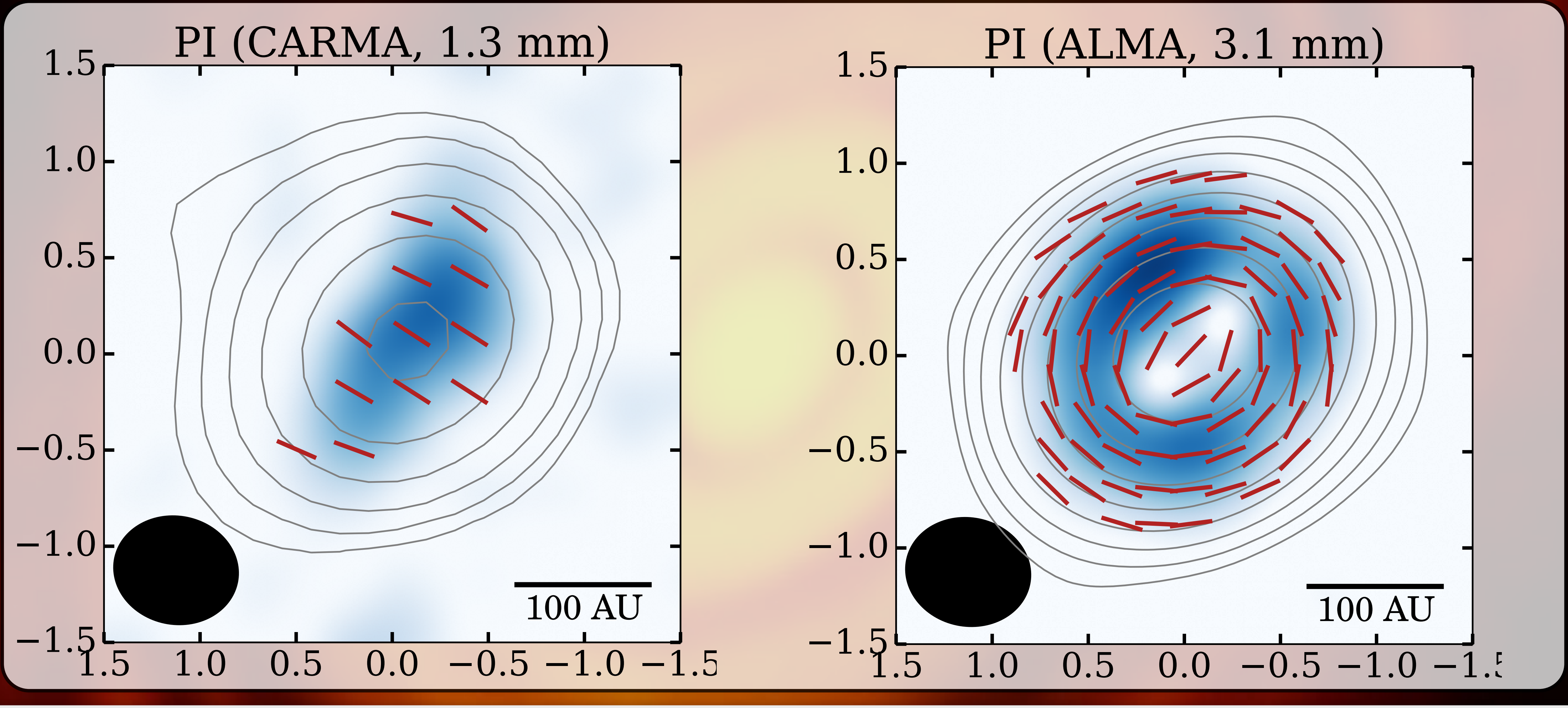
Millimeter-wave polarization as a tool of investigating planet formation

Kataoka et al., accepted in ApJL, arXiv:1707.01612

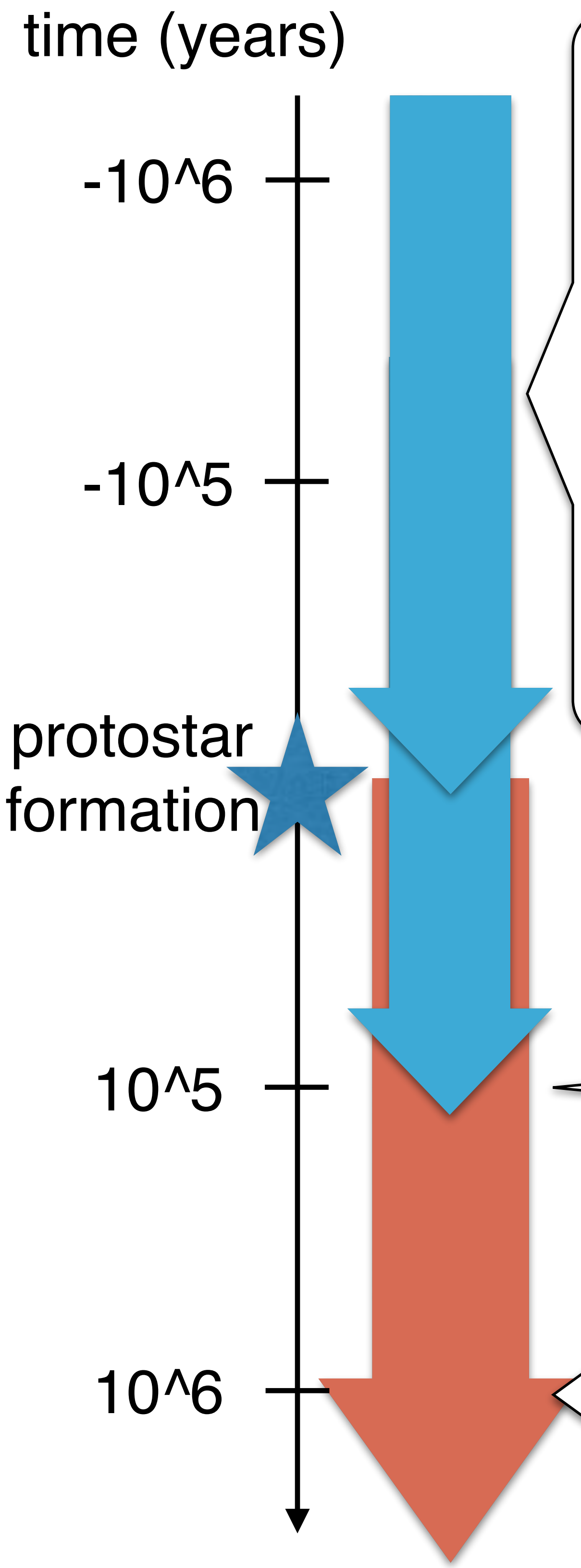


Akimasa Kataoka (NAOJ)

T. Muto (Kogakuin U.), M. Momose, T. Tsukagoshi (Ibaraki U.),

H.Nagai (NAOJ), A. Pohl (MPIA Heidelberg), I. W. Stephens (CfA), Kohji Tomisaka (NAOJ)

Star and disk formation



time (years)

-10^6

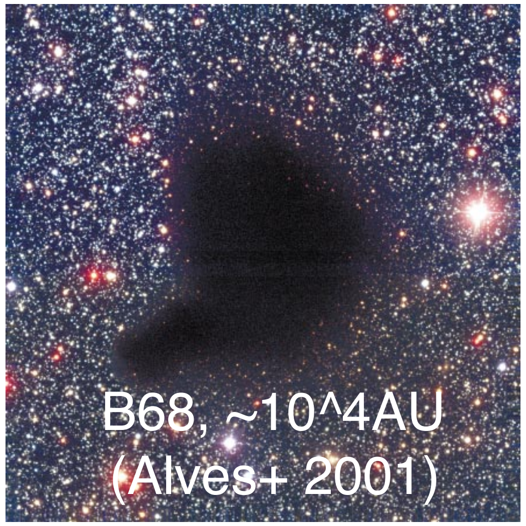
-10^5

protostar formation

10^5

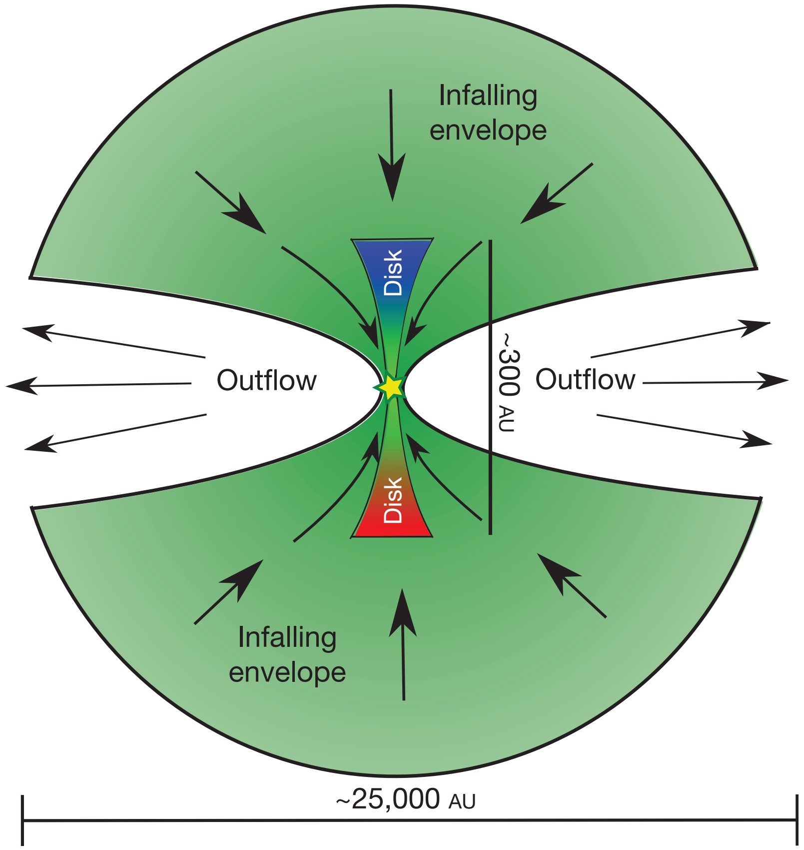
10^6

molecular cloud core

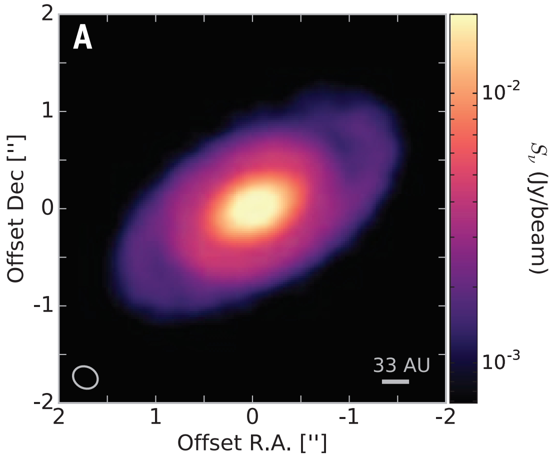


B68, ~10^4AU (Alves+ 2001)

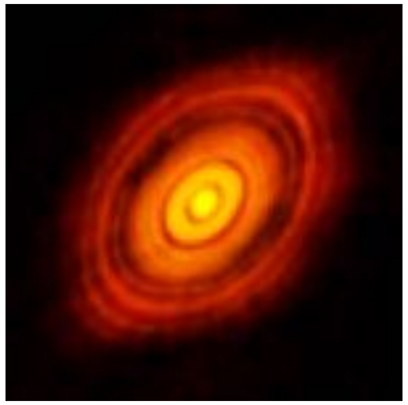
envelope + disk



L1527, envelope:10^4 AU, disk:10^2 AU (Tobin+ 2012)



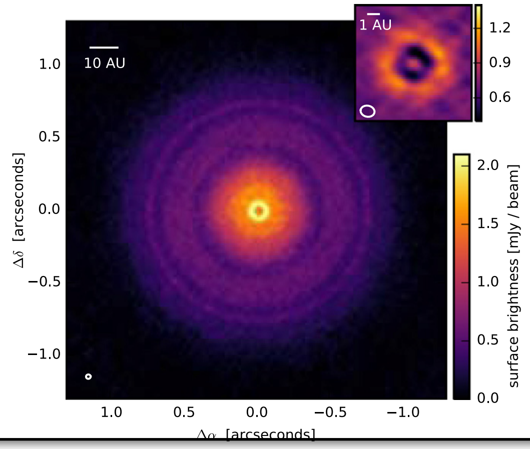
Elias 2-24 (Perez+ 2016)

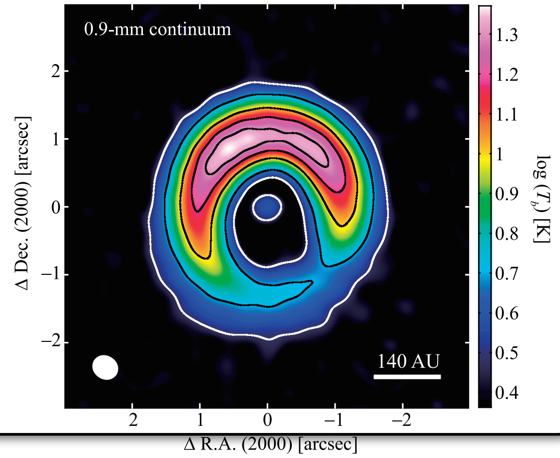


HL Tau (ALMA+ 2015)

protoplanetary disks

e.g., TW Hya (Andrews+ 2016)
HD 142527 (Fukagawa+ 2013)





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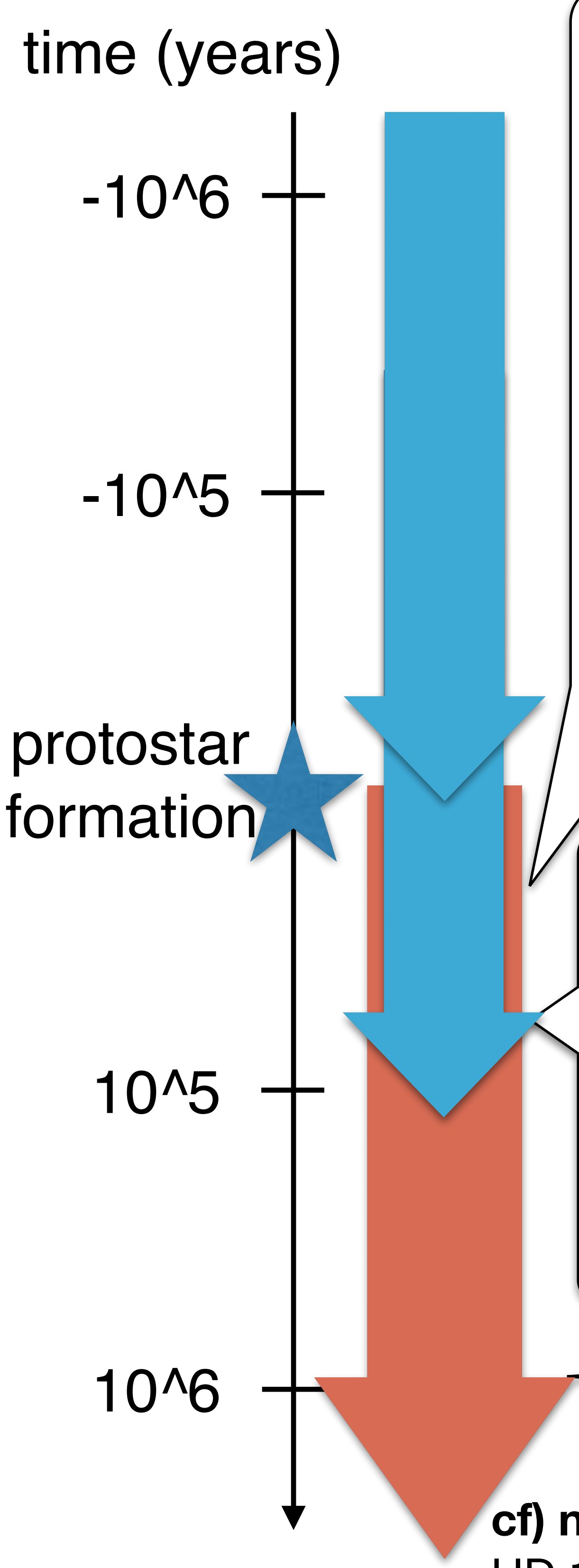
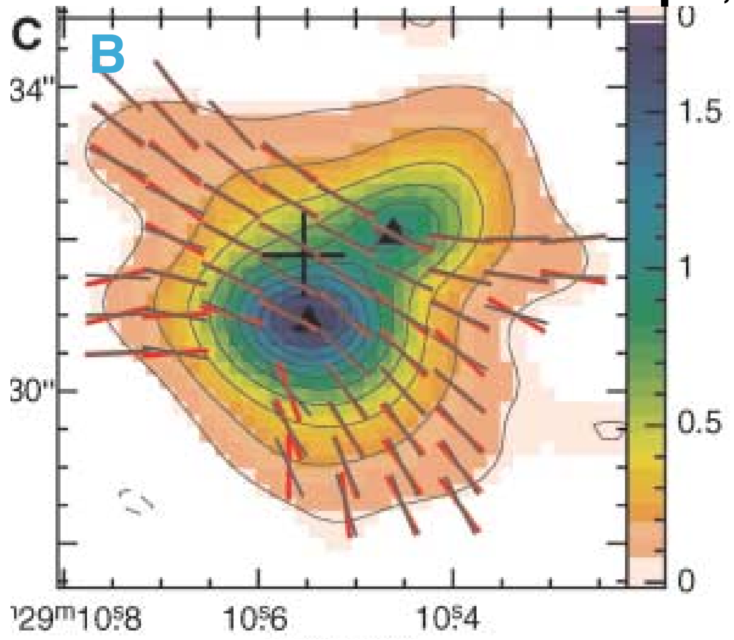
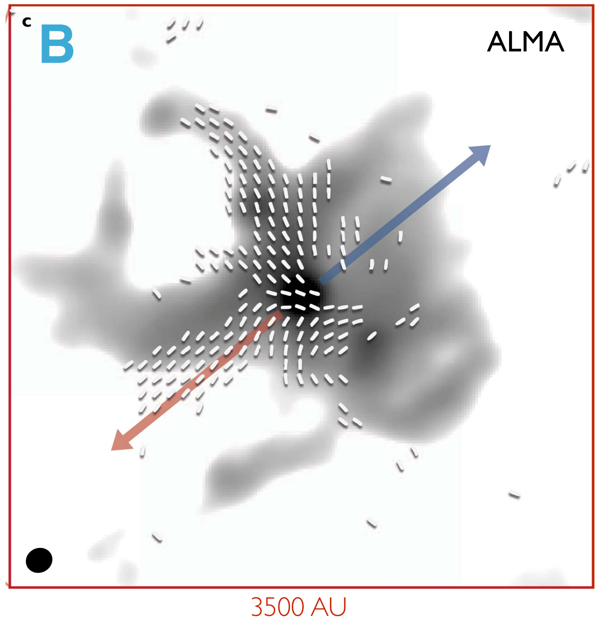
Polarization of star-disk system



Envelope, ~10^4 AU

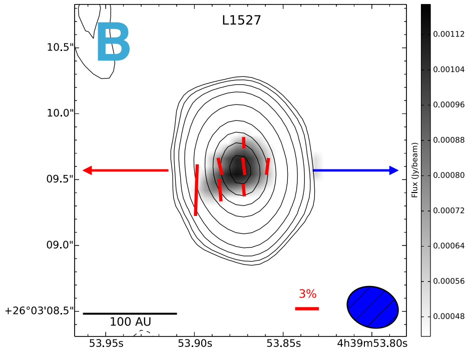


IRAS 4A(Girart et al. 2006)



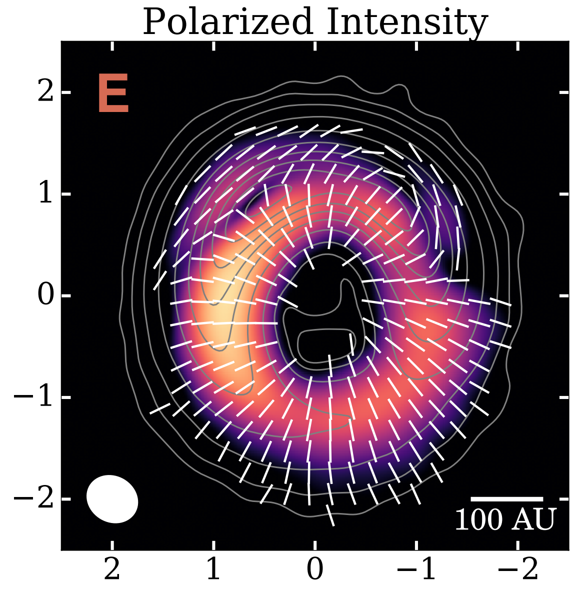
Ser-emb 8 (Hull et al. 2017)

embedded disks, ~10^2 AU

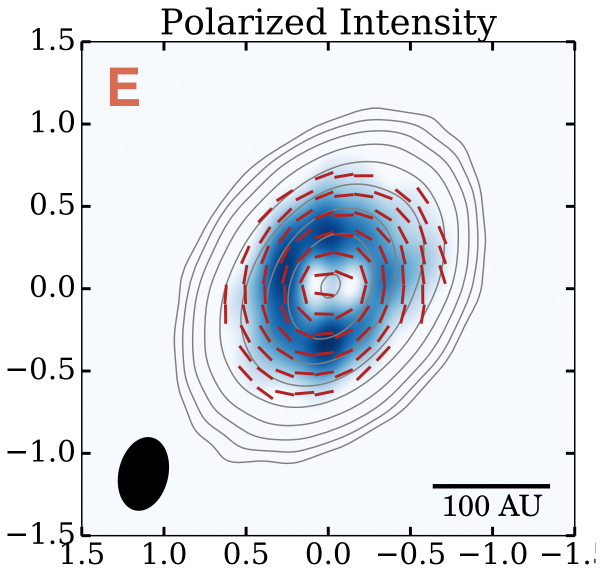


L1527 (Segura-Cox+ 2015)

protoplanetary disks, ~10^2 AU



HD 142527
(Kataoka et al. 2016b)

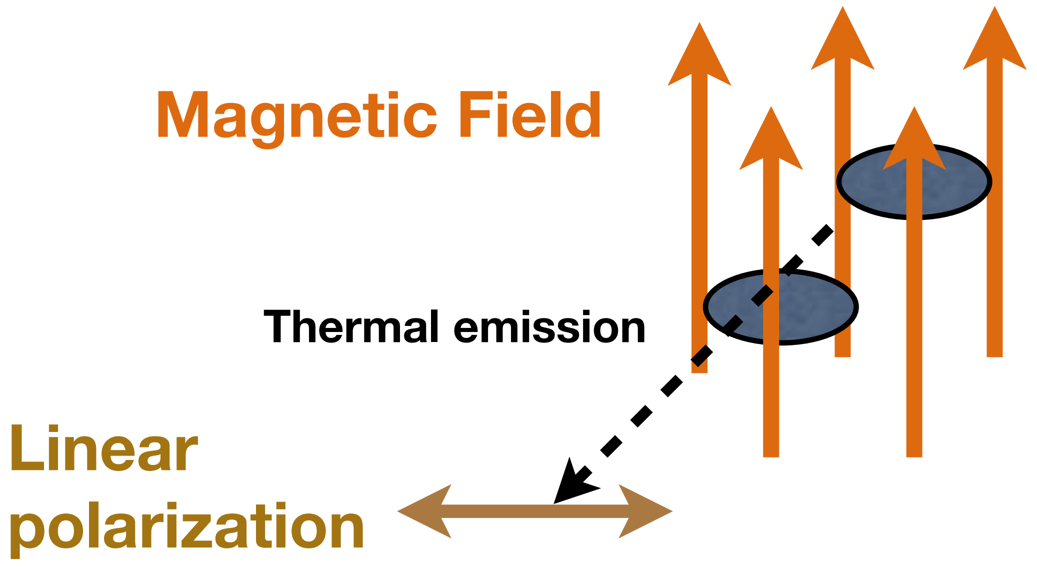


HL Tau
(Kataoka et al. 2017)

cf) non-detection of disks with SMA
HD 163296, TW Hya, GM Aur, DG Tau
(Hughes et al. 2009, 2013)

Polarization mechanisms

- **Alignment of elongated dust grains with magnetic fields**



e.g., Lazarian and Hoang 2007

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

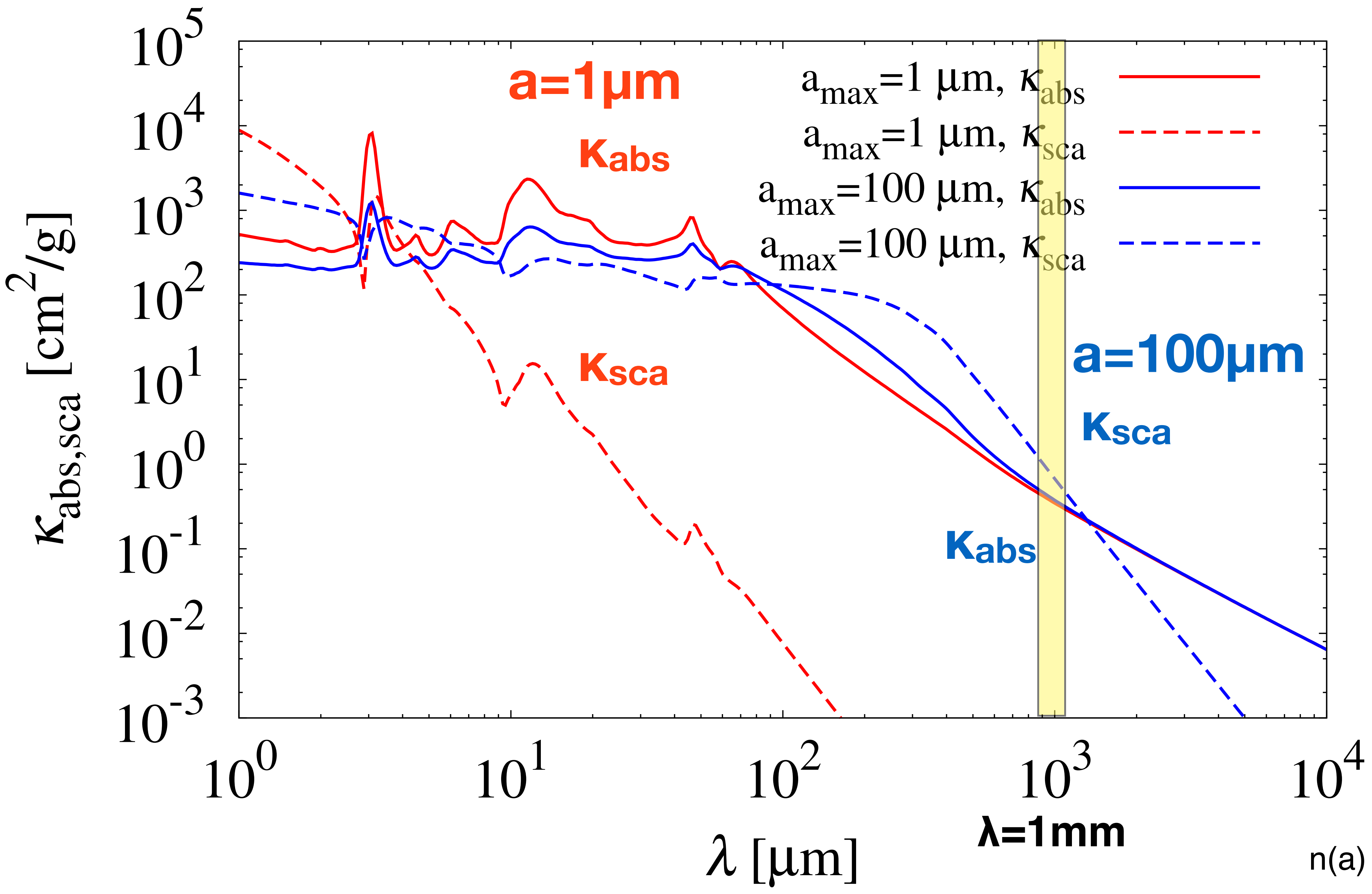
Kataoka et al. 2015

- **Alignment of elongated dust grains with radiation fields**

Tazaki, Lazarian et al. 2017

Absorption and scattering opacities

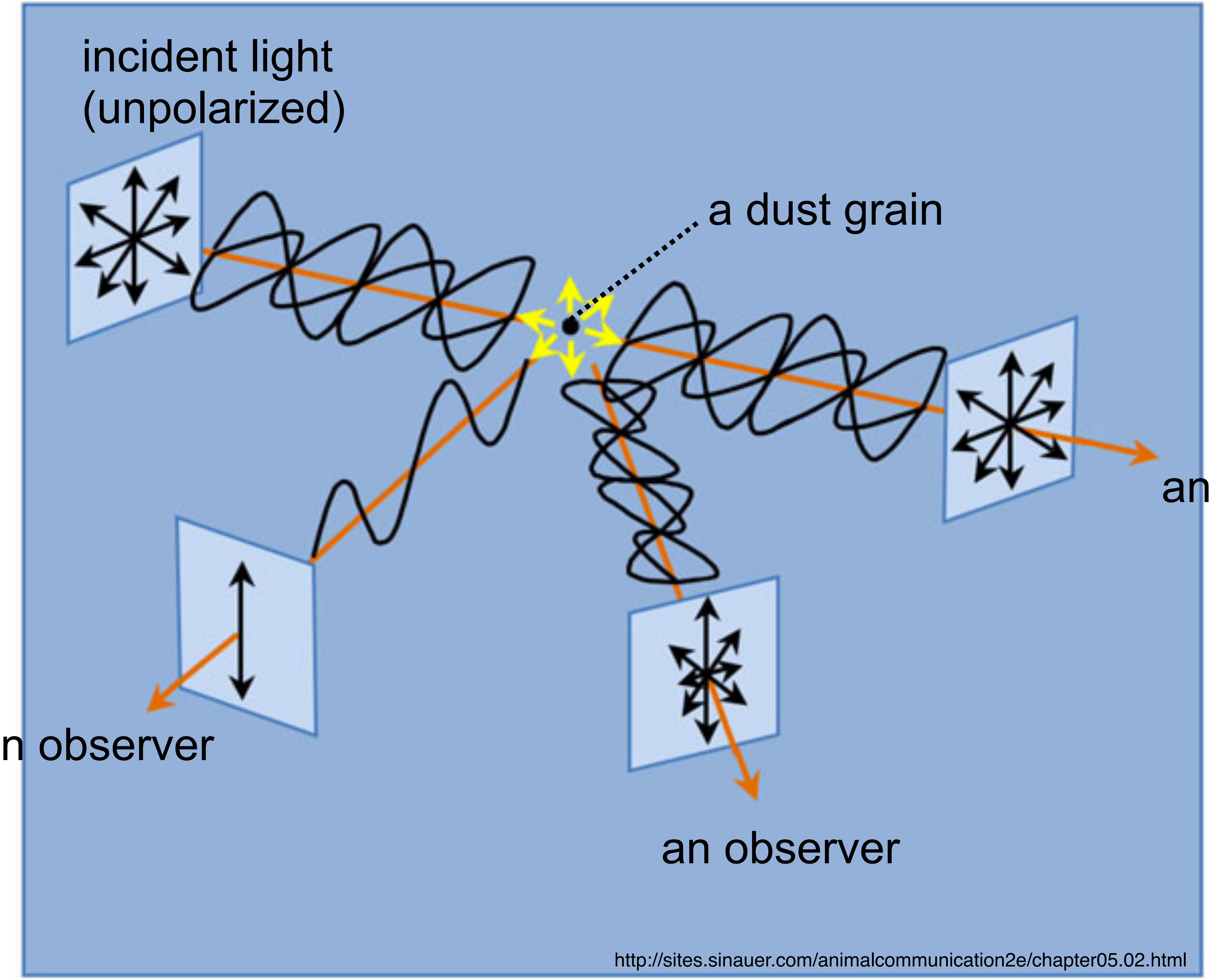
Grain opacity



$n(a) \propto a^{-3.5}$

Scattering of large dust grains can not be ignored.

Polarization due to scattering



incident light
(unpolarized)

a dust grain

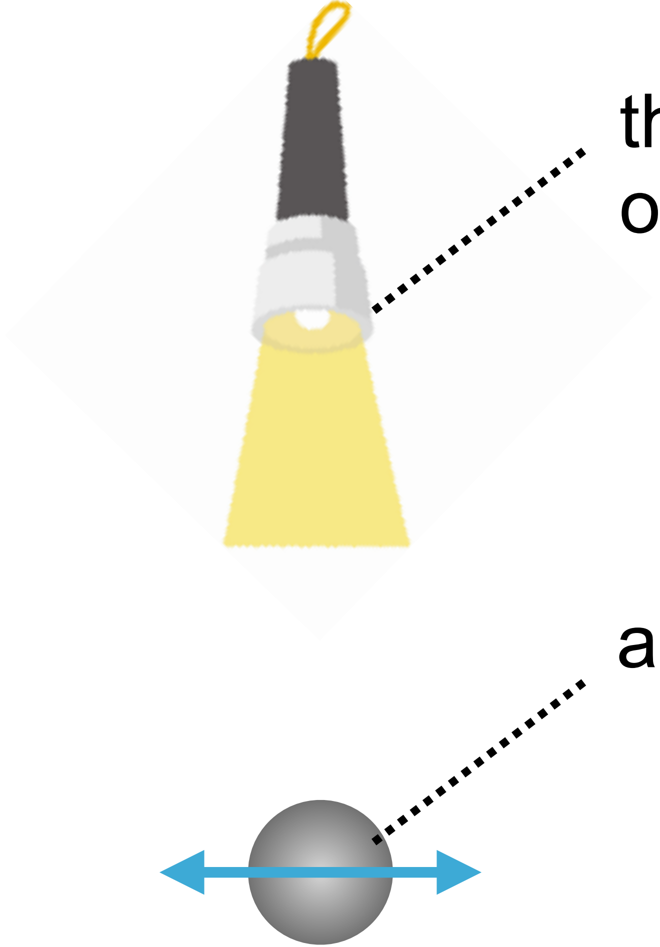
an observer

an observer

an observer

http://sites.sinauer.com/animalcommunication2e/chapter05.02.html

Polarization due to scattering



thermal dust emission
of other dust grains

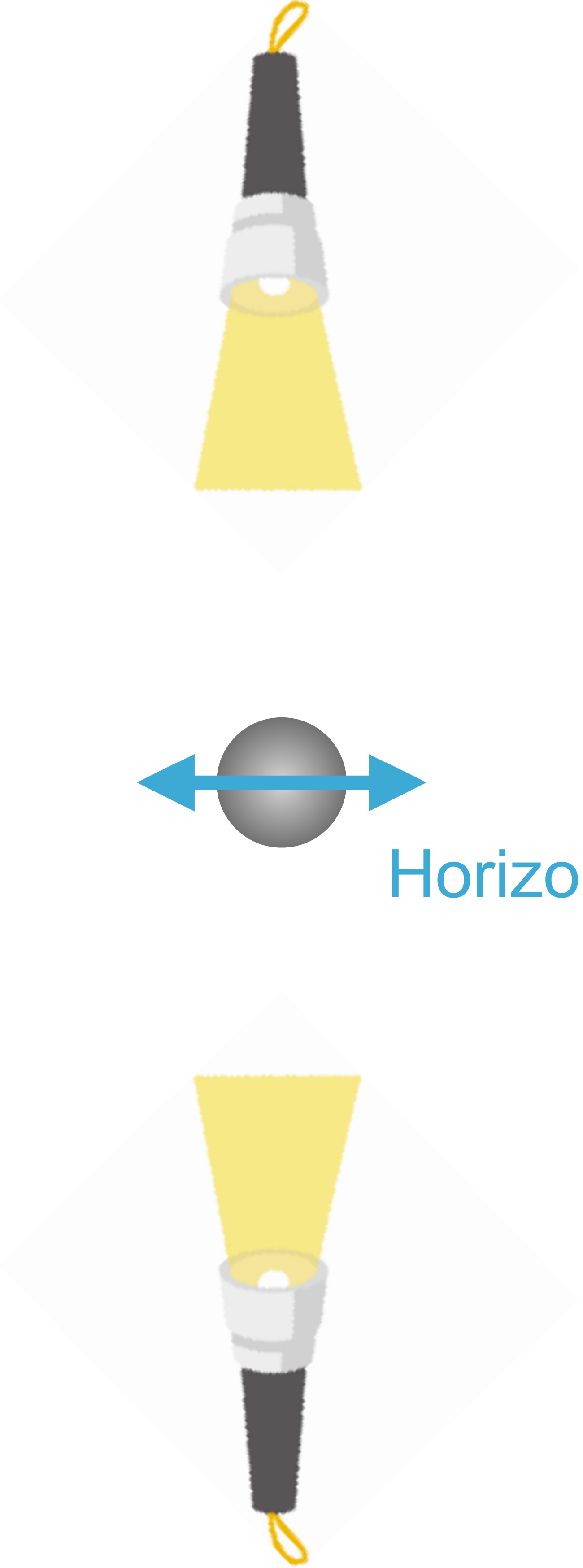
a dust grain

Horizontal Polarization

The observer is you.

(the line of sight is perpendicular to the plane of this slide)

Polarization due to scattering



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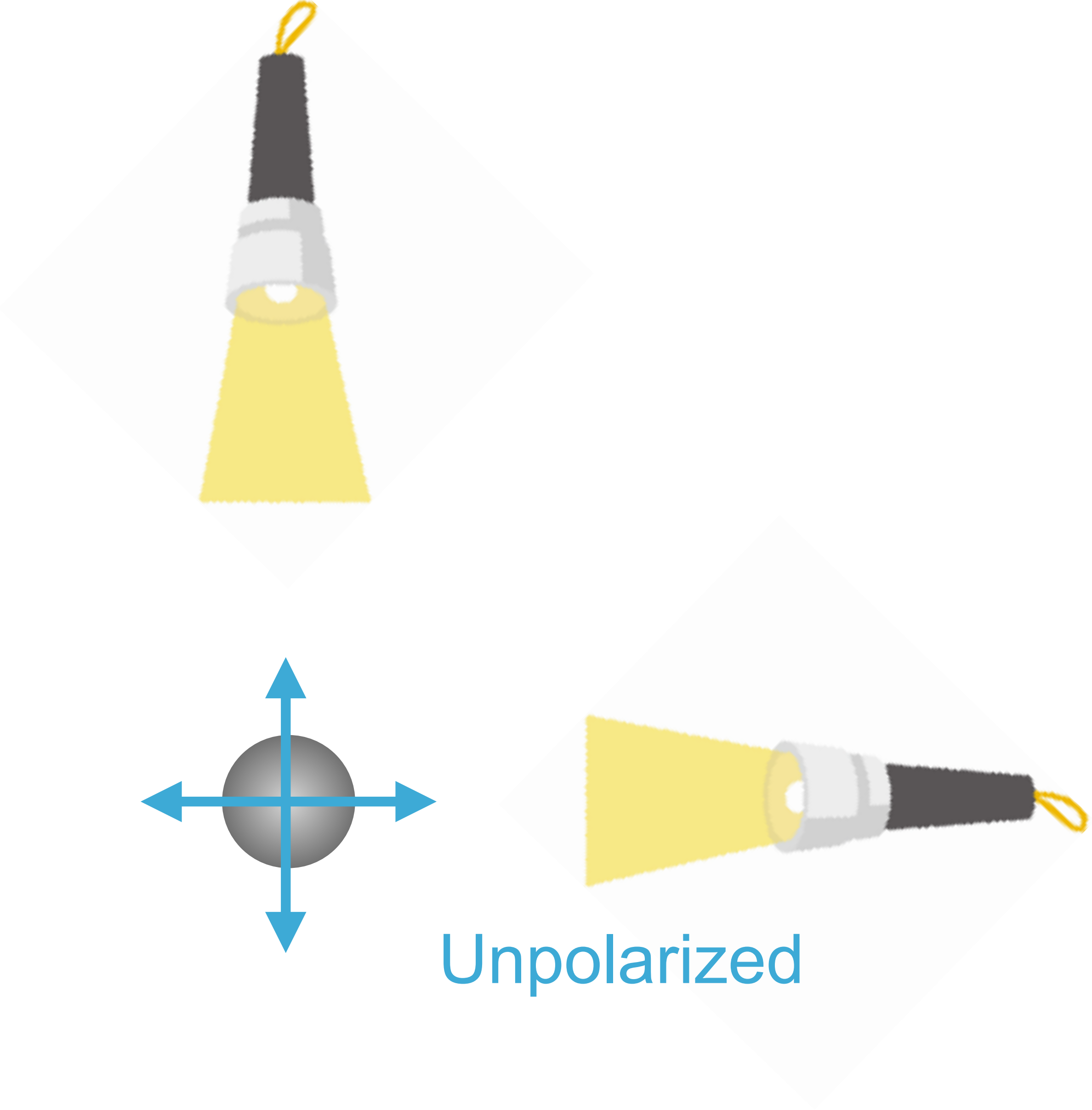
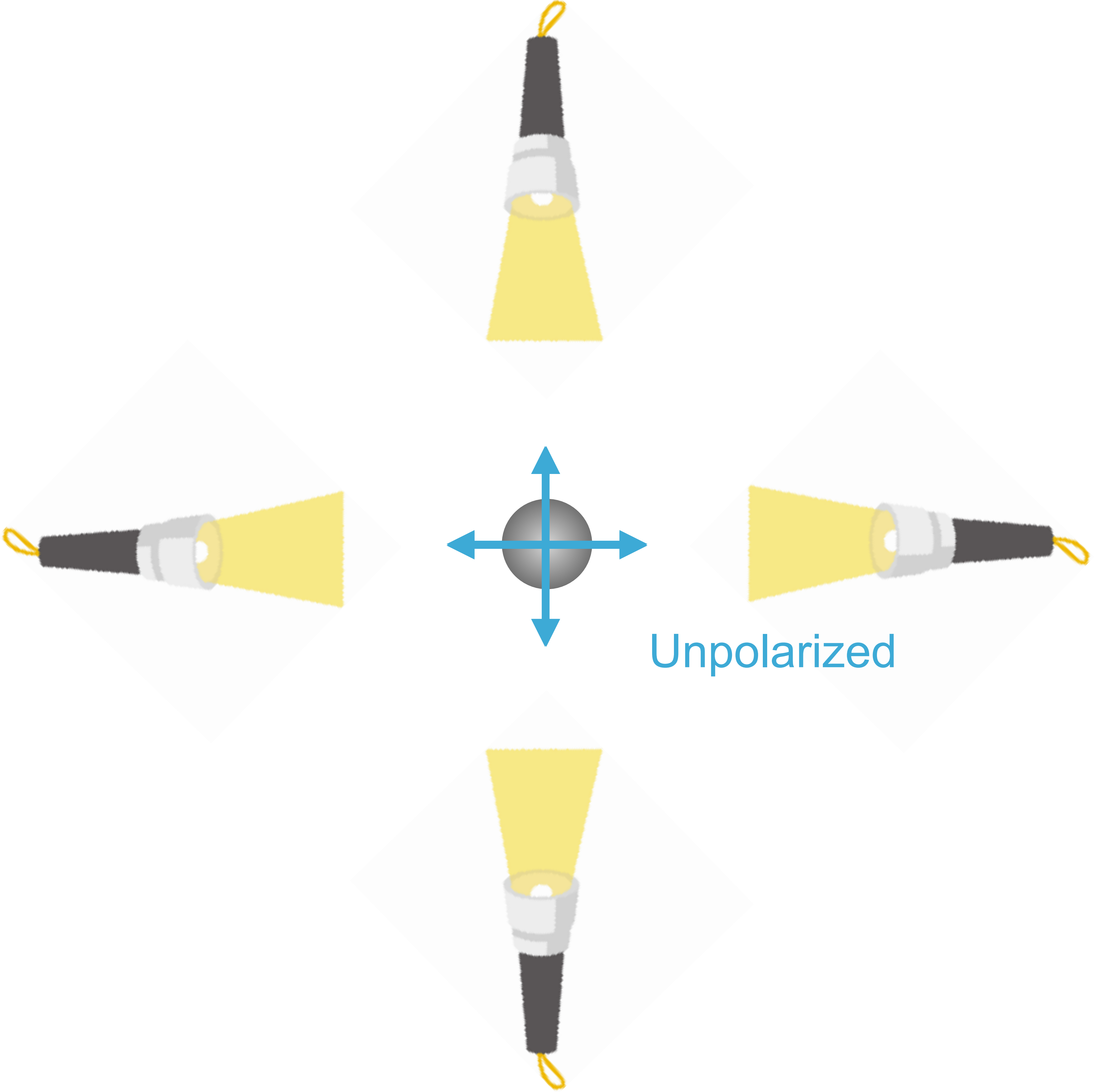
Polarization due to scattering



Polarization due to scattering



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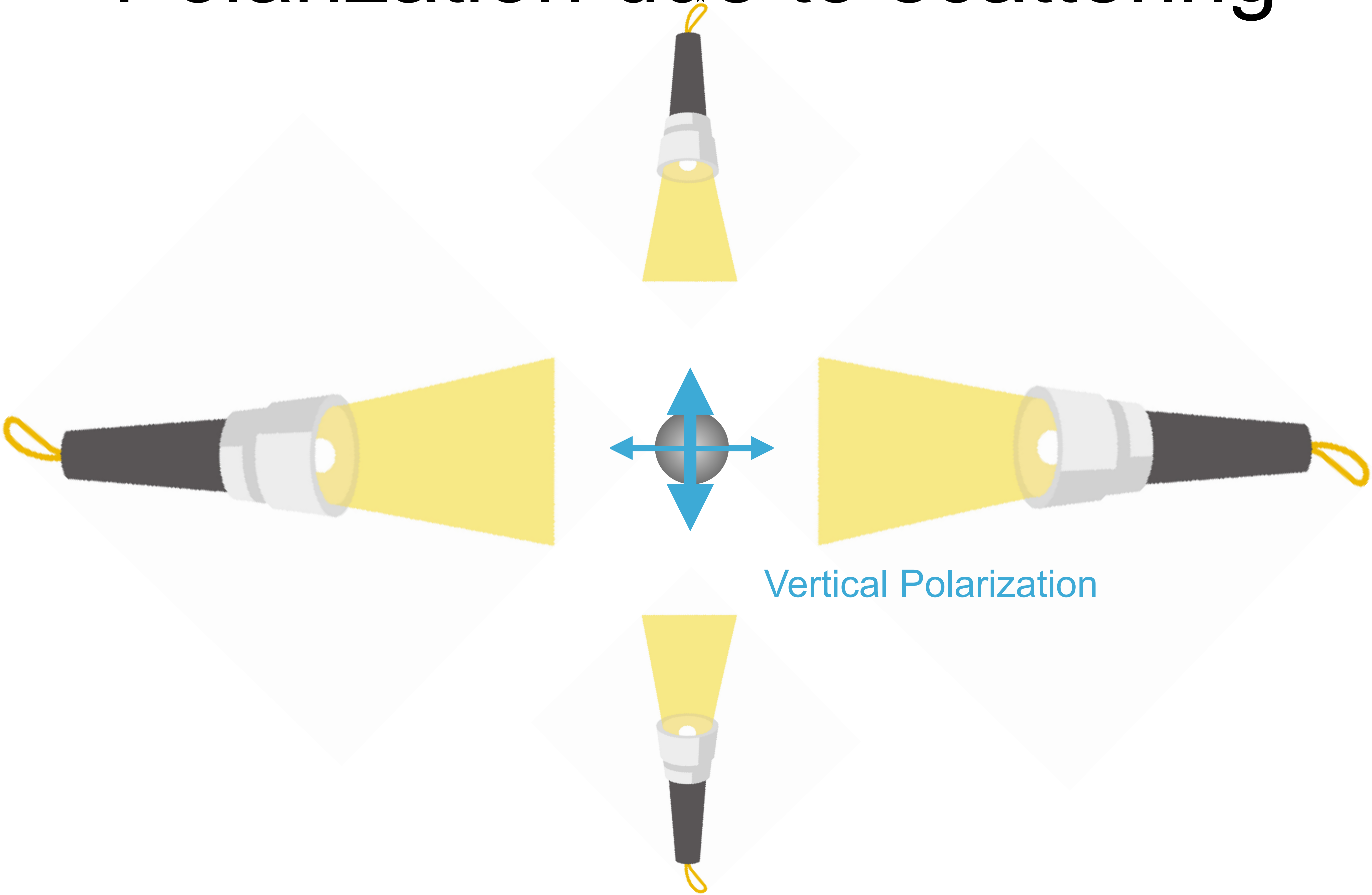
Polarization due to scattering



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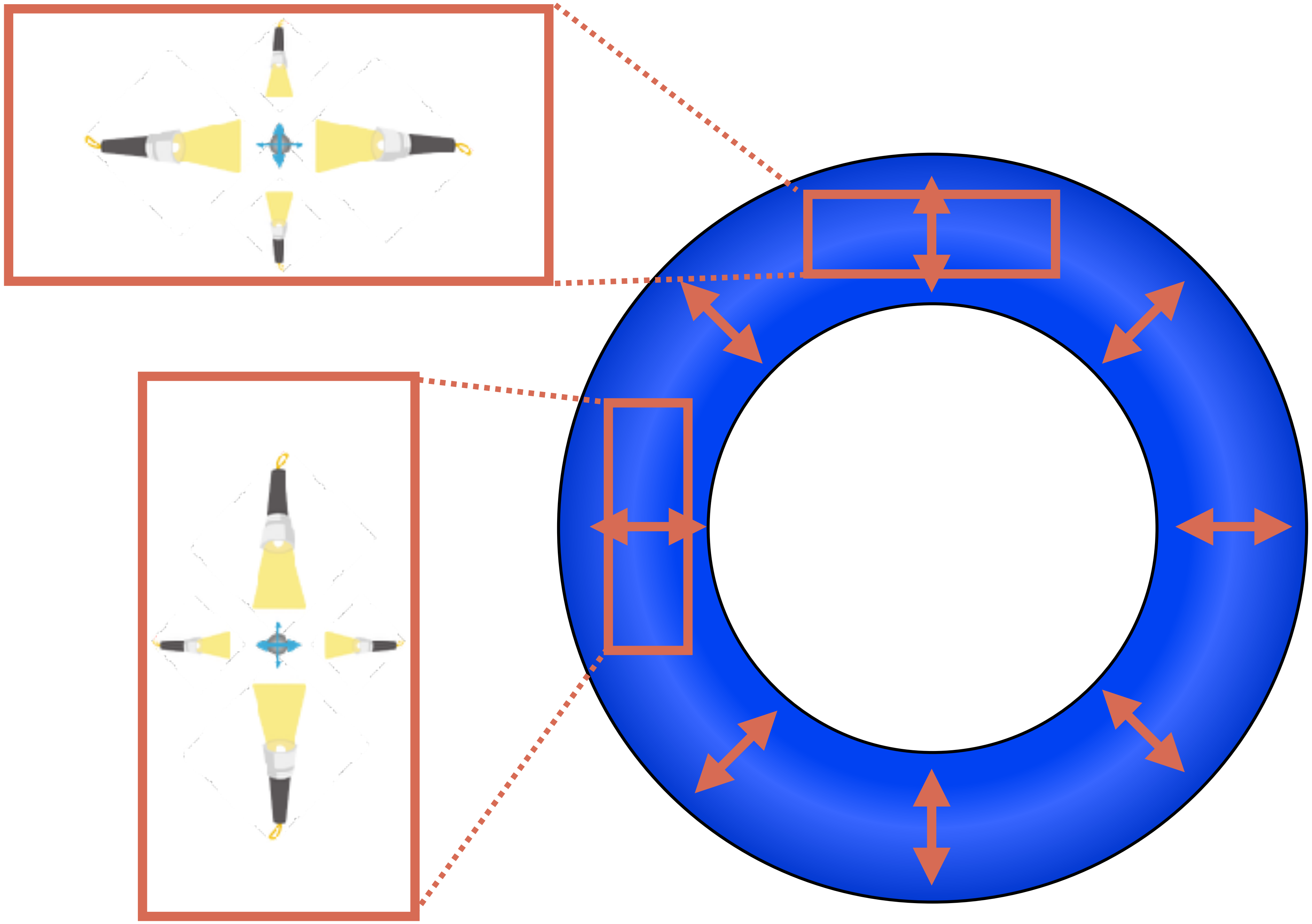
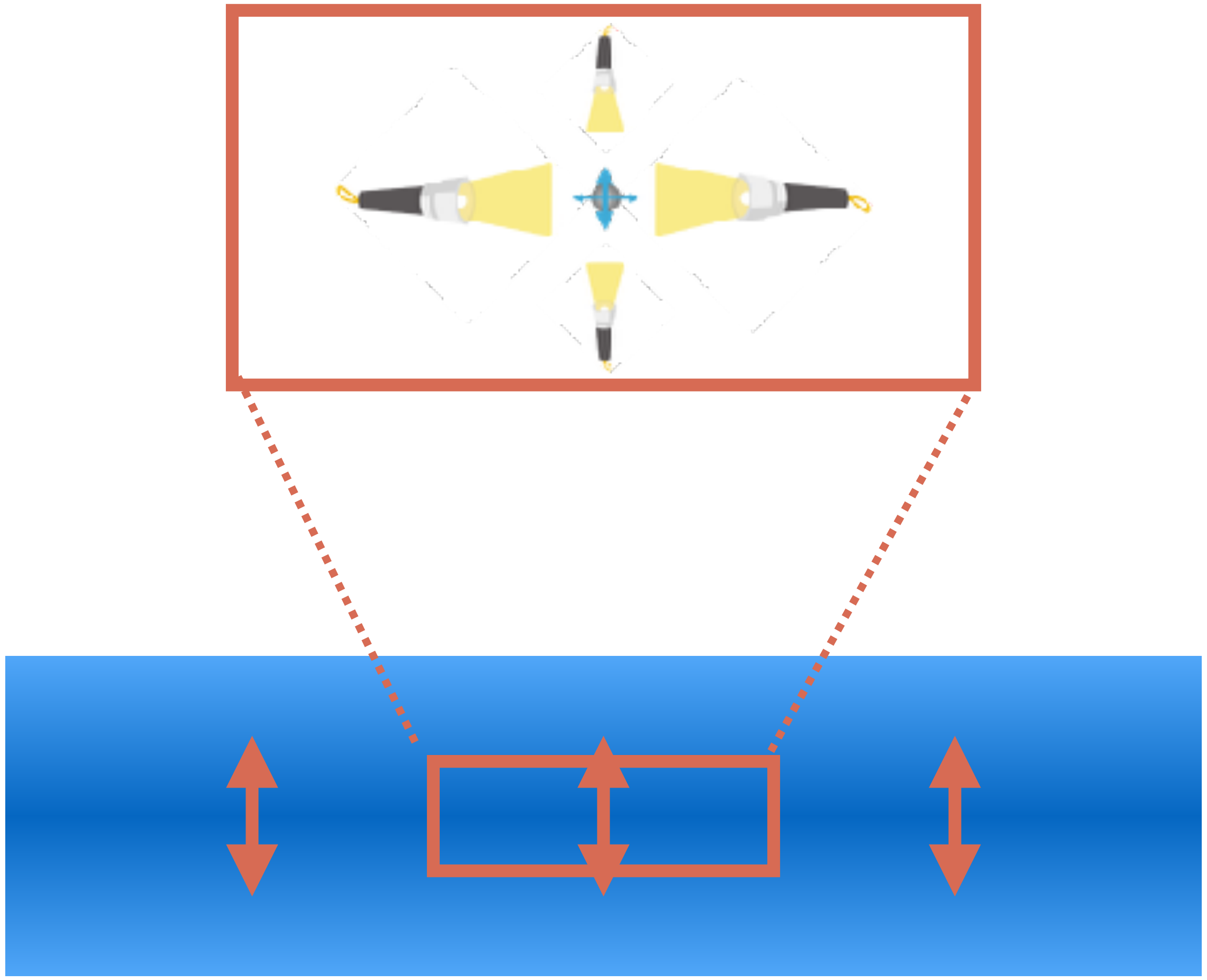
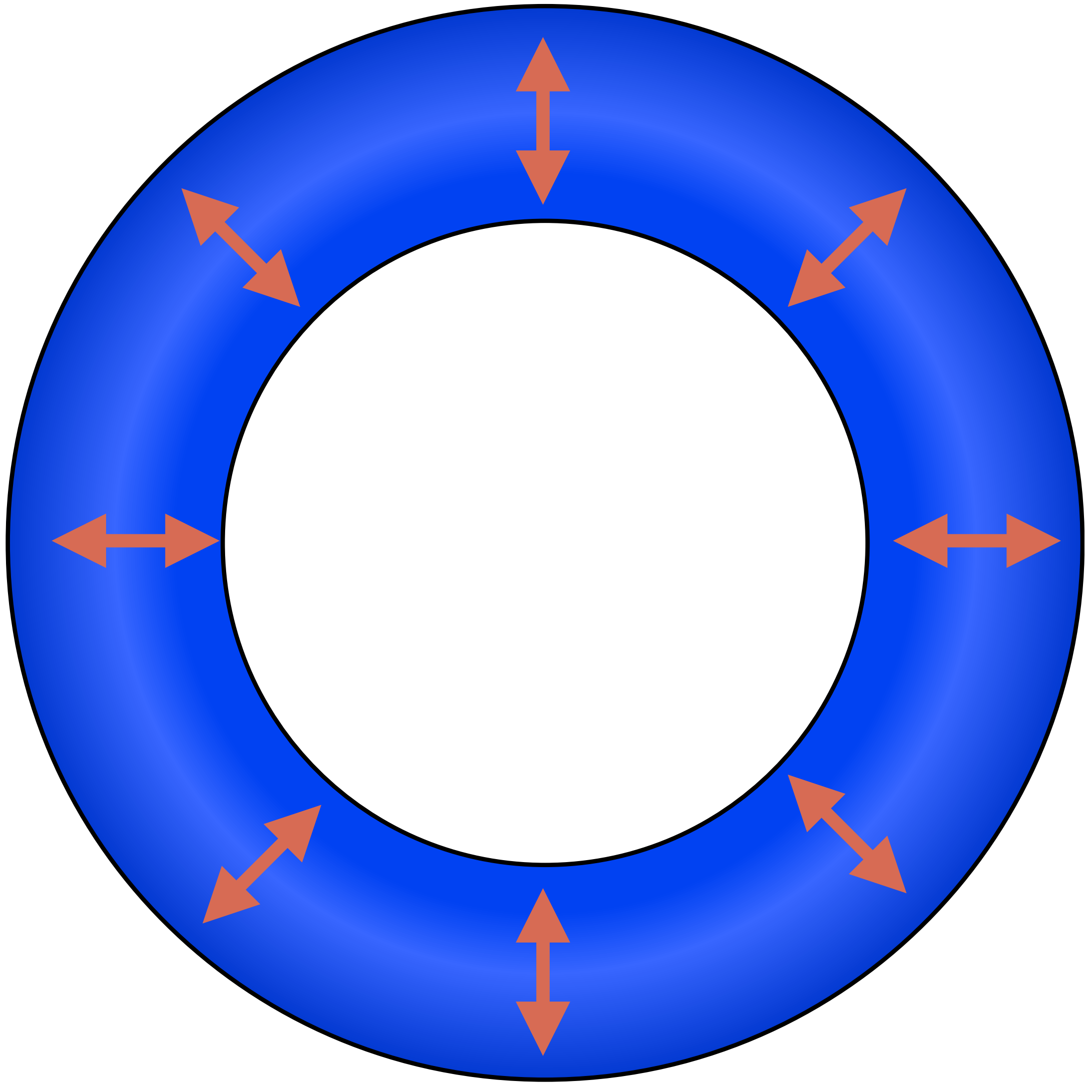
self-scattering in a face-on disk



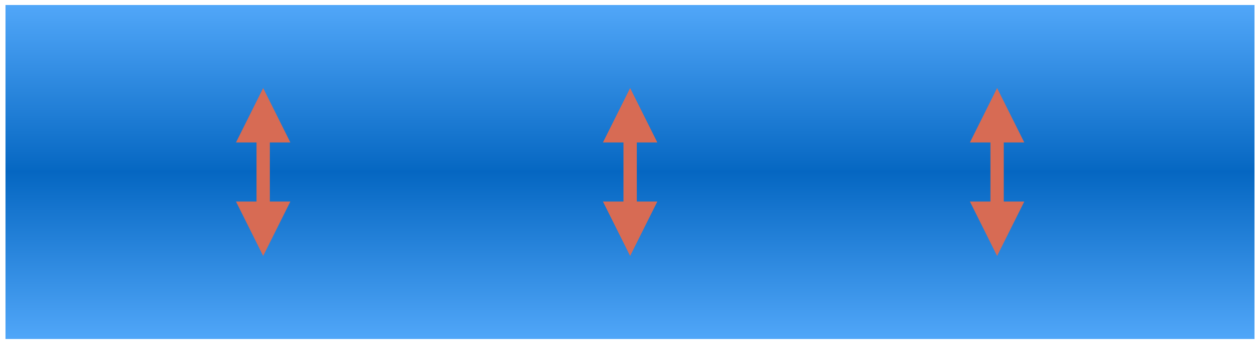
self-scattering in an edge-on disk



self-scattering in an inclined disk?

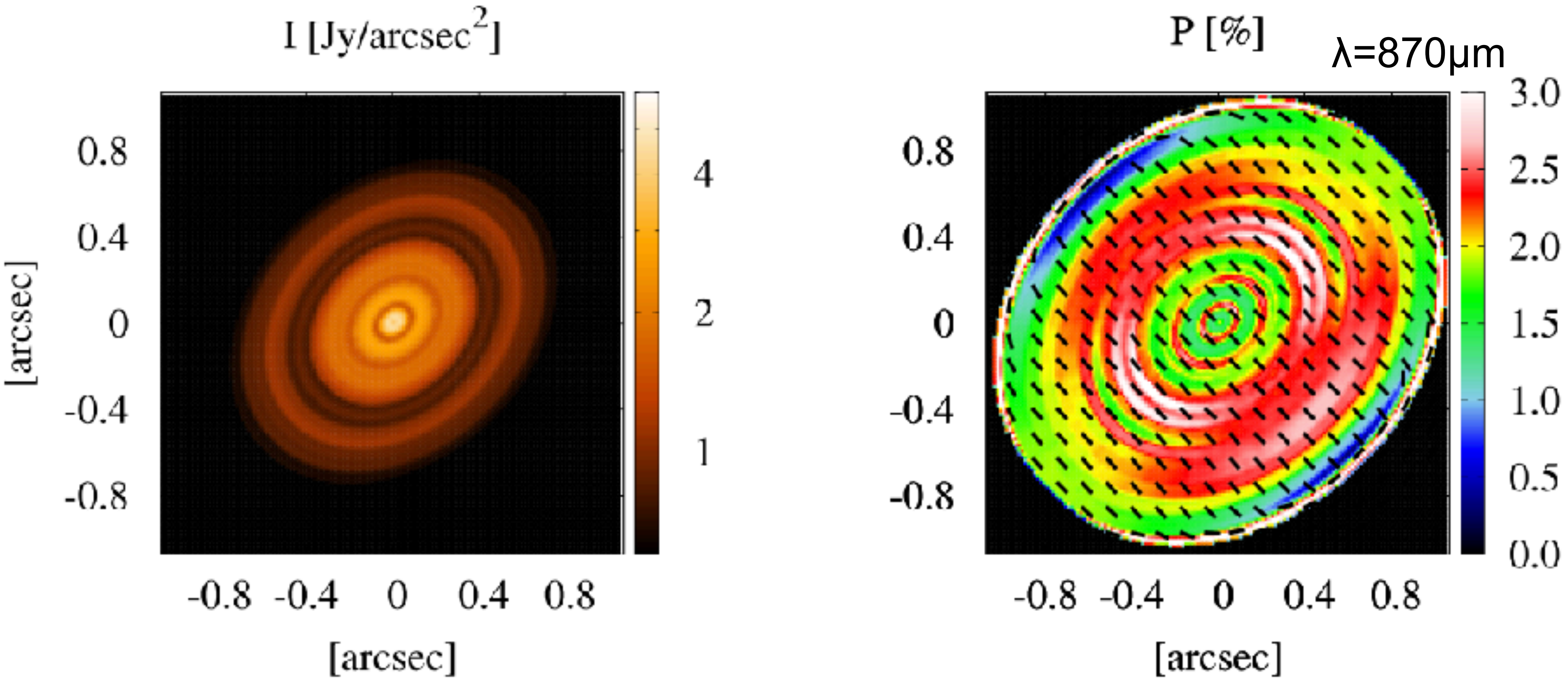


face-on like?



edge-on like?

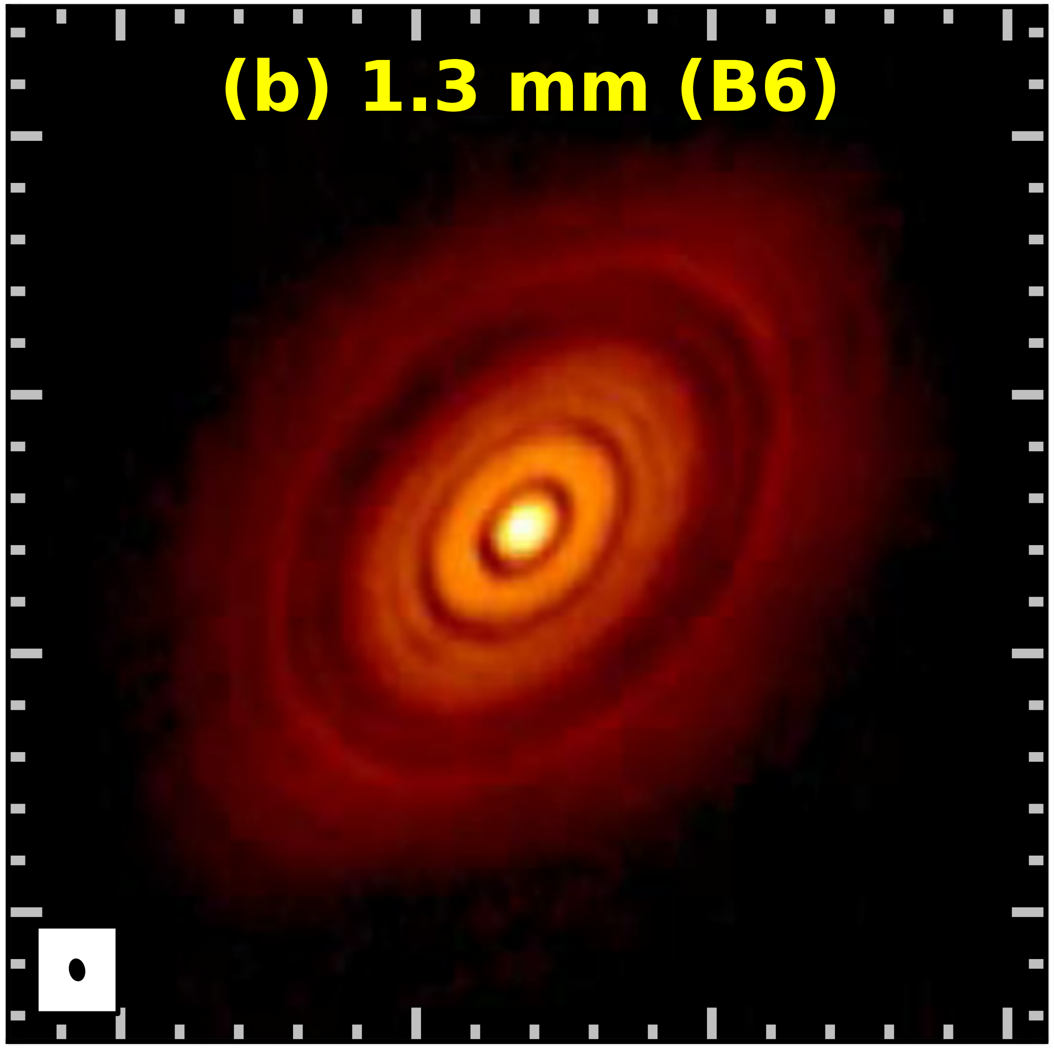
Case study - HL Tau

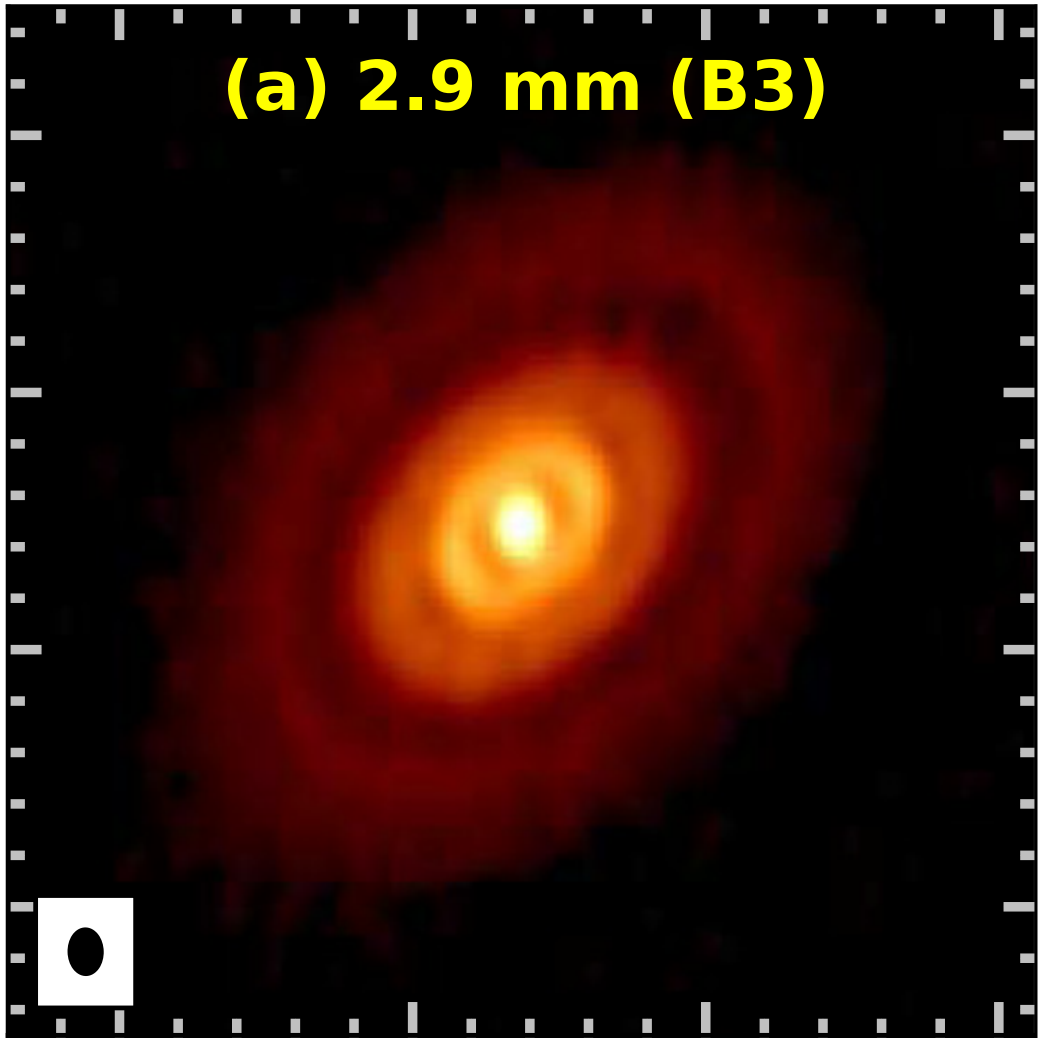


- i = 47° (ALMA Partnership 2015)
- The polarization vectors are parallel to the minor axis
  - The edge-on effects dominate the polarization in the HL Tau disk

Kataoka, et al., 2016a

HL Tau - continuum

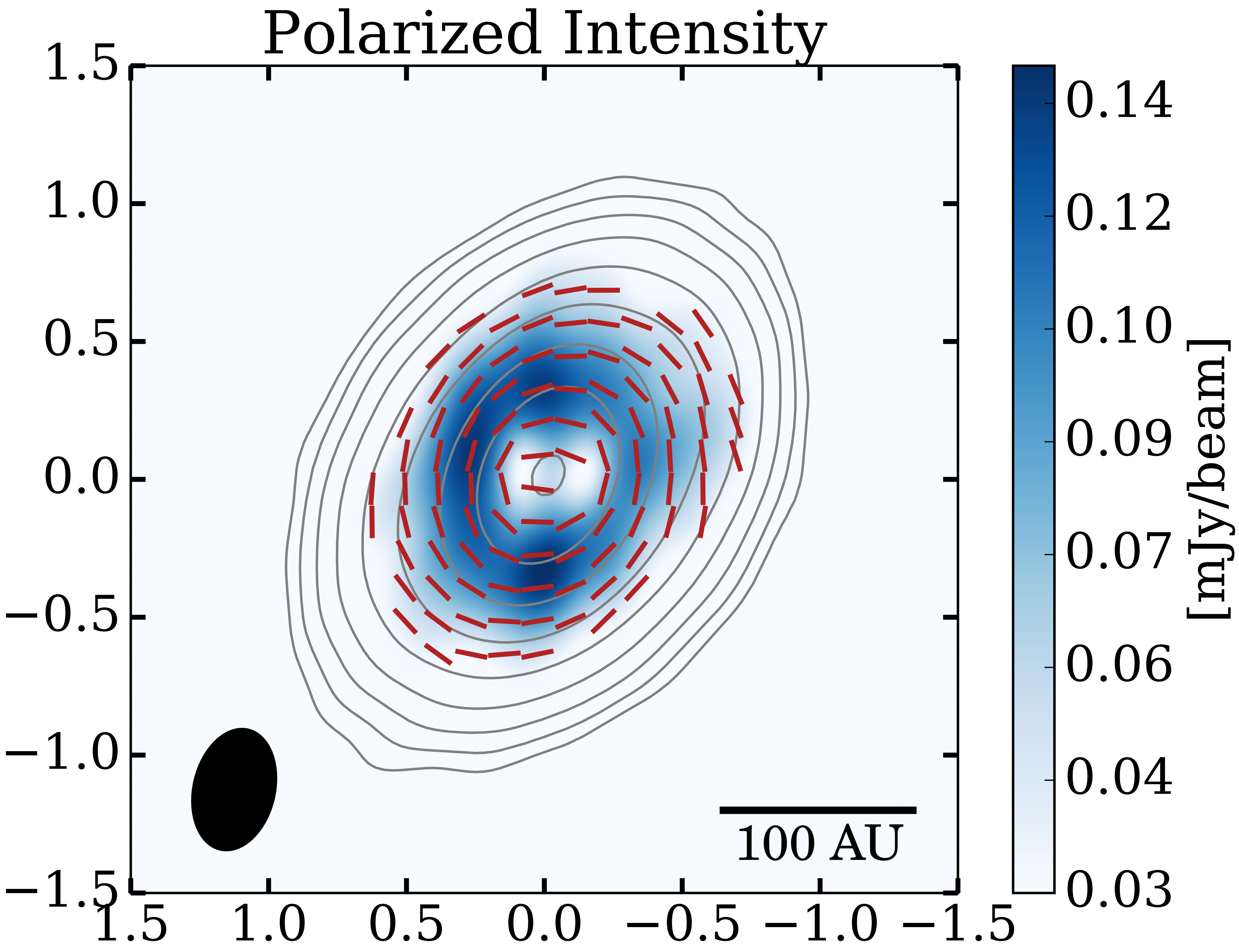




ALMA Partnership, 2015

- Polarization of HL Tau disk has been detected with CARMA at 1.3 mm and SMA at 0.87 mm (Stephens et al. 2014)
- We observed polarization of the HL Tau disk with ALMA at 3.1 mm

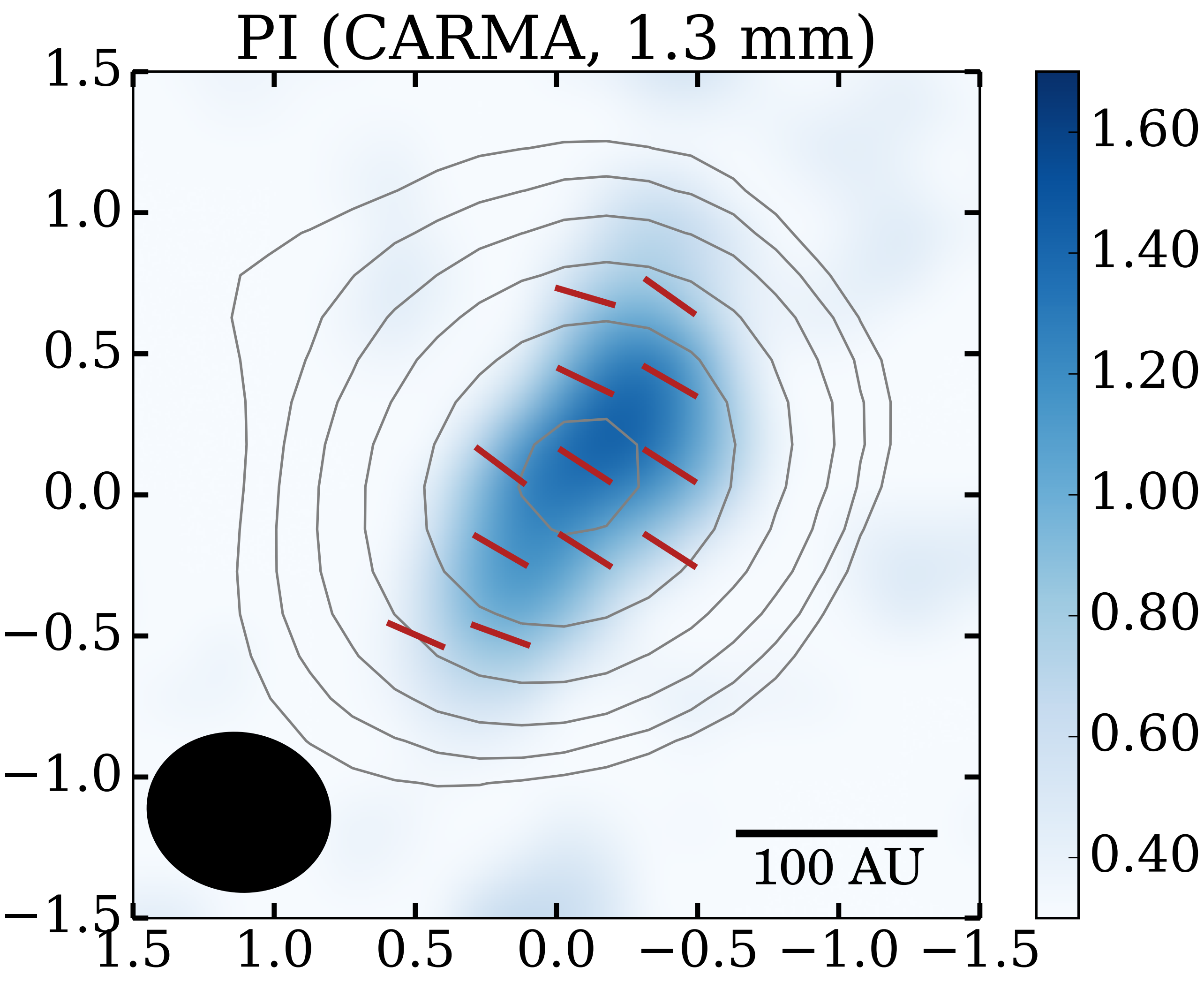
HL Tau polarization with ALMA



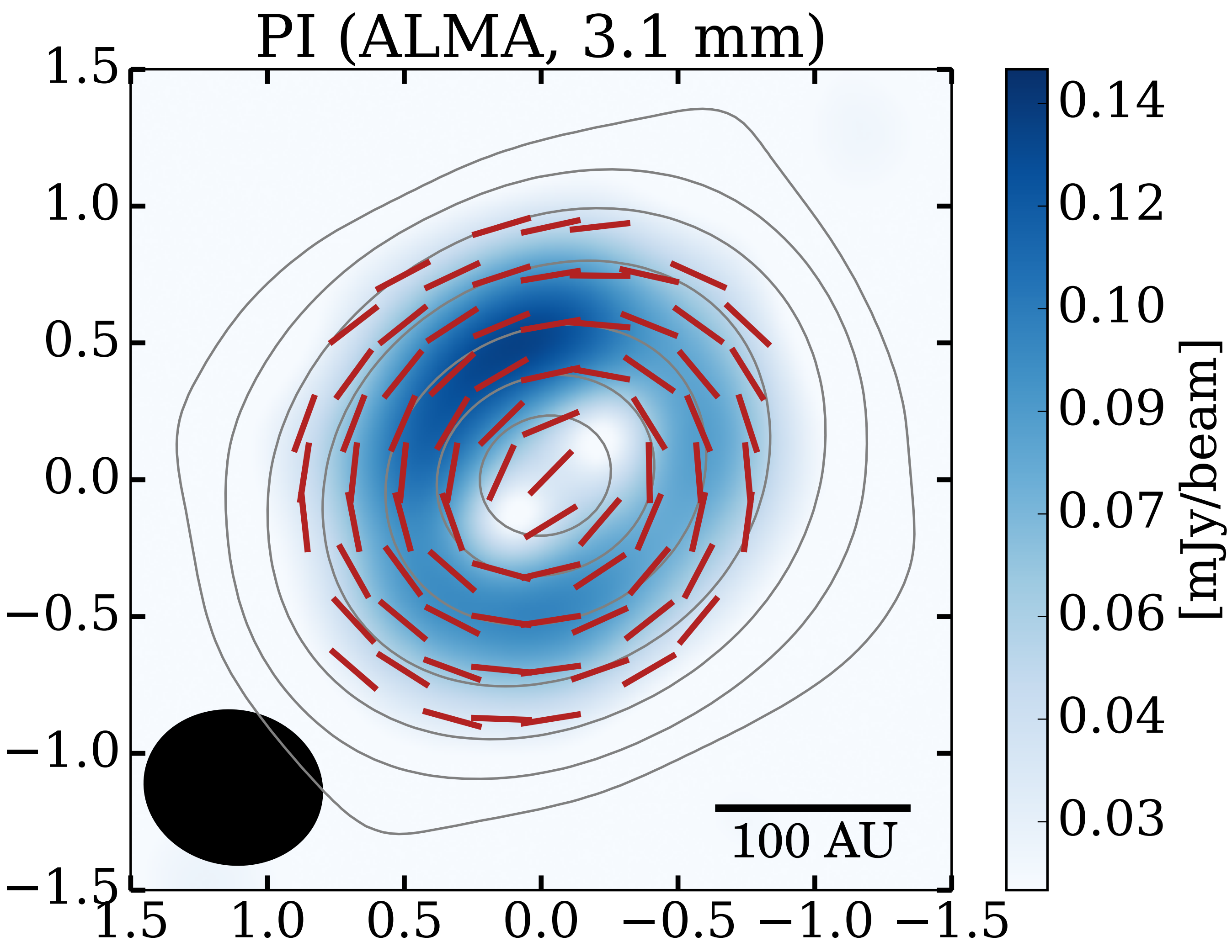
- **We find the azimuthal polarization vectors at 3.1 mm wavelength**
  - Alignment with the radiative flux (cf. Tazaki et al. 2017)
  - No longer aligned with the toroidal magnetic fields in disks

Kataoka, et al., 2017

wavelength dependence



data from Stephens et al., 2014

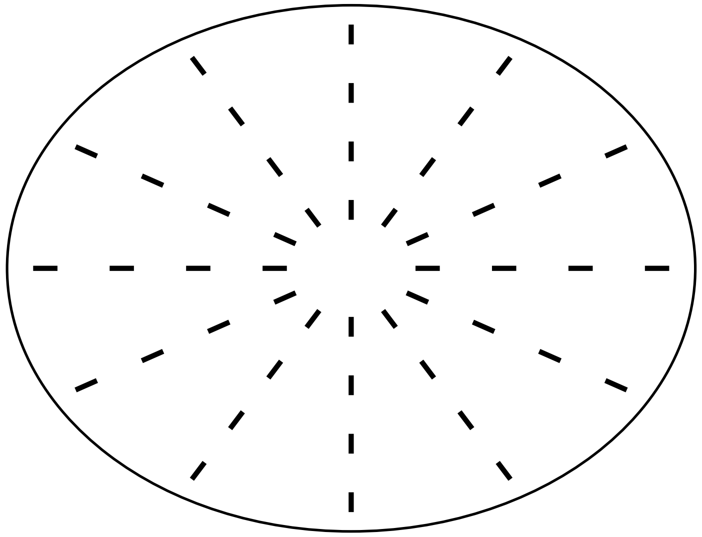


- The polarization vectors at 1.3 mm are parallel to the minor axis
- The polarization vectors at 3.1 mm are in the azimuthal direction

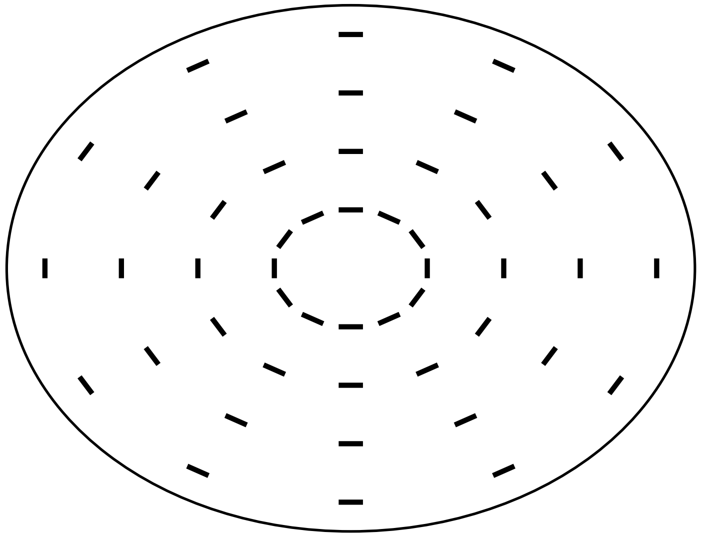
wavelength-dependent polarization in mm range

Polarization mechanisms

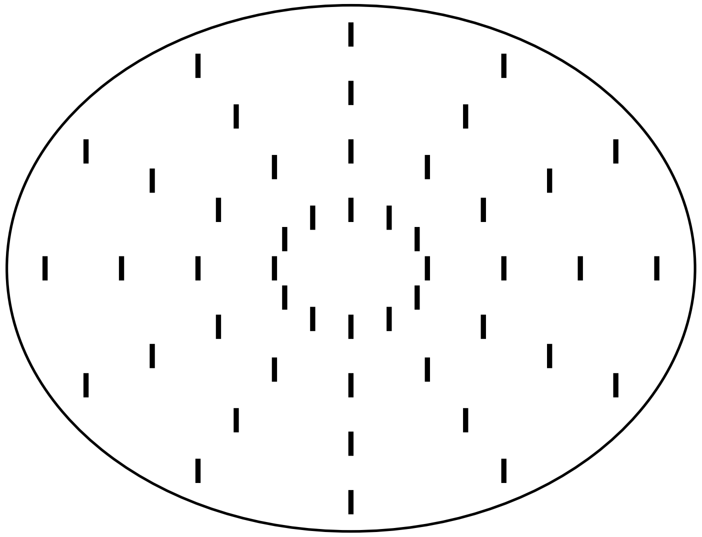
alignment with B-fields



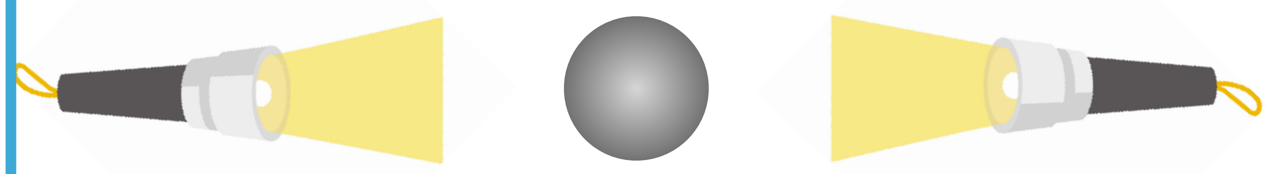
alignment with radiation



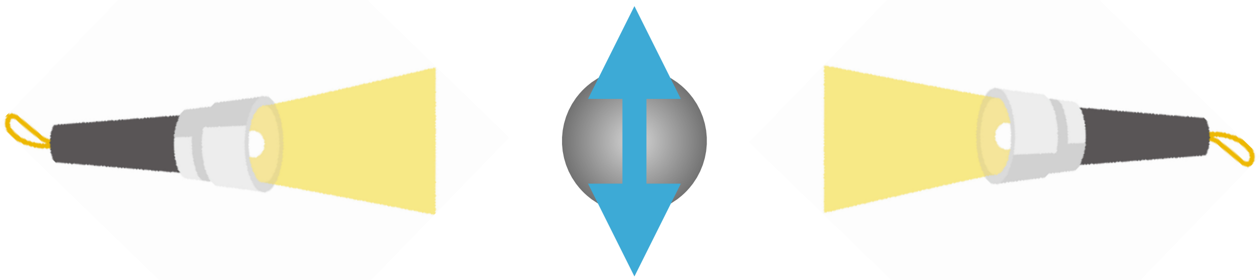
self-scattering



alignment with radiation



self-scattering



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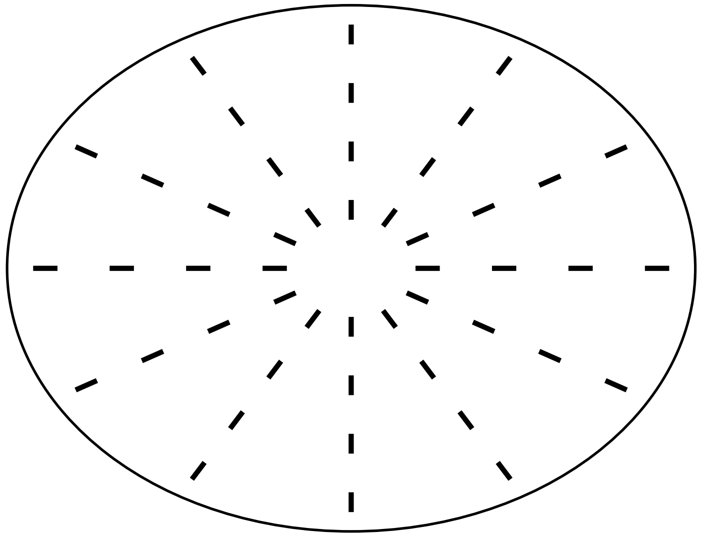
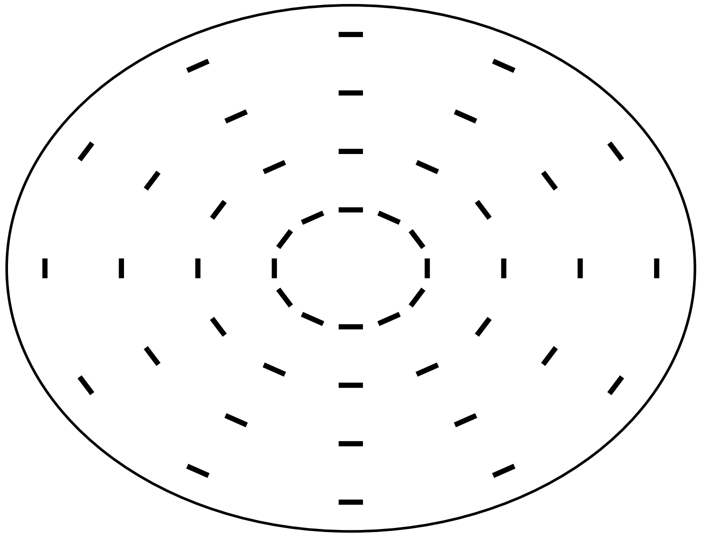
Polarization mechanisms

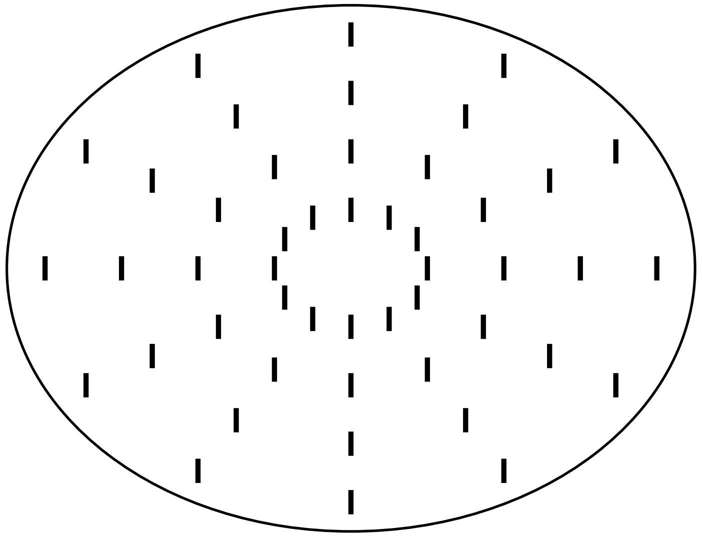
alignment with B-fields

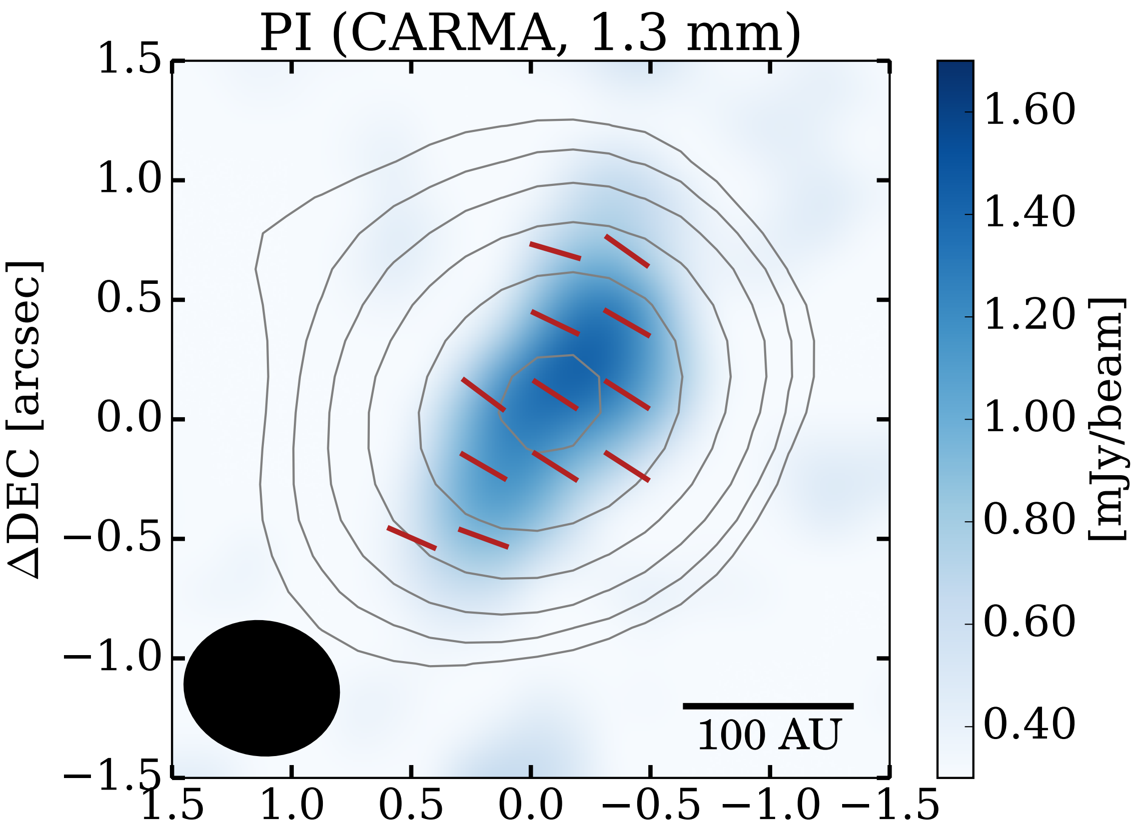


alignment with radiation

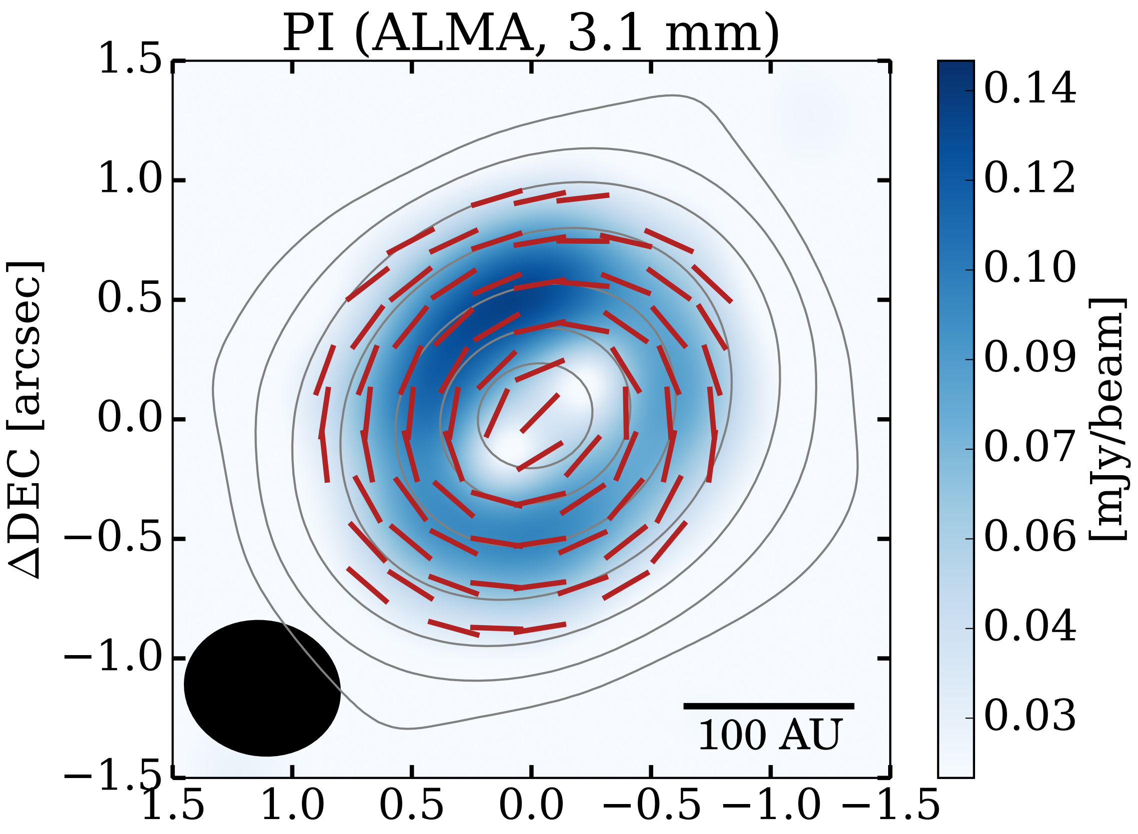


self-scattering





scattering dominated



rad. alignment dominated

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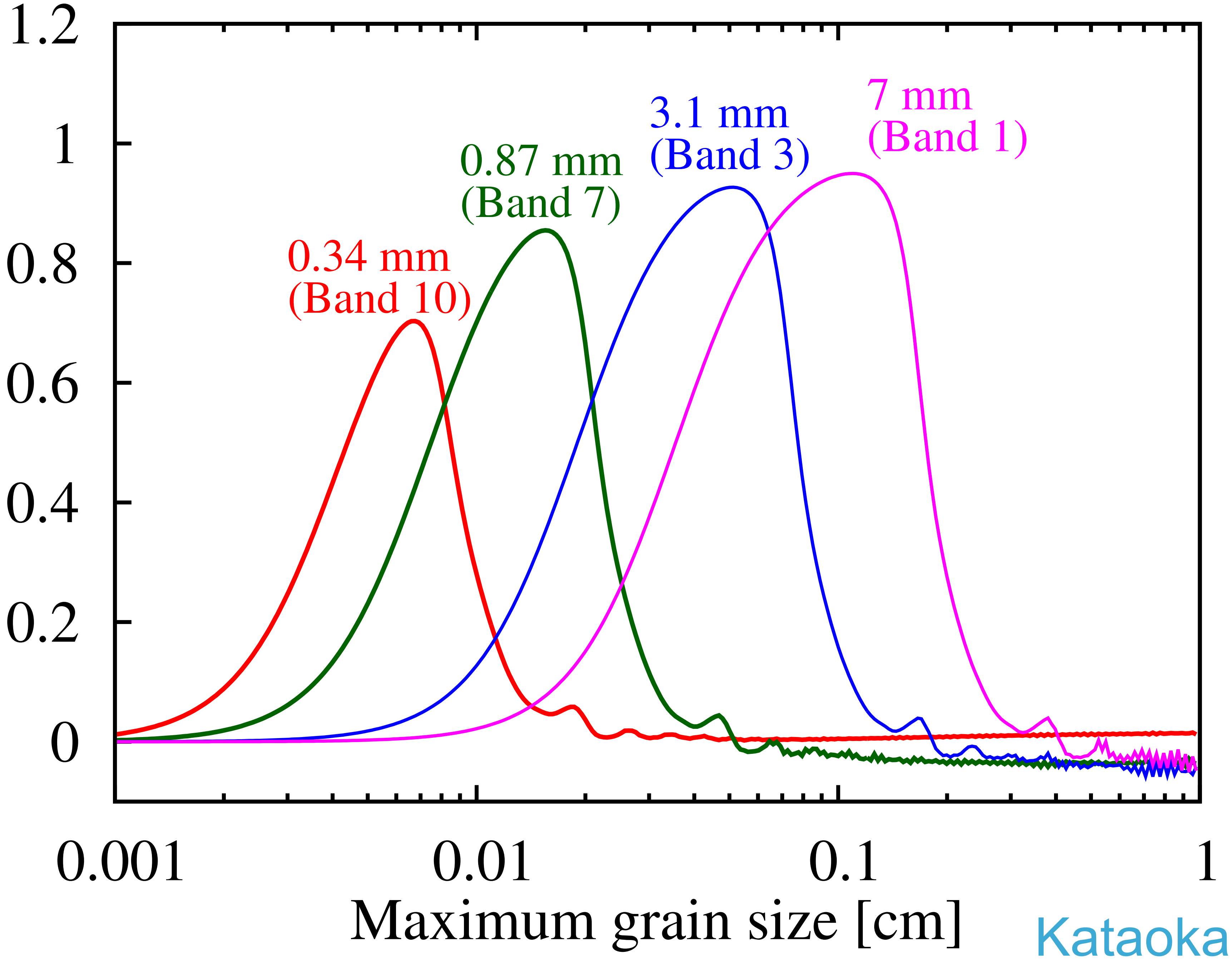
Grain size constraints by polarization

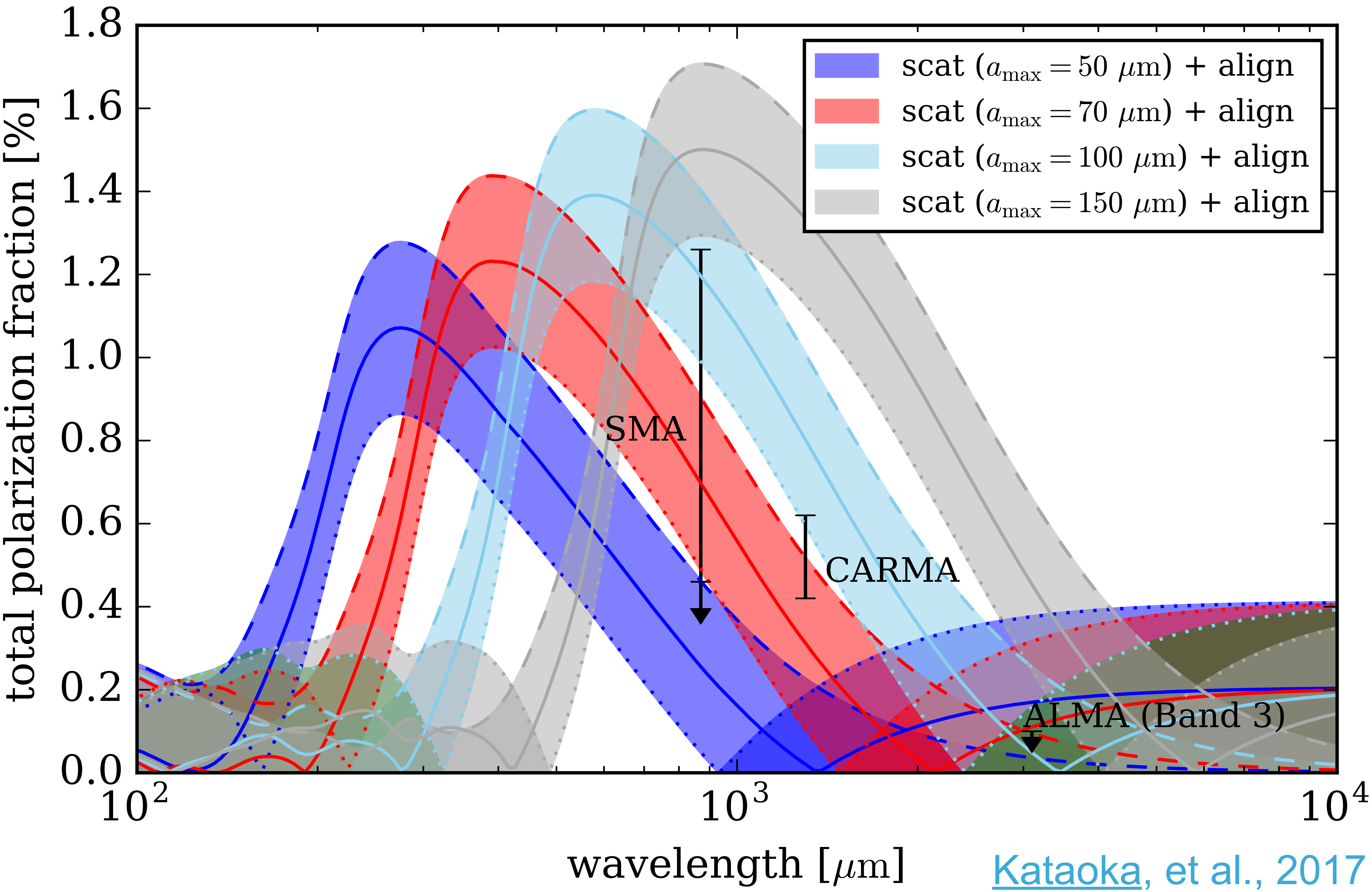
Expected polarization degree (scalable)



[Kataoka, et al., 2015](Kataoka)

Multi-wave polarization → constraints on the grain size

HL Tau polarization



Kataoka, et al., 2017

Conclusions

- We propose that multi-band mm-wave polarization observations would be a new method to constrain the grain size.
  - Two conditions for polarization at millimeter-wavelengths:
    1. The intensity has anisotropic radiation fields
    2. The maximum grain size is comparable to the wavelengths

(Kataoka et al., 2015, ApJ)

- We have observed polarization of HL Tau with ALMA
  - 3.1 mm polarization vectors are dominated by explained by the grain alignment, while 1.3 mm pol. vectors by the self-scattering.
  - The maximum grain size is constrained to be ~100 μm

((Kataoka et al. 2016a, ApJ, Kataoka et al. 2017, accepted in ApJL)