Novel views on planet formation and dust evolution

Connecting protoplanetary disk demographics with exoplanets, debris disks and exoplanet atmospheres

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DoA Tsinghua Colloquium
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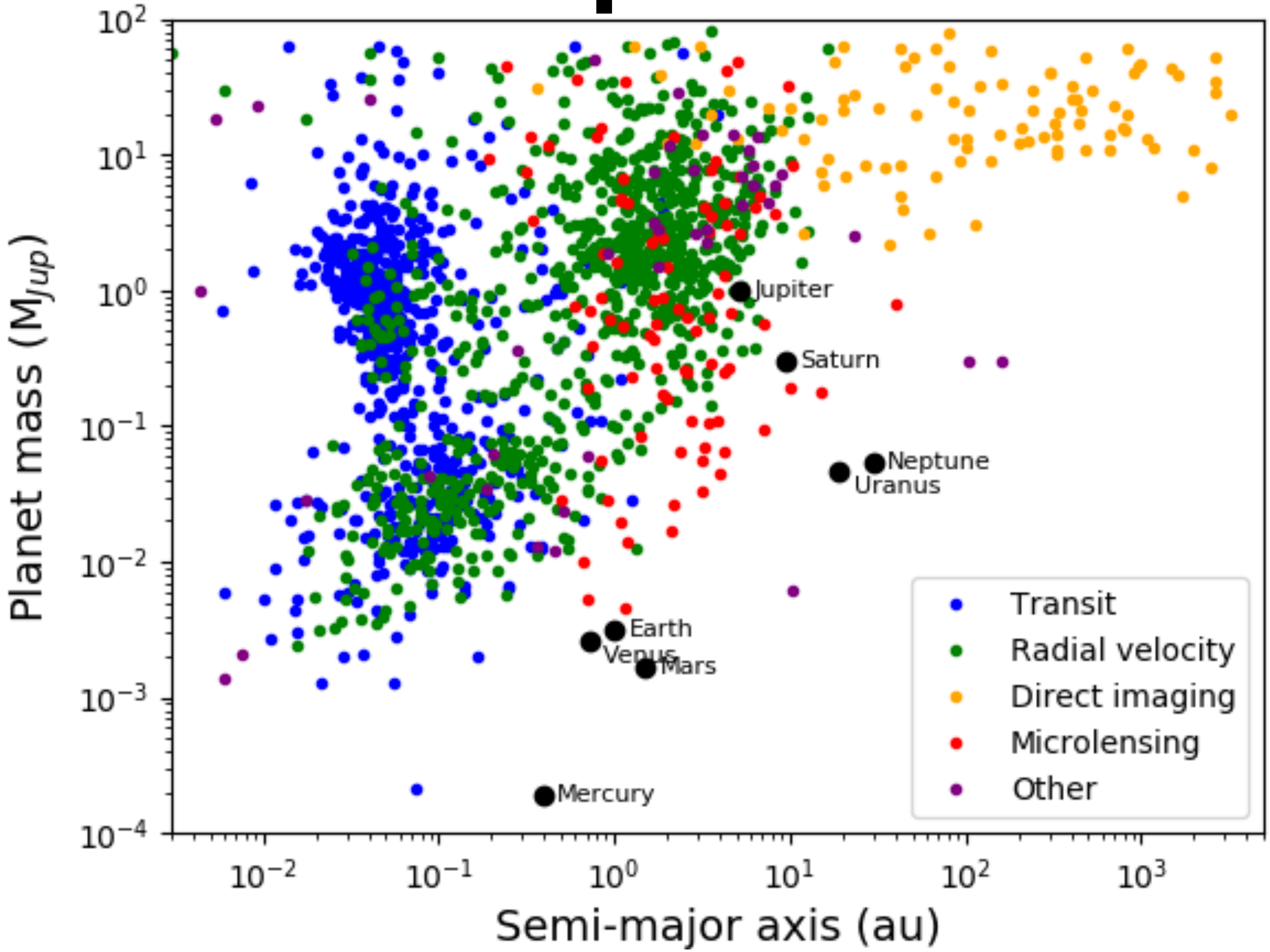
Sterrewacht Leiden

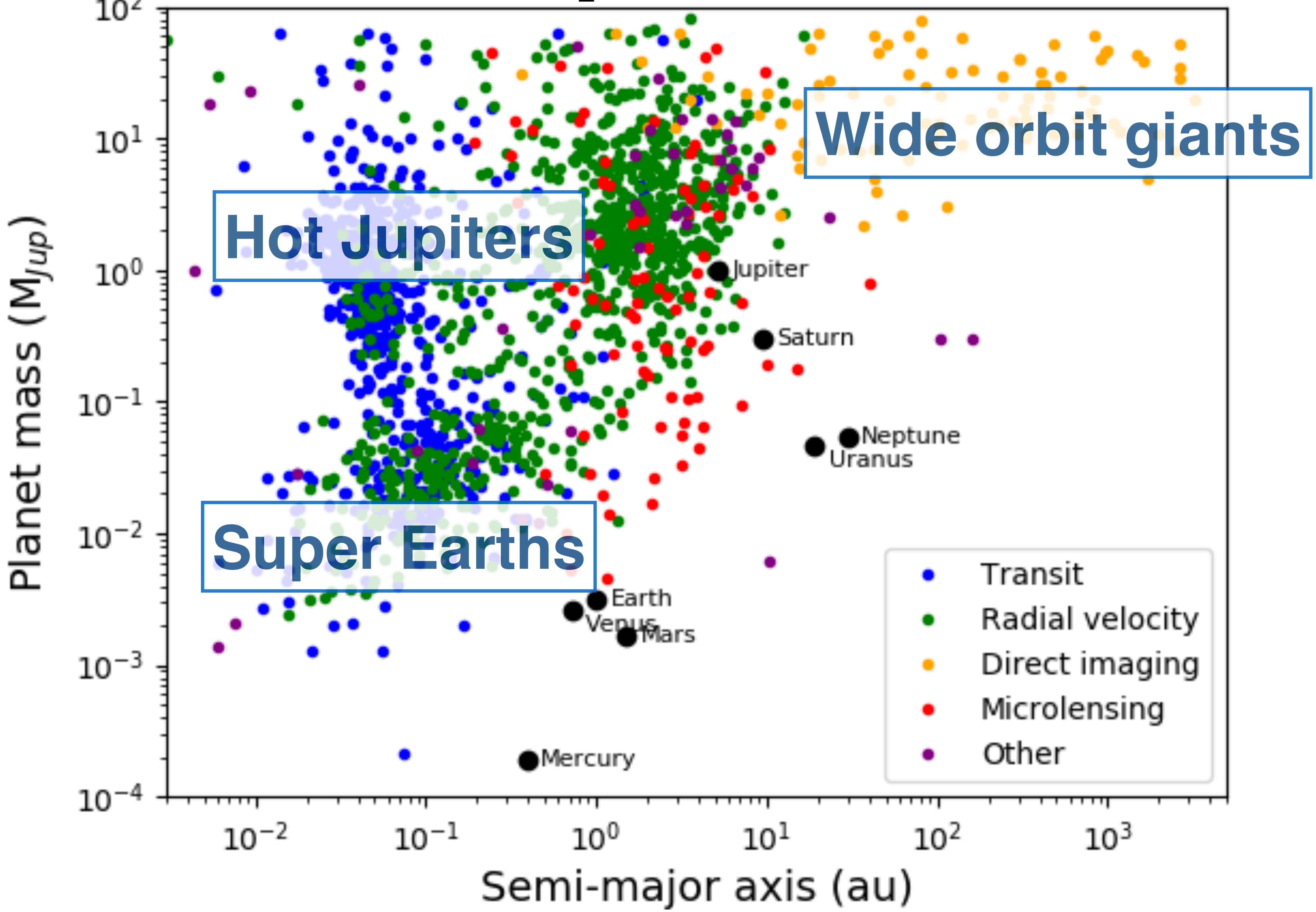
Exoplanets

4843 exoplanets!



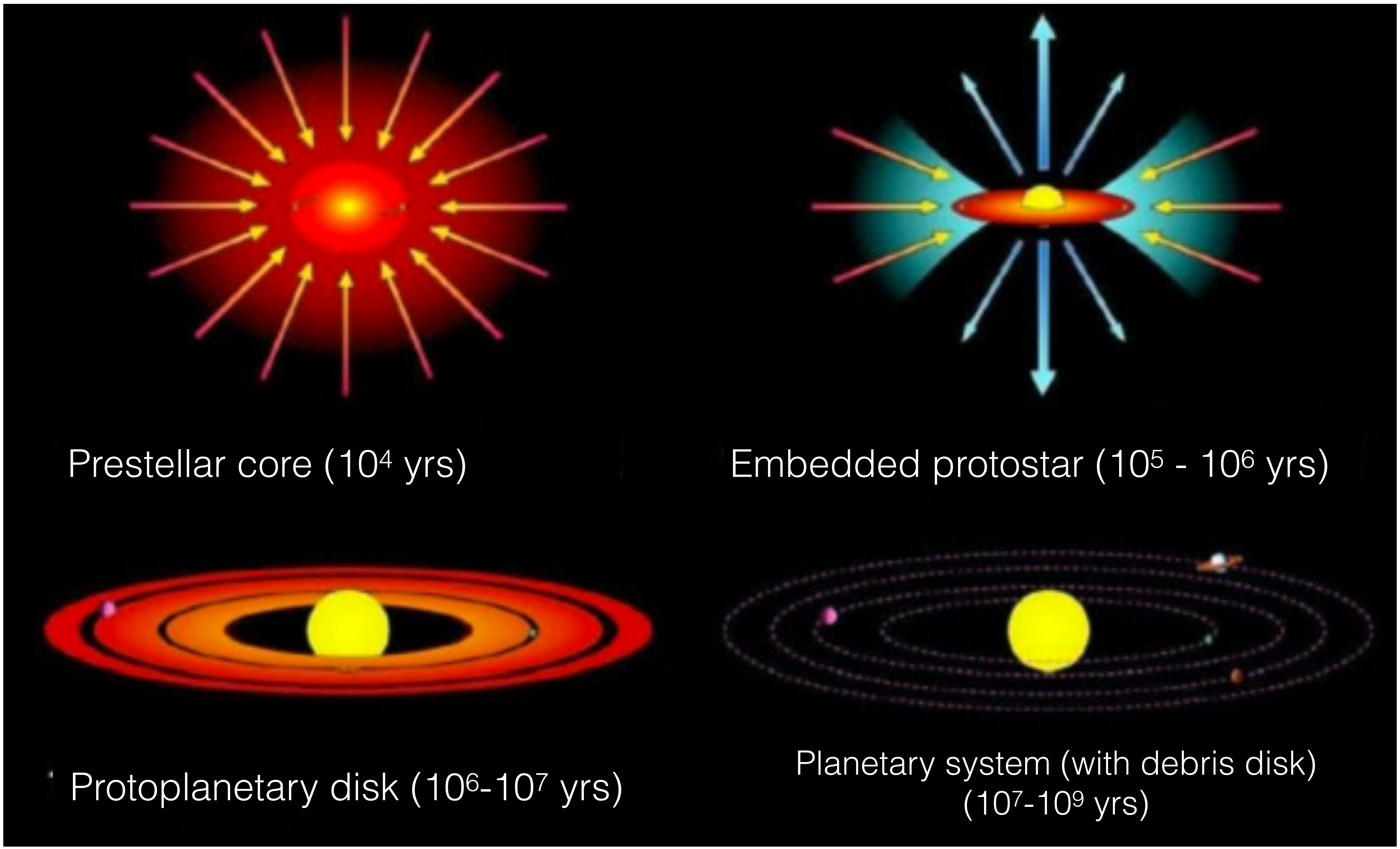
http://exoplanet.eu

Exoplanets



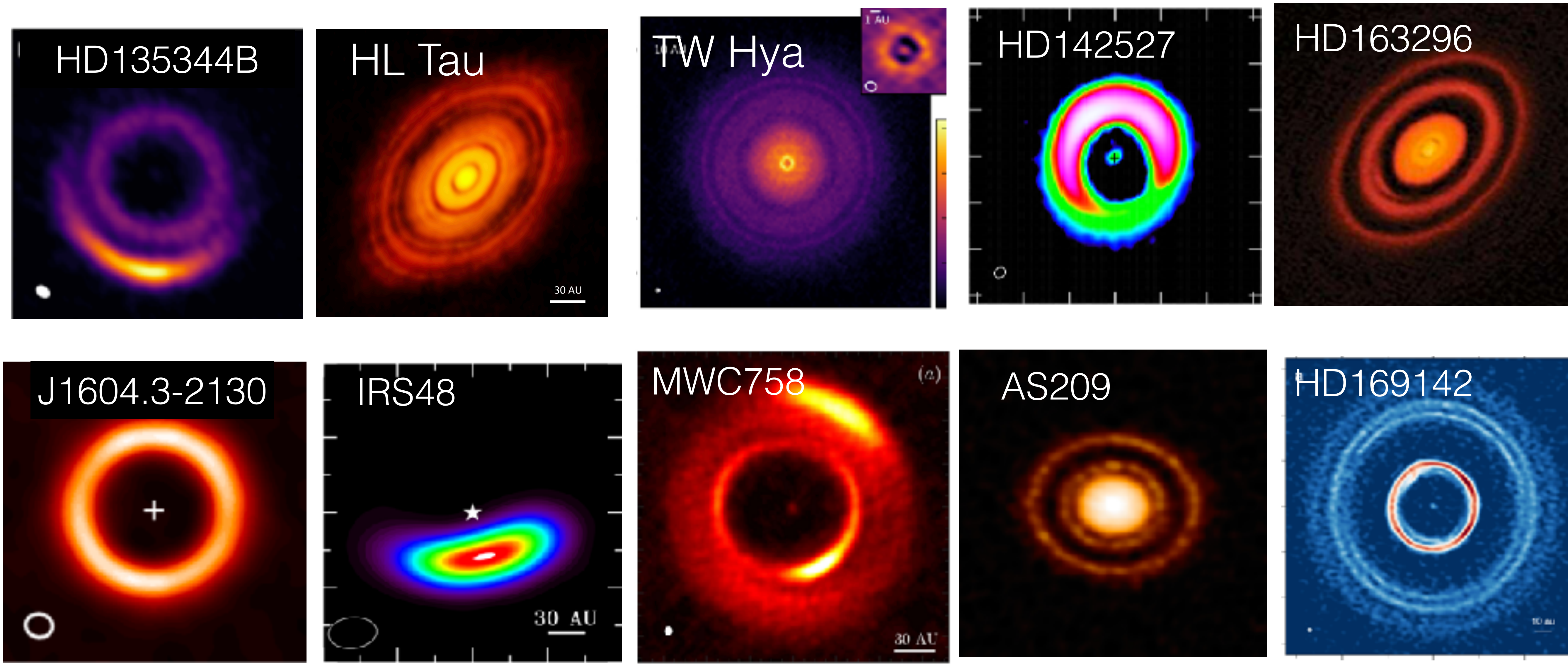
http://exoplanet.eu

Star and planet formation



Credit: Shu

ALMA disk observations



Typical resolution ~0.1"

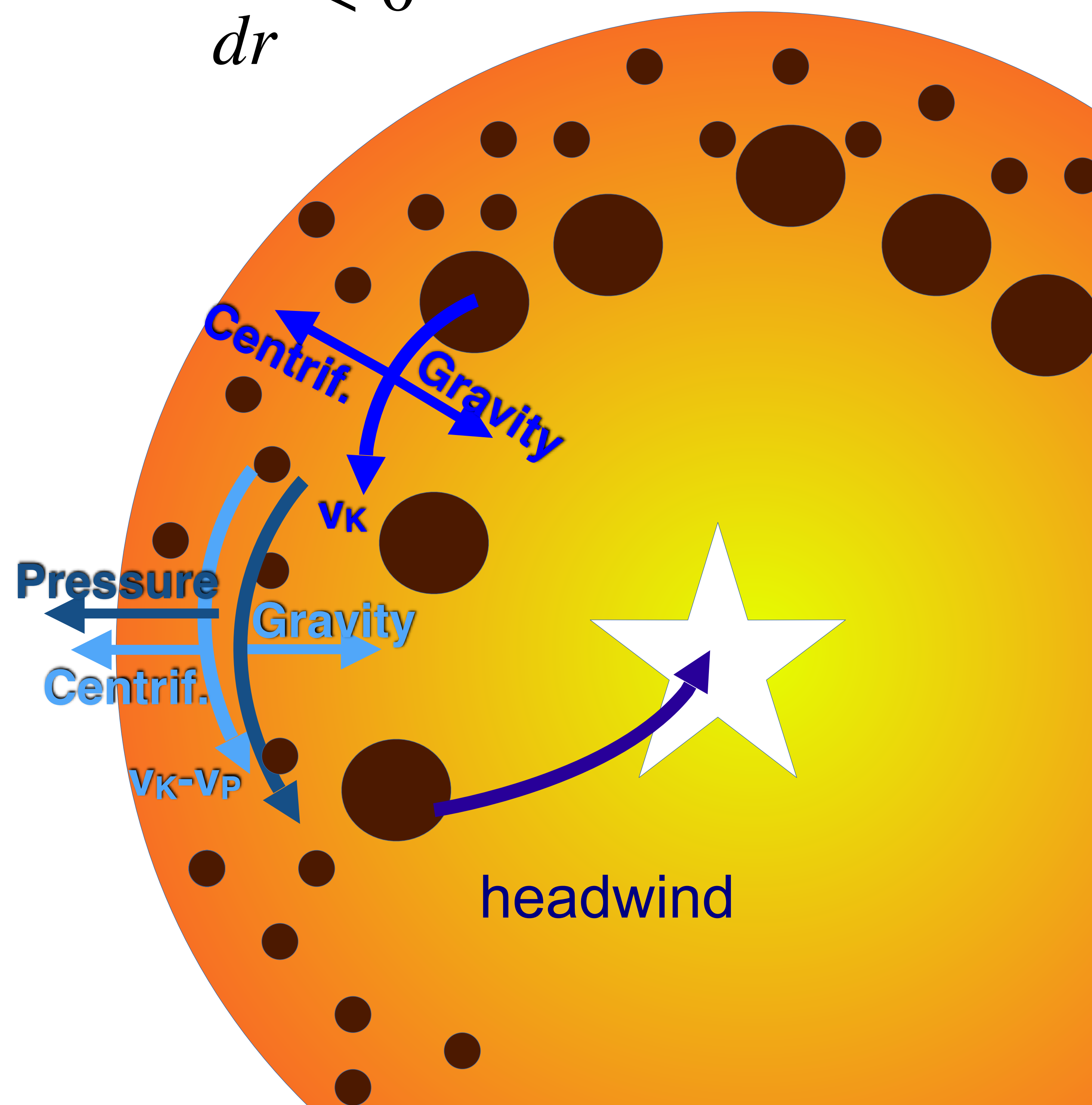
Enormous diversity of large-scale disk structures: origin?

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

Dust evolution

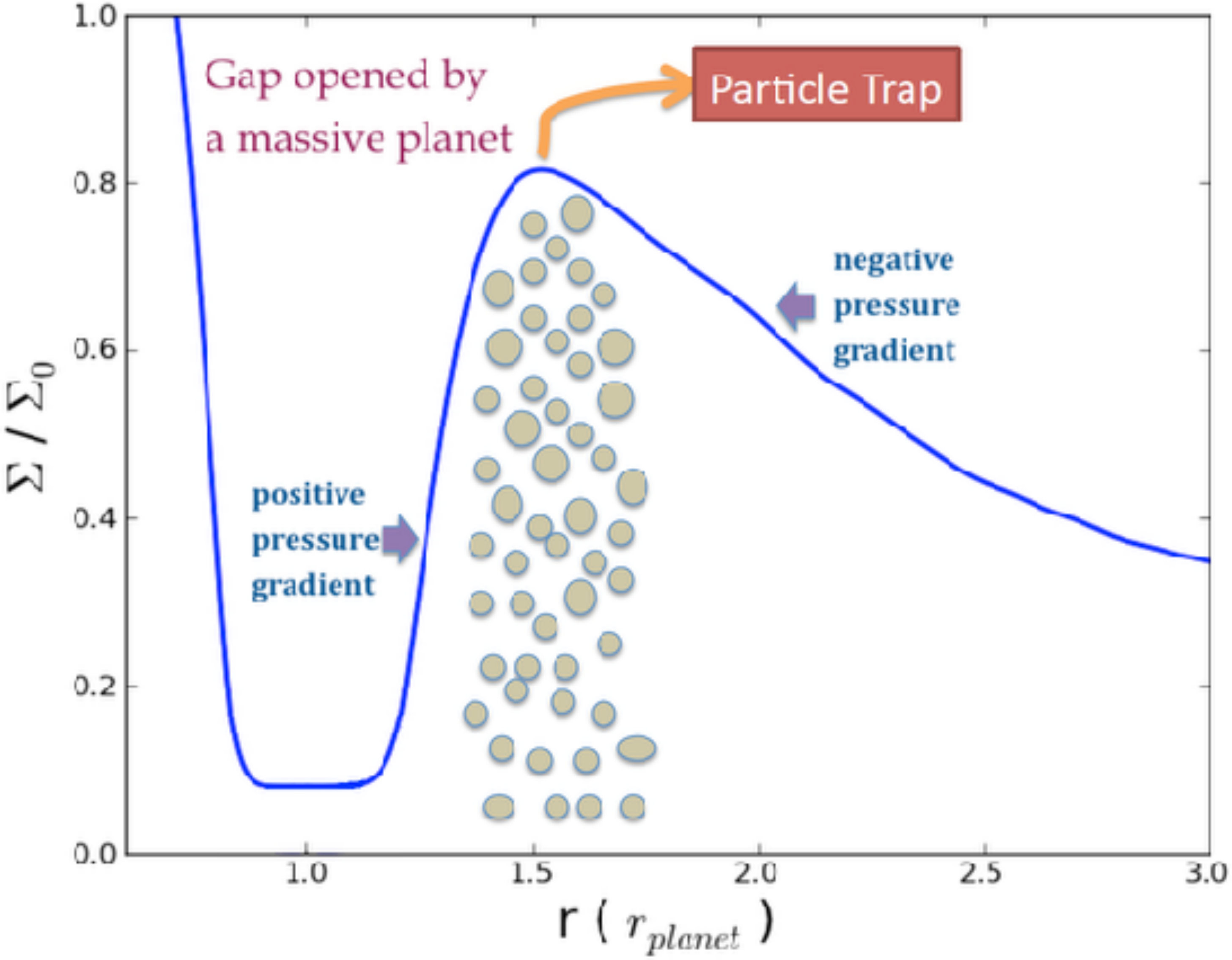
- Gas disk has a pressure gradient $\frac{dp}{dr} < 0$
  - Radial inward drift dust
- Large particles move towards high pressure

=> Need pressure bump to prevent radial drift

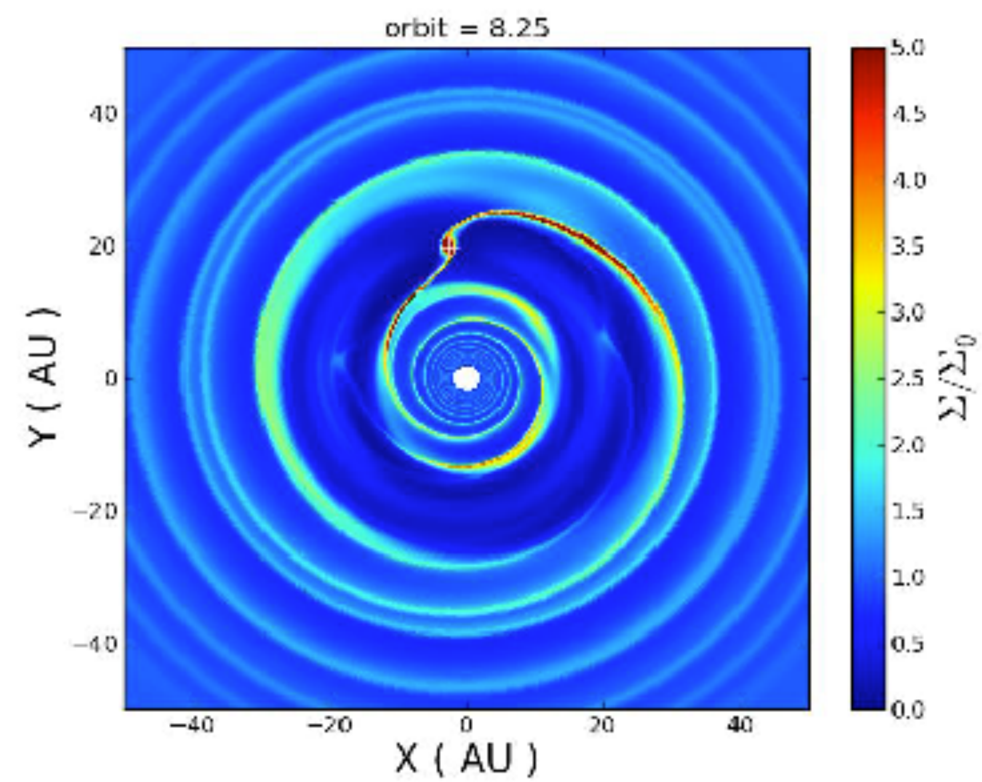


Weidenschilling 1977

Dust trapping



Rossby Wave Instability results in vortex: azimuthal dust trap



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

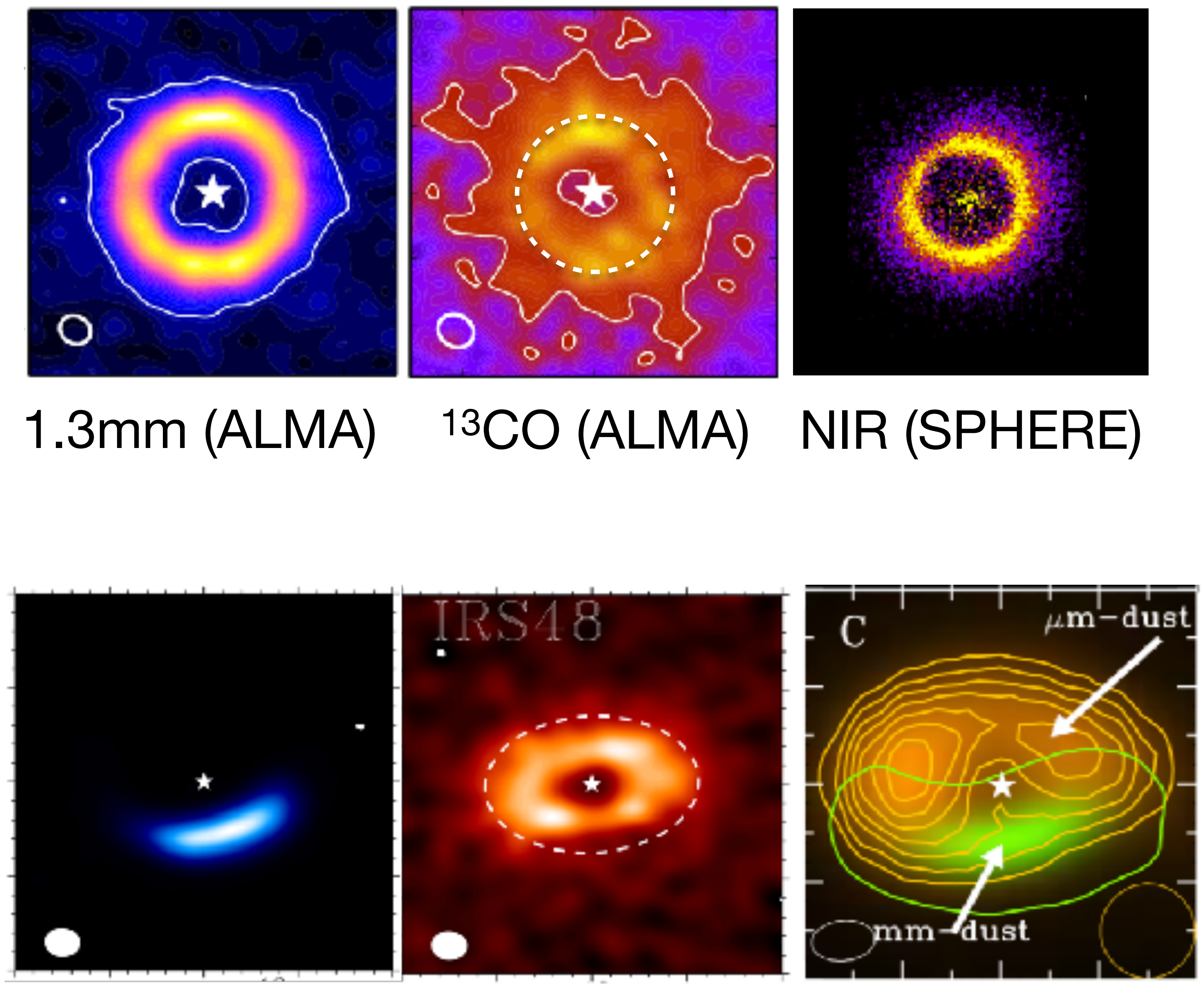
Barge & Sommeria 1995
Klahr & Henning 1997
Birnstiel et al. 2013

Dust trapping

Large trapped dust | **Gas** | **Small dust**

J1604-2130

IRS48



J1604-2130: 1.3mm (ALMA) | ^{13}CO (ALMA) | NIR (SPHERE)

IRS48: 0.5mm (ALMA) | ^{13}CO (ALMA) | MIR (VISIR)

Radial trapping

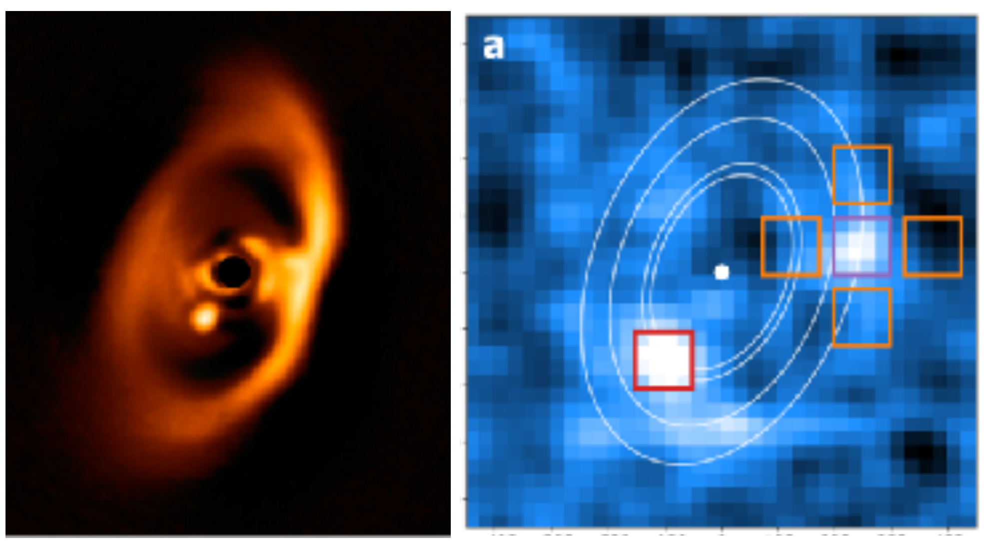
Segregation of mm-dust and gas/small grains shows trapping!

Azimuthal trapping

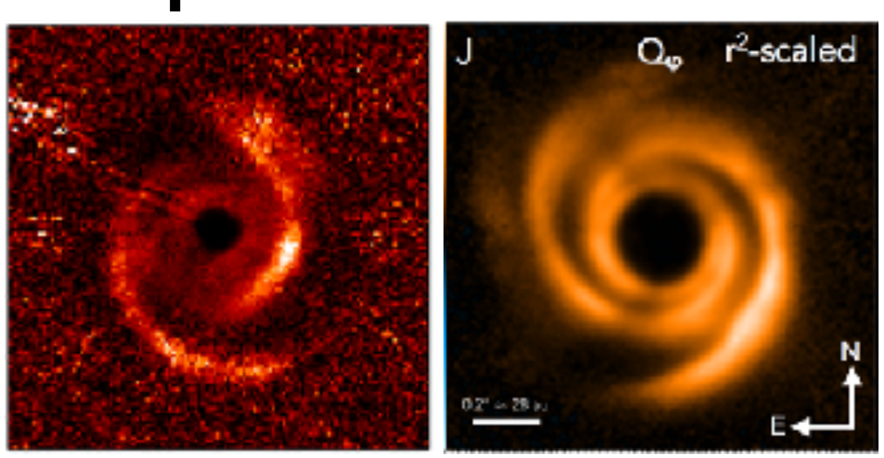
Pinilla et al. 2016
Van der Marel et al. 2013, 2016a
Dong, van der Marel, et al. 2017

Signatures of protoplanets in gaps

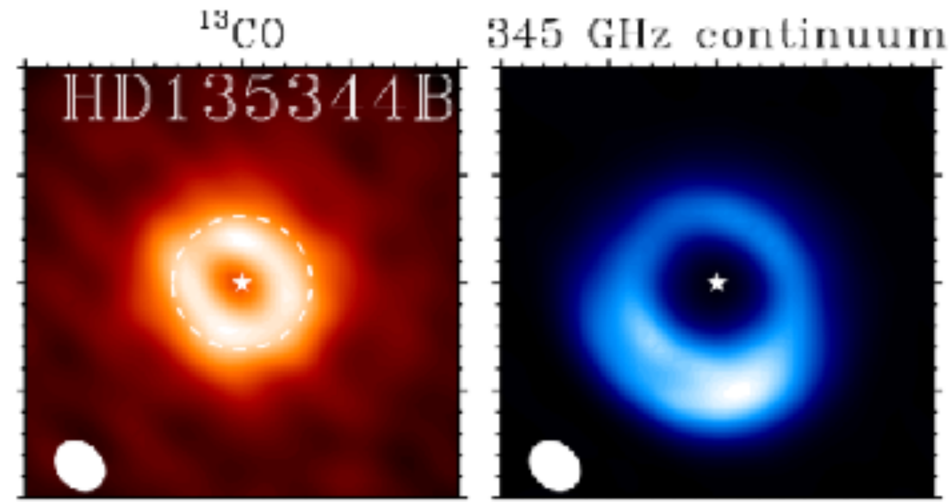
High contrast imaging: PDS70



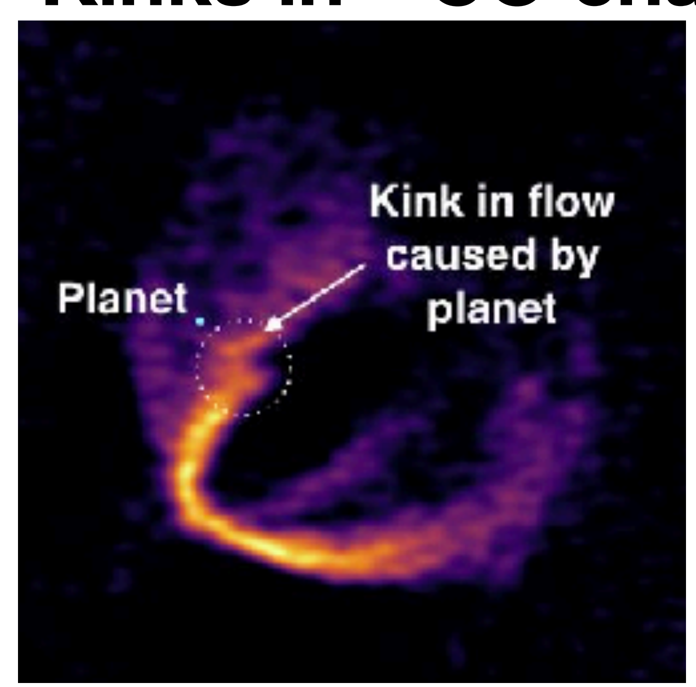
Spiral arms in NIR



Deep gas gaps in ^{13}CO



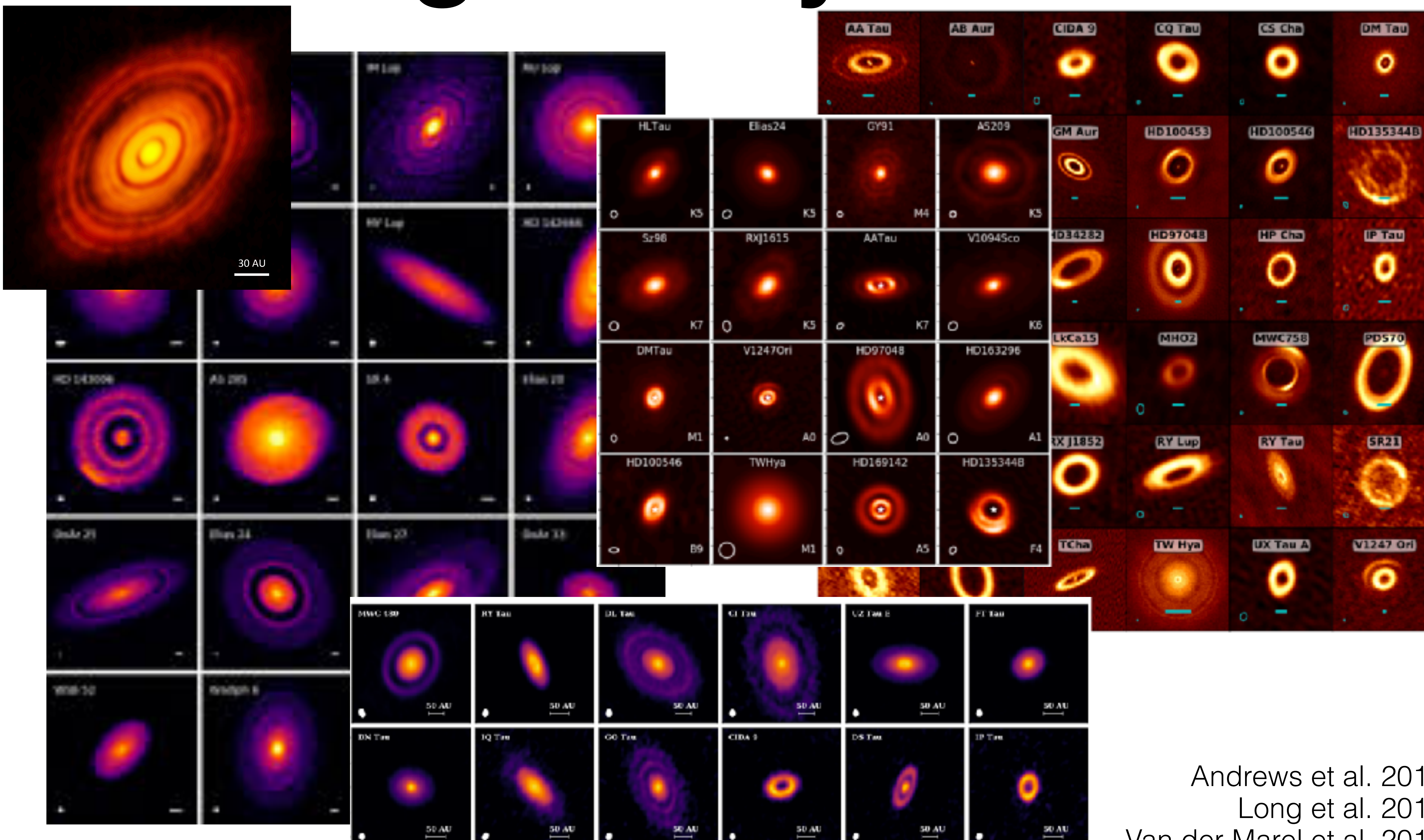
Kinks in ^{12}CO channel maps



Van der Marel et al. 2016,2021
Keppler et al. 2018
Haffert et al. 2019
Stolker et al. 2016
Benisty et al. 2017
Pinte et al. 2018

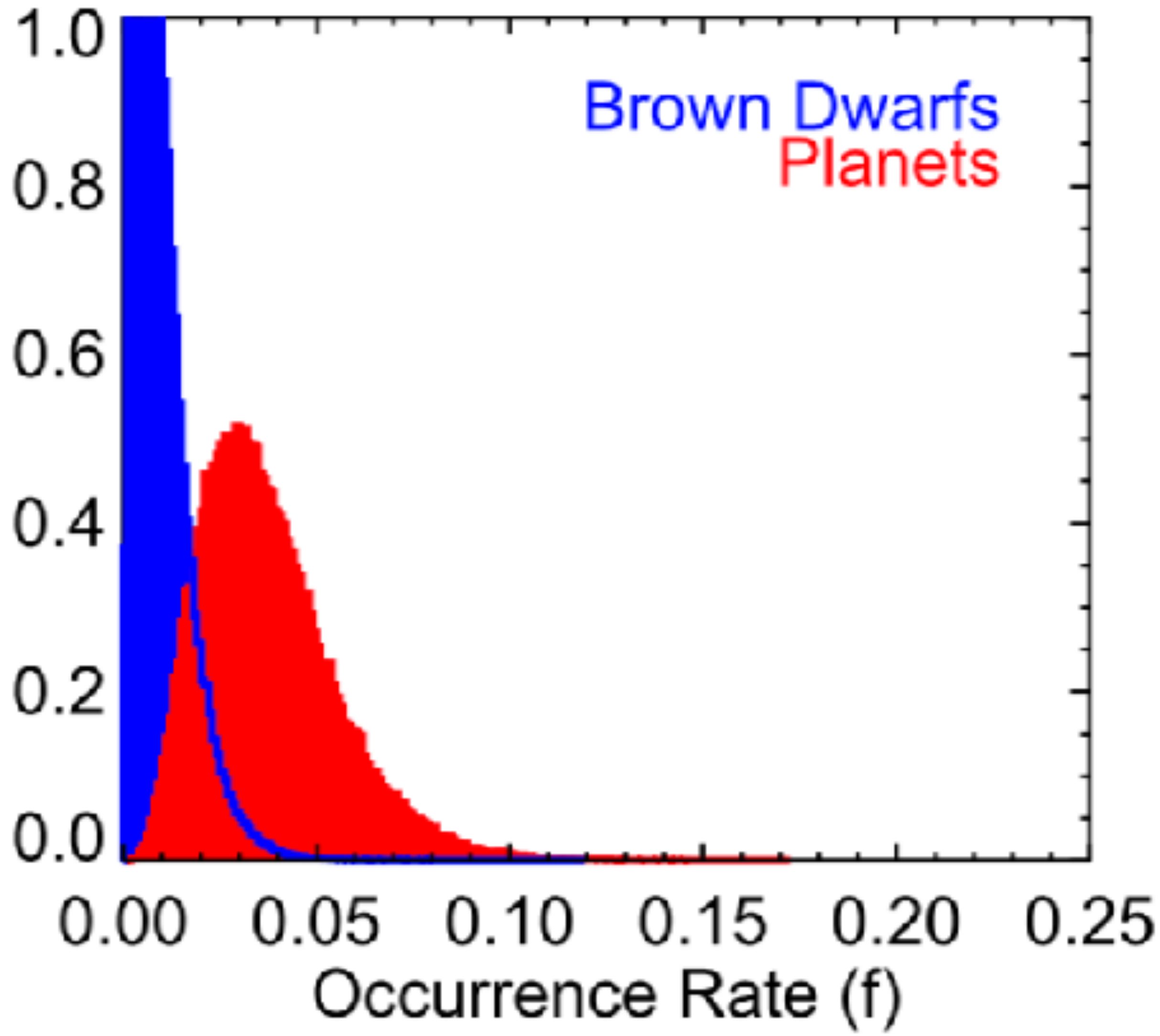
Mostly indirect: detection protoplanets is hard!

Rings everywhere!



Andrews et al. 2018
Long et al. 2018
Van der Marel et al. 2019
Francis & van der Marel 2020

Are all gaps caused by planets?



GPIES: Jovian planets (on wide orbits) are rare, only few %!

Nielsen et al. 2019 (GPIES)

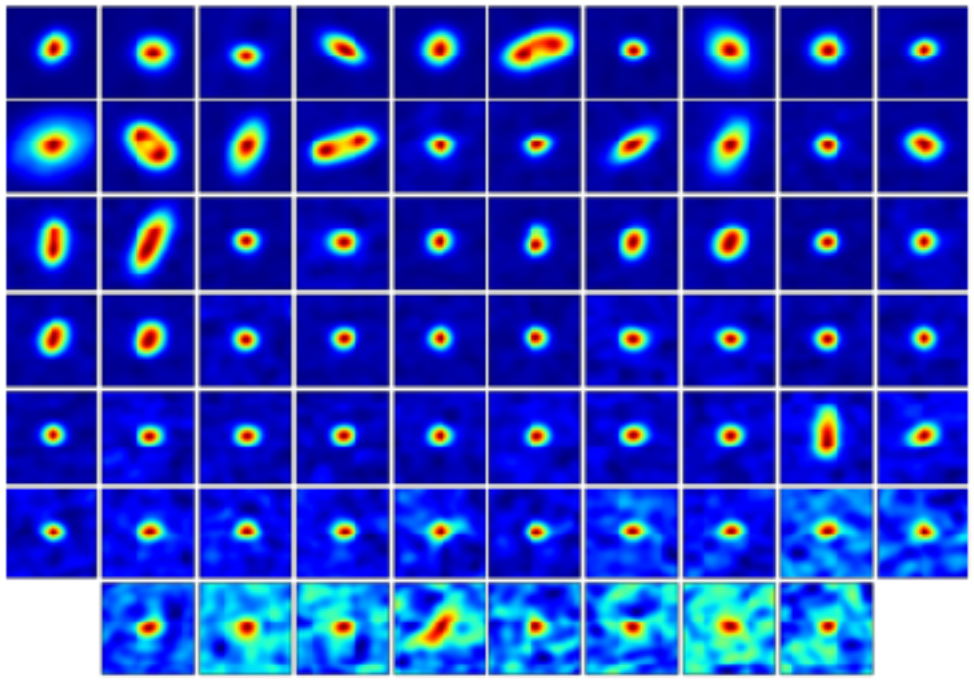
Problem: strong bias towards the brightest disks in high-res observations!

What is the bigger picture?

Lupus ALMA Disks Survey

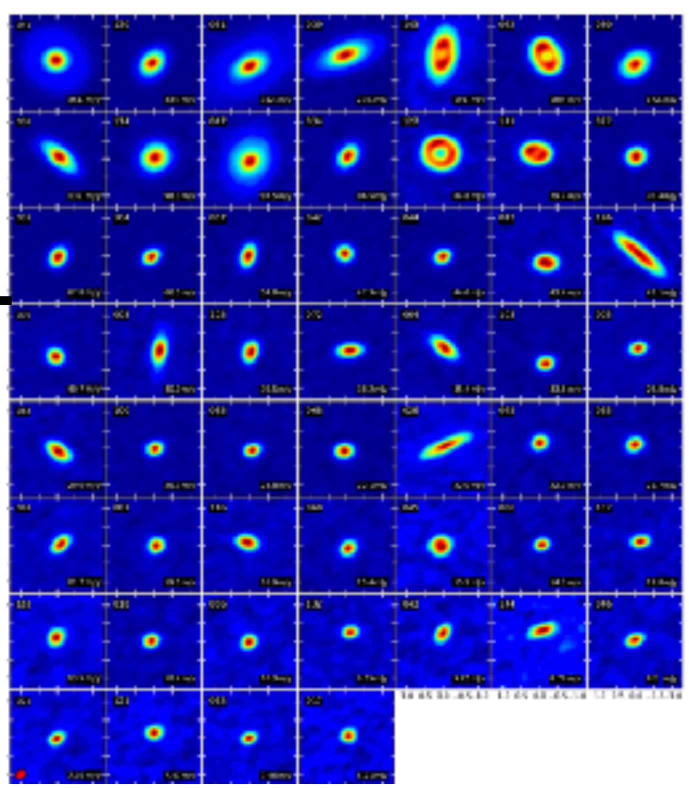
Large disk surveys

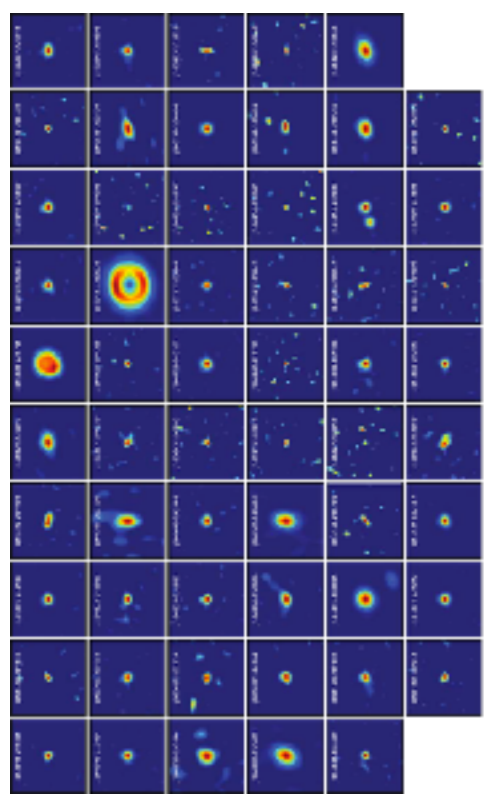
Lupus



- 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

Ophiuchus



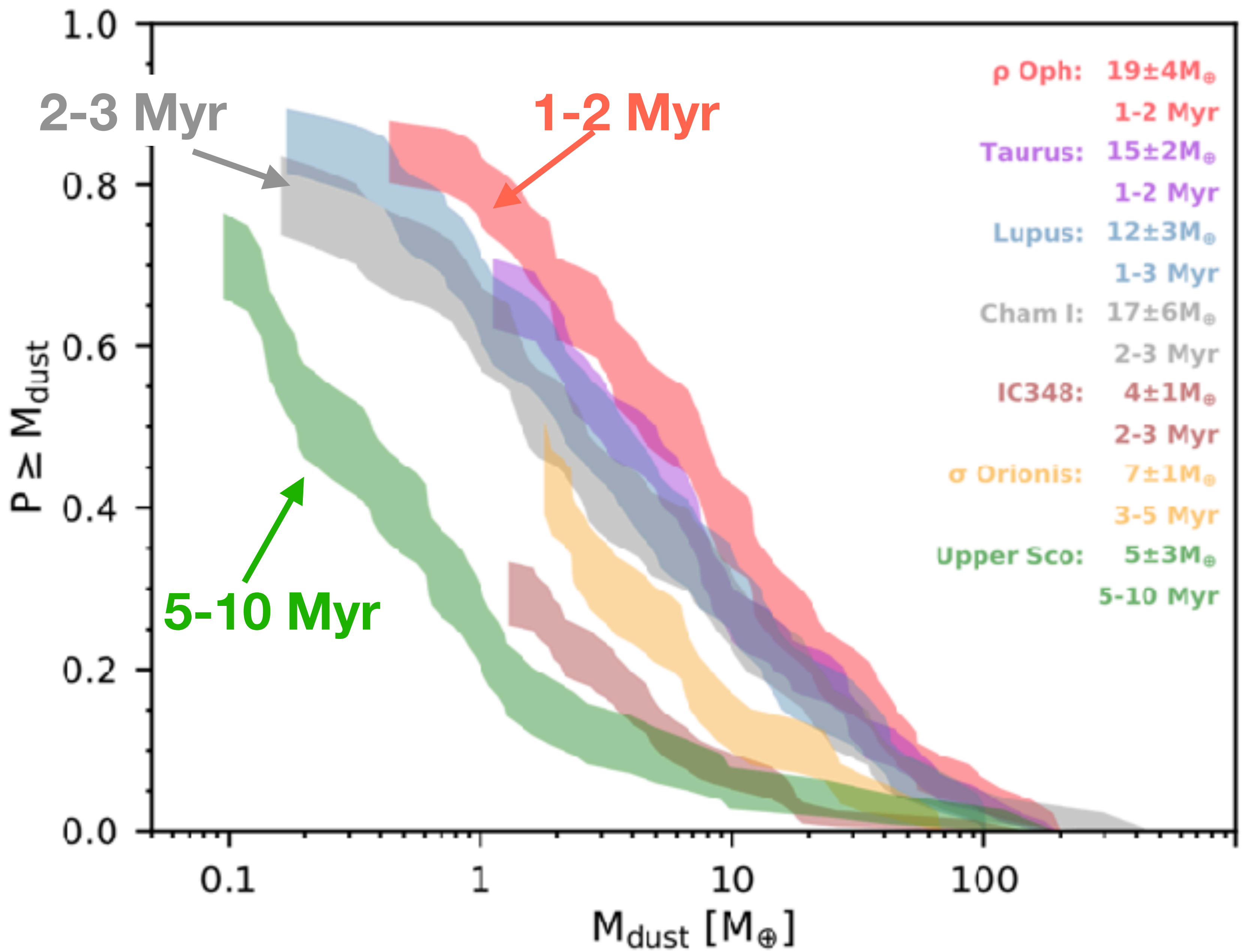


Upper Sco

=> Statistics of disk dust mass and evolution!

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

Disk evolution

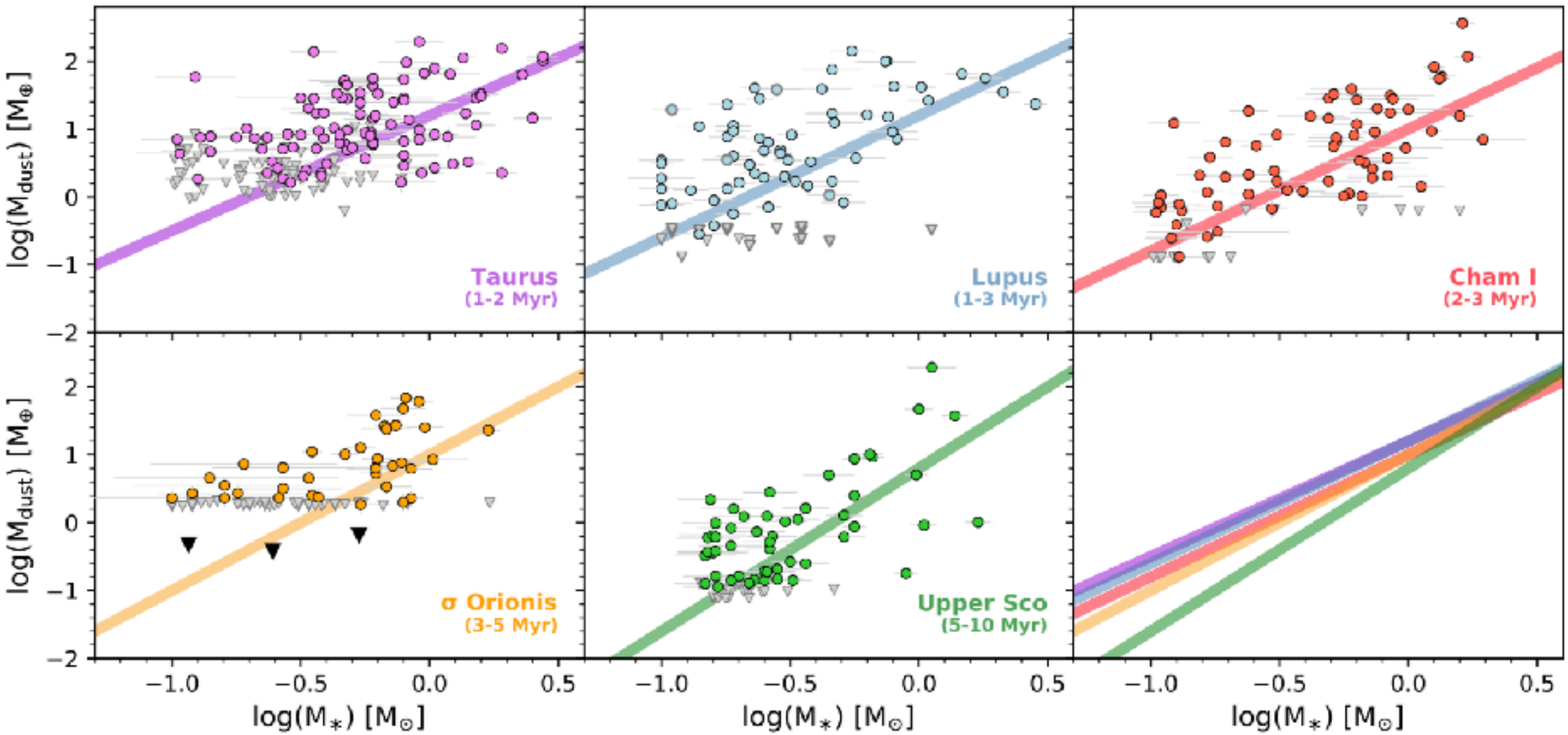


$$M_{\rm dust} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\rm dust})}$$

Disk dust mass decreases with age

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

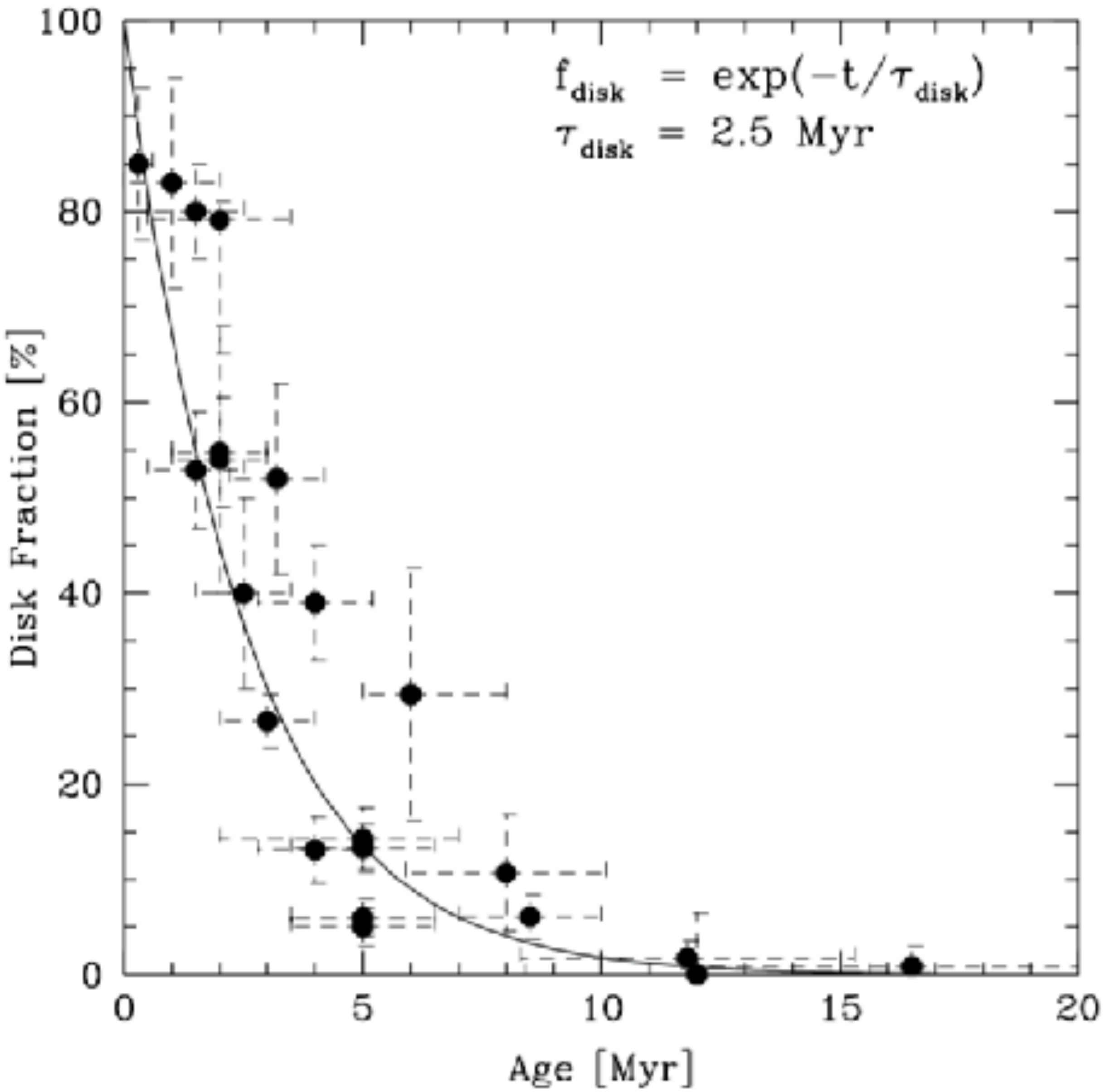
Disk evolution

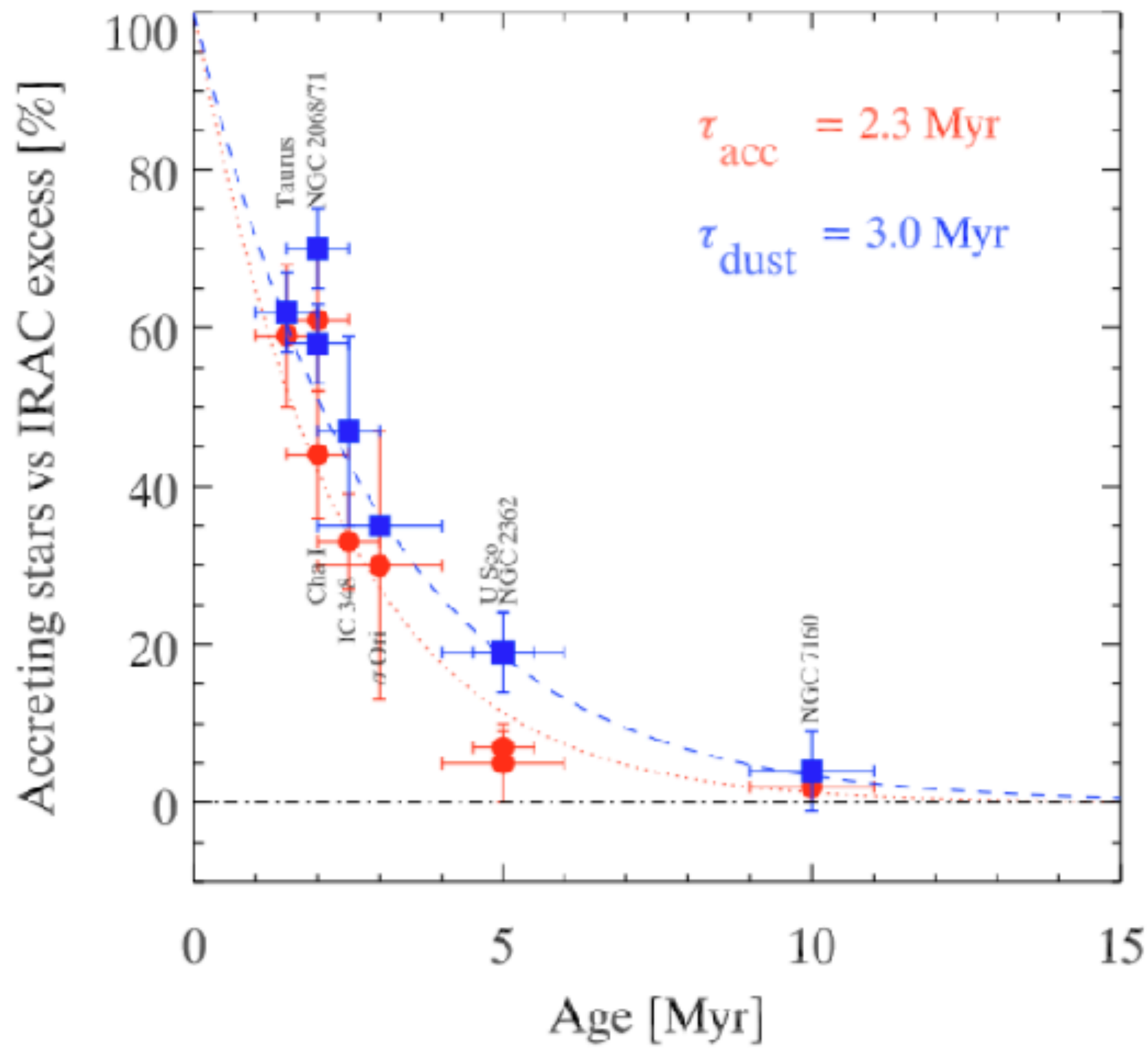


Disk dust mass scales with stellar mass
and decrease with age is stronger for low-mass

Ansdell et al. 2016, 2017

Disk evolution

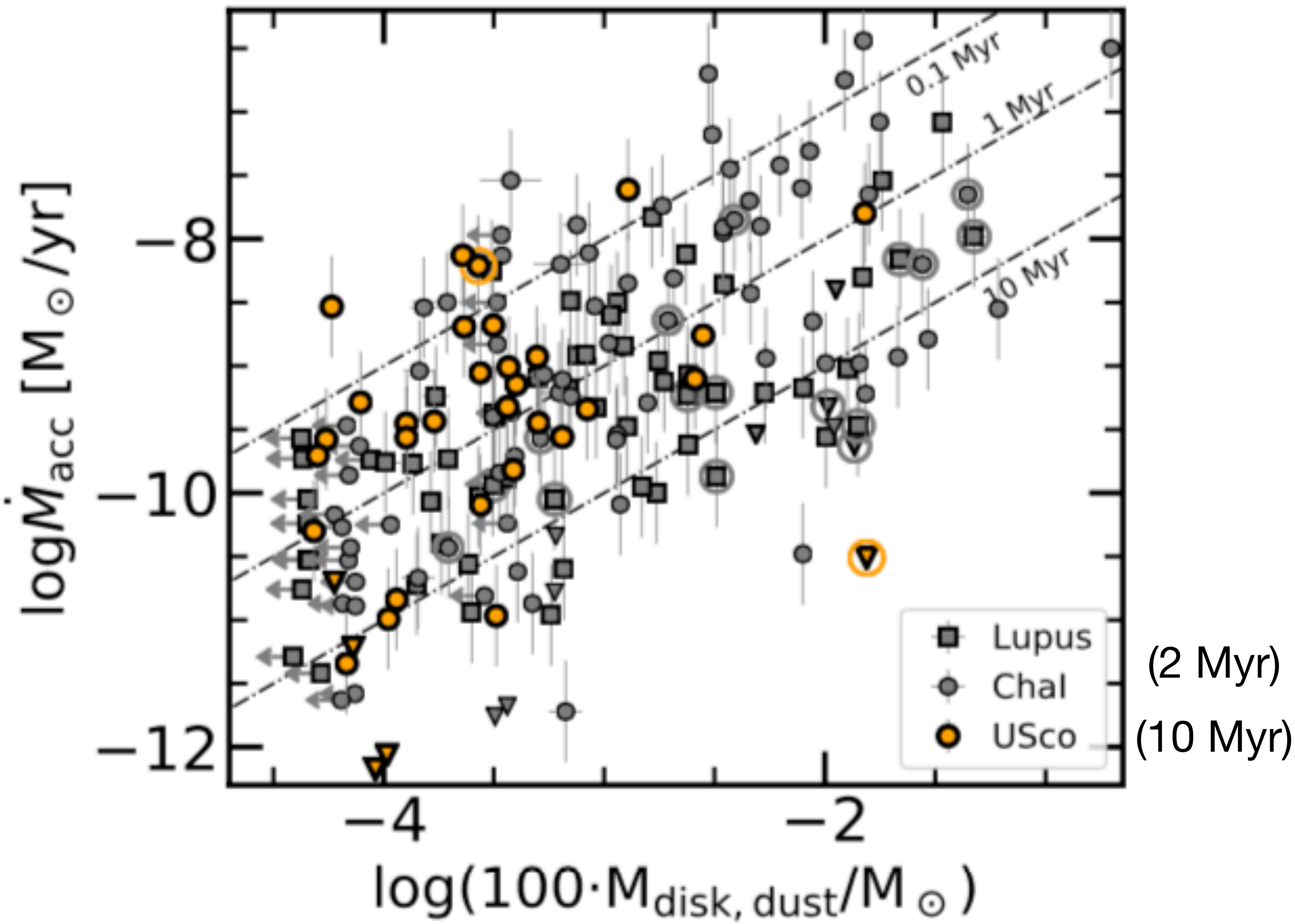




Infrared/accretion disk lifetime ~ 2-3 Myr

Mamajek 2009
Fedele et al. 2010

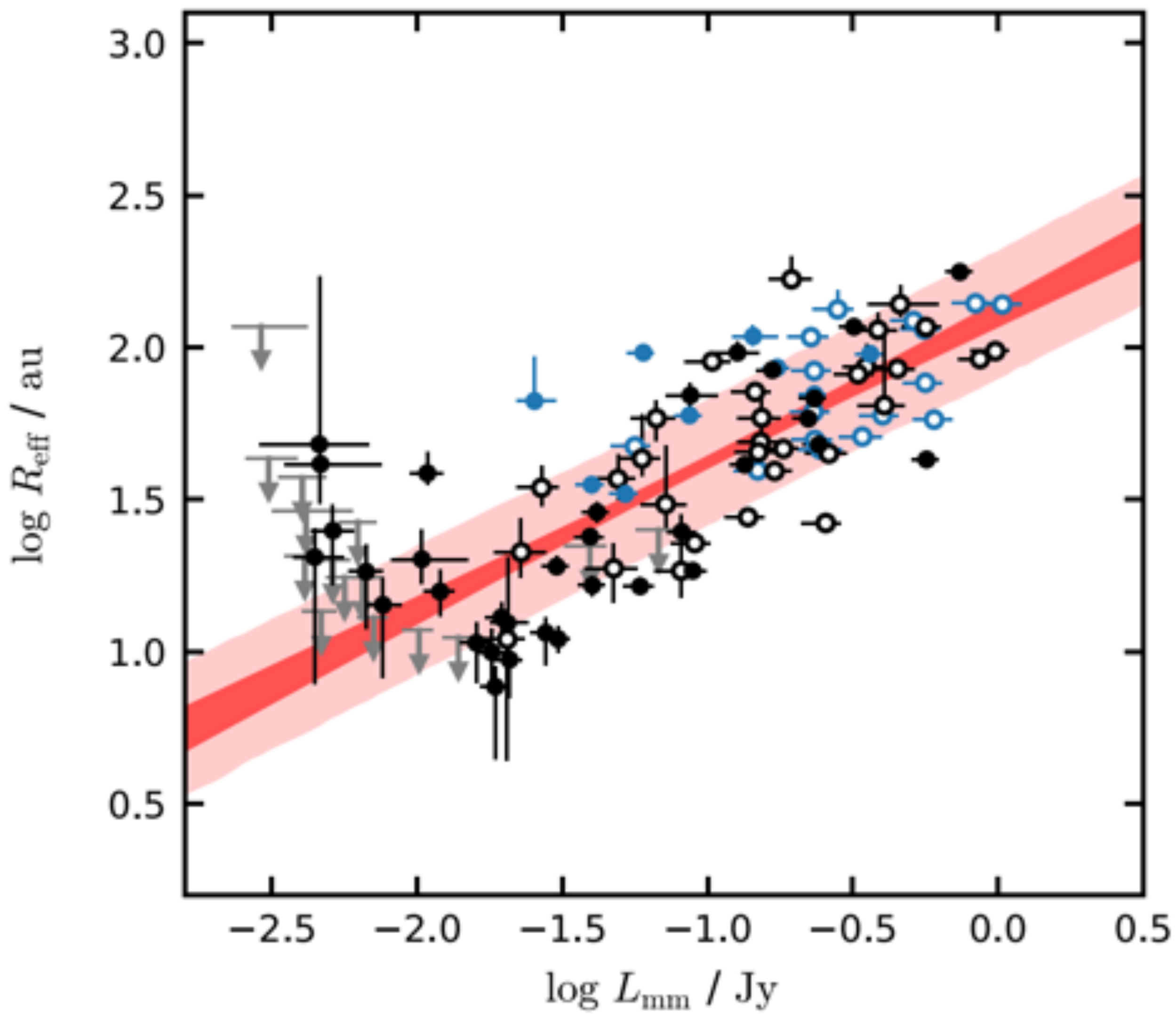
Disk evolution



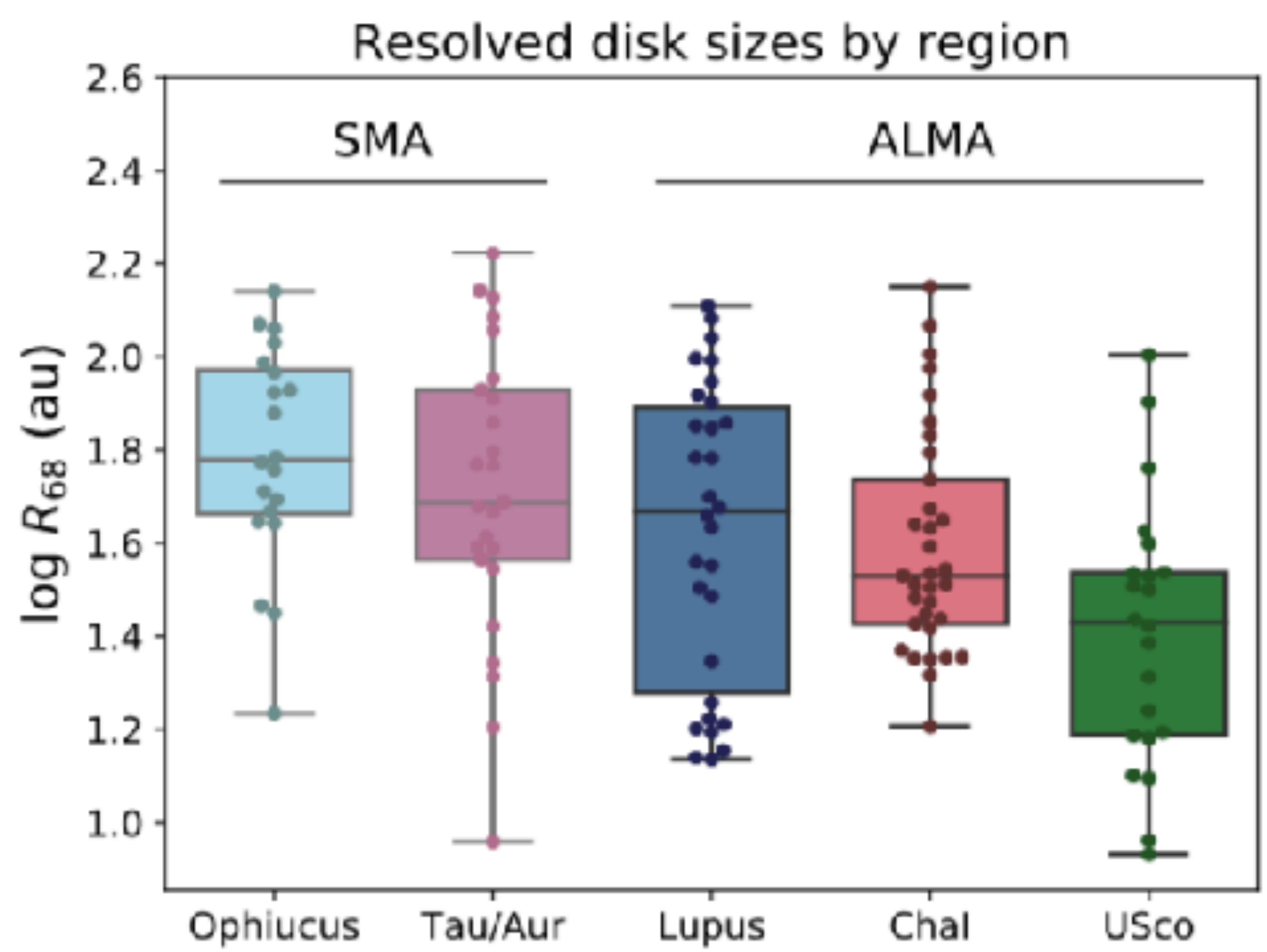
Large scatter in M_{acc}-M_{dust}: not tracing the same process?

Mulders et al. 2017
Manara et al. 2020

Disk evolution: dust size



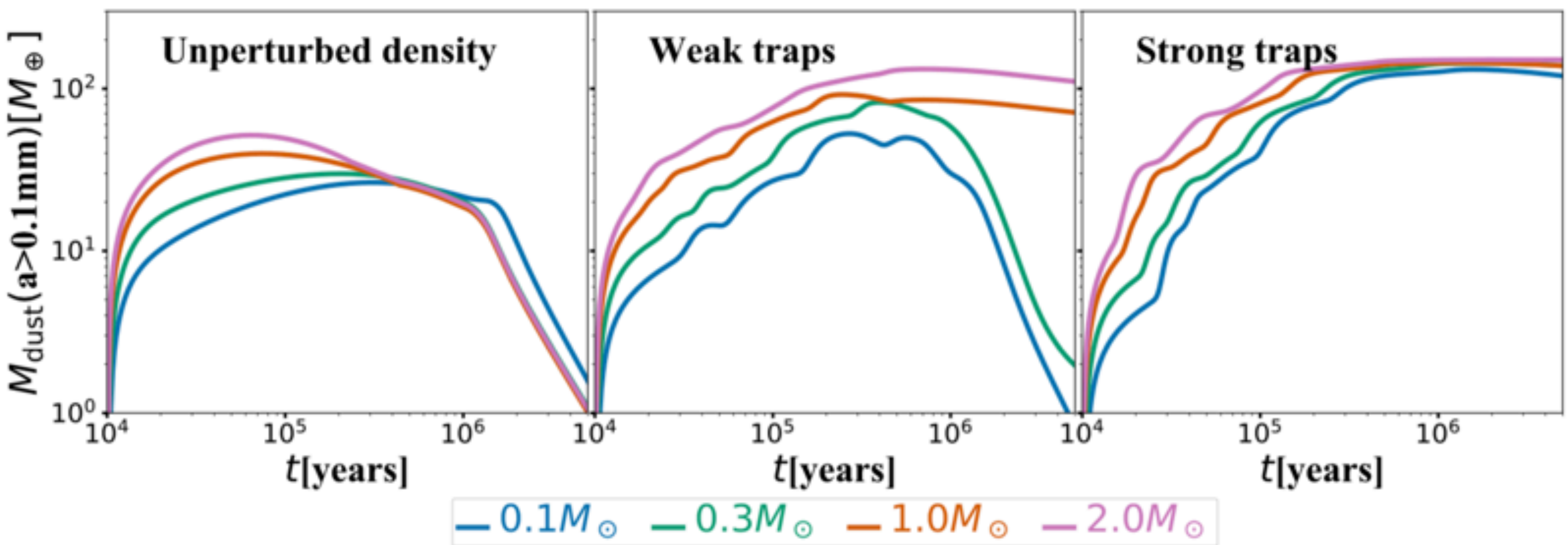
(=M_{dust})



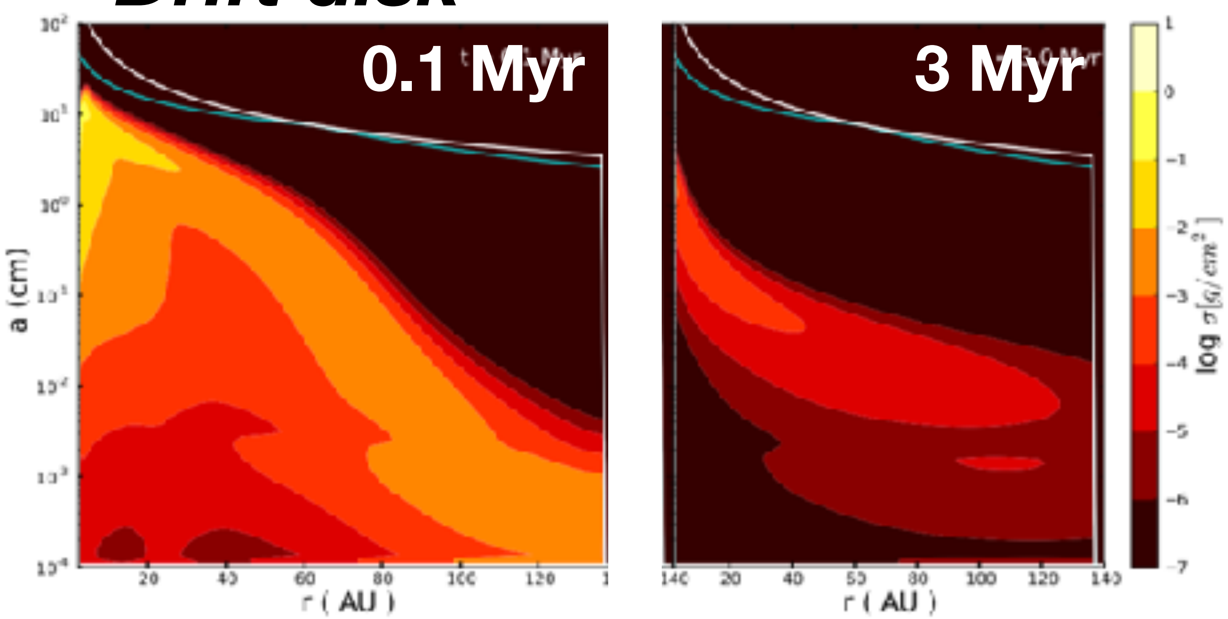
Disk dust size scales with dust mass and decreases with time: radial drift?

Hendler et al. 2020
Andrews et al. 2018

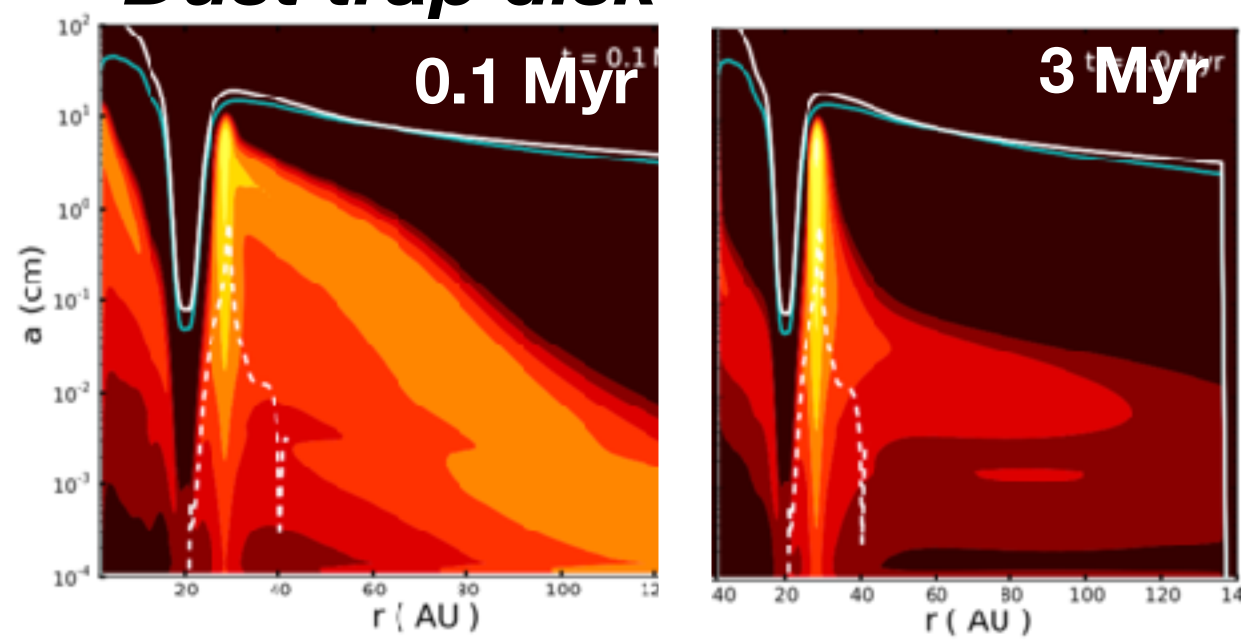
Dust evolution: 2 options



Drift disk



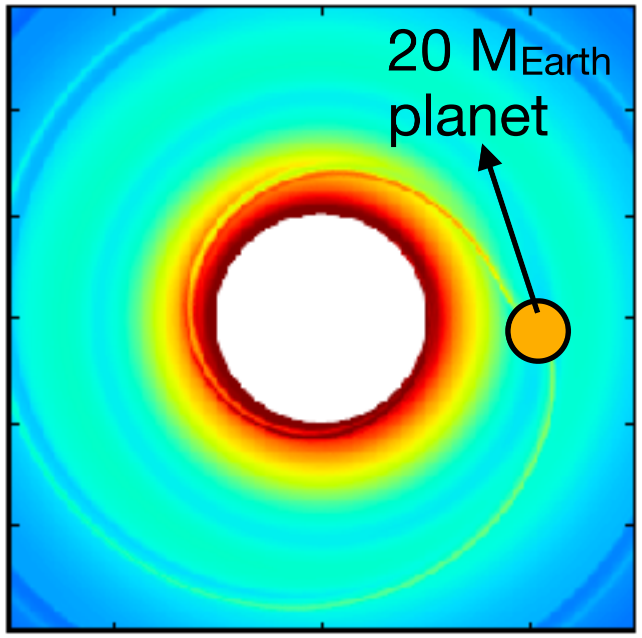
Dust trap disk



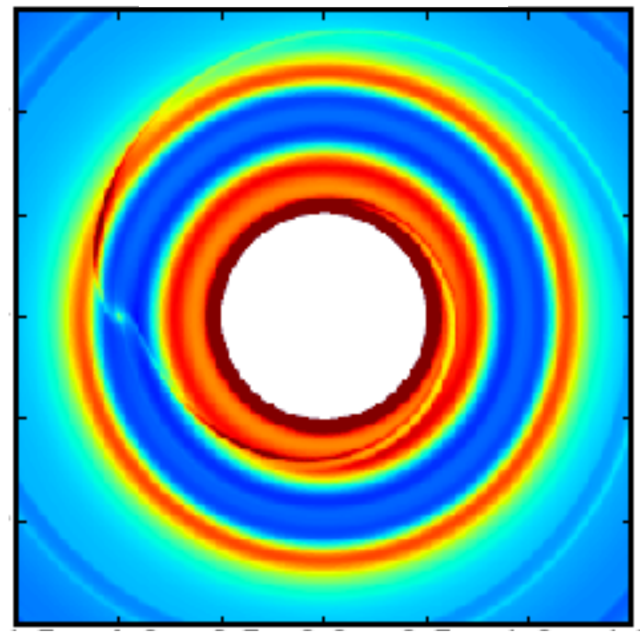
Pinilla et al. 2012, 2020

Dust traps

Gas

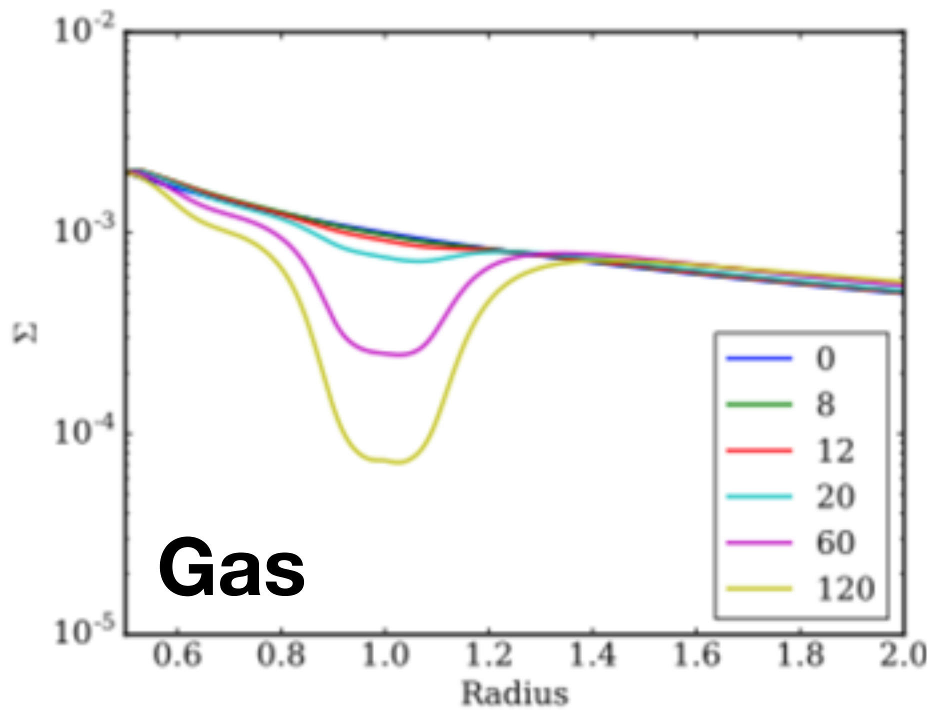


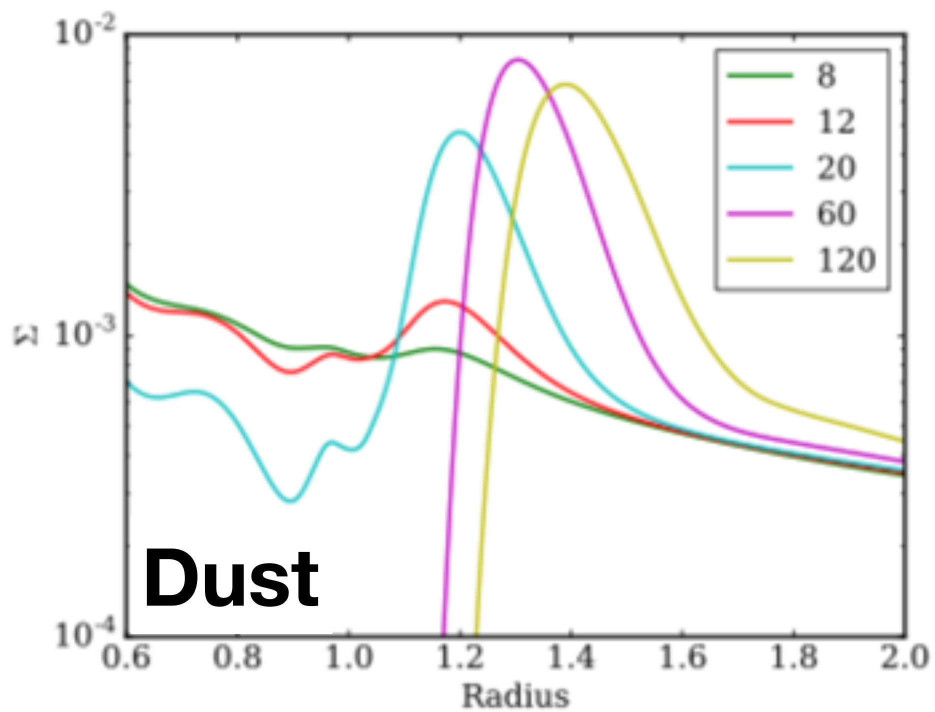
mm-dust



Minimum planet mass to create a dust trap is ~ 15-20 ME

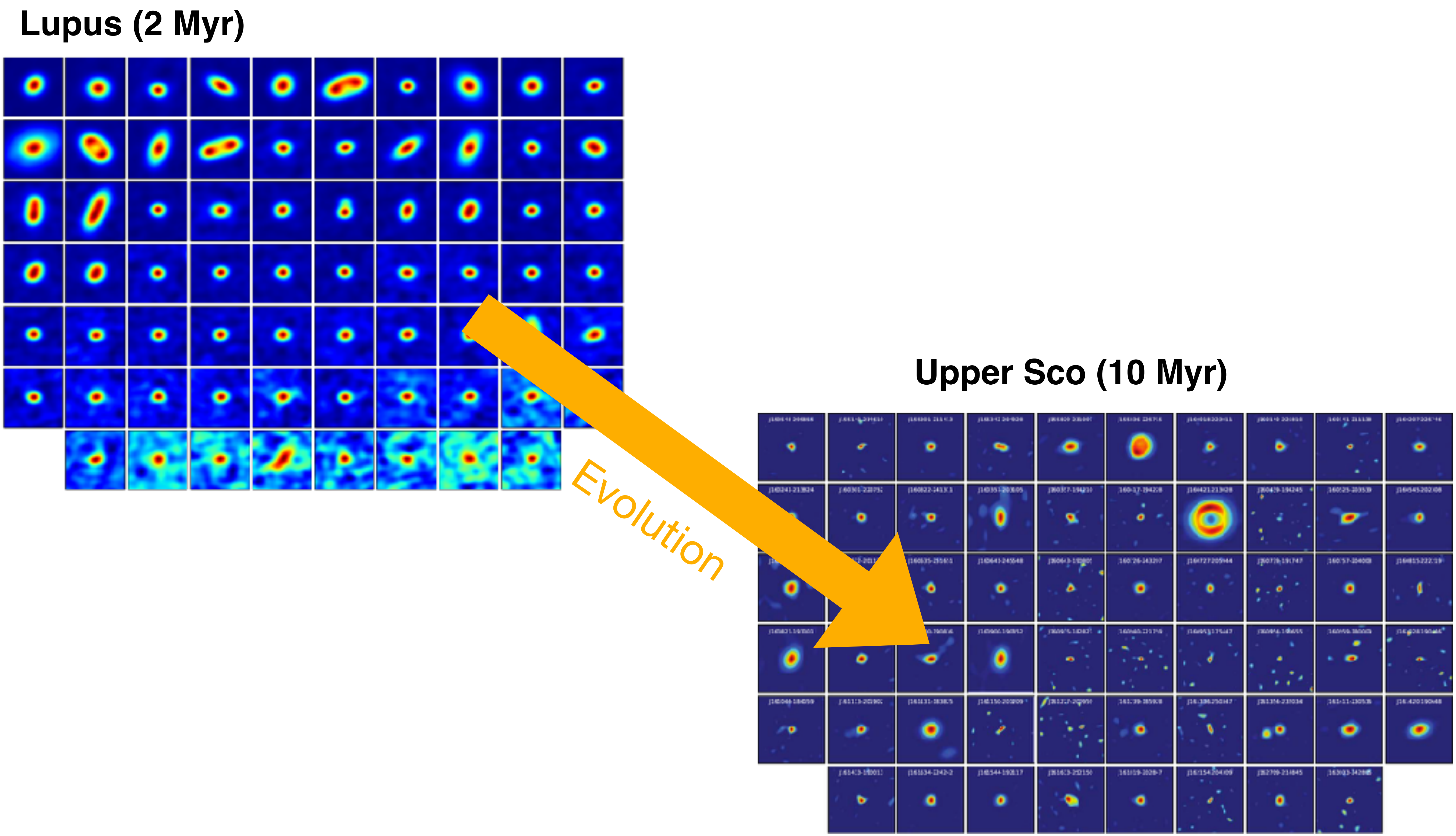
Gap depth different planet masses (in MEarth)





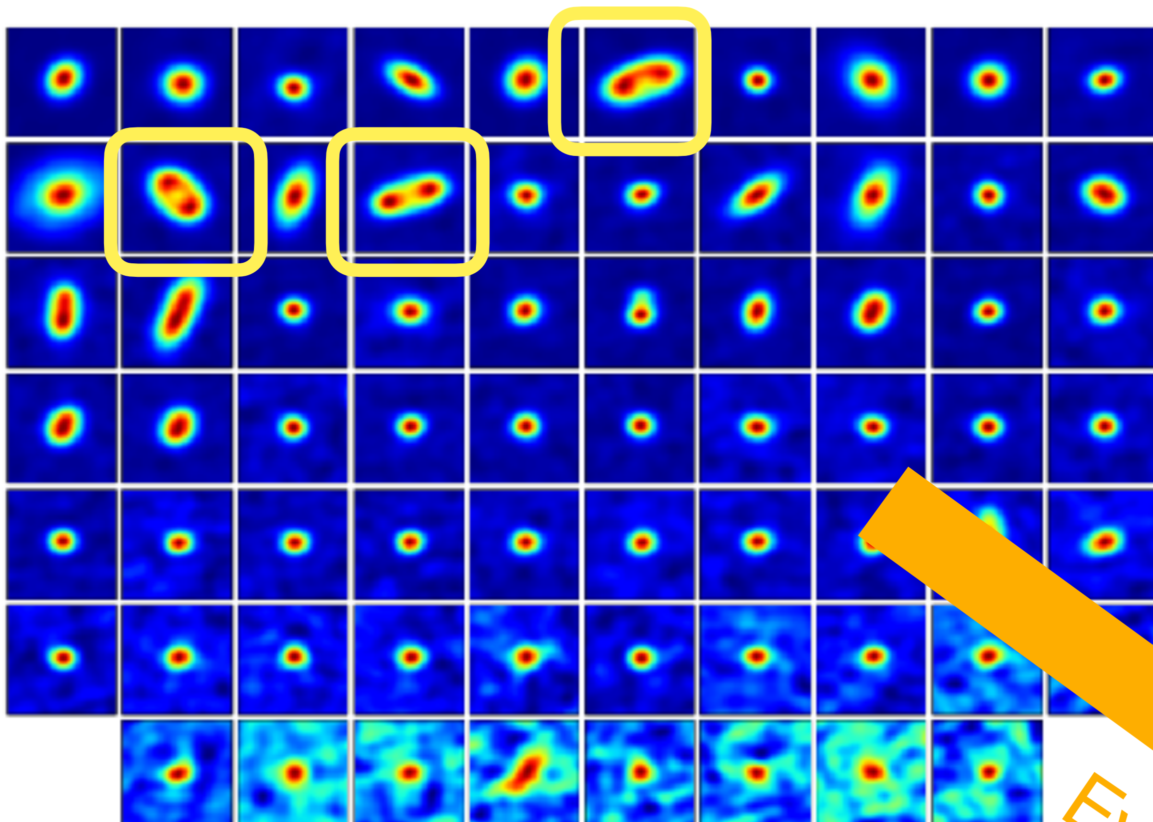
Rosotti et al. 2016
Sinclair et al. 2020

Large disk surveys



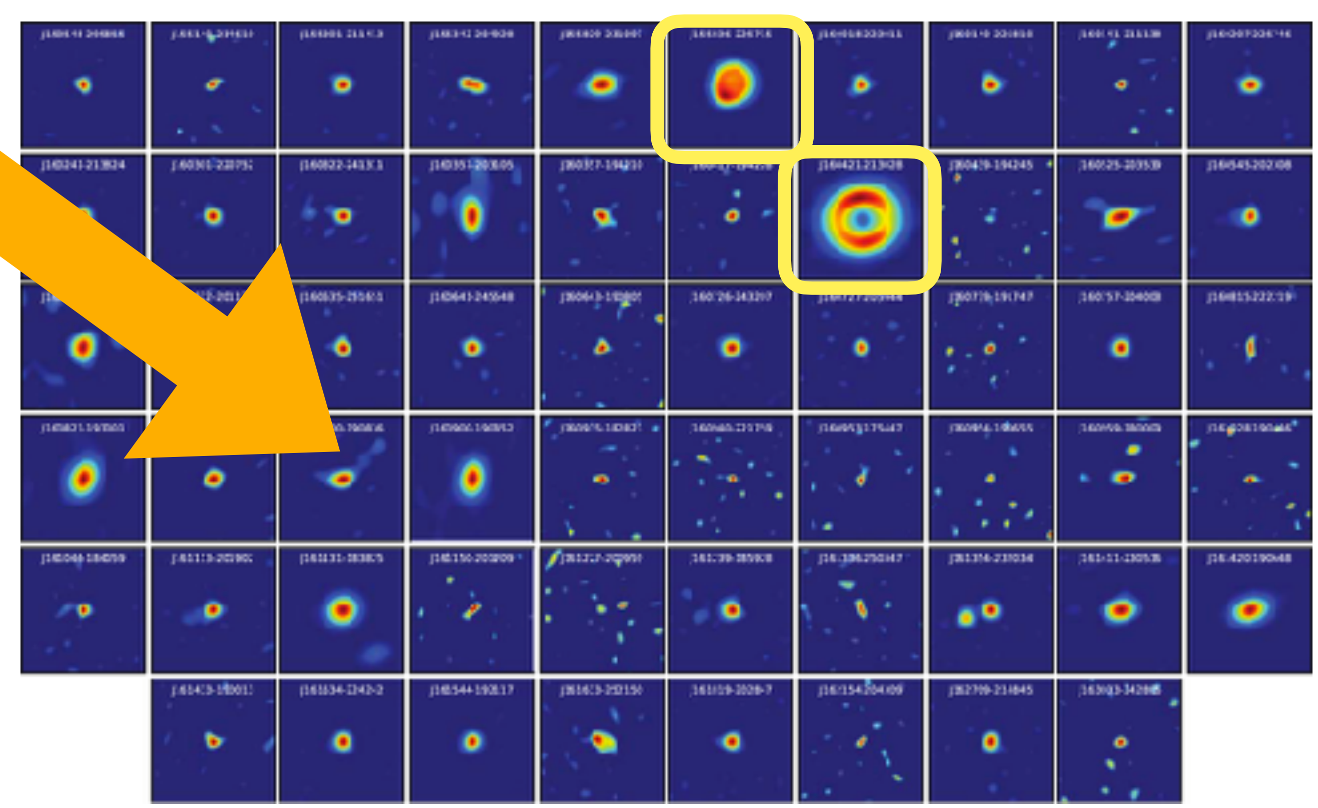
Large disk surveys

Lupus (2 Myr)



Evolution

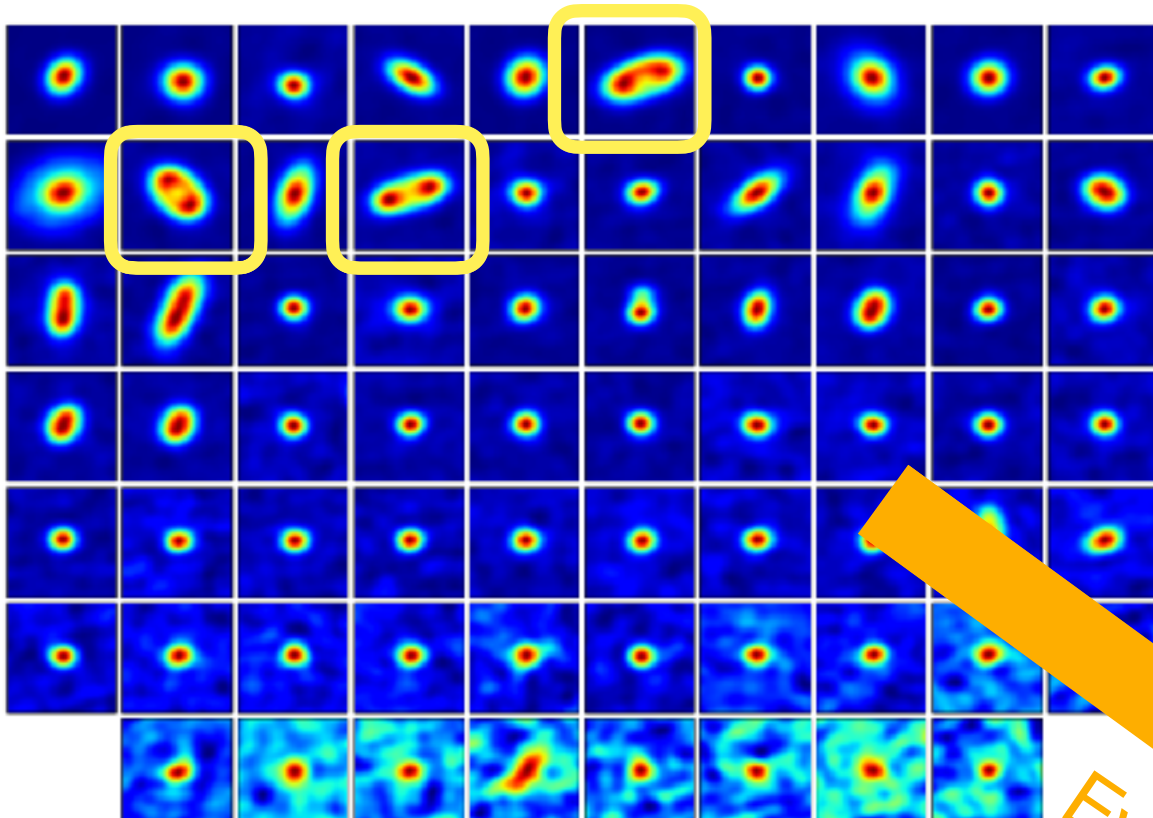
Upper Sco (10 Myr)

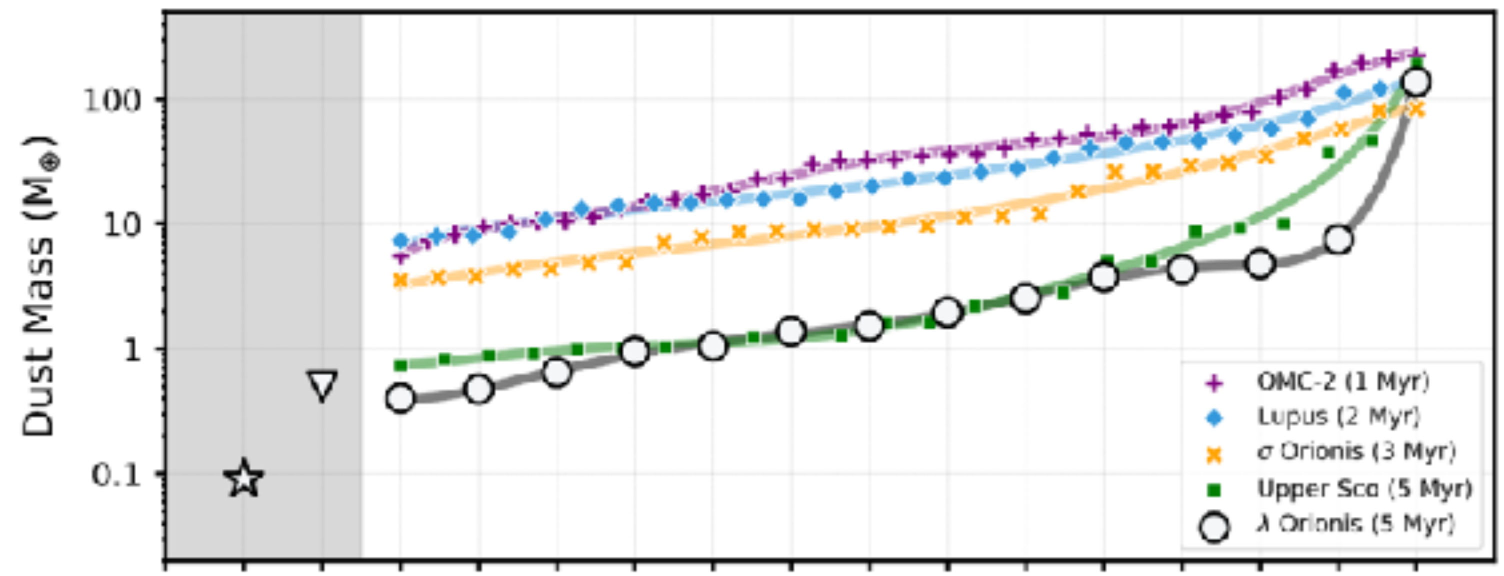


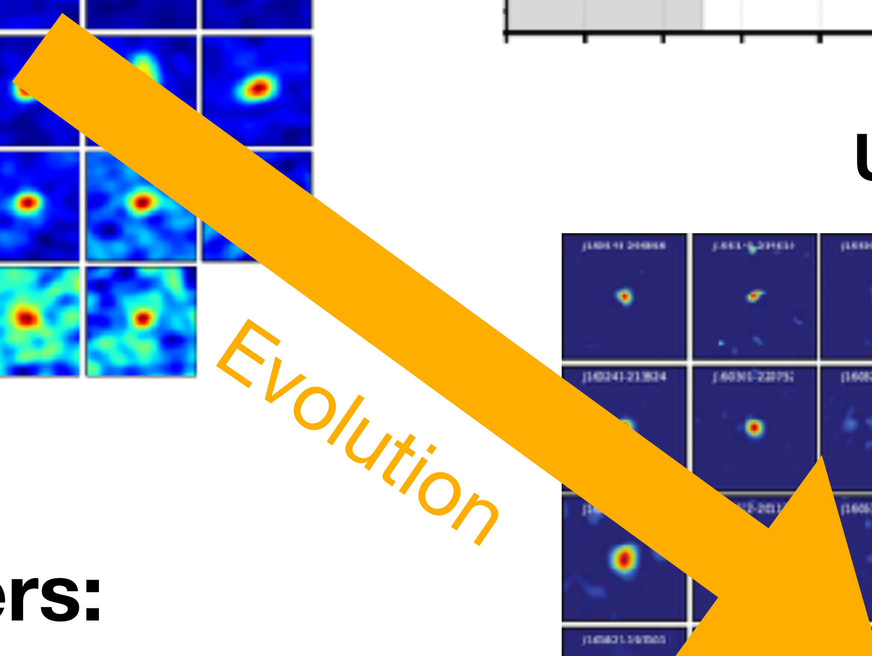
Massive outliers:
gapped disks
=> no drift

Large disk surveys

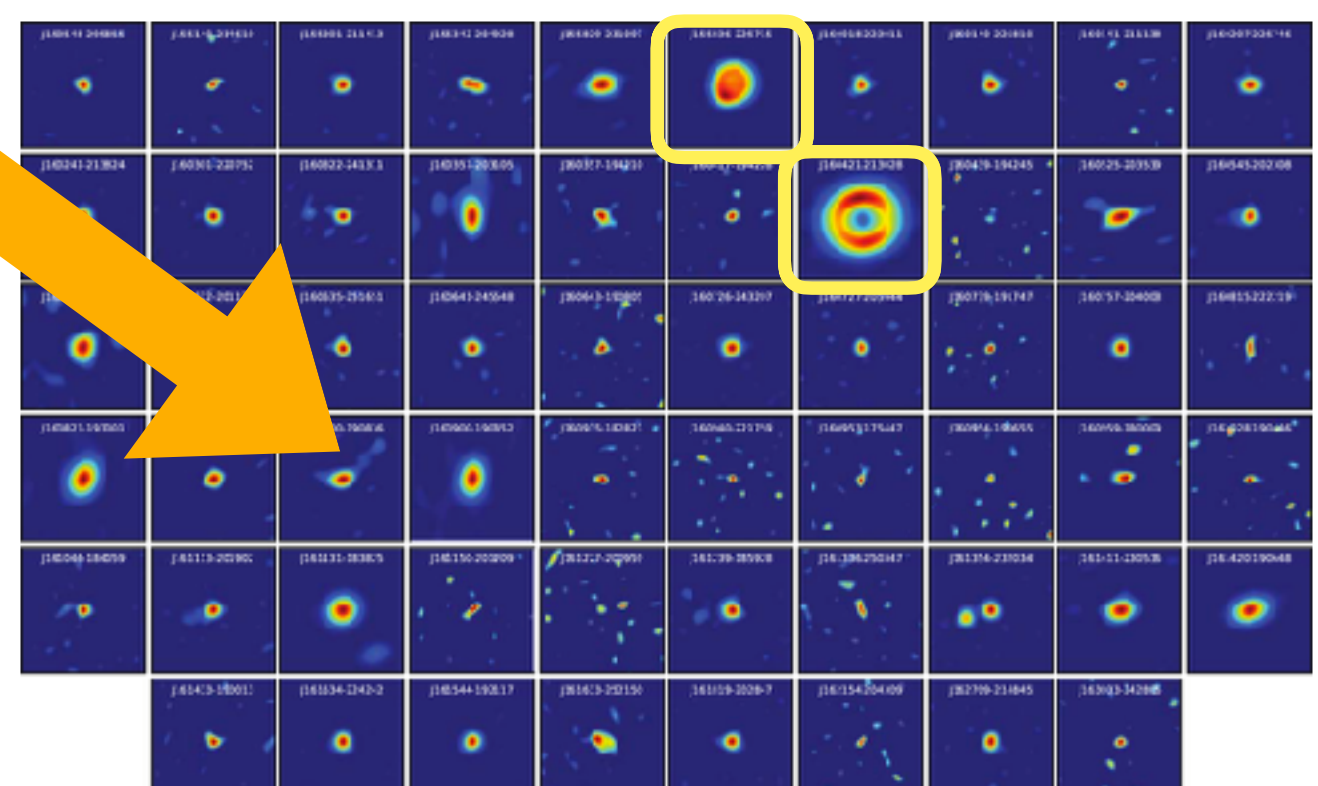
Lupus (2 Myr)







Upper Sco (10 Myr)



Massive outliers:
gapped disks
=> no drift

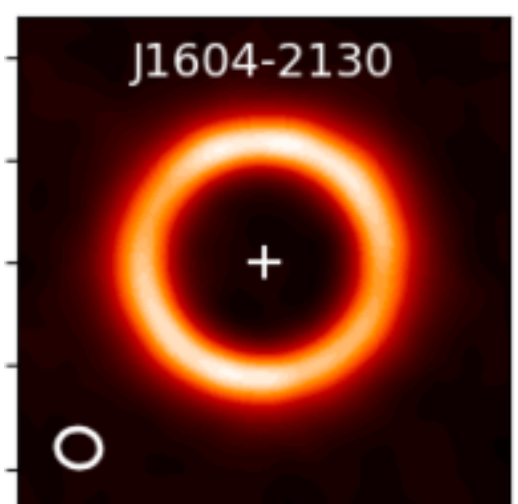
Ansdell et al. 2021

So how many disks are actually drift dominated or trap dominated?

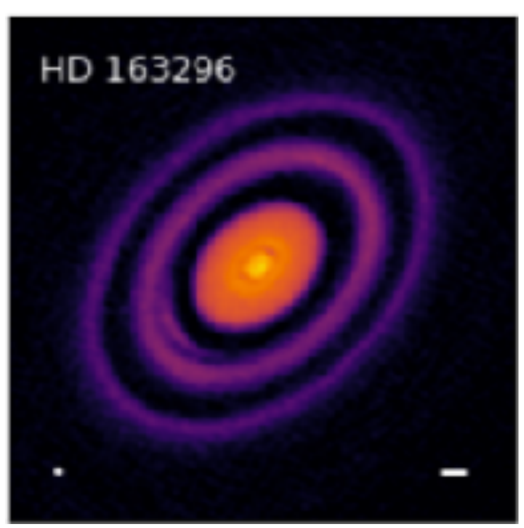
Disk survey across all regions

Sample
- 12 low-mass star forming regions (<300 pc)
- Ages 1-10 Myr
- 700 disks (Class II)
- Spectral types A0 - M6
- ALMA survey disk observations ~ 0.2-0.3" resolution + high-res for fraction of sample
- Measure M_{dust} , morphology and R_{dust}

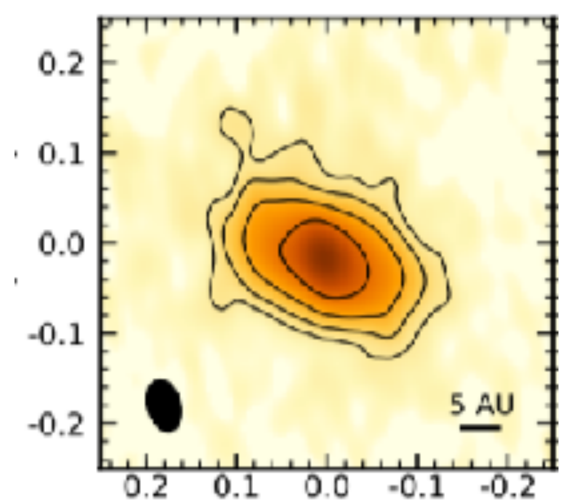
Classification



Transition disks with wide cavities, e.g. J1604-2130



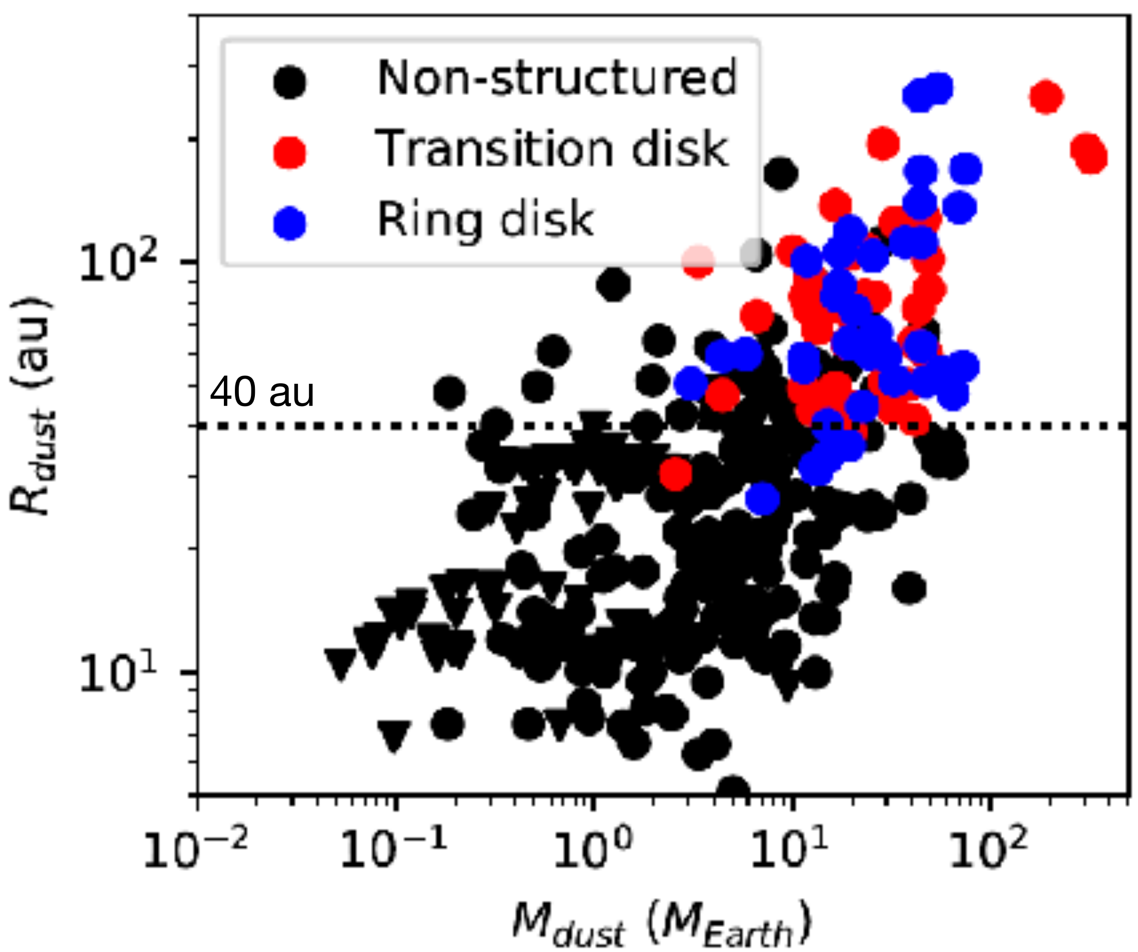
Ring disks with narrow gaps, e.g. HD163296

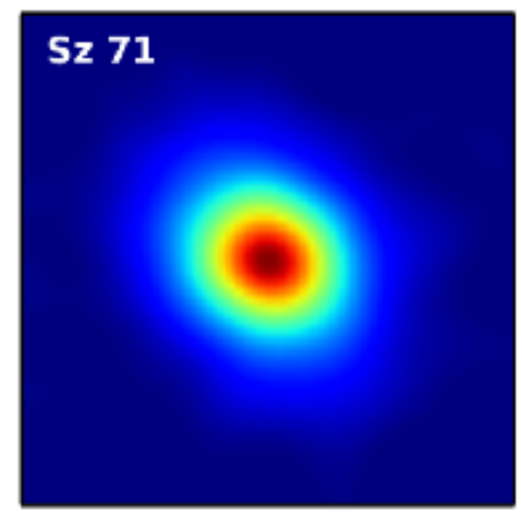


Compact and no gaps e.g. CX Tau (Facchini+2019)

Van der Marel & Mulders 2021

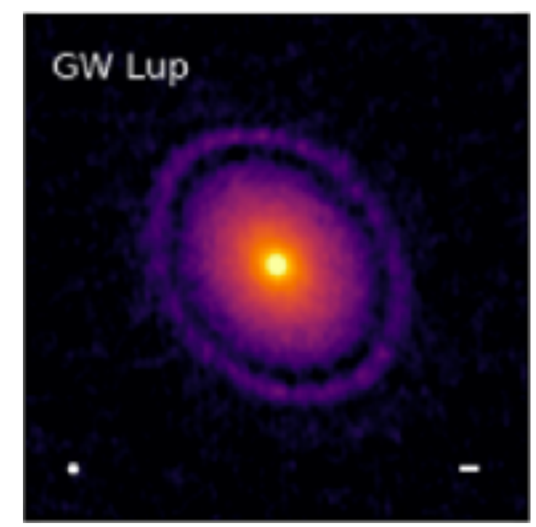
Disk survey across all regions





(0.30”)

=



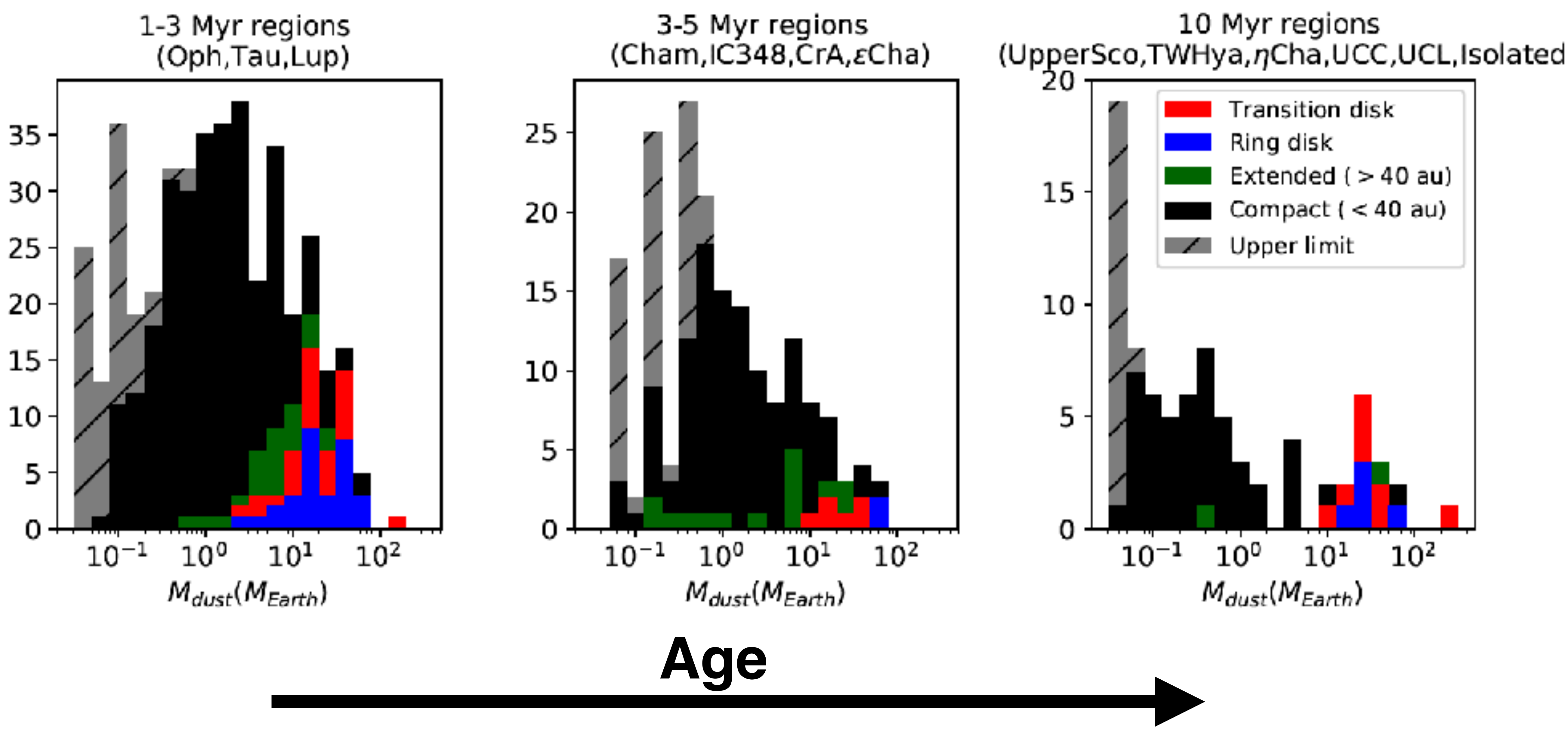
(0.04”)

Several dust disks no resolved structure, but Extended (>40 au):
=> likely gaps present because of dust evolution argument!

Van der Marel & Mulders 2021

Disk survey across all regions

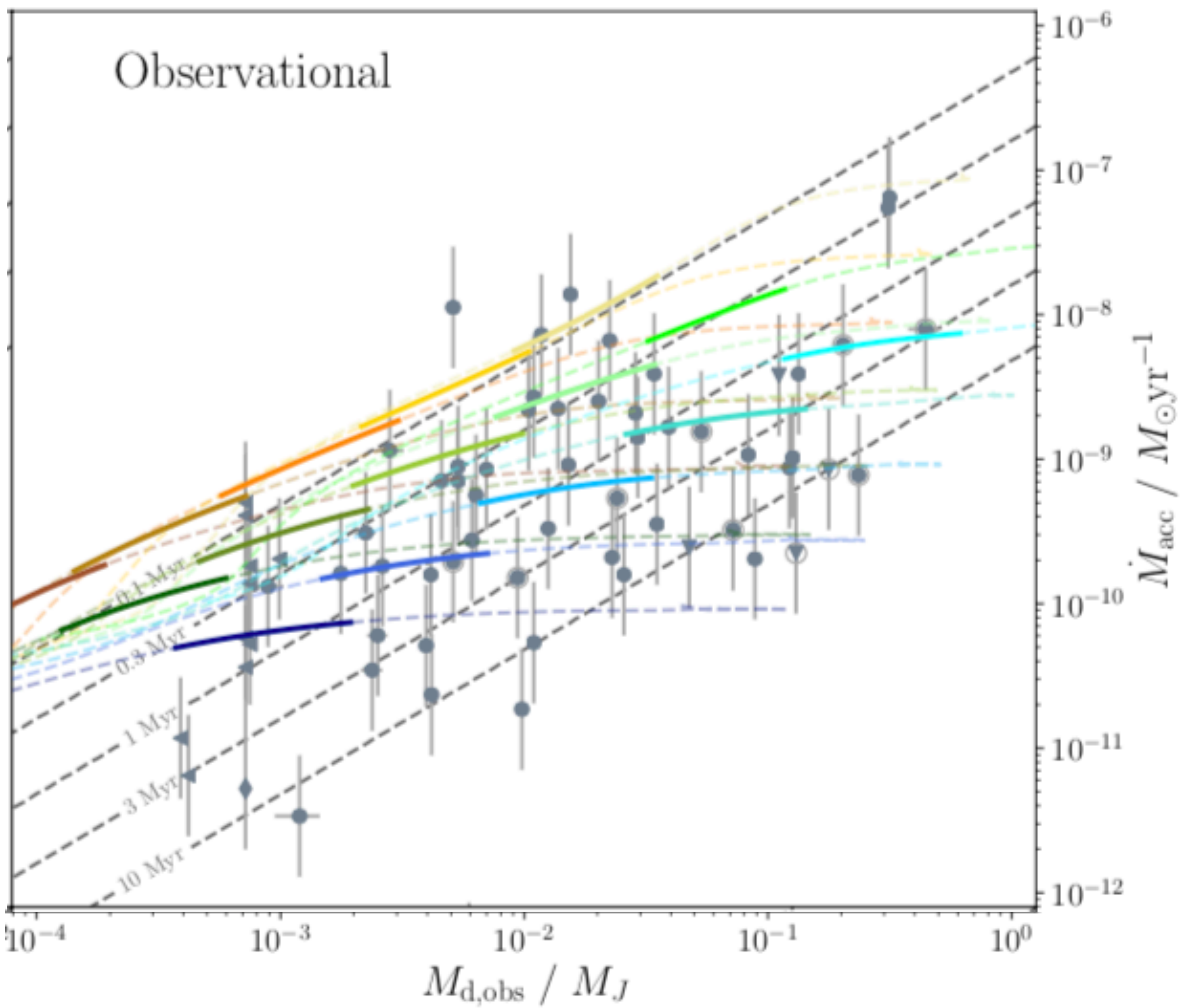
Distribution dust masses as function of age and disk type



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

Van der Marel & Mulders 2021

Also: separate dissipation routes



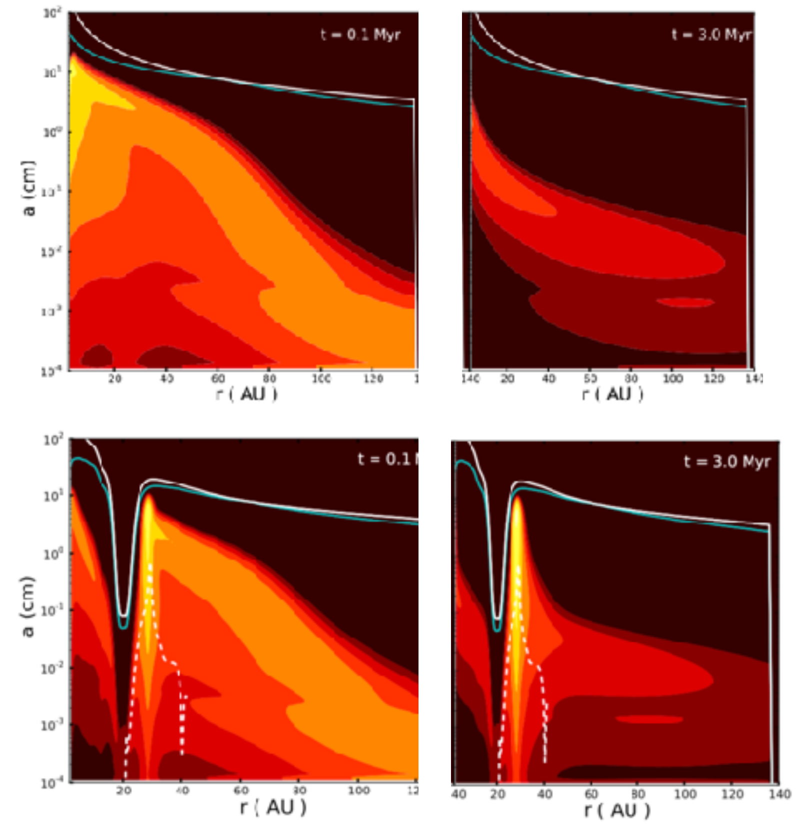
M_{acc}-M_{dust} scatter can be explained with viscous disk model including dust evolution and alpha ~ 10^{-3}

Sellek et al. 2020

Separate dissipation routes

Removal mm-sized pebbles

Drift and dust growth

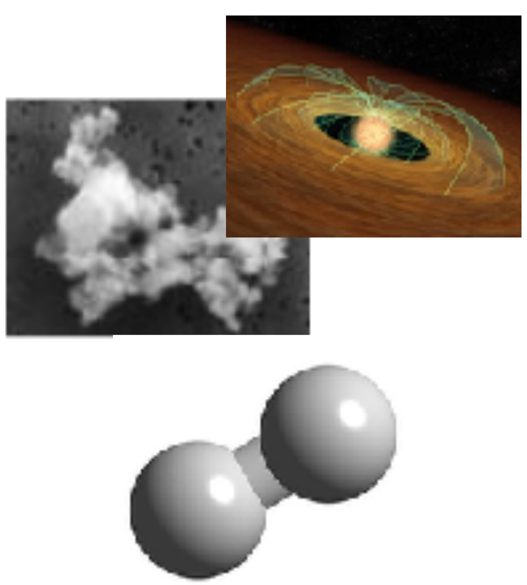


Drift disk

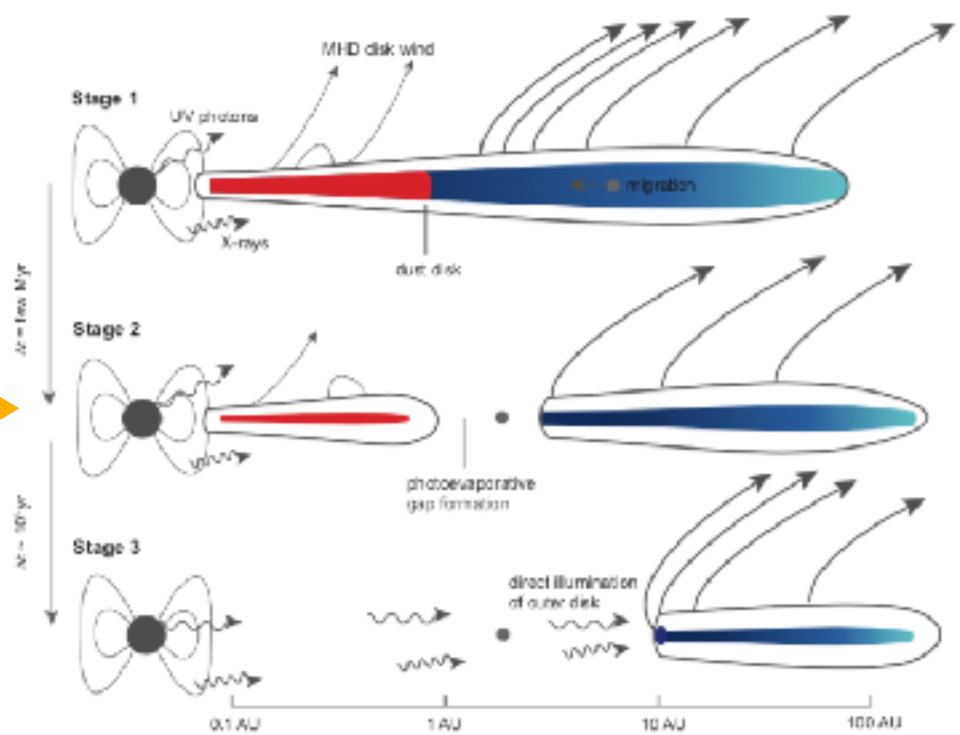
Dust trap disk

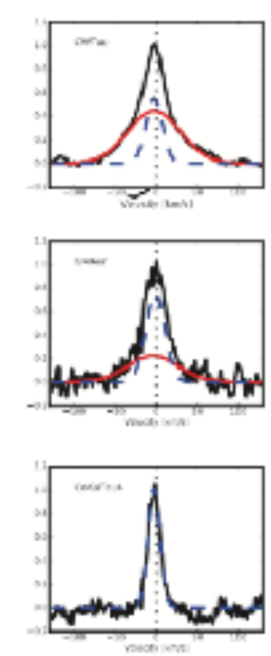
Tracer: ALMA (sub)mm continuum

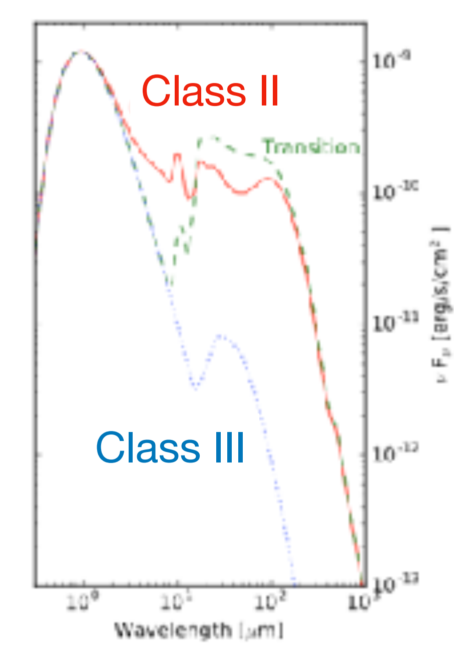
Removal micron-sized grains and gas/accretion



End accretion, photoevaporative clearing







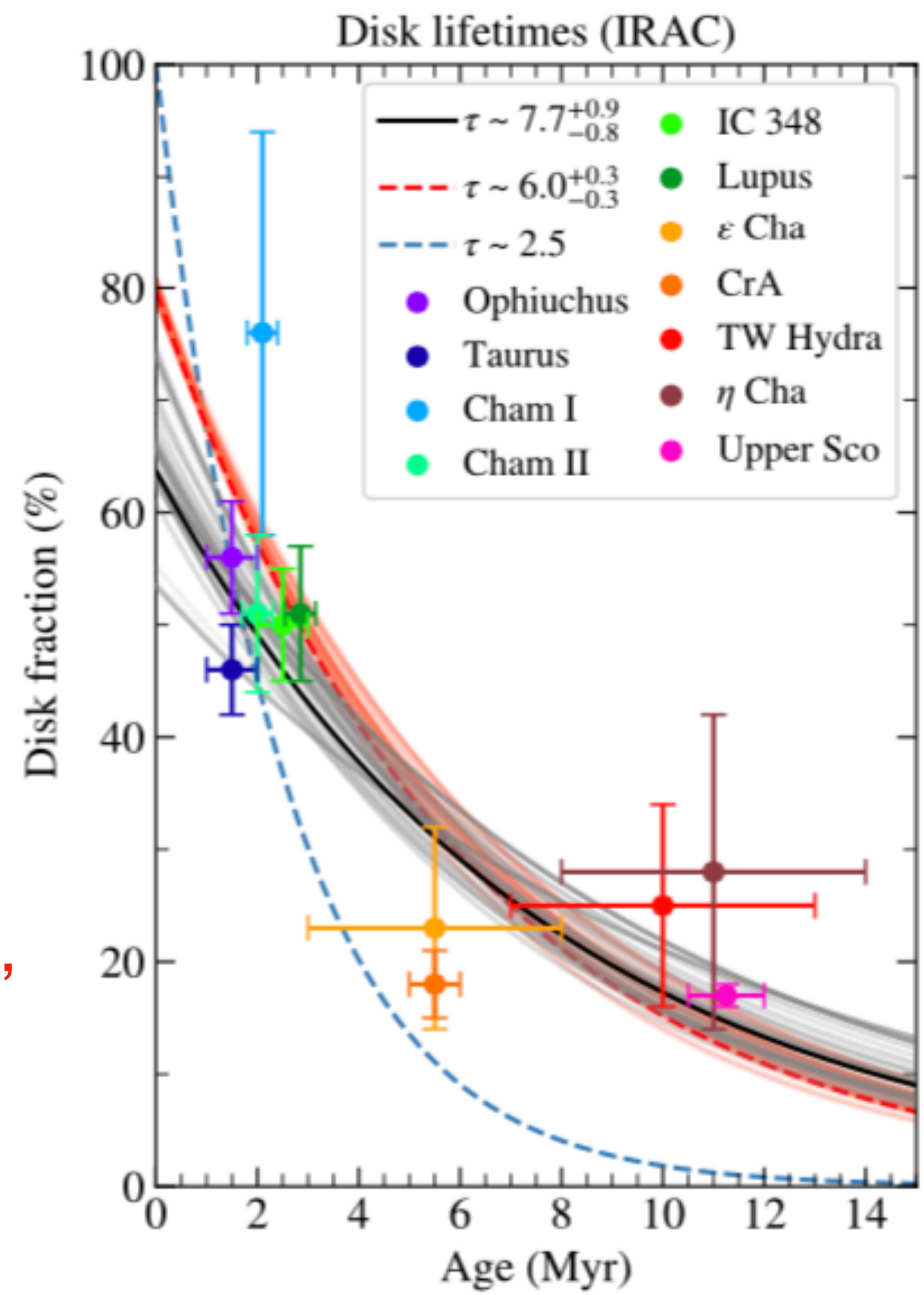
Tracers: accretion lines IR excess

Separate dissipation routes

Update infrared disk lifetime:

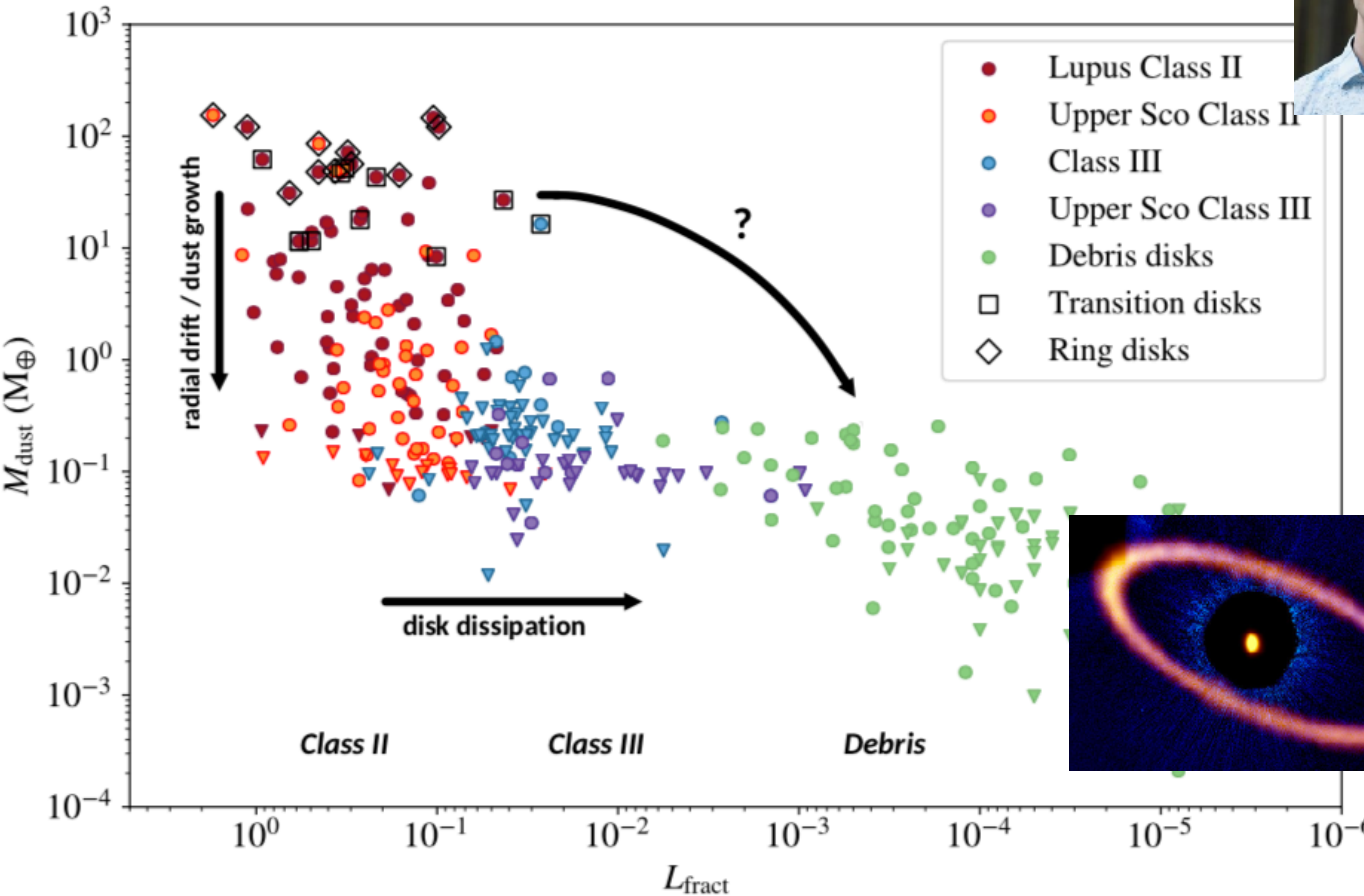
- Remove UV-dominated clusters (see Winter+2018 on external photoevaporation)
- Compute disk fraction with Gaia DR2 membership studies
- Fit with free power-law

For well-studied disks (with M_{dust}, M_{acc}),
IR disk lifetime is 7-8 Myr, not 3 Myr!



Michel, van der Marel & Matthews, in press

Separate dissipation routes



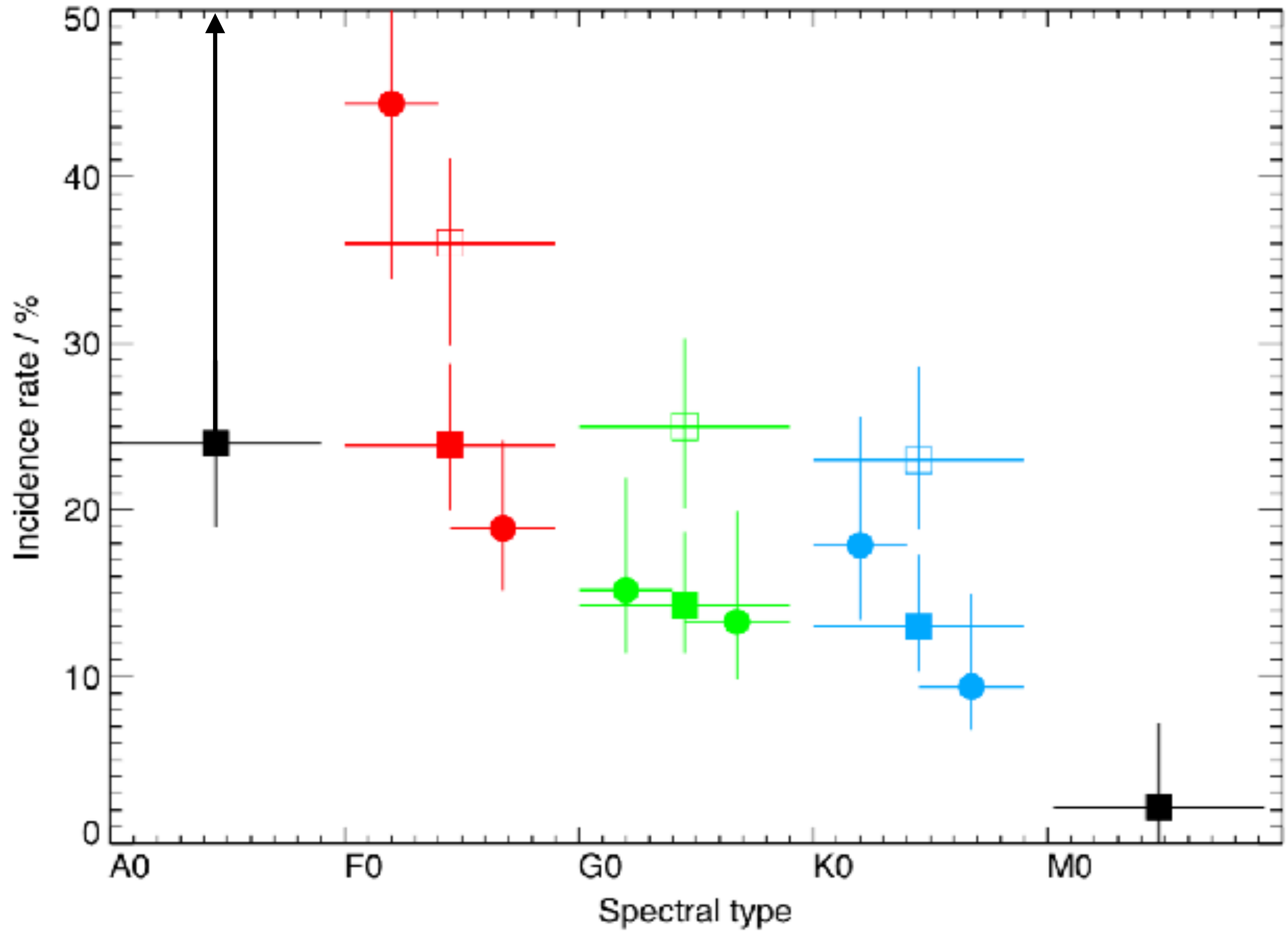
Arnaud Michel, Queens

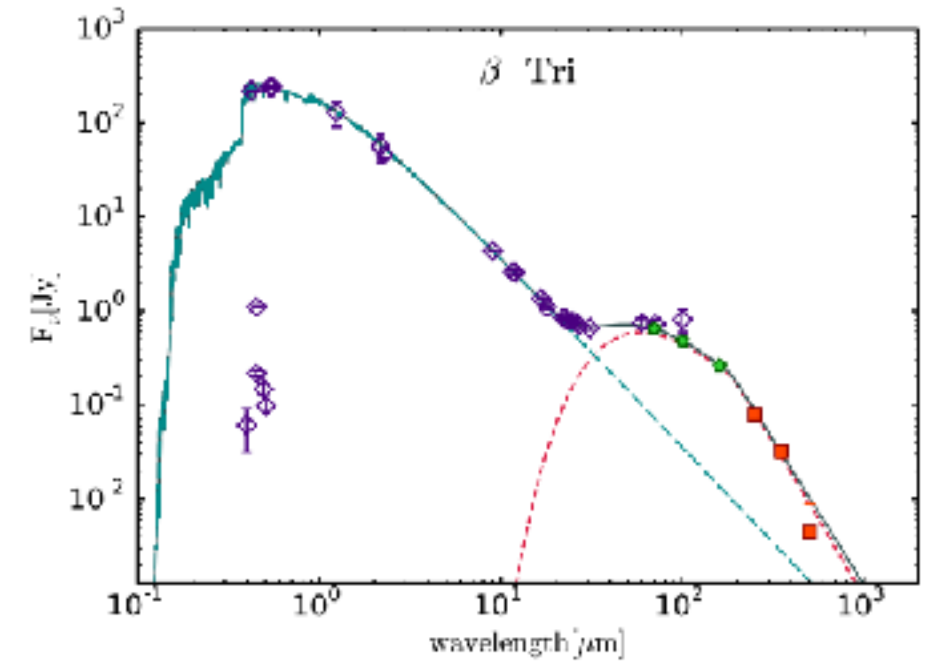
Are structured disks progenitors of debris disks?

Michel, van der Marel & Matthews, in press

Cold debris disks

Herschel DEBRIS survey

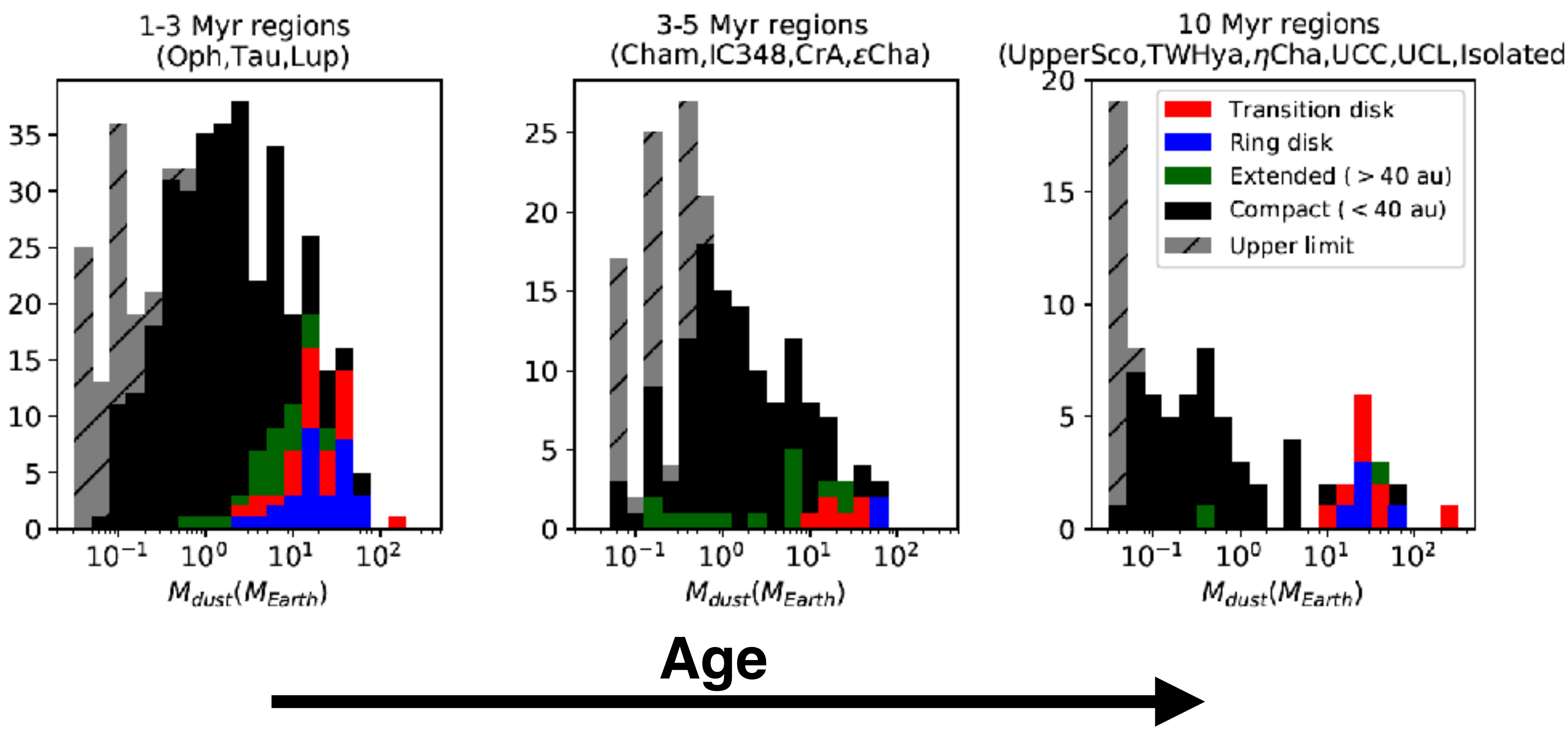




Debris disks less common around later type stars

Thureau et al. 2014
Sibthorpe et al. 2018

Recall: mm-dust evolution



Two separate evolutionary pathways:
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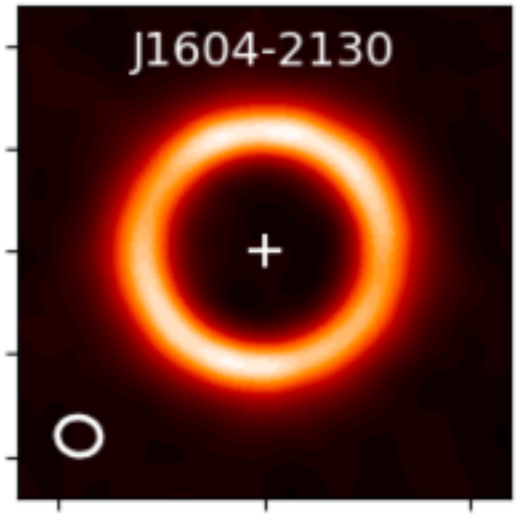
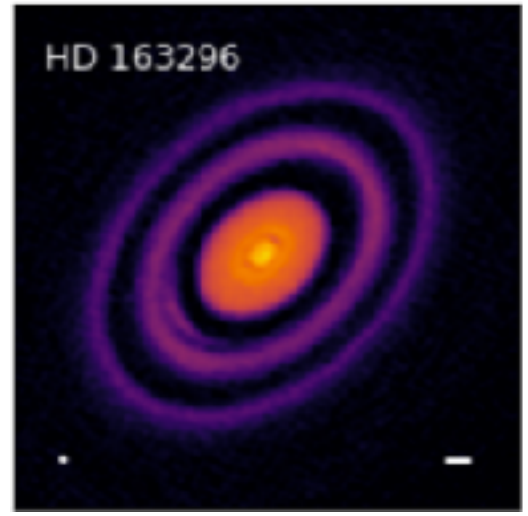
Van der Marel & Mulders 2021

Which planets form in which disks?



Transition disks with deep, wide cavities, e.g. J1604-2130



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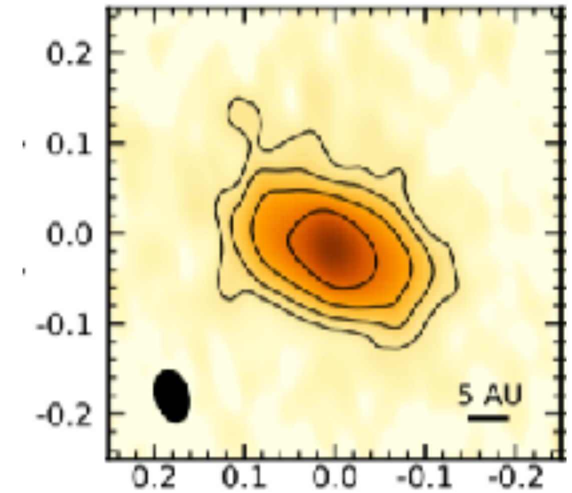
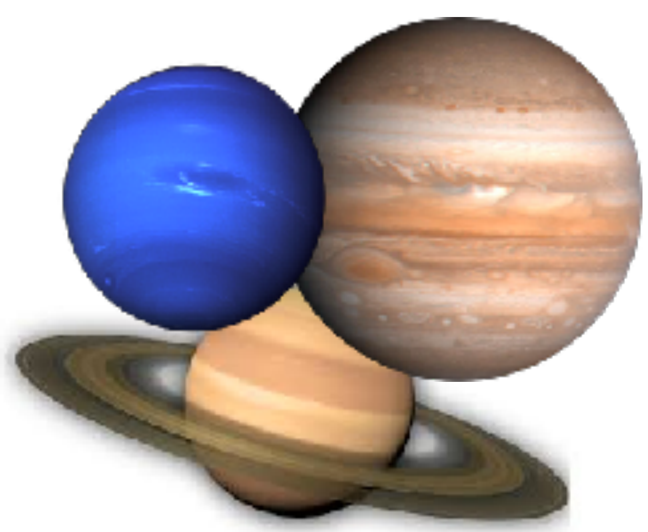


Compact and no gaps e.g. CX Tau (Facchini+2019)

Planet mass (M_{Earth})

>1000

vdMarel+2016,2021

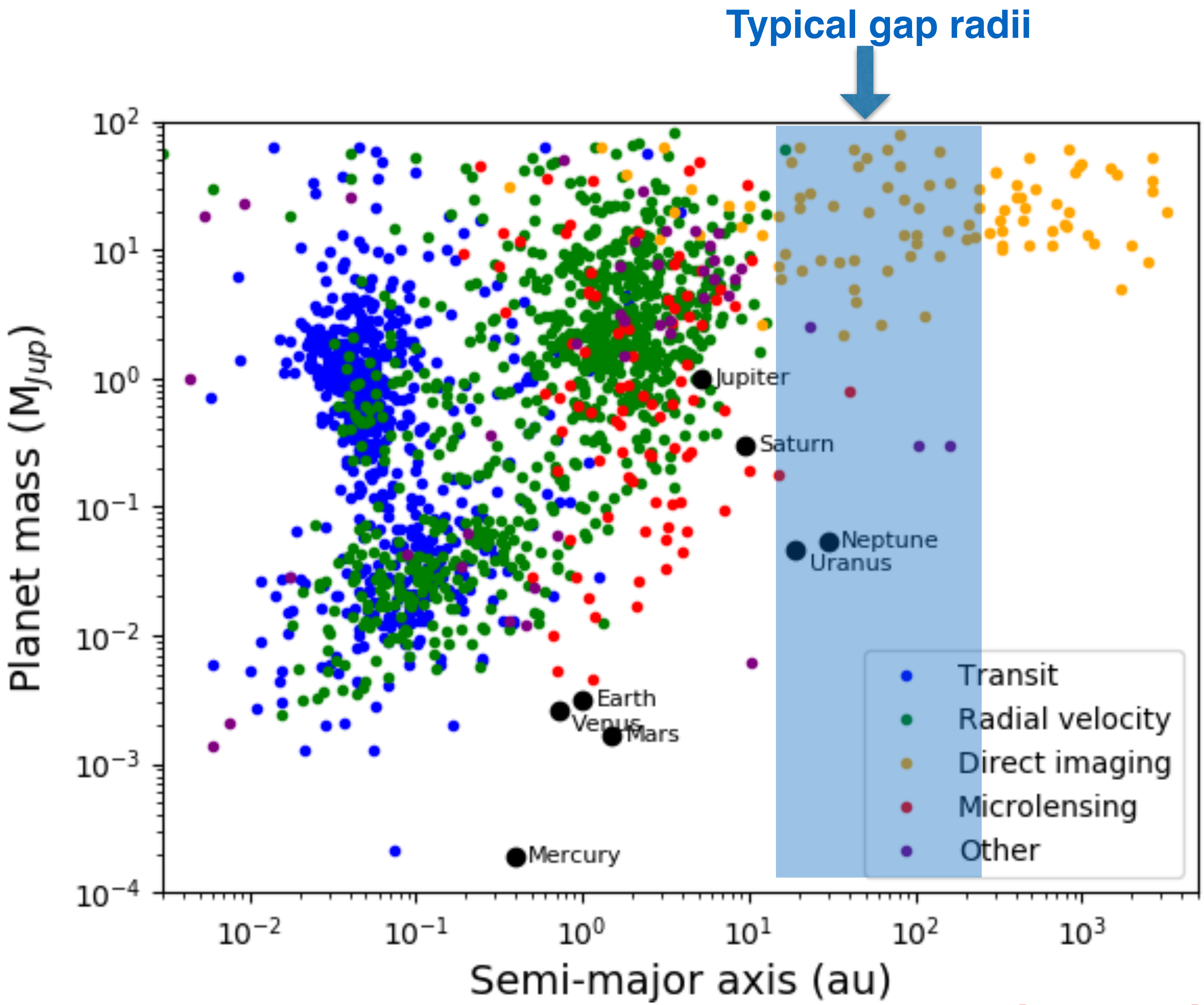


20-1000

Rosotti+2016

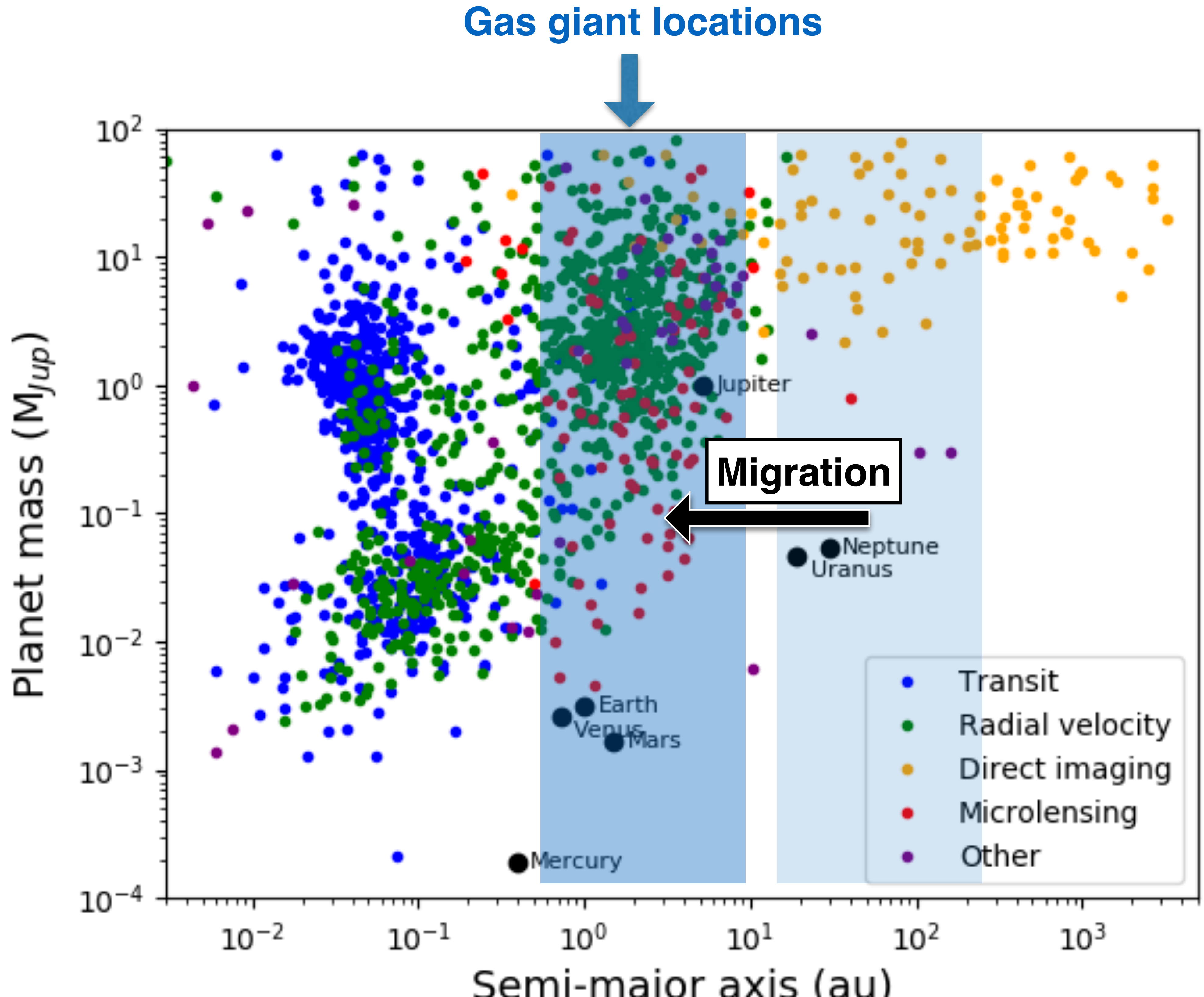
1-20

How to link with exoplanet demographics?



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

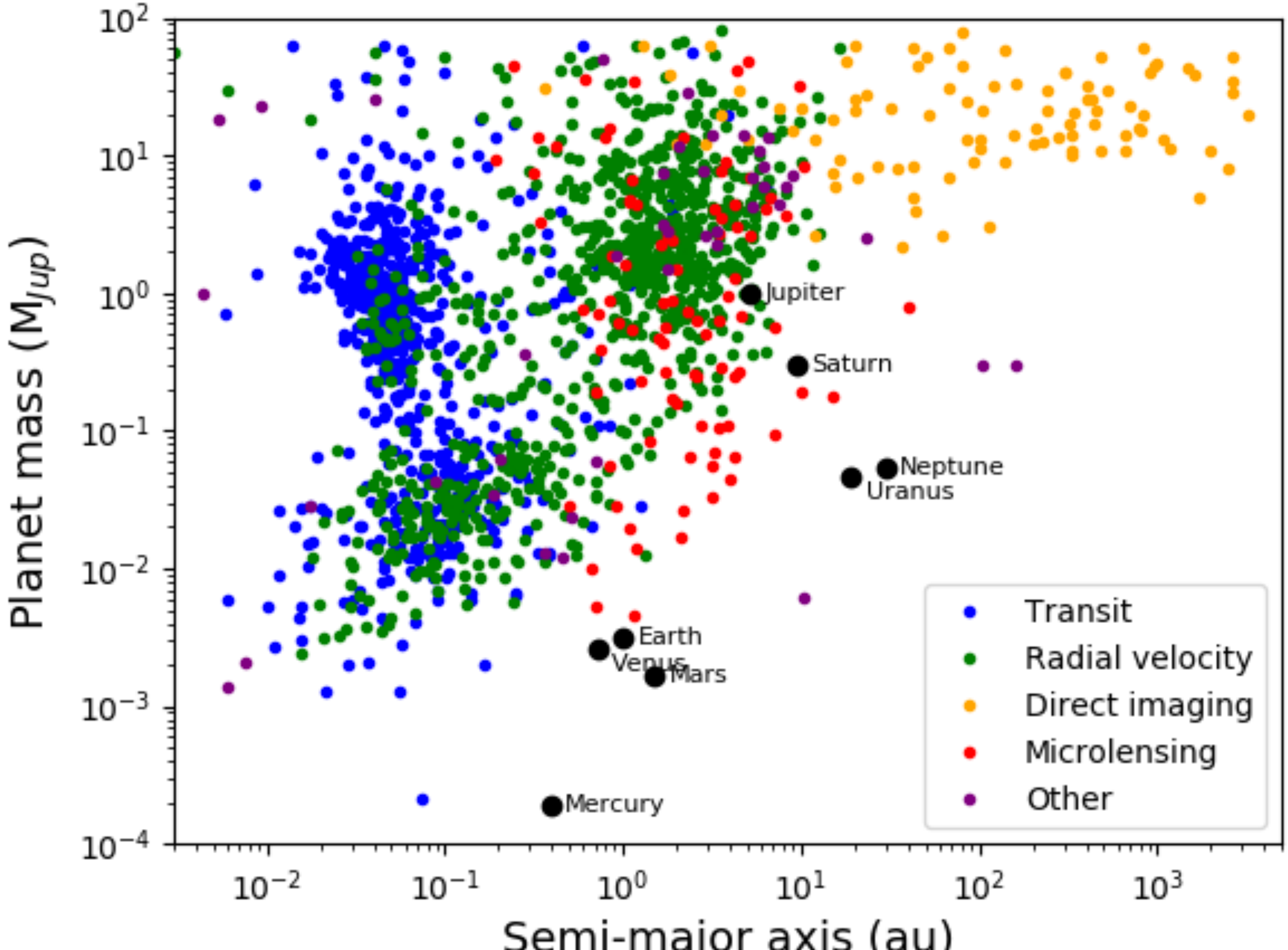
How to link with exoplanet demographics?



Lodato et al. 2019

Problem: exoplanets at wide orbits are rare: inward migration

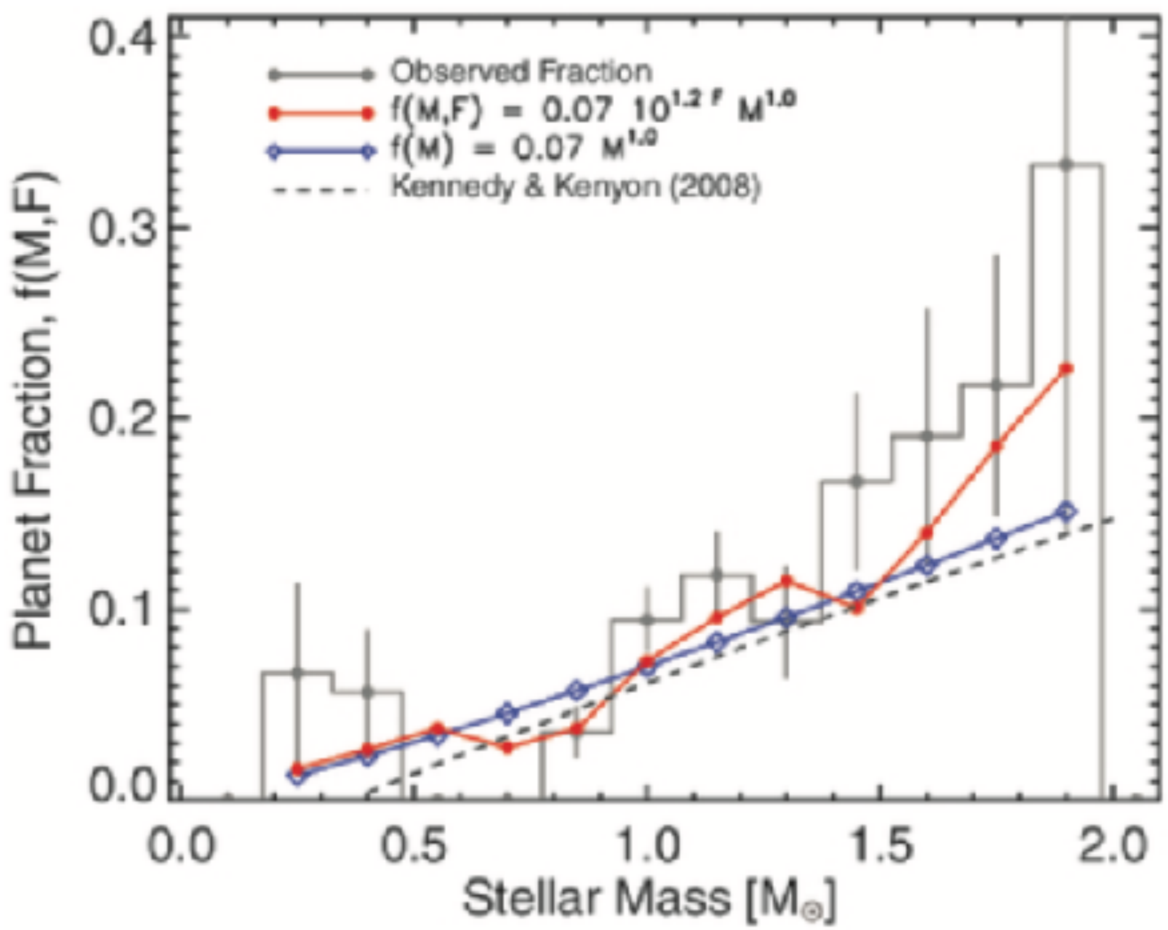
How to link with exoplanet demographics?

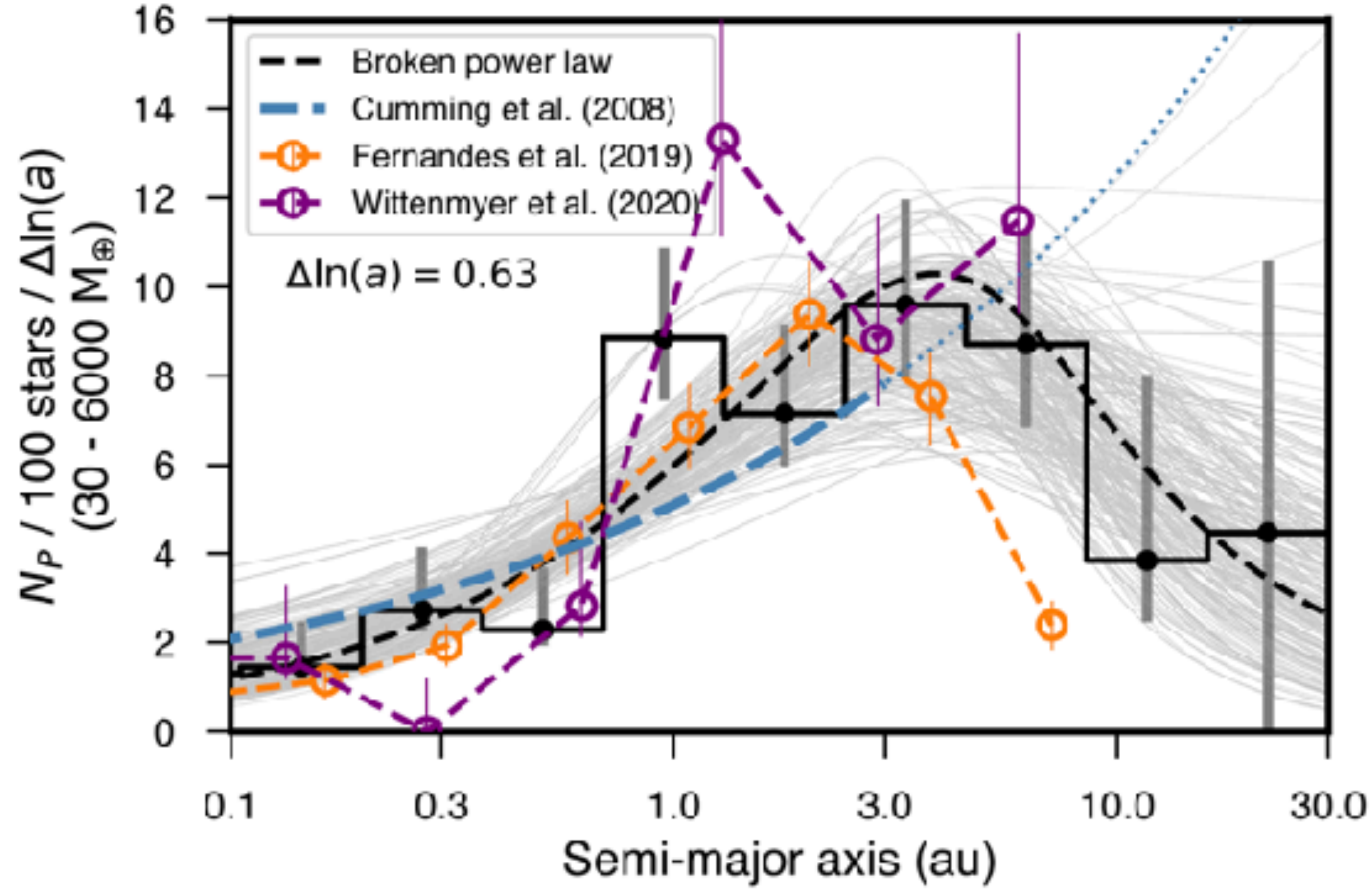


Problem: detection/selection biases

How to link with exoplanet demographics?

Giant planet occurrence
increases with stellar mass



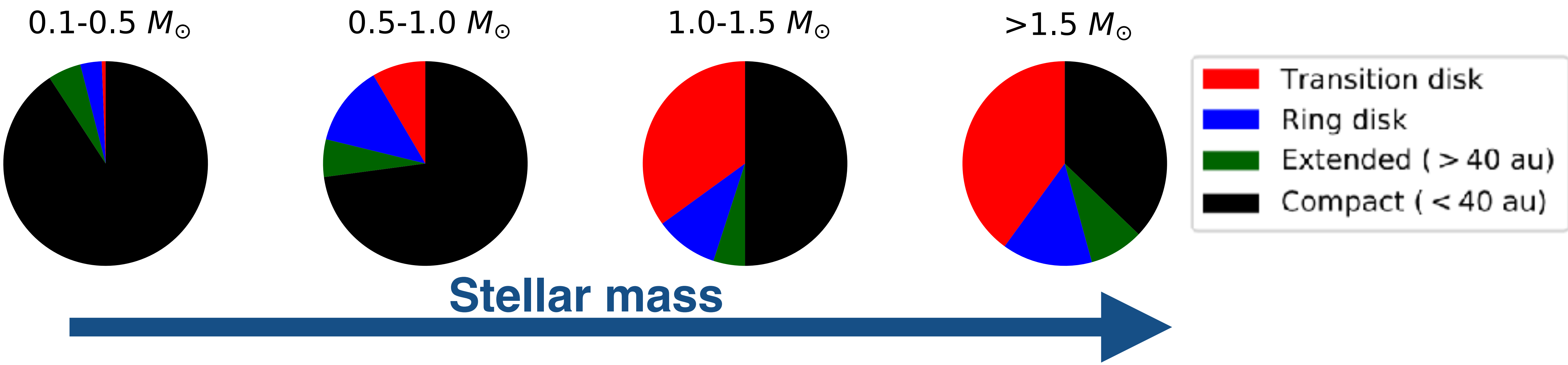


(after correction for detection biases)

Johnson et al. 2010
Fernandes et al. 2019
Fulton et al. 2021

Disk demographics

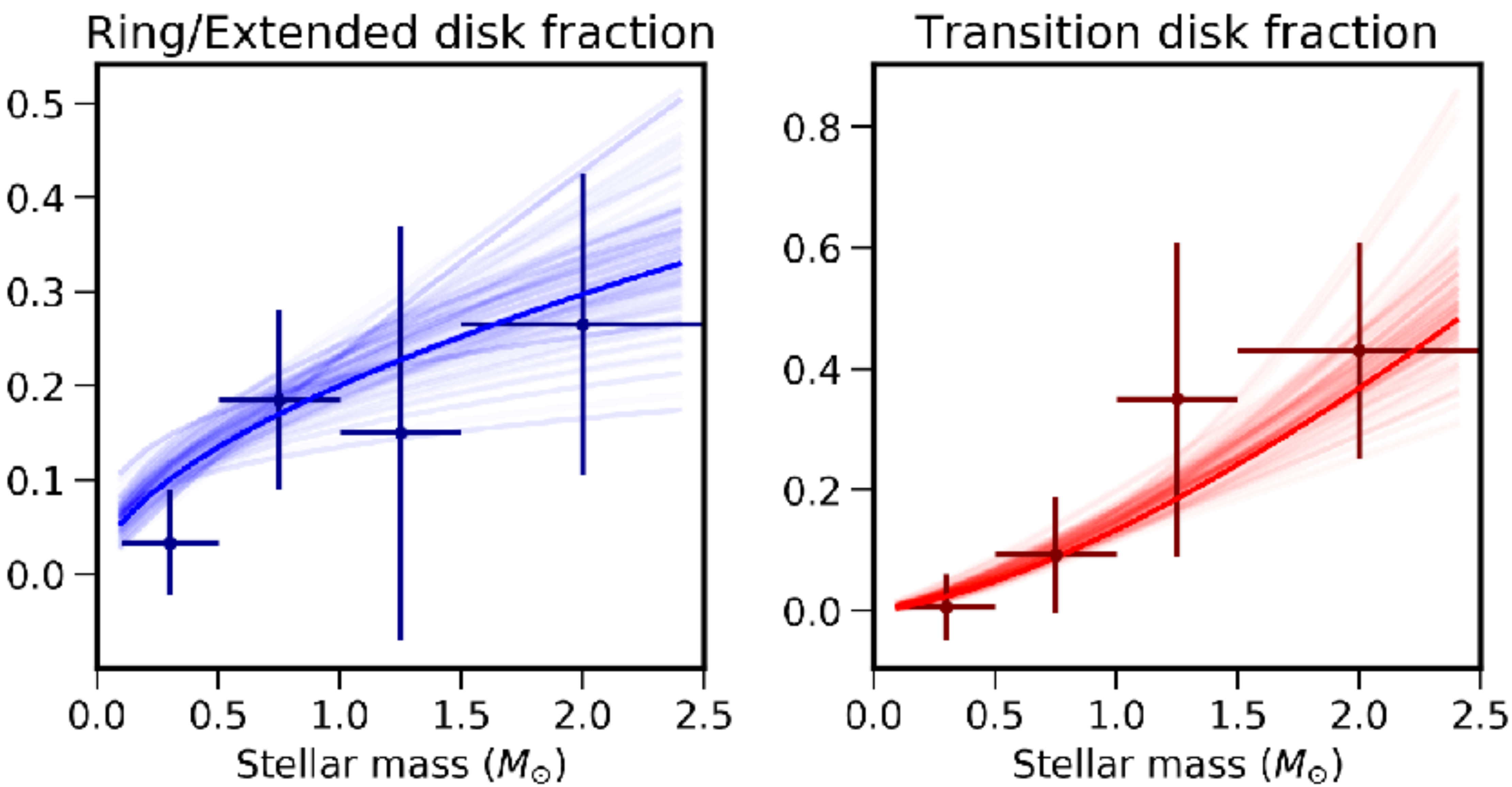
Stellar mass dependence of disks



Gapped disks are more common around more massive stars

Van der Marel & Mulders 2021

Disk demographics



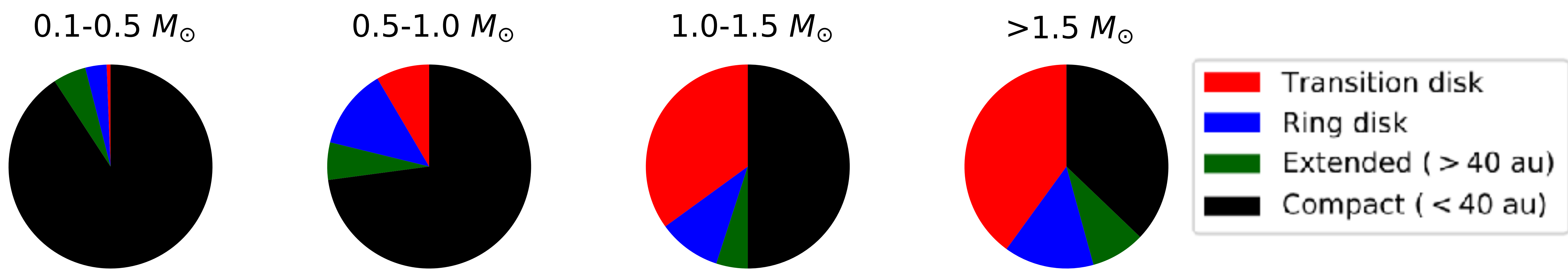
$$f(M_*) = C \cdot M_*^\alpha$$

Gapped disk occurrence is correlated with stellar mass

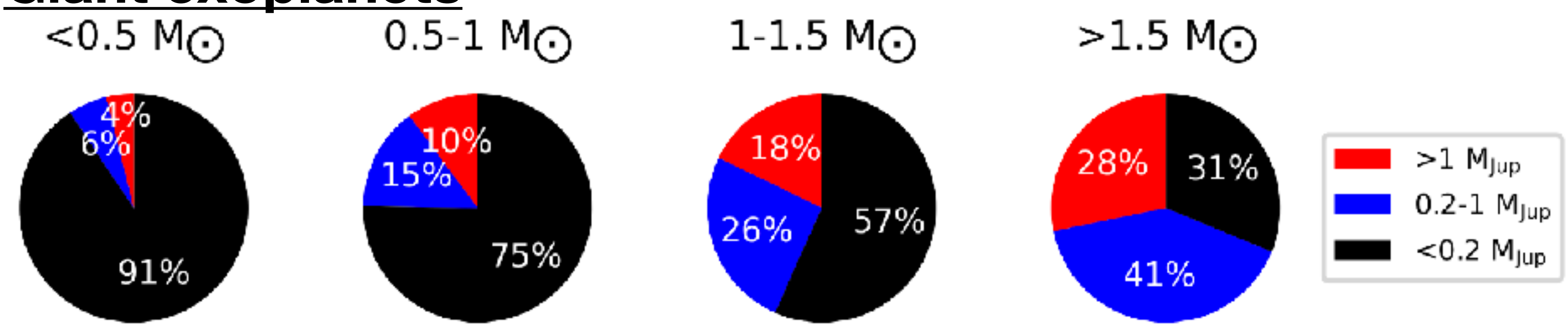
Van der Marel & Mulders 2021

Disk demographics: giant planets

Disks



Giant exoplanets

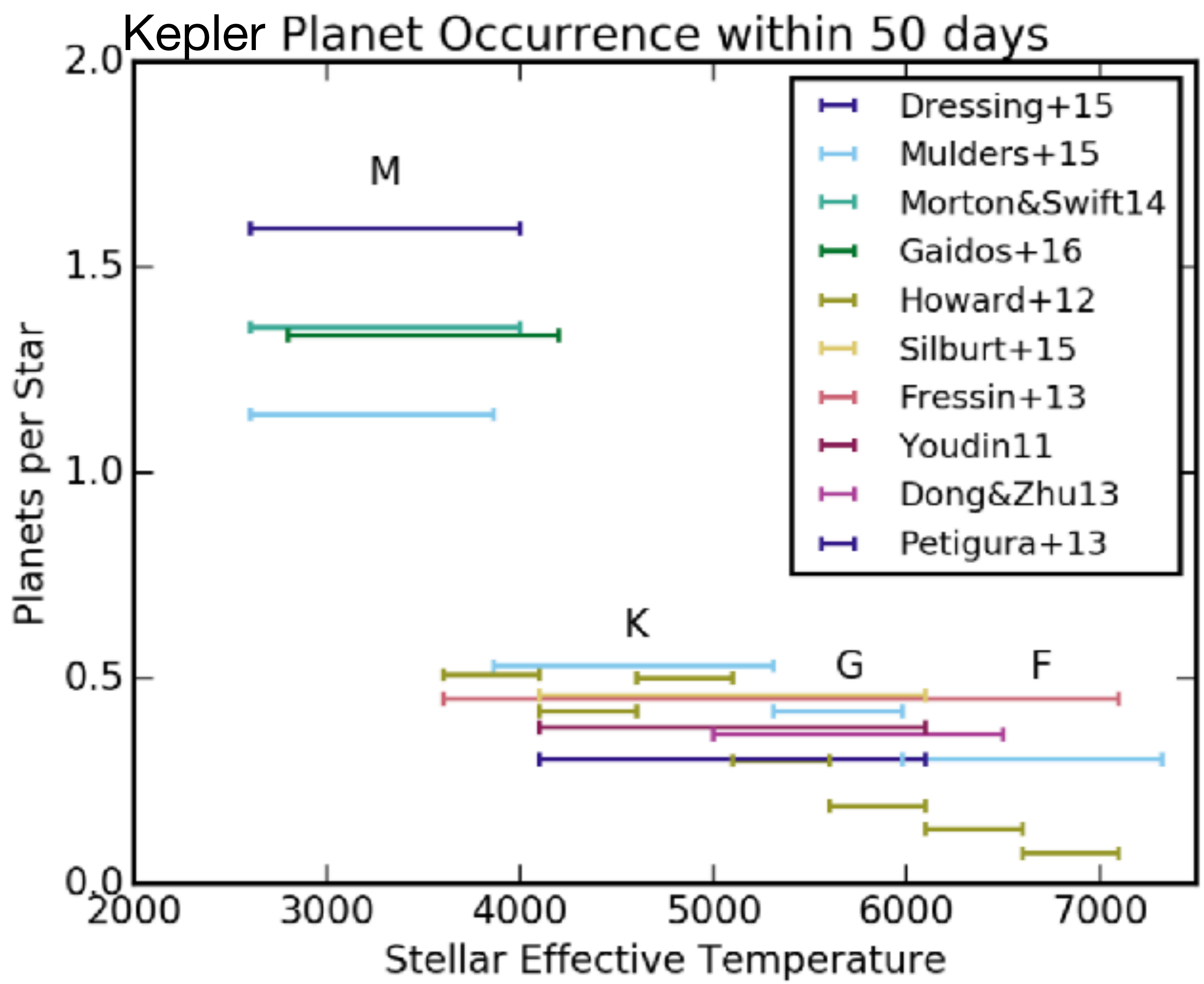


Match: disk gaps can be linked to giant planets (when there is migration)!

=> also link to debris disks!

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

Exoplanet demographics: super-Earths

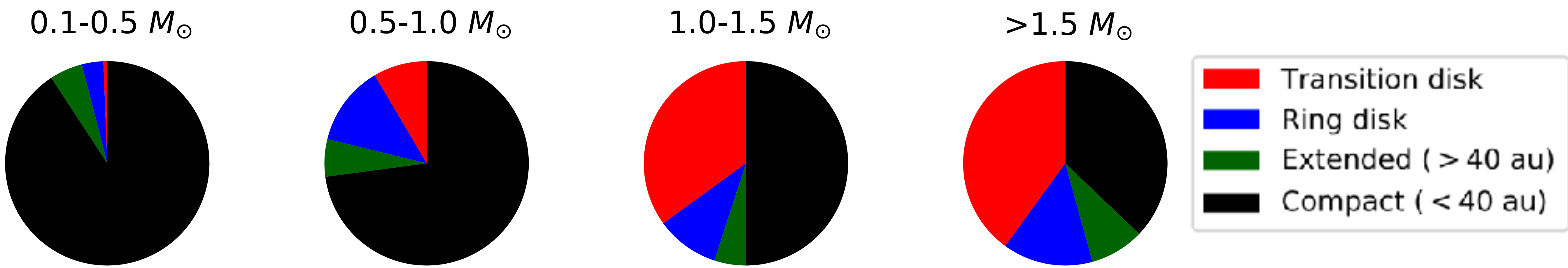


Super-Earth occurrence **decreases** with stellar mass

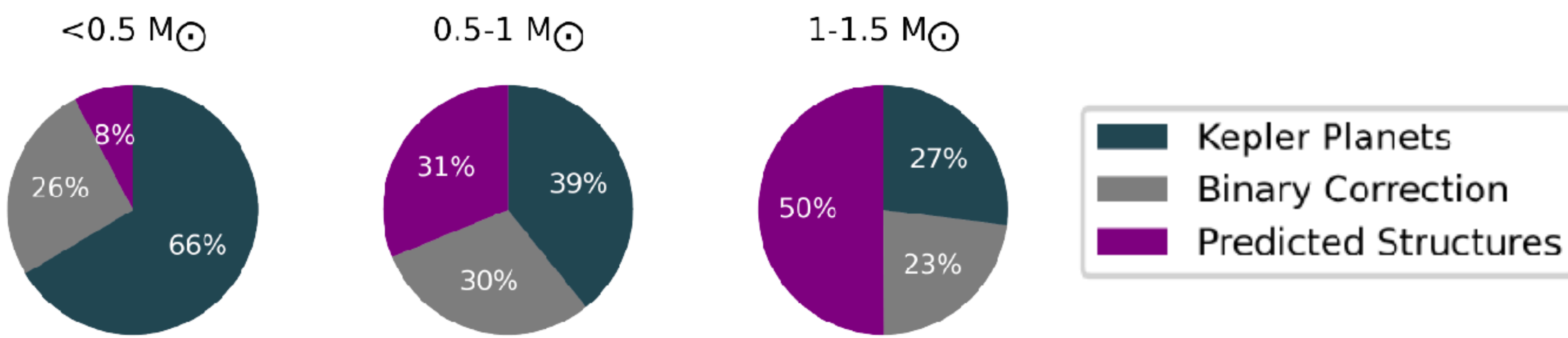
Mulders et al. 2015, 2018, 2019

Disk demographics: super-Earths

Disks



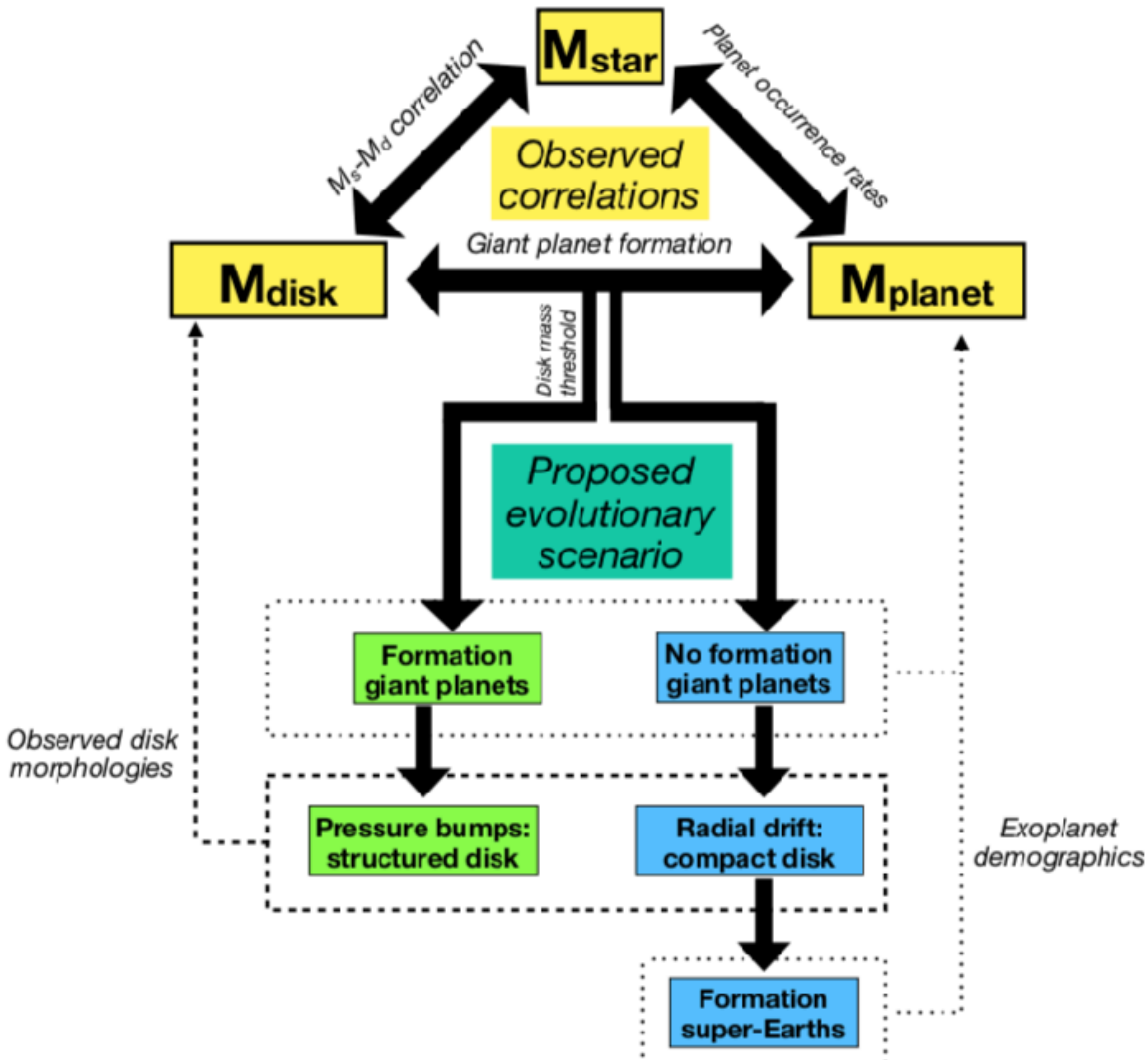
Close-in super-Earths (‘Kepler planets’)



Match: compact disks can be linked to super-Earths: increased pebble flux

Moe & Kratter 2019
Lambrechts et al. 2019
van der Marel & Mulders 2021

How does planet formation affect disk evolution?

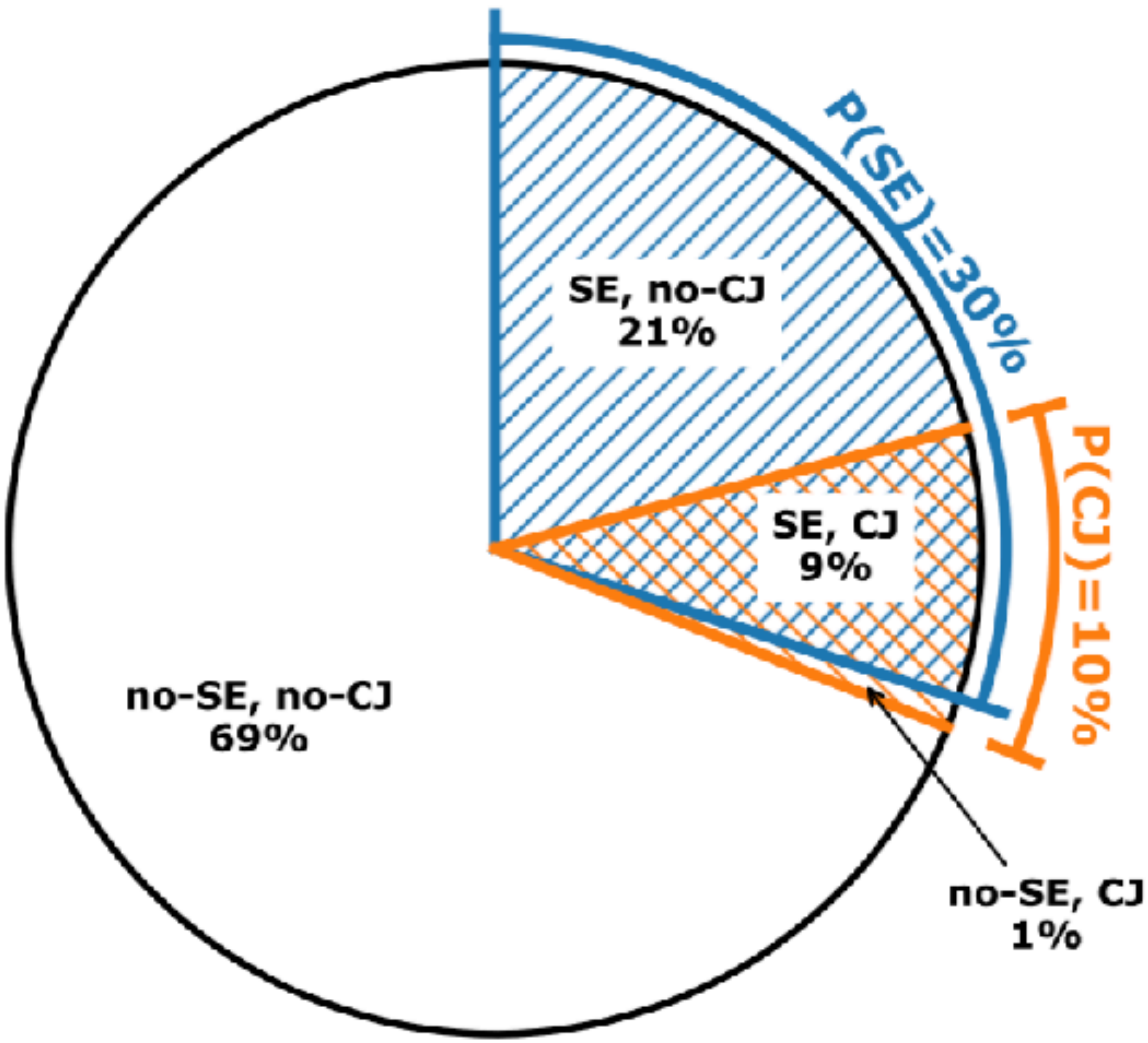


Explanation Solar System: no super-Earth

Van der Marel & Mulders 2021

Issue: correlation between Super-Earths and cold Jupiters?

For Solar mass stars, correlation found between cold Jupiter and Super-Earth presence

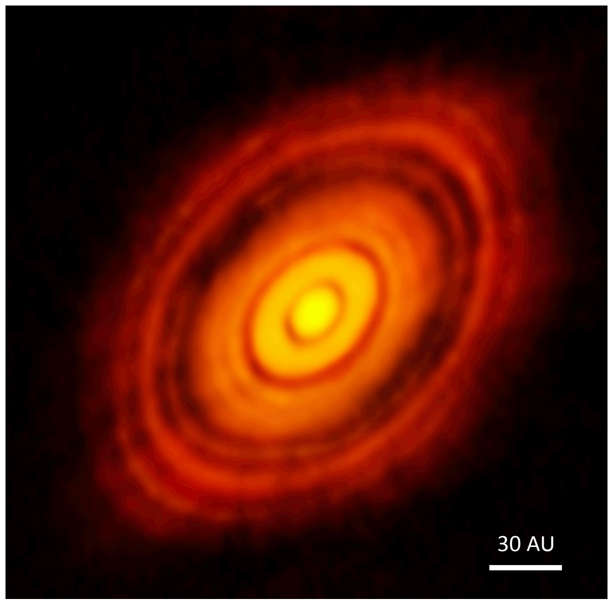


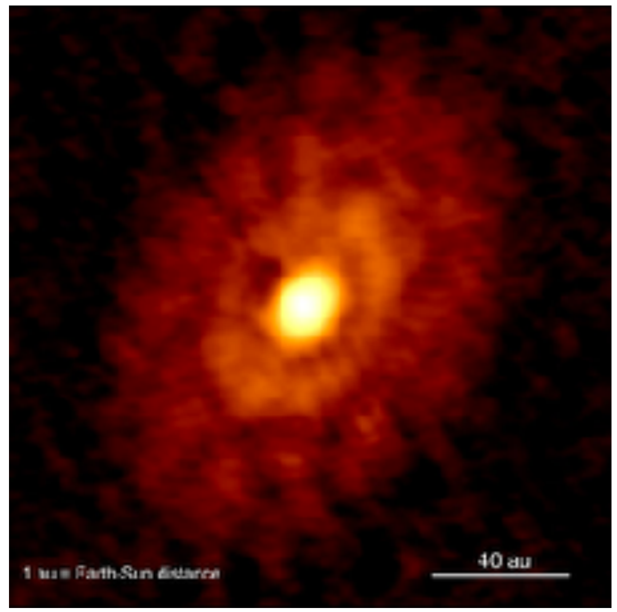
- Sample size?
- Definition Super-Earth?
- Limited to solar-mass stars?

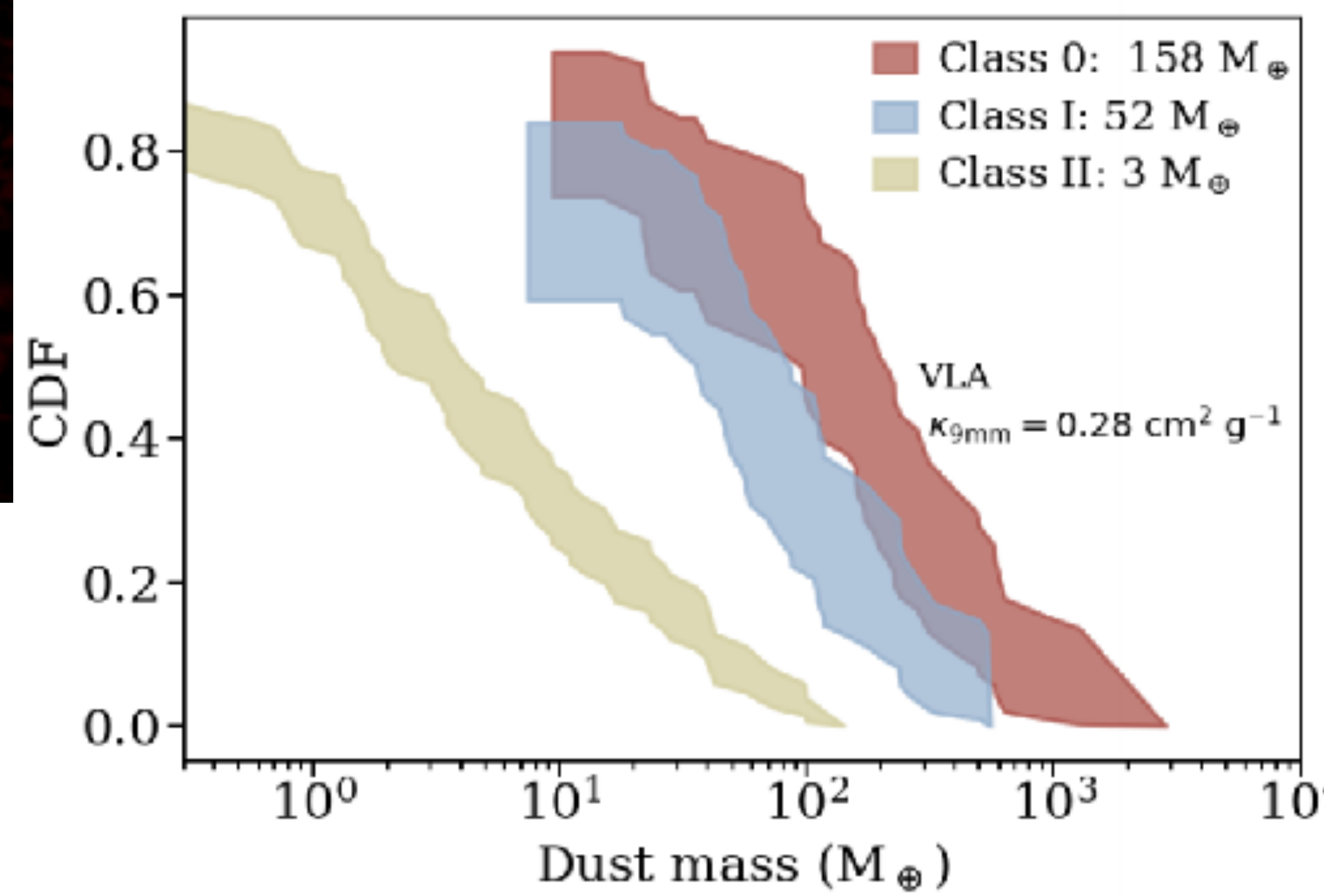
Zhu & Wu 2018
Herman et al. 2019

Consequence: giant planet formation must be early?

Disks of 0.5-1 Myr have gaps





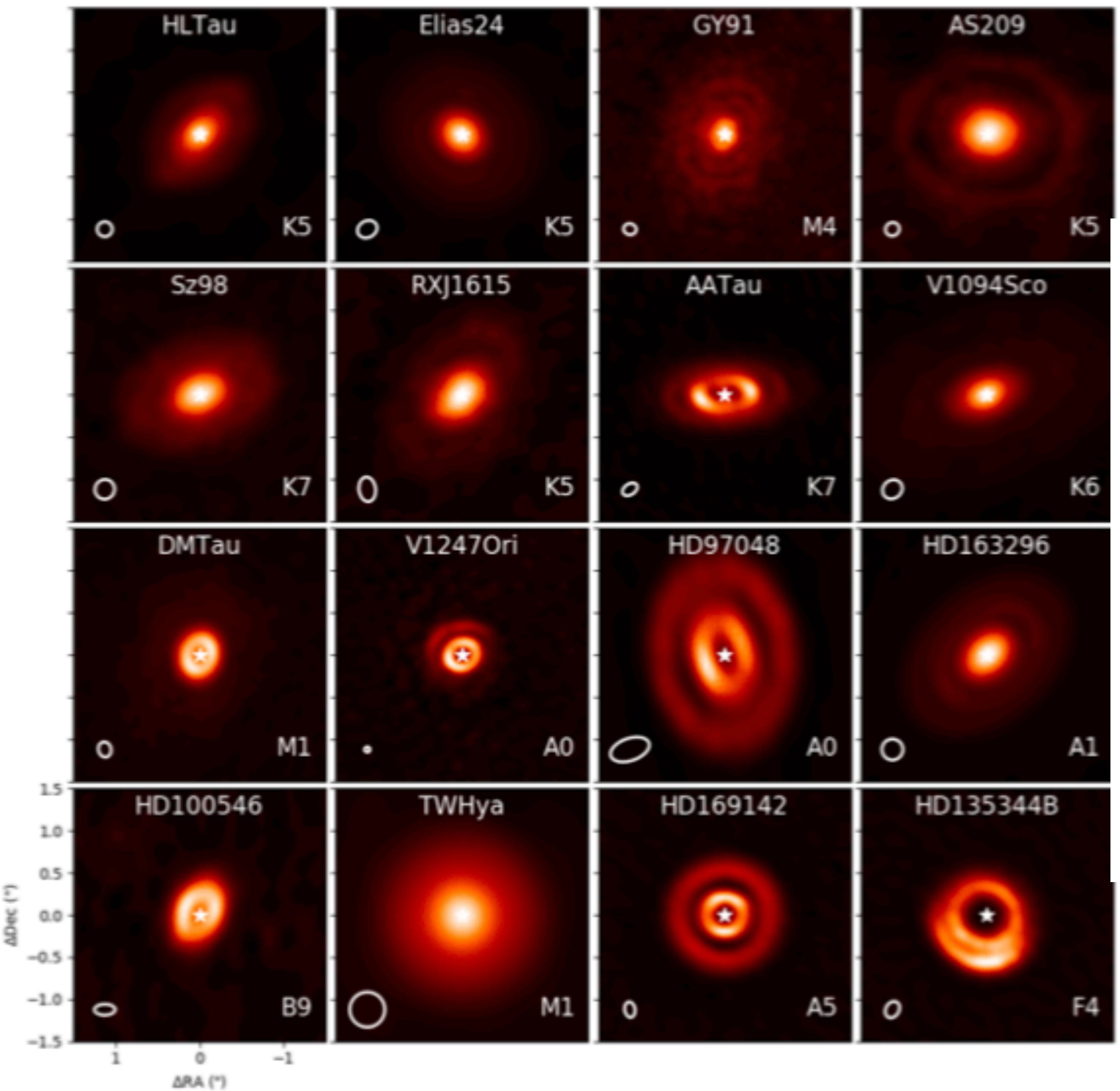


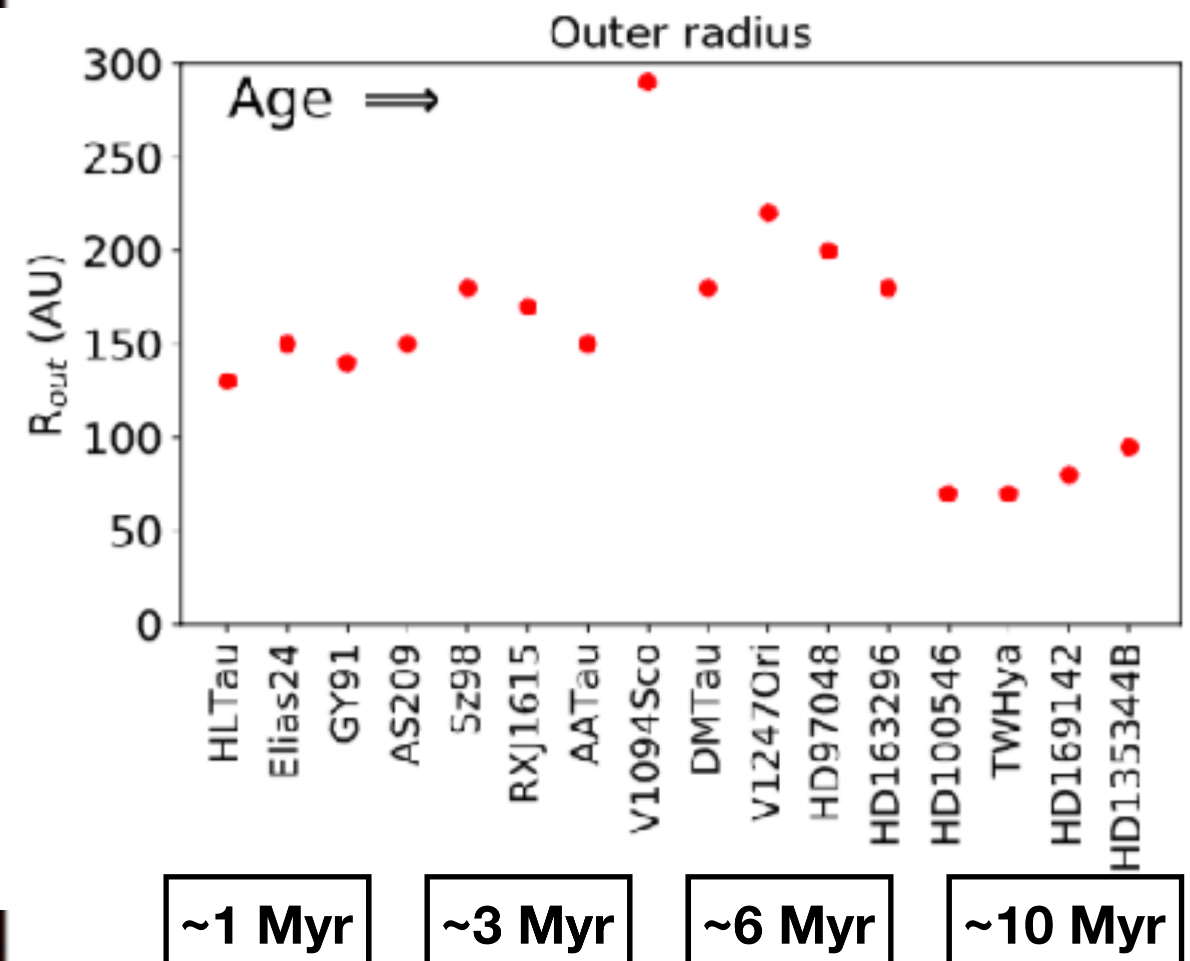
What do core accretion and gravitational instability models predict in embedded disk conditions?

Embedded disks have 50x more dust mass

Segura-Cox et al. 2020
Tychoniec et al. 2020

Consequence: dust traps follow migration inwards?

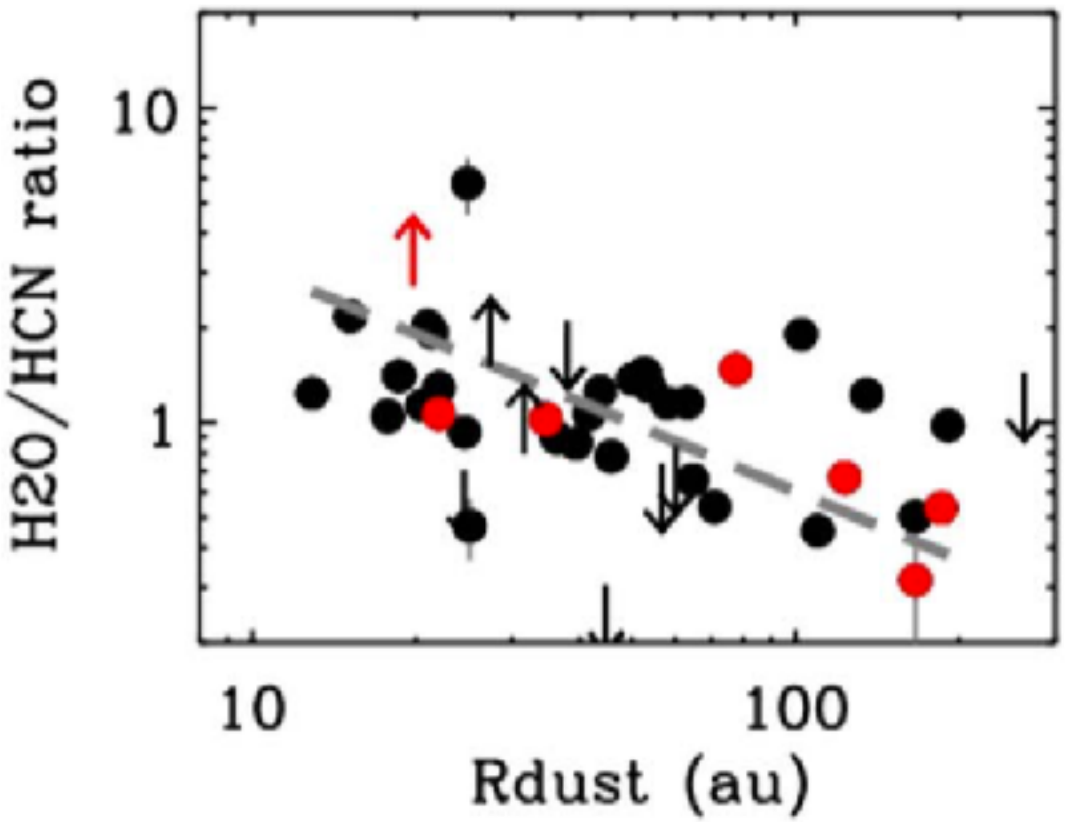


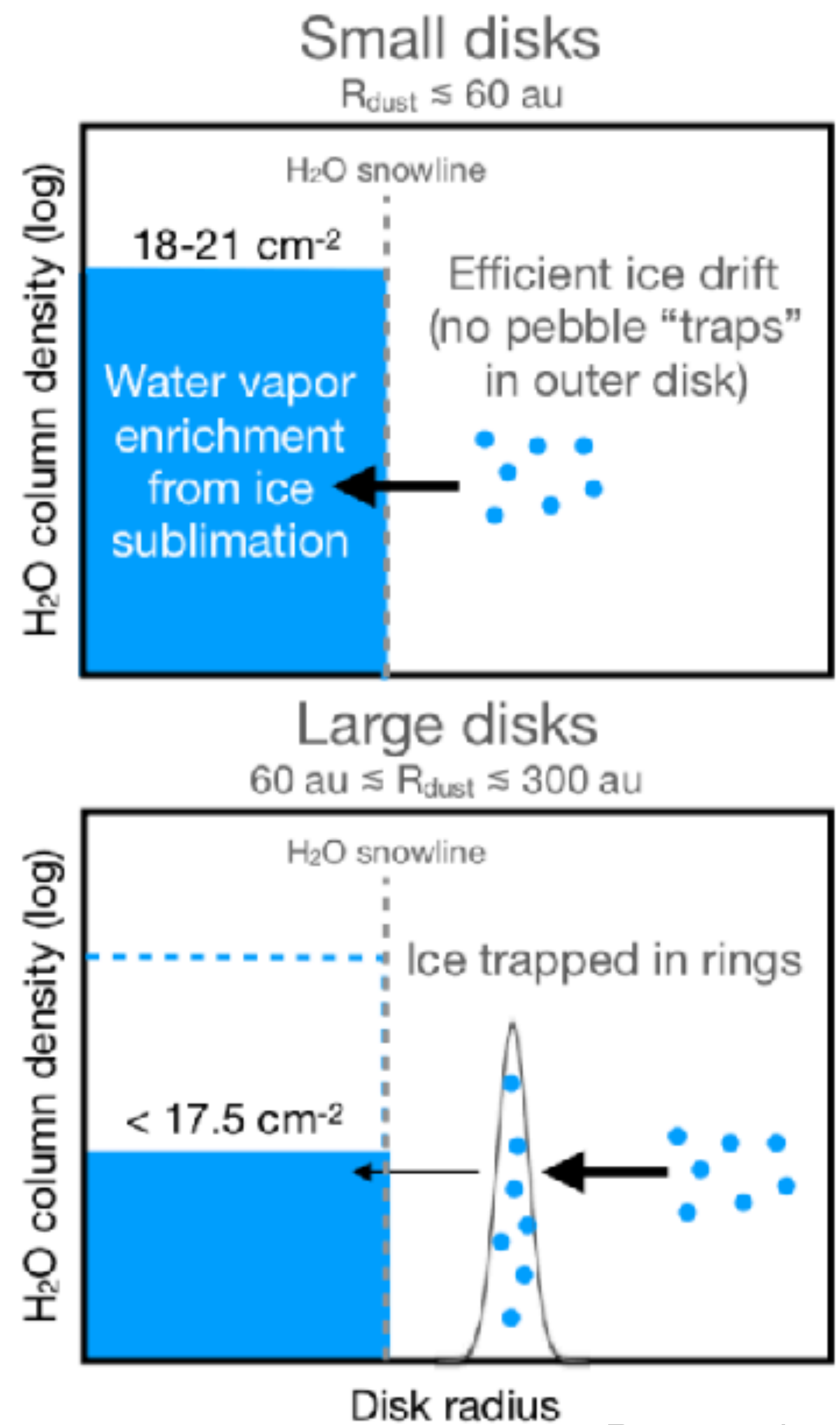


Van der Marel et al. 2019

Consequence: compact disks have no gaps?

H_2O anti-correlated with compact dust disks

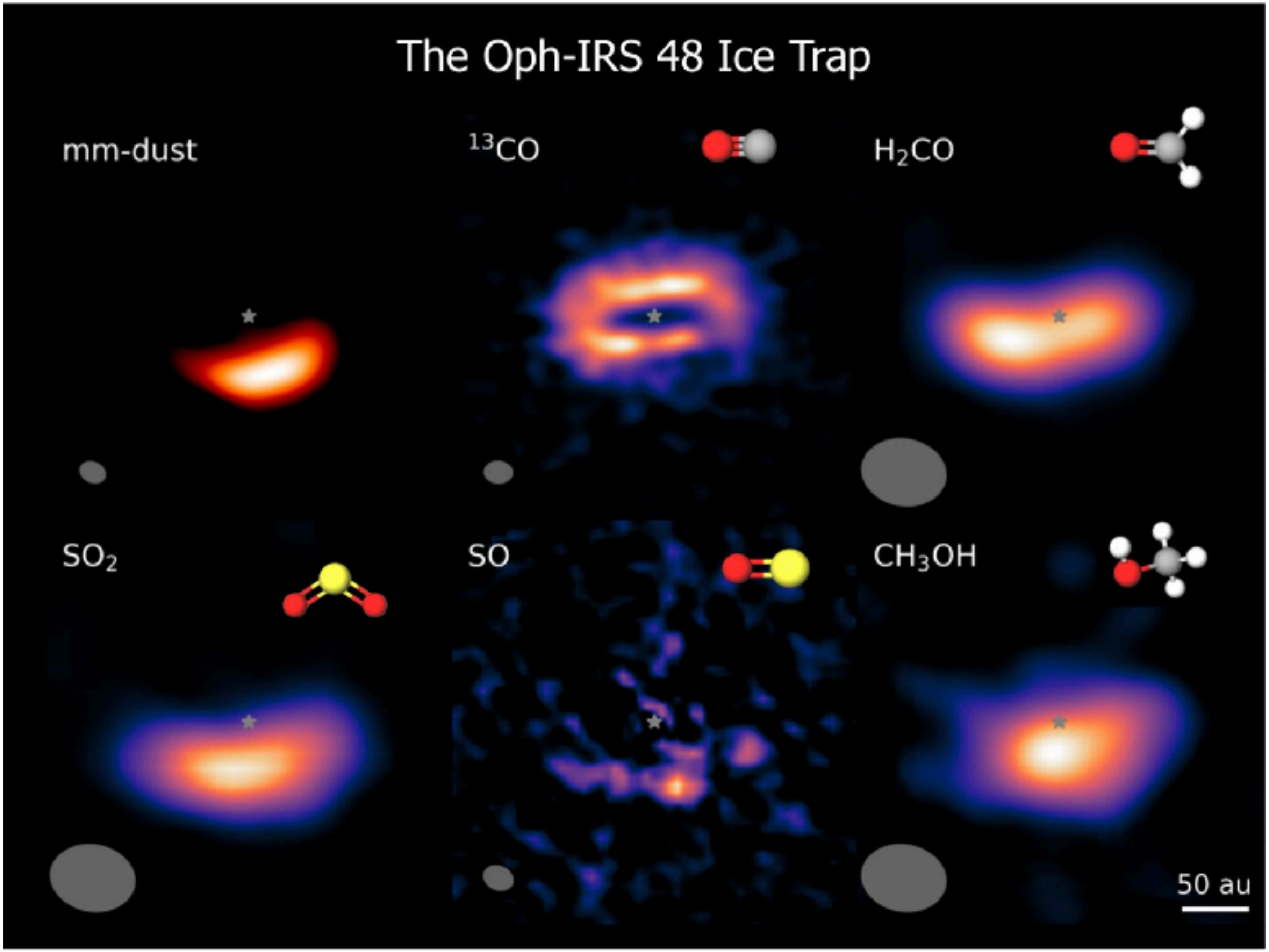




Dust transport regulates chemistry?

Banzatti et al. 2020
Kalyaan et al. 2021

Dust transport regulates ice chemistry?

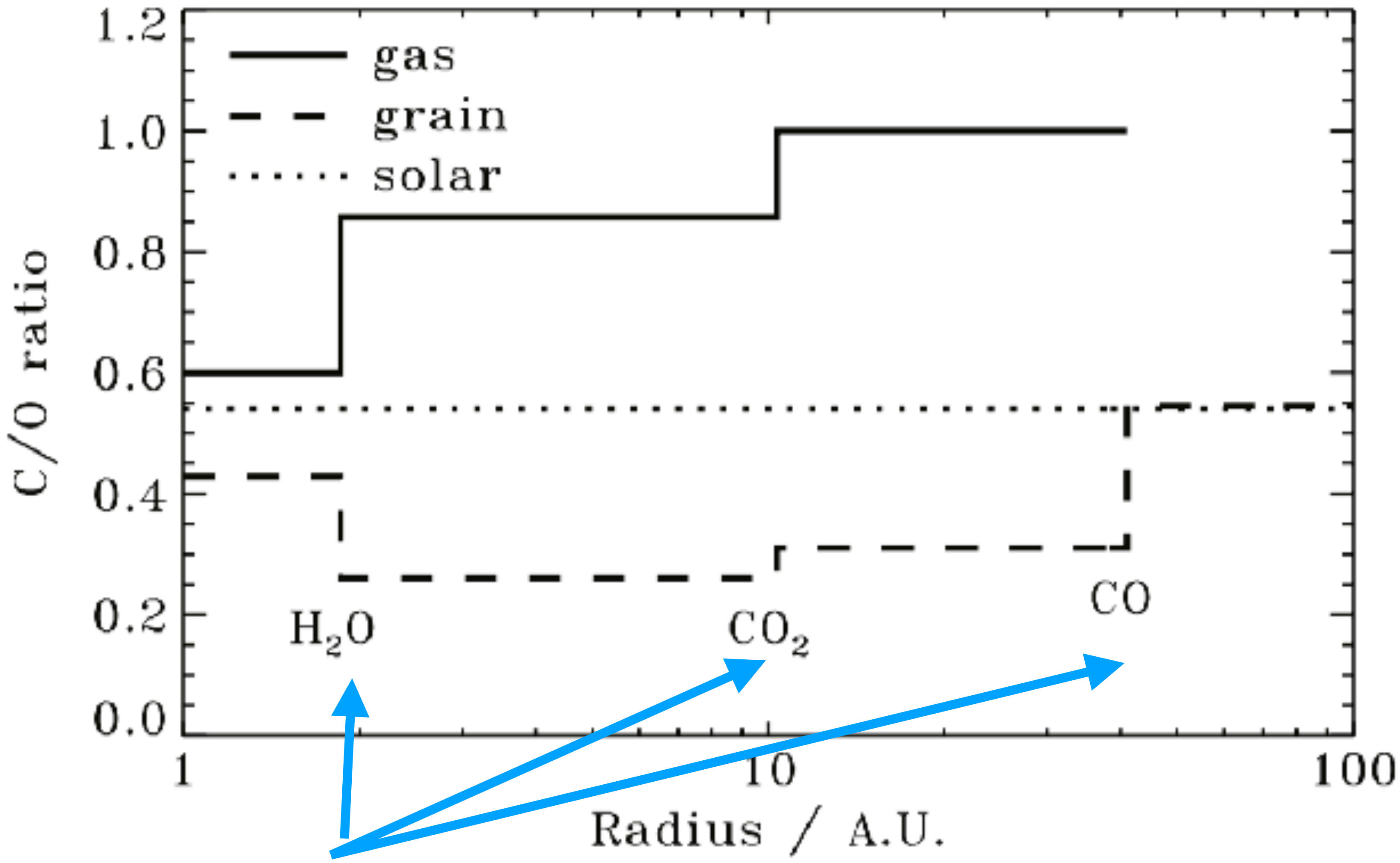


COMs and evidence for C/O < 1 in IRS 48 dust trap!

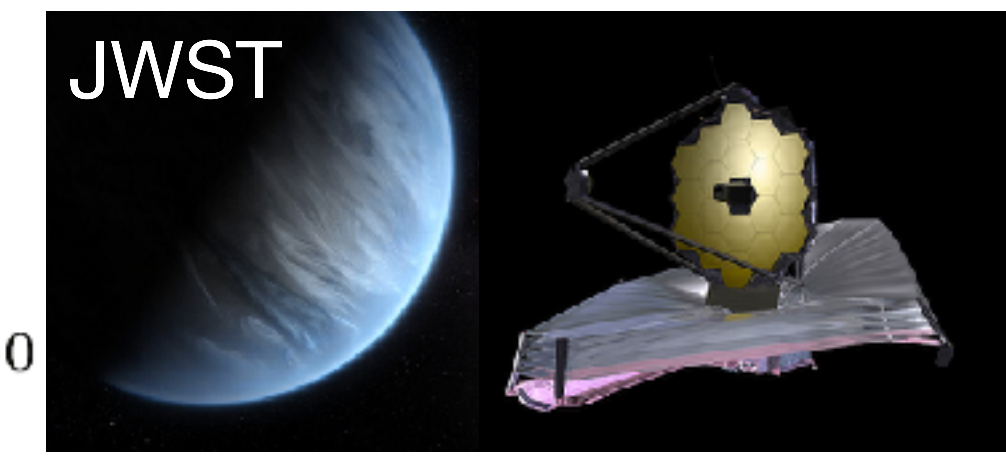
Van der Marel et al. 2021b
Booth et al. 2021b

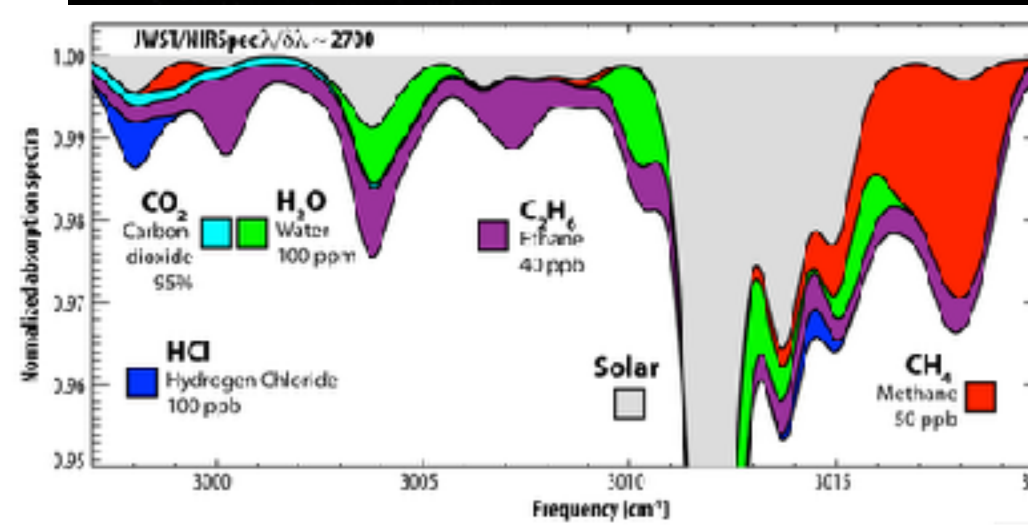
Why do we care about C/O?

Classical picture of C/O in disk: snowlines



Snowlines

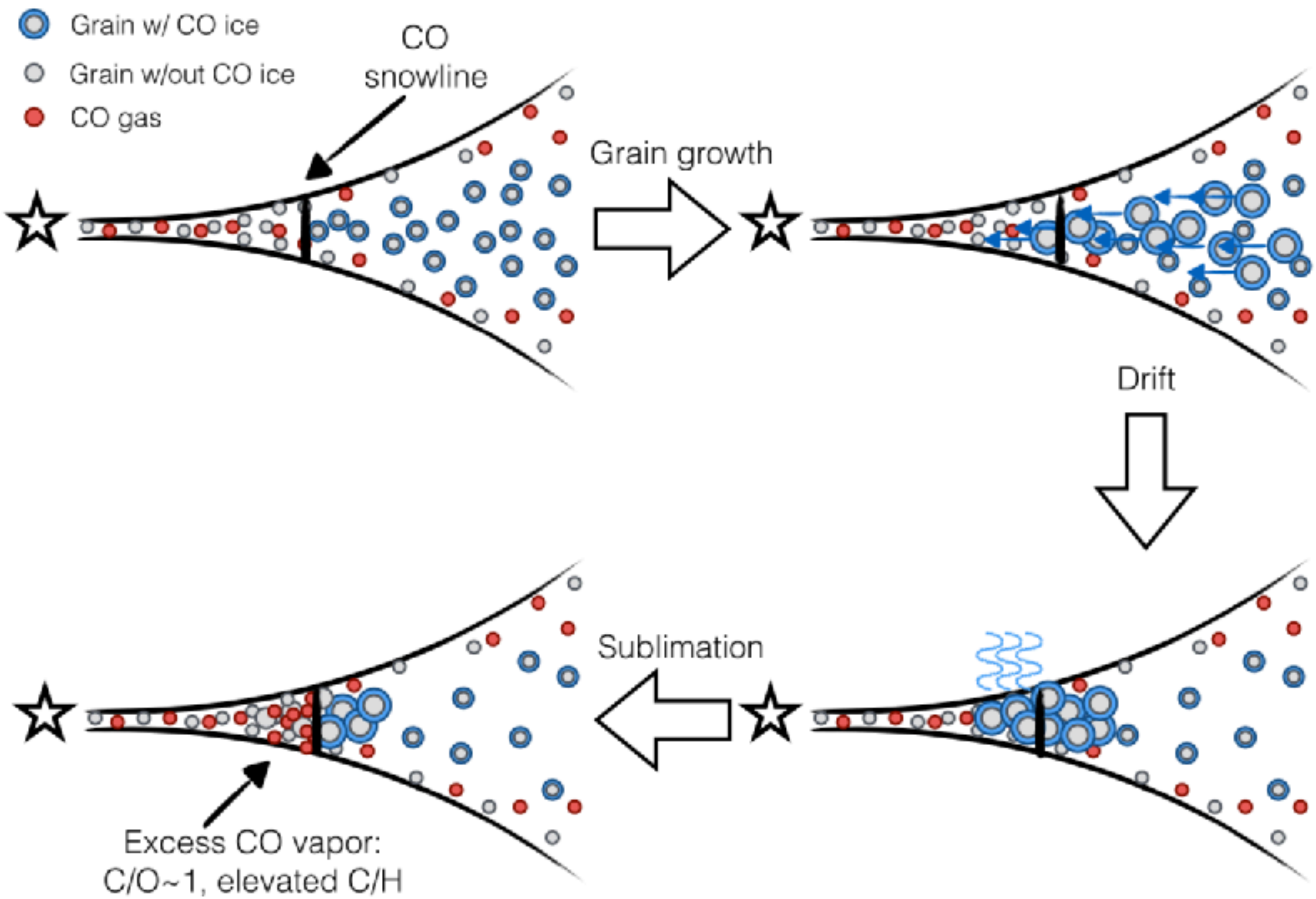




Link exoplanet atmospheric composition to formation location

Oberg et al. 2011

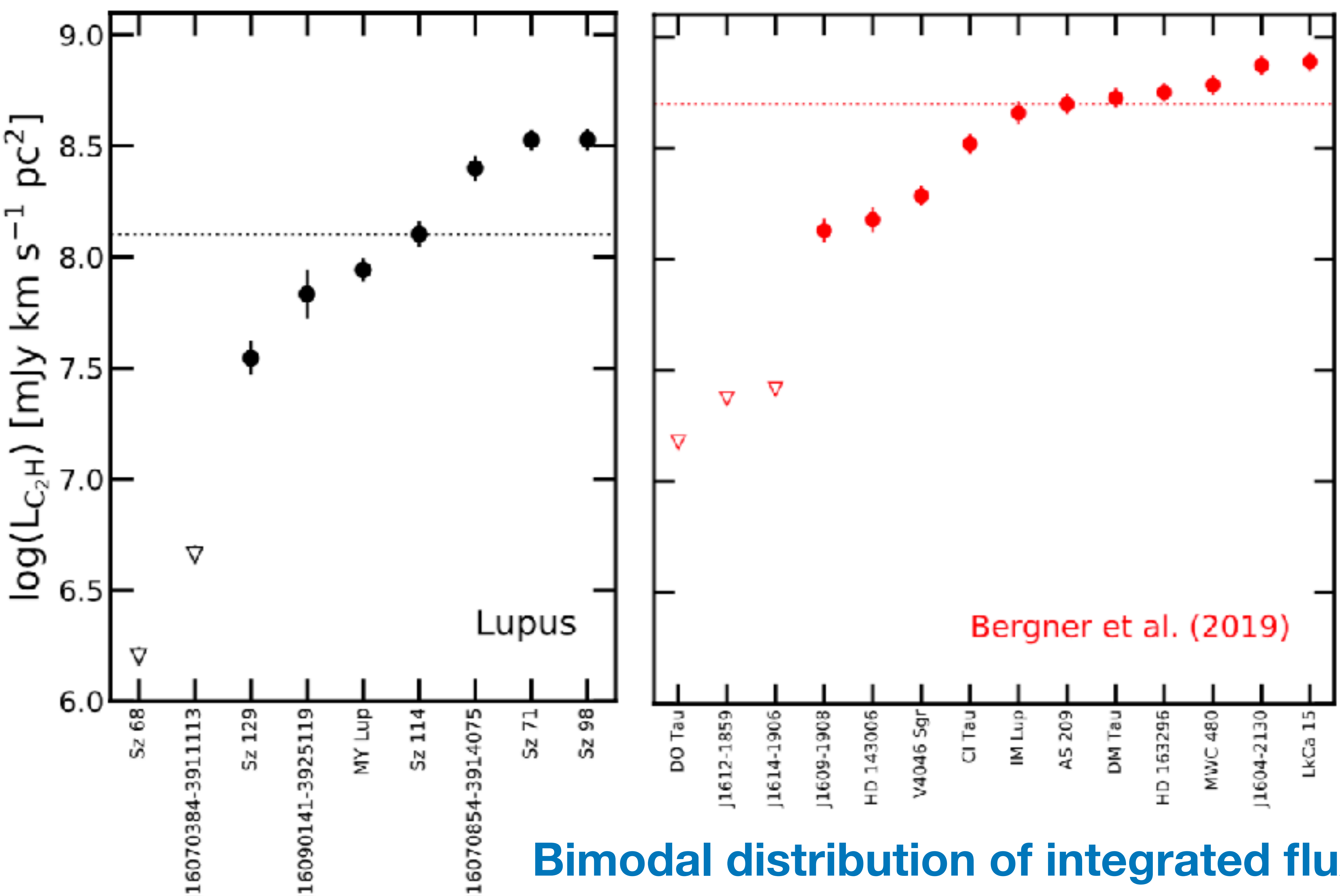
Dust transport regulate (ice) chemistry?



Dust pebble drift can cause CO depletion and **increase C/O > 1**

Oberg et al. 2016
Booth & Ilee 2019
Krijt et al. 2020

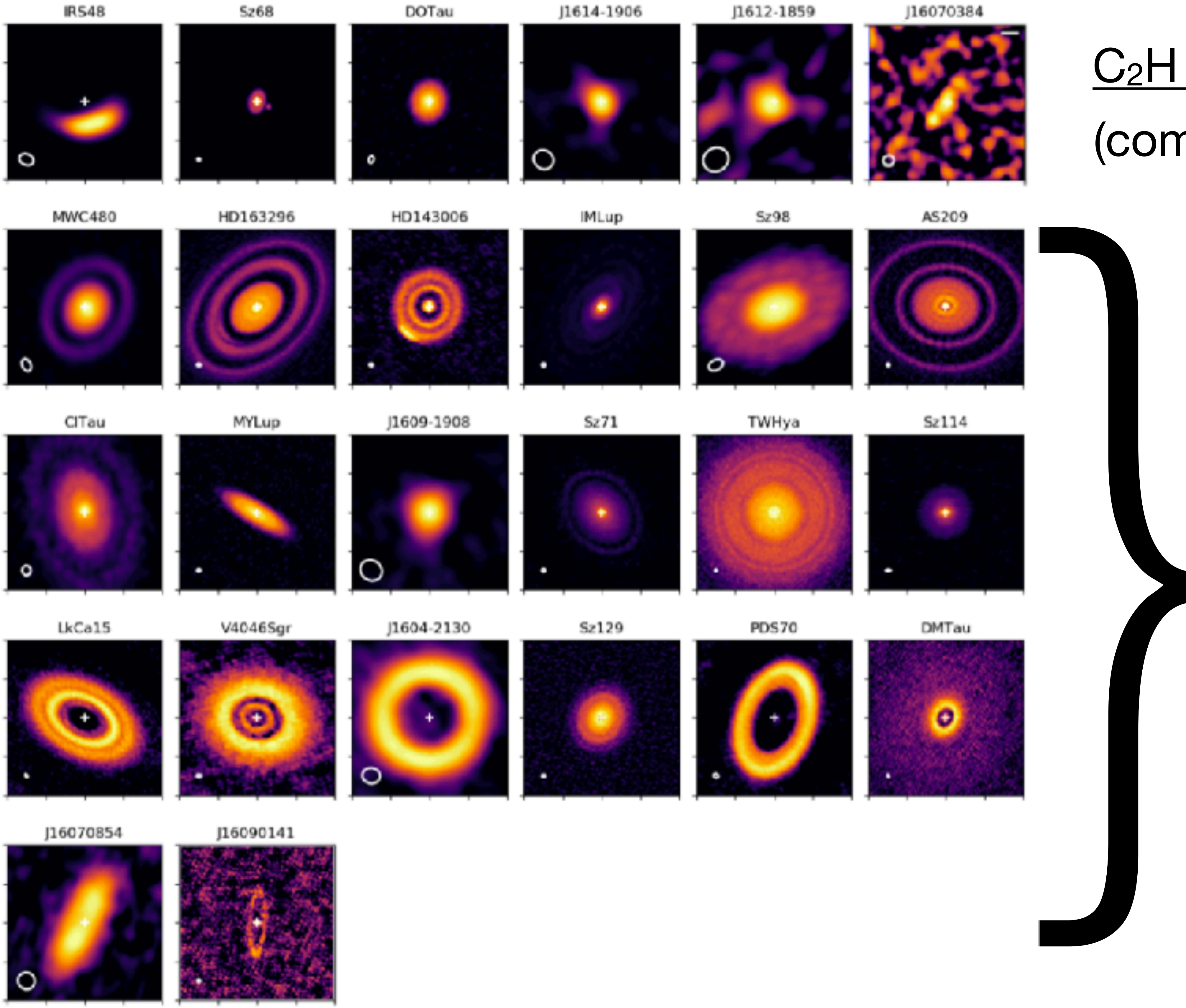
C_2H observations: measure of C/O



Bimodal distribution of integrated fluxes

Miotello et al. 2019
Bergner et al. 2019

Link with continuum substructure?



<u>C_2H non-detection</u>

(compact + IRS48)

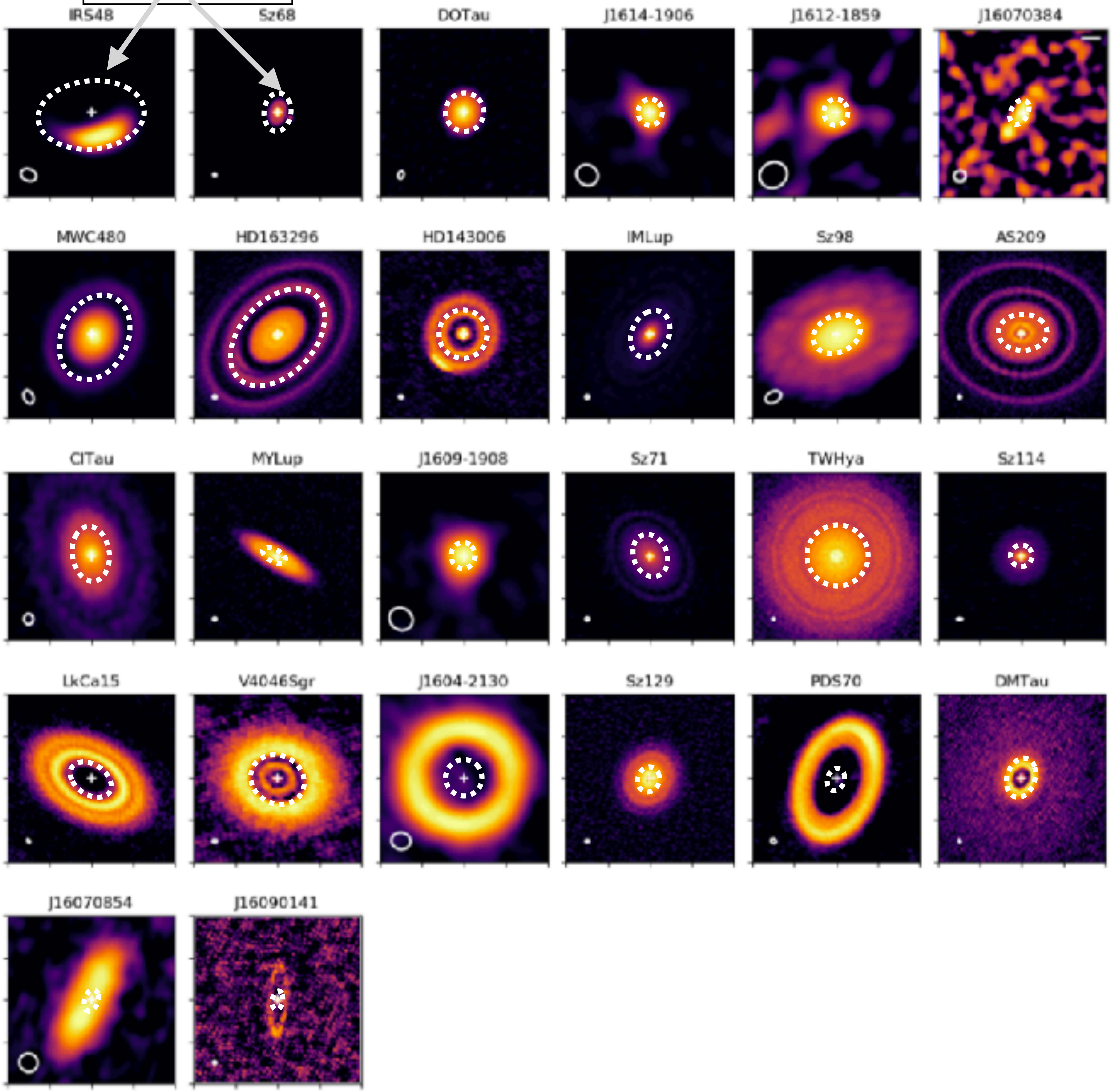
<u>C_2H detections</u>

(ring disks)

Van der Marel et al. 2021c

Link with CO snowline?

CO snowline
(22-30 K)



C_2H non-detection

(compact + IRS48)

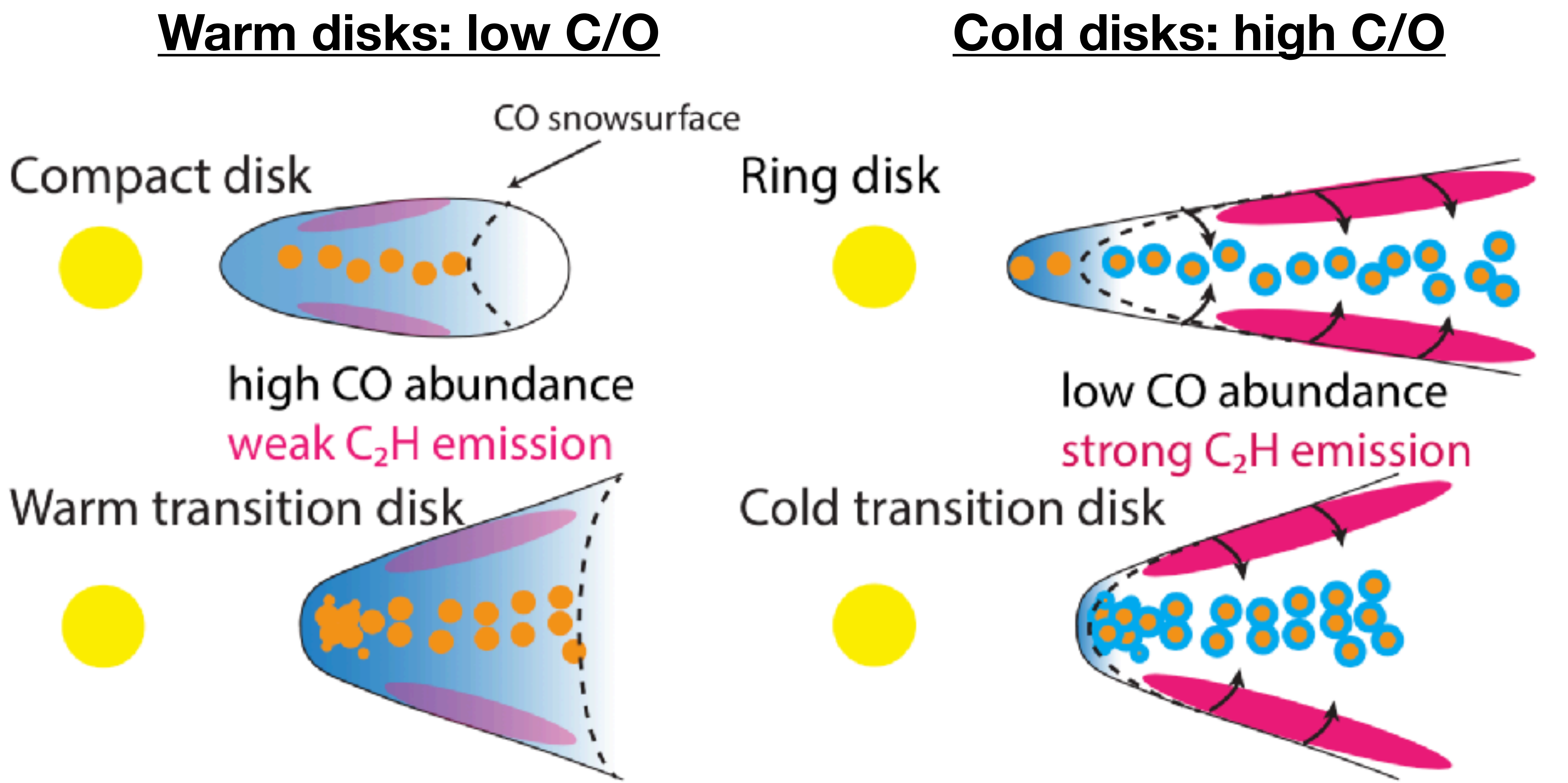
C_2H detections

(ring disks)

C_2H disks have icy dust reservoir outside CO snowline

Van der Marel et al. 2021c

Dust transport regulates (ice) chemistry?



Consequence: material accreted onto planet depends on snowlines AND dust transport

Van der Marel et al. 2021c

Summary

- There may be **two evolutionary pathways** for structured and compact disks, set by the presence/absence of pressure bumps
- **Decoupling mm-dust evolution** from gas/micron-dust evolution helps to understand the disk evolution process.
- **Disk lifetimes** of micron-dust may be as long as **8 Myr** when excluding UV-dominated regions
- Structured disks show a **stellar-mass dependence**
- Under the assumption of migration, there are **sufficient giant exoplanets** to explain the number of gapped disks
- **Super-Earths occurrence rates** match those of compact disks, suggesting they are related.
- Structured disks are likely progenitors of **debris disks**
- Dust transport has a profound effect on the **chemistry in disks**
- The **C/O ratio of exoplanet atmospheres** may be set by the interplay of snowlines and pressure bumps

Questions?