Lecture 4
Disk substructures and their connection to planets

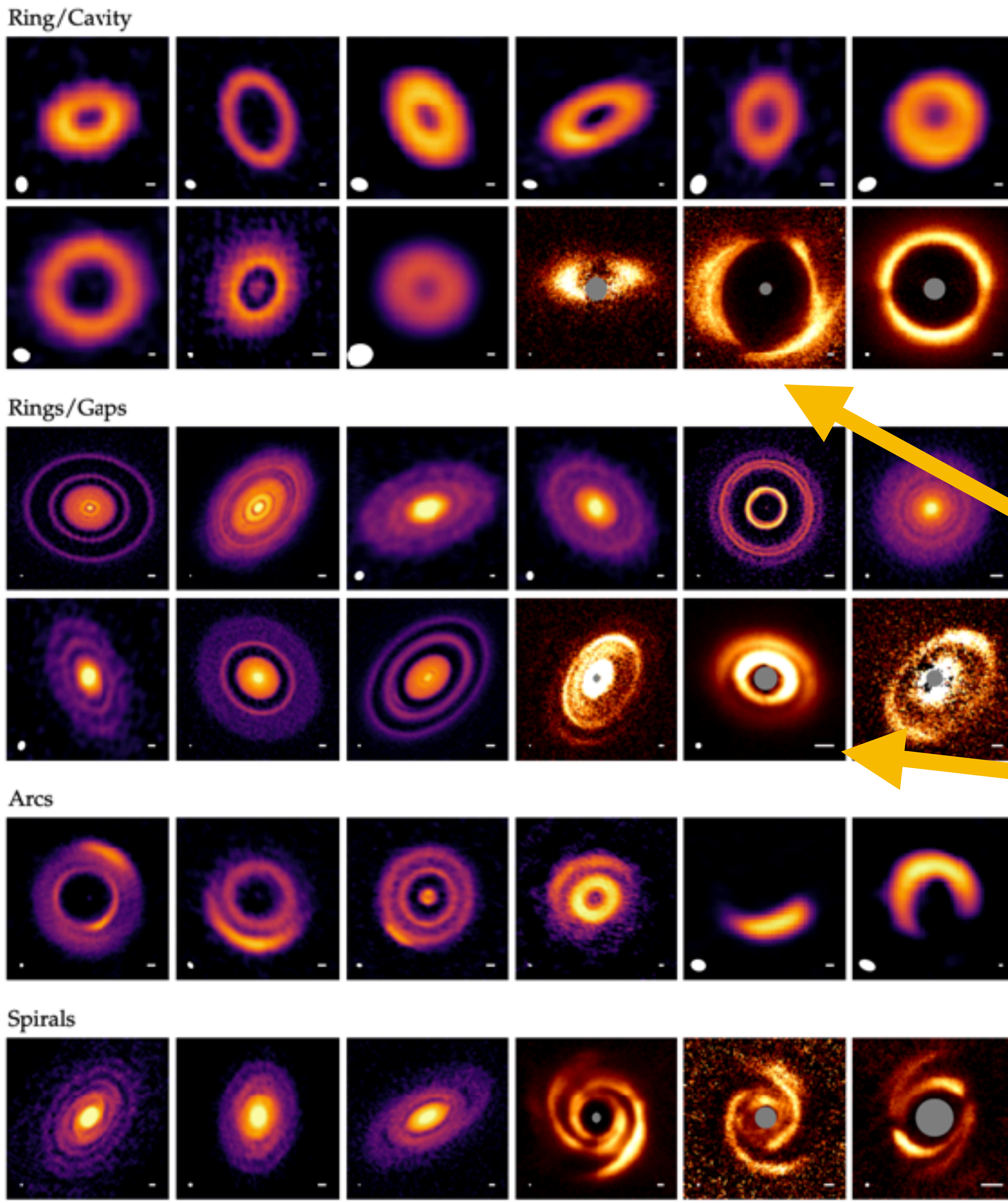
AstroTwin Colombia School 2022
Planet formation and ALMA

dr. Nienke van der Marel
Leiden Observatory

Contents

Overview substructures

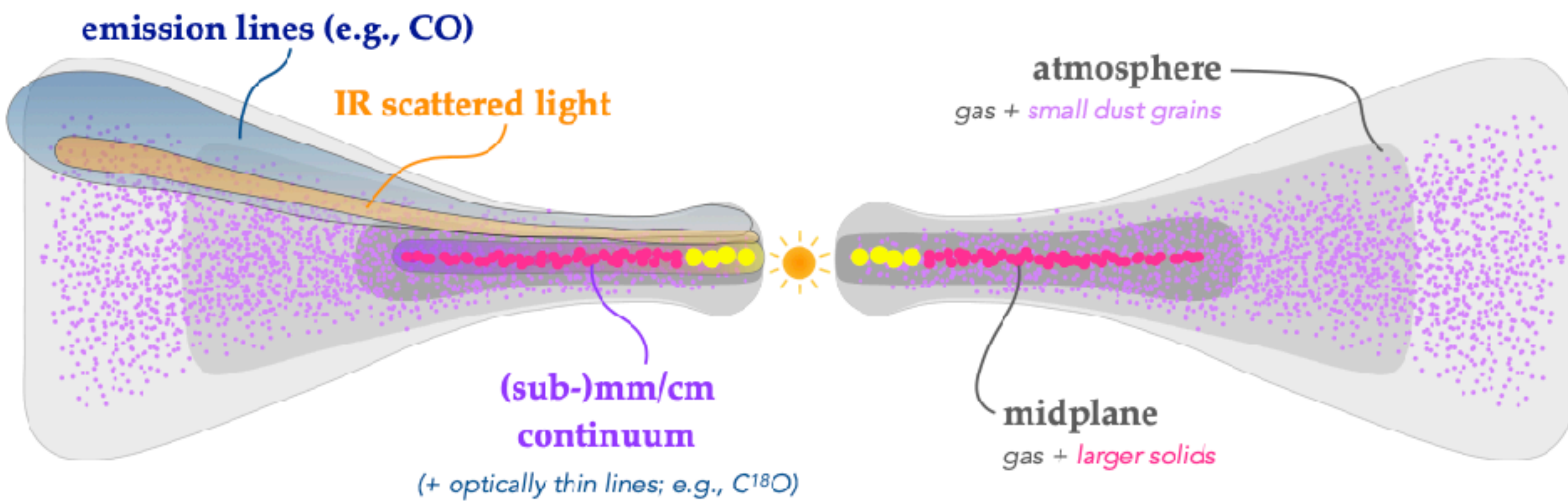
Mostly mm-observations



NIR observations (scattered light)

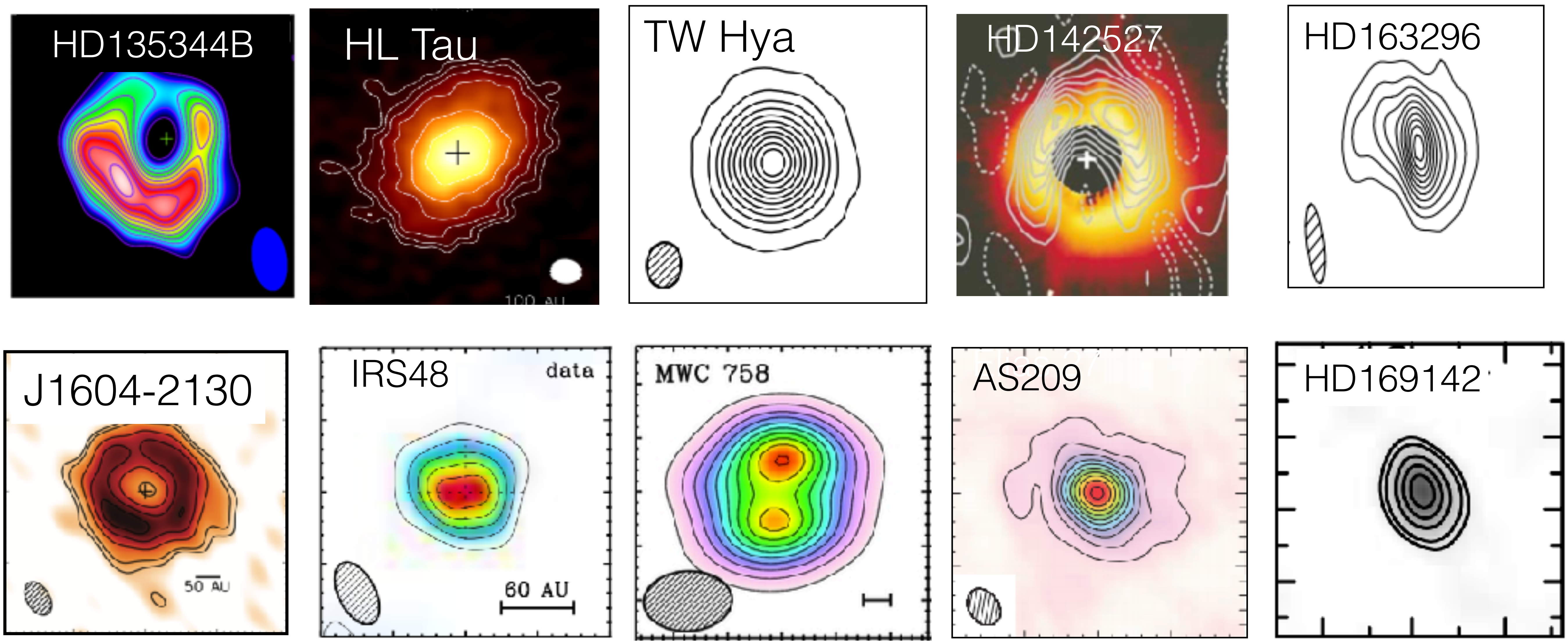
Andrews 2020

Disk structure



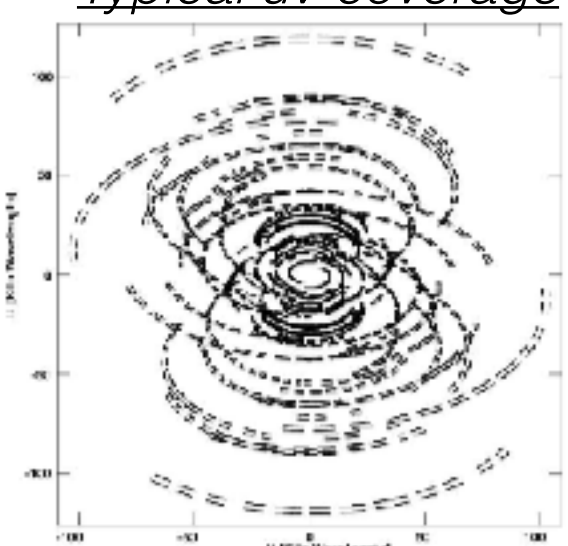
Andrews 2020

Pre-ALMA disk observations (mm)



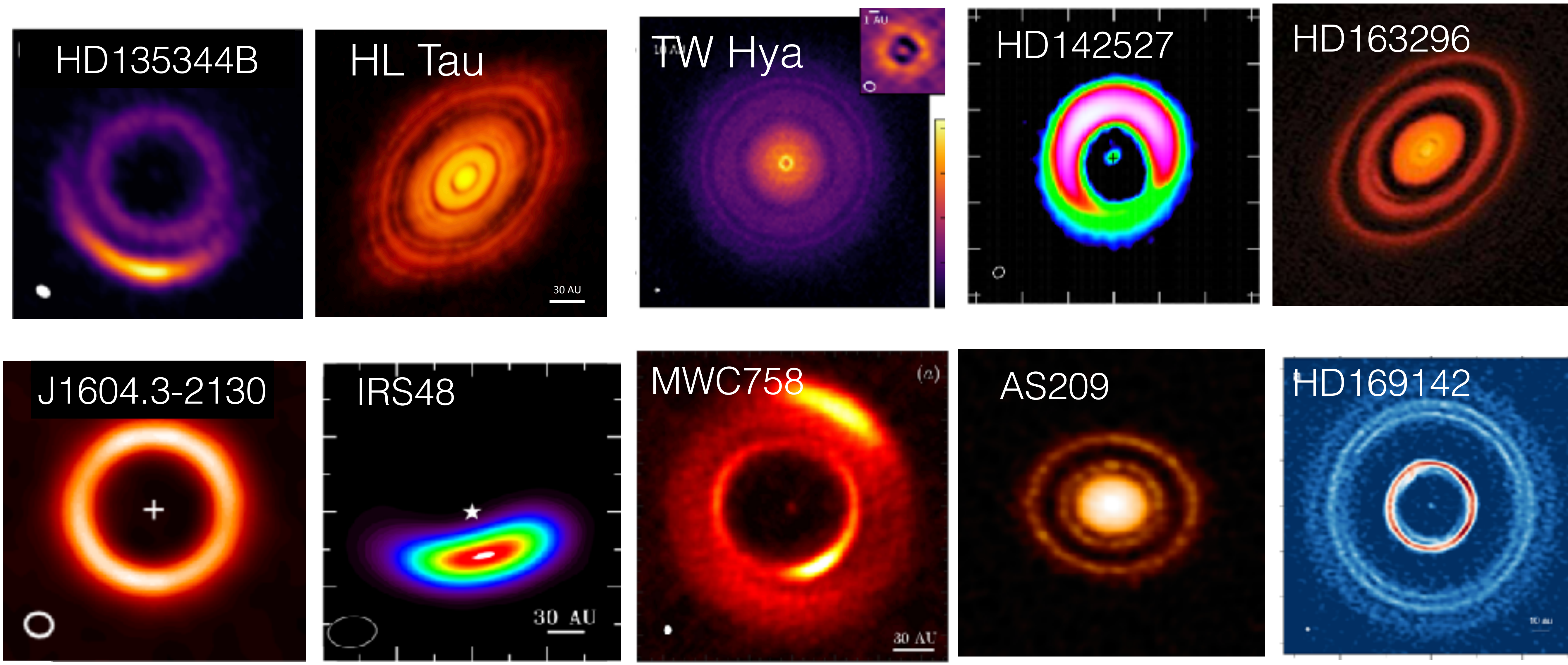
Typical resolution ~0.5-0.8”

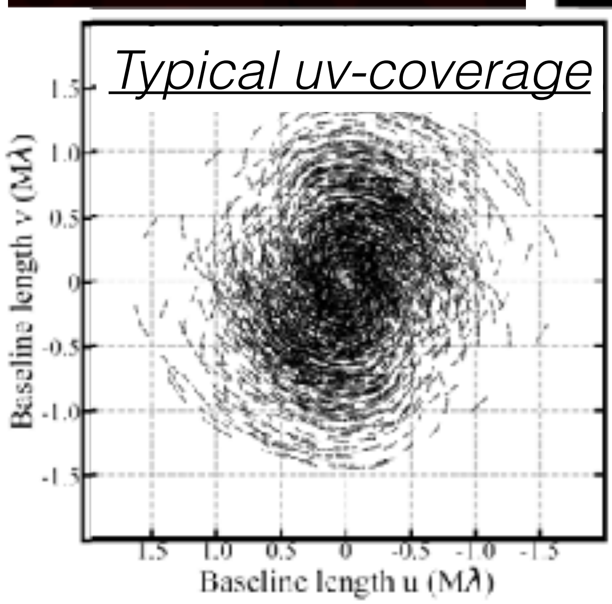
Typical uv-coverage



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 (mm)



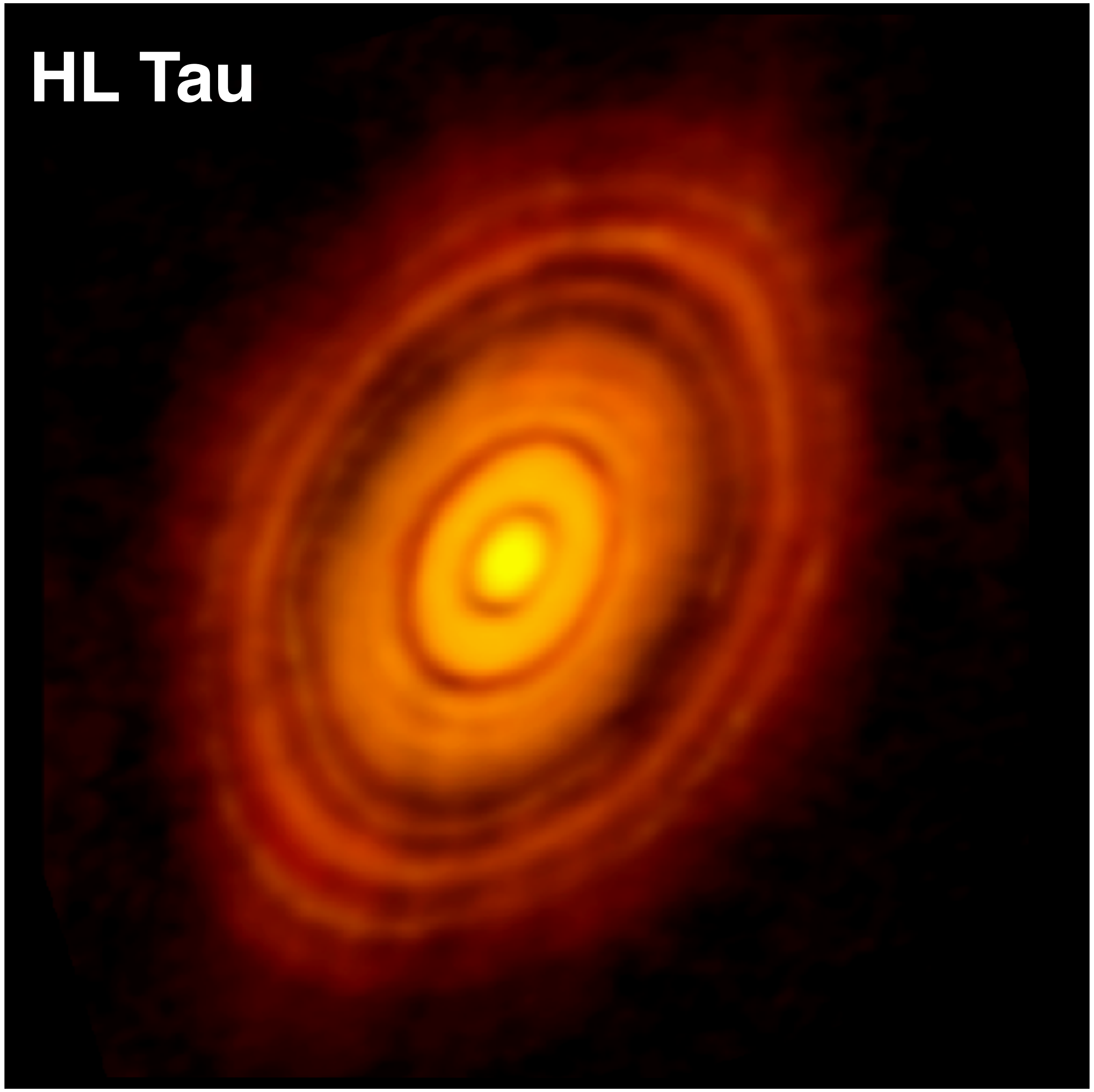


Typical resolution ~0.05-0.1"

Enormous diversity of large-scale (10-100 au) 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

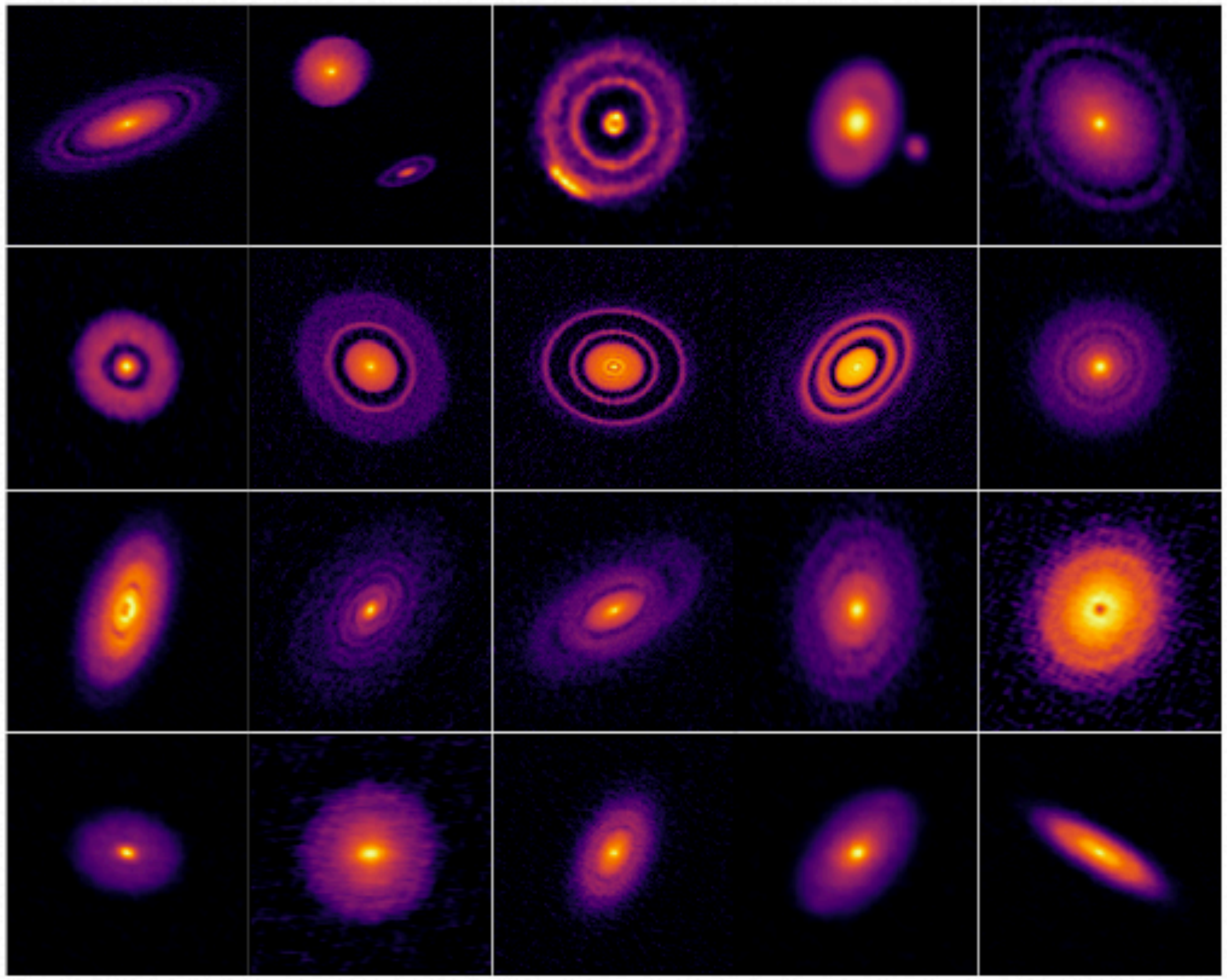
How it started:



Resolution ~0.05"

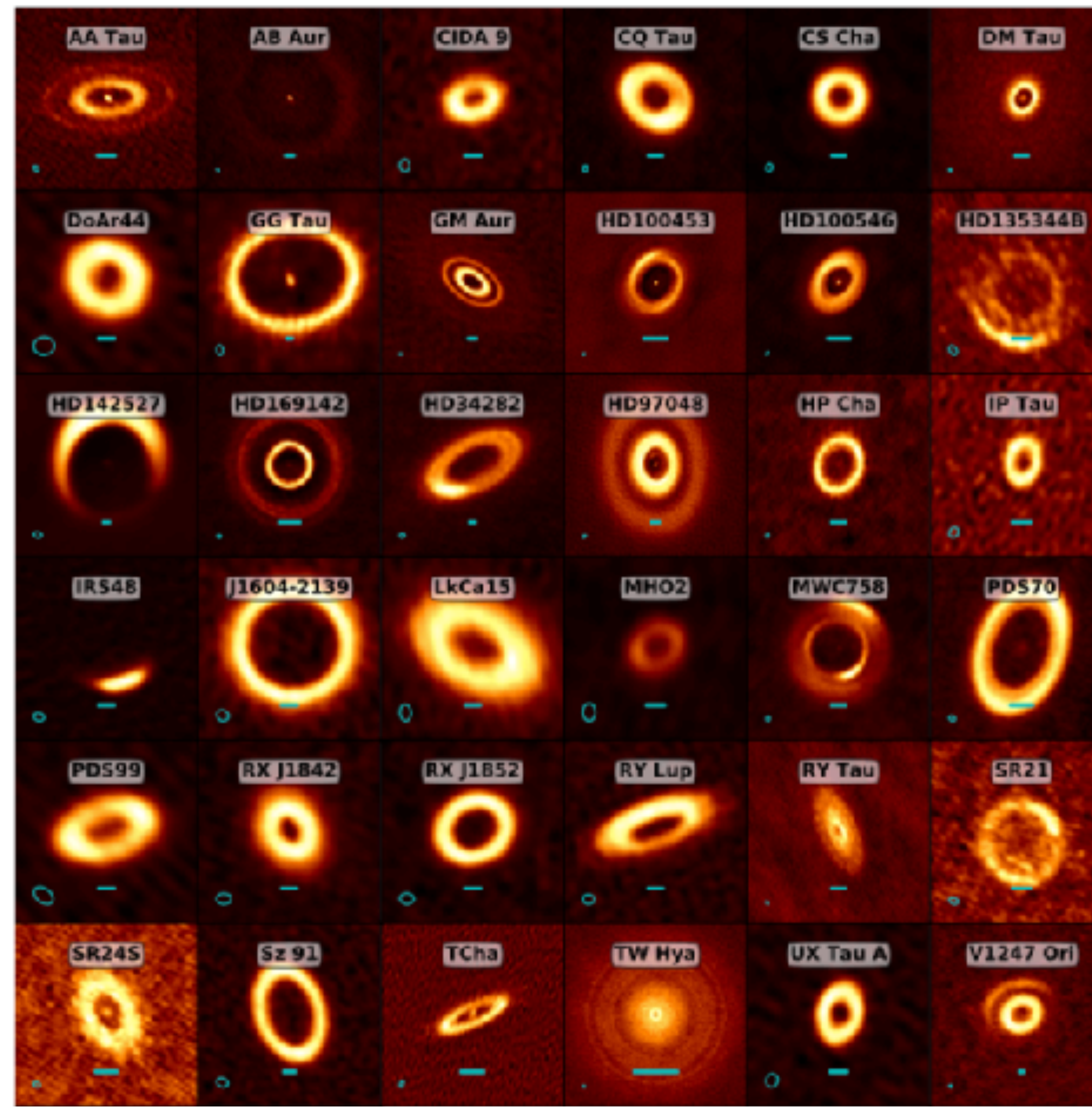
ALMA consortium et al. 2015

…and how it's going



DSHARP: gaps and rings

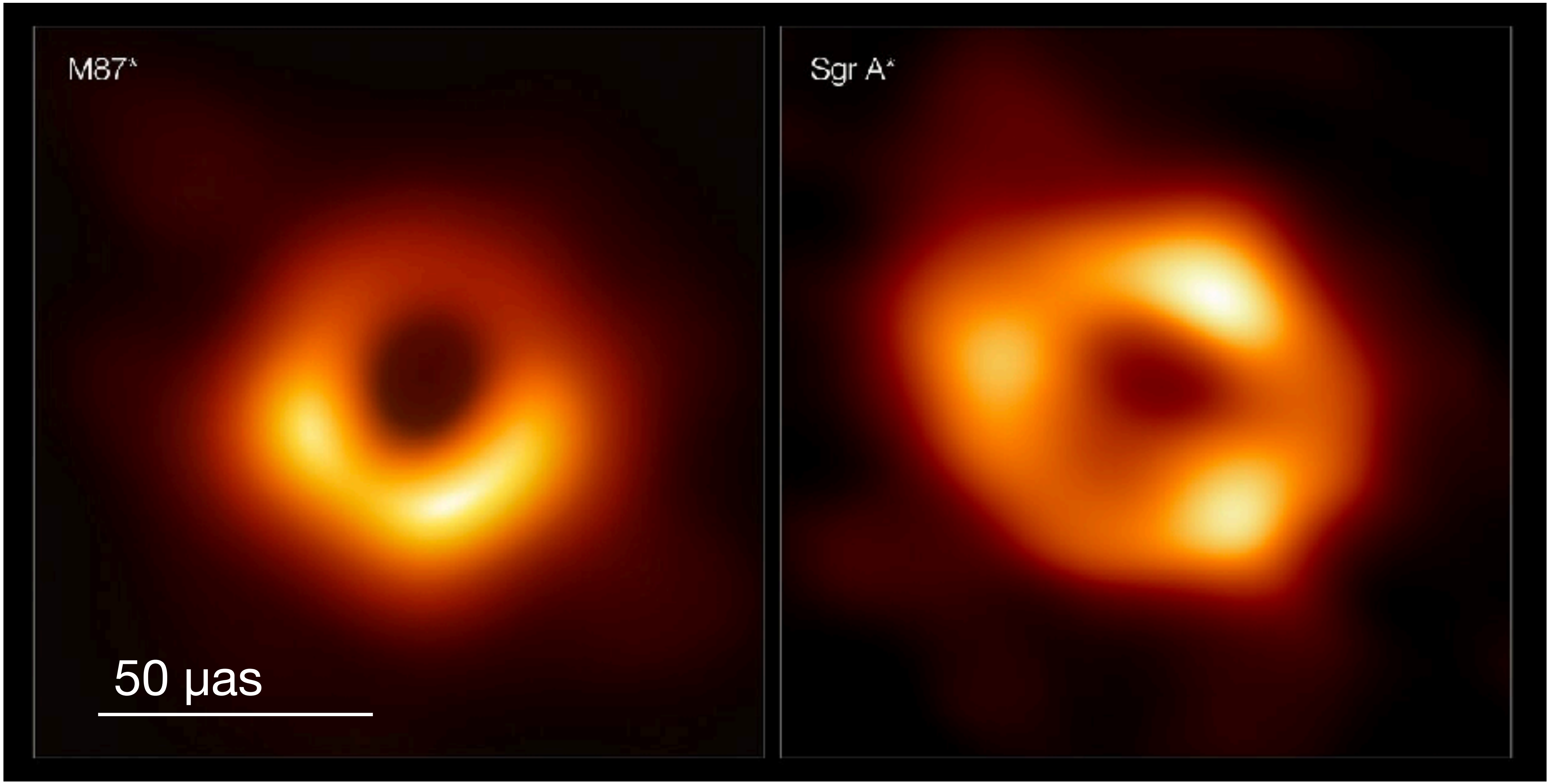
Typical resolution ~0.04" - 0.1"



Inner cavities

Andrews et al. 2018
Francis & van der Marel 2020

These are not protoplanetary disks!



(angular size 10,000 smaller than protoplanetary disk)

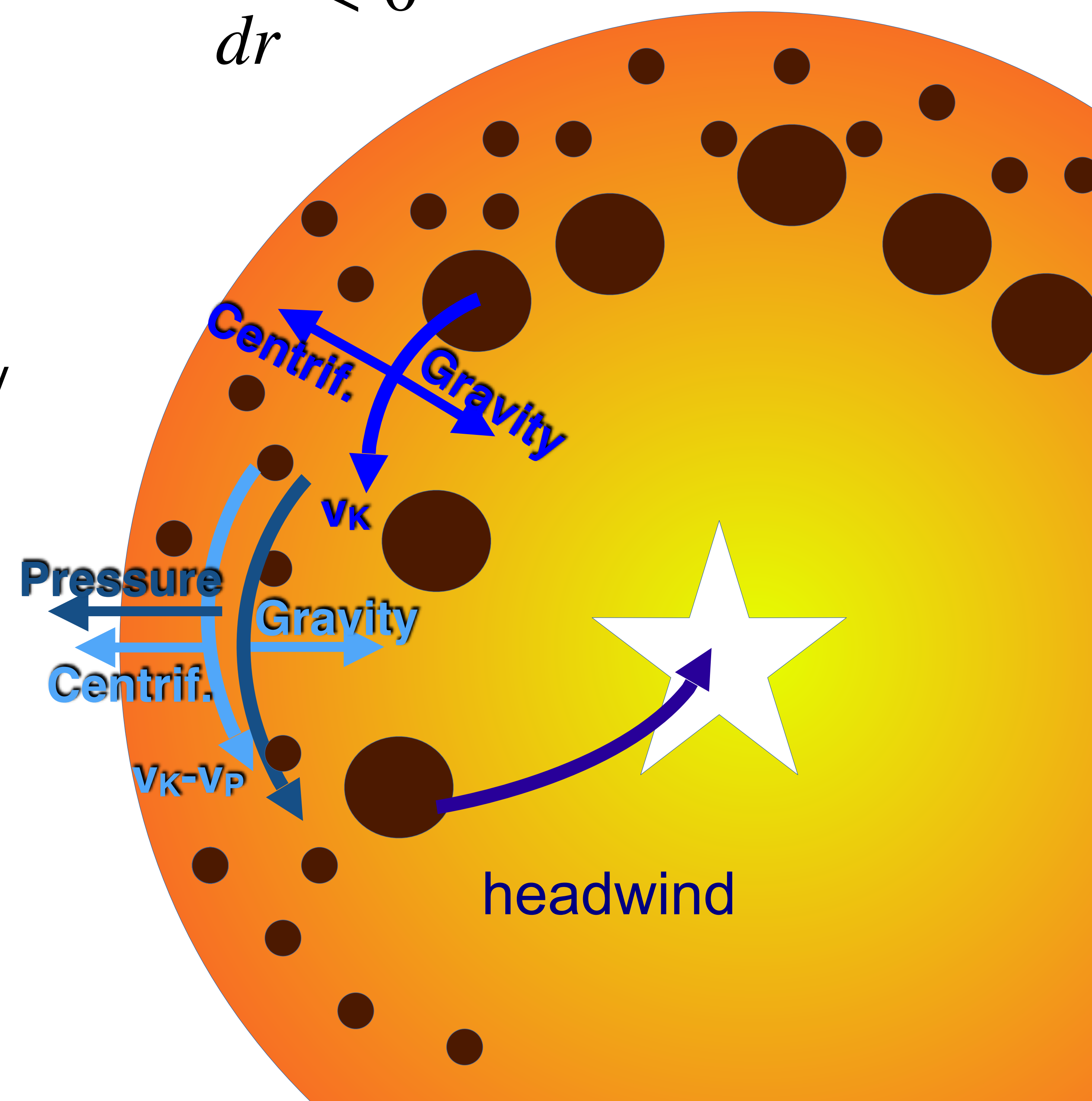
EHT consortium

So what's the origin of dust rings?

Recall:

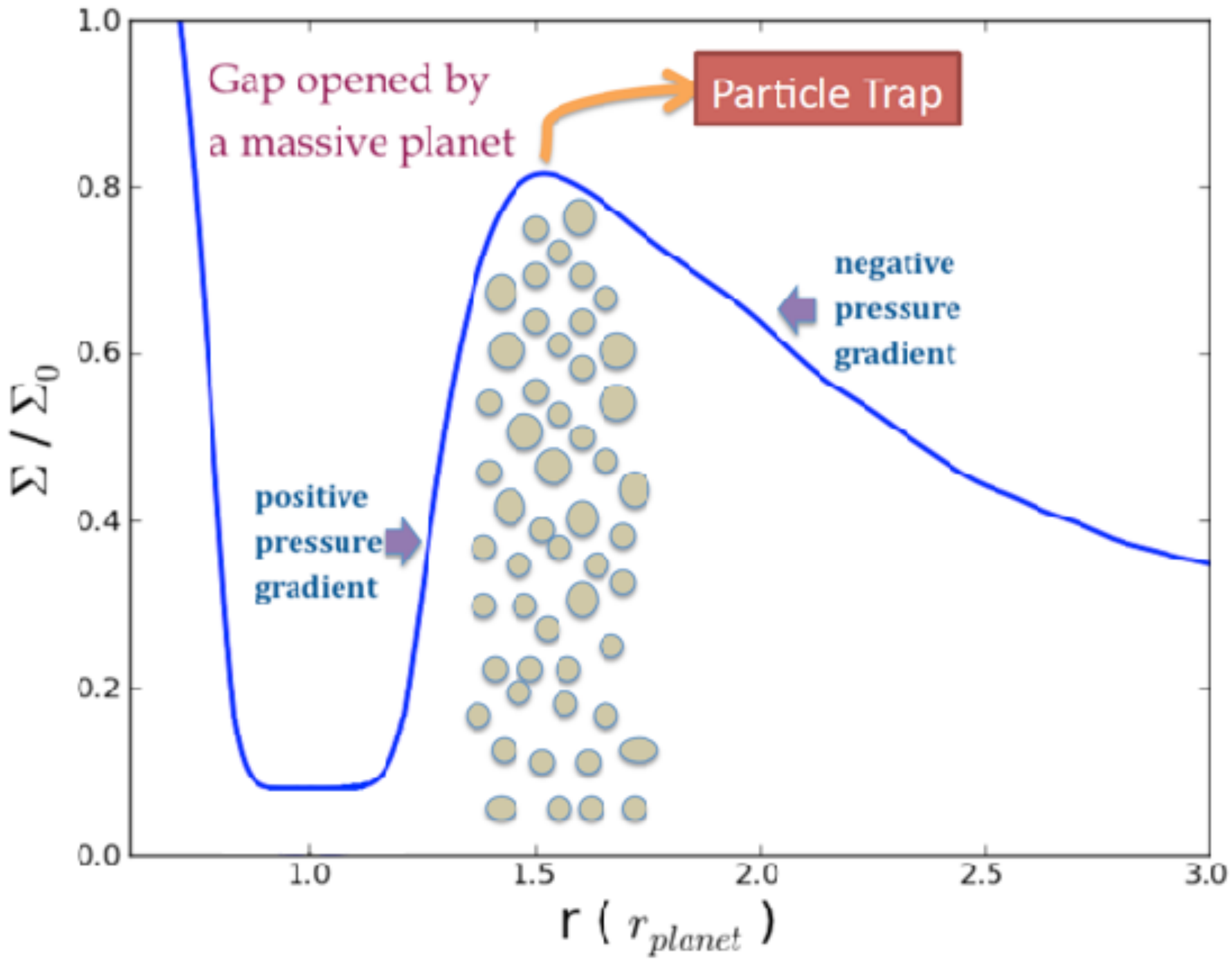
- Gas disk has a pressure gradient $\frac{dp}{dr} < 0$
  - Radial inward <u>drift</u> dust
- Large particles move towards high pressure
- Dust disk evolves differently than the gas disk

=> Need pressure bump to prevent radial drift

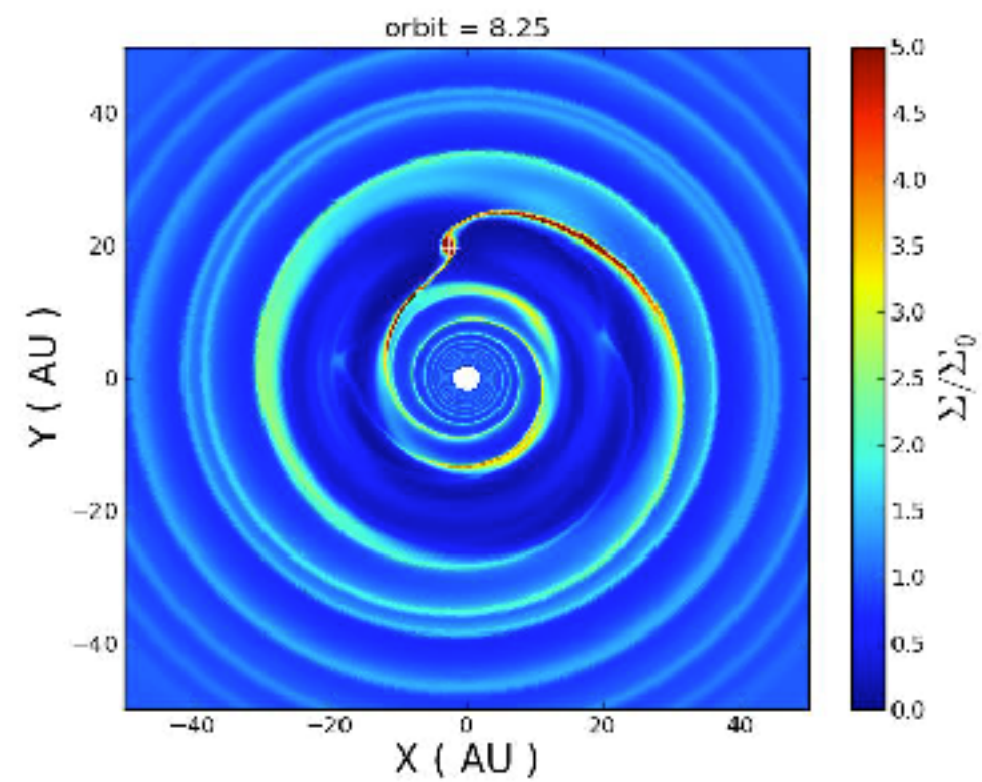


Weidenschilling 1977

Recall: dust trapping



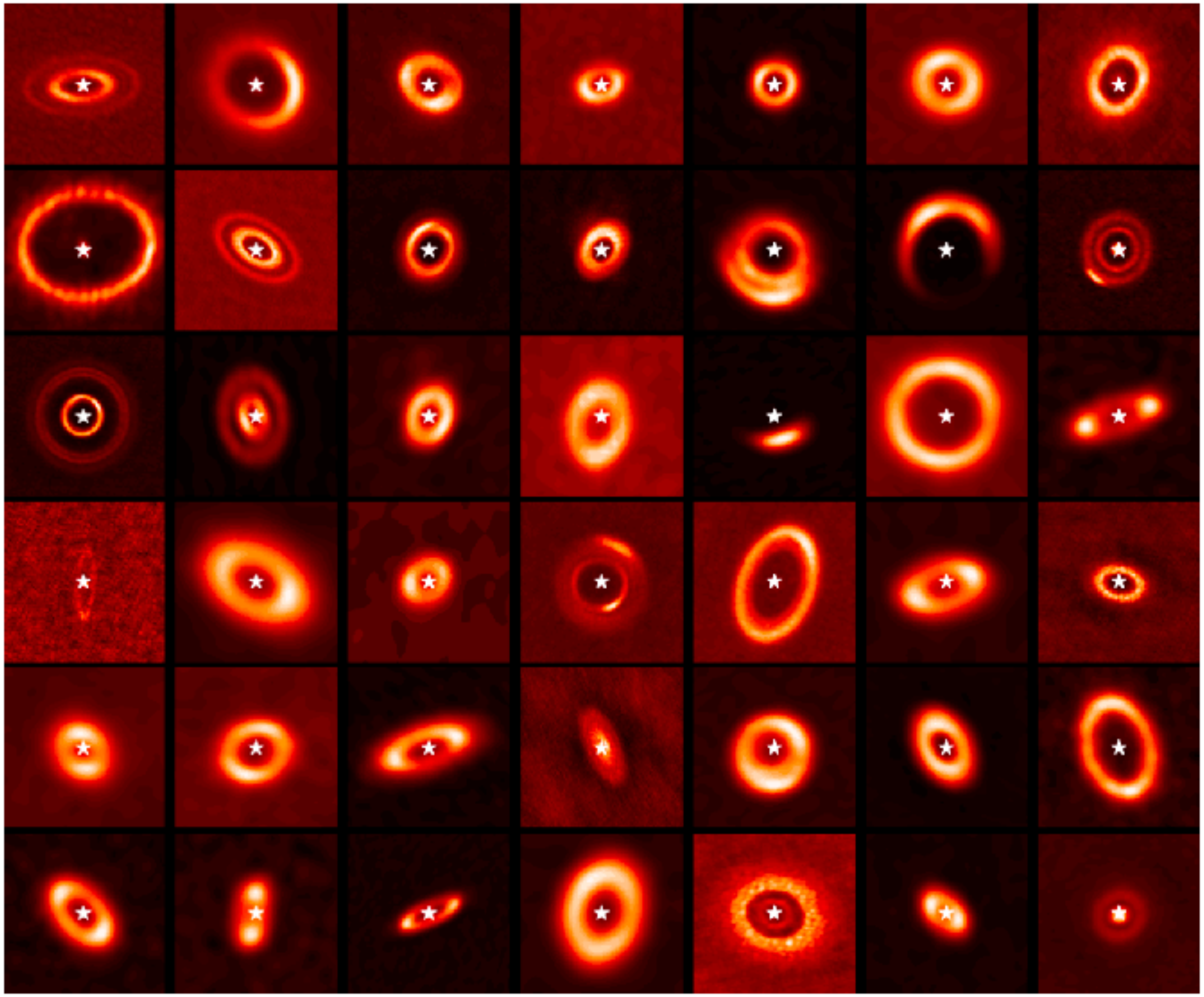
Rossby Wave Instability results in vortex: azimuthal dust trap



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

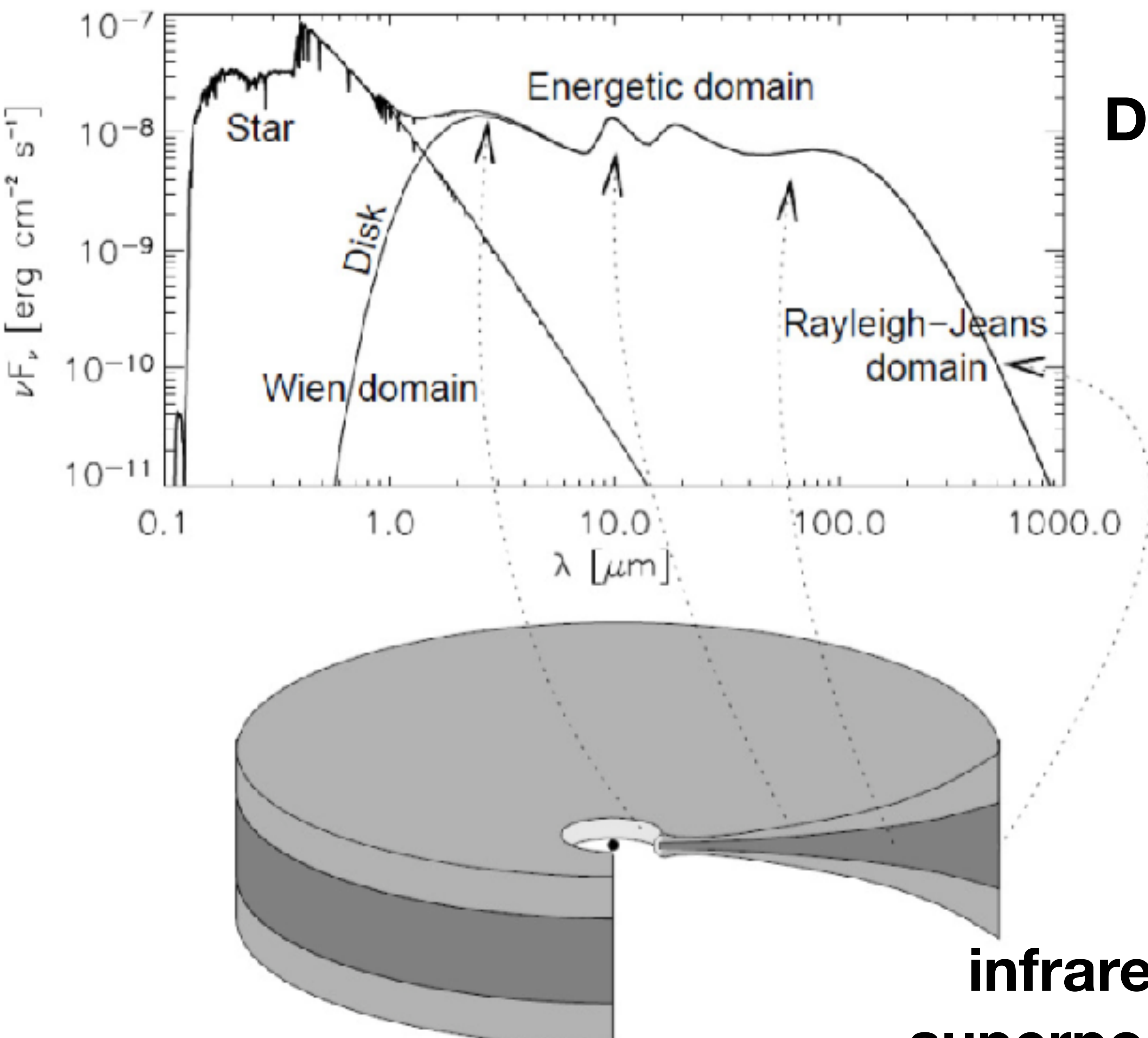
Barge & Sommeria 1995
Klahr & Henning 1997
Birnstiel et al. 2013

Large cavities / ‘transition disks’



Van der Marel 2022 (review)

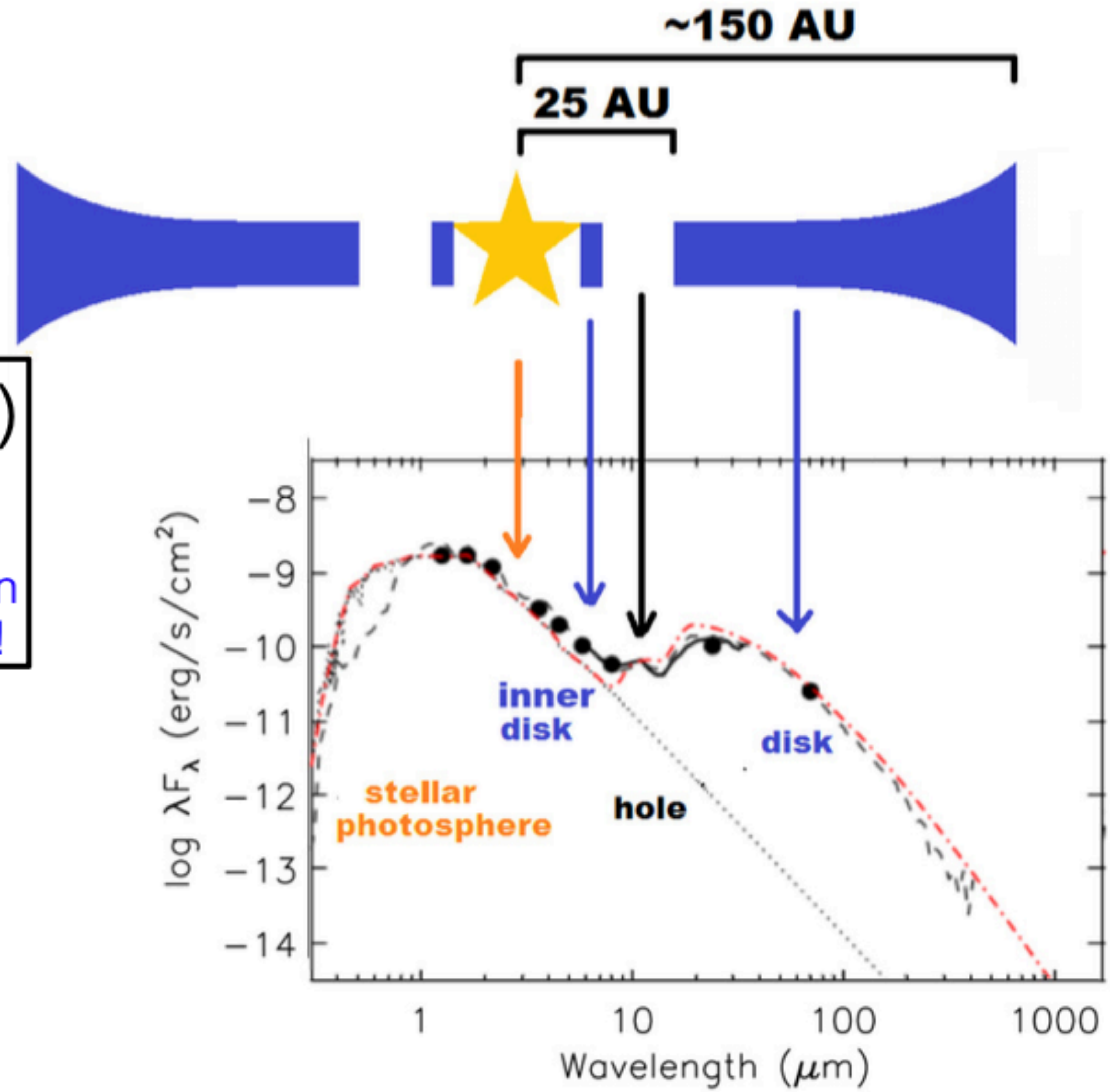
Recall: SED structure



Dust in disk gets heated up by the star: radial temperature gradient

infrared to mm emission: superposition of blackbodies

Transition disks

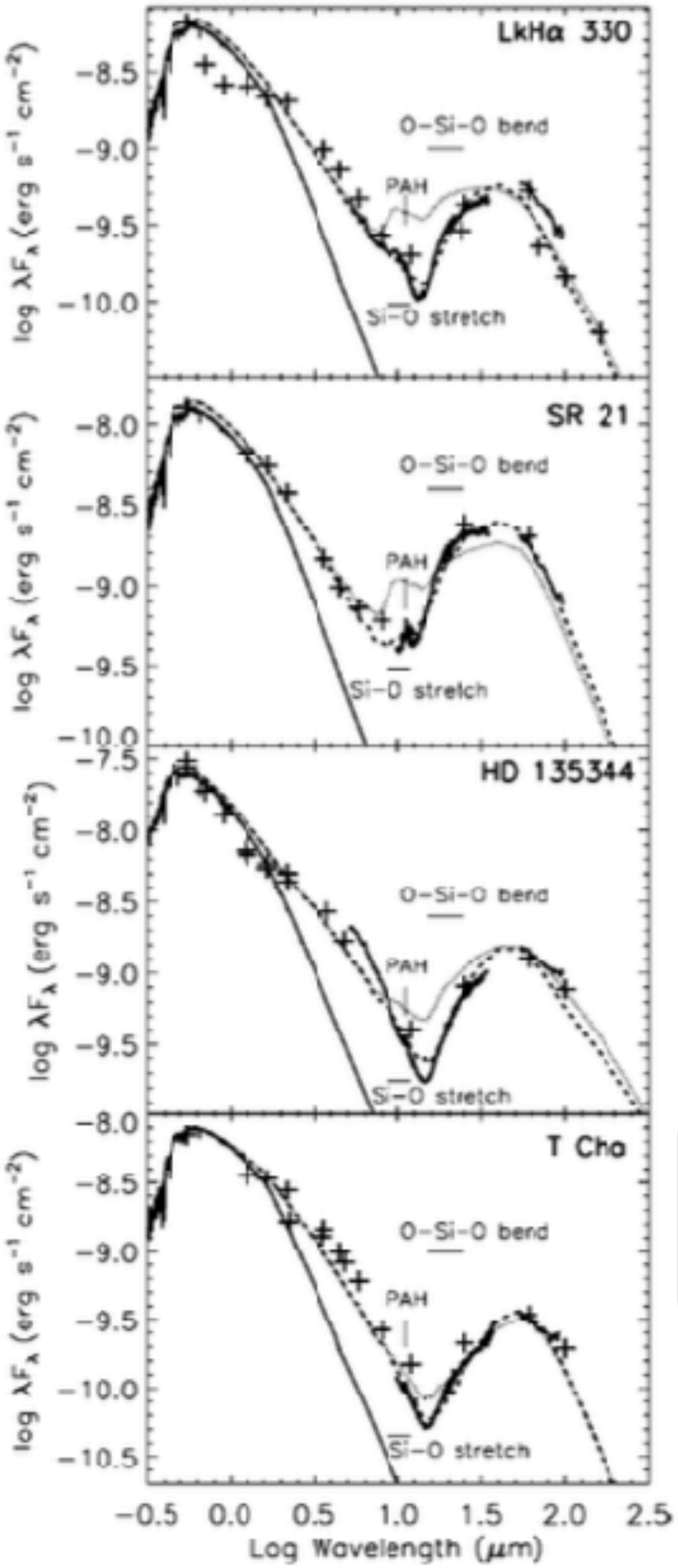


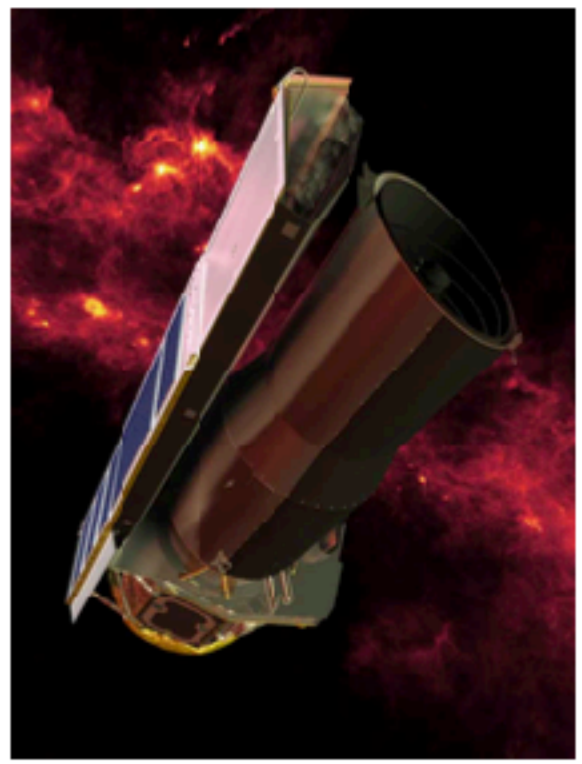
Transition(al) disks

Not necessarily an evolutionary term!

First discovery:
Strom et al. 1989

Transition disks

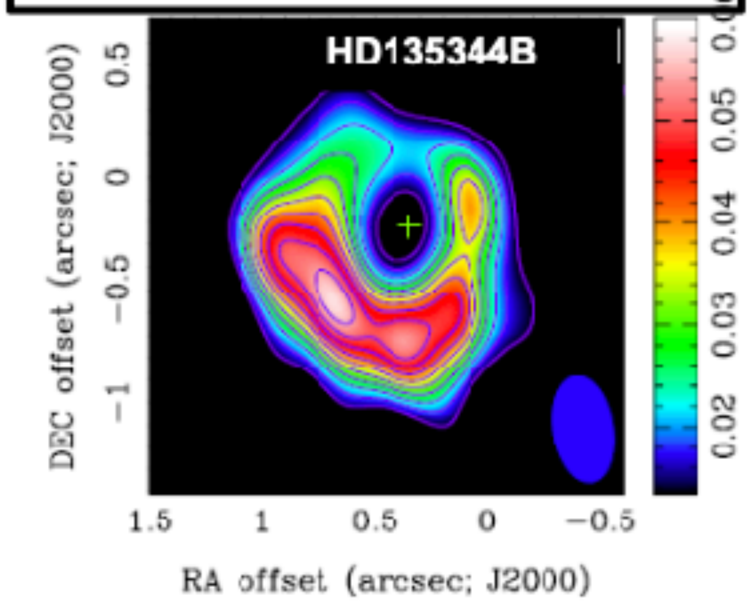


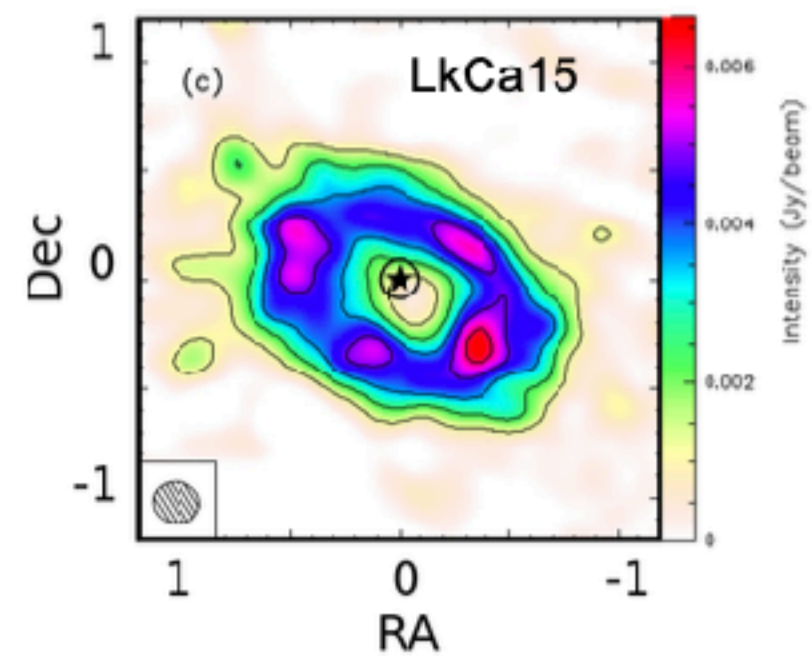


Spitzer infrared observations

Link with planet formation?

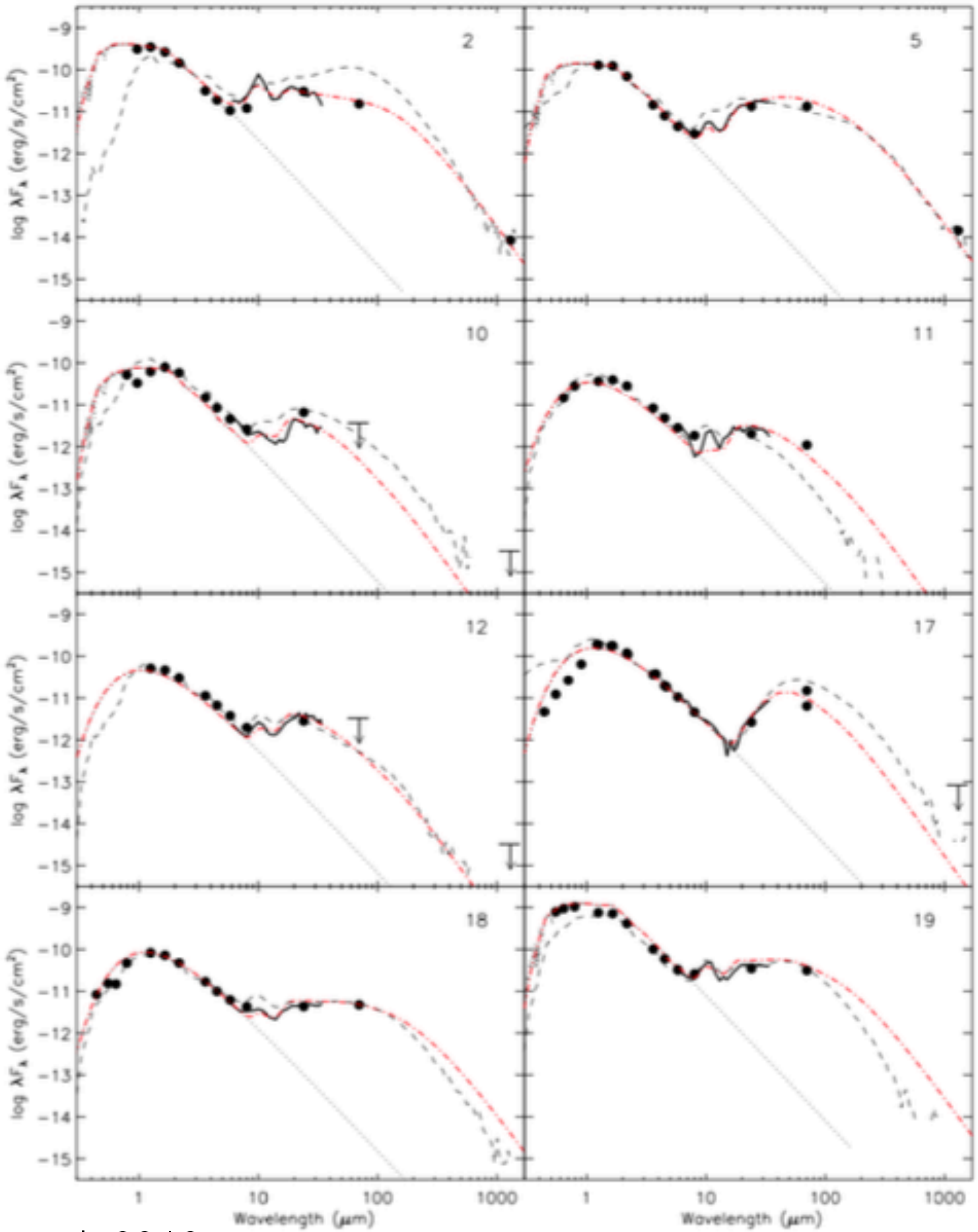
Pioneering millimeter interferometry (SMA. CARMA.PdBI)





Brown et al. 2007, 2009, Isella et al. 2010

Transition disks



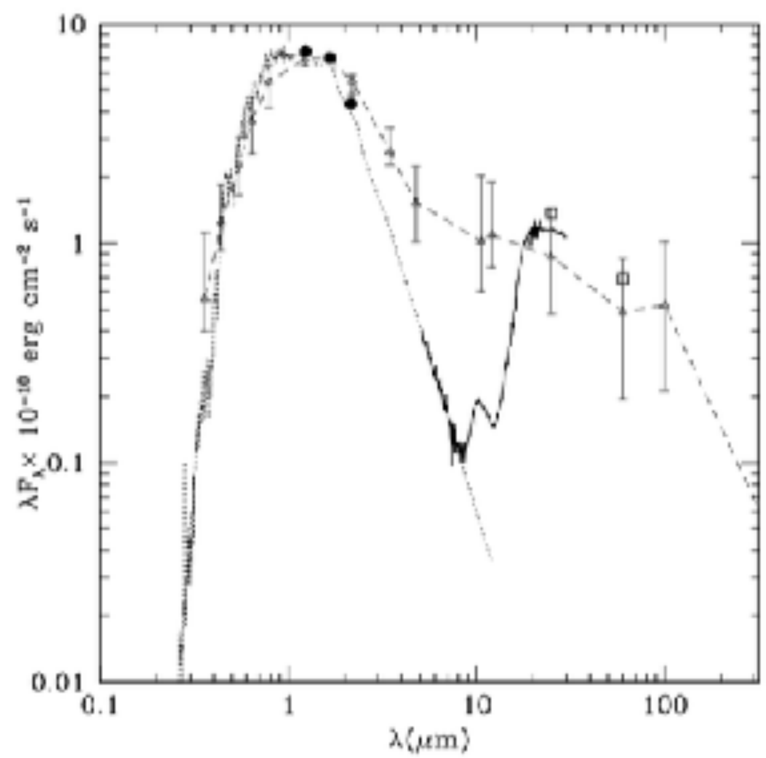
Merin et al. 2010

- Cavity sizes down to ~2 au from SEDs, but only largest cavities (>30 au) could be confirmed by mm interferometry
- Large range of color criteria used in the literature to identify transition disks and transition disk candidates (Spitzer): inconsistency
- SED analysis complex: extinction correction (spectral type), edge-on disks, radiative transfer effects
- Most TDs still accreting!

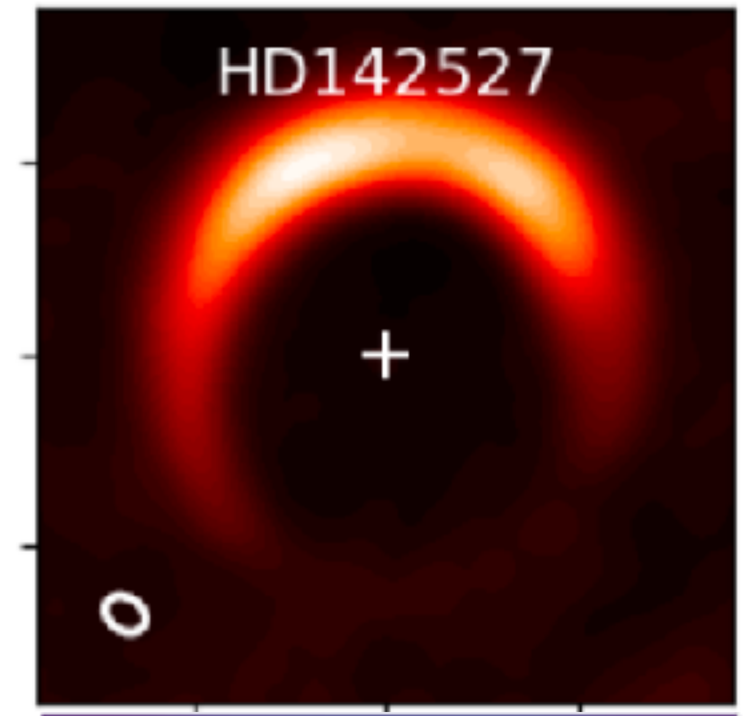
History: origin transition disk cavities?

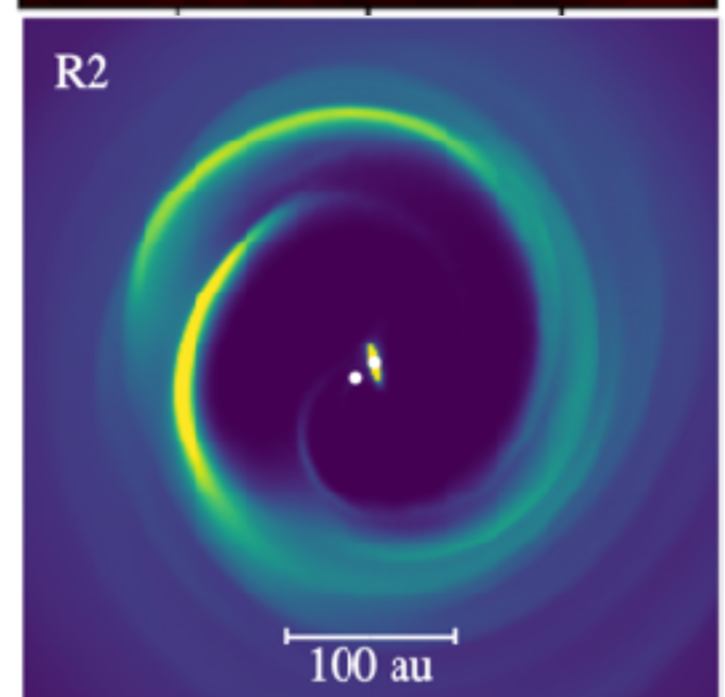
1. Binaries

CoKu Tau/4



10 au cavity, 8 au binary
(SED only: no ALMA image yet!)



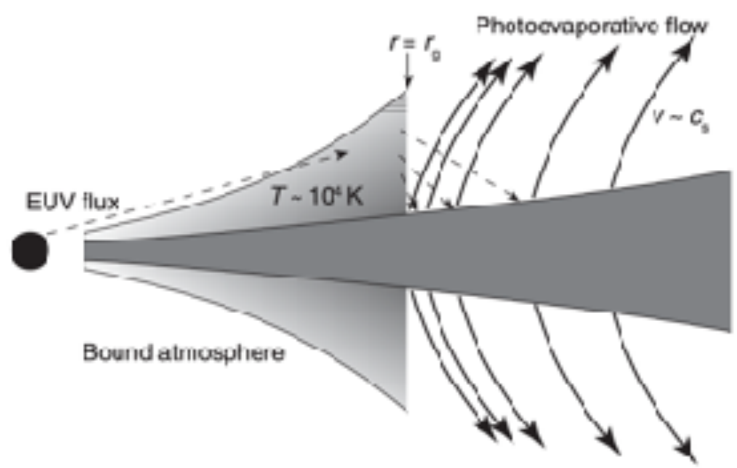


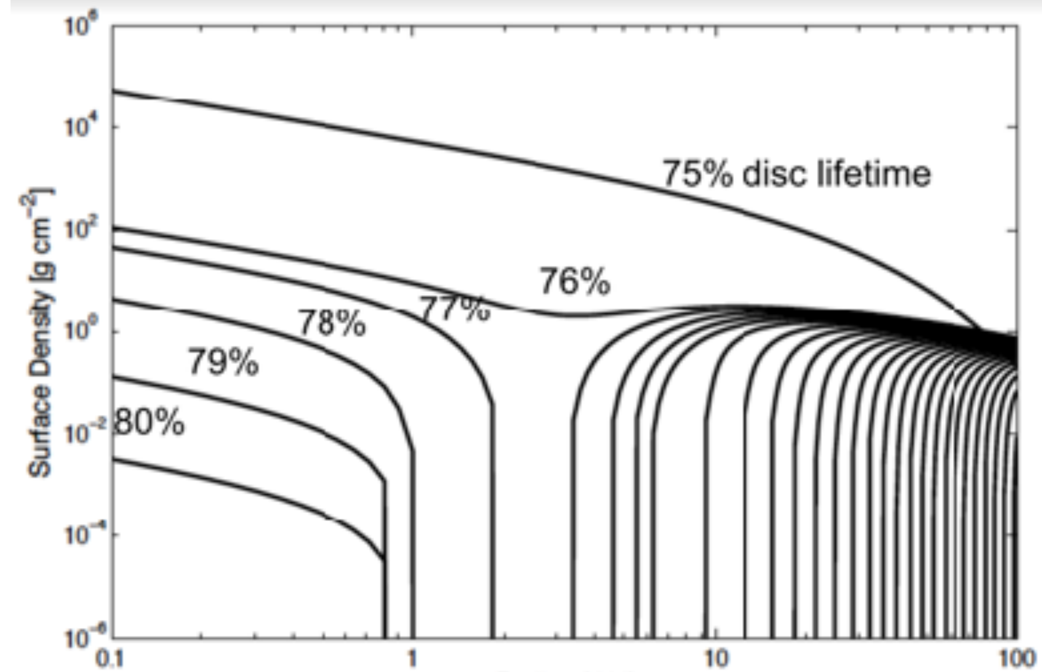
But binarity excluded for many TDs

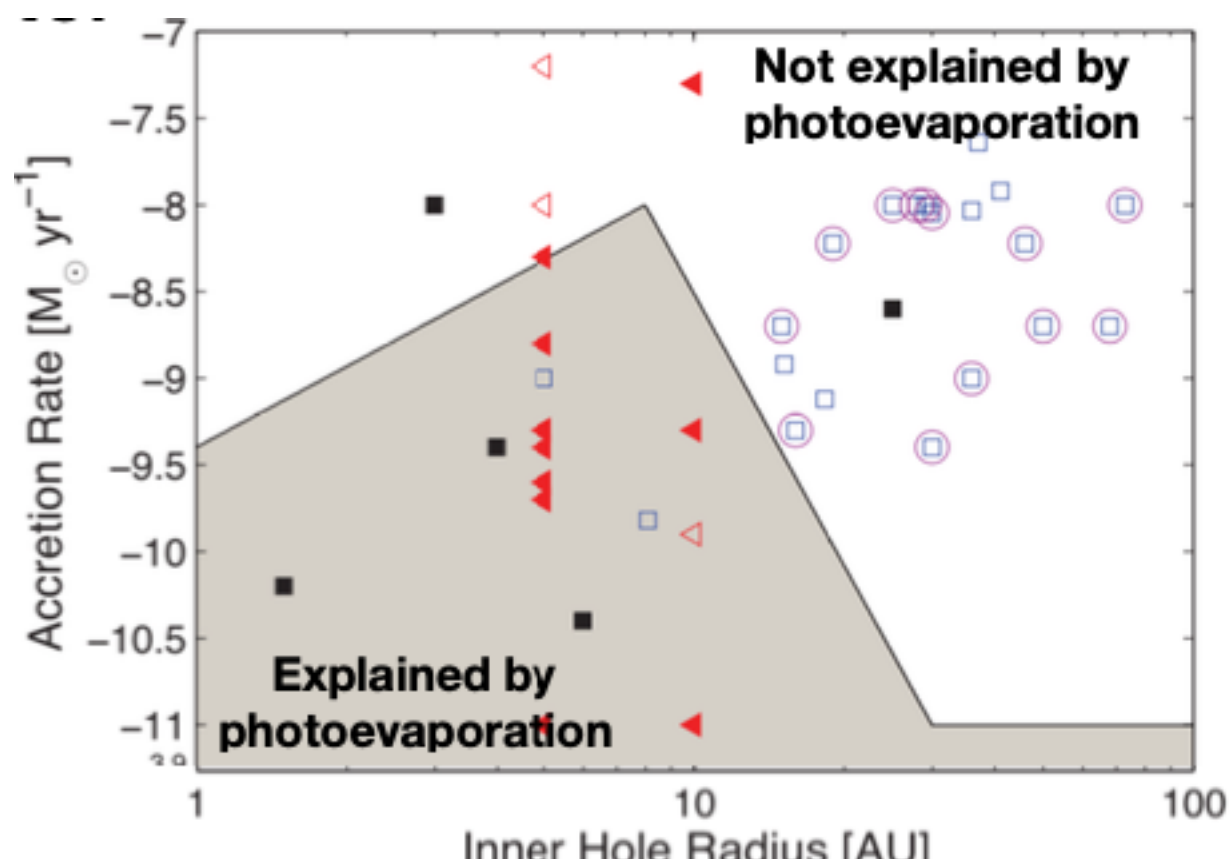
Ireland & Kraus 2008
Price et al. 2019

History: origin transition disk cavities?

2. Photoevaporation





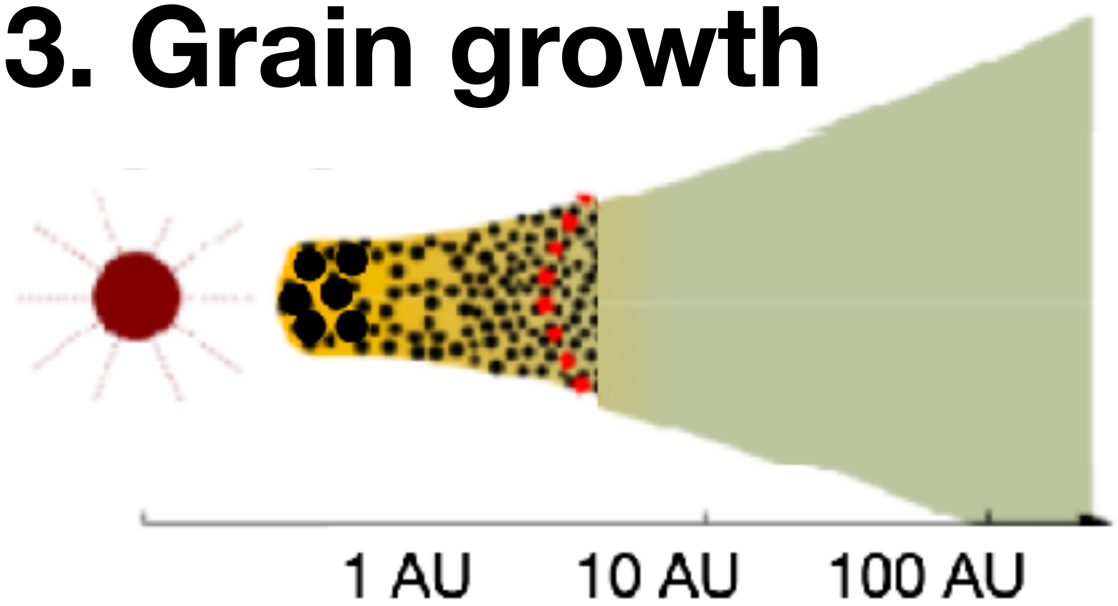


Problem: accretion rates in transition disks with large cavities too high and disk dust masses too large to be consistent with PE models

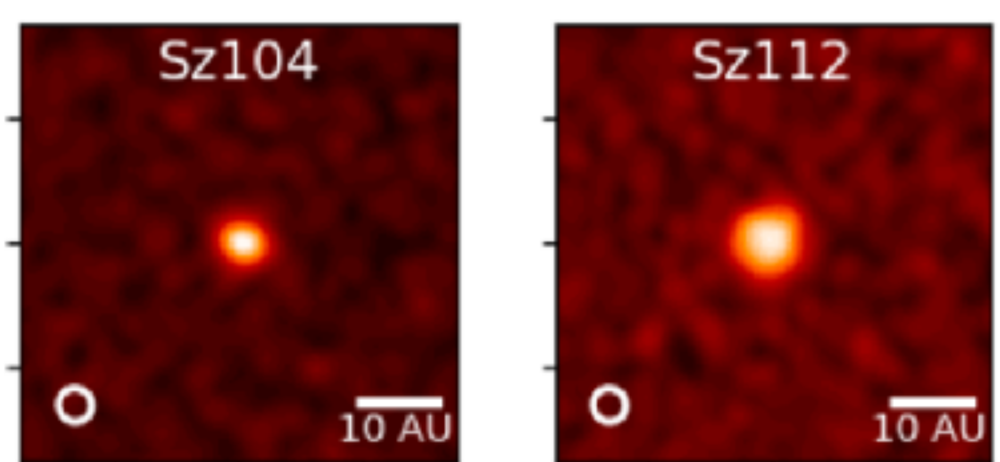
Owen & Clarke 2012
Ercolano & Pascucci 2017

History:
origin transition disk cavities?

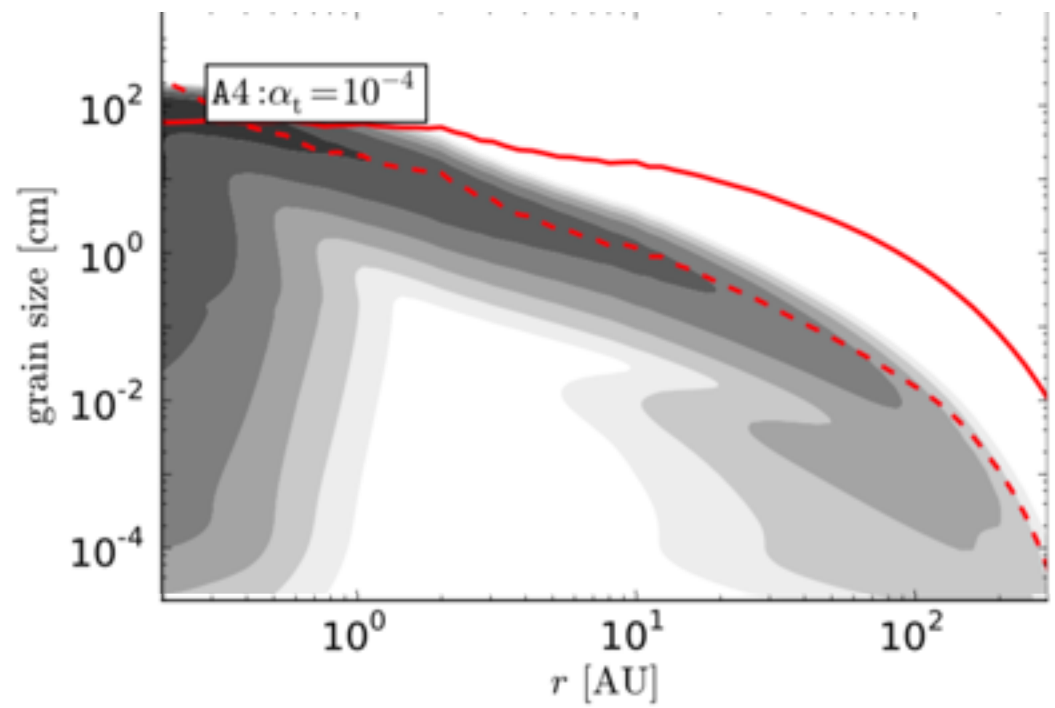
3. Grain growth

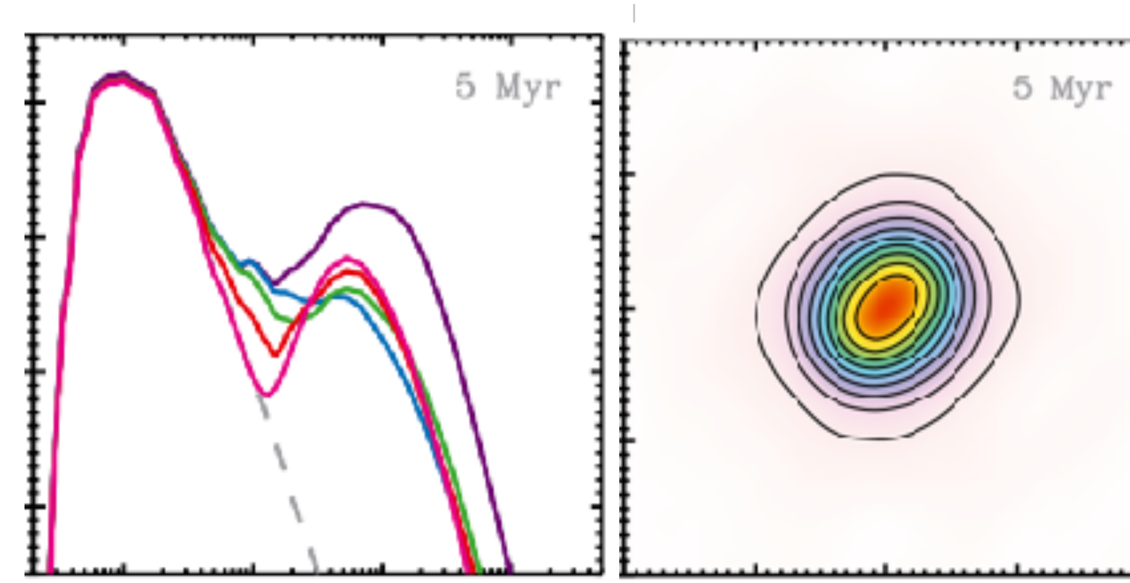


Grain growth in inner disk due to radial drift results in removal small grains, but not of mm-grains due to fragmentation: no inner cavity in mm!



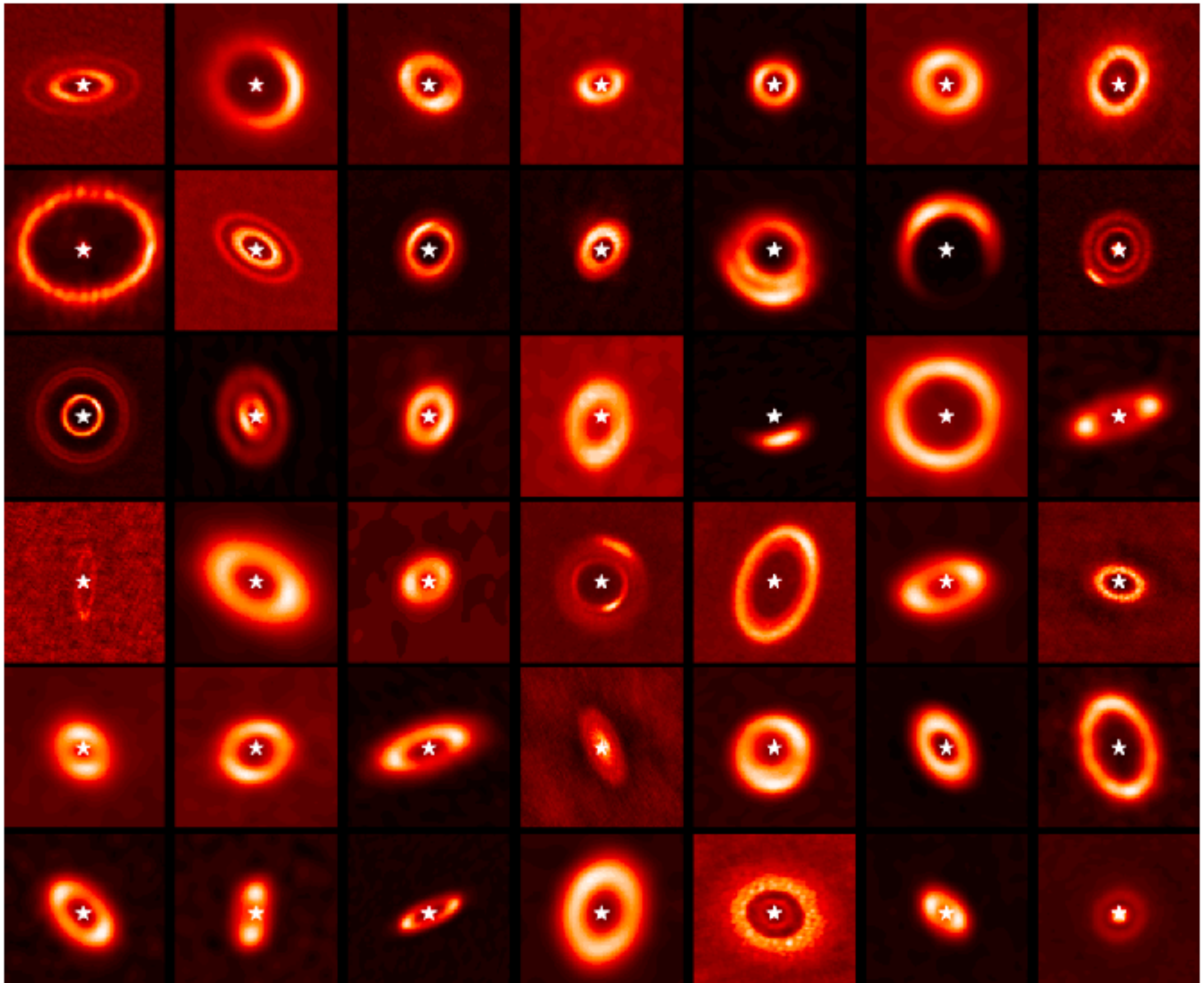
Observed drift disks?





Birnstiel et al. 2012
van der Marel et al. 2022

Transition disks with ALMA



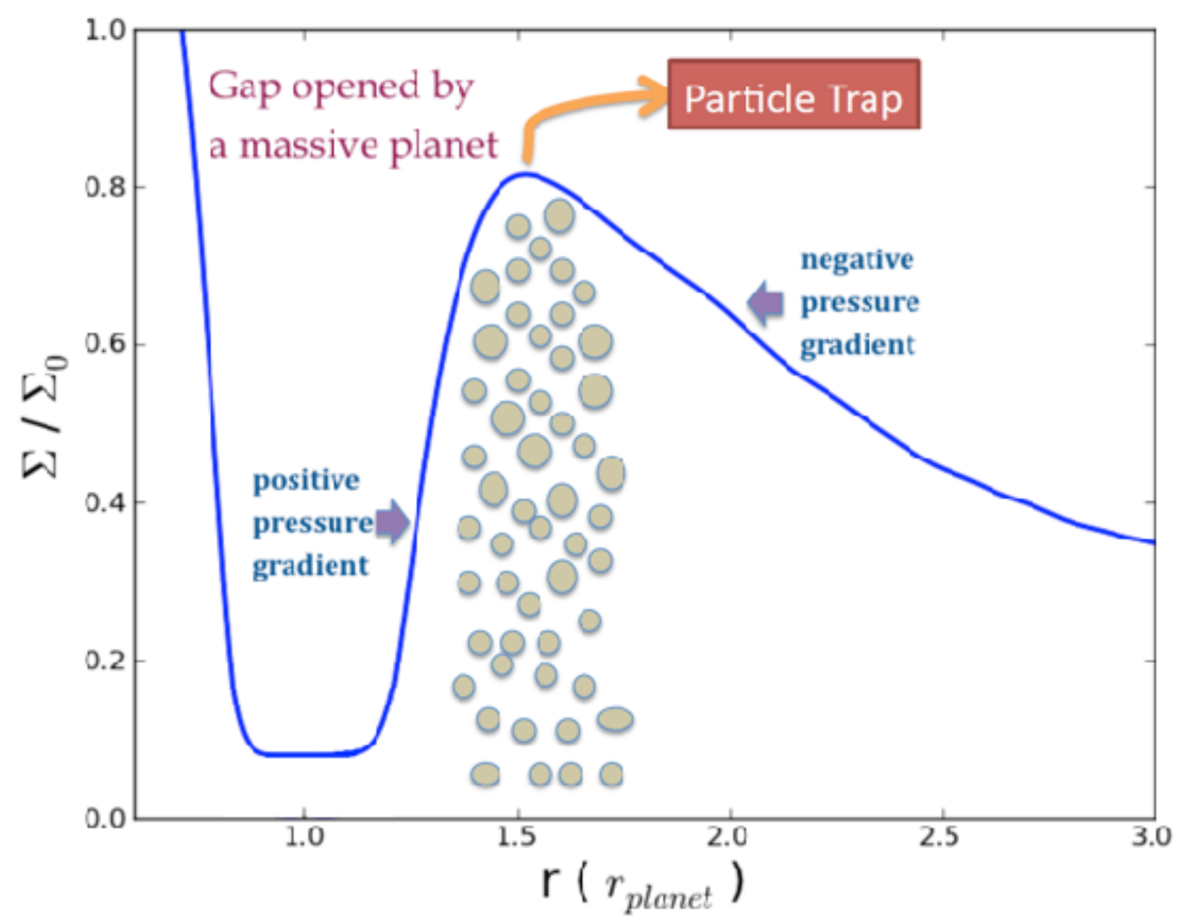
Disks with dust cavities > 20 au

Van der Marel 2022 (review)

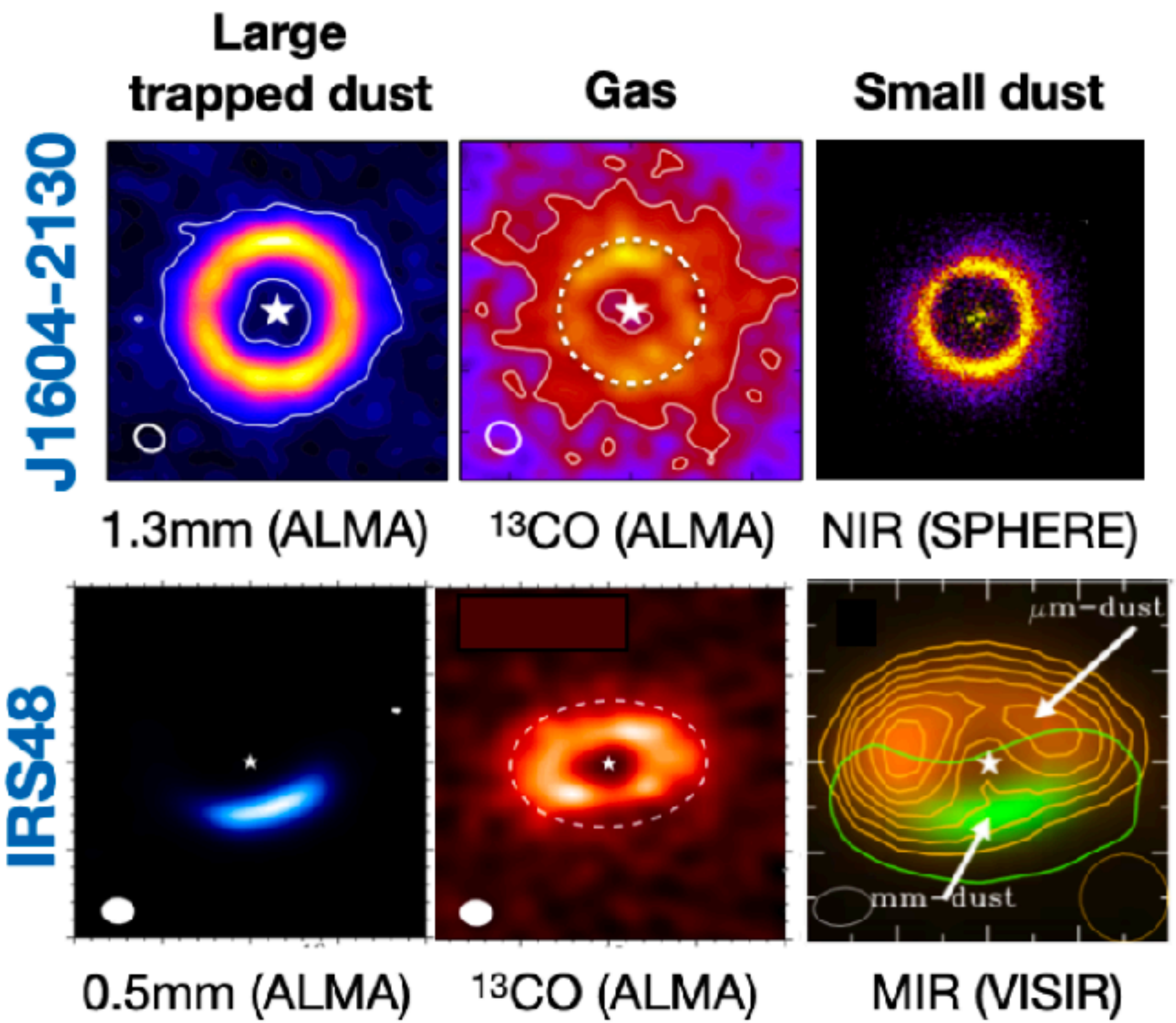
Transition disks with ALMA

All examples of dust traps in pressure bumps:

How do we know this?



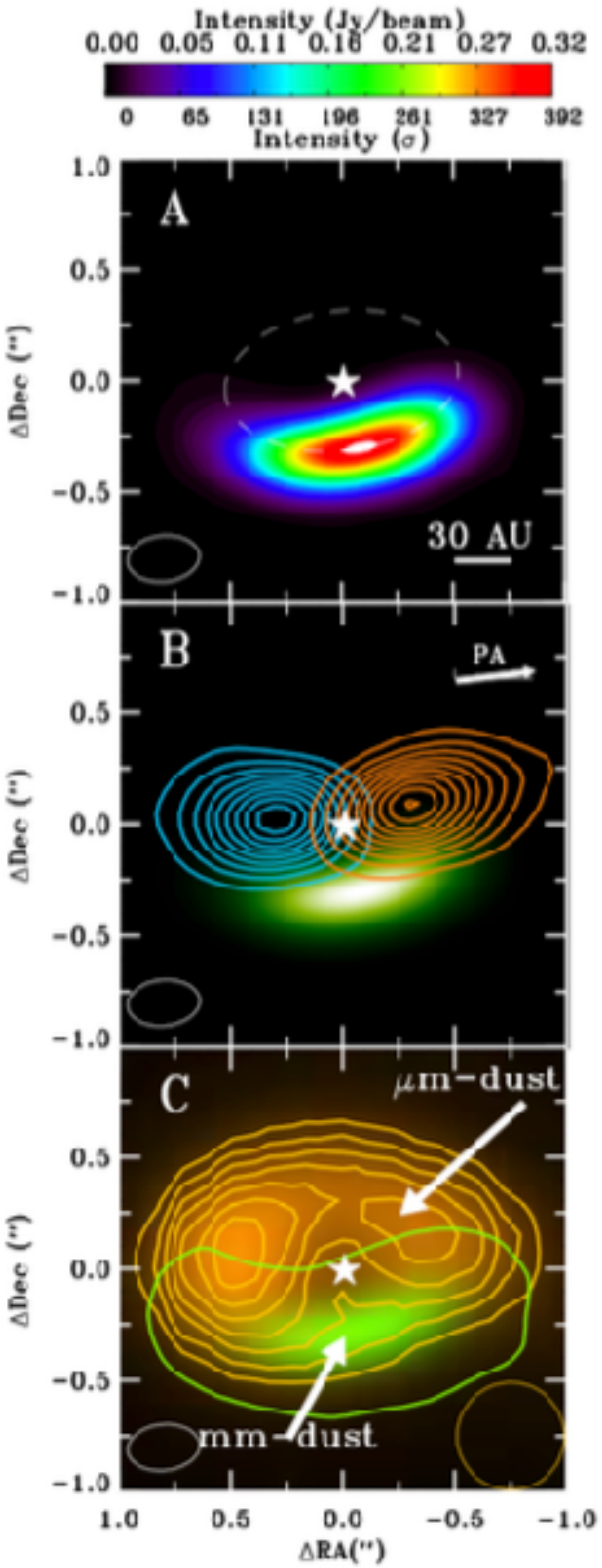
How do we know that these are dust traps?



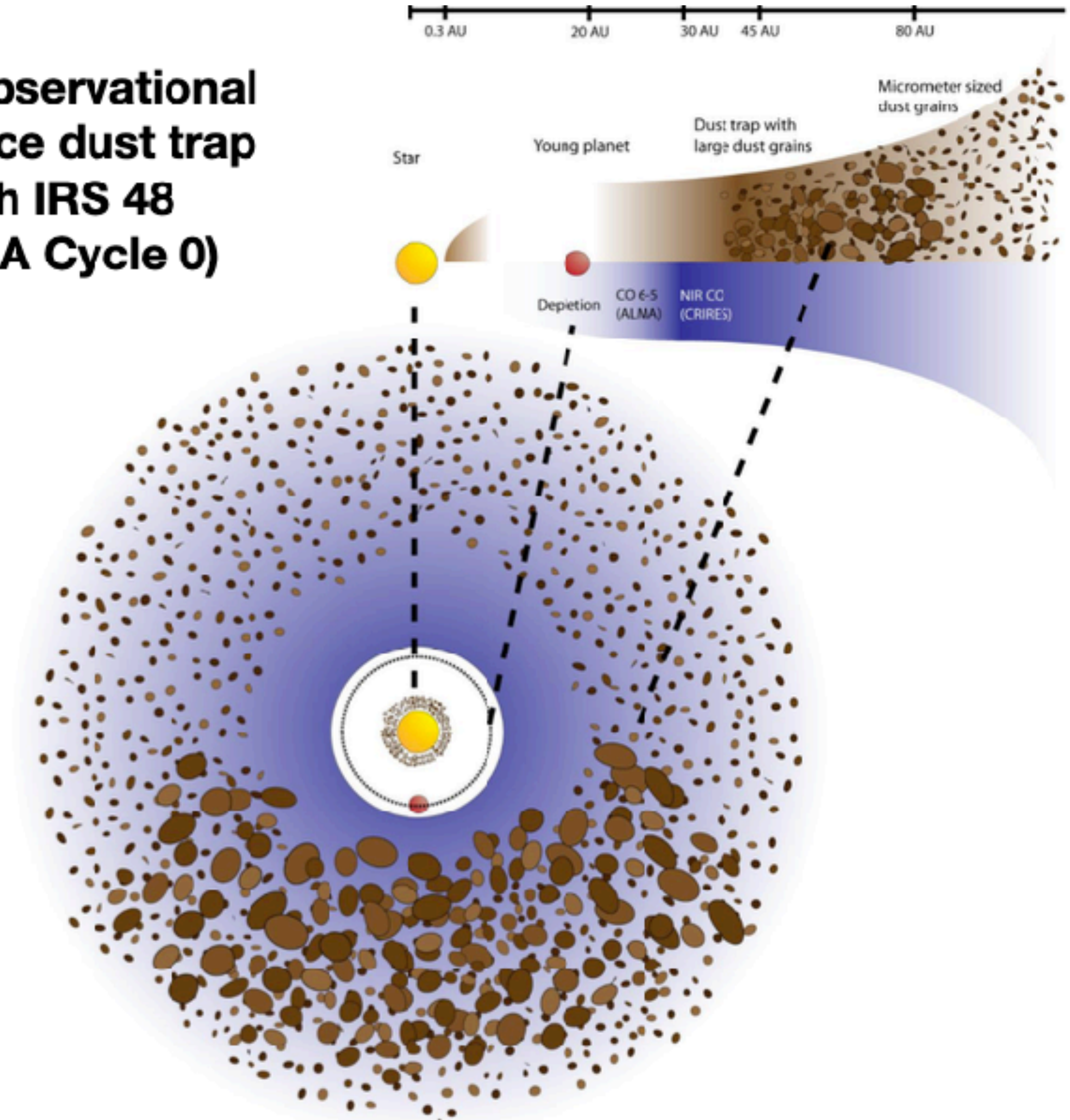
Radial trapping

Azimuthal trapping

The first dust trap



First observational evidence dust trap Oph IRS 48 (ALMA Cycle 0)



Predicted long time ago!

Letter to the Editor

Did planet formation begin inside persistent gaseous vortices?

P. Barge[1] and J. Sommeria[2]

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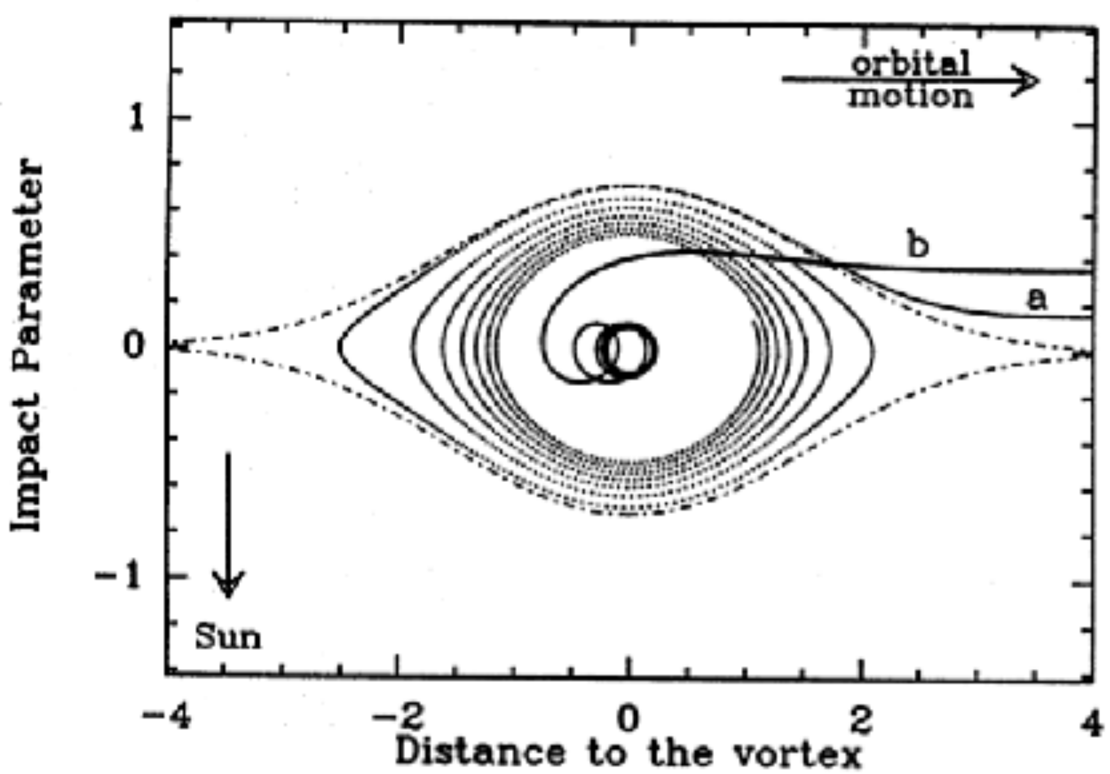
[2] Ecole Normale Supérieure de Lyon, Laboratoire de Physique, CNRS, 46 Allée d'Italie, F-69364 Lyon cédex 07, France



Particle-Trapping Eddies in Protoplanetary Accretion Disks

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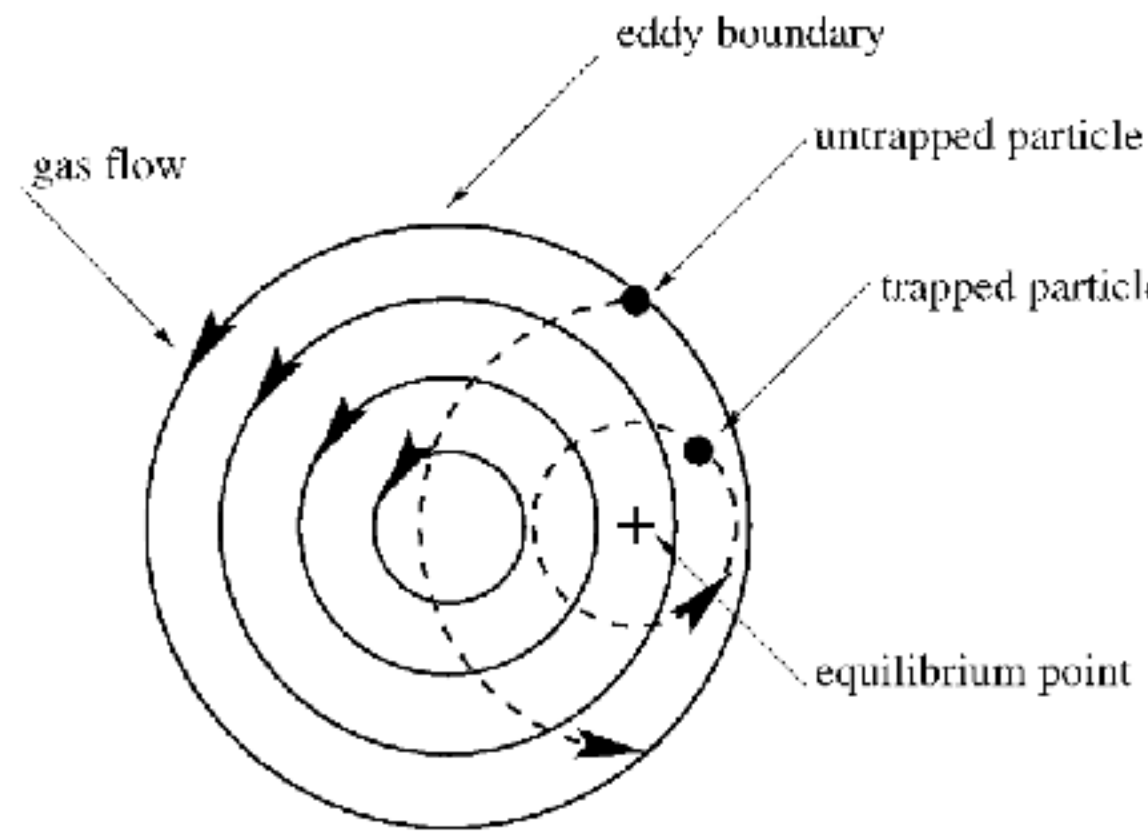
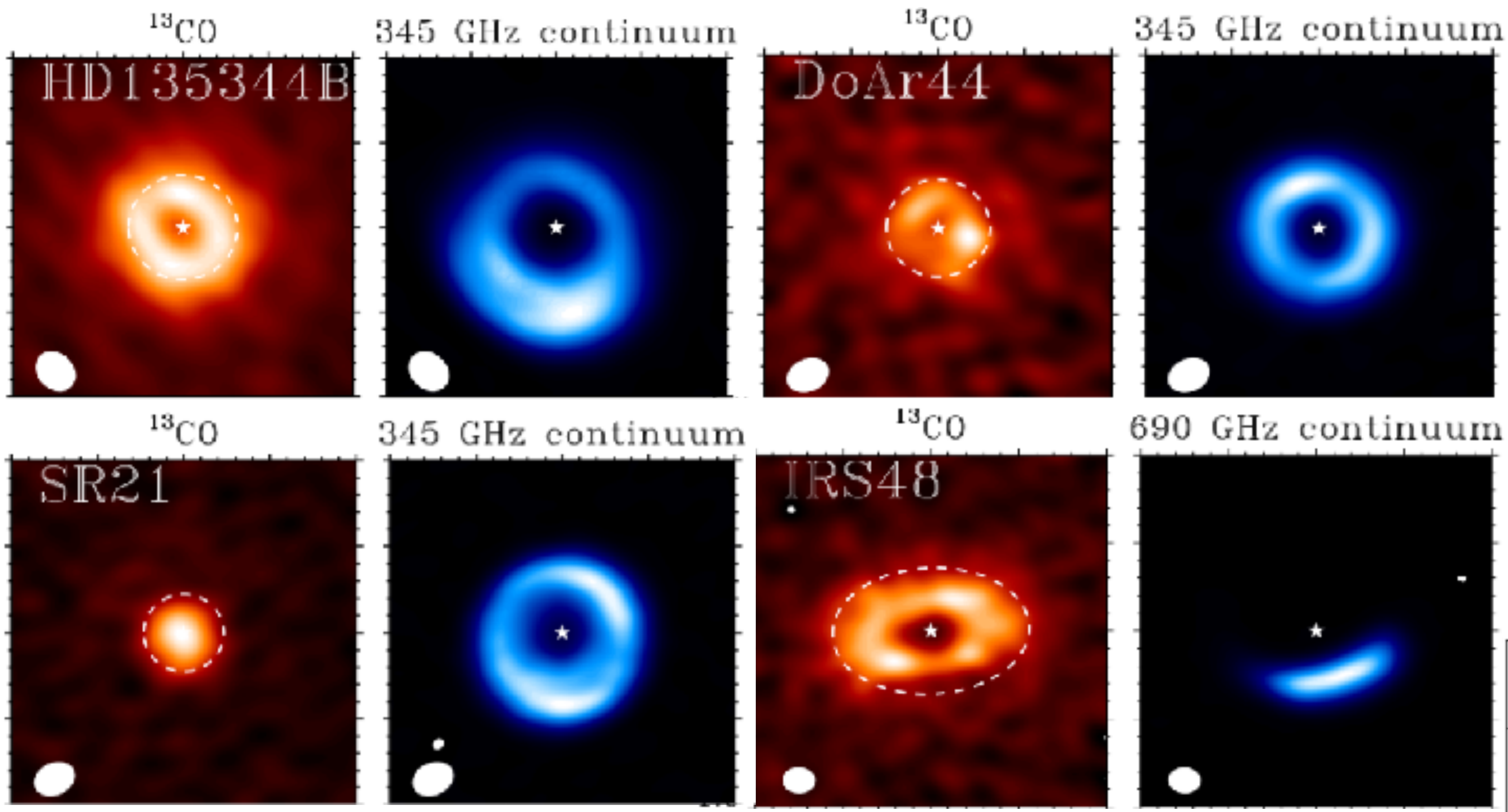
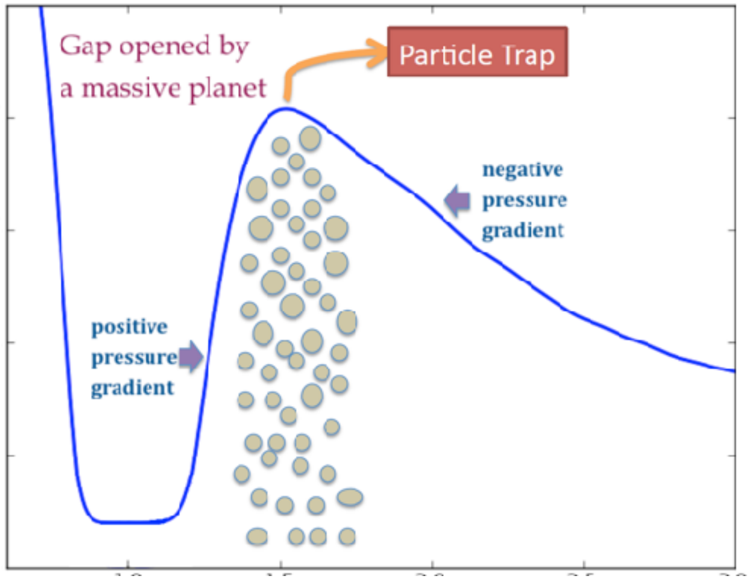
Received August 16, 1996; revised January 9, 1997



How do we know it's pressure bumps?

Spatially resolved CO isotopologue images of transition disks



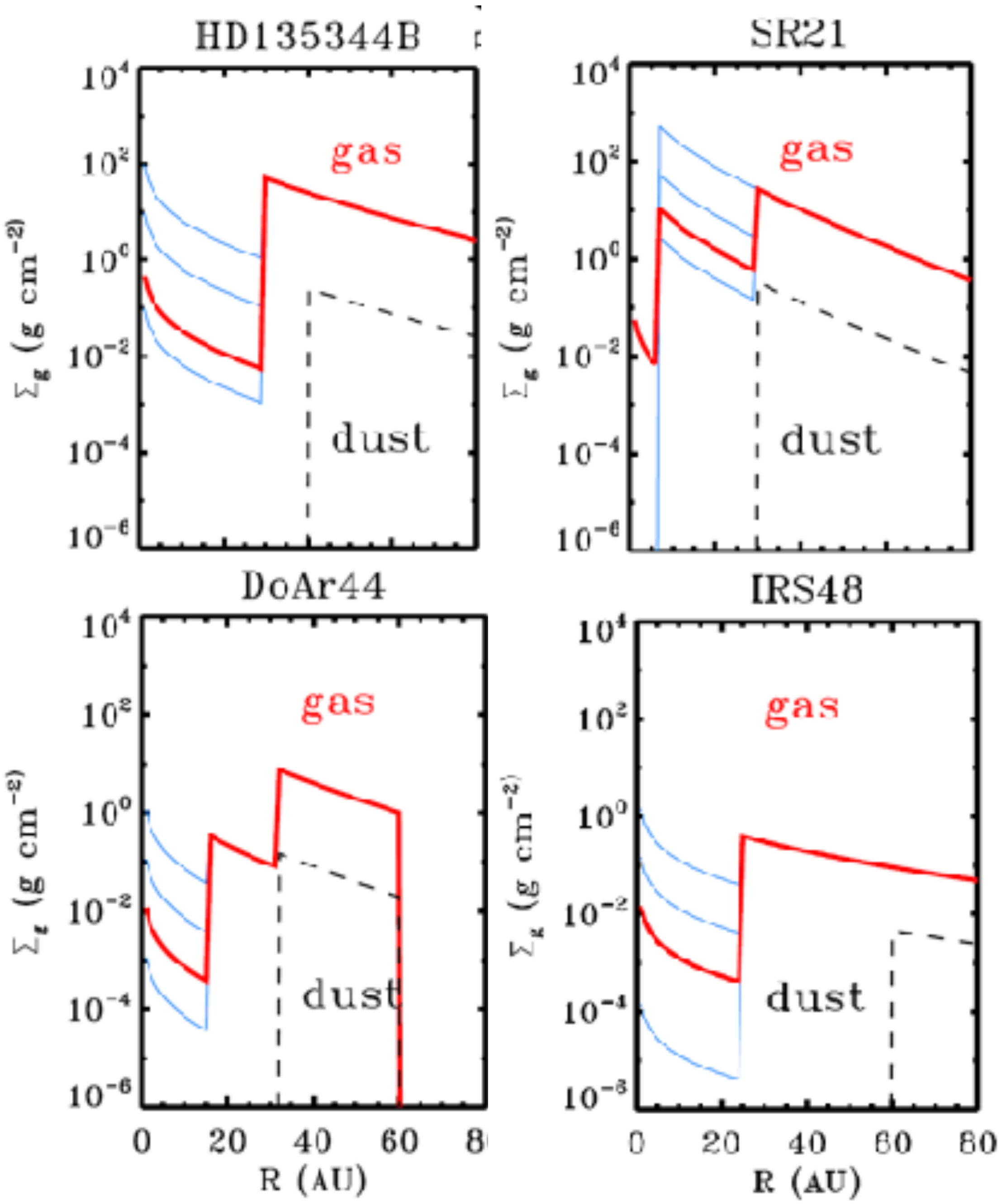


Gas cavities: signatures for planets!

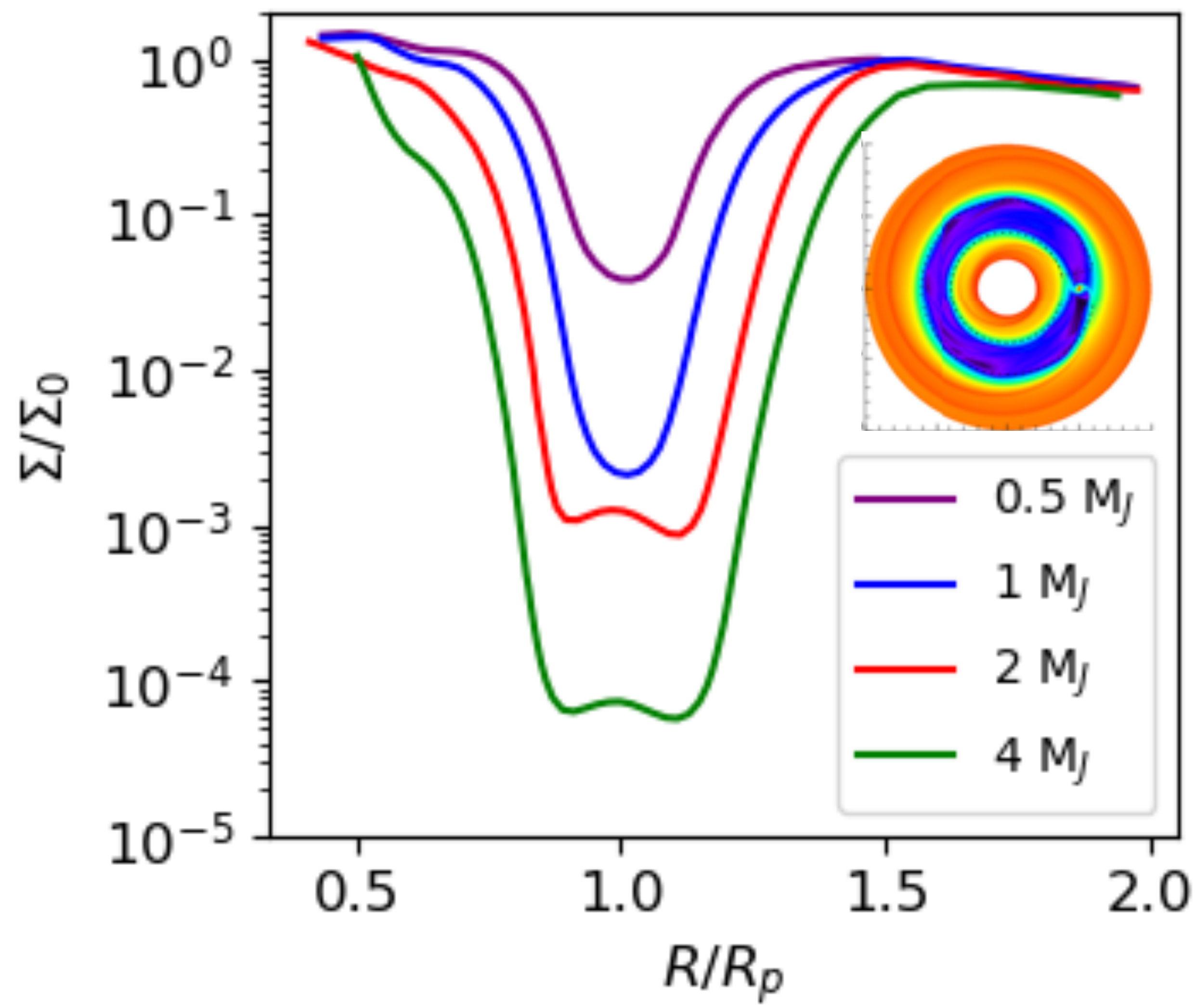
Van der Marel et al. 2016a

Gas cavities

More on CO analysis
in Lecture 5



Compare with planet-disk interaction simulations

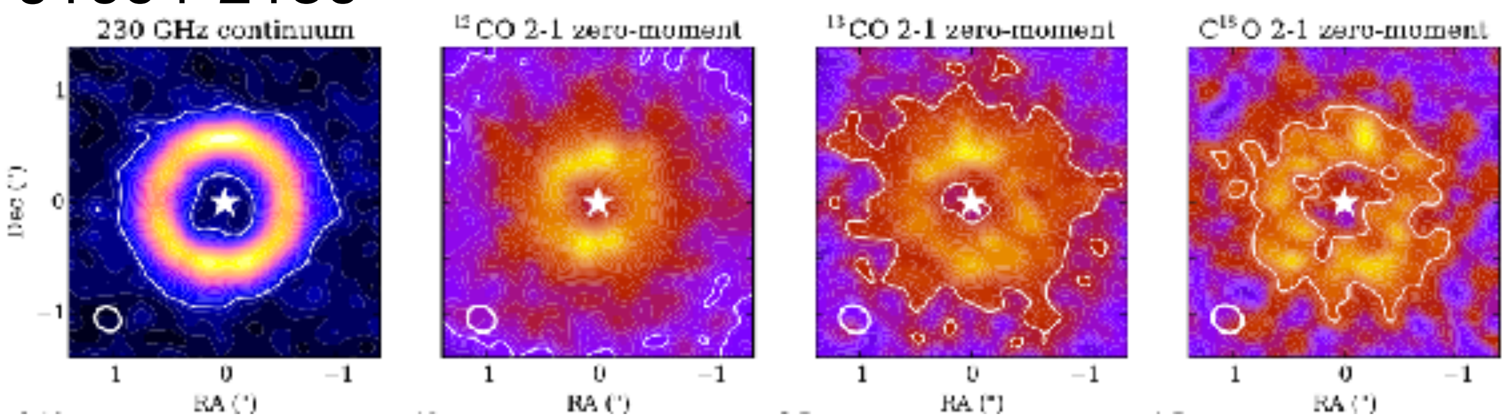


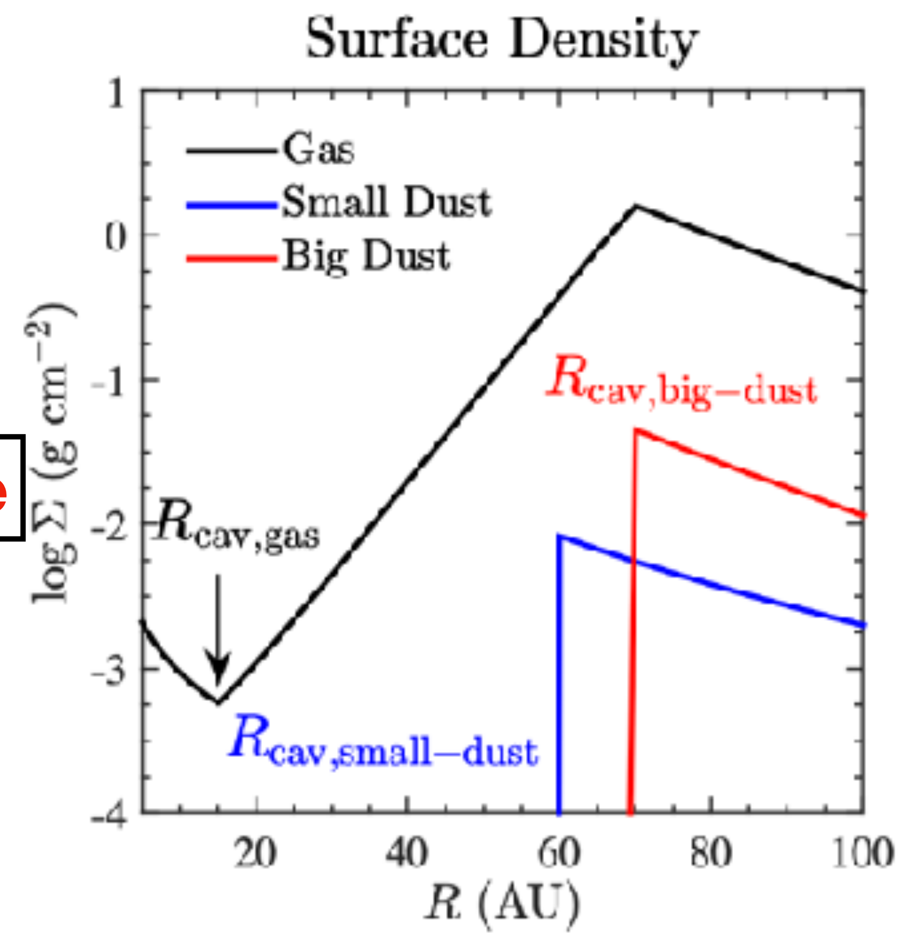
Deep wide gas gap
=> <u>massive planets</u> (~few M_{Jup}) at <u>tens of AU</u>
in disks with cavities

van der Marel et al. 2016a
Fung & Chiang 2016

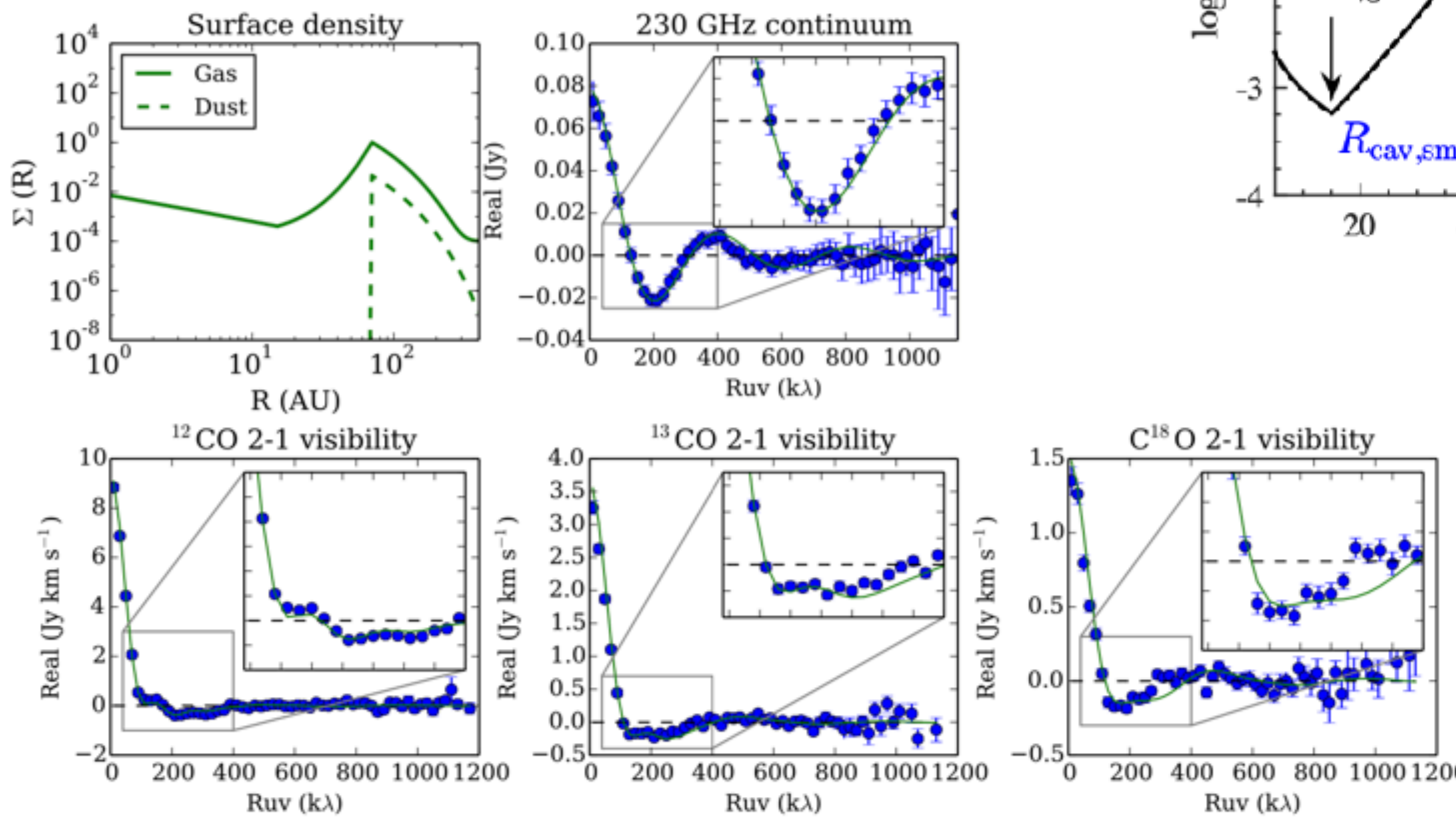
Gas cavities: gradual gap

J1604-2130





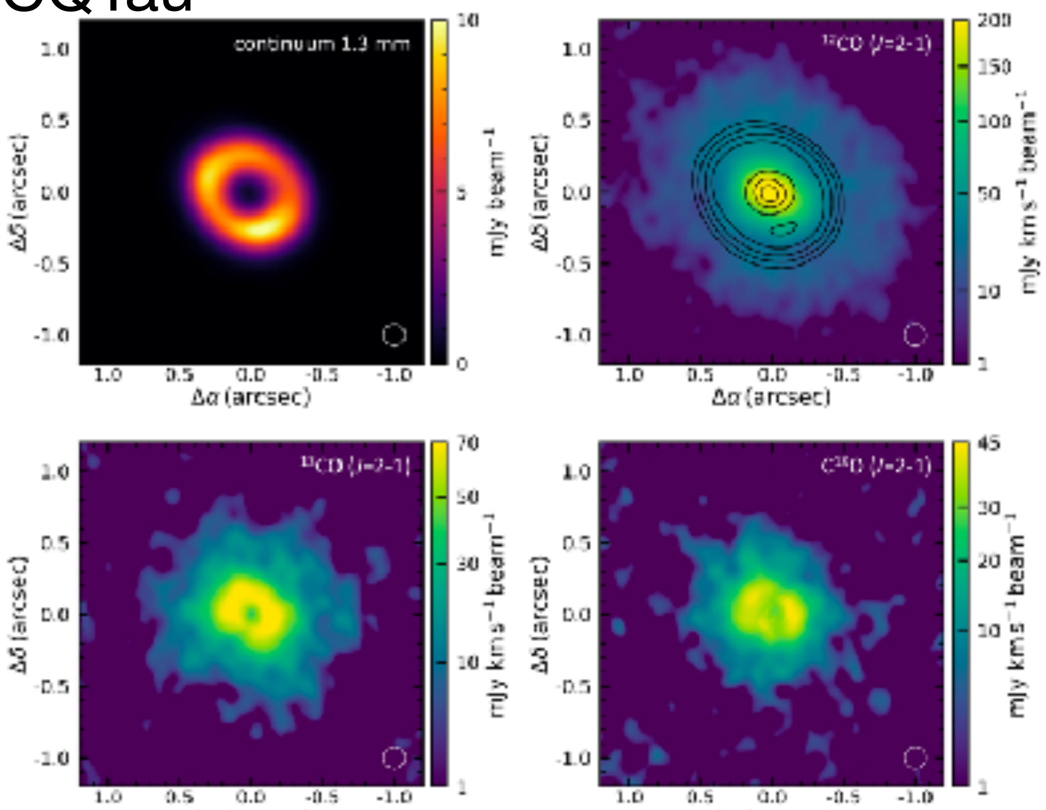
Resolved CO isotopologues: evidence for gradual slope



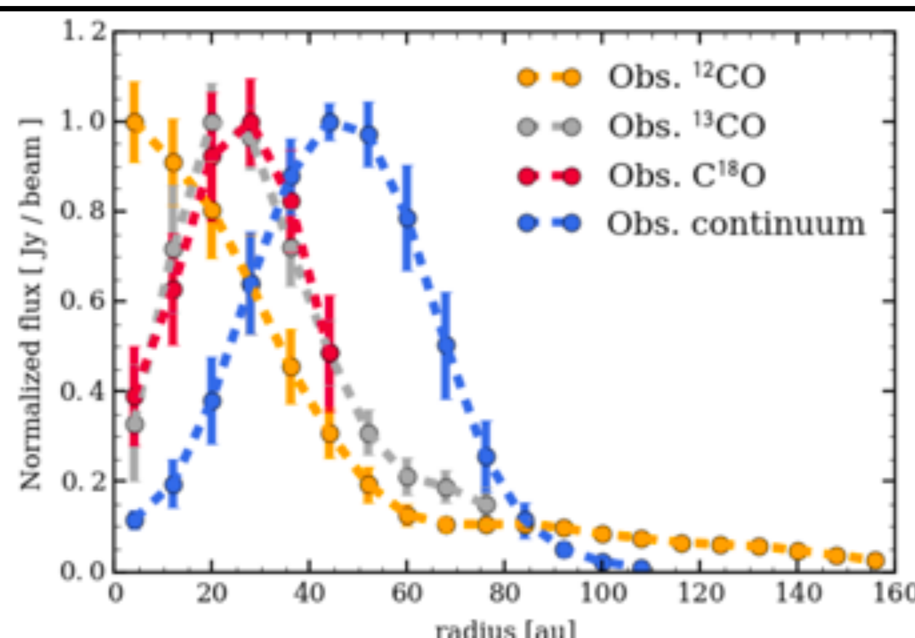
Dong et al. 2017

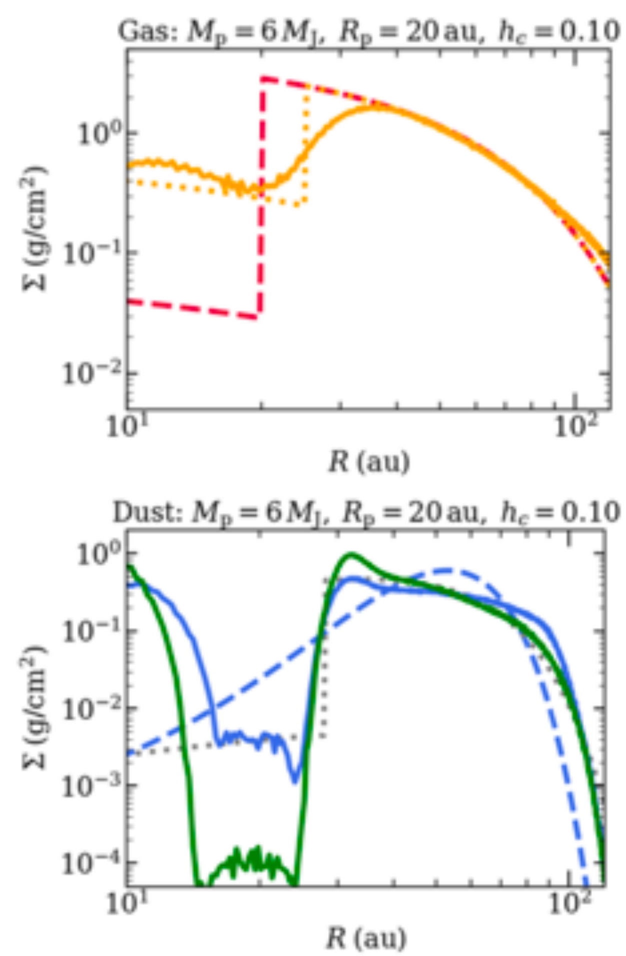
Gas cavities: gradual gap

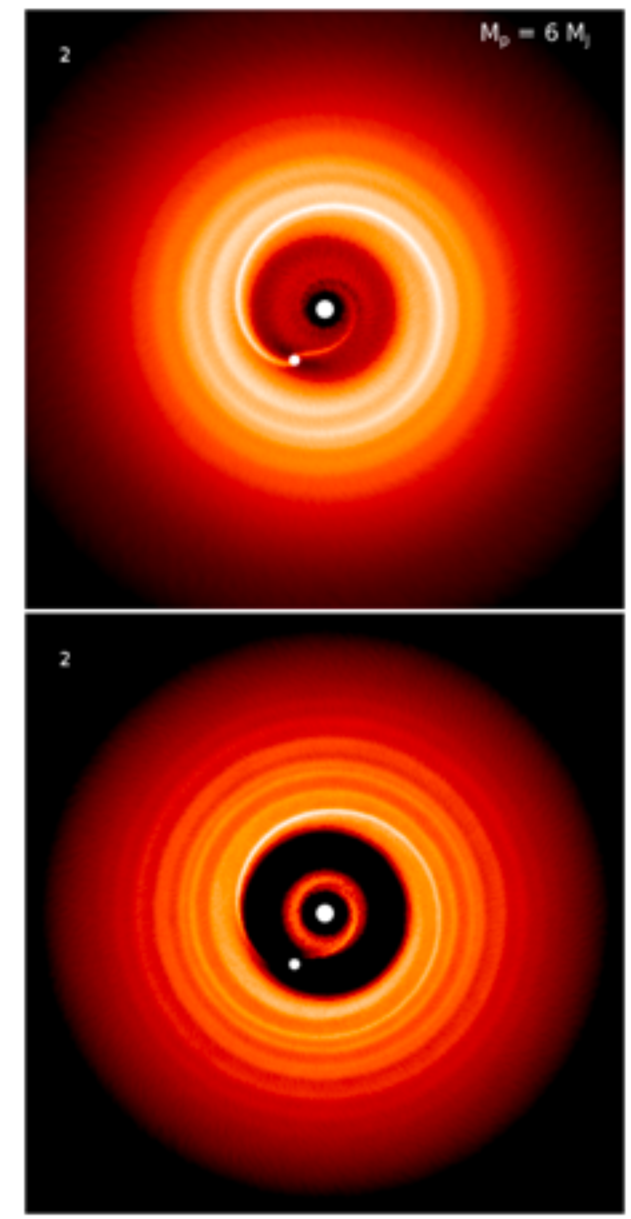
CQTau



Resolved CO isotopologues: comparison with planet-disk gap





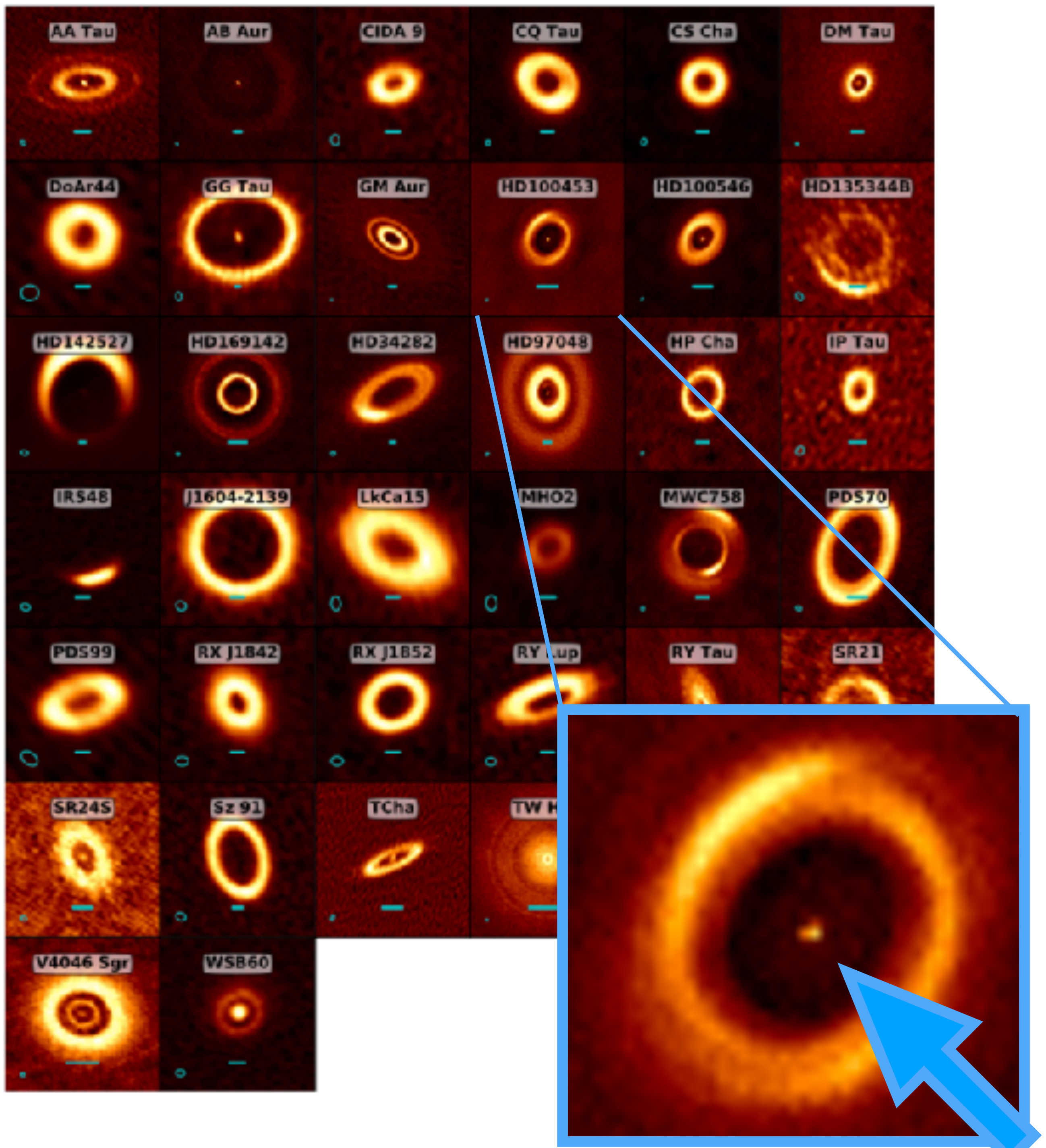


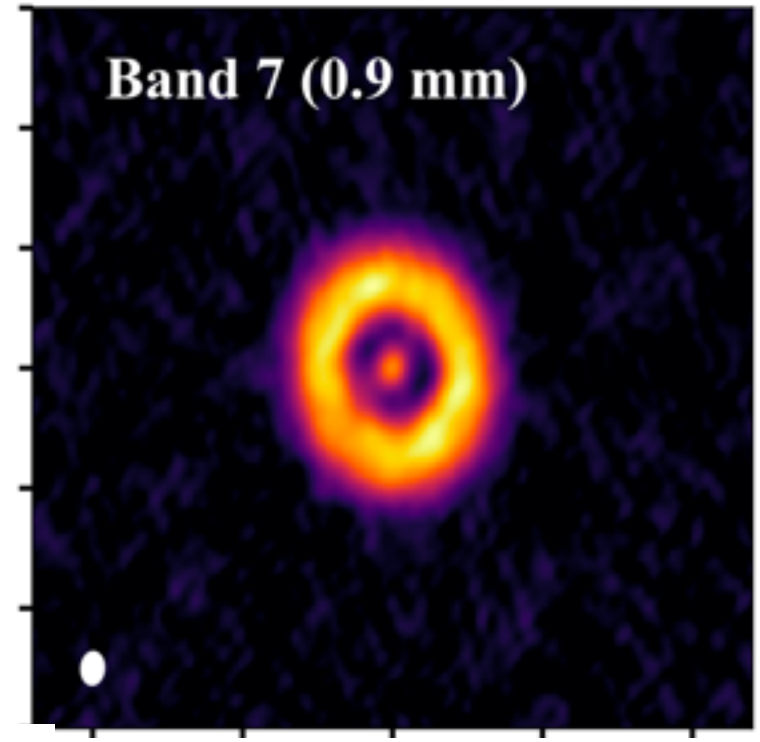
So why do we think it's planets?

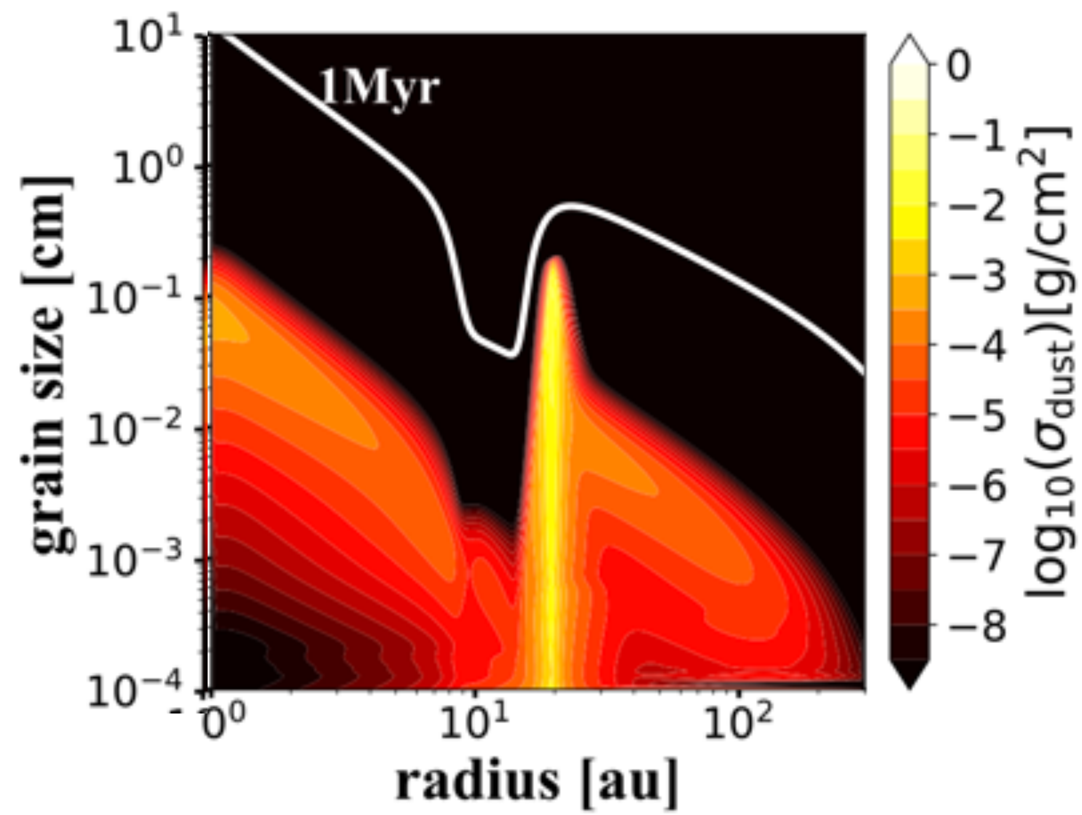
Gabellini et al. 2019

Inner disks: gaps!

Study inner disks with ALMA







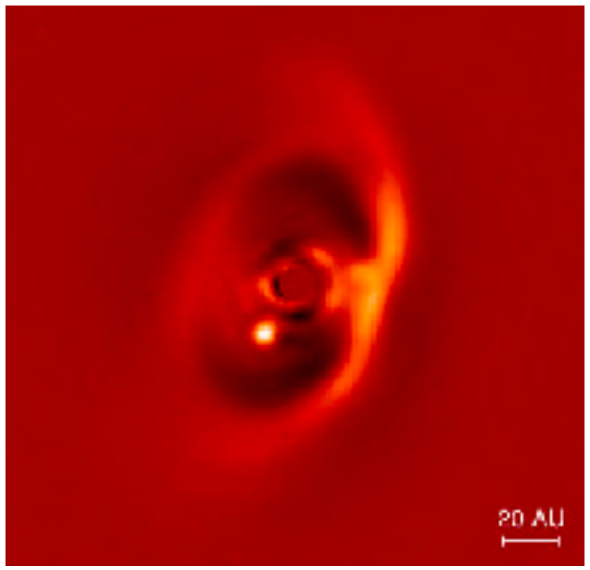
Francis & van der Marel 2020
Pinilla et al. 2021

So why do we think it's planets?

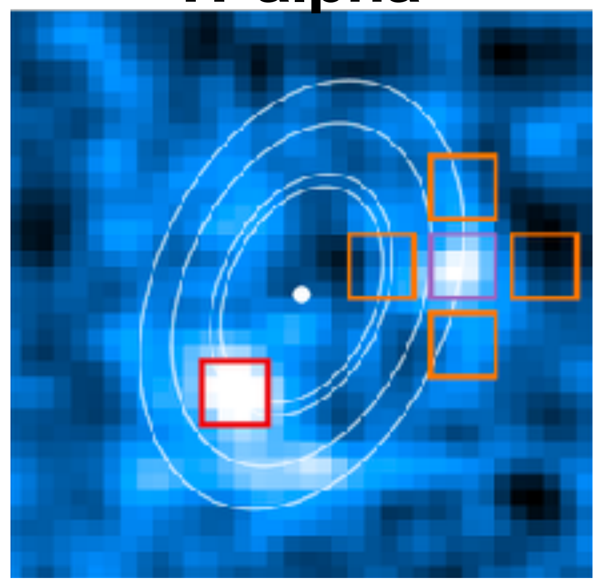
<u>First detections of protoplanets in cavities!</u>

PDS 70

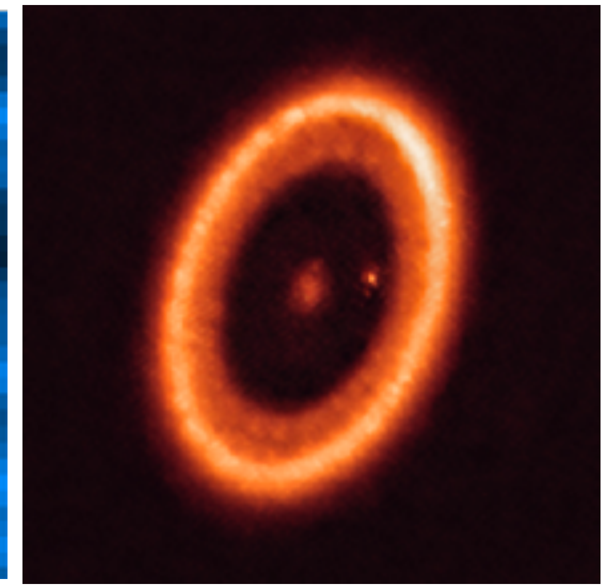
NIR



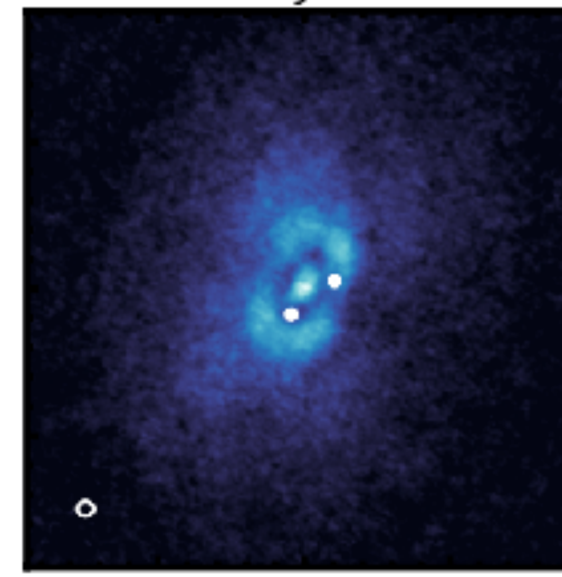
H-alpha



ALMA mm

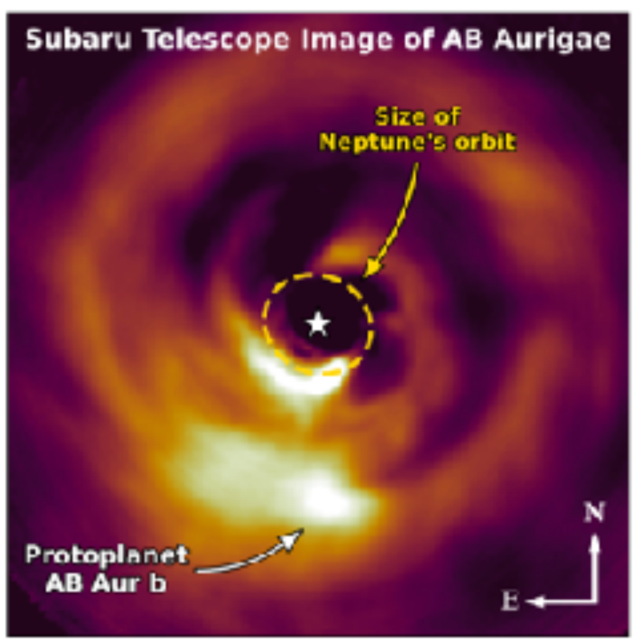


^{12}CO J=3-2

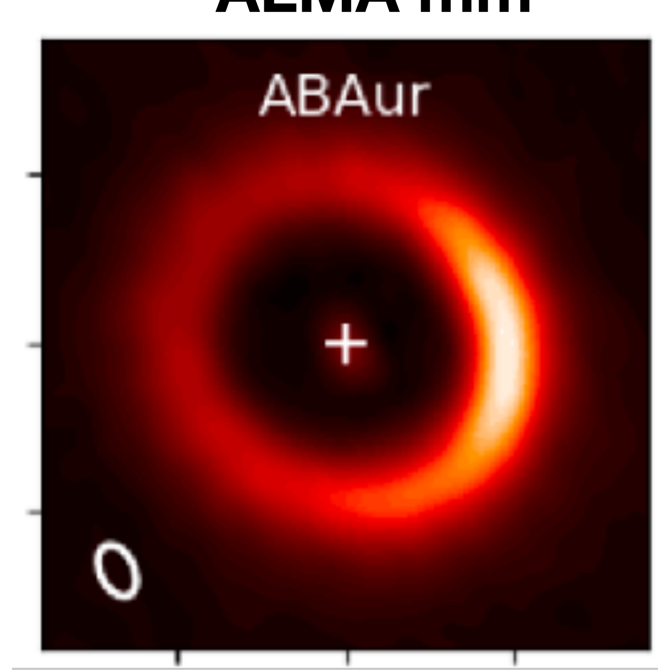


AB Aur

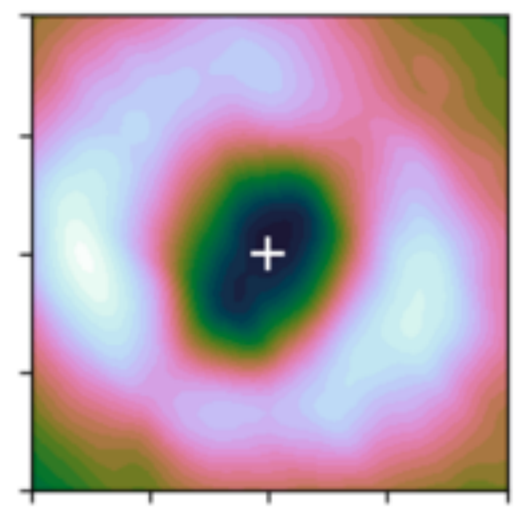
NIR



ALMA mm

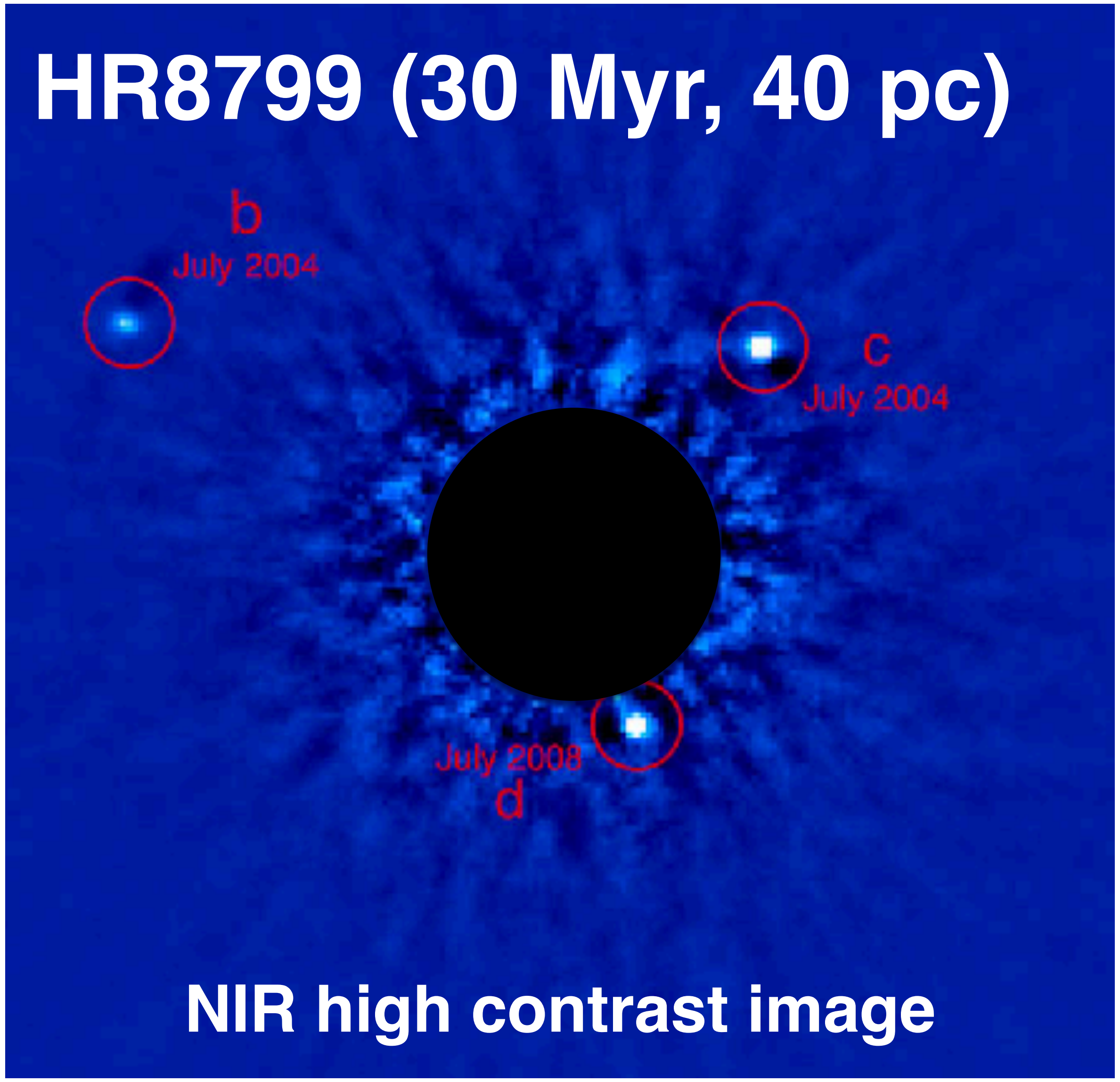


^{13}CO 2-1



e.g. Keppler et al. 2018, 2021, Haffert et al. 2019, Benisty et al. 2021, Facchini et al. 2021, Currie et al. 2022, van der Marel et al. 2021a

Finding planets with high contrast imaging



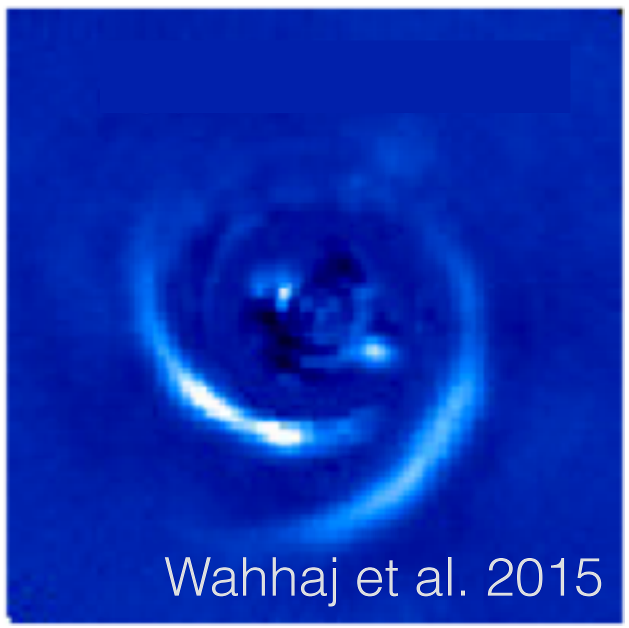
Difficulty: young protoplanetary disks are further away and much dustier…

Marois et al. 2008

Many `failed' detections…

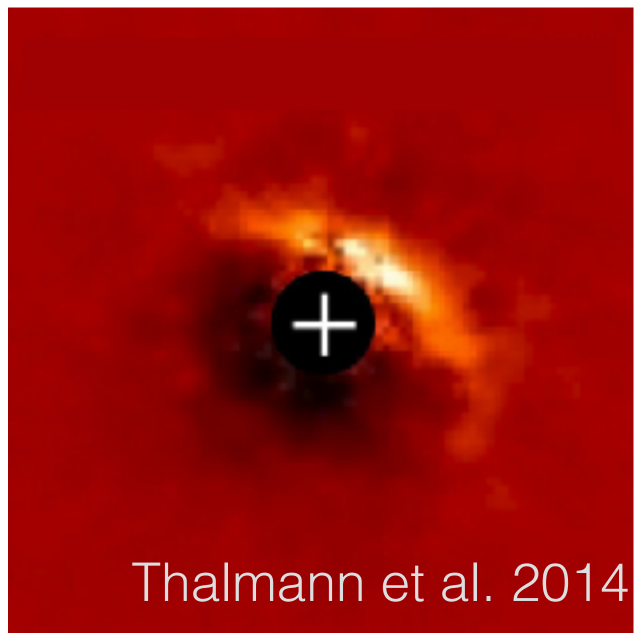
No other Jupiter-mass planets detected in disks!

HD135344B



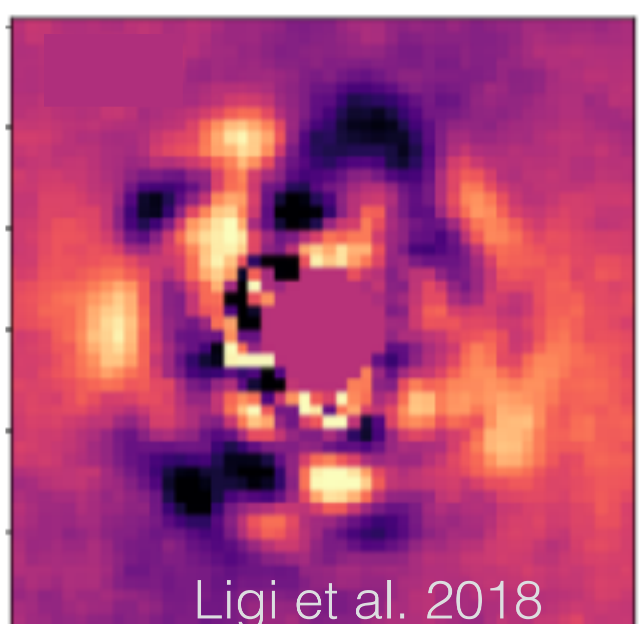
Wahhaj et al. 2015

LkCa15



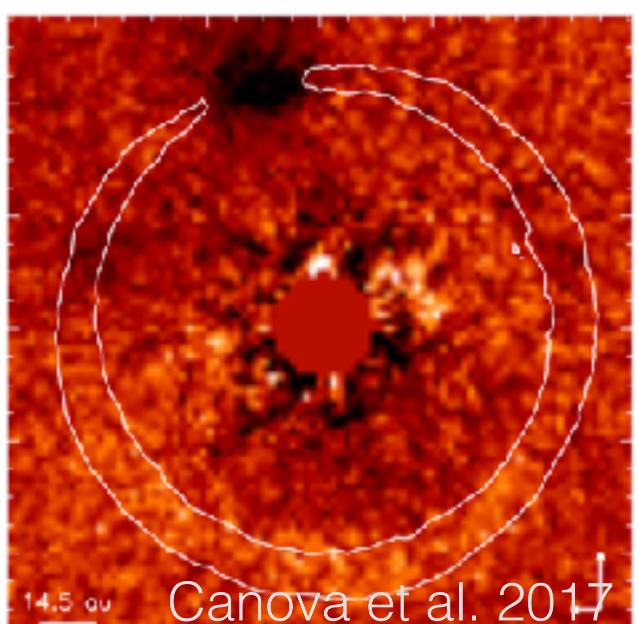
Thalmann et al. 2014

HD169142

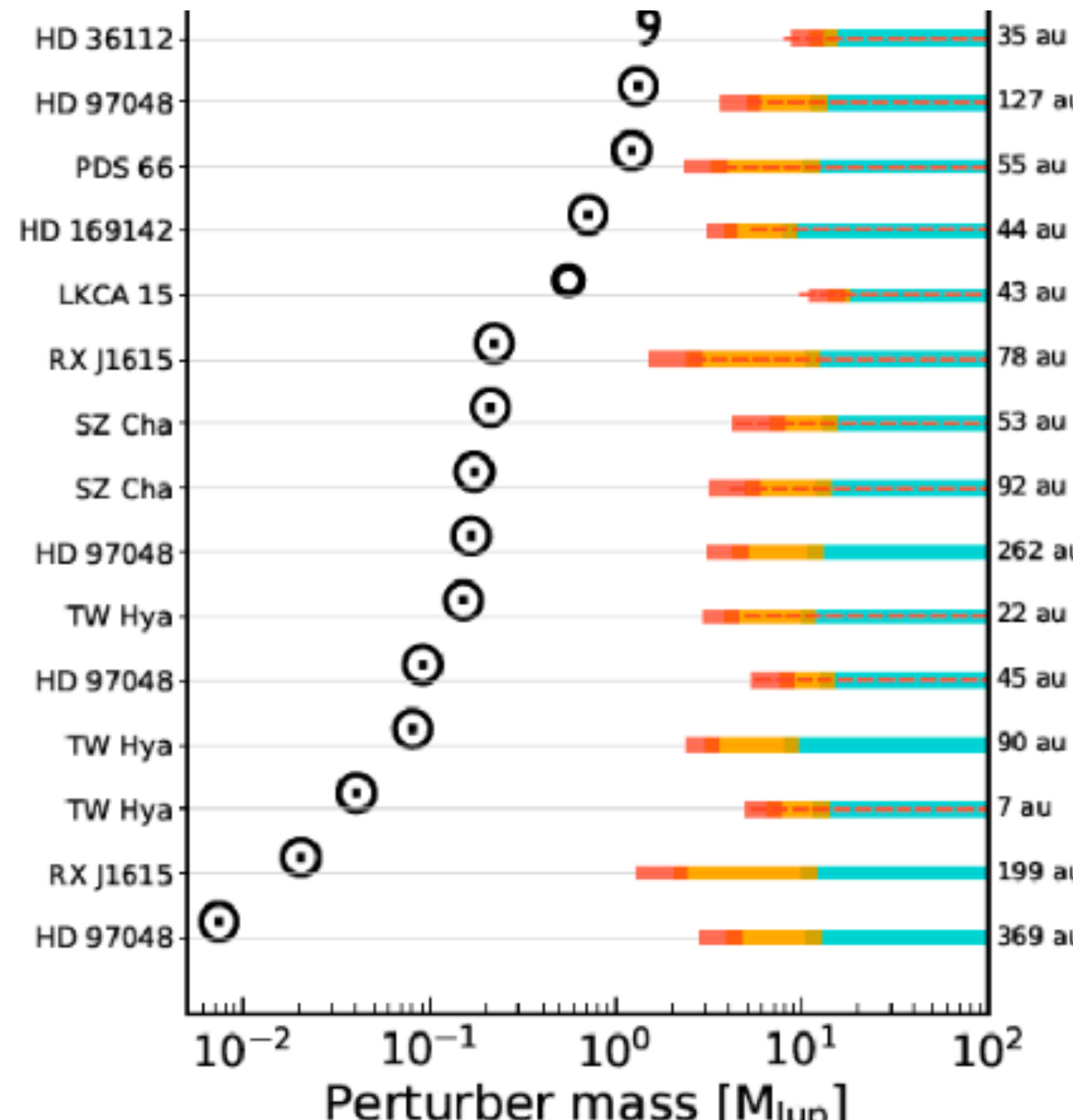


Ligi et al. 2018

J1604

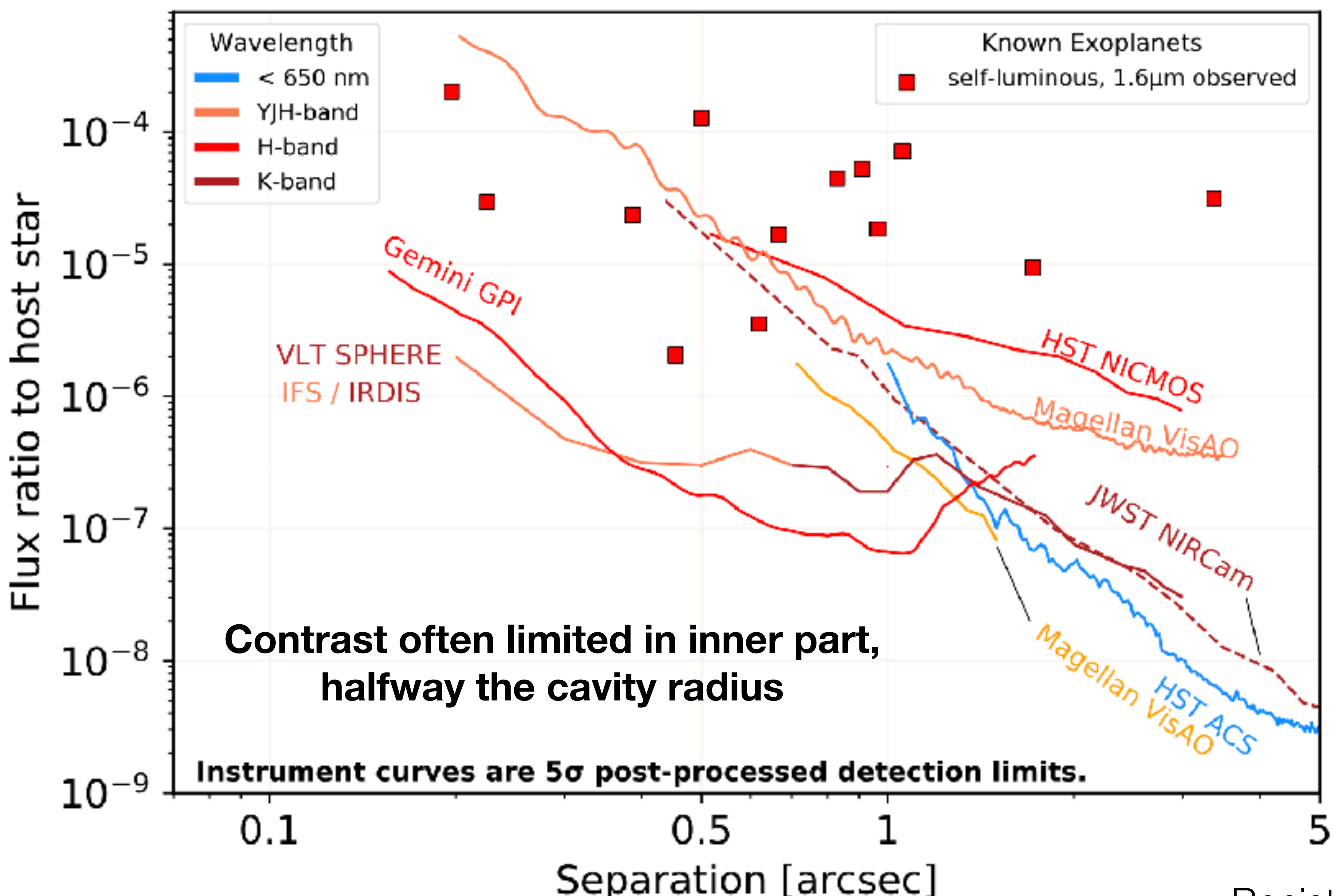


Canova et al. 2017



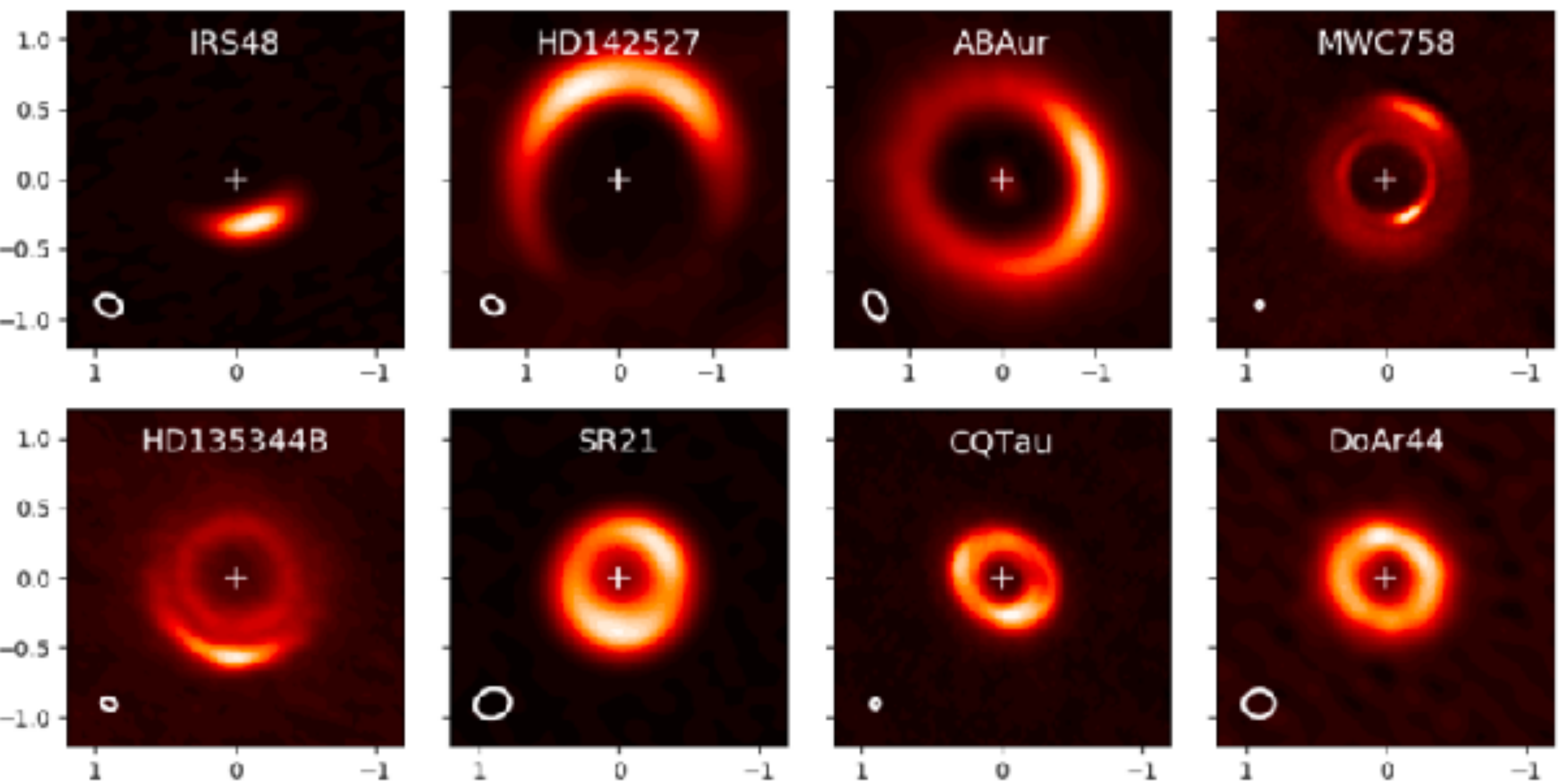
Van der Marel et al. 2021a
Asensio-Torres et al. 2021

Measurable contrast

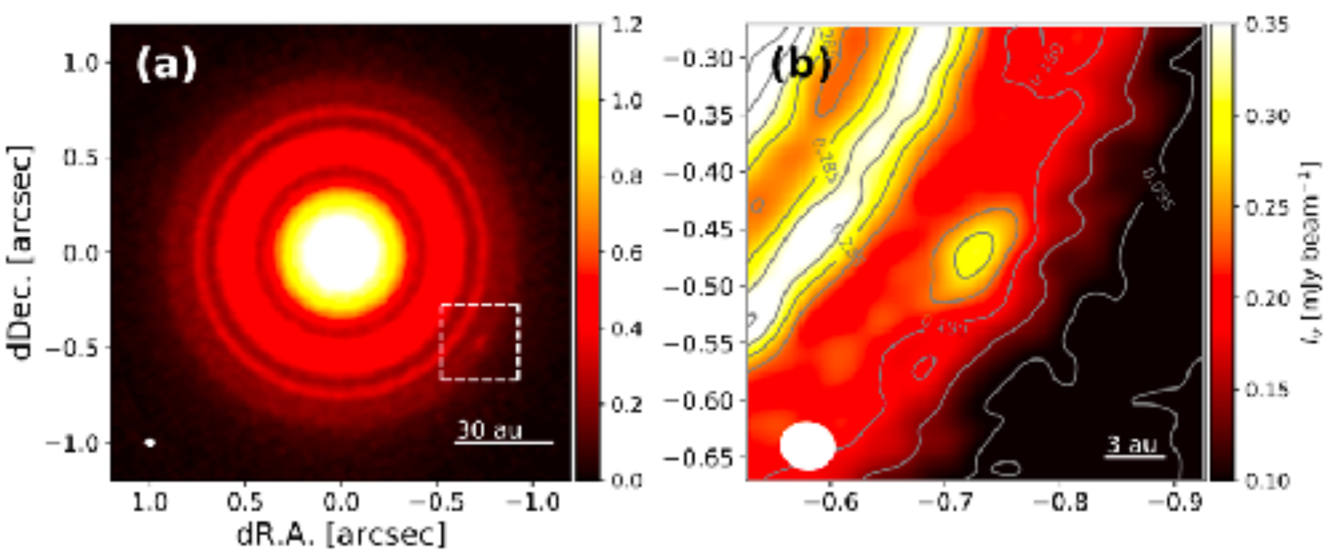


Benisty et al. 2022

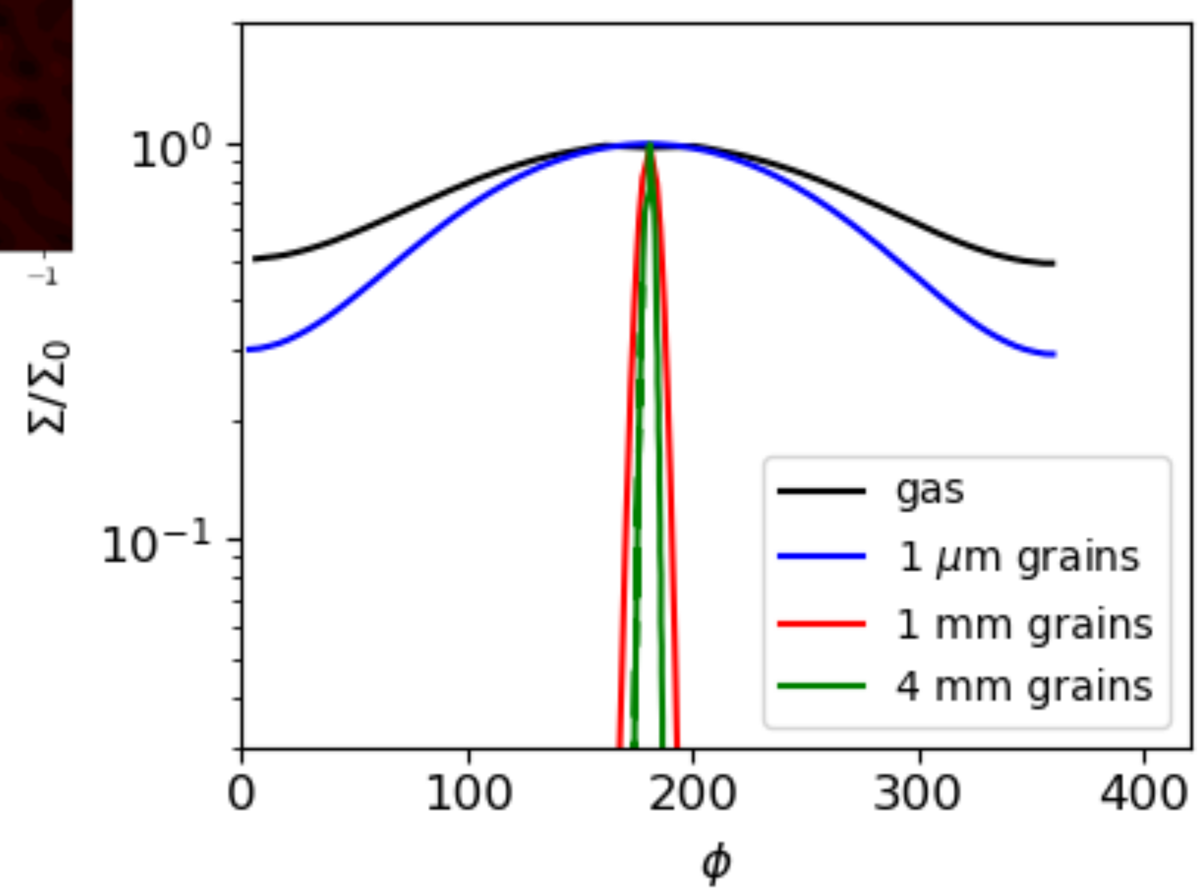
Asymmetries



Many dust asymmetries, large and small scale…



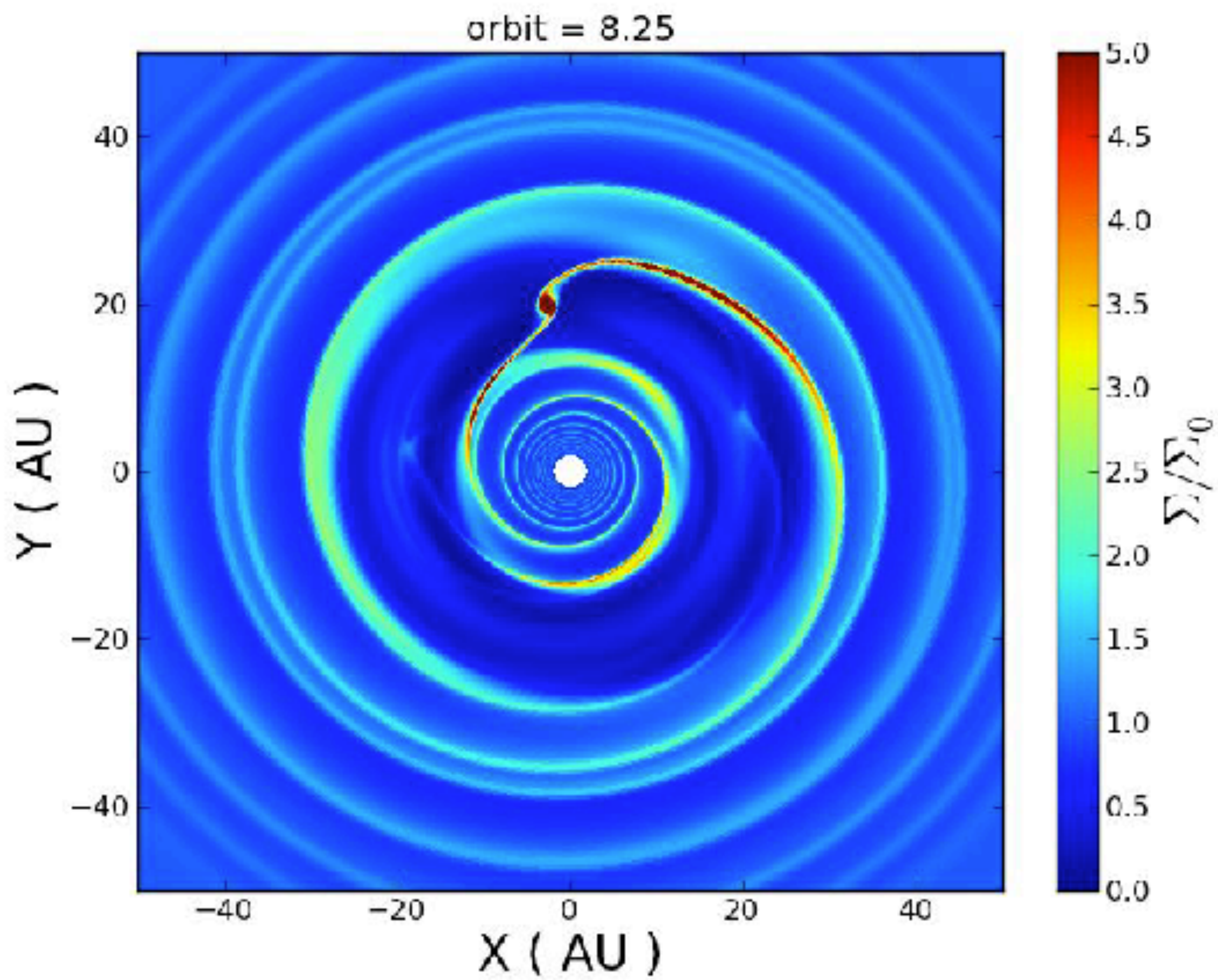
Dust evolution:
small azimuthal concentration of gas leads to strong concentration of mm grains

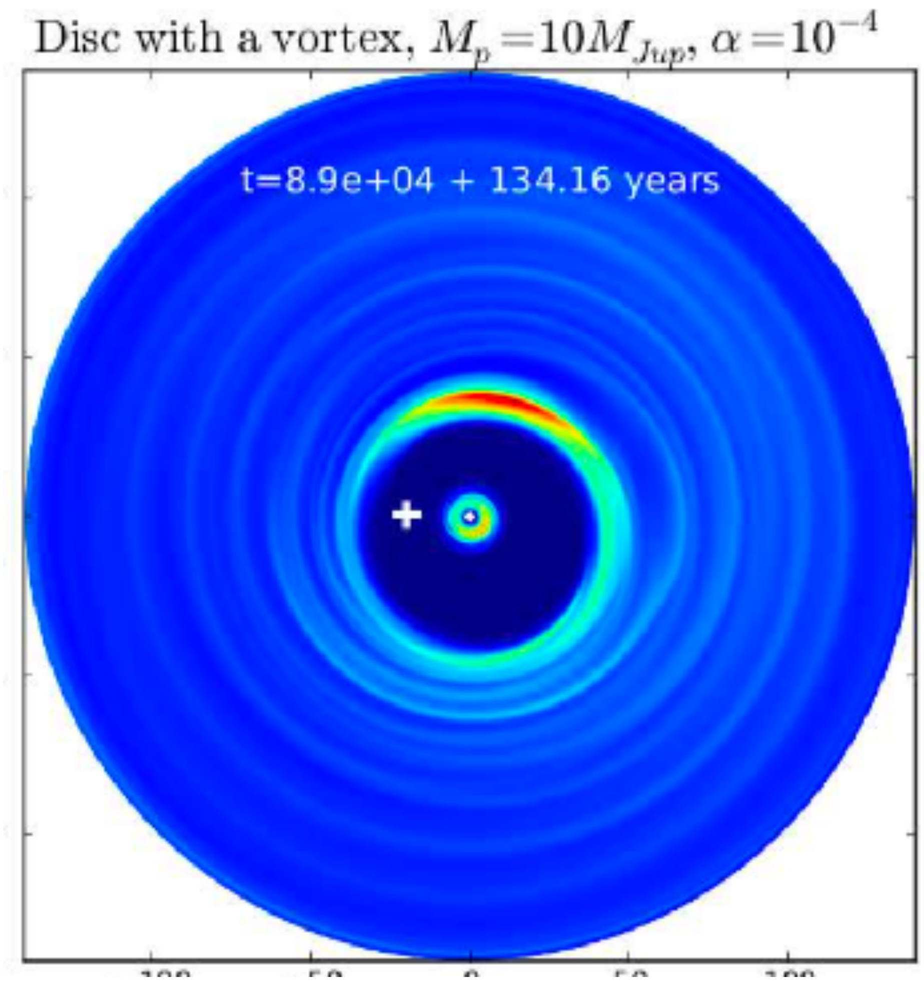


Van der Marel et al. 2021a
Birnstiel et al. 2013

Asymmetries: vortex

Rossby Wave Instability of pressure bump results in long-lived vortex: azimuthal dust trap



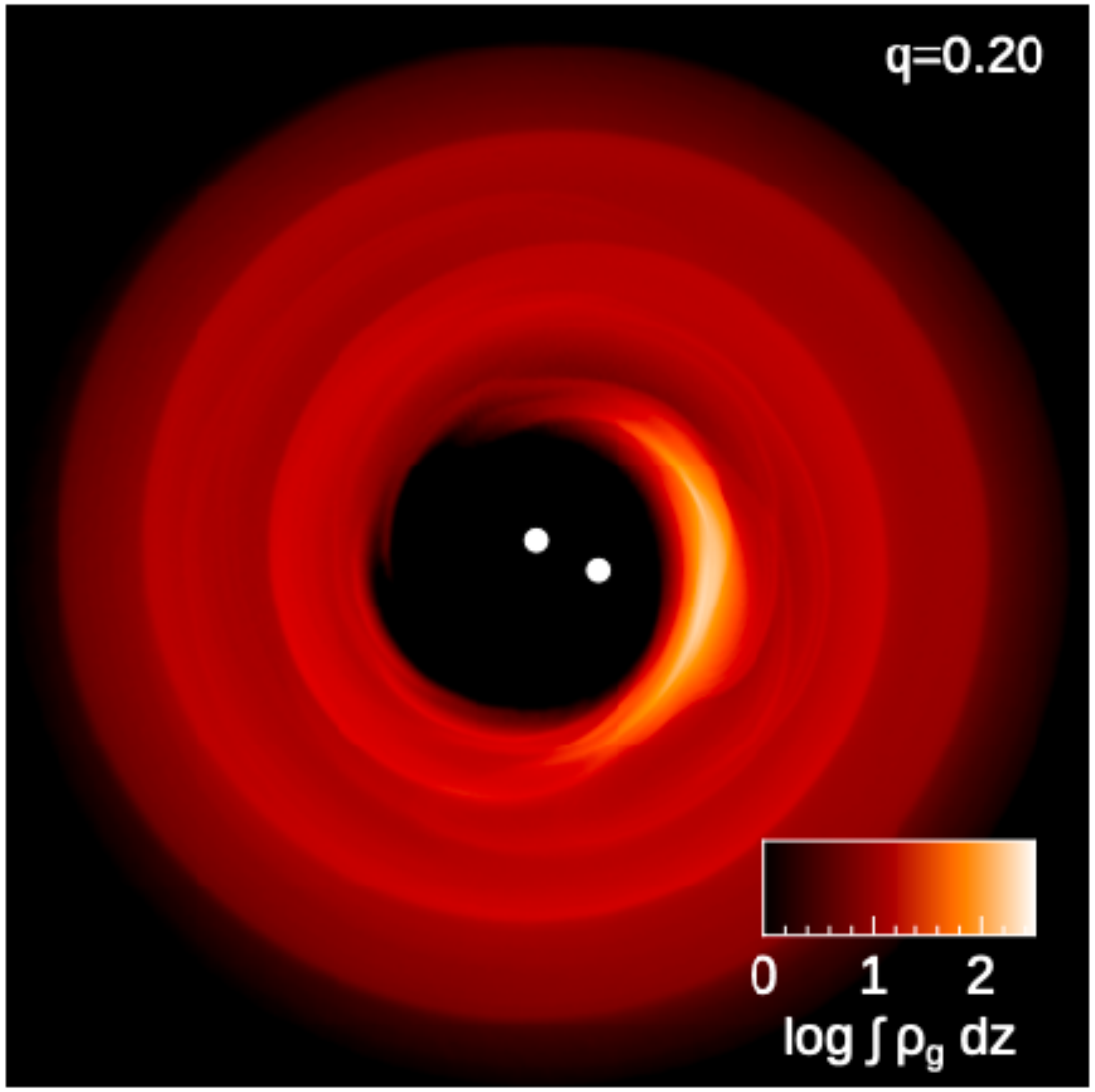


Problem: requires alpha ~ 10^{-4} (inconsistent with viscous disk model)

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

Asymmetries: horseshoe

If alpha is high, an alternative mechanism can explain asymmetries: development of a 'horseshoe' in eccentric circumbinary disk

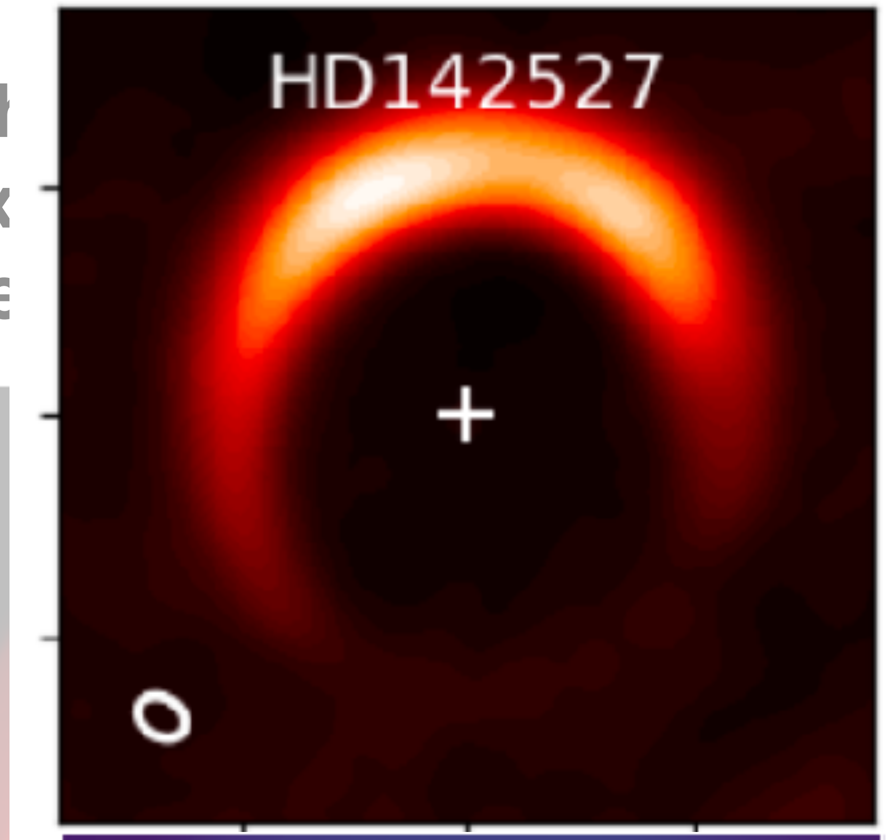


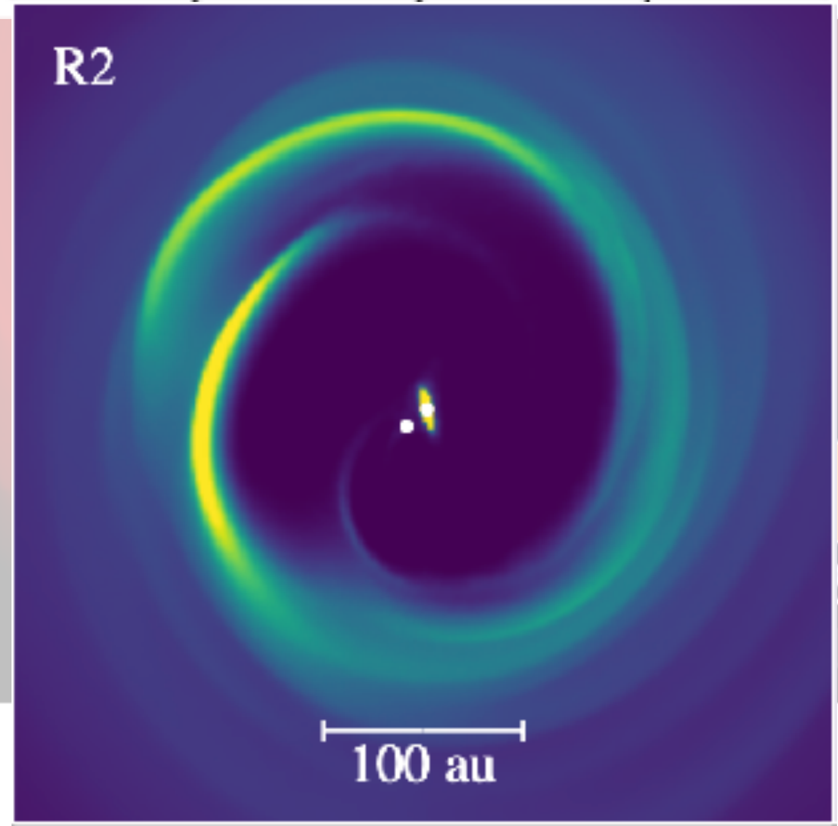
Do you remember where this may be the case?

Ragusa et al. 2016, 2020

Asymmetries: horseshoe

If alp| mechanism
can ex| opment of a
'horse| binary disk

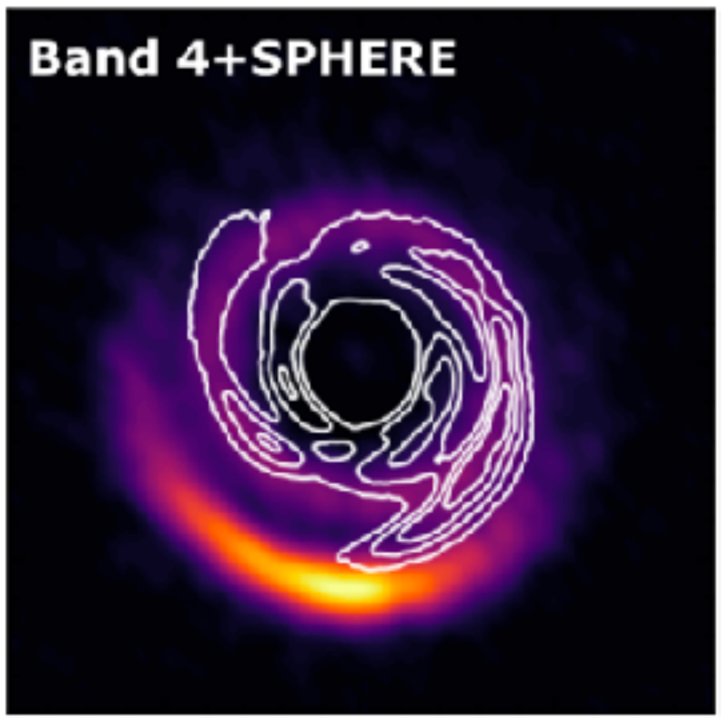


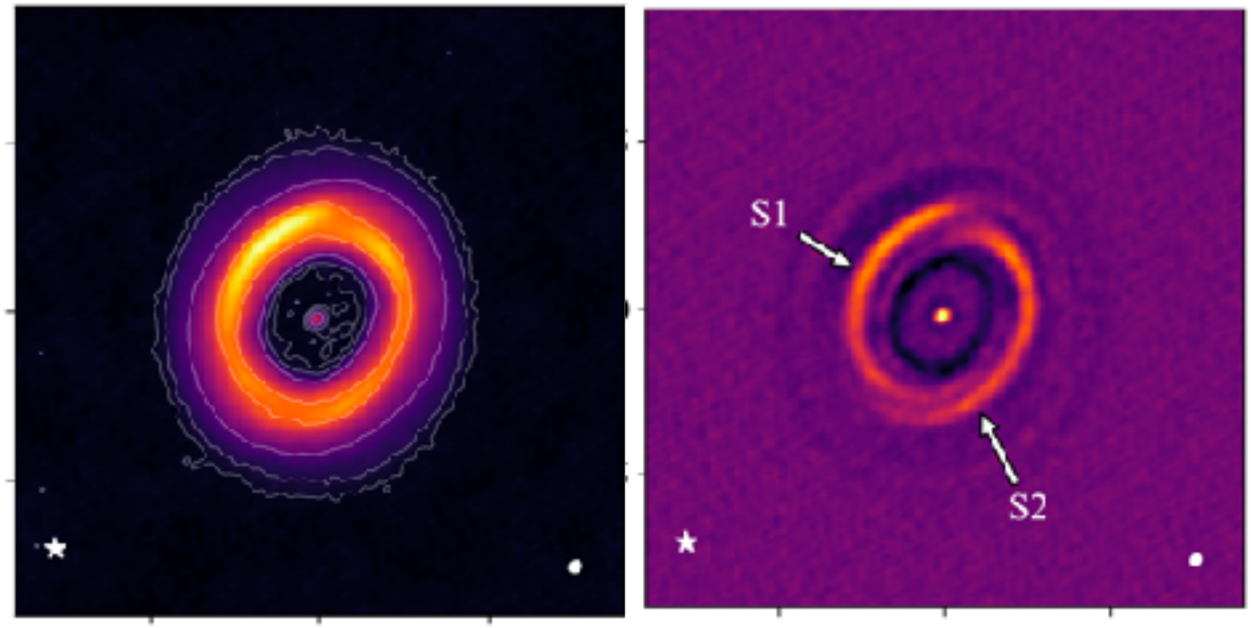


Essentially the distinction depends on the companion mass and the turbulence (alpha) value

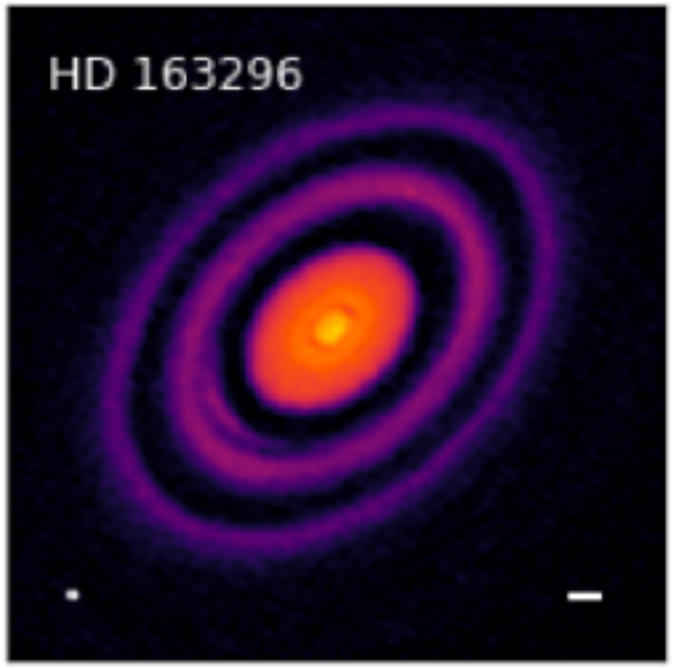
Ragusa et al. 2016, 2020
Price et al. 2018

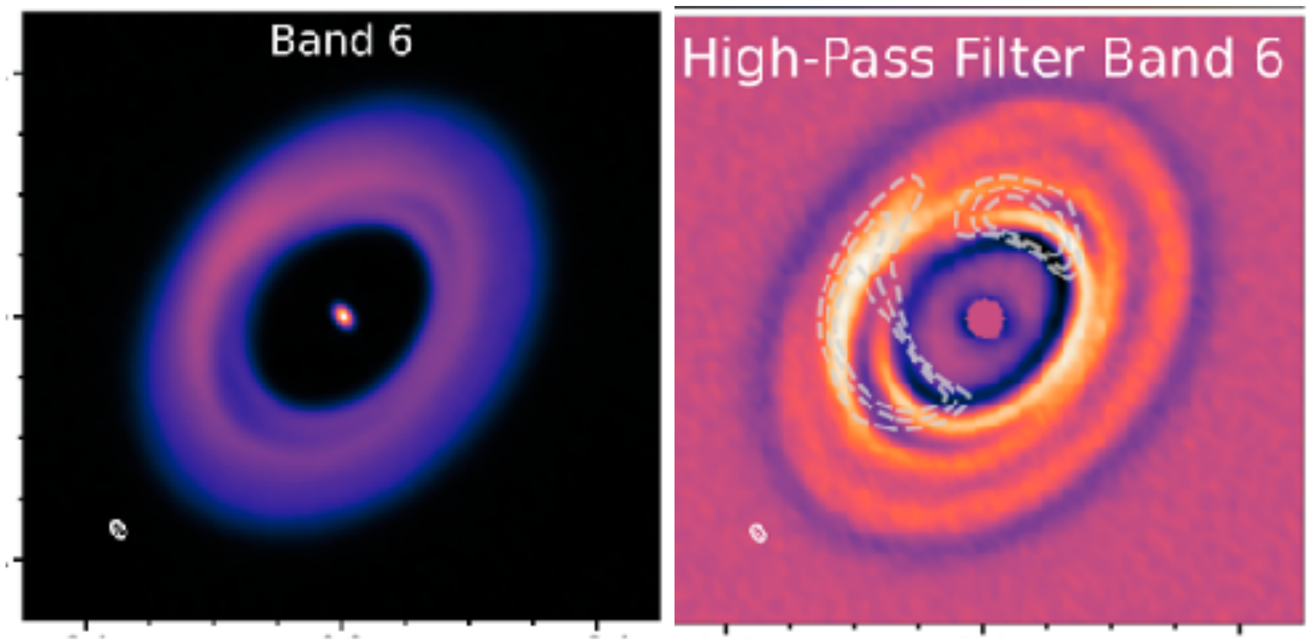
Asymmetries: spirals?





Several hints that spirals have a mm component: trapping seems unlikely (why?)

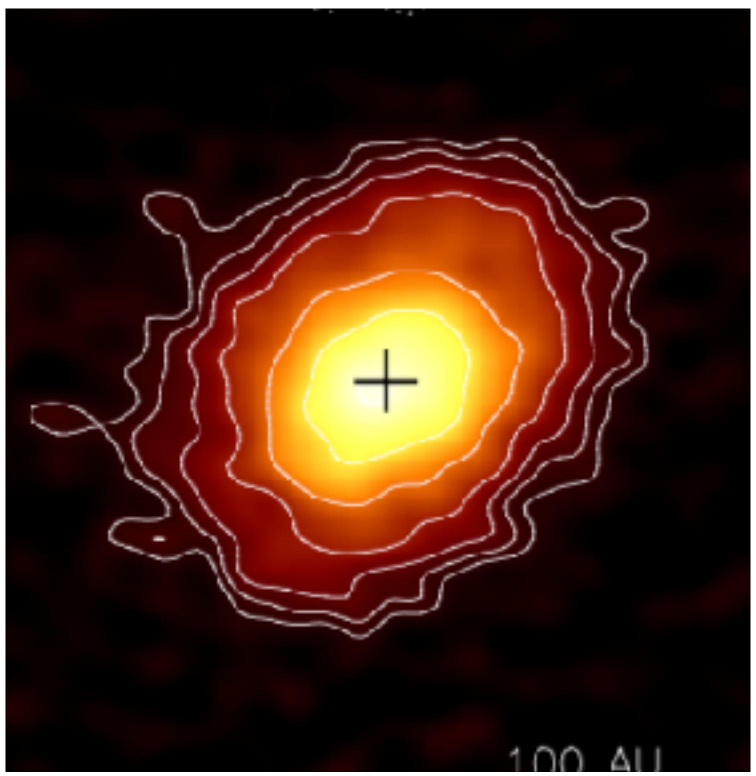


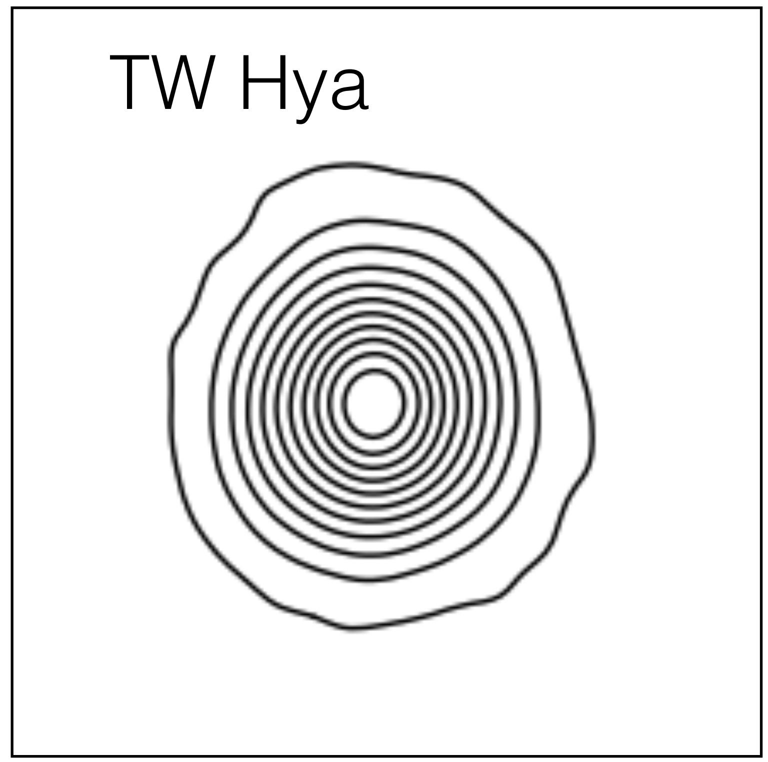


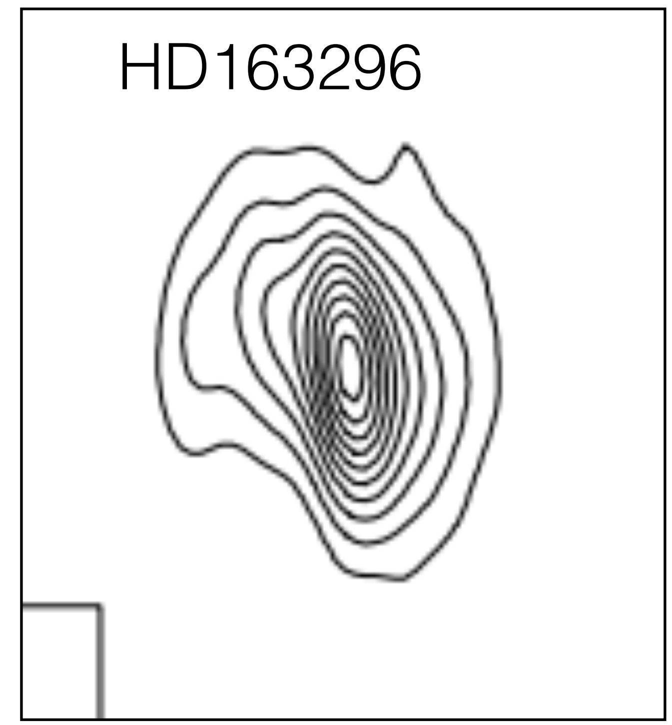
Cazzoletti et al. 2018
Andrews et al. 2018
Rosotti et al. 2019
Norfolk et al. 2022

Rings and gaps

“Smooth” disks at 0.2-0.3”….

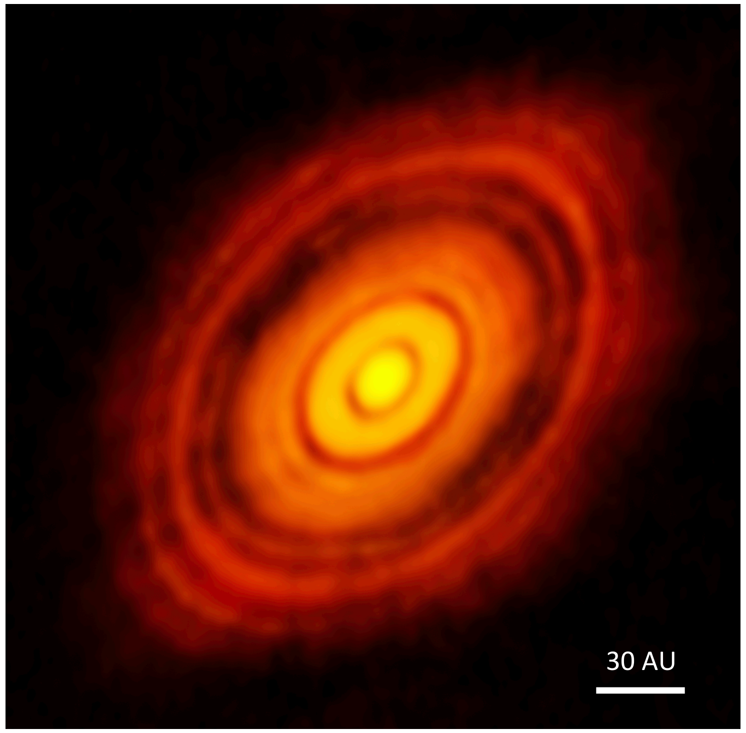


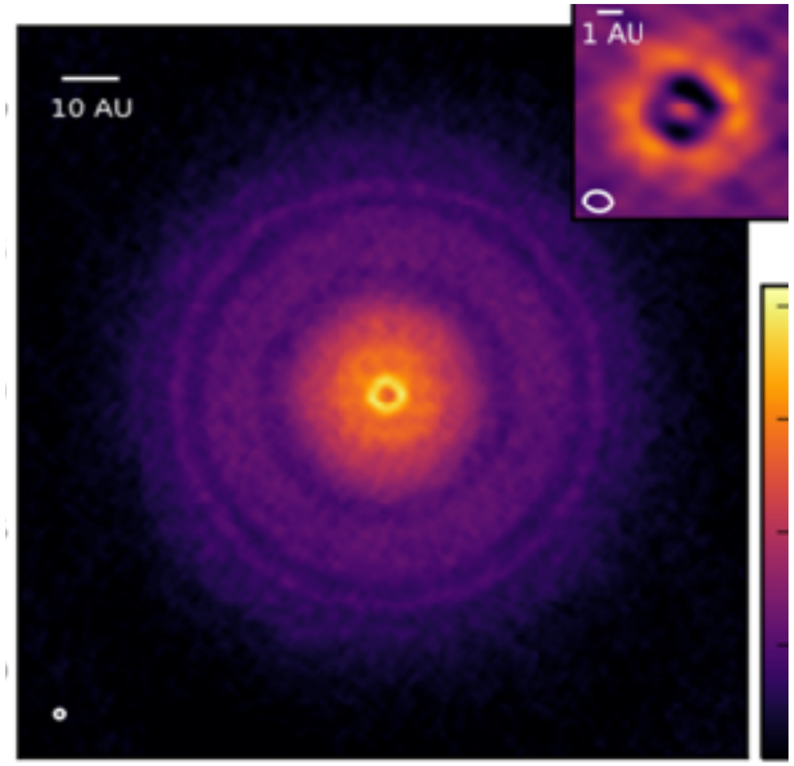


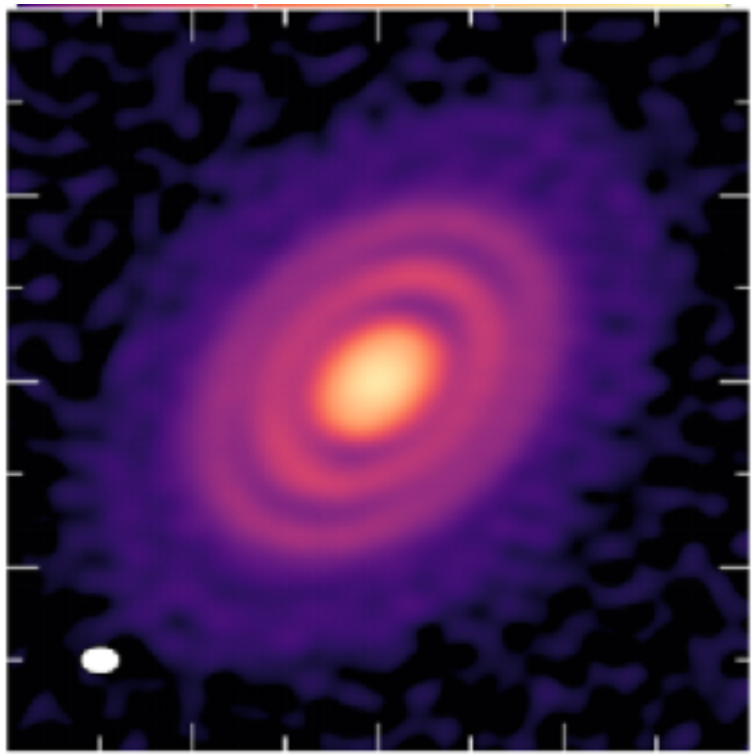


Rings and gaps

ALMA long baseline campaign: observations at 0.04" possible since 2015/2016!





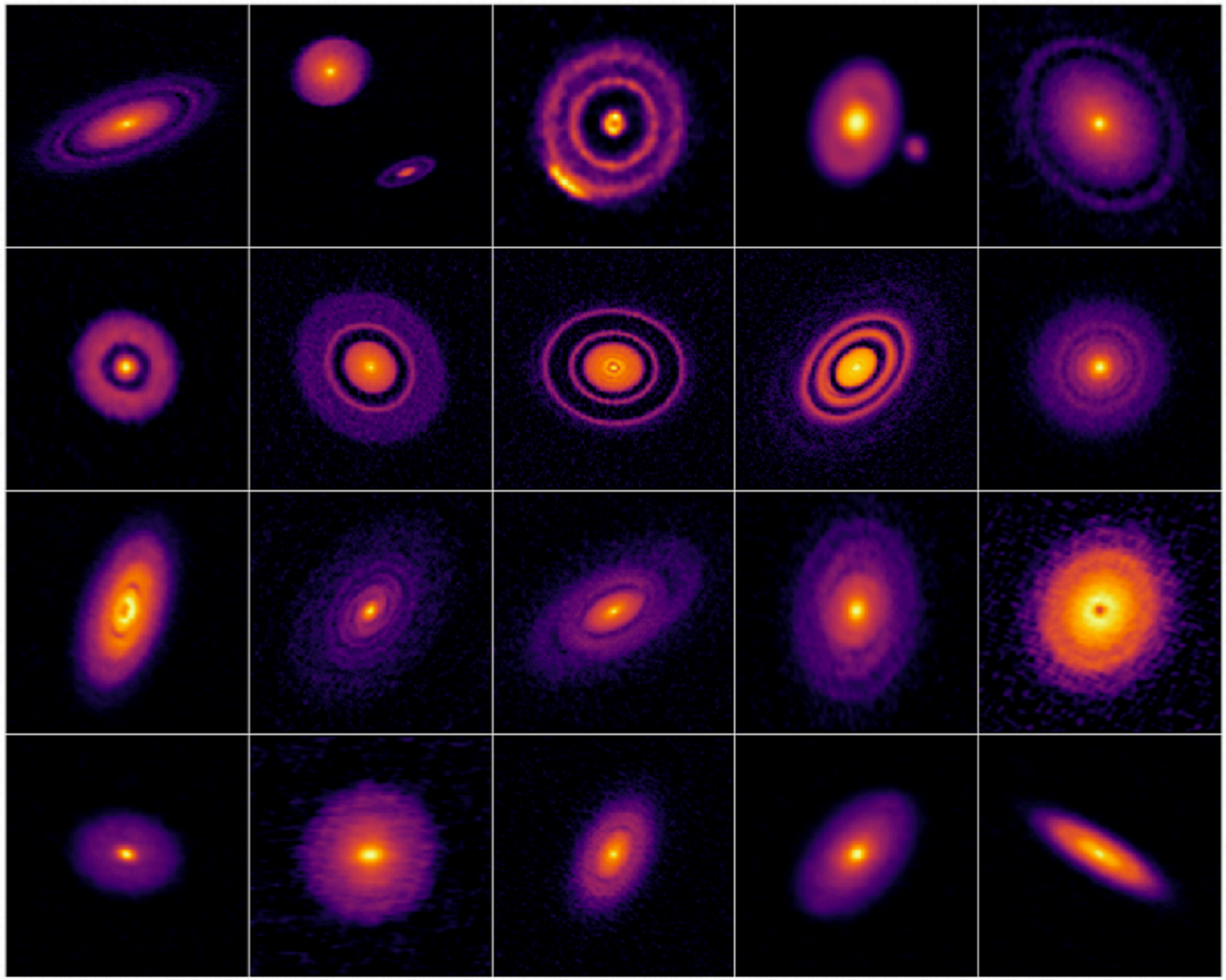


Suddenly <u>smooth</u> disks were shown to have many gaps and rings in their dust distribution, without a signature in their SED!

Why not?

ALMA consortium et al. 2015
Andrews et al. 2016
Isella et al. 2016

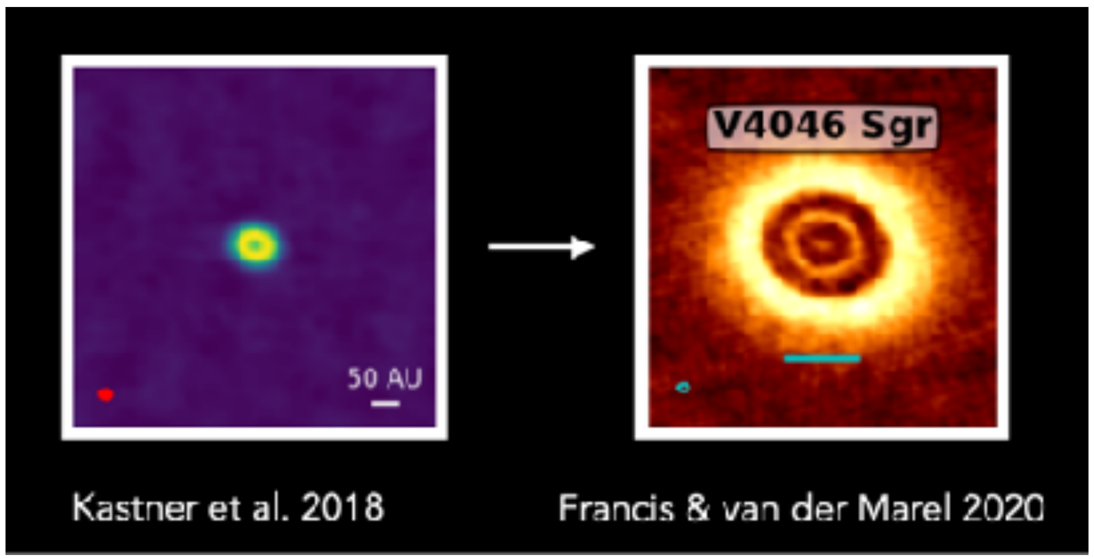
Rings and gaps

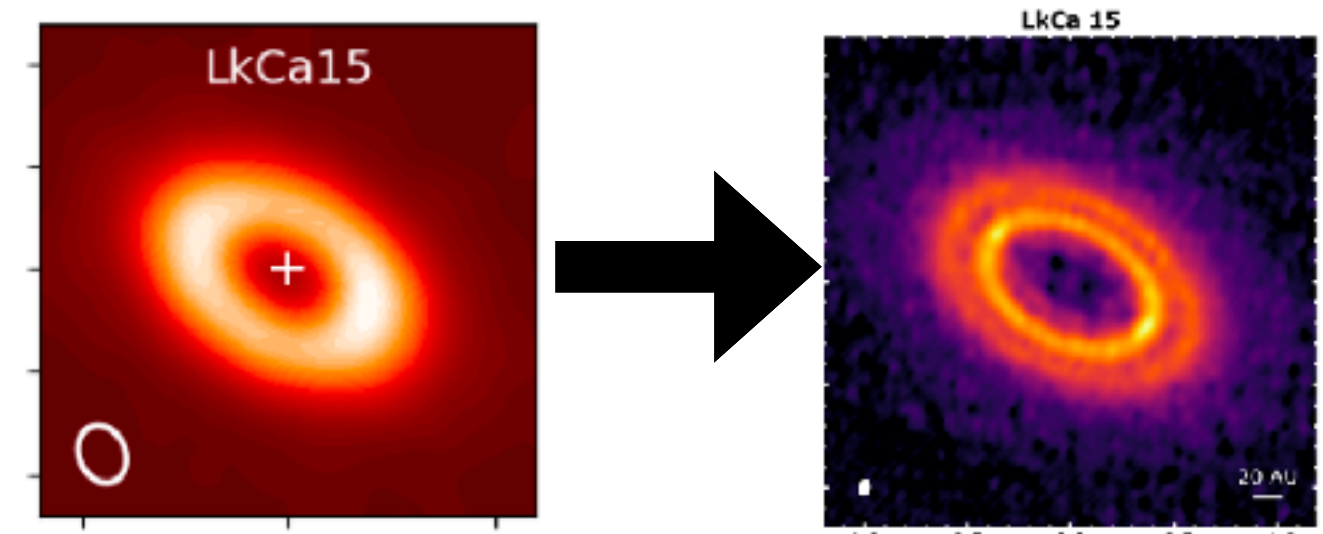


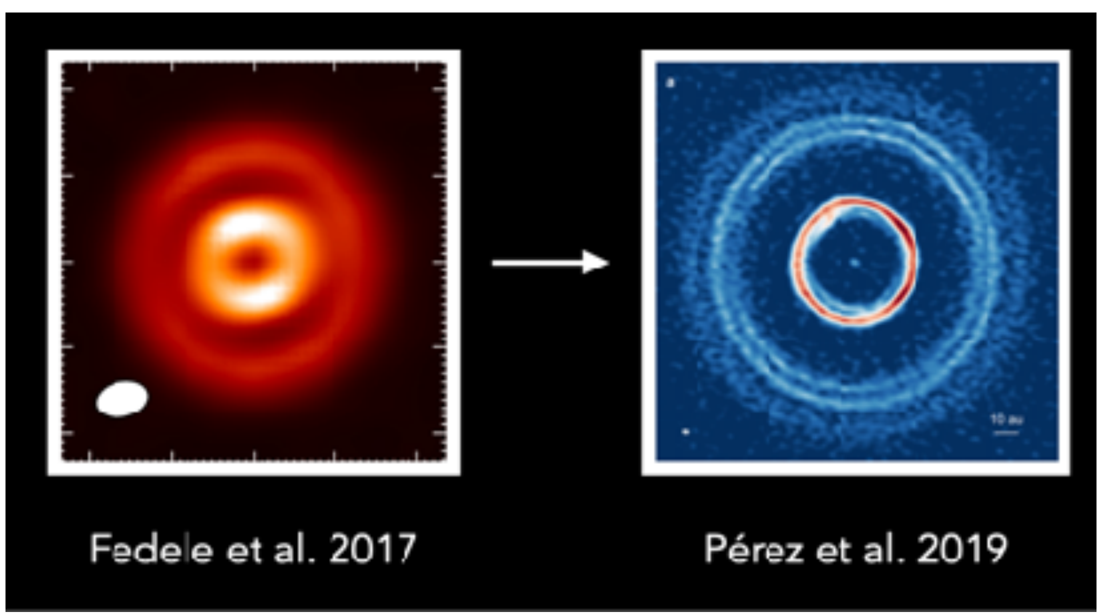
DSHARP: ALMA Large Program at 0.04":
Large diversity in ring/gap widths

Andrews et al. 2018

New gaps within rings







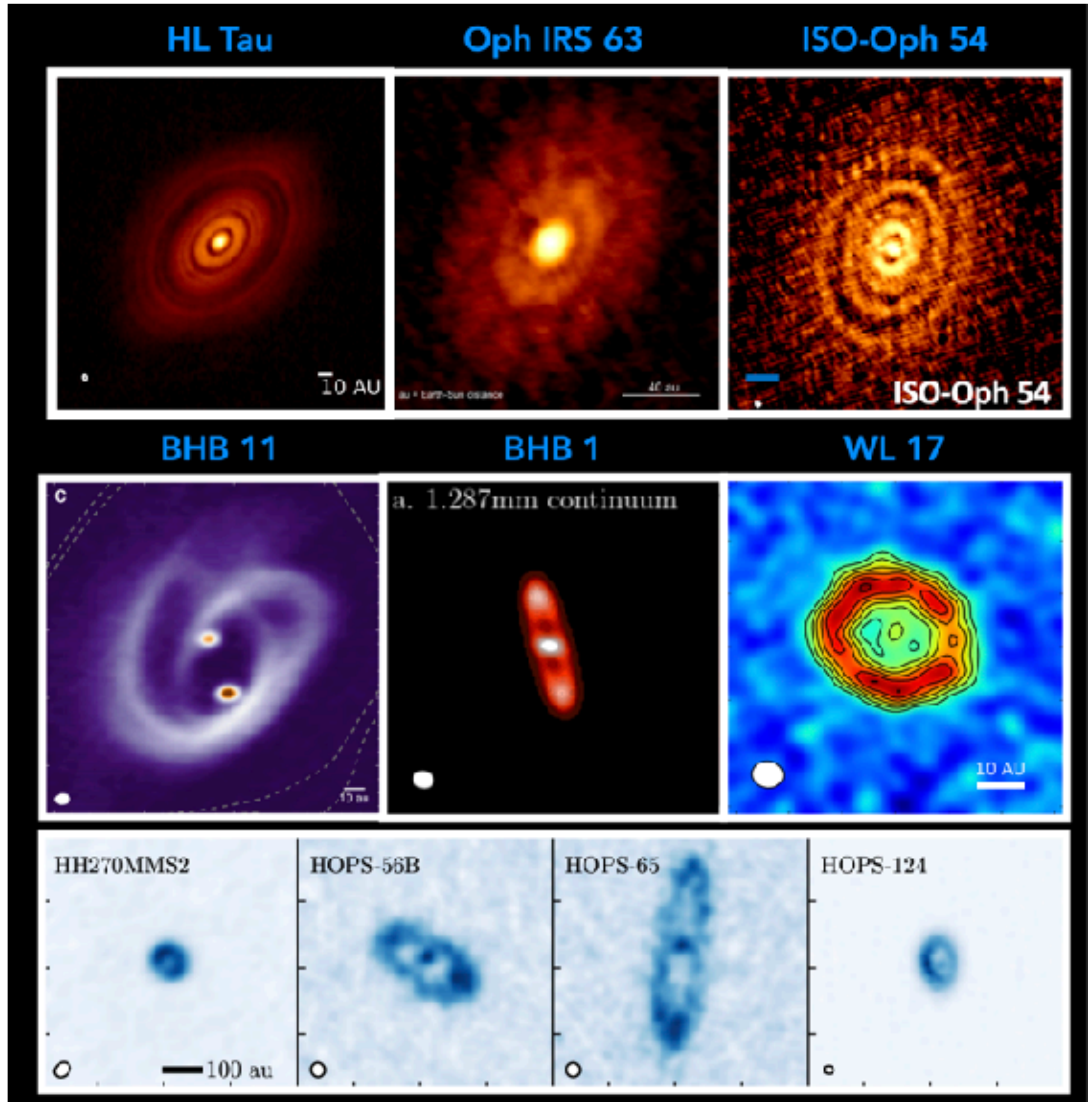
Higher resolution observations reveal rings in smooth disks, and sometimes even subrings in existing rings!

Rings and gaps in young disks

Rings and gaps are already seen at 0.5 Myr in embedded stage:

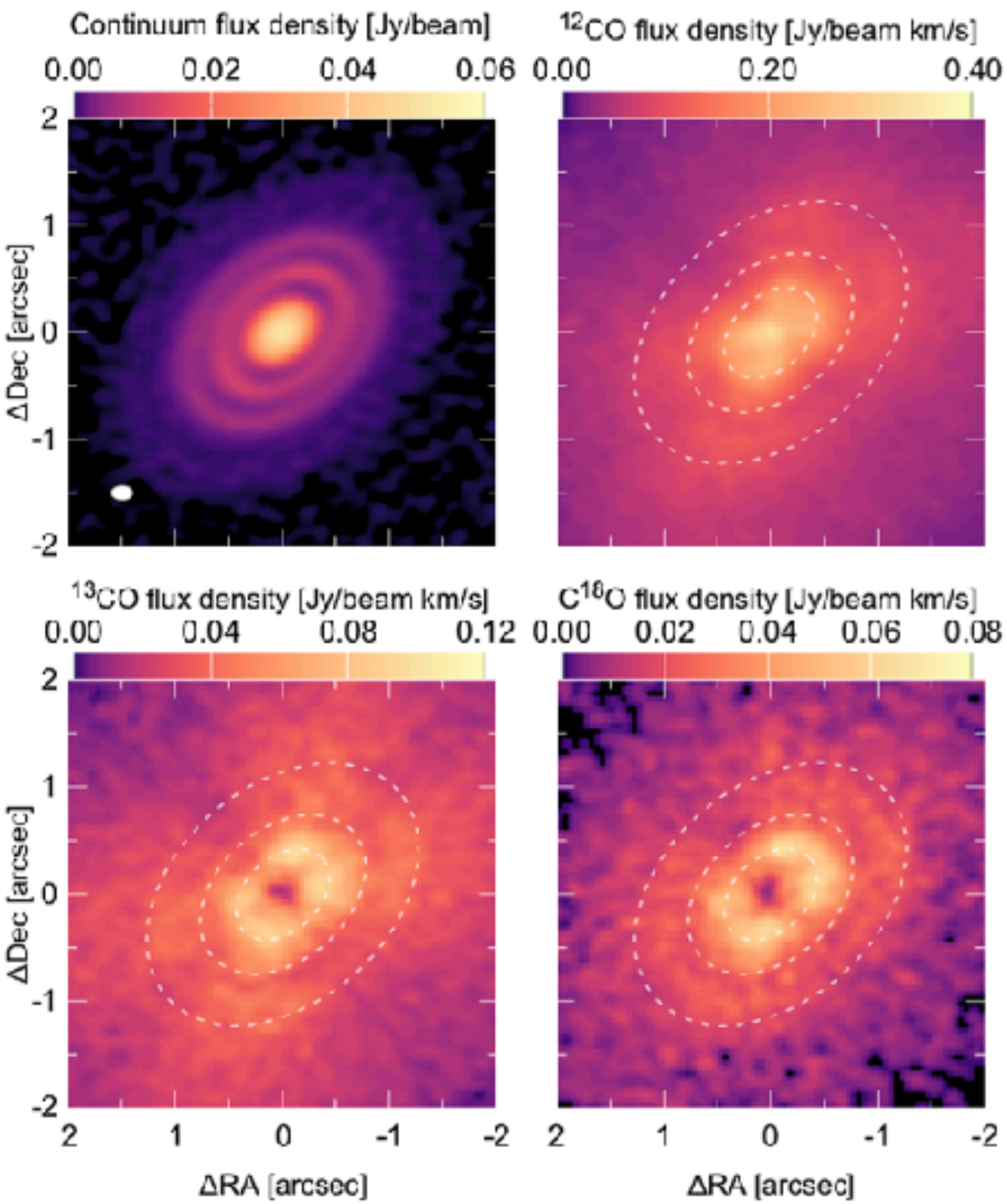
whatever causes them, it must happen rapidly.

How can we find out?

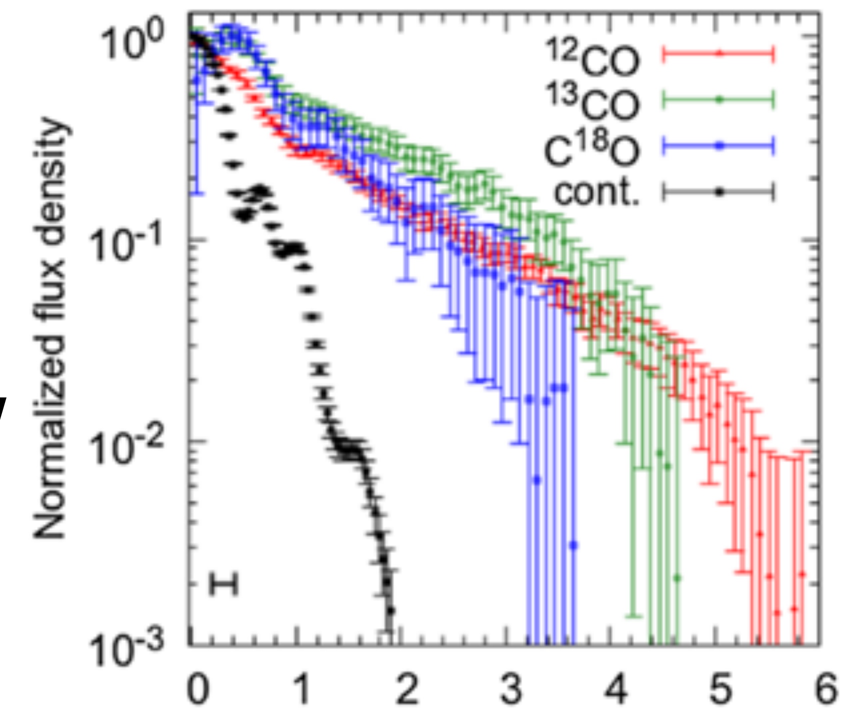


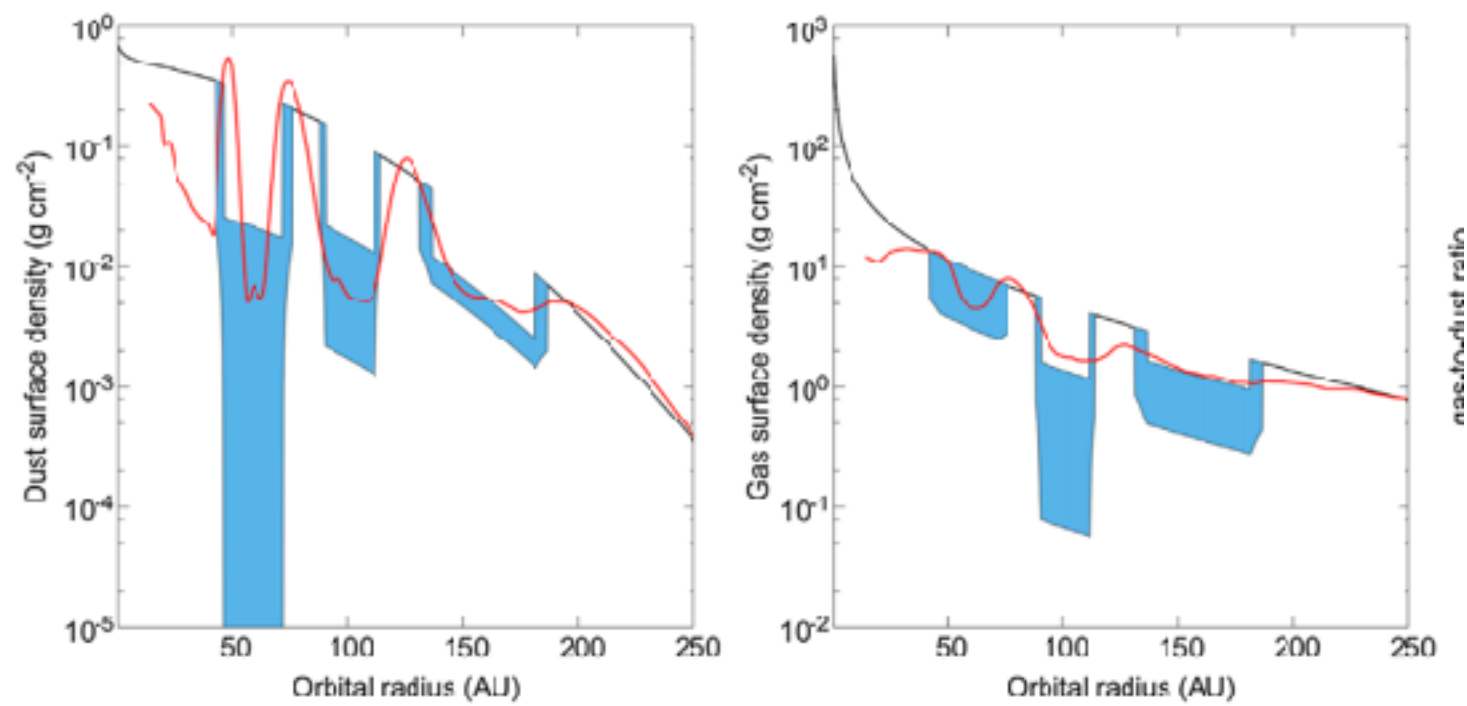
See, e.g., ALMA Partnership 2015, Tobin et al. 2016, Cieza et al. 2016, Sheehan & Eisner 2017, Alves et al. 2019, Lee et al. 2020, Sheehan et al. 2020, Alves et al. 2020, de Valon et al. 2020, Segura-Cox et al. 2021, Cieza et al. 2021

Gaps in gas?



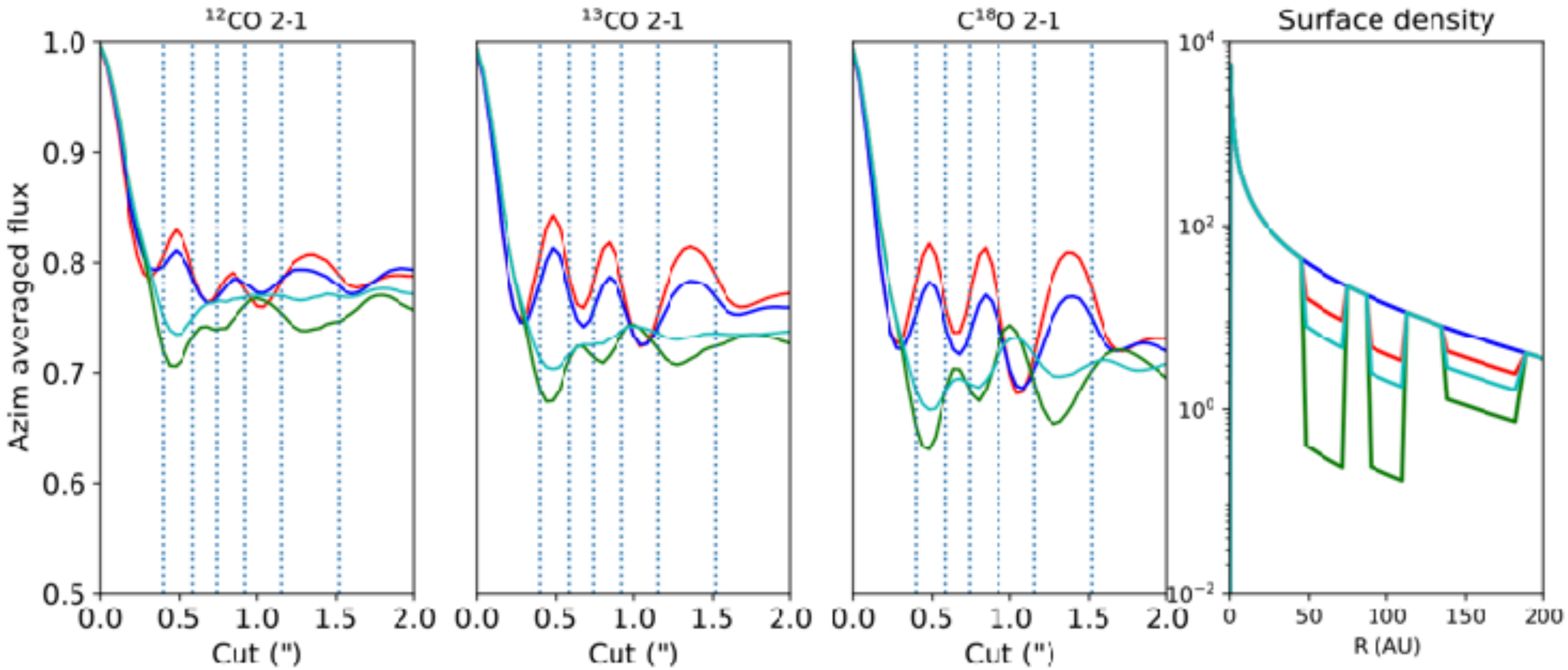
CO isotopologues in HD163296 show dips: gas gaps?





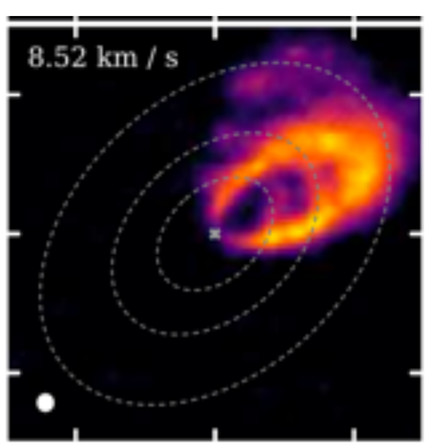
Isella et al. 2016

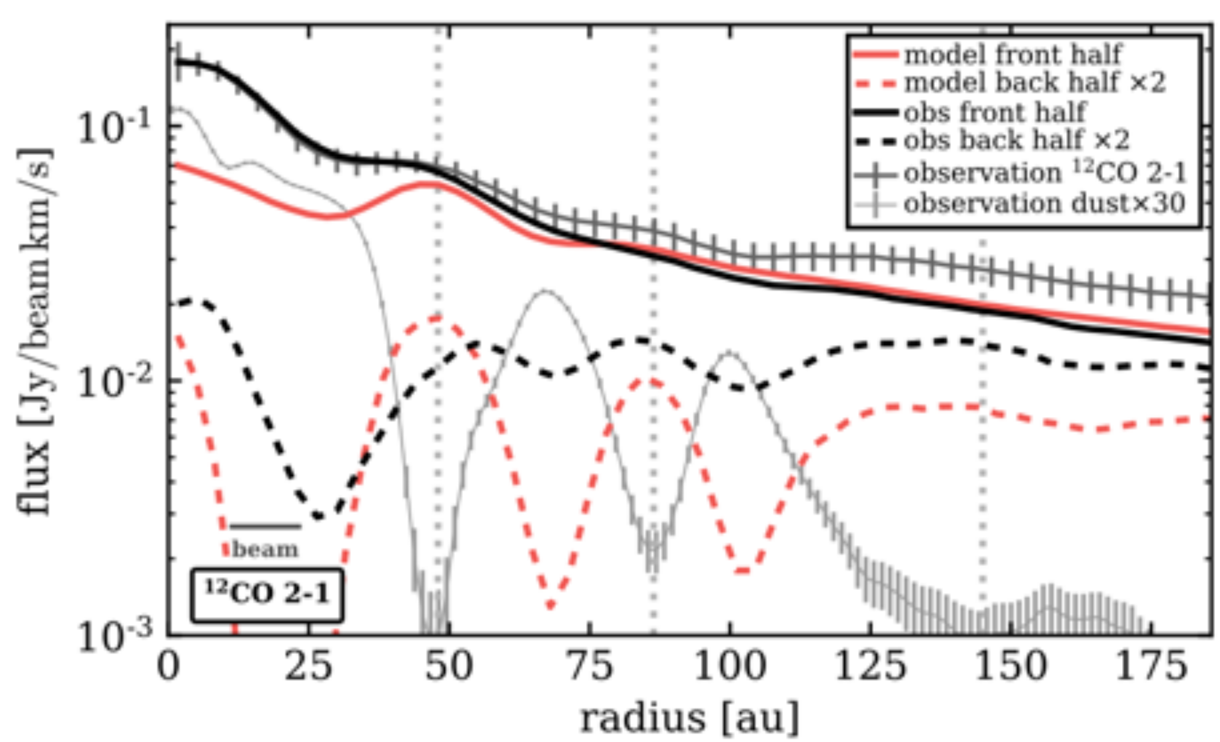
Not as easy as for TDs…



Gas temperature inside gaps changes due to gas-to-dust ratio

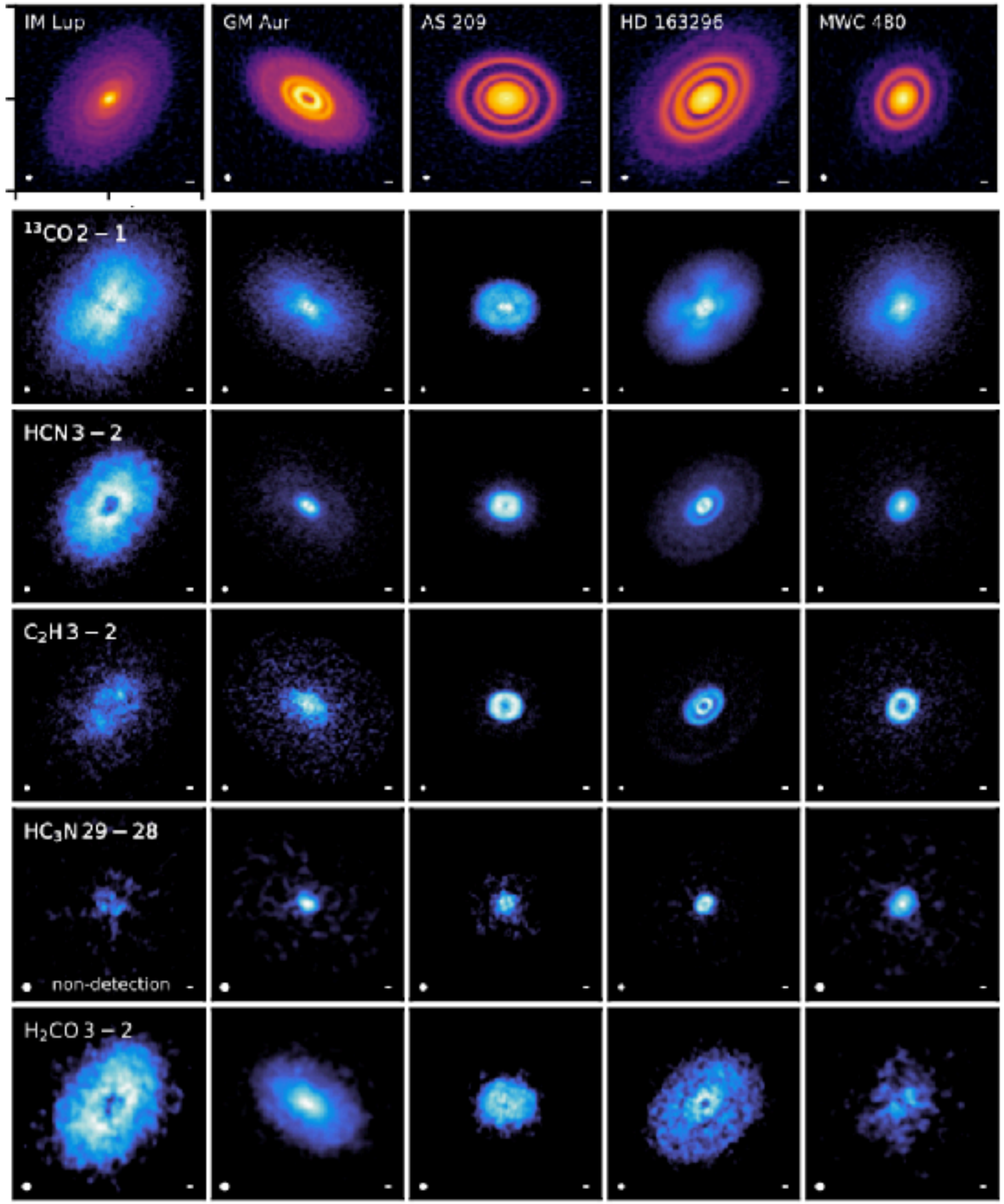
CO emission from the back side of the disk contributes in the gaps





Van der Marel et al. 2019
Rab et al. 2020

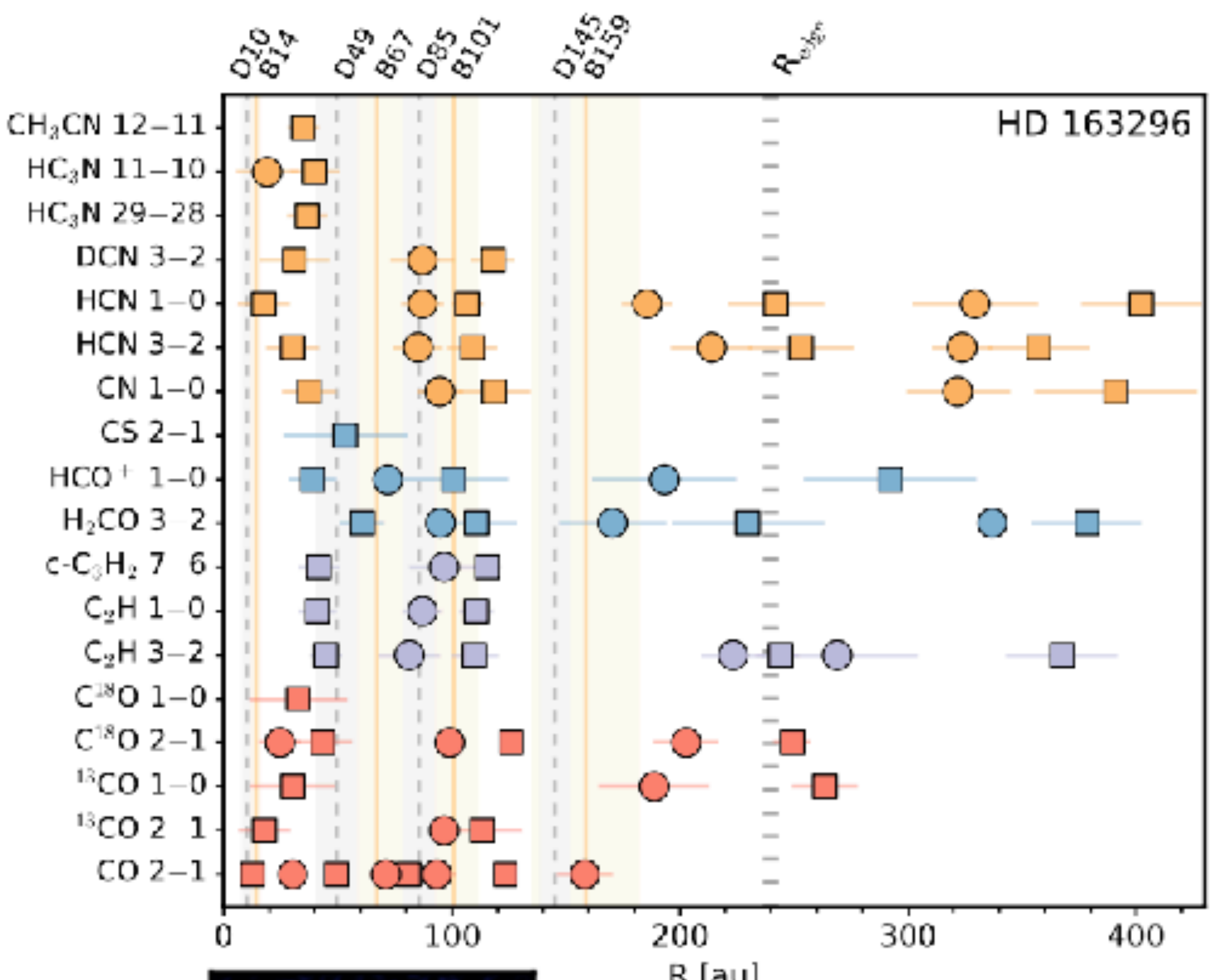
Rings and gaps in MAPS LP

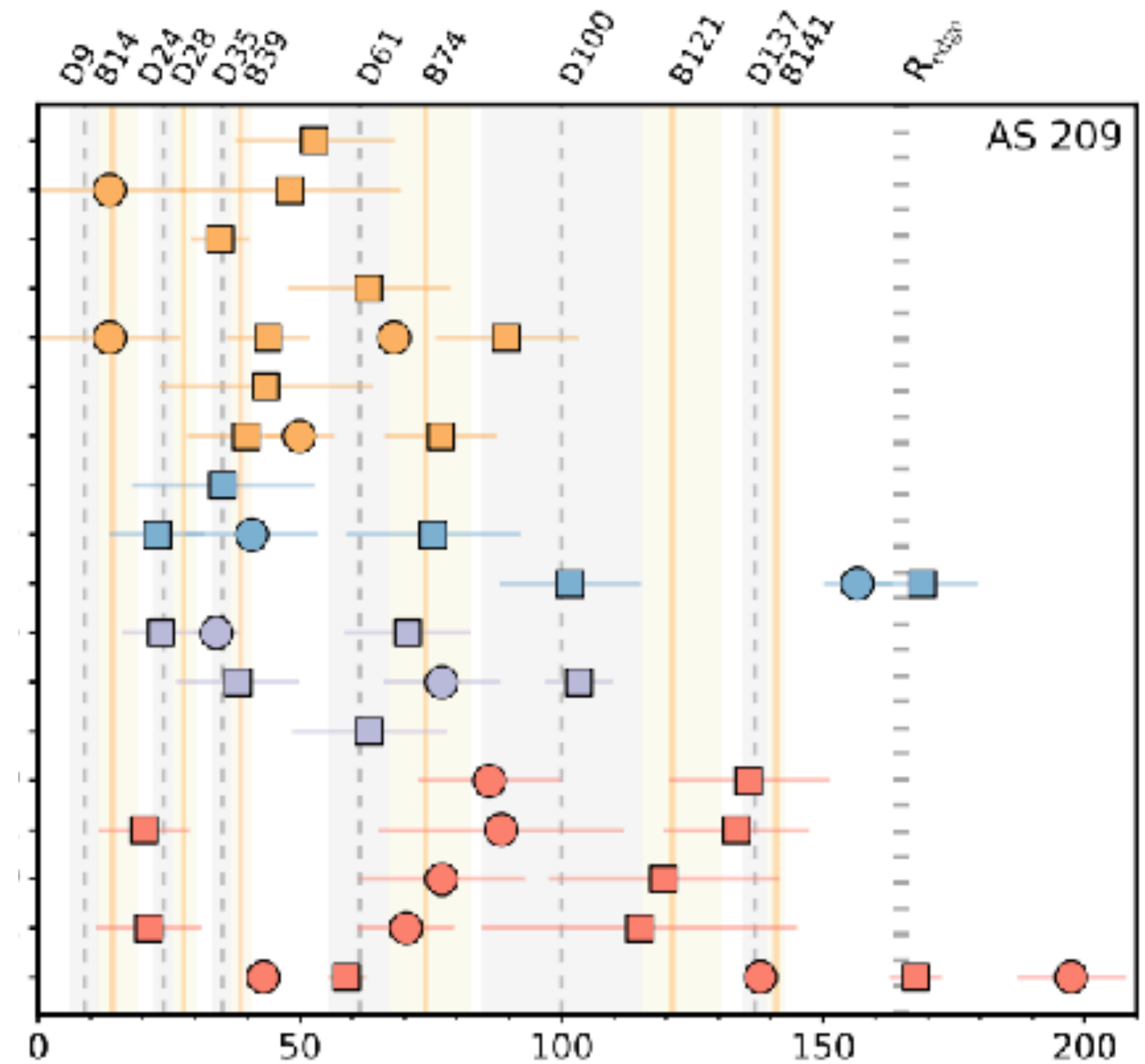


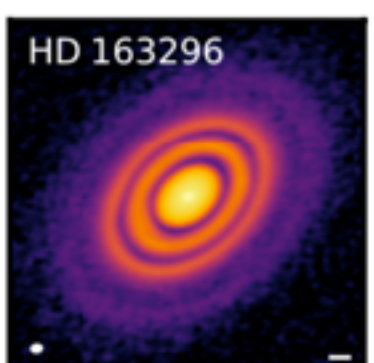
Large diversity in gaps in various molecules

Oberg et al. 2021 (MAPS)

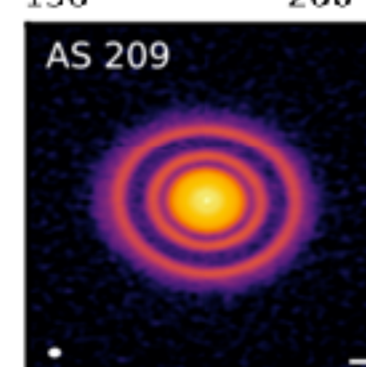
MAPS: molecular gaps?







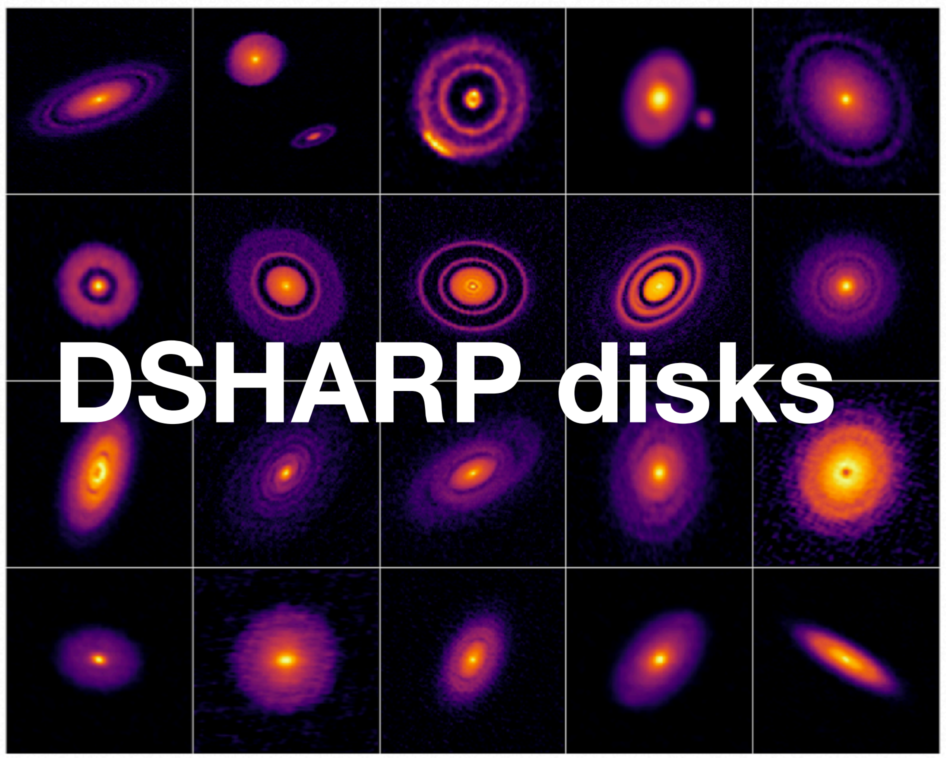
Some gaps in molecules overlap with dust, others do not: no clear link and other mechanisms than gap clearing must be responsible



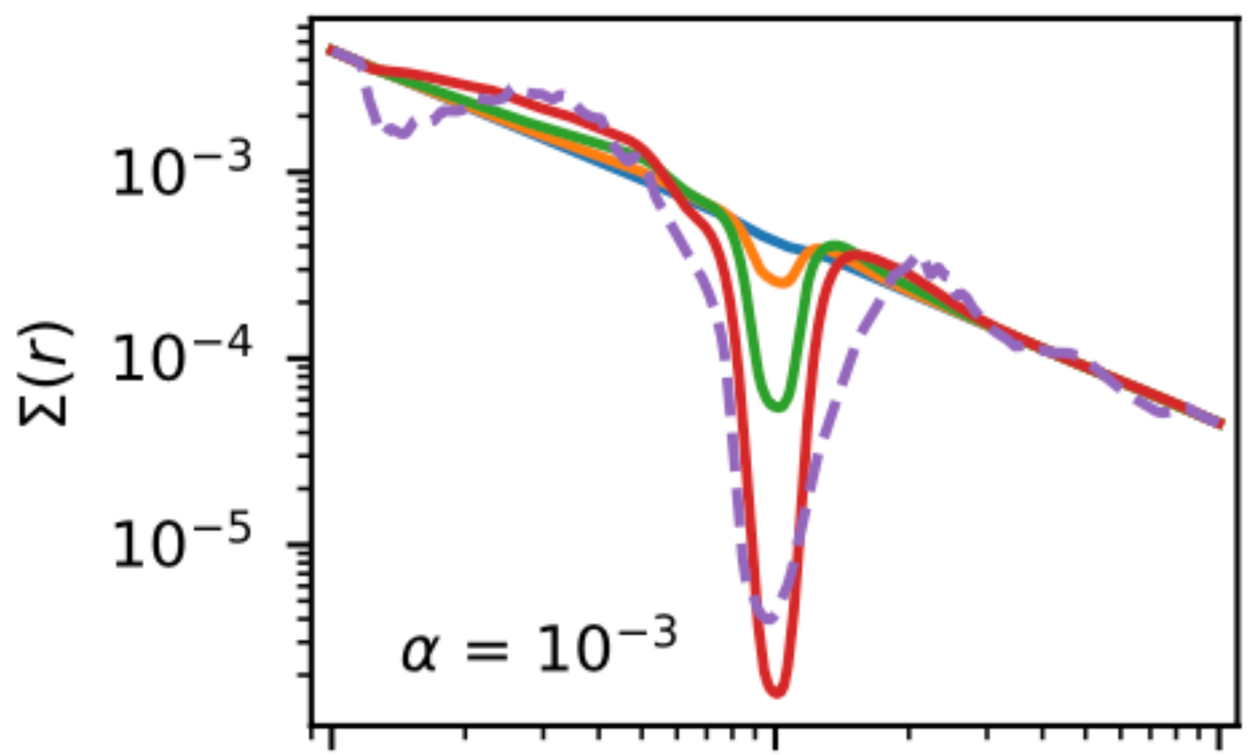
Law et al. 2021 (MAPS)

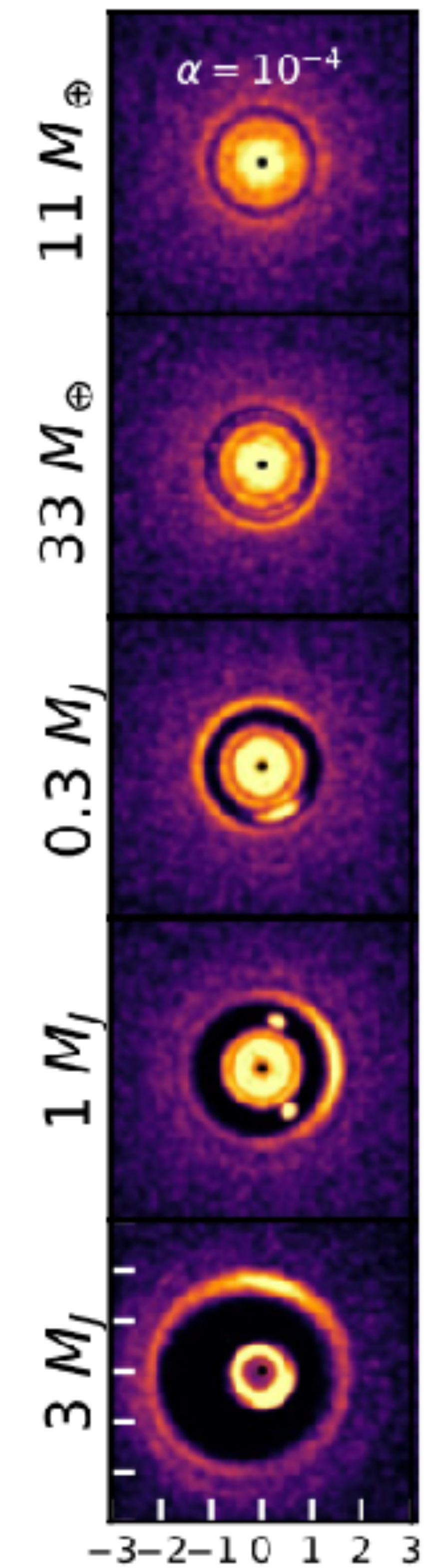
Origin rings and gaps

1. Planets



Hydrodynamic simulations of planet-gap clearing: reproducing the gaps widths in the DSHARP disks for a range of planet masses



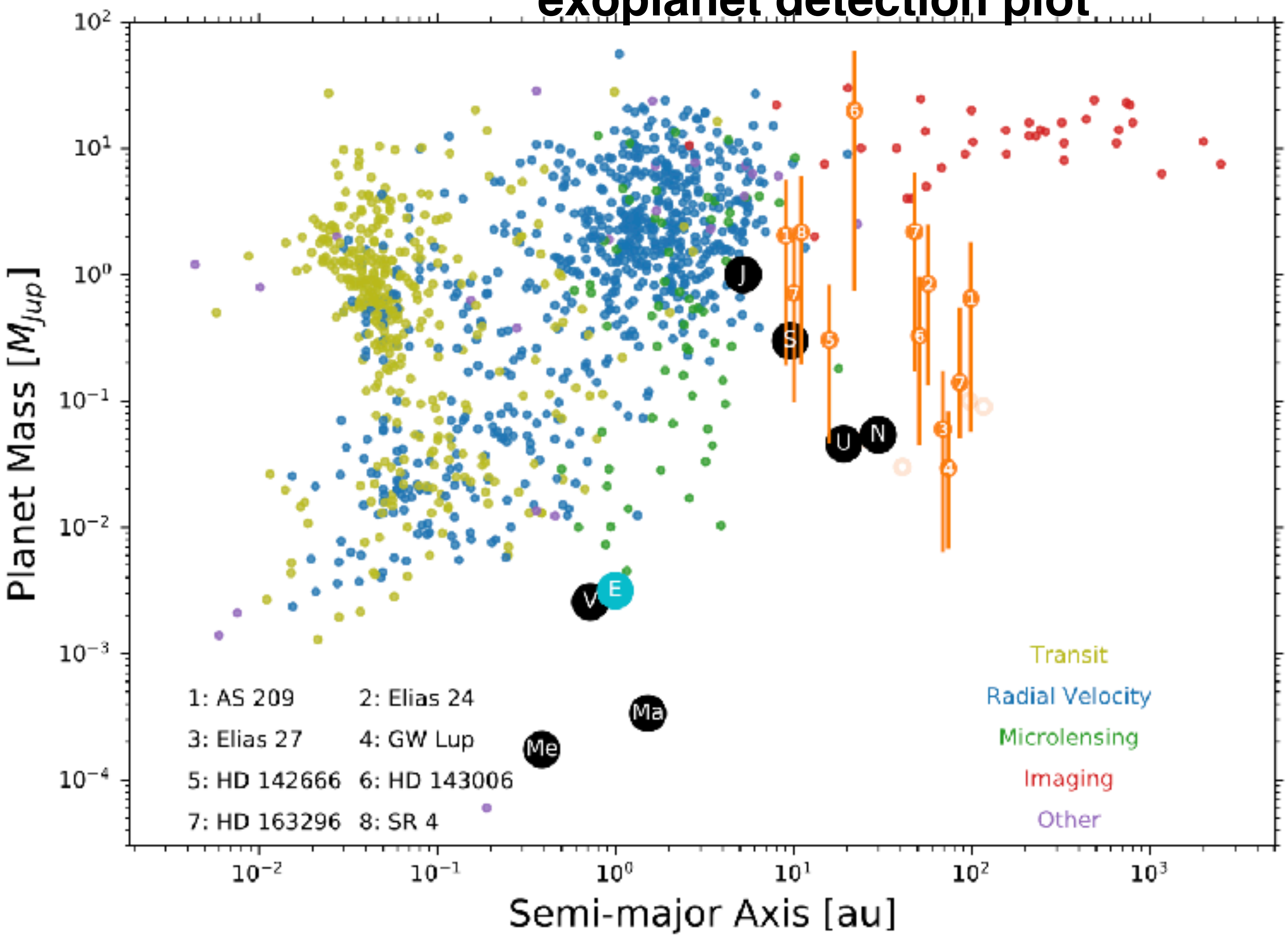


Zhang et al. 2018 (DSHARP)

Origin rings and gaps

1. Planets

Inferred planet masses and locations from DSHARP in exoplanet detection plot

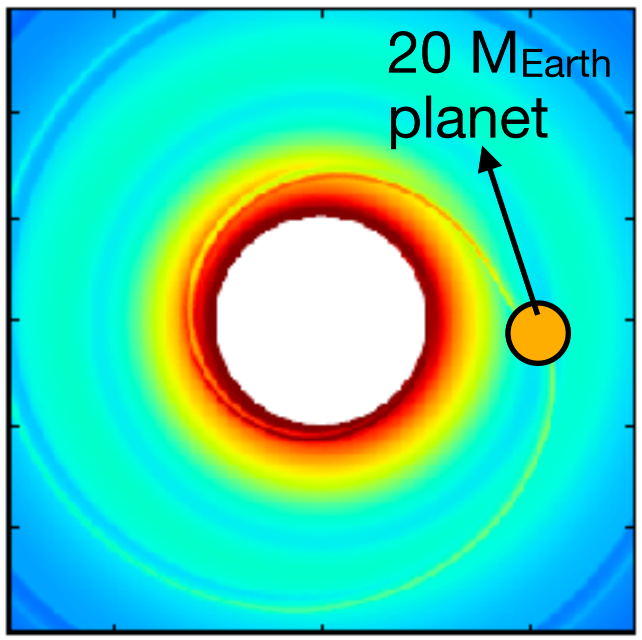


Zhang et al. 2018 (DSHARP)

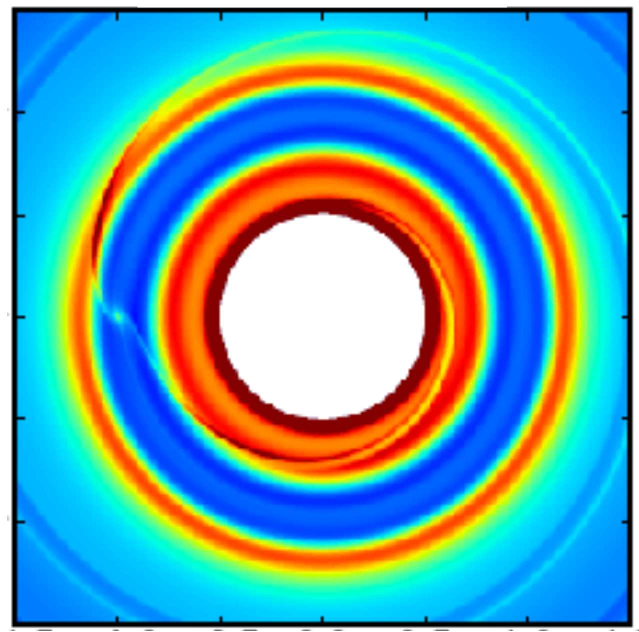
Origin rings and gaps

1. Planets

Gas



mm-dust

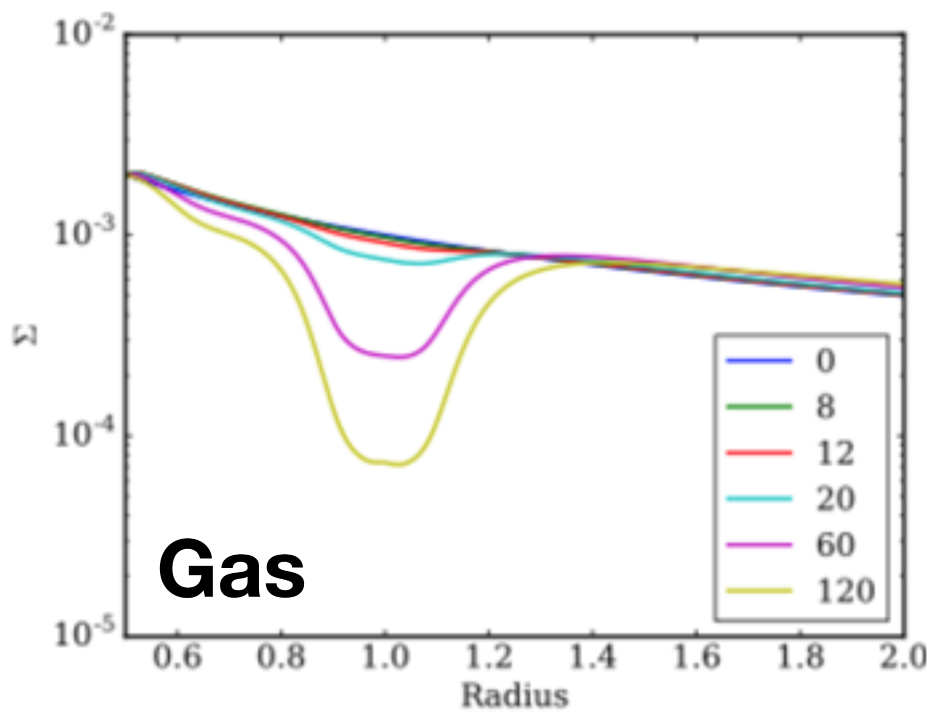


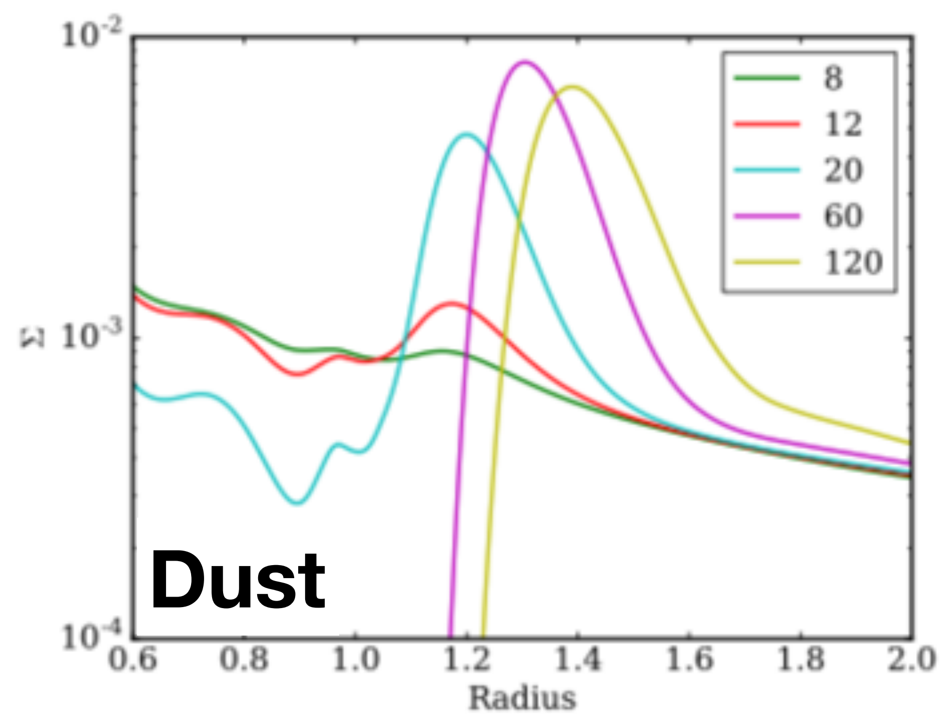
From simulations:

$$M_{\rm iso} \approx 20 \left(\frac{a}{5\ \rm AU}\right)^{3/4} M_{\rm E}.$$

Minimum M_p for a dust trap at large R is ~ 10-20 M_E ("pebble isolation mass")

Gap depth different planet masses (in M_{Earth})

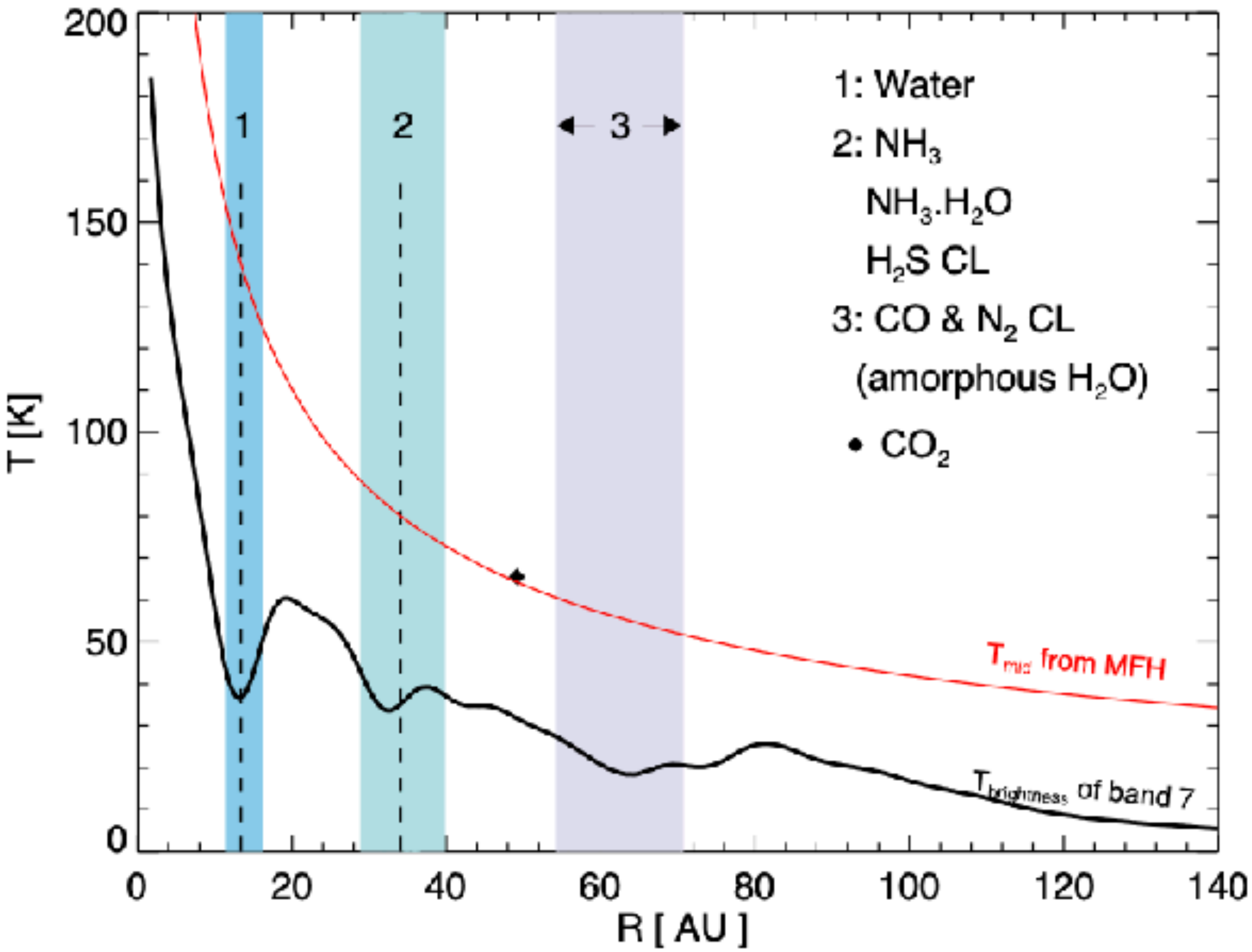




Lambrechts et al. 2014
Rosotti et al. 2016
Sinclair et al. 2020

Origin rings and gaps

2. Snowlines



Dips in continuum overlap with major snowlines: origin of dust rings due to increased sticking efficiency?

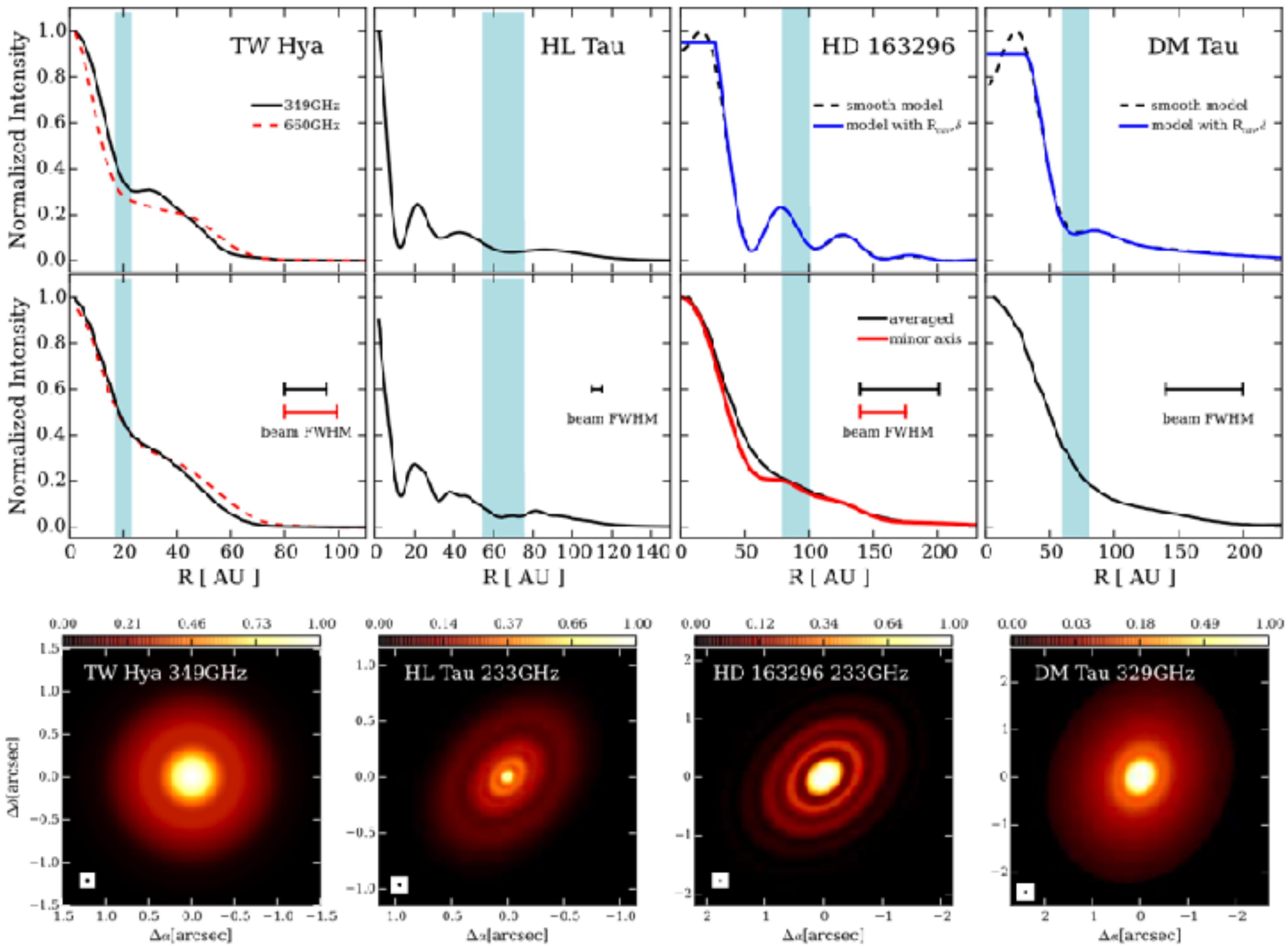
How do you determine a snowline location?

Zhang et al. 2015

Origin rings and gaps

2. Snowlines

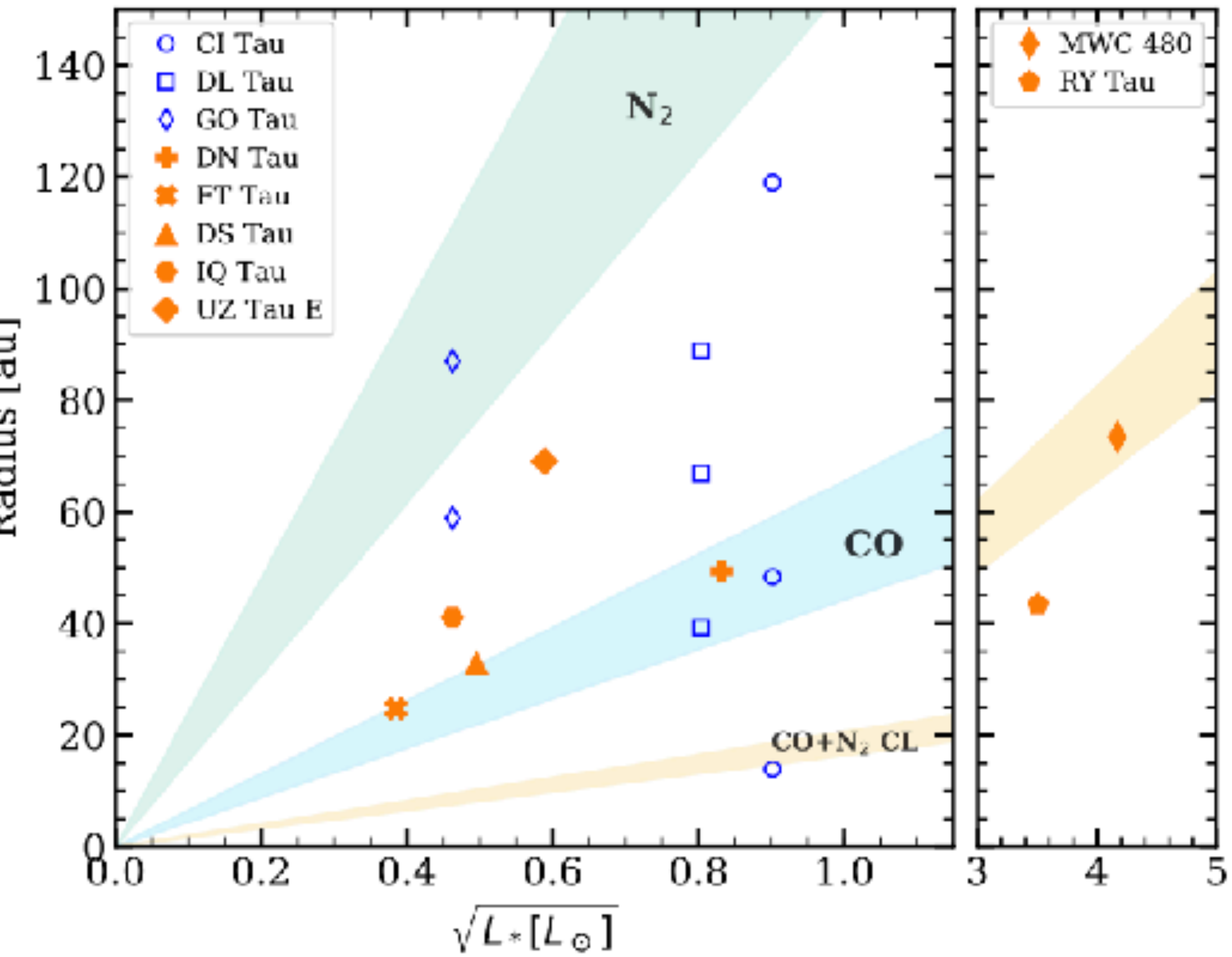
Enhanced continuum emission (`ring') just beyond CO snowline

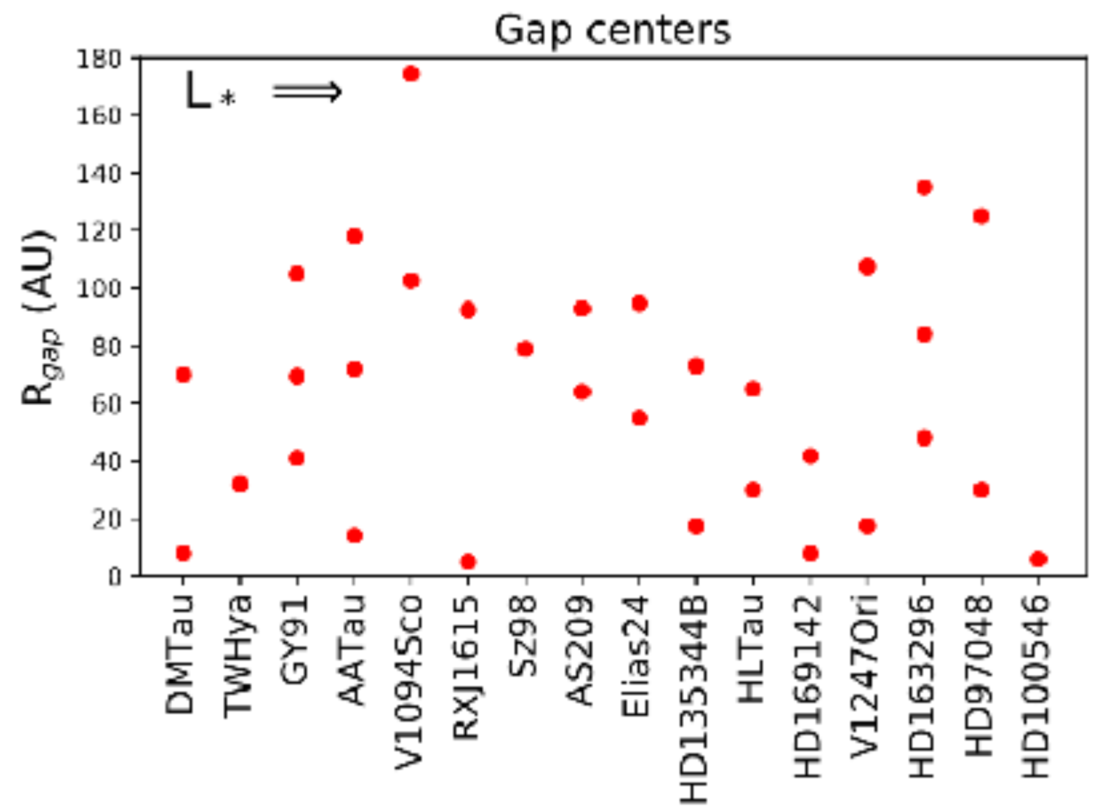


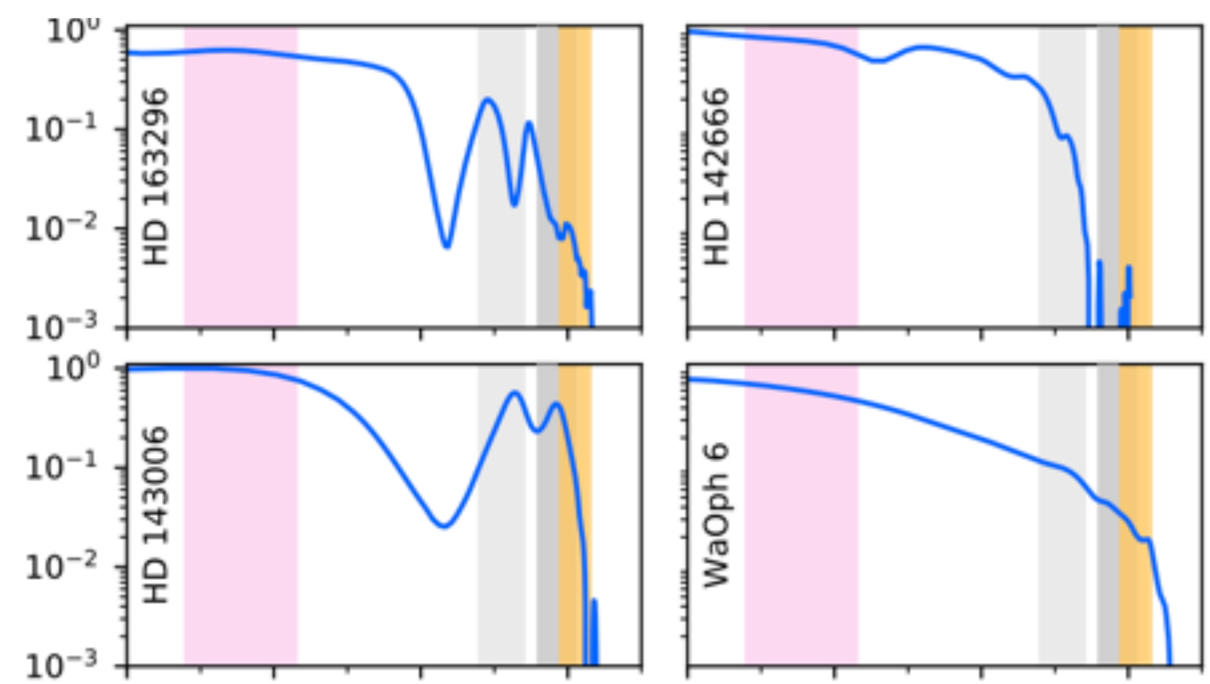
Zhang et al. 2016

Origin rings and gaps

2. Snowlines





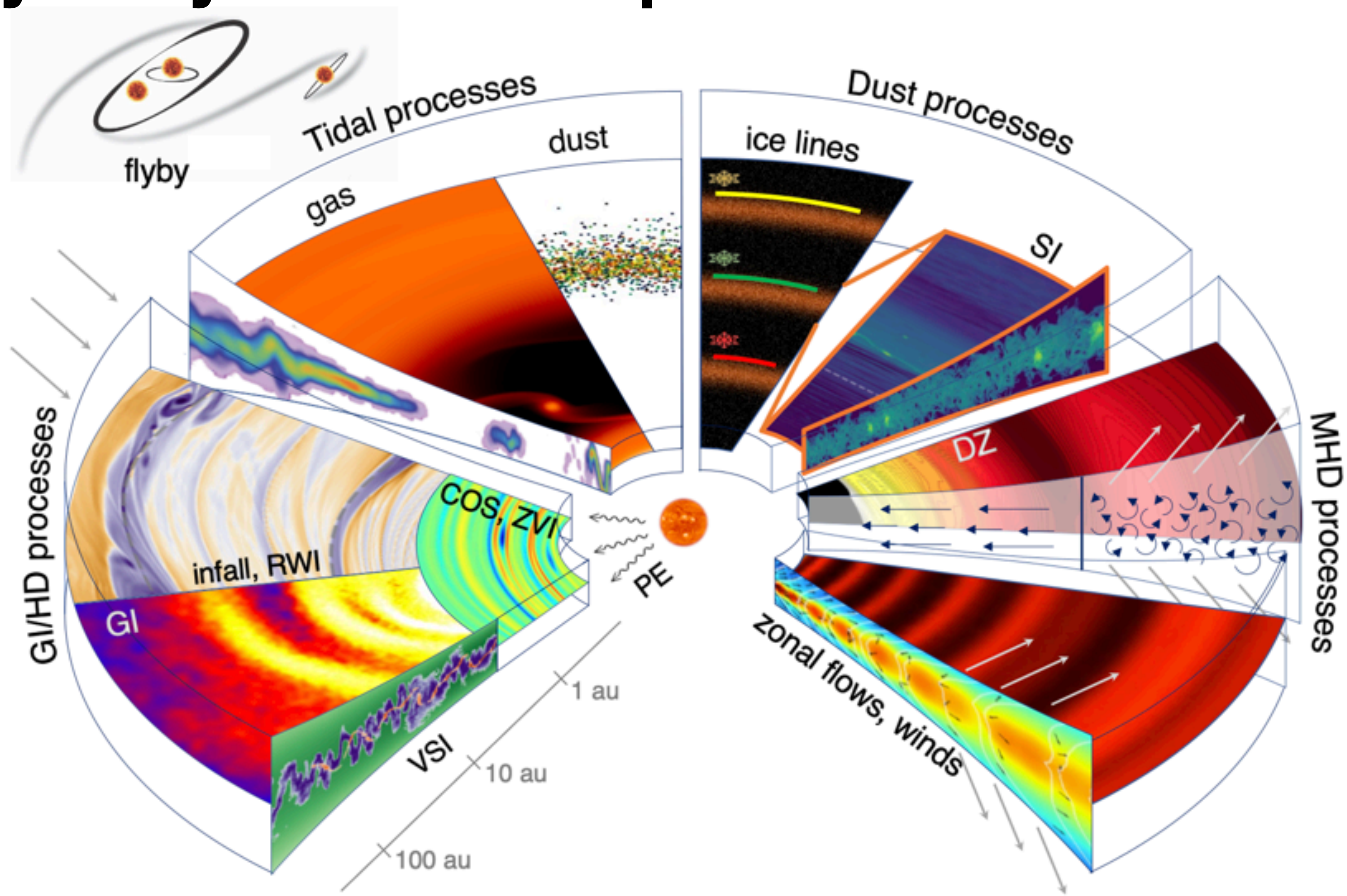


Larger samples: no consistent overlap between snowlines and gap locations

Long et al. 2018
Huang et al. 2018
van der Marel et al. 2019

Origin rings and gaps

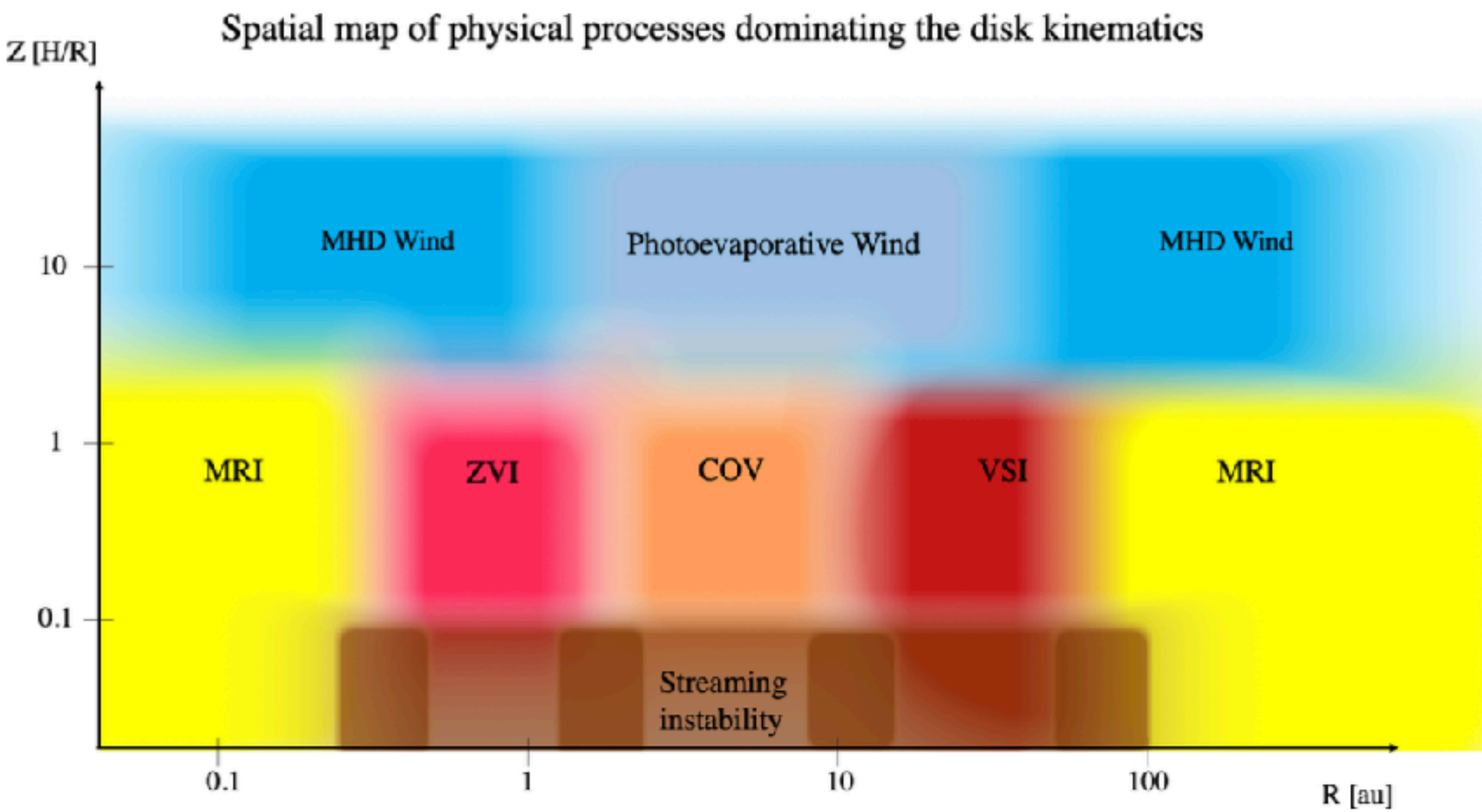
3. Hydrodynamic/MHD processes



Bae et al. 2022 (PPVII)

Origin rings and gaps

3. Hydrodynamic/MHD processes

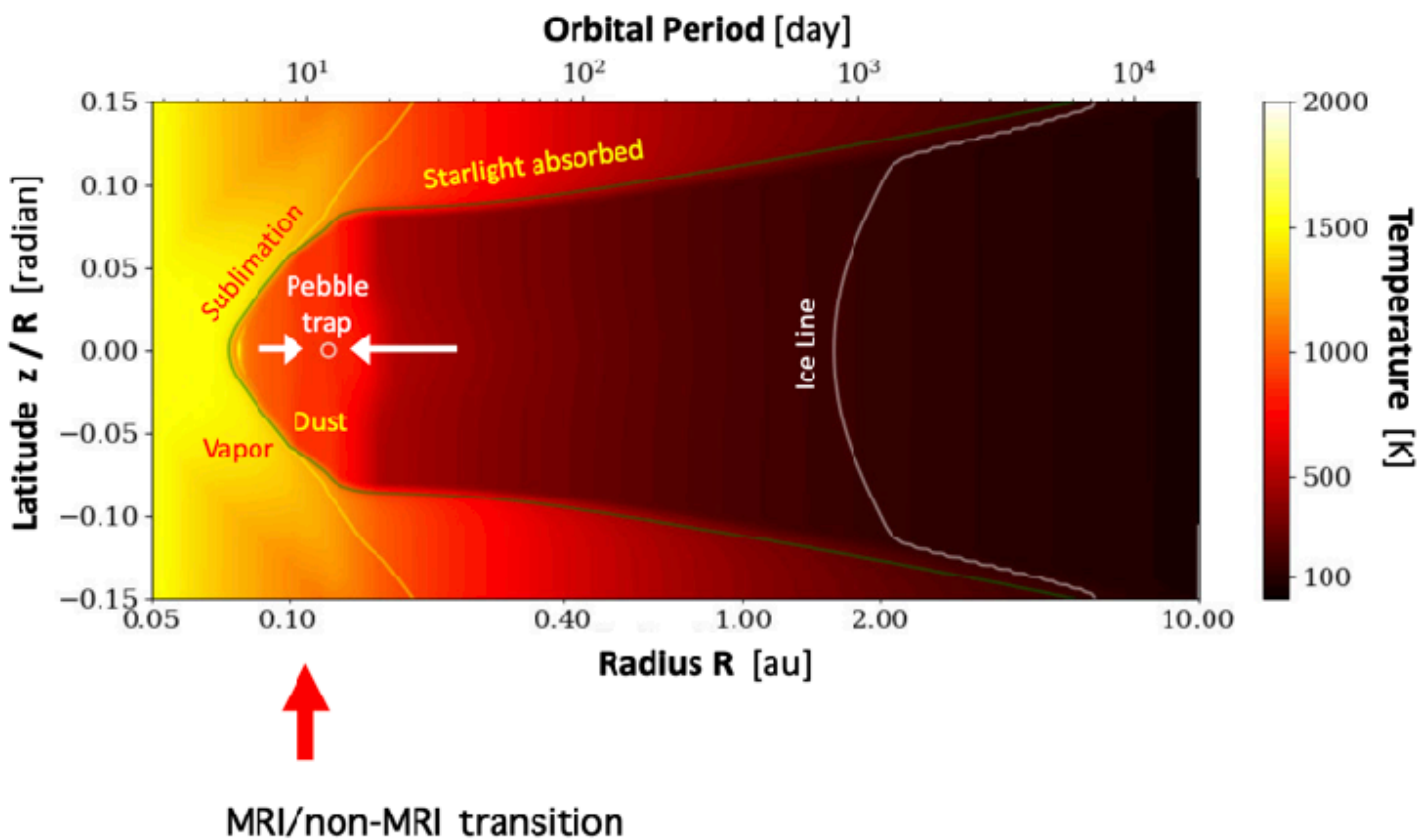


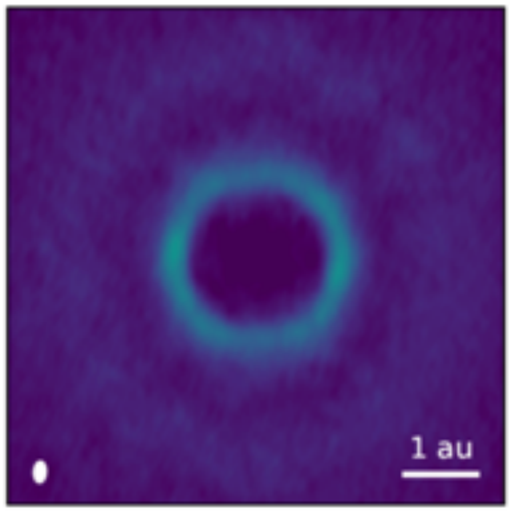
Different processes active in different regions of the disk

Lesur et al. 2022 (PPVII)

Origin rings and gaps

3. Hydrodynamic/MHD processes





What is the problem with this phenomenon?

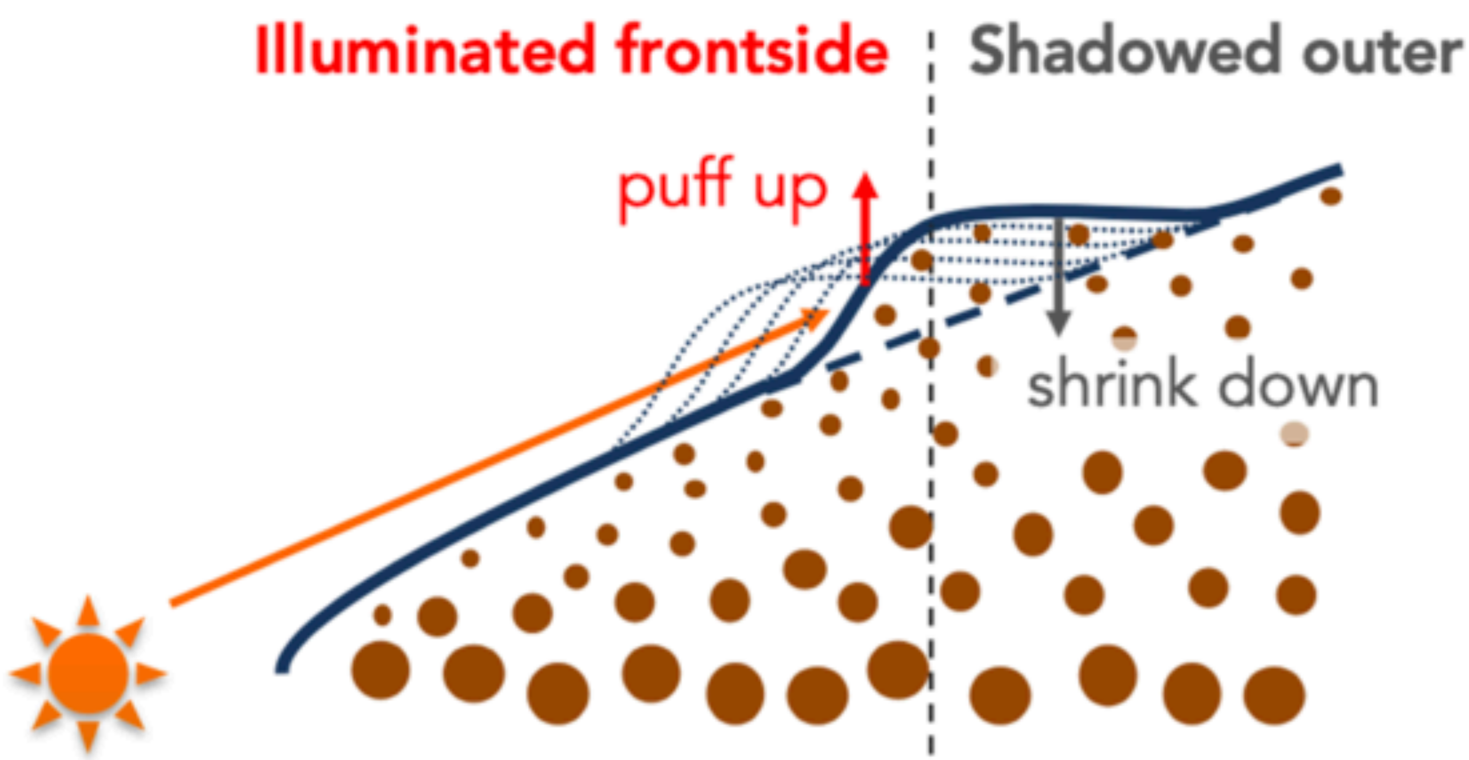
Flock et al. 2019

Origin rings and gaps

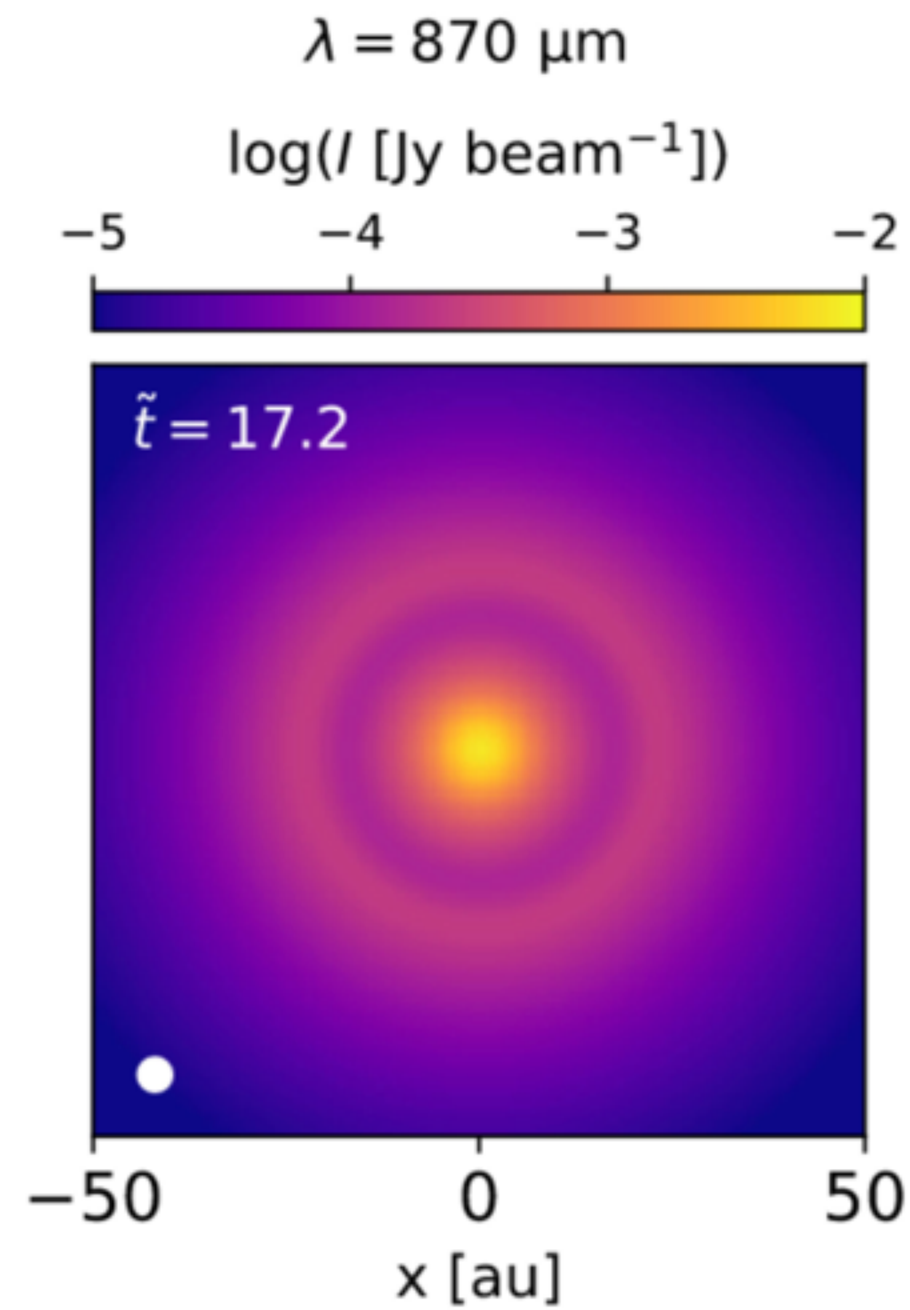
3. Hydrodynamic/MHD processes

Thermal wave instability

See also Watanabe & Lin 2008



Ueda, Flock, Birnstiel - ApJL 2021



Larger scales…

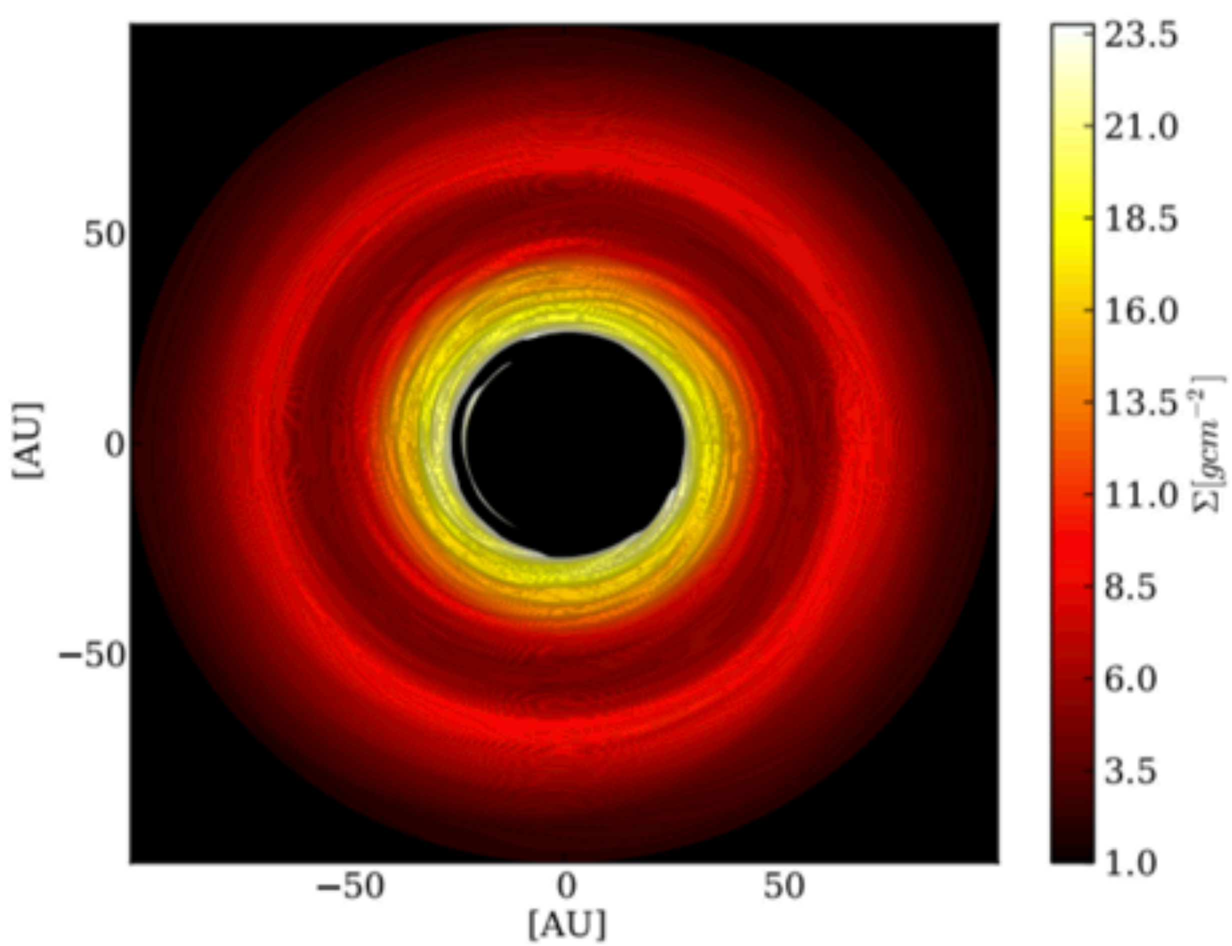
Ueda et al. 2021

Origin rings and gaps

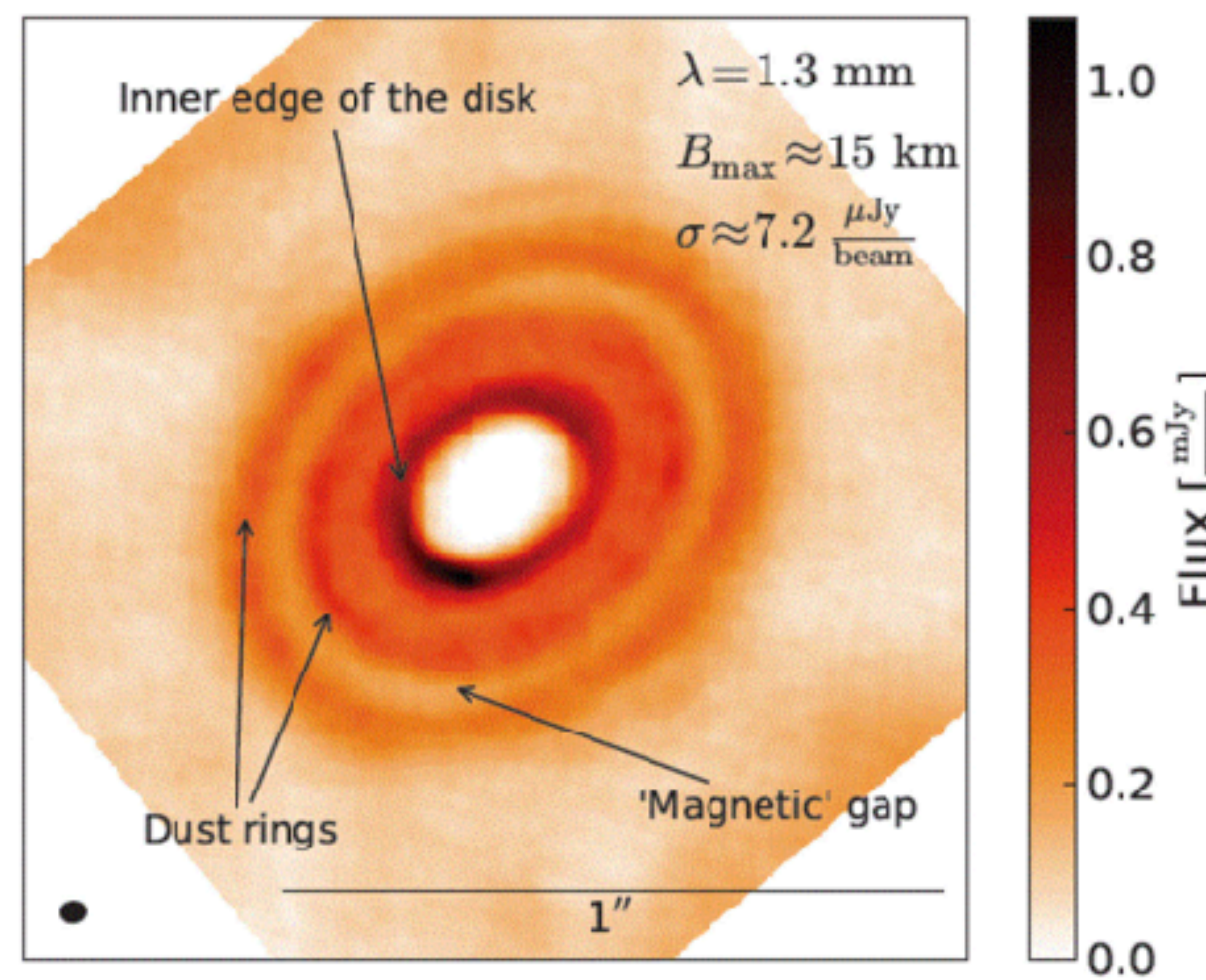
3. Hydrodynamic/MHD processes

Global 3D non-ideal MHD simulations

Surface density



Synthetic ALMA observation of the global model



Even larger scales… (outside dead zone)

Flock et al. 2015
Ruge et al. 2016

Origin rings and gaps

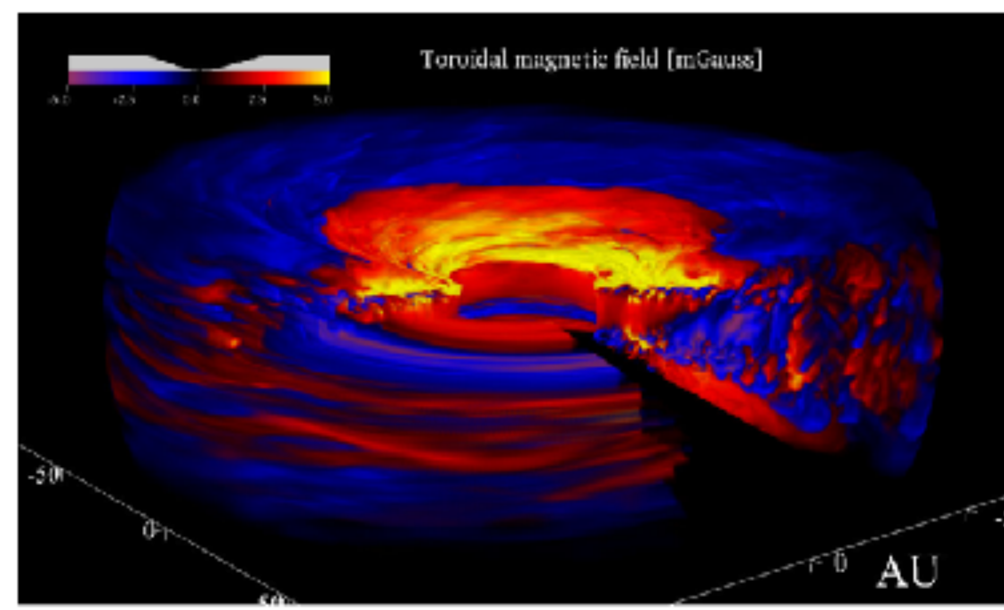
3. Hydrodynamic/MHD processes

Summary: many (magneto)hydrodynamic instabilities may be active in different parts of the disk which can lead to pressure bumps that trap the dust.

Quantifying their magnitude, lifetime and relative efficiency depends on many non-constrained disk observables, e.g. magnetic field, turbulence, etc.

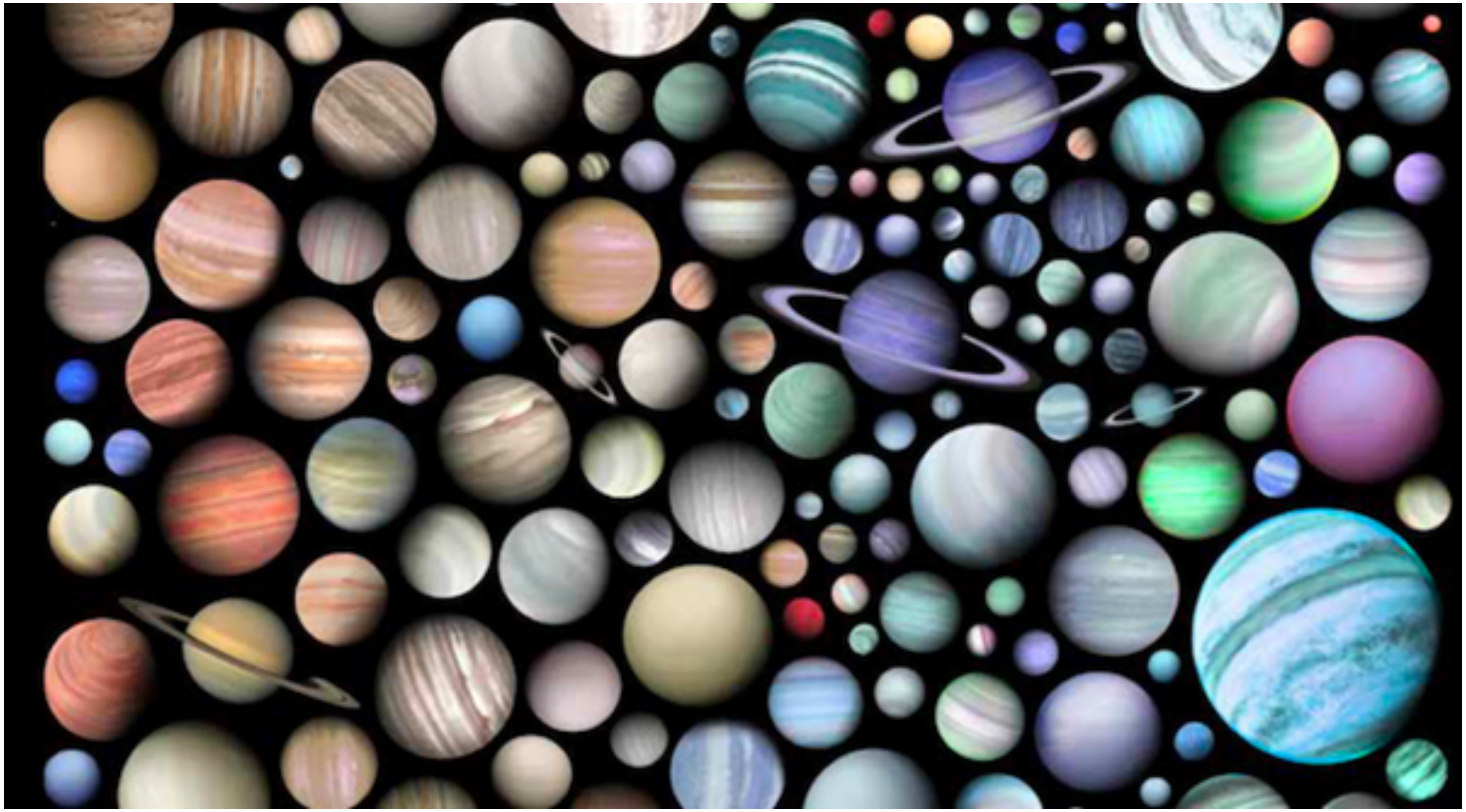
Without well-constrained statistics on observed dust rings and gaps it is extremely difficult to claim a mechanism to be responsible

Global 3D non-ideal MHD simulations



Overview:
Lesur et al. 2022 (PPVII)

So...can it be planets?



What do you think? Why yes/no?

So…it cannot be planets?

- …because the protoplanets are not detected in disks
- …because there are not so many giant exoplanets at such large orbital radii
- …because there are not so many giant exoplanets overall (~20% of all stars) while all disks appear to have gaps
- …because of the chicken-egg problem
- …because core accretion cannot explain planet formation at large orbital radii

So…it cannot be planets?

- …because the protoplanets are not detected in disks

But the sensitivity of HCI is still poor, especially close to the star

- …because there are not so many giant exoplanets at such large orbital radii

But the planets may migrate inwards

- …because there are not so many giant exoplanets overall (~20% of all stars) while all disks appear to have gaps

But the high-resolution observations are biased towards the brightest disks

- …because of the chicken-egg problem

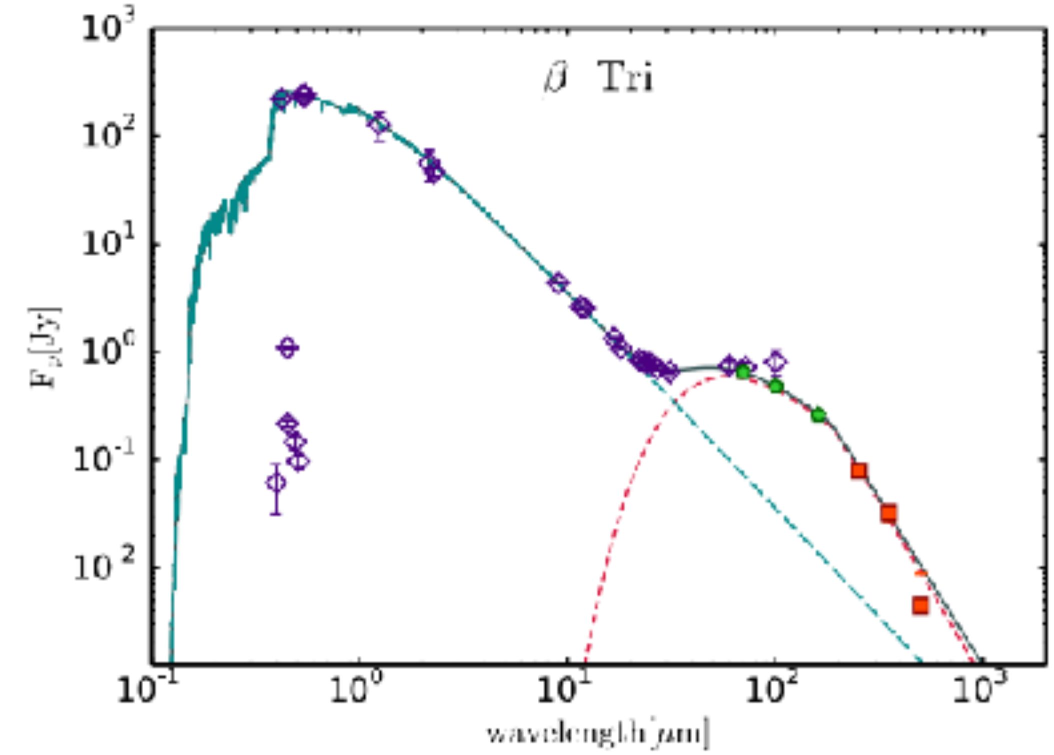
But the planets may have formed in dust traps in embedded conditions and we are just looking at remnants

- …because core accretion cannot explain planet formation at large orbital radii

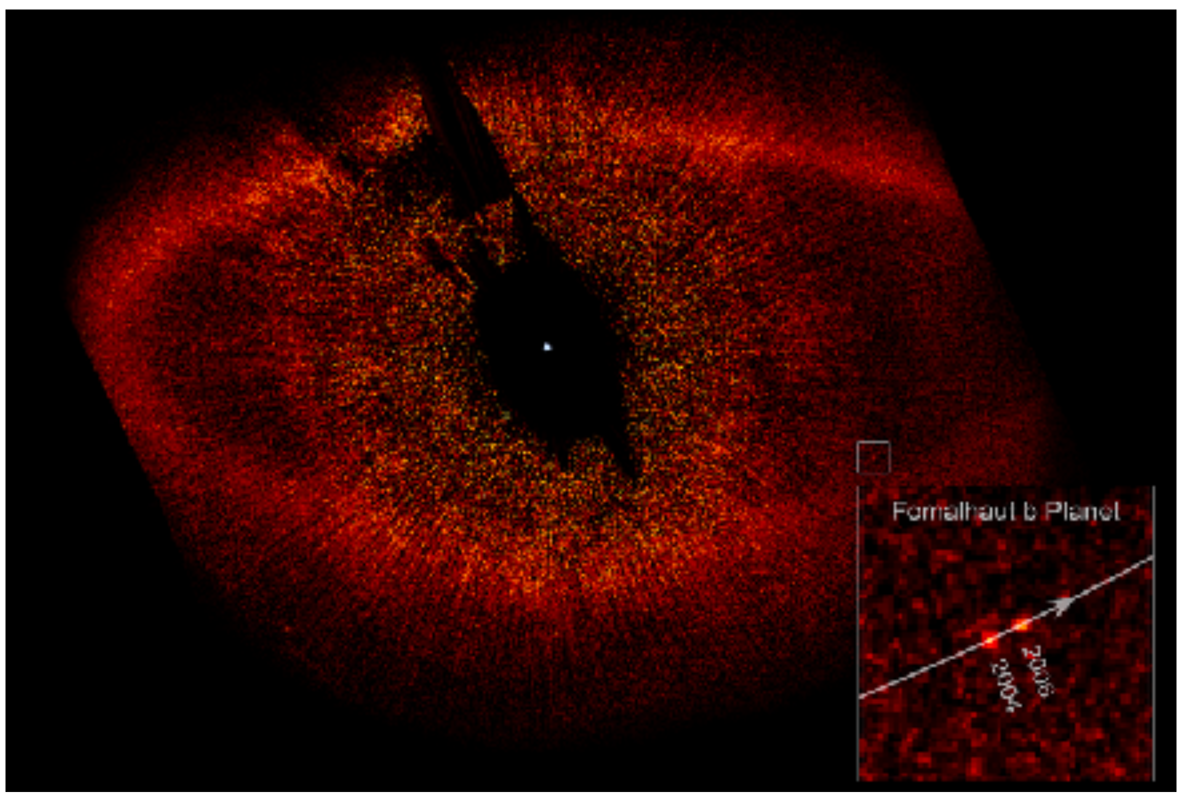
But core accretion has not been computed yet in realistic disk conditions (trapping, settling, embedded). Also GI?

Debris disks

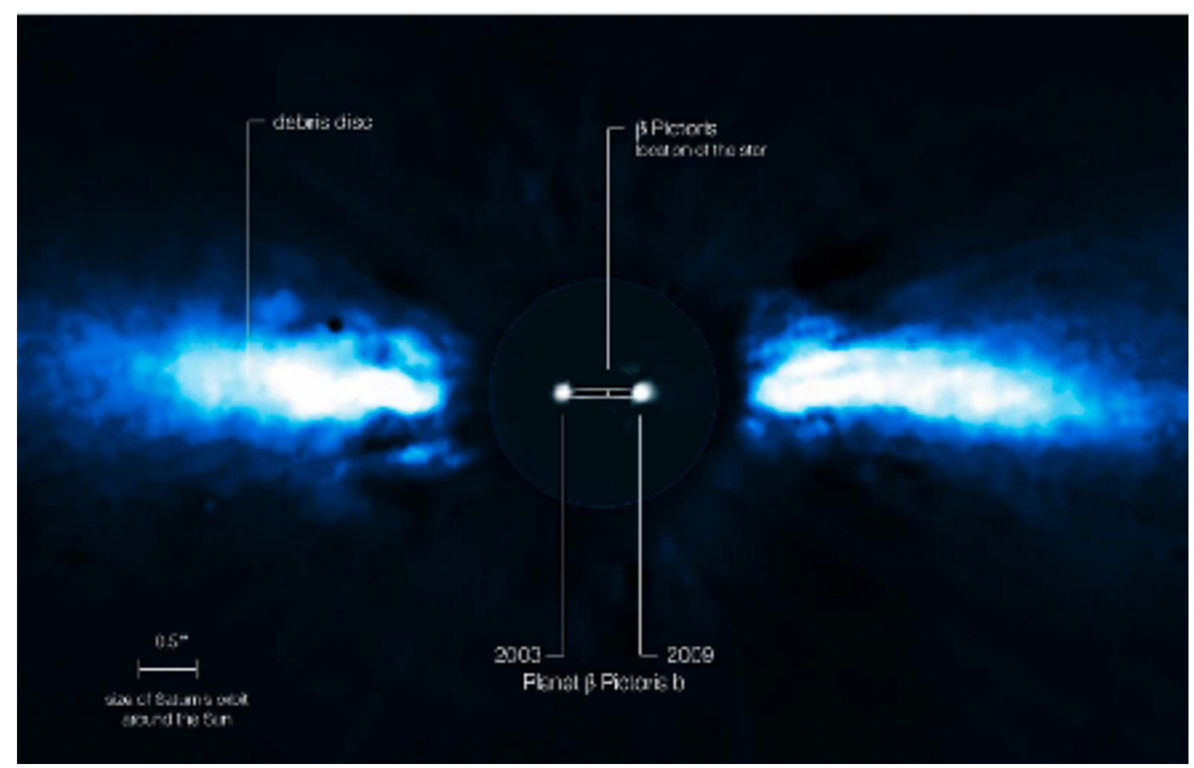
Planetesimal belts around stars > 10 Myr old (including main sequence stars)



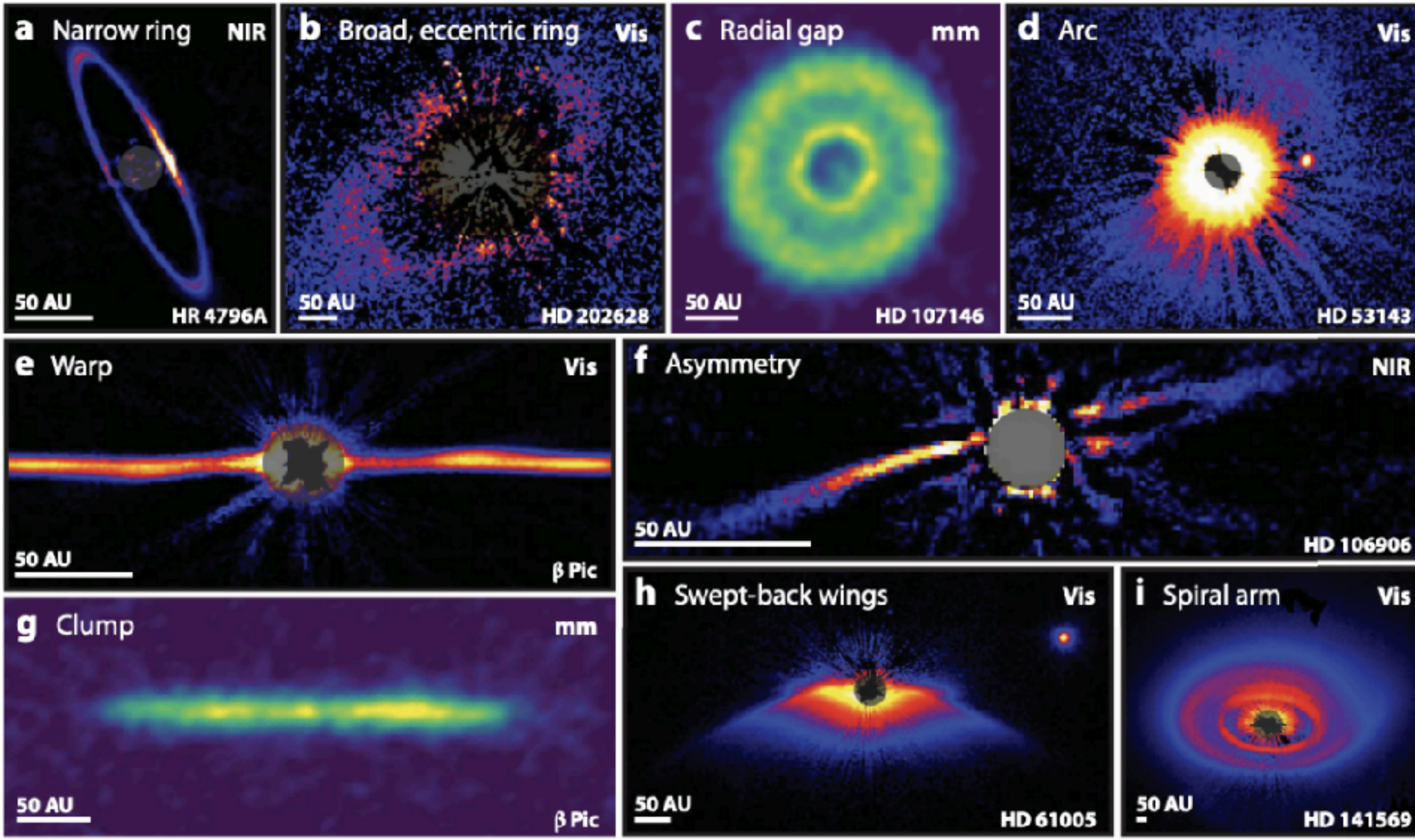
Typical SED: FIR excess only (Herschel!)



No more gas disk: dust is continuously replenished from collisions



Debris disks

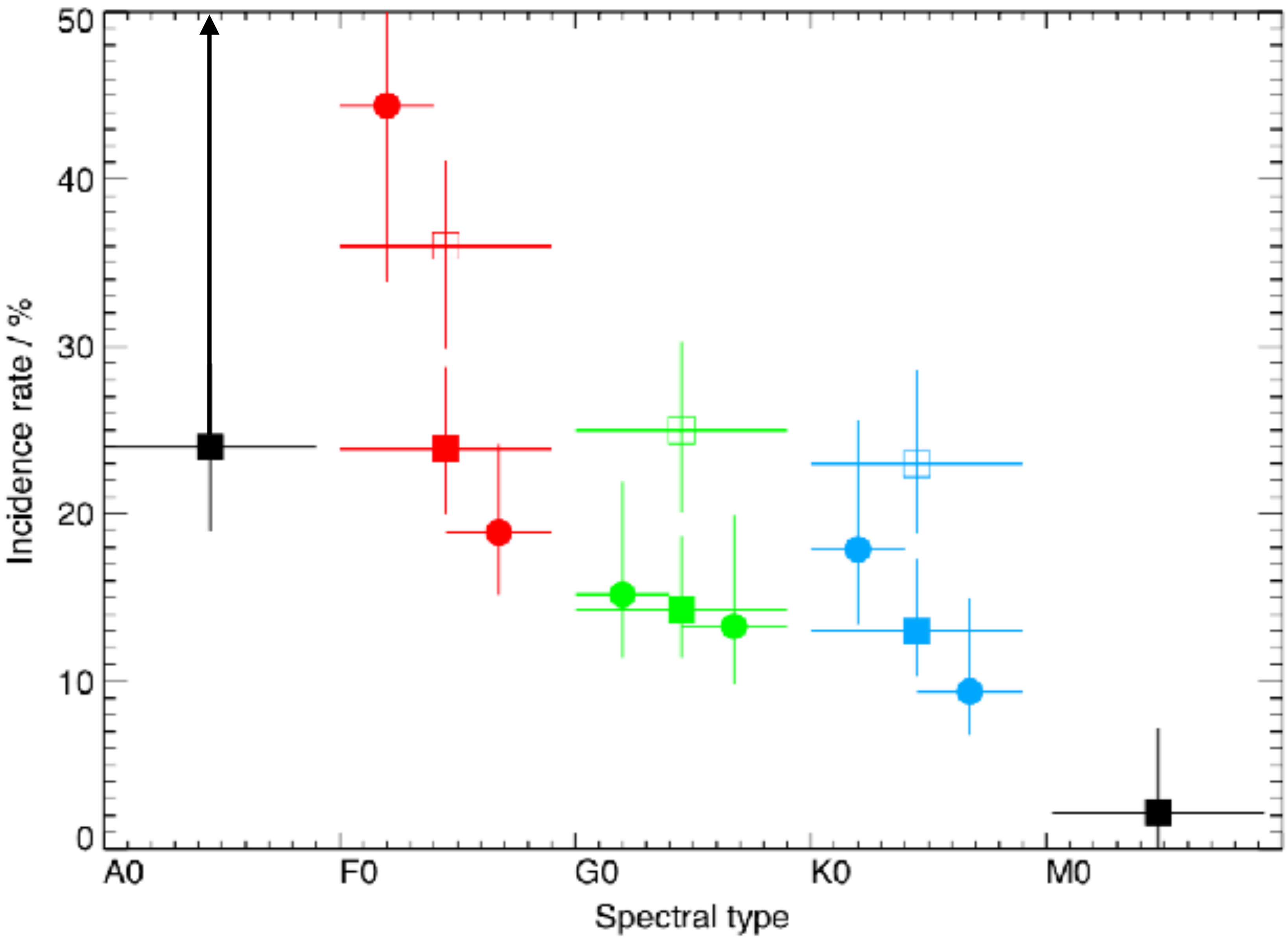


Large diversity of structures

Hughes et al. 2018

Debris disks

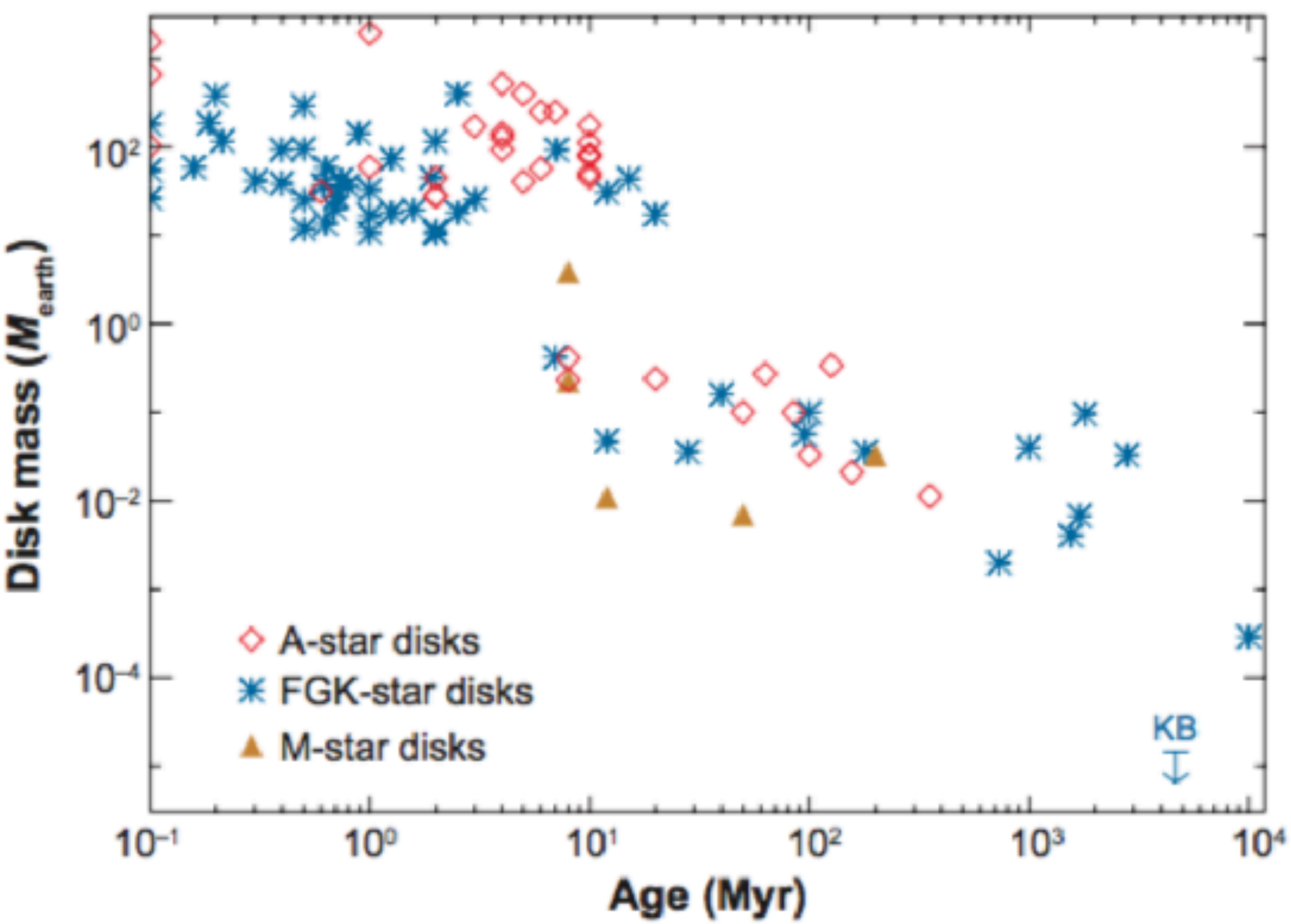
Herschel DEBRIS survey



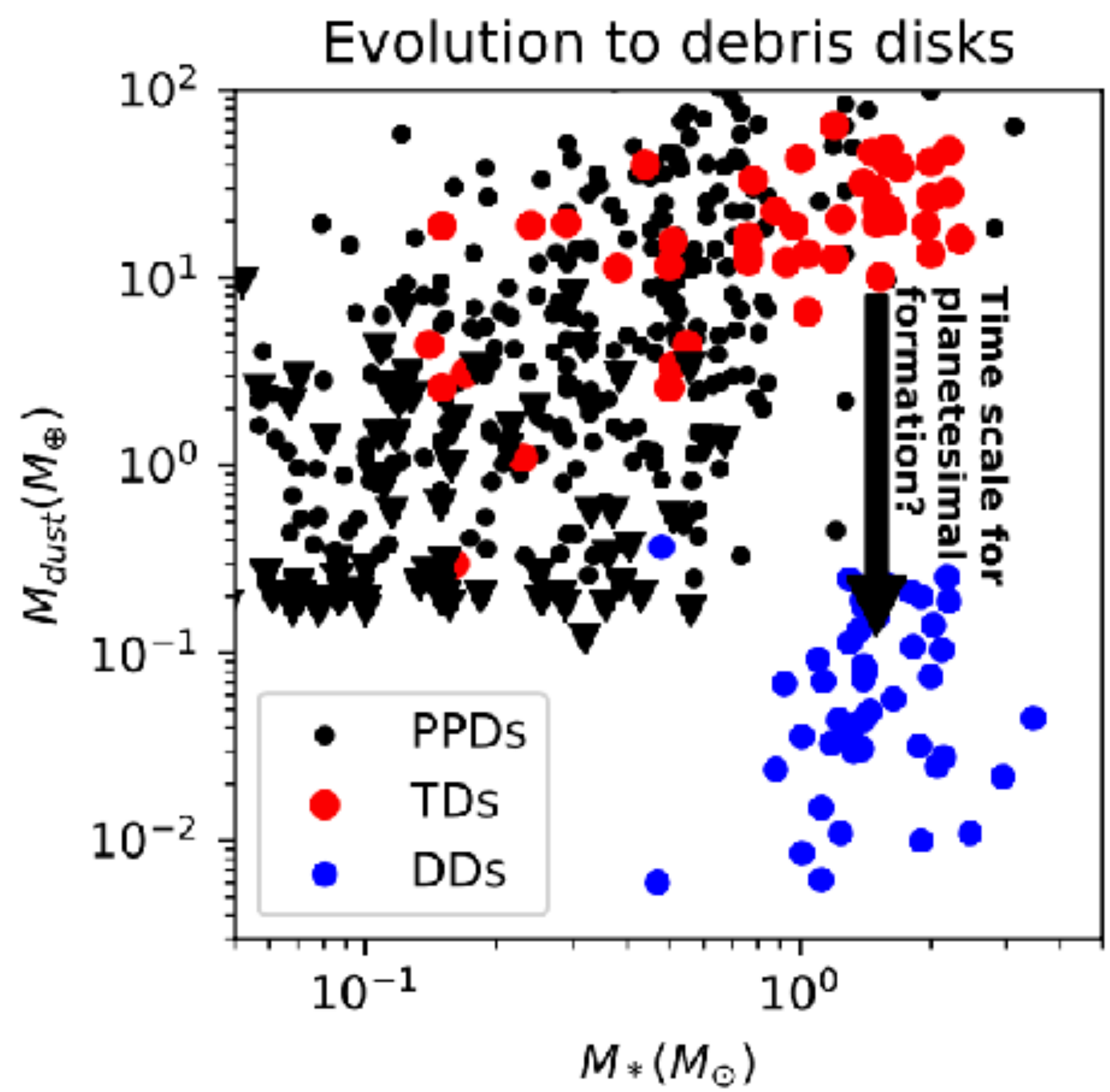
Debris disks are found throughout the sky: no longer part of star forming clusters (why?). Most often found around A stars because of brightness, and occurrence rate calculation indeed suggests that they may be less common around later type stars

Thureau et al. 2014
Sibthorpe et al. 2018
van der Marel & Mulders 2021

Debris disks

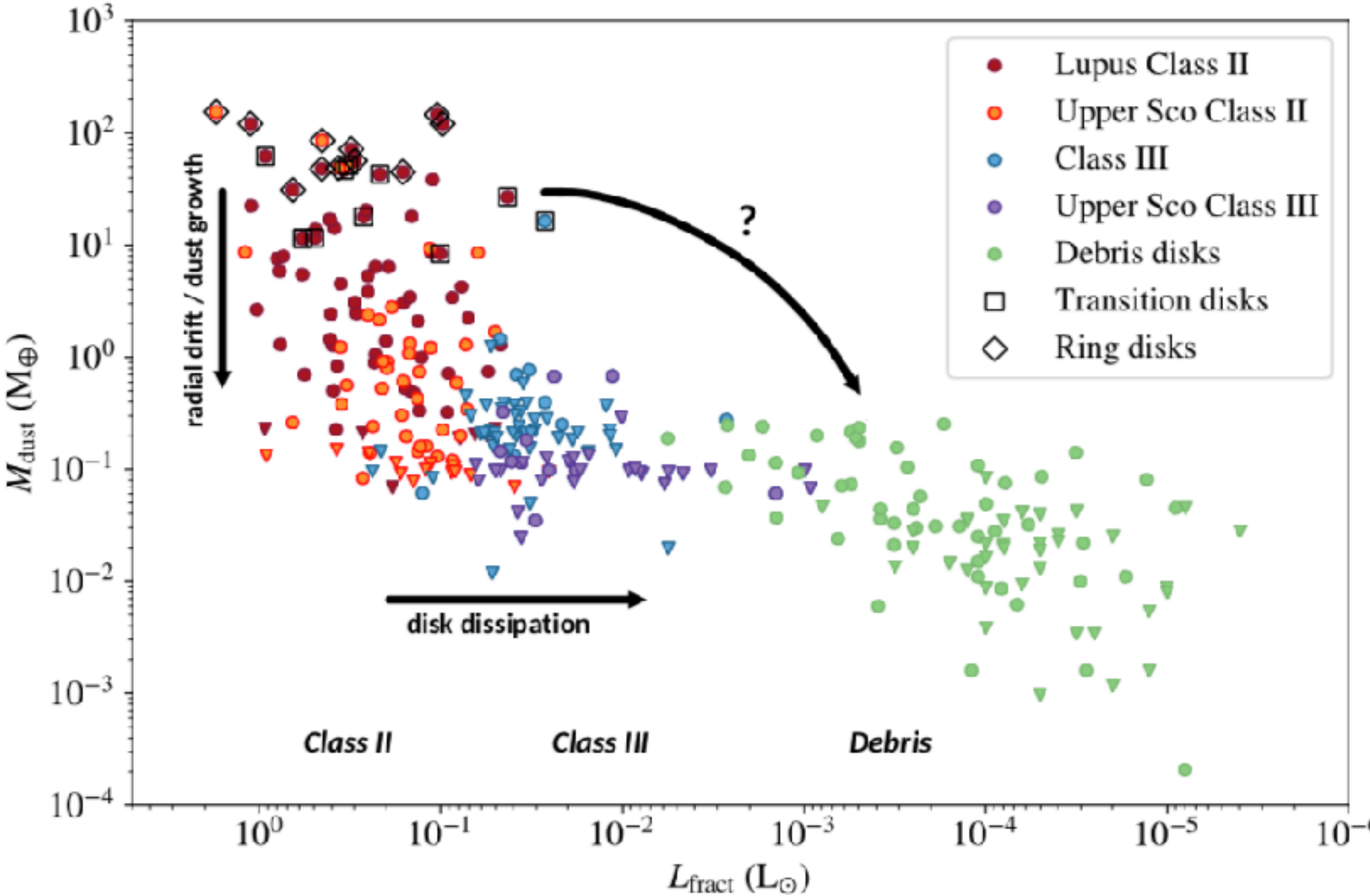


Dust masses of debris disks well below protoplanetary disks, but comparison only possible for $>M_{sun}$ stars



Wyatt et al. 2008
van der Marel 2022 (review)

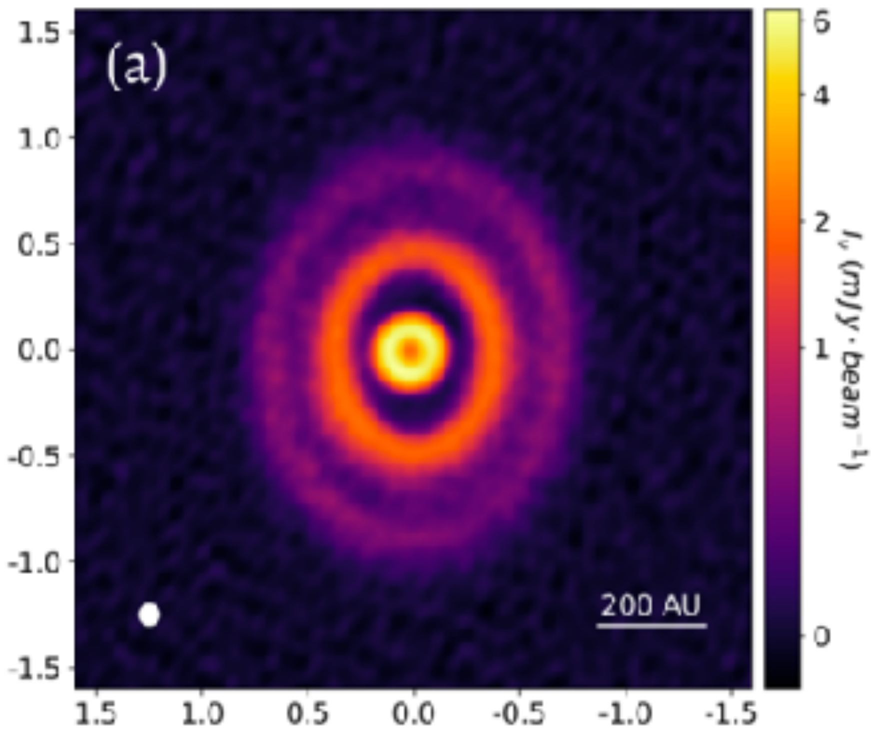
Debris disks

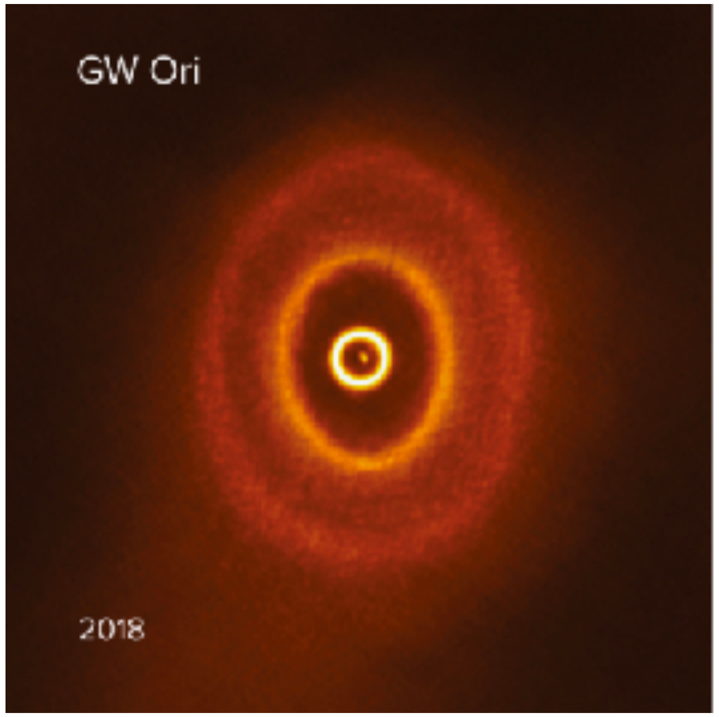


Michel, van der Marel & Matthews 2021
Najita et al. 2022
Zormpas et al. 2022

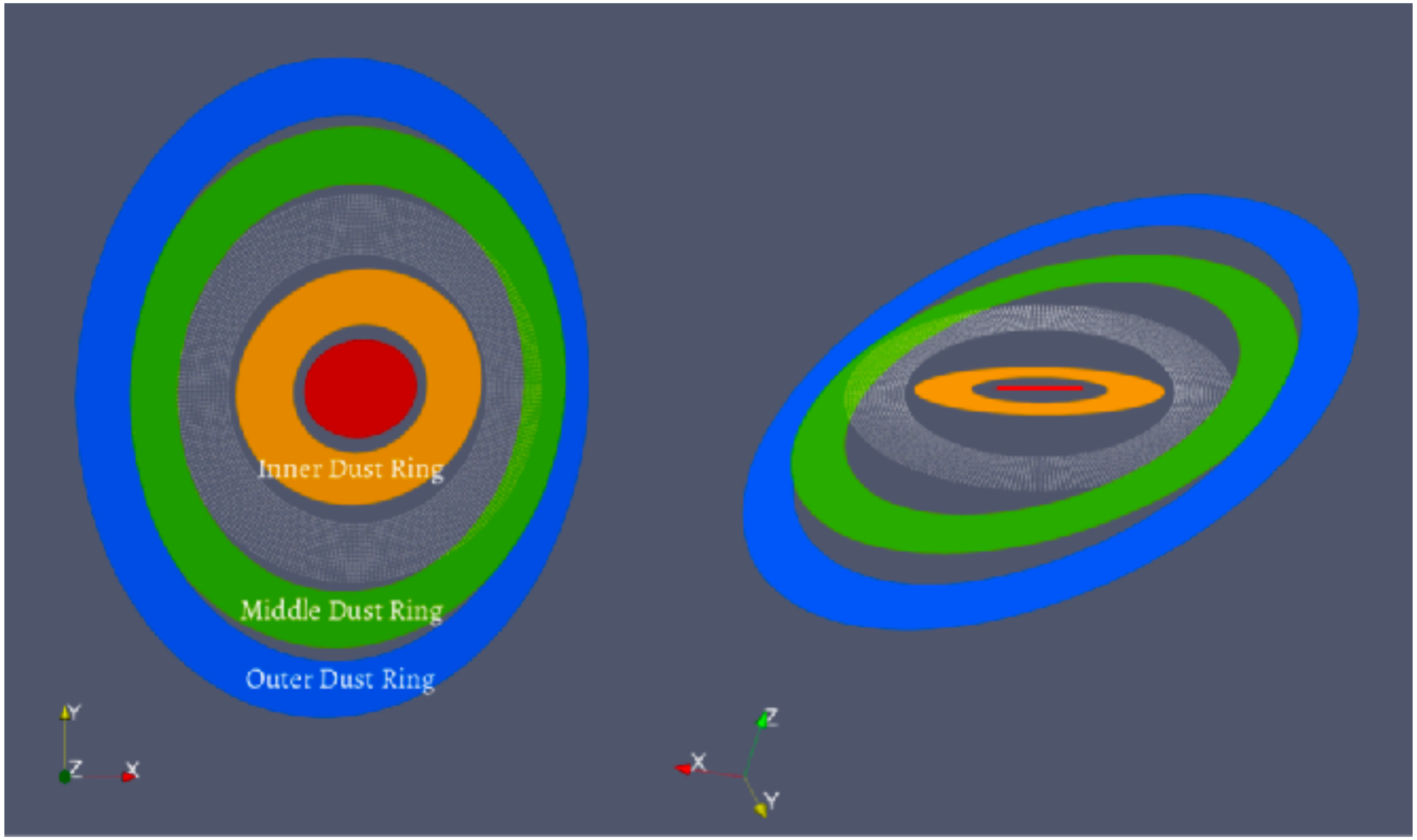
Are gapped disks progenitors of debris disks?

Misalignments





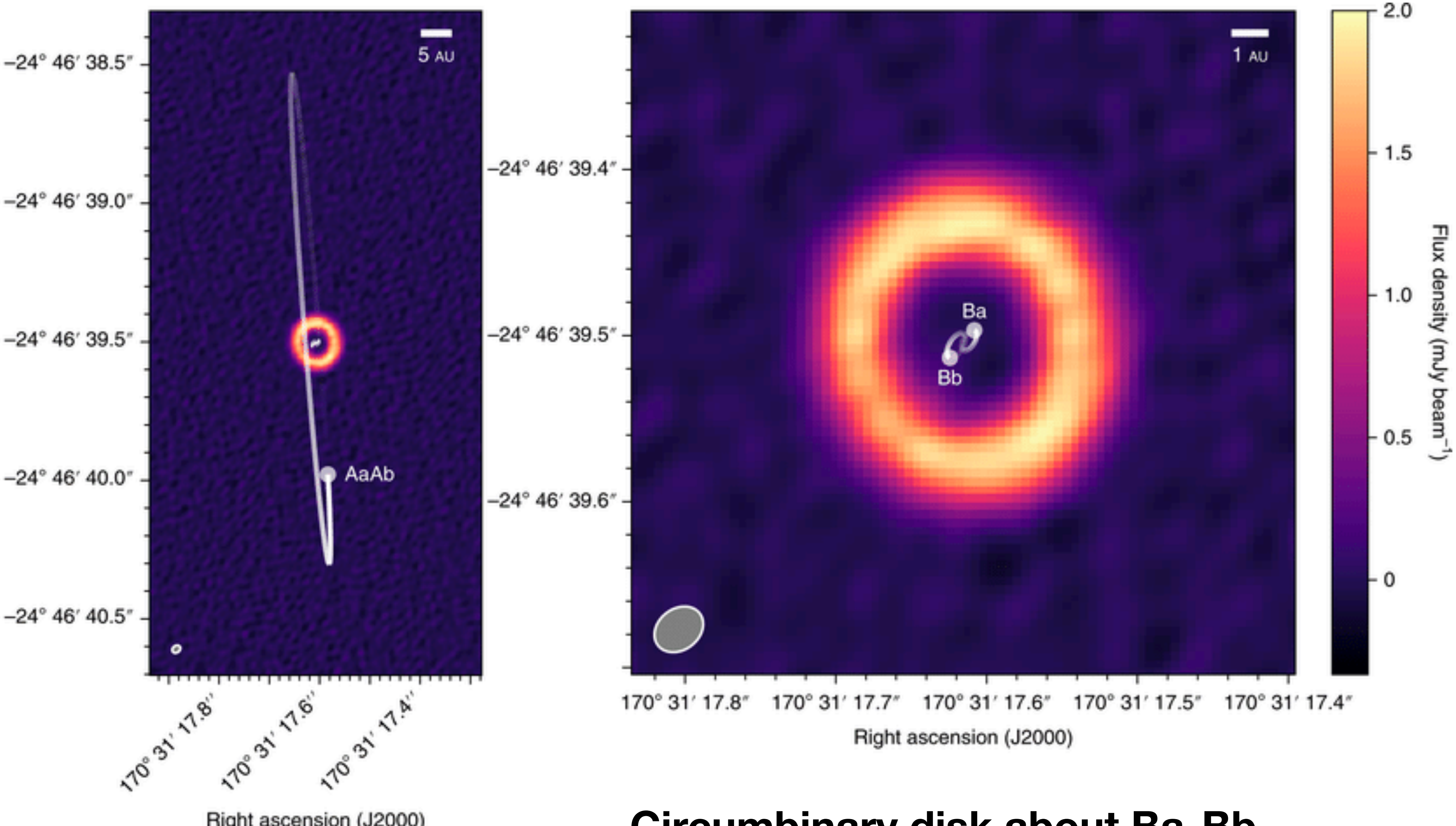
Same disk, higher resolution



Different orientations of different rings: dynamical effect of breaking of the disk, followed by precession?

Bi et al. 2020
Kraus et al. 2020

Misalignment

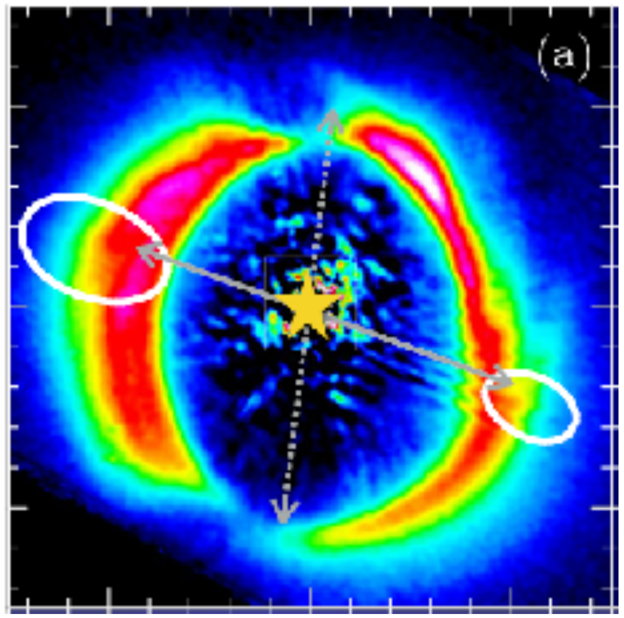


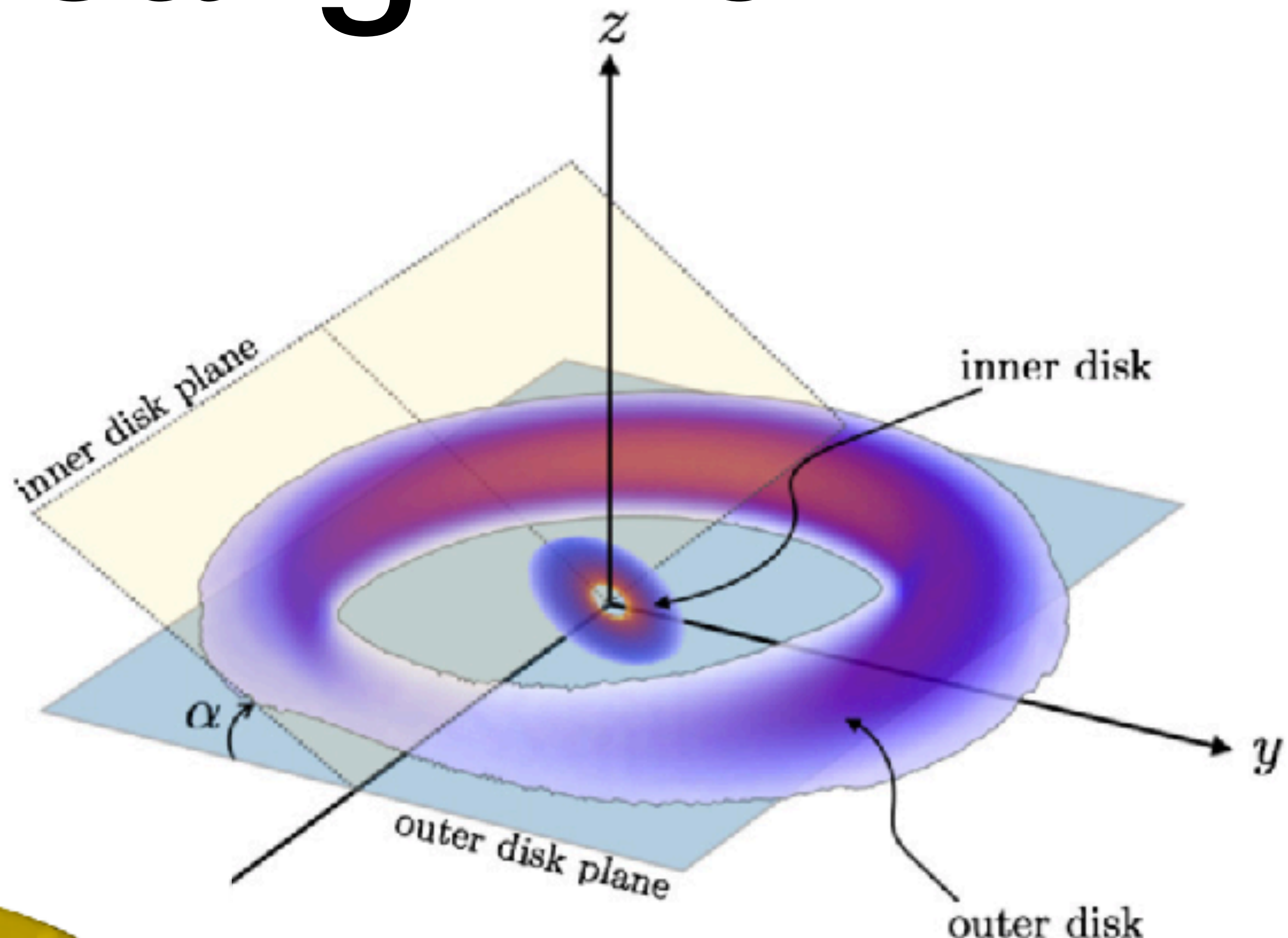
Circumbinary disk about Ba-Bb is orthogonal to orbit Aa-Ab star: polar orbit

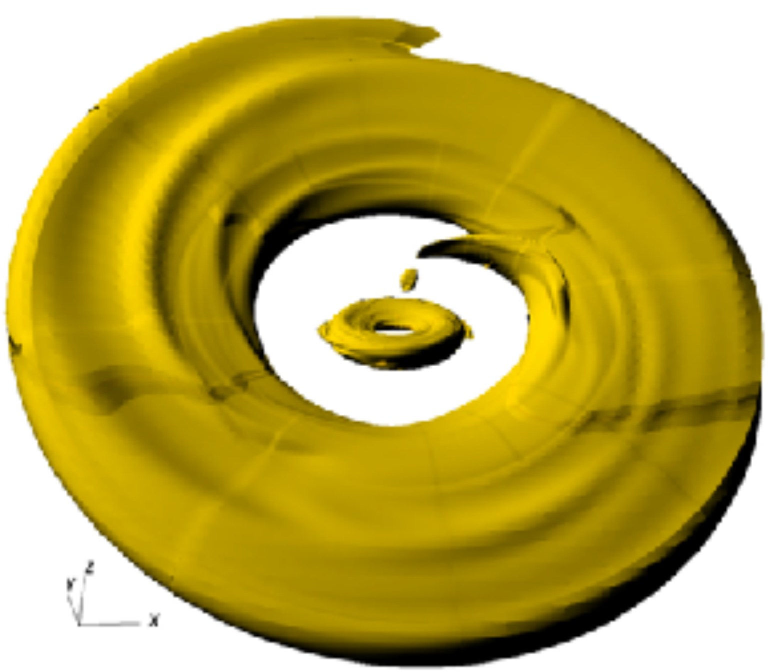
Kennedy et al. 2019

Misalignment

Shadows in scattered light







Simulation: precession inner disk

Shadows in NIR image can be explained if the inner disk is misaligned, casting a shadow on the outer ring

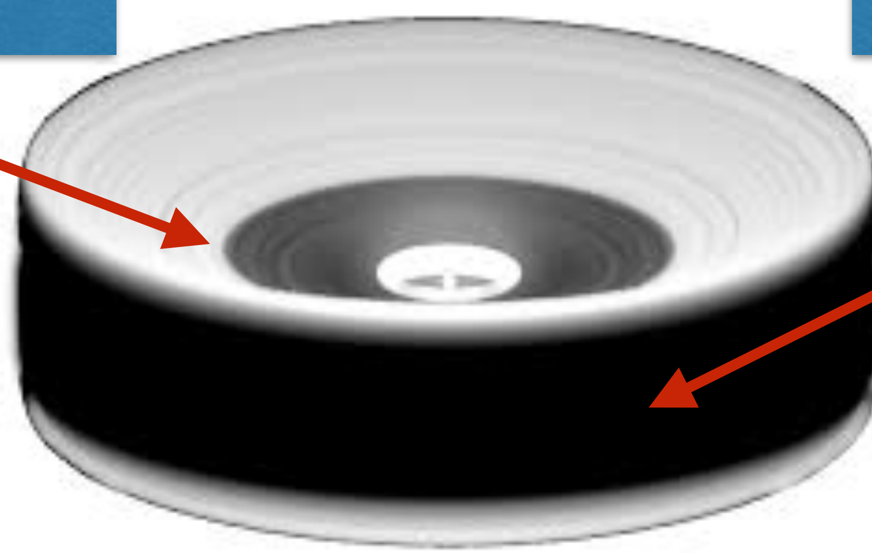
Misalignment when the disk is 'broken' and precessed

Marino et al. 2015
Zhu 2019

NIR imaging: surface layers of small dust grains

Scattered light
surface layers
opt thick

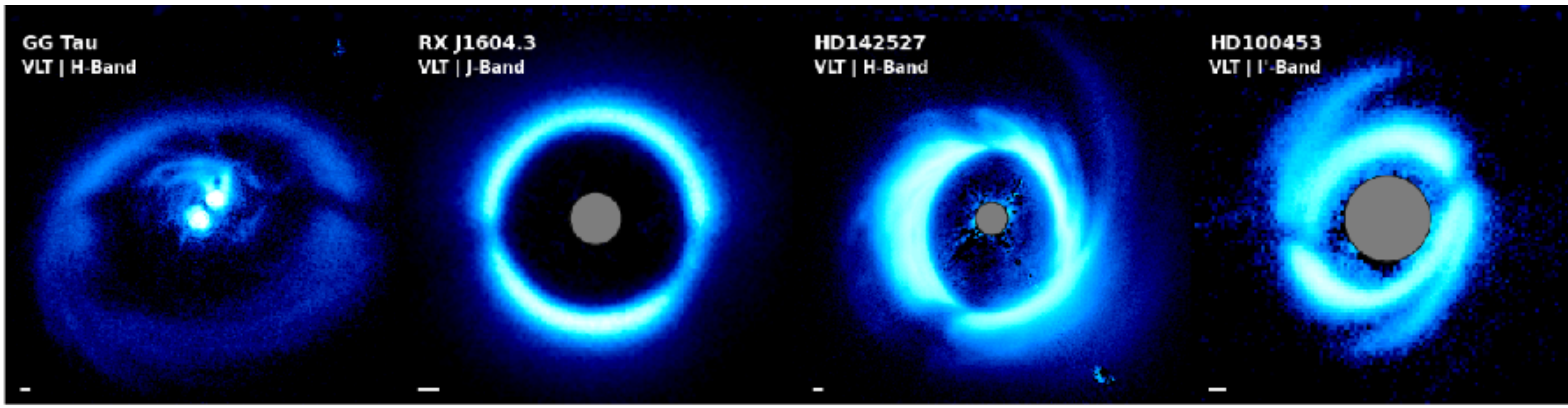
mm emission
mid plane
opt thin

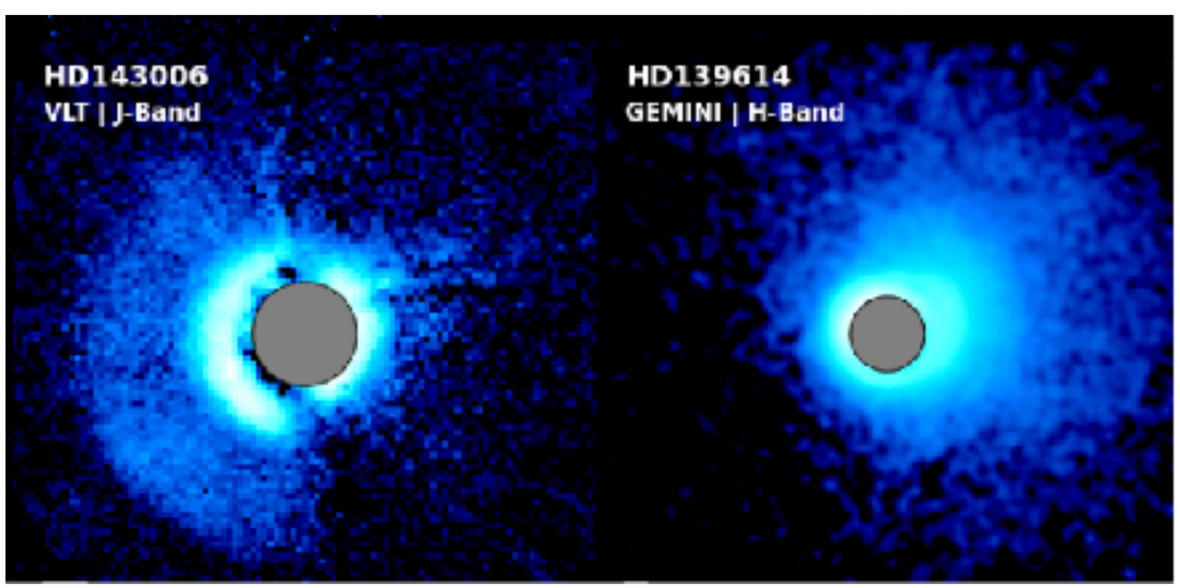


Gemini/Subaru/VLT/Keck:

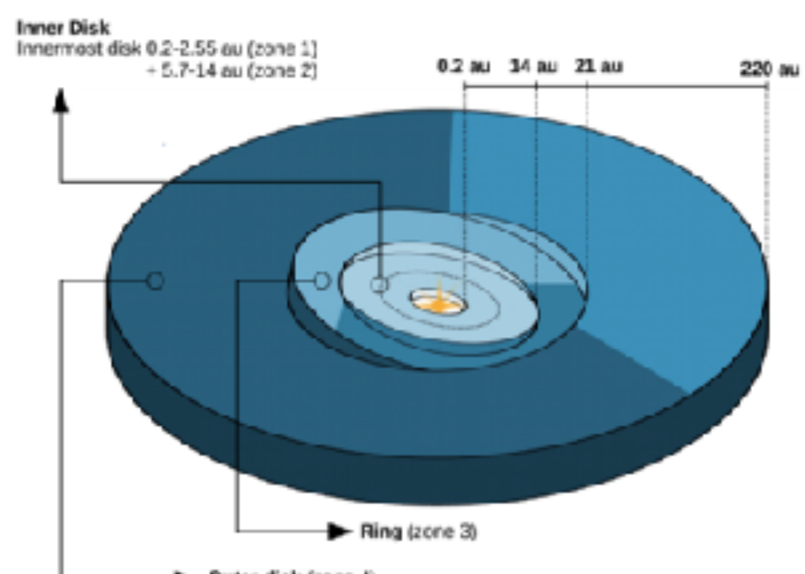
Scattered light/polarized light

Shadows



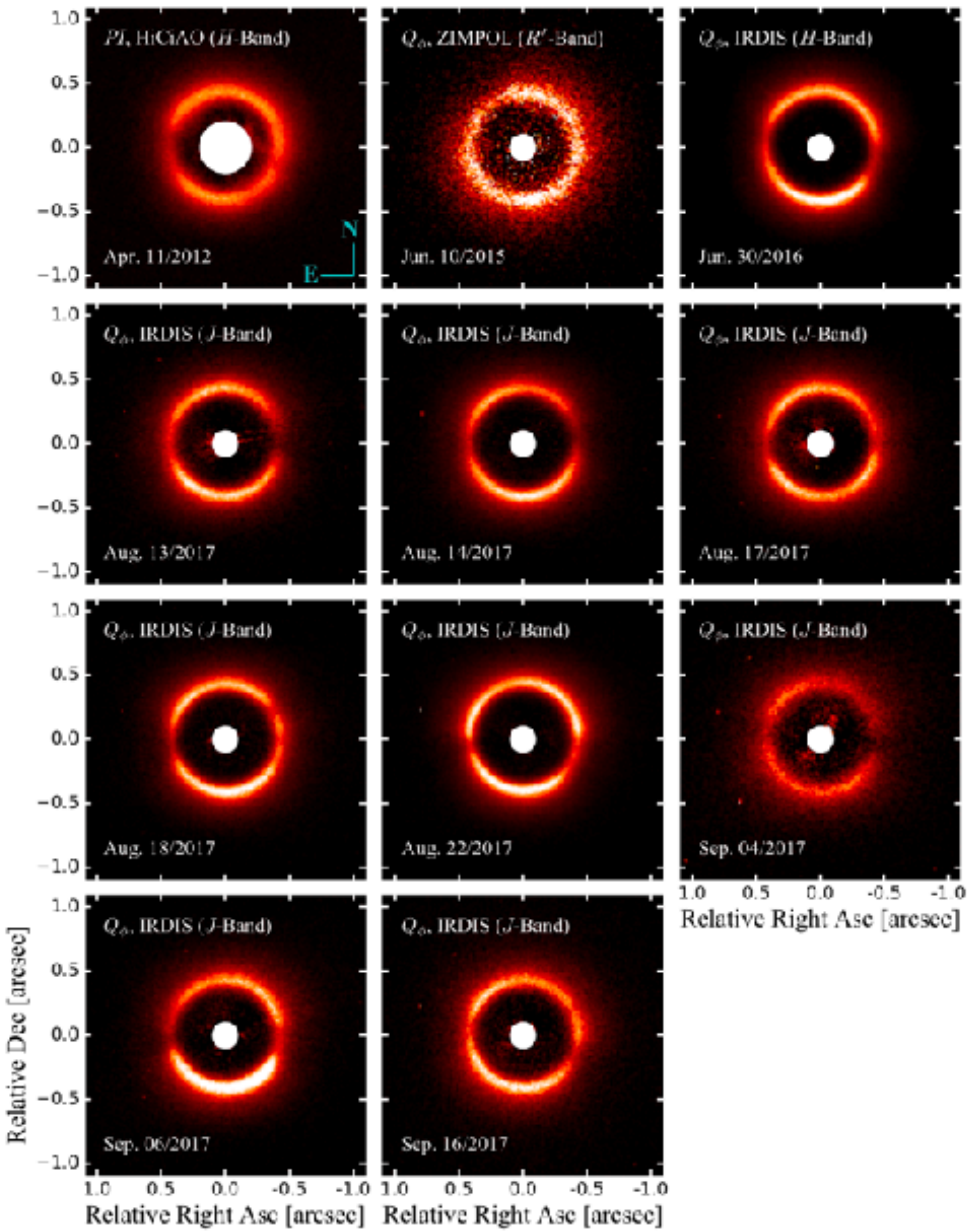


Narrow shadows are seen in several disks, as well as broad shadows that block half of the disk



Benisty et al. 2022 (PPVII)
Muro-Arena et al. 2020

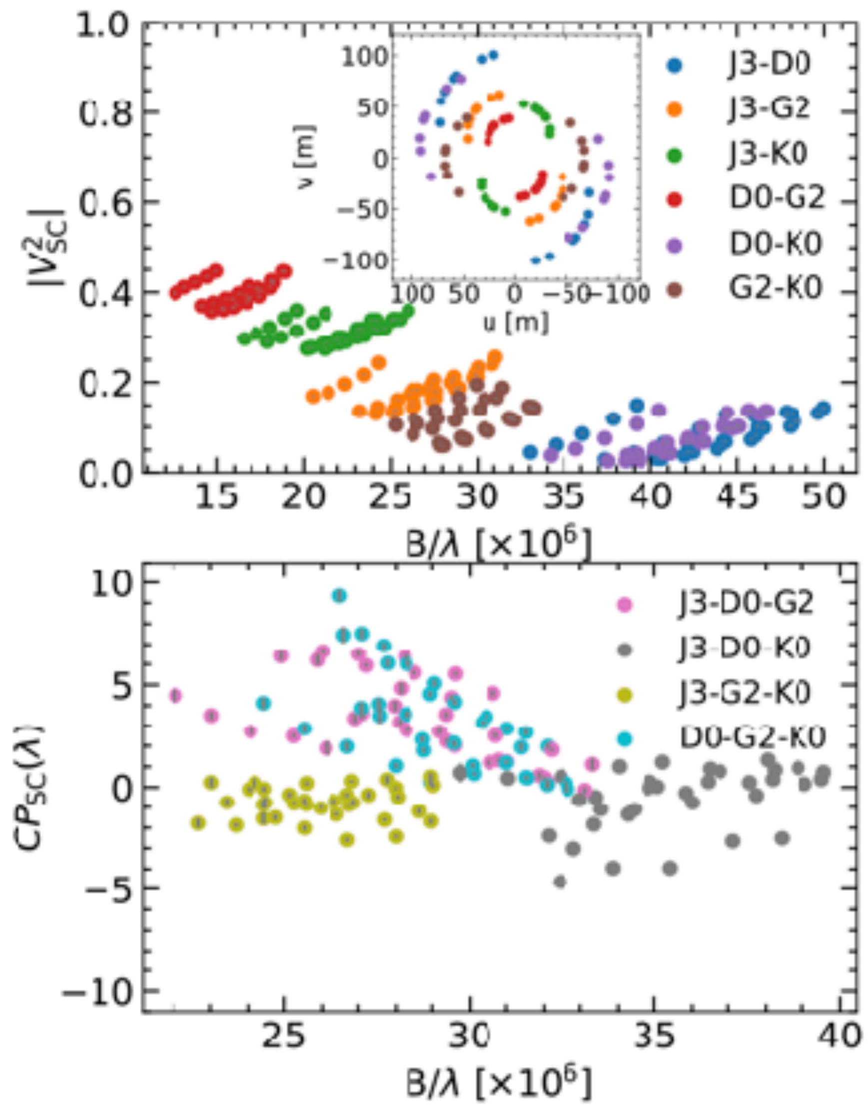
Shadows

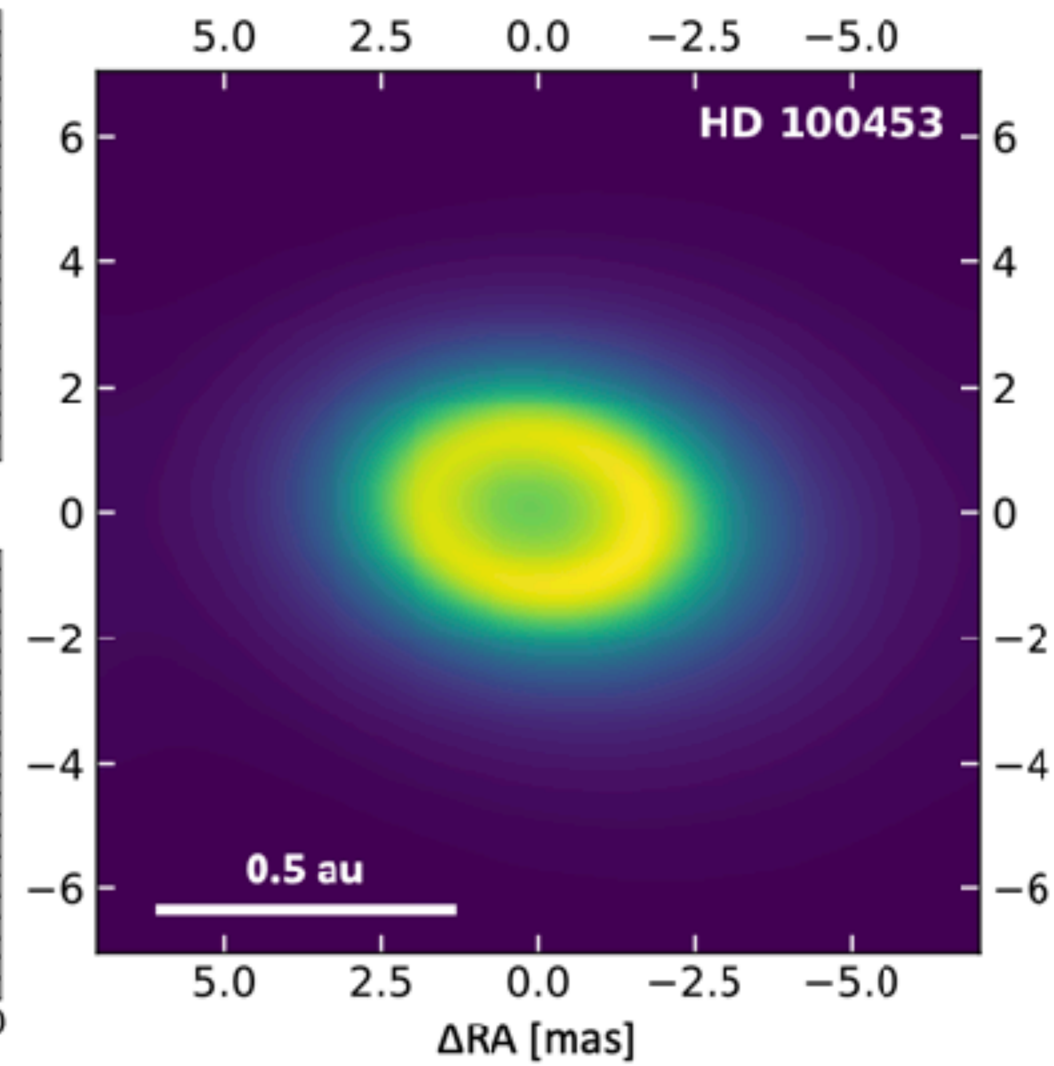


Monitoring of the J1604 disk shows that the shadows rock around azimuthally over months-years timescales

Pinilla et al. 2018

VLTI: inner disks

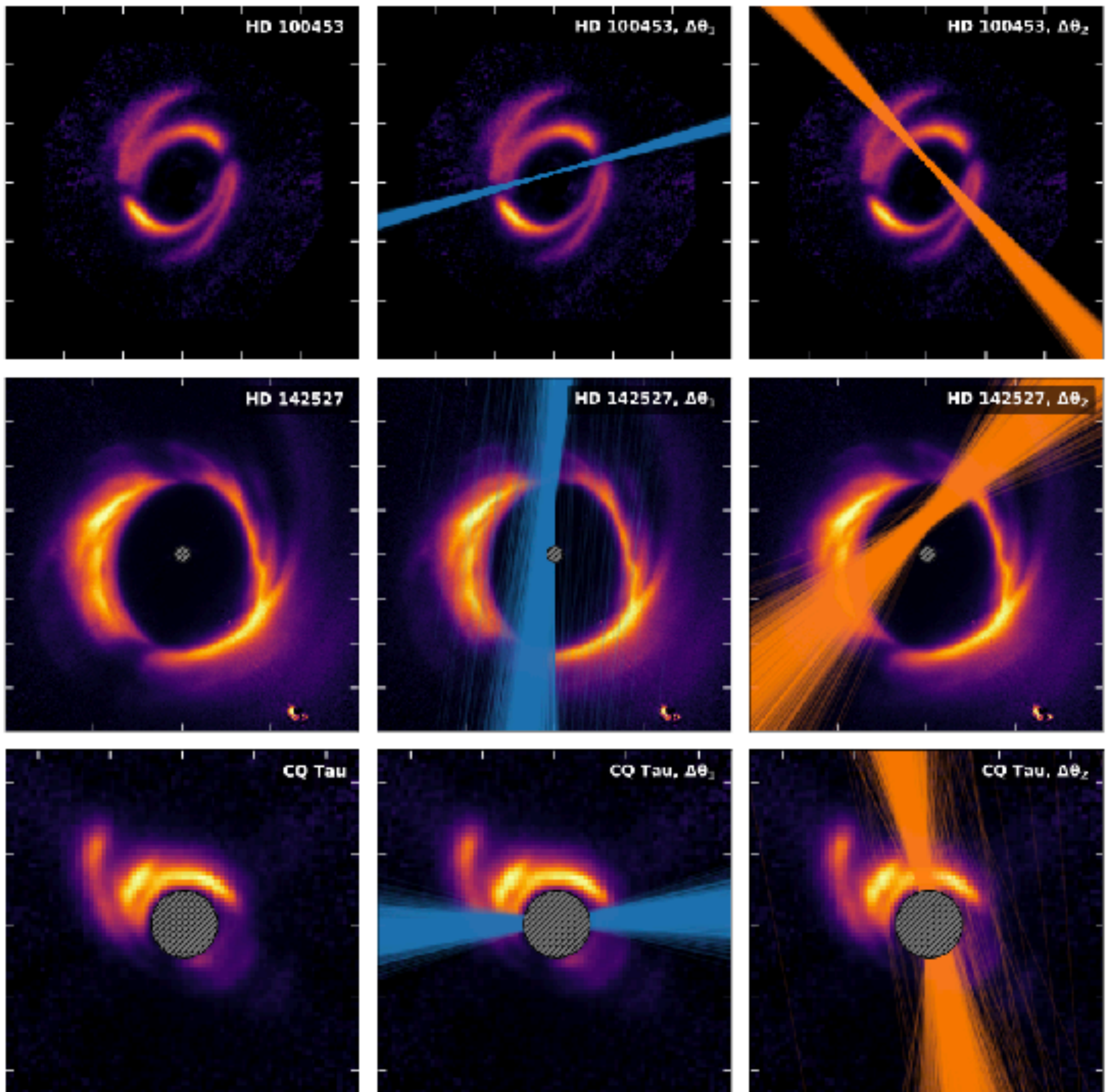




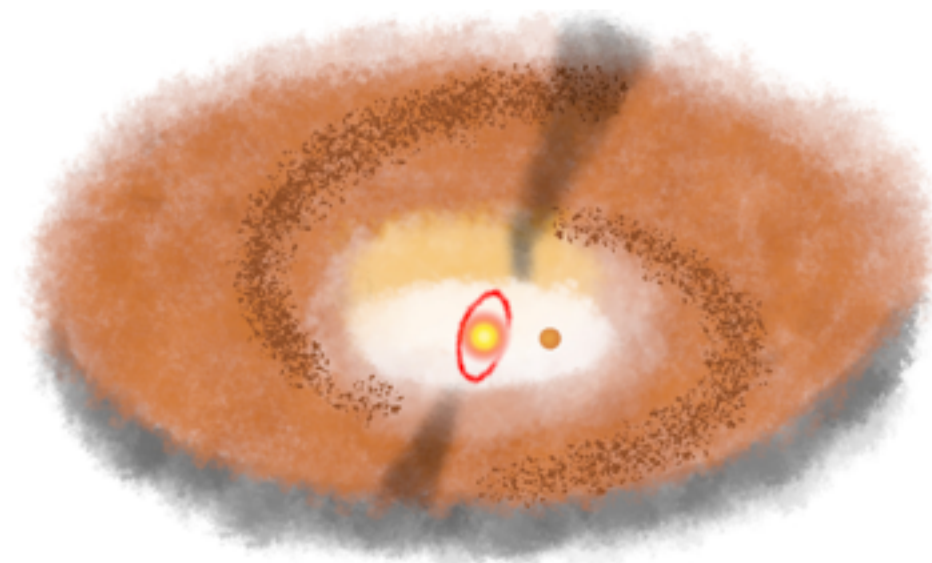
VLTI only has 4 telescopes (NIR wavelengths), so interferometry is tricky: fitting model image to visibilities rather than imaging the data

Perrault et al. 2019
Kluska et al. 2020
Bohn et al. 2022

Misalignment: VLTI + shadows



A ring model can have 2 possible orientations, but the shadows in NIR help to distinguish between those!

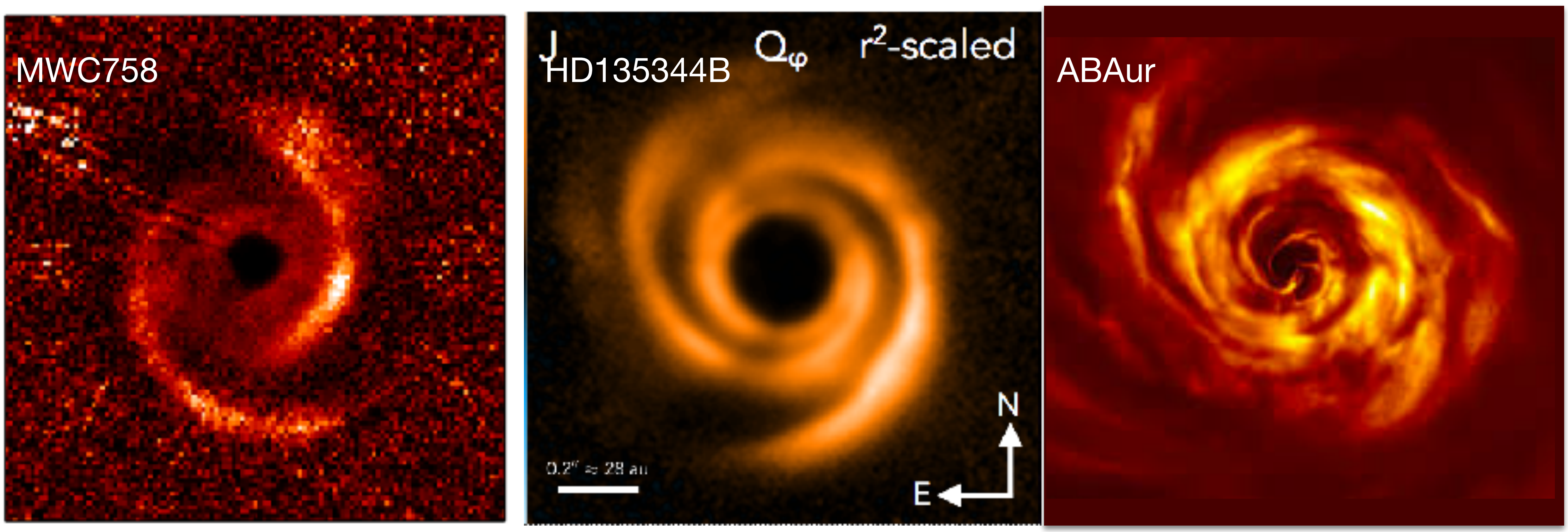


Spirals, shadow lanes, misaligned inner disk

Bohn et al. 2022
Benisty et al. 2022 (PPVII)

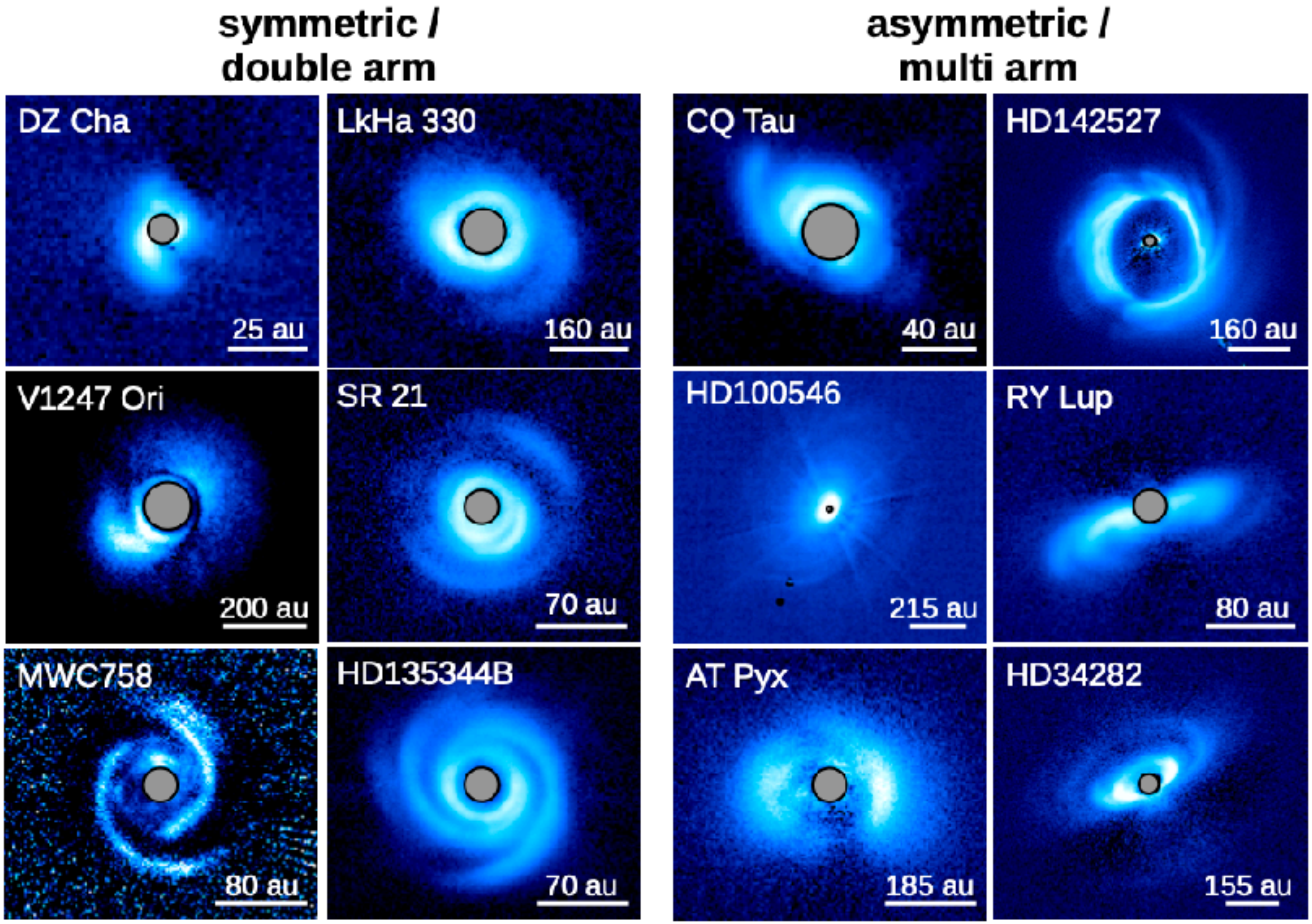
Spirals (in NIR)

Some famous examples of spiral arms detected in scattered light imaging



Benisty et al. 2015, Stolker et al. 2016, Boccaletti et al. 2019

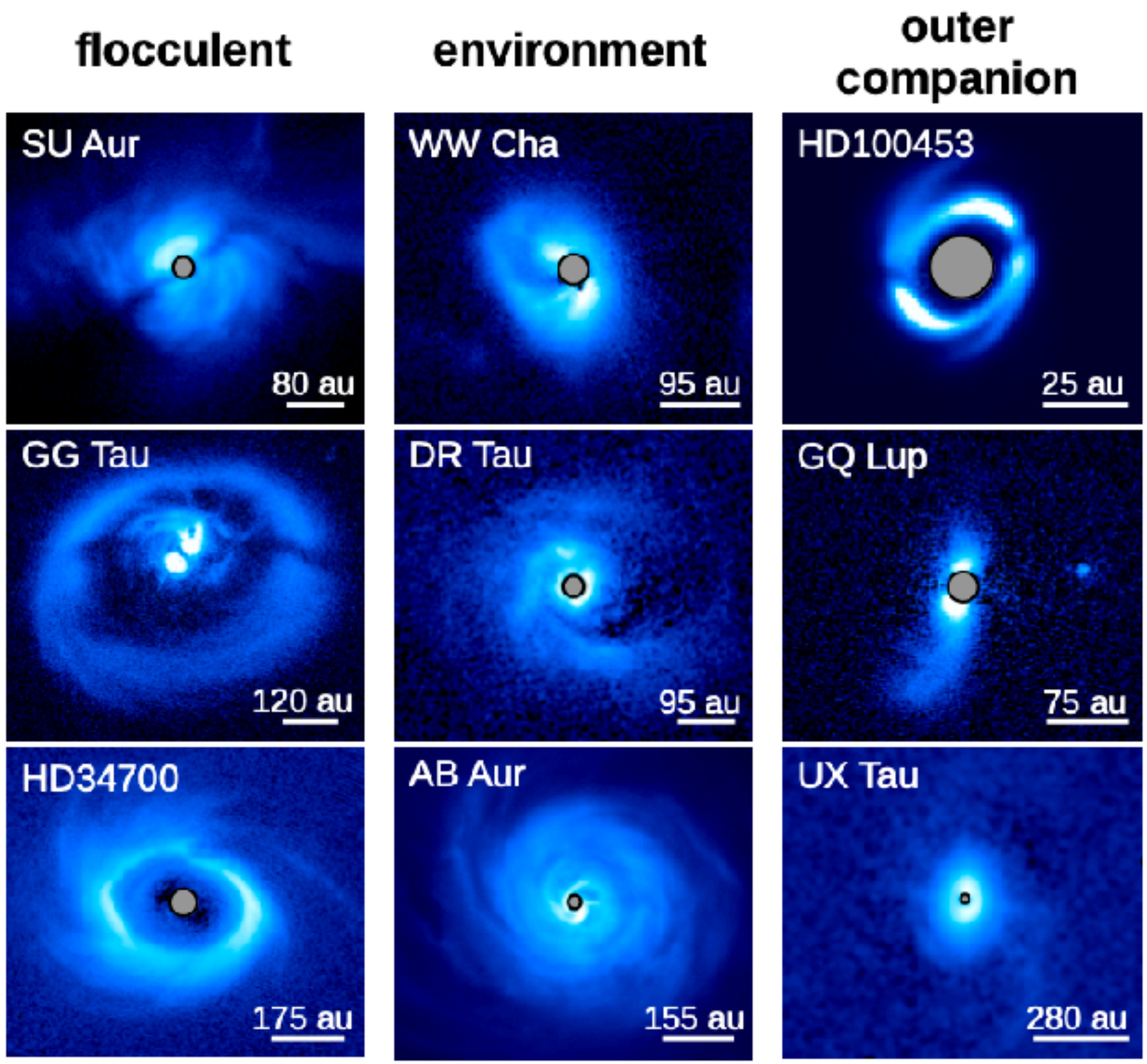
Spirals (in NIR)



Large diversity in spiral structures…

Benisty et al. 2022 (PPVII)

Spirals (in NIR)



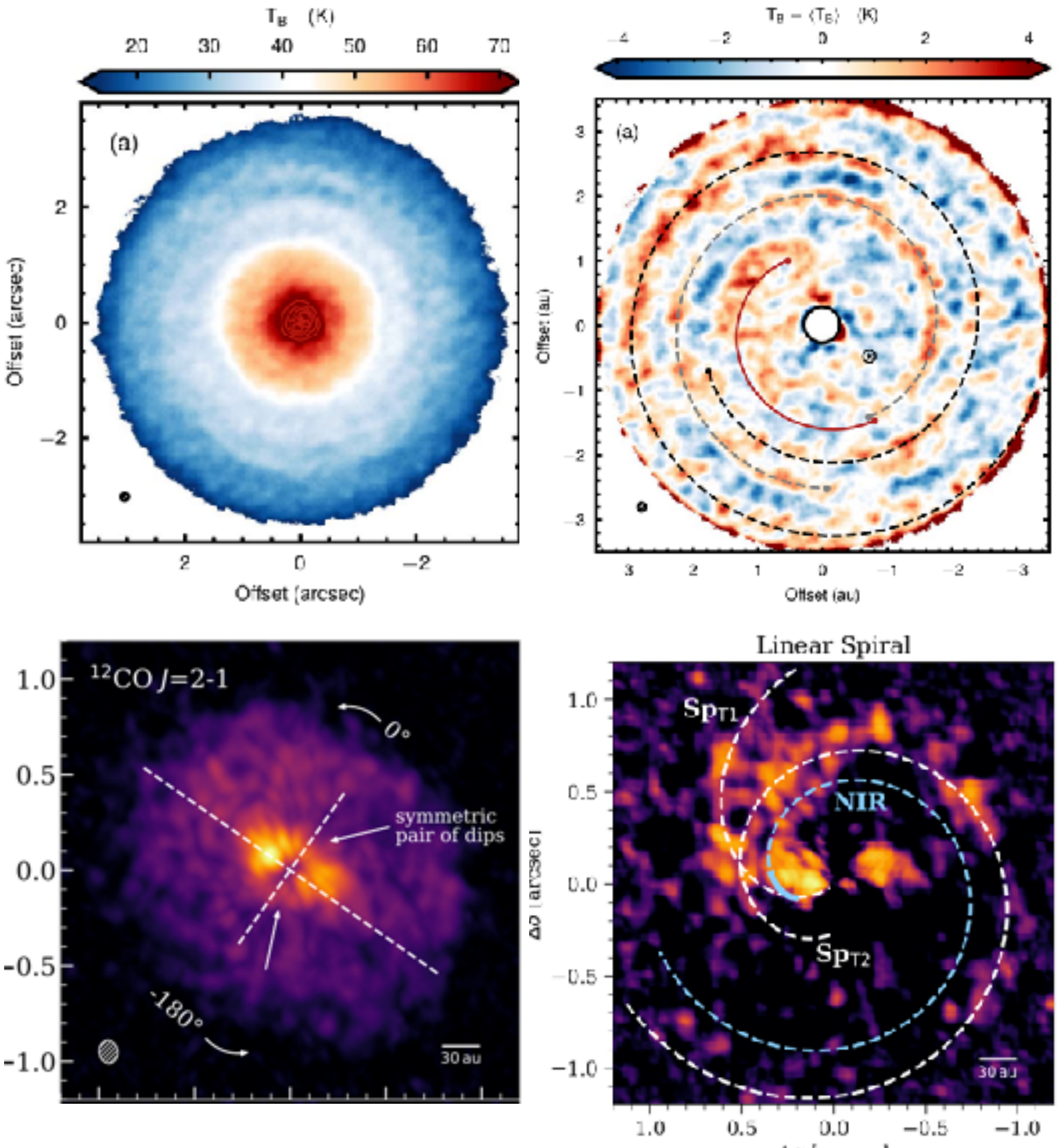
Environment clearly plays a role

Large diversity in spiral structures…

Benisty et al. 2022 (PPVII)

Spirals (in CO)

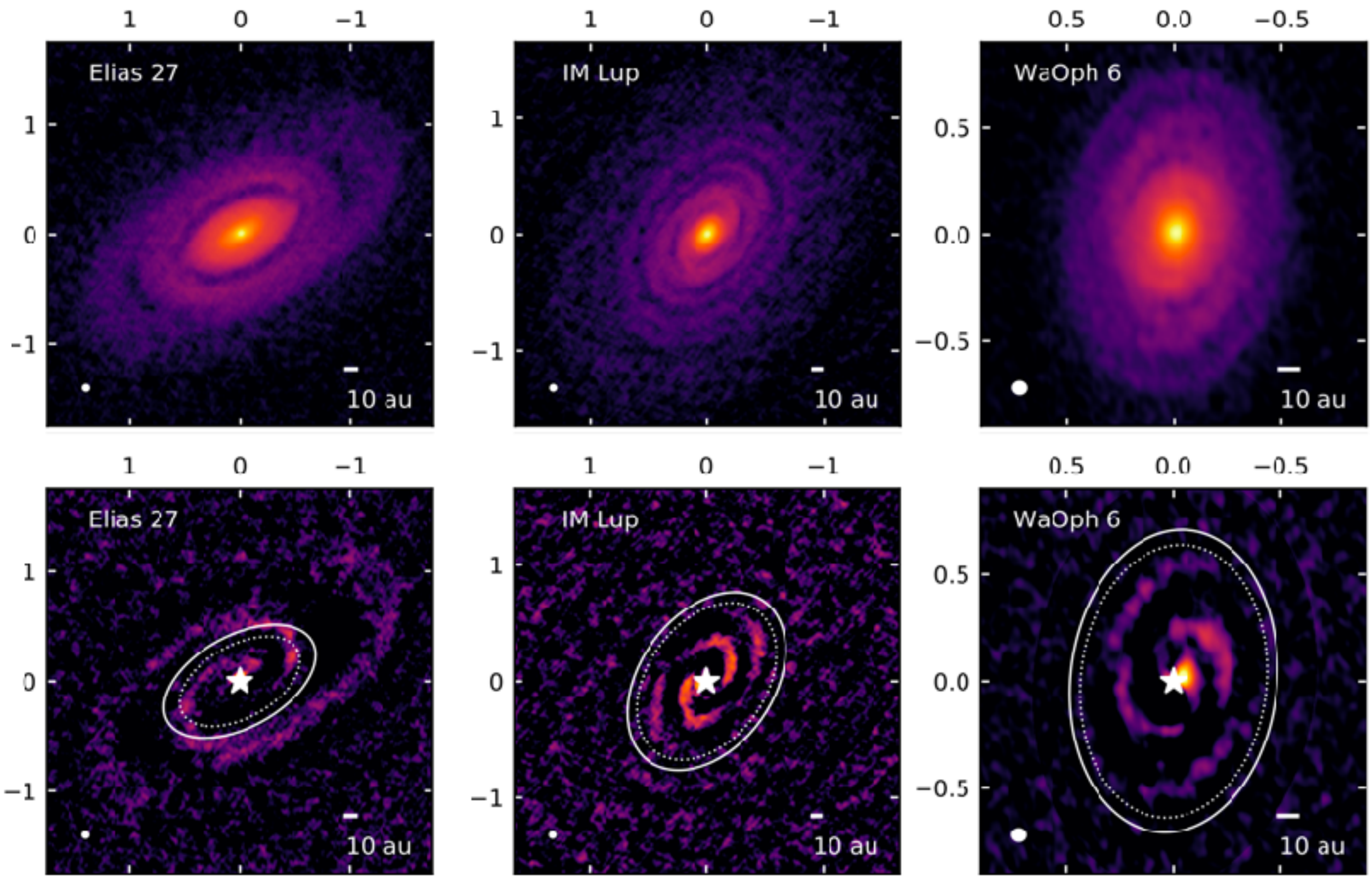
In ^{12}CO residuals



When subtracting an axisymmetric intensity model from the zero-moment ^{12}CO map, sometimes spiral arms become visible. High angular resolution required

Wolfer et al. 2019, 2022, Teague et al. 2019

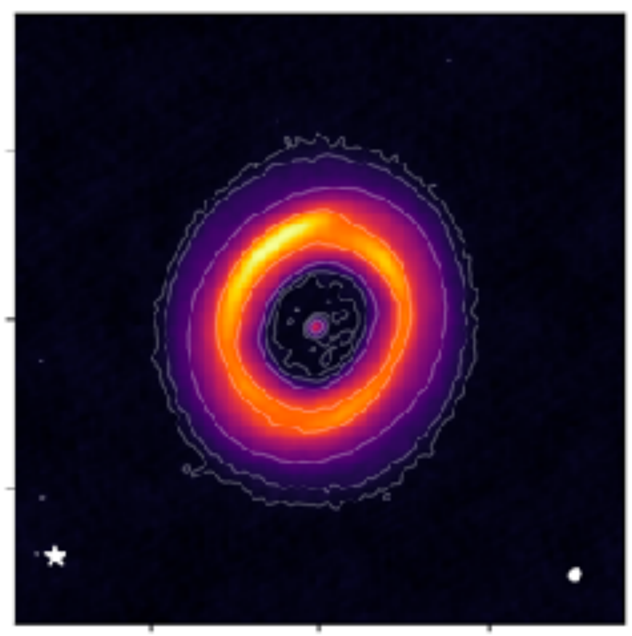
Spirals (in mm)

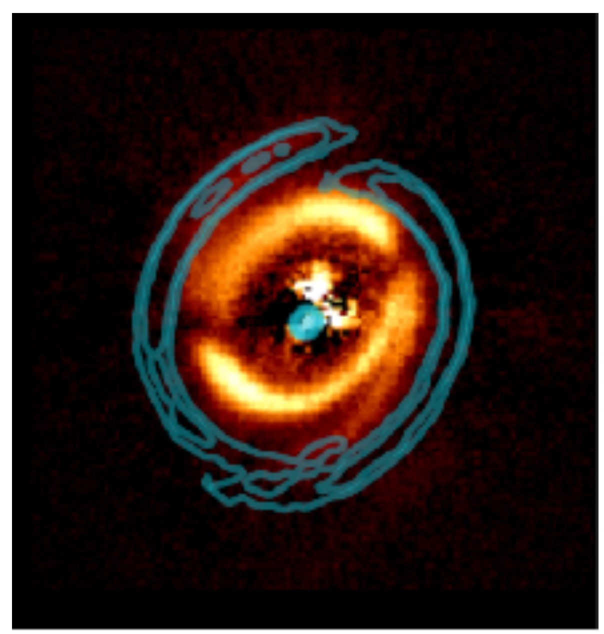


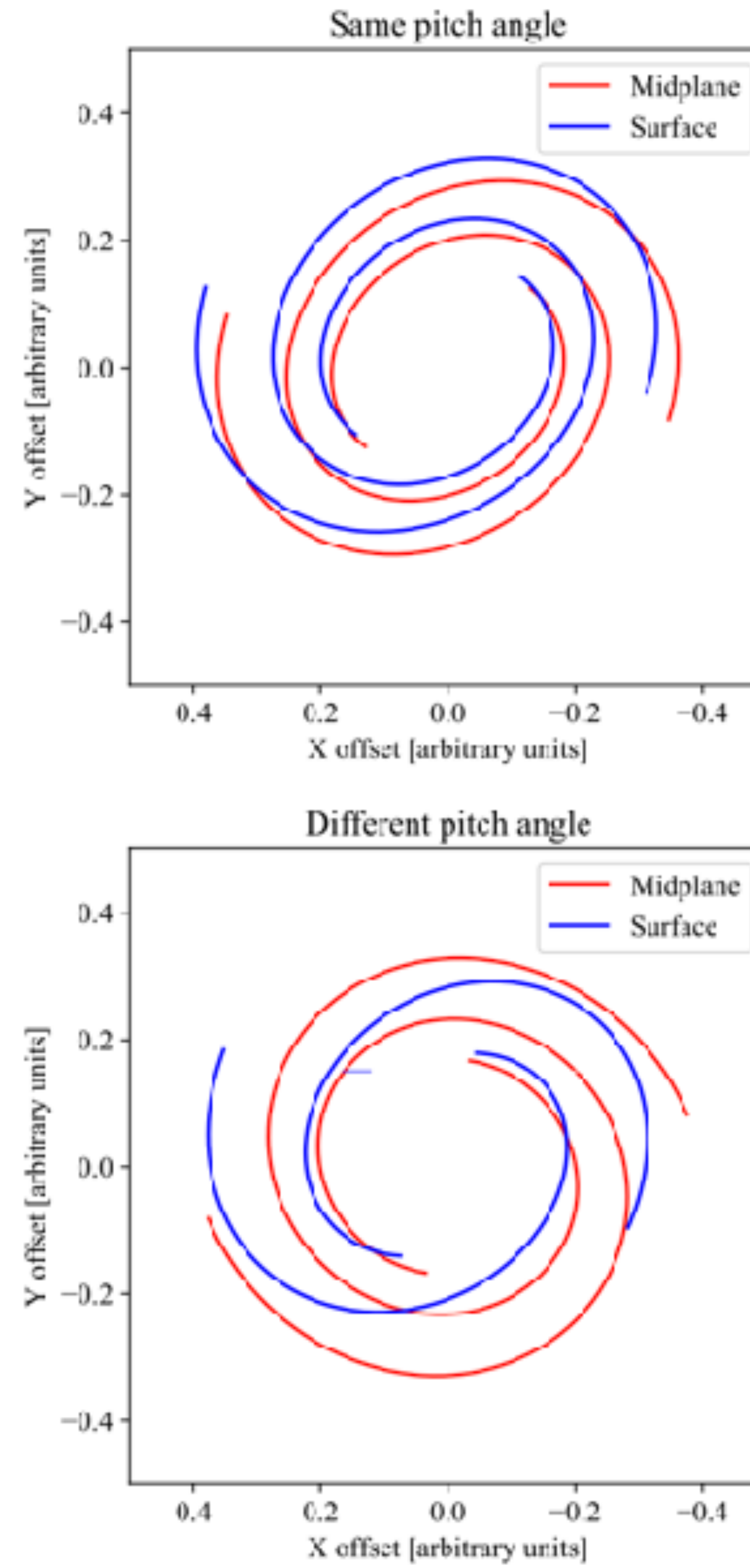
Also in ALMA millimeter images, spiral structures are sometimes visible: again more clear after subtracting axisymmetric model

Huang et al. 2018
Paneque-Carrena et al. 2021

Spirals NIR vs mm





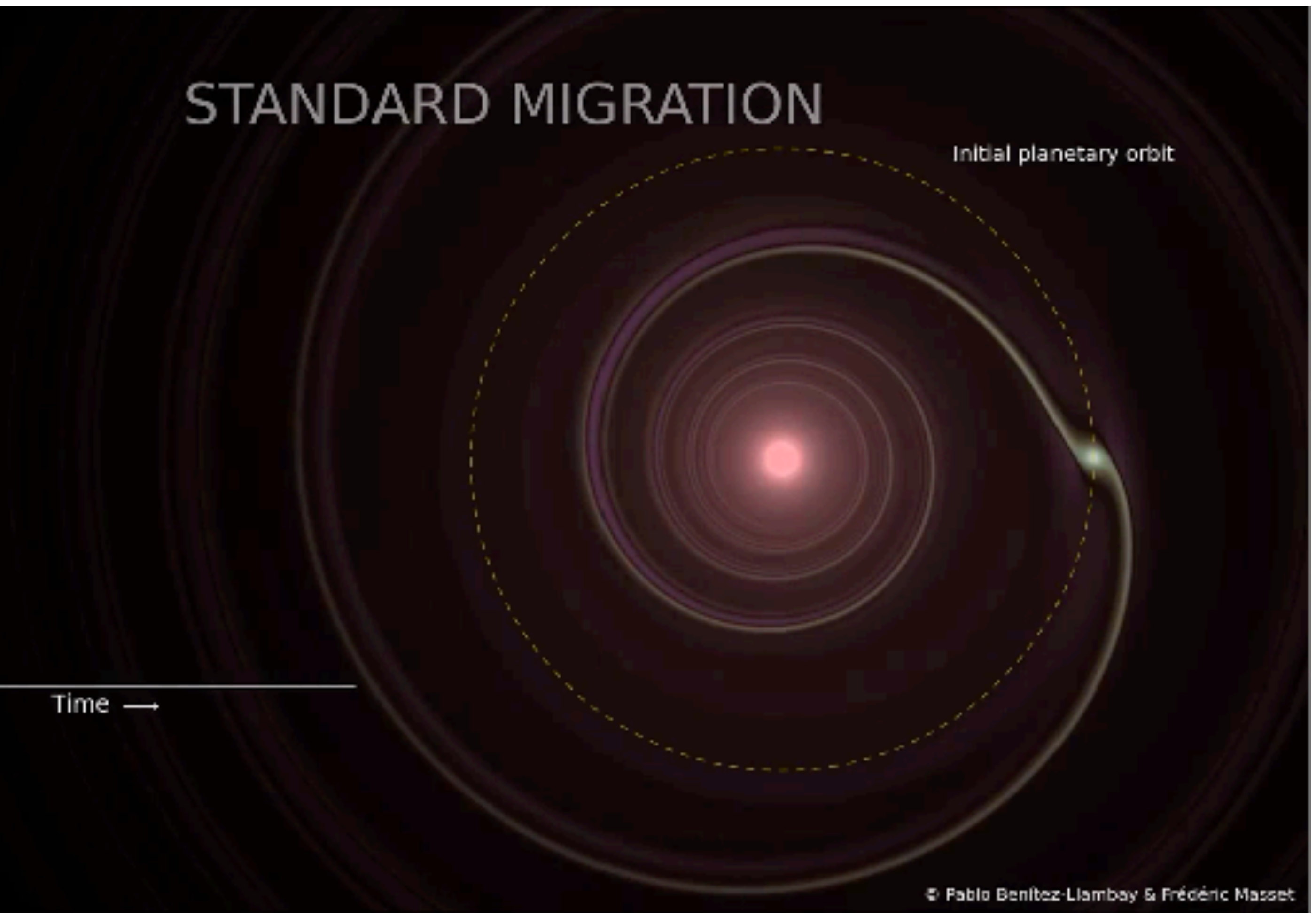


As the opening angle is different for NIR vs mm, this implies that the temperature is different at each height (vertical temperature structure)

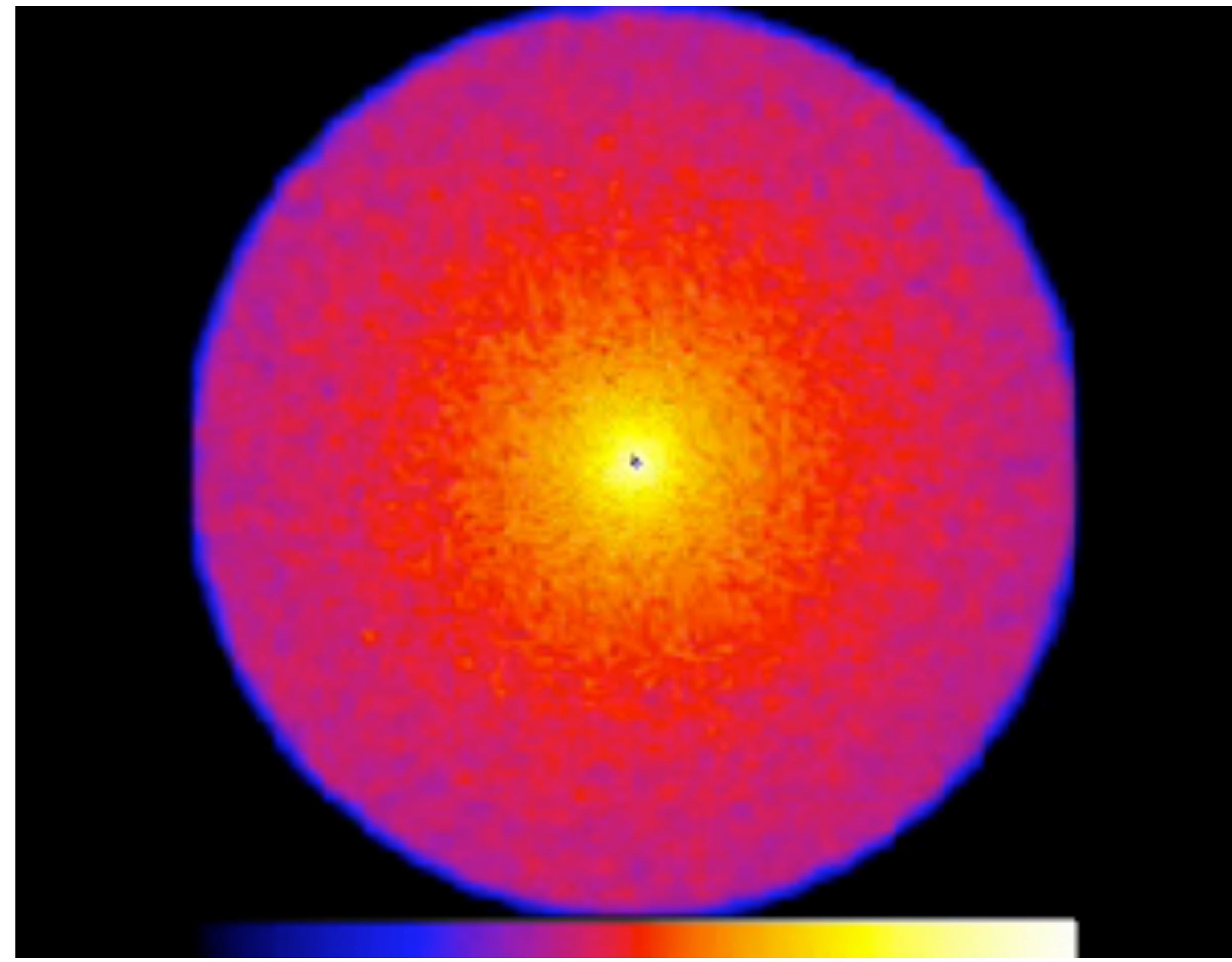
Rosotti et al. 2019

Origin spirals?

Planet spiral density waves



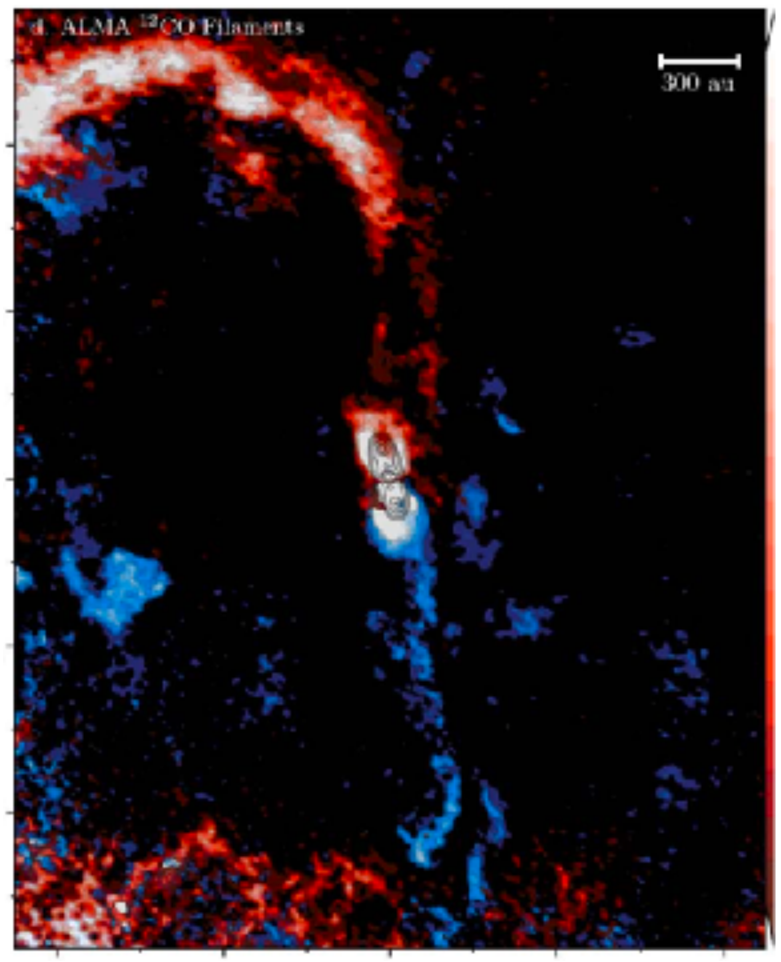
Gravitational instability

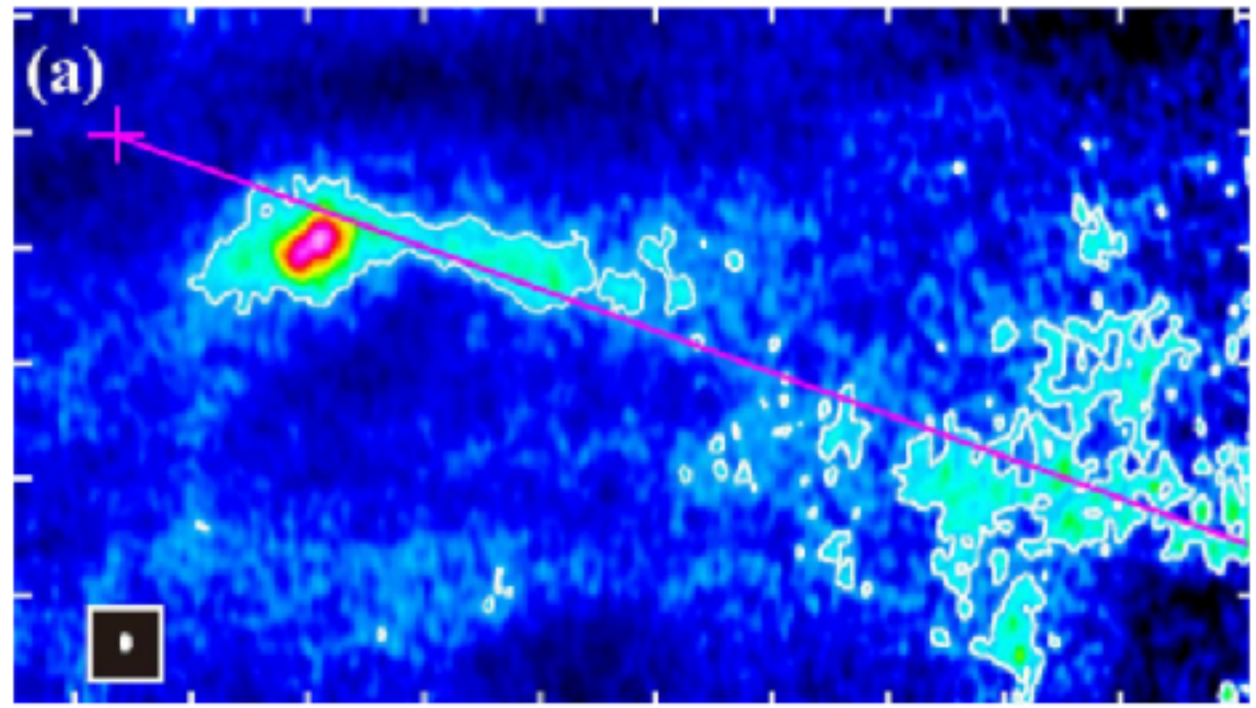


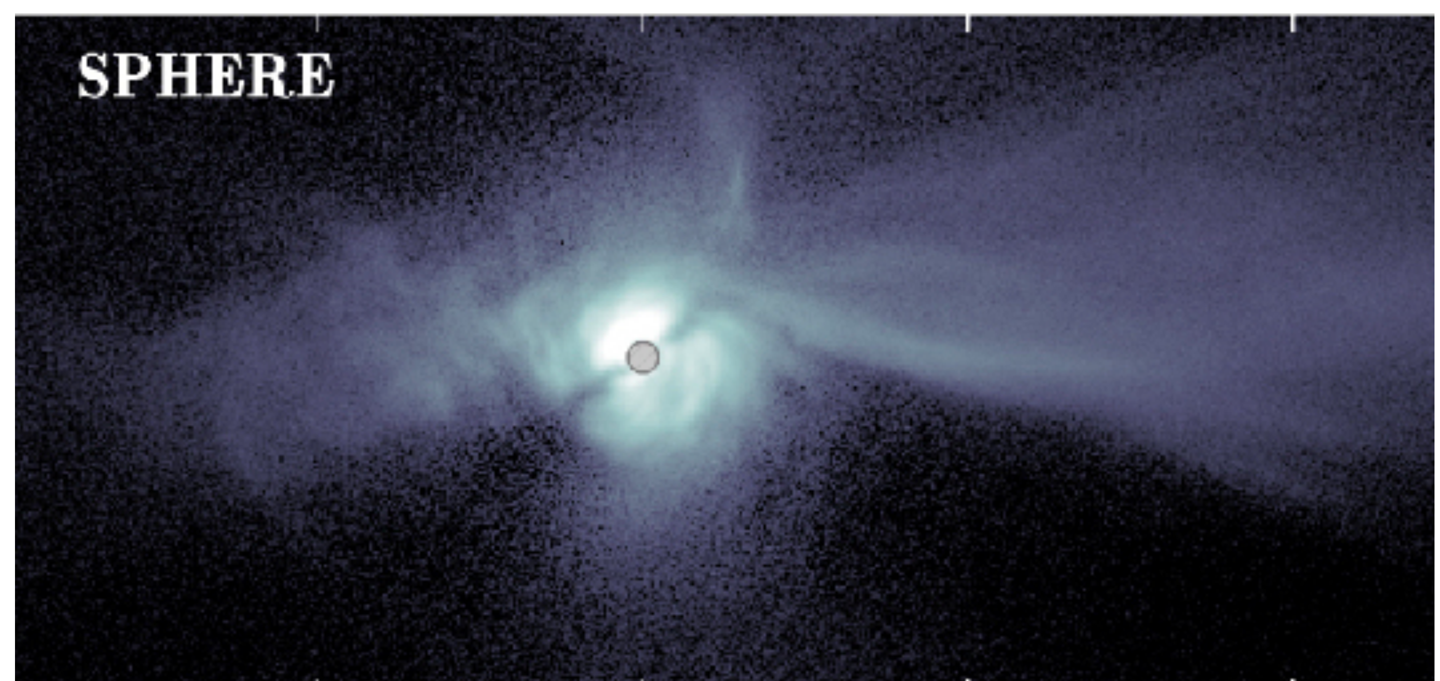
The spirals seen in mm emission are often associated with gravitational instability, as their disk masses are large. The NIR/CO spirals are more scale height/ temperature variations (as the underlying mm disk looks very different) so more likely due to dynamical interaction. Not fully conclusive yet!

Credits:
Pablo Benitez-Llambay, Ken Rice

Streamers (NIR/CO)







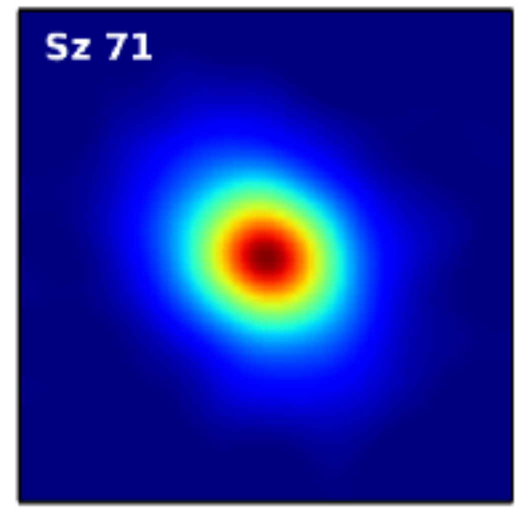
In younger systems, often evidence for large-scale tails/streamers (infalling material). Possibly cloud feeding the disk.

Alves et al. 2020
Akiyama et al. 2019
Ginski et al. 2021

Detectability of substructures

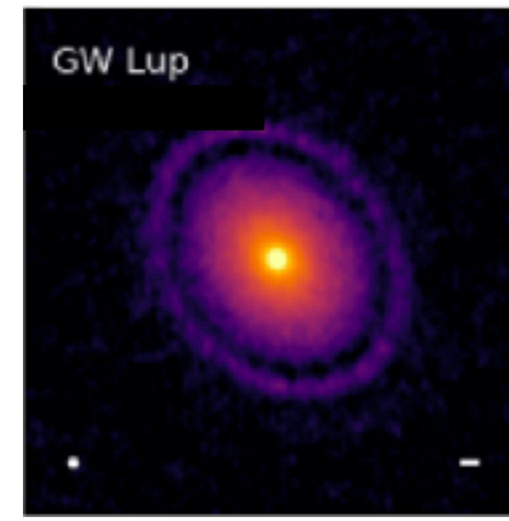
The detection of substructures is resolution dependent: high-resolution images reveal gaps in previously thought 'smooth' disks

Transition disks with >30 au cavities were already resolved pre-ALMA

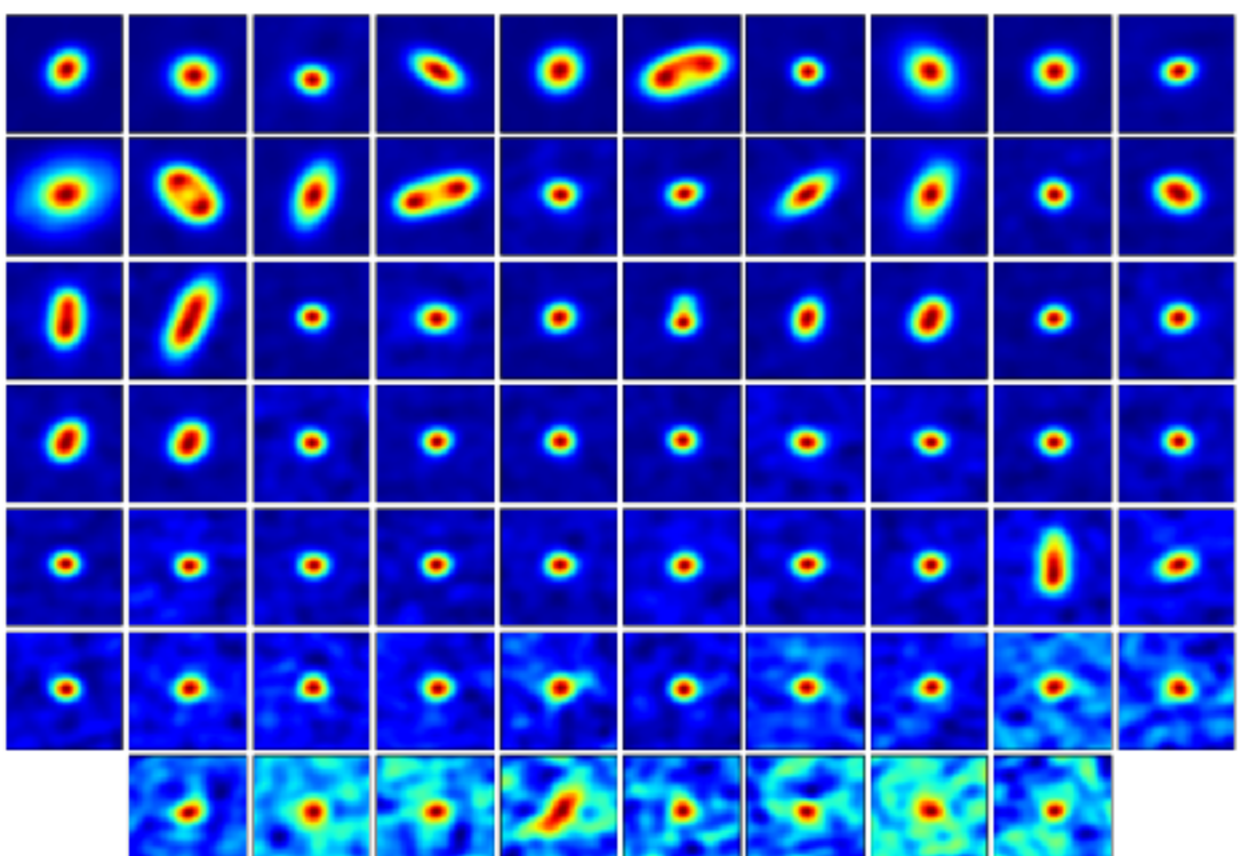


(0.30”)

=



(0.04”)

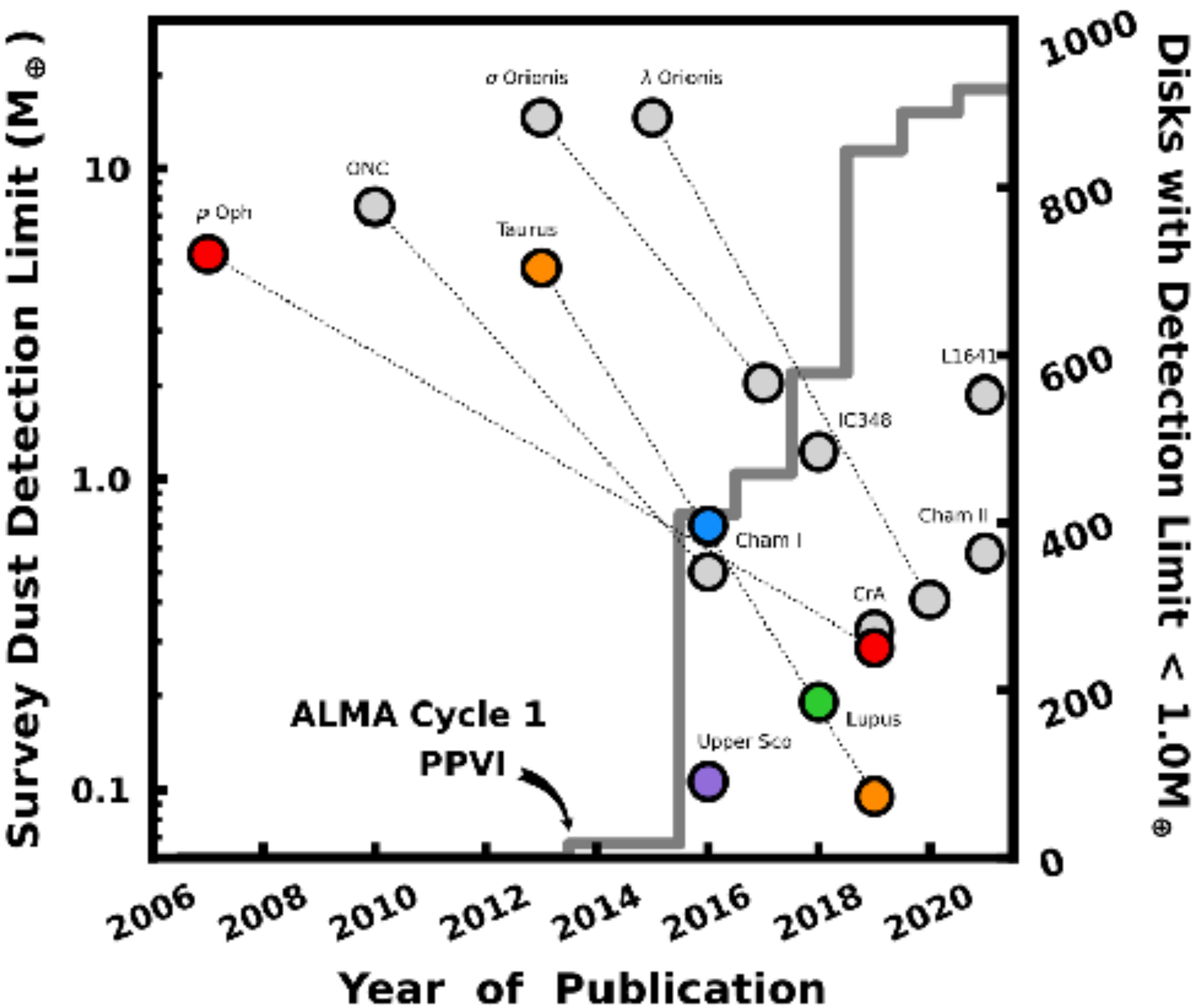


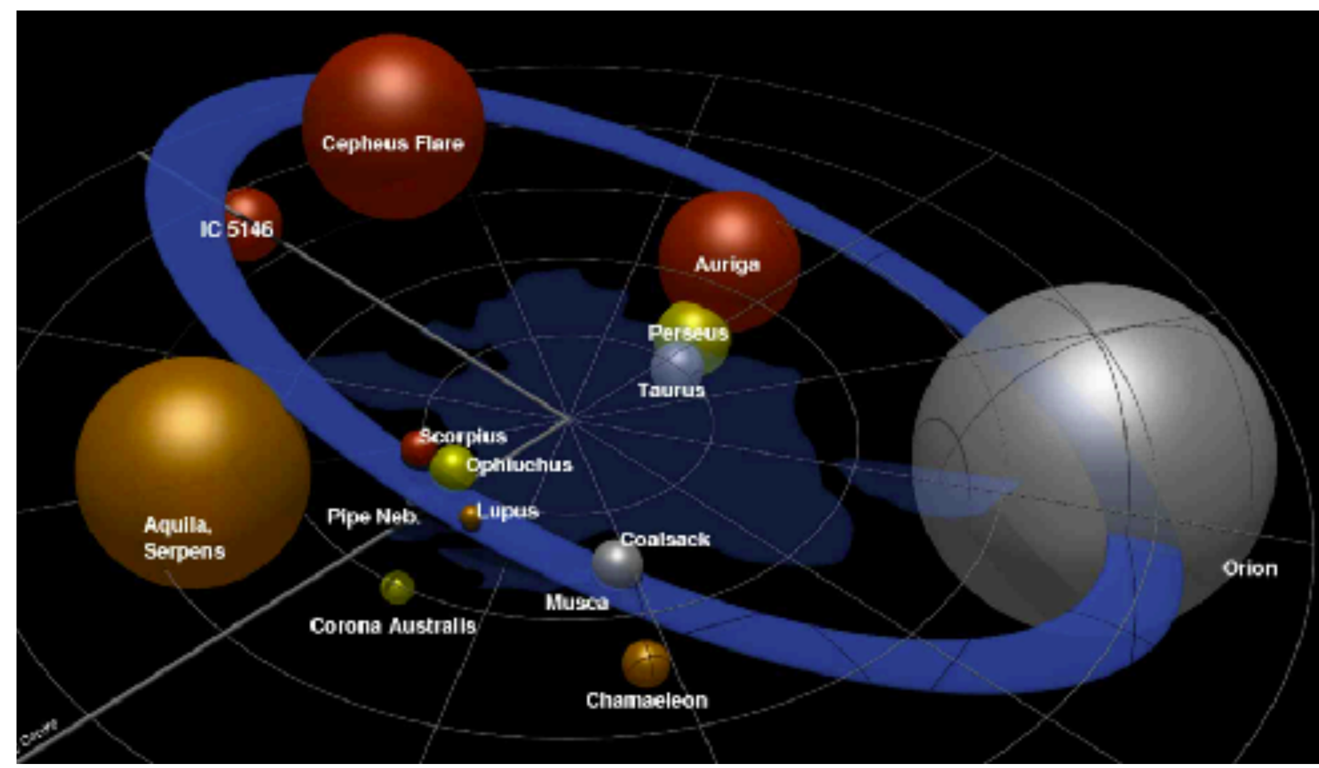
'Complete' disk surveys in nearby star forming regions are taken at moderate resolution of 0.25”, only subsamples followed up at high resolution

Transition disks were pre-selected based on their SED, but also many new transition disks with cavities >20 au discovered without dip in SED

Ansdell et al. 2016

Number of disks mapped with ALMA (low-res)

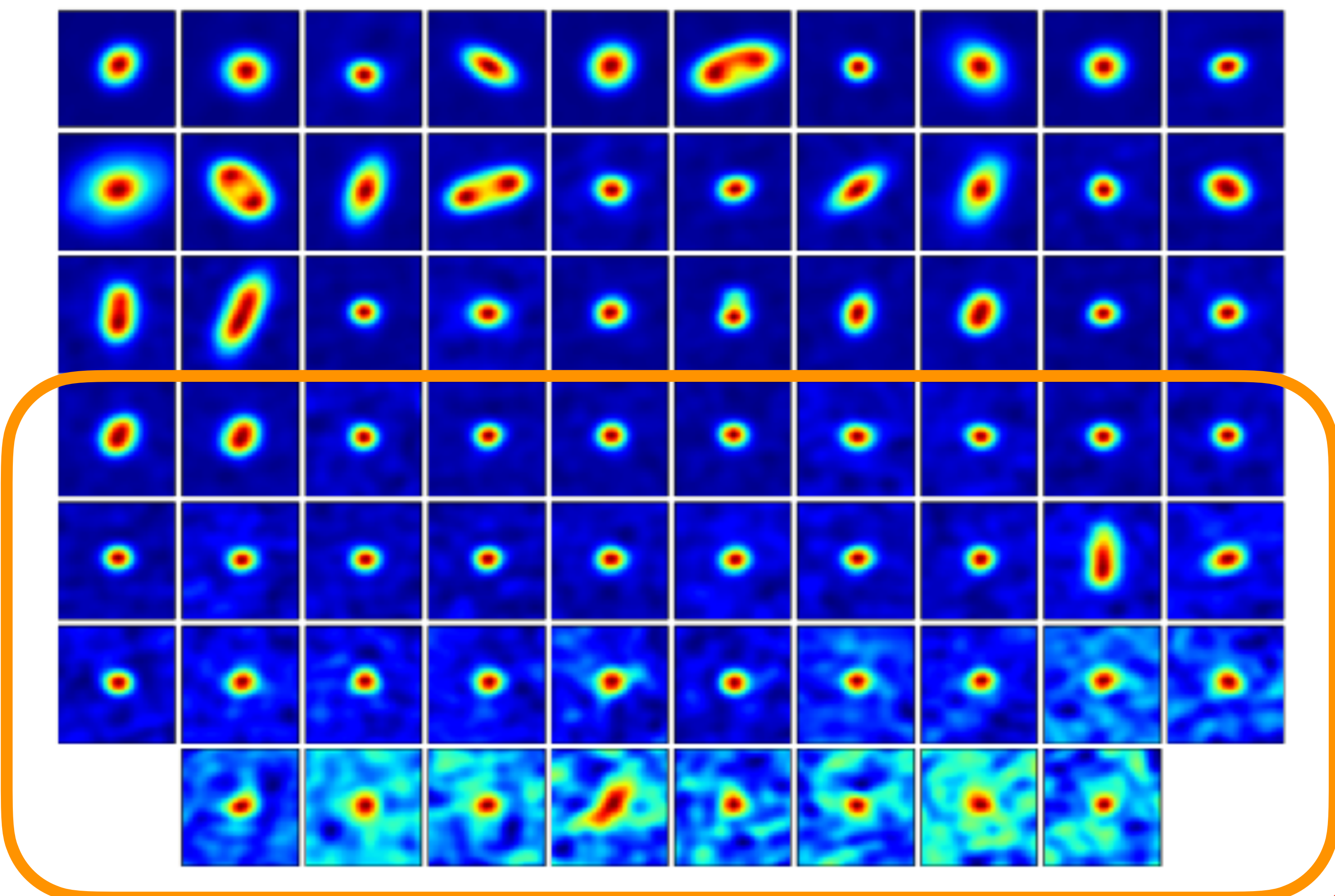


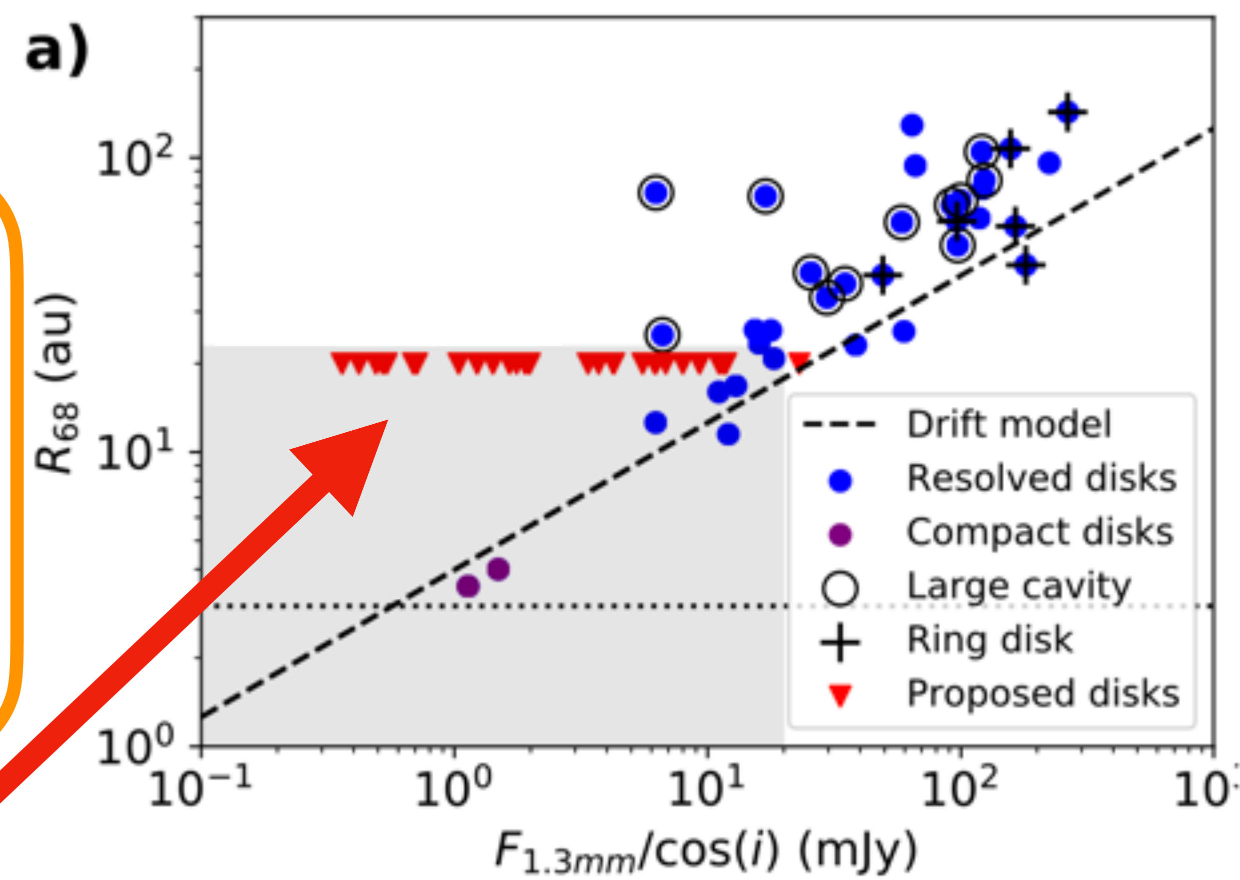


Essentially all nearby young clusters <250 pc are covered, first by Spitzer (SEDs) and now by ALMA (mm images)

Manara et al. 2022 (PPVII)

Number of disks mapped with ALMA (low-res)

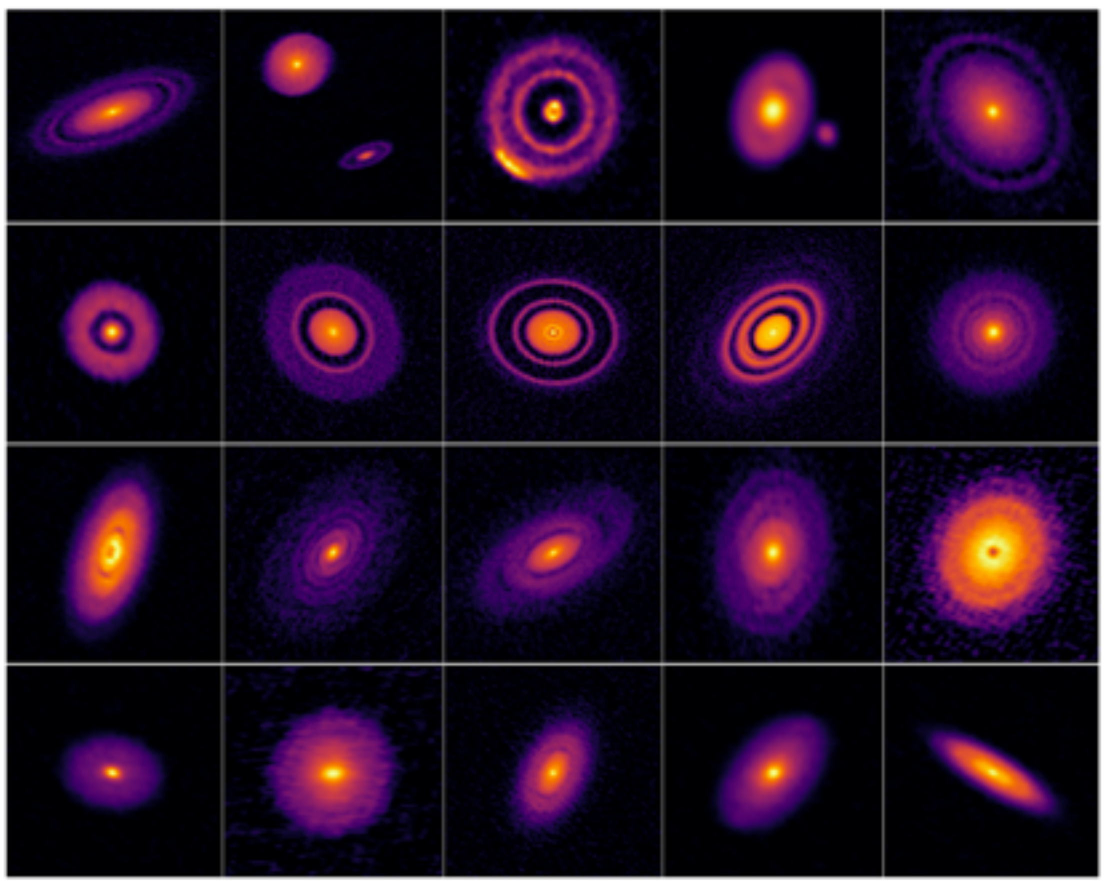




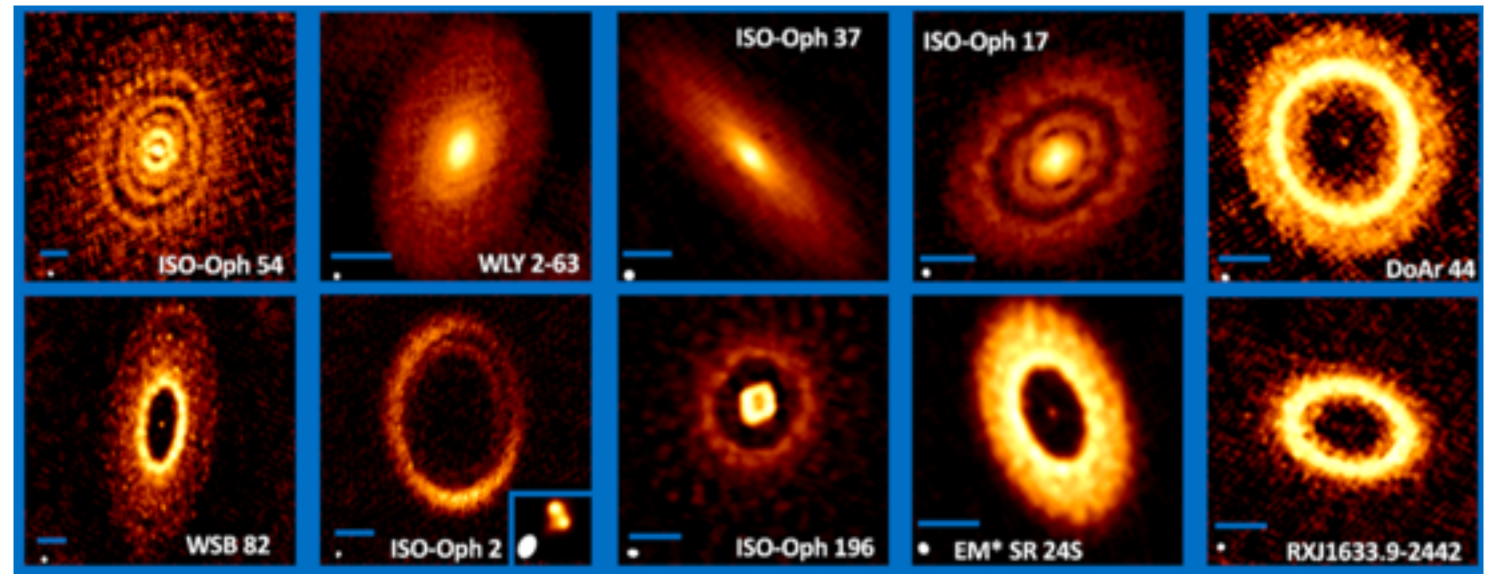
Lupus Survey: half of the detected disks are unresolved at 0.2"!

Ansdell et al. 2016
van der Marel (private comm)

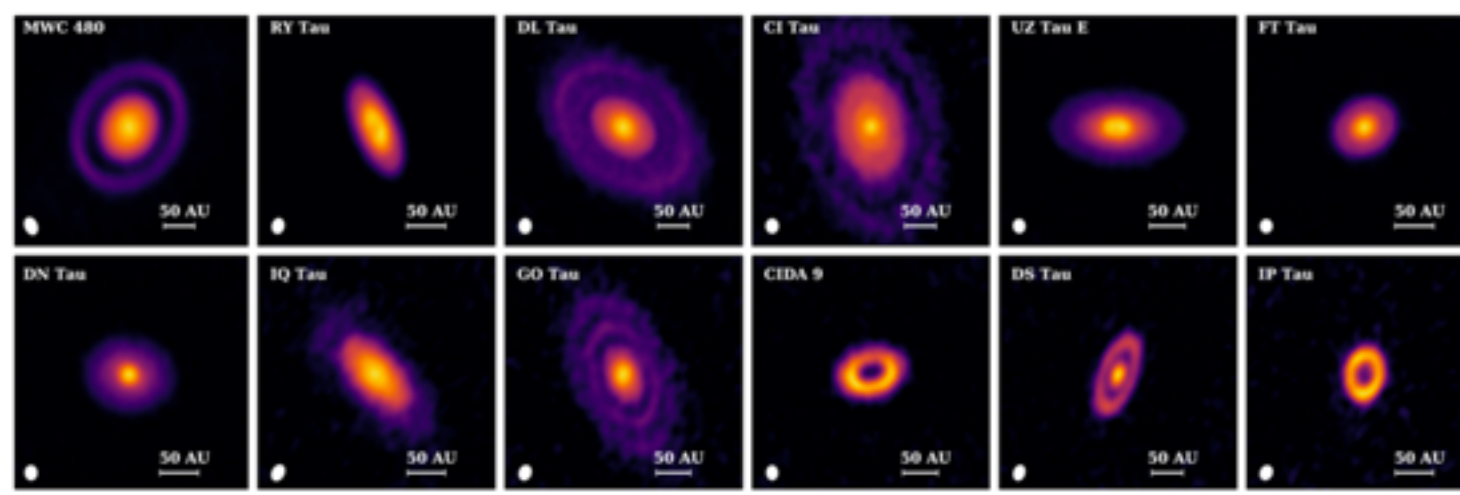
Selection bias



DSHARP (Andrews et al. 2018): Selected targets with bright peak millimeter continuum fluxes

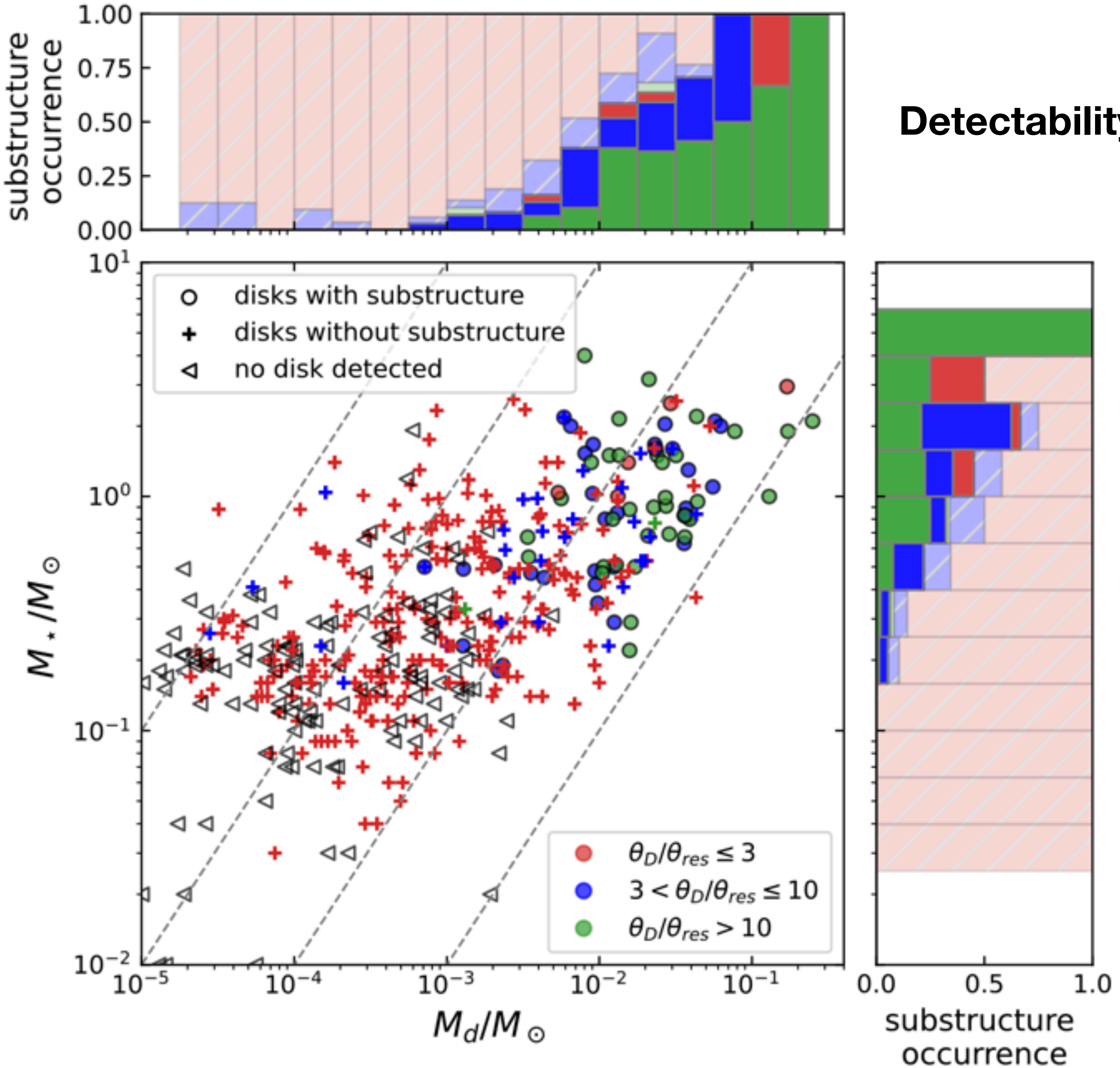


ODISEA (Cieza et al. 2021): Selected targets in Ophiuchus that had bright millimeter continuum emission



Long et al. 2018, 2019: Selected targets with spectral types earlier than M3

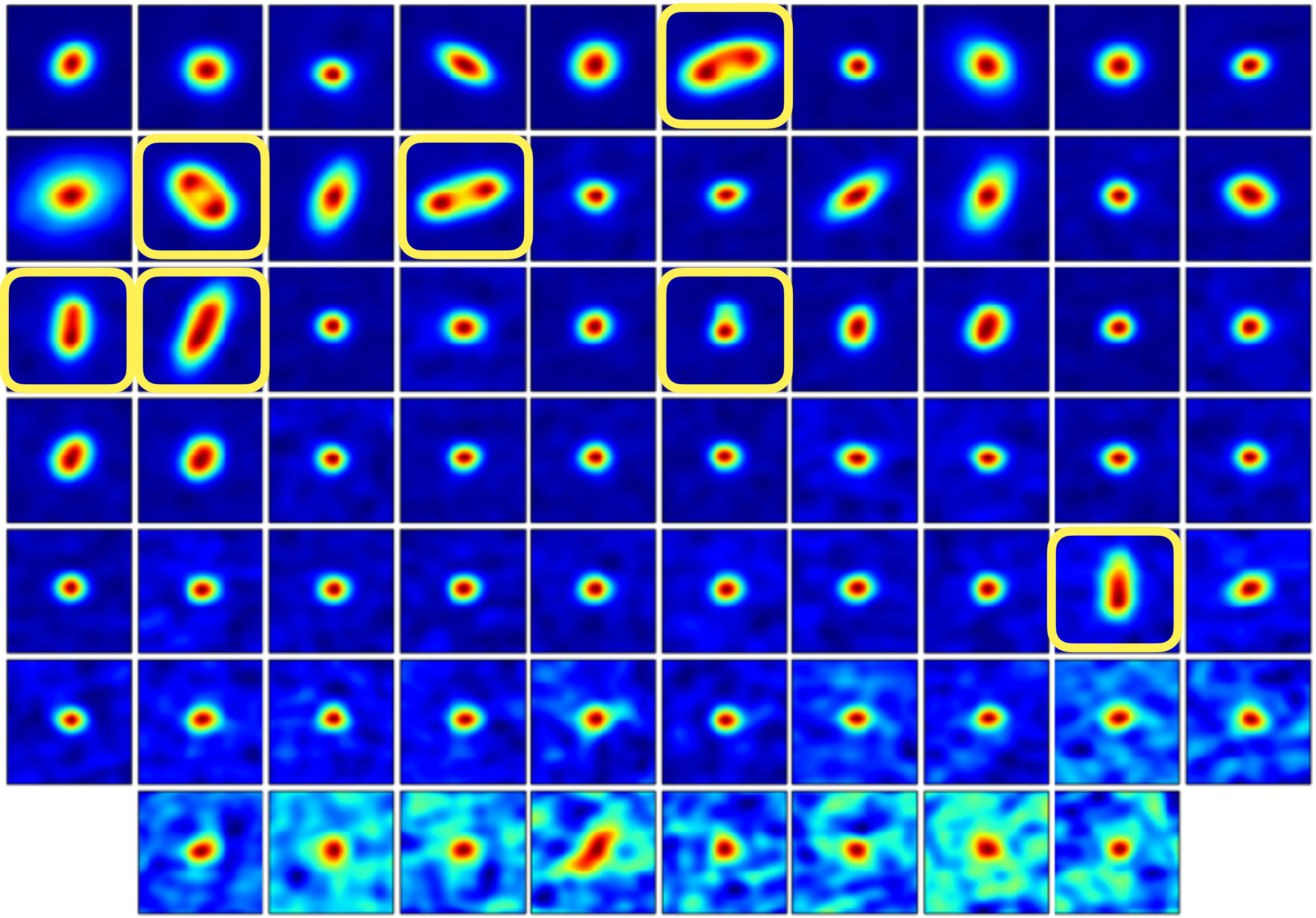
Detectability of substructures



Detectability depends on resolution!

Bae et al. 2022 (PPVII)

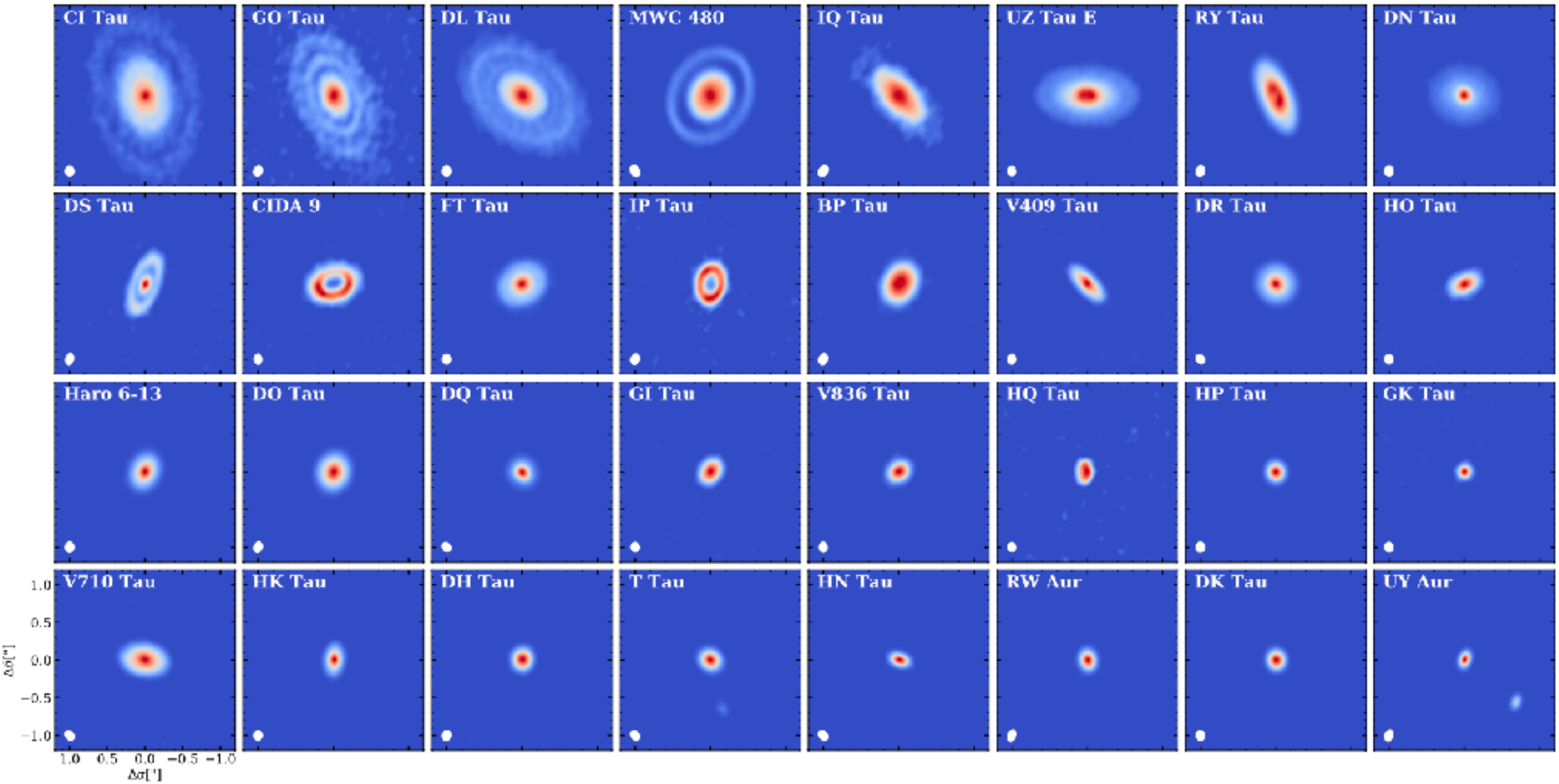
Occurrence rates



Transition disks in Lupus at 0.25": 11 TDs with cavities > 15 au in 68 detections: ~16%

Van der Marel et al. 2018, 2022

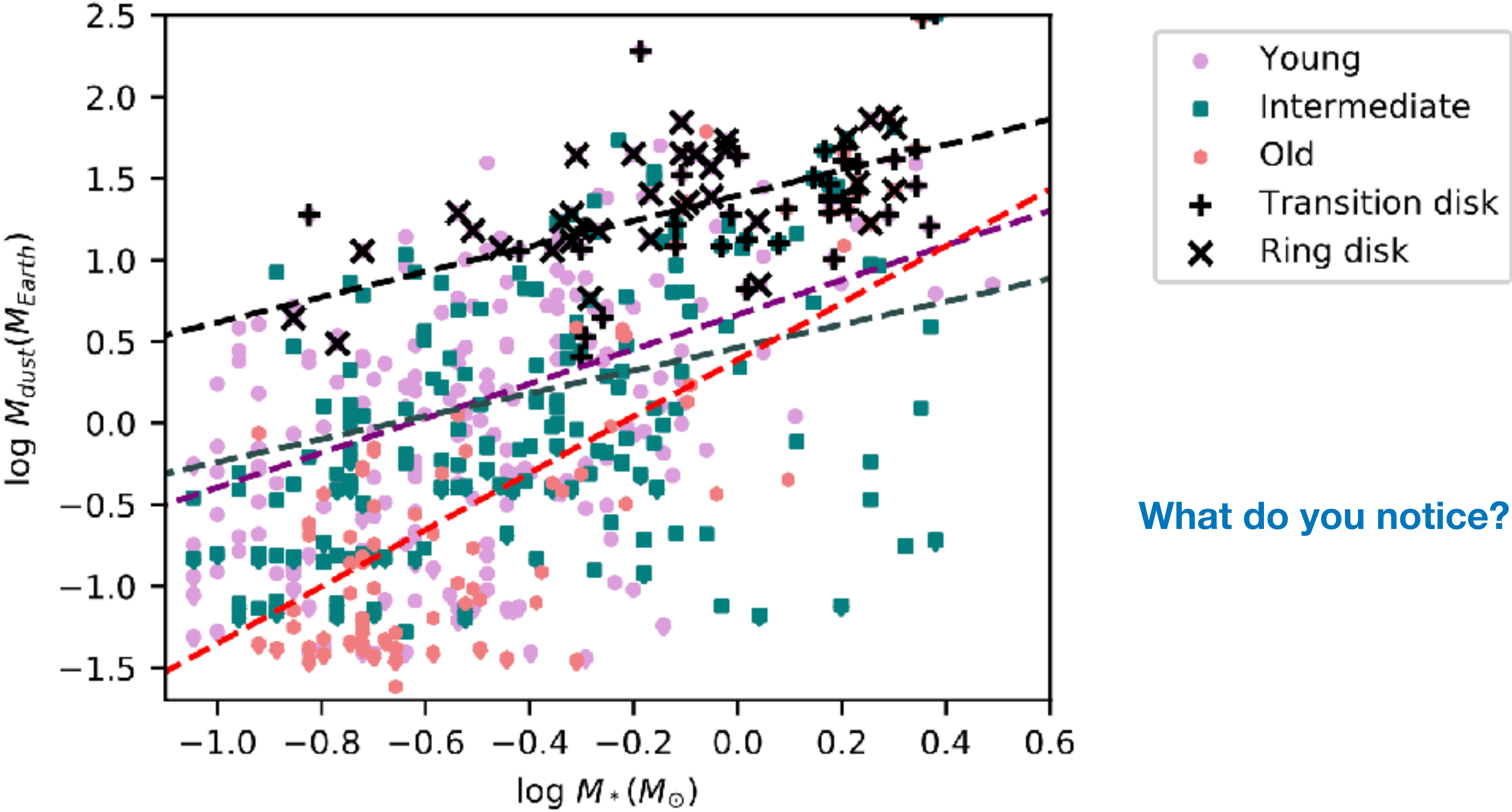
Occurrence rates



Disks with substructures in Taurus for stars A0-M2: half of the single stars have substructure

Long et al. 2019

Occurrence rates

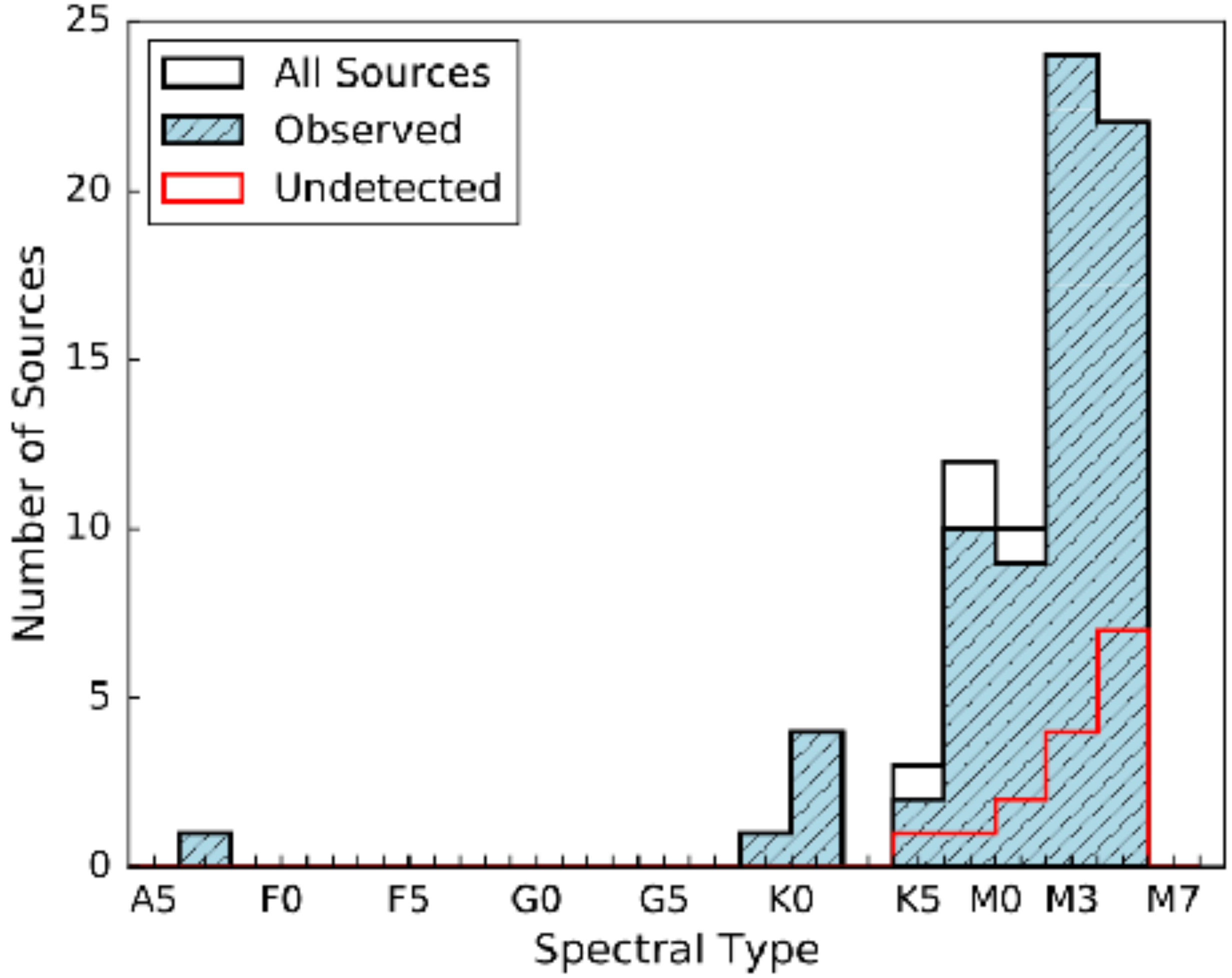


What do you notice?

What do you know about the IMF?

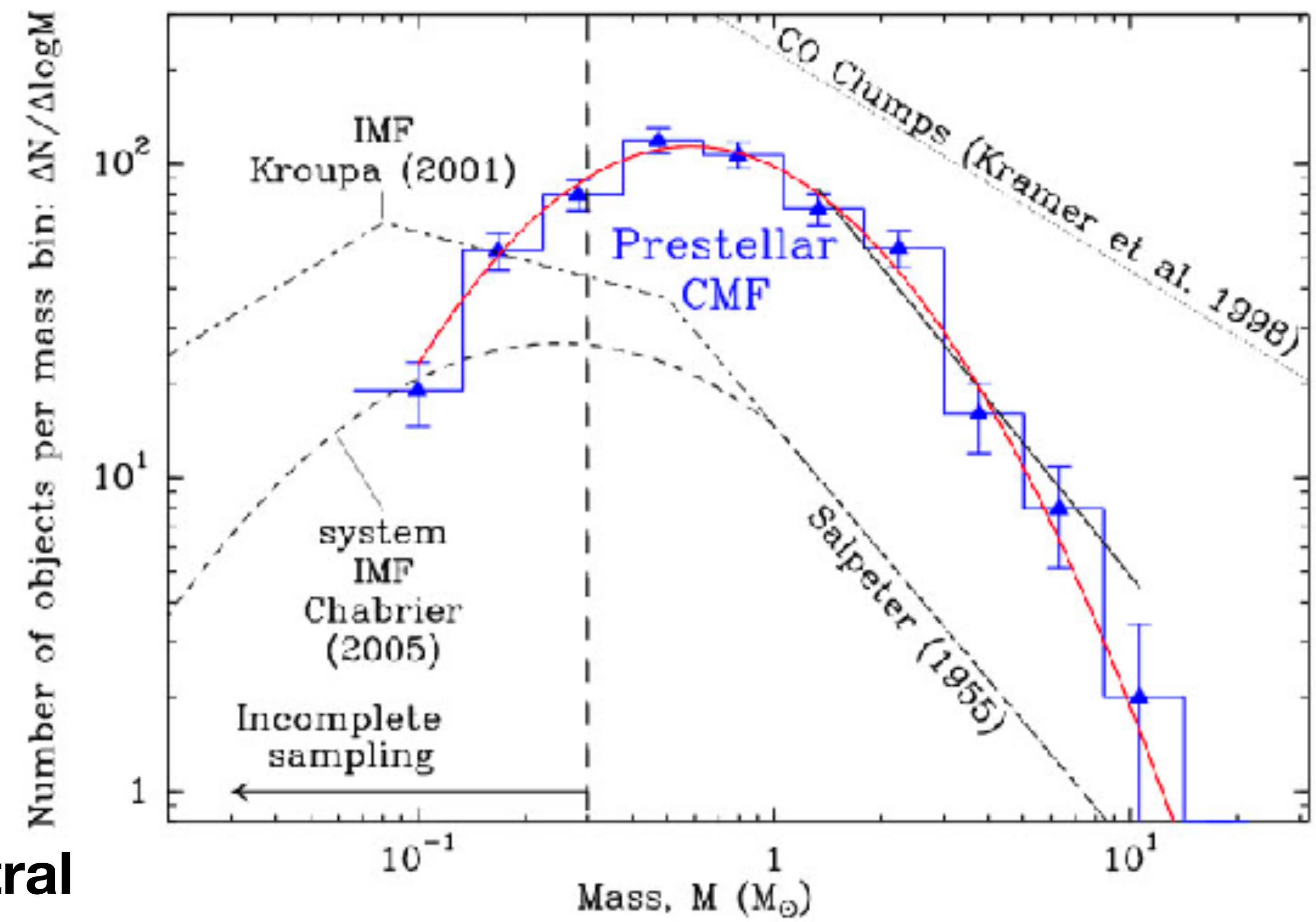
Van der Marel & Mulders 2021

The IMF



Stellar distribution in Lupus

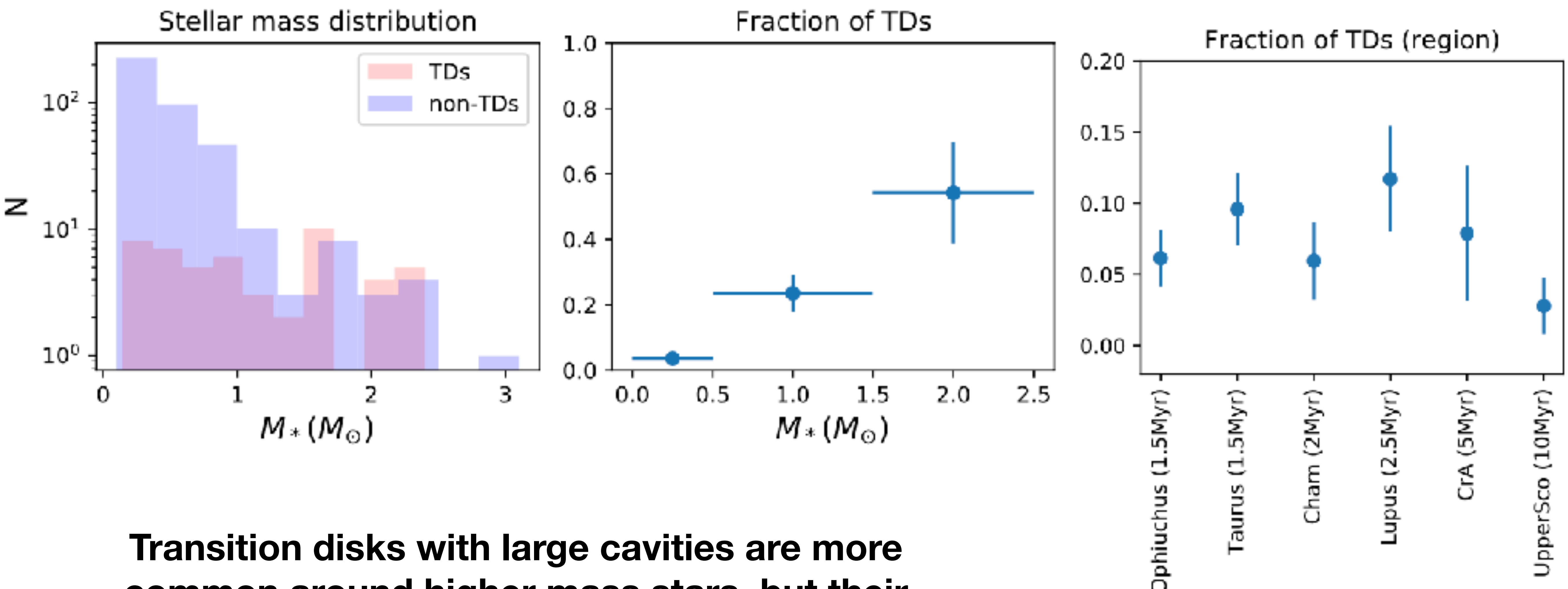
Overall stellar mass distribution main-sequence stars (and core mass function)



Most common stars are ~M2-M3 spectral type or 0.3 M_{sol}: Herbig stars and even Solar mass stars are bright, but rare!

Ansdell et al. 2016

Occurrence rates TDs

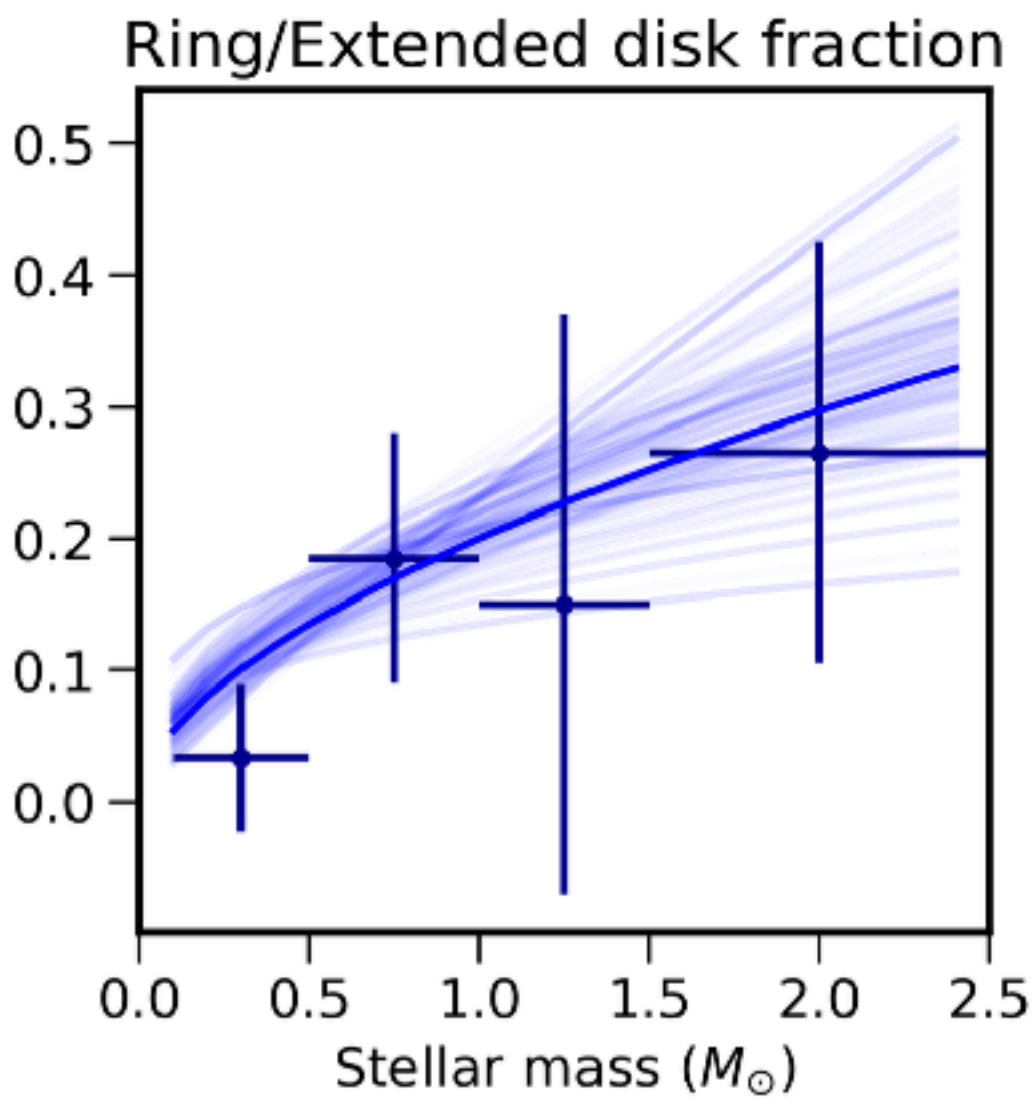


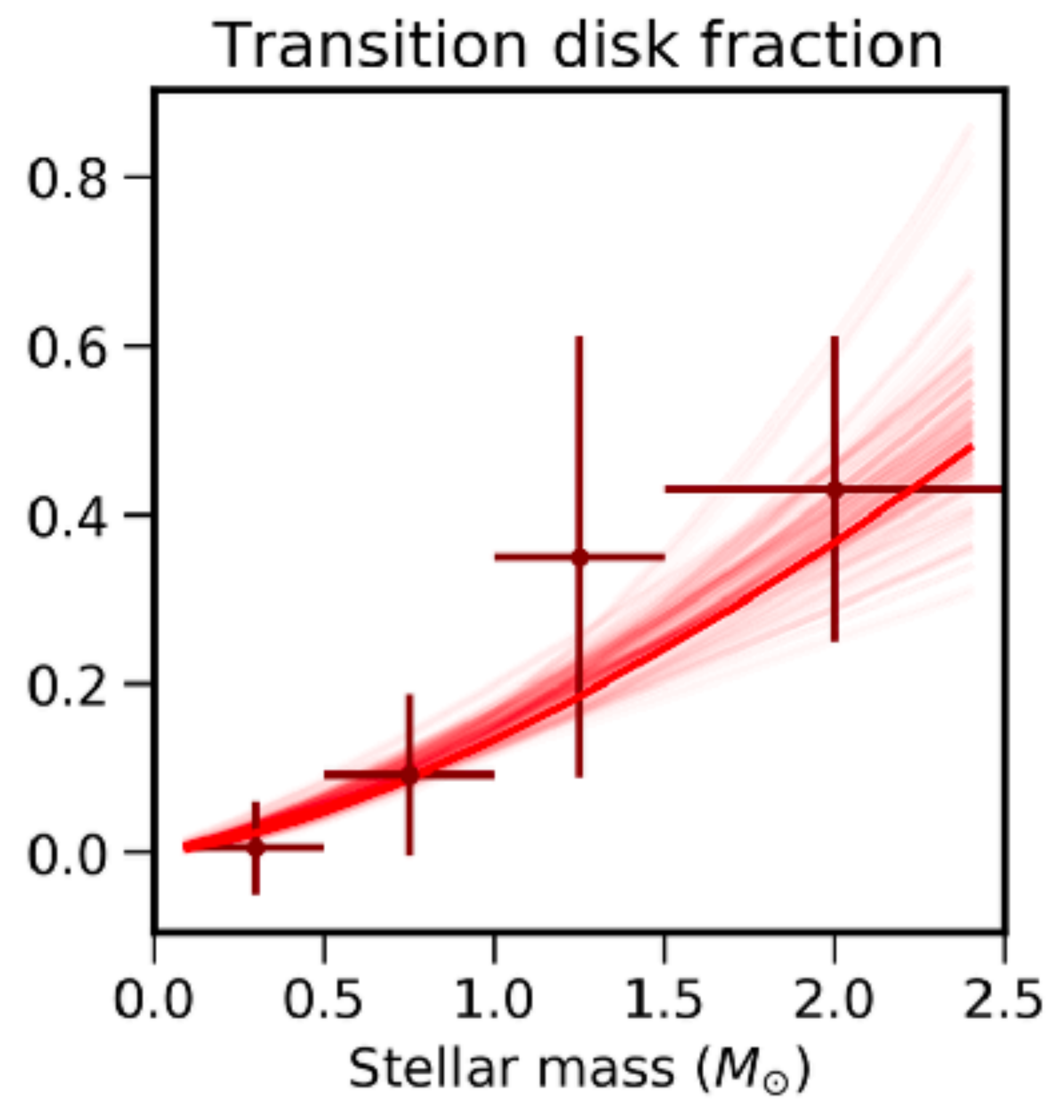
Transition disks with large cavities are more common around higher mass stars, but their overall occurrence does not significantly decrease with age

Van der Marel 2022 (review)

Occurrence rates gapped disks

In this study: extended disks >40 au at low-resolution are assumed to have large scale gaps, considering Long et al. 2019



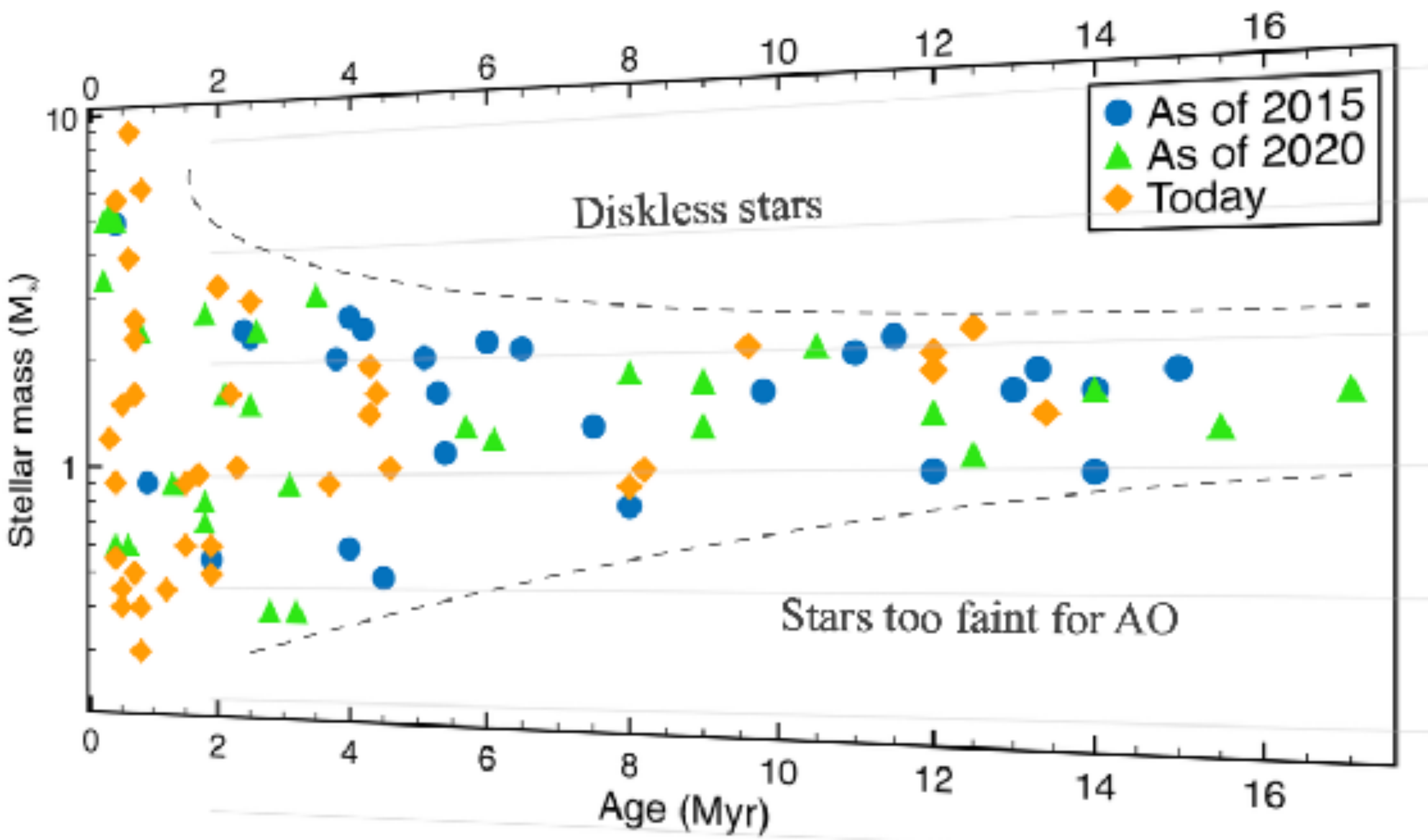


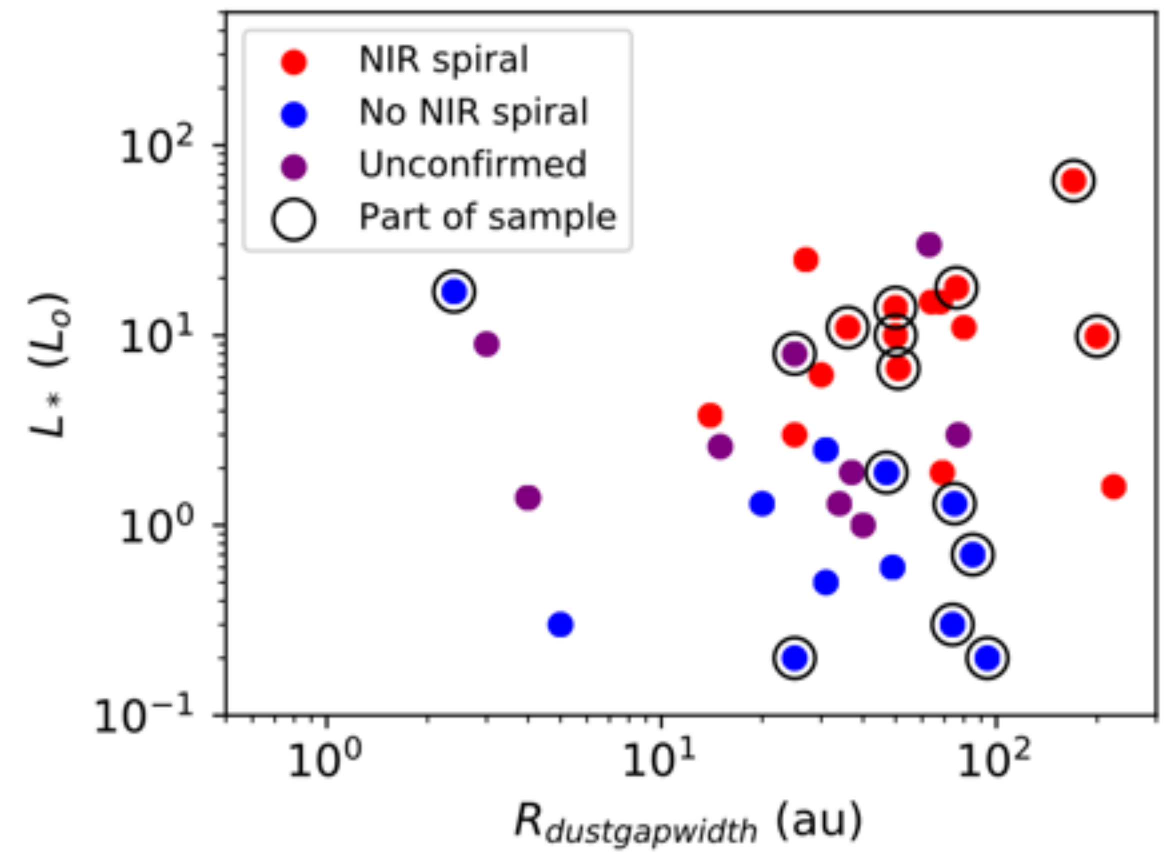
Clear stellar mass dependence in both transition disks and ring disks

Van der Marel & Mulders 2021

What about spirals in NIR?

Strong bias in detectability due to AO requirement: only bright optical stars targeted: *<u>incomplete</u>* sample, but decent coverage of parameter space of stellar mass and age





Spirals are most commonly detected in disks with wide gaps and a high luminosity: possibly related to detectability?

Benisty et al. 2022 (PPVII)
van der Marel et al. 2021a

Summary

- Substructures are often detected in bright disks, but resolution-dependent
- Gaps can be related to planets, but also various other phenomena
- Spirals are seen in various wavelength and their exact origin remains debated.

Questions?

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