Millimeter-wave polarization of protoplanetary disks

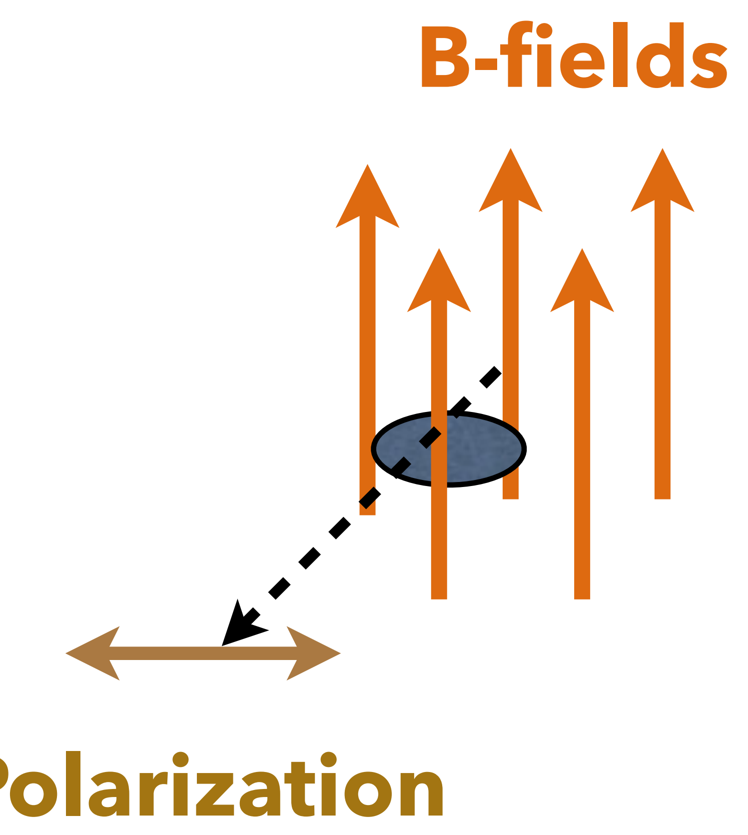
Akimasa Kataoka (NAOJ)

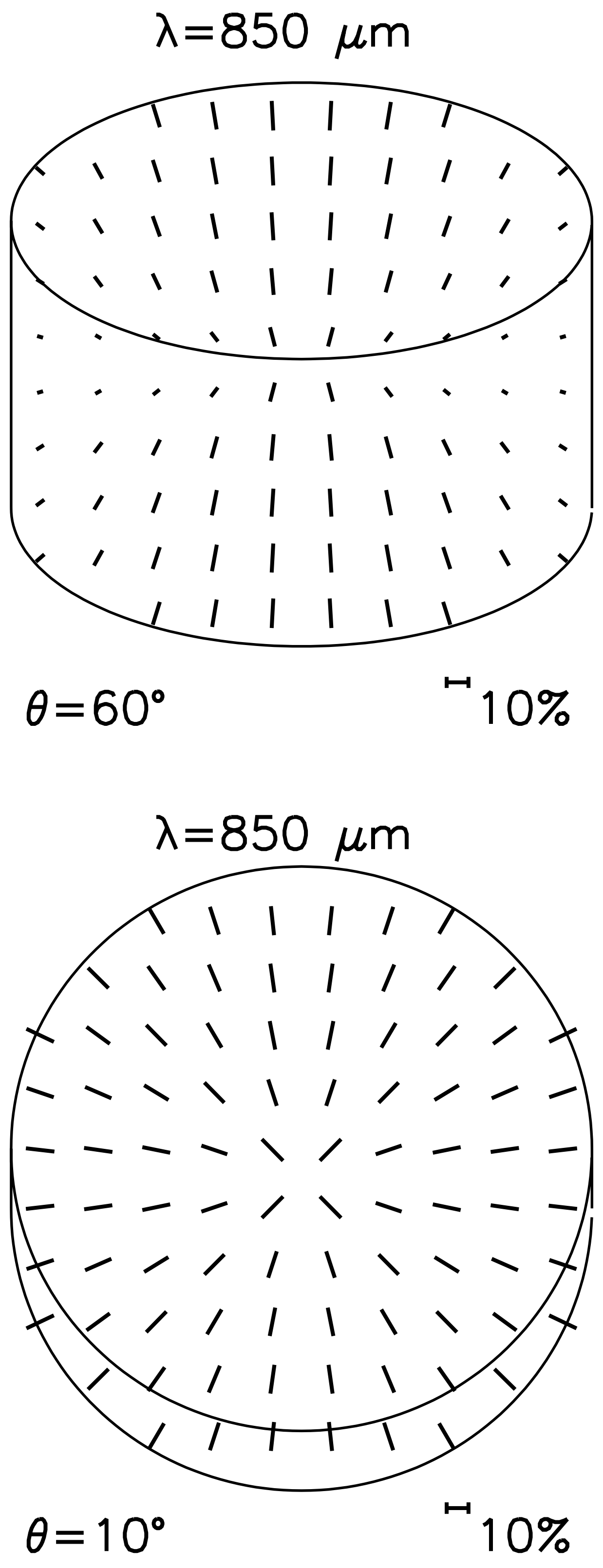
Stay-home logo by NAOJ

Before 2015 - what had been expected and achieved?

Theory

Radiative Torque Alignment



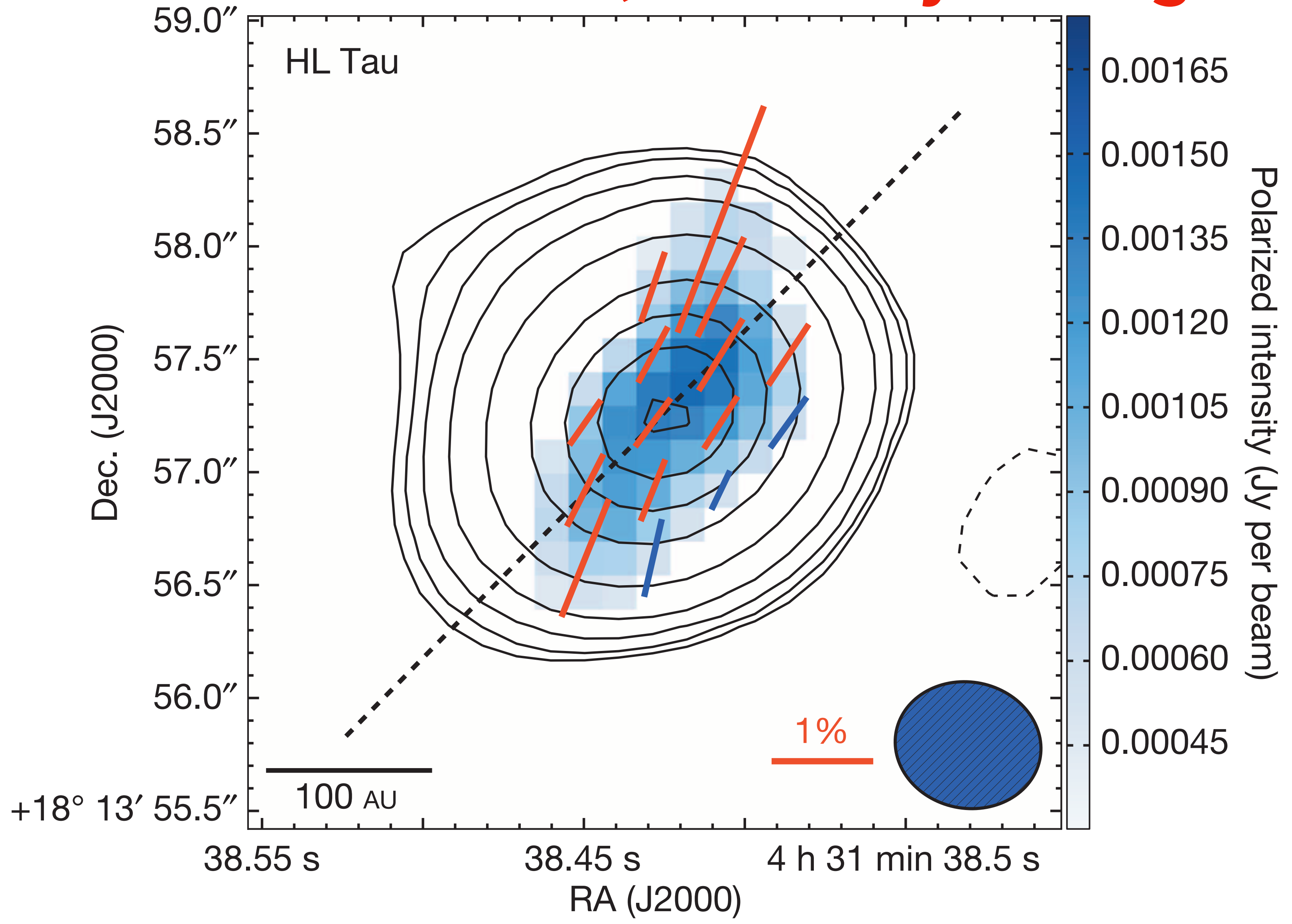


e.g., Draine and Weingartner 1997, Lazarian 2007, Cho and Lazarian 2007…

Observations

Non-detection on HD 163296, TW Hya.
GM Aur and DG Tau (Hughes et al. 2009, 2013).

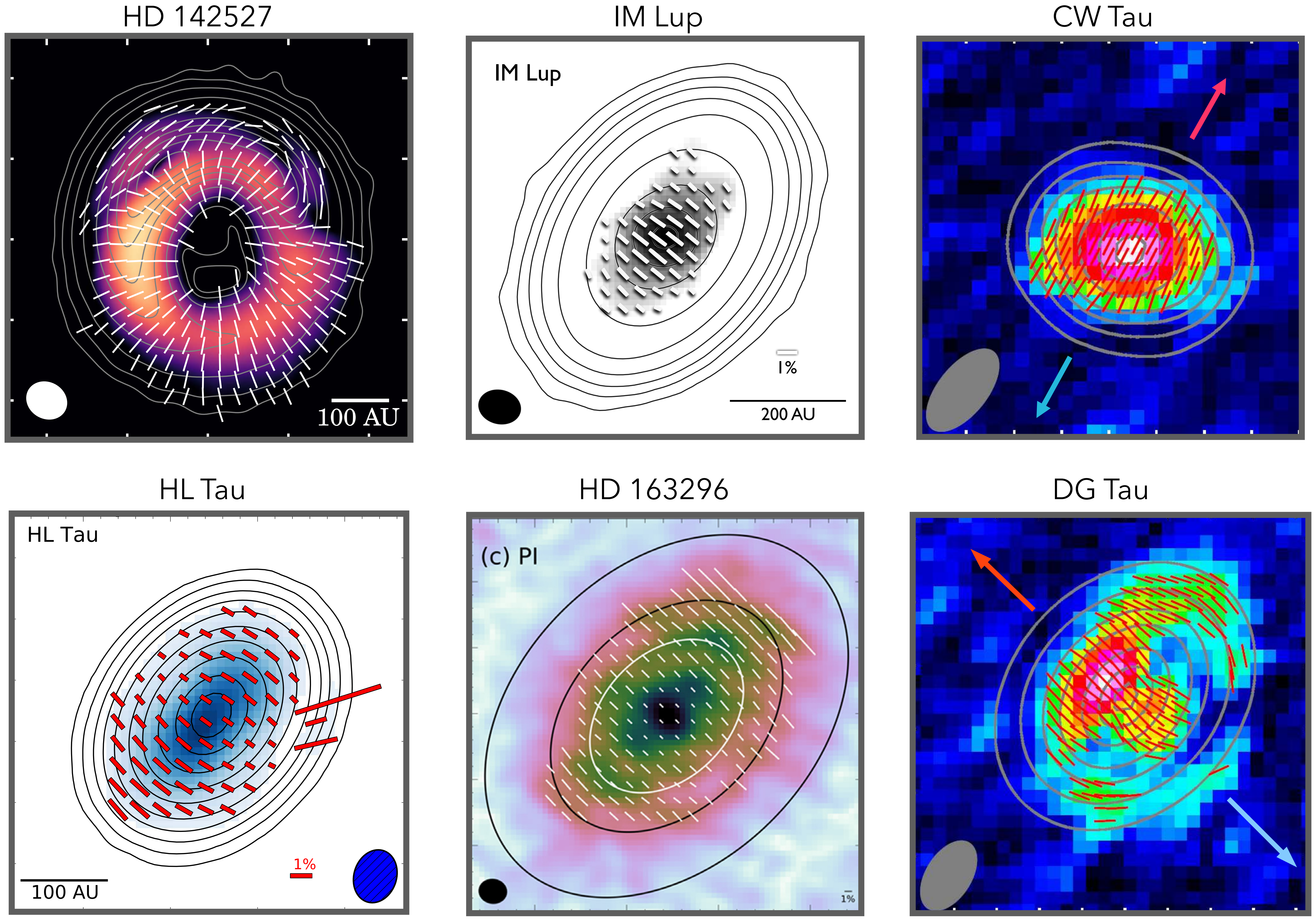
inferred B vectors (rotated by 90 degrees)



2 sigma detection by CARMA and SMA
(Stephens et al. 2014)

After 2015 - ALMA polarization and progress of theory

ALMA polarization (Class II disks)



Kataoka et al. 2016, Hull et al. 2018, Bacciotti et al. 2018, Dent et al. 2019, Stephens et al. 2017, cf. Kataoka et al. 2017, Ohashi et al. 2018

Dramatic progress in 5 years

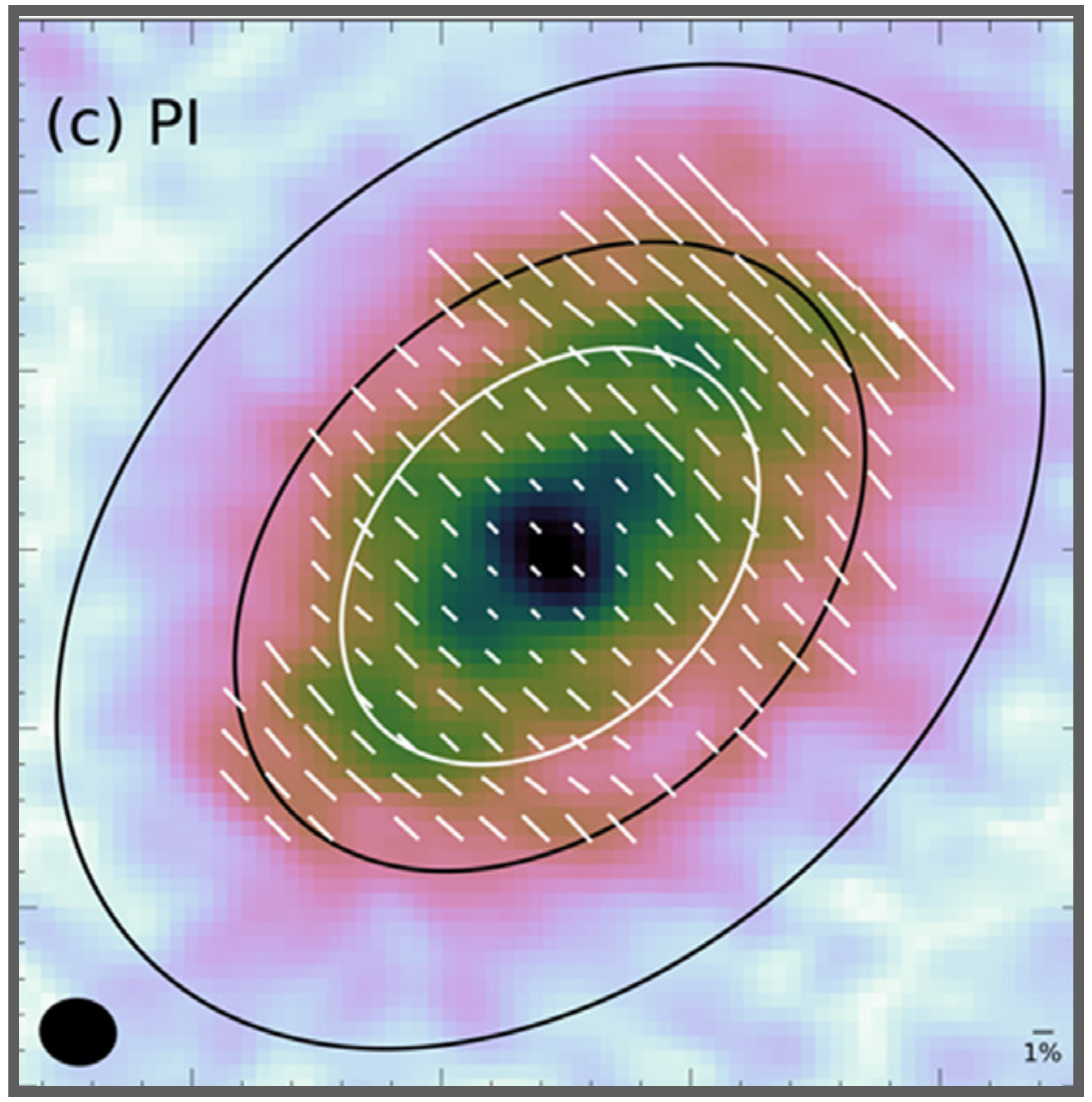
- **ALMA observations -** many polarimetric detections at 870, 1.3, and 3.1 mm wavelengths
- **Self-scattering -** a new idea of origin of polarization
- **Direction of the aligned grains** - grains may be aligned, but not with the direction of B-fields

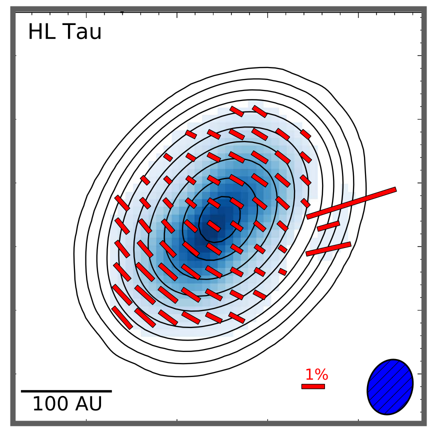
Motivation 1: polarization morphologies

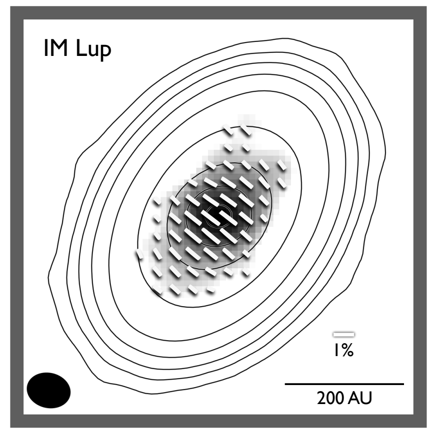
ALMA polarization of smooth and inclined disks, around a low-mass stars, with scales less than 100 au

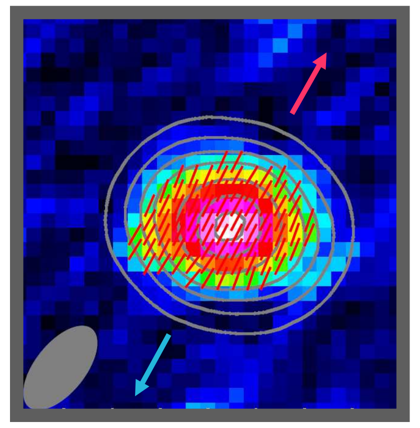
Parallel to the minor axis

HD 163296 (0.9 mm)





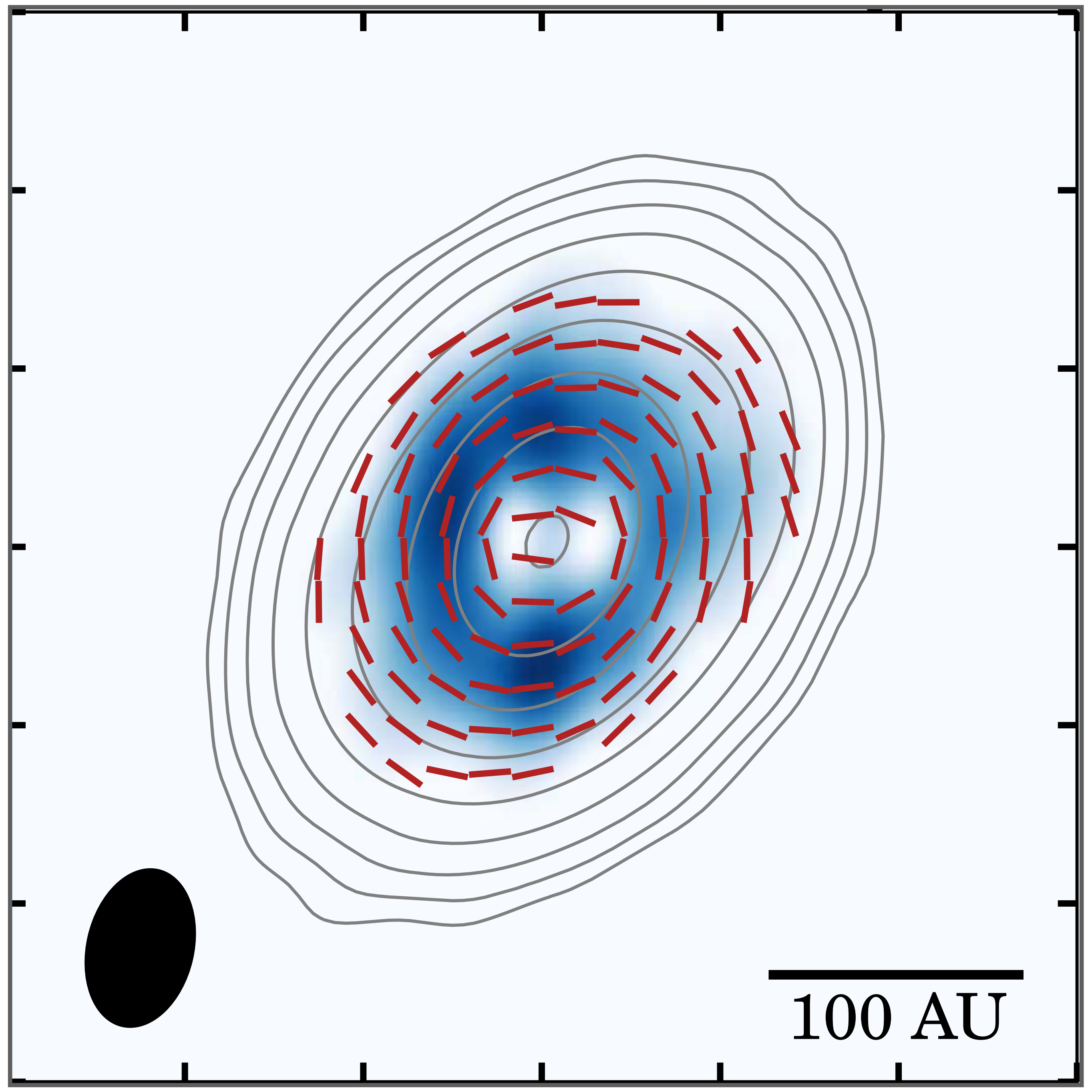


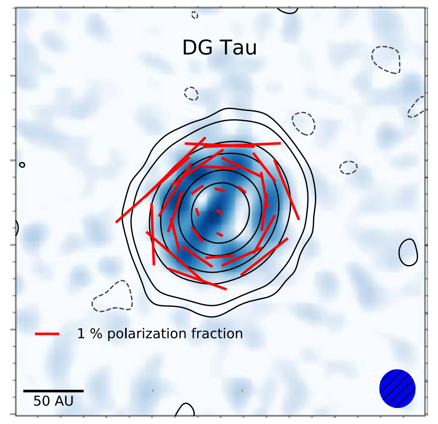


Dent et al. 2019, Stephens et al. 2017, Hull et al. 2018, Bacciotti et al. 2018…

Azimuthal

HL Tau (3 mm)

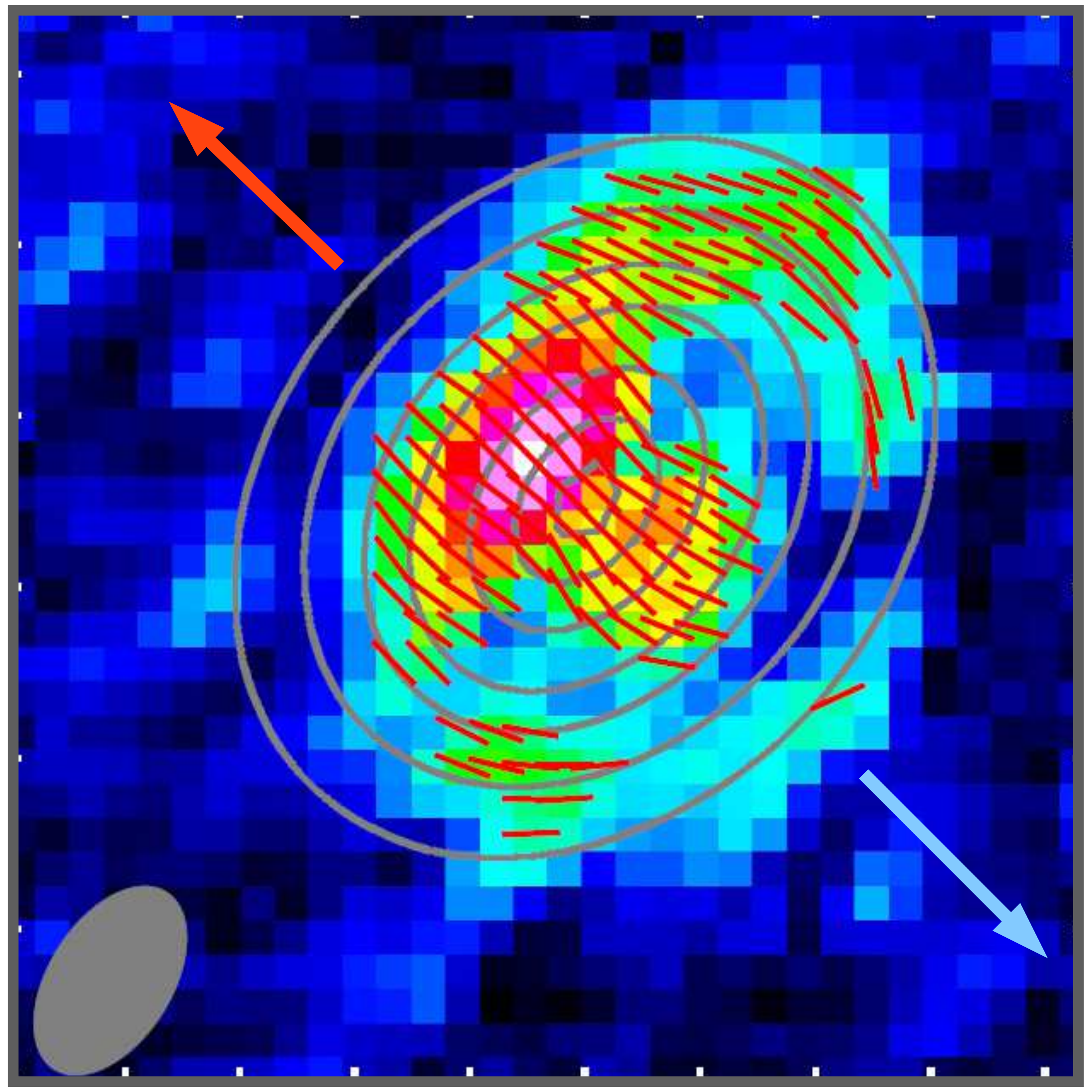


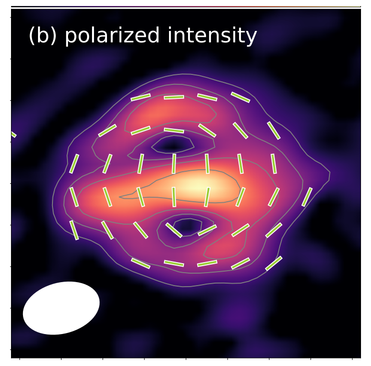


Kataoka et al. 2017, Harrison et al. 2019…

Mixture

DG Tau (0.9 mm)

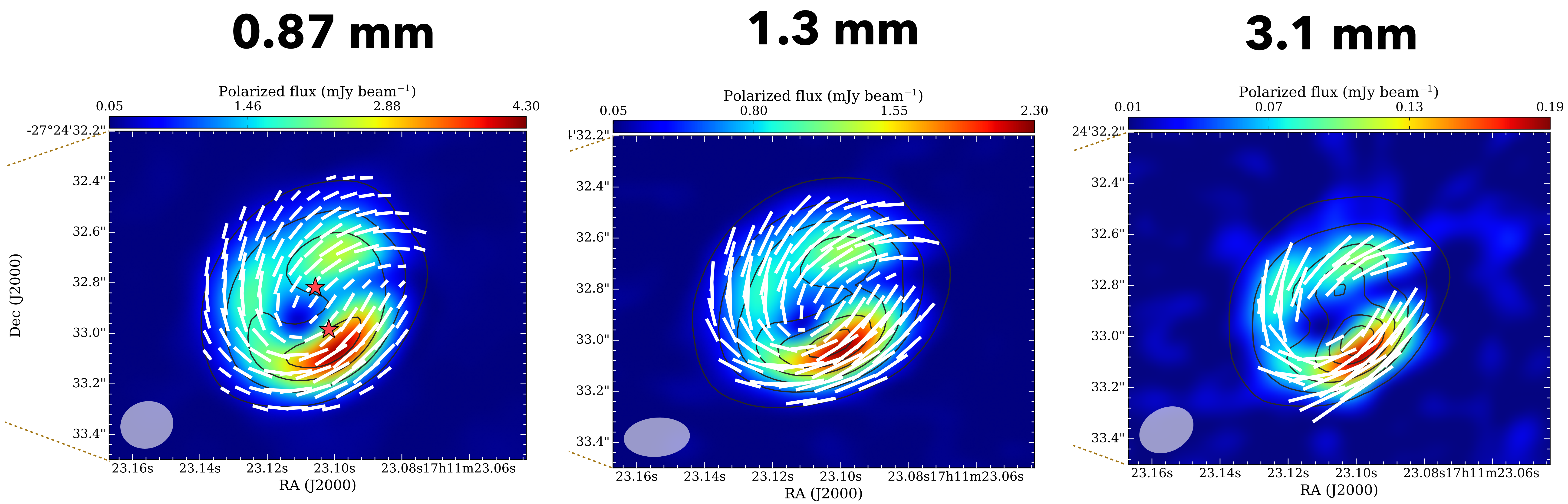




Bacciotti et al. 2018, Mori et al. 2019…

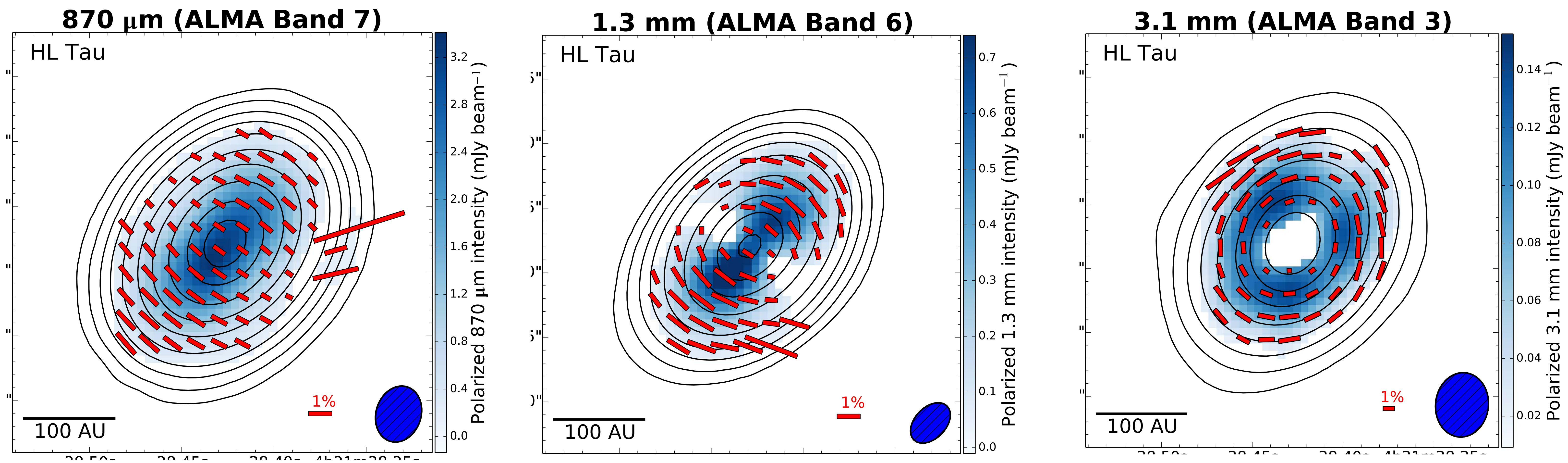
Motivation 2: wavelength dependence

BHB07-11 (Class I)



Alves et al. 2018

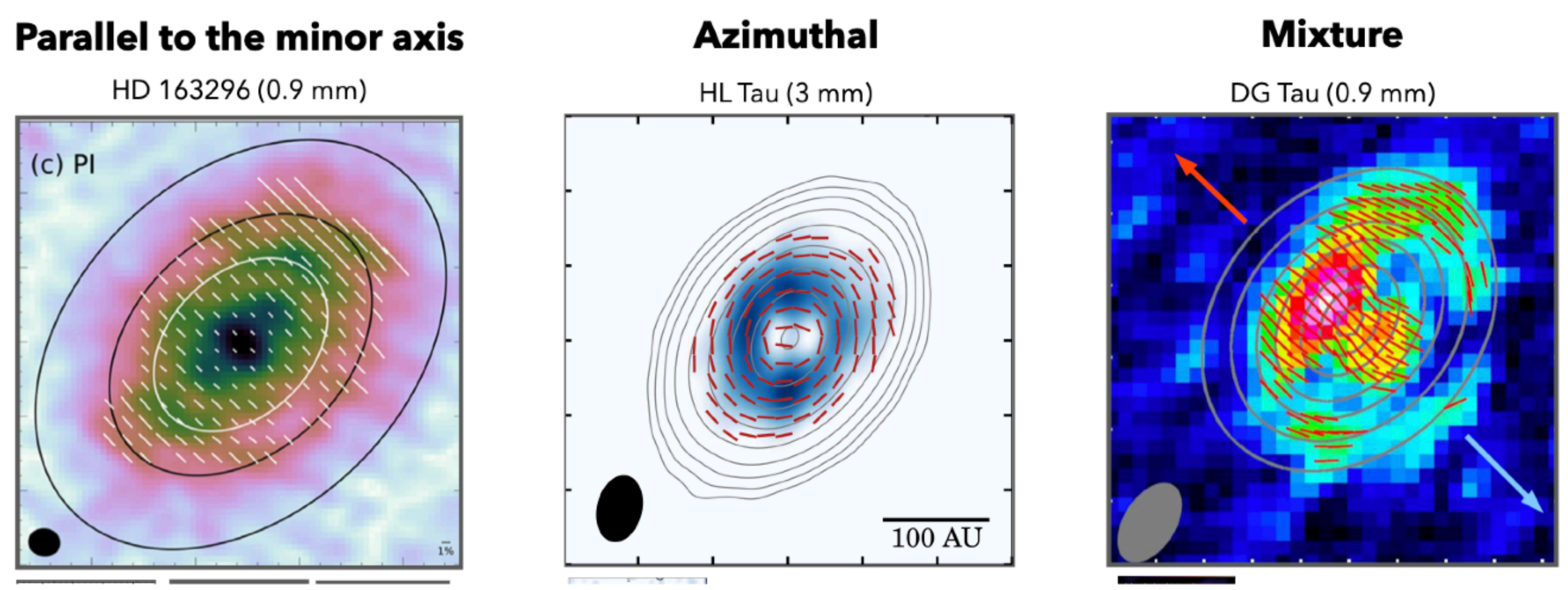
HL Tau (Class I-II)



Kataoka et al. 2017, Stephens et al. 2017

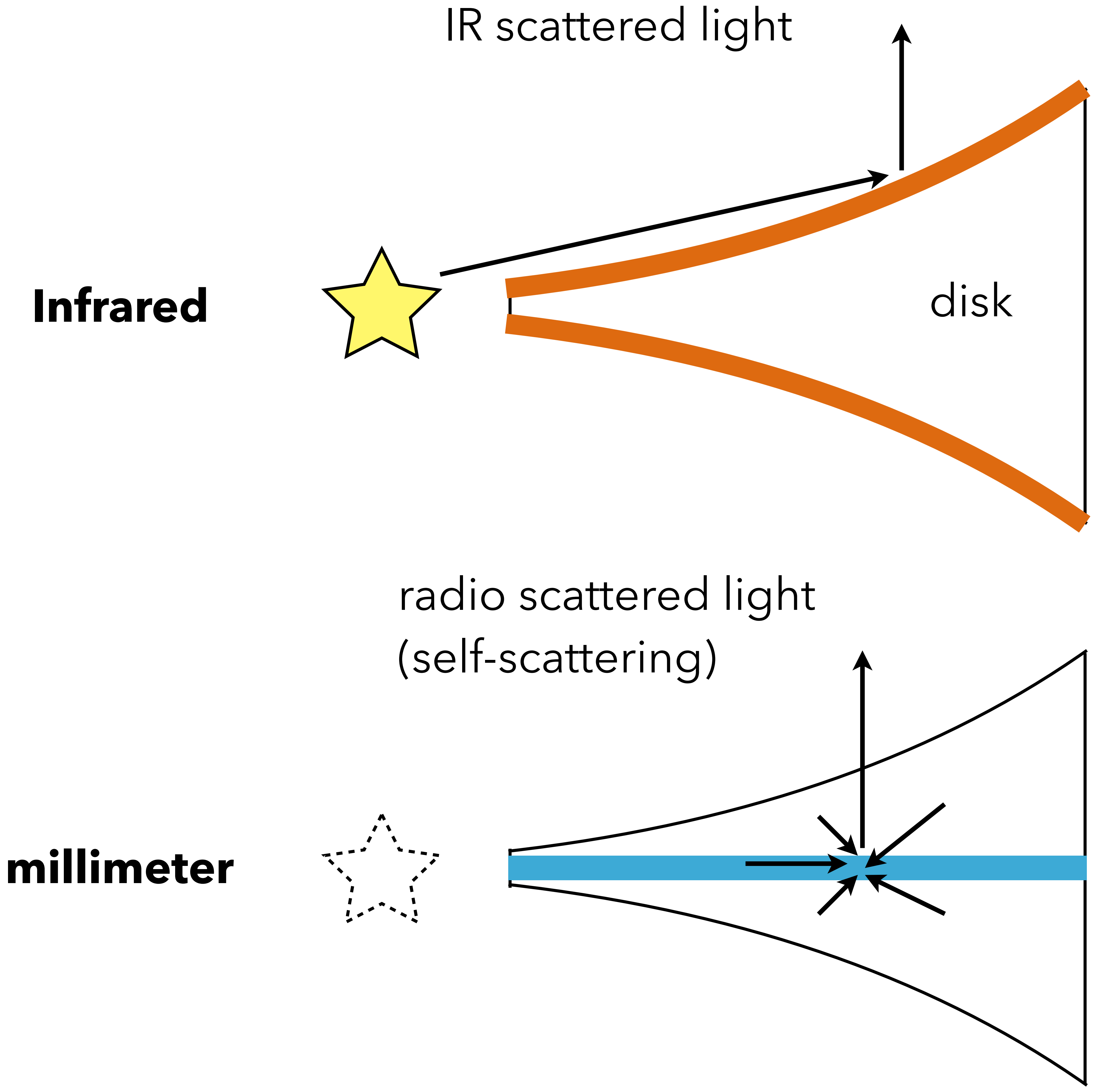
What I would like to discuss today is …

- Introduction (~5 min., done)
  - Pre-ALMA era and ALMA discovery of diverse morphologies of polarization.
- **Theories/models (~20 min.)**
  - **Self-scattering polarization**
  - **Grain alignment in protoplanetary disks**
- Basic interpretations (~5 min.)
- Implications to planet formation? What can be and cannot be explained by the theories? Recent progress? (~15 min.)



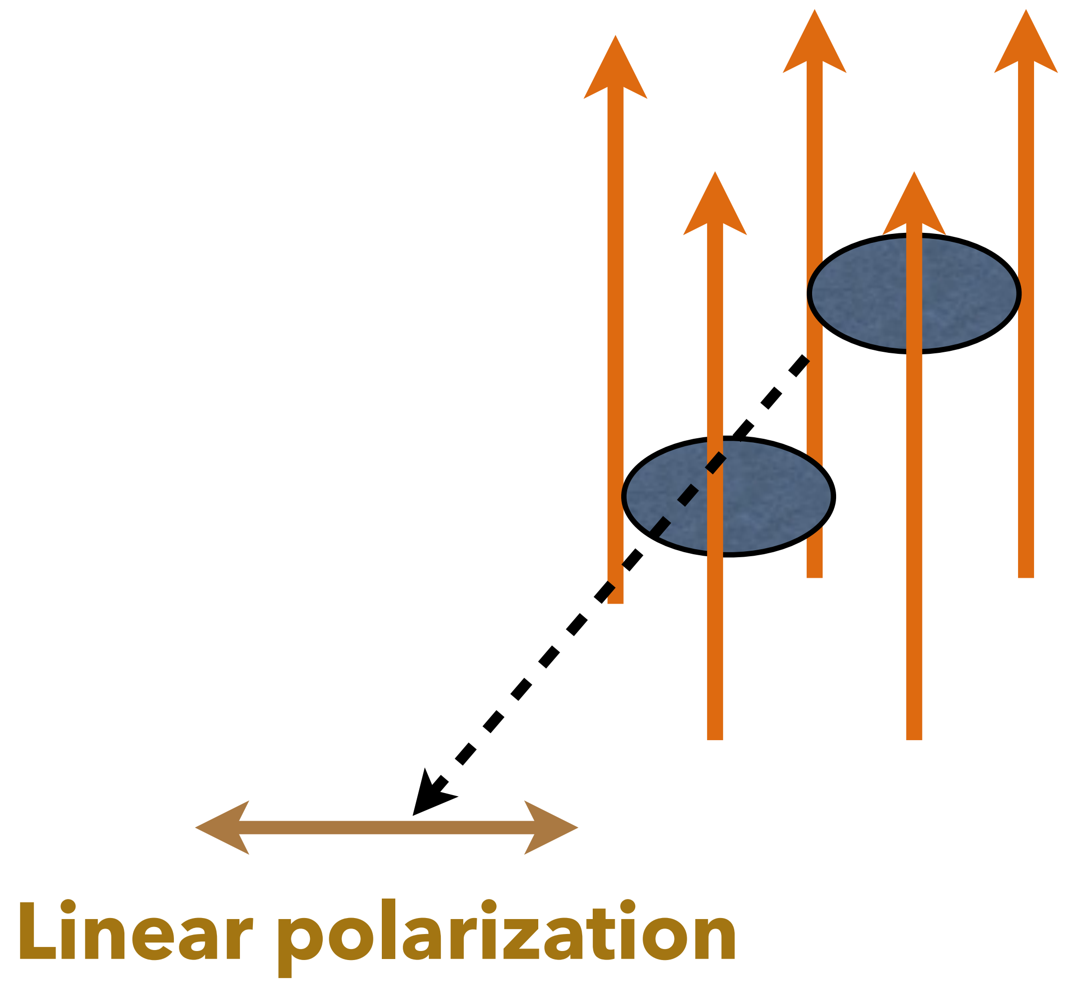
Polarization mechanisms

Self-scattering



Kataoka et al. 2015

Grain alignment

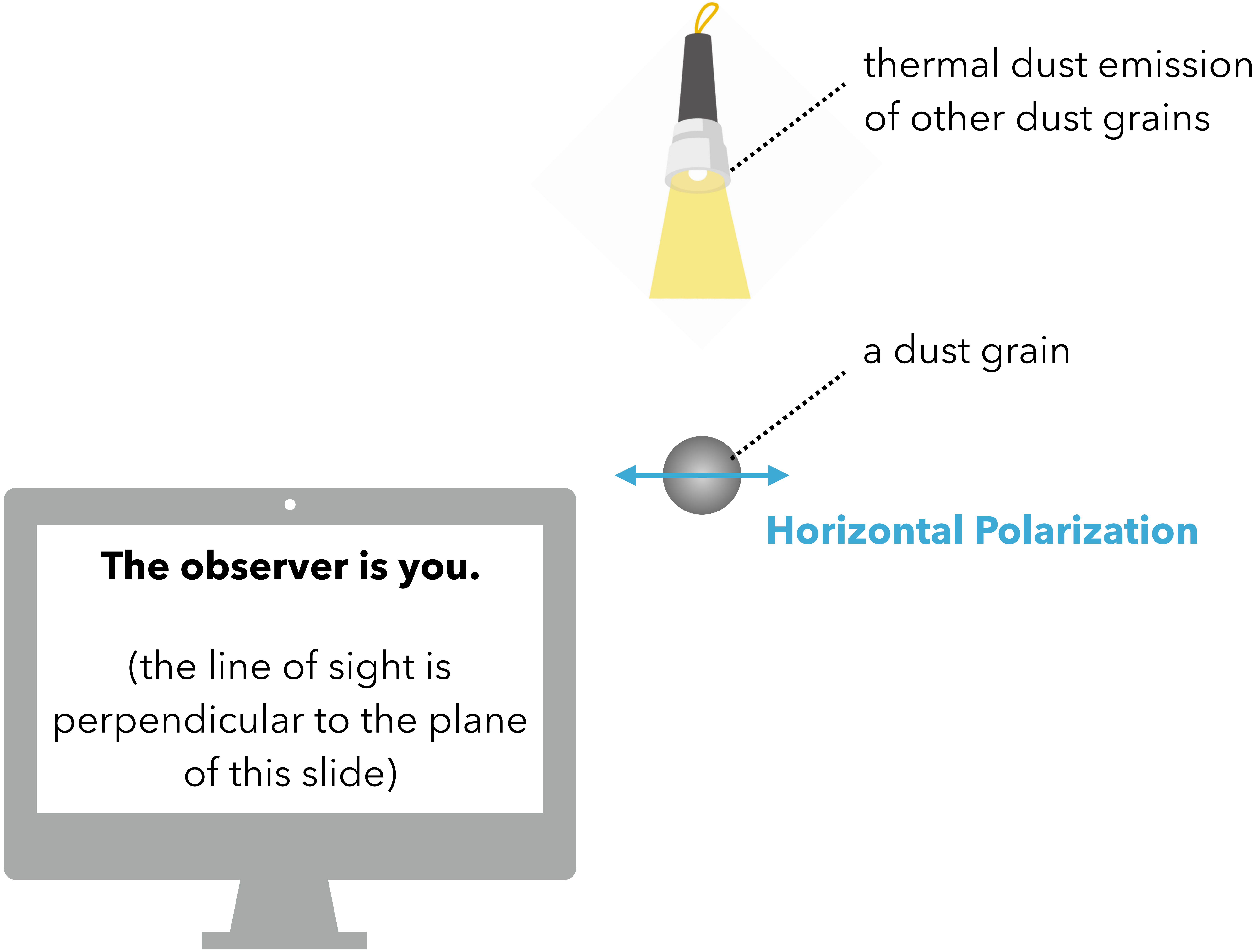


Directions
- B-fields
- radiation
- gas flow

e.g., Cho and Lazarian 2007, Tazaki et al. 2017, Lazarian and Hoang 2007, Kataoka et al. 2019

Note: dust grains at midplane do not receive stellar photons

Polarization due to scattering



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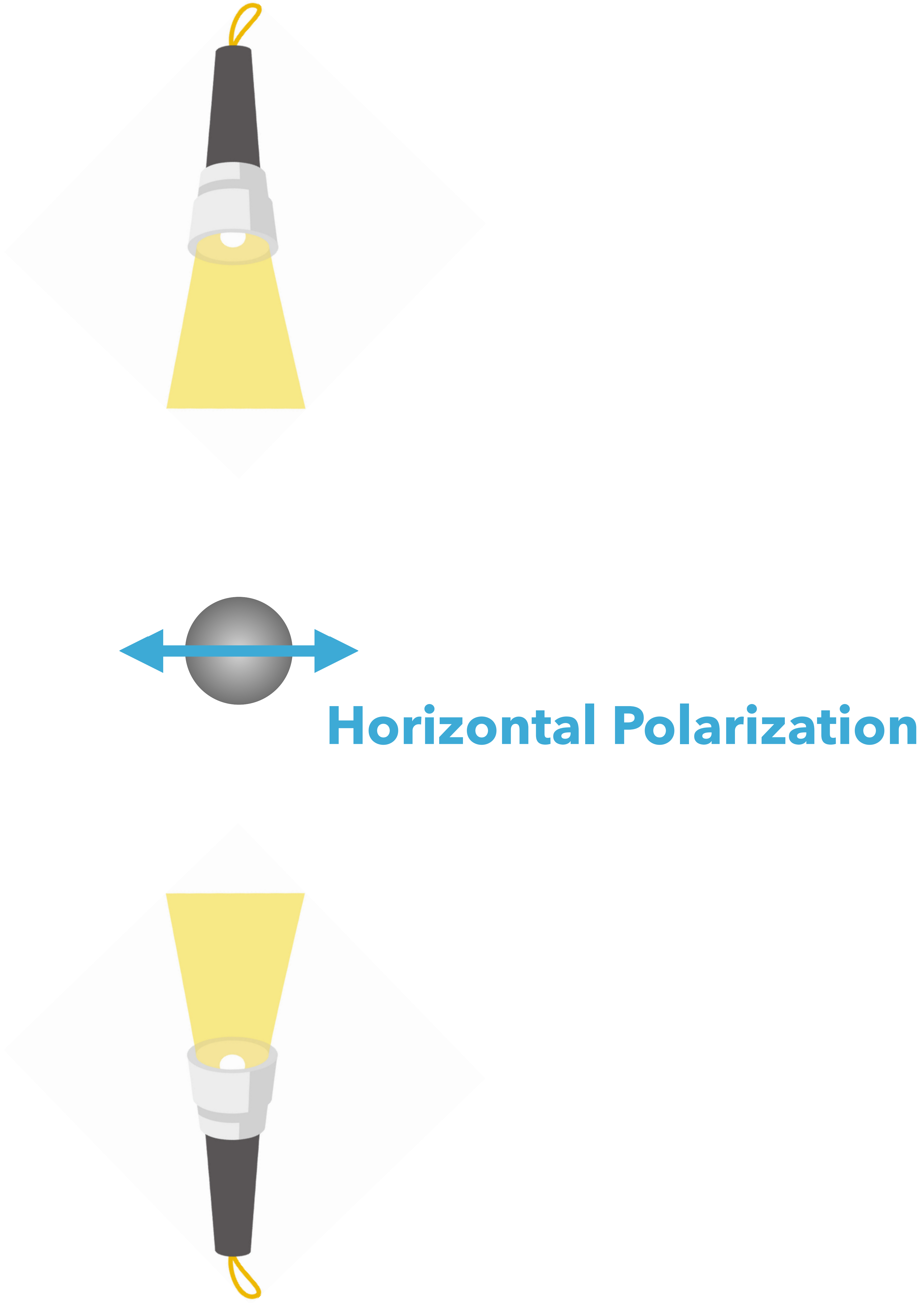
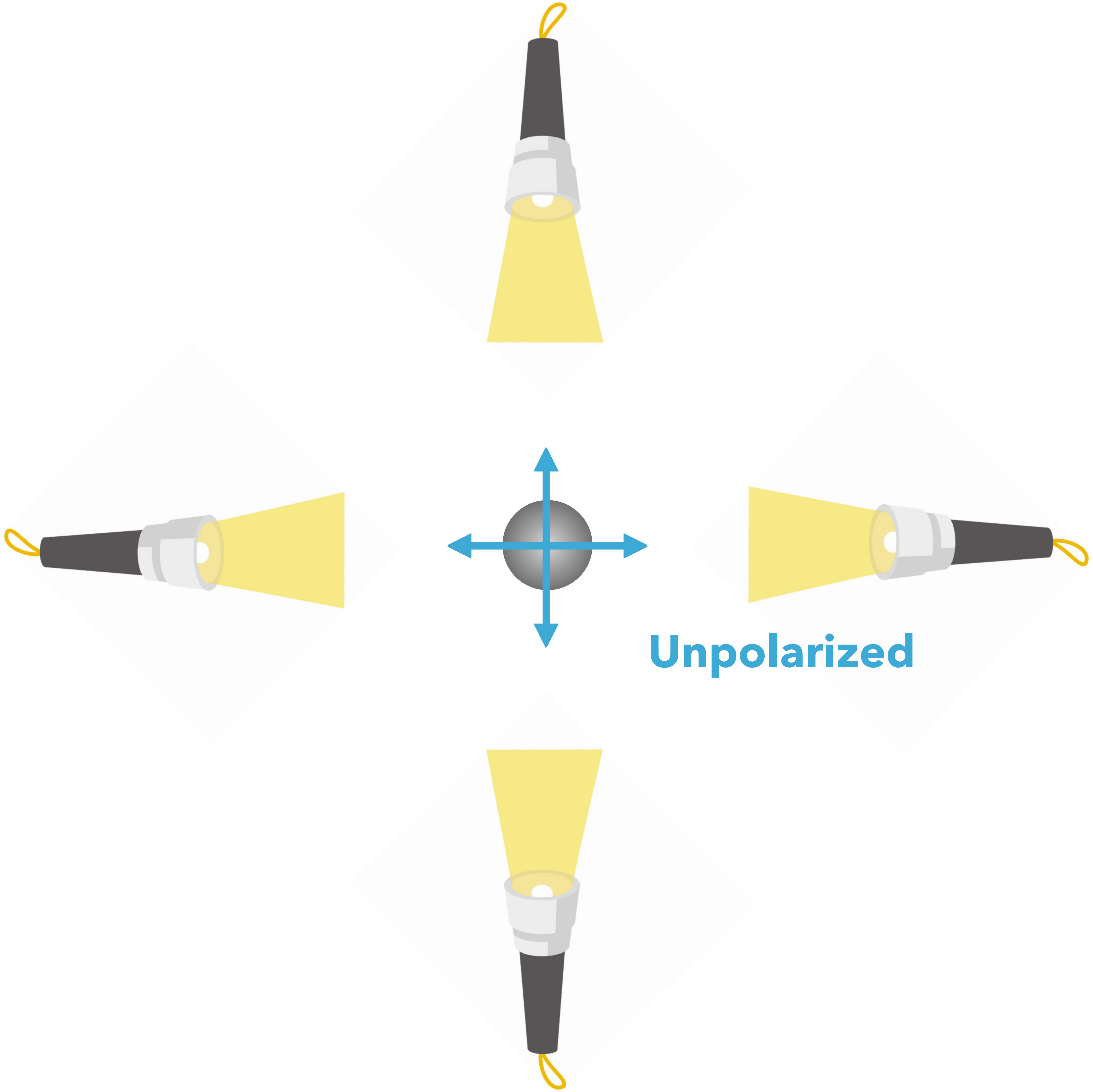


Akimasa Kataoka (NAOJ)

Polarization due to scattering



Akimasa Kataoka (NAOJ)

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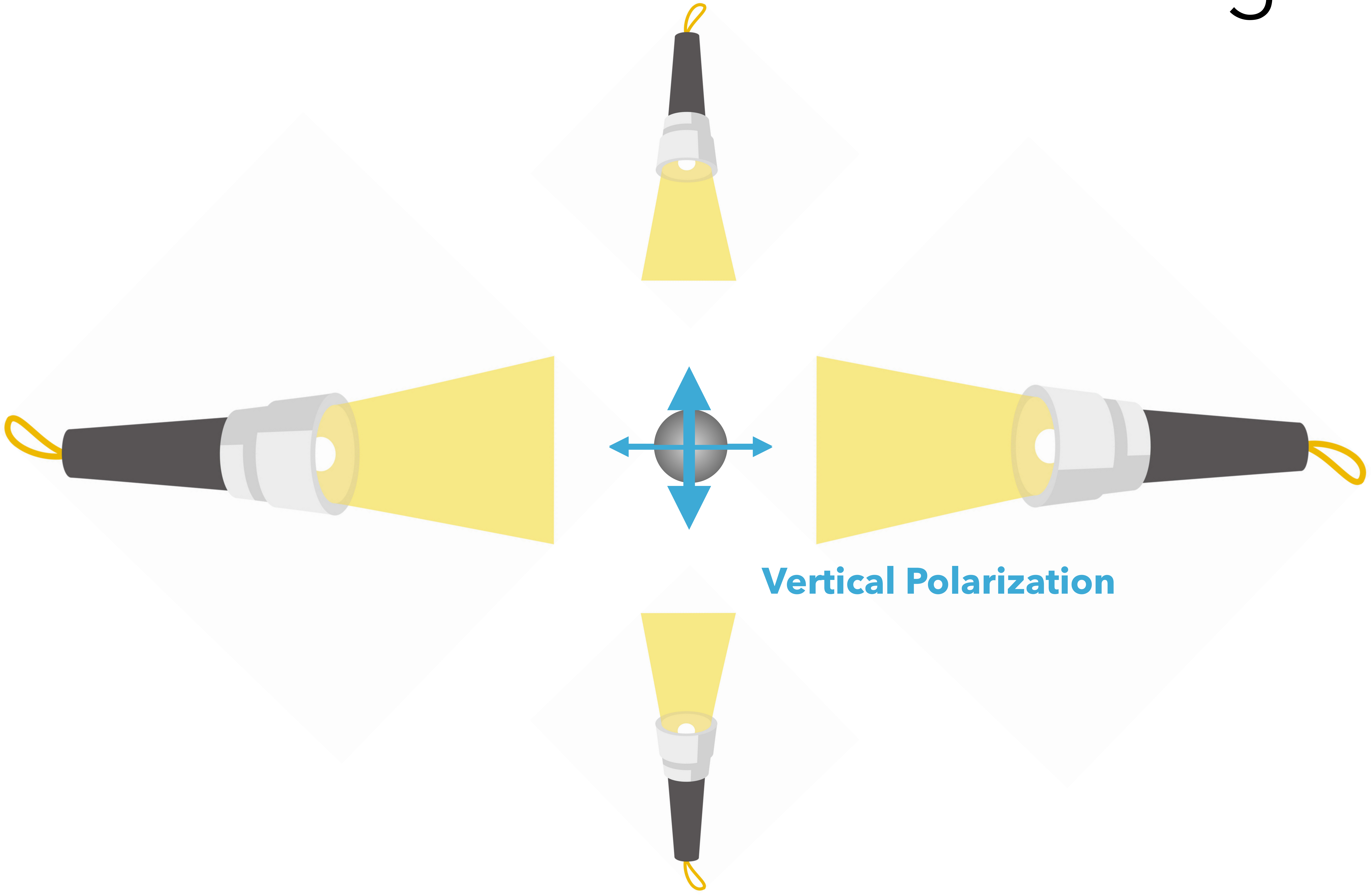

Akimasa Kataoka (NAOJ)

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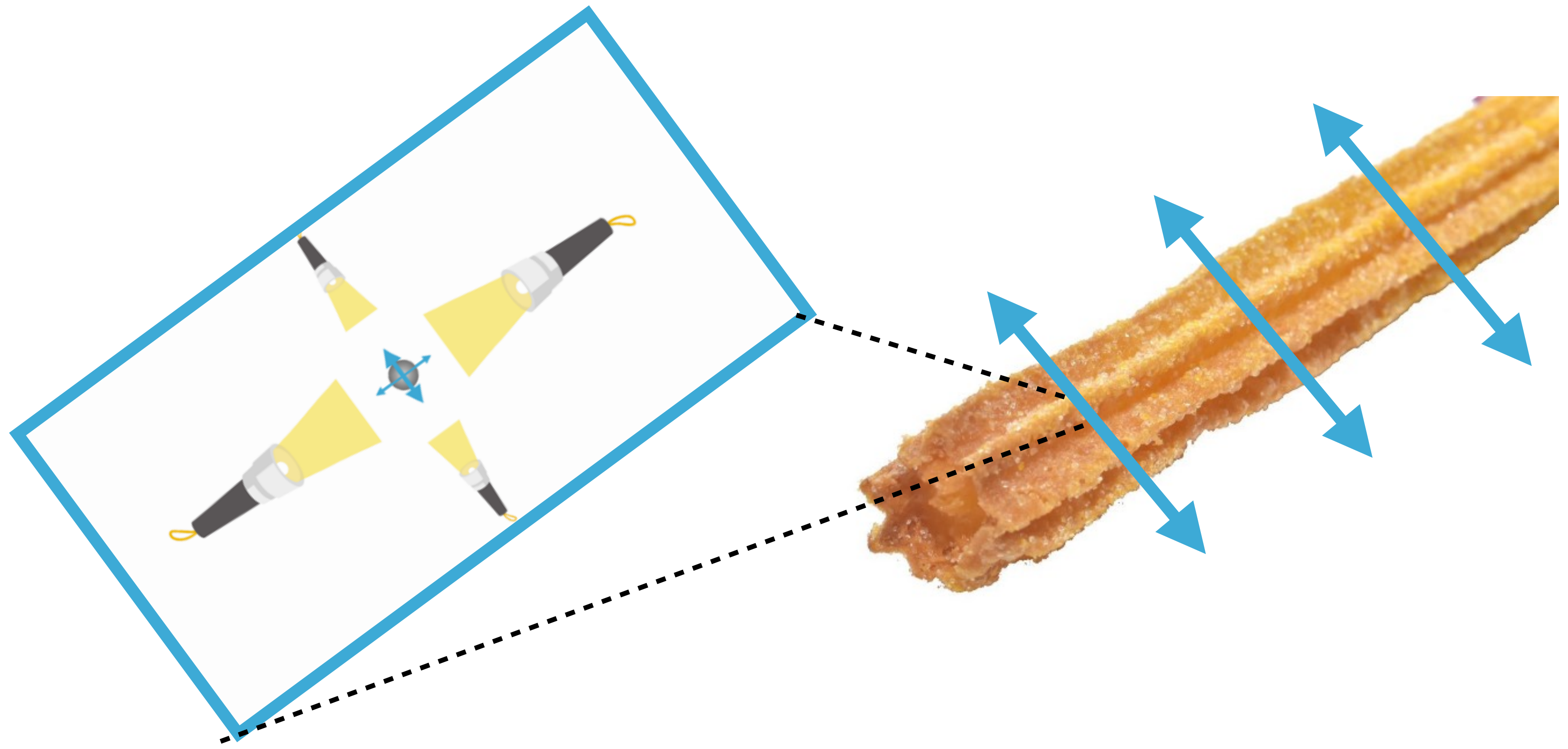
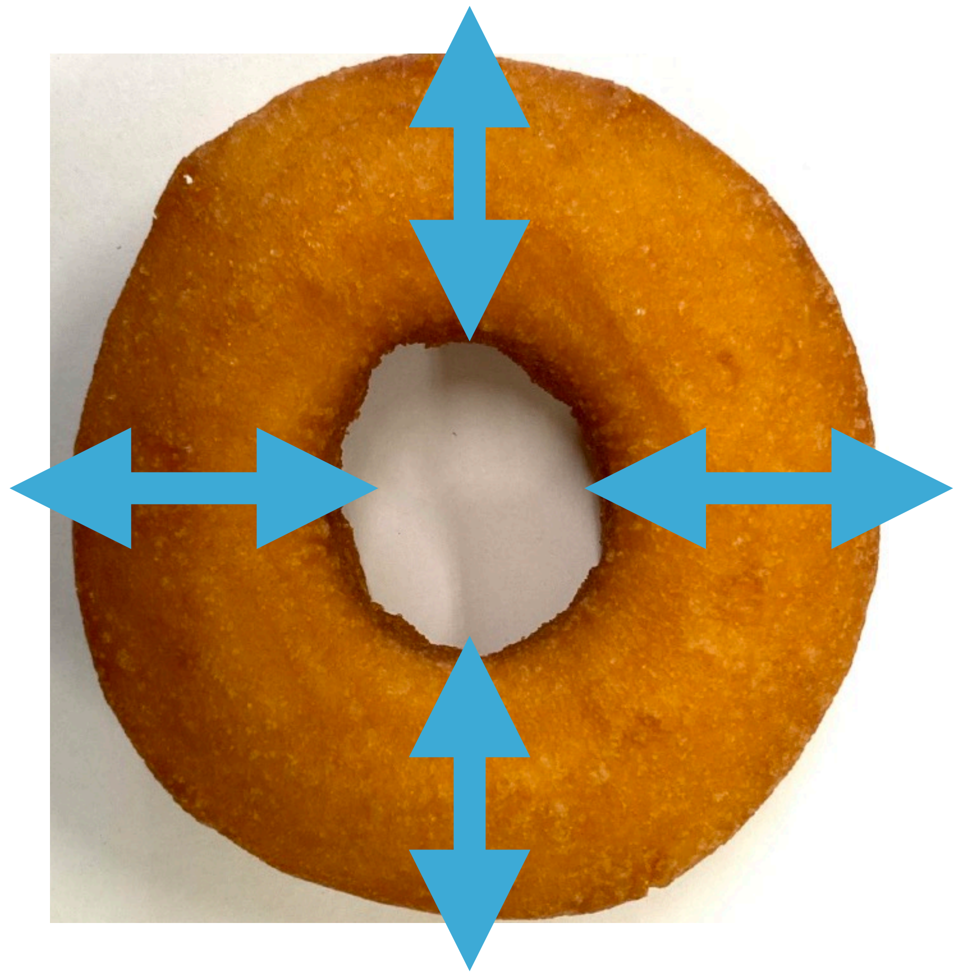


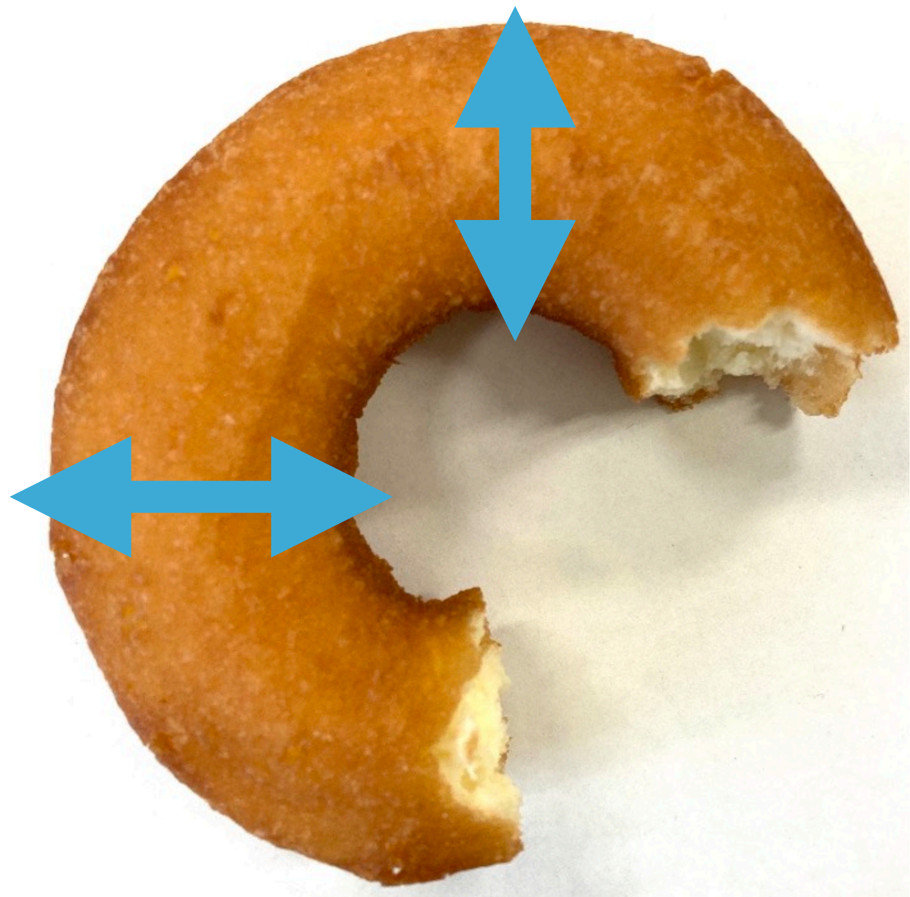
Polarization is perpendicular to a tube-like structure

Ring (face-on)



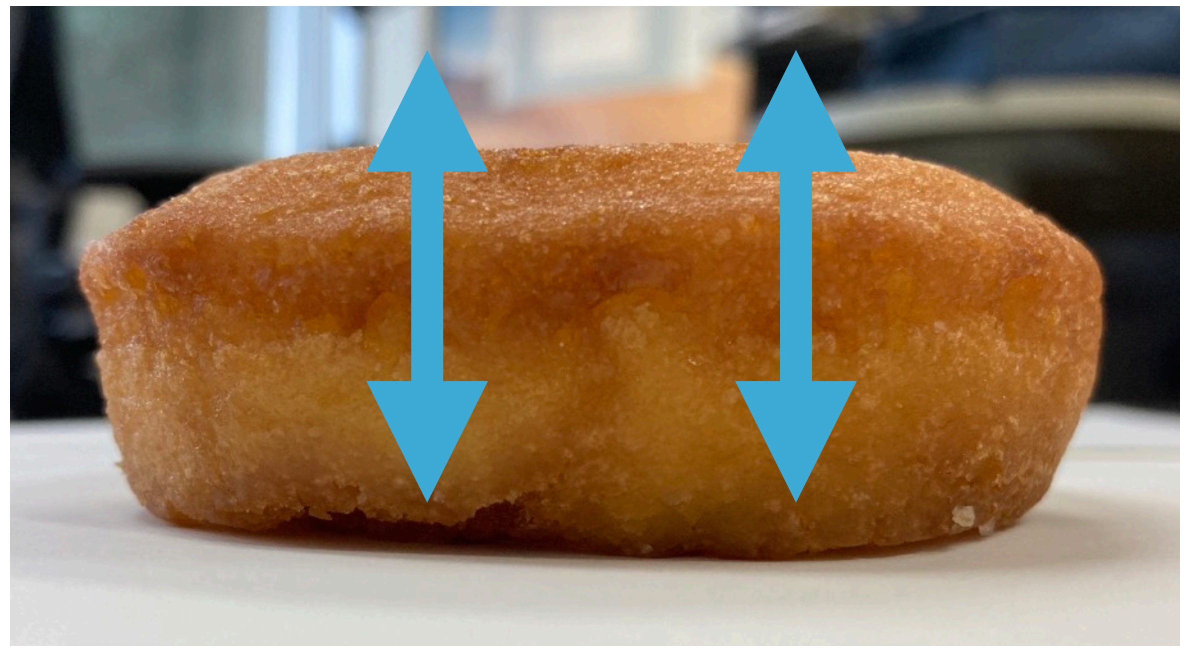
radial

Lopsided (face-on)



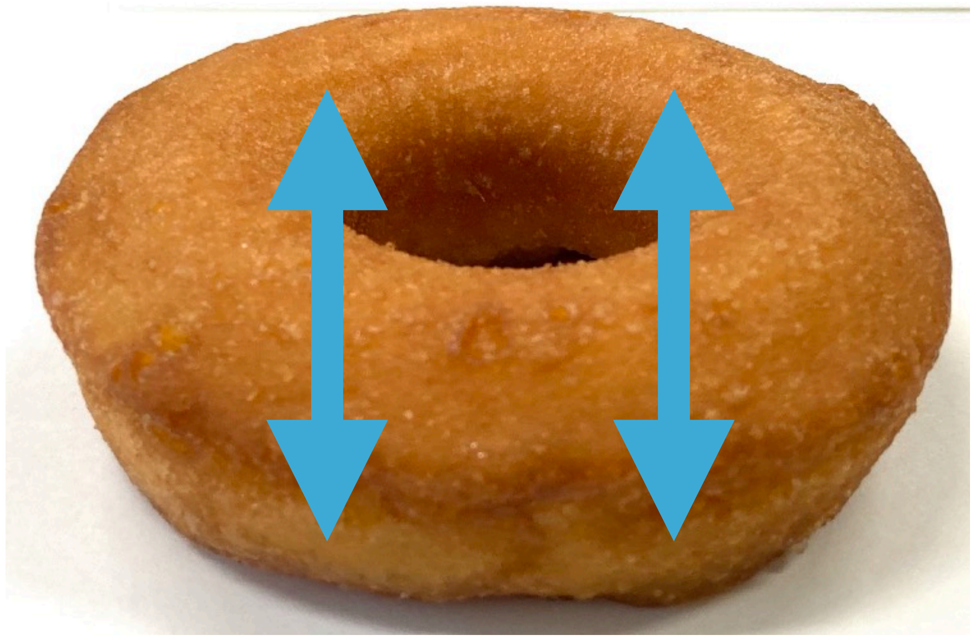
radial

edge-on view



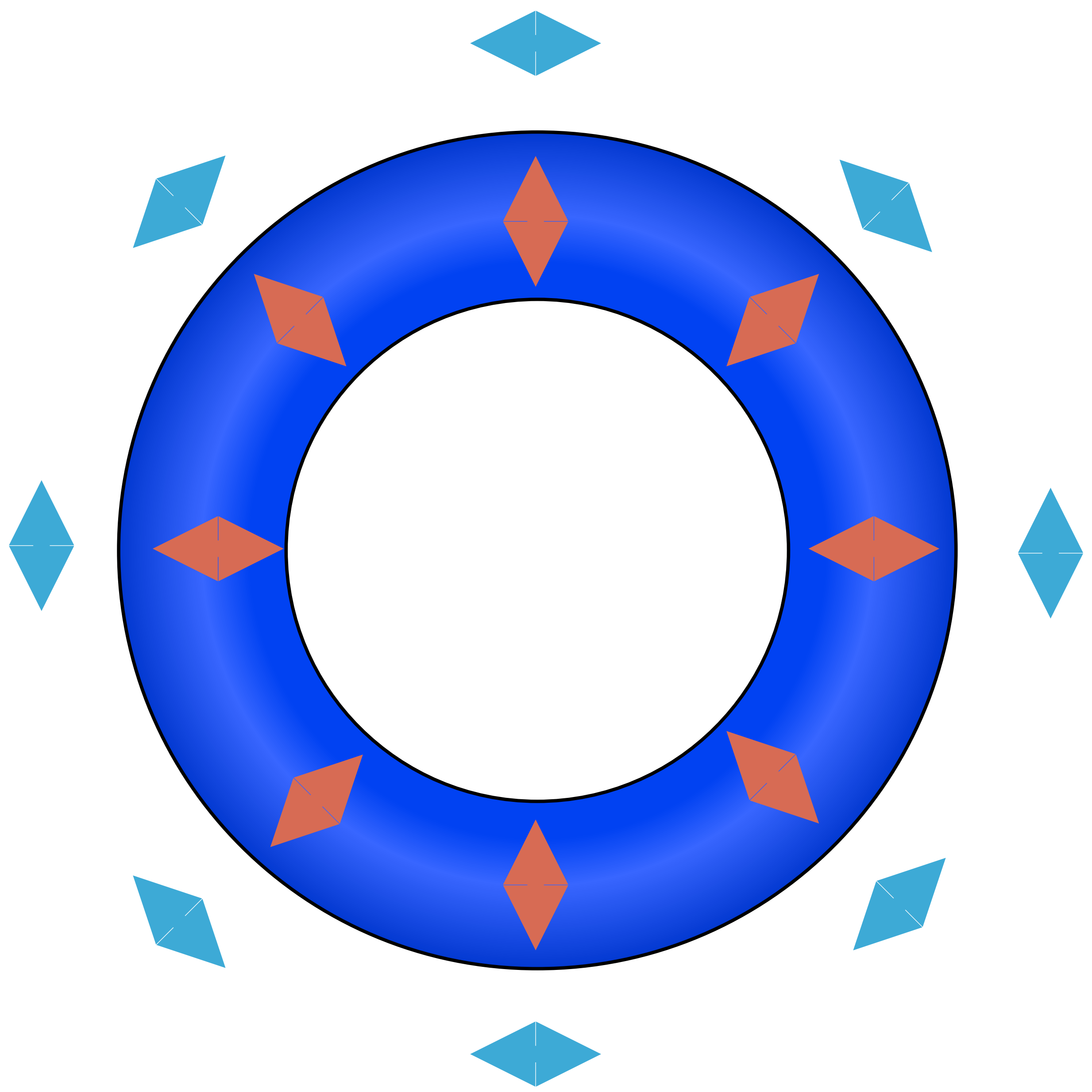
vertical

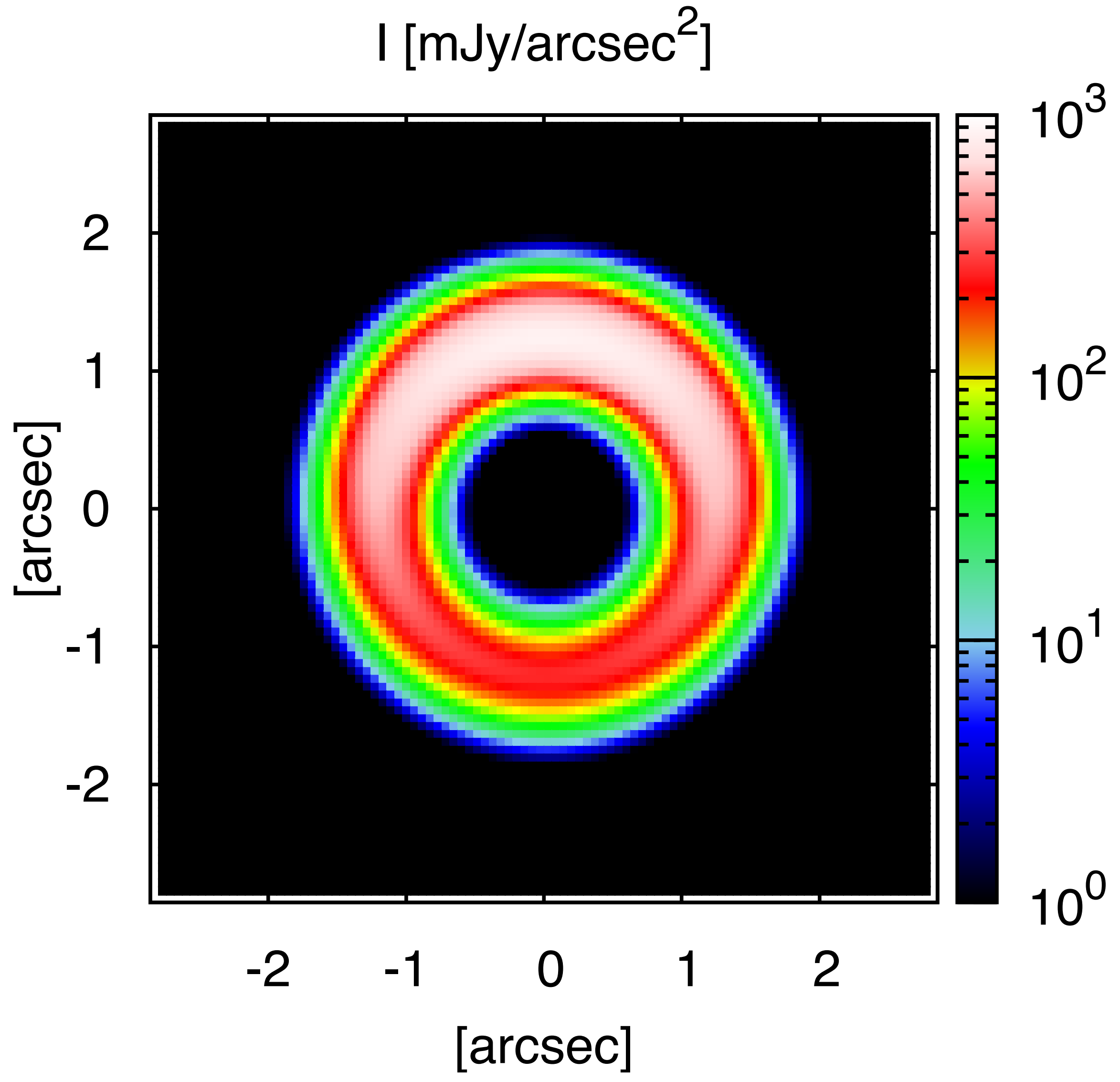
inclined disk

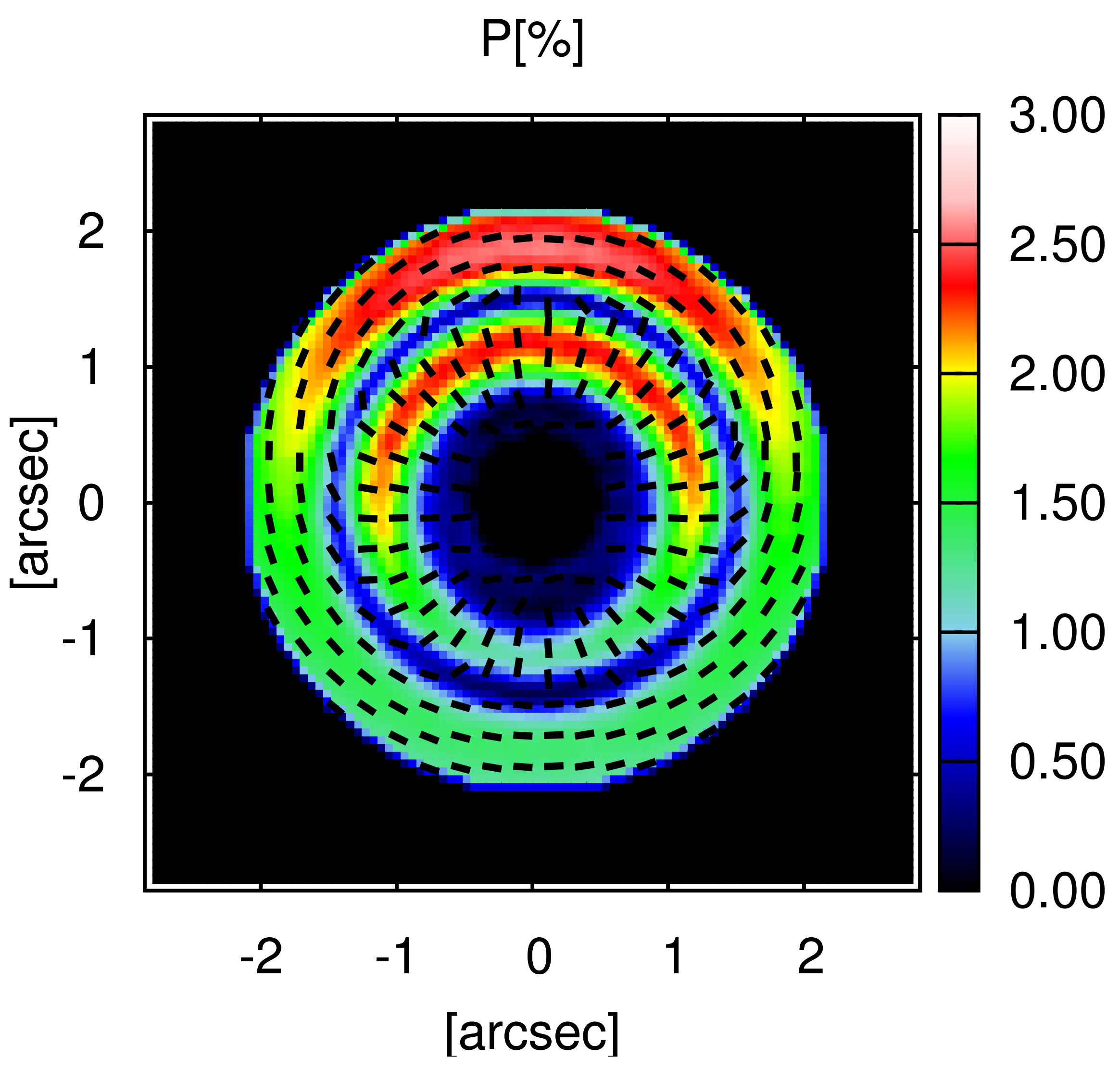


parallel to minor axis

Radiative transfer calculations



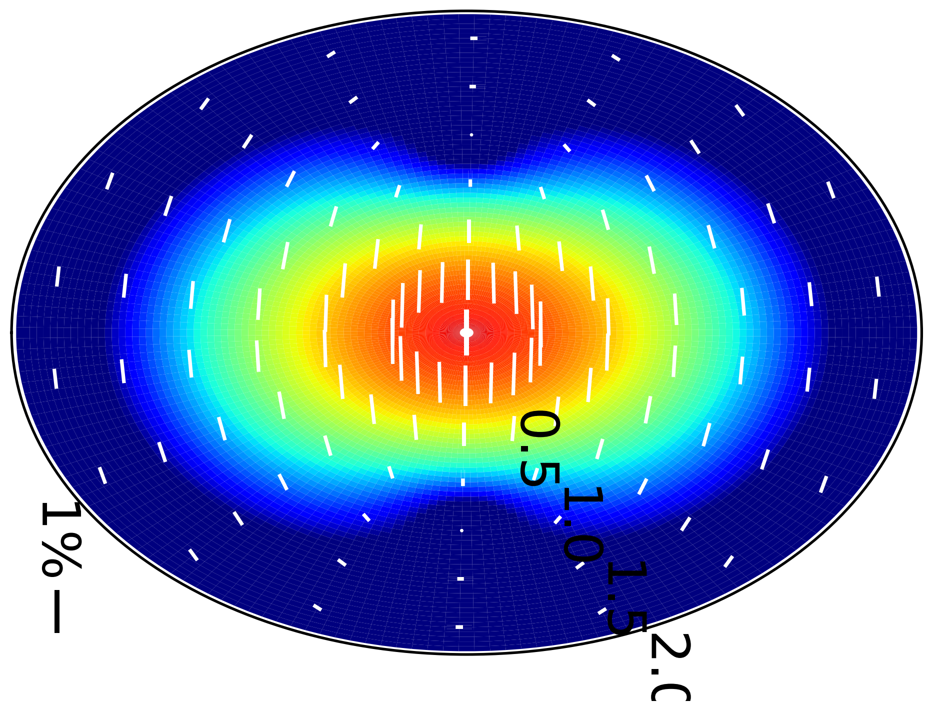


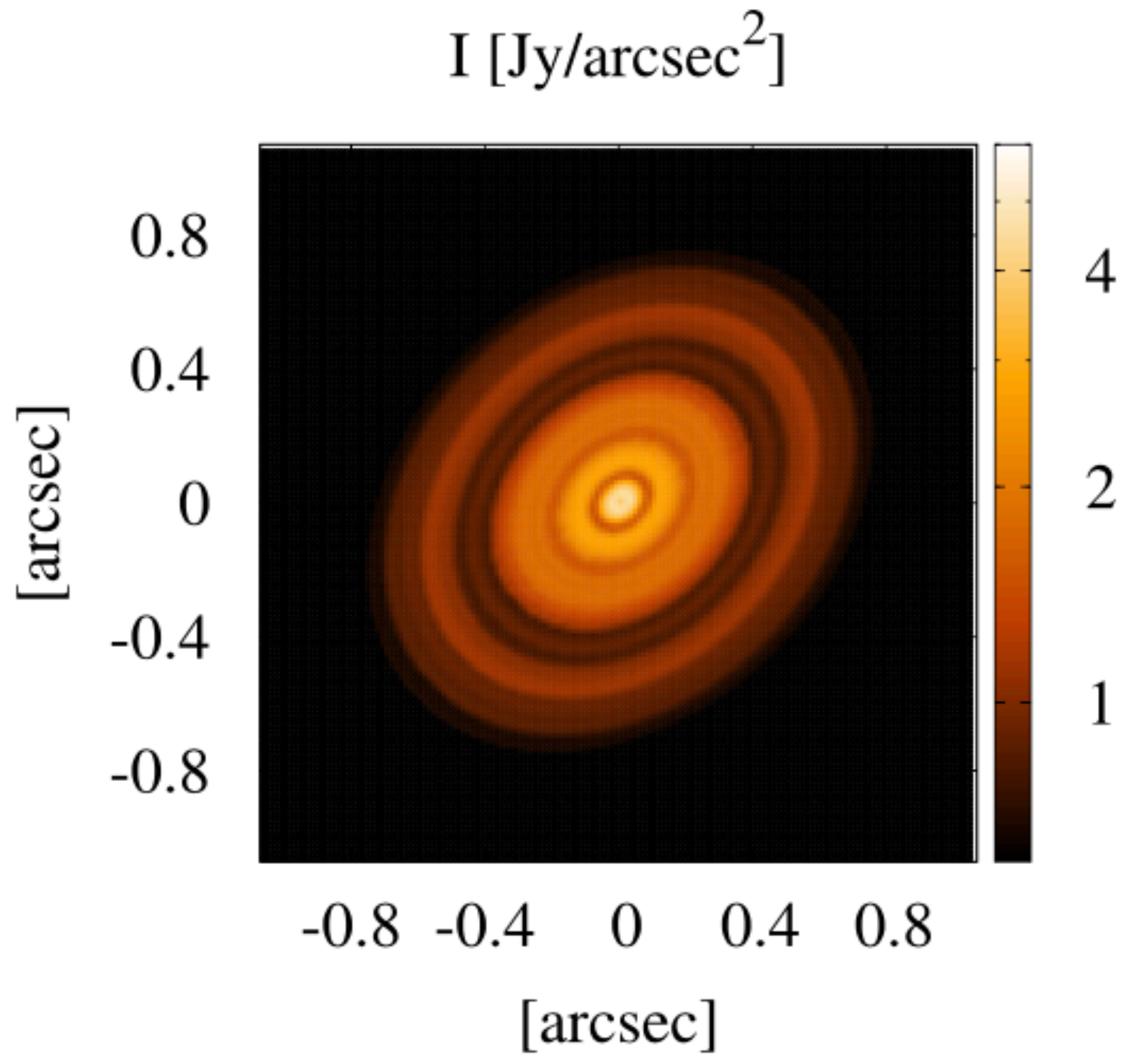


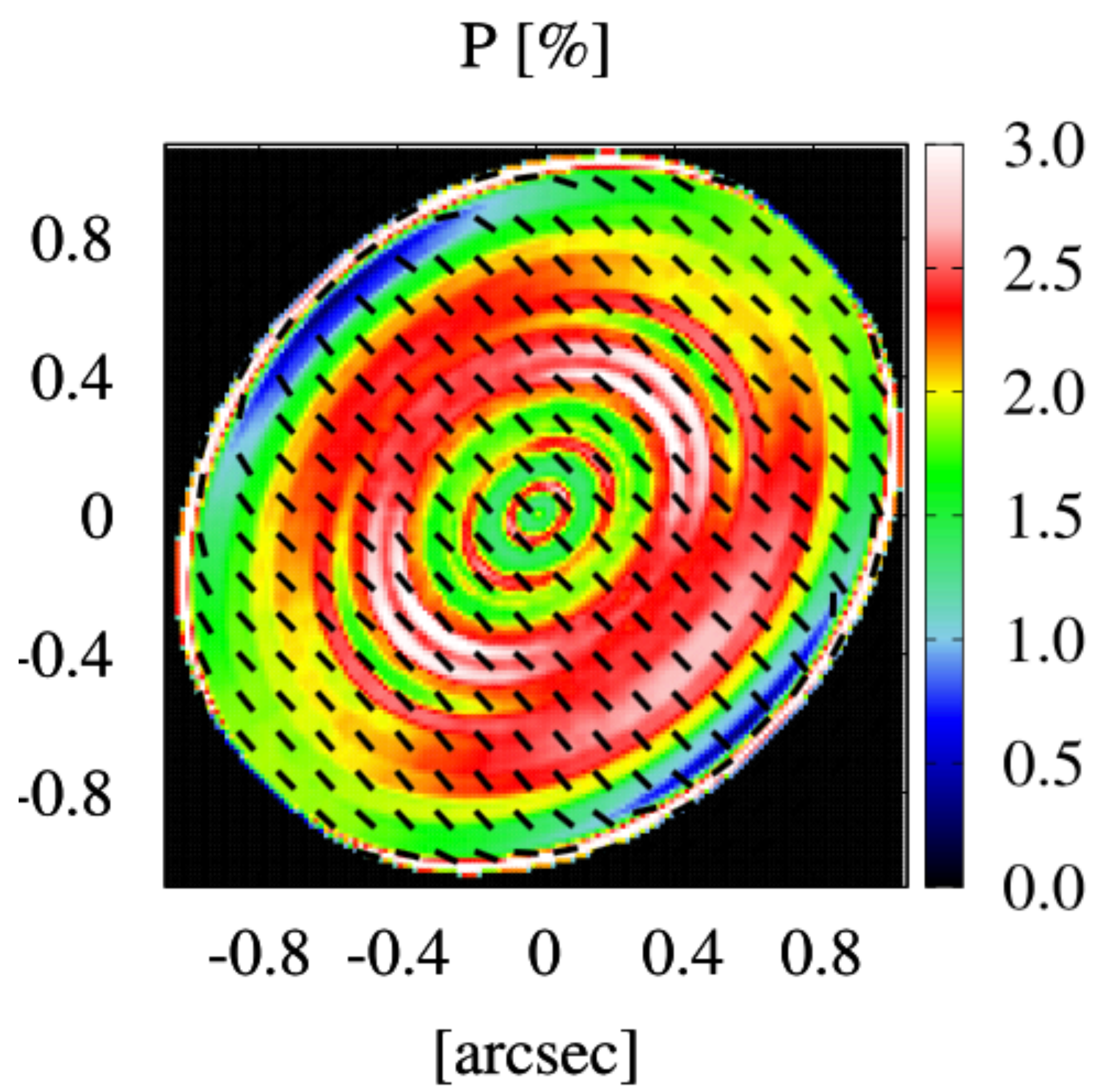
Pol. vectors

Radial inside,
azimuthal outside

Kataoka, et al., 2015, Ohashi et al. 2020,…







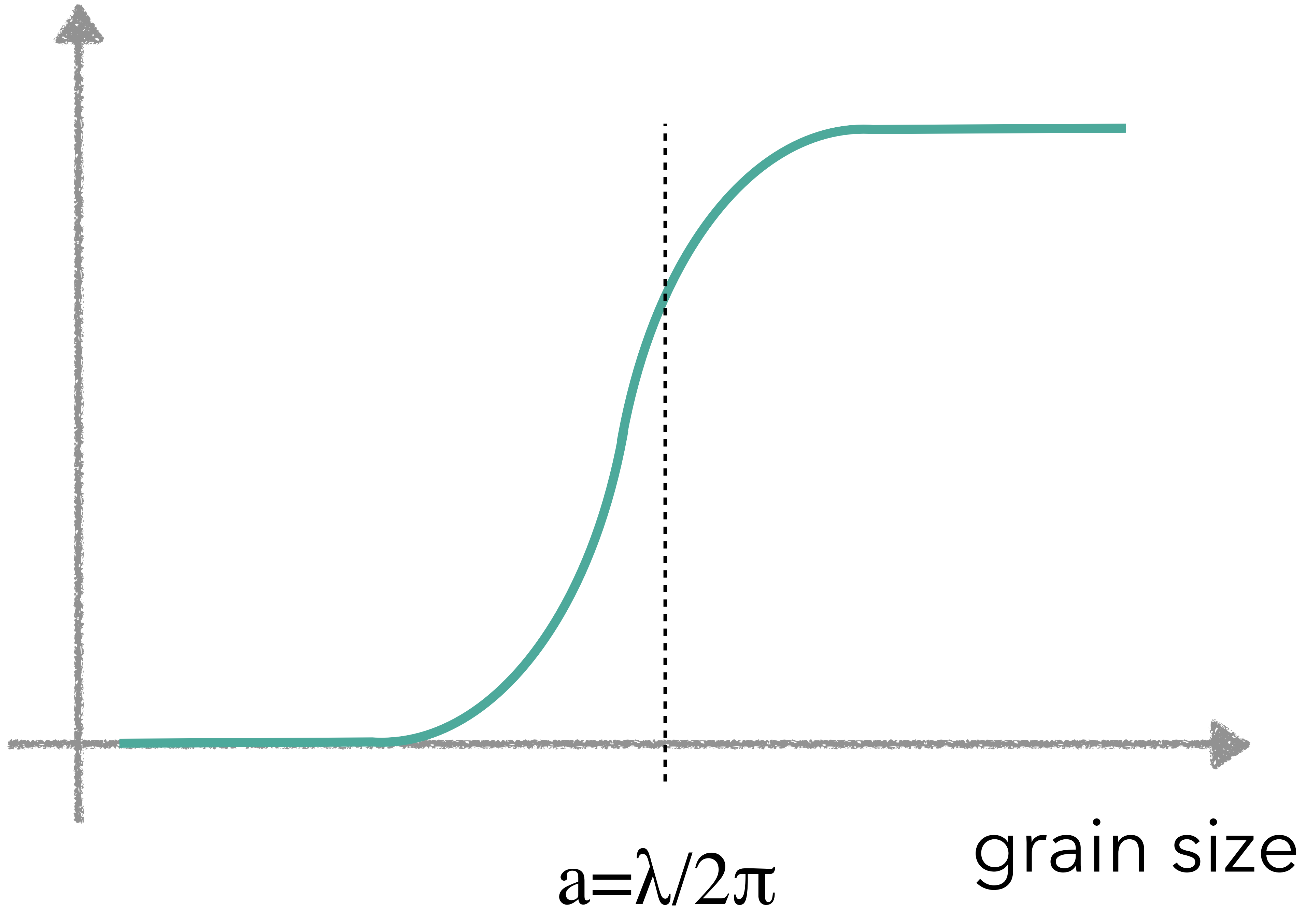
Parallel to the
disk minor axis

Kataoka, et al., 2016a, Yang et al. 2016, Dent et al. 2019, Okuzumi and Tazaki 2019, Ohashi and Kataoka 2019, Lin et al. 2020, Brunngräber and Wolf 2020 …

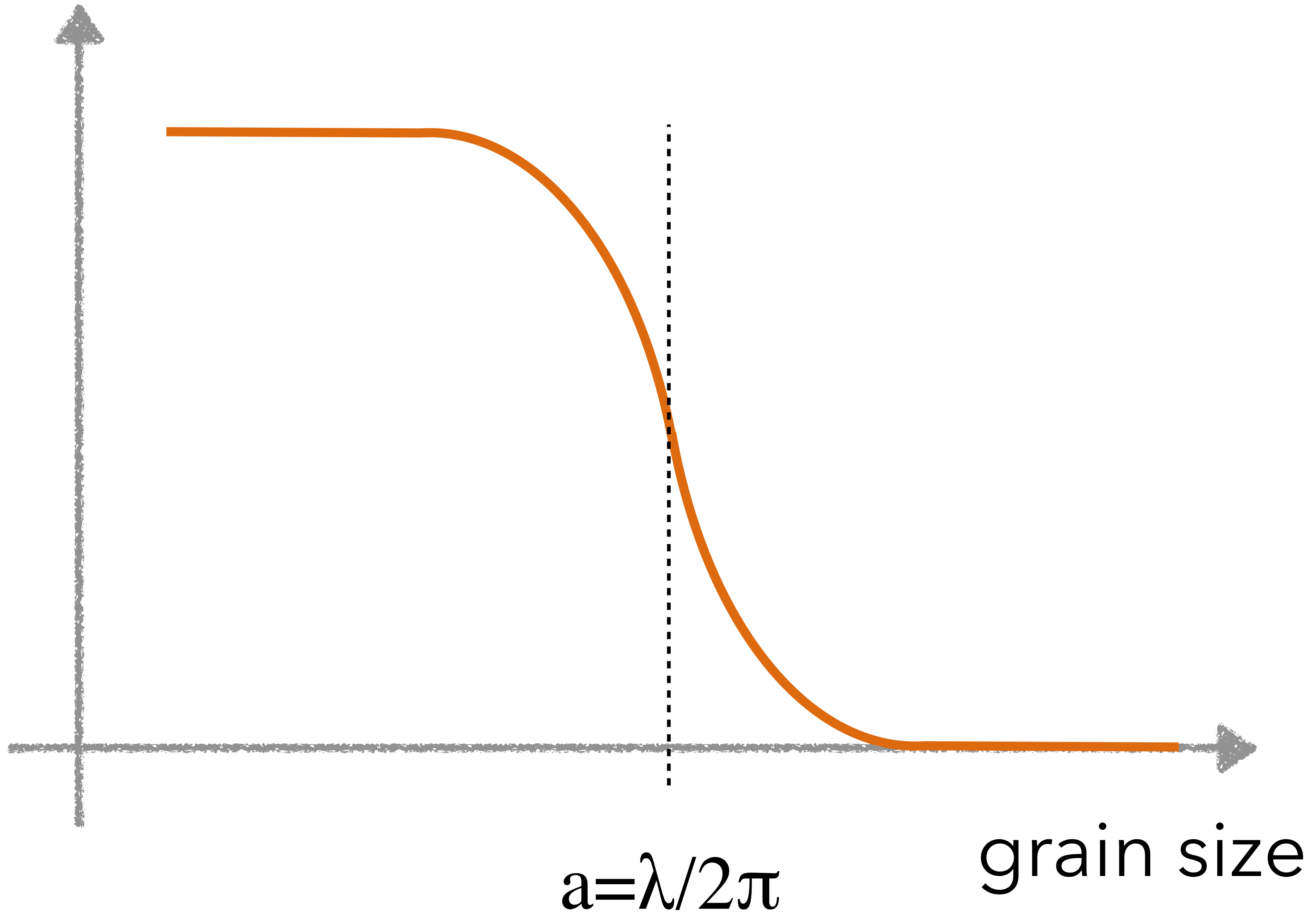
what can we learn from self-scattering?

Assumption: spherical dust grains

Albedo = efficiency of scattering



Polarization at single scattering

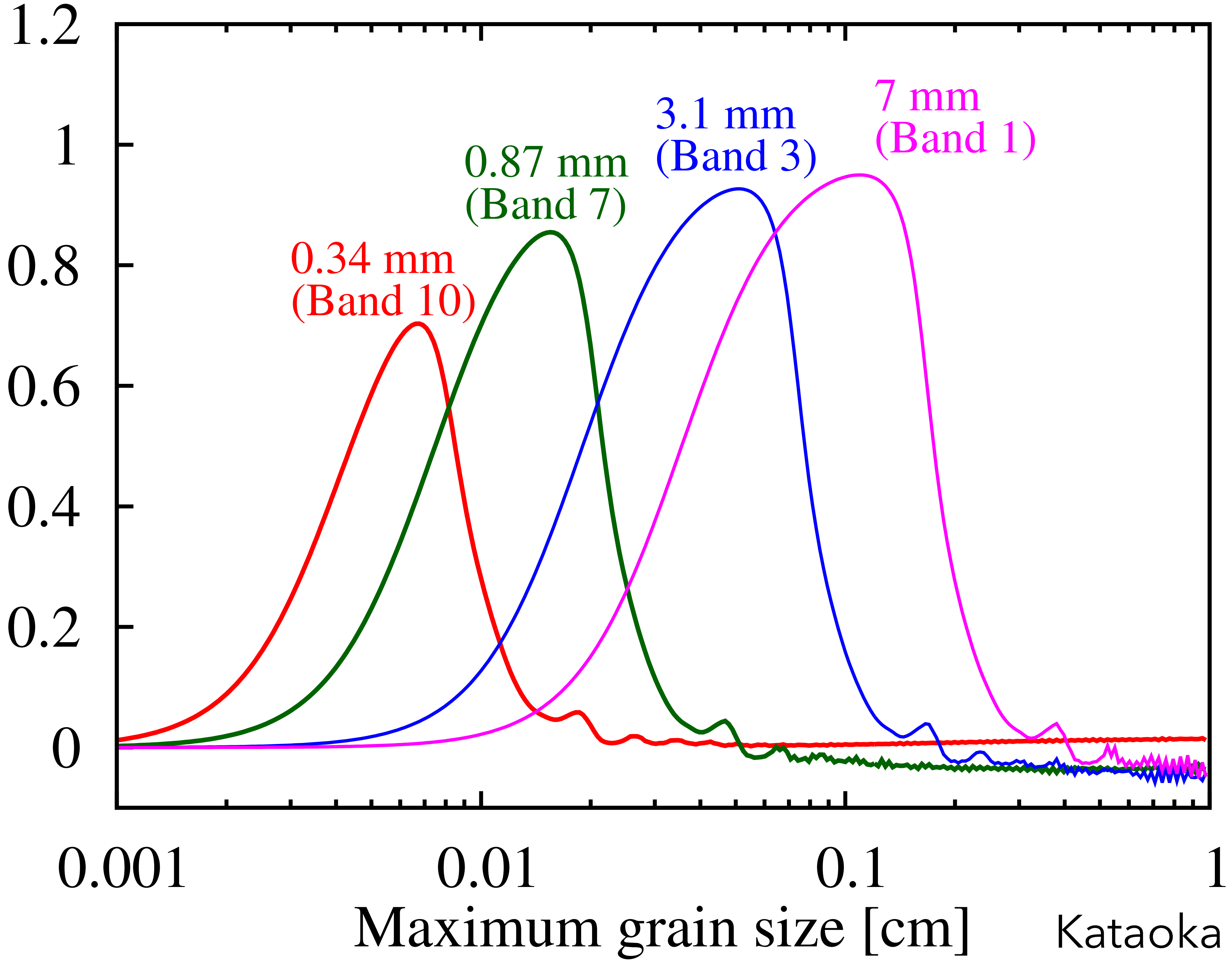


Scattering-induced polarization is detectable only when a=λ/2π

what can we learn from self-scattering?

Anisotropies of radiation field at the observed wavelengths. × **Grain size** = **Polarization**

Prediction of polarization fraction

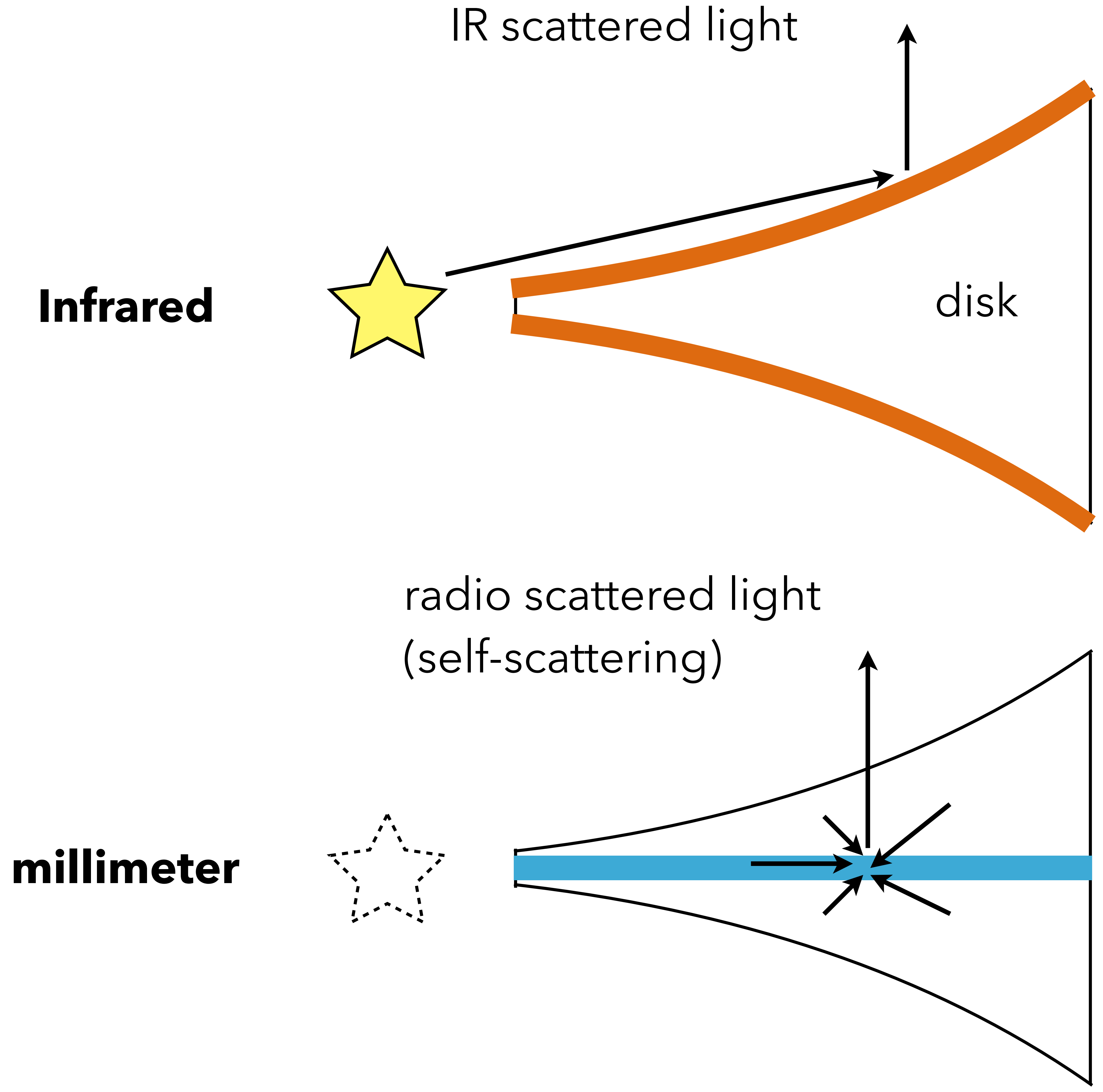


Kataoka et al., 2015

(grain size) ~ λ/2π

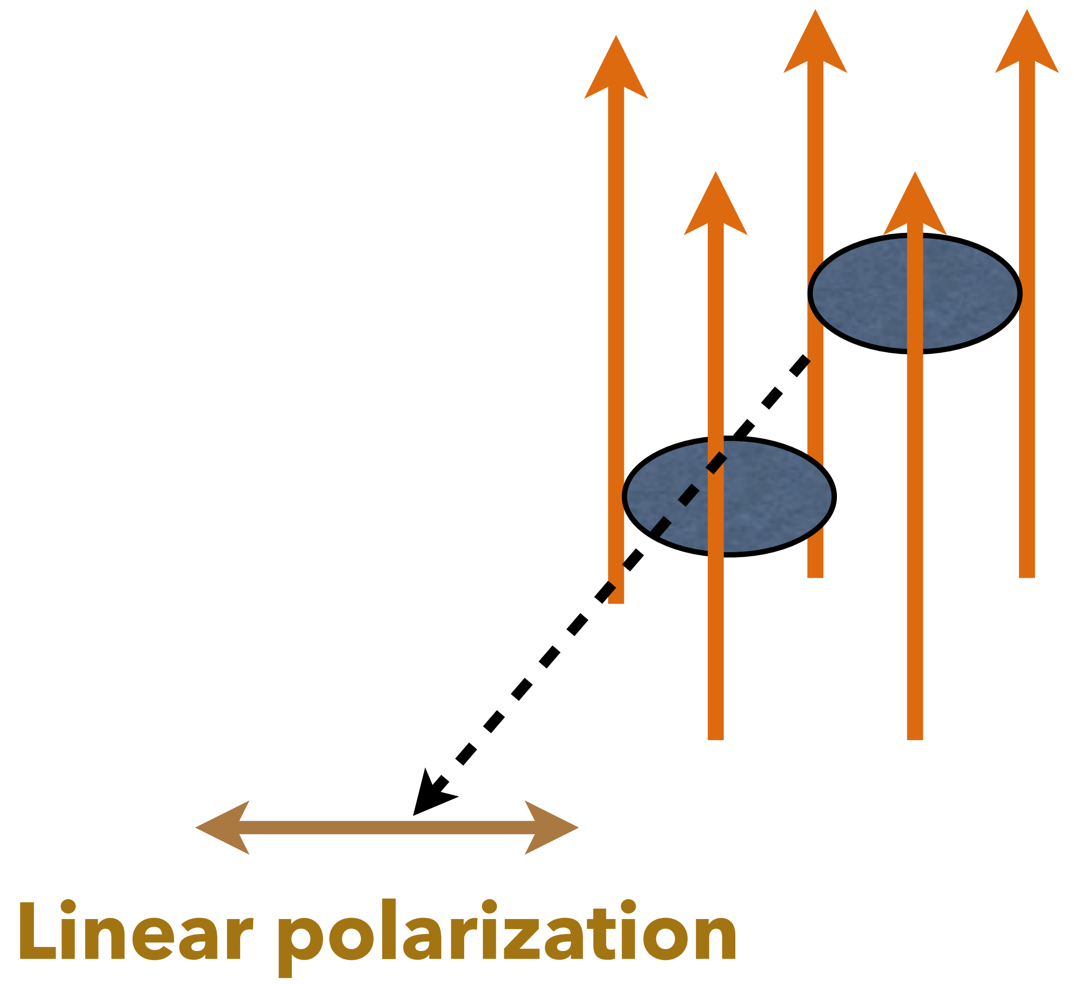
Polarization mechanisms

Self-scattering



Kataoka et al. 2015

Grain alignment



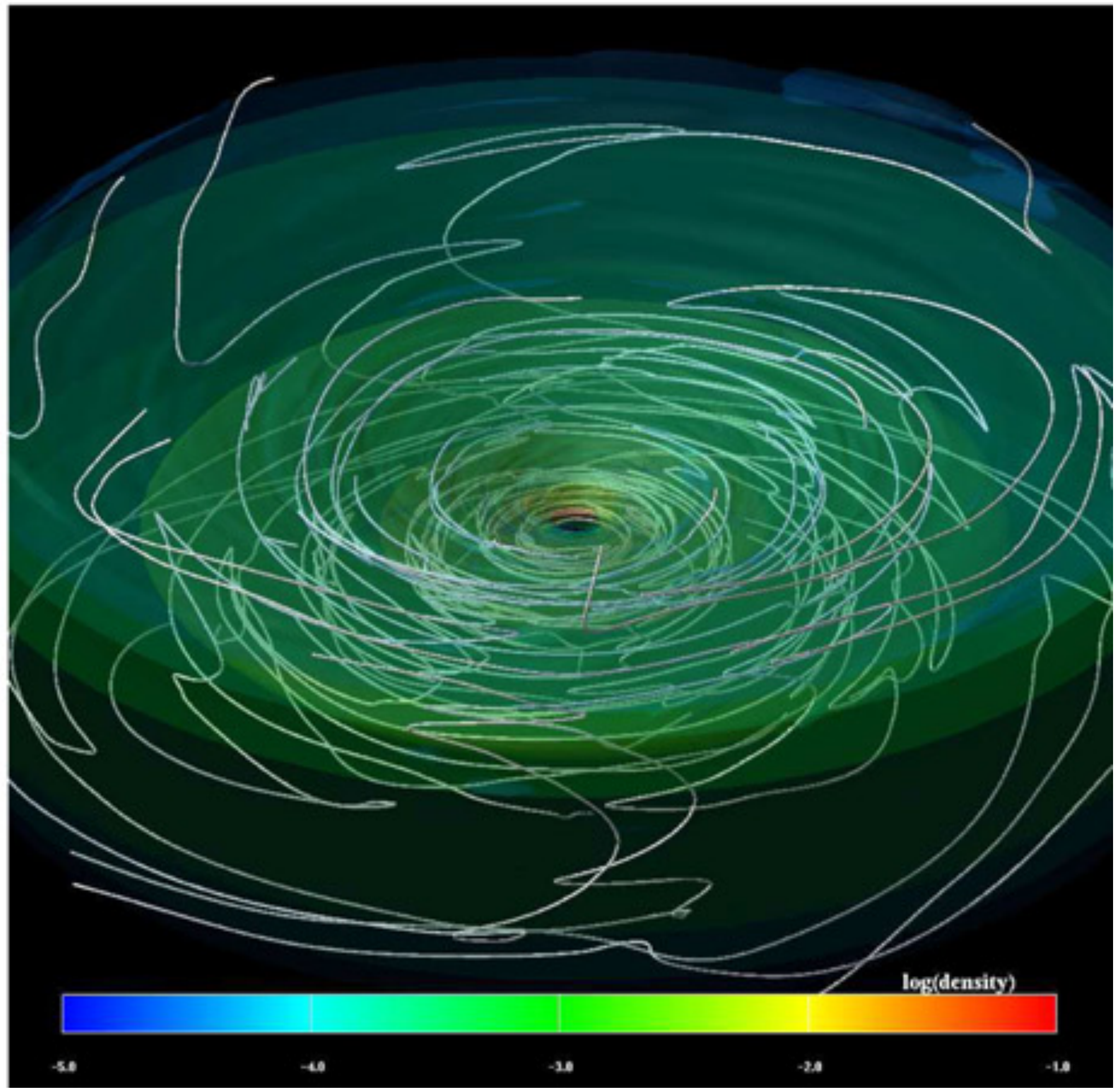
Directions
- B-fields
- radiation
- gas flow

e.g., Cho and Lazarian 2007, Tazaki et al. 2017, Lazarian and Hoang 2007, Kataoka et al. 2019

Note: dust grains at midplane do not receive stellar photons

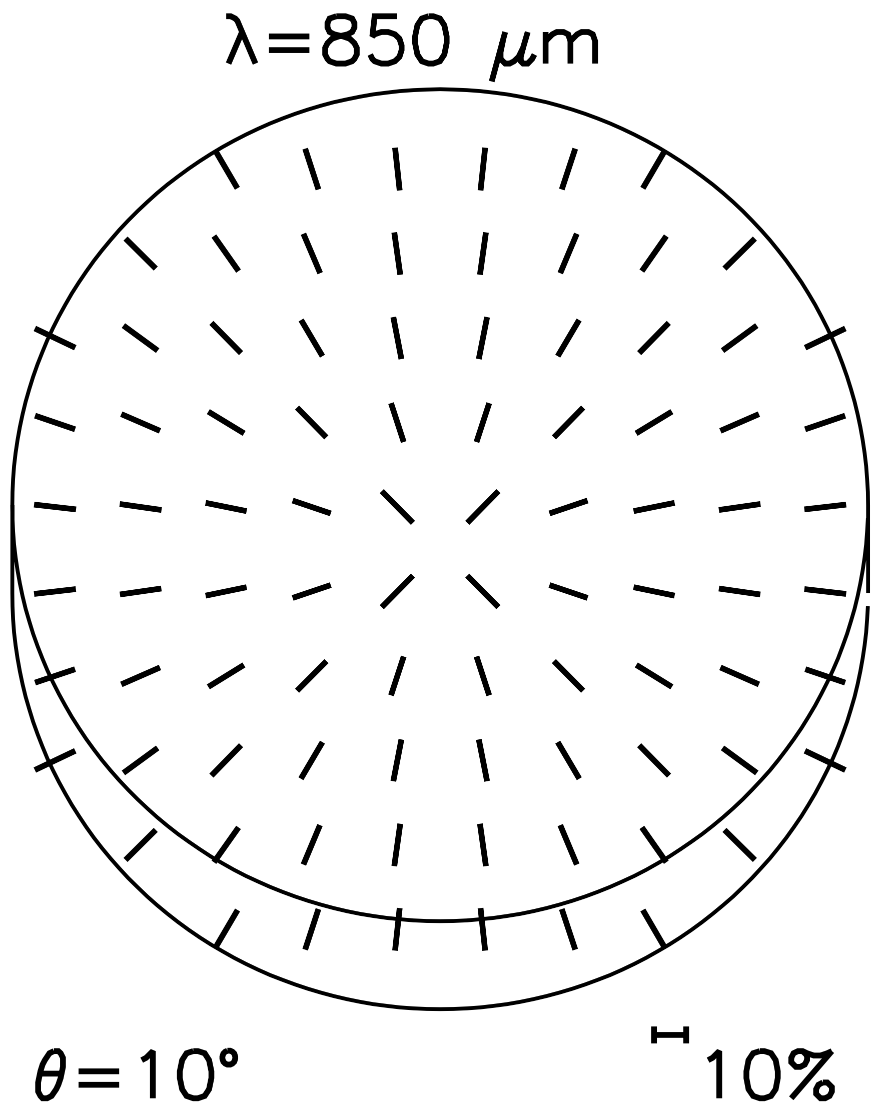
If grains are aligned with B-fields…

Toroidal magnetic fields

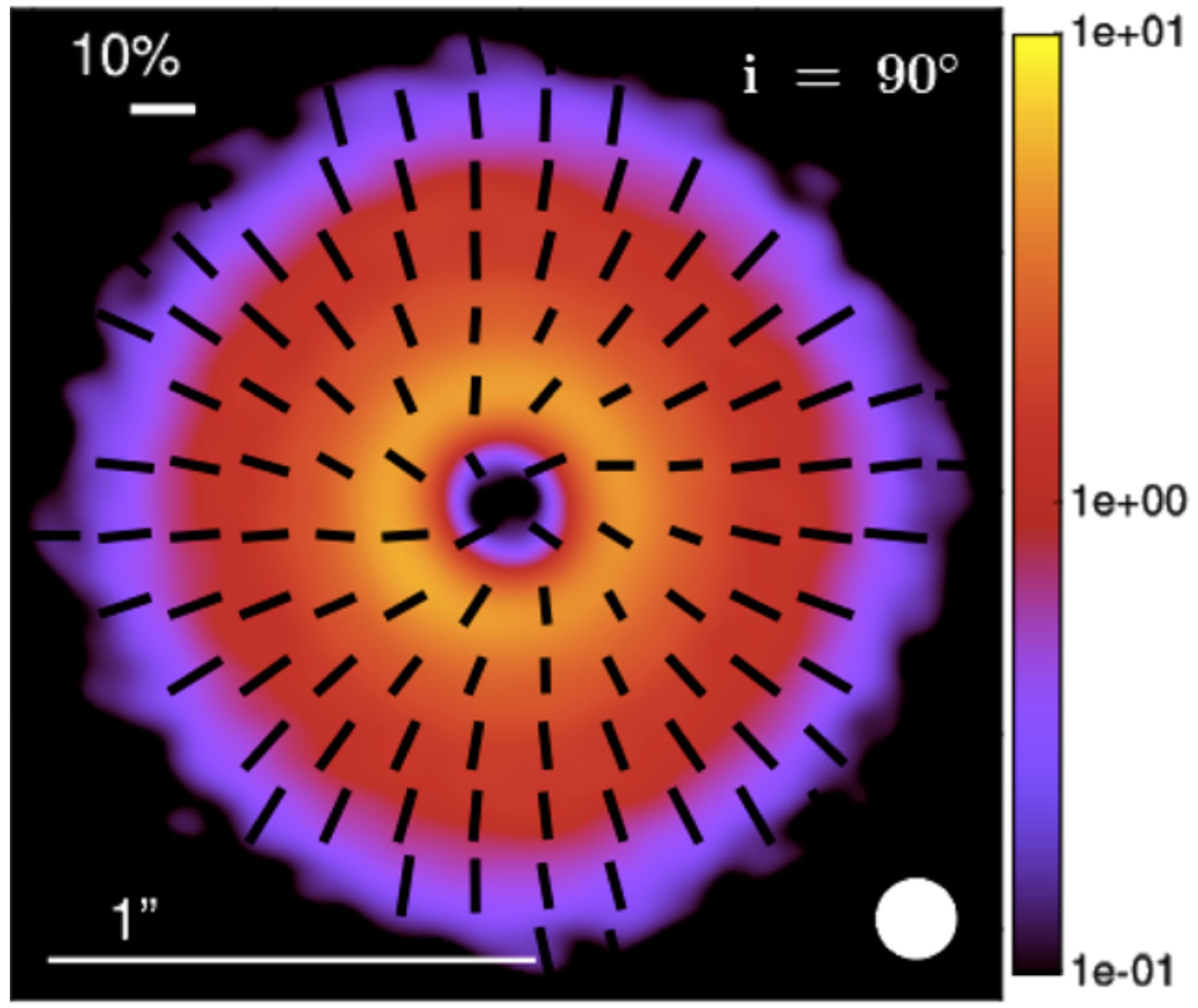


Suzuki et al. 2014

Synthetic polarimetric observations



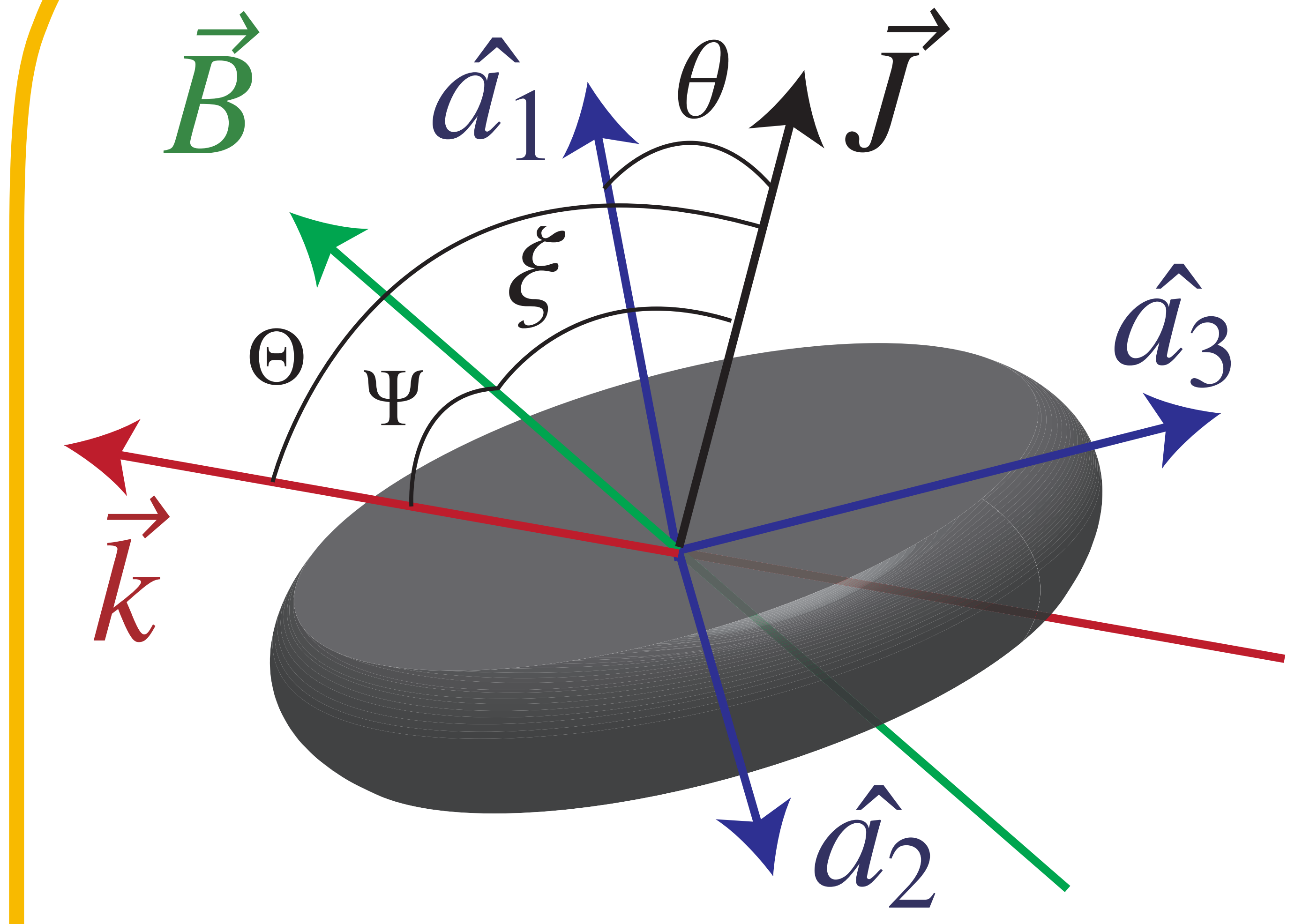
Cho and Lazarian 2007

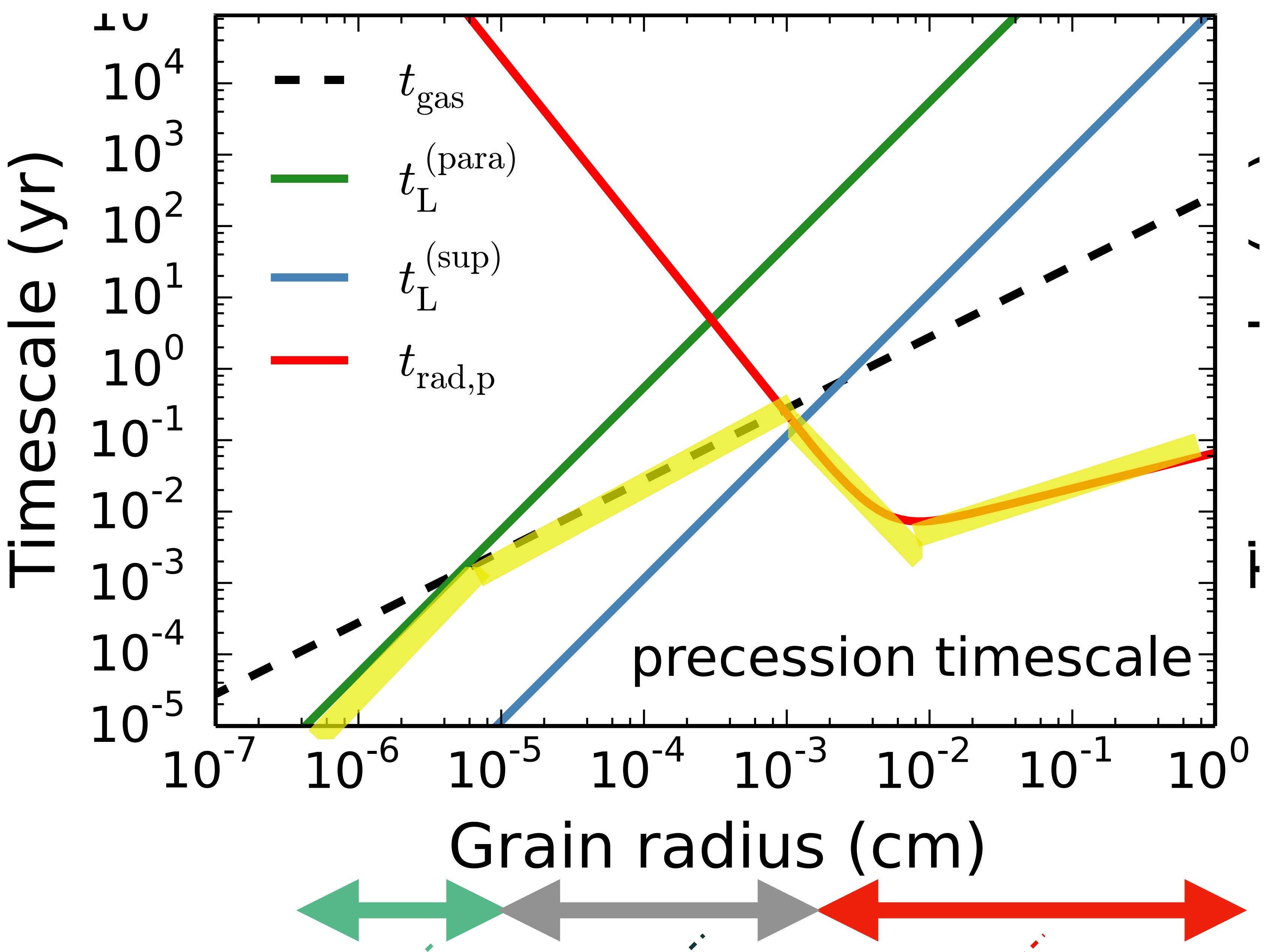


Bertrang et al. 2014

Dust alignment at disk midplane

Dominant alignment mechanisms

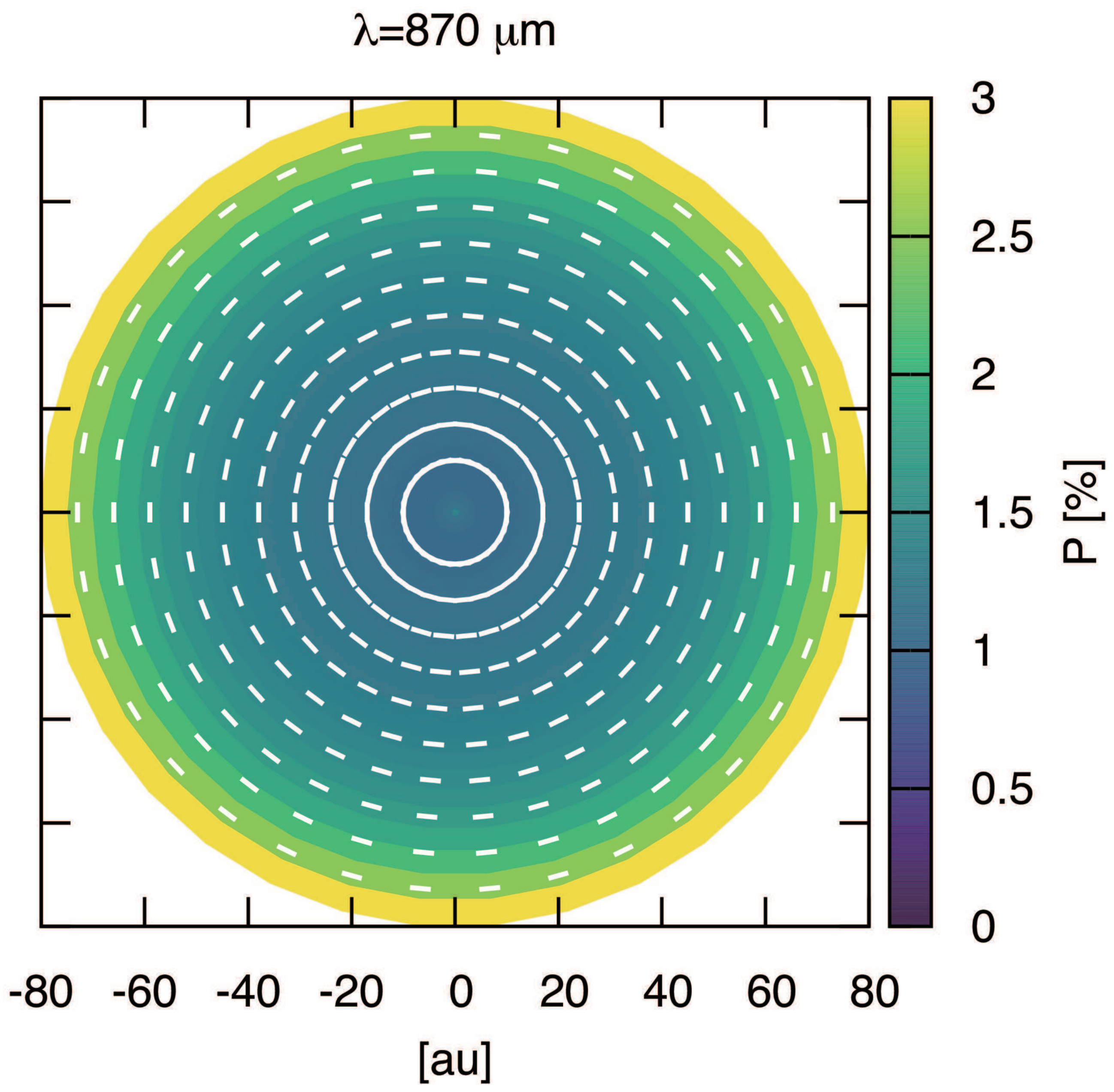




Aligned with B-fields

No alignment

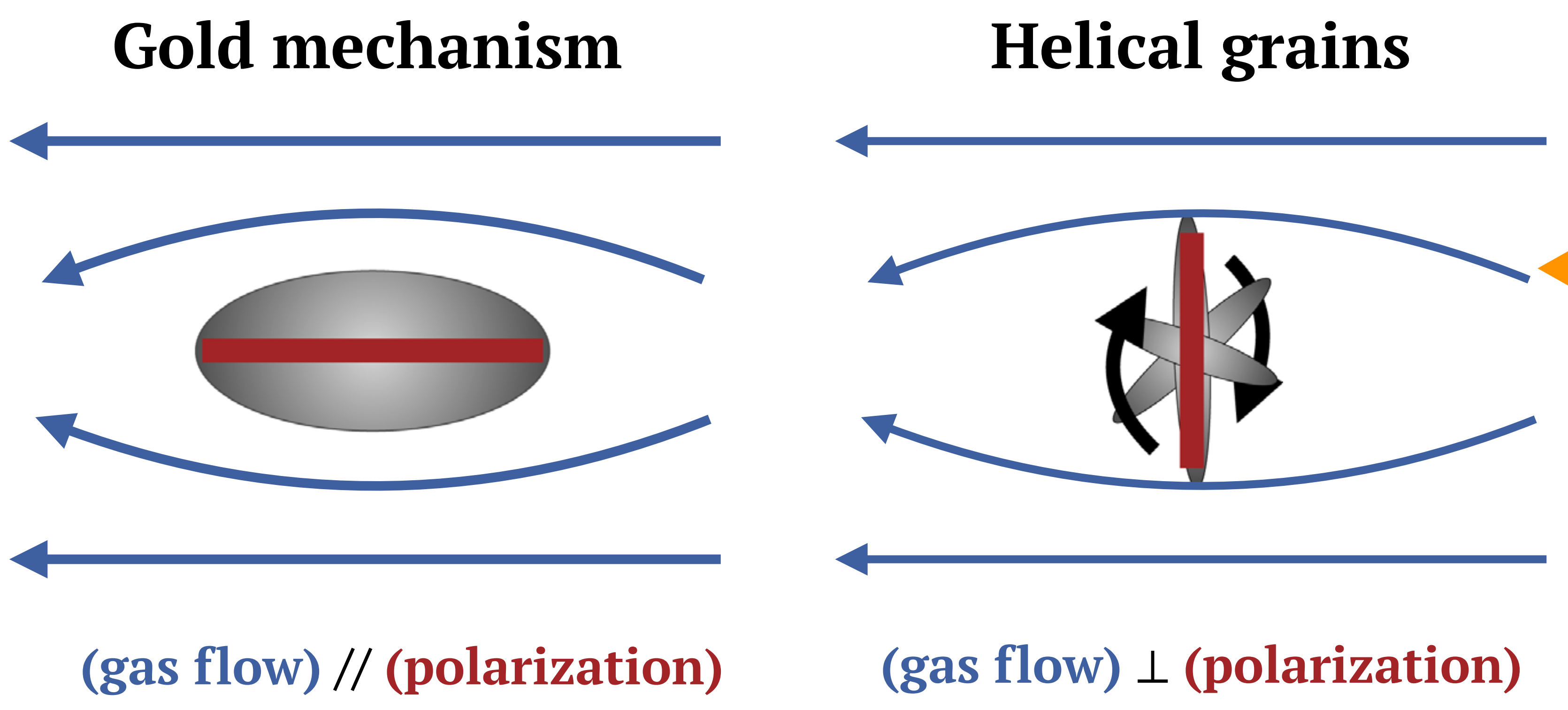
Aligned with radiation

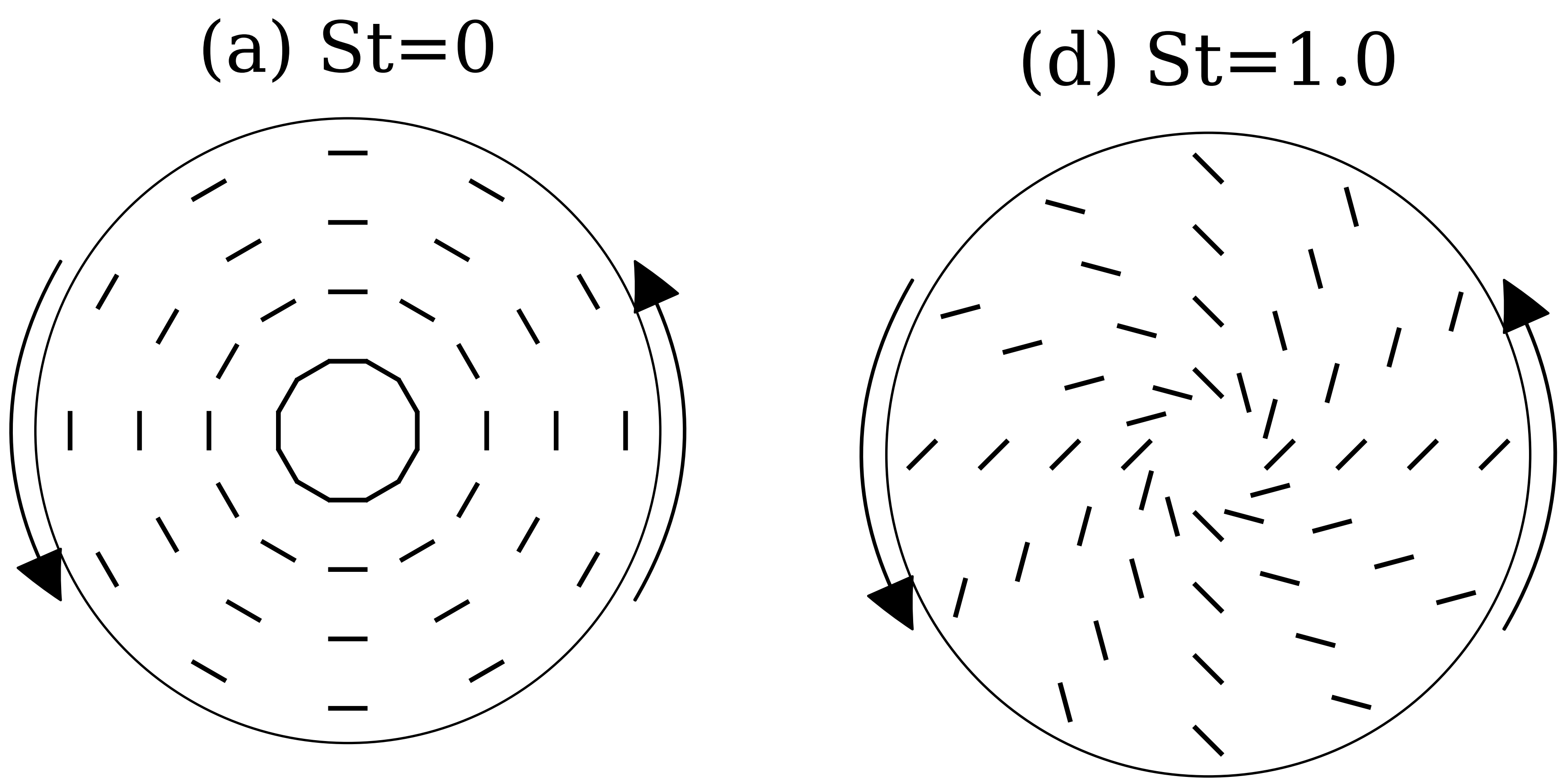


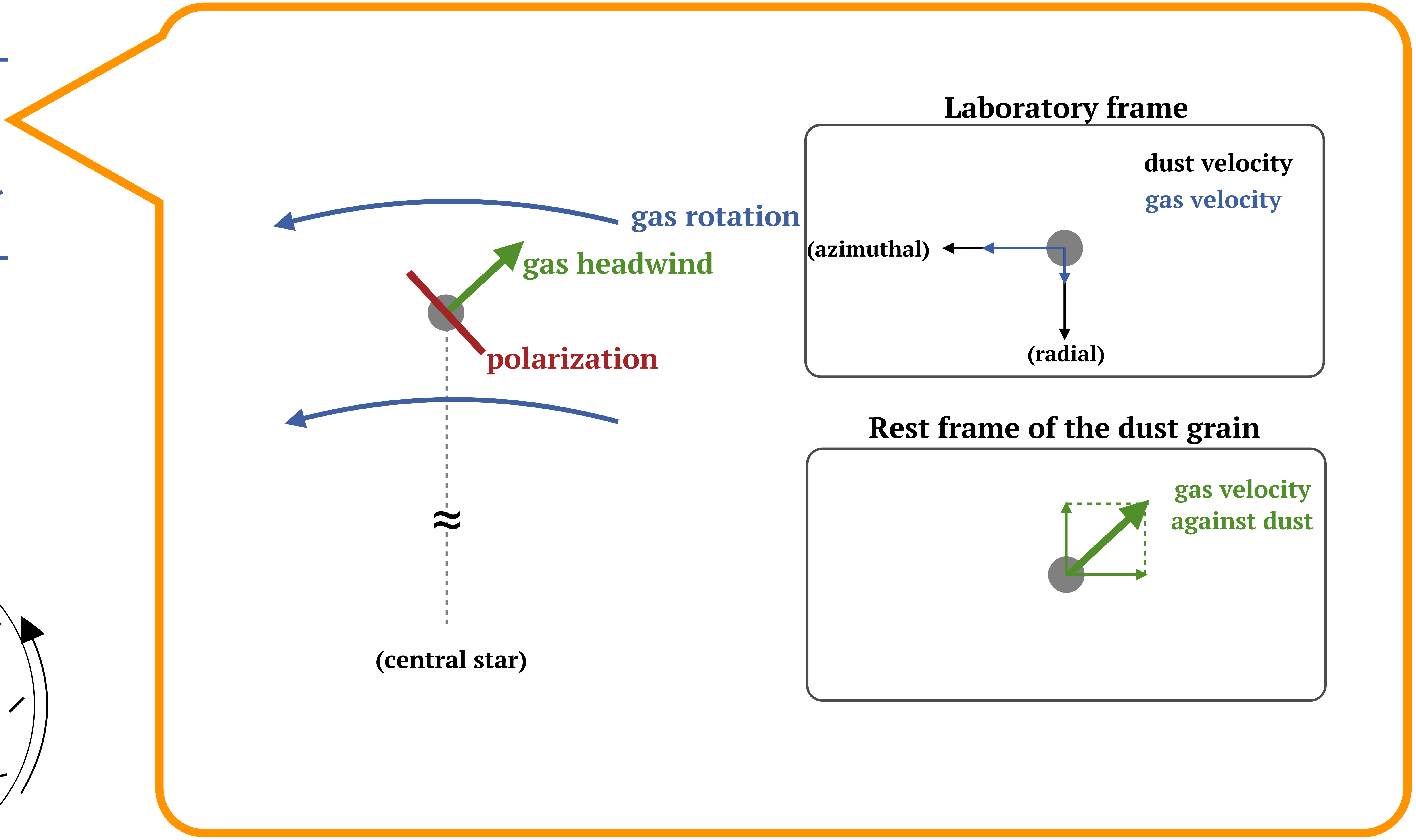
- Polarization vectors are perpendicular to the radiation flux

Tazaki et al. 2017

Mechanical alignment?





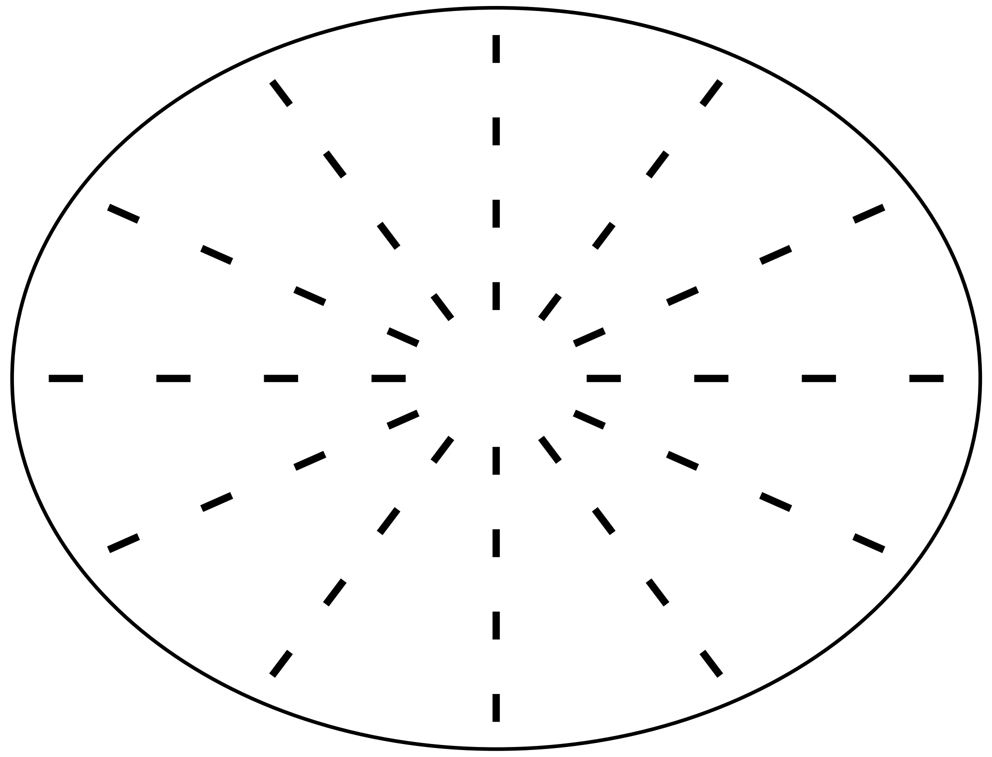


Kataoka et al. 2019

(See Gold 1952, Hoang 2018 for the microphysics of mechanical alignment)

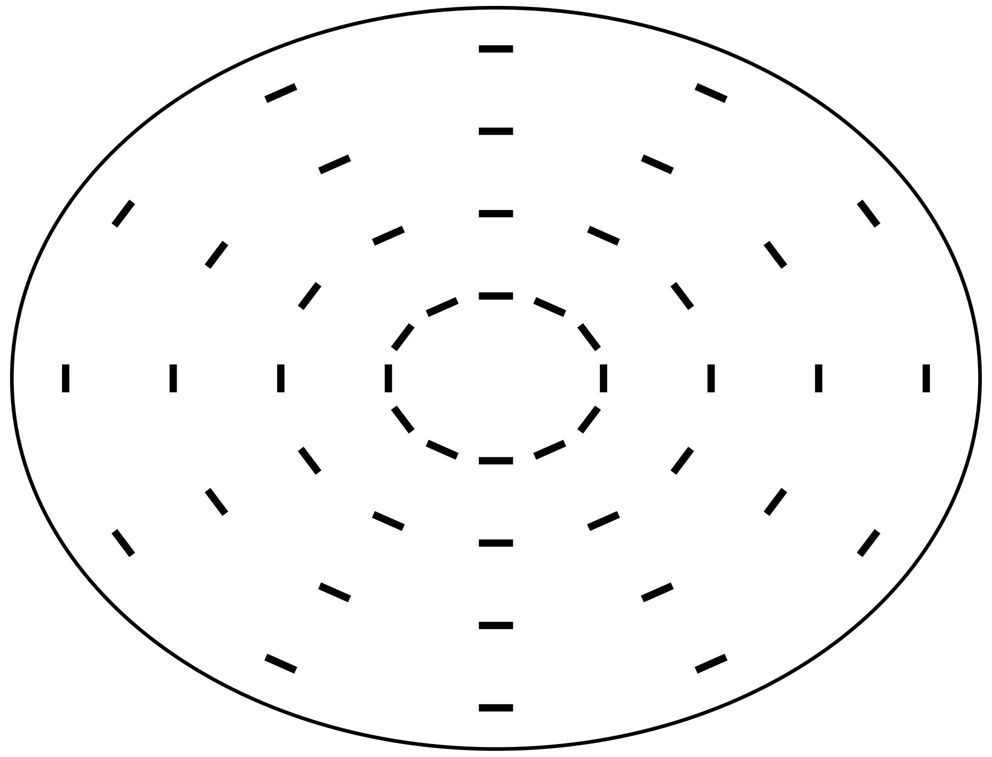
Summary of polarization morphologies

alignment with B-fields

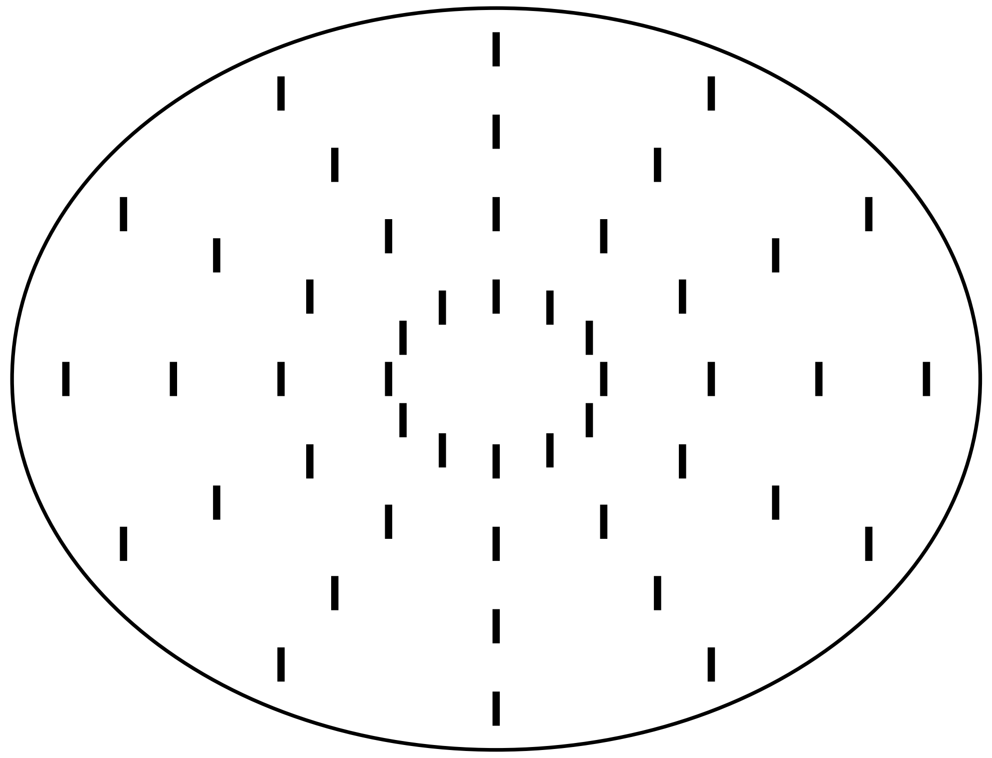


- **toroidal B-field case**

alignment with radiation

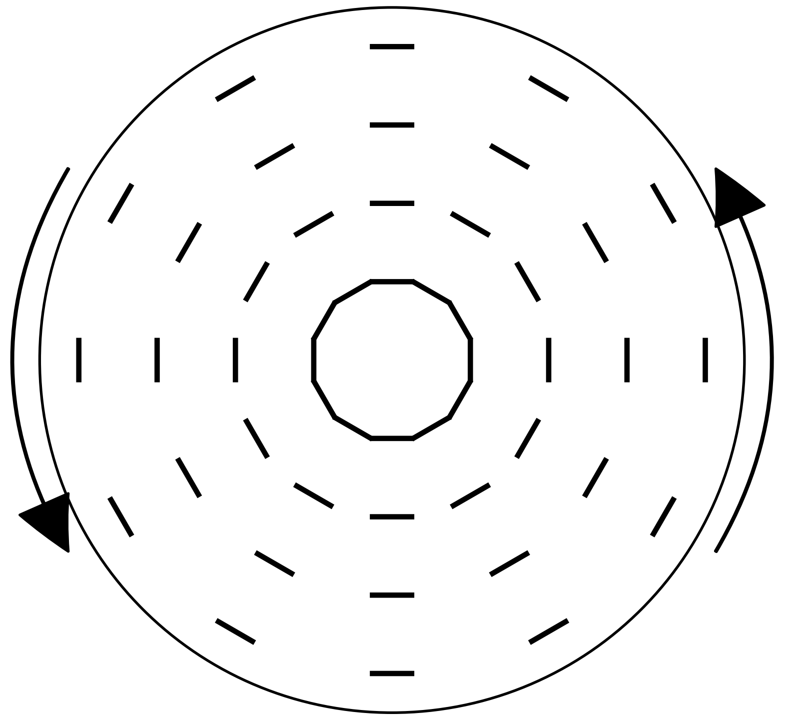


self-scattering

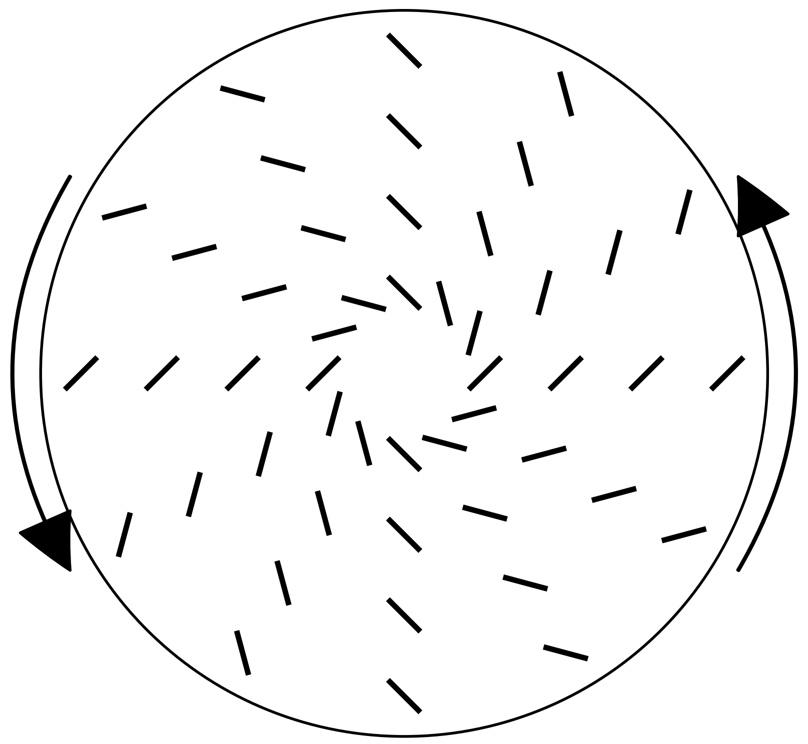


alignment with gas flow

(a) St=0



(d) St=1.0



wavelength independent ⟷ **wavelength dependent**

Kataoka et al. 2017, 2019, Ohashi et al. 2018

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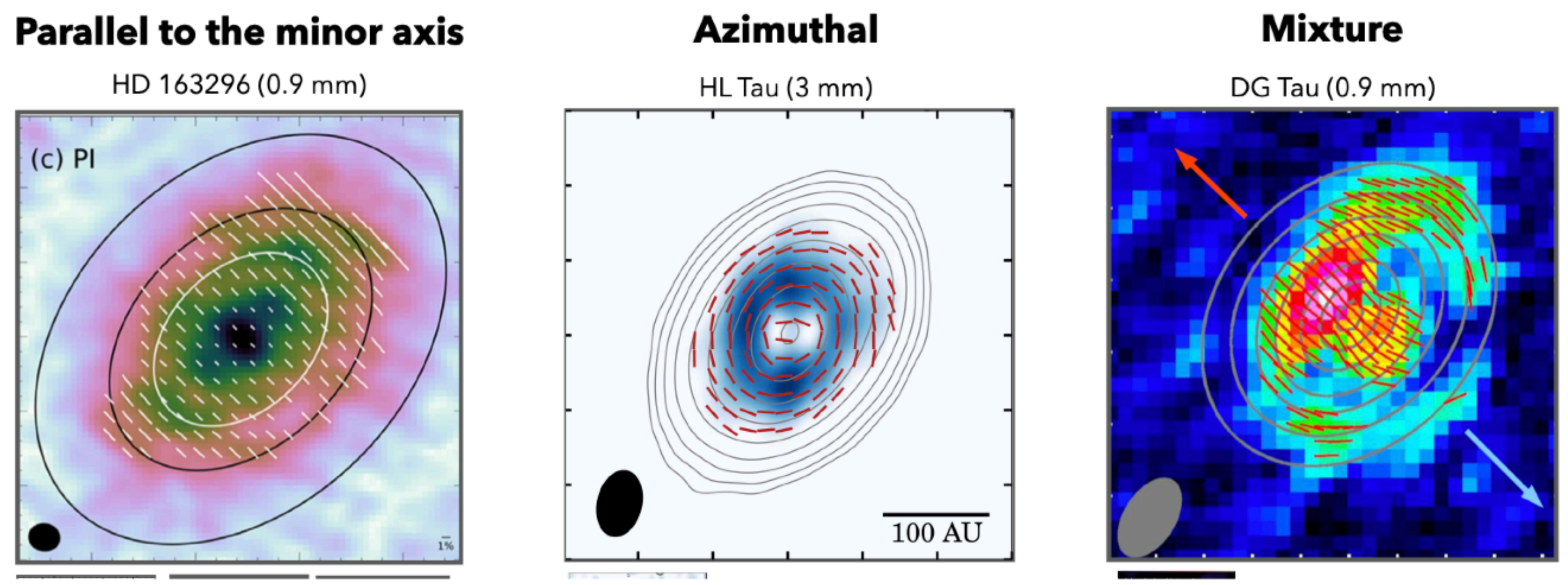
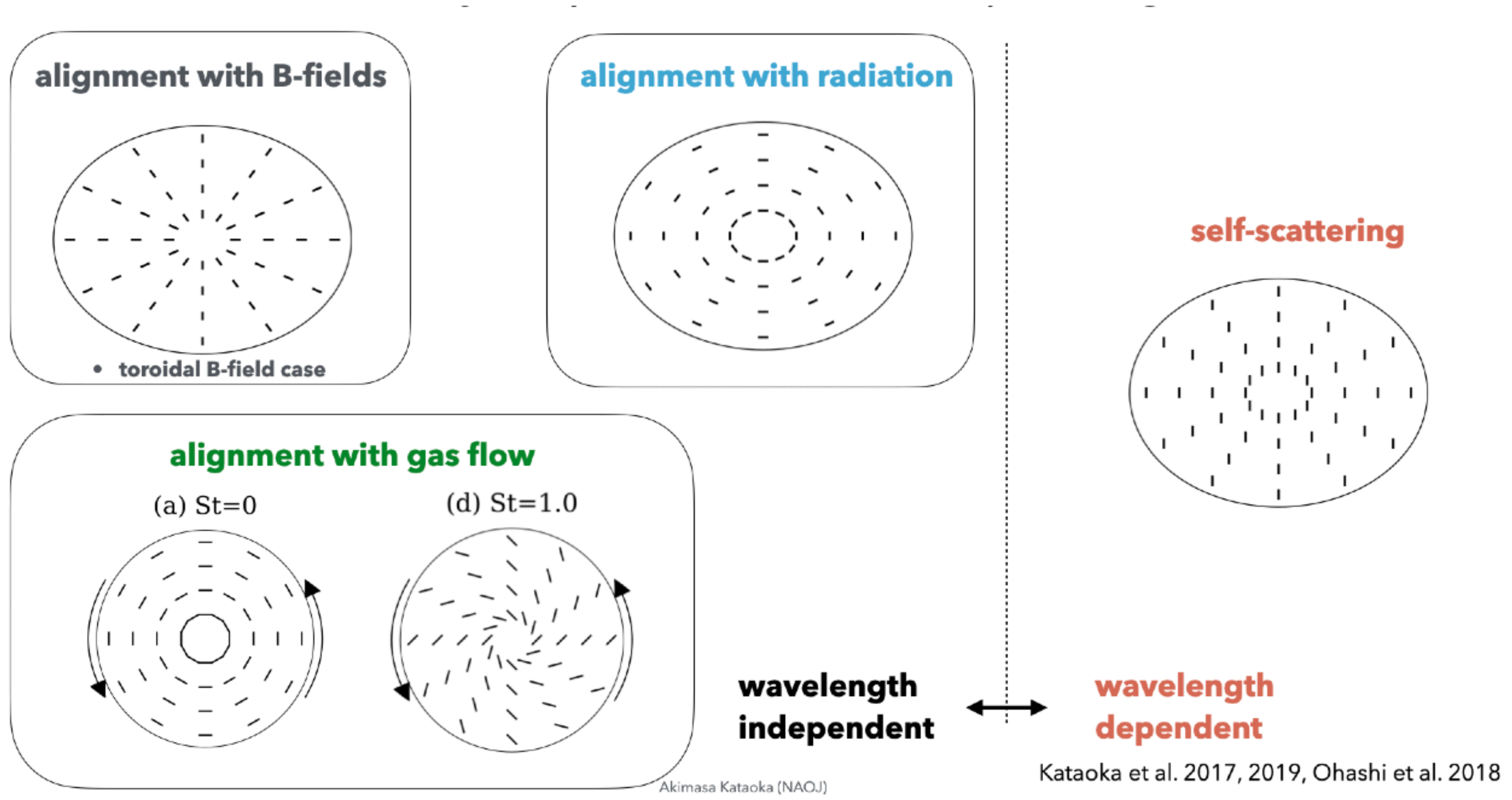


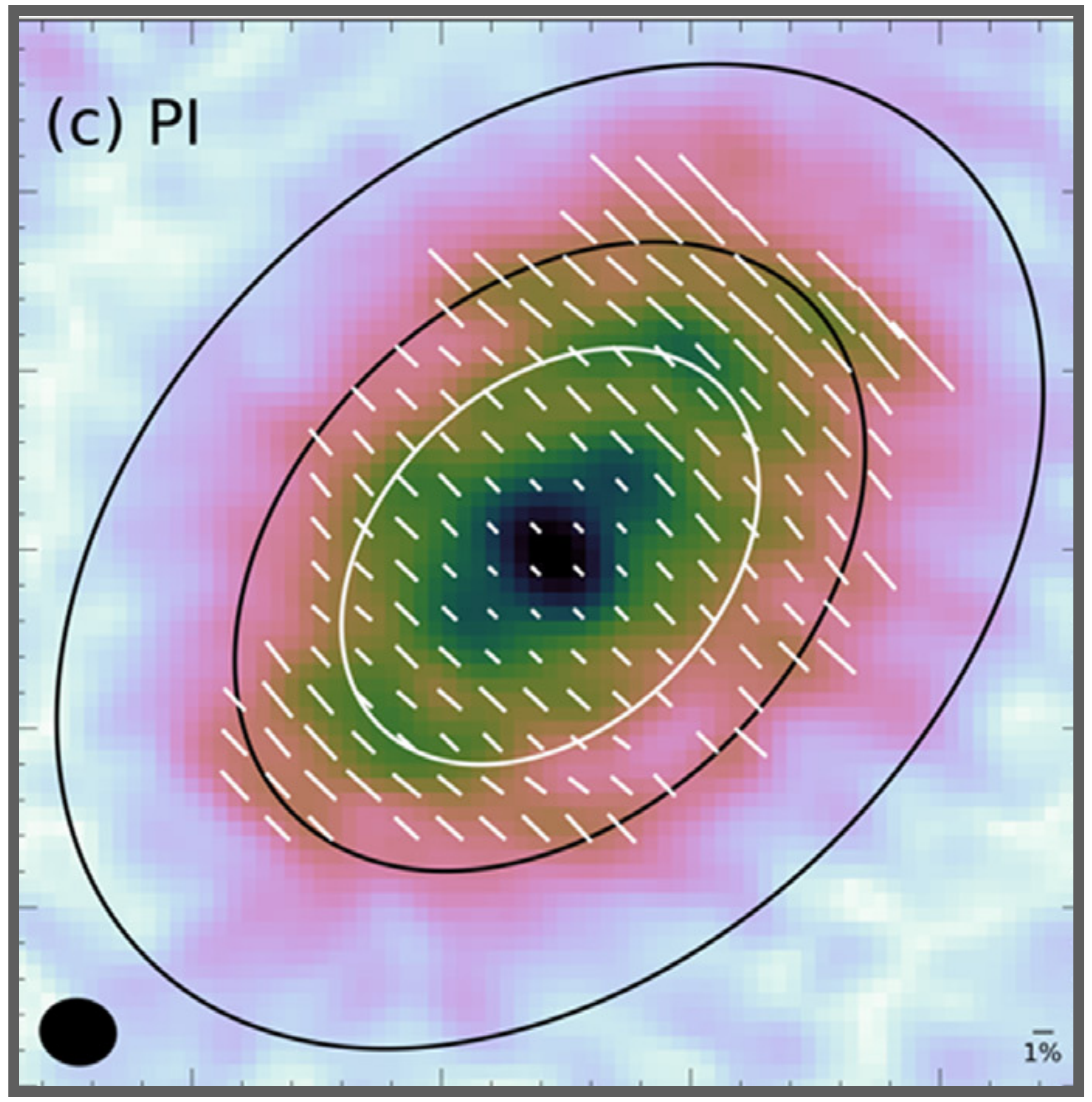


Motivation 1: the polarization morphologies

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)

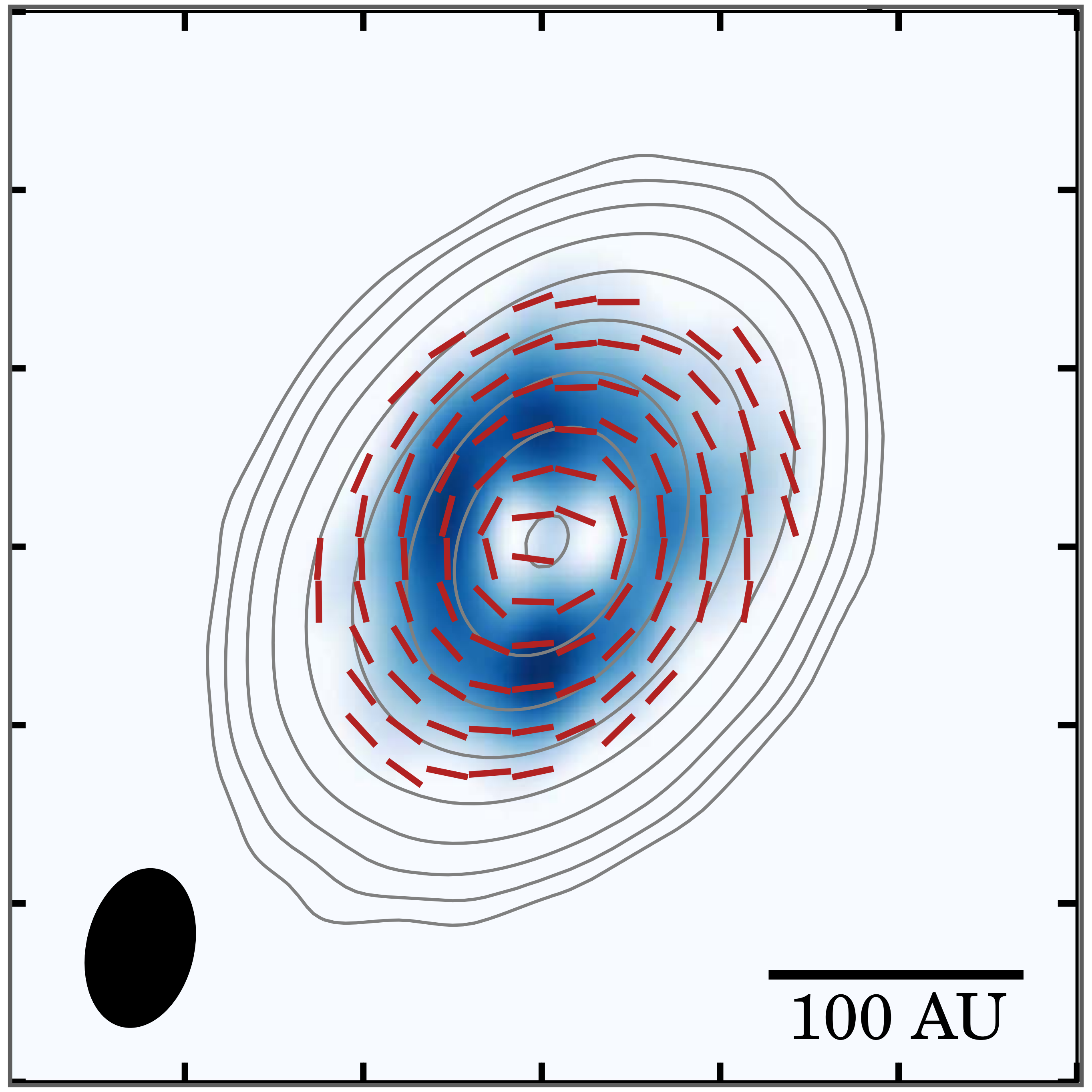


Dent et al. 2019

Self-scattering

Azimuthal

HL Tau (3 mm)

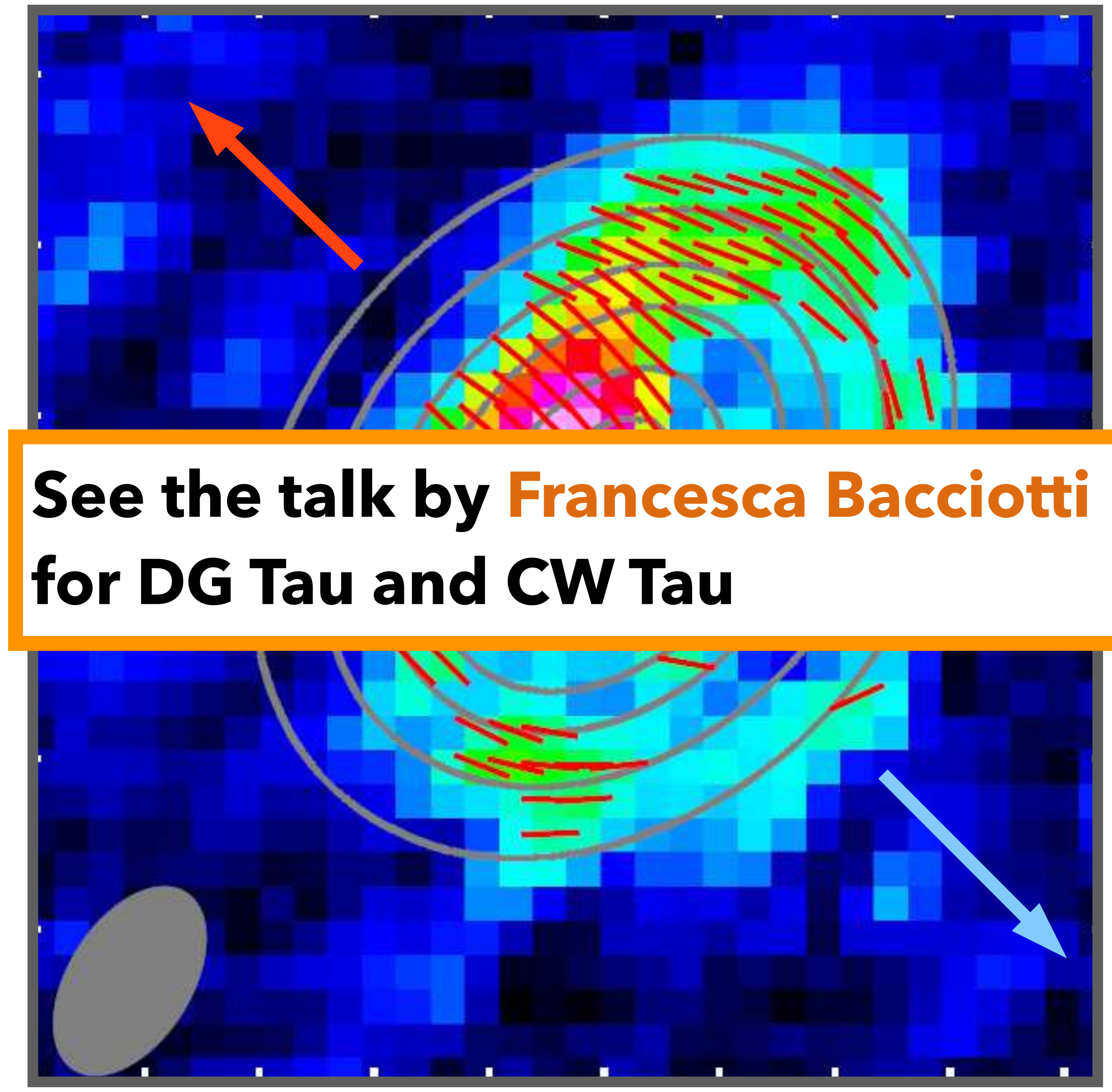


Kataoka et al. 2017

Alignment with radiation? gas flow?

Mixture

DG Tau (0.9 mm)



See the talk by Francesca Bacciotti for DG Tau and CW Tau

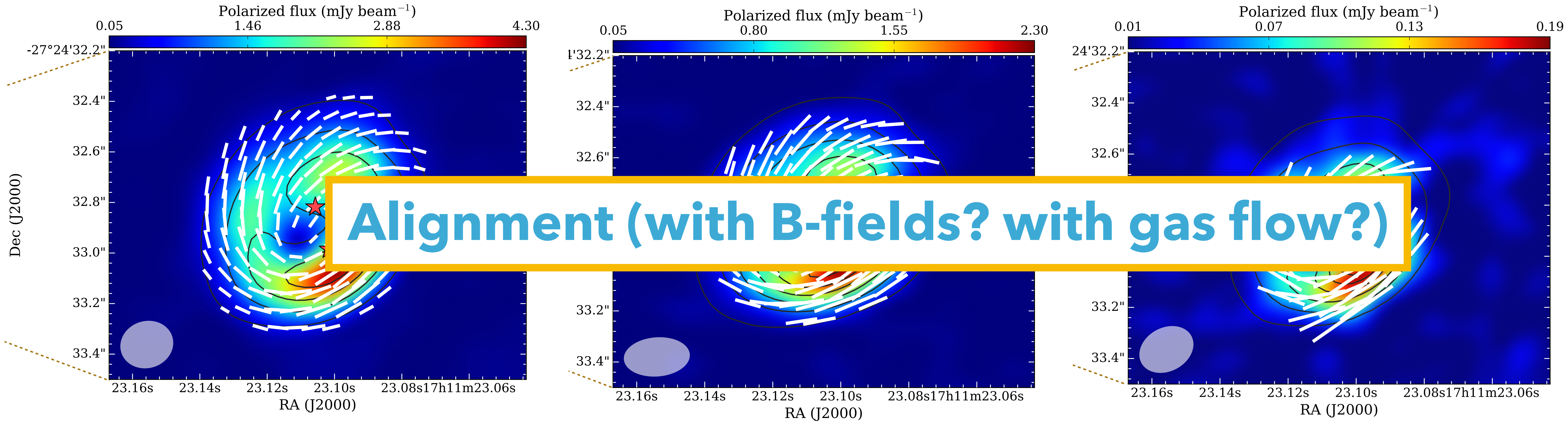
Bacciotti et al. 2018

Center: self-scattering
outer part: self-scattering? Alignment?

Motivation 2: wavelength dependence

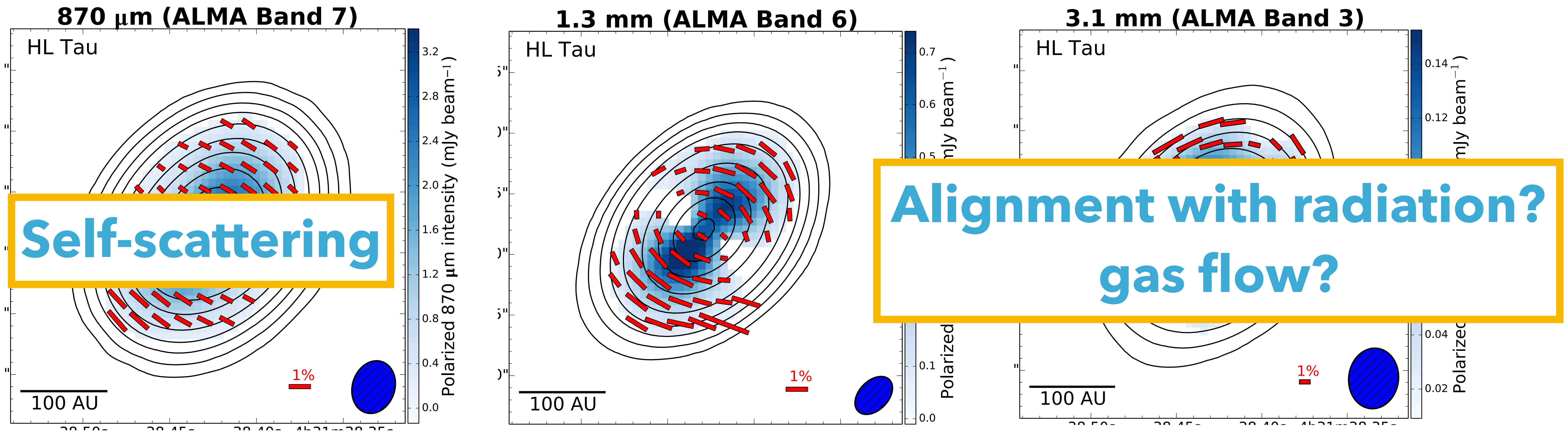
0.87 mm **1.3 mm** **3.1 mm**

BHB07-11 (Class I)



Alves et al. 2018

HL Tau (Class I-II)



Kataoka et al. 2017, Stephens et al. 2017

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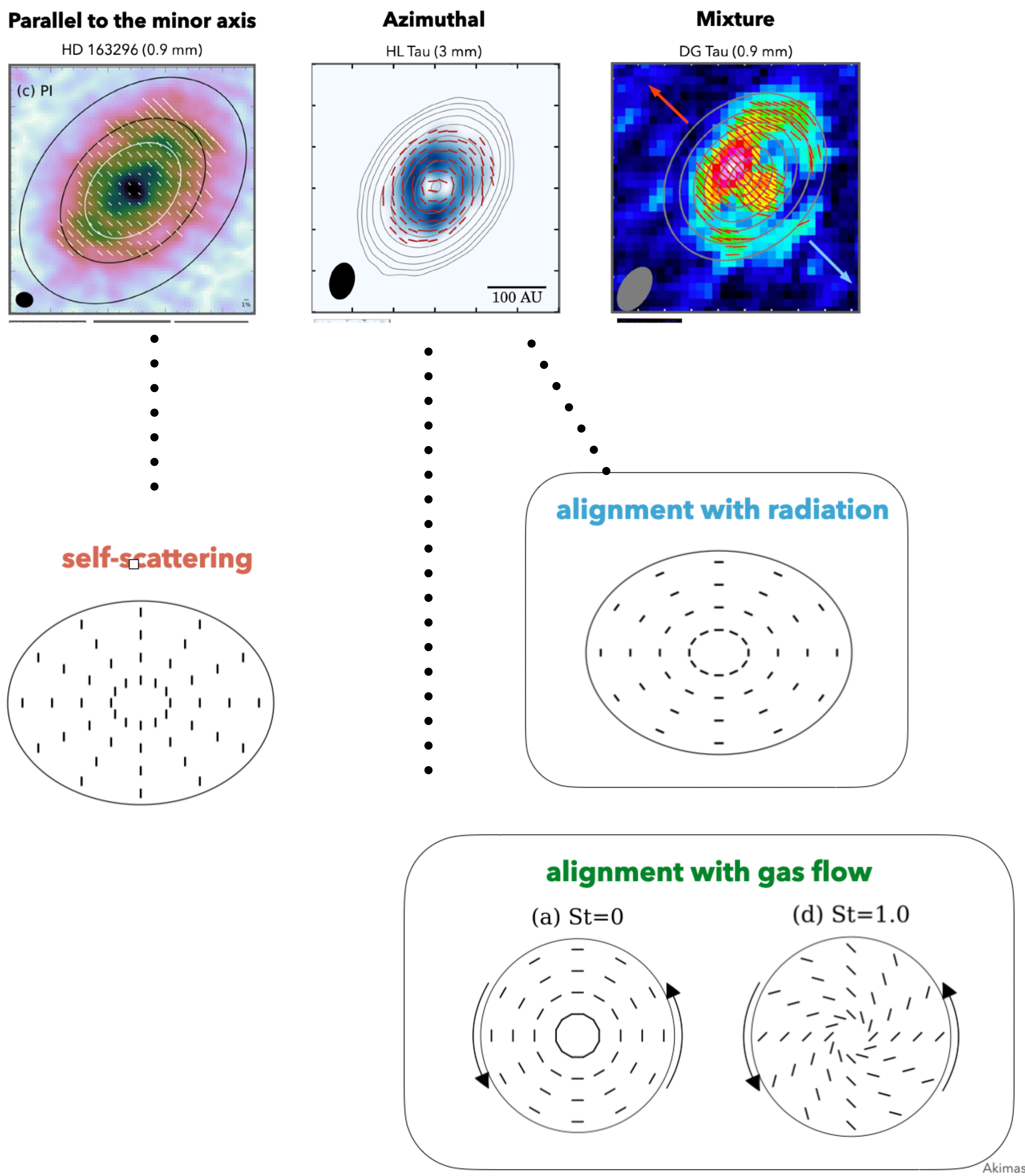
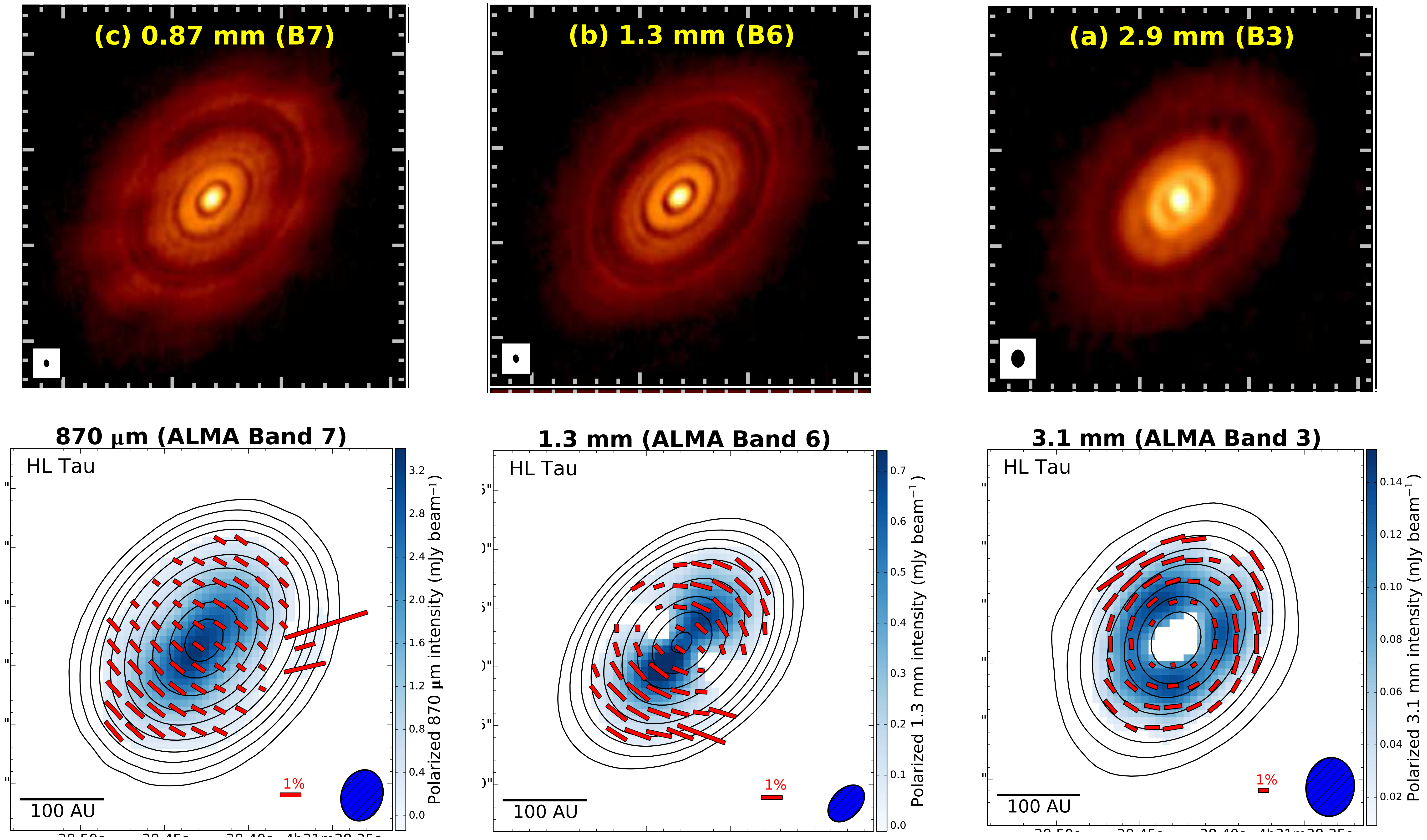
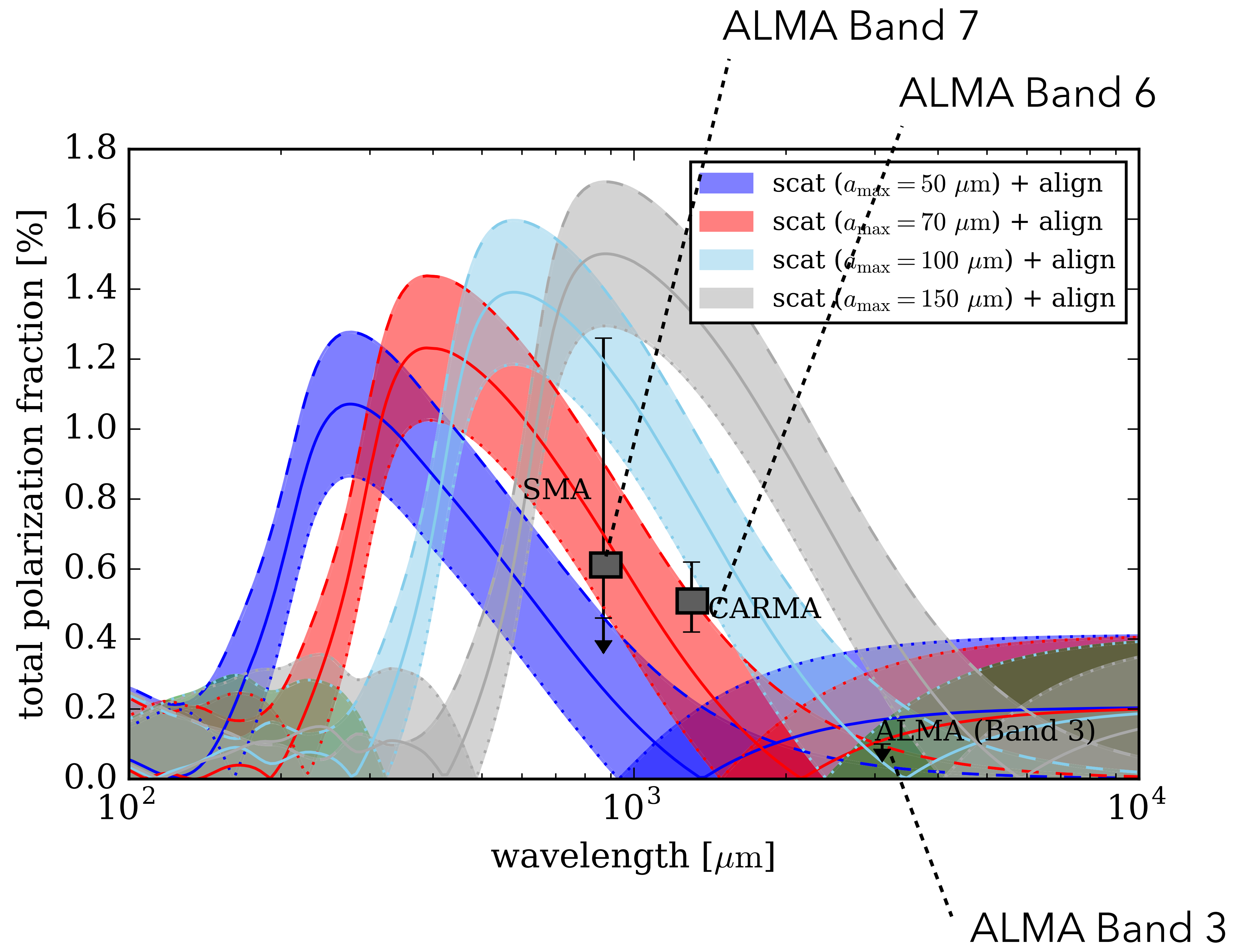


~100 μm sized grains?

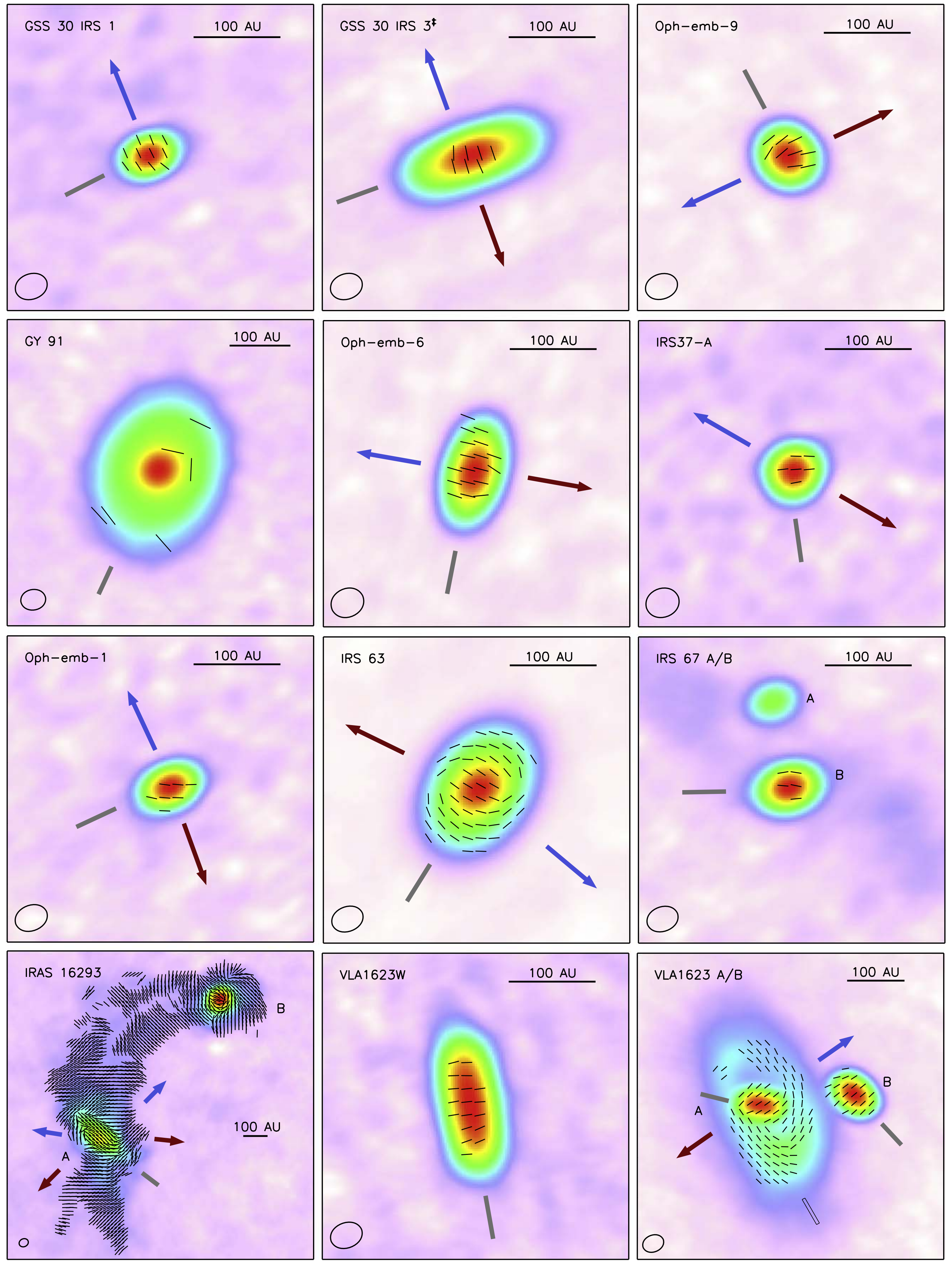


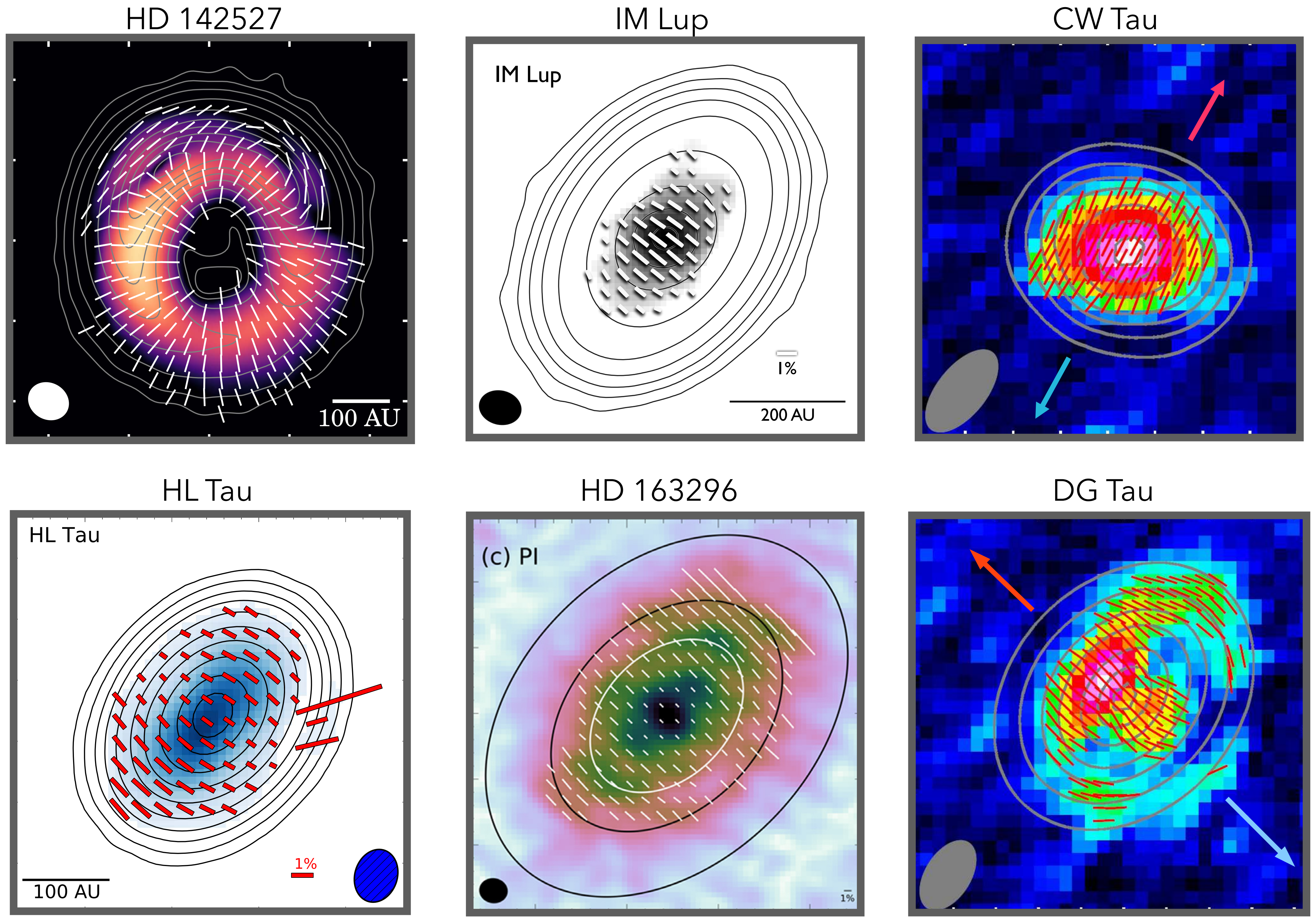
ALMA Partnership 2015, Stephens et al. 2017



Kataoka et al. 2017, modified

~100 μm sized grains?

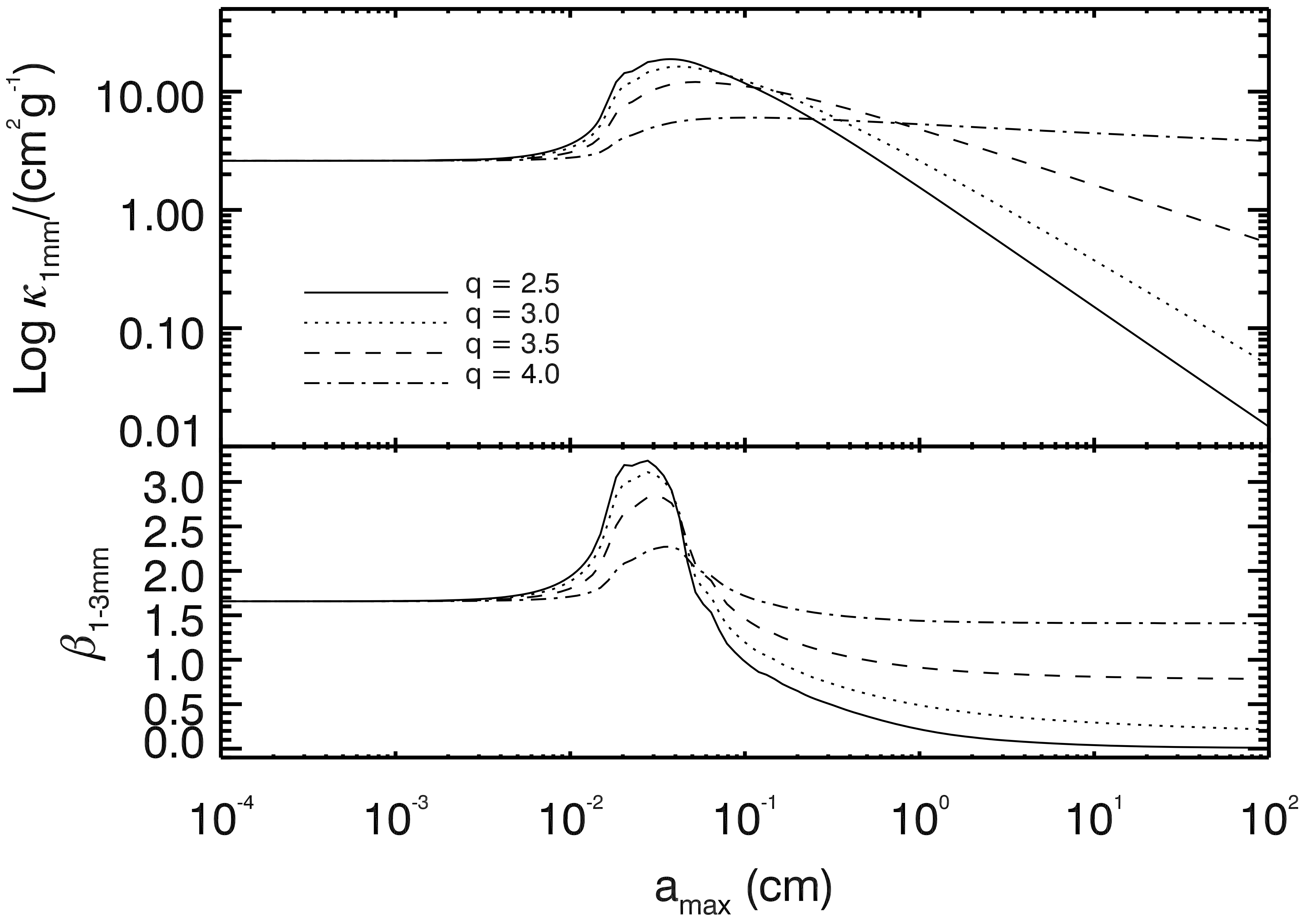




Many disks show self-scattering at 0.9 mm
→ **Do disks have dust grains with size of ~ 100 μm?**

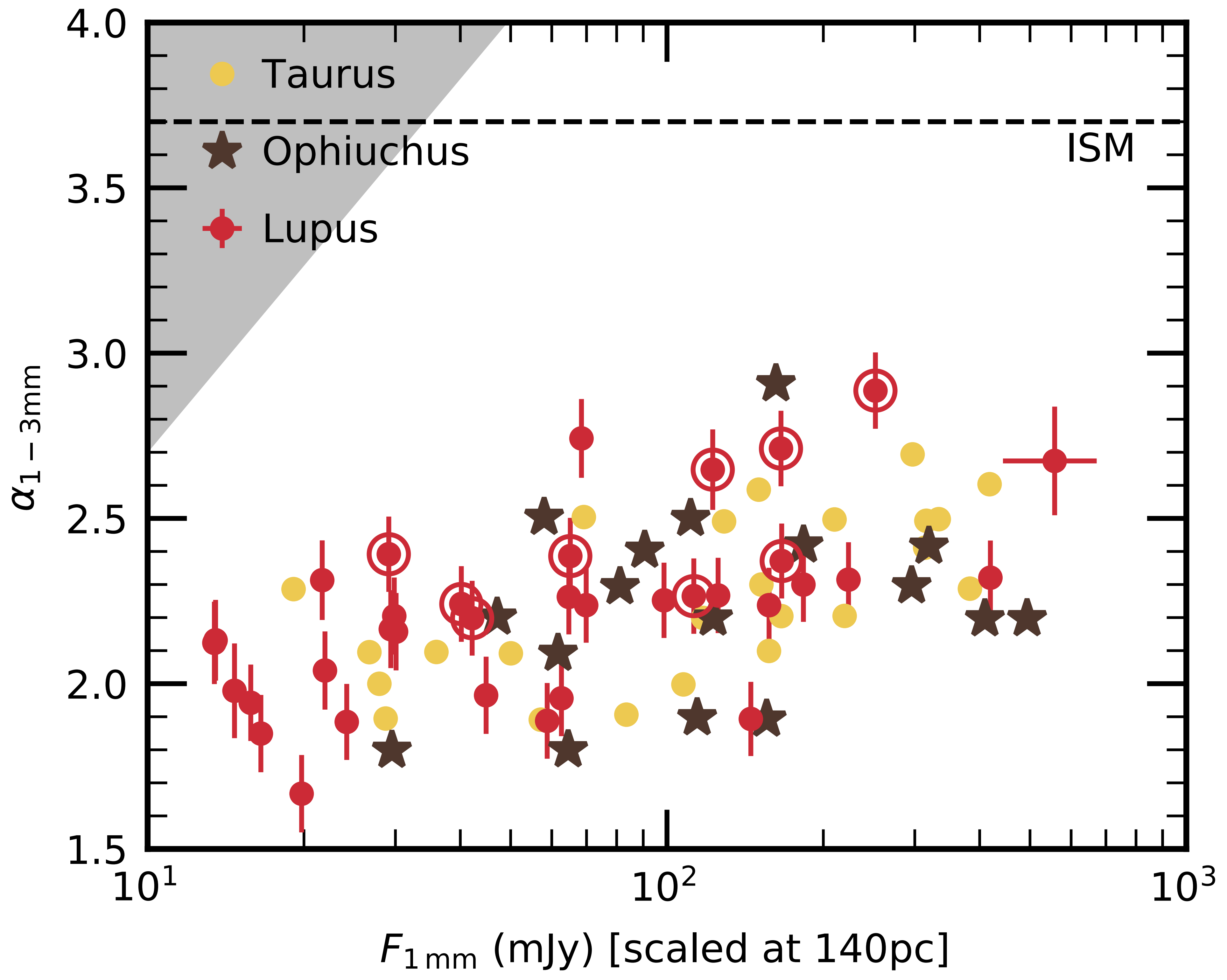
<u>Kataoka</u> et al. 2016, Hull et al. 2018, Bacciotti et al. 2018, Dent et al. 2019, Stephens et al. 2017, Kataoka et al. 2017, Ohashi et al. 2018, Sadavoy et al. 2019

Spectral index vs. grain size



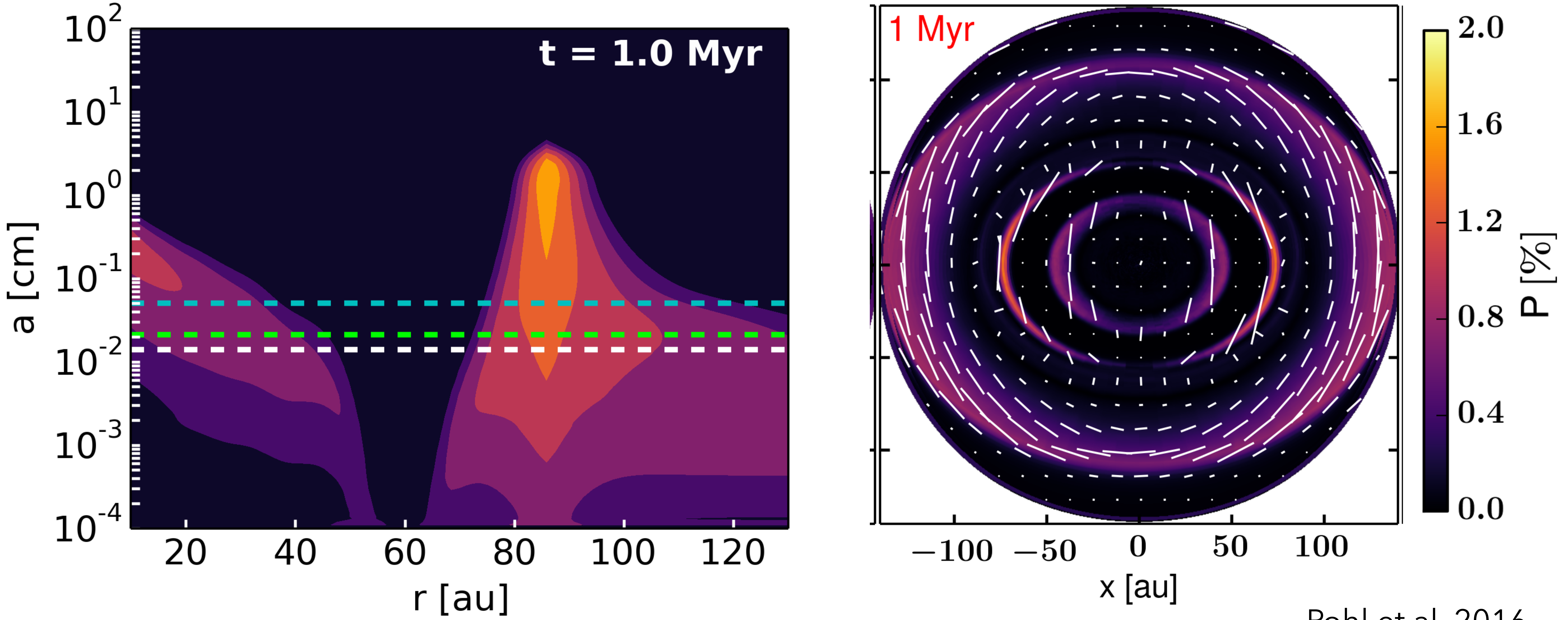
Ricci et al. 2010a

(cf. Miyake and Nakagawa 1993, Pollack etl. 1994…)



Tazzari et al. 2020a

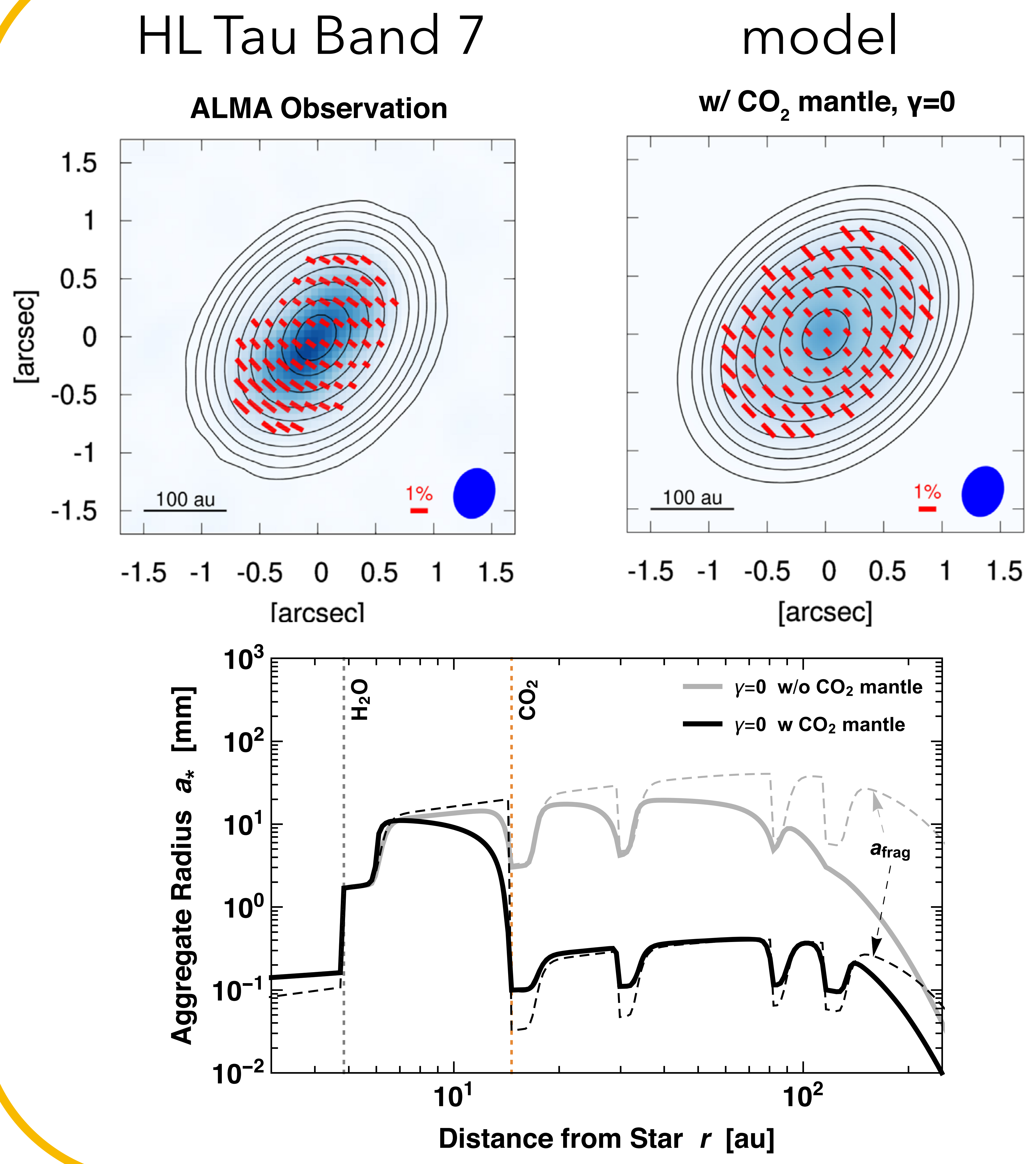
Prediction from grain growth theory



Pohl et al. 2016

If grains has radial size distribution, P[%] is too weak to be detected

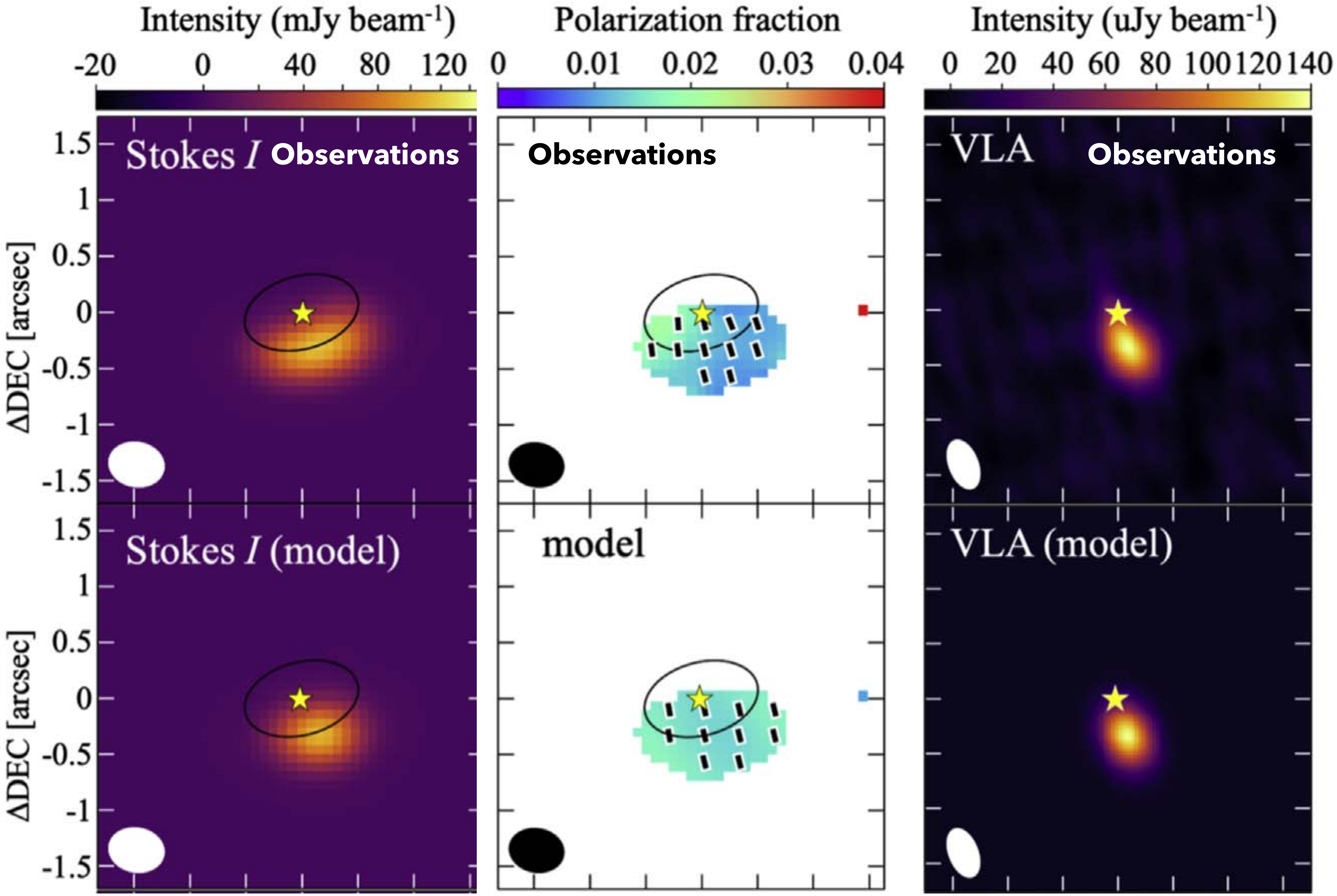
One idea: flat gas surface density



- How can we achieve 100 μm grain size for the entire region?
  - Non-sticky (=fragile) dust grains, such as covered by CO_2 mantle
  - Radially flat gas surface density, that makes radially flat grain size

Okuzumi and Tazaki 2019

Another idea: optically thick disk

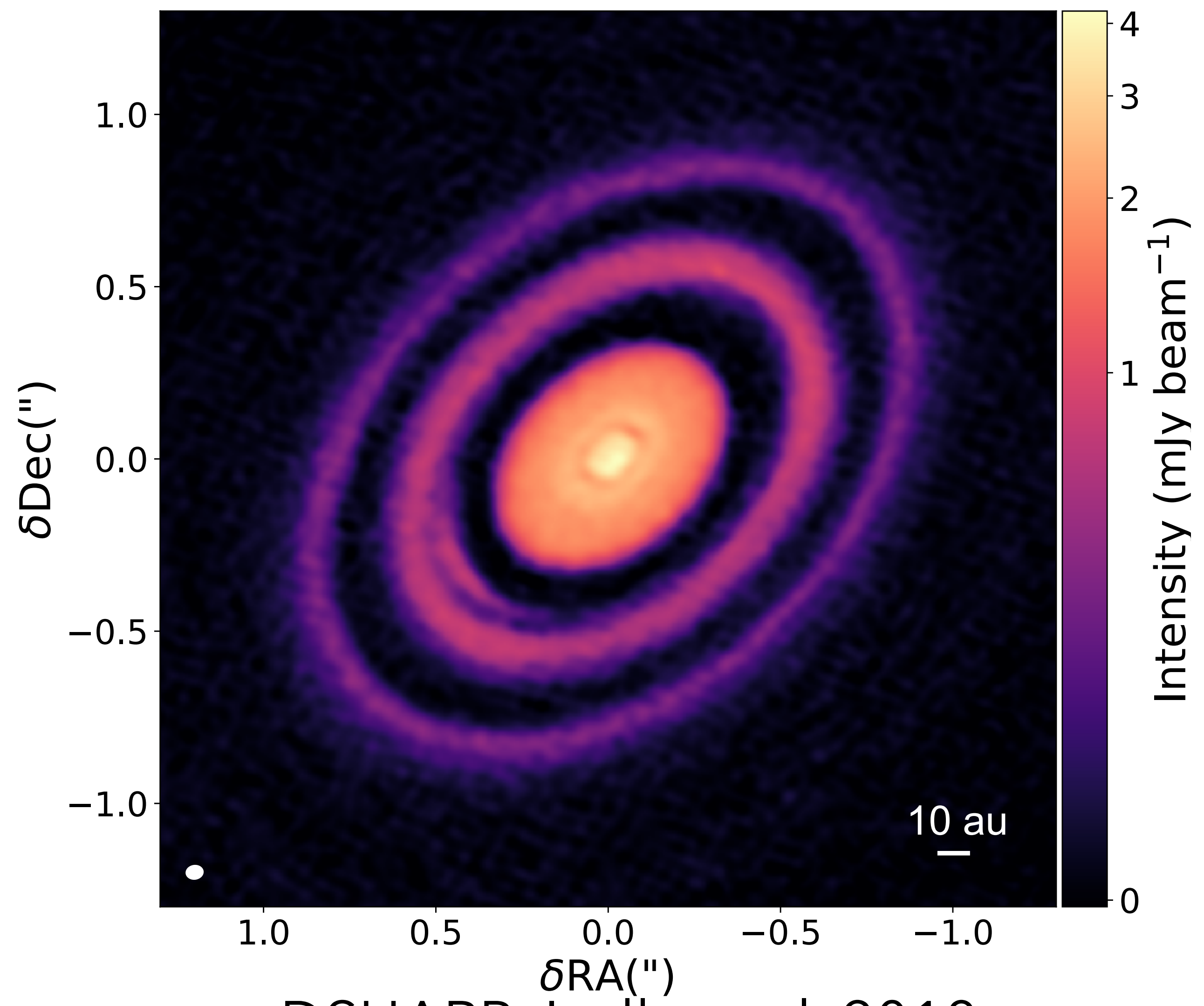


- IRS 48 - lopsided disk
- How can we explain both polarization at 0.9mm bright emission at 8.8 mm (VLA)?
- **Best model: very optically thick dust (τ ~ 7.3) at 0.9 mm**

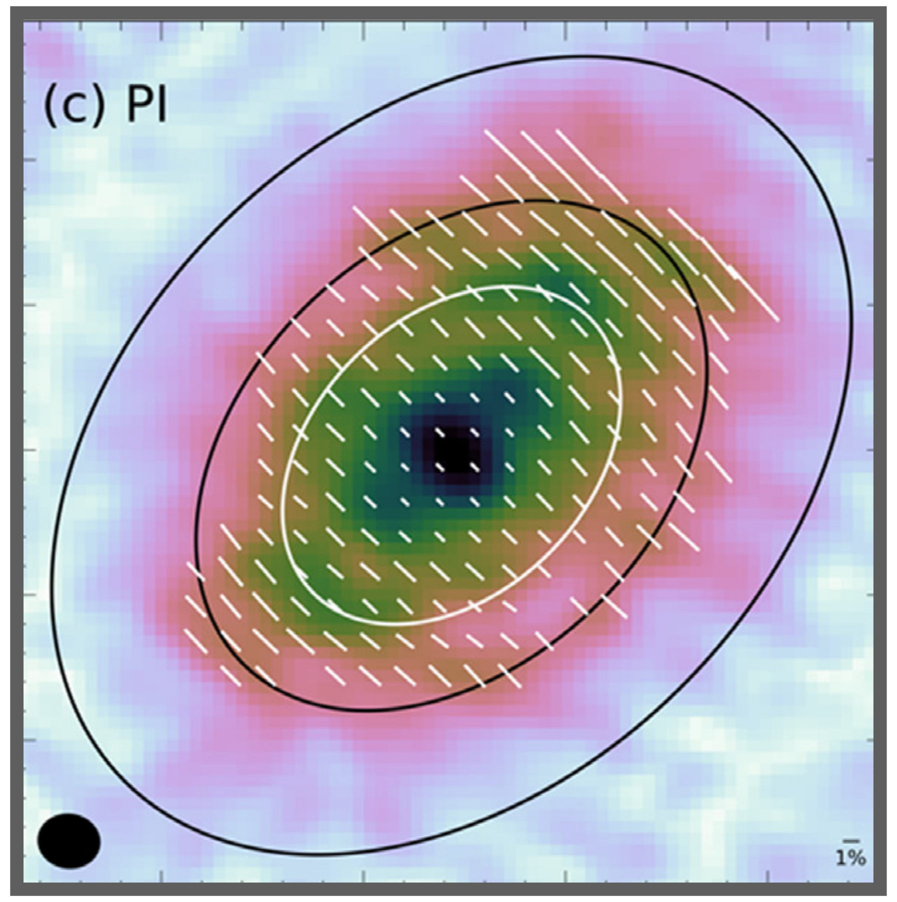
Ohashi et al. 2020

Polarization and substructures

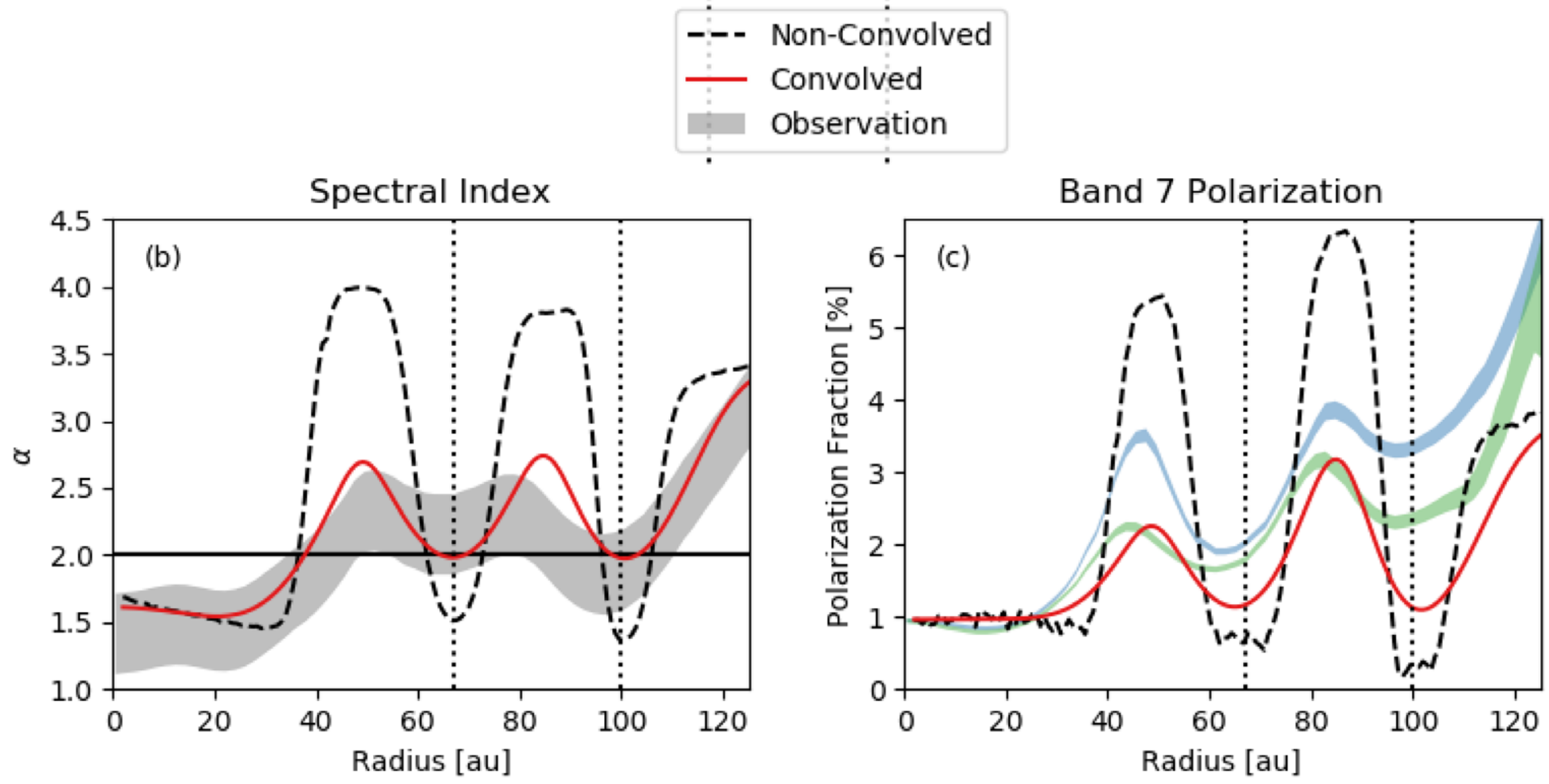
HD 163296



DSHARP; Isella et al. 2018



Dent et al. 2019

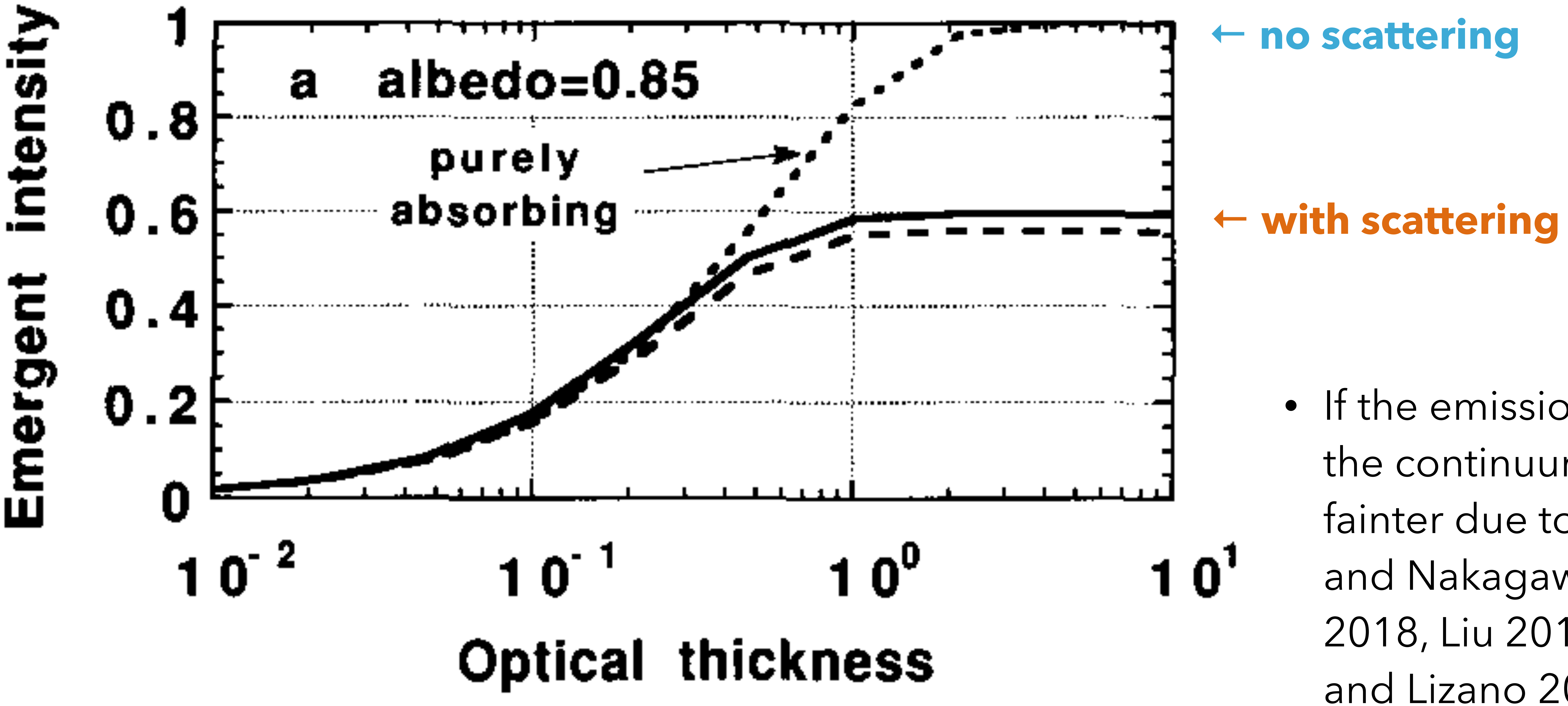


- Even if assuming100 μm grains, beam convolution of optically thick rings (α~2) and thin gaps (α~4) can explain both spectral index and polarization.

Lin et al. 2020

(See also Ohashi and Kataoka 2019)

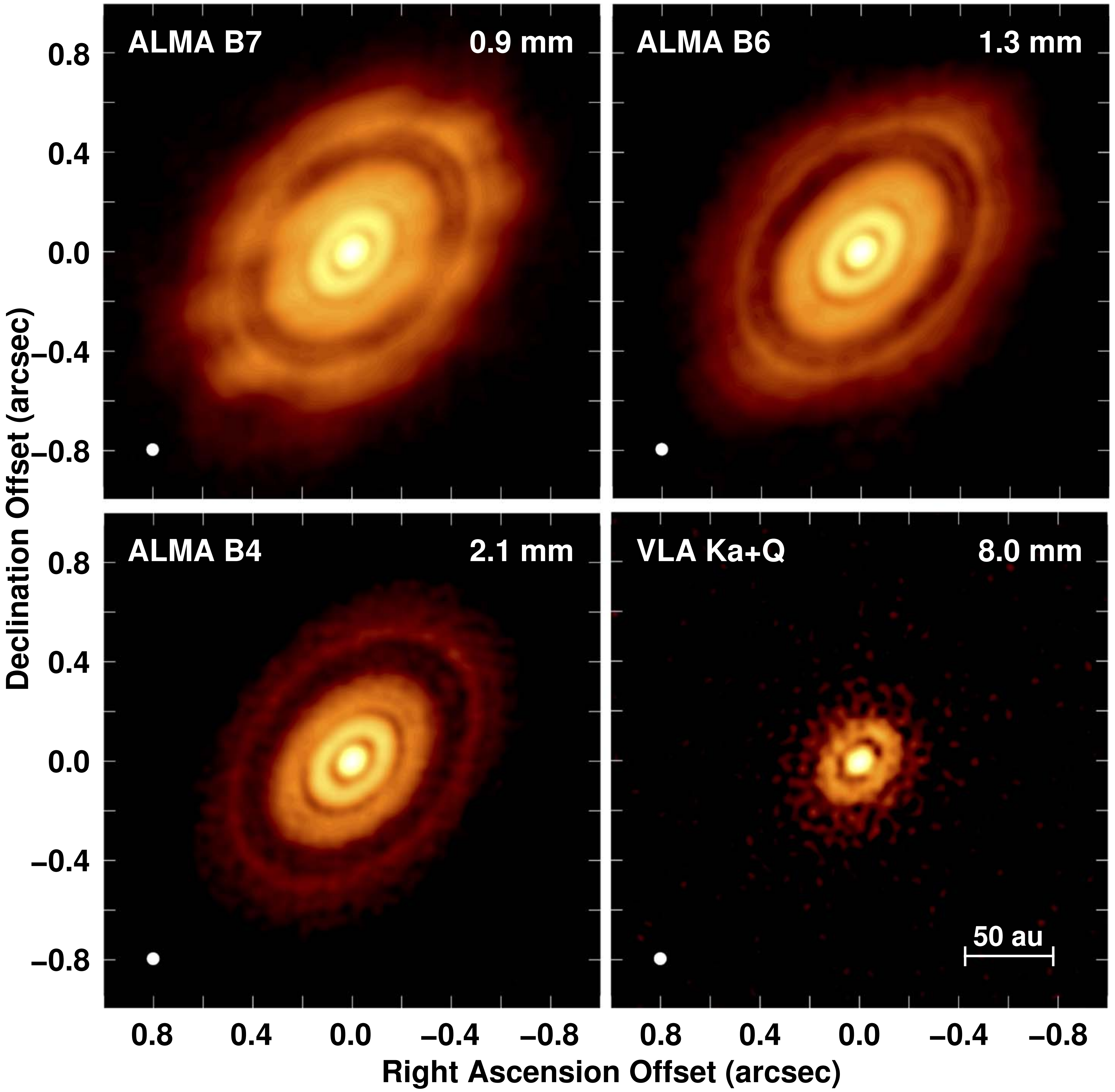
Scattering makes disk continuum fainter

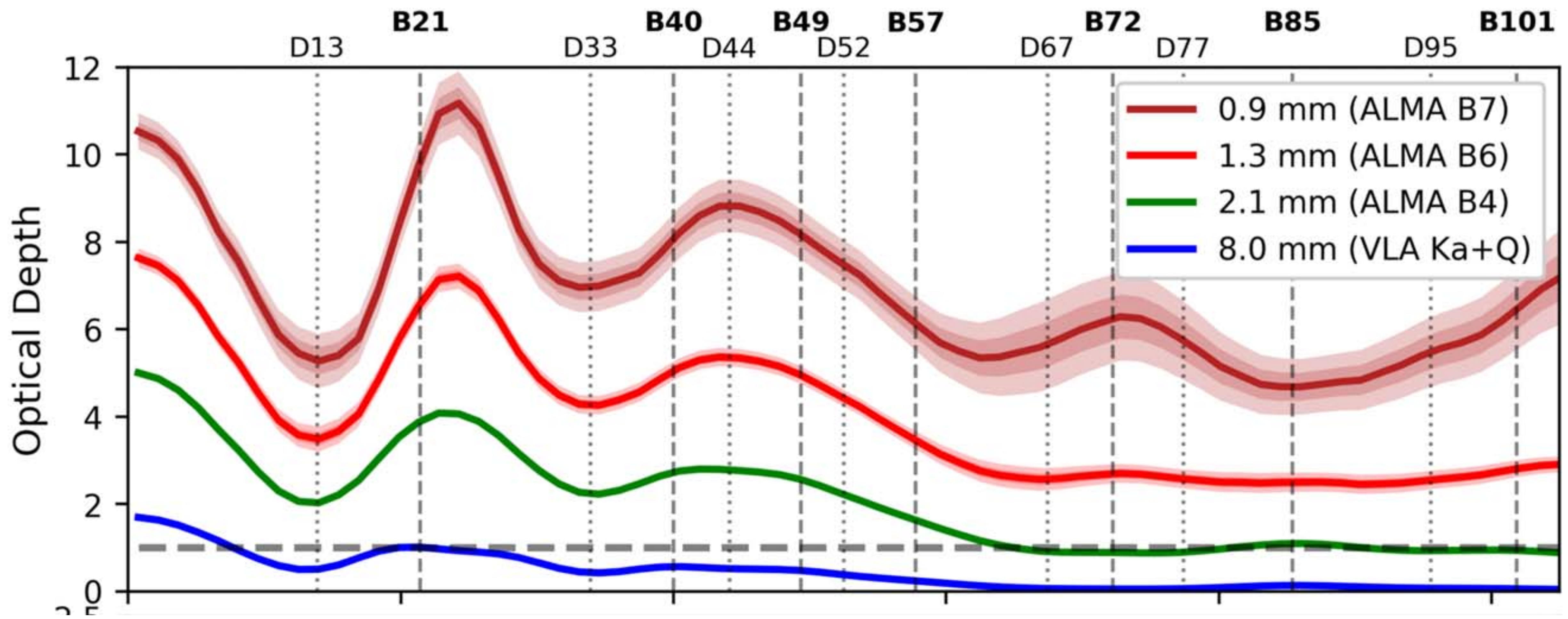


Miyake and Nakagawa 1993

- 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)

Full modeling on radial profile - HL Tau





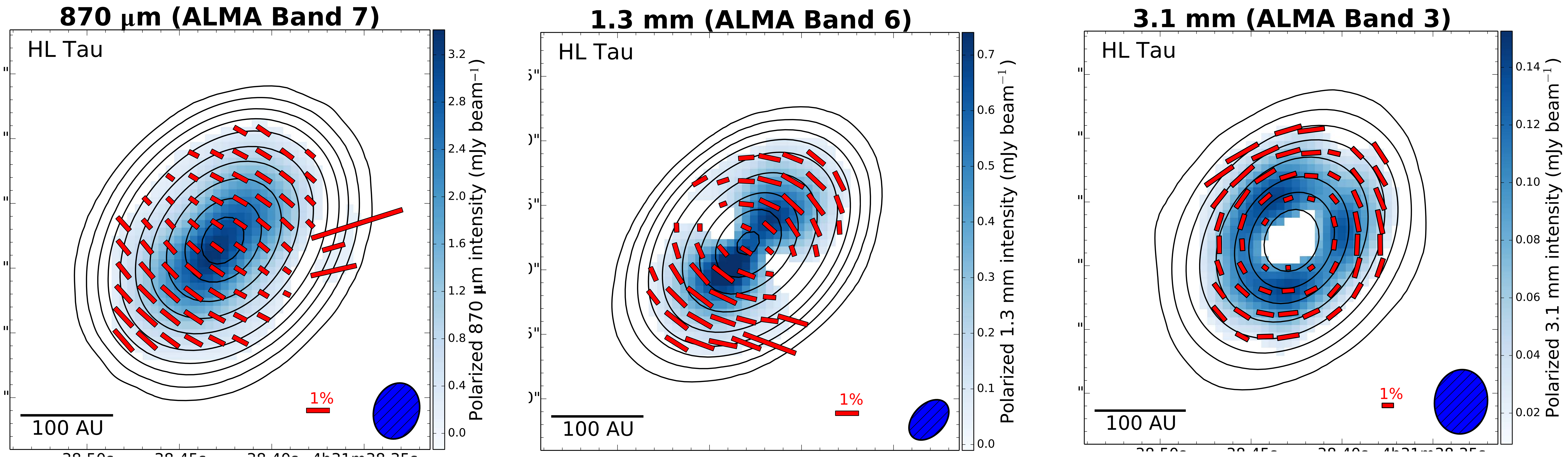
- Optical depth is > 10 (!) at rings and ~5 at gaps at 870 micron

Carrasco-Gonzalez et al. 2019

(See Ueda et al. 2020 for TW Hya)

See the talks by Anibal Sierra for the similar analysis on several targets with MAPS data and Enrique Macias for TW Hya

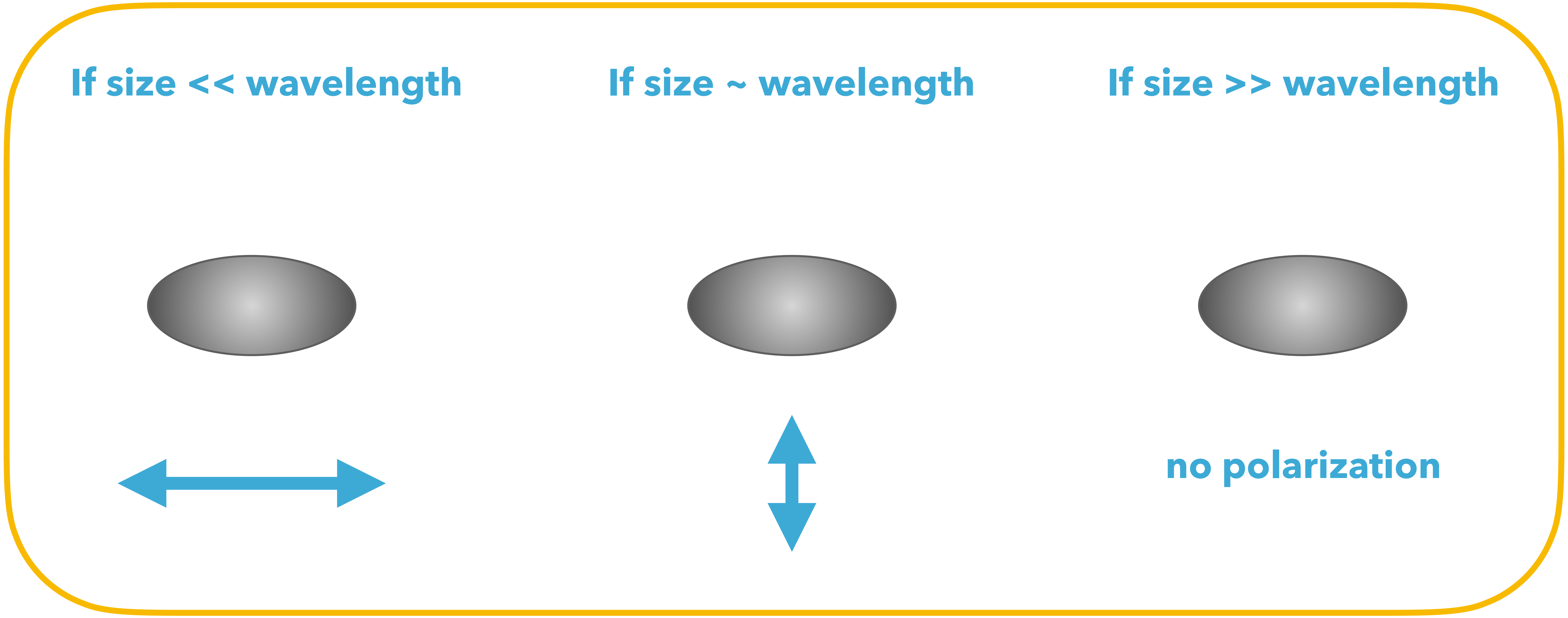
Is the alignment-induced polarization wavelength dependent?



Self-scattering

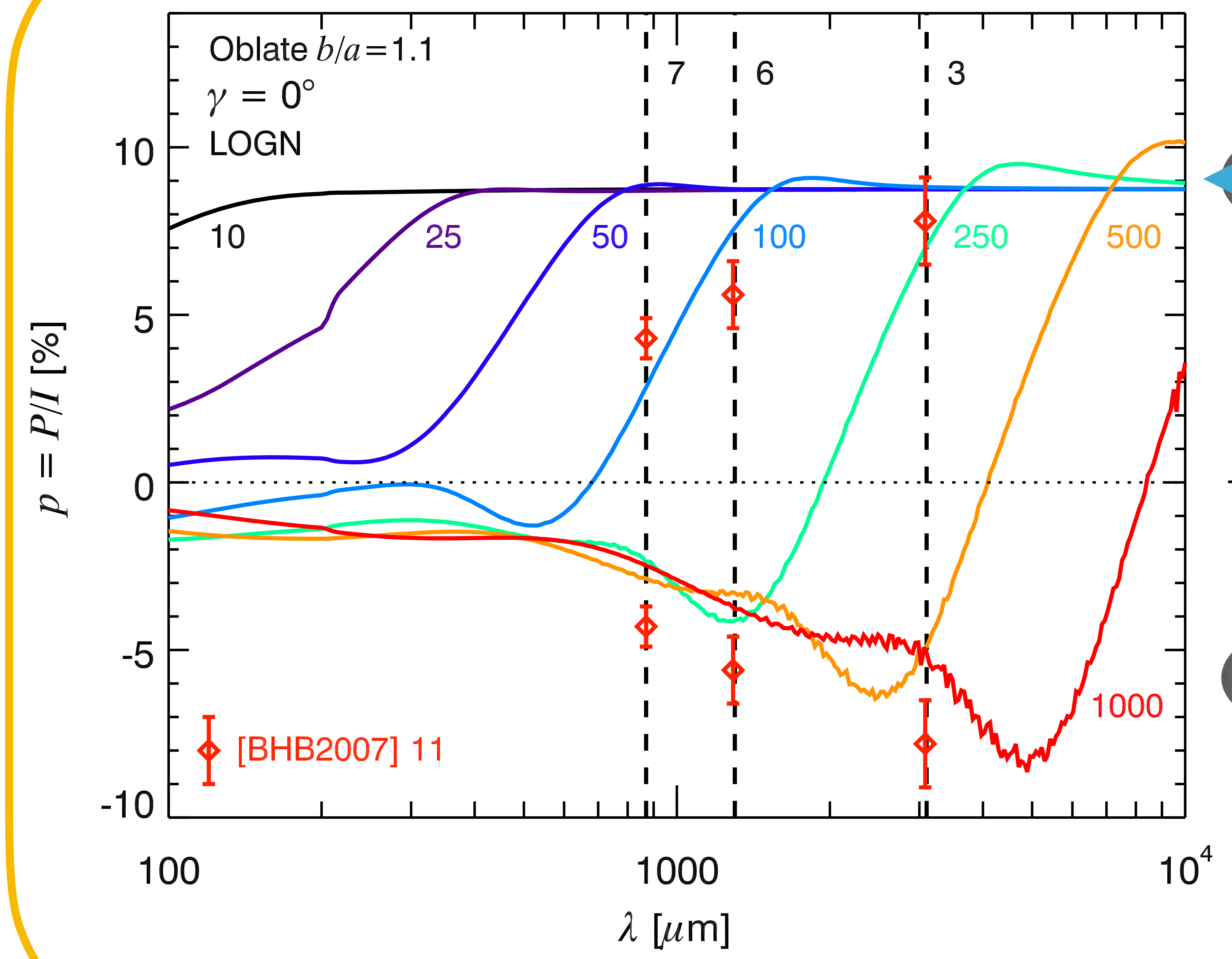
Alignment with radiation?

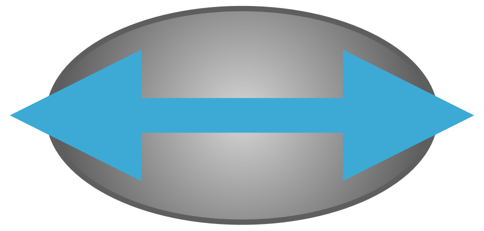
Wavelength dependence in alignment

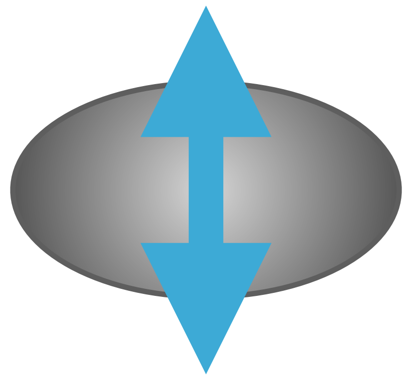


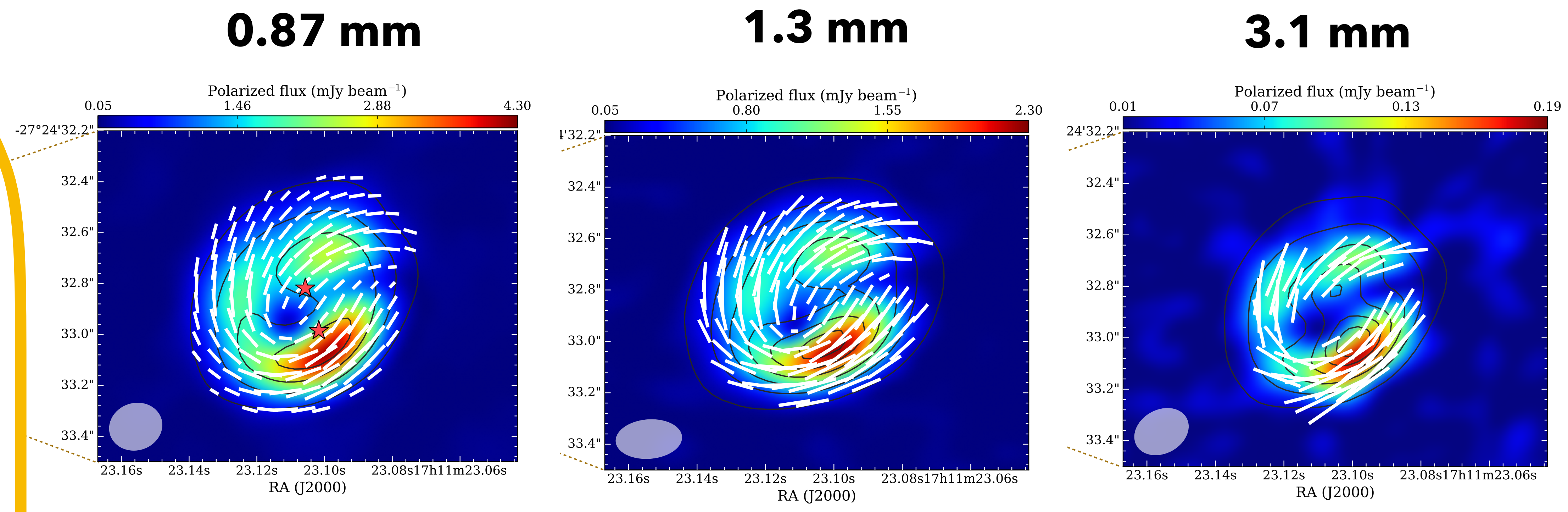
See next page for more details.

Wavelength dependence in alignment









Alves et al. 2018

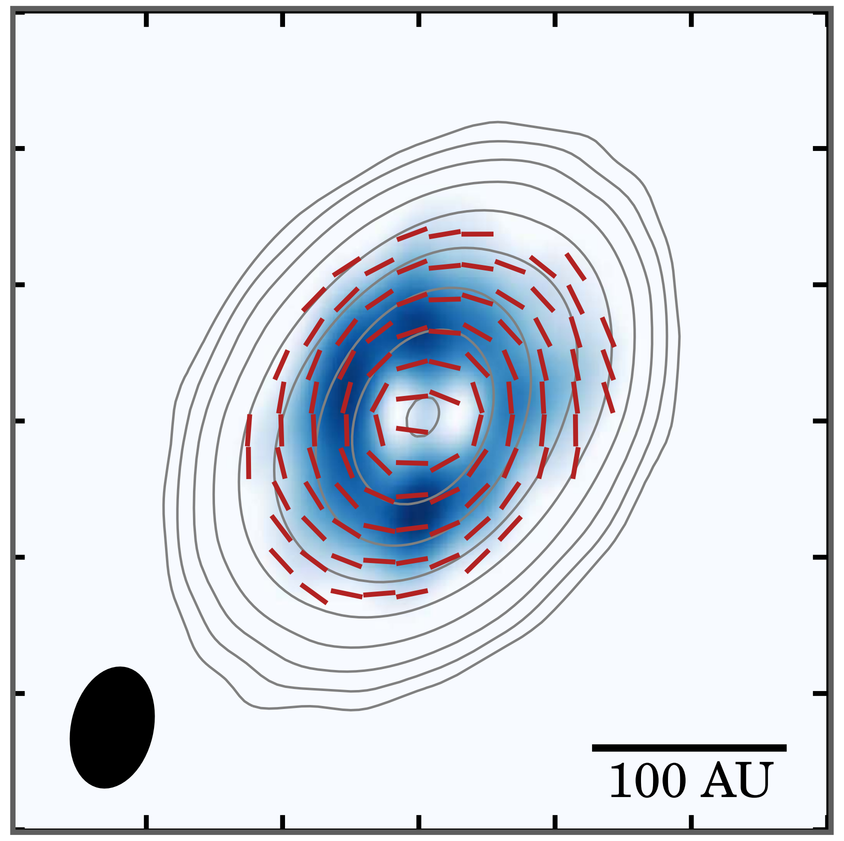
- If a<λ : polarization parallel to the major axis
- If a~λ : polarization reversal
- If a>λ : no polarization

Guillet et al. 2020

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

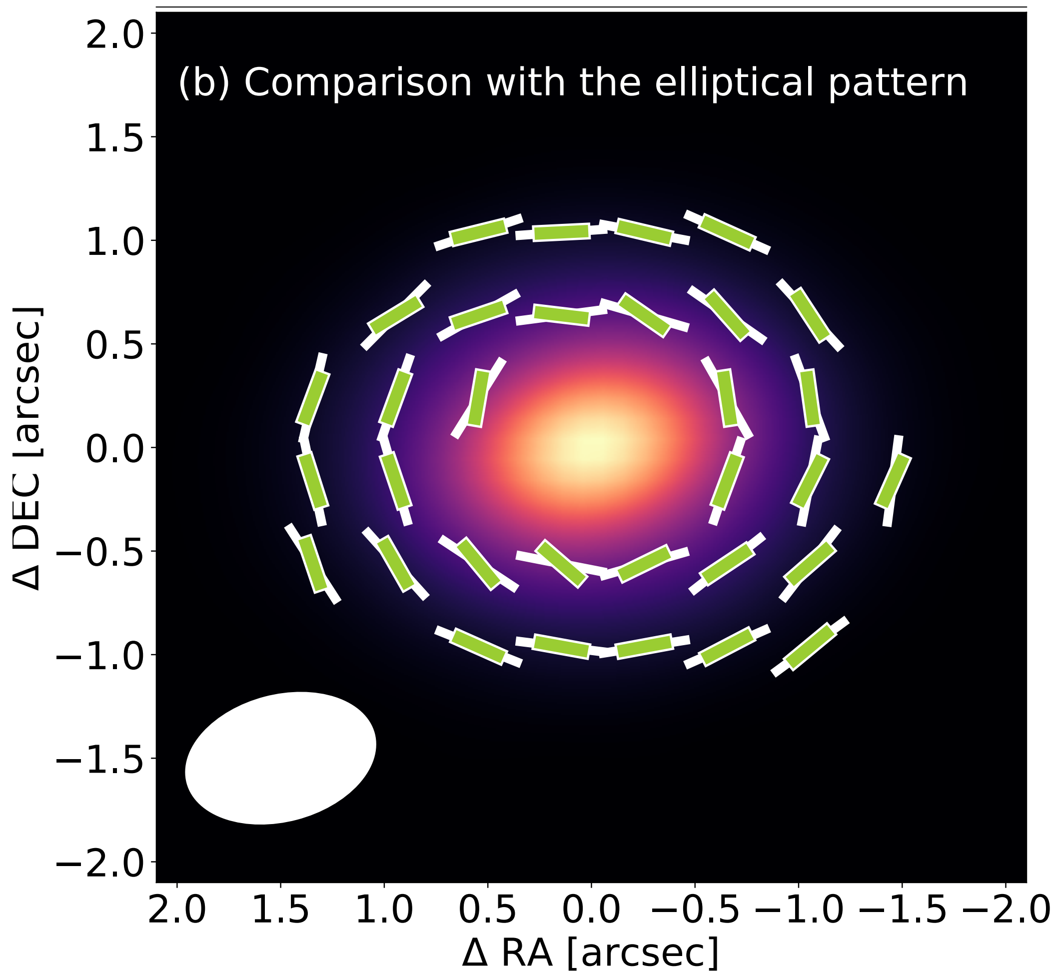
azimuthal polarization: mechanical alignment?

HL Tau (3 mm)

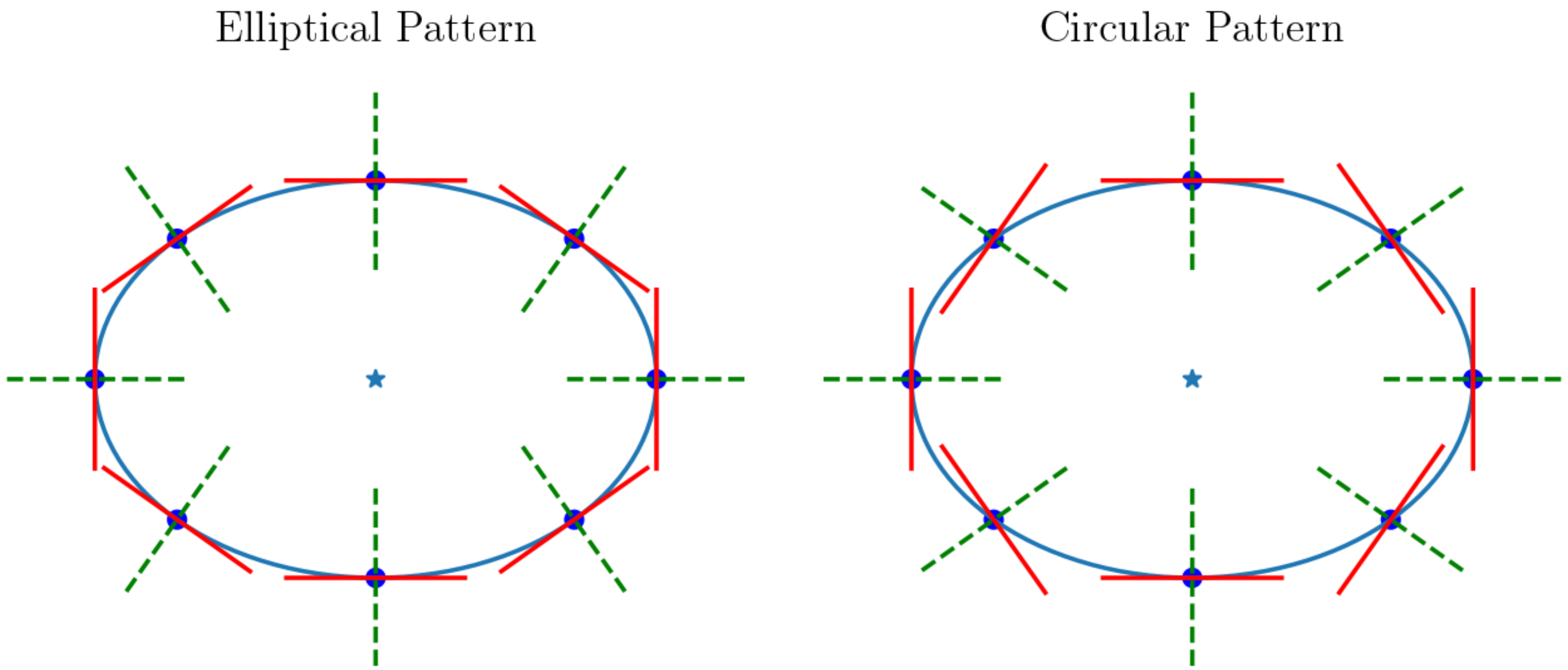


Kataoka et al. 2017

AS 209 (0.9 mm)



Mori et al. 2019

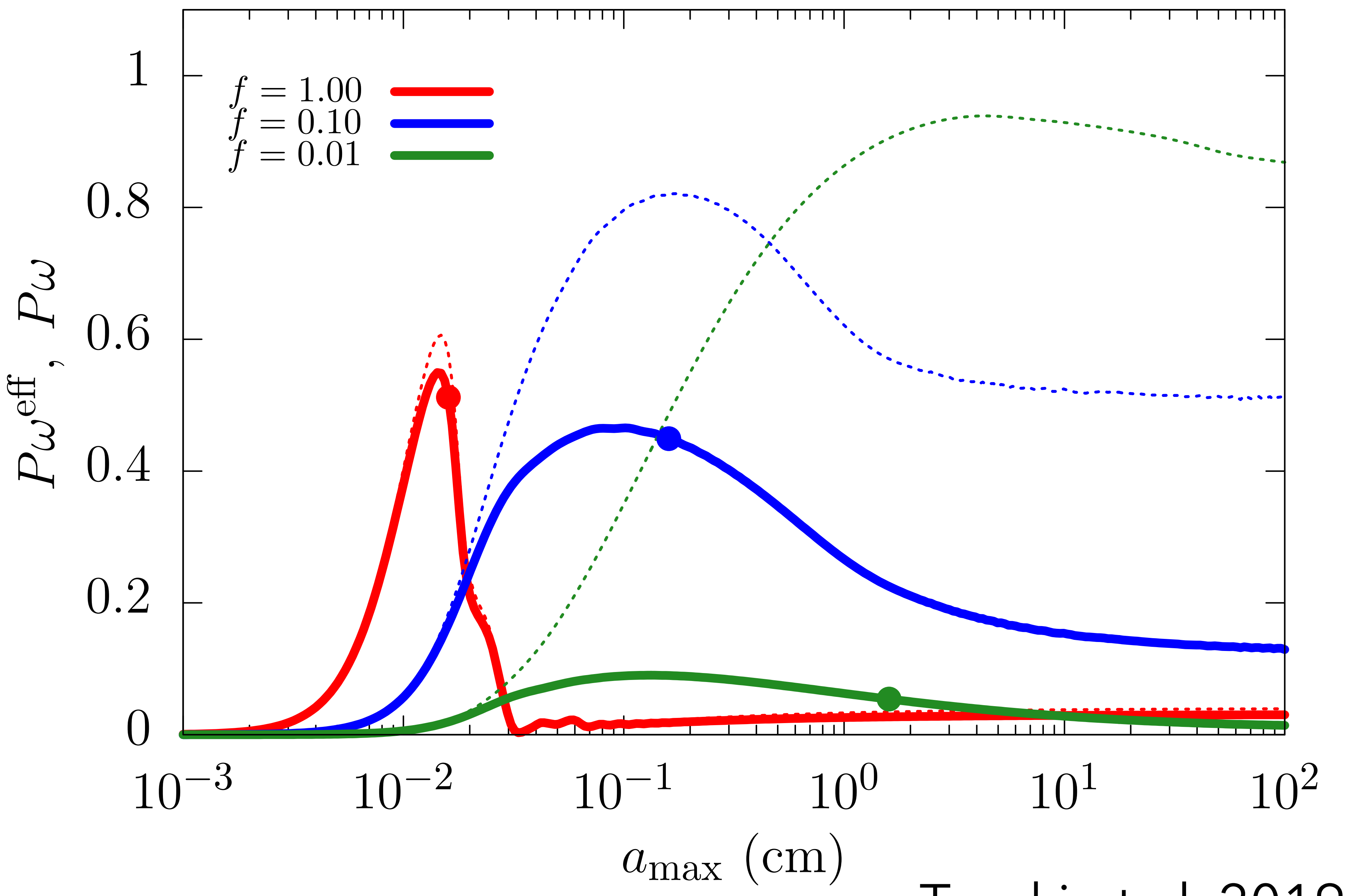


- If grains are aligned with radiation gradients, polarization pattern would be circular.
- HL Tau Band 3 shows elliptical pattern, which is inconsistent with alignment with radiative flux but with gas flow. But it requires supersonic flow.

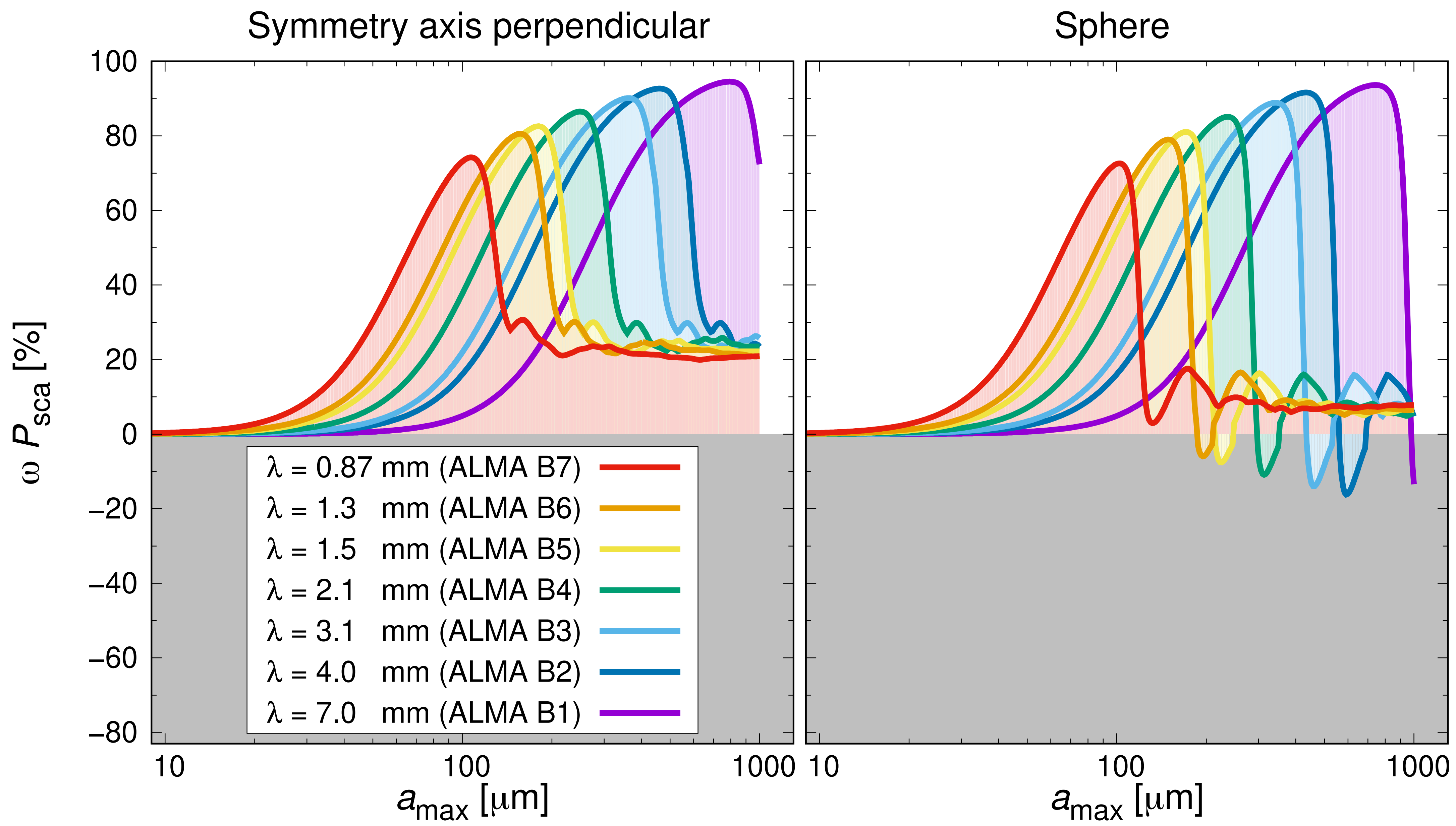
Yang et al. 2019

(See Mori and Kataoka 2021 for radiative transfer simulations)

non-spherical grains?



Tazaki et al. 2019



Kirchschlager and Bertrang et al. 2020

- If grains are porous, polarization can be detectable in a wider size range, but the fraction gets smaller.
- If grains are non-spherical, even large grains can emit polarization at 870 micron wavelengths.

(See also Bertrang and Wolf 2017)

See the talks by Ryo Tazaki and Florian Kirchschlager

Line polarization

- **Non-detection of CN circular polarization**
  - TW Hya (Vlemmings et al. 2019)
  - See Mazzei et al. 2020 for radiative transfer for Zeeman effect
- **Non-detection (?) of CO linear polarization**
  - HD 142527 and IM Lup (Stephens et al. 2020)

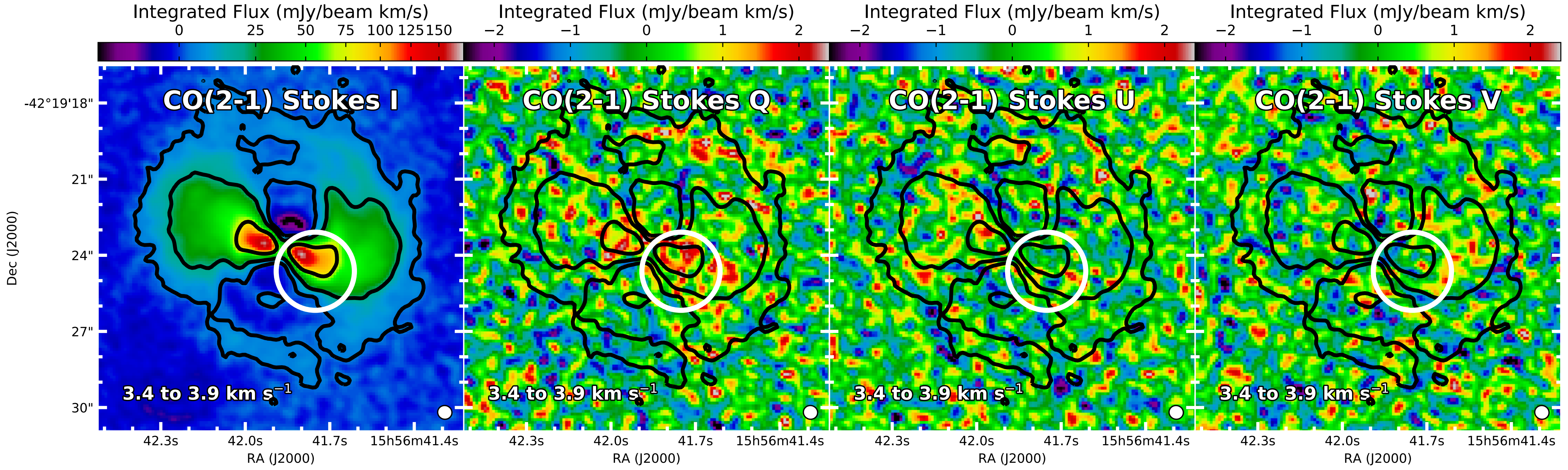


Figure 14. HD 142527 *IQUV* moment 0 maps over the velocity range shown in the bottom left of the panel, which is the pink shaded area shown in Figure 12. The spectra in Figure 12 is the average spectra taken at the location of the white circle.

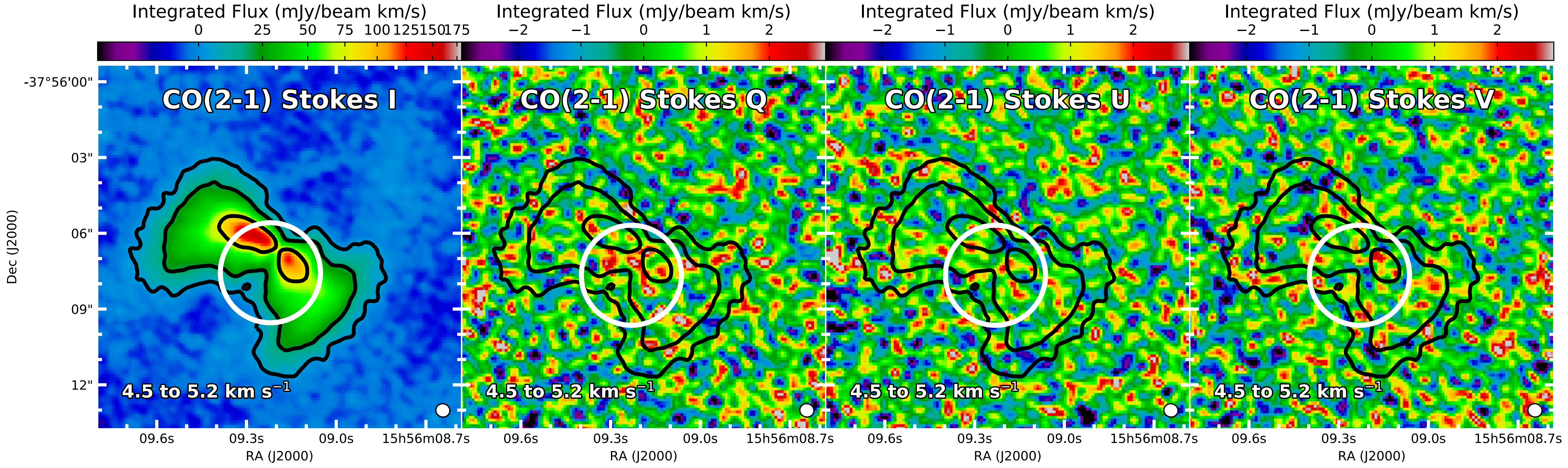


Figure 15. IM Lup *IQUV* moment 0 maps over the velocity range shown in the bottom left of the panel, which is the pink shaded area shown in Figure 13. The spectra in Figure 13 is the average spectra taken at the location of the white circle.

See the talks by Rachel Harrison for upper limit on AS 209 and Boy Lankhaar for more prediction

Stephens et al. 2020

Summary

- **Millimeter polarization of protoplanetary disks**
  - Disks show combination/superposition of self-scattering and alignment-induced polarization.
- **Grain size inconsistency**
  - Many disks show self-scattering polarization at 0.9 mm, which indicates 100 μm grains.
  - Radially flat gas surface density and fragile grains? Optically thick disks? Optically thick substructures?
- **Grain microphysics**
  - Porosity? Mie regime? Fundamental discussion on alignment physics is missing.
- **Line polarization - no robust detection so far**