Intersection between ALMA data and VLTI data for ring disk structures

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MATISSE Science meeting
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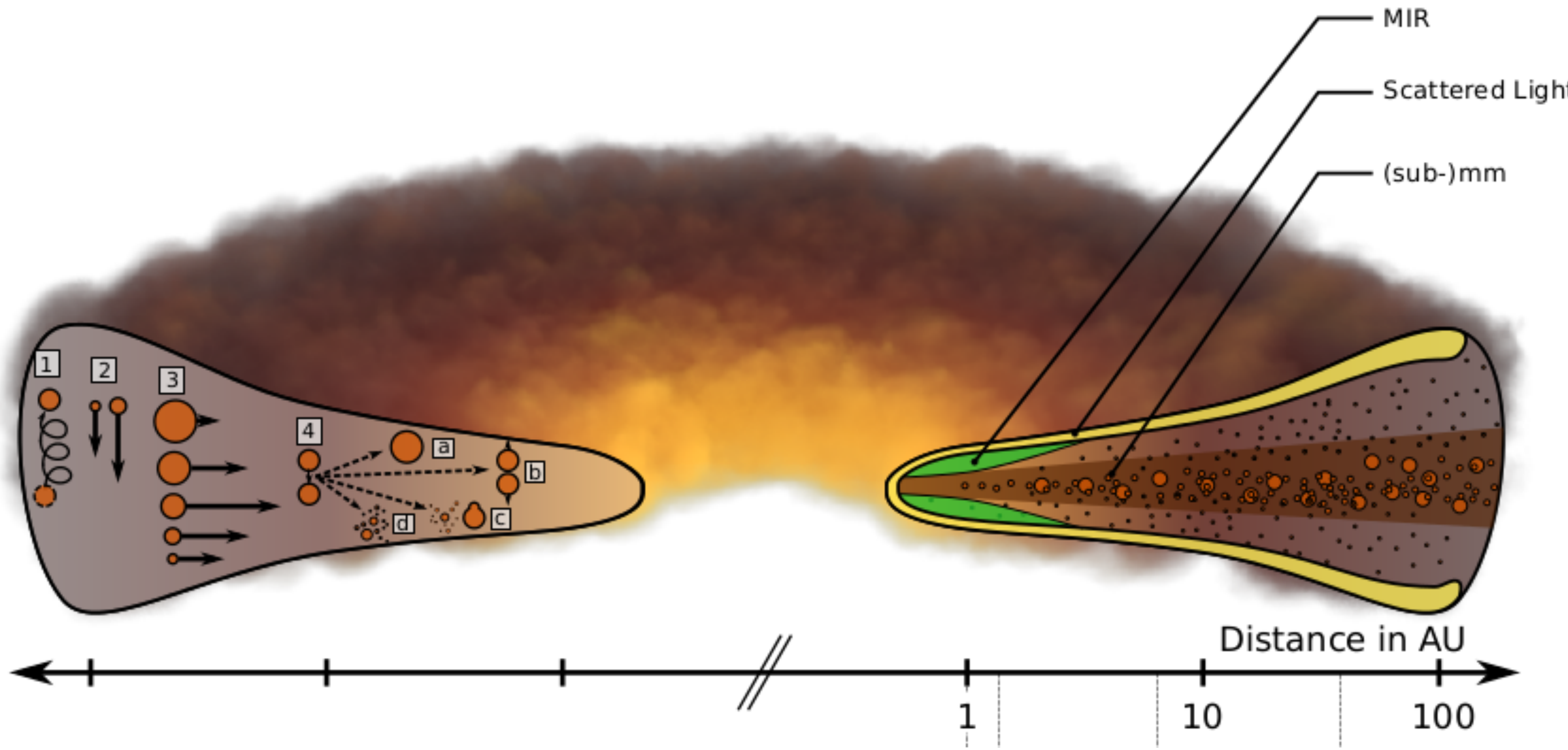
Sterrewacht Leiden

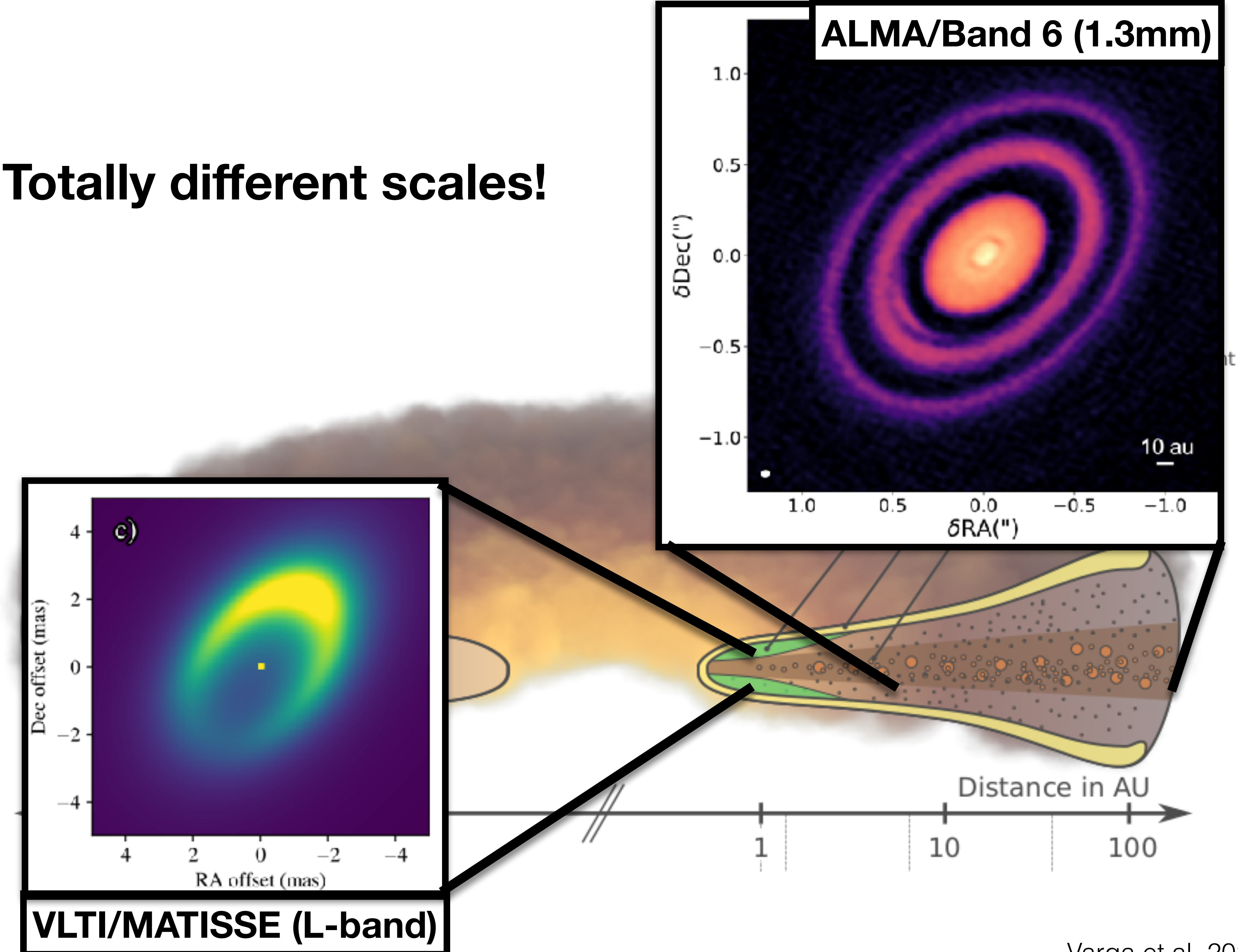
Protoplanetary disks

Emitting layers



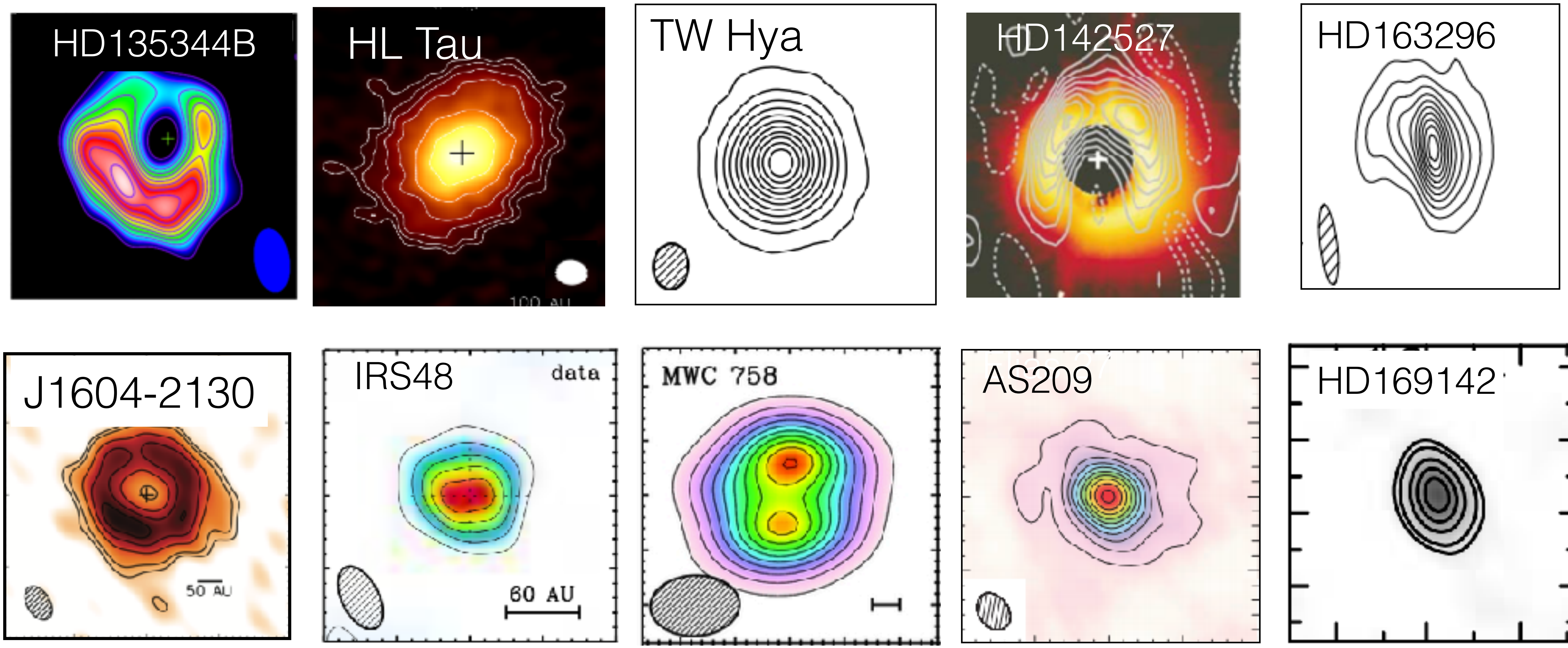
Testi et al. 2014

Totally different scales!



Varga et al. 2021
Isella et al. 2018

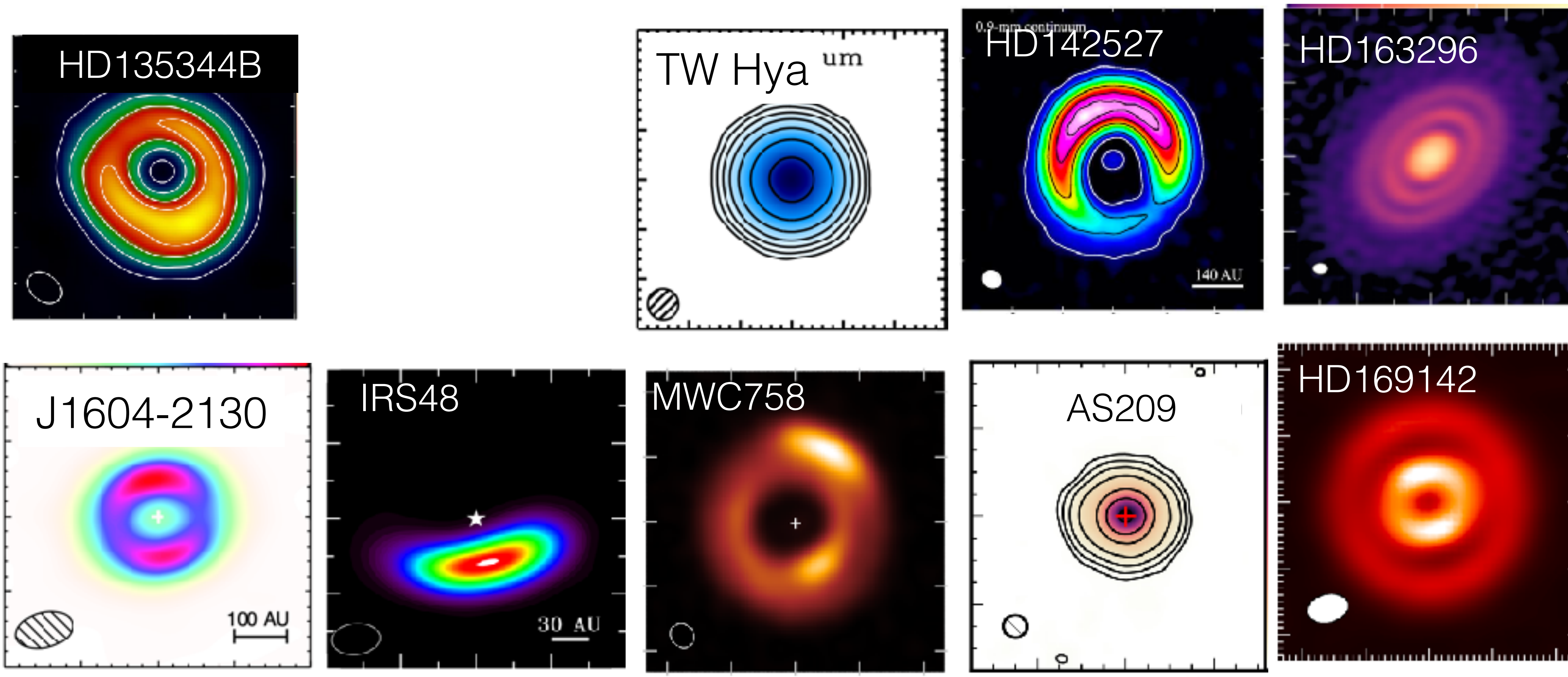
Revolution of ALMA (pre-ALMA)



Typical resolution ~0.5-0.8"

Andrews et al. 2011 & 2012, Brown et al. 2009 & 2012, Isella et al. 2007, Kwon et al. 2011, Matthews et al. 2012, Ohashi et al. 2008, Perez et al. 2012, Raman et al. 2006

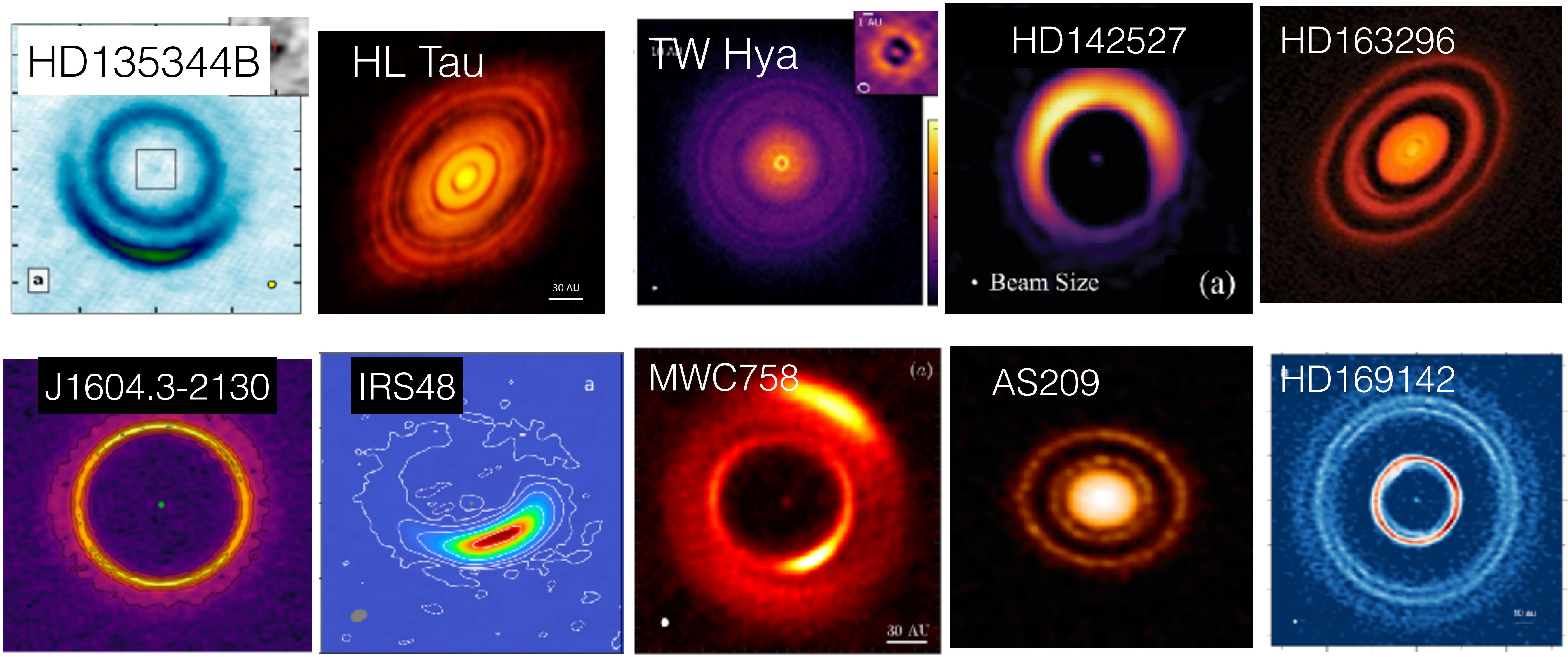
Revolution of ALMA (Early Science)



Typical resolution ~0.3-0.5"

Perez et al. 2014, Qi et al. 2013, Fukagawa et al. 2013, Isella et al. 2016, Zhang et al. 2014, van der Marel et al. 2013, Boehler et al. 2018, Huang et al. 2016, Fedele et al. 2017

Revolution of ALMA (long baseline)



Typical resolution ~0.05-0.1"

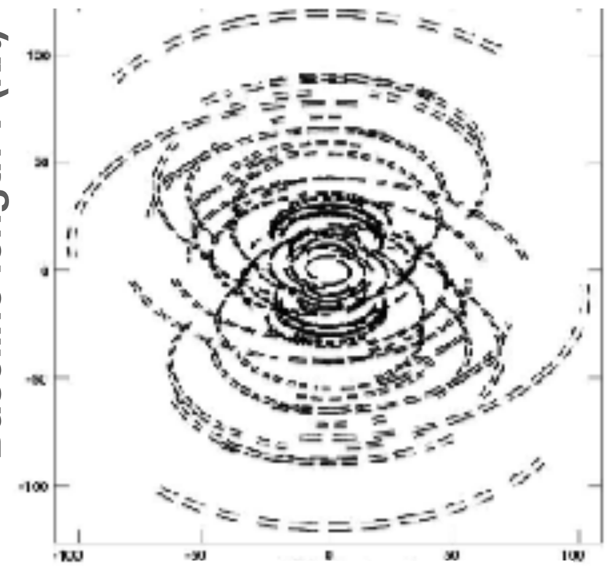
Casassus et al. 2021, ALMA consortium et al. 2015, Andrews et al. 2016, Yamaguchi et al. 2020, Andrews et al. 2018, Stadler et al. 2022, Yang et al. 2023, Dong et al. 2018, Perez et al. 2018

ALMA vs VLTI

UV-coverage

Typical uv-coverage pre-ALMA

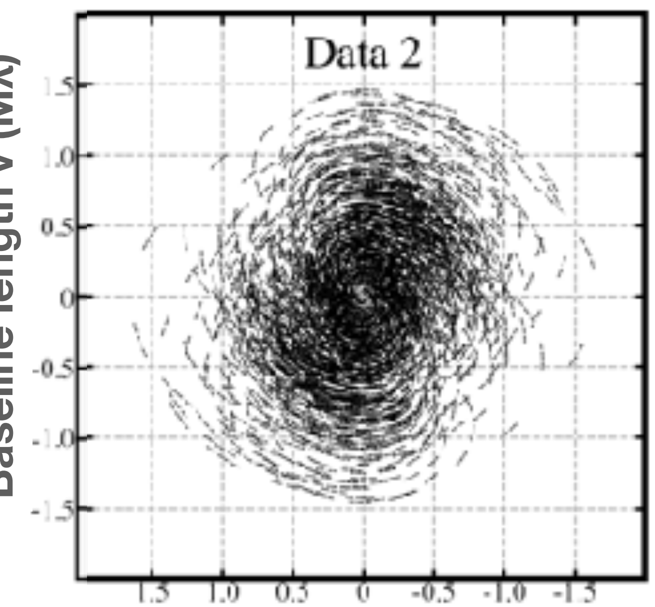
Baseline length v (kλ)



Baseline length u (kλ)

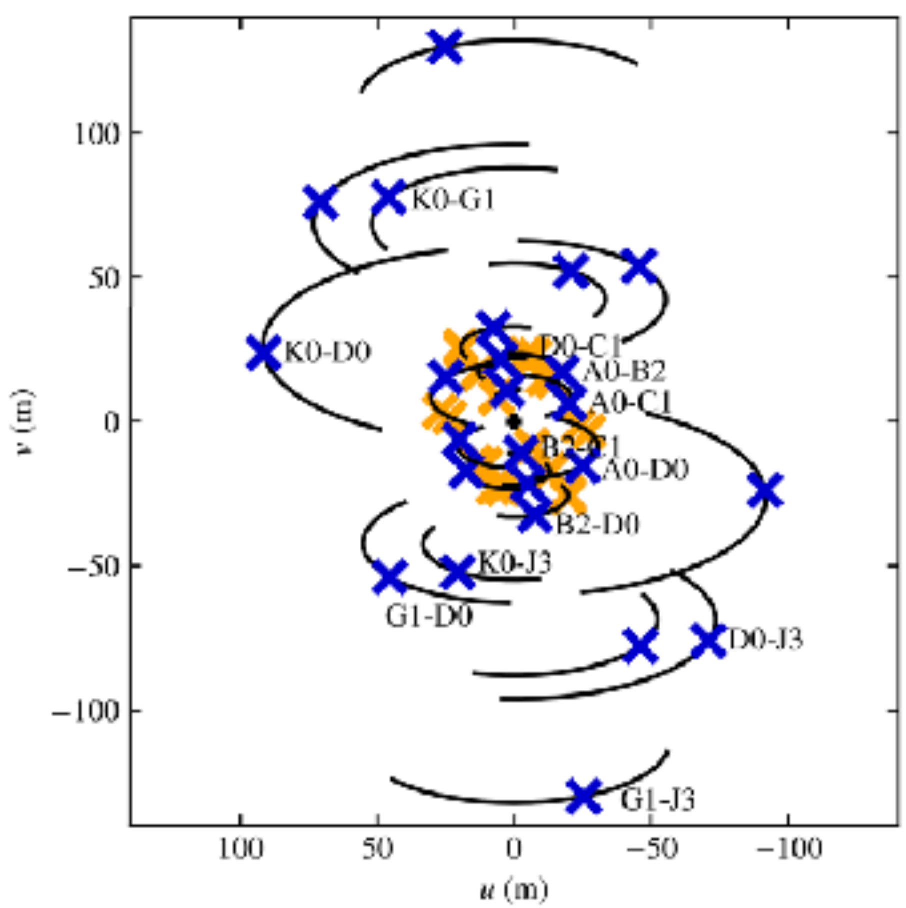
Typical uv-coverage ALMA

Baseline length v (Mλ)



Baseline length u (Mλ)

Typical uv-coverage MATISSE



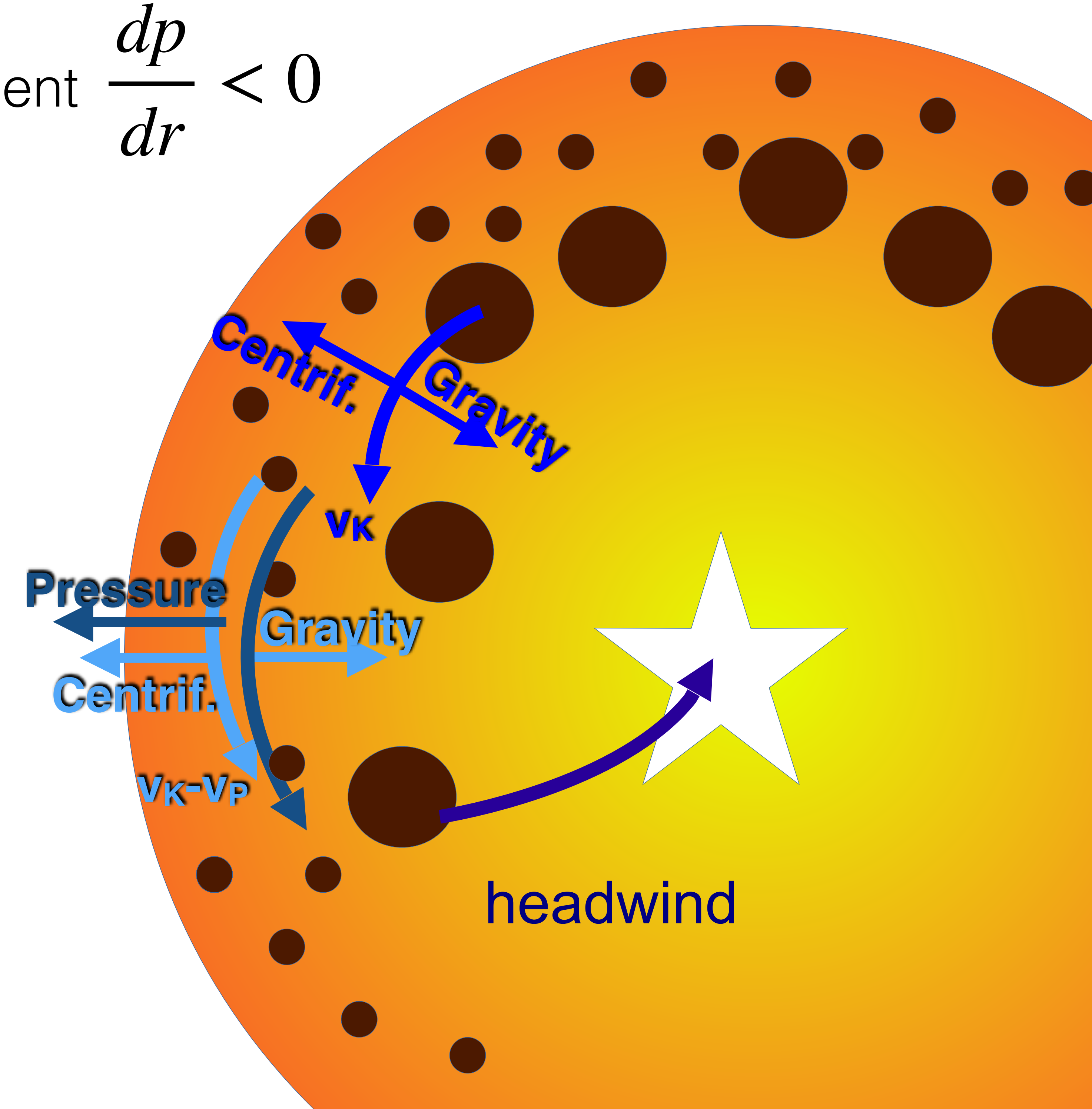
Varga et al. 2021

So what's the origin of dust rings?

Recall:

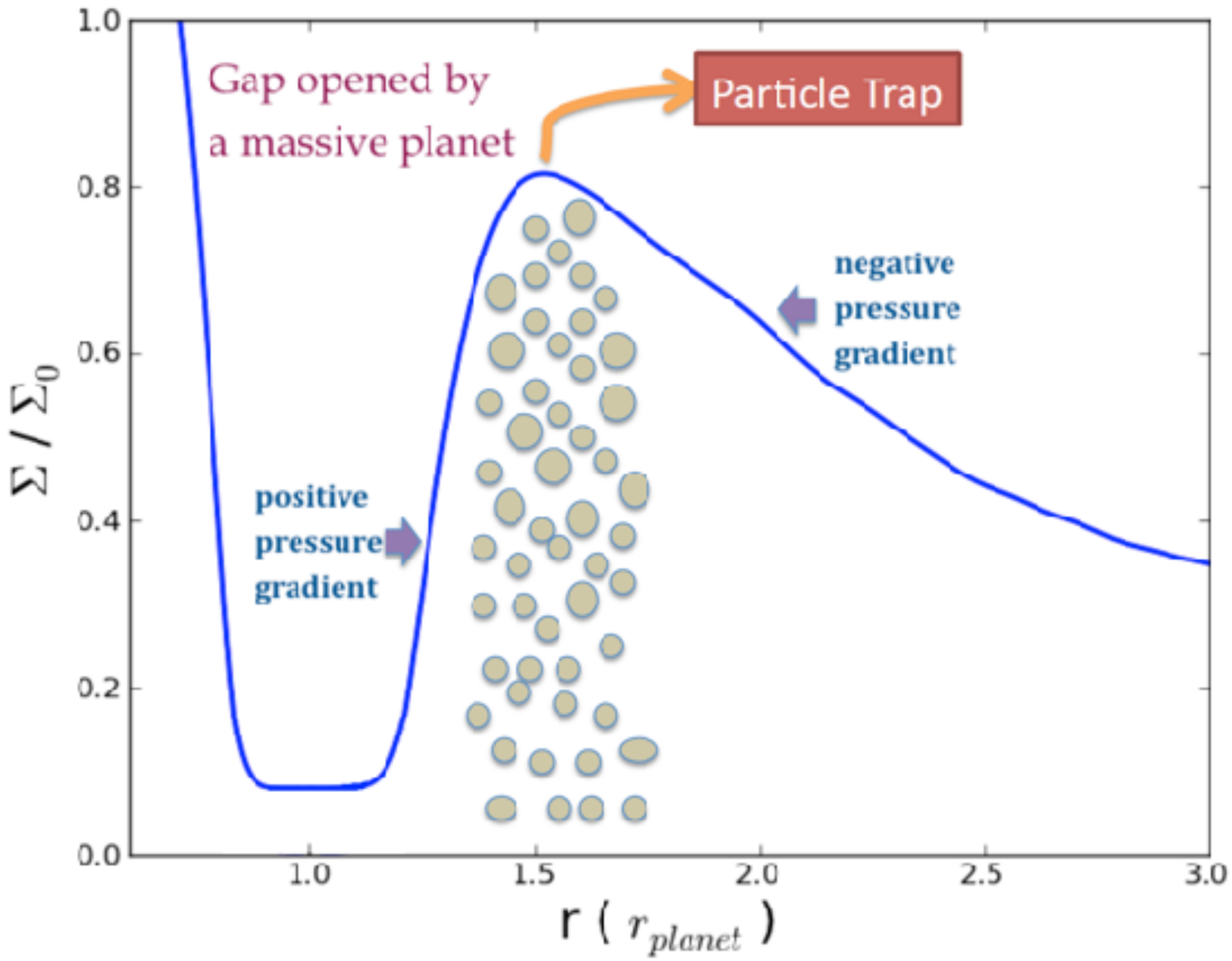
- Gas disk has a pressure gradient $\frac{dp}{dr} < 0$
  - Radial inward drift dust
- Large particles move towards high pressure
- Dust disk evolves differently than the gas disk

=> Need pressure bump to prevent radial drift

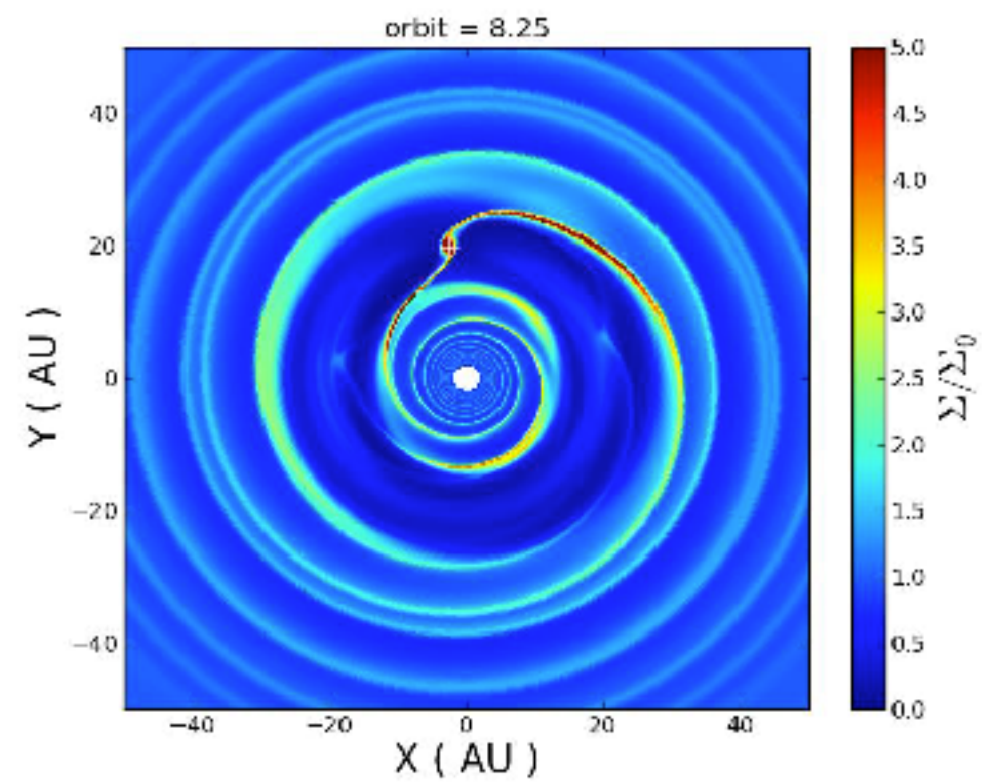


Weidenschilling 1977

Dust trapping



Rossby Wave Instability results in vortex: azimuthal dust trap



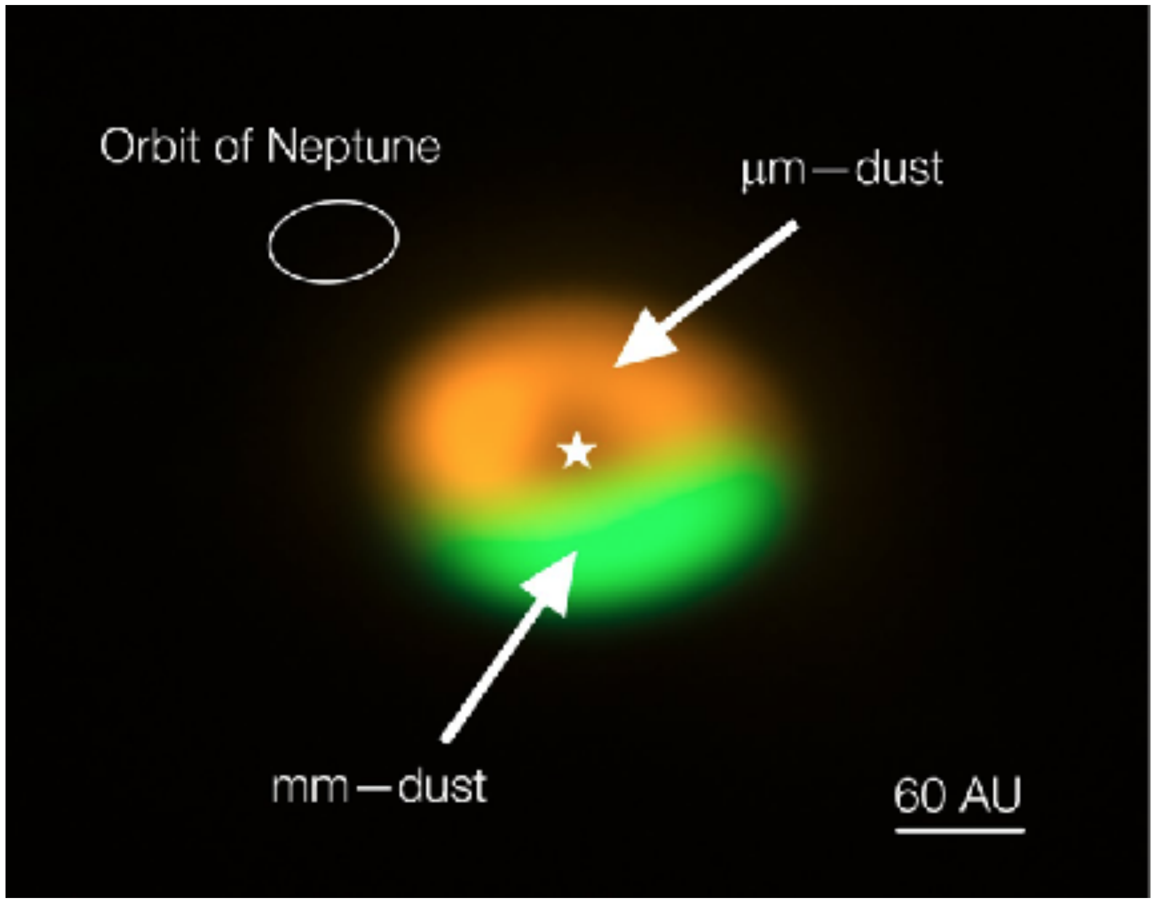
Varniere et al 2007
Pinilla et al. 2012
Zhu et al. 2012

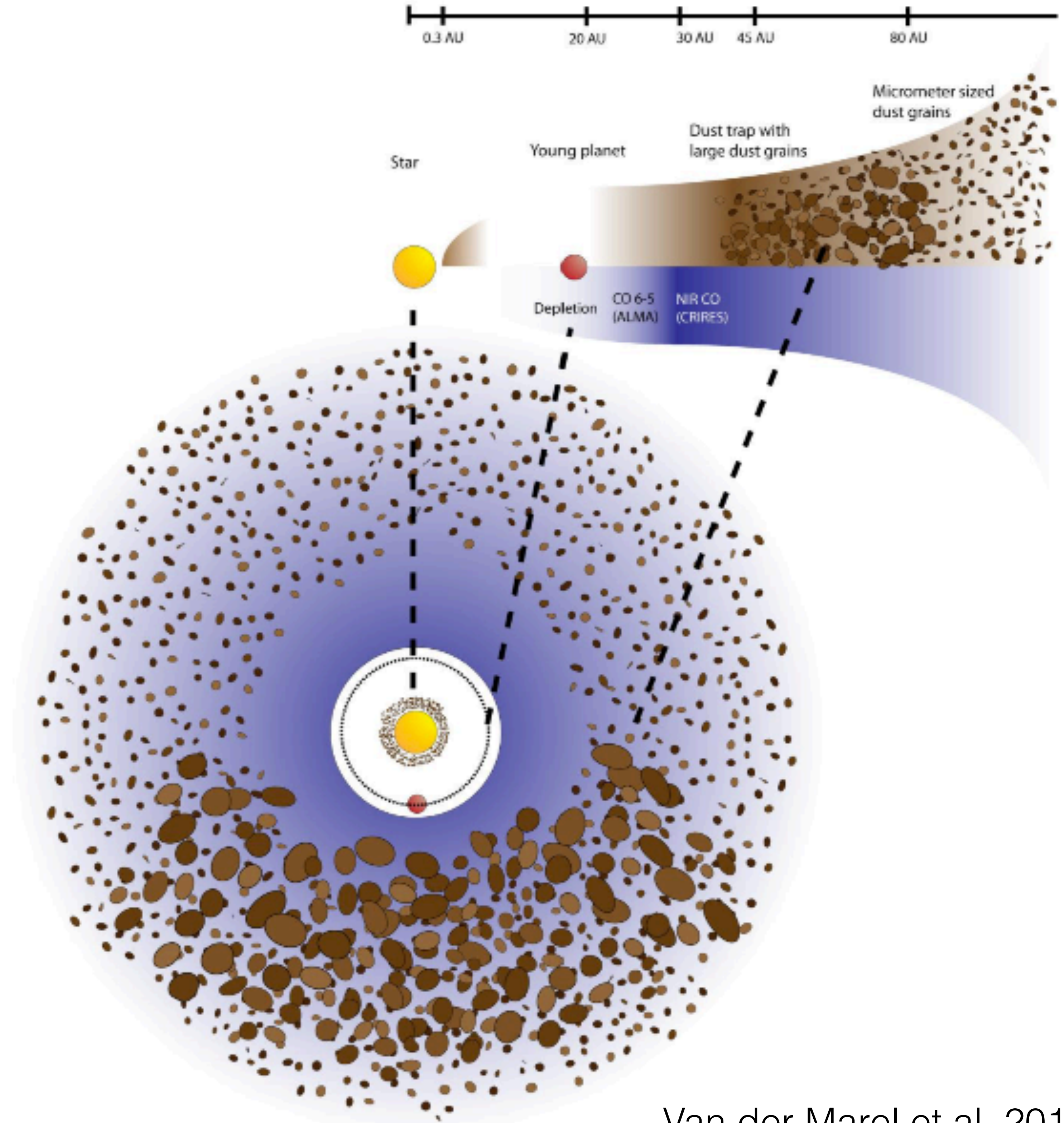
Barge & Sommeria 1995
Klahr & Henning 1997
Birnstiel et al. 2013

Problem:
dust traps require planets?

Recognize dust trapping

Distribution large vs small grains/gas





Segregation between large and small dust (and gas) is evidence for trapping

Van der Marel et al. 2013

What sets drift/trapping efficiency

- **Stokes number: property of particle**

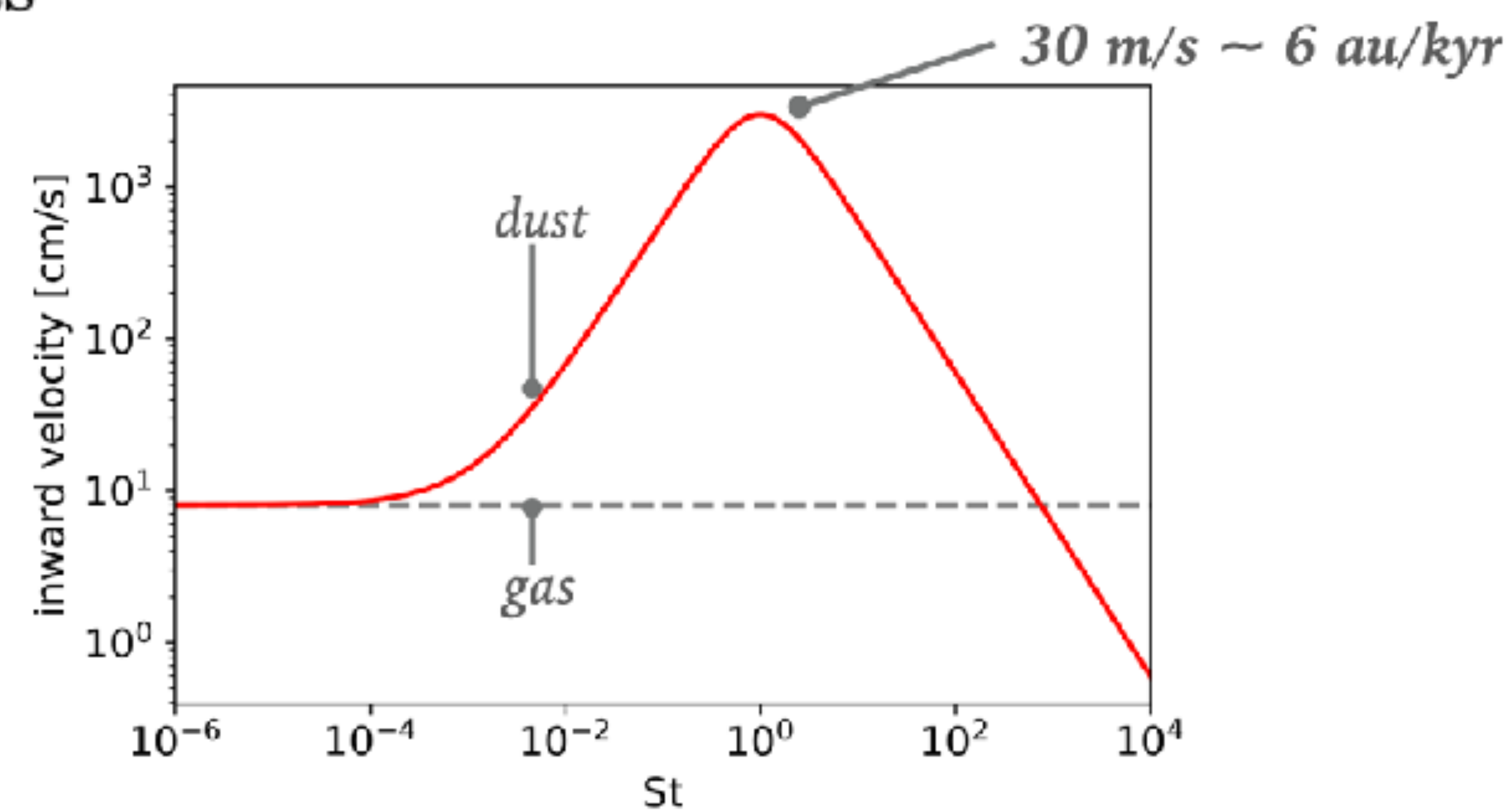
a = grain size

$$\mathrm{St} = \frac{t_{\rm stop}}{t_{\rm orb}} = \frac{\pi}{2}\frac{a\rho_\bullet}{\Sigma_{\rm gas}}$$

(`Epstein regime')

Gas surface density

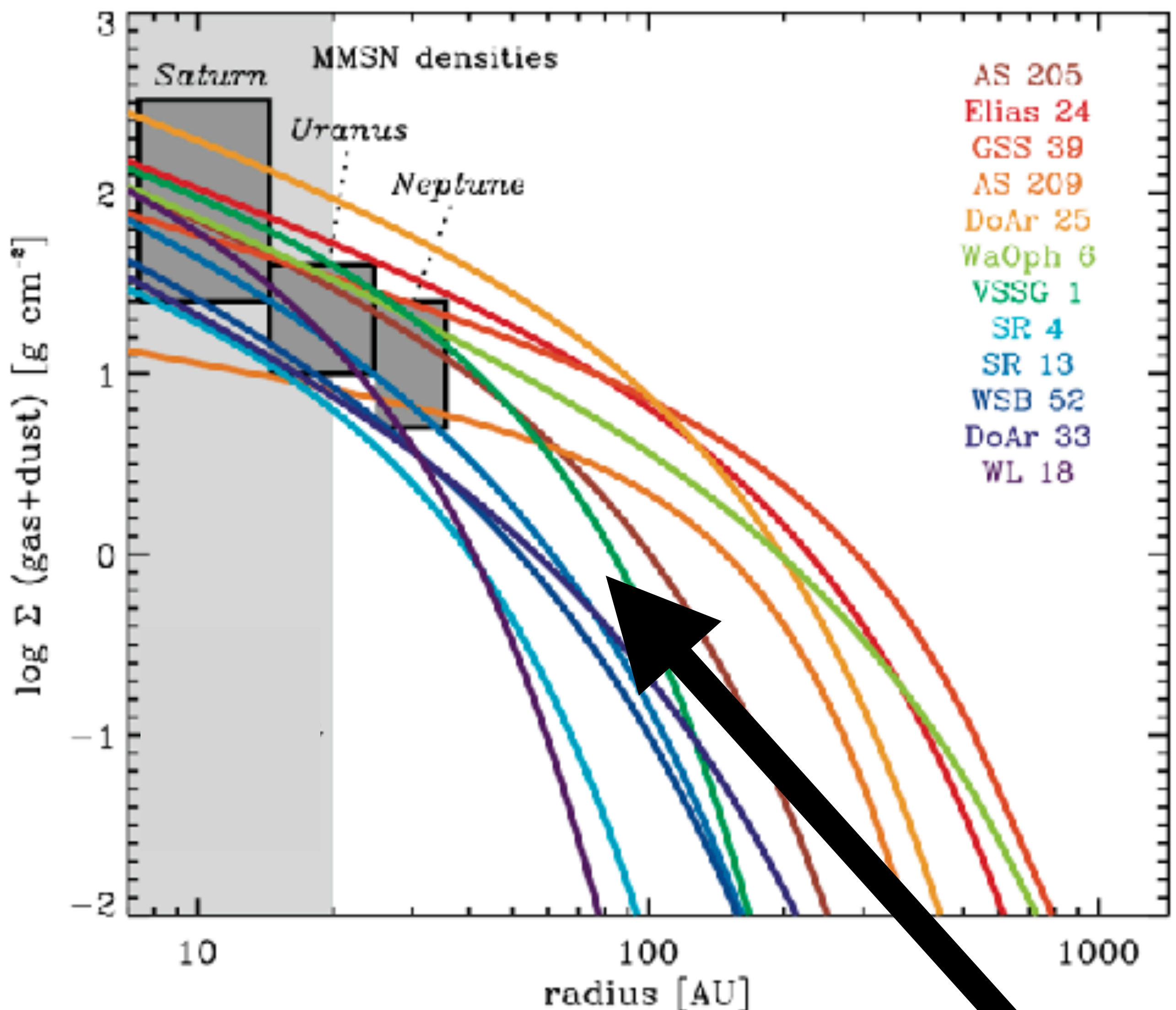
Drift velocity based on Stokes number



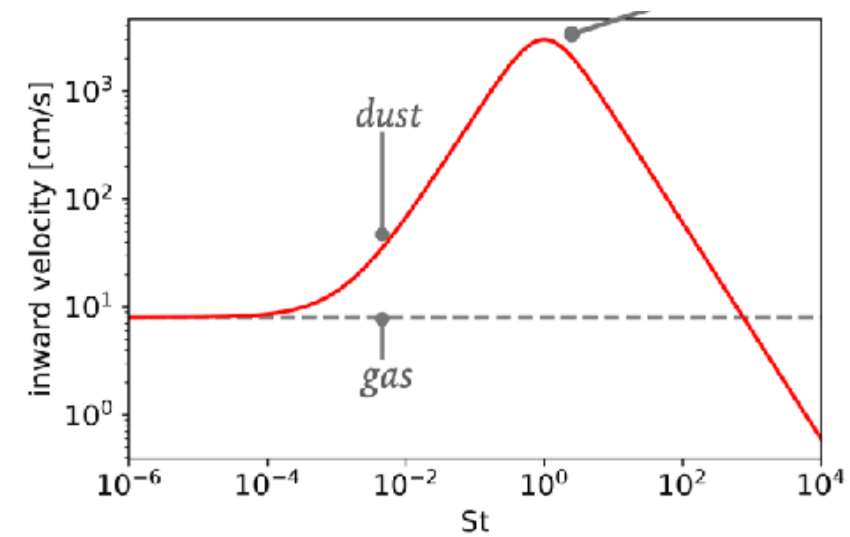
Drazkowska et al. 2023 (PPVII)

What sets drift/trapping efficiency

Stokes numbers



$$\mathrm{St} = \frac{\pi}{2} \frac{a\rho_\bullet}{\Sigma_{\mathrm{gas}}}$$



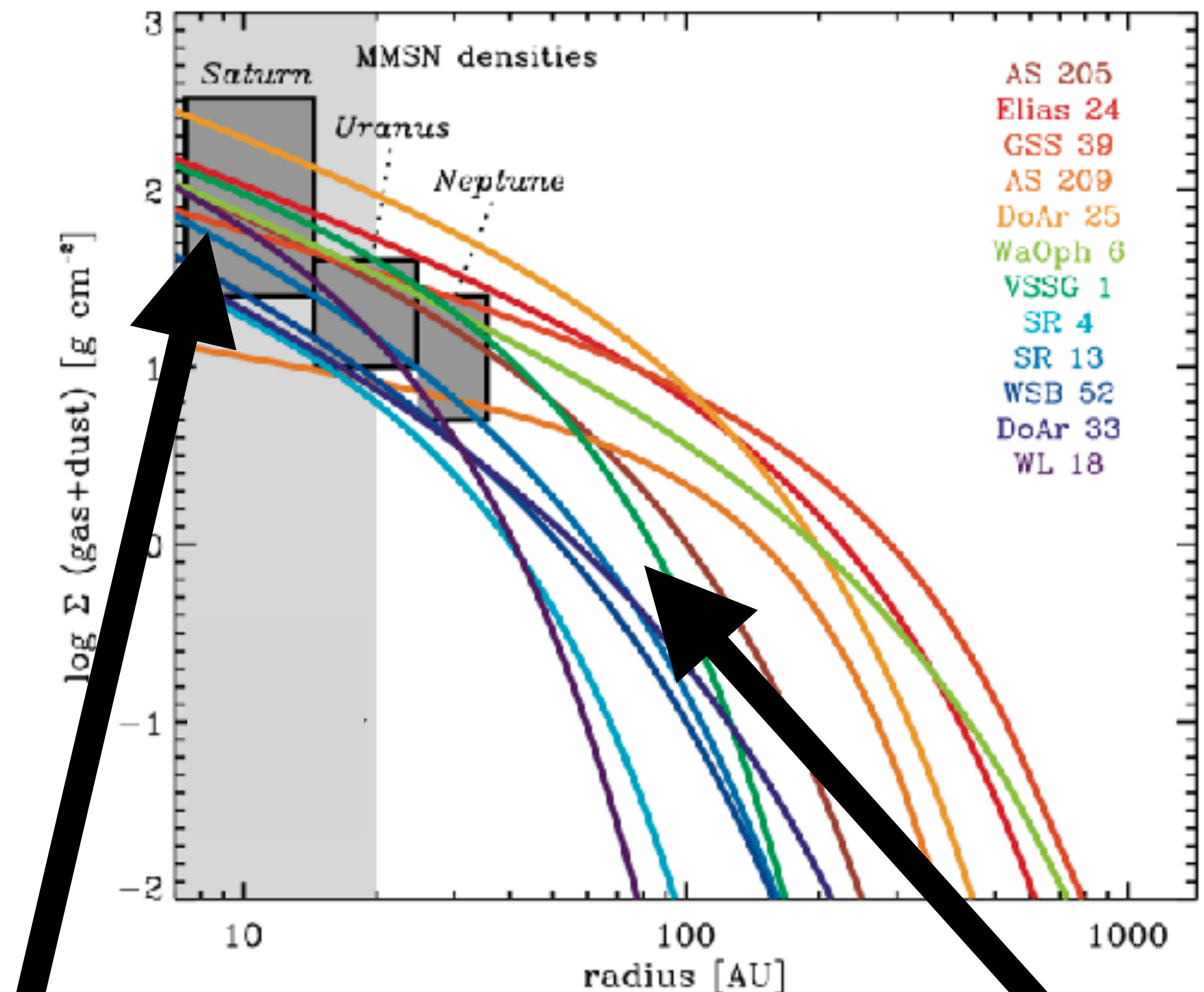
At 100 au, mm-grains (ALMA) have St ~ 10^{-2} - 10^{0}: => efficient drift/trapping

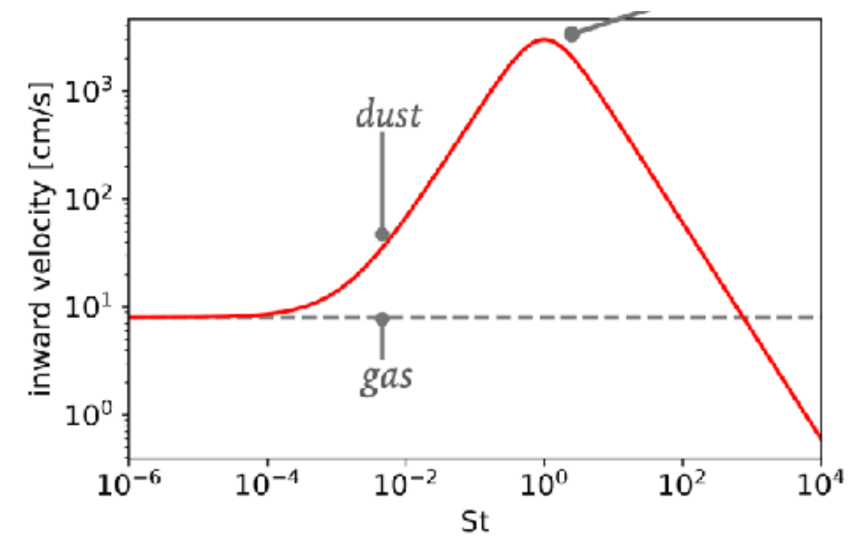
Williams & Cieza 2011

What sets drift/trapping efficiency

Stokes numbers

$$\mathrm{St} = \frac{\pi}{2}\frac{a\rho_\bullet}{\Sigma_{\mathrm{gas}}}$$





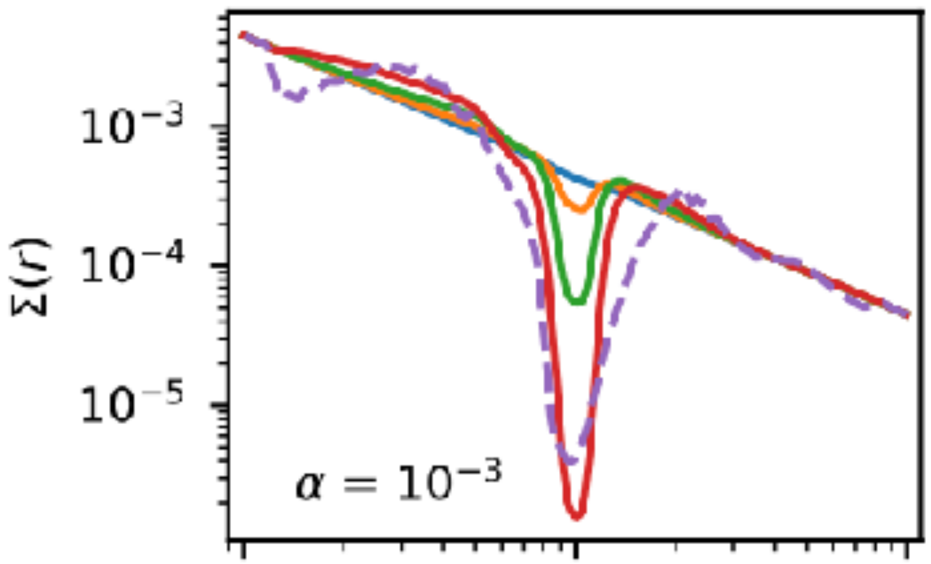
At 1 au, 10 micron-grains (MATISSE)
have St ~ 10^{-4} - 10^{-6}:
=> no efficient drift/trapping

At 100 au, mm-grains (ALMA)
have St ~ 10^{-2} - 10^{0}:
=> efficient drift/trapping

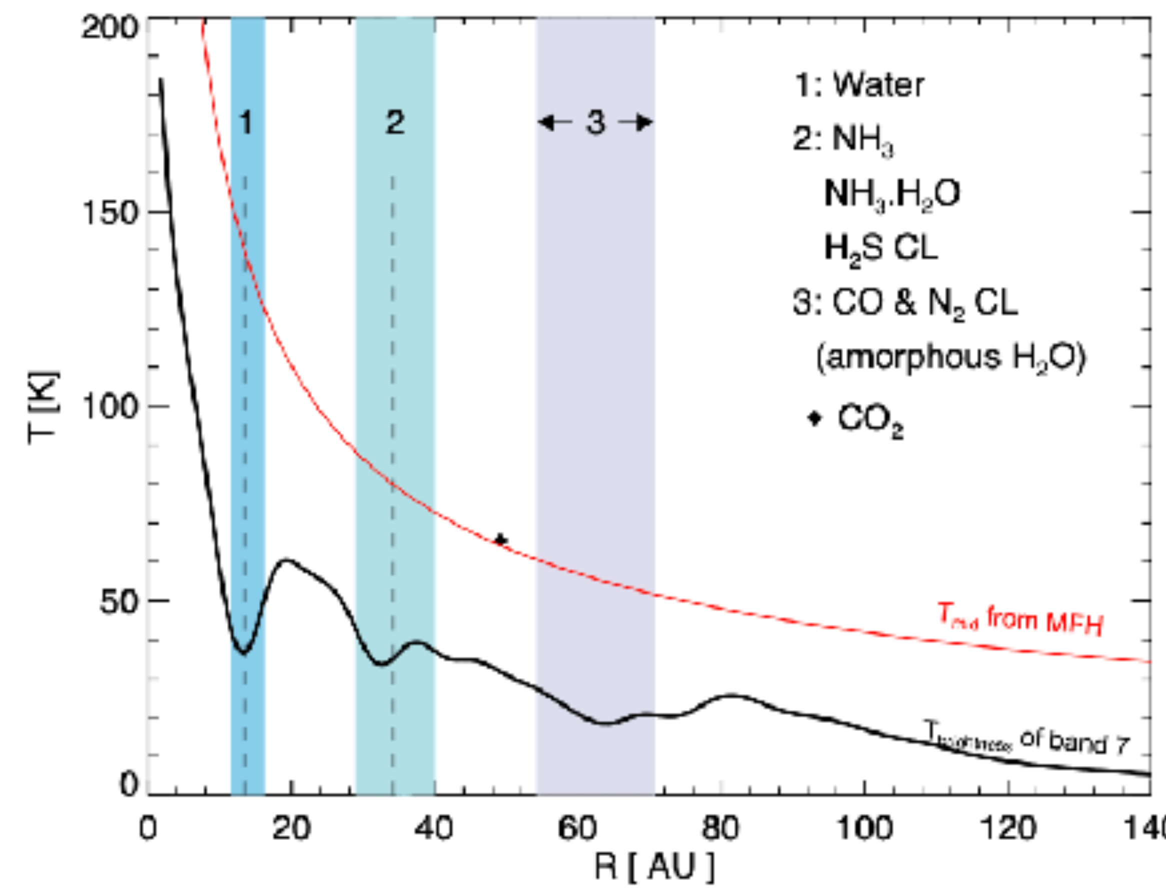
===> Do not expect to observe real dust traps (concentrations) in inner regions: dust follows the gas

Origin dust traps

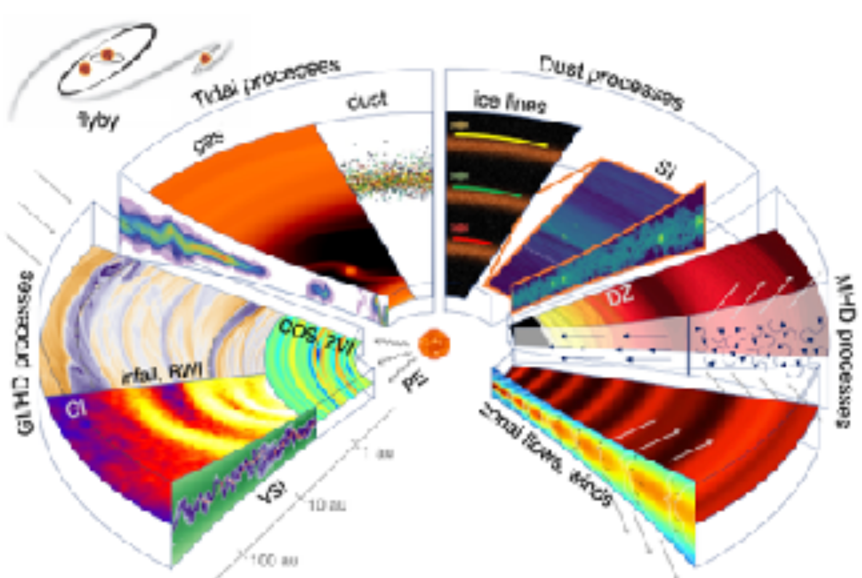
1. **Planets**
   (difficult to explain formation and occurrence at gap radii)



2. Snowlines: enhanced dust growth at snowline radii
(later disproven for larger samples)



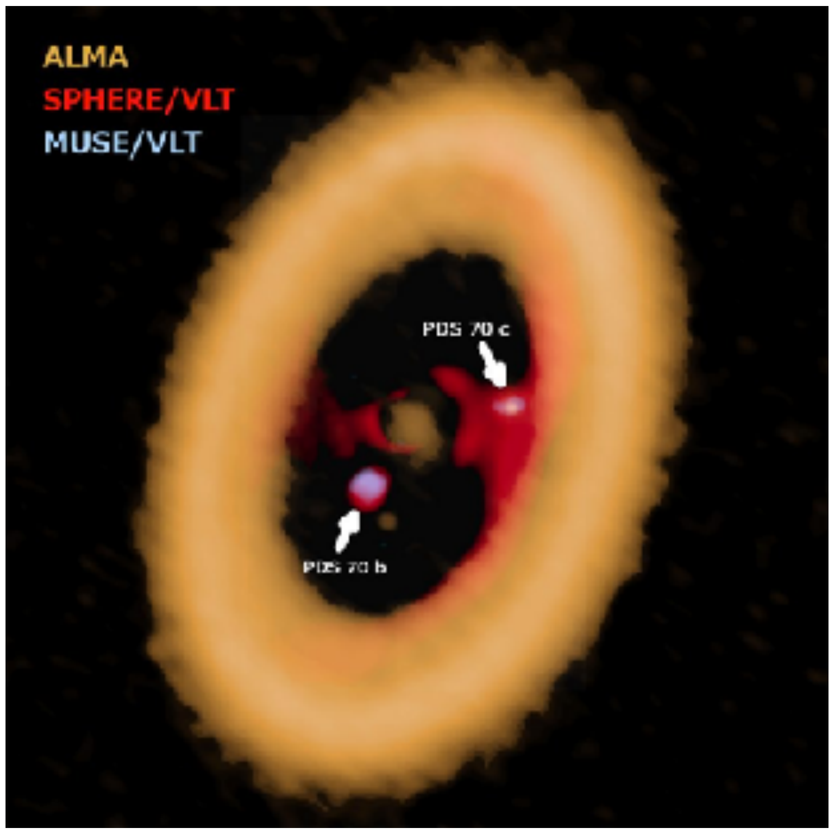
3. Hydrodynamic/MHD instabilities
(hard to prove or disprove)



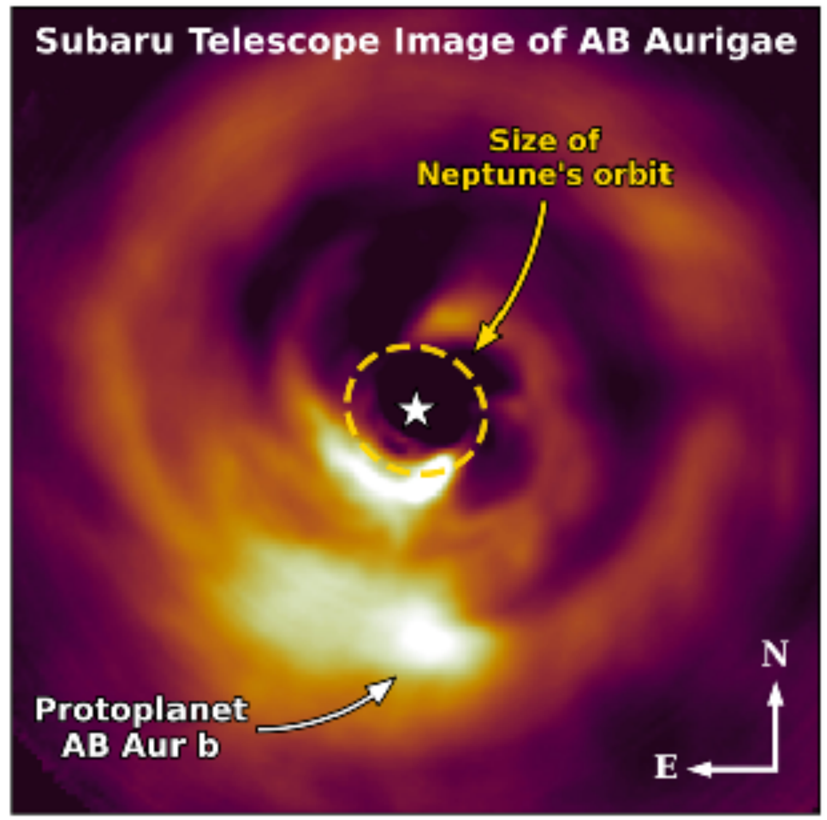
Zhang,S. et al. 2018
Zhang,K. et al. 2015
Long et al. 2018, van der Marel et al. 2019
Andrews 2020

Why we think it's planets

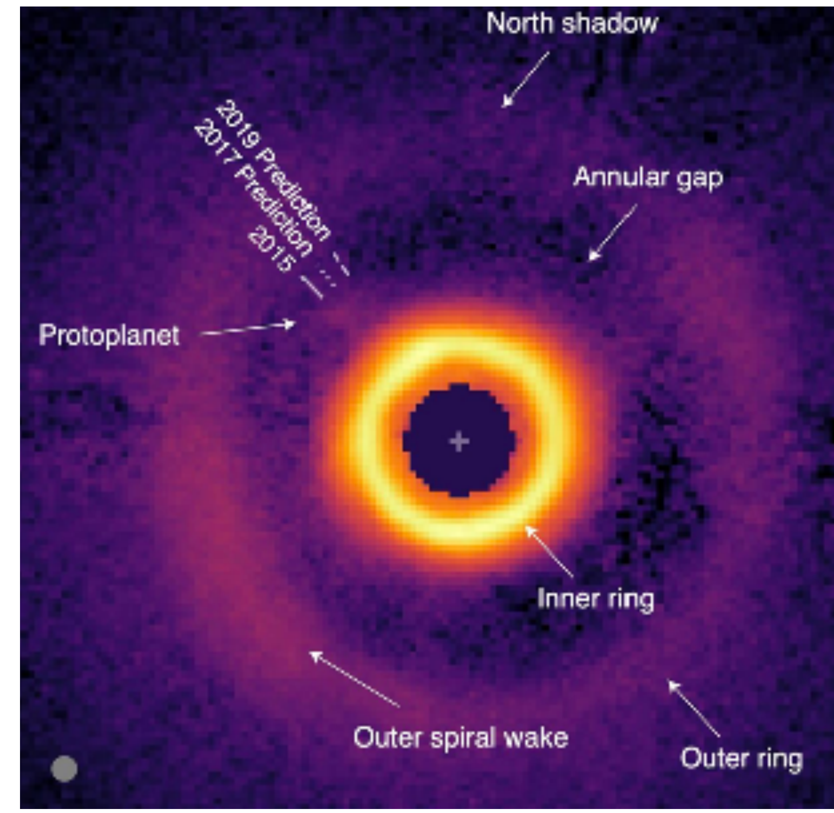
Direct detections of protoplanets



PDS70 b+c



AB Aur b



HD169142 b

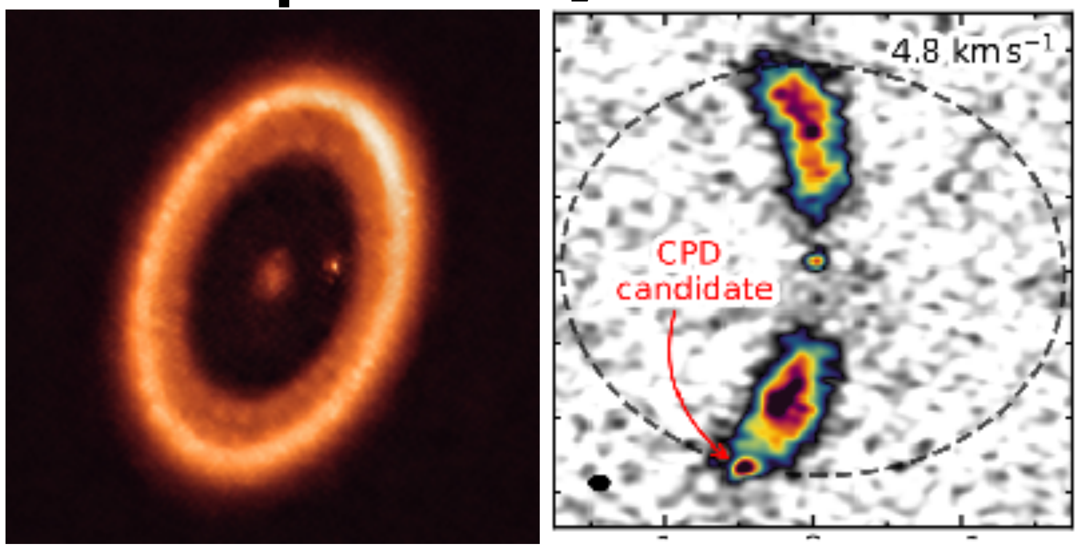
Super-Jovian protoplanets at wide (>20 au) orbits inside dust cavities

Planets and dust gaps (not traps) at few au detectable with MATISSE?

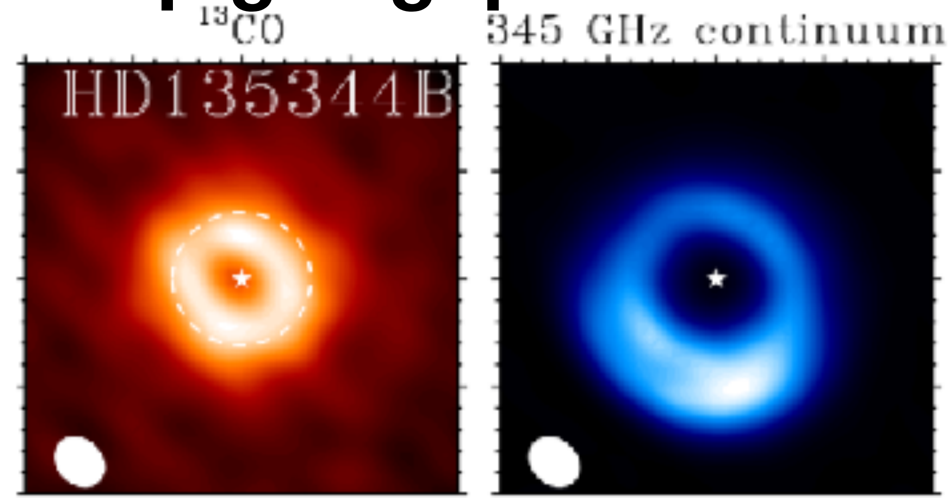
e.g. Keppler et al. 2018, 2021, Haffert et al. 2019, Currie et al. 2022, Hammond et al. 2023

Why we think it's planets

Circumplanetary disks

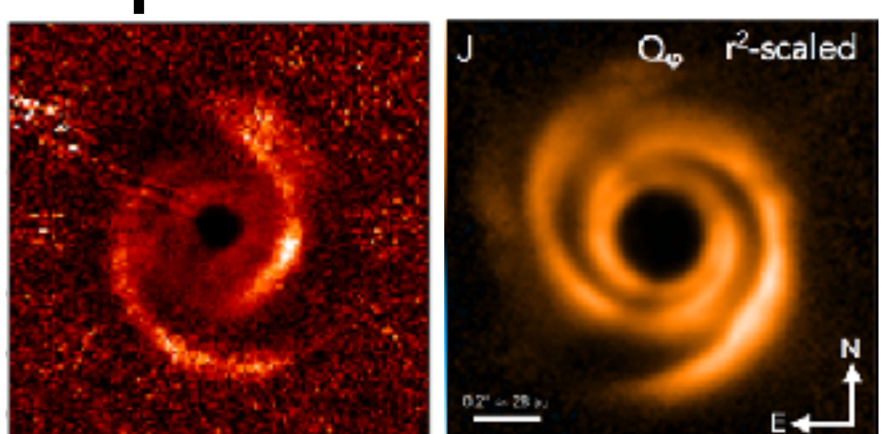


Deep gas gaps in $^{12\&13}CO$

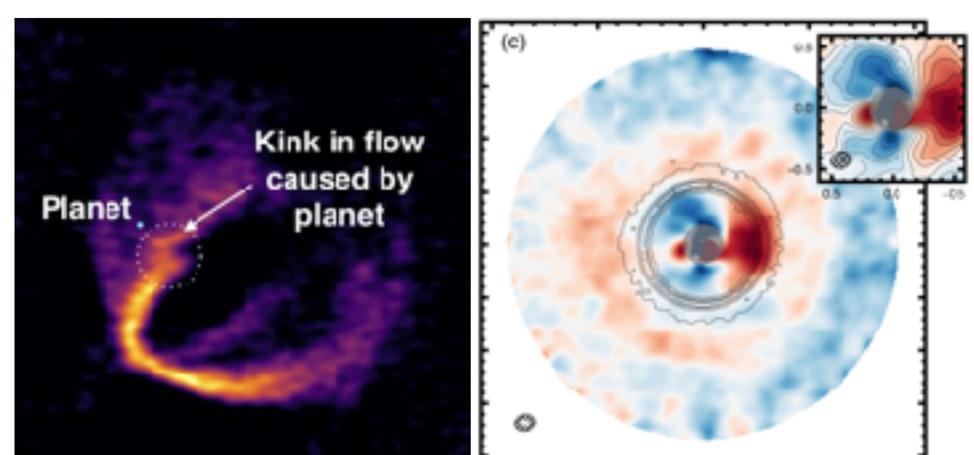


Indirect evidence for (super-)Jovian protoplanets at wide orbits

Spiral arms in NIR



Non-Keplerian motion in line cubes



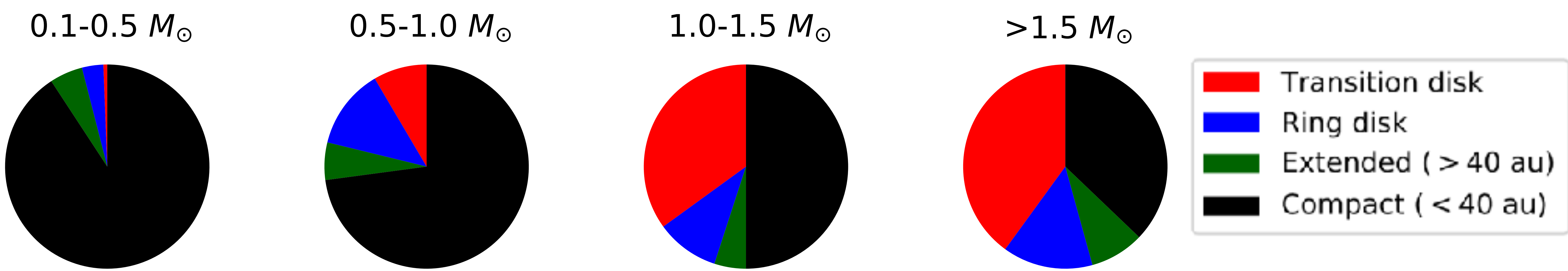
Mostly indirect: detection protoplanets is hard!

Benisty et al. 2021
Bae et al. 2022
Stolker et al. 2016
Benisty et al. 2017
Pinte et al. 2018
Stadler et al. 2022
VdMarel et al. 2016,2021

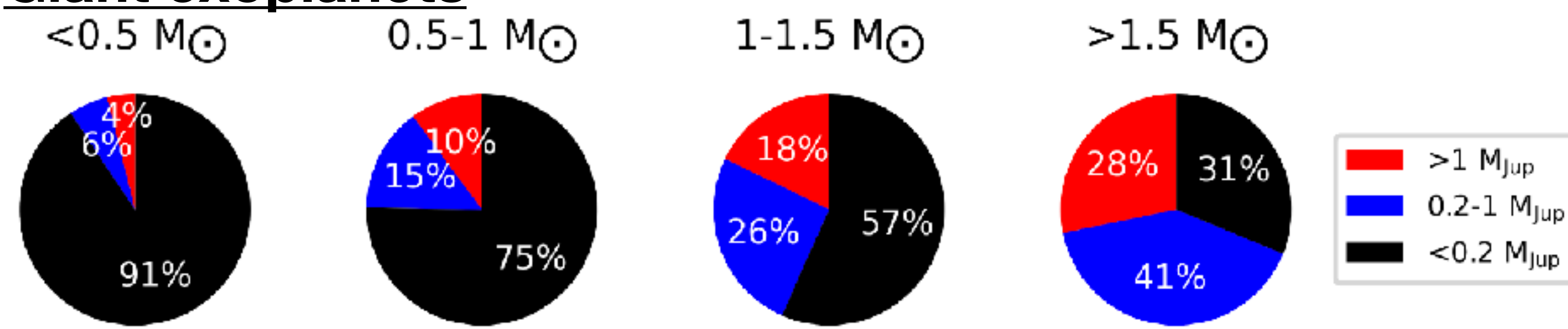
Why we think it’s planets

Giant exoplanets: stellar mass dependence

Disks

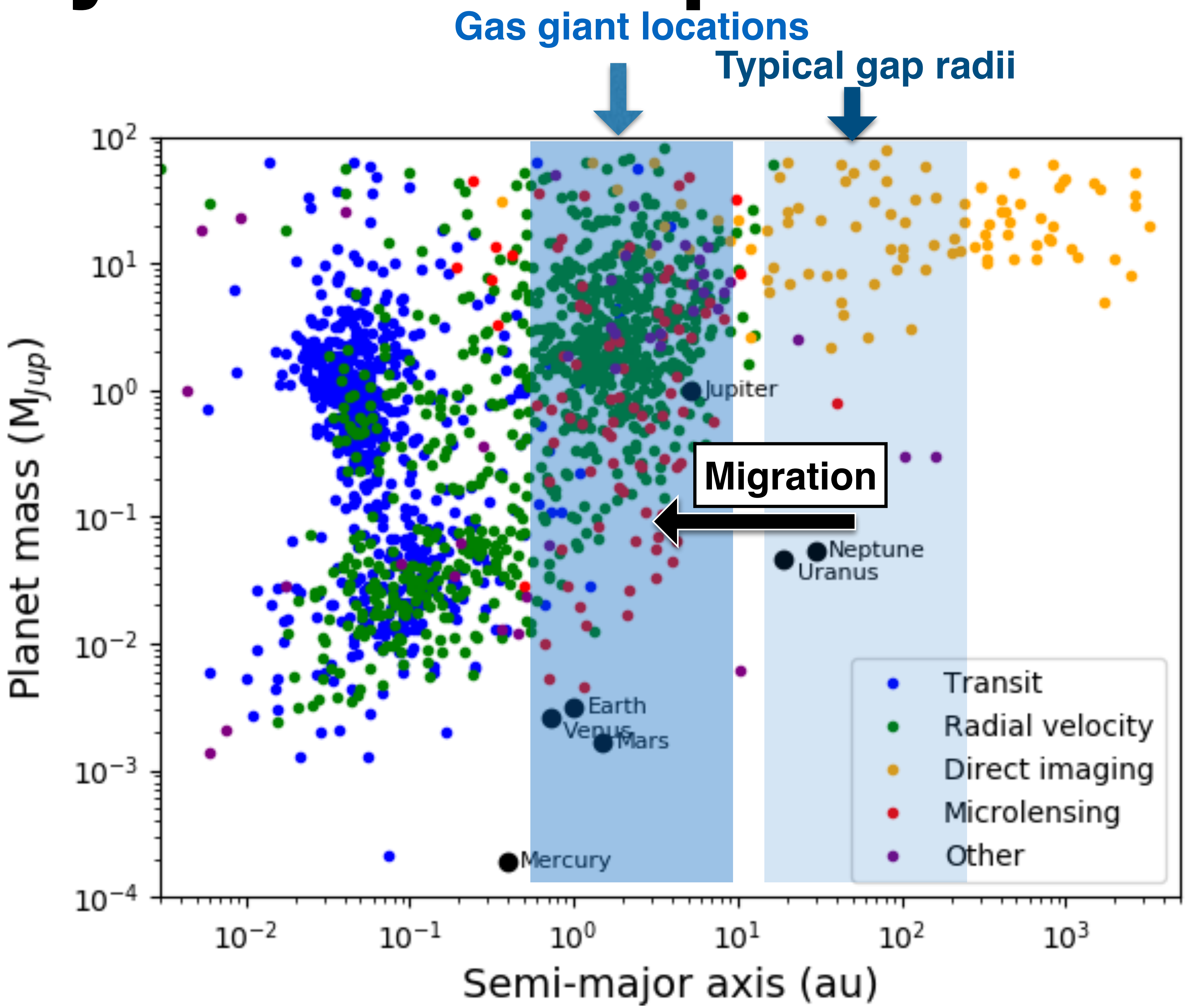


Giant exoplanets



van der Marel & Mulders 2021

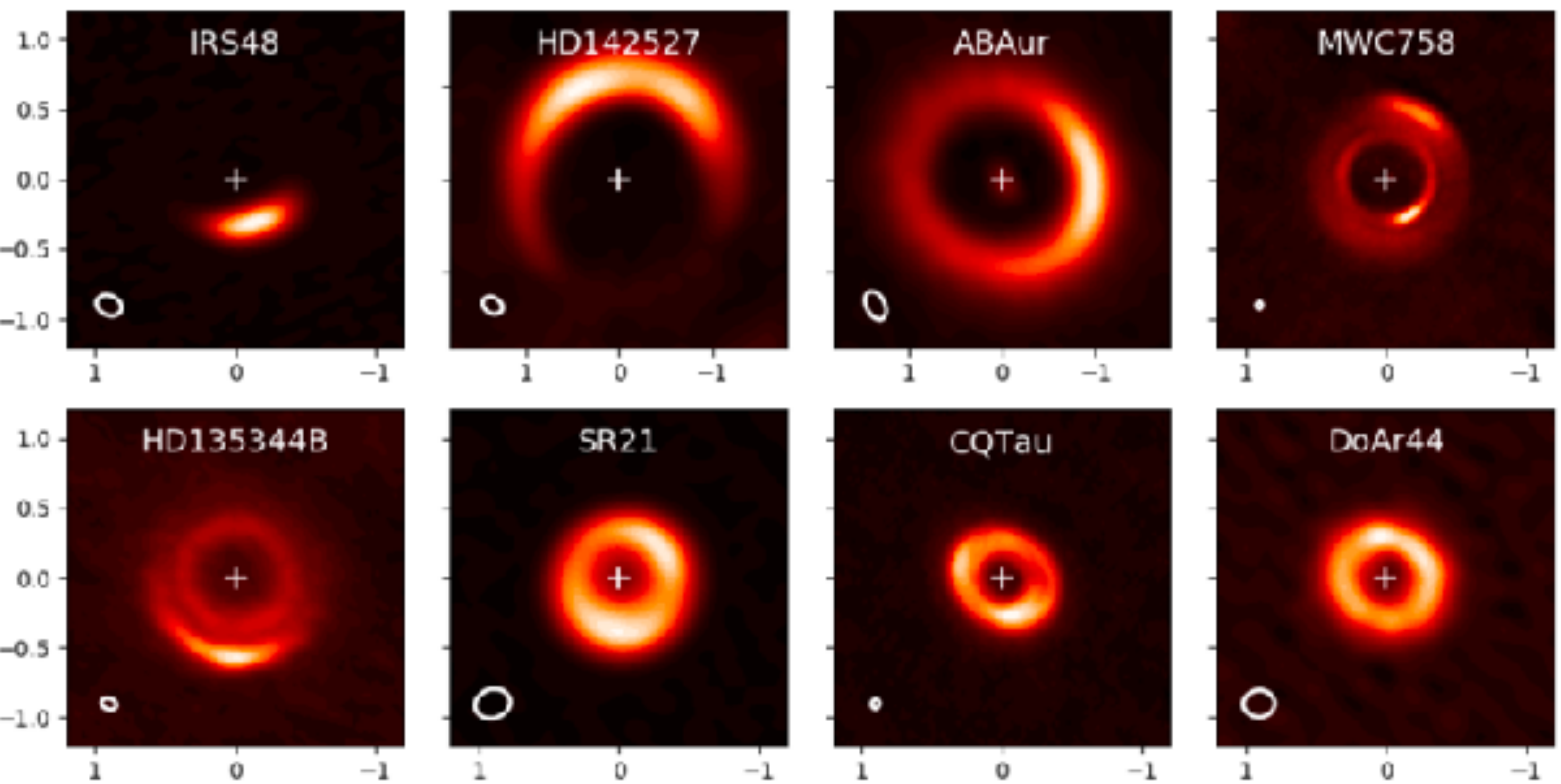
Why we think it's planets



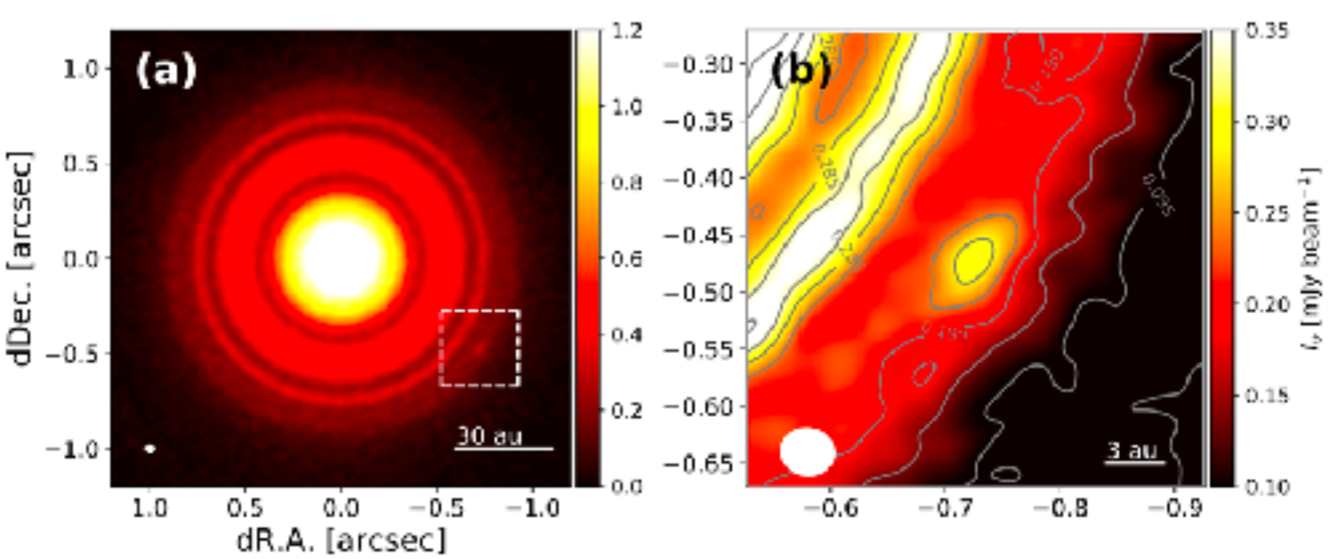
Exoplanets at gap orbits are rare: inward migration?

Lodato et al. 2019

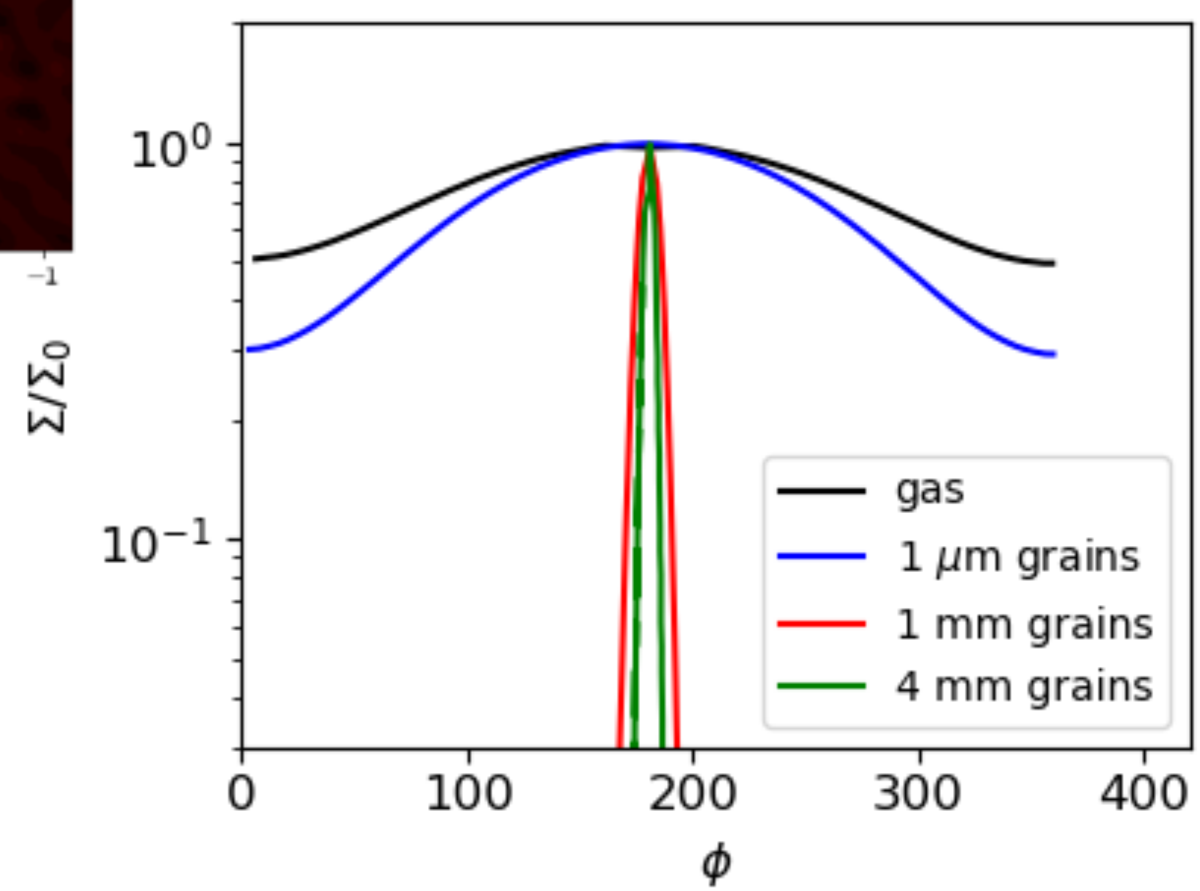
Asymmetries



Many dust asymmetries, large and small scale…



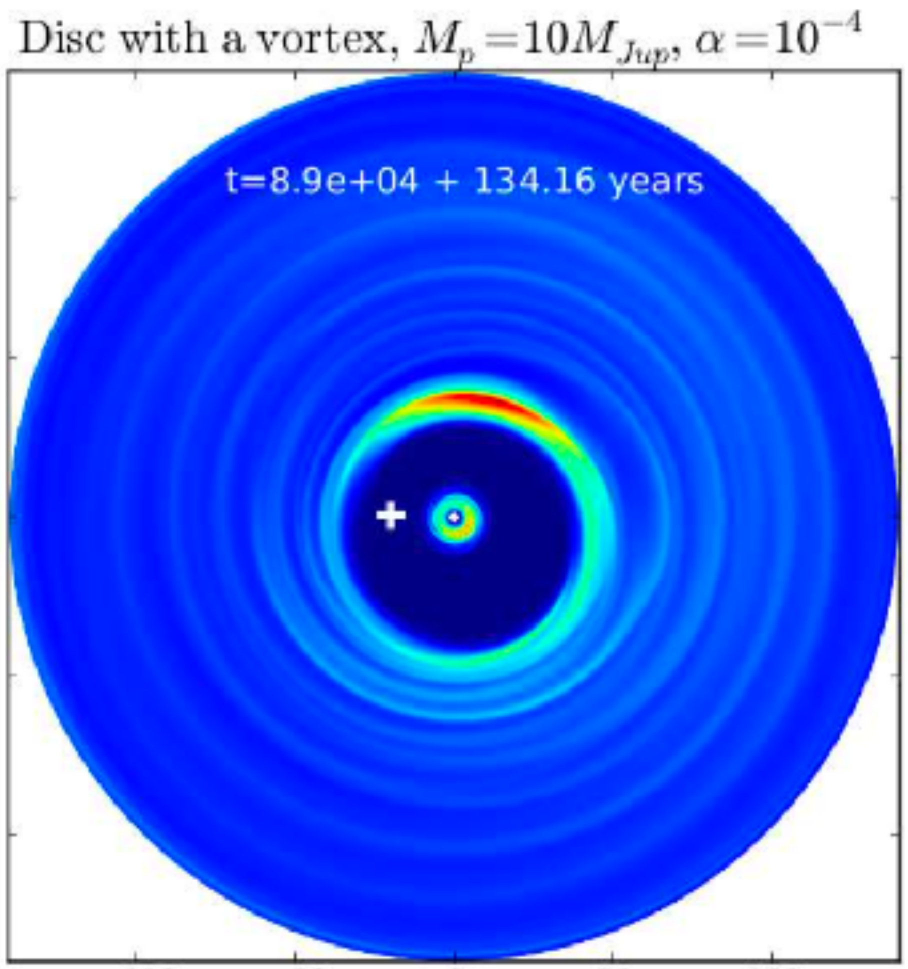
Dust evolution:
small azimuthal concentration of gas leads to strong concentration of mm grains



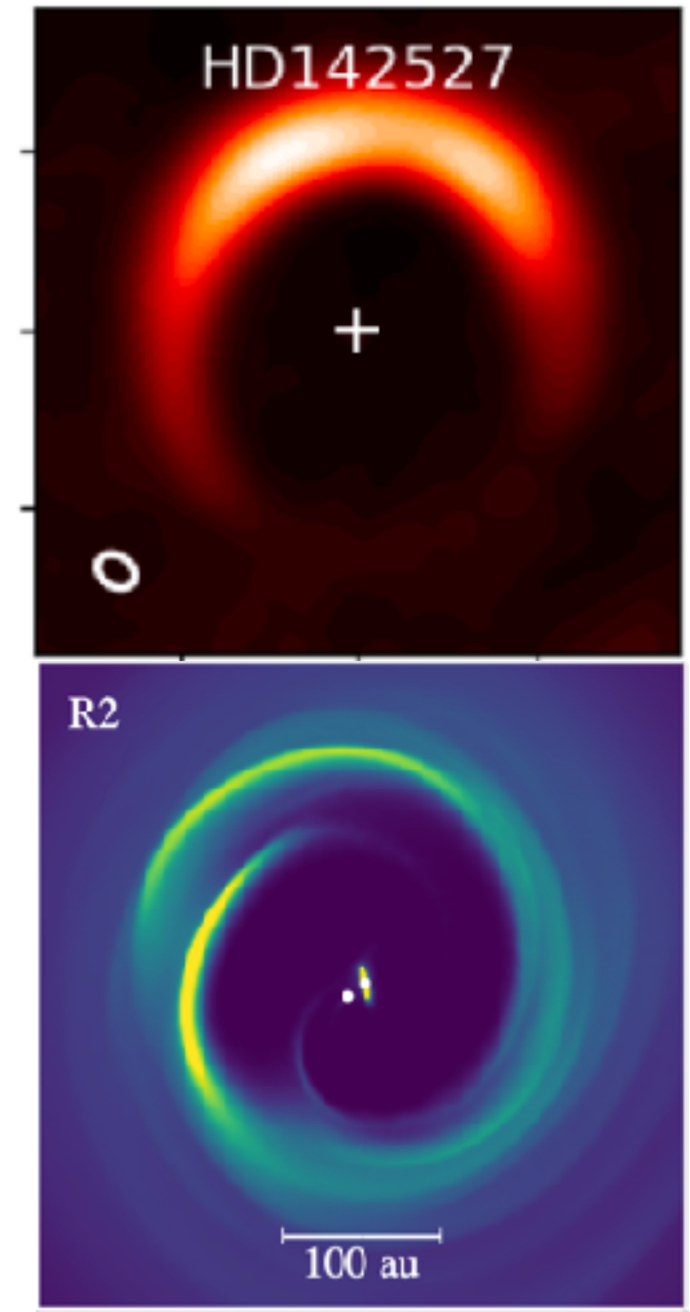
Van der Marel et al. 2021a
Birnstiel et al. 2013

Asymmetries

1. Rossby wave instability leading to vortices



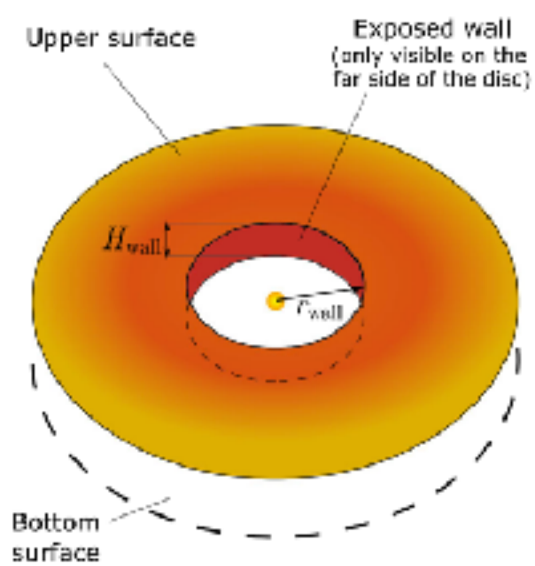
2. Horse shoe by eccentric stellar companion

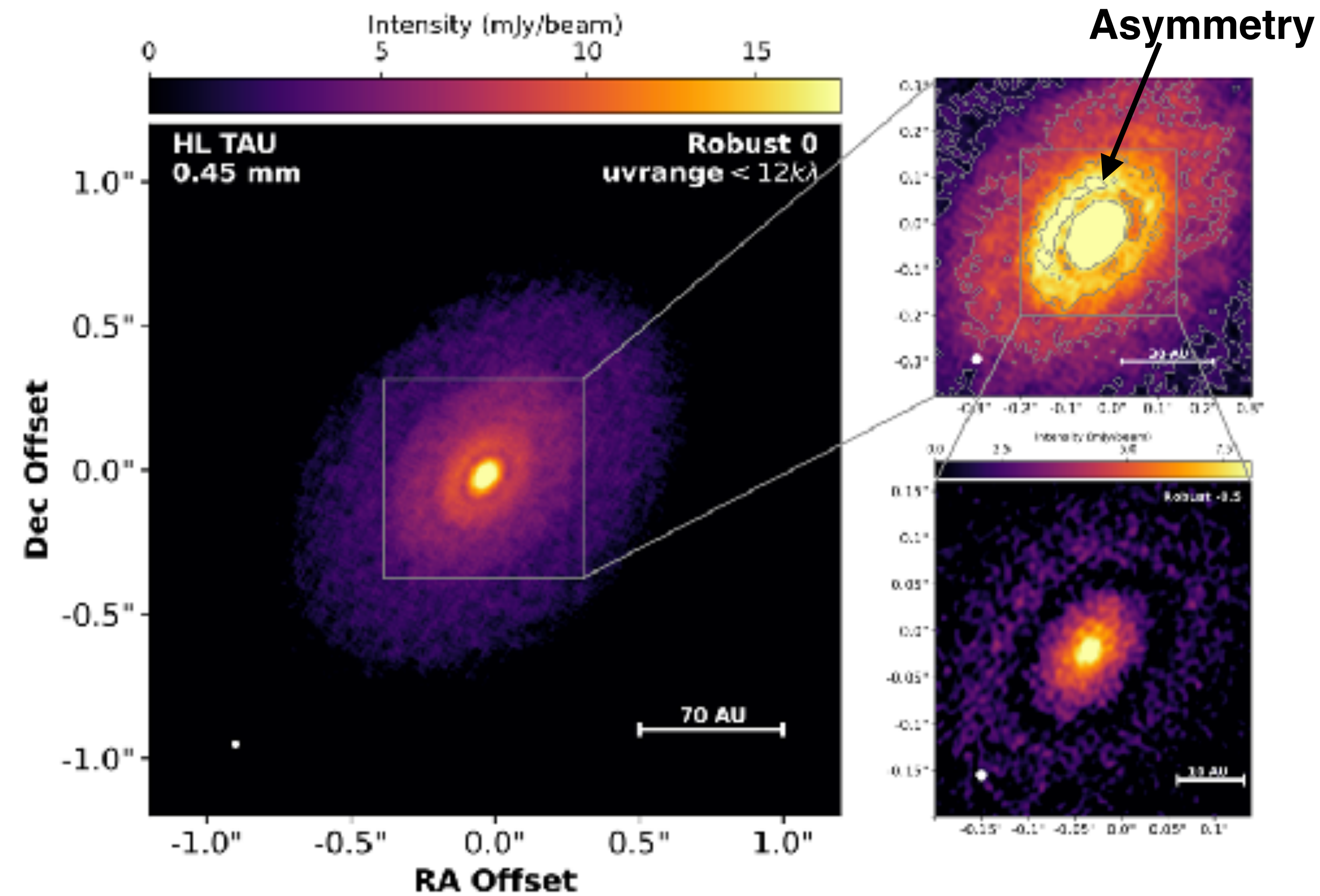


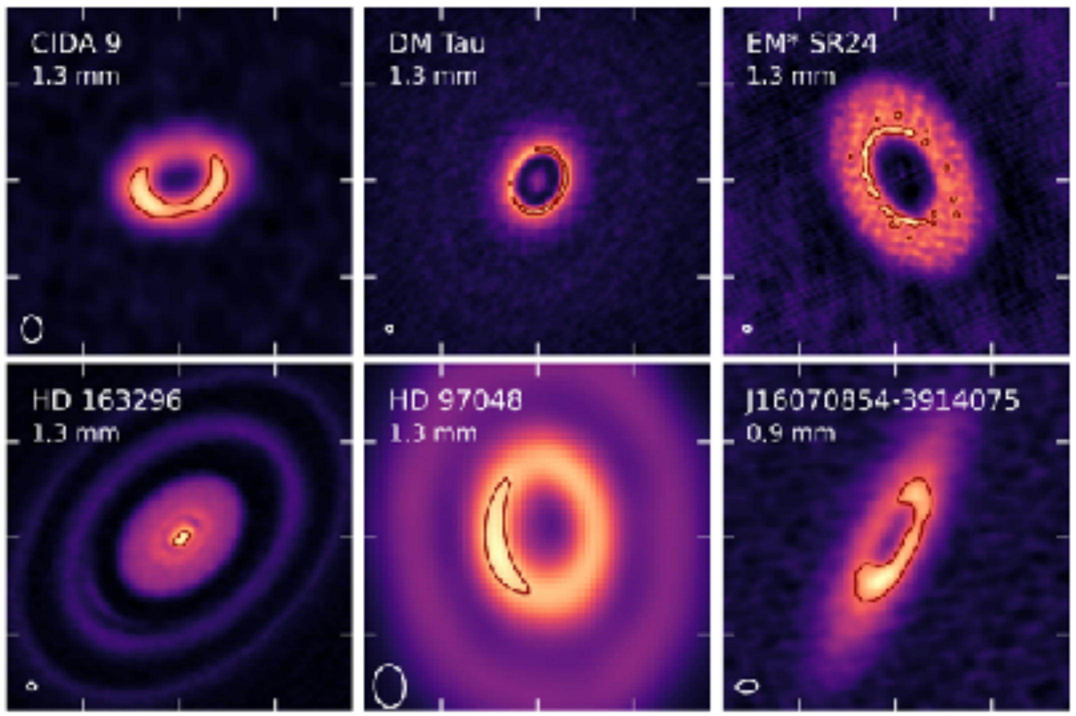
Ragusa et al. 2016, 2020
Price et al. 2018

Asymmetries

3. Apparent asymmetry due to optically thick emission/ scale height







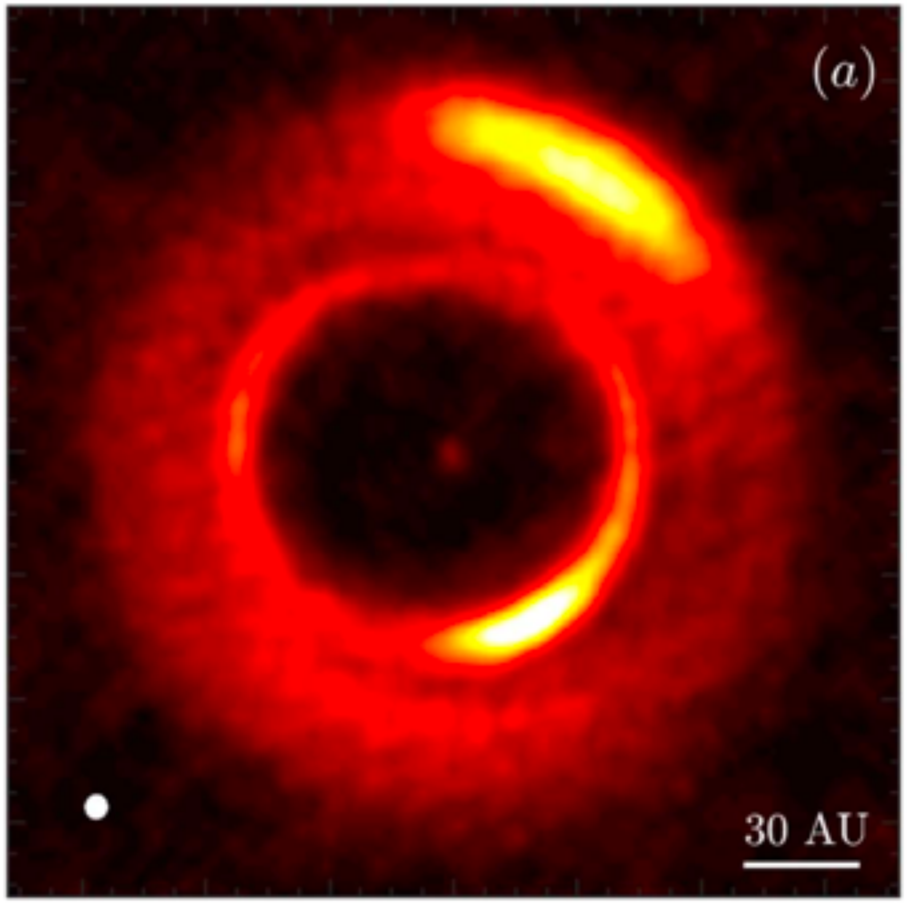
Effect also likely to be visible in dust rings at thermal infrared!

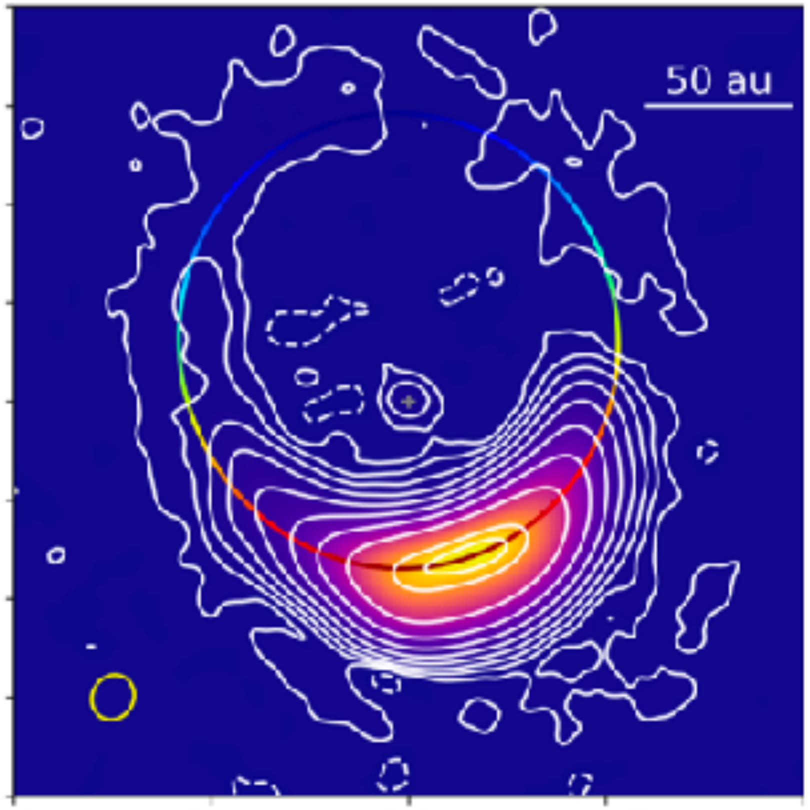
Guerra-Alvarado et al. 2024
Ribas et al. 2024

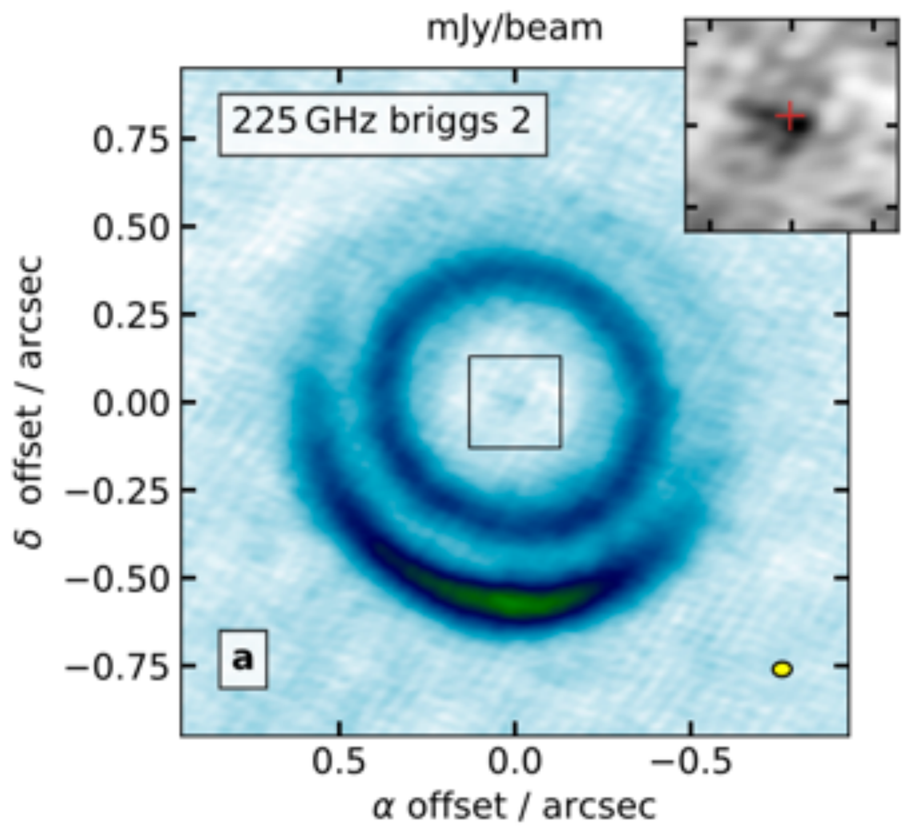
Asymmetries

Eccentric disk rings

Using inner disk and/or stellar position: eccentric rings with e~0.1

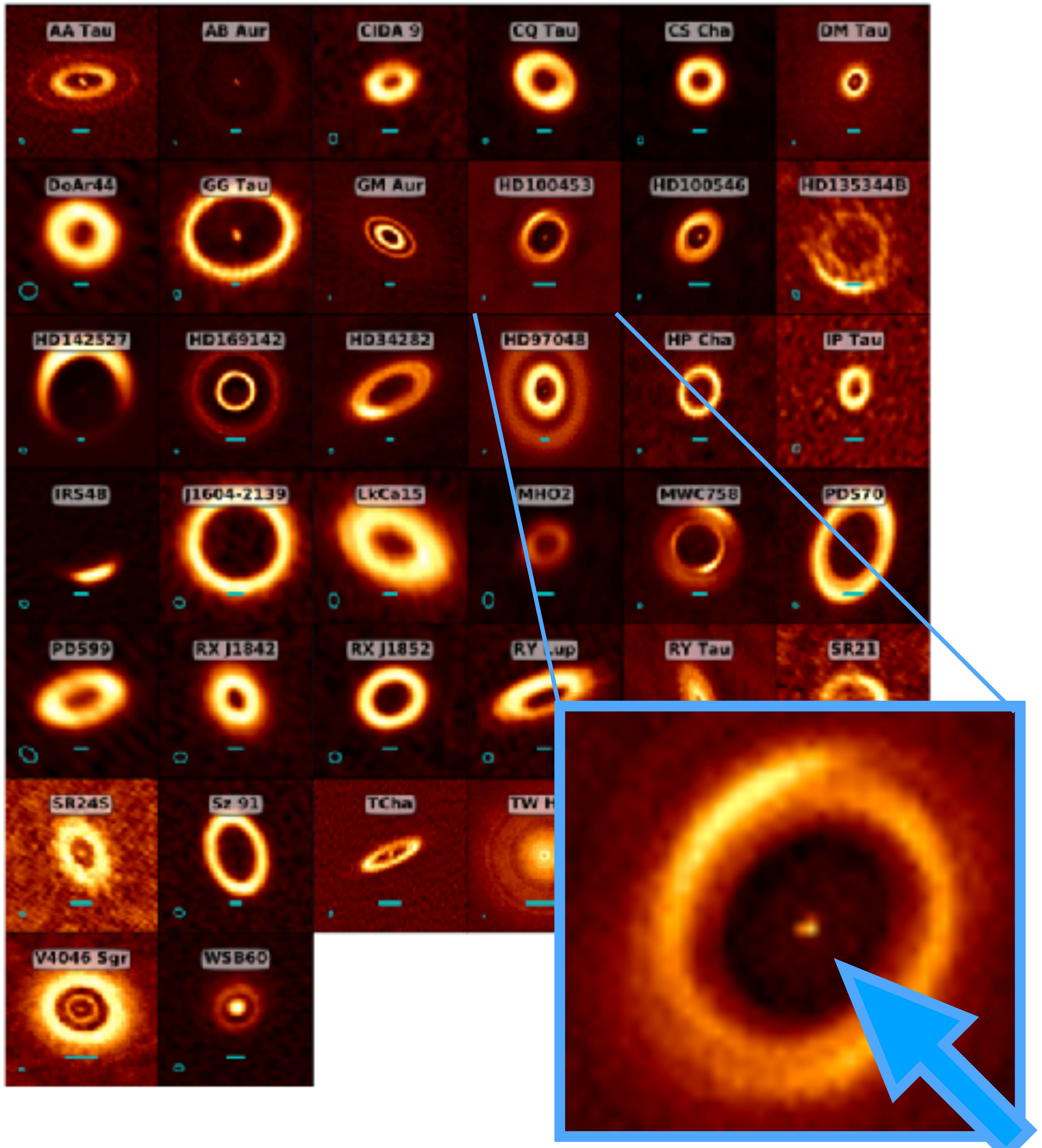


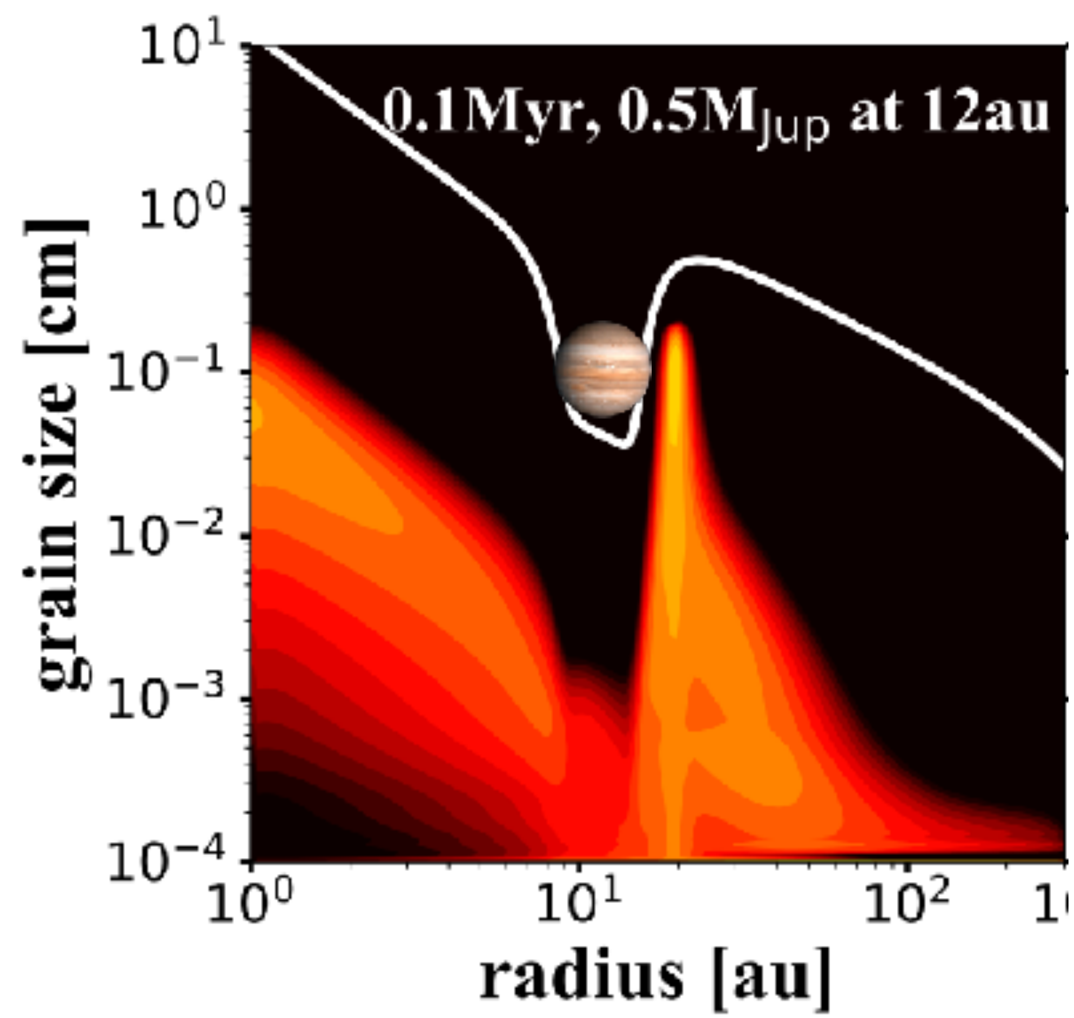




Dong et al. 2018
Yang et al. 2023
Casassus et al. 2021

Inner dust disks



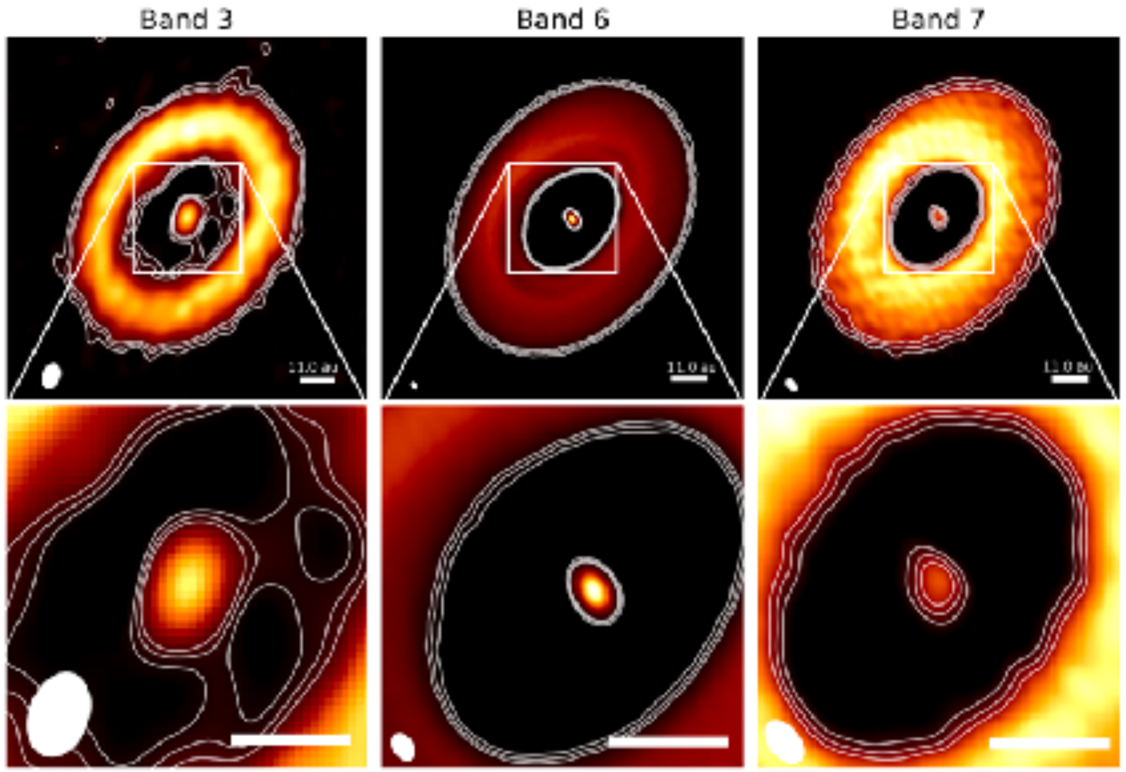


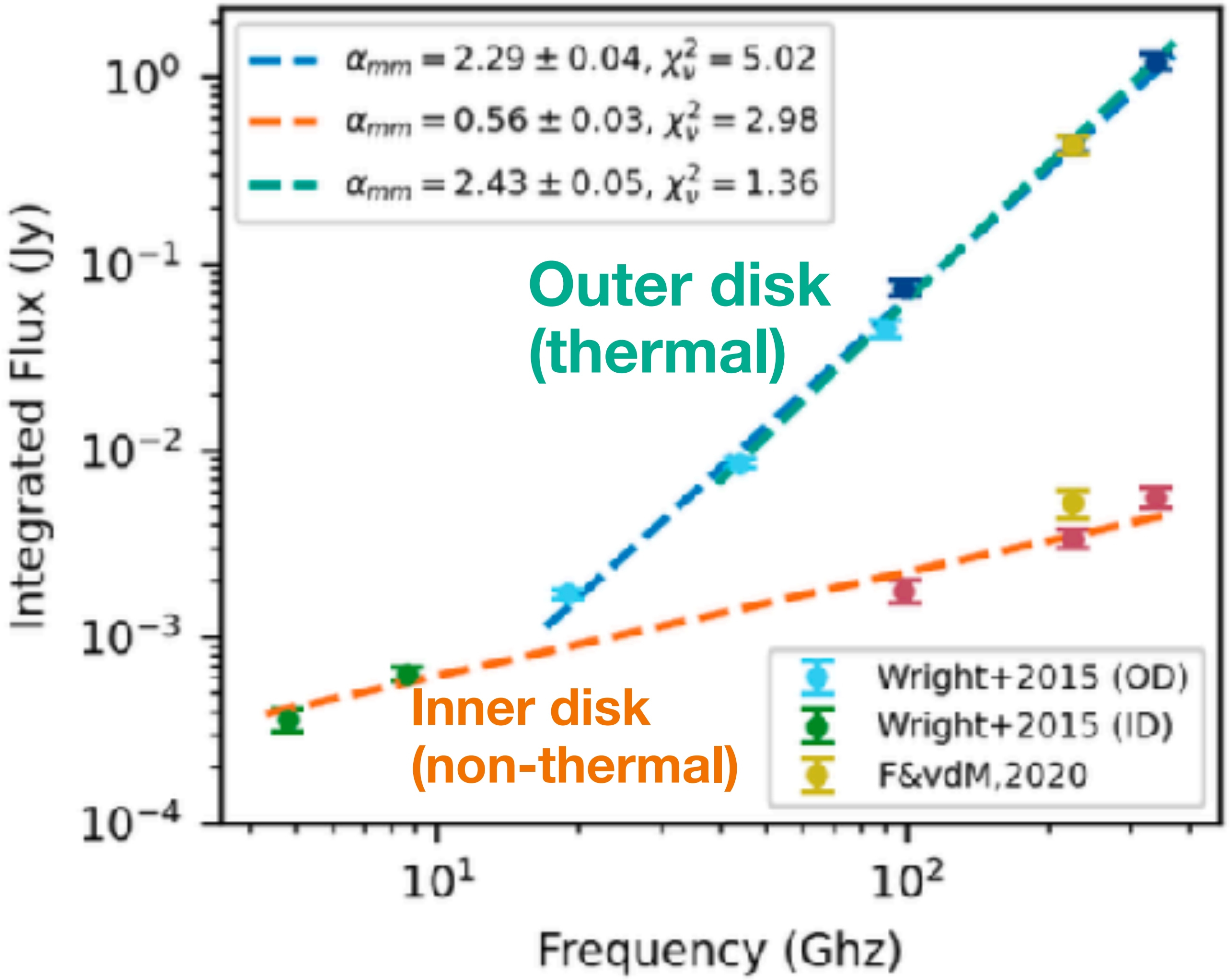
Inner dust disks suggest small dust grains flow through the gap and grow in inner disk

Francis & van der Marel 2020
Pinilla et al. 2021

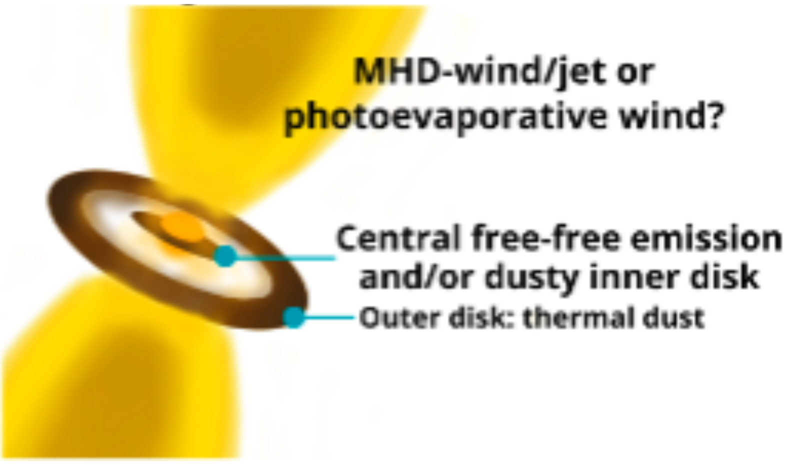
Inner dust disks

Multi-wavelength analysis mm-cm wavelengths





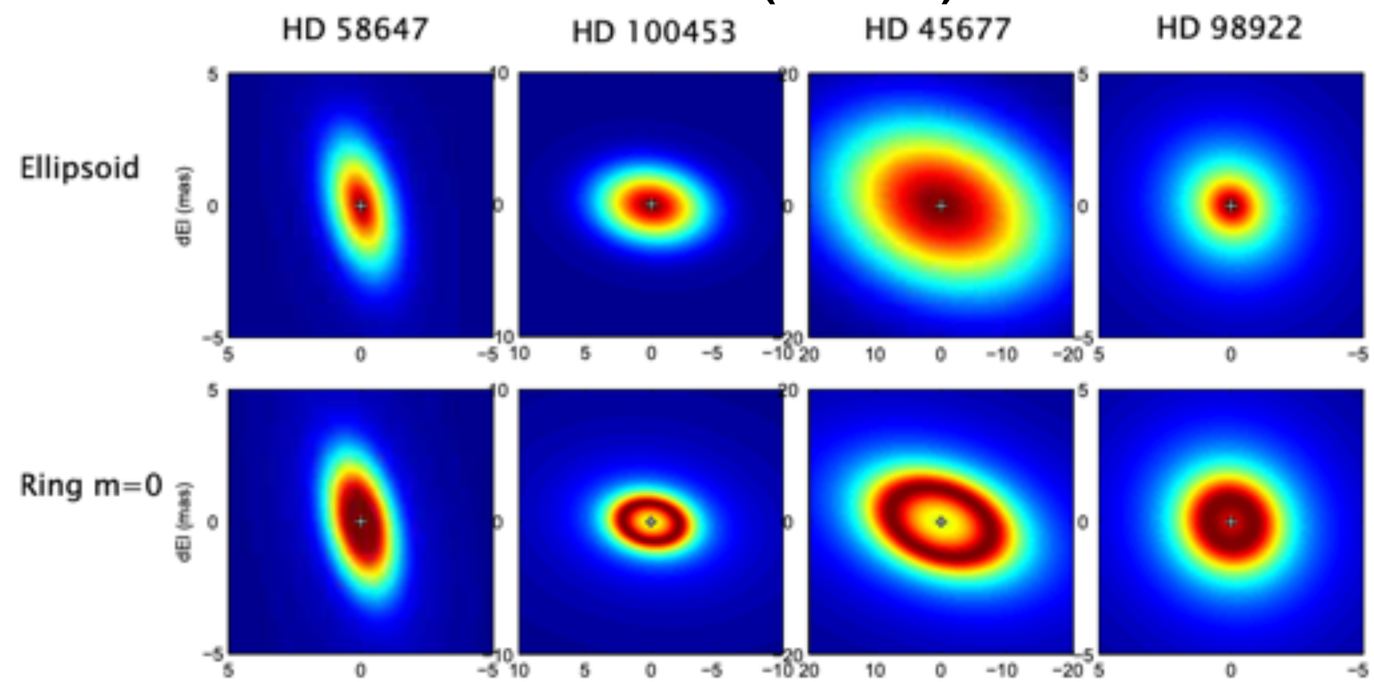
Free-free emission: ionized gas from launching area of MHD disk wind/jet

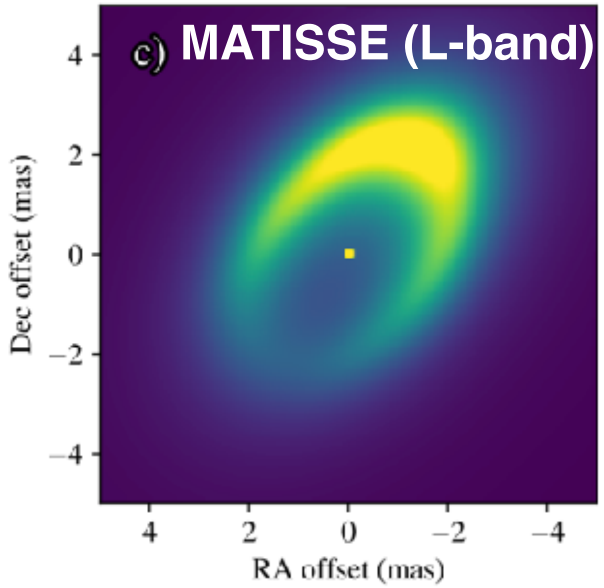


Rota et al. 2024

Inner dust disks

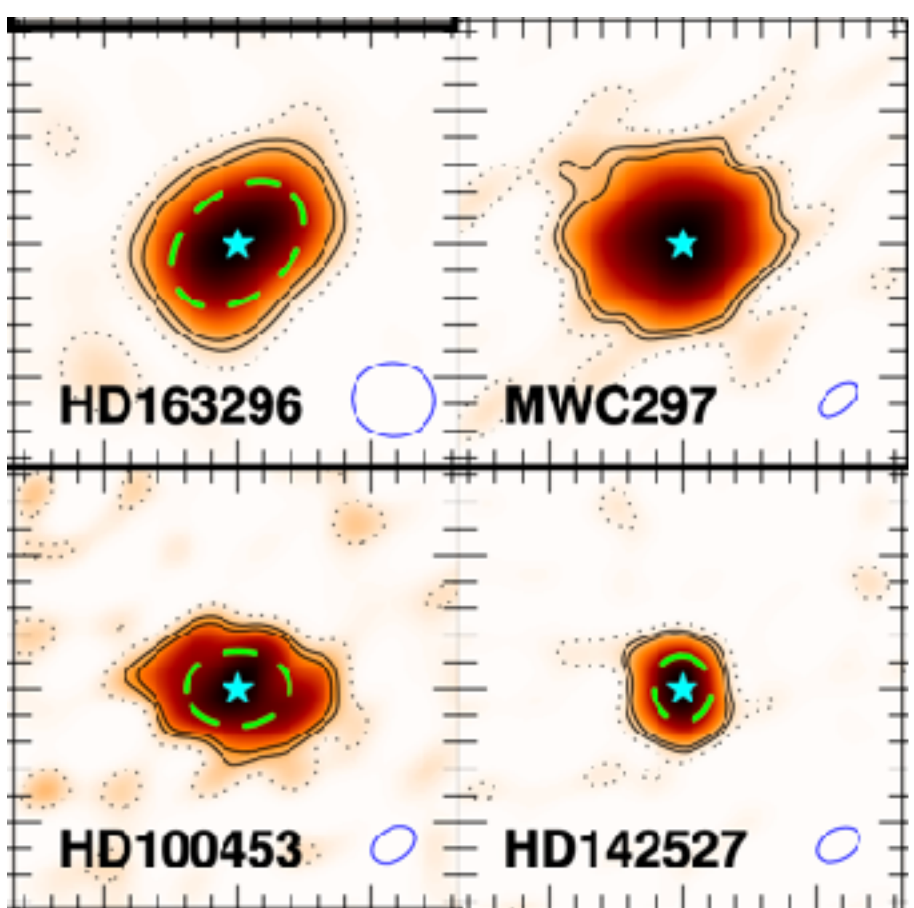
PIONIER (H-band)



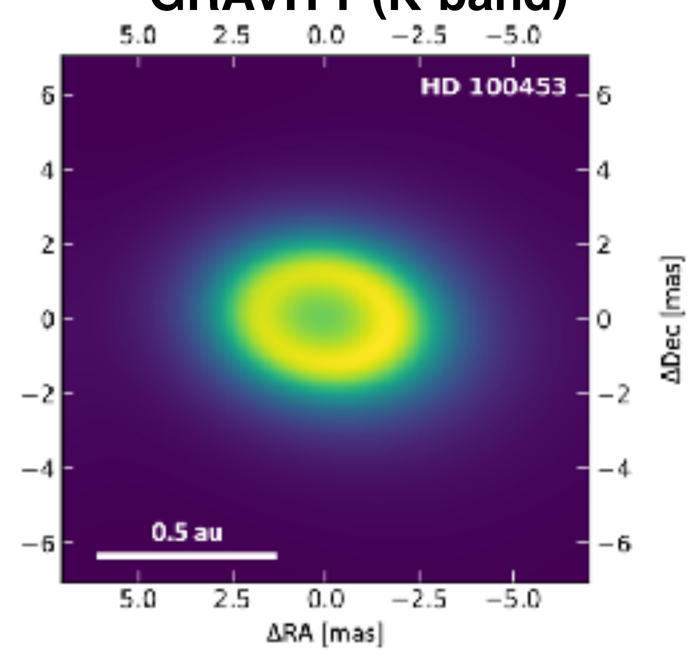


Inner disks of micron-sized dust grains have already been imaged with VLTI!

PIONIER (H-band)



GRAVITY (K-band)



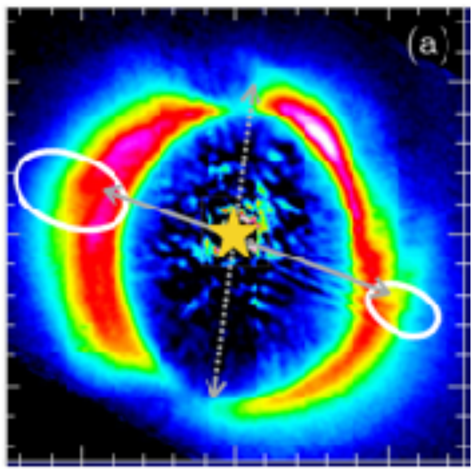
See also talk Luna van Haastere

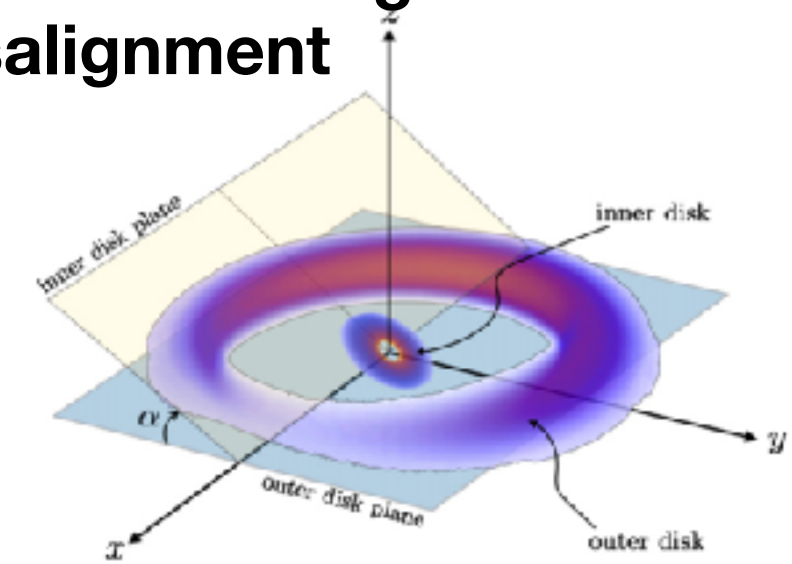
Lazareff et al. 2017, GRAVITY+Perraut et al. 2019, Kluska et al. 2020, Bohn et al. 2022, Varga et al. 2021

Inner dust disks

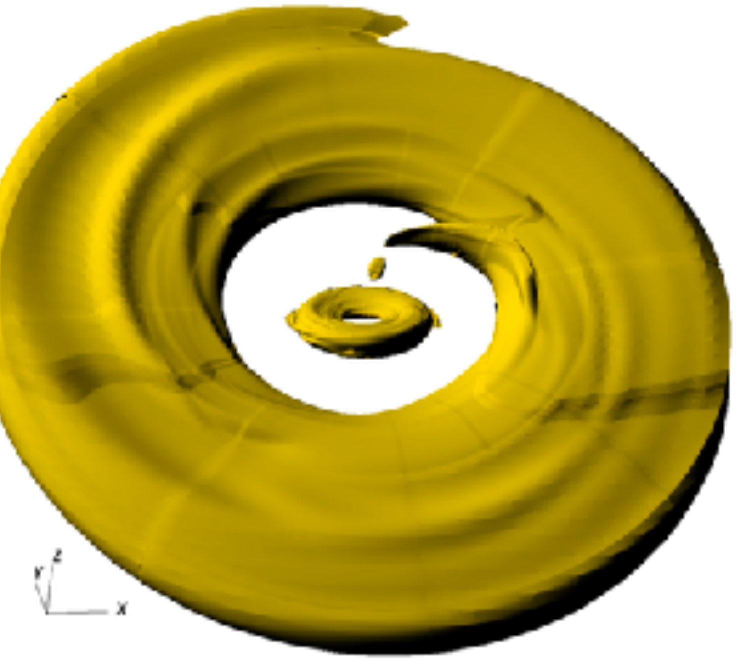
Misalignment

Shadows in scattered light suggest misalignment

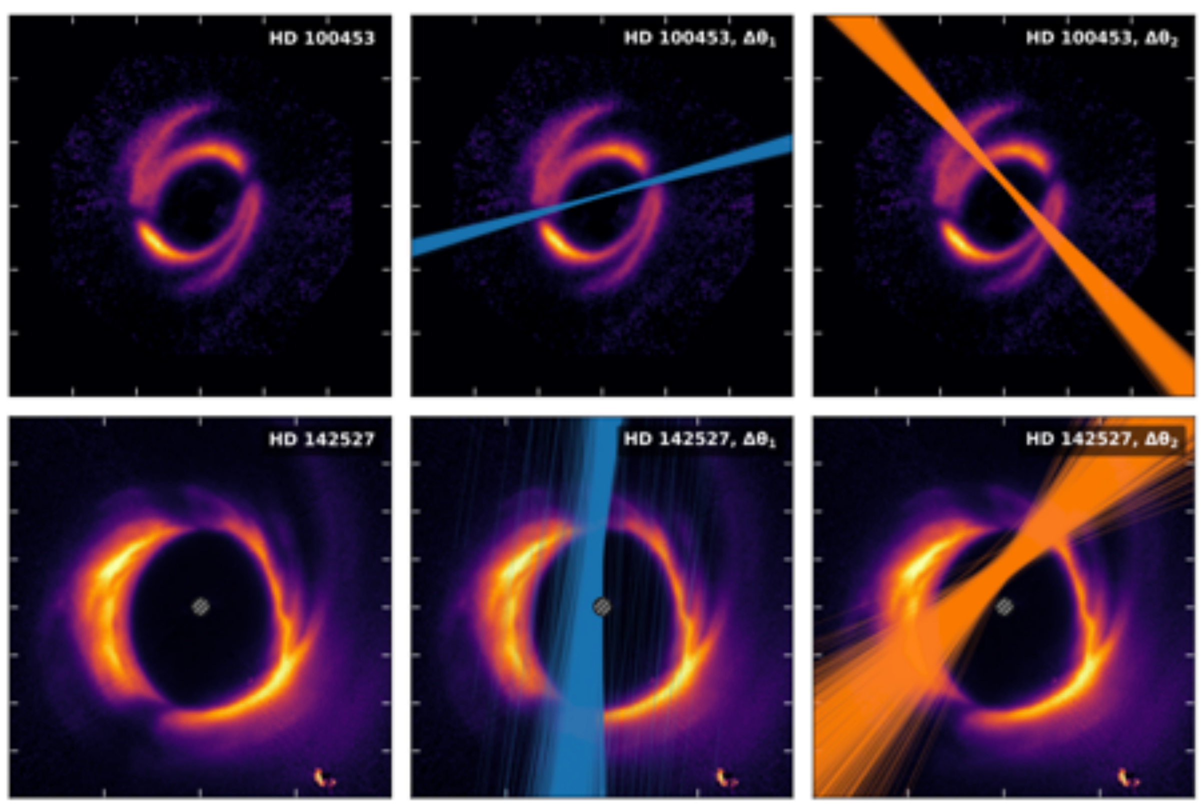




Simulation: precession inner disk as planet 'breaks' the disk



Disentangling orientation combining VLTI with scattered light images



Marino et al. 2015
Zhu et al. 2019
Bohn et al. 2022

Dust ring properties

Multi-wavelength analysis

Basic relations in continuum emission:

Flux

$$F_\nu = \int B_\nu(T)(1 - e^{-\tau_\nu})d\Omega$$

Dust surface density

$$\tau_\nu = \frac{\kappa_\nu \Sigma_{dust}}{\cos i}$$

Temperature

$$\kappa_\nu \sim n(a) \propto a^{-p}, a_{max}$$

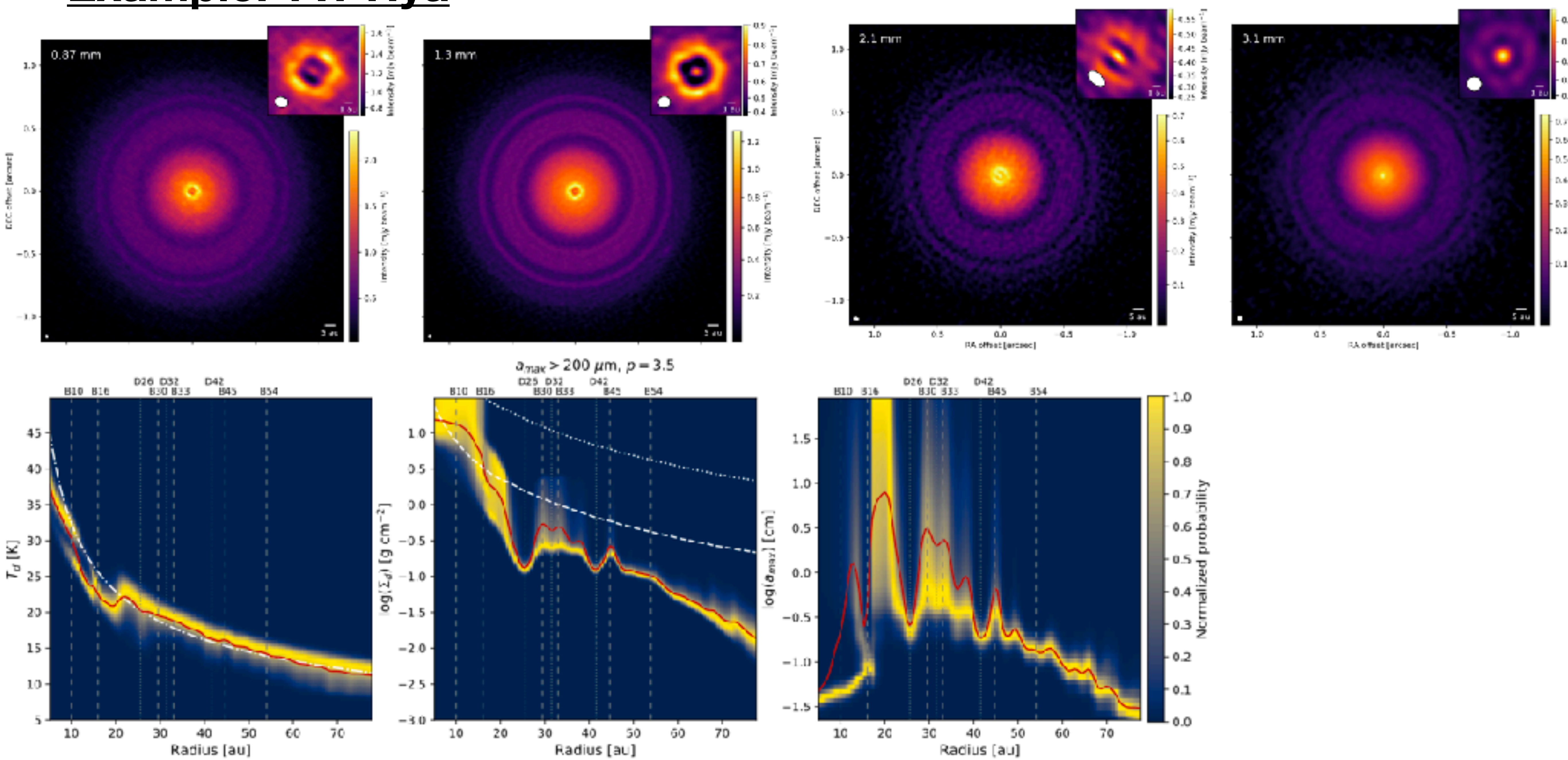
Grain size distribution

Spatially resolved multi-wavelength data at 3 or more wavelengths can disentangle these 3 disk parameters!

Dust ring properties

Multi-wavelength analysis

Example: TW Hya



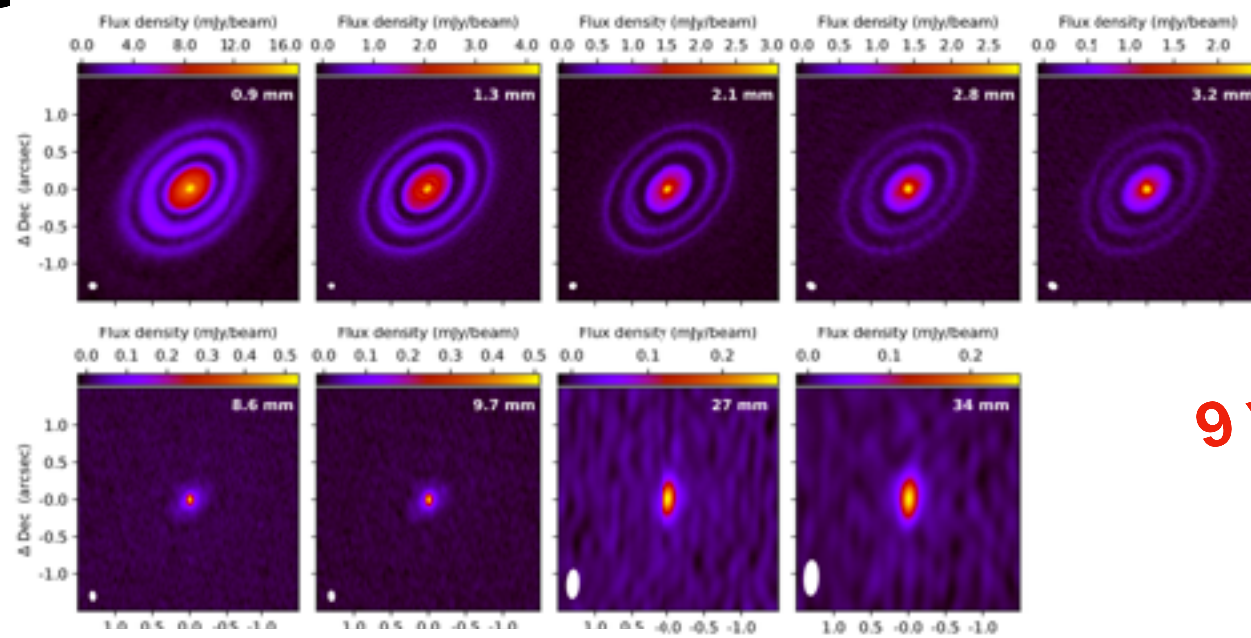
Macias et al. 2021

Dust ring properties

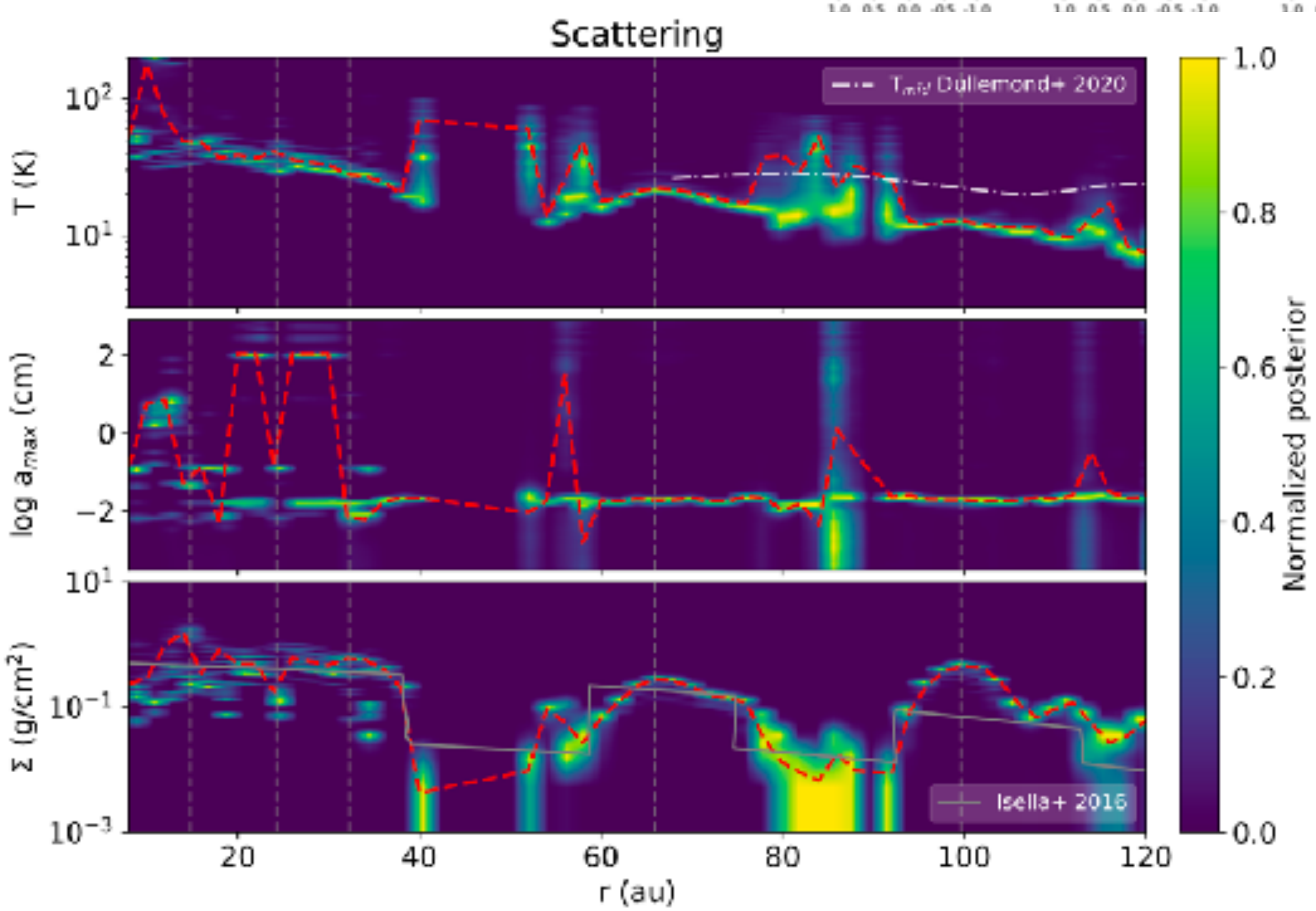
Multi-wavelength analysis

<u>Example: HD163296</u>

More stringent constraints on dust properties and optical depth



9 wavelengths!
(ALMA+VLA)



Can multi-wavelength infrared data constrain dust properties in inner region?

Guidi et al. 2022

Summary

- Dust rings observed with ALMA are thought to be caused by pressure bumps at the edge of wide-orbit planet gaps
- Dust rings observed at IR VLTI unlikely to be dust traps
- Dust asymmetries at mm and IR can have different origins
- Inner dust disks with ALMA could be free-free emission, but those in IR can be used to study e.g. misalignments
- Multi-wavelength analysis of ALMA has been used to infer dust properties, potential at IR?