ALMA observations of protoplanetary disks: I

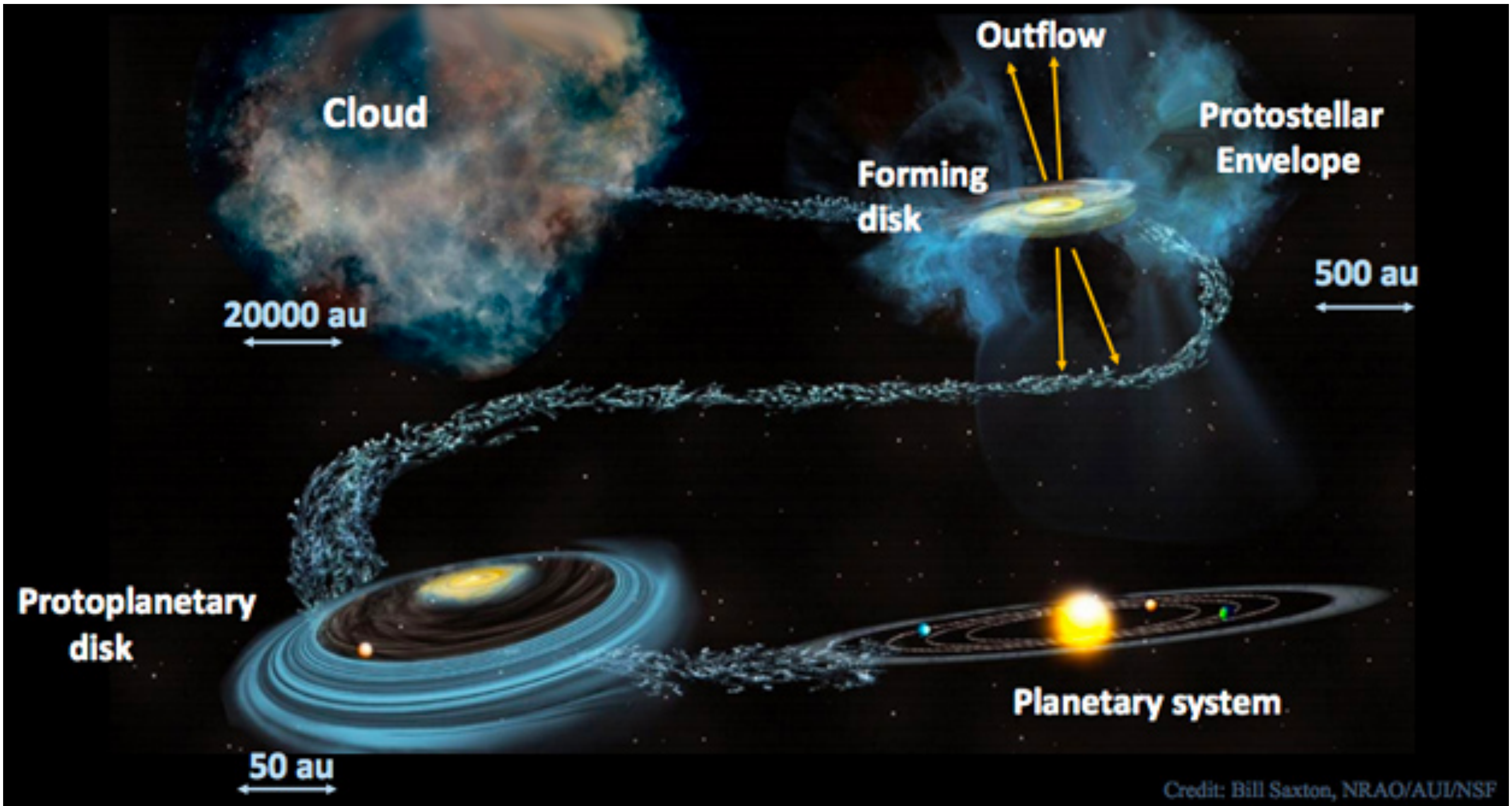
Dustbusters school 2024

Nienke van der Marel
Leiden Observatory
January 22nd

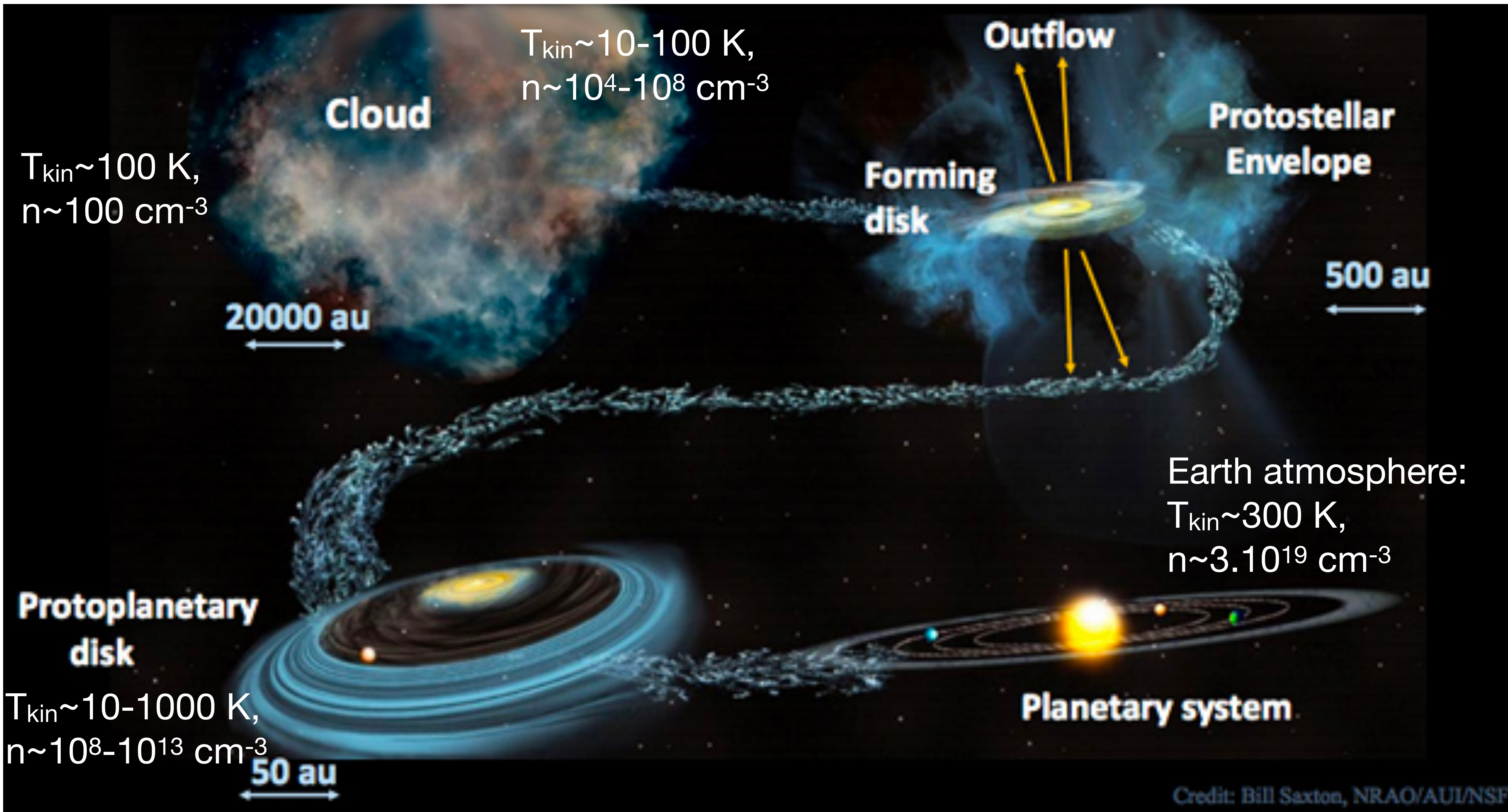
Sterrewacht Leiden

Protoplanetary disks

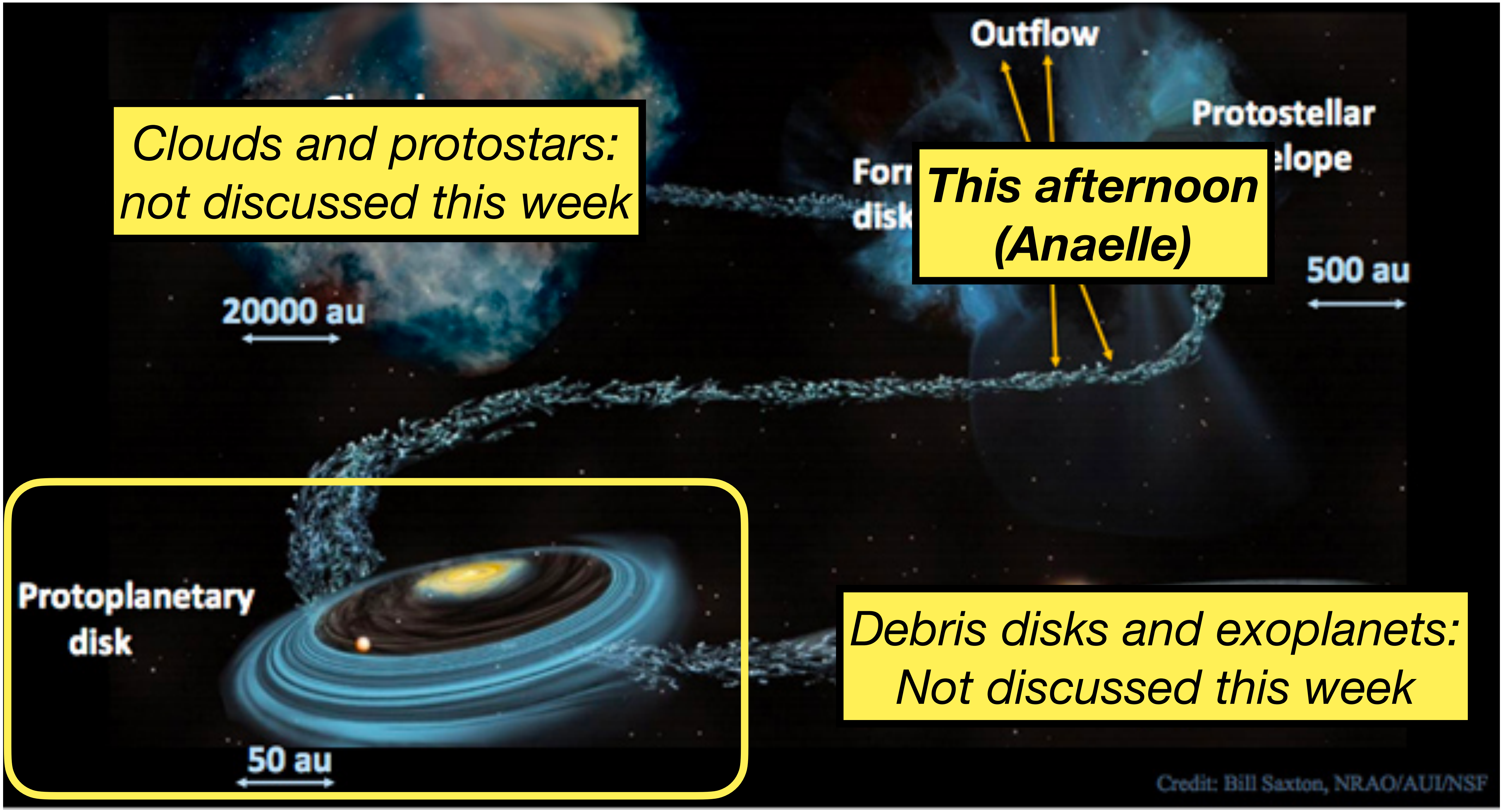
Protoplanetary disks



Conditions


Tkin~10-100 K,
n~10^4-10^8 cm^-3
Cloud
Outflow
Protostellar
Envelope
Tkin~100 K,
n~100 cm^-3
Forming
disk
500 au
20000 au
Earth atmosphere:
Tkin~300 K,
n~3.10^19 cm^-3
Protoplanetary
disk
Tkin~10-1000 K,
n~10^8-10^13 cm^-3
50 au
Planetary system
Credit: Bill Saxton, NRAO/AUI/NSF

Protoplanetary disks



Contents today (‘dust’)

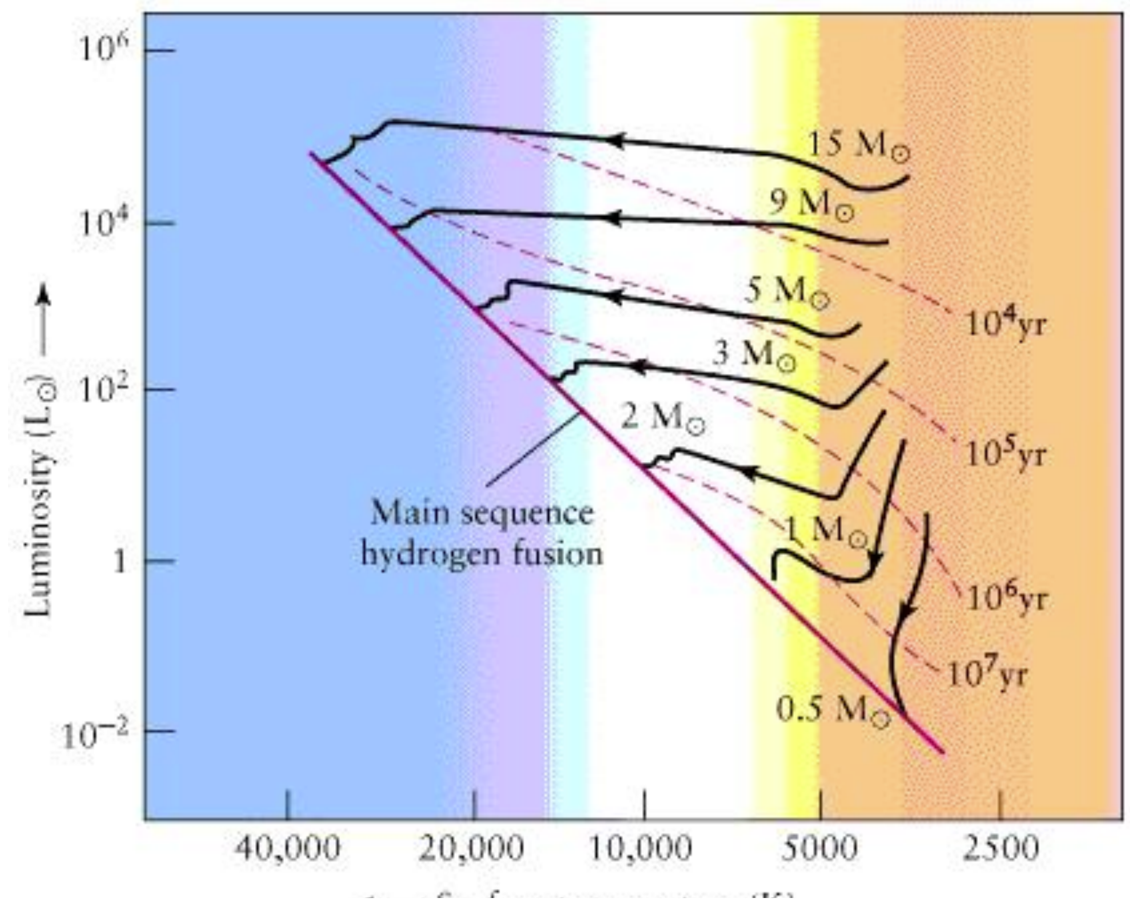
1. Brief history of disk observations
2. Pre-ALMA interferometers
3. Disk dust structure
4. Dust mass
5. Trends
6. Dust substructures
7. Multi-wavelength analysis
8. Polarisation
9. Interferometric imaging and visibility curves

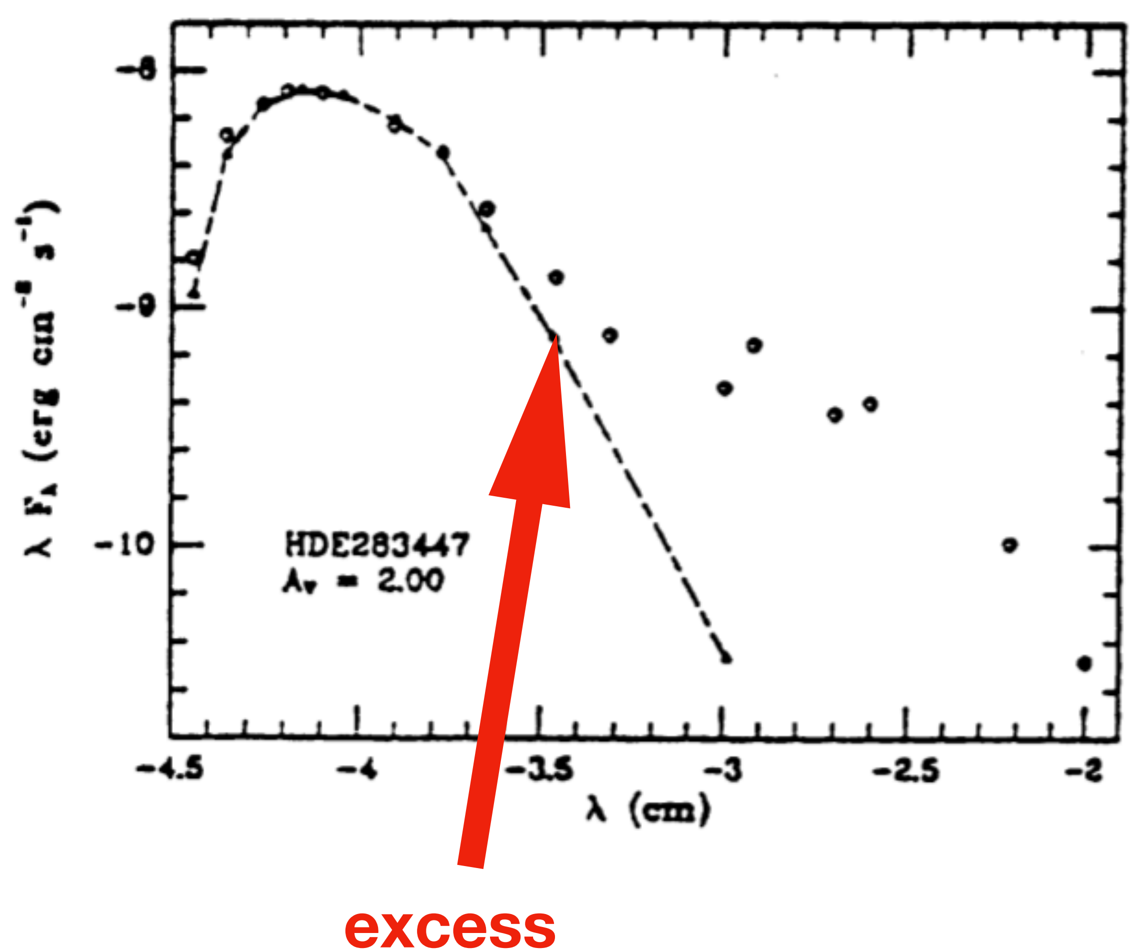
=> tomorrow: gas (molecular line emission and chemistry)

What (and when) was the first evidence that disks existed?

History of disks

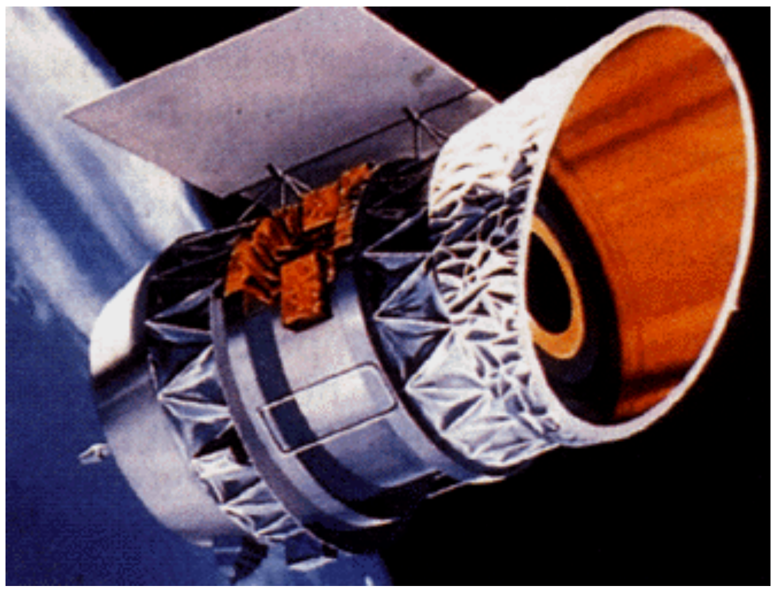
- 1950s: realization existence **young stars**
  - **overluminous** compared to stars of same SpT
  - found in **dark clouds**
  - strong Hα and UV excess: **accretion**
- 1960s-1980s: '**excess emission**' at (near) infrared found in young stars => first evidence of a dusty disk
  - Photometry only, no images: Spectral Energy Distributions (**SED**)
  - Dust continuum only, no lines
- 1980s-2000s: first **infrared (space) telescopes**



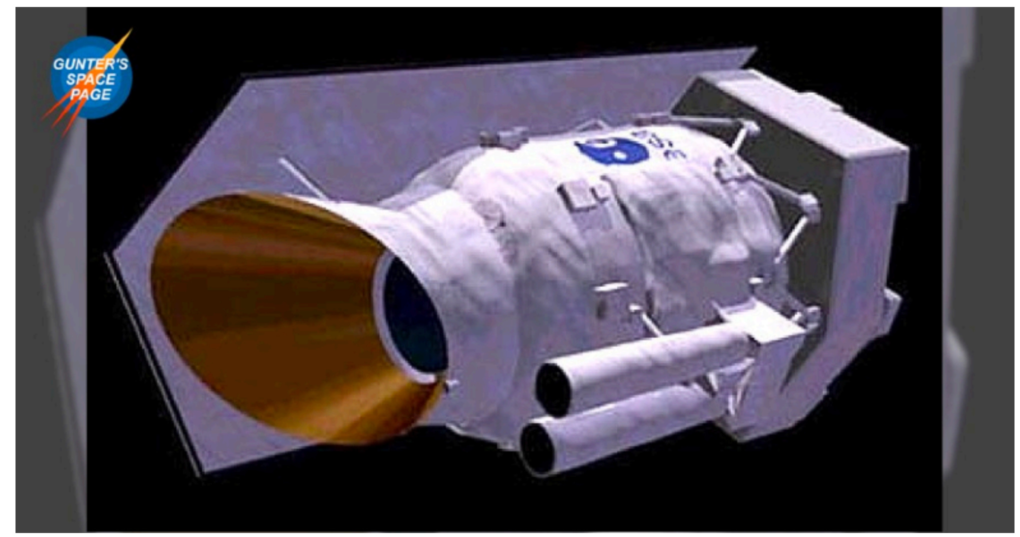


History of disks

IRAS (1983, 57 cm):
12-100 micron

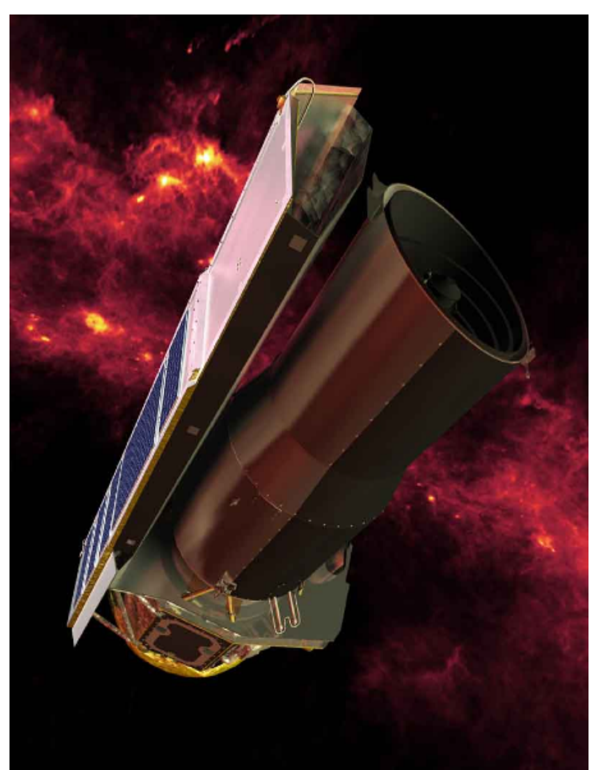


ISO (~1994-1996, 60 cm):
2-200 micron, incl. spectroscopy

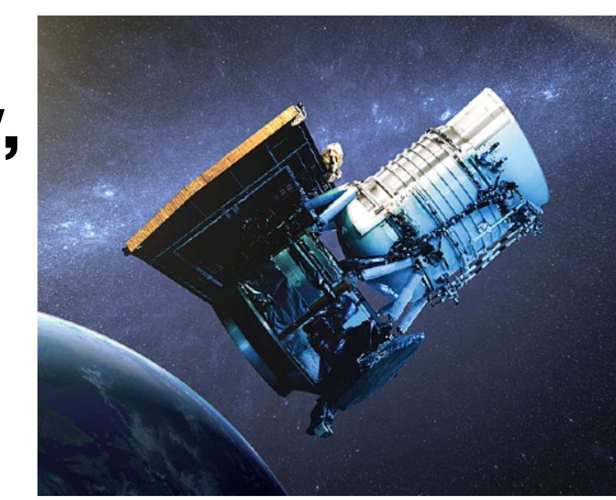


What is the main issue of these early infrared telescopes w.r.t disks?

Spitzer (~2003-2009, 85 cm):
3-70 micron, incl. spectroscopy



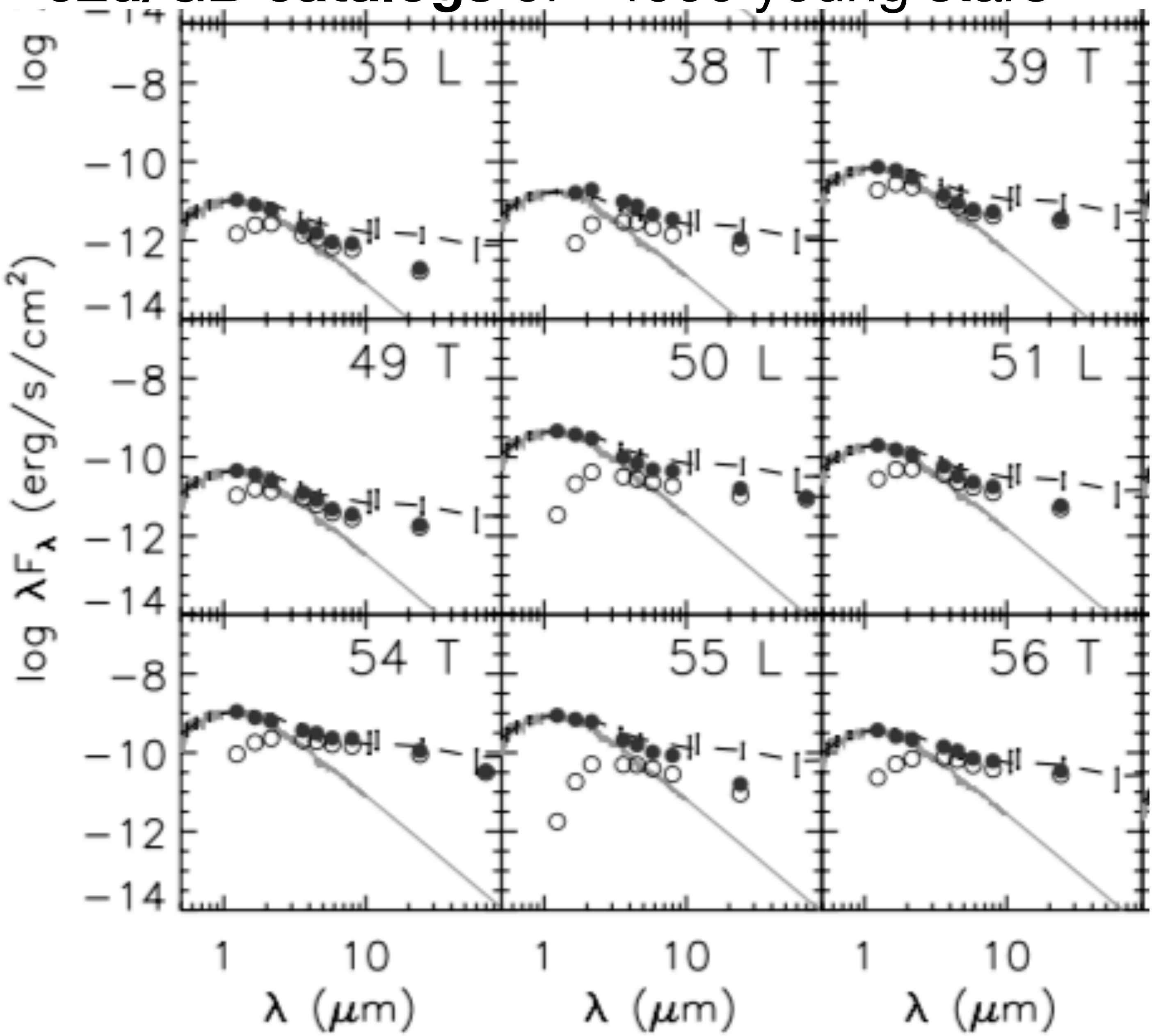
WISE (~2009-now, 40 cm):
2-24 micron,
full-sky mapping

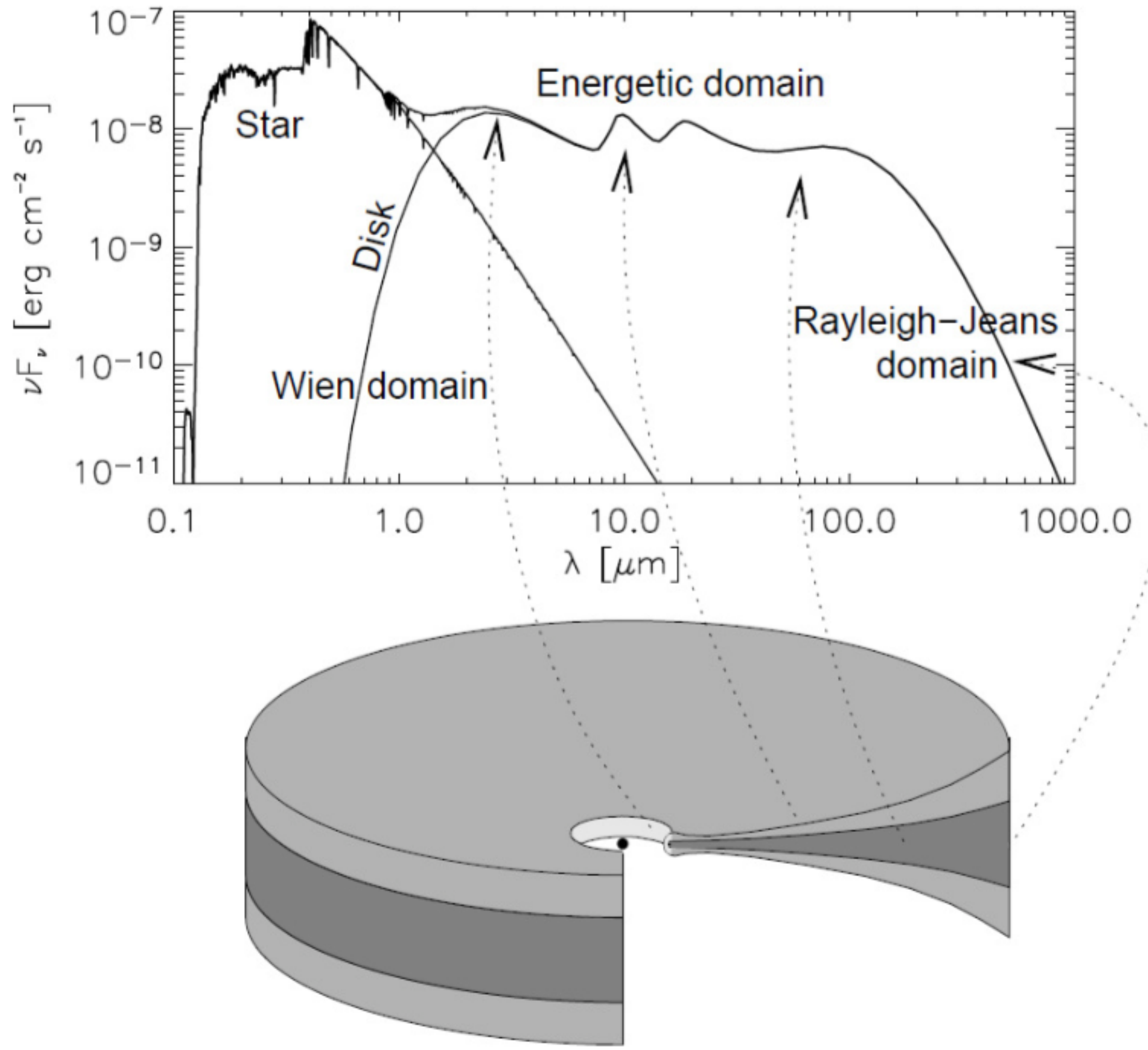


History of disks

SEDs

Construction SED from **photometric points** at multiple wavelengths: Spitzer resulted in **c2d/GB catalogs** of ~4000 young stars

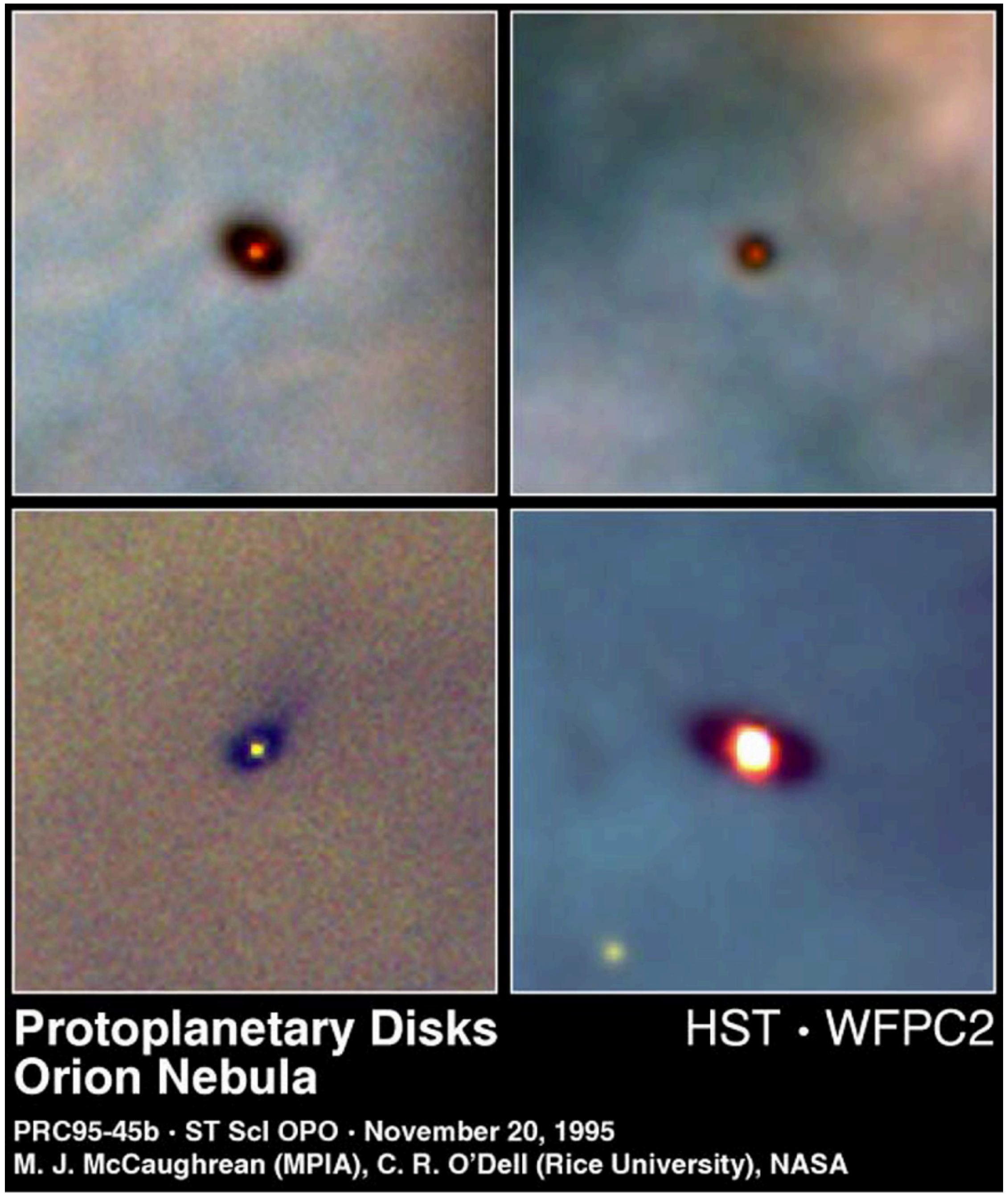




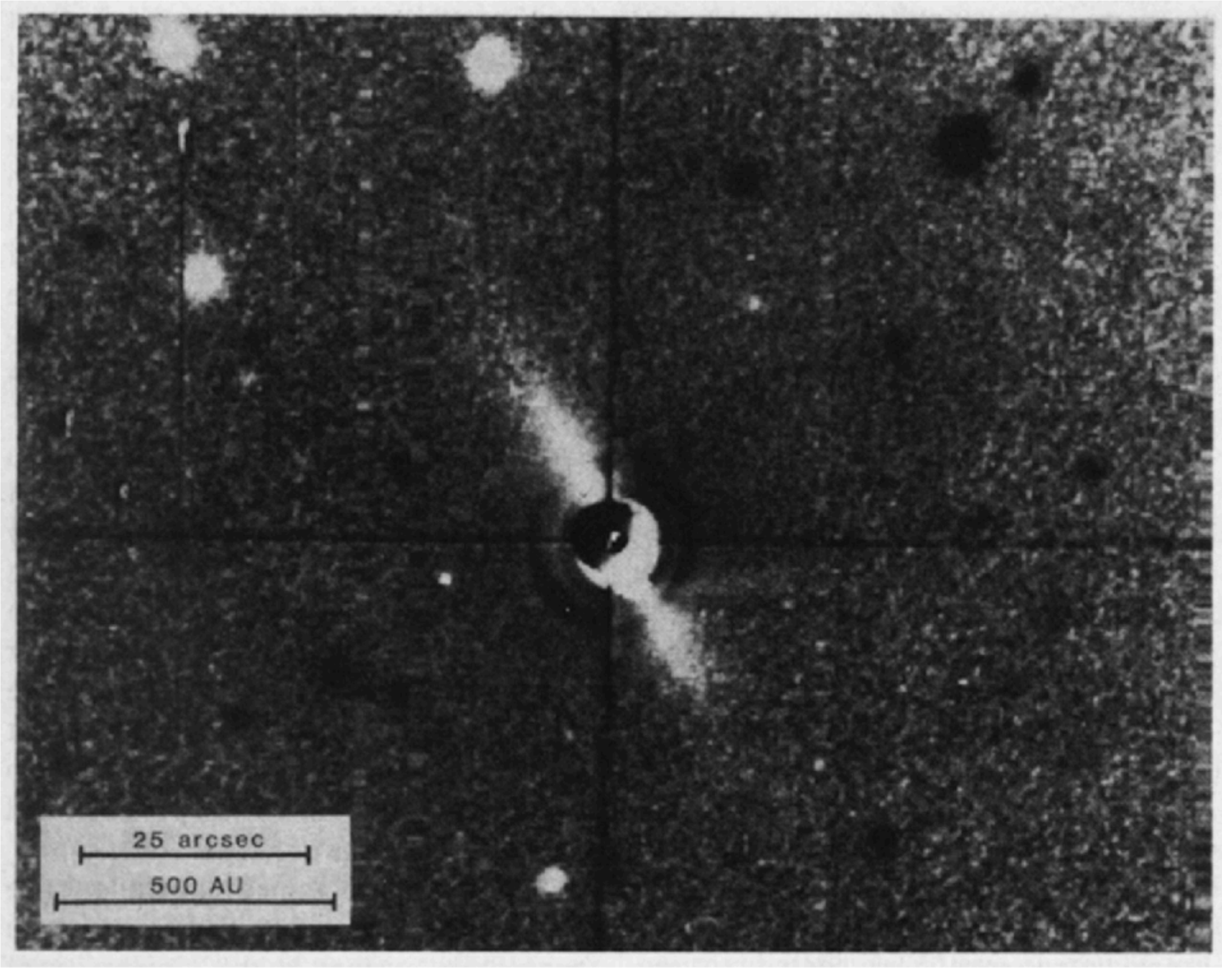
Superposition of **blackbodies** (dust): SED provides some information on disk **dust structure**

First disk images

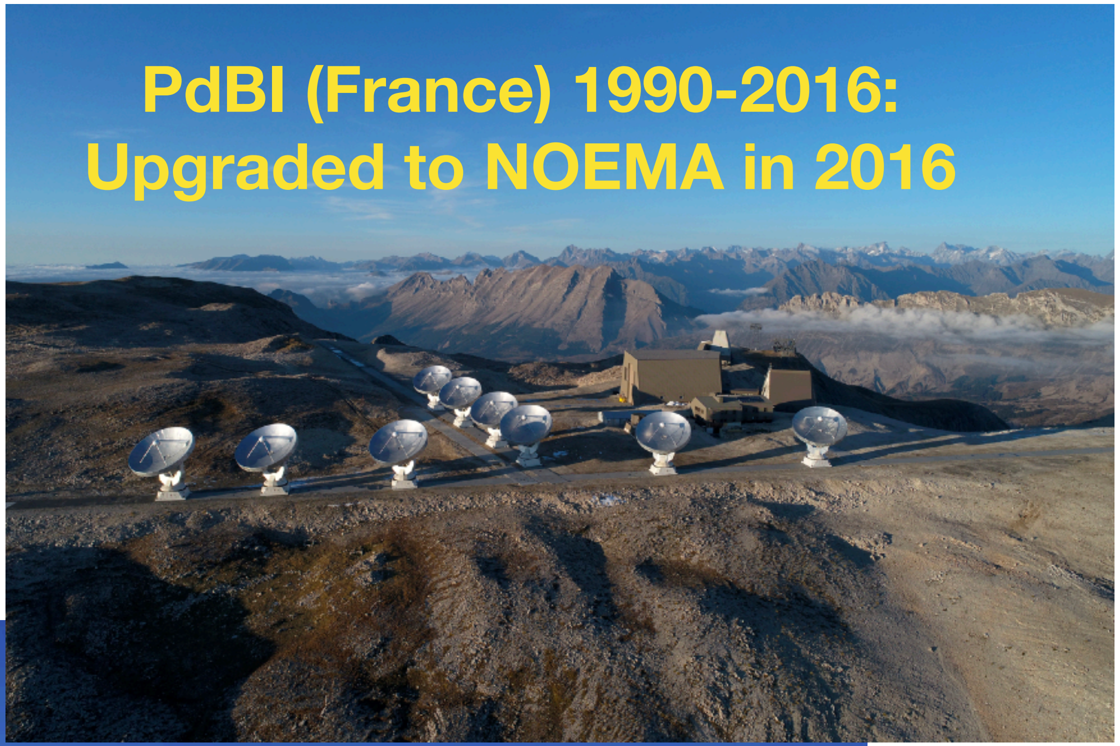
1995: 'proplyds' seen with Hubble in Orion



1984: Beta pic (debris disk) in optical scattered light: edge-on

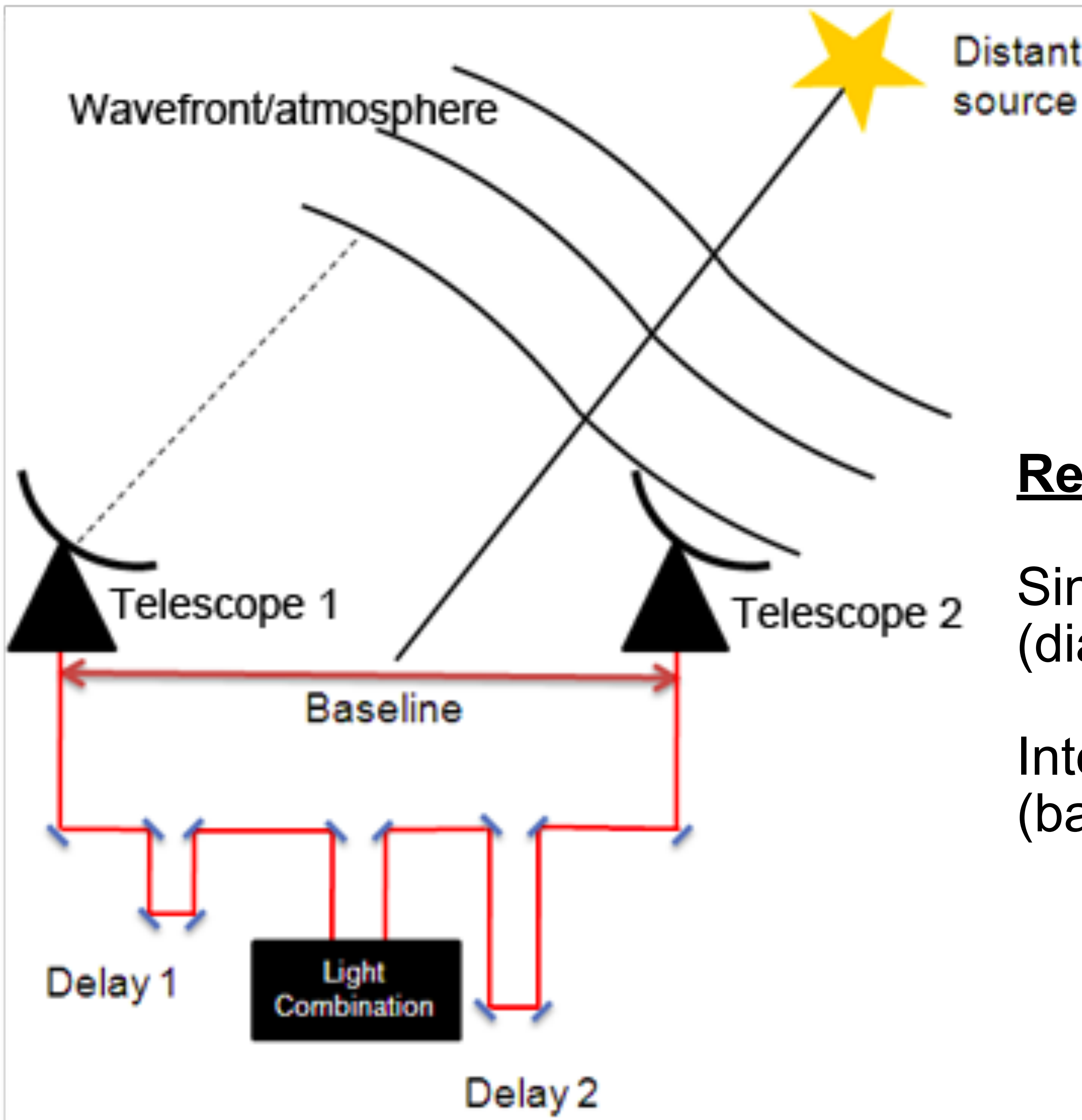


A new era of disk imaging: millimeter interferometry



How does interferometry give higher resolution?

Interferometry



Resolution:

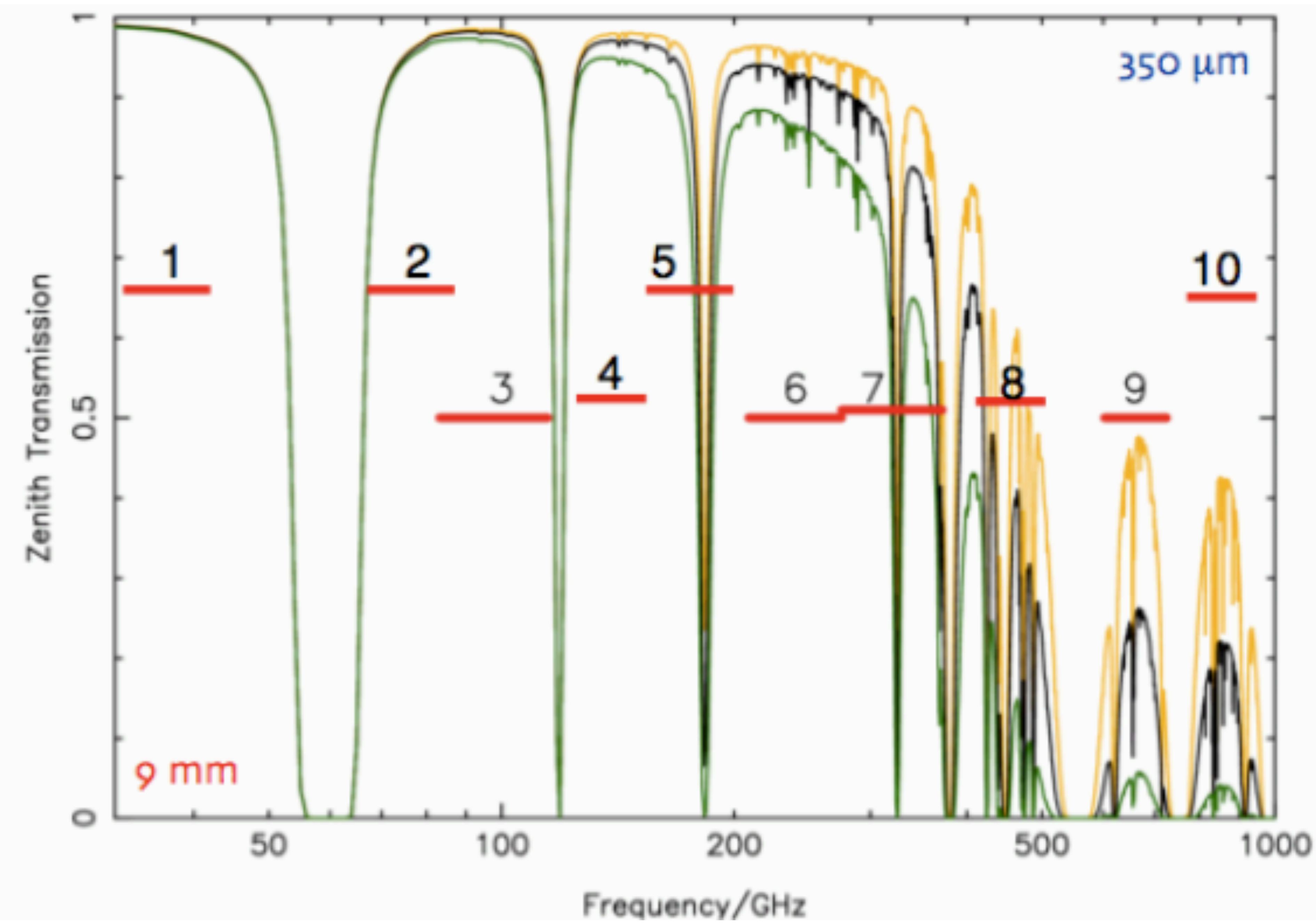
Single dish: (diameter) $R \sim \lambda/D$

Interferometer (baseline length) $R \sim \lambda/B$

At 1mm:
B~500 m: R~0.4"
B~10 km: R~0.02"

ALMA

ALMA
Observing bands



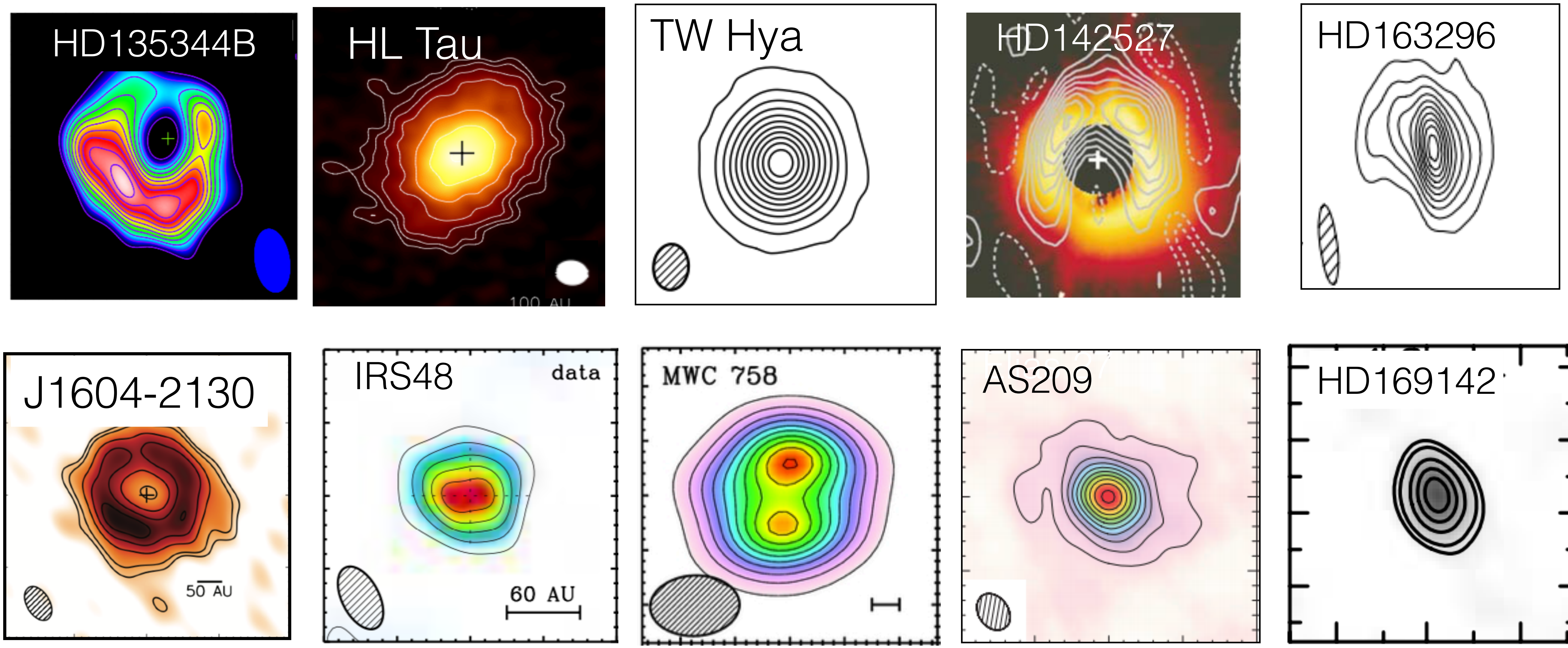
Most commonly used for disk dust imaging with ALMA:

- **<u>Band 6</u>**
  = 230 GHz = 1.3mm
- **<u>Band 7</u>**
  = 345 GHz = 0.85mm

- **Band 9 (0.45mm):**
  optically thick

- **Band 4 (2mm), Band 3 (3mm):**
  fainter emission

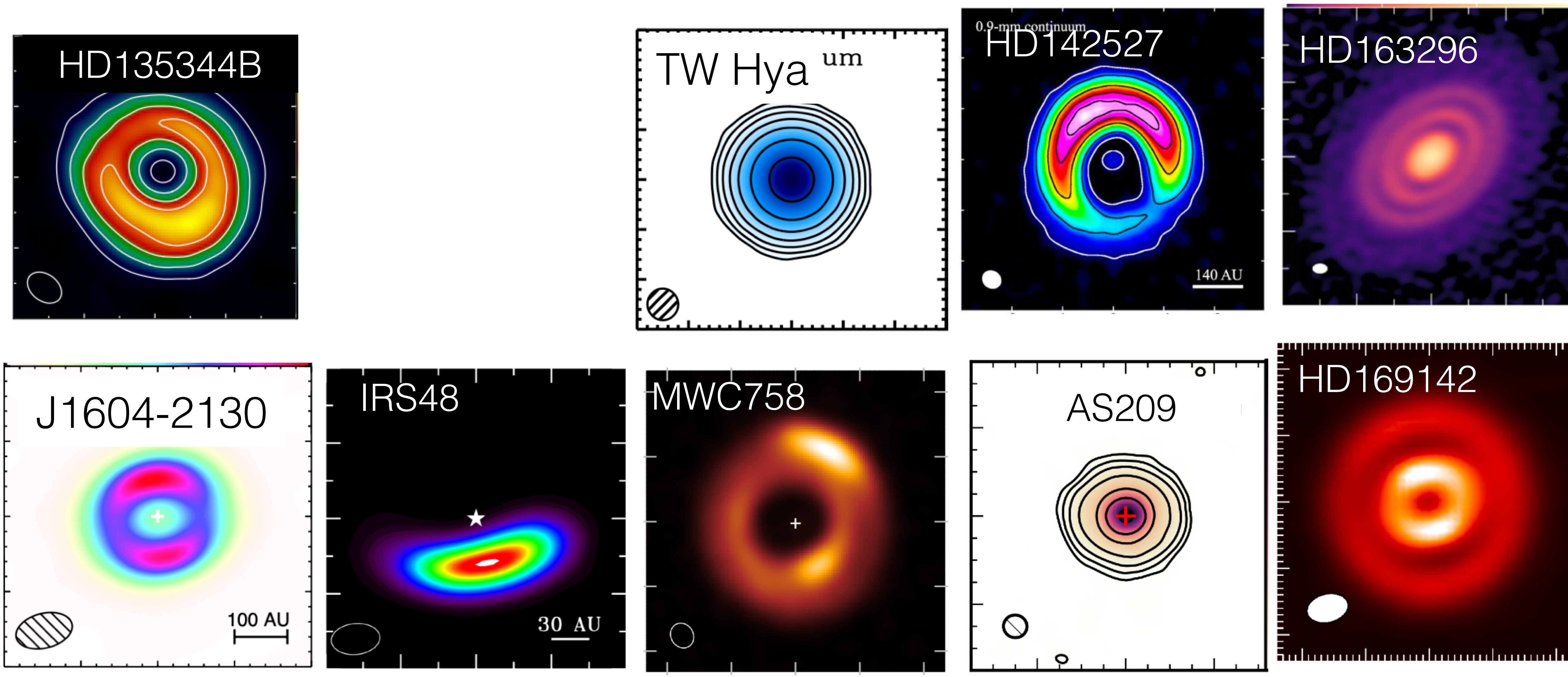
Revolution of ALMA (pre-ALMA)



Typical resolution ~0.5-0.8”

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

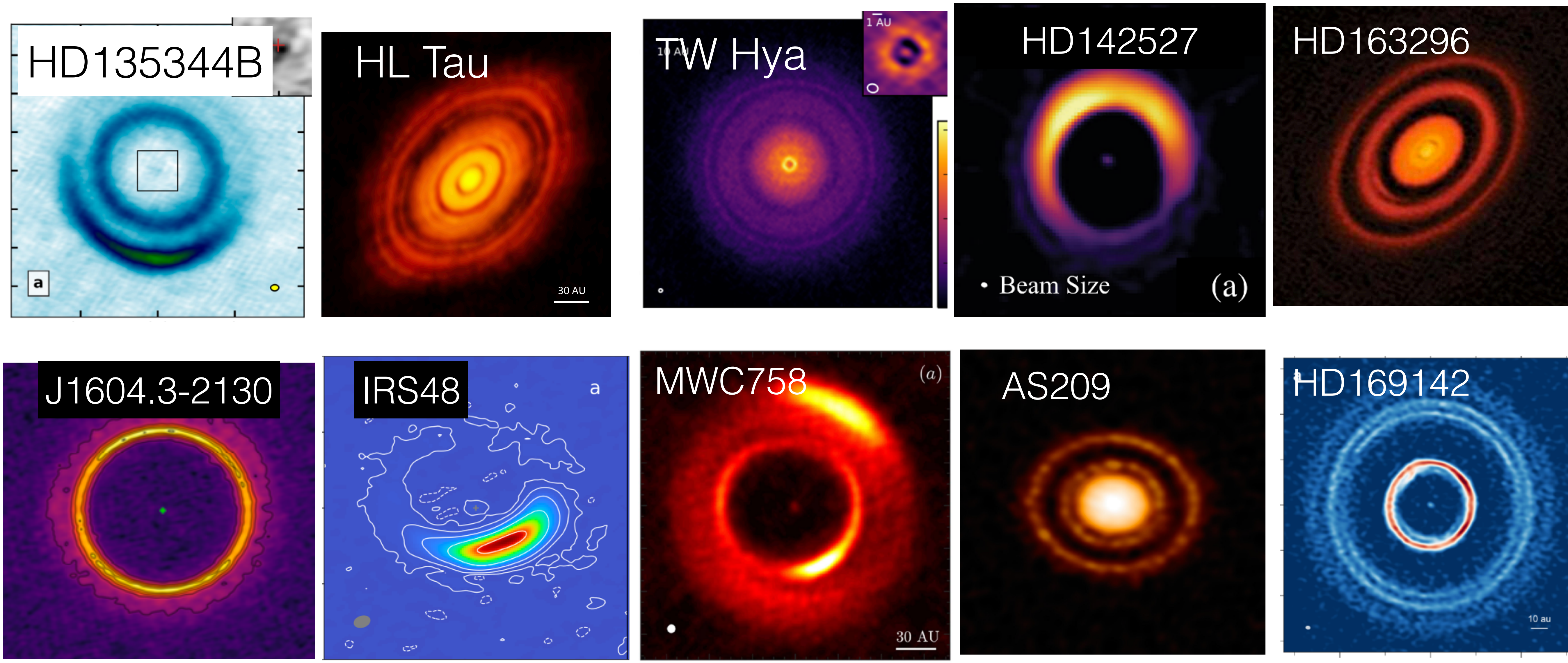
Revolution of ALMA (Early Science)



Typical resolution ~0.3-0.5"

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

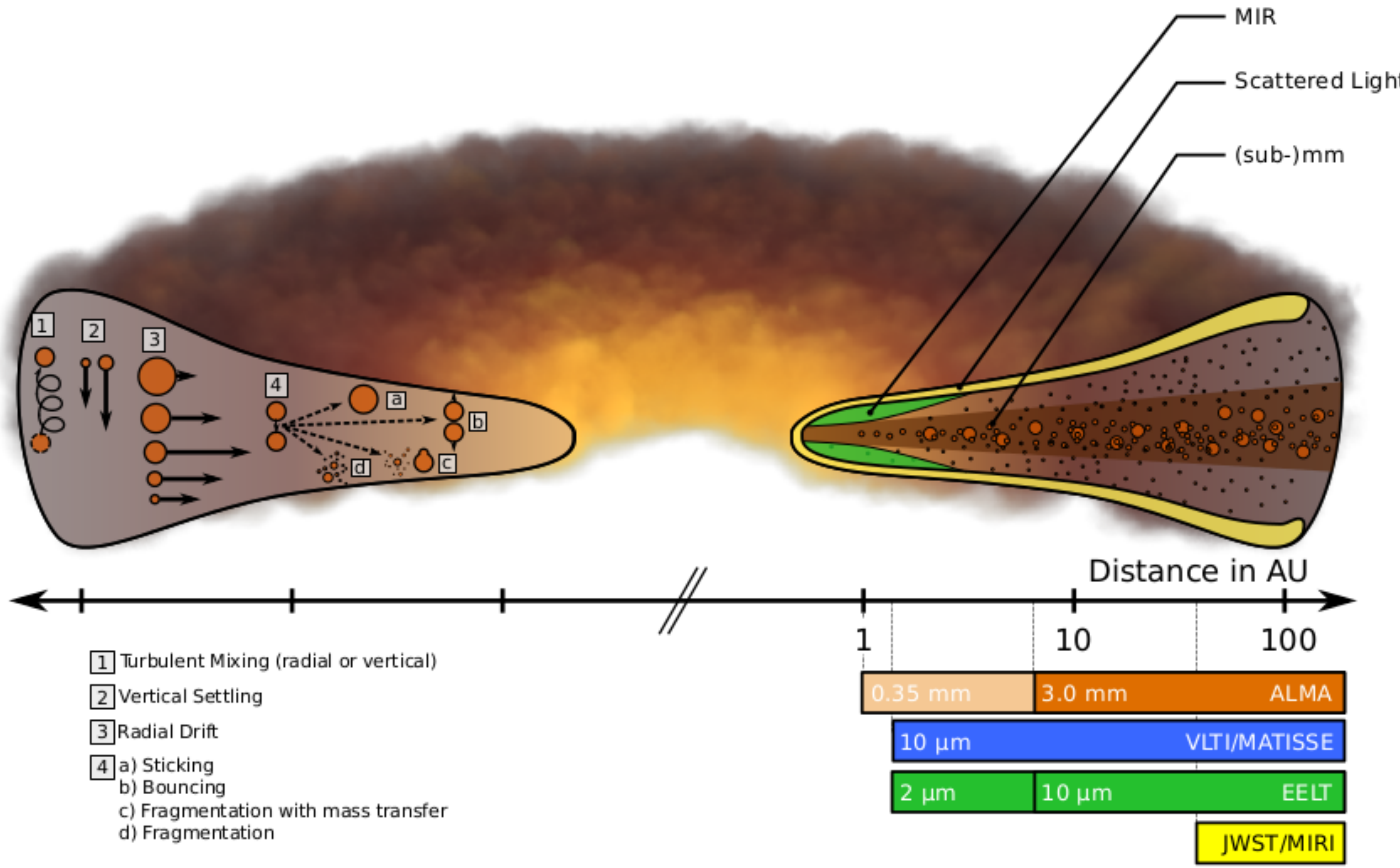
Revolution of ALMA (long baseline)



Typical resolution ~0.05-0.1"

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

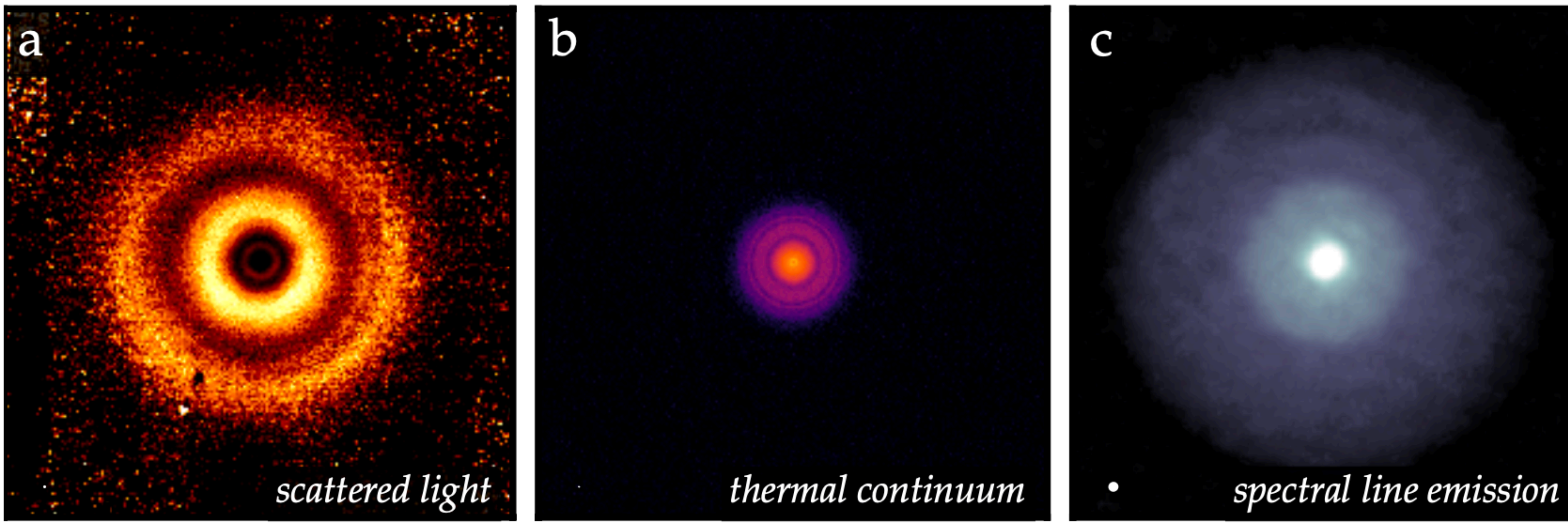
Disk dust structure



Dust structure disk: ISM ratio gas/dust = 100/1

Testi et al. 2014

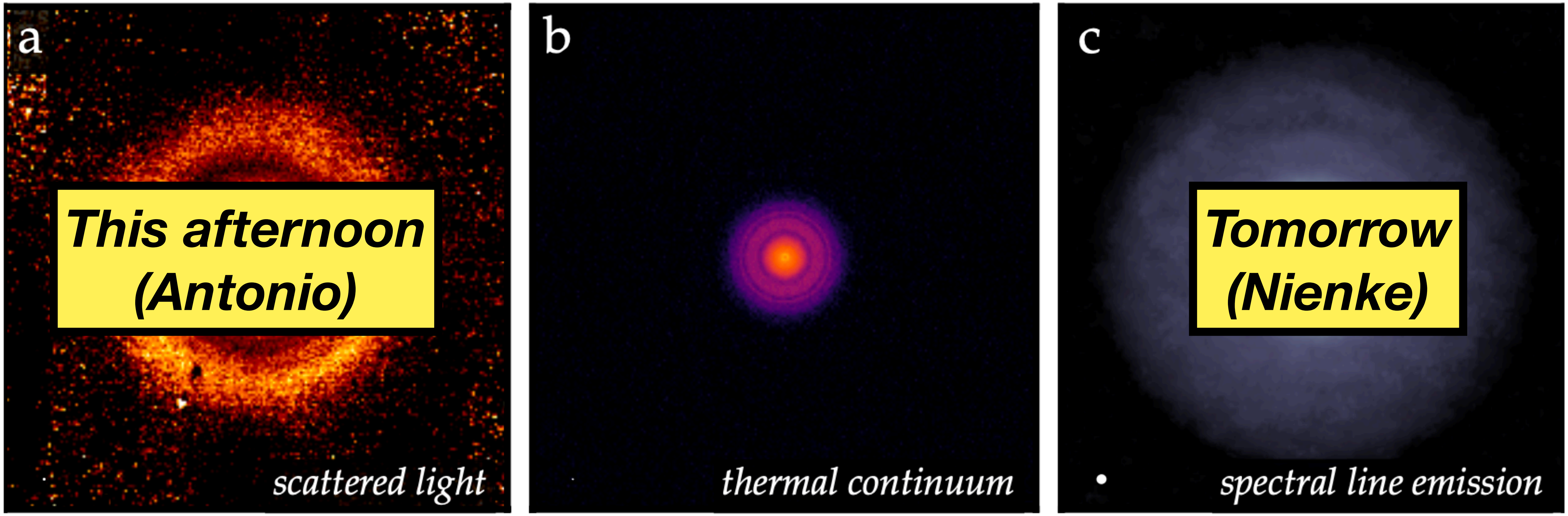
Disk dust structure



Gas and millimeter dust show very different distributions, and gas is the bulk component of the disk

Andrews 2020

Disk dust structure

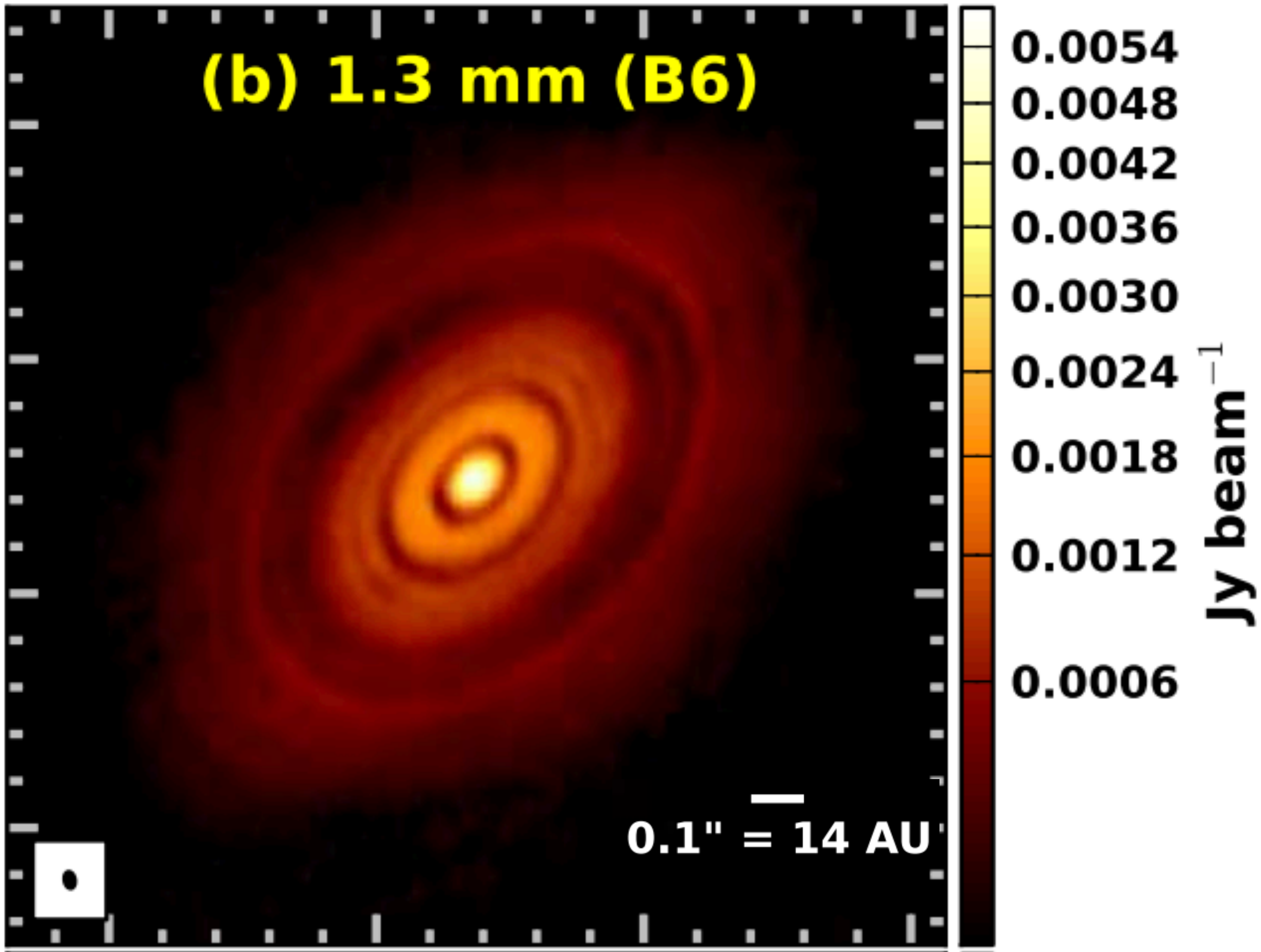


**Gas and millimeter dust show very different distributions,
and gas is the bulk component of the disk**

Andrews 2020

Disk dust structure

HL Tau:
Distance = 147 pc (Gaia DR3)
SpT = K5
Teff = 4400 K
Stellar mass = 1.7 M_{sun}
Stellar luminosity = 6 L_{sun}

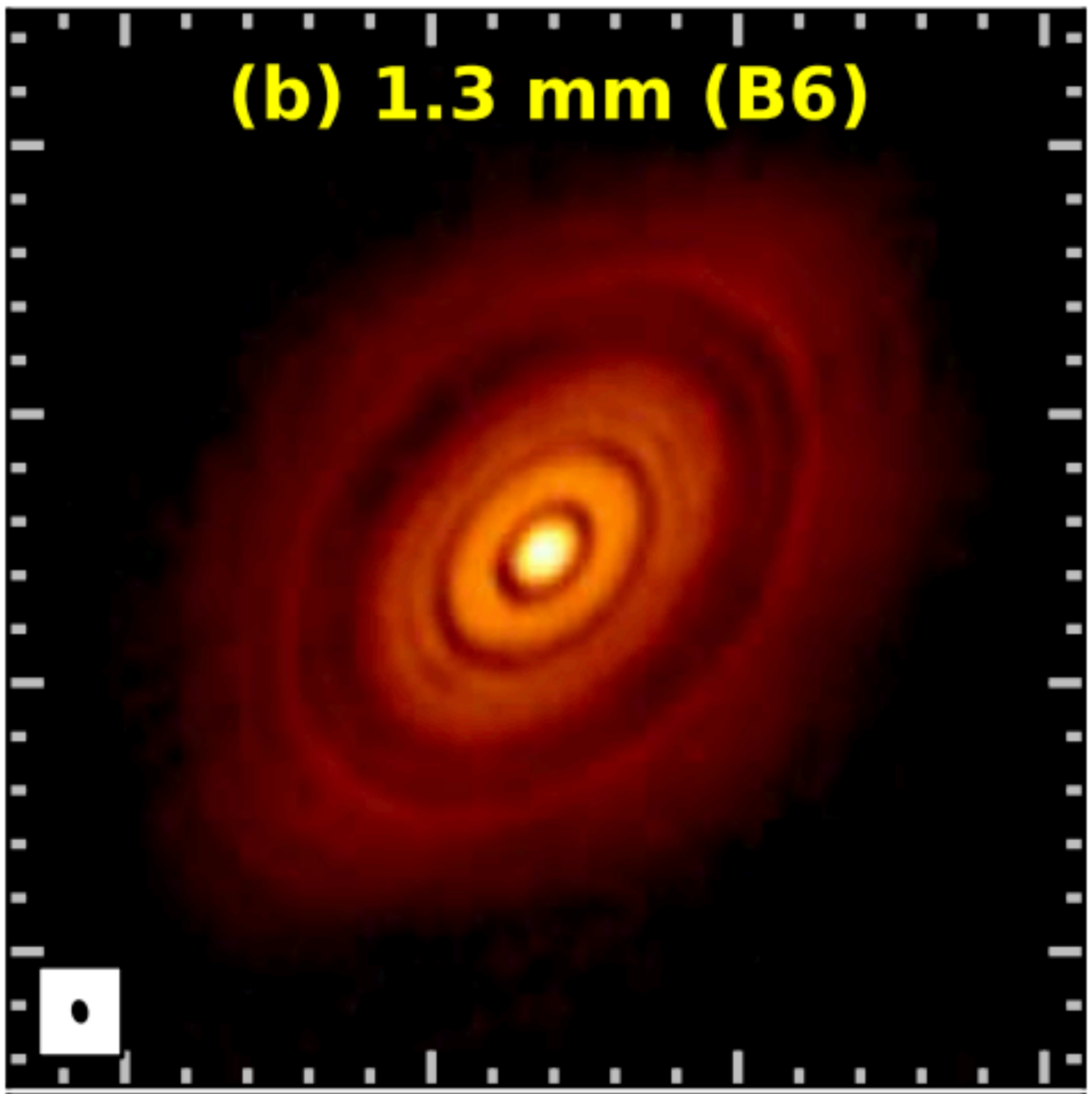


Beam: 0.035x0.022”, PA=11°

Assuming we have the fits file and the stellar properties, what properties can we measure directly in this disk image? And what can we infer?

ALMA consortium et al. 2015
Pinte et al. 2016

Disk dust structure



Direct:

1. Image properties
   (Peak flux, rms, total flux)
2. Orientation (position angle, inclination)
3. Disk radius
4. Ring/gap radii and widths

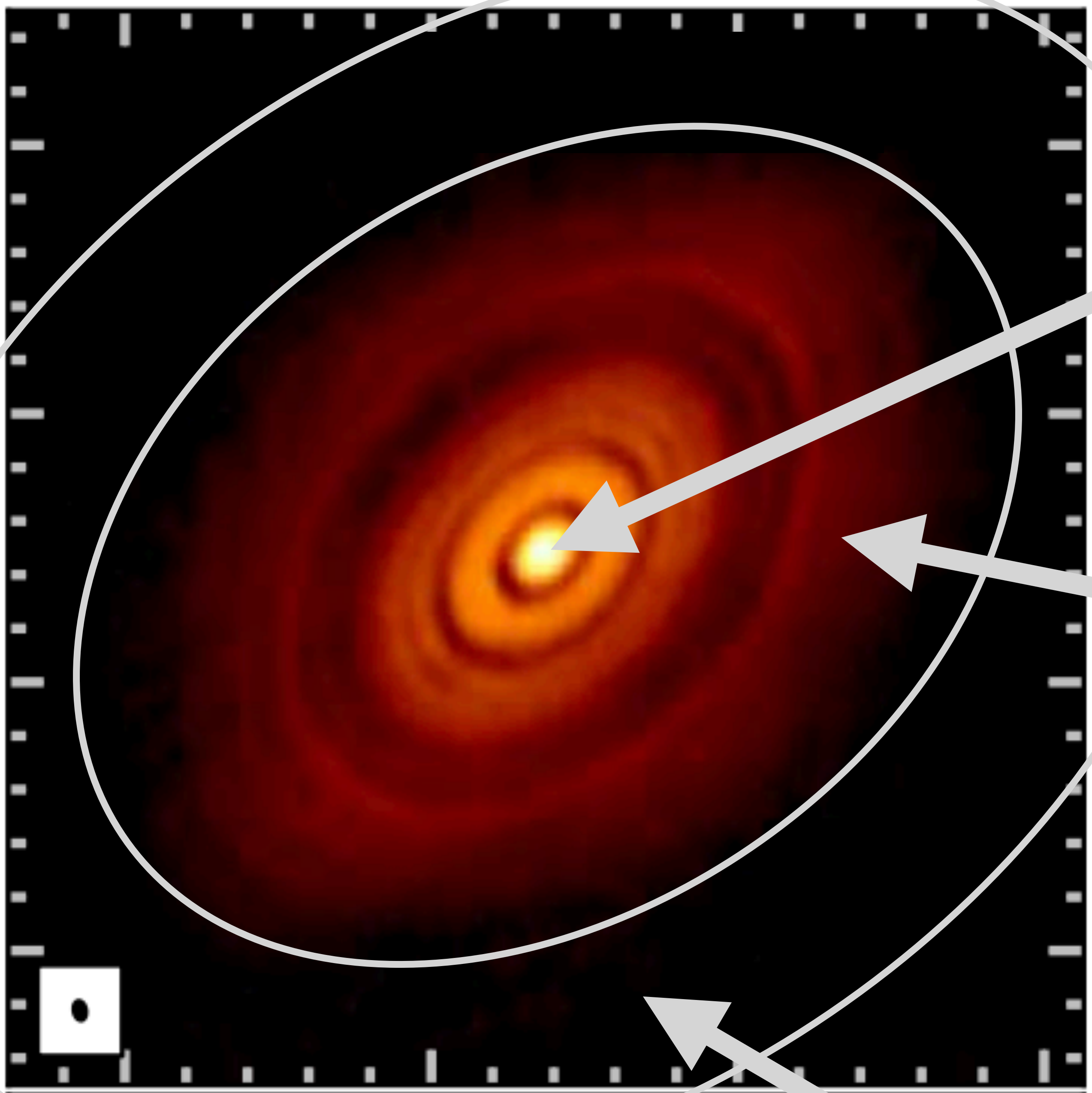
Indirect:

1. Disk dust mass
2. Dust surface density
3. Vertical height (settling)

Disk dust structure

CASA tool:
imstat

Image properties



Peak = maximum value in disk region [mJy/beam]

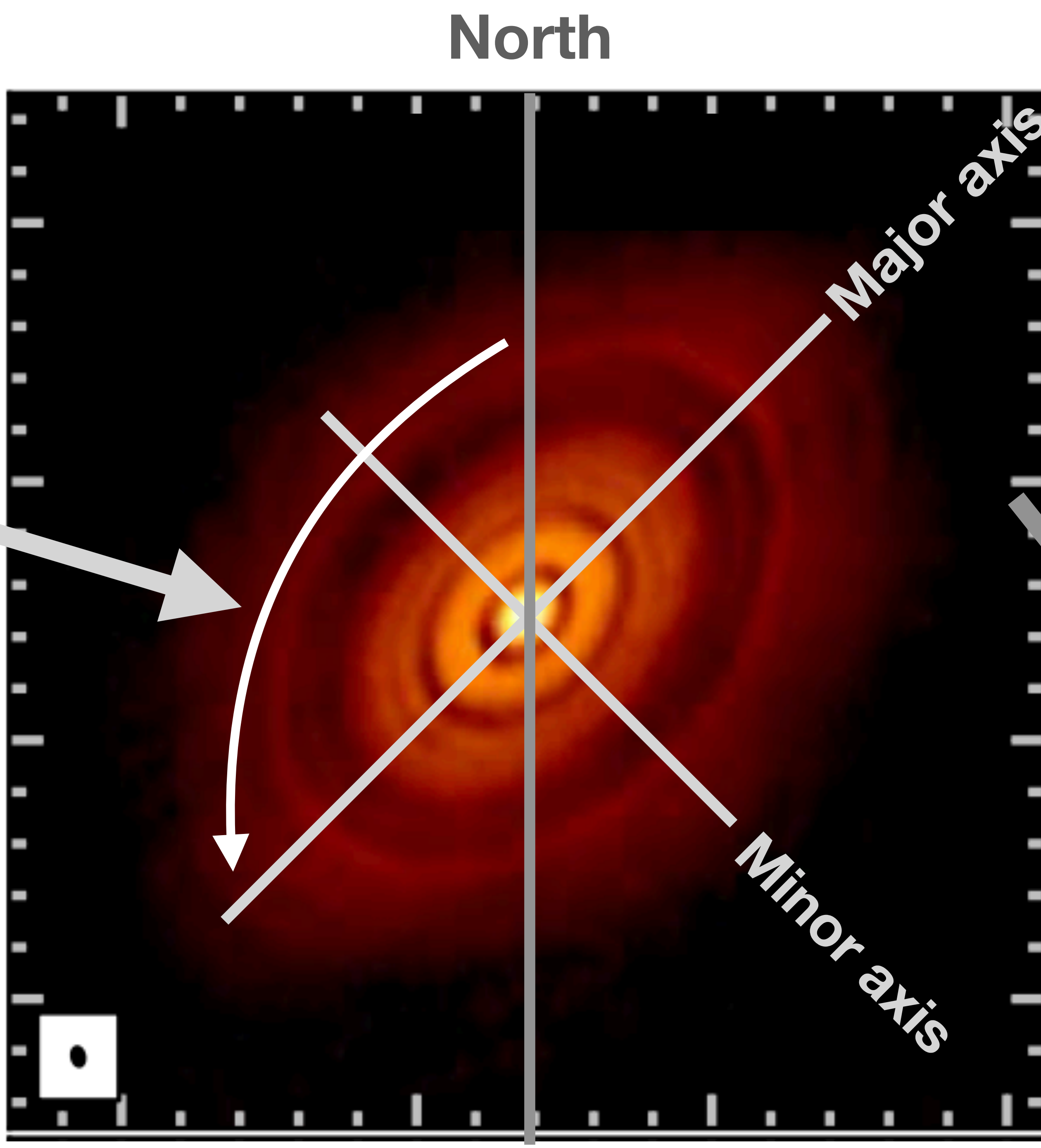
Integrated flux = sum of all values in disk region/#pixels in beam OR sum of all values >3.rms/ #pixels in the beam OR peak (if unresolved) [mJy]

RMS = sqrt(variance) in region around the disk [mJy/beam]

Signal-to-noise ratio (SNR) = peak/RMS

Disk dust structure

Orientation

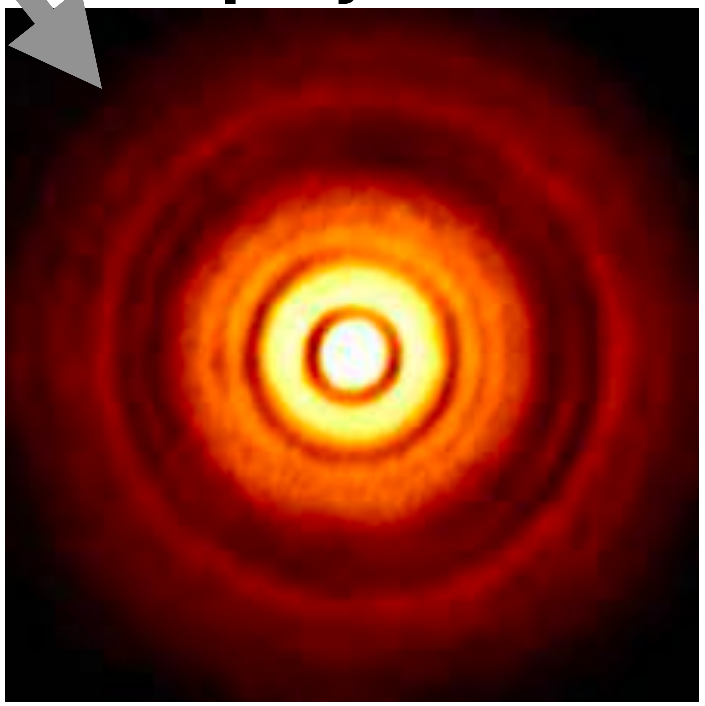


Position angle (PA): major axis measured East-of-North

Inclination (i): cos(i) = minor/major

OR deproject until shape is a circle

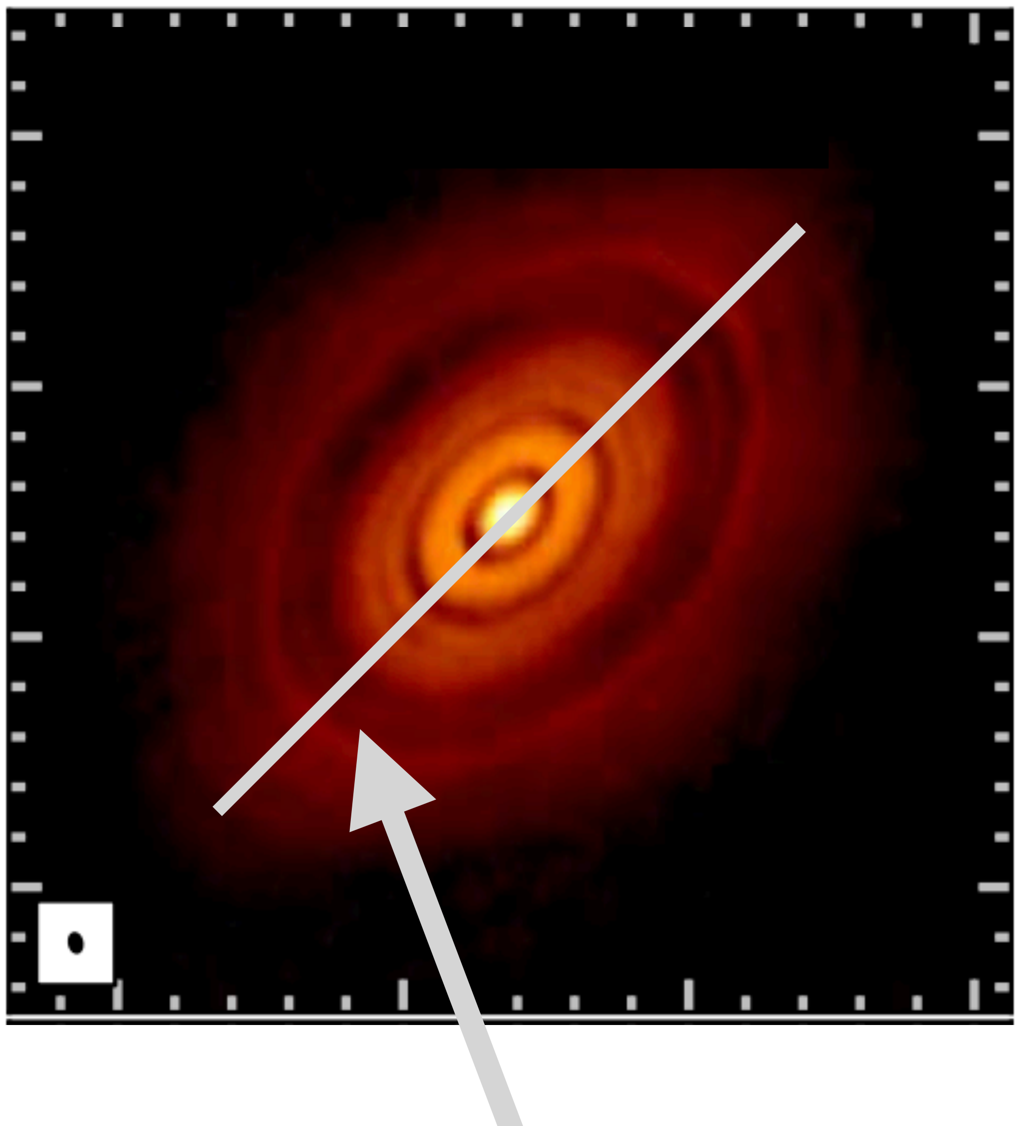
Deprojection



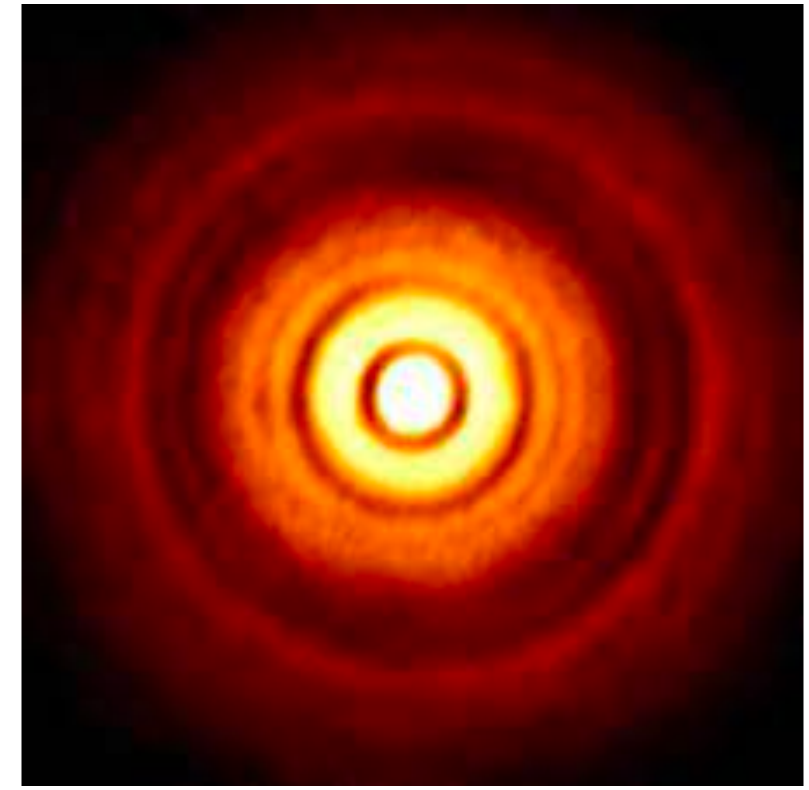
CASA tool: uvmodelfit or imagefit

Disk dust structure

Disk radius

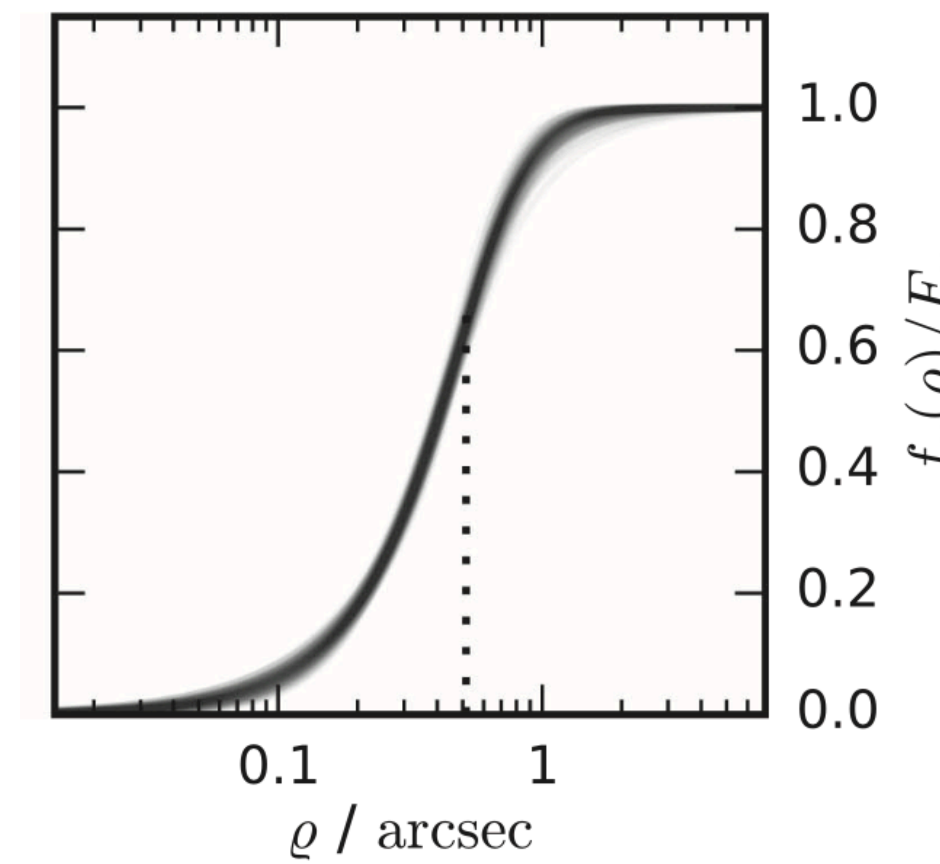


Half of diameter major axis (FWHM of (2D-)Gaussian fit)



Curve of growth:

Measure flux within circular aperture and find radius where flux = 0.68*total flux

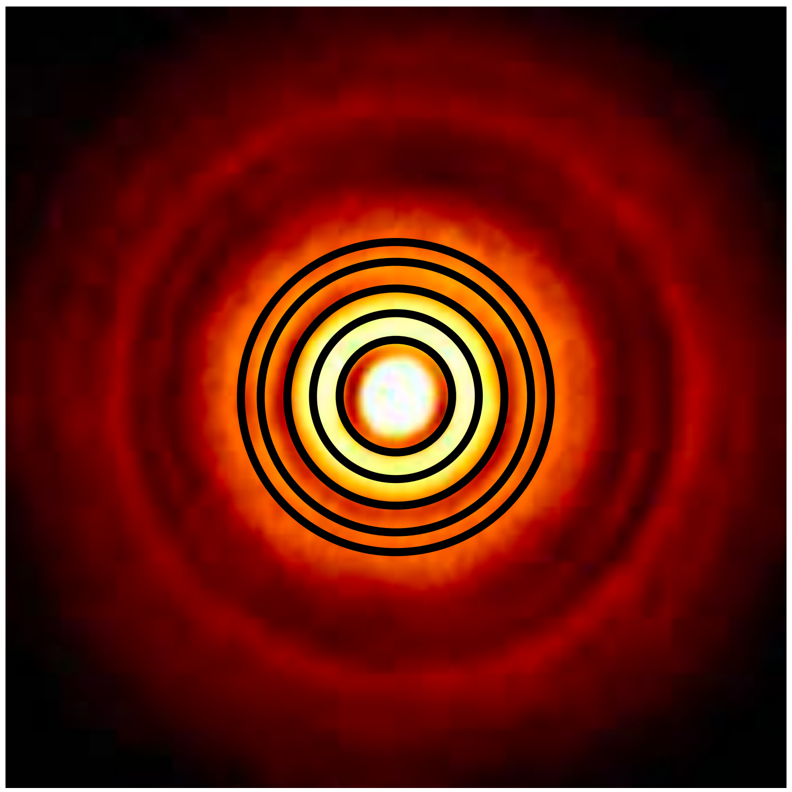


CASA tool: uvmodelfit or imagefit

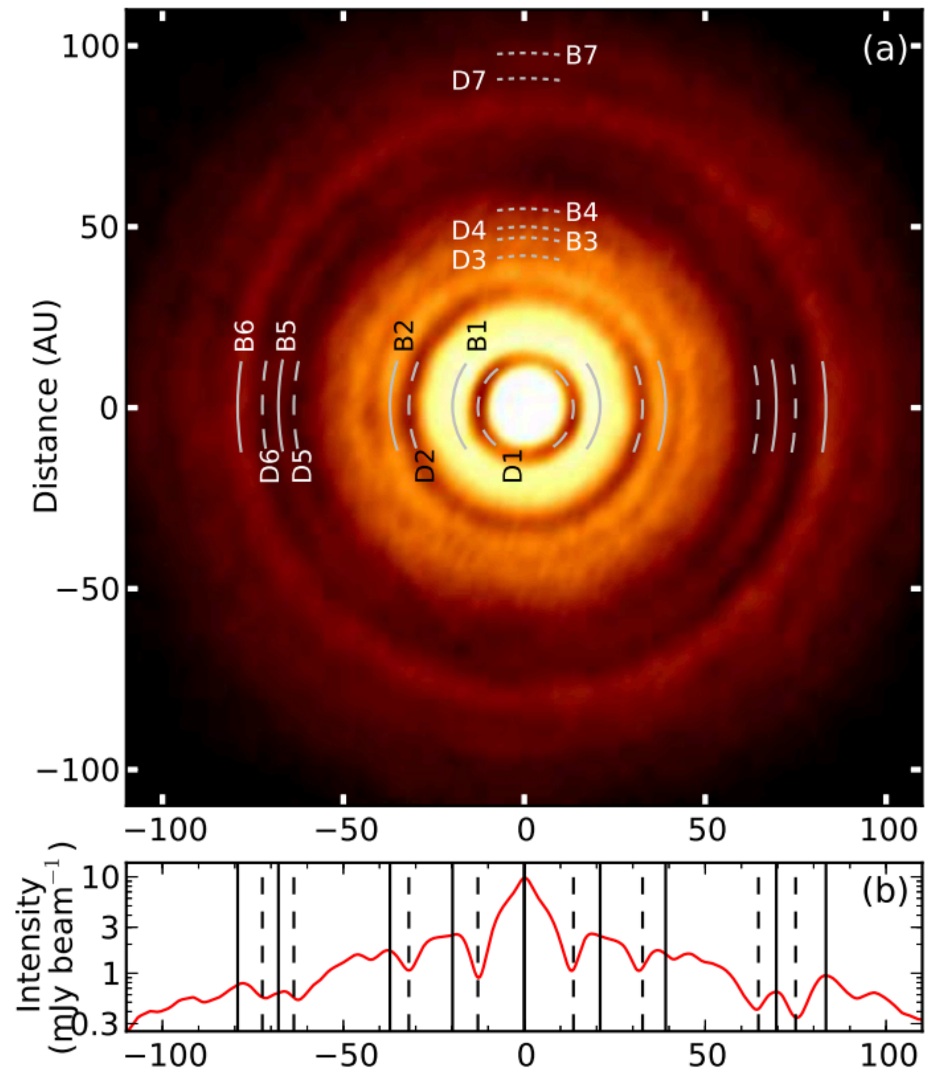
Tripathi et al. 2017

Disk dust structure

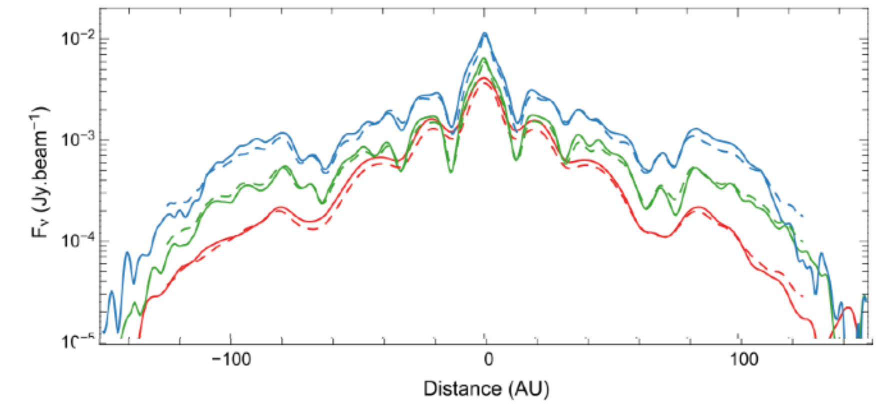
Ring/gap structure



Radial profile: azimuthal average in narrow rings in deprojected image



Find maxima and minima in radial profile (e.g. fitting Gaussians)



Sometimes logarithmic or normalized profiles, or profile starting from zero

ALMA consortium et al. 2015
Pinte et al. 2016

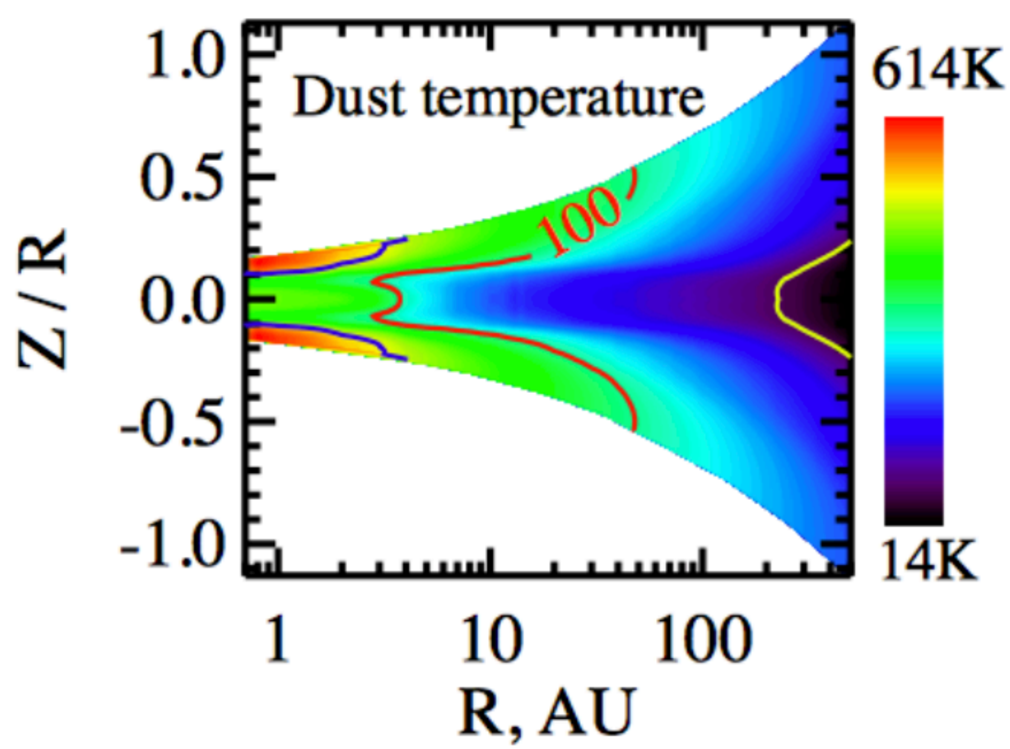
Measure dust mass

Inferred from total flux

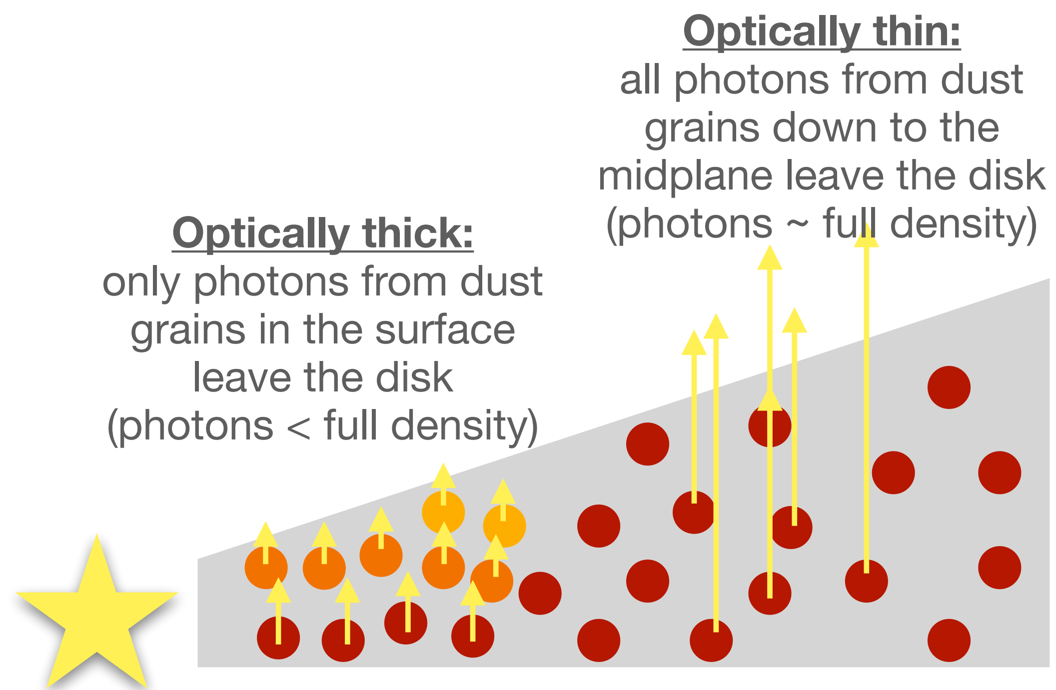
$$M_{dust} = \frac{B_\nu(T = 20K)\kappa_\nu F_\nu}{d^2}$$

Assuming dust emission is optically thin and mostly 20 K

Reality dust temperature:



What is optical depth?



What is origin dust mass equation?

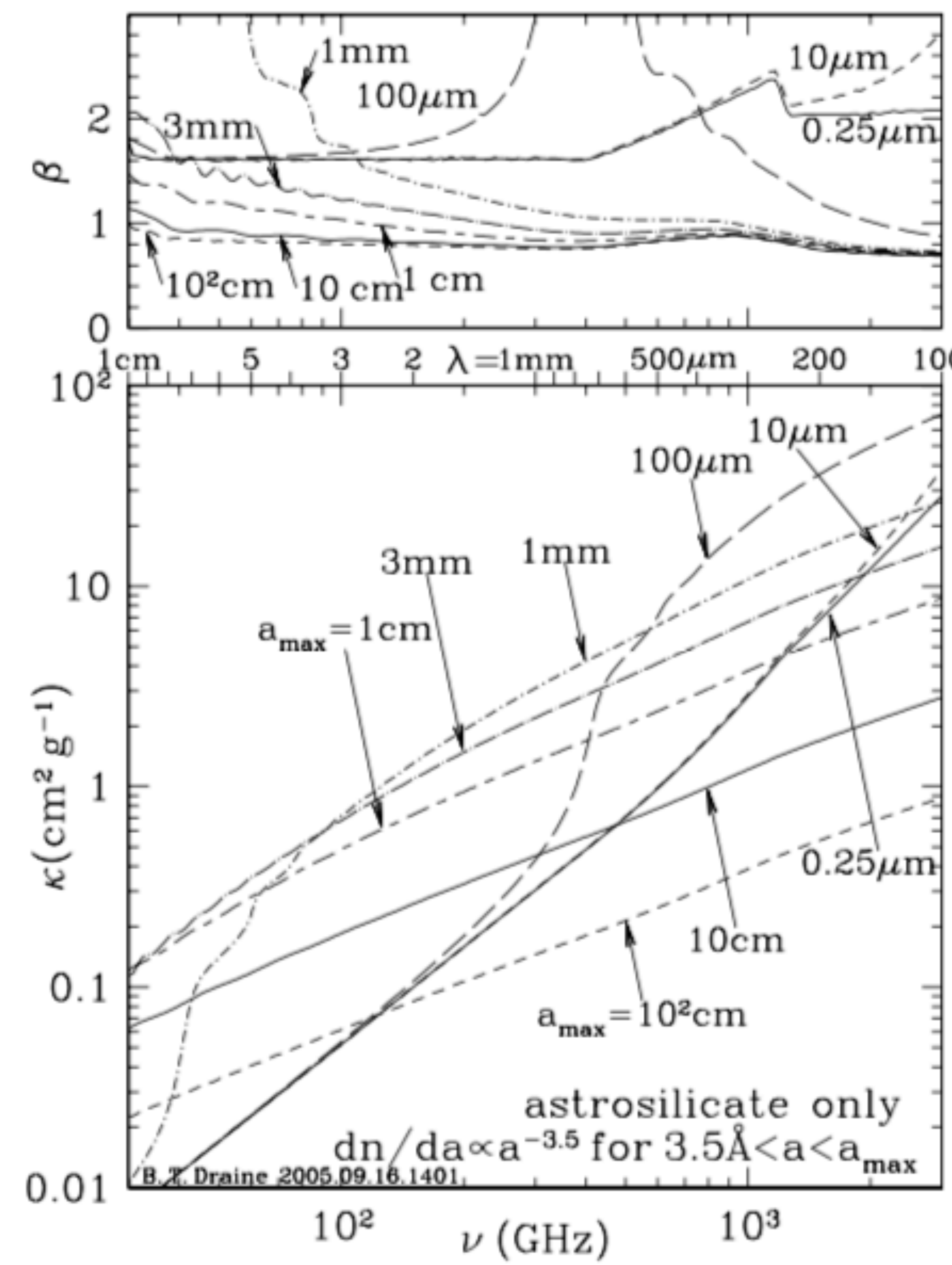
Dust opacity wavelength dependence: at wavelength λ you are sensitive to grains up to size ~3 λ

Dust

- Flux density (Jansky = erg s^{-1} cm^{-2} Hz^{-1}) $$F_\nu = \int I_\nu d\Omega$$
- Specific intensity (erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}) $$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu})$$
- Planck function $$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$
- Optical depth $$\tau_\nu = \frac{\kappa_\nu \Sigma_{dust}}{\cos i}$$
- Dust opacity $$\kappa_\nu \sim \nu^\beta$$

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

+ composition



Hildebrand 1983
Draine 2006

How do we compute the dust mass?

Dust

Optically thin: $\tau_\nu << 1$:

$$F_\nu = \int I_\nu d\Omega$$

Power-law surface density: $\Sigma_d(r) = \Sigma_c \left(\frac{r}{r_c}\right)^{-1}$

$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu})$$

Dust mass: $M_{dust} = \int_0^R \Sigma_{dust}(r) 2\pi r dr$

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

Now you can compute M_{dust} as function of F_ν in optically thin regime and cos(i)=1 (face-on)

$$F_\nu = \int B_\nu(T)\tau_\nu(r) d\Omega$$

$$= \int_0^R B_\nu(T)\kappa_\nu \Sigma_{dust}(r) \frac{2\pi r dr}{d^2} = \frac{B_\nu(T)\kappa_\nu M_{dust}}{d^2} \longrightarrow \boxed{M_{dust} = \frac{B_\nu(T)\kappa_\nu F_\nu}{d^2}}$$

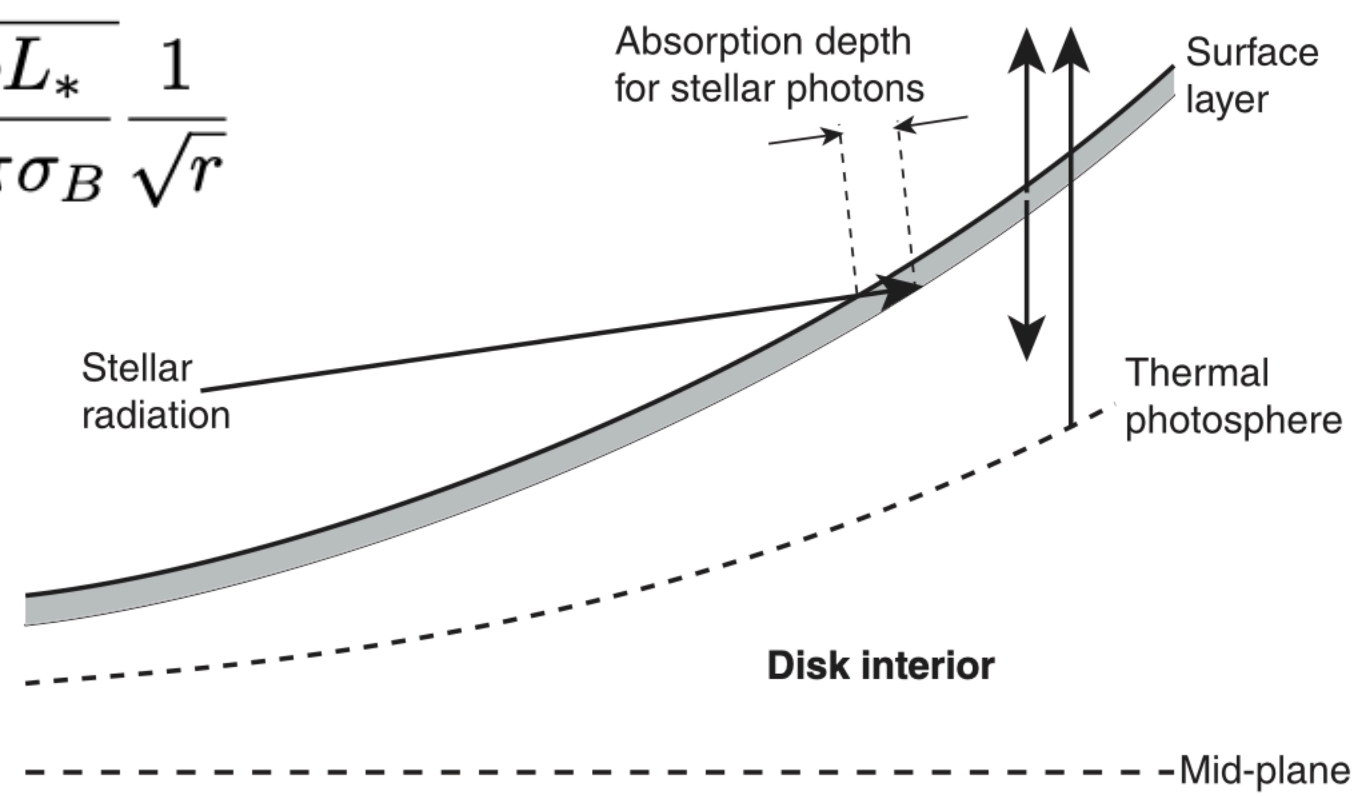
Dust temperature

Disk temperature ~ received stellar radiation

Passively heated, flared disk in radiative equilibrium has the following temperature:

$$T(r) = \Big(\frac{\phi L_*}{8\pi\sigma_B r^2}\Big)^{1/4} = \sqrt[4]{\frac{\phi L_*}{8\pi\sigma_B}}\frac{1}{\sqrt{r}}$$

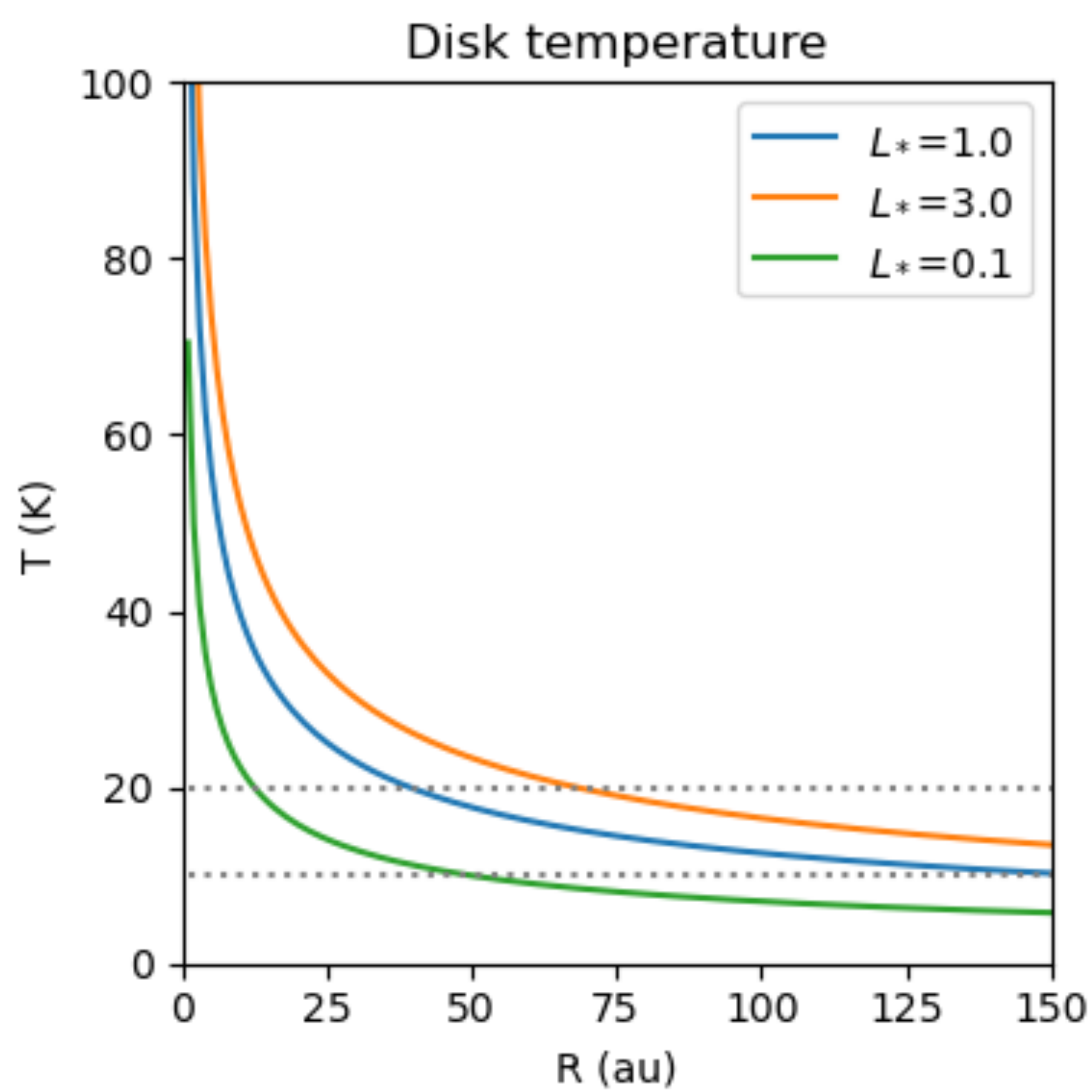
With phi the flaring angle (generally taken as 0.02)



Chiang & Goldreich 1997
Dullemond et al. 2001

Dust temperature

$$T(r) = \left(\frac{\phi L_*}{8\pi\sigma_B r^2}\right)^{1/4} = \sqrt[4]{\frac{\phi L_*}{8\pi\sigma_B}}\frac{1}{\sqrt{r}}$$



Assume that bulk of the disk is at 50-150 au => 10-20 K

General assumption:
use average temperature (20 K) to compute dust mass

$$M_{dust} = \frac{B_\nu(T=20)\kappa_\nu F_\nu}{d^2}$$

Rayleigh-Jeans approximation

Additional step

Rayleigh-Jeans: $$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

Approximation: $h\nu \ll k_{\mathrm{B}}T$ (Valid in mm wavelengths)

$$B_\nu(T(r)) = \frac{2\nu^2 k_B T(r)}{c^2} \longrightarrow B_\nu(T) \sim \nu^2$$

Remember: $\kappa_\nu \sim \nu^\beta$

Rayleigh-Jeans approximation

Rayleigh-Jeans: $B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$

Approximation: $h\nu \ll k_\mathrm{B}T$

$$B_\nu(T(r)) = \frac{2\nu^2 k_B T(r)}{c^2} \longrightarrow B_\nu(T) \sim \nu^2$$

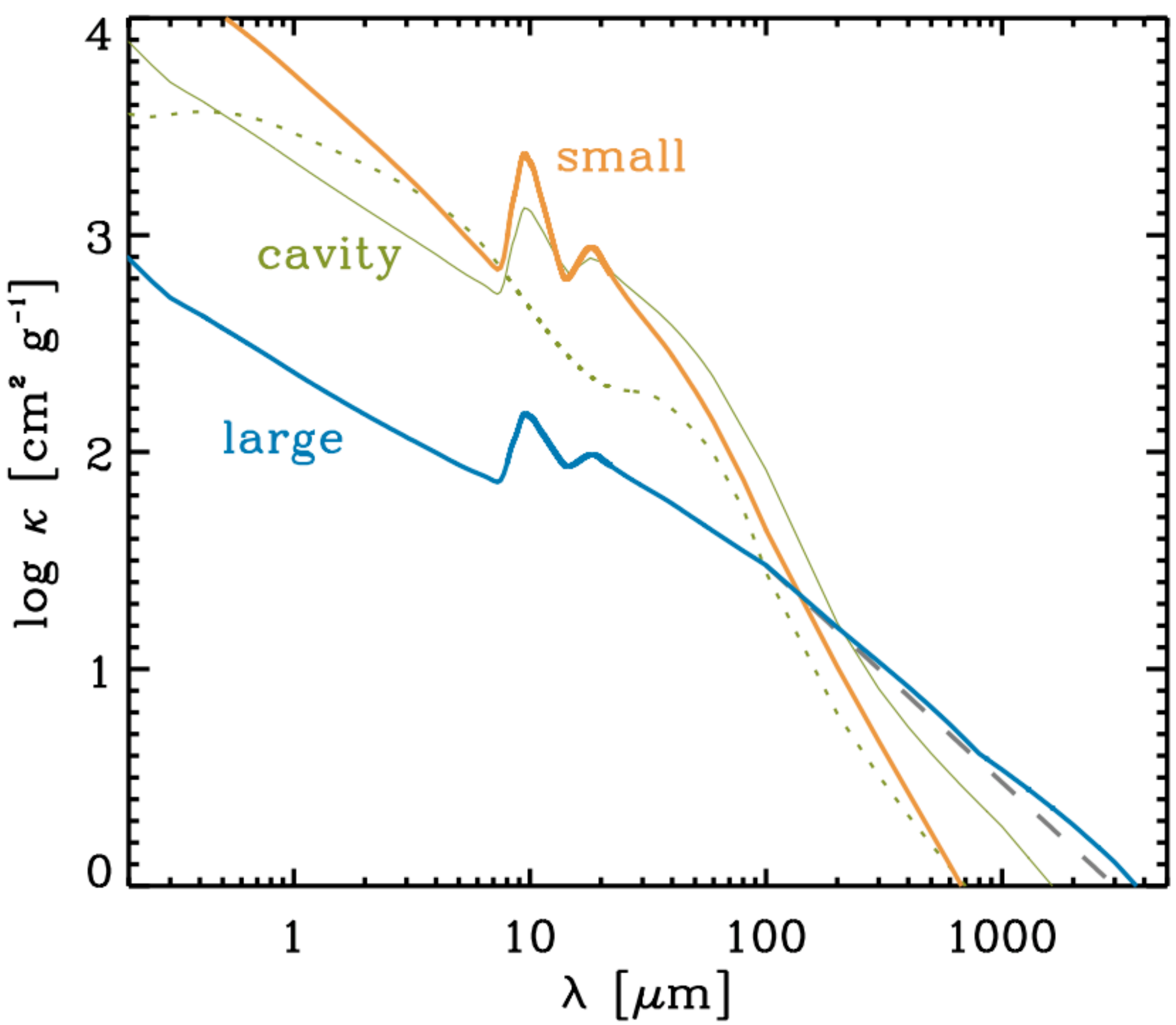
Remember: $\kappa_\nu \sim \nu^\beta$

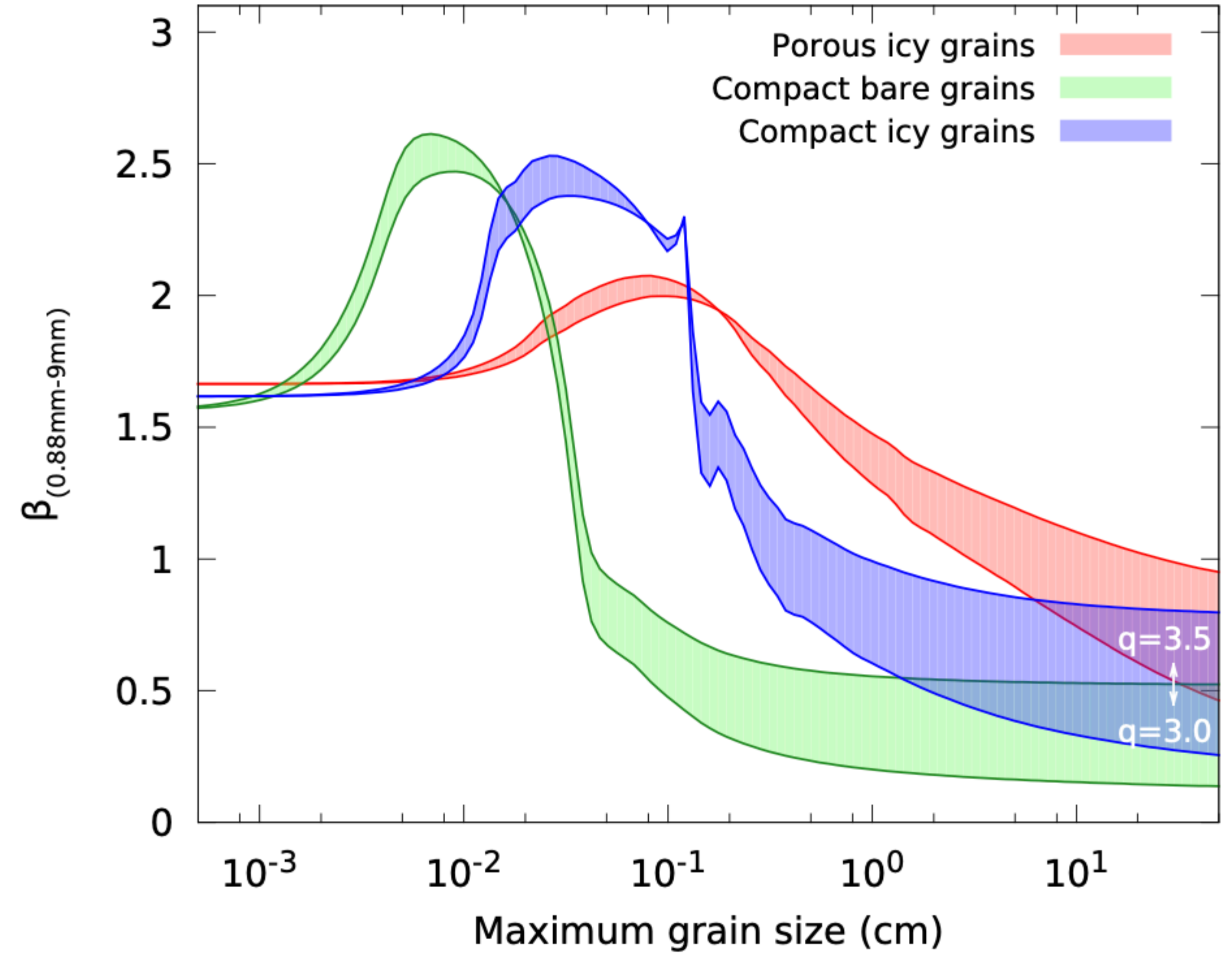
Rayleigh-Jeans + Opt thin regime: $F_\nu = \frac{B_\nu(T)\kappa_\nu M_{dust}}{d^2} \longrightarrow F_\nu \sim \nu^2\kappa_\nu \sim \nu^{2+\beta} \sim \nu^\alpha$

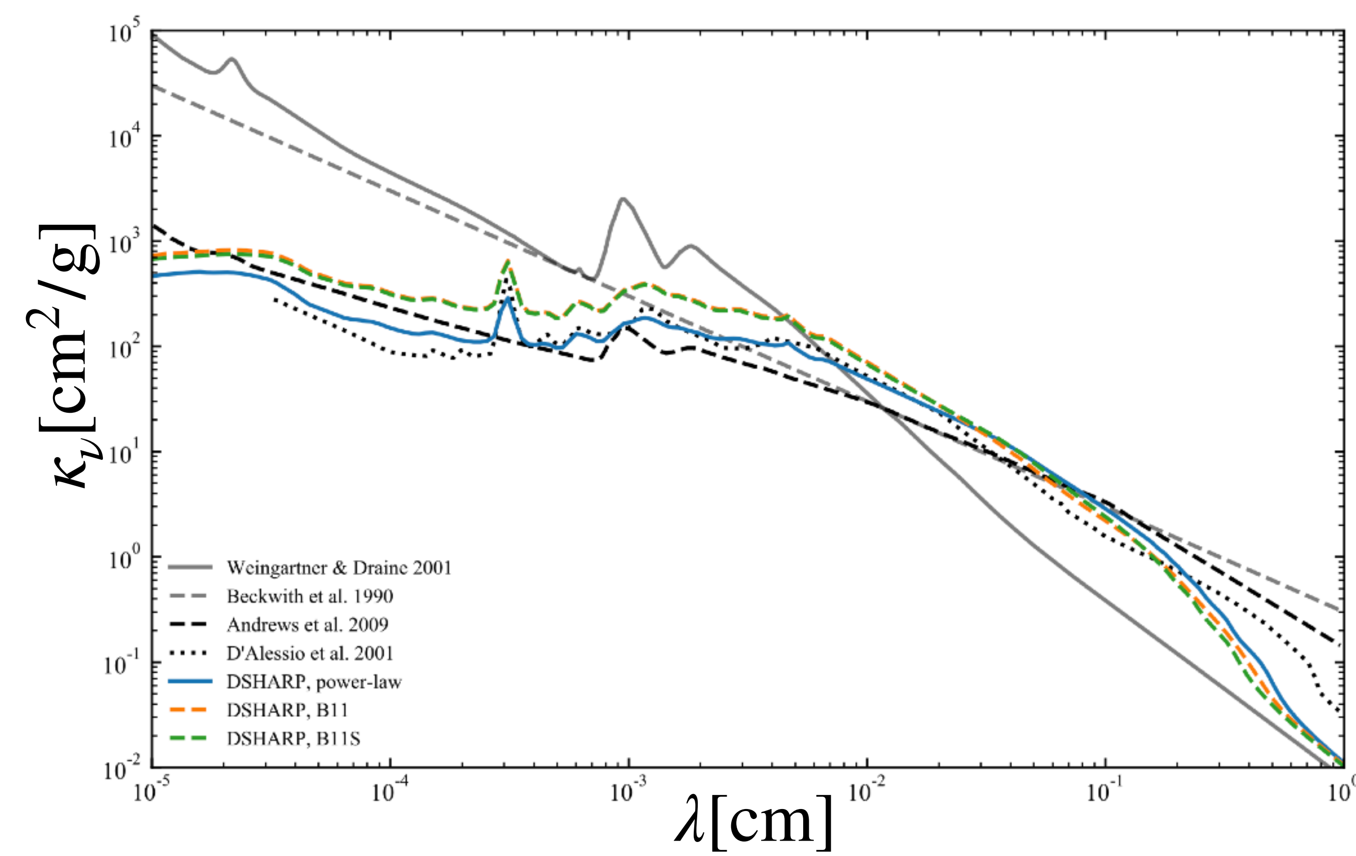
So the spectral index alpha can provide us the dust opacity β in the assumption of opt. thin emission

Dust opacity

Dust opacity $\kappa_\nu \sim \nu^\beta$







Dust opacity depends on assumed grain properties: generate table at https://github.com/birnstiel/dsharp_opac

Testi et al. 2014
Andrews et al. 2011
Birnstiel et al. 2018

What if dust is optically thick?

$$F_\nu = \int I_\nu d\Omega$$

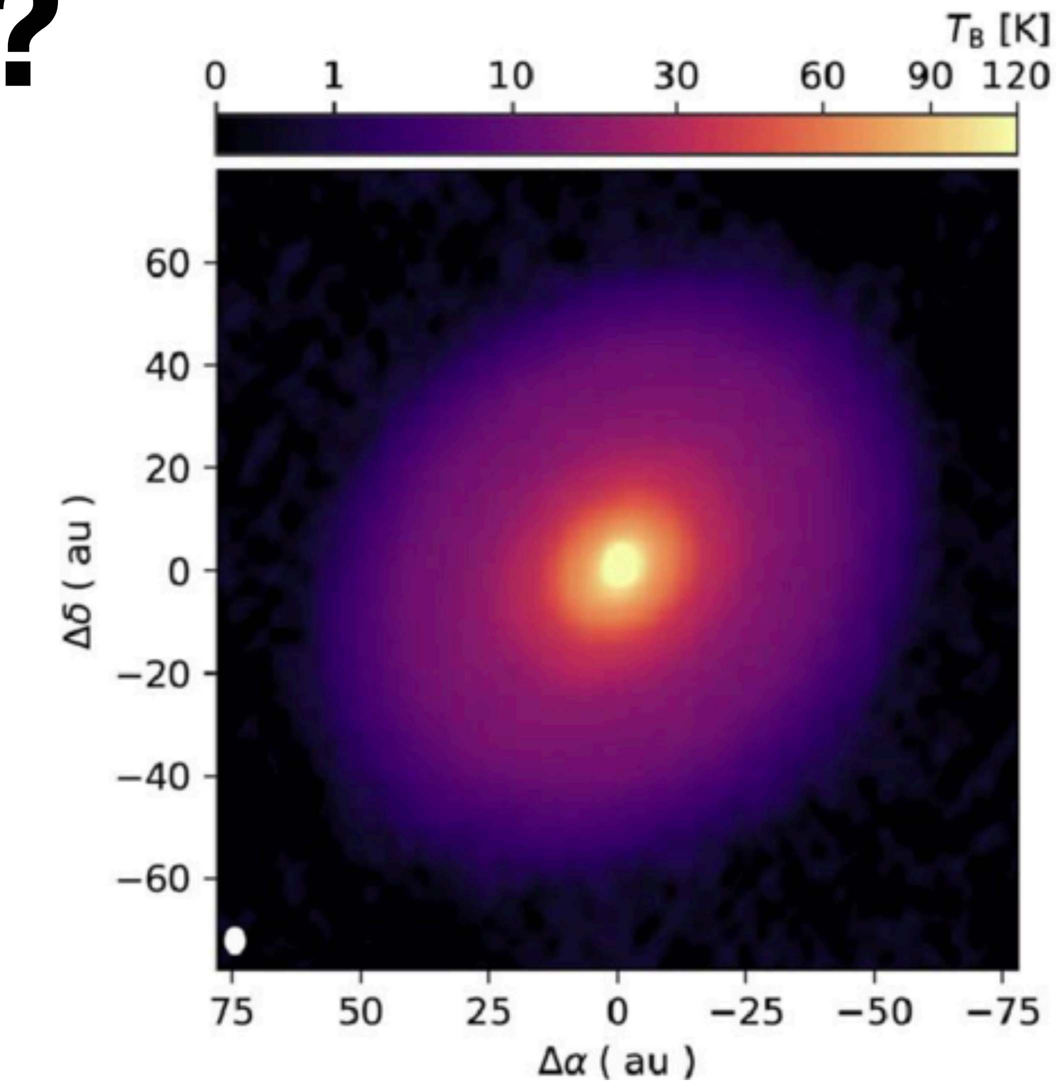
$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu}) \;\; = B_\nu(T) \qquad \tau_\nu > 1$$

$$F_\nu \sim \nu^2 \cancel{\kappa_\nu} \sim \cancel{\nu^{2+\beta}} \sim \nu^\alpha \longrightarrow M_{dust} \neq \frac{B_\nu(T)\kappa_\nu F_\nu}{d^2}$$

Spectral index α no longer represents the dust opacity and the <u>dust mass is underestimated</u>

Check optical depth?

Example (Ohashi et al. 2023)

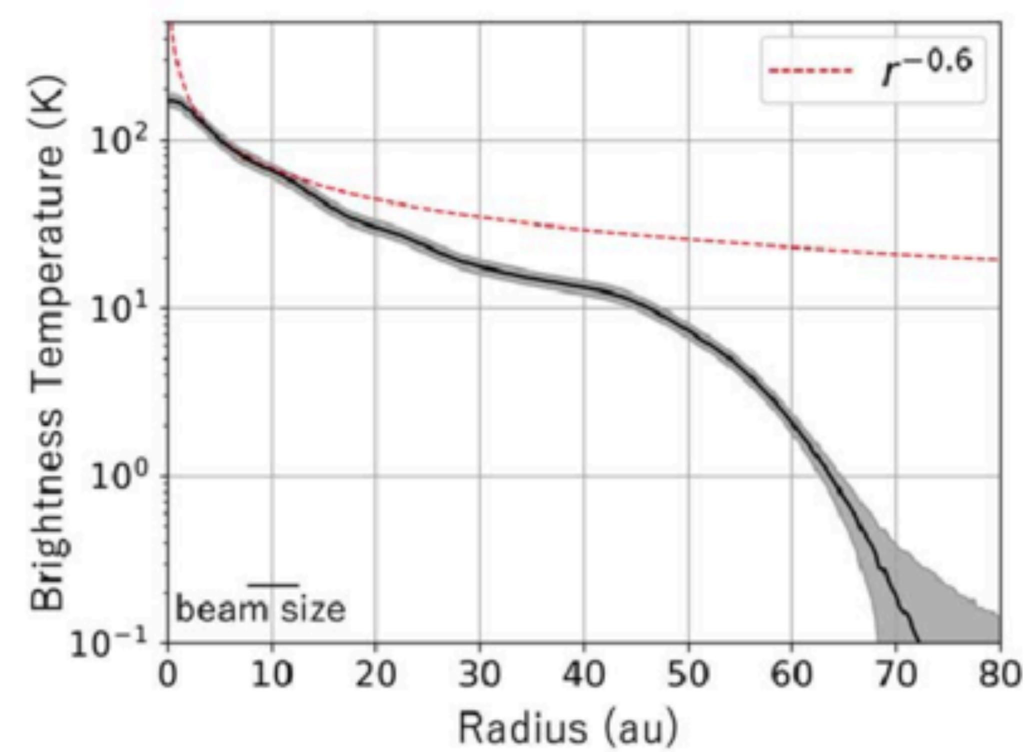


If emission is **spatially resolved**, we can check if the emission is **optically thick** by comparing the emission with the **local temperature**

If optically thick:

$$F_\nu(r) = B_\nu(r, T) \approx \frac{2\nu^2 k_B T(r)}{c^2} \propto T(r)$$

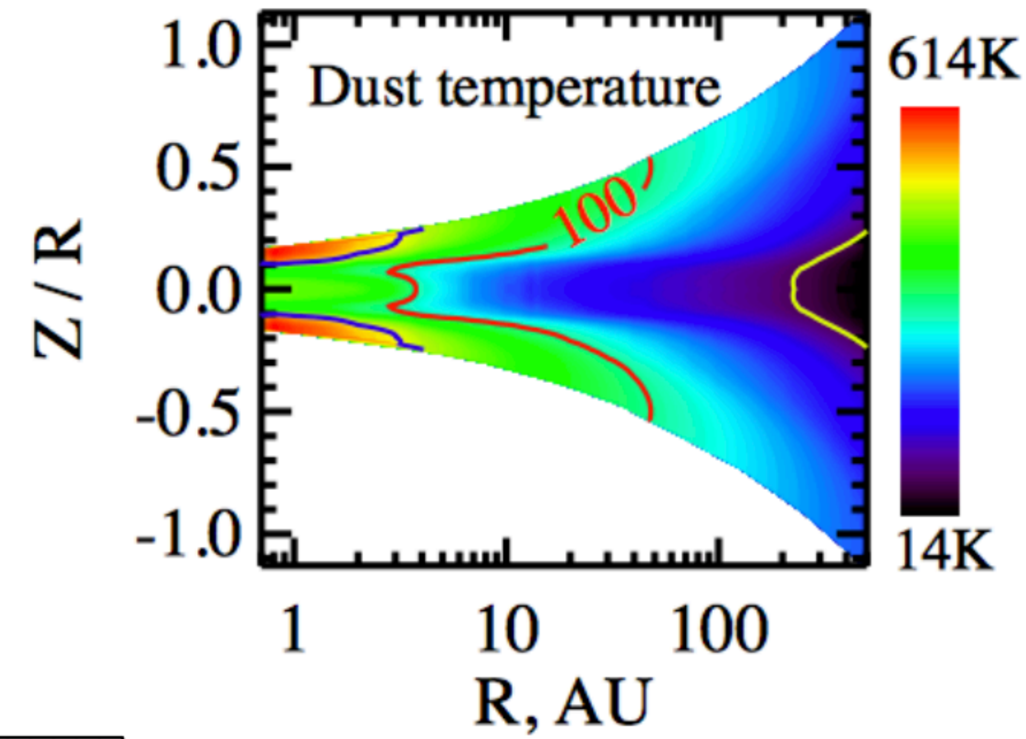
Compute the **'brightness temperature' T_b** from the measured flux and compare with the physical temperature at that location: if comparable, the emission is likely optically thick

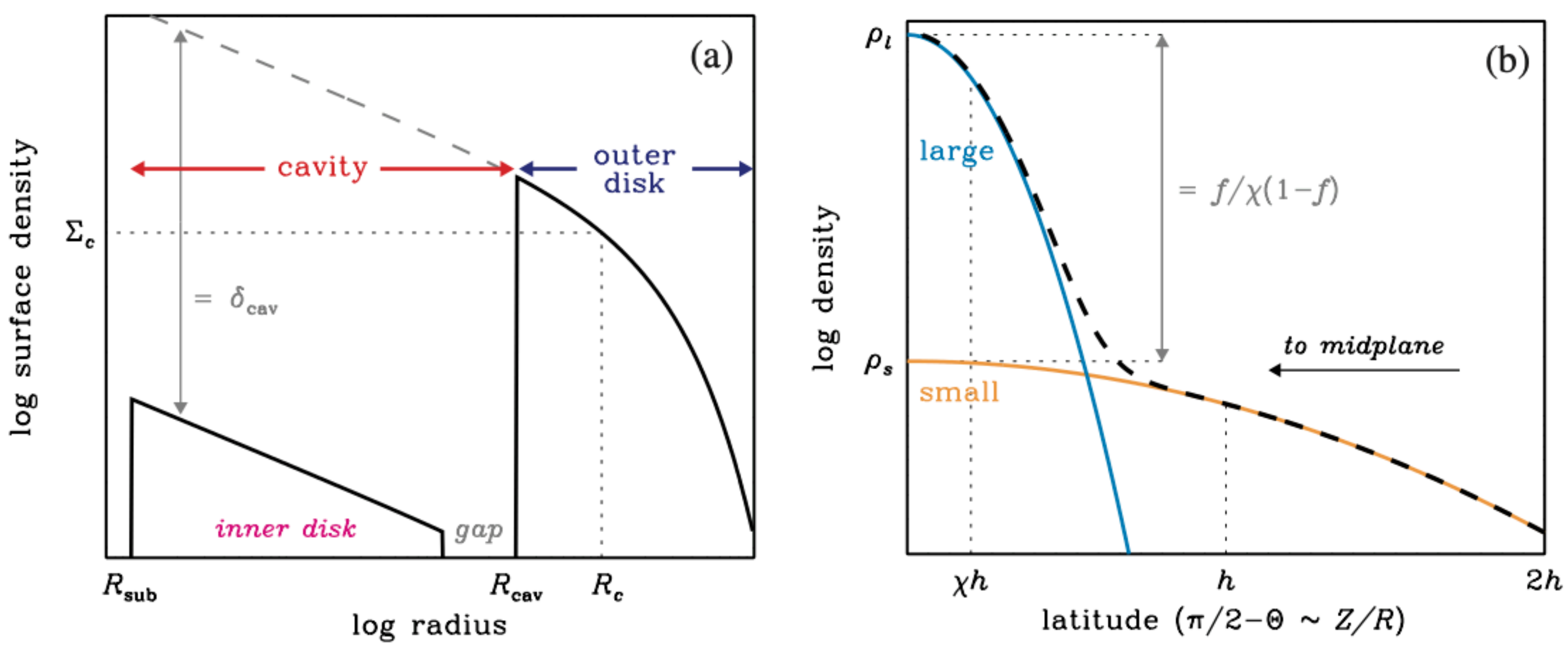


Dust radiative transfer

Surface density

- **Radiative transfer modeling**: compute $\mathbf{T_{dust}}$ and $\boldsymbol{\tau}$ throughout the disk based on given **Σ(r)** and **h(r)** and input **star**, then ray-trace expected **emission I(r)** to compare with data





$$\Sigma_g = \Sigma_c \left(\frac{R}{R_c}\right)^{-\gamma} \exp\left[-\left(\frac{R}{R_c}\right)^{2-\gamma}\right]$$

$$\rho_l = \frac{f\Sigma}{\sqrt{2\pi}\,R\,\chi h} \exp\left[-\frac{1}{2}\left(\frac{\pi/2-\Theta}{\chi h}\right)^2\right]$$

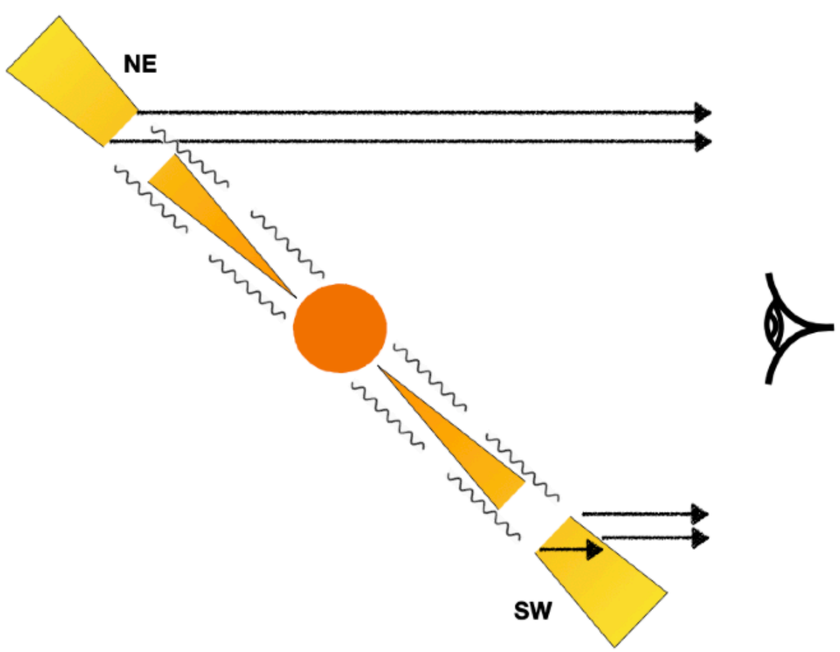
<u>Example codes (available online)</u>:
RADMC-3D
MCFOST
MCMAX

e.g. Andrews et al. 2011

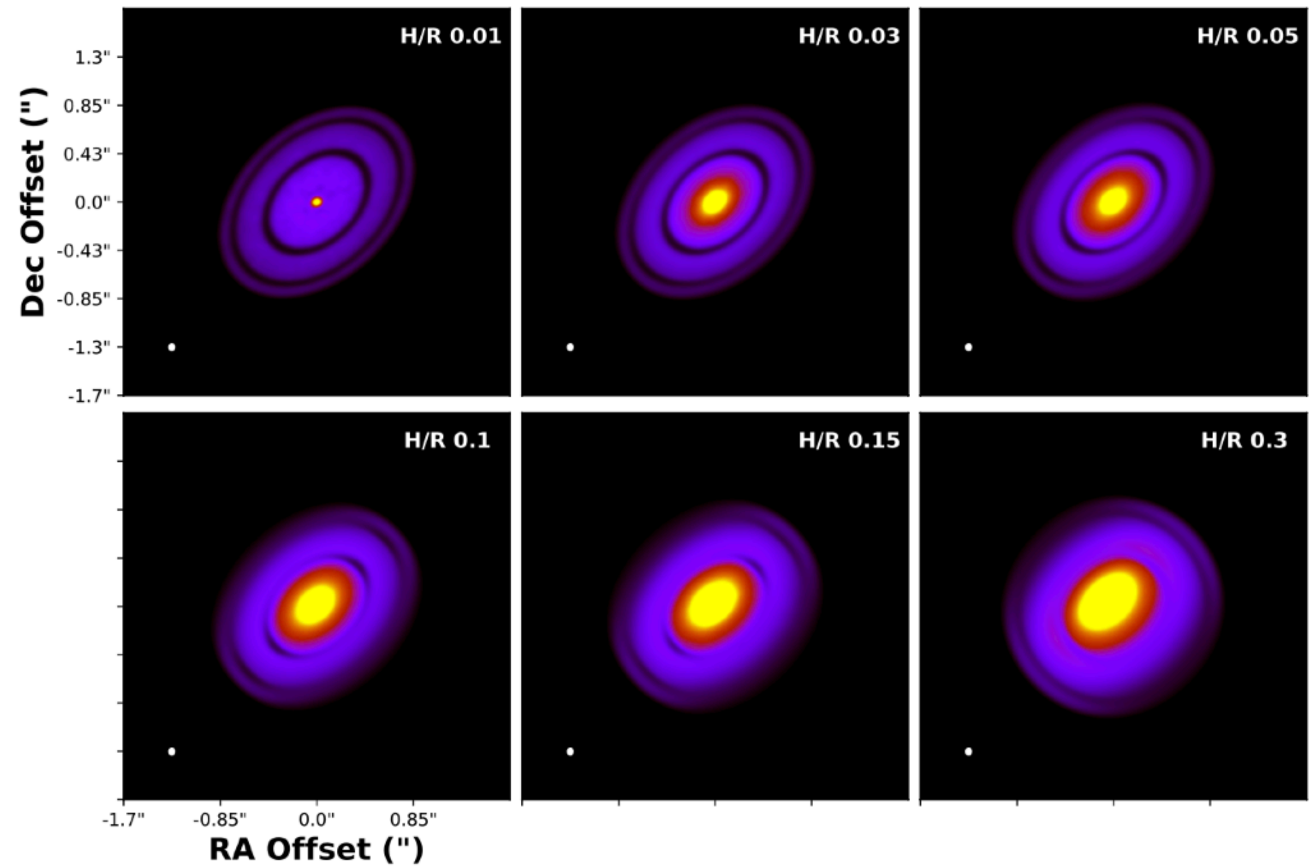
Dust radiative transfer

Scale height

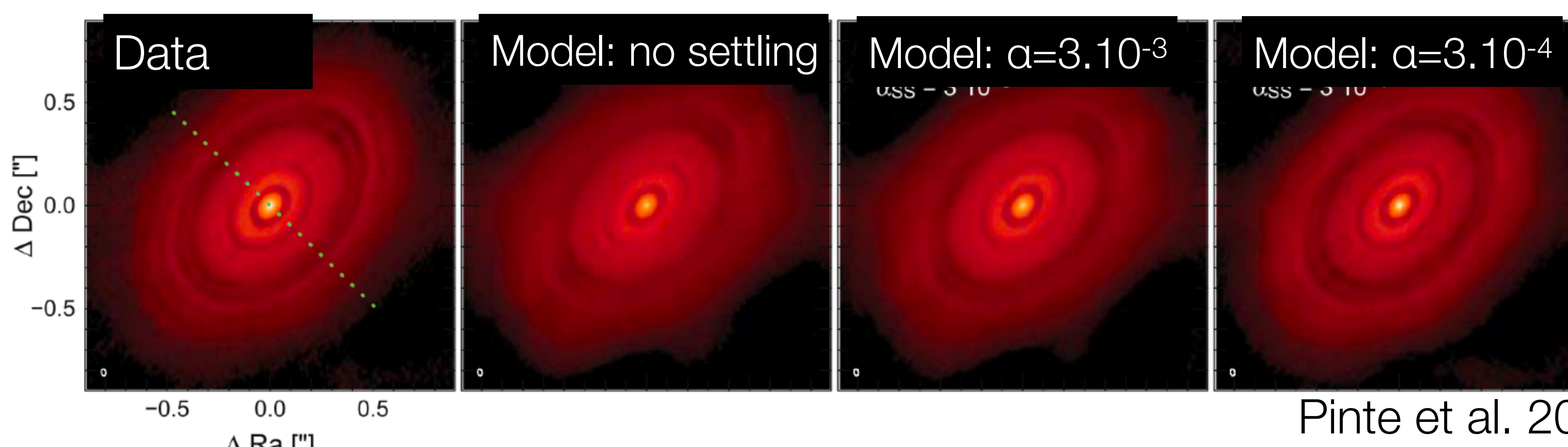
- Scale height ('flaring') of **inclined** disk can be determined by radiative transfer => **shadowing** effects, **hiding** gaps, apparent **asymmetries** => in particular for optically thick emission!



Example embedded disk model IRAS4A:



Example HL Tau:
determine turbulence alpha ~10^{-4} to explain strong settling

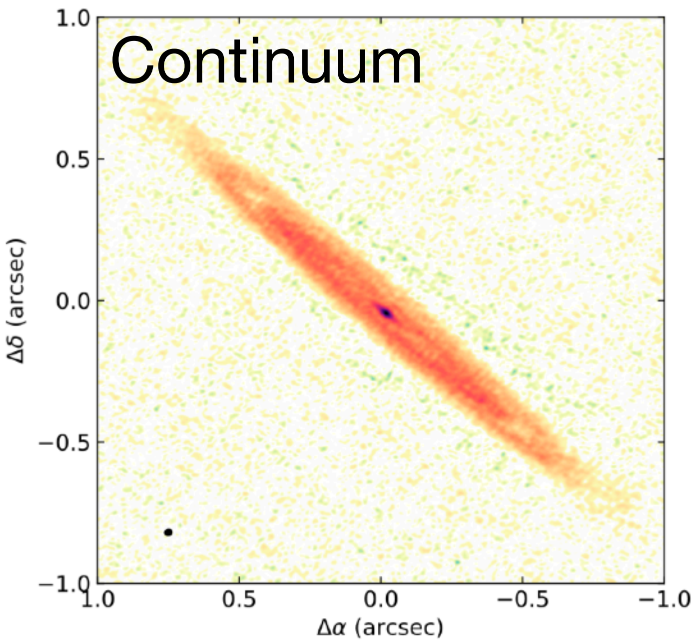


Pinte et al. 2016
Guerra Alvarado et al. 2023, in press

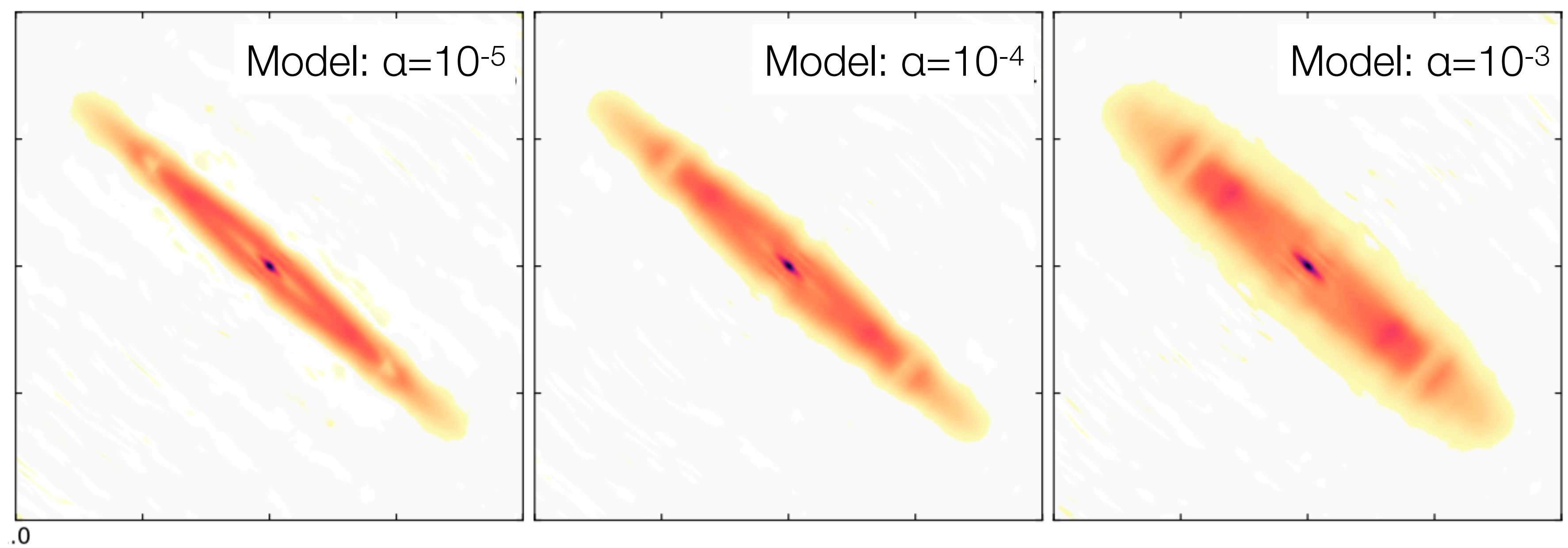
Dust radiative transfer

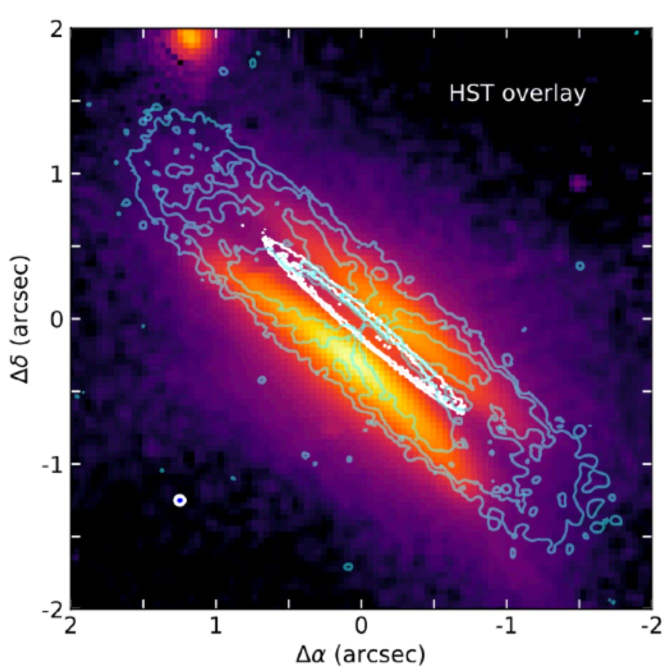
Scale height: fully edge-on disk

Oph163131: highly settled mm-dust disk with h=0.5/100 au



Radiative transfer models: alpha-viscosity ~10^{-5}





Overlay on HST scattered light

Villenave et al. 2022

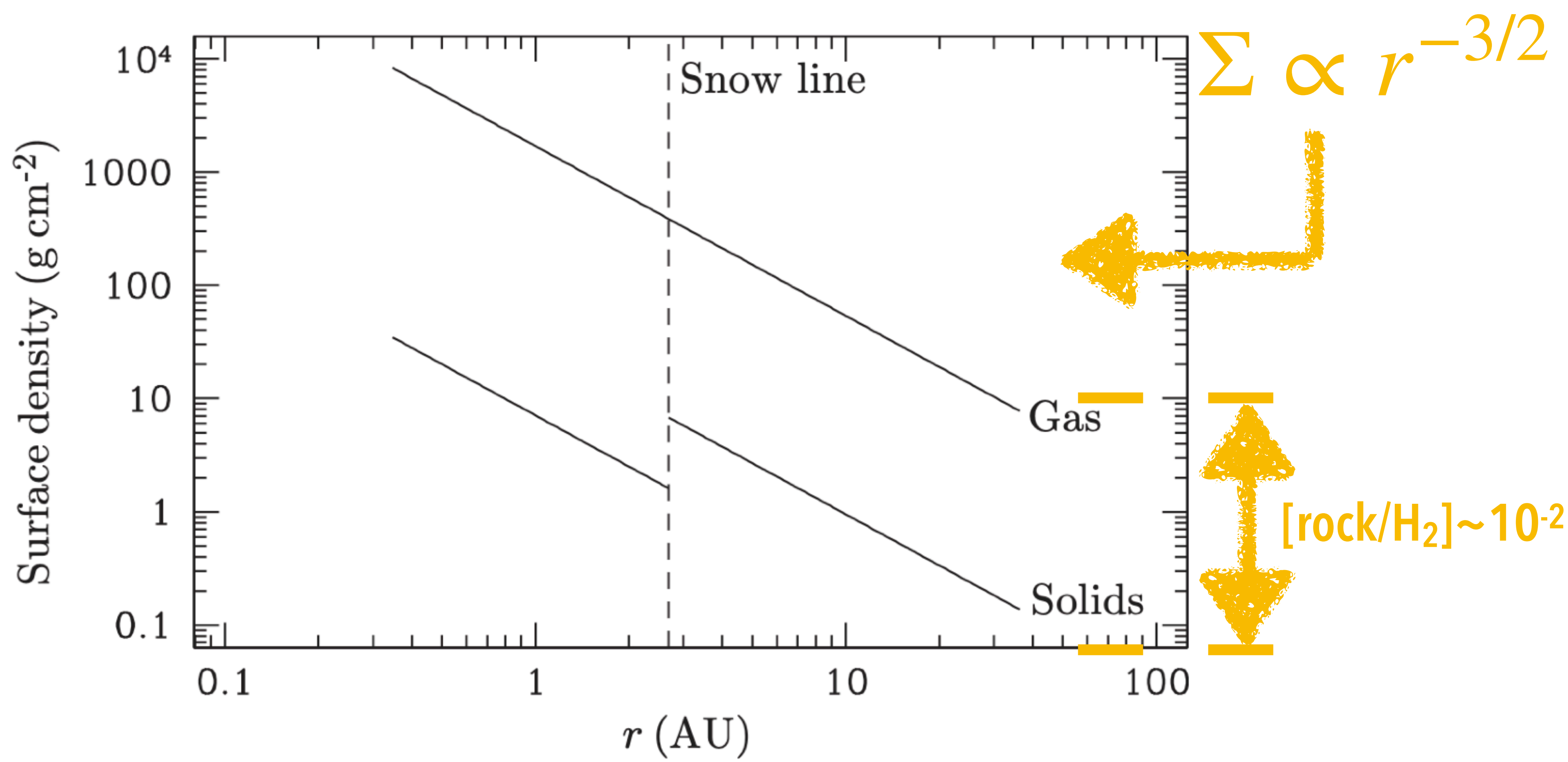
Dust mass

Relevance: solid reservoir for planet formation

Solar System: cannot go back in time and measure disk mass, but can estimate the minimum amount of material needed: The Minimum Mass Solar Nebula

1. Take amount of solid mass per planet and multiply by Solar composition
2. Divide in annuli and distribute mass across each planet orbit: gas surface density
3. Compute the solid surface density considering the H_2O snowline

Total gas: ~0.01 M_{Sun}
Total dust: ~ 30 M_{Earth}



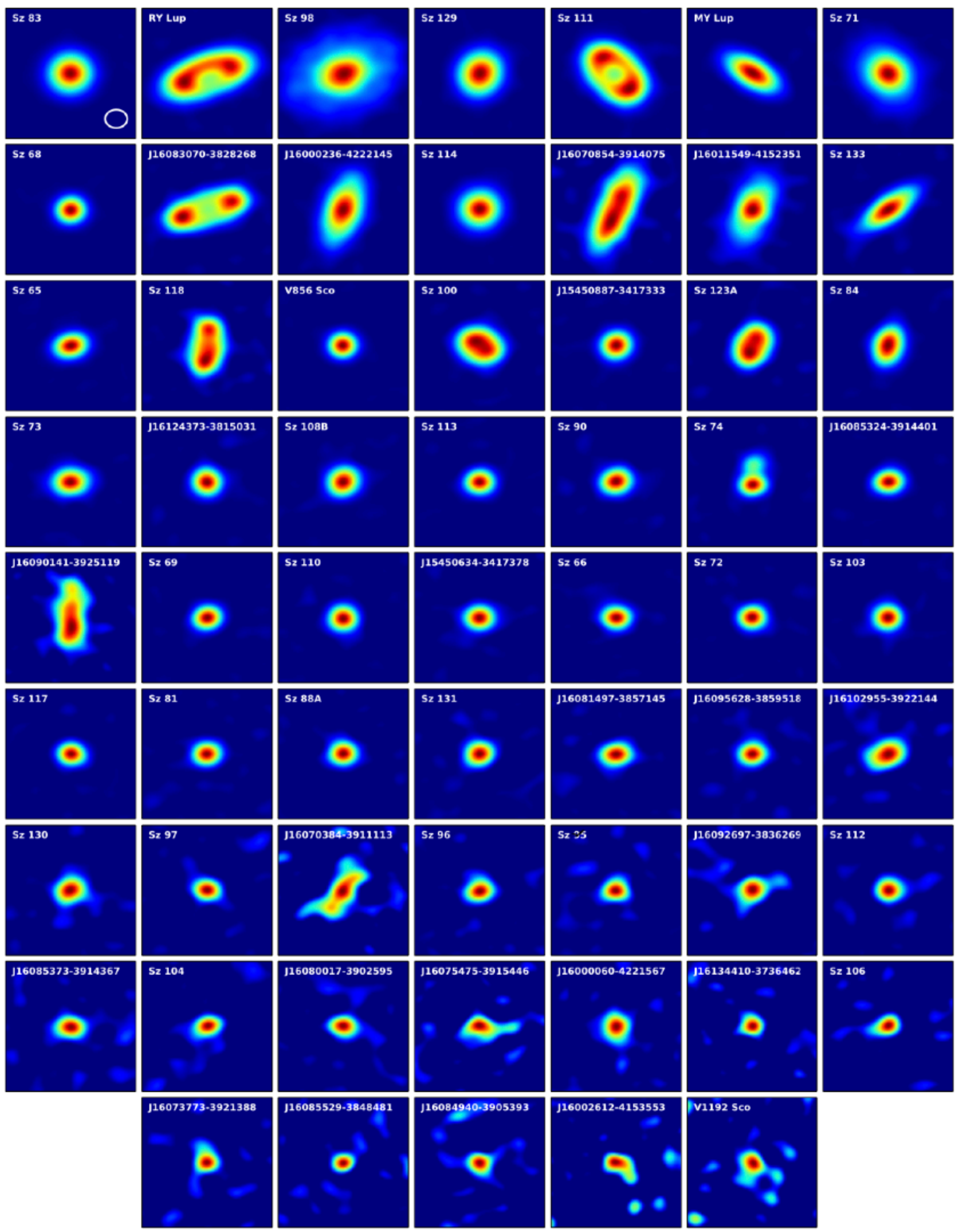
Why is this insufficient to use for exoplanetary systems?

Weidenschilling 1977
Hayashi 1981

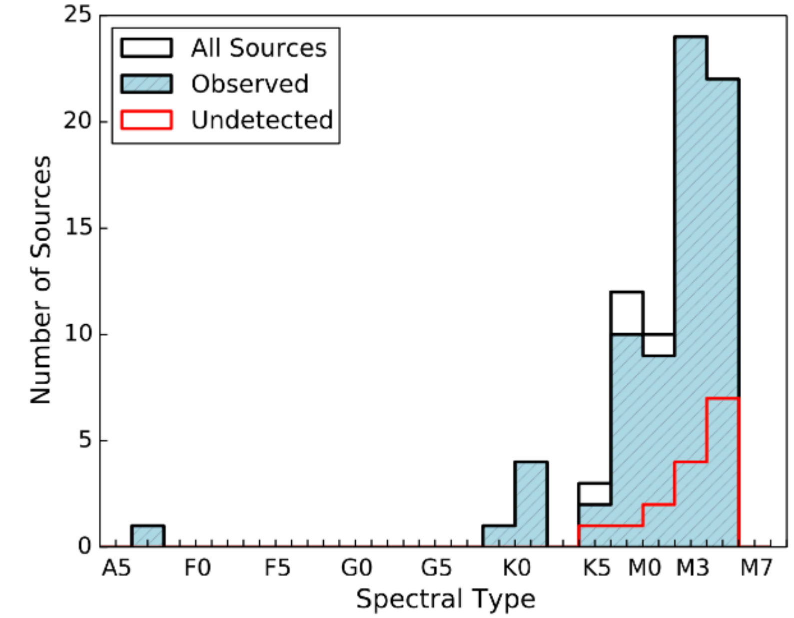
Dust mass observations

ALMA snapshot surveys

Example: disks in Lupus



+ 27 non-detections (upper limits)



- Map all Class II disks across IMF in cluster with ALMA in continuum (B6/B7)
- Low-resolution: typically 0.25” (~35 au)
- Snapshot surveys of 1-2 min/source
- Almost 100 disks per SF region
- Continuum flux provides estimate disk dust mass
- Some disks show resolved gaps, but mostly no substructure due to resolution

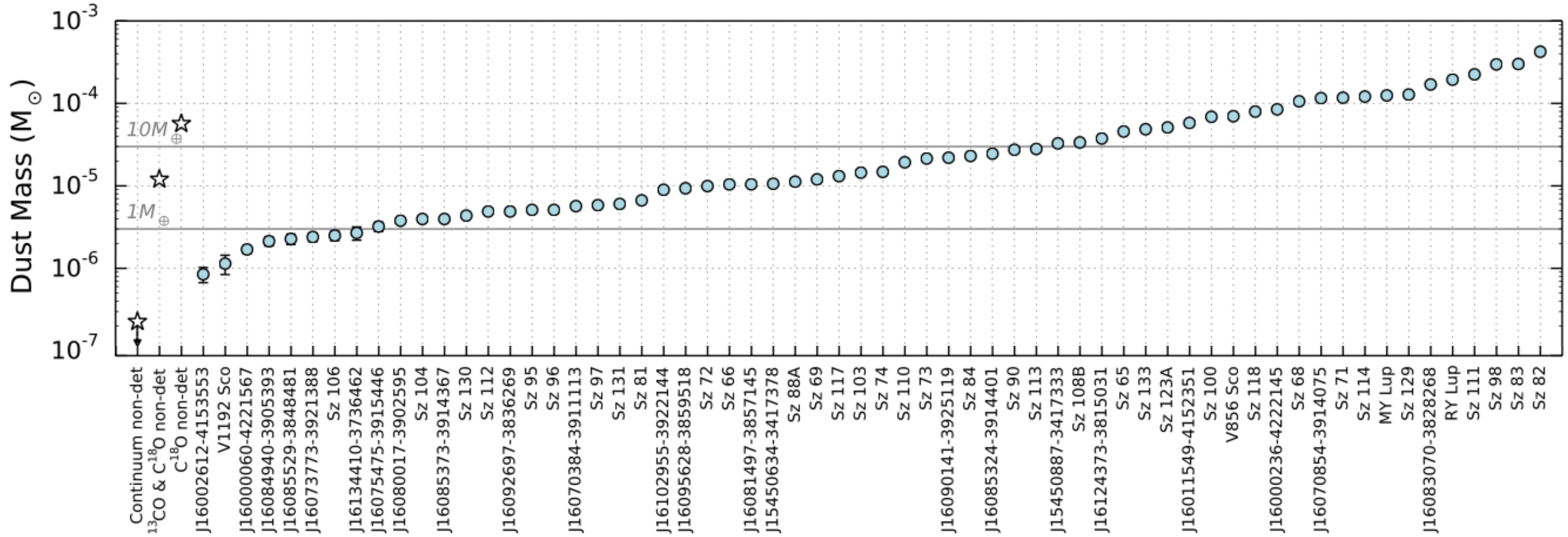
$$M_{dust} = \frac{B_\nu(T = 20K)\kappa_\nu F_\nu}{d^2}$$

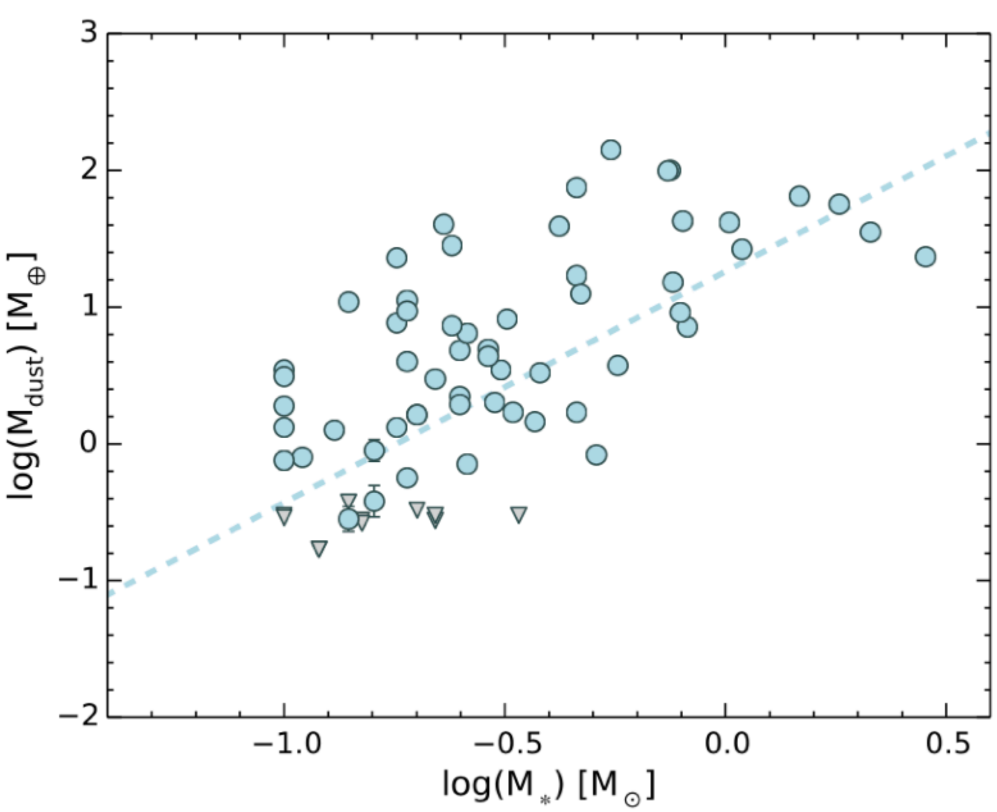
Ansdell et al. 2016

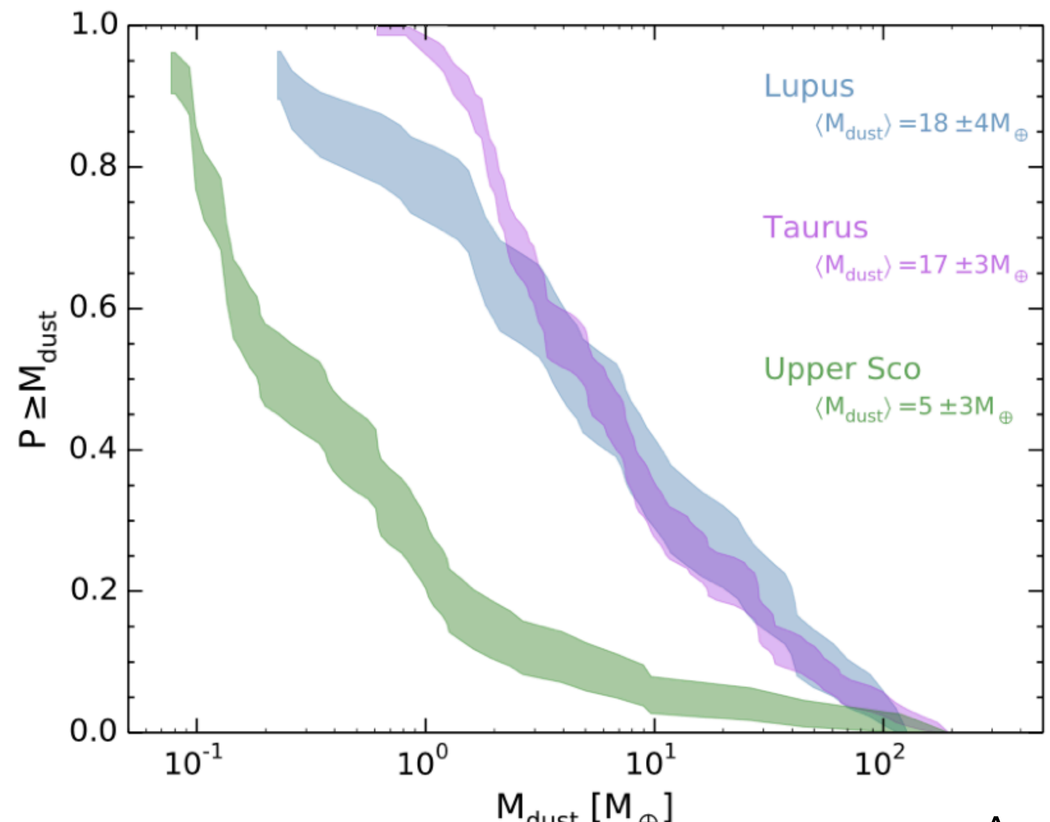
Dust mass observations

Lupus disk survey

What trends do you notice?





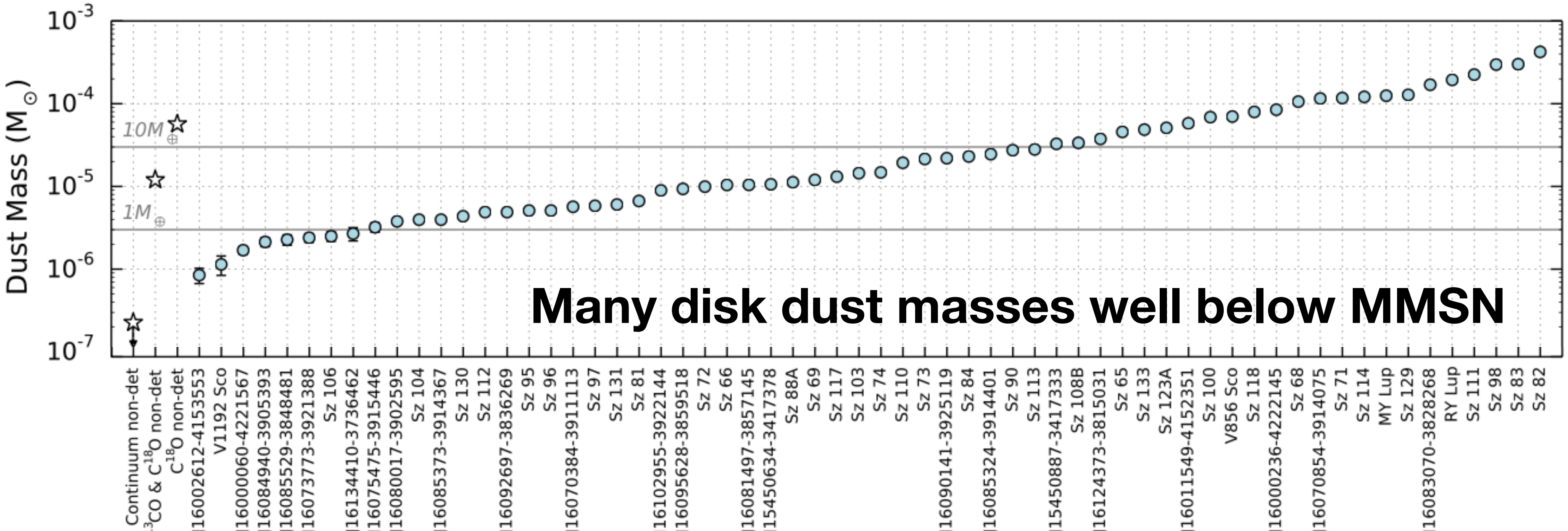


Ansdell et al. 2016

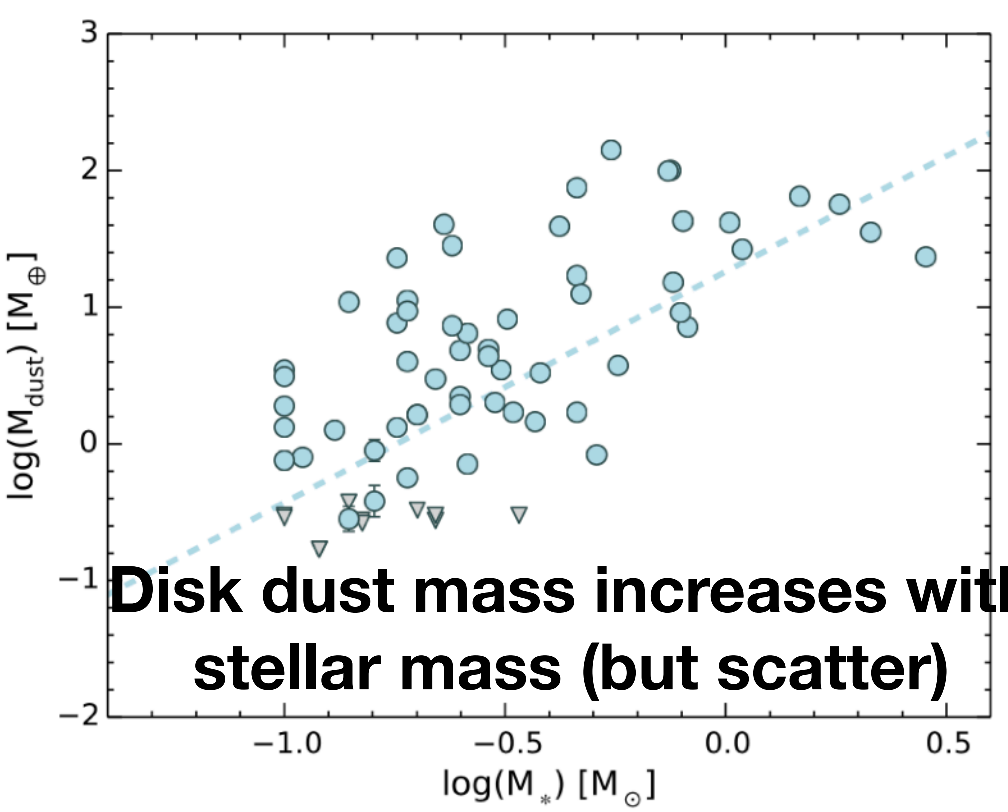
Dust mass observations

Lupus disk survey

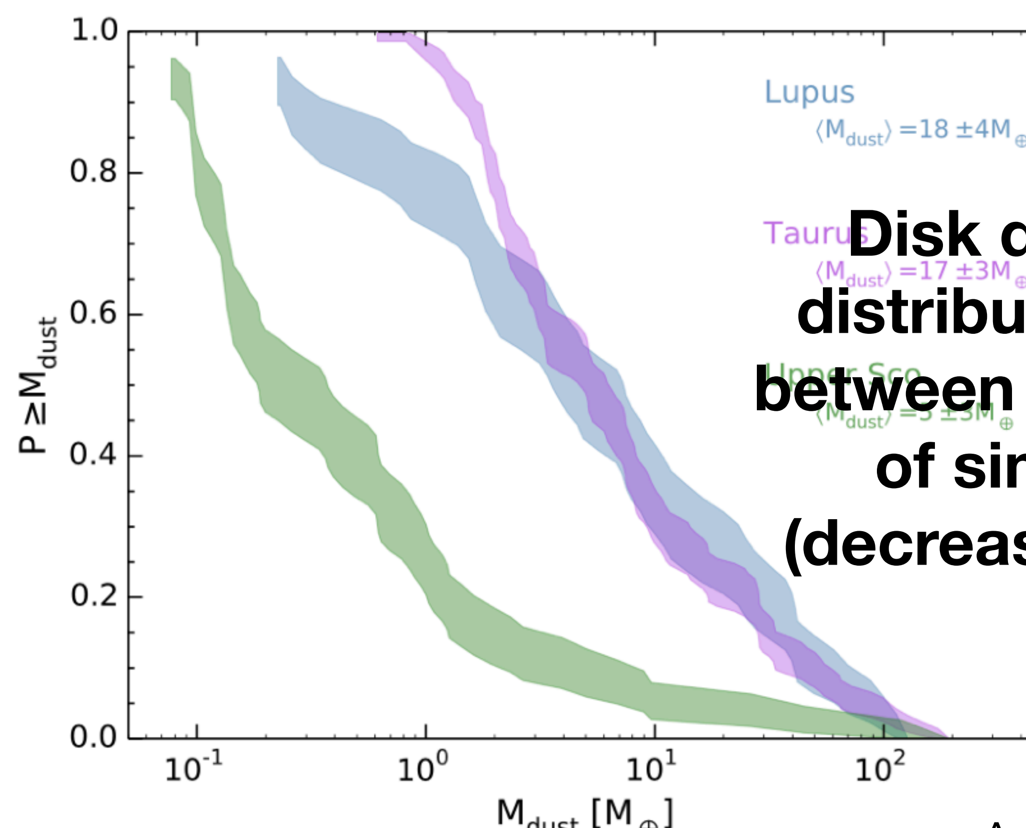
What trends do you notice?



Many disk dust masses well below MMSN



Disk dust mass increases with stellar mass (but scatter)

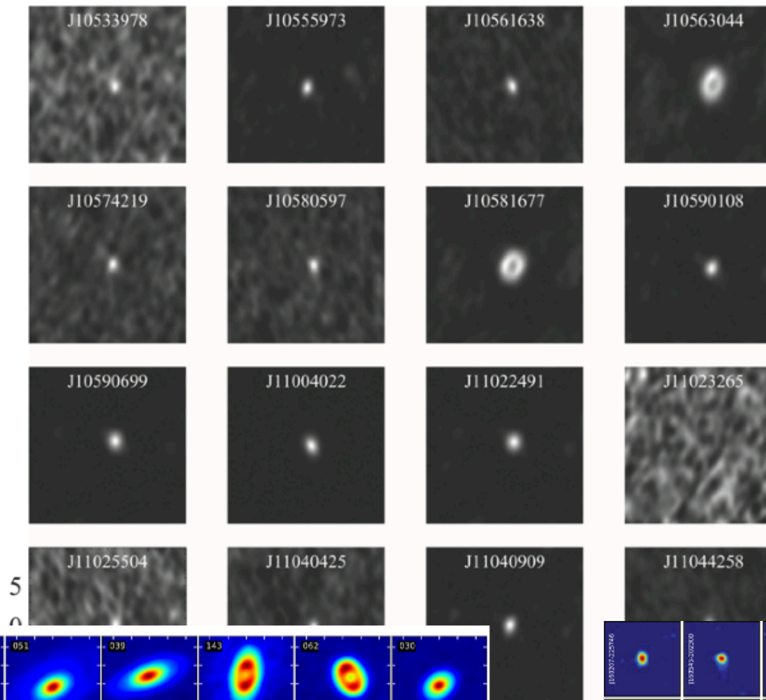


Disk dust mass distribution similar between with regions of similar age (decrease with age)

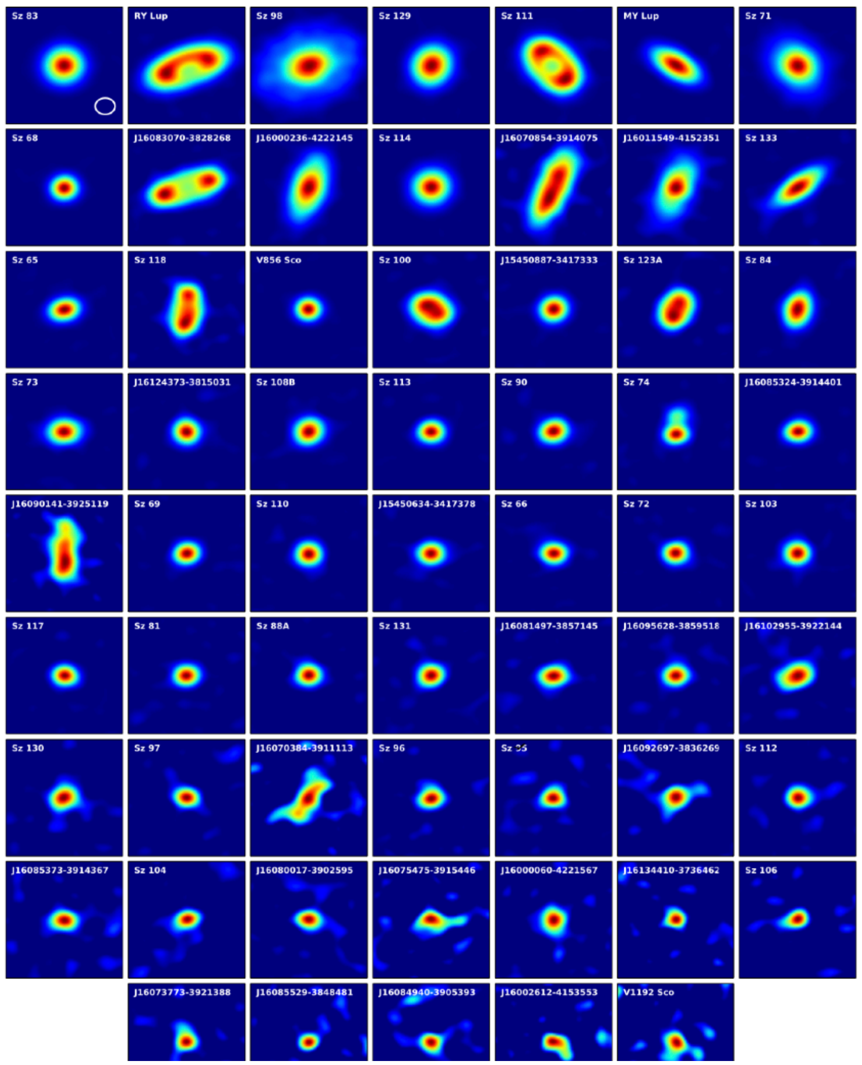
Ansdell et al. 2016

Dust mass trends

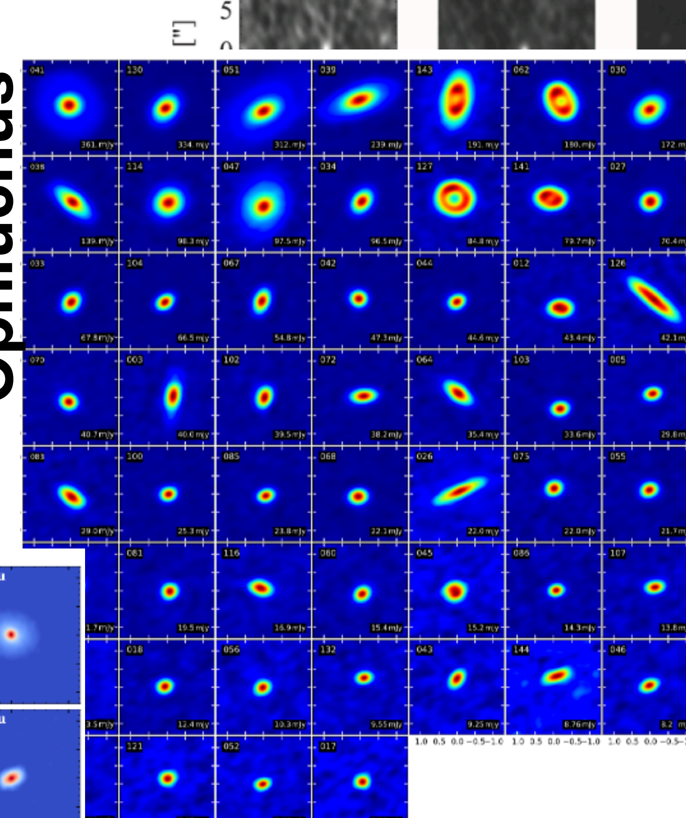
Chamaeleon

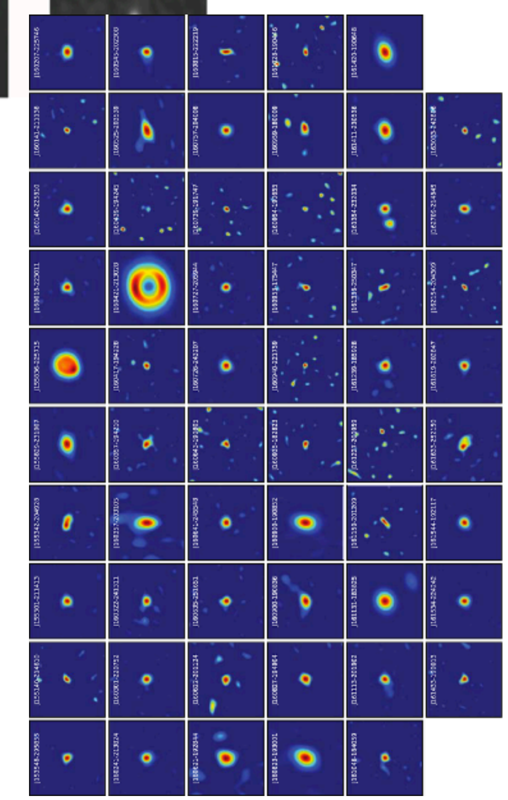


Lupus

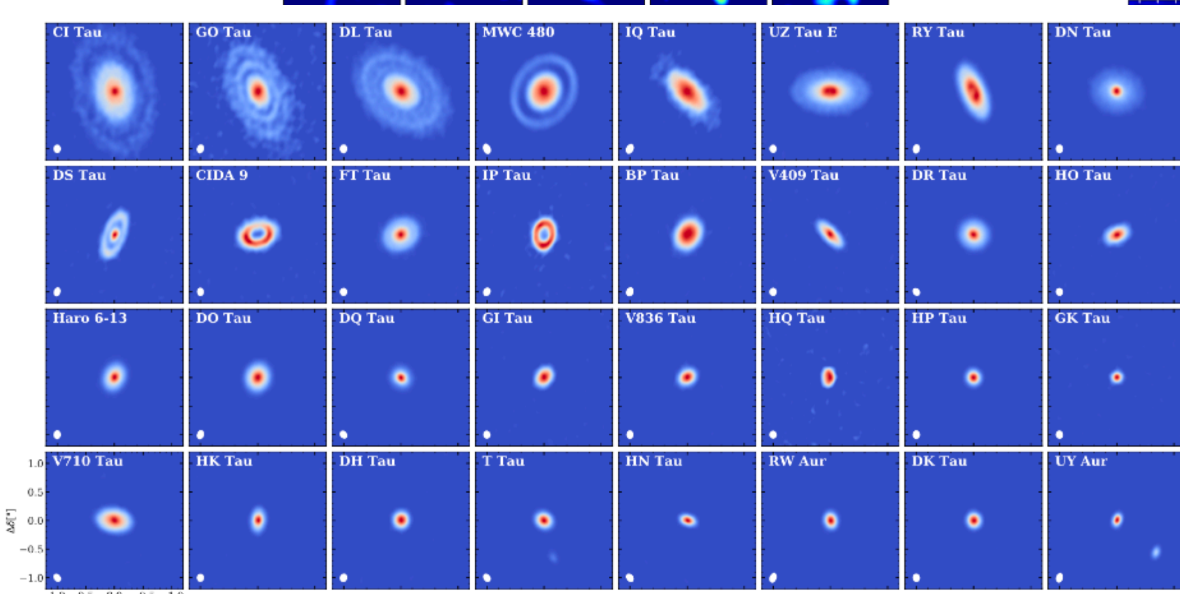


Ophiuchus





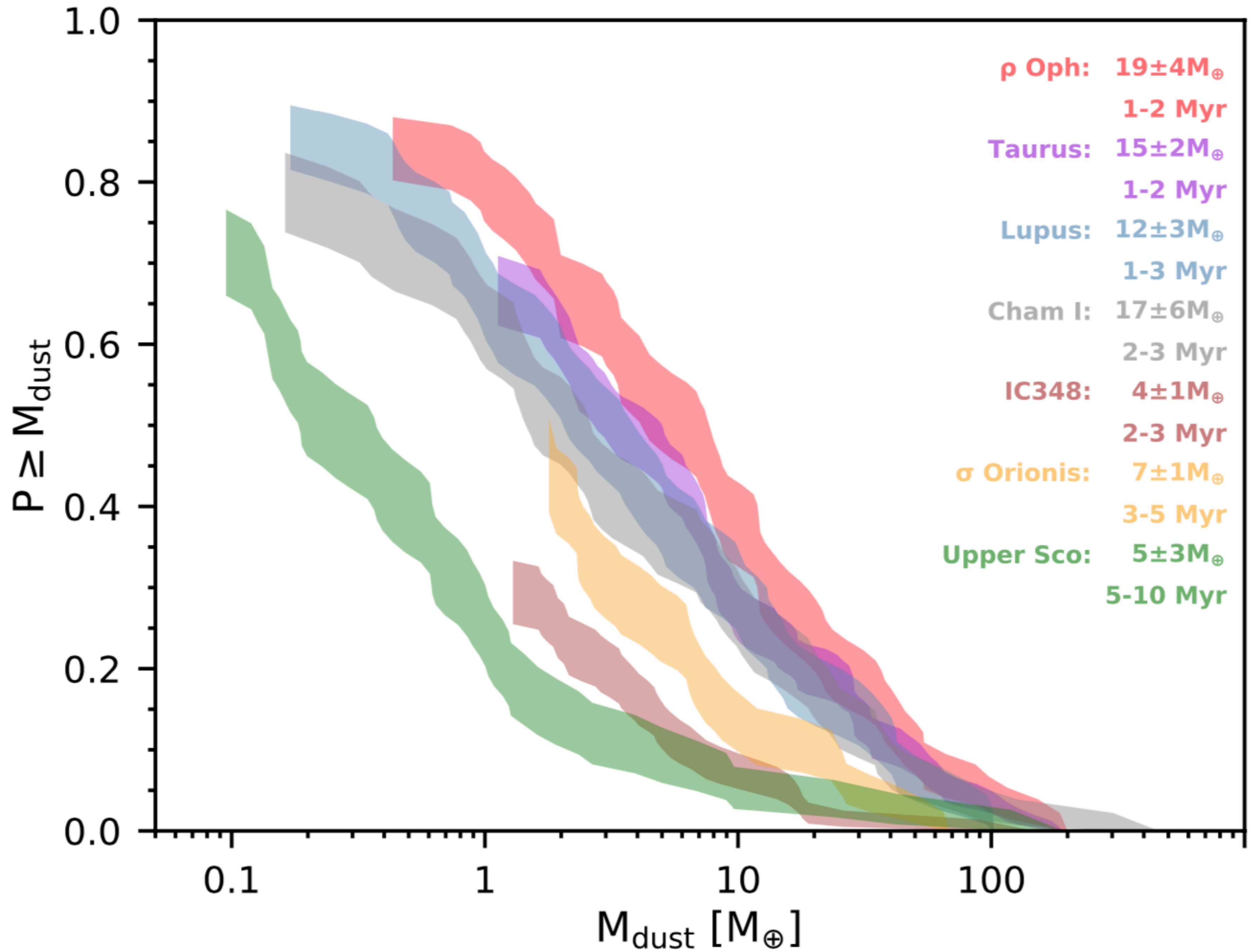
Upper Sco



Subset Taurus

Ansdell et al. 2016, Barenfeld et al. 2016,
Pascucci et al. 2016, Cieza et al. 2018,
Long et al. 2019

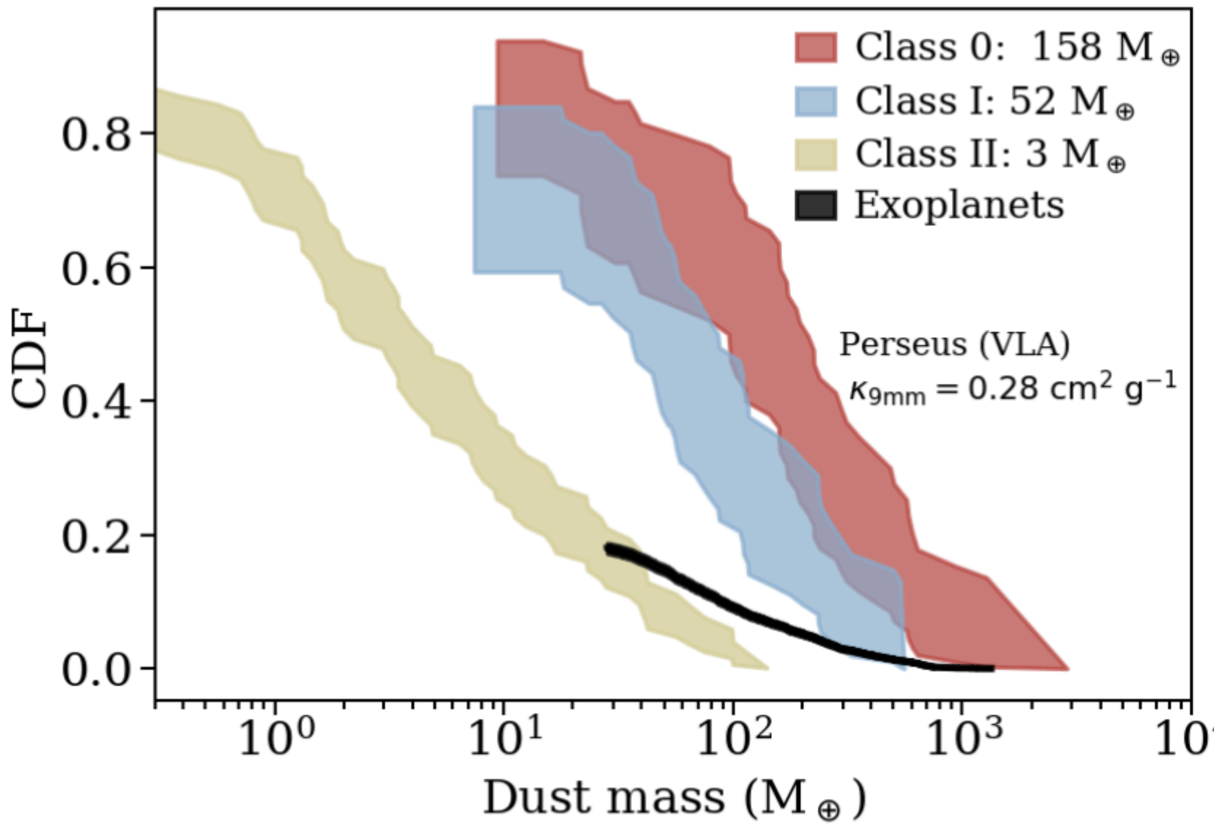
Dust mass trends

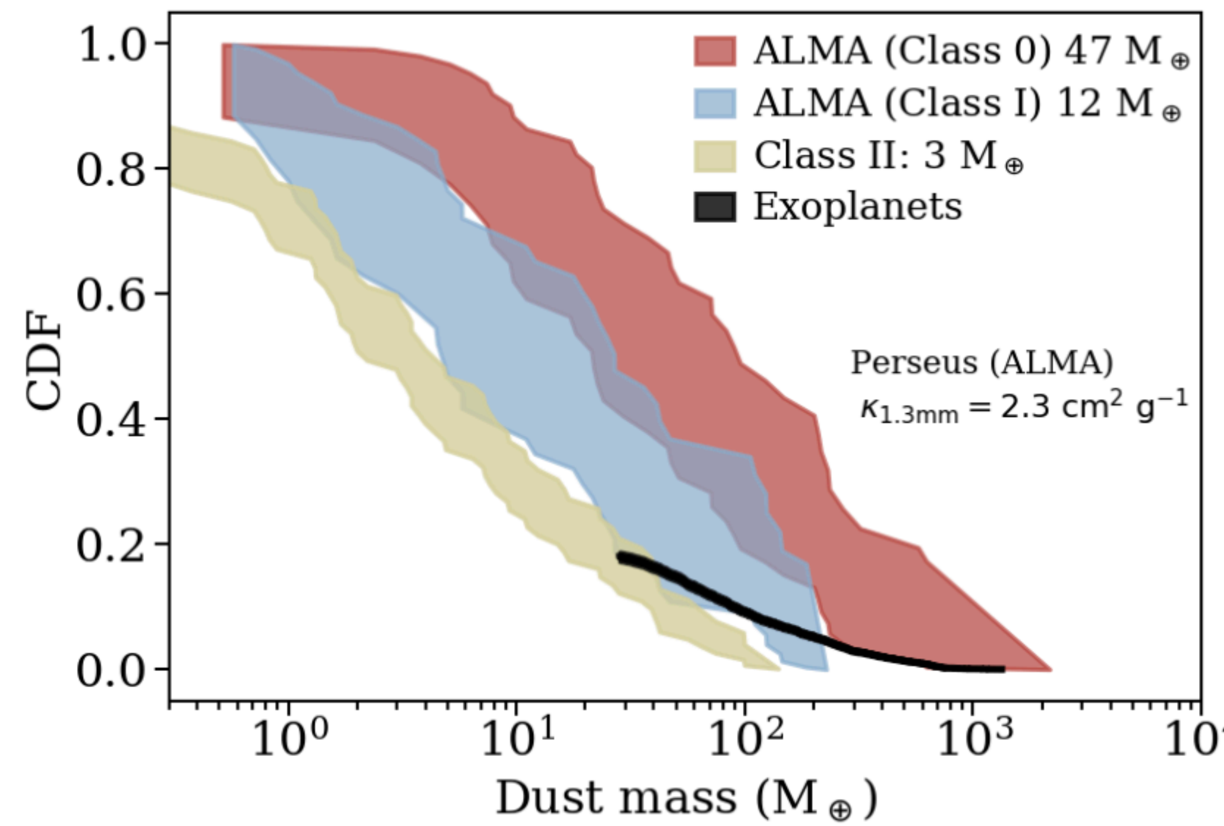


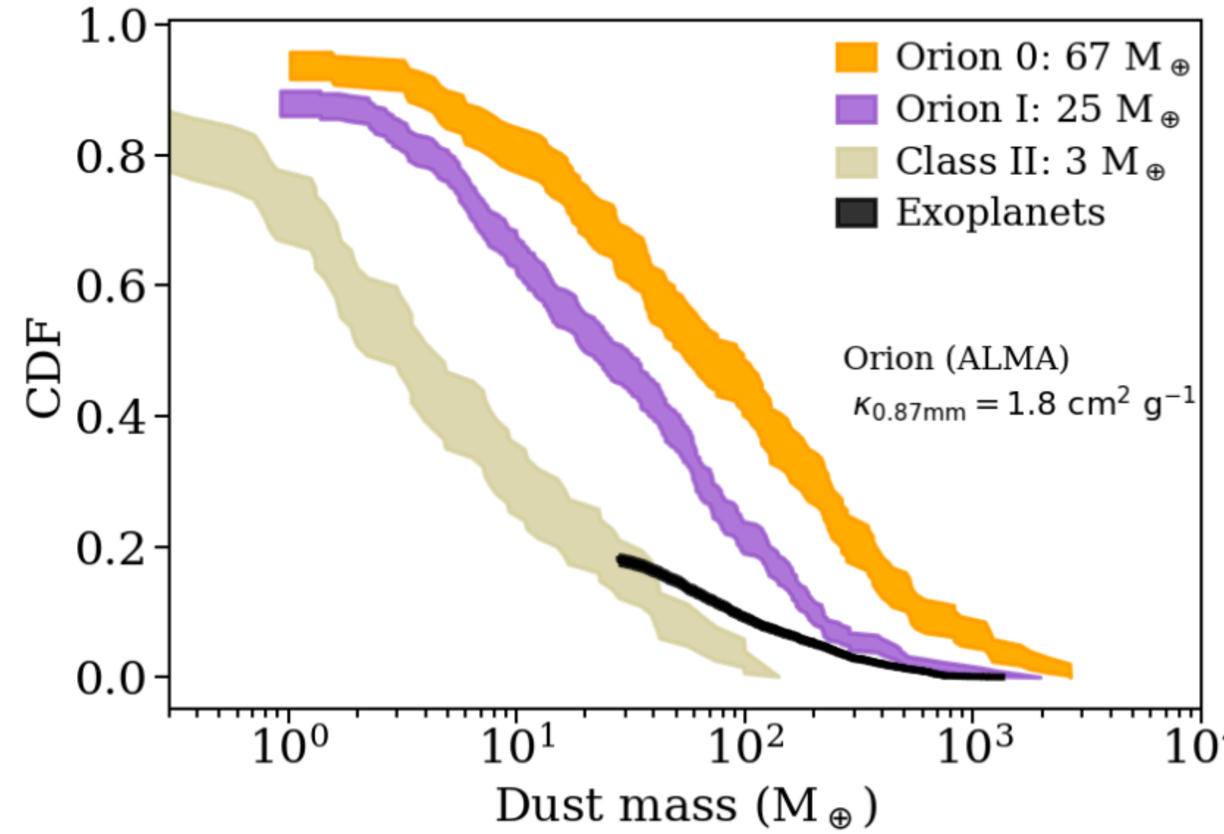
Observed dust mass decreases with age:
decrease of mm-dust grains or change in opacity?

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

Dust mass trends





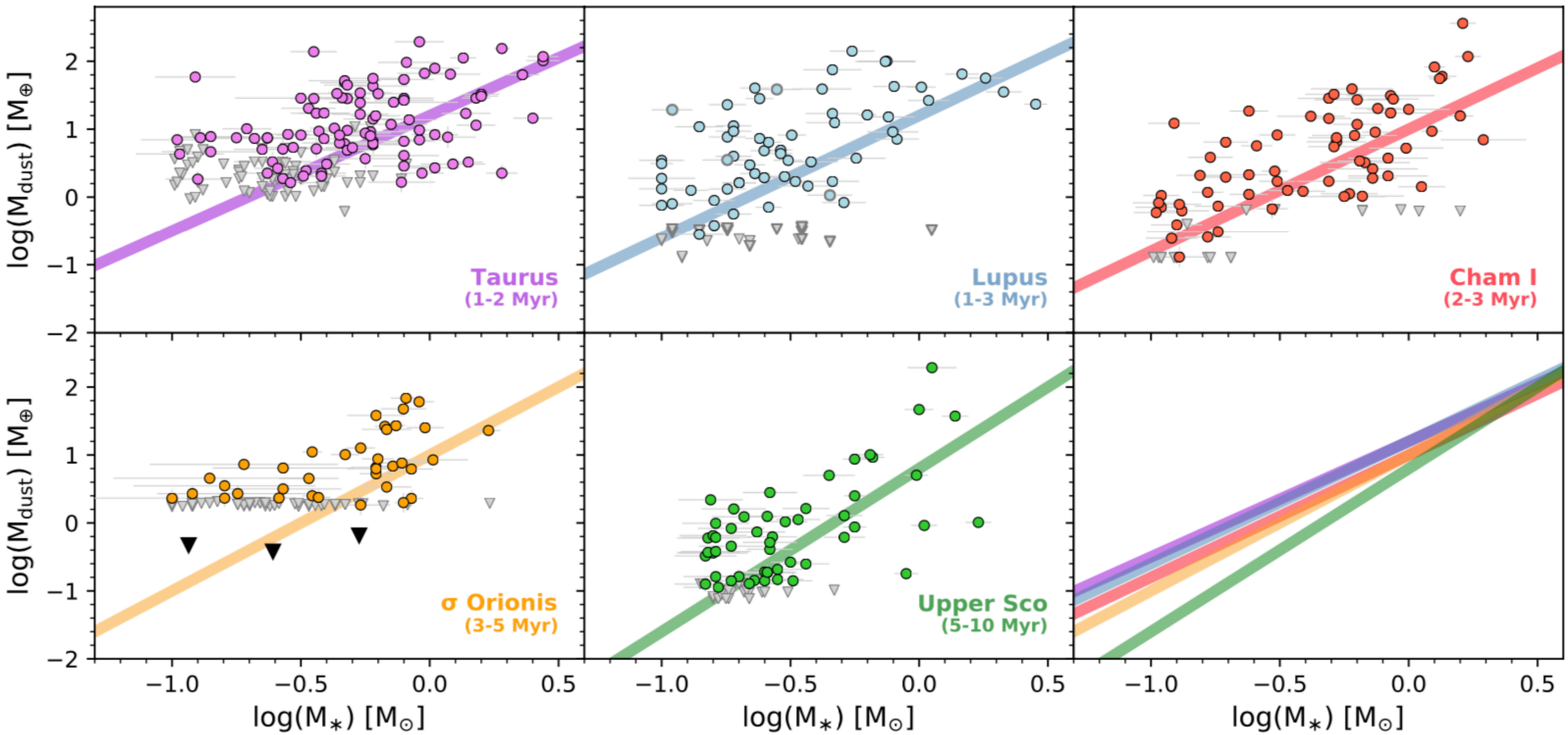


Decrease in dust mass already seen from Class 0 to Class II stage, even at longer wavelengths:

not just dust opacity change!

Tobin et al. 2020
Tychoniec et al. 2020

Dust mass trends

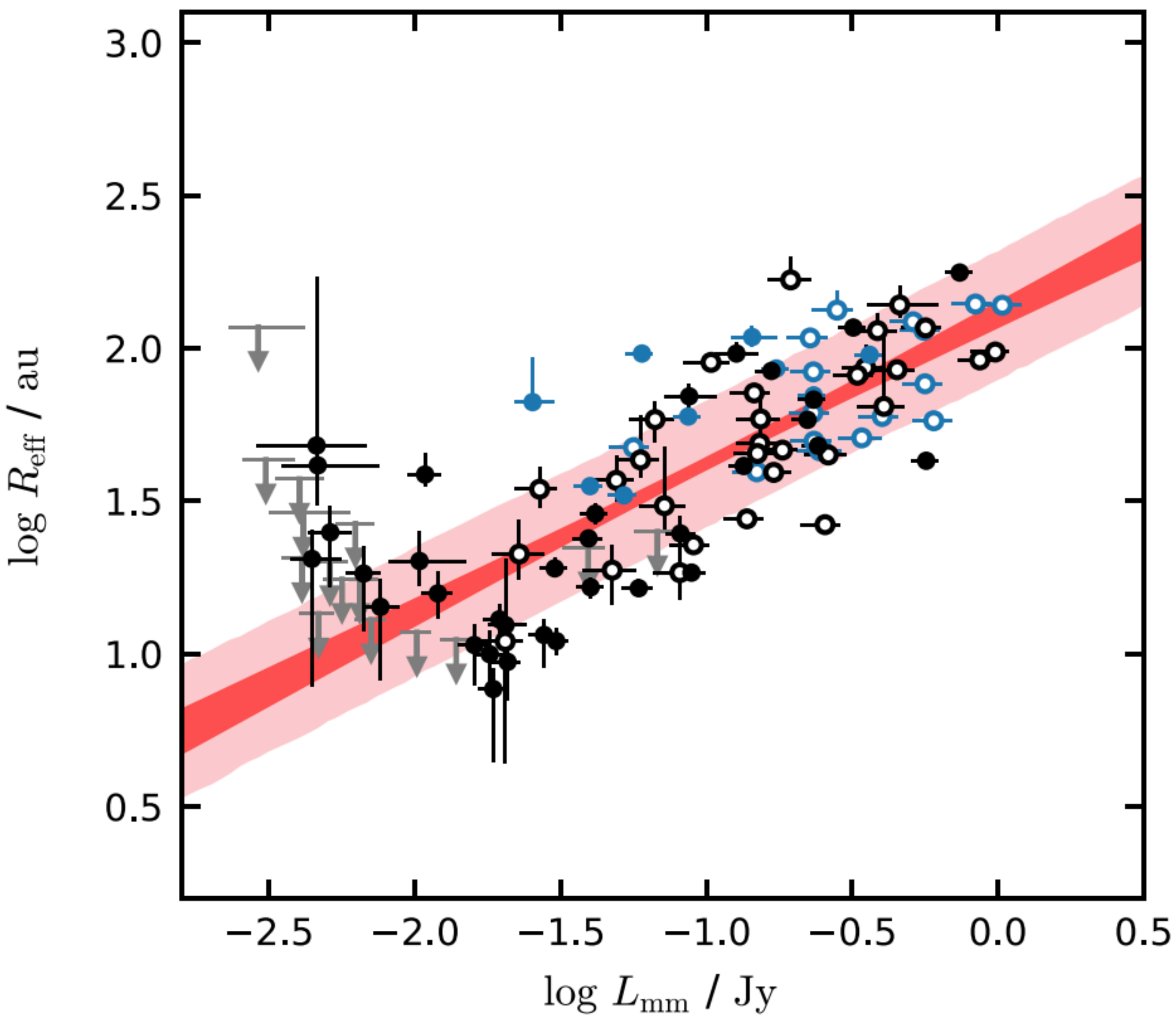


Disk dust mass scales with stellar mass
and decrease with age is stronger for low-mass

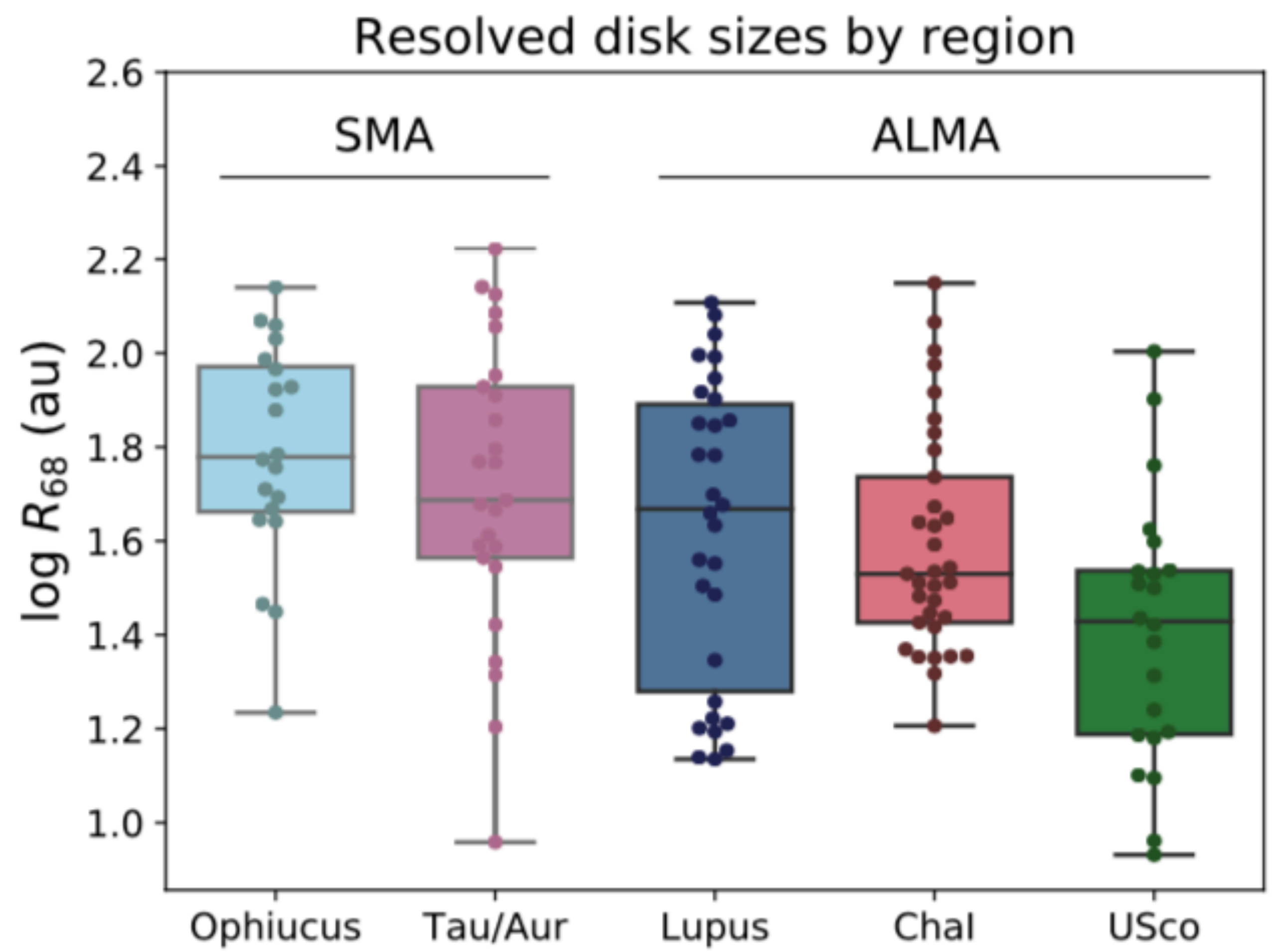
Ansdell et al. 2016, 2017

Dust mass trends

Trend disk dust size



(=M_{dust})

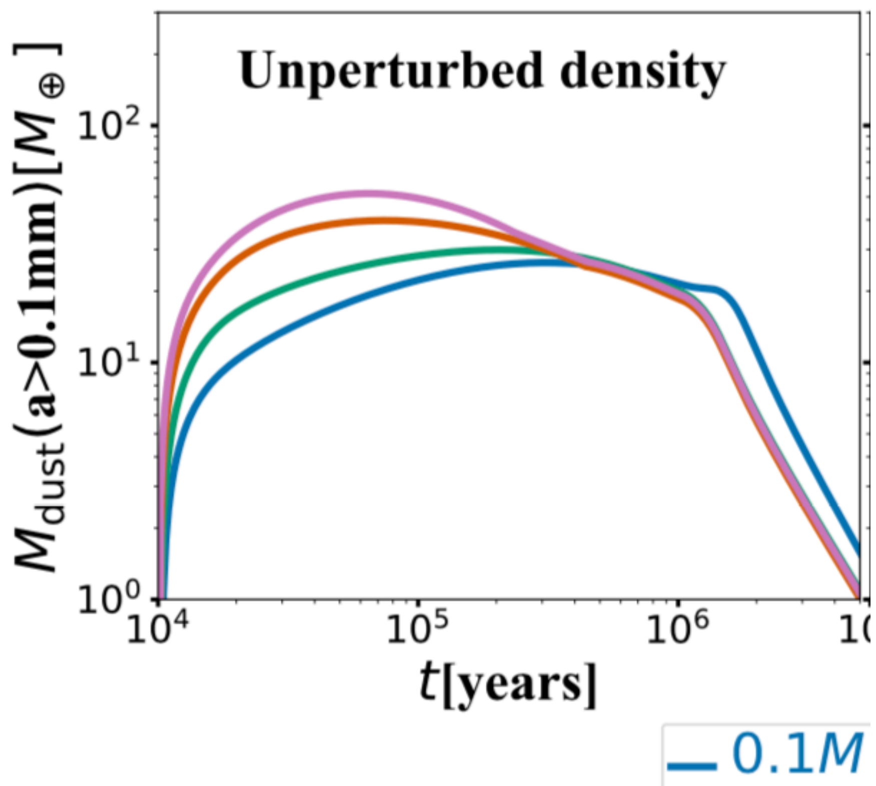


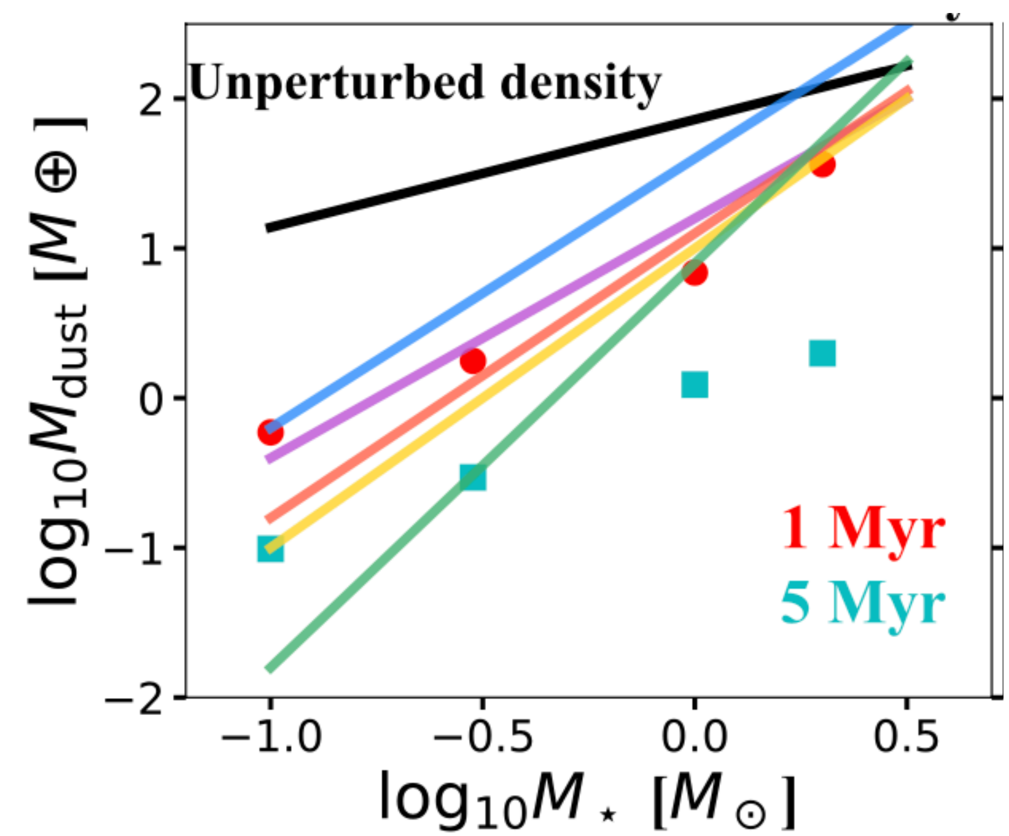
Disk dust size scales with dust mass and decreases with time

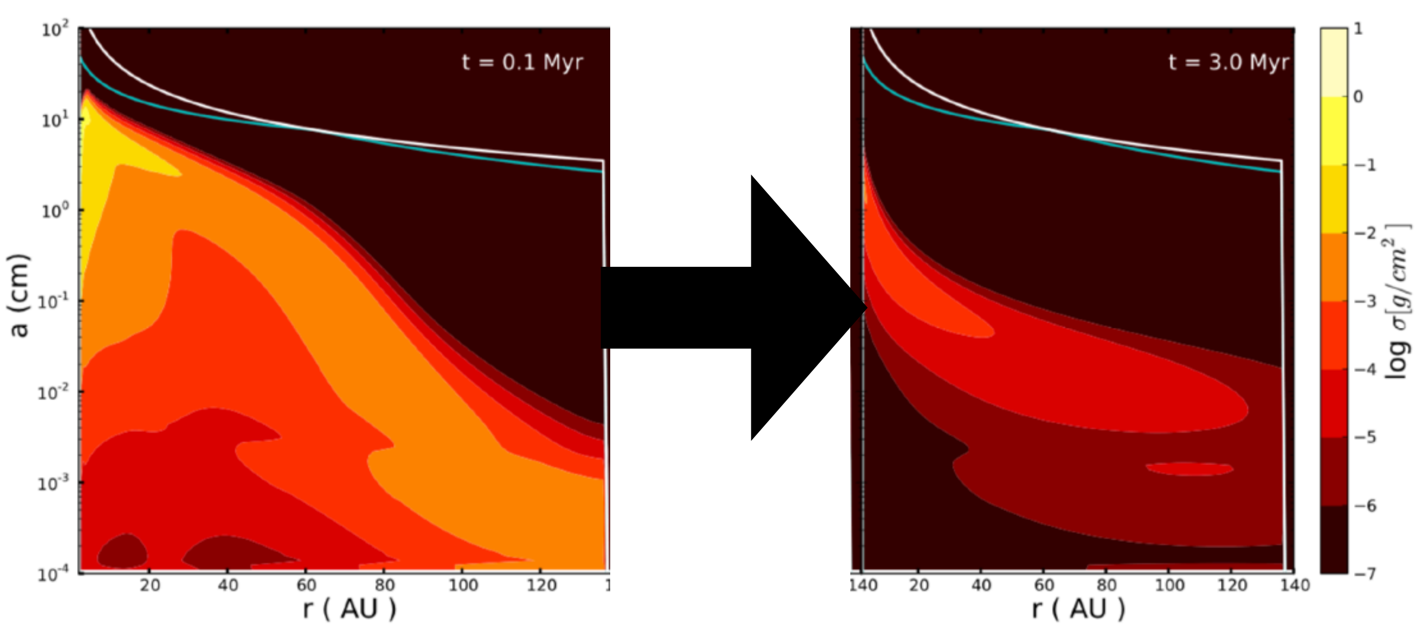
Hendler et al. 2020
Andrews et al. 2018

Dust mass trends

Dust evolution: radial drift





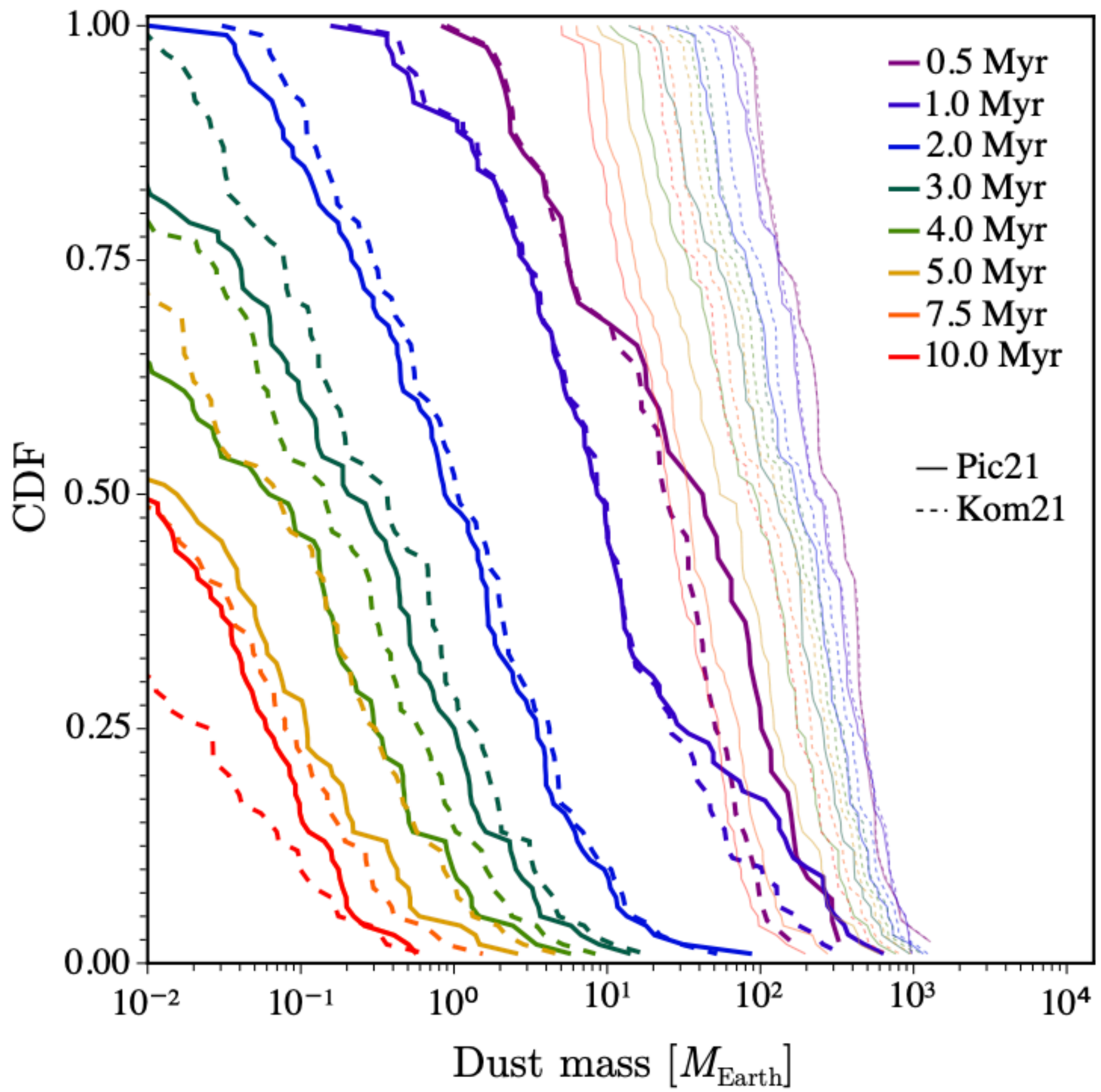


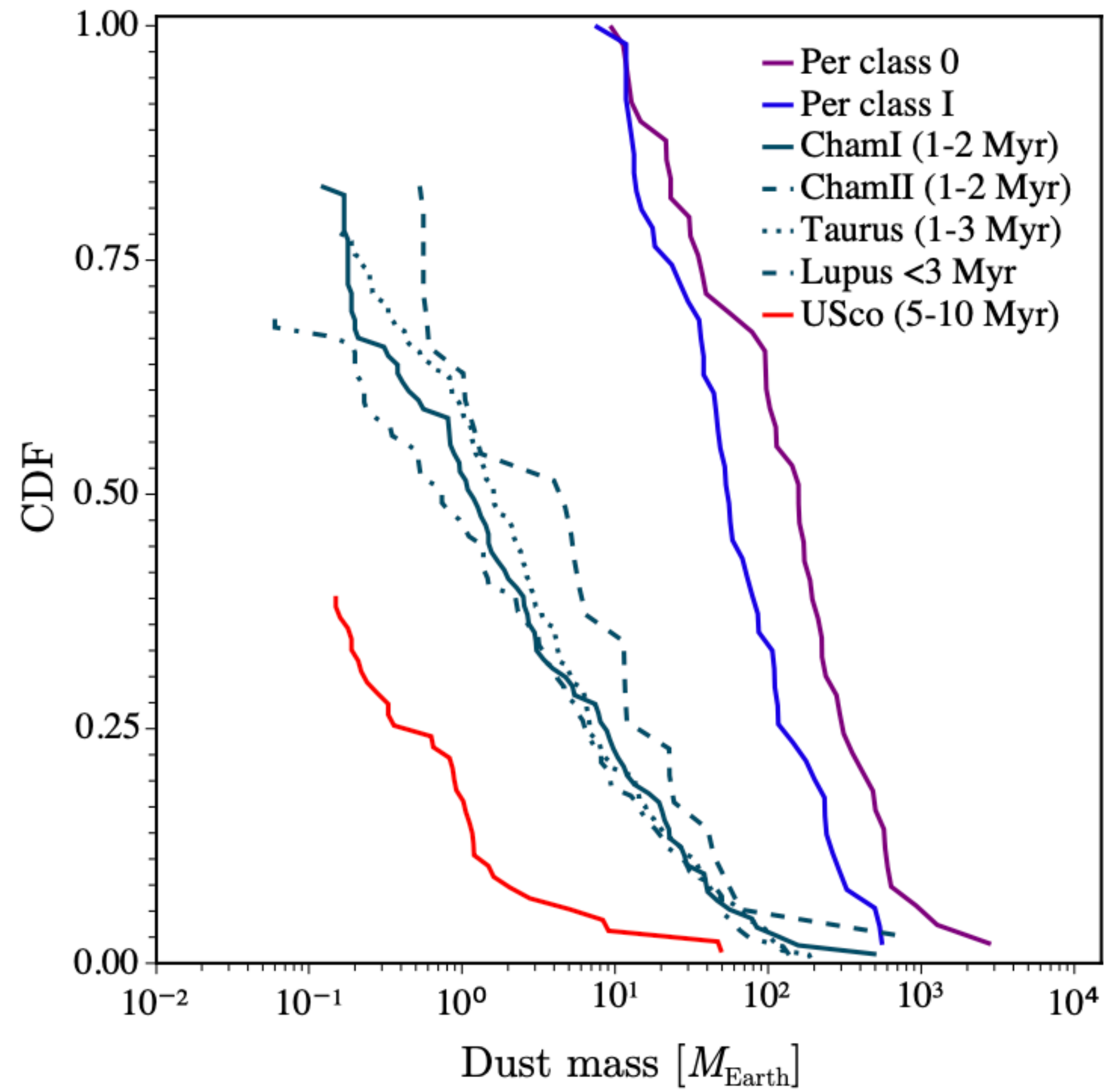
Radial drift decreases the dust mass over time, but not fully reproducing trend

Pinilla et al. 2012, 2020

Dust mass trends

Disk models





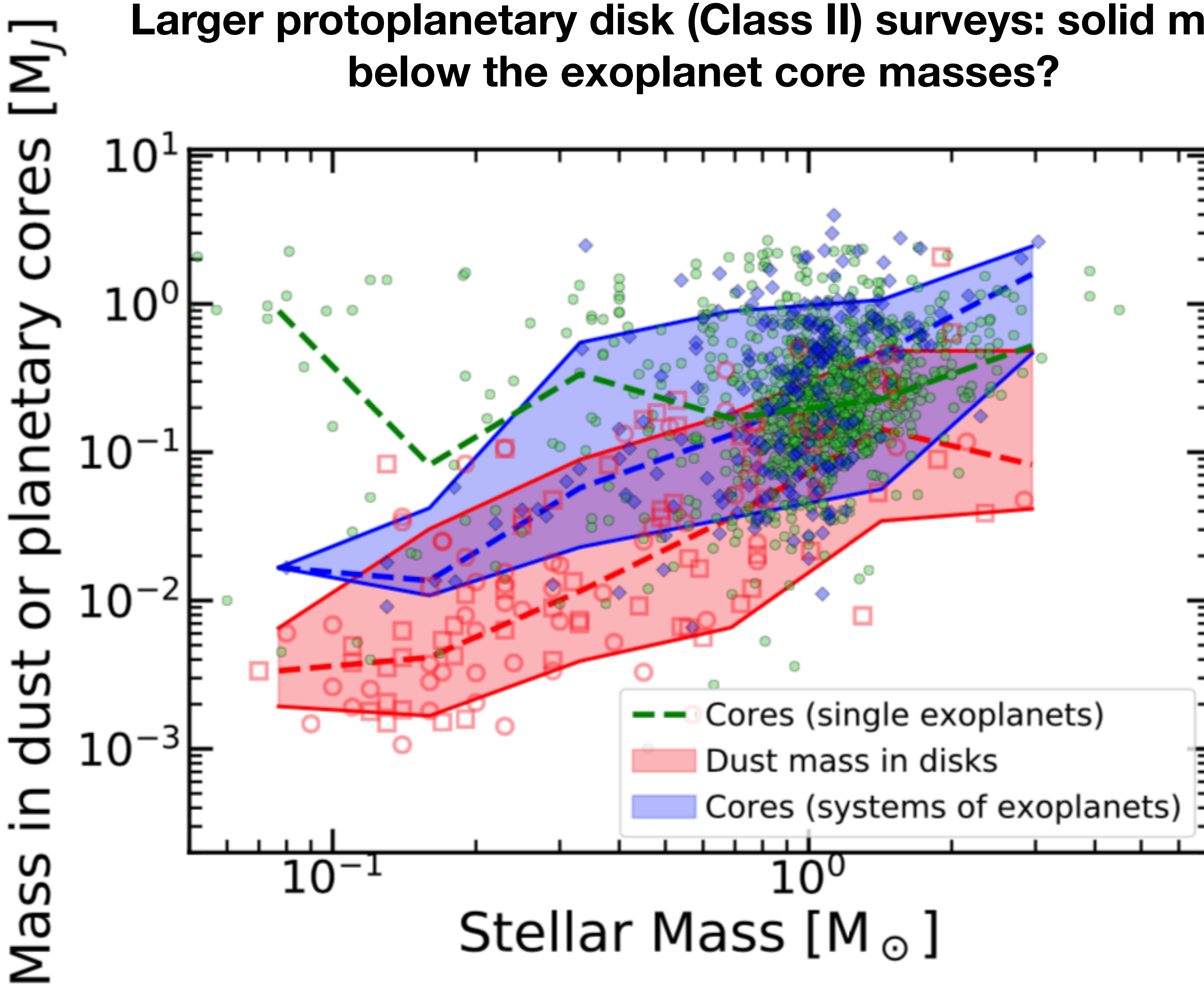
Disk population synthesis: dust mass evolution is consistent with majority of disks being drift-dominated

Appelgren, Lambrechts & van der Marel 2023

Dust mass trends

Solid mass budget

Larger protoplanetary disk (Class II) surveys: solid mass below the exoplanet core masses?

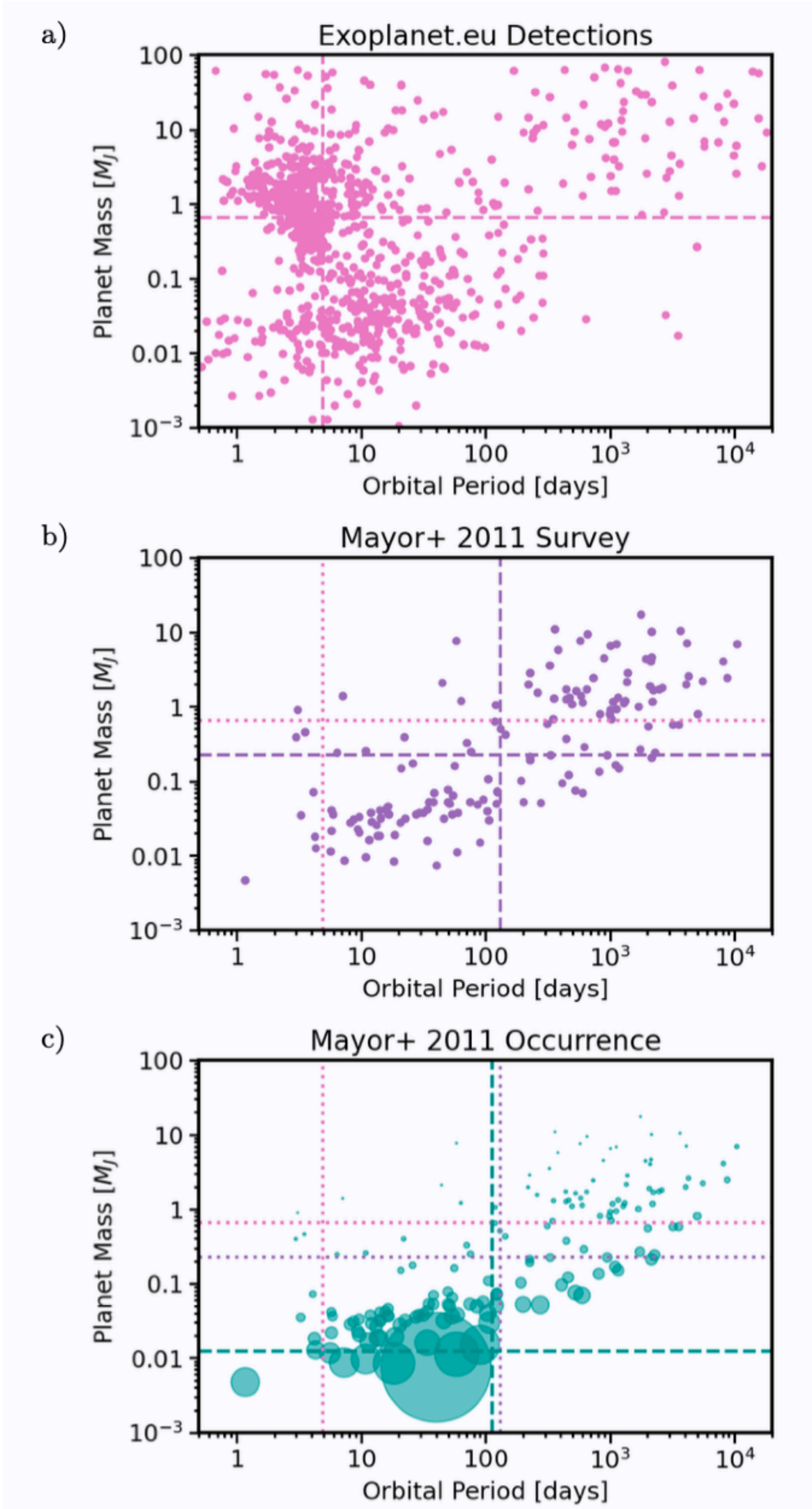


Exoplanets already formed before Class II stage?

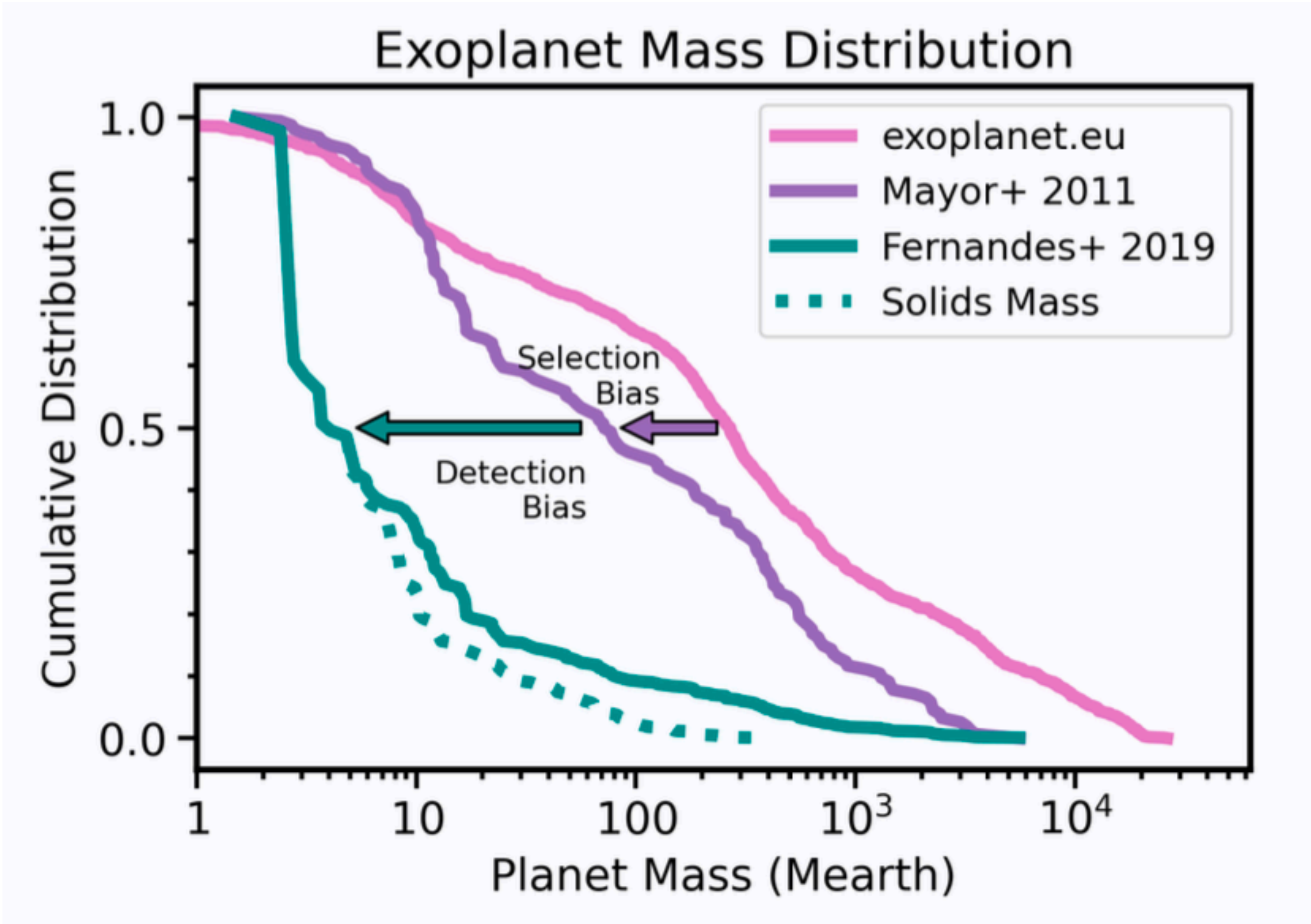
Manara et al. 2018

Dust mass trends

Revised: Solid mass budget



Careful! Exoplanet detection catalog is not a complete or unbiased survey

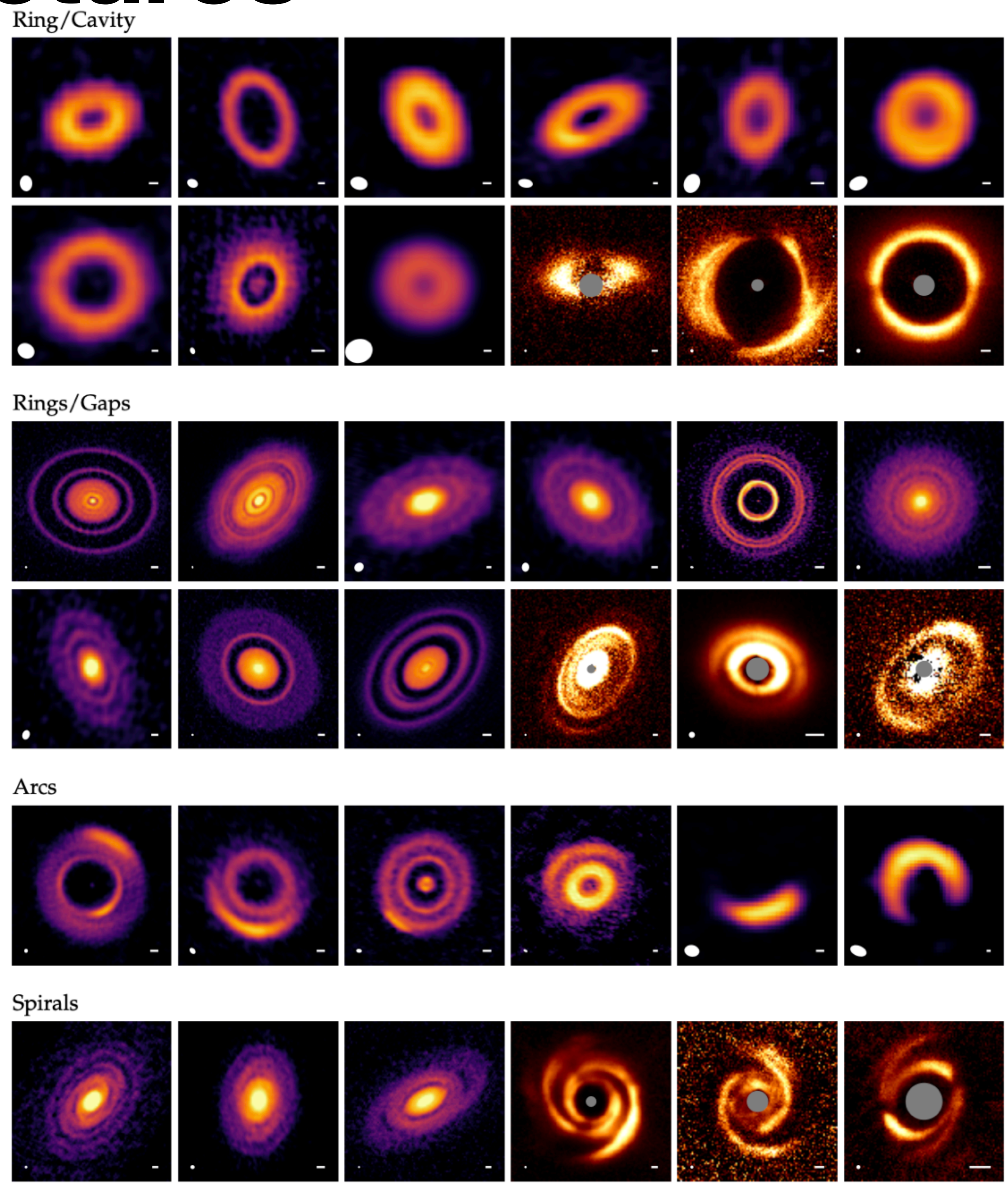


Need to correct for selection and detection biases to get the 'true' exoplanet mass budget

Mulders et al. 2021

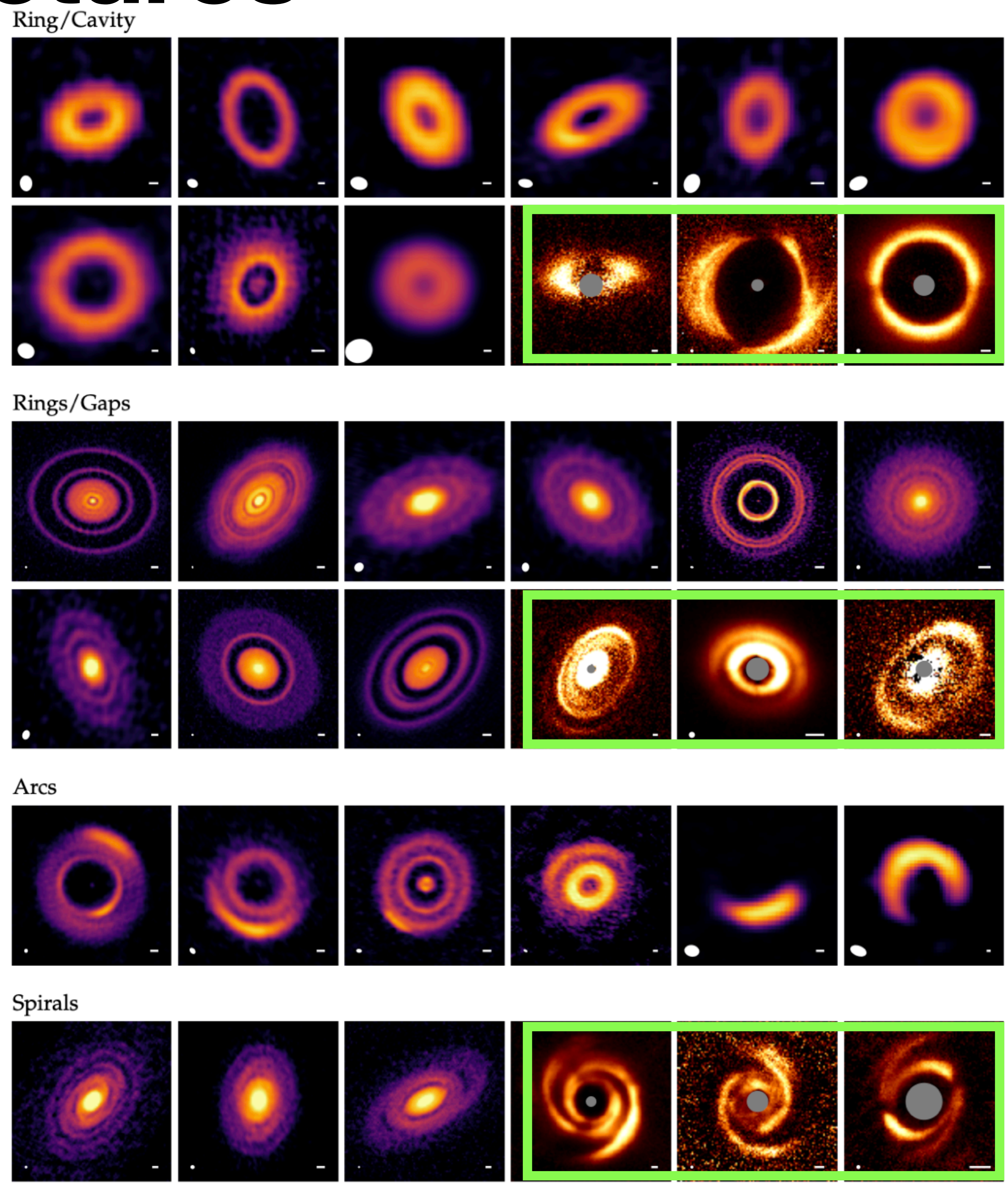
Dust substructures

- When you go to higher angular resolution: large diversity of substructures
- Distinguish:
    - Inner cavity
    - Rings/gaps
    - Arcs/crescents/asymmetries
    - Spirals



Andrews 2020 (ARAA)

Dust substructures



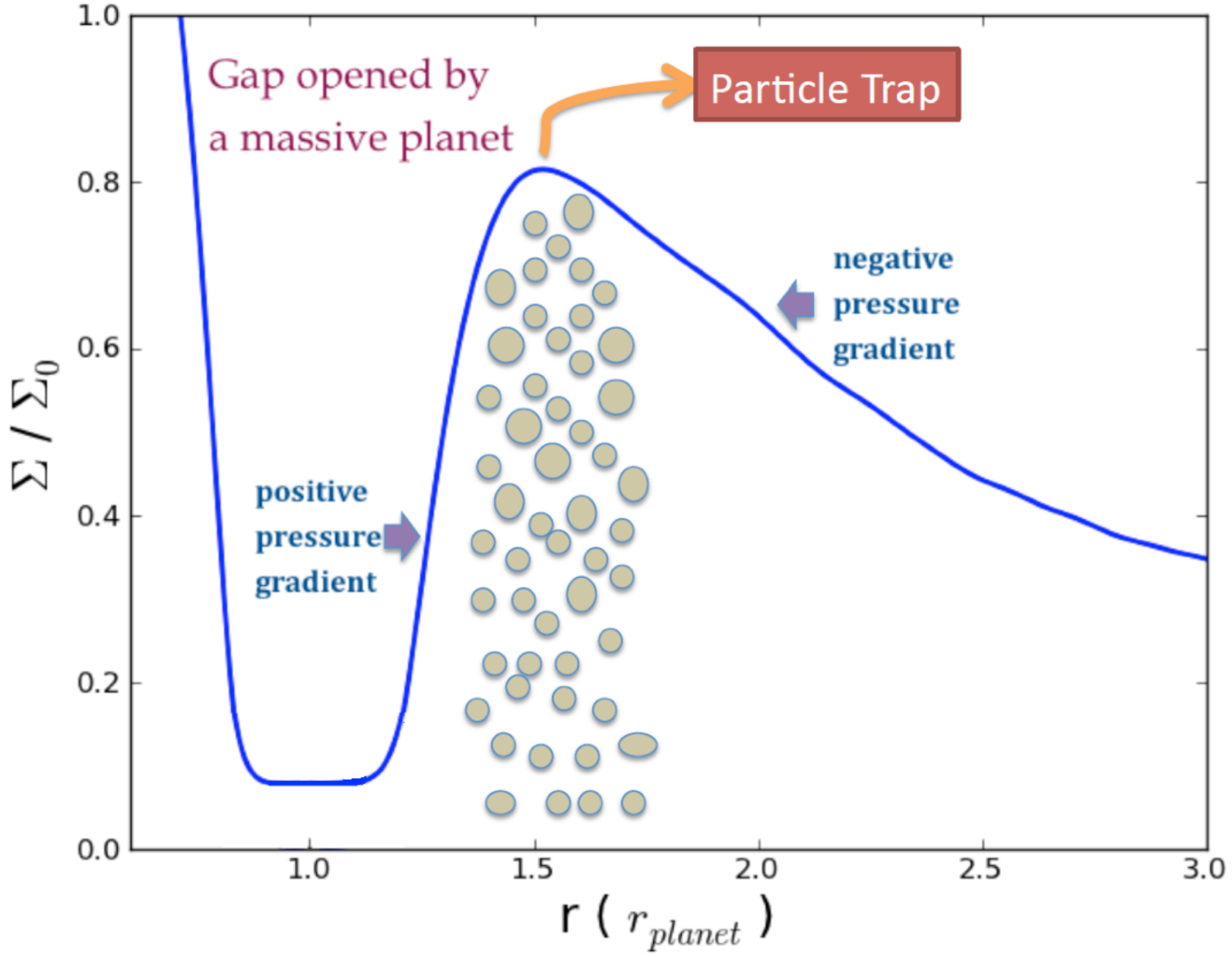
- Scattered light images not discussed now (different from ALMA: surface layers, small grains)

This afternoon (Antonio)

Andrews 2020 (ARAA)

Dust substructures

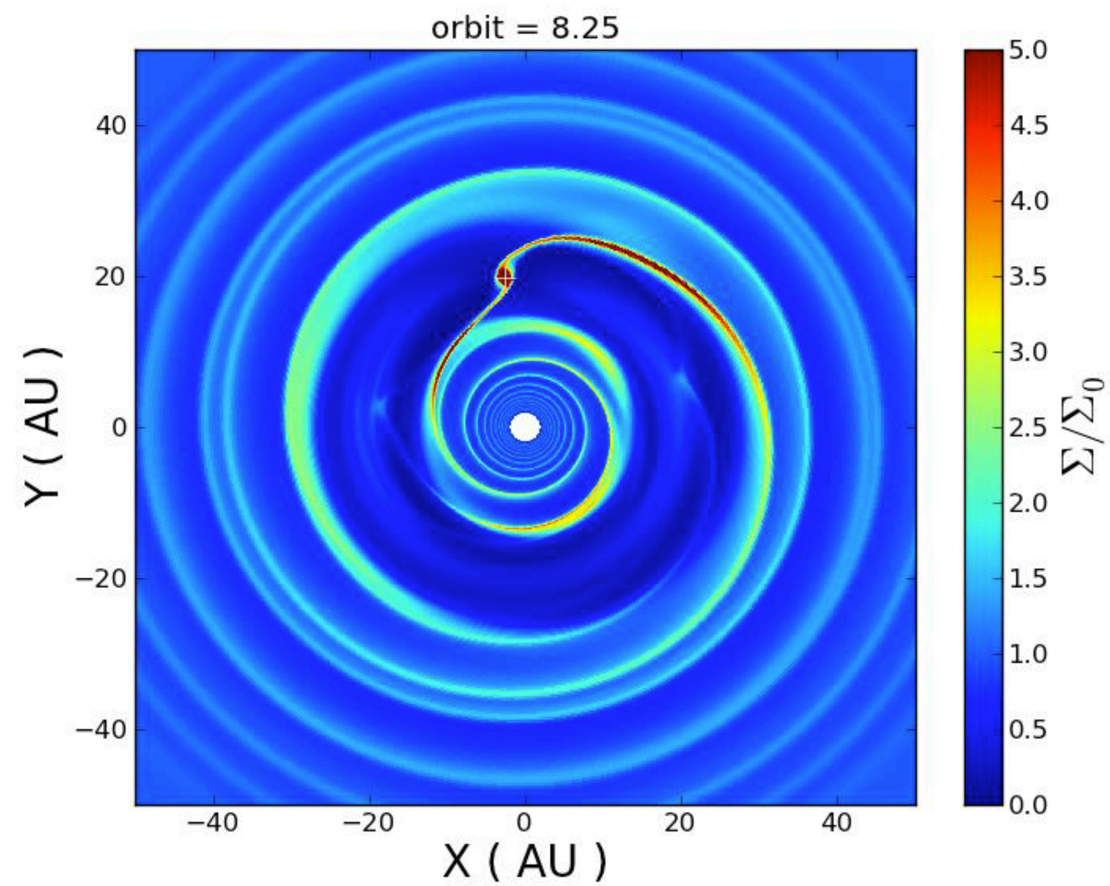
Origin: dust traps in pressure bumps



Pressure bump (e.g. caused by a planet) creates a radial dust trap => ring

Dust dynamics (Jean-Francois)

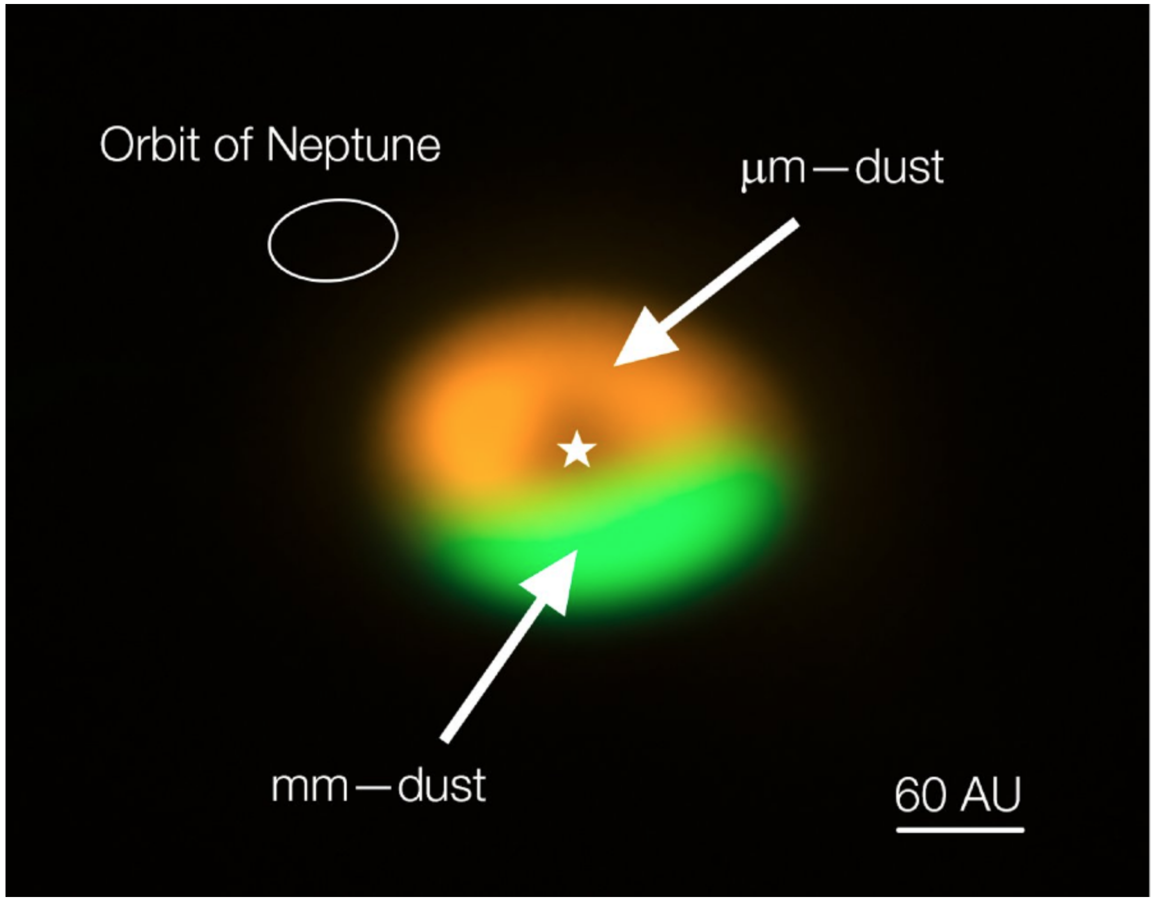
Rossby Wave Instability of pressure bump results in long-lived vortices: azimuthal pressure bump => asymmetry

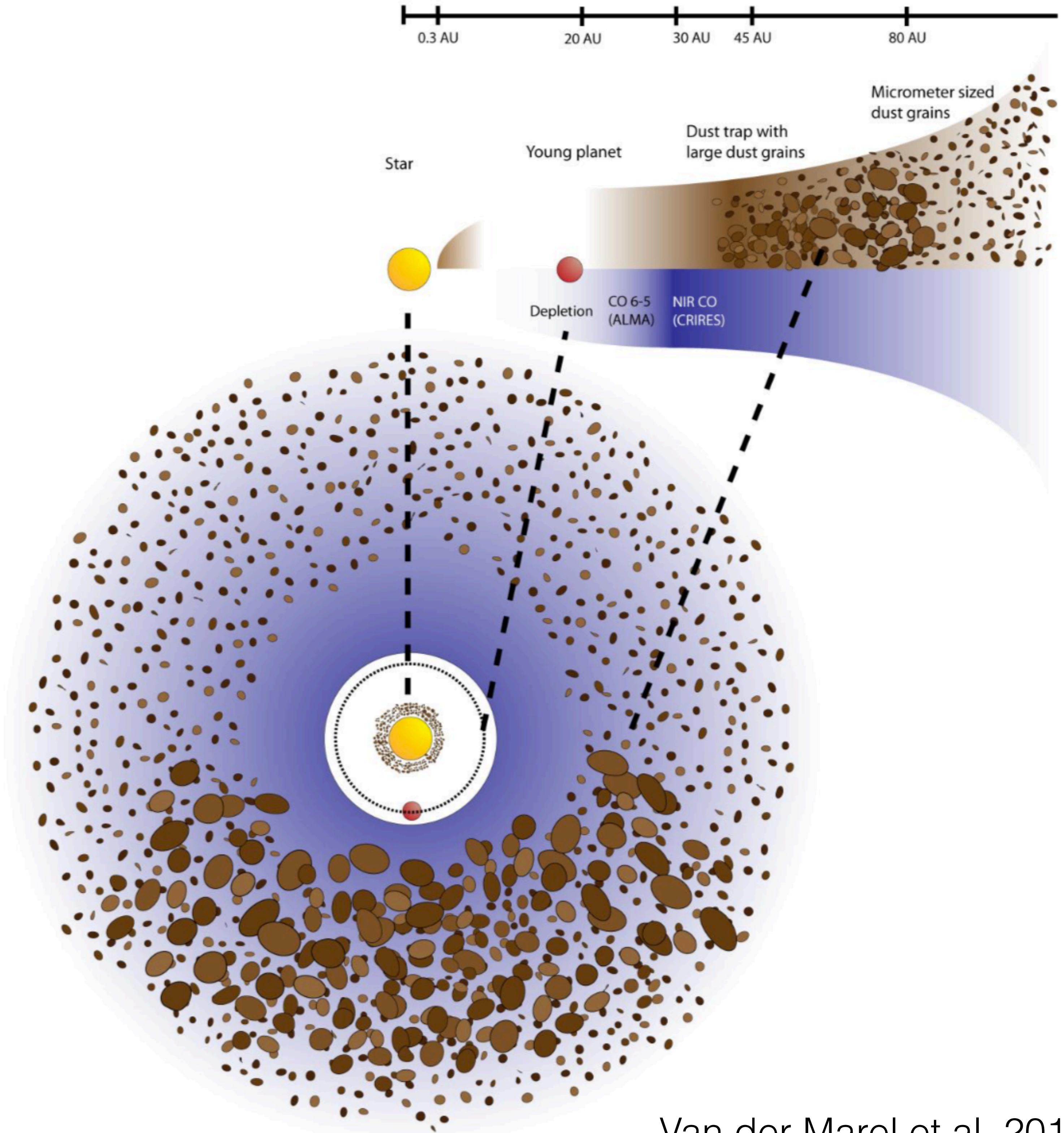


Instabilities (Sijme-Jan)

Dust traps

How it started

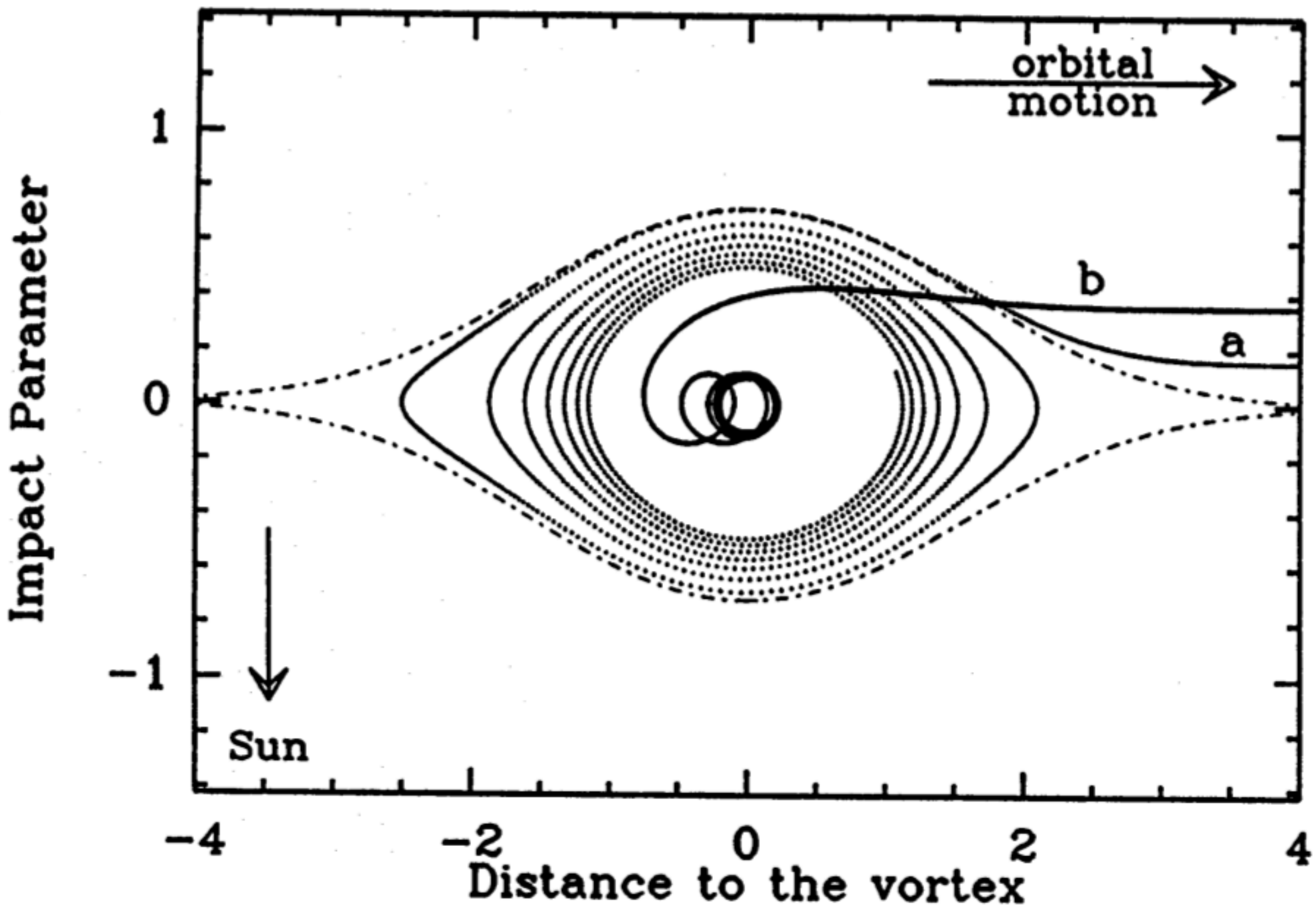




Van der Marel et al. 2013

Dust traps

How it REALLY started



Barge & Sommeria 1995
Klahr & Henning 1997

Problem:
dust traps require planets?

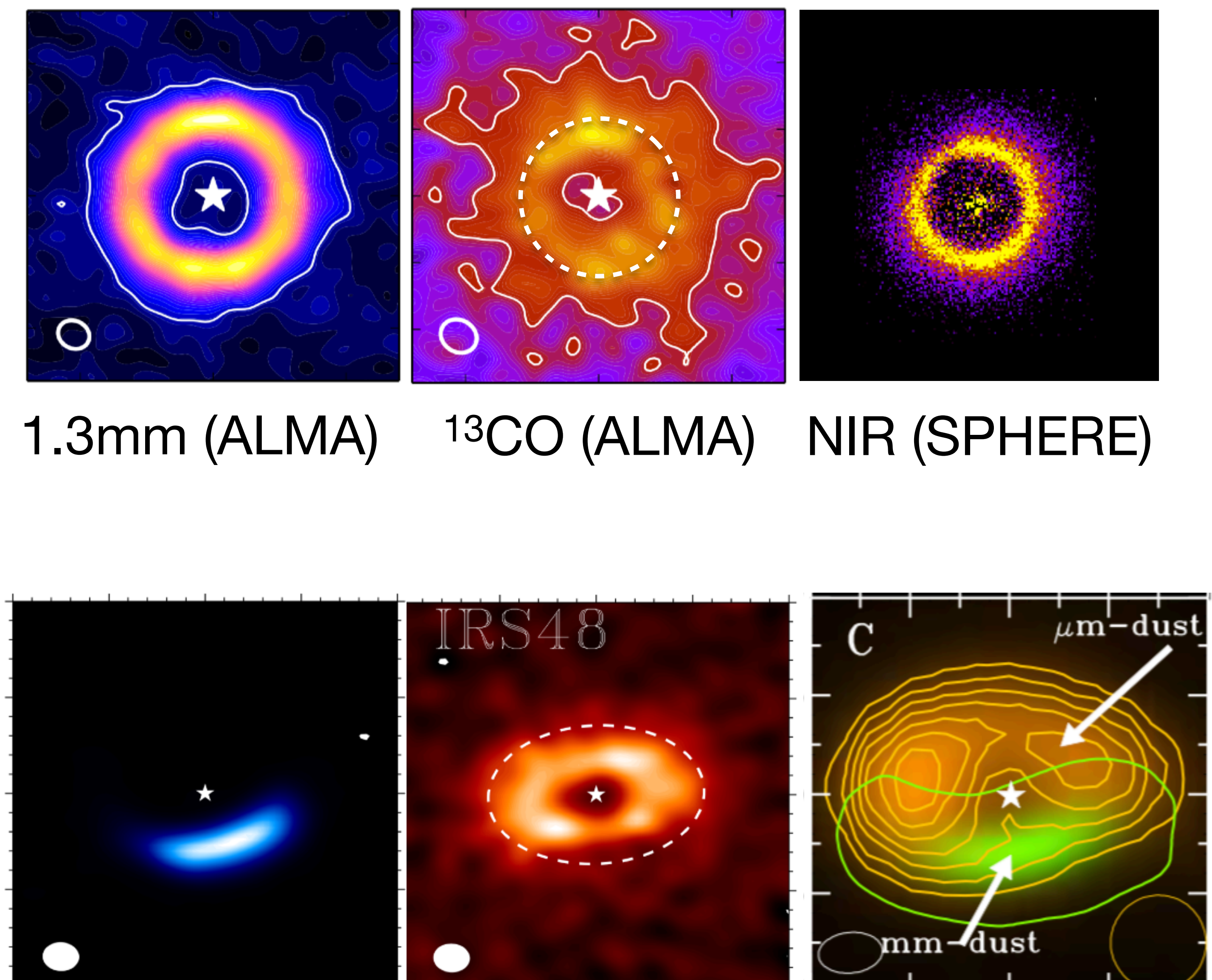
Dust trapps

Observational evidence

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

J1604-2130

IRS48



1.3mm (ALMA) | ^{13}CO (ALMA) | NIR (SPHERE)

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

Radial trapping

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

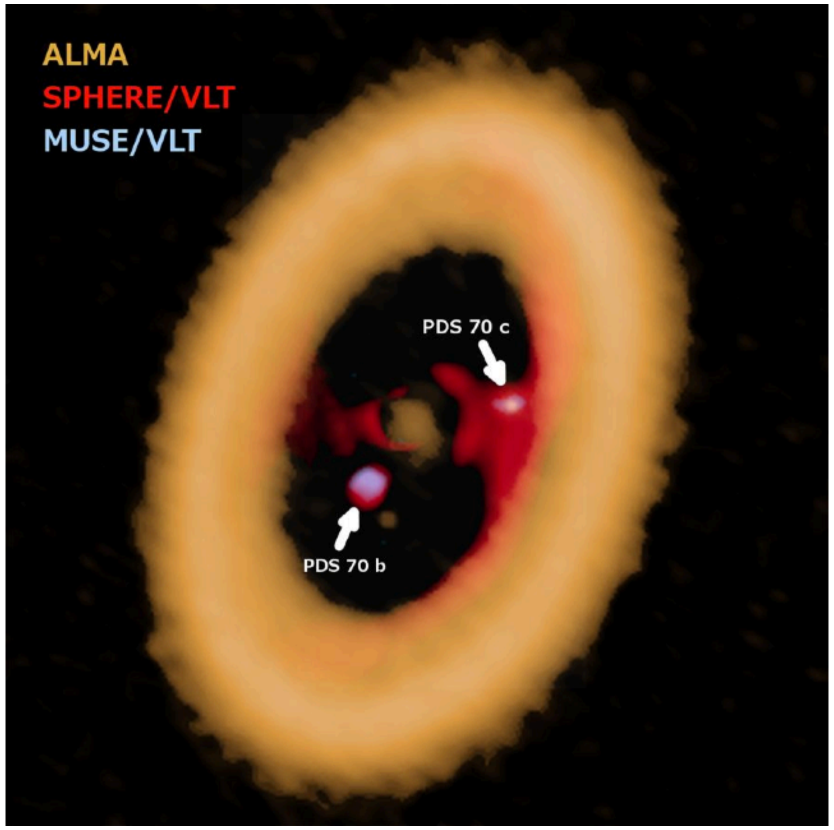
Azimuthal trapping

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

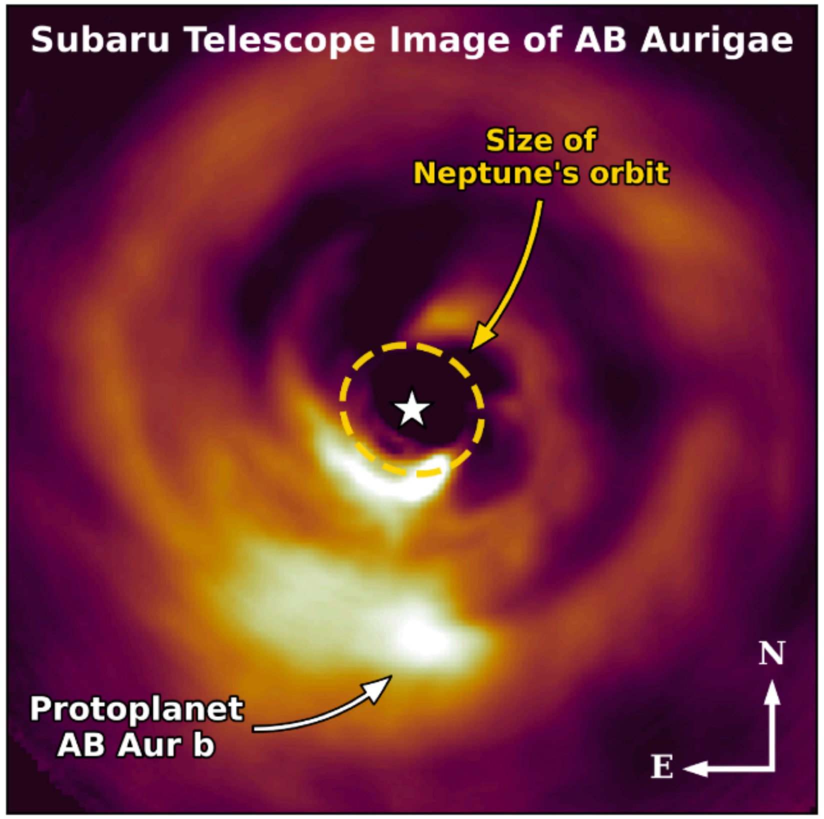
Dust traps by planets

Observational evidence

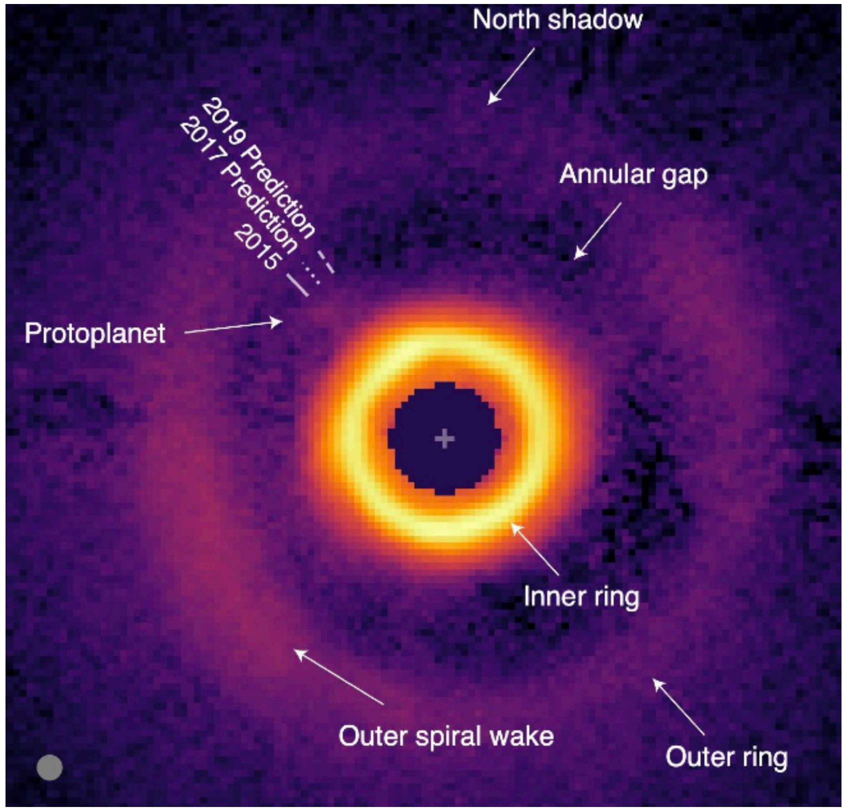
+ lots of indirect evidence in other gaps



PDS70 b+c



AB Aur b

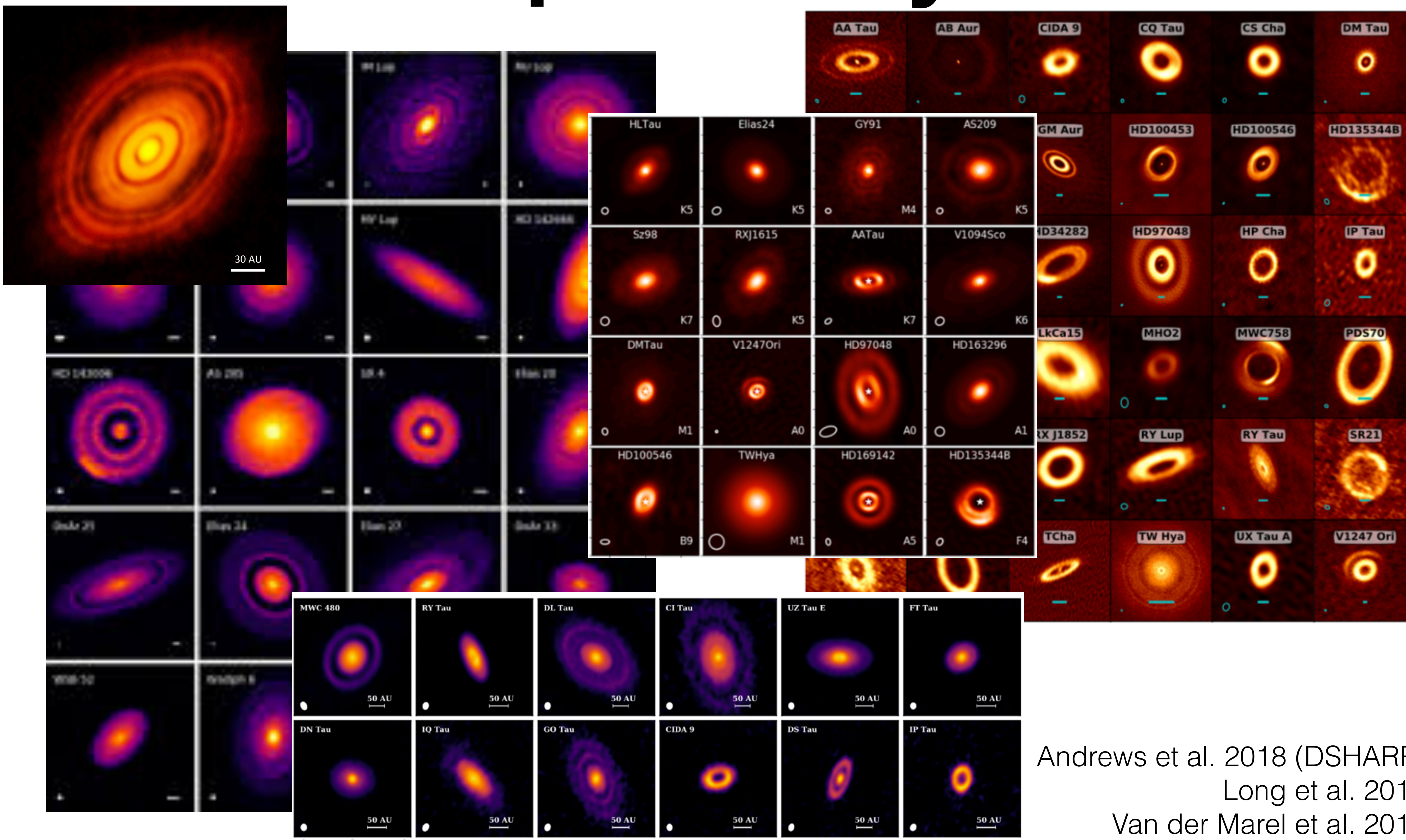


HD169142 b

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

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

Dust traps everywhere!

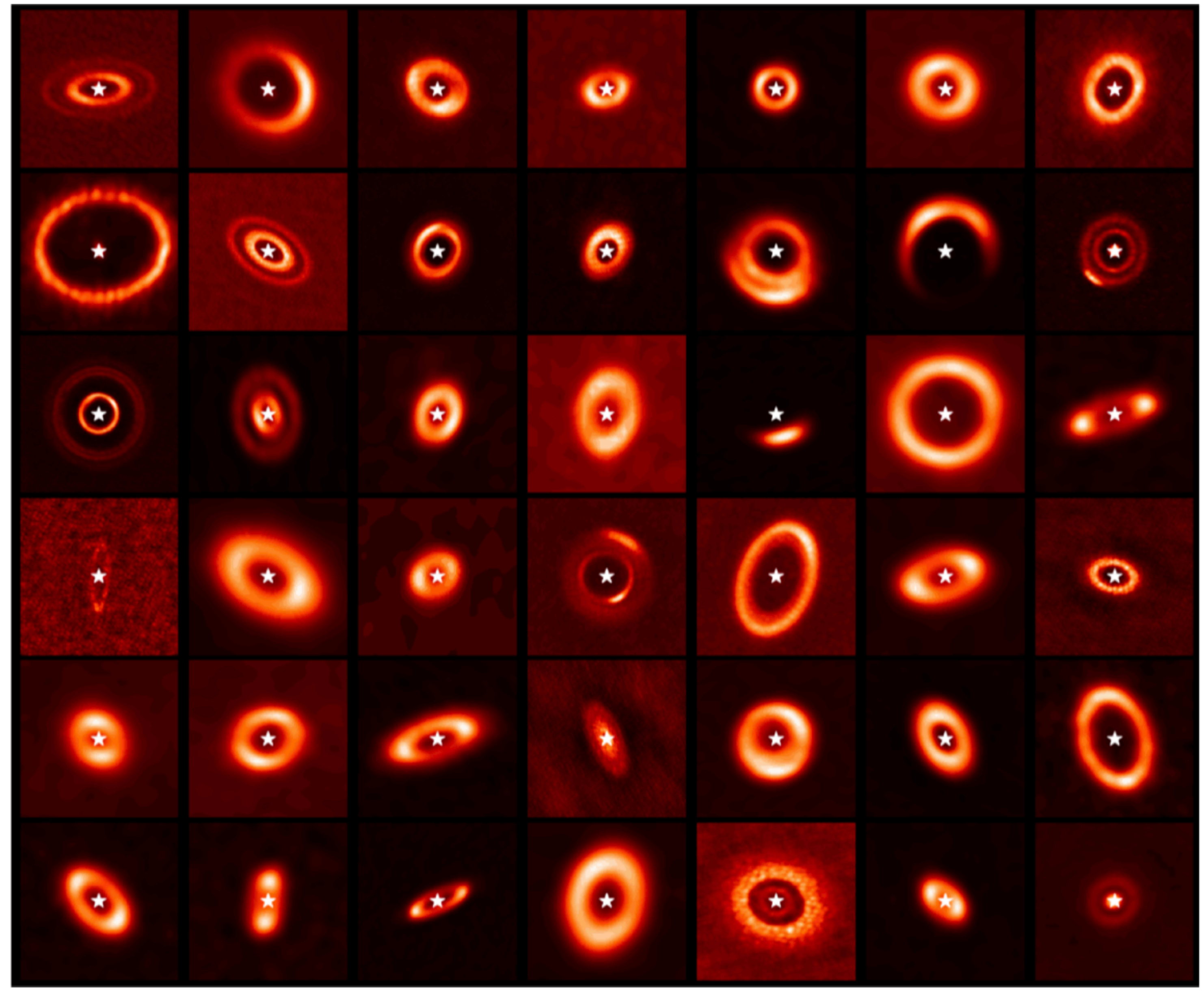


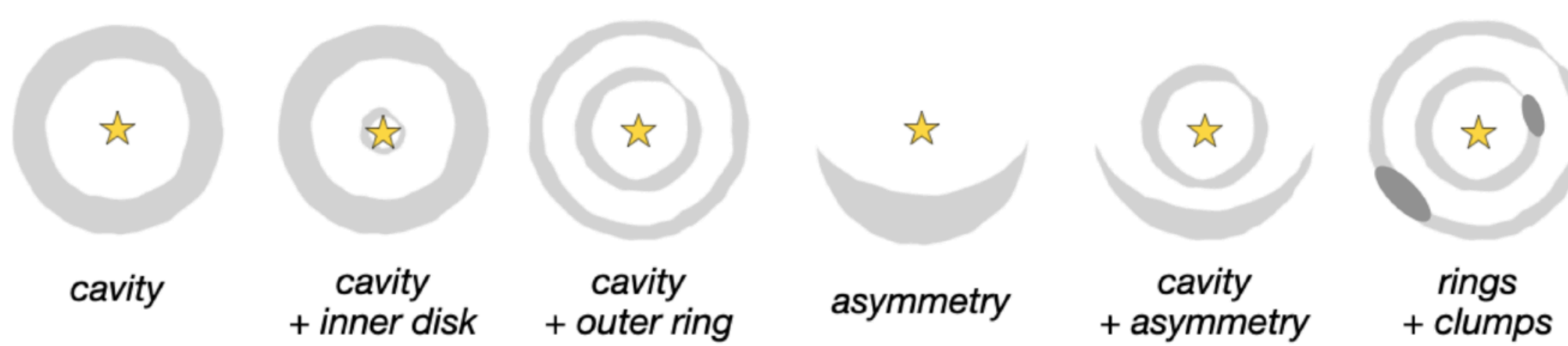
Andrews et al. 2018 (DSHARP)
Long et al. 2018
Van der Marel et al. 2019
Francis & van der Marel 2020

Inner cavities

Transition disks

- Inner cleared dust cavity (resolved: 15-150 au!)
- Due to large cavity radius: already resolved pre-ALMA!
- Sometimes asymmetries or multiple rings (outer gaps)
- Sometimes small inner dust disk
- Traditionally called ‘transition disk’



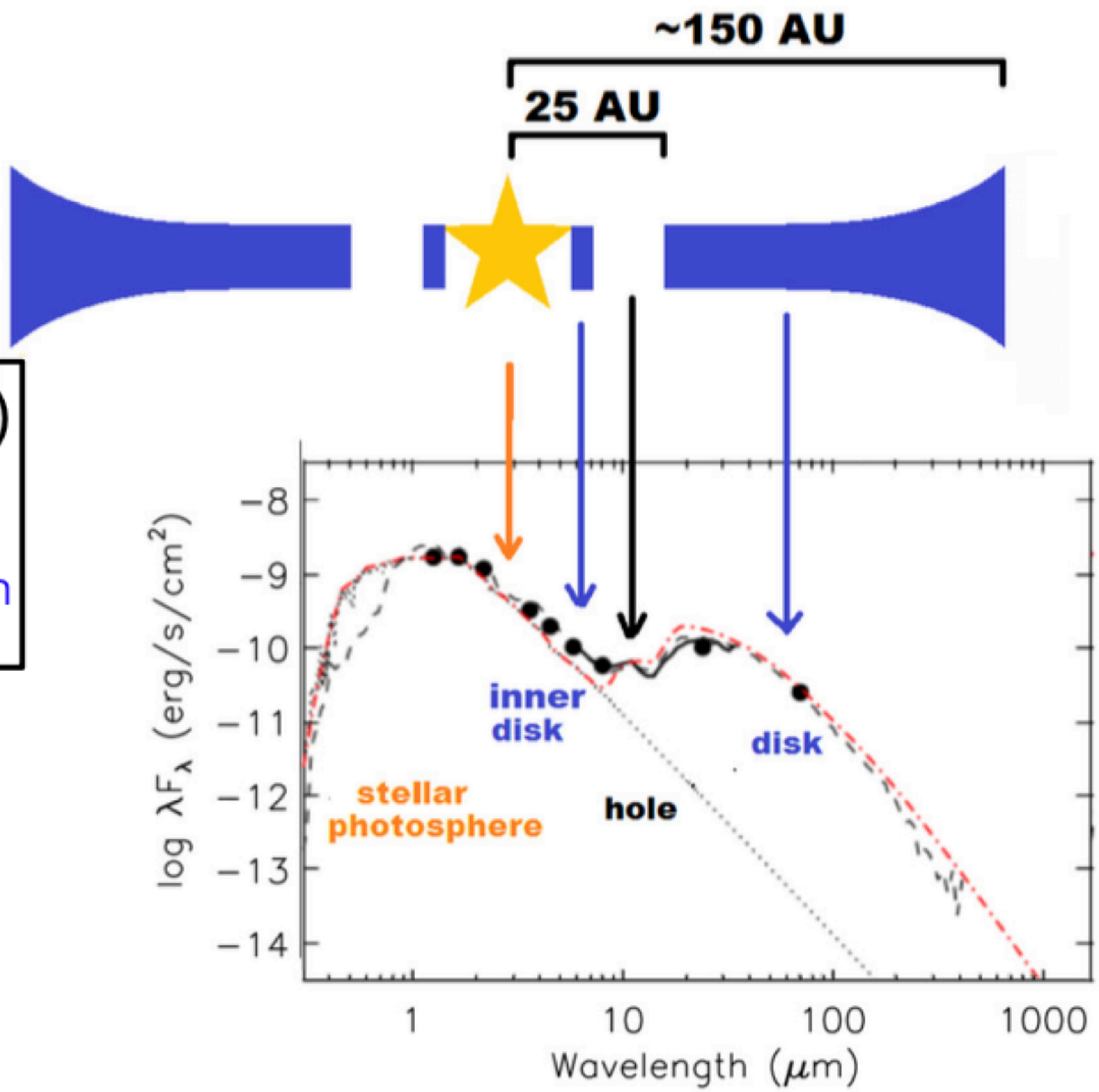


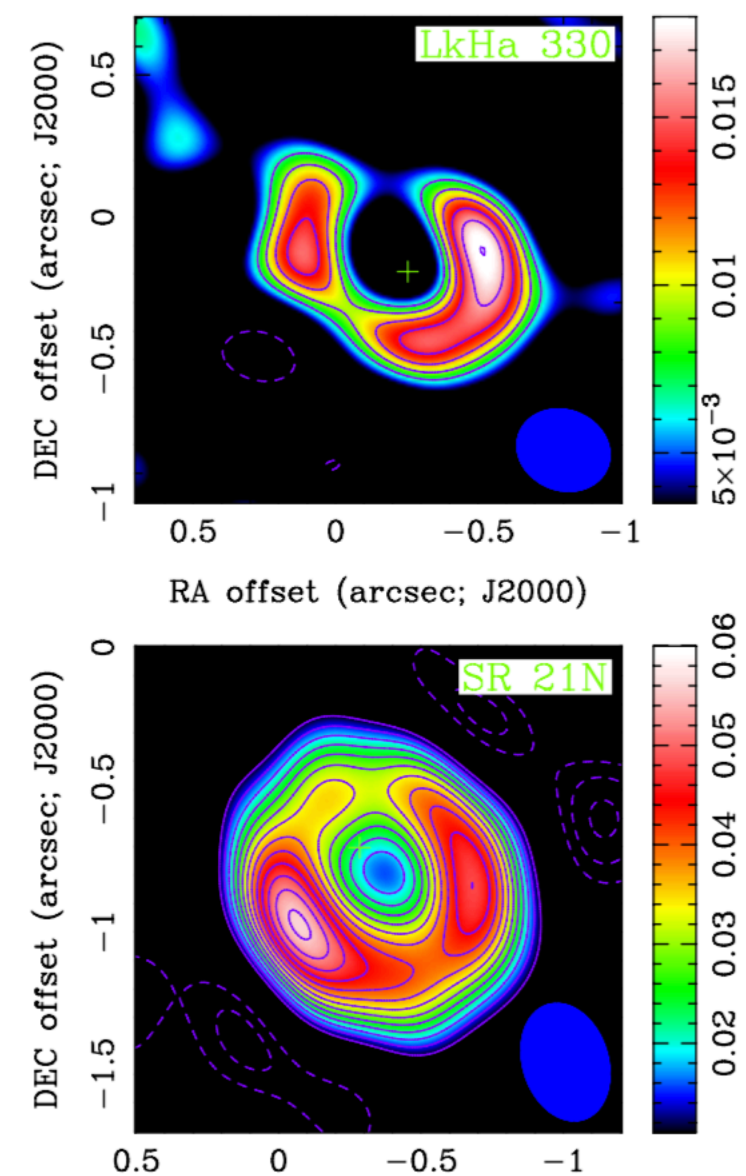
Van der Marel 2023 (EPJ+)

Inner cavities

Transition disks

First resolved images with SMA:





Transition(al) disks

Not necessarily an evolutionary term!

First discovery:
Strom et al. 1989

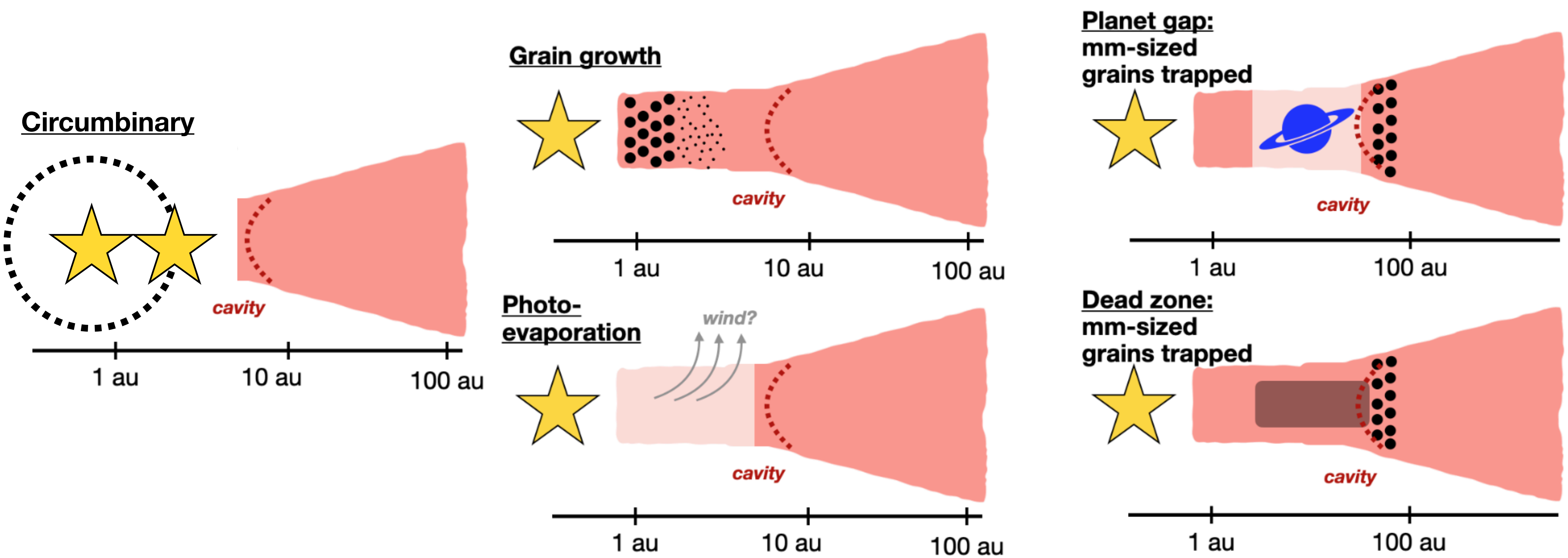
Inner cavity already revealed in SED deficit: 'lack of warm dust'

Van der Marel 2015 (PhD)
Brown et al. 2009, Andrews et al. 2011

Inner cavities

Origin: many other proposed mechanisms

Due to hypothesis that giant planets cannot easily form at large orbital radii (and lack of protoplanet detections until 2018!), many other mechanisms were proposed to explain transition disks pre-ALMA

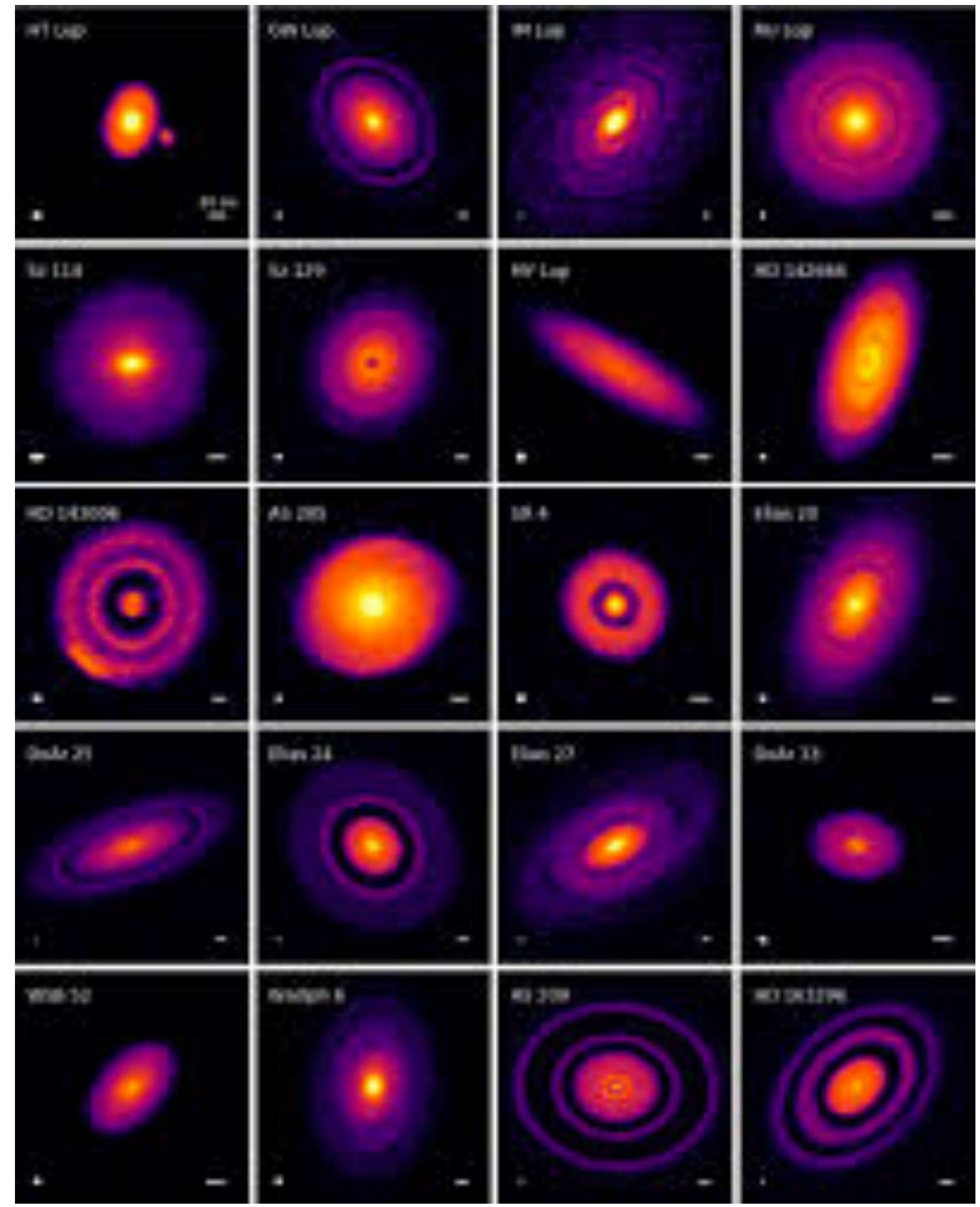


With multiple protoplanet detections, perhaps planet formation models to be reconsidered…

Van der Marel 2023 (EPJ+)
Espaillat et al. 2014

Rings and gaps

- High-resolution ALMA images (0.05” and better): many (if not all) large disks show rings and gaps of varying widths at 10s of au radius
- Initial discovery: HL Tau (2015)
- Big step: DSHARP survey (2018, Andrews et al. 2018)
- General solution radial drift problem!



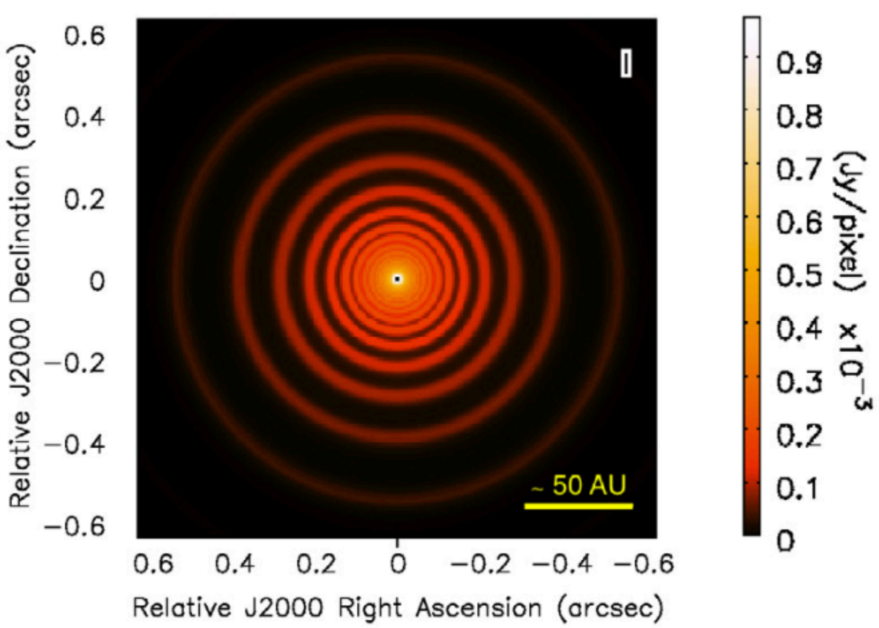
Andrews et al. 2018

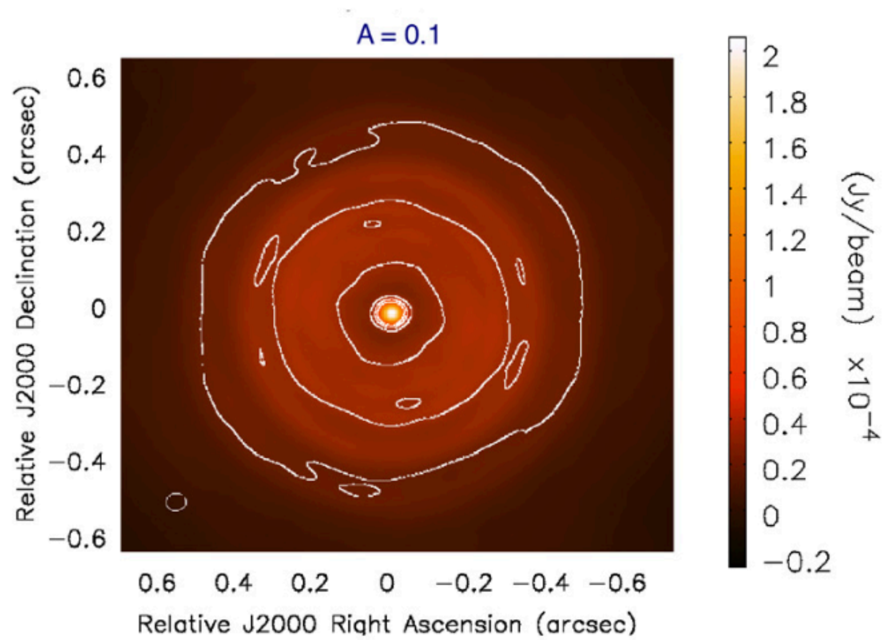
Rings and gaps

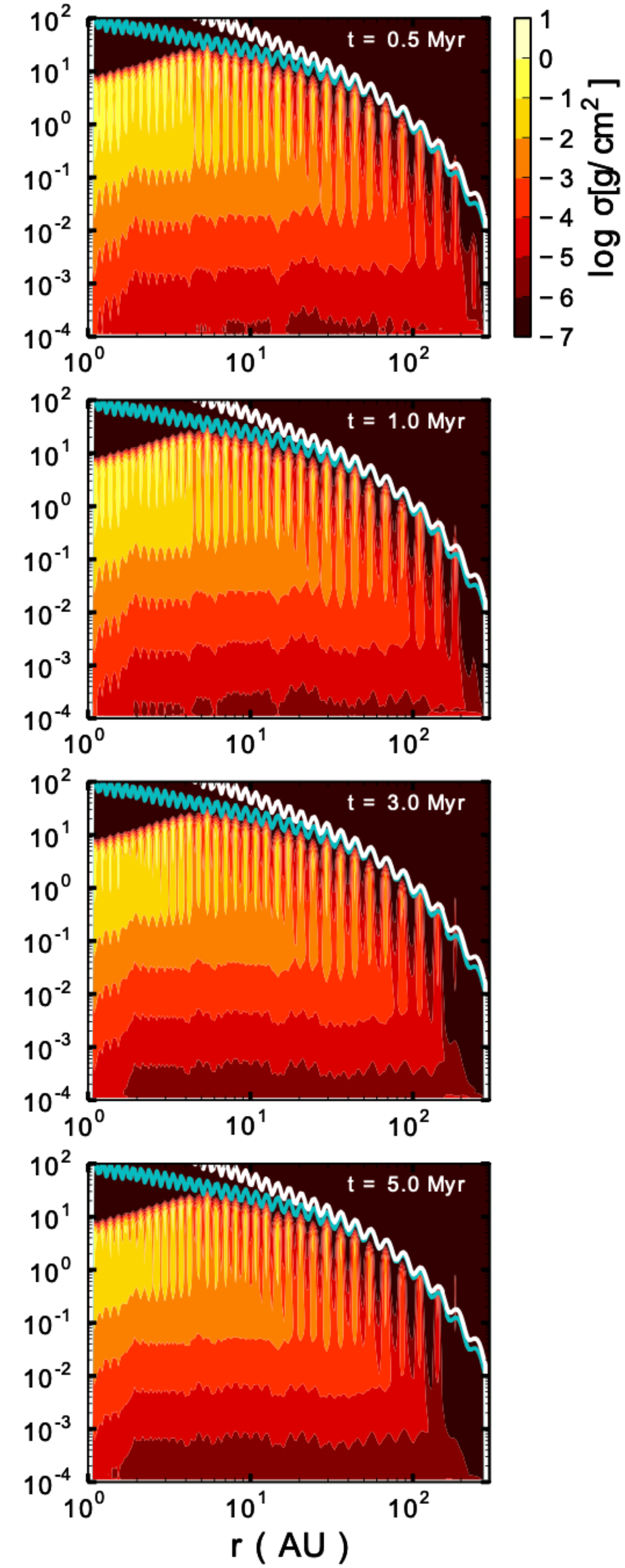
Solution radial drift problem

- Long-standing issue in 2000s: high mm-dust masses and extended dust disks (>50 au), even known pre-ALMA
  => how to prevent radial drift?

- Idea: some type of pressure bumps throughout the disk ('zonal flows')







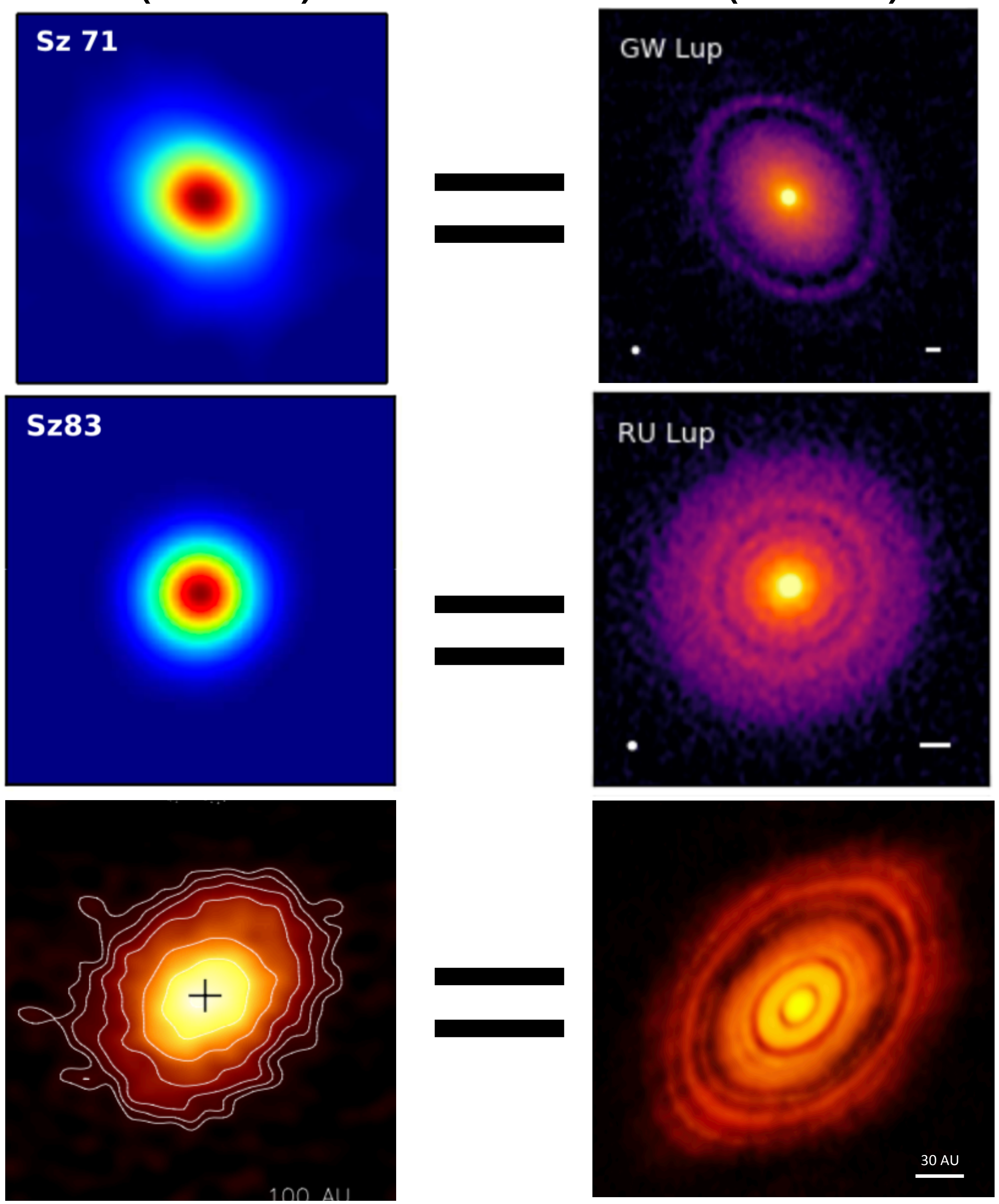
=> rings smoothed out at low resolution

Pinilla et al. 2012a

Rings and gaps

Importance angular resolution

(0.30”) (0.04”)



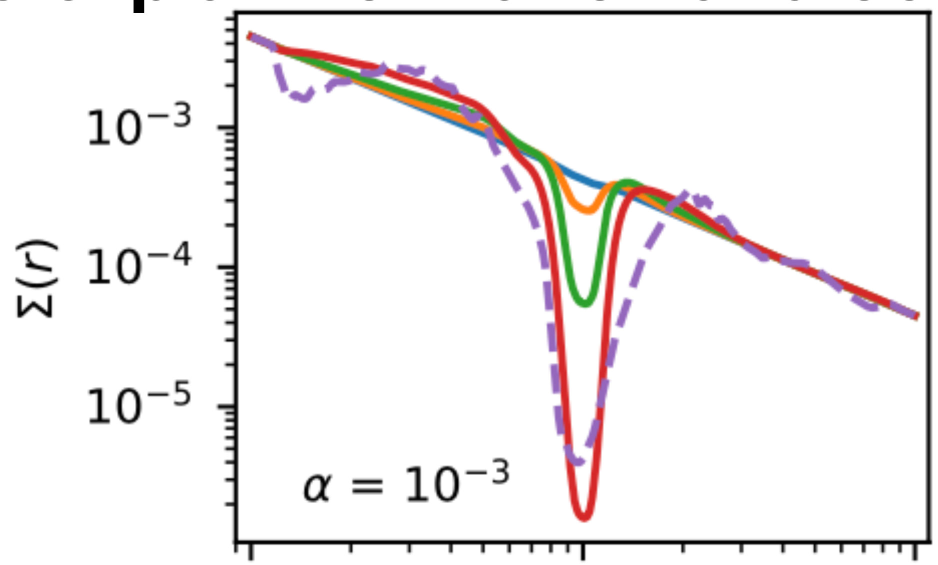
At low resolution, these gaps and rings were simply not detectable: always be careful with statements on lack of substructure

Ansdell et al. 2018
Andrews et al. 2018

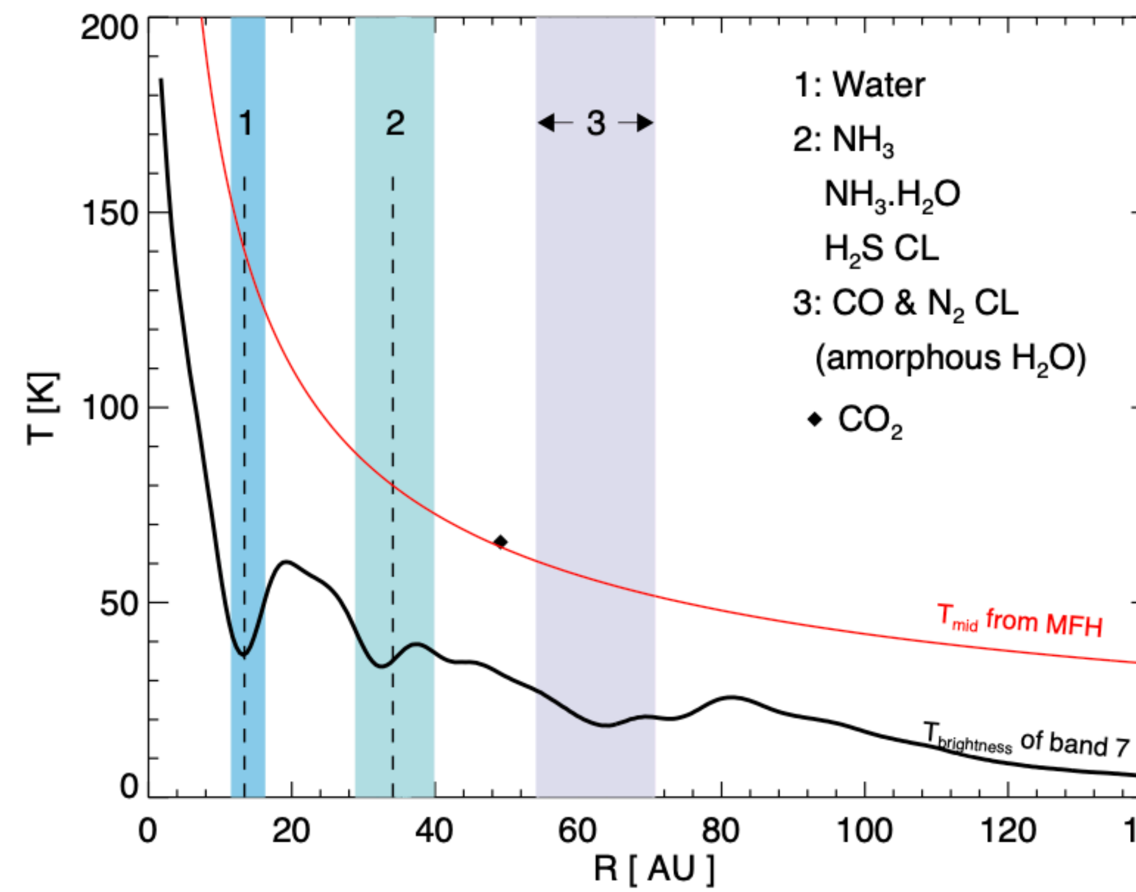
Rings and gaps

Origin

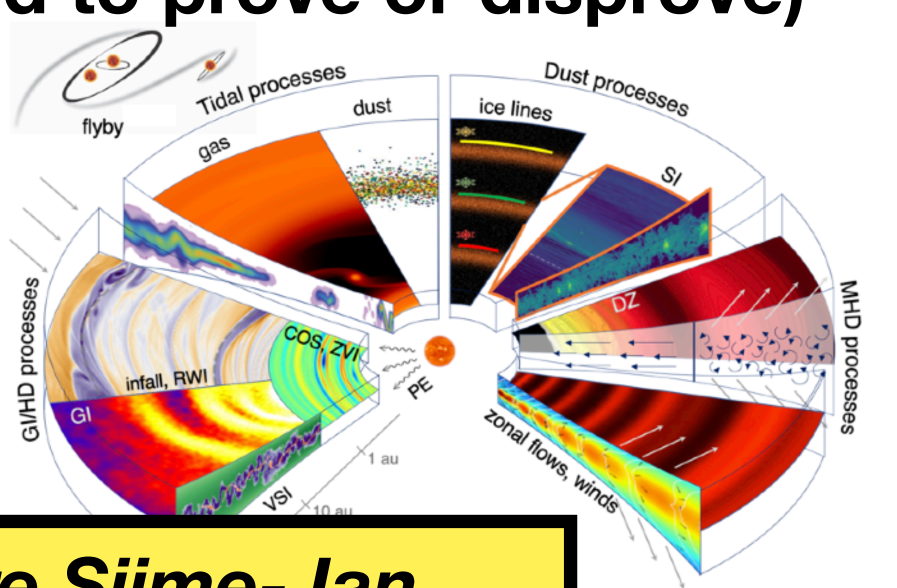
1. Planets clearing their orbits (difficult to explain formation and occurrence)



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



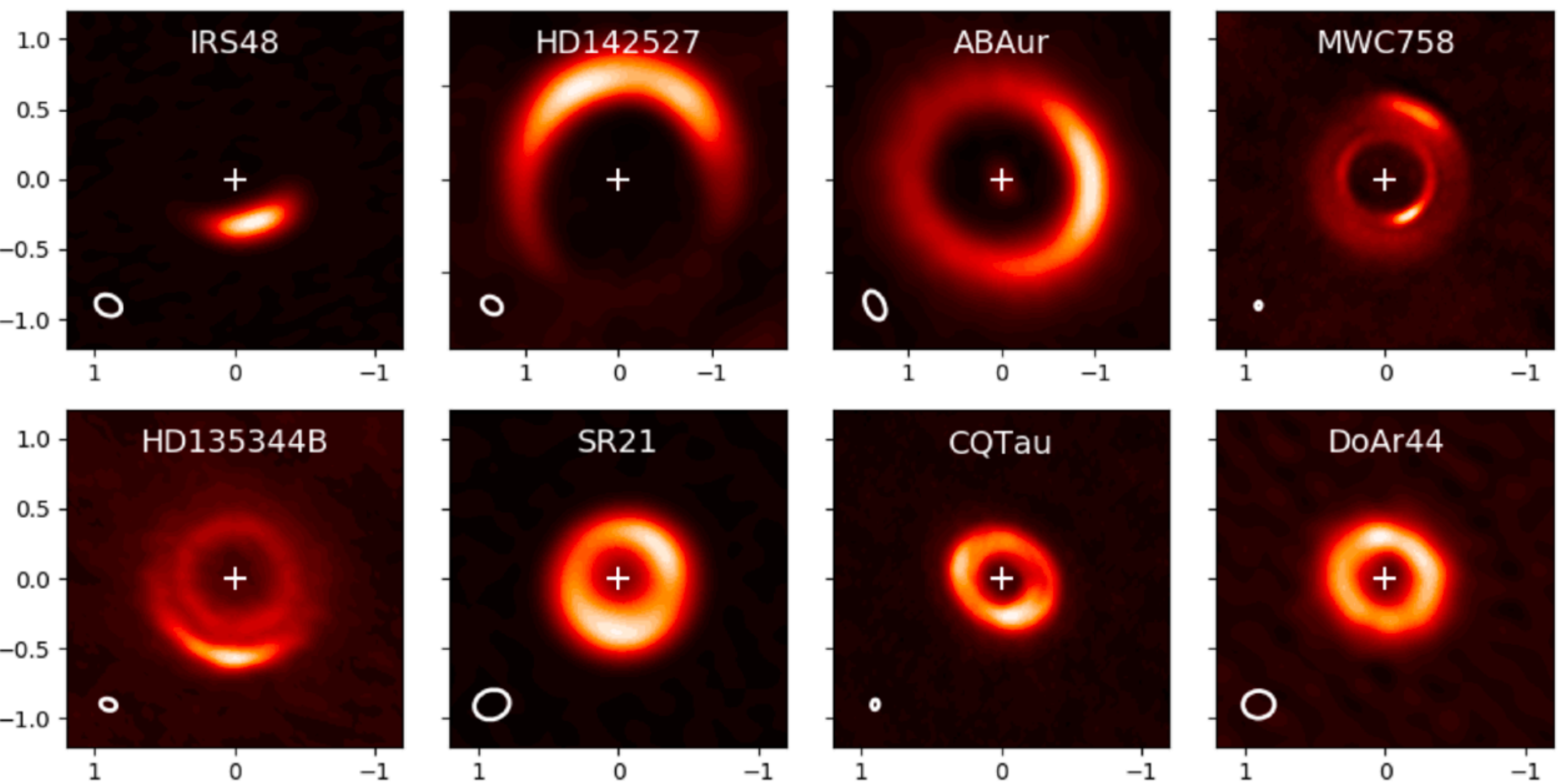
3. Hydrodynamic/MHD instabilities (hard to prove or disprove)



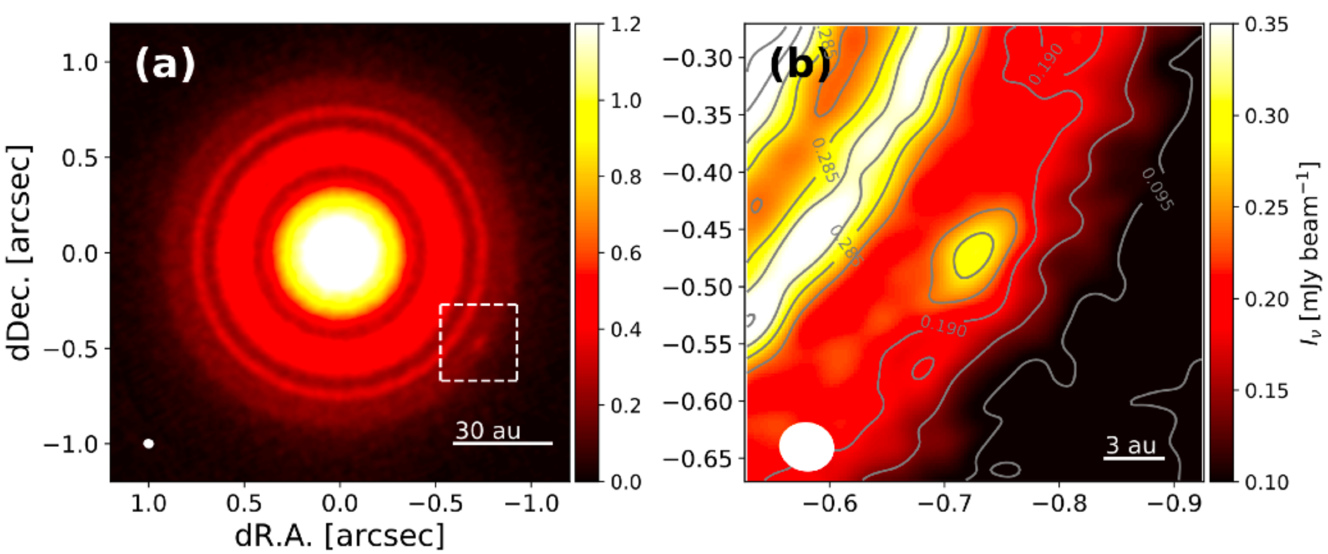
Lecture Sijme-Jan

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

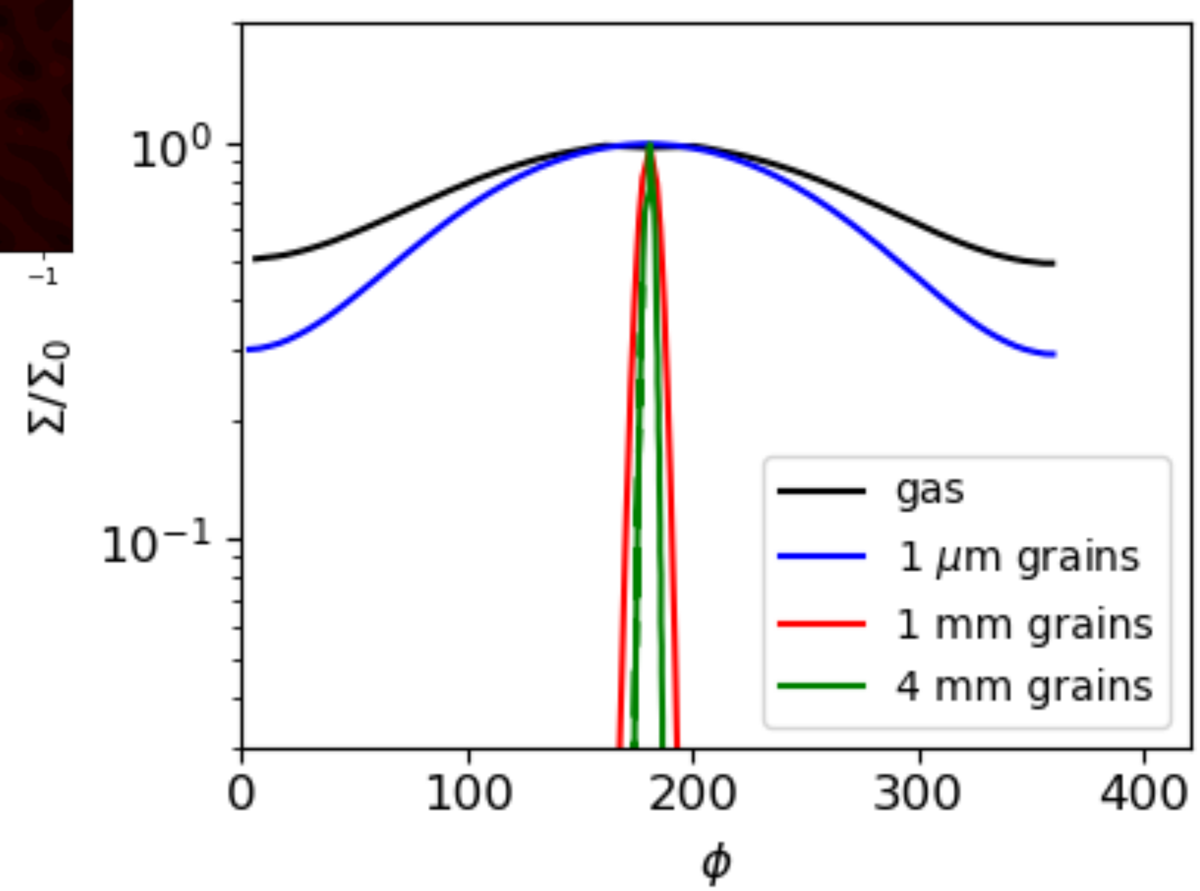
Asymmetries



Many dust asymmetries, large and small scale…



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

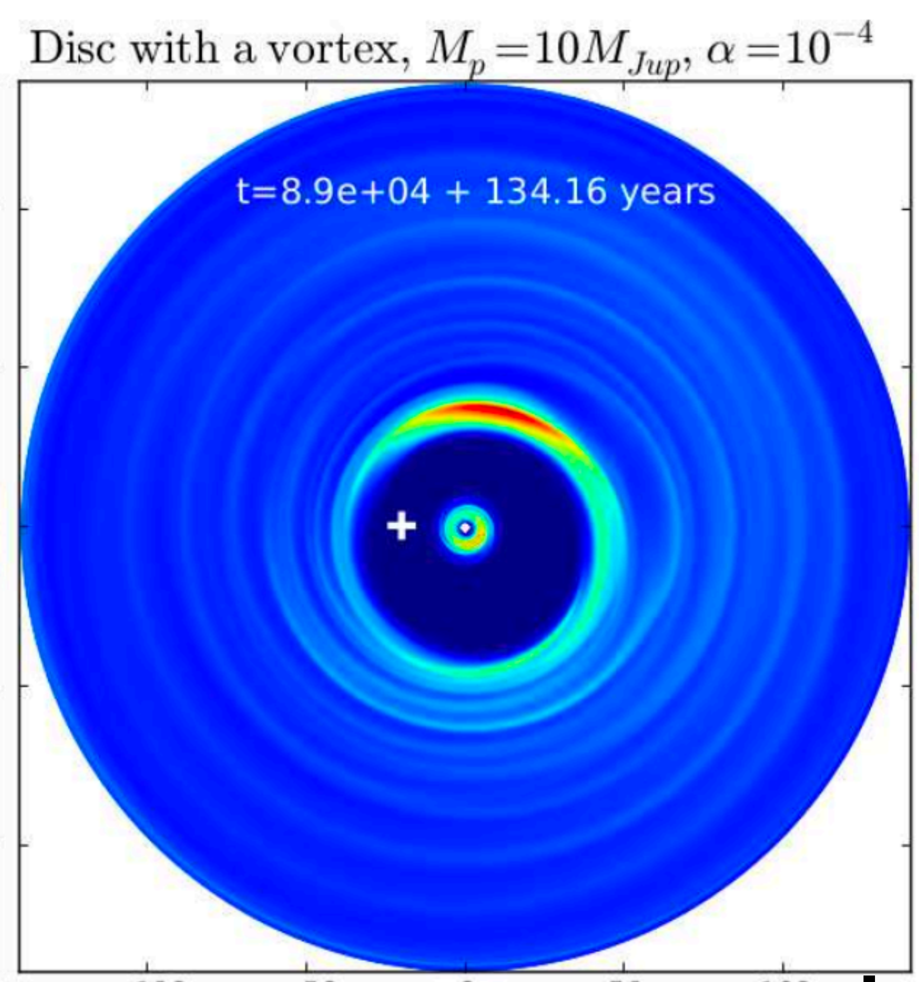


Van der Marel et al. 2021a
Birnstiel et al. 2013

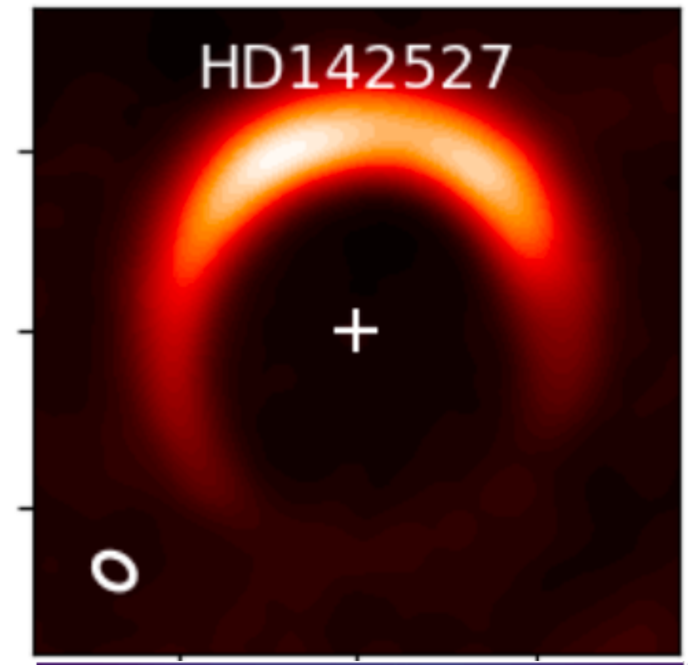
Asymmetries

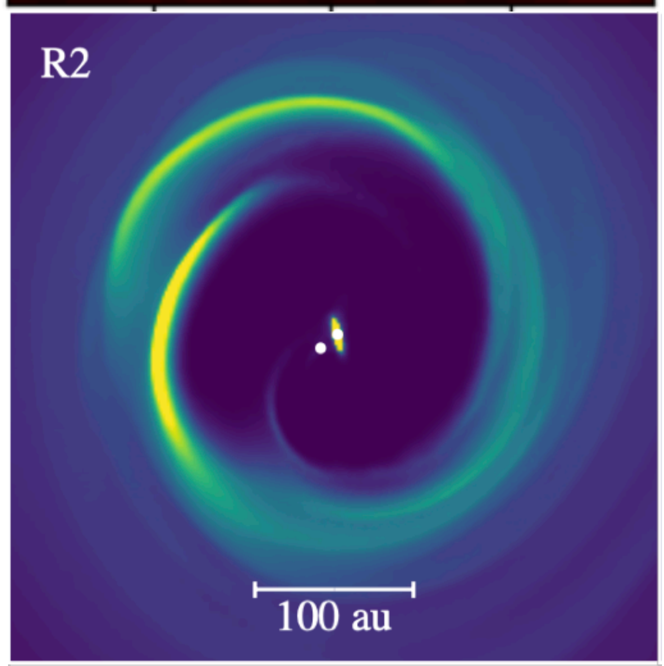
Origin

1. Rossby wave instability leading to vortices
=> requires pressure bump (planet?) + low viscosity
$\alpha \sim 10^{-4}$)



2. Horse shoe by eccentric stellar companion
=> requires companion + any viscosity



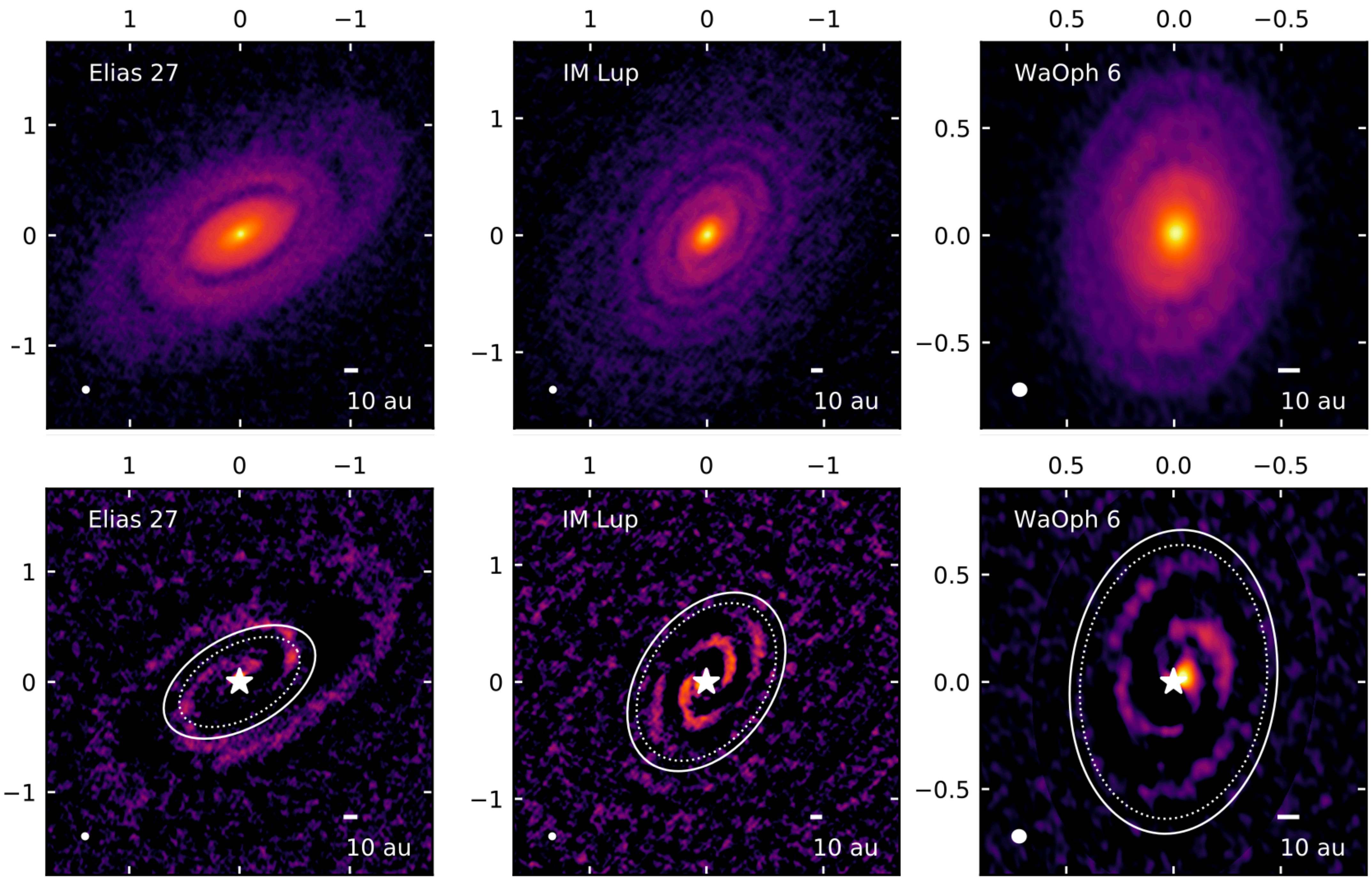


Inconclusive without companion detections

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

Spirals in mm

Evidence gravitational instability?

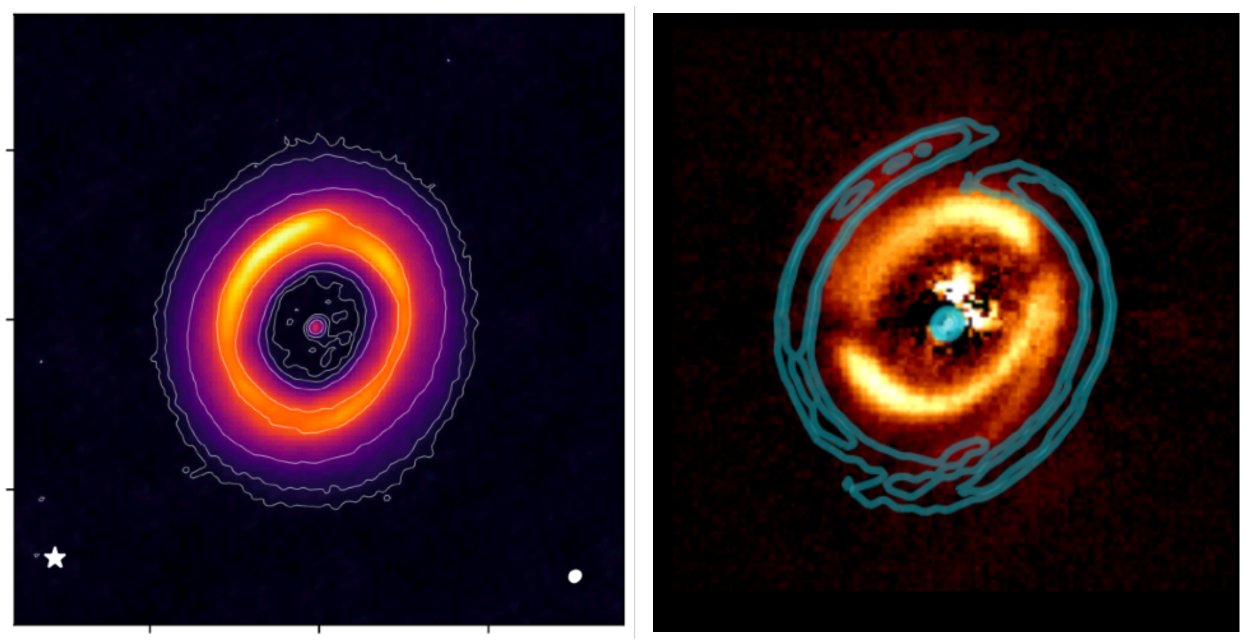


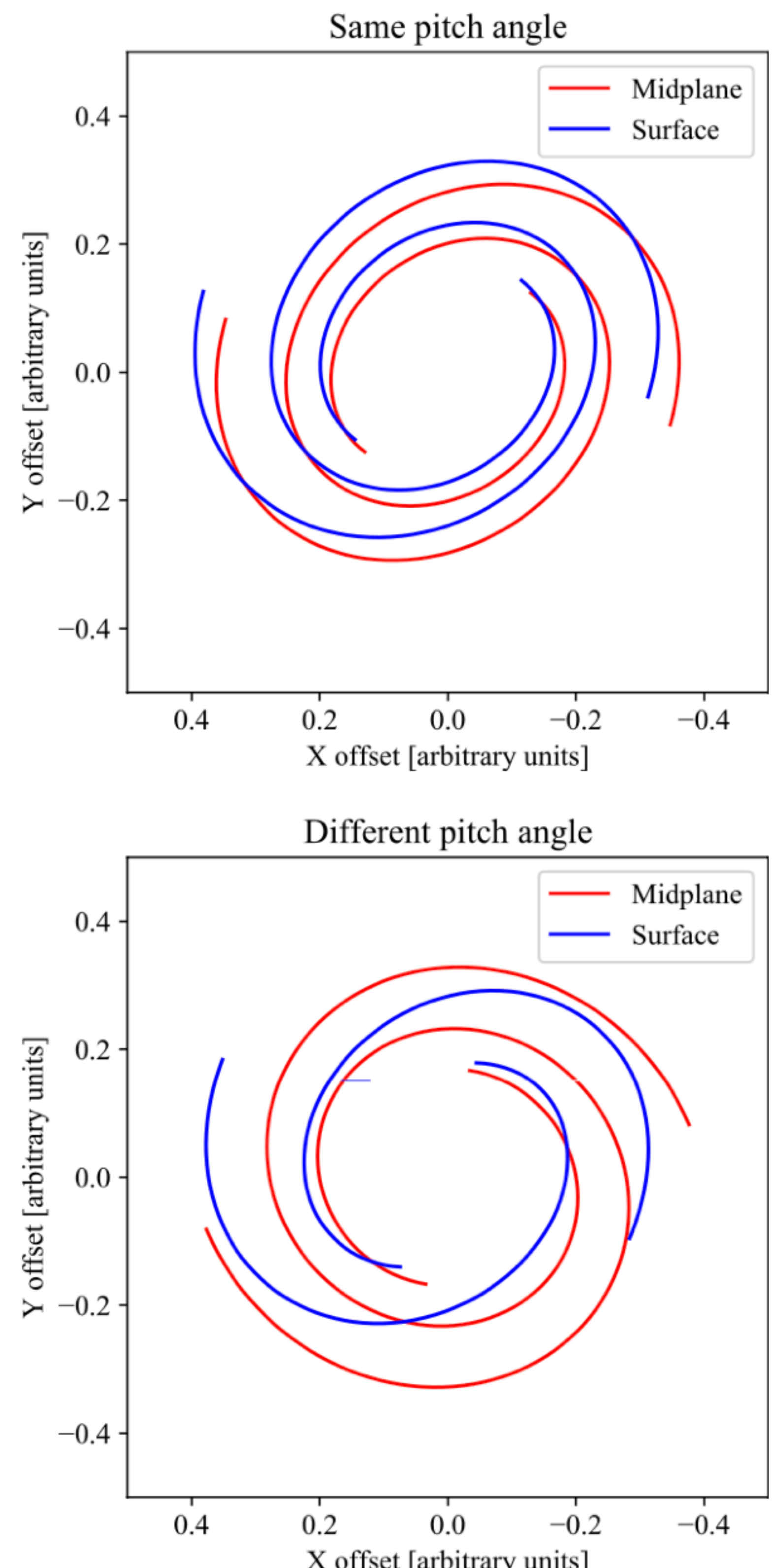
Spirals more clear after subtracting axisymmetric model

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

Spirals in mm

Link with NIR spirals?





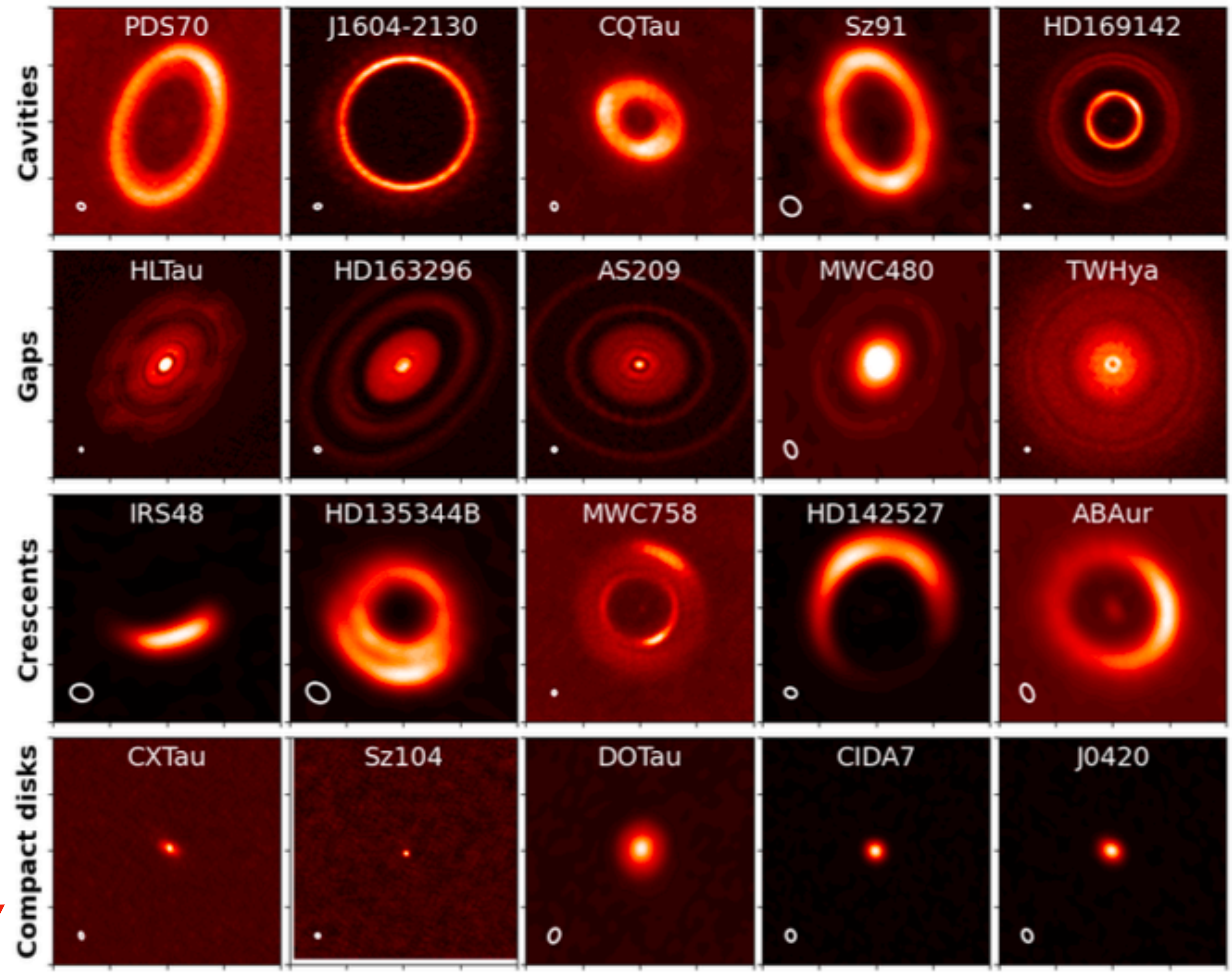
As the opening angle is different for NIR vs mm, this implies that the temperature is different at each height (vertical temperature structure)

Lecture Antonio

Rosotti et al. 2019

Compact disks

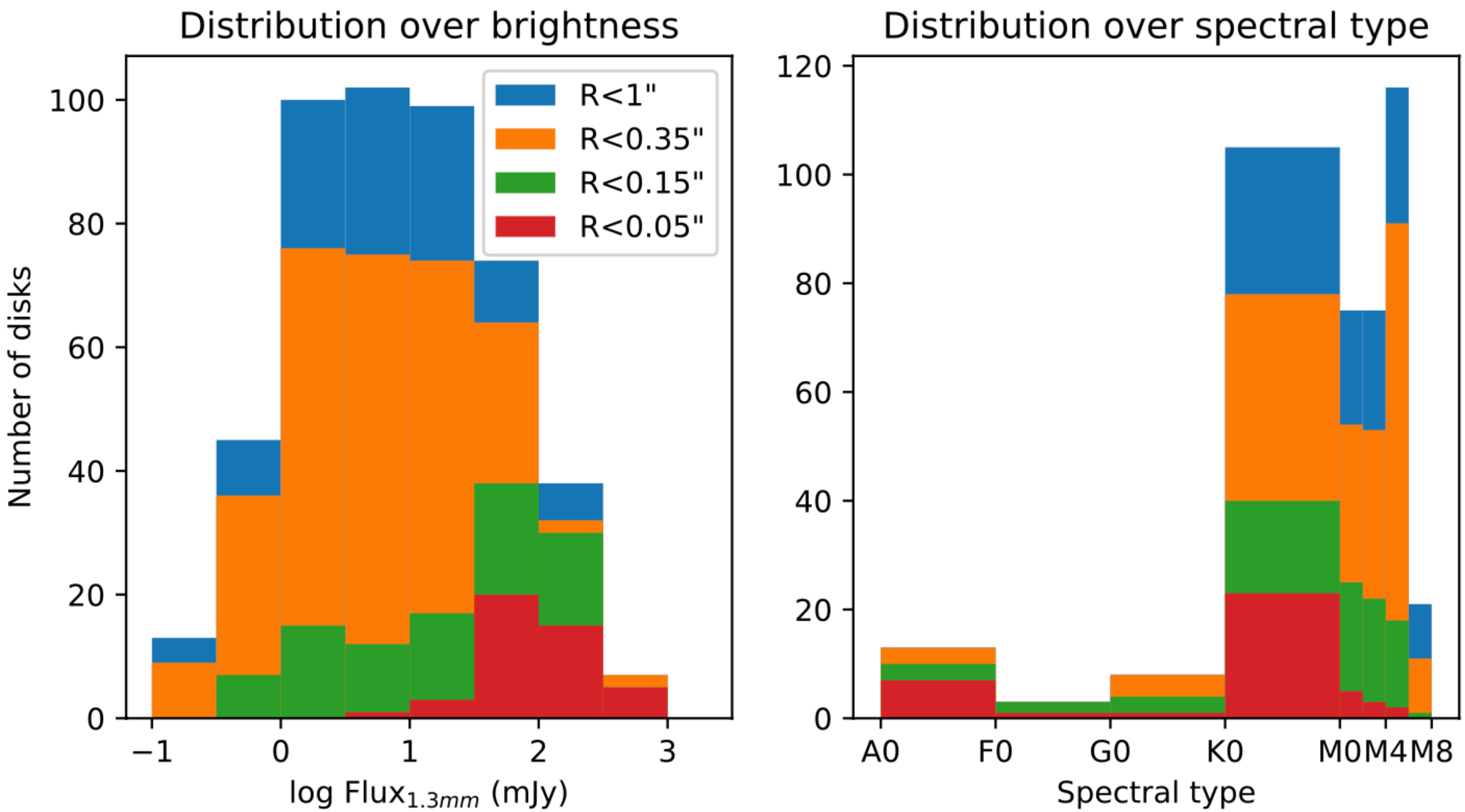
- Other high-resolution discovery:
  compact dust disks (<5 au radius)
- Tiny in radius compared to structured disks
- Unclear if substructure scales down
- Mostly unresolved in current ALMA observations (limit <15 au)



Van der Marel & Pinilla 2023
van der Marel et al. 2022 (arXiv)

Substructures

Detection bias



Strong **biases** in selection disks for **high-resolution observations** that can resolve substructure: clear preference for massive disks and early-type stars (=> brighter => less observing time)

Therefore, **difficult** to make statements on occurrence substructures

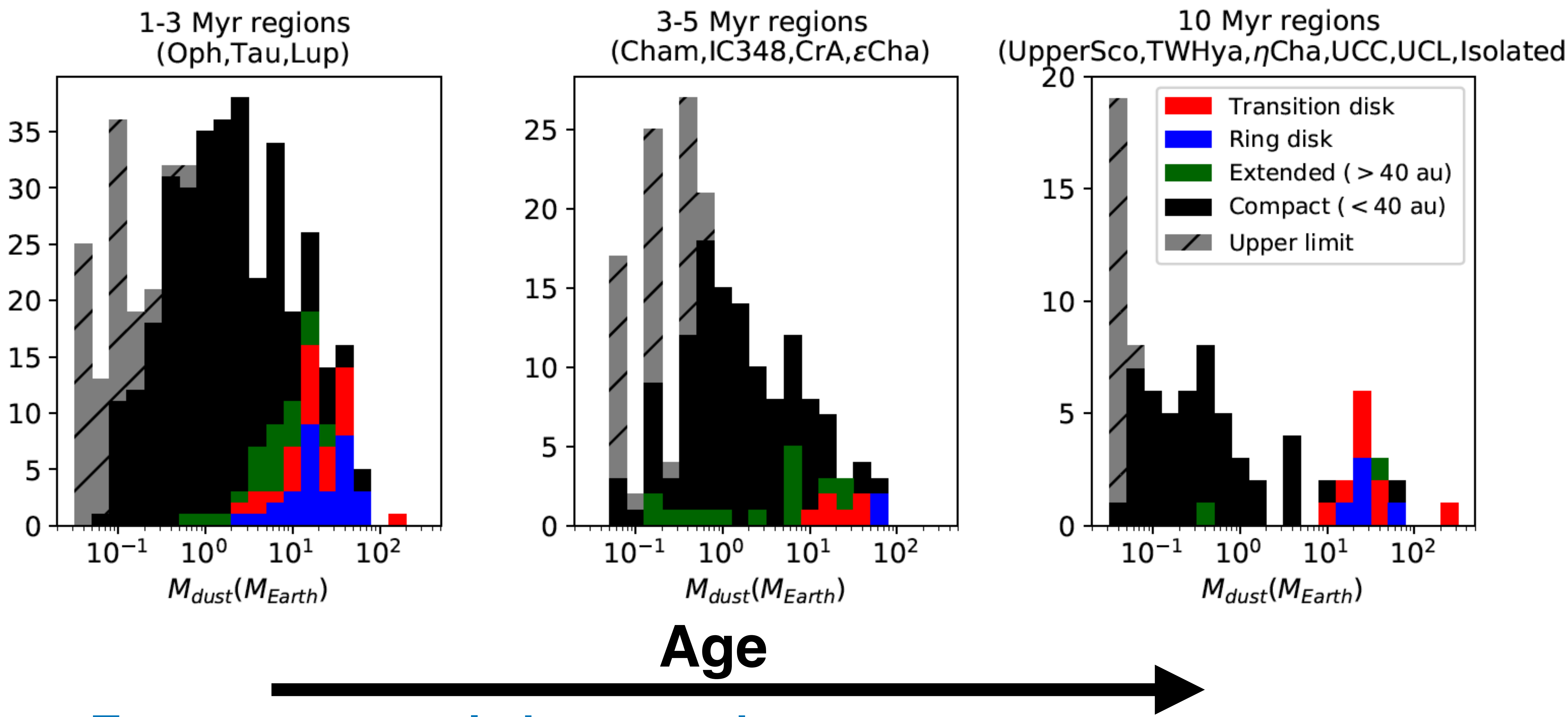
Van der Marel & Pinilla 2023 (arXiv)

See also Bae et al. 2023 (PPVII)

Substructures

Occurrence

<u>Distribution dust masses as function of age and disk type</u>



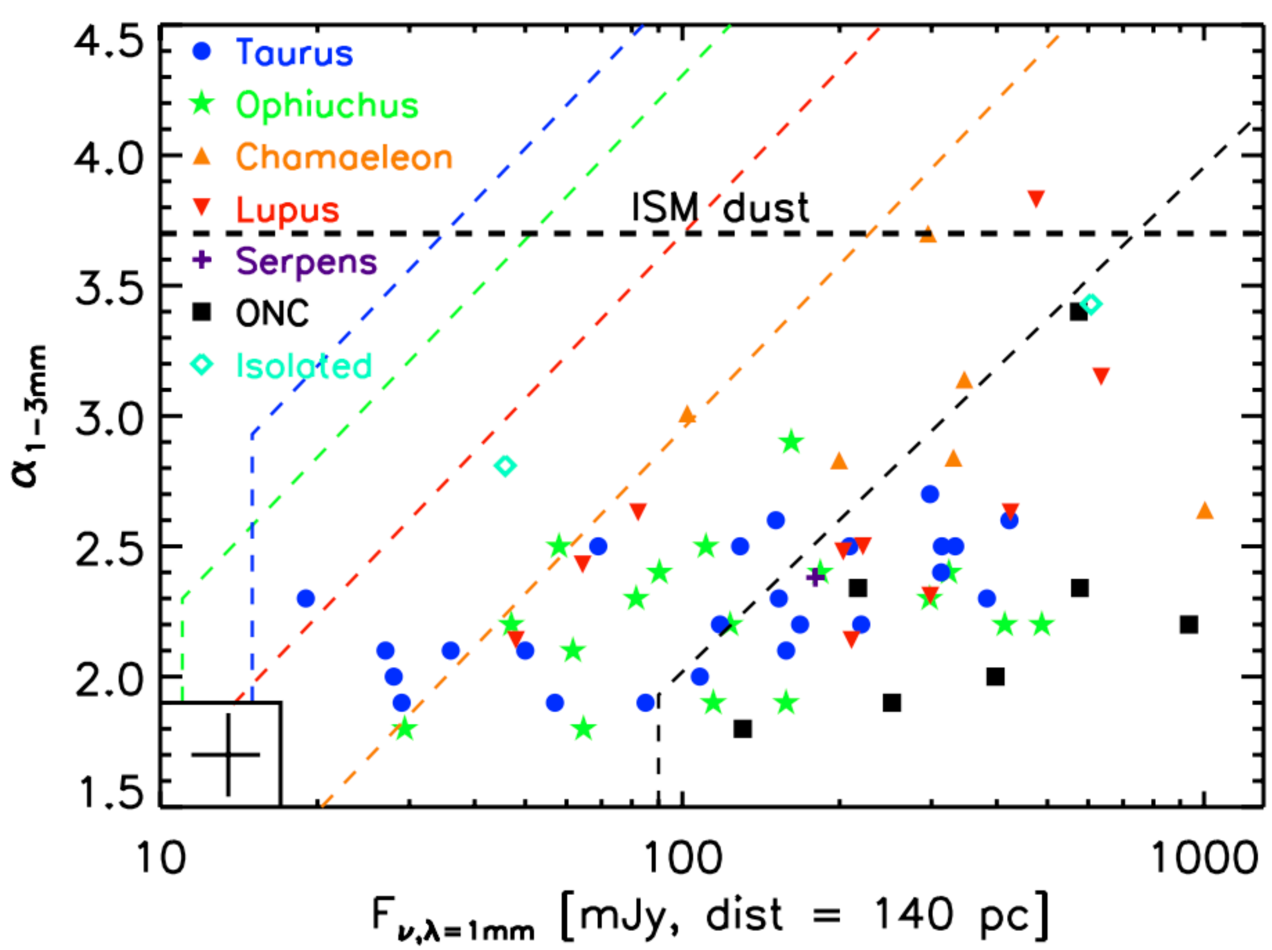
Two separate evolutionary pathways:
the structured disks (15%) and compact disks (85%)
where compact disks evolve according to radial drift

Van der Marel & Mulders 2021

Multi-wavelength analysis

Classical: derive spectral index

- Multi-wavelength 2 fluxes: $F_\nu \propto \nu^\alpha$
- Rule of thumb α
  - 3.7 (ISM)
  - 2.0-3.0 (mm-grains/opt. thick)
  - (<)2.0 (optically thick)
  - -1 < 0 < 1 (free-free emission, non-thermal)



Recall equations:

$$F_\nu = \int I_\nu d\Omega$$

$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu})$$

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

$$\kappa_\nu \sim \nu^\beta$$

Thin + RJ:

$$F_\nu \sim \nu^2 \kappa_\nu \sim \nu^{2+\beta} \sim \nu^\alpha$$

Thick:

$$\alpha \nsim 2 + \beta$$

No longer directly related to dust opacity

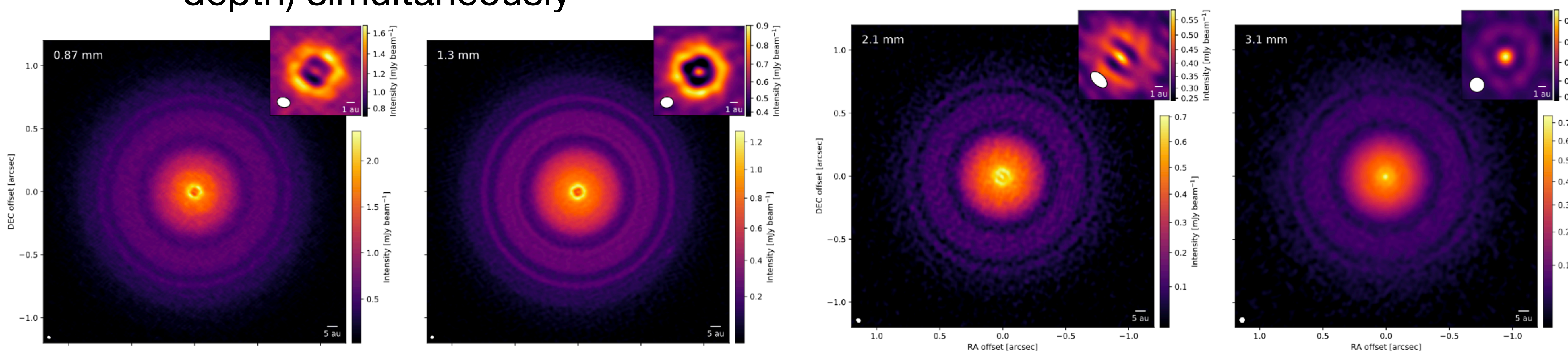
Testi et al. 2014

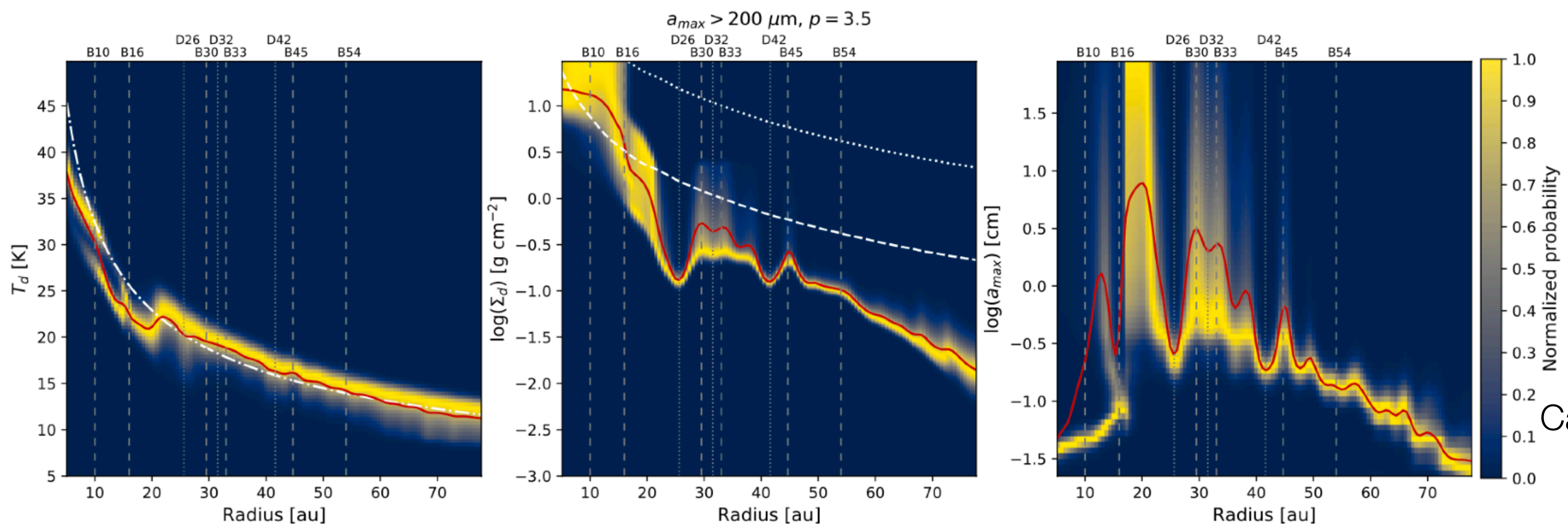
Multi-wavelength analysis

Modern approach

If you have 3 wavelengths or more, spatially resolved:

- Fit dust opacity (grain size), temperature and surface density (optical depth) simultaneously



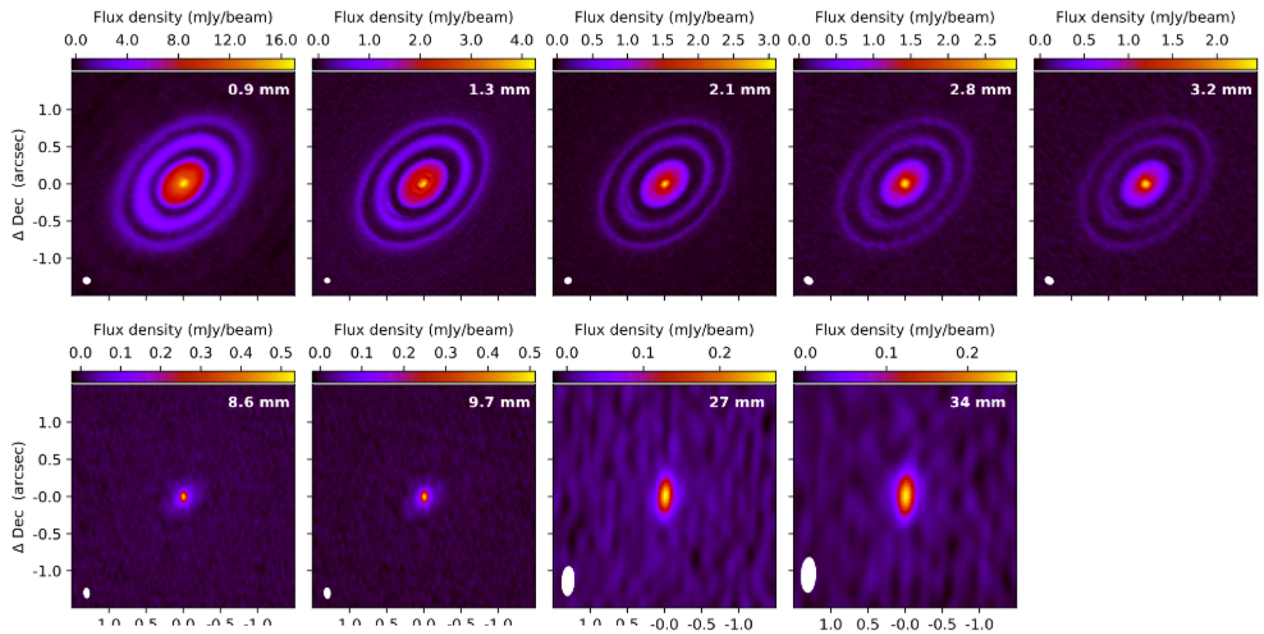


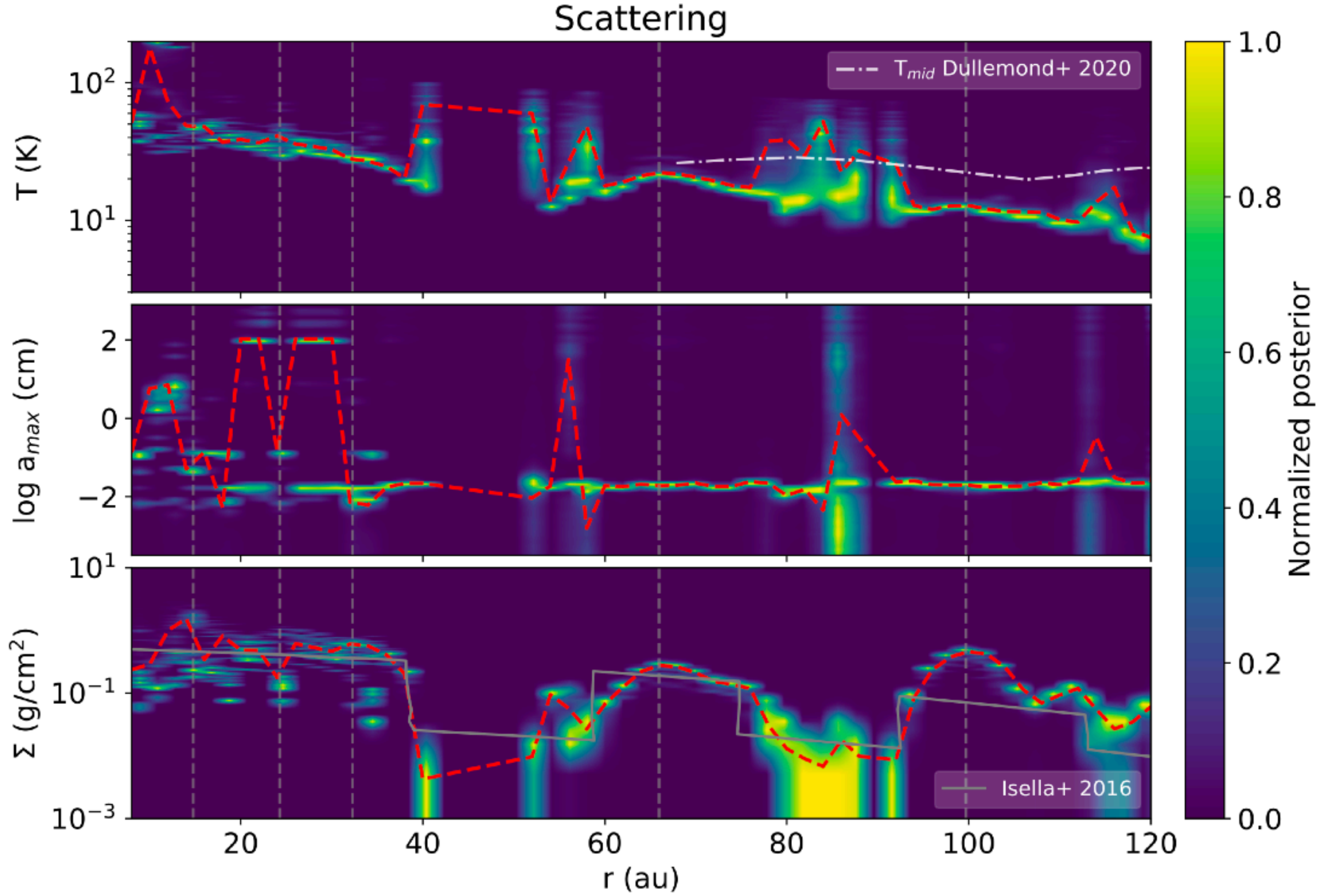
Carrasco-Gonzalez et al. 2019
Macias et al. 2021
Sierra et al. 2021 (MAPS)

Multi-wavelength analysis

Modern approach

HD163296:
9 wavelengths
(ALMA + VLA)





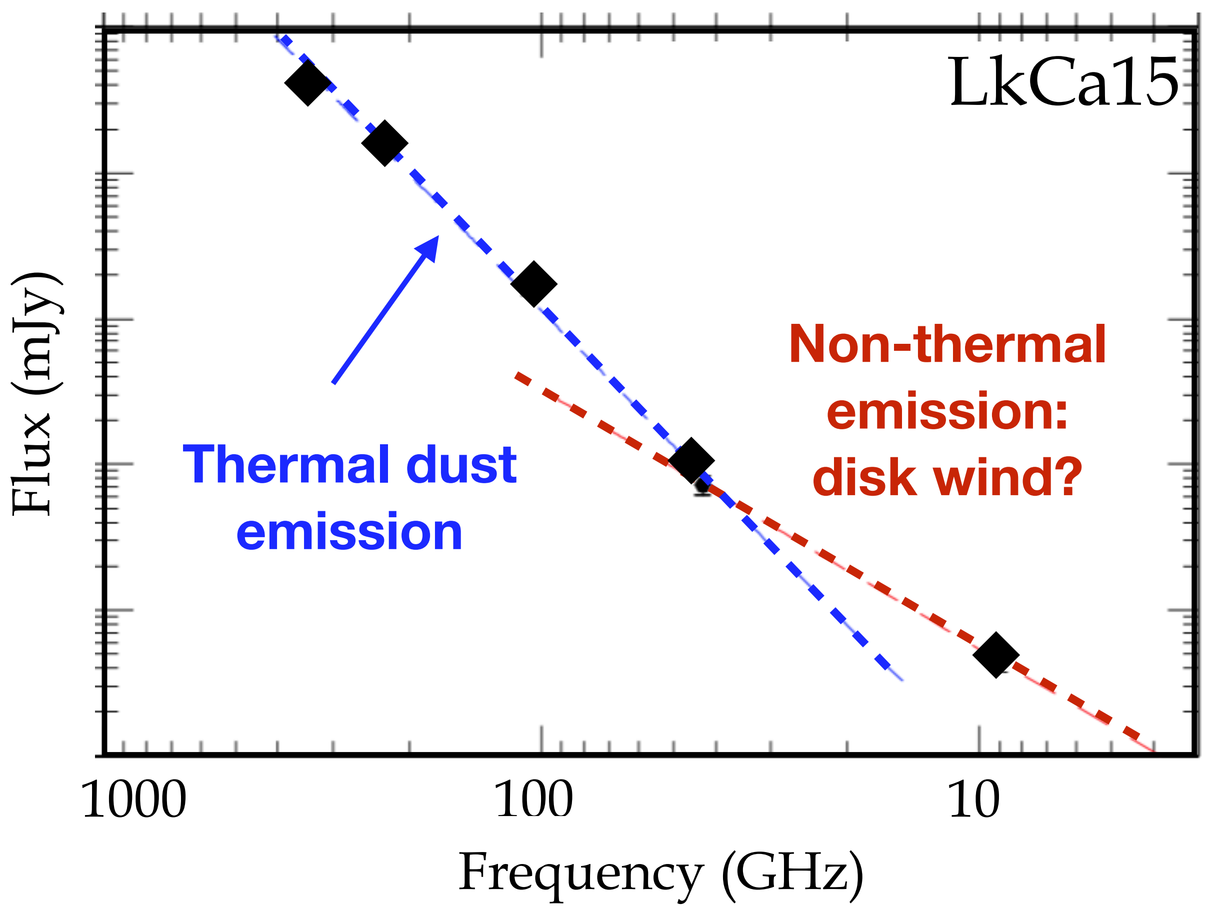
More stringent constraints on dust properties and optical depth

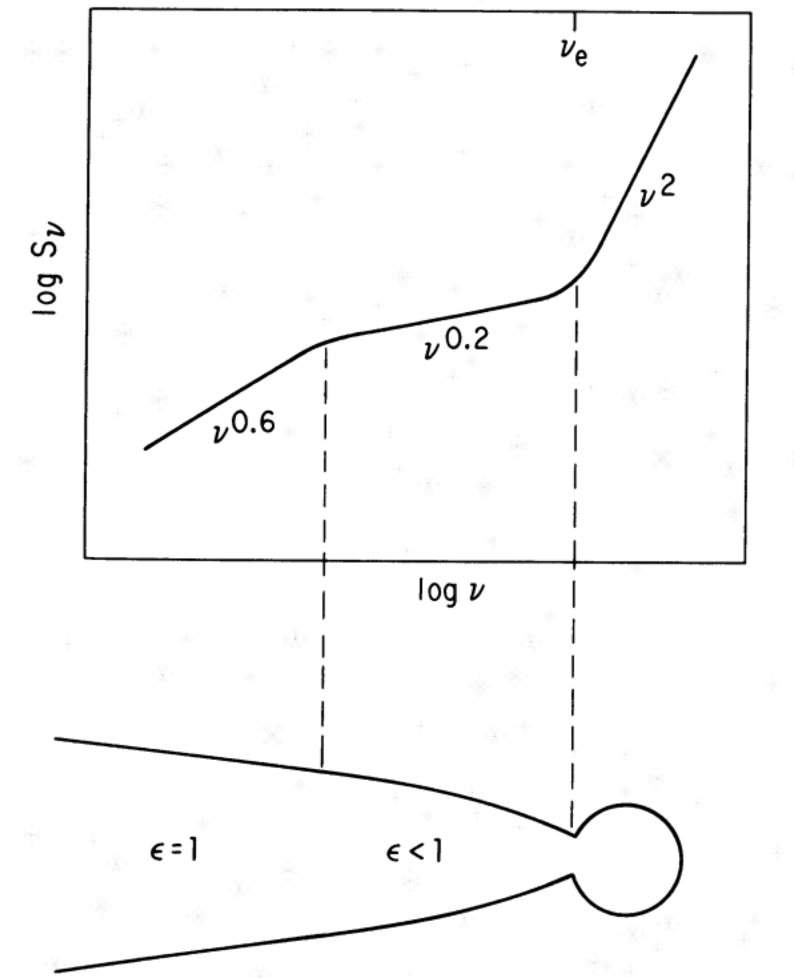
Guidi et al. 2022

Multi-wavelength analysis

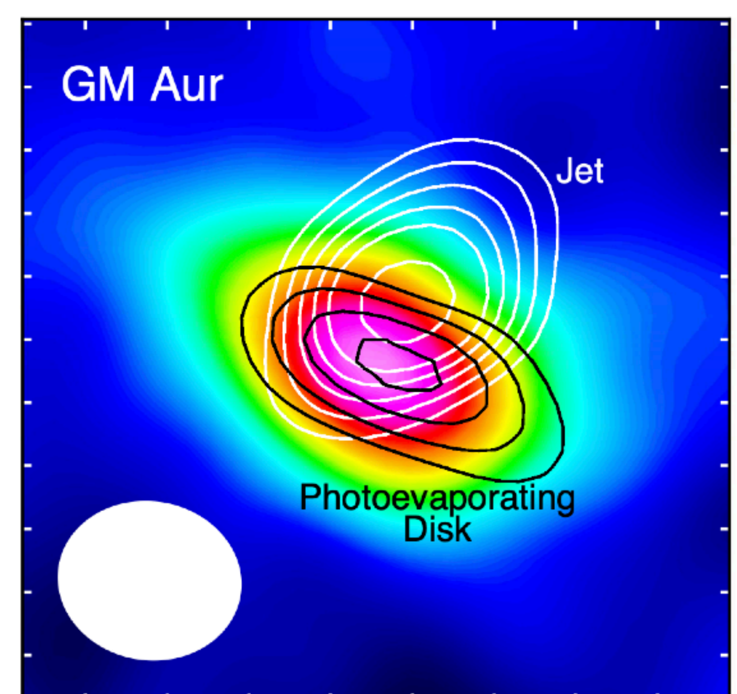
Free-free emission

Observed non-thermal emission at 10 GHz for disk-integrated flux





Spatially resolved jet at 3 cm (VLA)

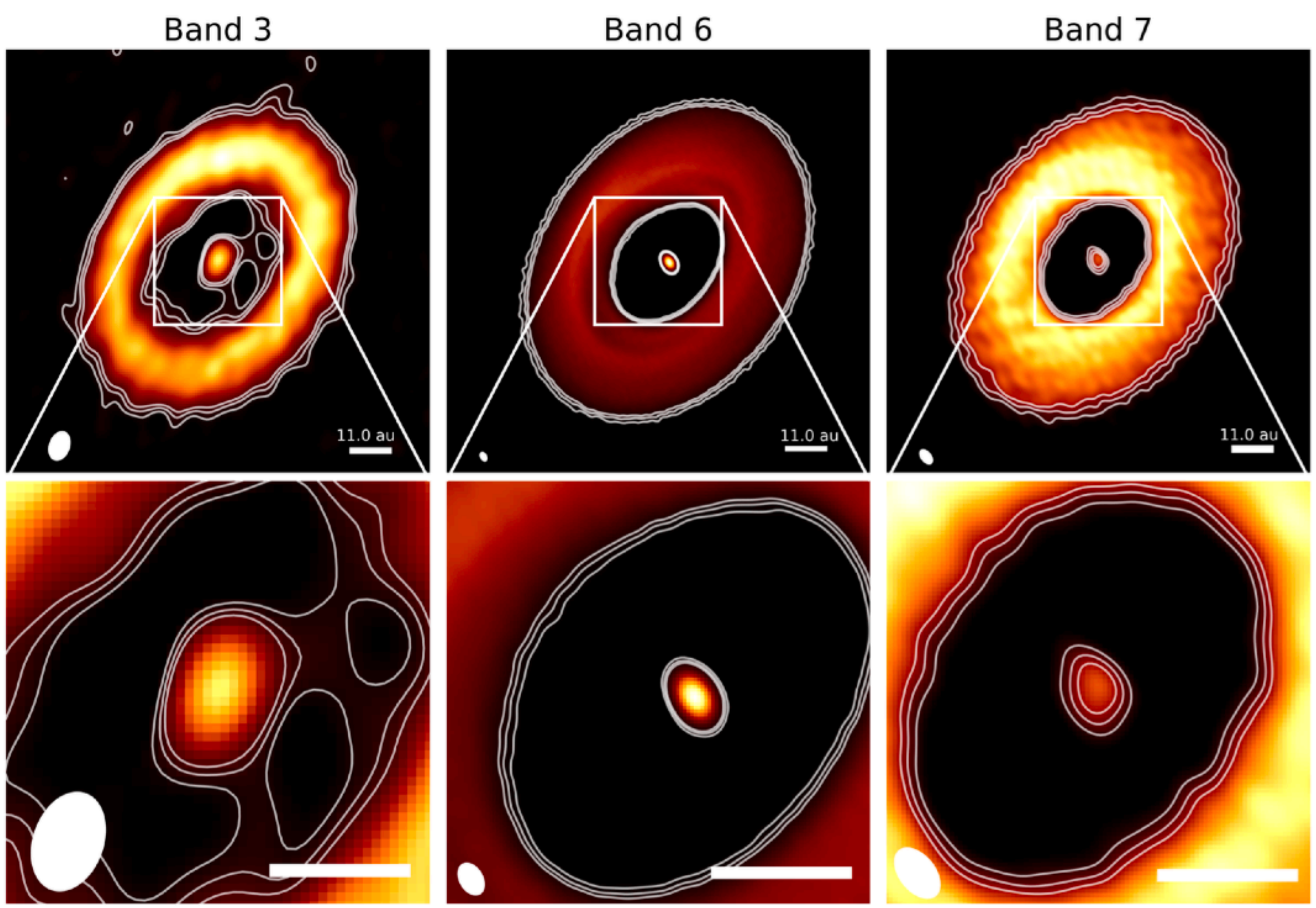


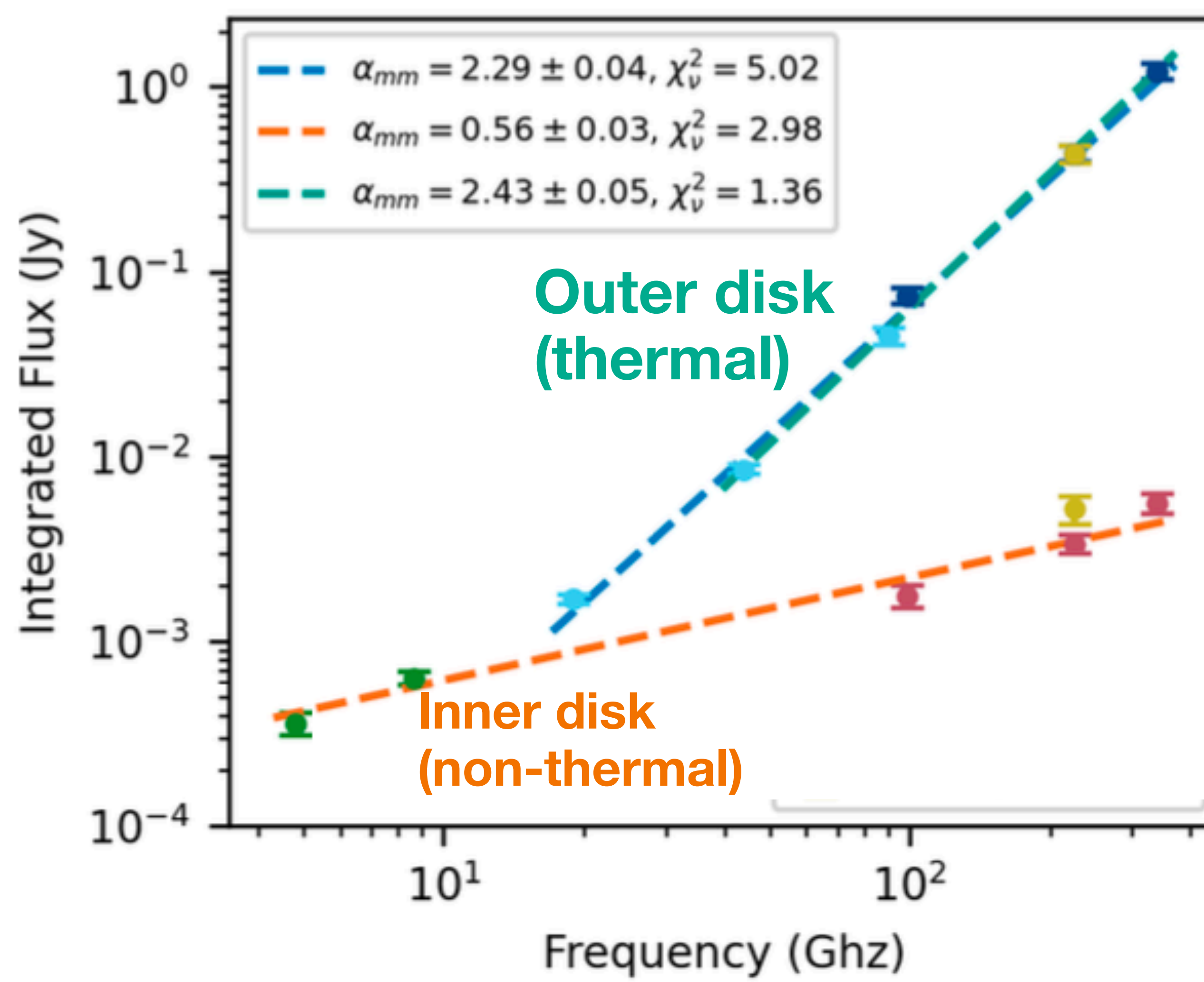
Zapata et al. 2016
Reynolds 1986
Macias et al. 2016
Mohan et al. 2022

Multi-wavelength analysis

Free-free emission: “inner disks” in transition disks

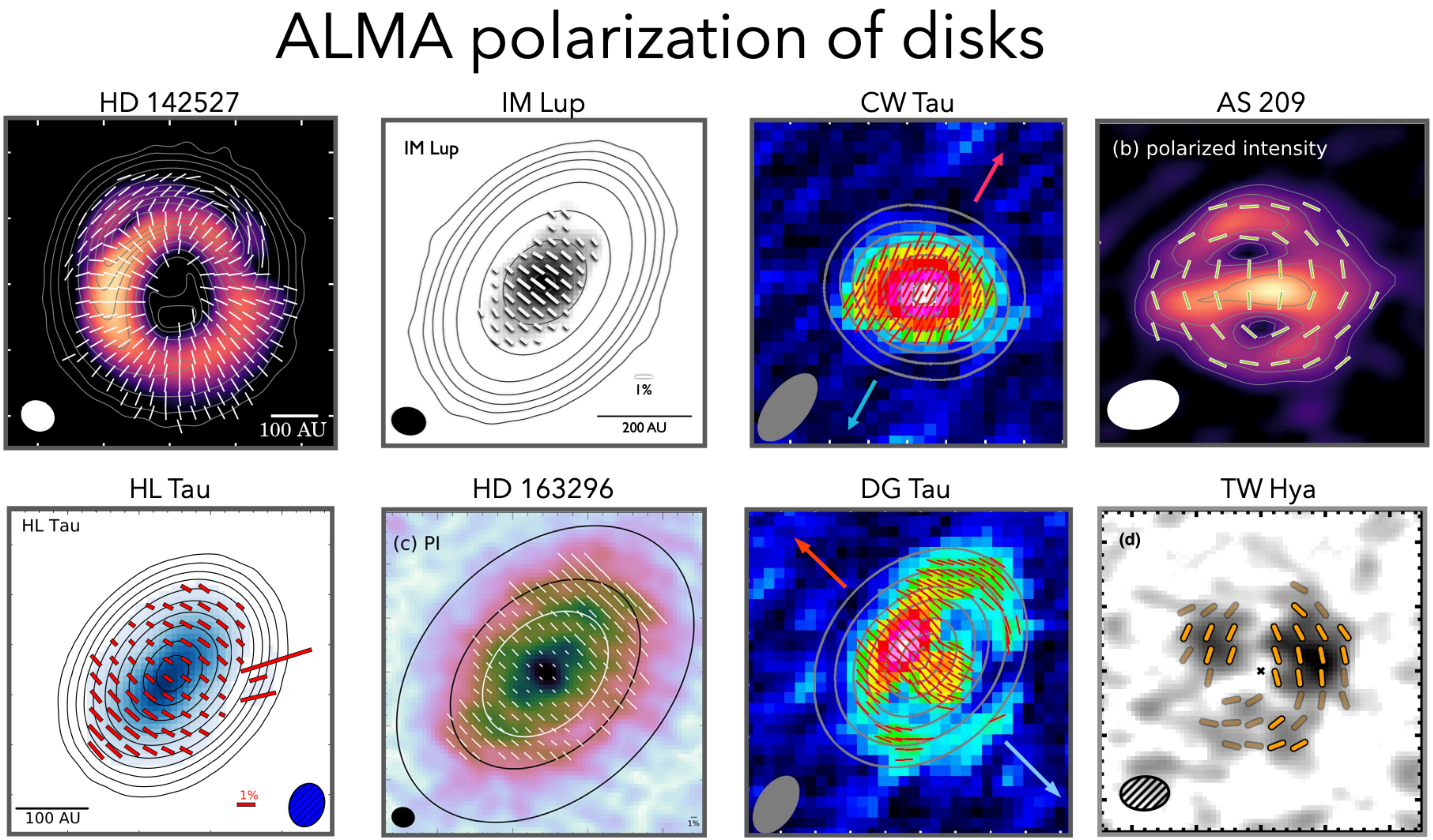
100 GHz   230 GHz   345 GHz





Rota et al. 2024 (in press)

Polarisation

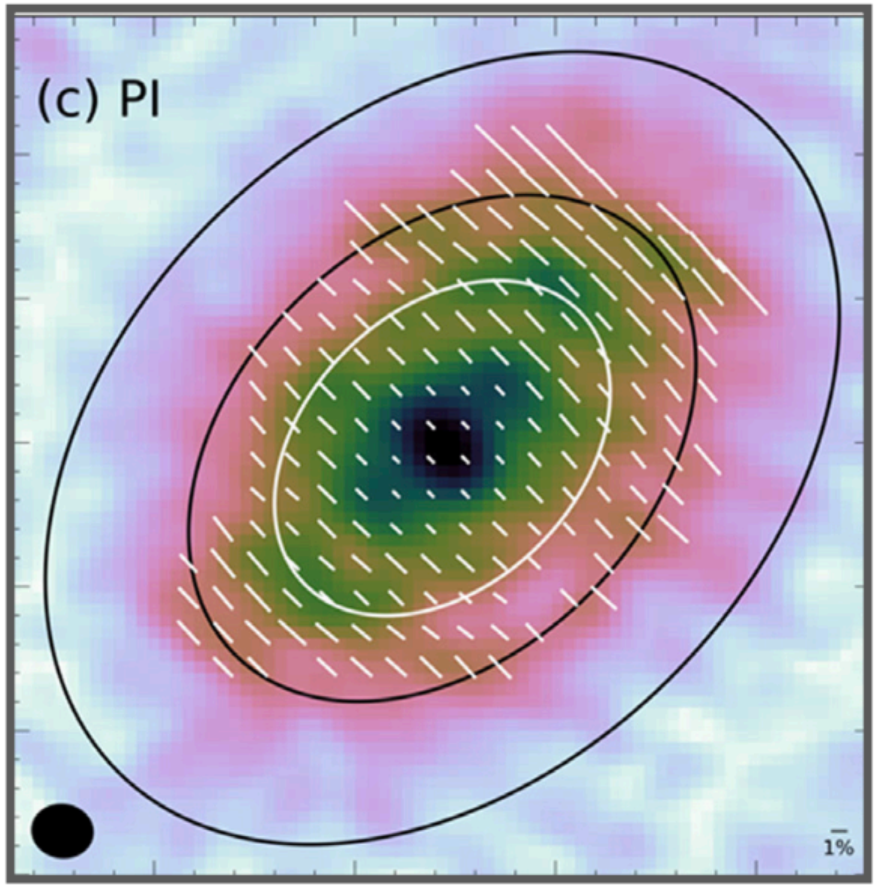


Kataoka et al. 2016, Hull et al. 2018, Bacciotti et al. 2018,
Dent et al. 2019, Stephens et al. 2017, Kataoka et al. 2017,
Ohashi et al. 2018, Mori et al. 2019, Teague et al. 2021

Polarisation

Parallel to the minor axis

HD 163296 (0.9 mm)

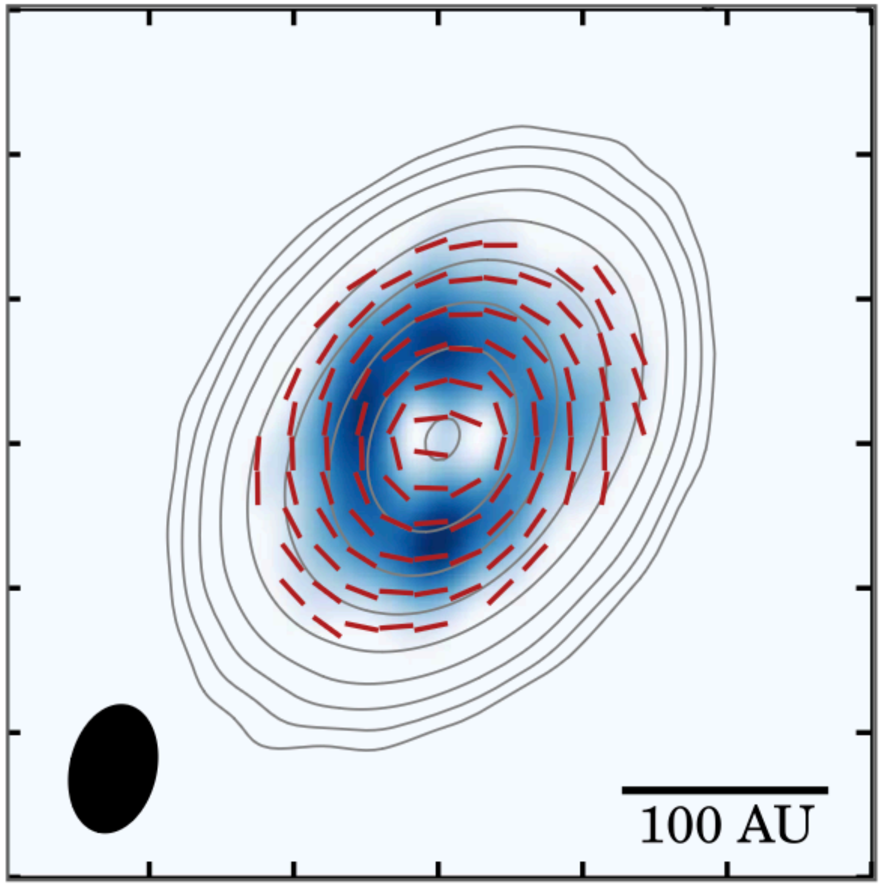


Dent et al. 2019

Self-scattering

Azimuthal

HL Tau (3 mm)

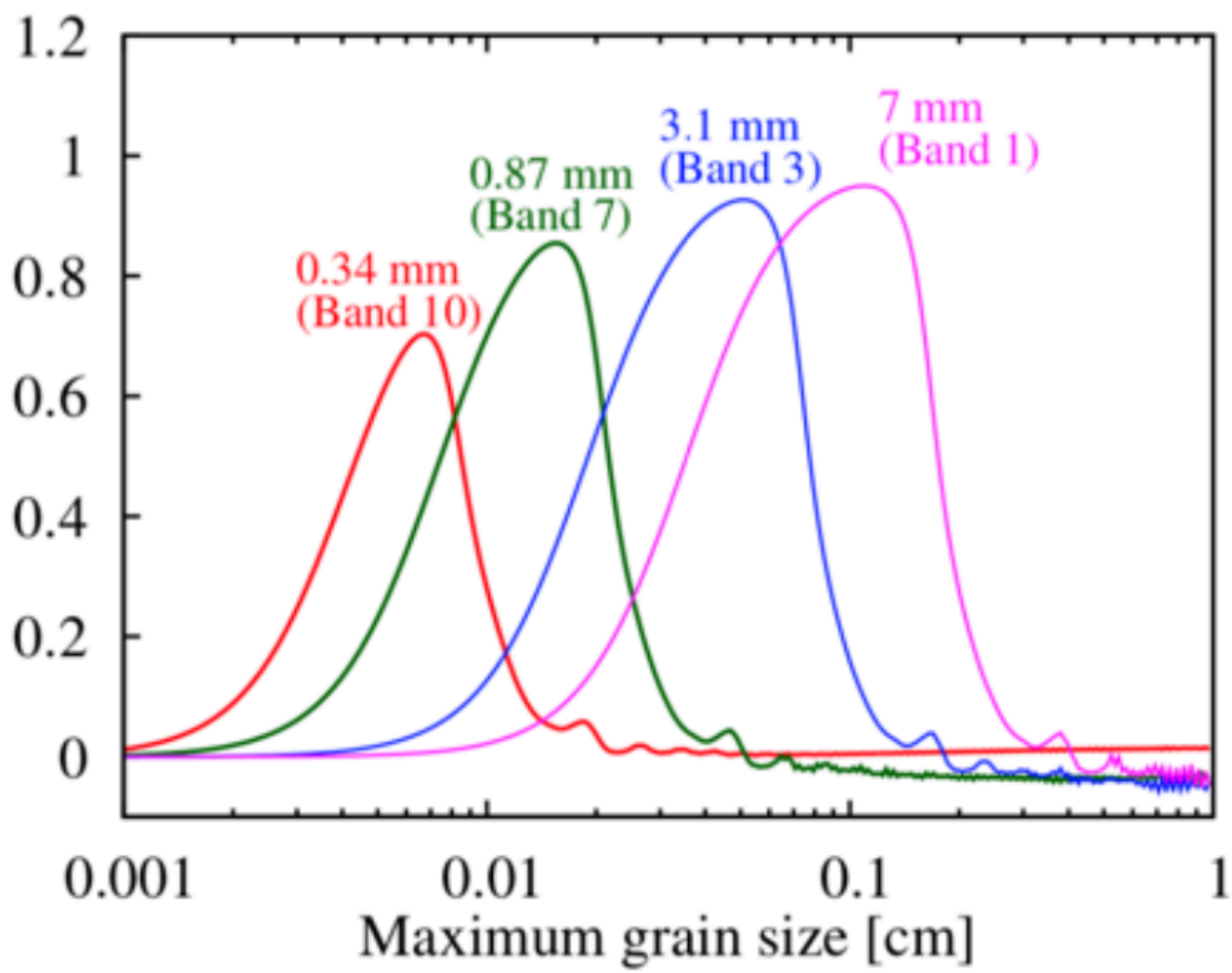


Kataoka et al. 2017

Intrinsic polarization of aligned dust grains

Polarisation

- Polarization due to scattering: only detectable when a ~ λ/2π

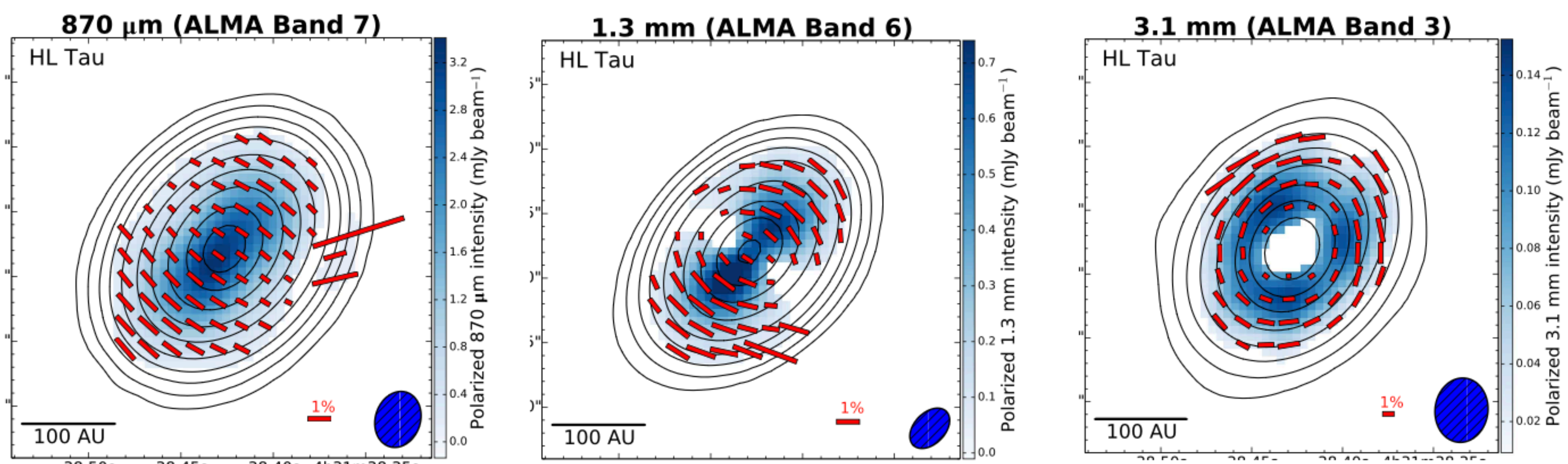


Kataoka et al. 2015

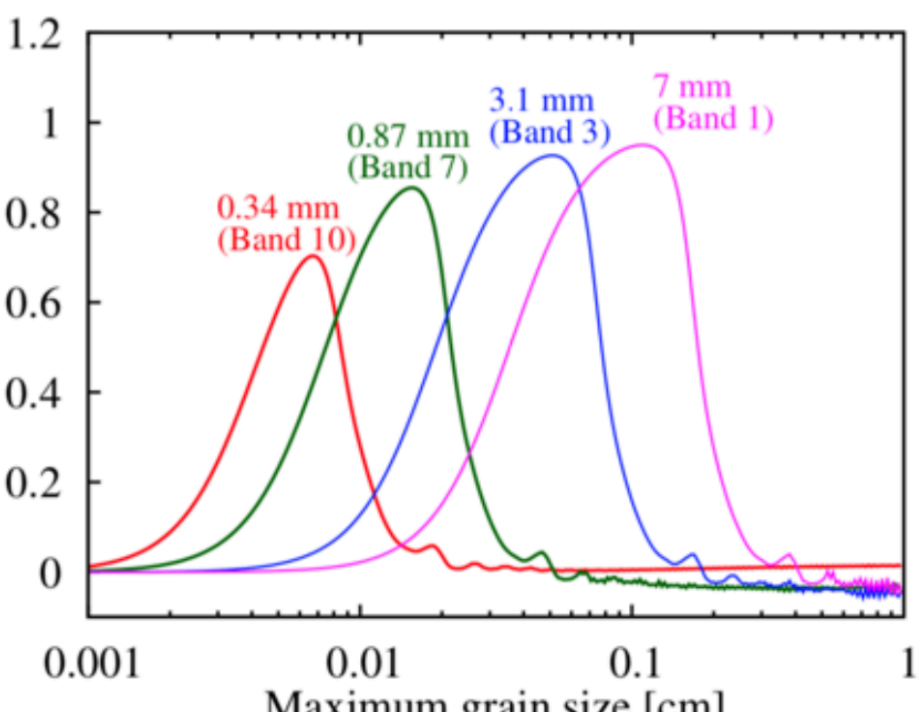
Polarisation

Measure polarisation in multiple wavelengths: transition from self-scattering to intrinsic polarisation by dust alignment

HL Tau



Self-scattering + Intrinsic polarization of aligned dust grains



Self-scattering visible in Band 7, not in Band 6/3 => maximum grain size must be <100 micron!

Kataoka et al. 2017

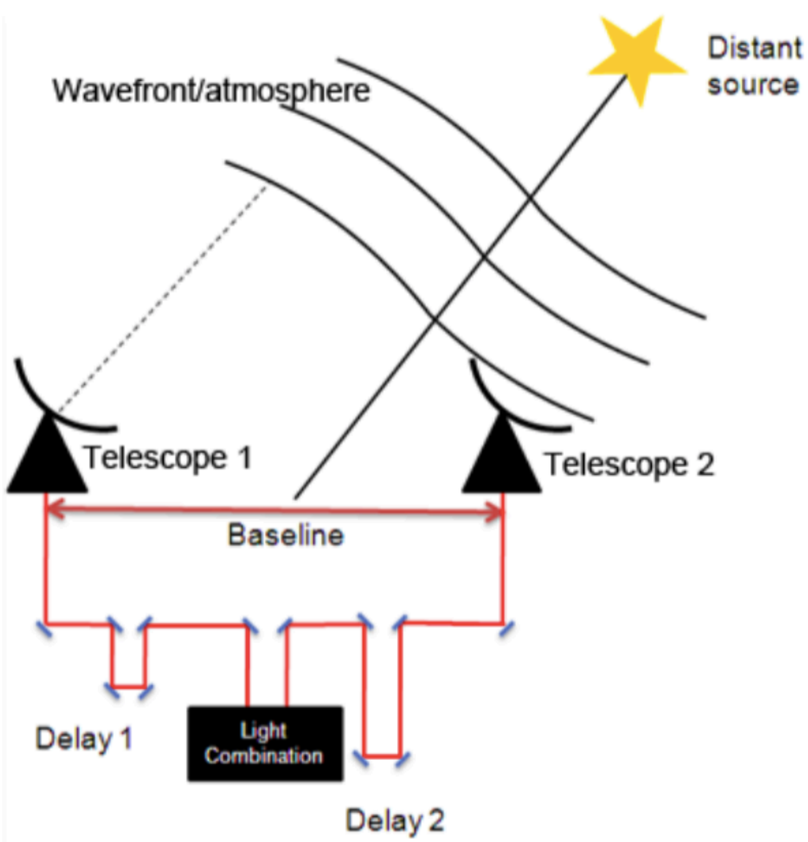
How large are the dust grains in disks?

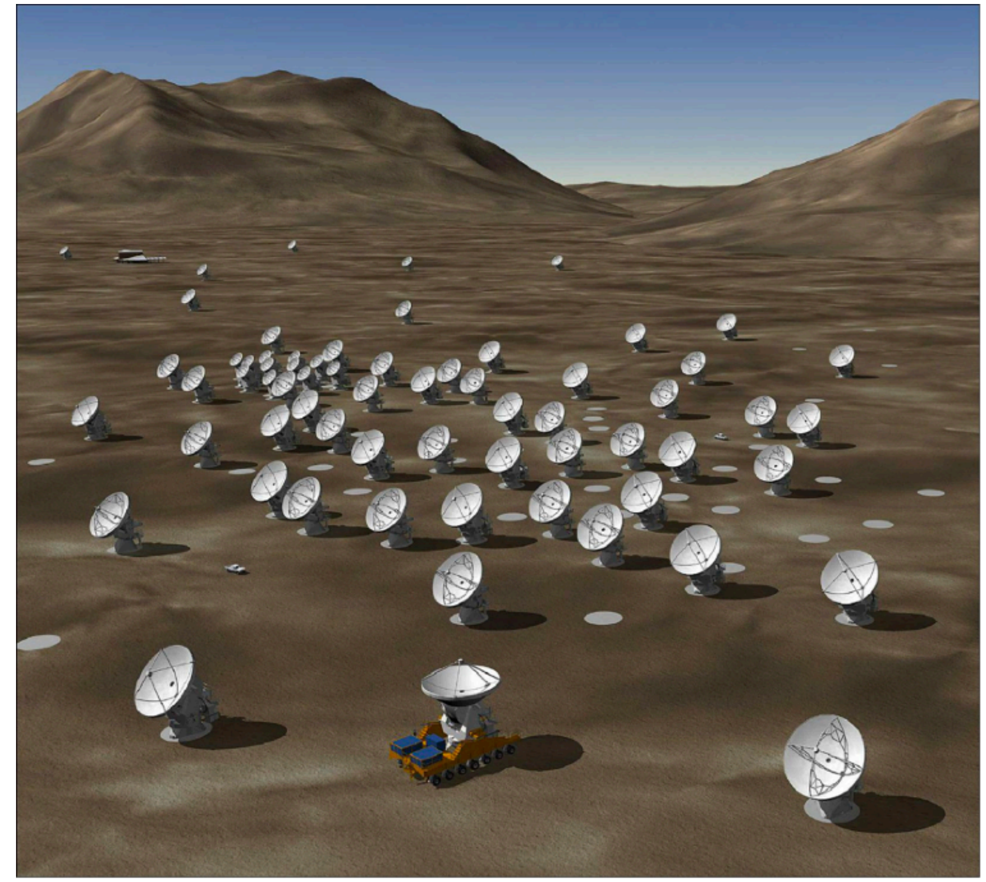
Debate is still on-going!

From MIAPP meeting 2021

How to interpret interferometric images

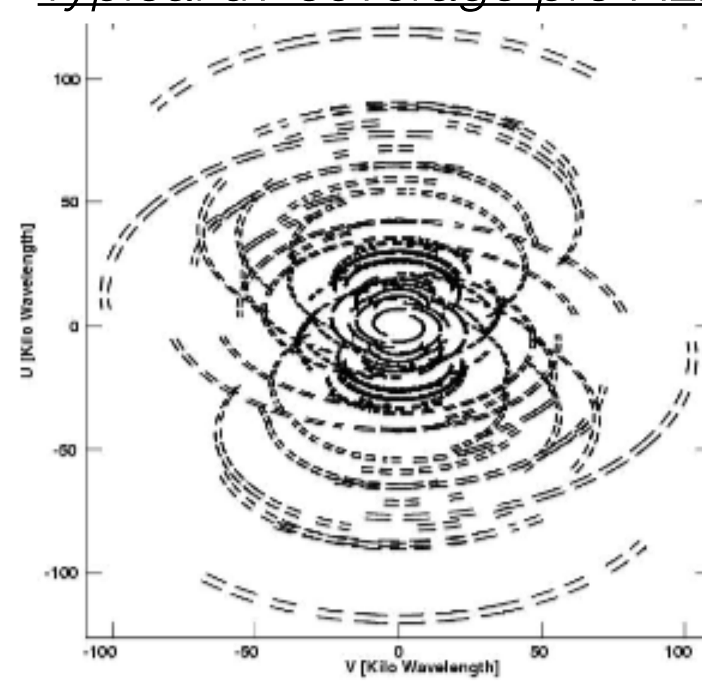
What is uv-coverage



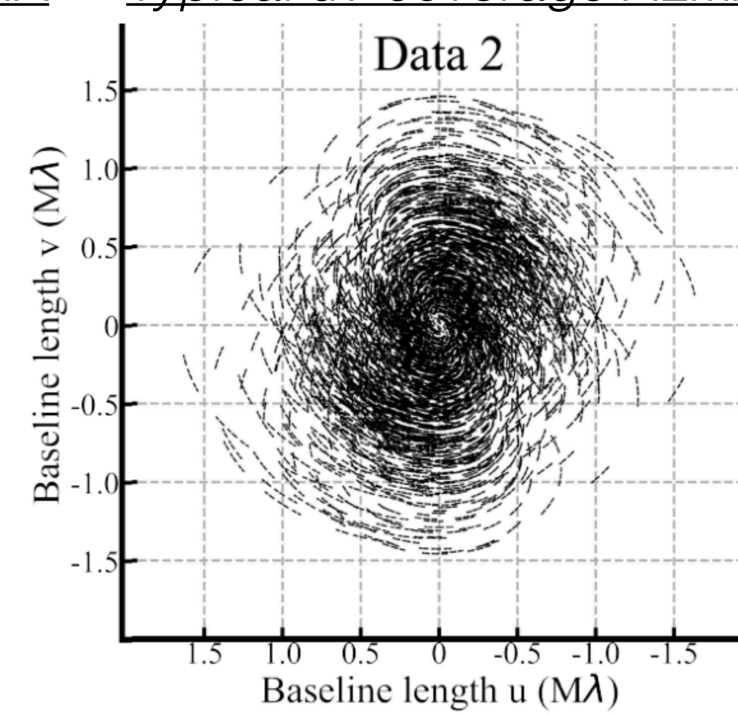


- **Each pair of antennas gives measurements for one uv-point**
- **Earth rotation increases uv-points**
- **All uv-points: uv-coverage**
- **Fourier transform uv-coverage <=> resolution beam**
- **Large uv-point = long baseline = small resolution element**

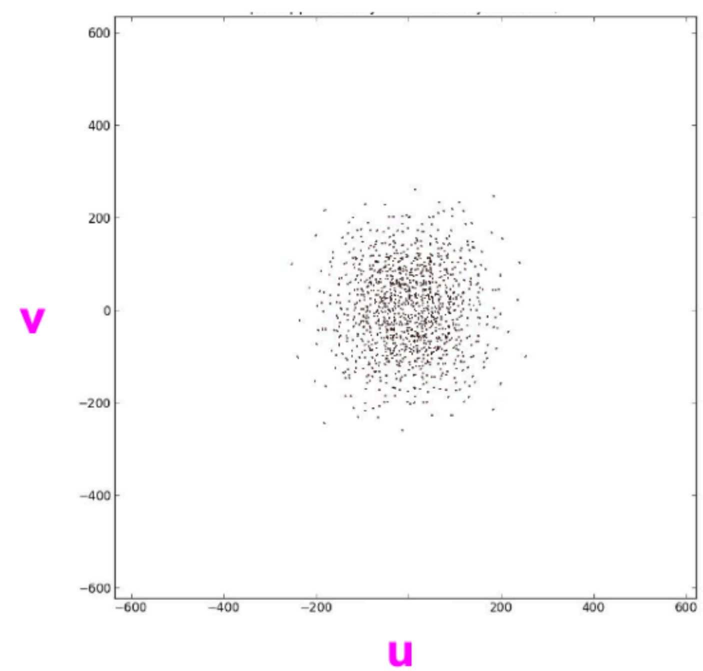
Typical uv-coverage pre-ALMA

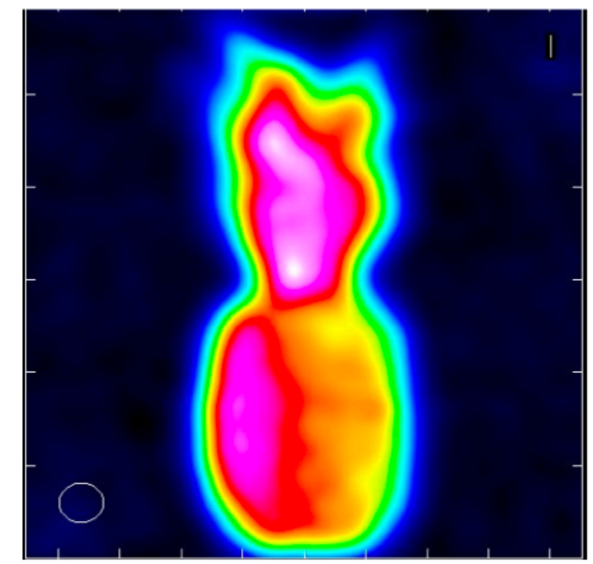


Typical uv-coverage ALMA



Demo uv-coverage

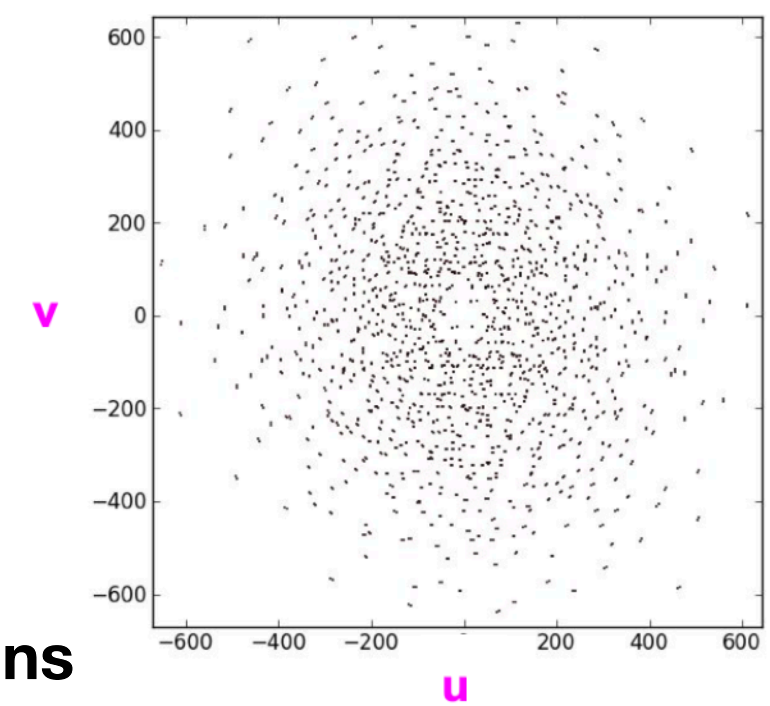


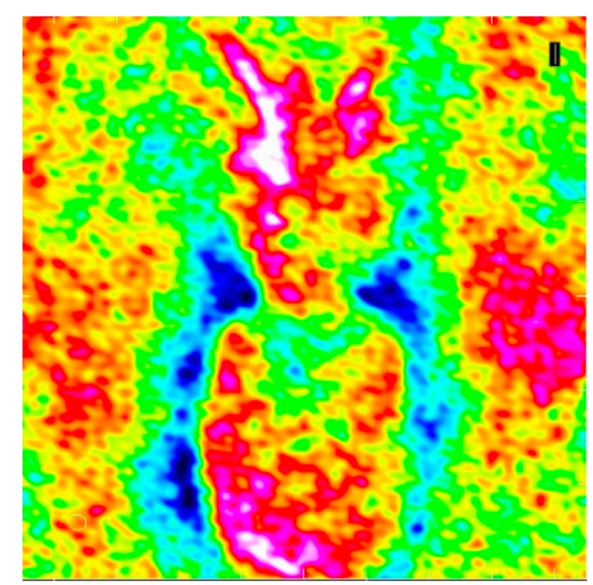


- **Different configurations: different uv-coverage (spatial sampling)**
- **Extended array: sampling small scales**
- **Compact array: sampling large scales**

Fourier Domain (uv-plane) Sampling

What ALMA sees:

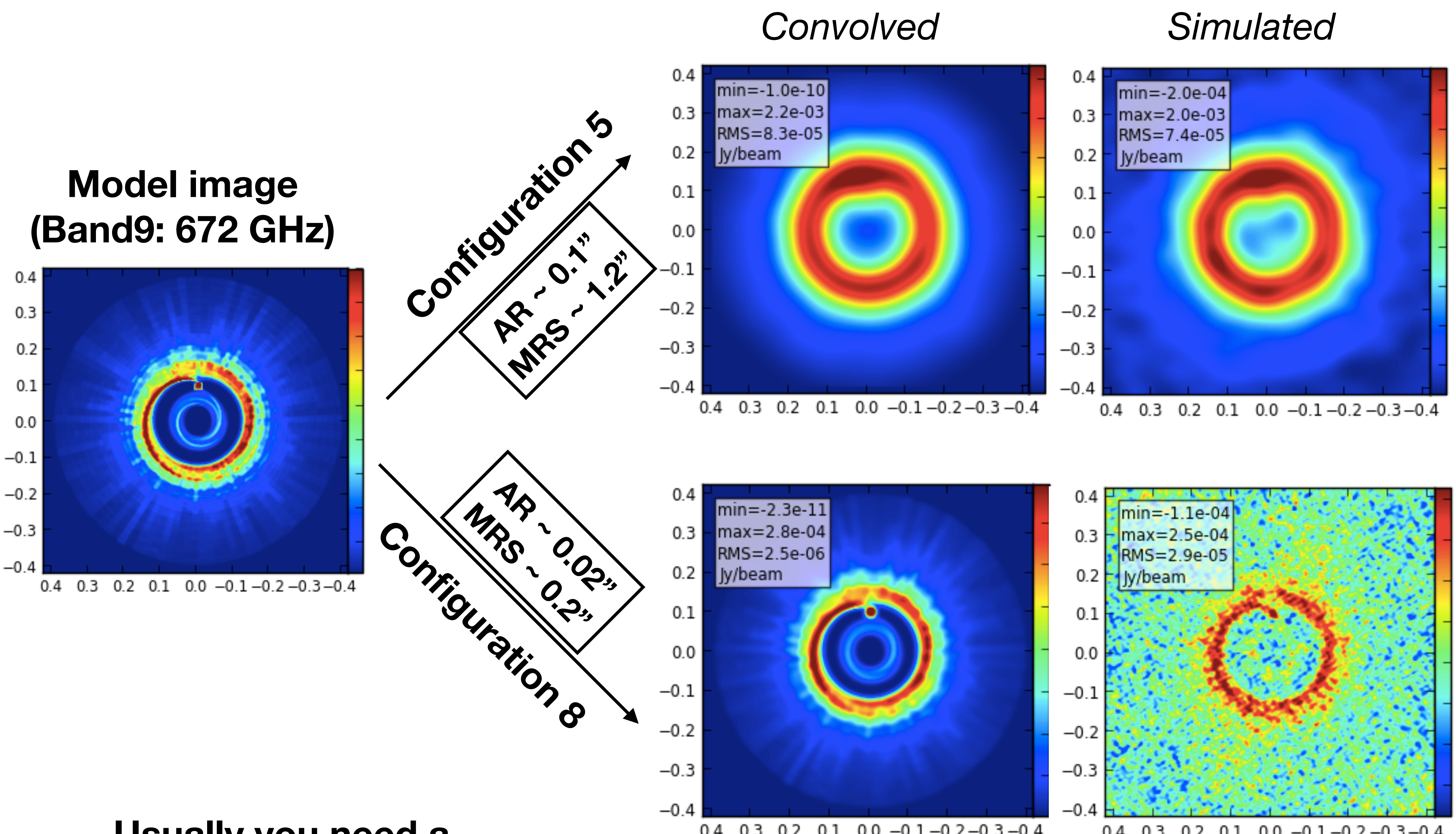




Usually you need a combination of 2 configurations to map all scales

Credits: Logan Francis

Demo uv-coverage



Usually you need a combination of 2 configurations to map all scales

Note that only 2/3 of total flux is recovered in C8

Visibility curves

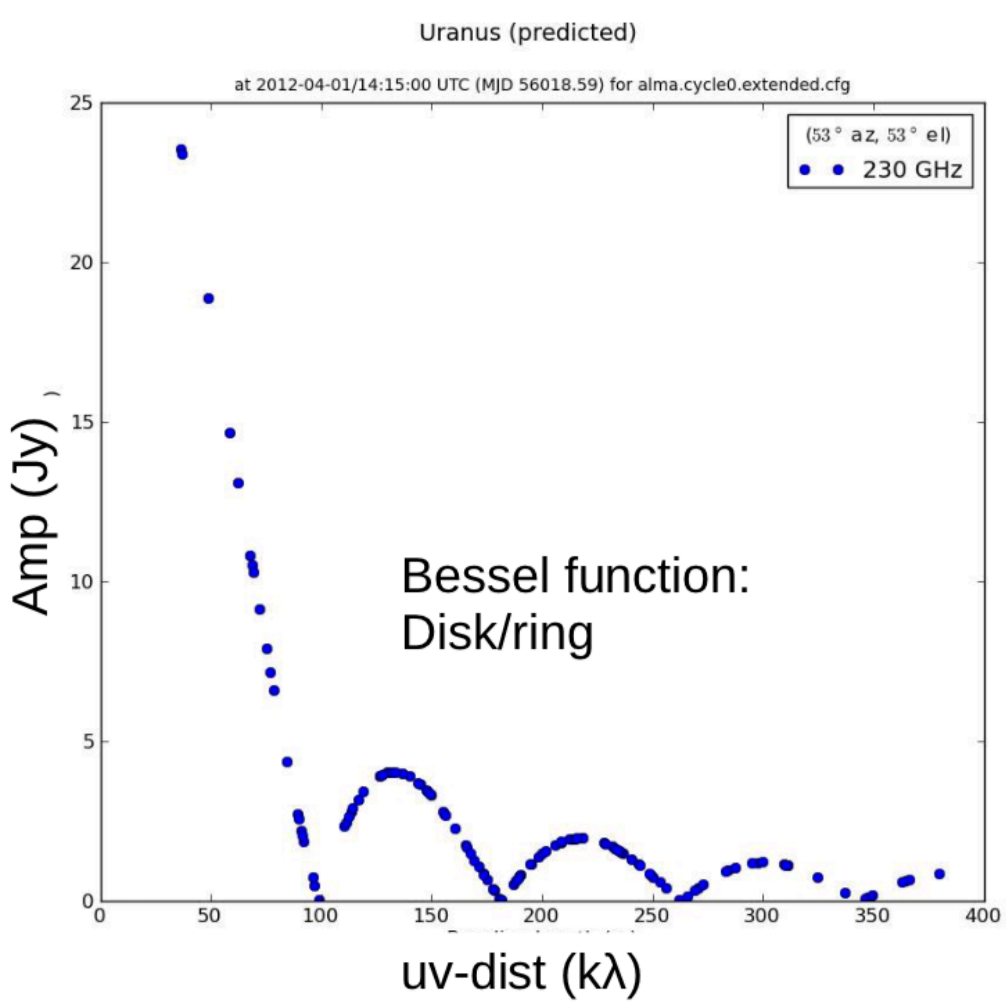
Thinking in Fourier space

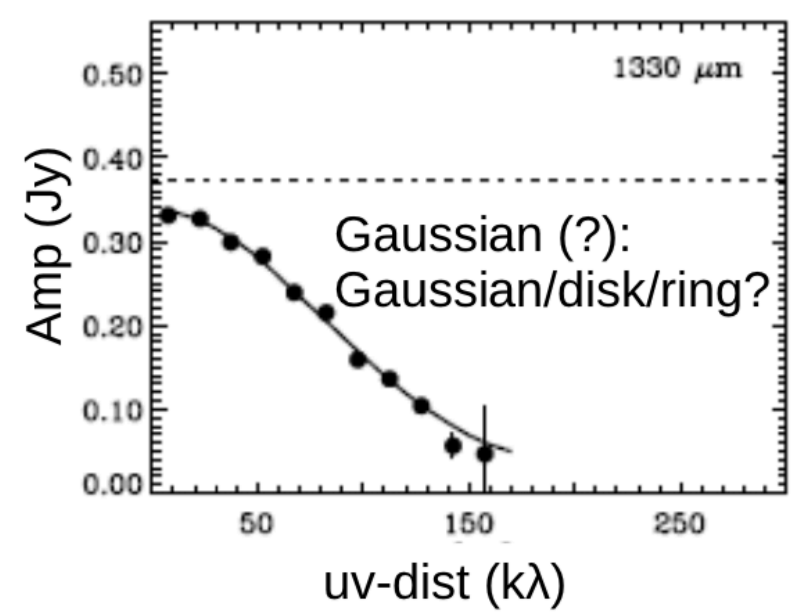
Visibility curves

Thinking in Fourier space

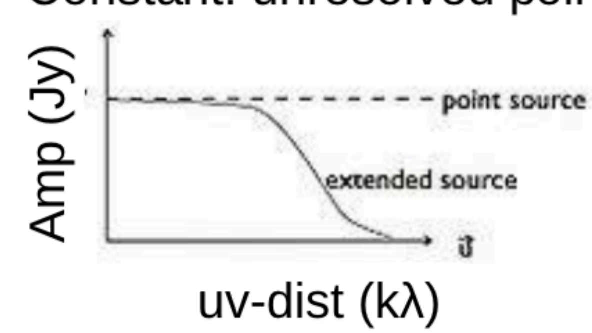
- To prevent issues with incomplete sampling, interpretation and model fitting can be done directly in the uv-plane: visibility data

- Remember: visibility is Fourier transform of the image!





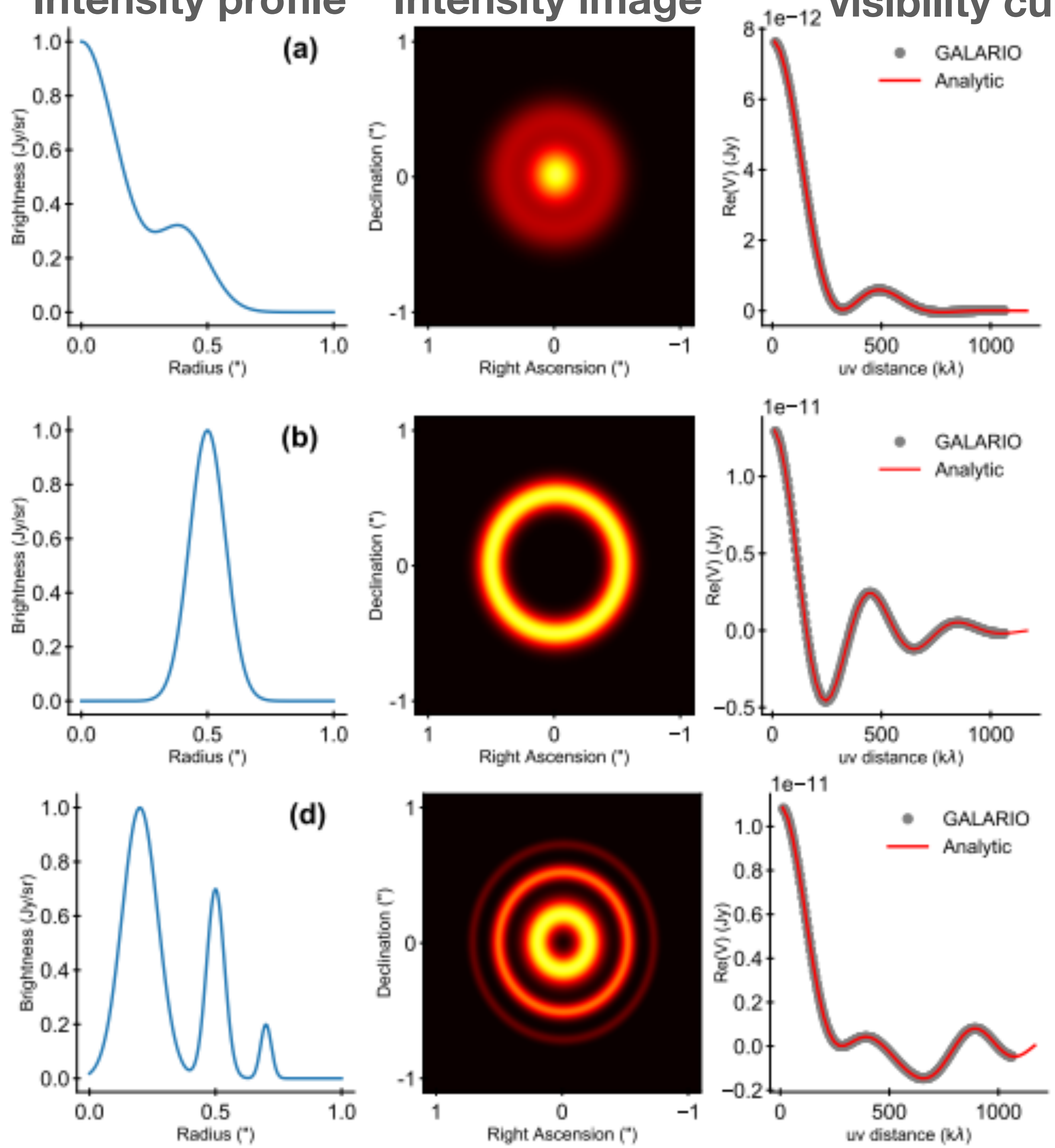
Constant: unresolved point source



Visibility curves

Thinking in Fourier space

Intensity profile | Intensity image | Fourier transform: visibility curve



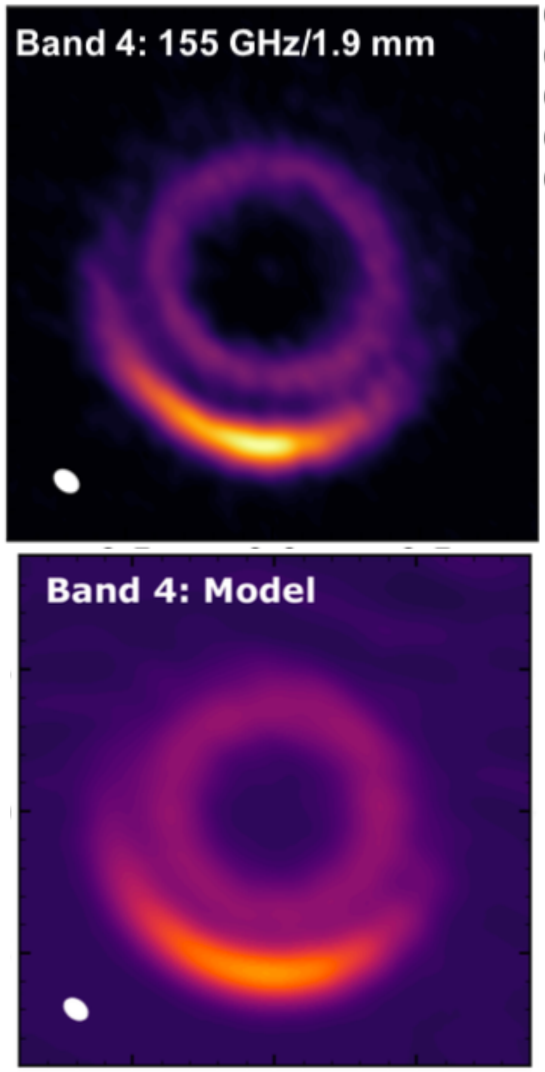
Galario software: Fourier transform a given model profile or model image onto the observed uv-points, and find a best fit to the data with MCMC modeling

Want to learn more? Check Galario on GitHub (Tazzari et al. 2018)
https://github.com/mtazzari/galario

Tazzari et al. 2018

Visibility fitting

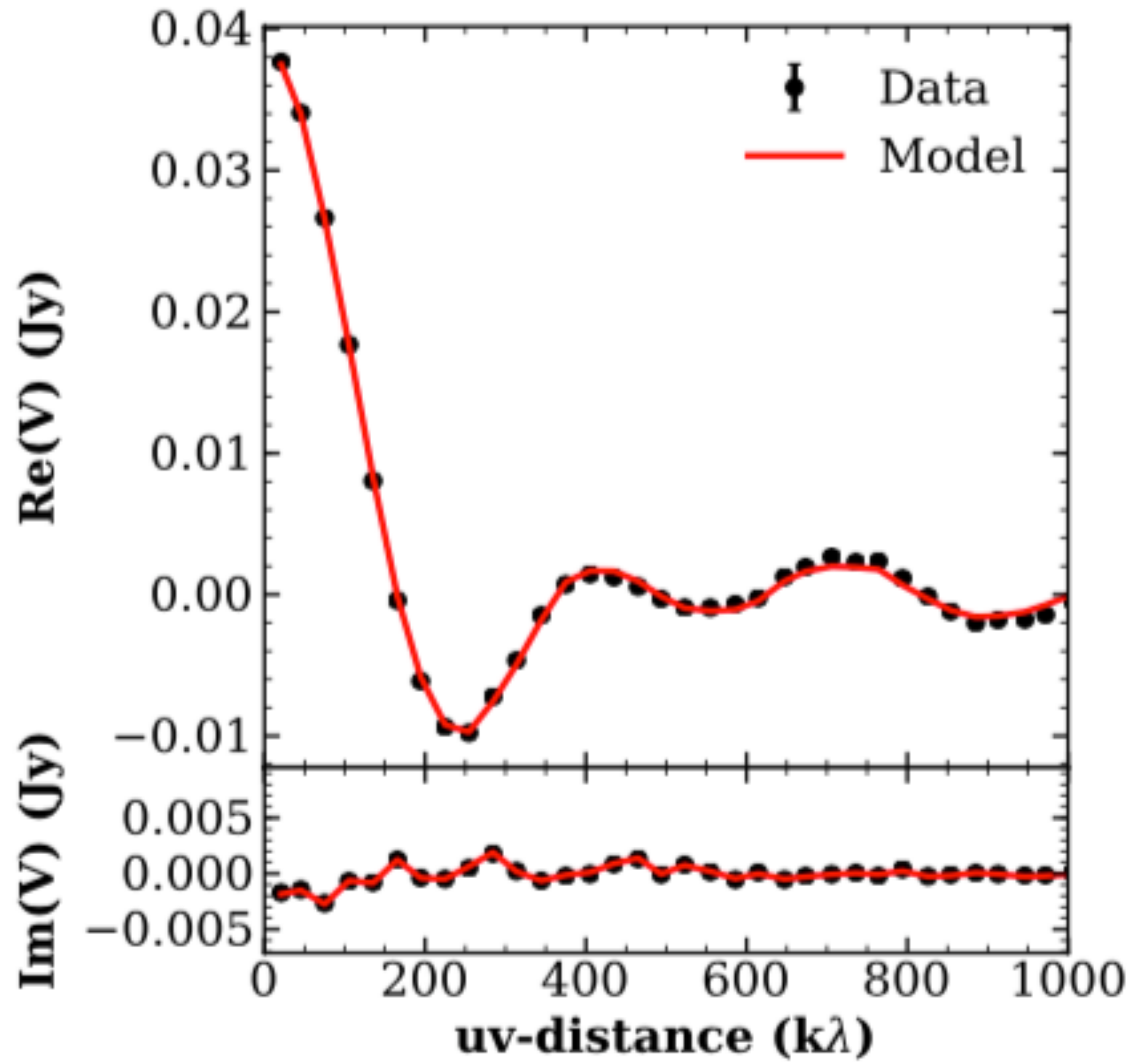
Example: HD135344B



Model: $F_1(r,\theta)*F_2(r,\theta)$ with

$$F_1(r,\theta) = F_\mathrm{R} e^{-(r-r_\mathrm{R})^2/2\sigma_\mathrm{R}^2}$$

$$F_2(r,\theta) = \begin{cases} F_\mathrm{V} e^{-(r-r_\mathrm{V})^2/2\sigma_{\mathrm{V},r}^2} e^{-(\theta-\theta_\mathrm{V})^2/2\sigma_{\mathrm{V},\theta 1}^2}, & \theta \leq \theta_\mathrm{V} \\ F_\mathrm{V} e^{-(r-r_\mathrm{V})^2/2\sigma_{\mathrm{V},r}^2} e^{-(\theta-\theta_\mathrm{V})^2/2\sigma_{\mathrm{V},\theta 2}^2}, & \theta > \theta_\mathrm{V} \end{cases}$$



Real and imaginary parts of the visibility: Amplitude is sqrt(Real² + Imag²)

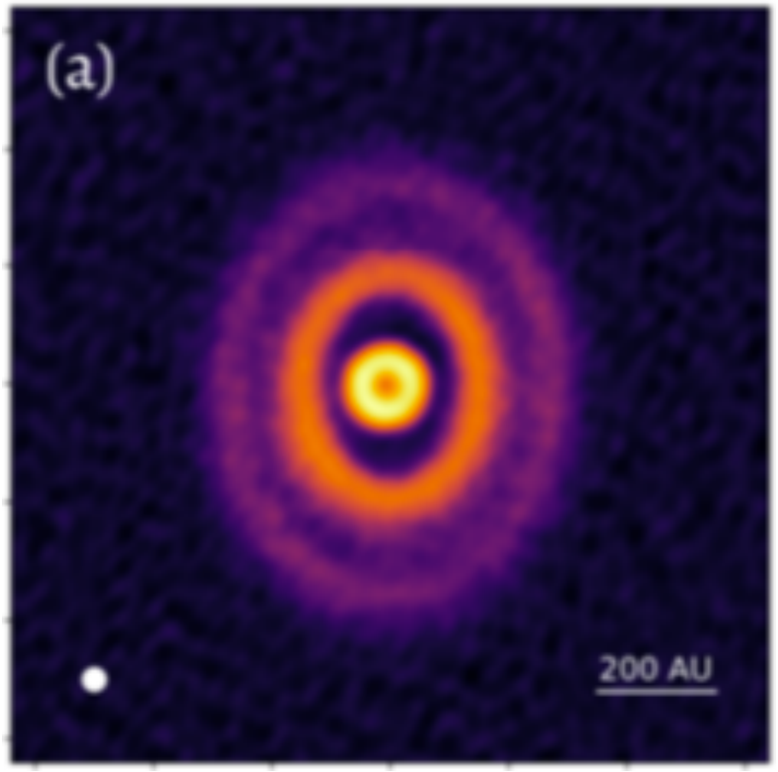
Uv-distance = sqrt(u²+v²)

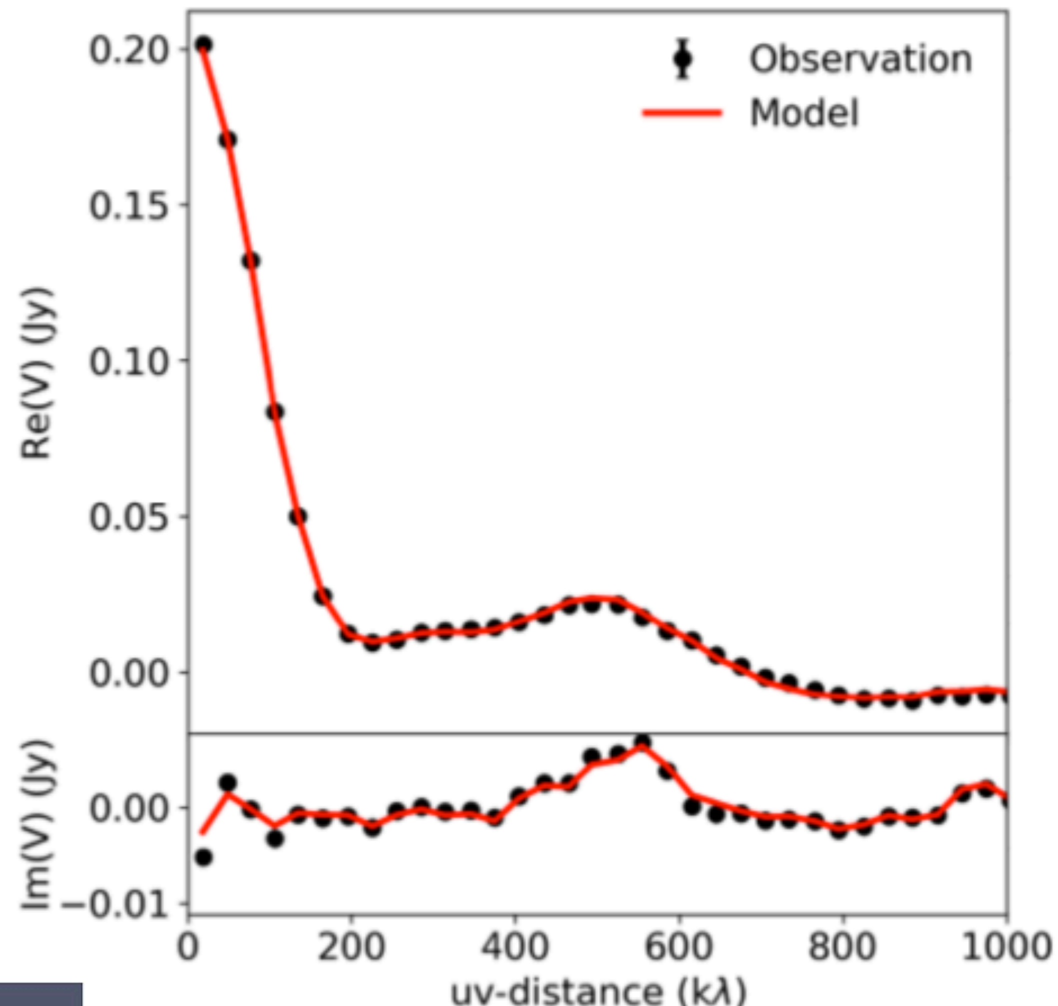
12 parameters!

Cazzoletti et al. 2019

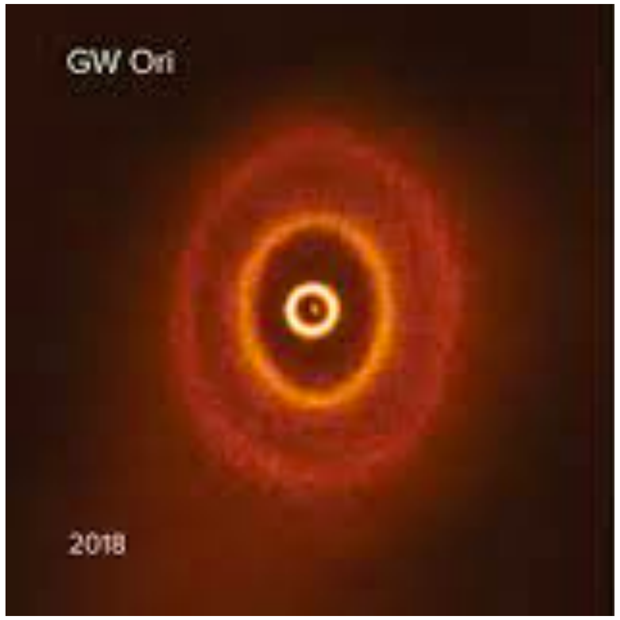
Visibility fitting

Example: GW Ori

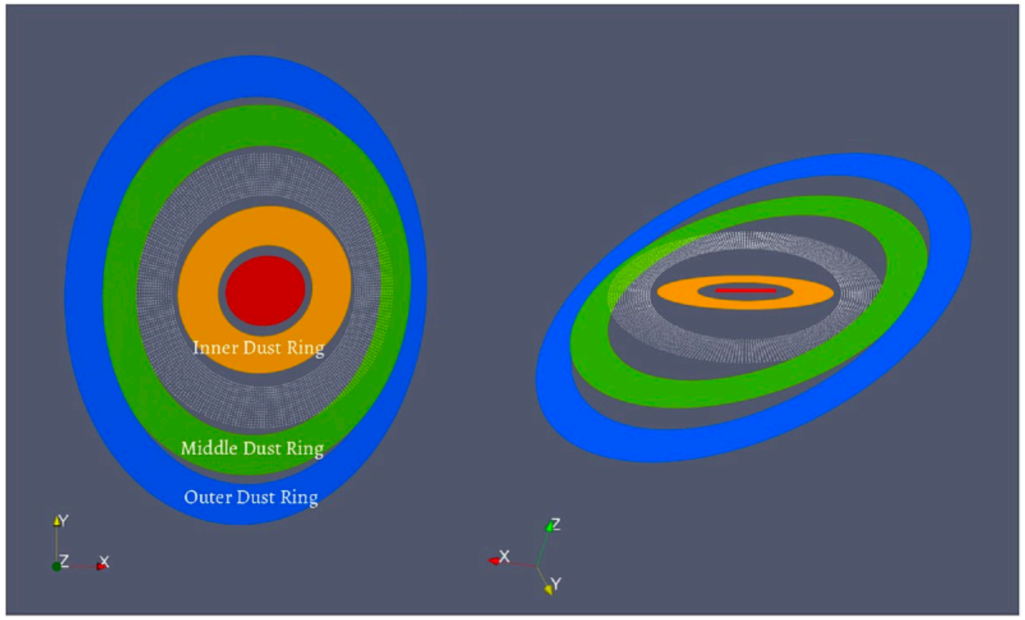




Later published high-res image:



Three rings with different orientations and centers



Bi et al. 2020
Kraus et al. 2020

Questions?