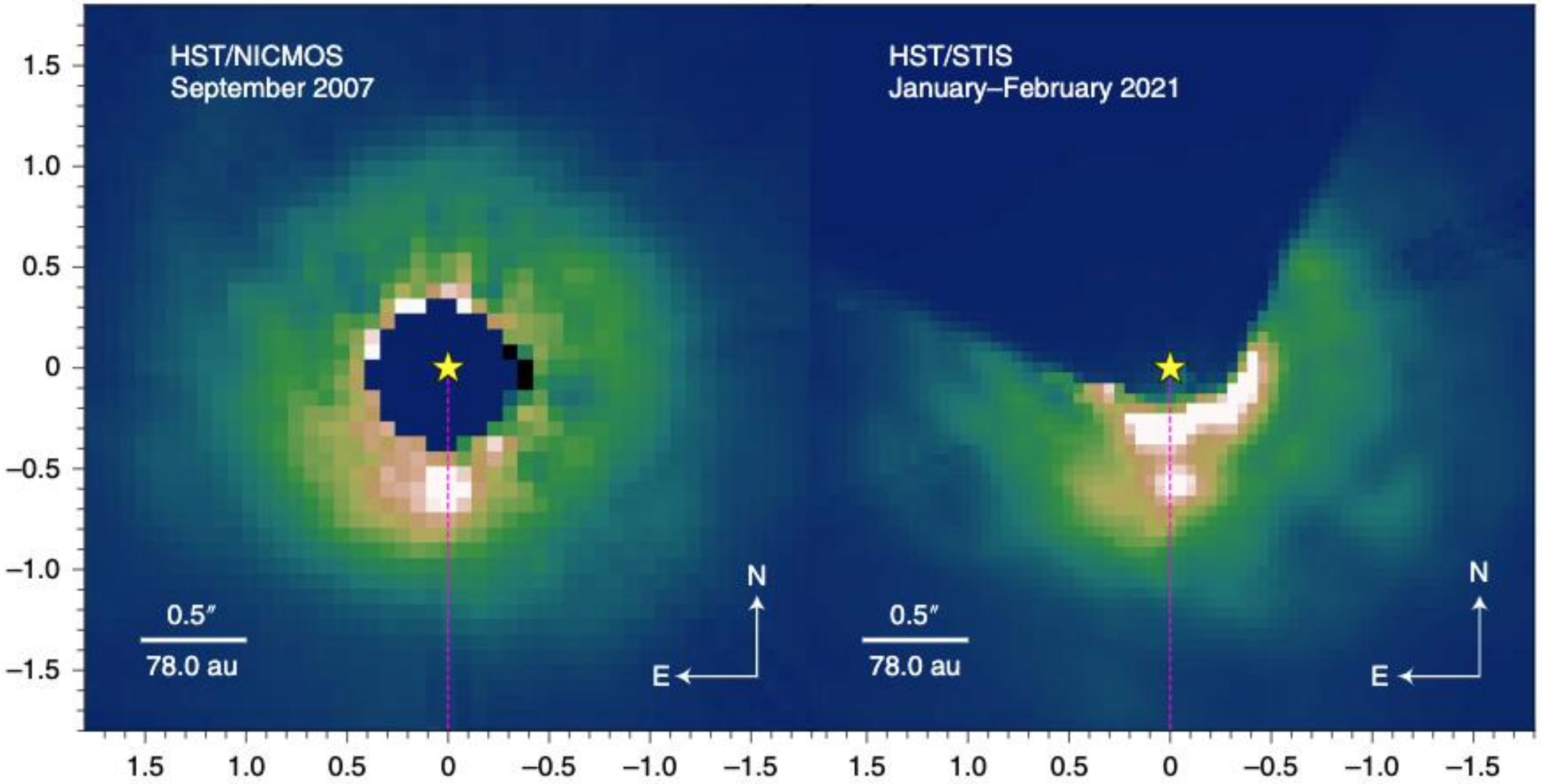


AB Aur b: CHARIS



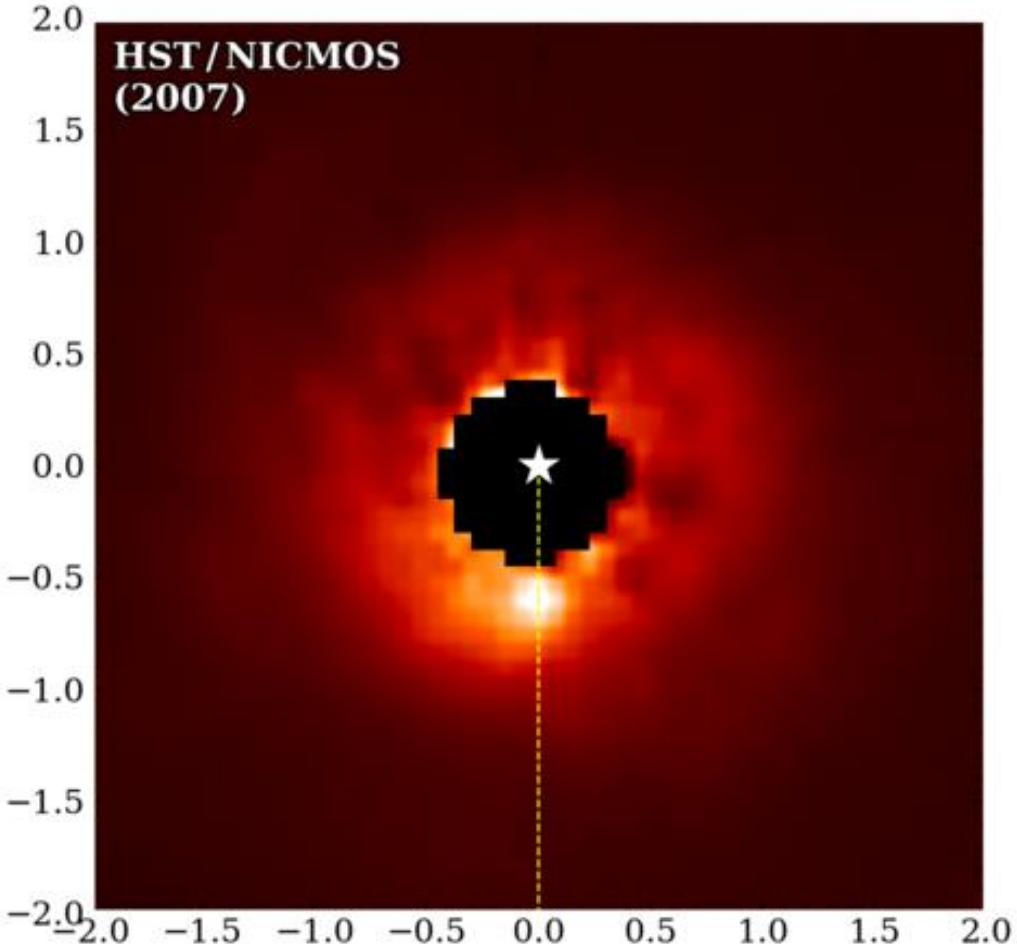
Currie et al (+Lyra) 2022

AB Aur b: HST

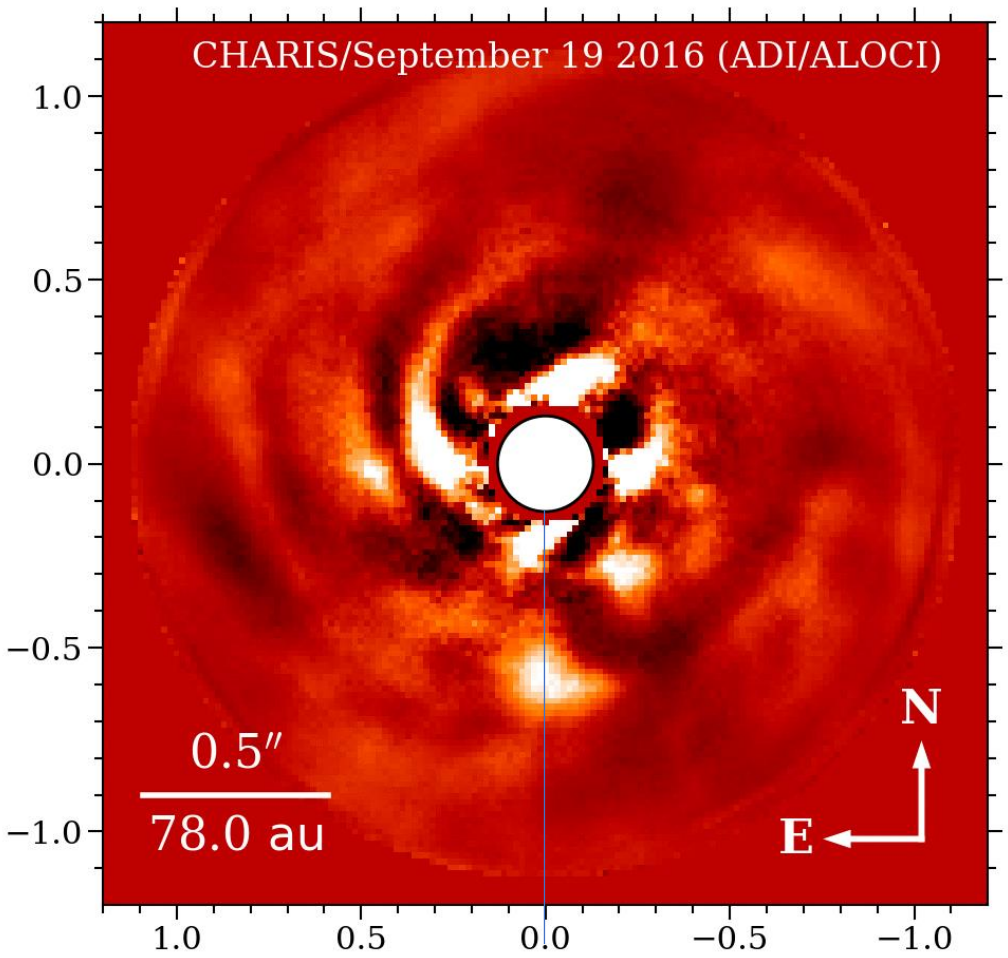


Currie et al (+Lyra) 2022

AB Aur b: Evidence for Orbital Motion



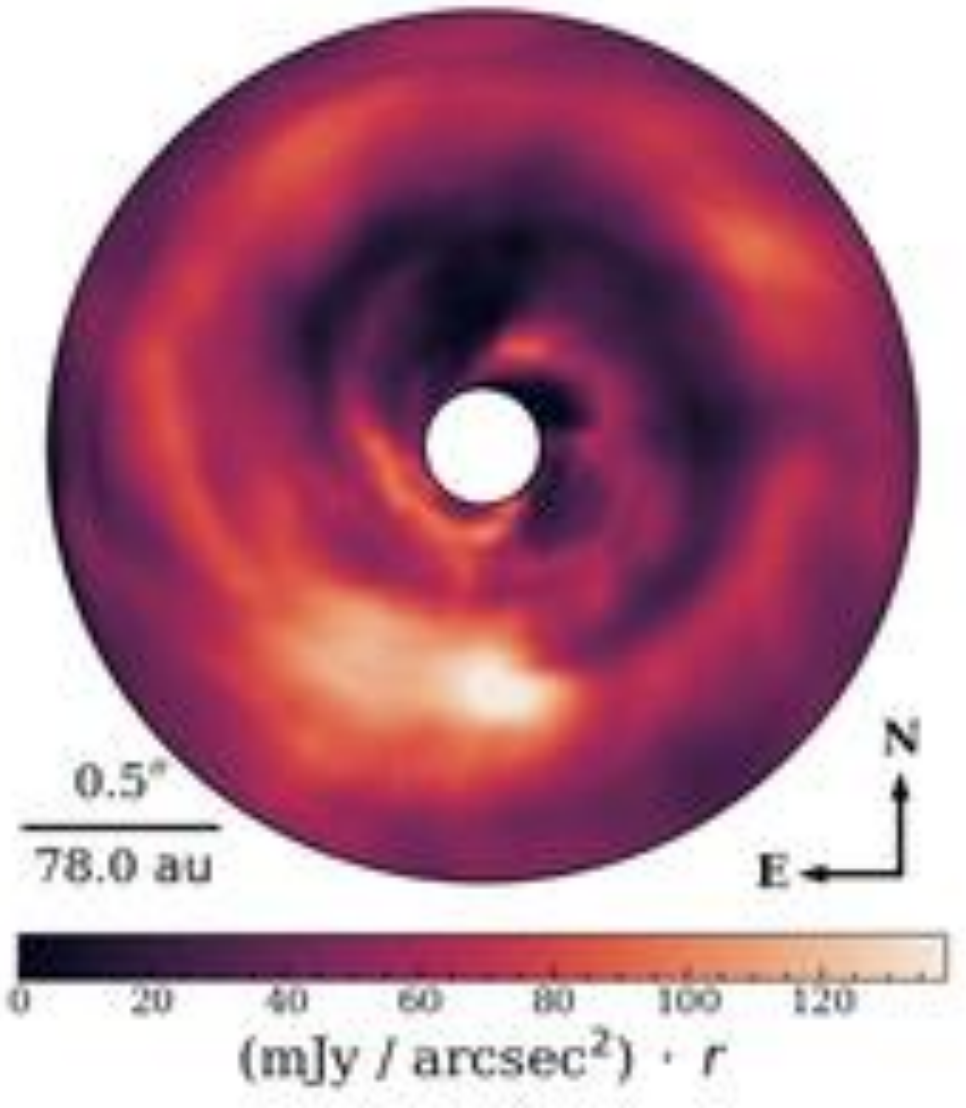
HST: Oct 2007 to Jan 2021



SCExAO: Sept 2016 to Oct 2020

Currie et al (+Lyra) 2022

What is it?

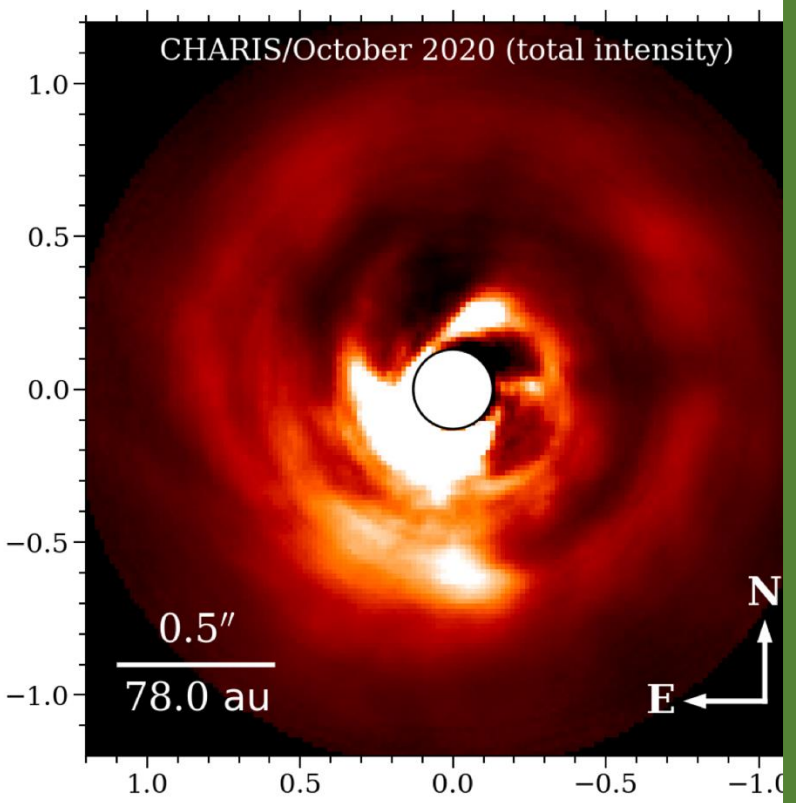


- Disk feature?
- Planet?

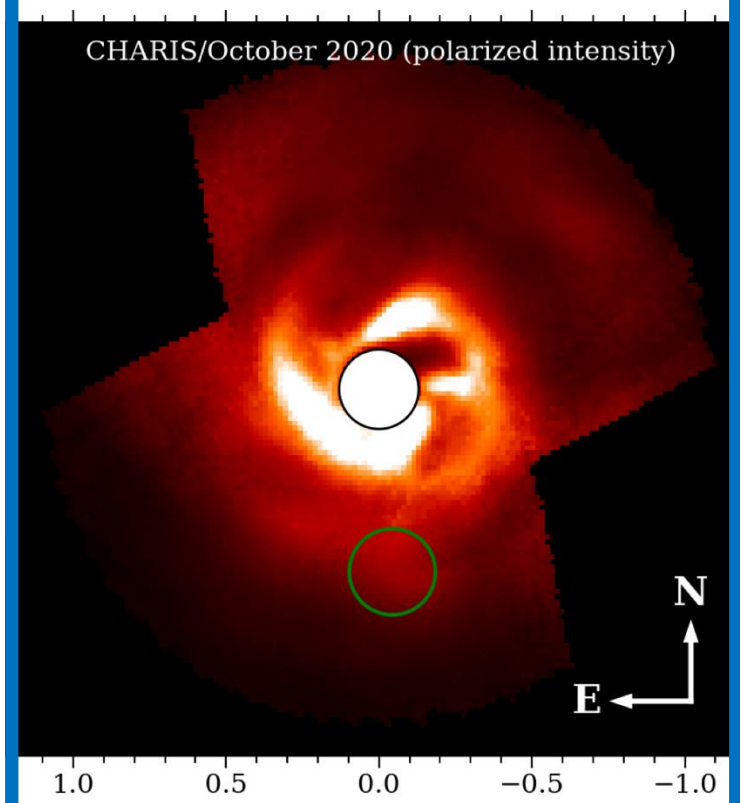
Currie et al (+Lyra) 2022

AB Aur b: Emission

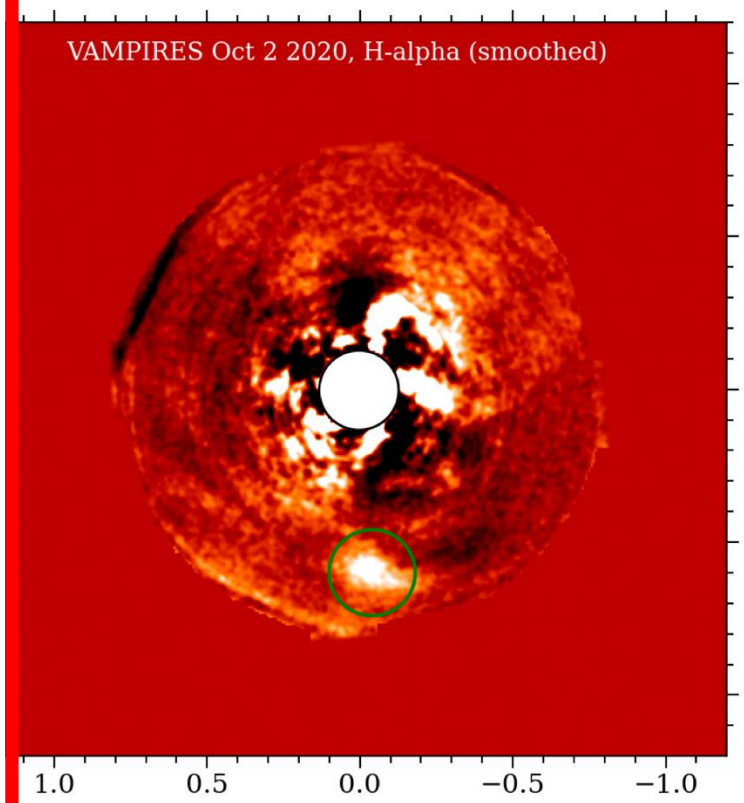
Detection in total intensity



Non-detection in polarized light

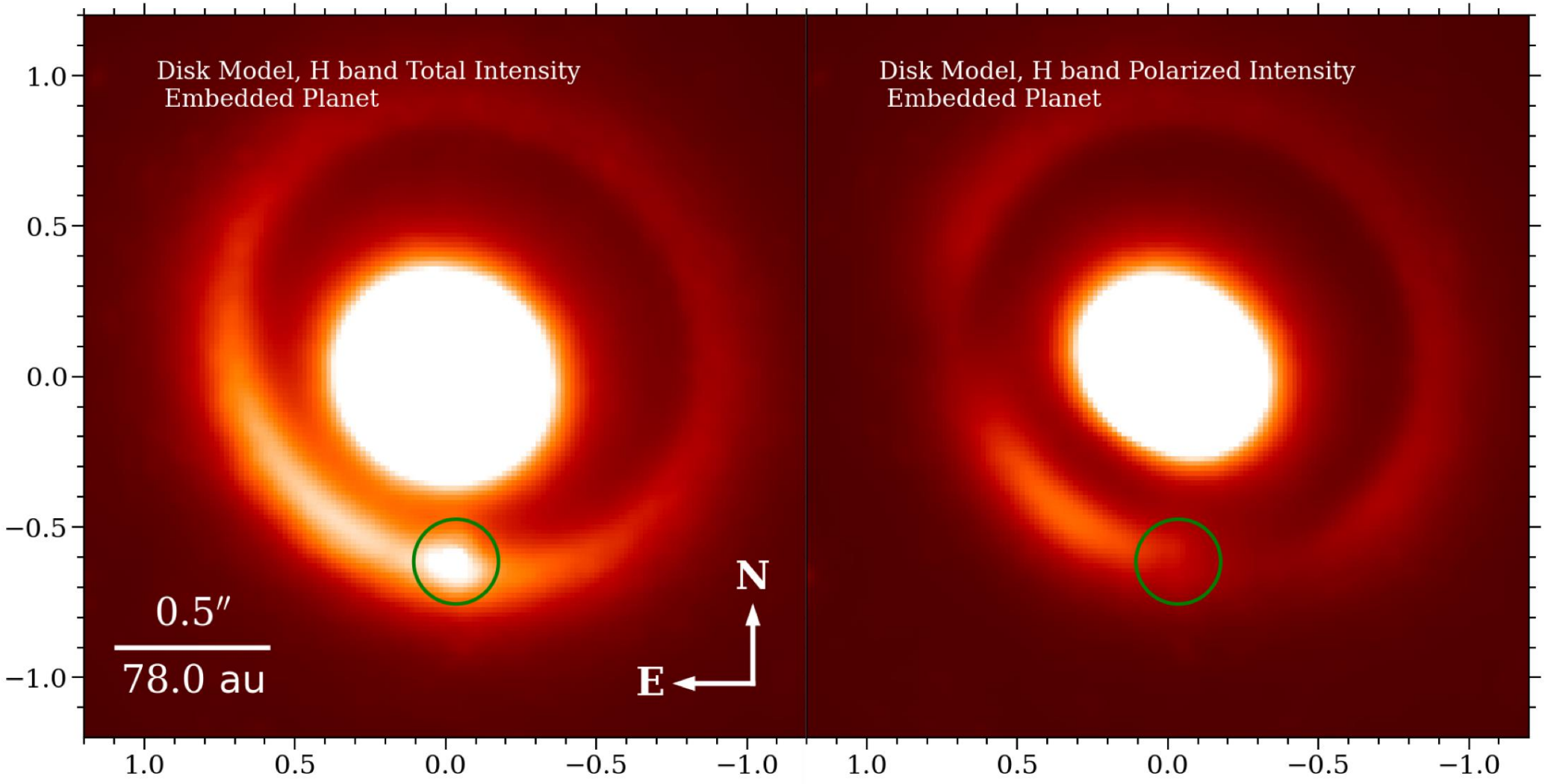


Detection in H-alpha



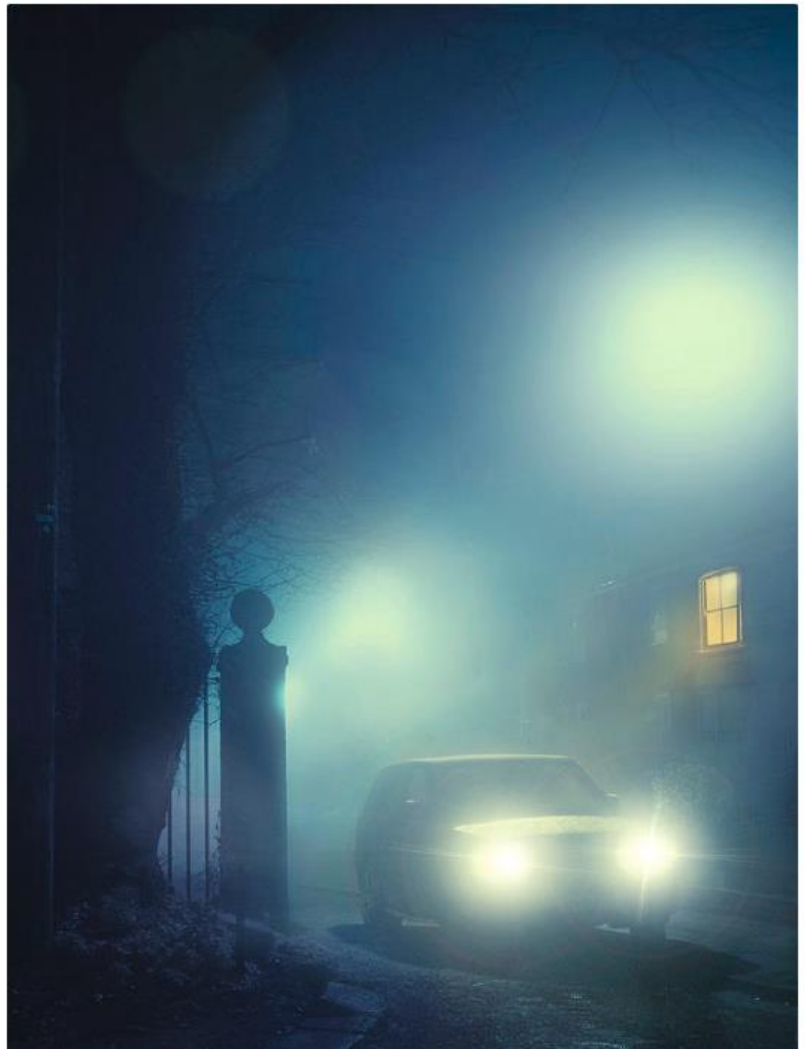
Currie et al (+Lyra) 2022

Explaining AB Aur b's Appearance

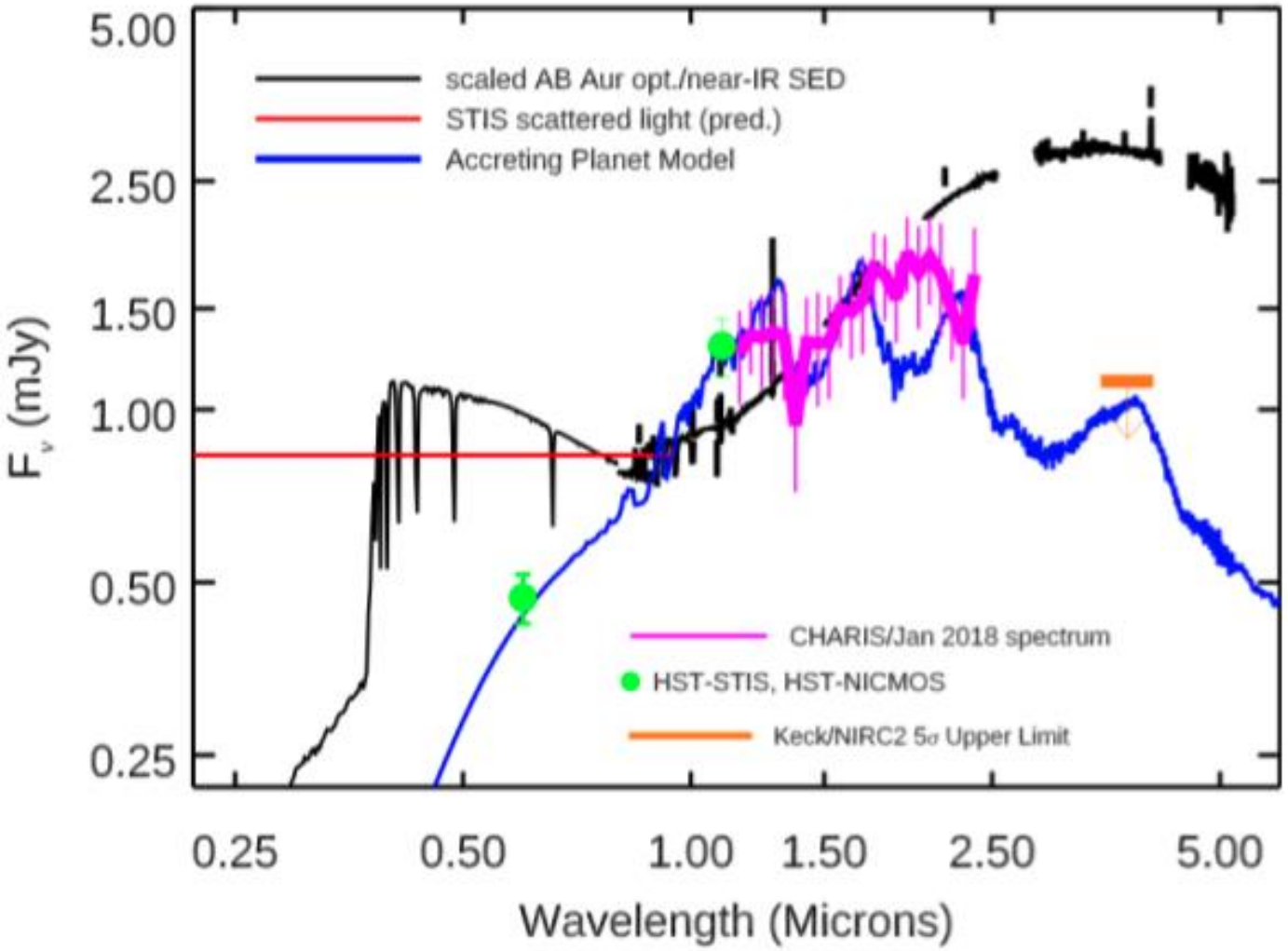


Embedded blackbody point source
appears spatially extended because of reprocessing from the disk

Analogy: seeing a lamp through fog



AB Aur b: Spectrum



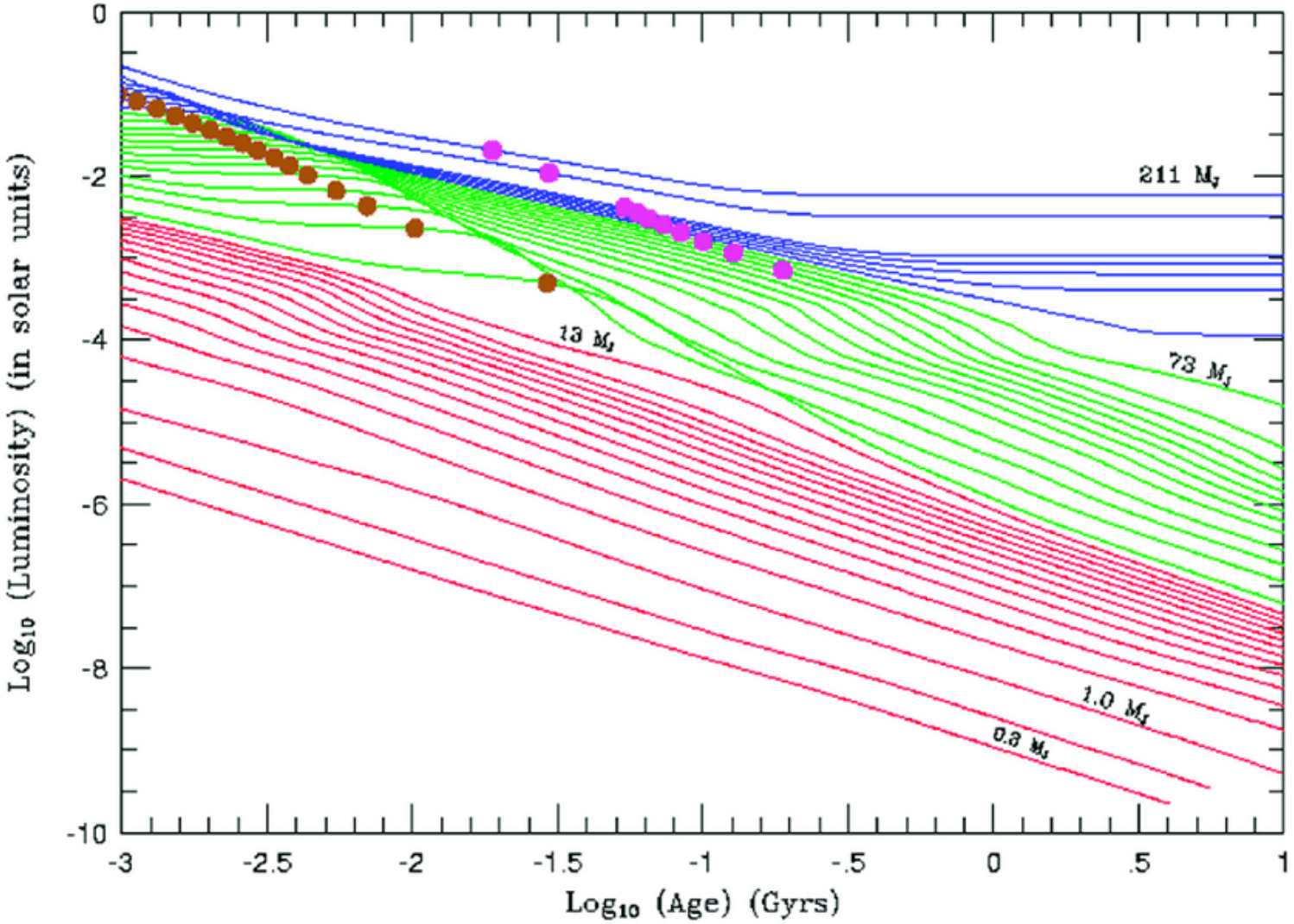
Inconsistent with pure scattered starlight;

Reproduced by ~2000 K thermal source + ~10,000K magnetospheric accretion source

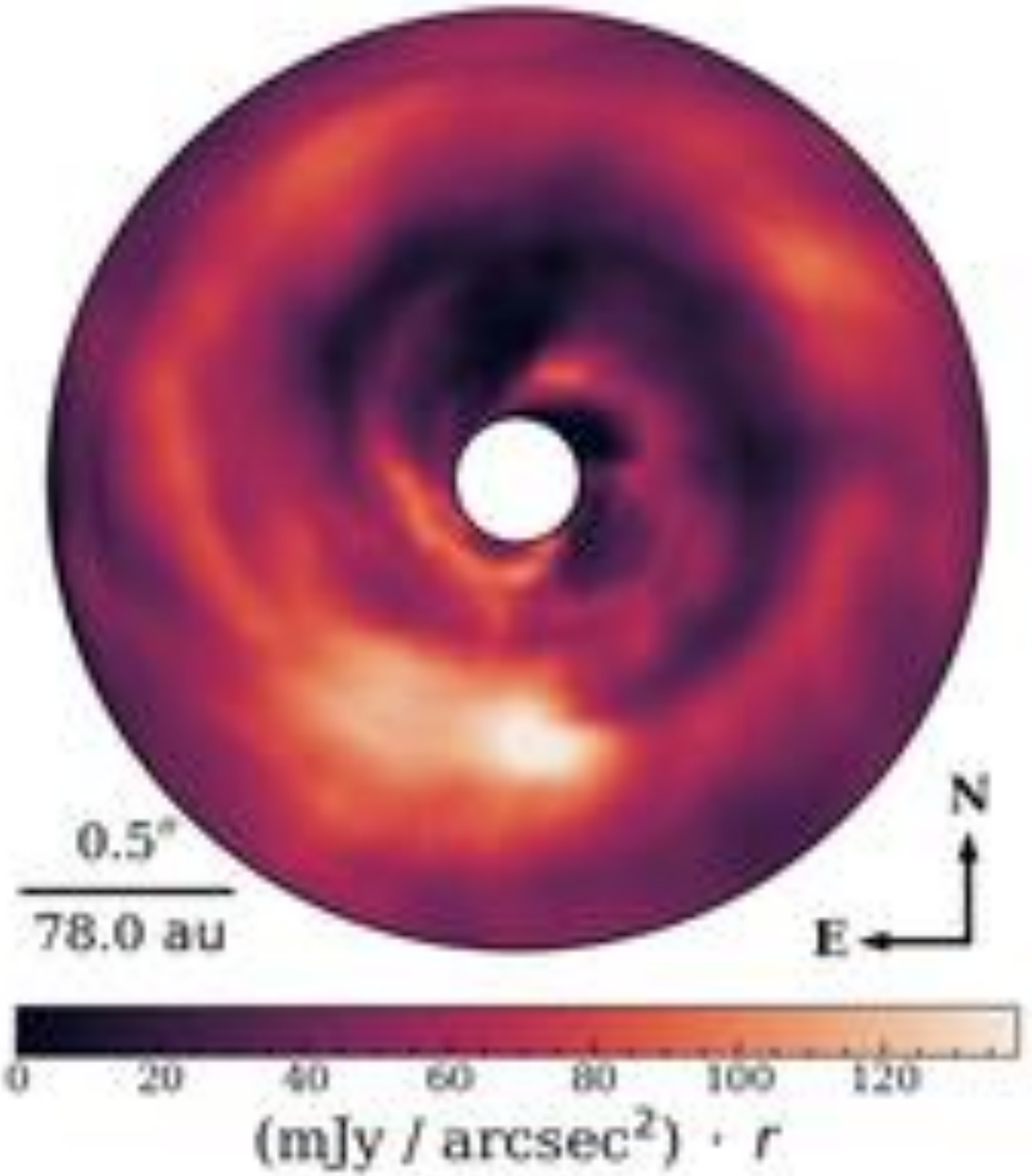
Luminosity consistent with ~9-12 M_J object

Currie et al (+Lyra) 2022

Luminosity of Substellar Objects



Burrow et al. 2012



Photometric constrains

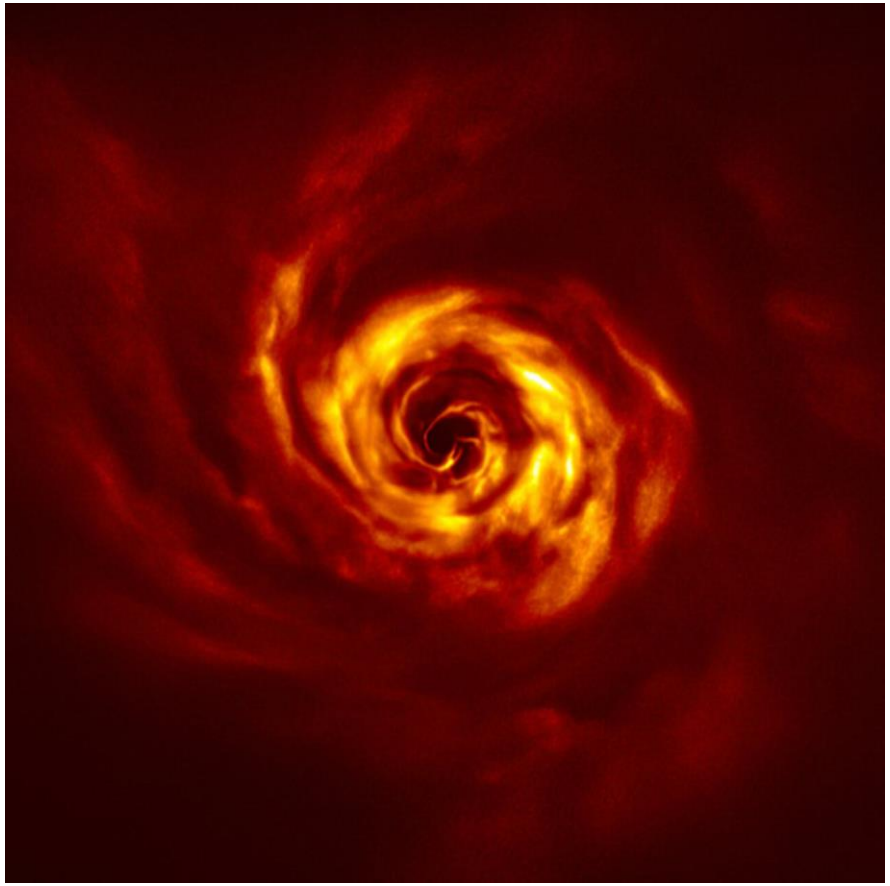
- Detection at J (1.25 mm), H (1.65 mm)
- Weaker at K (2.2 mm)
- No detection at Lp (3.8 mm)
- Colors suggest 2300 K

A planet is *plausible*

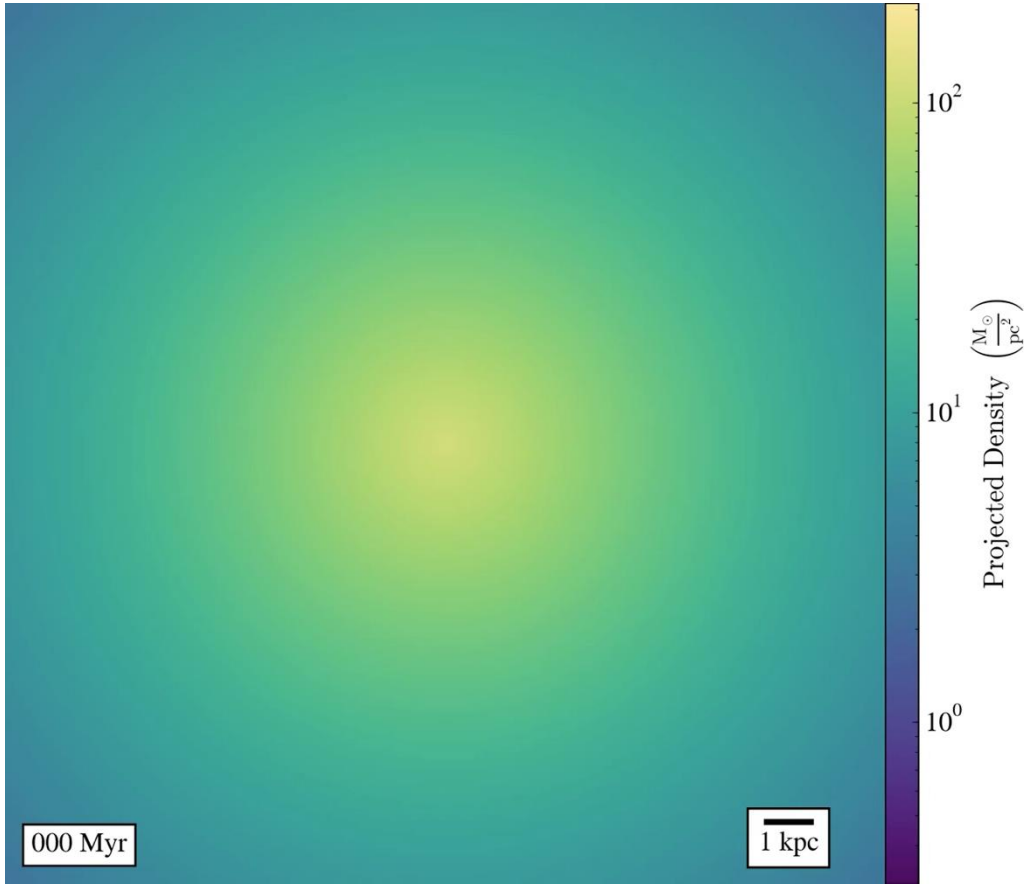
- Gravitational Instability or Core Accretion?

Currie et al (+Lyra) 2022

AB Aur



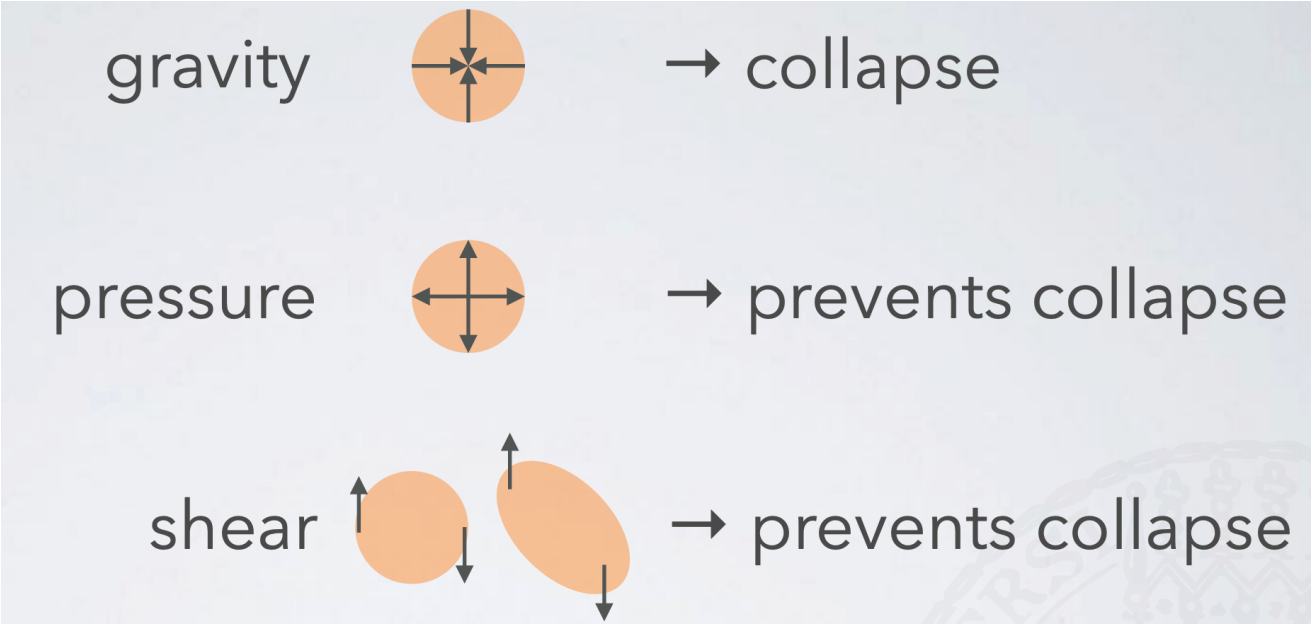
Gravitational Instability model

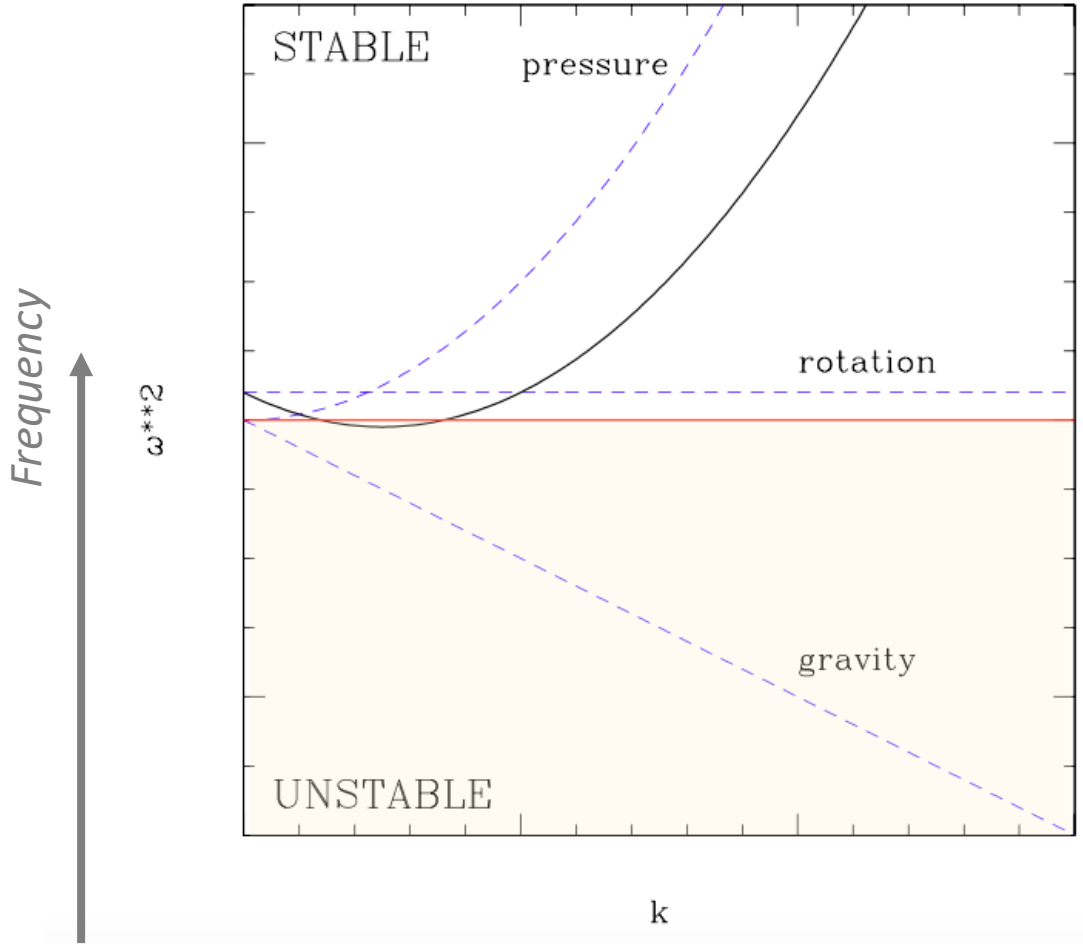


Safronov-Toomre Stability

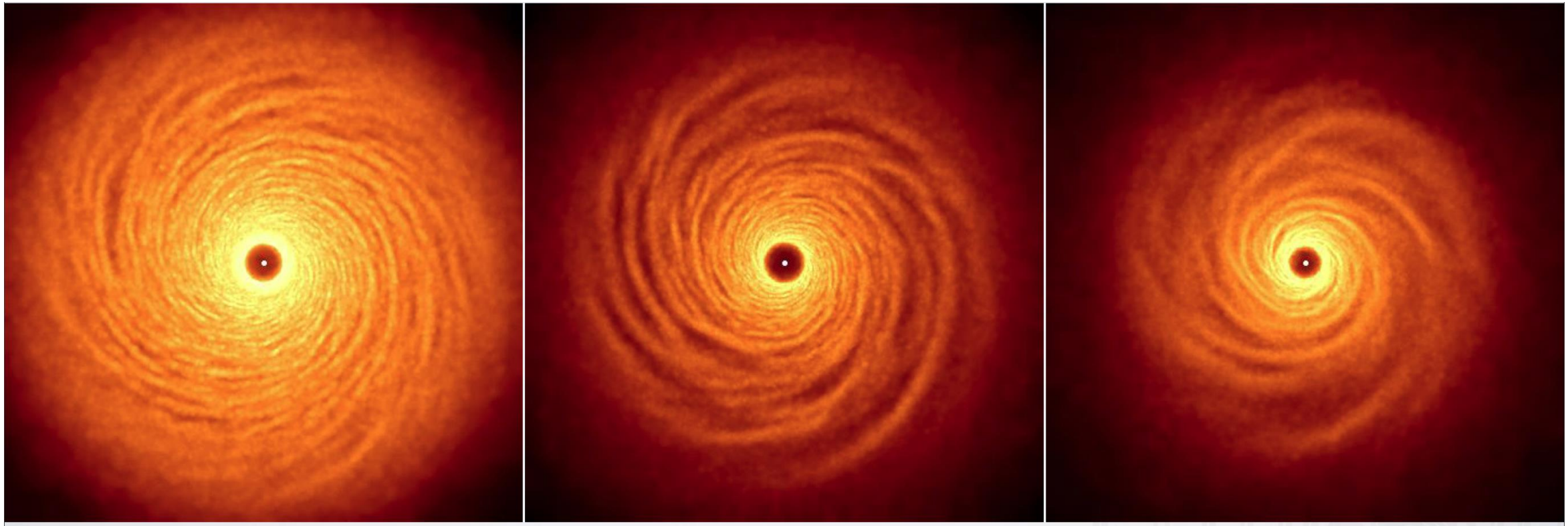
$$Q = c_s \Omega / (\pi G \Sigma) < 1 \text{ (instability)}$$

c_s = sound speed
Ω = Keplerian frequency
Σ = column density



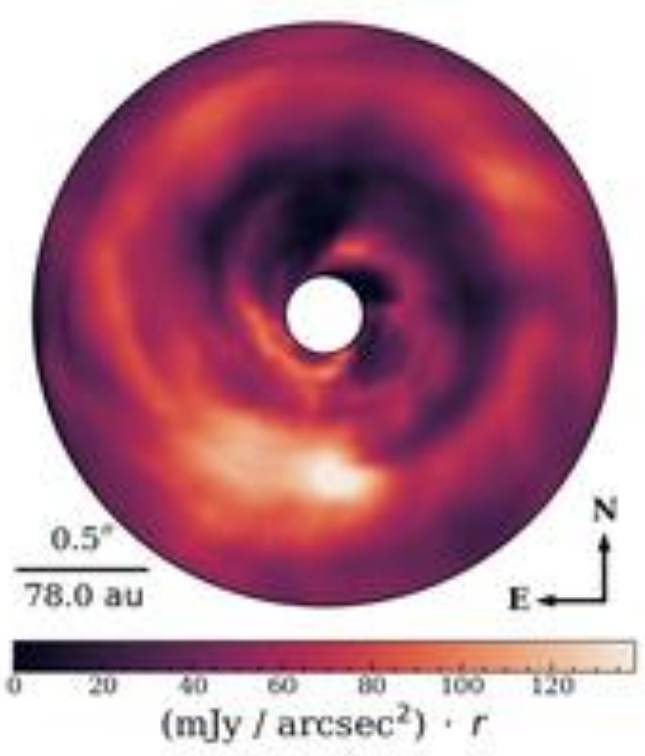


What is the density of the AB Aur Disk?



$M_{\text{disk}}/M_\star = 0.05$ $M_{\text{disk}}/M_\star = 0.1$ $M_{\text{disk}}/M_\star = 0.25$

Density Estimate



if (AB Aur b is a planet seen through haze) **then**:

optical depth ~ 1

$\tau = \kappa \rho_d H$

$\rho_d \sim 1/(\kappa H)$
$\sim 10^{-14}\ g/cm^3$

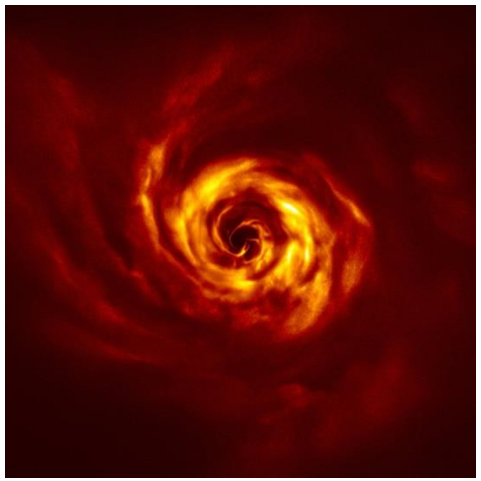
$\rho_g \sim 10^{-12}\ g/cm^3$

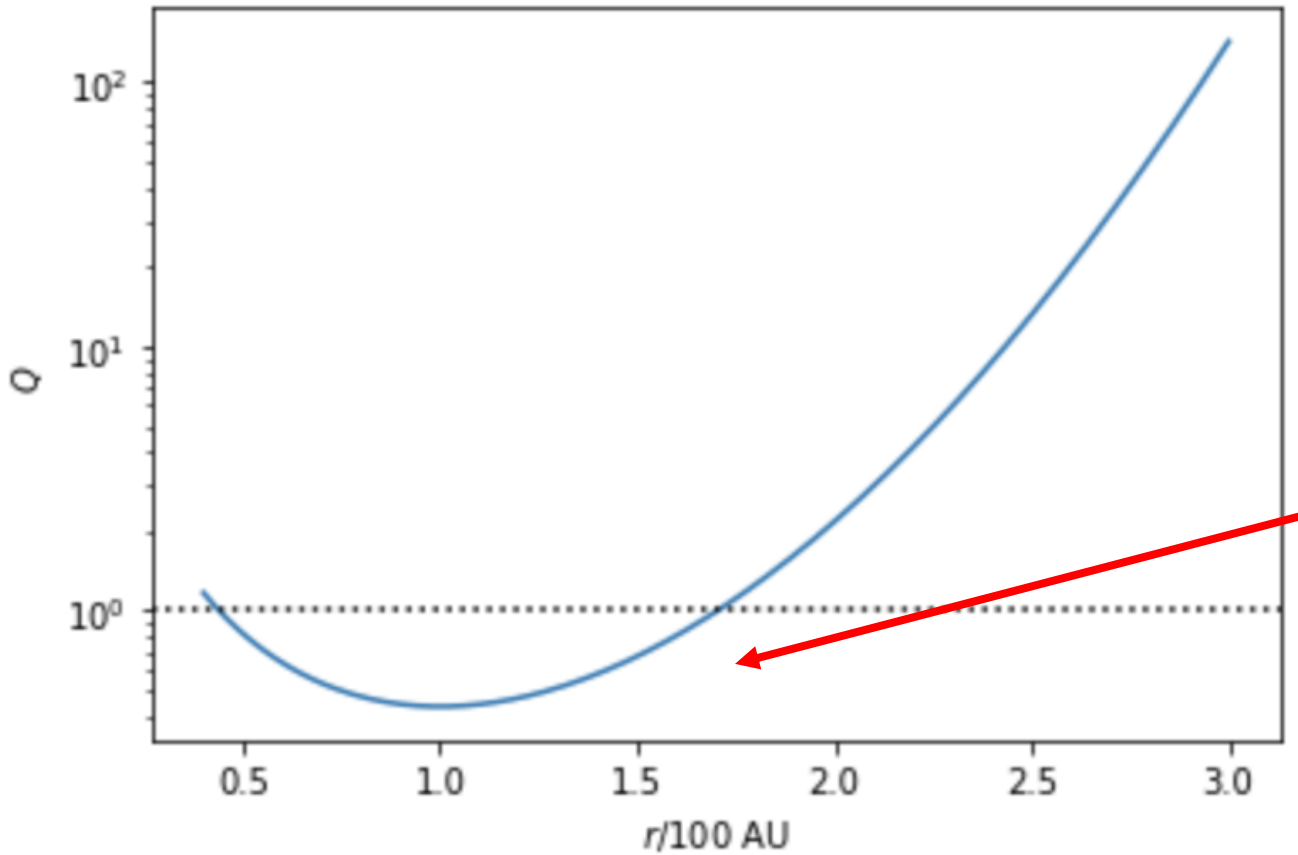
$\Sigma \sim 3\ g/cm^2$

Toomre Q of the disk

$$\Sigma = \Sigma_0 \exp\left[-\left(\frac{r}{r_0}\right)^2\right]$$

$$Q = \frac{c_s \Omega}{\pi G \Sigma}$$

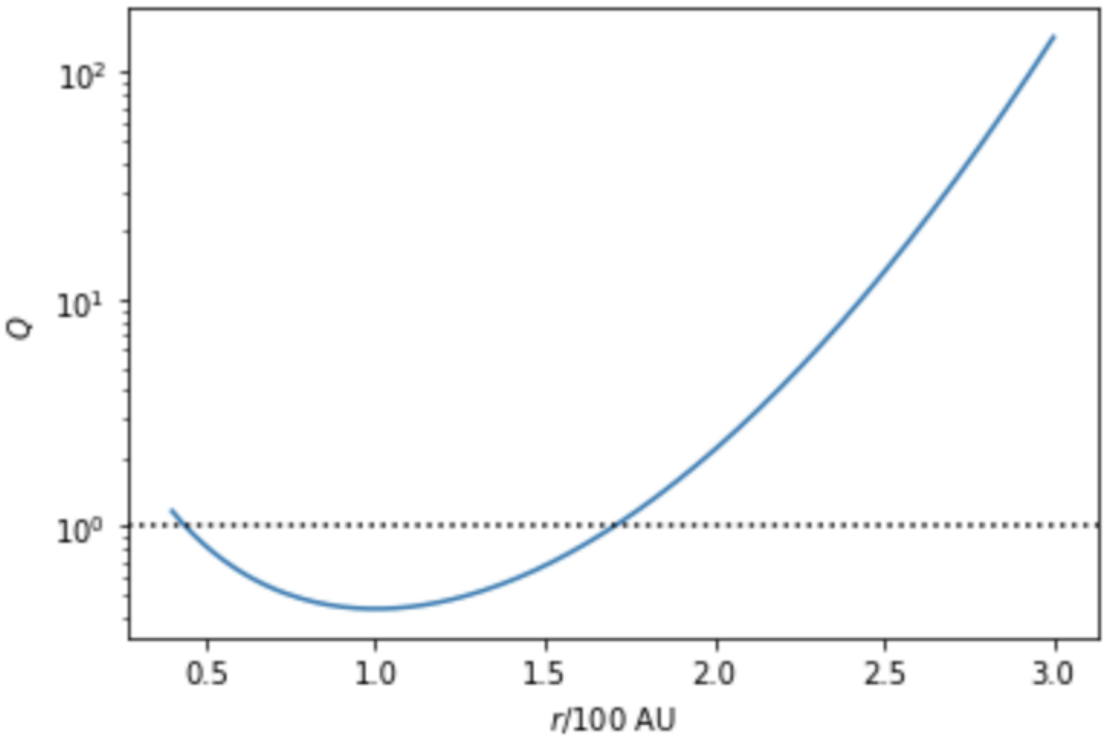


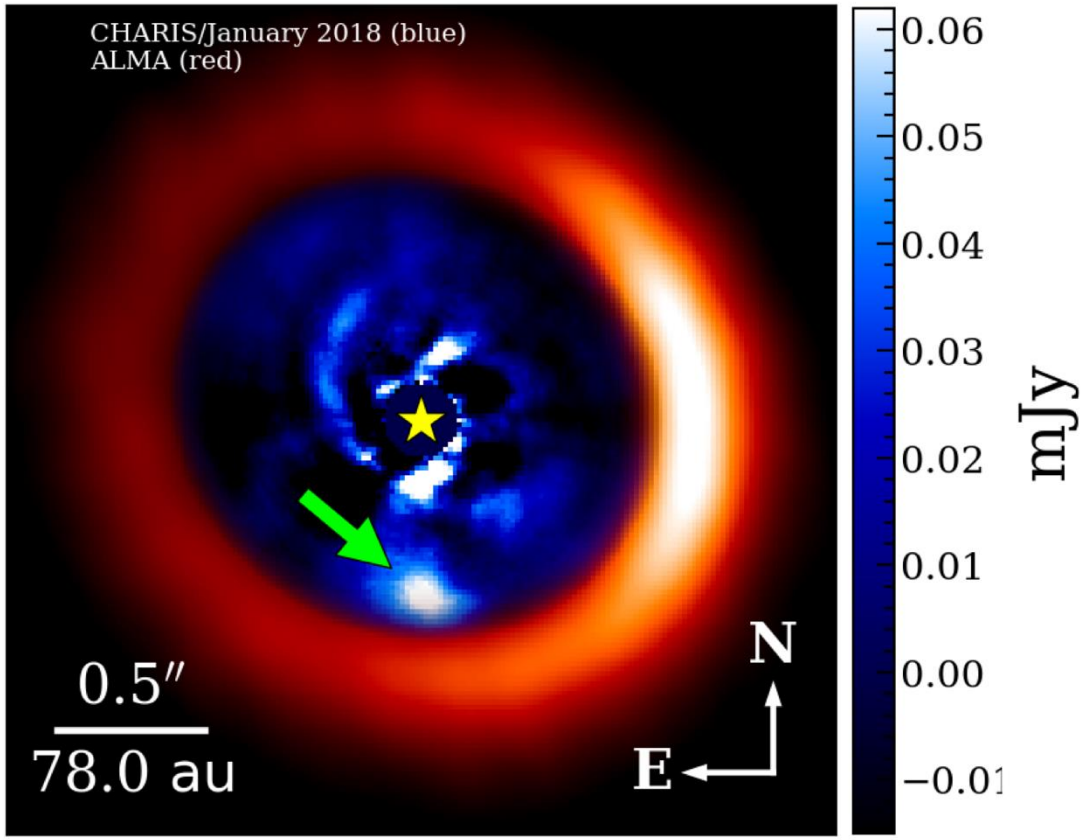


Gravitationally Unstable!

Currie et al (+Lyra) 2022

Consistent with the pebble ring

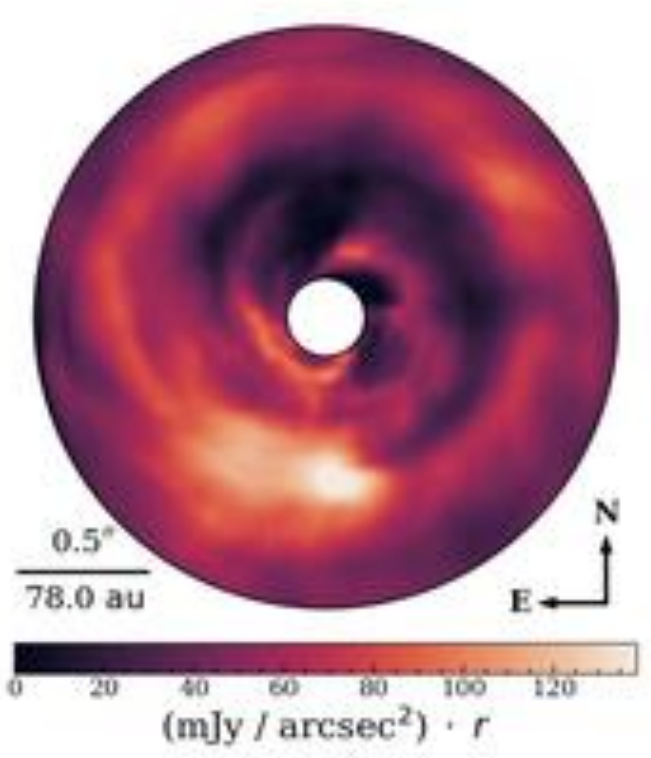


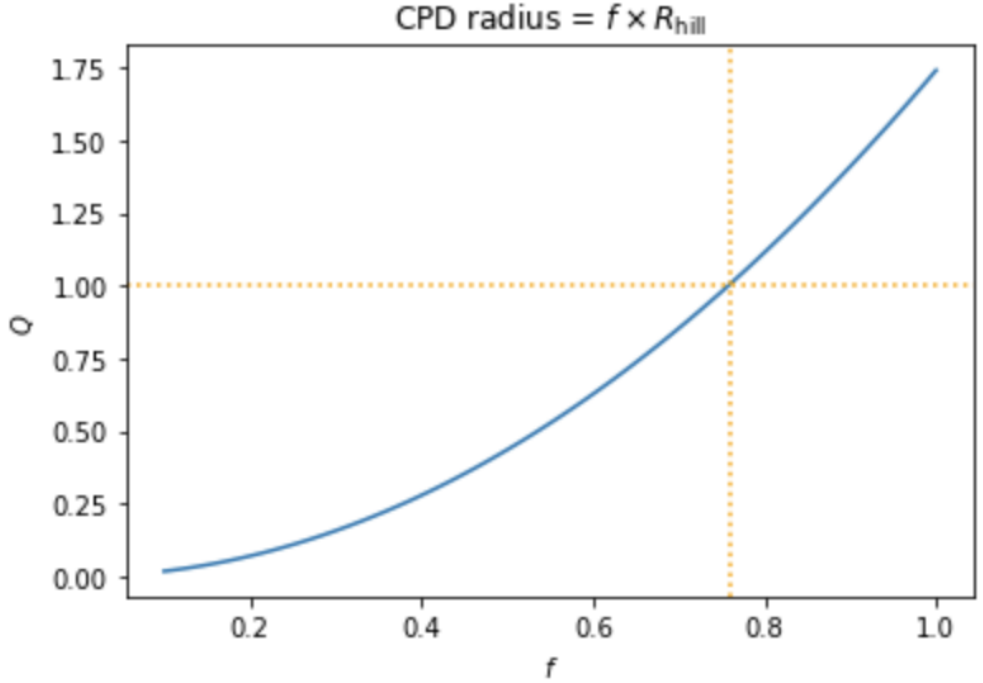


Currie et al (+Lyra) 2022

Toomre Q of the clump

- 10 Jupiter masses, spread over area $\pi(fR_{Hill})^2$
- T = 2000 K
- r = 100 AU

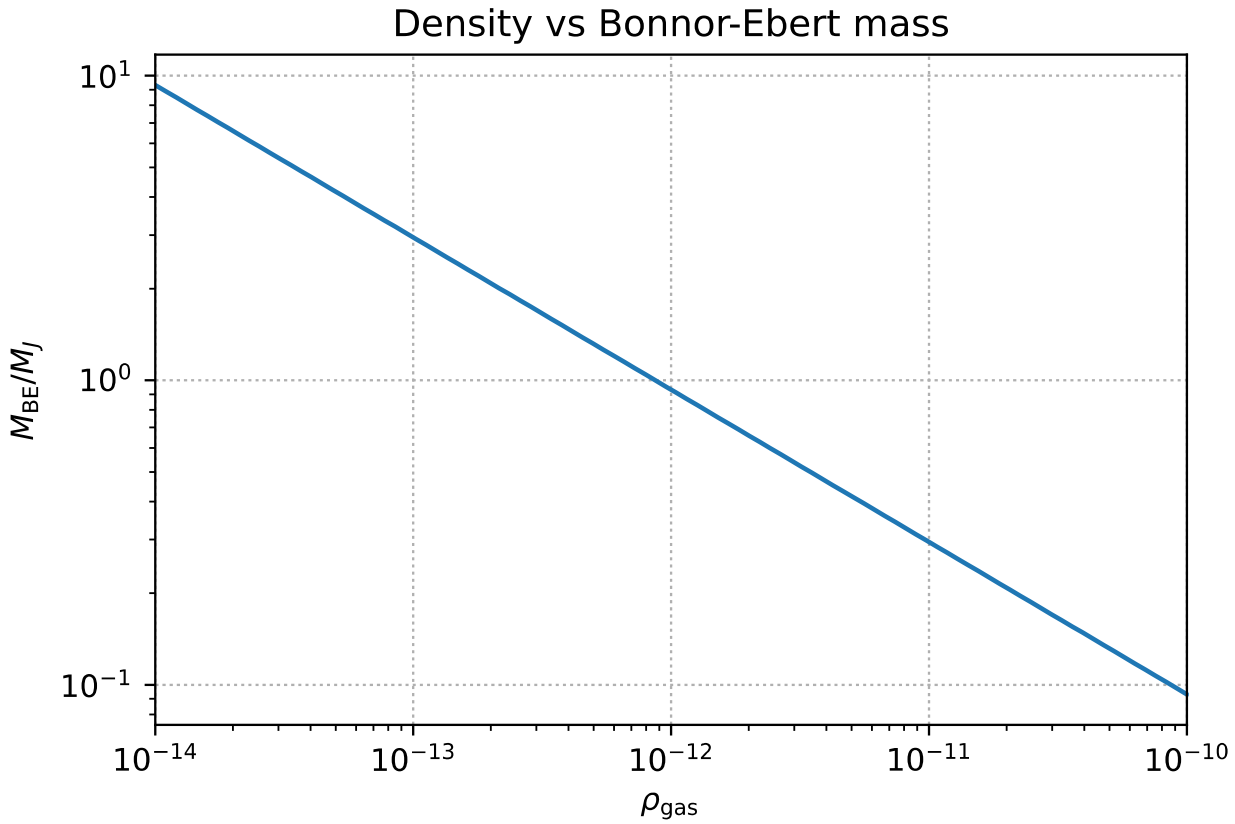




The clump is consistent with a Q~1 clump filling its Hill sphere.

Currie et al (+Lyra) 2022

Bonnor—Ebert mass

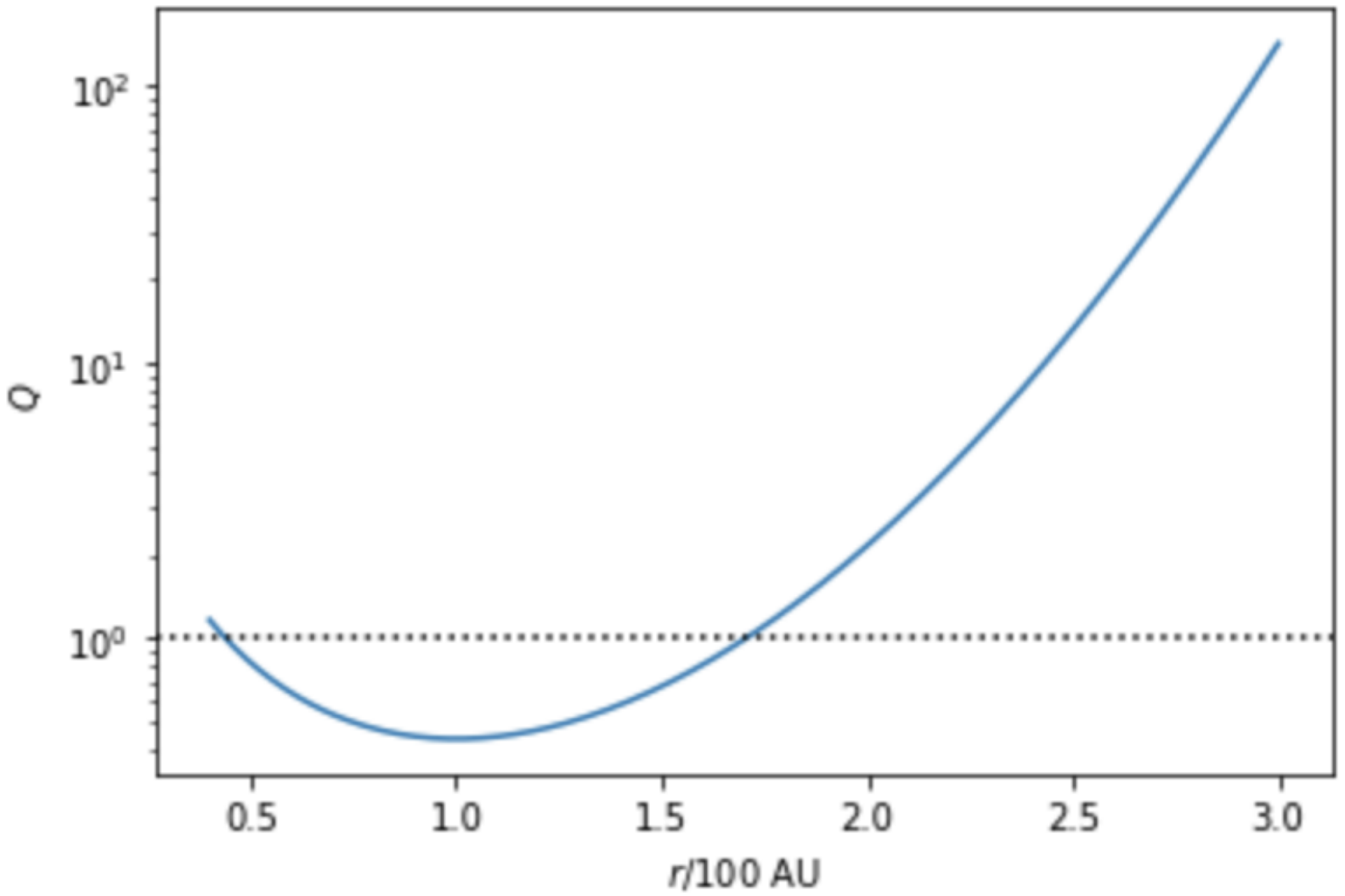


- T = 30K
- γ = 1.4

$$M_{BE}(p_0) = \frac{225}{32\sqrt{5\pi}} \frac{c_s^4}{(aG)^{3/2}} \frac{1}{\sqrt{p_0}}$$

Consistent with Jupiter-mass!

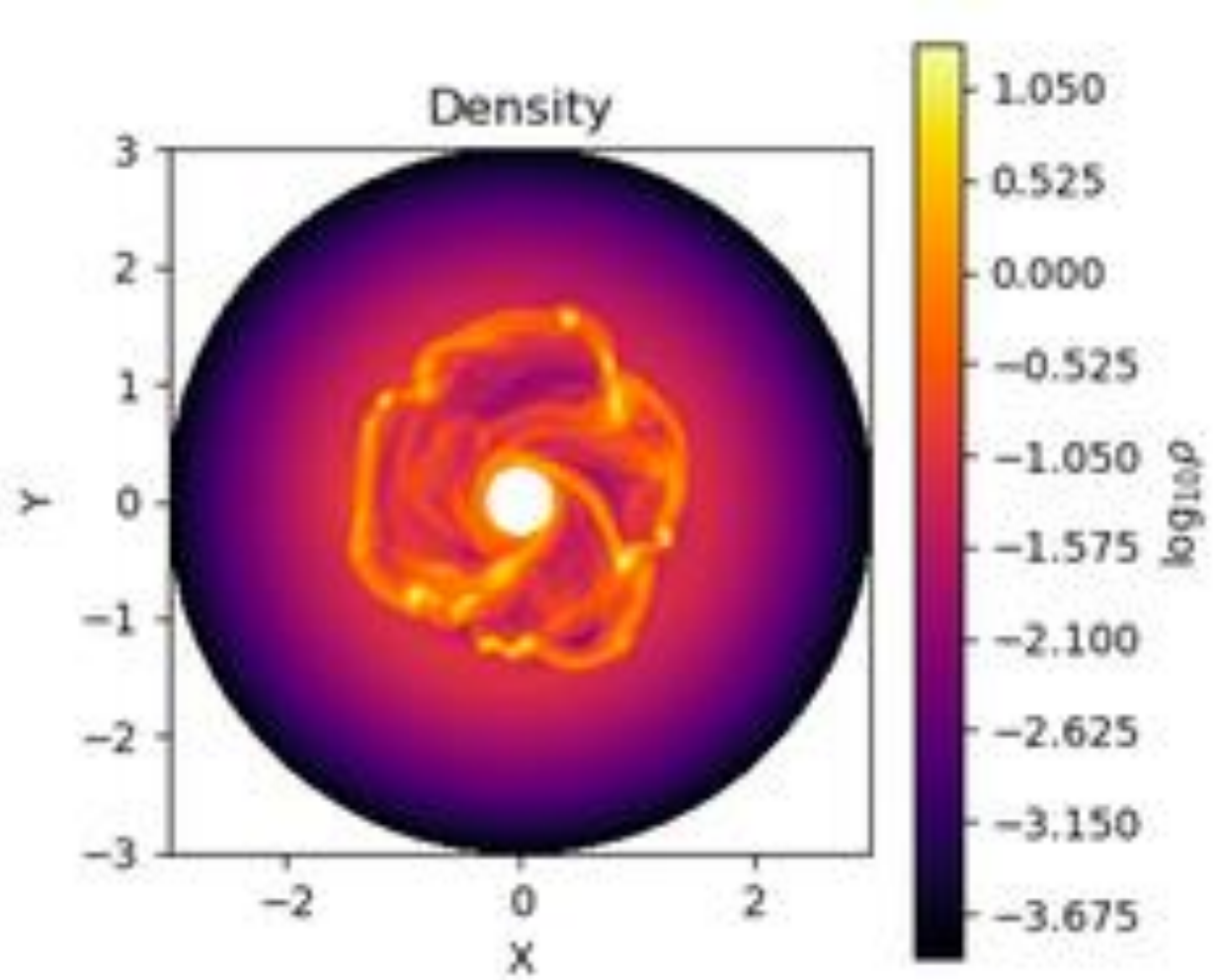
Currie et al (+Lyra) 2022

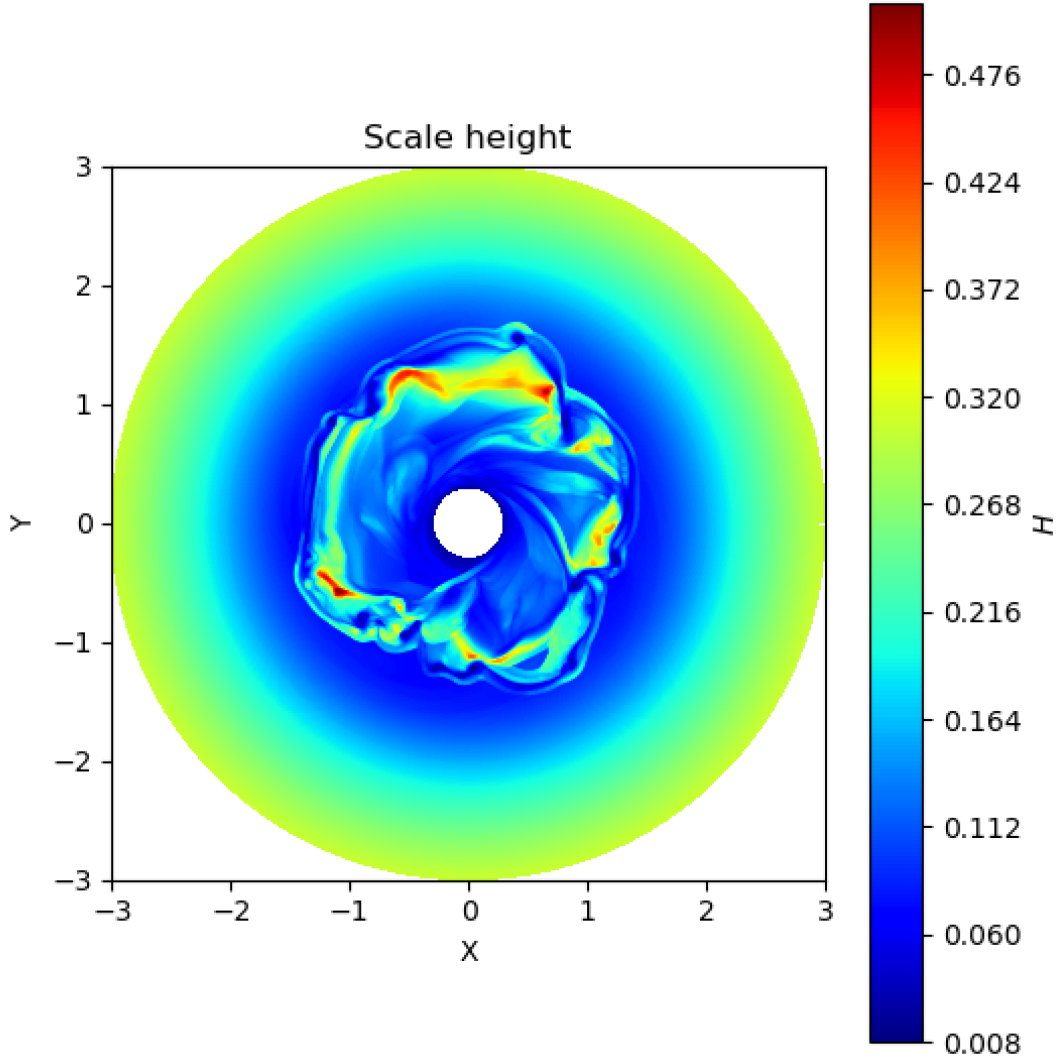


Model

- 2D rϕ Resolution 432 x 864
- Log grid $\Delta r / r$ = const
- Radial range 30 – 300 AU
- Exponential truncated disk
- β-cooling: 10 orbits at 100 AU

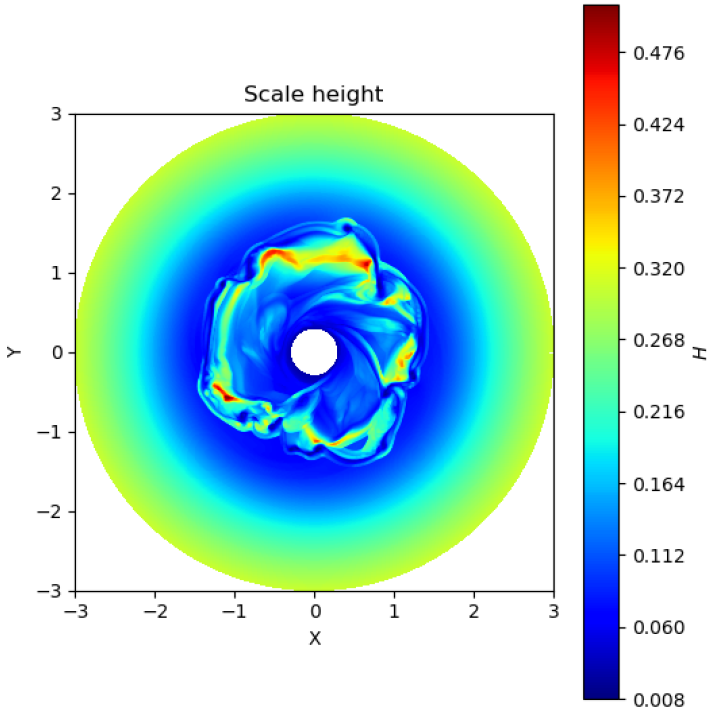
Currie et al (+Lyra) 2022

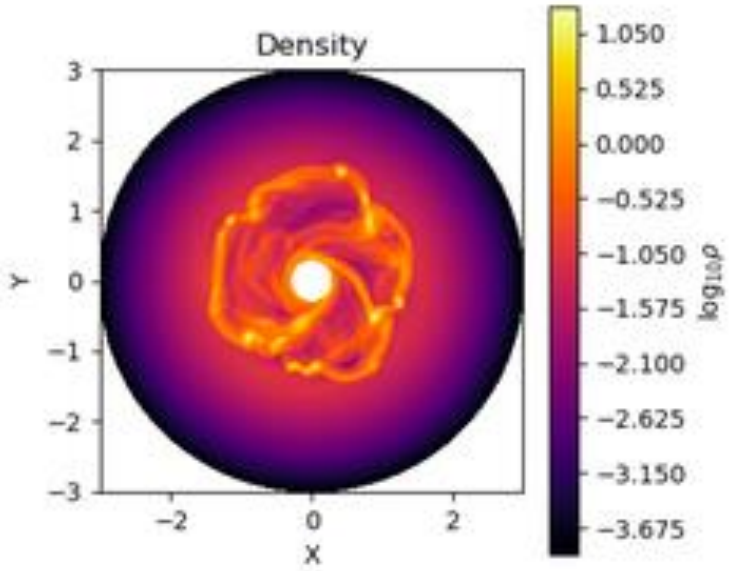


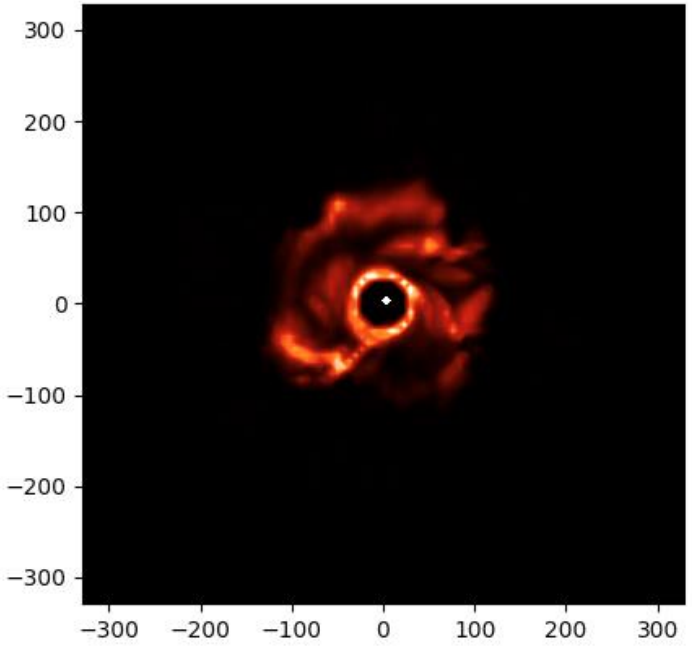


Currie et al (+Lyra) 2022

Synthetic Image with RADMC-3D





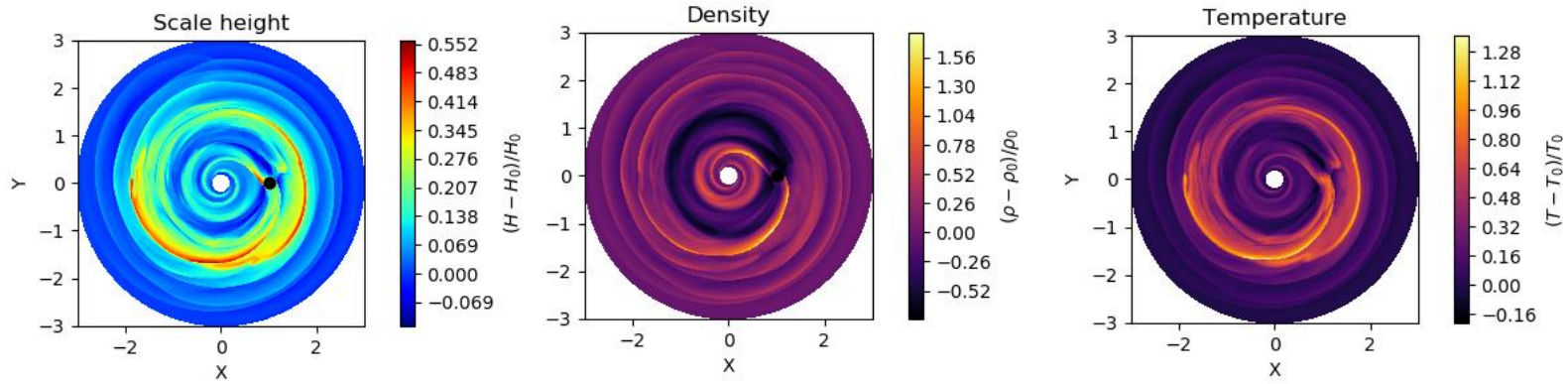


10^7 photons

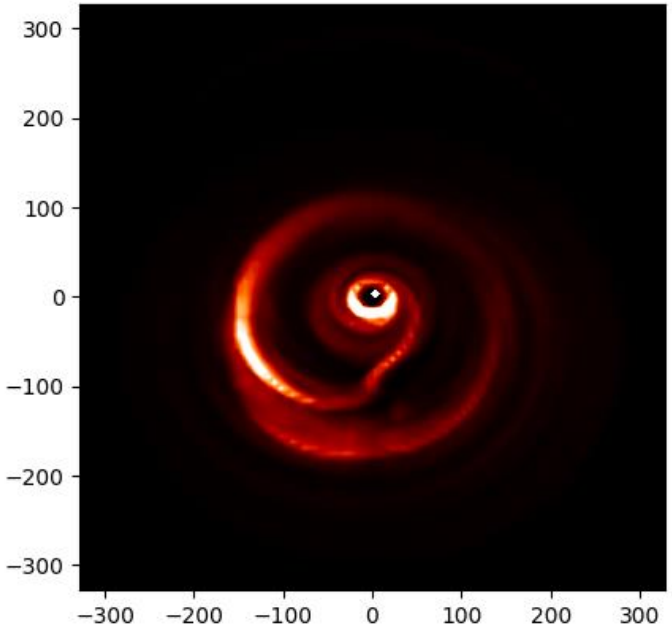
2.2 microns

Currie et al (+Lyra) 2022

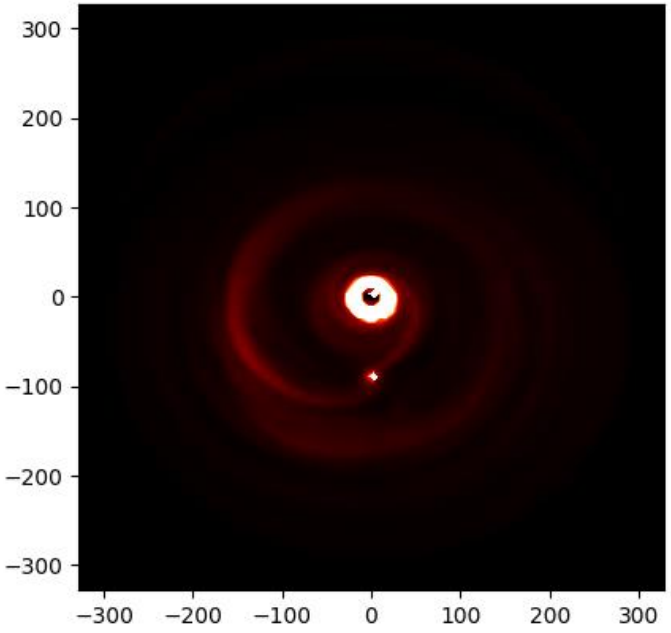
Control Model without Self-Gravity



1.6 micron

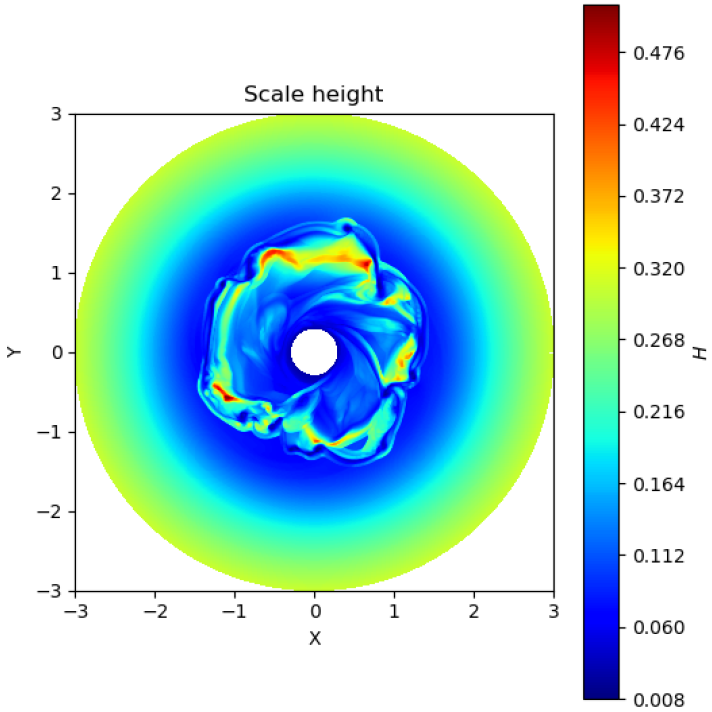


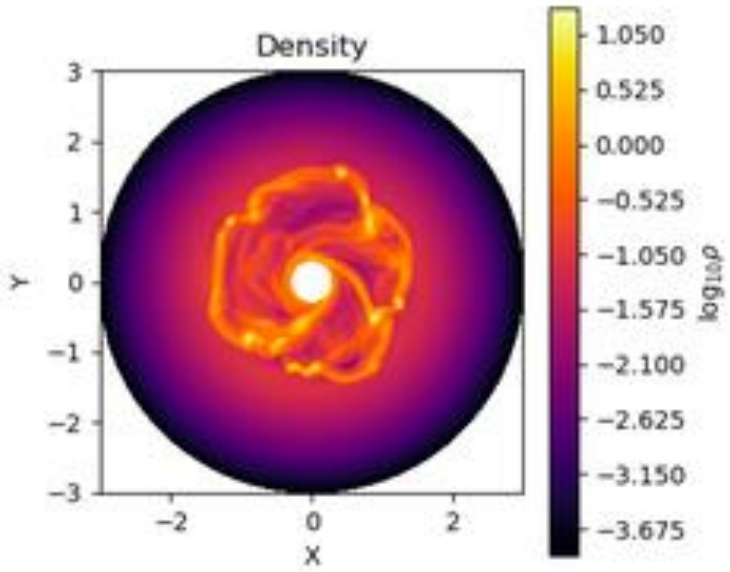
3.8 micron

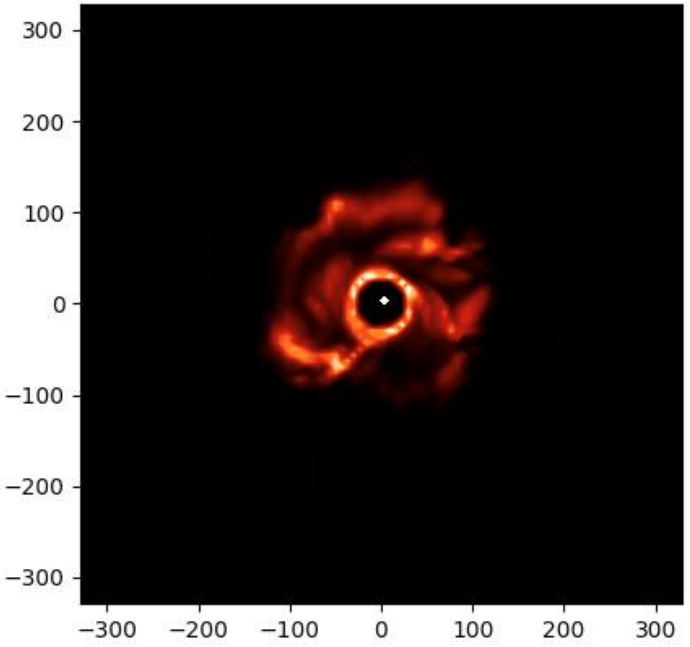


Currie et al (+Lyra) 2022

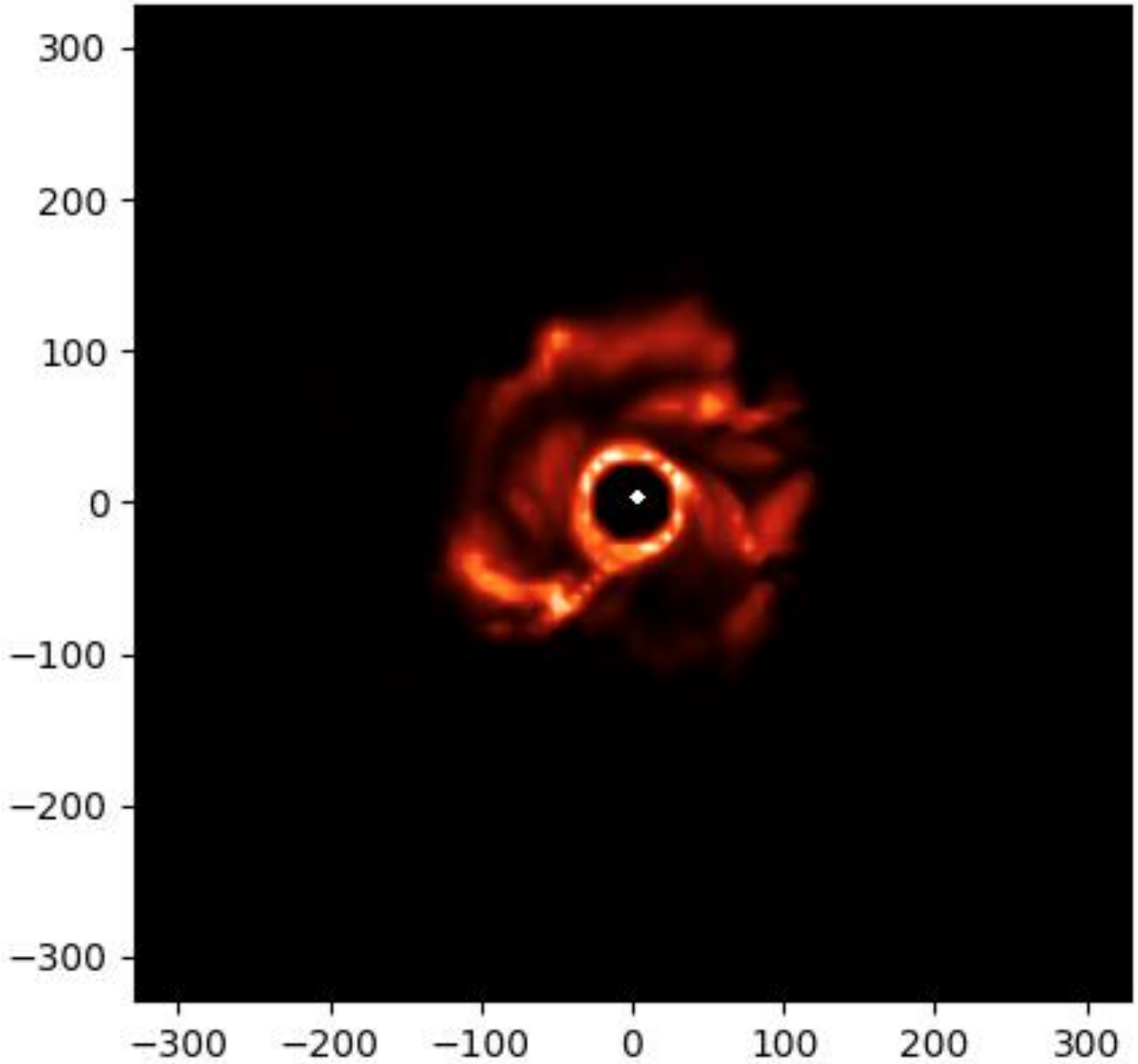
AB Aur model



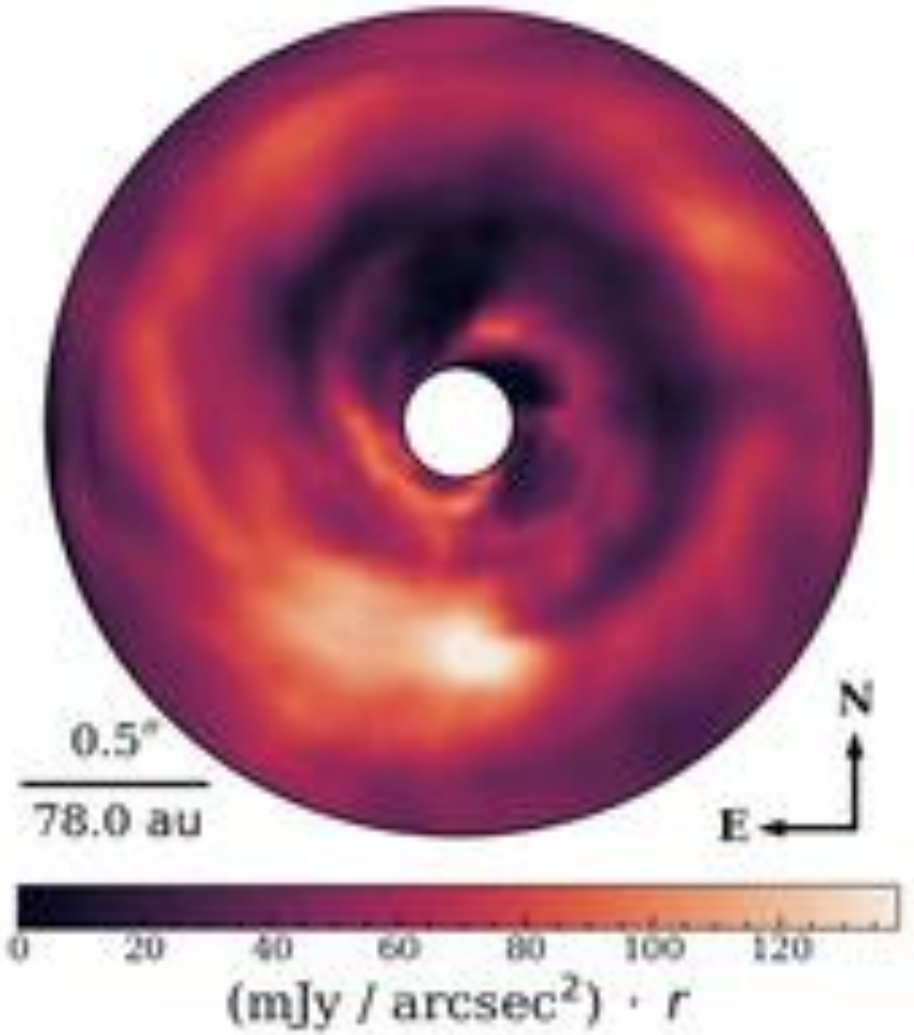


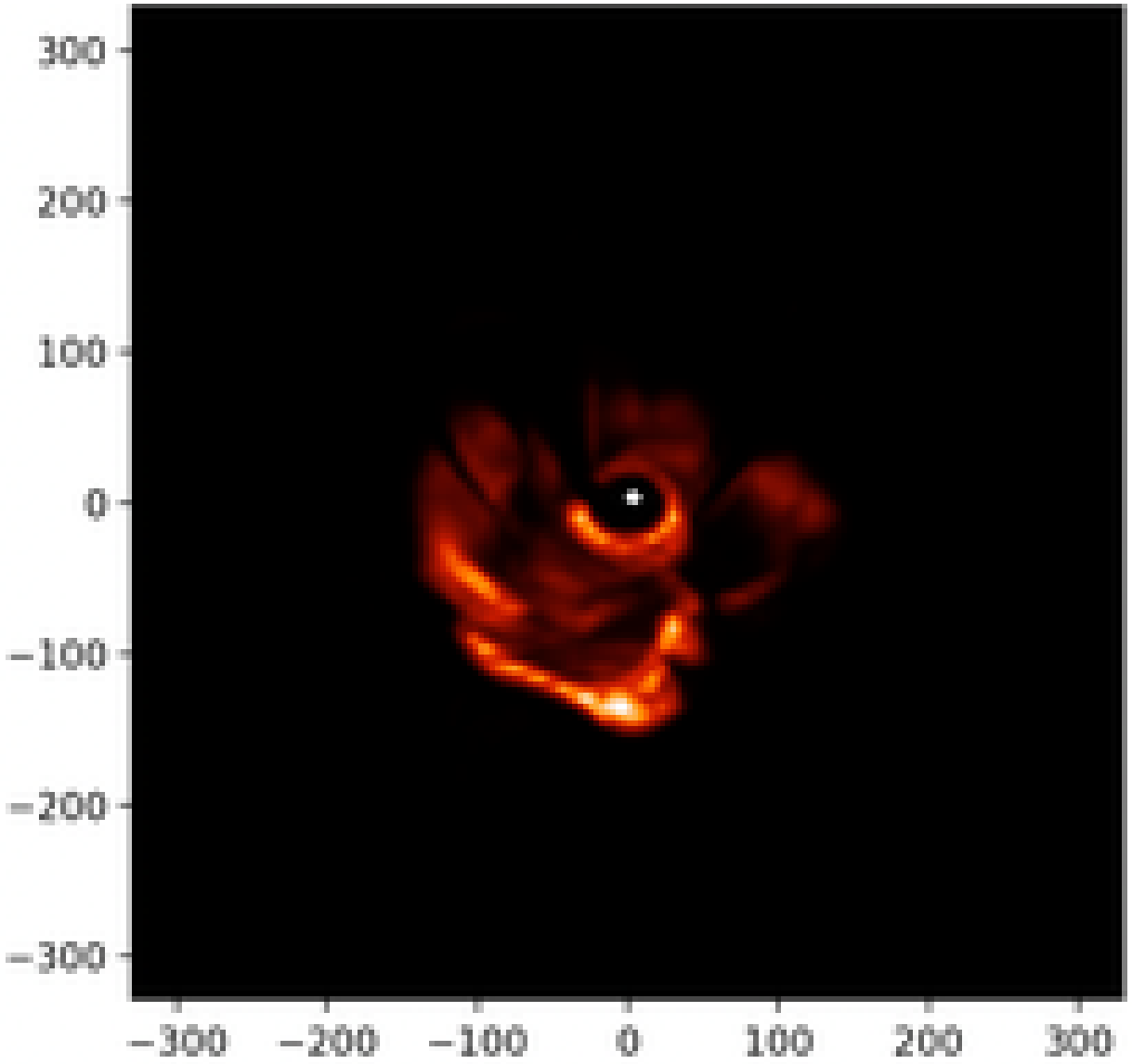


Currie et al (+Lyra) 2022



Currie et al (+Lyra) 2022

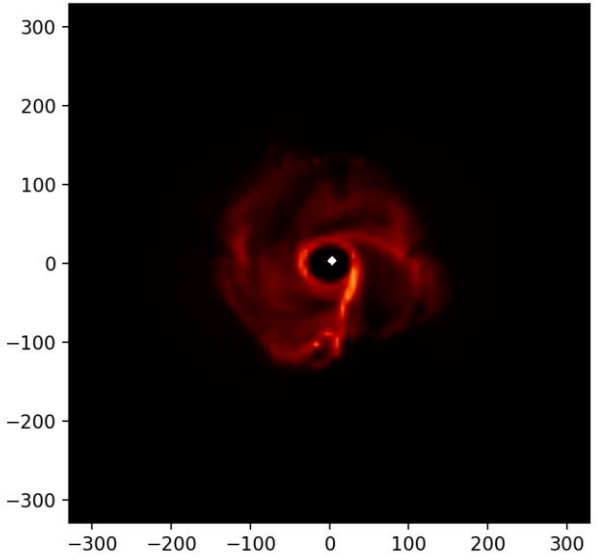




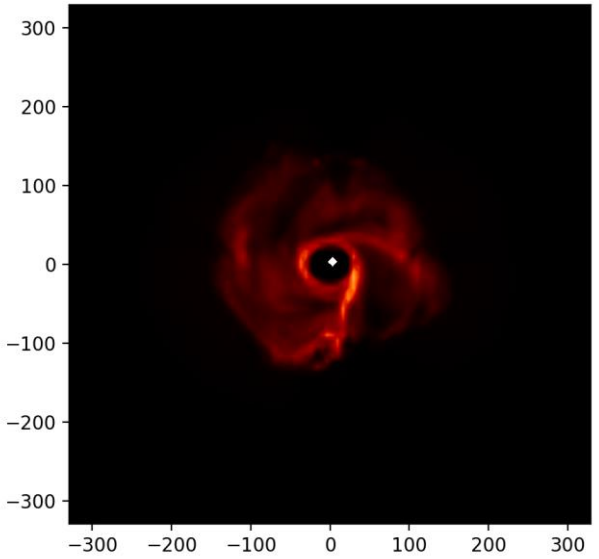
Currie et al (+Lyra) 2022

Synthetic Image + Planet

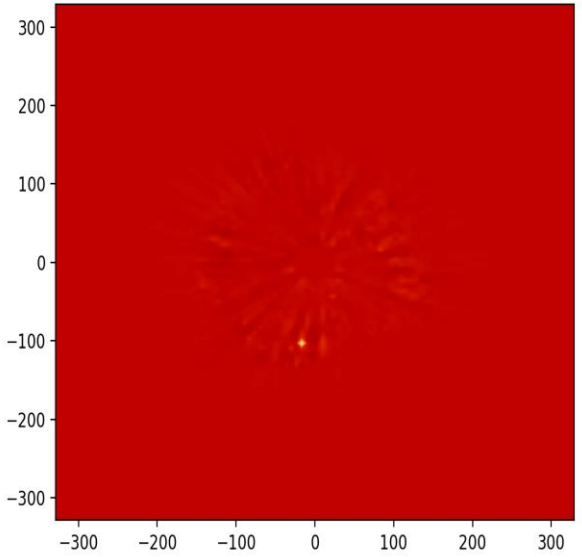
Star + GI Blob



Star



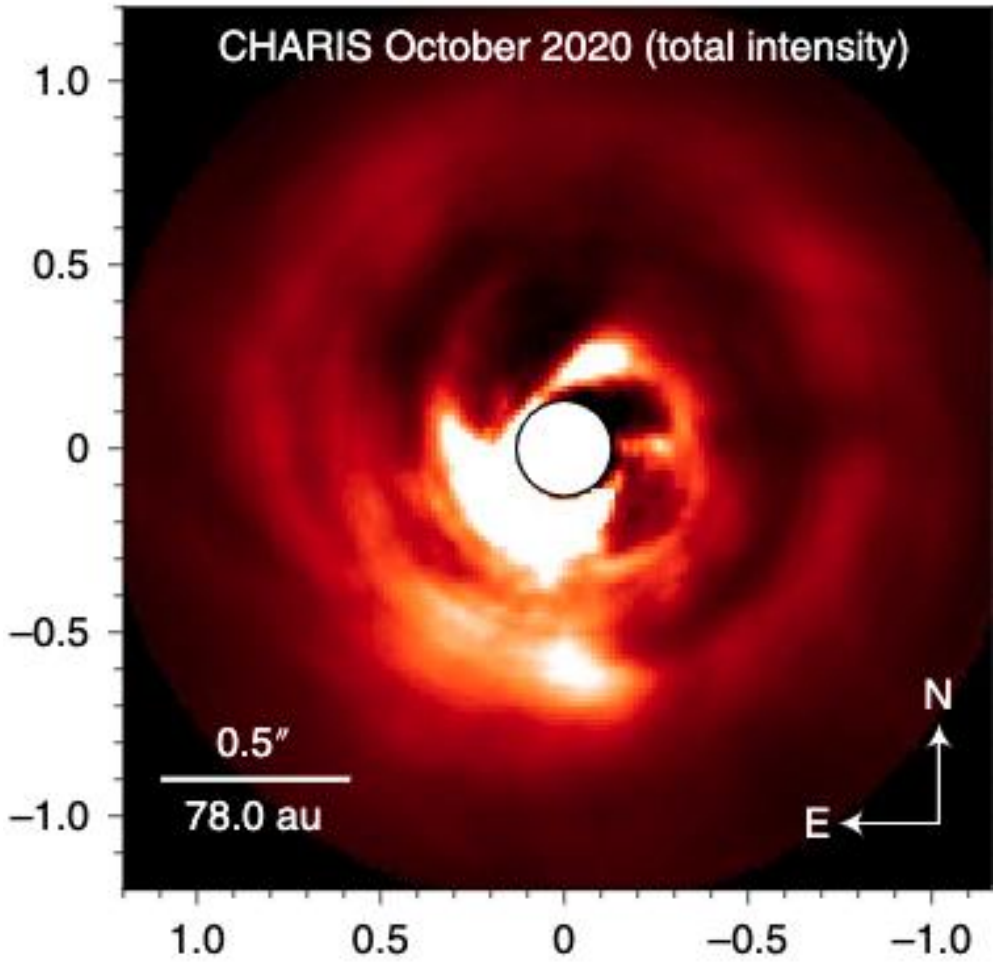
Subtraction

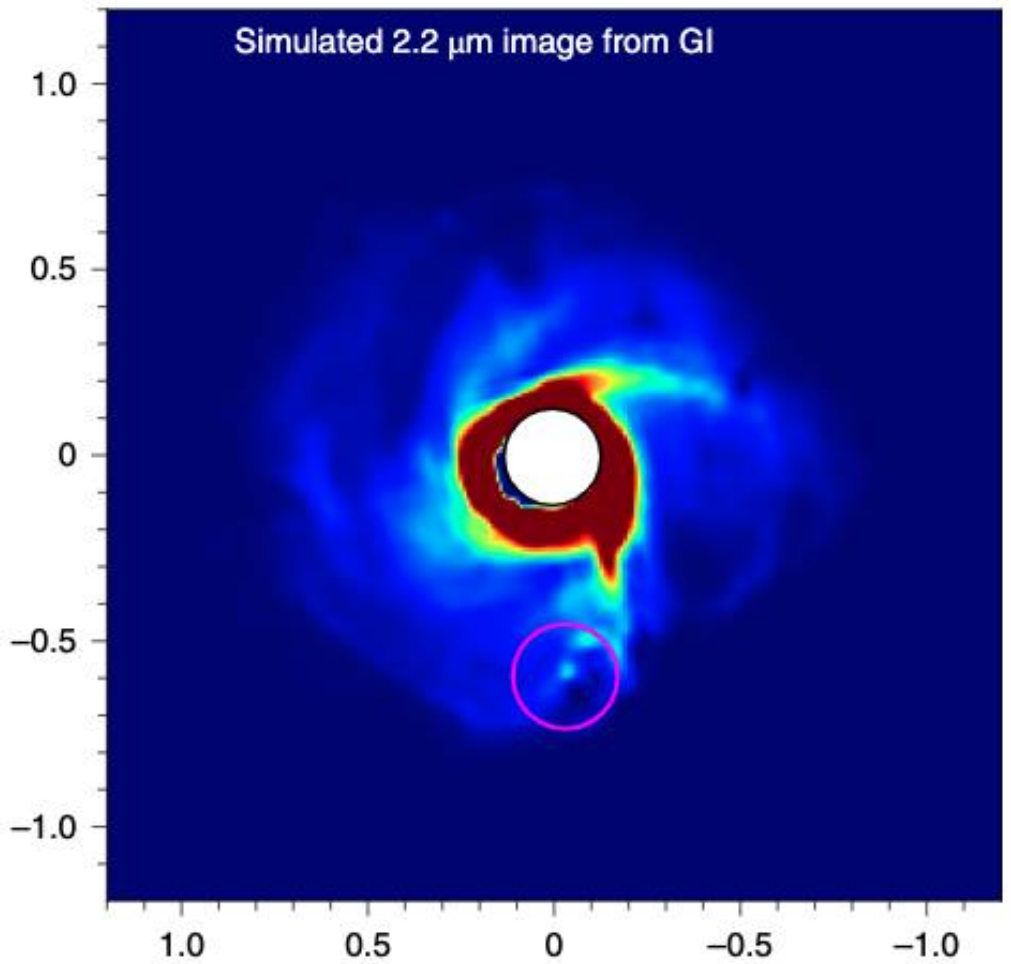


- 2.2 microns
- 1e6 photons
- Blob: 2 R_J, 5000K, 2.5 x 10^{-3} Lsun

Currie et al (+Lyra) 2022

AB Aur b's Formation





Currie et al (+Lyra) 2022

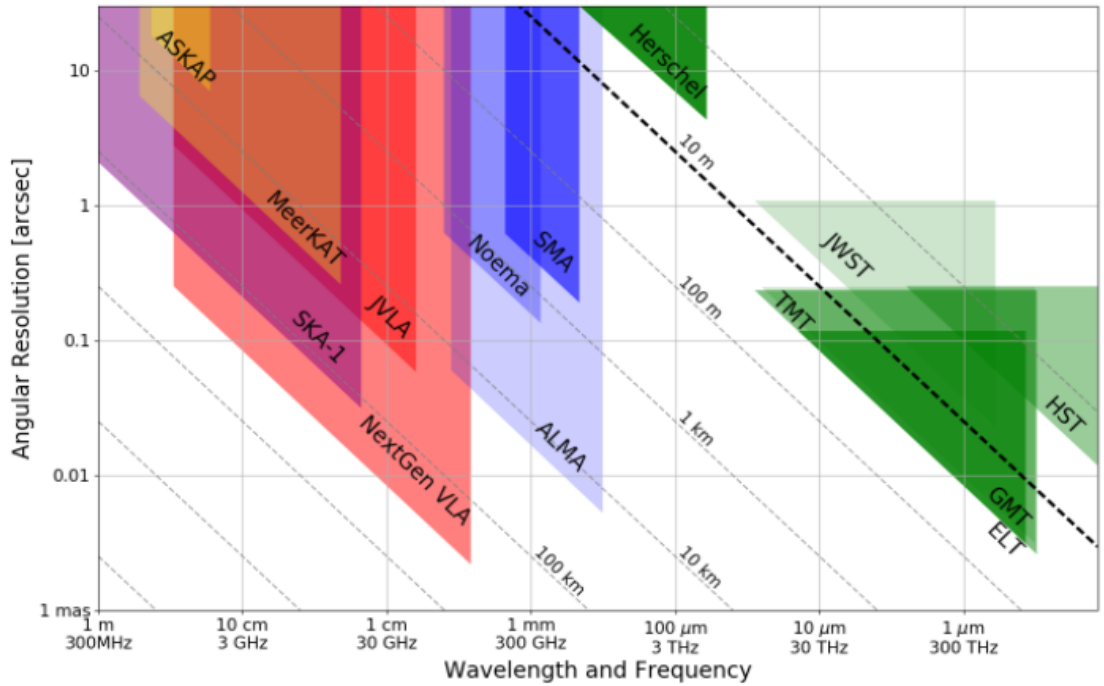
The future

After nearly 15 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)

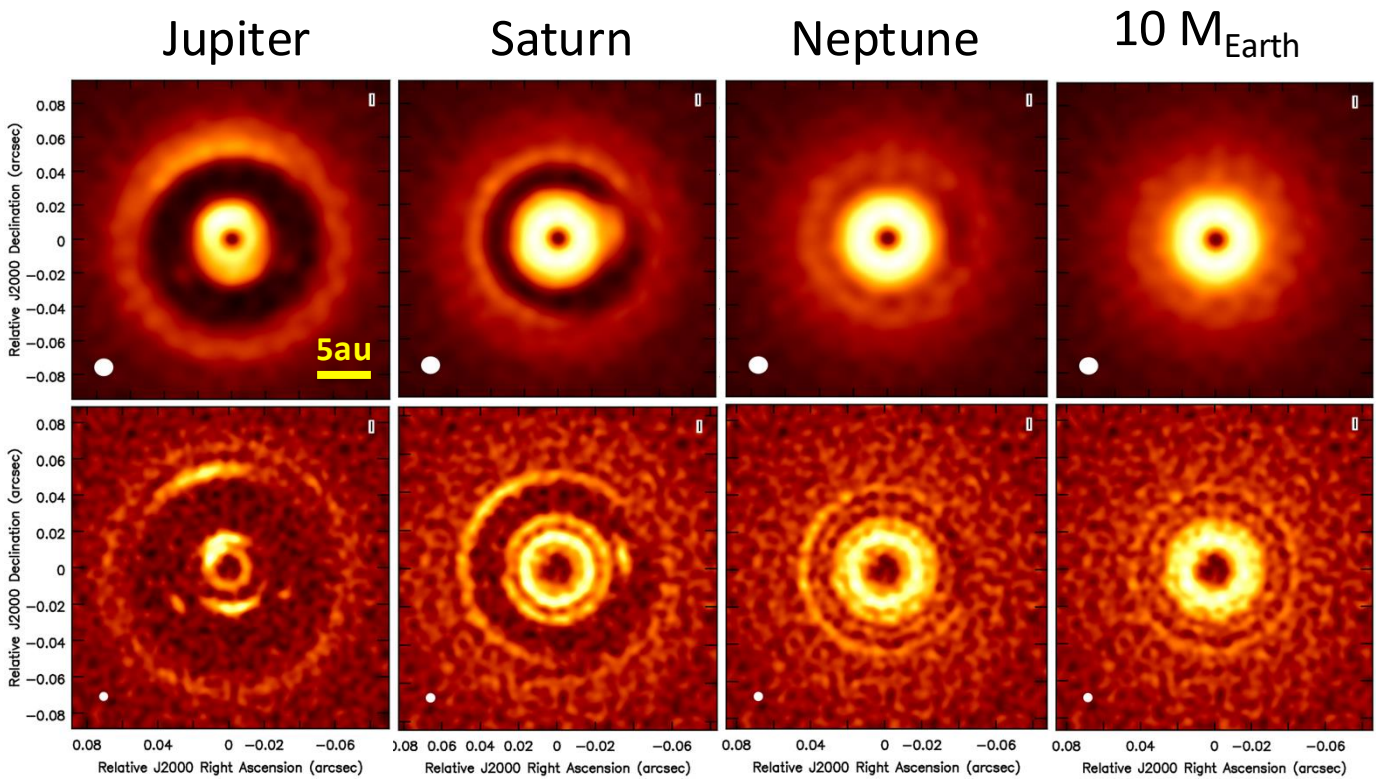


Planets at 5AU

ALMA @ 0.87mm

ngVLA @ 3mm

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

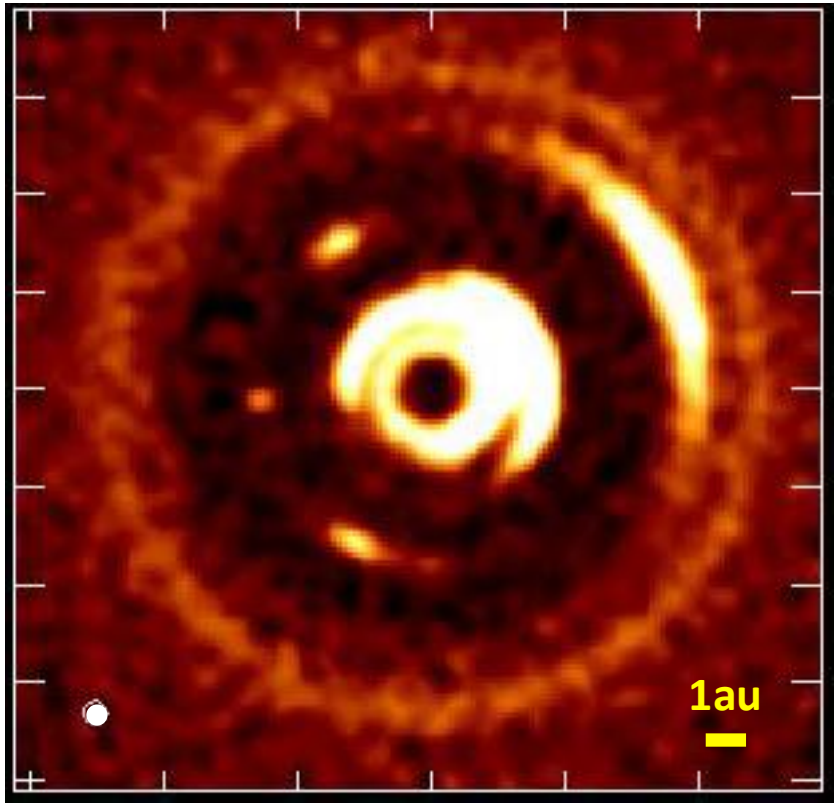


ngVLA identifies gaps/substructures down to ~5-10 M_{Earth}

Ricci et al. 2018

ngVLA: Proper motions

Jupiter at 5 AU



Ricci et al. 2018

Conclusions

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

- **Shocks from high-mass planets**
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  - Density derived from optical depth ~ 1 implies Q~1
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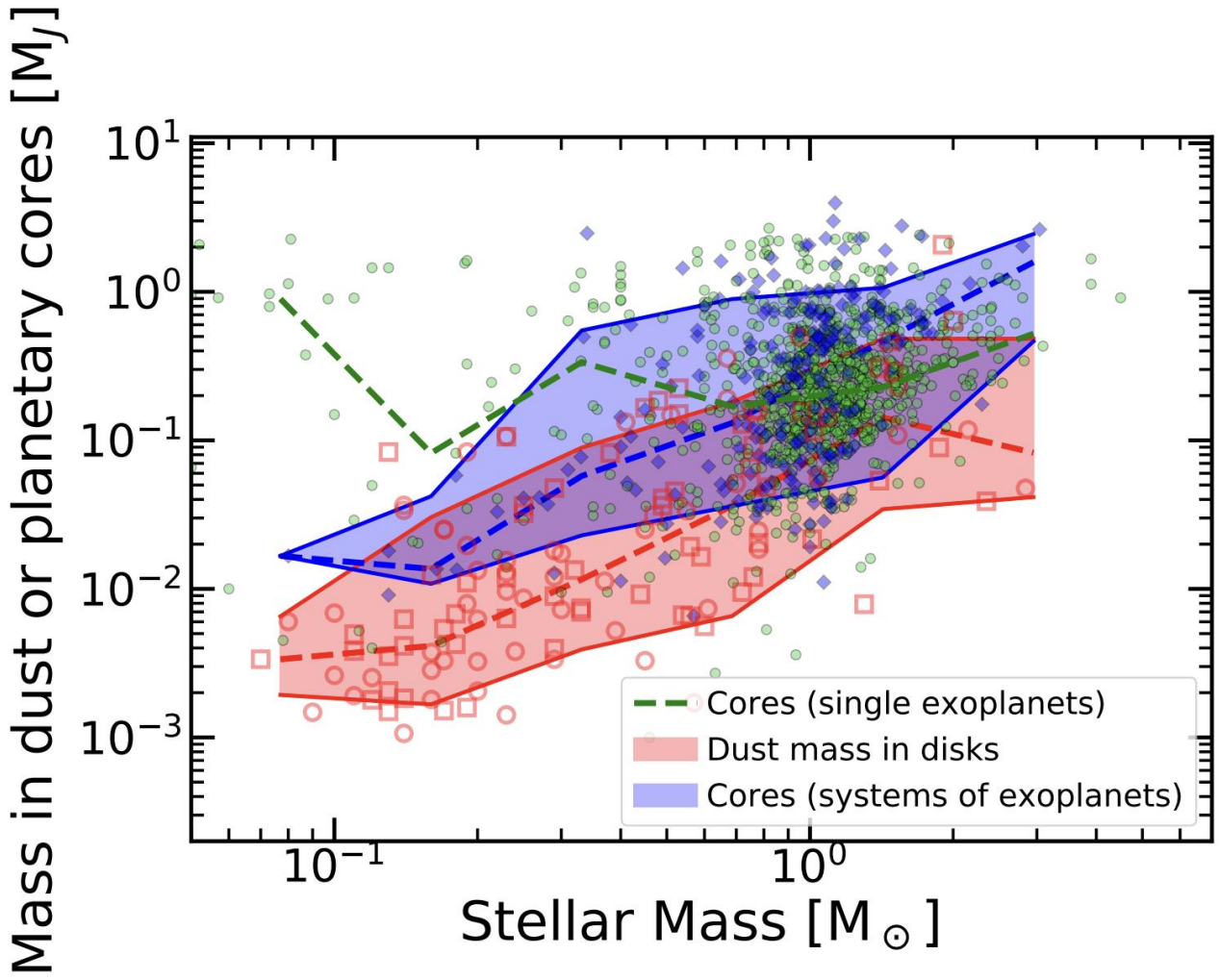
    - Bonnor-Ebert mass 1-10 M_J for this disk pressure
    - 10 M_J blob spread over ~ 1 Hill radius at measured temperature also implies Q~1.

The Missing Mass Problem

Exoplanets have more mass than the disks



Manara et al. (2018)

What gives?

Mass is derived by:

$$\Sigma_{d,\mathrm{obs}} = \frac{\langle I_\nu \rangle}{B_\nu \kappa_\nu}$$

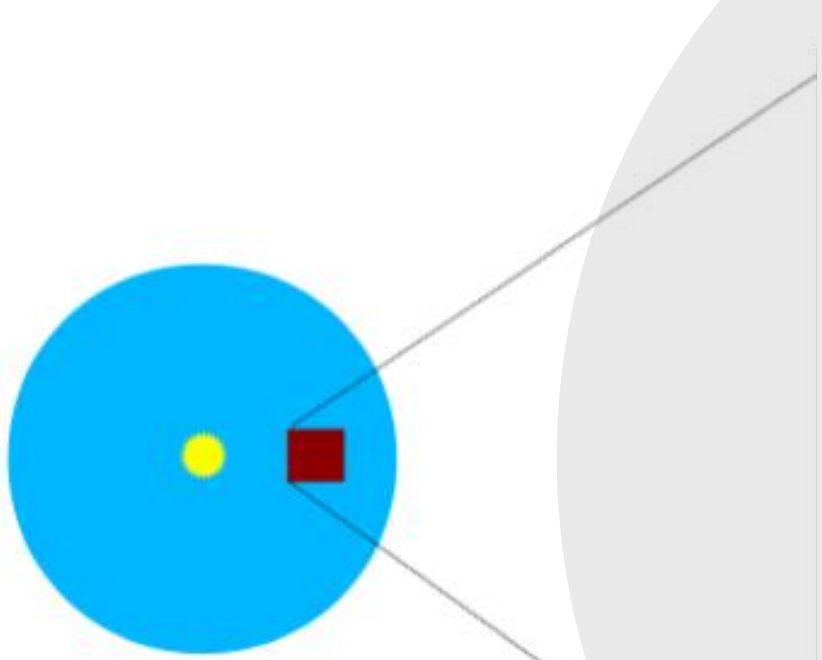
Assumptions:

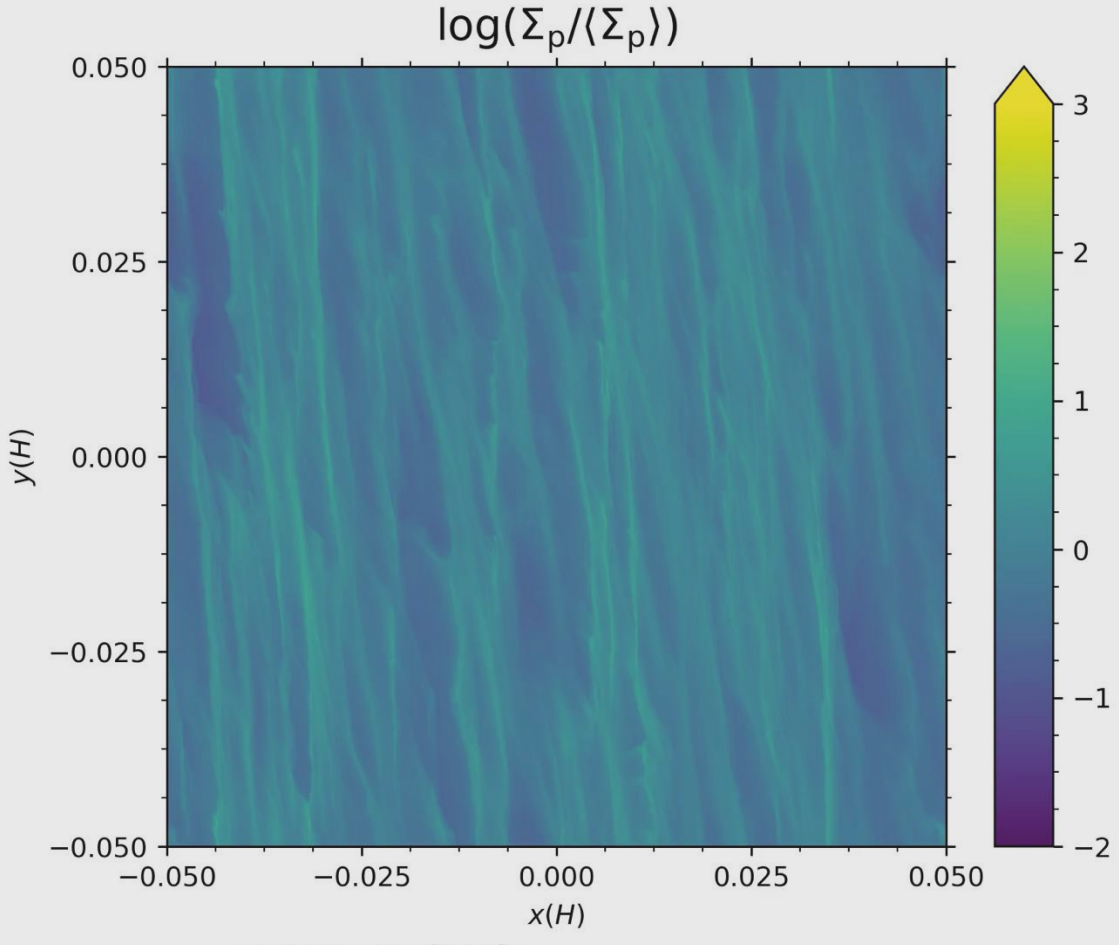
Homogeneous

Optically thin

No scattering

Small-Scale Turbulence Concentrates the Grains

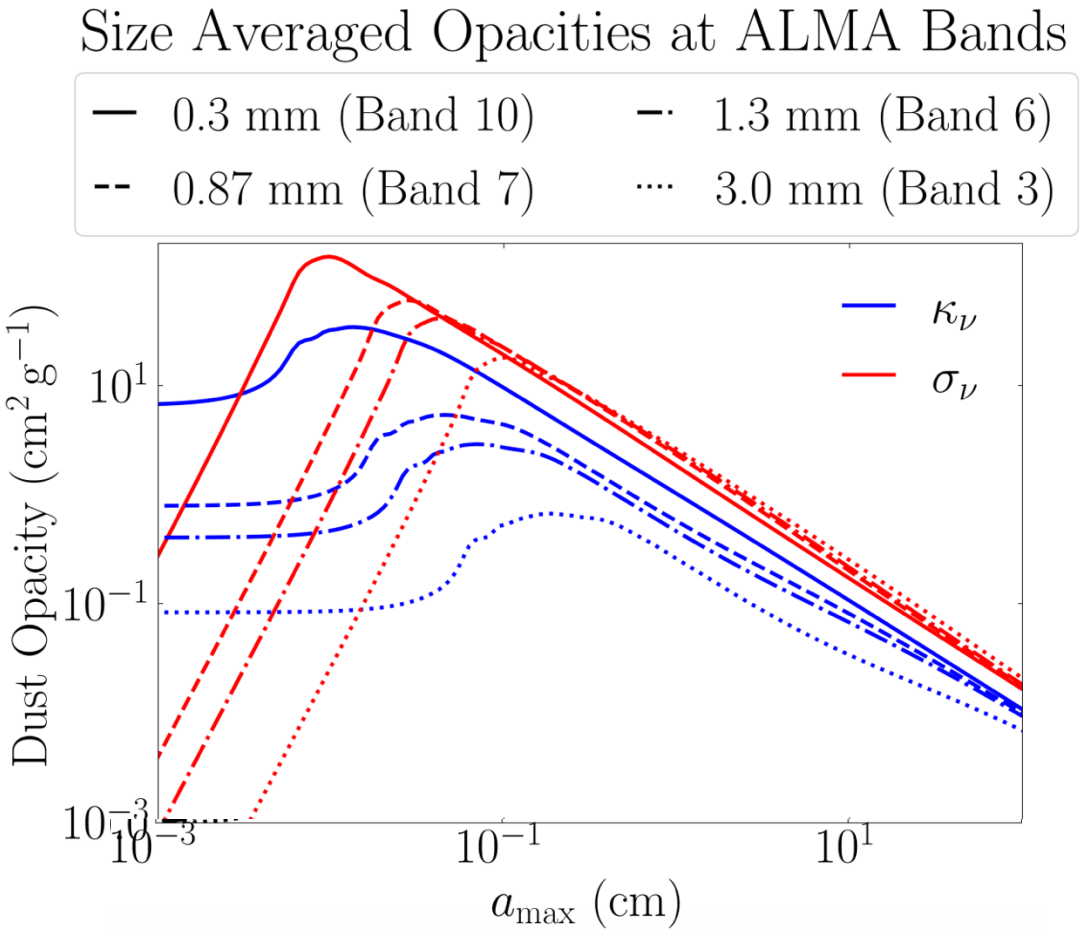


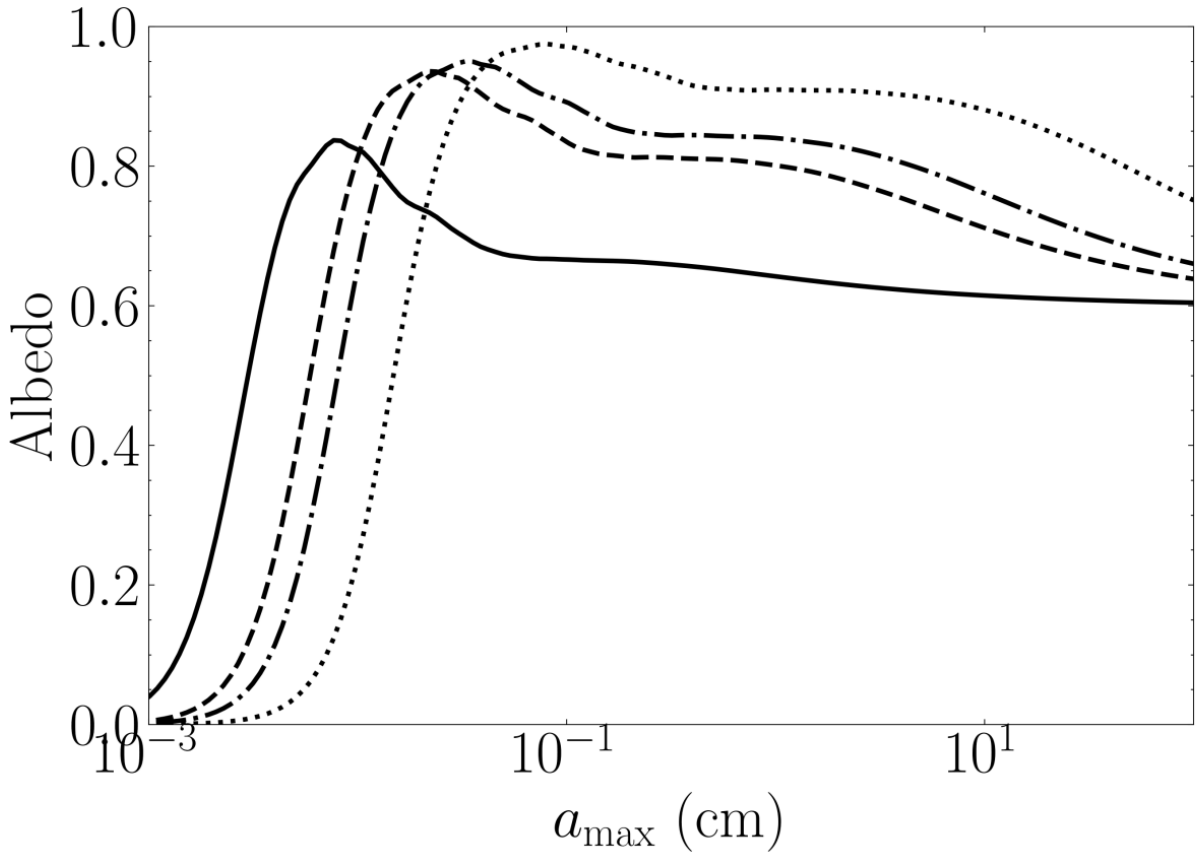


Animation by: Rixin Li

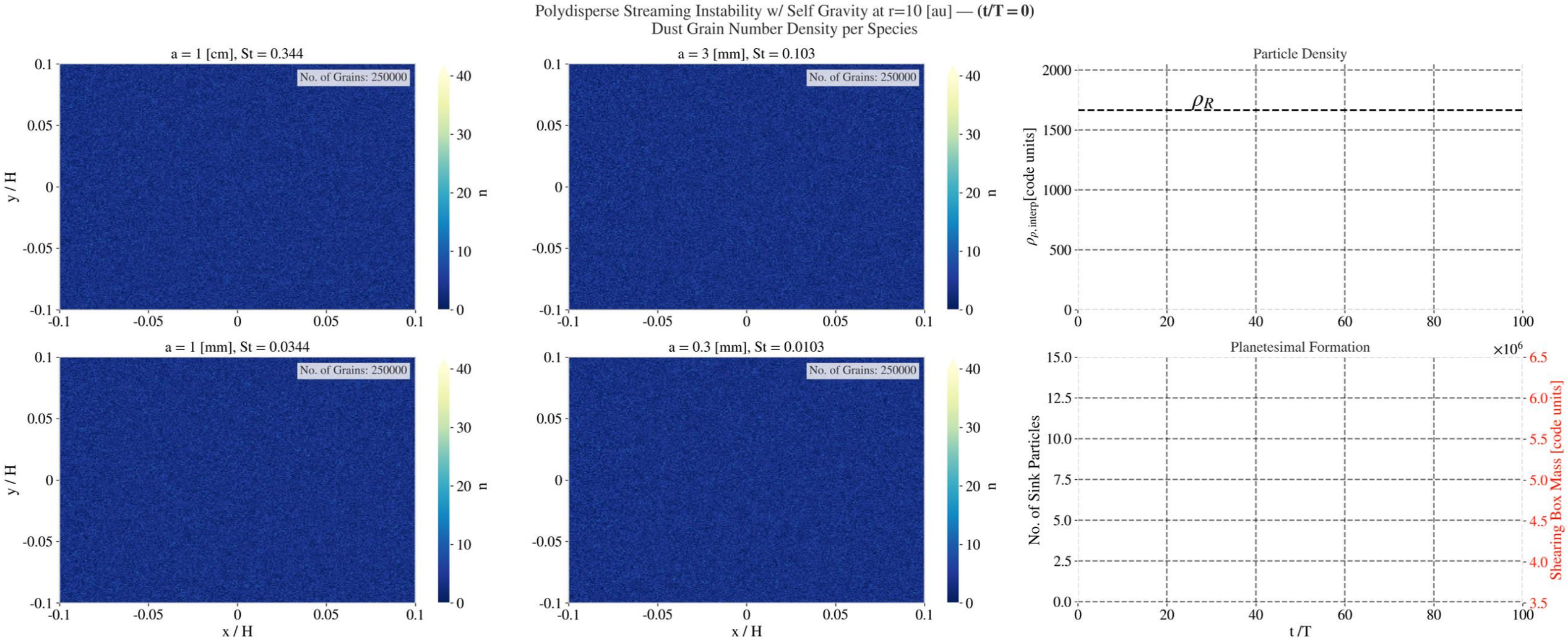
Youdin & Goodman ‘05, Johansen & Youdin ‘07, Youdin & Johansen+ ‘07, Kowalik+ ’13, Lyra & Kuchner ‘13, Schreiber+ ‘18, Klahr & Schreiber ’20, Simon+ ‘16, ‘17, Carrera+ ‘15, ‘17, ‘20, Gole+ ’20, Li+ ‘18, ‘19, Abod+ ’19, Nesvorny+ ’19

Scattering





Godines & Lyra + (2025)



Godines & Lyra + (2025)

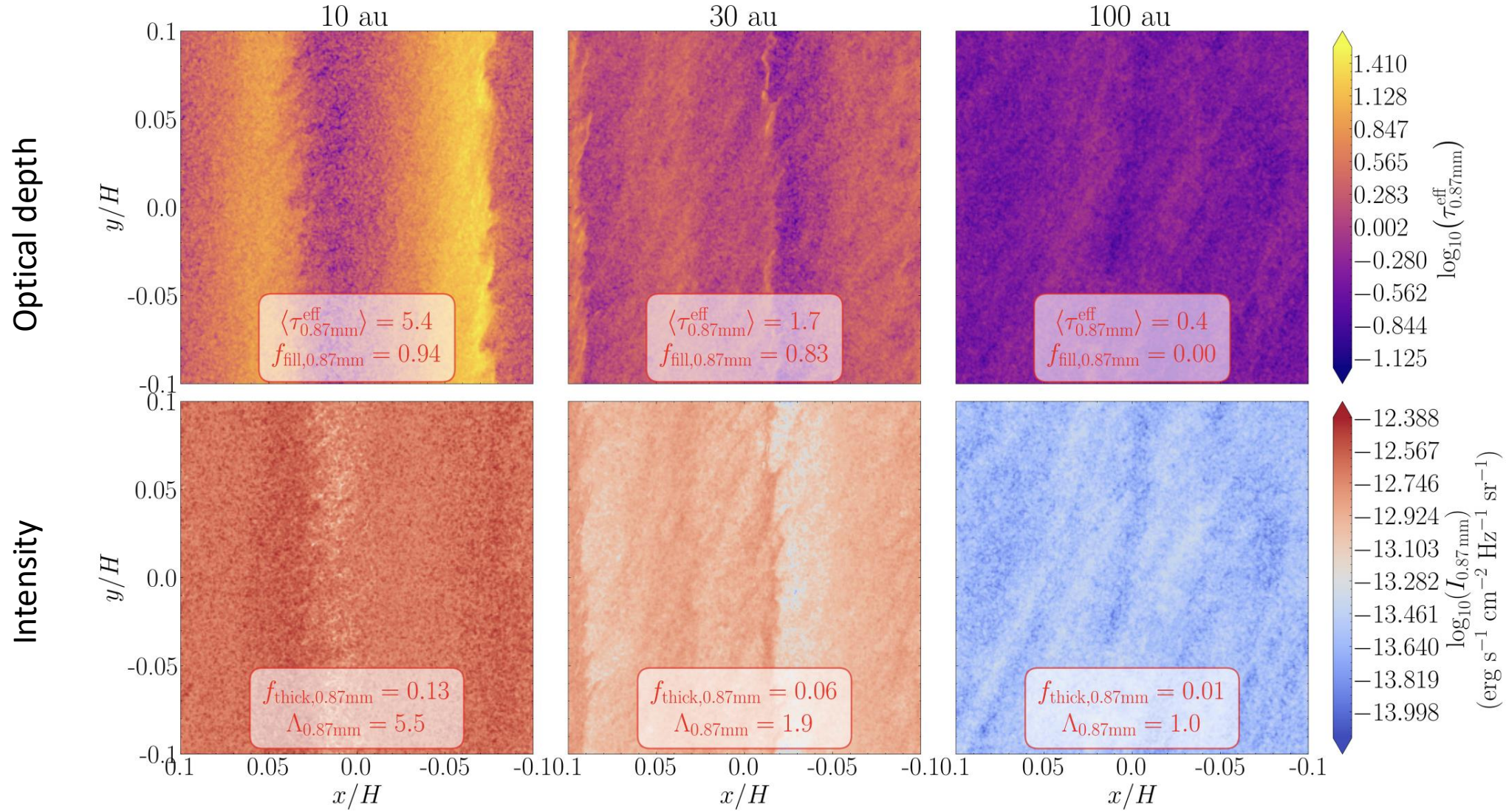
Optical Depth and Mass Excess

f_{fill}: filling factor

(fraction of pixels that are optically thick)

$\Lambda = m_{true}/m_{obs}$

(mass excess)



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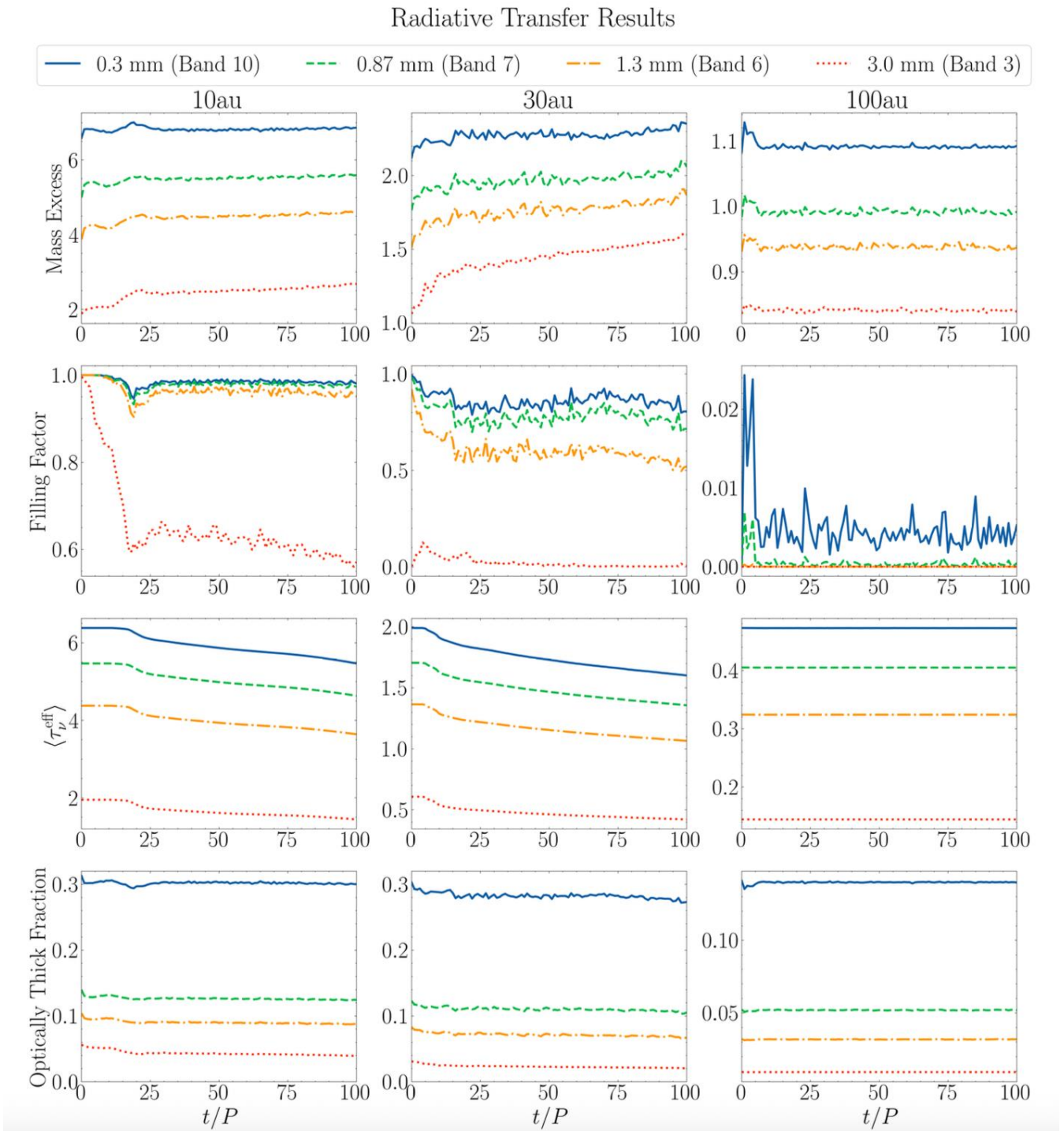

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    - 10 M_J blob spread over ~ 1 Hill radius at measured temperature also implies Q~1.

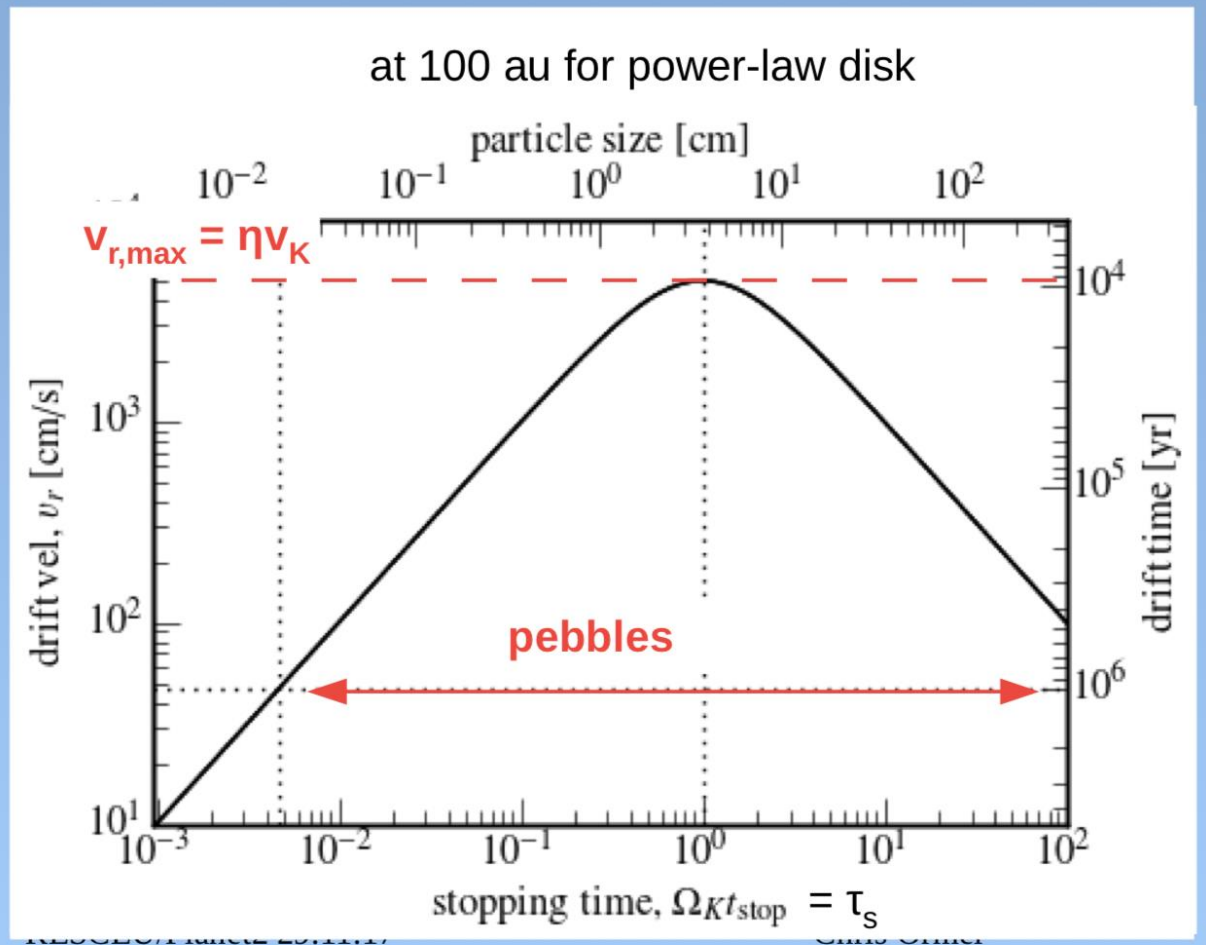
- **Missing Mass Problem (Disks vs Exoplanets)**
  - Factor 2-7 in mass taking into account scattering and unresolved (sub-beam scale) turbulence

Pebble definition

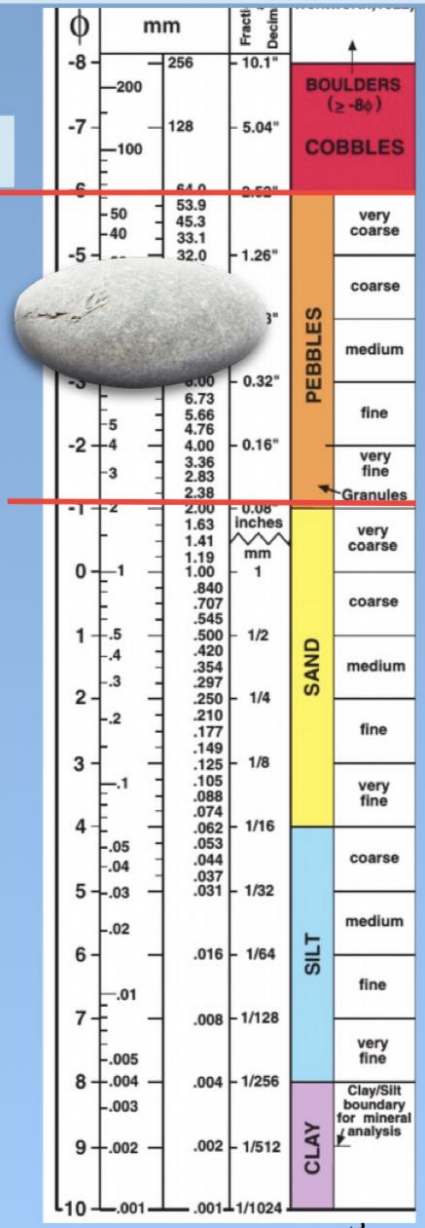
Geologist: *particles 2 mm < d < 6.4 cm*

Astrophysical: *particles that drift*

at 100 au for power-law disk



6.4 cm



1 dm

1 cm

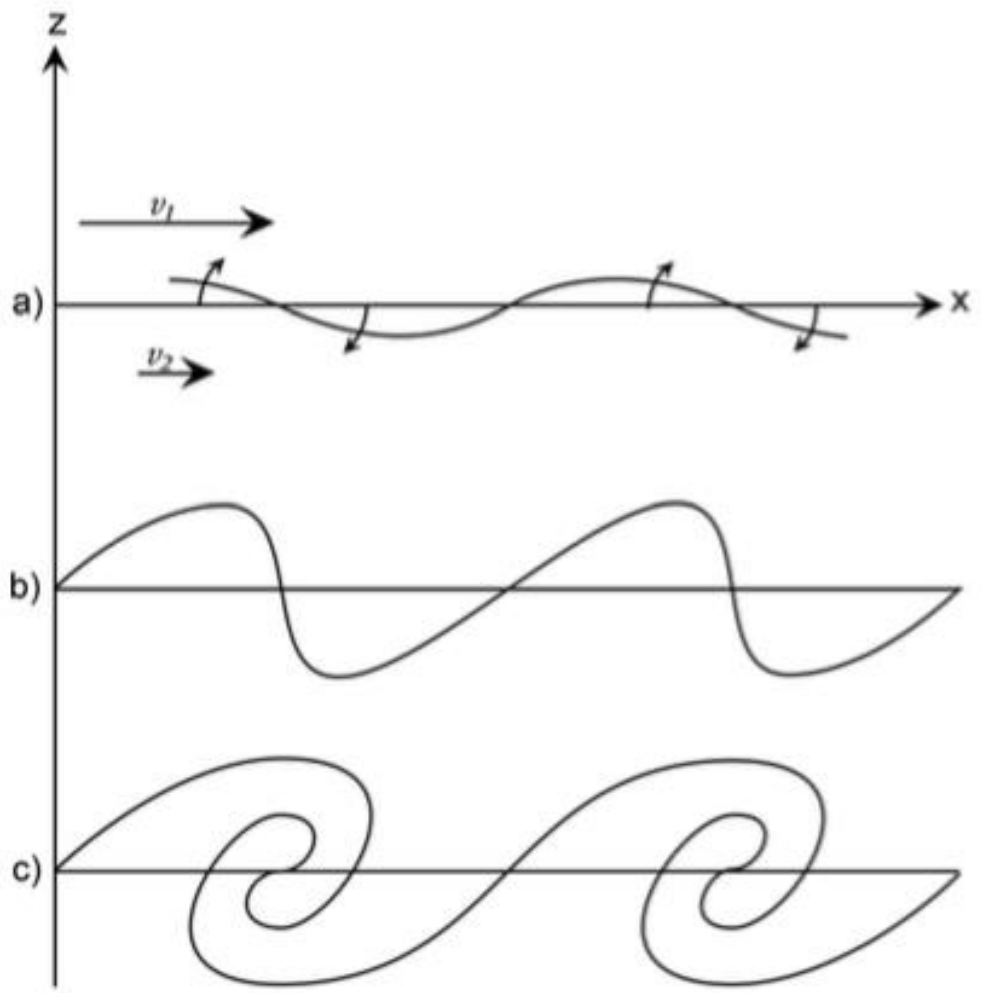
1 mm

100 μm

10 μm

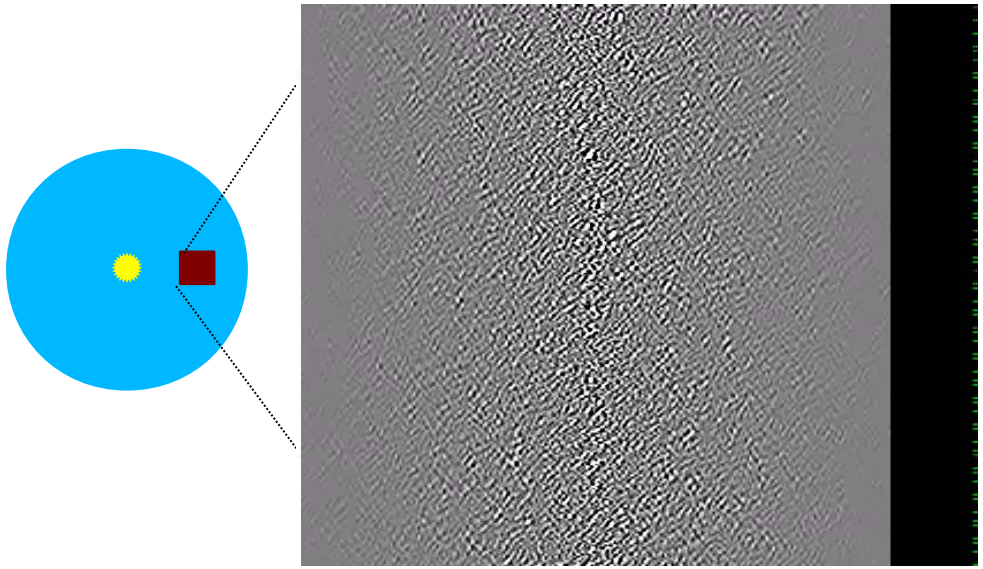
1 μm

Kelvin-Helmholtz Instability



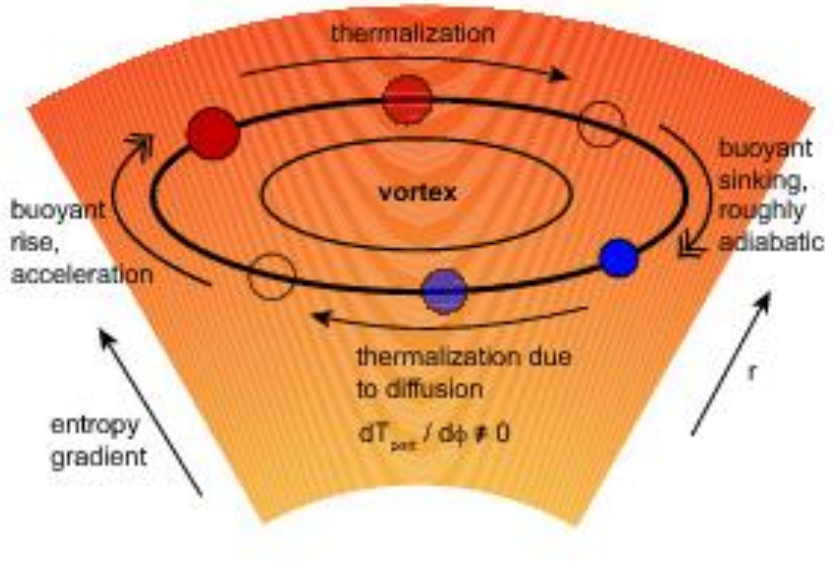
Lovelace & Hohlfeld 1978, Toomre 1981, Papaloizou & Pringle (1984), Hawley (1987), Lovelace et al (1999), Li et al. (2000), Varniere & Tagger (2005), Cheng & Youdin (2023).

Convection



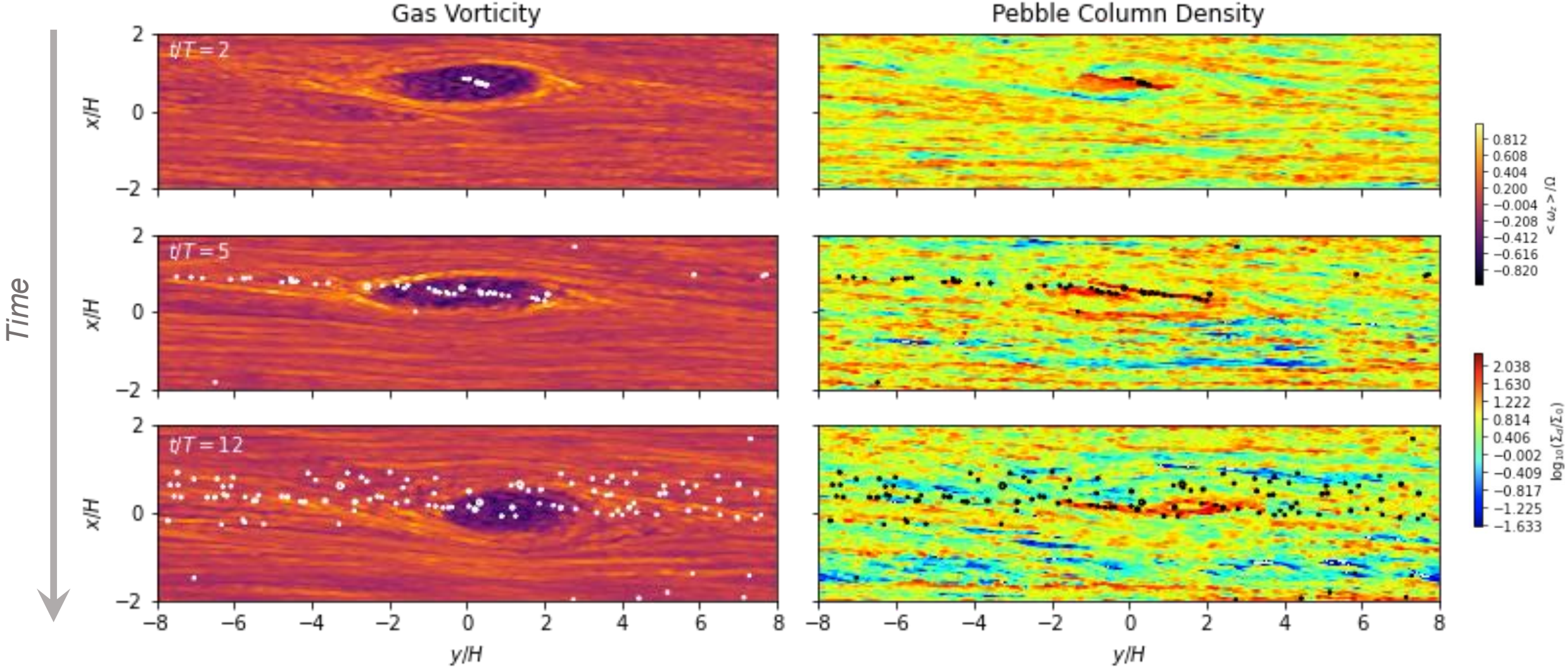
Lyra & Klahr (2011)
Klahr & Hubbard (2014)
Lyra (2014)
Latter (2016)
Volponi (2016)
Reed & Latter (2021)
Raettig et al. (2021)

Sketch of the
Convective Instability



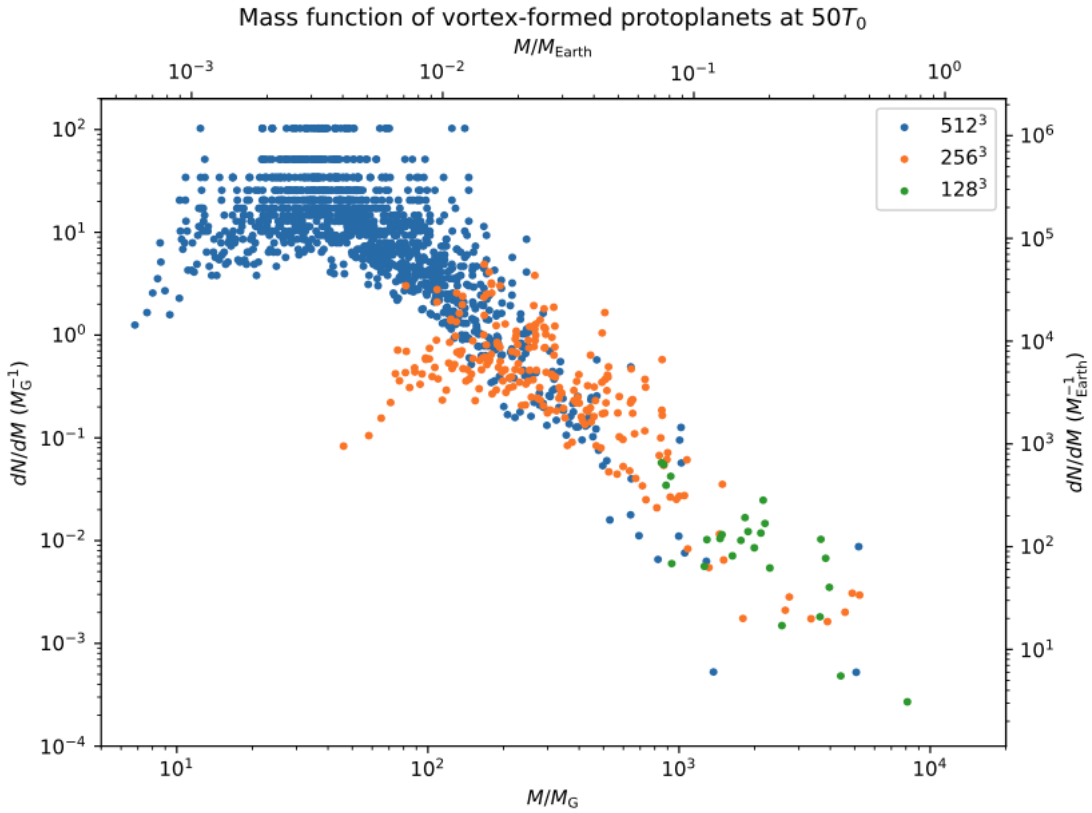
Armitage (2010)

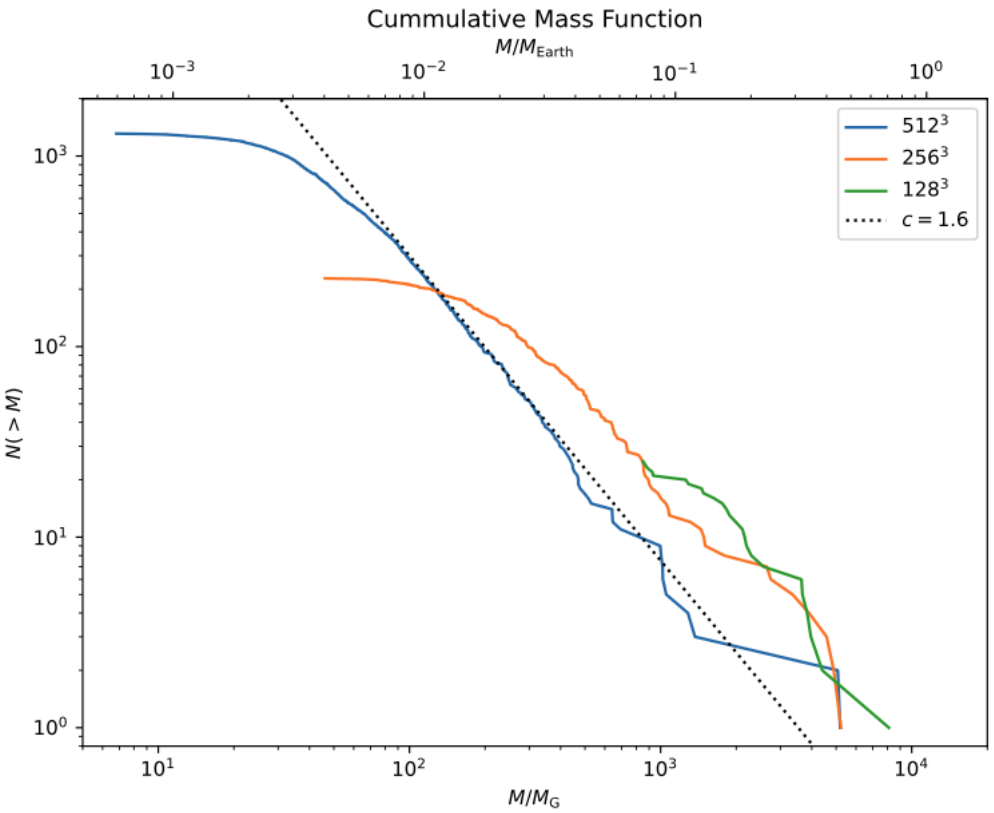
Vortex Trapping



Lyra et al. (2024)

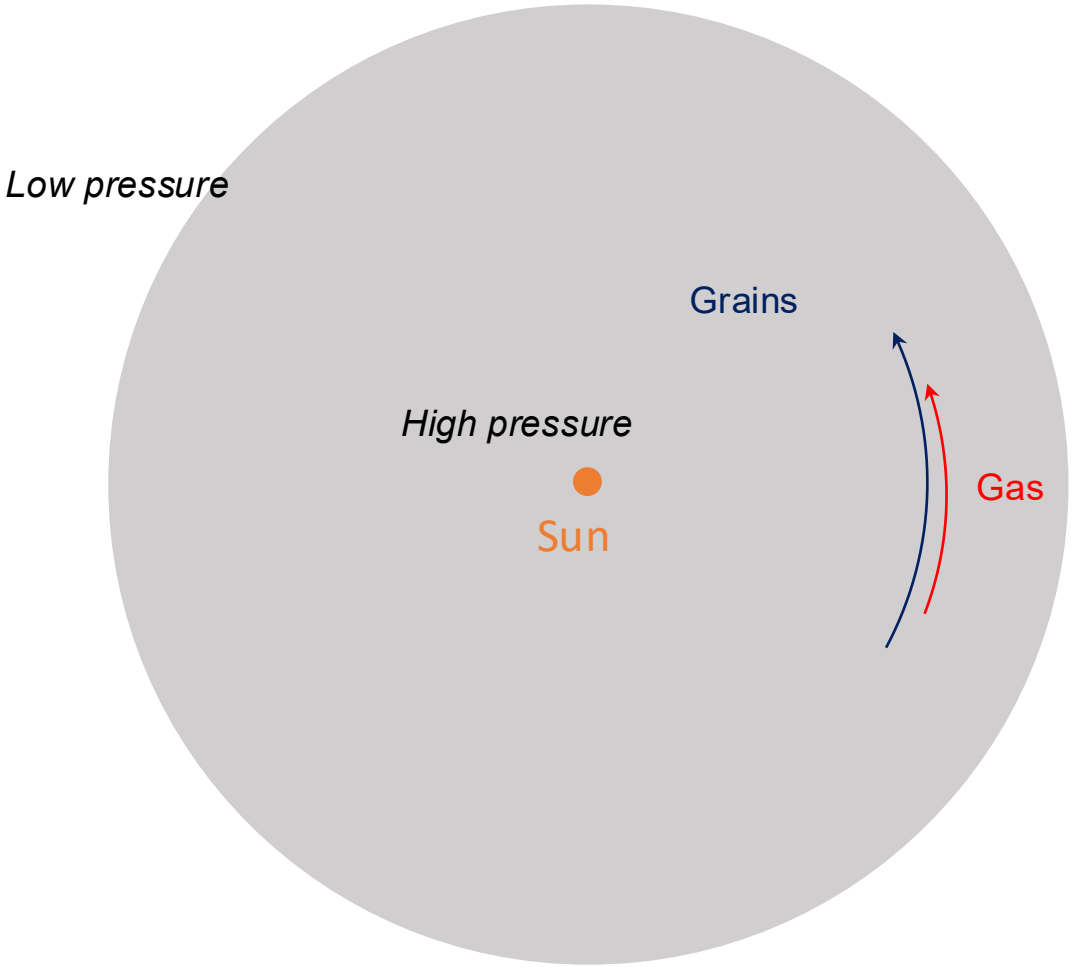
Vortex Trapping – Initial Mass Function





Lyra et al. (2024)

Headwind and Grain Drift



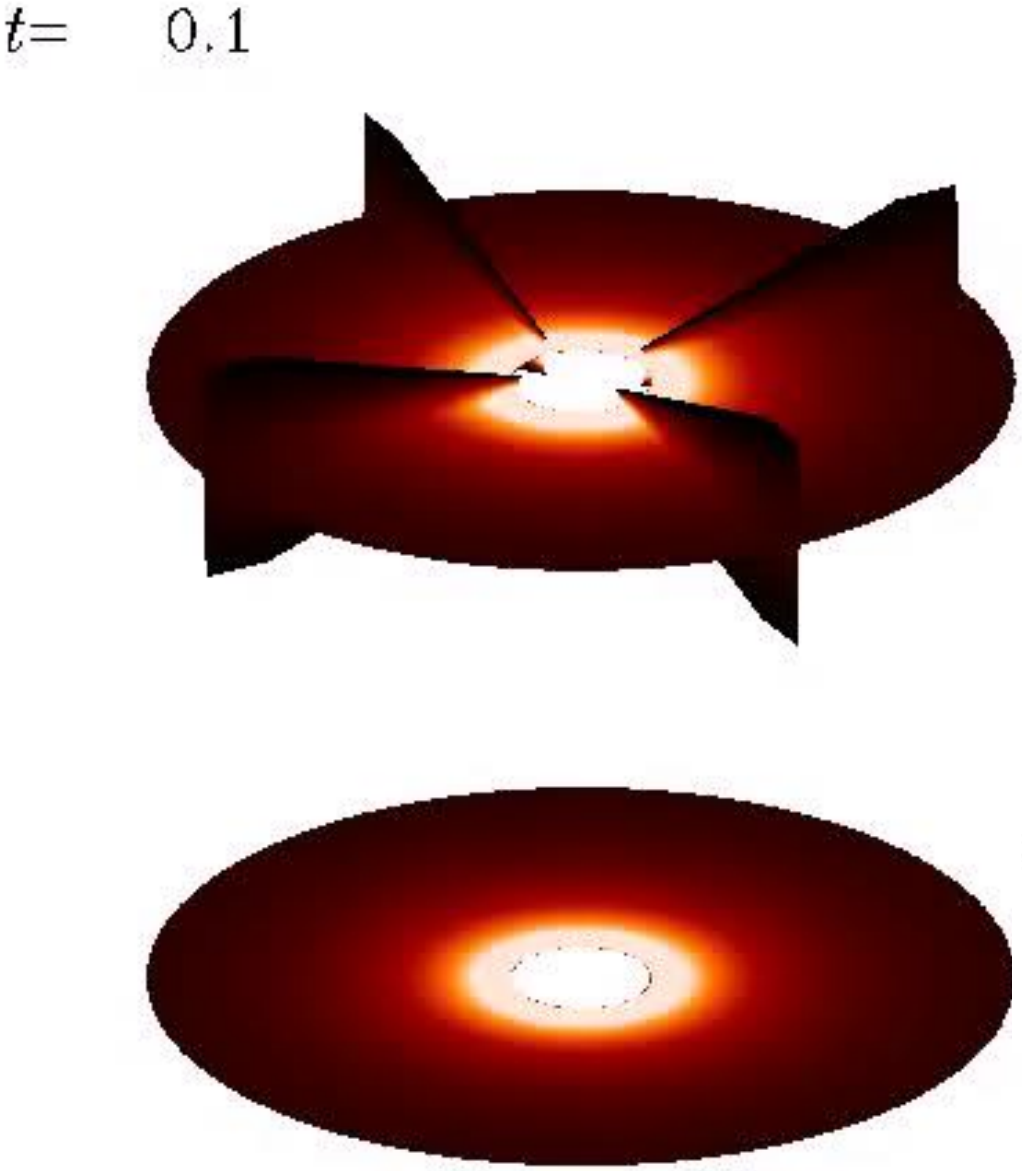
The gas has some pressure support (sub-Keplerian).

The grains do not feel gas pressure (Keplerian).

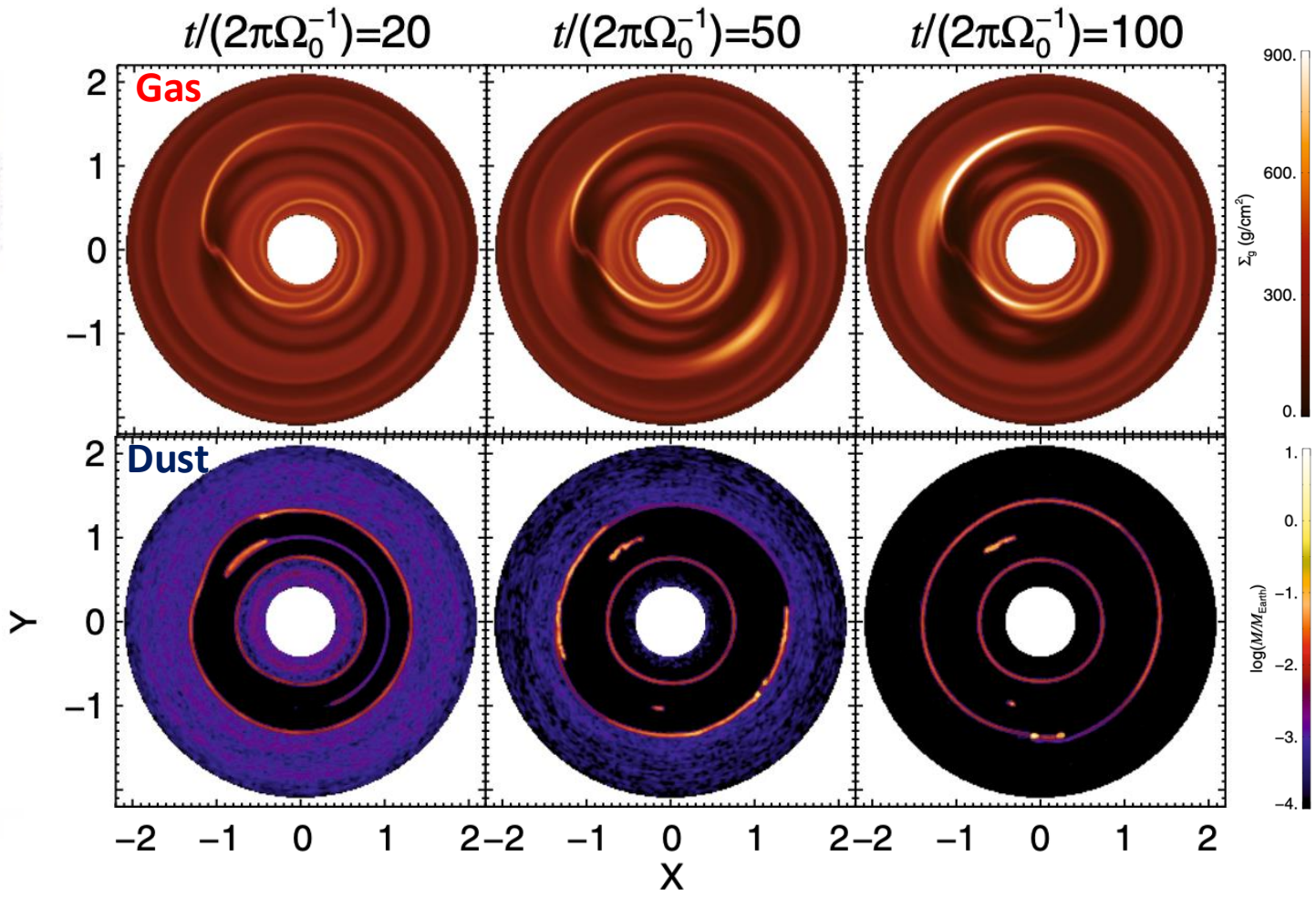
PDS 70 and PDS 70b

Keppler et al. (2018); Isella et al. (2019); Benisty et al. (2021) Balsalobre-Ruza et al. (2023)

Planetary traps

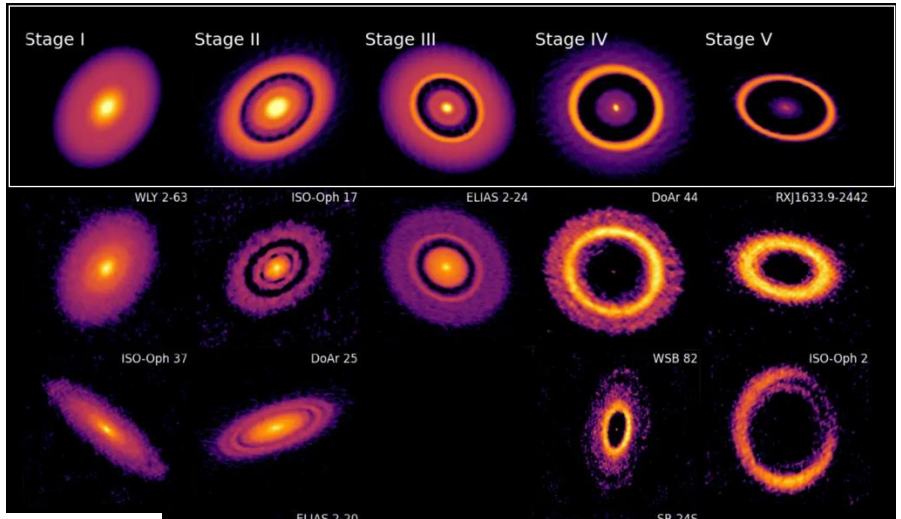


Time



Lyra et al (2009b)

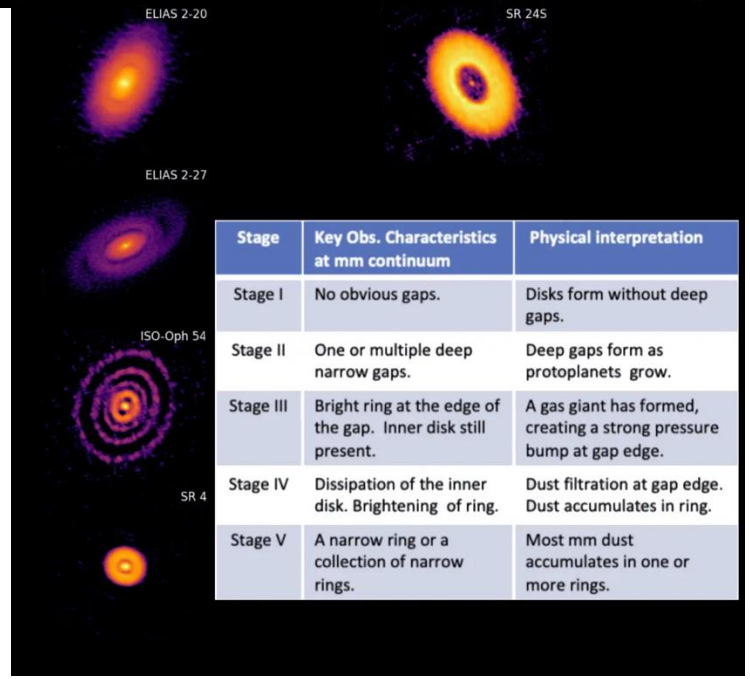
Time series of planet formation?



Press Releases

ALMA Inspires New Models for the Evolution of Planet-Forming Disks

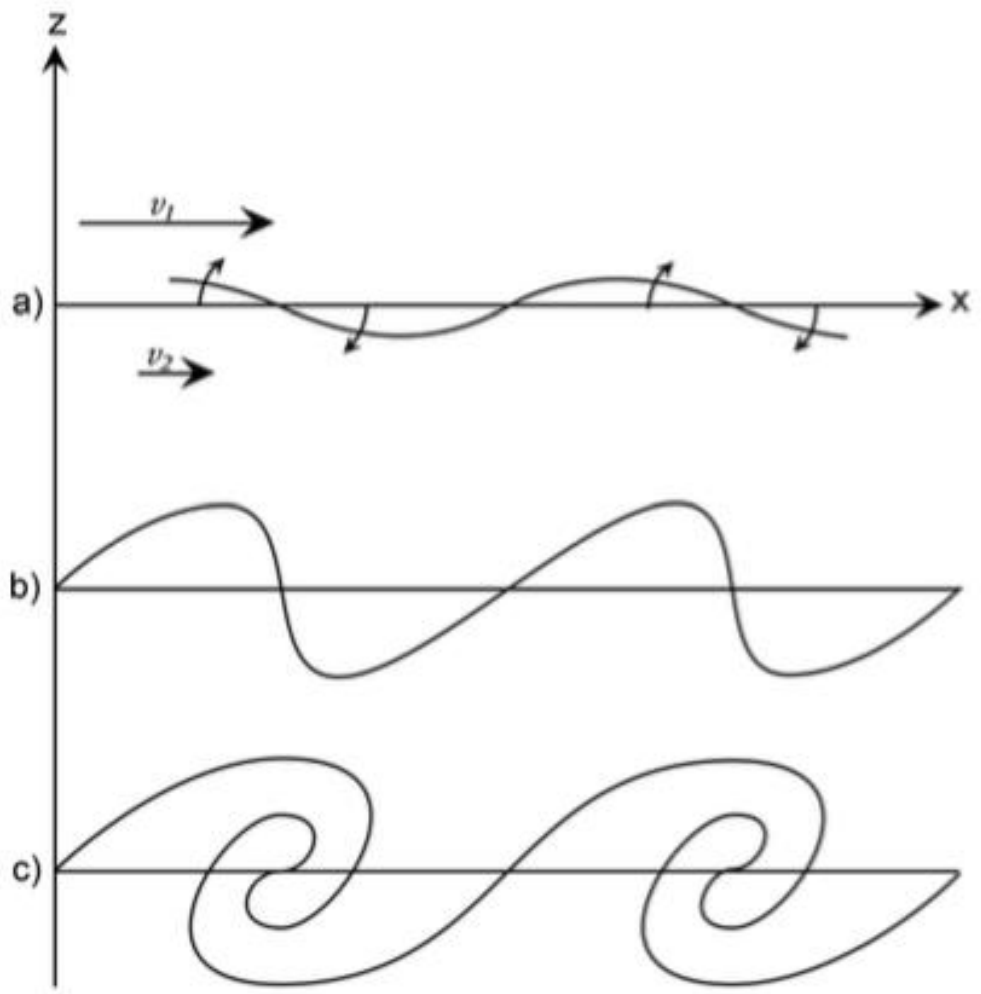
6 May, 2025 / Read time: **7 minutes**



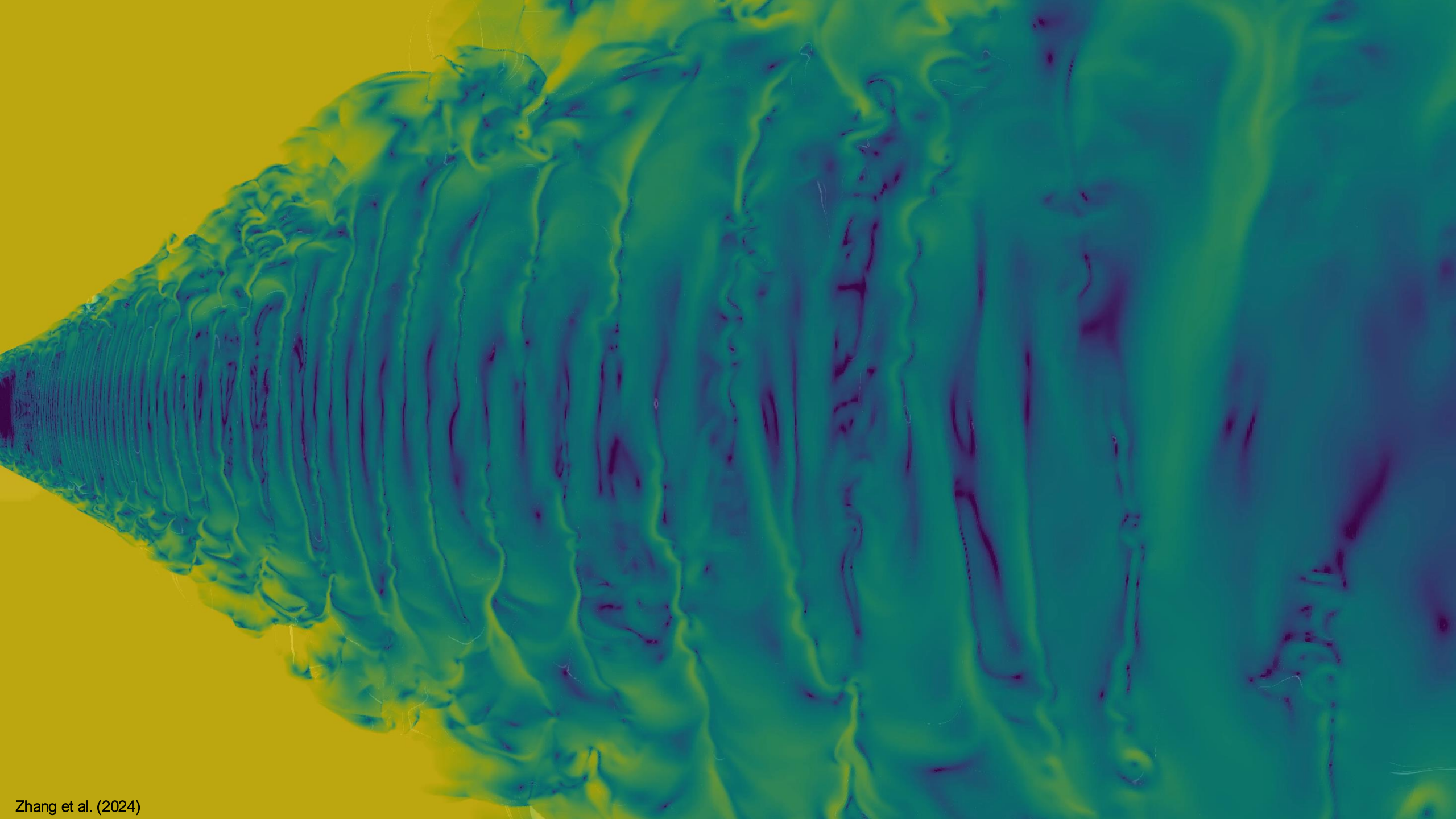
Stage	Key Obs. Characteristics at mm continuum	Physical interpretation
Stage I	No obvious gaps.	Disks form without deep gaps.
Stage II	One or multiple deep narrow gaps.	Deep gaps form as protoplanets grow.
Stage III	Bright ring at the edge of the gap. Inner disk still present.	A gas giant has formed, creating a strong pressure bump at gap edge.
Stage IV	Dissipation of the inner disk. Brightening of ring.	Dust filtration at gap edge. Dust accumulates in ring.
Stage V	A narrow ring or a collection of narrow rings.	Most mm dust accumulates in one or more rings.

Orcajo et al. (2025)

Kelvin-Helmholtz Instability



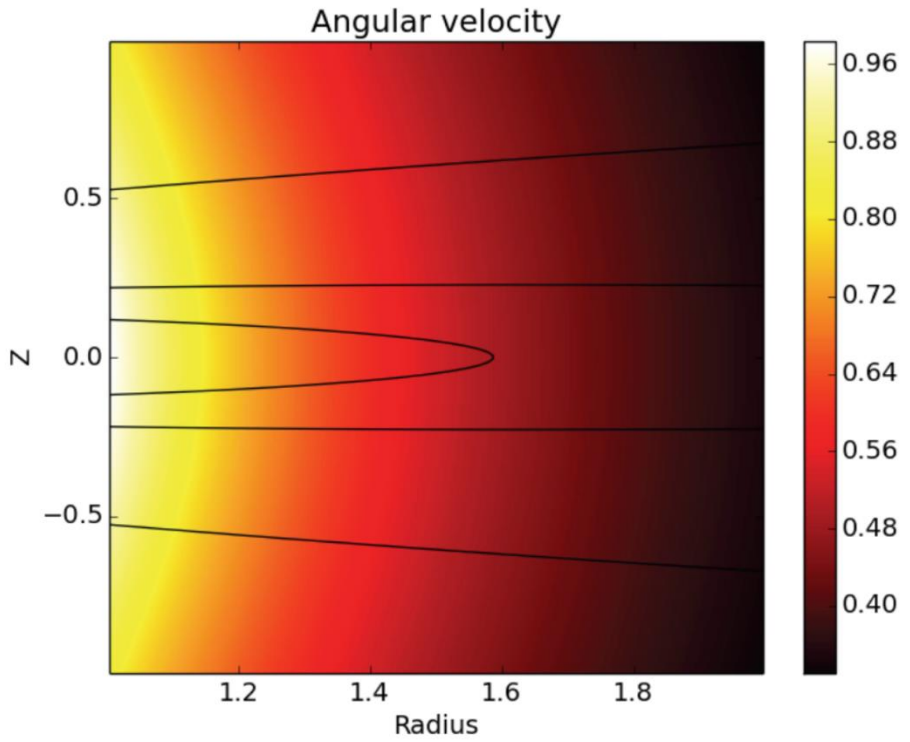
Lovelace & Hohlfeld 1978, Toomre 1981, Papaloizou & Pringle (1984), Hawley (1987), Lovelace et al (1999), Li et al. (2000), Varniere & Tagger (2005), Cheng & Youdin (2023).

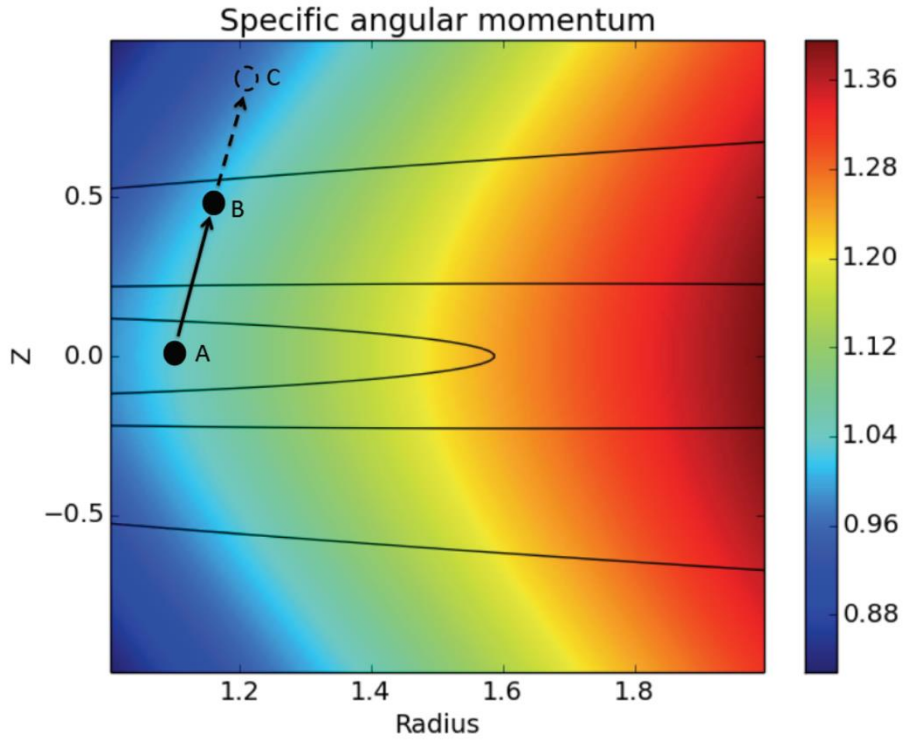


Zhang et al. (2024)

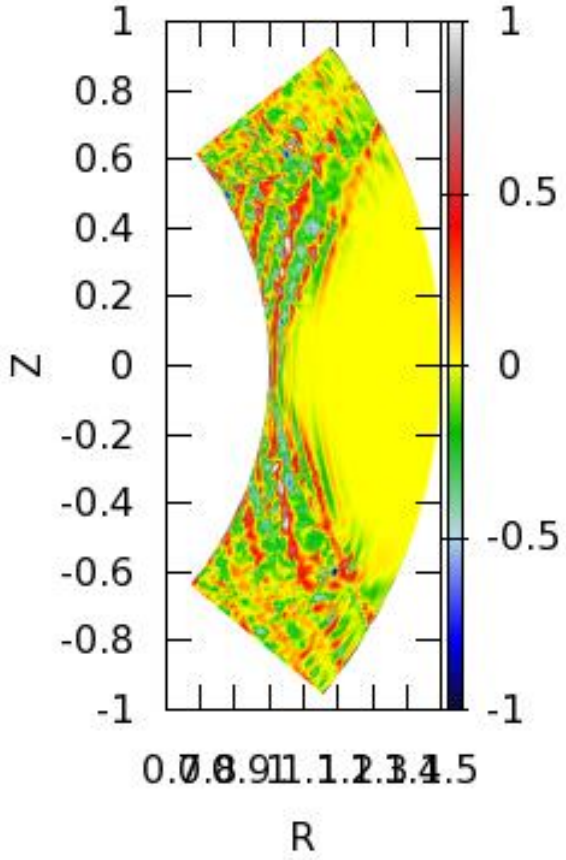
Vertical shear instability

Angular velocity not constant in cylinders: unstable





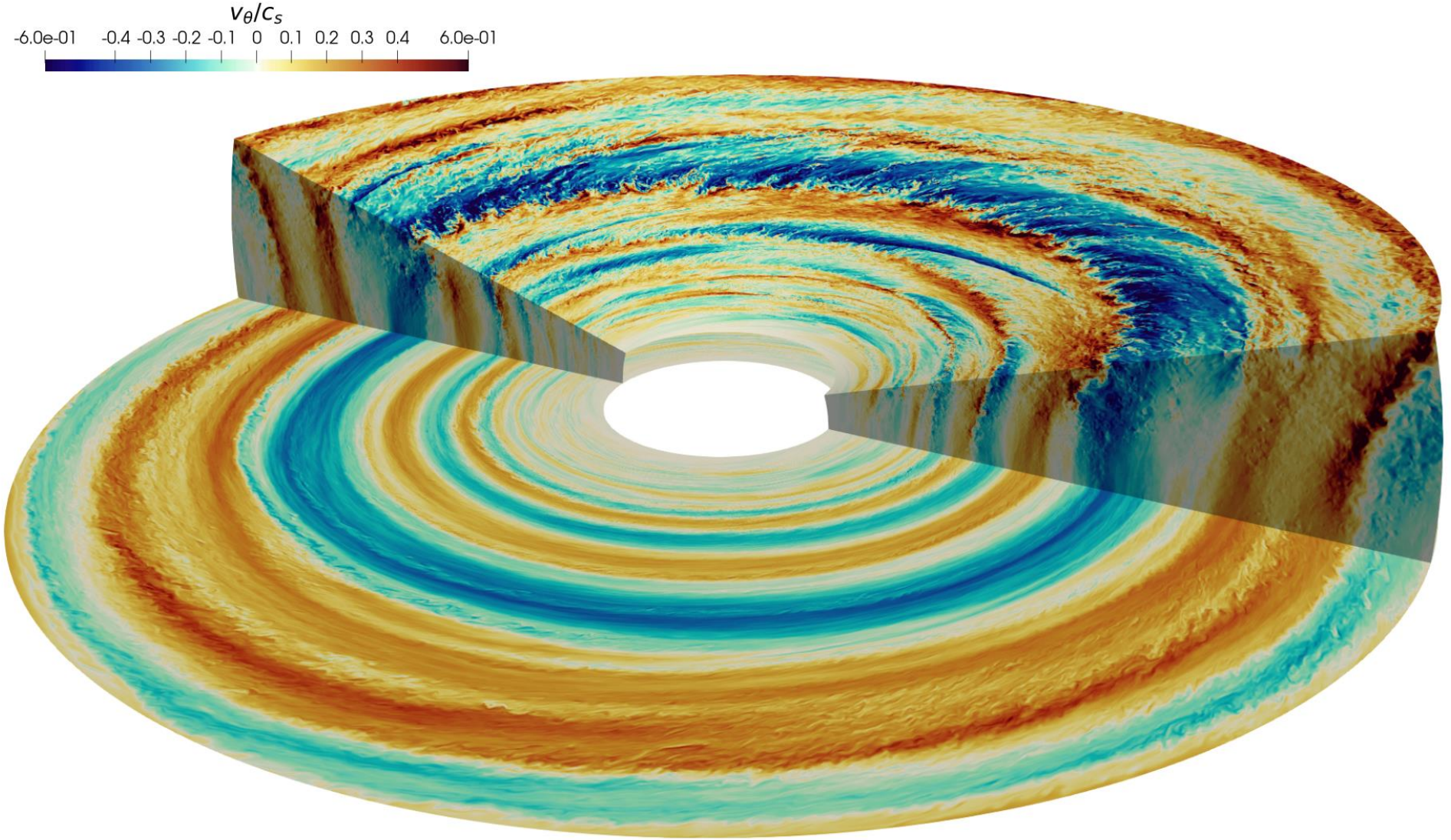
Fromang & Lesur (2017)



Nelson et al. (2013)

Urpin & Brandenburg (1998), Urpin (2003), Nelson et al. (2013),
Barker & Latter (2015), Fromang & Lesur (2017), Flock et al. (2020), Zhang et al. (2024)

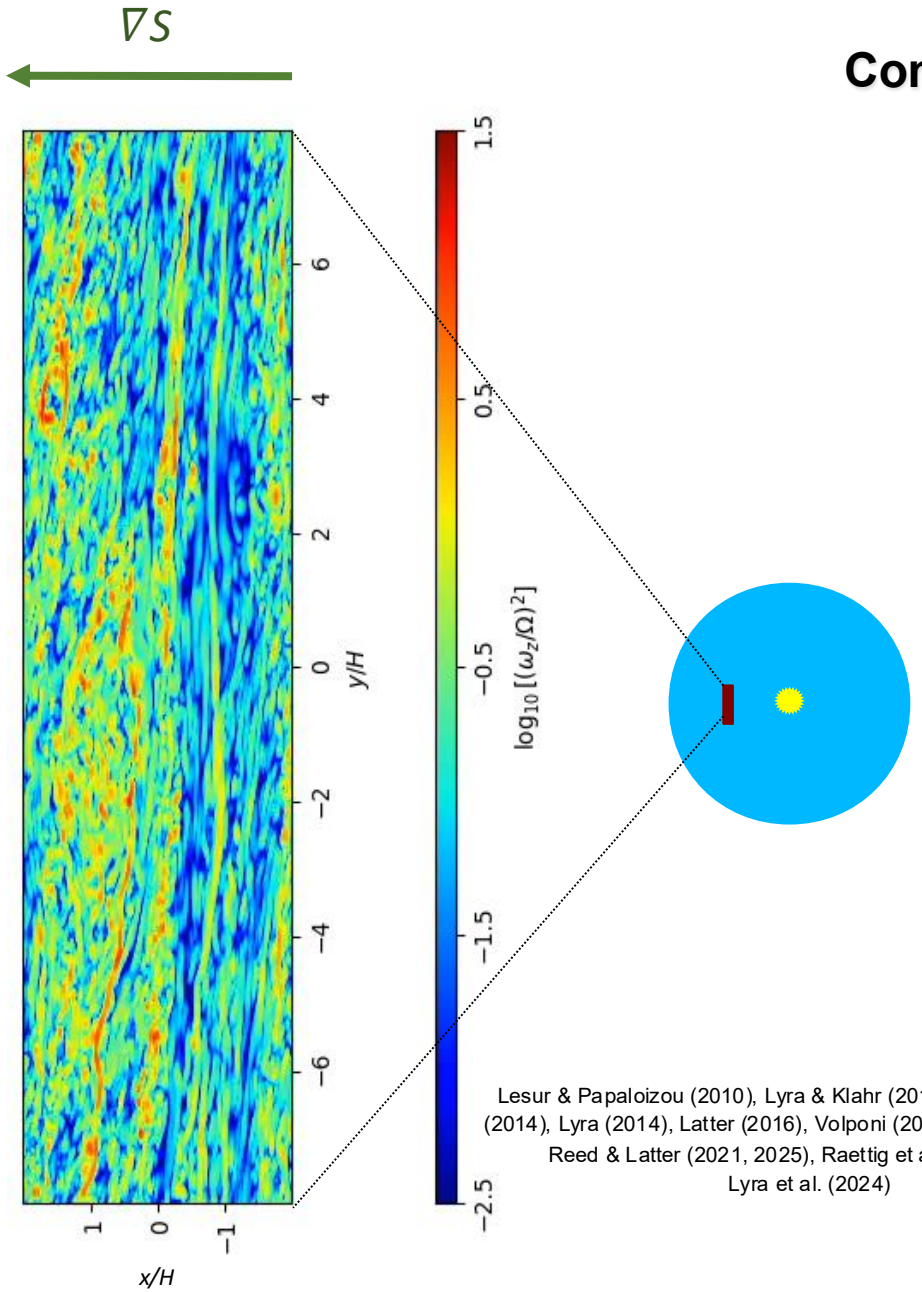
Vertical shear instability



Resolution 3872 x 2000 x 12544
Run on 4096 GPUs

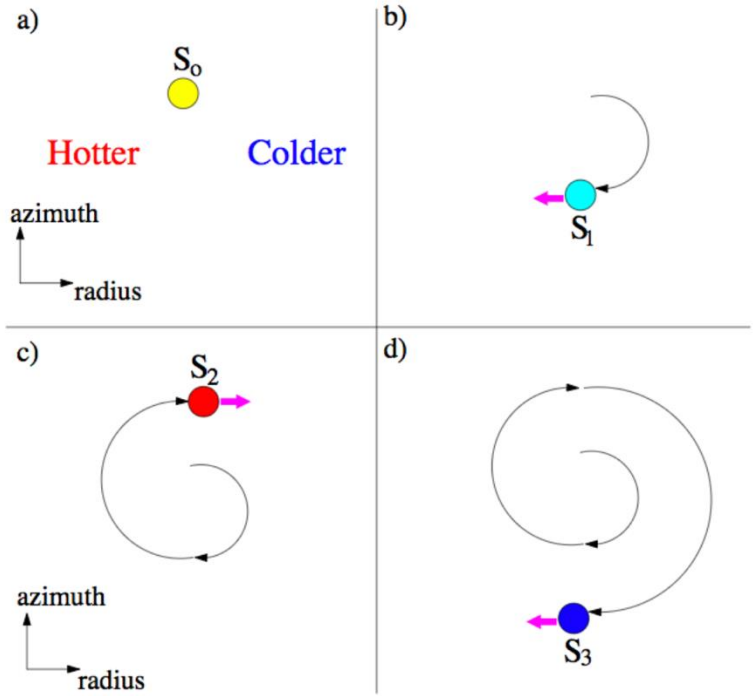
Lesur et al (2025)

Convective Overstability



Lesur & Papaloizou (2010), Lyra & Klahr (2011), Klahr & Hubbard (2014), Lyra (2014), Latter (2016), Volponi (2016), Lyra et al. (2018), Reed & Latter (2021, 2025), Raettig et al. (2015, 2021) Lyra et al. (2024)

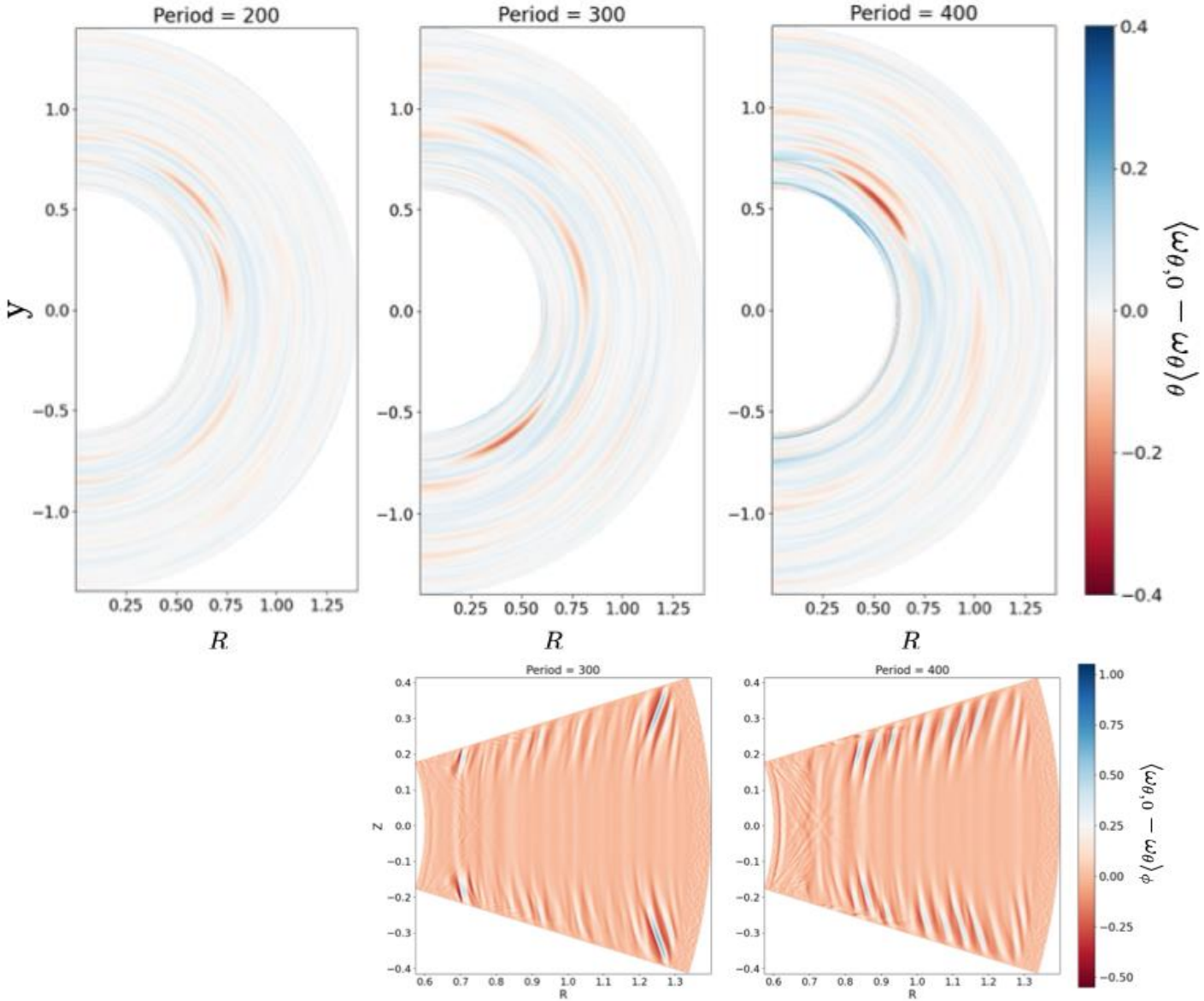
Sketch of the
Convective Overstability



Latter (2016)

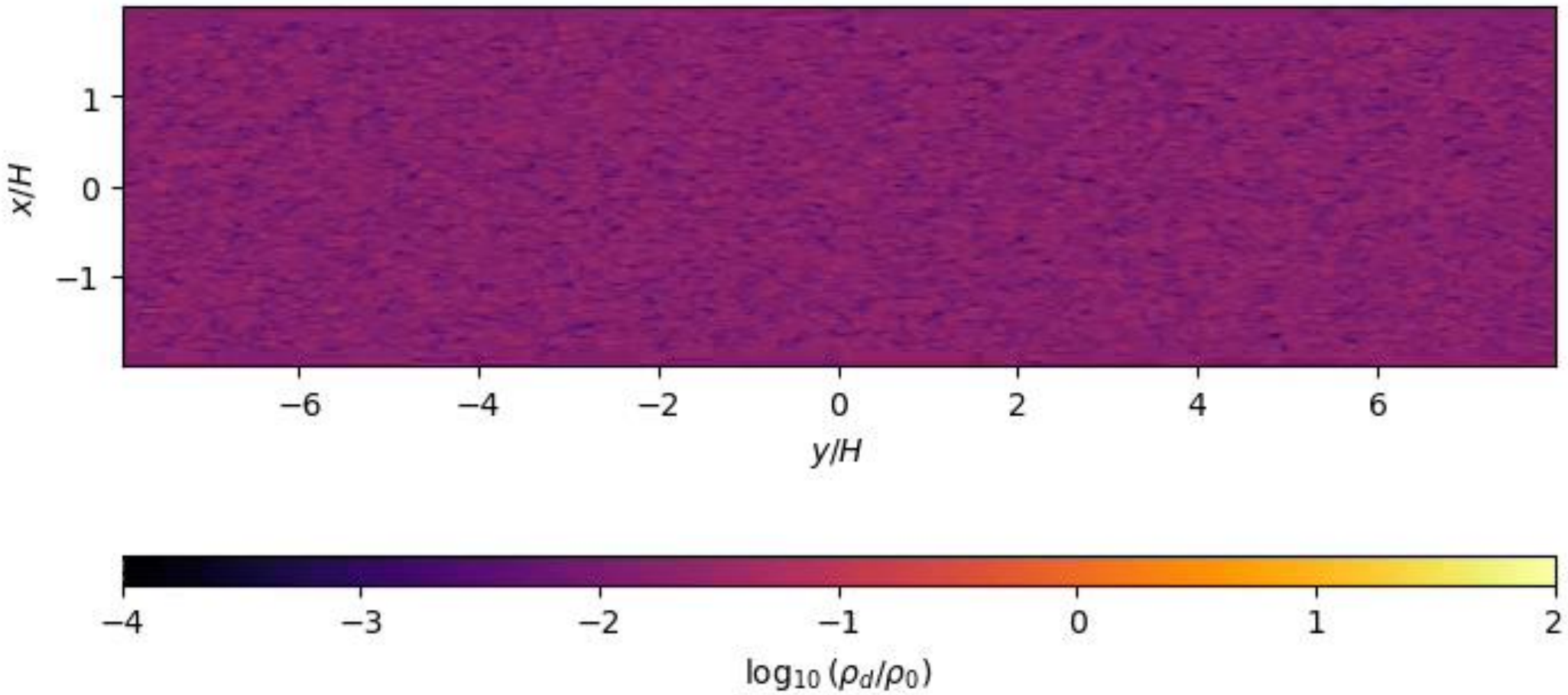
Convective Overstability

Global 3D Model
with vertical stratification



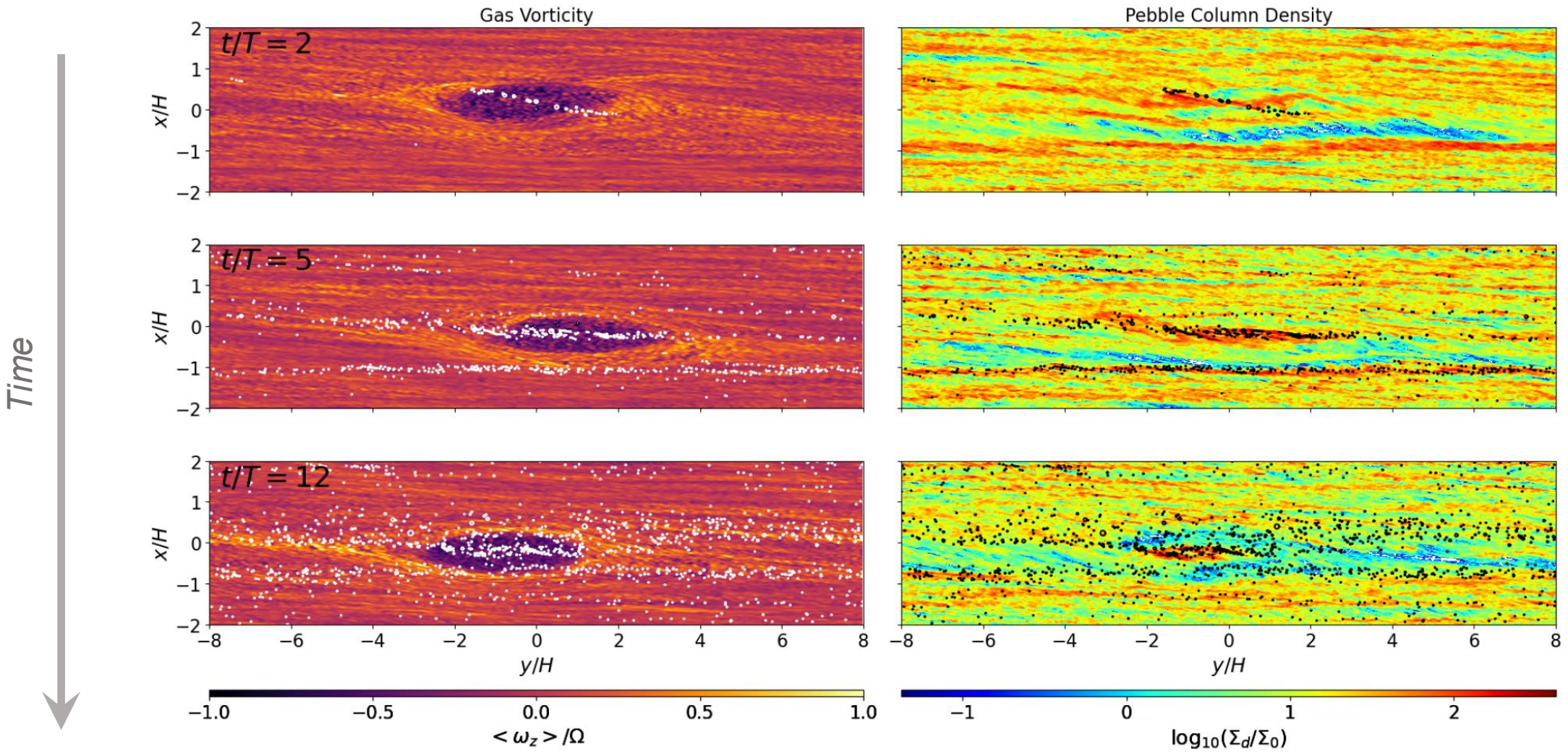
Sengupta & Lyra (in prep)

Gravitational Collapse



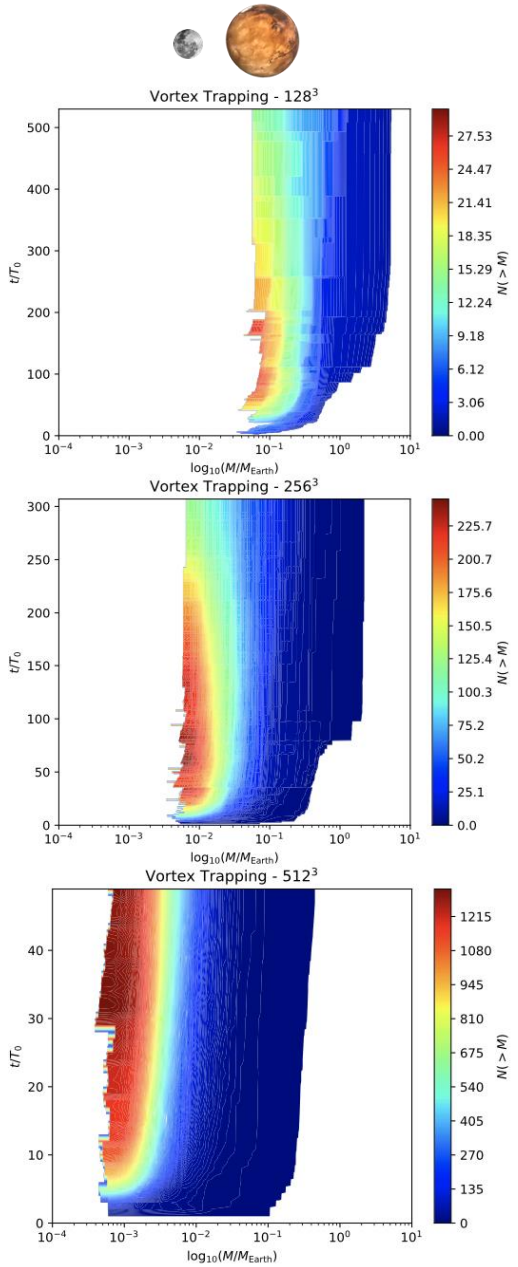
Lyra et al. (2024)

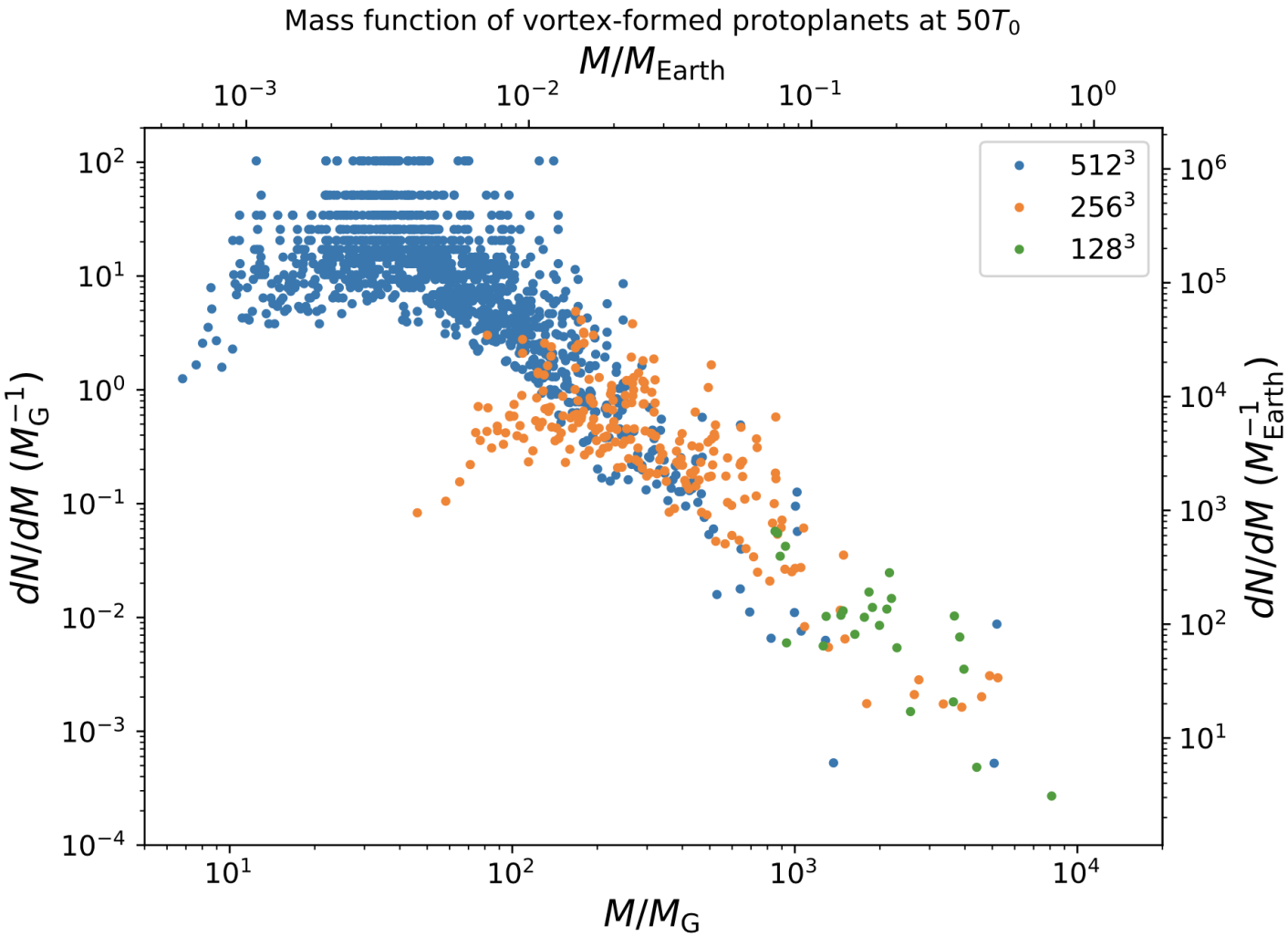
Gravitational Collapse



Lyra et al. (2024)

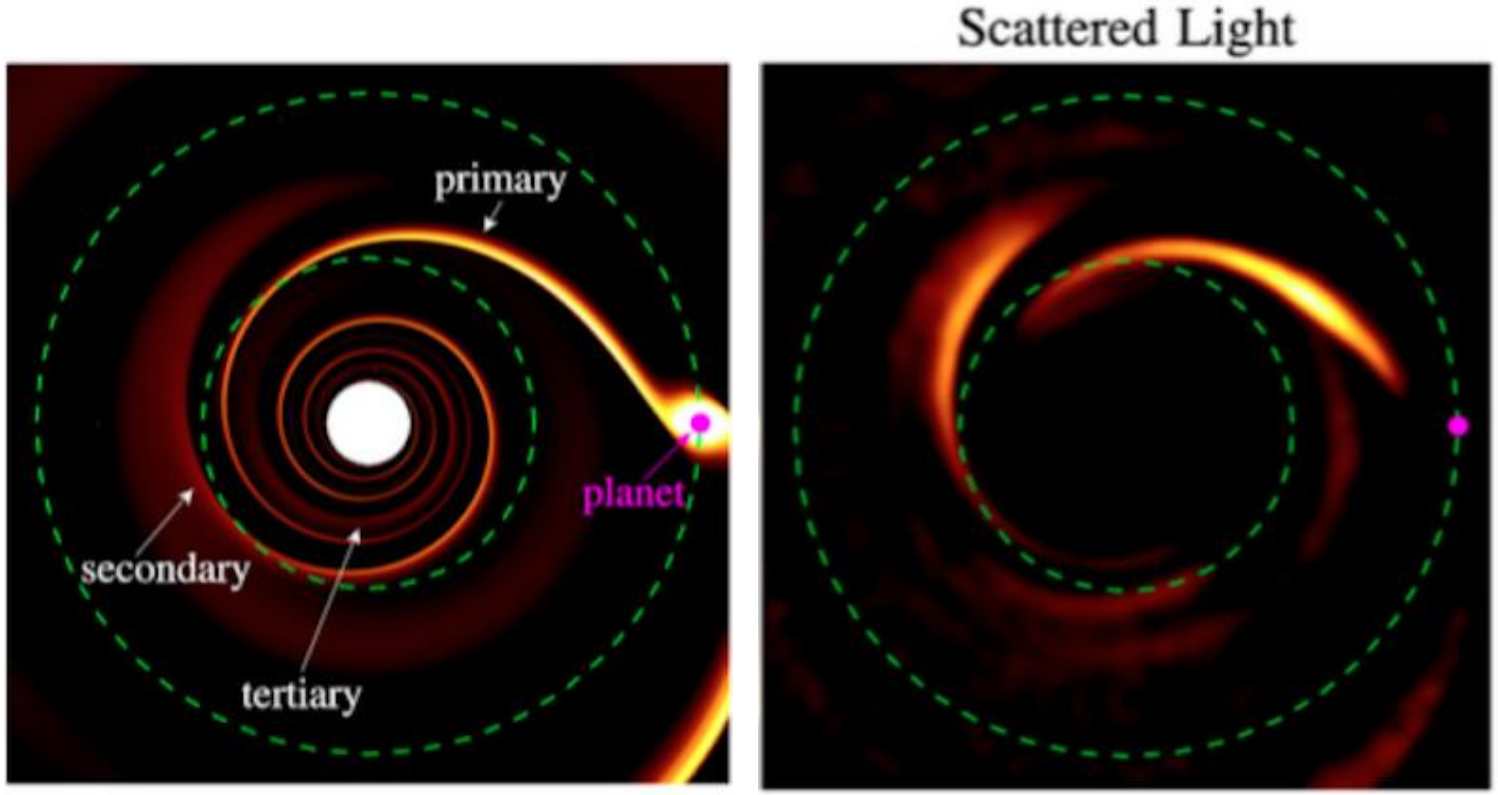
Convergence (or lack thereof)





Lyra et al. (2024)

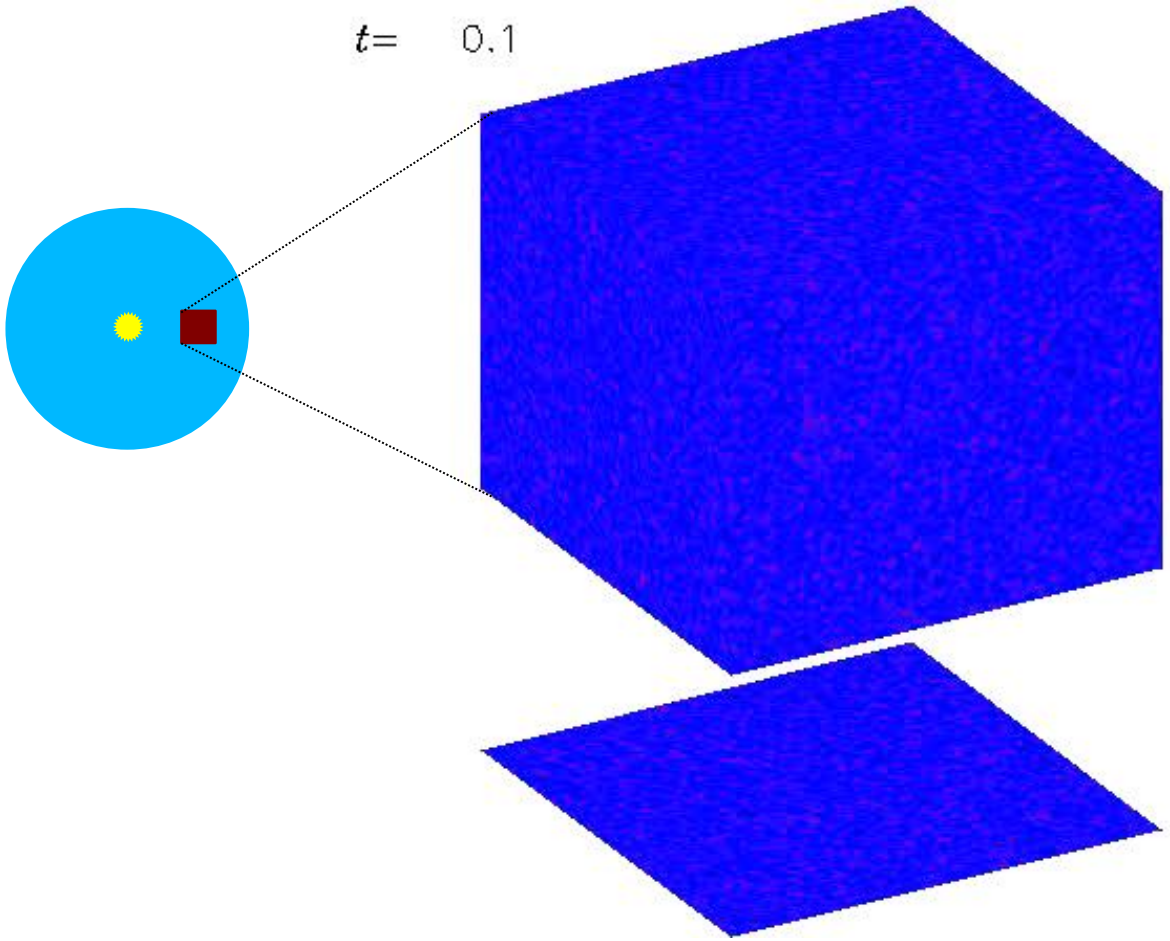
Primary and Secondary spiral arms

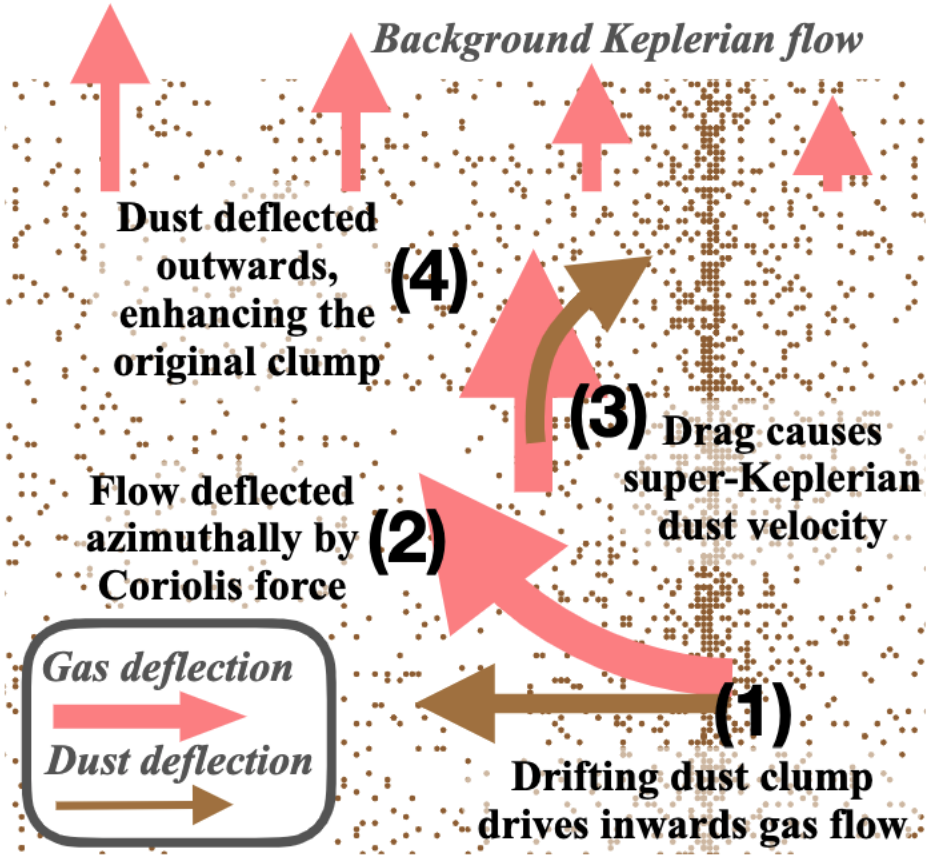


Fung & Dong (2015)

Streaming Instability

The dust drift through the gas is hydrodynamically unstable

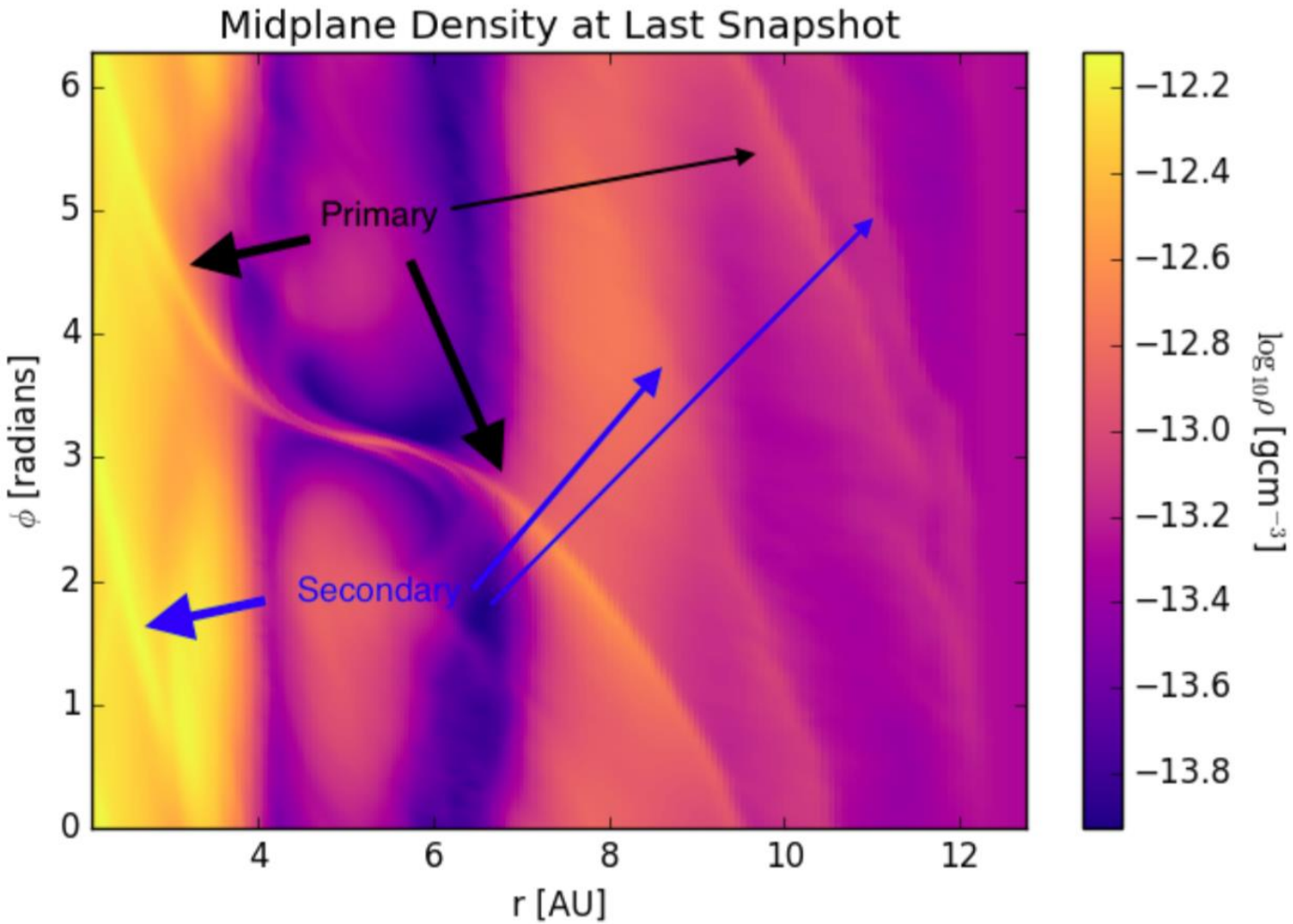




Lesur et al. (2022)

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

Primary and Secondary spiral arms



Hord & Lyra + (2017)