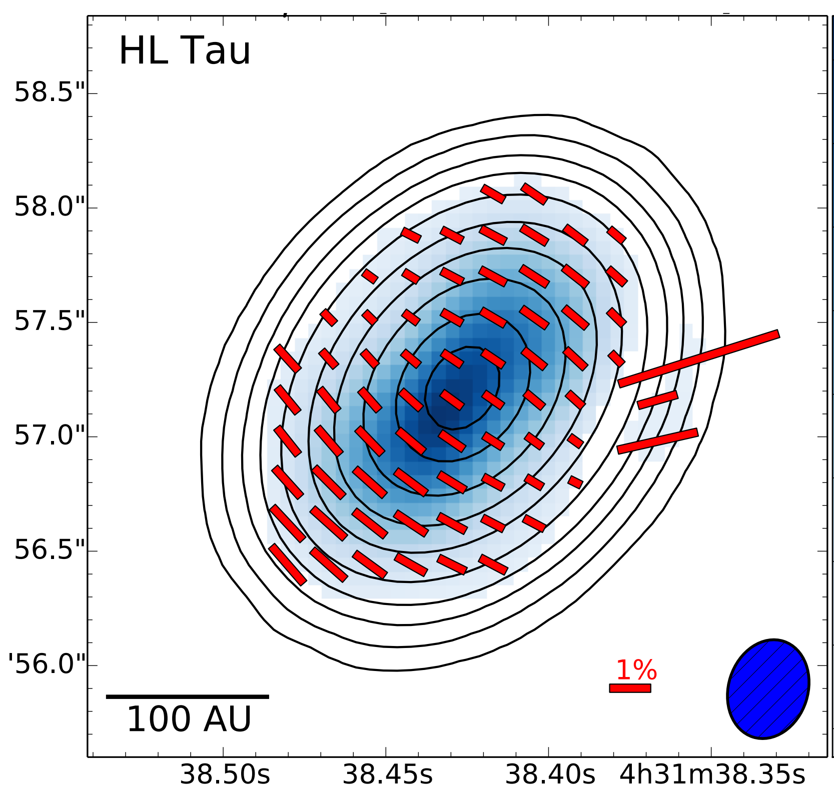
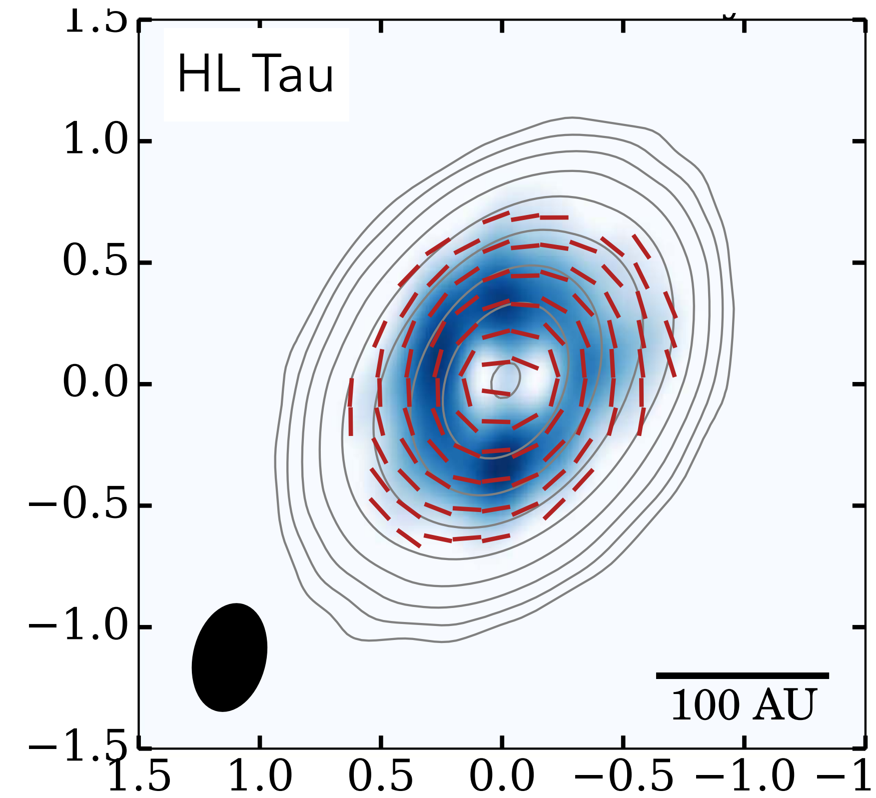
Millimeter-wave polarization of protoplanetary disks: alignment or scattering?

ALMA Band 7 (870 μm)



Stephens et al. 2017

ALMA Band 3 (3.1 mm)



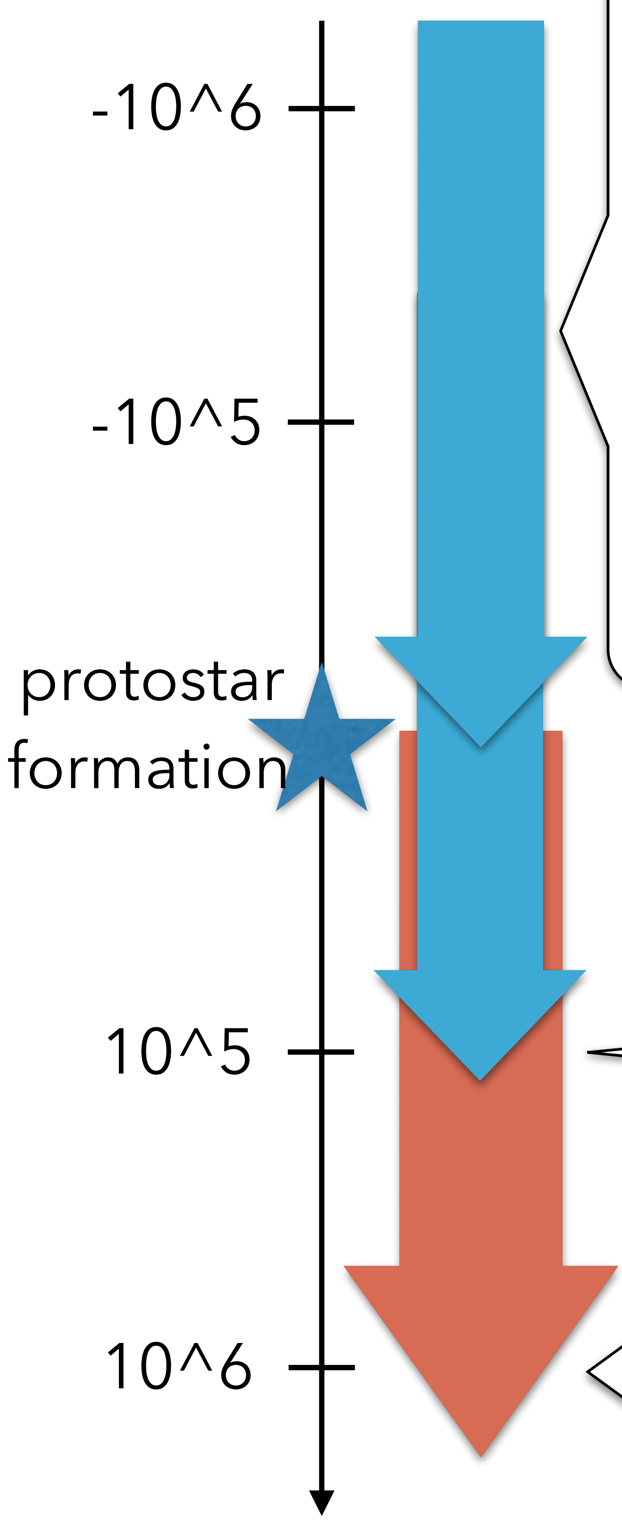
Kataoka et al. 2017

Scattering ⟷ **Alignment**

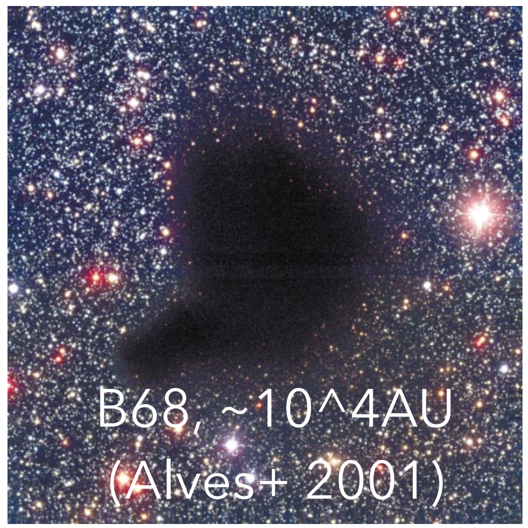
Akimasa Kataoka (NAOJ)

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)

Star and disk formation

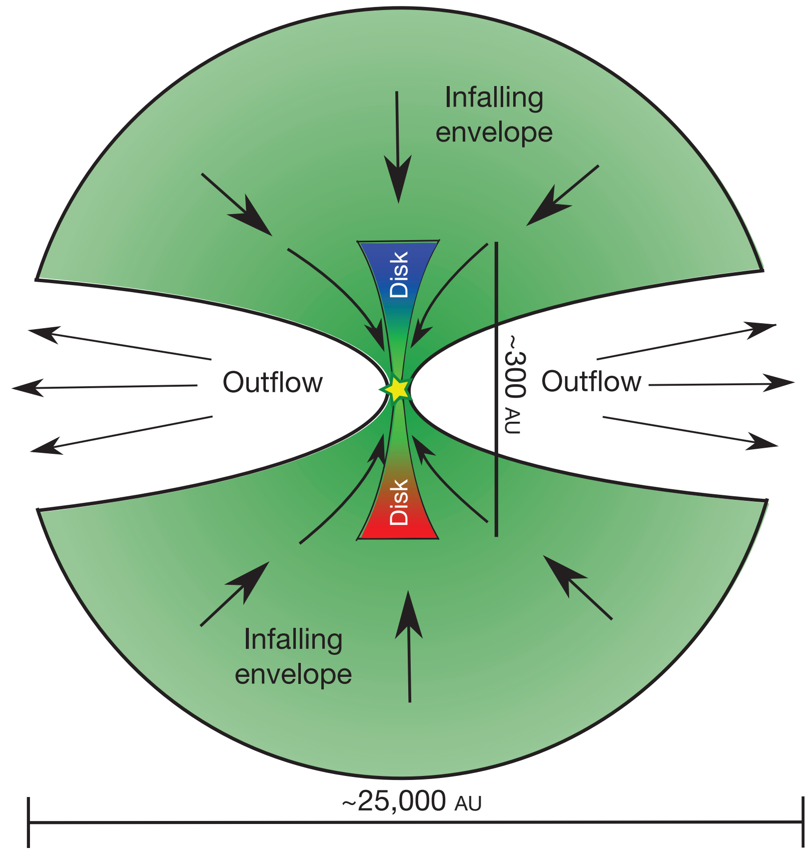


molecular cloud core

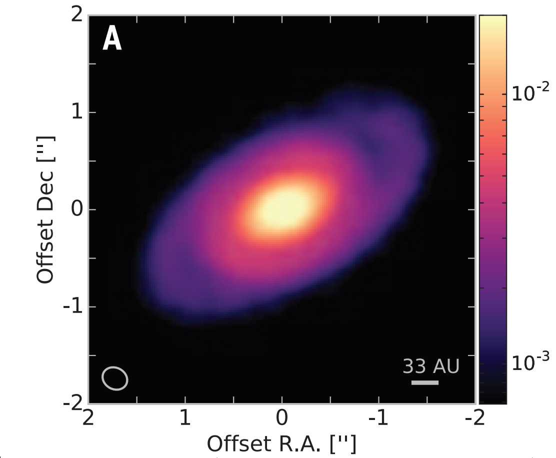


B68, ~10^4AU (Alves+ 2001)

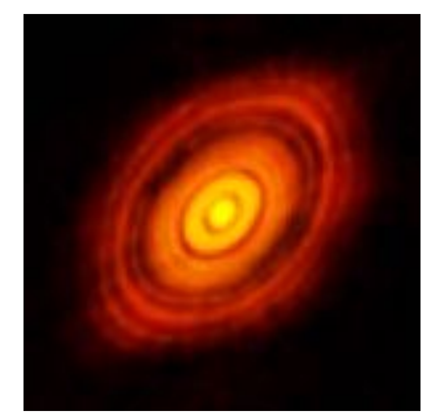
envelope + disk



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



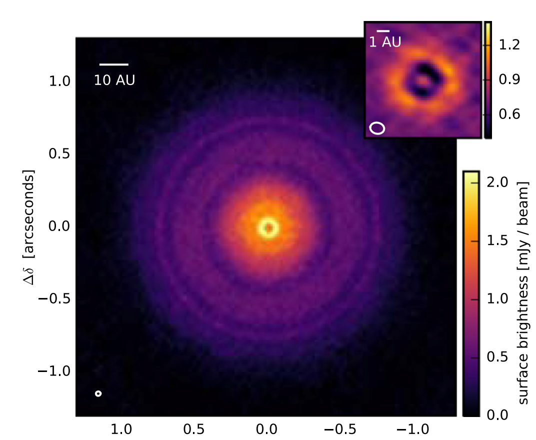
Elias 2-24 (Perez+ 2016)

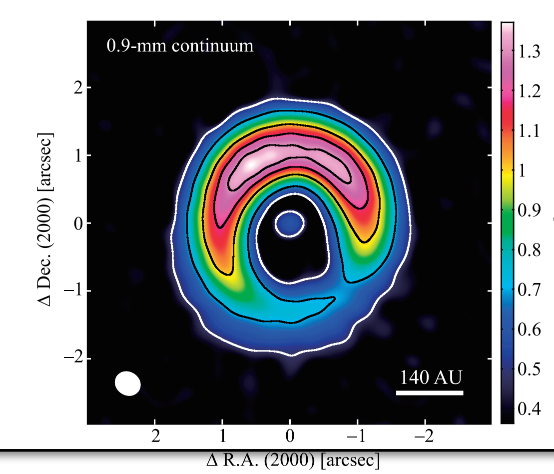


HL Tau (ALMA+ 2015)

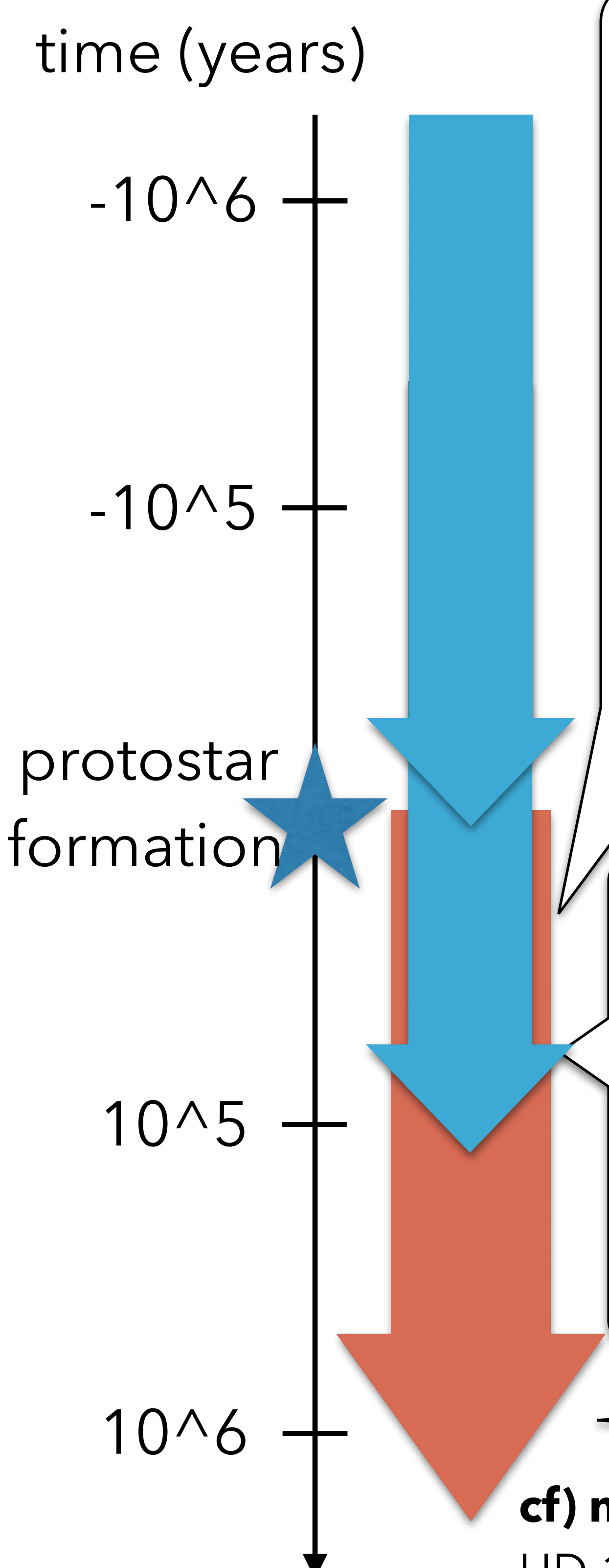
protoplanetary disks

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

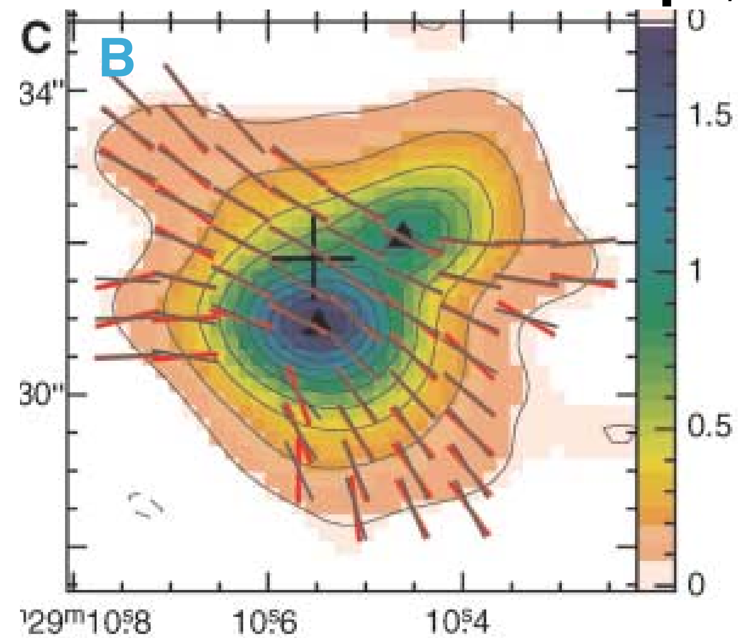




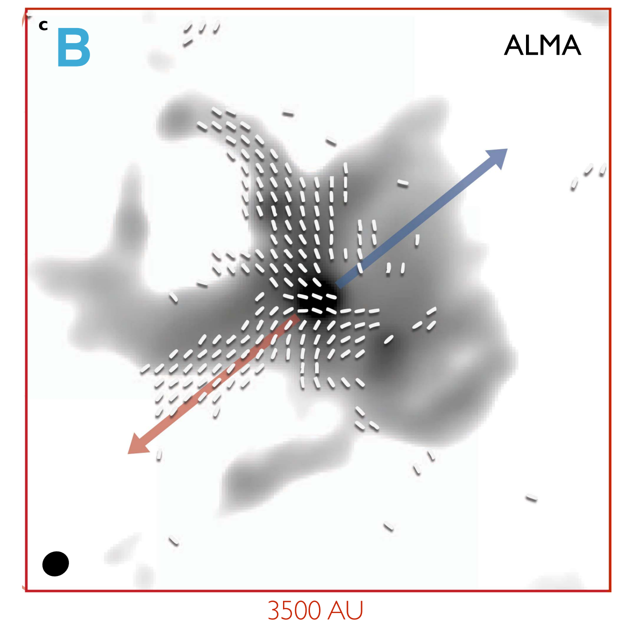
Polarization of star-disk system



Envelope, ~10^4 AU

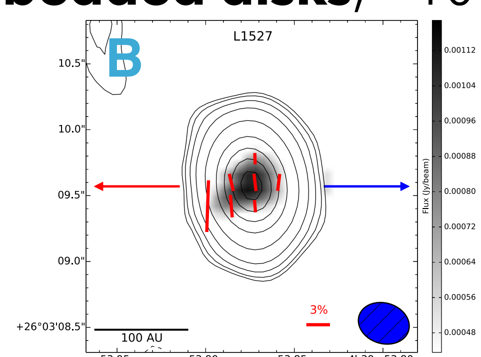


IRAS 4A(Girart et al. 2006)



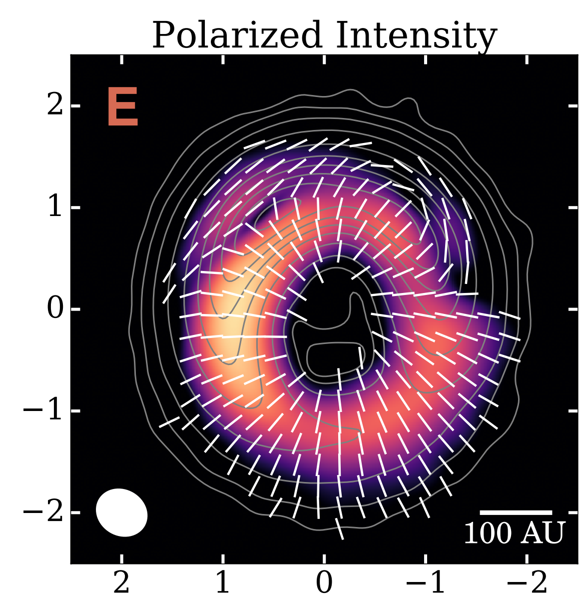
Ser-emb 8 (Hull et al. 2017)

embedded disks, ~10^2 AU

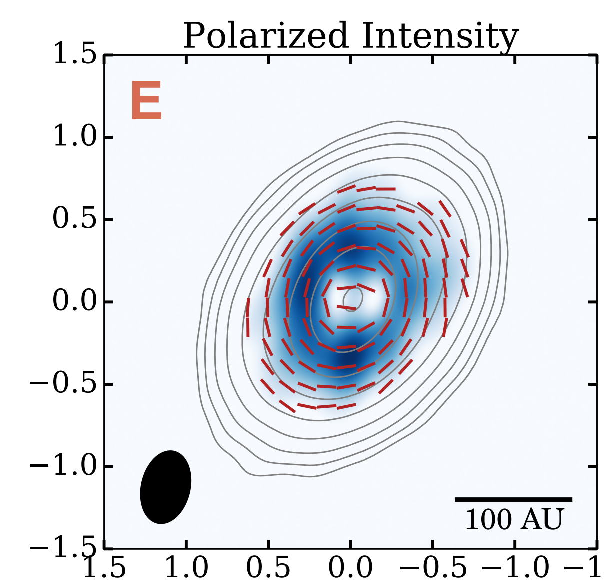


L1527 (Segura-Cox+ 2015)

protoplanetary disks, ~10^2 AU



HD 142527
(Kataoka et al. 2016b)

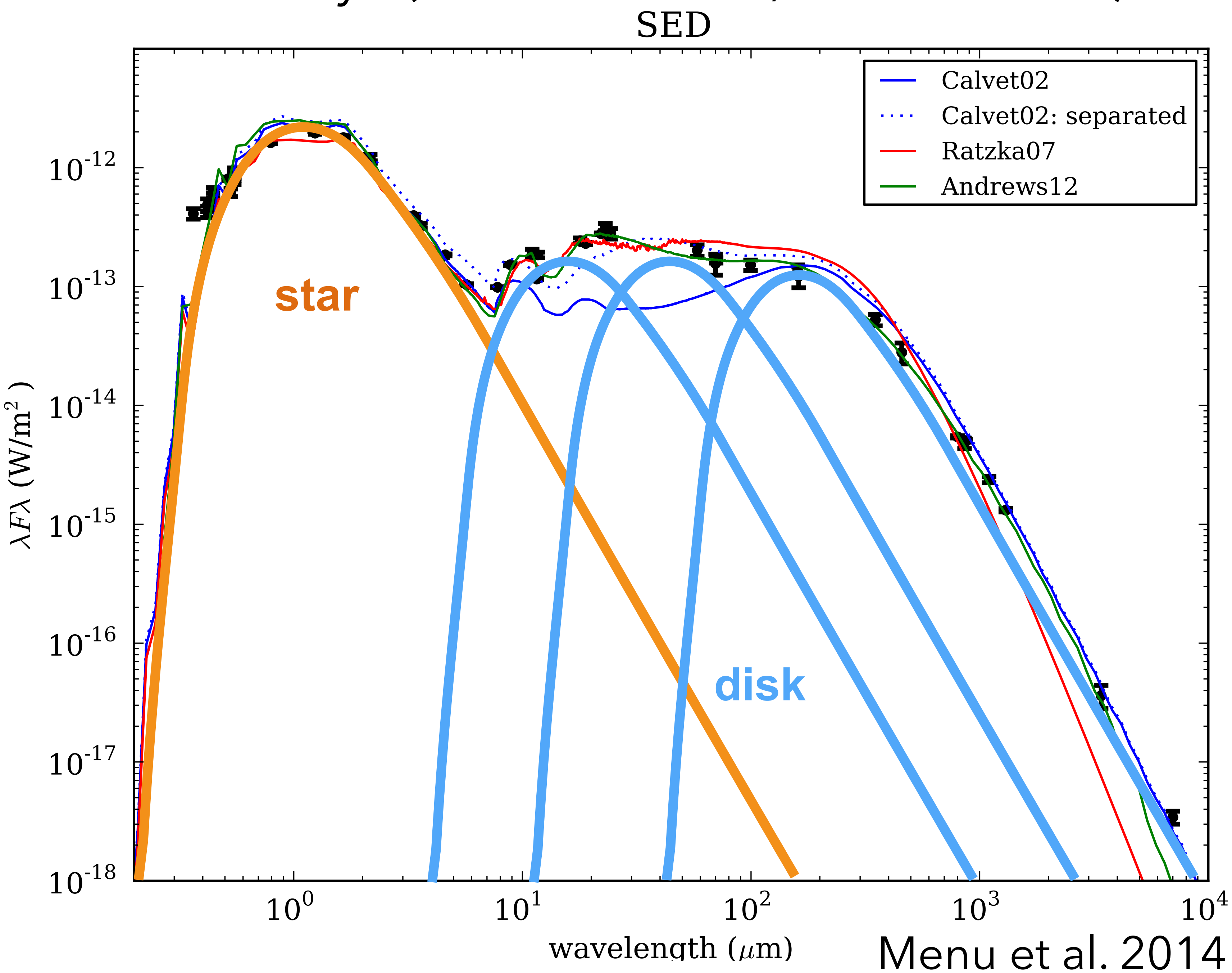


HL Tau
(Kataoka et al. 2017)

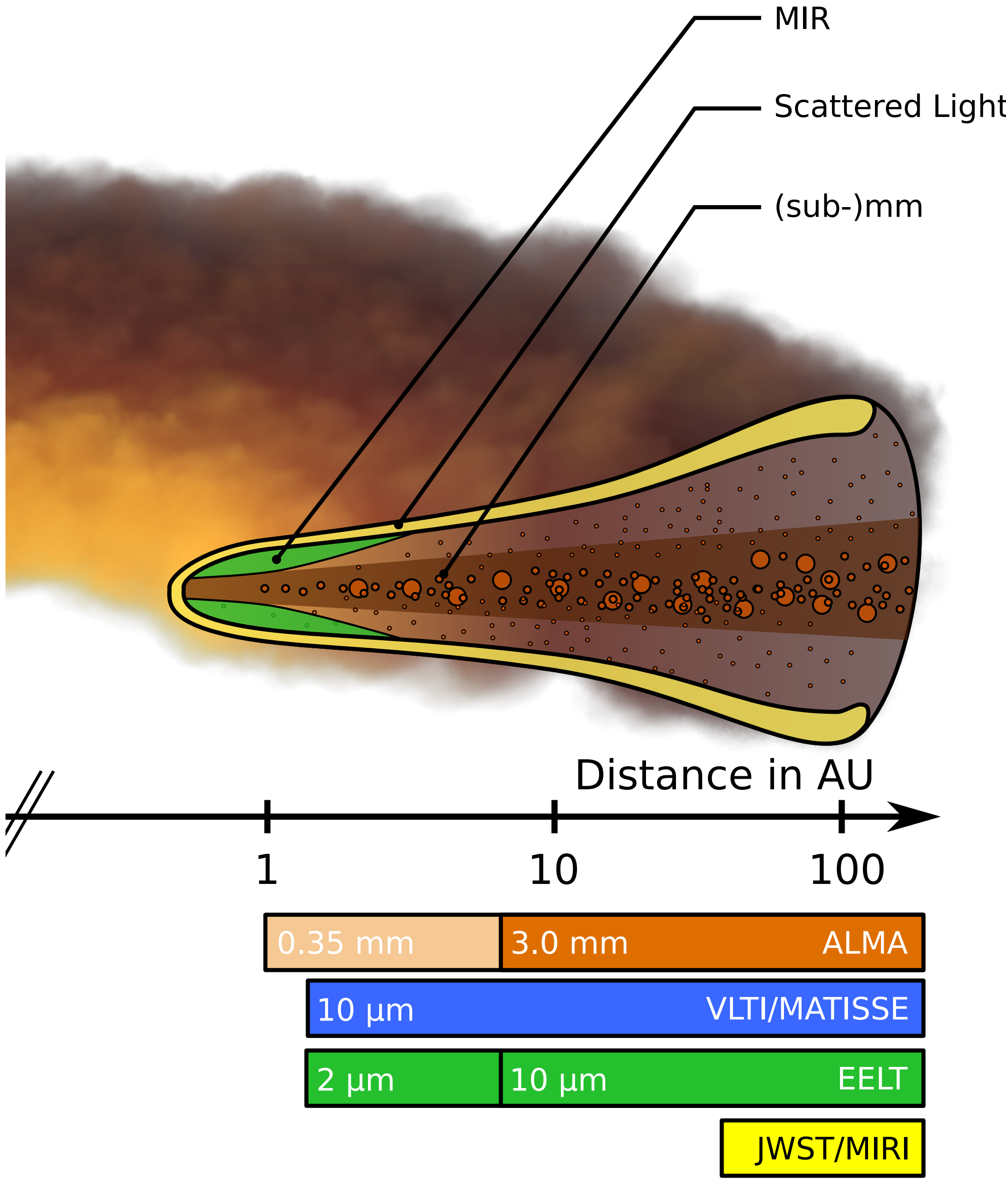
cf) non-detection of disks with SMA
HD 163296, TW Hya, GM Aur, DG Tau
(Hughes et al. 2009, 2013)

SED of a protoplanetary disk

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



Menu et al. 2014

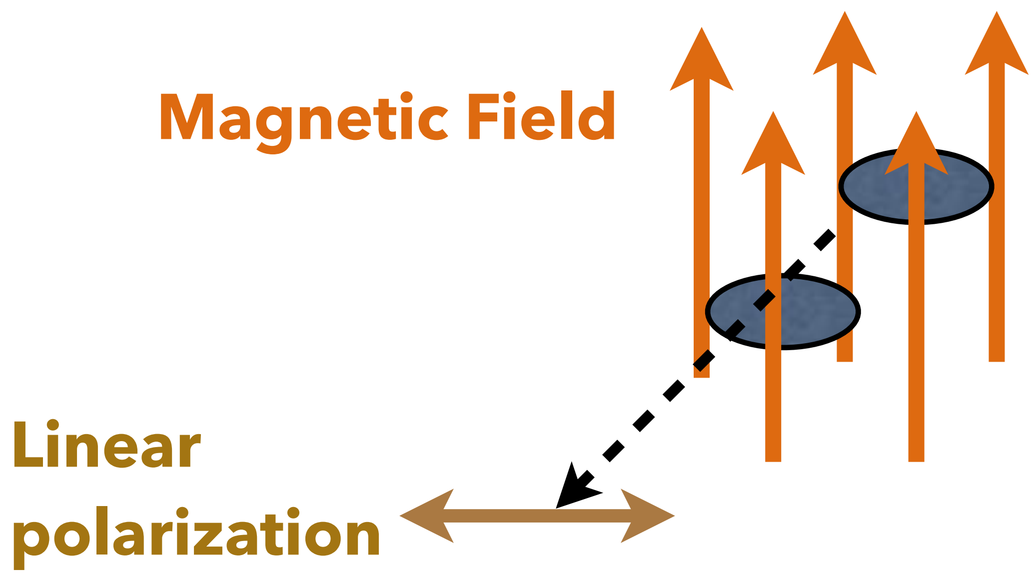


Testi et al. 2014

- 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

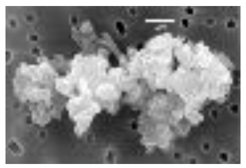
2. **The self-scattering of thermal dust emission**

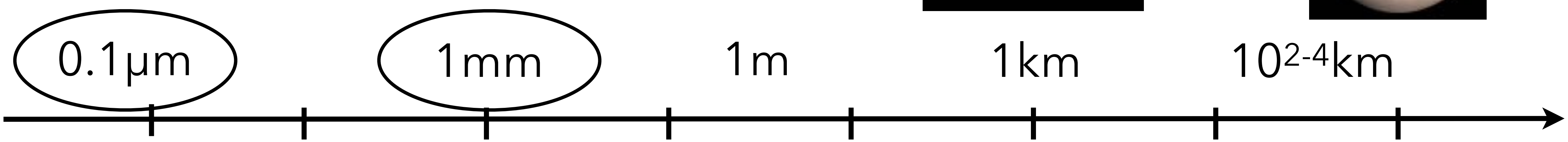
Kataoka et al. 2015

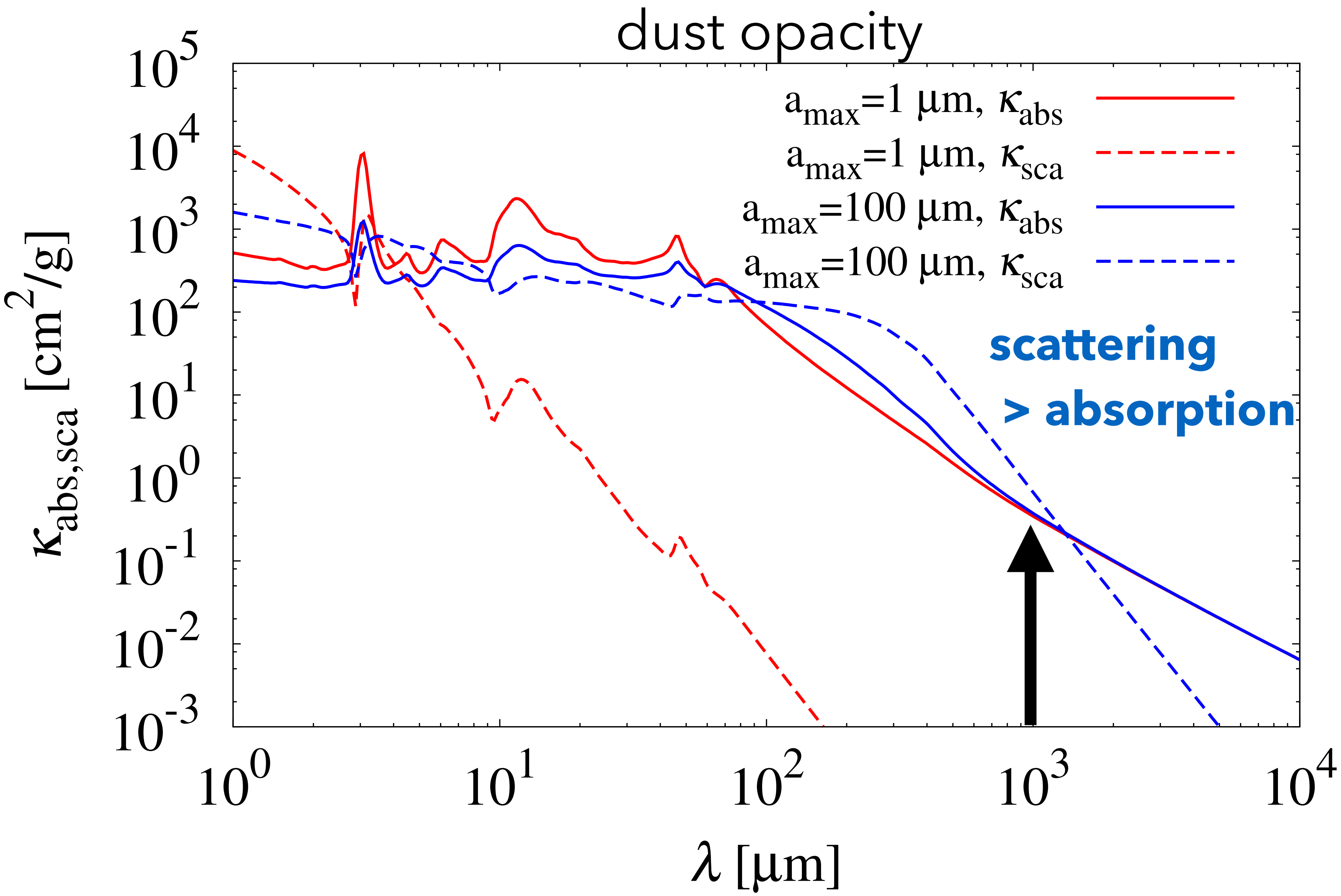
3. **Alignment of elongated dust grains with radiation fields**

Tazaki, Lazarian et al. 2017

Dust is big in disks





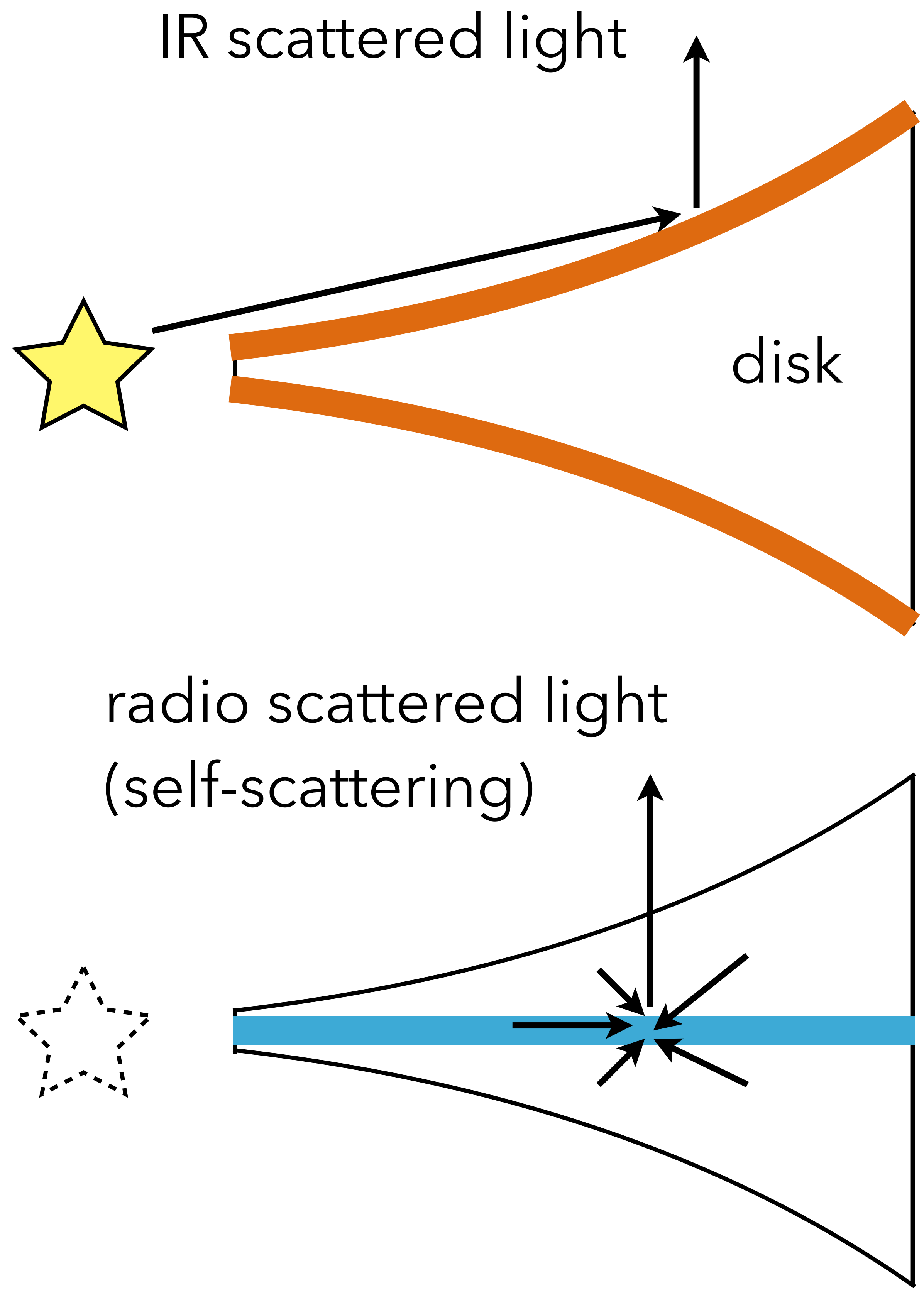


Akimasa Kataoka (NAOJ)

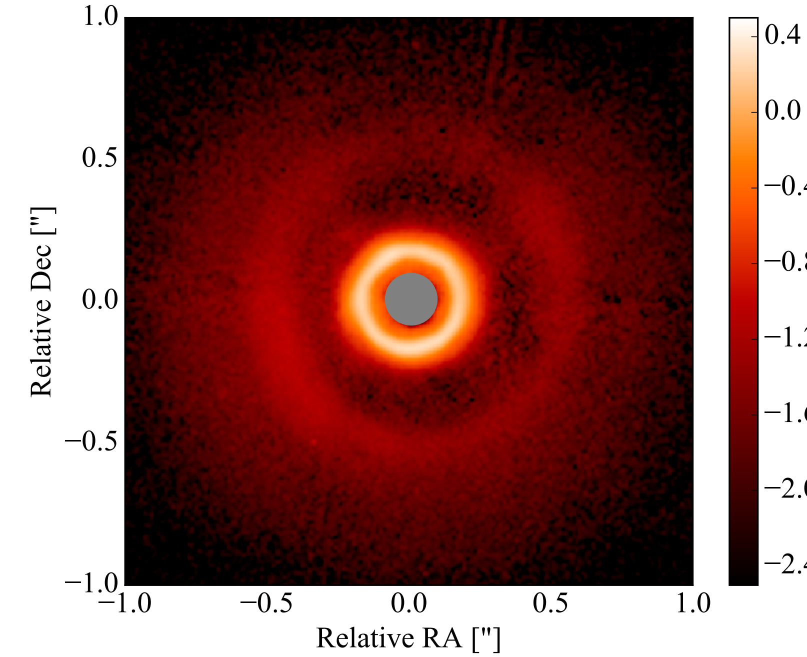
Light source of scattering

Infrared

millimeter



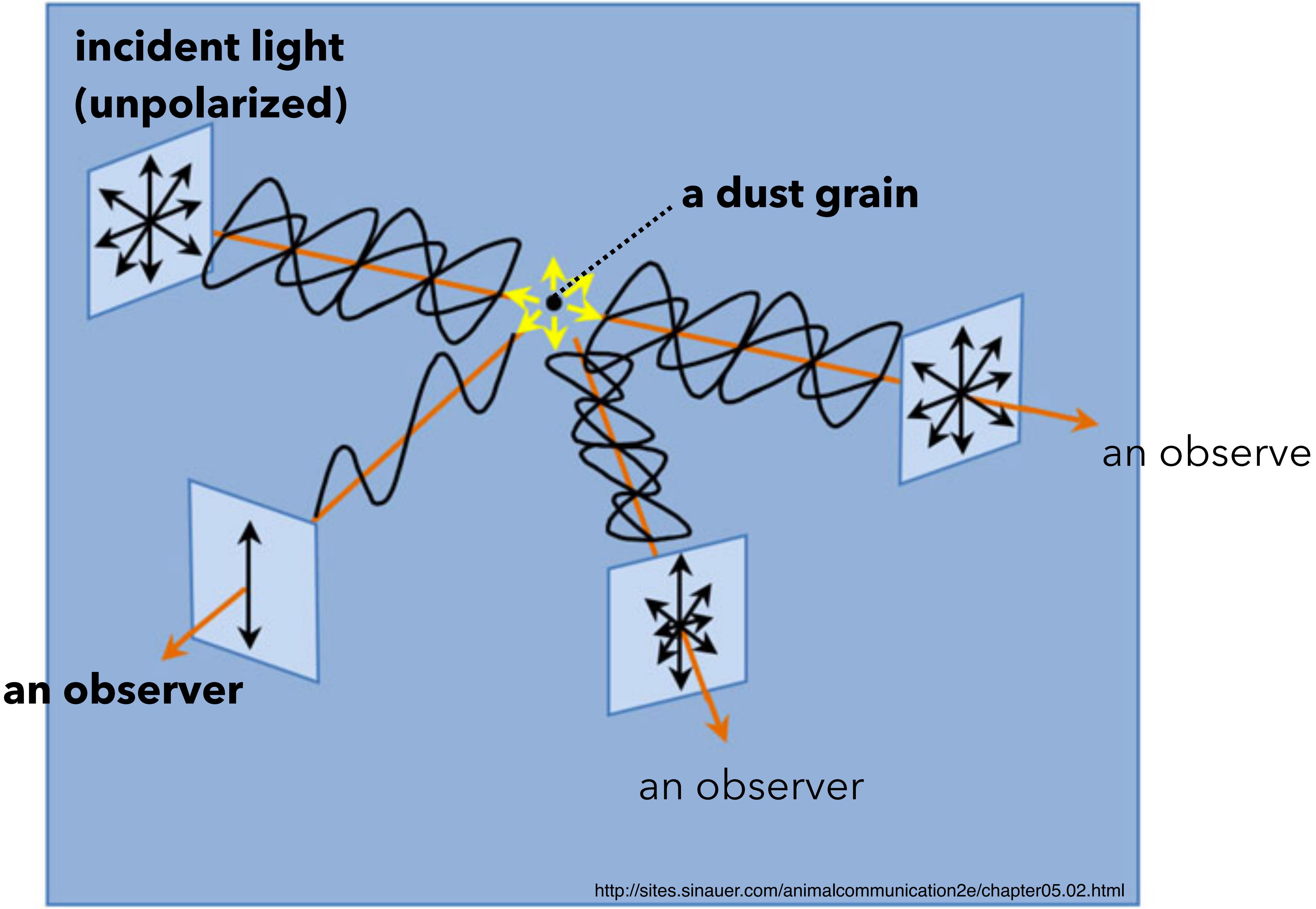
example (face-on, PI)



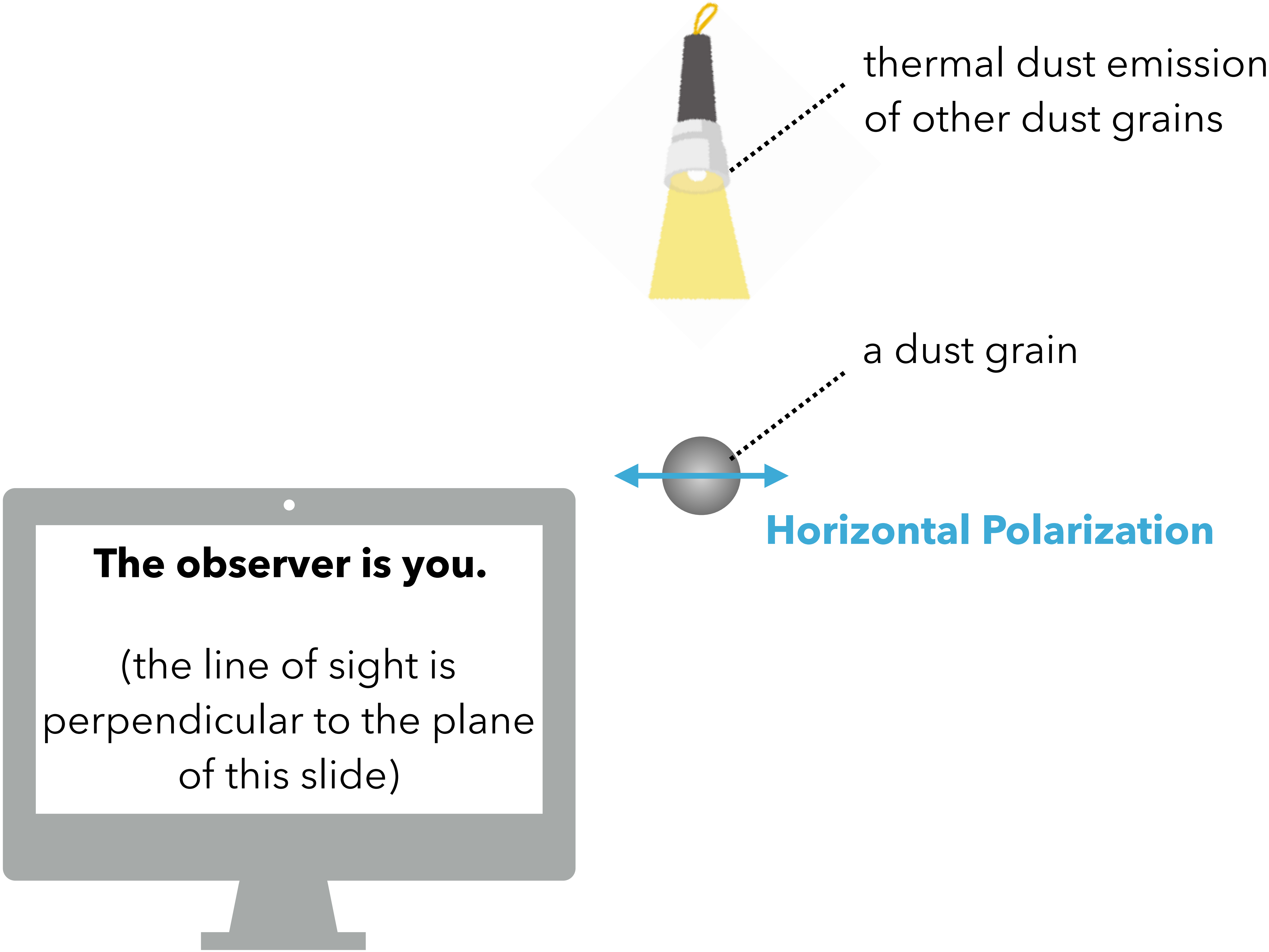
Pohl et al. 2017

?

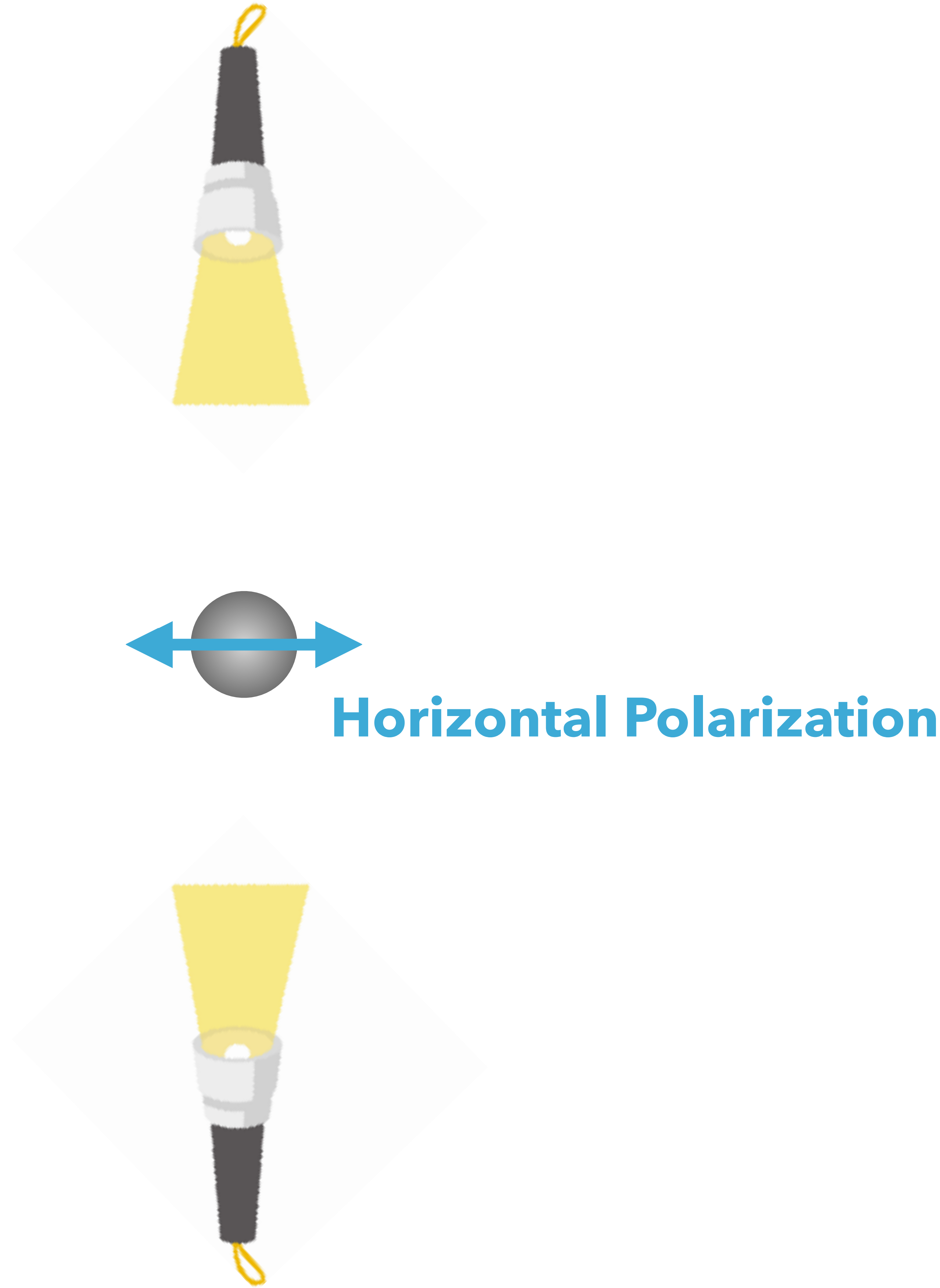
Polarization due to scattering



Polarization due to scattering

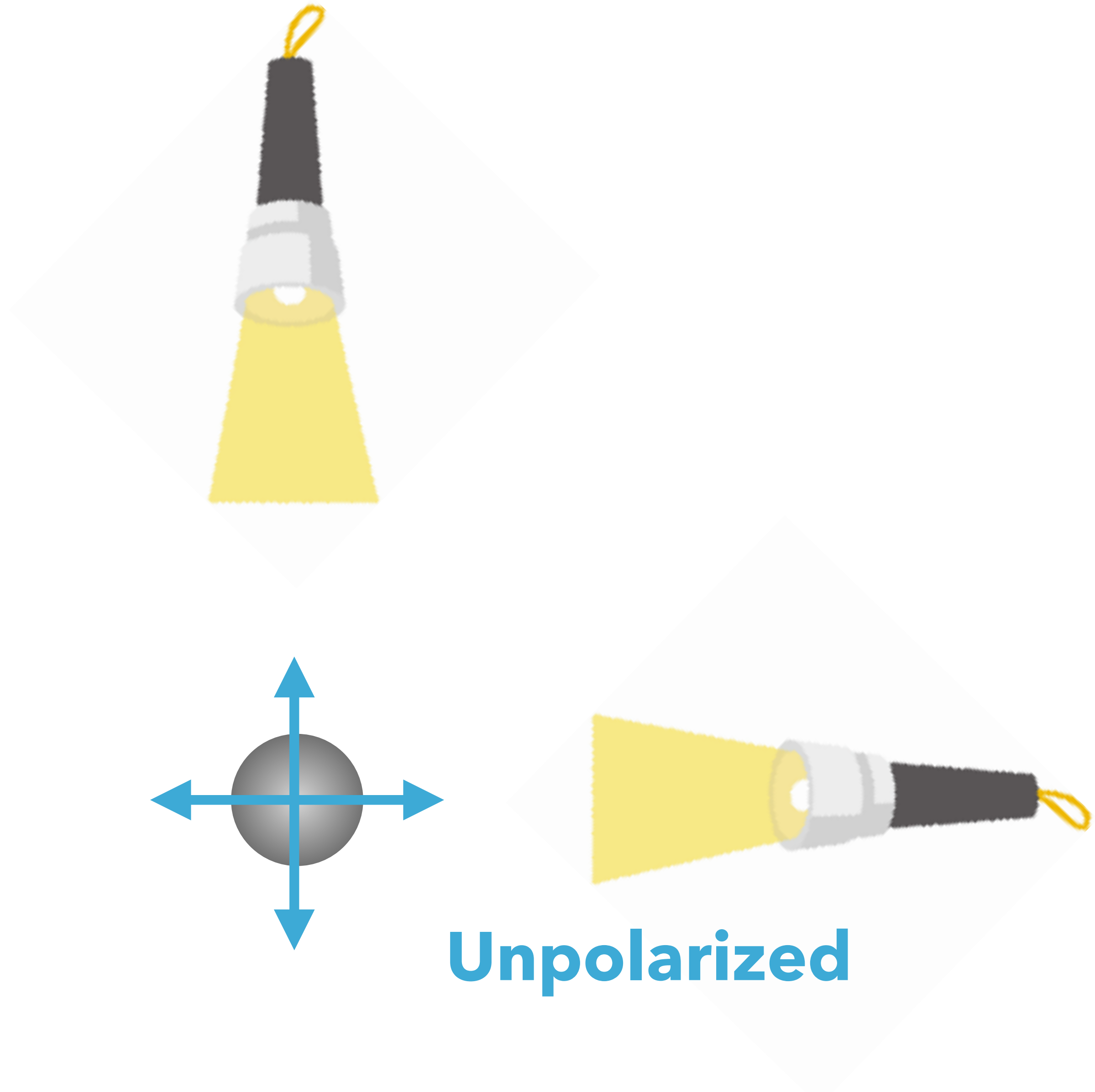


Polarization due to scattering

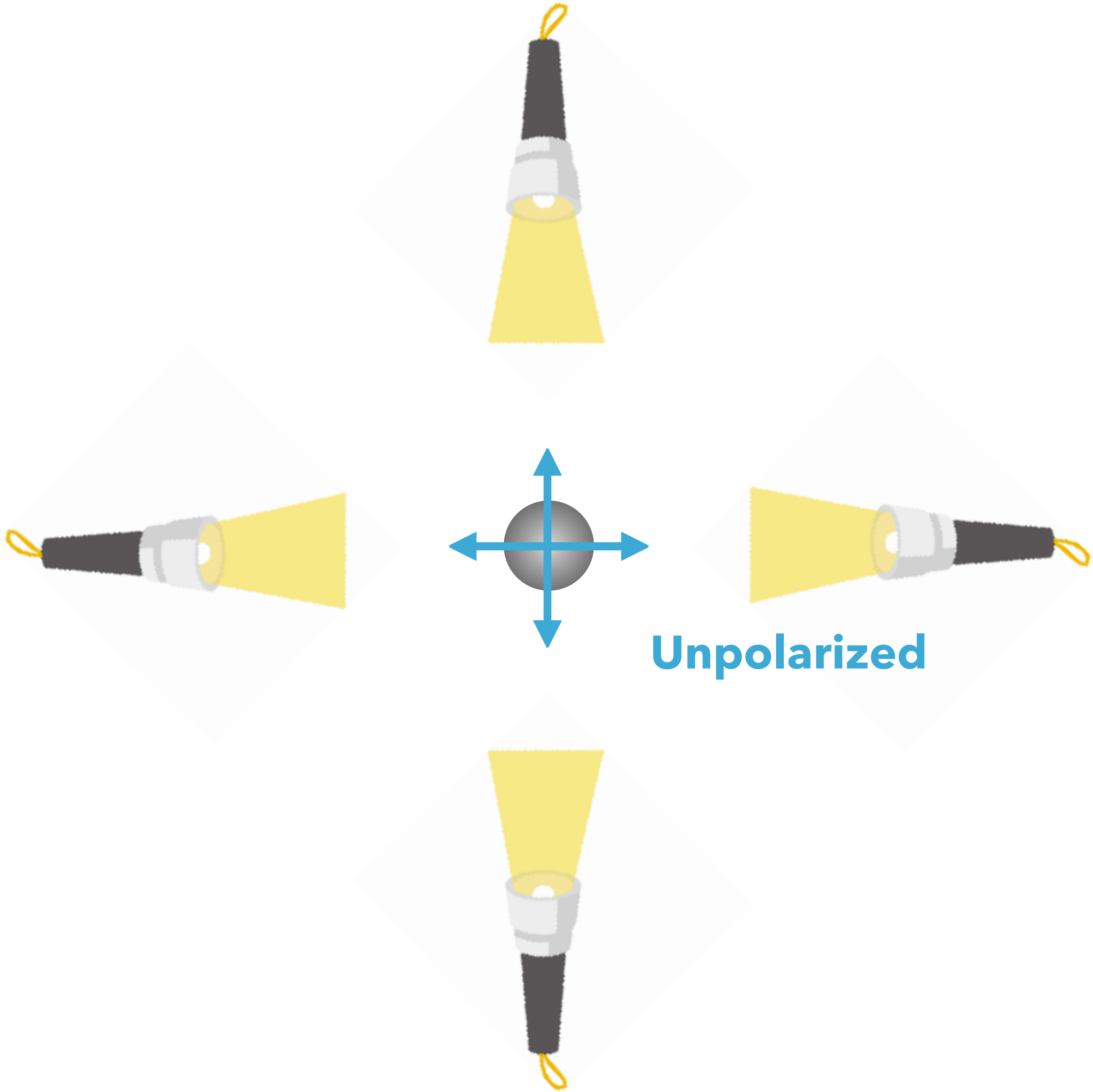


Akimasa Kataoka (NAOJ)

Polarization due to scattering

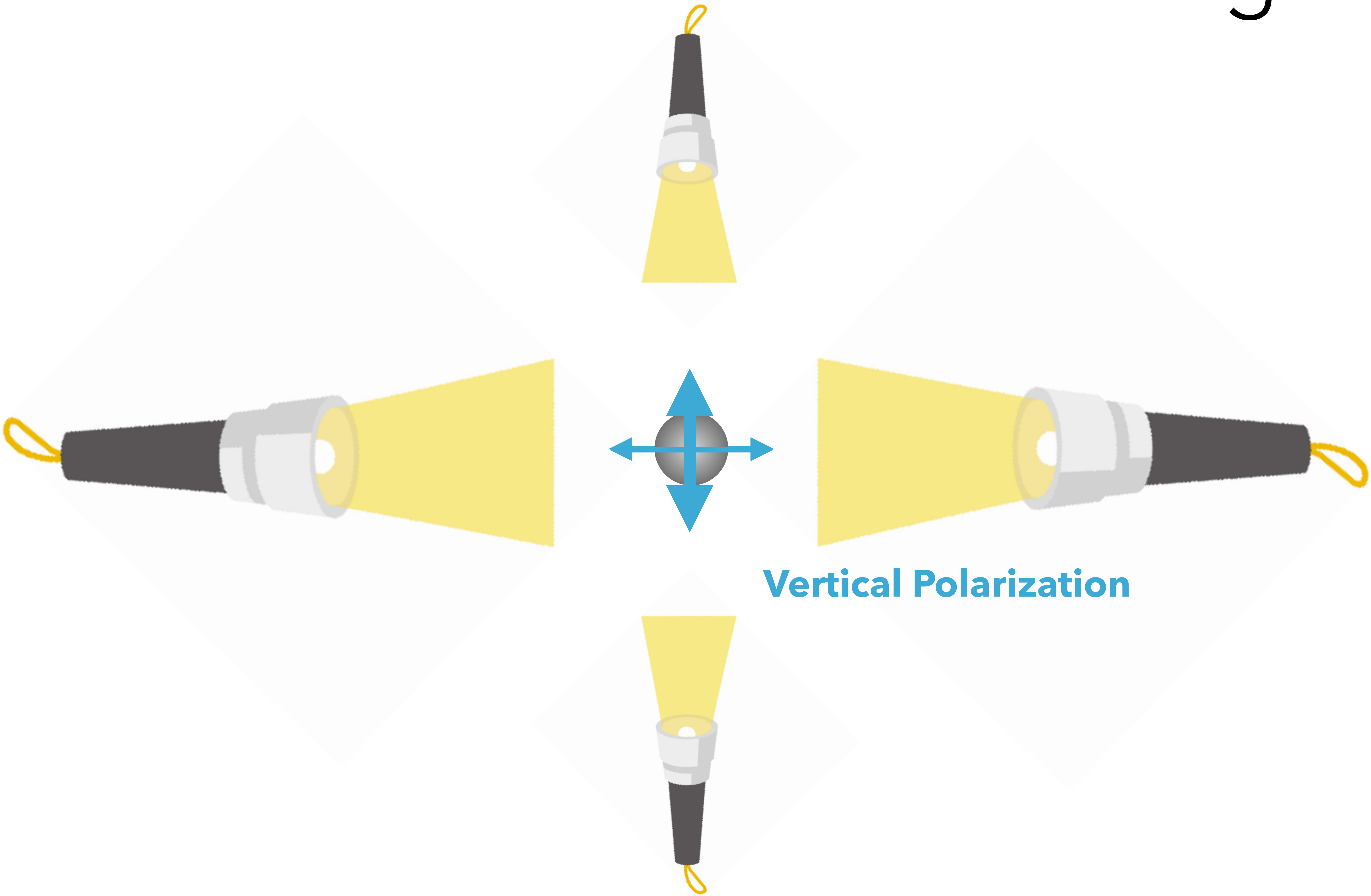


Polarization due to scattering



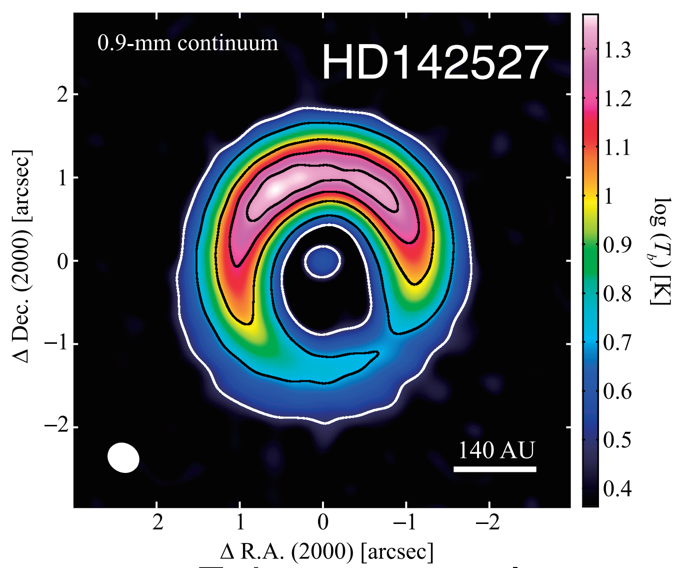
Akimasa Kataoka (NAOJ)

Polarization due to scattering

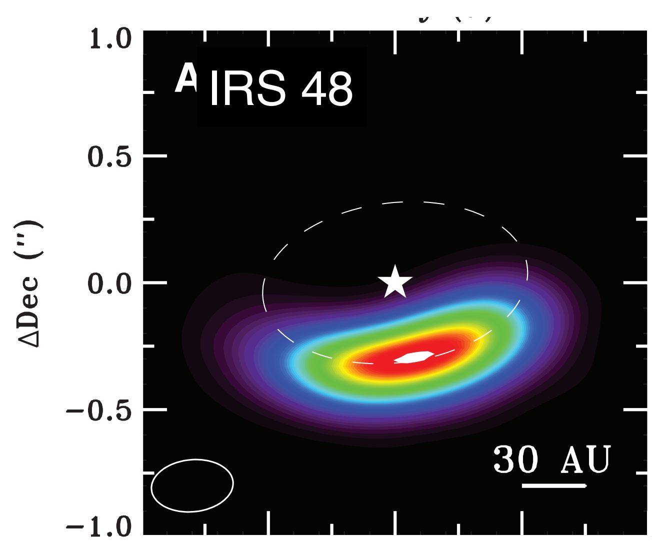


Akimasa Kataoka (NAOJ)

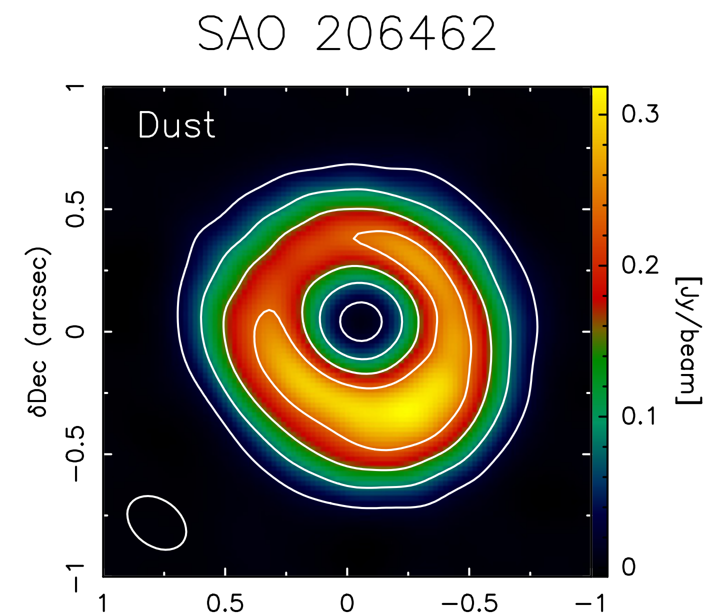
Protoplanetary disks



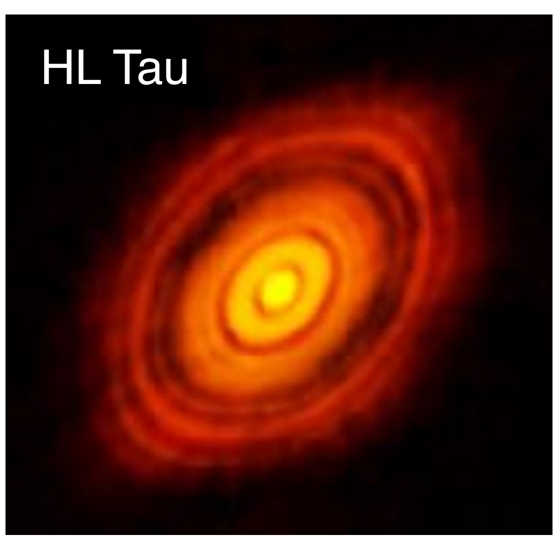
Fukagawa et al. 2013



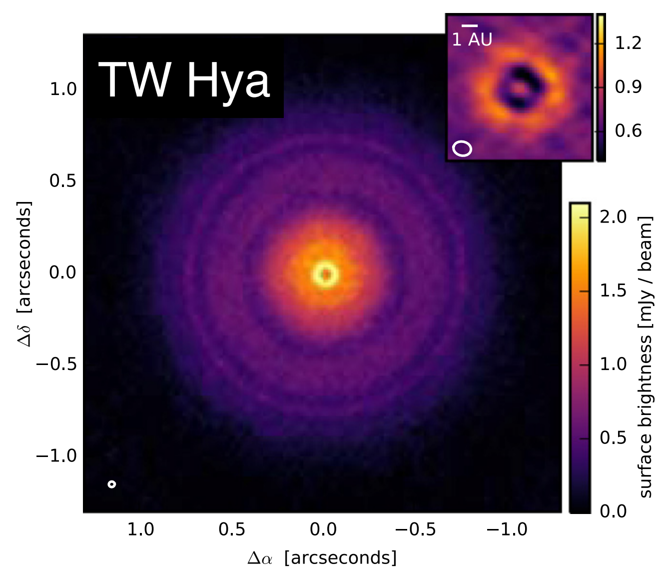
van der Marel et al. 2013



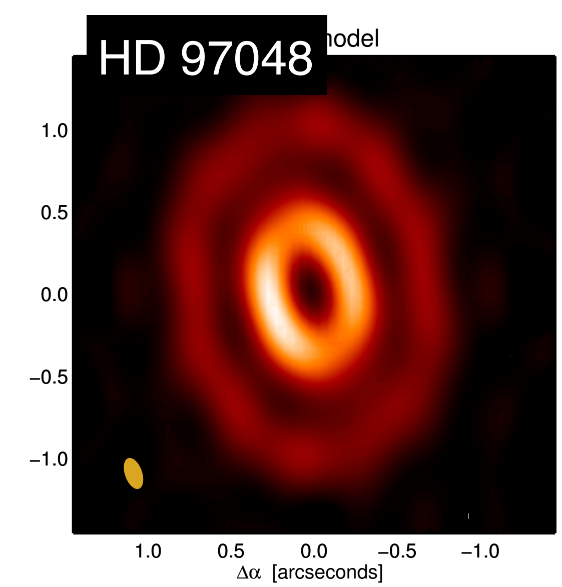
Perez et al. 2014



ALMA Partnership 2015



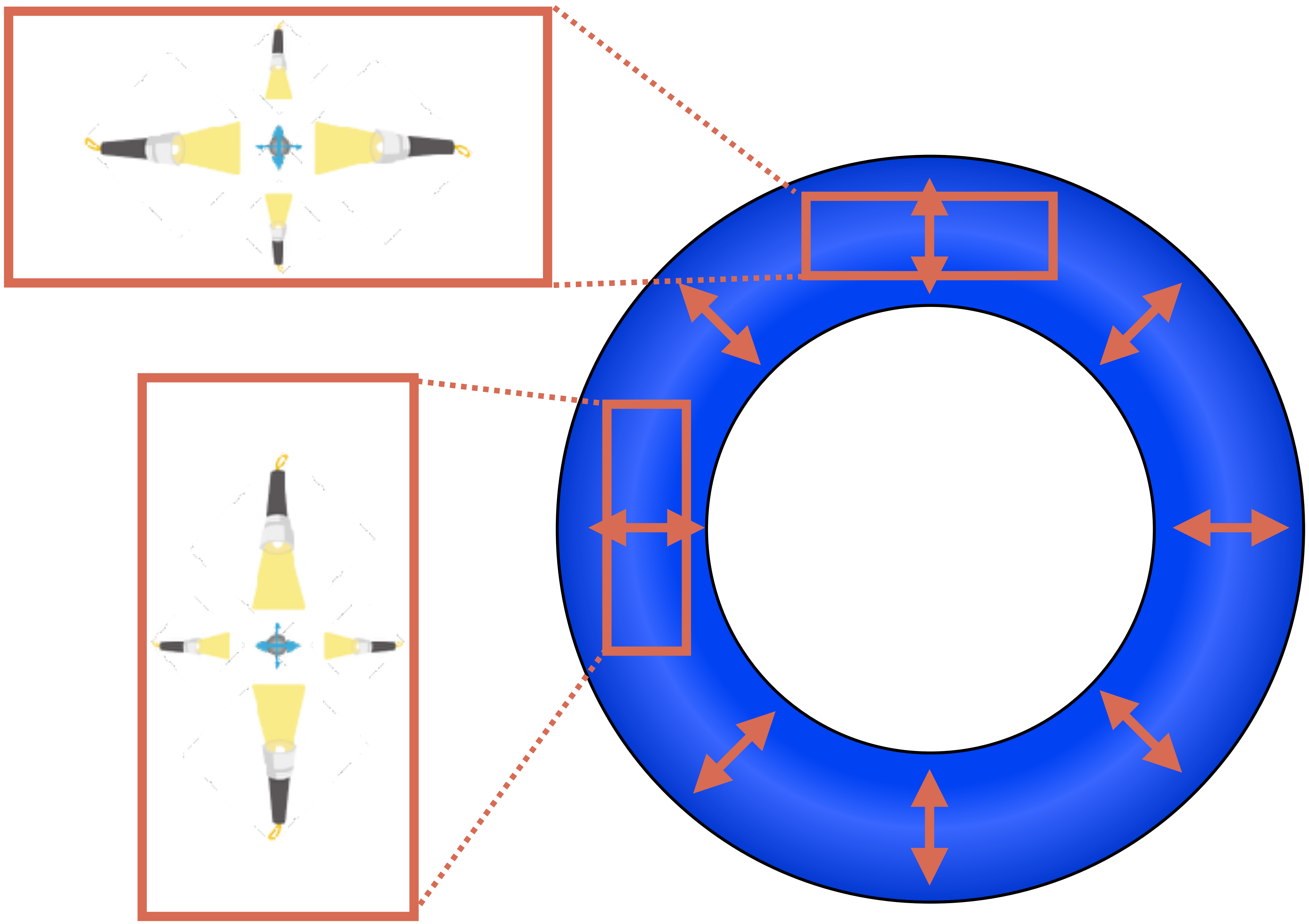
Andrews et al. 2016



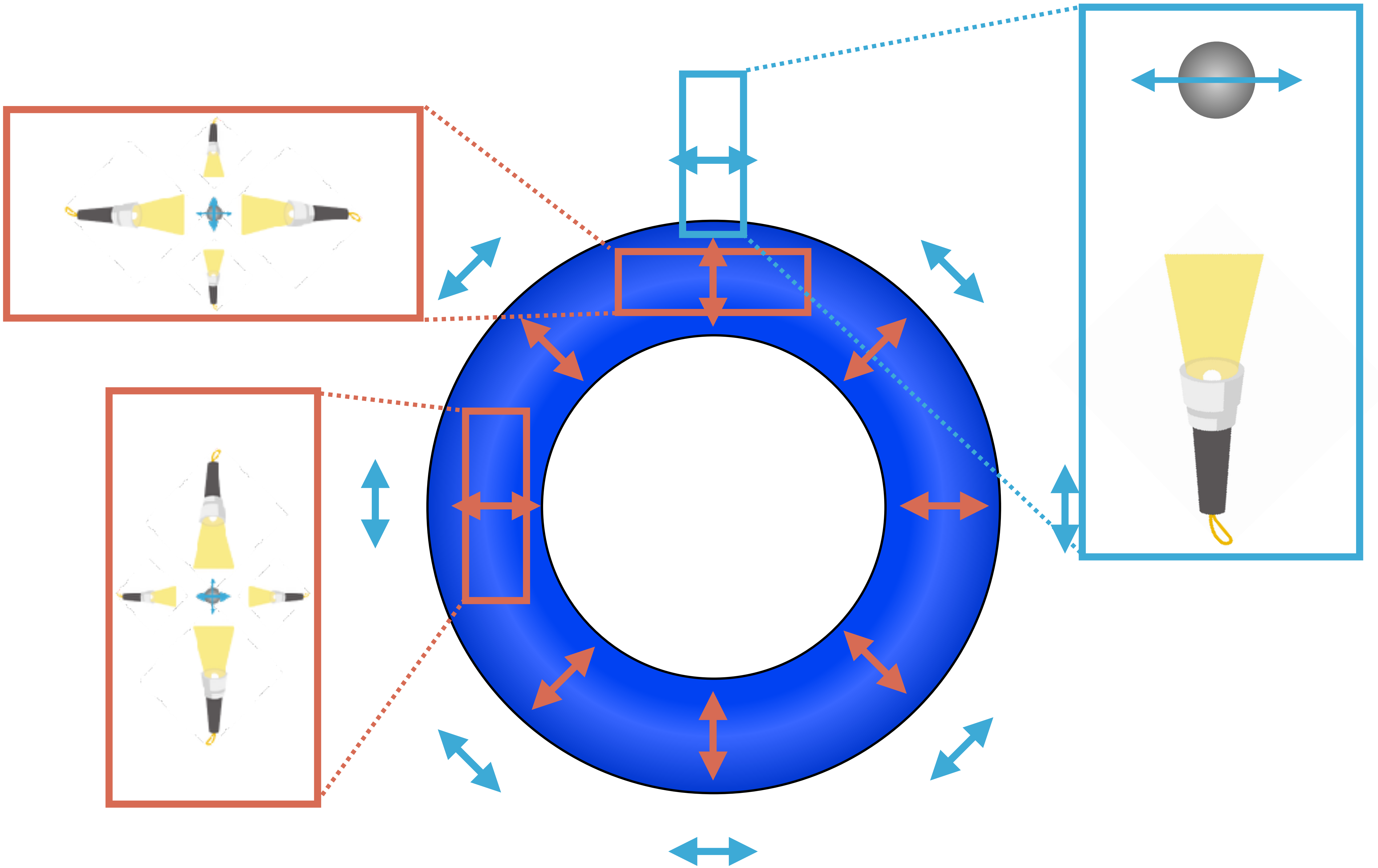
van der Plas et al. 2016

Anisotropic thermal emission at mm wavelengths

self-scattering in a protoplanetary disk

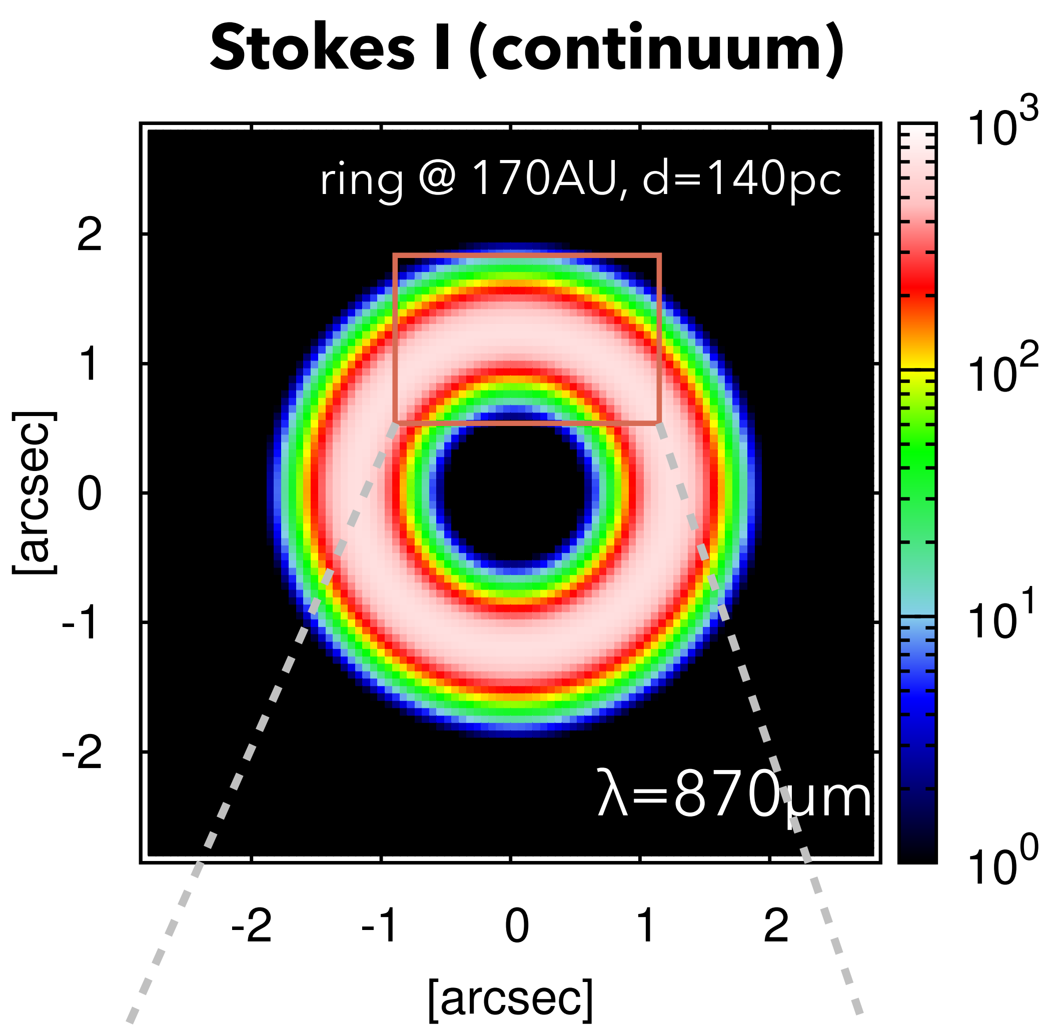


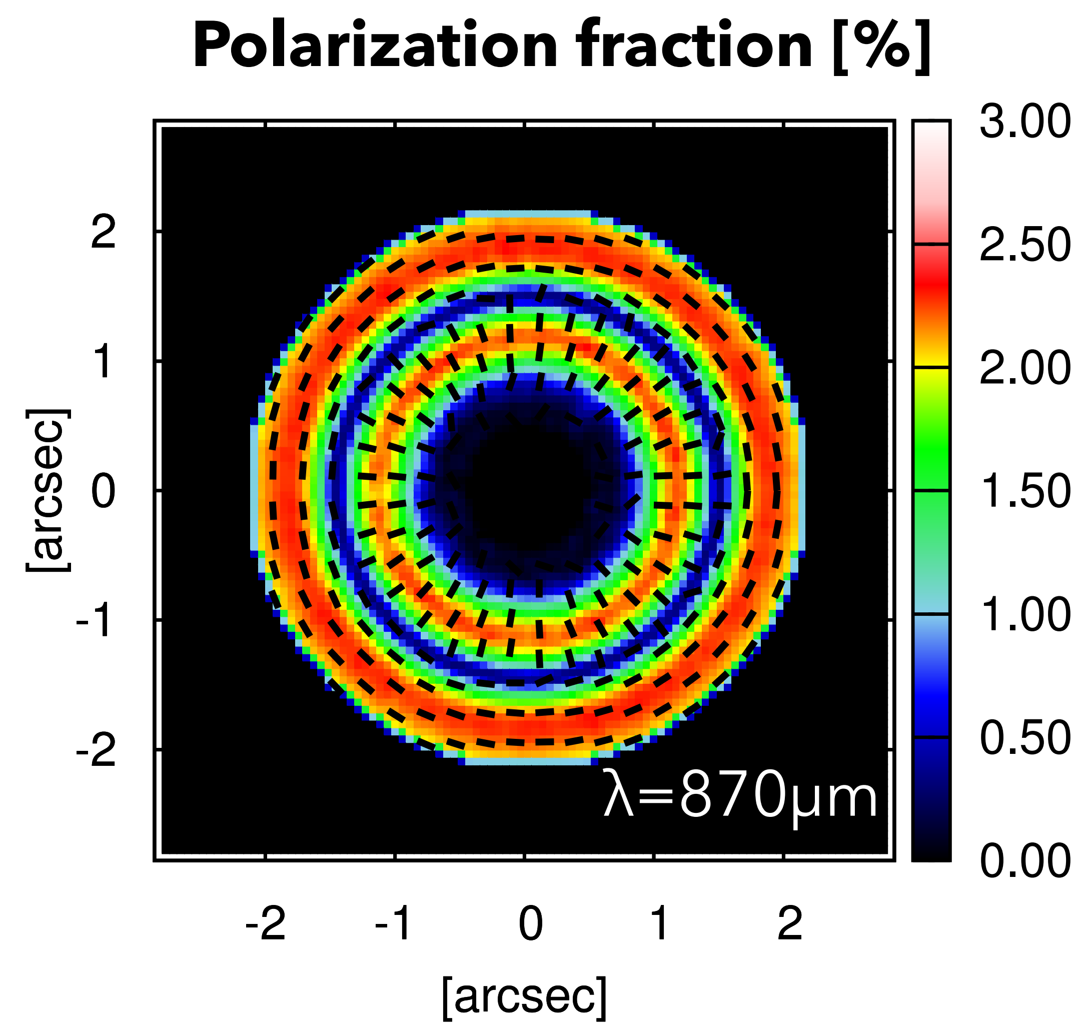
self-scattering in a protoplanetary disk

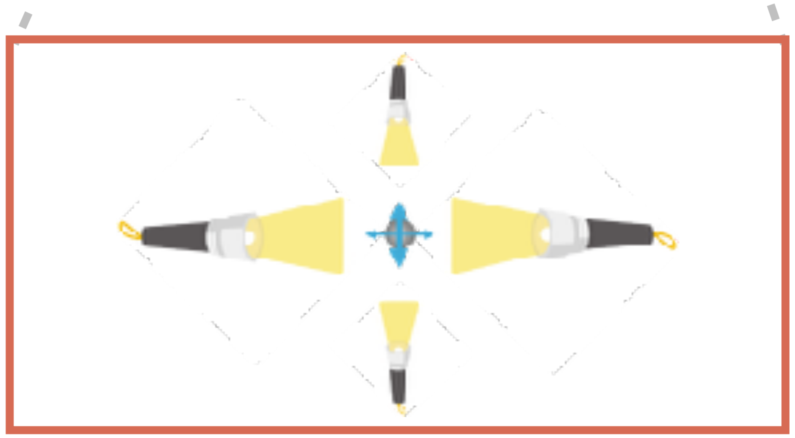


Akimasa Kataoka (NAOJ)

Theoretical prediction





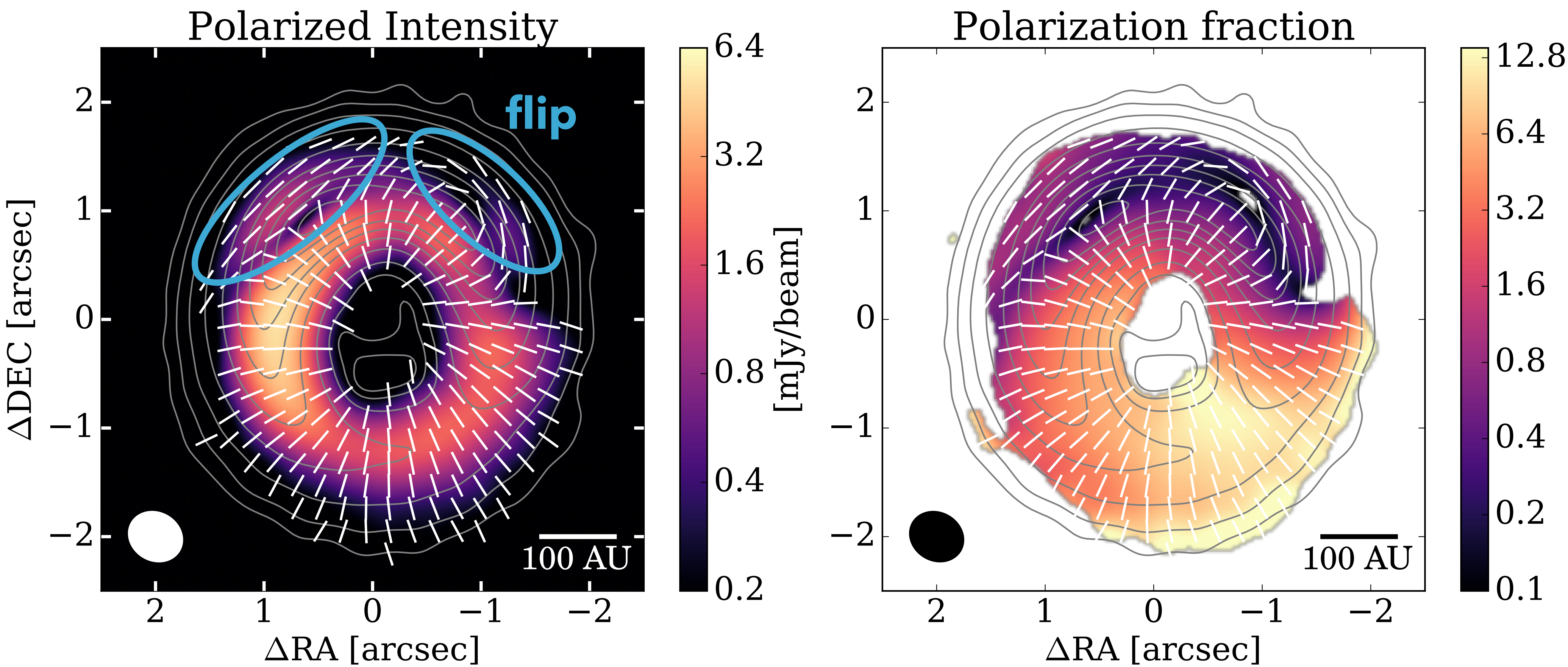


Anisotropy → net polarization

The polarization degree is as high as 2.5%
→detectable with ALMA

Kataoka, et al., 2015

ALMA observation of HD 142527



- **Flip of polarization vectors**
  - Change of the direction of radiative flux - evidence of the self-scattering (Kataoka et al. 2015)

Kataoka, et al., 2016b

Conditions of dust grains for polarization

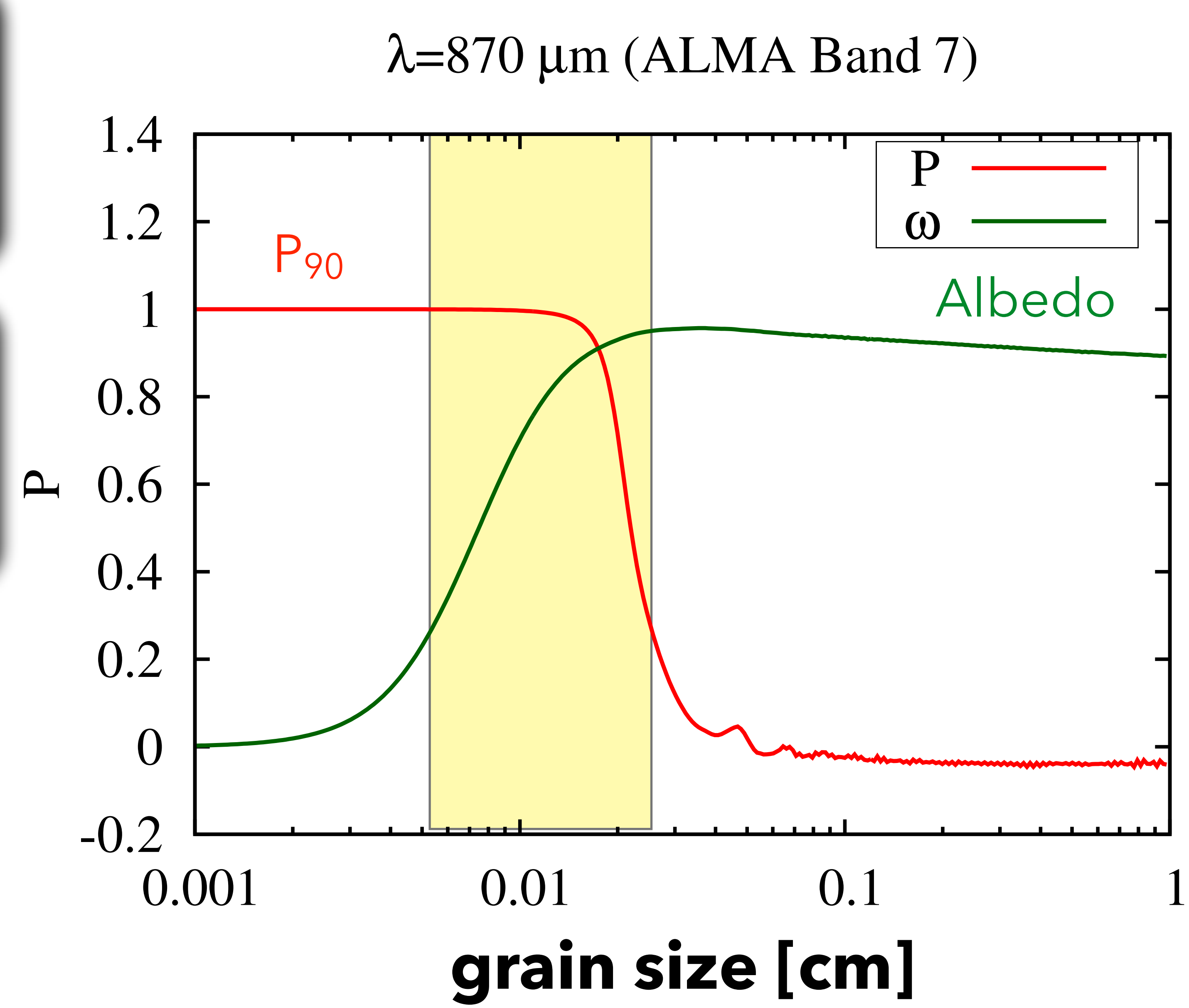
- For efficient scattering

  (grain size) >~ λ

- For efficient polarization

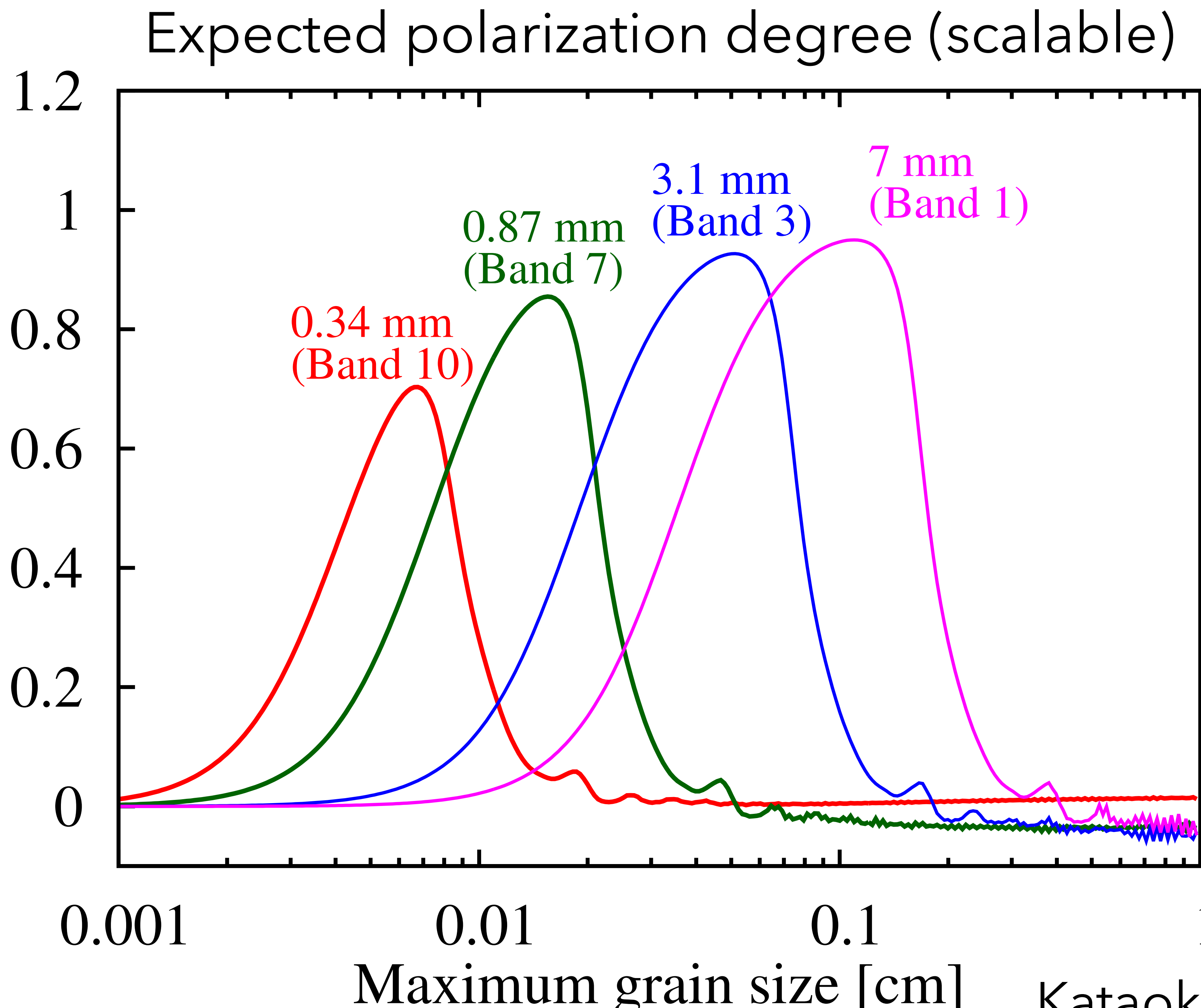
  (grain size) <~ λ

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

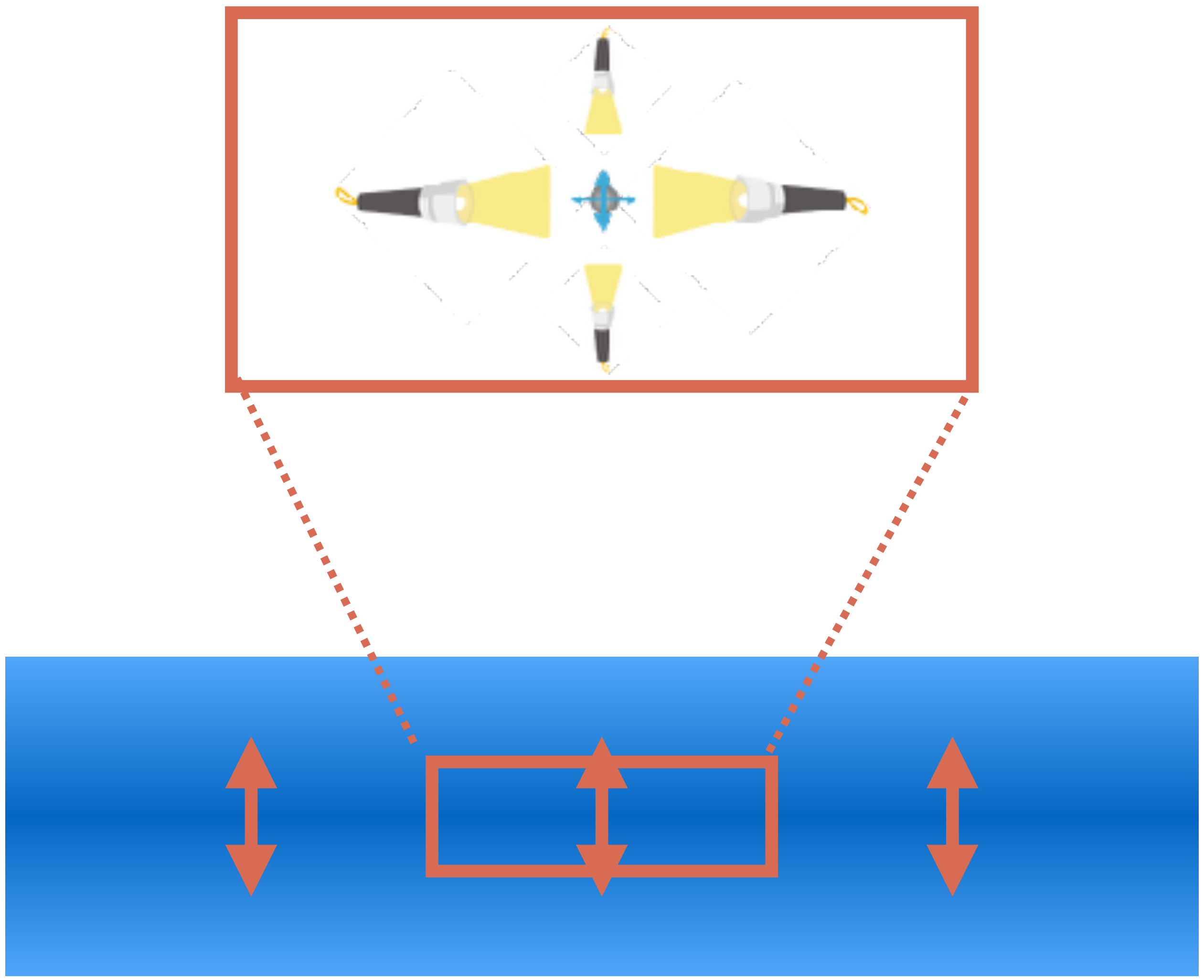
Grain size constraints by polarization



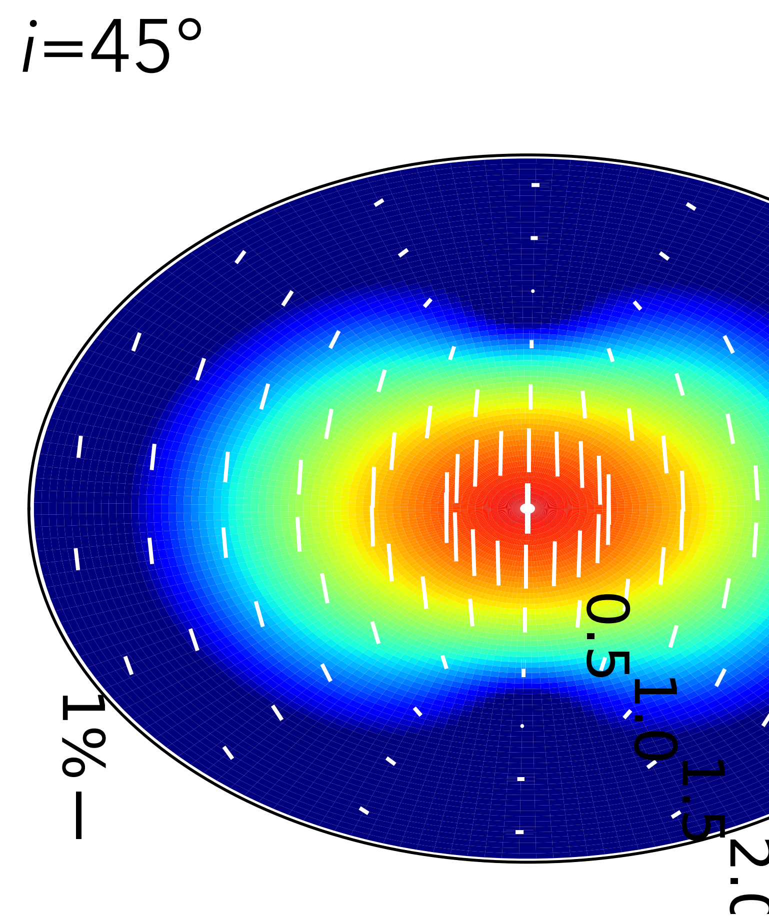
Kataoka, et al., 2015

Multi-wave polarization → constraints on the grain size

self-scattering in an inclined disk



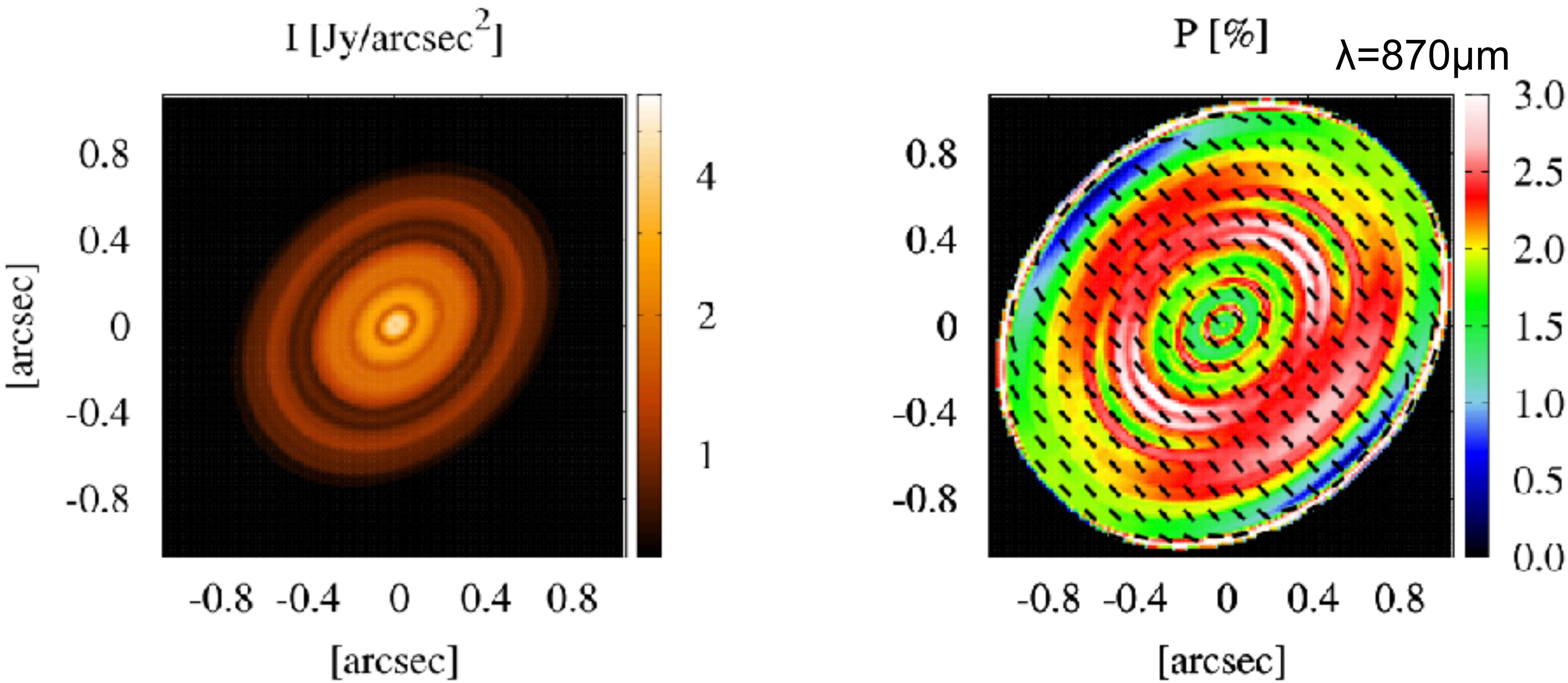
(disk, edge-on view)



Yang, Li, et al. 2016

See also Kataoka et al. 2016a

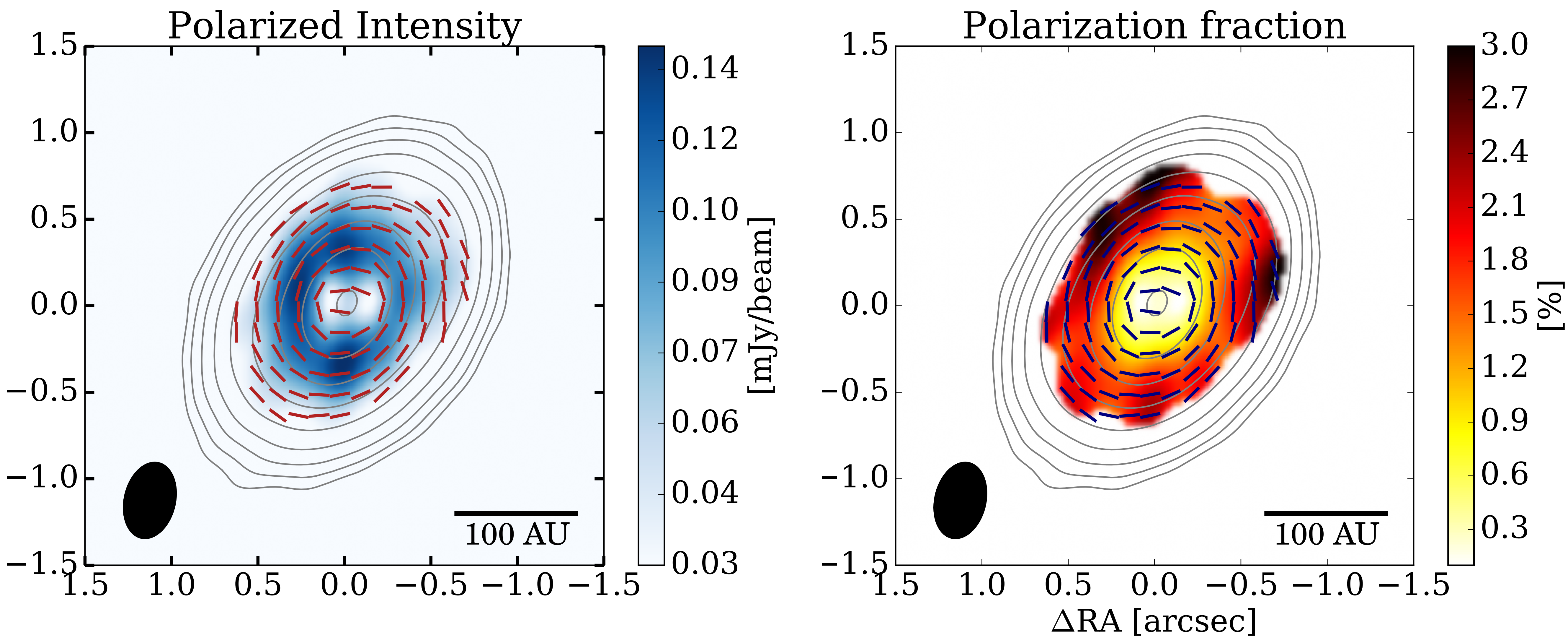
HL Tau pol. - prediction



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

Kataoka, et al., 2016a (see also Yang et al. 2016)

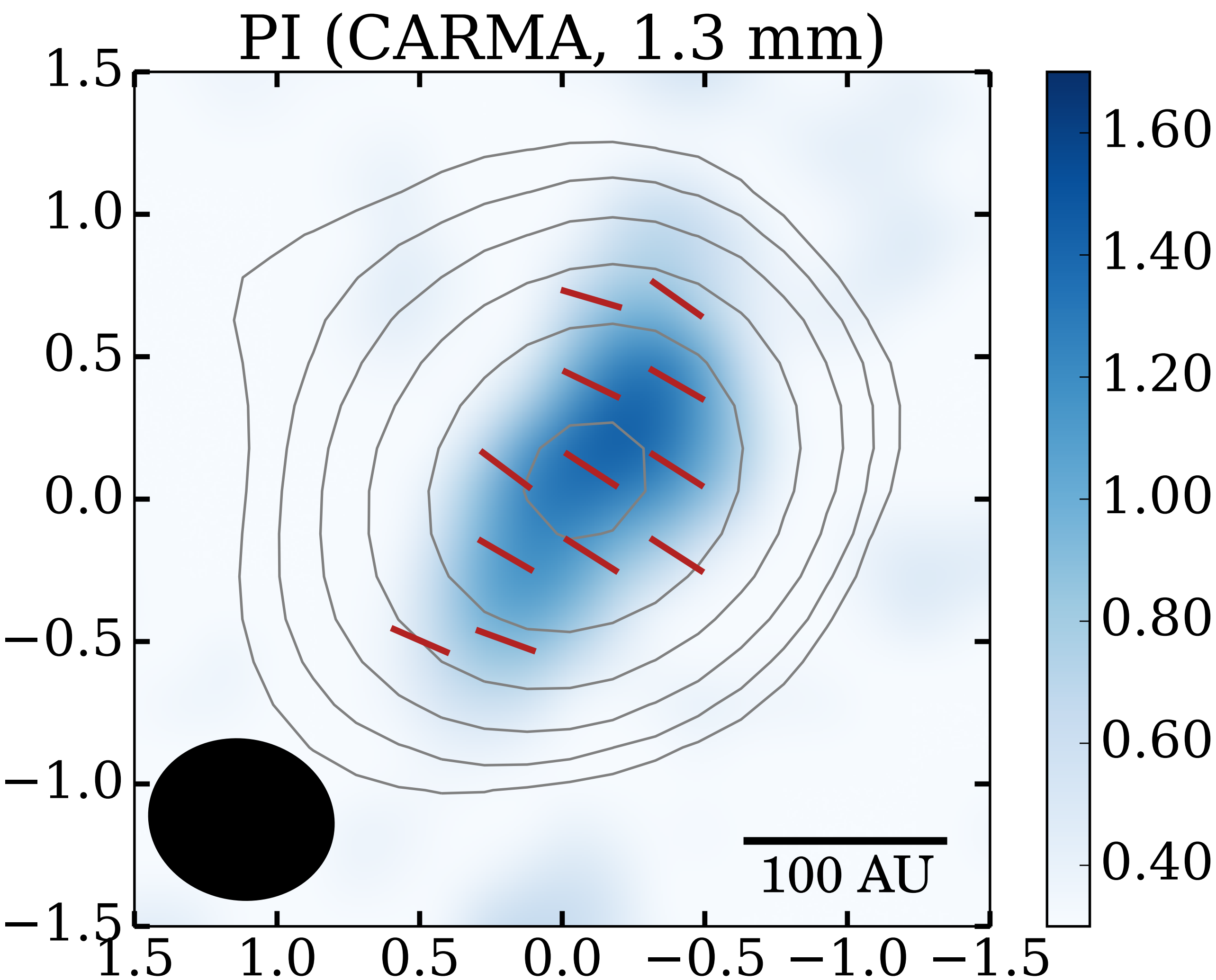
HL Tau polarization with ALMA



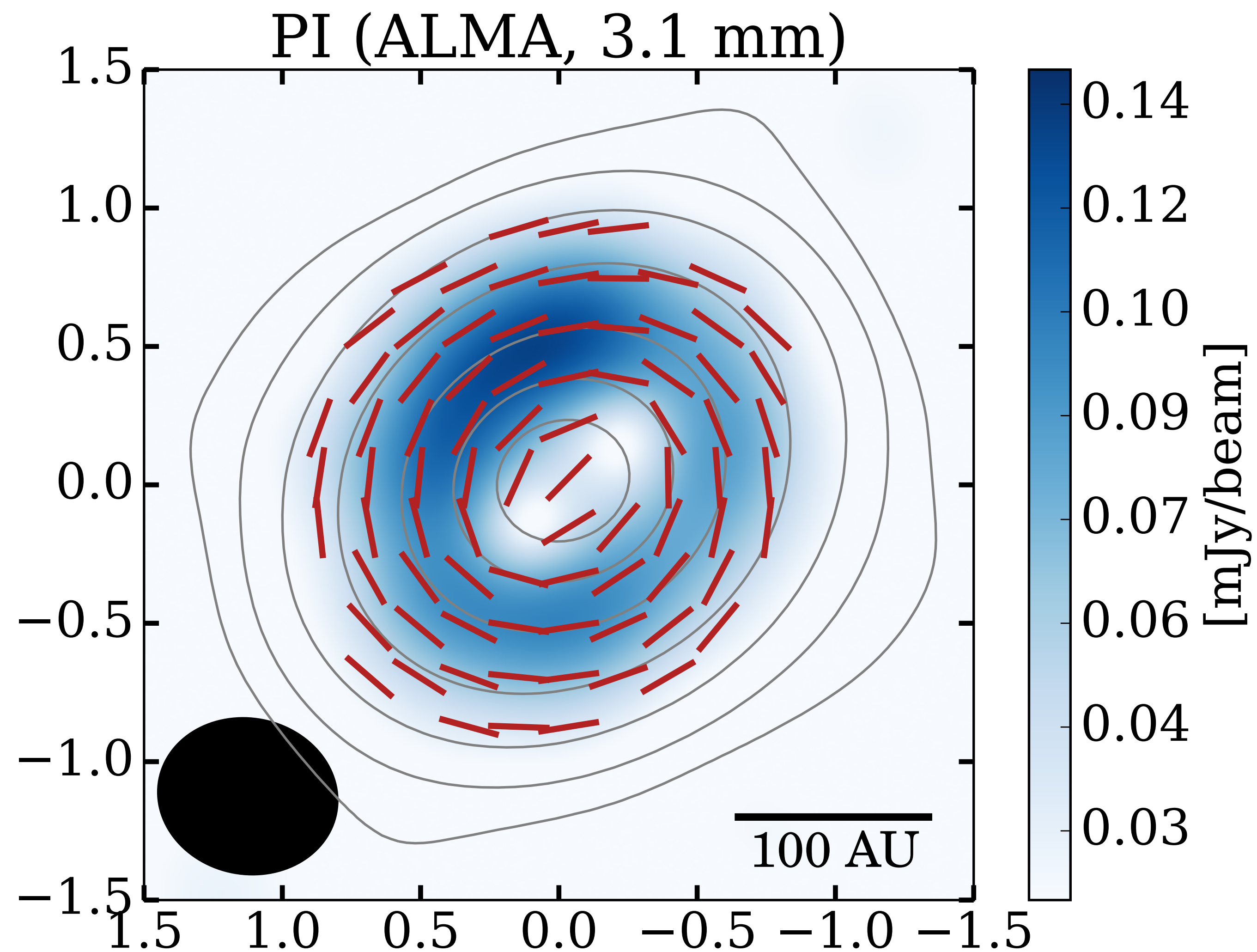
- **We find the azimuthal polarization vectors at 3.1 mm wavelength**

Kataoka, et al., 2017

HL Tau polarization



data from Stephens et al., 2014

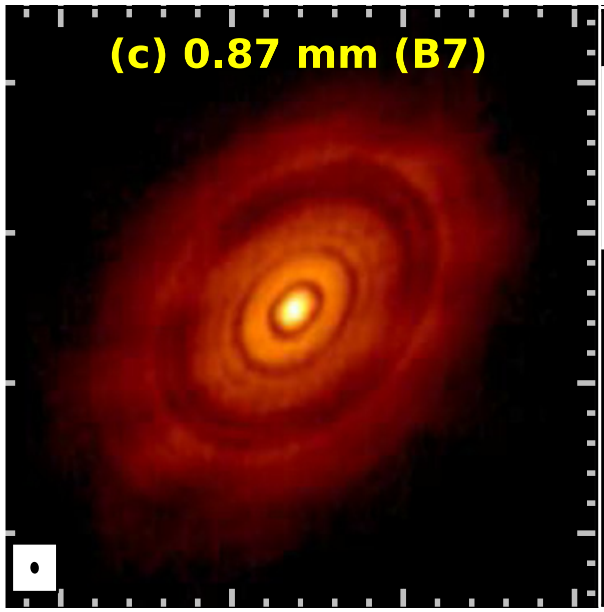


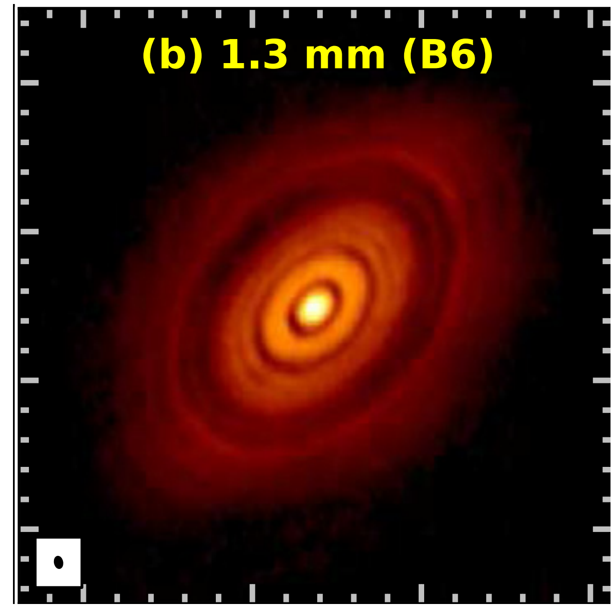
Kataoka, et al., 2017

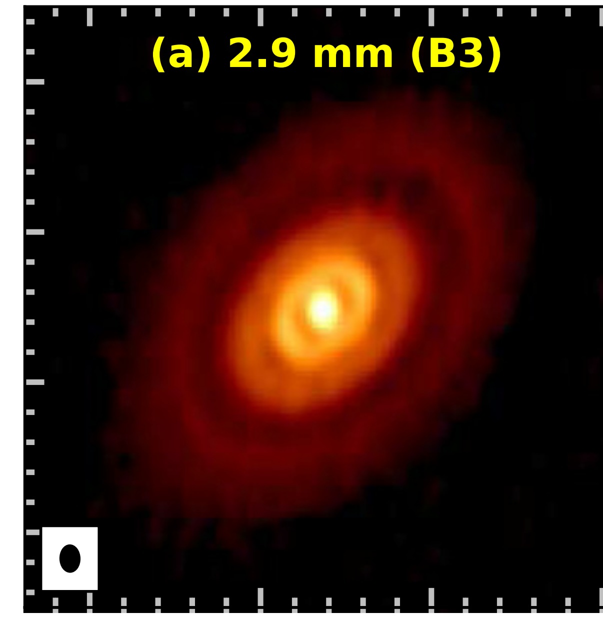
- The polarization vectors at 1.3 mm are parallel to the minor axis
- The polarization vectors at 3.1 mm are in the azimuthal direction

wavelength-dependent polarization in mm range

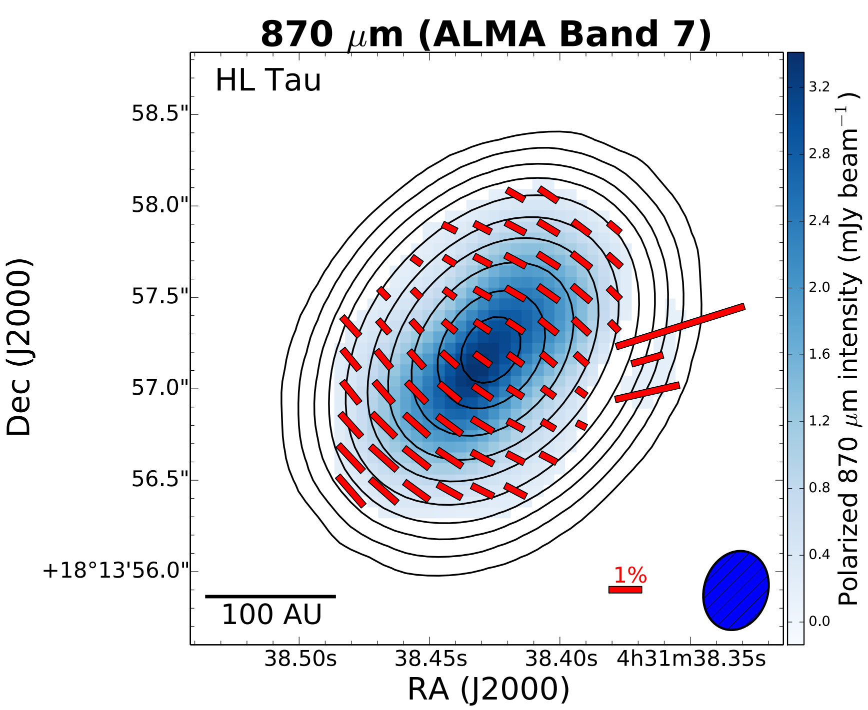
ALMA observation: HL Tau

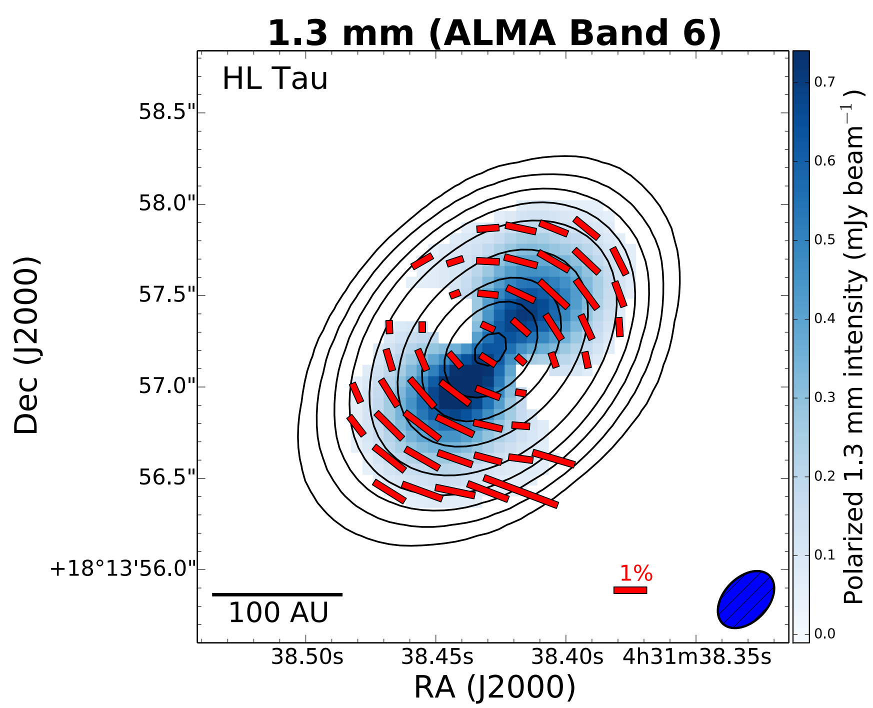




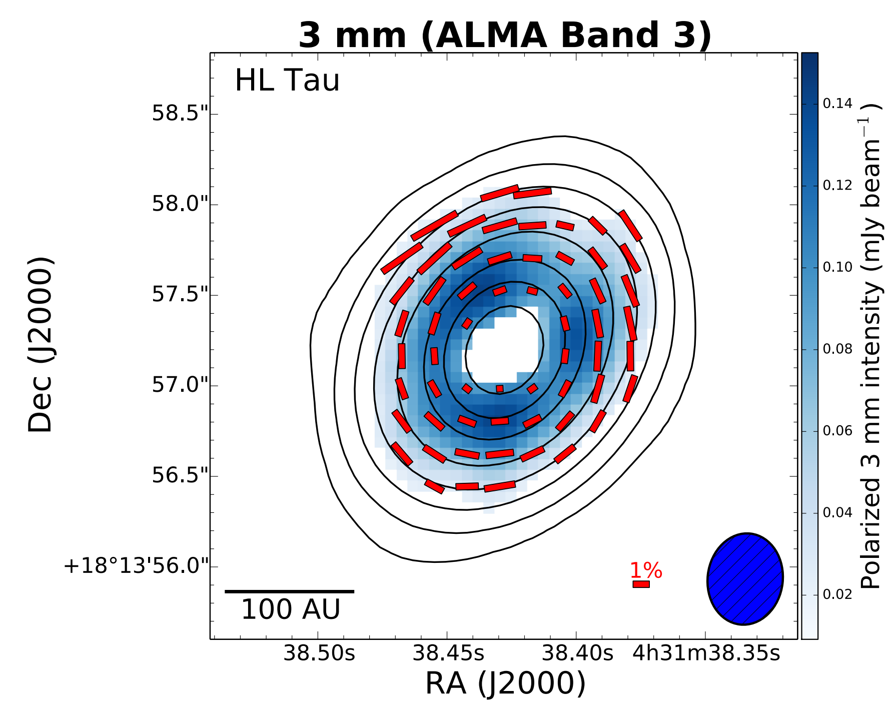


ALMA Partnership 2014





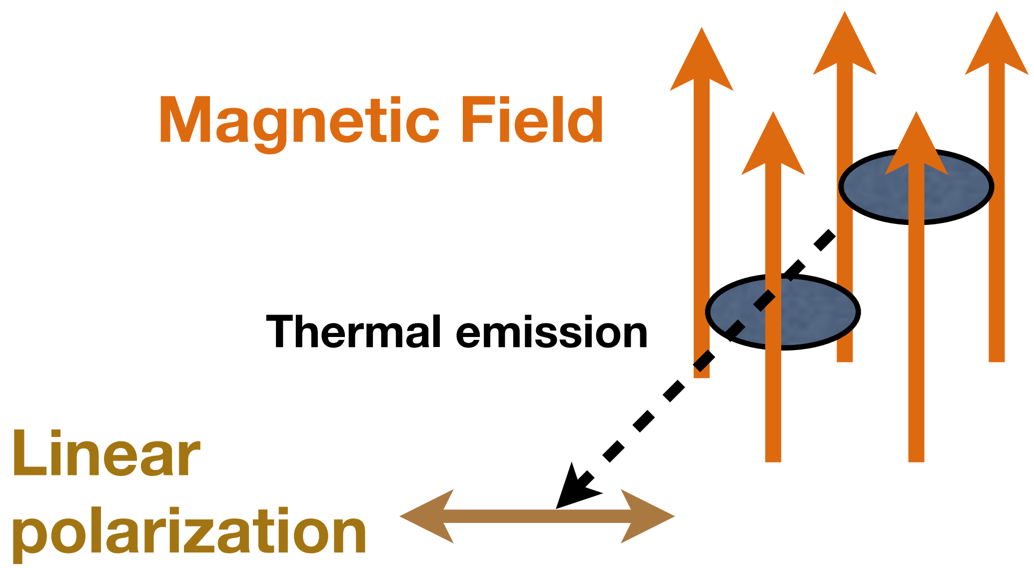
Stephens et al. 2017



Kataoka et al. 2017

Polarization mechanisms

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



e.g., Lazarian and Hoang 2007

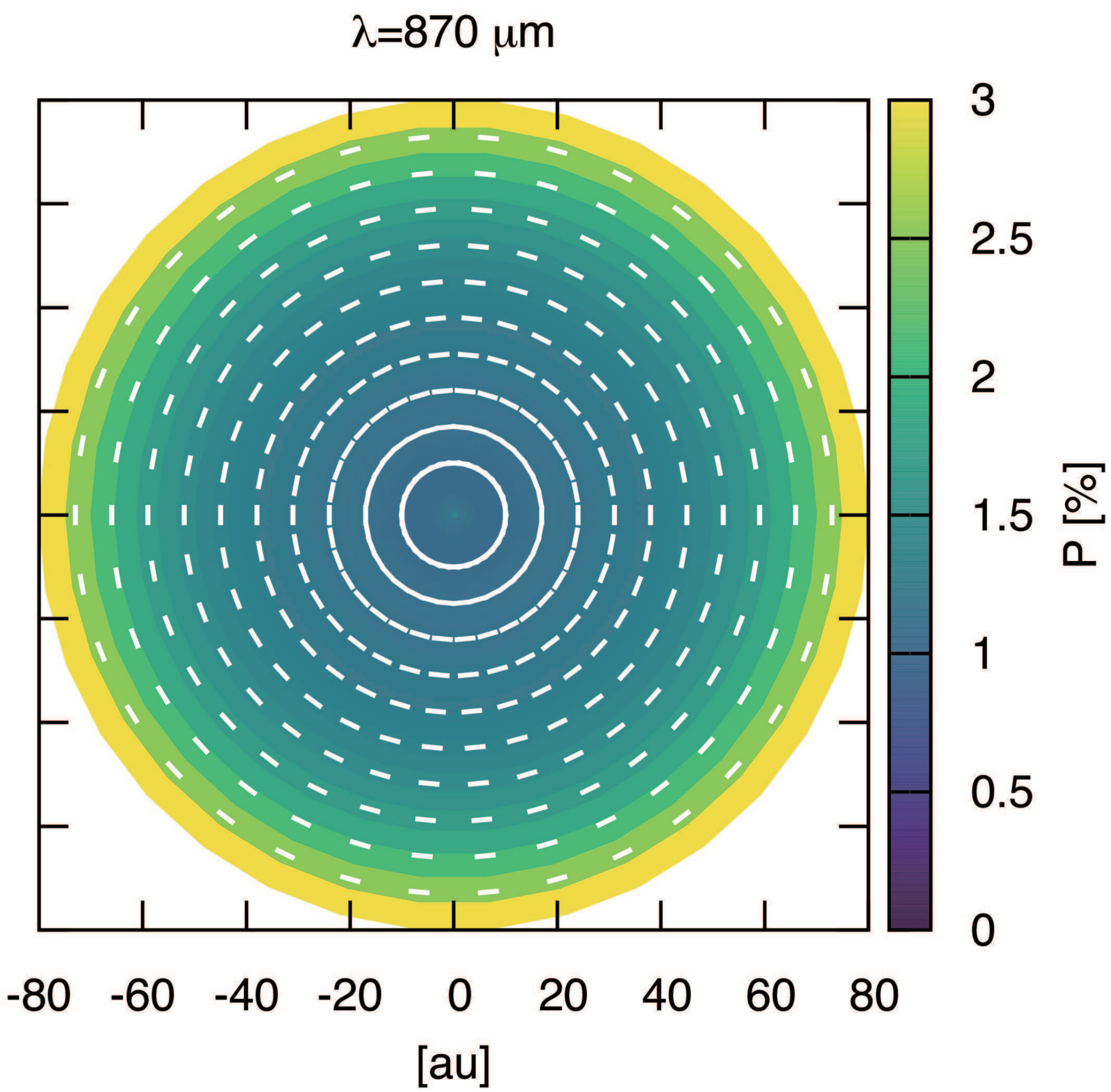
2. **The self-scattering of thermal dust emission**

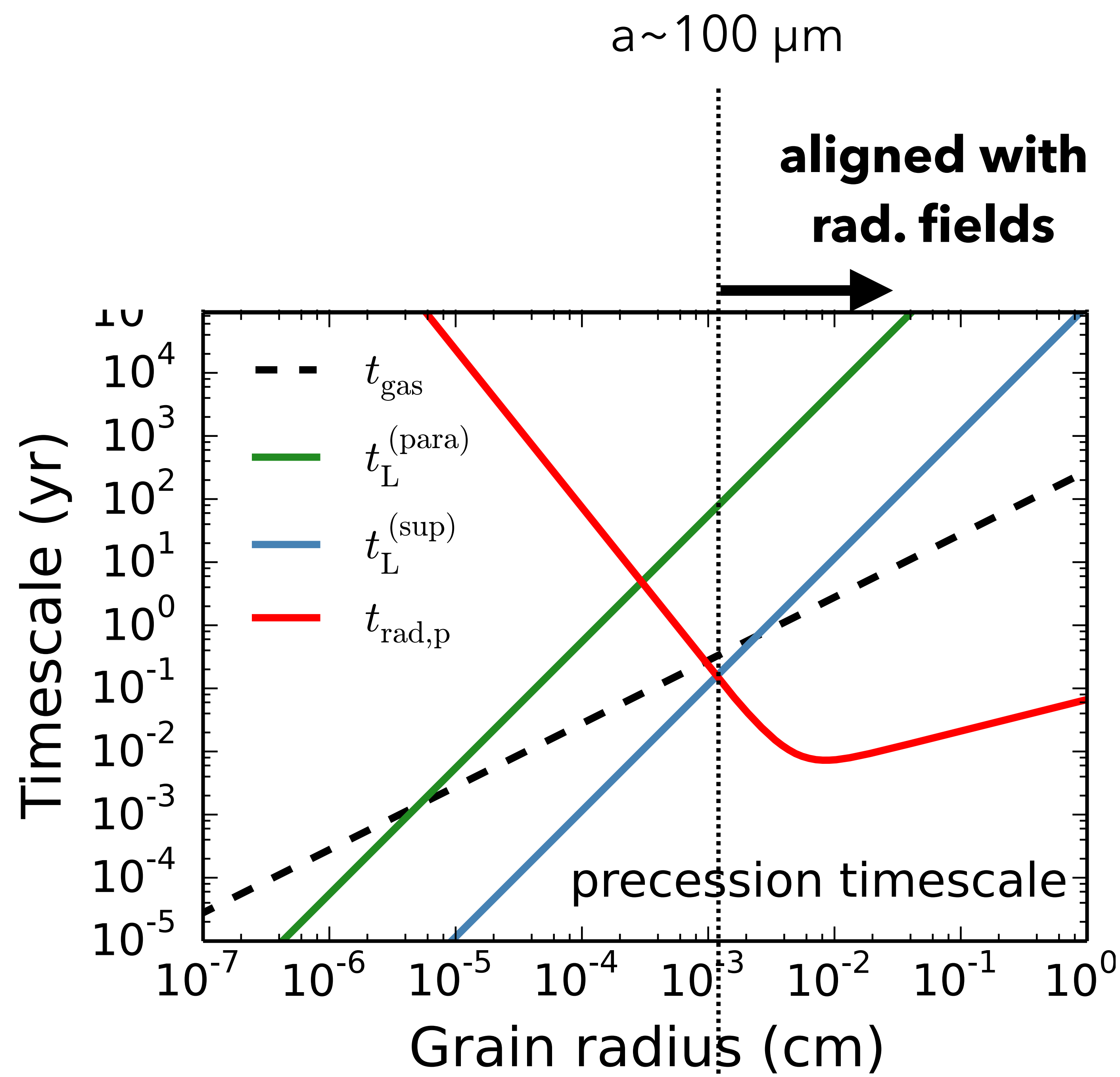
Kataoka et al. 2015

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

Tazaki, Lazarian et al. 2017

Alignment with radiation fields

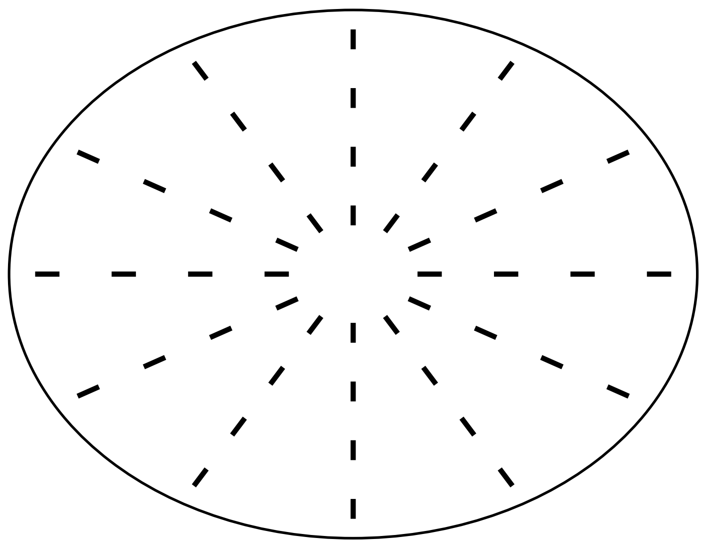




Tazaki, Lazarian et al. 2017

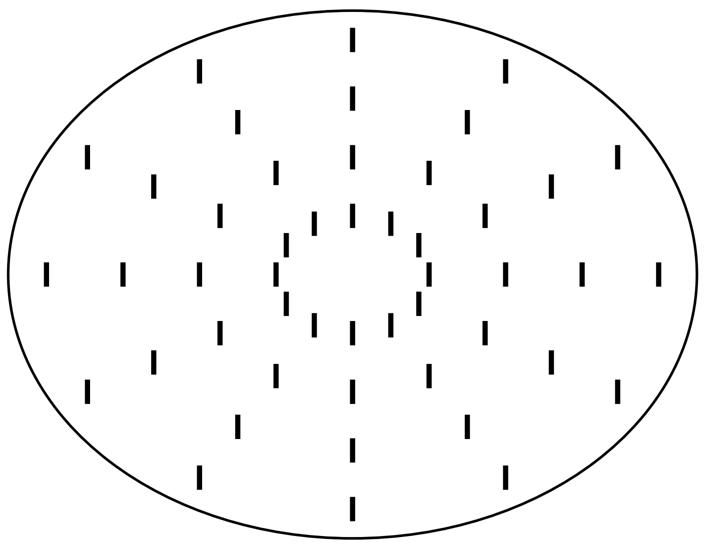
Polarization mechanisms

alignment with B-fields



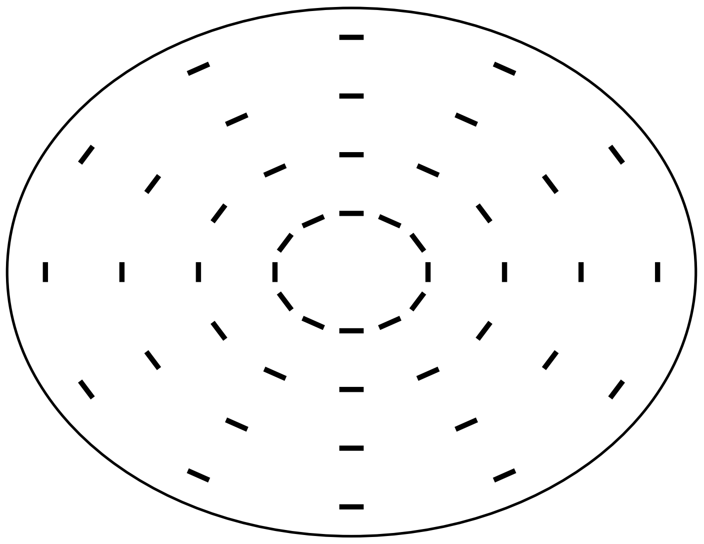
- Toroidal magnetic fields are assumed

self-scattering



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

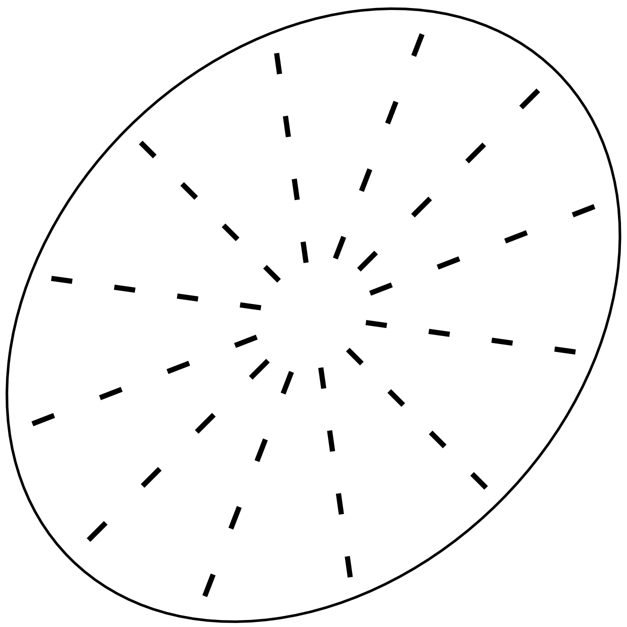
alignment with radiation



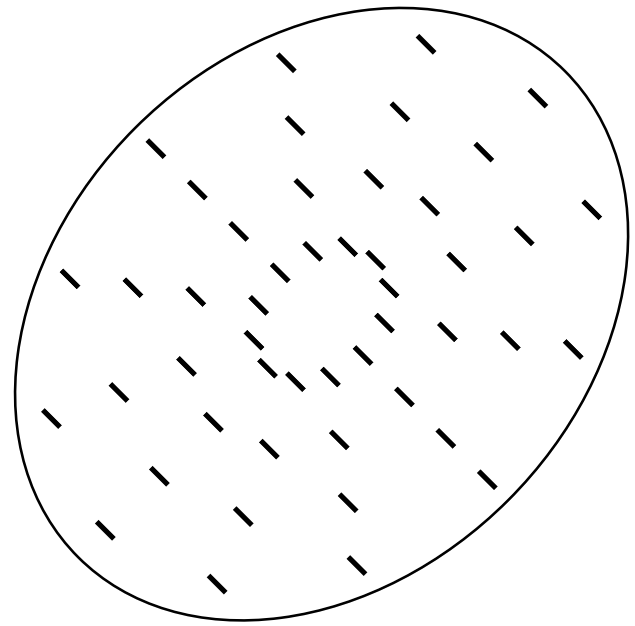
- Grains are needed to be big (~>100um)
- Radiation gradient is in the radial direction.

Wavelength dependence

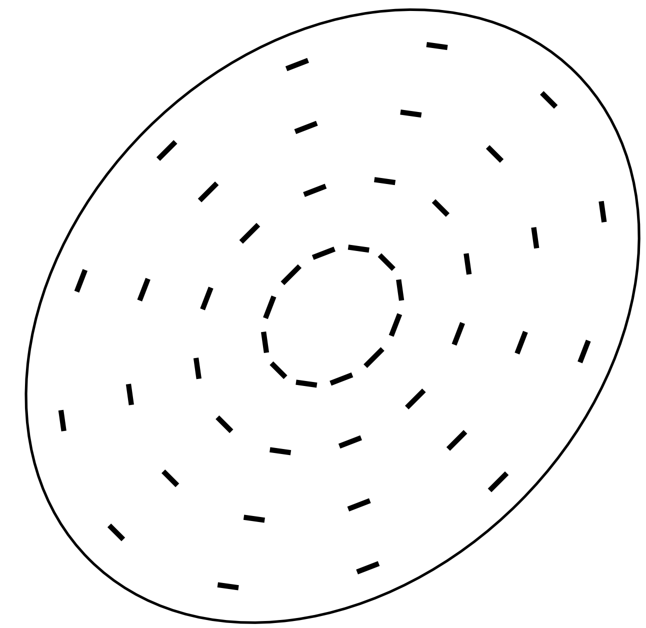
alignment with B-fields



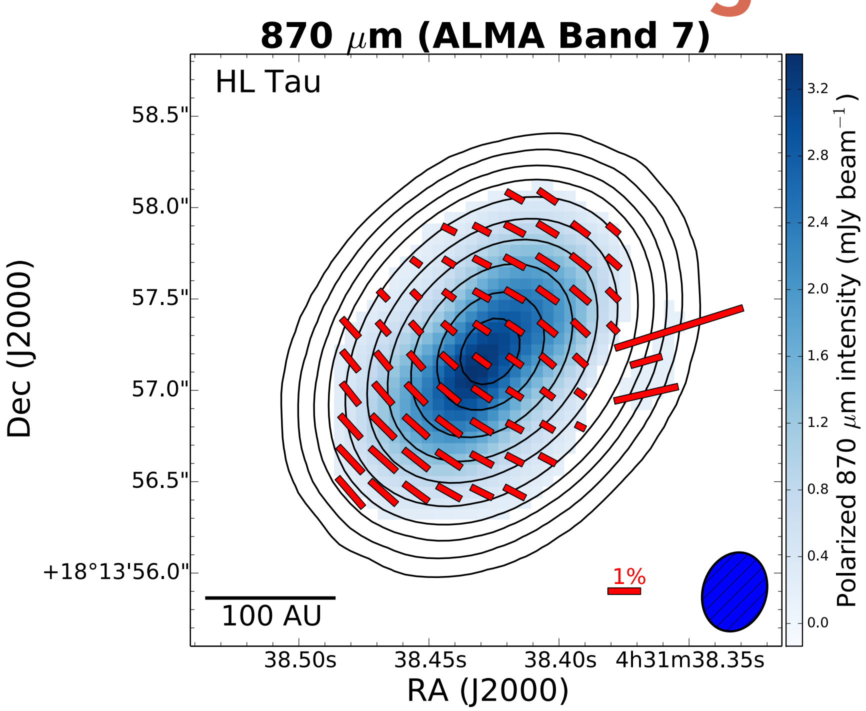
self-scattering



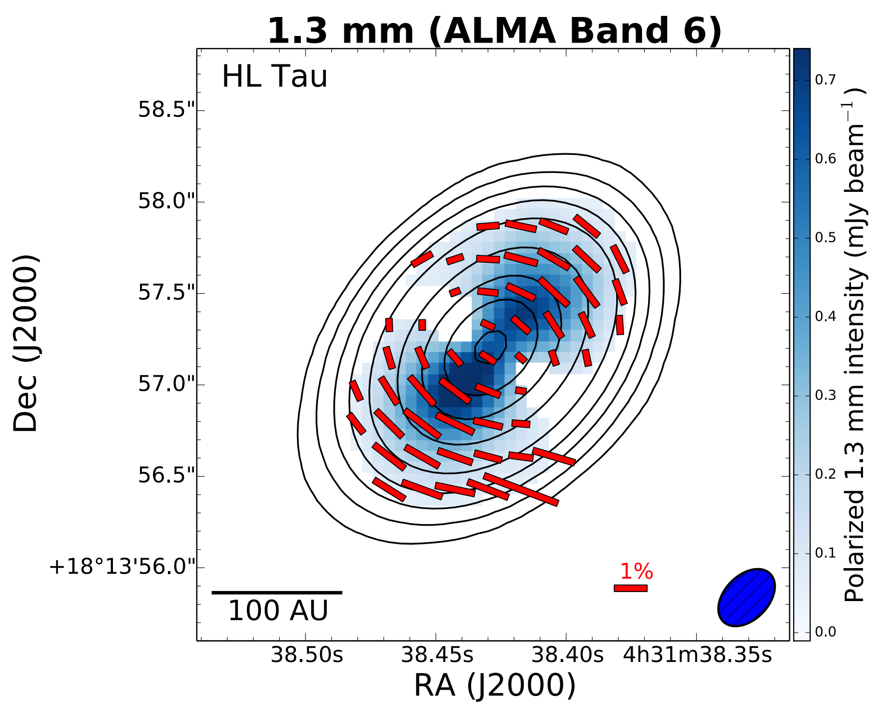
alignment with radiation



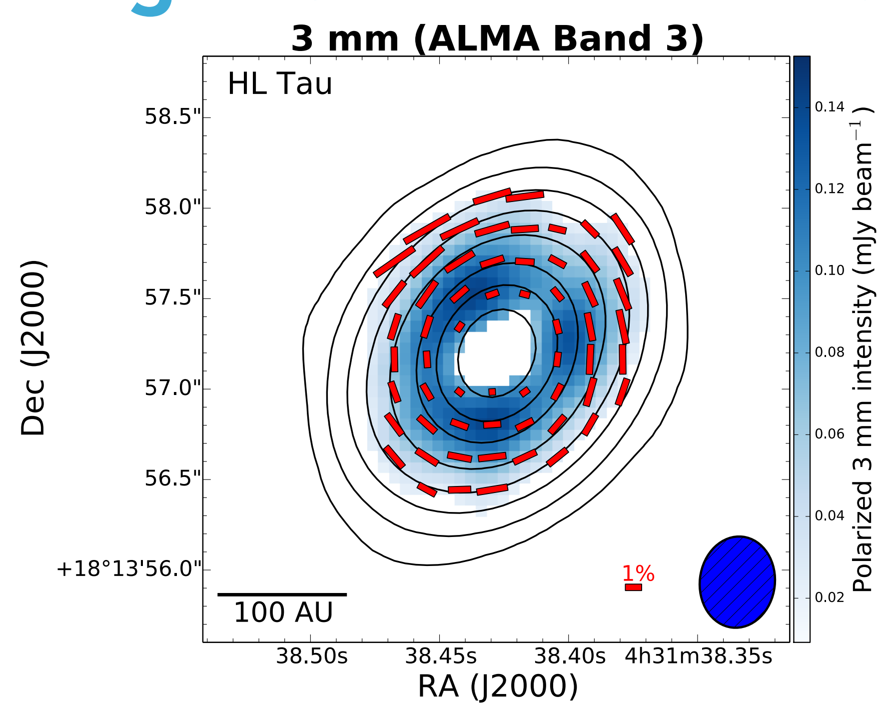
self-scattering



mixture

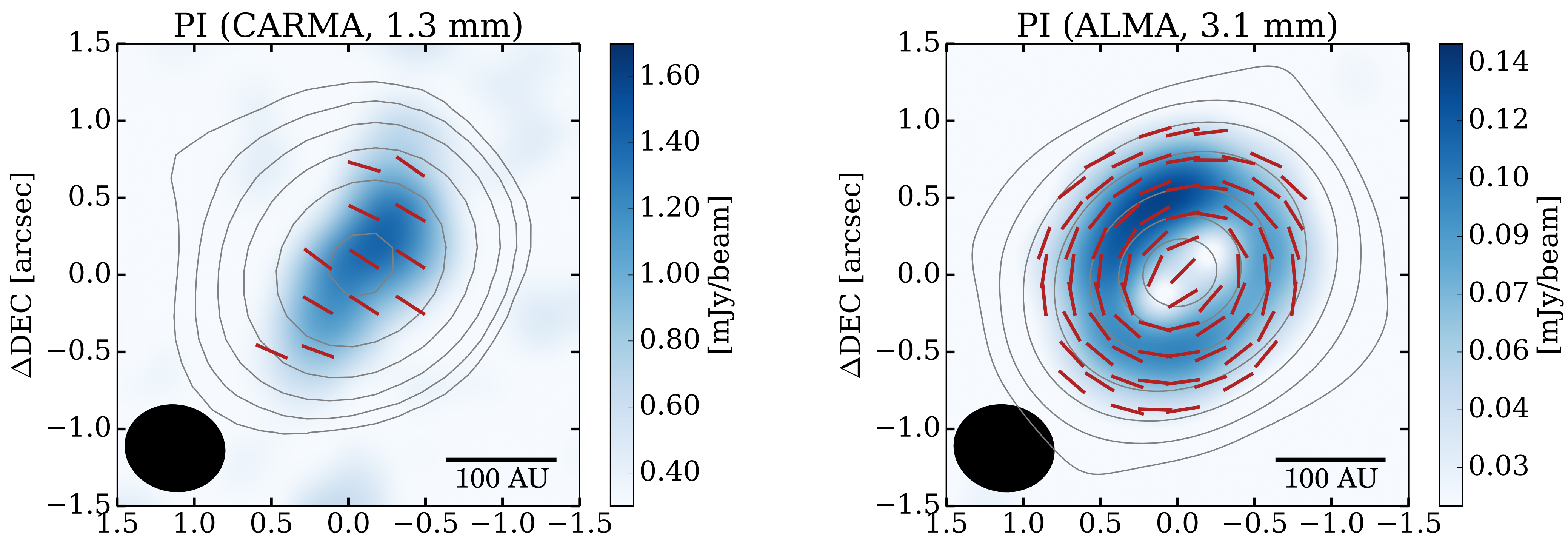


alignment with radiation

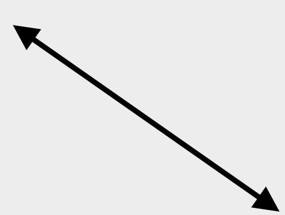


Stephens et al. 2017 (see also Kataoka et al. 2017)

Total polarization fraction



integrating



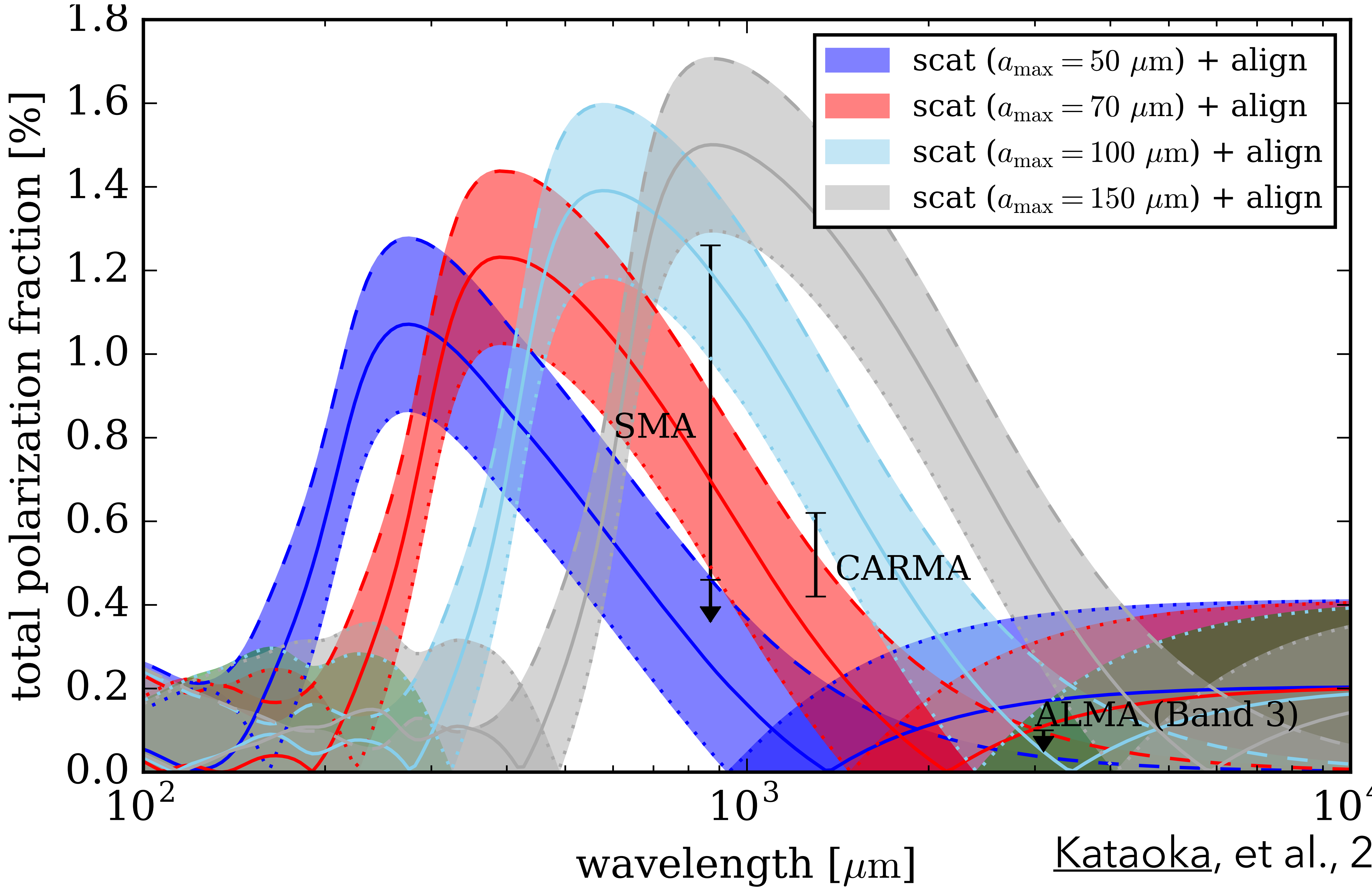
0.5%

no polarization

<0.1%

We can extract the self-scattering components

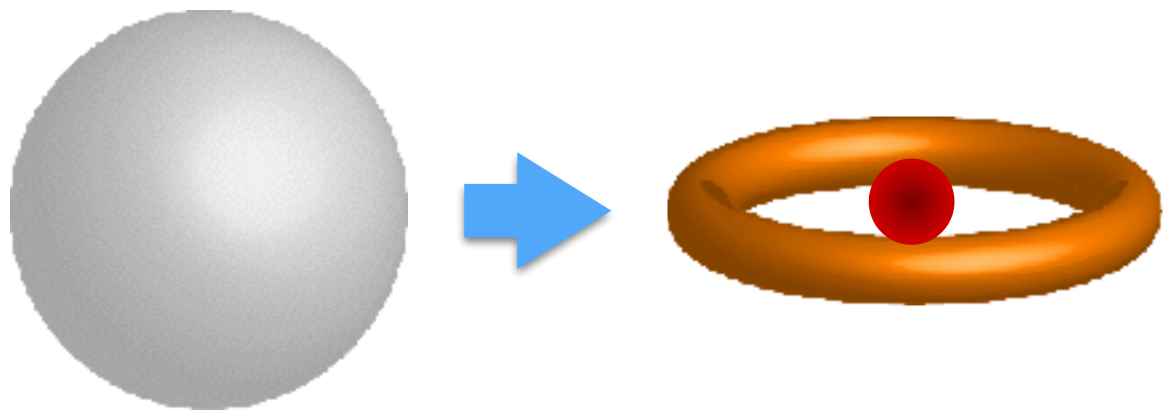
HL Tau polarization

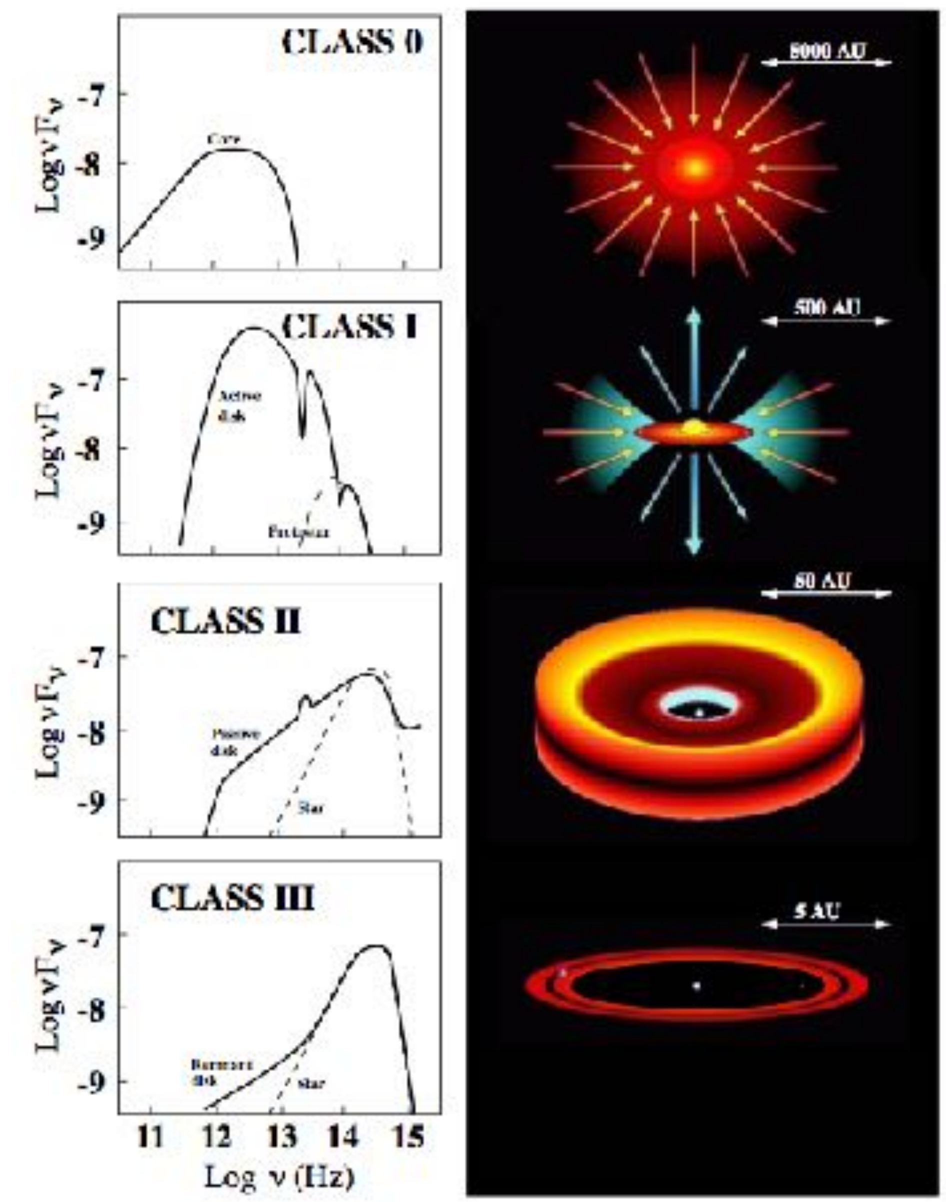


Kataoka, et al., 2017

The maximum grain size is ~ 70 μm

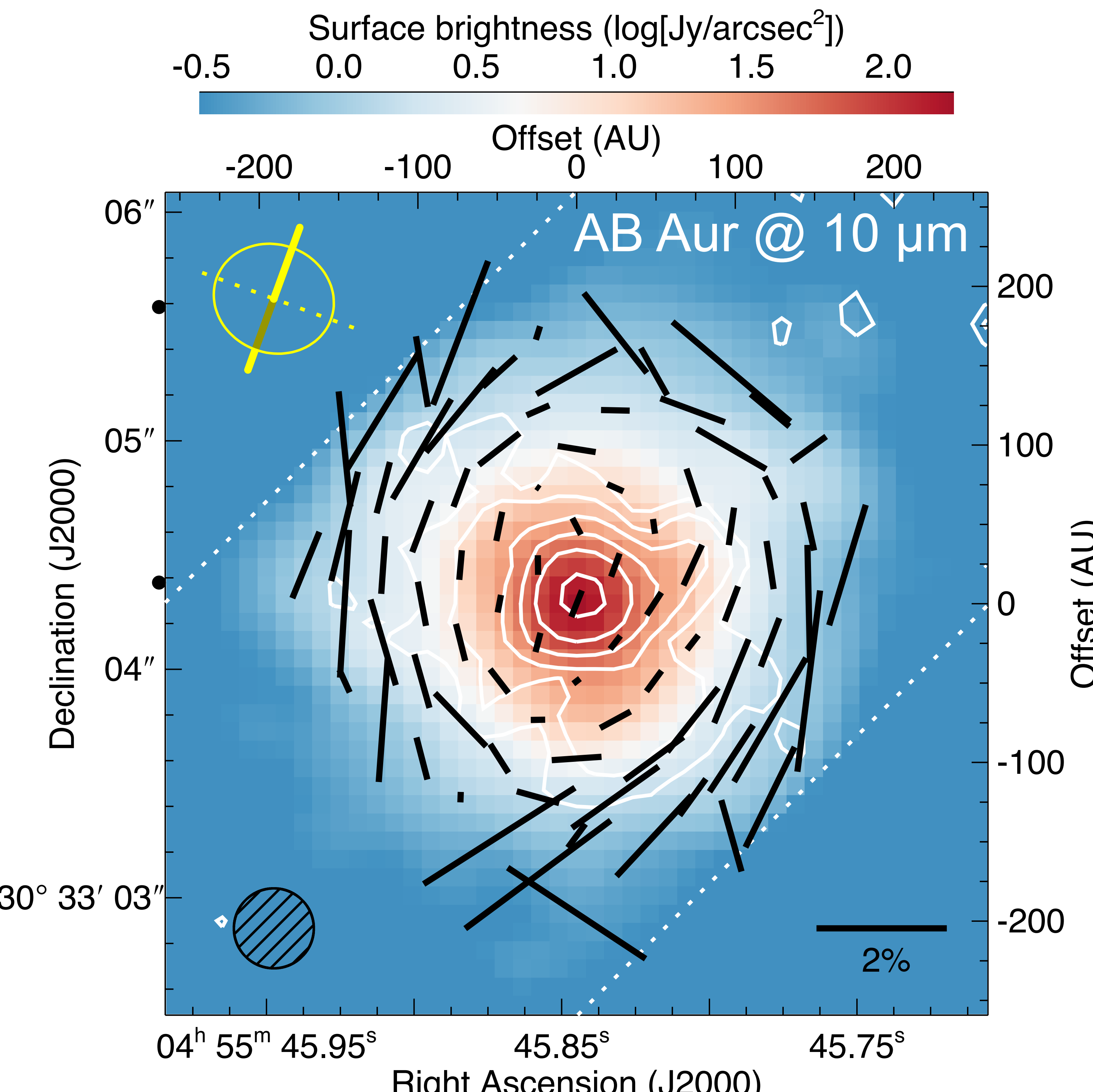
Star and disk formation

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



A.Isella

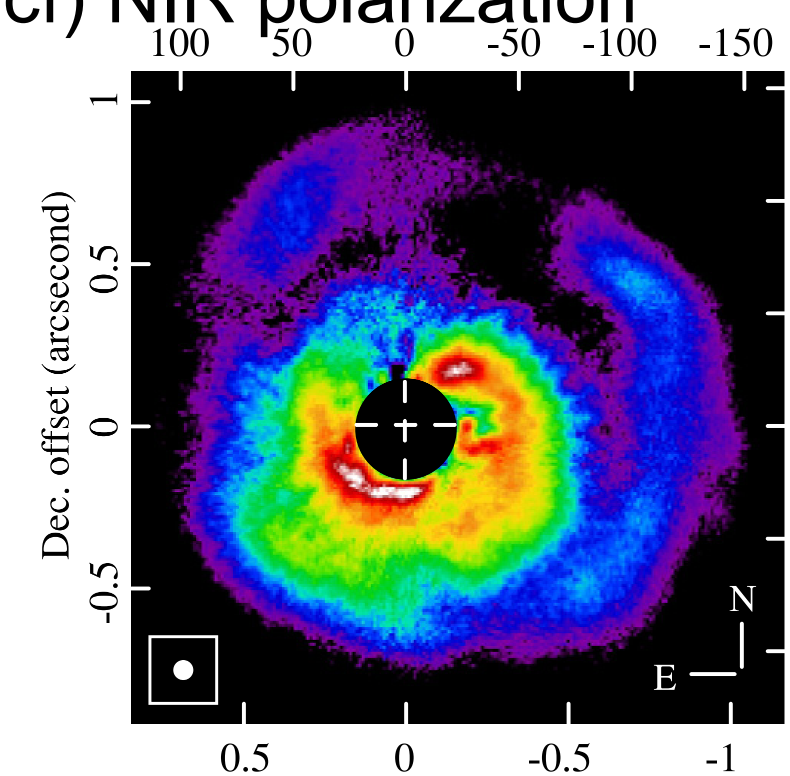
10μm polarization



Dan Li, et al., 2016

- Inner part - grains are aligned with poloidal B-fields at surface
- Outer part - the self-scattering-induced polarization

cf) NIR polarization



Hashimoto et al., 2011

Current understandings

1μm — 10μm — 100μm — 1mm

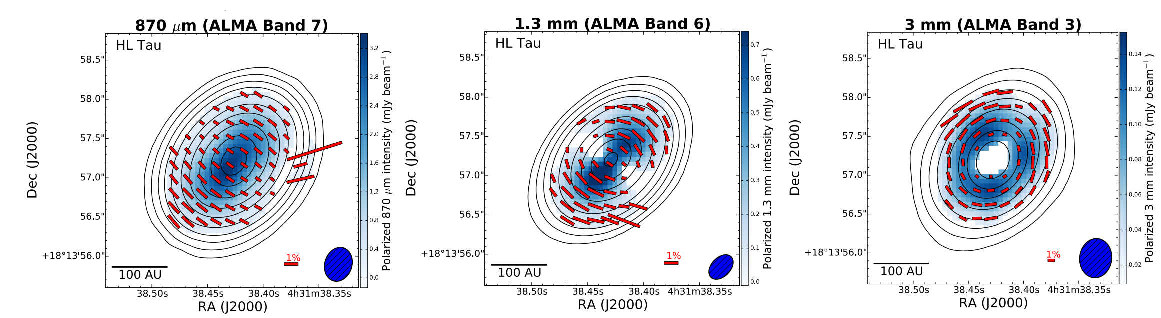
scattering of photons of central star

Alignment with B-field?

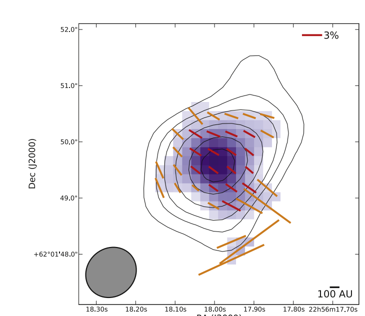
Alignment with rad-fields

scattering (?)

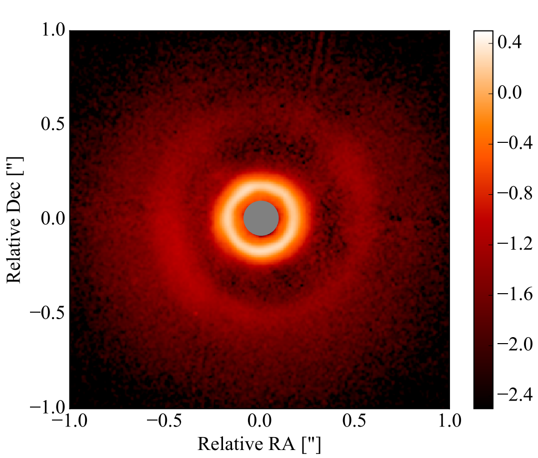
scattering



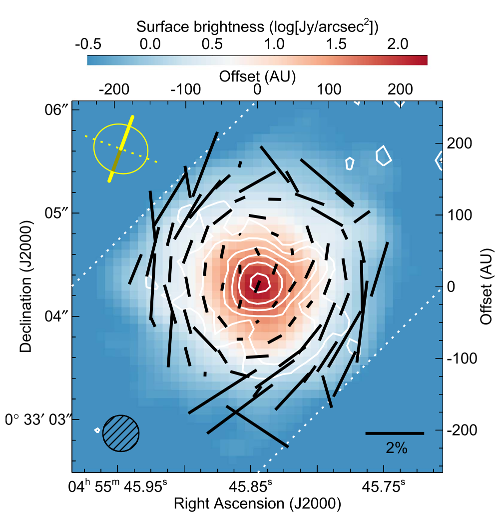
Stephens et al. 2017 (see also Kataoka et al. 2017)



Fernández-Lopez et al., 2016



Pohl, et al., 2017

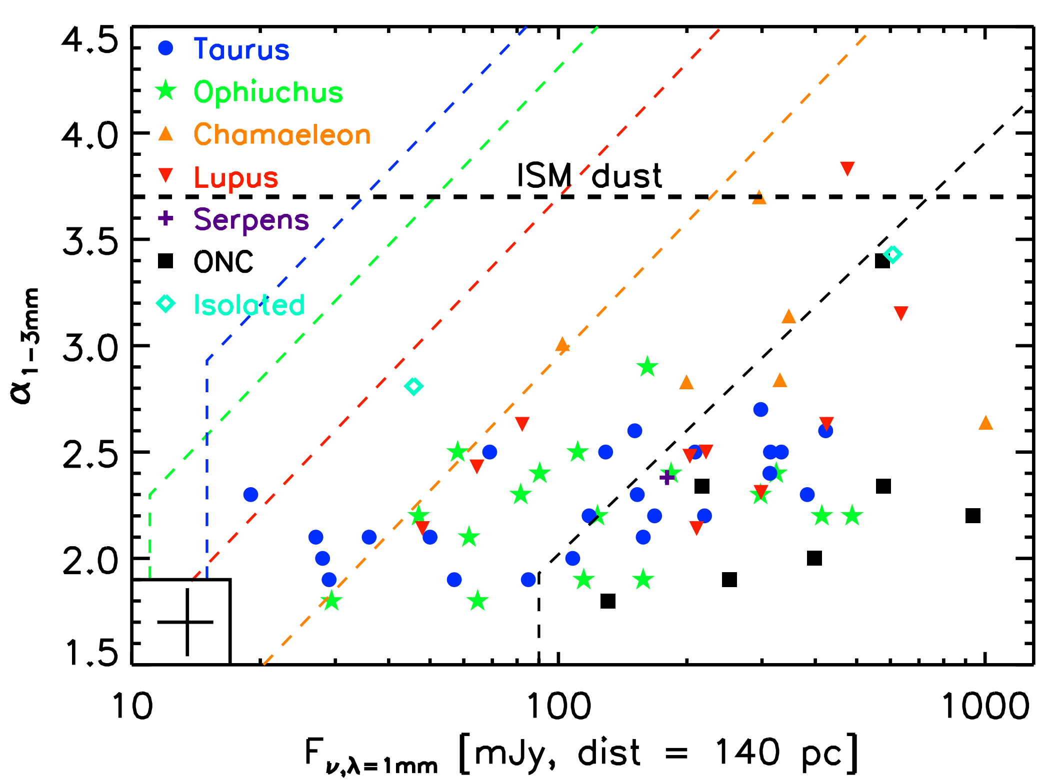


Li, et al., 2016

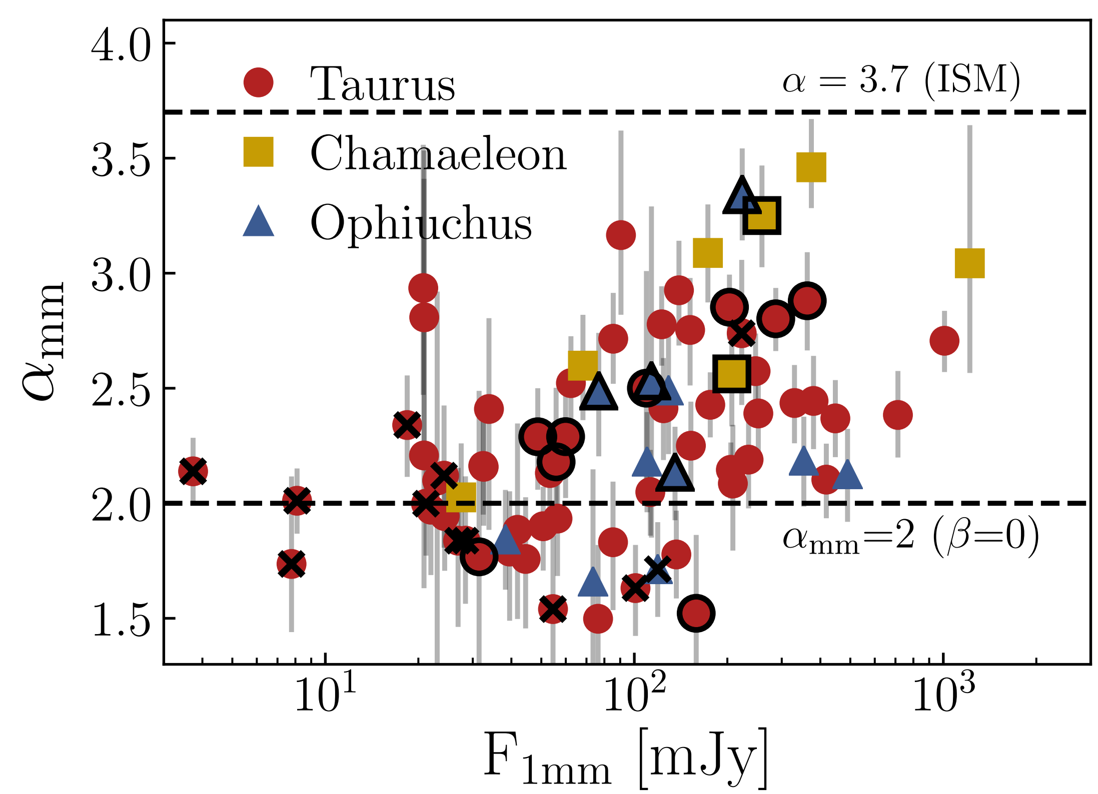
What’s missing in theory?

- **Alignment** - What’s the condition for the transition from the alignment with B-fields to that with rad. fields. Grain size? Is the iron inclusion necessary? Conditions for the gas turbulence?

- **Scattering** - Scattering properties of porous dust aggregates is missing. Is the grain growth significant even at Class 0 stages?



Testi et al., 2014



Ribas et al., 2017

Conclusions

- We propose that **the self-scattering of thermal dust emission** can produce millimeter-wave polarization. The conditions are:
  1. The intensity has anisotropic radiation fields
  2. The maximum grain size is comparable to the wavelengths

(Kataoka et al., 2015, ApJ)

- We have detected the **polarization of HD 142527** with ALMA
  - The orientations of polarization vectors are consistent with the self-scattering model.

(Kataoka et al. 2016b, ApJL)

- 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 ~70 μm

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