ALMA polarization and particle sizes in protoplanetary disks

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30+10 min. talk, on October 5th 2021, MIAPP

I know how you feel 🙁

- **Polarization?**
  - Magnetic fields! (I wish it were the case.)
  - Complicated! Never understood! (me too.)
- **Scattering at millimeter wavelengths?**
  - Negligible! (it's not negligible both in continuum and polarization at millimeter wavelengths.)

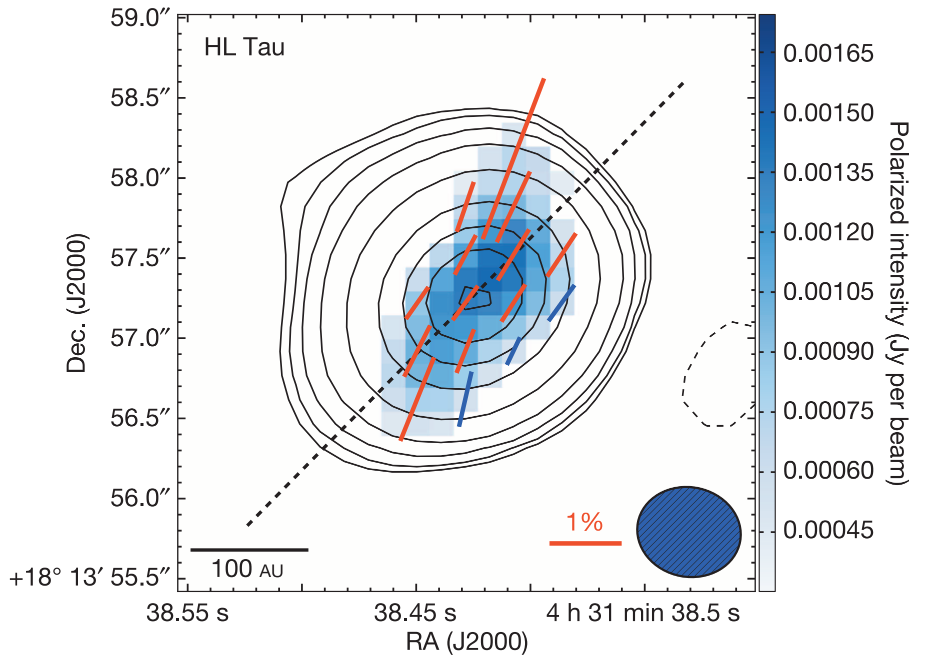
Today's topics and goals

- Summarizing ALMA polarization observations (See Anibal's talk for scattering effects on continuum)
- Putting them onto the discussion table of planet formation.
    - Grain size tension - spectral index infers millimeter-centimeter dust grains while polarization infers ~100 μm dust grains.
        - Do optically thick components solve the problem?
        - What kind of observations is missing?

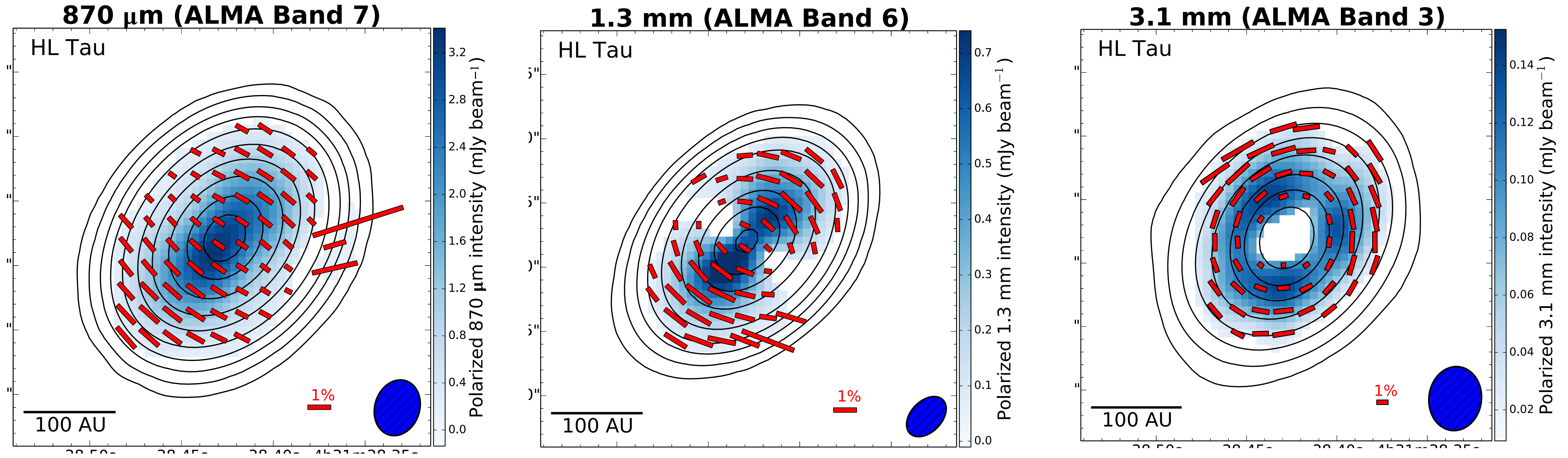
polarization observations before and after ALMA

- ALMA offers polarization between Band 7 (0.9 mm) and Band 3 (3.1 mm).
- Before ALMA, there was only one detection of linear polarization from HL Tau (Stephens et al. 2014, and see papers by Meredith Hughes for other disks).
- **~10-20 detections of linear polarization of continuum.**
    - Most of detections are made at Band 7. Some disks show transitions from Band 7 to 3.
- Line polarization is still under discussion (see next slide).

CARMA and SMA



Note: red vectors are polarization vectors rotated by 90 degrees

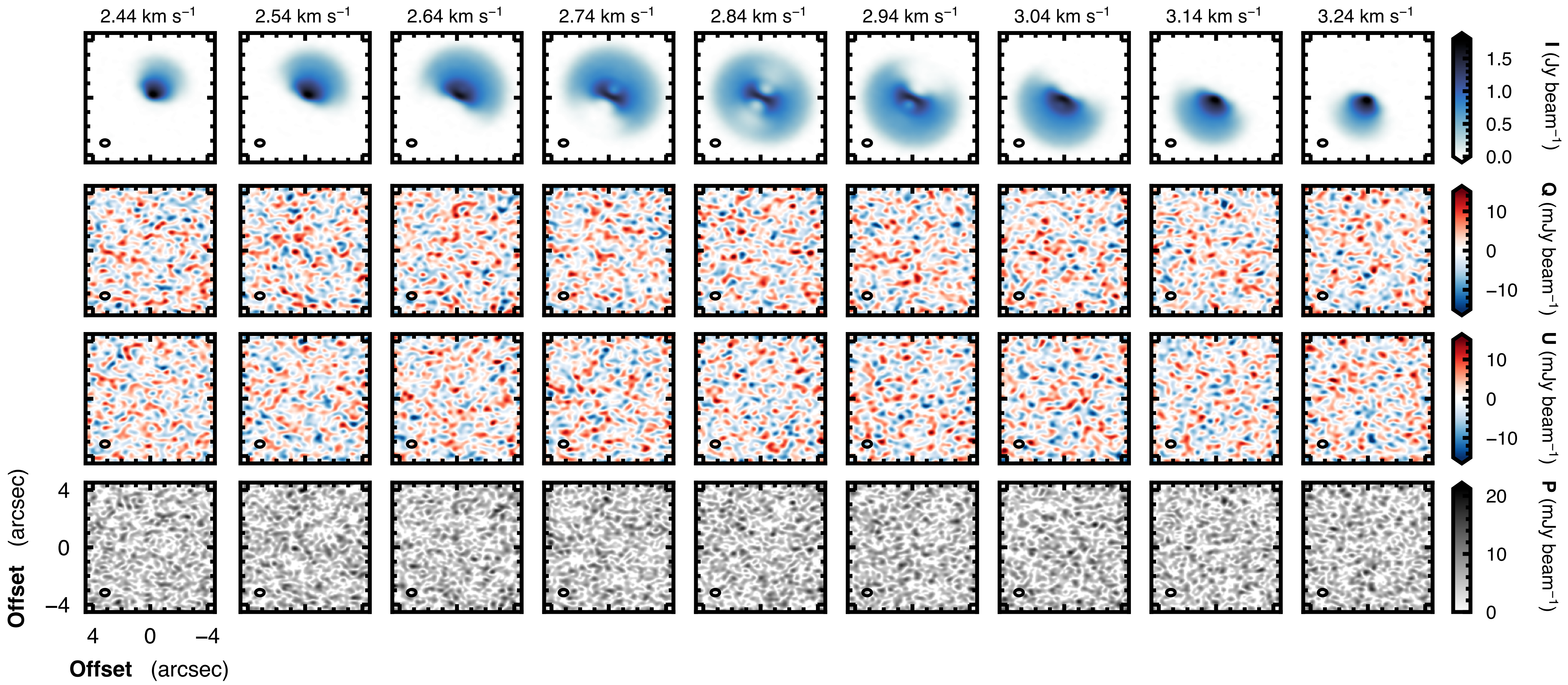


Note: red vectors are polarization vectors

Stephens et al. 2014, 2017

Molecular line polarization

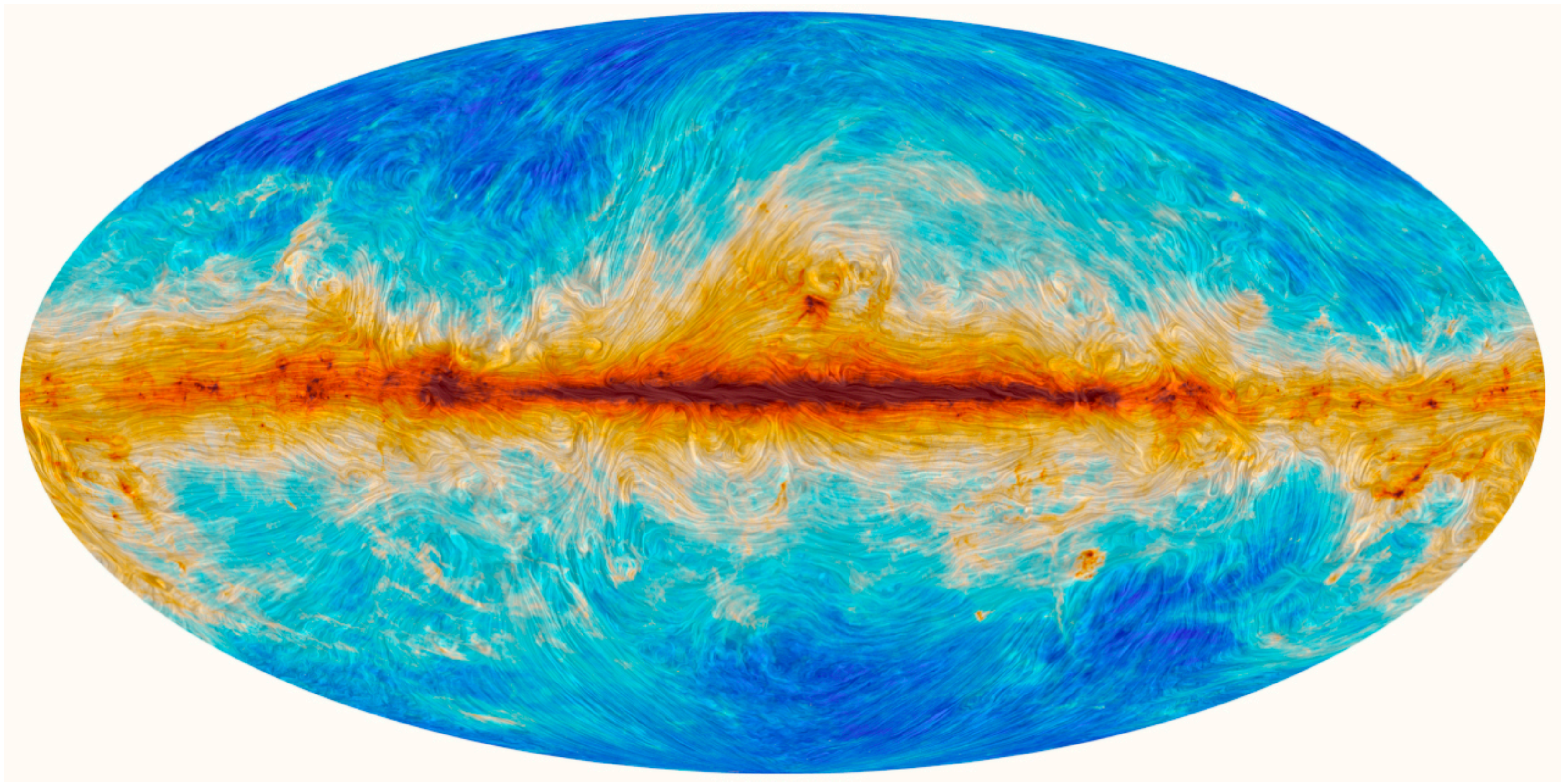
- **Non-detection of CN circular polarization**
  - TW Hya (Vlemmings et al. 2019)
  - AS 209 (Harrison et al. 2021)
- **Tentative detection of CO linear polarization**
  - HD 142527 and IM Lup (Stephens et al. 2020)
  - TW Hya (Teague et al. 2021)



No CO polarization is detected in channel maps, but stacking analysis shows detections of linear polarization in line wings.

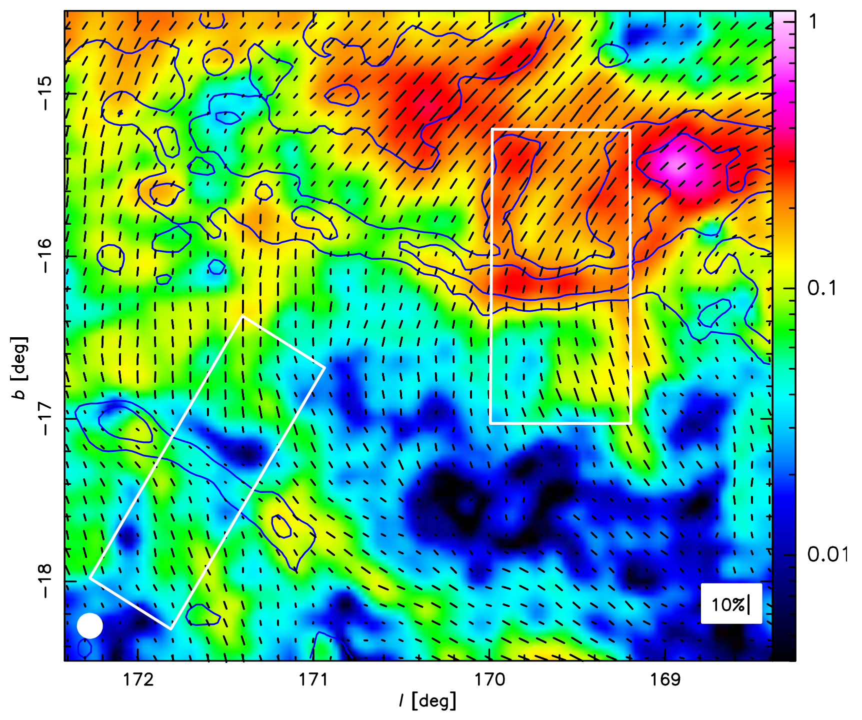
Teague et al. 2021

millimeter polarization in different scales



Galactic scale

Taurus

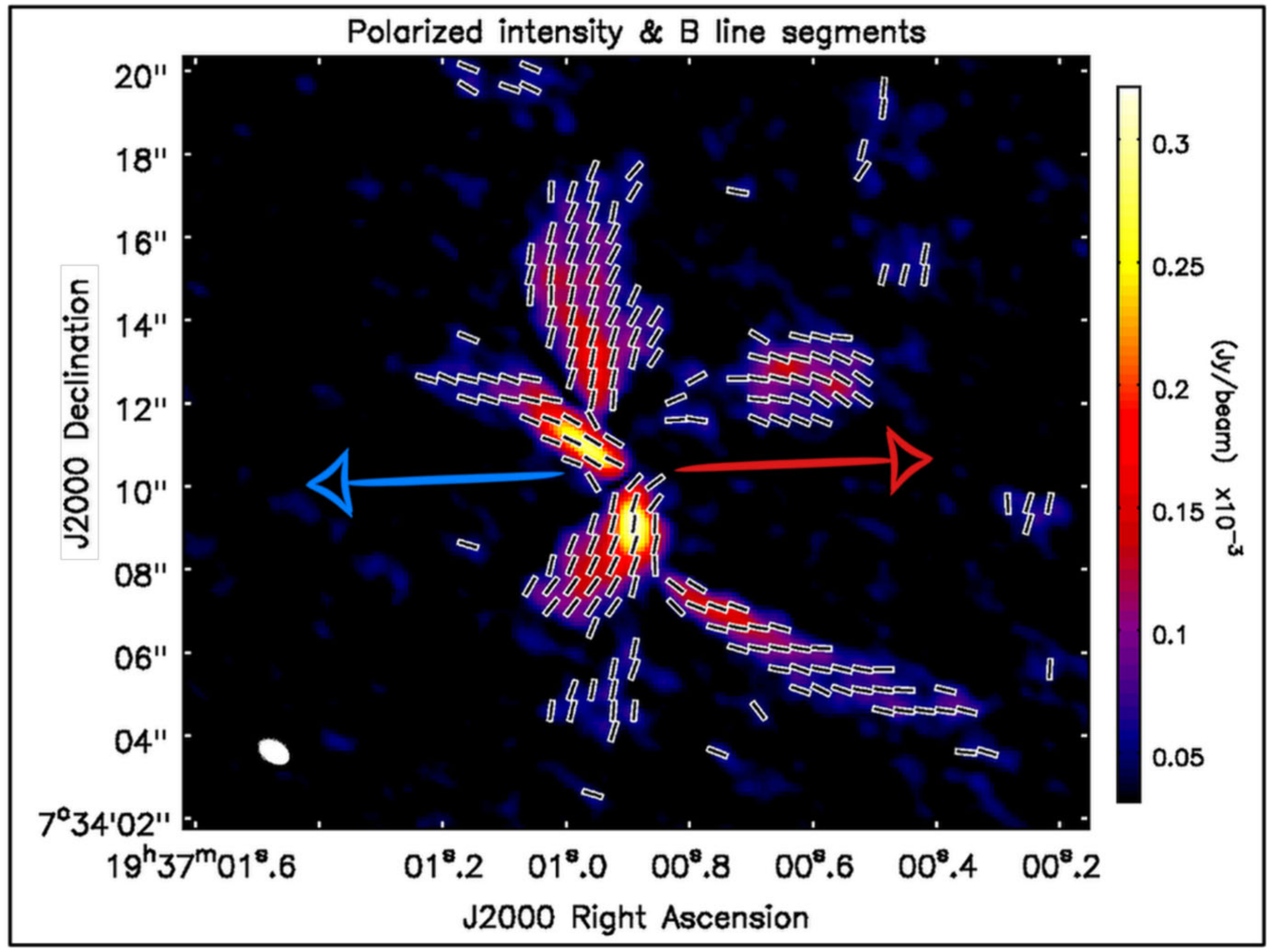


Planck collaboration XXXIII. 2016

Cloud scale

(~ several degrees; ~ 1-10 pc scale)

B335

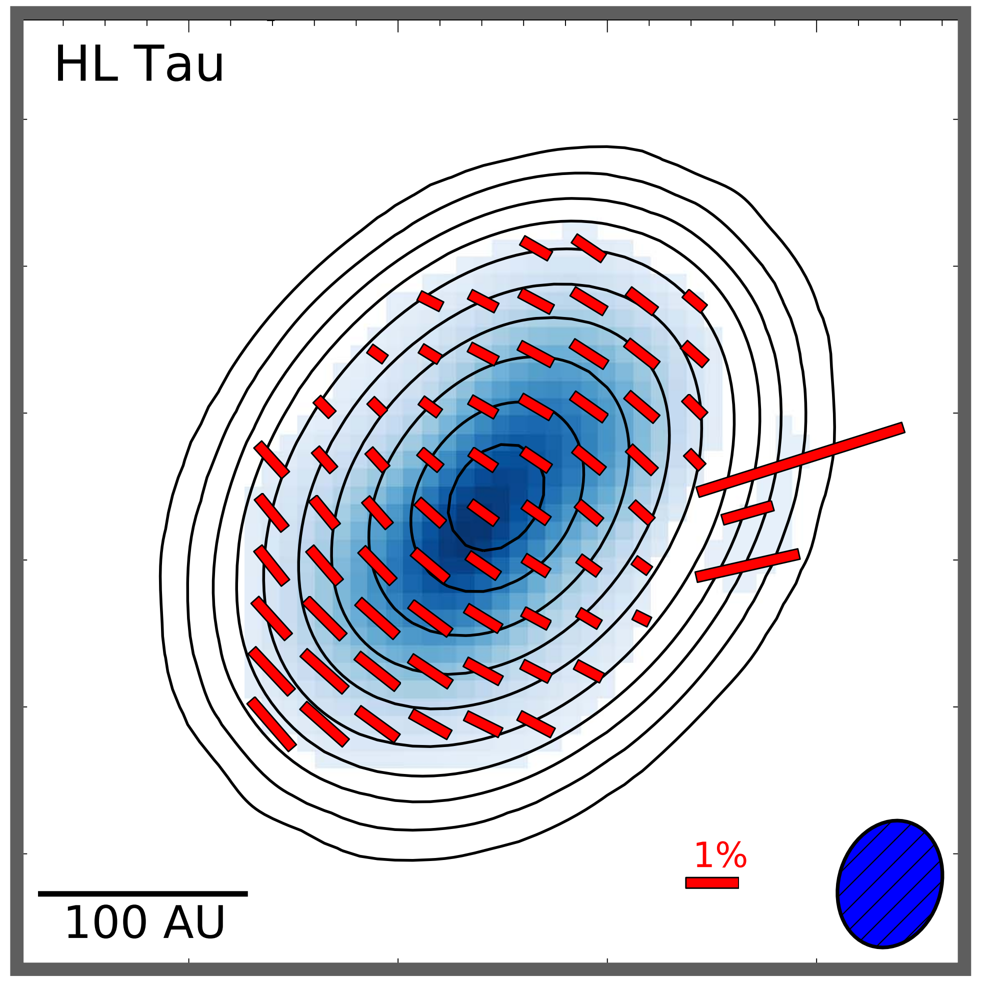


Maury et al. 2018

Core scale

(~several arcmin; ~1000 au scale)

HL Tau

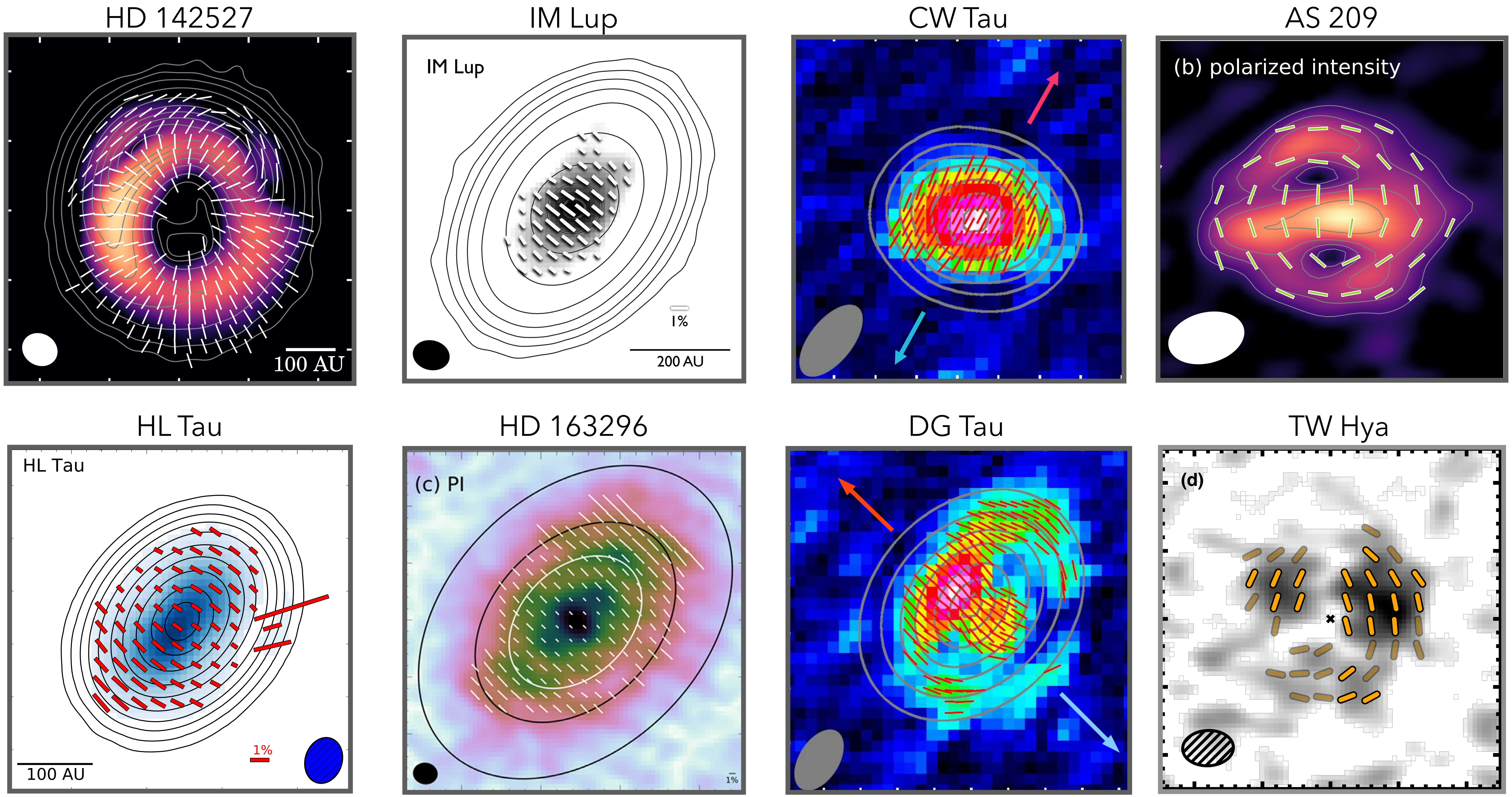


Stephens et al. 2017

Disk scale

(~several arcsec; ~100 au scale)

ALMA polarization of disks



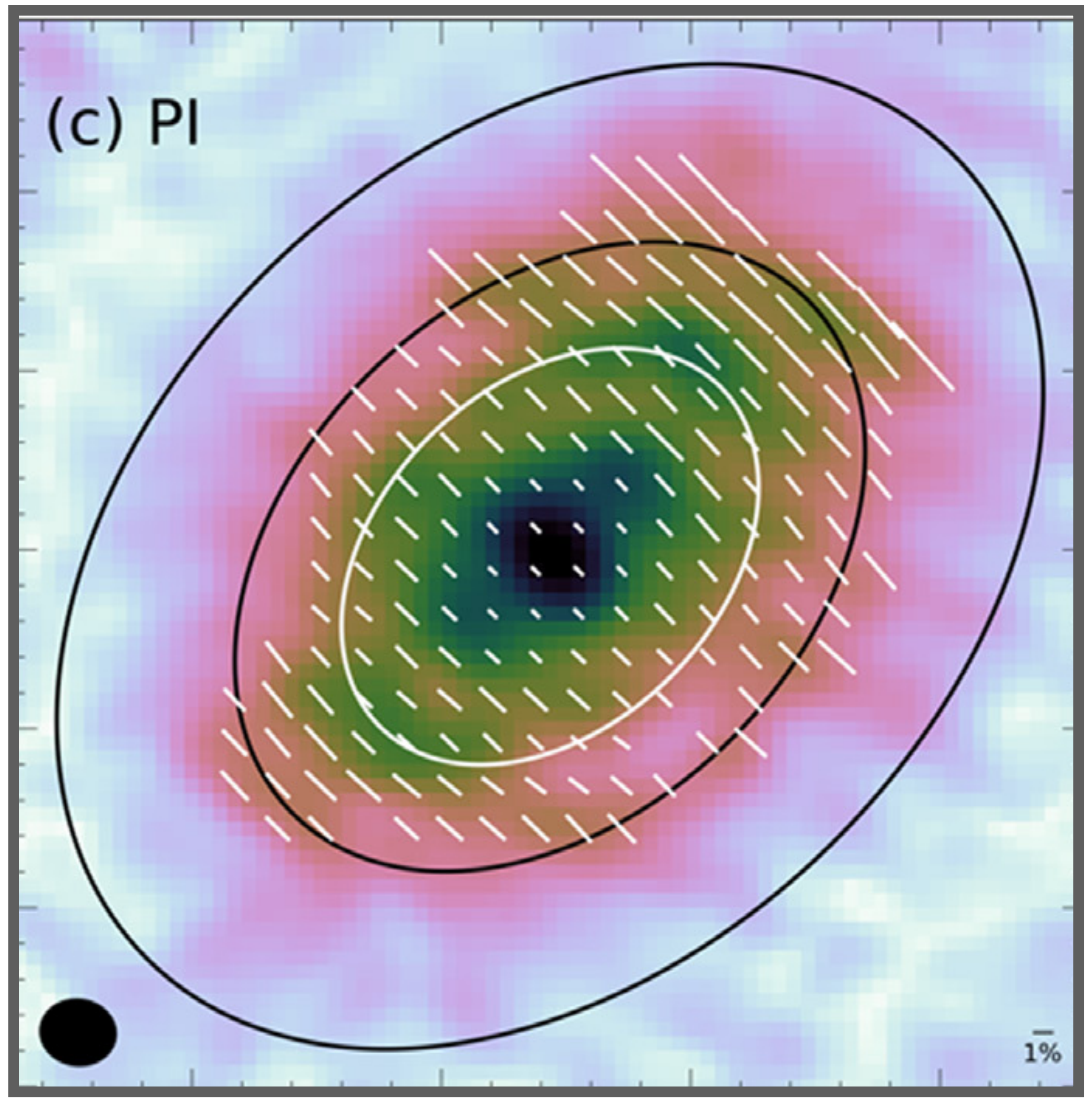
Kataoka et al. 2016, Hull et al. 2018, Bacciotti et al. 2018, Dent et al. 2019, Stephens et al. 2017, Kataoka et al. 2017, Ohashi et al. 2018, Mori et al. 2019, Teague et al. 2021

Current understandings of polarization

ALMA polarization of smooth and inclined disks, around a low-mass stars, with scales less than 100 au

Parallel to the minor axis

HD 163296 (0.9 mm)

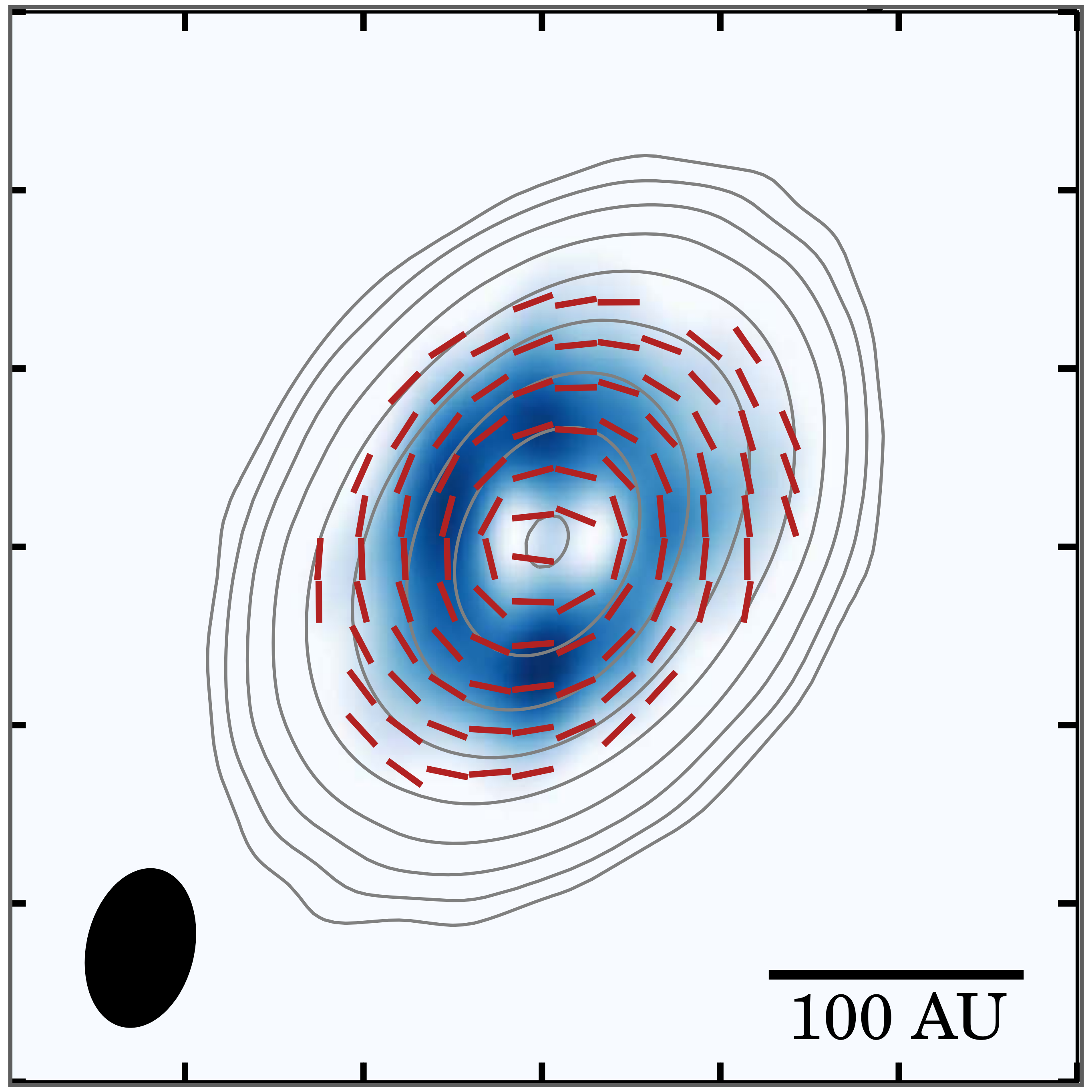


Dent et al. 2019

Self-scattering

Azimuthal

HL Tau (3 mm)



Kataoka et al. 2017

Intrinsic polarization of aligned dust grains

wavelength dependence

0.87 mm **1.3 mm** **3.1 mm**

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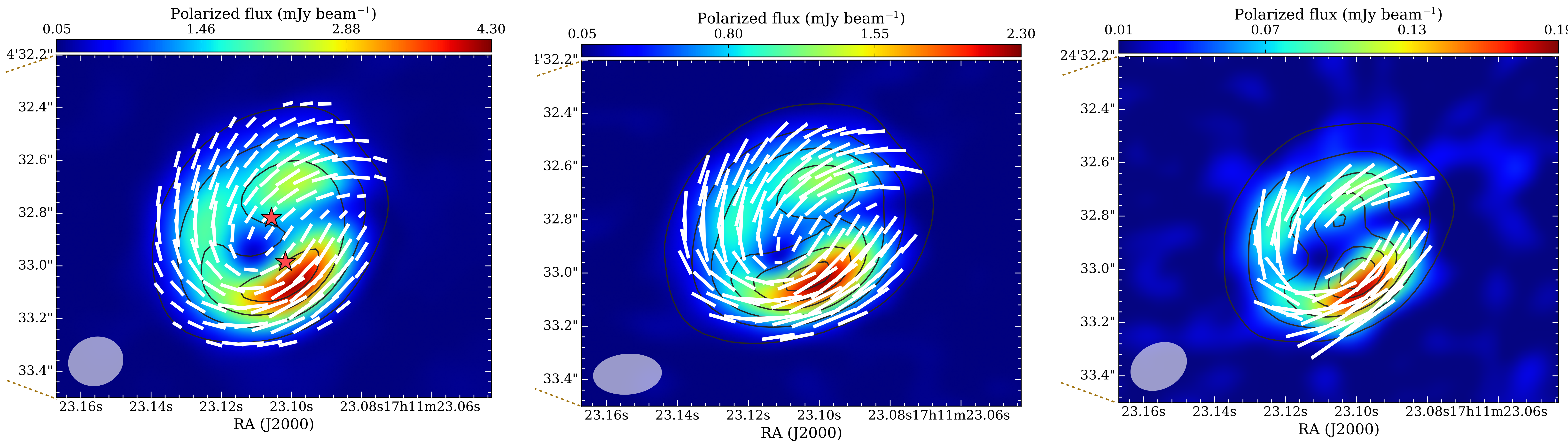
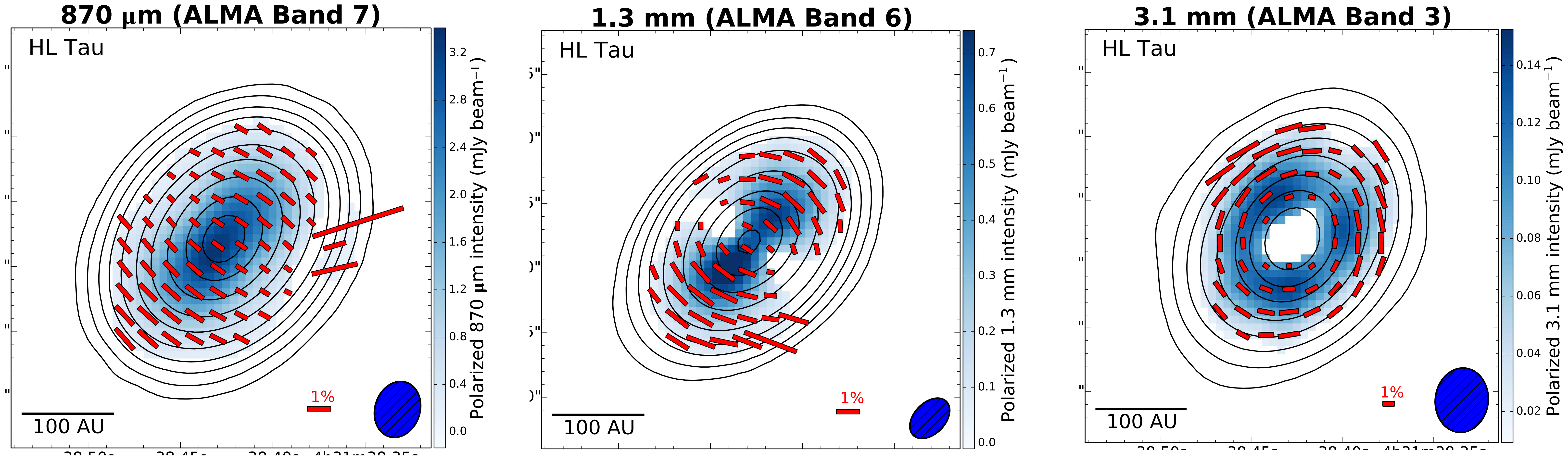


Intrinsic polarization of aligned dust grains

Alves et al. 2018

HL Tau



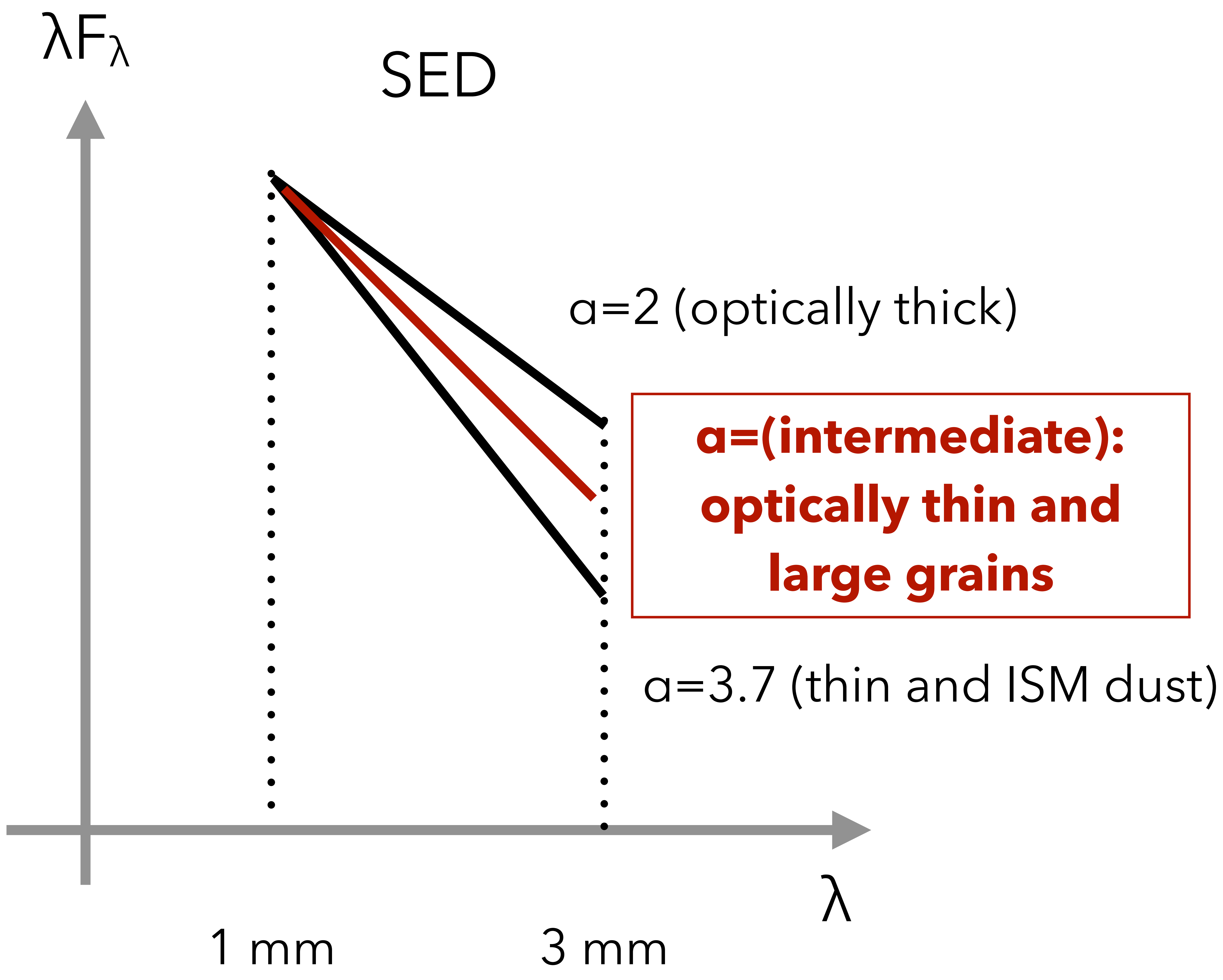
Self-scattering + Intrinsic polarization of aligned dust grains

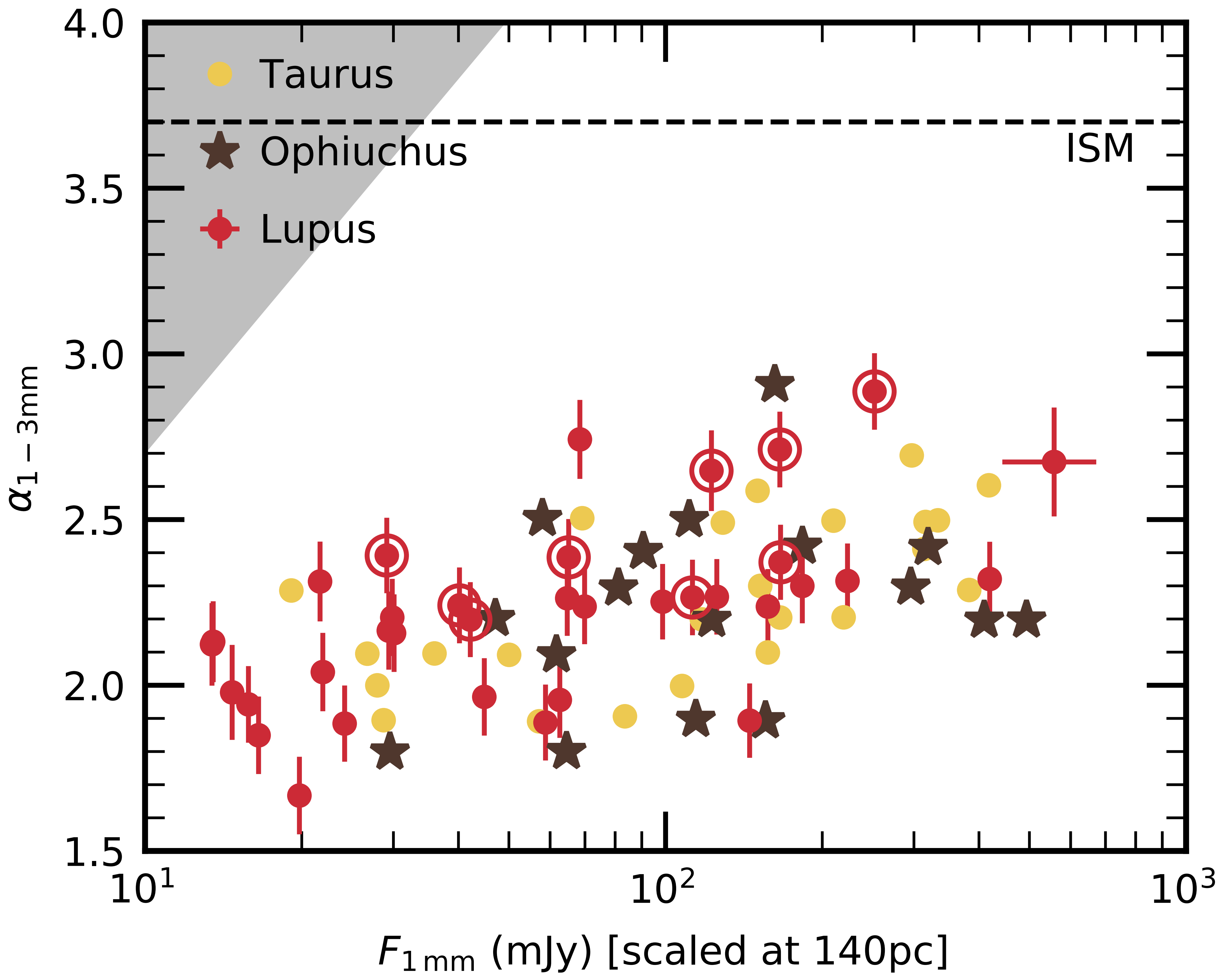
Kataoka et al. 2017, Stephens et al. 2017

Dust grain size

spectral index vs. polarization

How do we measure the dust grain size?



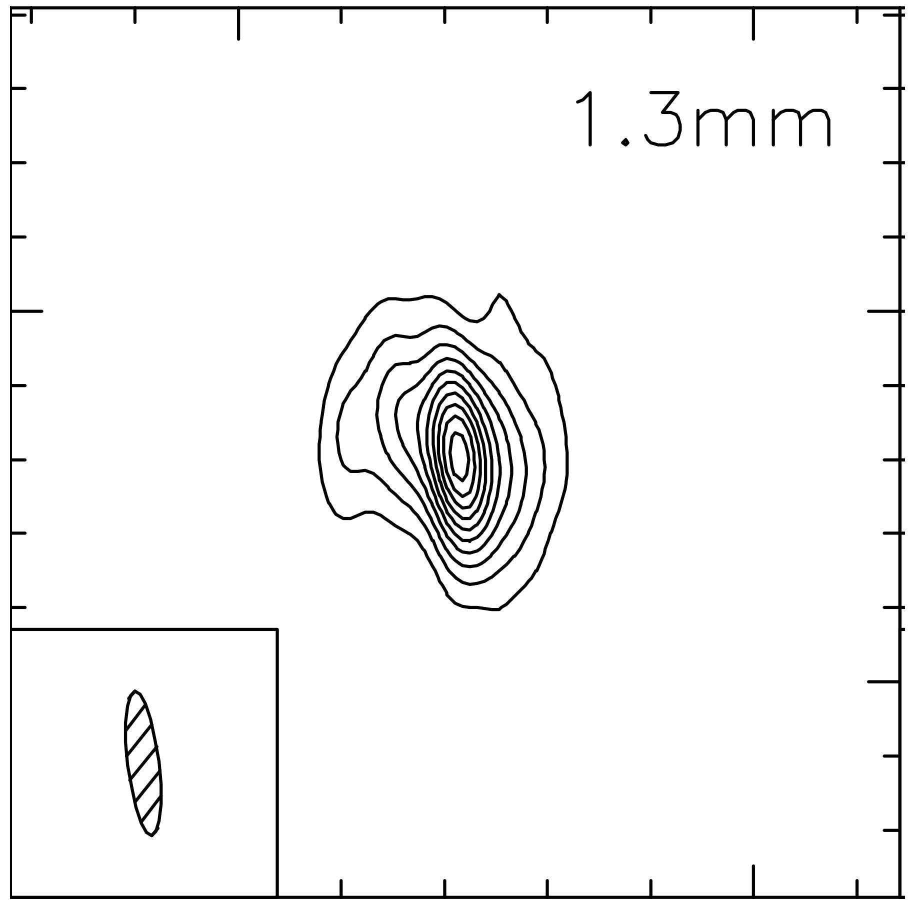


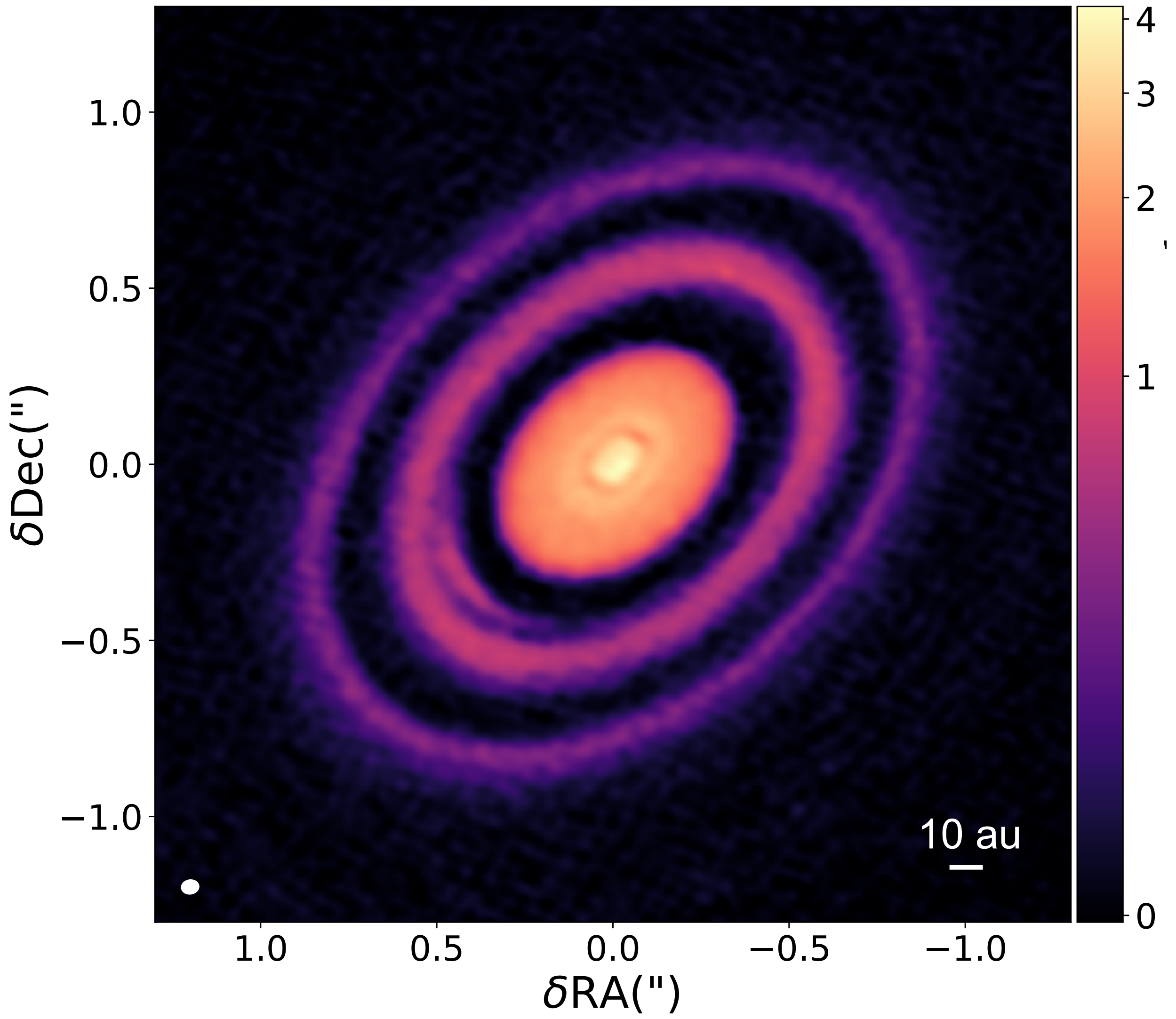
a = 2.0 - 3.0 → β = 0-1
→ large (millimeter) grains!

Tazzari et al. 2020a; see Beckwith and Sargent 1991, Isella et al. 2007, Ricci et al. 2010 …

IRAM

ALMA





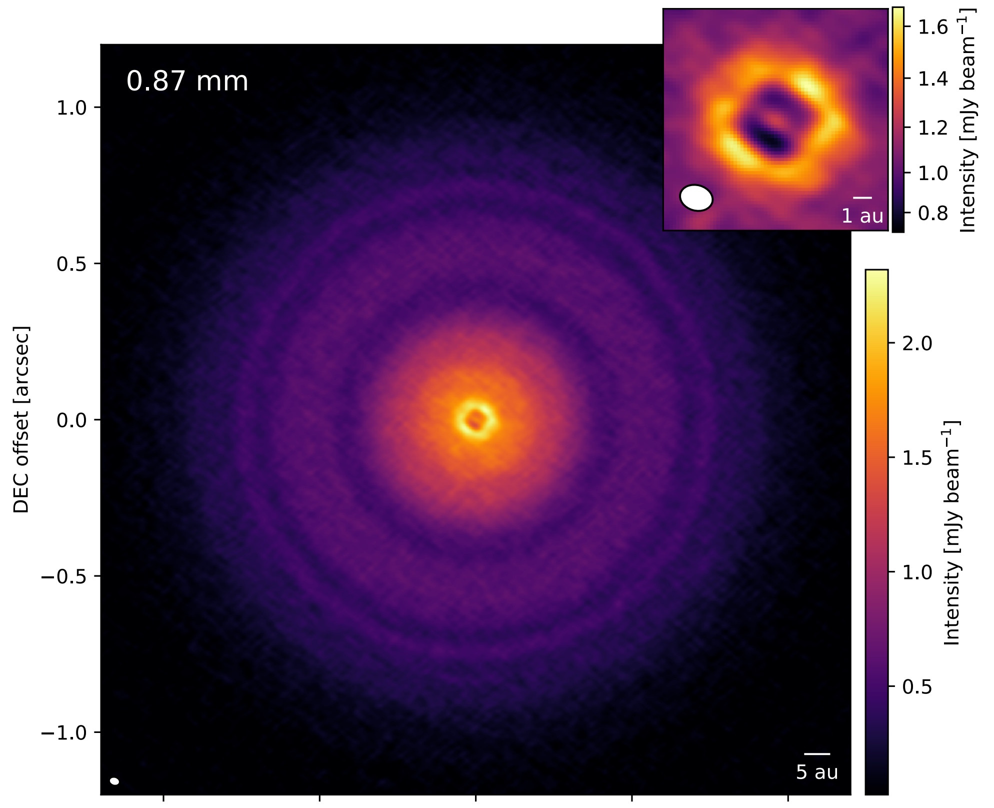
optically thick ring (α=2) + thin gaps (α≈3.7) = intermediate α

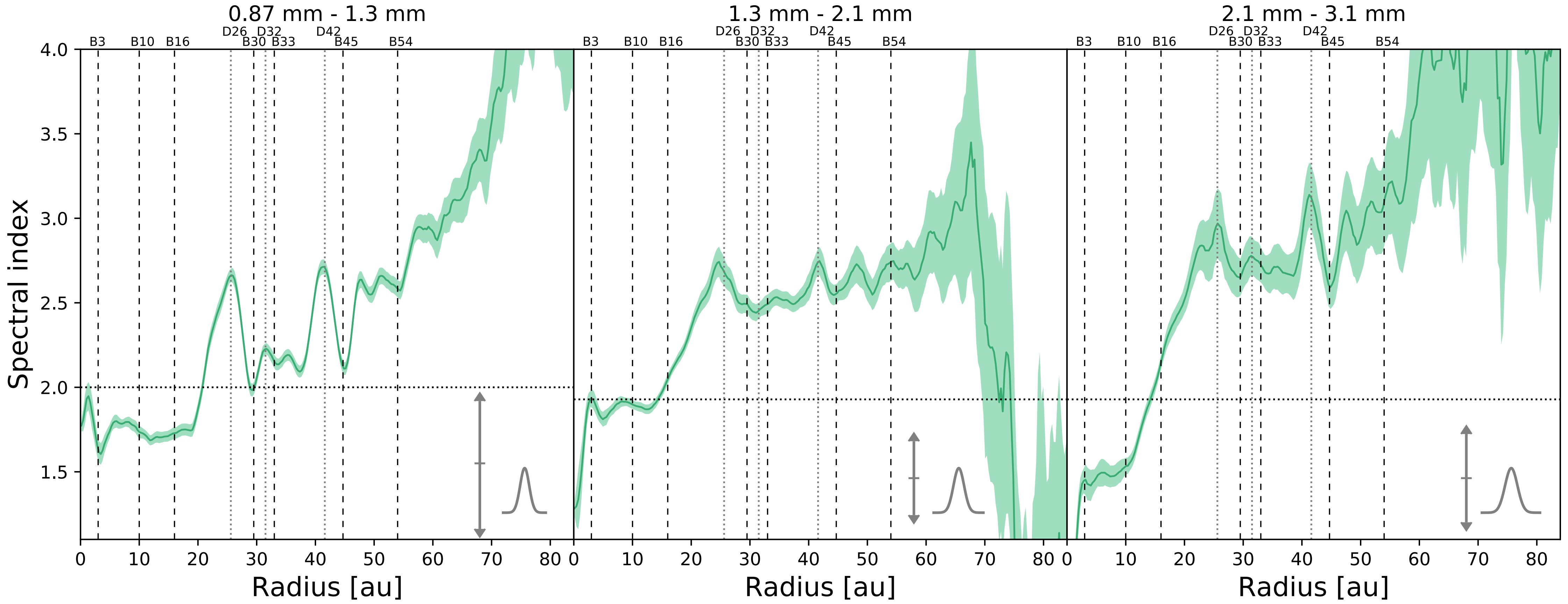
→Misinterpretation as grain growth?

Isella et al. 2007, Isella 2018; see Ricci et al. 2012

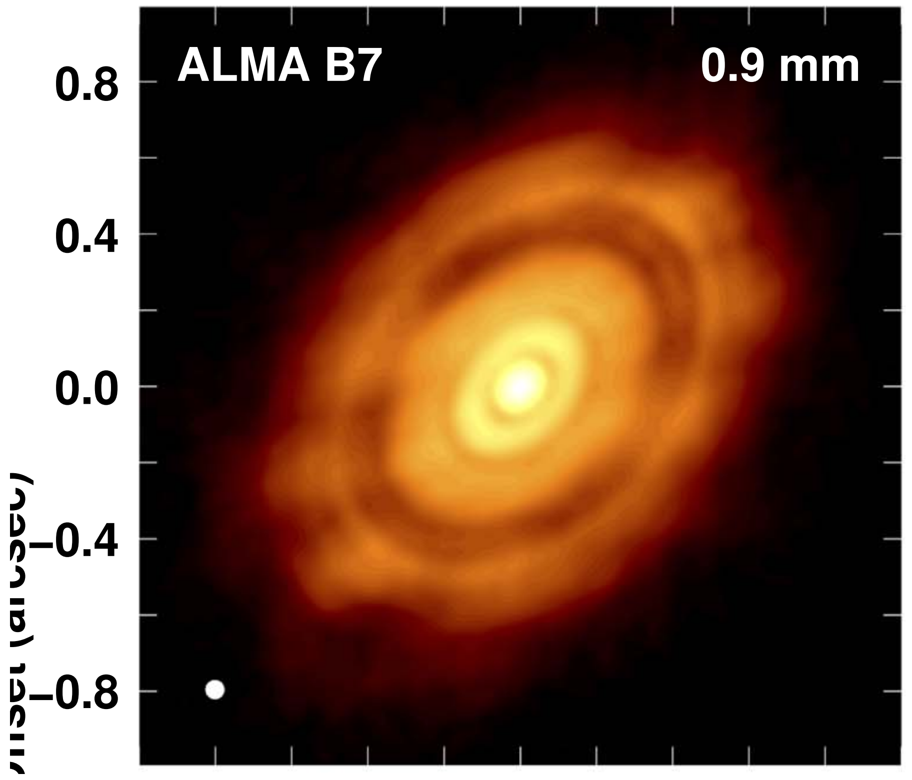
Spectral index and inferred grain size

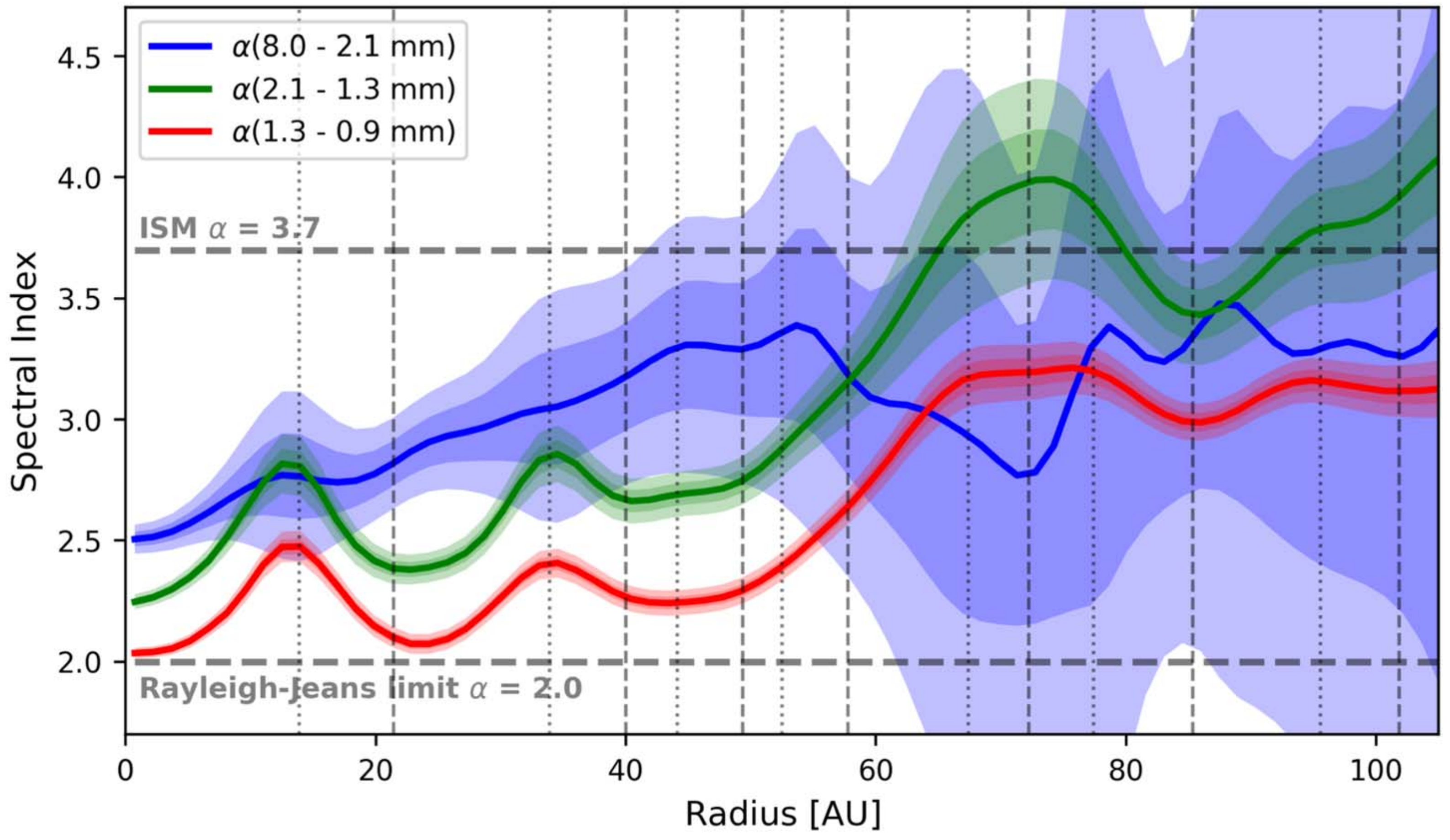
TW Hya





HL Tau



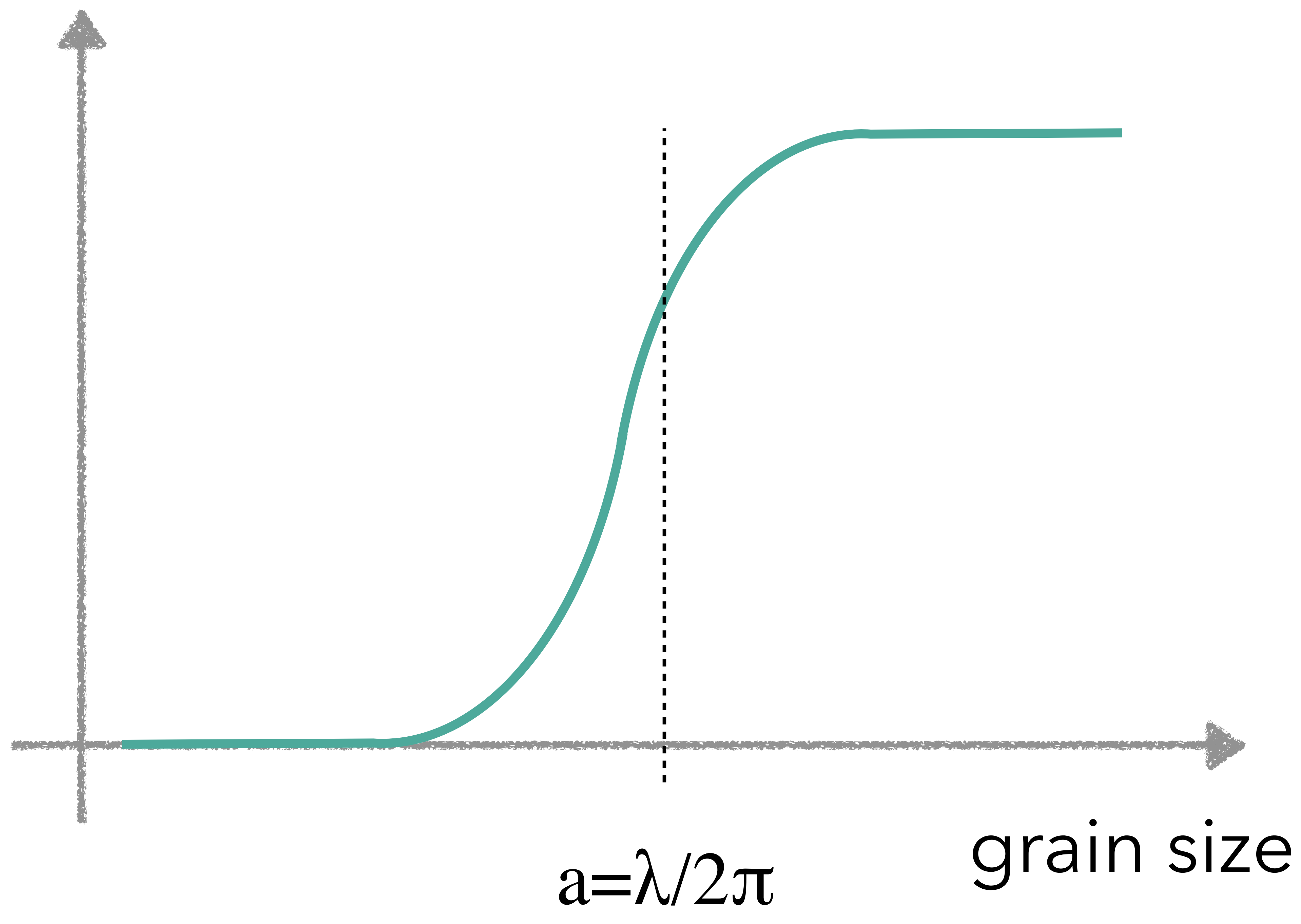


Macias et al. 2021, Carrasco-Gonzalez et al. 2019; see also Perez et al. 2012

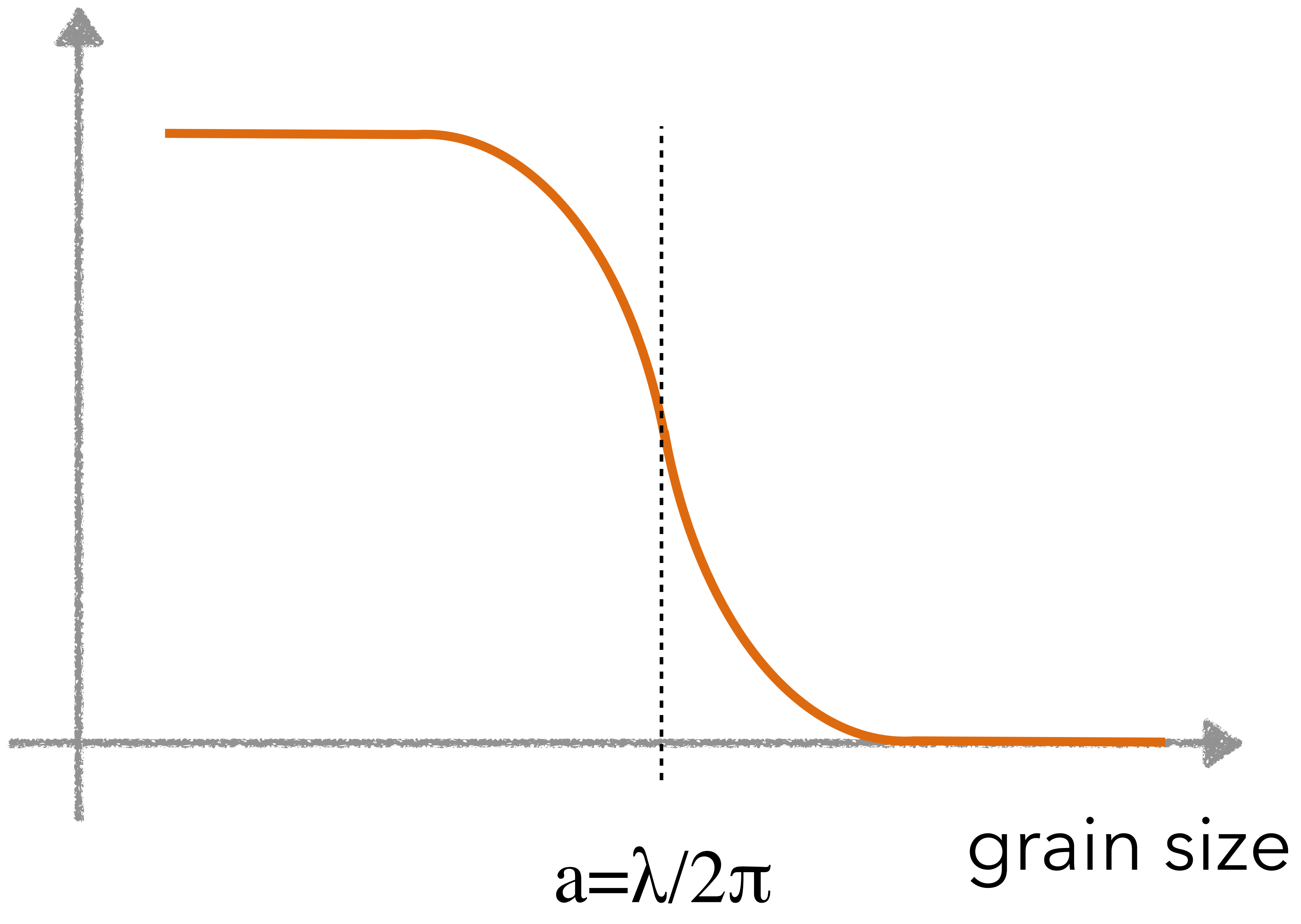
dust grain size inferred from self-scattering

Assumption: spherical dust grains

Albedo = efficiency of scattering



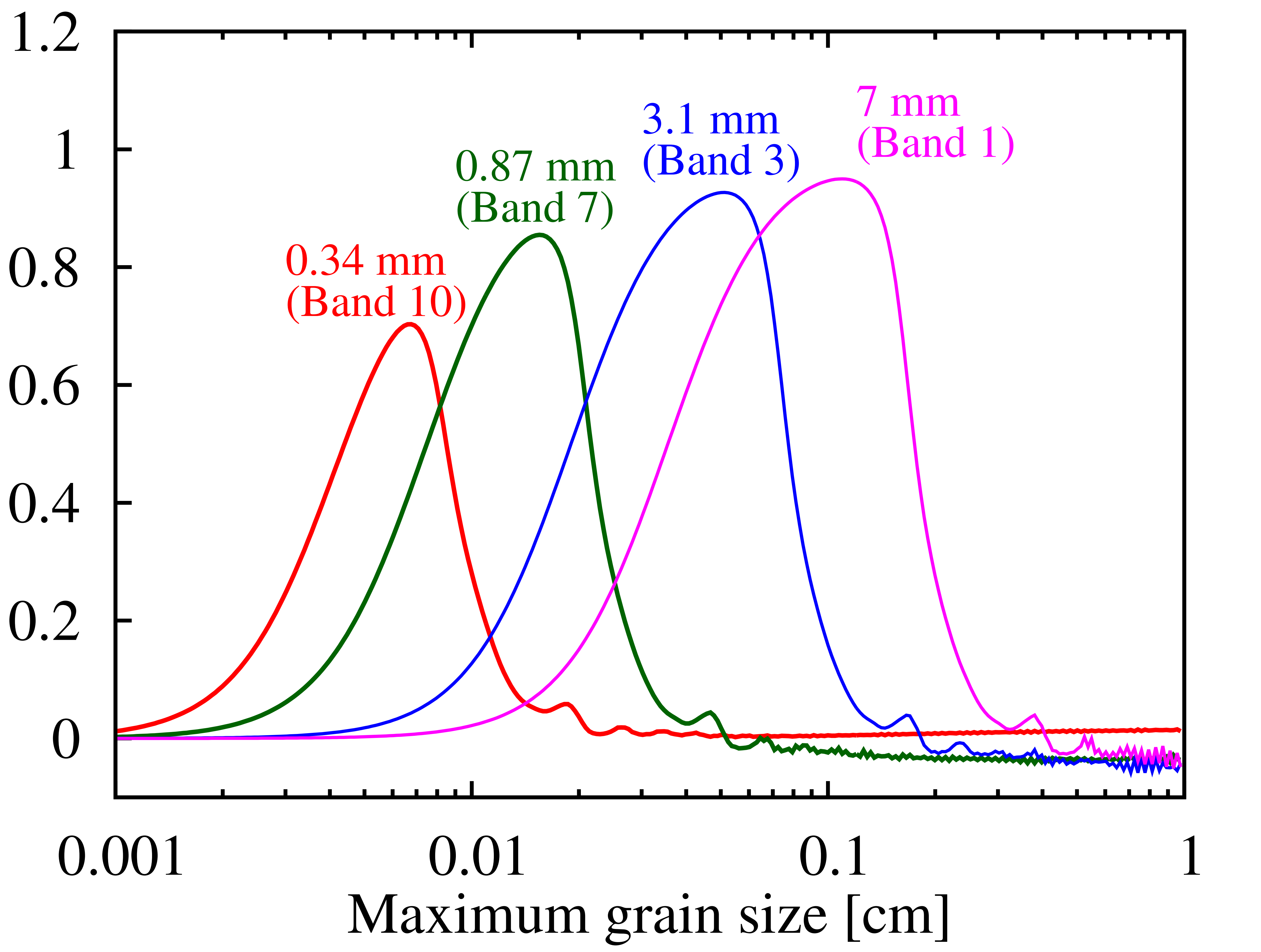
Polarization at single scattering



Scattering-induced polarization is detectable only when a=λ/2π

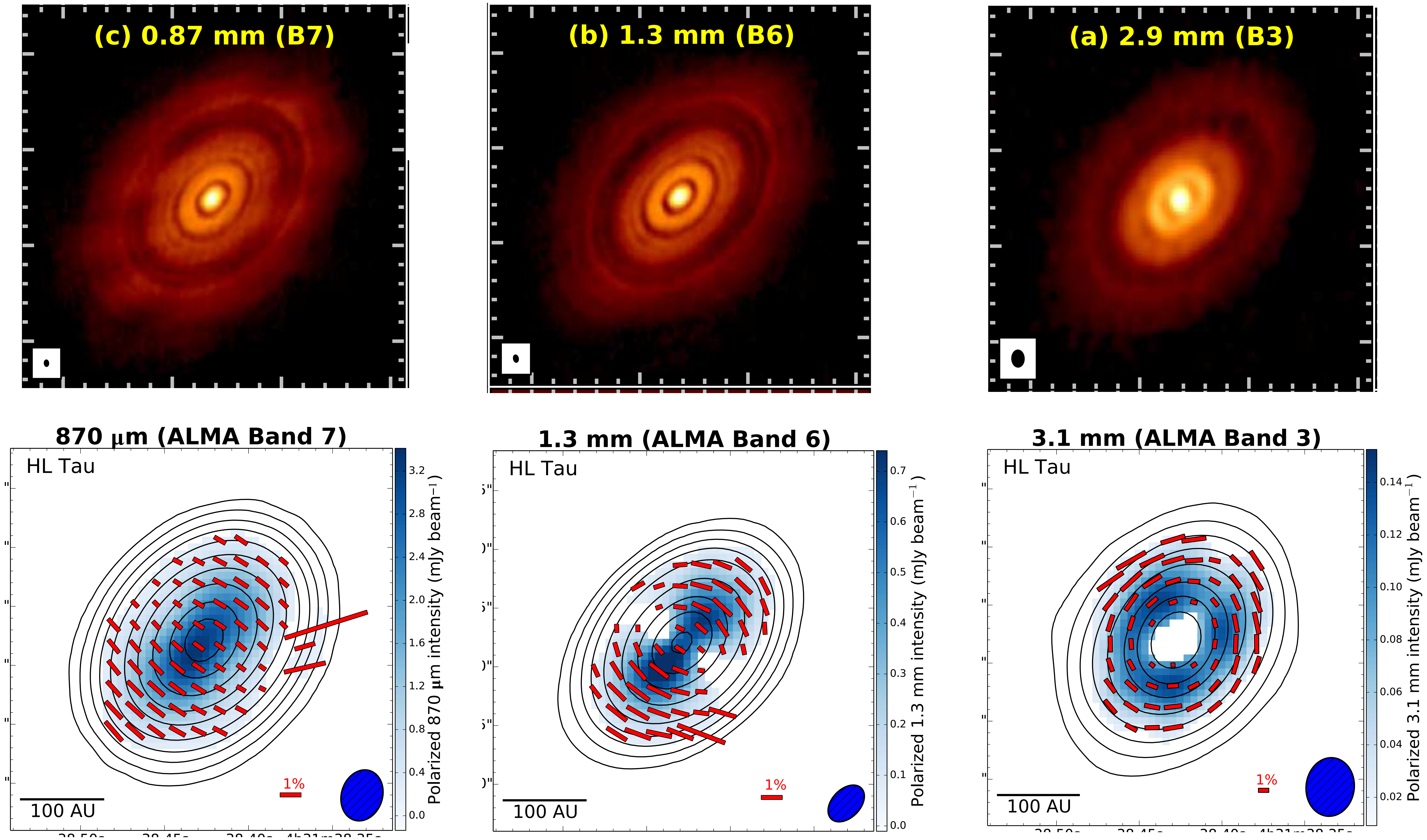
Grain size measurements by self-scattering

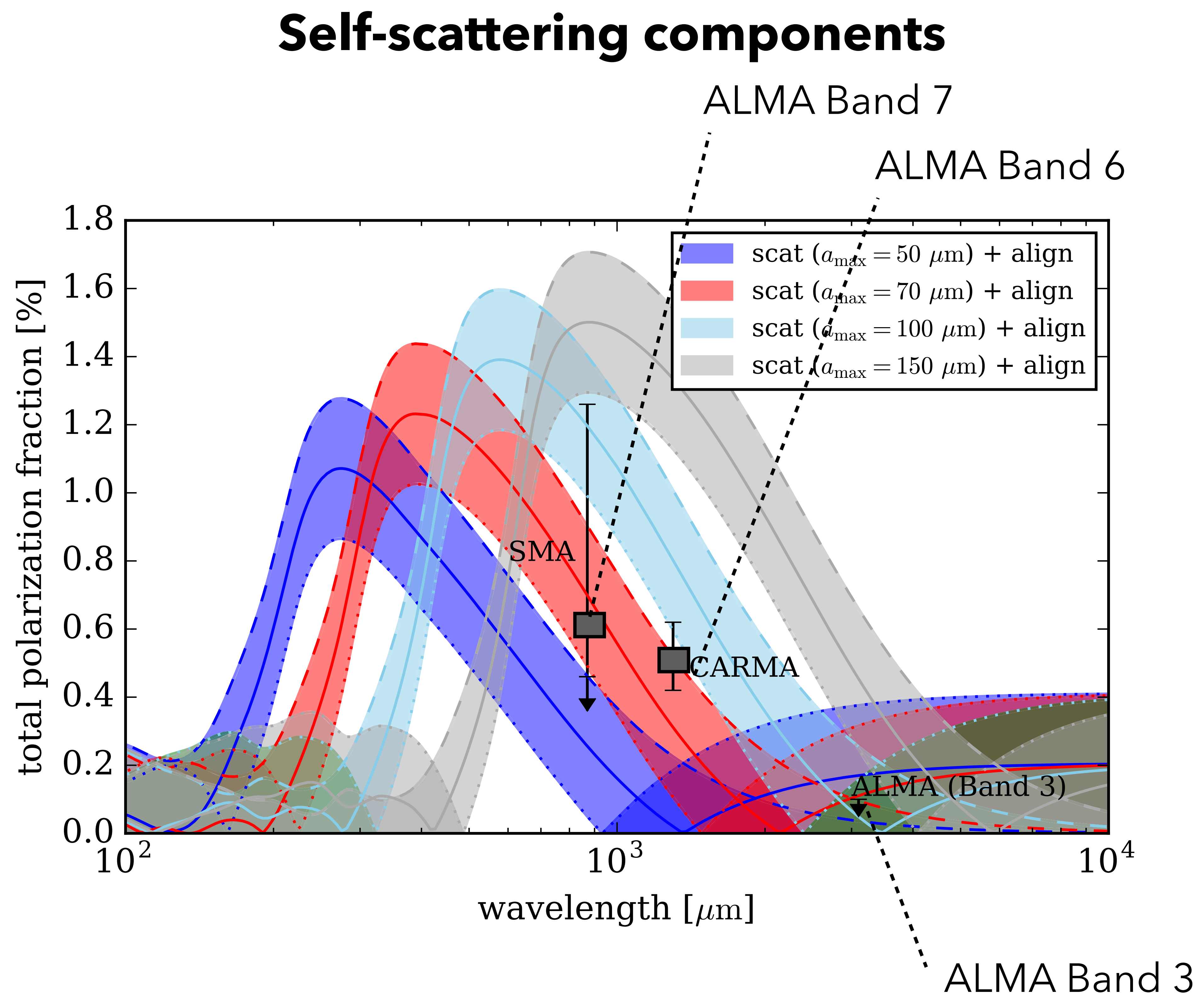
Prediction of polarization fraction



Kataoka et al., 2015

~100 μm sized grains?





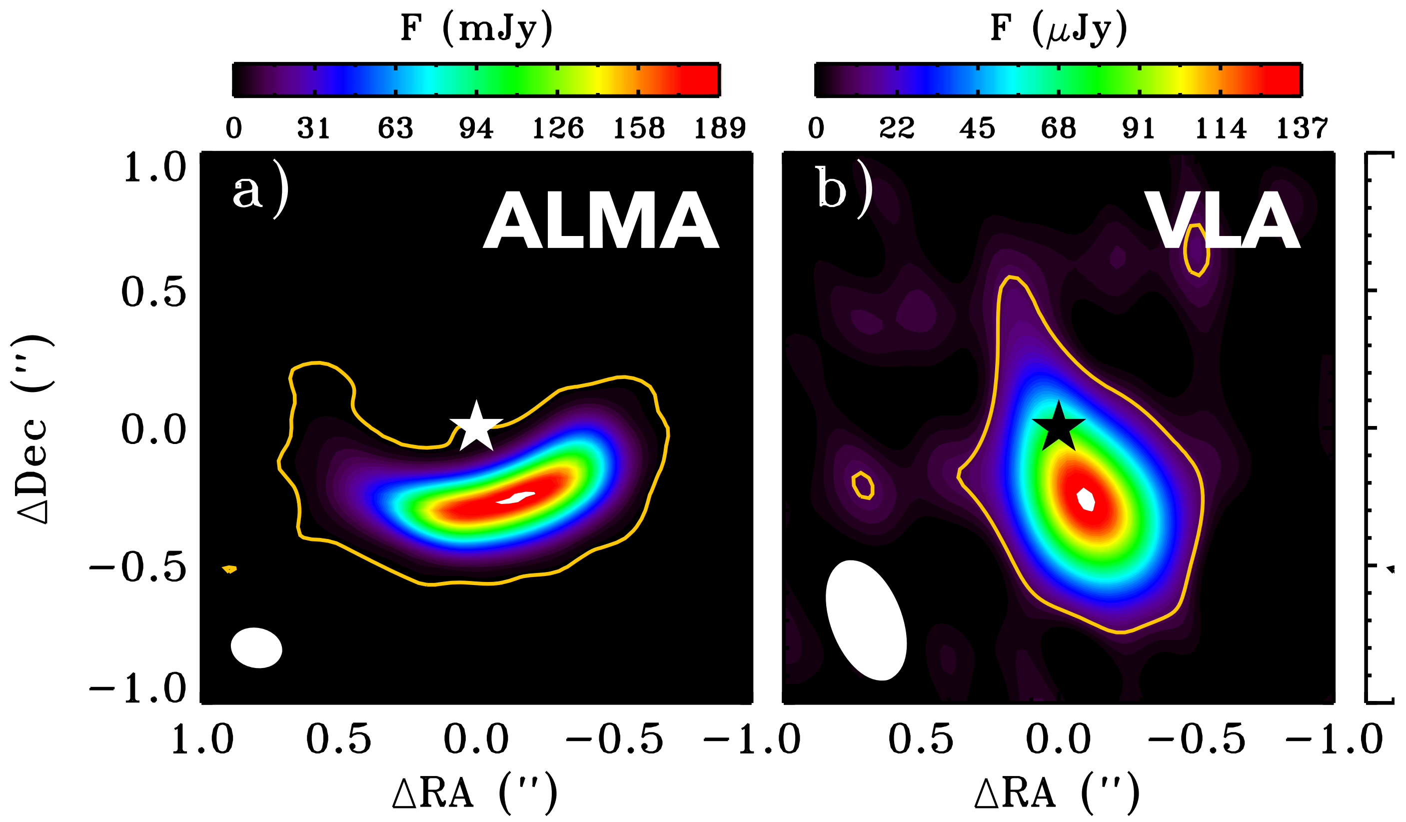
ALMA Partnership 2015, Stephens et al. 2017

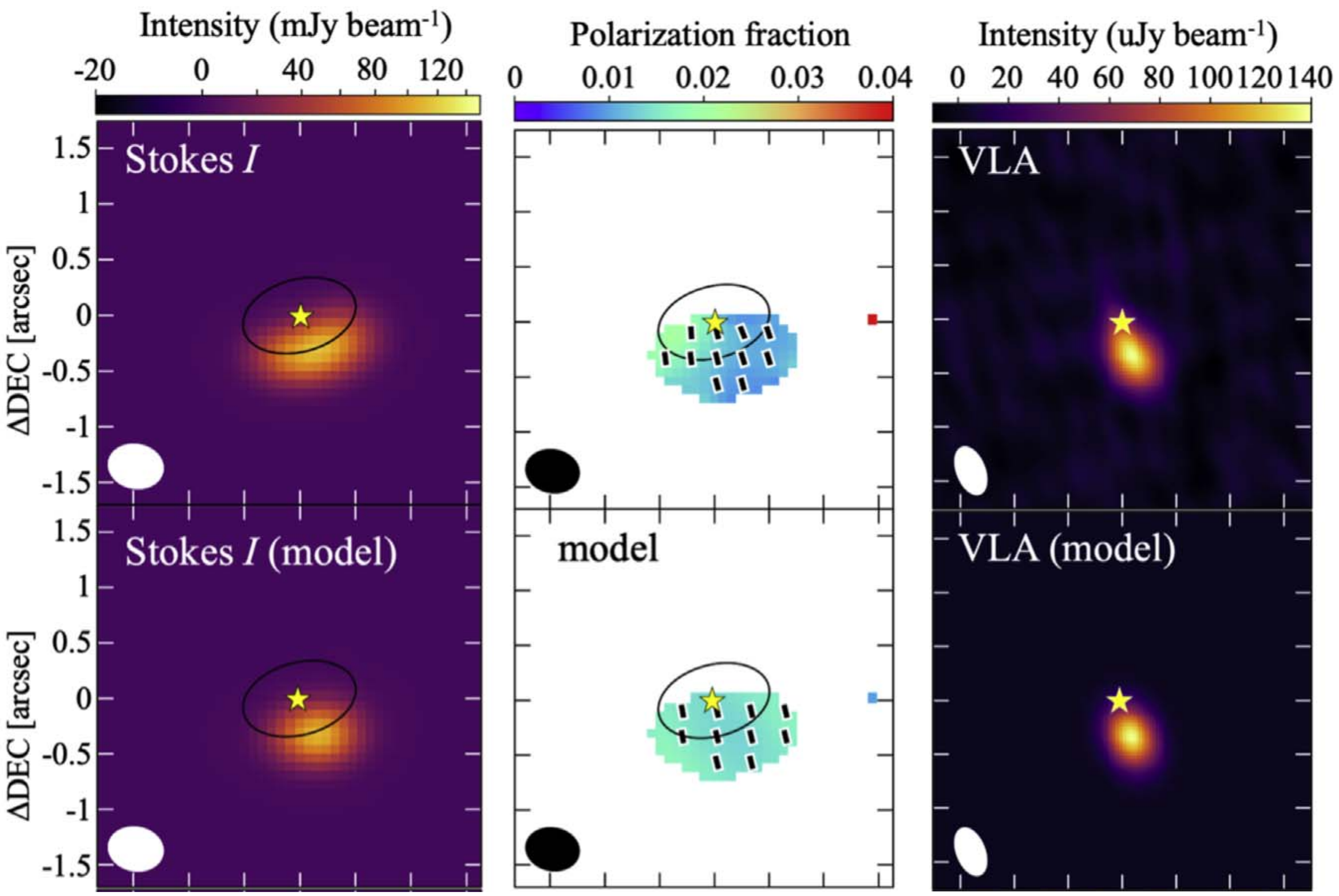
Kataoka et al. 2017, modified

How do we solve the problem?

spectral index vs. polarization

optically thick disk? case of IRS 48



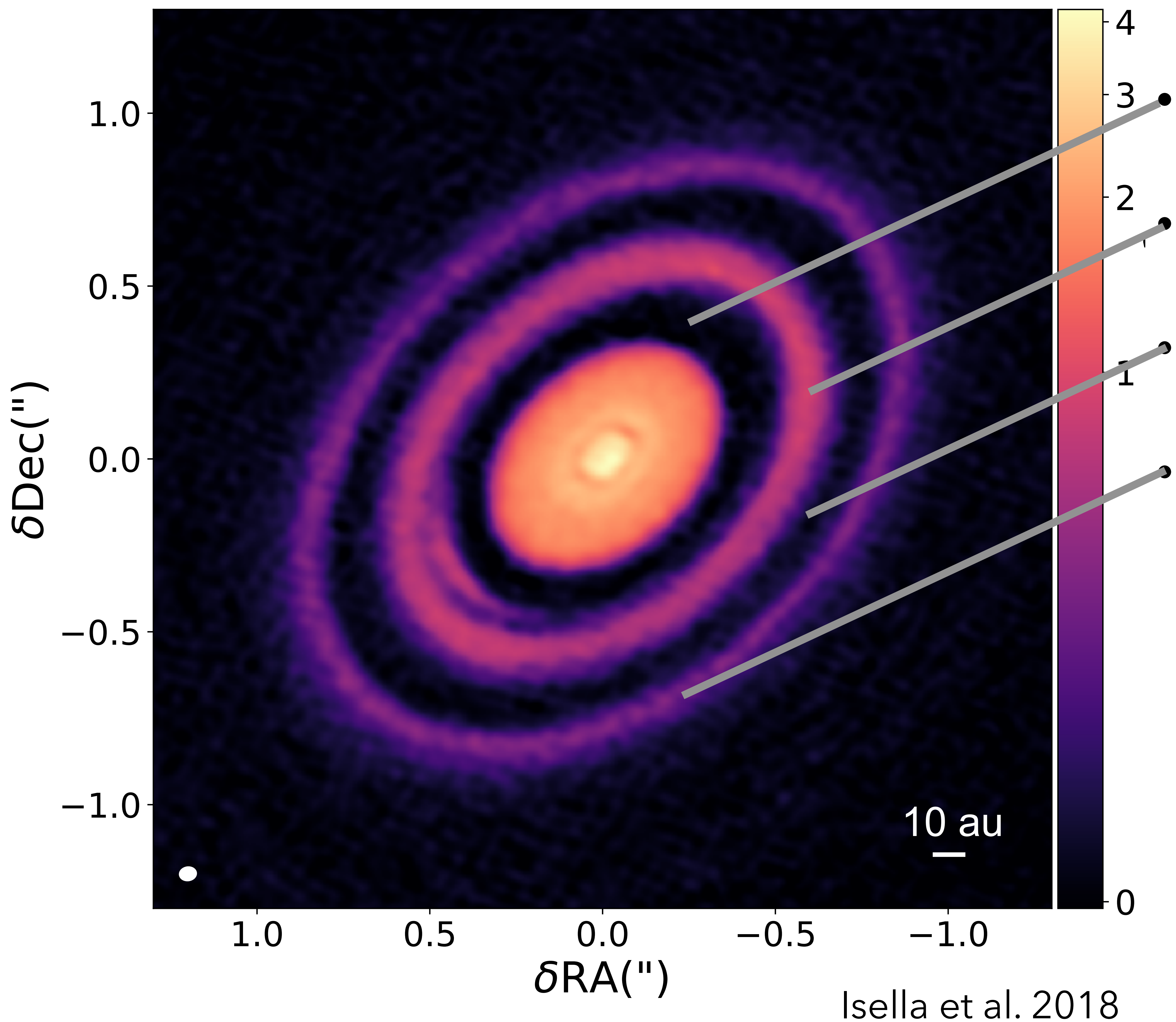


- How can we explain ALMA emission at 0.45 mm and bright emission at 8.8 mm (VLA)?
  - Concentrated centimeter size dust grains (van der Marel et al. 2015)
- But the model cannot explain new detection of polarization at 0.9 mm.
  - **Best model: extremely optically thick dust (τ ~ 7.3) at 0.9 mm**
  - large grains may be hidden at midplane, but not necessary

Ohashi, Kataoka, van der Marel, et al. 2020

Optically thick substructures? case of HD 163296

Continuum (ALMA Band 6, λ=1.3mm)



D45 gap

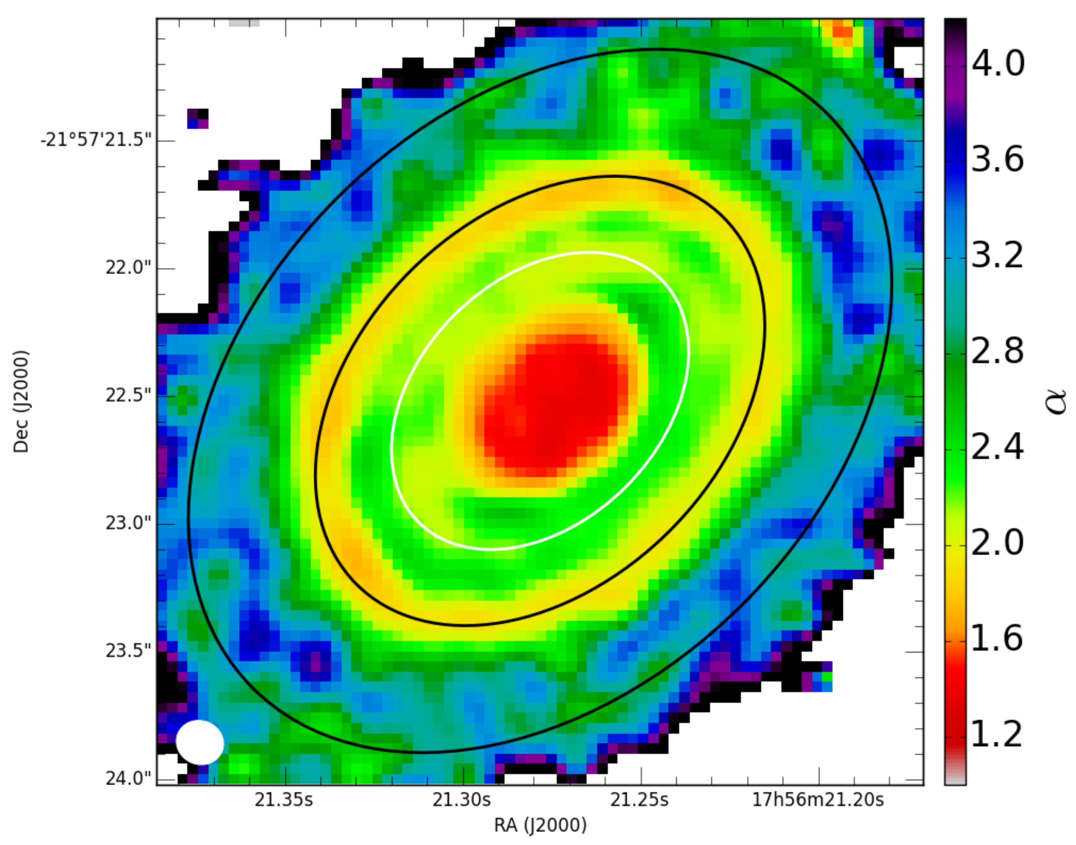
B67 ring

D86 gap

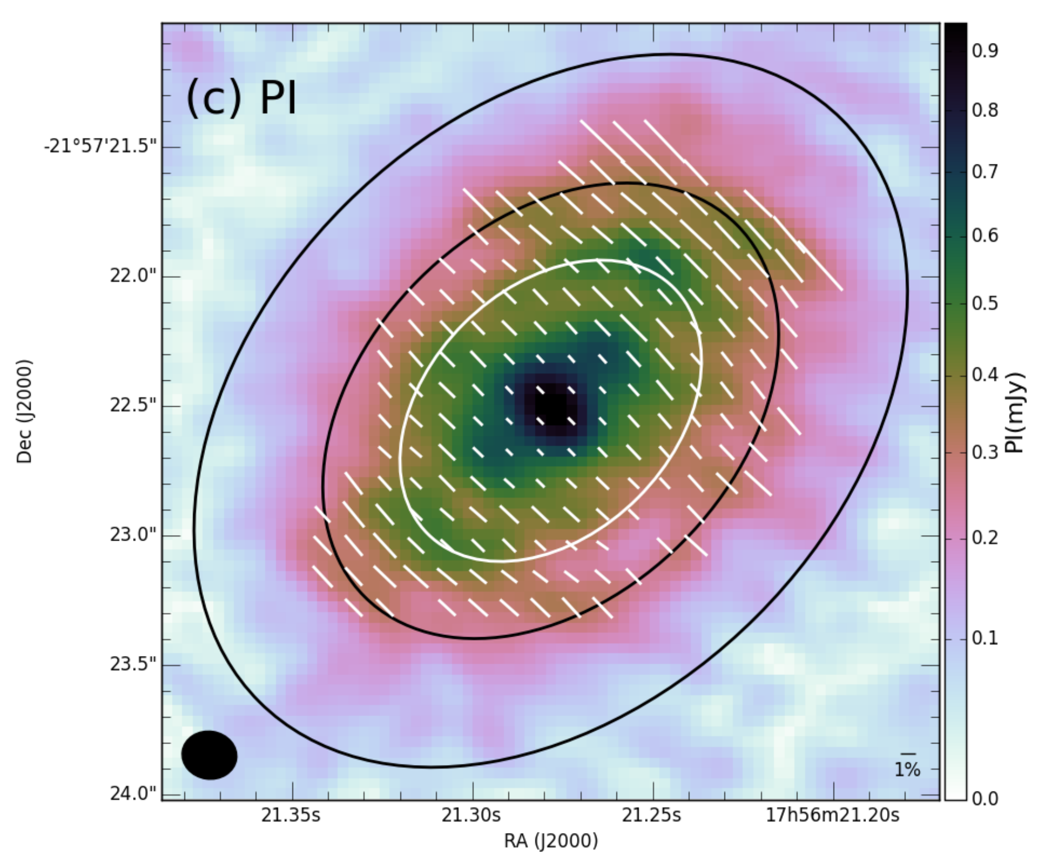
B100 ring

Isella et al. 2018

Spectral index

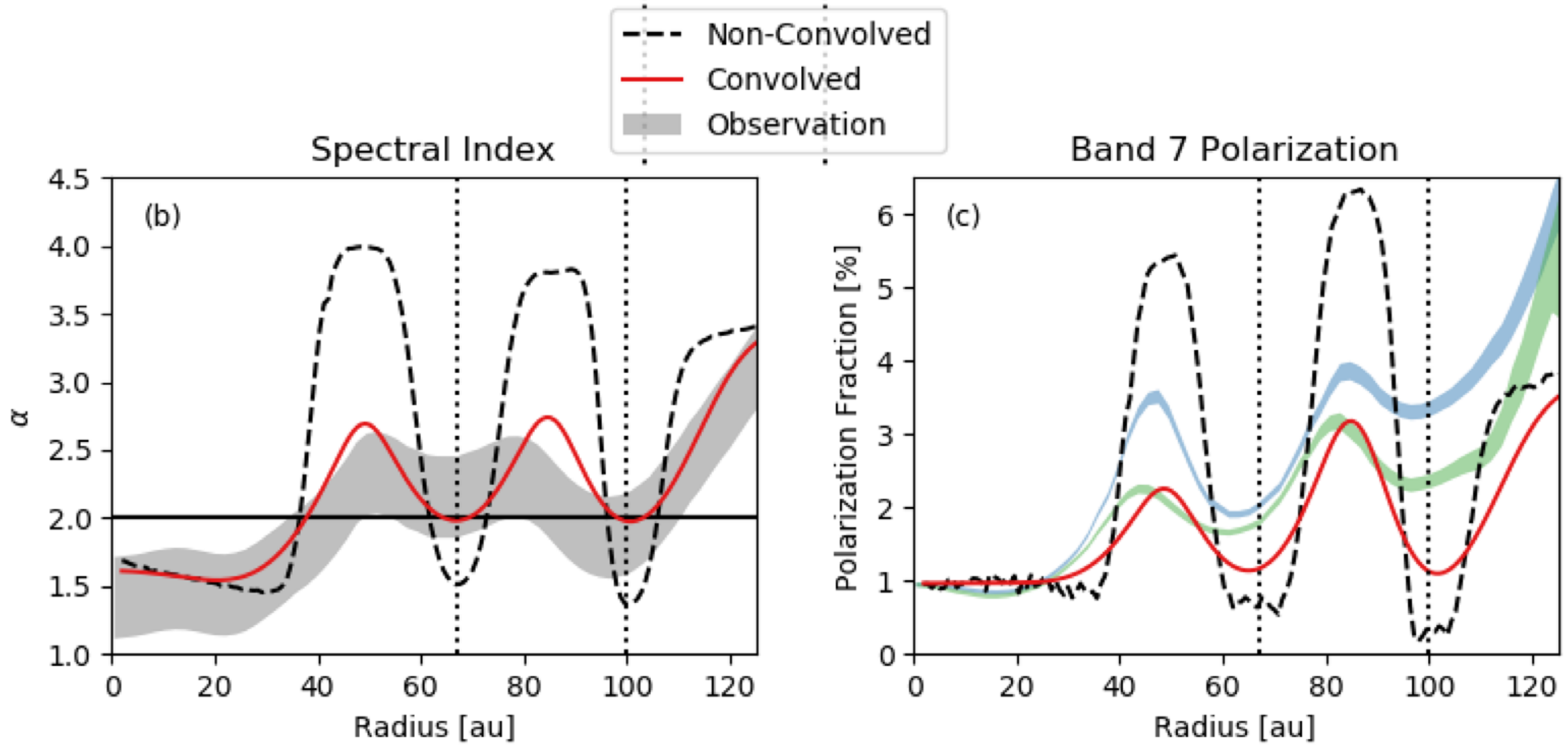


Polarization



Dent et al. 2018

Optically thick rings?

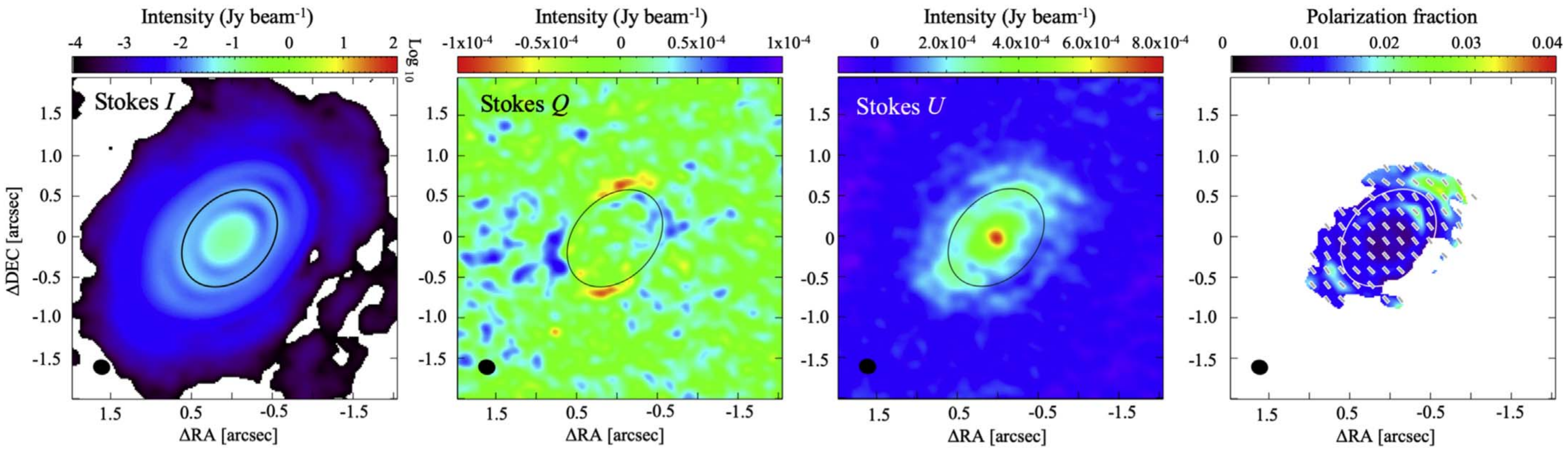


- Observations by Dent et al. 2019

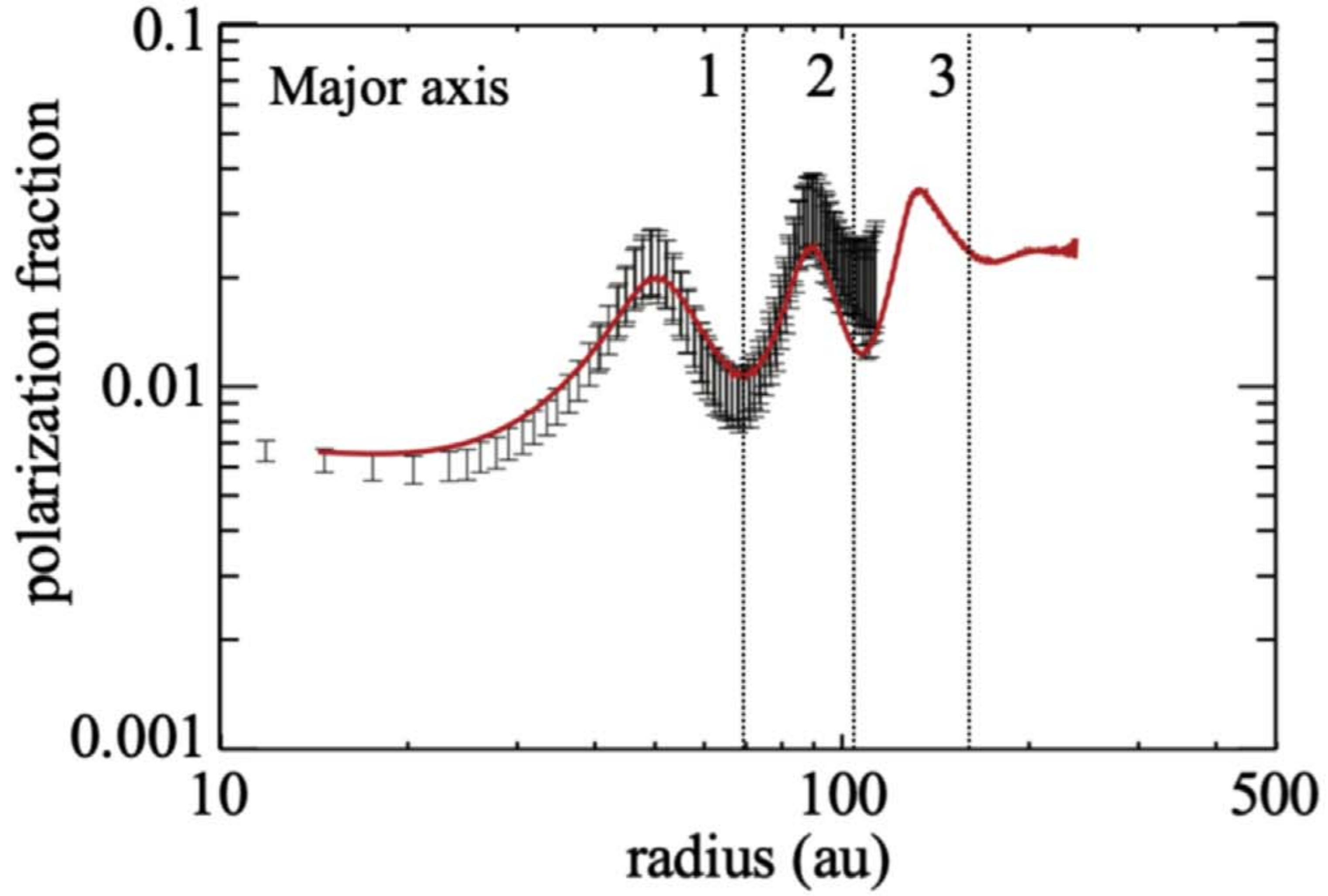
- Beam convolution of optically thick rings (α~2) and thin gaps (α~4) can explain both spectral index and polarization.

Daniel Zhe-Yu Lin et al. 2020

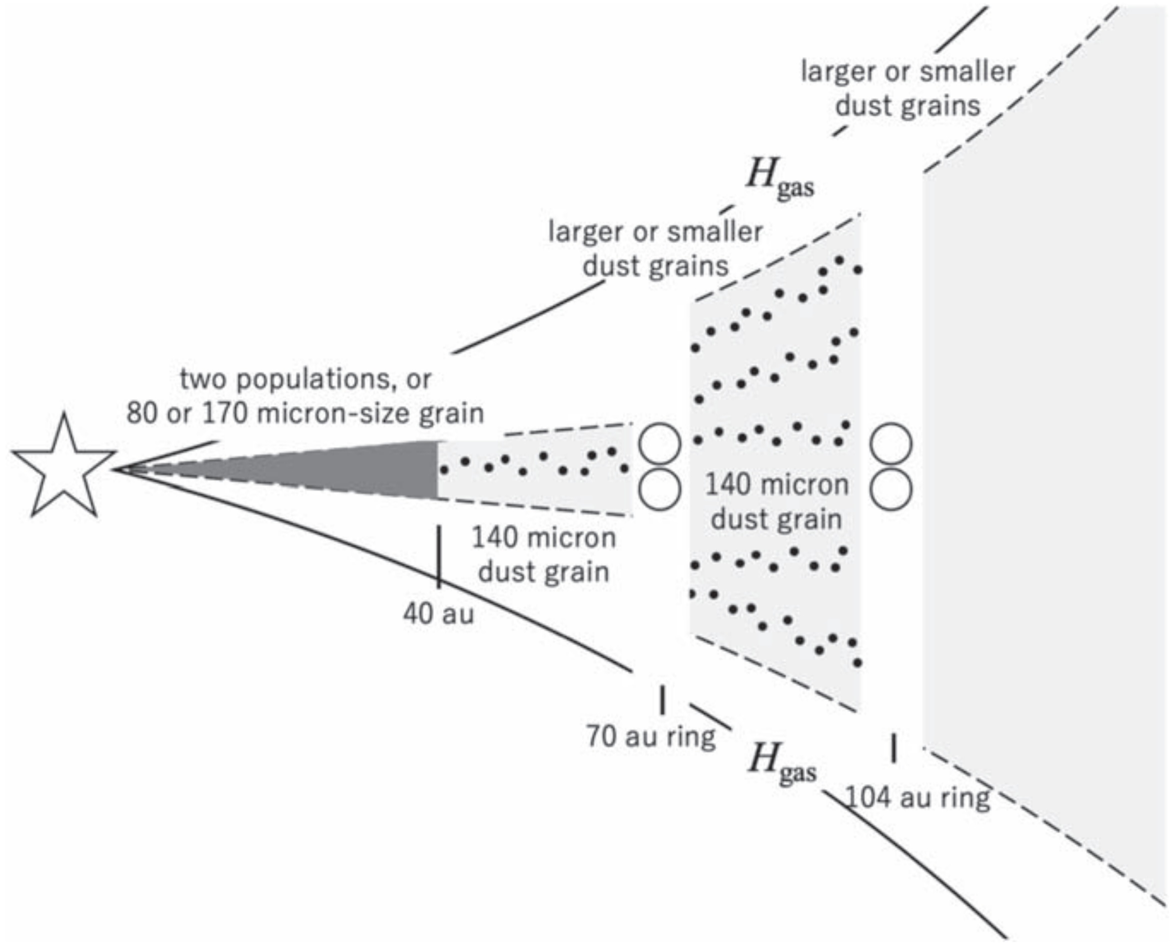
Polarization and substructures



Best fit model

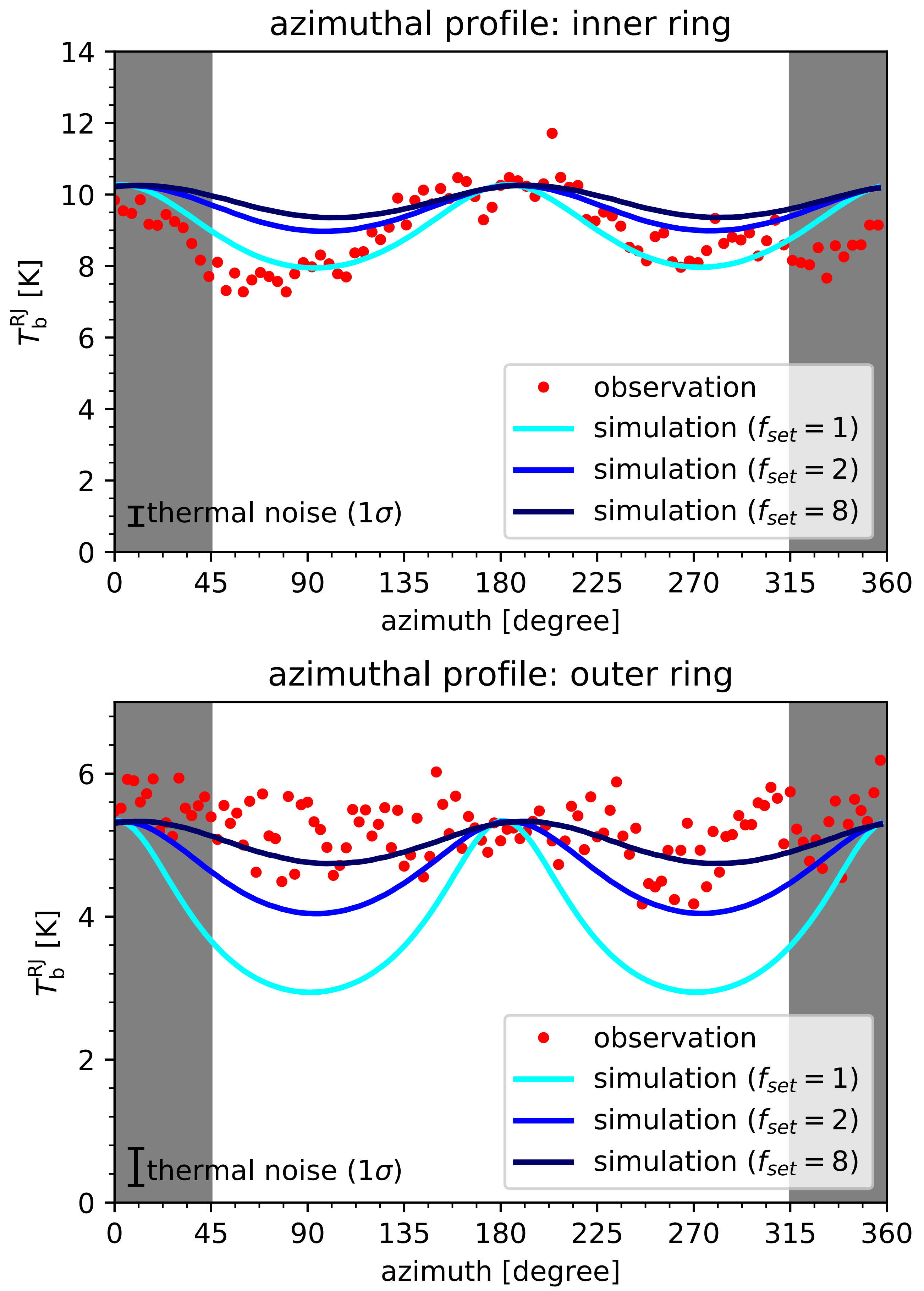


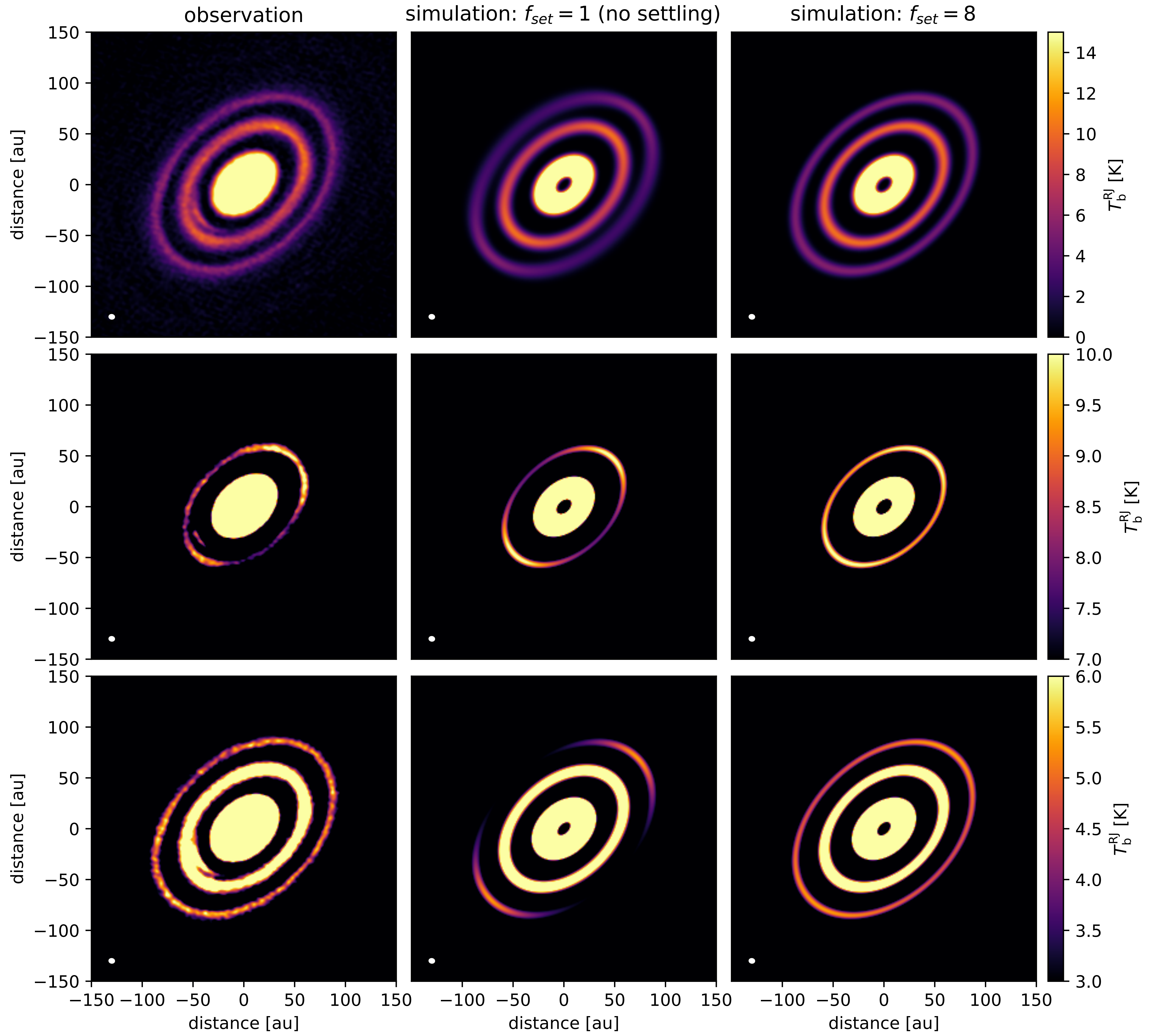
- **Observations: polarization fraction is higher at gaps and lower at rings**
  - Gaps: consistent with model with a_max = 140 μm, which has the maximum polarization efficiency.
  - Rings: size range around 140 μm is excluded. Consistent with millimeter size grains (but not necessary).



Ohashi and Kataoka 2019

Indirect measurements of dust size



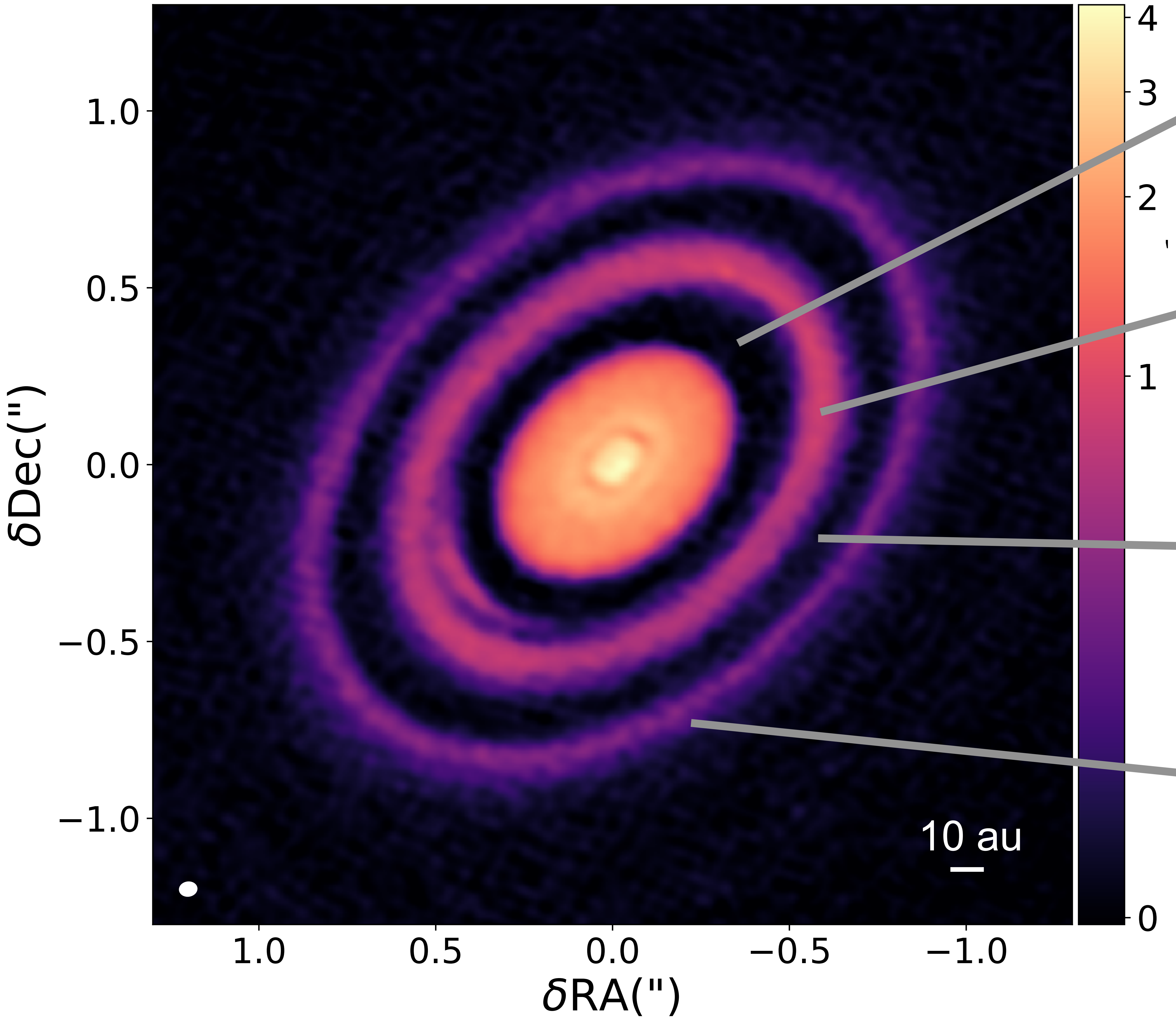


- **Inner ring (B67) is puffed up**
- **Outer ring (B100) is settled.**

Doi and Kataoka 2021

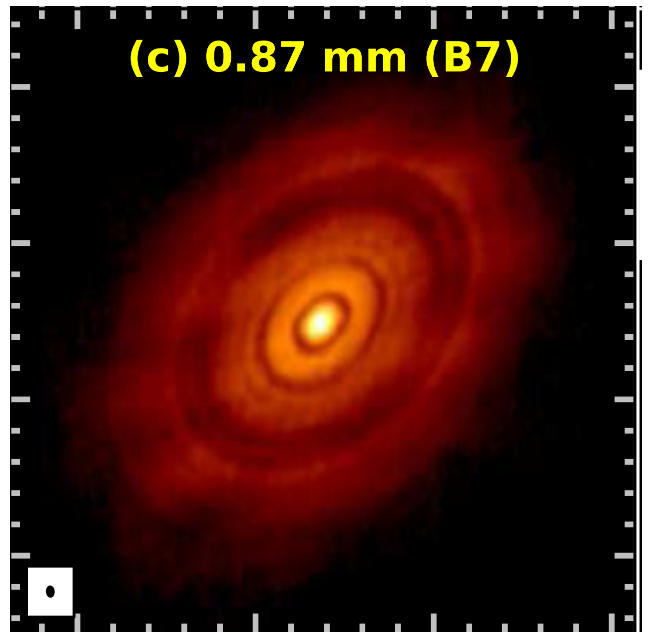
What we learned about HD 163296

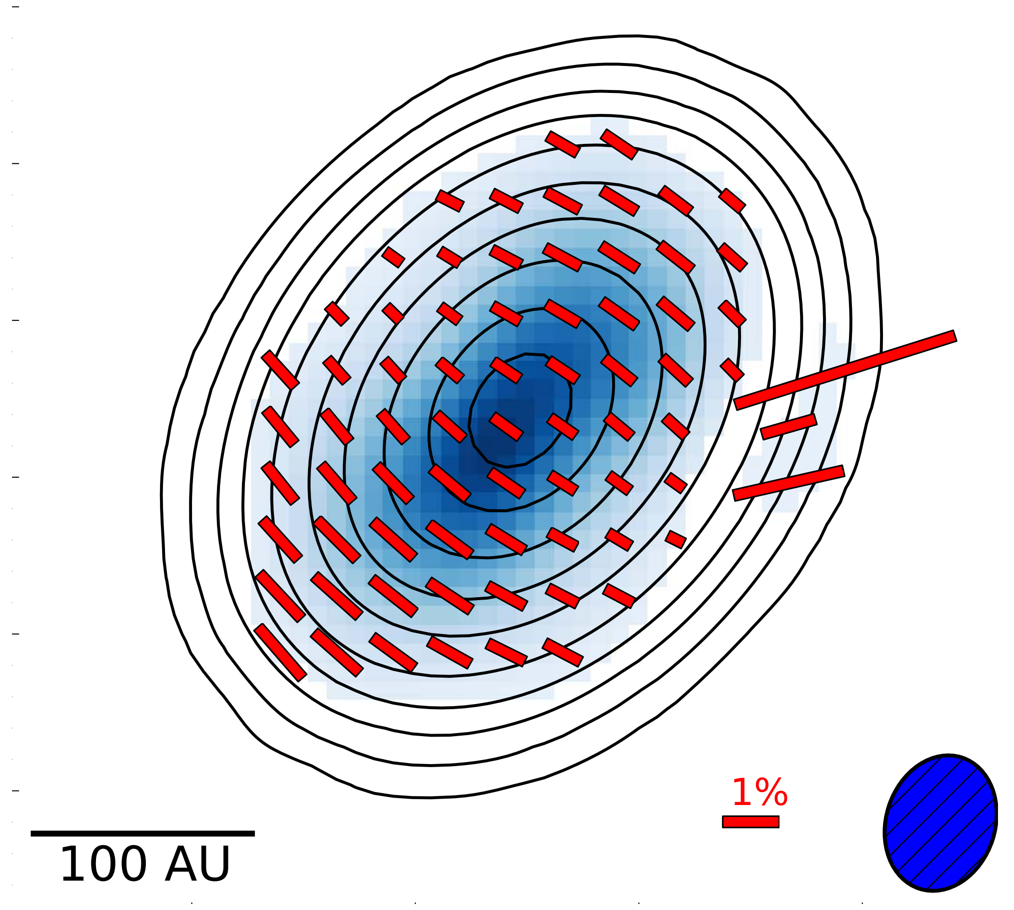
Continuum (ALMA Band 6, λ=1.3mm)



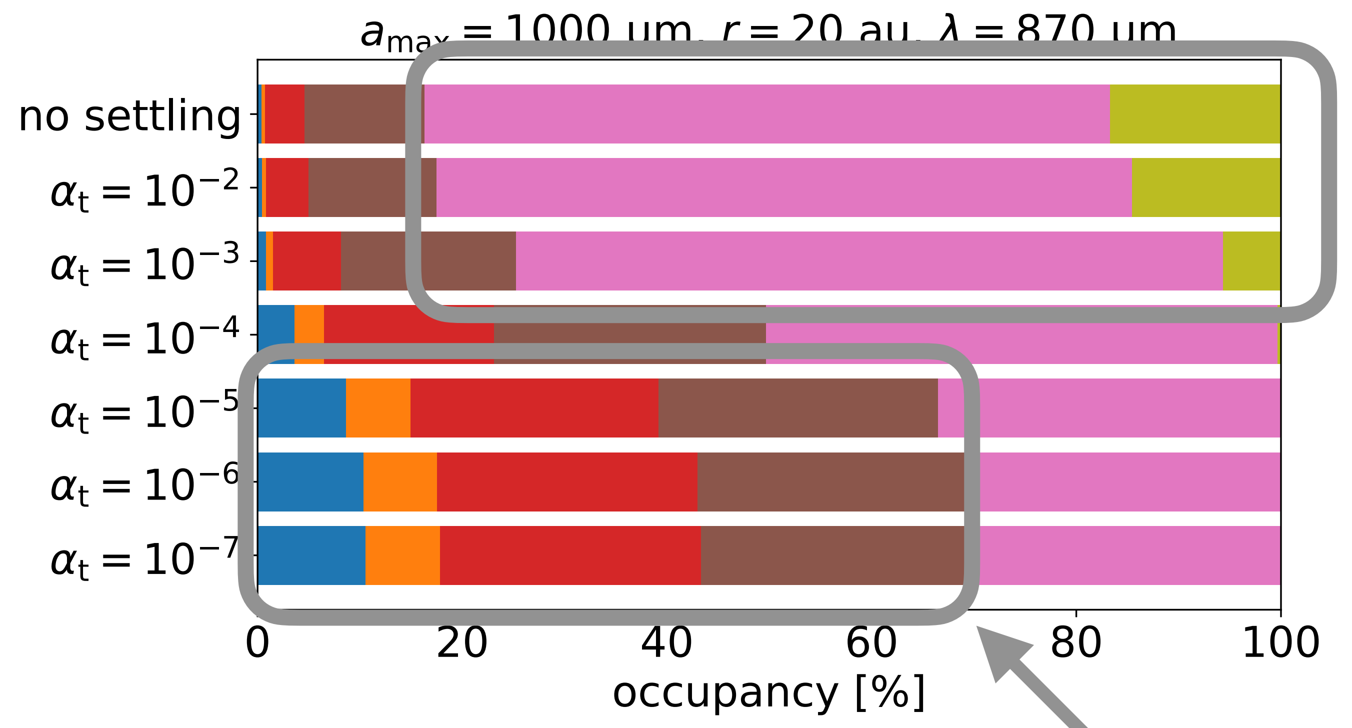
- **D45 gap**
  - Full of 140 μm grains (polarization)
- **B67 ring**
  - Low spectral index but puffed up. **optically thick small grains are likely**
- **D86 gap**
  - Full of 140 μm grains (polarization)
- **B100 ring**
  - Low spectral index and settled. **Millimeter-centimeter grains are likely.**

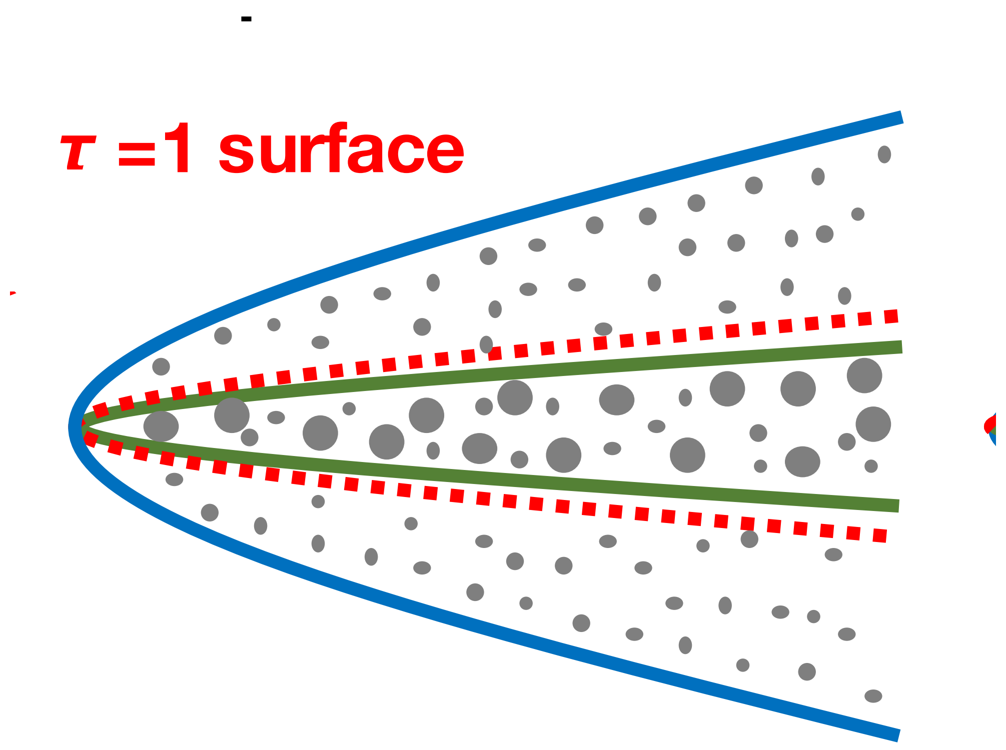
Do optically thick components solve everything?



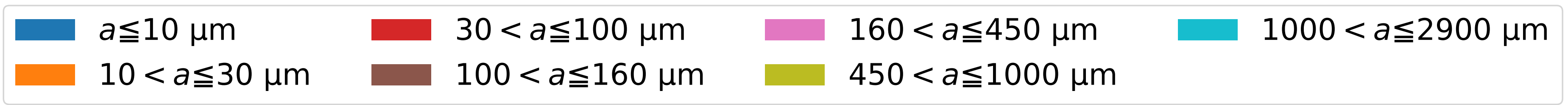


high a ; large dust grains dominates the emission





low a; small dust grains dominates the emission



We assume n∝a^{-3.5}, and set a_max=1 mm and change vertical turbulence strength

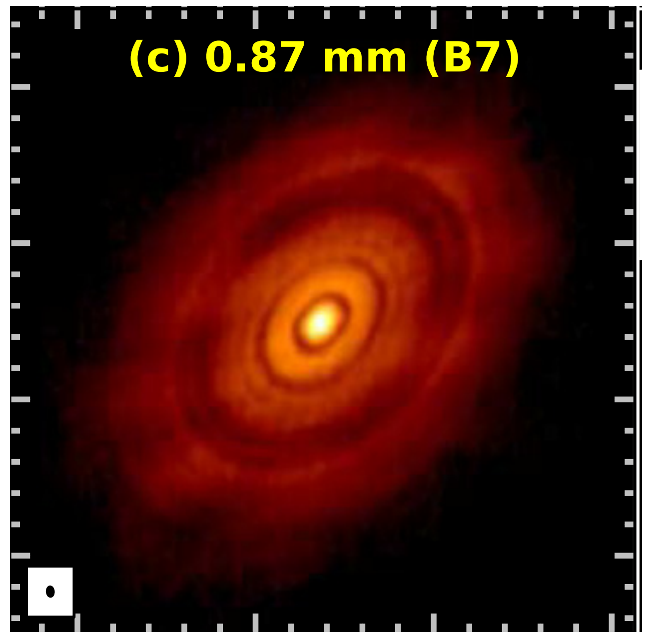
Modeling on the SED and polarization of the **central part** of HL Tau

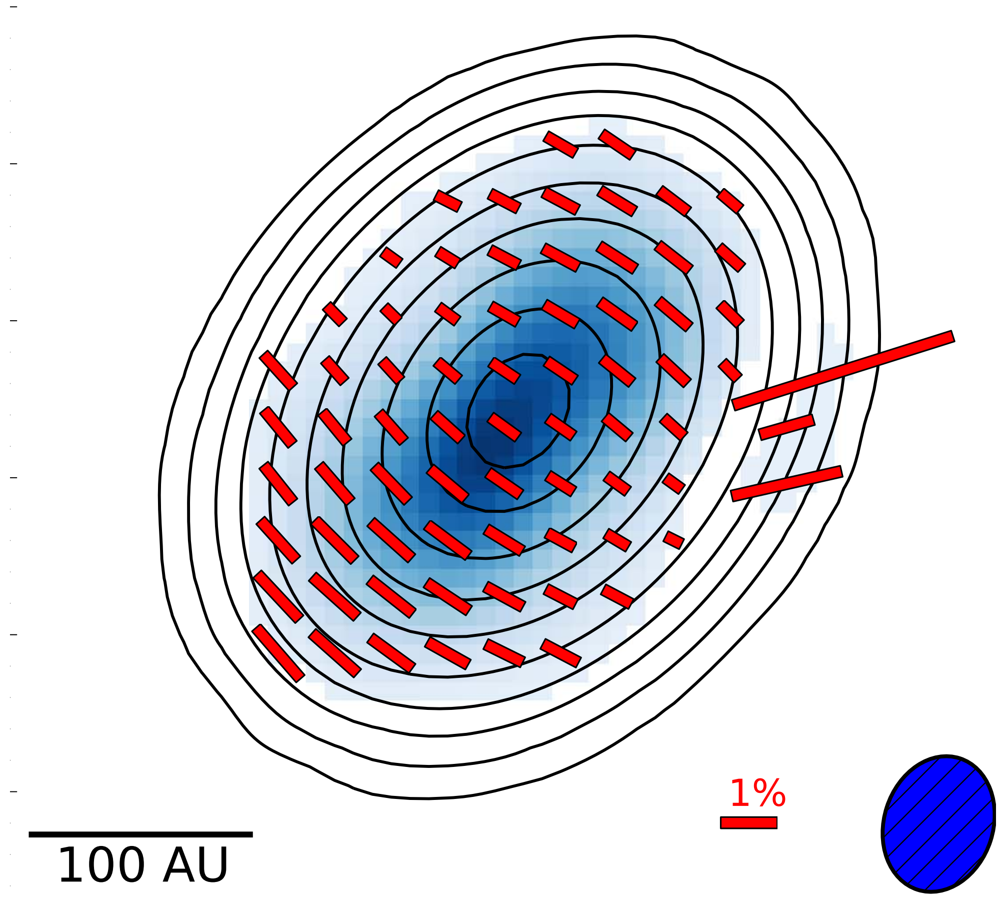
- Turbulent a must be lower than 10^{-5}

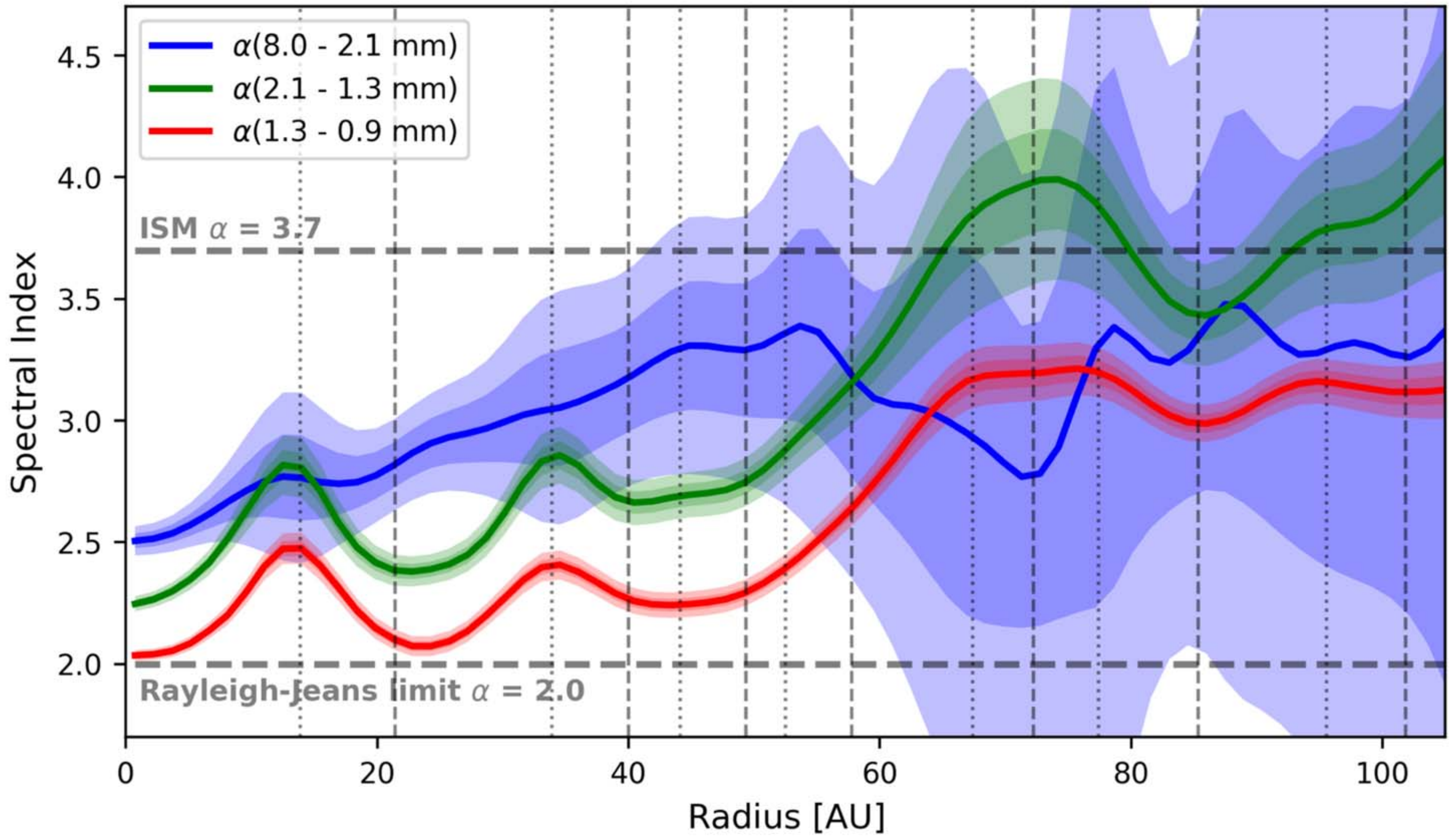
ALMA Partnership 2015, Stephens et al. 2017, Carrasco-Gonzalez et al. 2019

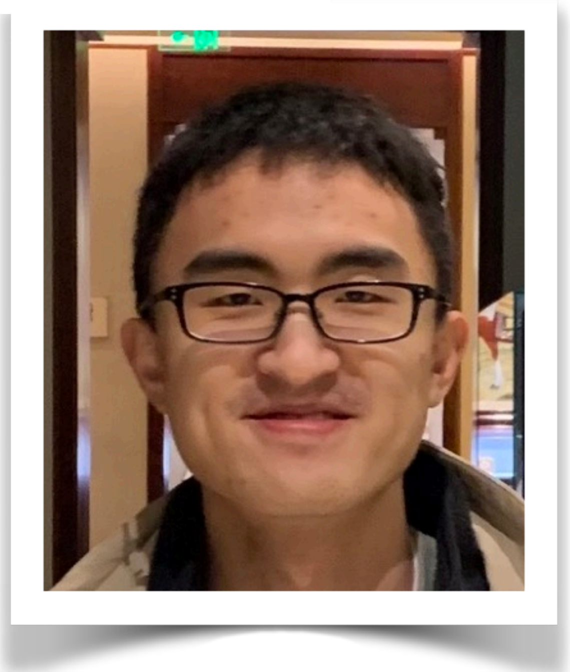
Ueda, Kataoka et al. 2021

Do optically thick components solve everything?









Outer part of the disk (>60 au) is optically thin but emitting self-scattering polarization

- Millimeter dust grains are unlikely

- Porosity must be included to reproduce spectral index.

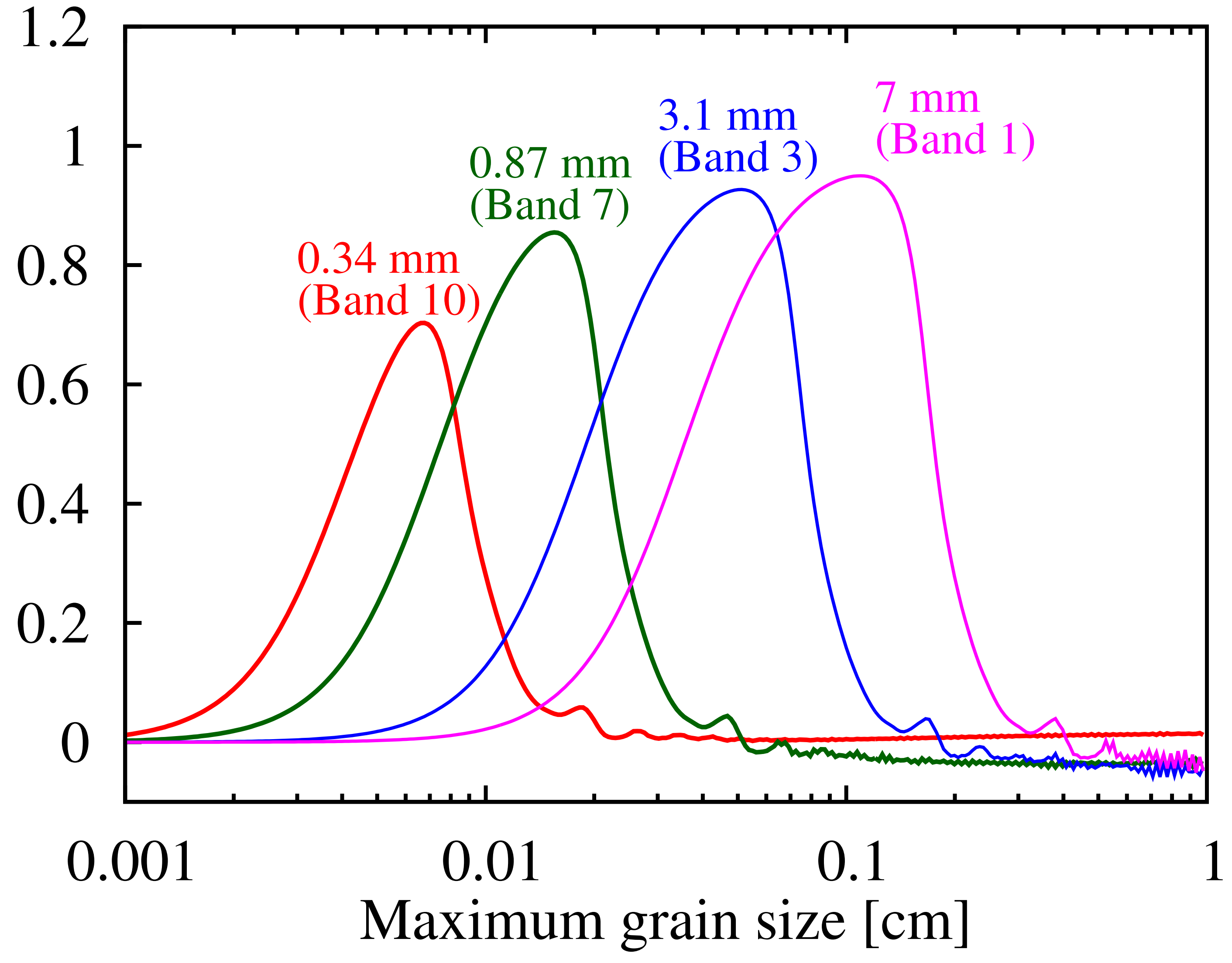
ALMA Partnership 2015, Stephens et al. 2017, Carrasco-Gonzalez et al. 2019

Shanjia Zhang et al., in prep.

Short summary: where are millimeter dust size grains?

- **We want to explain both detection of polarization at 0.9 mm and low spectral index at millimeter wavelengths.**
  - We need optically thick components, which reduces the spectral index.
  - If the dust grains have size of millimeter but hidden in midplane, the disk turbulence must be low (such as α to be 1e-5).
    - Otherwise, millimeter dust grains are stirred up and polarization becomes weaker
  - If the emission is optically thin and dust grains are large (~mm), polarization is too weak to be detected.

Prediction of polarization fraction



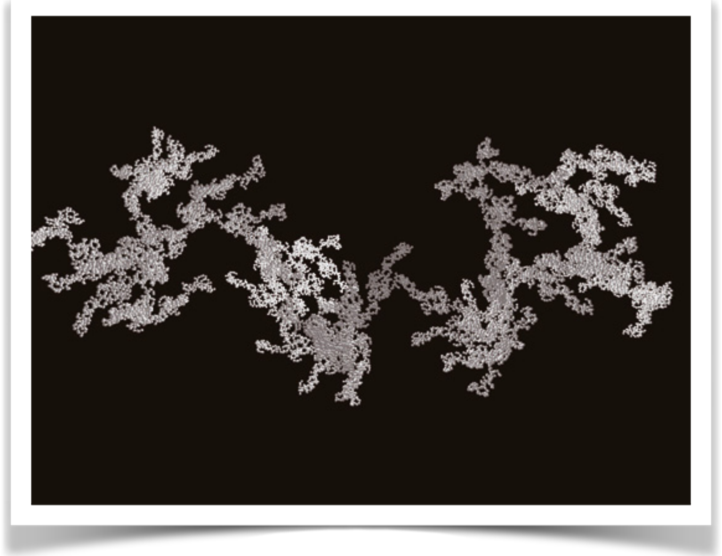
Kataoka et al., 2015

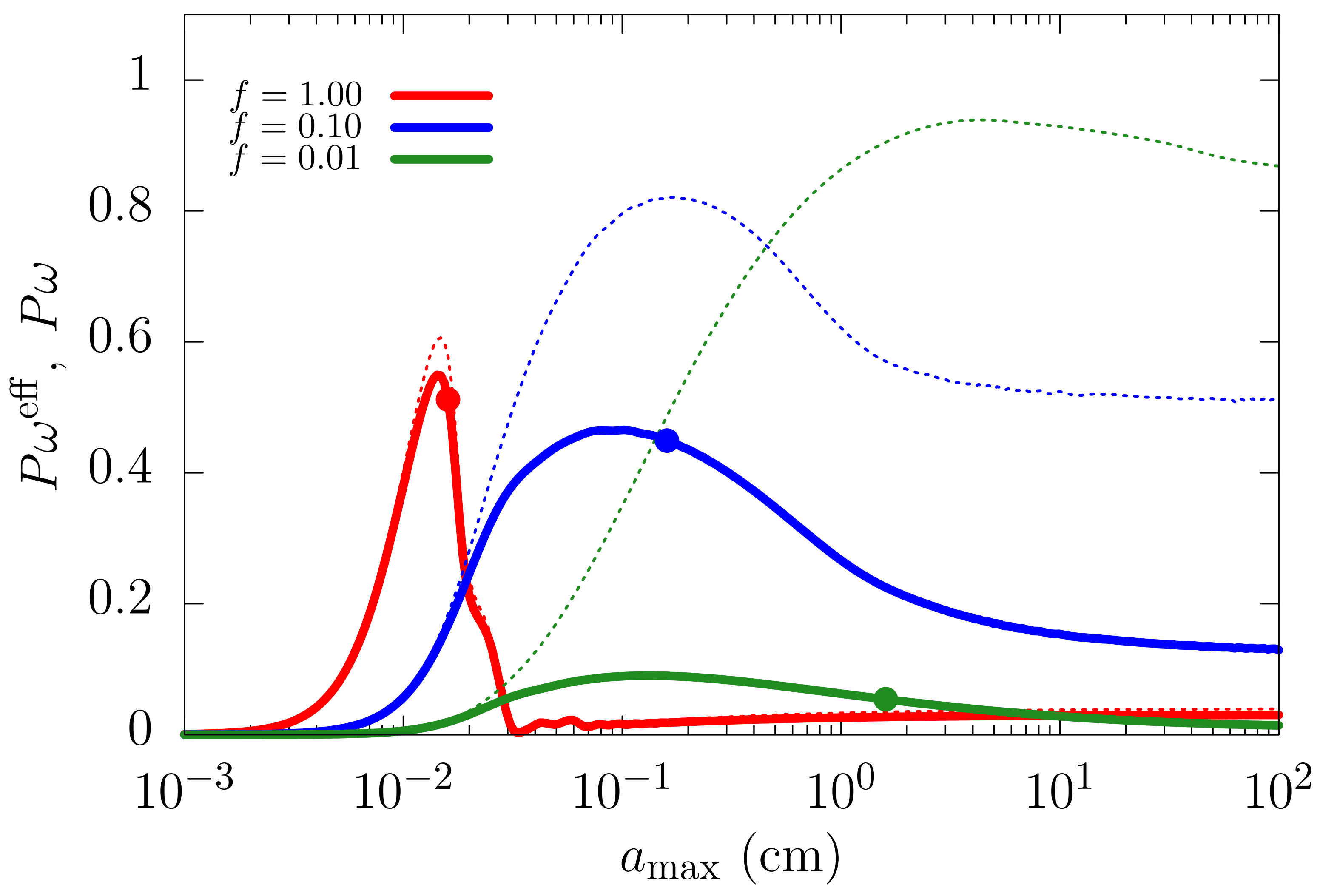
Dust microphysics

porosity? needle-like dust grains?

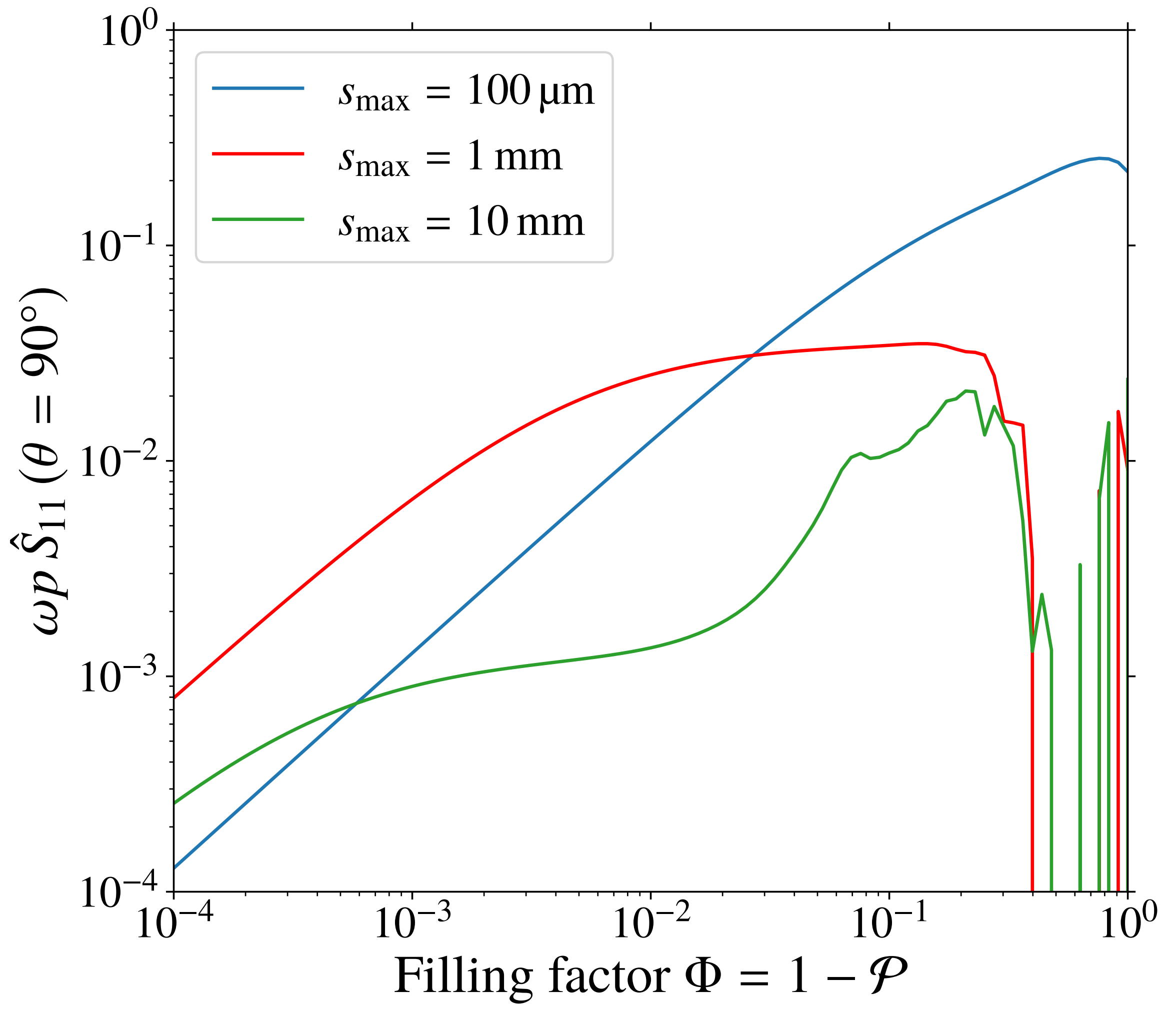
Self-scattering by porous dust grains?

Example of porous dust grains





Tazaki et al. 2019



R. Brunngräber and S. Wolf 2021

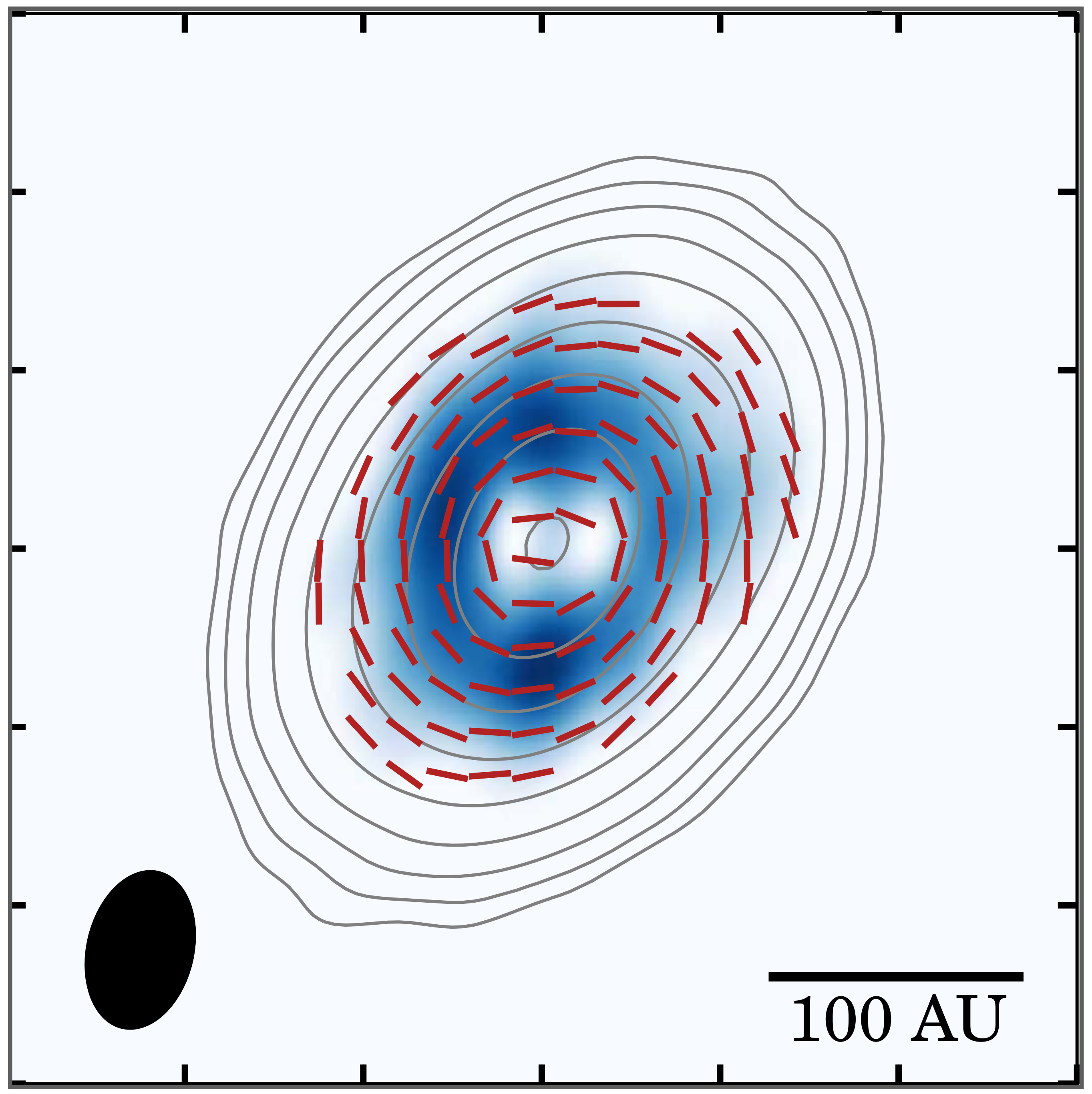
- Extremely porous dust grains (filling factor ~0.01 or smaller) are ruled out.

- filling factor of ~0.3 has the highest polarization efficiency

See also Kirchschlager and Bertrang et al. 2020, Bertrang and Wolf 2017

Fundamental physics of grain alignment is missing

Azimuthal

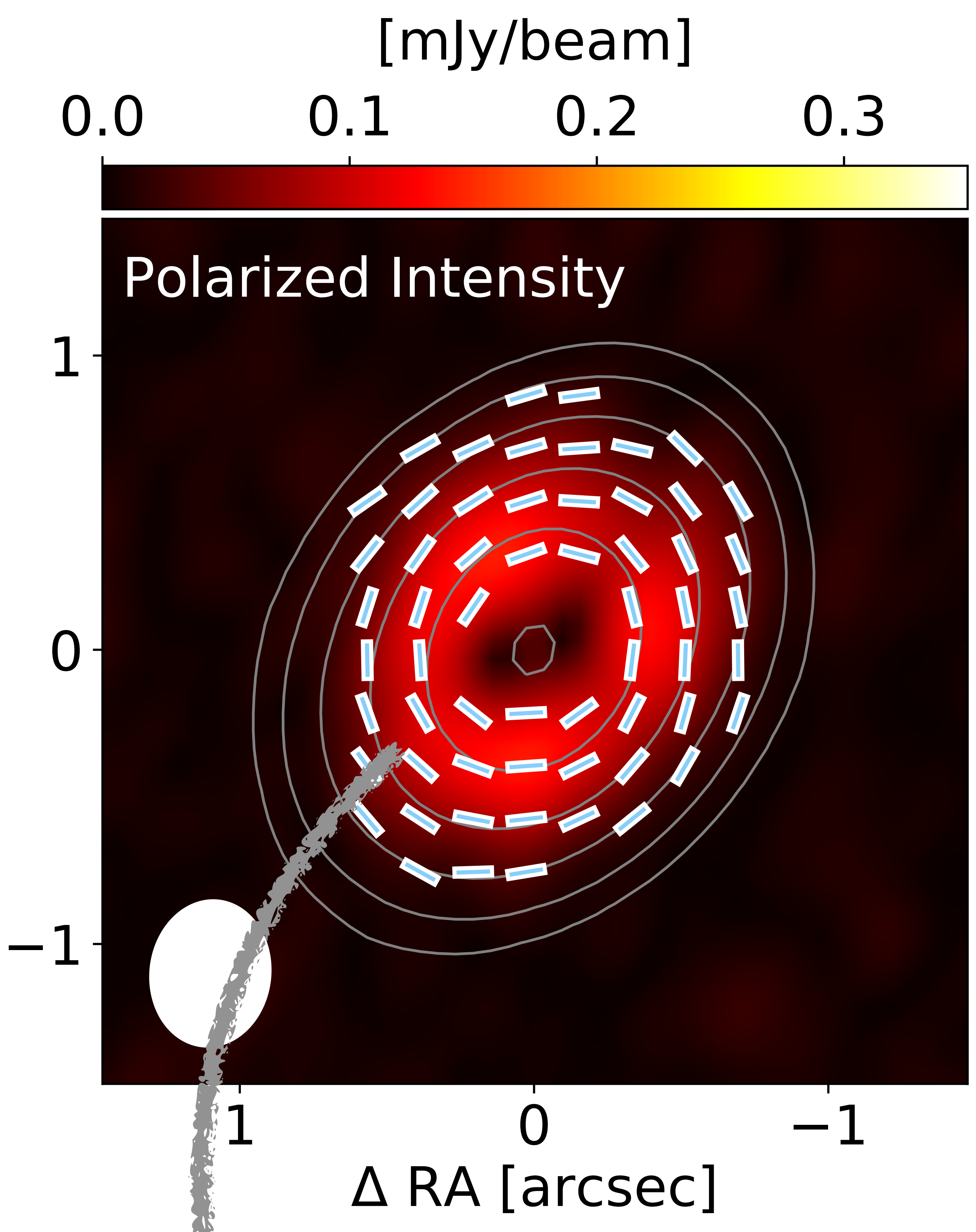


Intrinsic polarization of aligned dust grains

- B-fields alignment is unlikely because it suggests radial pattern of magnetic fields.
- The observed azimuthal pattern was first interpreted as radiative grain alignment (Tazaki et al. 2017, Kataoka et al. 2017)
- However, polarization morphologies are not consistent with the radiative grain alignment (Yang et al. 2019)
- **Aerodynamic alignment of needle-like grains is morphologically likely** but it requires supersonic motion (i.g., Gold 1952), which is not the case in disks (Yang et al. 2019, Mori and Kataoka 2021)

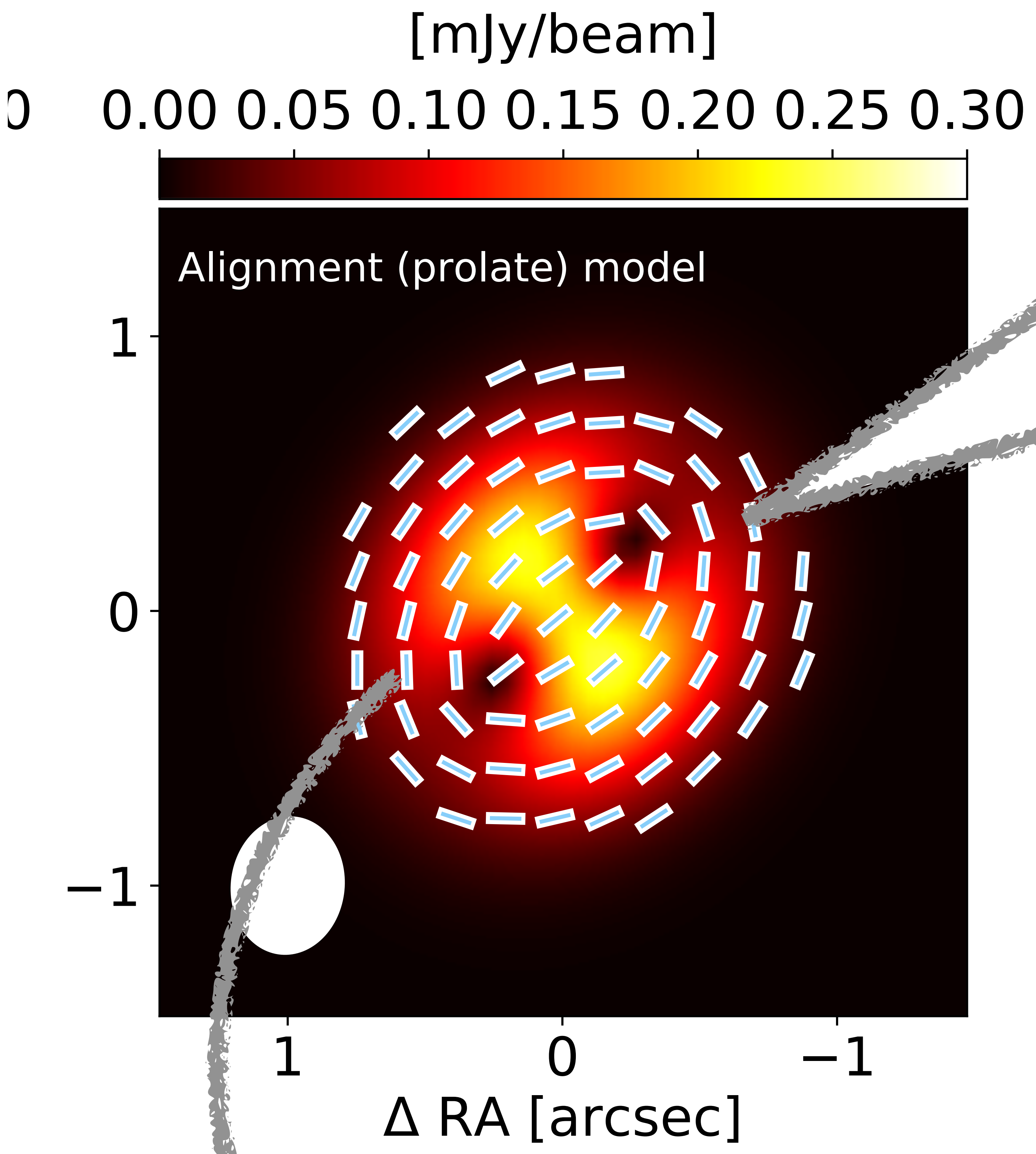
Alignment model of HL Tau at 3 mm

Observations



Azimuthally uniform polarized intensity

Dust alignment modeling



Polarization is stronger at the minor axes

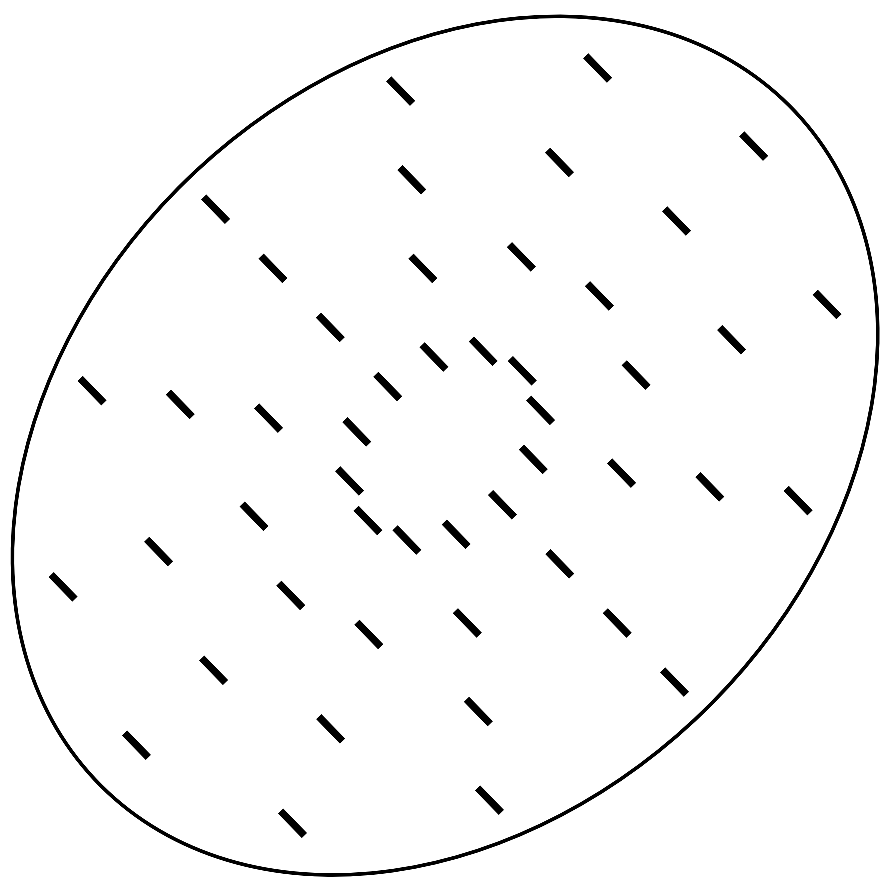
Imagine this…

Oblate dust is not likely …

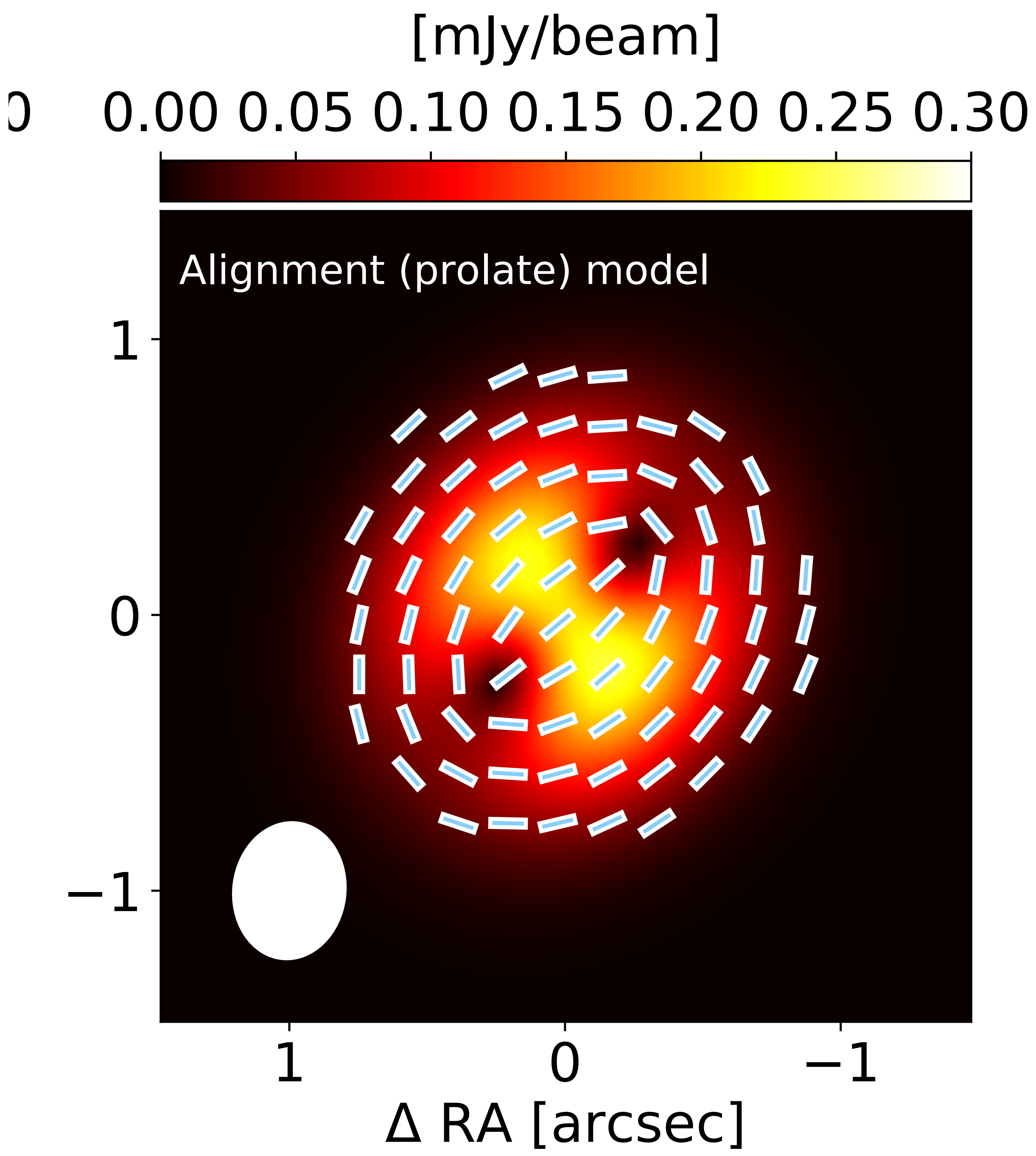
Mori and Kataoka 2021

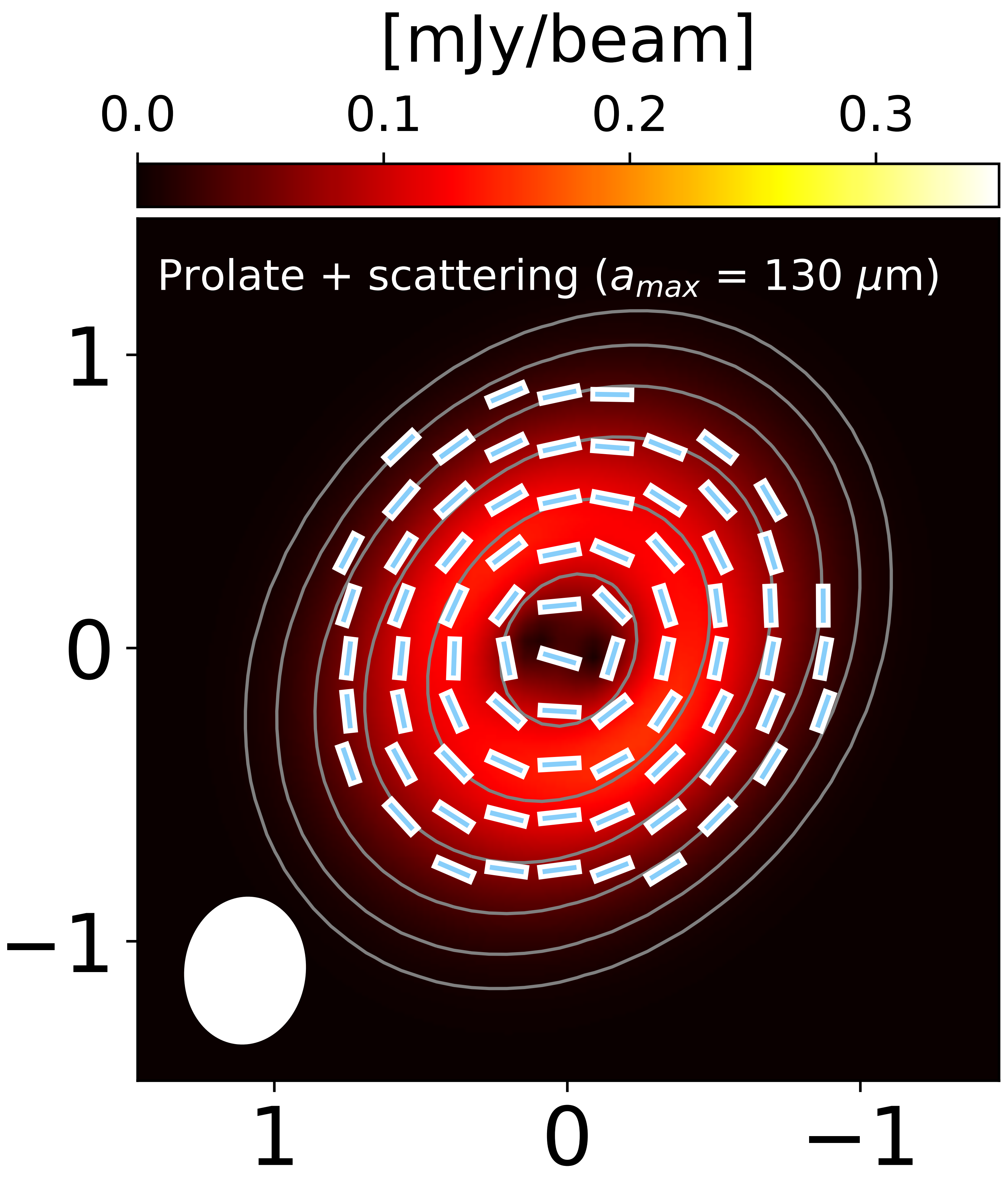
Full modeling of polarization at 3.1 mm

Self-scattering



Alignment

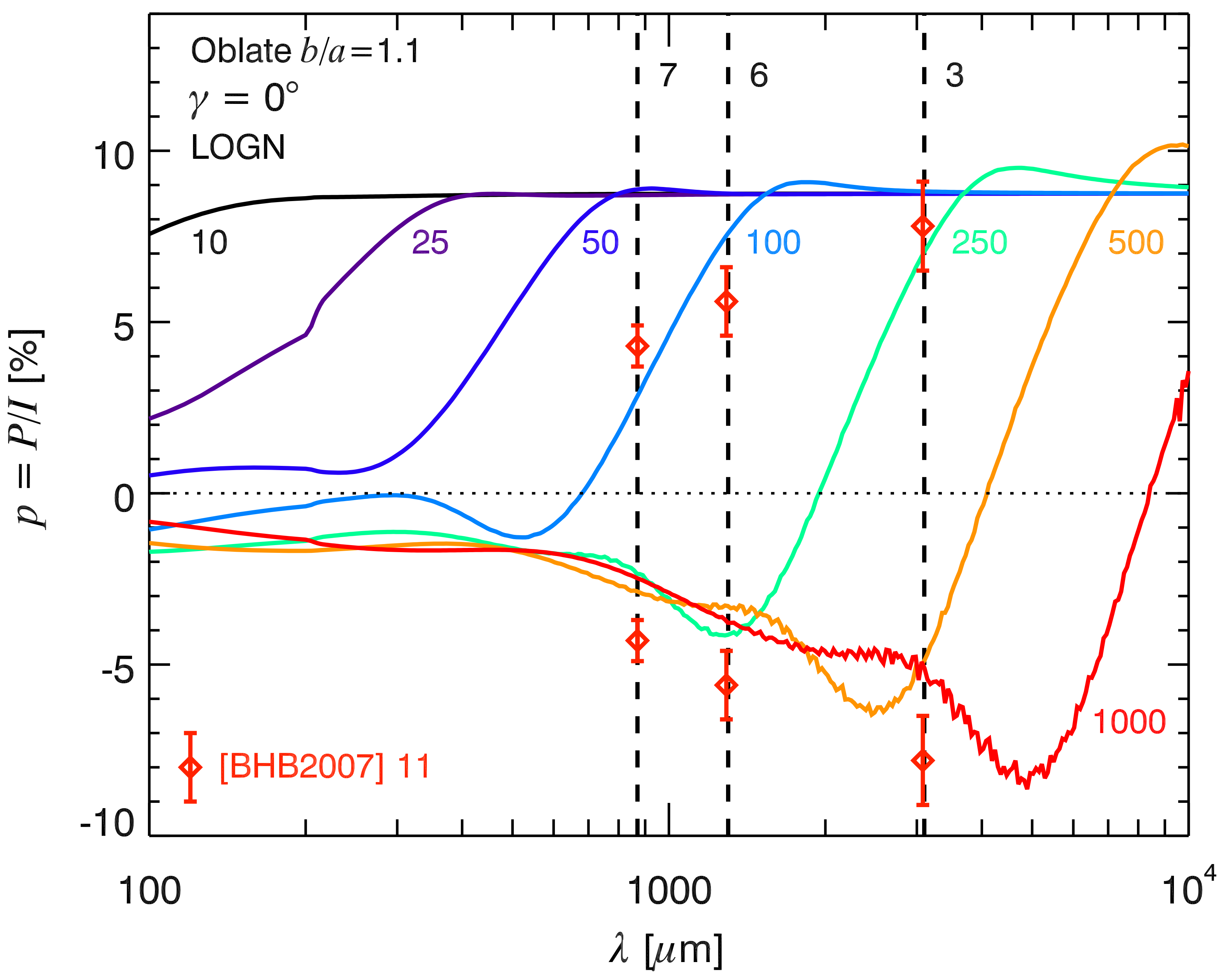


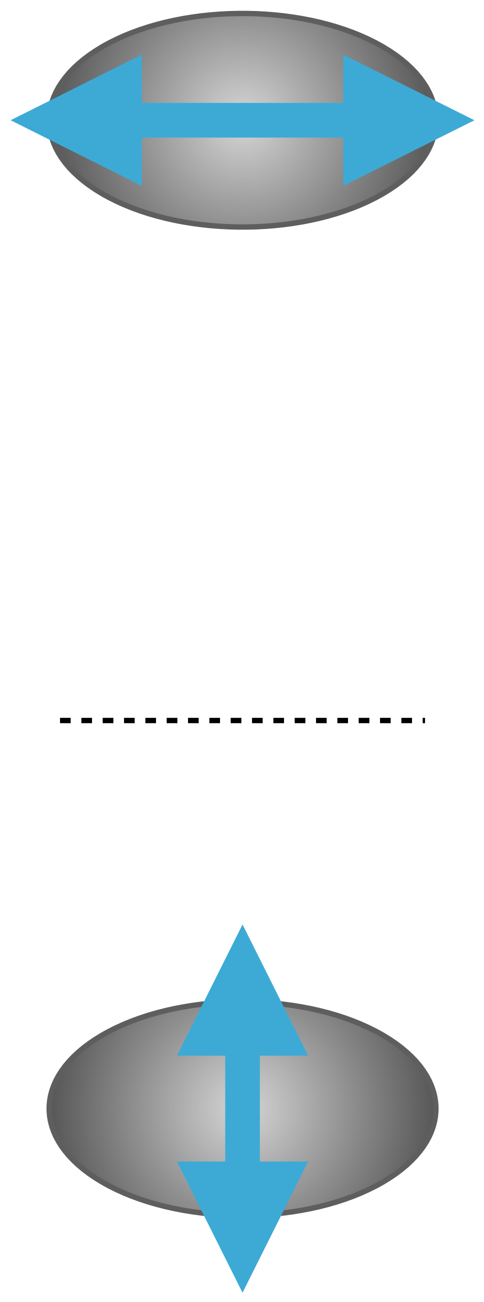


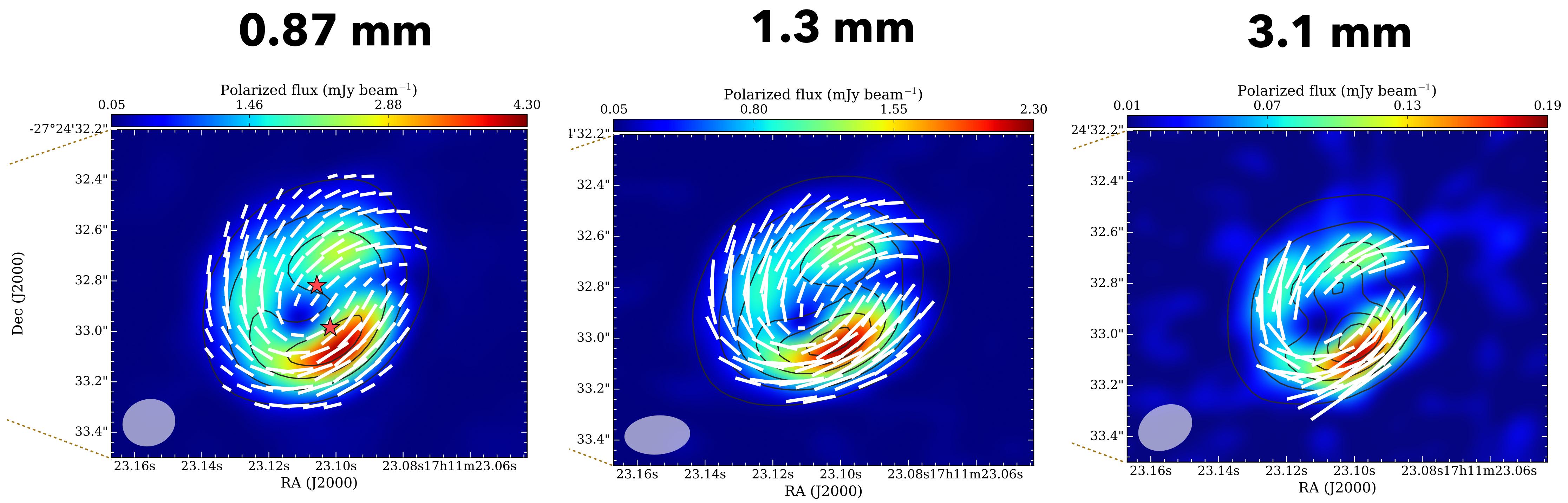
~0.5 % polarization comes from self-scattering even at 3 mm wavelength

Mori and Kataoka 2021

Wavelength dependence of aligned dust grains







Alves et al. 2018

- If a<λ : polarization parallel to the major axis
- If a~λ : polarization reversal
- If a>λ : no polarization

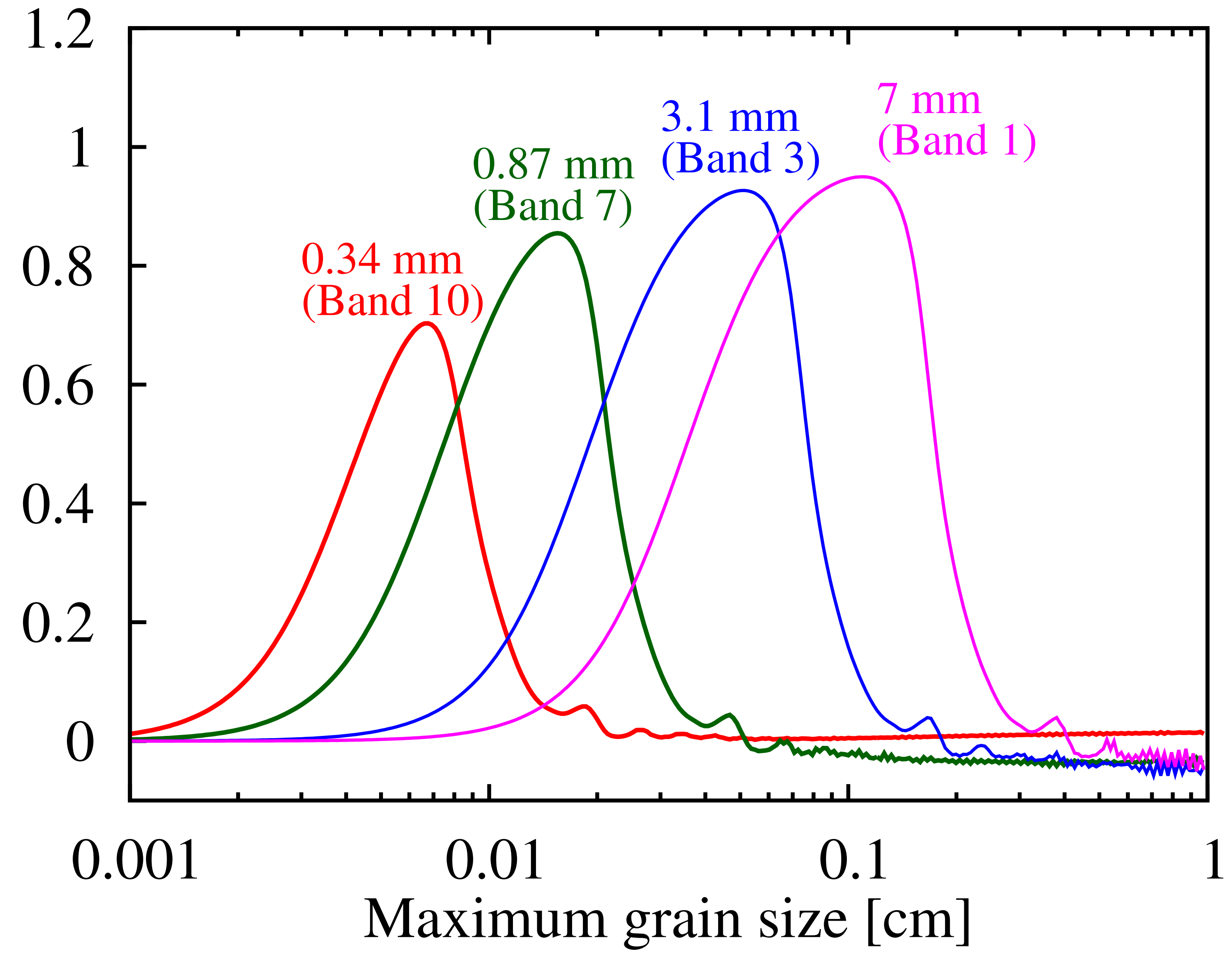
Guillet et al. 2020

(See also Brunngräber and Wolf 2019, Kirchschlager et al. 2019)

Summary and discussions

- **Grain size inconsistency; spectral index vs. polarization**
  - Optically thick components with ~ 100 μm dust grains help to explain low spectral index and polarization
    - IRS 48; extremely optically thick dust grains
    - HD 163296; optically thick rings and thin gaps
    - HL Tau; outer part lacks a good explanation with 1 mm grains
- **Fundamental physics for understanding alignment is missing.**
- **Missing observations**
  - Polarimetric substructures
  - Long wavelength continuum observations (e.g., VLA).
    - Note: ngVLA polarization will directly observe millimeter size grains

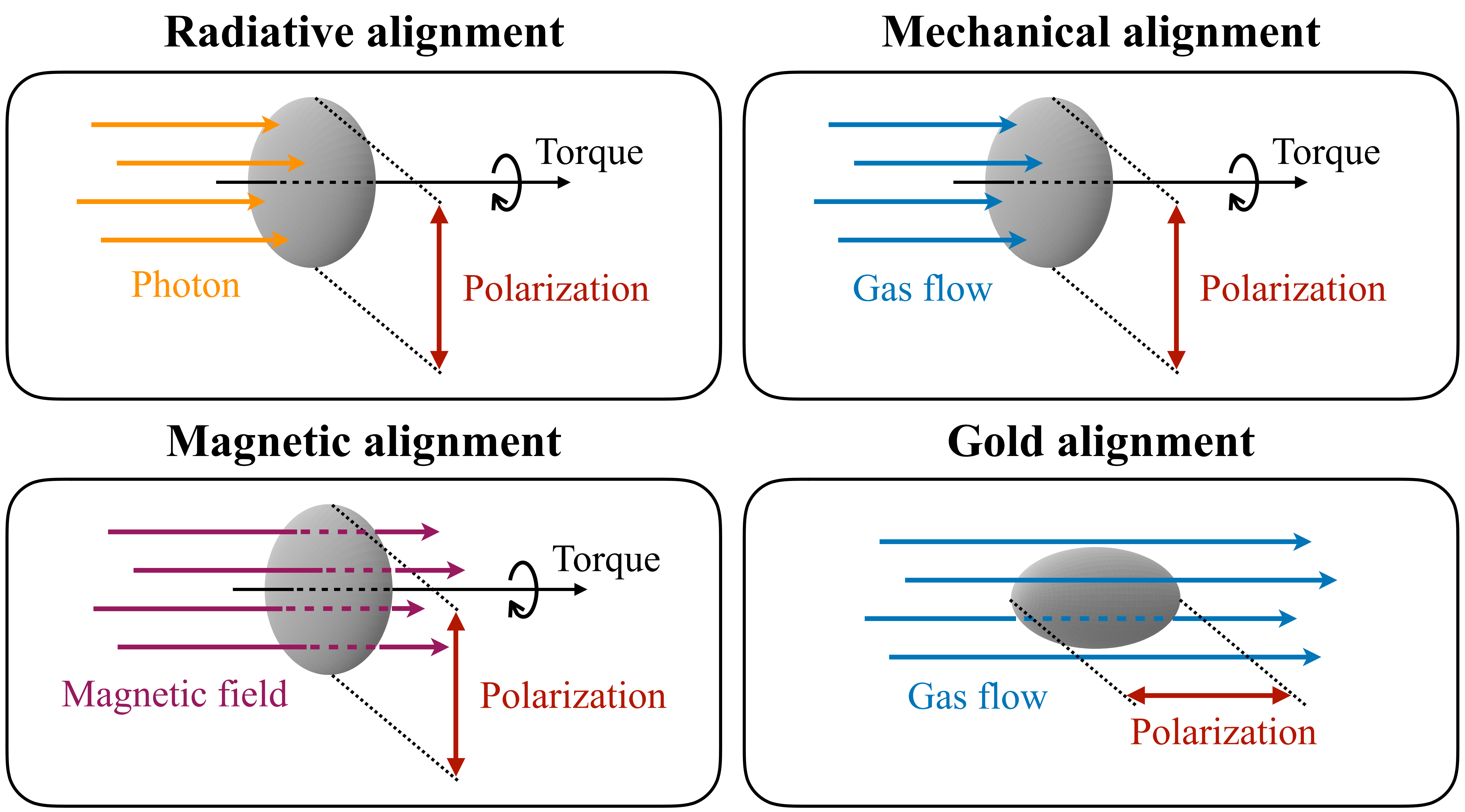
Prediction of polarization fraction

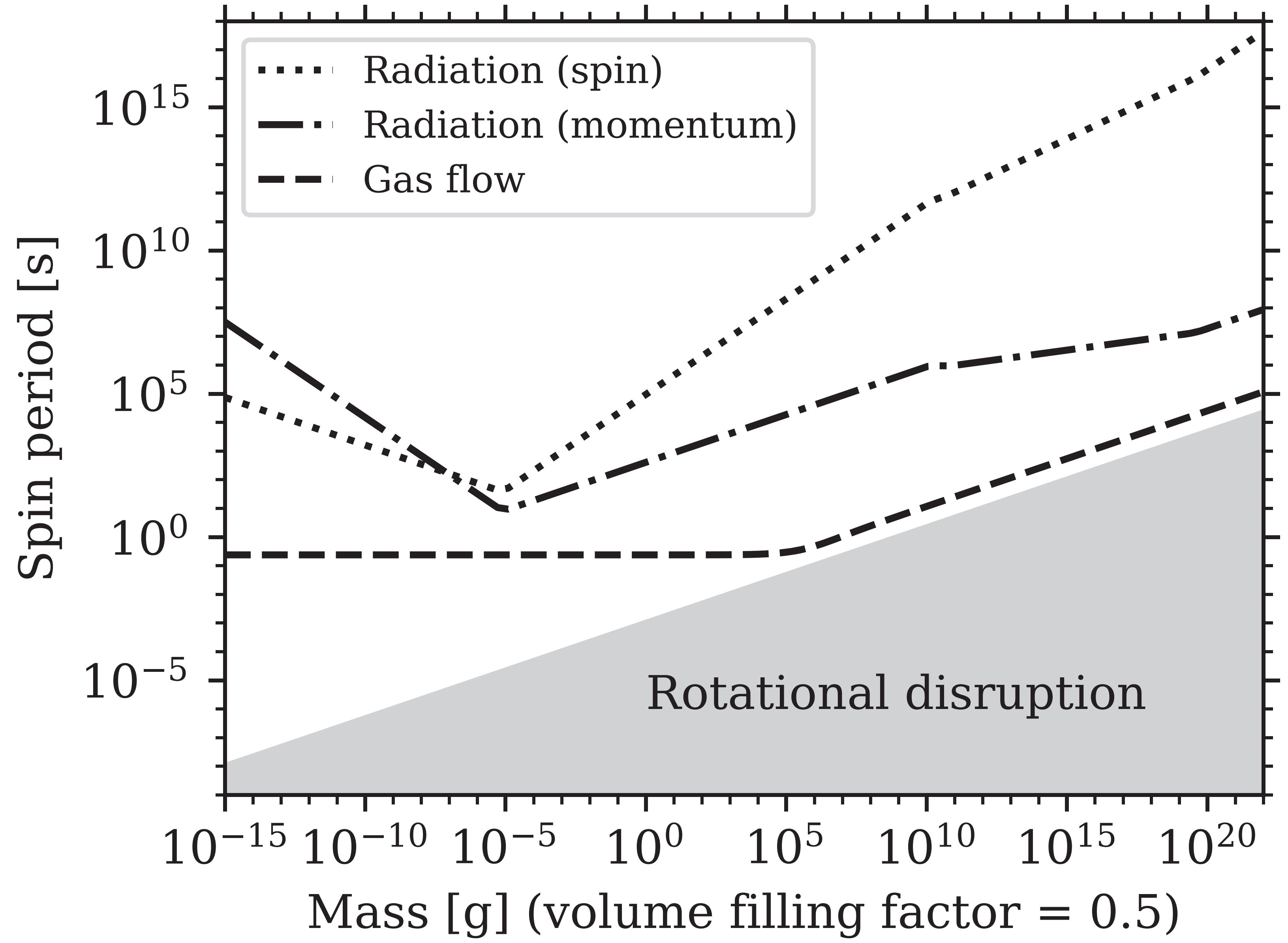


Kataoka et al., 2015

Additional materials

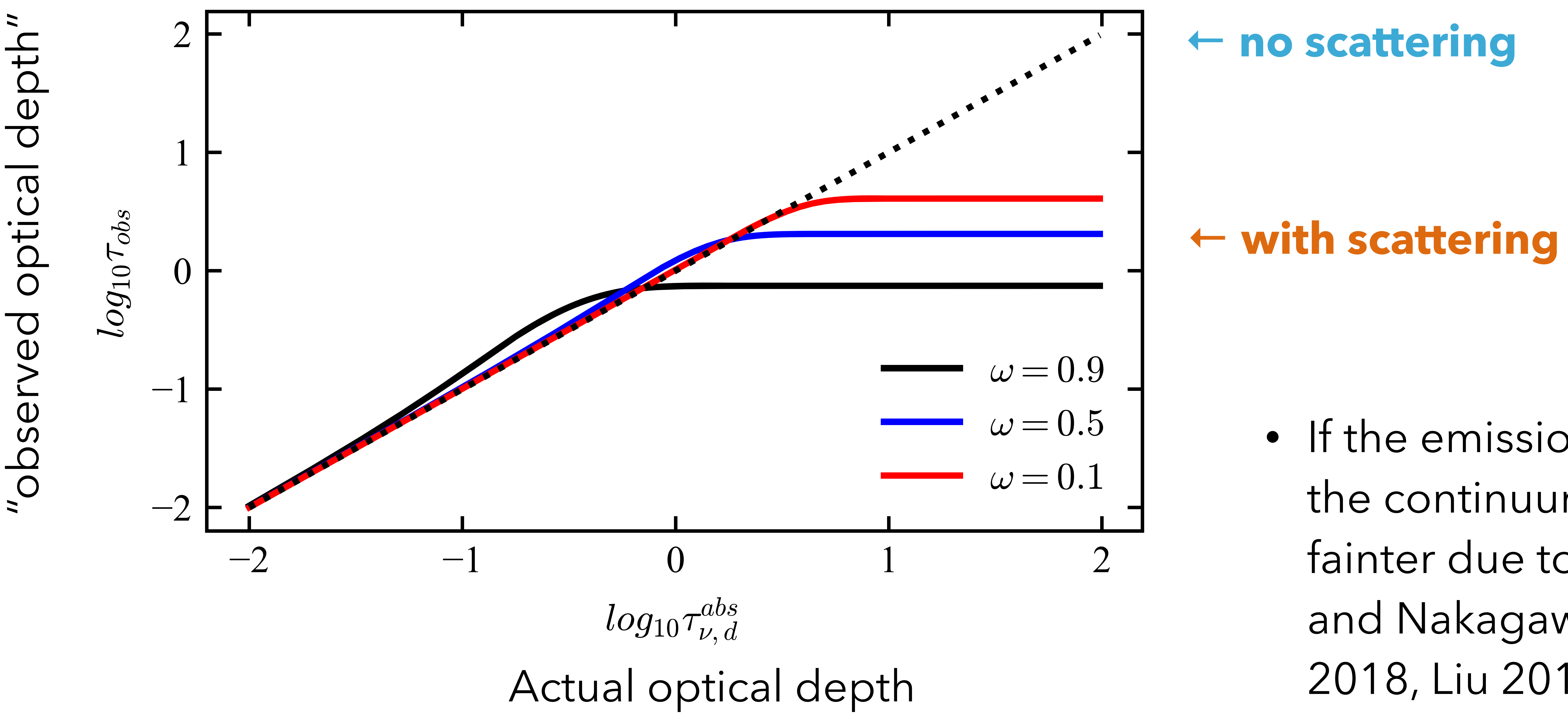
Dominant dust spinning mechanisms





Tatsuuma and Kataoka 2021

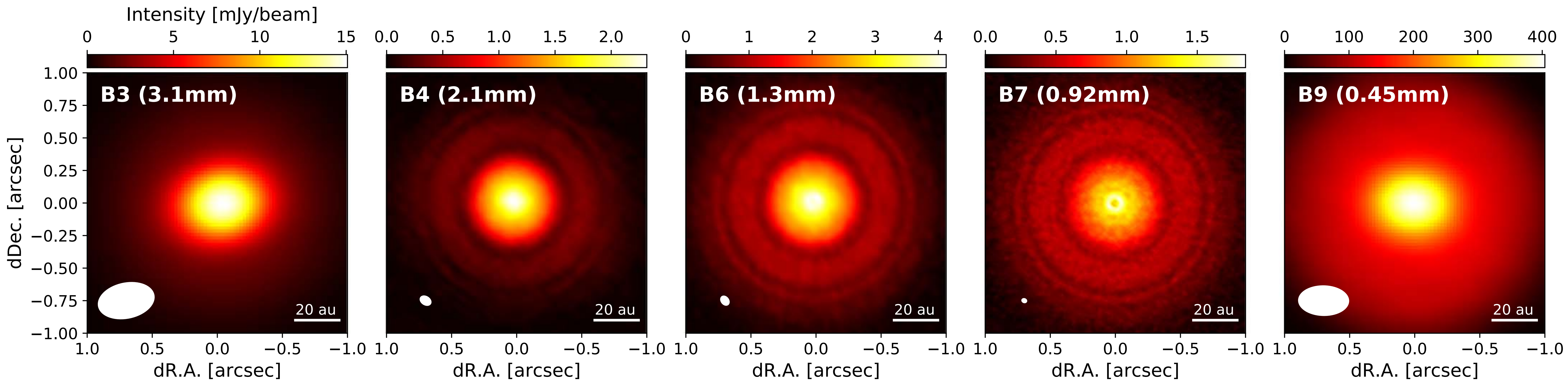
Scattering makes disk continuum fainter



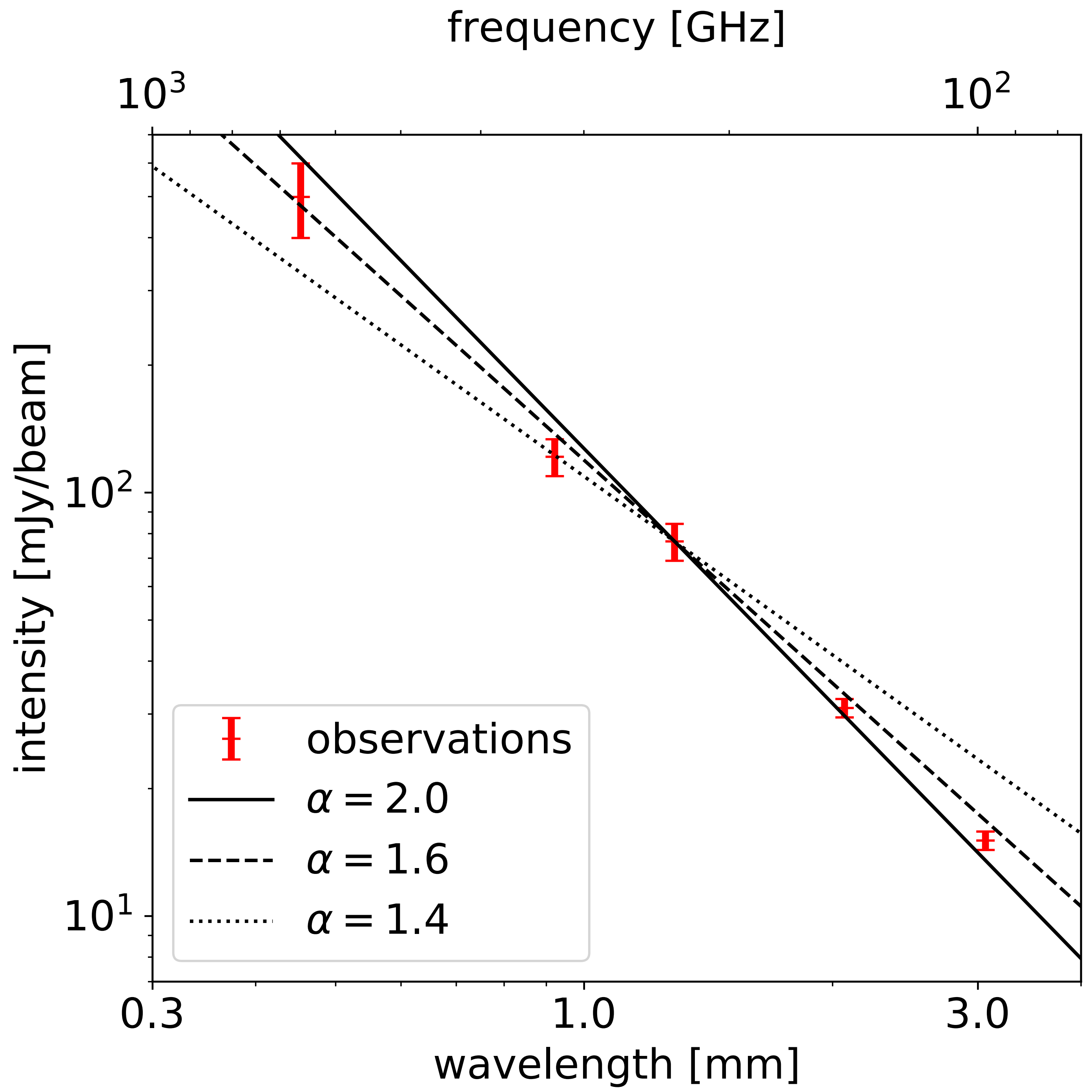
Zhu et al. 2019

- If the emission is very optically thick, the continuum emission becomes fainter due to dust scattering (Miyake and Nakagawa 1993, Birnstiel et al. 2018, Liu 2019, Zhu et al. 2019, Sierra and Lizano 2020)

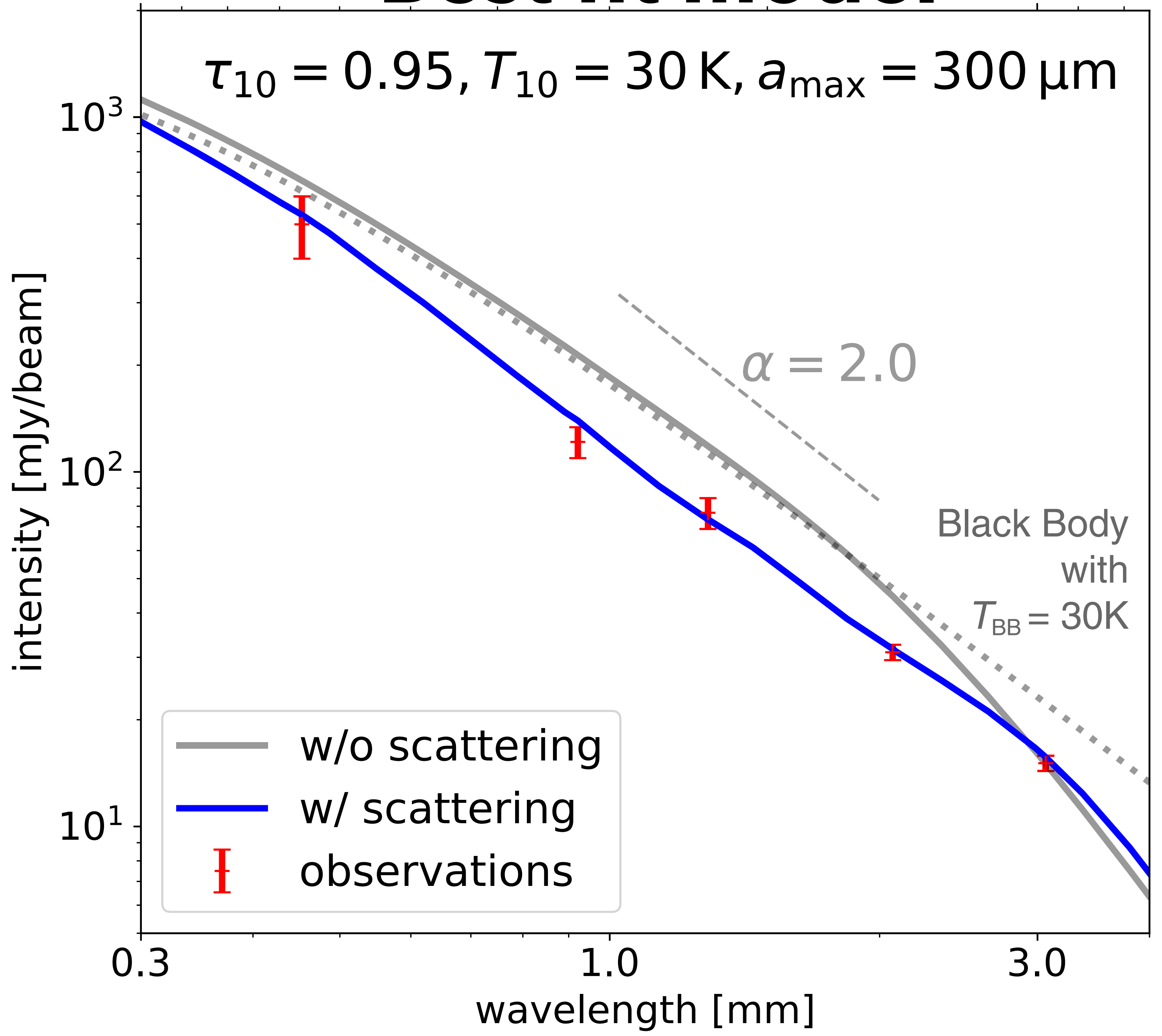
Scattering makes disks fainter - TW Hya



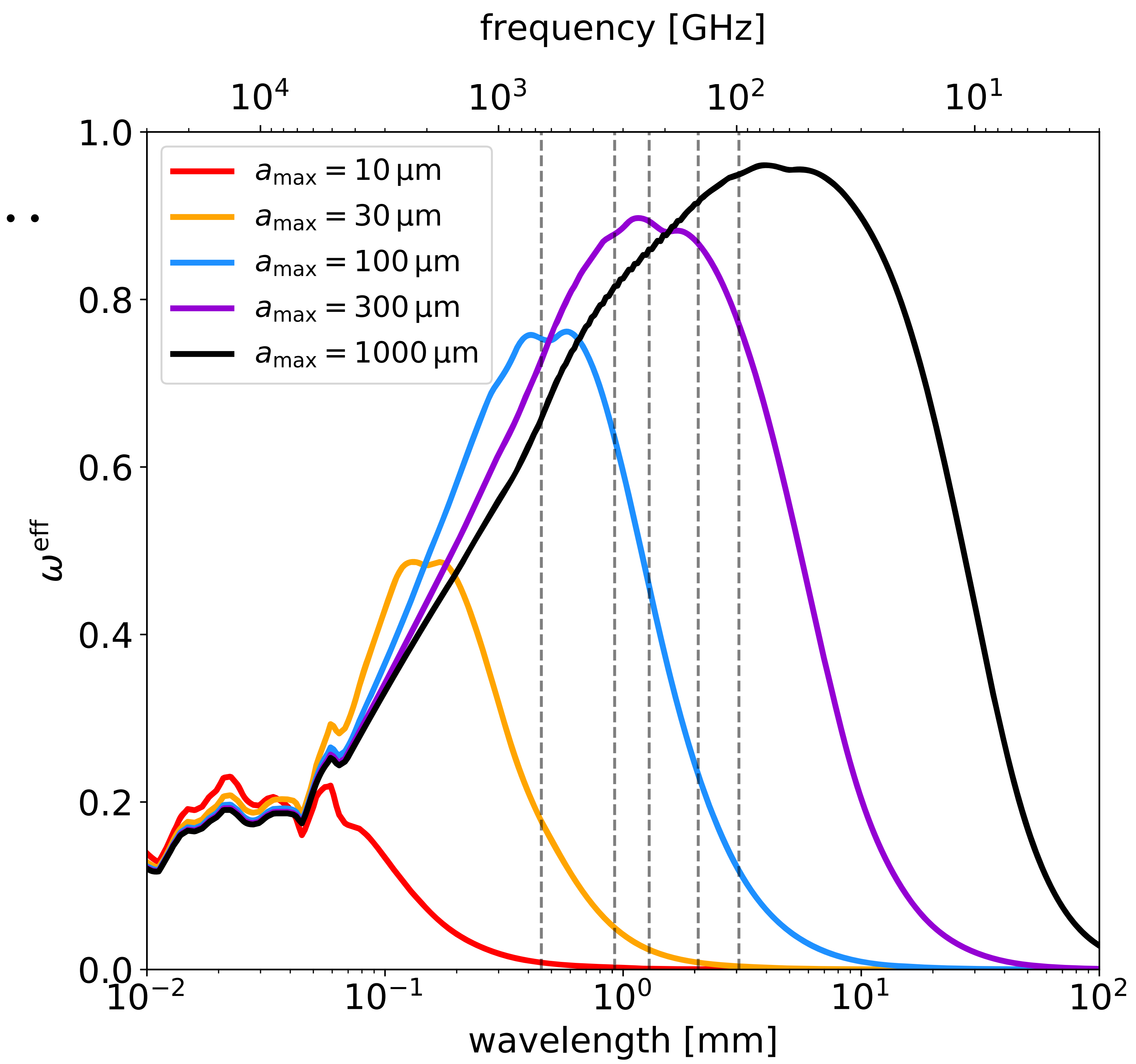
If we try to fit the SED of the center (<20 au) with a power-law model…



Best fit model



Albedo of dust grains



Ueda, Kataoka et al. 2020