The impact and origin of dust gaps in planet-forming disks

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Leiden Observatory

“Our Galactic Ecosystem: Opportunities and diagnostics in the infrared and beyond”

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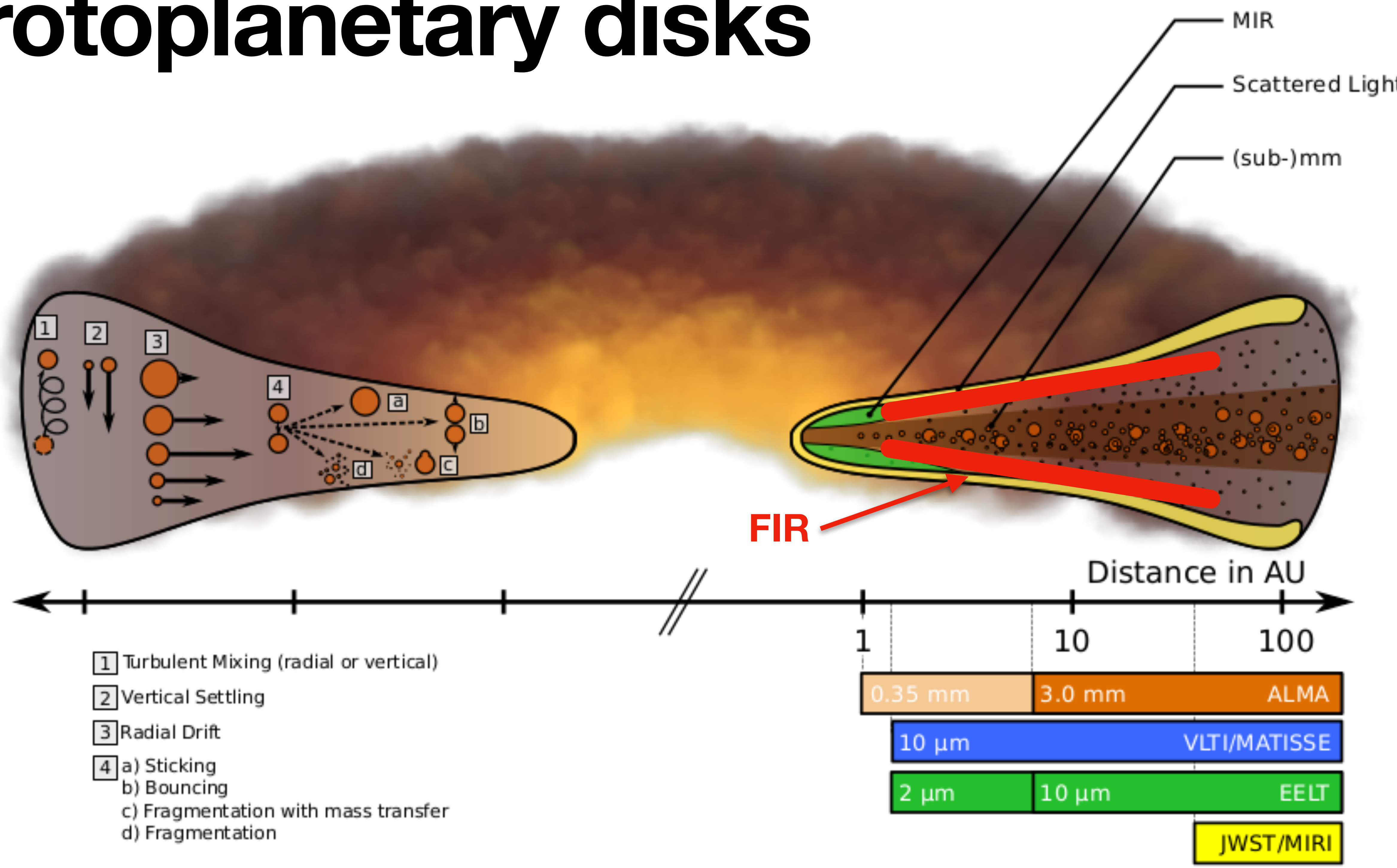
Sterrewacht Leiden

Protoplanetary disks

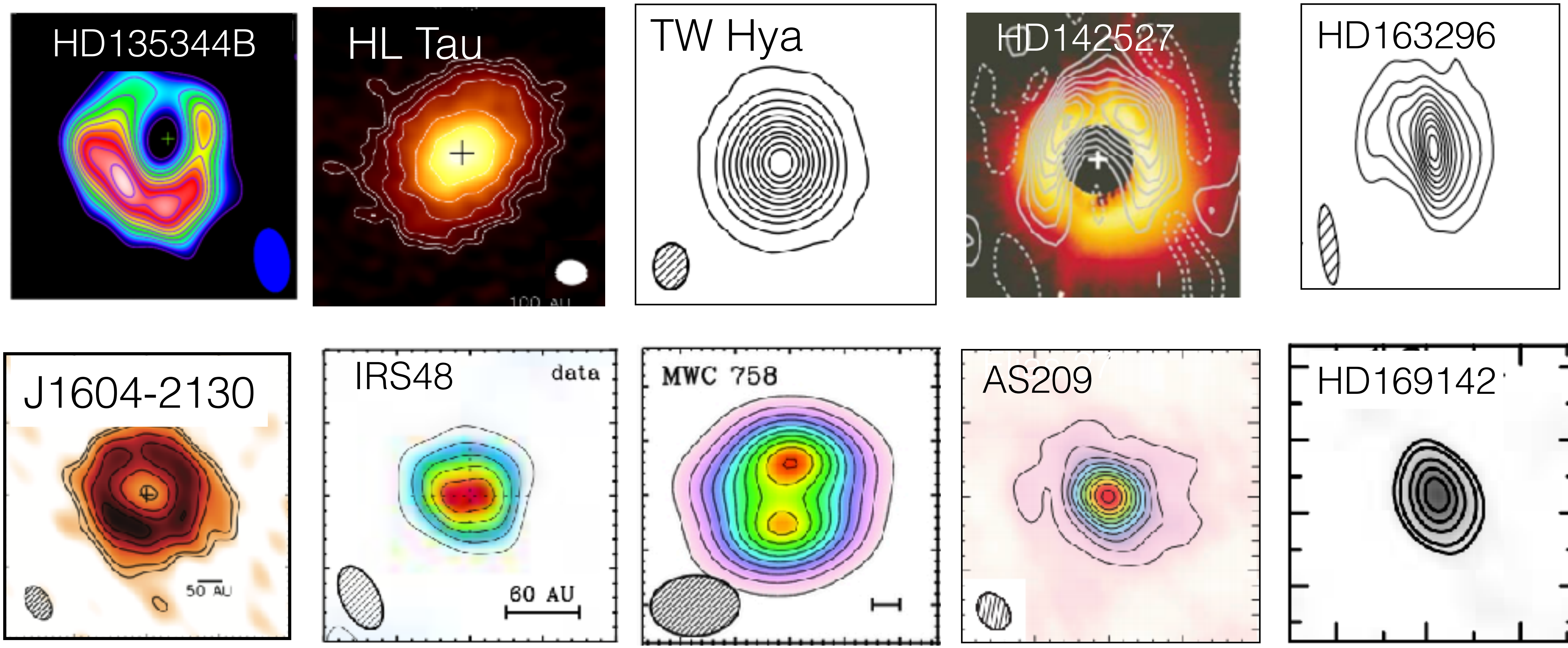


- Distances ~ 100-200 pc
- Sizes ~ 100 au/1 arcsec
- Ages ~ 1-10 Myr

Need for subarcsec resolution…

Testi et al. 2015

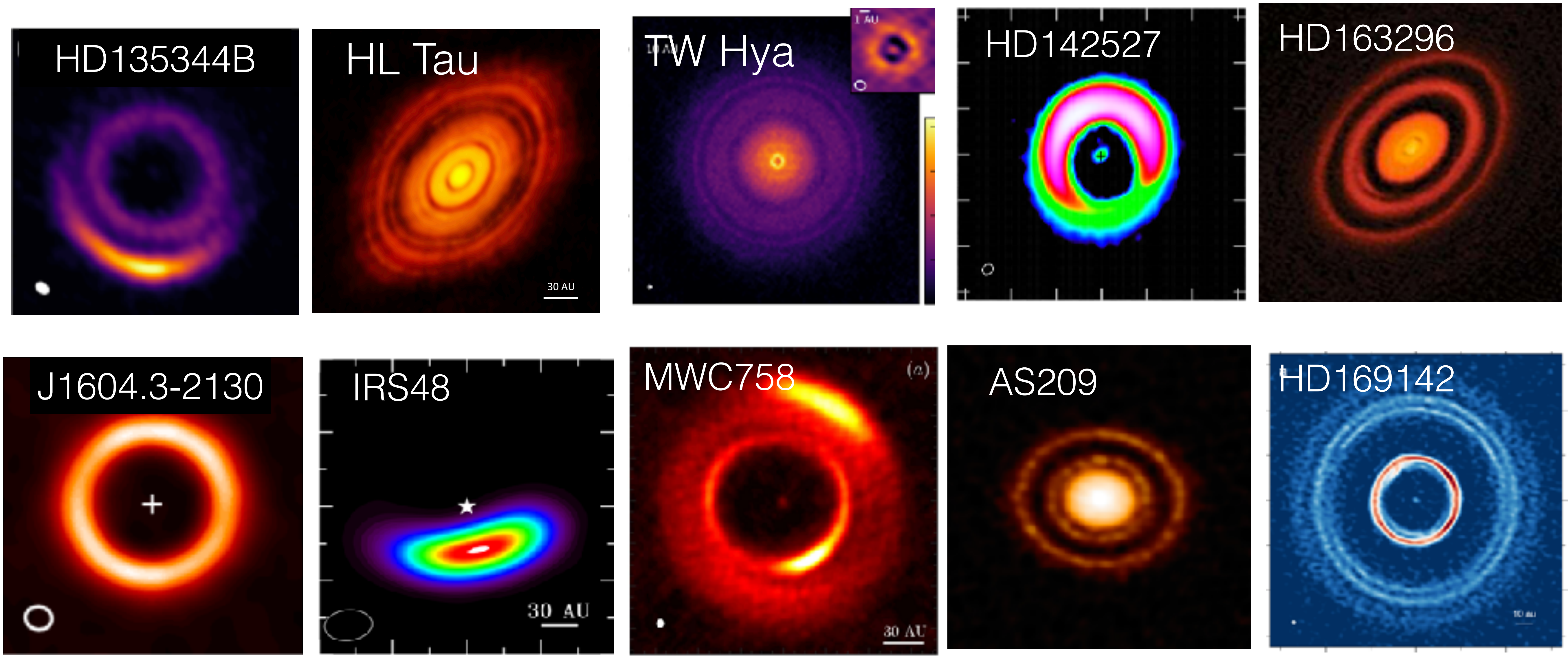
Pre-ALMA disk observations



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

ALMA disk observations

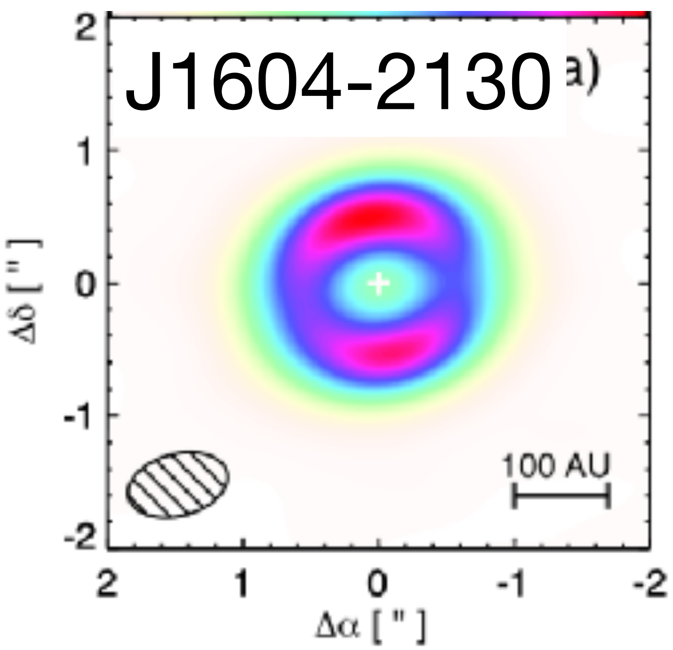


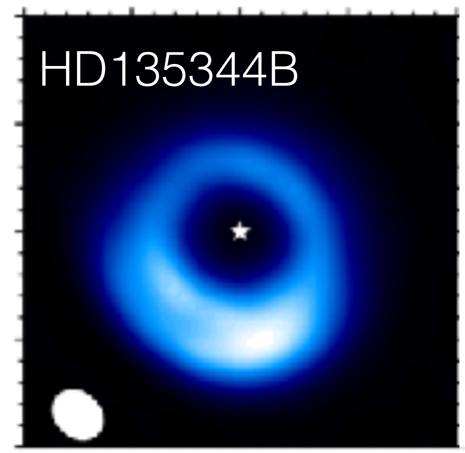
Typical resolution ~0.05-0.1"

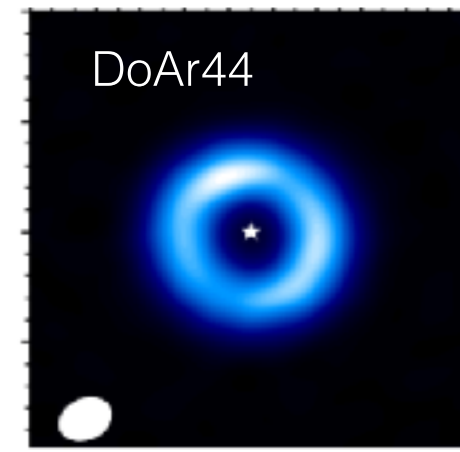
Enormous diversity of large-scale dust structures!

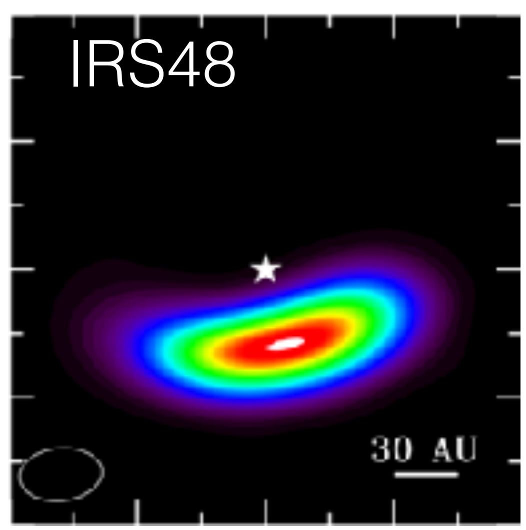
ALMA et al. 2015; Andrews et al. 2016, 2018; Boehler et al. 2017, Cazzoletti et al. 2018; Dong et al. 2018; Fedele et al. 2017; Isella et al. 2016; Perez et al. 2019; Van der Marel et al. 2013, 2016a & 2020

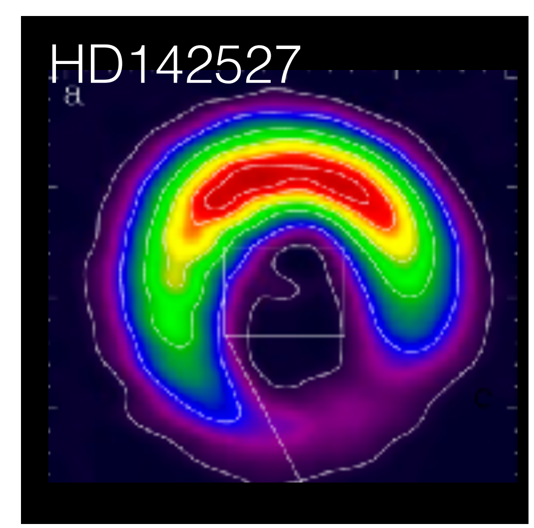
How it started: transition disks







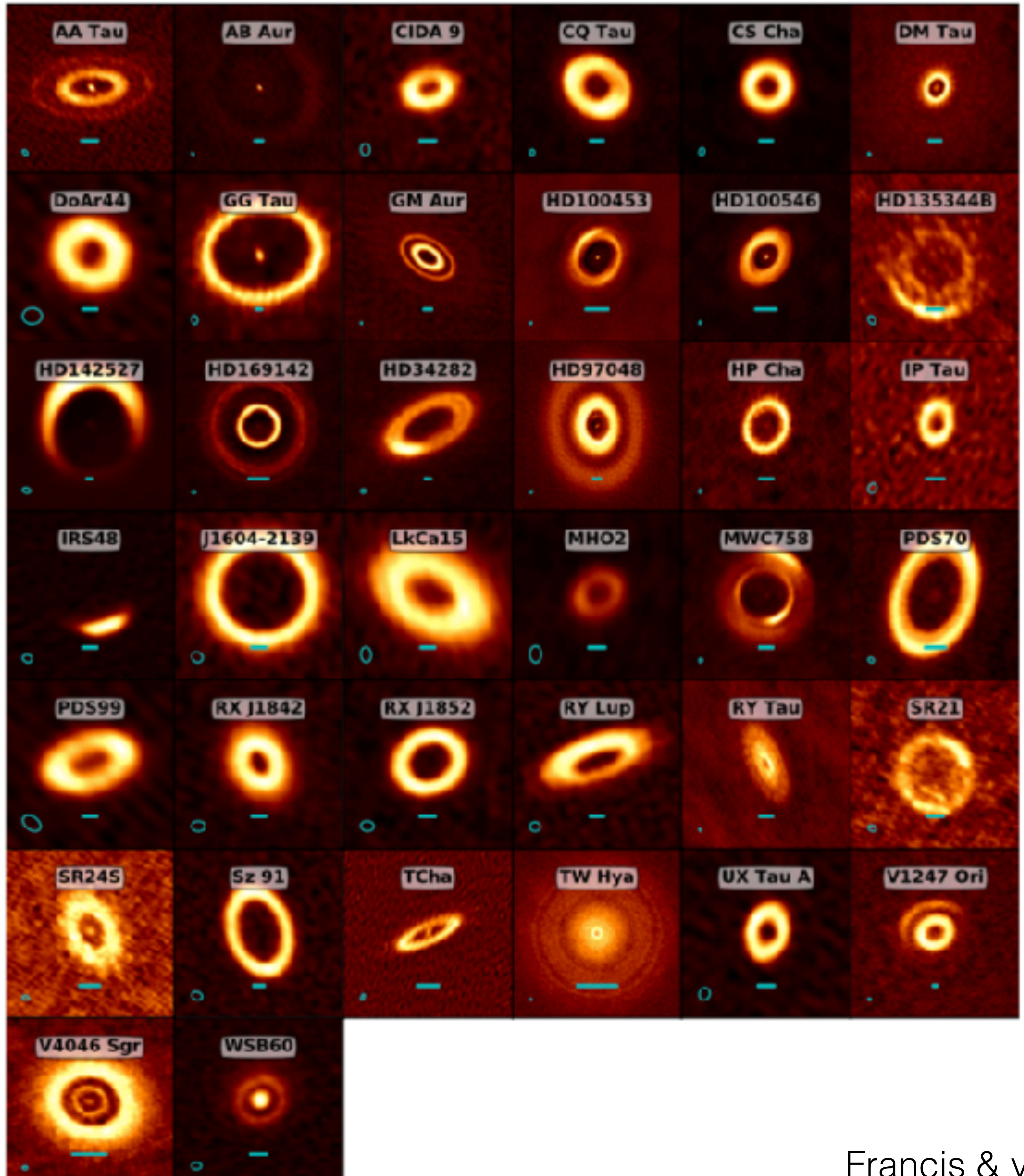




Typical resolution ~0.25"

Casassus et al. 2013
Zhang et al. 2014
Van der Marel et al. 2013, 2015, 2016

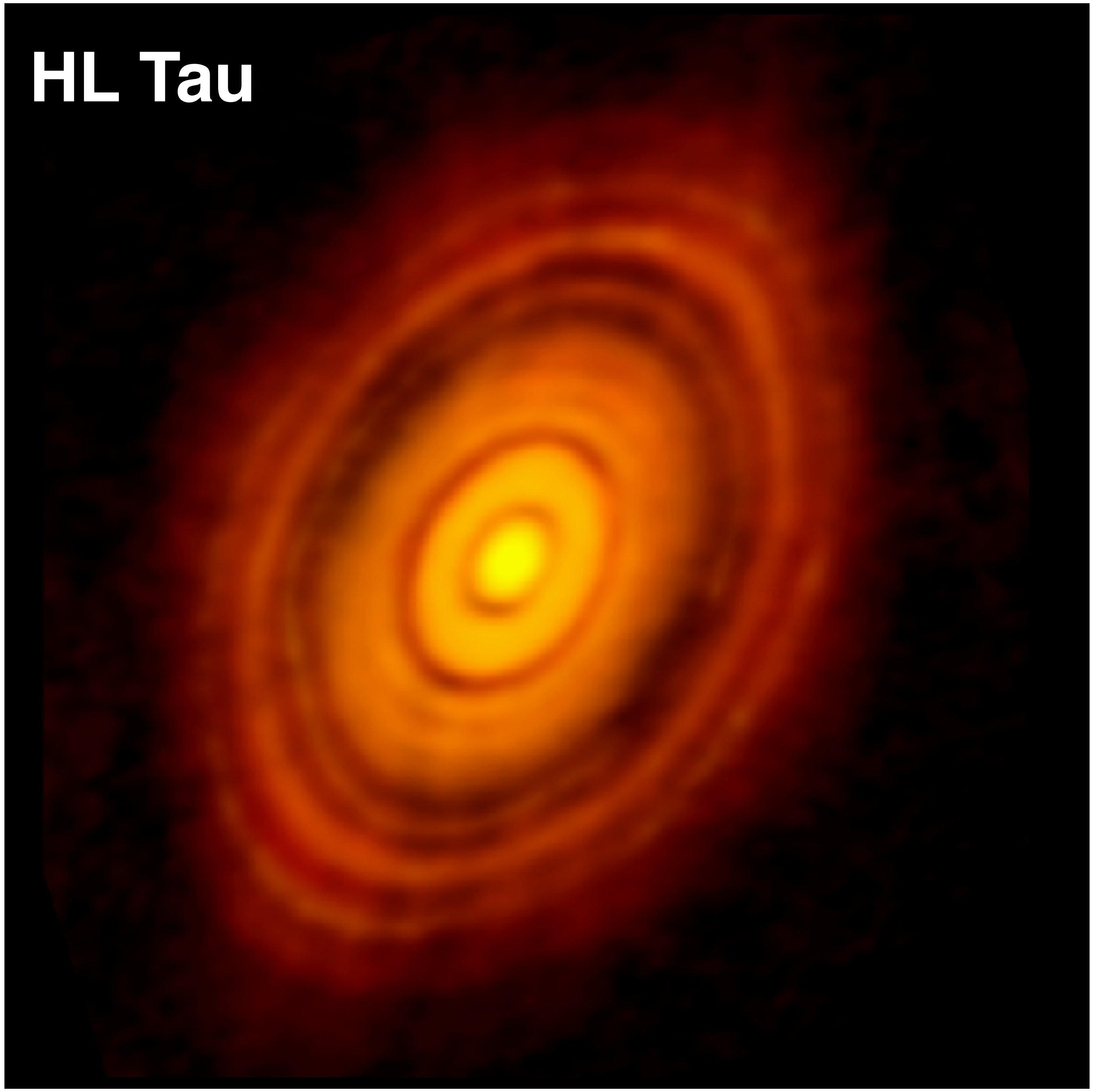
…and how it's going



Typical resolution ~0.1"

Francis & van der Marel 2020

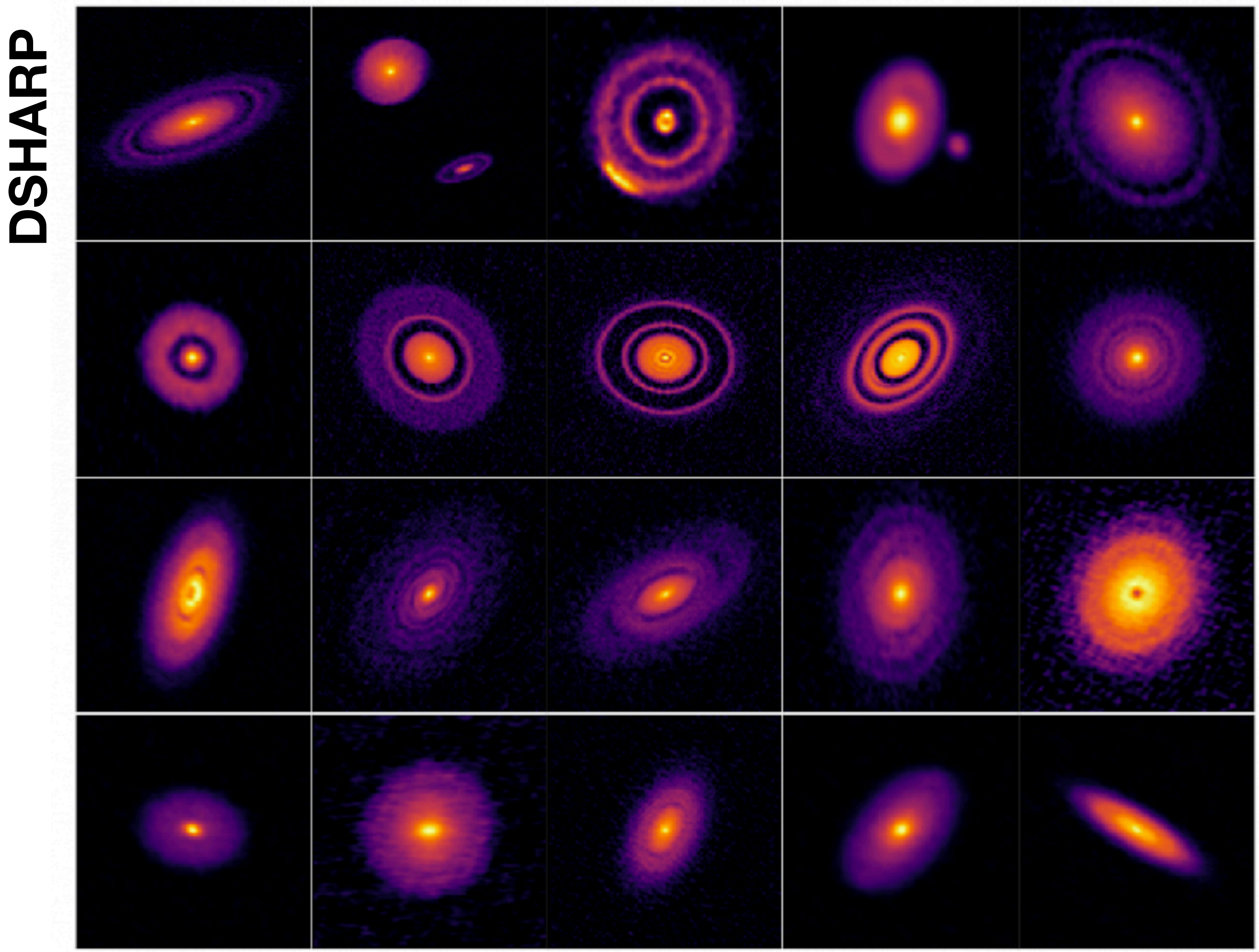
..and (again) how it started:



Typical resolution ~0.05”

ALMA consortium et al. 2015

…and how it's going



Typical resolution ~0.035"

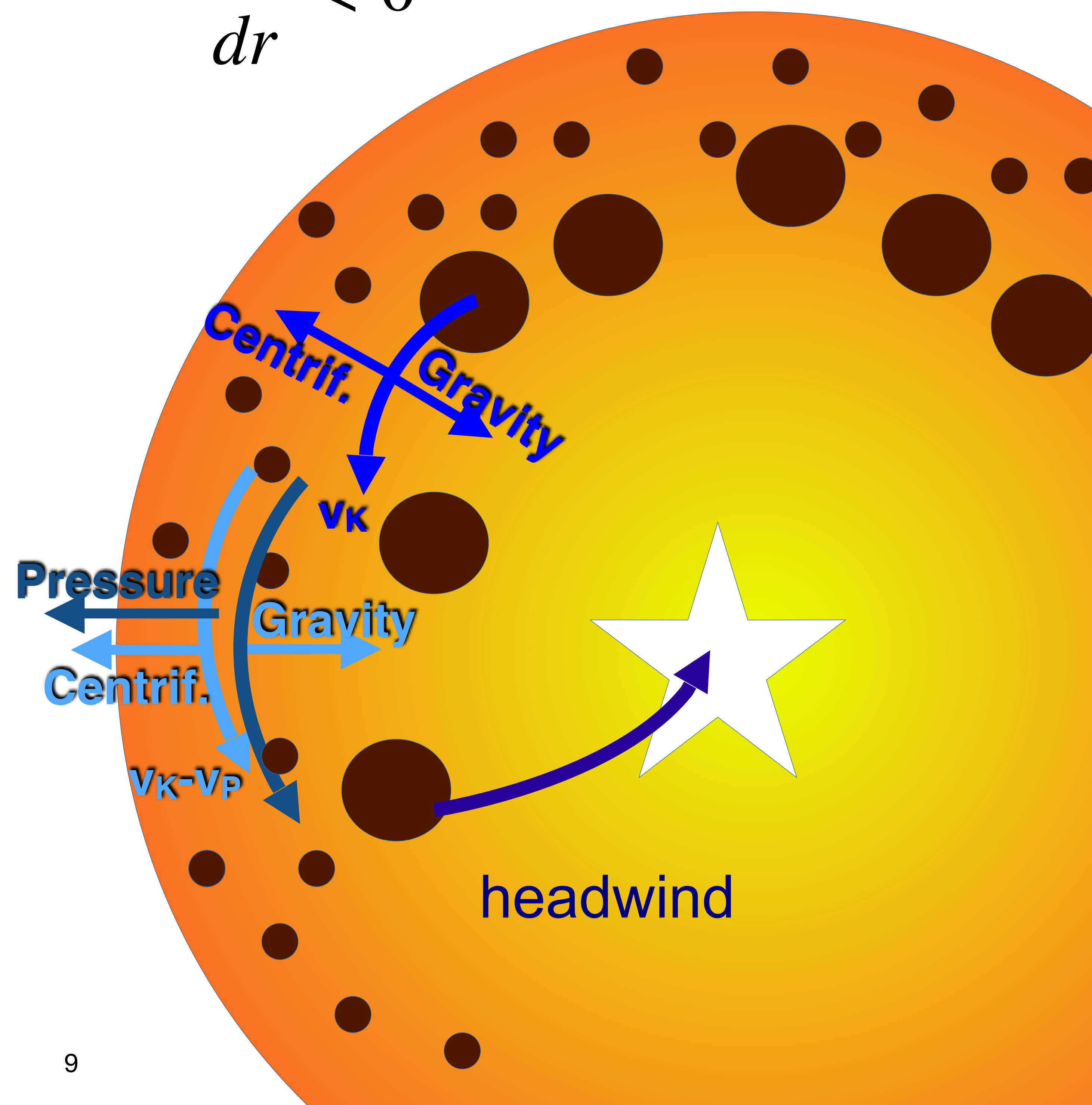
=> What's the origin of dust gaps and rings?

Andrews et al. 2018

Dust evolution

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

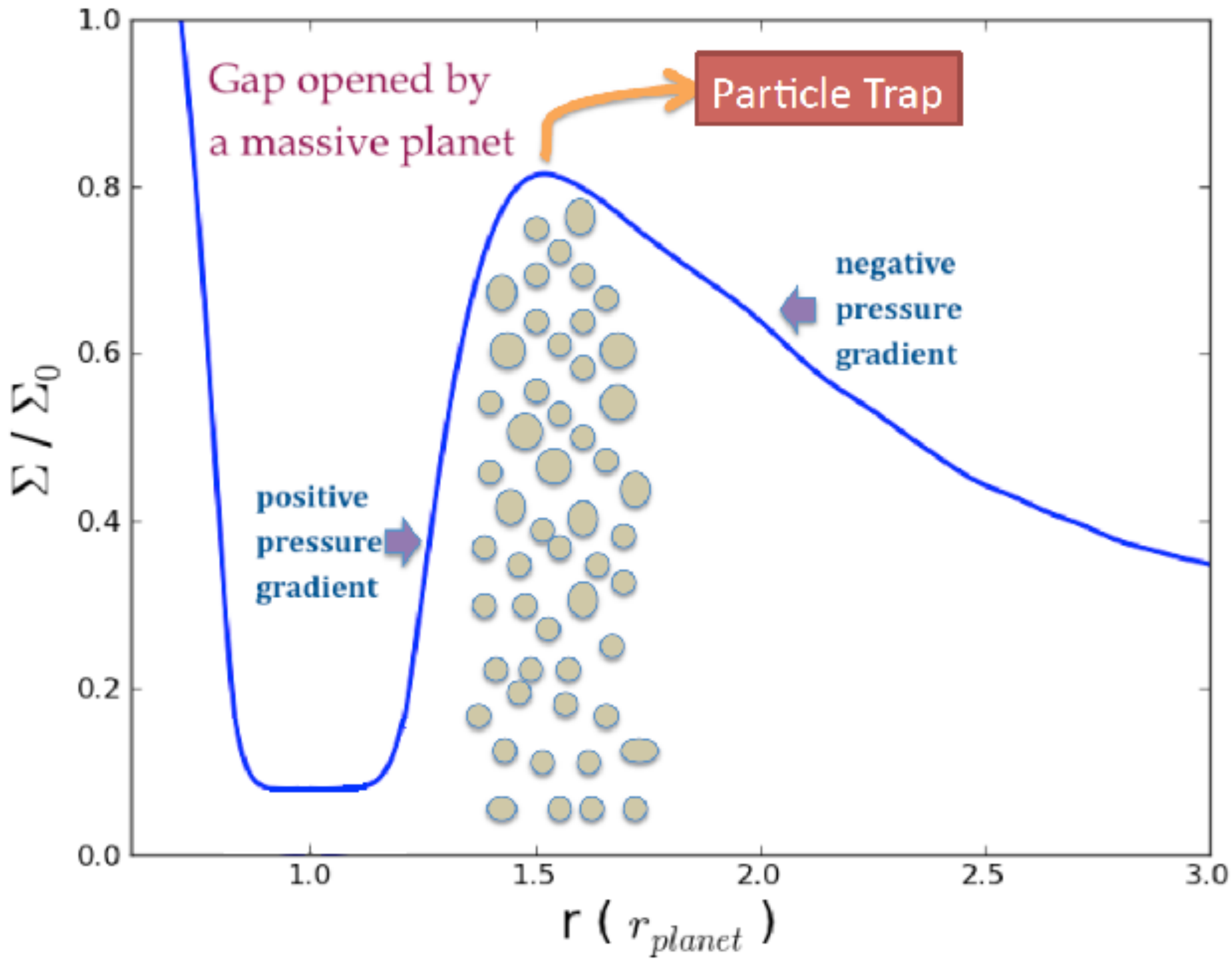
=> Need pressure bump to prevent radial drift



Weidenschilling 1977

Dust evolution: trapping

- Pressure bump in outer disk
  => through drag forces, large dust gets trapped



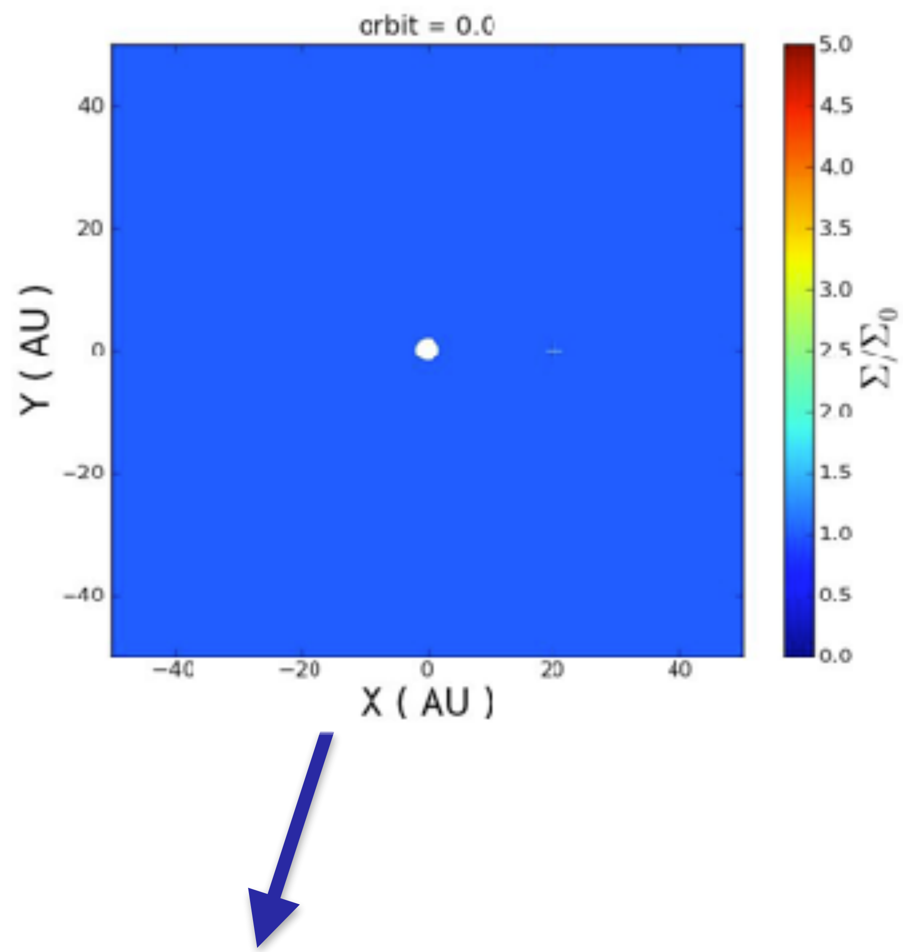
=> Rings (gap edges) are pressure bumps!

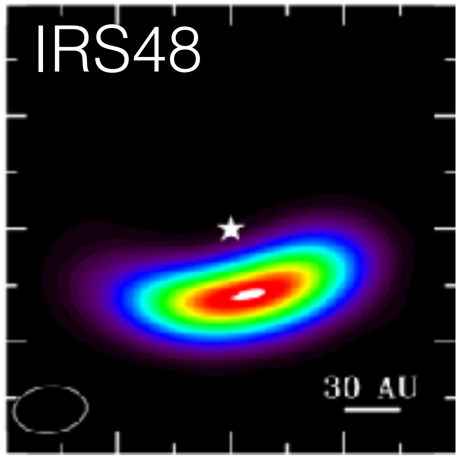
Varniere et al 2007
Pinilla et al. 2012
Zhu et al. 2012

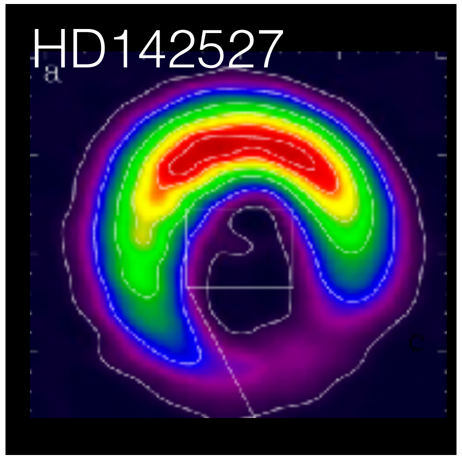
Dust evolution: trapping

- What is the origin of the azimuthal asymmetries?
- Pressure bump develops Rossby Wave instability*
  => form long-lived vortices
  => azimuthal trapping
  => dust asymmetry

gas simulation



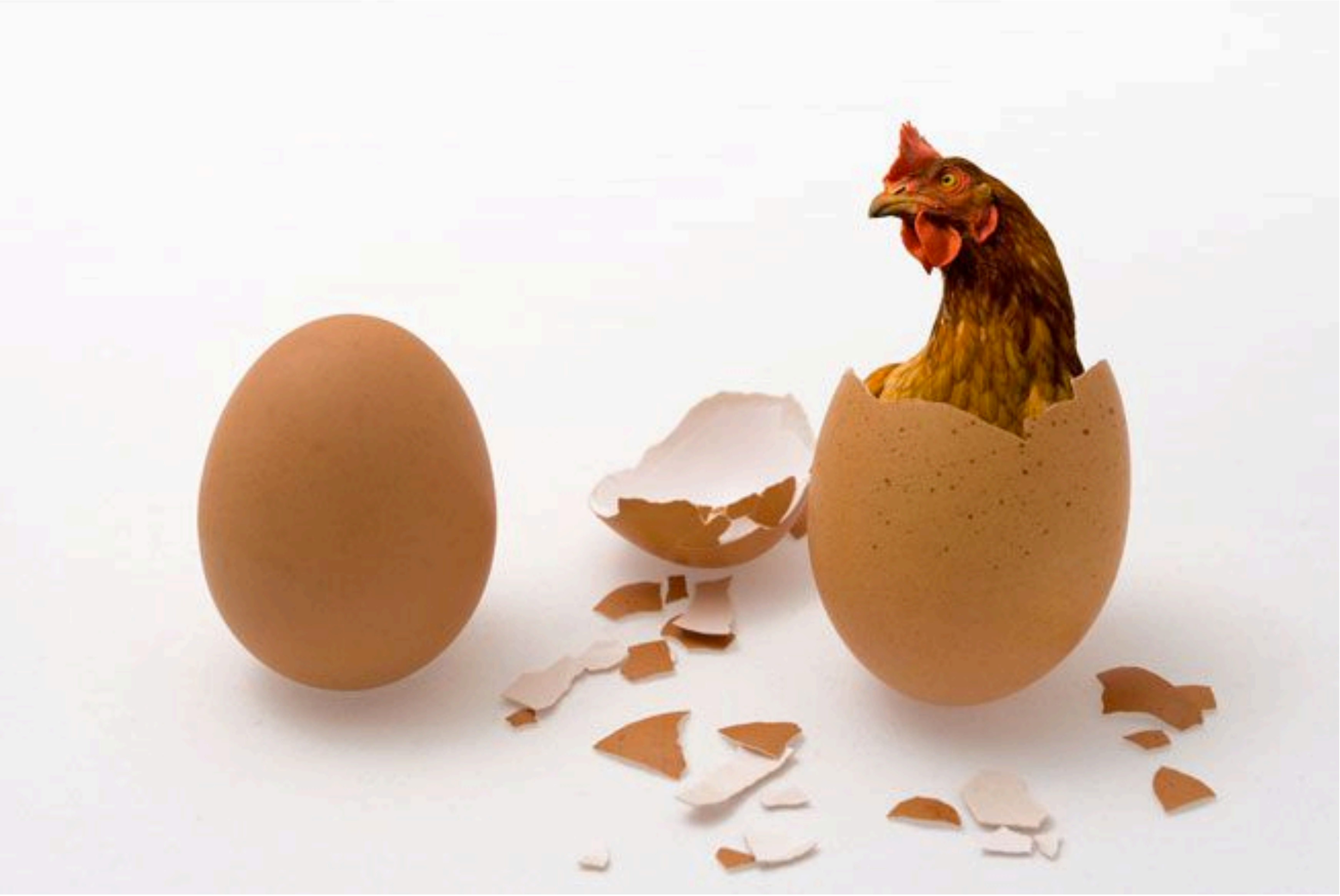




*)Kelvin-Helmholtz instability

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

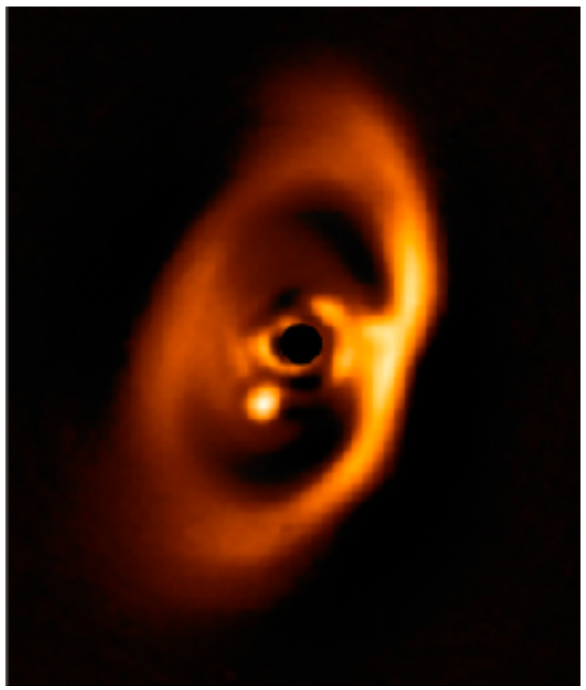
Problem:
dust traps require planets?



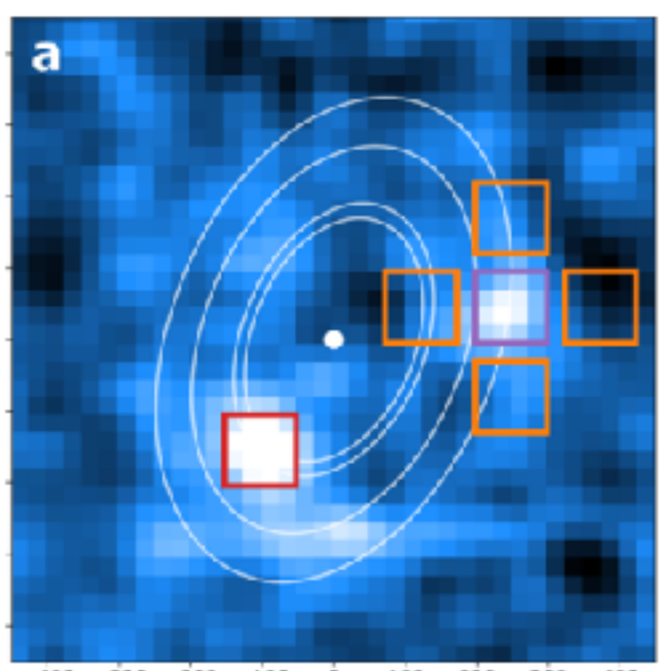
Why we think it's planets

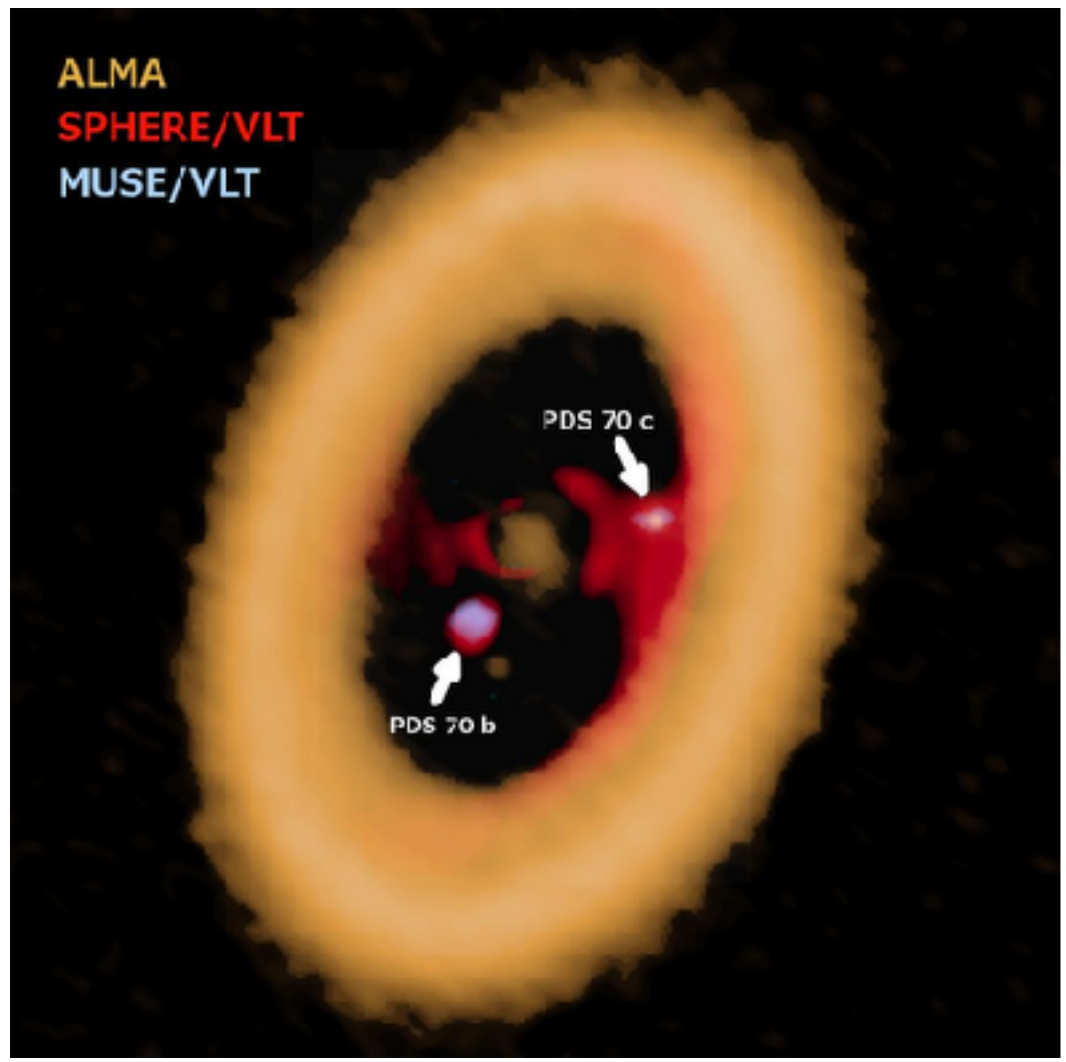
PDS70: two planets!

NIR

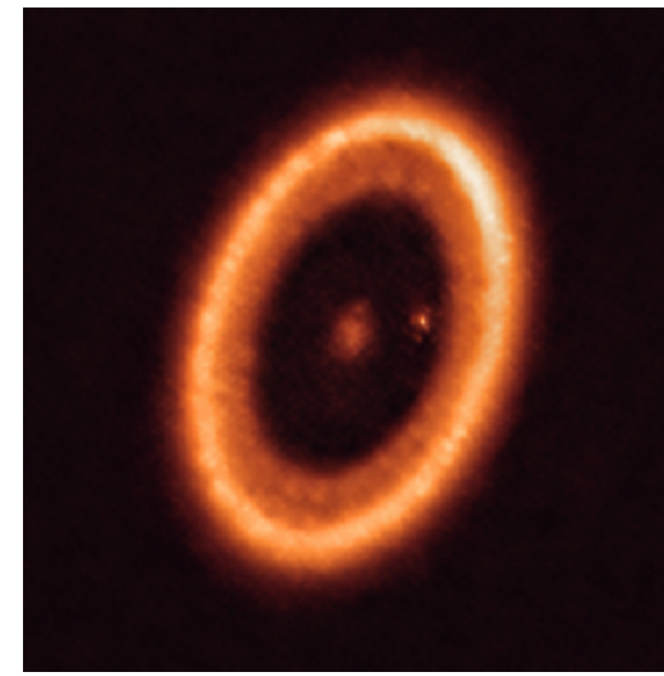


H-alpha

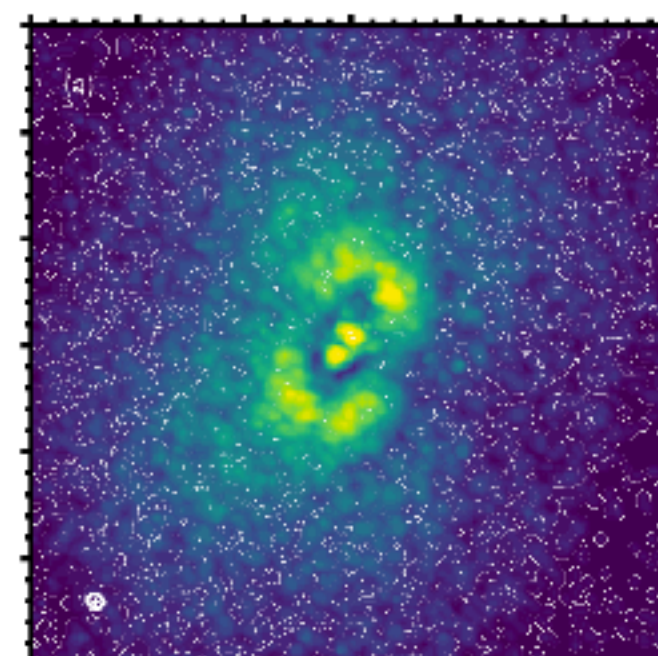




Continuum



^{12}CO emission

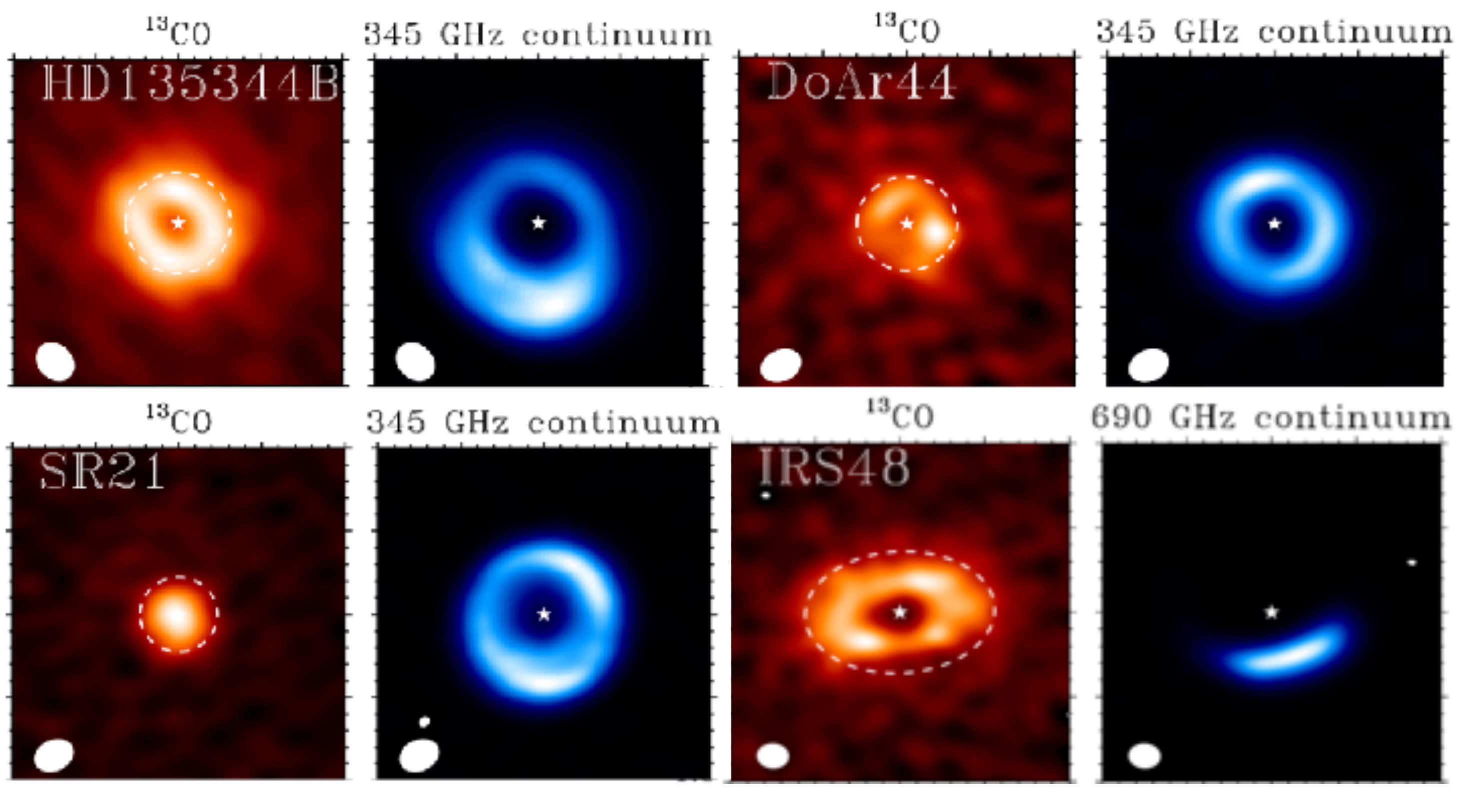


Keppler et al. 2018, 2021,
Muller et al. 2018, Haffert et al. 2019,
Isella et al. 2019, Benisty et al. 2021

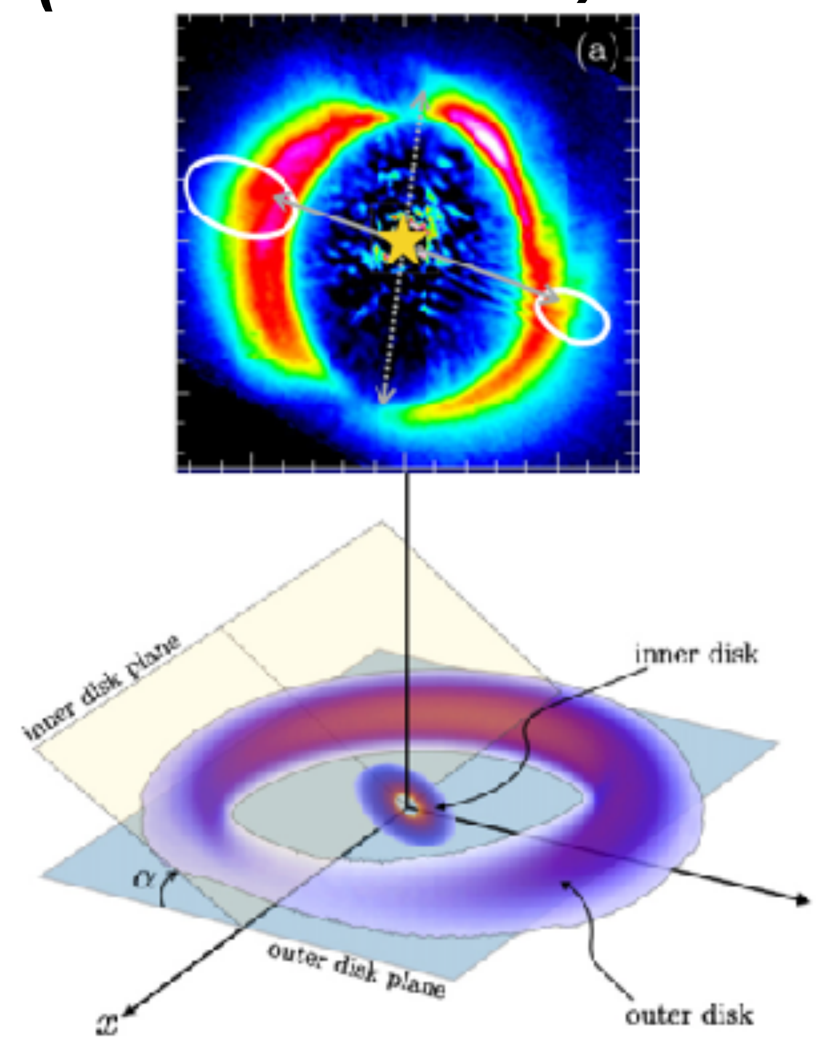
Why we think it's planets

Other signatures

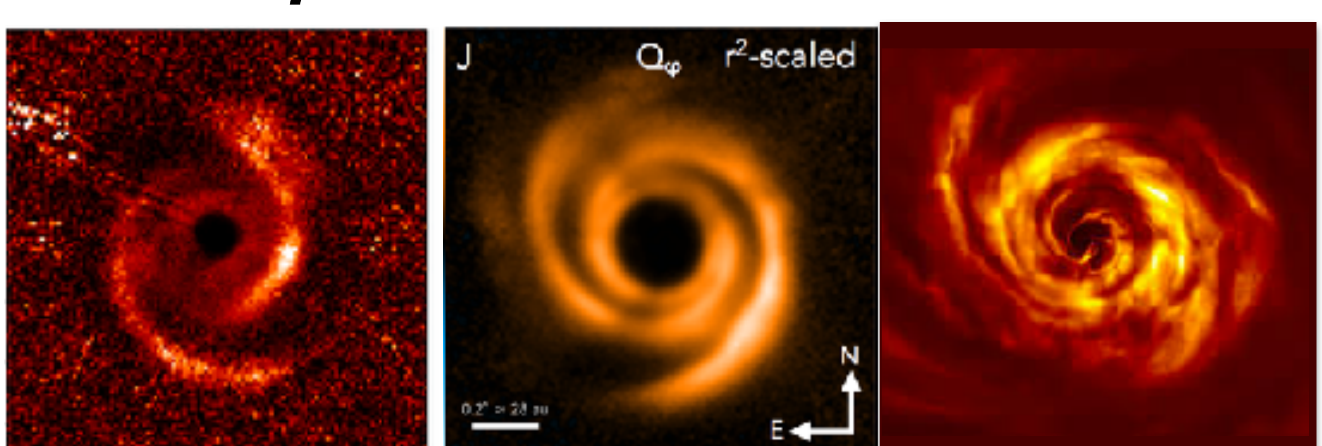
Gas gaps in ^{13}CO



Misaligned inner disks (shadows in NIR)



Spiral arms in NIR

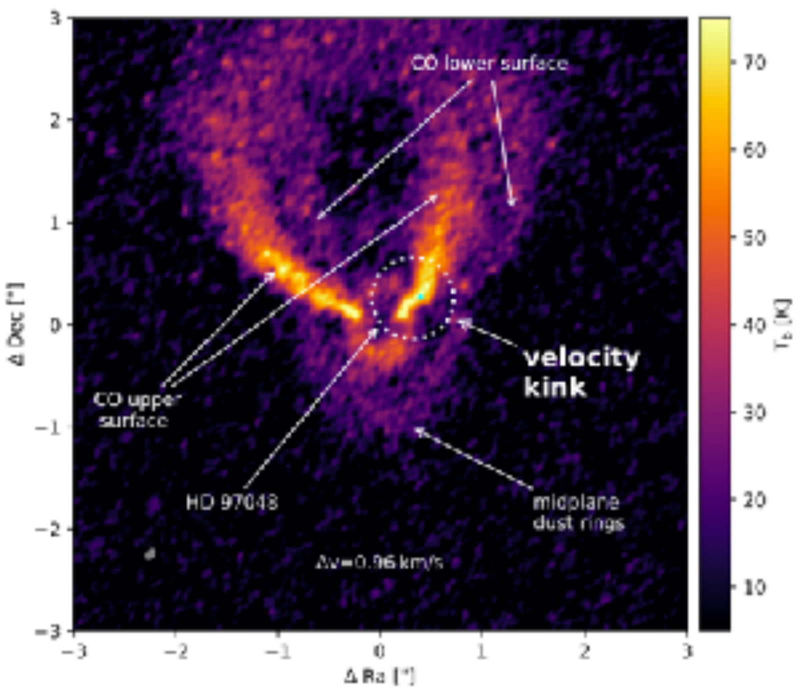


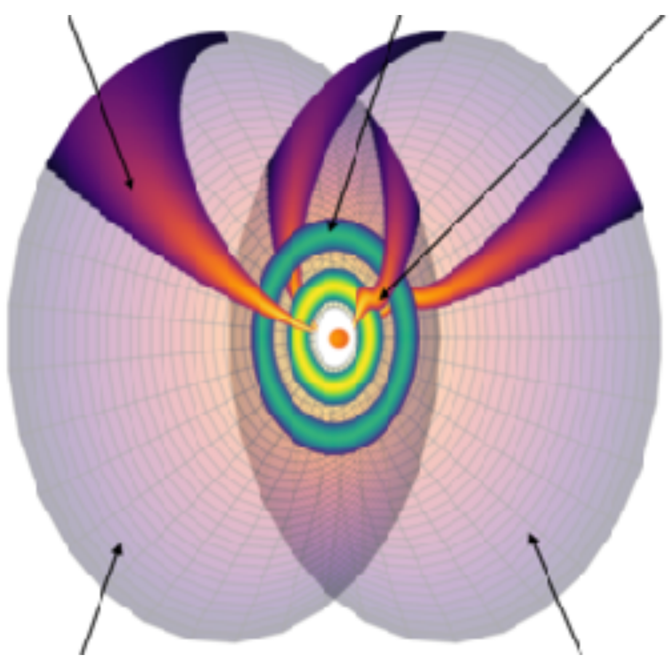
Van der Marel et al. 2016
Dong et al. 2015, 2016, 2018
Marino et al. 2015
Casassus et al. 2015

Why we think it's planets

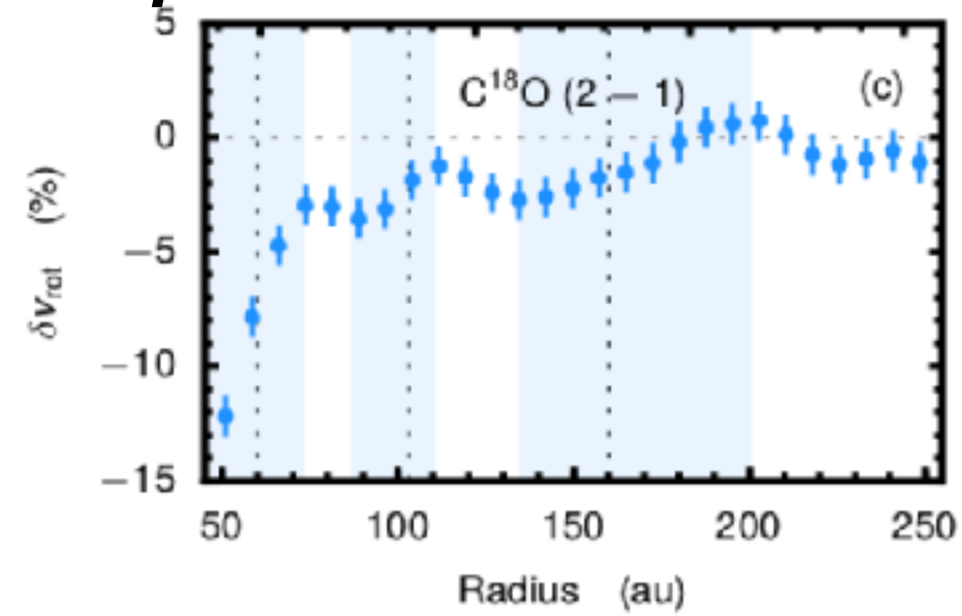
Kinematics

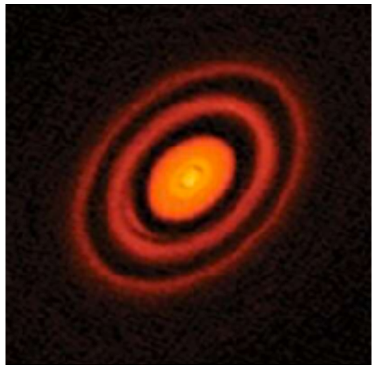
Velocity kinks



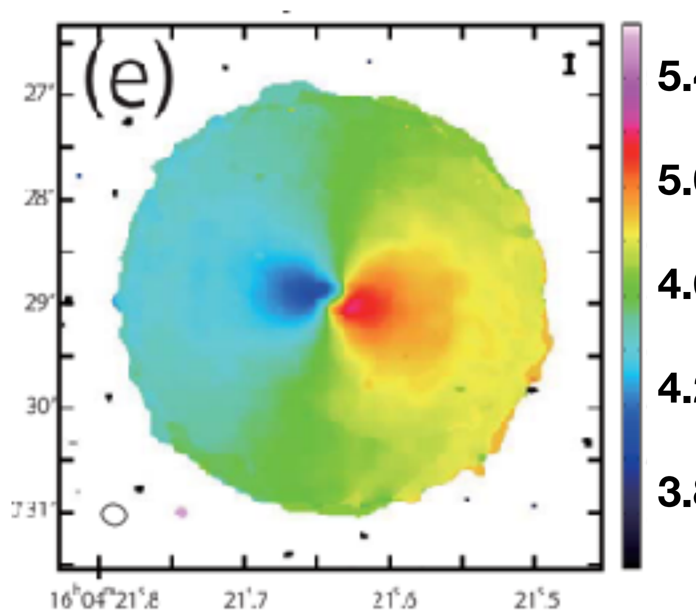


Deviations from Keplerian rotation

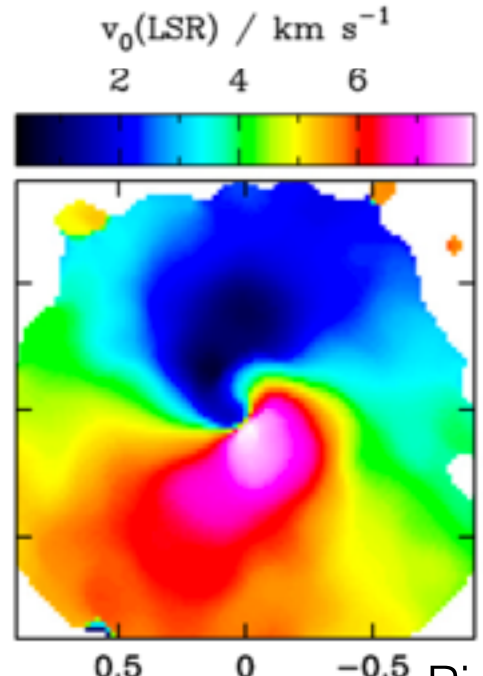




Warps



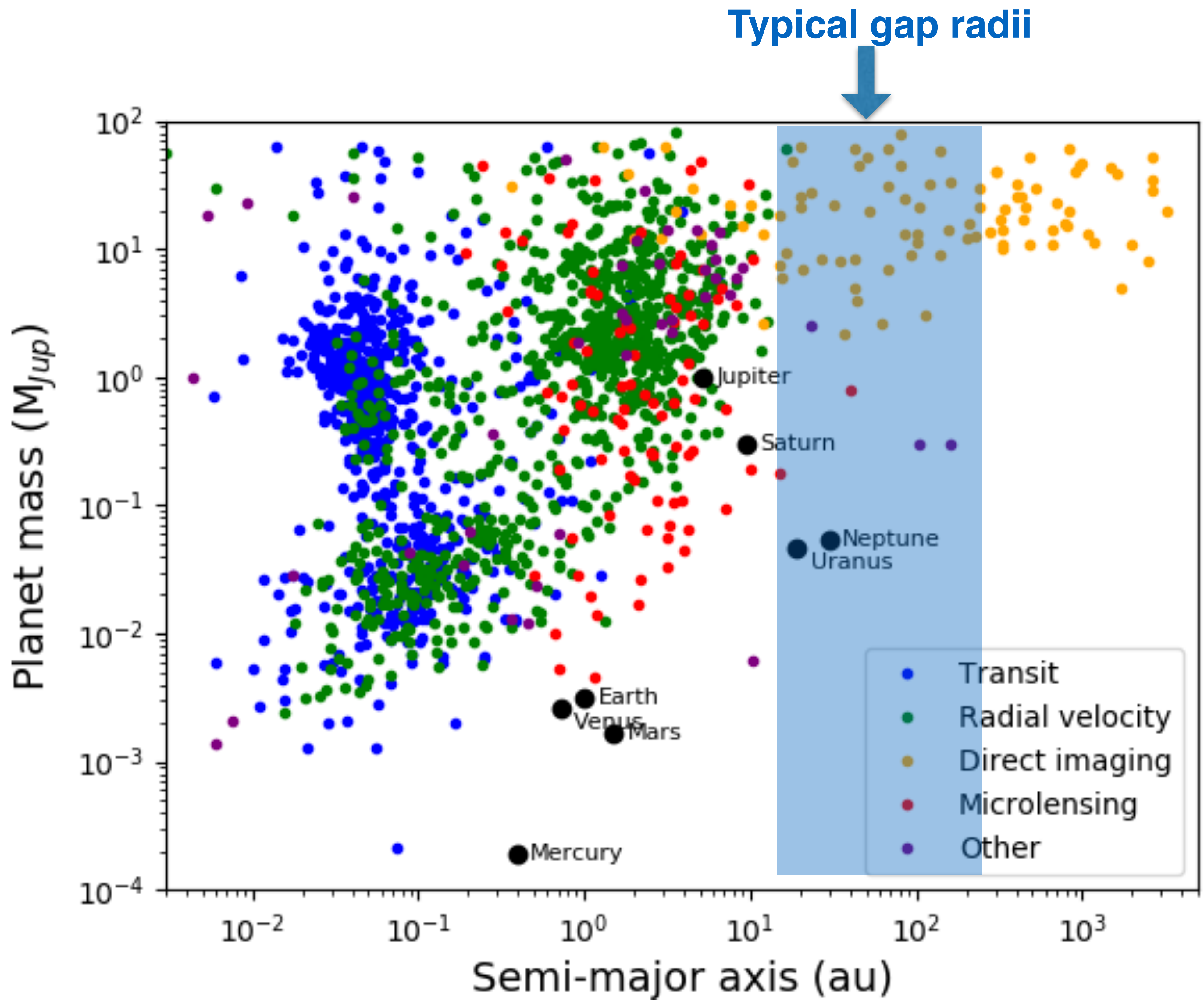
J1604-2130



HD142527

Teague et al. 2018
Pinte et al. 2018, 2019
Mayama et al. 2018
Casassus et al. 2015

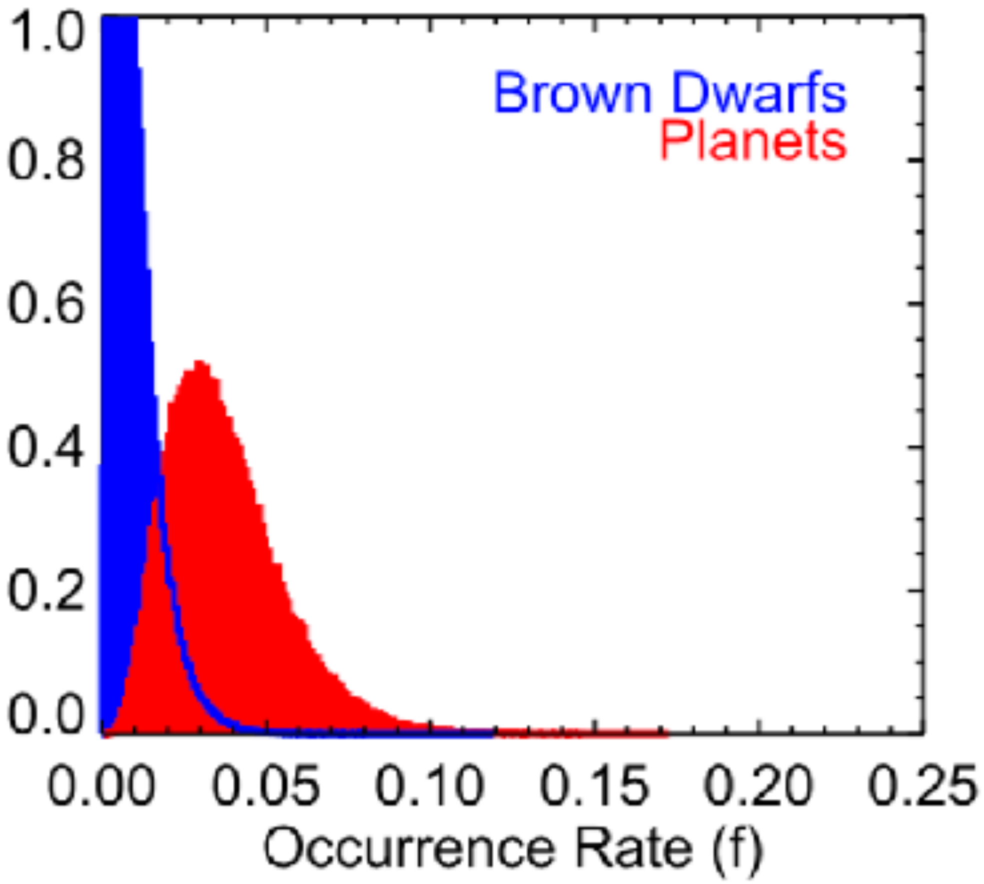
Why it may not be planets



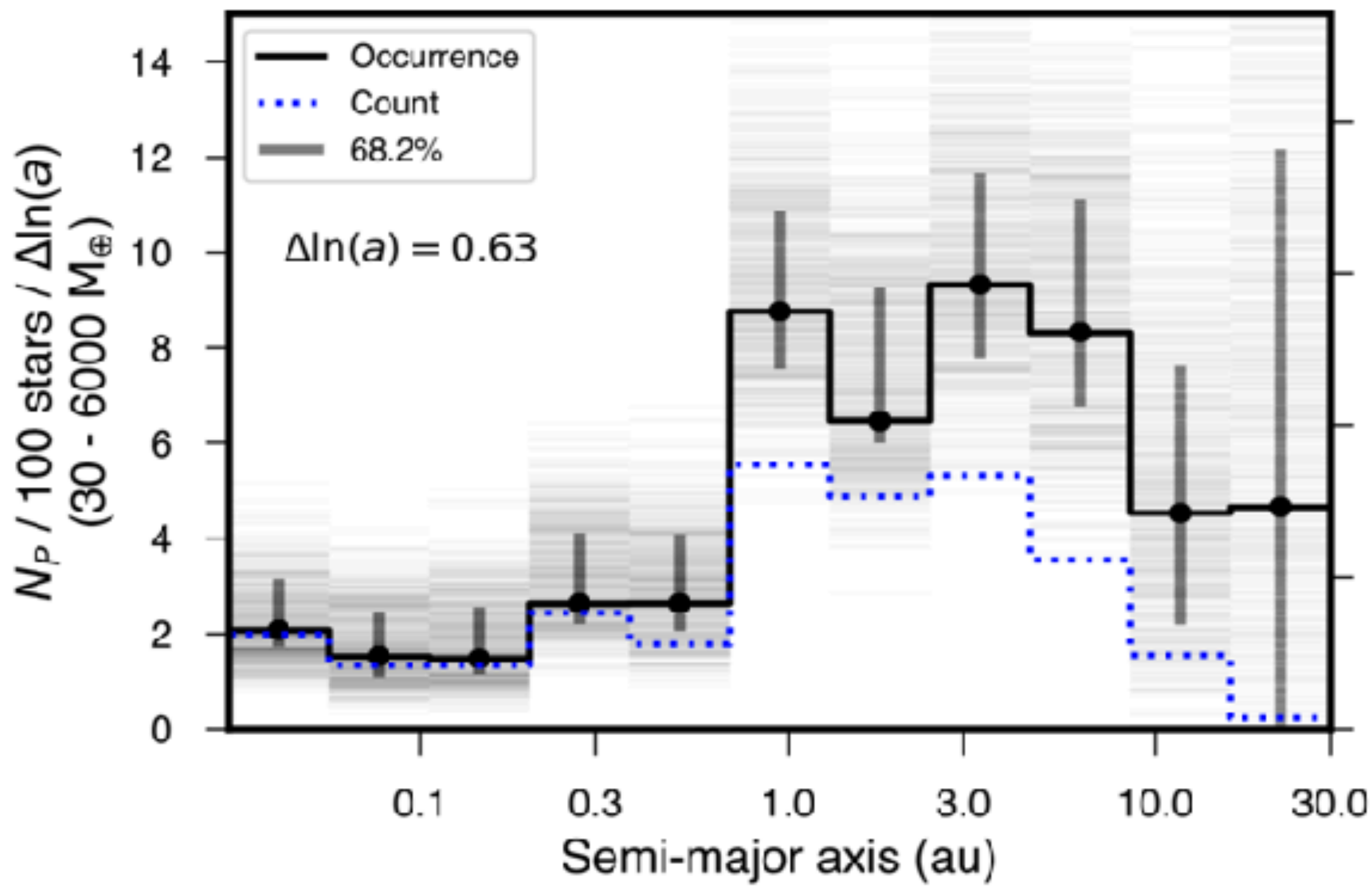
Problem: exoplanets at wide orbits are rare (few %)

Why it may not be planets

Direct imaging:
(5-13 M_{Jup} at 10-100 au)

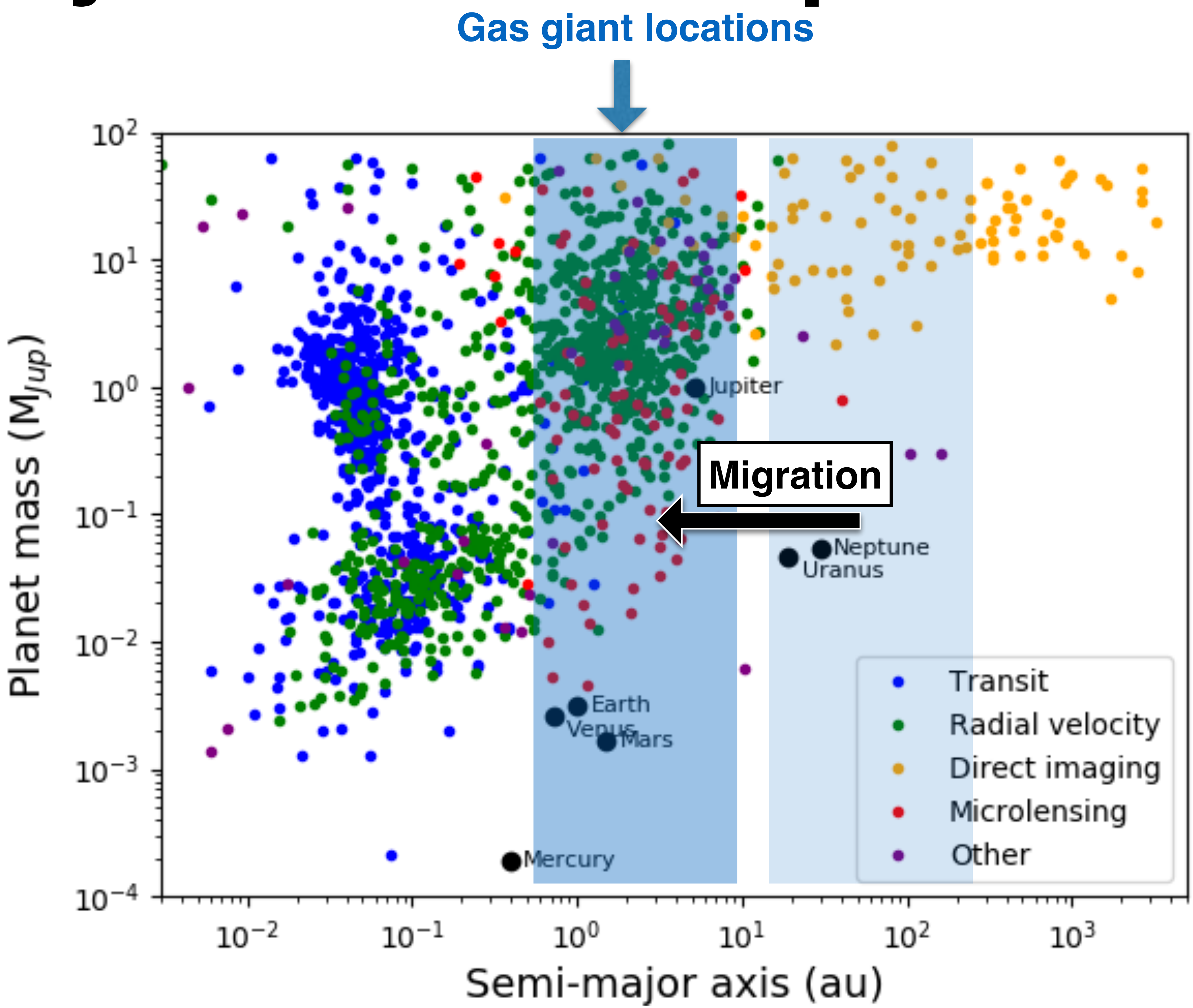


Radial velocity surveys:
(0.1-18 M_{Jup} at 0.1-20 au)



Nielsen et al. 2019 (GPIES)
Fulton et al. 2021 (CLS)

Why it could still be planets



Lodato et al. 2019
van der Marel & Mulders 2021

Solution: inward migration, but still not enough giant planets?

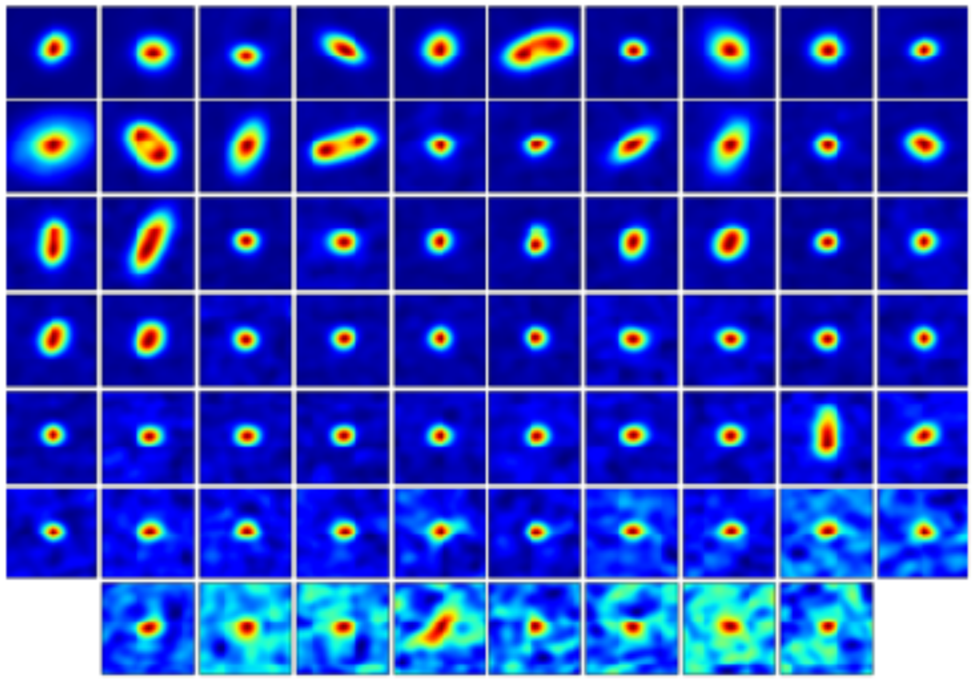
Problem: strong bias towards the brightest disks in high-res observations!

What is the bigger picture?

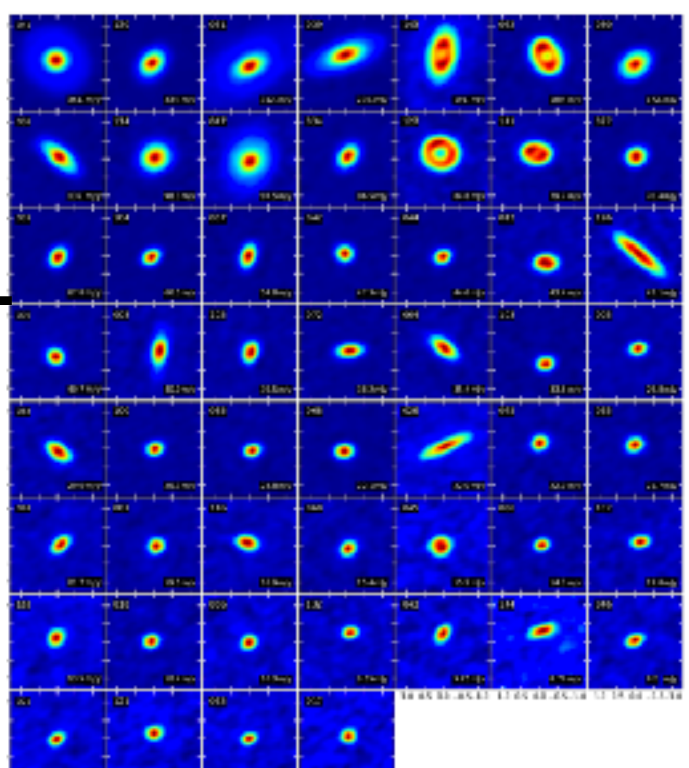
Lupus ALMA Disks Survey

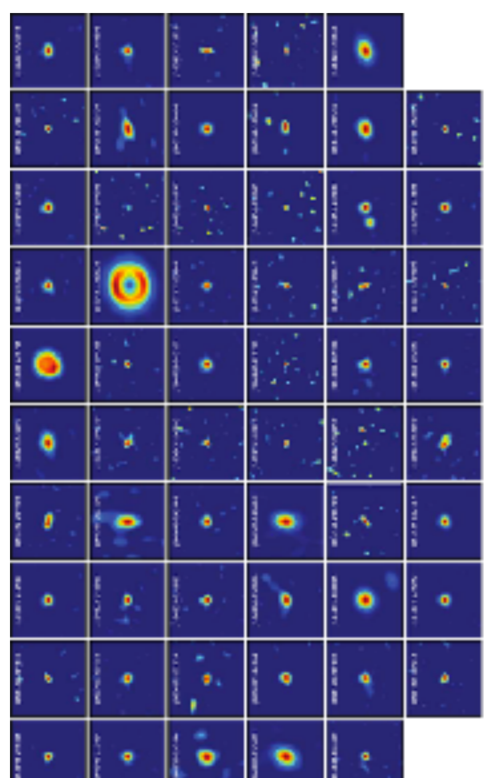
Large ALMA disk surveys

Lupus



Ophiuchus





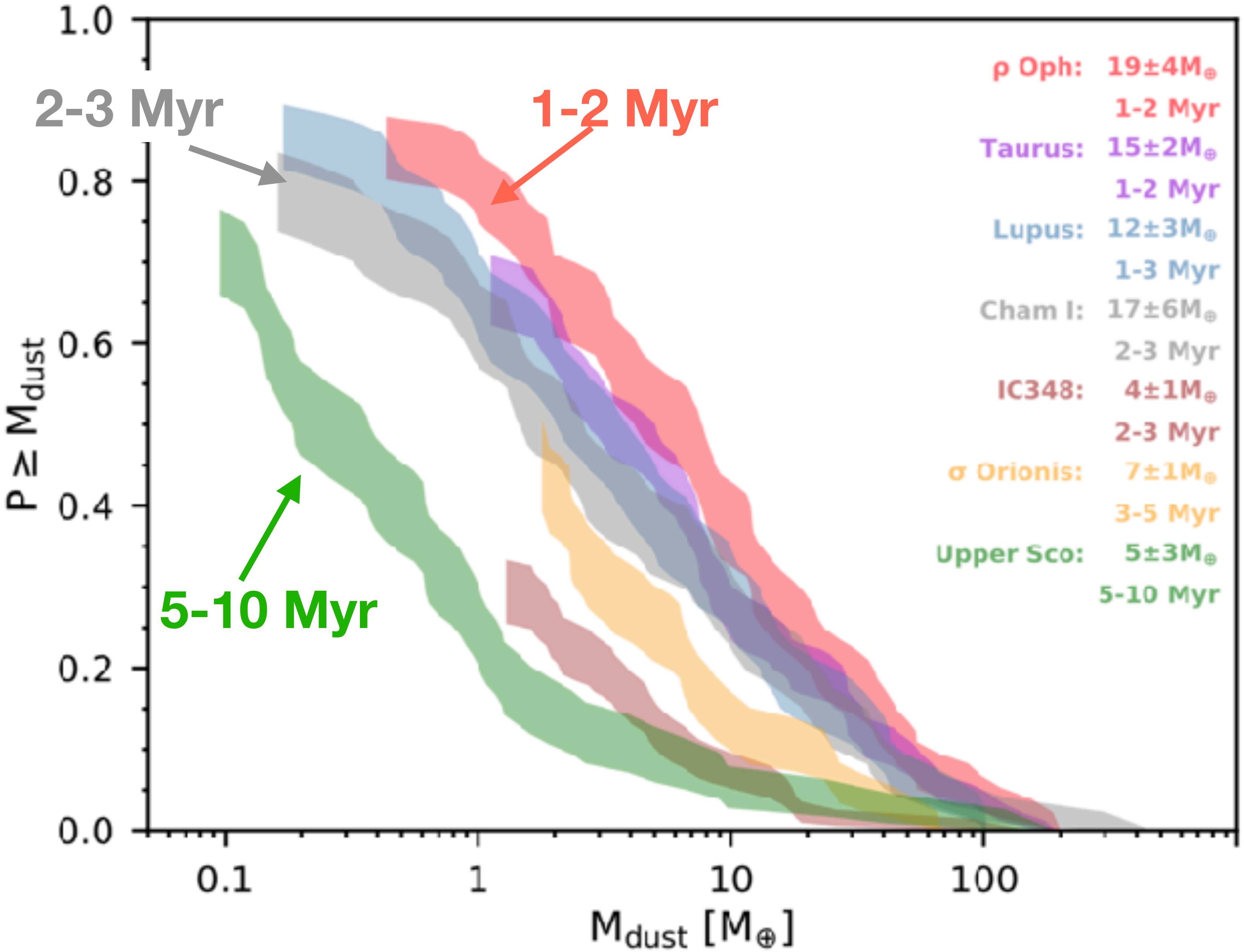
Upper Sco

- Snapshot surveys of 1-2 min/source
- Hundreds of disks in SF regions
- Regions of 1-10 Myr old
- Continuum flux provides disk dust mass

=> Statistics of disk dust mass and evolution!

Ansdell et al. 2016, 2018
Barenfeld et al. 2016
Cieza et al. 2018

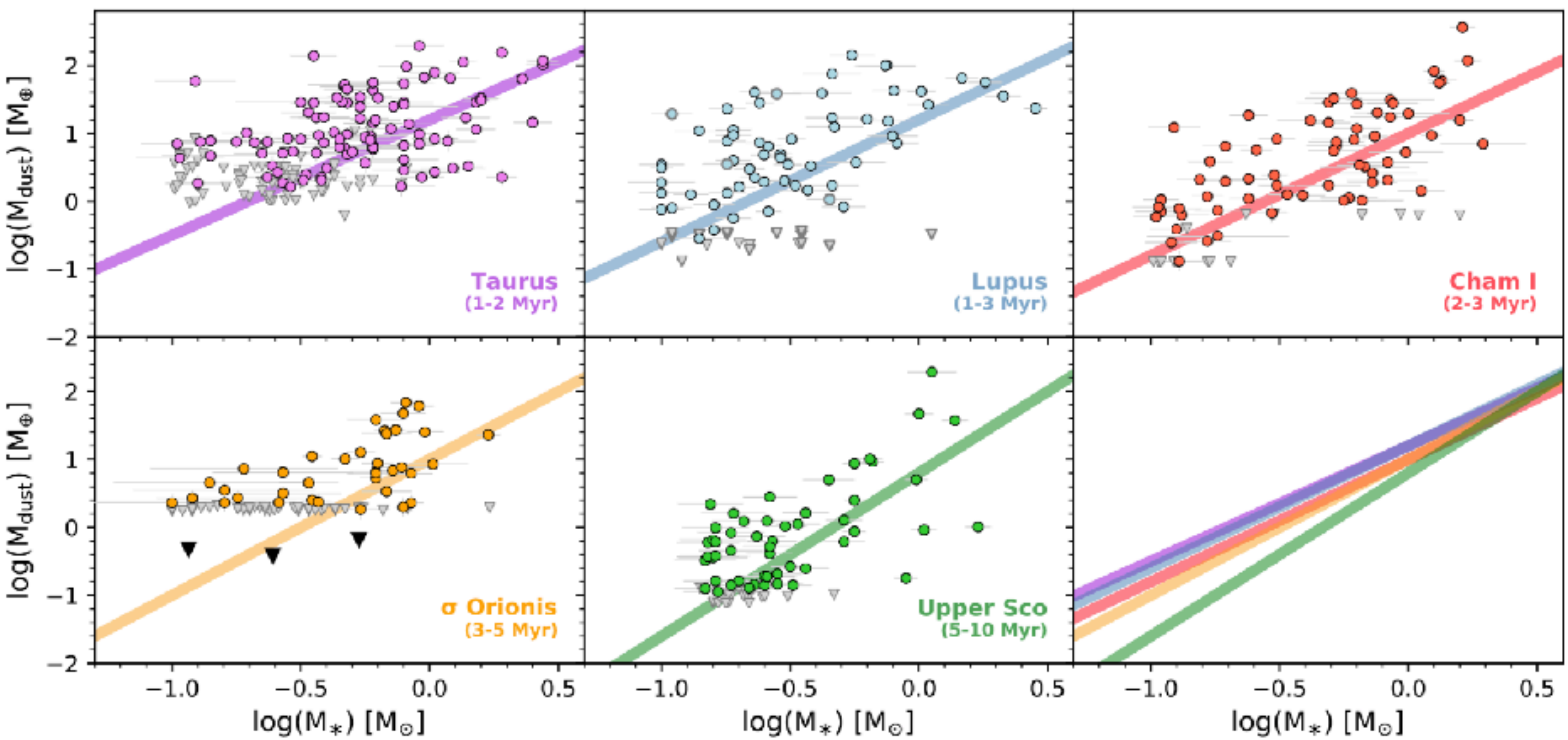
Disk evolution: mm-dust



Disk dust mass decreases with age

Ansdell et al. 2016, 2017
Cieza et al. 2018

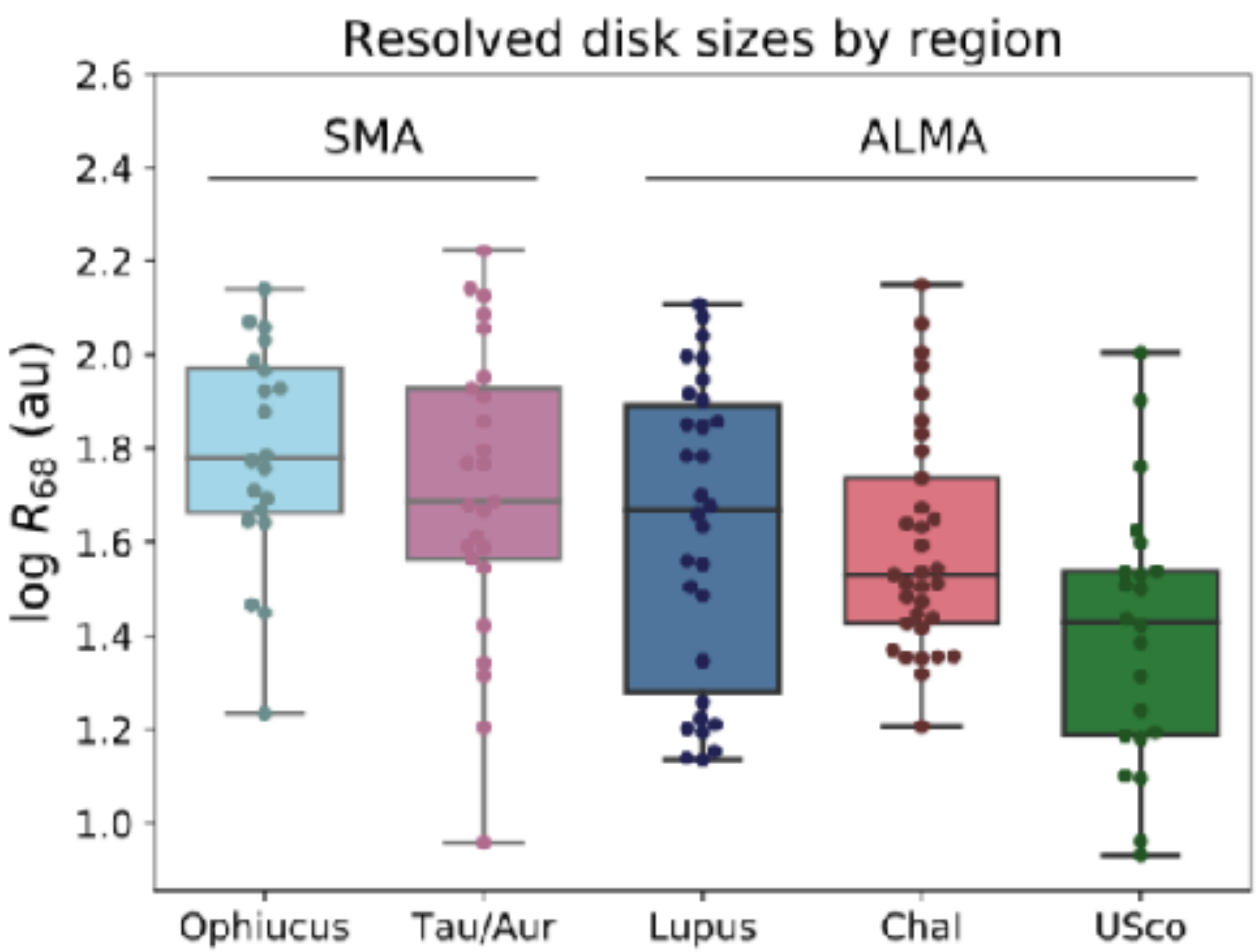
Disk evolution: mm-dust



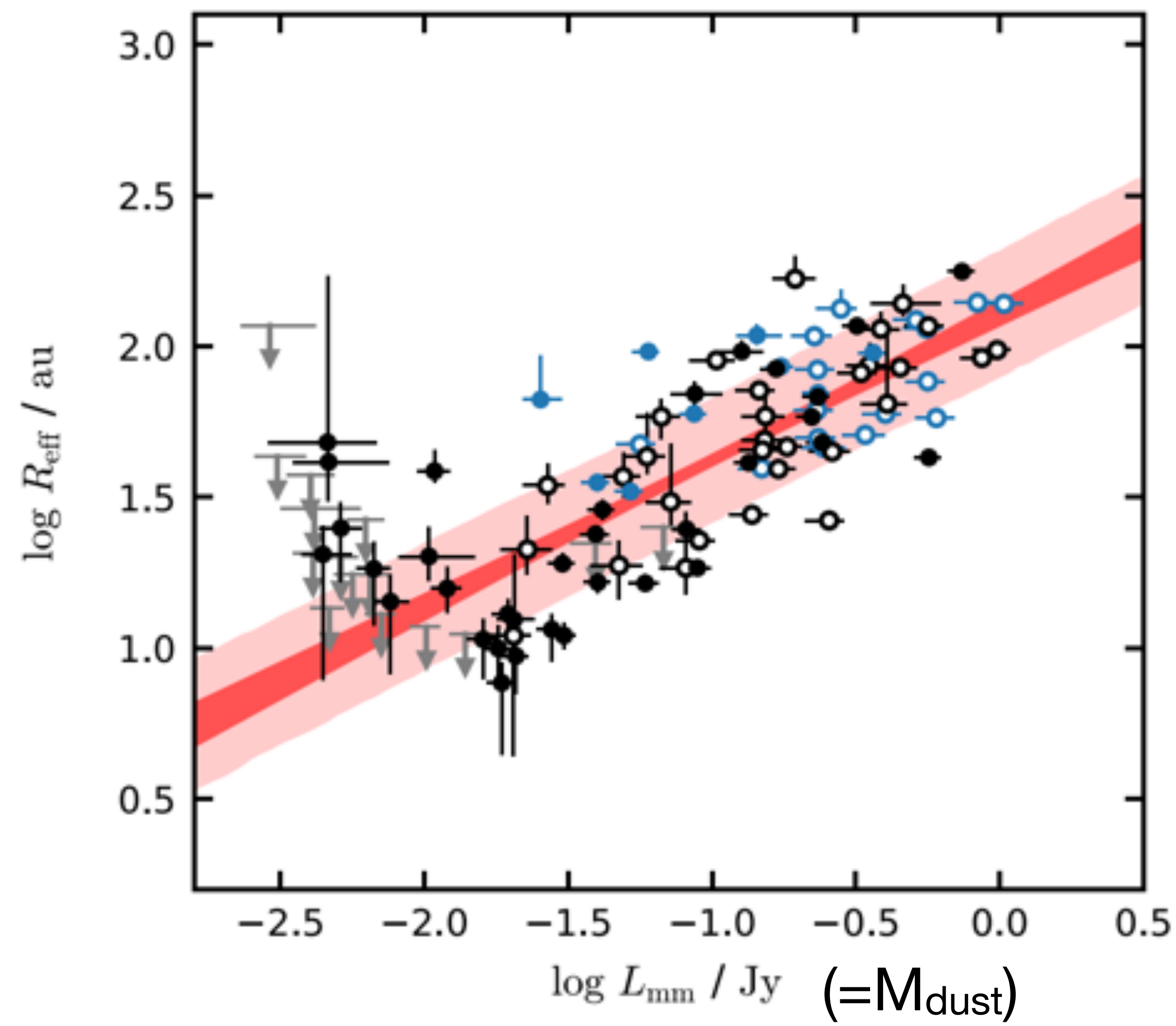
Disk dust mass scales with stellar mass
and decrease with age is stronger for low-mass

Ansdell et al. 2016, 2017

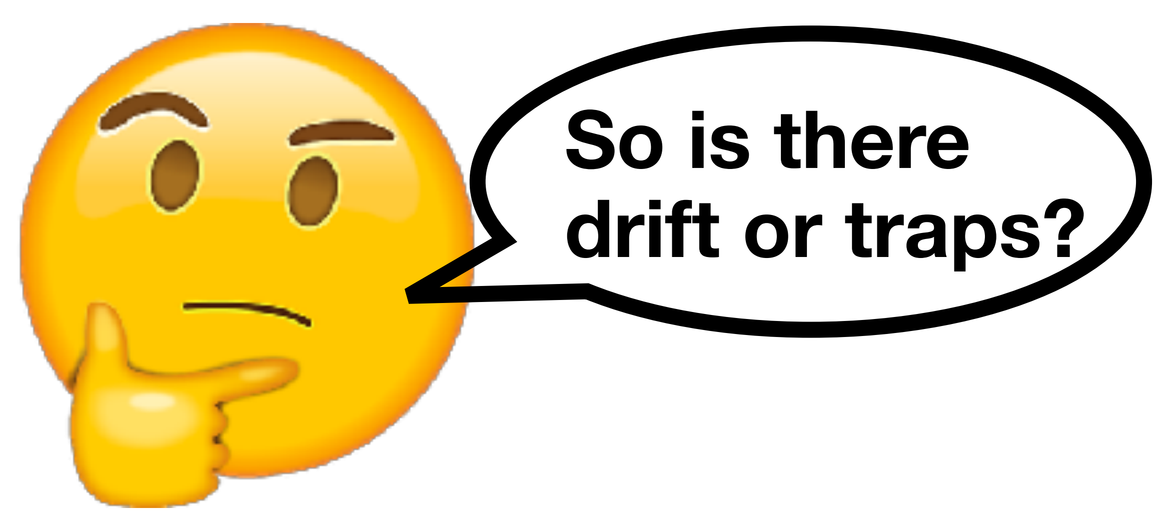
Disk evolution: mm-dust



Age

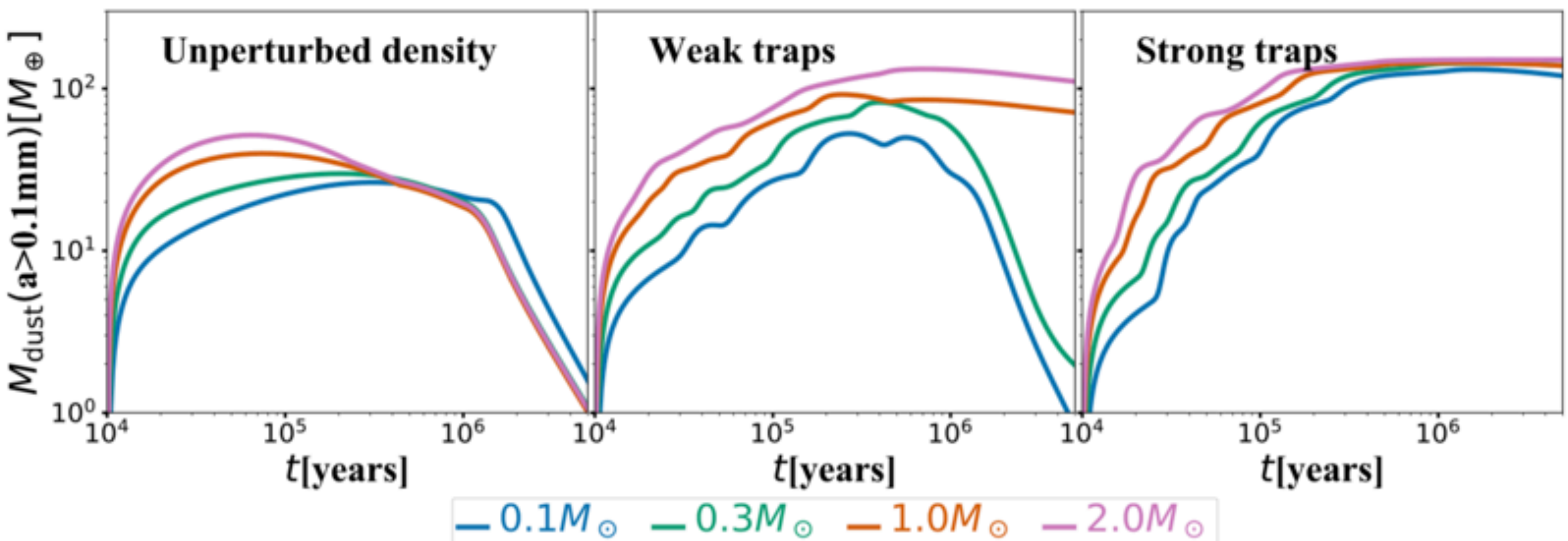


Disk dust size scales with dust mass and decreases with time: radial drift?

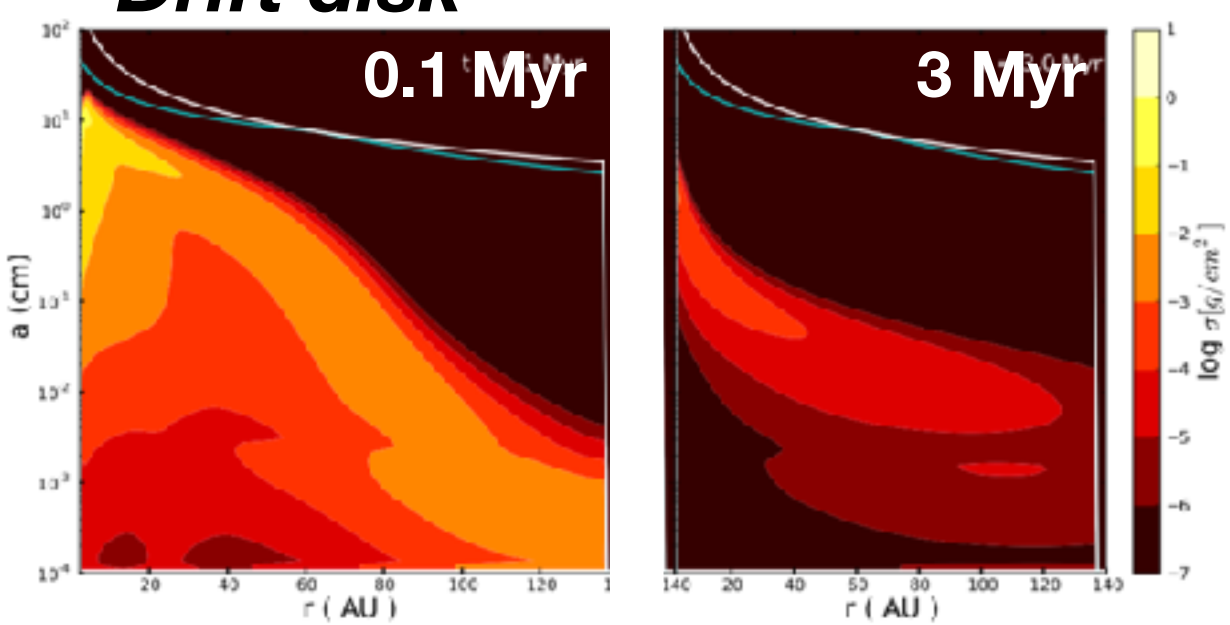


Hendler et al. 2020
Andrews et al. 2018
Tazzari et al. 2017, 2021

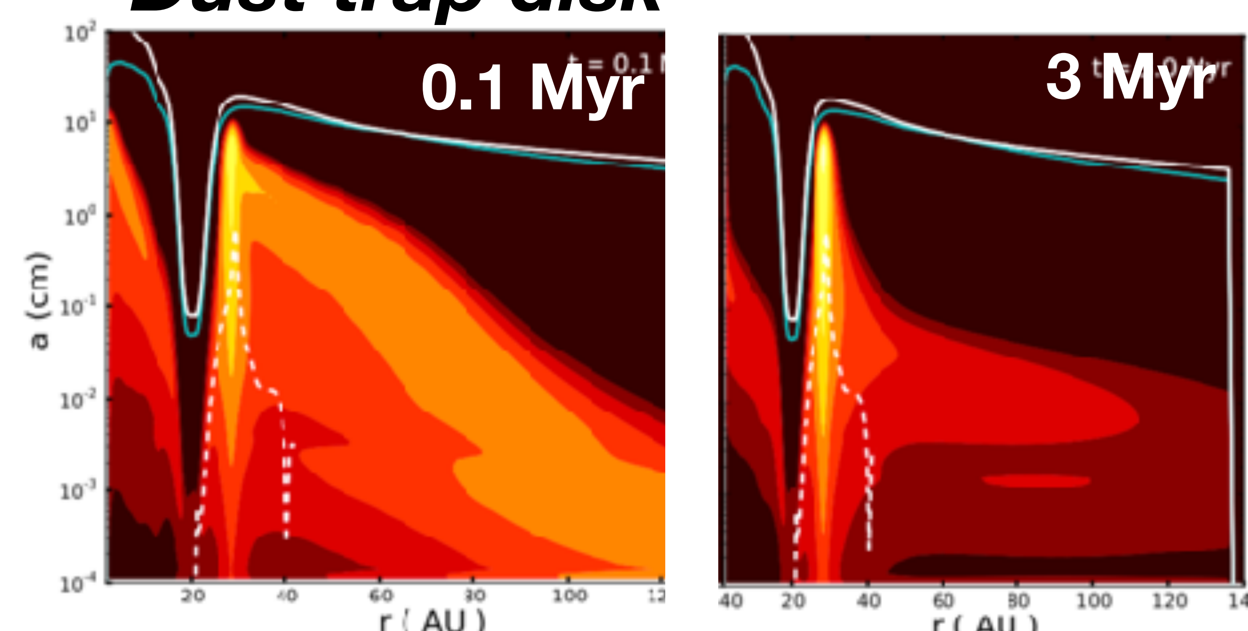
Dust evolution: 2 options



Drift disk



Dust trap disk

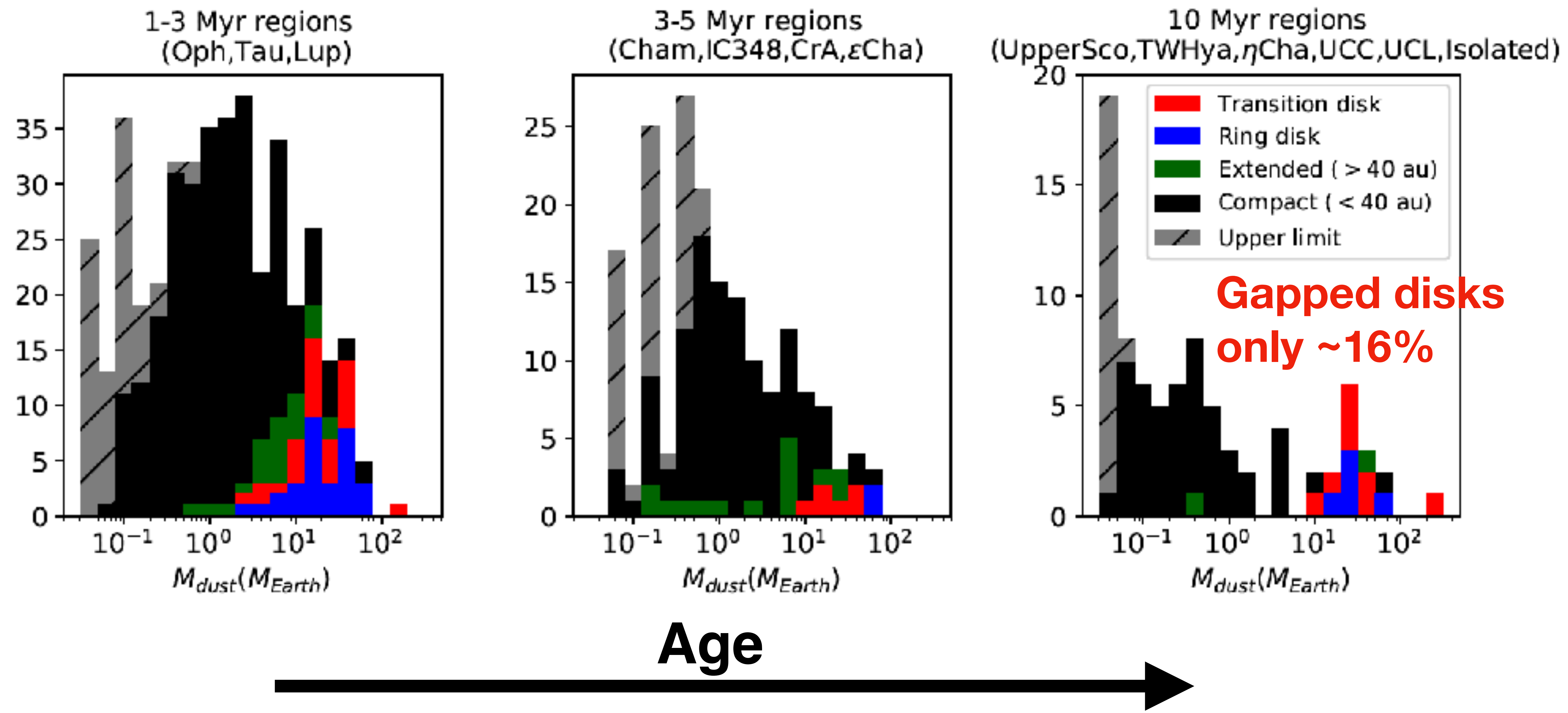


Minimum mass to halt drift:
pebble isolation mass (~10 M_E)

Pinilla et al. 2012, 2020
Lambrechts et al. 2014

Large(st) ALMA survey (collection ~700 disks)

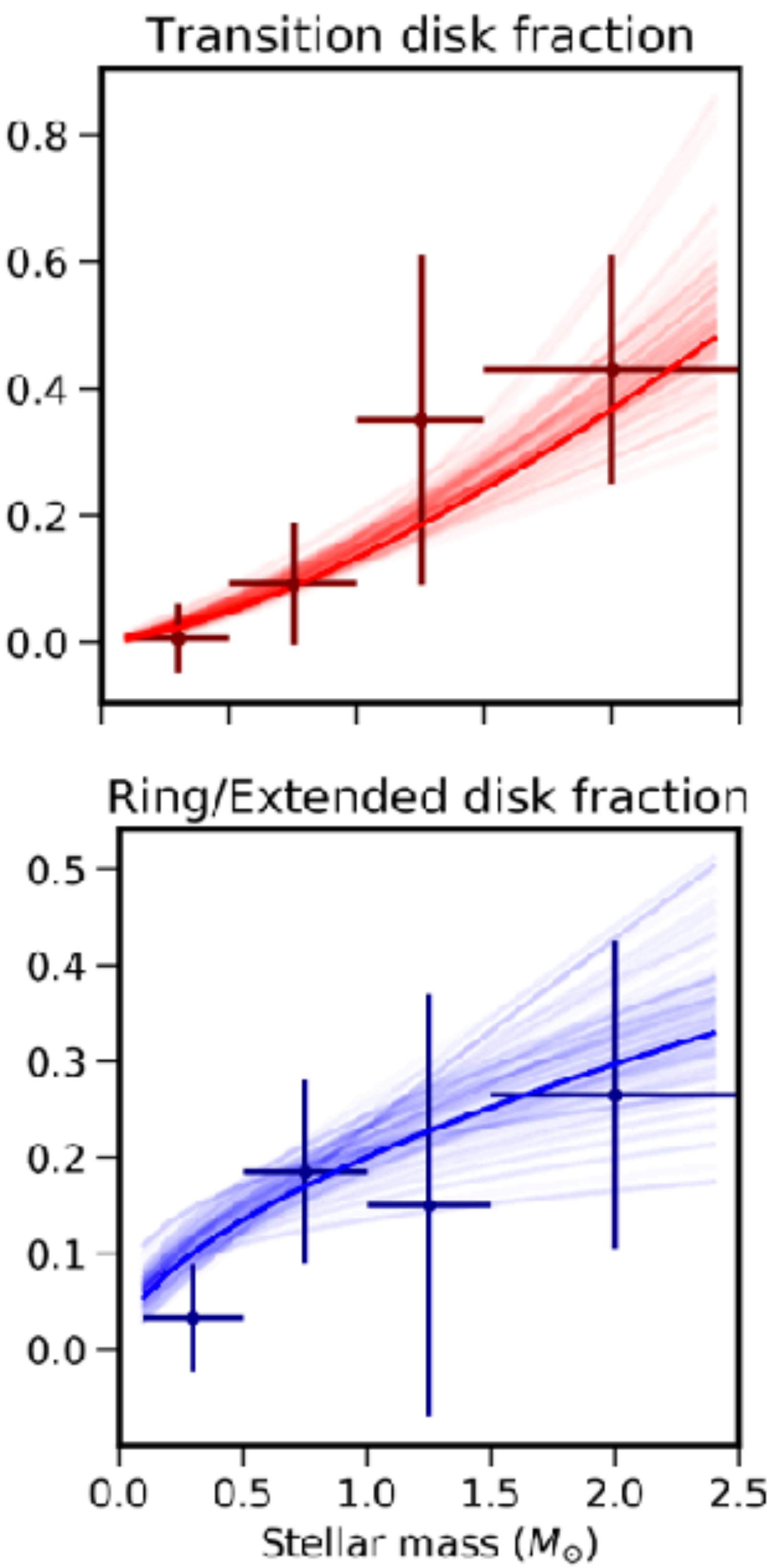
Distribution dust masses as function of age and disk type



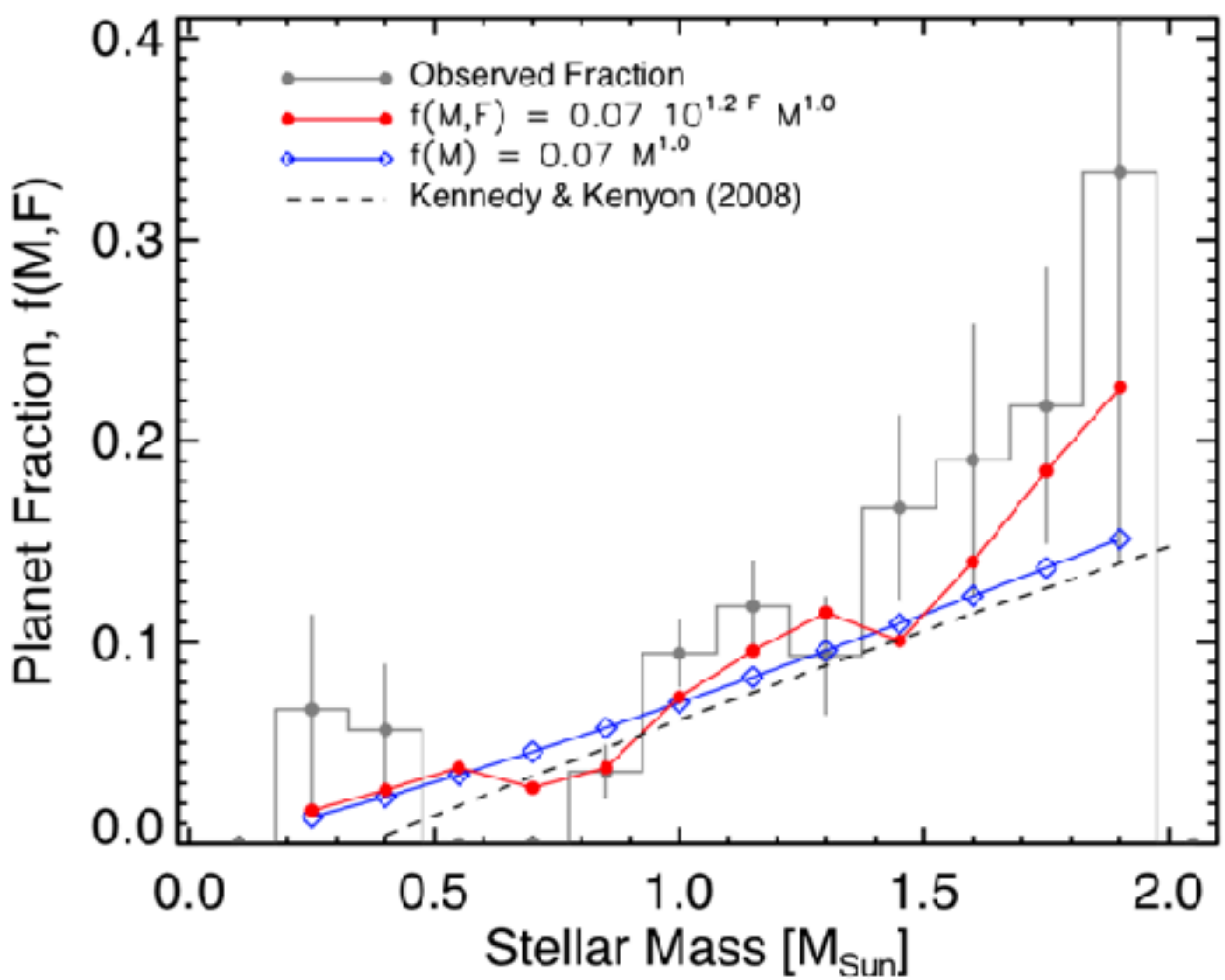
Two separate evolutionary pathways:
the (large-scale) gapped disks and drift disks

Van der Marel & Mulders 2021

Gapped disks vs exoplanets



Stellar mass dependence in gapped disks: link with giant exoplanets?

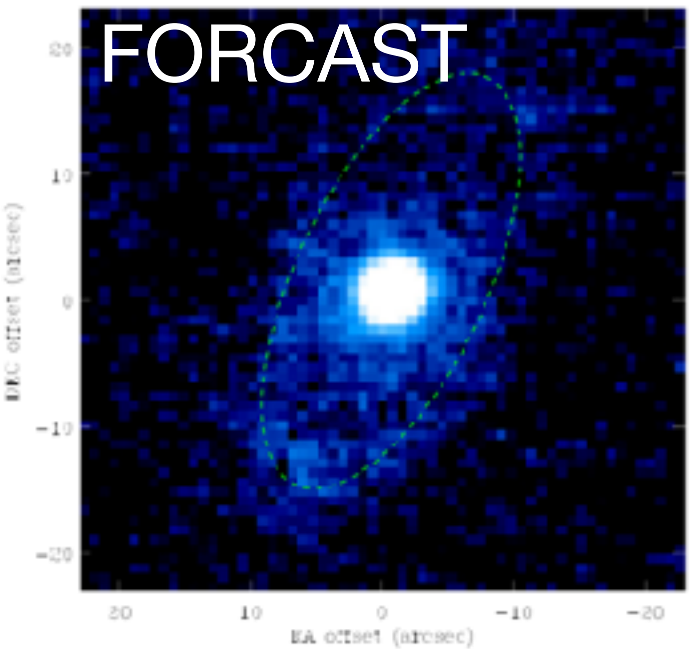


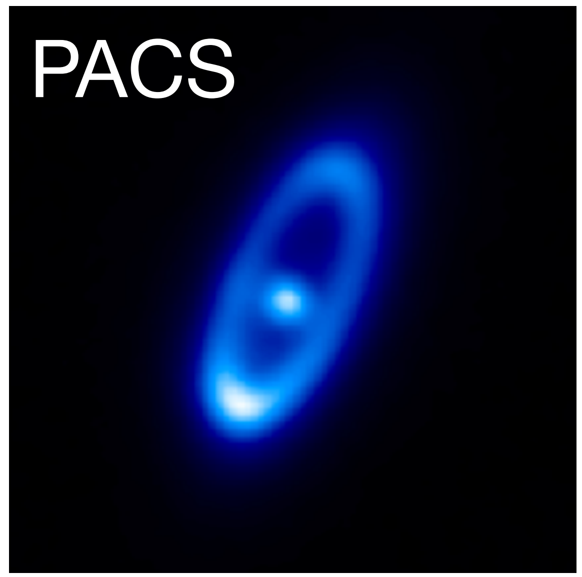
Van der Marel & Mulders 2021
Johnson et al. 2010
Mulders 2018

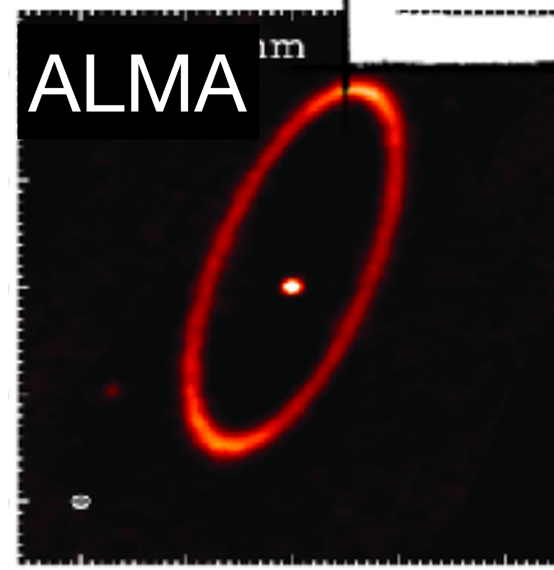
Debris disks (Kuiper belt analogs)

Note: debris disks much fainter but closer

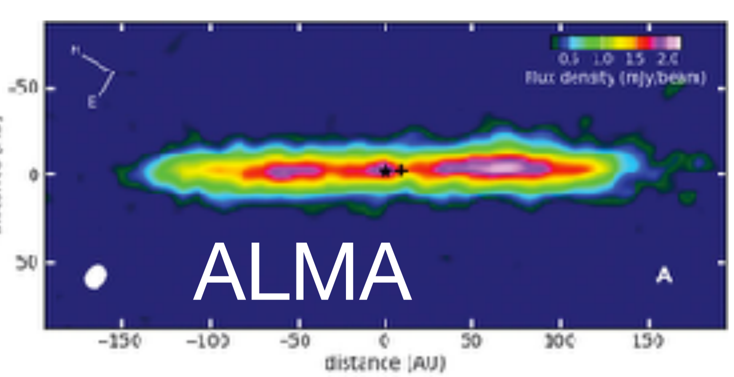
Formalhaut

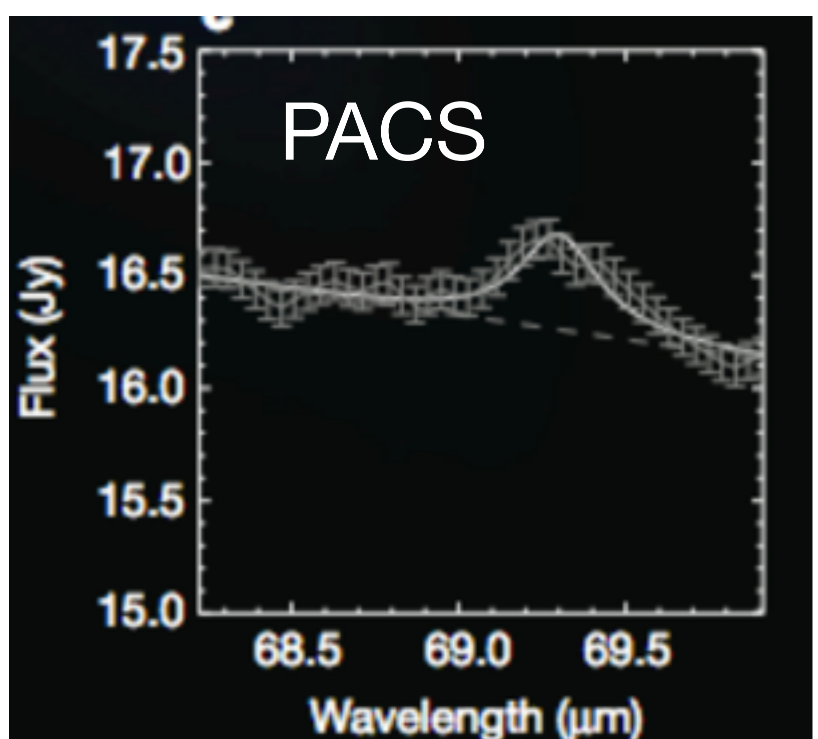




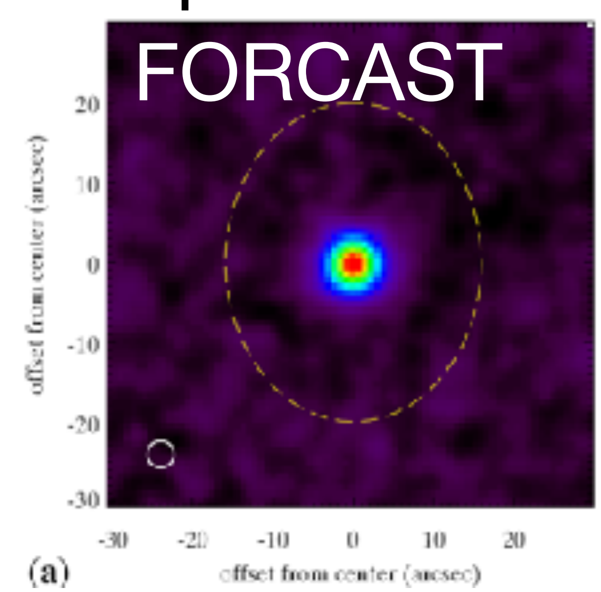


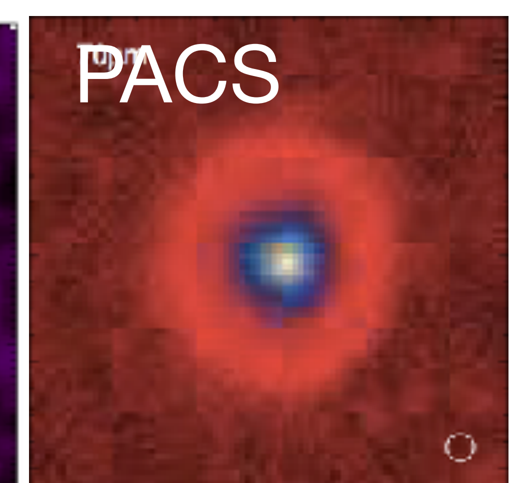
Beta Pic





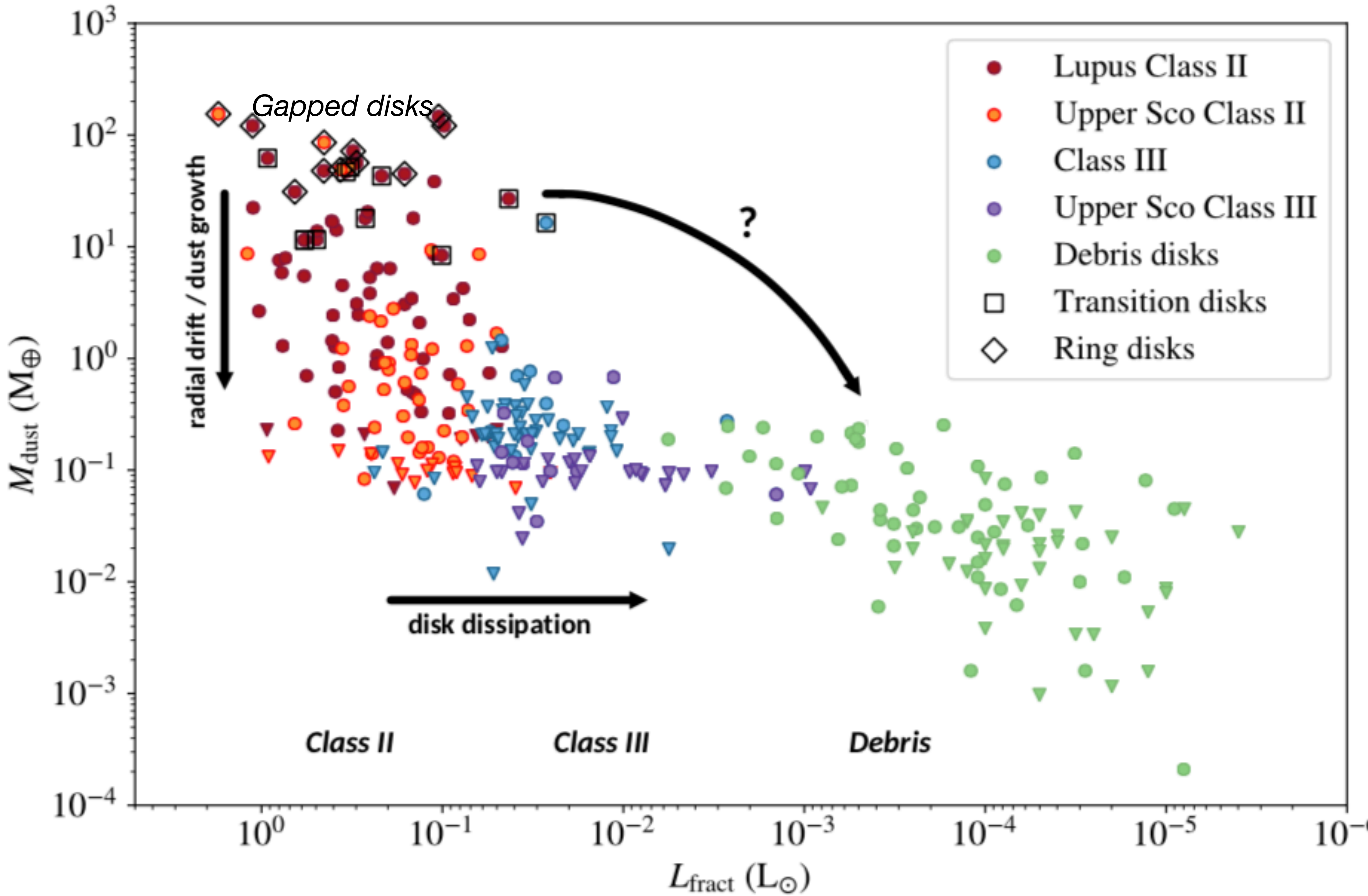
Epsi Eri





Adams et al. 2019, Acke et al. 2012, MacGregor et al. 2017, Den et al. 2014, de Vries et al. 2012, Su et al. 2017, Greaves et al. 2014

Dust traps progenitors debris disks?

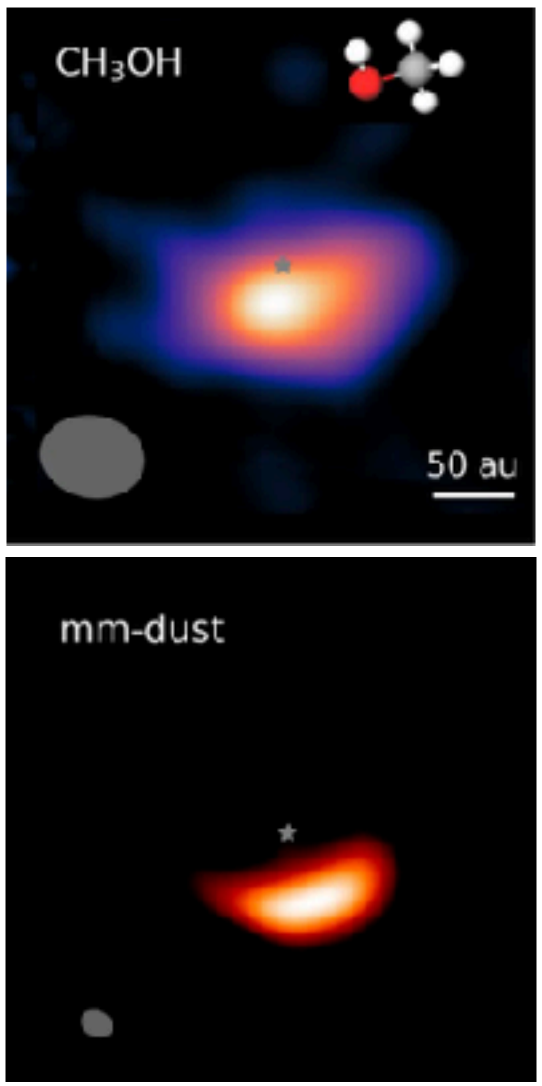


(IR excess)

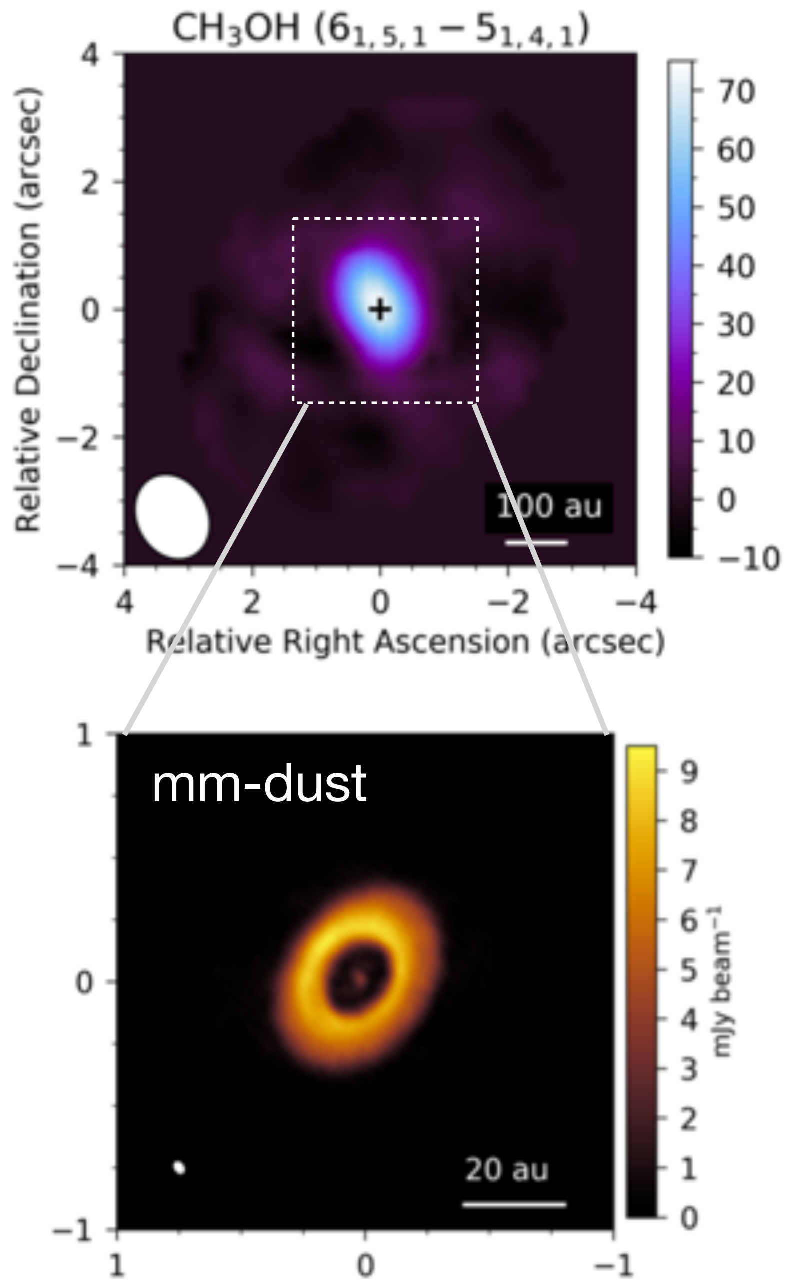
Michel et al. 2021
Najita et al. 2021

Dust traps as ice traps?

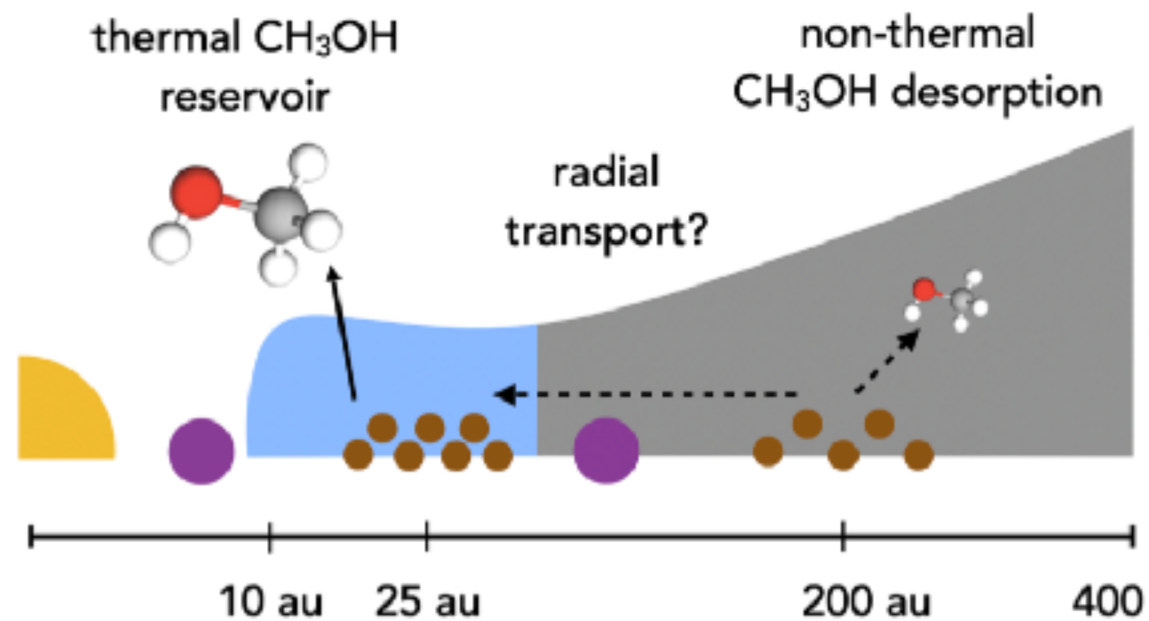
IRS48



HD100546



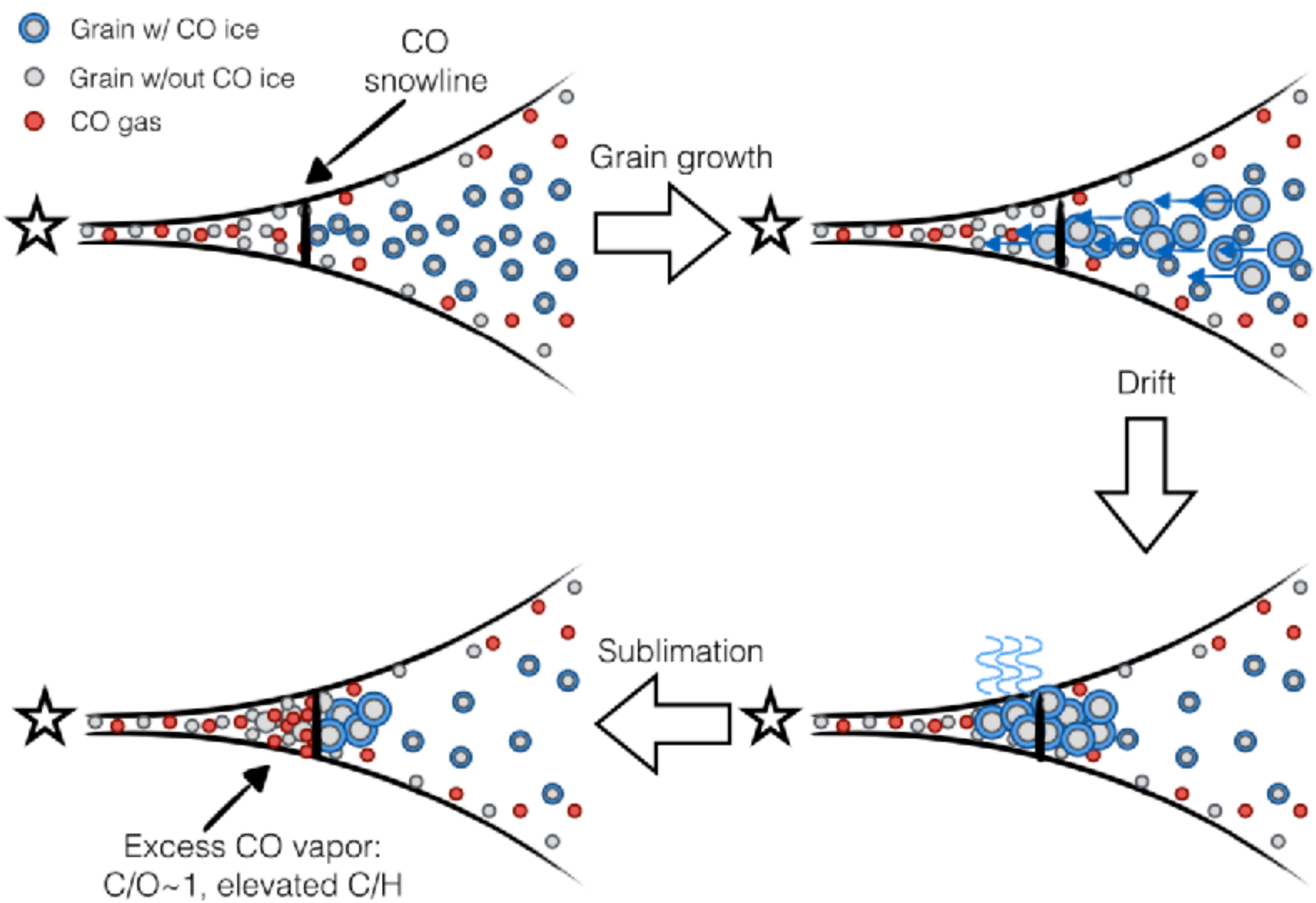
Ice product CH_3OH detected at dust trap locations



Evidence for icy inheritance/transport

Booth et al. 2021a
van der Marel et al. 2021b

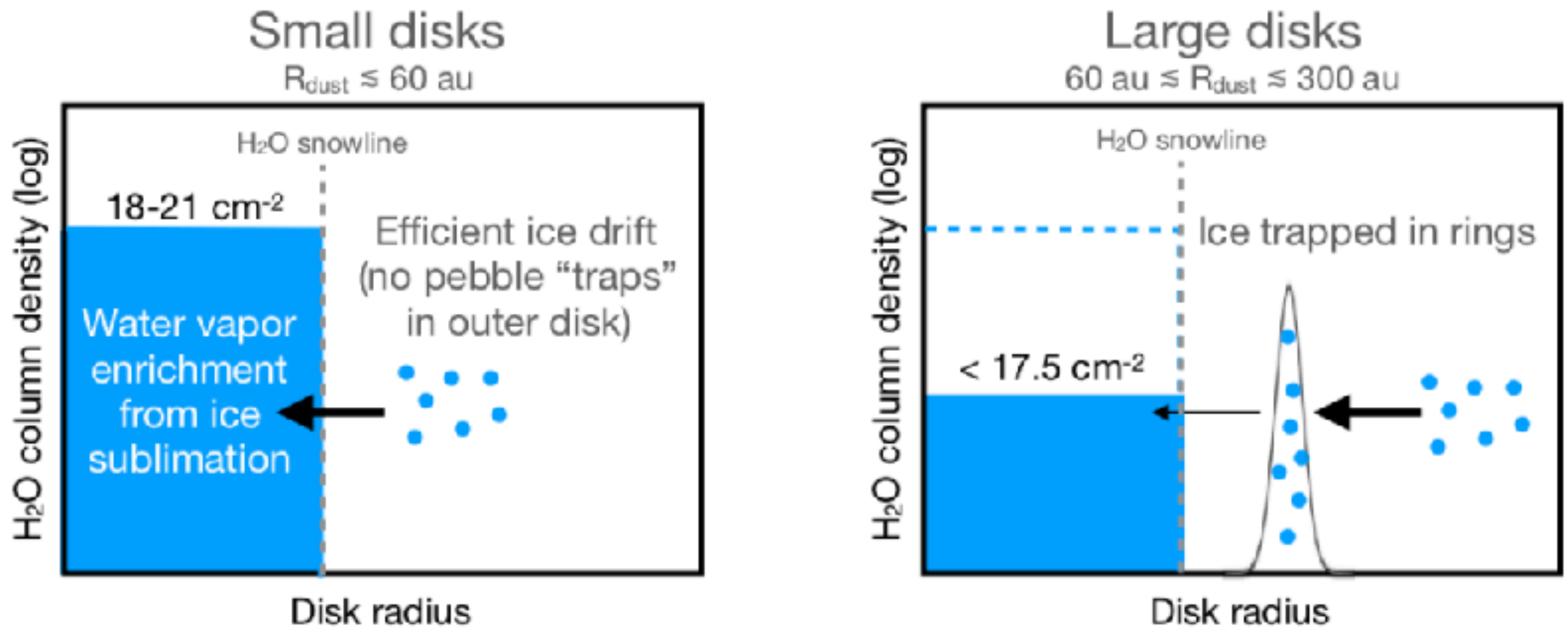
Dust drift as ice drift?



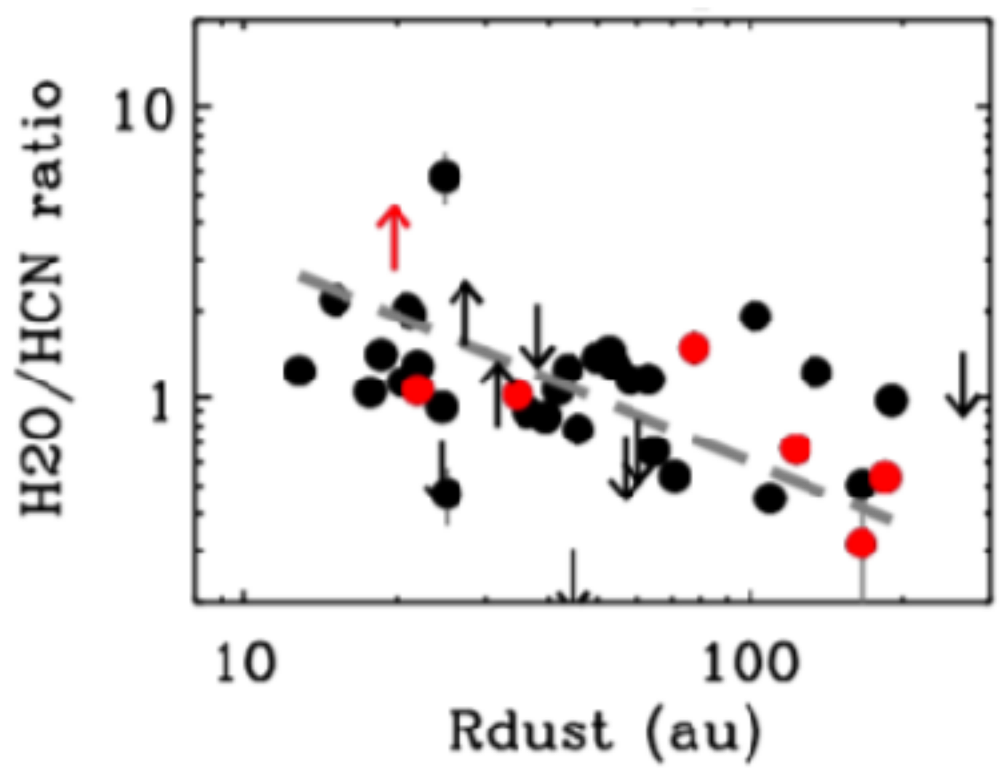
Icy dust drift can cause CO depletion

e.g. Oberg et al. 2016, McClure 2019, 2020
Booth & Ilee 2019, Krijt et al. 2020

Dust drift as ice drift?

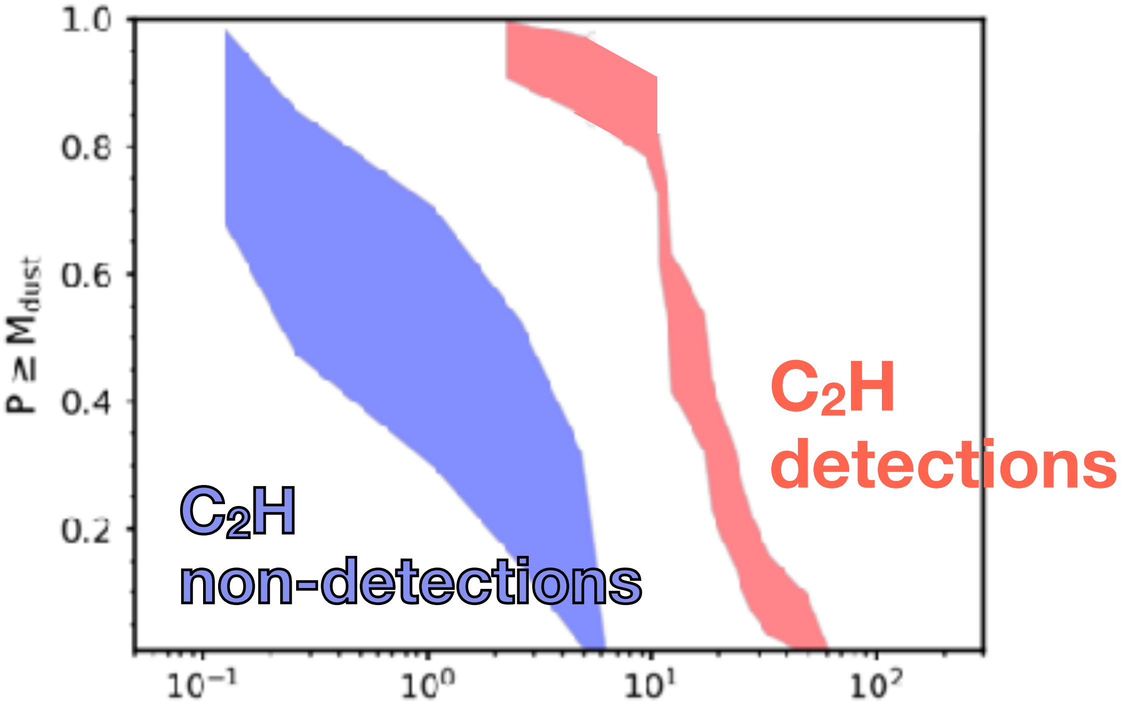


Two types of disks: possible explanation for elevated warm H_2O in compact disks



Banzatti et al. 2020
Kalyaan et al. 2021

Dust drift as ice drift?

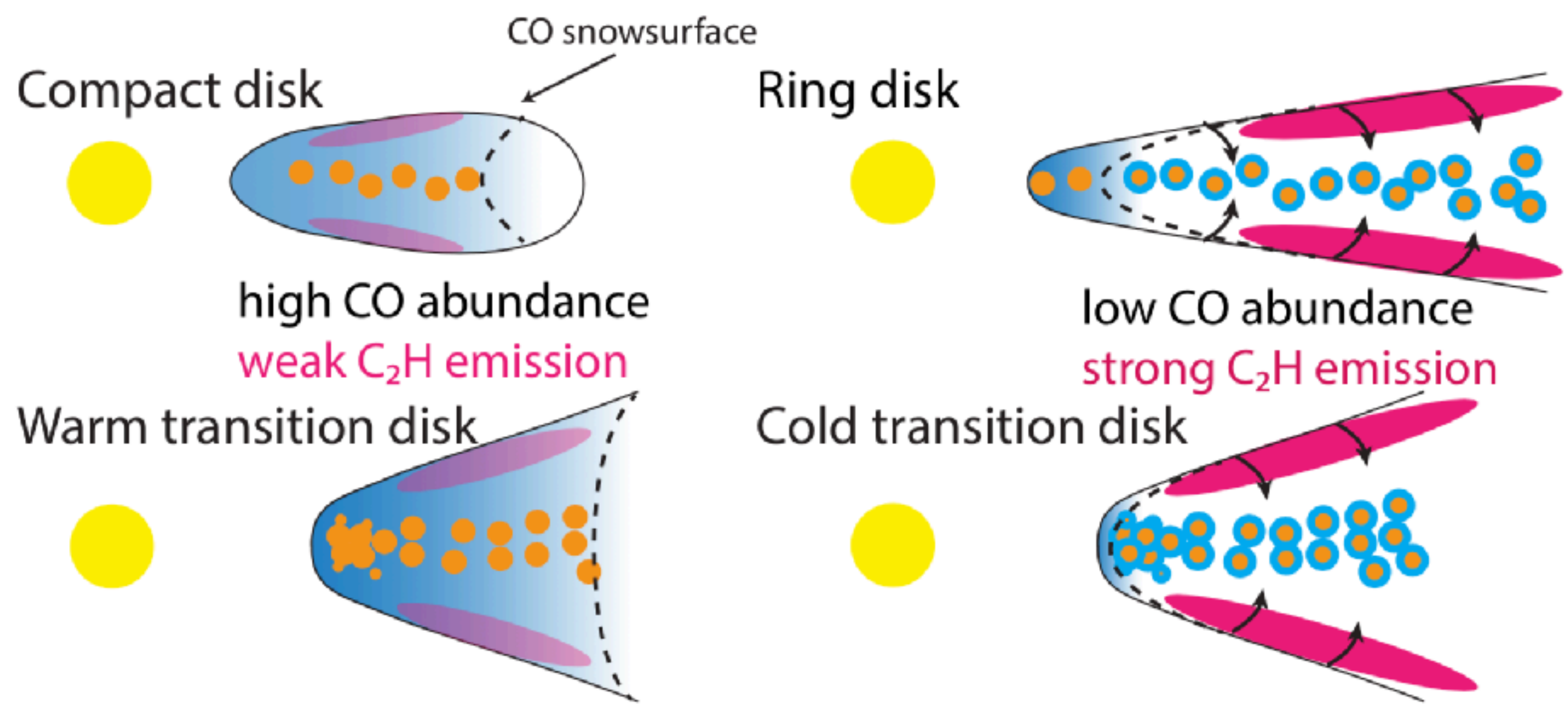


Dust mass outside CO snowline (M_E)

Icy dust transport and trap location determines disk chemistry?

Warm trap: low C_2H

Cold trap: high C_2H

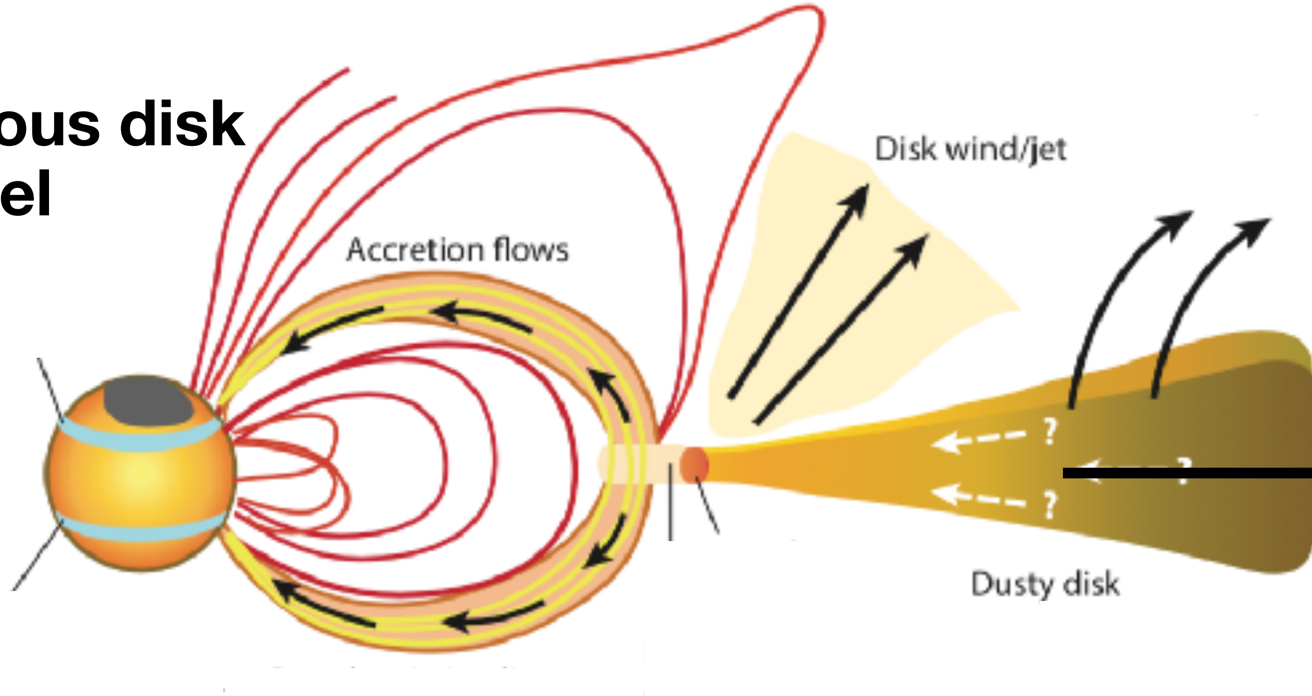


Can we trace chemical effects of transport in (F)IR?

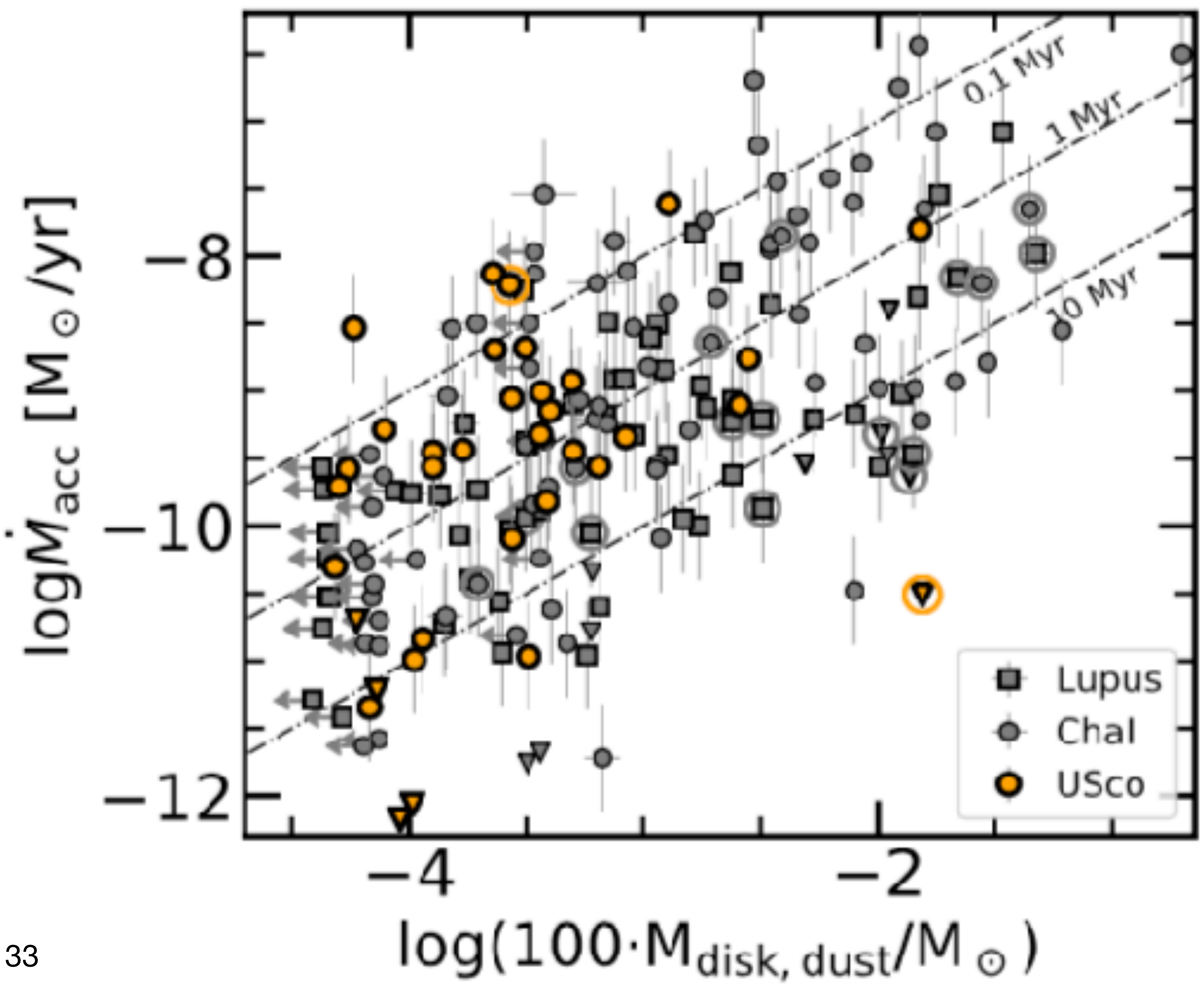
Van der Marel et al. 2021c

Disk evolution

Viscous disk model



Viscous spreading to conserve angular momentum: require turbulence alpha~10^{-2} (through MRI)

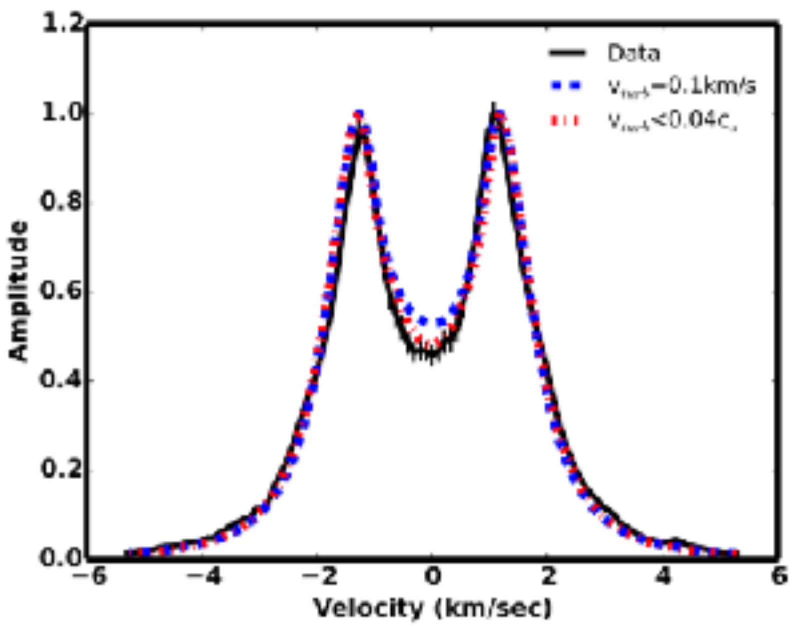


Large scatter in M_{acc}: inconsistent with model?

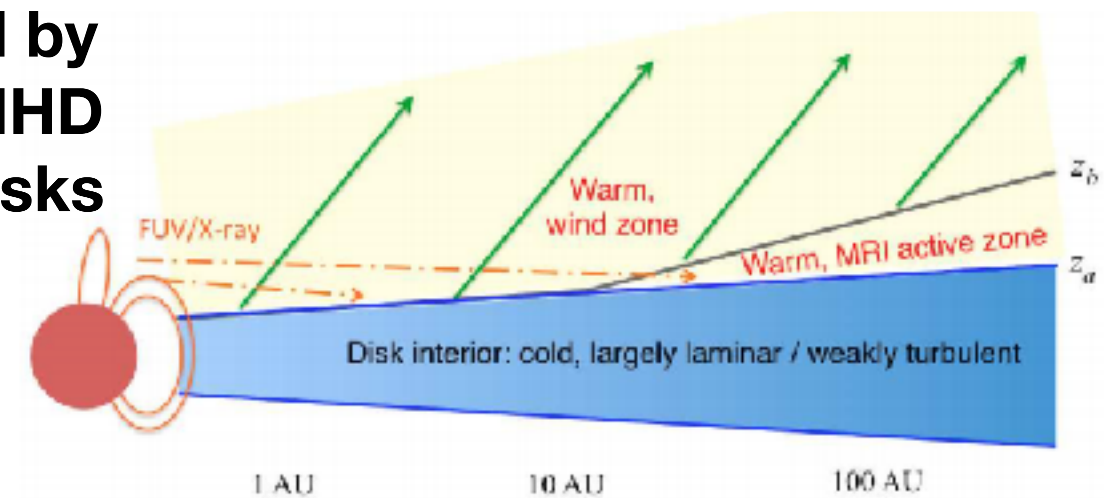
Hartmann 2016
Mulders et al. 2017
Manara et al. 2020

Disk evolution: alpha-disk model

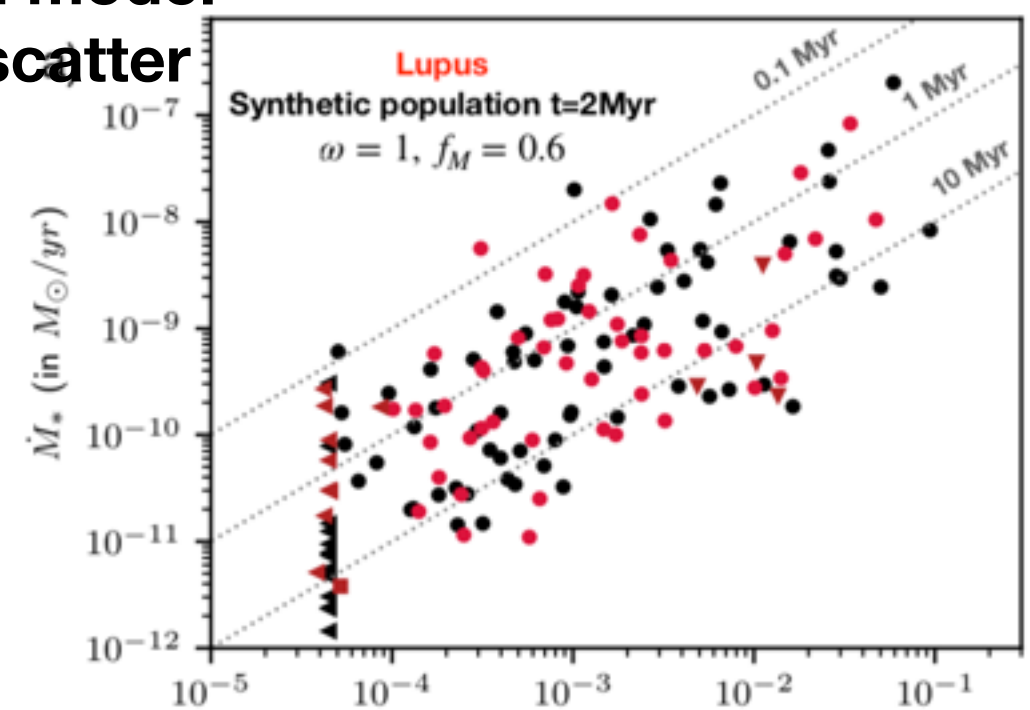
Line width measurements
v_{turb} <0.04 c_s



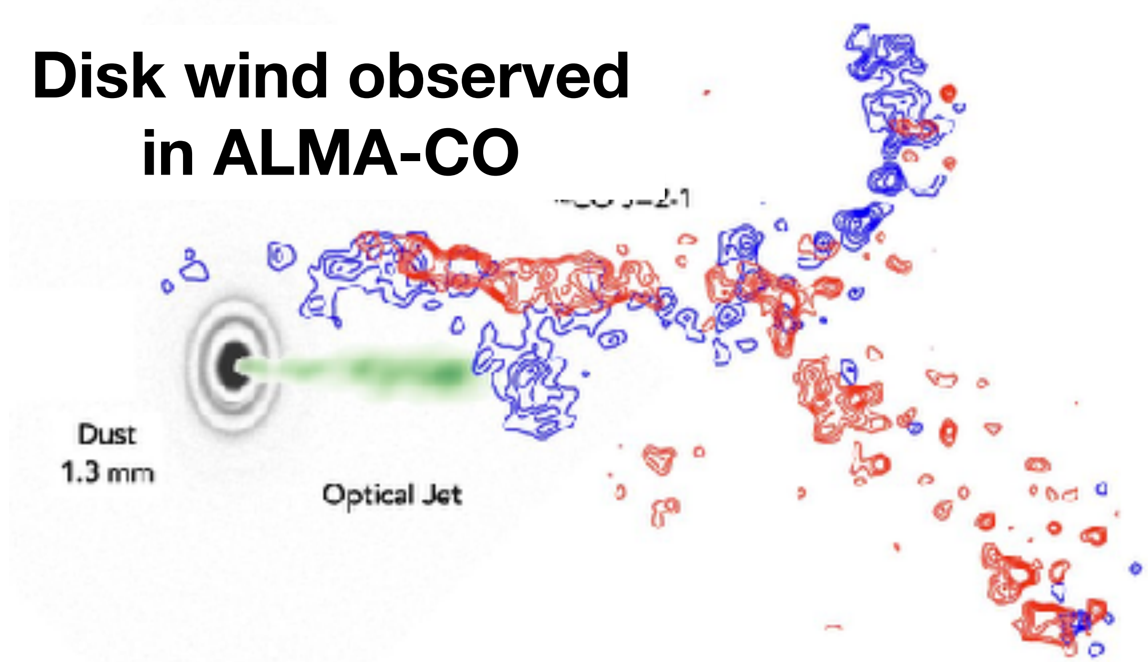
MRI suppressed by non-ideal MHD effects in disks



MHD-wind model predicts scatter



Disk wind observed in ALMA-CO

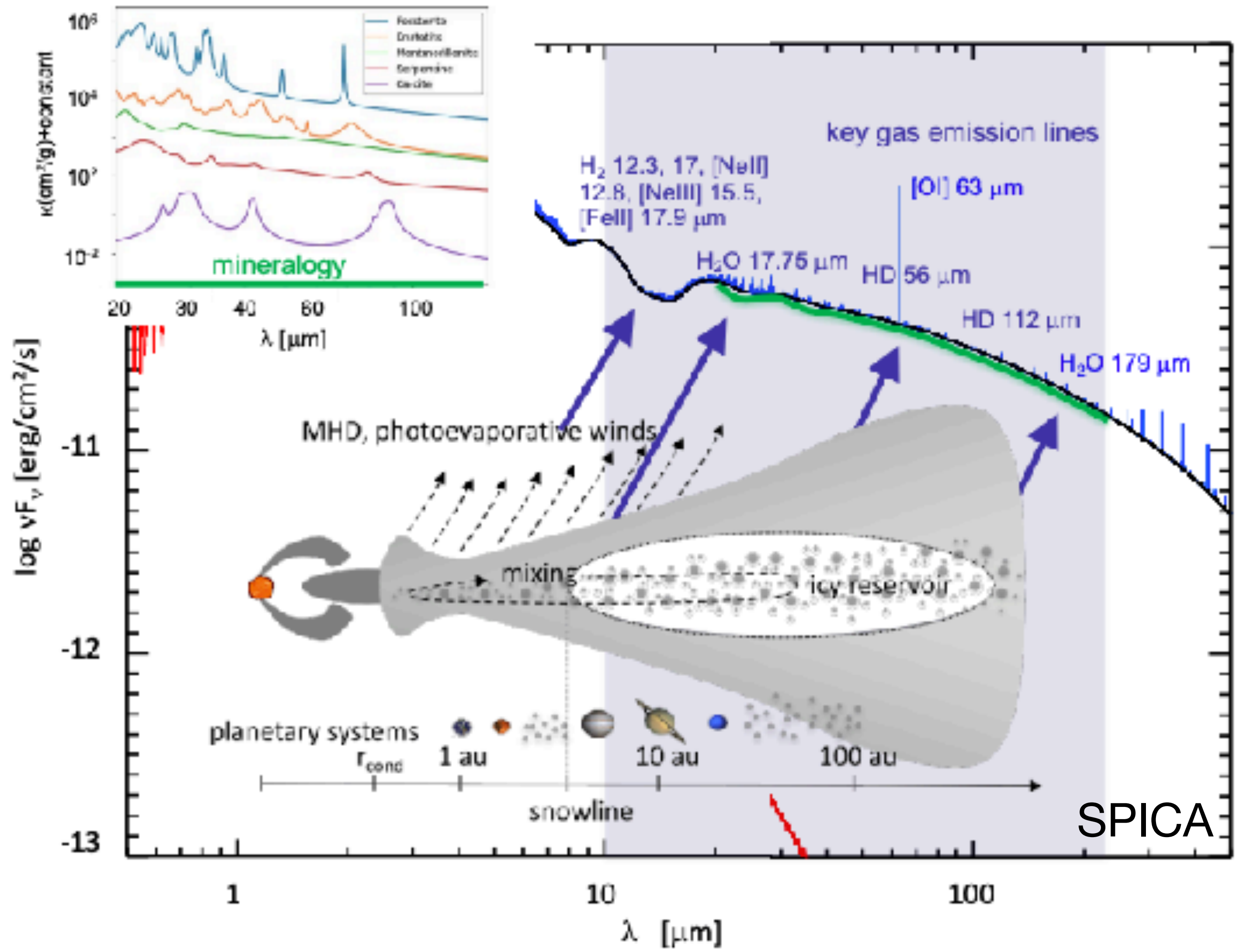


Can we trace disk wind in FIR?

Flaherty et al. 2016
Bai & Stone 2013
Booth et al. 2021c
Tabone et al. 2021

What can we learn in unresolved (F)IR?

- Warm molecular/atomic lines surface layers: ice transport?
- Kinematic signatures disk surface/disk wind?
- H_2O ice features: ice composition and history
- Grain size distribution in debris disks
- Mineralogy/ grain composition (dust processing)



Need for high sensitivity

Kamp et al. 2021

Summary

- Large-scale dust gaps are likely caused by giant planets, assuming inward migration
- Dust mass evolution can be understood by a combination of drift and trapping
- Dust traps may be the progenitors of debris disks
- Dust transport may set the disk (ice) chemistry
- Disk evolution may be driven by winds
- Many more research to be done!