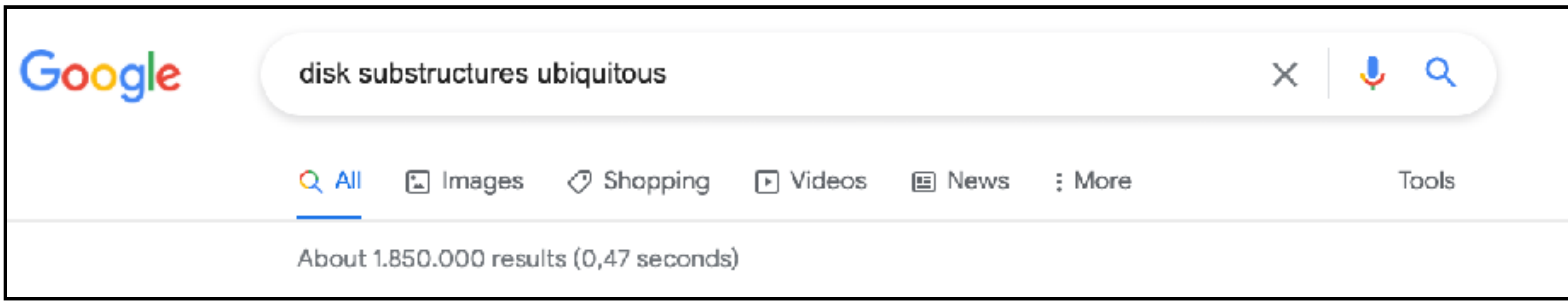
Structure formation in planet forming disks

Summary week 1

Nienke van der Marel
MIAPP
Leiden Observatory
October 8th 2021

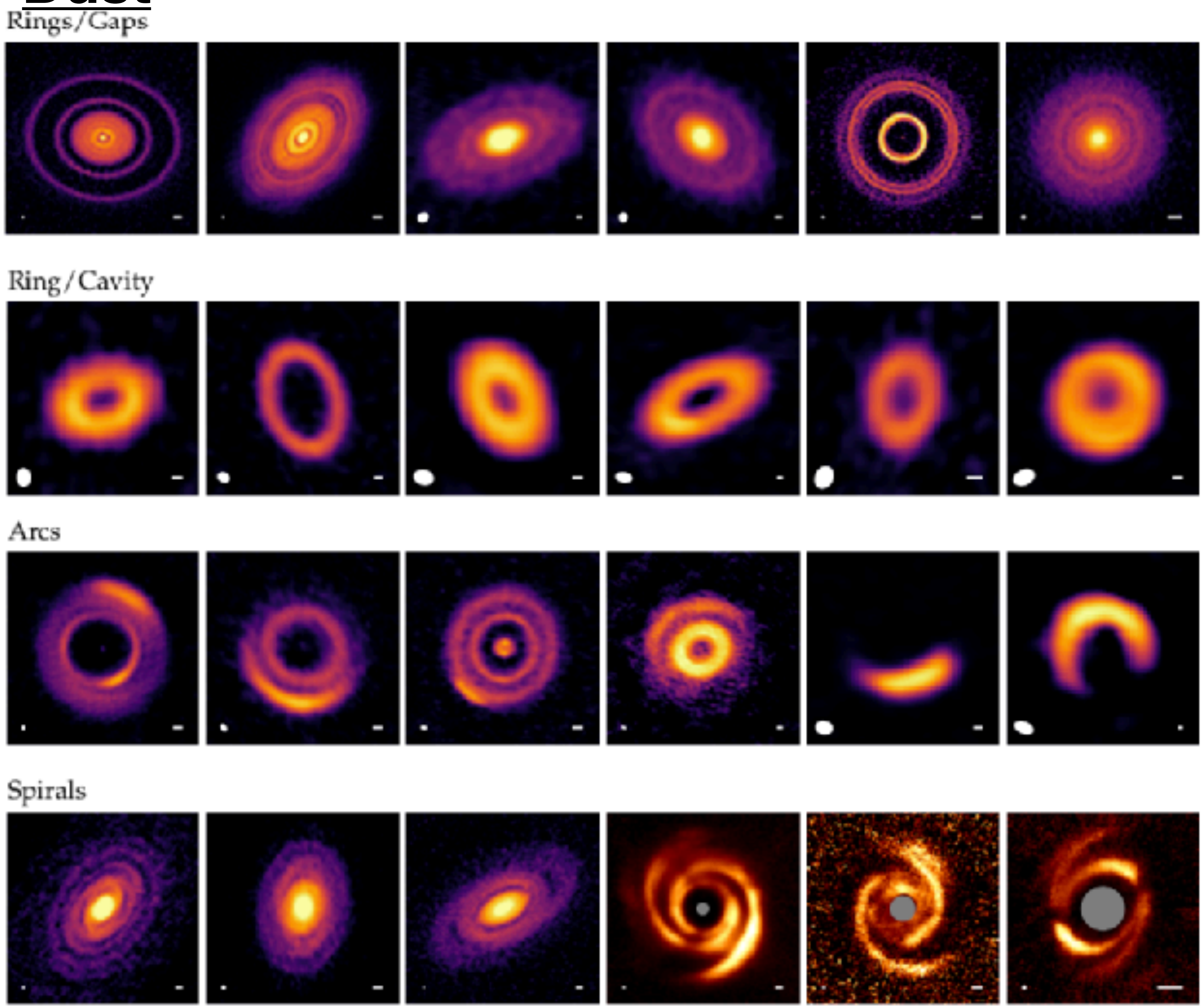
“Substructures in disks are ubiquitous”

Jane Huang, Jaehan Bae, Mario Flock, Jeff Jennings



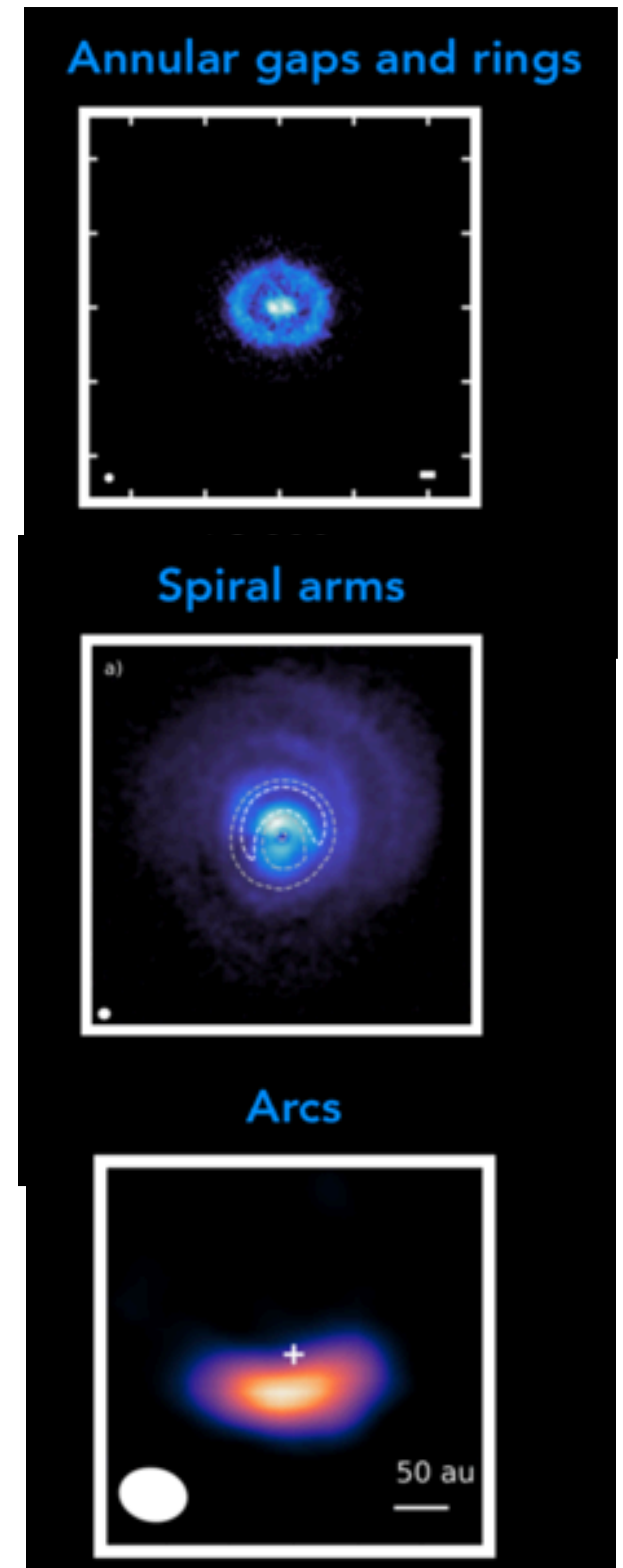
Substructures (observations)

Dust



Andrews (2020)

Molecular lines

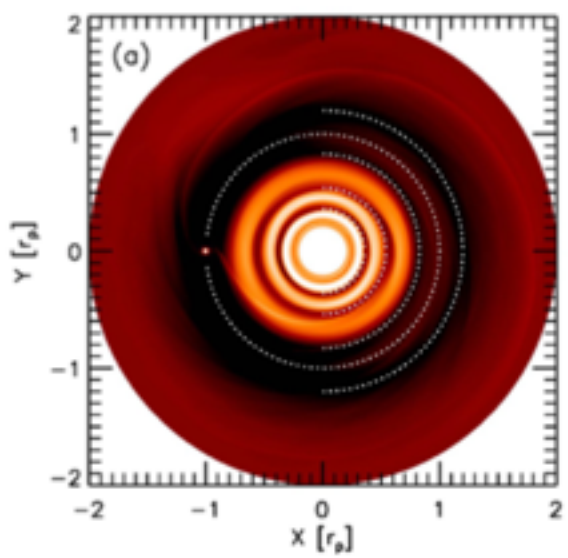


Talks Huang, Bae, van Dishoeck

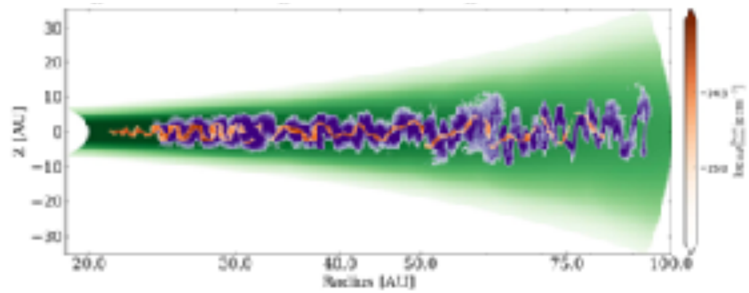
Substructures (simulations)

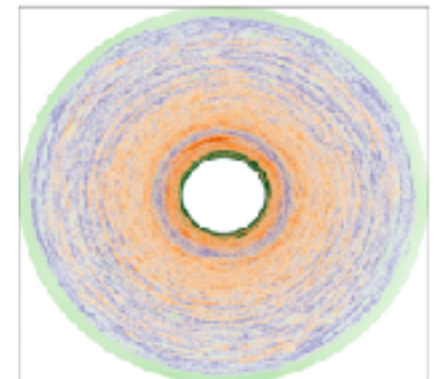
Gaps:

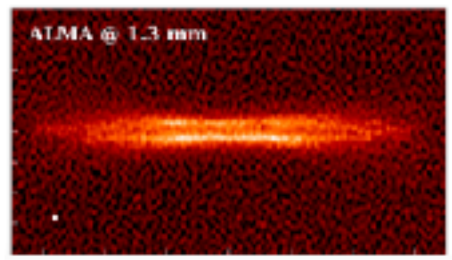
Companion



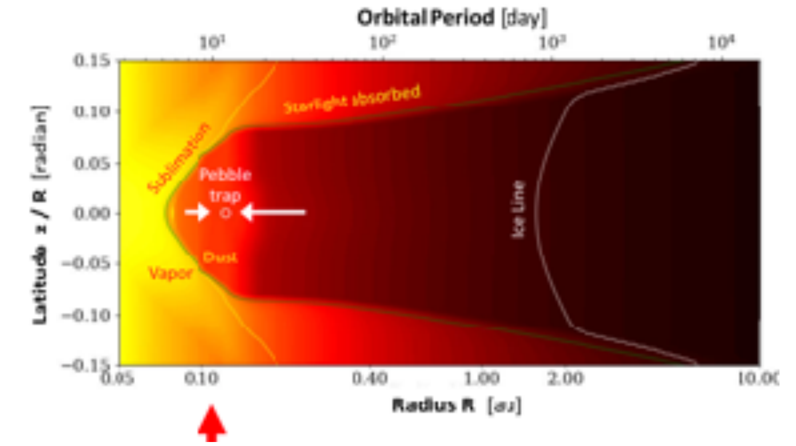
VSI



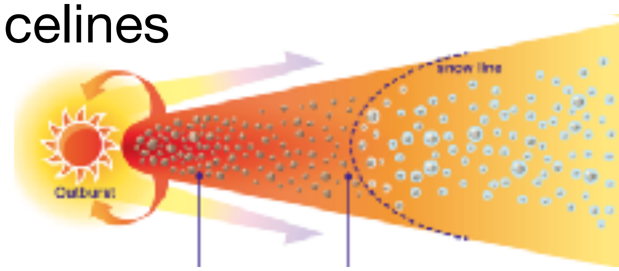




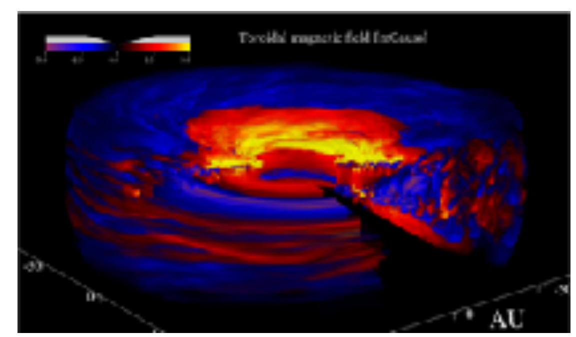
Inner dead zone



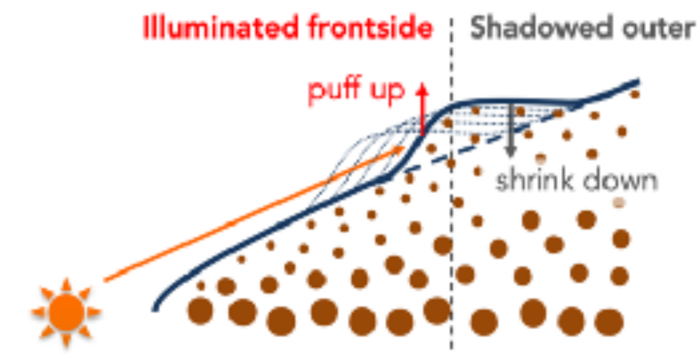
Icelines



Outer dead zone

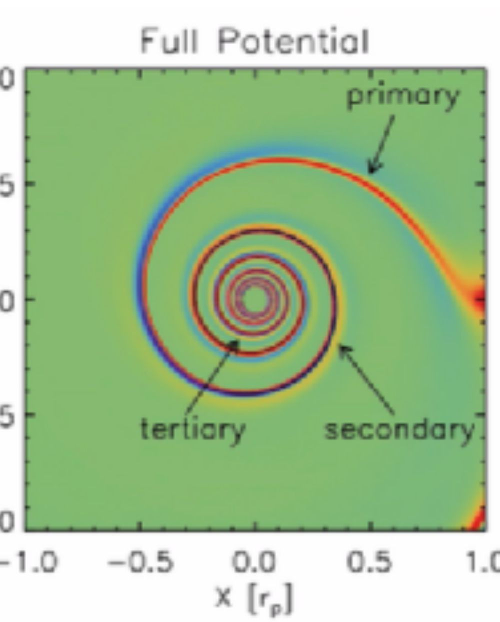


Thermal Wave Instability

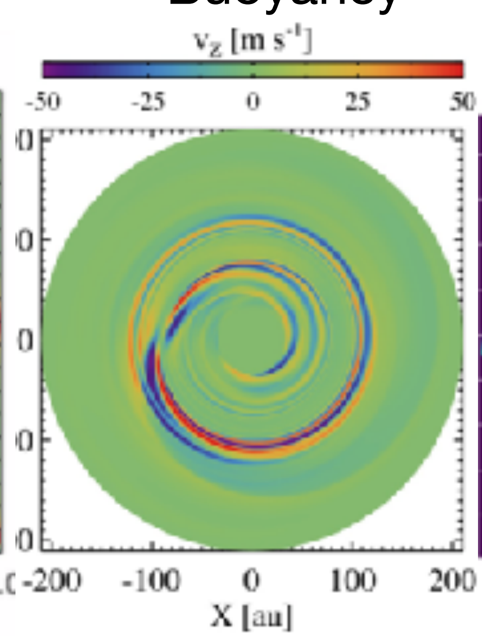


Spirals:

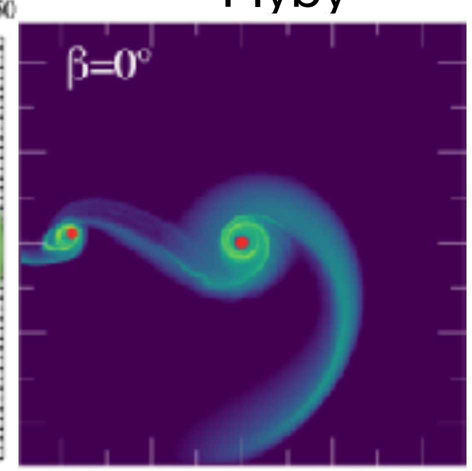
Lindblad



Buoyancy

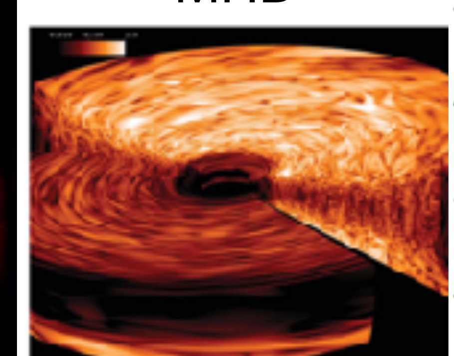


Flyby

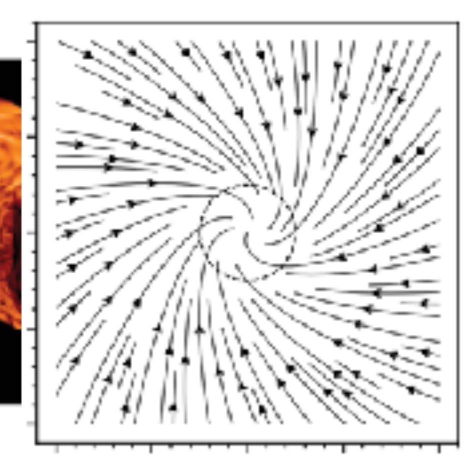


GI

MHD



Infall

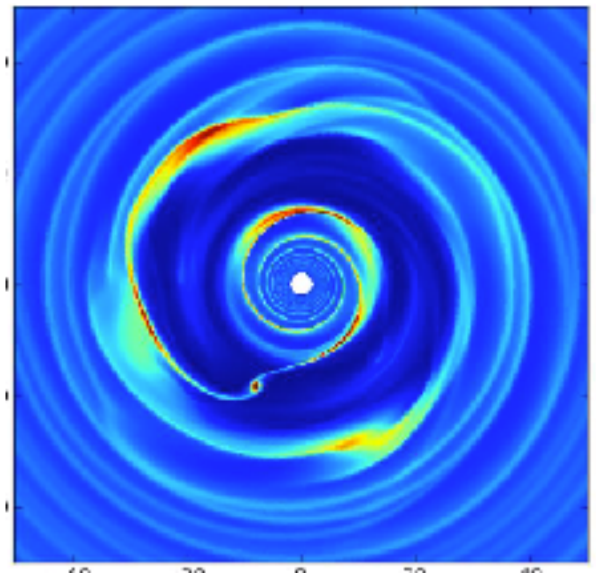


Talks Flock, Bae

Substructures (simulations)

<u>Asymmetries:</u>

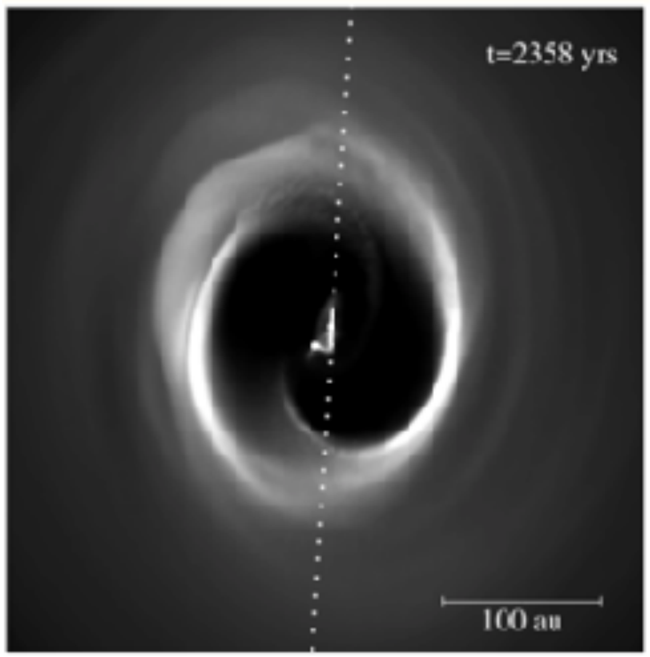
Vortex (Rossby wave instability)



- Infall
- Planet
- Accretion transition

- Triggers non-detectable spirals
- Dust grains trapped ahead (peak shift)
- Planet growth speed/mass and h/r important (Hammer+2017,2019,2021)
- Weakened by dust feedback, self-gravity, turbulence

Lump/horseshoe



- Binary companion
- Not weakened by turbulence
- No self-gravity: no peak shift?

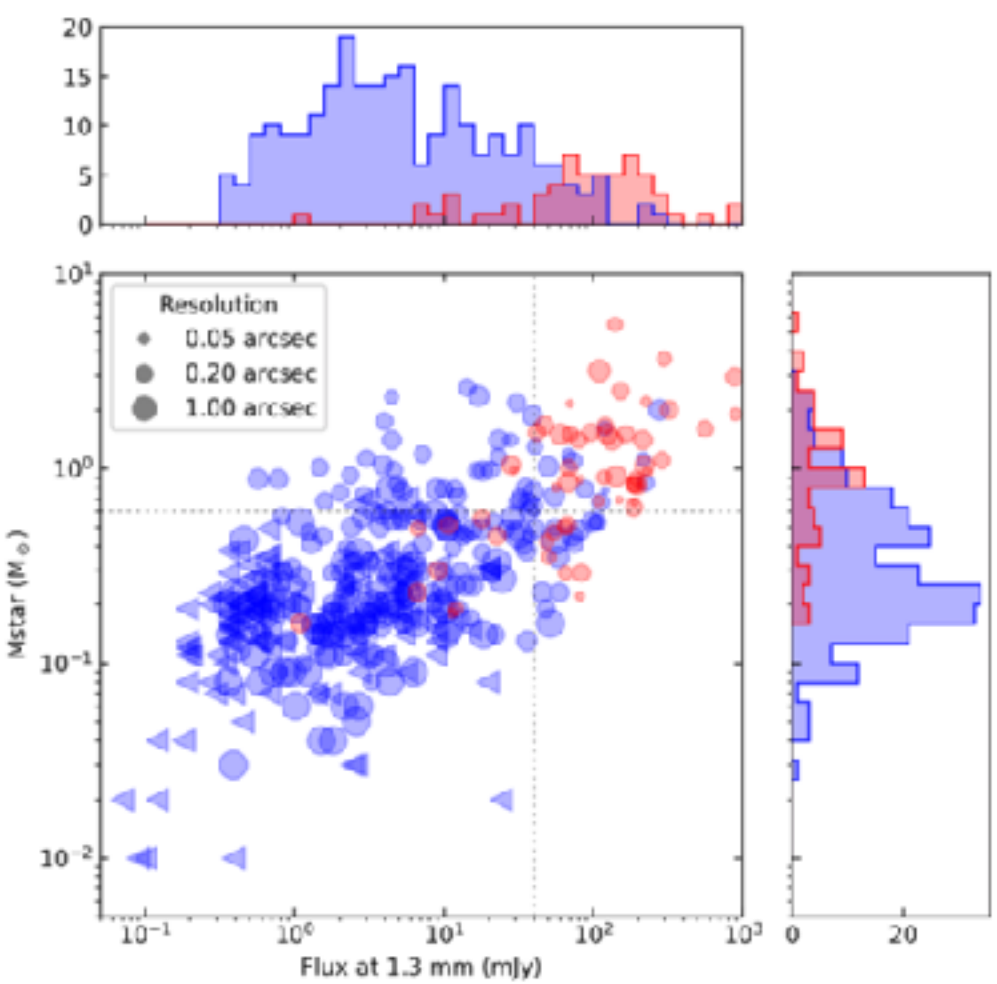
Need to find companions, measure turbulence or (maybe) measure peak shift to distinguish

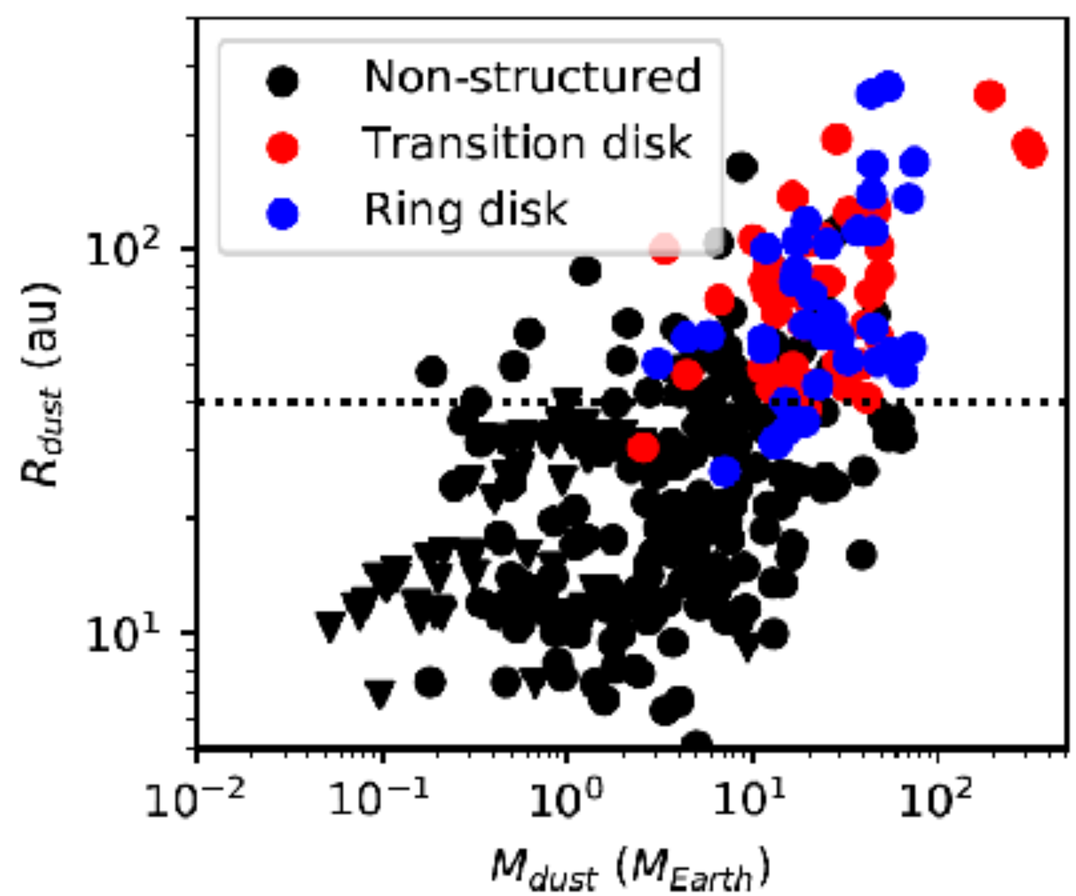
Talks Zhu, Hammer

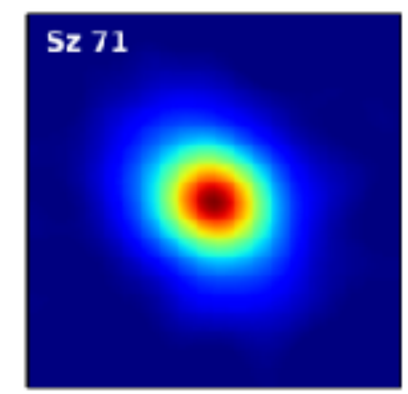
How common are substructures?

1. High-resolution are biased towards most massive disks (ALMA) and most luminous stars (OIR)

2. Detectability of substructures (or: “scale of detectable substructures”) depends on spatial resolution!

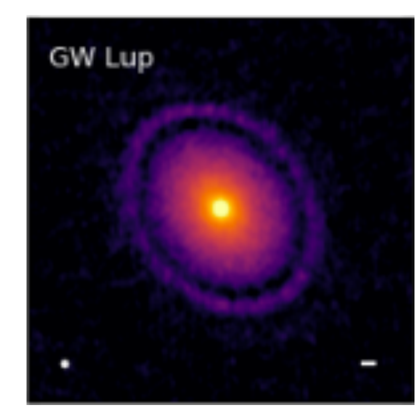






(0.30”)

=



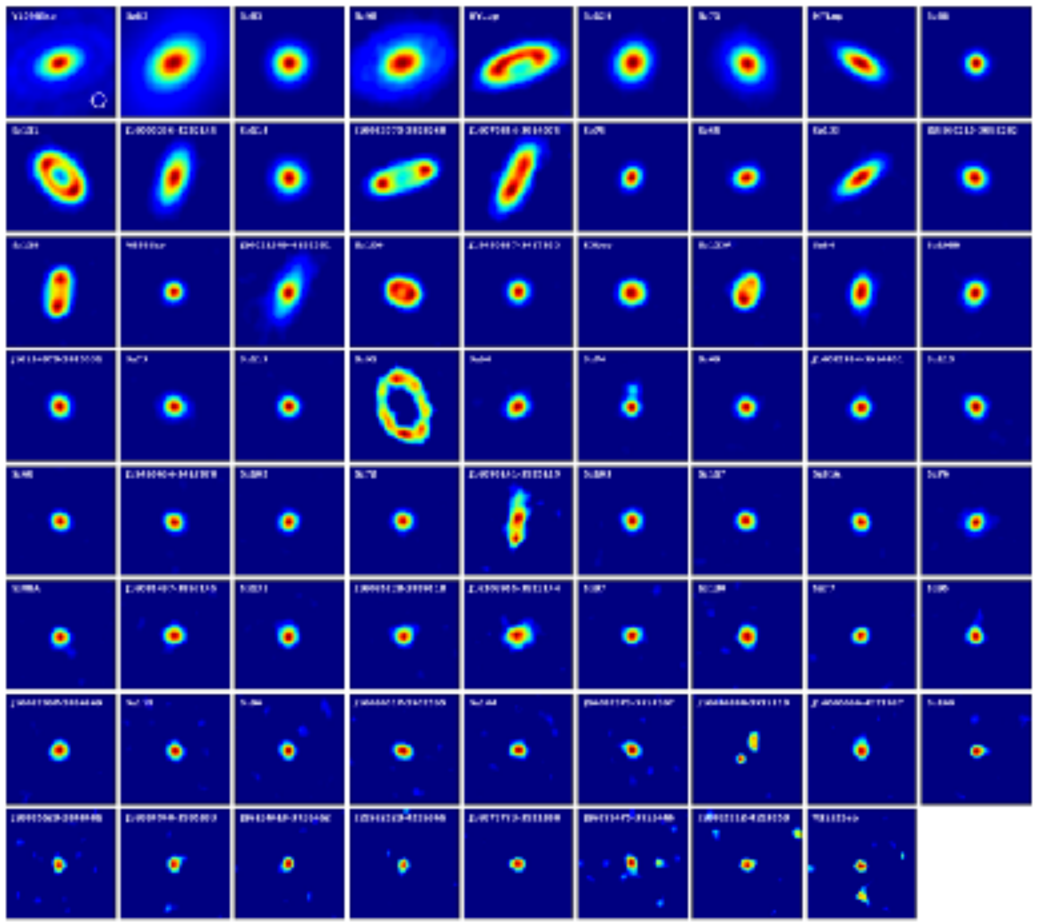
(0.04”)

Talk Bae

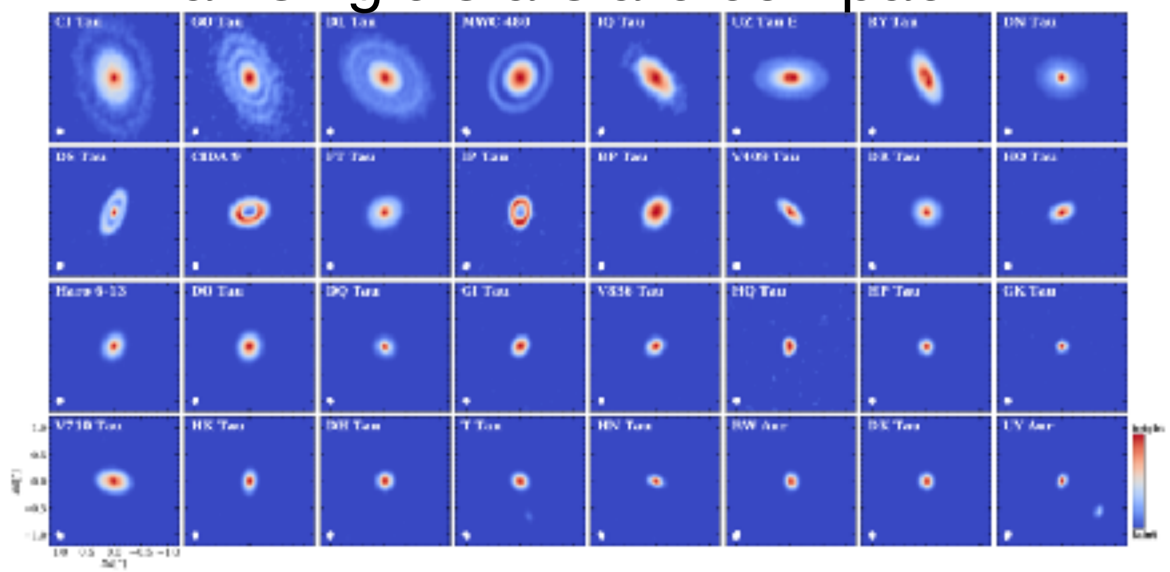
Van der Marel & Mulders 2021

How common are compact disks?

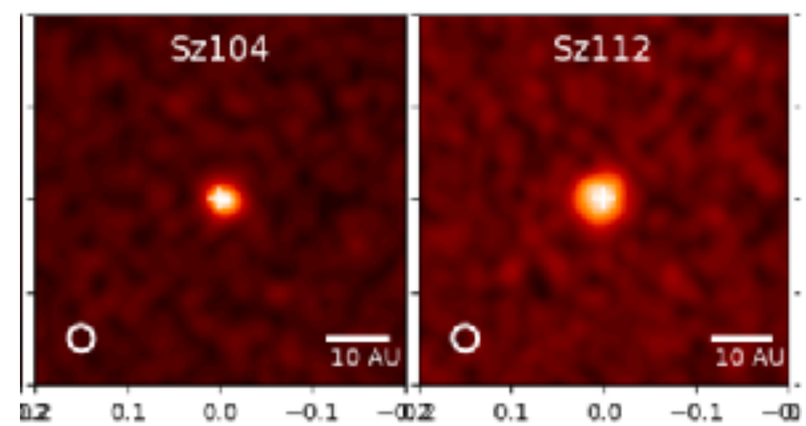
Lupus survey at 0.24”:
71/95 detected, 25/71 resolved!



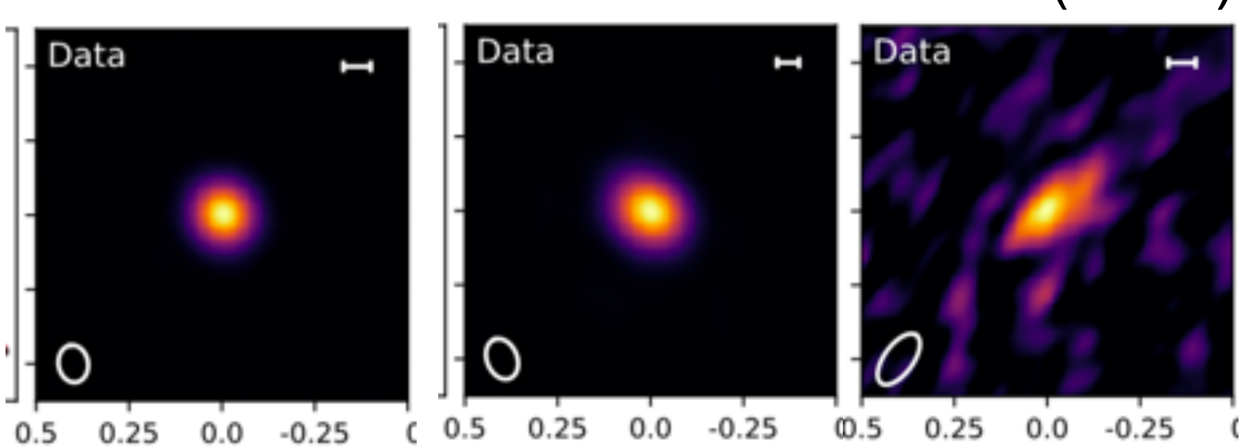
Taurus survey at 0.1”:
half single stars are compact

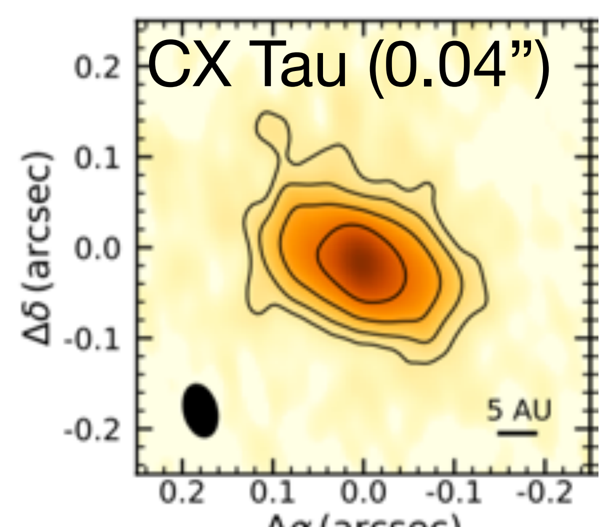


2 Lupus disks
(0.025”):
~4 au



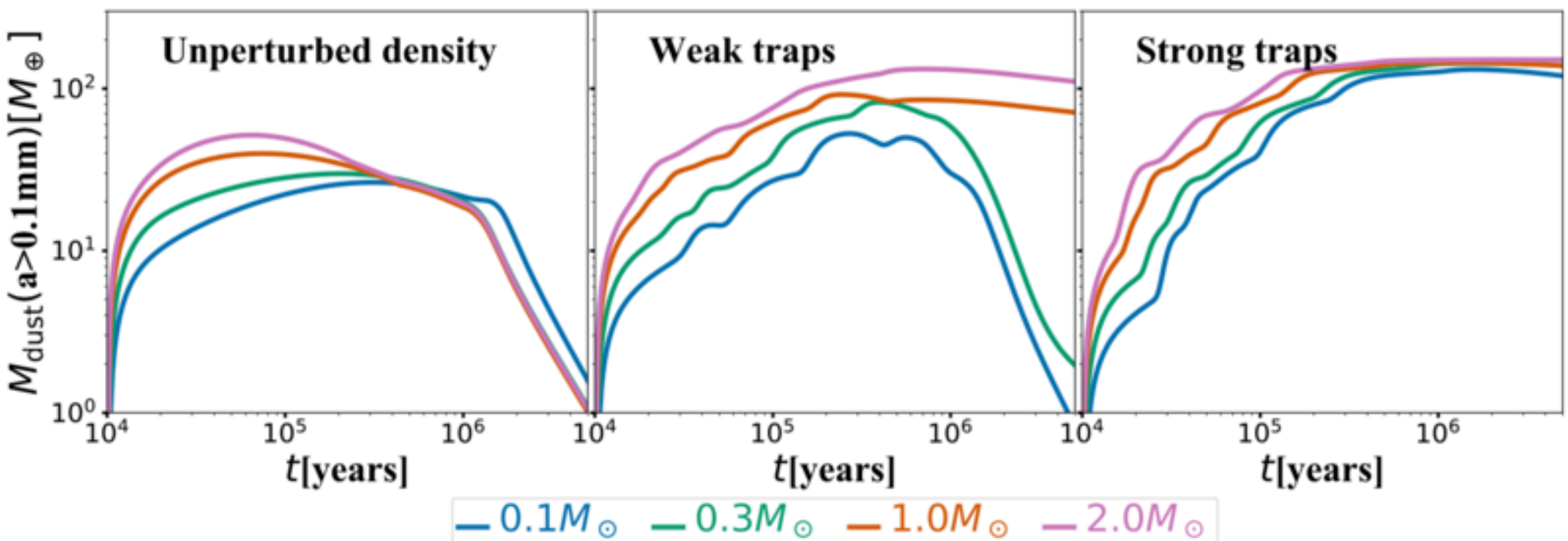
CIDA 7 J0420 J0415 (0.08”)



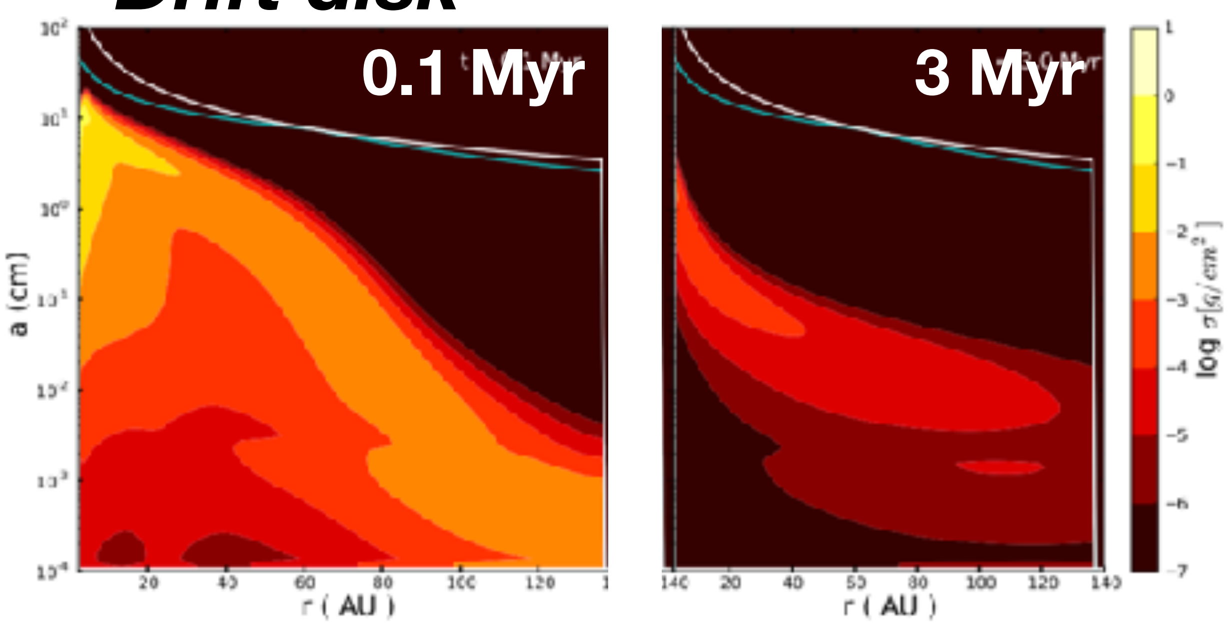


Ansdelle et al. 2018
Facchini et al. 2019
Kurtovic et al. 2021
Long et al. 2019
Van der Marel et al. in prep.

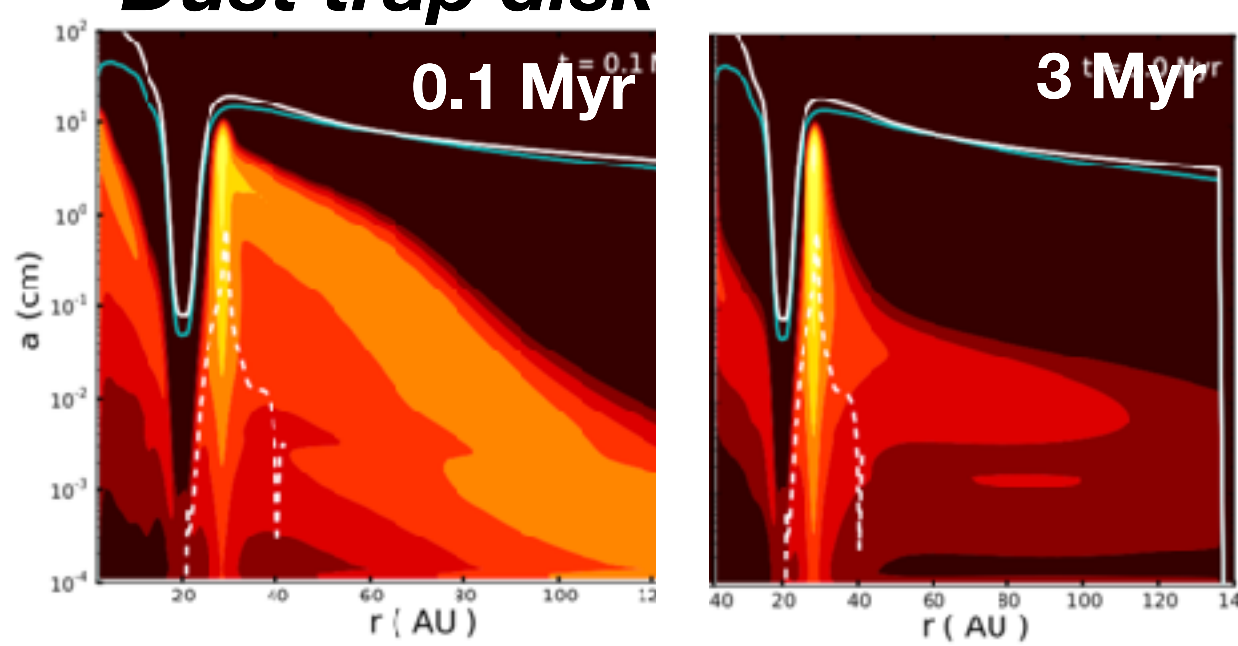
What does dust evolution tell us?



Drift disk

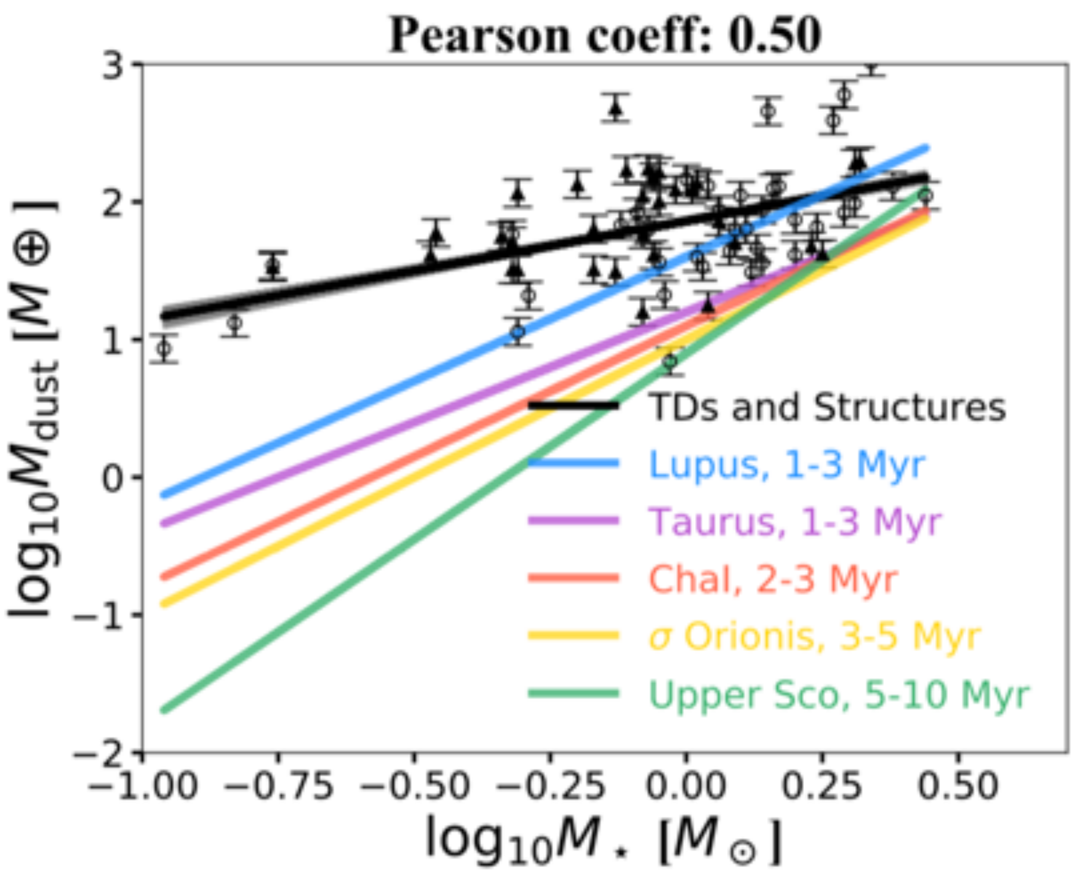


Dust trap disk



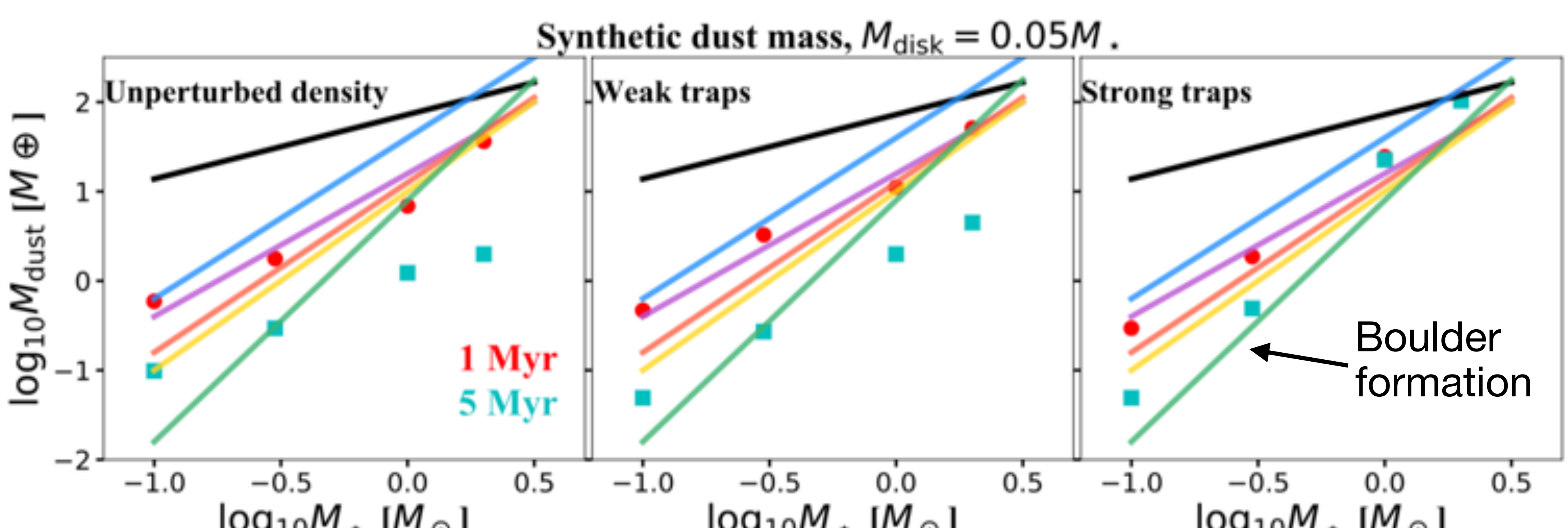
Pinilla et al. 2012, 2020

What does dust evolution tell us?



<u>Observations</u>:

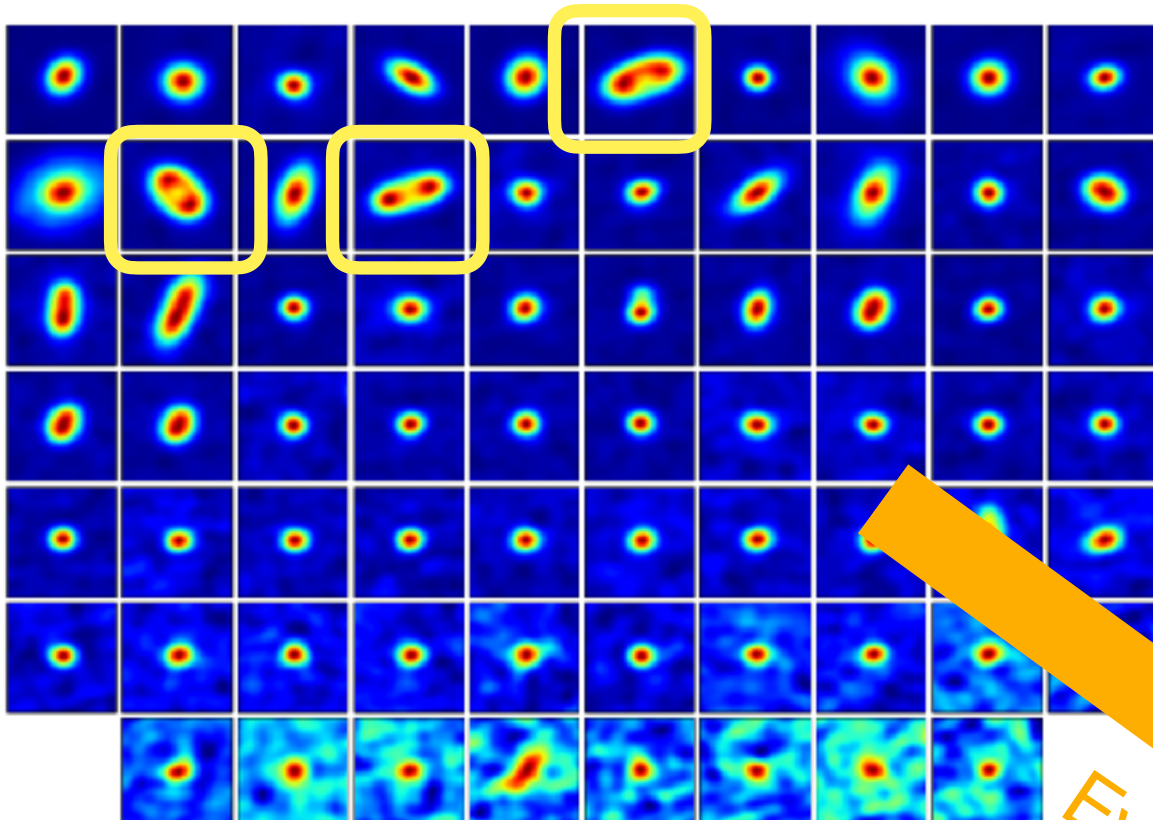
- Correlation between dust mass and stellar mass steepens with time
- Structured disks no drop (traps!)
- Strongest drop at low-mass stars (drift!)

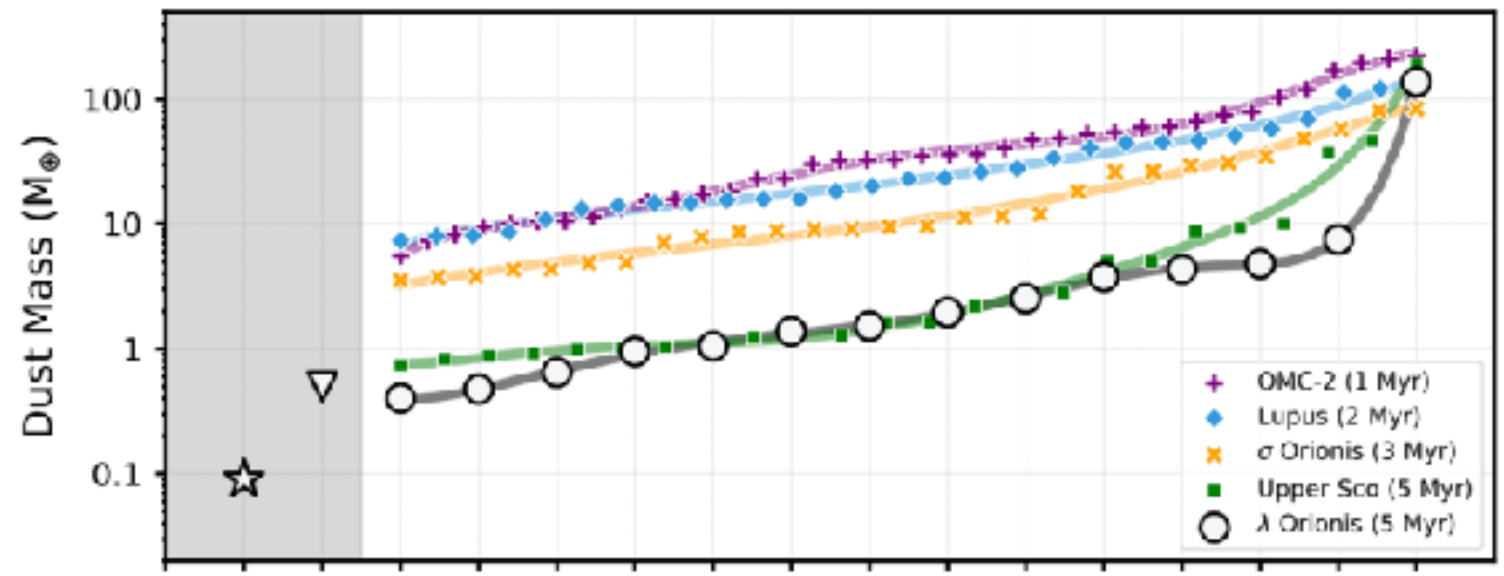


Pinilla et al. 2020

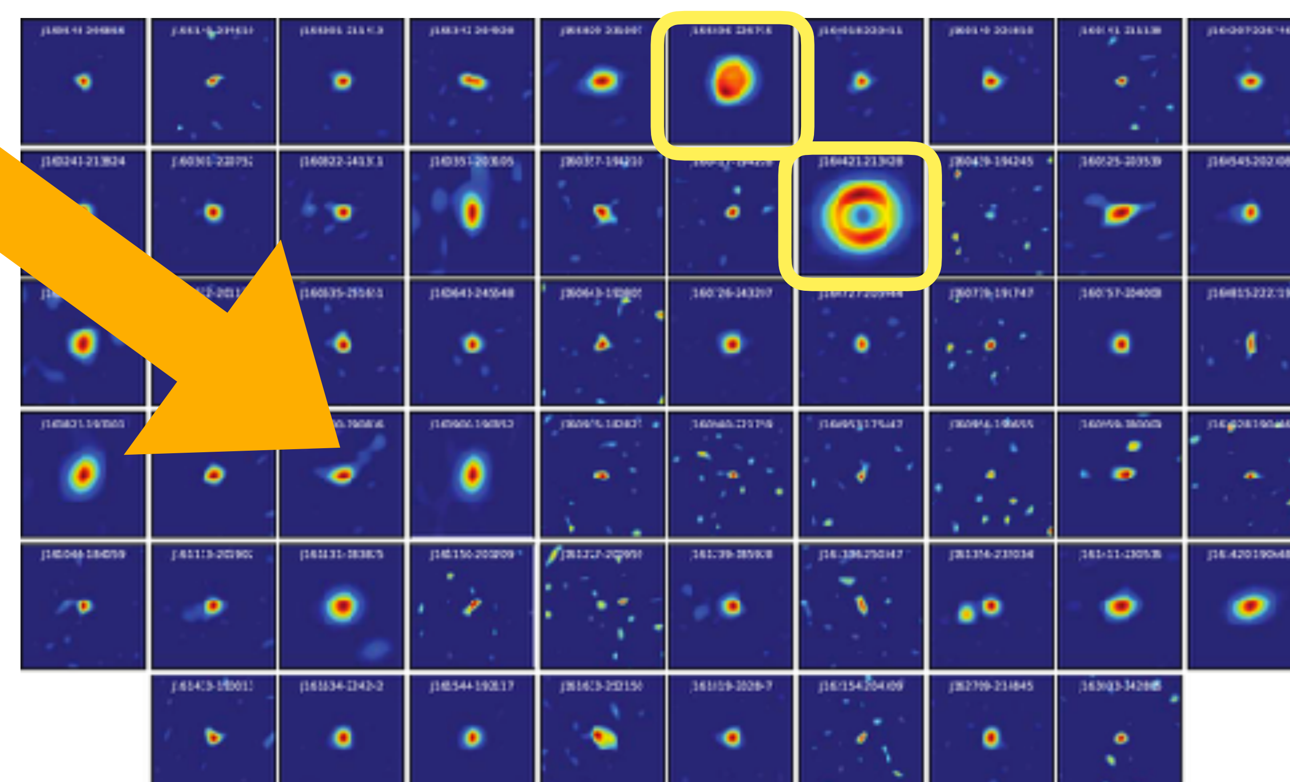
Evolution of disks?

Lupus (2 Myr)





Upper Sco (10 Myr)



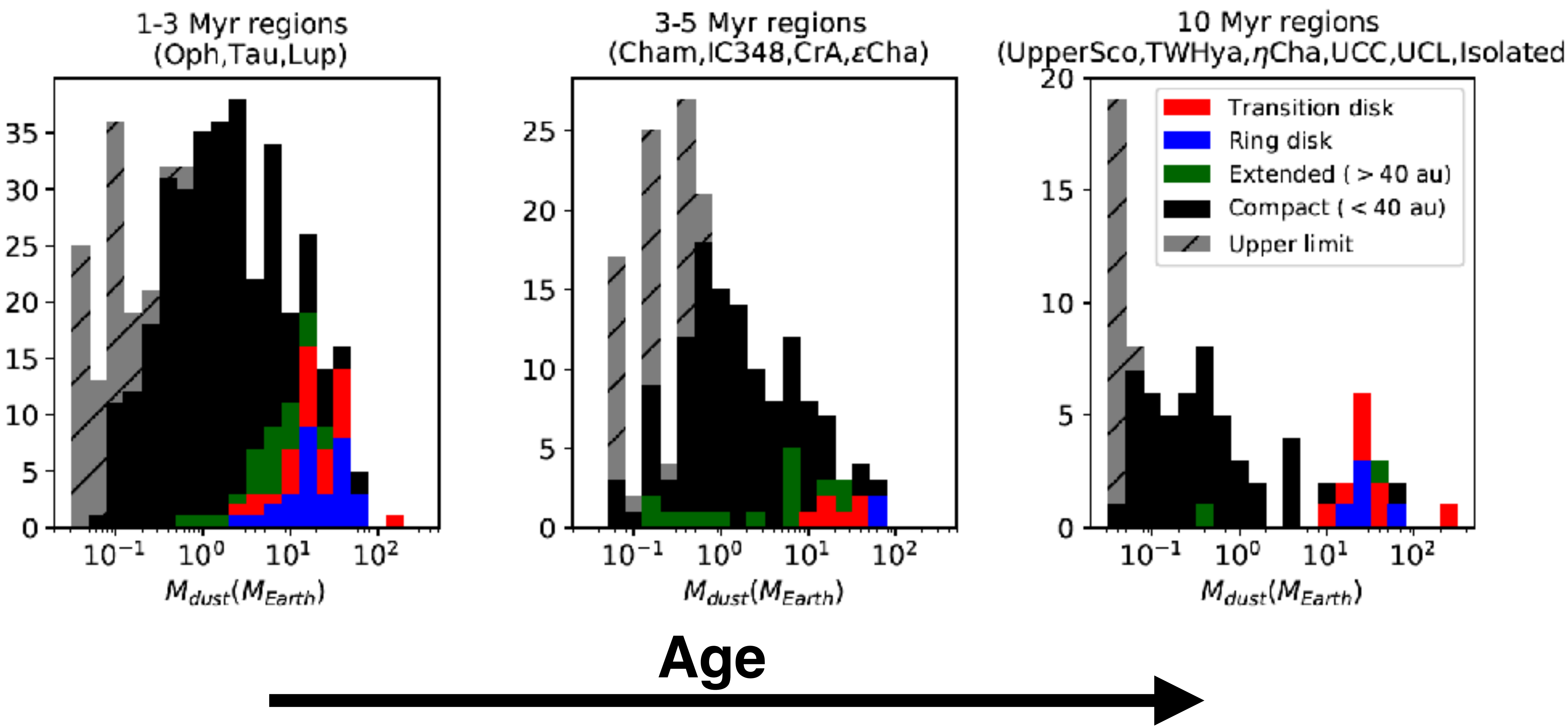
Evolution

Massive outliers:
gapped disks
=> no drift

Ansdell et al. 2021

Evolution of disks?

Sample 700 disks: occurrence of large scale (R>25 au) substructure ~17%



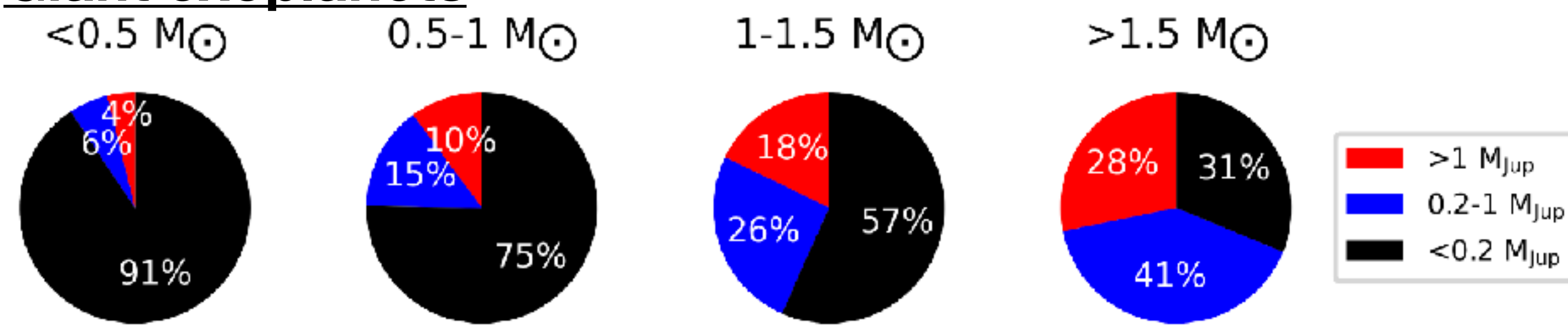
Two separate evolutionary pathways:
the structured disks and compact disks (drift!)

Van der Marel & Mulders 2021

How common are substructures (stellar mass)?

Disks

Giant exoplanets

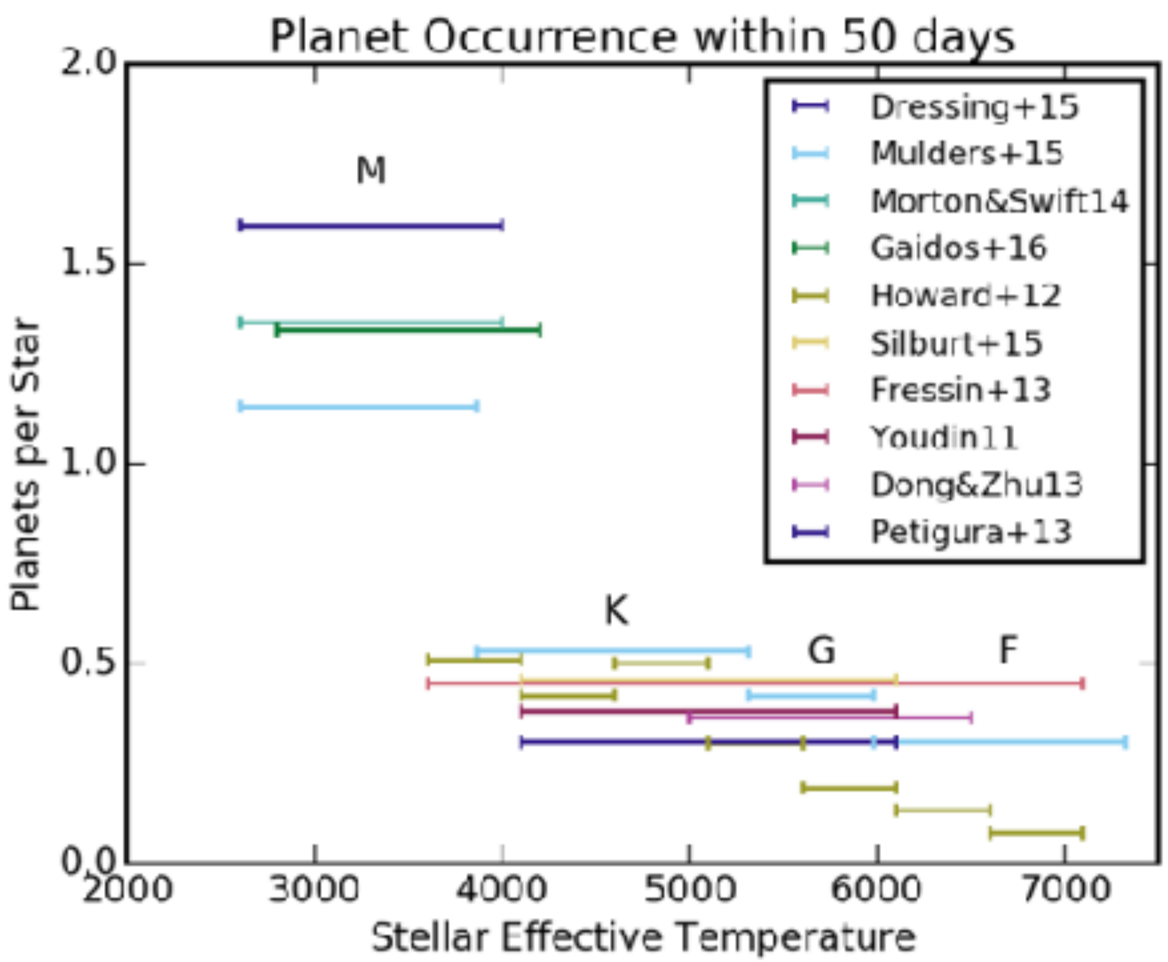


Match: disk gaps can be linked to giant planets (when there is migration)!

=> Stellar mass dependence also explains steepening in M_{dust} - M_{star} plot

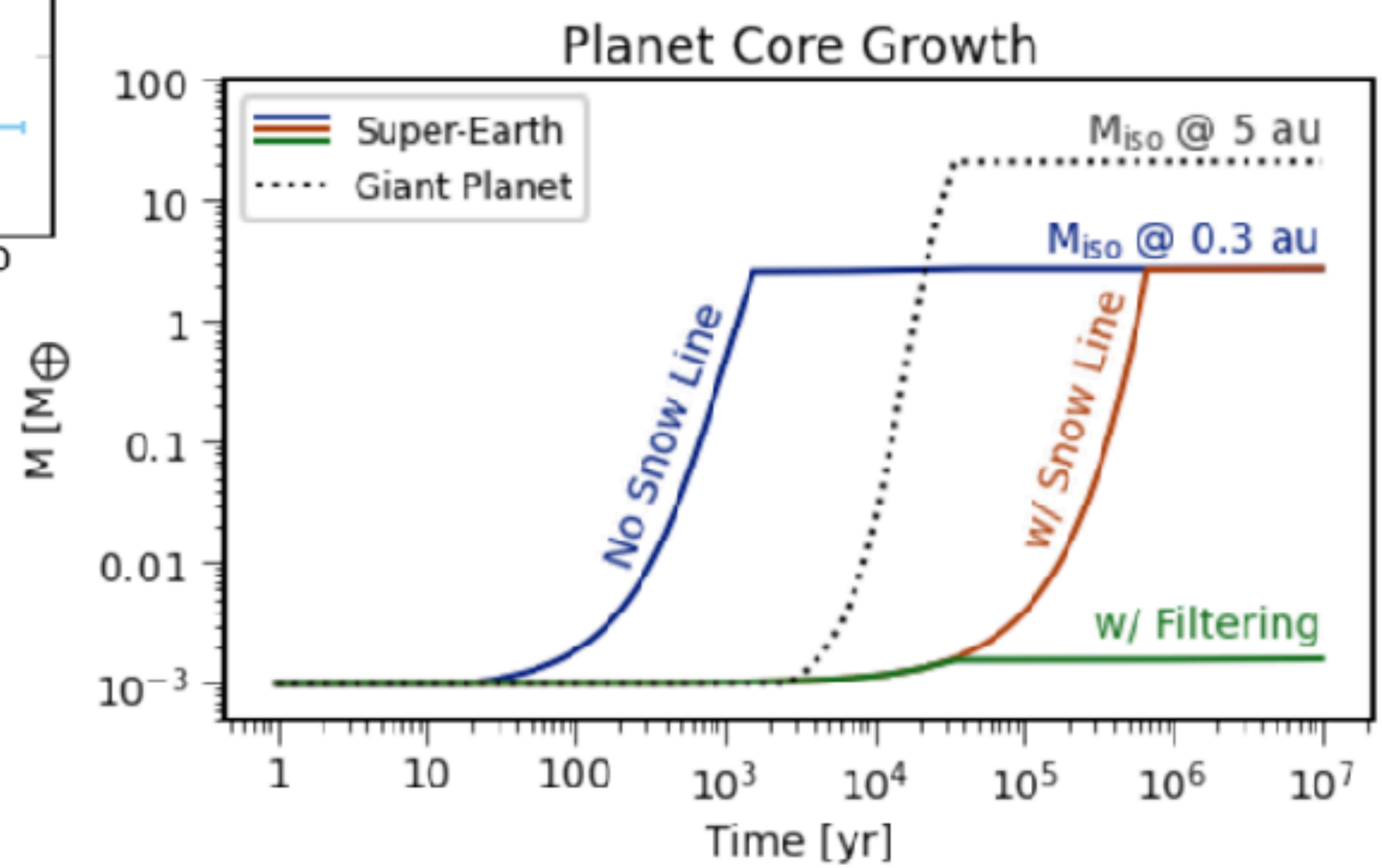
Mayor et al. 2011
Fernandes et al. 2019
van der Marel & Mulders 2021

What happens with the compact disks?



Super-Earth occurrence **decreases** with stellar mass, just like compact disks:

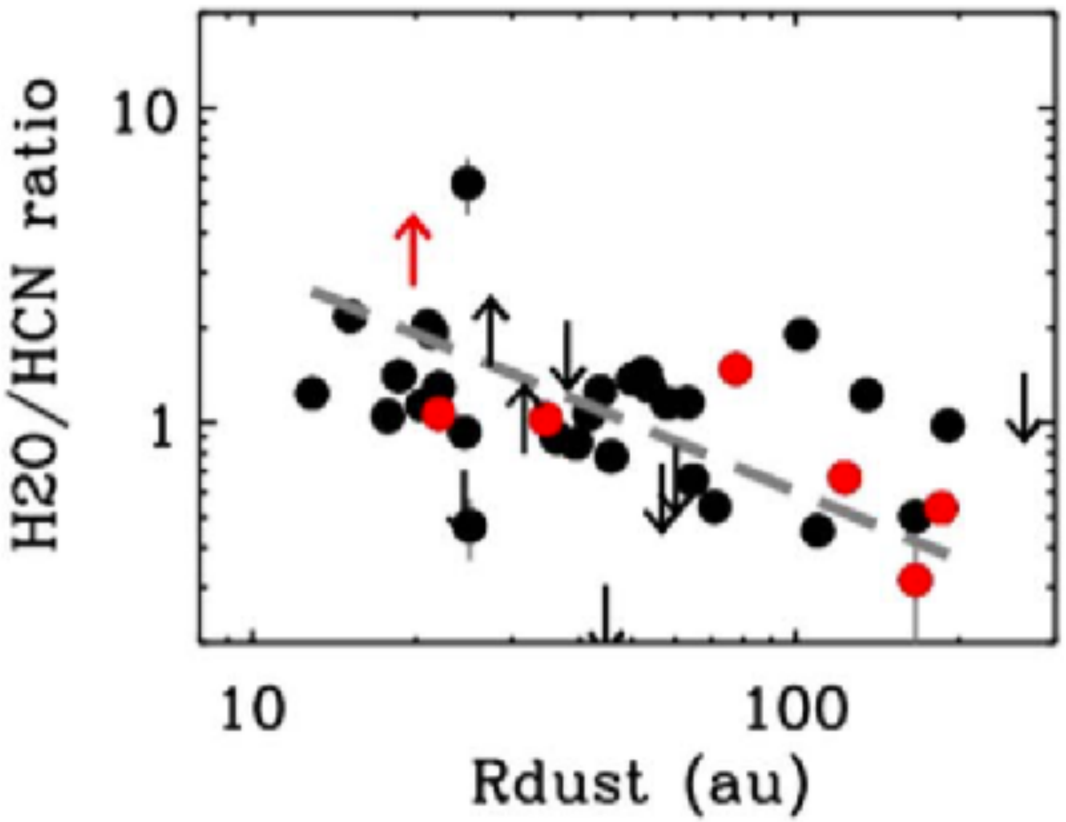
=> A giant planet prevents radial drift and thus super-Earth formation

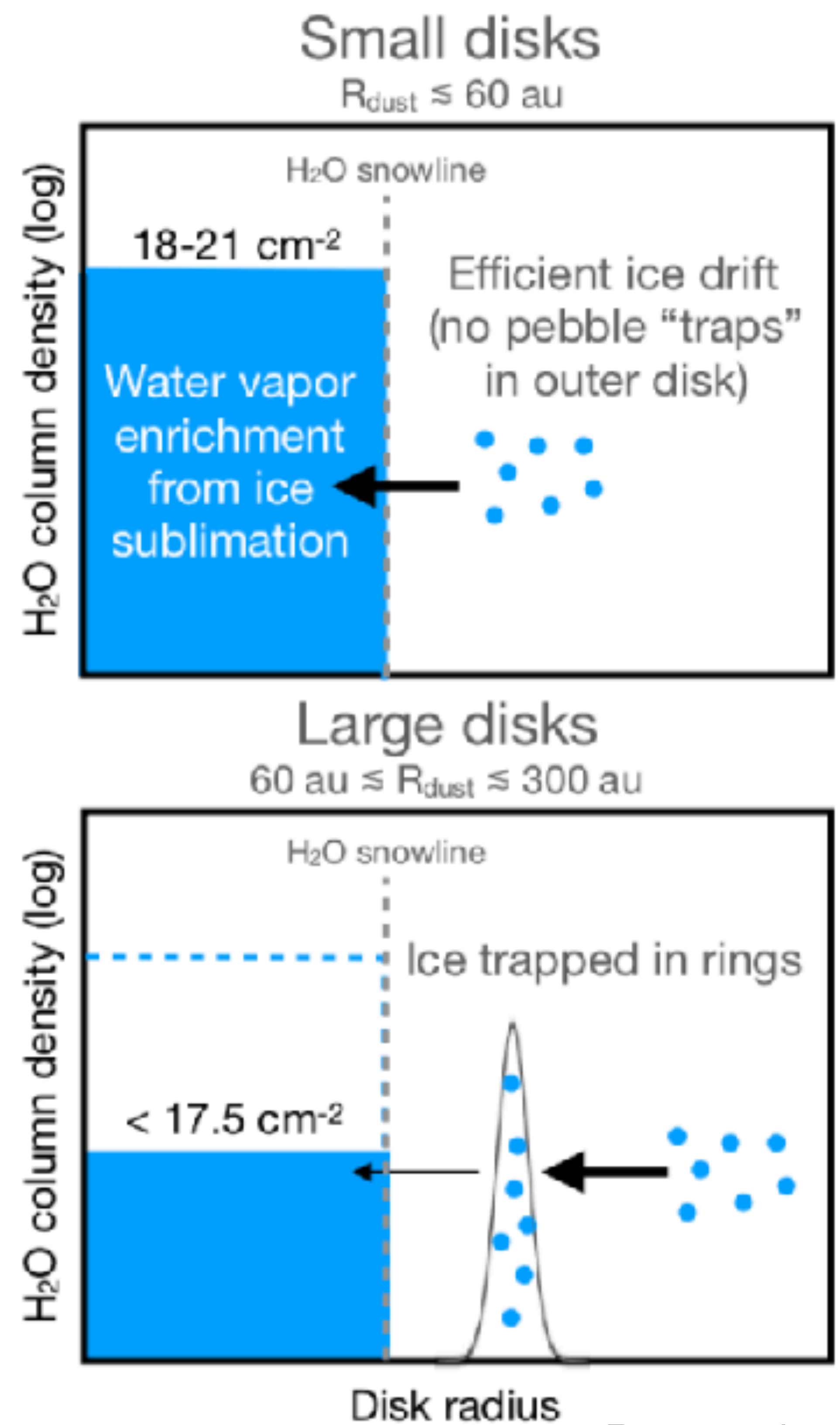


Mulders et al. 2015, 2018, 2019, 2021
Lambrechts et al. 2019
Van der Marel & Mulders 2021

Are compact disks really compact?

H_2O anti-correlated with compact dust disks

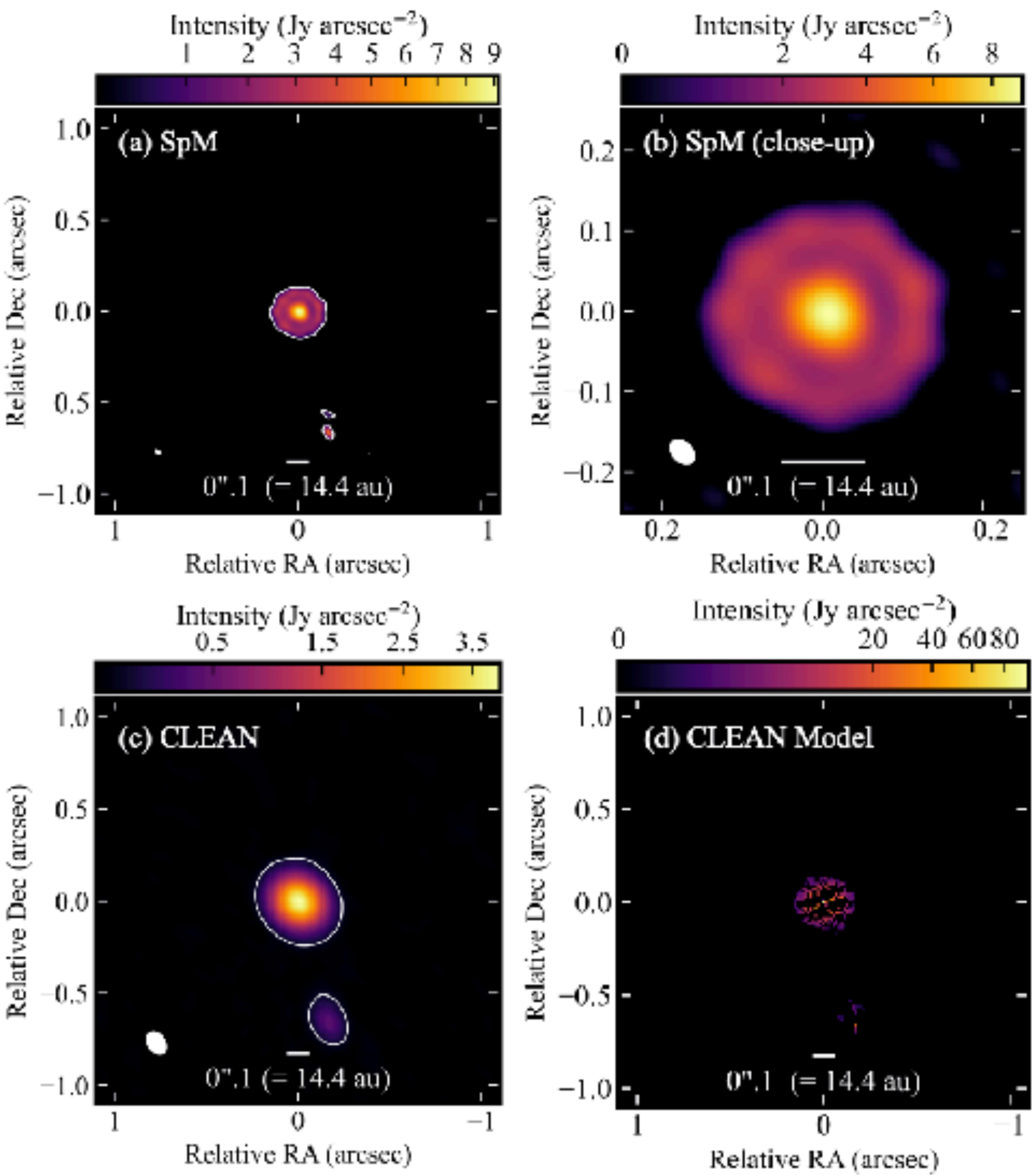




Banzatti et al. 2020
Kalyaan et al. 2021

Are compact disks really compact?

Re-imaging improves resolution by factor 3: super resolution (0.03")



We need more high-resolution data (and techniques!) of compact disks.

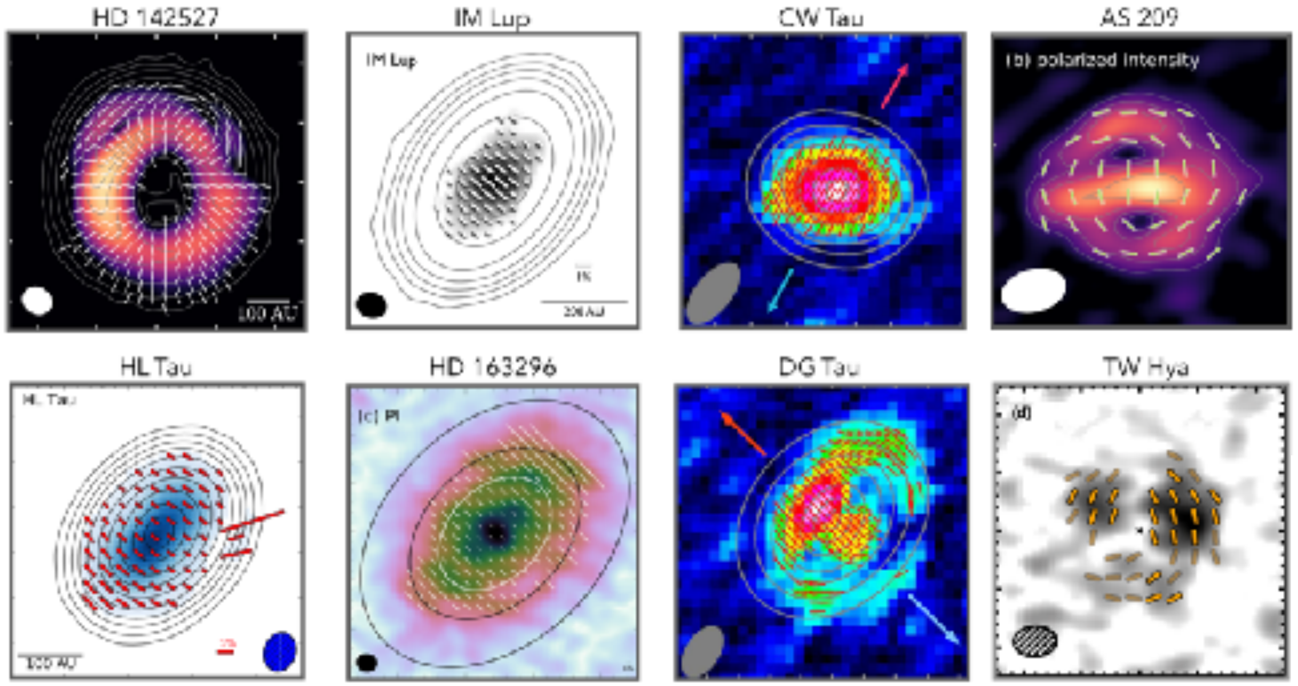
Talk Jennings

Yamaguchi et al. 2021
Jennings et al. subm.

How large are the dust grains?

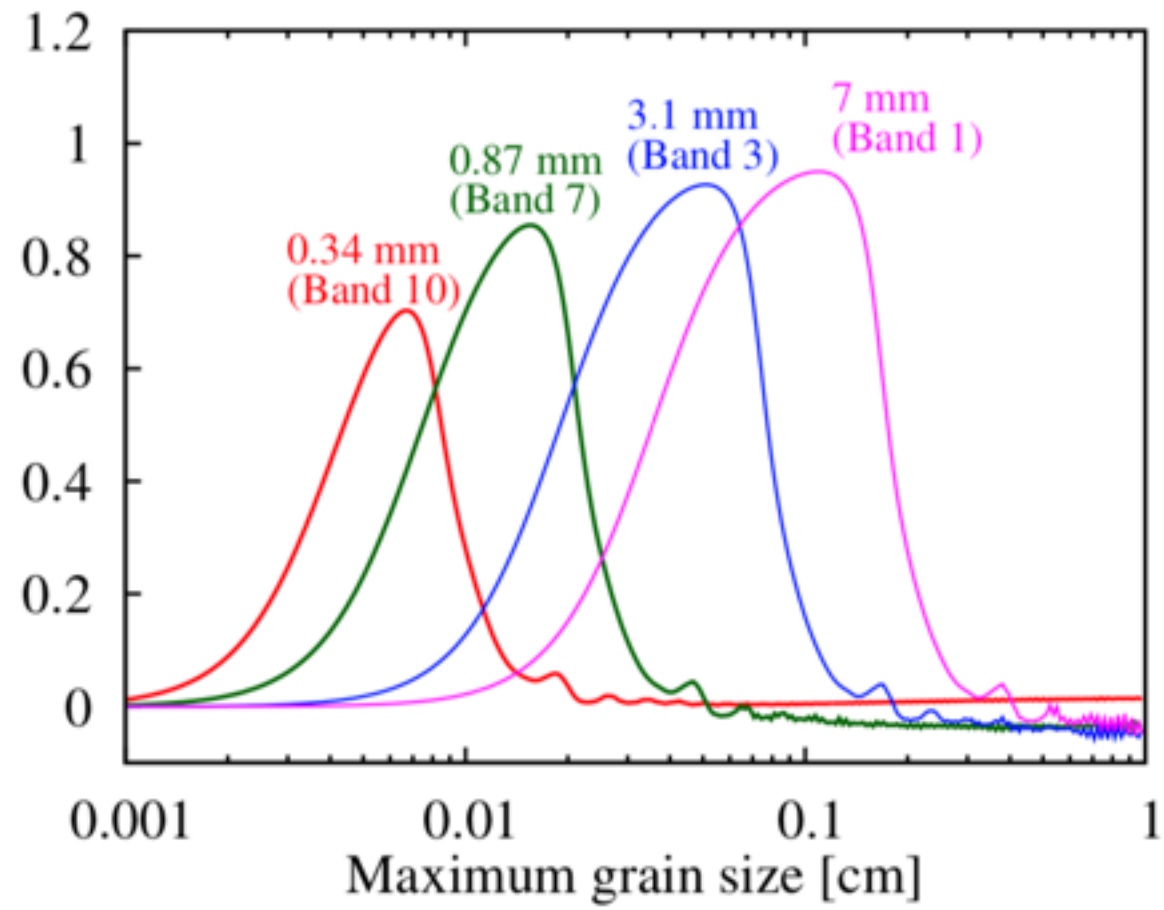
Polarization

ALMA polarization of disks



- ALMA polarization measurements between Band 3 and 7
- 10-20 disks in polarization (some multi-wavelength)
- Polarization due to scattering: only detectable when a ~ λ/2π

Prediction of polarization fraction

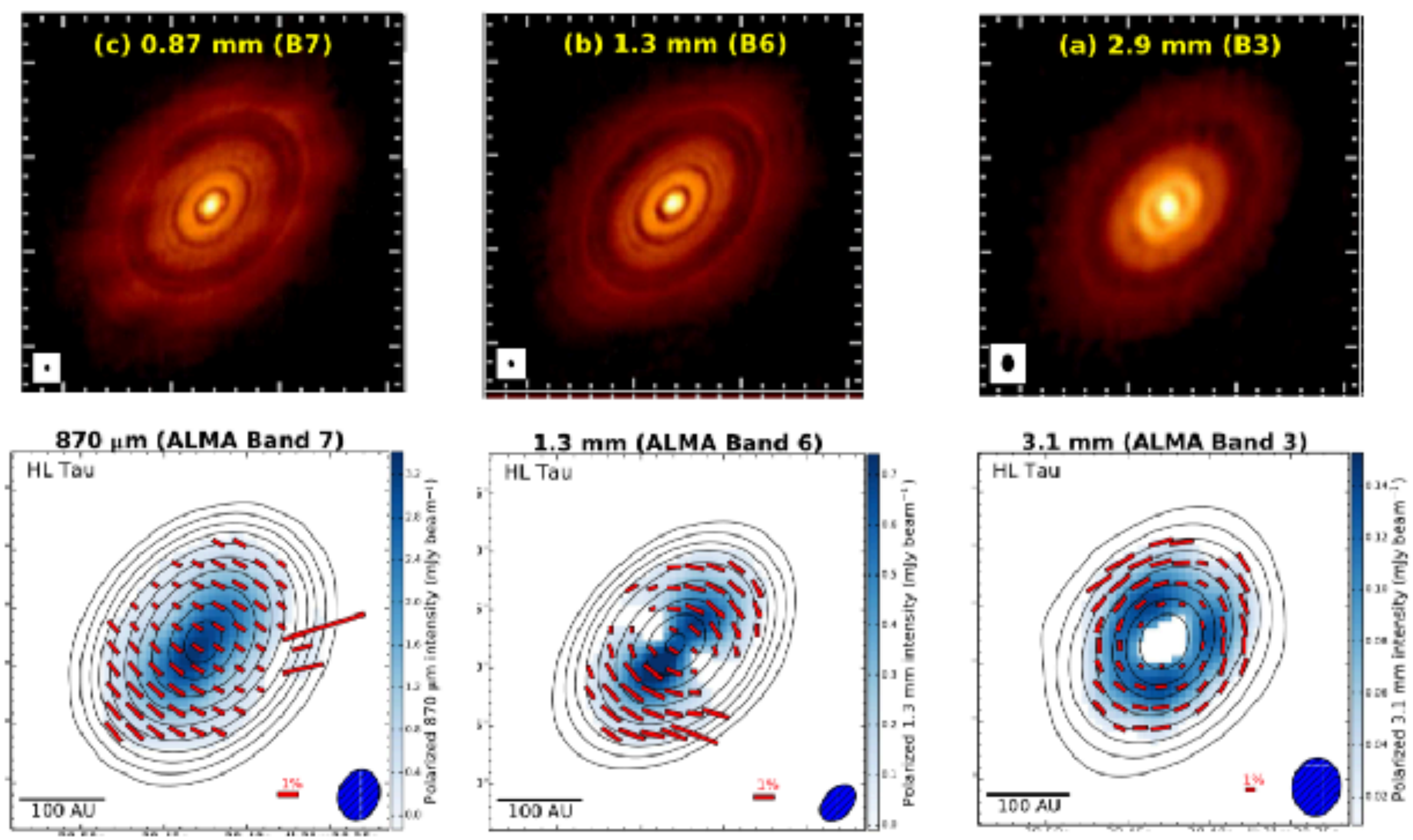


Kataoka et al., 2015

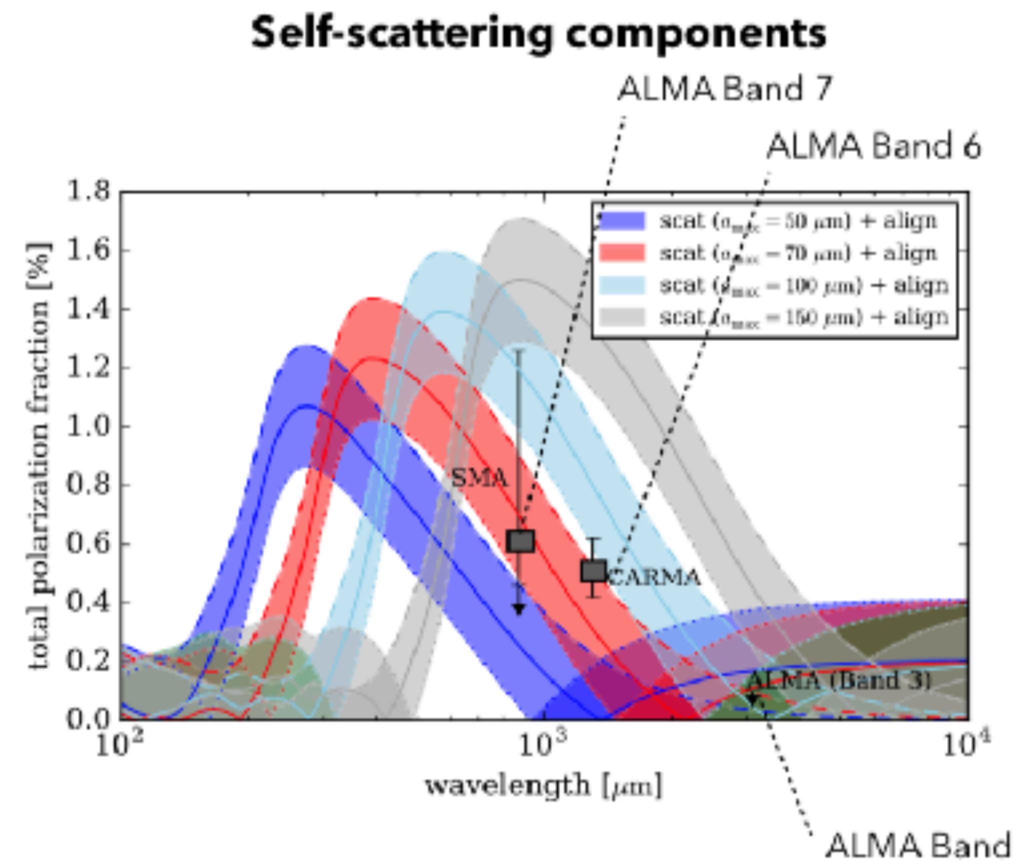
Talk Kataoka

Polarization

~100 μm sized grains?



ALMA Partnership 2015, Stephens et al. 2017

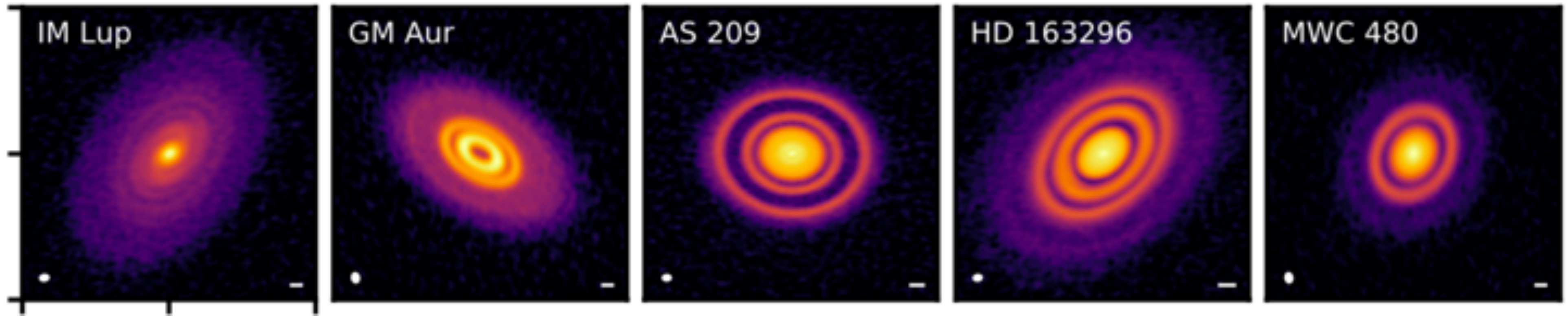


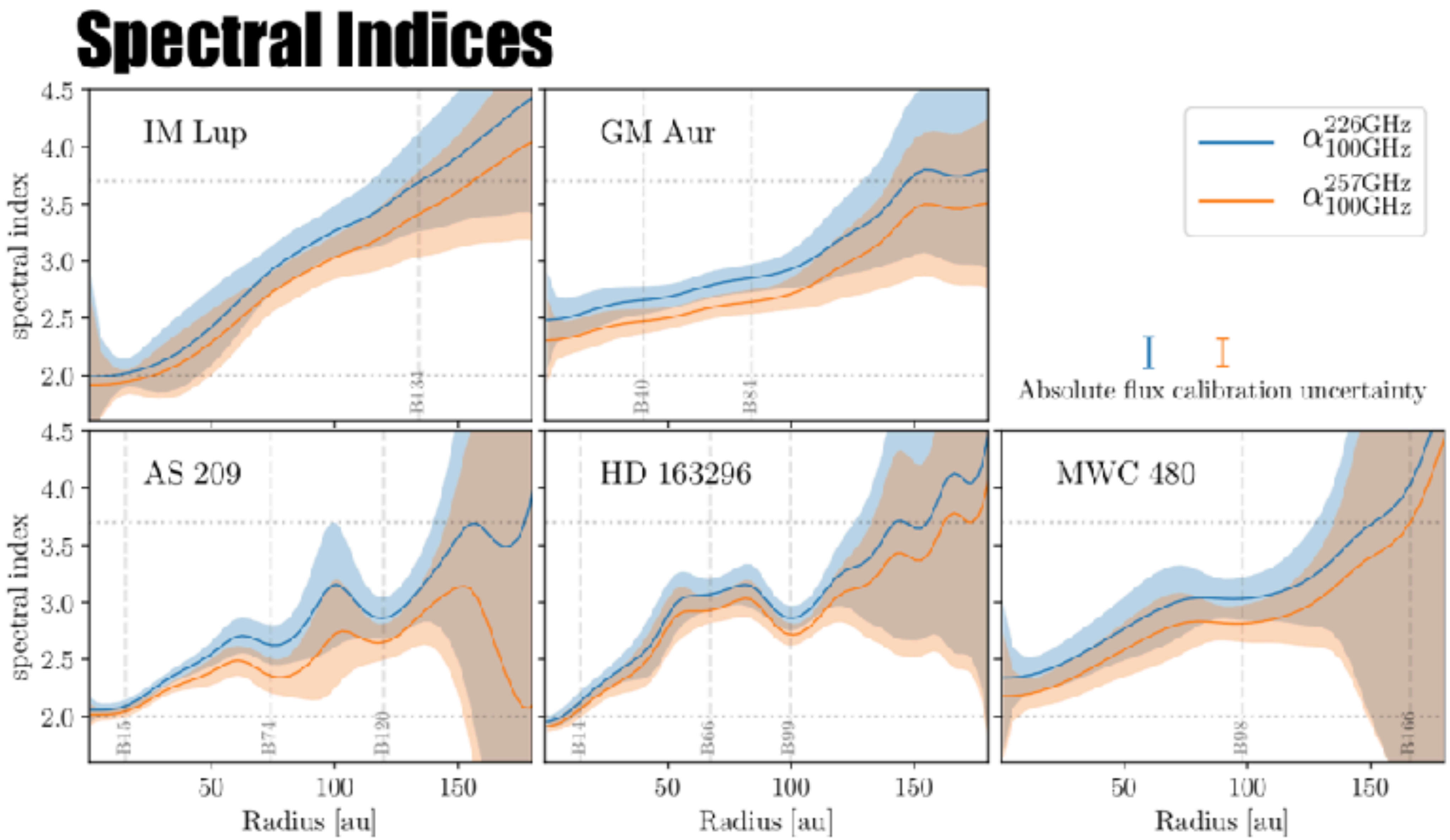
Kataoka et al. 2017, modified

Talk Kataoka

Spectral index: resolved analysis

MAPS:
multi-wavelength

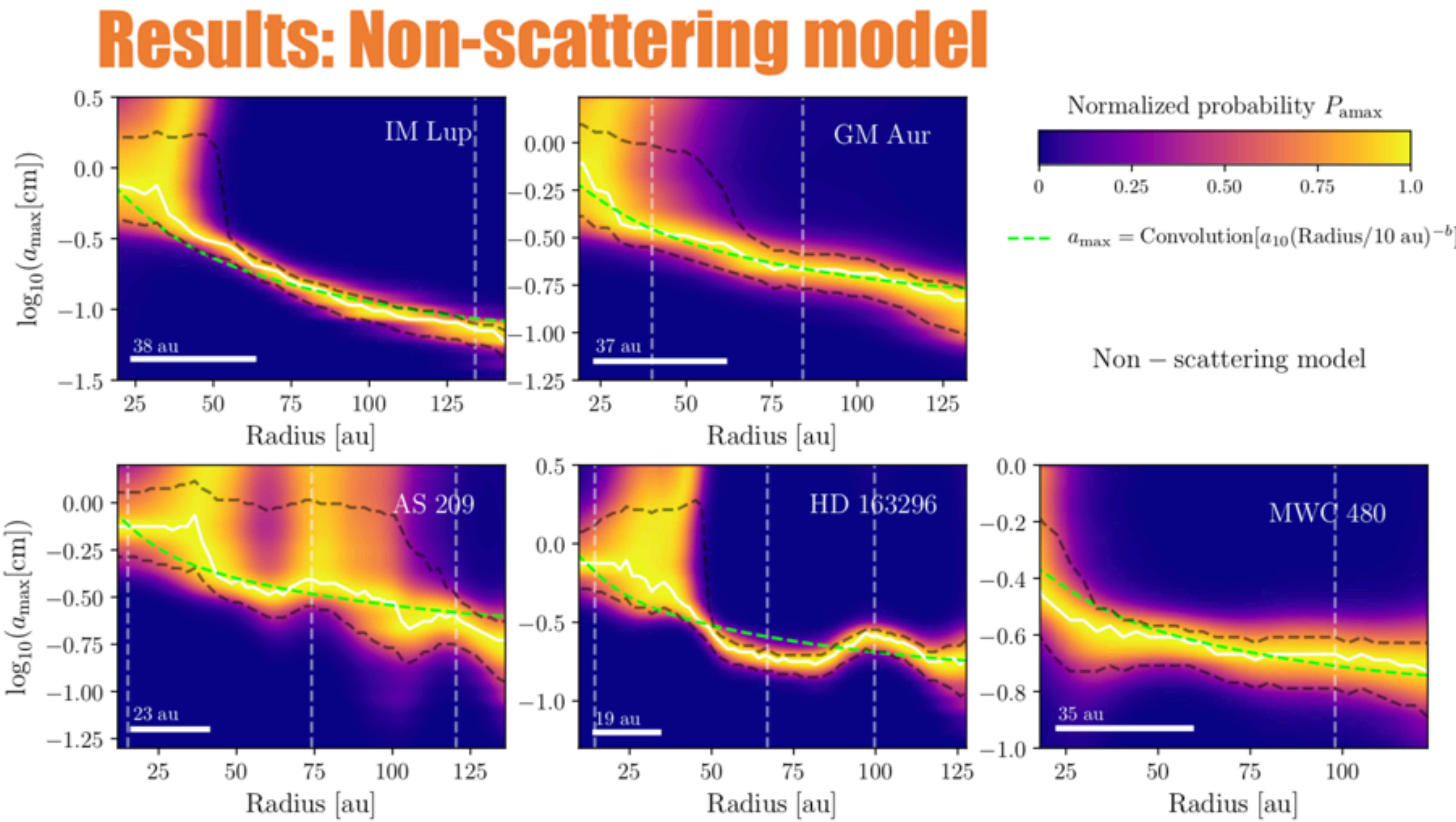




Talk Sierra

Sierra et al. 2021 (MAPS)

Spectral index



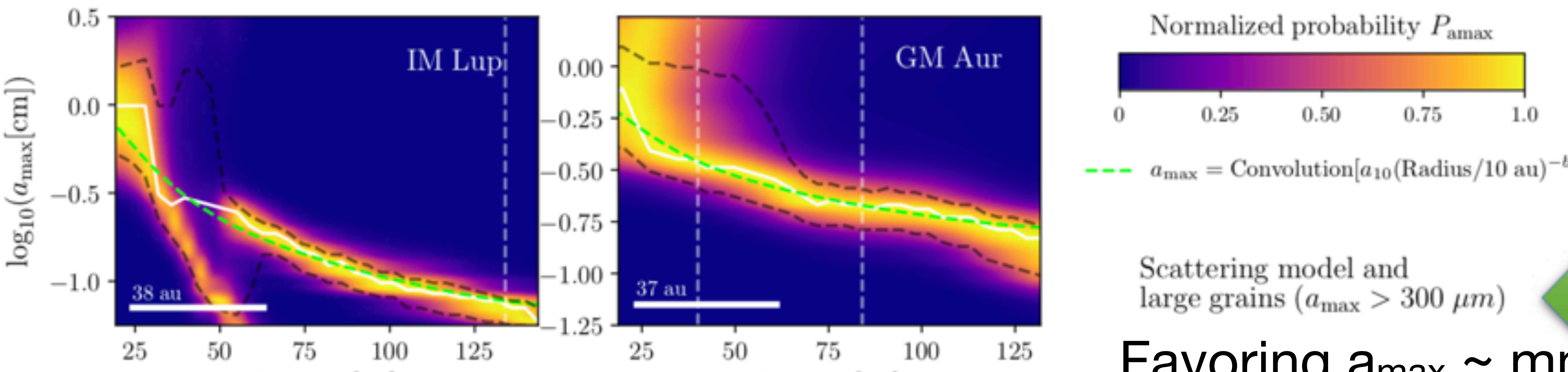
Favoring a_{max} ~ mm

Talk Sierra

Sierra et al. 2021 (MAPS)

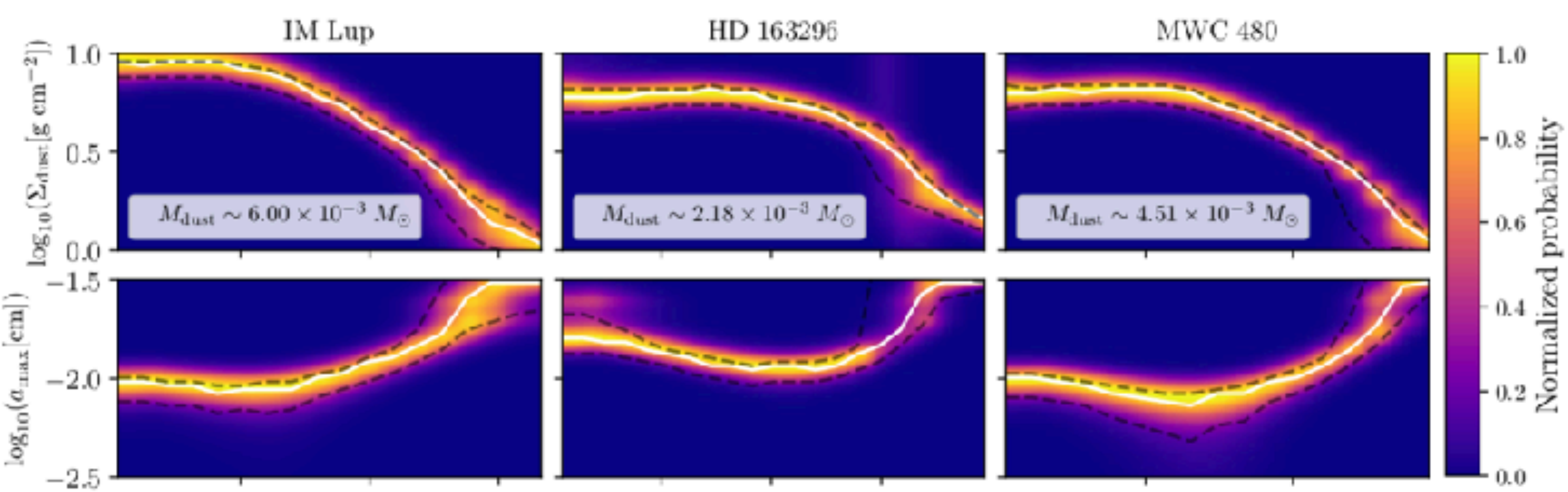
Spectral index: two solutions with scattering

Results: Scattering model



Favoring a_{max} ~ mm

Results: Scattering model [small grains < 300 microns]

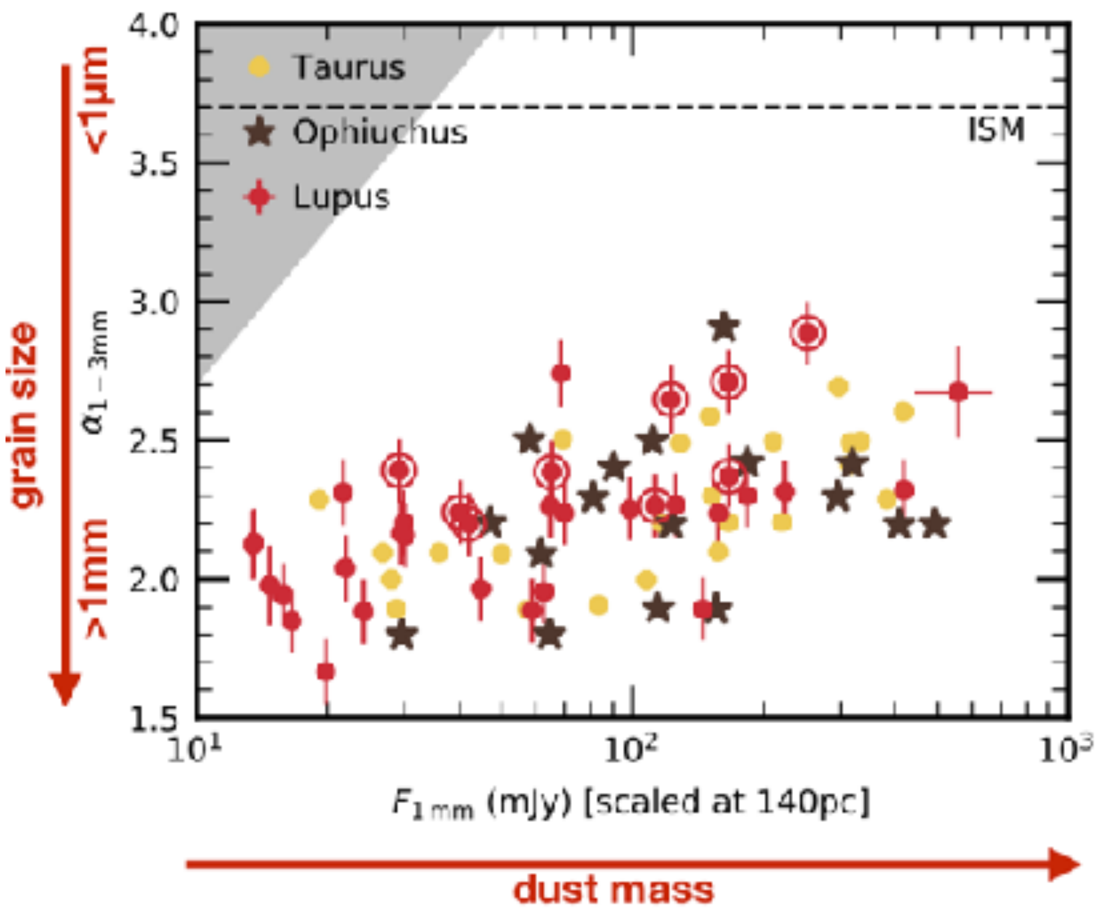


Small grains not favored: gravitationally unstable and inconsistent with 7mm

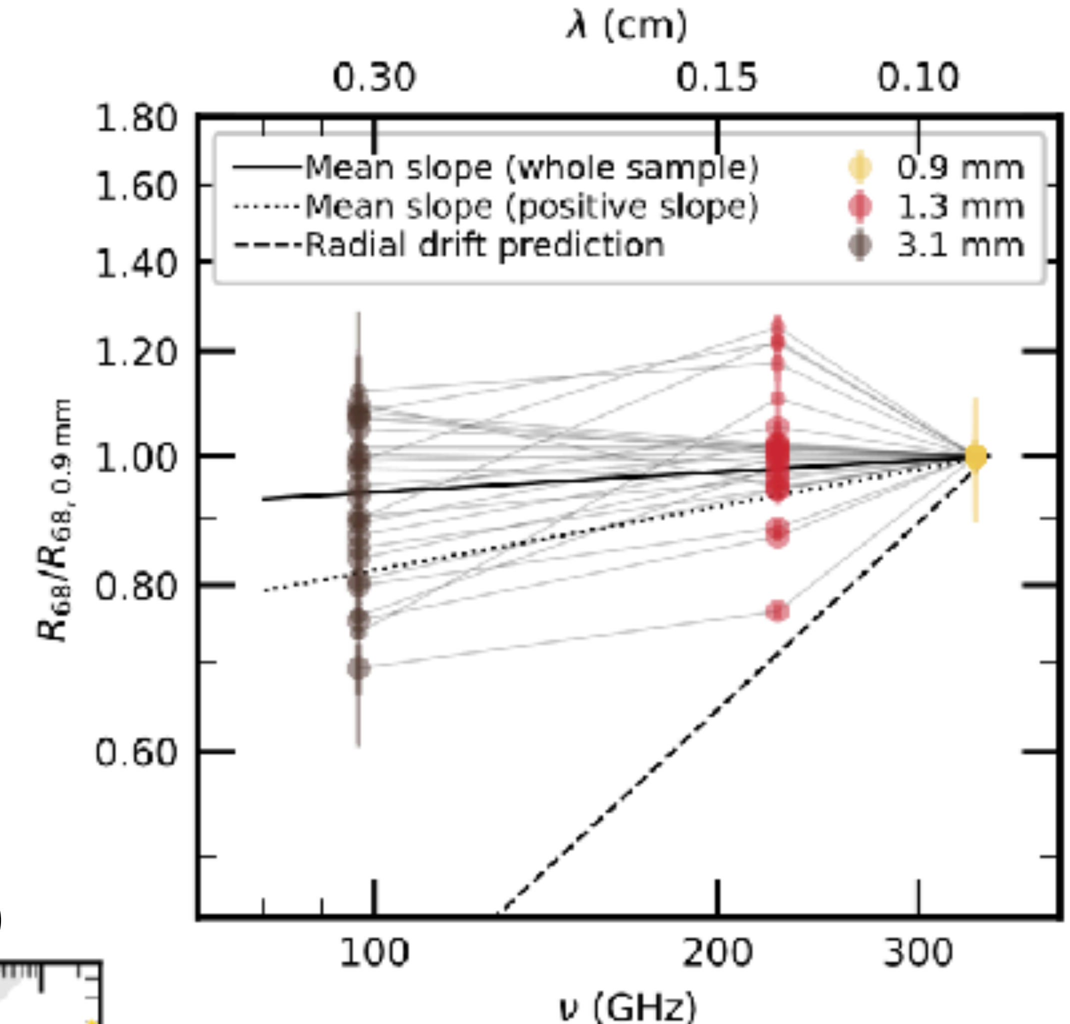
Talk Sierra

Sierra et al. 2021 (MAPS)

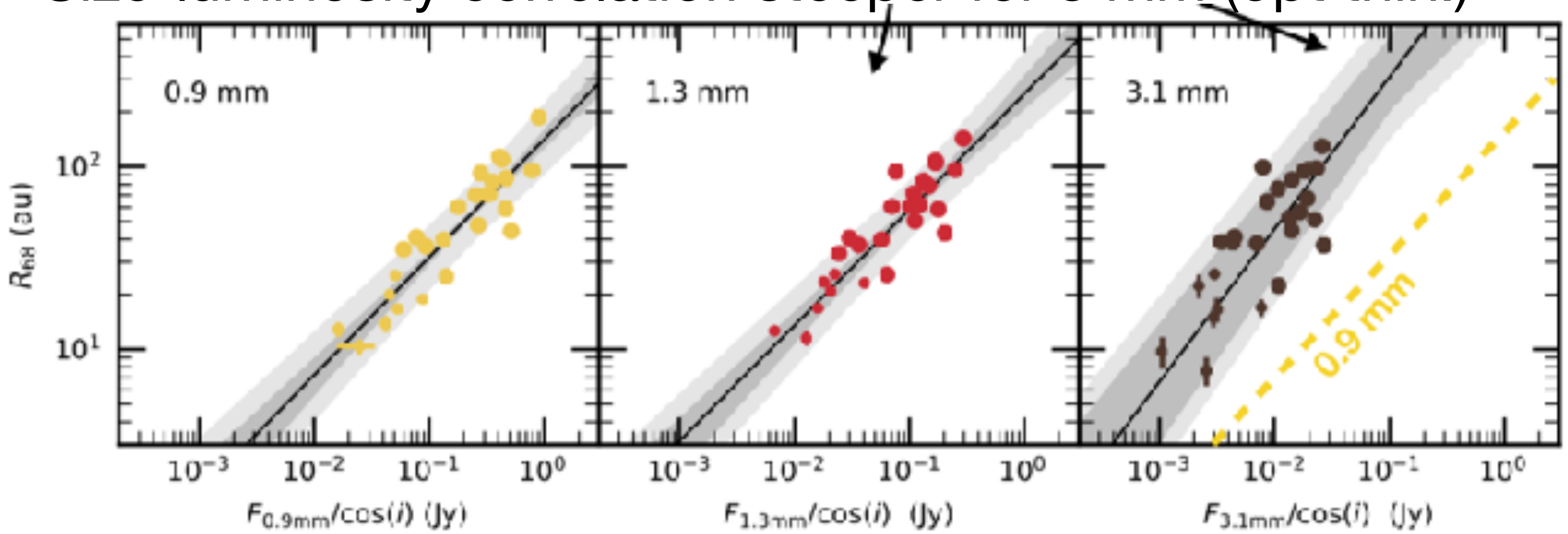
Spectral index: surveys



Lupus:



Size-luminosity correlation steeper for 3 mm (opt thin!)

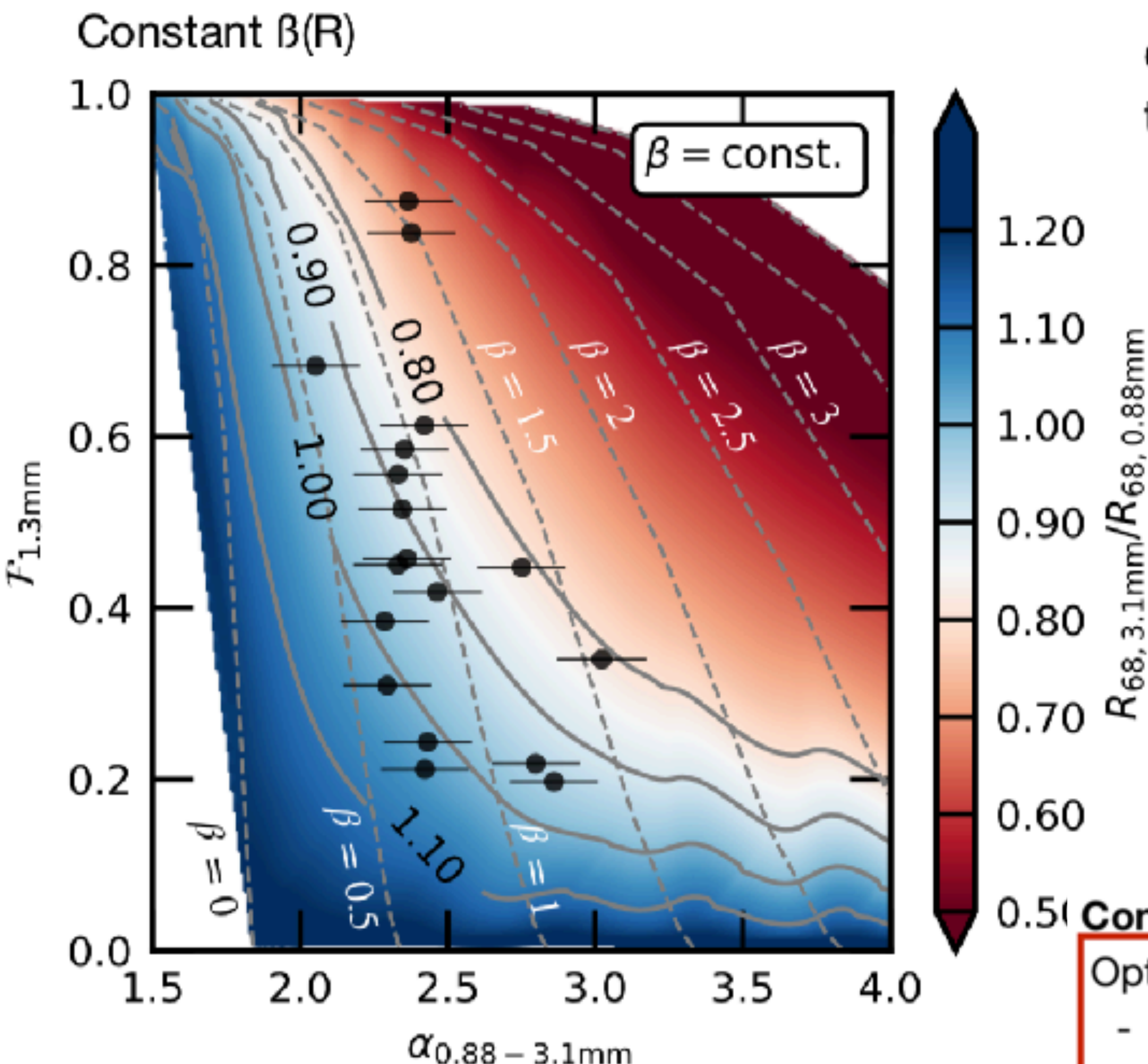


- Nearly identical radii
- R_{3mm} is ~90% $R_{0.9mm}$

Talk Tazzari

Tazzari et al. 2021

Spectral index: surveys



Grains must be **large** ($a_{\max} \geq 1$ mm) throughout the disc to reproduce:

- radii

$$R_{68,3.1\,\mathrm{mm}}/R_{68,0.88\,\mathrm{mm}} \approx 1$$

- sp. index

$$2.4 \leq \alpha_{0.9-3.1\,\mathrm{mm}} \leq 3.0$$

- opt. thick fractions

$$0.2 \leq \mathscr{F}_{1.3\,\mathrm{mm}} \leq 0.6$$

Observational constraints

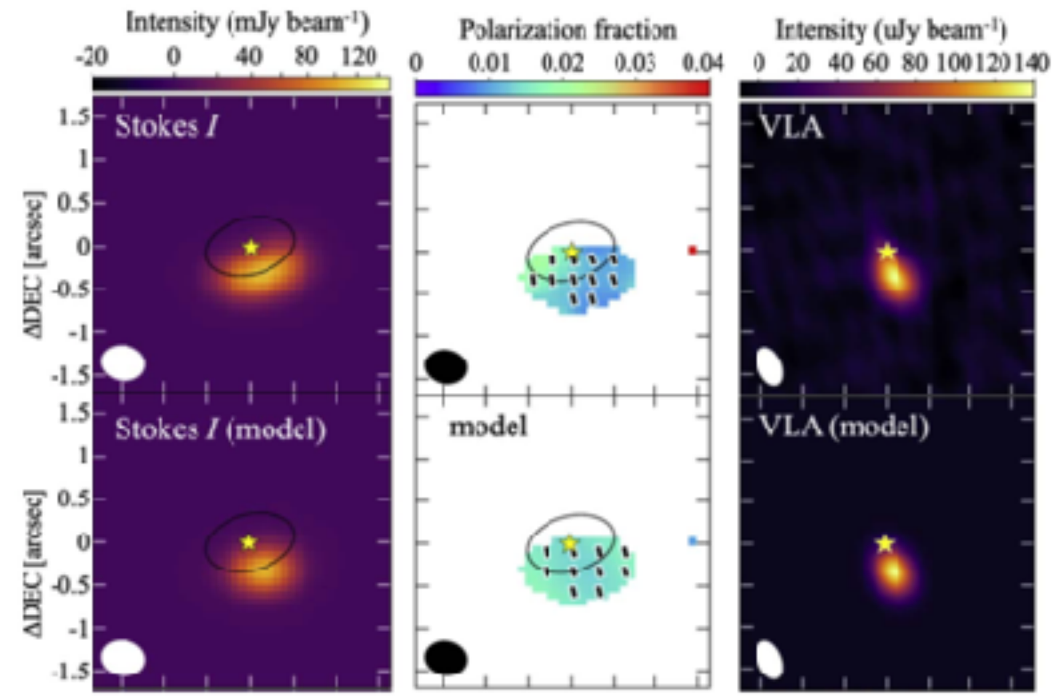
Conclusions:

Opt thick sub-structures is not disfavoured in *general*, but:

- opt thick structures + small grains (beta~2): contrived
- opt thick structures + larger grains (beta~1): possible
- opt thick strucutres **of** large grains (high albedo): possible and do not require opt thin background
    - $\lambda \geq 7$ mm observations will help discriminate

Talk Tazzari

So how to solve the discrepancy with polarization?



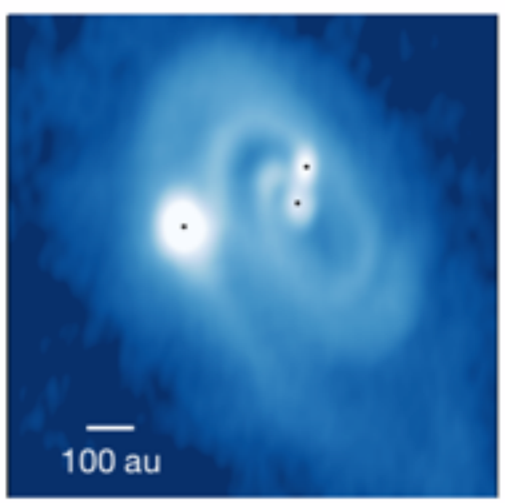
- Very optically thick emission: large grains hidden in mid-plane
- But such extreme settling requires $\alpha \sim 10^{-5}$
- Difficult to include vertical structure in spectral index modelling: too many parameters
- Microphysics: porous grains? Alignment? Larger samples?

We need ngVLA to resolve large grains

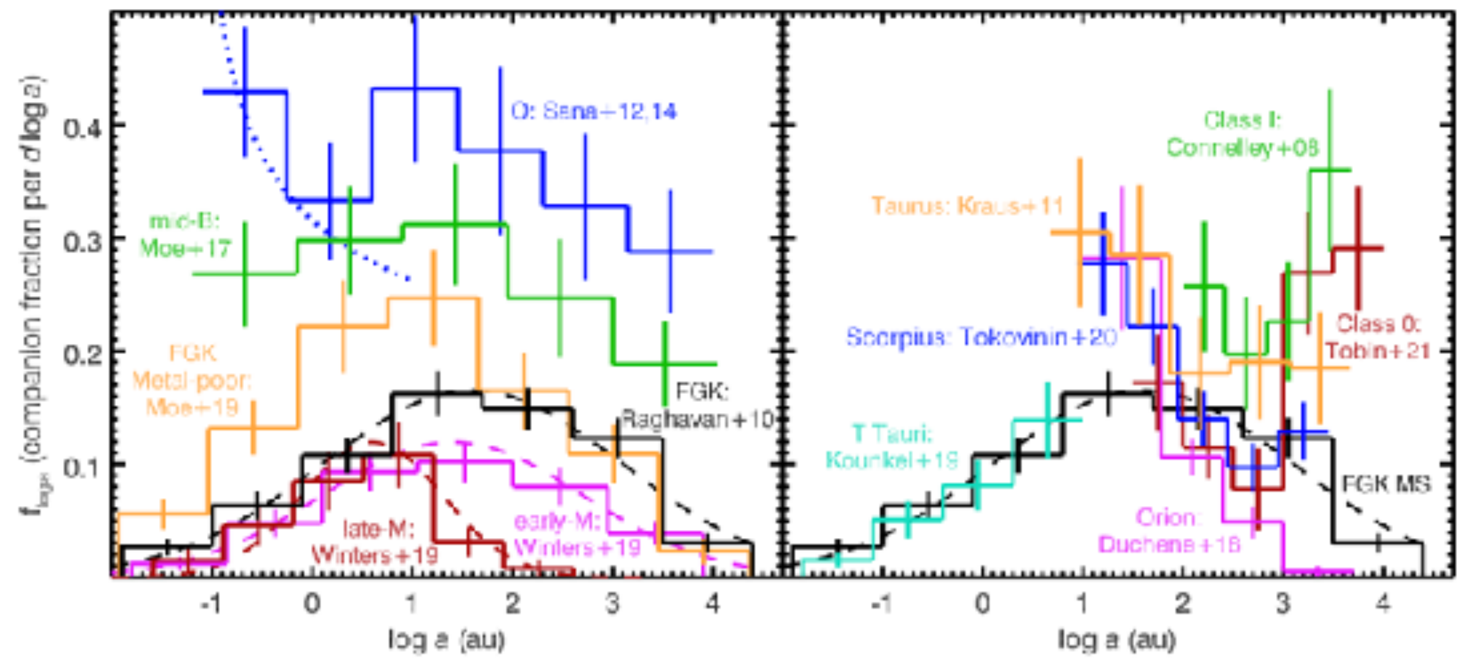
Talks Kataoka, Sierra, Tazzari

Multiplicity

Multiplicity complicates many disk processes and is not well constrained in young clusters….

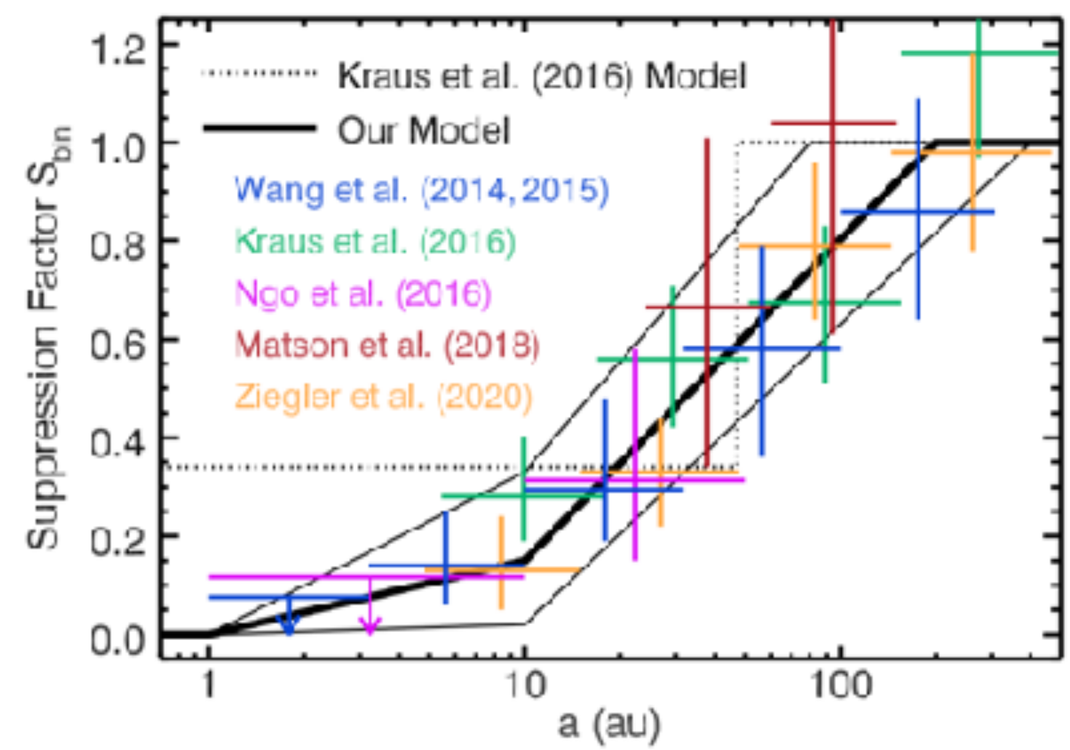


Disk fragmentation more likely to result in stellar than planetary companion



Variation in separation distribution between different stars

Planet formation suppressed in binaries, depending on separation



Talk Kratter

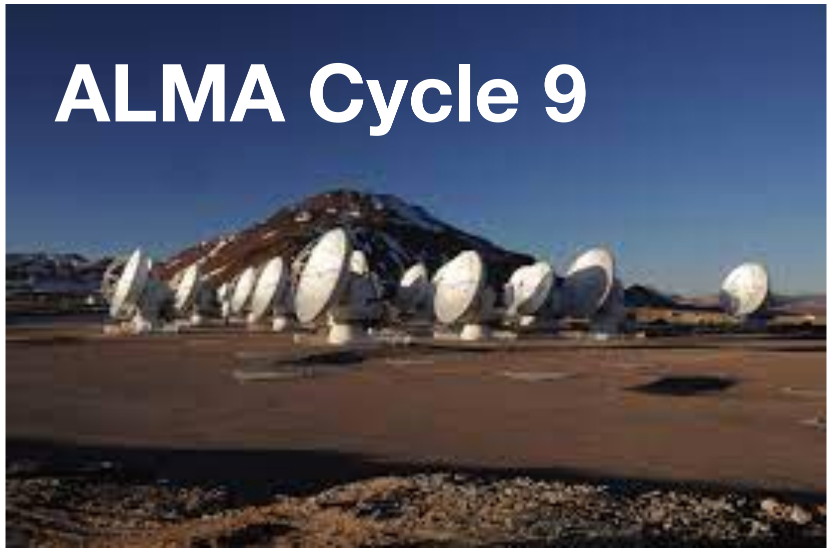
Summary

- Substructures are ubiquitous in disk simulations (but not necessarily due to planets!)

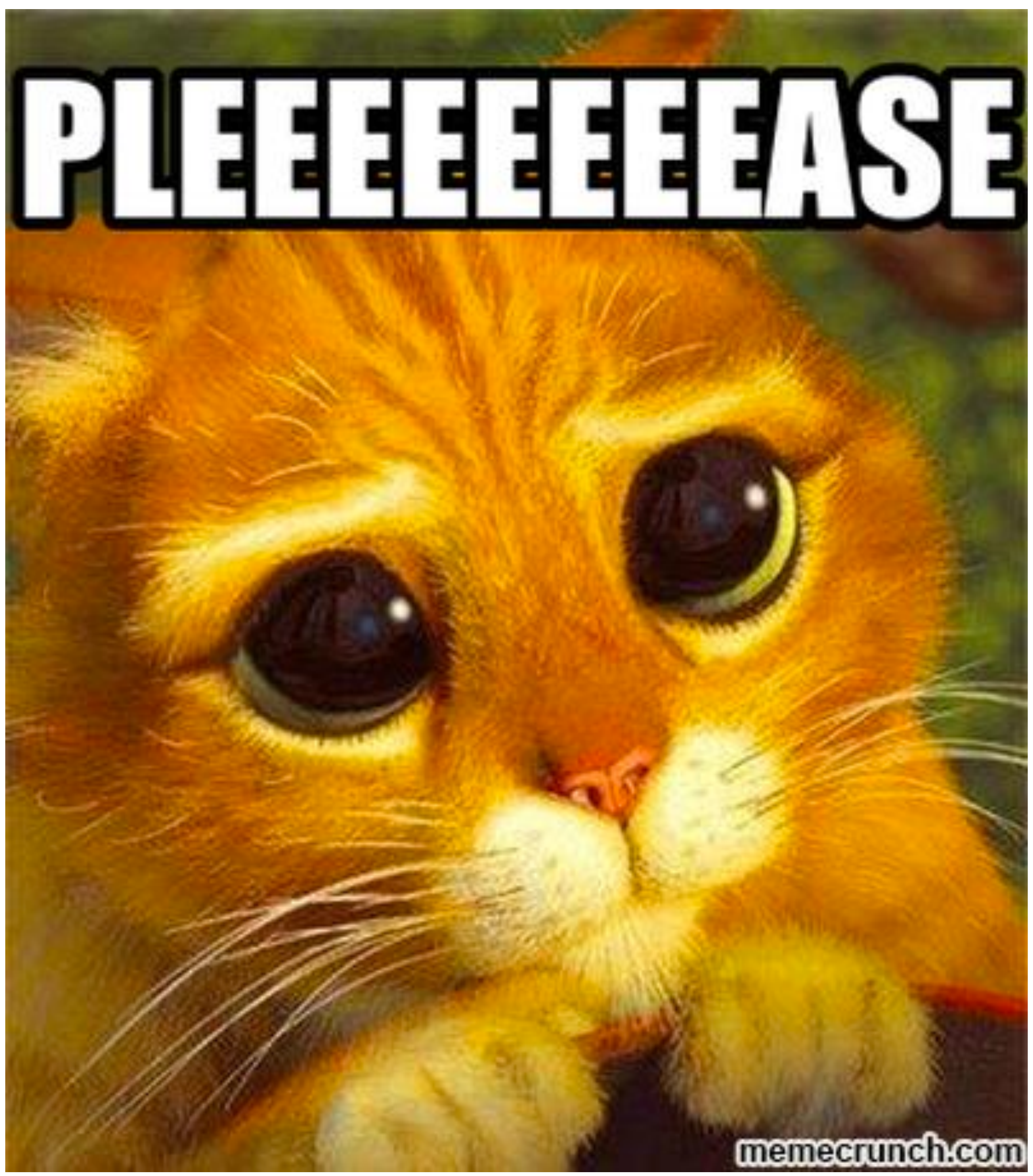
- Substructures in disk observations may be ubiquitous (but not necessarily at large spatial scales!)

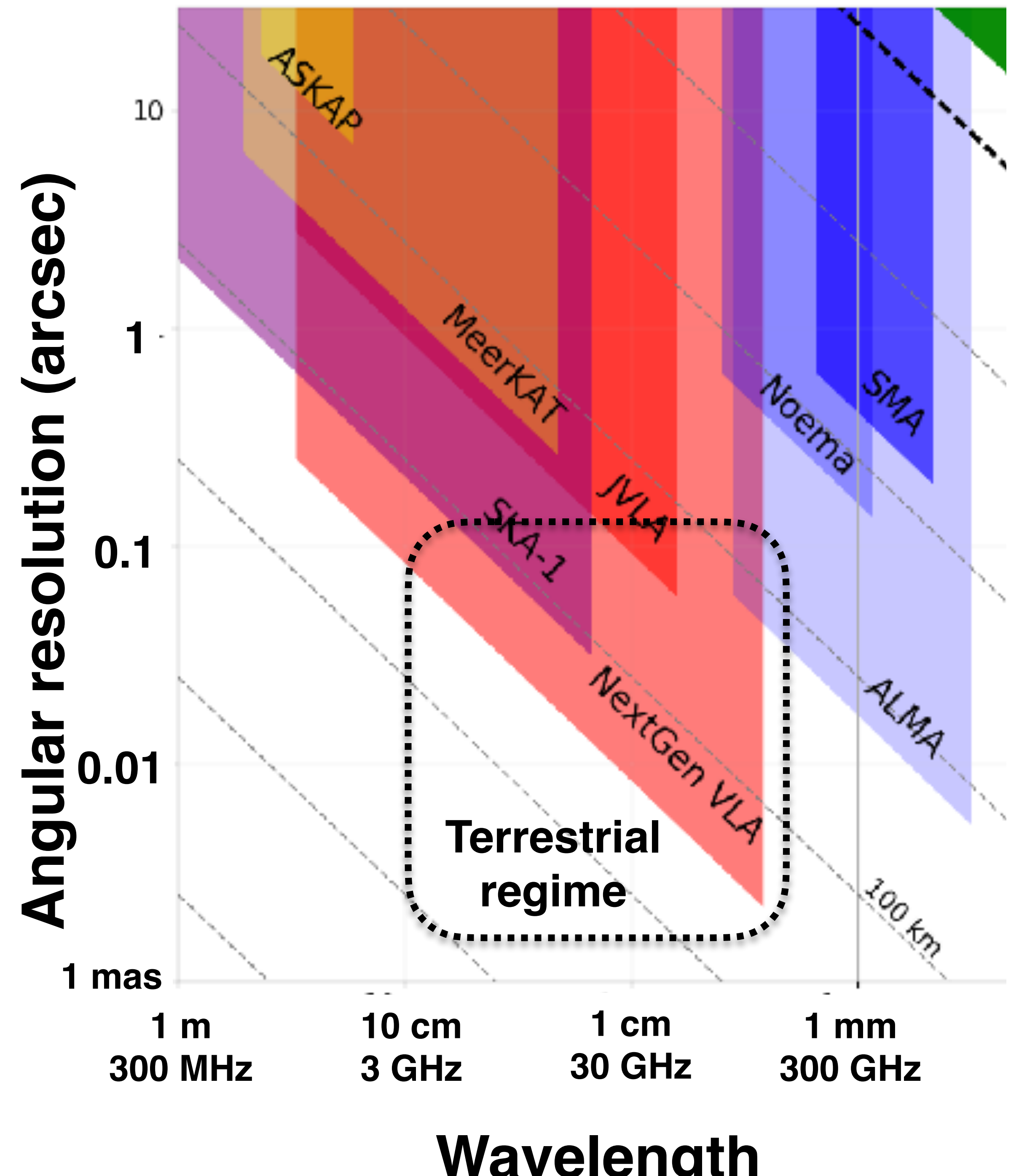
- Deep, high-resolution, uniform observations are required of both dust and gas to link data to simulations of large and small disks

- Cm observations may provide the answers to the grain size discussion


ALMA Cycle 9


ngvla


PLEEEEEEEEEASE
memecrunch.com


ASKAP
MeerKAT
JVLA
SKA-1
NextGen VLA
Noema
SMA
ALMA
100 km
Terrestrial regime
Angular resolution (arcsec)
10
1
0.1
0.01
1 mas
1 m
300 MHz
10 cm
3 GHz
1 cm
30 GHz
1 mm
300 GHz
Wavelength