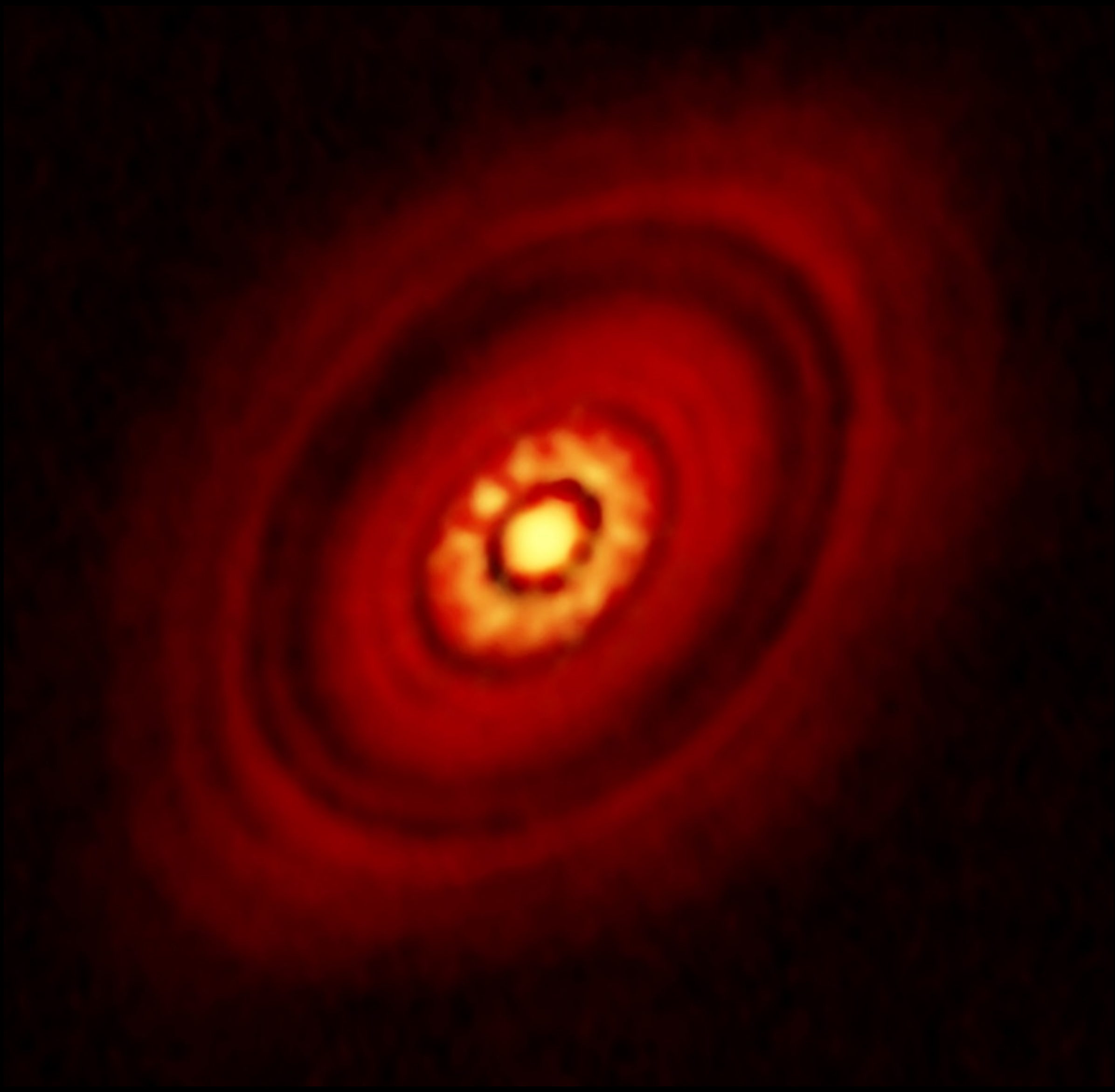
Particle Distribution in Protoplanetary Disks



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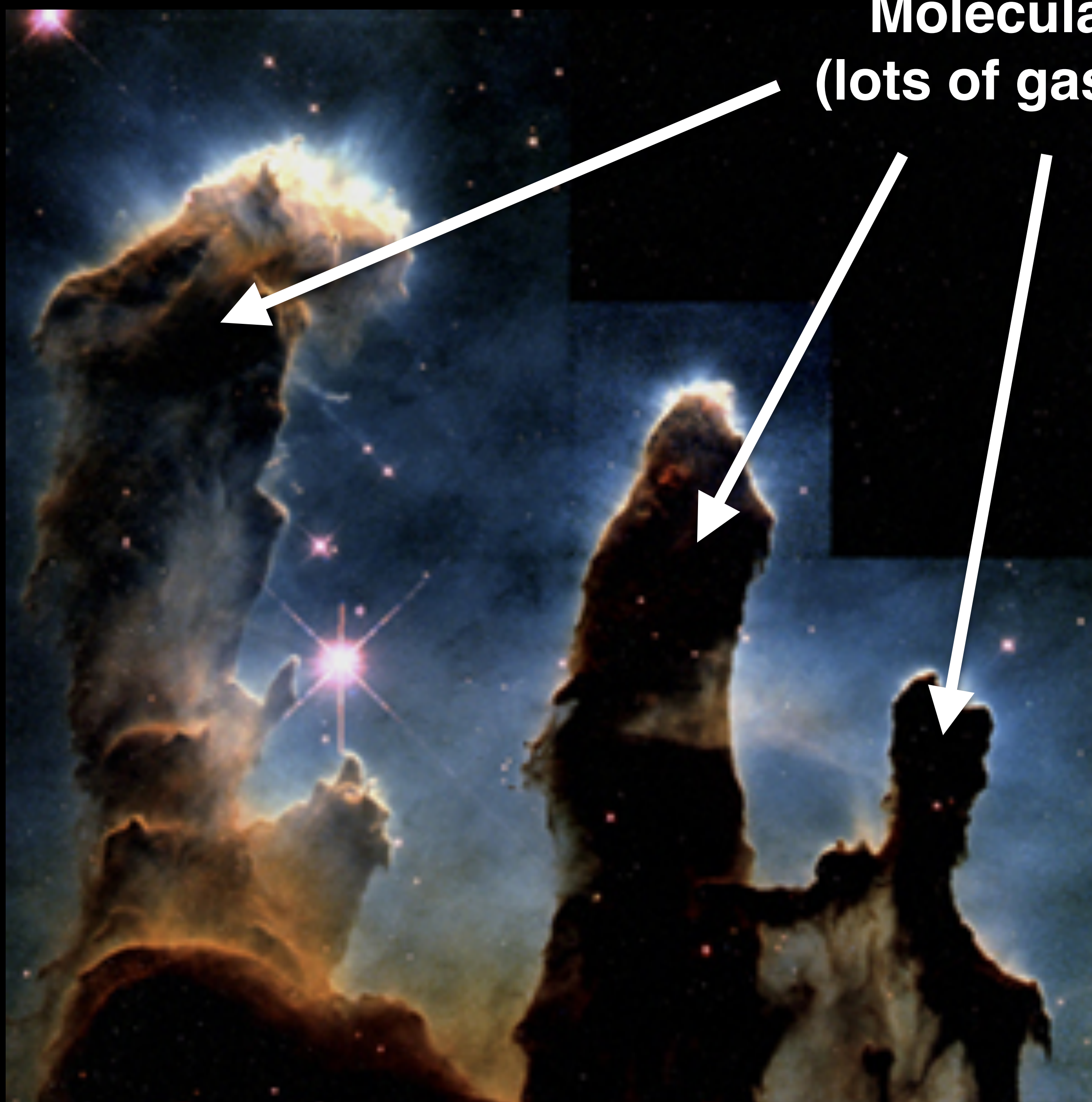
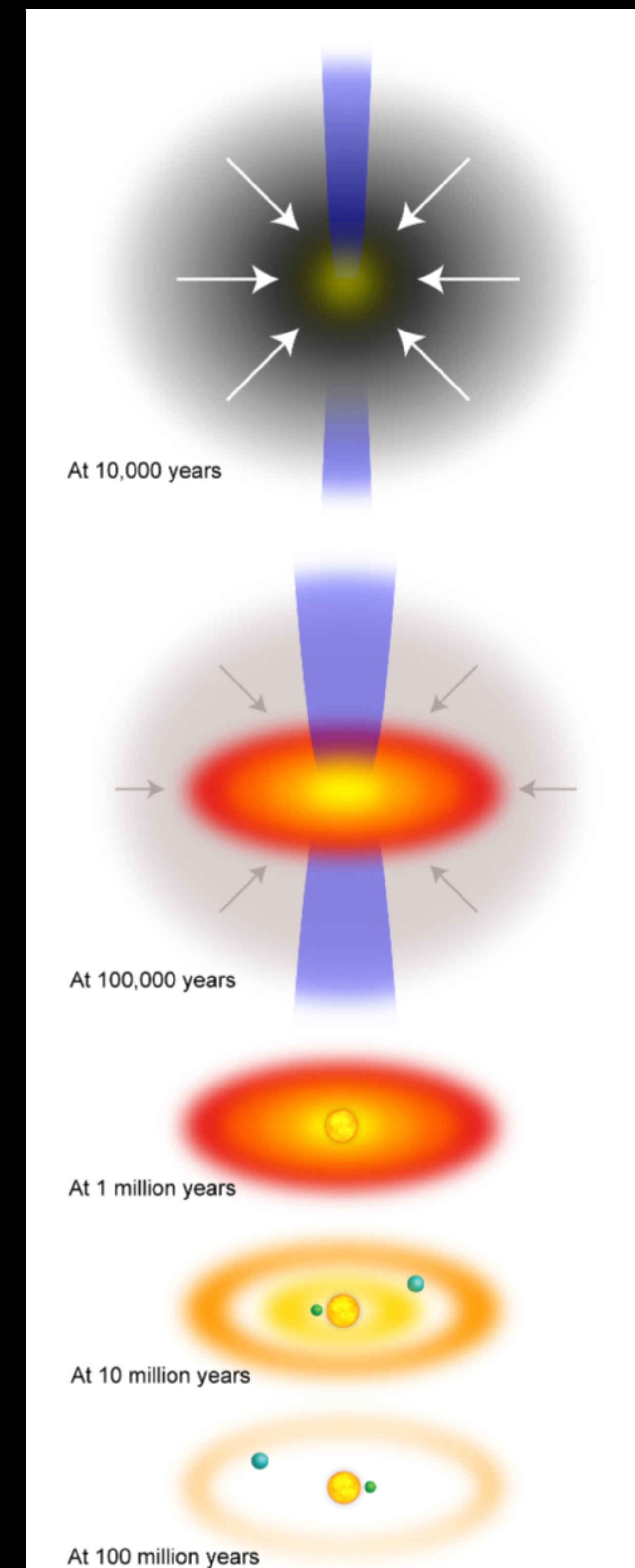
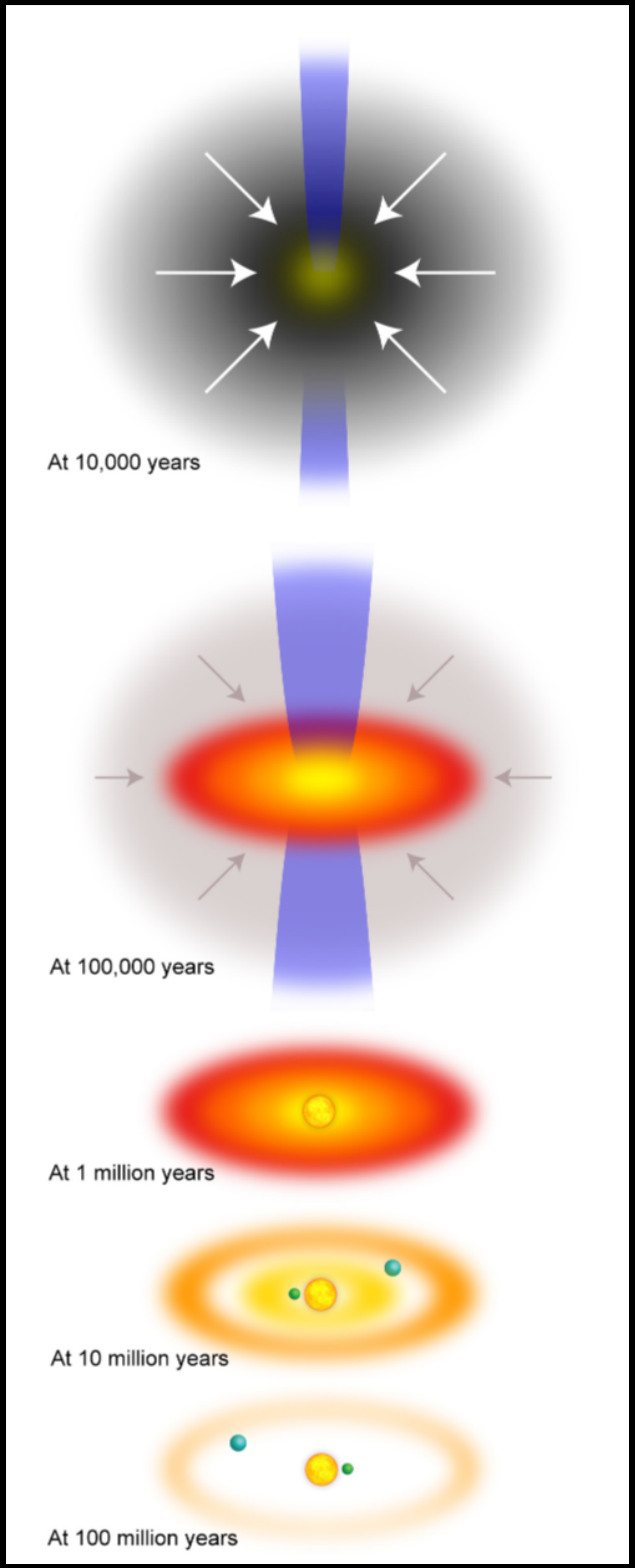
How do stars and planets form?

Molecular clouds
(lots of gas and dust)





How do stars and planets form?



First object is formed: the protostar

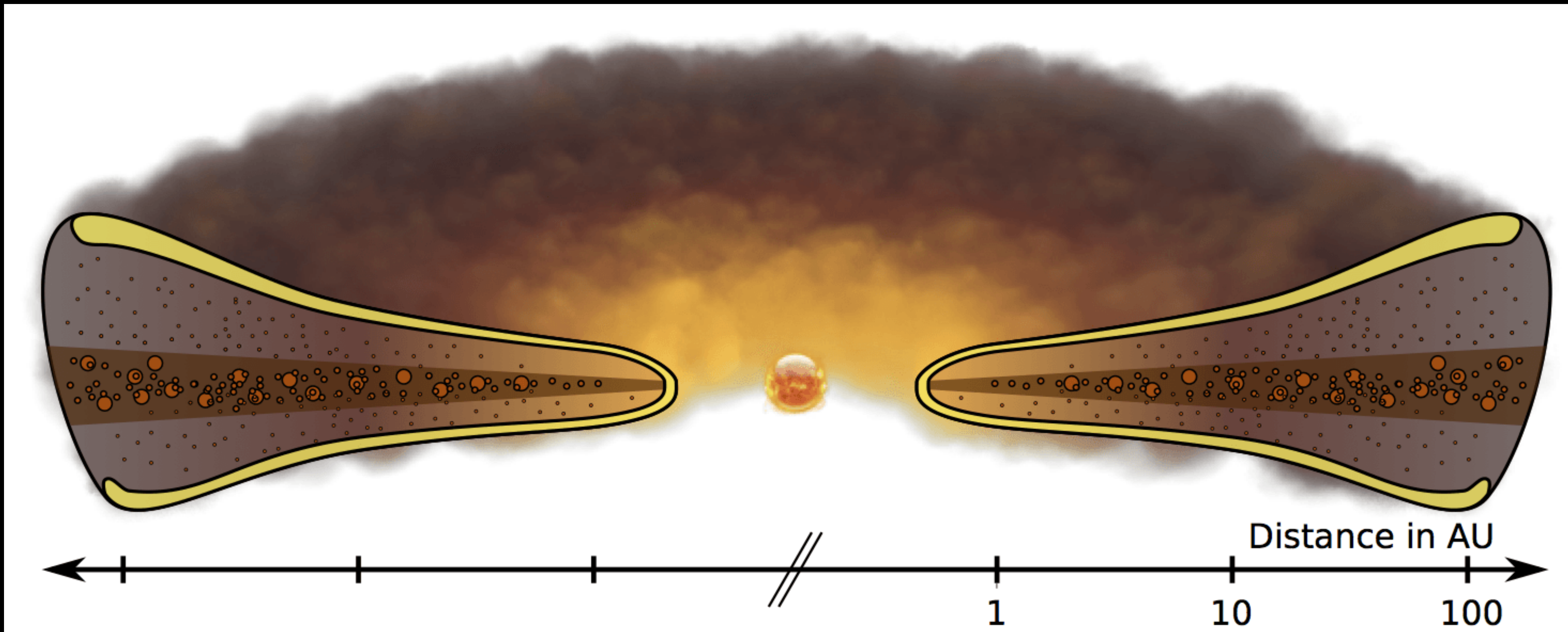
An accretion disk is formed

Jets and outflows: powerful collimated bipolar winds

Accretion and winds stop, remaining material in the disk evolve to form a planetary system

Planetary systems are a “side effect” of Star Formation

PROTOPLANETARY DISKS



Made of gas (~90%) and dust (~10%)

Most of the gas is accreted to the protostar

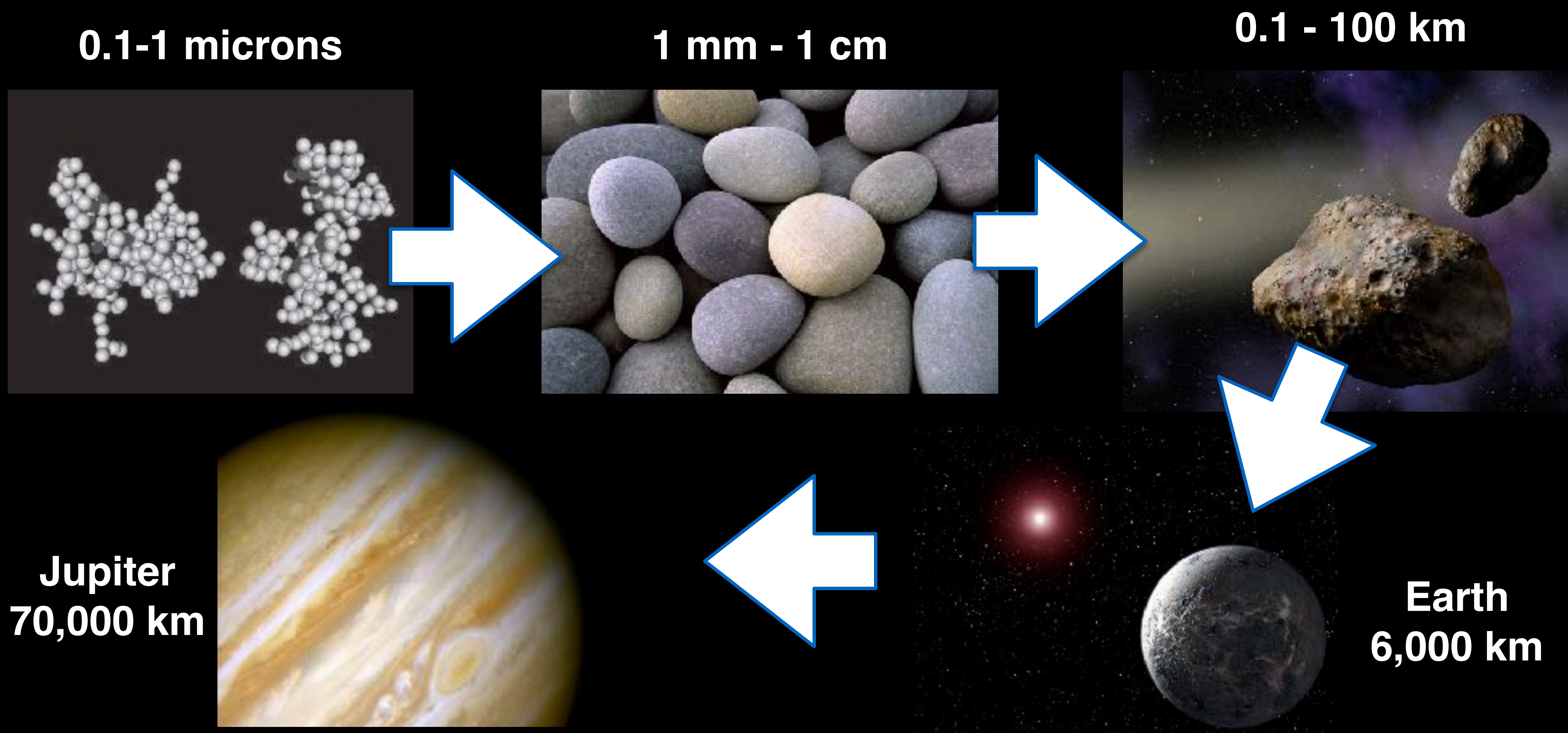
We believe that the dust evolve to form terrestrial planets and the core of giants gaseous planets

HOW AND WHEN PLANETS FORM?

We still do not know… but we have some ideas

Dust should gradually grow to form planetesimals

Micron-sized dust grains —> km-sized rocks



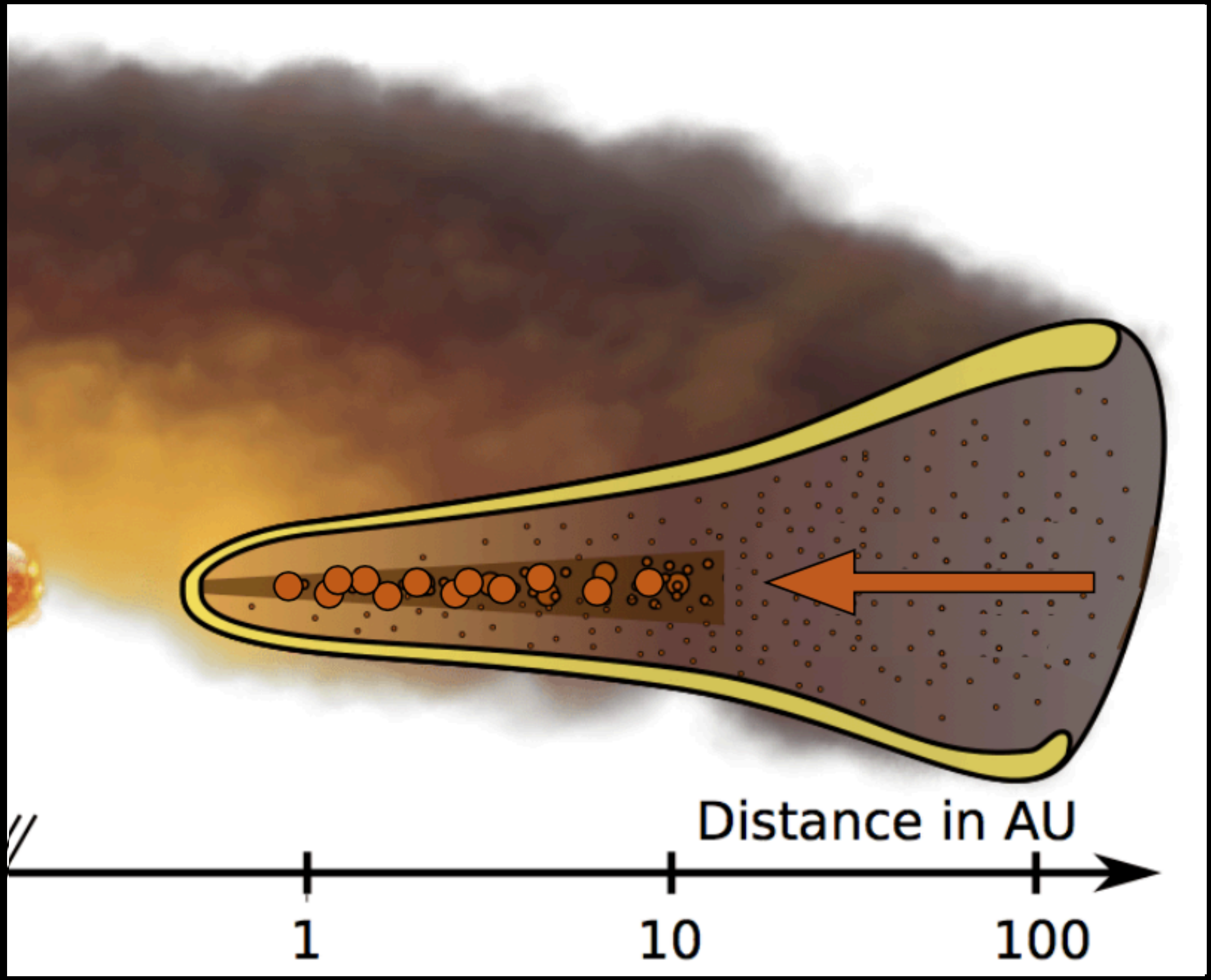
Difficult to explain; several theoretical problems.

Small grains (sub-mm): coupled to the gas

Large grains (mm-cm): affected by drag forces

Higher pressures in mid-plane → Vertical Settling

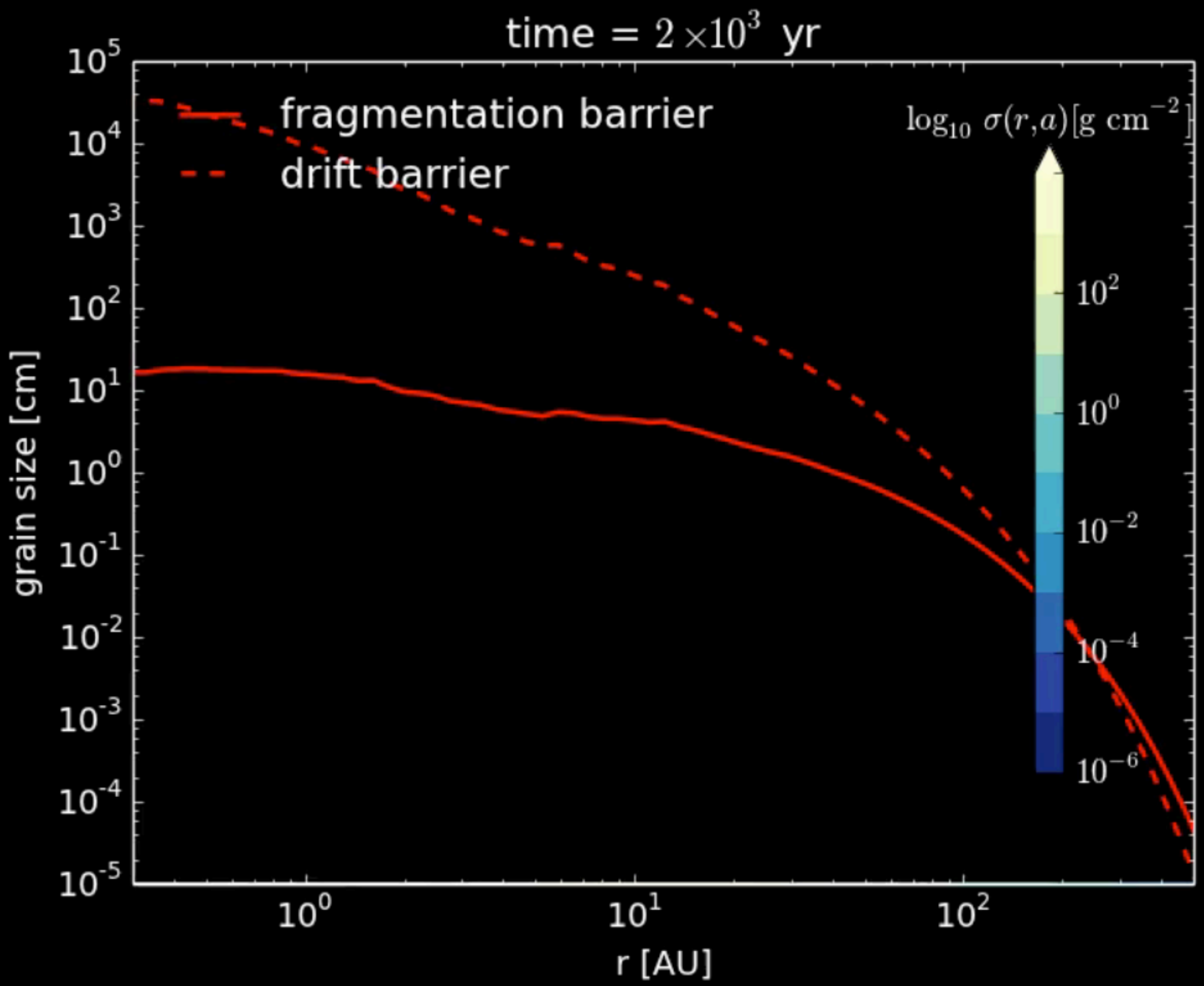
Higher pressures closer to the star → Radial Drift



Near the star, probability of fragmentation increases

Then, they are accreted into the star

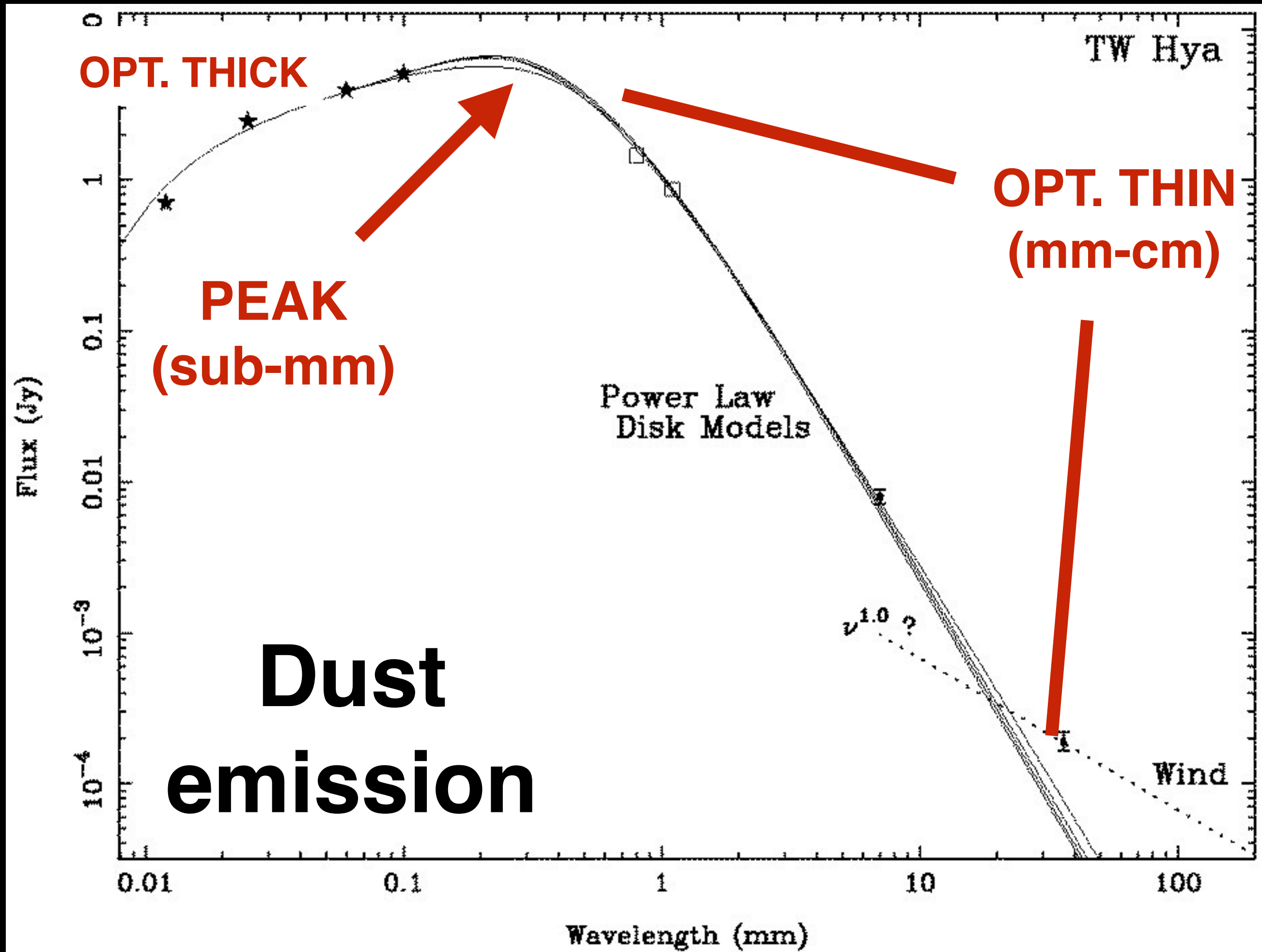
Drift and fragmentation timescale << growth timescale



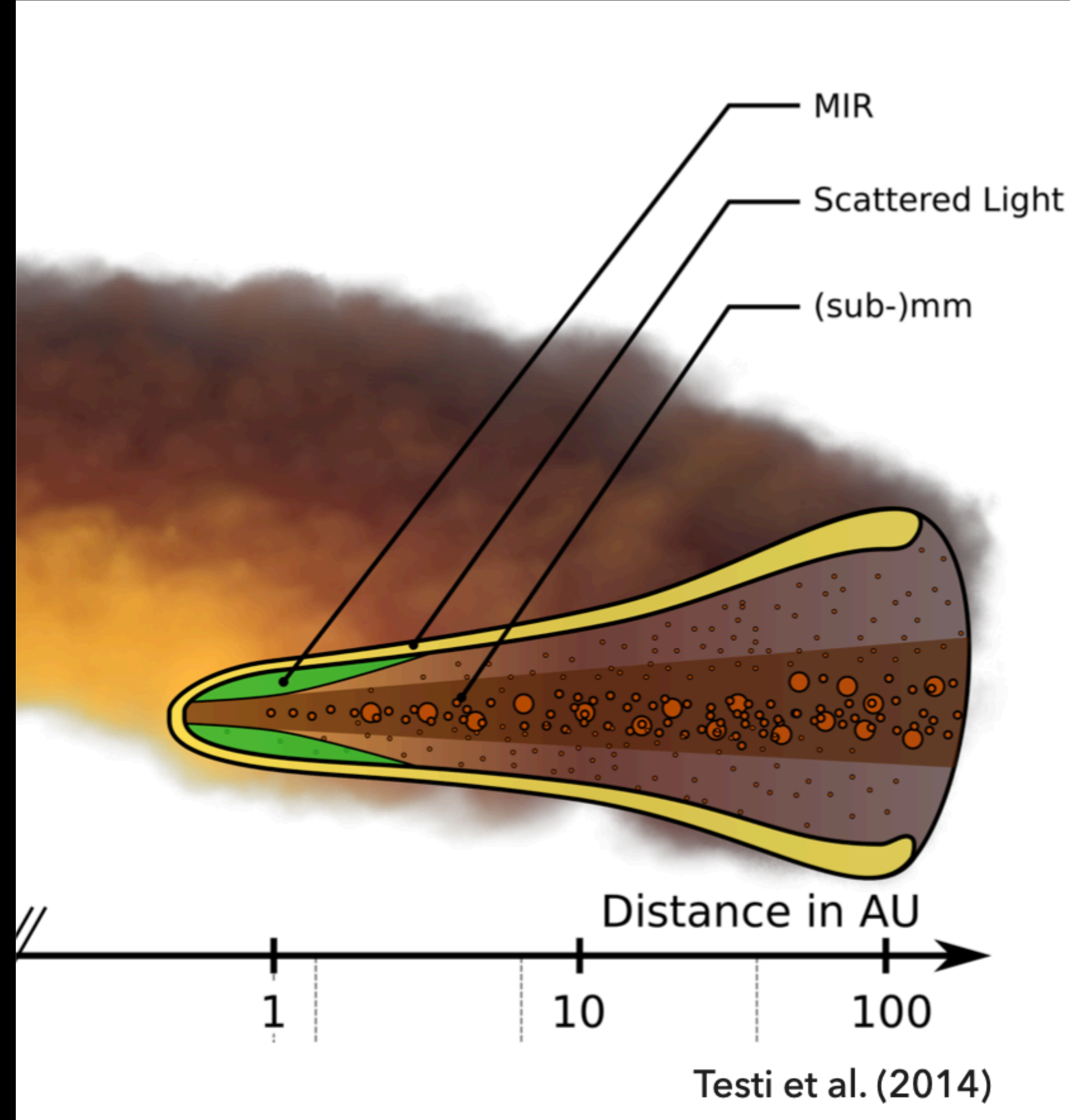
Theoretically, difficult to explain particles > 1 m

(See Francois lecture!!)

Credits: T. Birnstiel



Dust transparency

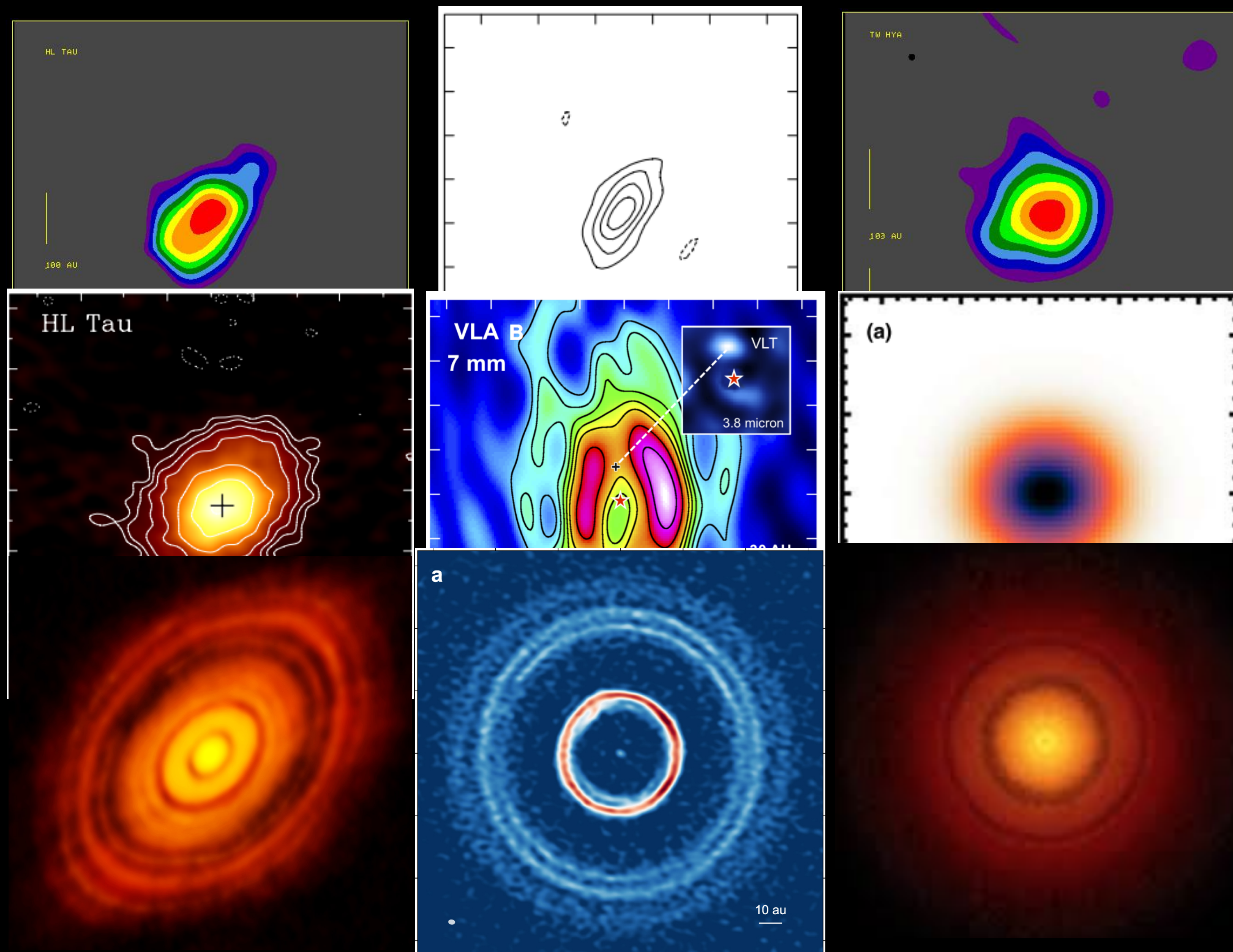


Optical/IR —> Large extinction (specially earliest stages)

mm-cm wavelengths —> mid-plane

We also need very high angular resolution:
1 AU @ 100 pc ~10 mas —> Interferometry

	HL Tau ~1 Myr	HD 169142 ~ 5 Myr	TW Hya ~10 Myr
1990s			
2000s			
2020s			



Very Large Array (VLA)

27 antennas
30 m diameter

Maximum extension ~30 km
Maximum resolution ~40 mas

New Mexico
(USA)

Atacama Large Millimeter Array (ALMA)

66 antennas
7 and 12 m diameter

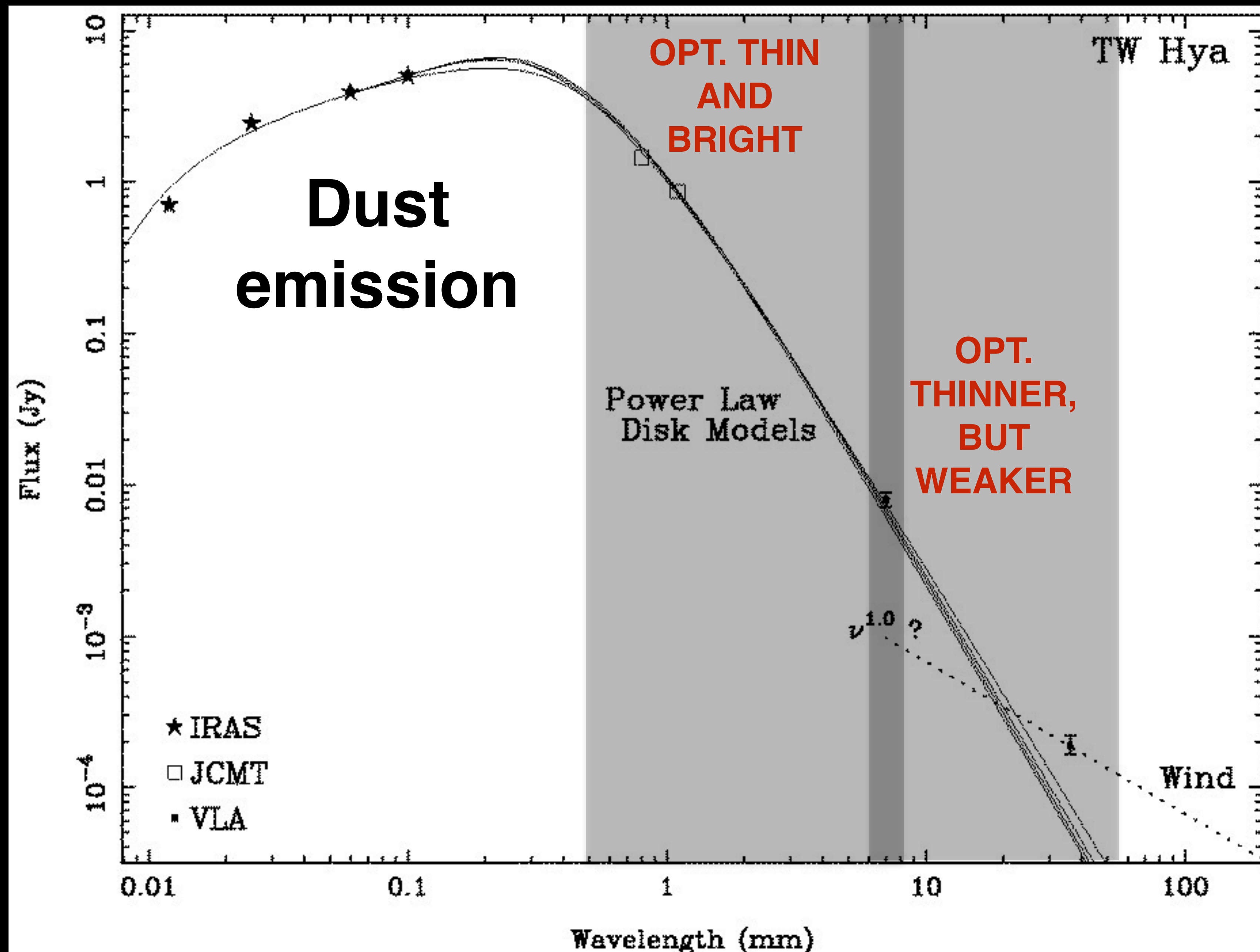
Maximum extension ~ 16 km

Maximum resolution ~ 10 mas

Atacama (Chile)
5,000 m altitude

ALMA
< 10 mm

VLA
> 6 mm



Dust transparency →

Both allow to study dust emission at scales of a few astronomical units

pre-ALMA Era

Obtaining physical parameters of the dust

Absorption-only approximation

Absorption only

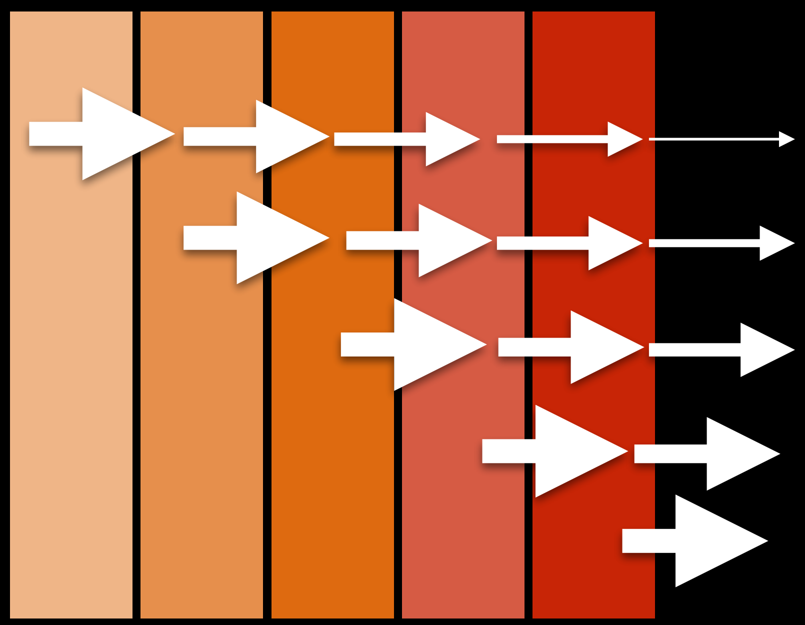
$$I_\nu = B_\nu(T_{dust})(1 - e^{-\tau_\nu})$$

$$T_B = T_{dust}(1 - e^{-\tau_\nu})$$

- $B_\nu(T_{dust})$: Black Body LTE
- $(1 - \ldots)$: Emission
- $e^{-\tau_\nu}$: Extinction

Optical depth –> $\tau_\nu = \Sigma_{dust}\ \kappa_\nu$

- Σ_{dust}: Dust Density
- κ_ν: Mass absorption Coefficient



Observer

Absorption only

$$I_\nu = B_\nu(T_{dust})(1 - e^{-\tau_\nu}) \qquad T_B = T_{dust}(1 - e^{-\tau_\nu})$$

Optical depth –> $\tau_\nu = \Sigma_{dust}\ \kappa_\nu$

<u>Optically THICK</u>

$$\tau_\nu >> 1 \qquad I_\nu \simeq B_\nu(T_{dust}) \qquad T_B \simeq T_{dust}$$

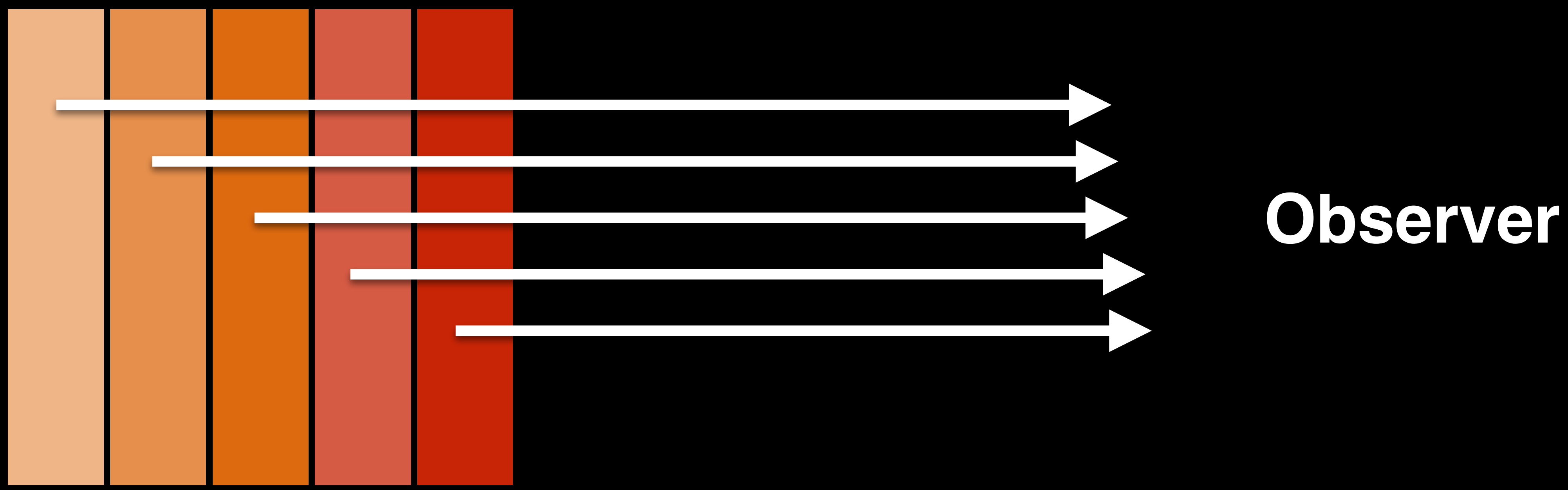
Absorption only

$$I_\nu = B_\nu(T_{dust})(1 - e^{-\tau_\nu}) \qquad T_B = T_{dust}(1 - e^{-\tau_\nu})$$

Optical depth –> $\tau_\nu = \Sigma_{dust}\ \kappa_\nu$

Optically THIN

$$\tau_\nu << 1 \qquad I_\nu \simeq B_\nu(T_{dust})\ \tau_\nu \qquad T_B \simeq T_{dust}\ \tau_\nu$$



Absorption only

Optically THIN

$$\tau_\nu << 1 \qquad I_\nu \simeq B_\nu(T_{dust})\ \tau_\nu \qquad T_B \simeq T_{dust}\ \tau_\nu$$

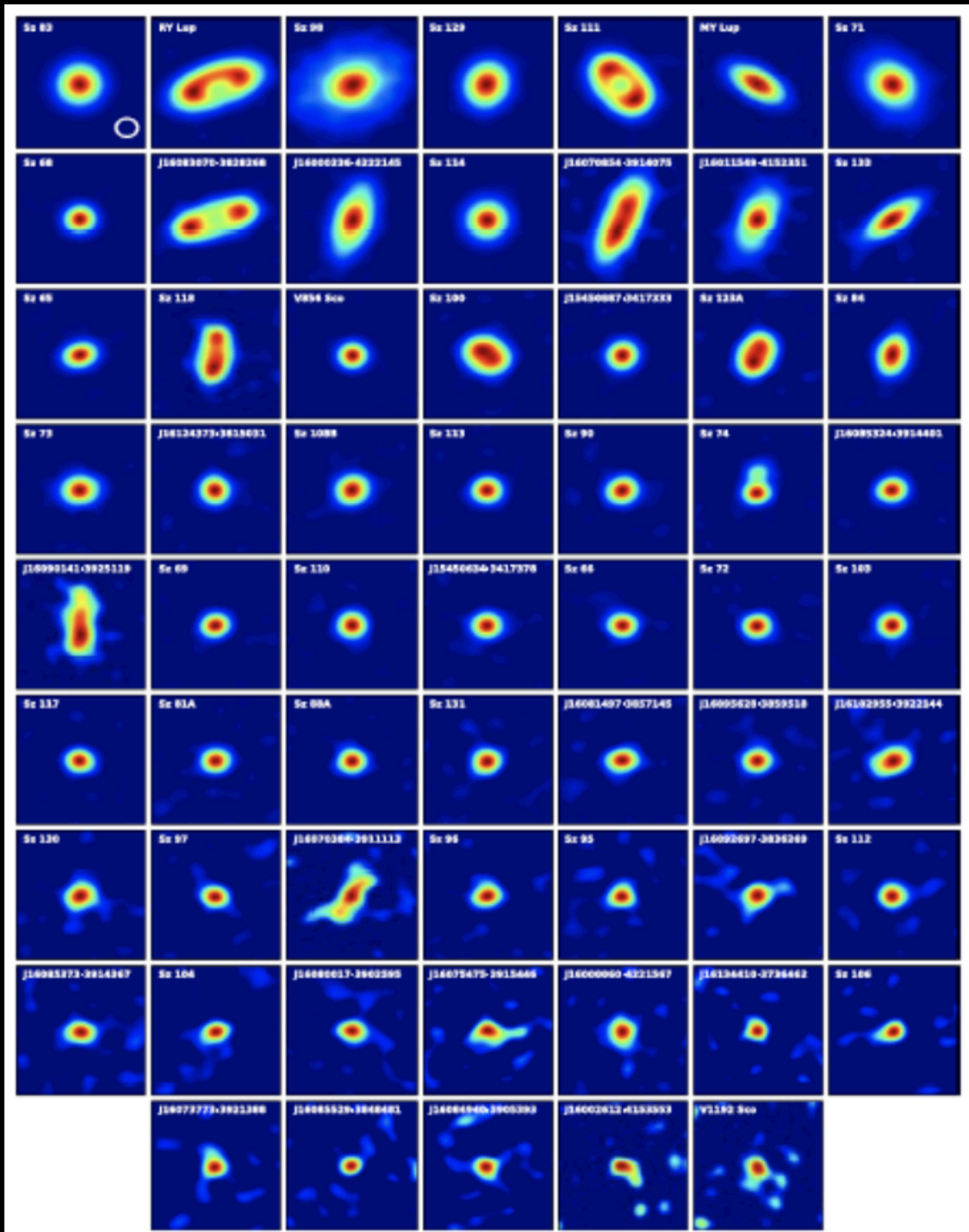
Total flux → F_ν

Source diameter → d^2

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

Average absorption coefficient → κ_ν

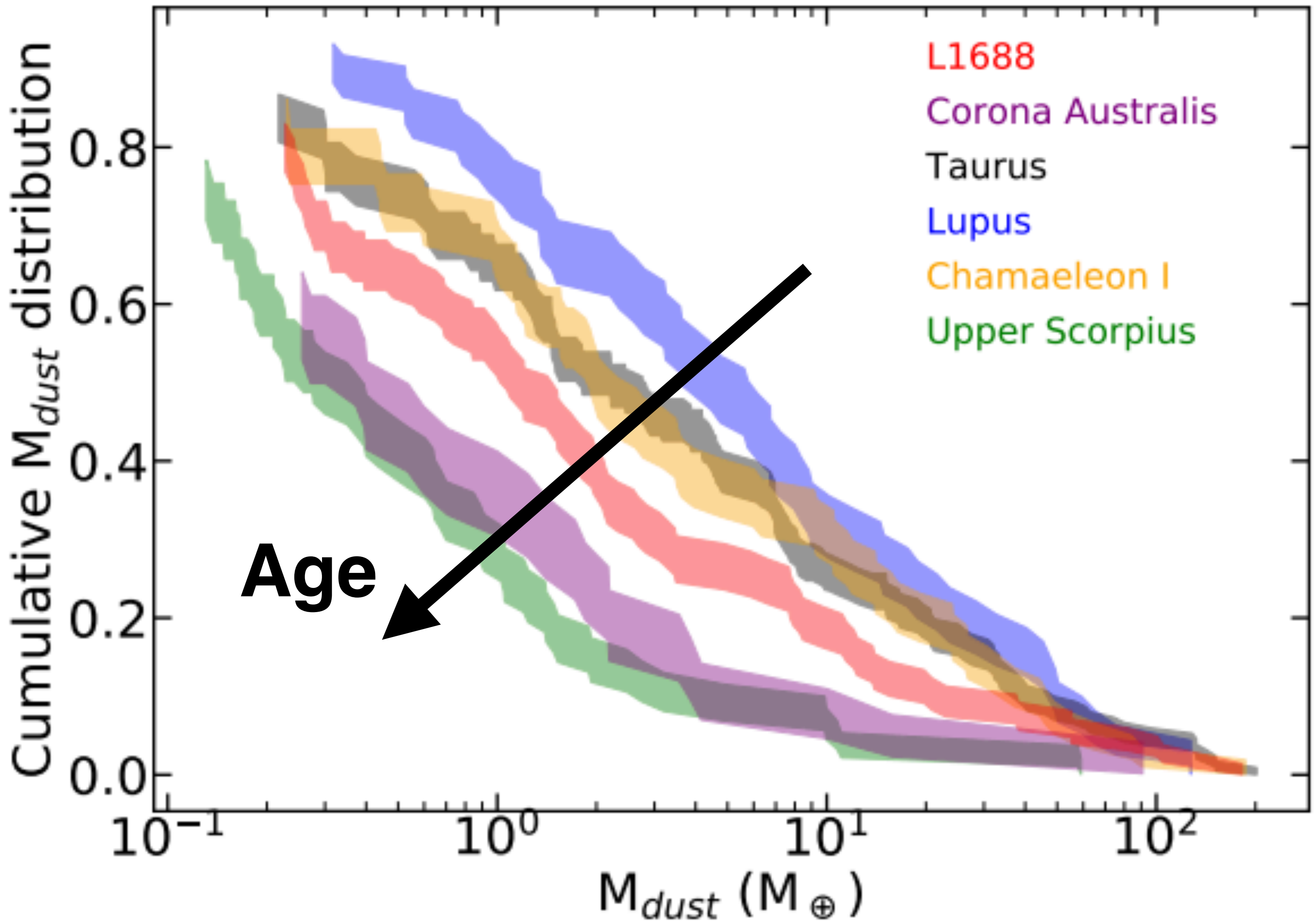
Average Temperature → T_{dust}



ALMA observations of Lupus

Ansdell et al. 2016

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



Testi et al. 2022

Table 1. Characteristic age of the regions.

Name	Median age (Myr)	25% (Myr)	75% (Myr)
Corona Australis	0.6	0.5	2.1
L1688	1.0	0.5	2
Taurus	0.9	0.5	1.7
Lupus	2.0	1.3	3.6
Chamaeleon I	2.8	1.4	6.6
Upper Scorpius	4.3	2.7	7.6

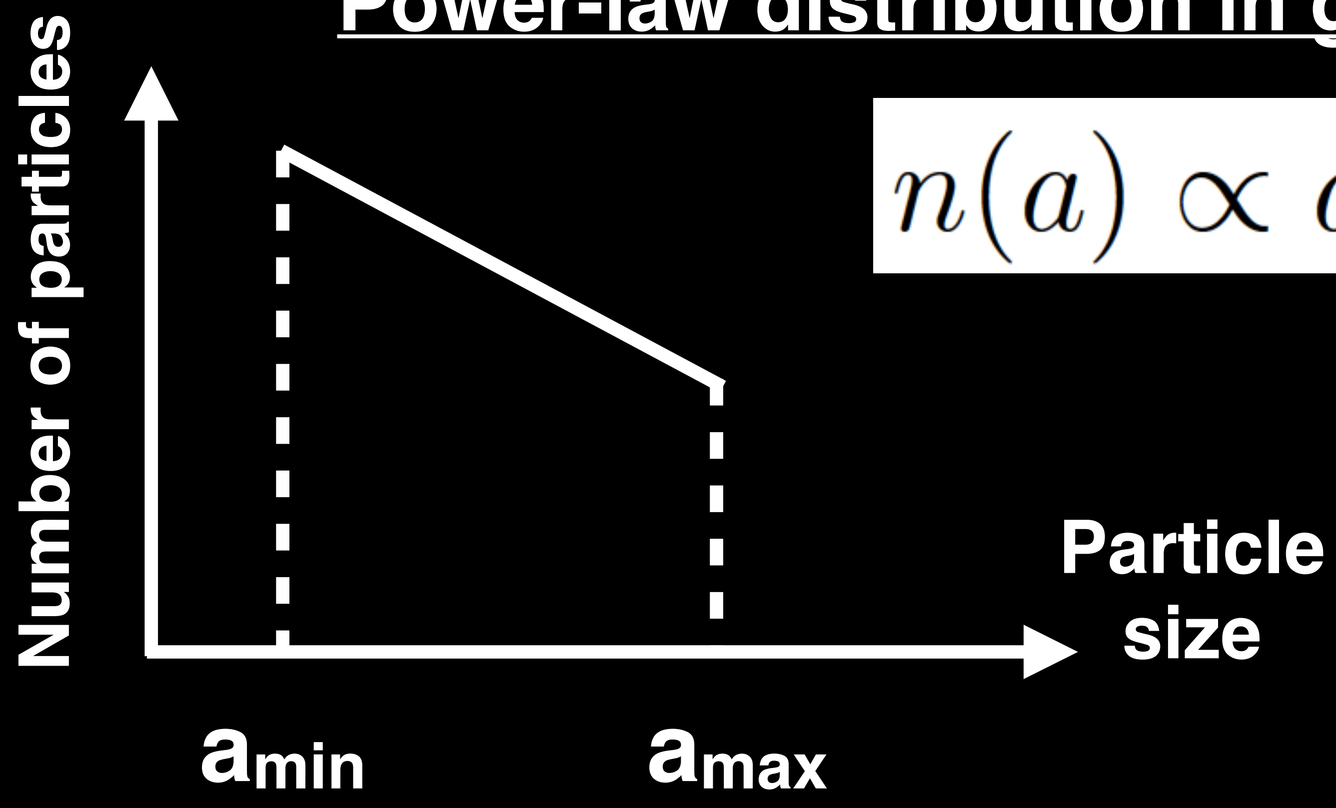
Notes. Median, lower and upper quartiles of the age of the stars in each region, derived from a comparison with the Baraffe et al. (2015) evolutionary tracks. In computing the ages, we considered only stars with masses in the range $0.15 \leq M_\star/M_\odot \leq 1.0$.

Mass budget problem:

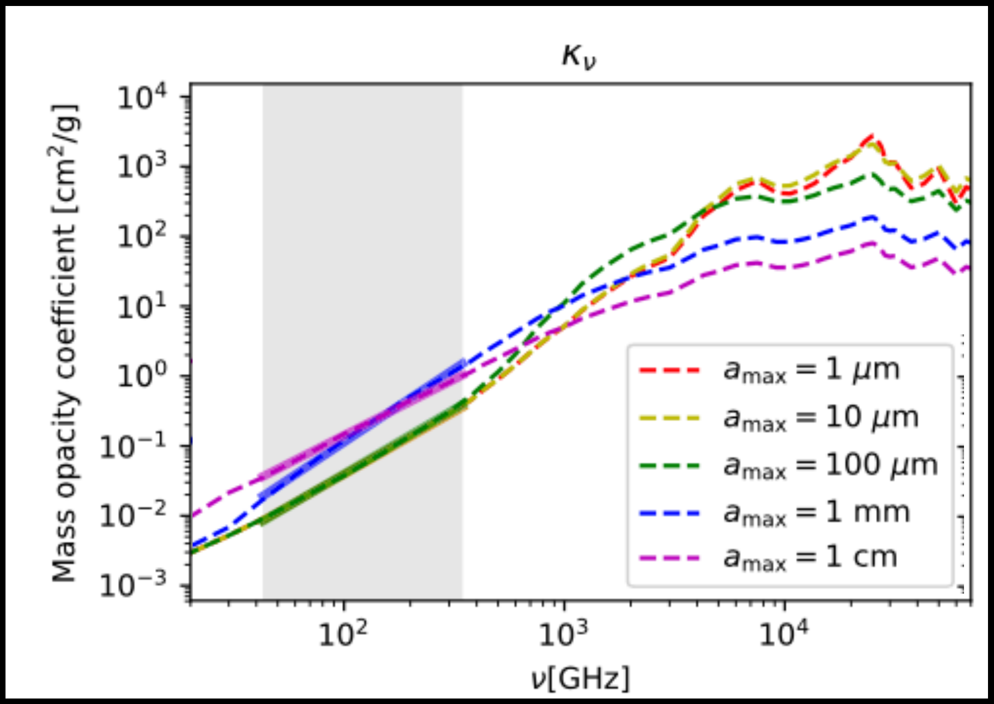
After 1 Myr, there is not too much dust mass

Planets should form very fast

Power-law distribution in grain sizes



$$n(a) \propto a^{-p}; a_{\rm min} < a < a_{\rm max}$$

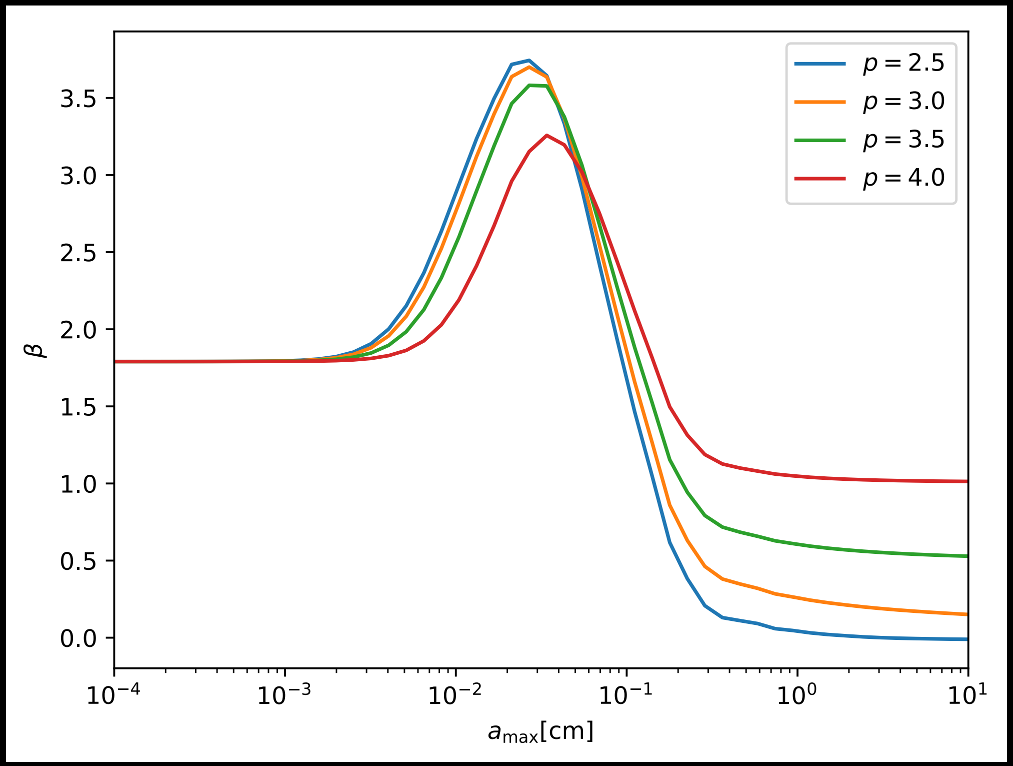


Power-law dependence of opacity

This is ok in the millimeter wavelength range for millimeter-sized particles (D'Alessio et al. 2001)

$$\kappa_\nu = \kappa_0(\nu/\nu_0)^\beta$$

$$\tau_\nu = \tau_0(\nu/\nu_0)^\beta$$



Absorption only

Optically THIN

$$\tau_\nu << 1 \qquad I_\nu \simeq B_\nu(T_{dust})\ \tau_\nu \qquad T_B \simeq T_{dust}\ \tau_\nu$$

$$\tau_\nu = \Sigma_{dust}\ \kappa_\nu \propto \nu^\beta$$

$$I_\nu \simeq B_\nu(T_{dust})\ \tau_\nu \propto \nu^{2+\beta}$$

$$\beta = f(a_{amax})$$

Optically thin limit

$\tau_\nu << 1$

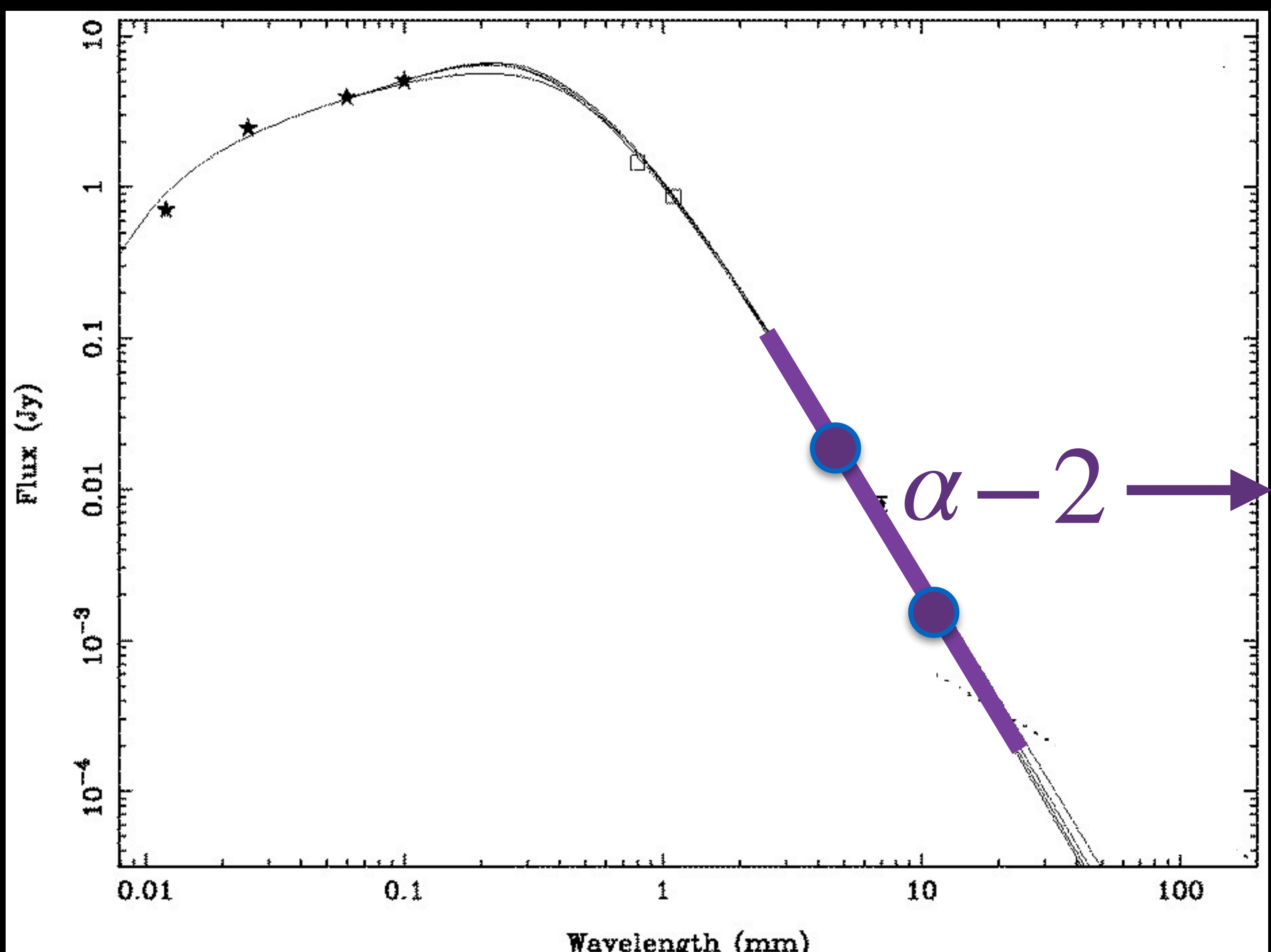
Rayleigh-Jeans approximation

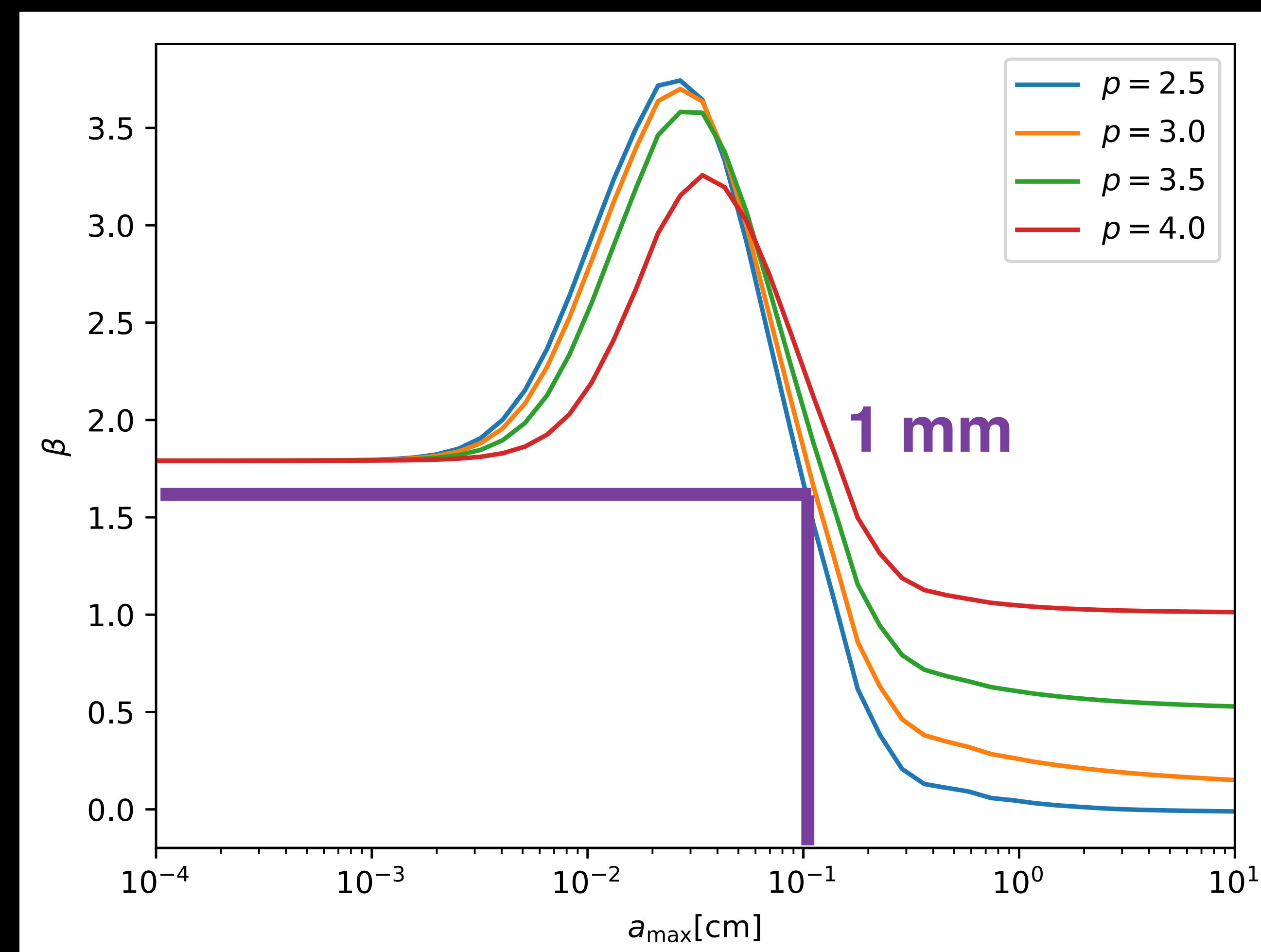
$T_{dust} \uparrow\uparrow$

Absorption only

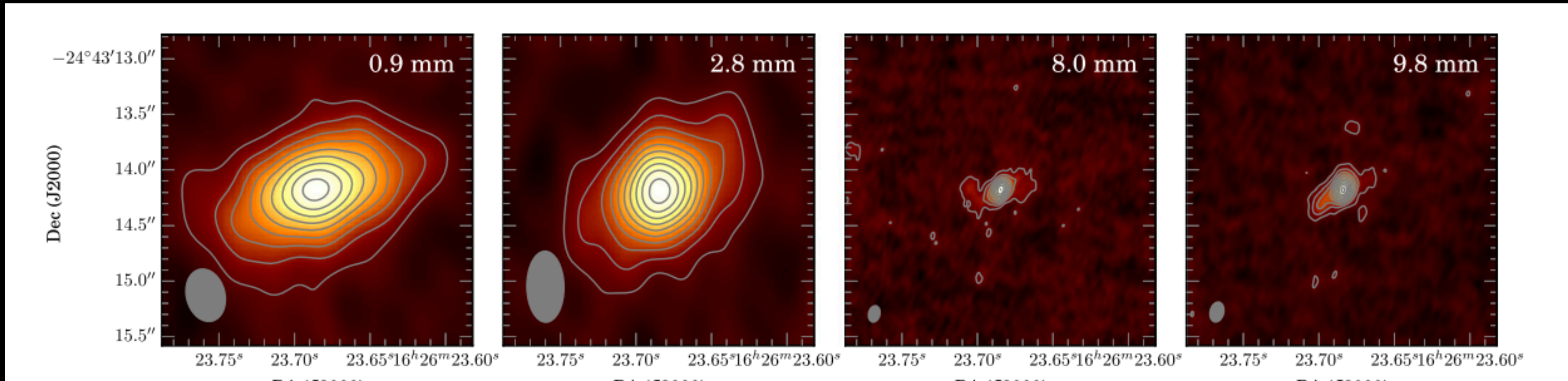
κ_ν

$\longrightarrow I_\nu \propto \nu^{2+\beta}$

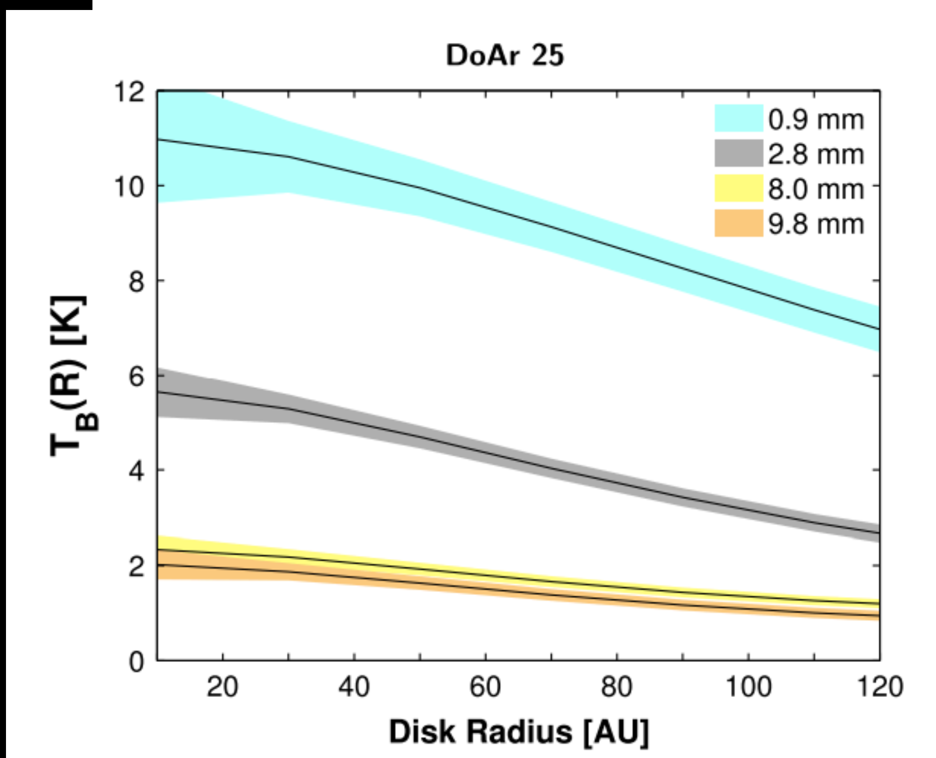


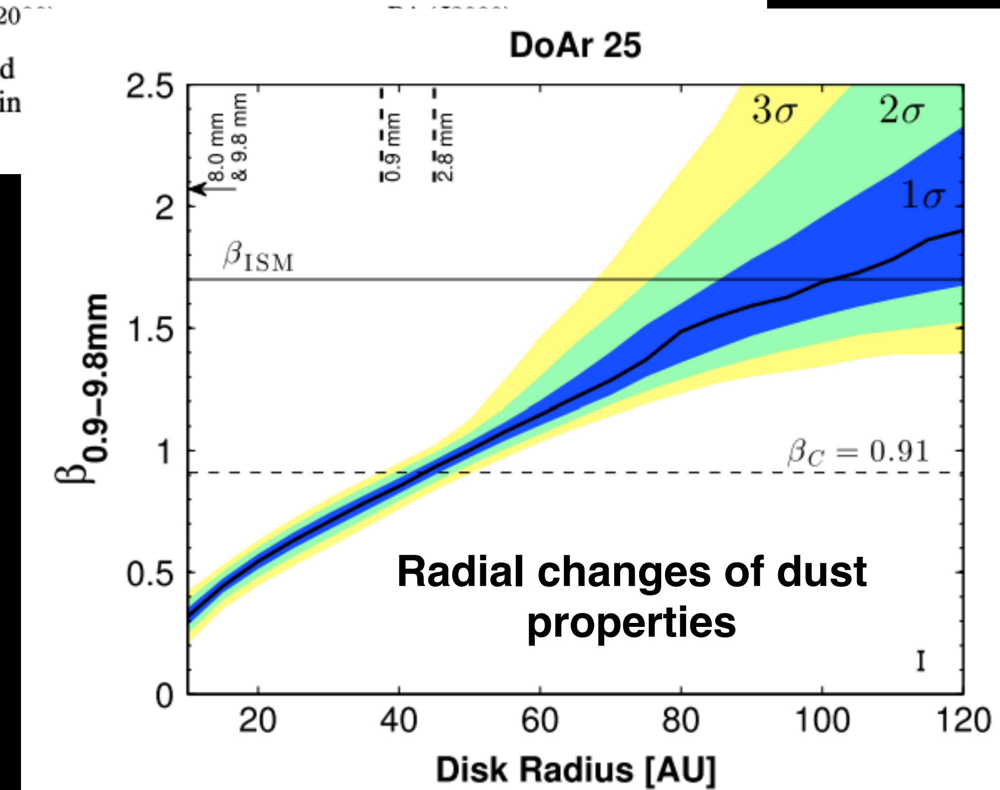


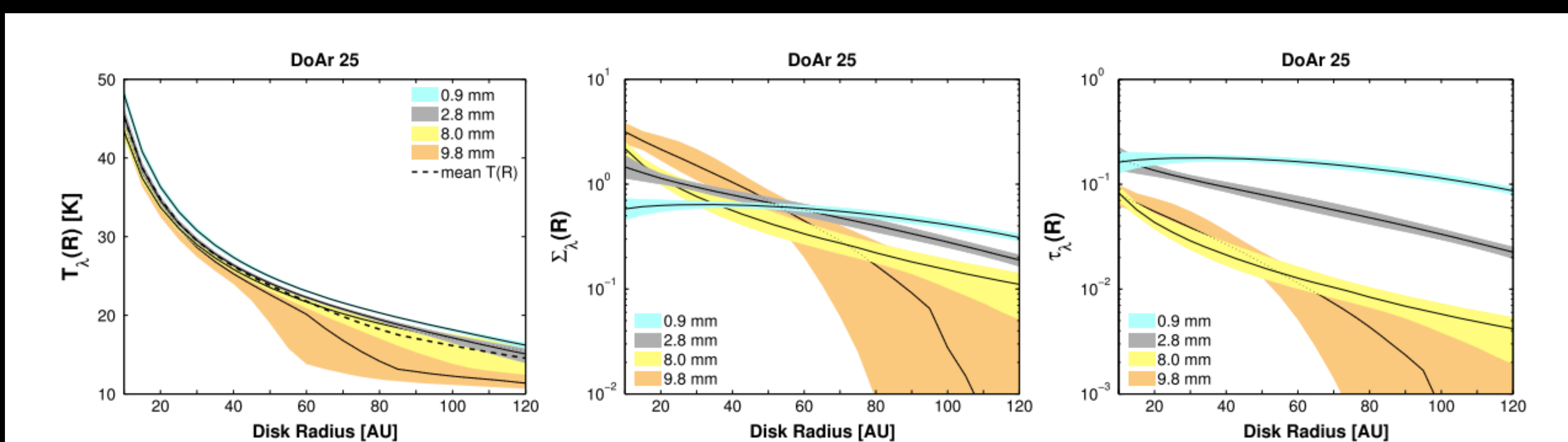
Spectral index between two optically thin wavelengths gives information about the particle size



ward the young star DoAr 25, observed
distance), with contours drawn at 3σ in







Pérez et al. 2015

MODELING OF HIGH MILLIMETER IMAGES IN THE PRE-ALMA ERA

Large particles (up to meters) are present in disks with some Myrs

But, radial drift is very important. Large particles are highly concentrated at the center of the disks

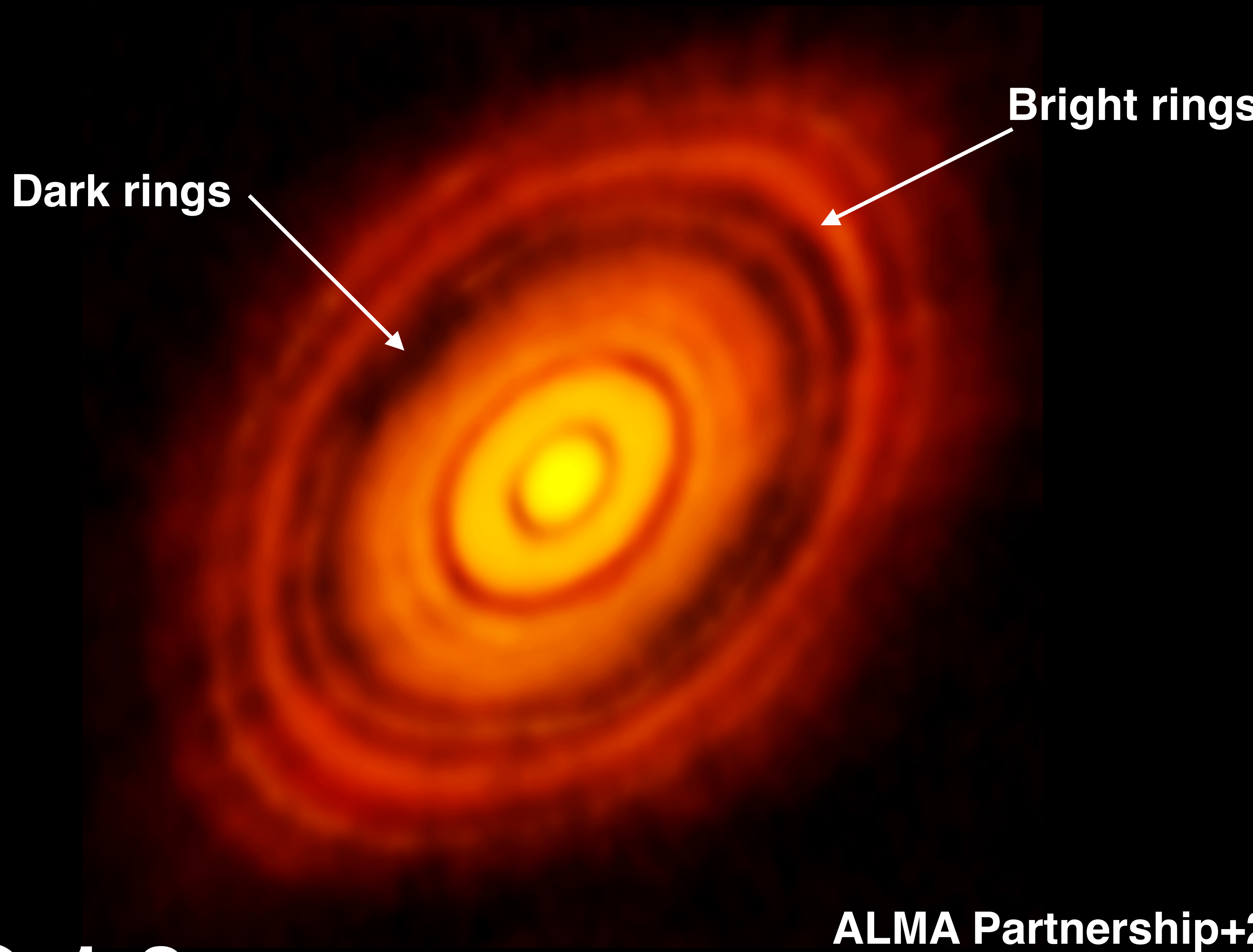
Planet formation takes place only at the central parts?

ALMA Era

Disks are more complicated
and
Scattering is important

October 2014

The era of ALMA began

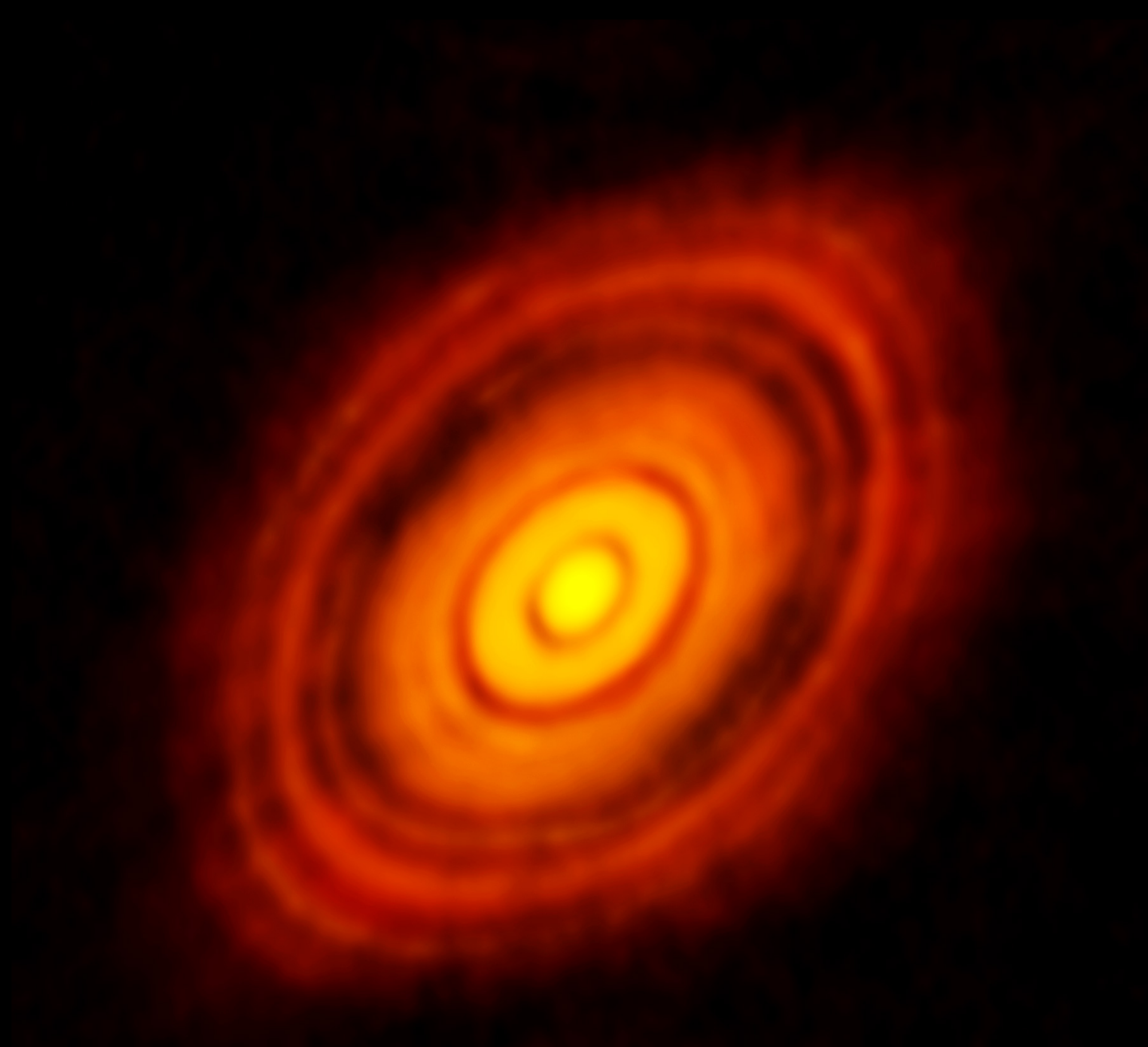


HL Tau @ 1.3 mm

ALMA Partnership+2015
(press release published in October 2014)

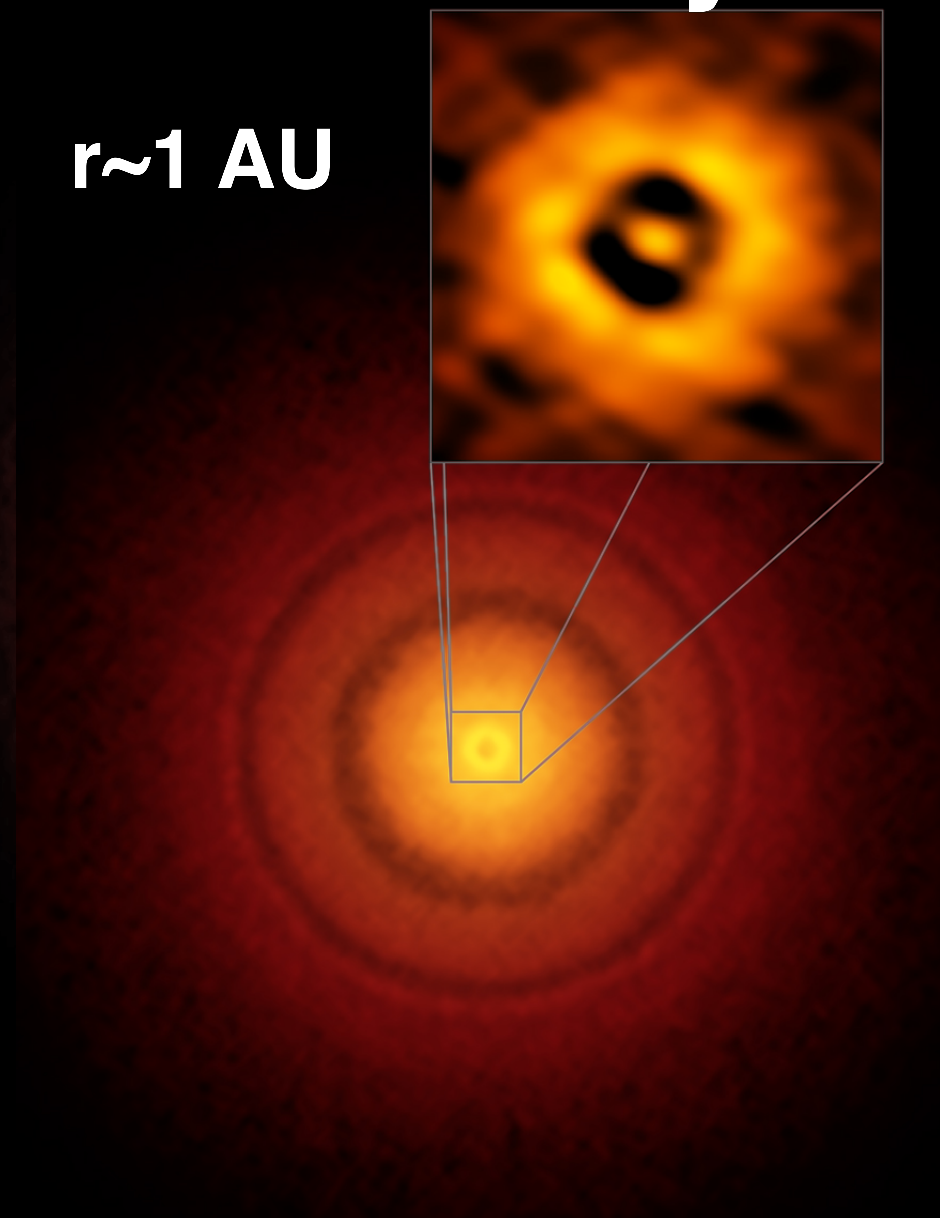
Two “solar system” analogues

HL Tau
~1 million years



ALMA Partnership+2015

TW Hya
~10 million years

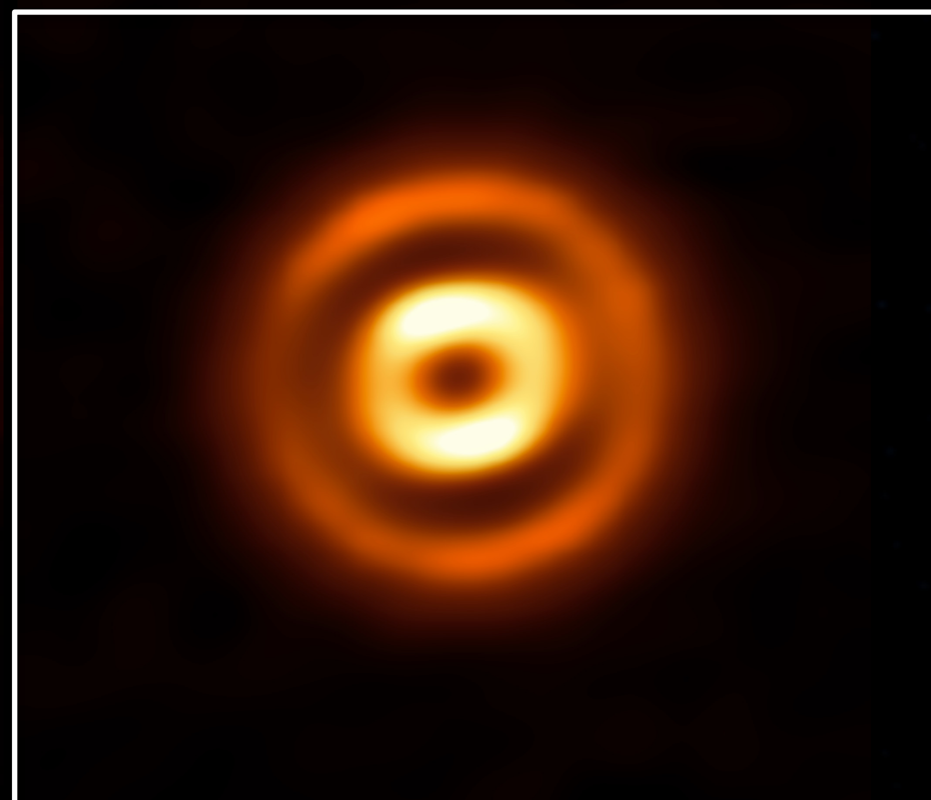


Andrews+2016

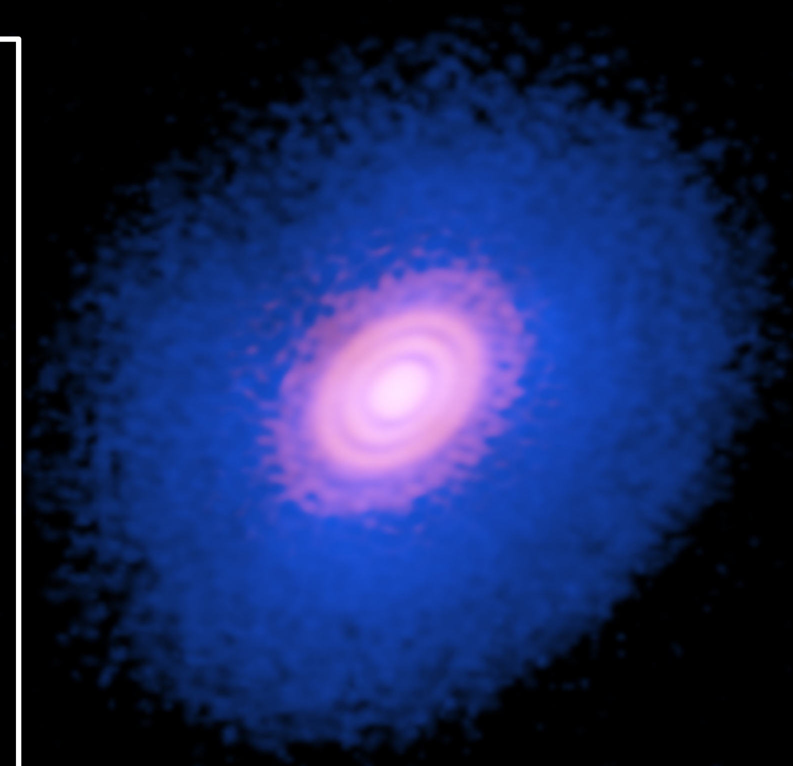
More disks… more rings and gaps

Zhang+2015

Pérez+2016

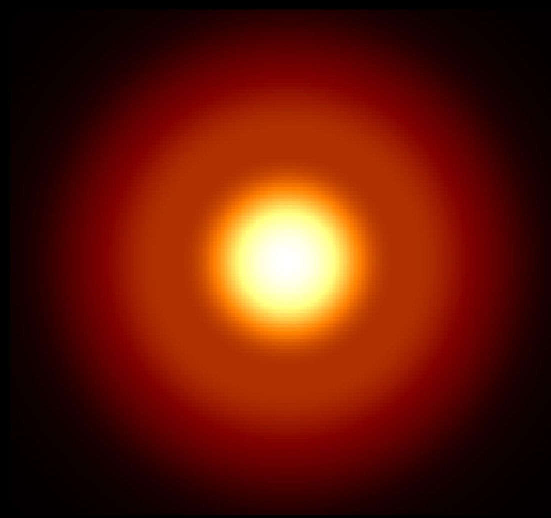


Fedele+2017



Isella+2017

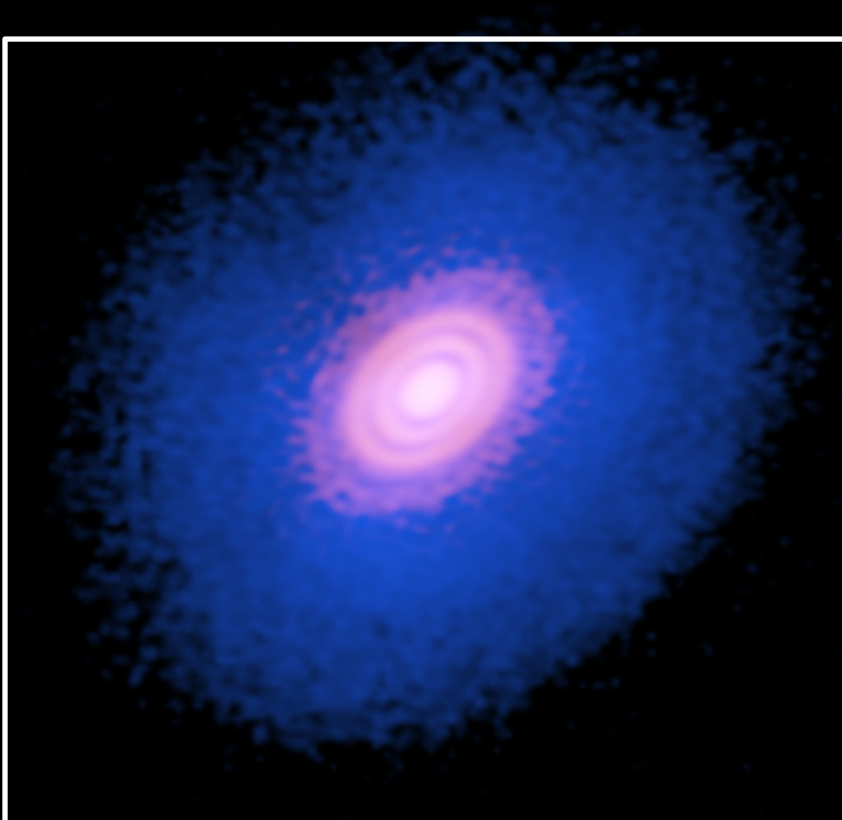
More disks… more rings and gaps



Zhang+2015

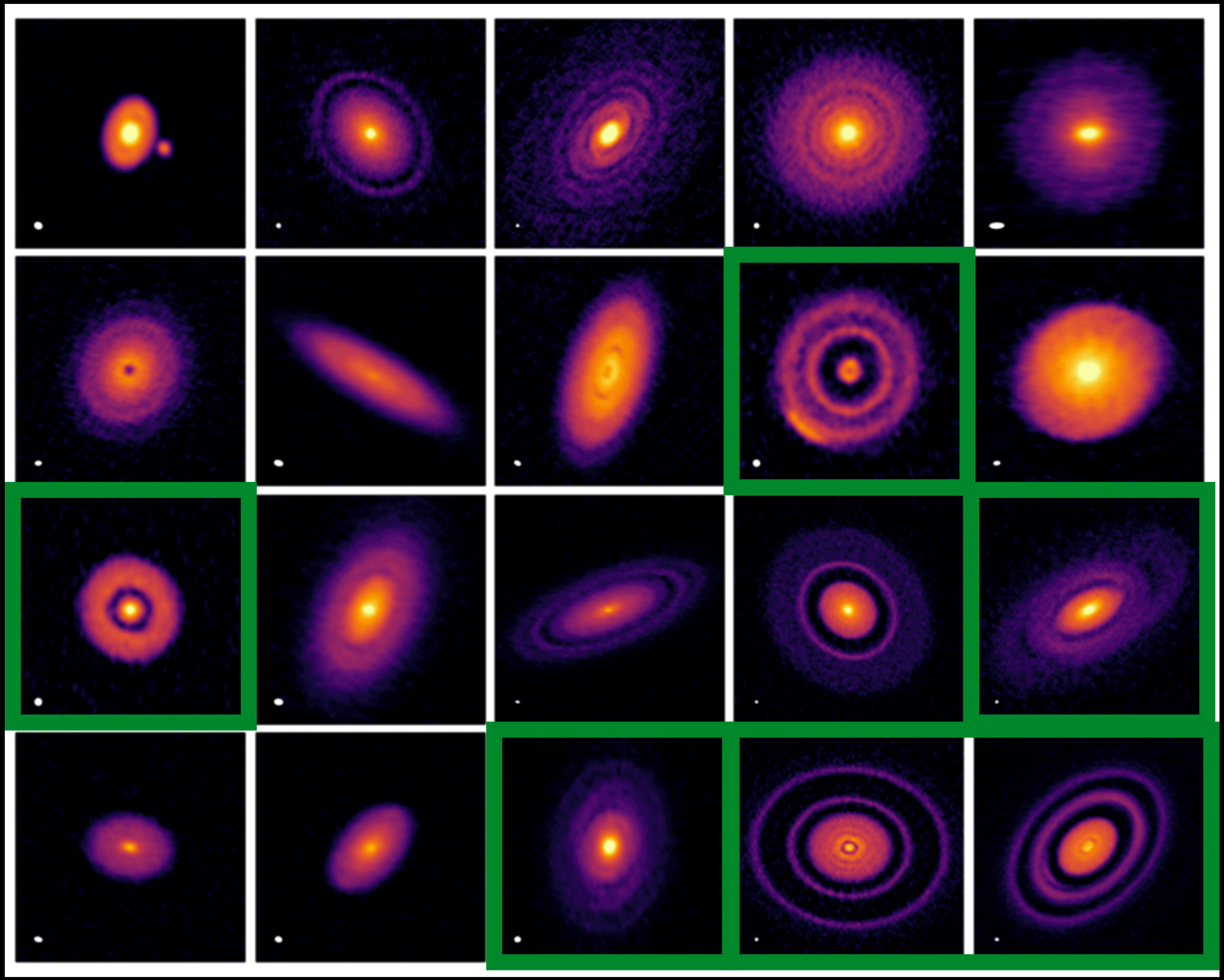
Pérez+2016

Fedele+2017

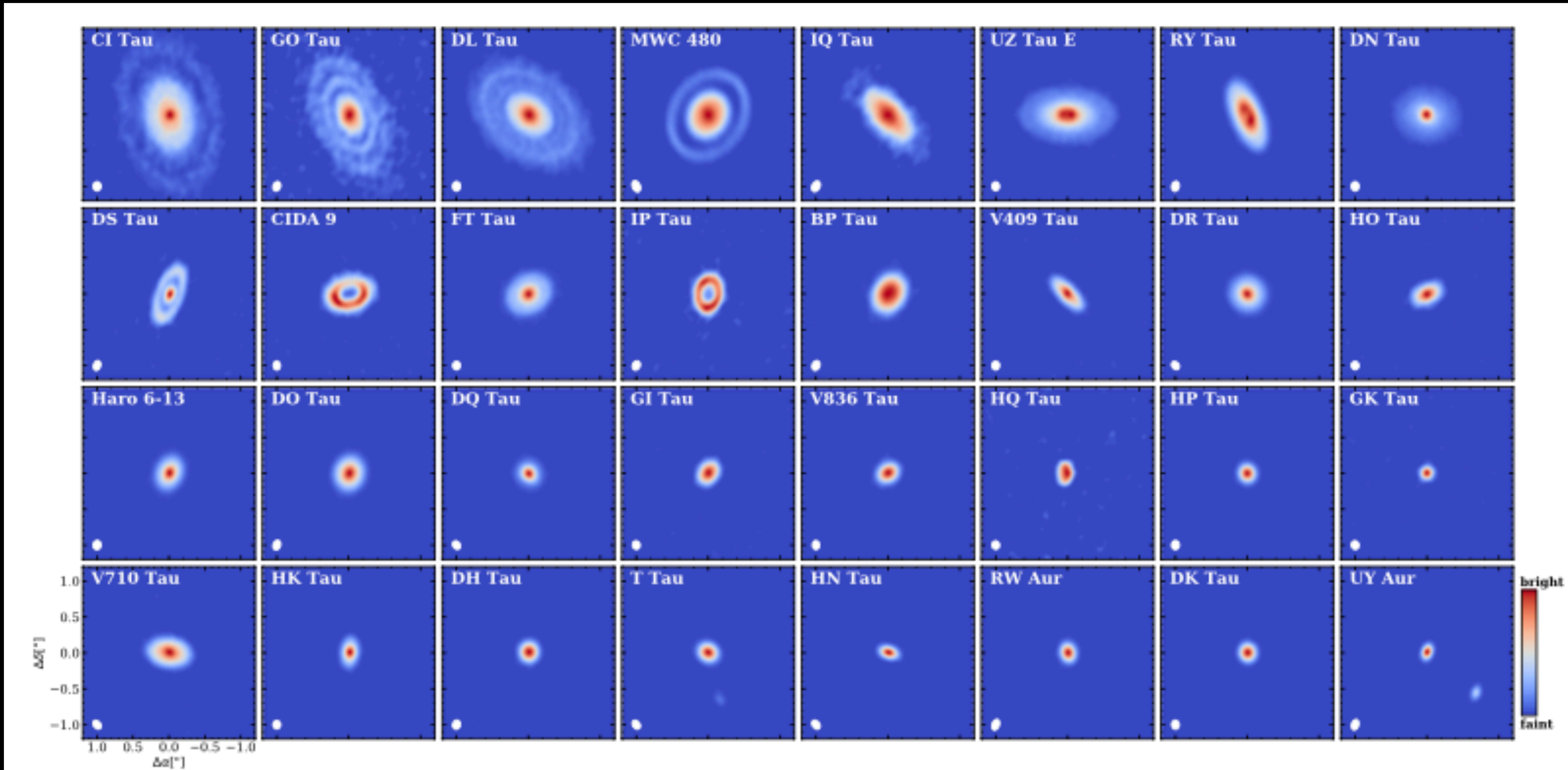


Isella+2017

Almost all disks show rings and gaps



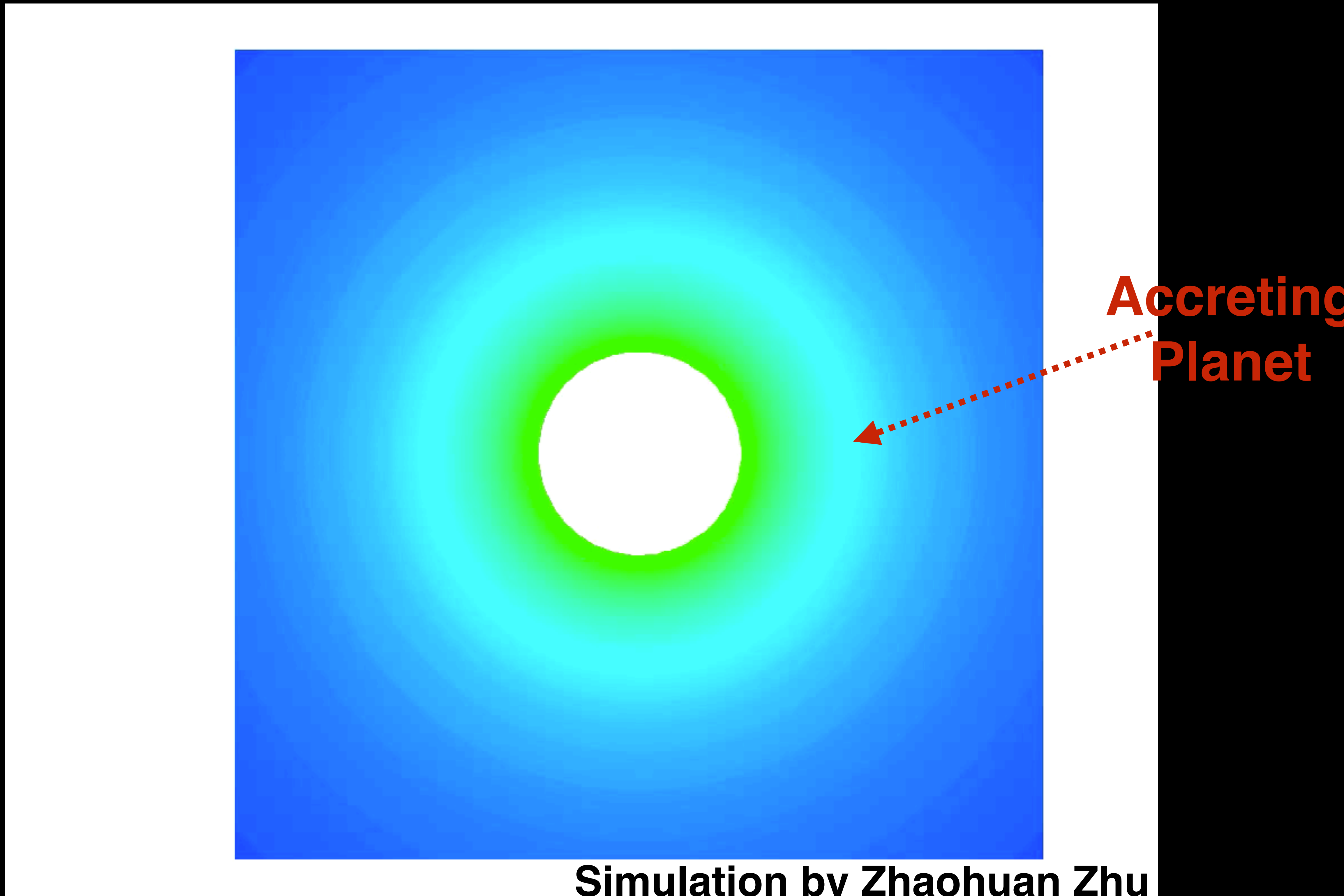
D-SHARP project ; Andrews et al. (2018)



ALMA Taurus Survey ; Long et al. (2019)

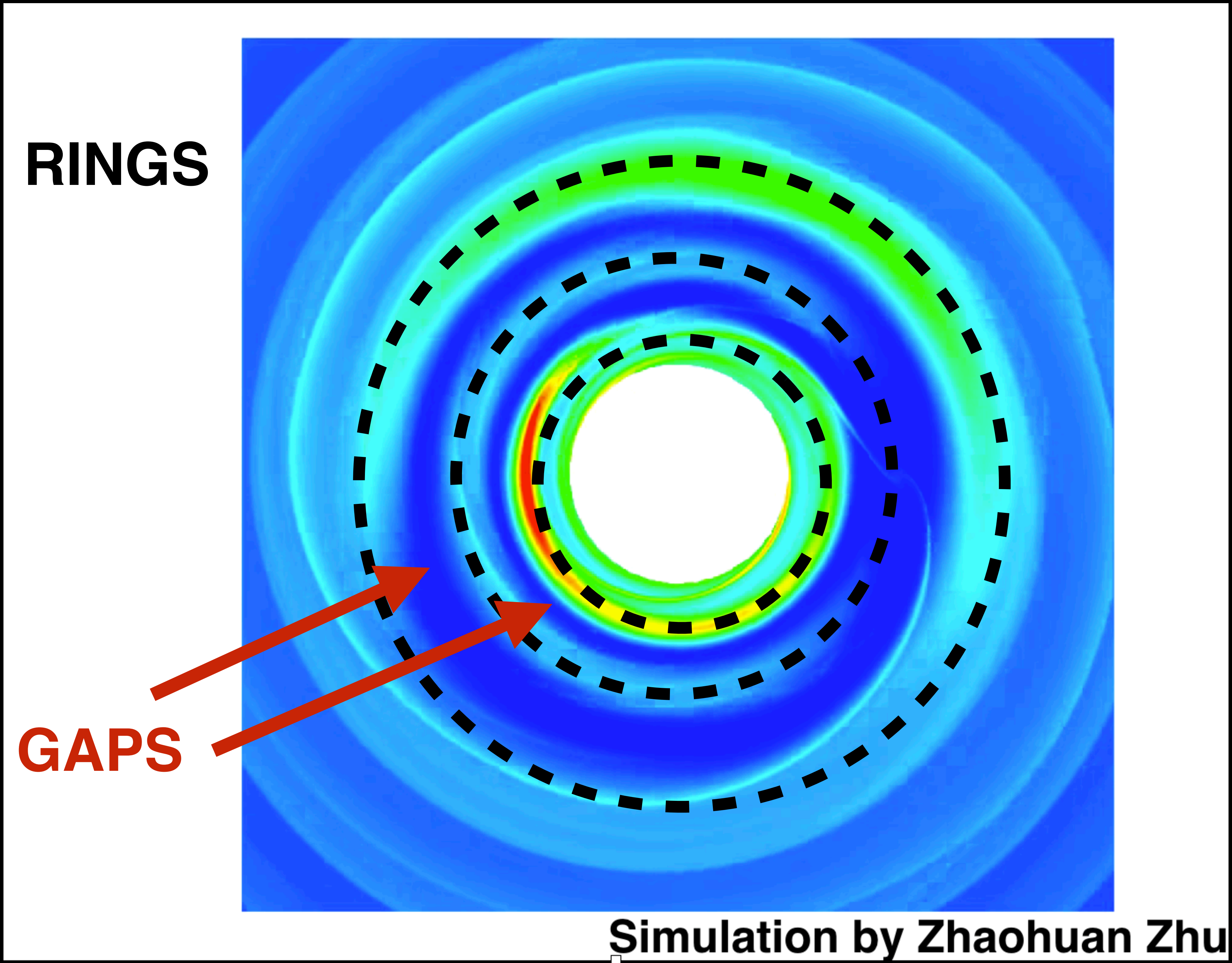
Also more compact disks; we do not know how is their structure

WE KNOW WHAT HAPPENS WHEN A PLANET IS FORMING



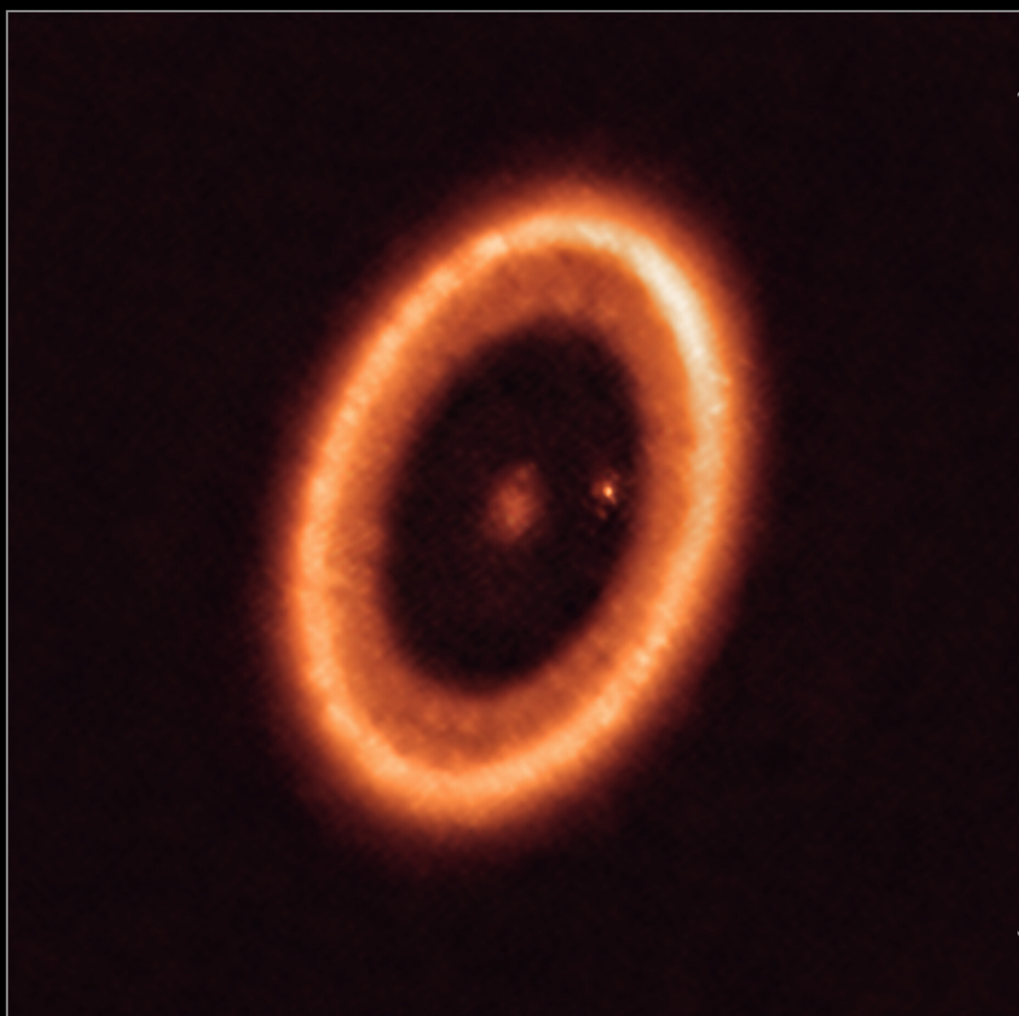
An accreting protoplanet dramatically changes the structure of the disk

WE KNOW WHAT HAPPENS WHEN A PLANET IS FORMING



An accreting protoplanet dramatically changes the structure of the disk

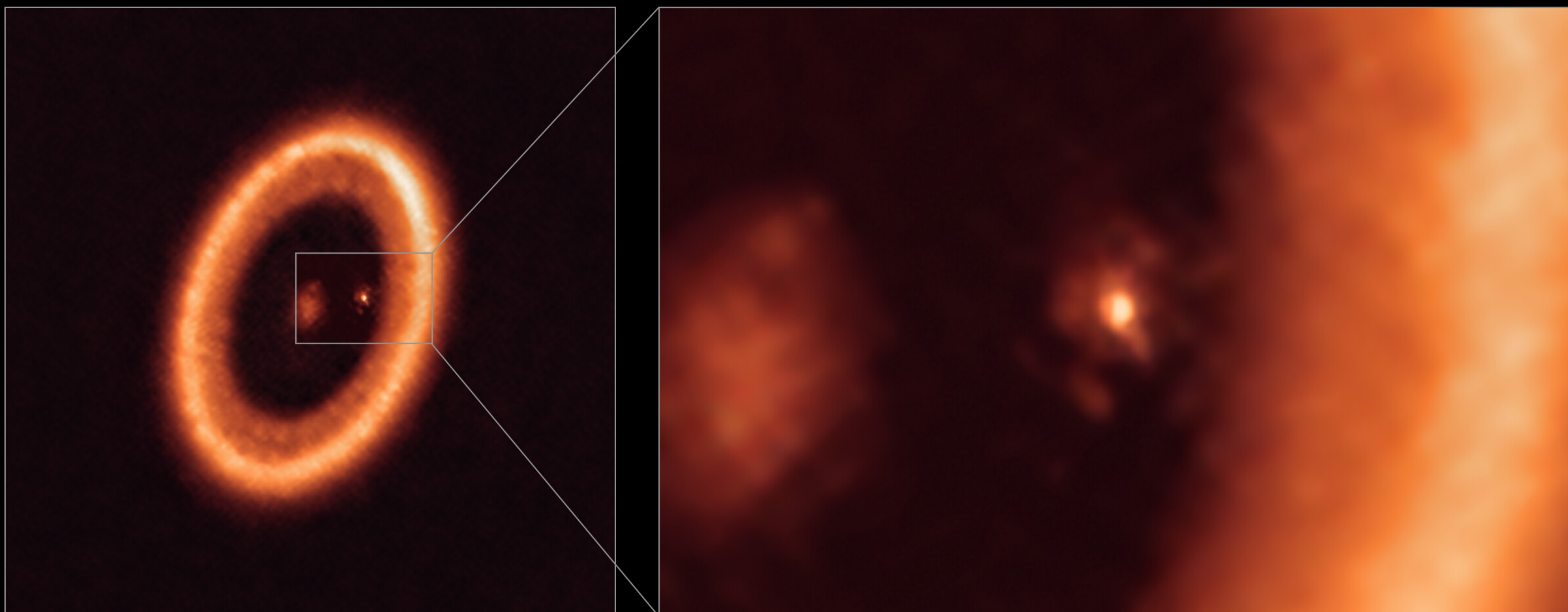
PDS 70



Direct detection of a protoplanet

Benisty+2021

PDS 70



Direct detection of a protoplanet

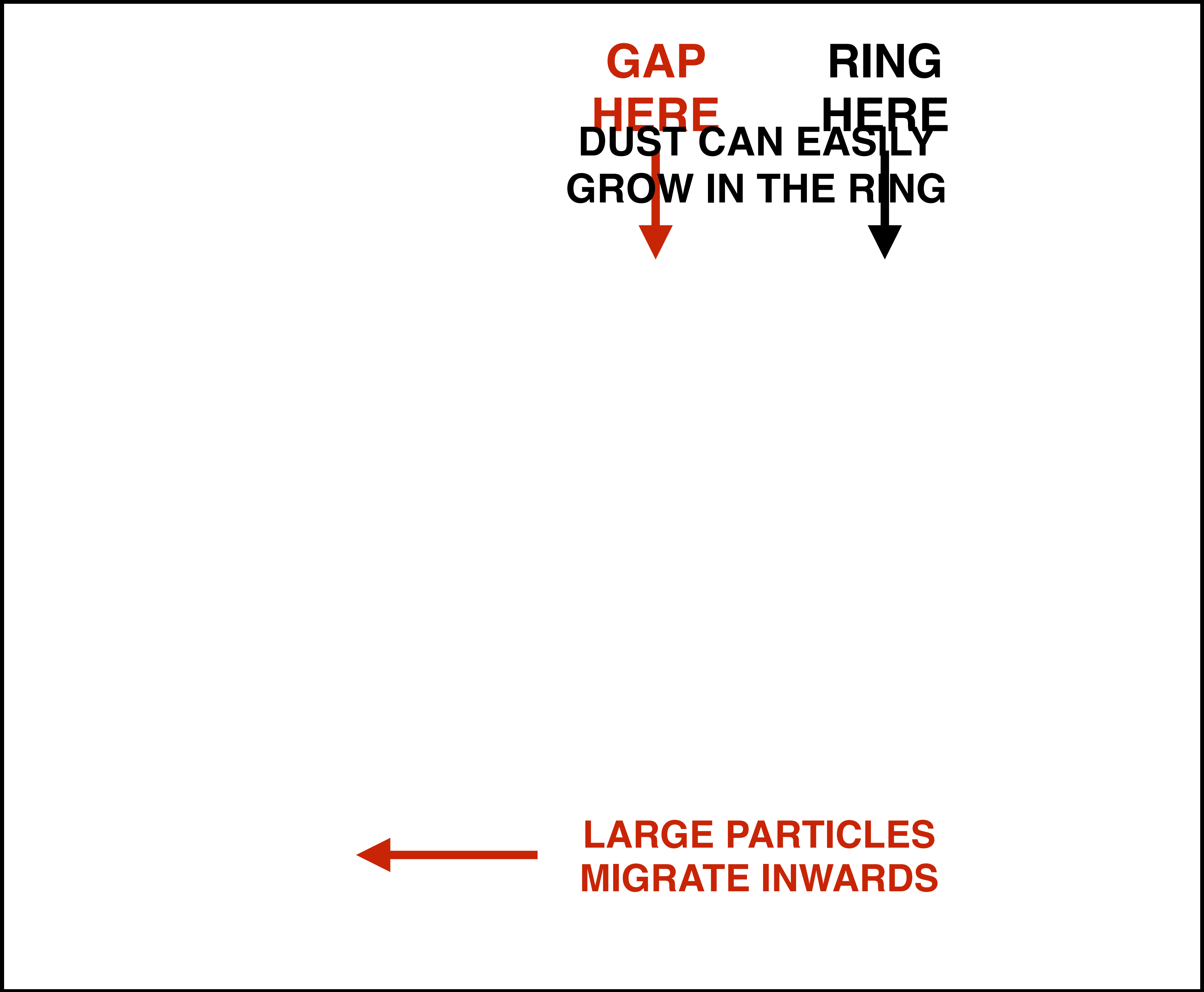
Circumplanetary Disk

Benisty+2021

But planets are not always the answer

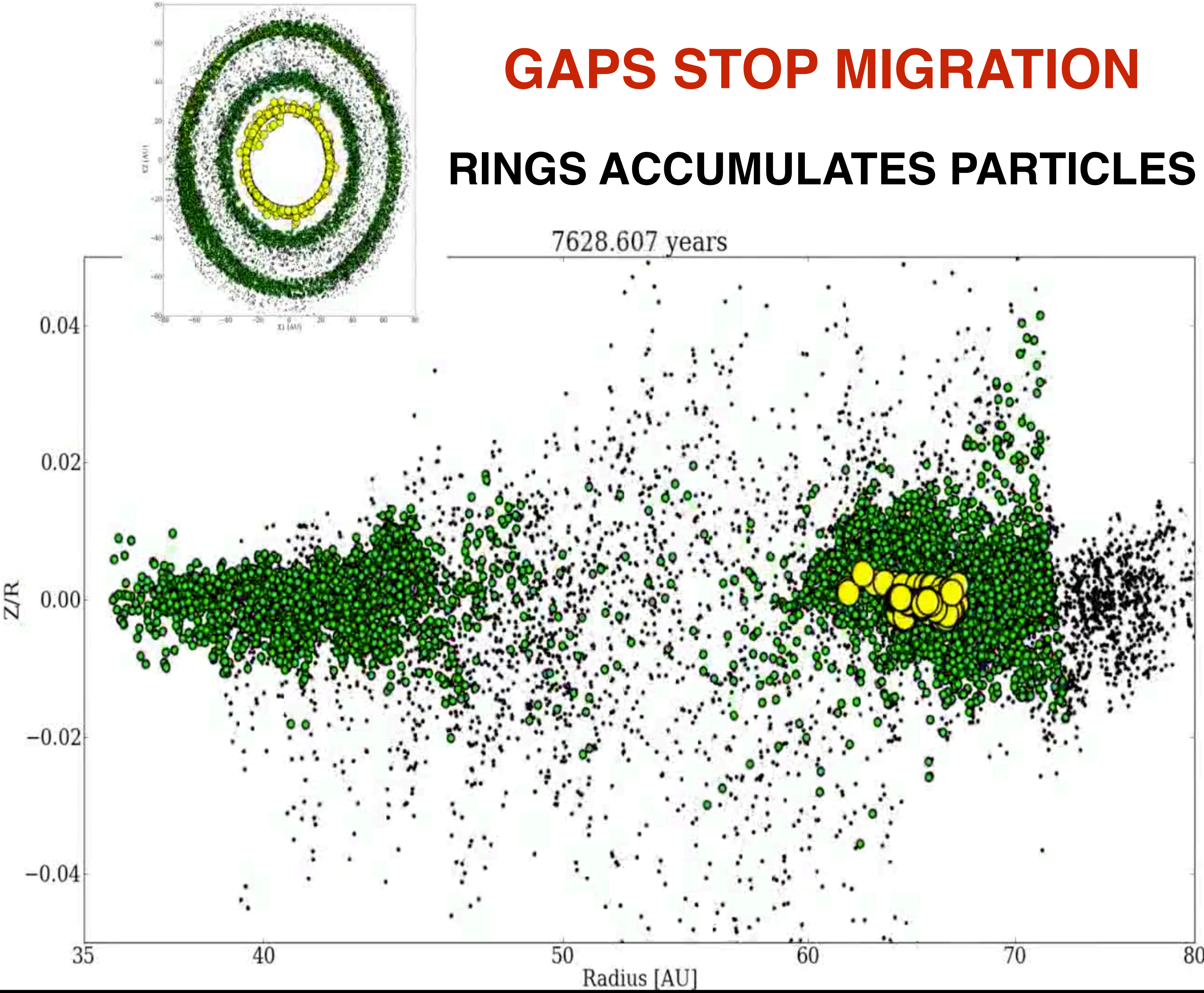
Several mechanisms have been proposed to form rings and gaps

Gaps, Rings and non-axisymmetric structures in protoplanetary disks
(Flock+2015; Ruge+2016)

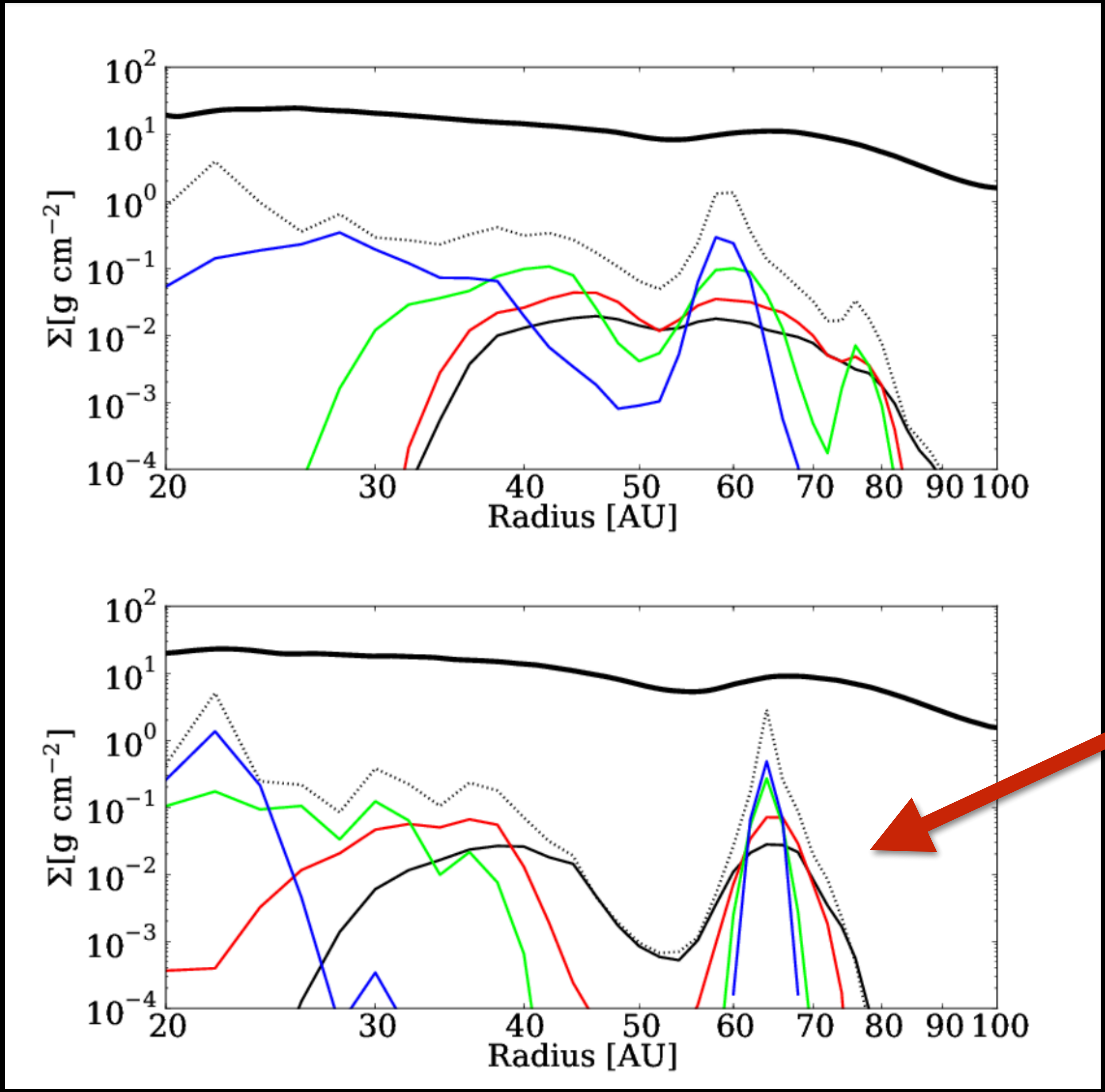


GAPS STOP MIGRATION

RINGS ACCUMULATES PARTICLES



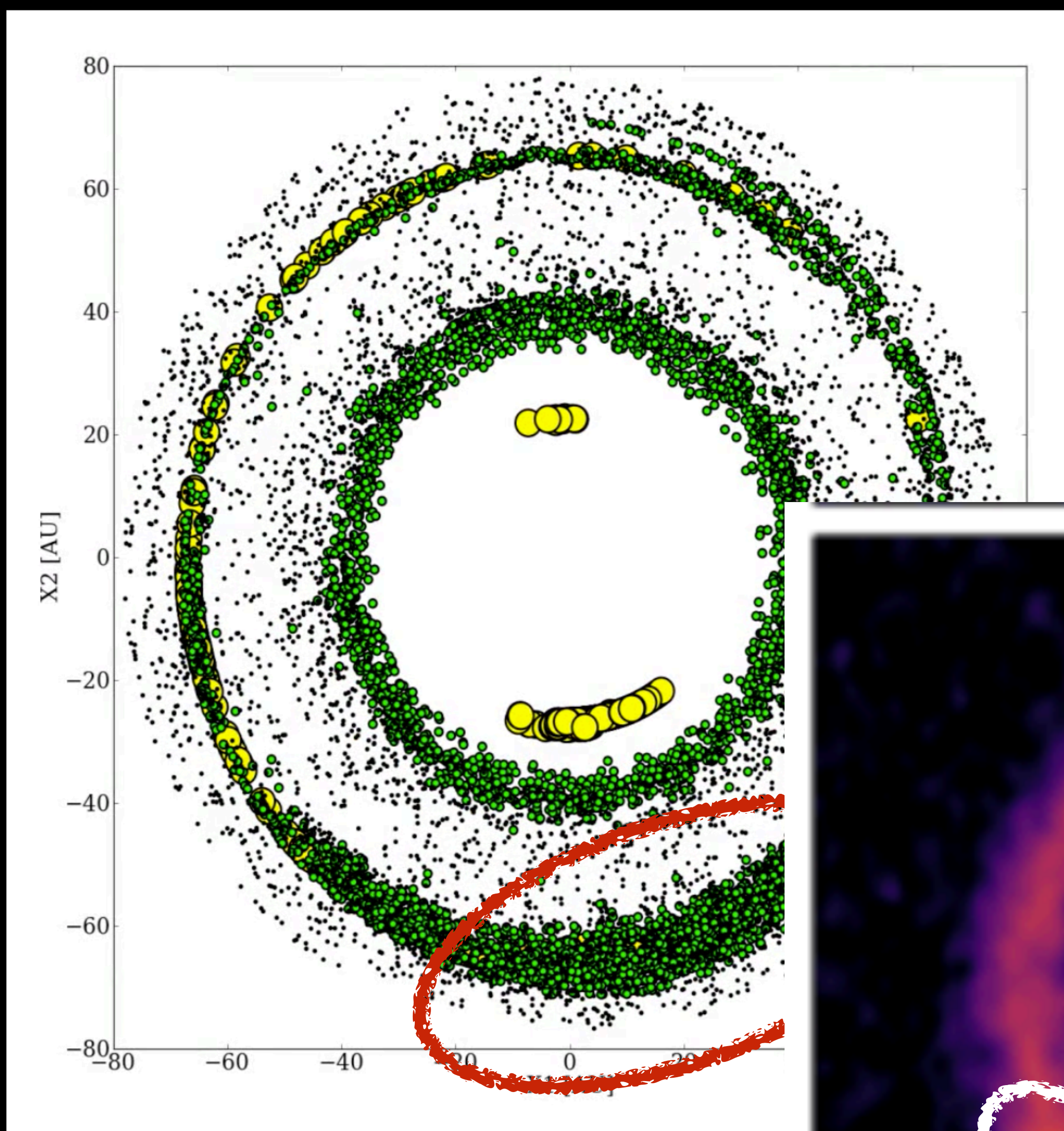
Rings CONCENTRATE large dust grains



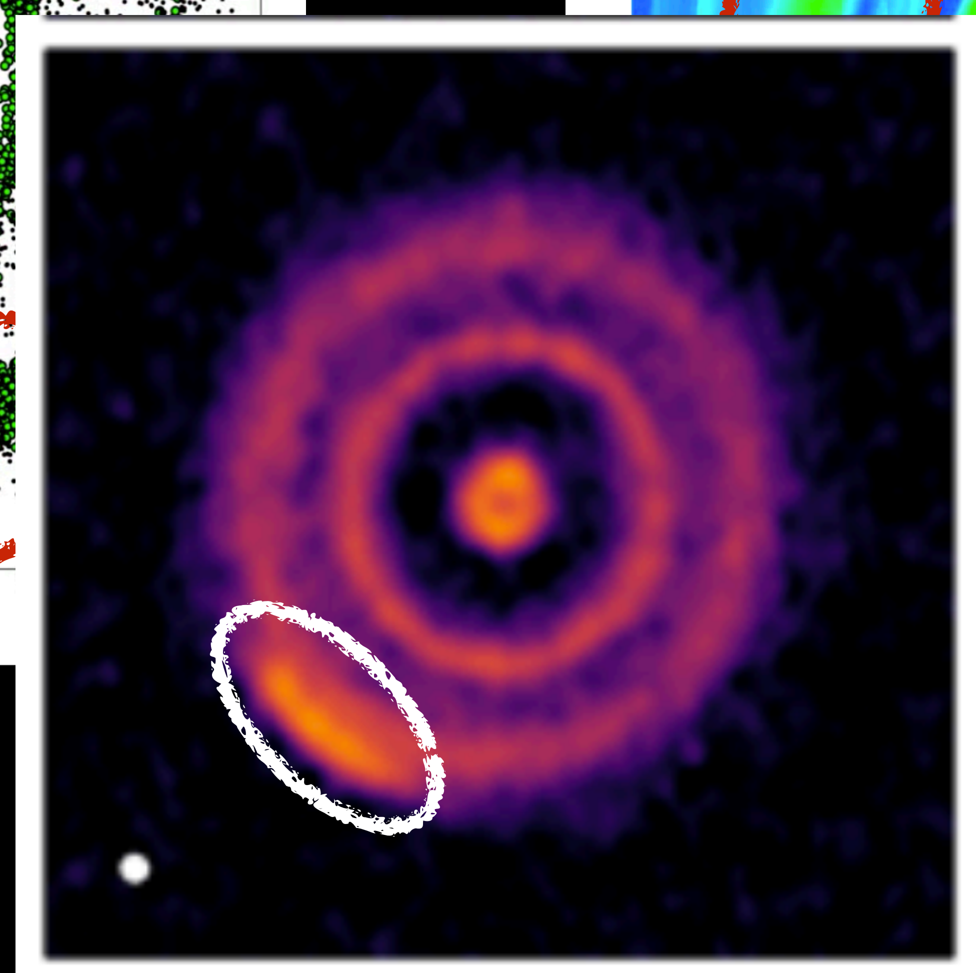
Large dust grains concentrate at the center of the ring

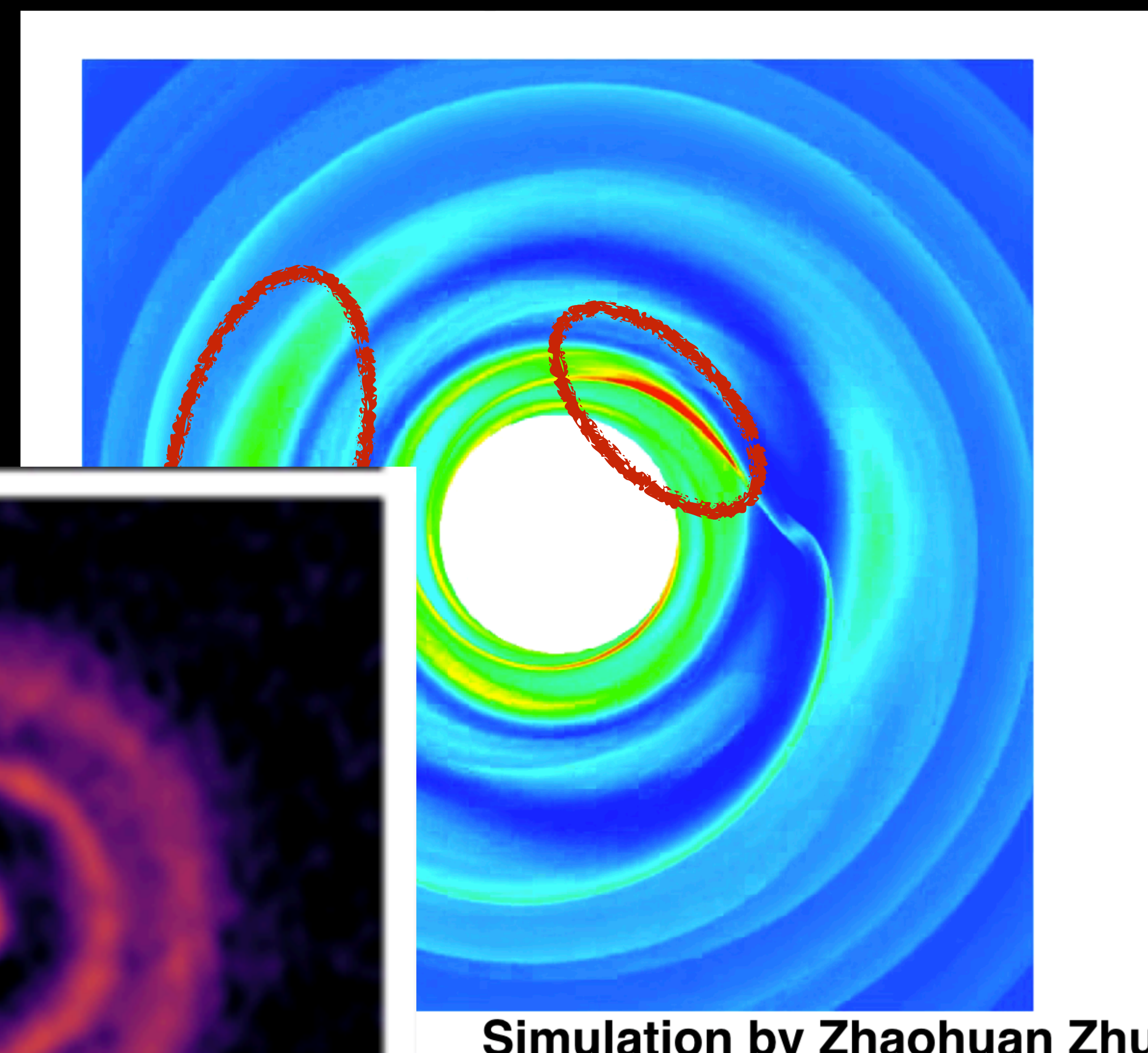
Flock+2015; Ruge+2016

Rings are unstable and they form VORTICES



Flock+2015;
Ruge+2016

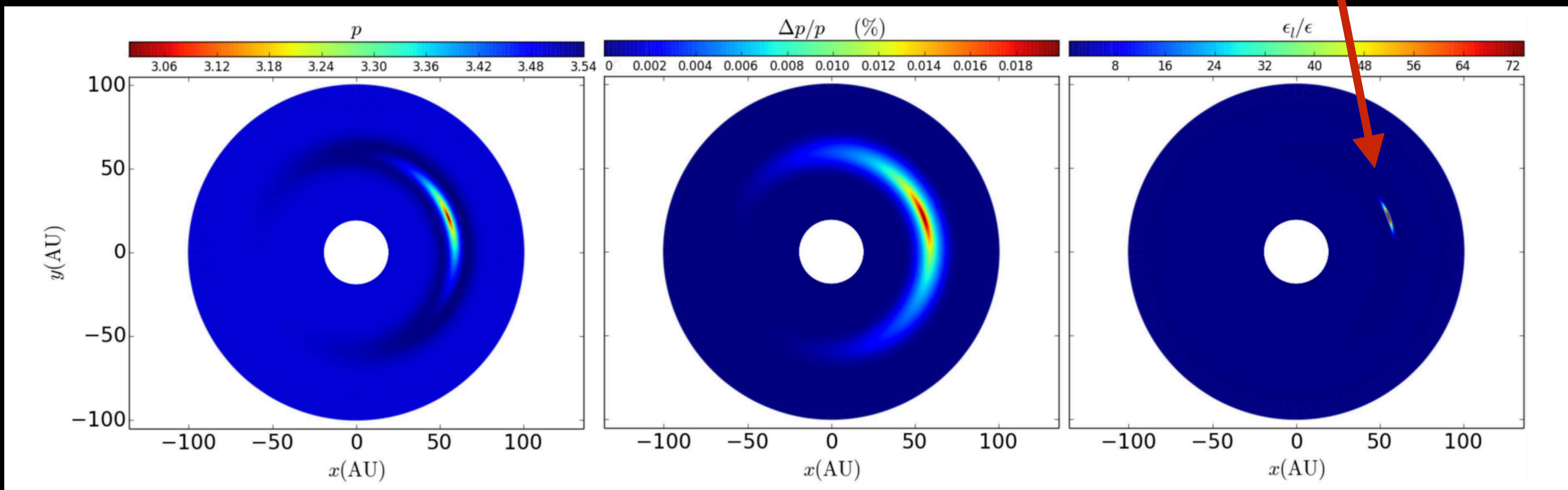




… and vertices also CONCENTRATE larger dust grains

LARGE PARTICLES TRAPPED

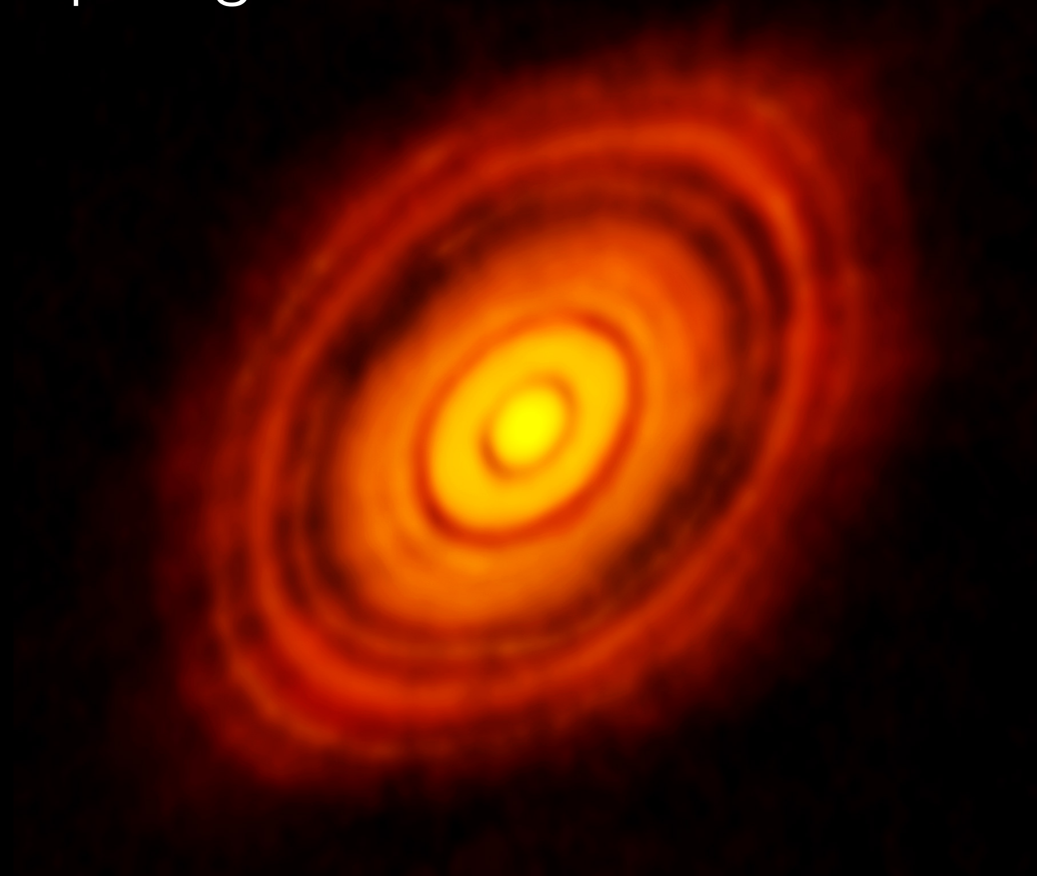
DUST TRAPS



Sierra et al. 2017

The most important result from ALMA:
Particle distribution is not smooth
Dense <u>rings</u> and <u>gaps</u> are frequent

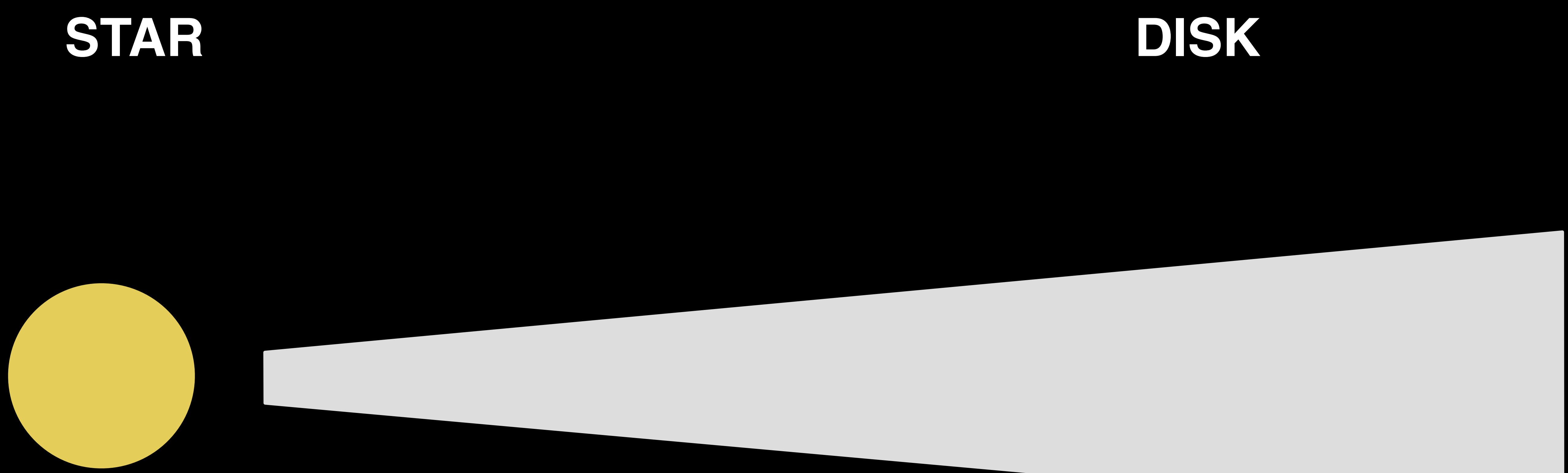
Dense rings are actually excellent places to form planets…
They naturally stop <u>migration</u> and <u>accumulate</u> large dust grains



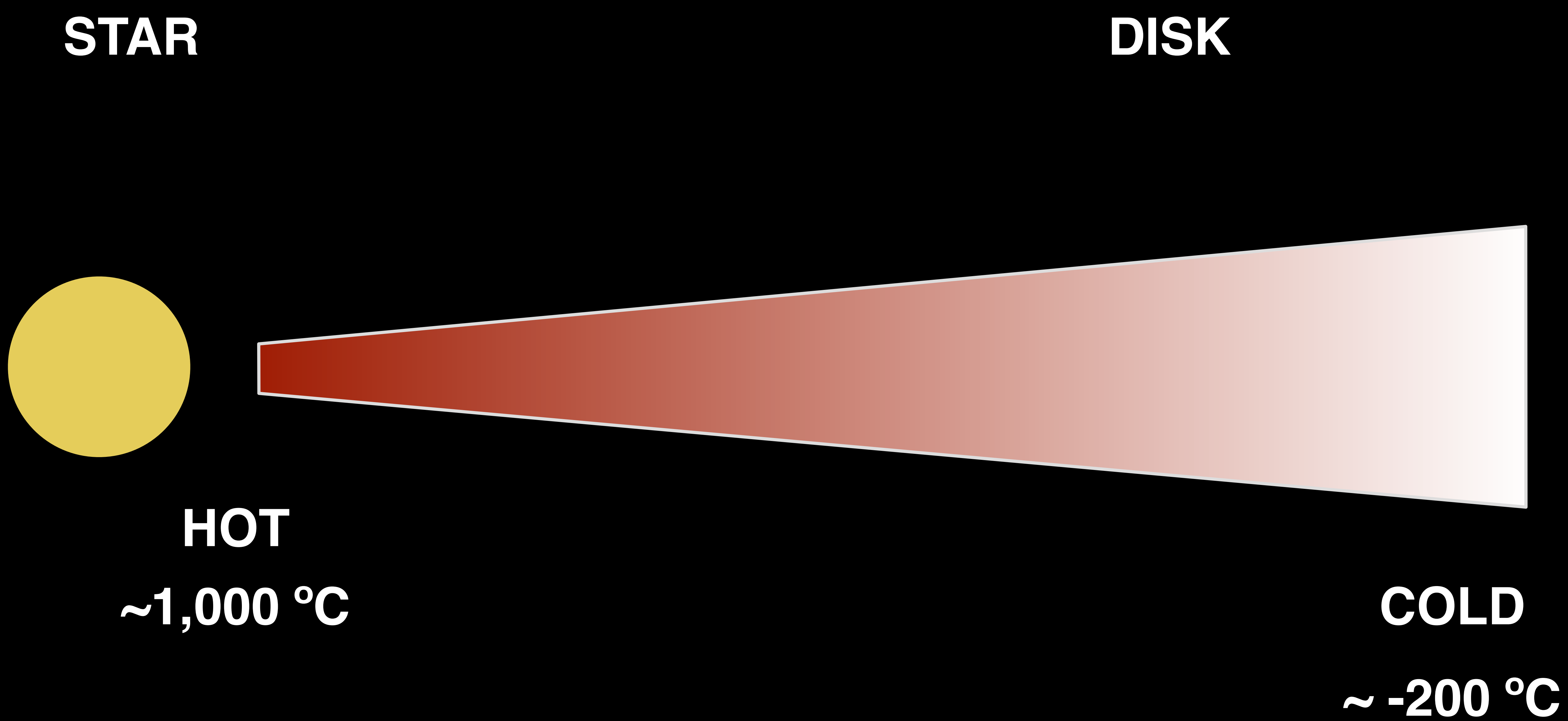
Are rings and gaps always a consequence of the presence of already formed protoplanets?
Or
Are rings and gaps a necessary condition to trigger the formation of planets?

PLANETESIMAL FORMATION AT THE ICE LINES

PLANETESIMAL FORMATION AT THE ICE LINES



PLANETESIMAL FORMATION AT THE ICE LINES



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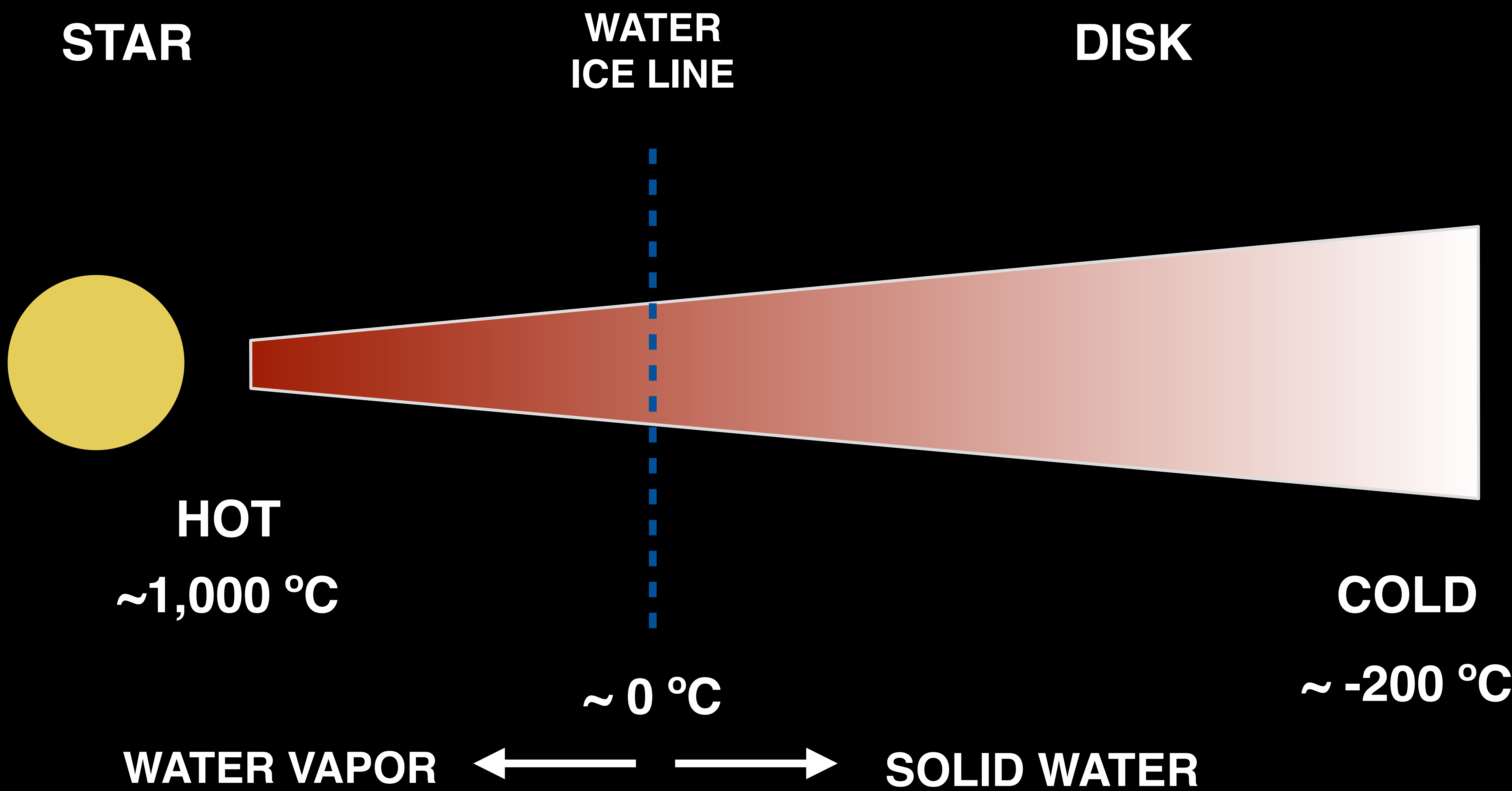

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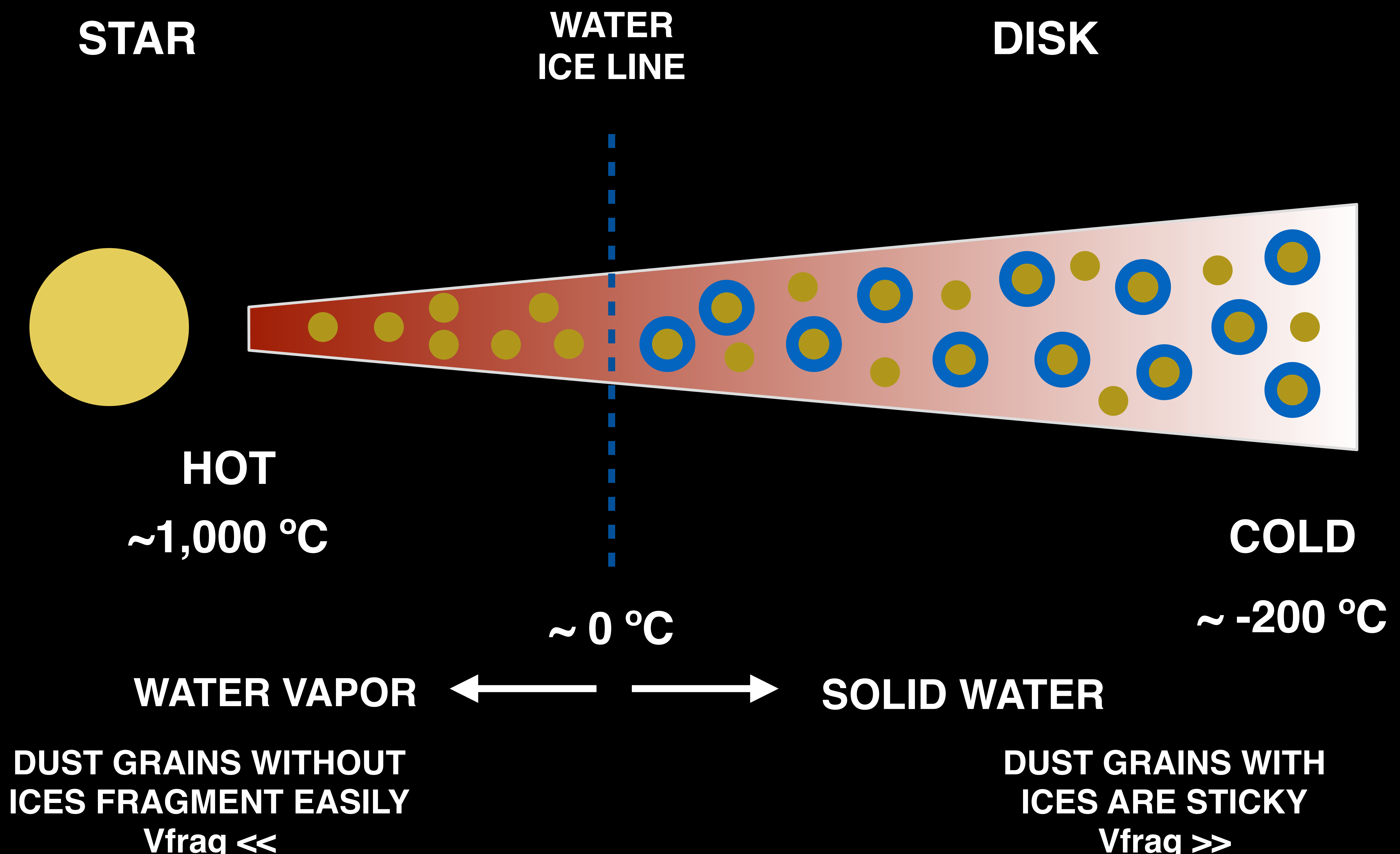

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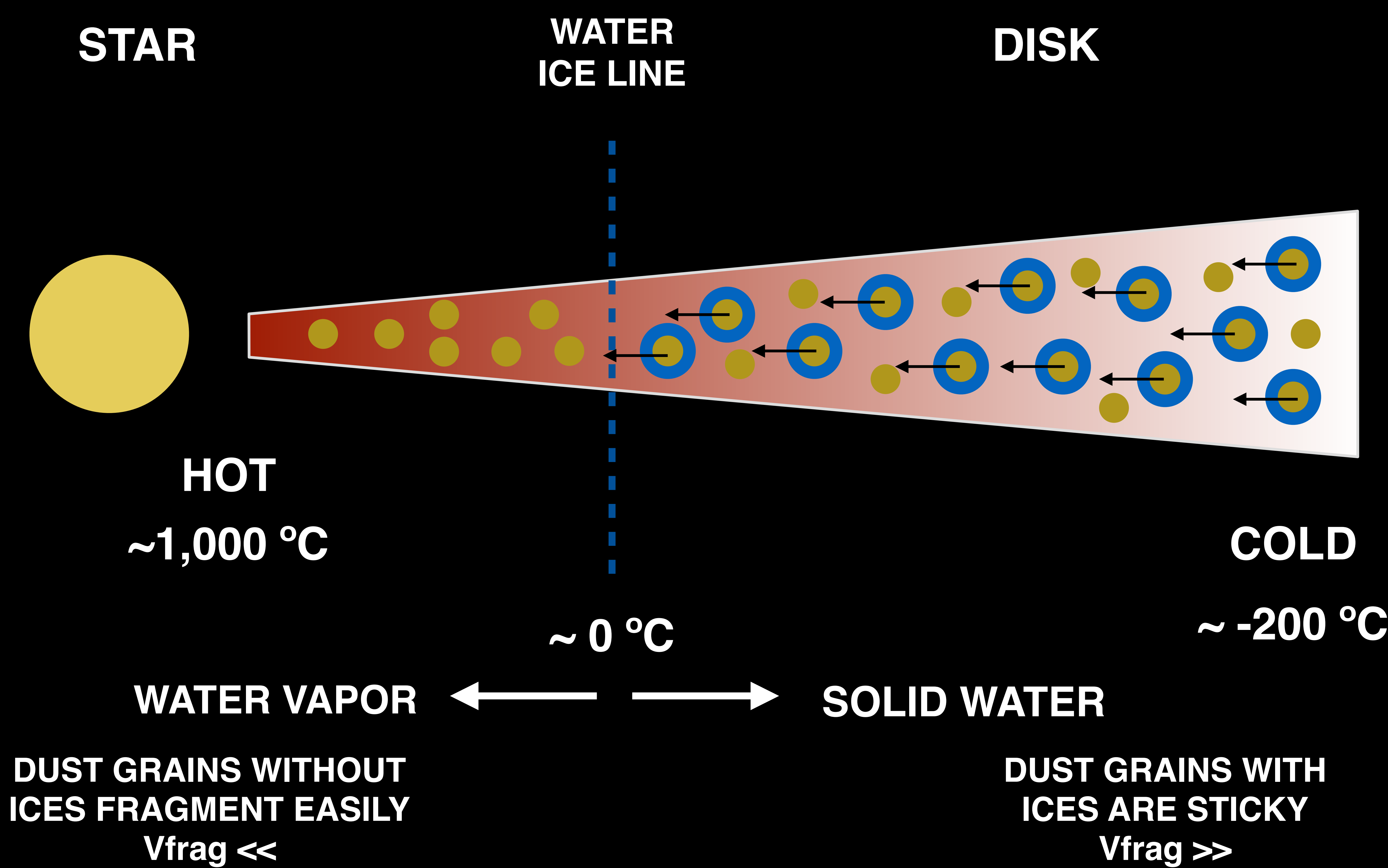

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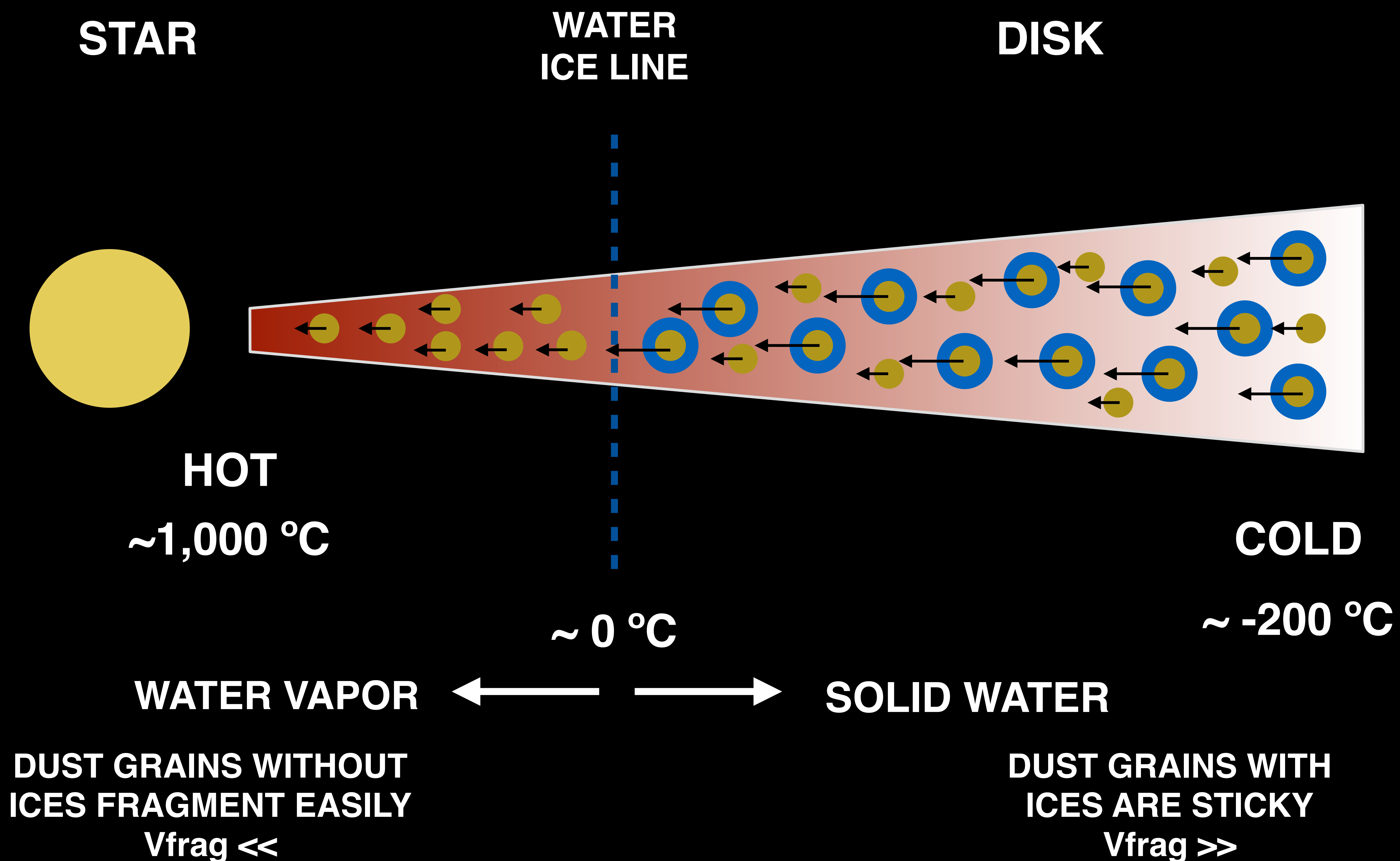

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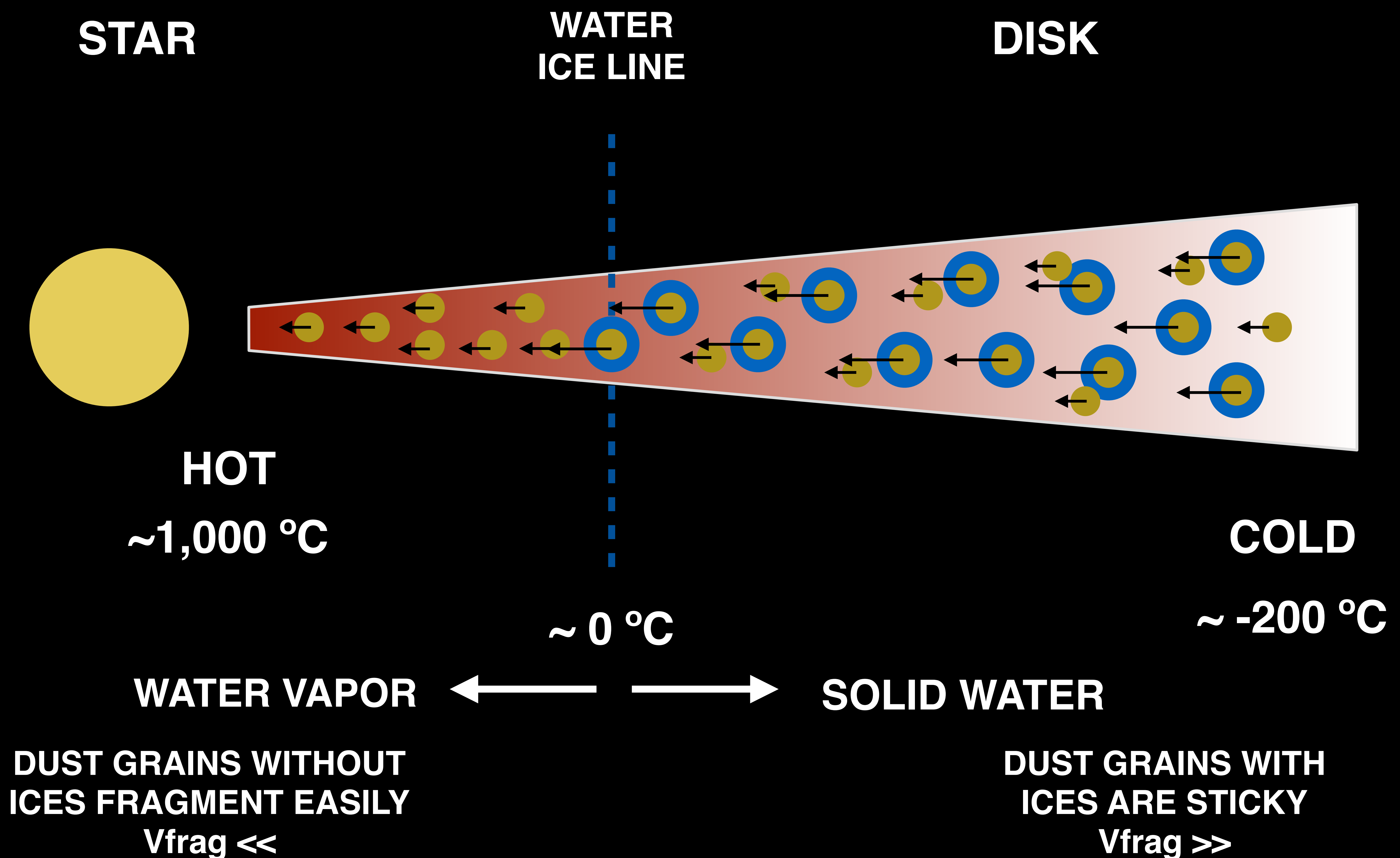
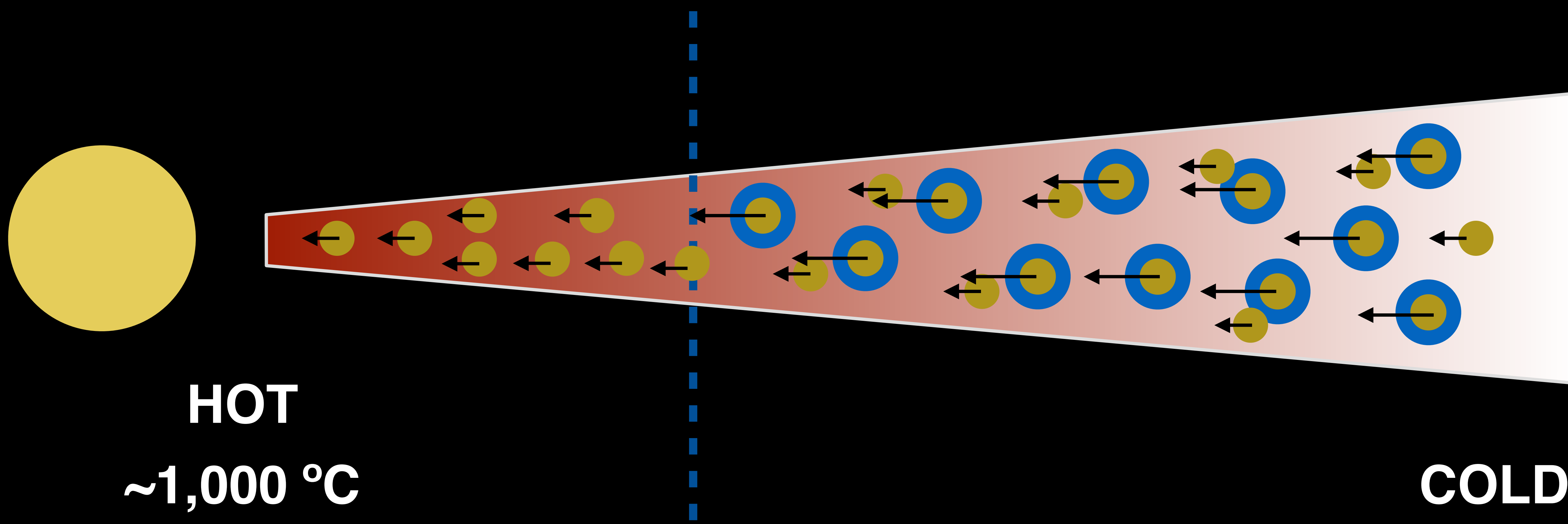


PLANETESIMAL FORMATION AT THE ICE LINES

STAR

WATER
ICE LINE

DISK



HOT

~1,000 ºC

COLD

~ -200 ºC

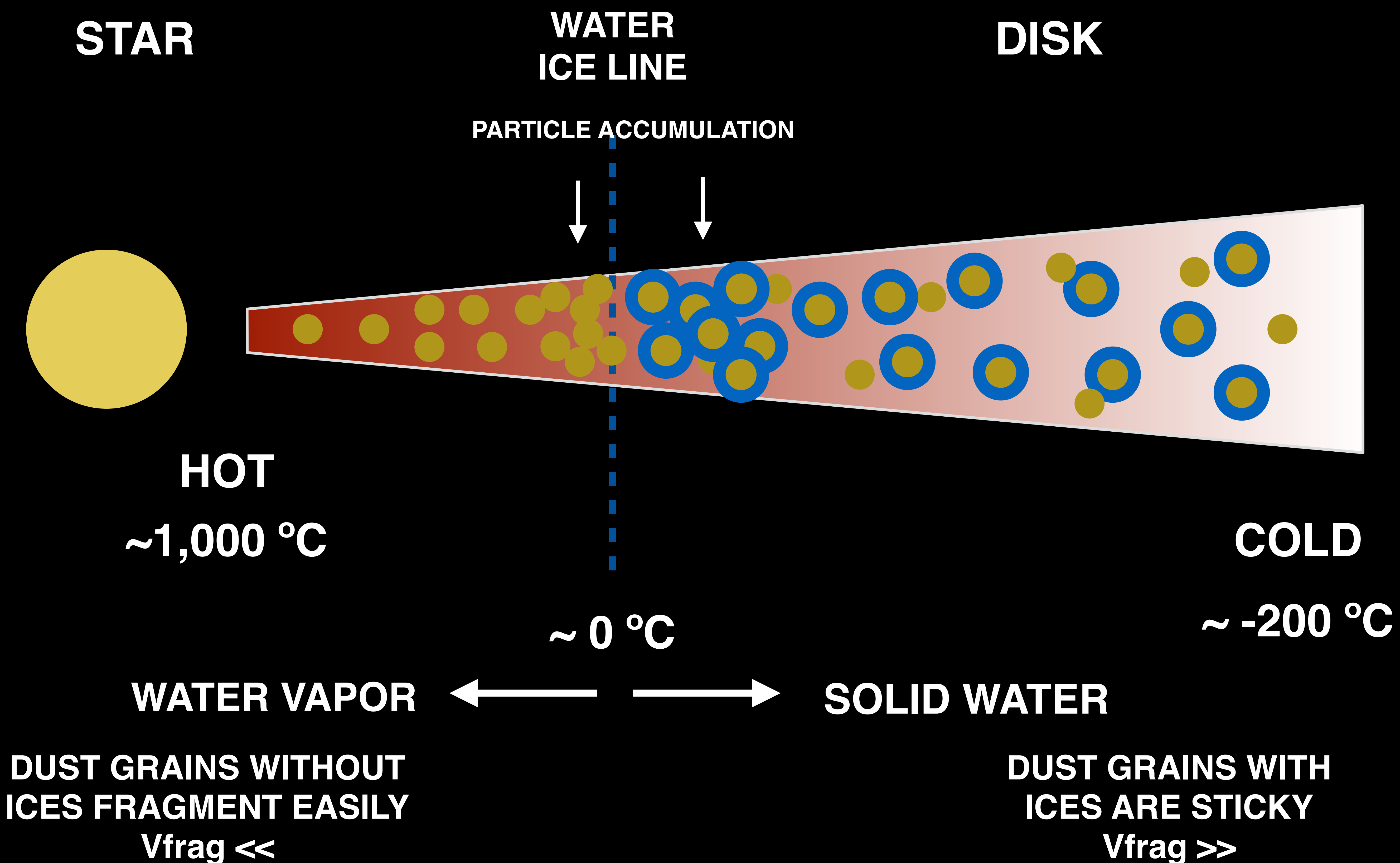
~ 0 ºC

WATER VAPOR ← → SOLID WATER

DUST GRAINS WITHOUT
ICES FRAGMENT EASILY
Vfrag <<

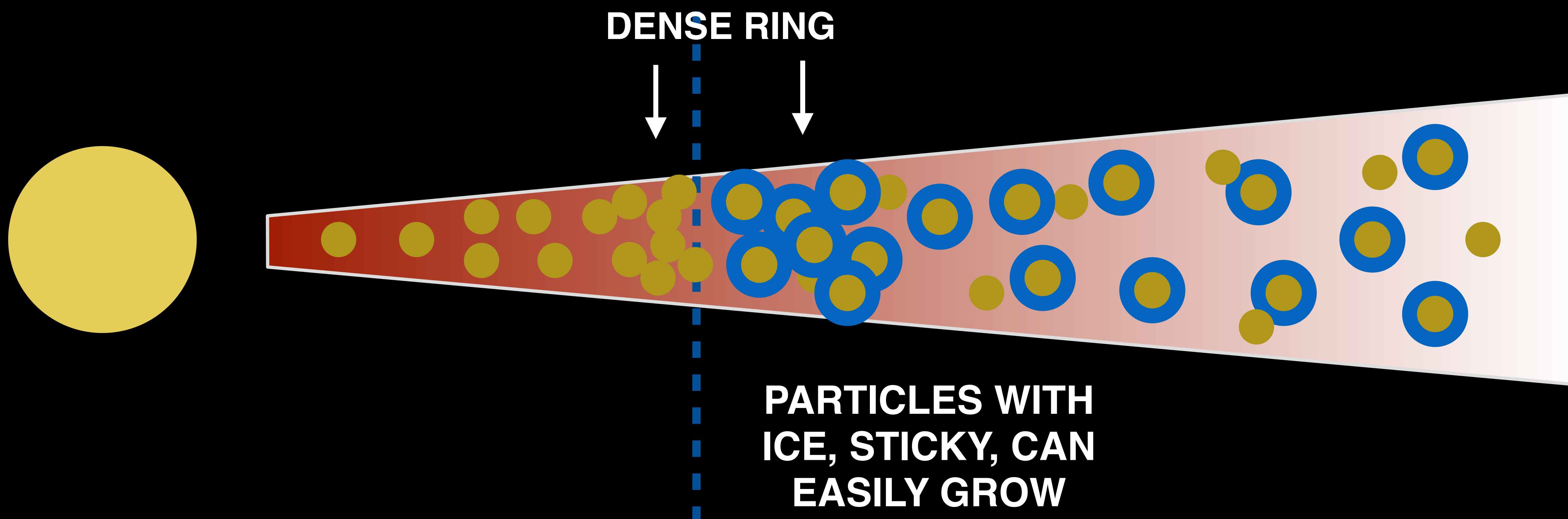
DUST GRAINS WITH
ICES ARE STICKY
Vfrag >>

PLANETESIMAL FORMATION AT THE ICE LINES



PLANETESIMAL FORMATION AT THE ICE LINES

HIGH DENSITY OF
PARTICLES AT THE ICE LINE



PLANETESIMALS
WITH WATER

NOW, ALMA ALLOWS TO STUDY PARTICLE SIZE DISTRIBUTION IN DETAIL

…But, there is a problem

Optically thin limit

$\tau_\nu << 1$

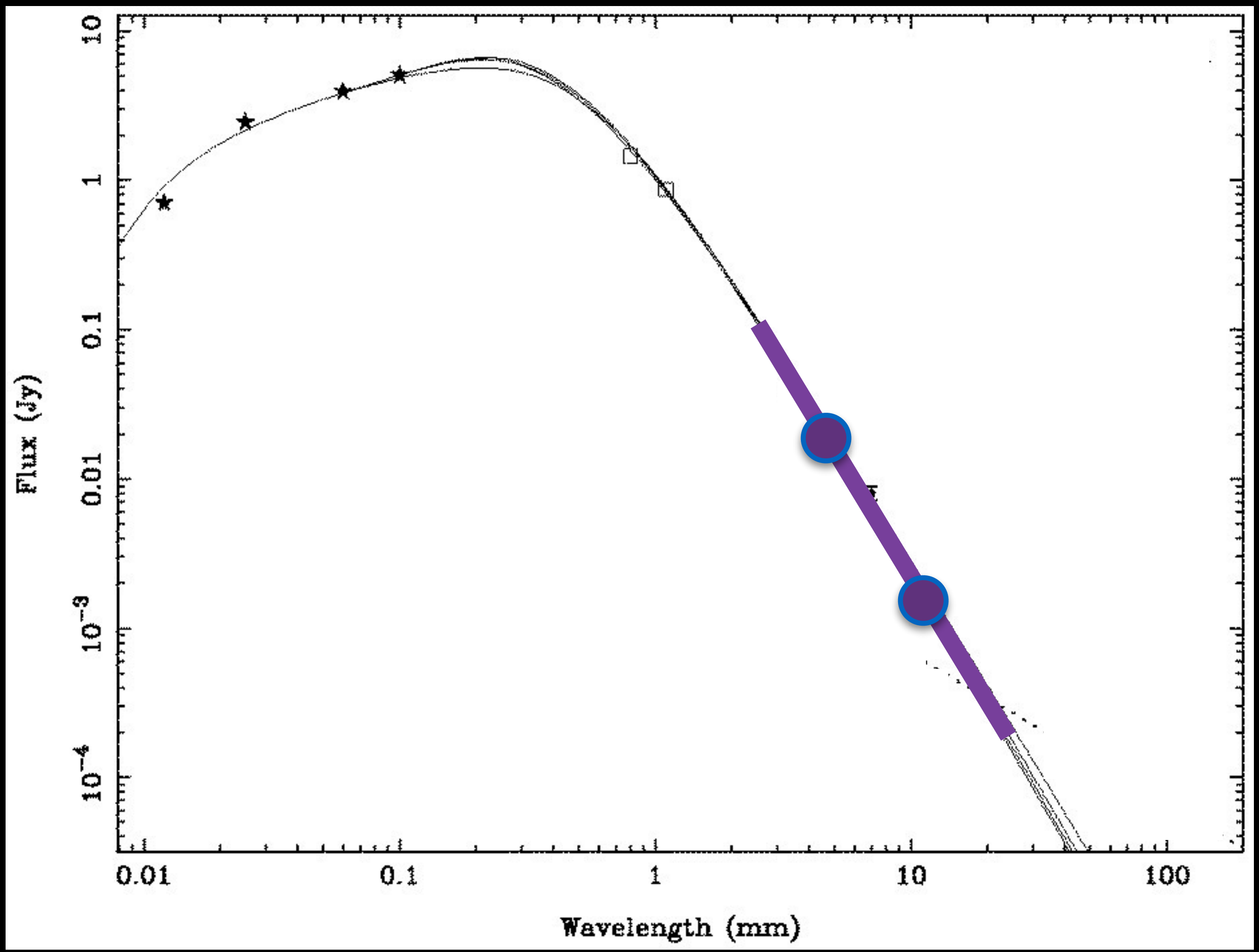
Rayleigh-Jeans approximation

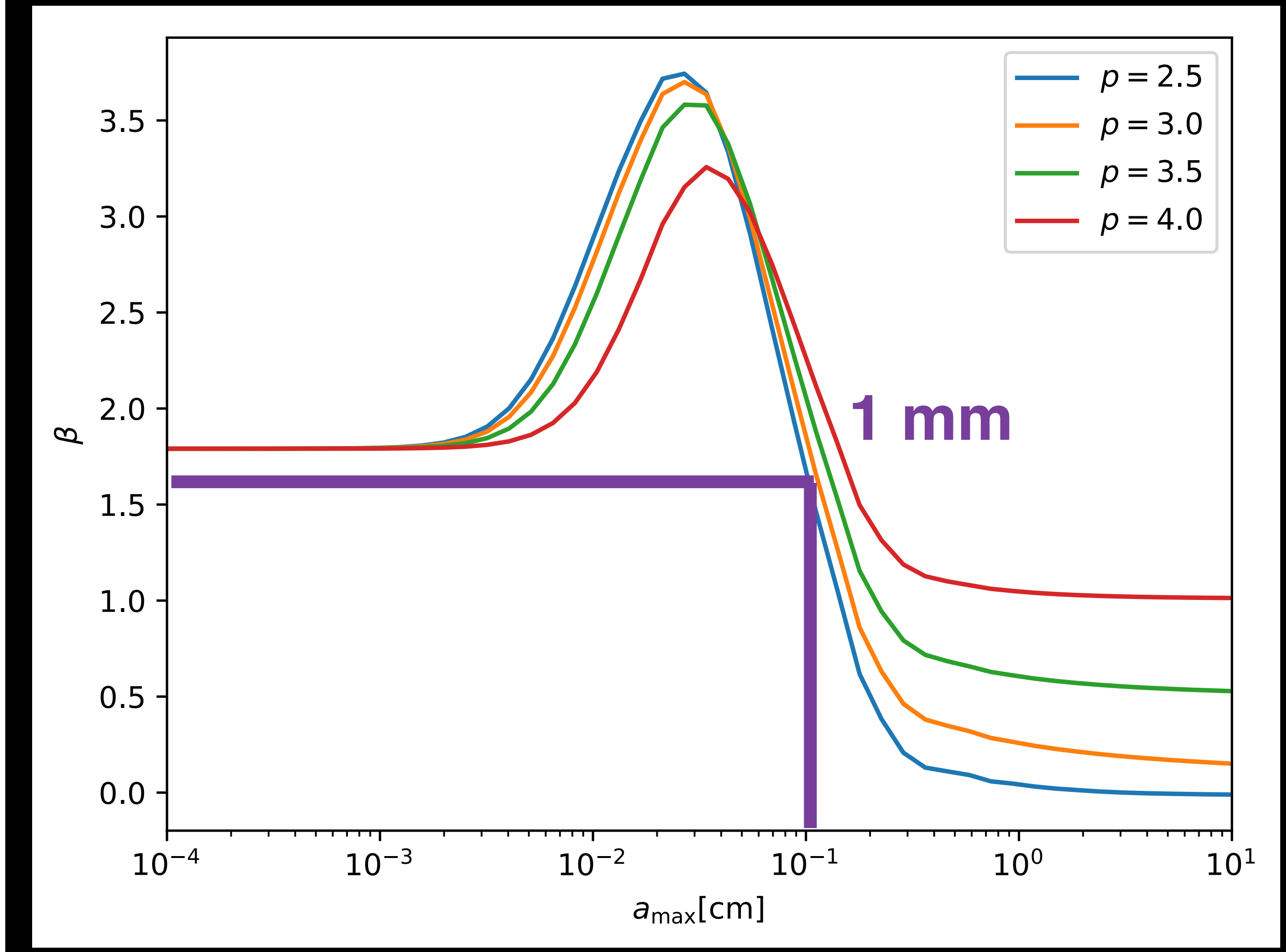
$T_{dust} \uparrow\uparrow$

Absorption only

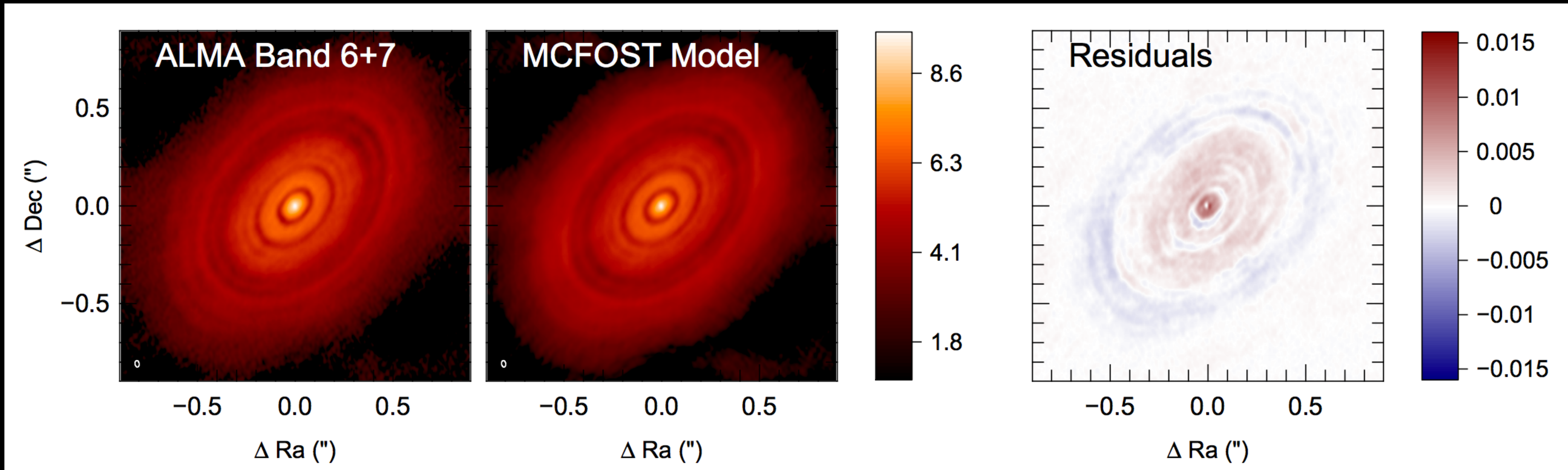
κ_ν

$\longrightarrow I_\nu \propto \nu^{2+\beta}$

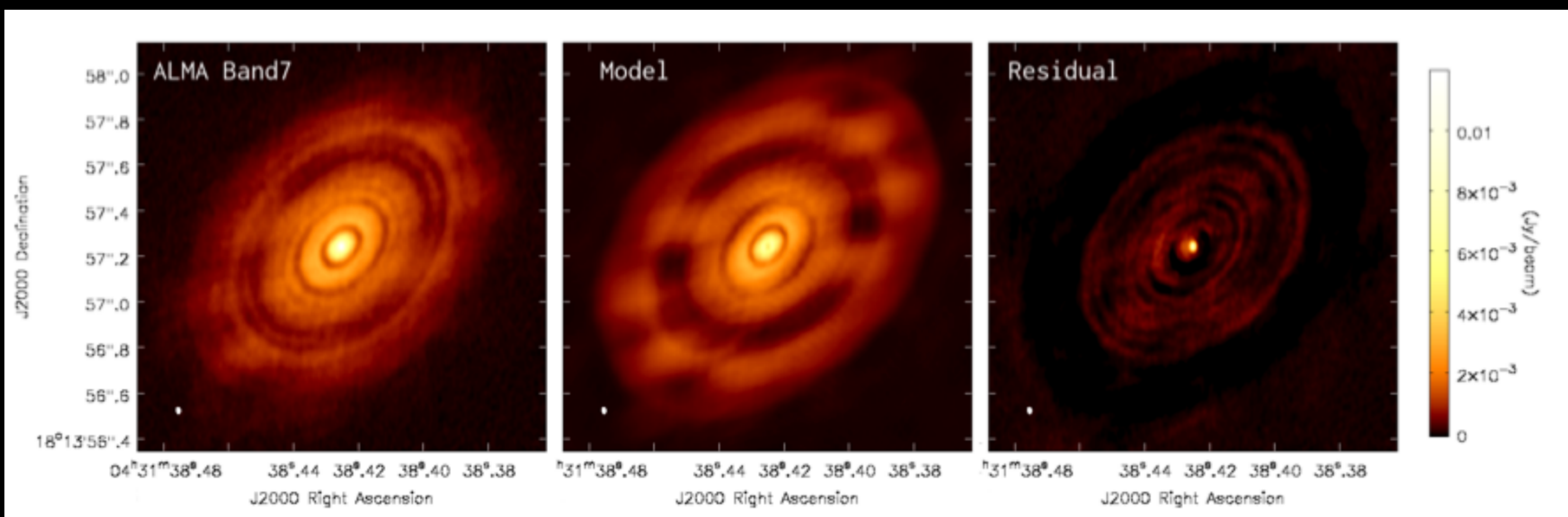




Spectral index between two optically thin wavelengths gives information about the particle size

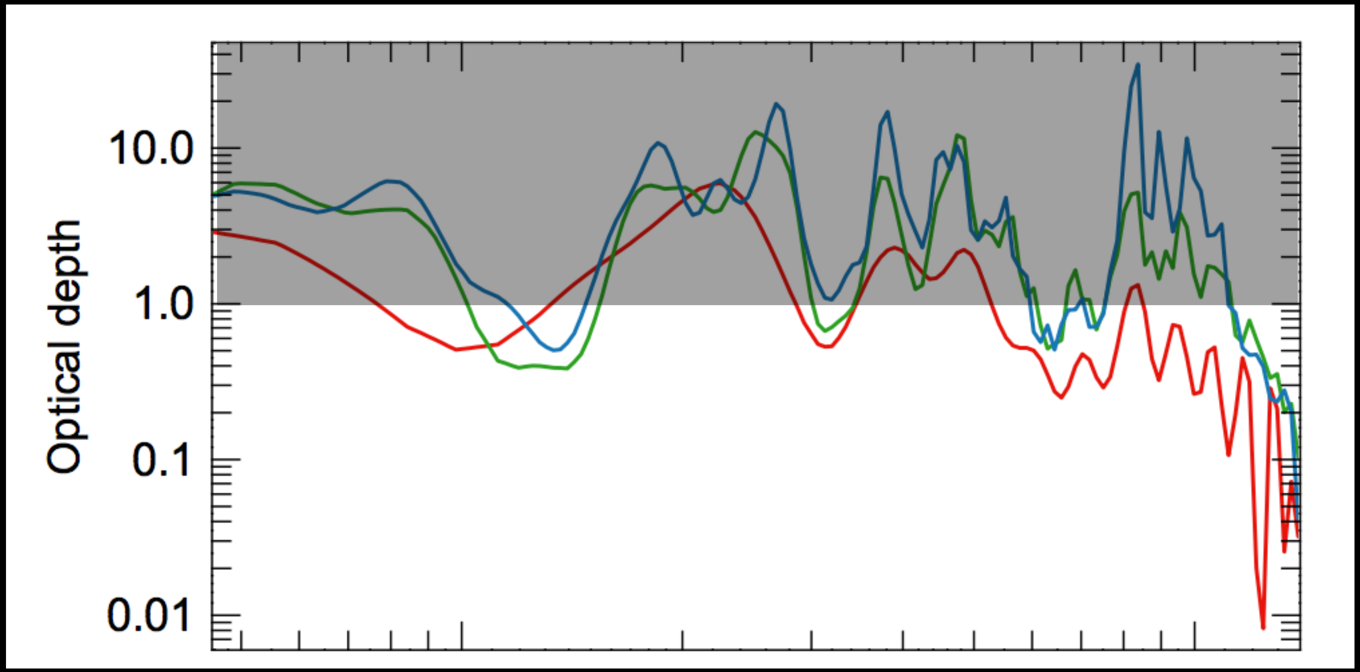


Pinte+2016

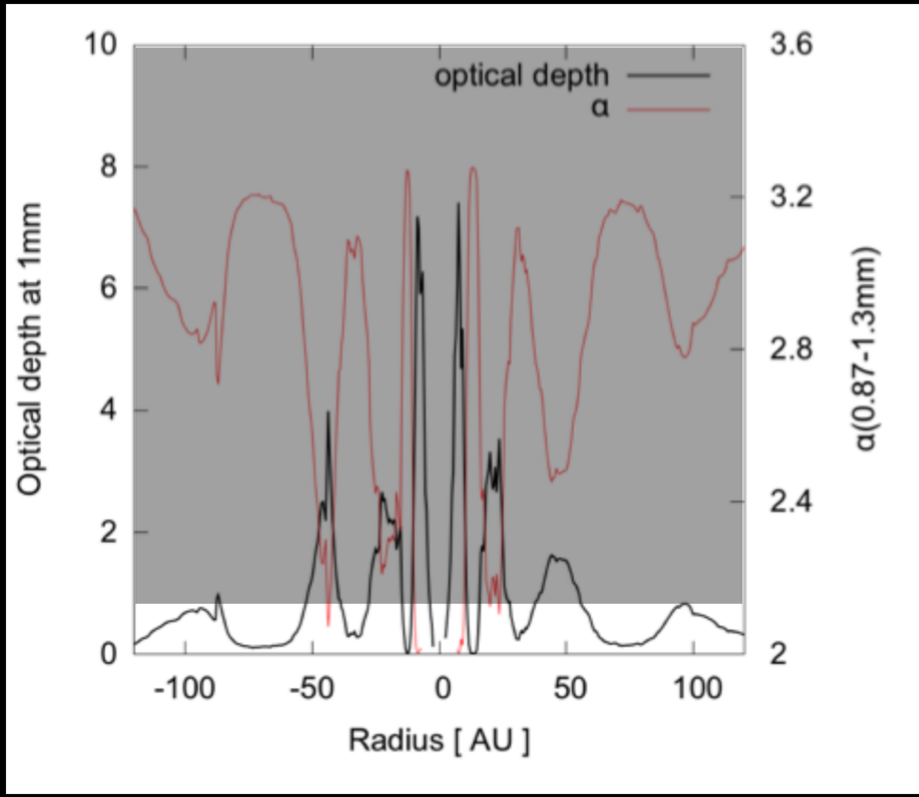


Jin+2016

Emission at all ALMA wavelengths is **optically thick**



Pinte+2016



Jin+2016

Absorption only

$$I_\nu = B_\nu(T_{dust})(1 - e^{-\tau_\nu}) \qquad T_B = T_{dust}(1 - e^{-\tau_\nu})$$

Optical depth –> $\tau_\nu = \Sigma_{dust}\ \kappa_\nu$

<u>Optically THICK</u>

$$\tau_\nu >> 1 \qquad I_\nu \simeq B_\nu(T_{dust}) \qquad T_B \simeq T_{dust}$$

IN OPTICALLY THICK REGIONS WE ONLY SEE THE SURFACE

Optically thin limit

$\tau_\nu << 1$

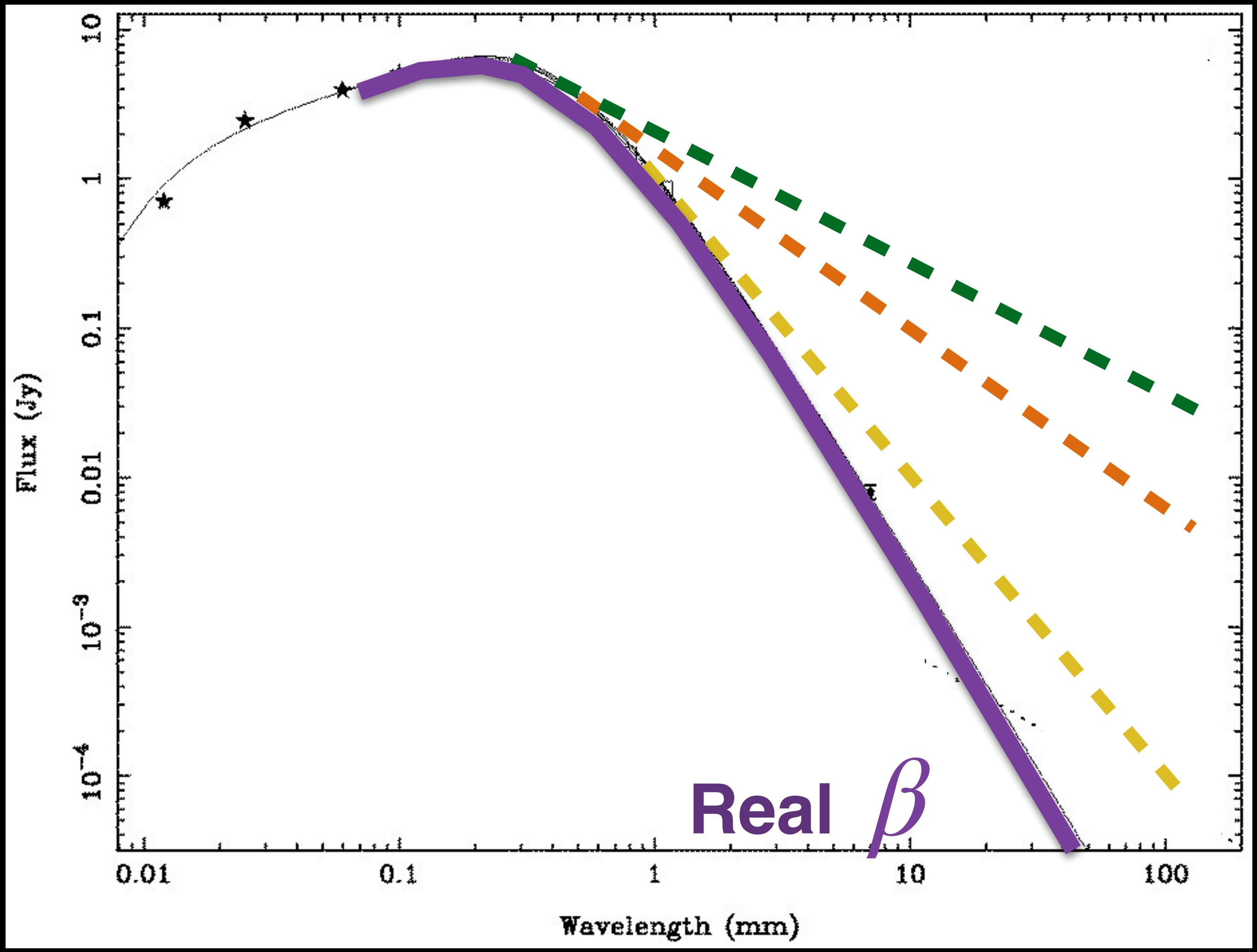
Rayleigh-Jeans approximation

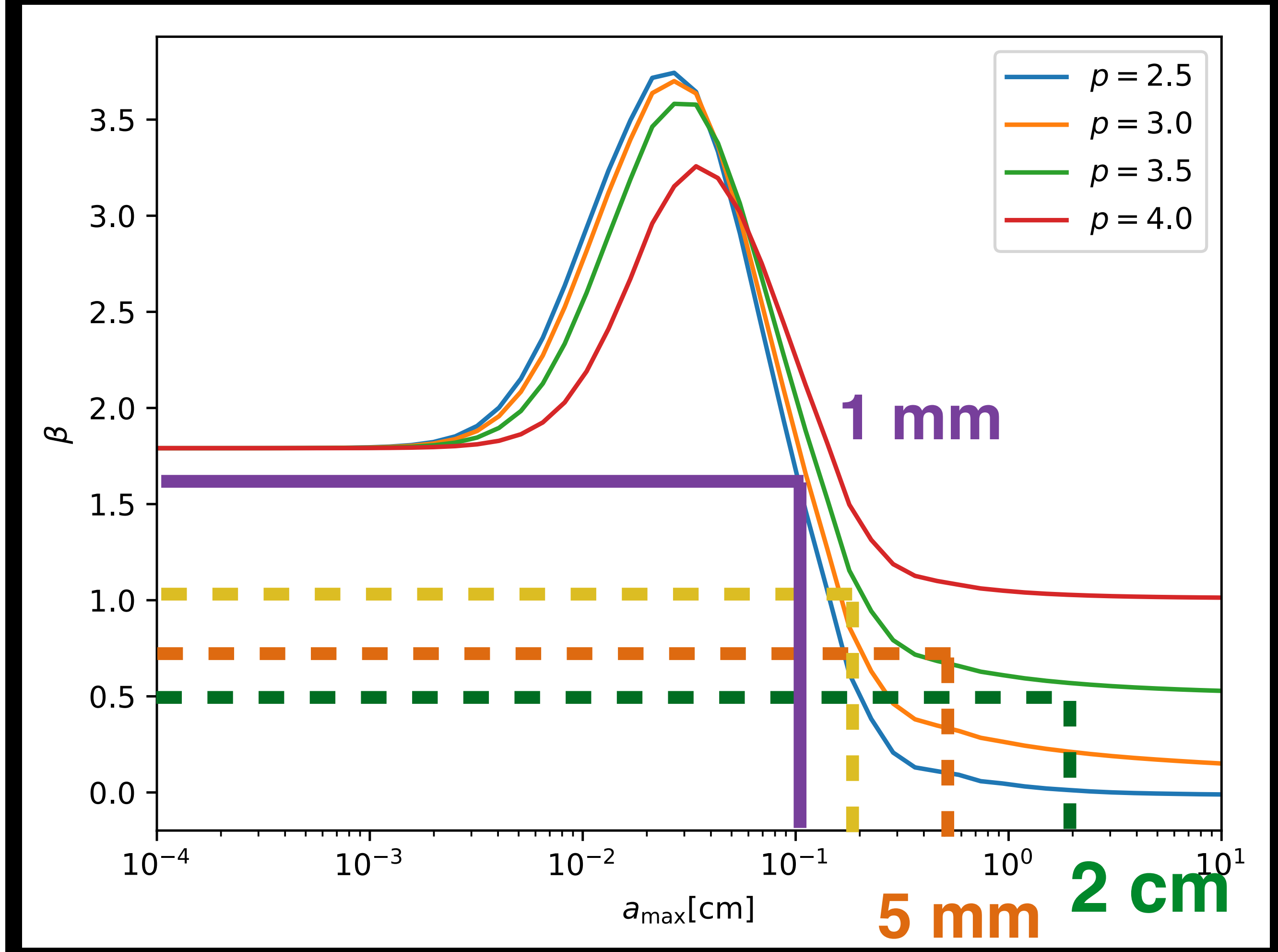
$T_{dust} \uparrow\uparrow$

Absorption only

κ_ν

$\longrightarrow I_\nu \propto \nu^{2+\beta}$

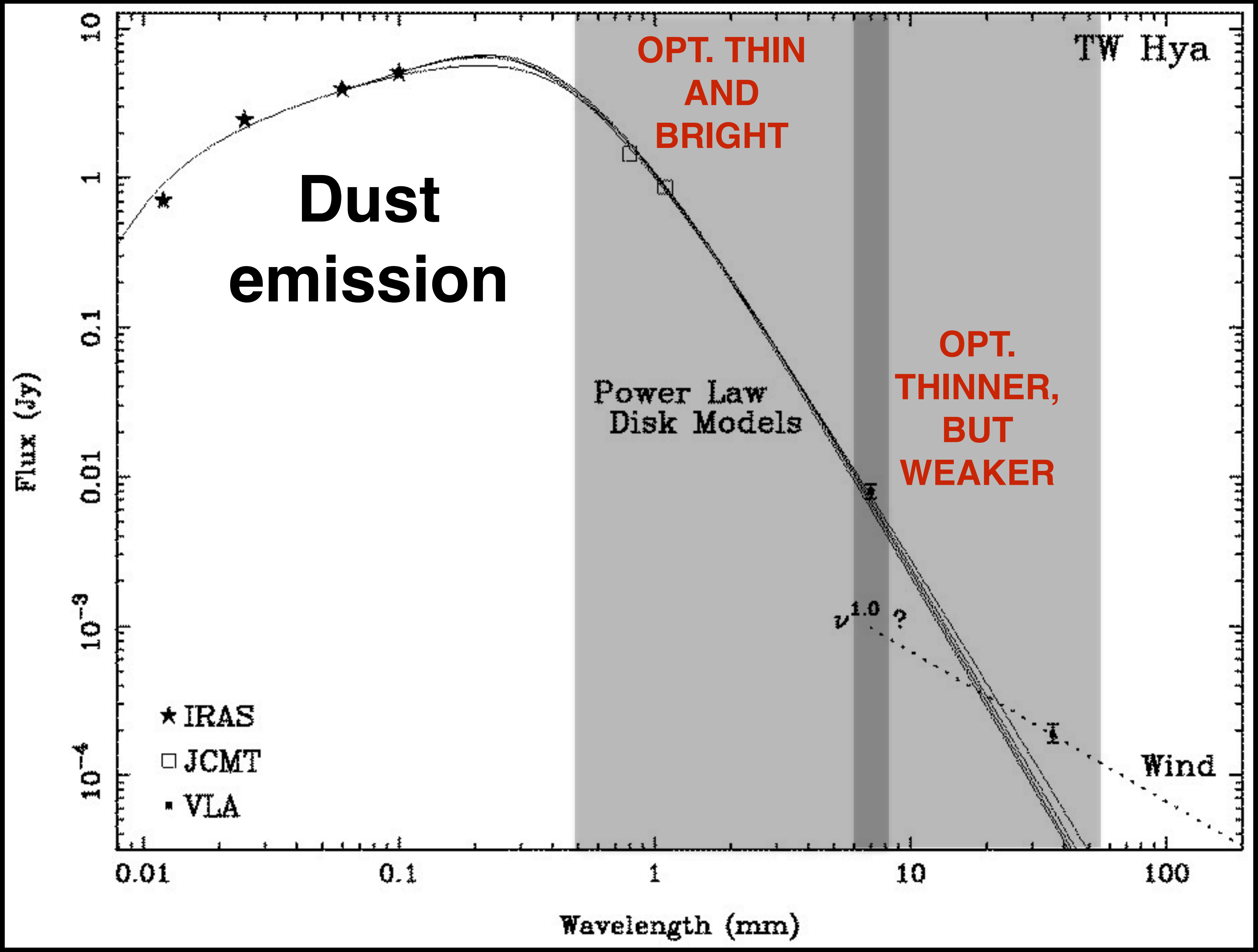




2 mm

Using optically thick wavelengths, we wrongly estimate larger particles

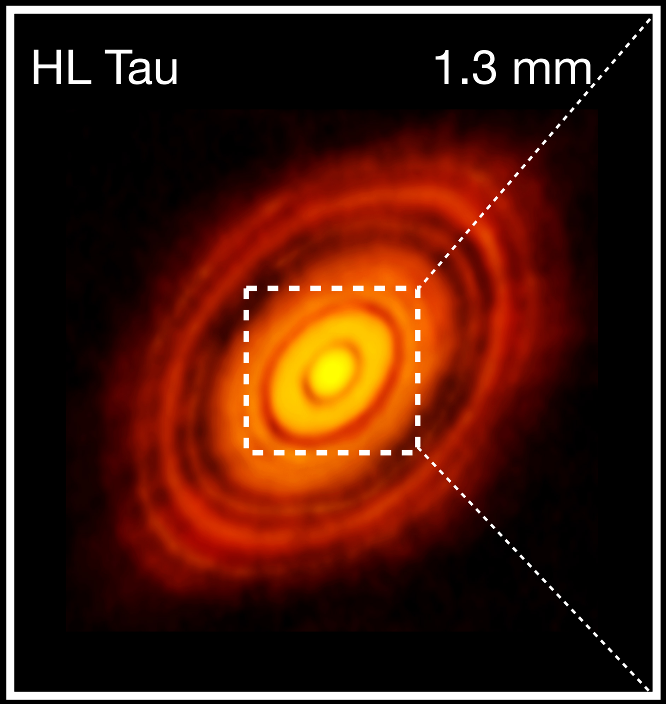
ALMA < 10 mm   VLA > 6 mm

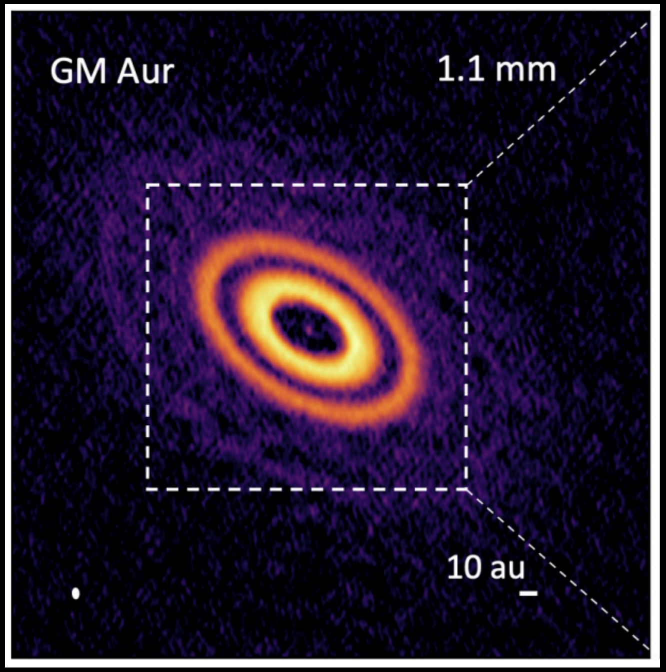


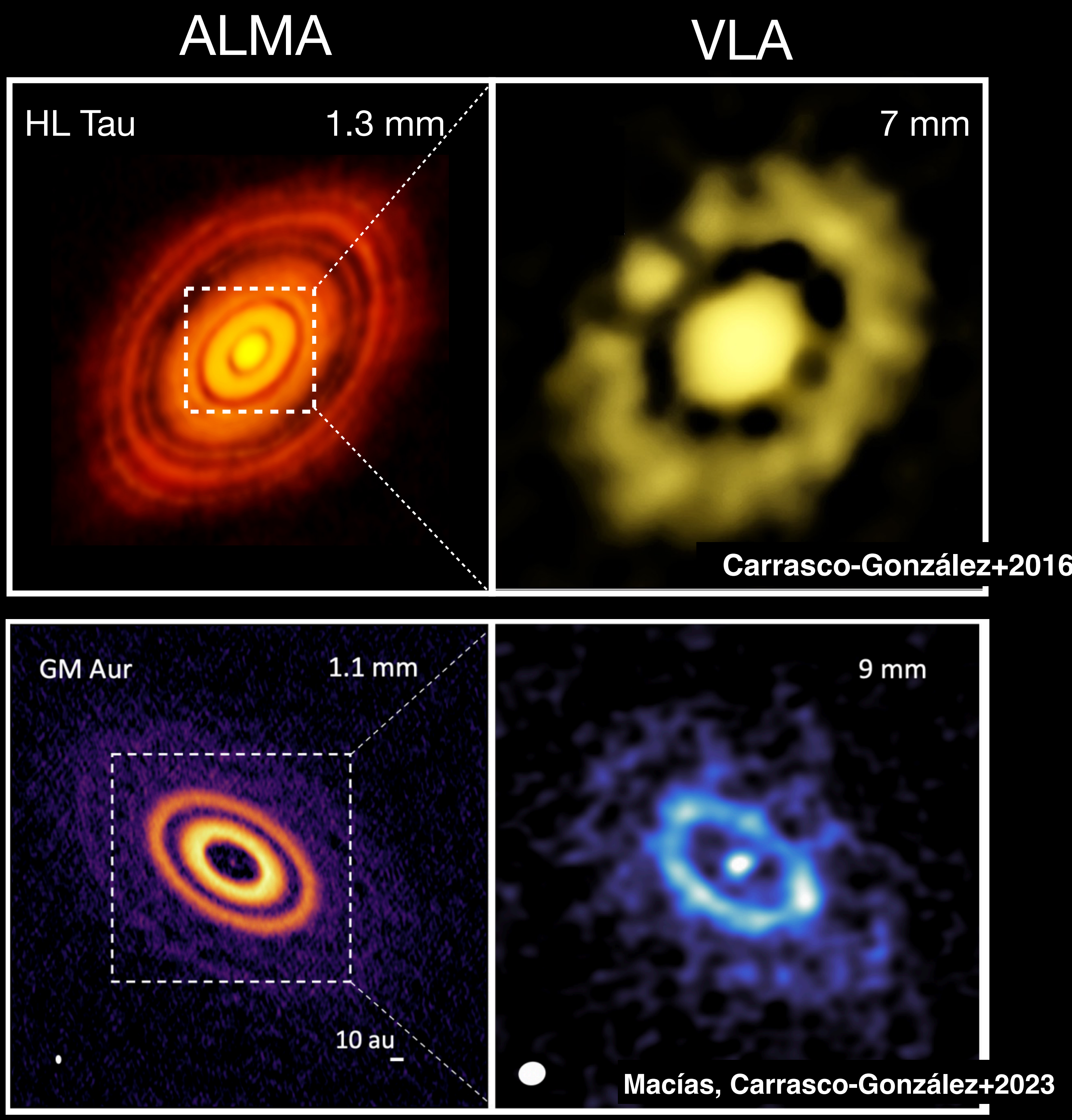
Dust transparency →

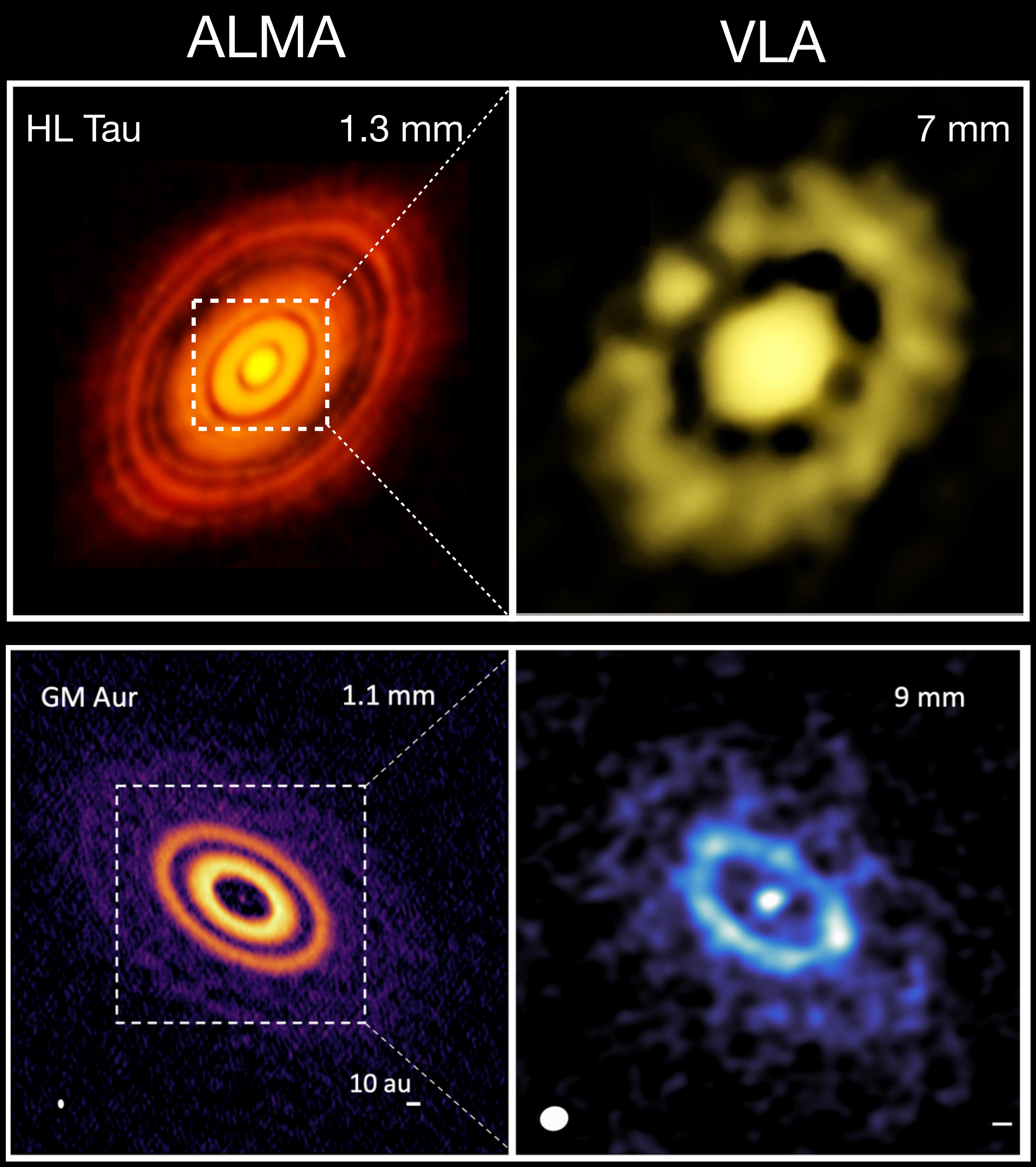
We need high quality images at longer wavelengths

ALMA





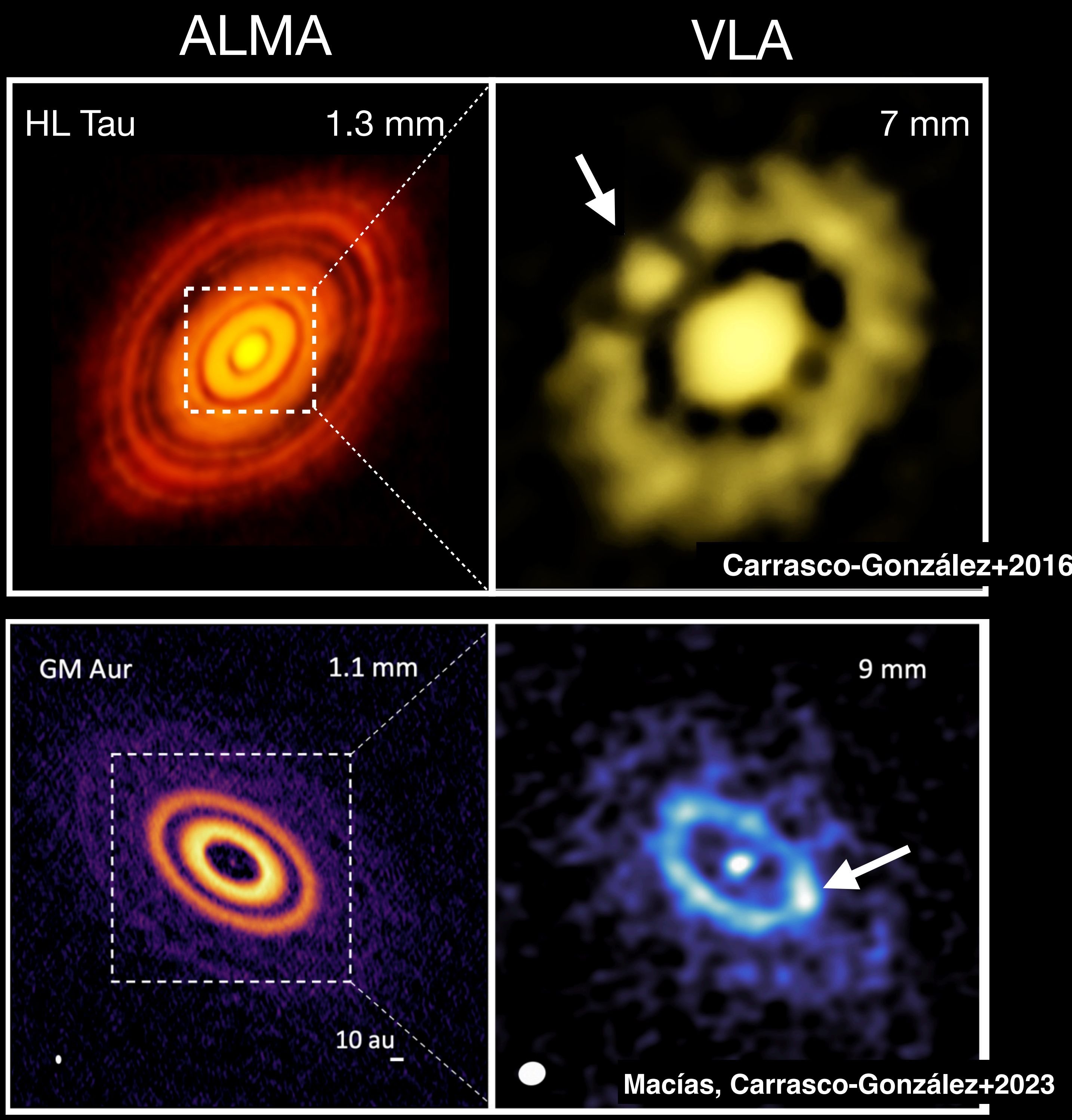

ALMA
VLA
HL Tau
1.3 mm
7 mm
Carrasco-González+2016
GM Aur
1.1 mm
9 mm
10 au
Macías, Carrasco-González+2023



At wavelengths ~ 1 cm, emission is optically thinner and trace location of large particles

Carrasco-González+2016

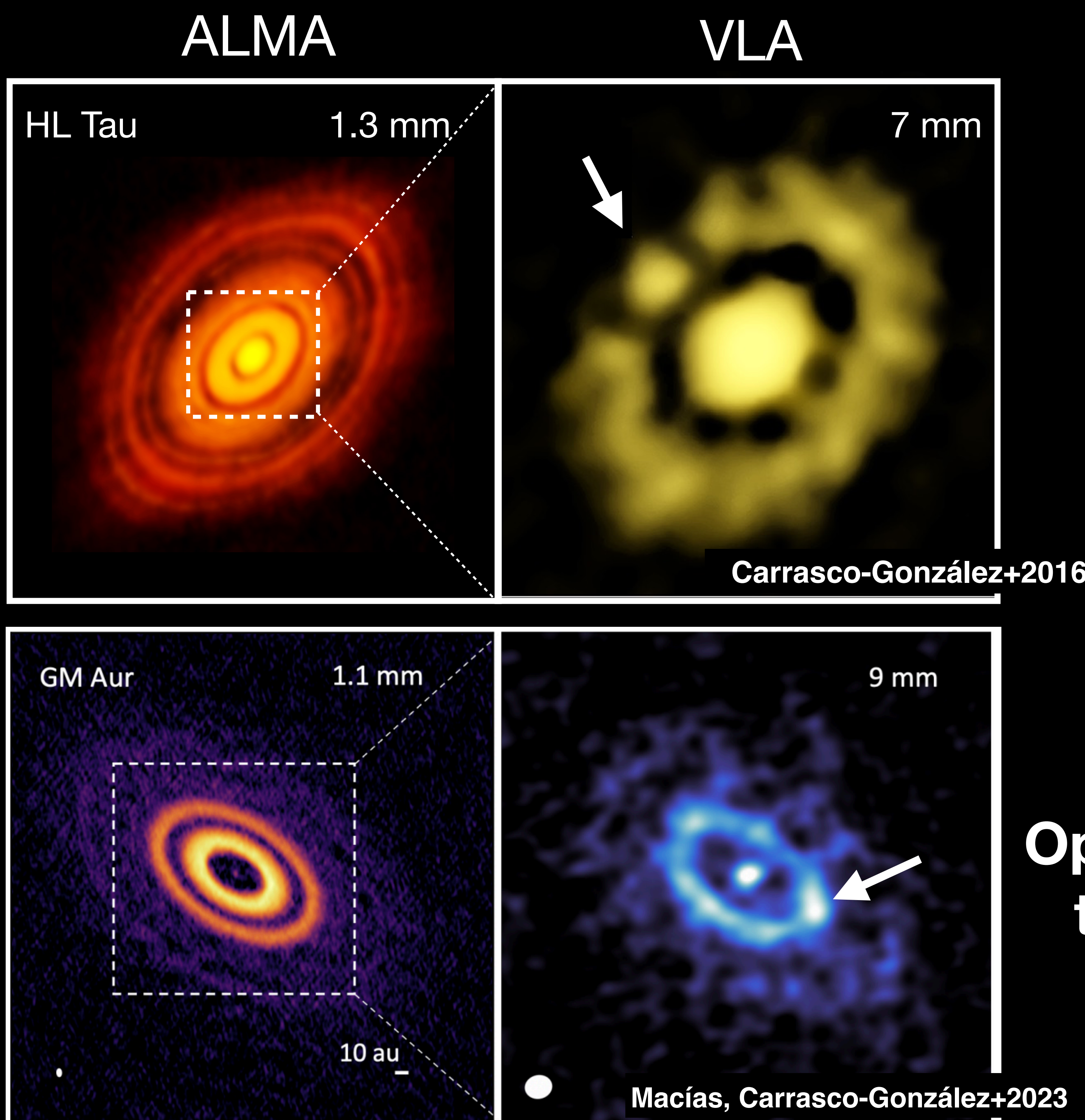
Macías, Carrasco-González+2023



At wavelengths ~ 1 cm, emission is optically thinner and trace location of large particles

Dense clumps within the rings are now visible

These are likely the initial stages of protoplanets



At wavelengths ~ 1 cm, emission is <u>optically thinner</u> and trace location of <u>large particles</u>

Dense <u>clumps</u> within the rings are now visible

These are likely the <u>initial stages</u> of protoplanets

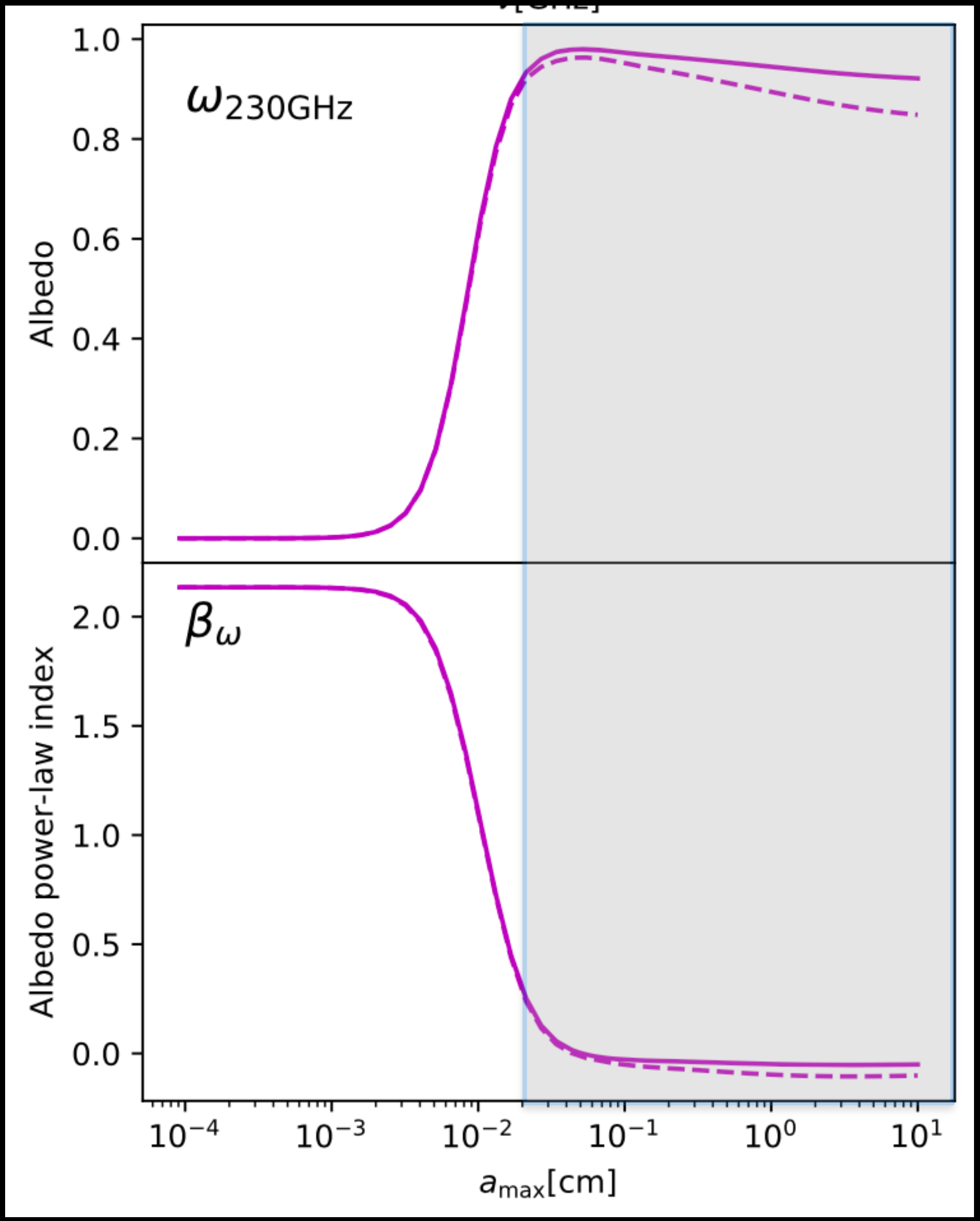
Optically thin emission is sensitive to the <u>dust content</u> in the rings

Actually, much more complicated…
Usual expression assumes opacity is dominated only by absorption

$$\tau_\nu = \Sigma_{\rm dust}\chi_\nu = \Sigma_{\rm dust}(\kappa_\nu + \sigma_\nu) = \tau_\nu^{\rm abs} + \tau_\nu^{\rm sca}.$$

Albedo —>

$$\omega_\nu = \frac{\sigma_\nu}{\kappa_\nu + \sigma_\nu} = \frac{\tau_\nu^{\rm sca}}{\tau_\nu^{\rm abs} + \tau_\nu^{\rm sca}}.$$



In a protoplanetary disk, at millimeter wavelengths, opacity is most probably dominated by scattering

Simple case, thin disk:

$$I_\nu = \int_0^{\tau_\nu/\mu} S_\nu(T) e^{-t/\mu} \frac{dt}{\mu}$$
$$= B_\nu(T)[(1 - \exp(-\tau_\nu/\mu)) + \omega_\nu F(\tau_\nu, \omega_\nu)],$$

where

$$F(\tau_\nu, \omega_\nu) = \frac{1}{\exp(-\sqrt{3}\,\epsilon_\nu \tau_\nu)(\epsilon_\nu - 1) - (\epsilon_\nu + 1)} \times \left[\frac{1 - \exp(-(\sqrt{3}\,\epsilon_\nu + 1/\mu)\tau_\nu)}{\sqrt{3}\,\epsilon_\nu \mu + 1} + \frac{\exp(-\tau_\nu/\mu) - \exp(-\sqrt{3}\,\epsilon_\nu \tau_\nu)}{\sqrt{3}\,\epsilon_\nu \mu - 1} \right].$$

$$\tau_\nu = \Sigma_{\rm dust} \chi_\nu = \Sigma_{\rm dust}(\kappa_\nu + \sigma_\nu) = \tau_\nu^{\rm abs} + \tau_\nu^{\rm sca}.$$

$$\omega_\nu = \frac{\sigma_\nu}{\kappa_\nu + \sigma_\nu} = \frac{\tau_\nu^{\rm sca}}{\tau_\nu^{\rm abs} + \tau_\nu^{\rm sca}}.$$

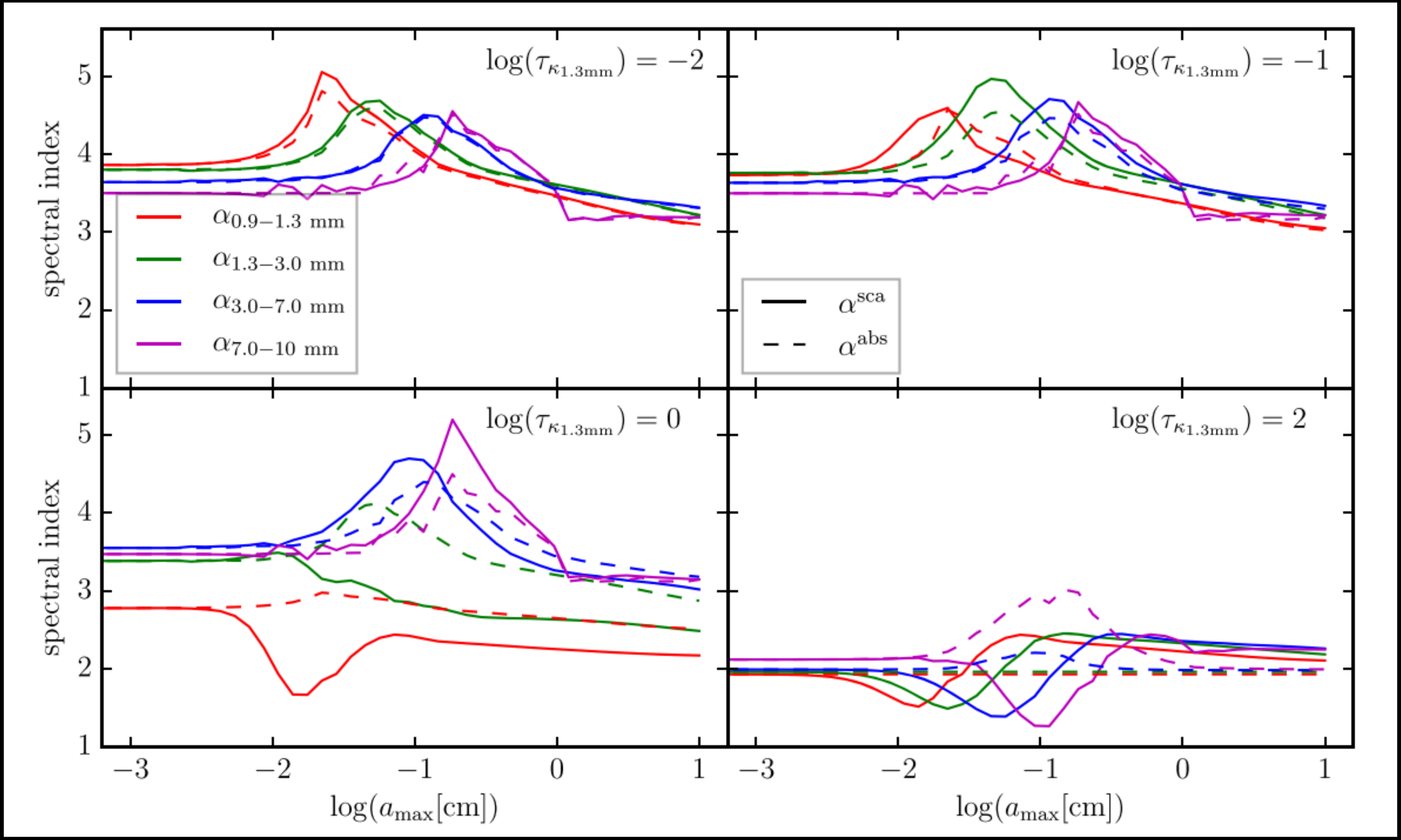
$$\epsilon_\nu = \sqrt{1 - \omega_\nu}.$$

$$\mu = \cos(i).$$

Different wavelengths trace dust at different heights in the disk

This expression is valid if the temperature of the different layers is not very different

Spectral index is extremely difficult to interpret



Zhu et al. 2019
Sierra et al. 2020

Simple case, thin disk:

$$I_\nu = \int_0^{\tau_\nu/\mu} S_\nu(T) e^{-t/\mu} \frac{dt}{\mu}$$
$$= B_\nu(T)[(1 - \exp(-\tau_\nu/\mu)) + \omega_\nu F(\tau_\nu, \omega_\nu)],$$

where

$$F(\tau_\nu, \omega_\nu) = \frac{1}{\exp(-\sqrt{3}\,\epsilon_\nu \tau_\nu)(\epsilon_\nu - 1) - (\epsilon_\nu + 1)} \times \left[\frac{1 - \exp(-(\sqrt{3}\,\epsilon_\nu + 1/\mu)\tau_\nu)}{\sqrt{3}\,\epsilon_\nu \mu + 1} + \frac{\exp(-\tau_\nu/\mu) - \exp(-\sqrt{3}\,\epsilon_\nu \tau_\nu)}{\sqrt{3}\,\epsilon_\nu \mu - 1}\right].$$

$$\tau_\nu = \Sigma_{\rm dust}\chi_\nu = \Sigma_{\rm dust}(\kappa_\nu + \sigma_\nu) = \tau_\nu^{\rm abs} + \tau_\nu^{\rm sca}.$$

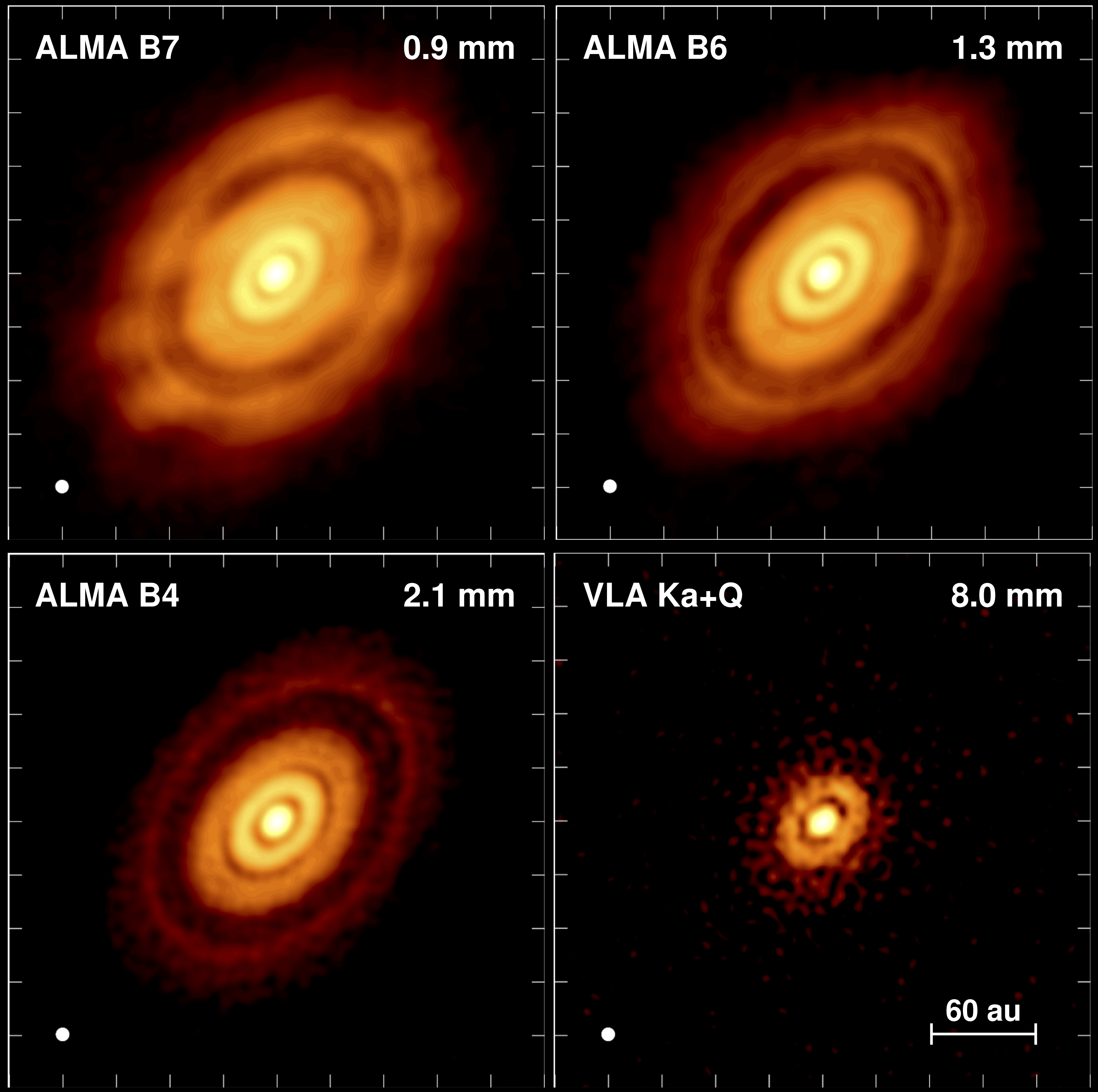
$$\omega_\nu = \frac{\sigma_\nu}{\kappa_\nu + \sigma_\nu} = \frac{\tau_\nu^{\rm sca}}{\tau_\nu^{\rm abs} + \tau_\nu^{\rm sca}}.$$

$$\epsilon_\nu = \sqrt{1 - \omega_\nu}.$$

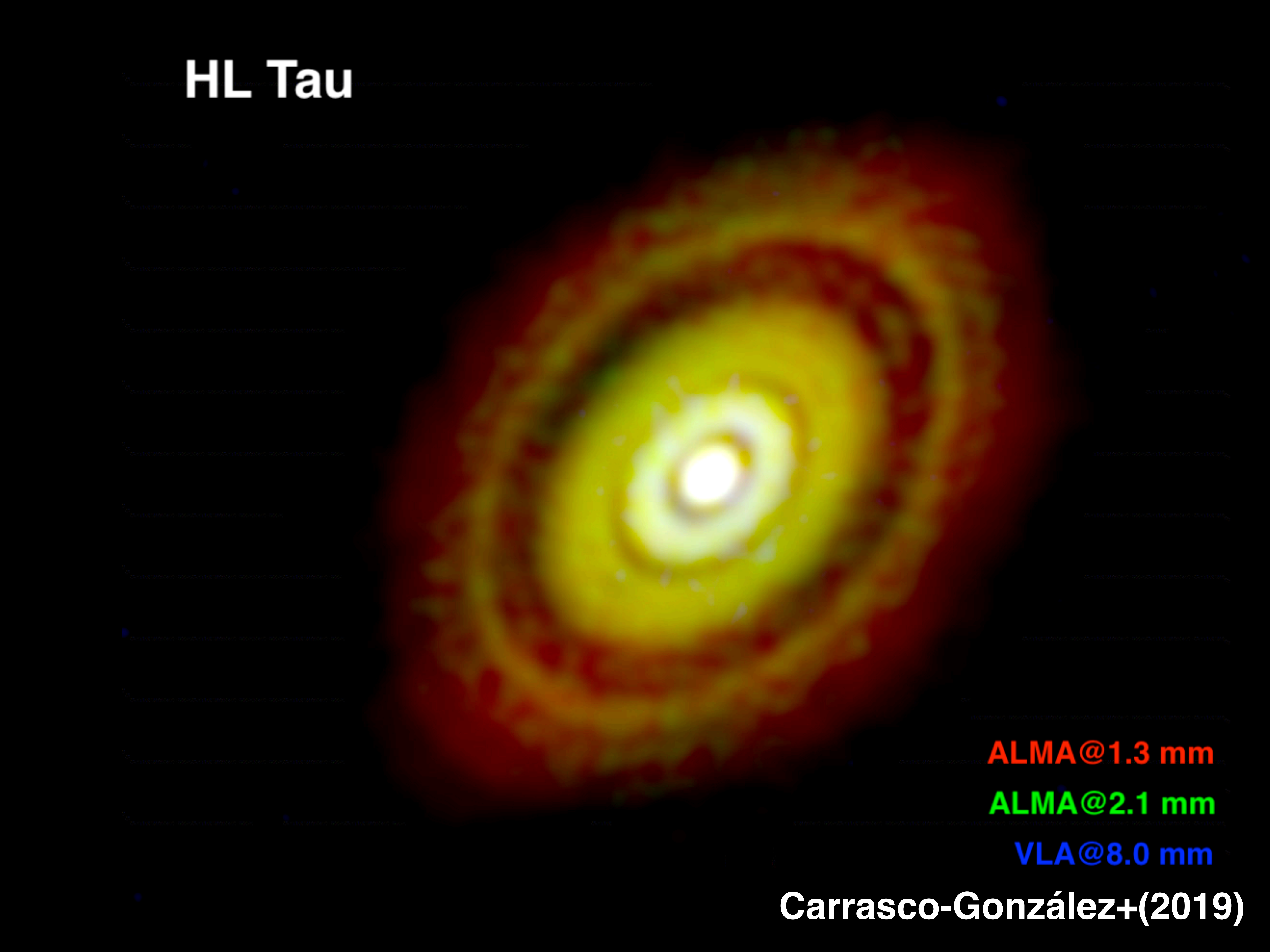
$$\mu = \cos(i).$$

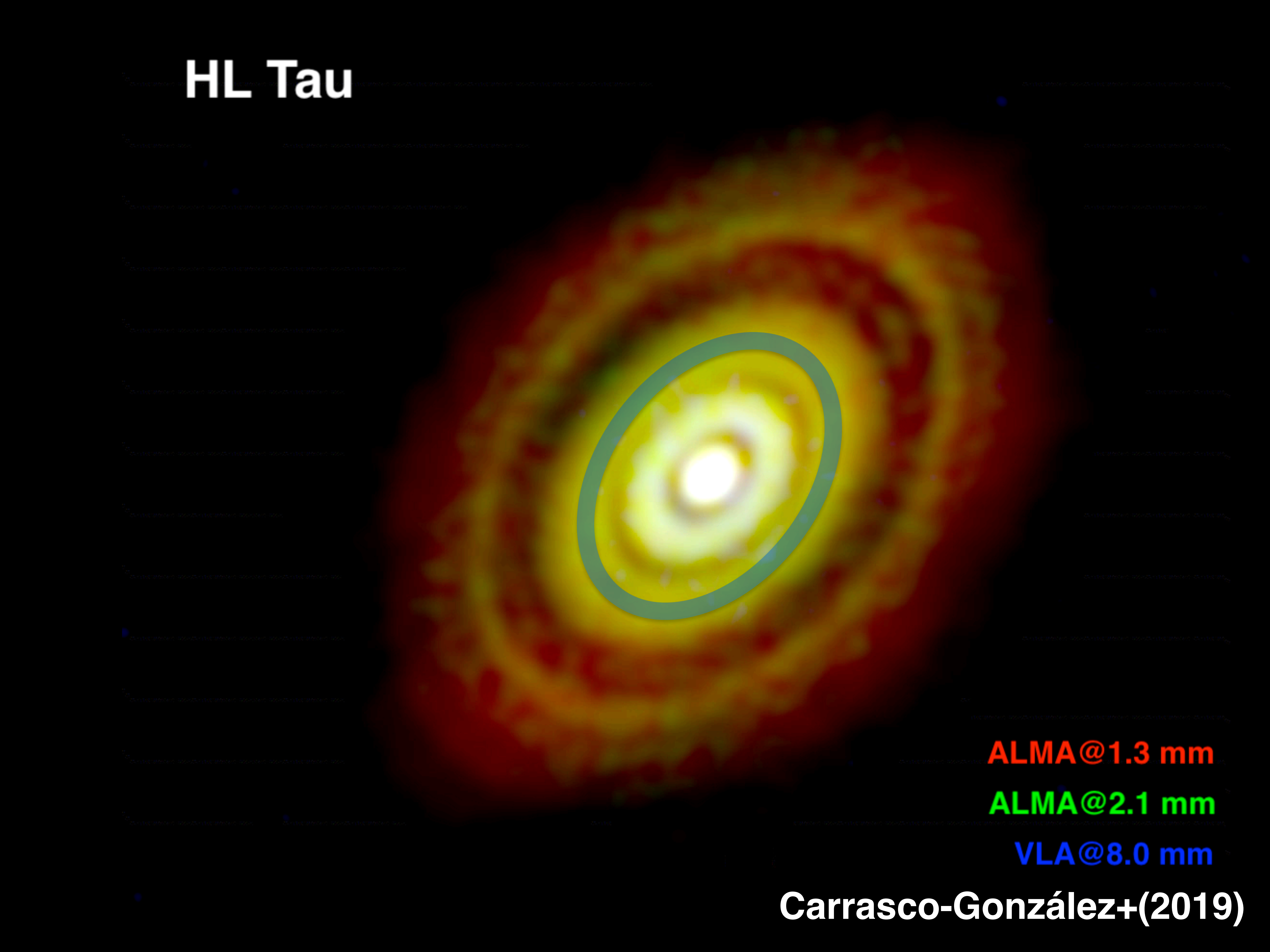
Only depends on three free parameters:

$T_{\rm dust}$, $\Sigma_{\rm dust}$, $a_{\rm max}$ **(p=3.5)**



Carrasco-González+(2019)


HL Tau
ALMA@1.3 mm
ALMA@2.1 mm
VLA@8.0 mm
Carrasco-González+(2019)


HL Tau
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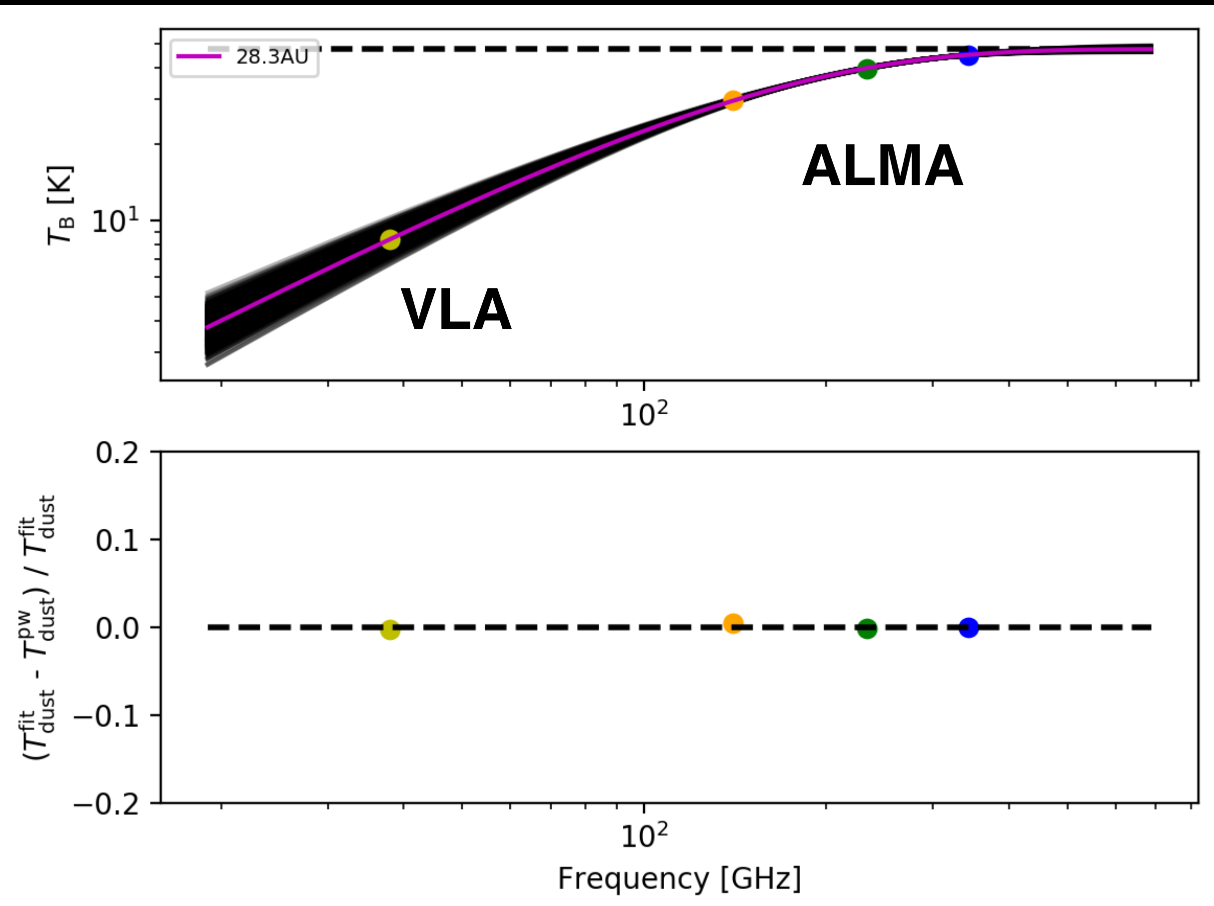
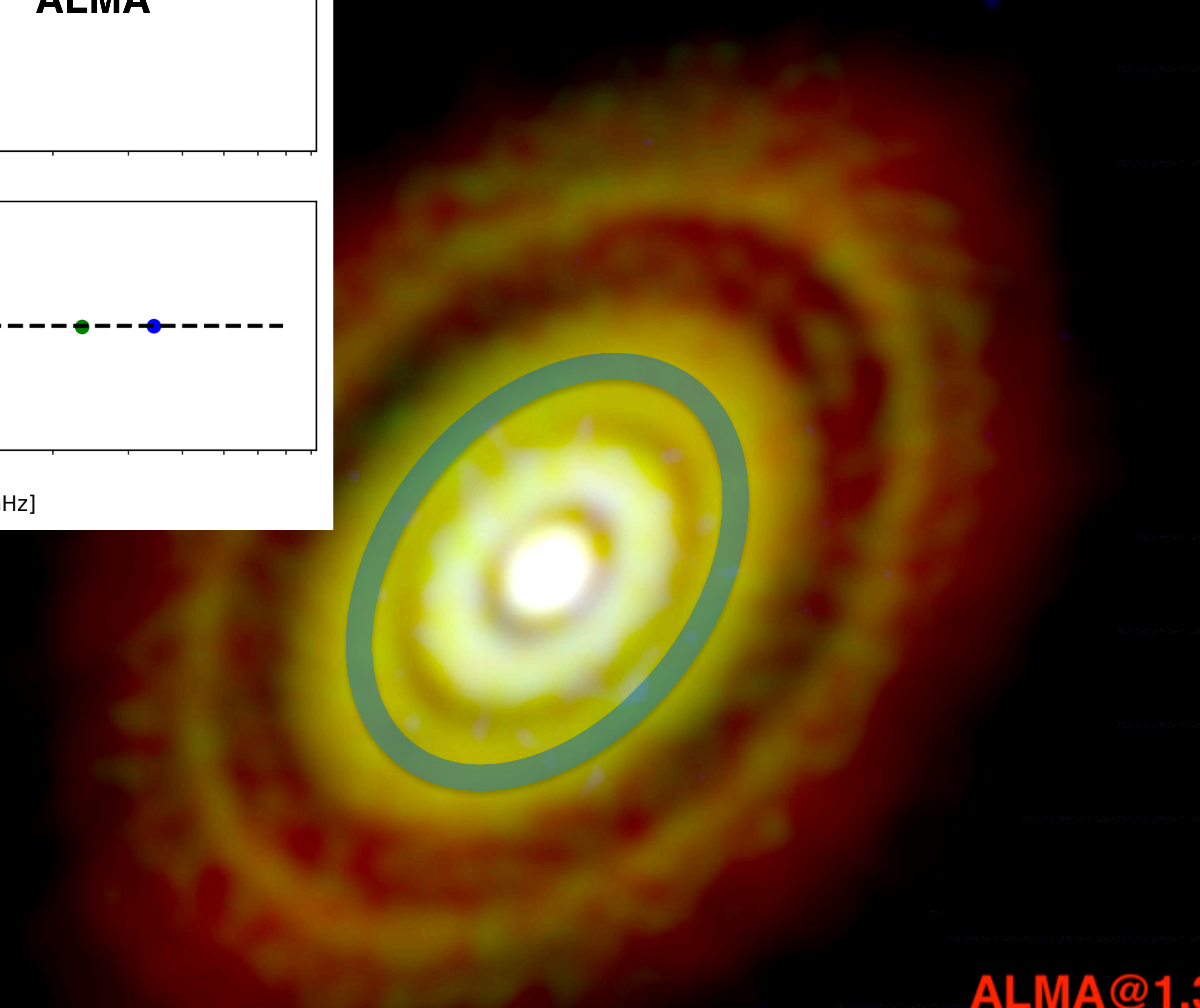
Carrasco-González+(2019)





SED fitting at each radius —> $T_{dust}(r)$, $\Sigma_{dust}(r)$, $a_{max}(r)$

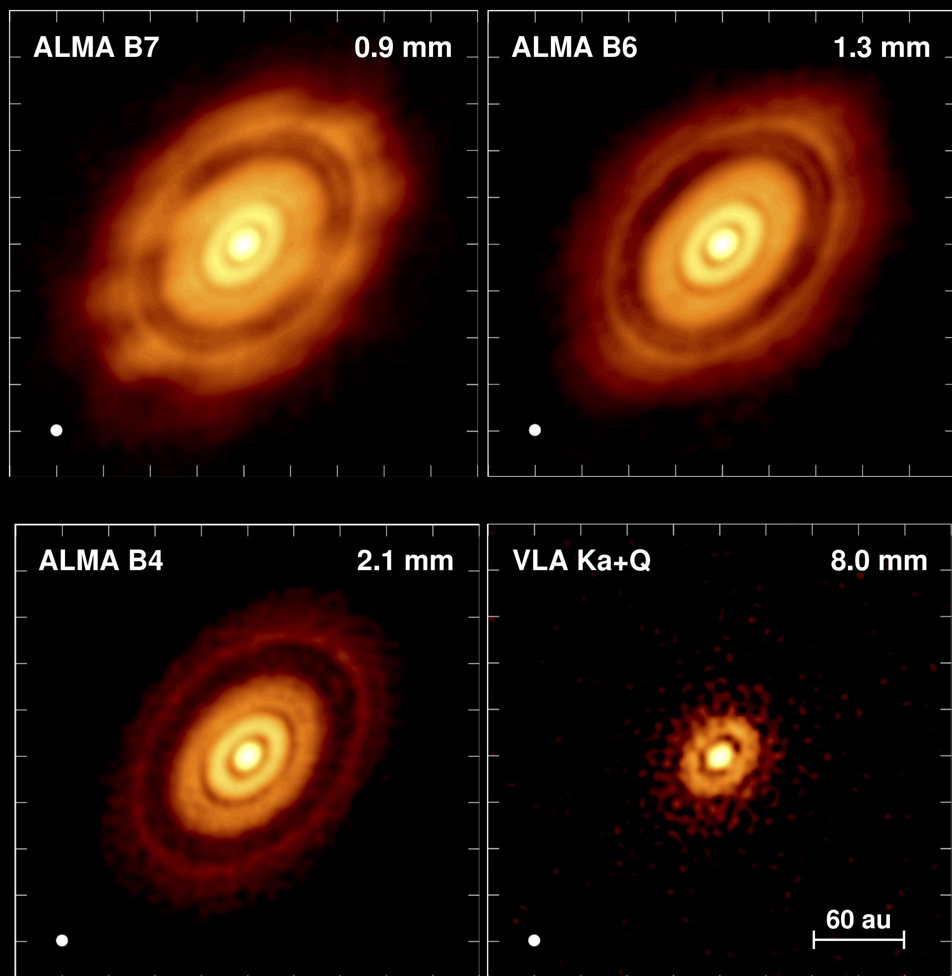
ALMA@1.3 mm

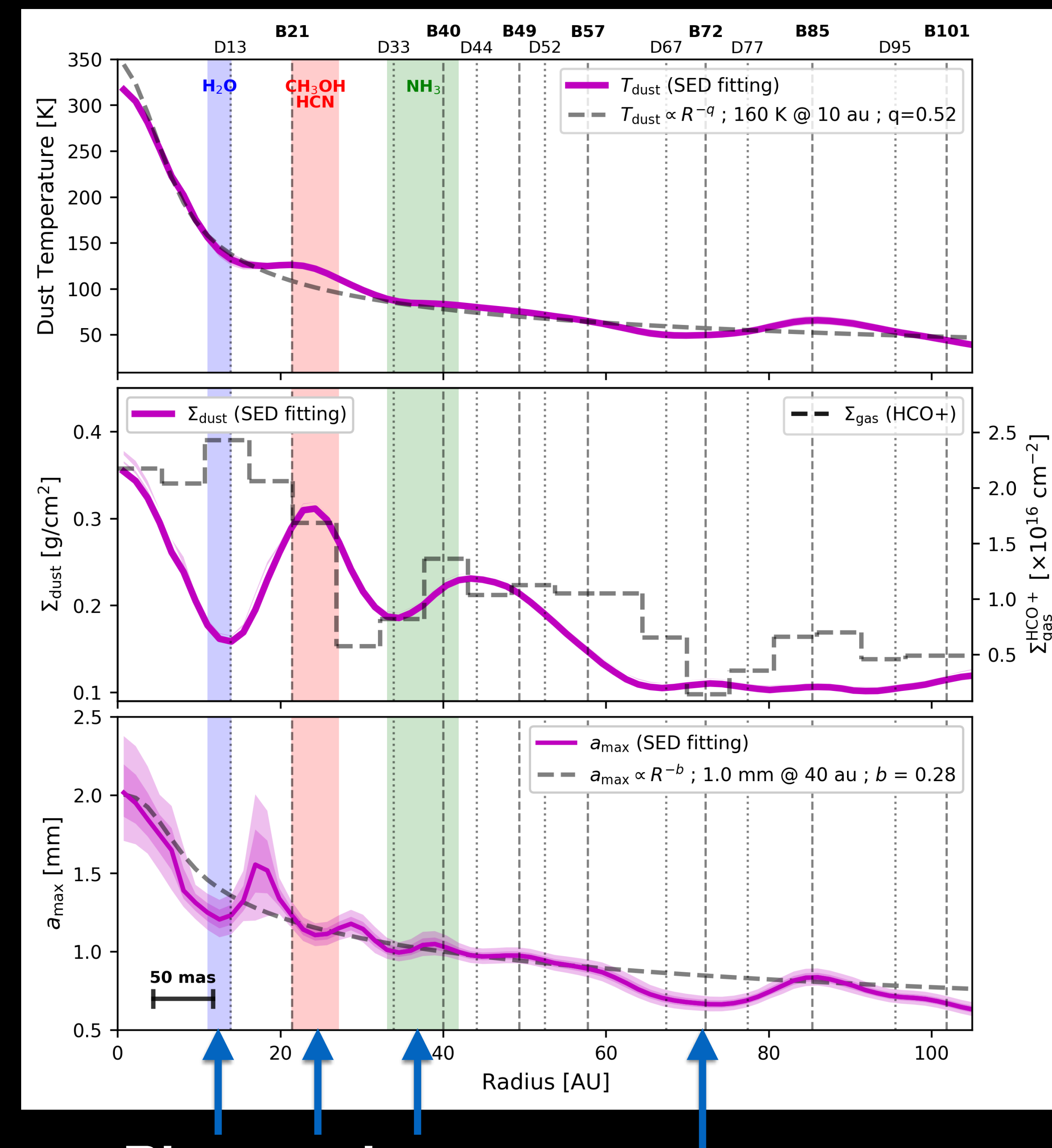
ALMA@2.1 mm

VLA@8.0 mm

Carrasco-González+(2019)

The radial distribution of dust particle properties





High quality multi-wavelength Observations

Rings and gaps At ice lines

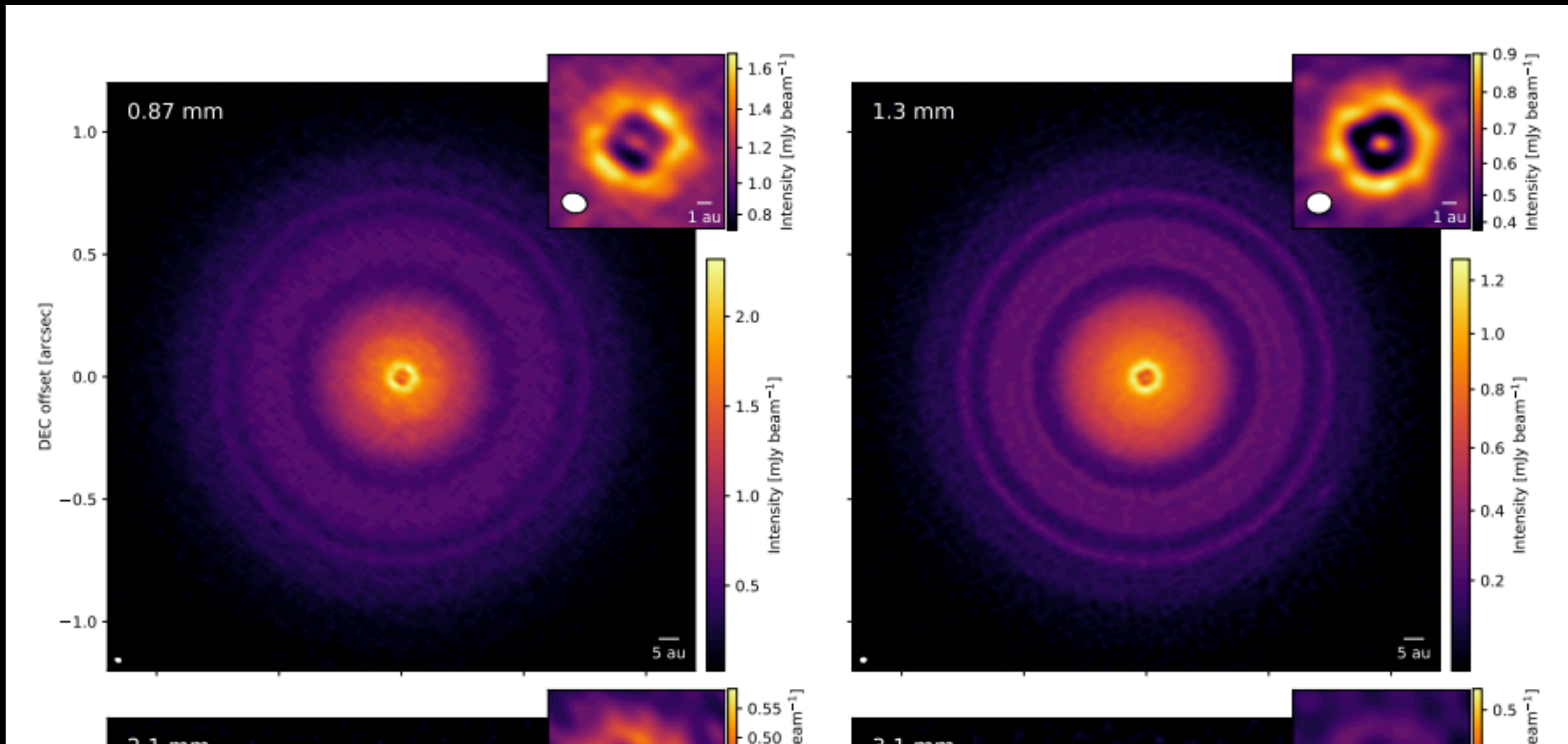
Planet carving @ 70 au

Mass is 3 times higher than previous modeling

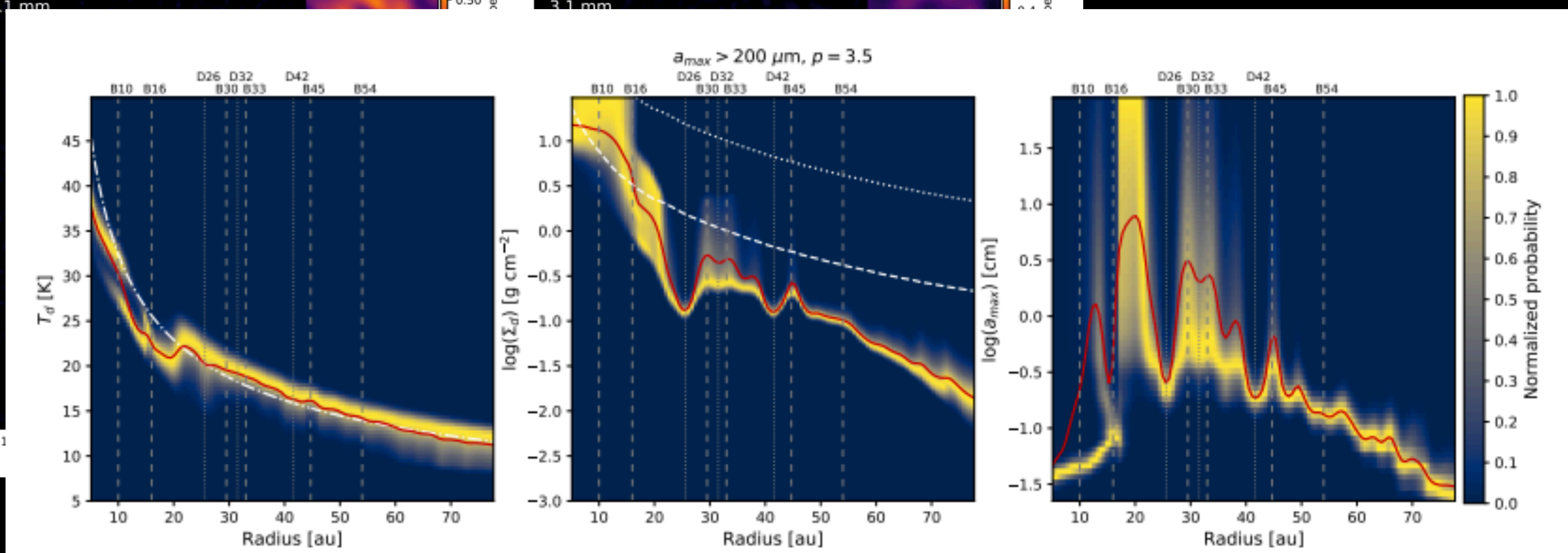
Carrasco-González+2019

TW Hya

ALMA images



Particles > 1 cm



Macías et al. (2021)

<u>MODELING OF HIGH QUALITY MILLIMETER IMAGES</u>

(Including the effect of scattering)

Particles have grown up to mm/cm sizes after some Myrs

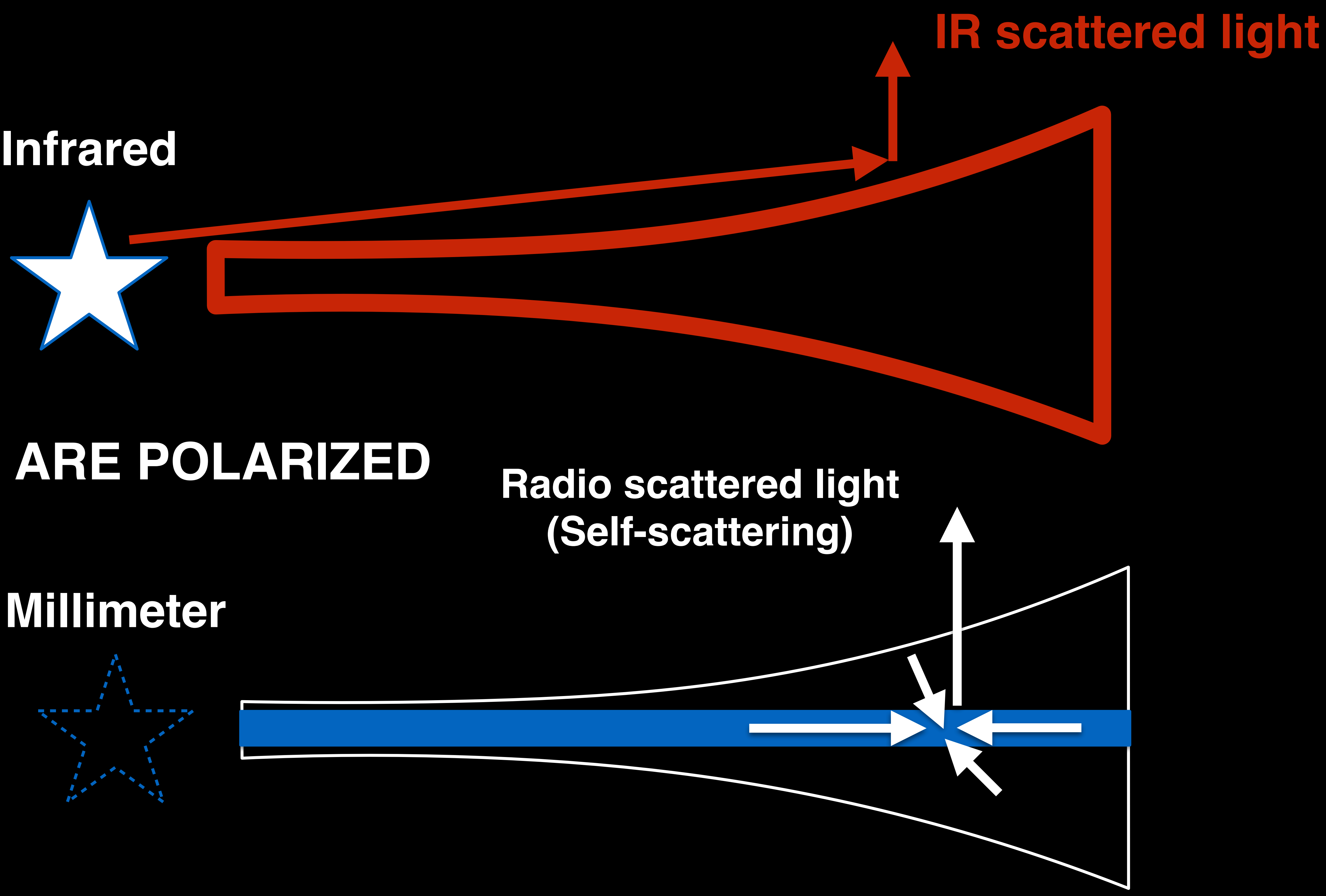
mm/cm are pebbles —> necessary to form planetesimals by accretion (e.g. streaming instability)

But, planetesimal formation would start after several Myrs

SCATTERING IS IMPORTANT

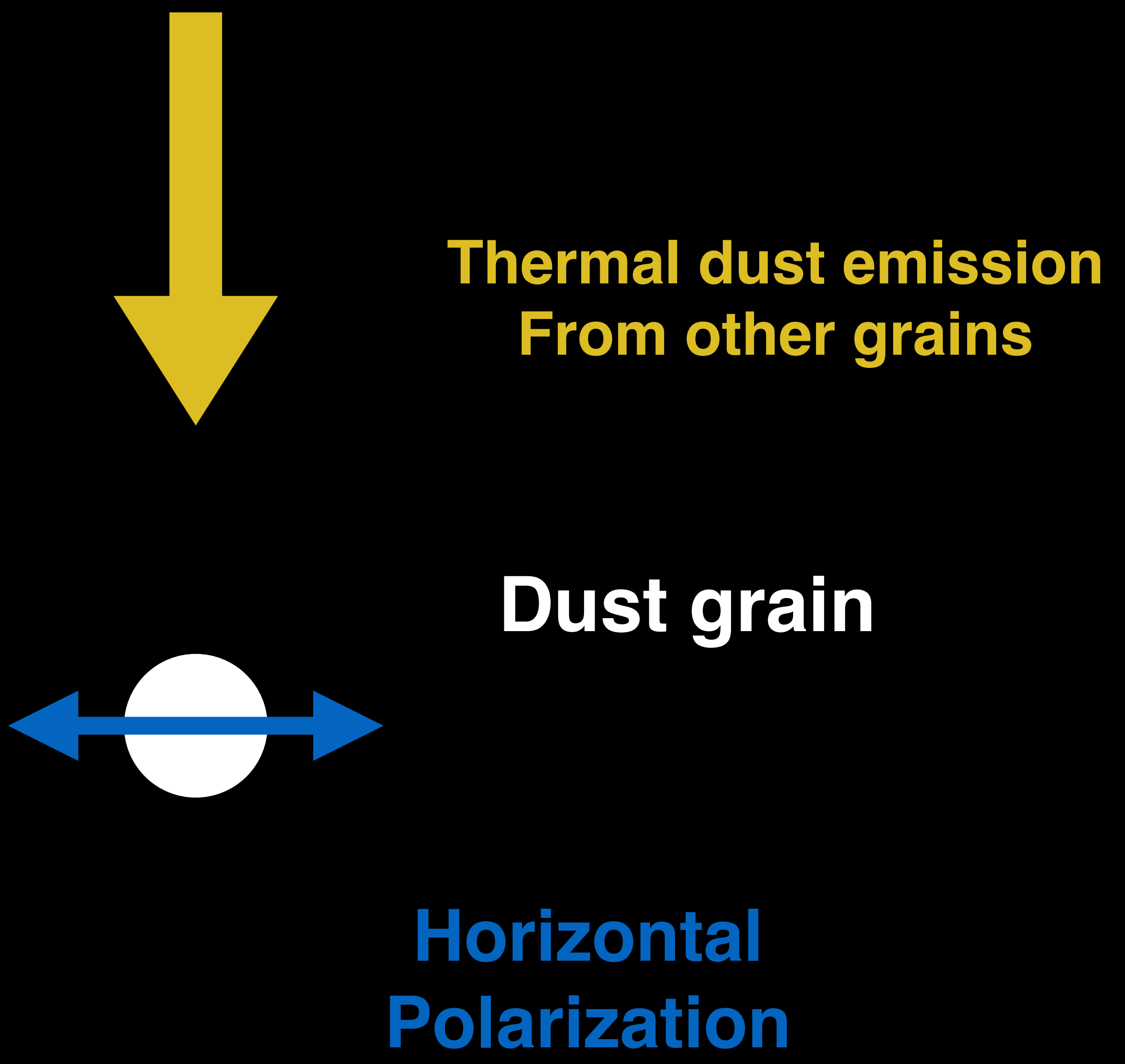
POLARIZATION FROM
DUST SELF-SCATTERING

Light source of scattering



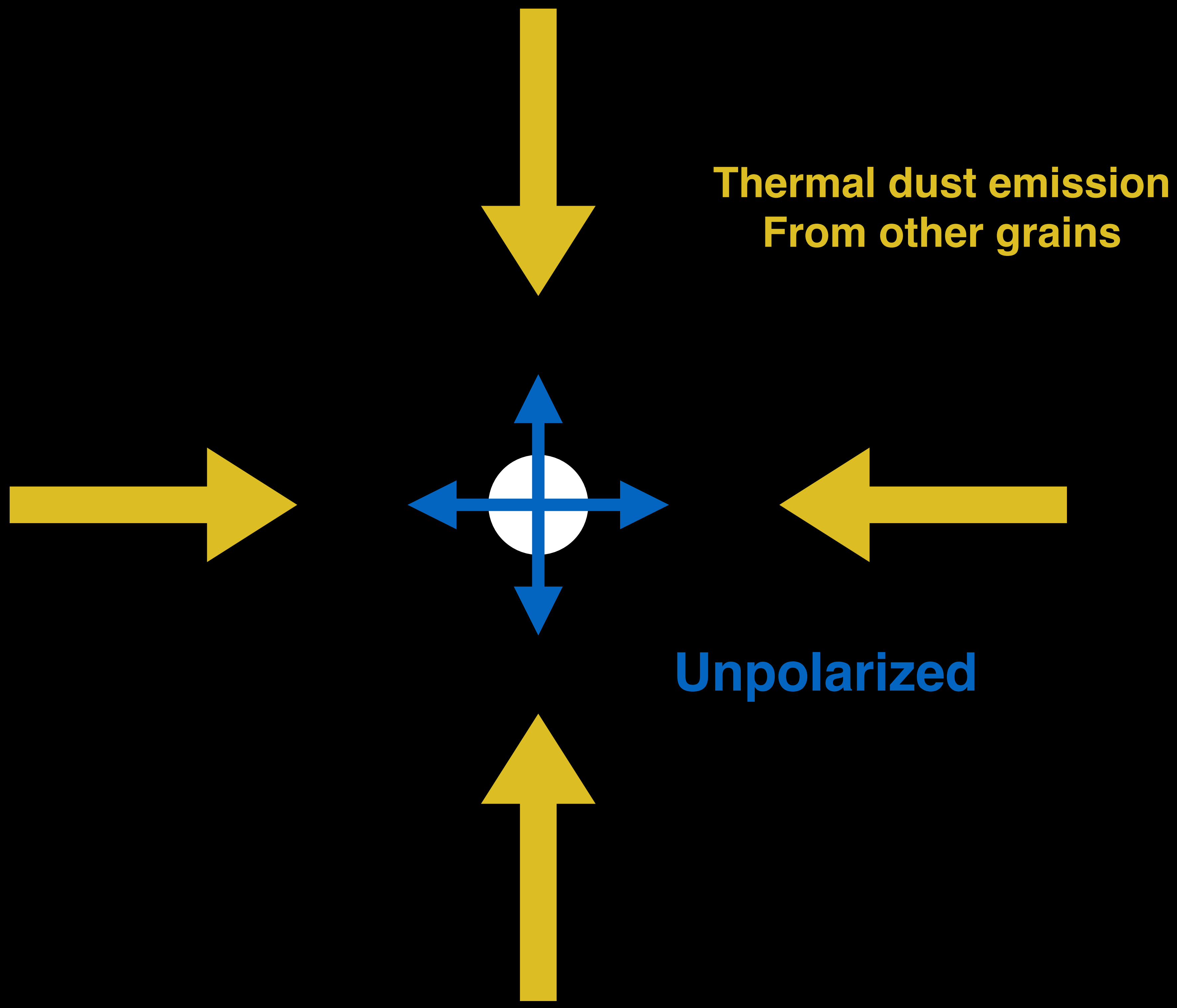
BOTH ARE POLARIZED

Polarization due to dust self-scattering



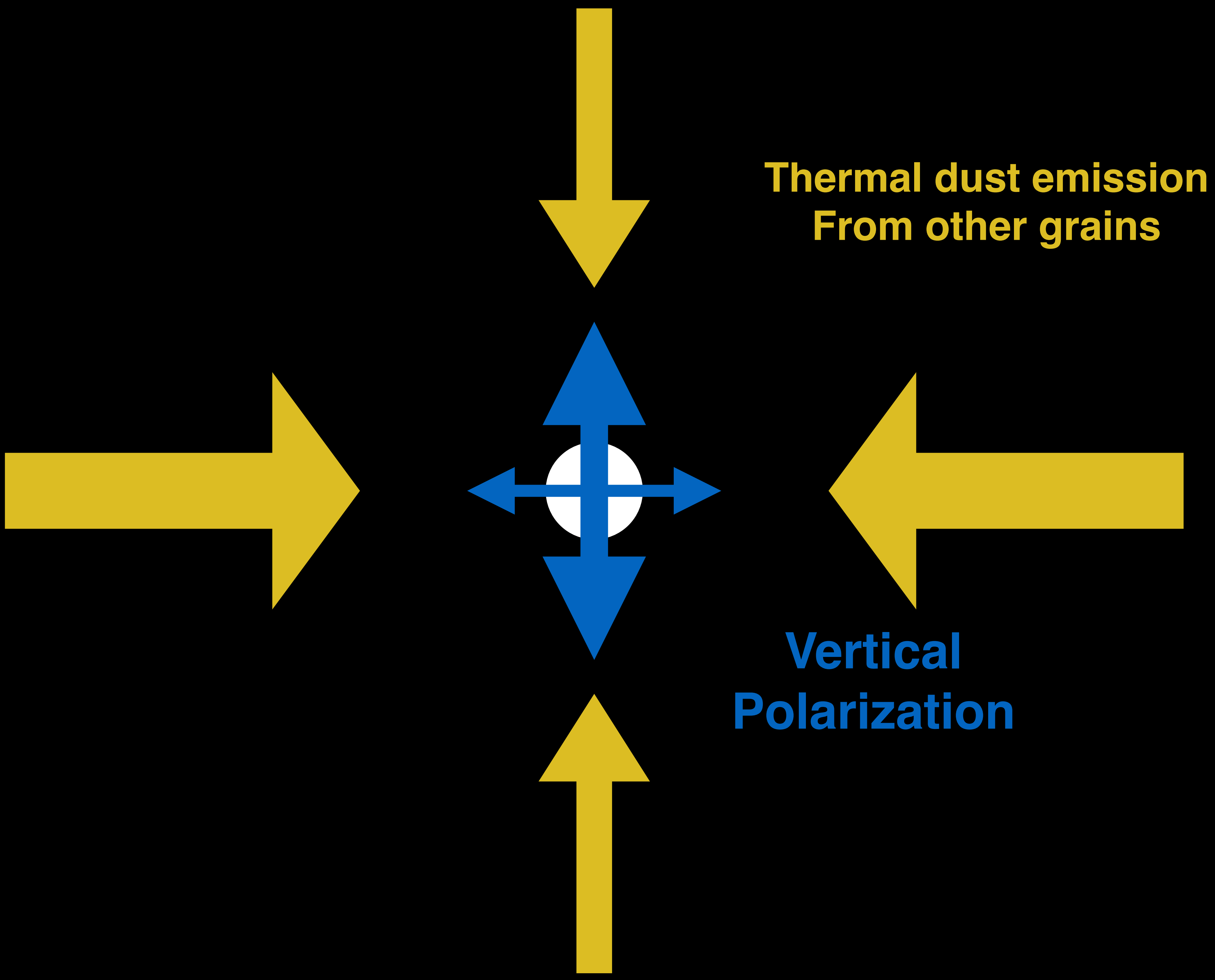
You are the observer

Polarization due to dust self-scattering



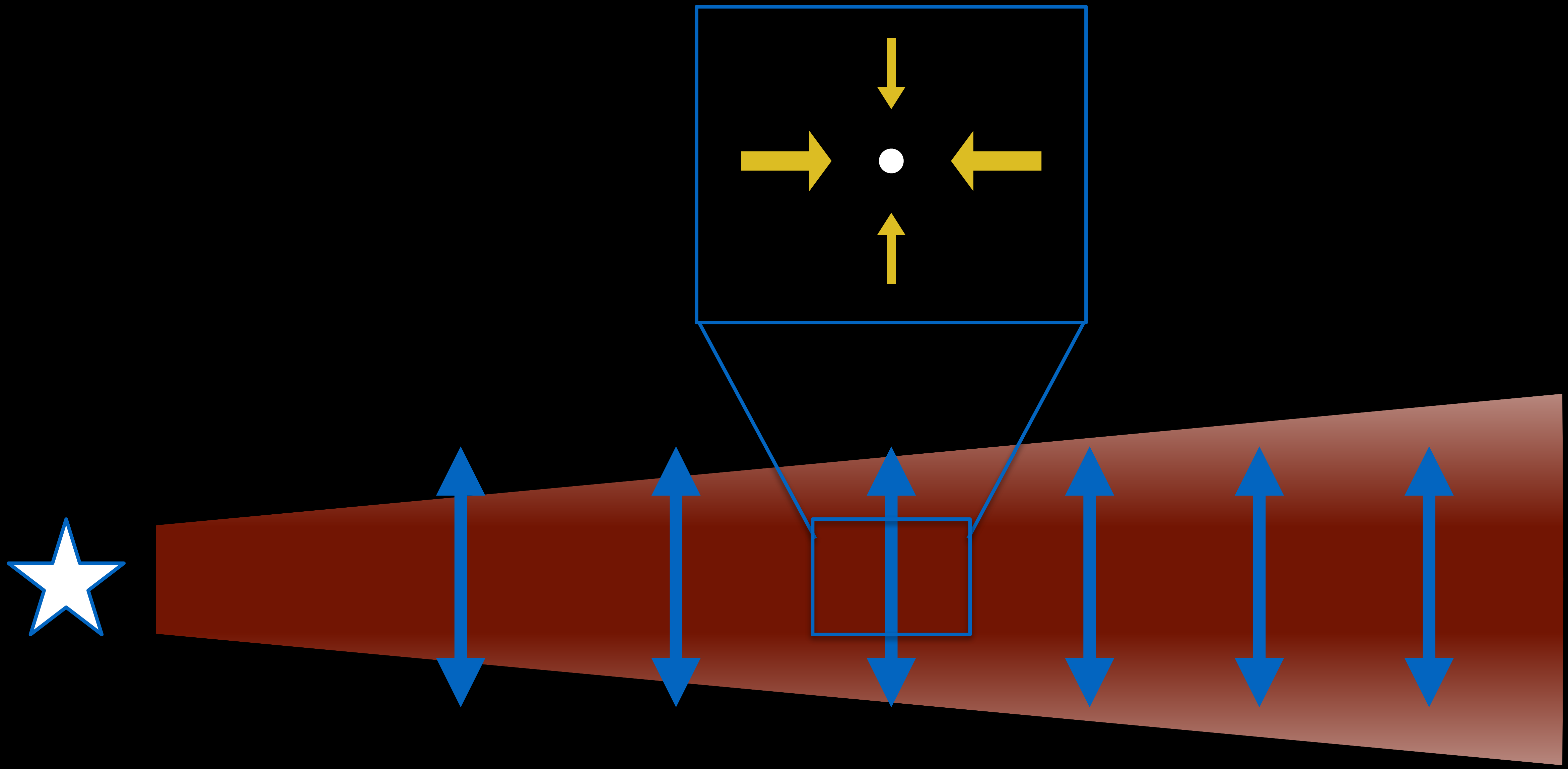
You are the observer

Polarization due to dust self-scattering



You are the observer

Polarization due to dust self-scattering



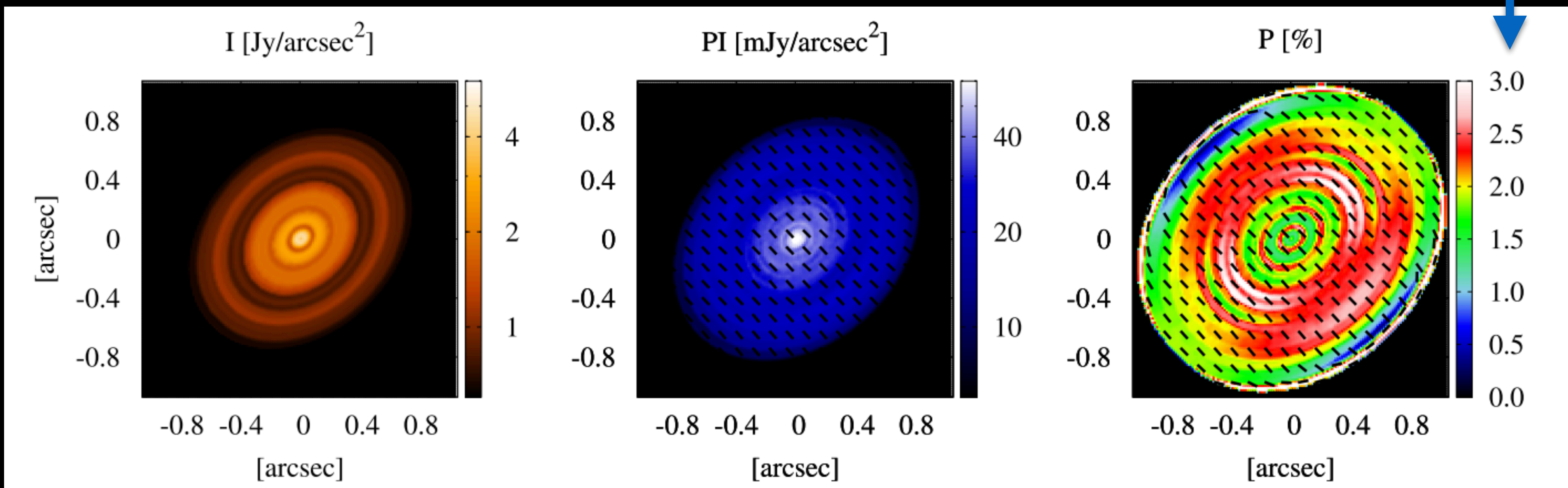
Edge-on disk

You are the observer

Polarization due to dust self-scattering

Predictions for an inclined disk

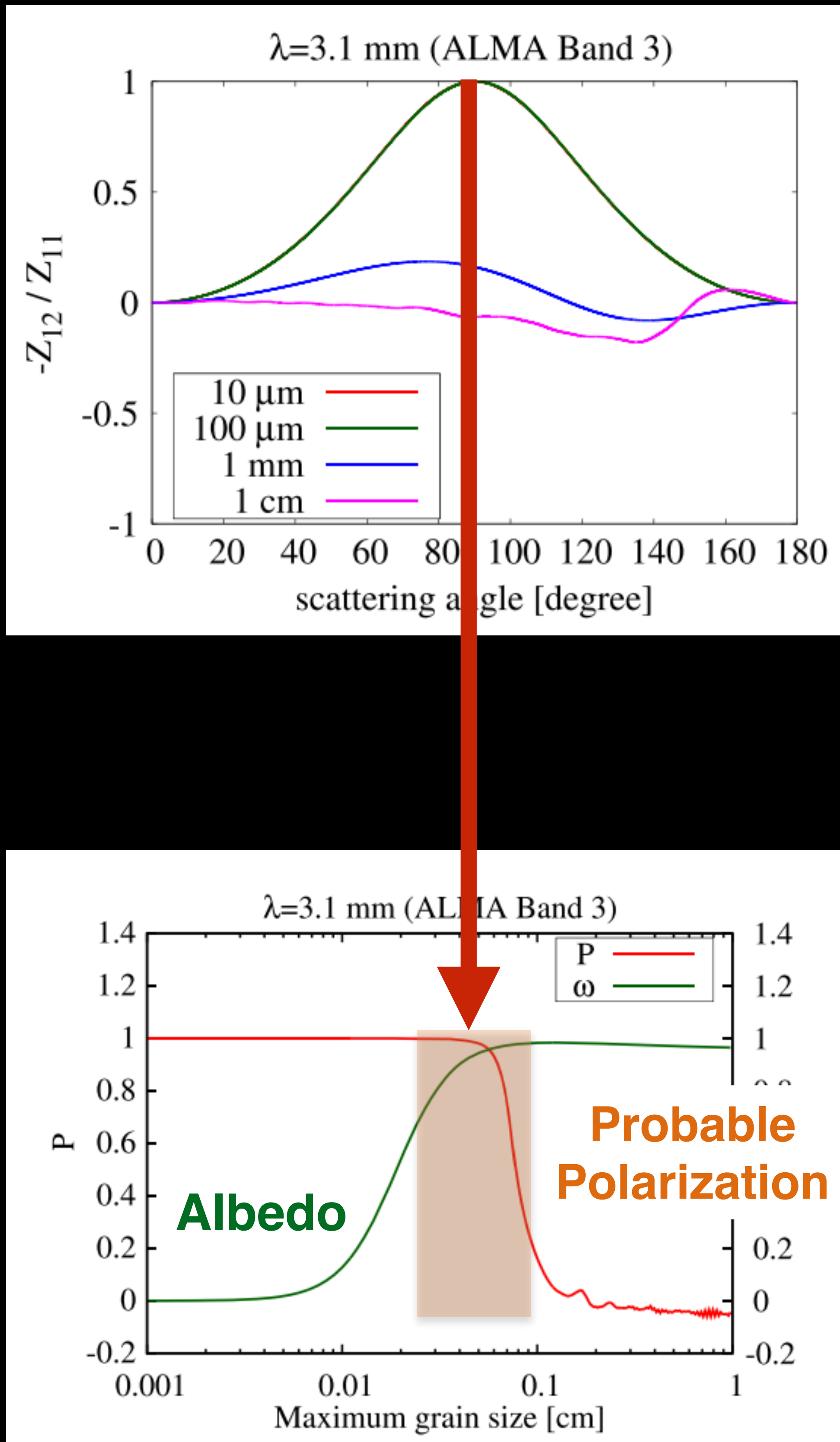
Very low polarization degree !!



POLARIZATION VECTORS PARALLEL TO THE MINOR AXIS

Kataoka et al. 2016

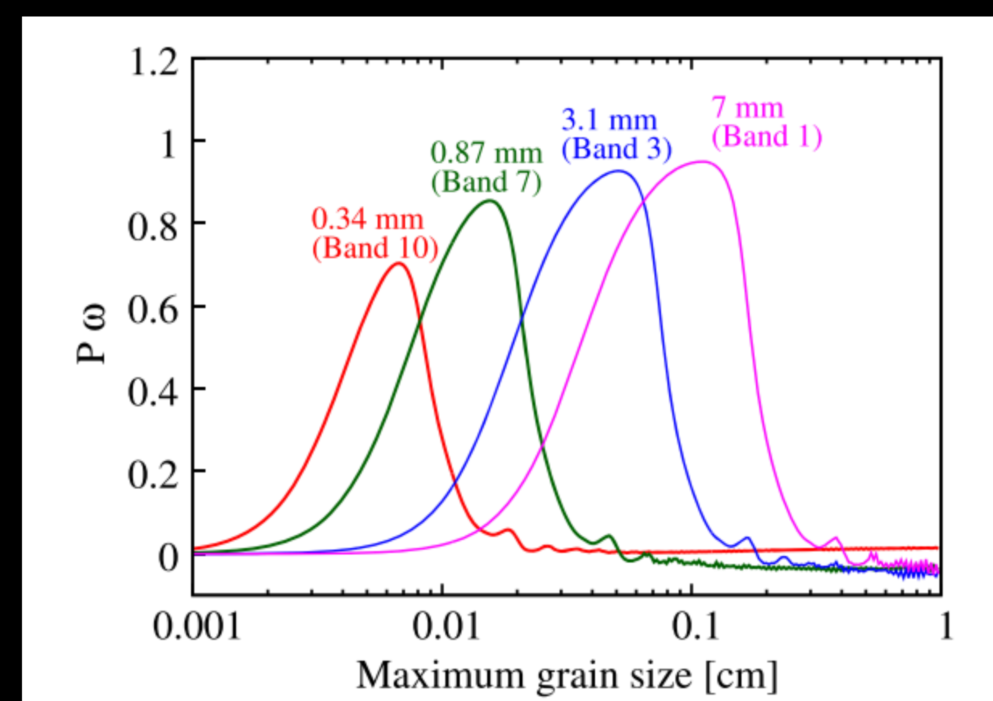
Polarization due to dust self-scattering



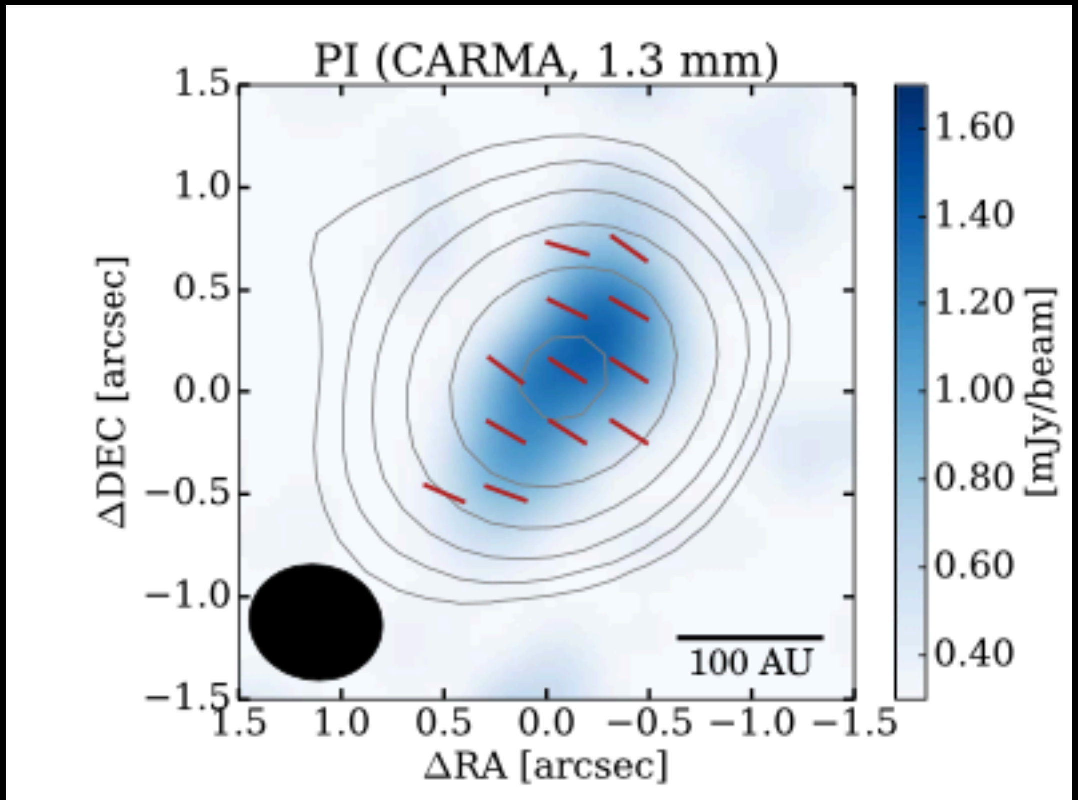
For a given amax,
maximum polarization
Is expected at

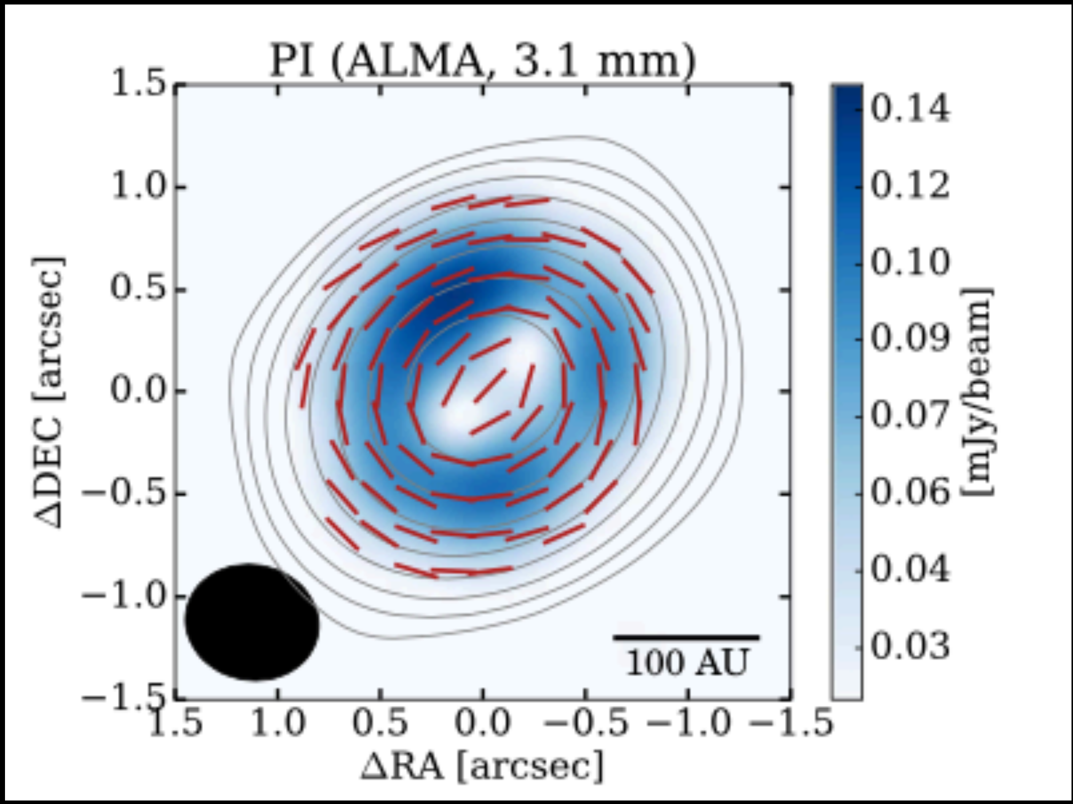
$$\lambda_{Max\ Pol} \simeq 2\ \pi\ a_{max}$$

Relatively narrow
wavelength range



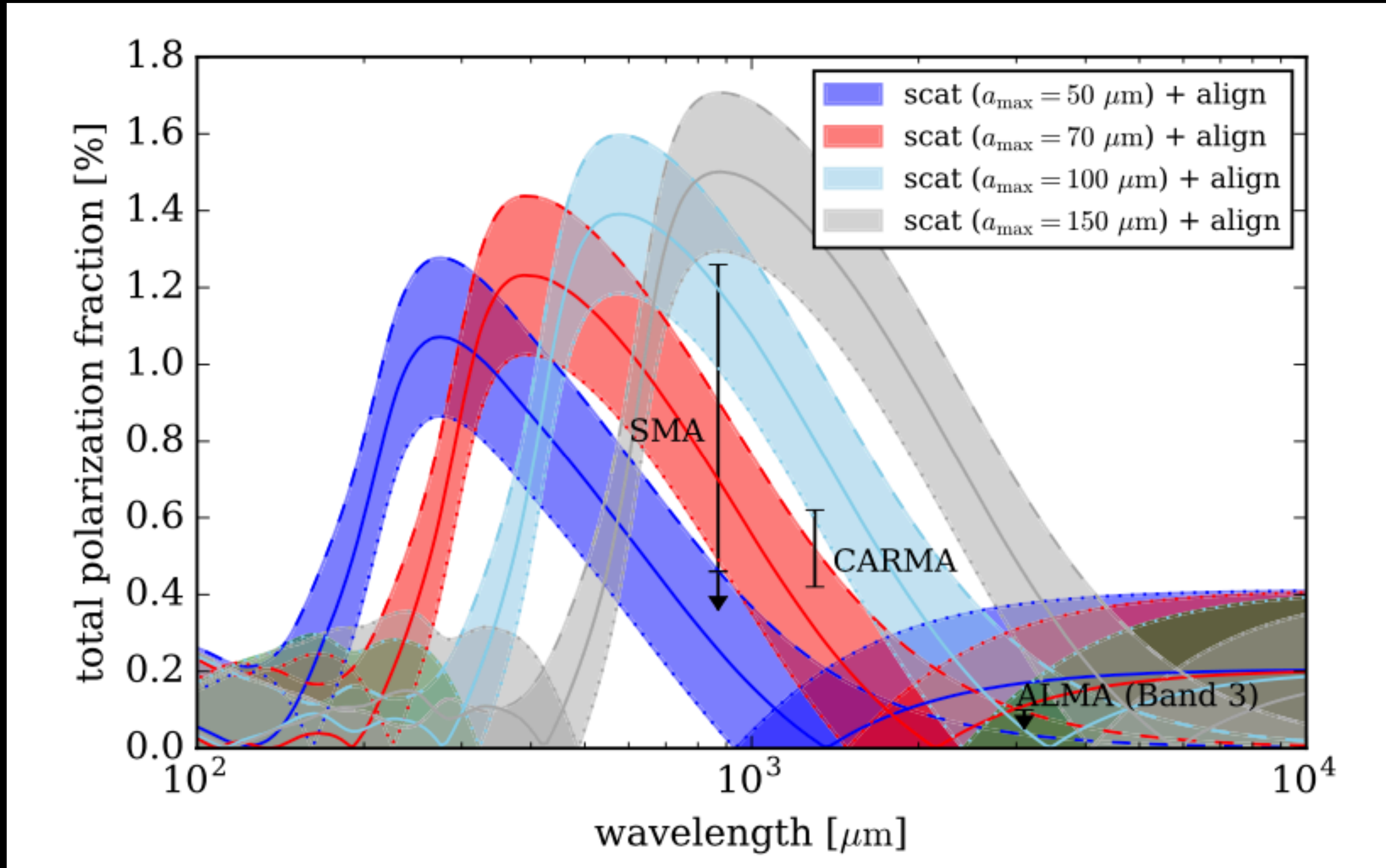
Polarization Observations of HL Tau



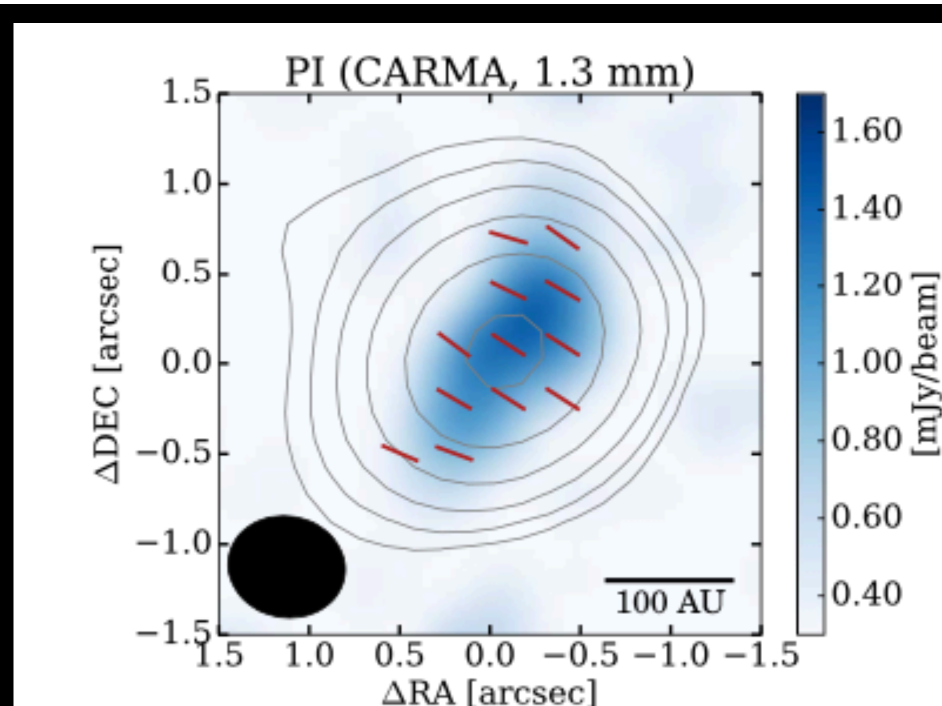


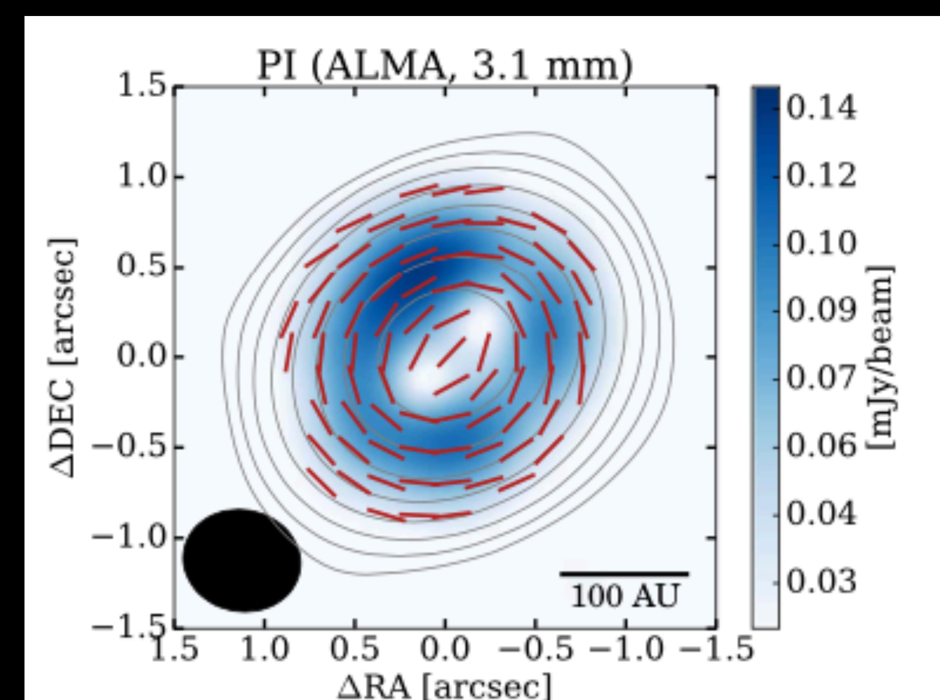
POLARIZATION IS DOMINATED BY DUST SELF-SCATTERING

POLARIZATION IS DOMINATED BY DUST THERMAL EMISSION BY ELONGATED (INTRINSICALLY POLARIZED) AND ALIGNED PARTICLES



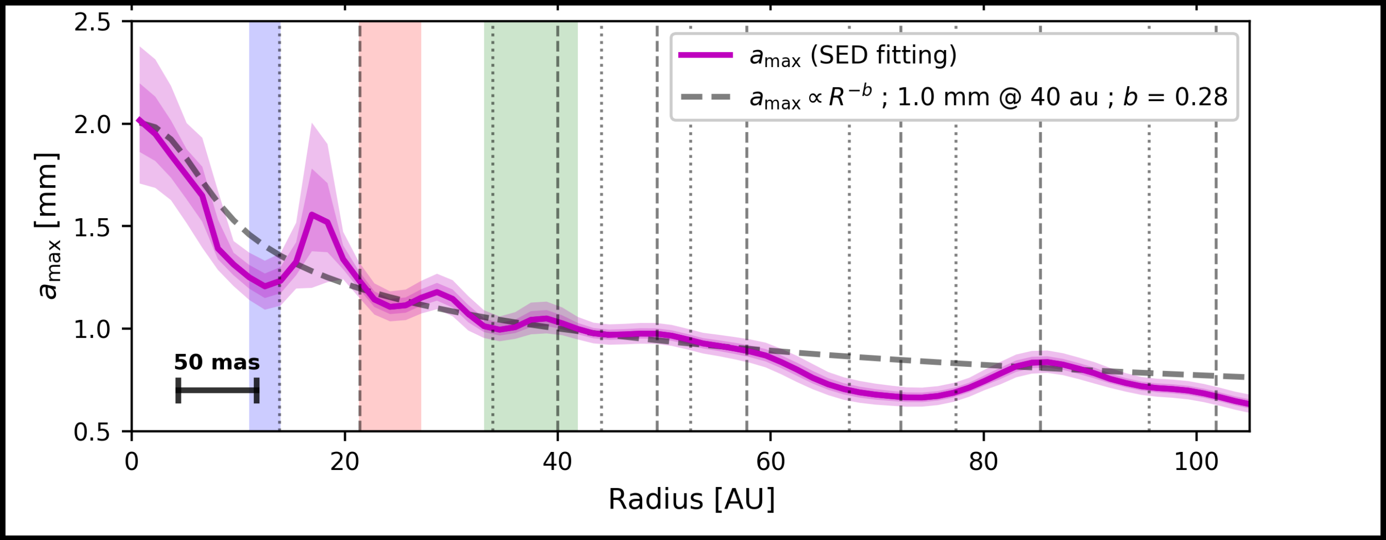
a_{max} = 100 um





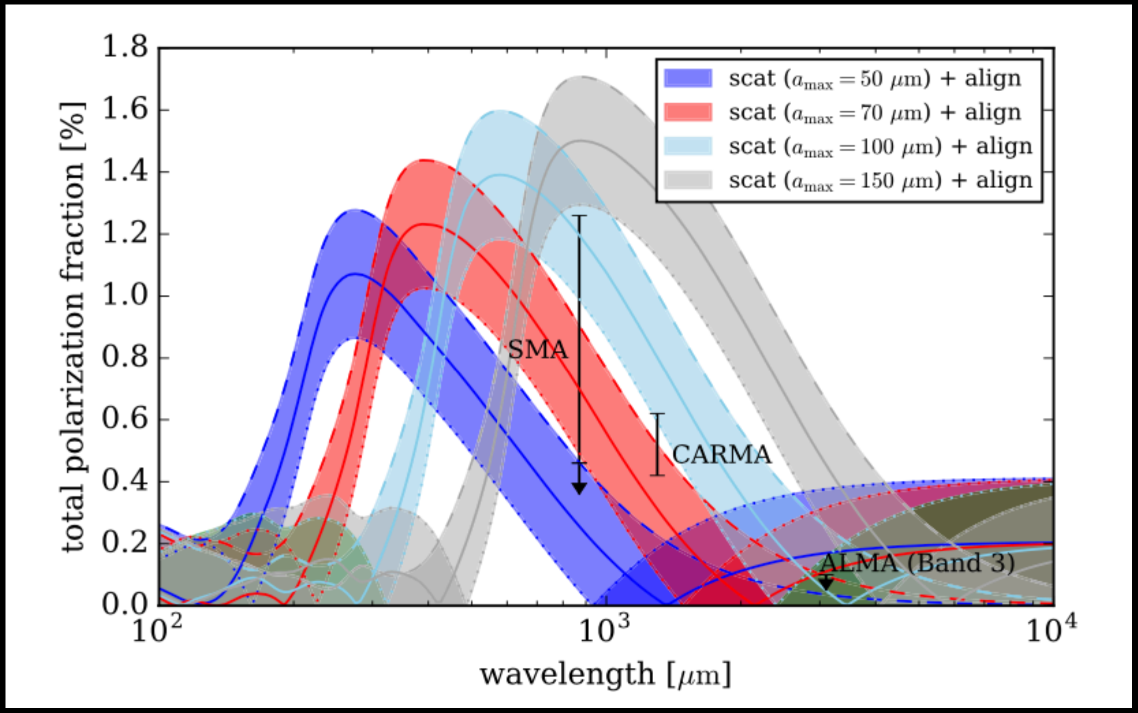
SELF-SCATTERING

NO SCATTERIING



Analysis of the SED -> A few millimeters (Carrasco-González et al. 2019)

Planetesimal formation can start



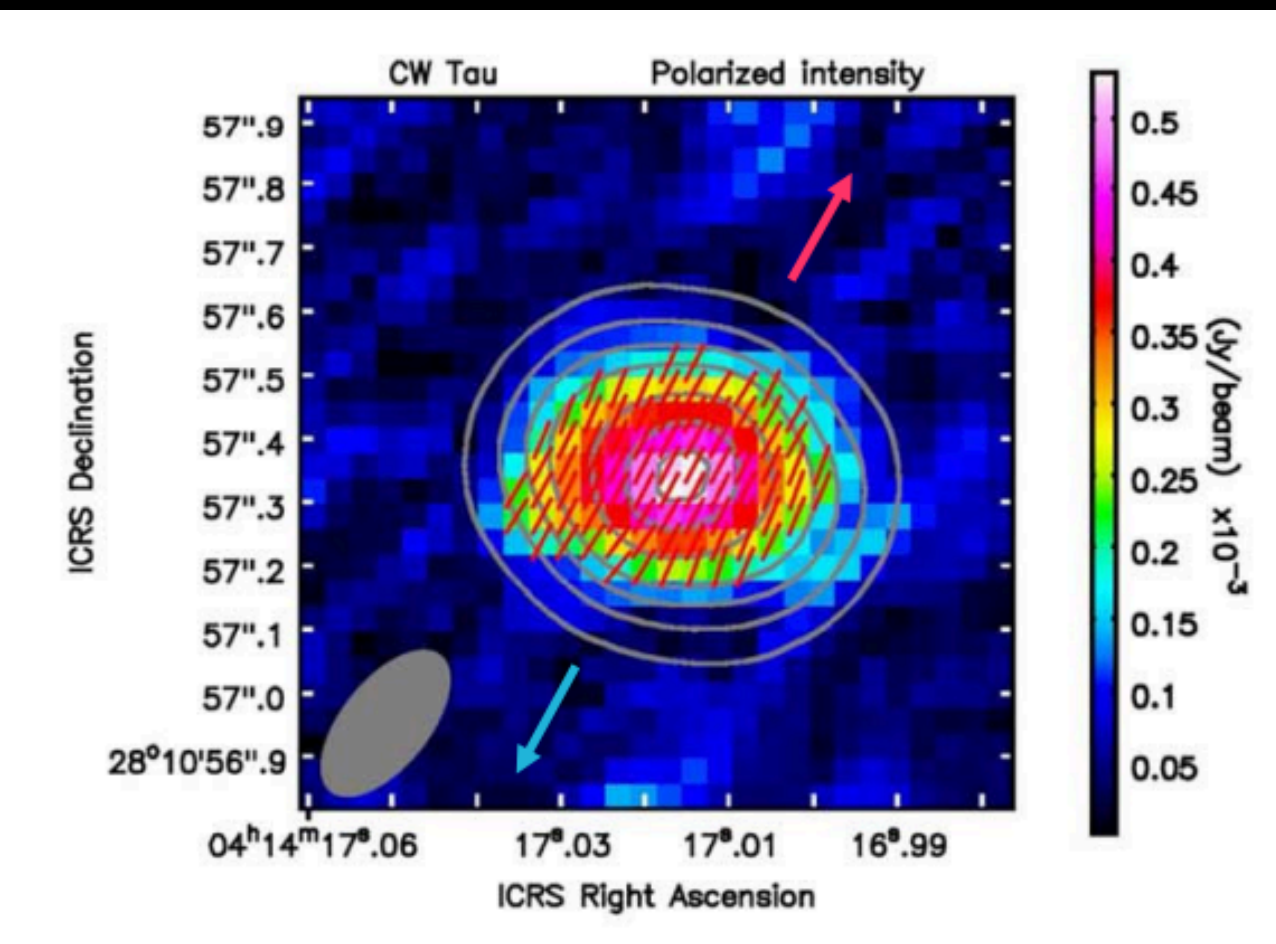
Polarization -> 100 microns (Kataoka et al. 2017)

Dust should still grow a factor of 10

BOTH ARE CORRECT FORMALISMS
SAME DISK
DIFFERENT RESULTS

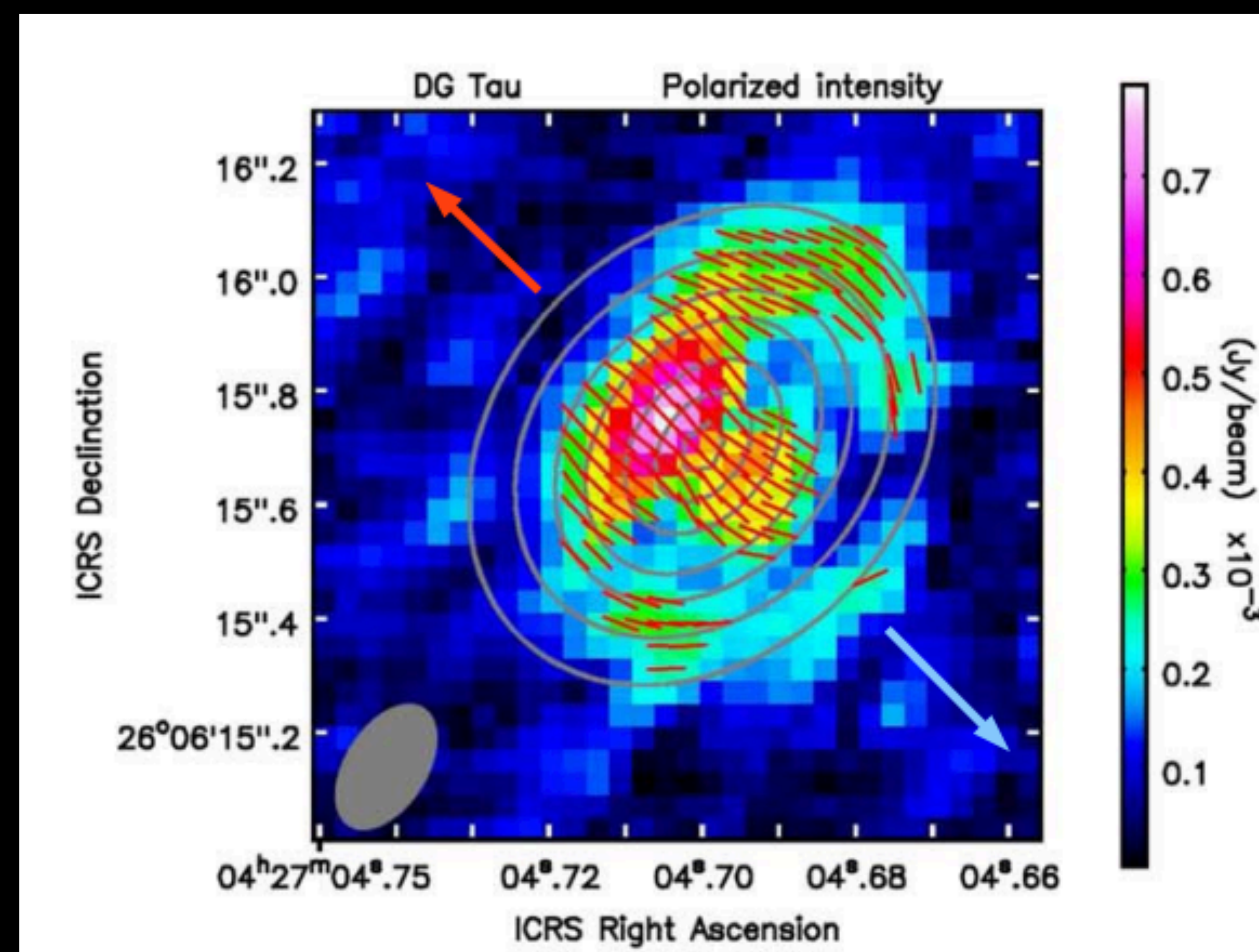
Polarization in other disks, similar results

At this rate of dust growth, we will never form planets



Amax = 100-150 microns

Amax = 50-70 microns



Bacciotti et al. 2018

DISCREPANCY BETWEEN CONTINUUM AND POLARIZED EMISSION

POSSIBLE SOLUTIONS

Resolution

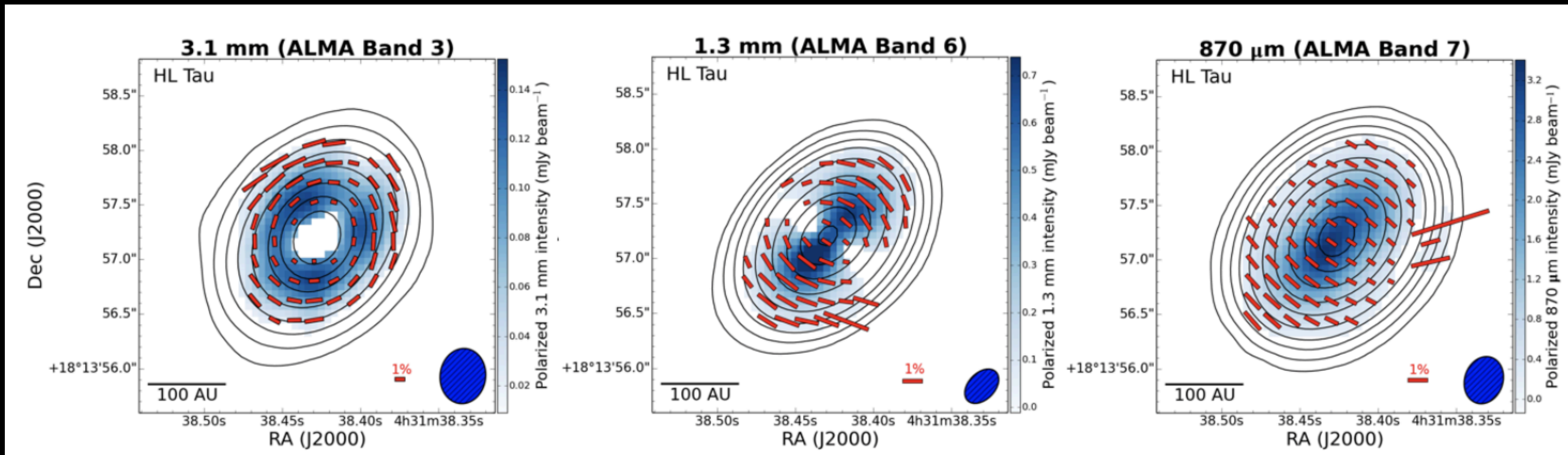
We are looking at different parts of the disk

Non-spherical particles

Porosity

RESOLUTION

Stephens et al. 2017

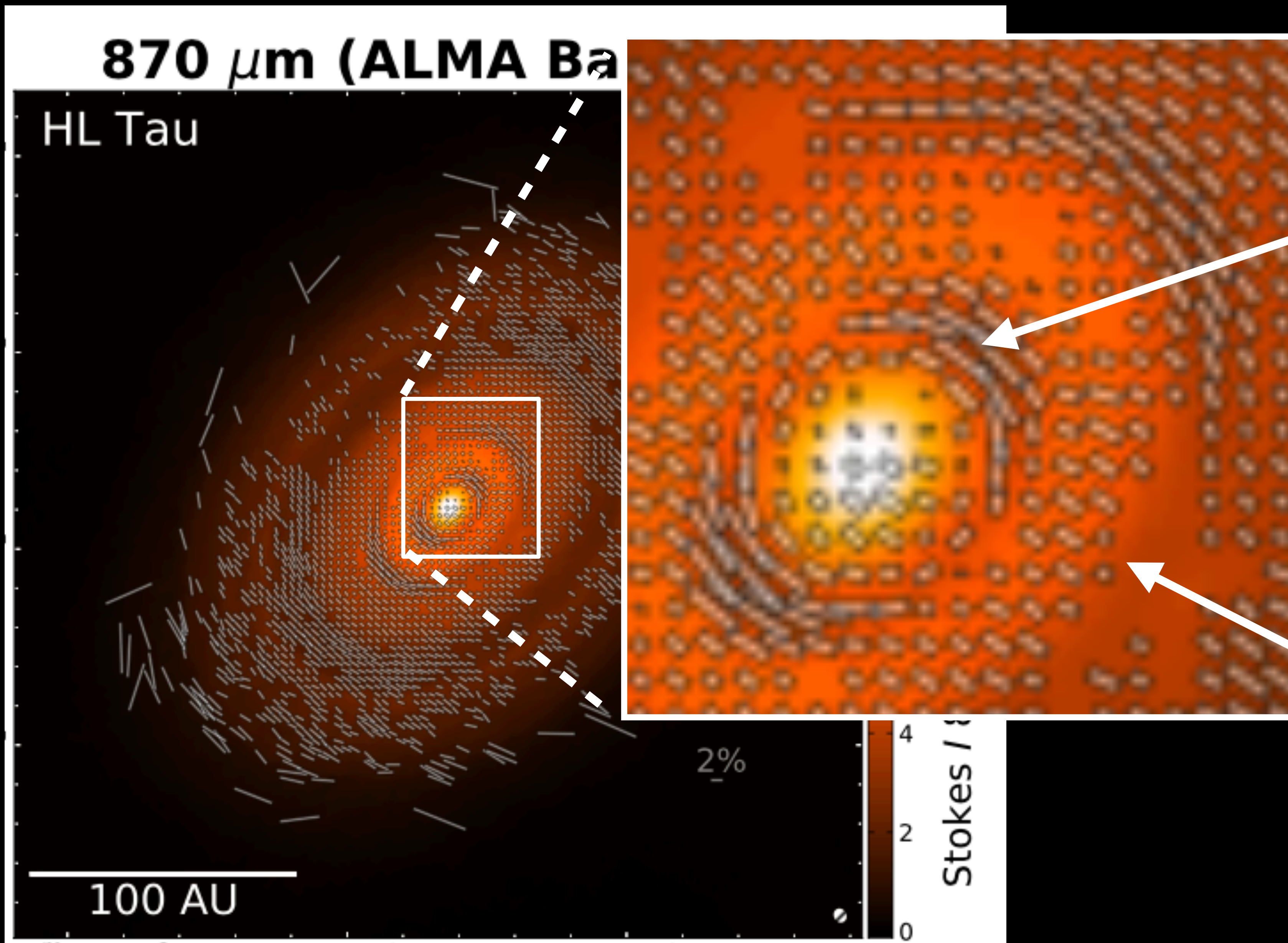


Optical Depth →

But, we know that HL Tau has substructures

Is this an effect of poor resolution?

RESOLUTION



GAPS

Circular pol. pattern
Higher Pol. Deg
Thermal emission from aligned grains

RINGS

Self-scattering
Lower pol. deg

The effect of poor resolution is to emphasize polarization from rings

But still, small particles in the rings

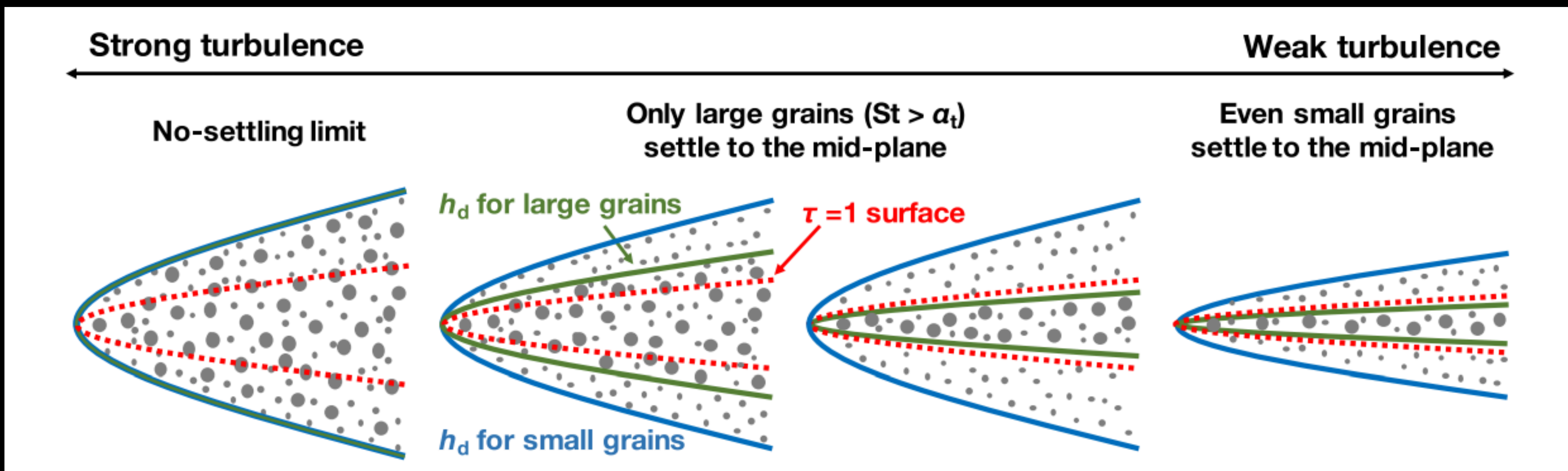
Stephens et al. 2023
(including Kataoka and Carrasco-González)

WE ARE LOOKING AT DIFFERENT PARTS IN THE DISK

The Astrophysical Journal, 913:117 (10pp), 2021 June 1
https://doi.org/10.3847/1538-4357/abf7b8

Impact of Differential Dust Settling on the SED and Polarization: Application to the Inner Region of the HL Tau Disk

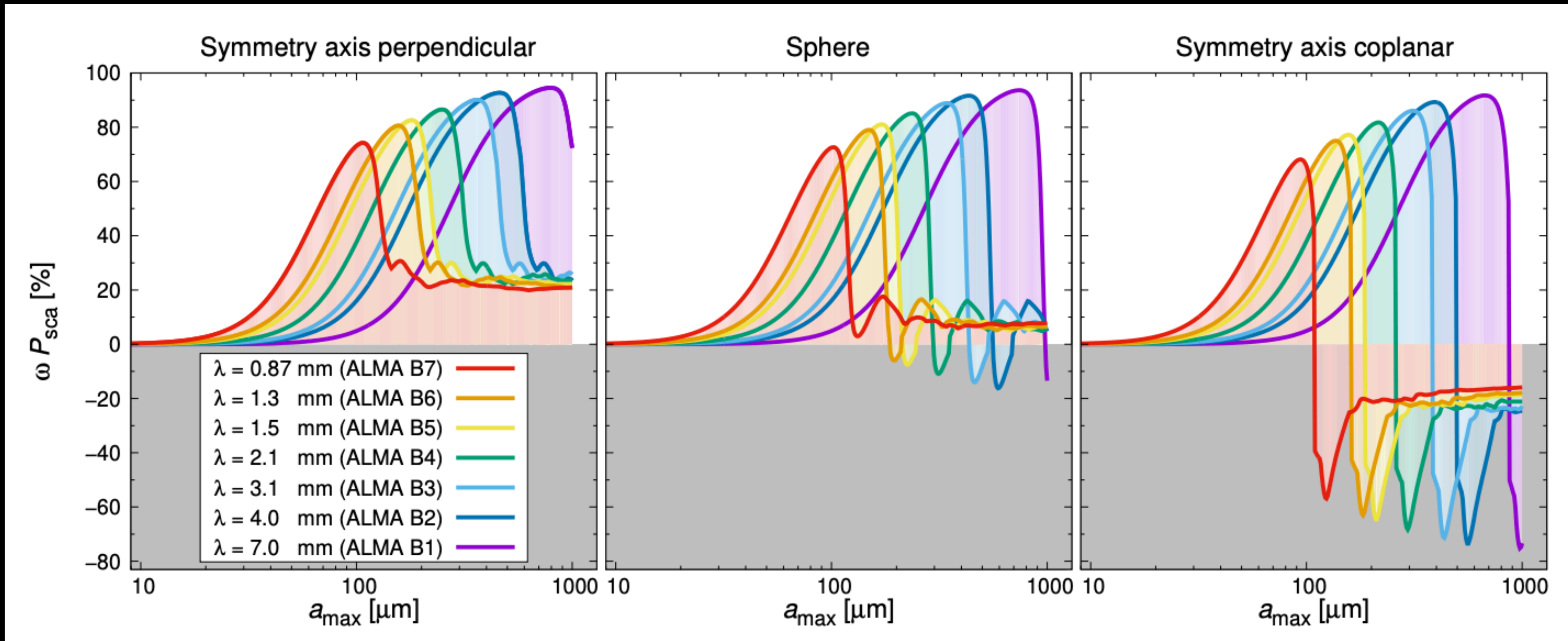
Takahiro Ueda[1], Akimasa Kataoka[1], Shangjia Zhang[2], Zhaohuan Zhu[2], Carlos Carrasco-González[3], and Anibal Sierra[4]



Millimeter-sized dust grains are possible if very weak turbulence
But expected polarization is too low

Ueda et al. 2021
(including Kataoka and Carrasco-González)

NON-SPHERICAL DUST GRAINS



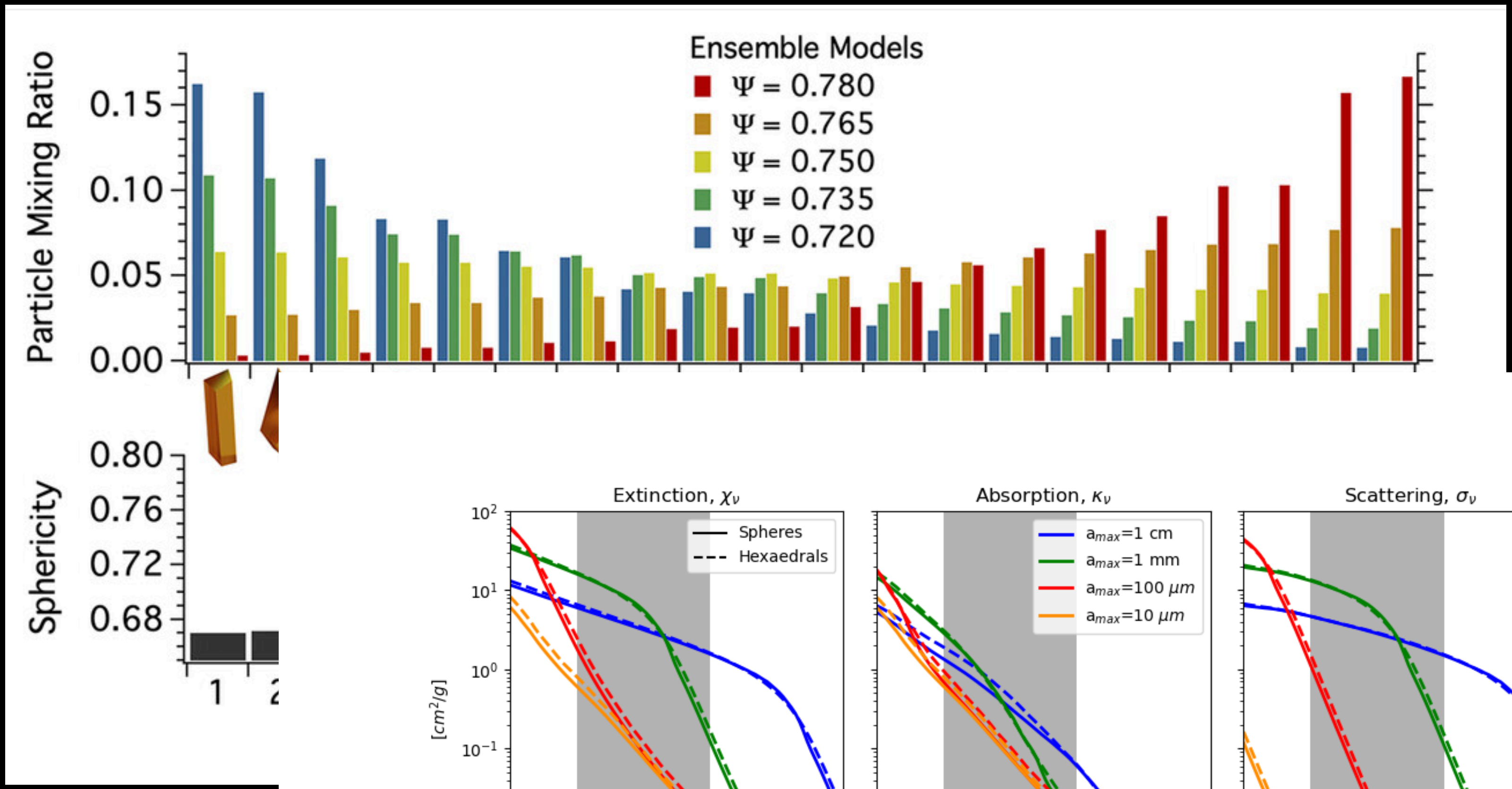
Aligned Spheroids

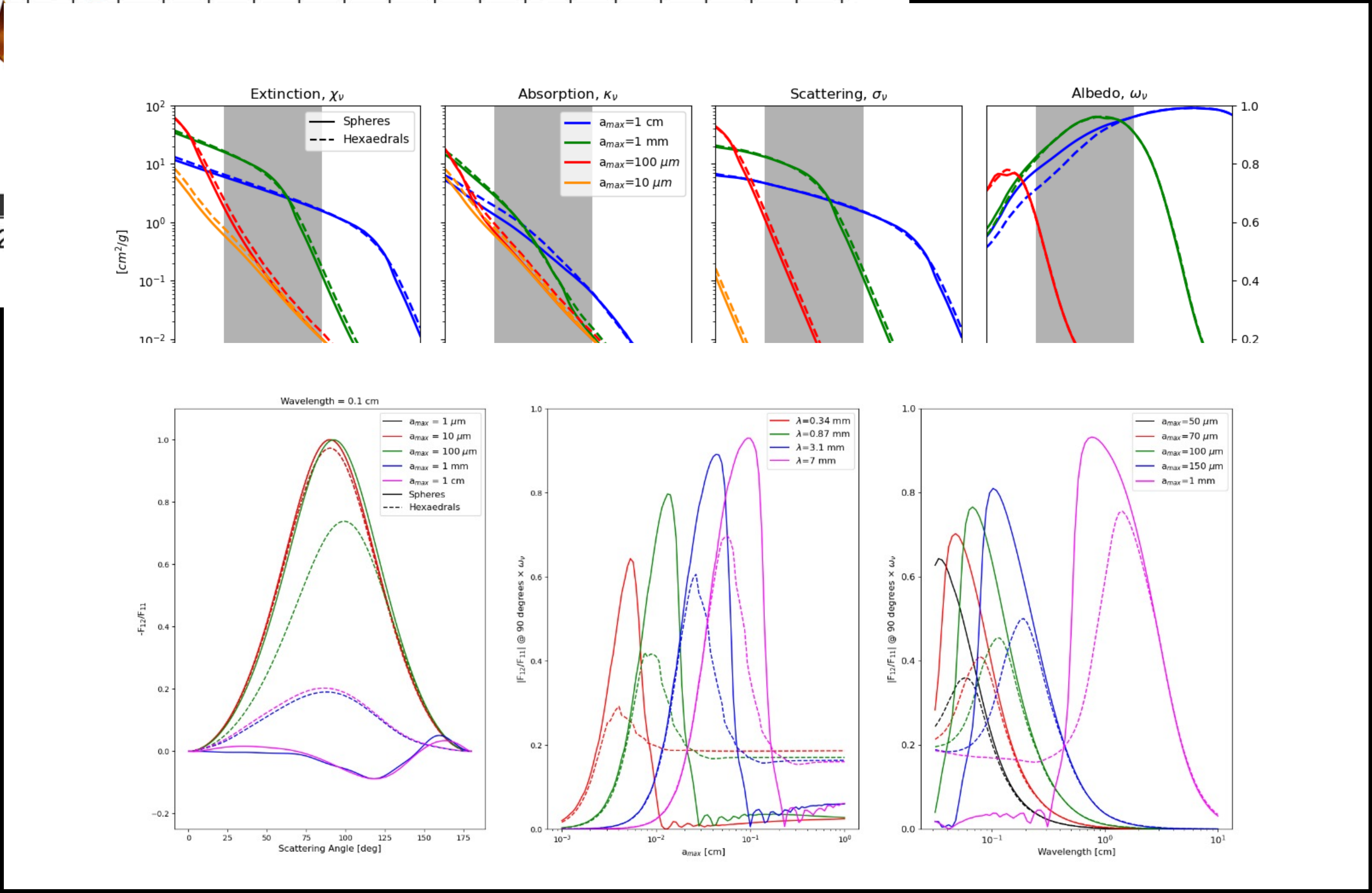
They can produce polarization at very different wavelengths

But too low

Kirschschlager & Bertrang 2020

NON-SPHERICAL DUST GRAINS





Distribution of hexaedrals (Saito et al. 2021)

Carrasco-González & Guirado

DISCREPANCY BETWEEN CONTINUUM AND POLARIZED EMISSION

POSSIBLE SOLUTIONS

~~Resolution~~

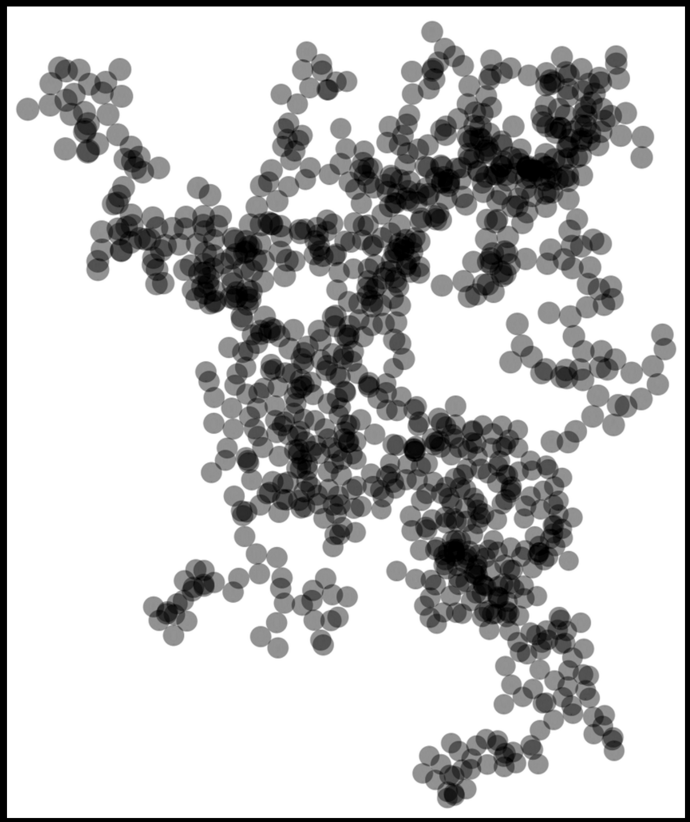
~~We are looking at different parts of the disk~~

~~Non-spherical particles~~

Porosity

POROSITY

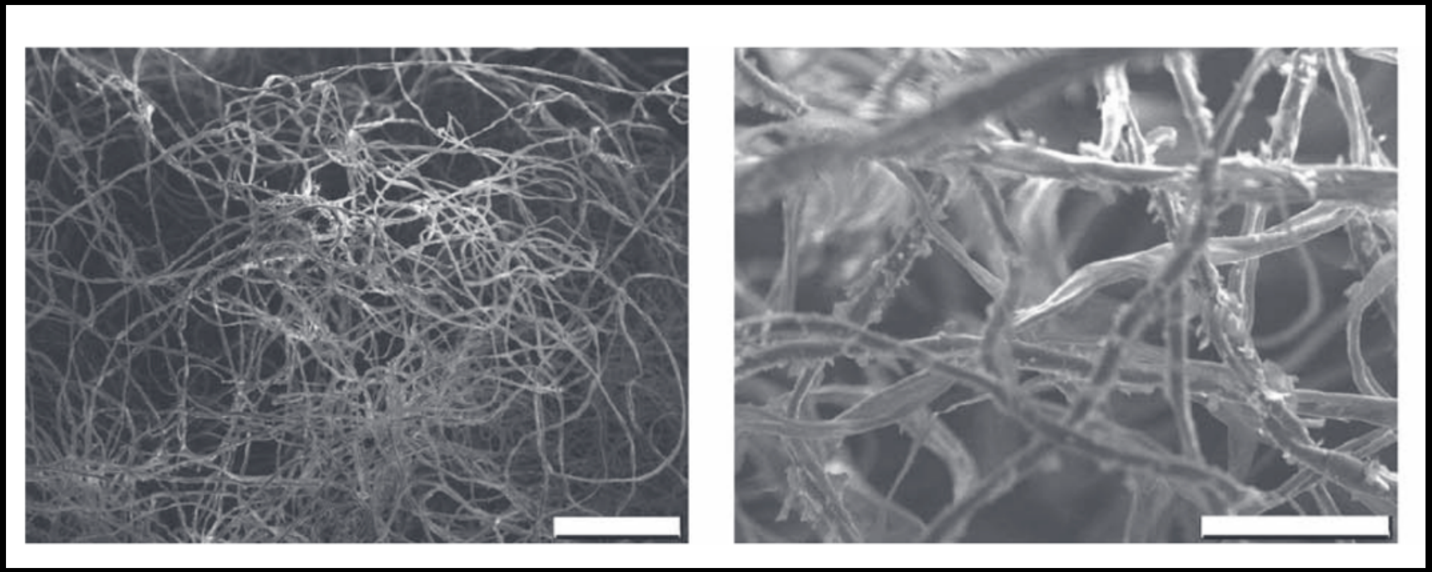
Grain growth models predict something like this (fractal)



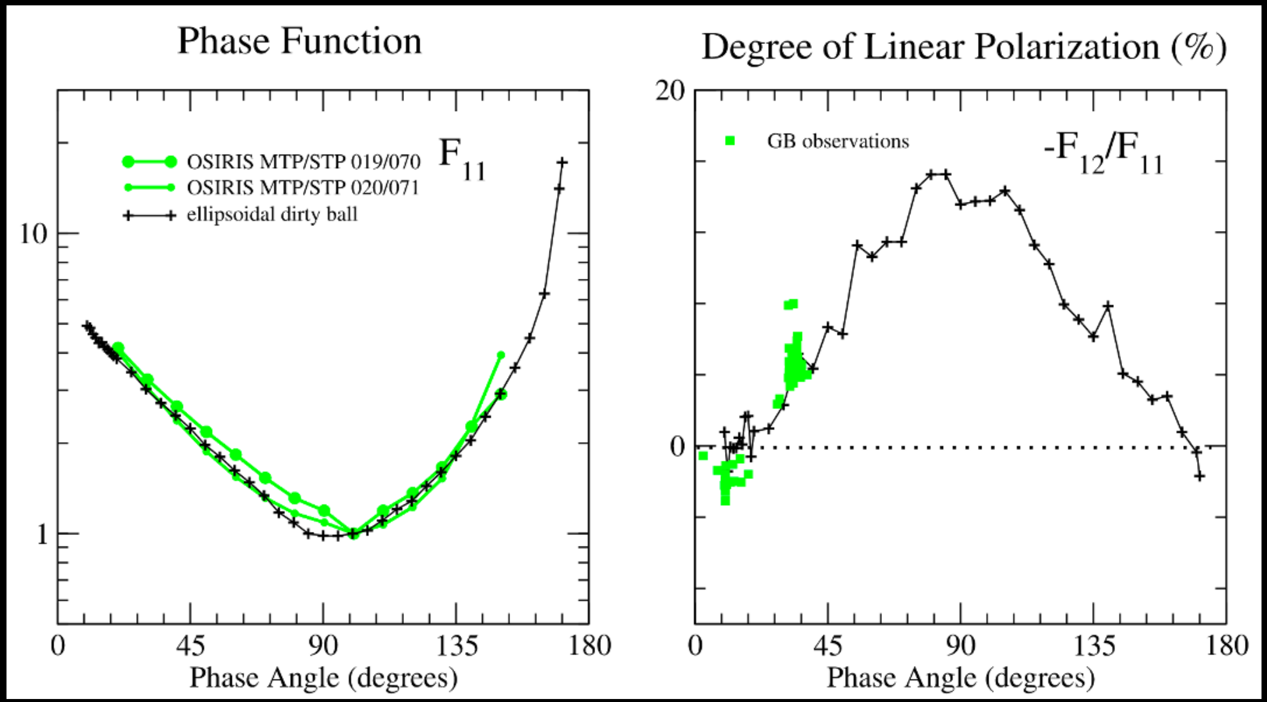
Highly porous —> 0.99+

e.g. Simon et al. 2022, Estrada et al. 2022

In comets, we have "seen" something like this

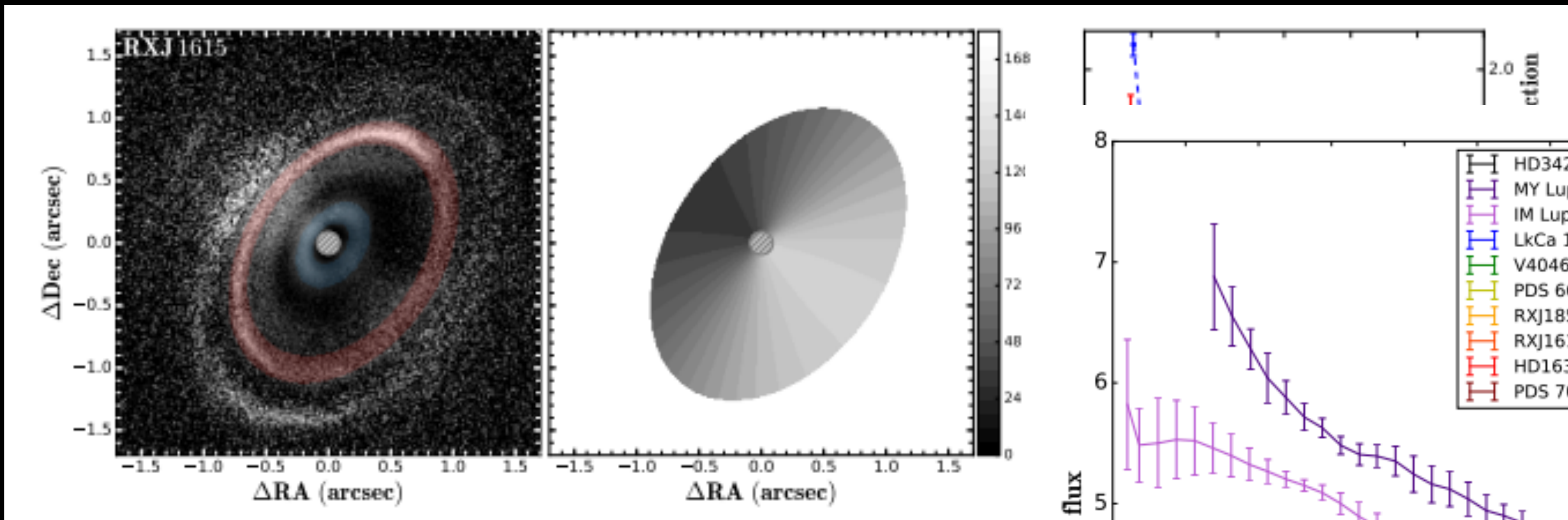


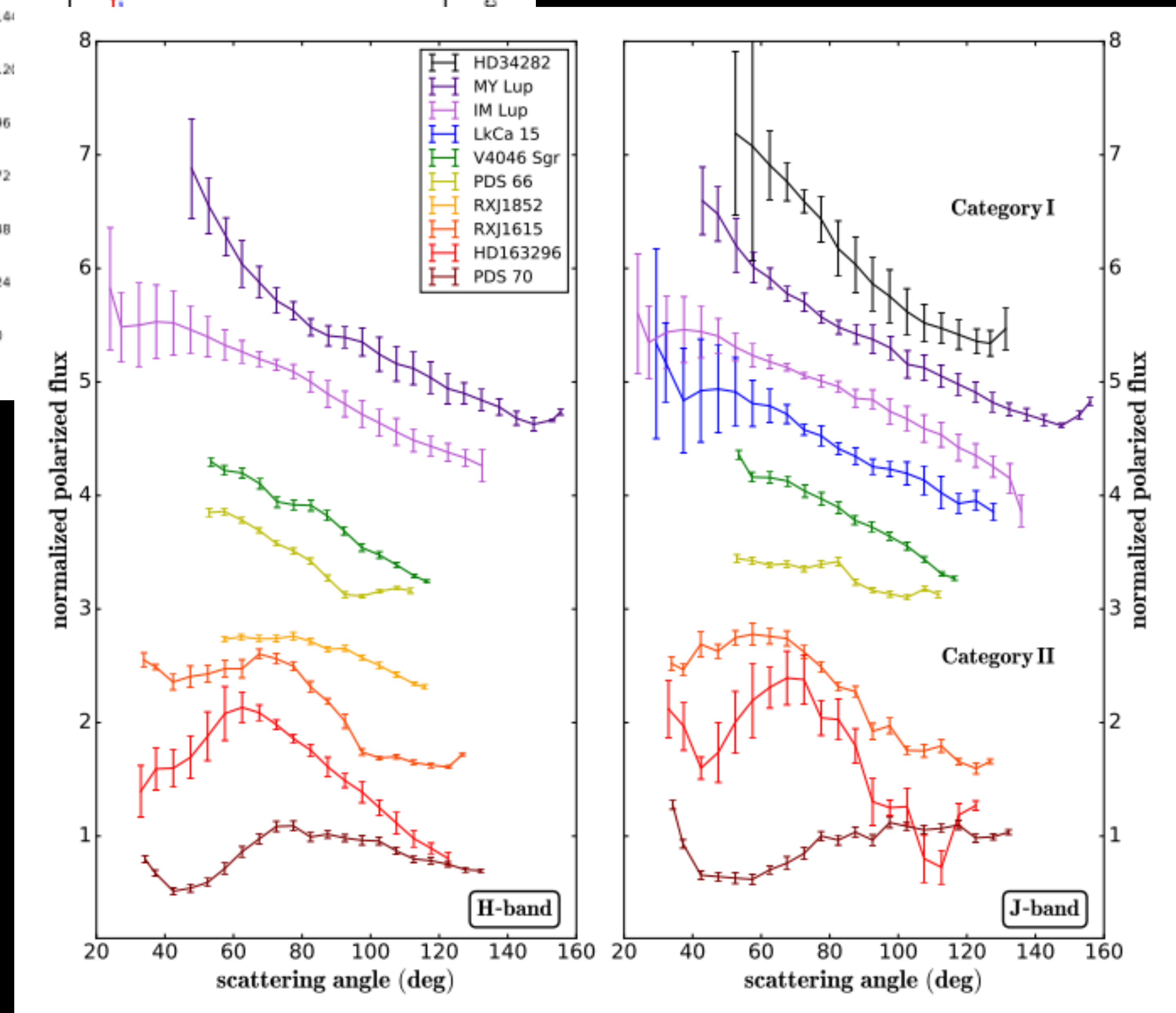
Dirty cotton!!



Gómez et al. 2020
Olga Muñoz Lecture!

POROSITY IN PROTOPLANETARY DISKS





IR scattered light
from porous grains

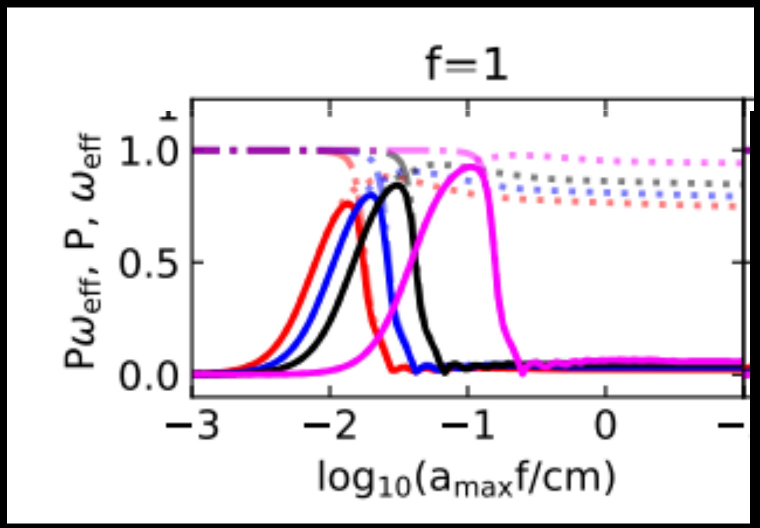
Two categories:
I -> High porosity (fractals)
II -> Low porosity

But this are the smaller particles
in the disk, located in the surface

Ginski et al. 2023

POROSITY IN THE MID-PLANE?

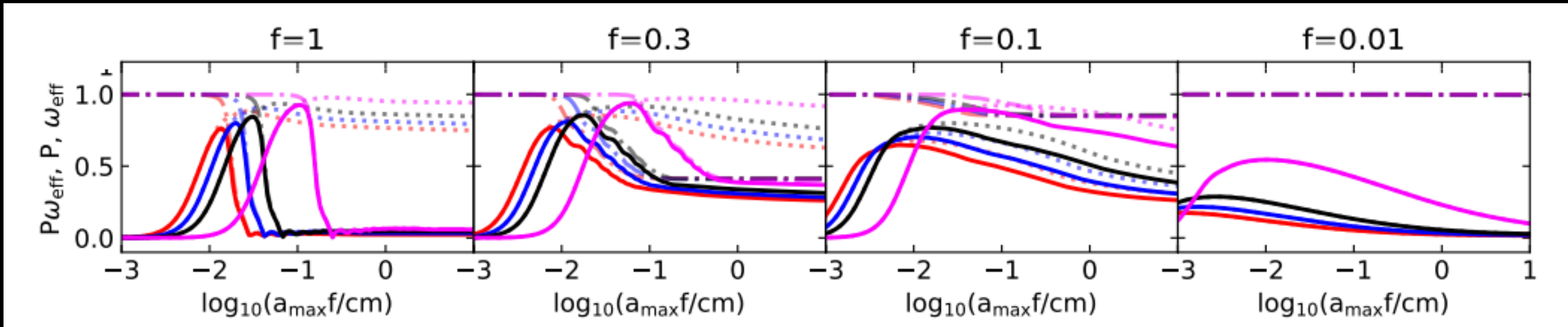
Sphere



$$\lambda_{Max\ Pol} \simeq 2\ \pi\ a_{max}$$

POROSITY IN THE MID-PLANE?

Sphere **Moderately porous** **Highly porous**



$$\lambda_{Max\ Pol} \simeq 2\ \pi\ a_{max}$$

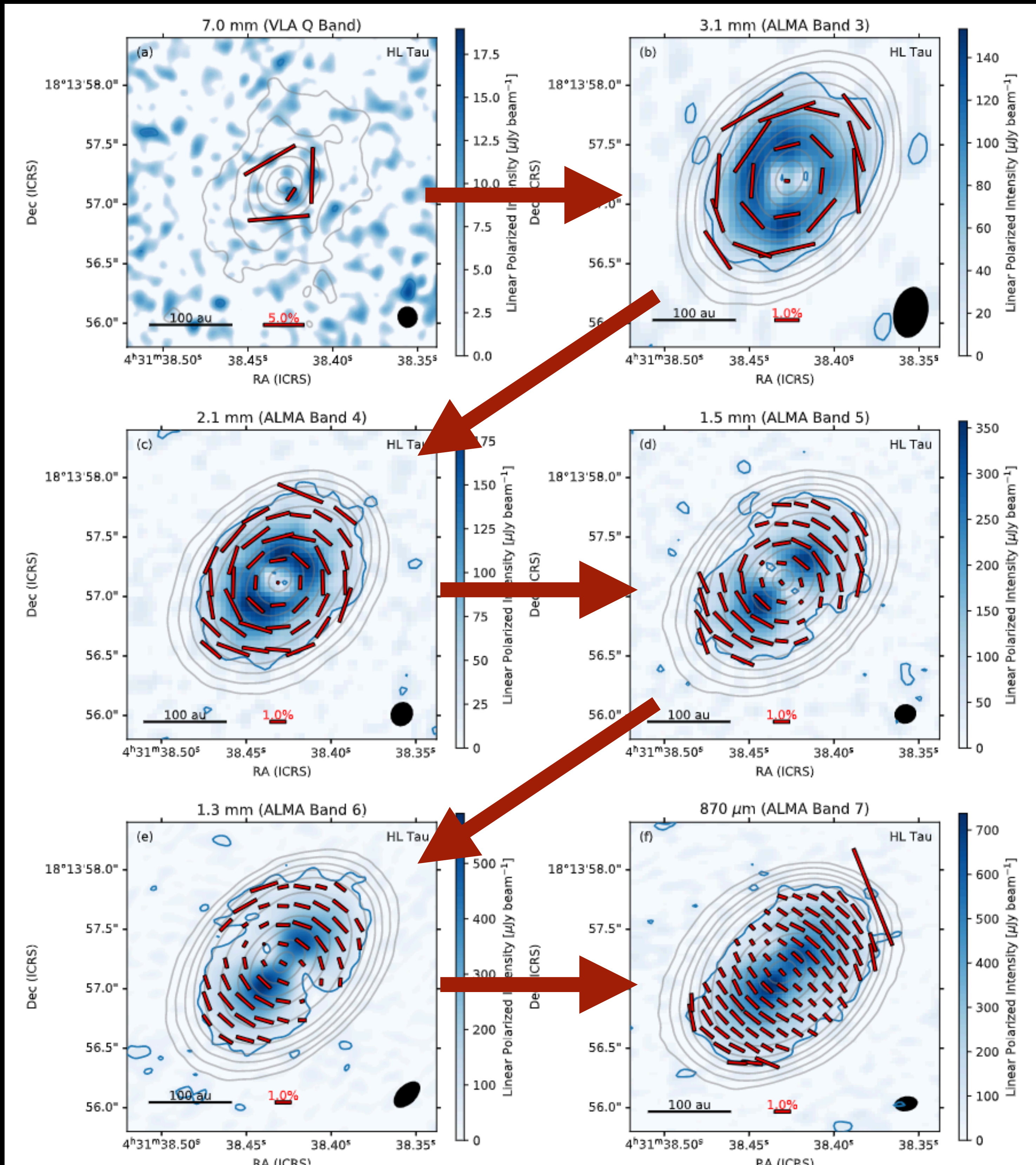
Porosity makes possible polarization in a very wide range of wavelengths

HL Tau —> Porosity 70-97%

Zhang et al. 2023
(including Kataoka and Carrasco-González)

POROSITY

Dominated by aligned grains

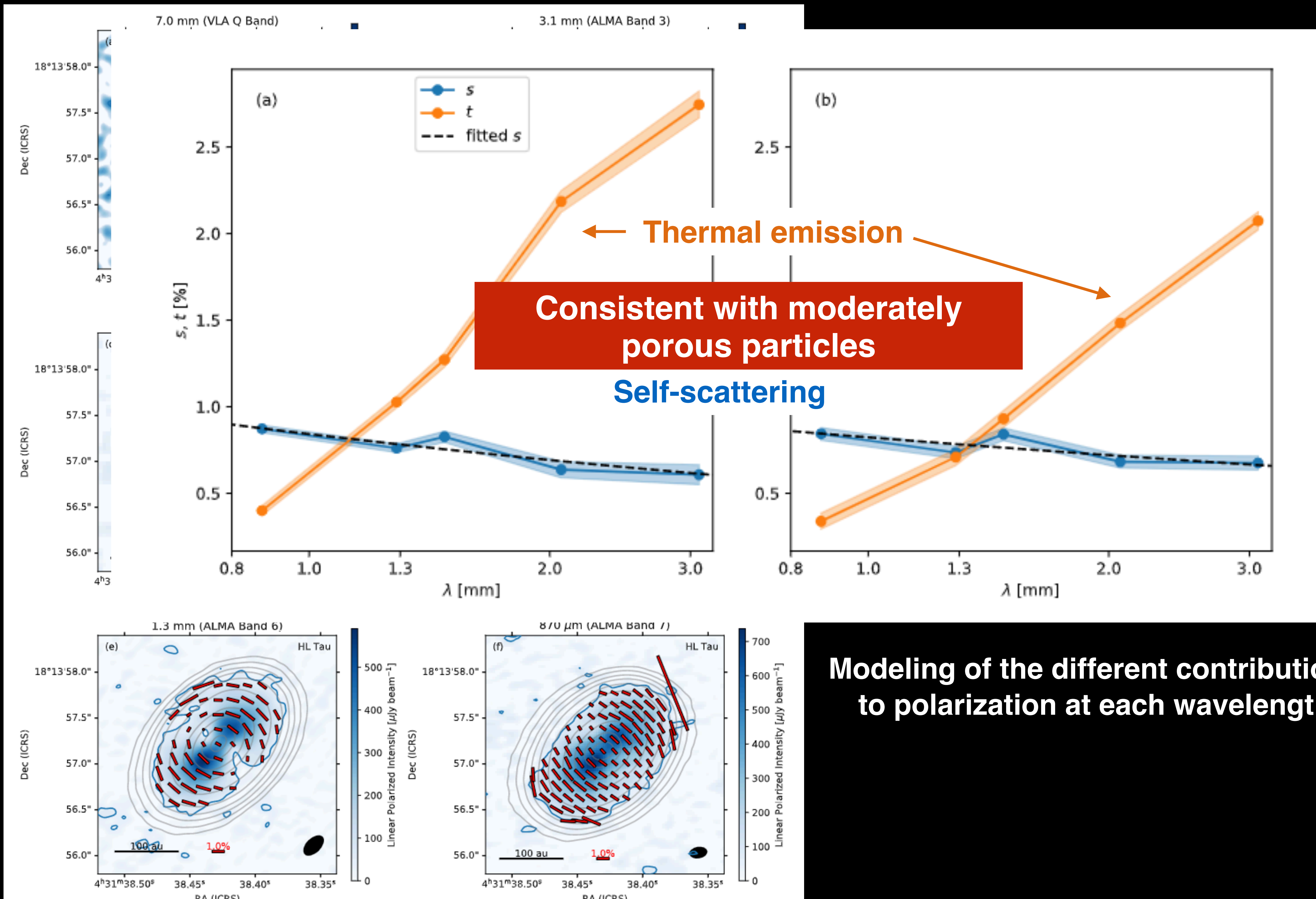


Dominated by self-scattering

Modeling of the different contributions to polarization at each wavelength

Lin et al. 2023 (including Kataoka and Carrasco-González)

POROSITY



Modeling of the different contributions to polarization at each wavelength

Lin et al. 2023
(including Kataoka and Carrasco-González)

IMPLICATIONS OF POROUS GRAINS

Particles are larger

HL Tau (1 Myr): ~10 cm

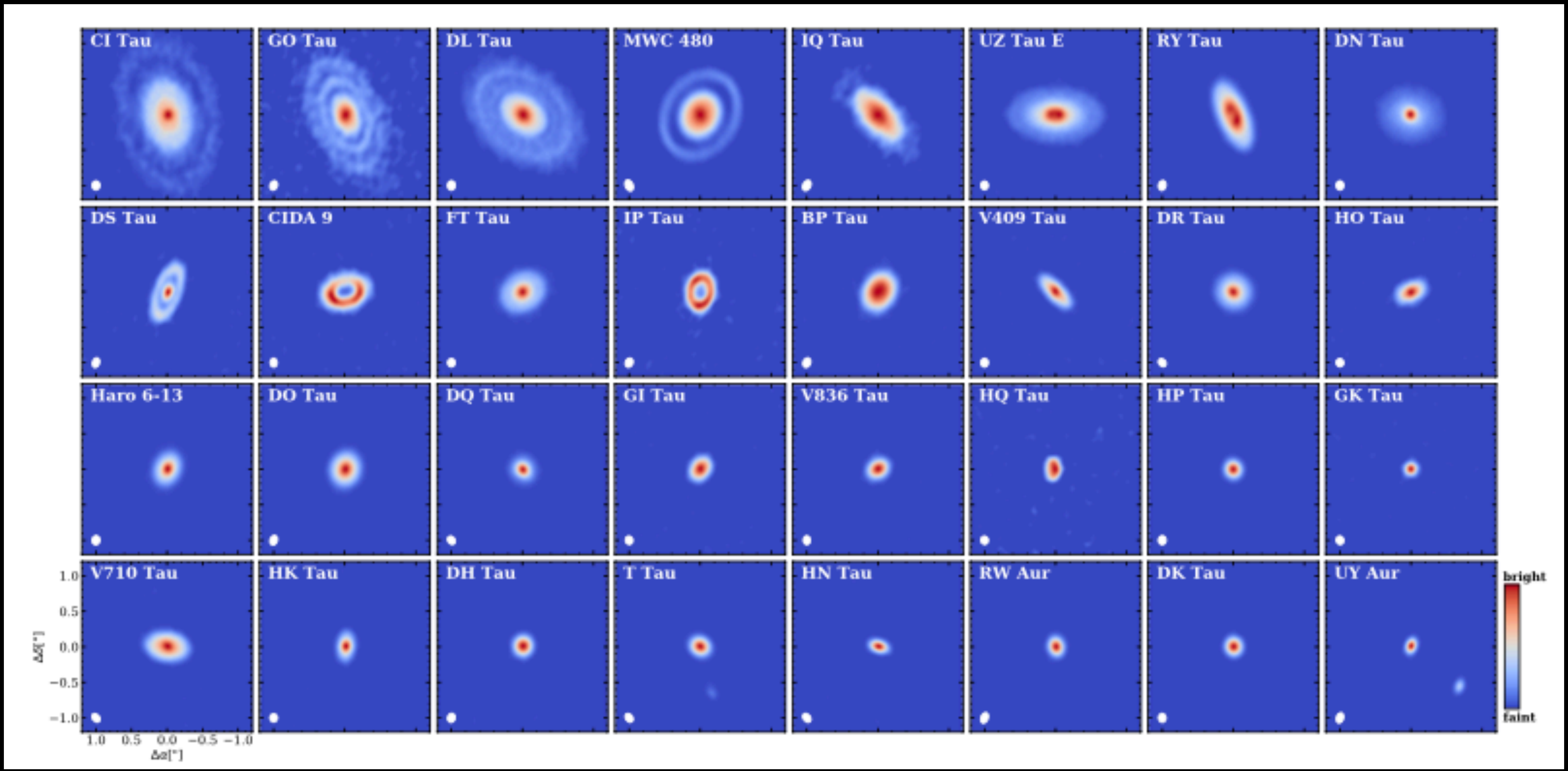
Dust mass is larger

> 6 times larger than with compact solid spheres

WE NEED TO USE OPACITIES CALCULATED FOR REALISTIC POROUS PARTICLES

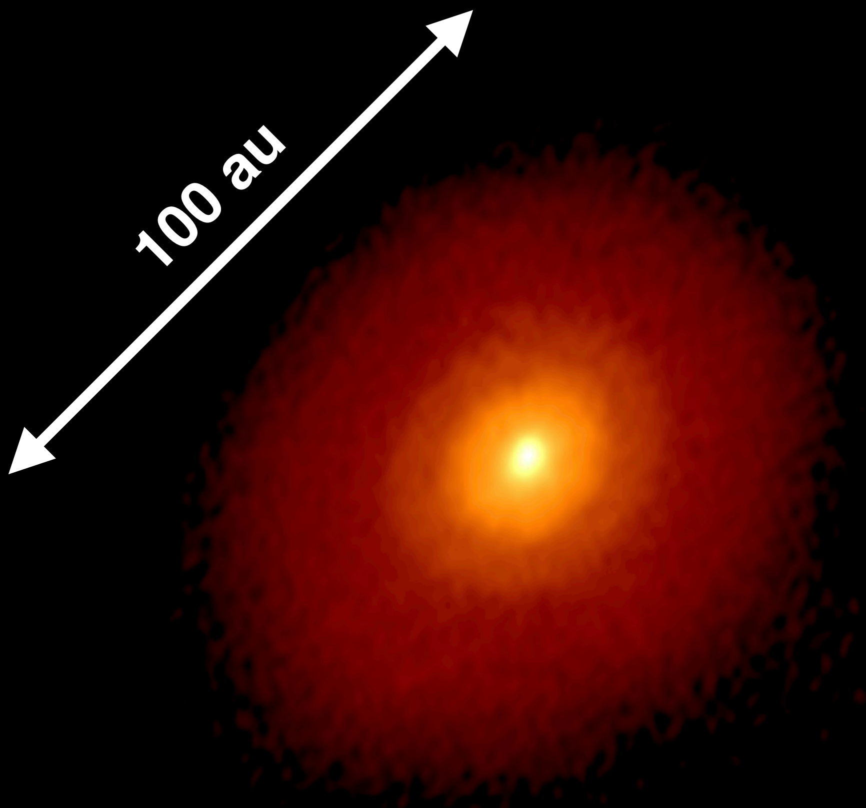
OPEN QUESTIONS AND FUTURE

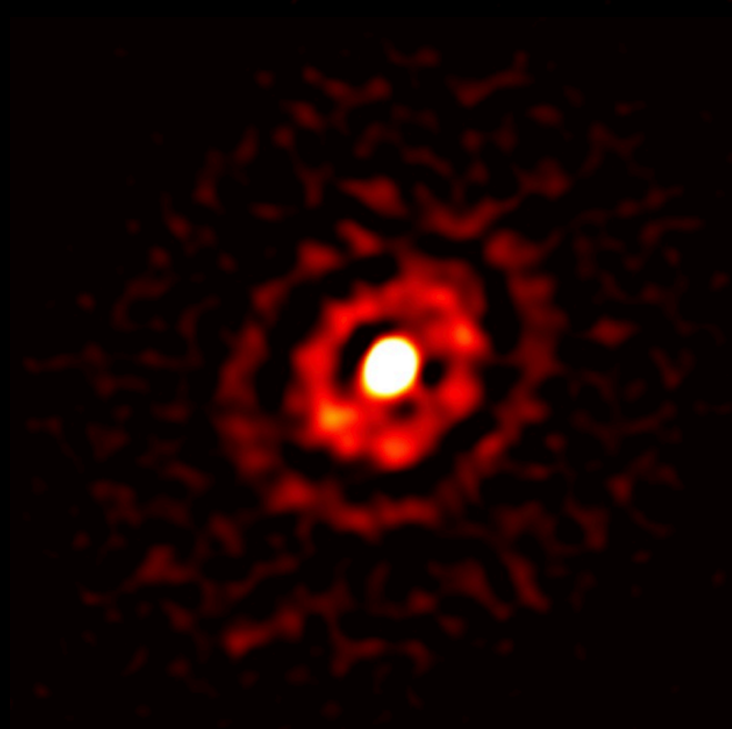
COMPACT DISKS AND INTERNAL PARTS OF EXTENDED DISKS

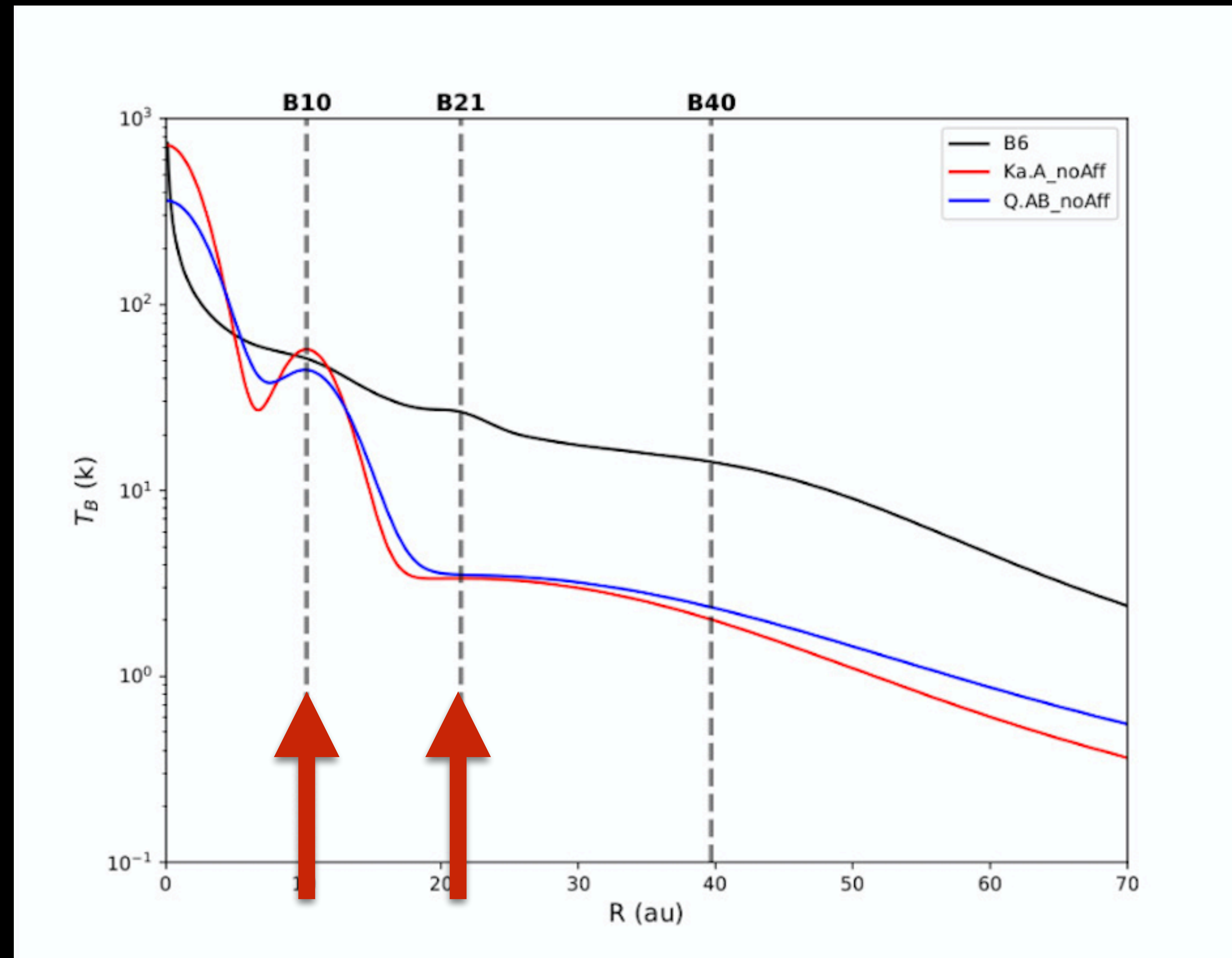


ALMA Taurus Survey ; Long et al. (2019)

COMPACT DISKS AND INTERNAL PARTS OF EXTENDED DISKS





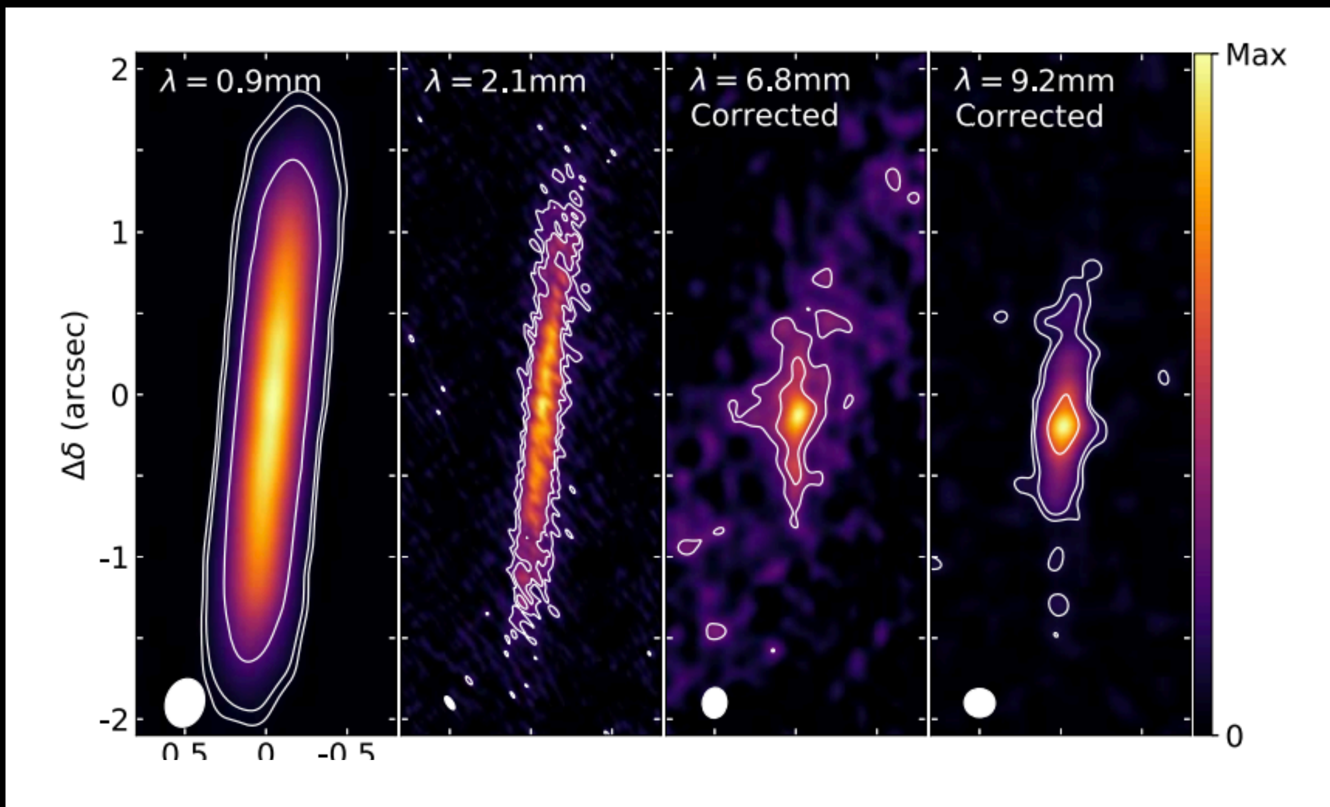


Compact and optically thick disk

Substructures are revealed at longer wavelengths

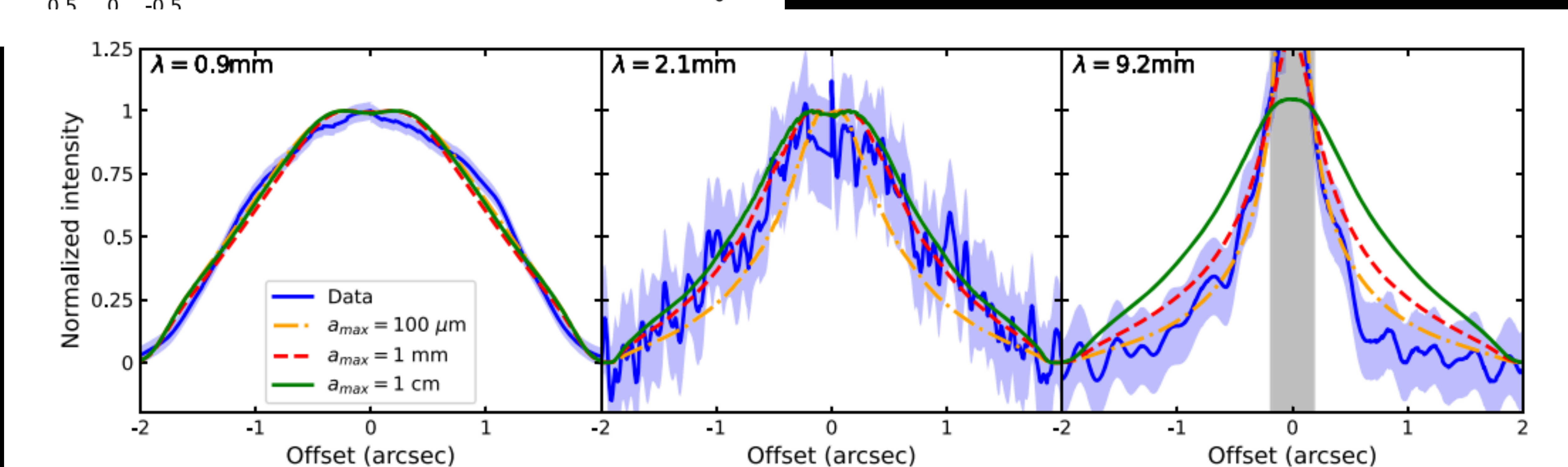
Carrasco-González et al., in prep

VERTICAL STRUCTURE



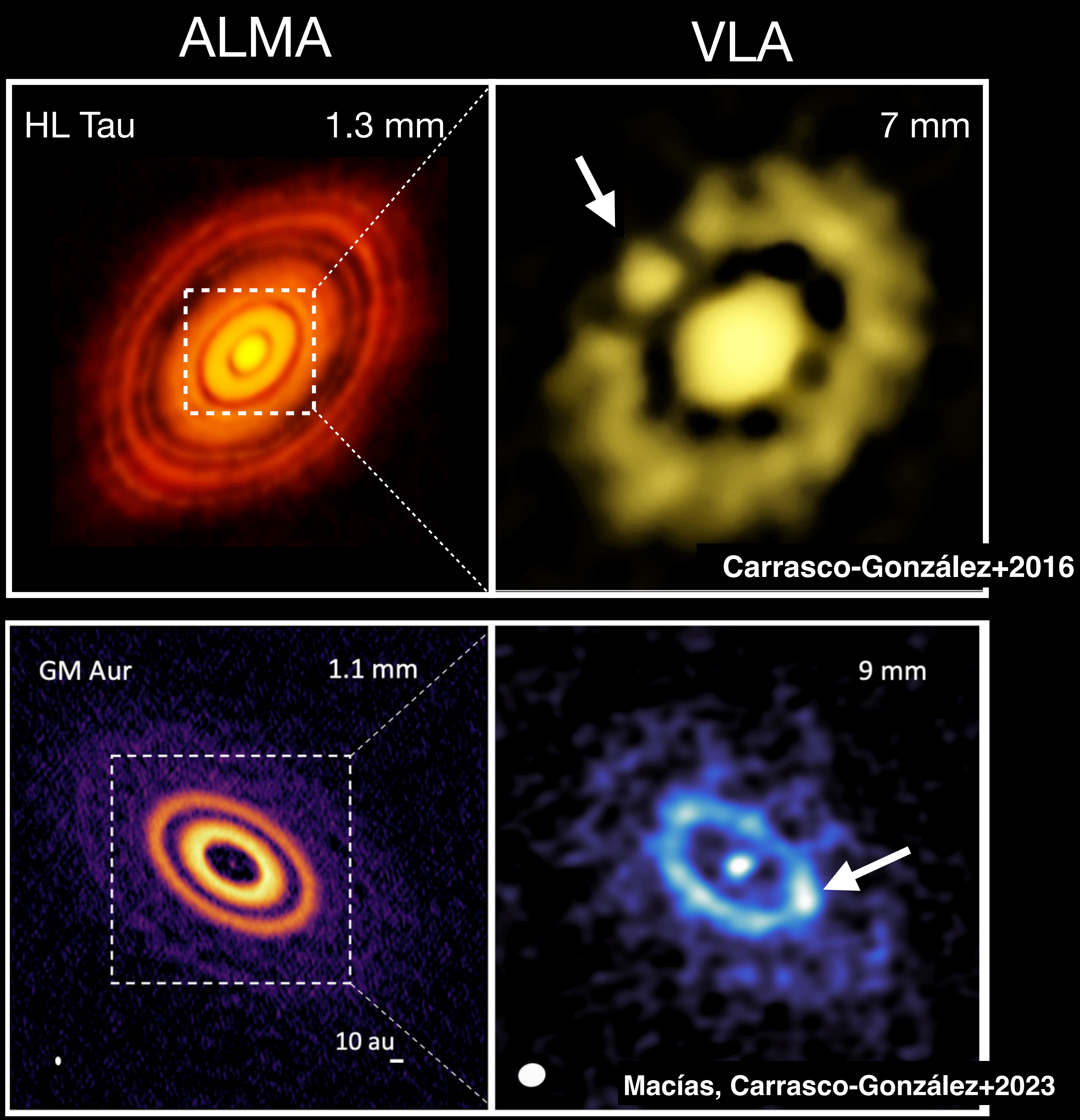
Modeling of edge-on disks

Class I disk -> moderate dust settling (1-6 au at 100 au)



Villenave et al. 2023

OBSERVATIONS AT LONGER WAVELENGTHS



VLA Q

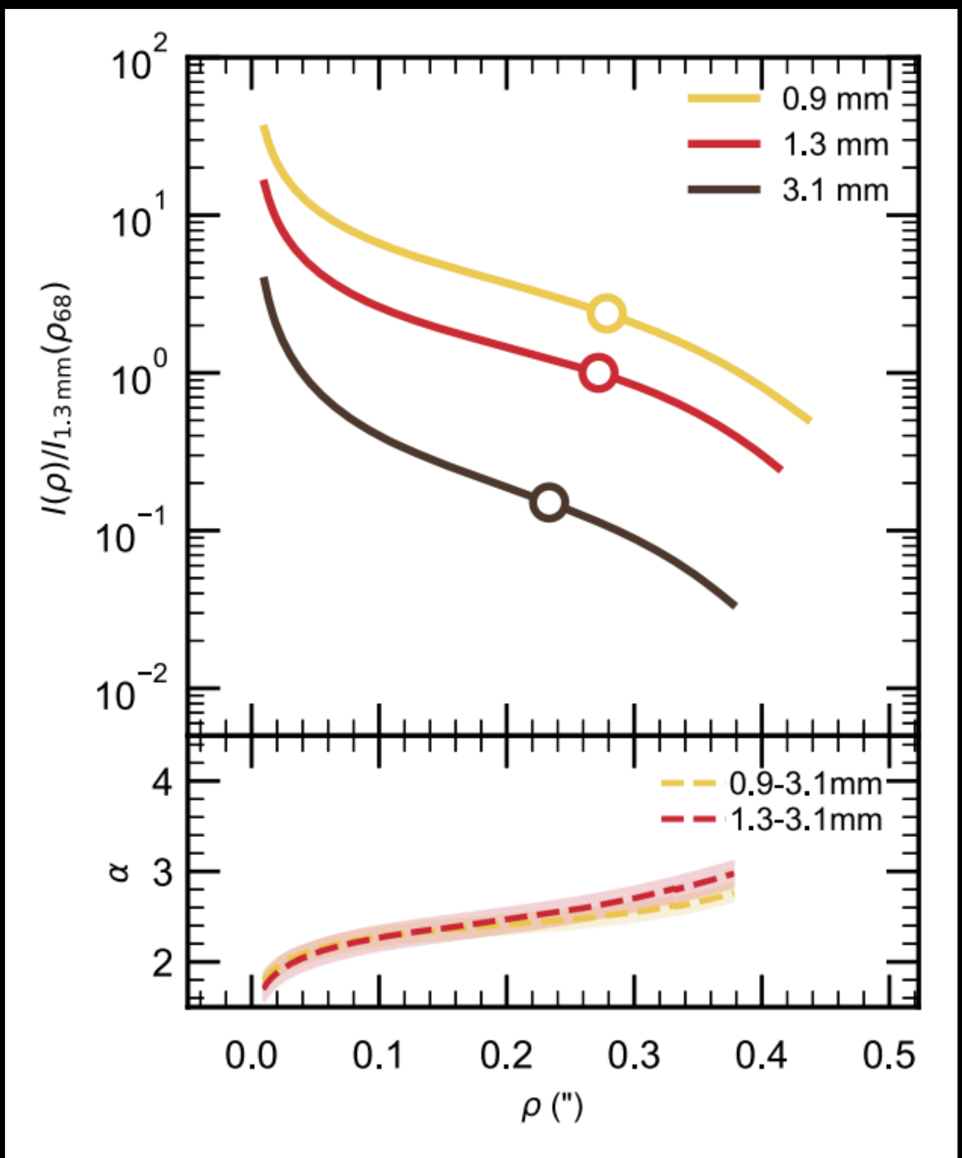
40 mas ~ 5 au
Low sensitivity

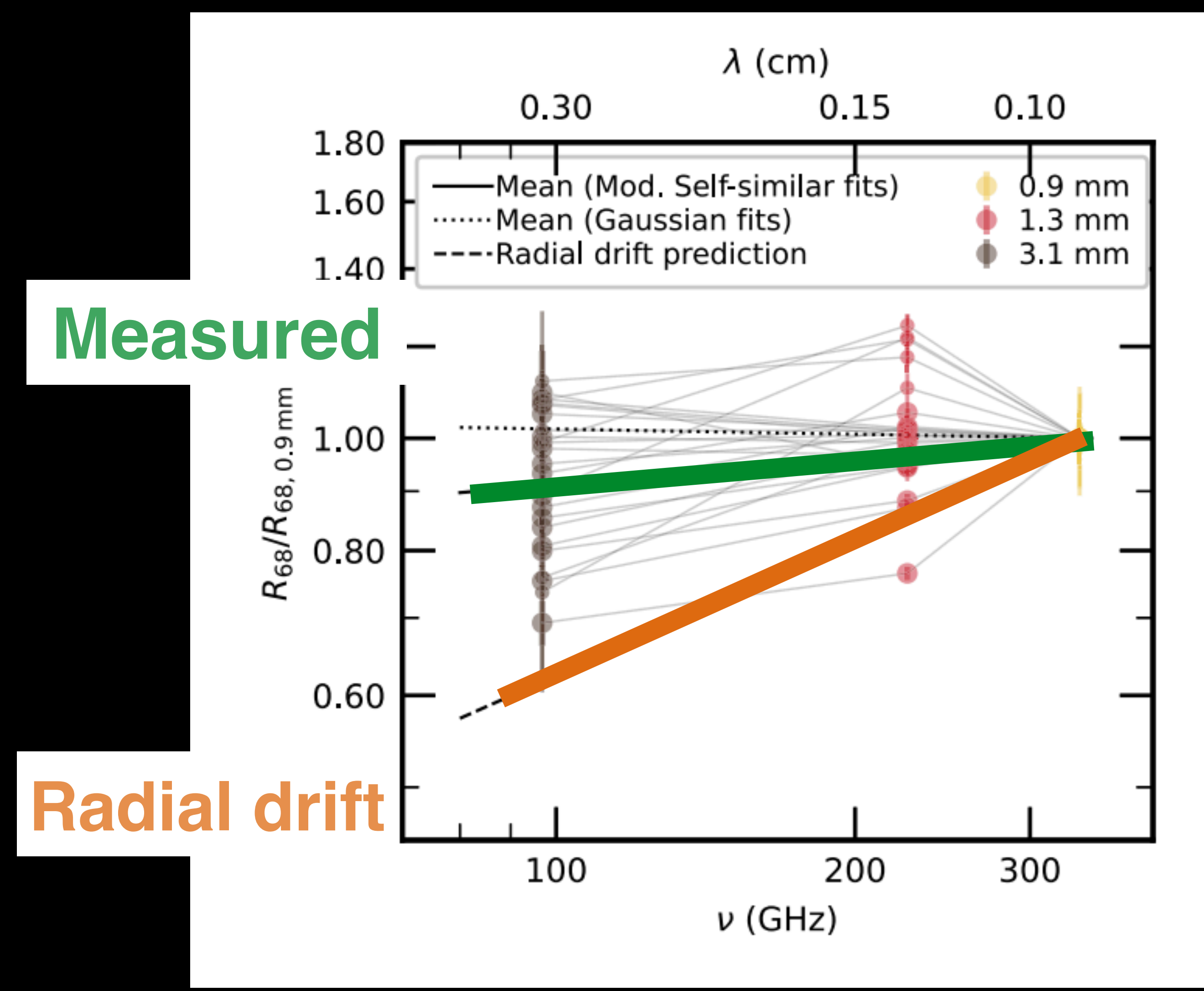
ALMA B1

Lower resolution
Same sensitivity
Higher Image Fidelity

MID-RESOLUTION OBSERVATIONS

Comparison of disk size between different wavelengths → **Distribution of particles of different sizes**





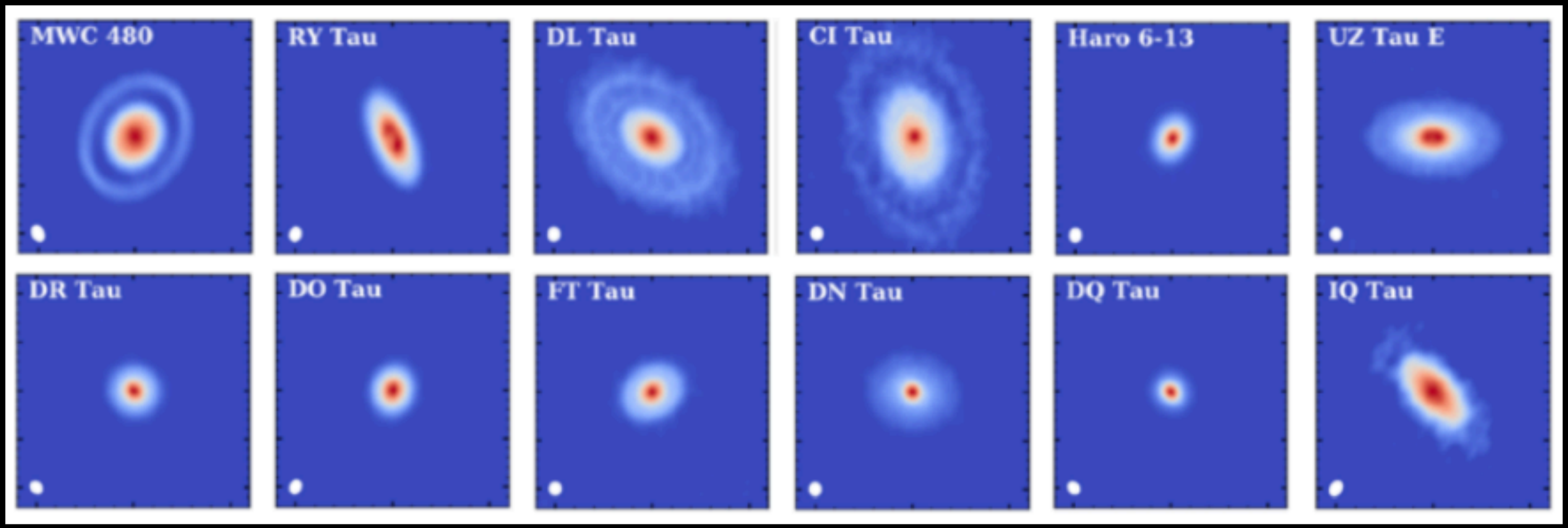
ALMA Survey in Lupus

Necessary to extend to longer wavelengths

Tazzari et al. 2021

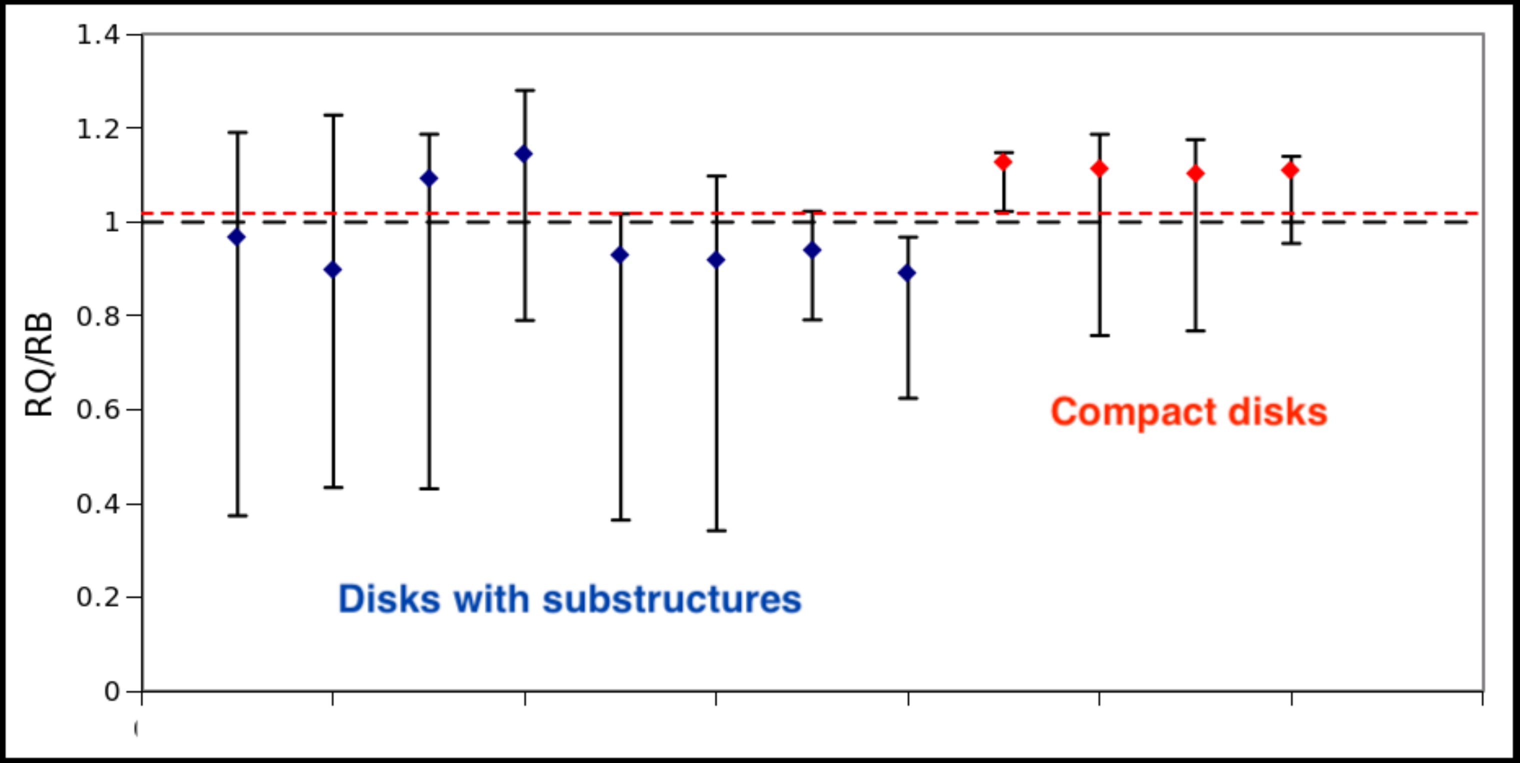
MID-RESOLUTION OBSERVATIONS

ALMA & VLA Survey in Taurus



Long et al. 2019

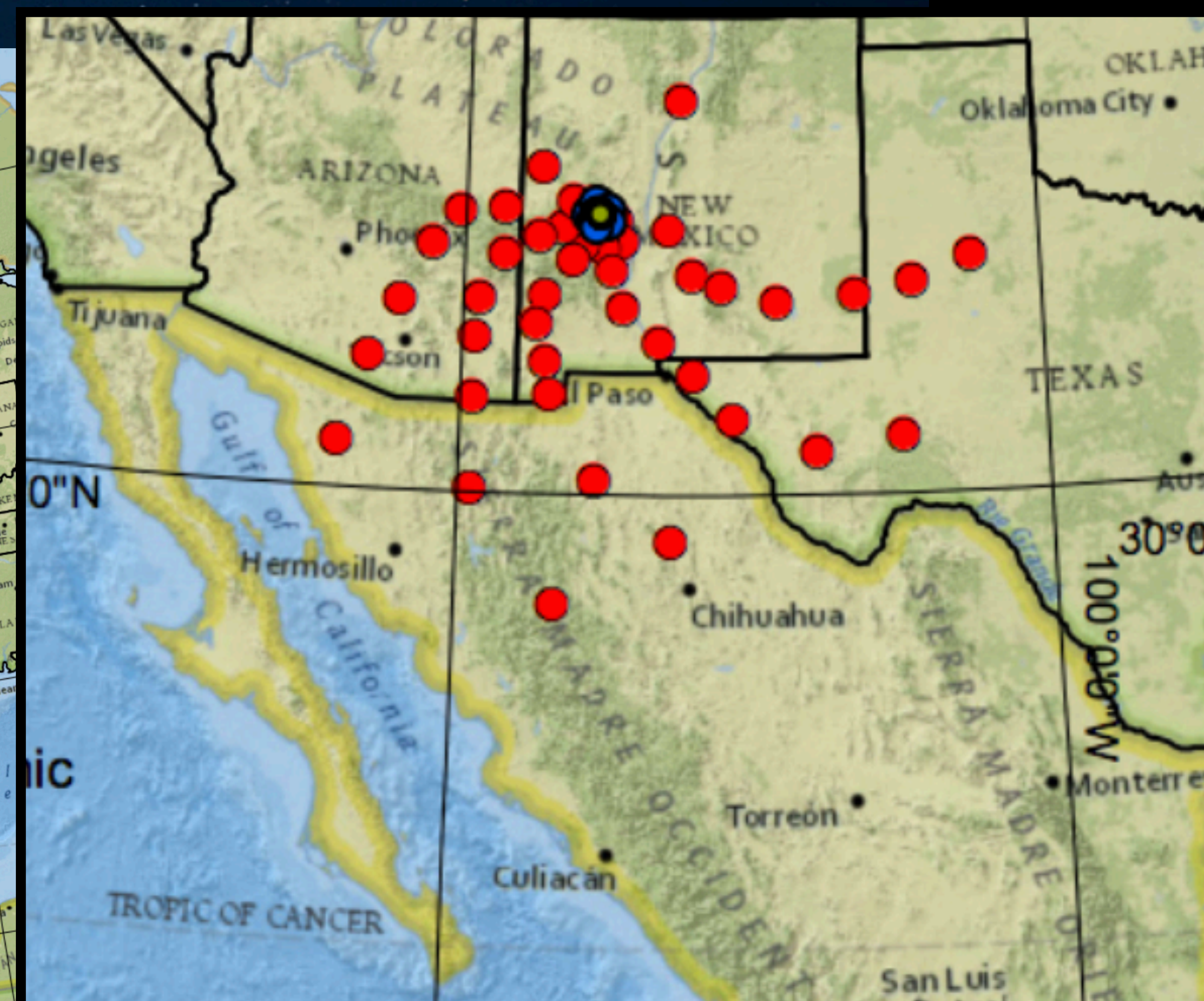
Preliminary results: mm particles seem to be everywhere



Carrasco-González et al., in prep

ngvla

Next Generation Very Large Array



10x sensitivity
10x resolution

THANKS