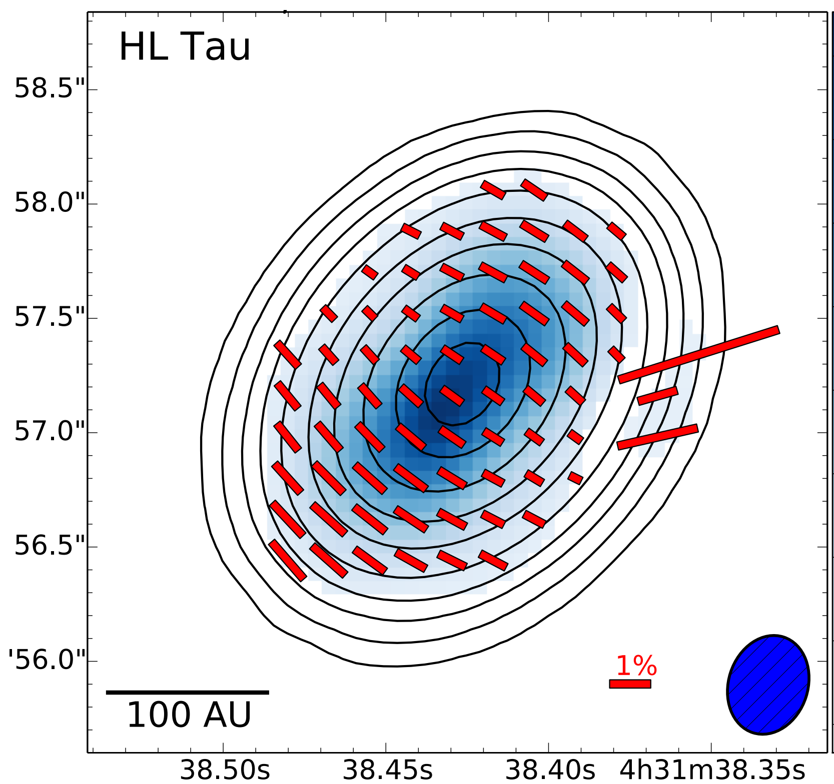
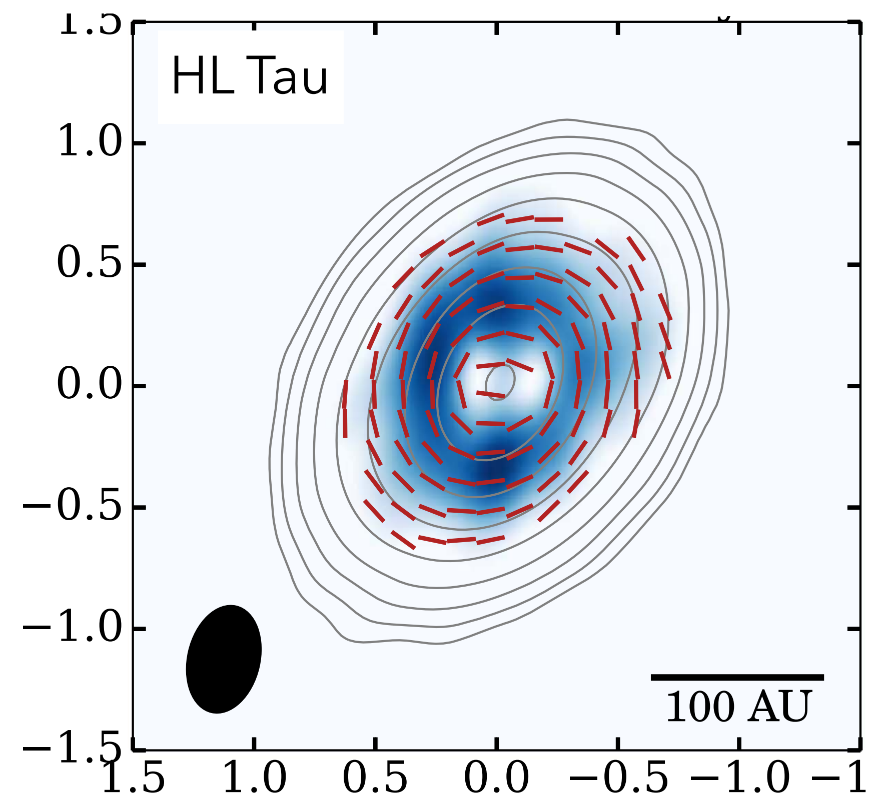
ALMA polarization of HL Tau
- investigating planet formation -

ALMA Band 7 (870 μm)



Stephens et al. 2017

ALMA Band 3 (3.1 mm)



Kataoka et al. 2017

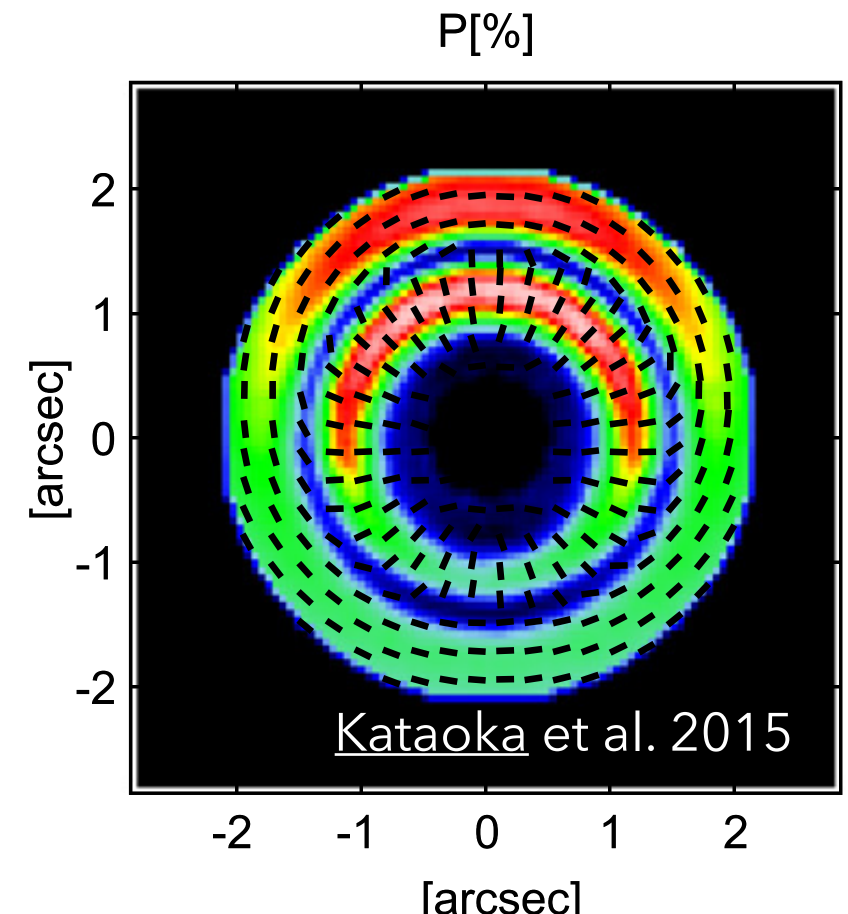
Scattering ⟷ **Alignment**

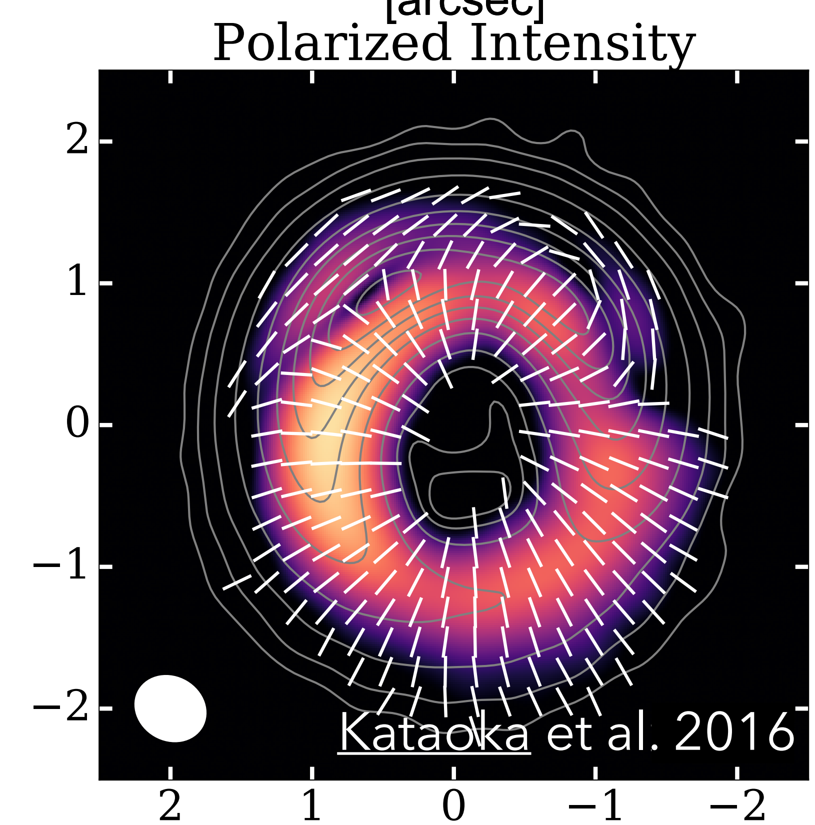
Akimasa Kataoka (NAOJ fellow, NAOJ)

T. Muto (Kogakuin U.), M. Momose, T. Tsukagoshi (Ibaraki U.), H.Nagai (NAOJ), M. Fukagawa (Nagoya U.), H. Shibai (Osaka U.), T. Hanawa (Chiba U.), K. Murakawa (Osaka-S.), Kees Dullemond, Adriana Pohl (Heidelberg)

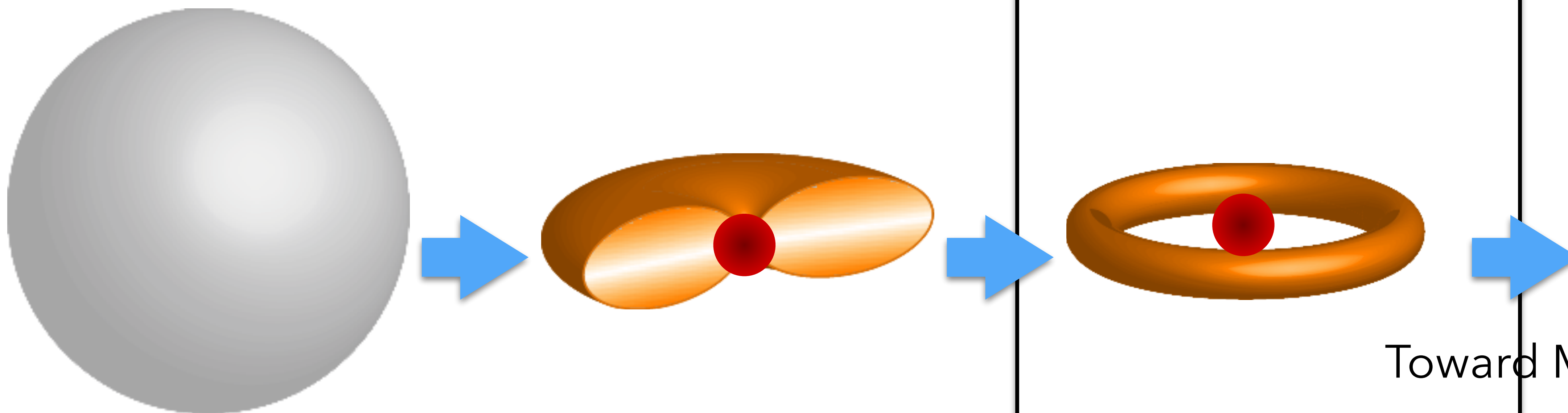
Today's talk

- **Old and new theories for explaining millimeter-wave polarization**
    1. Alignment with magnetic fields
    2. Self-scattering of thermal dust emission
    3. Alignment with radiation fields
- **Testing the theory with ALMA polarization observations**
    - HD 142527 - morphology of pol. vectors
    - HL Tau - wavelength dependence





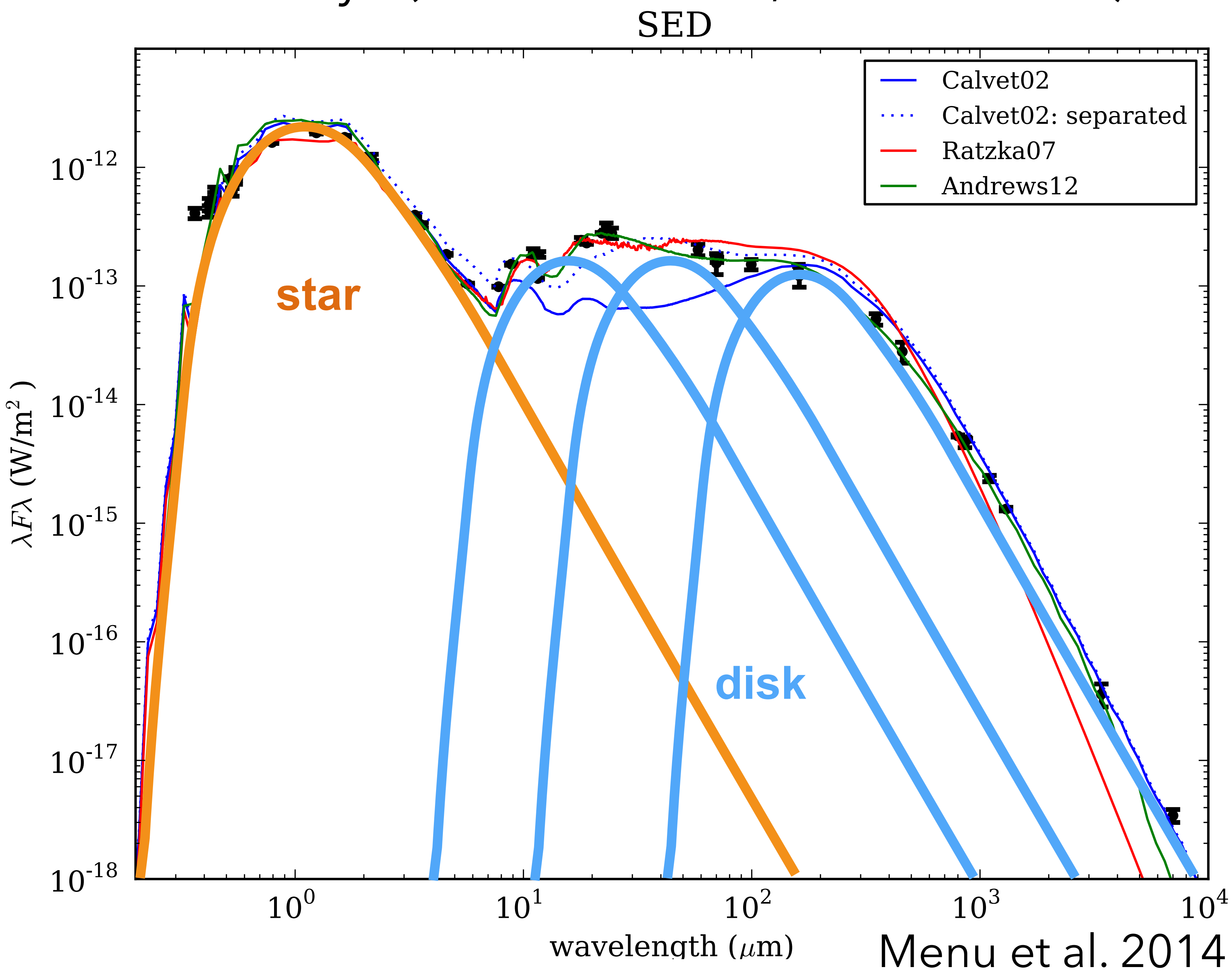
Star and disk formation



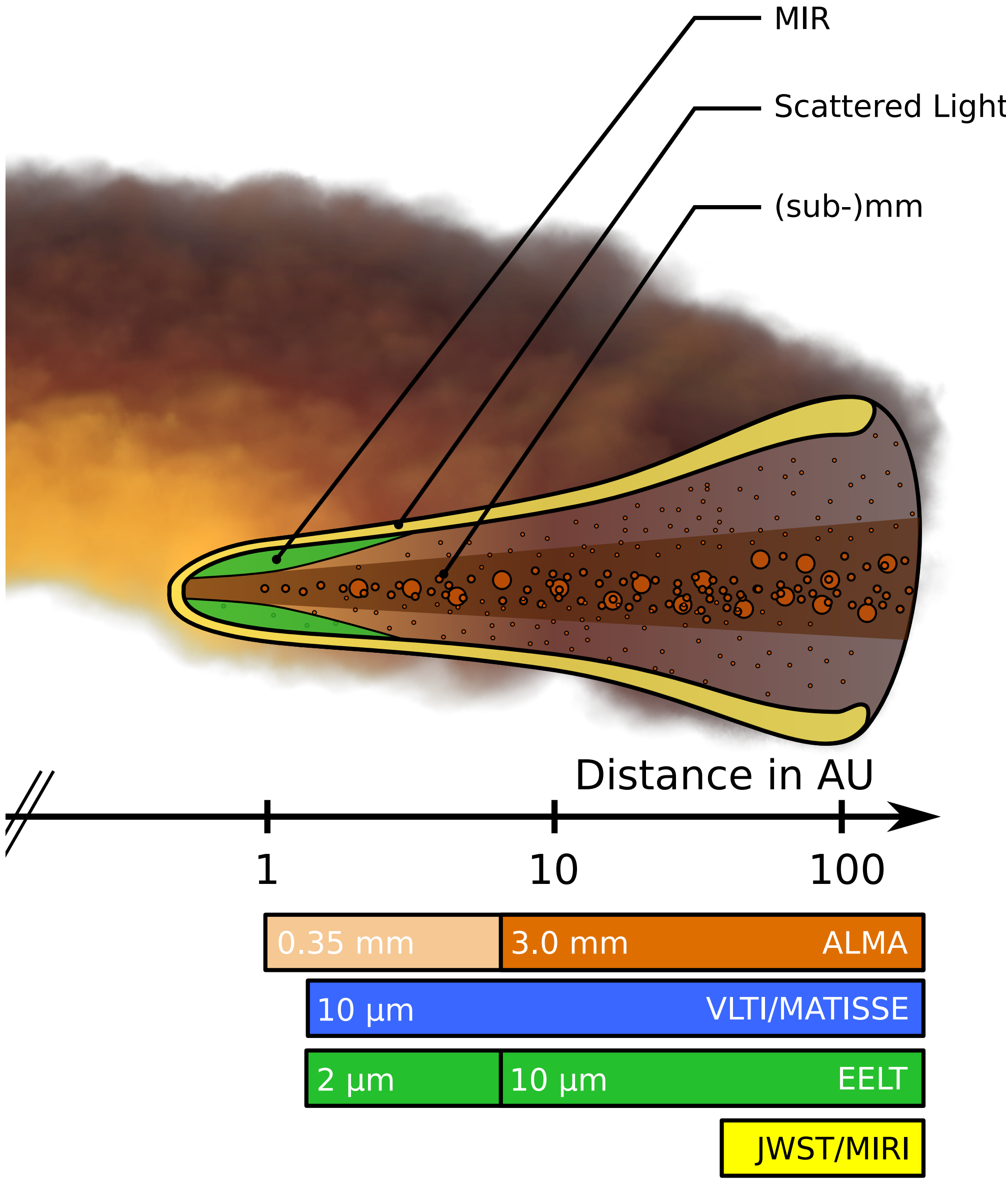
	Molecular cloud cores	Protostar and envelope	Protostar and **protoplanetary disk**
Timescale	~10^{4-6} years	~10^{4-5} years	**~10^{6-7} years**
Spatial scale	~0.1 pc =20,000 AU ~ 200 arcsec	~1,000 AU ~10 arcsec	~100 AU **~1 arcsec**
Key physics	magnetic fields or turbulence?	jets, outflows	**grain growth**

SED of a protoplanetary disk

- TW Hya ($M_{star} = 0.6\ M_\odot$, T_{eff} = 4000 K)



Menu et al. 2014

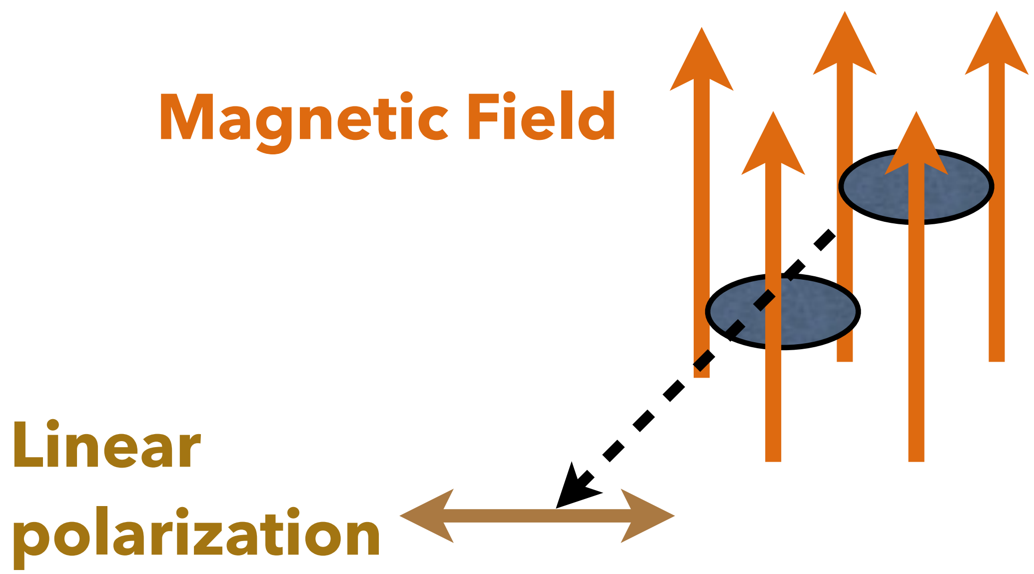


Testi et al. 2014

- The millimeter emission is thermal dust emission from the disk.
- How can we polarize the thermal dust emission?

Polarization mechanisms

1. **Alignment of elongated dust grains with magnetic fields**



e.g., Lazarian and Hoang 2007

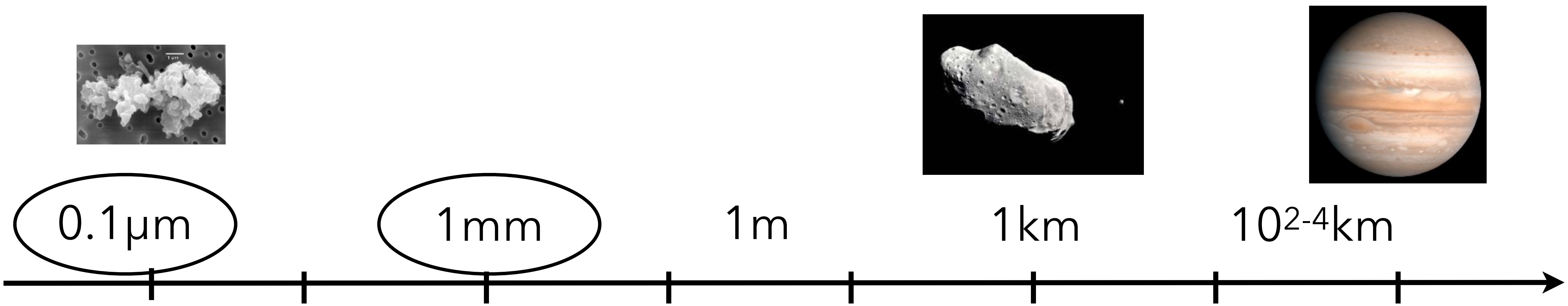
2. **The self-scattering of thermal dust emission**

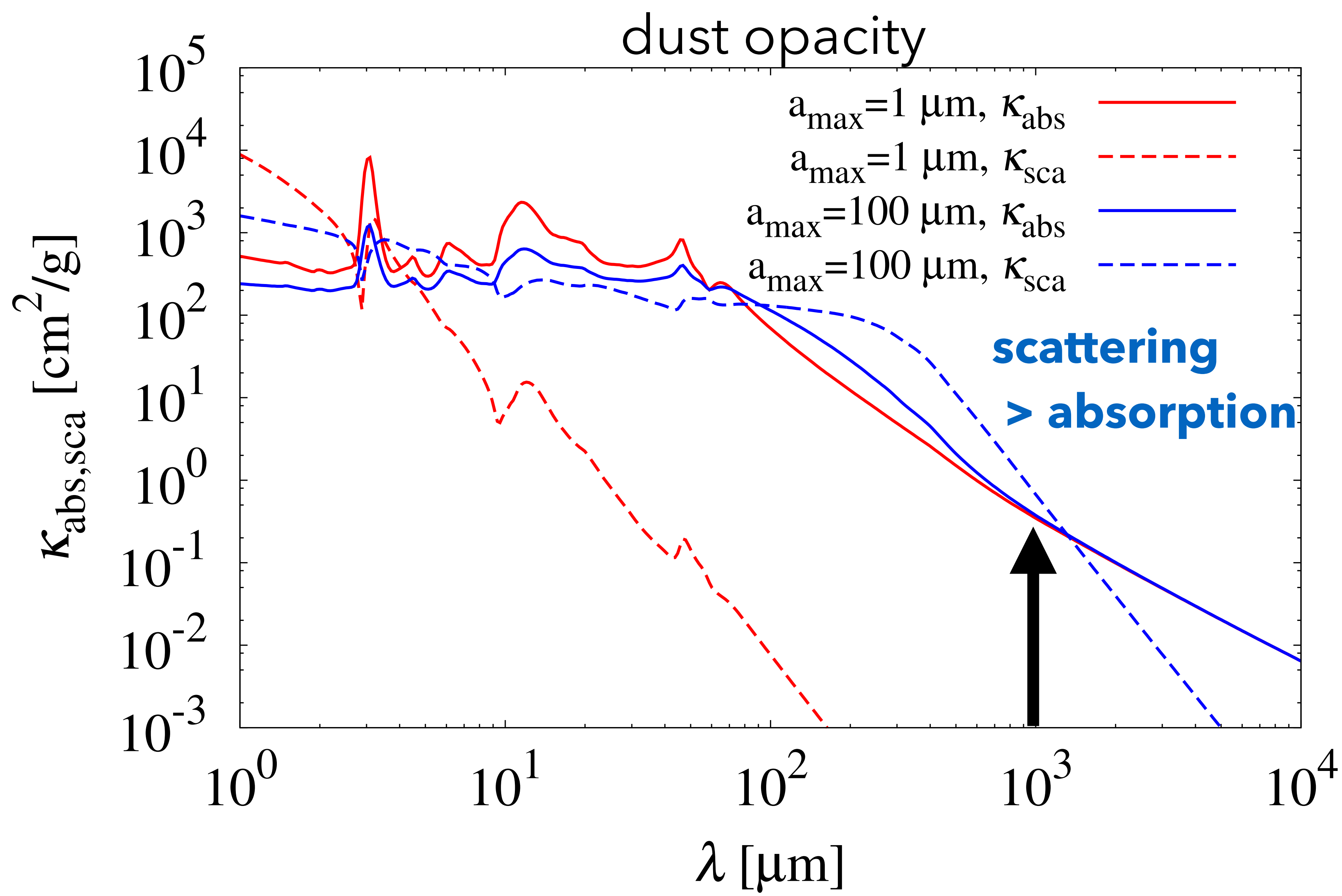
Kataoka et al. 2015

3. **Alignment of elongated dust grains with radiation fields**

Tazaki, Lazarian et al. 2017

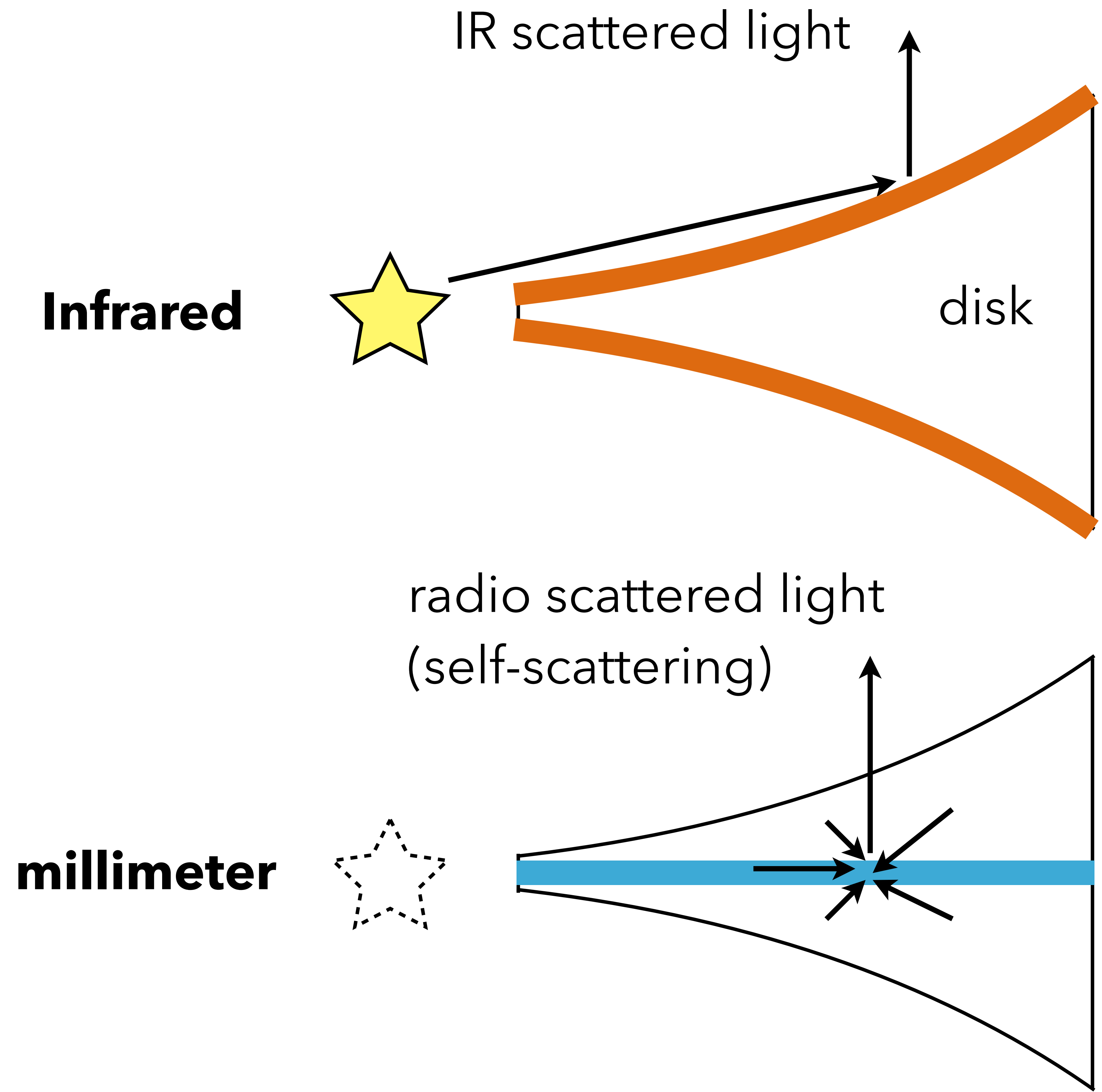
Dust is big in disks



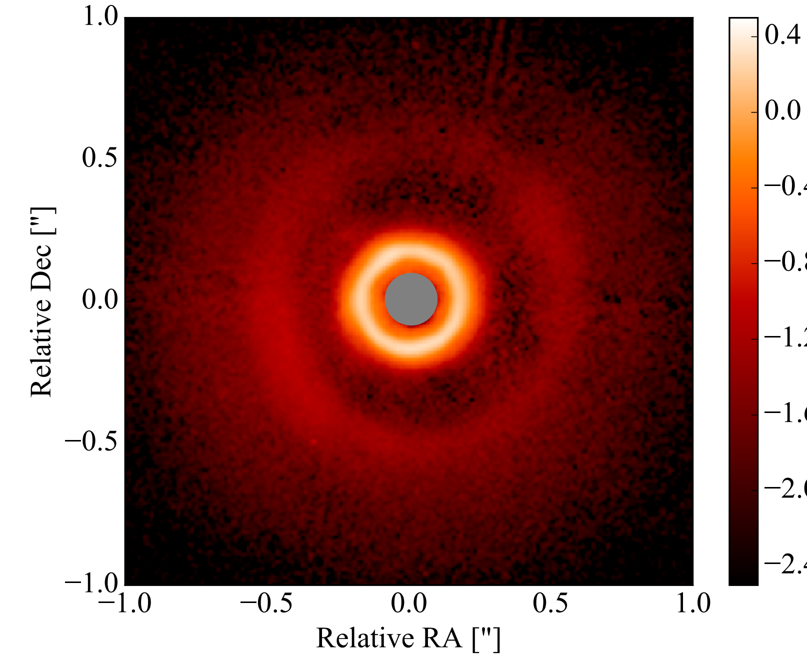


Akimasa Kataoka (NAOJ fellow)

Light source of scattering



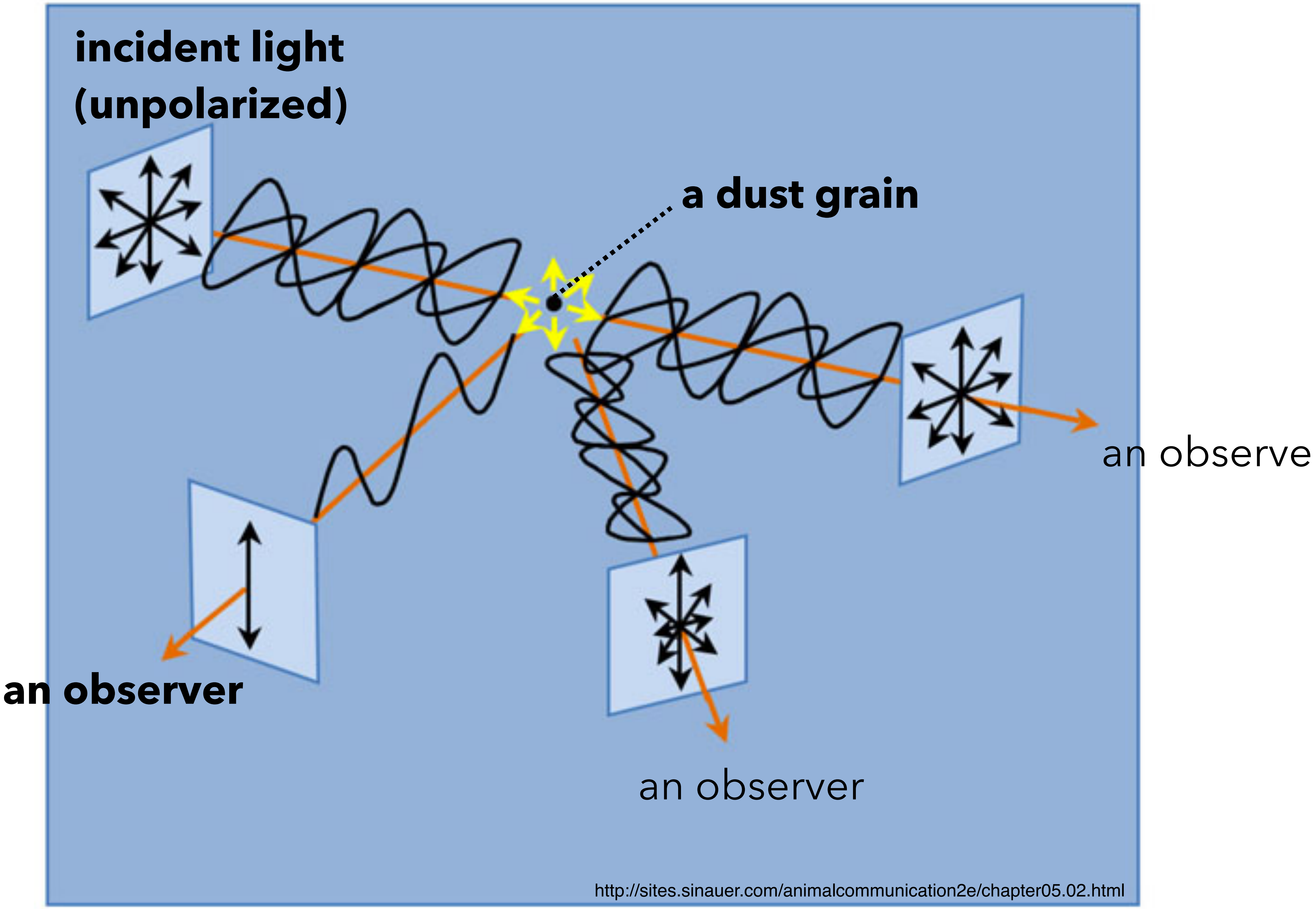
example (face-on, PI)



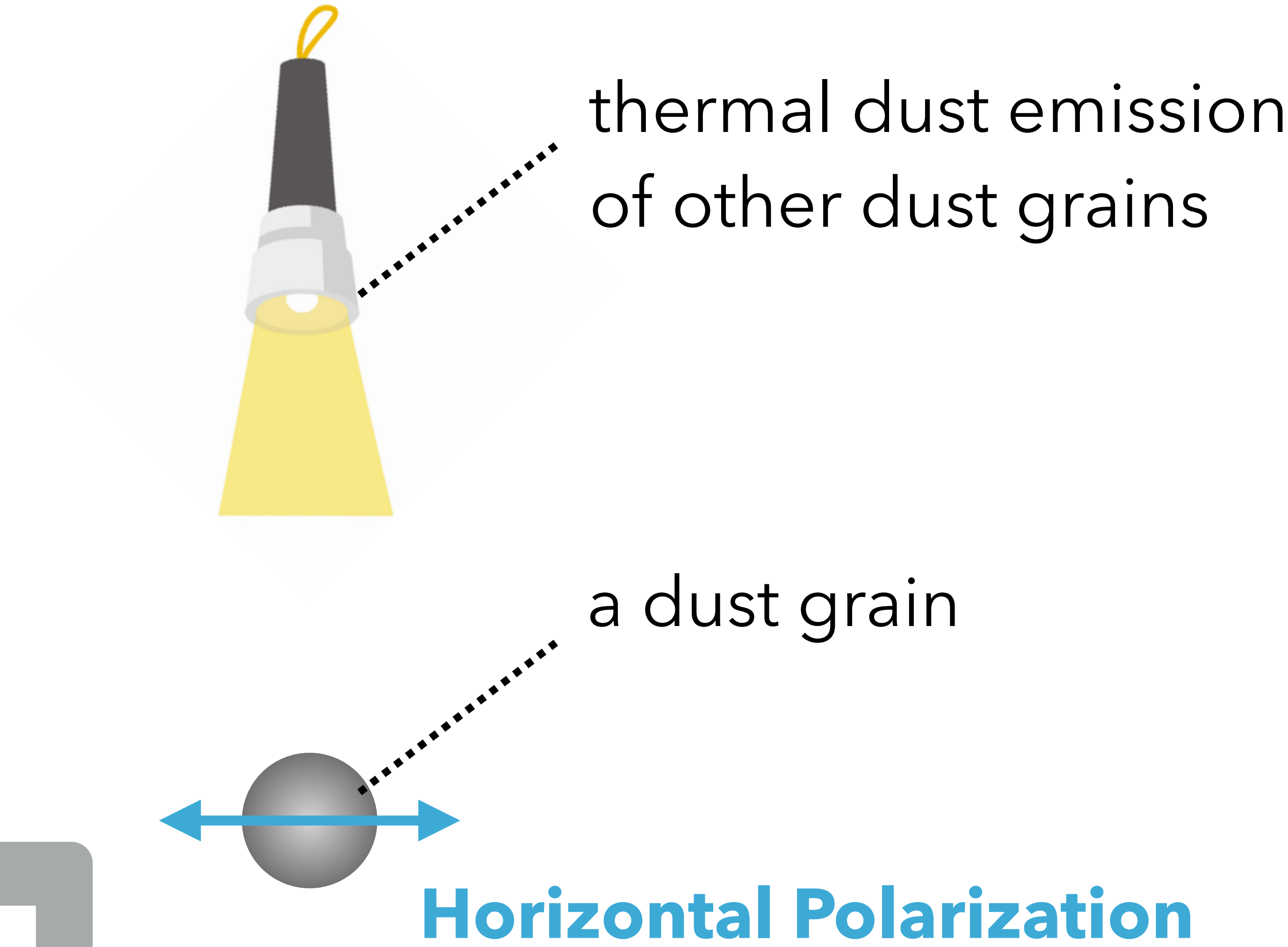
Pohl et al. 2017

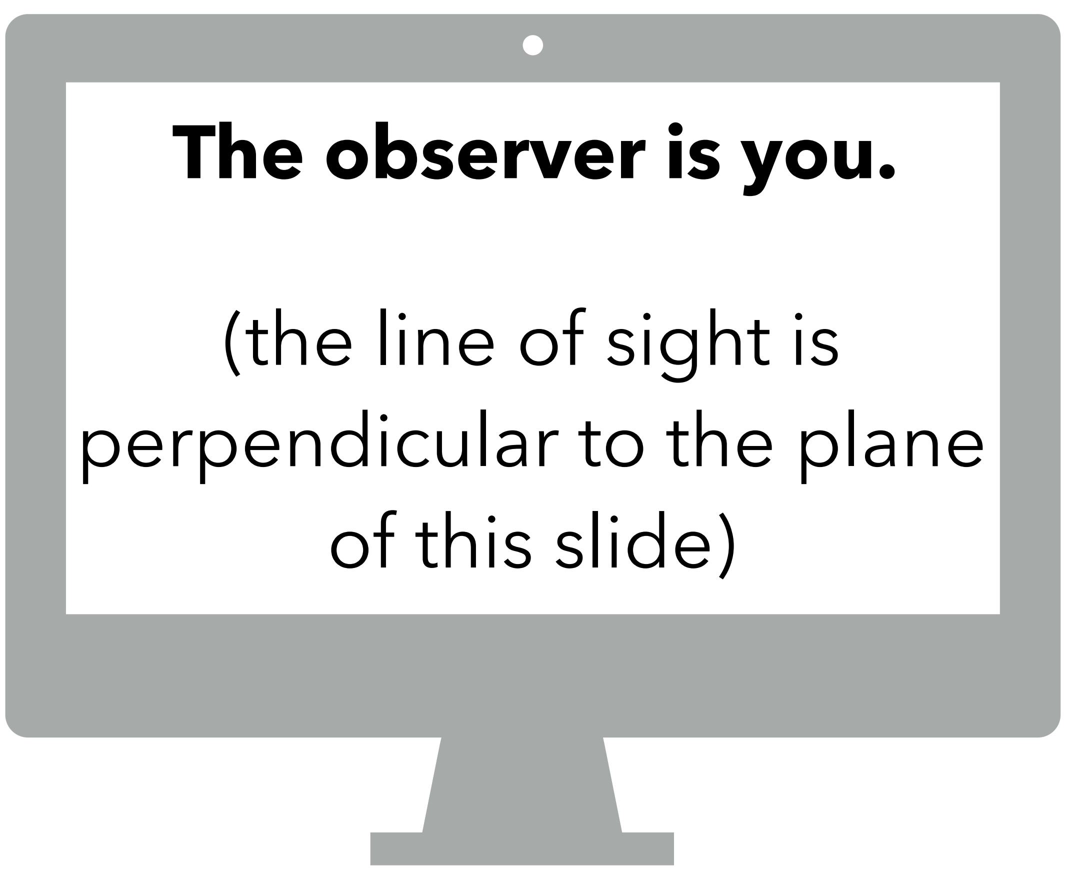
?

Polarization due to scattering

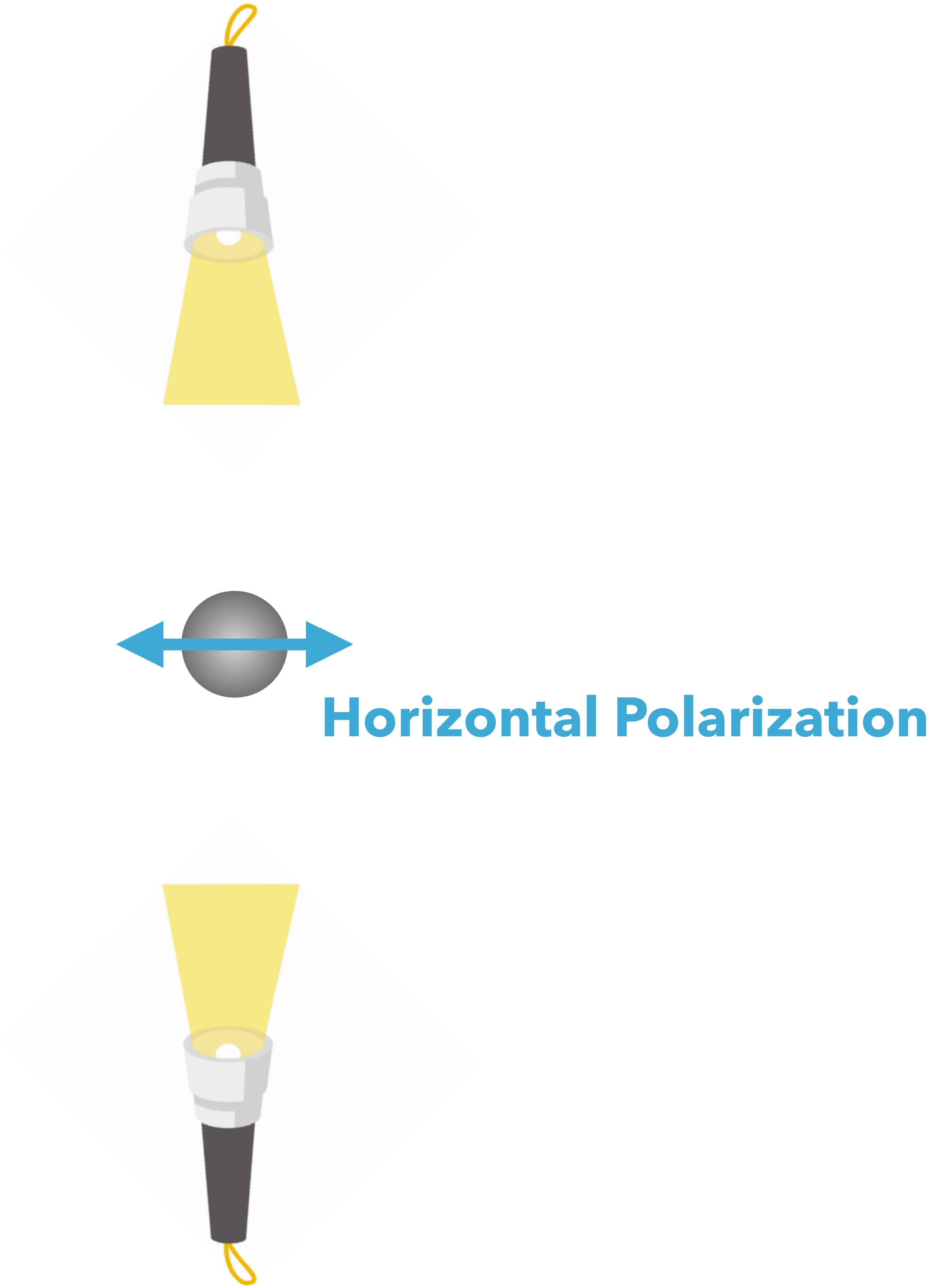


Polarization due to scattering



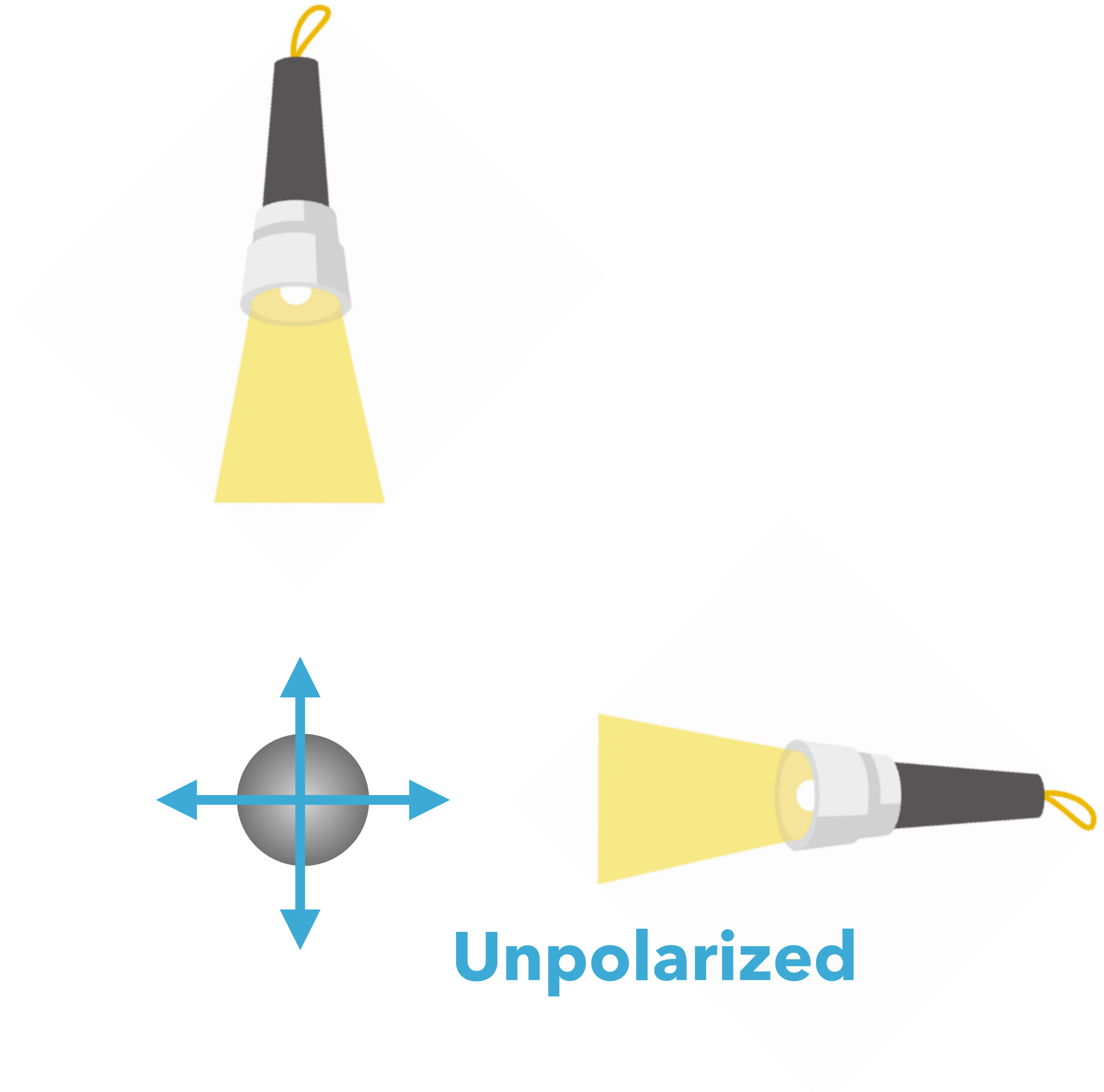


Polarization due to scattering

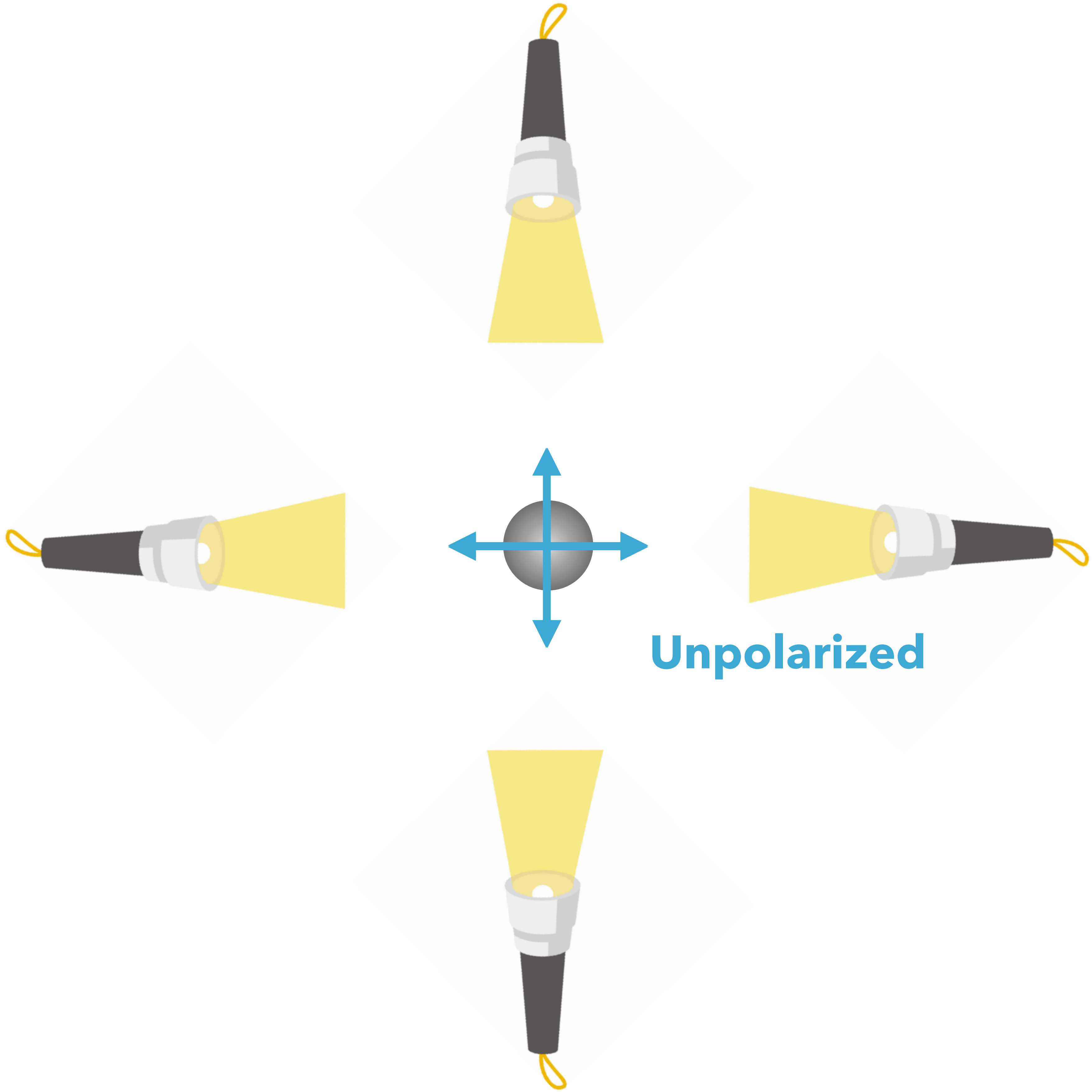


Akimasa Kataoka (NAOJ fellow)

Polarization due to scattering

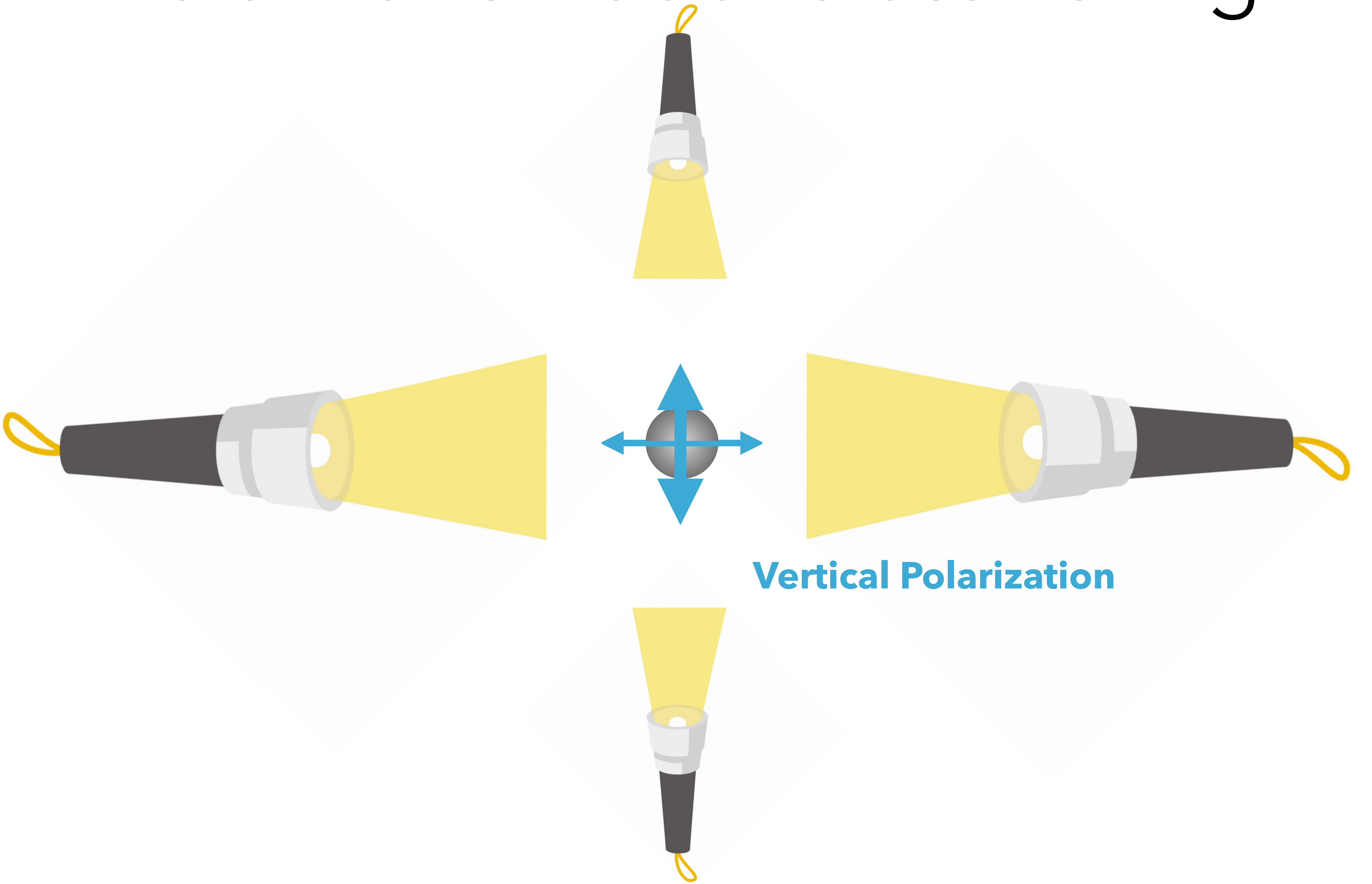


Polarization due to scattering



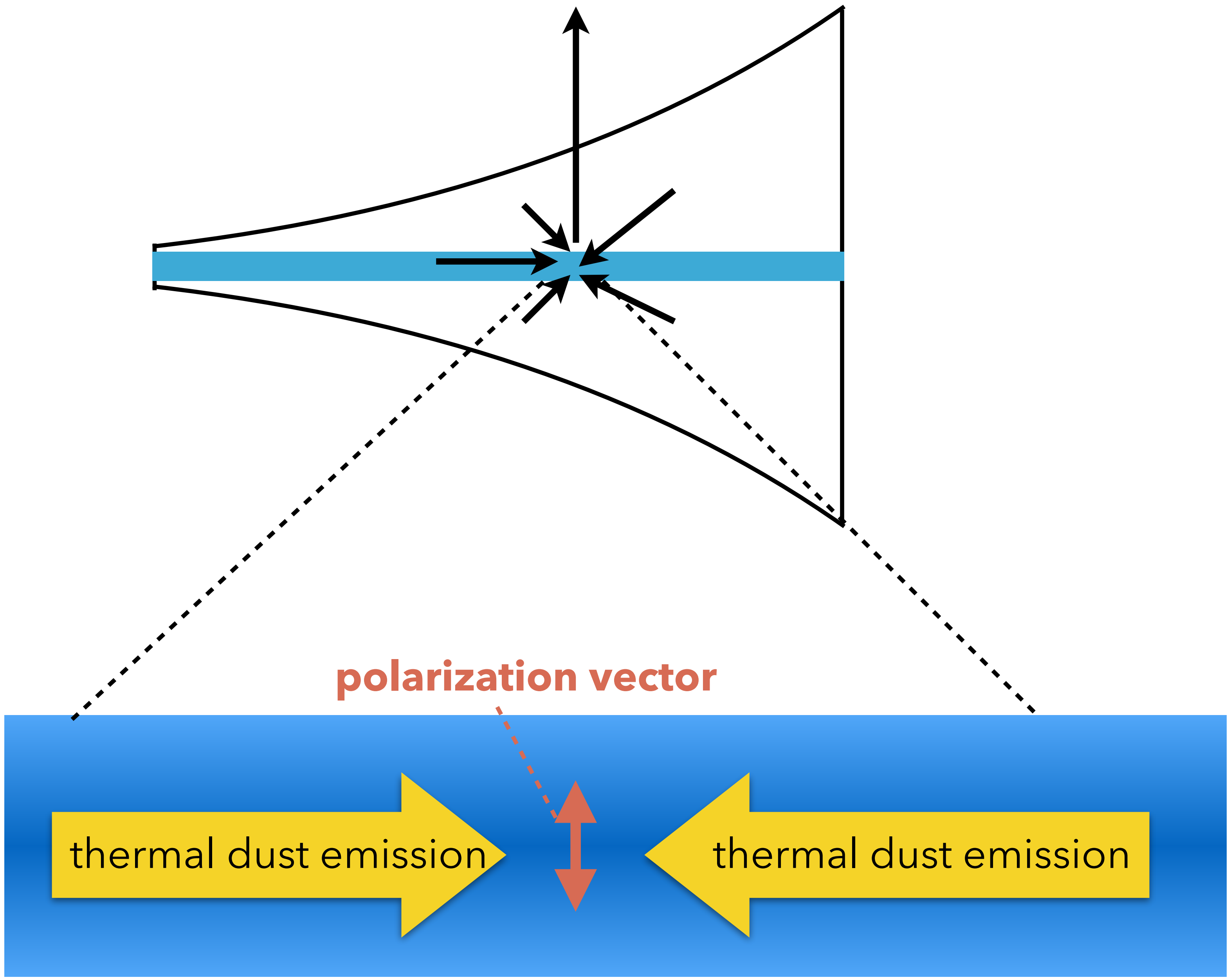
Akimasa Kataoka (NAOJ fellow)

Polarization due to scattering

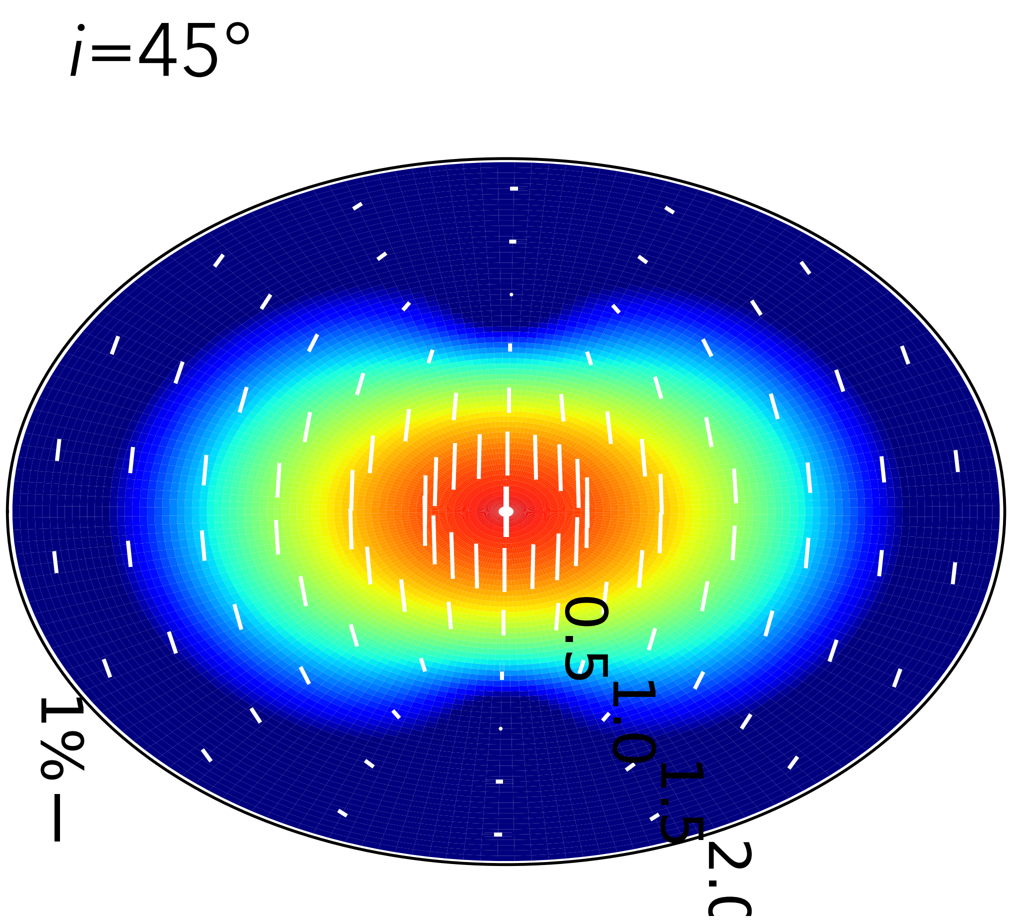


Akimasa Kataoka (NAOJ fellow)

self-scattering in an inclined disk



(disk, edge-on view)



Yang, Li, et al. 2016

See also Kataoka et al. 2016a

Conditions of dust grains for polarization

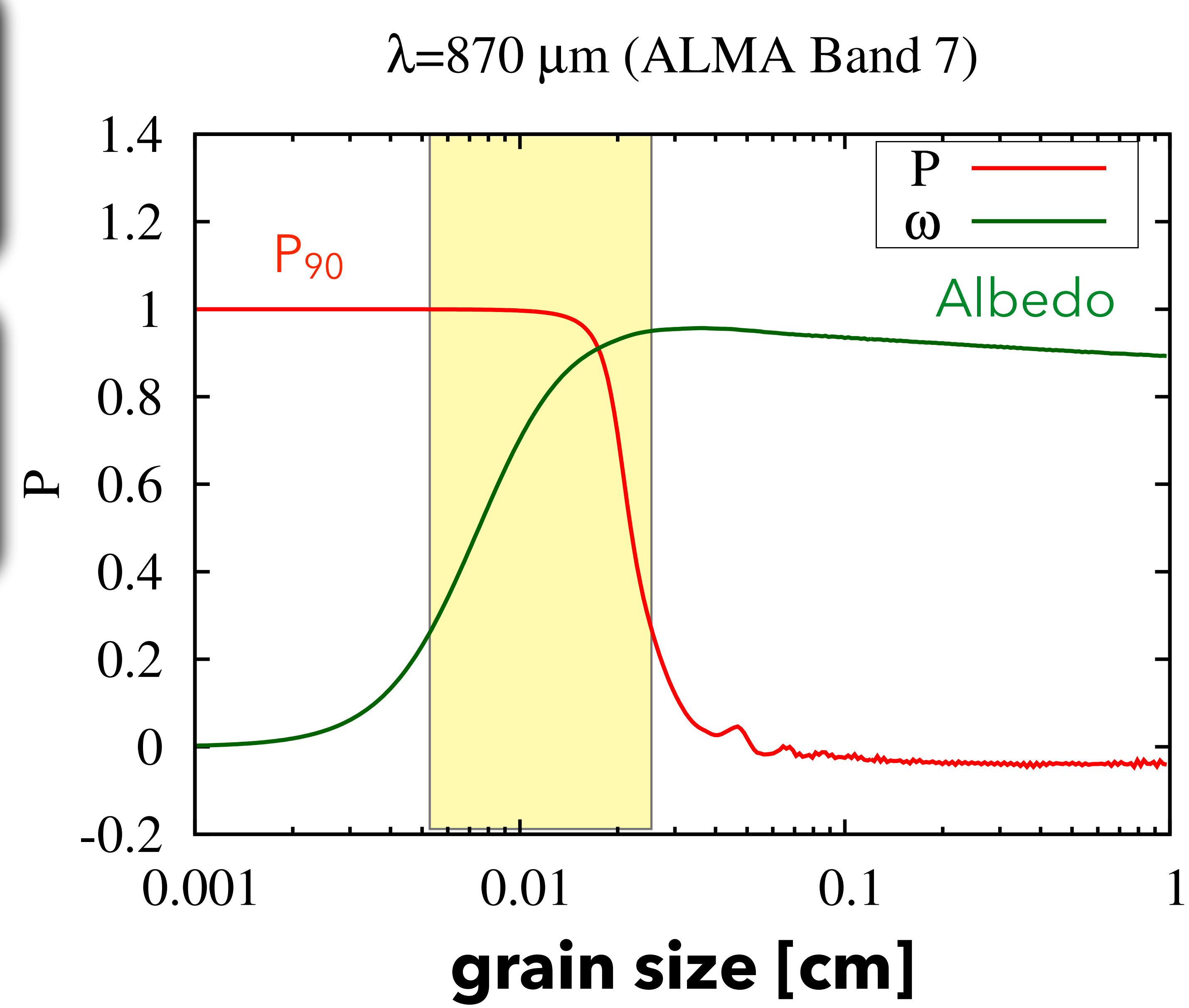
- For efficient scattering

  (grain size) >~ λ

- For efficient polarization

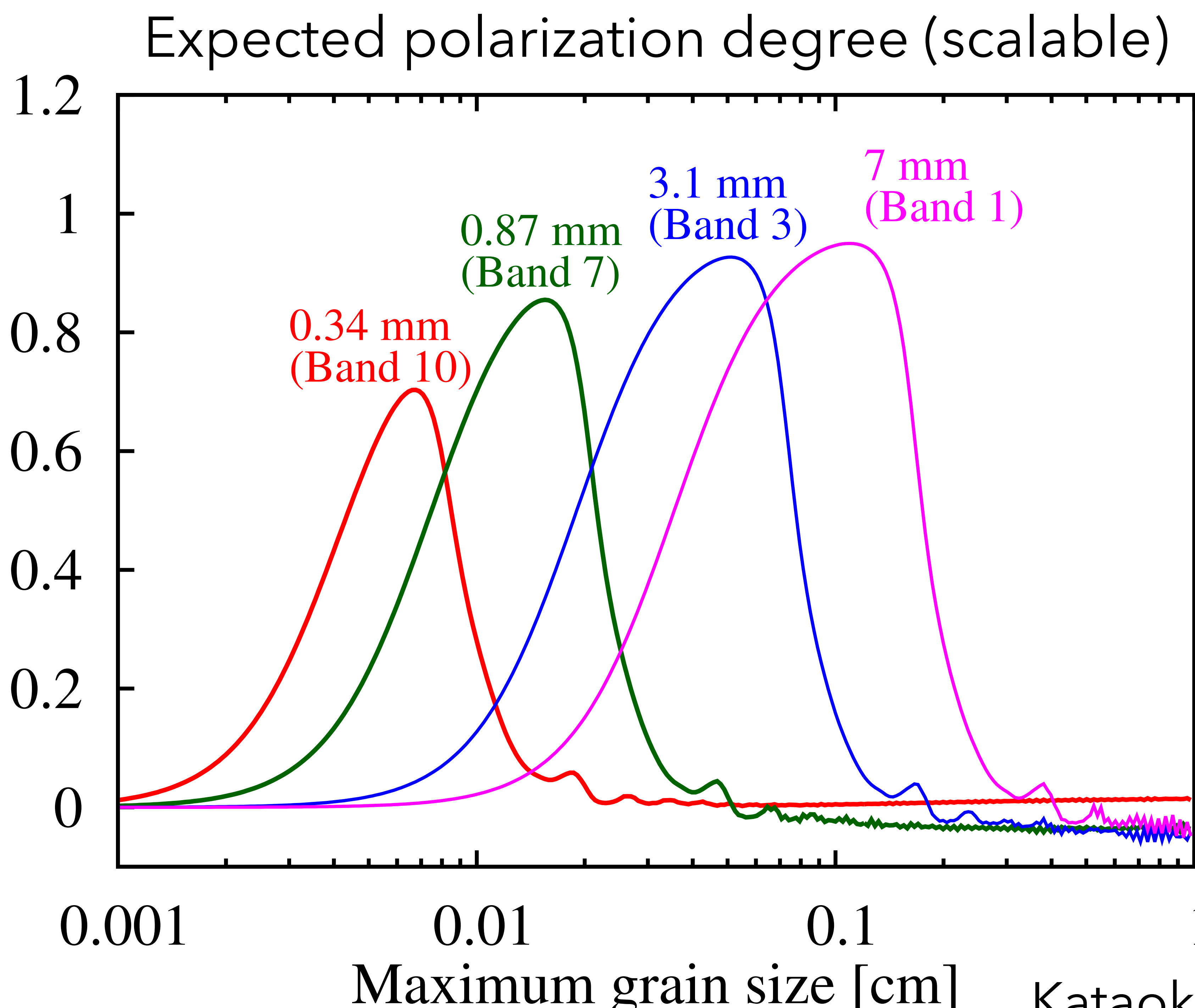
  (grain size) <~ λ

There is a grain size which contributes most to the polarized emission



If (grain size) ~ λ/2π, the polarized emission due to dust scattering is the strongest

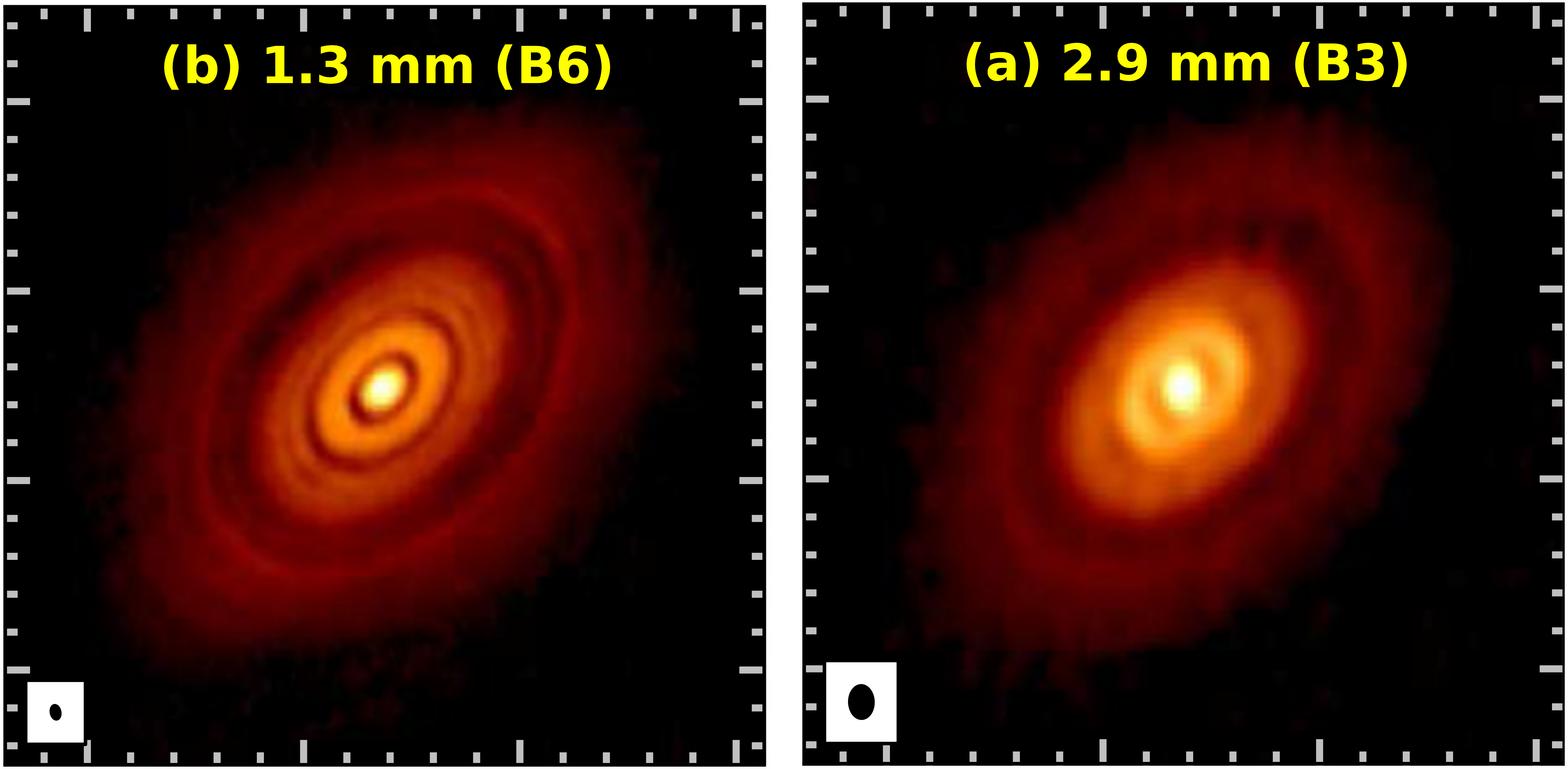
Grain size constraints by polarization



Kataoka, et al., 2015

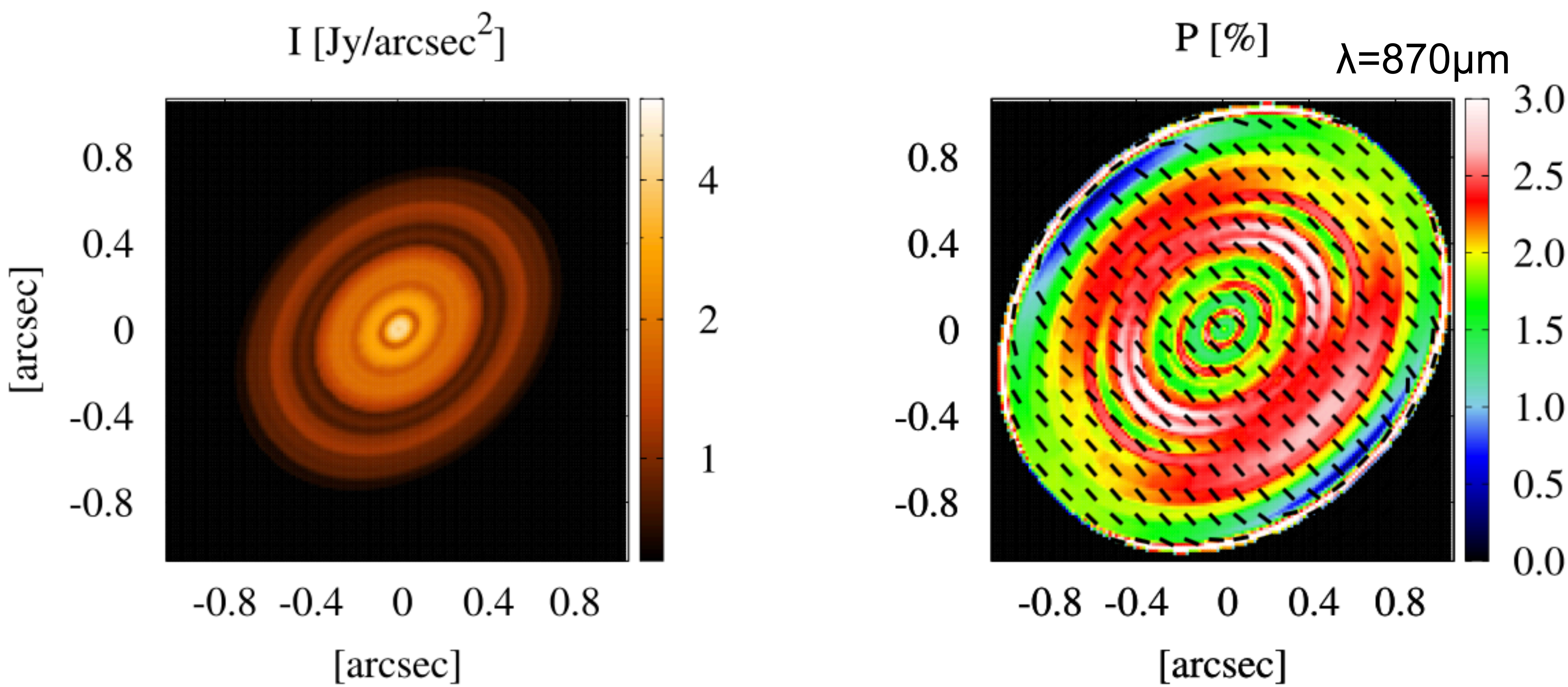
Multi-wave polarization → constraints on the grain size

HL Tau - continuum



ALMA Partnership, 2015

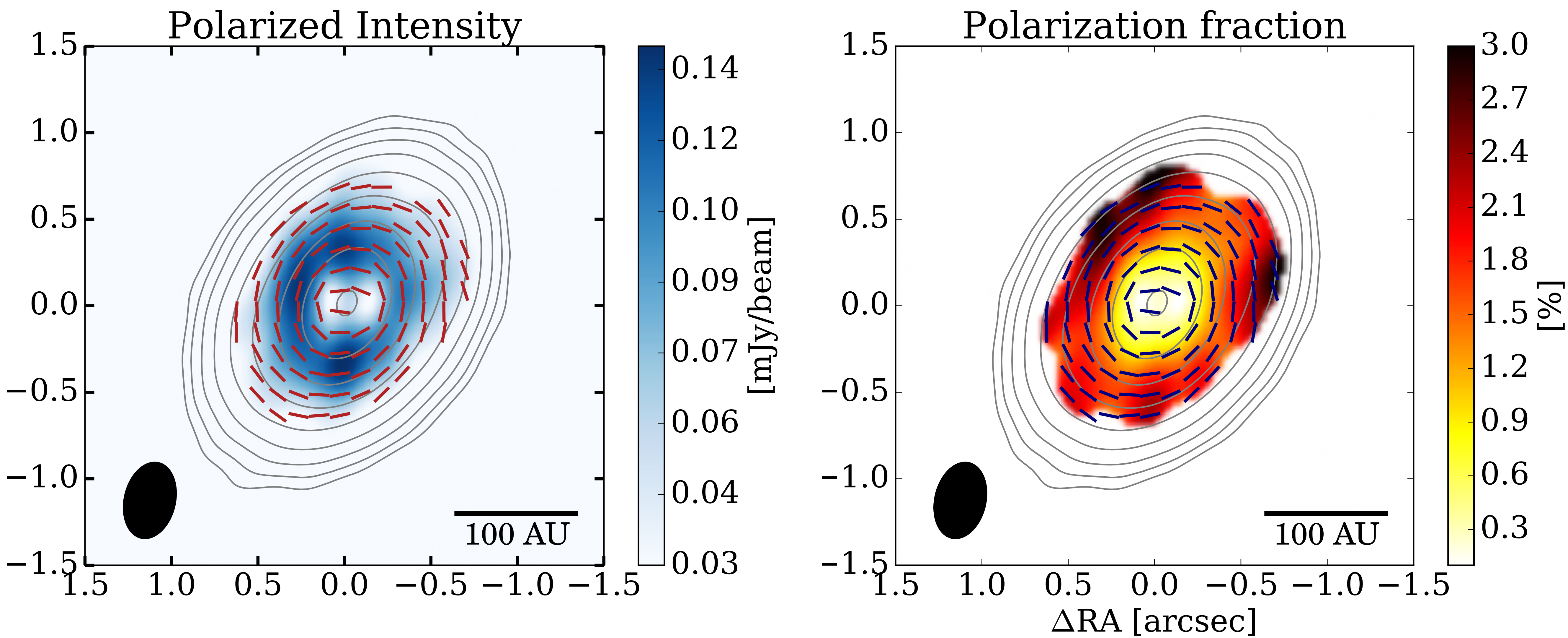
HL Tau pol. - prediction



- i = 47° (ALMA Partnership 2015)
- The polarization vectors are parallel to the minor axis

<u>Kataoka</u>, et al., 2016a (see also Yang et al. 2016)

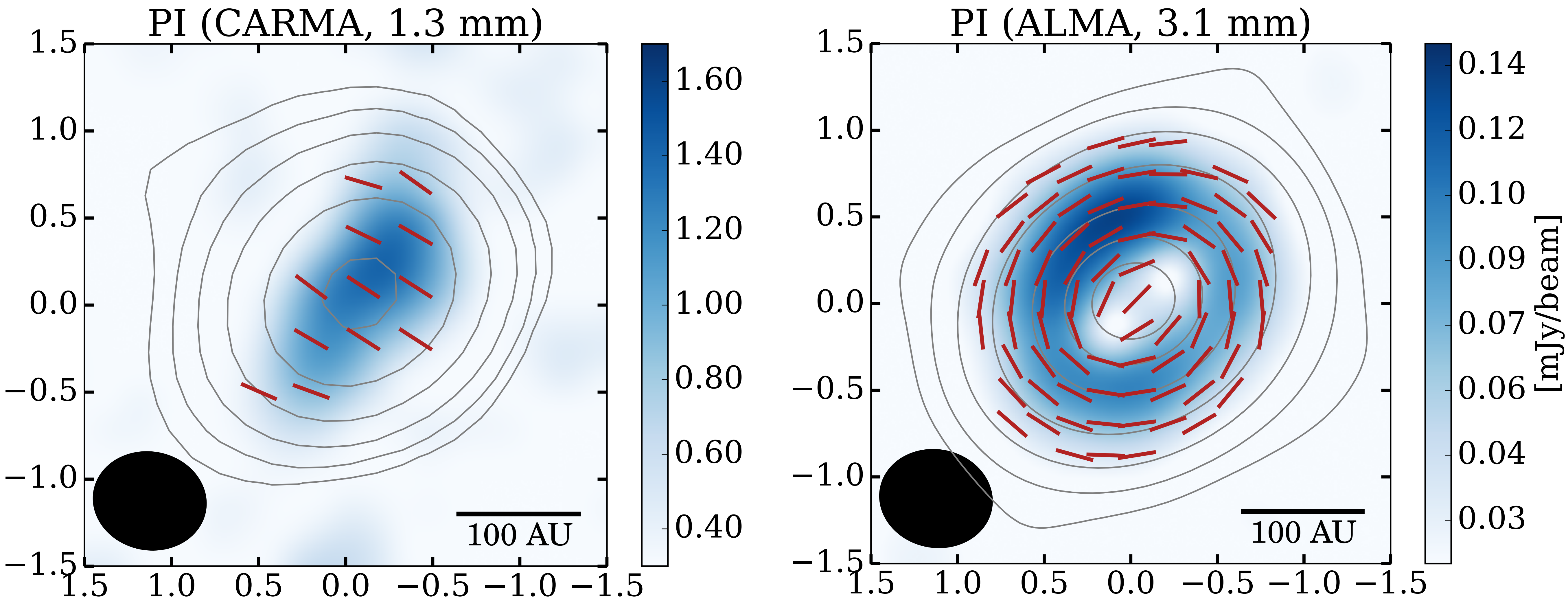
HL Tau polarization with ALMA



- **We find the azimuthal polarization vectors at 3.1 mm wavelength**

Kataoka, et al., 2017

HL Tau polarization



data from Stephens et al., 2014

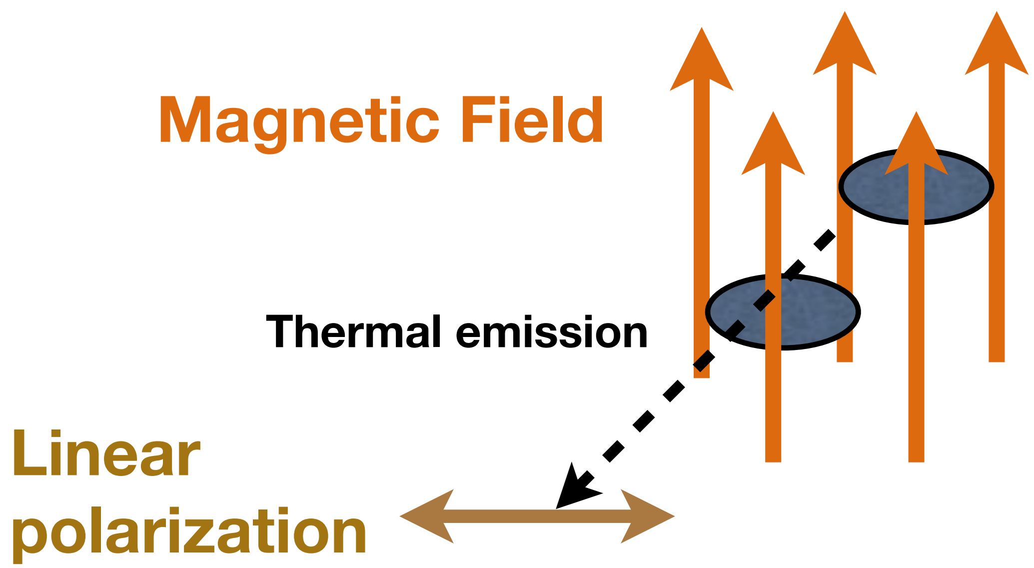
Kataoka, et al., 2017

- The polarization vectors at 1.3 mm are parallel to the minor axis
- The polarization vectors at 3.1 mm are in the azimuthal direction

wavelength-dependent polarization in mm range

Polarization mechanisms

1. **Alignment of elongated dust grains with magnetic fields**



e.g., Lazarian and Hoang 2007

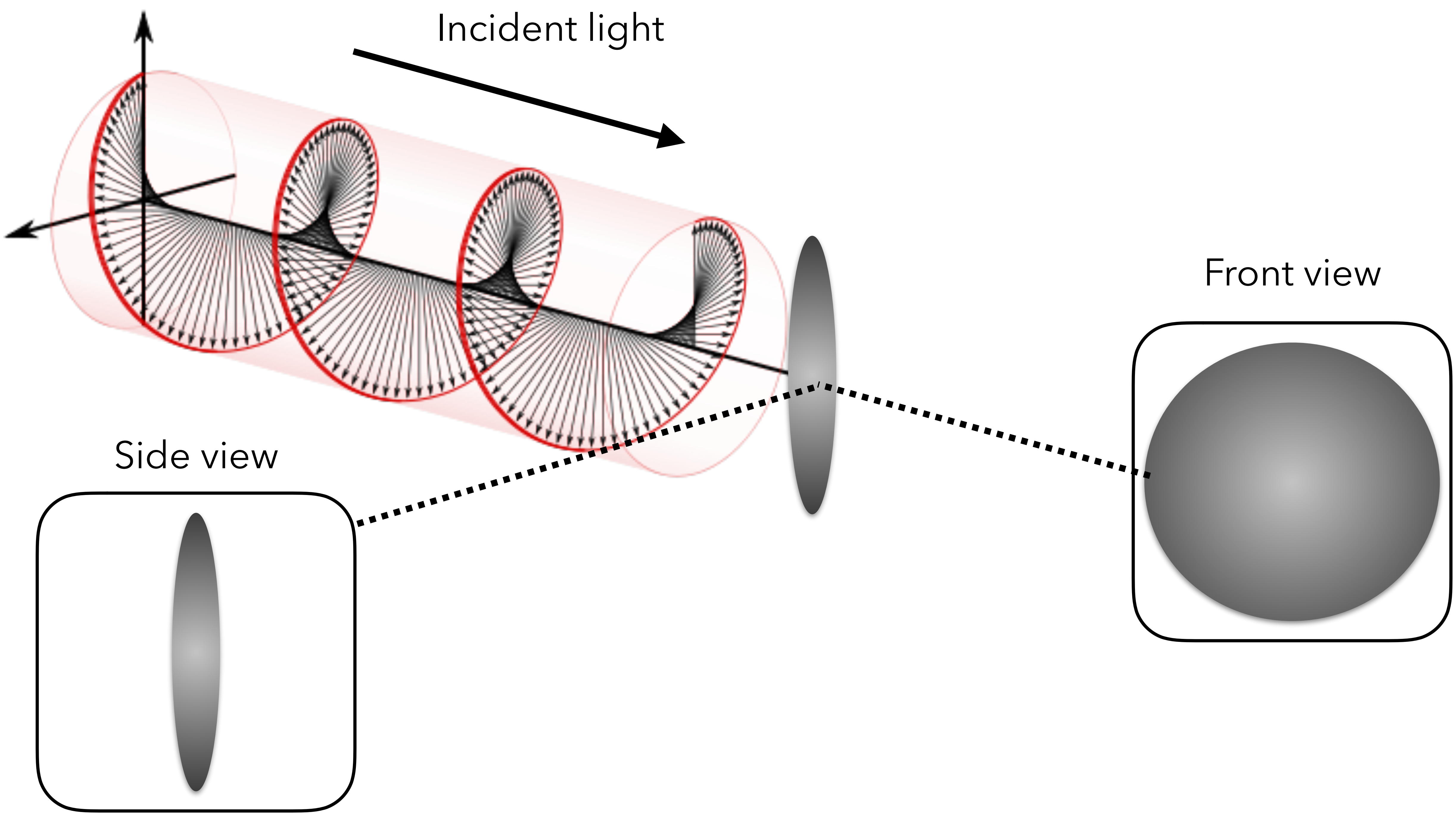
2. **The self-scattering of thermal dust emission**

Kataoka et al. 2015

3. **Alignment of elongated dust grains with radiation fields**

Tazaki, Lazarian et al. 2017

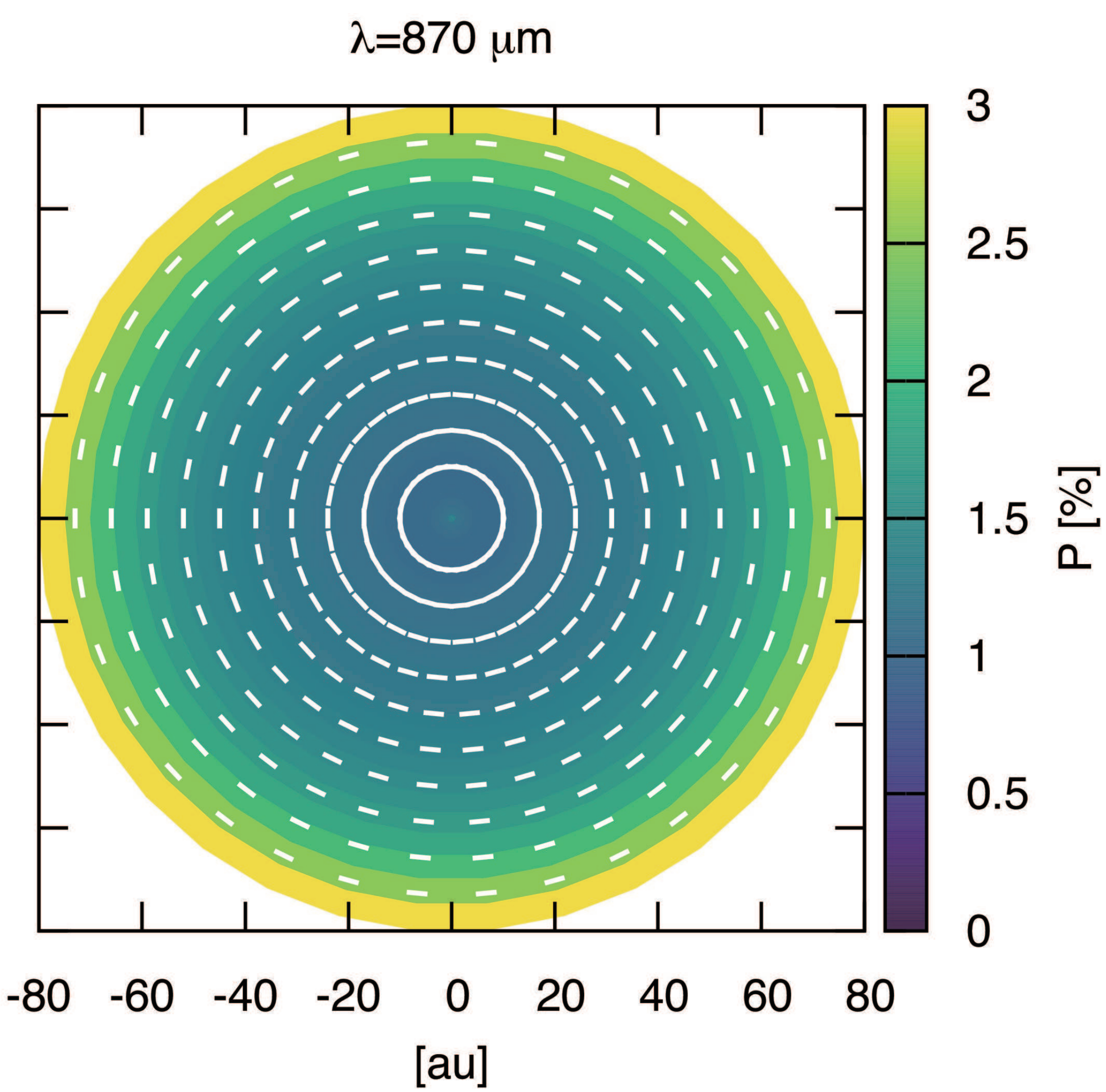
Alignment with radiation fields

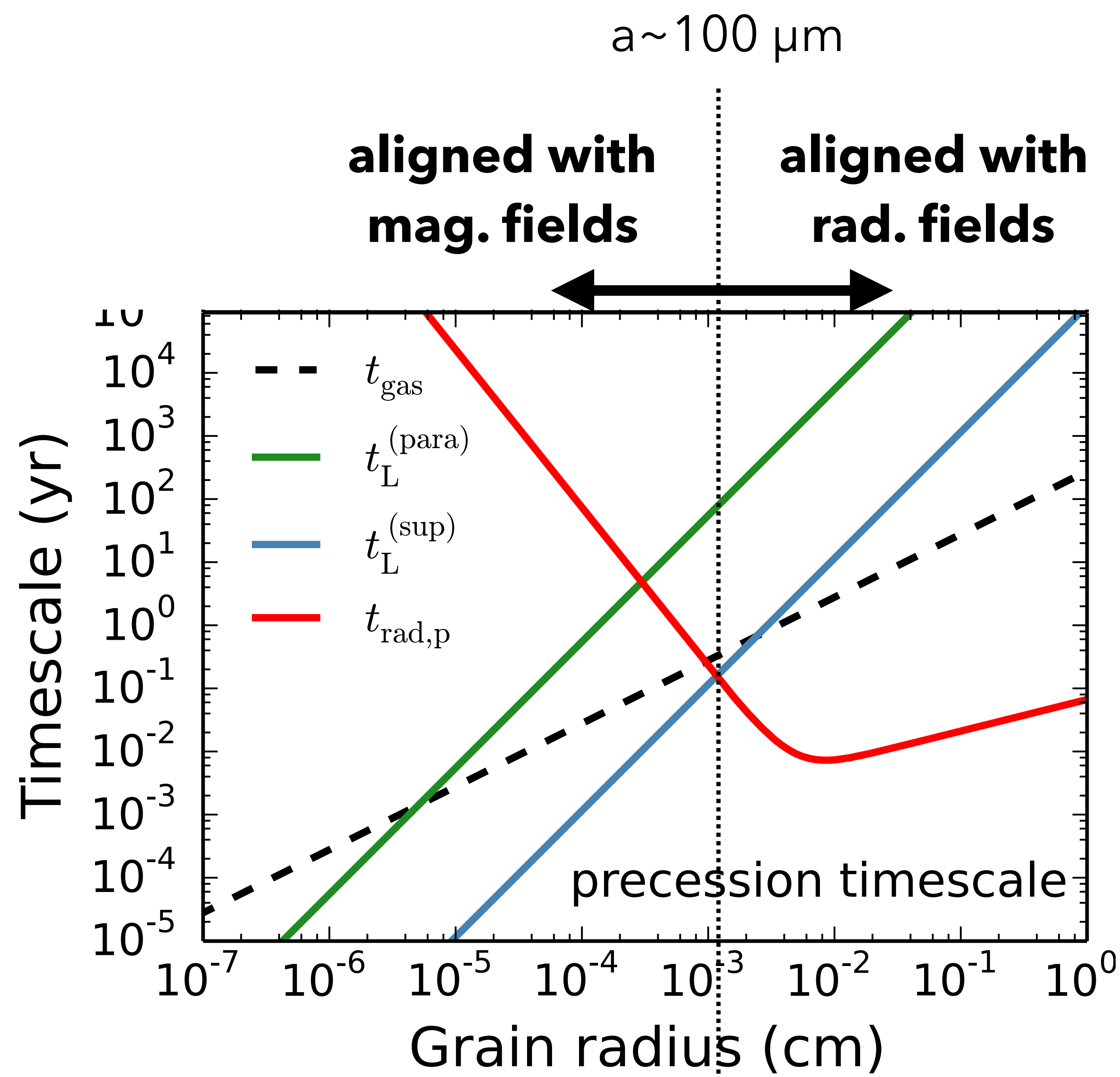


If dust grains have a helicity, they emit intrinsic polarization.

Tazaki, Lazarian et al. 2017

Alignment with radiation fields

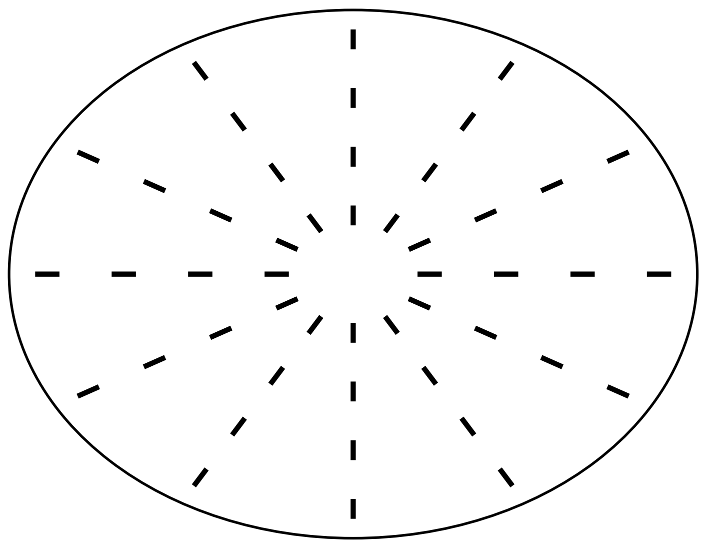




Tazaki, Lazarian et al. 2017 (see also Lazarian and Hoang 2007)

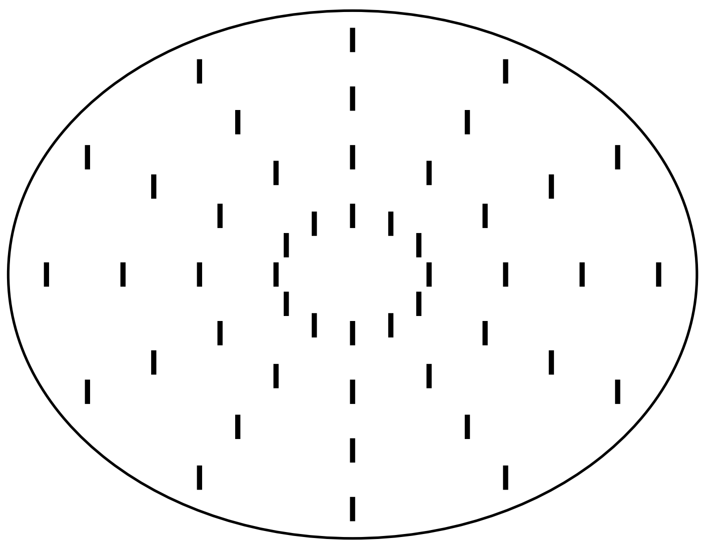
Polarization mechanisms

alignment with B-fields



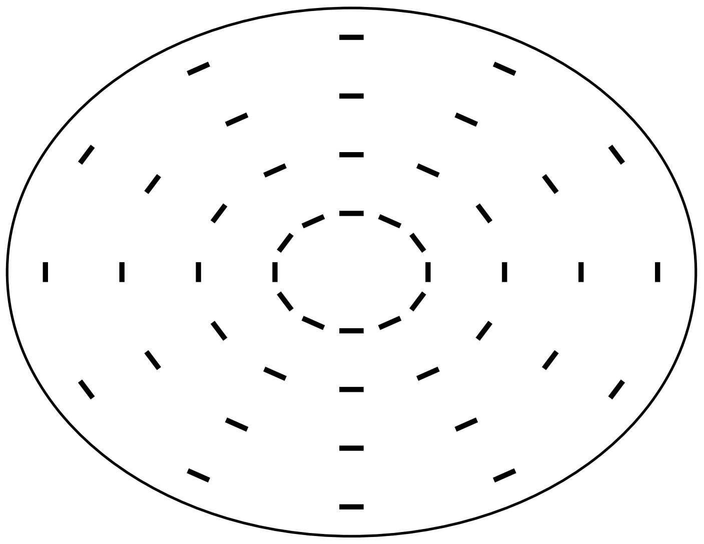
- Toroidal magnetic fields are assumed

self-scattering



- Inclination-induced scattering -> parallel to the minor axis
- Grain size is a ~λ/2π: strong wavelength dependence

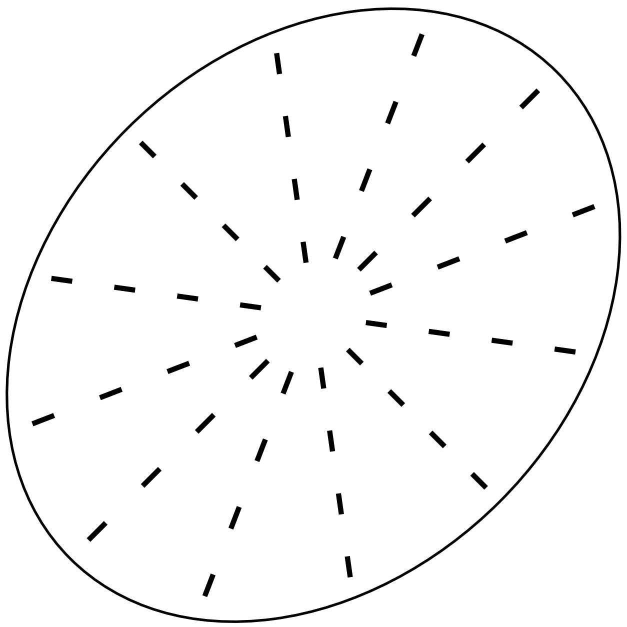
alignment with radiation



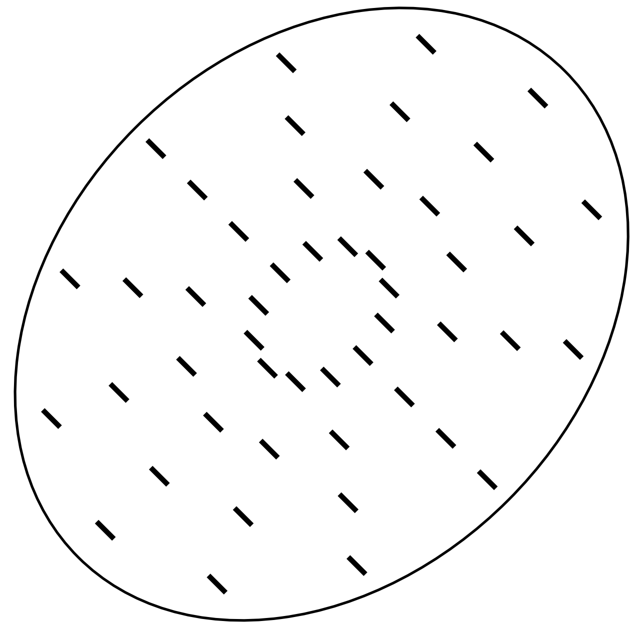
- Grains are needed to be big (~>100um)
- Radiation gradient is in the radial direction.

Polarization mechanisms

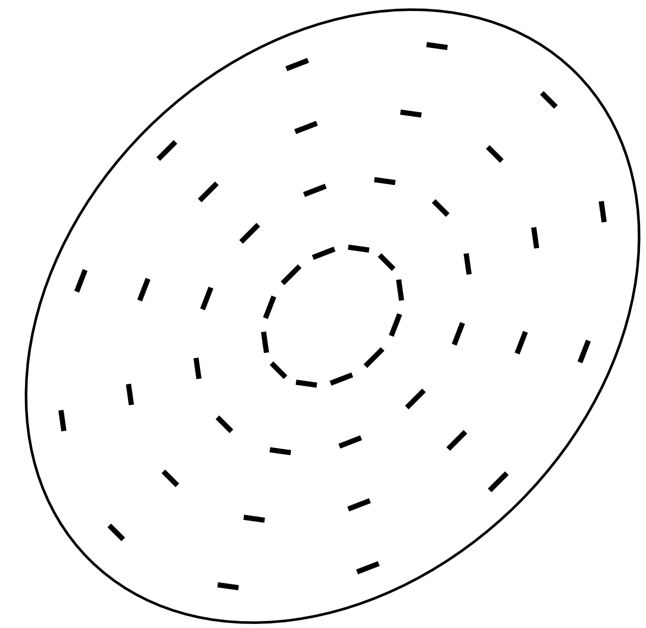
alignment with B-fields

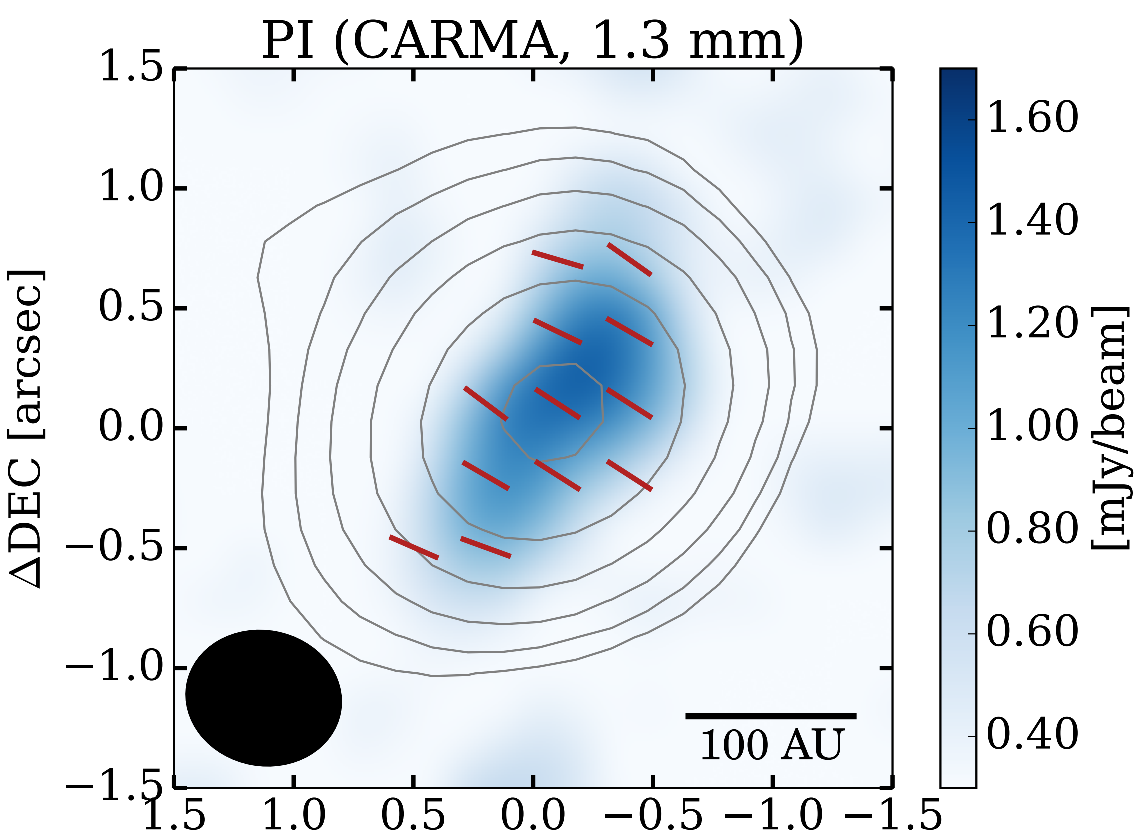


self-scattering

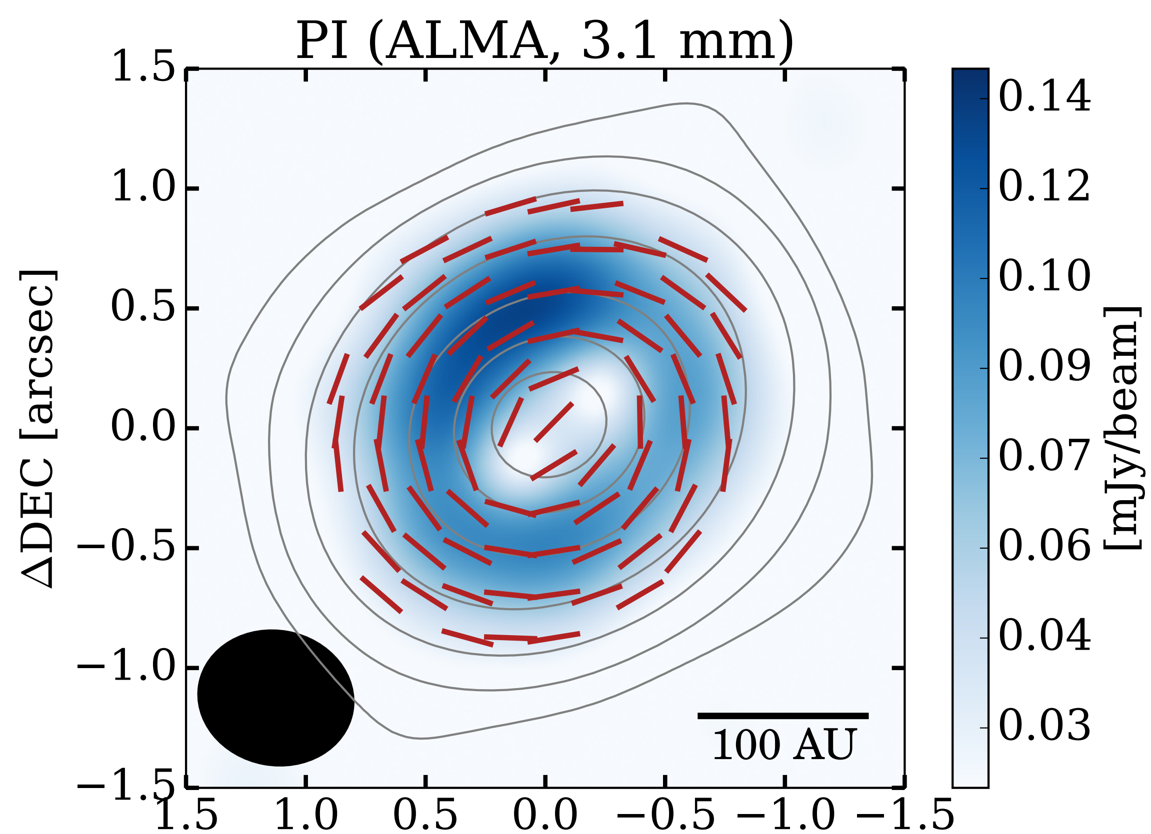


alignment with radiation



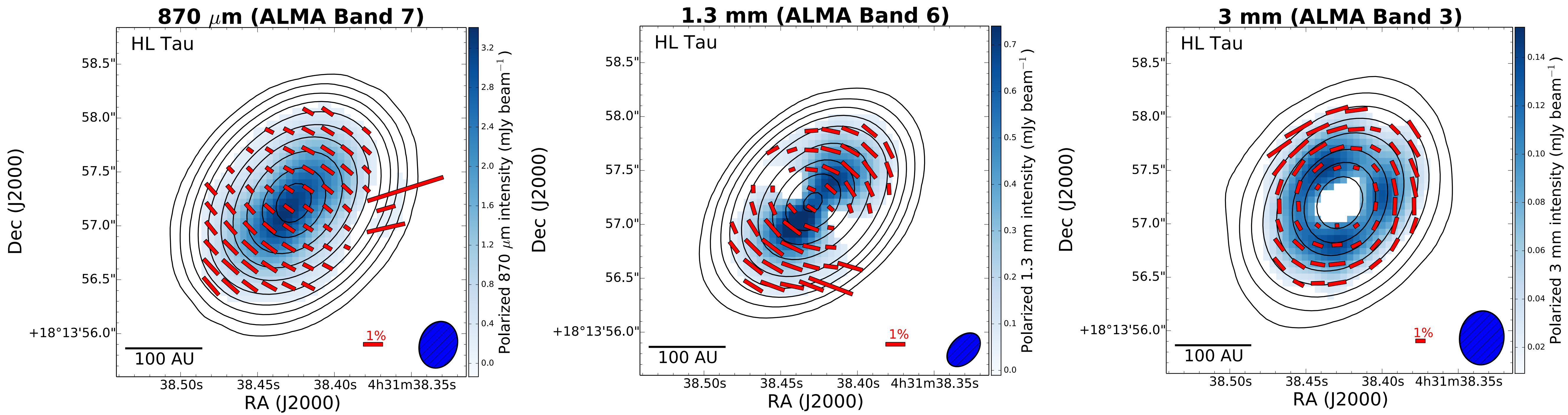


self-scattering



alignment with radiation

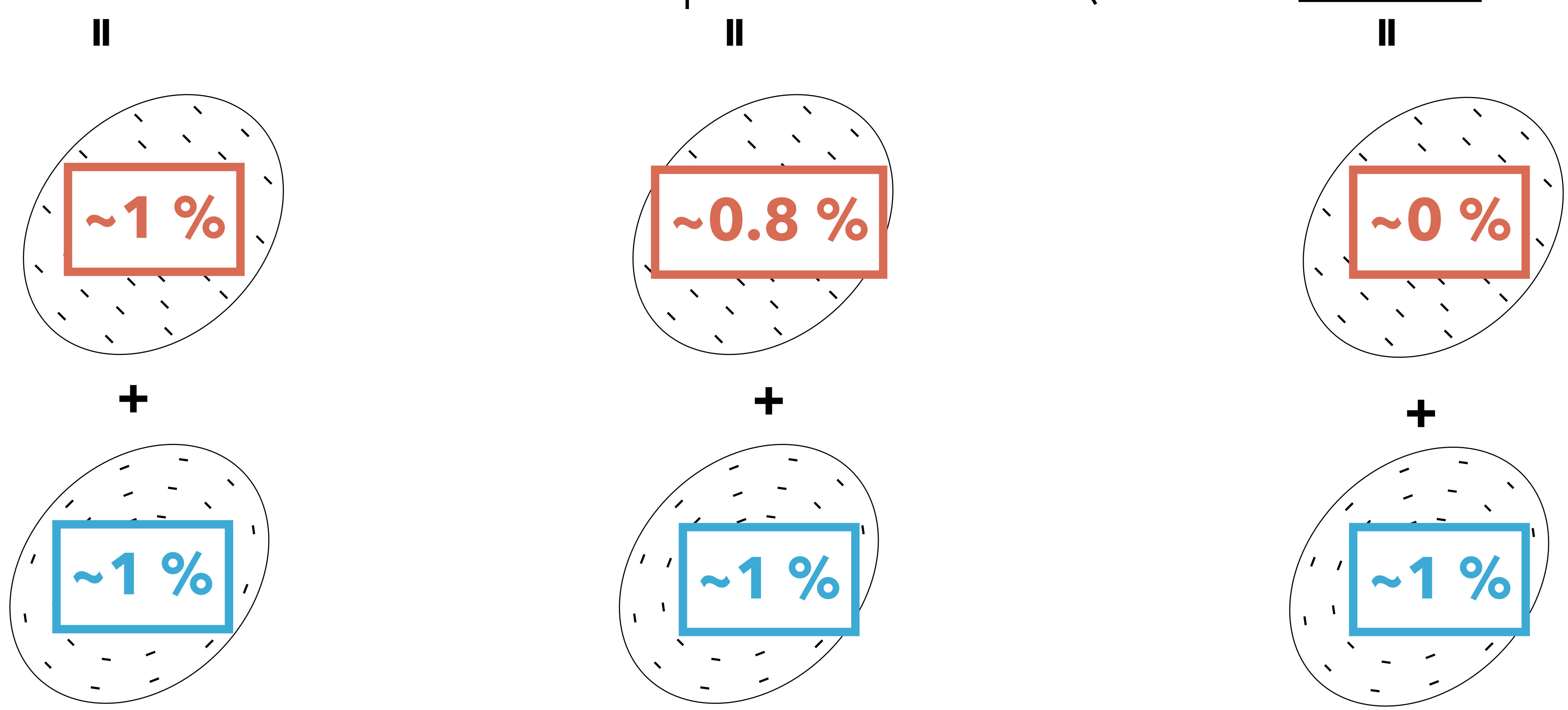
Wavelength dependence



Stephens et al. 2017 (see also Kataoka et al. 2017)

self-scattering

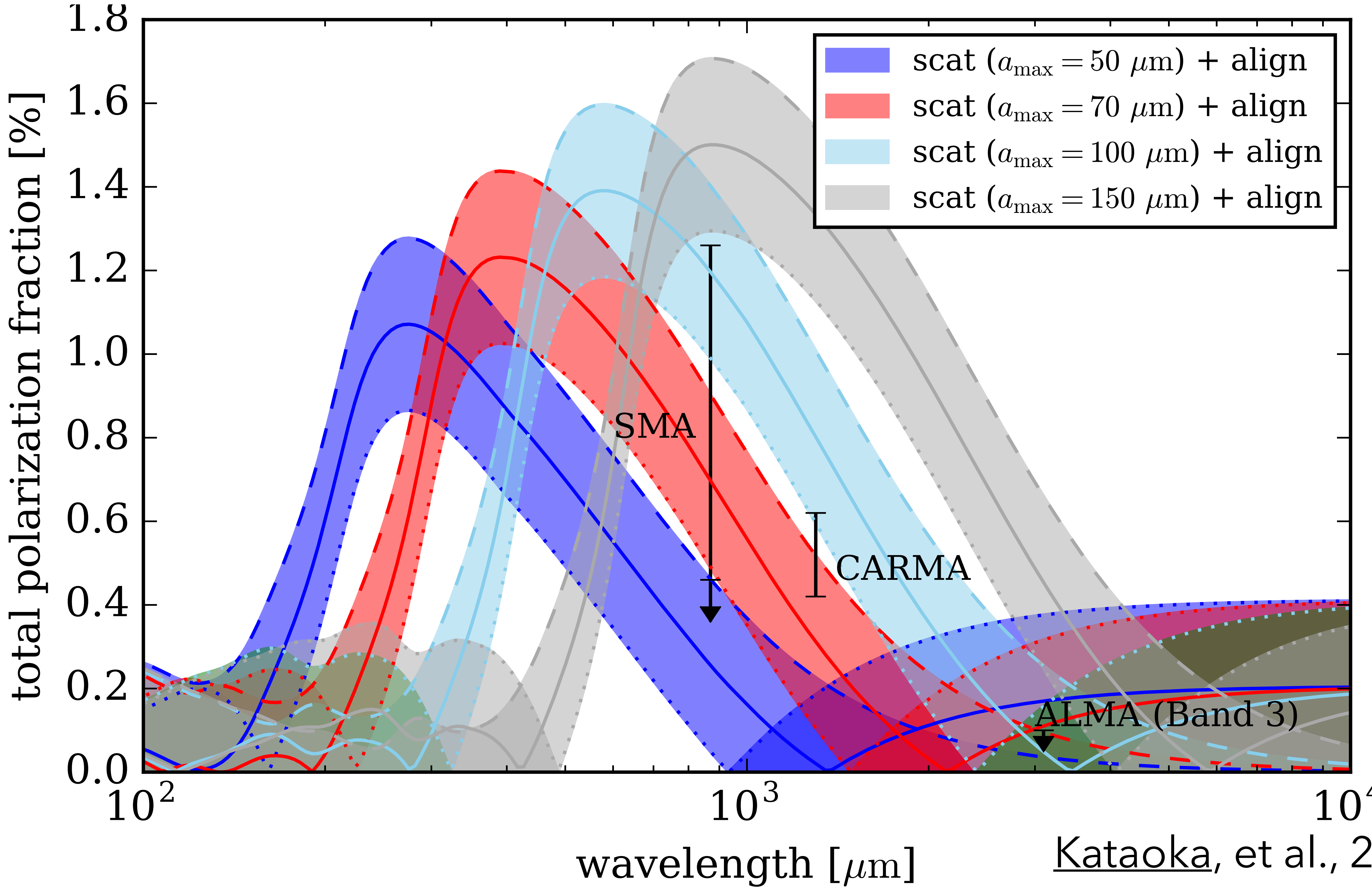
alignment with rad.



*Numbers are based on very rough estimate

Akimasa Kataoka (NAOJ fellow)

HL Tau polarization



Kataoka, et al., 2017

The maximum grain size is ~ 70 µm

Summary

Theories

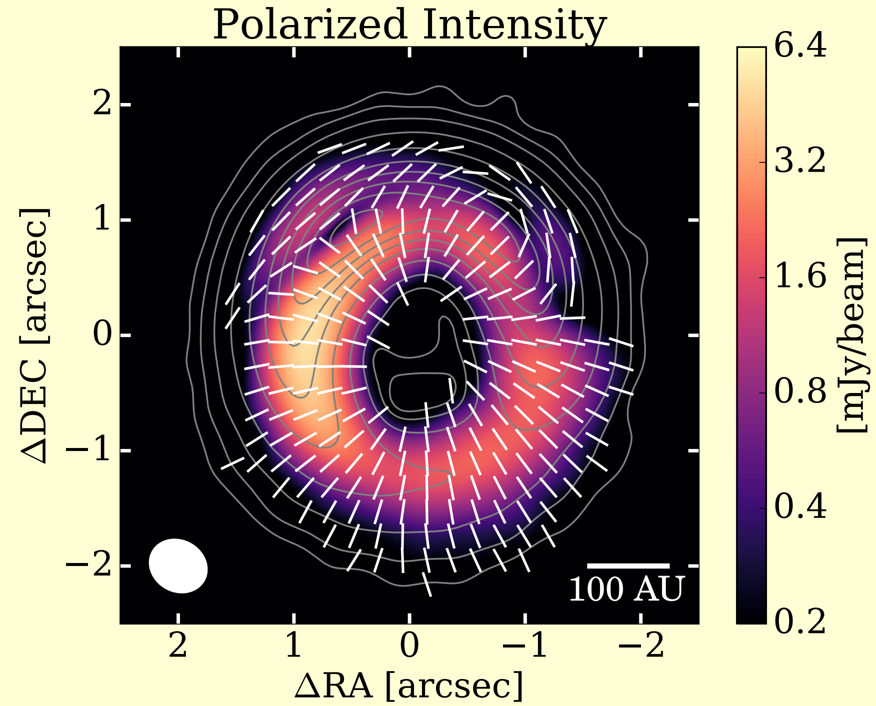
1. **Alignment with (toroidal) magnetic fields.**
2. **Self-scattering of thermal dust emission**
3. **Alignment with radiation fields**

Implications to planet formation

if **(2)** self-scattering works, the grain size is ~ λ/(2π)

Observations

- **HD 142527**
  - **2 (+1,3?)**



- **HL Tau 2+3 (1 is ruled out)**