Lecture on Radiative Transfer

1st FARGO3D Workshop

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Overview

Today

- Aim and motivation
- What / why / how
- Why is radiative transfer hard?
- Basics
  - Radiative transfer equation
  - Assumptions
  - Ways of solving the RT equation
  - Examples

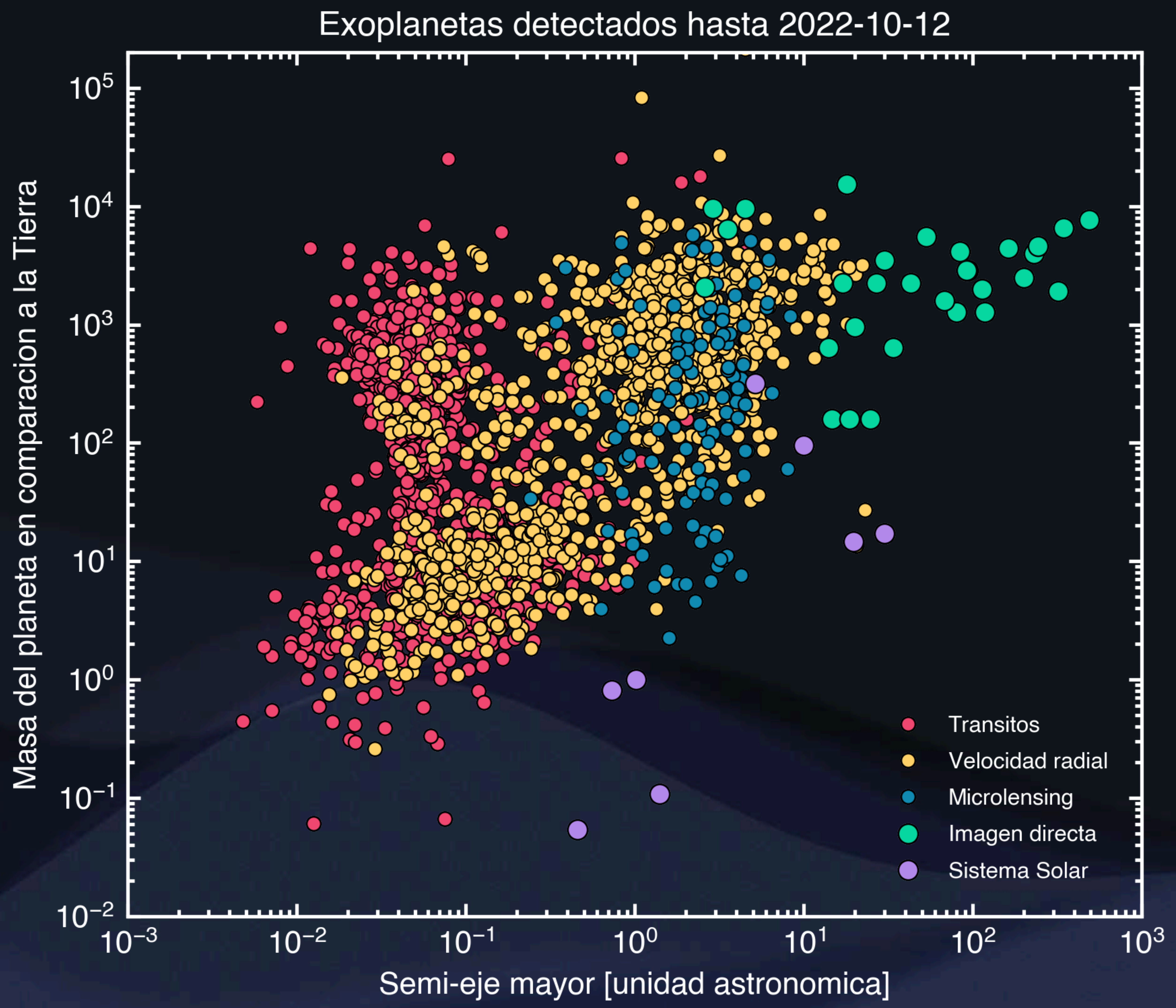
Tomorrow

- What are important things that we learn from observations that can inform our simulations?
- Dusty media (opacities, masses, etc)
  - What dominates the opacities, and hence, what we see?
- Gas kinematics (line emission)
- Scattering and polarized light

What do observations tell us

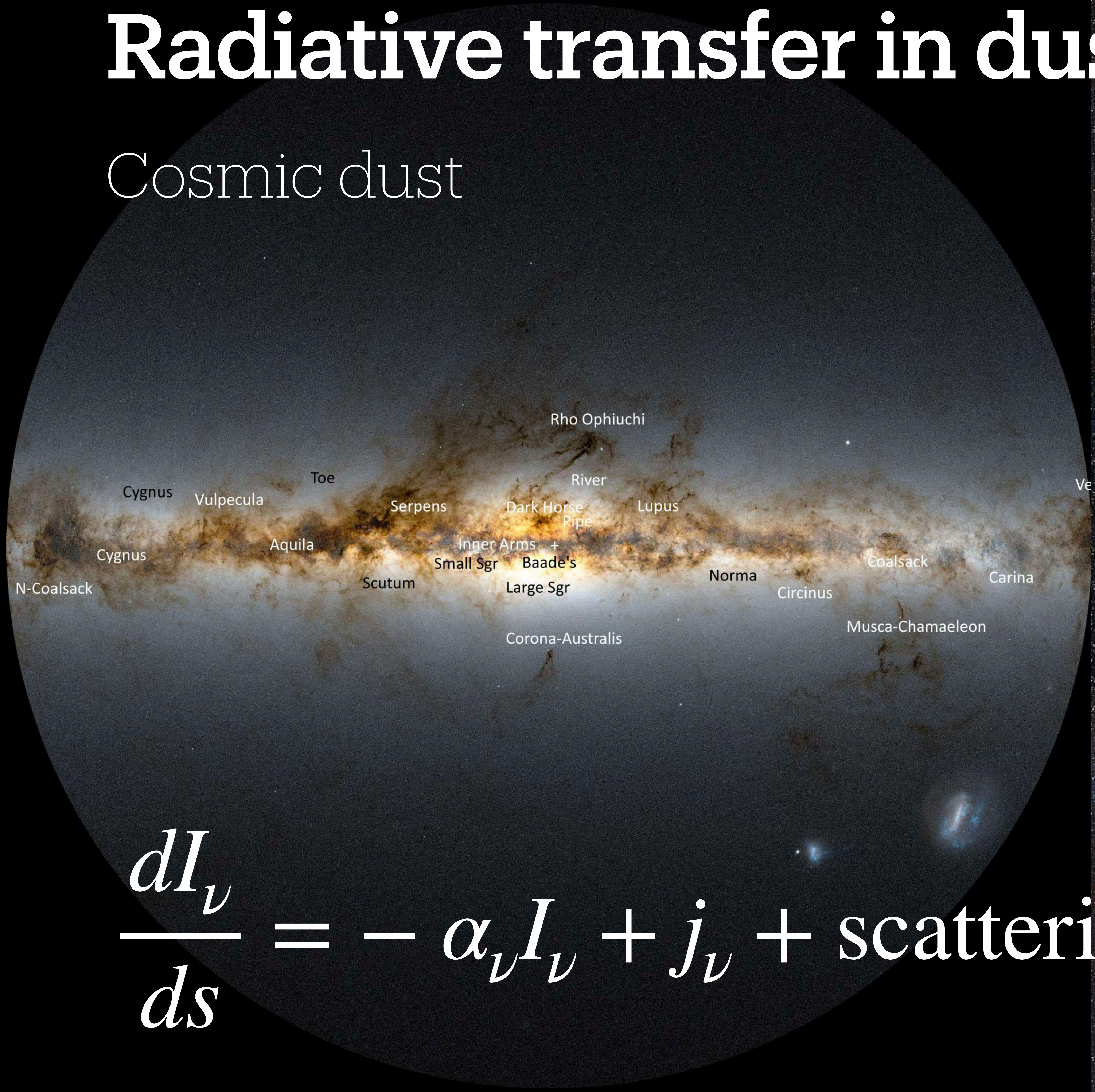
That can inform our models

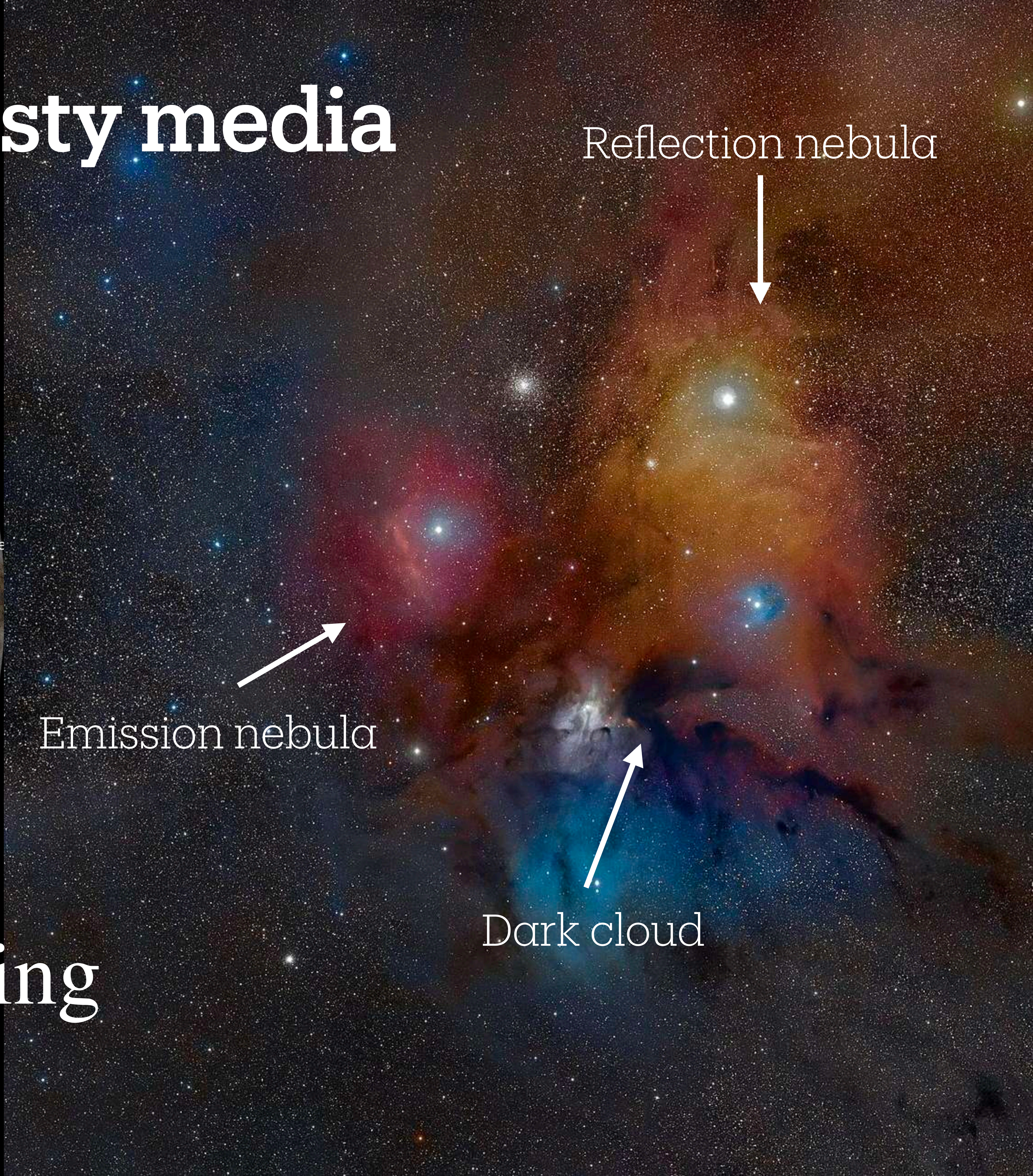
- Nature is robustly and efficiently forming planets circling a diverse array of stars and environments (Lissauer et al. 2023, Nomura et al. 2023).
- Our Solar System is unusually different from the norm.
- Exoplanetary systems often are more compact, with several planets within an AU (Earth-Sun distance)
- Sometimes exhibiting remarkably organized architectures (Weiss et al. 2023).
- Interestingly, super-earths and mini-neptunes are surprisingly common (Lissauer et al. 2023).



Radiative transfer in dusty media

Cosmic dust

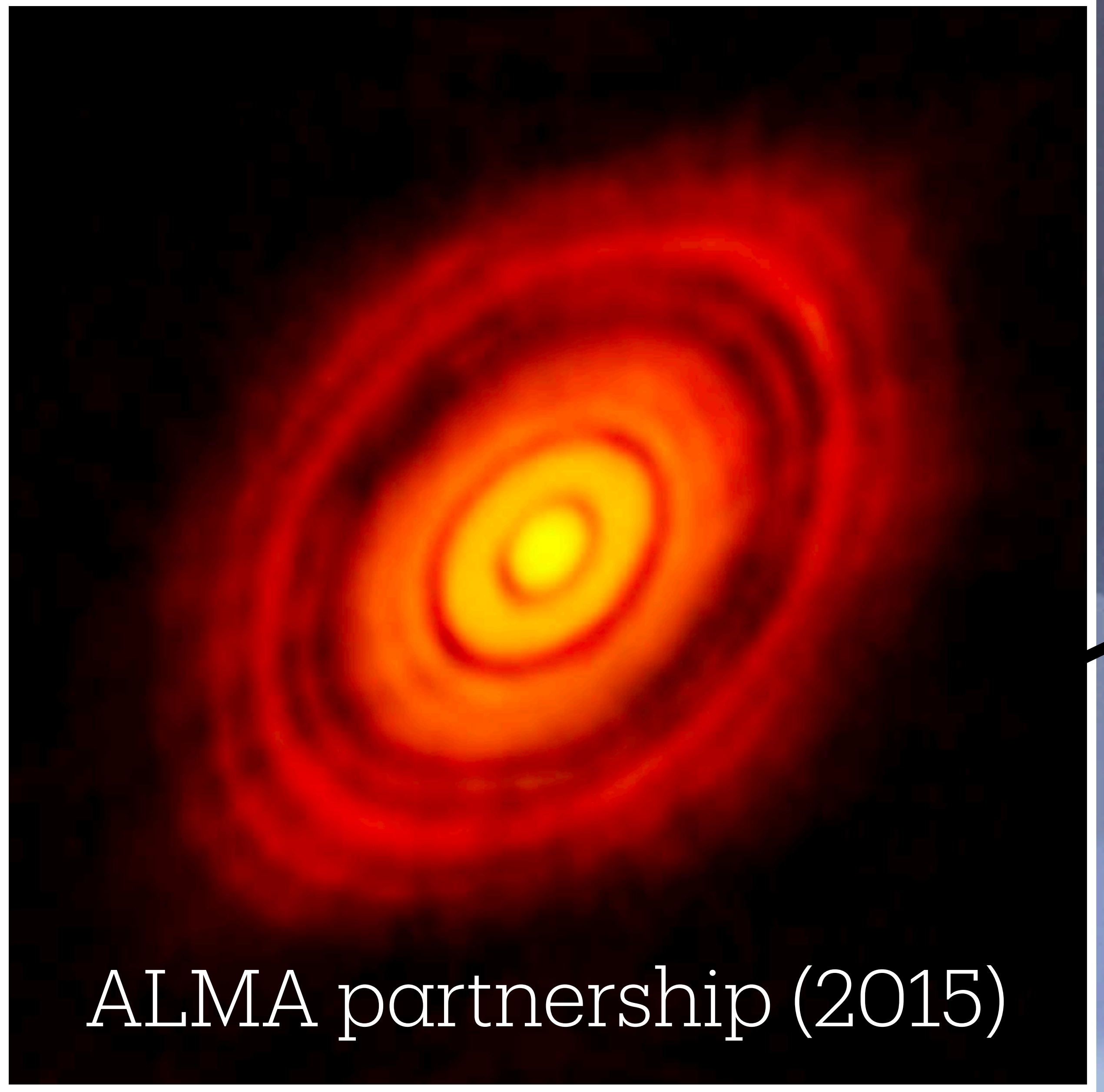




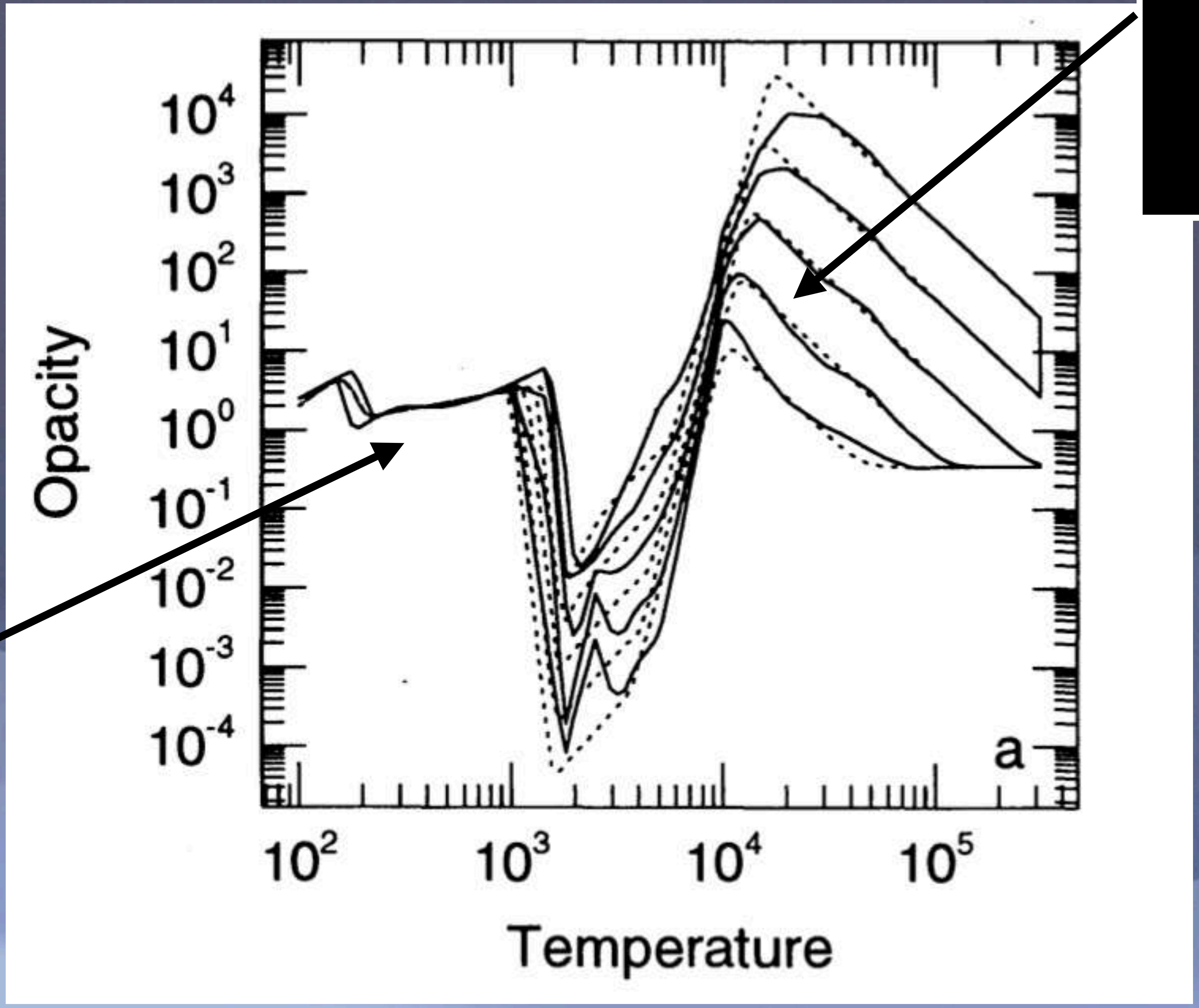
$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu + \text{scattering}$$

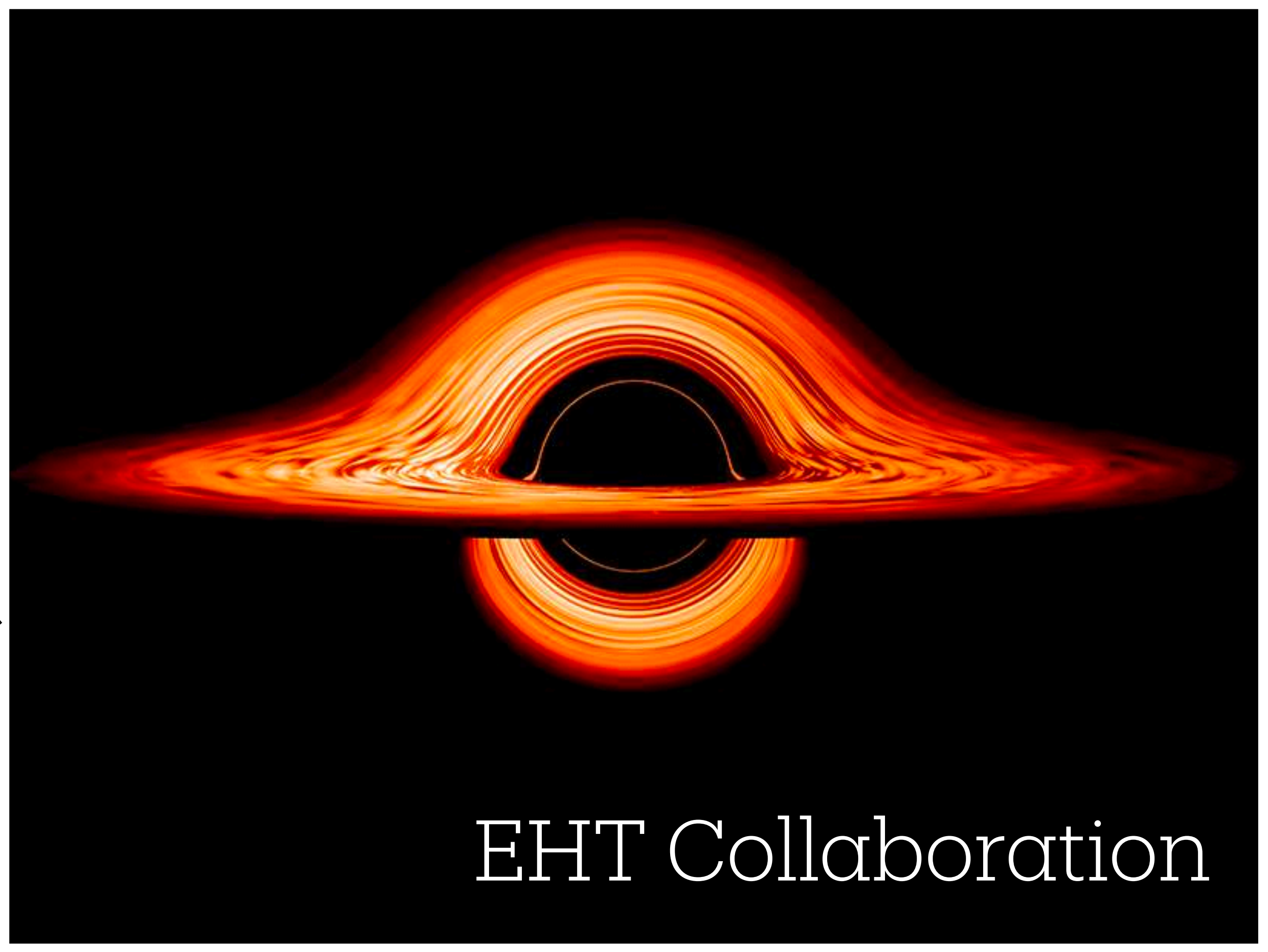
What dictates what we see?

It has to do with opacities κ_ν



Bell & Lin (1994)

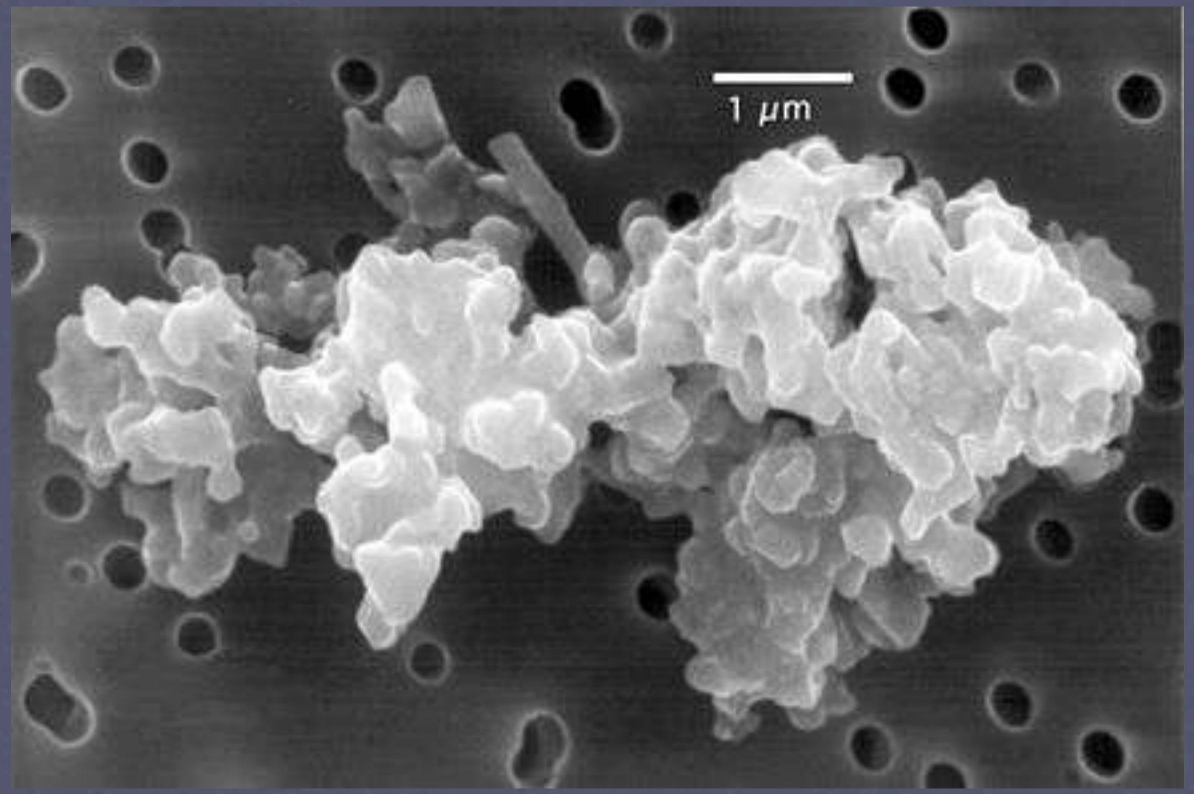




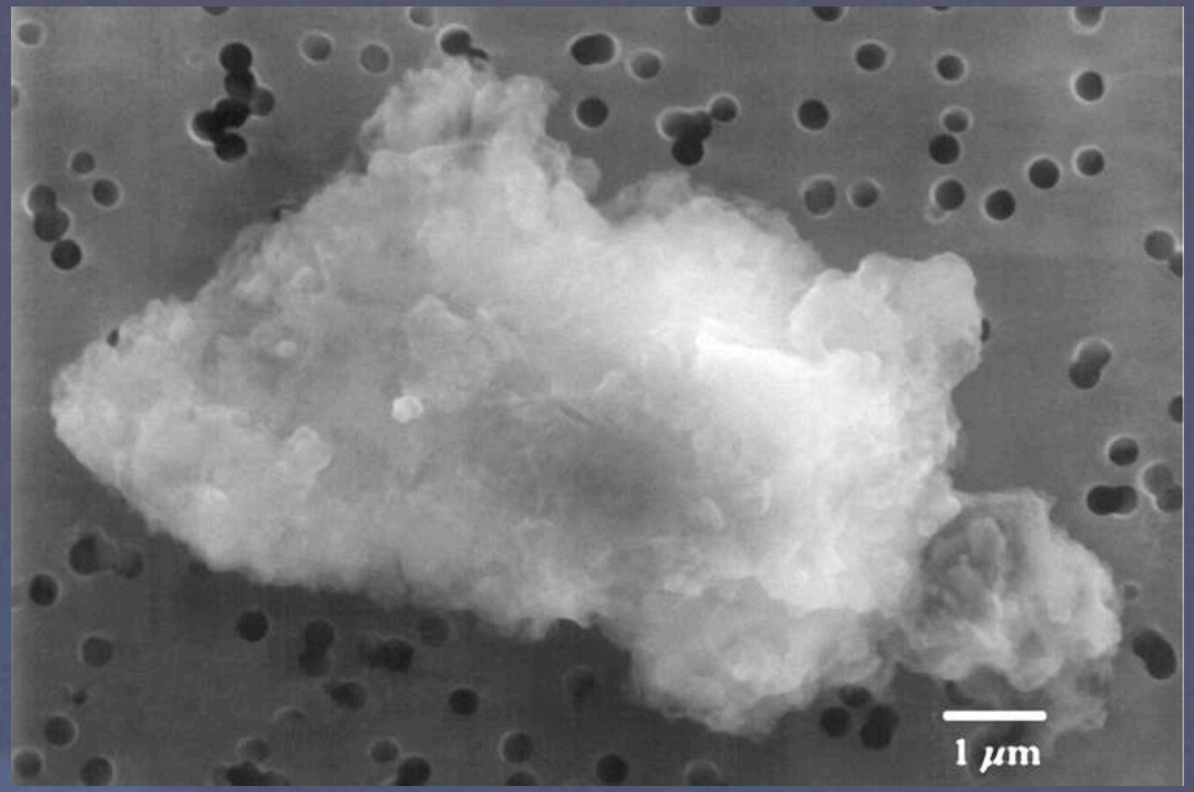
Opacities

How are they calculated?

- The value of kappa will depend on many variables:
  - Composition (most common are silicates, carbonaceous materials, and ices (water, CO, etc) - is it a mix?
  - Shape - are they really spherical?
  - Porosity - fractal structures?
  - Use of correct optical constants (people are trying to measure this here in labs)

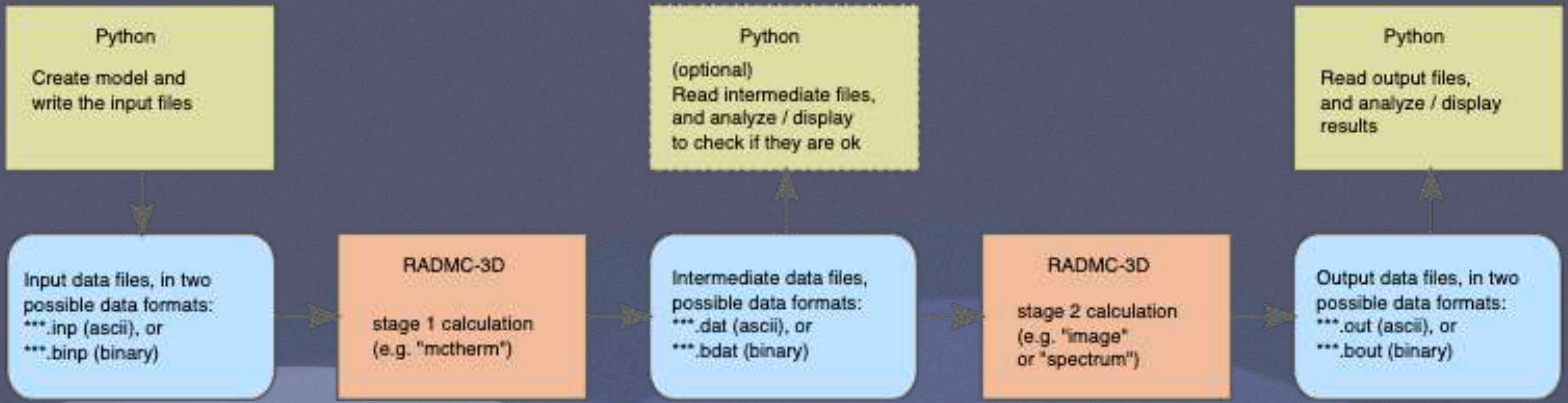


Chondrites



Simulation by Alexander Seizinger

When you run an RT calculation



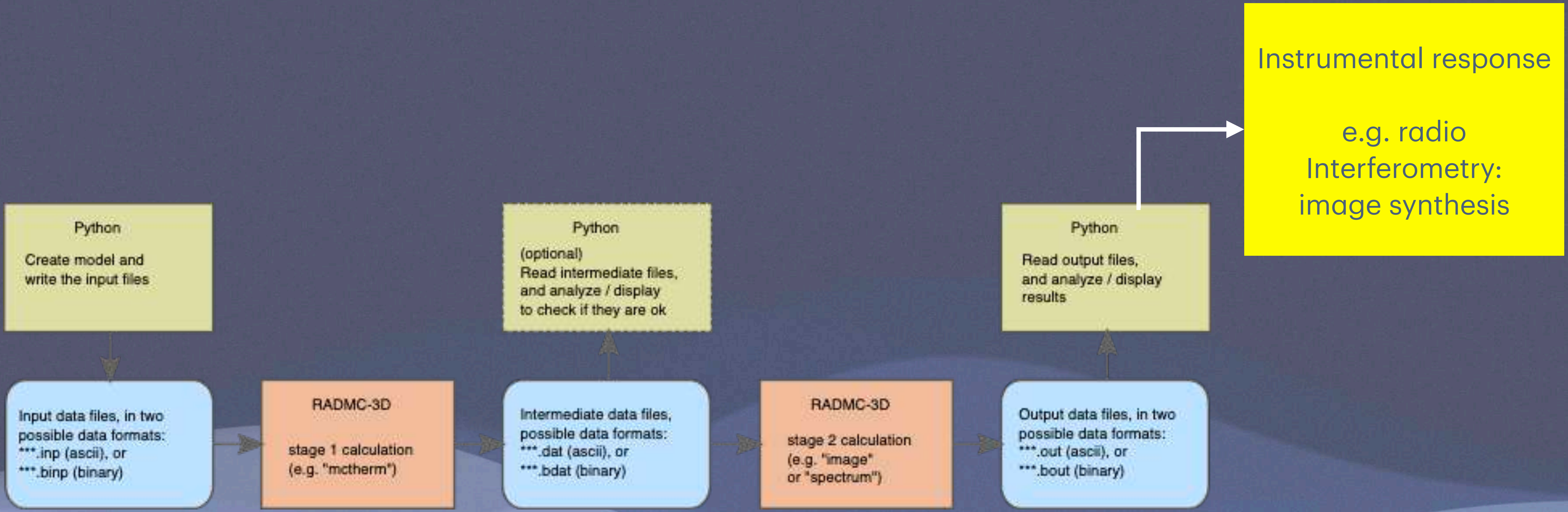
Input a parametric model or a snapshot of a hydro simulation

(Skip if you know -and trust- the temperature)

Could be any typical observable (image, cube, spectrum, a flux)

+input physics


When you run an RT calculation



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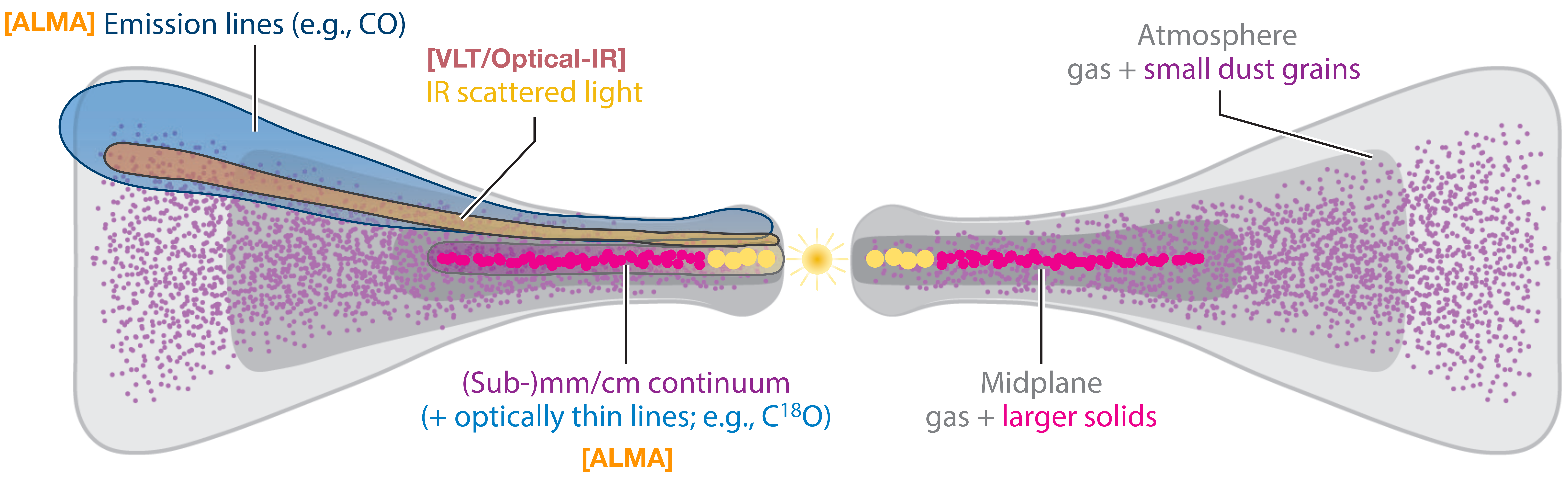
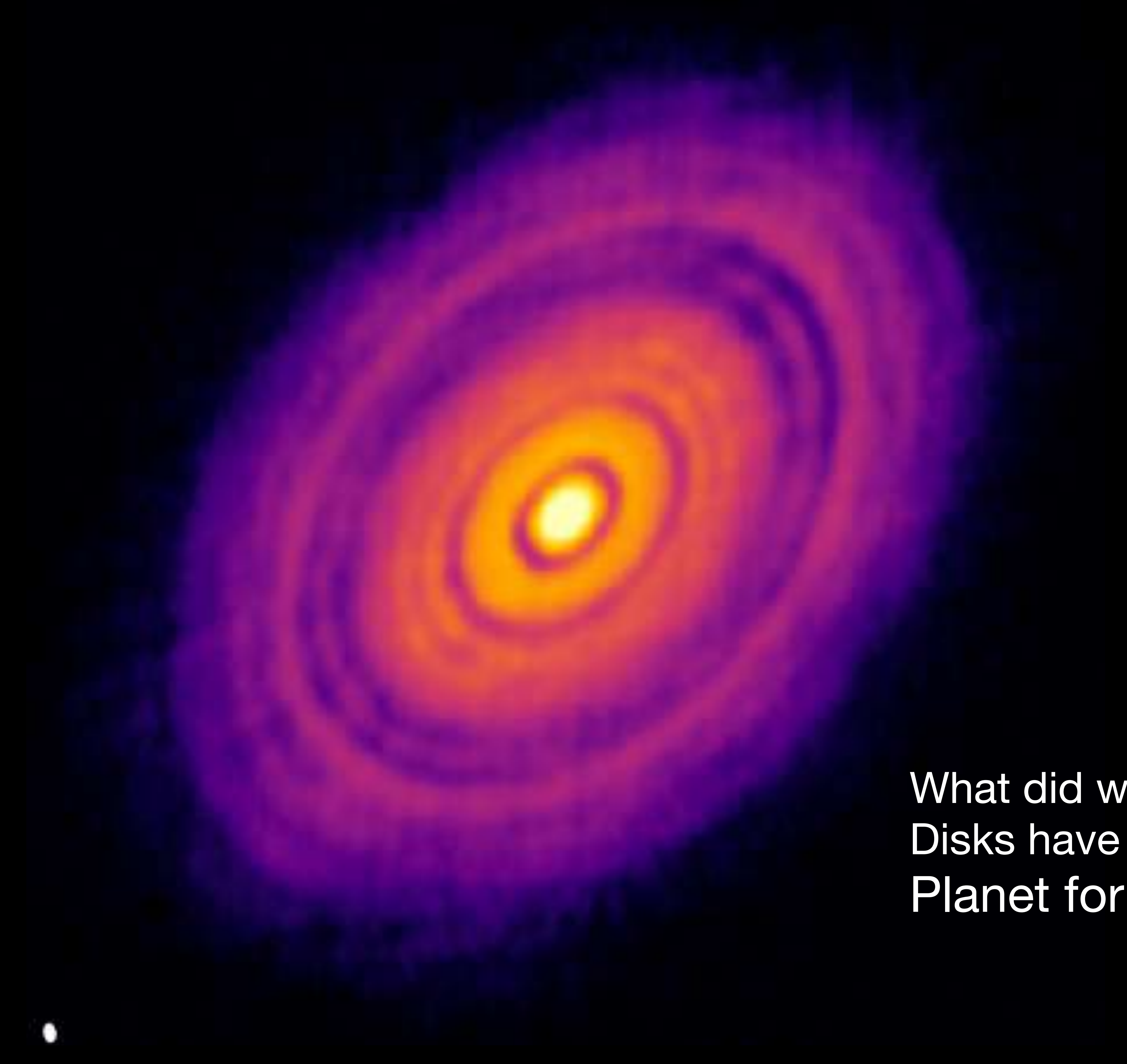
Observational primer: anatomy of a disk observation

Andrews 2020, ARA&A



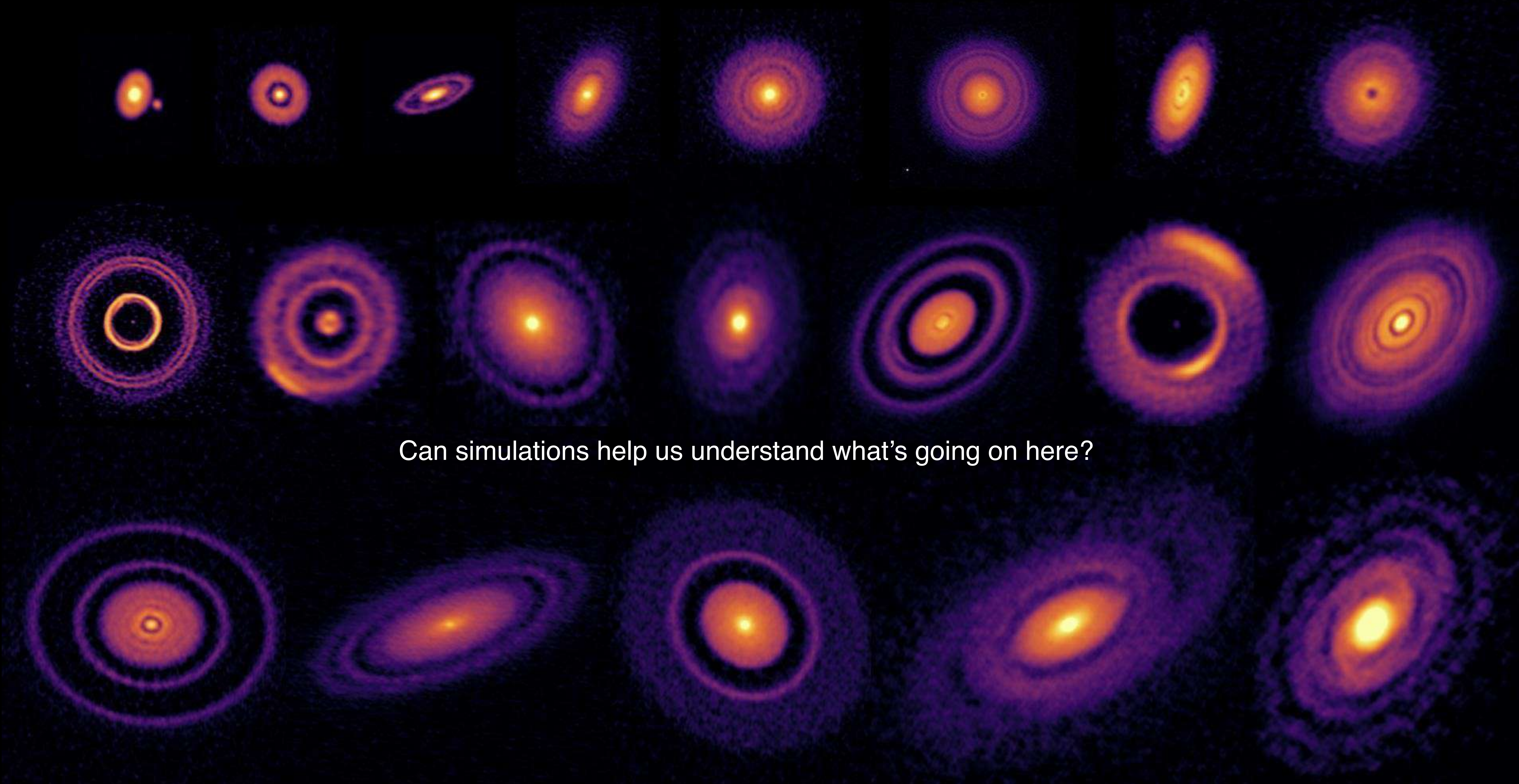
2014/2015



What did we learn?

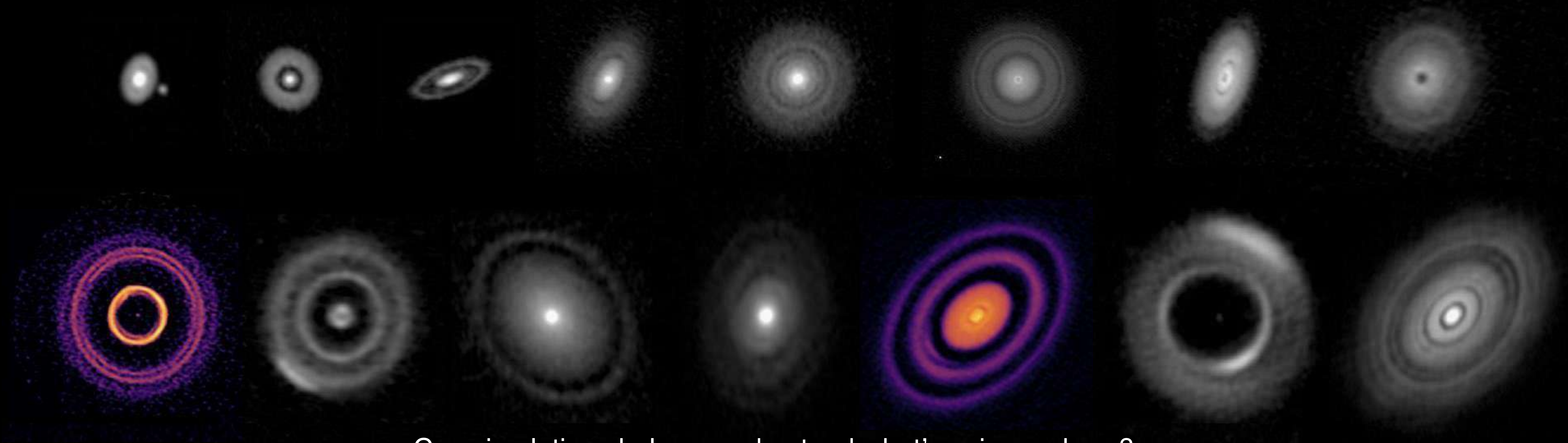
Disks have rings and substructures!

Planet formation might start early! (earlier than 0.5 Myr)



Can simulations help us understand what’s going on here?

Adapted from ALMA partnership (2015), DSHARP (Andrews et al. 2018), Dong et al. (2018), and Pérez et al. (2019), for Astro2020, National Academy Press



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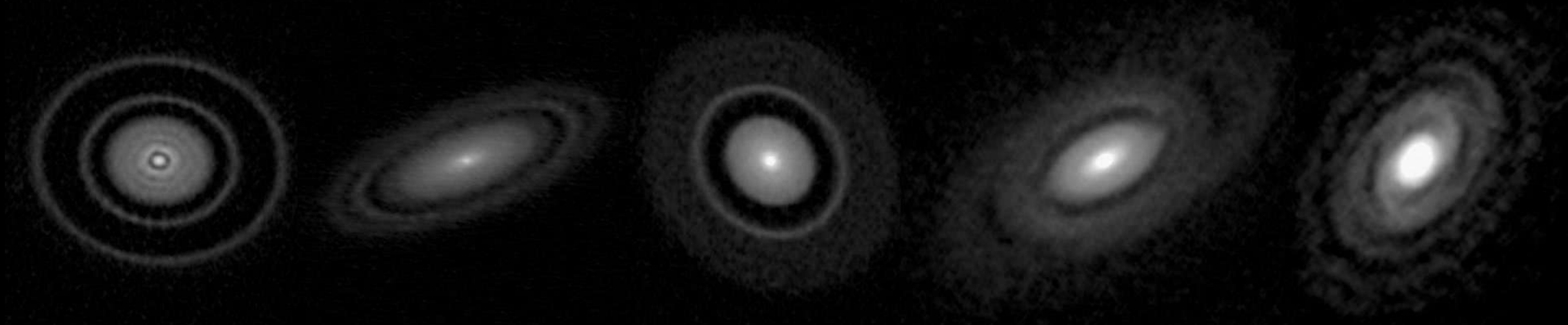

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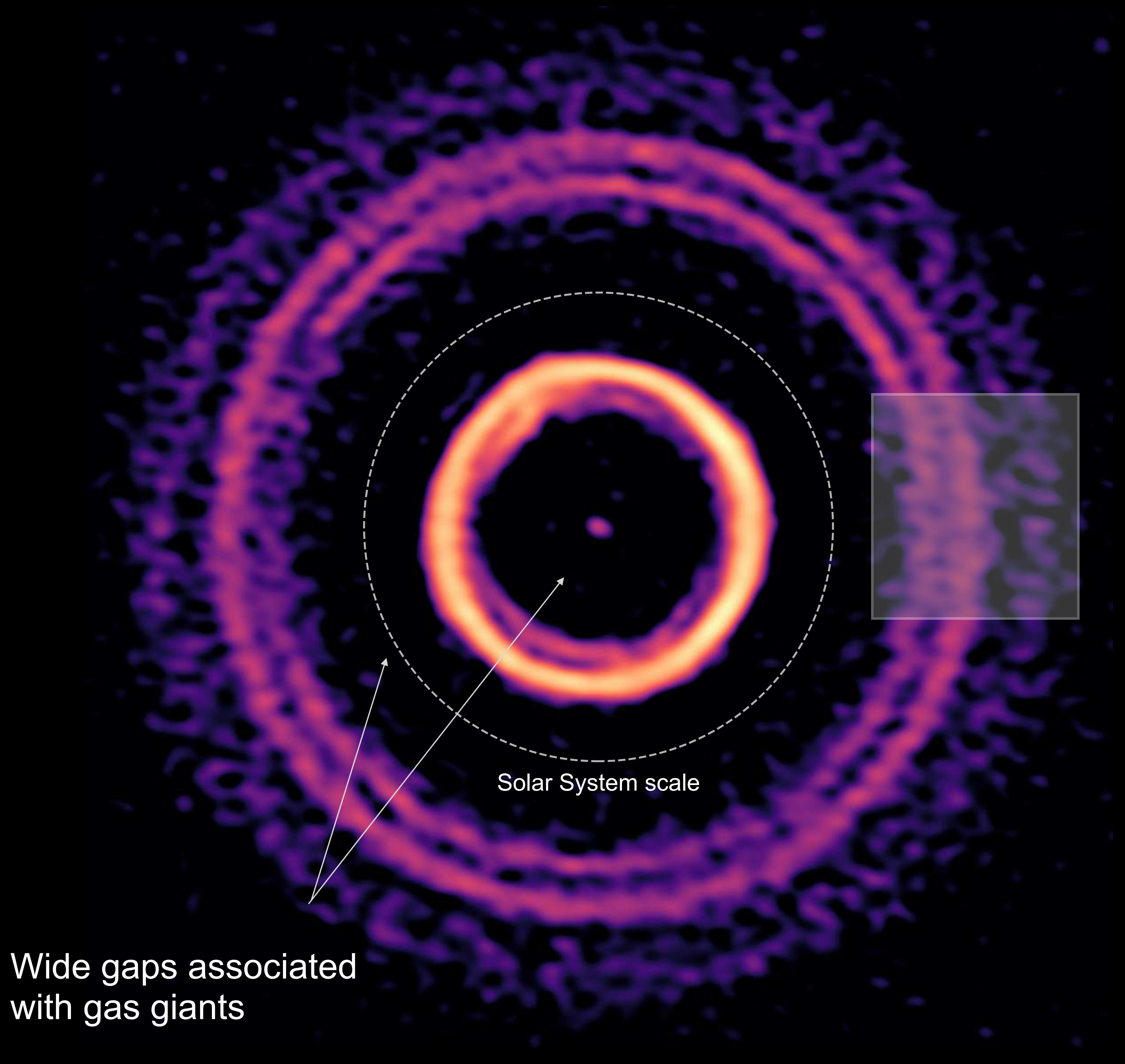
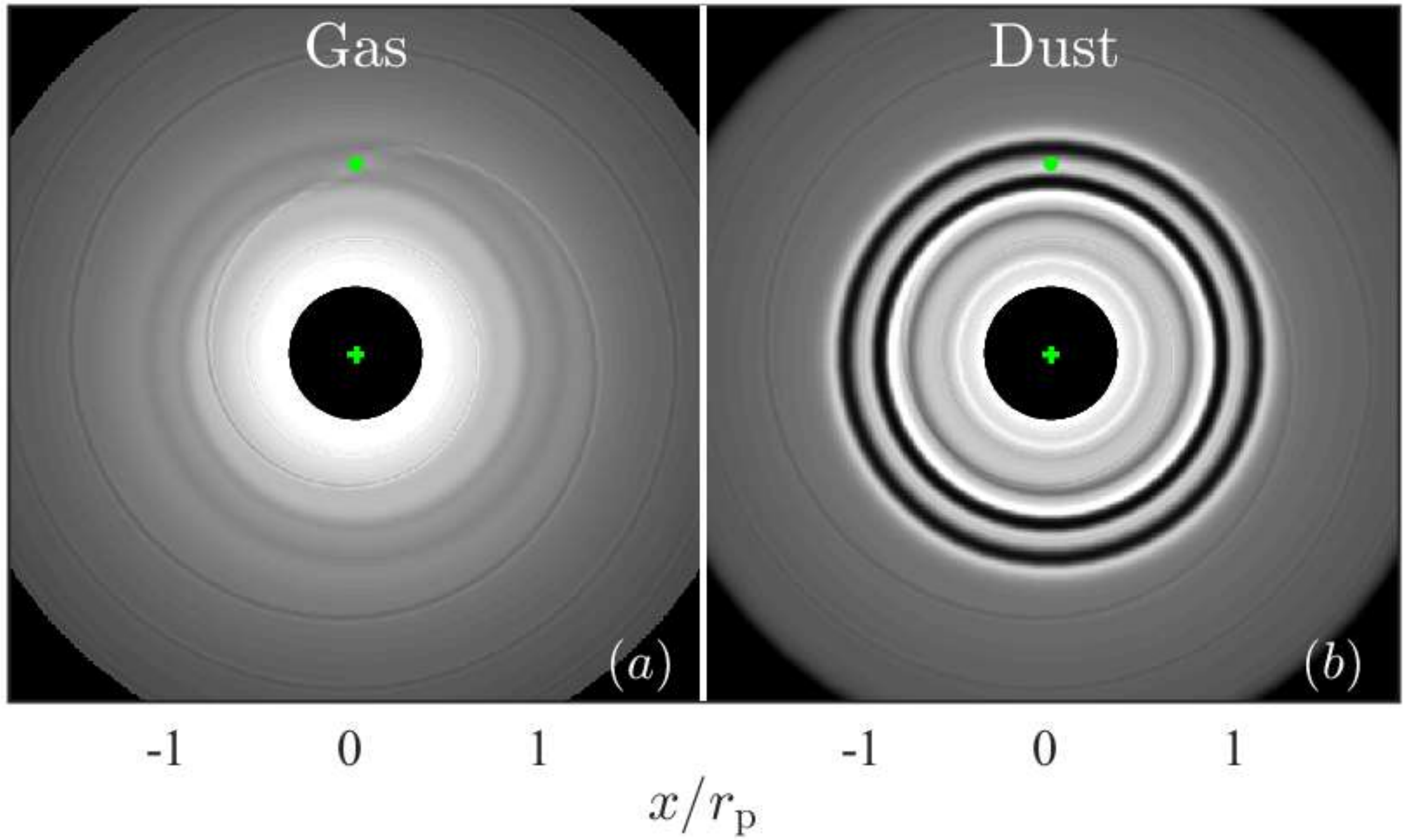
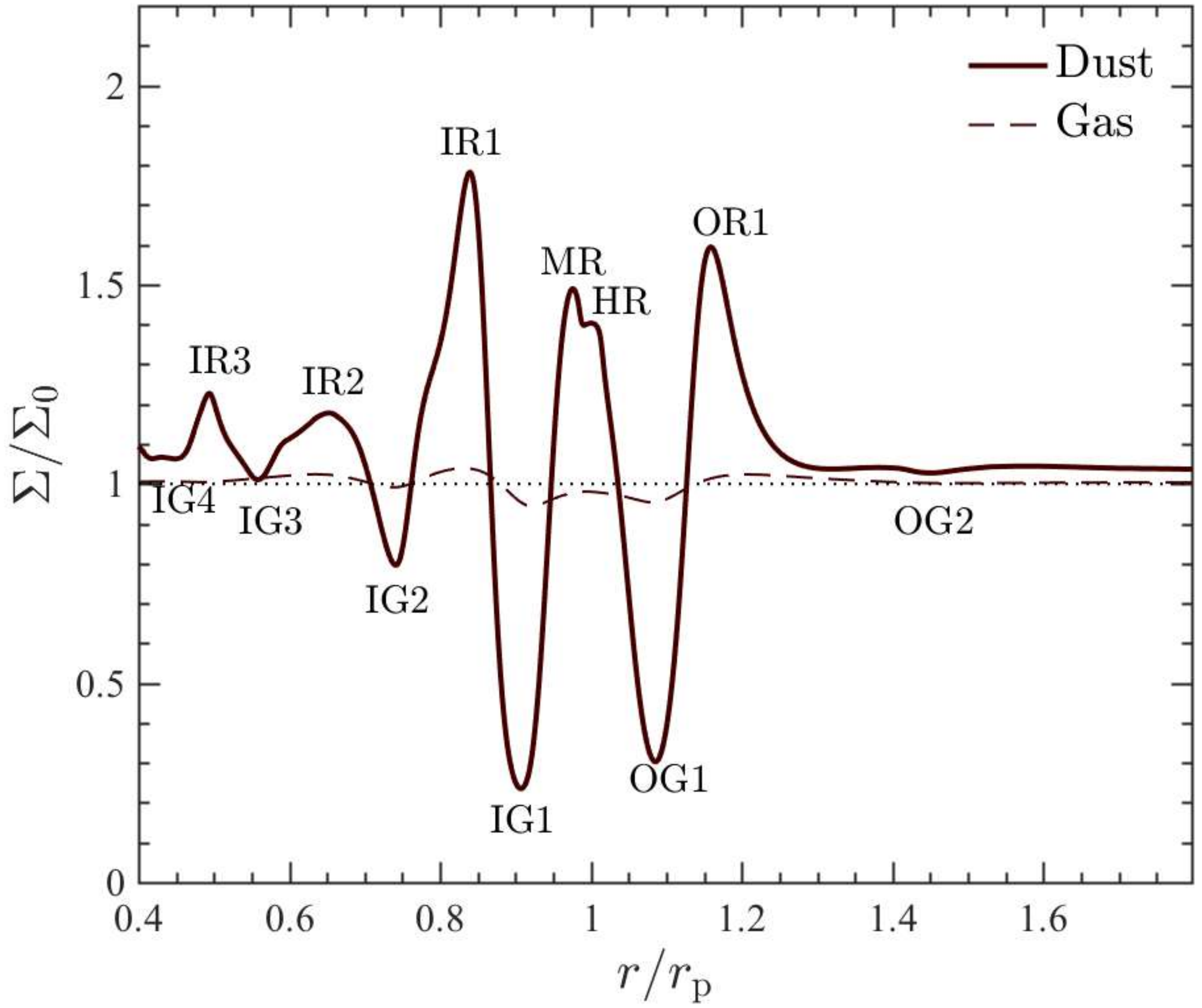
2019: super-Earth size planets can produce (three!) rings



ALMA 1.3 mm image of HD169142 (Perez et al. 2019)





Two gaps, one planet

Due to launching, shocking, and dissipation of two primary density waves.

Dong et al. (2017, 2018)

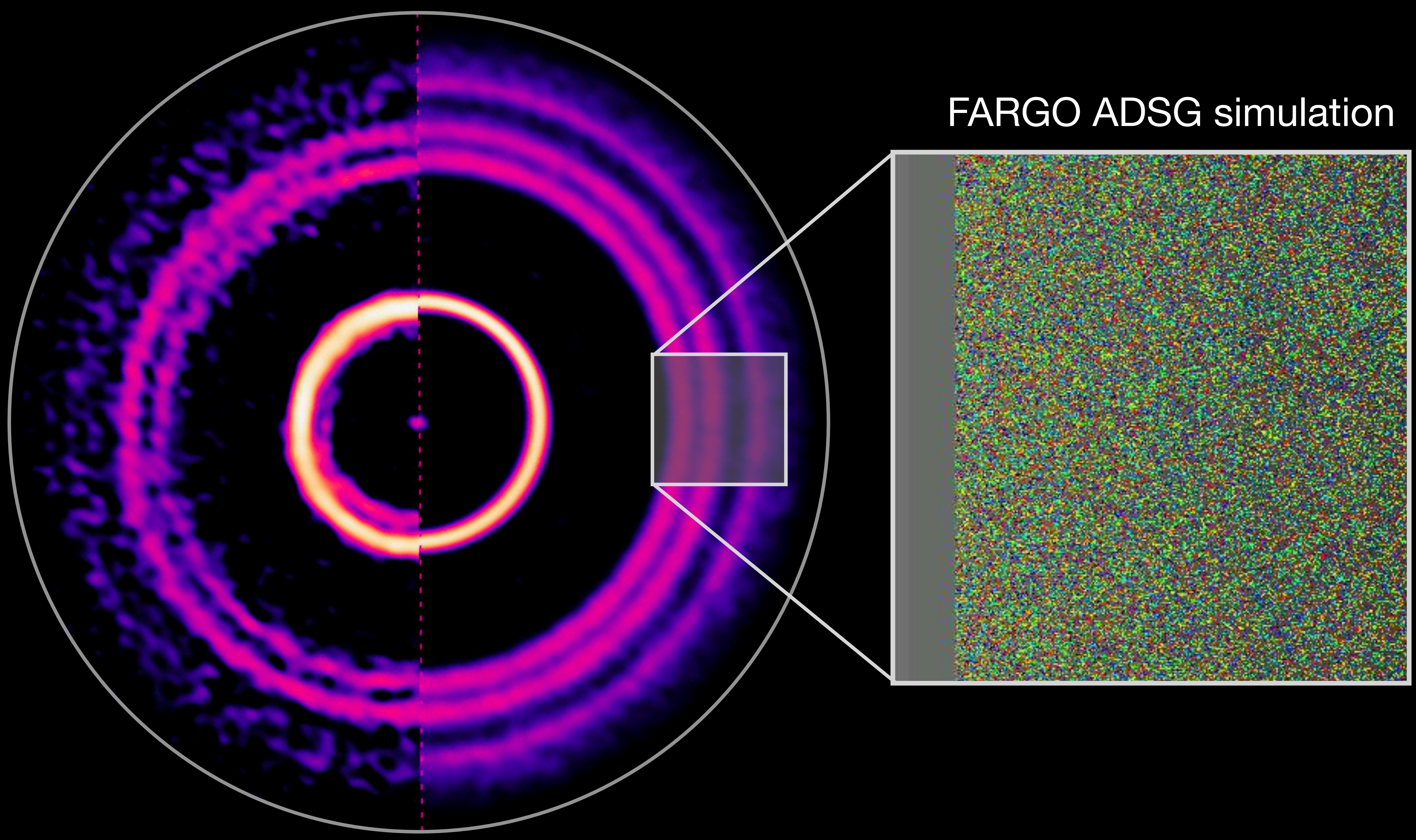
Goodman & Rafikov (2001)

Low viscosity disk:

$$\frac{r_\mathrm{OG1} - r_\mathrm{IG1}}{r_\mathrm{p}} \approx 2.9 \left(\frac{\boxed{\gamma} + 1}{12/5} \boxed{\frac{M_\mathrm{p}}{M_\mathrm{th}}} \right)^{-2/5} \boxed{\left(\frac{h}{r} \right)}$$

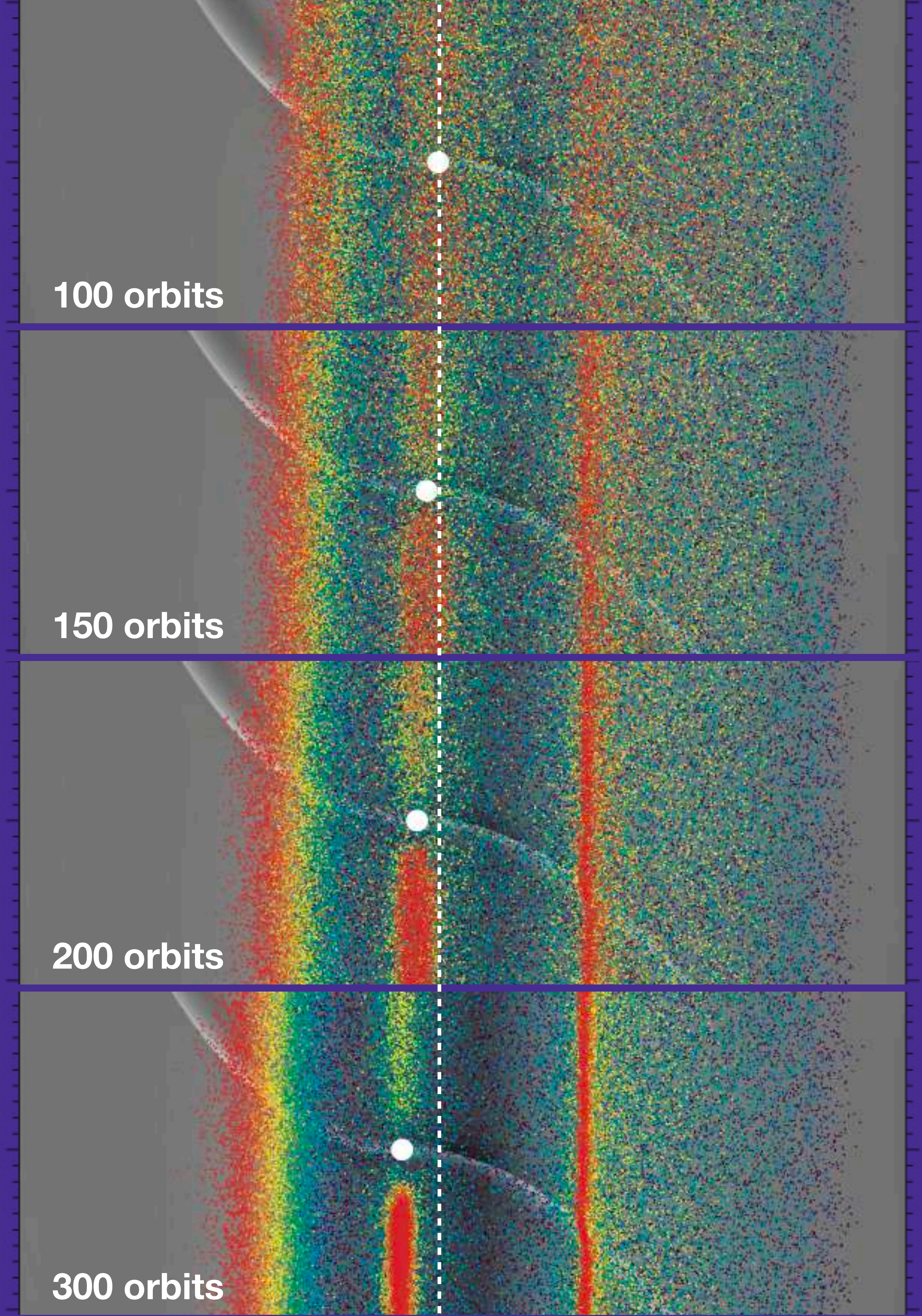
Also: dependence on choice of EOS (Miranda & Rafikov 2019)

2019: super-Earth size planets can produce (three!) rings



The dust and gas are perturbed by a small planet sculpting the outer regions of a disk. The fine rings are composed of dust particles which are trapped into concentric structures by pressure waves.

Adapted from Pérez et al. (2019)



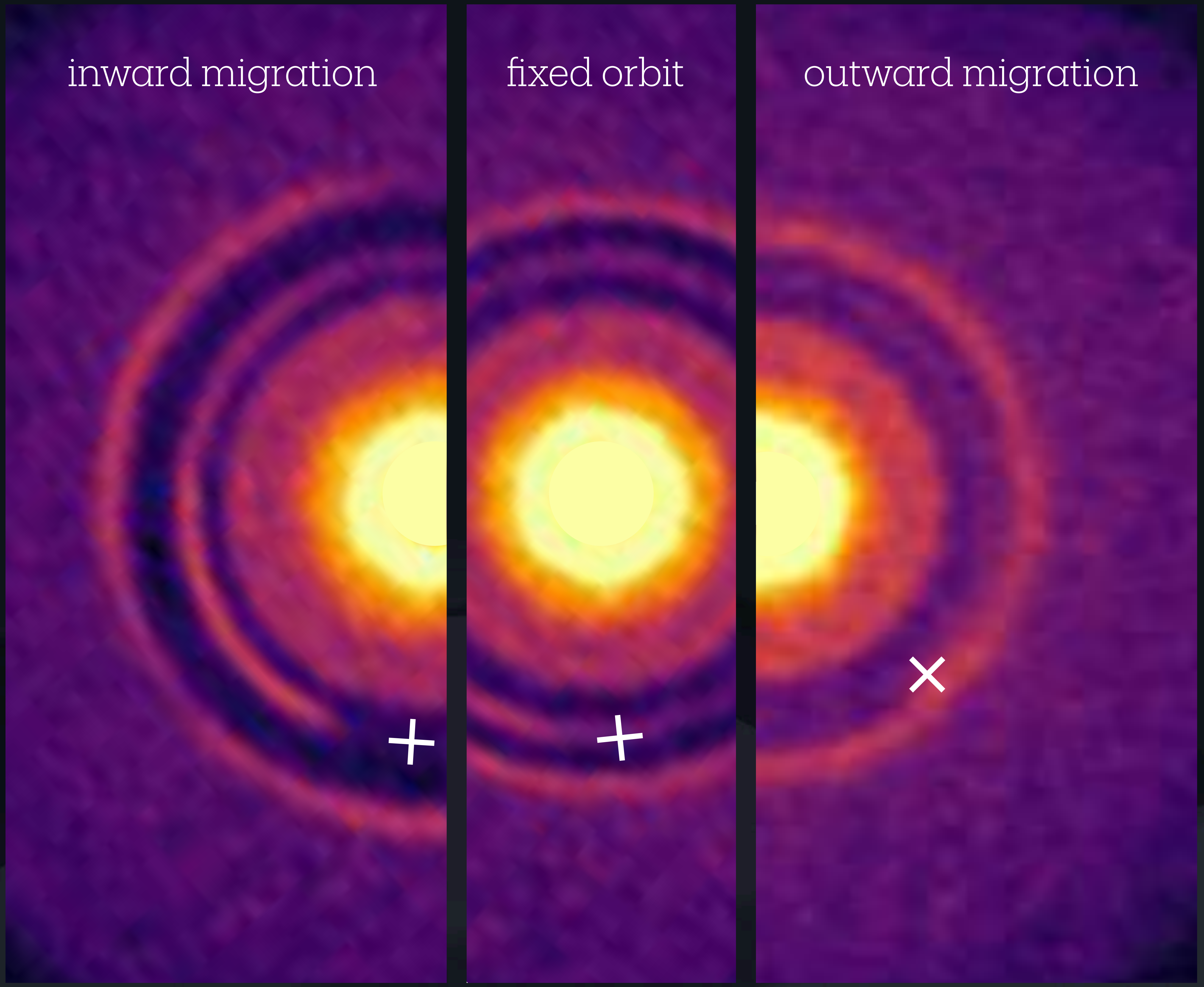
Locations of the rings (mutual separations) suggest the planet is migrating

~1 au / 10k years

Migration predictions with FARGO3D multi fluid

(Weber et al. 2019)

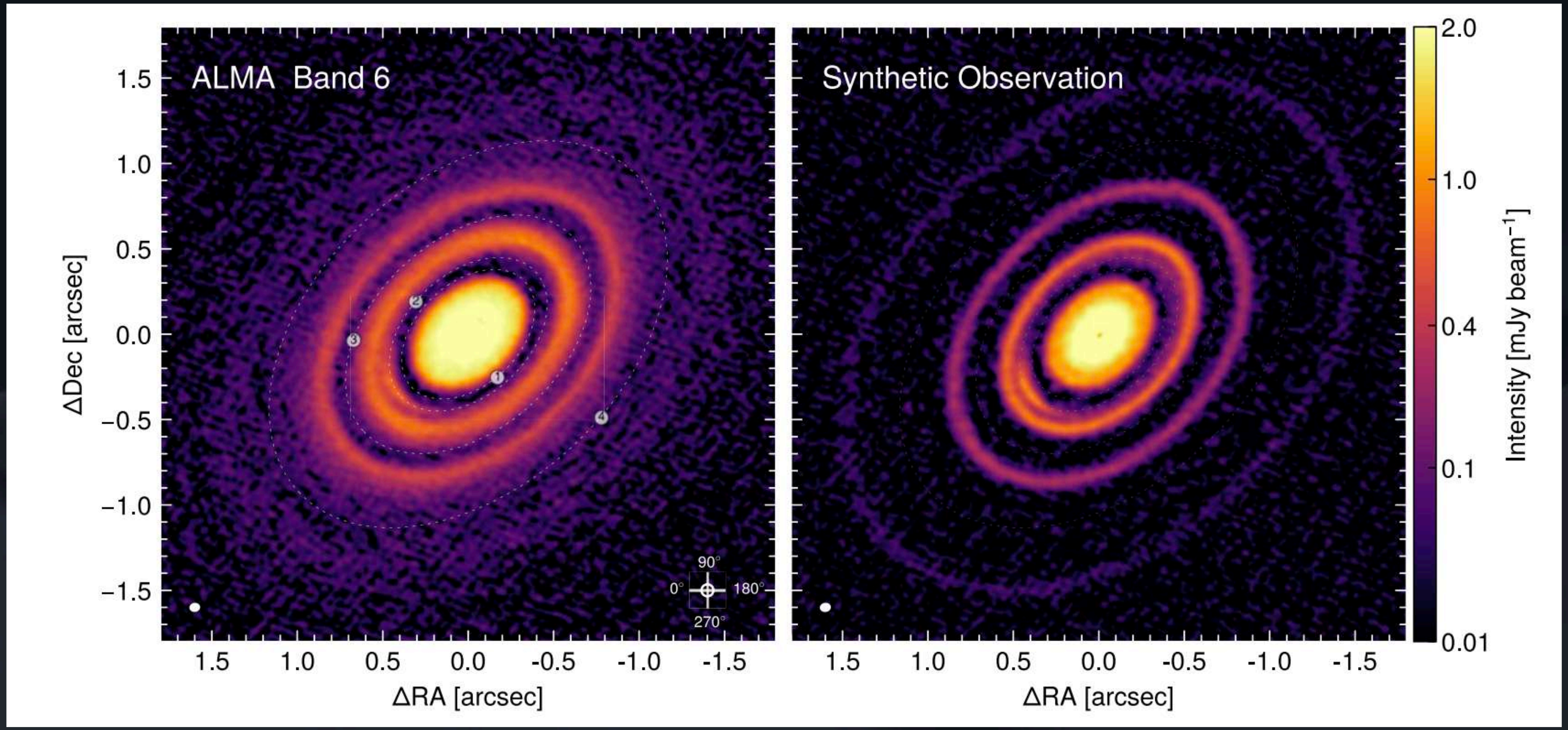
- Different migration directions and rates produce distinct substructures.

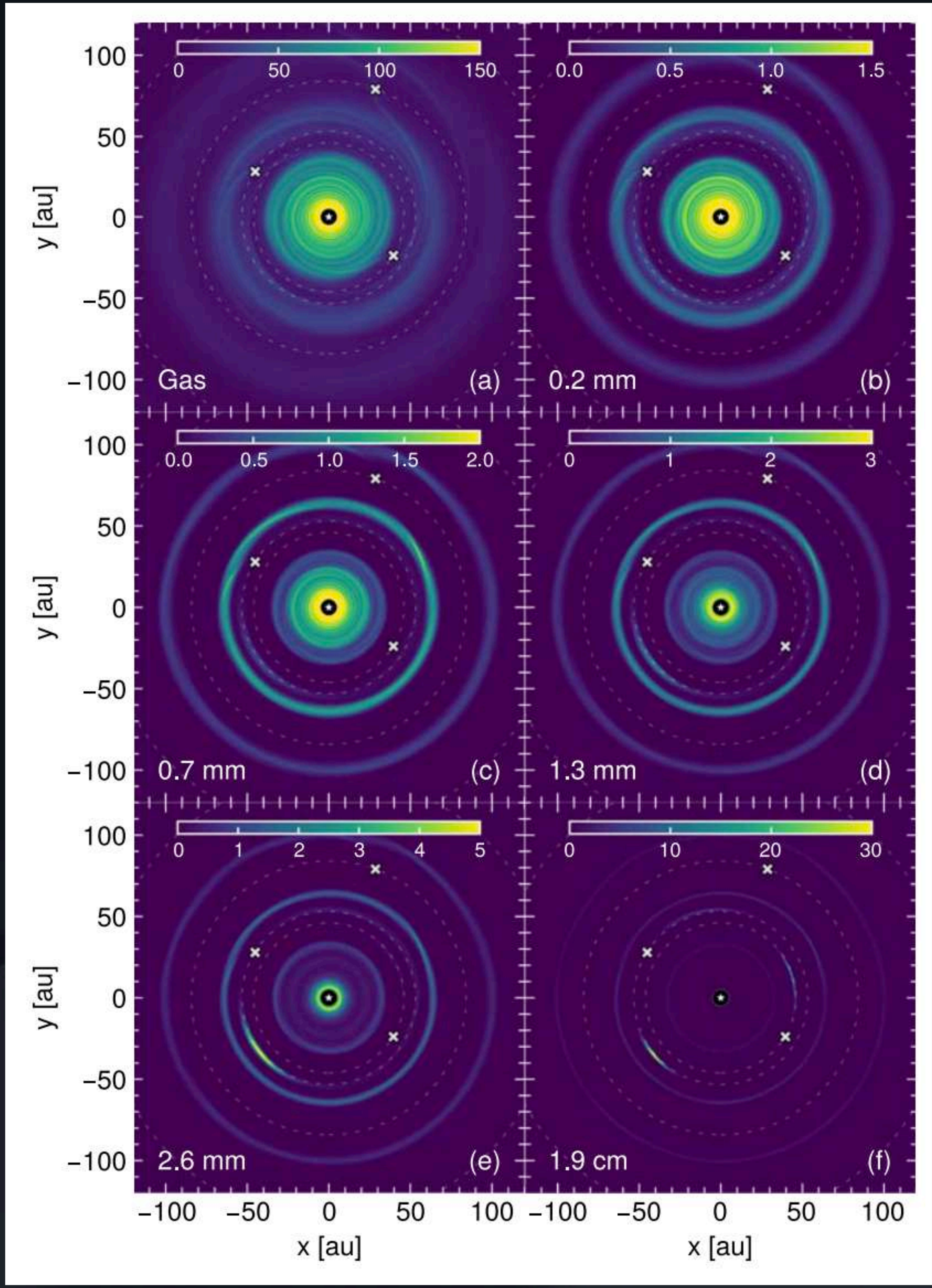


HD163296

Juan Garrido-Deutelmoser et al. (2023)

- Reproduces the crescent as a dust accumulation in L5 of the outer planet in a 2 planet-carved gap





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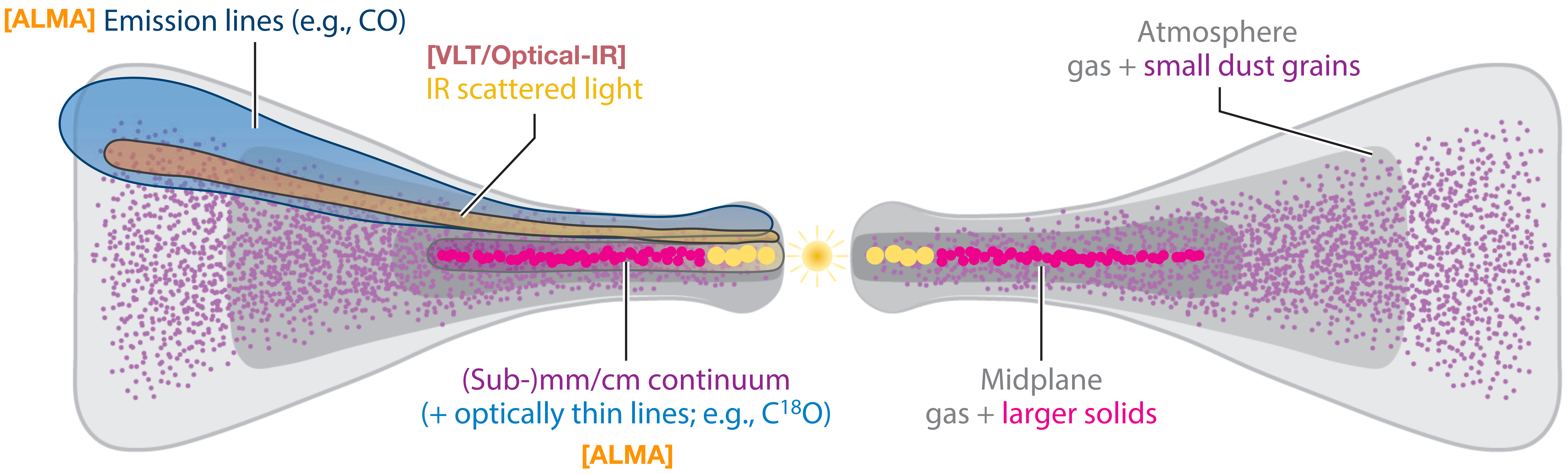
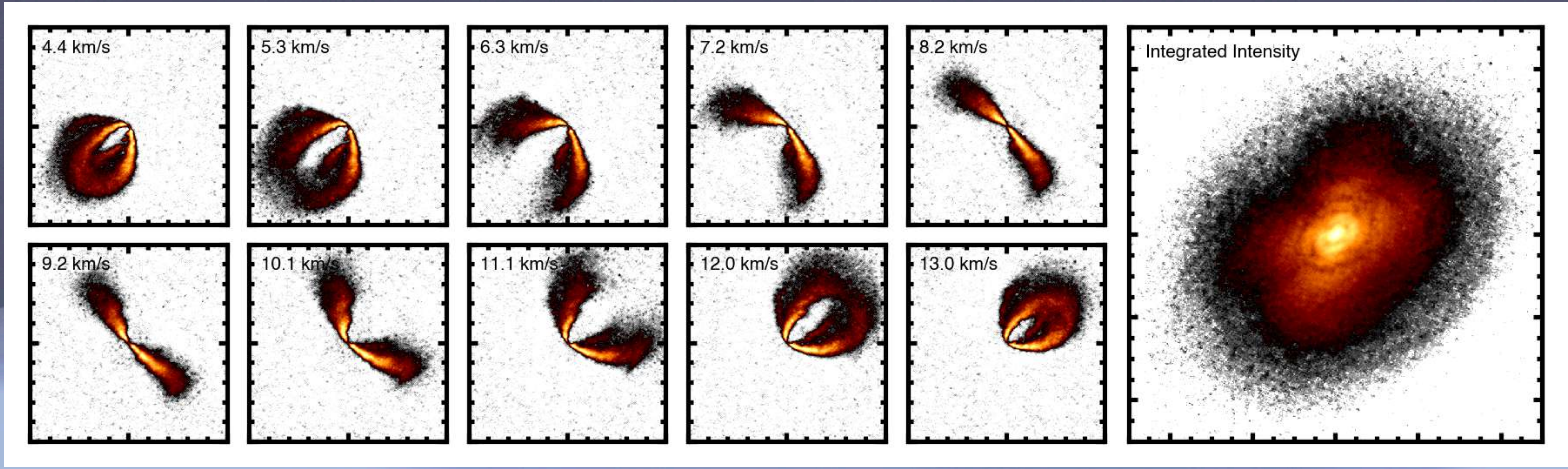


Disk kinematics / Butterfly pattern (see Horne & Marsh 1986)

In contrast to dust, the opacities of gas are usually dominated by lines.

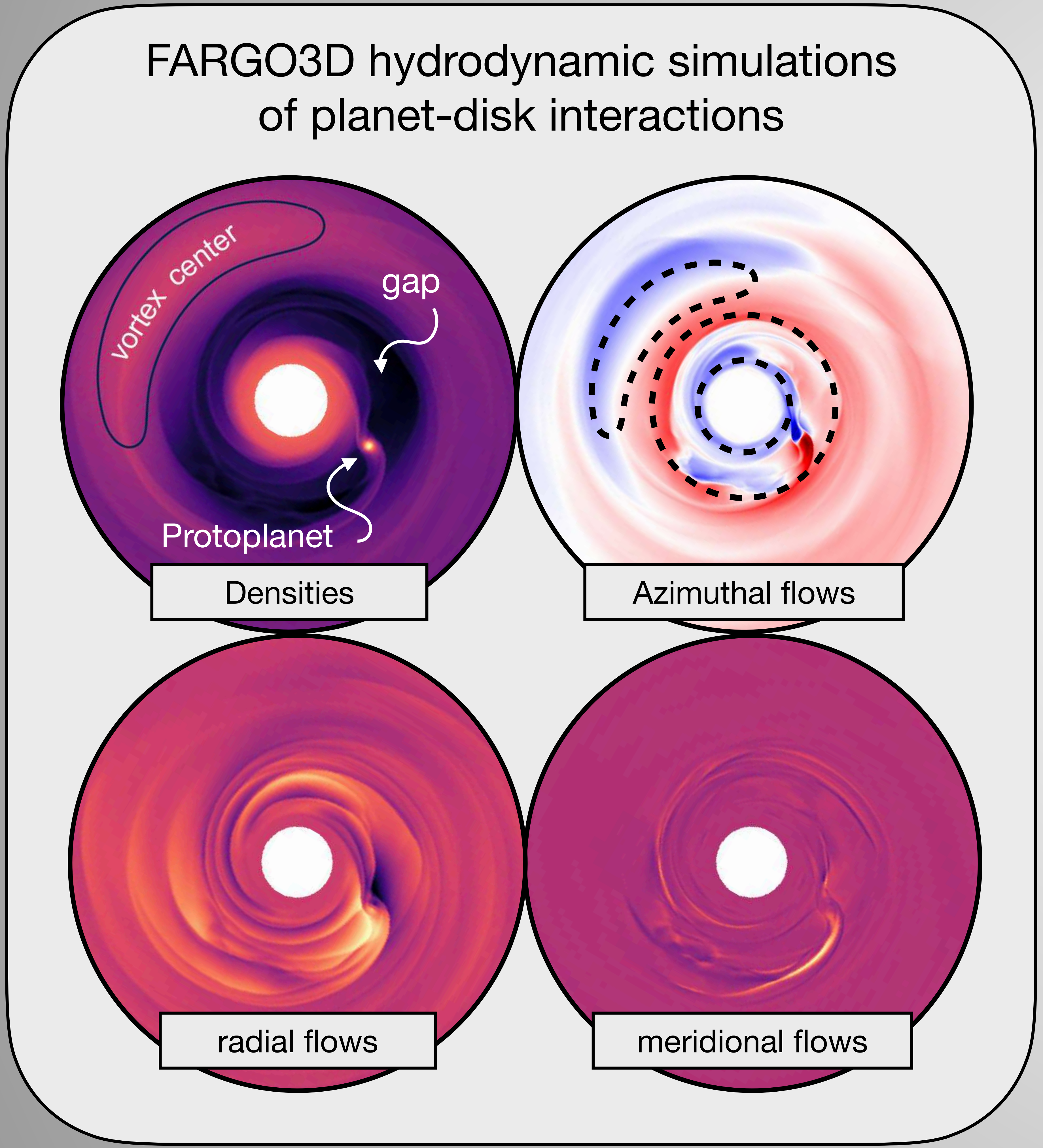
$$v_0 = {\color{magenta}v_\phi} \sin i \cos \phi + v_{\mathrm{LSR}}$$

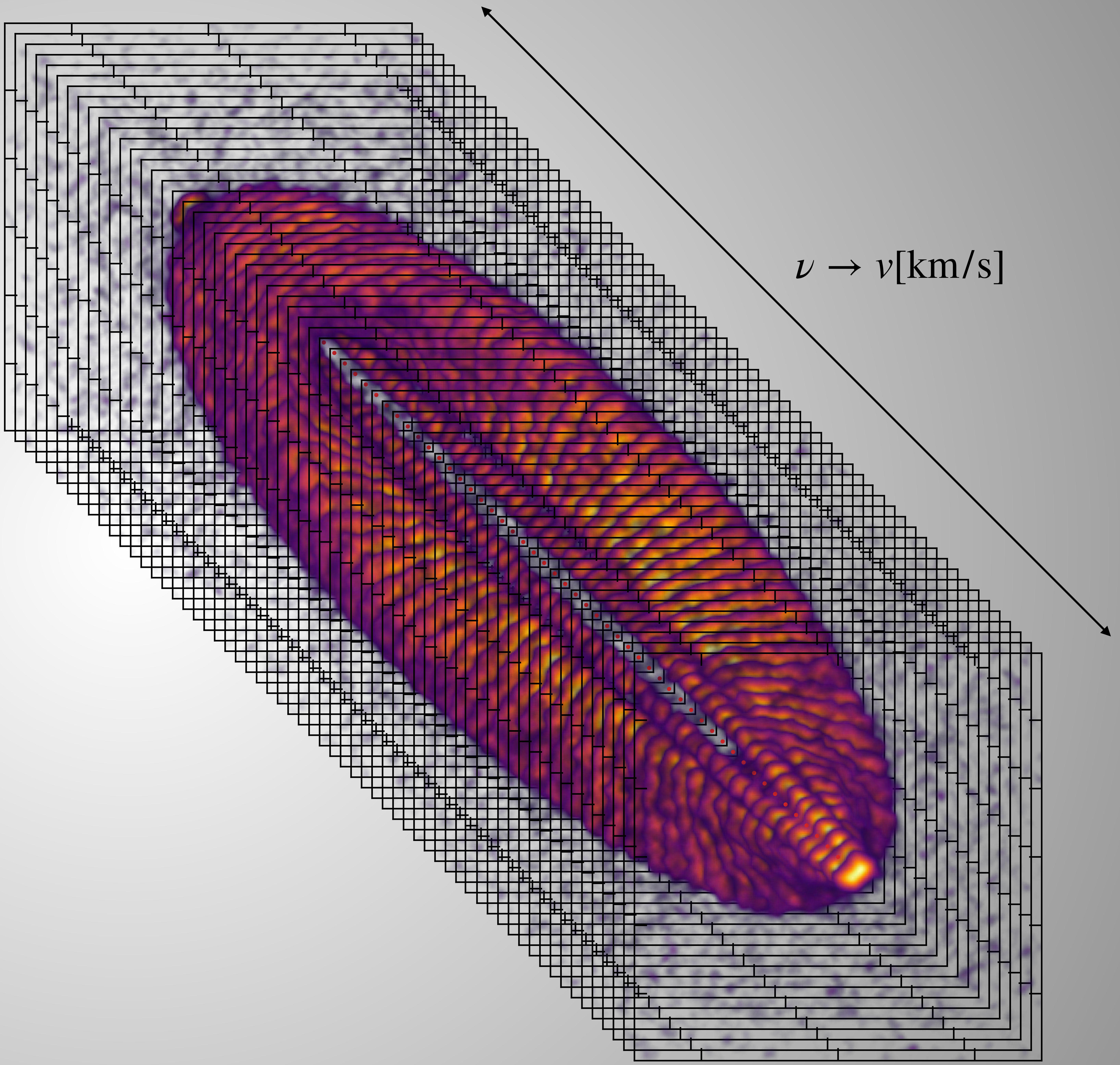
Gas observations with ALMA are similar to a “tomography” of the disk. But instead of looking for tumors, we look for planets.



12CO emission in the disk around HD 163296 (Andrews+2018, Isella+2019).
From *Visualising the Kinematics of Planet Formation* by Disk Dynamics Collaboration

Example gaseous disk inclination ~20 deg

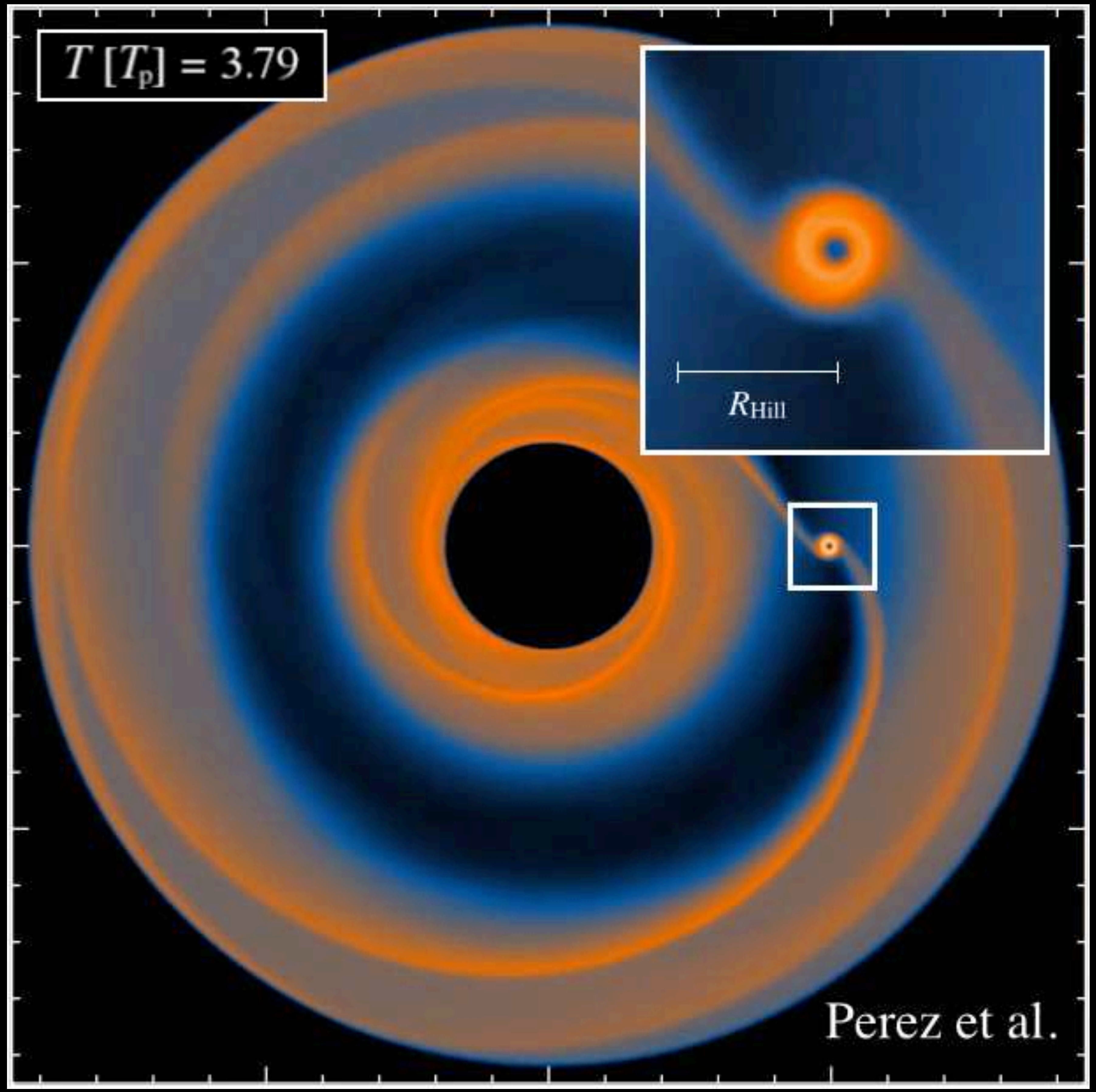




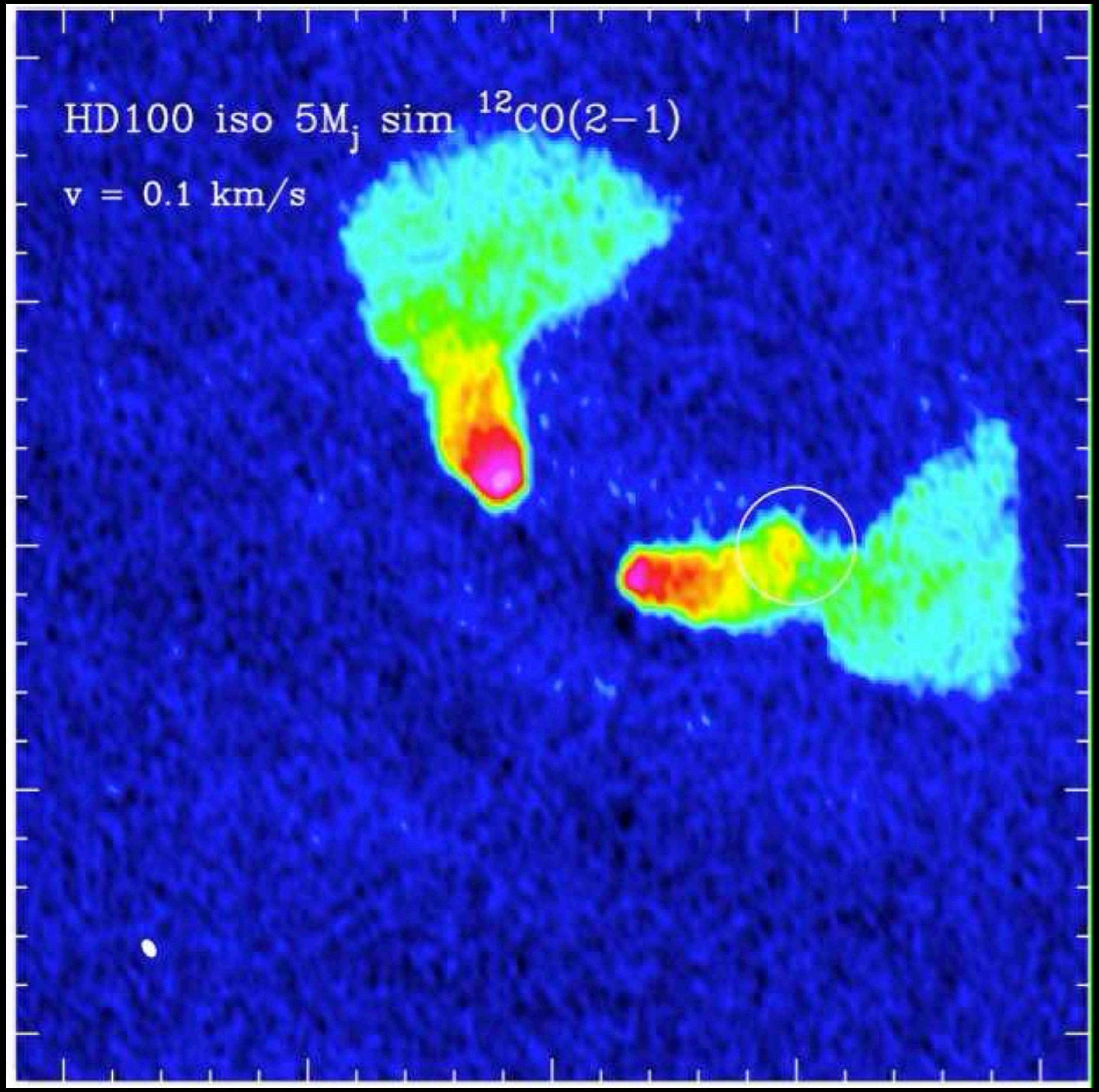
Young exoplanet detection via kinematics

A method to reveal young exoplanets via their dynamical interaction with their protoplanetary disk.

Our original prediction from Perez et al. (2015).



Simulation

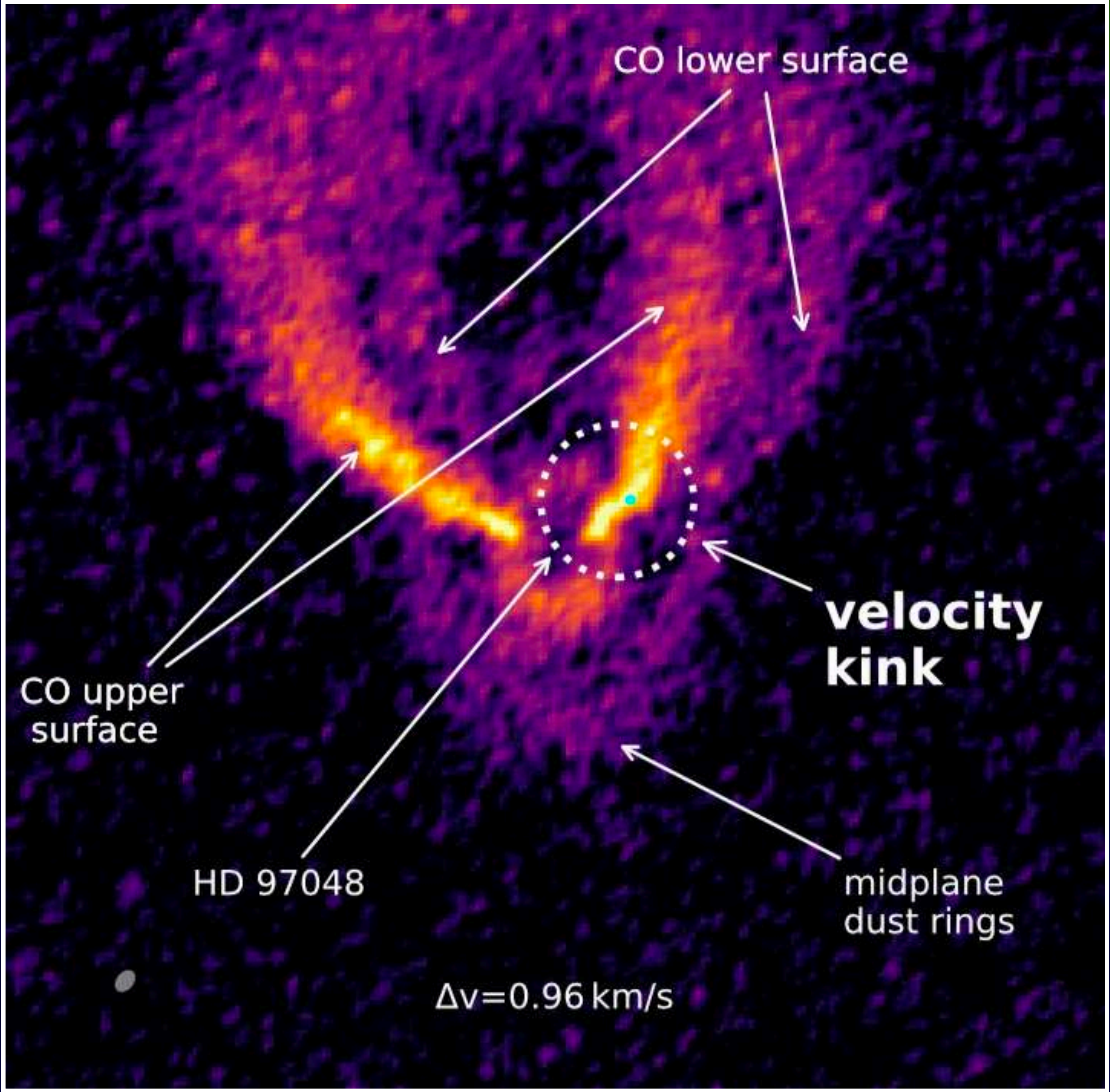


Prediction


Young exoplanet with a
circumplanetary disk

Our predictions were confirmed in 2018 and 2019

These are now called “**disk kinematic**” detections



HD 97048 (Pinte et al. (2019), *Nature Astronomy*), see also AS209 by Fedele et al. (2023), Bae et al. (2022)

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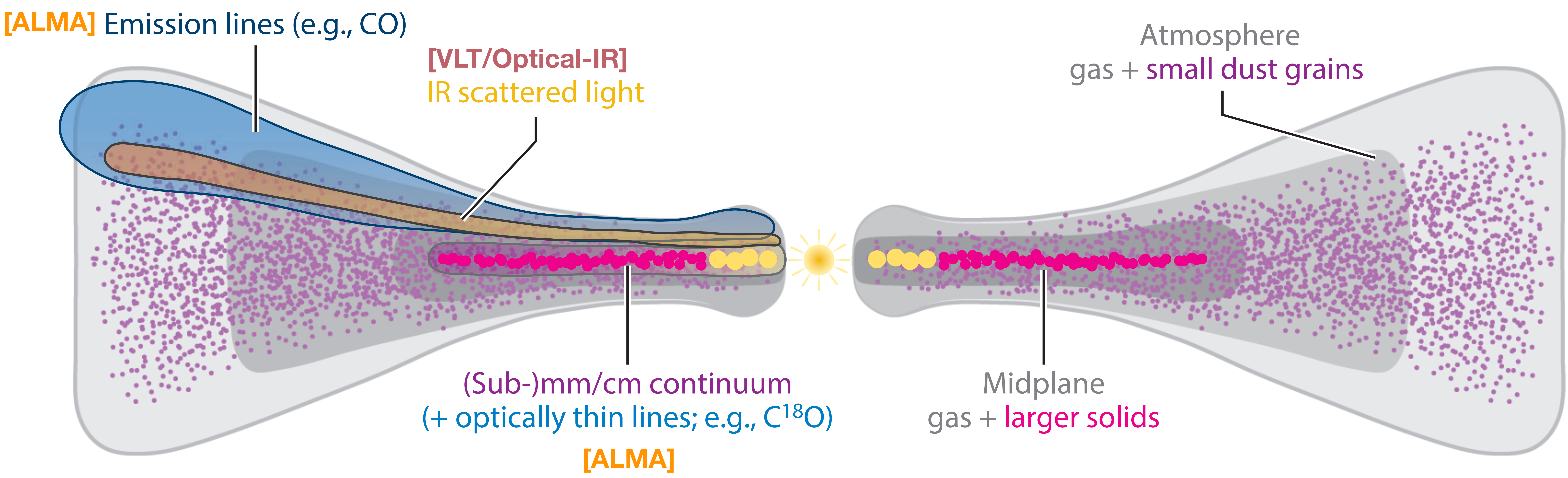


Radiation transfer equation w/ scattering

Scattering (absorption and re-emission) makes things siginificantly harder

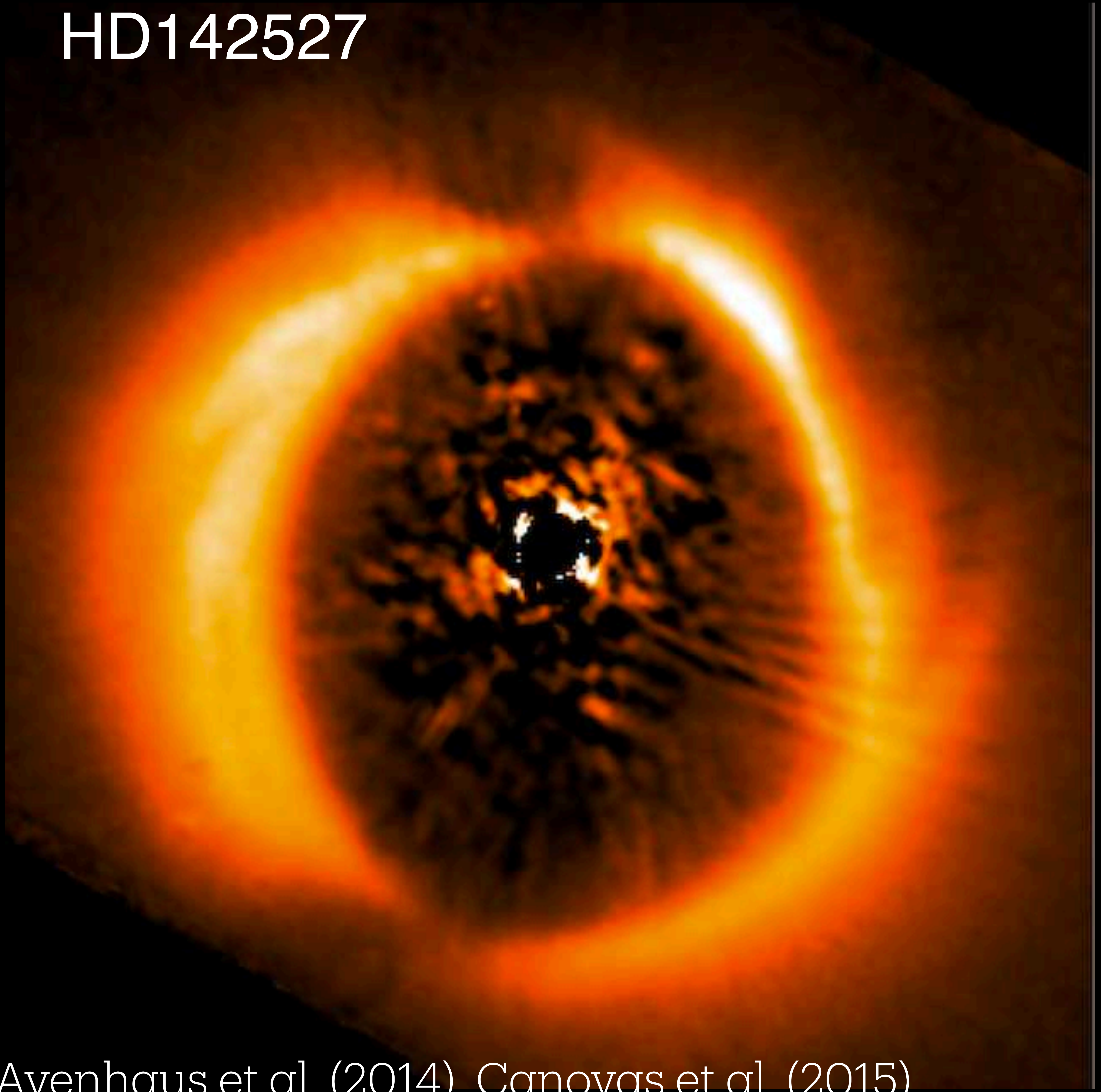
scattering phase function

$$\frac{dI_\nu}{ds} = -\alpha_\nu^{\text{ext}} I_\nu + \alpha_\nu^{\text{abs}} B_\nu + \alpha_\nu^{\text{scat}} \frac{1}{4\pi} \int_\Omega \psi(\vec{n}, \vec{n}')\, I_\nu \, d\Omega$$

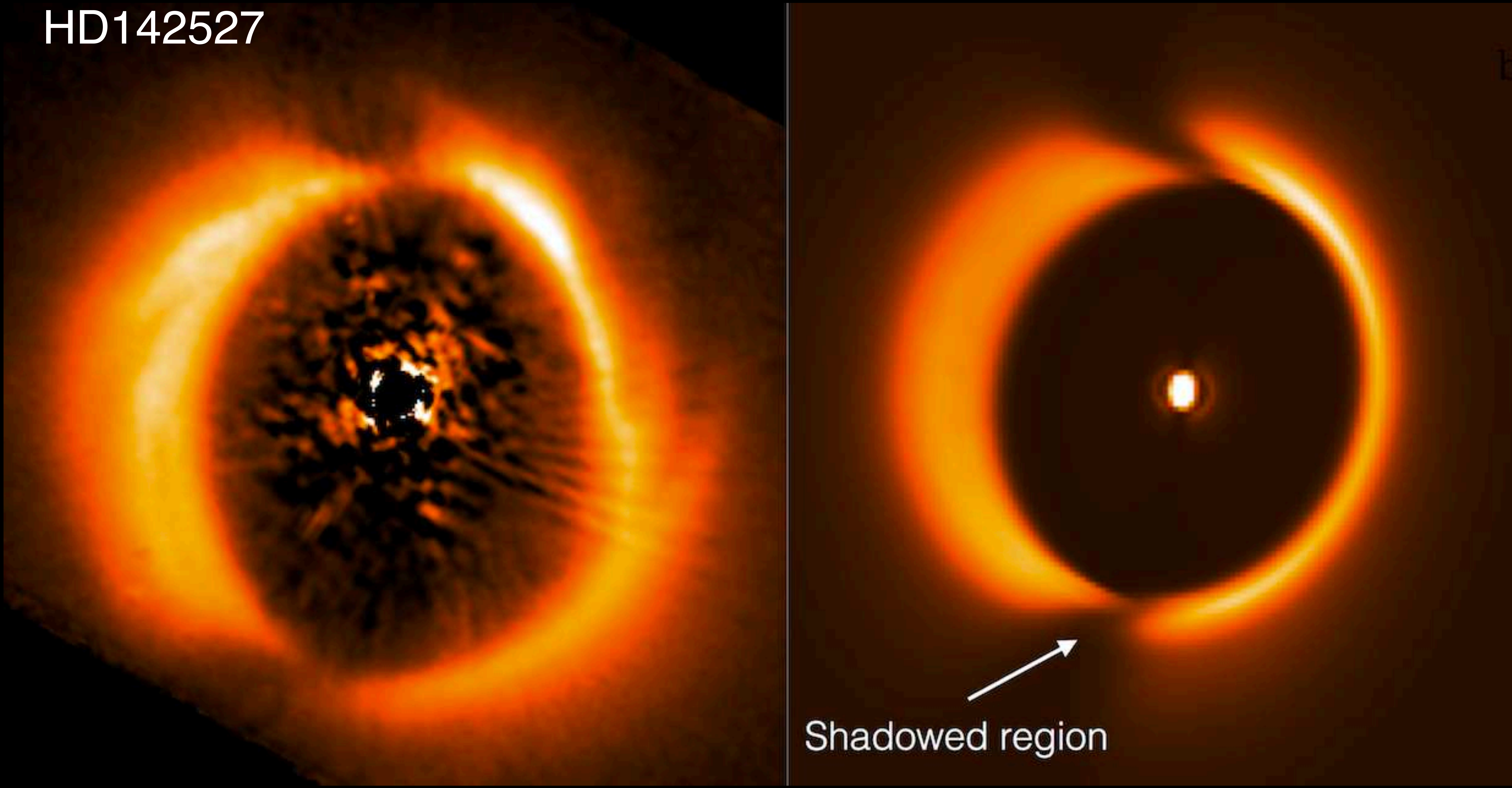
abs + scattering

Describes the anisotropy of scattering. Gives you the probability that a photon coming from direction **n** will be scattered towards the direction **n'**.

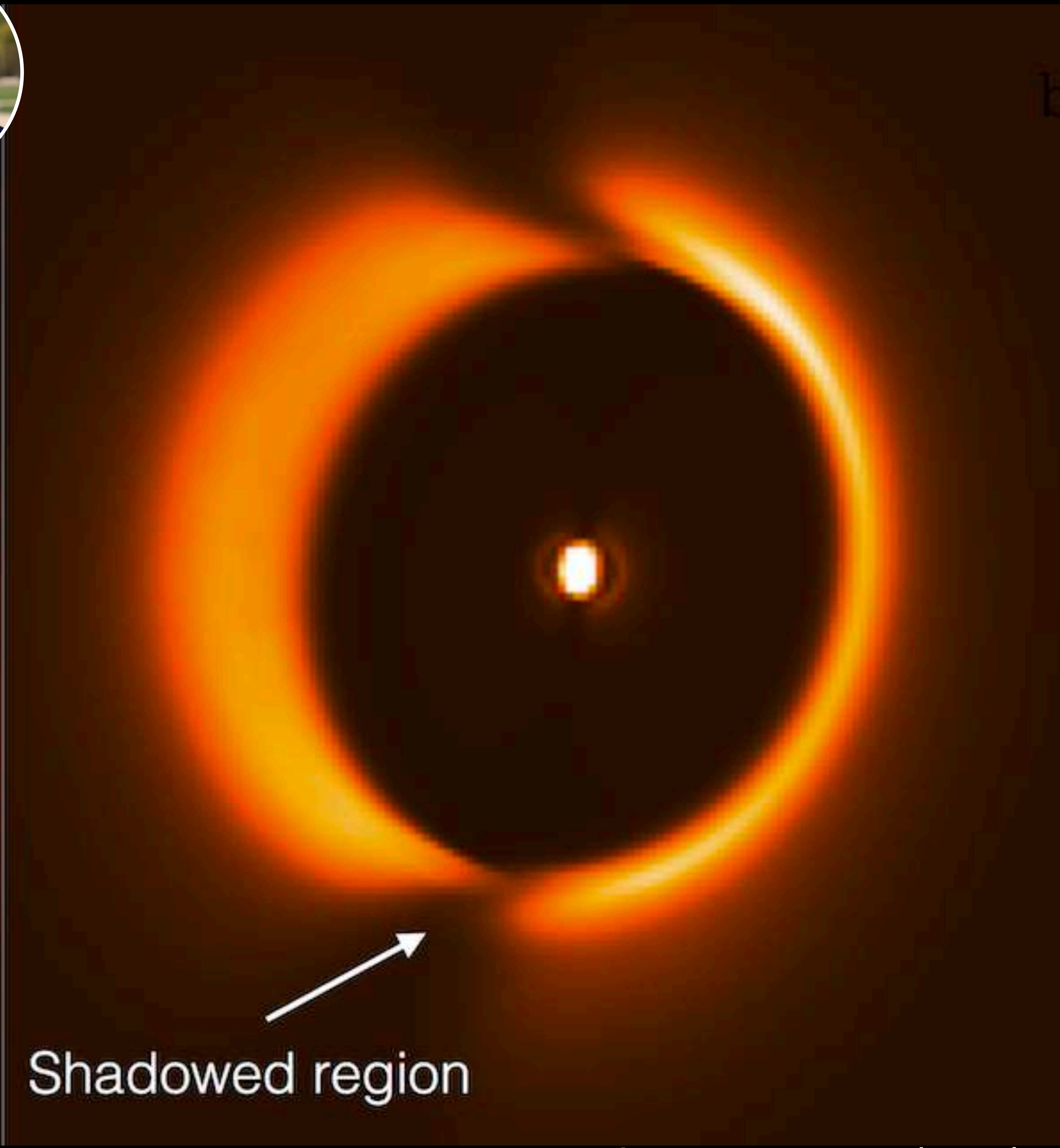
When doing polarization, 1) **the phase function becomes the Muller matrix**, 2) **the absorption coefficients become vectors**.



Avenhaus et al. (2014), Canovas et al. (2015)


HD142527
Shadowed region

2015



Marino, Pérez & Casassus (2015)

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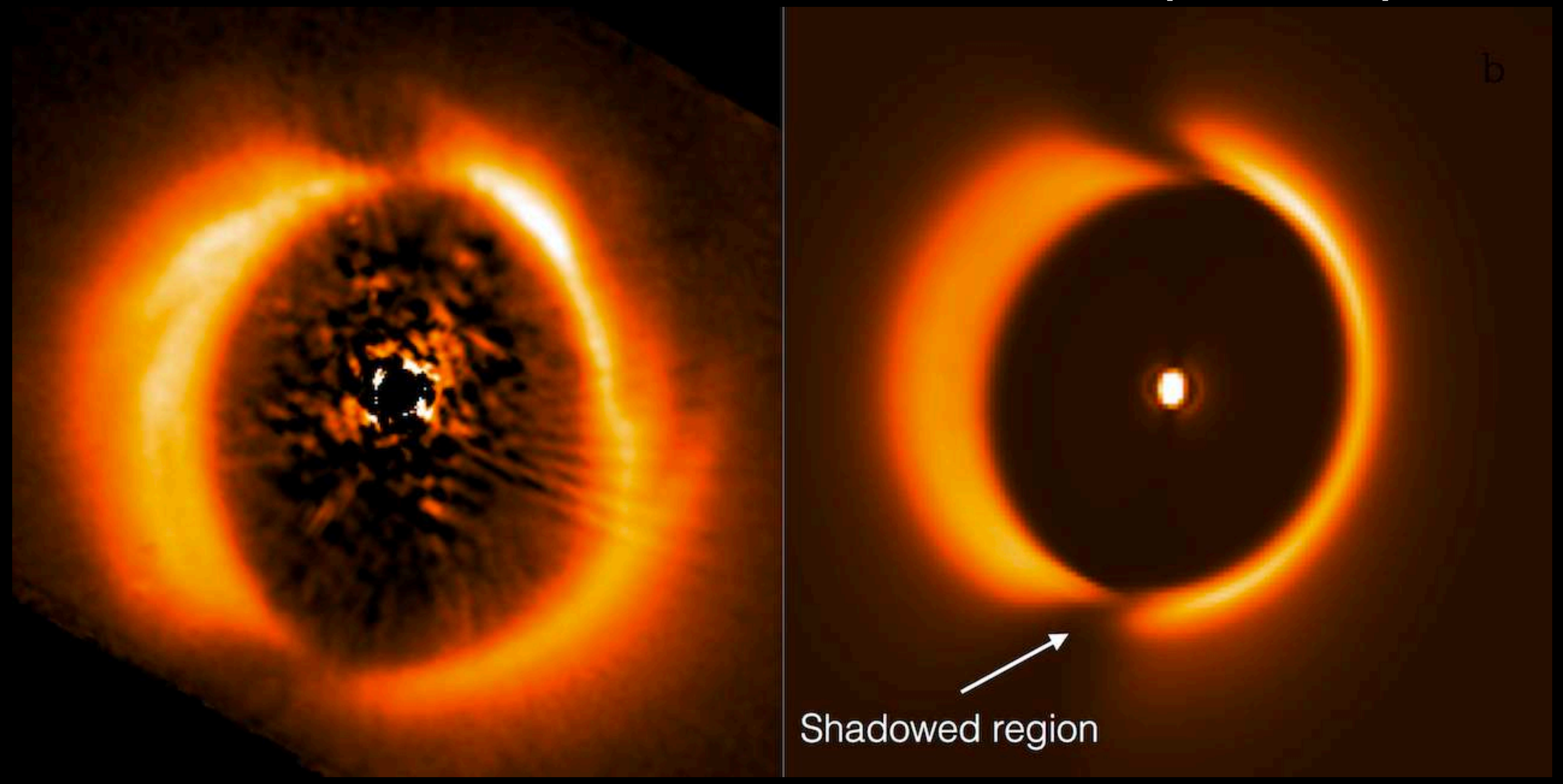
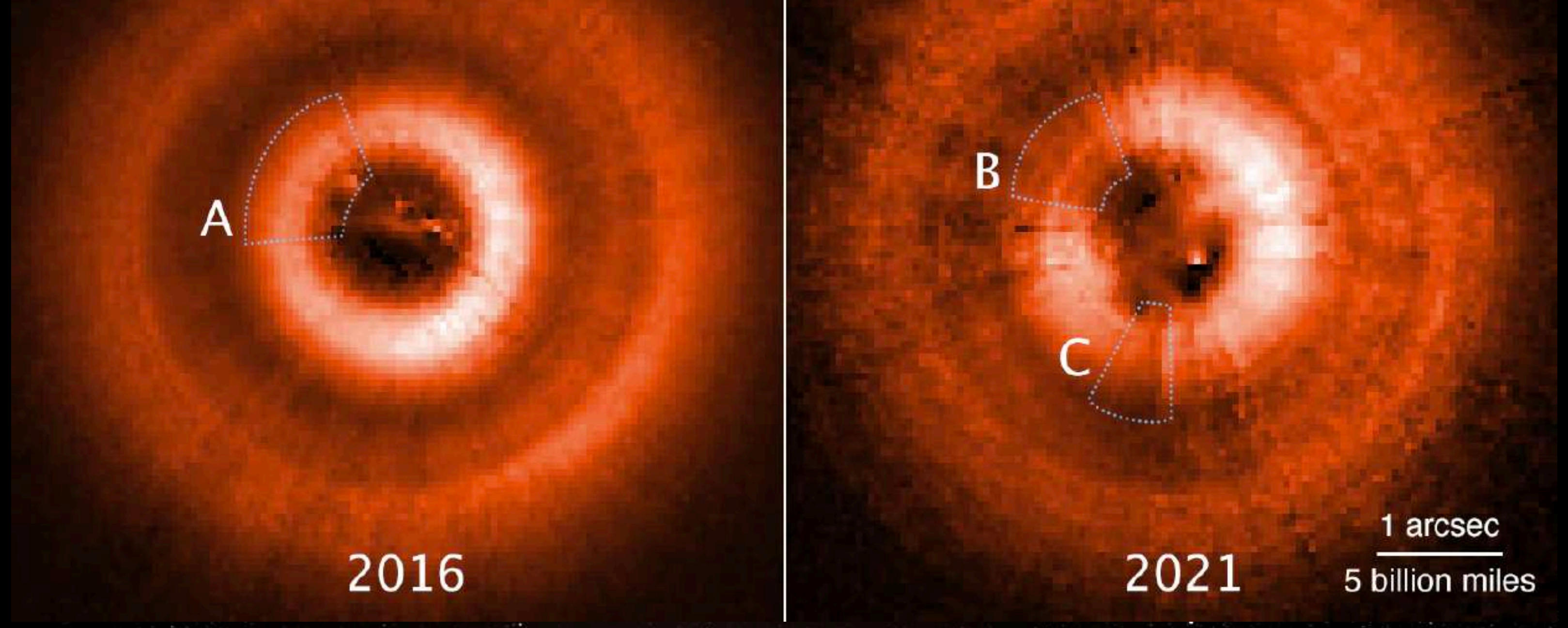
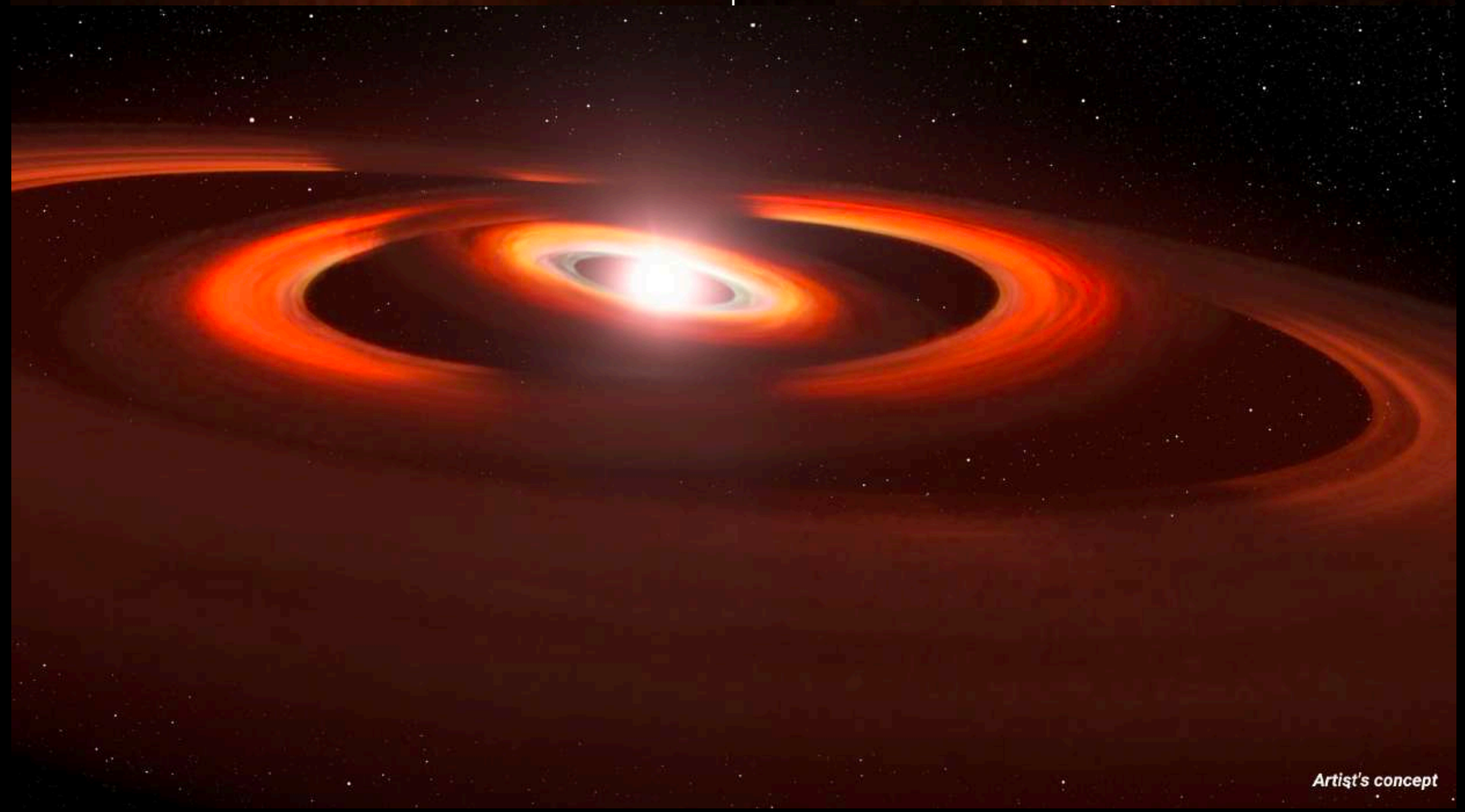
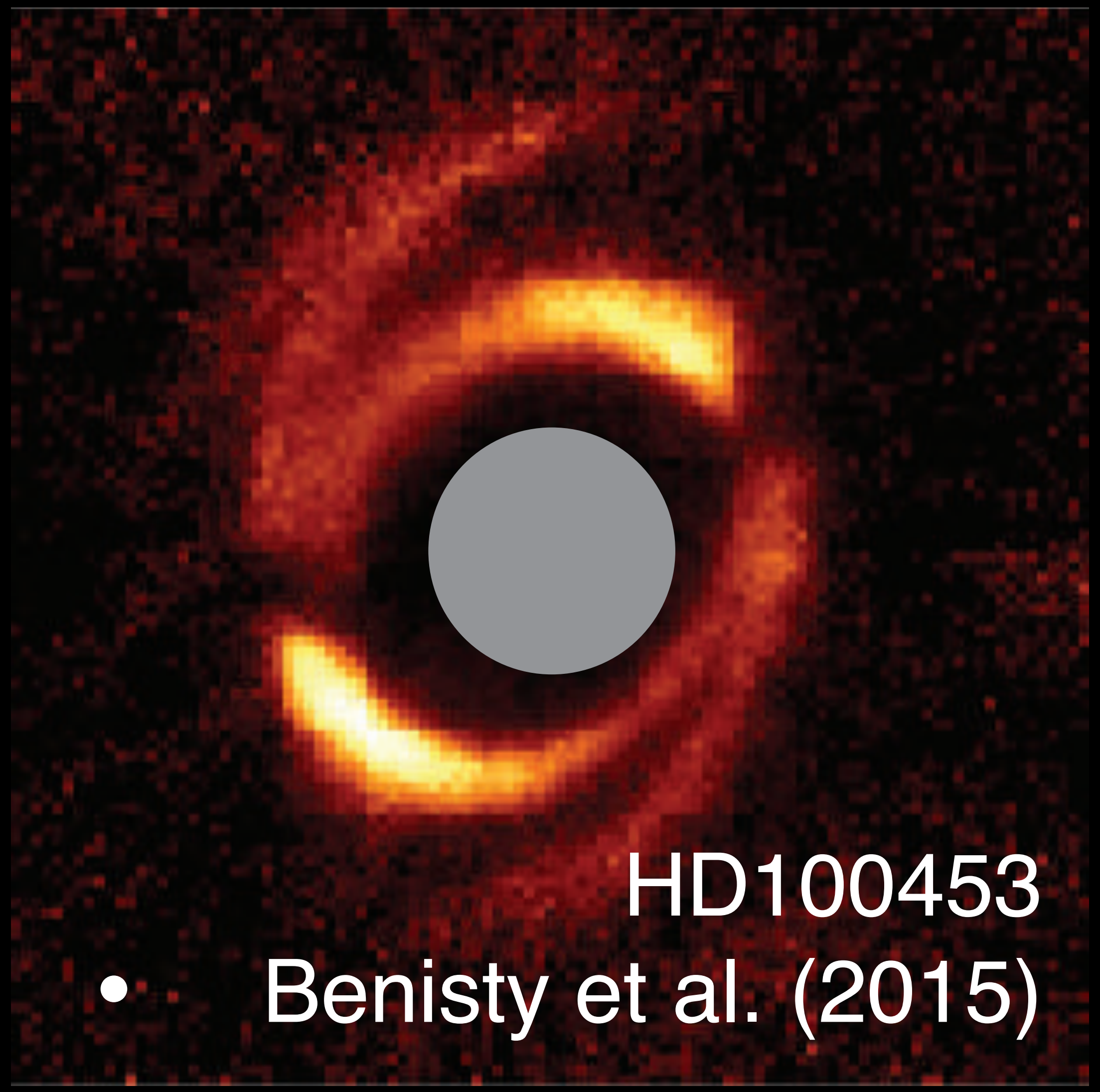


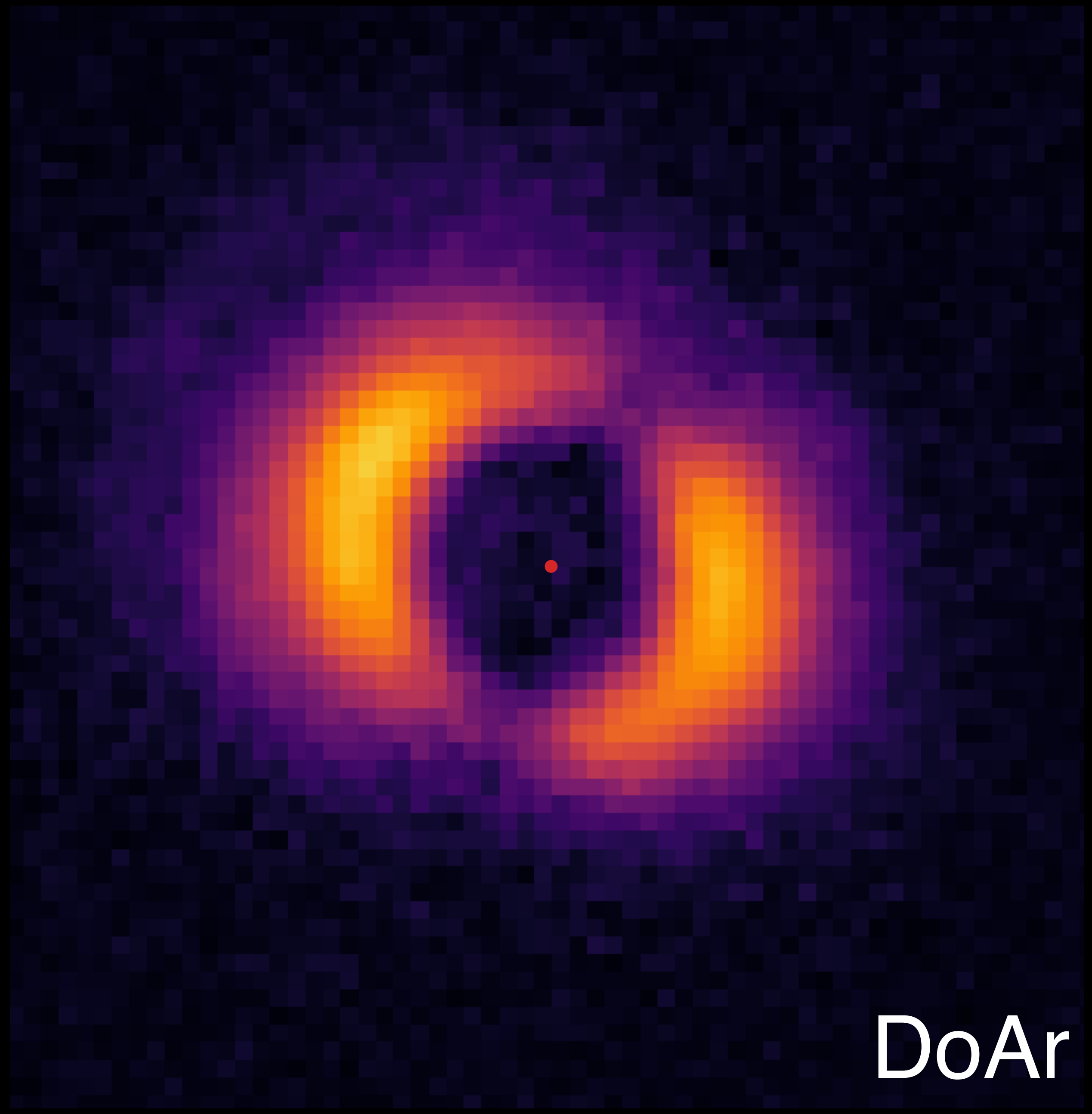
TW Hya, Debes et al. (2023)



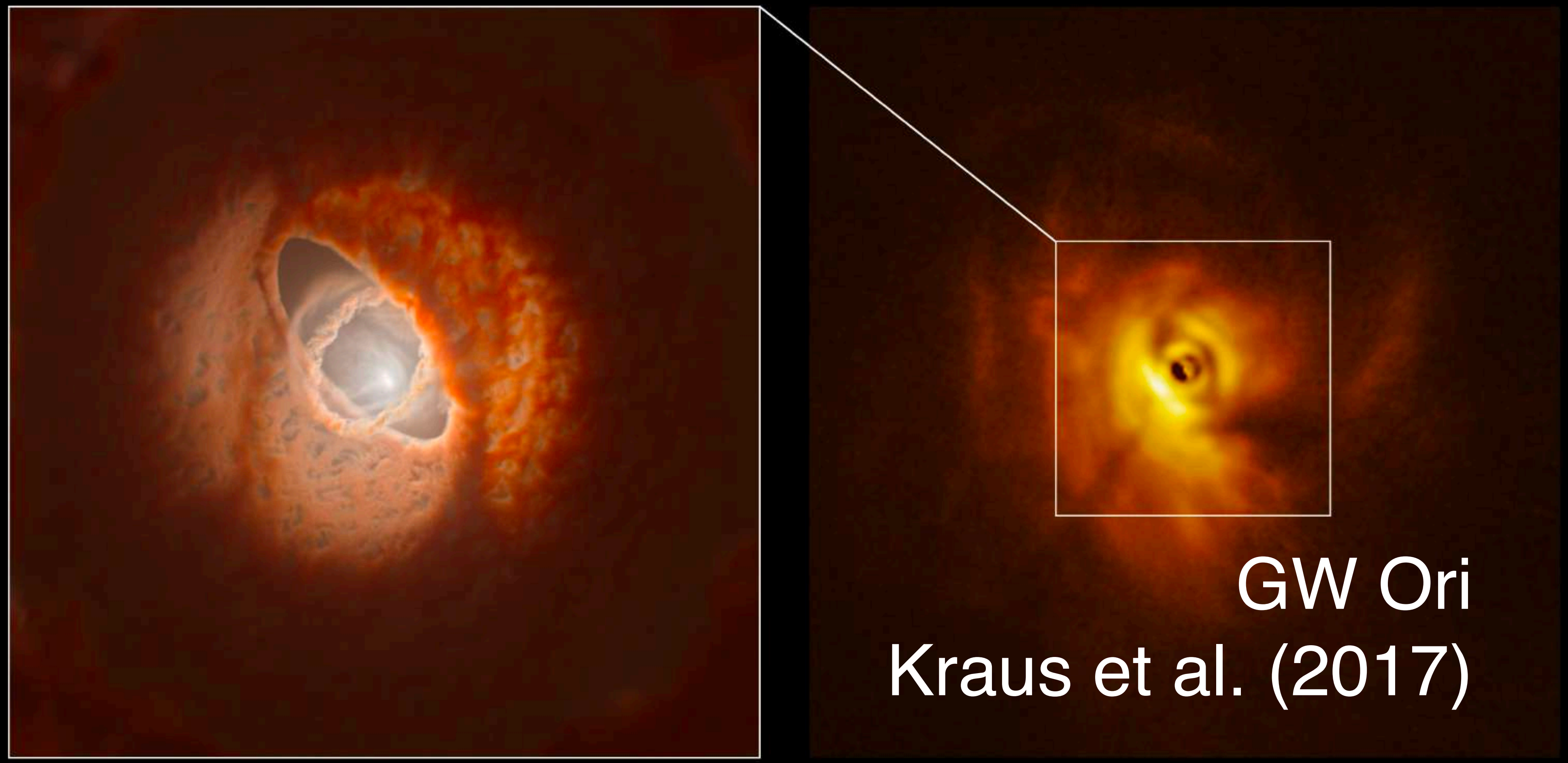




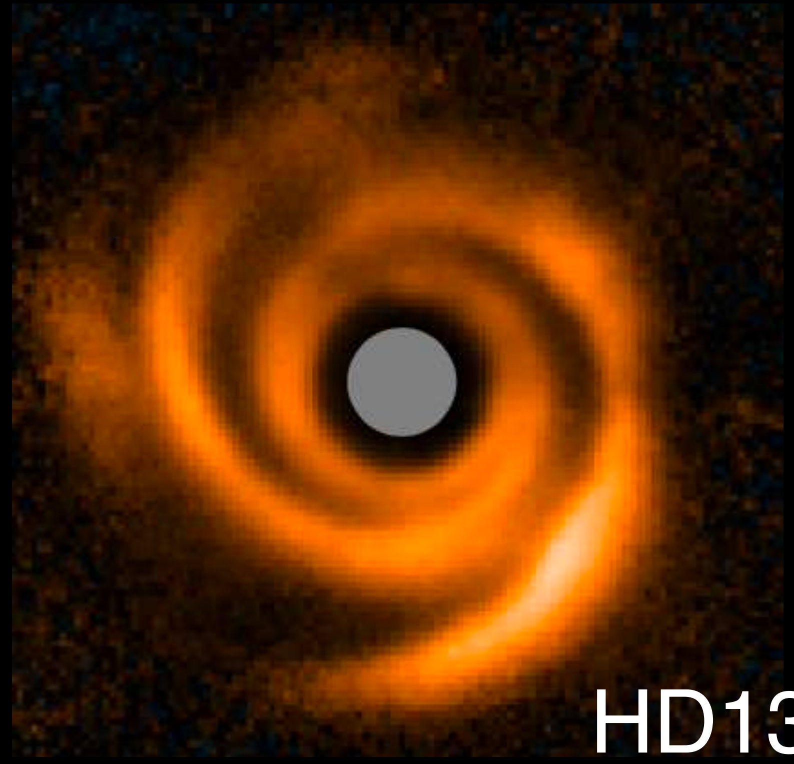
HD100453
Benisty et al. (2015)



DoAr 44
Carla Arce-Tord et al. (2023)



GW Ori
Kraus et al. (2017)



HD135344B
Stolker et al. (2016/2017)

Thanks

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