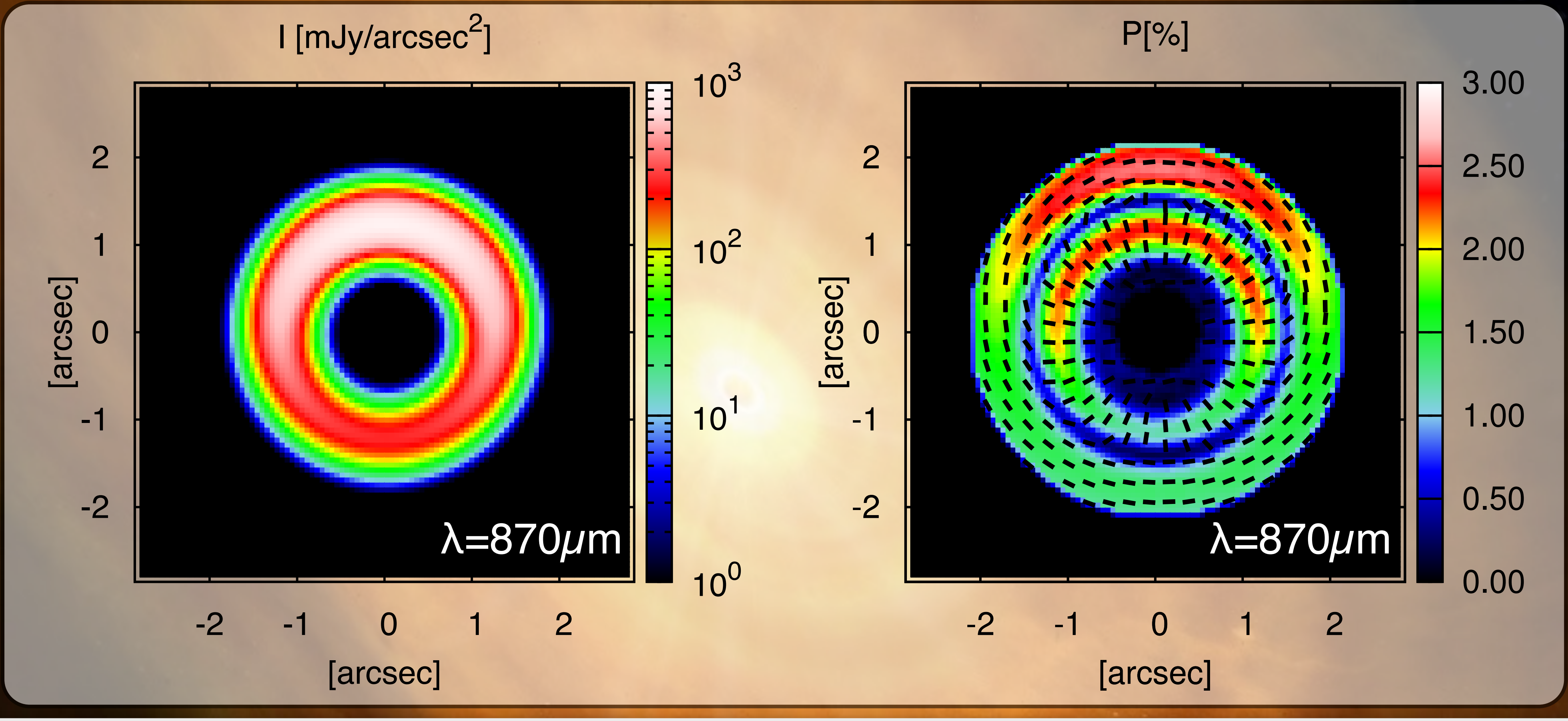
Millimeter-wave polarization as a tool of investigating planet formation

Kataoka et al., 2015, 2016a,b

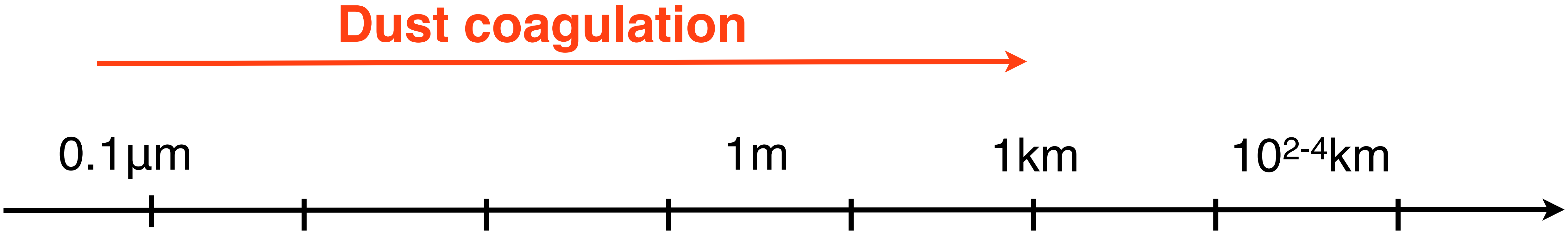


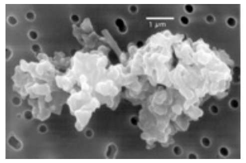
Akimasa Kataoka (Humboldt fellow at Heidelberg University)

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

H. Shibai (Osaka U.), T. Hanawa (Chiba U.), K. Murakawa (Osaka-S.), Kees Dullemond, Adriana Pohl (Heidelberg)

Planet Formation





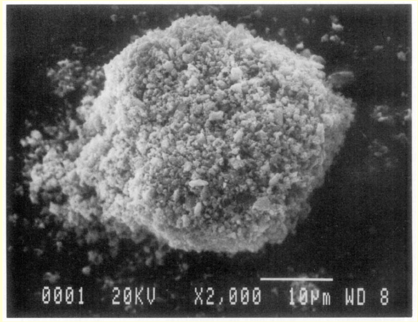
dust grains

Microphysical problems

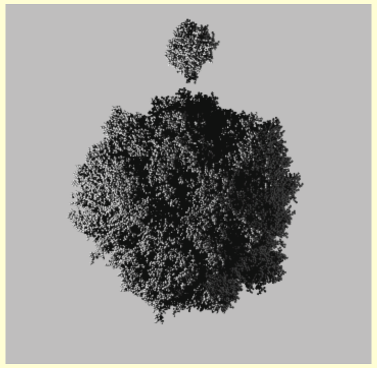
planetesimals

planets

Numerical simulations / Laboratory experiments

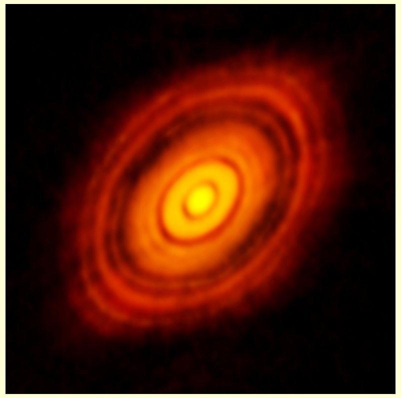


Blum & Münch 1993



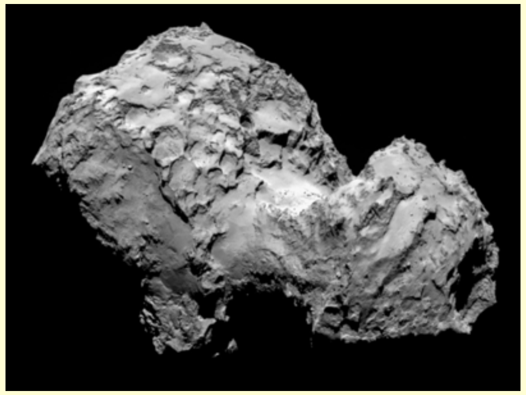
Wada et al. 2013

Astronomical Observations



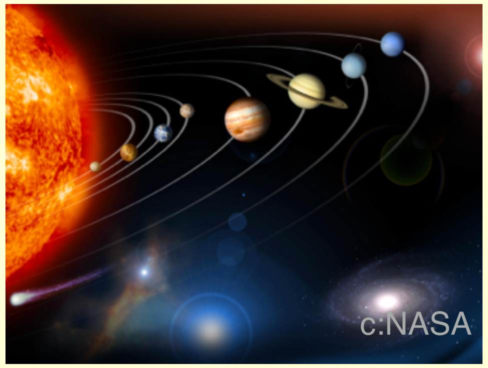
ALMA Partnership 2015

Comets



Rosetta mission

(extra)solar system

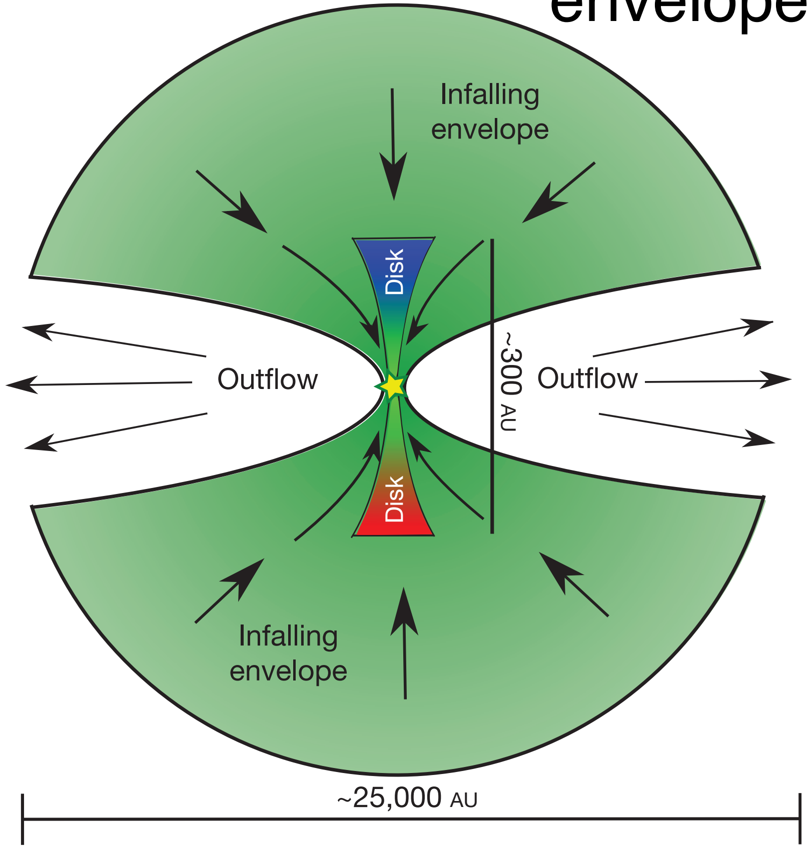


Star and disk formation

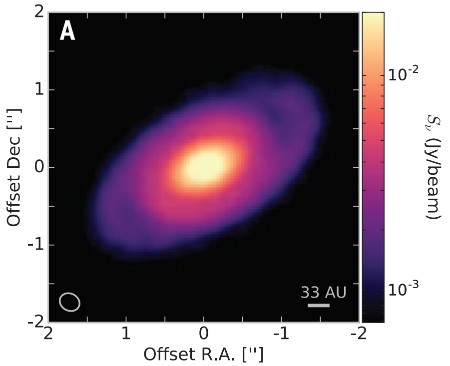
molecular cloud core

B68, ~10^4AU (Alves 2001)

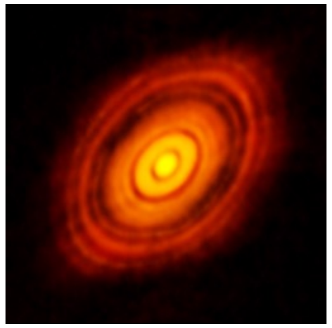
envelope + disk



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

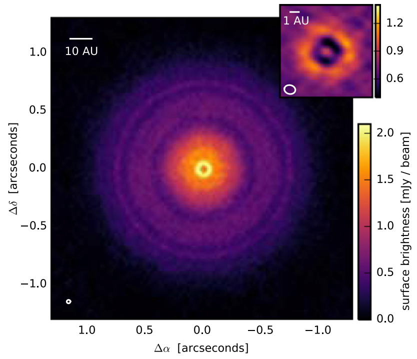


Elias 2-24 (Perez 2016)

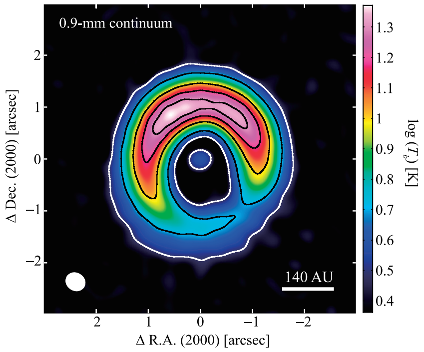


HL Tau (ALMA 2015)

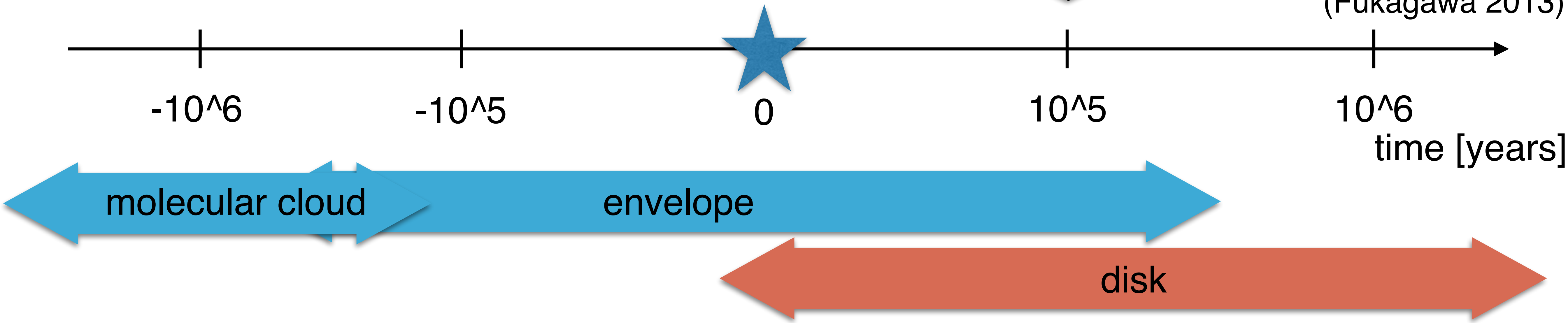
disk



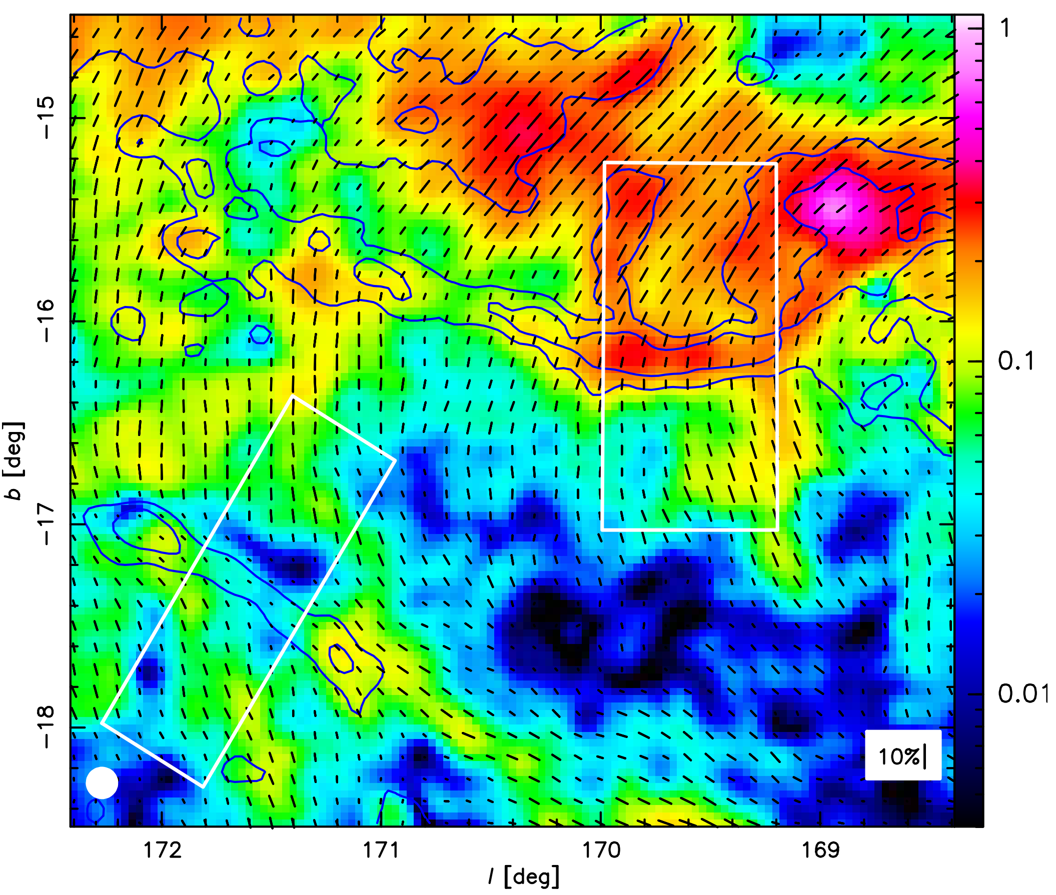
TW Hya
(Andrews 2016)



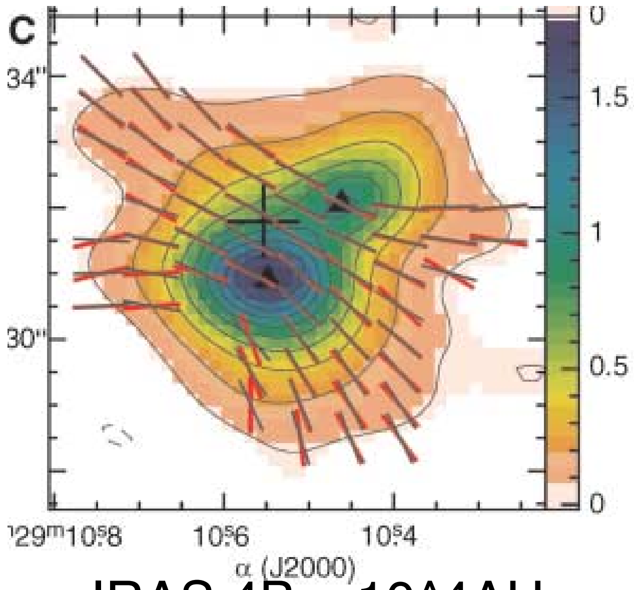
HD 142527
(Fukagawa 2013)



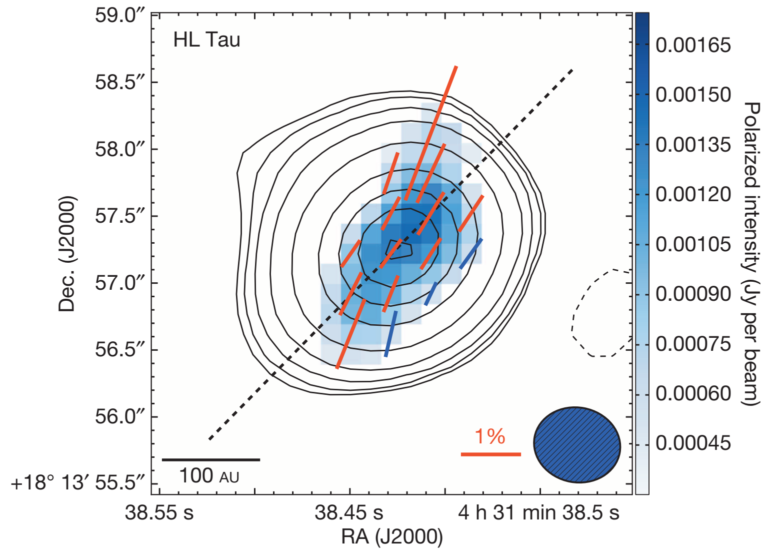
Polarization of star-disk system



Taurus region (Planck, XXXIII, 2015)



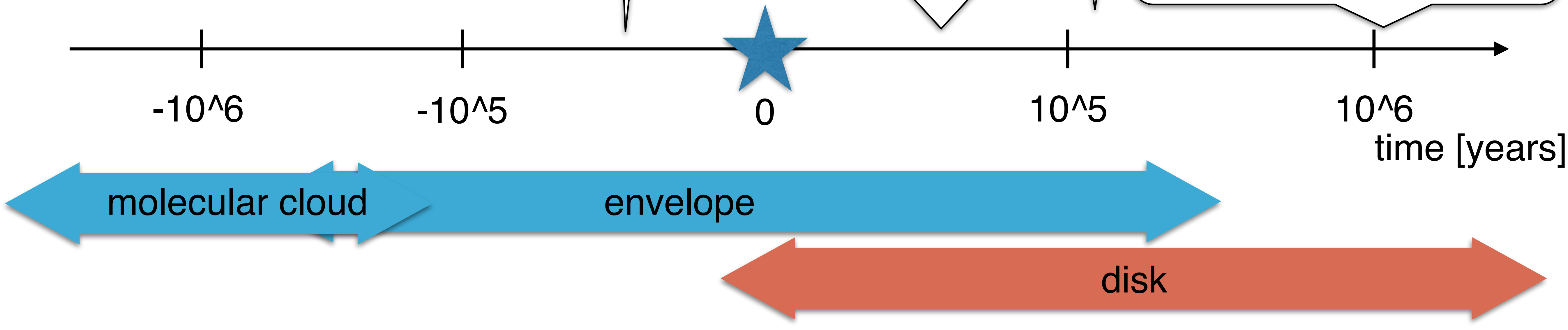
IRAS 4B, ~10^4AU
(Girart et al. 2006)



HL Tau, ~10^2AU
(Stephens et al. 2014)

pol. detection of disk components, (Rao et al. 2014, Segura-cox et al. 2015)

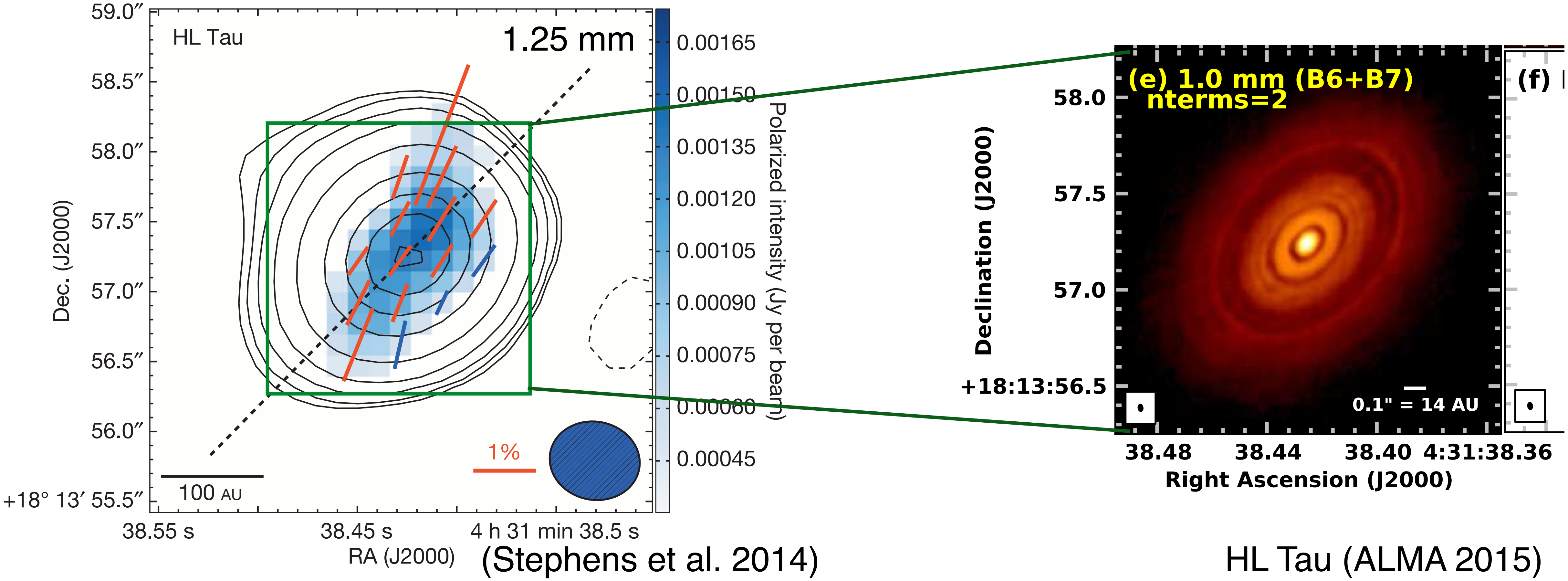
non-detection of disks at later-stages
HD 163296, TW Hya, GM Aur, DG Tau
(Hughes et al. 2009, 2013)



-10^6
-10^5
0
10^5
10^6
time [years]

molecular cloud
envelope
disk

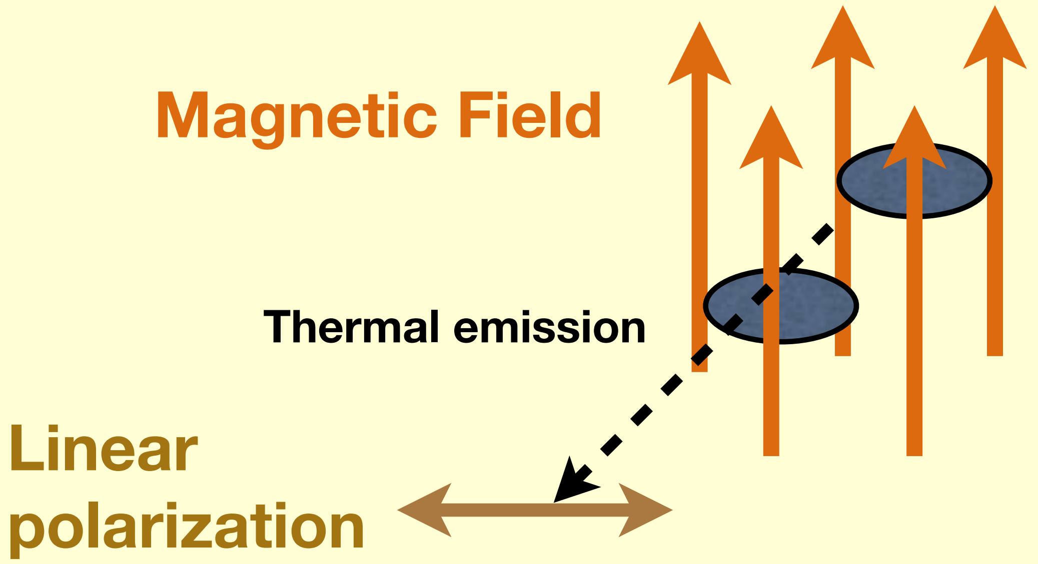
Polarization of HL Tau



(Stephens et al. 2014)

HL Tau (ALMA 2015)

Mechanism: Grain alignment

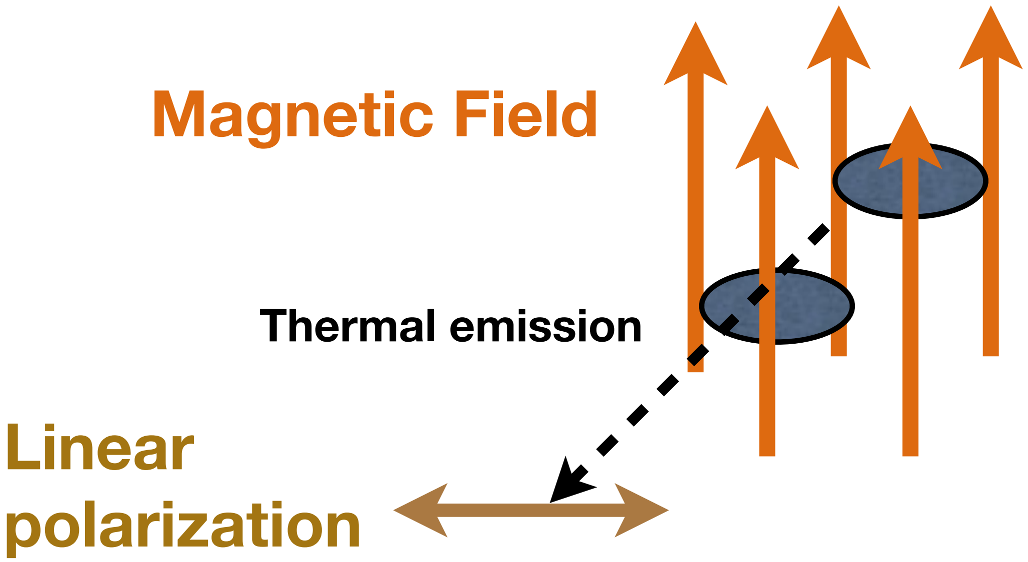


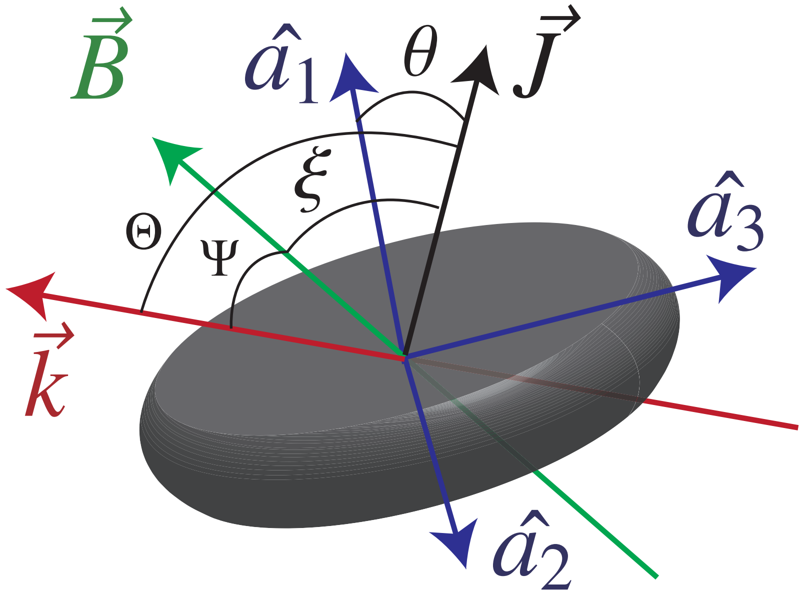
Toroidal magnetic fields from edge-on view?
-> No because the inclination is 46 degrees

The mechanism of polarization might be totally different?

Polarization mechanisms

- **Alignment of elongated dust grains**



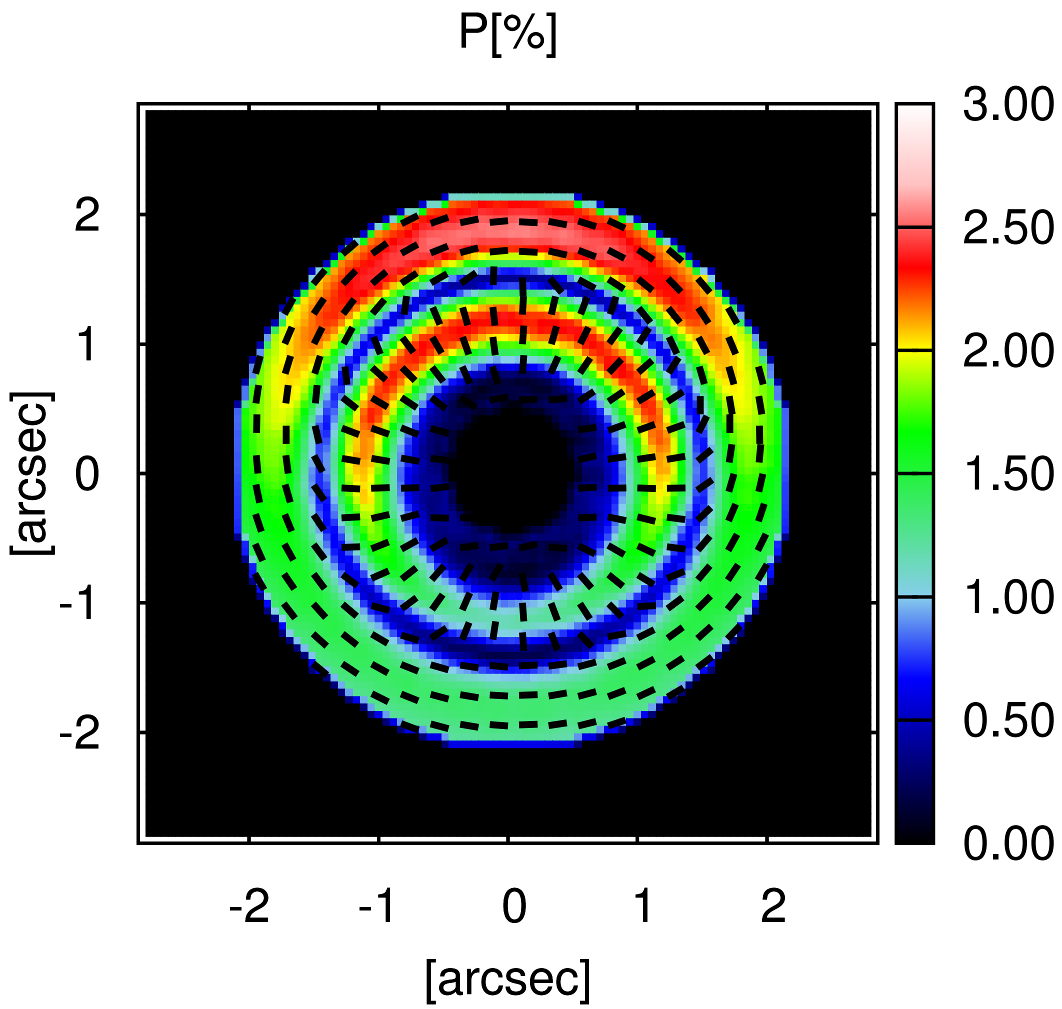


Alignment with B-fields
(e.g., Lazarian and Hoang 2007)

Alignment with radiation fields
(Lazarian and Hoang 2007,
Tazaki, Lazarian et al. 2017)

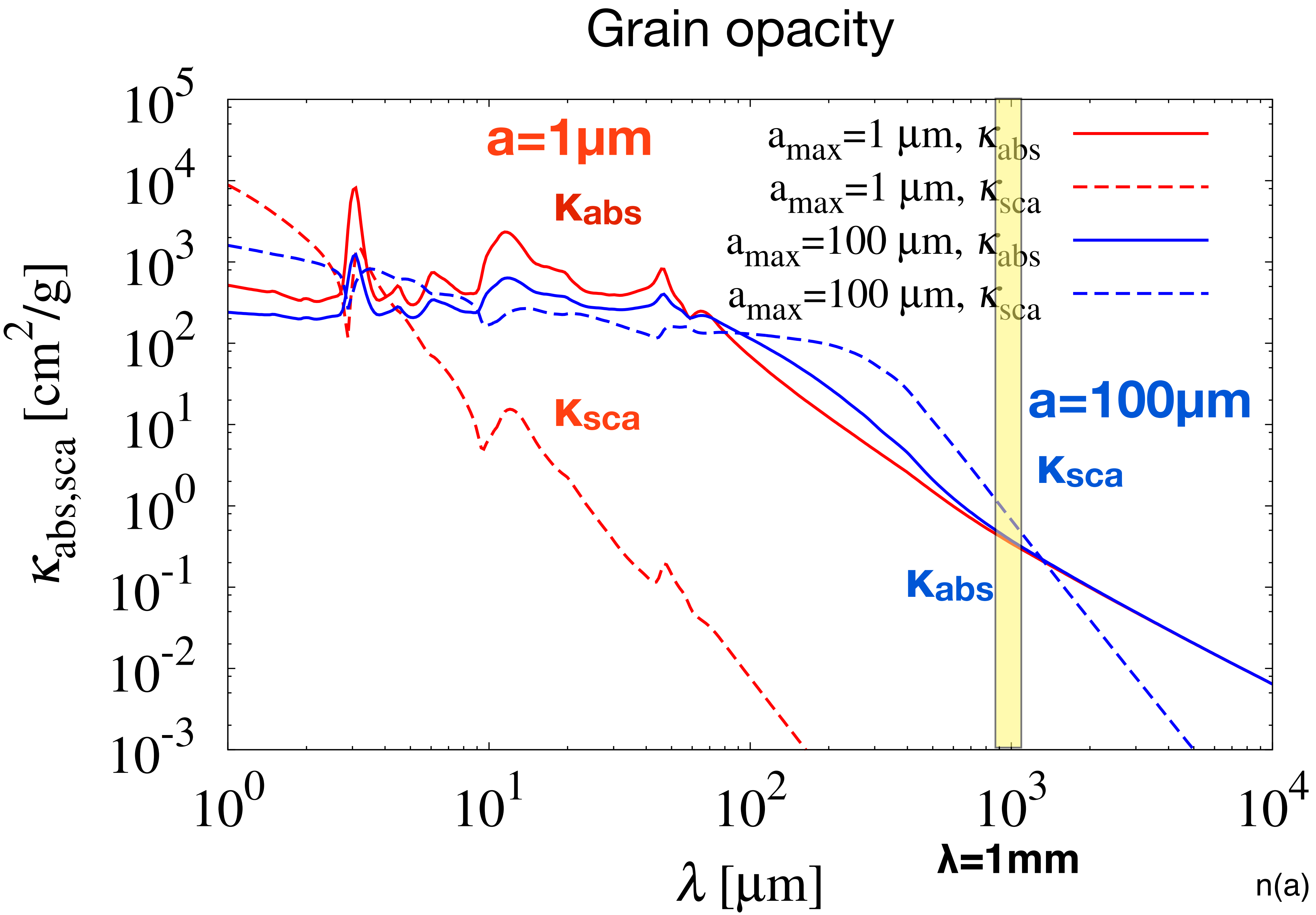
- **Scattering at millimeter wavelengths (this talk)**

  1. Scattering opacity is too low? -> grain growth
  2. No light source of the scattering? -> self-scattering



theory - millimeter polarization due to dust scattering

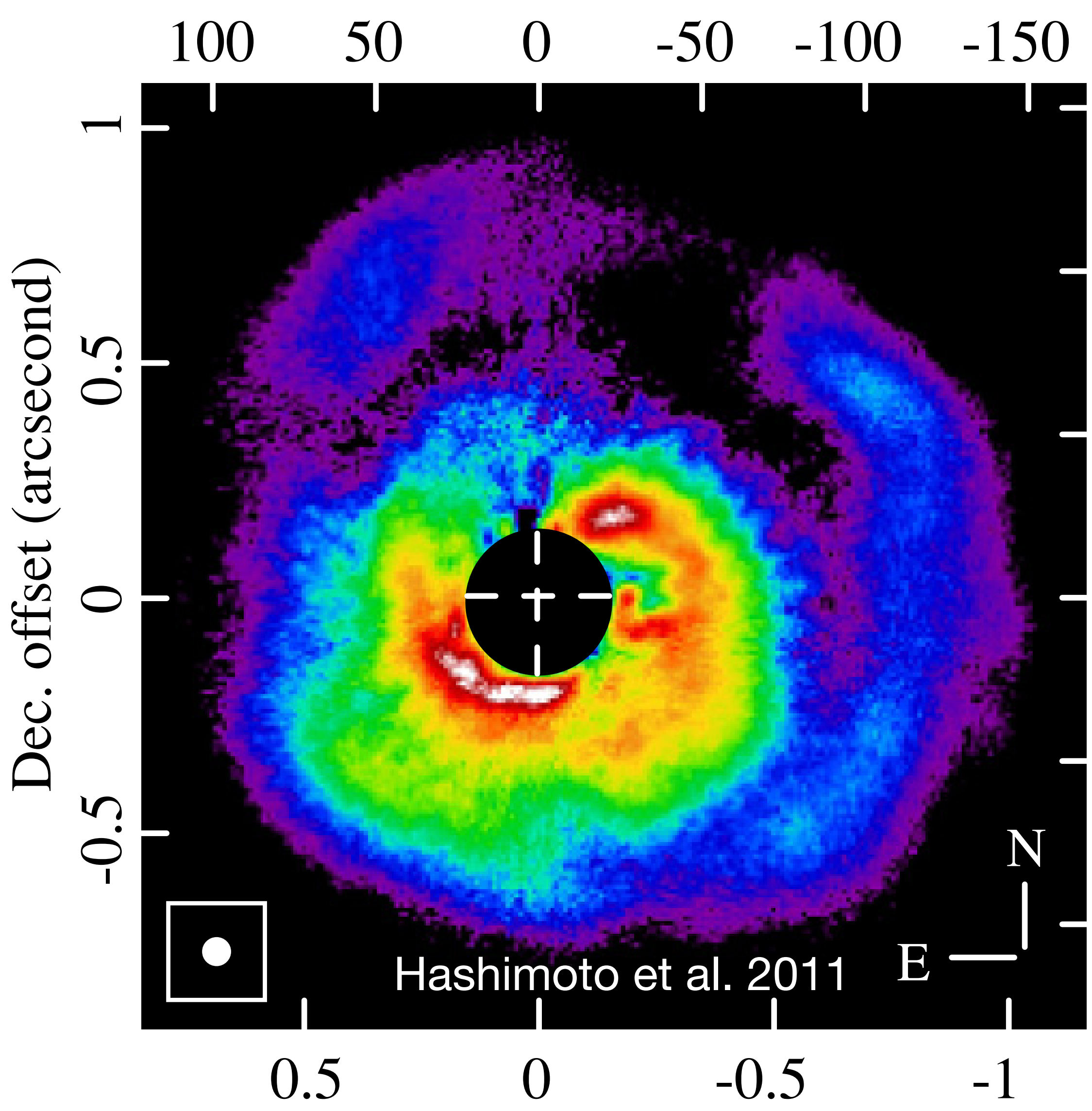
Absorption and scattering opacities



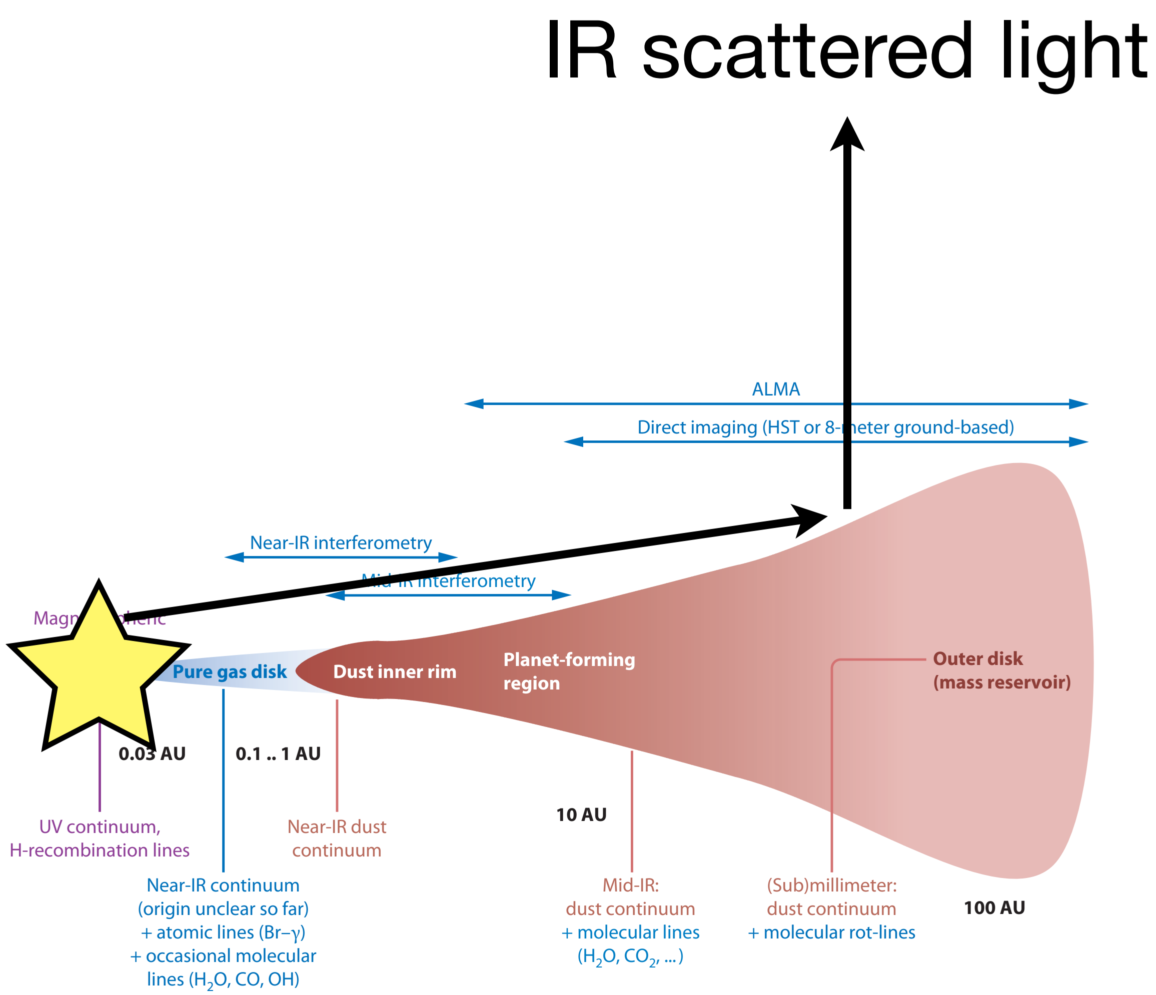
$n(a) \propto a^{-3.5}$

Scattering of large dust grains can not be ignored.

A light source of scattering?



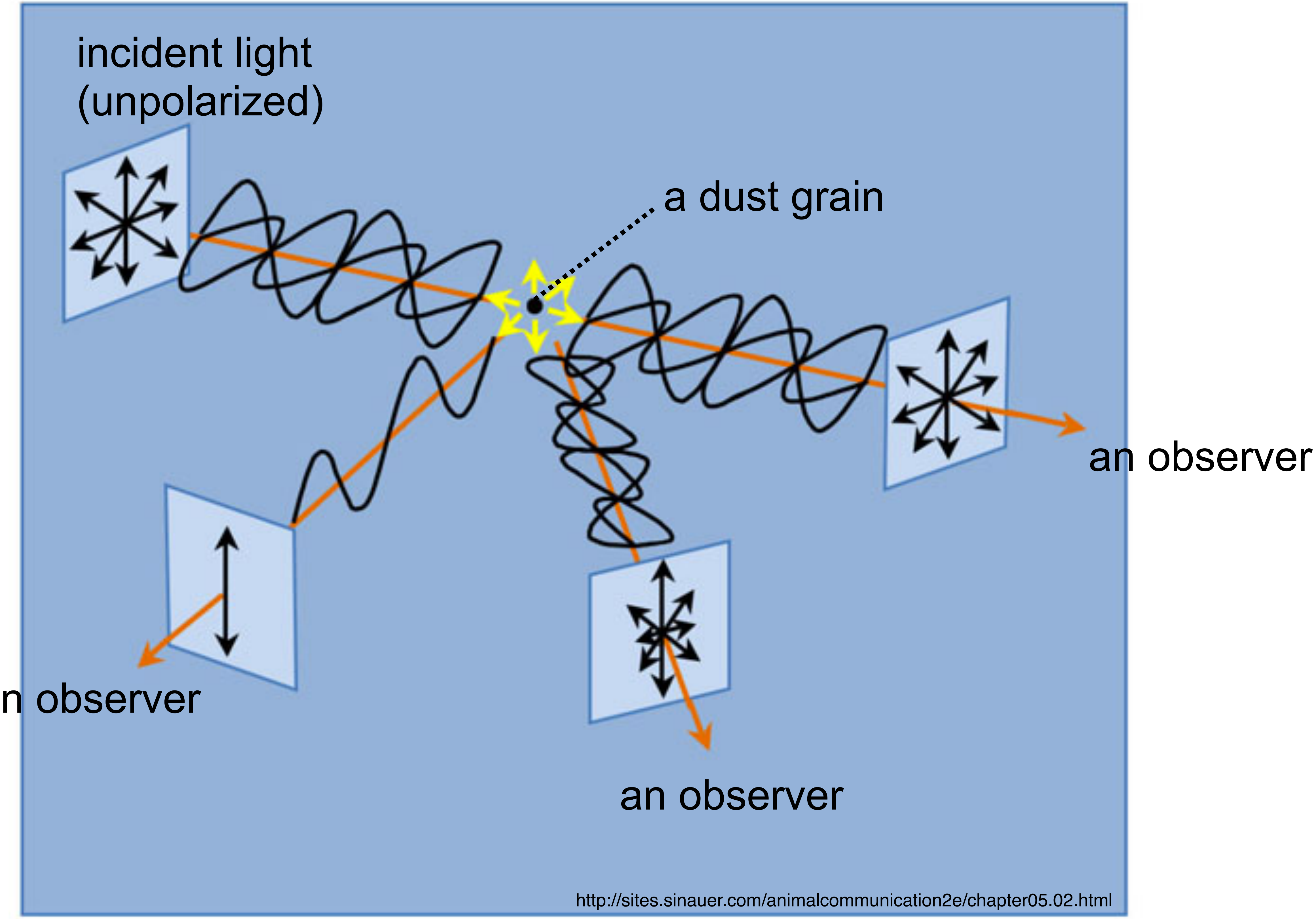
Hashimoto et al. 2011



However, the central star is dark at mm wavelengths.

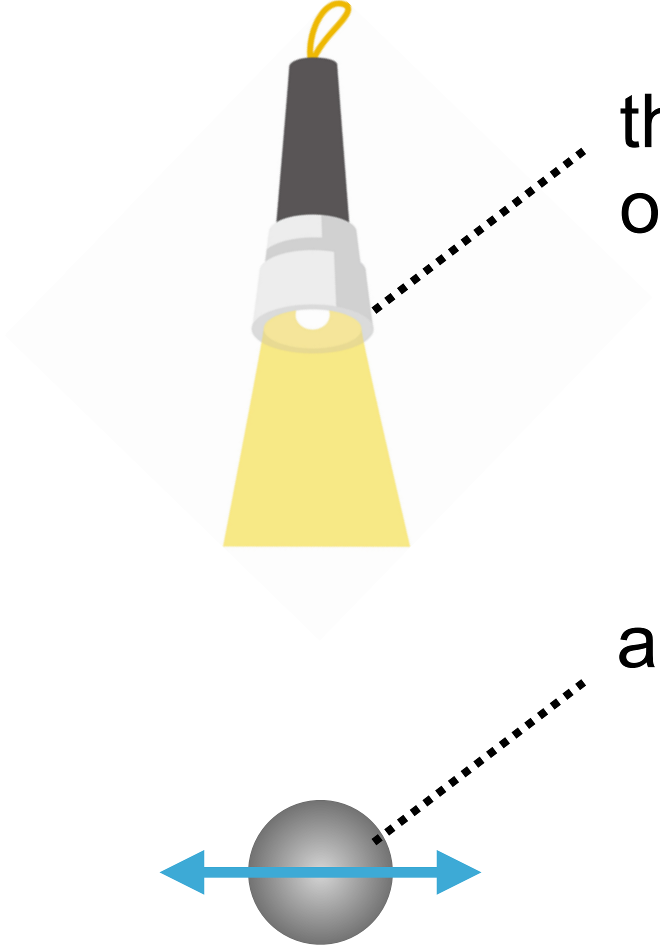
We introduce the self-scattering of thermal dust emission.

Polarization due to scattering



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

Polarization due to scattering



thermal dust emission
of other dust grains

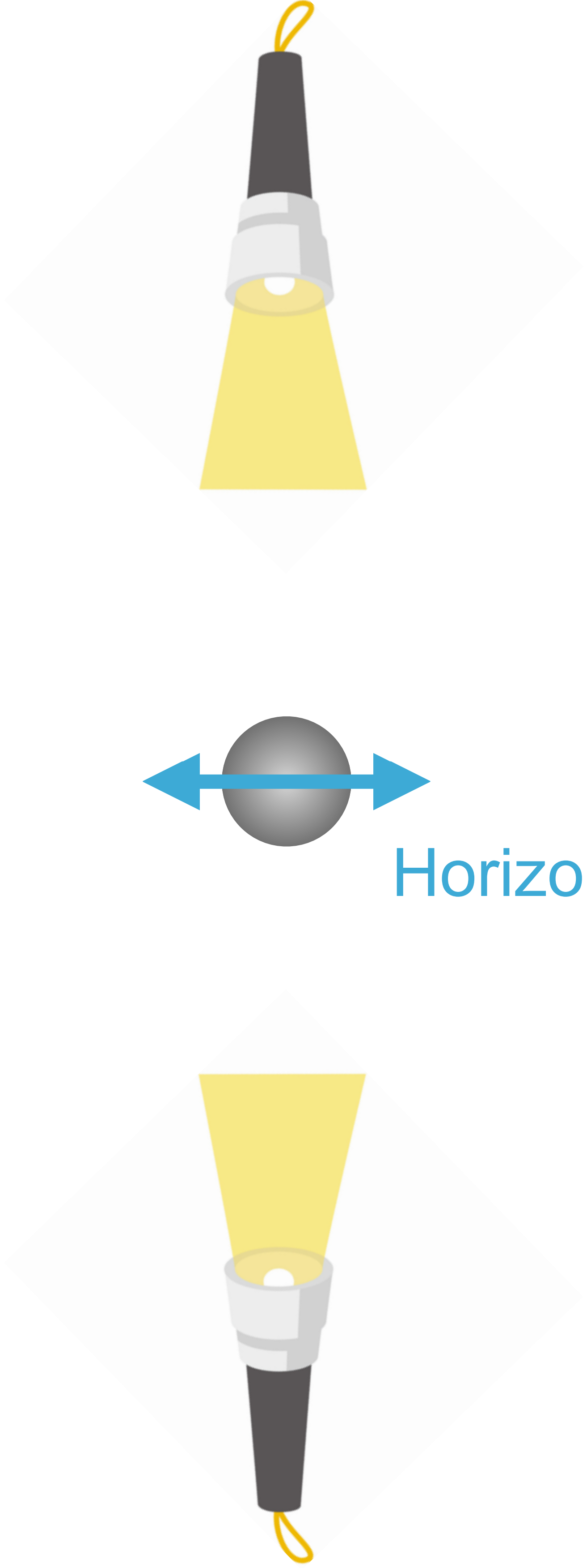
a dust grain

Horizontal Polarization

The observer is you.

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

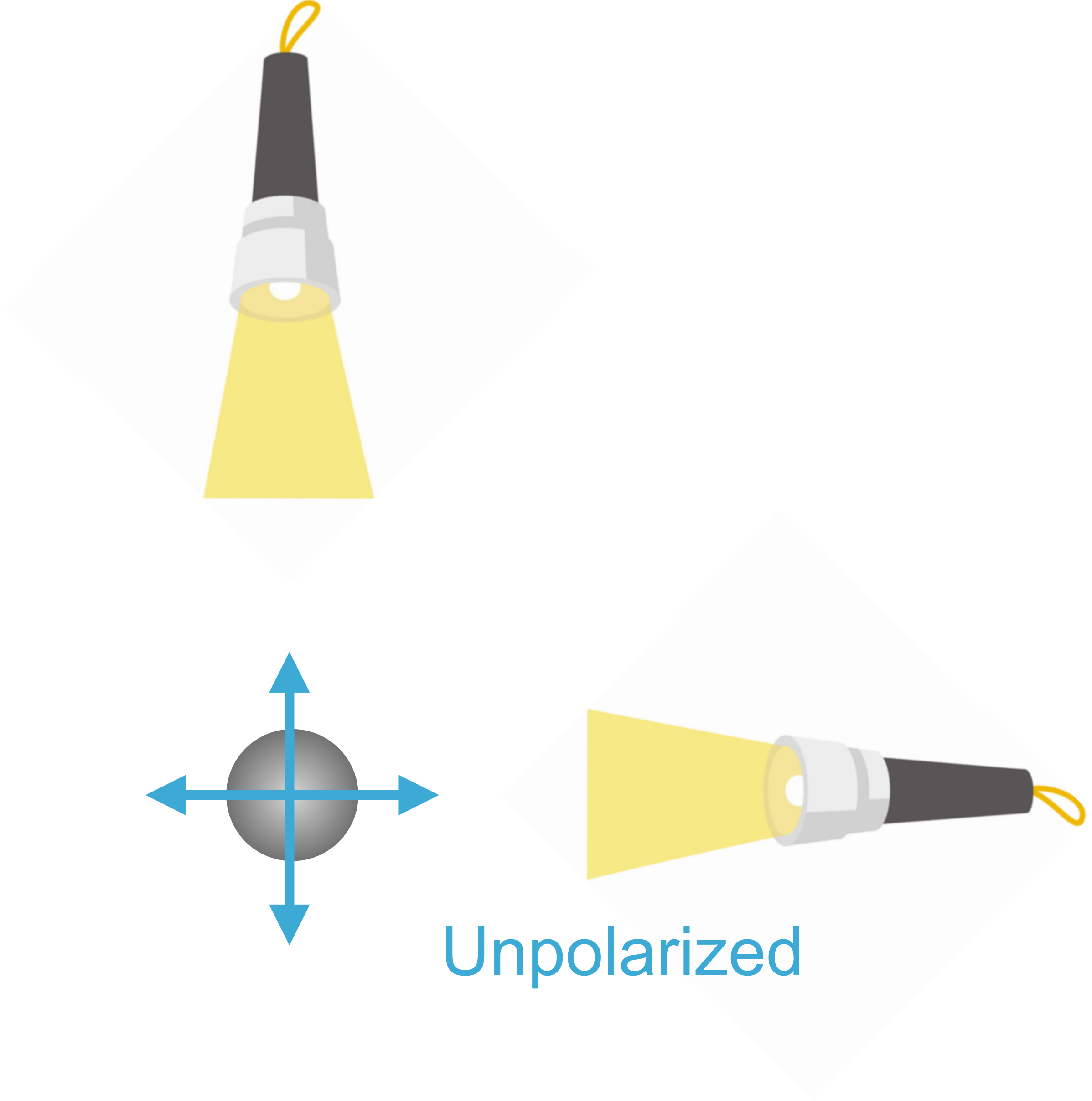
Polarization due to scattering



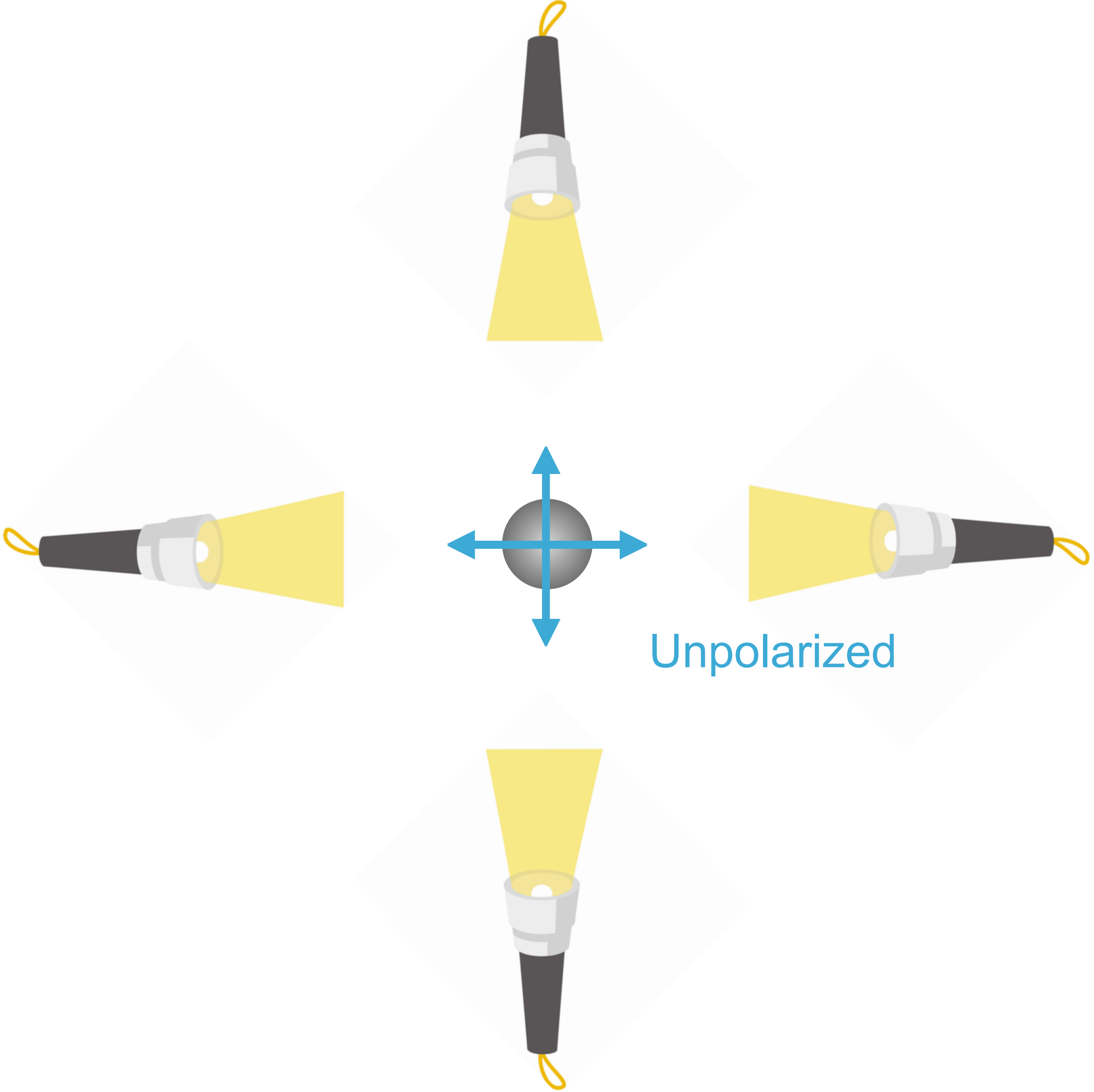
Horizontal Polarization

Akimasa Kataoka (Humboldt fellow, Heidelberg University)

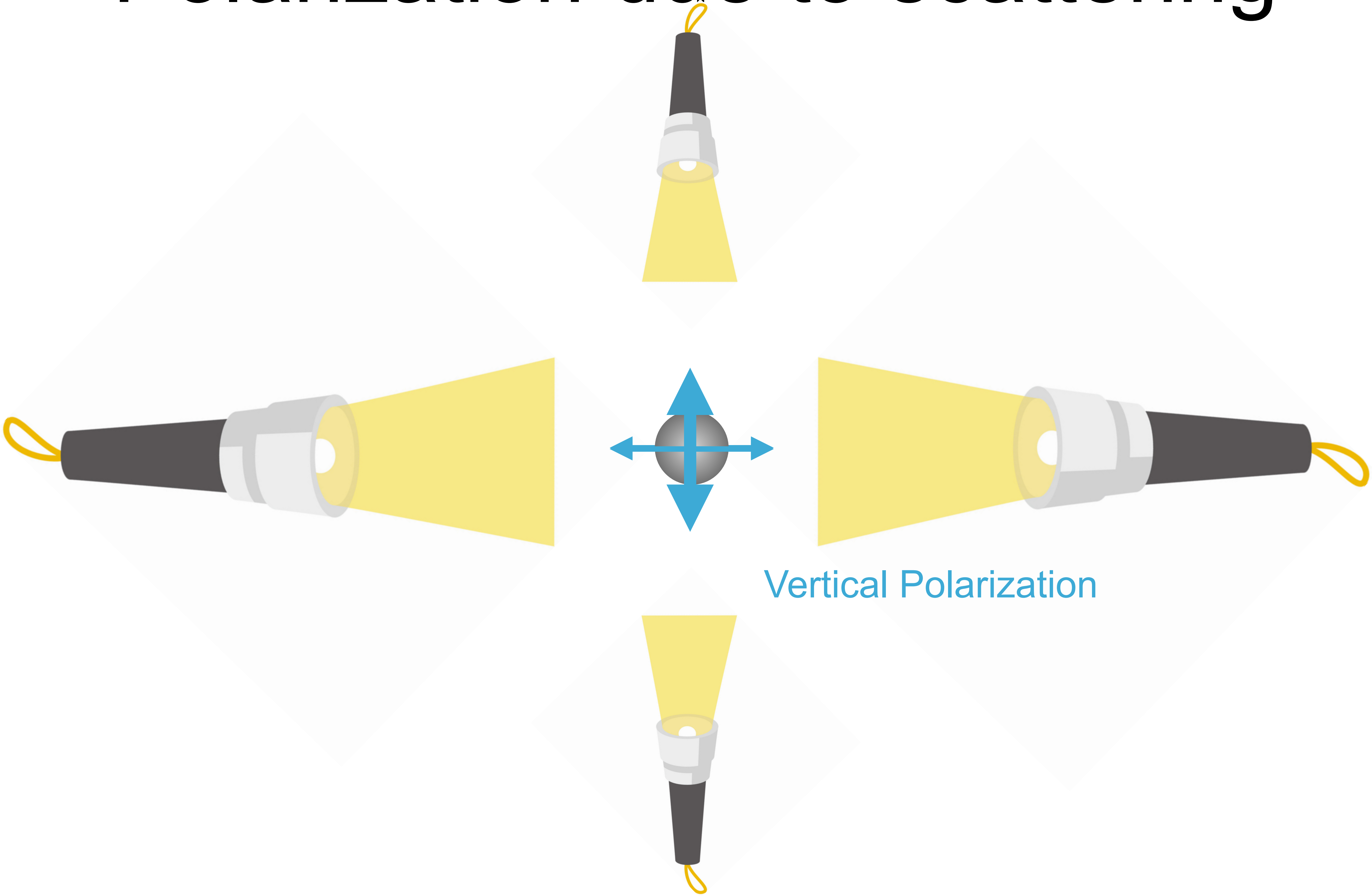
Polarization due to scattering



Polarization due to scattering



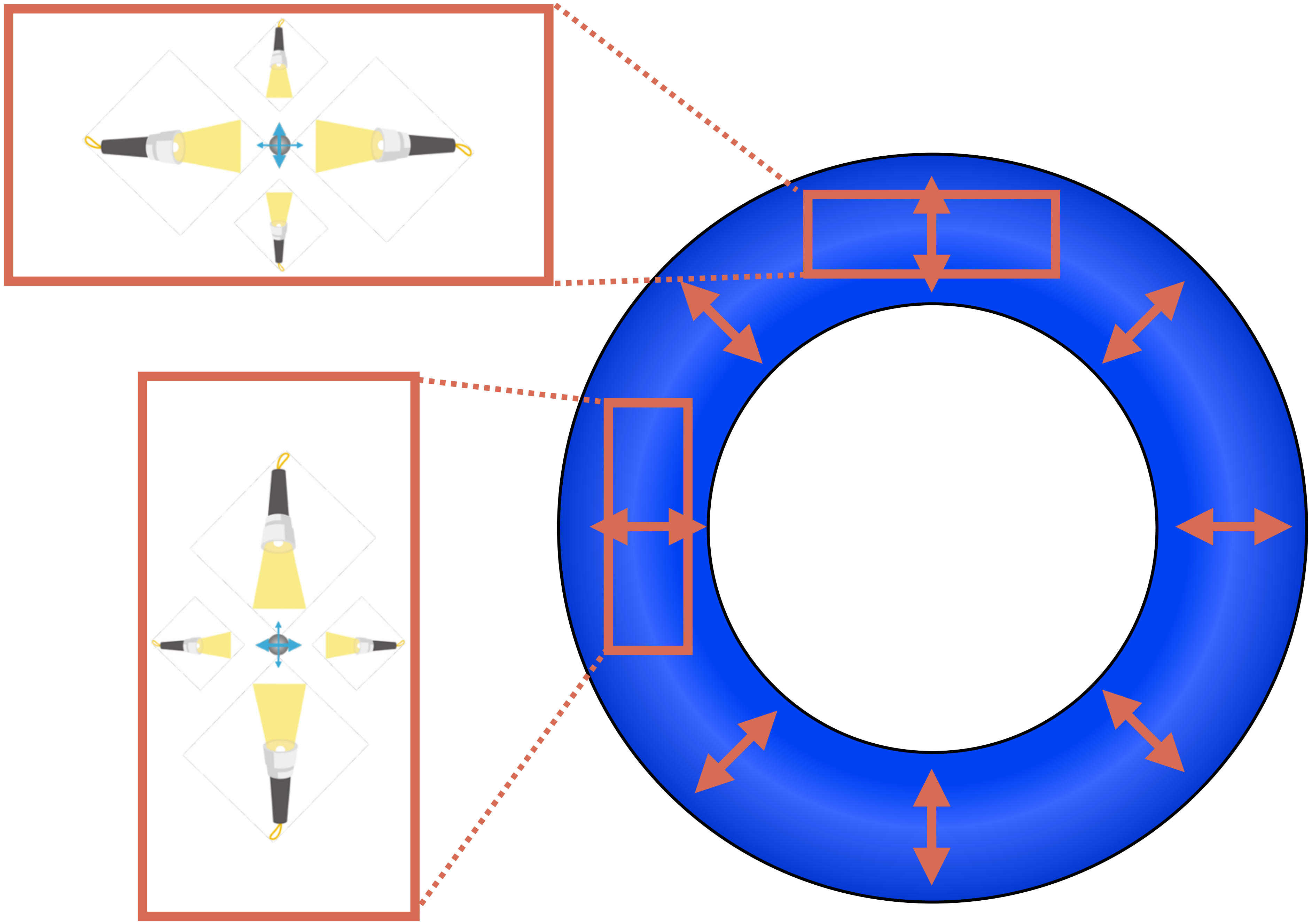
Polarization due to scattering



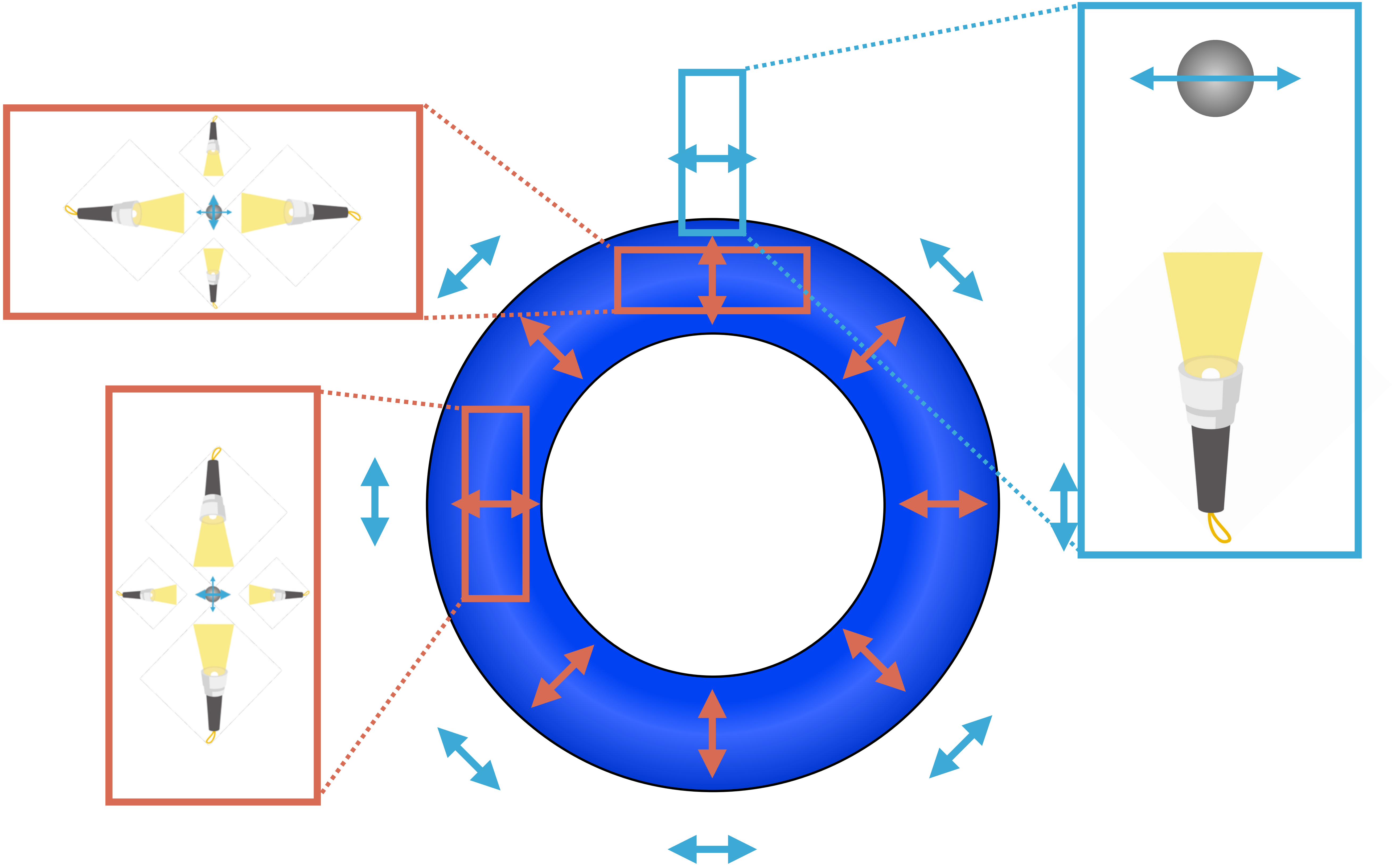
Vertical Polarization

Akimasa Kataoka (Humboldt fellow, Heidelberg University)

self-scattering in a protoplanetary disk

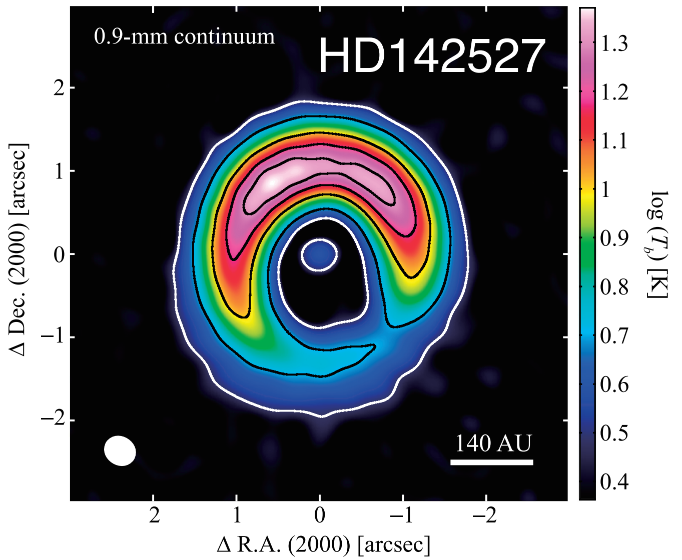


self-scattering in a protoplanetary disk

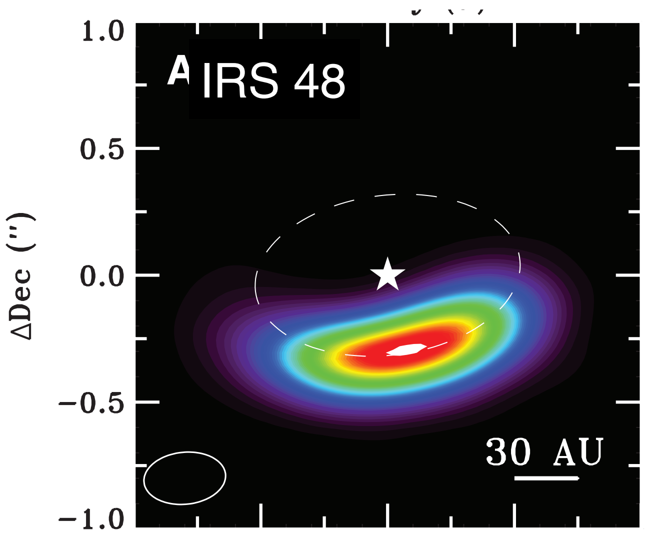


Akimasa Kataoka (Humboldt fellow, Heidelberg University)

Protoplanetary disks

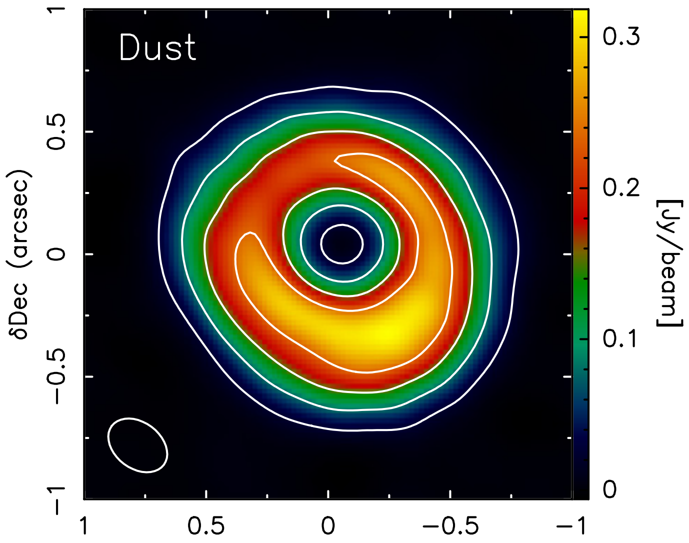


Fukagawa et al. 2013

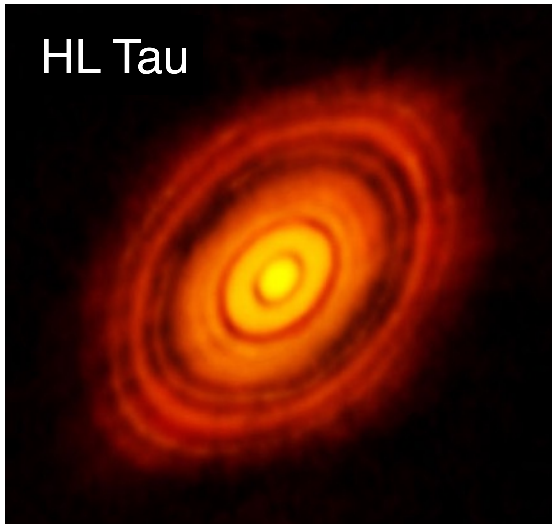


van der Marel et al. 2013

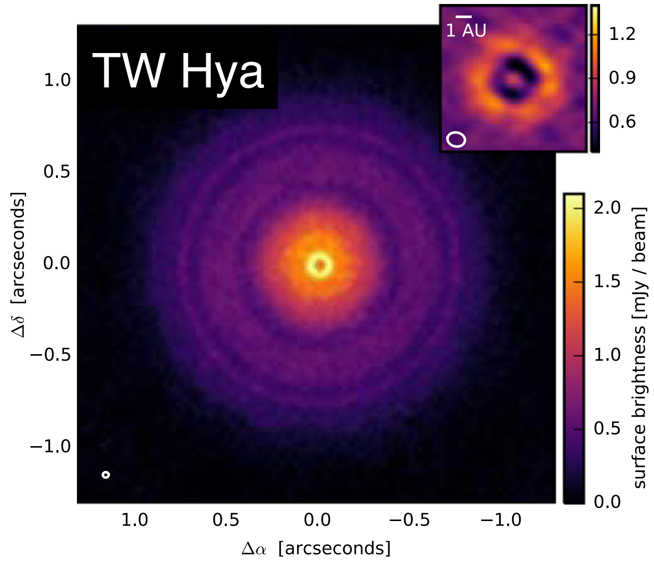
SAO 206462



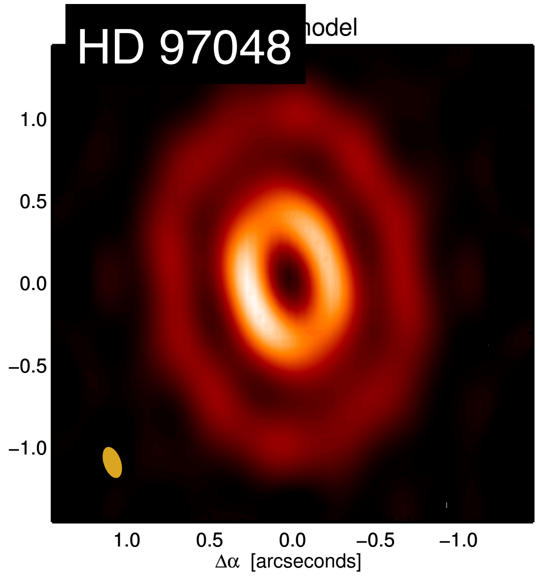
Perez et al. 2014



ALMA Partnership 2015



Andrews et al. 2016

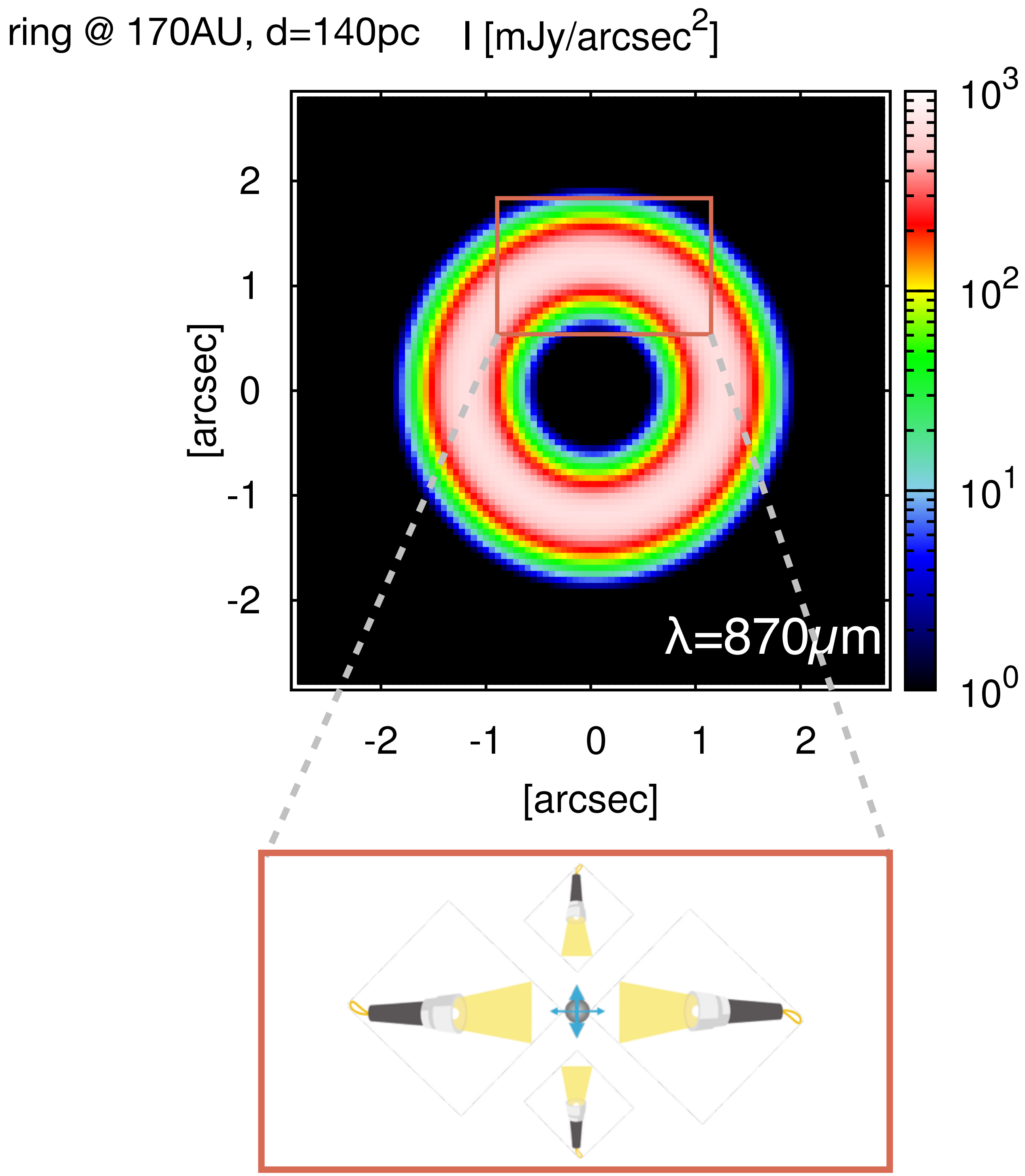


van der Plas et al. 2016

Anisotropic thermal emission at mm wavelengths

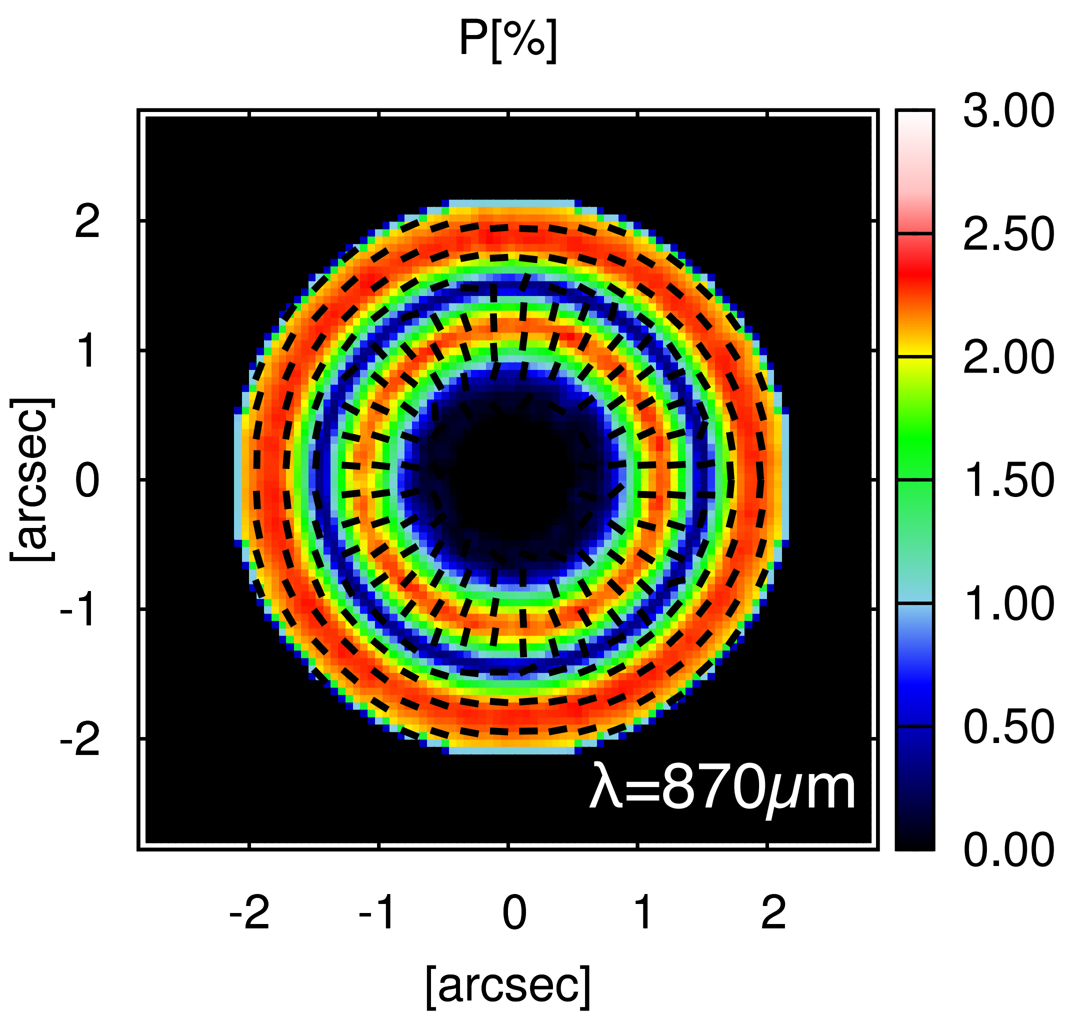
Theoretical prediction

Stokes I (continuum)



Anisotropy → net polarization

Polarization degree

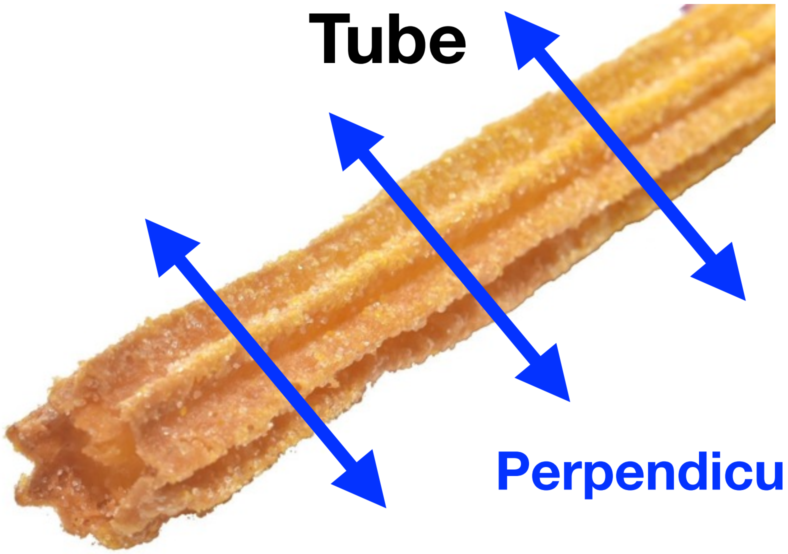


The polarization degree is as high as 2.5%
→detectable with ALMA

Kataoka, et al., 2015

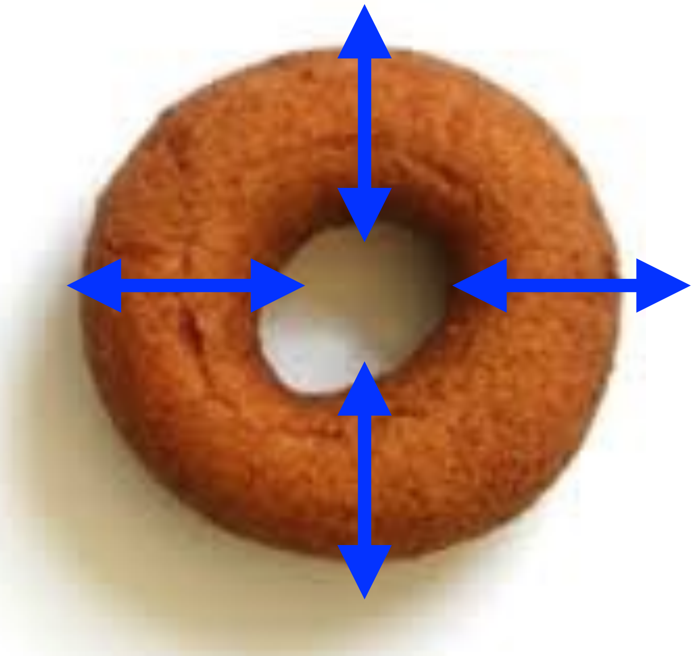
Not only rings…

Tube



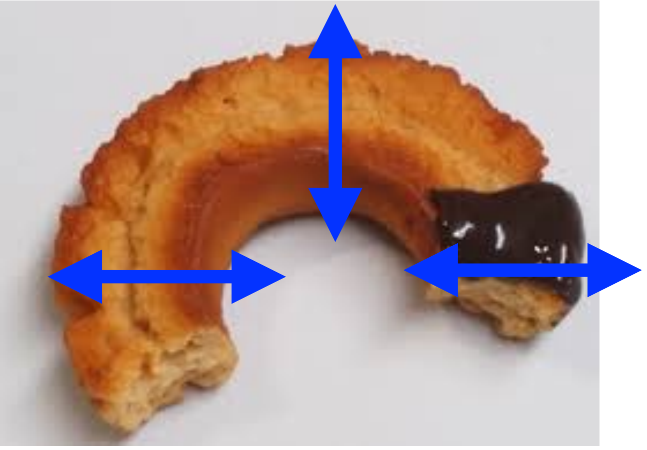
Perpendicular

Ring (face-on)



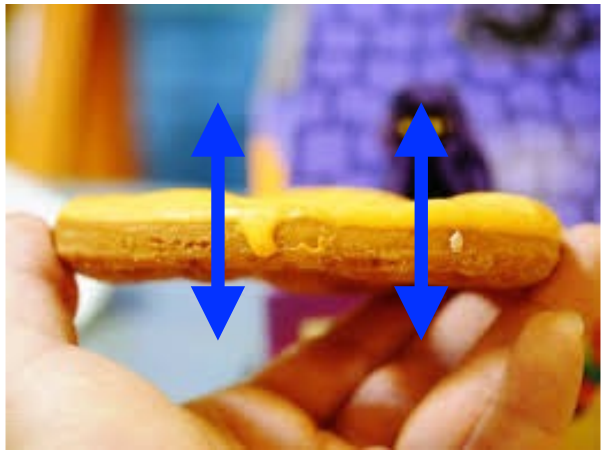
radial

Lopsided (face-on)



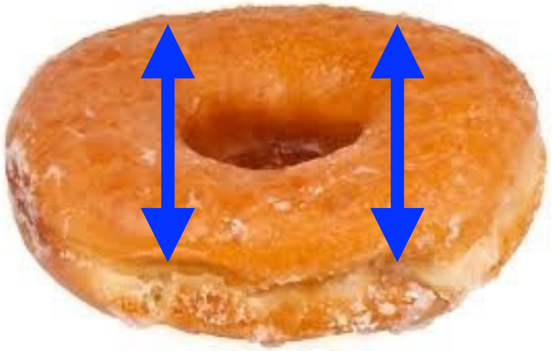
radial

edge-on view



vertical

inclined disk



along minor axis

Condition of dust grains for polarization

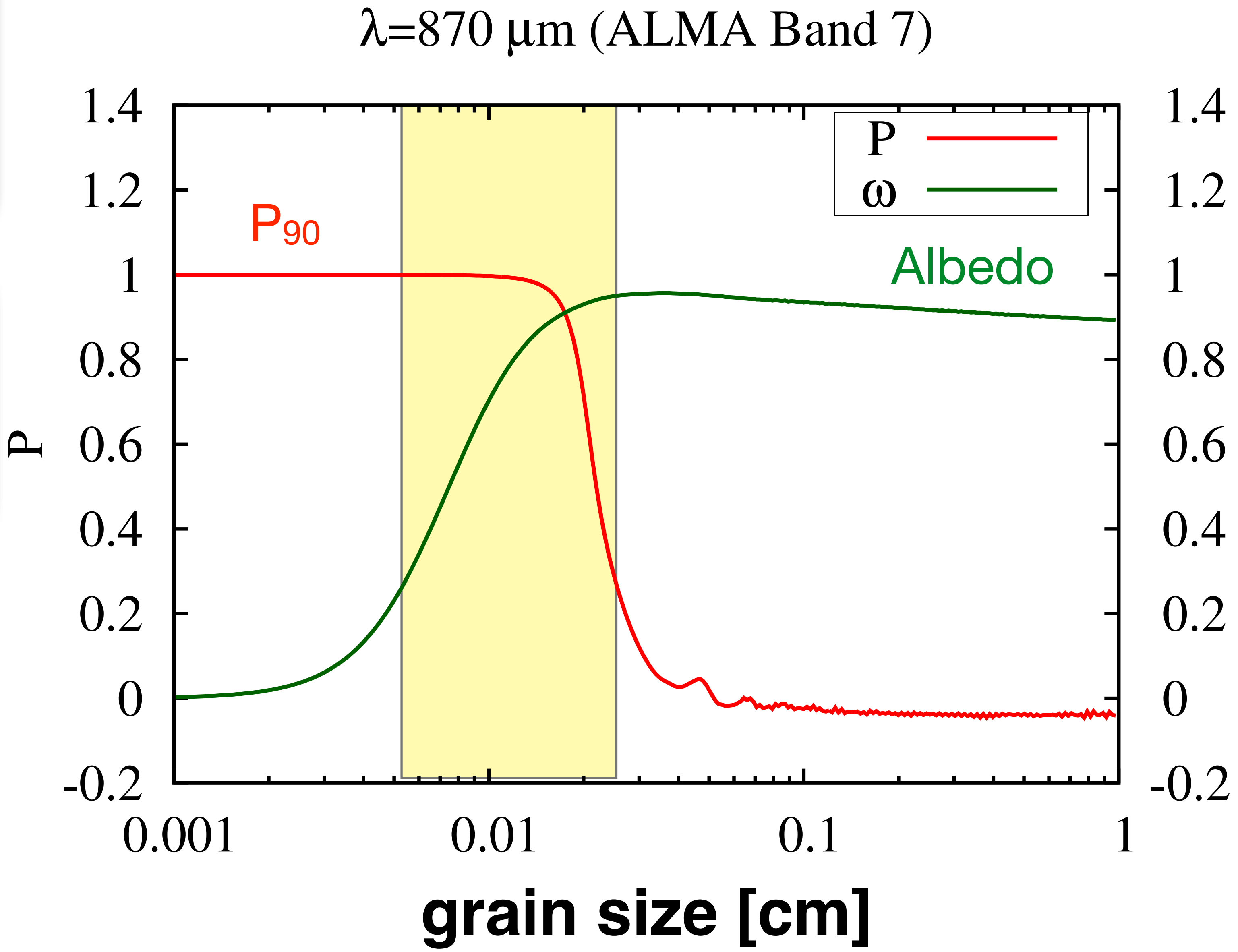
- For efficient scattering

  (grain size) >~ λ

- For efficient polarization

  (grain size) <~ λ

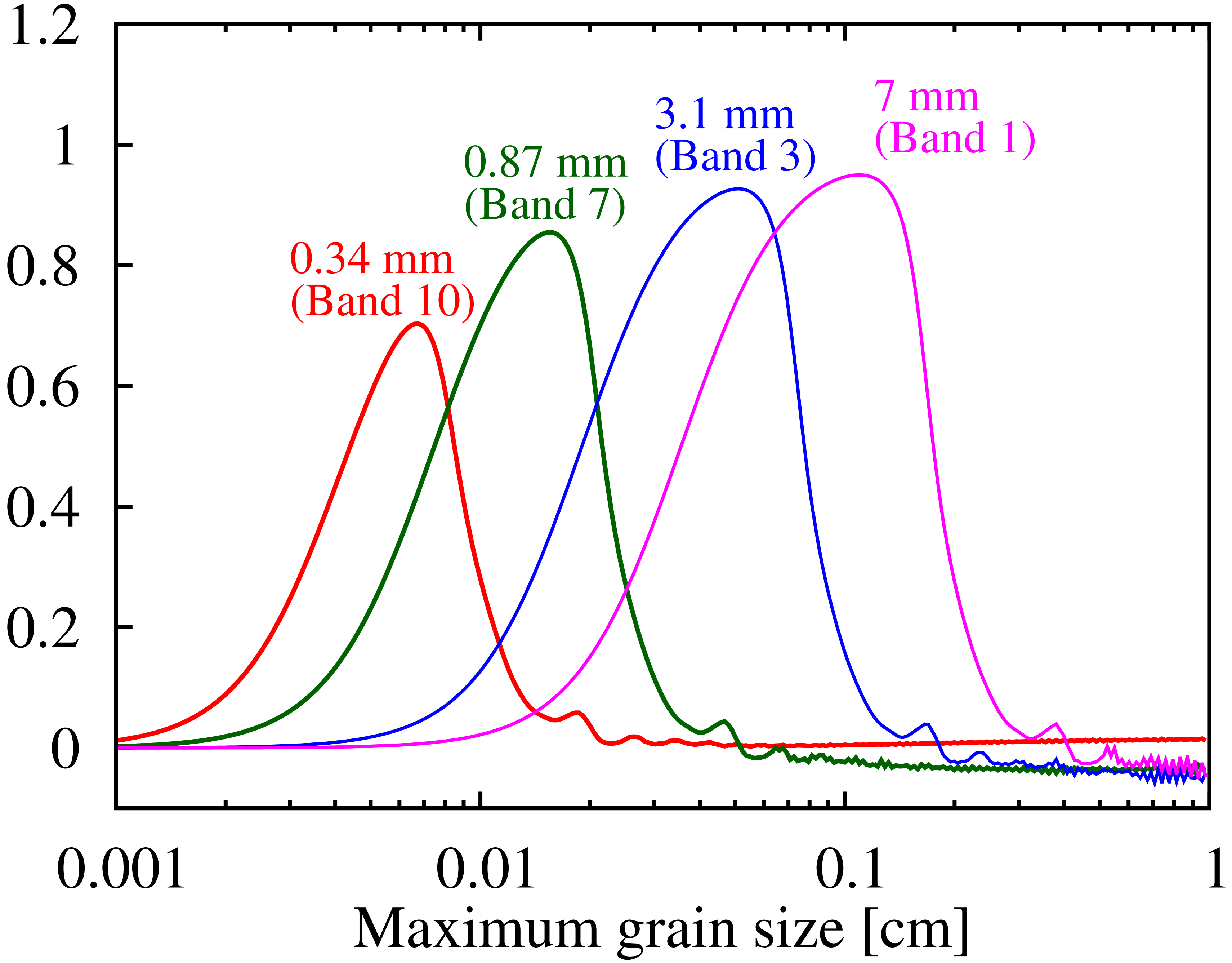
There is a grain size which contributes most to the polarized emission



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

Grain size constraints by polarization

Expected polarization degree (scalable)



Multi-wave polarization → constraints on the maximum grain size

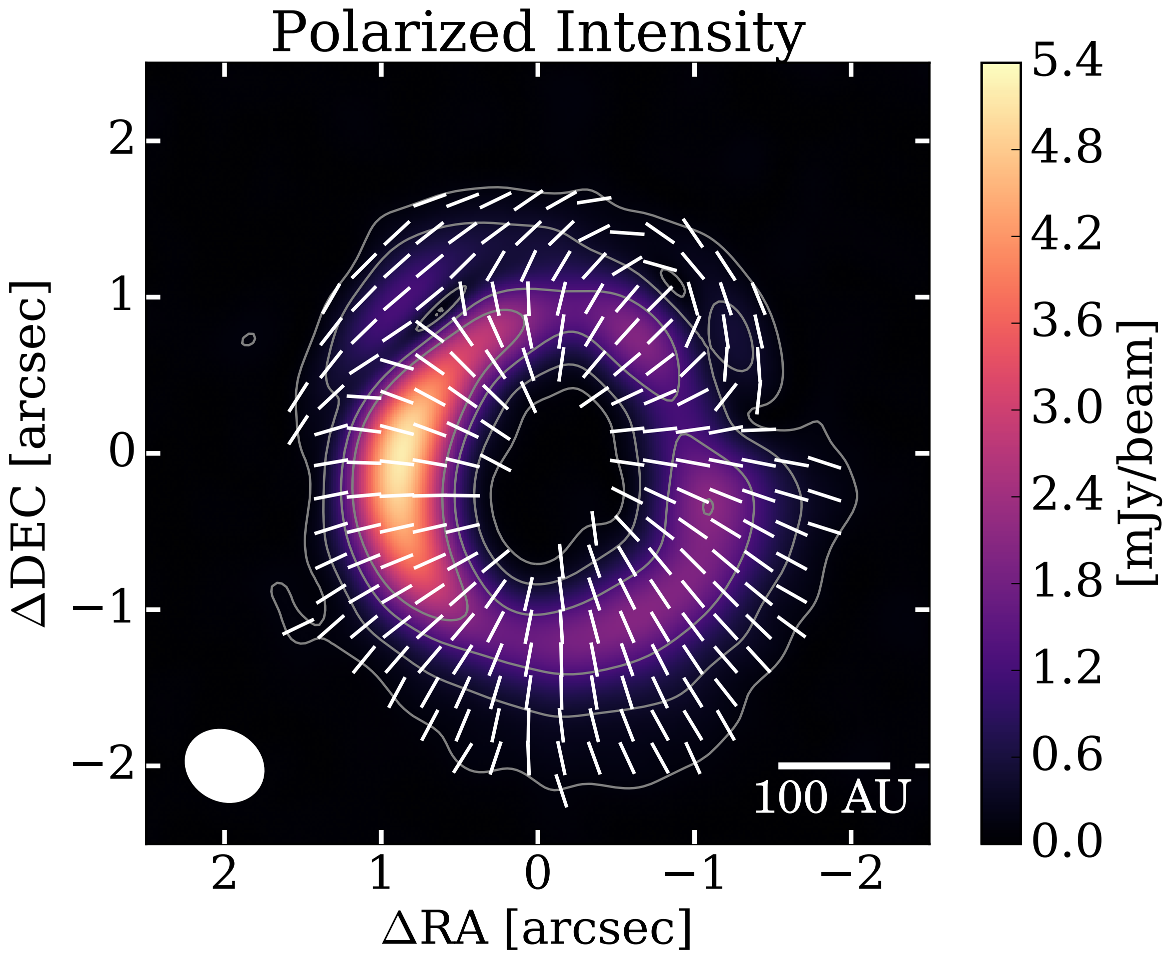
Short summary: what can we learn?

Anisotropies of radiation field at the observed wavelengths. (Predictable from Stokes I continuum) × **Grain size** (Measurable) = **Polarization**

Rings, lopsided, inclined, ⋯ × $a_{max} \approx \lambda/2\pi$ → detection

× grains are too small or too large → non-detection

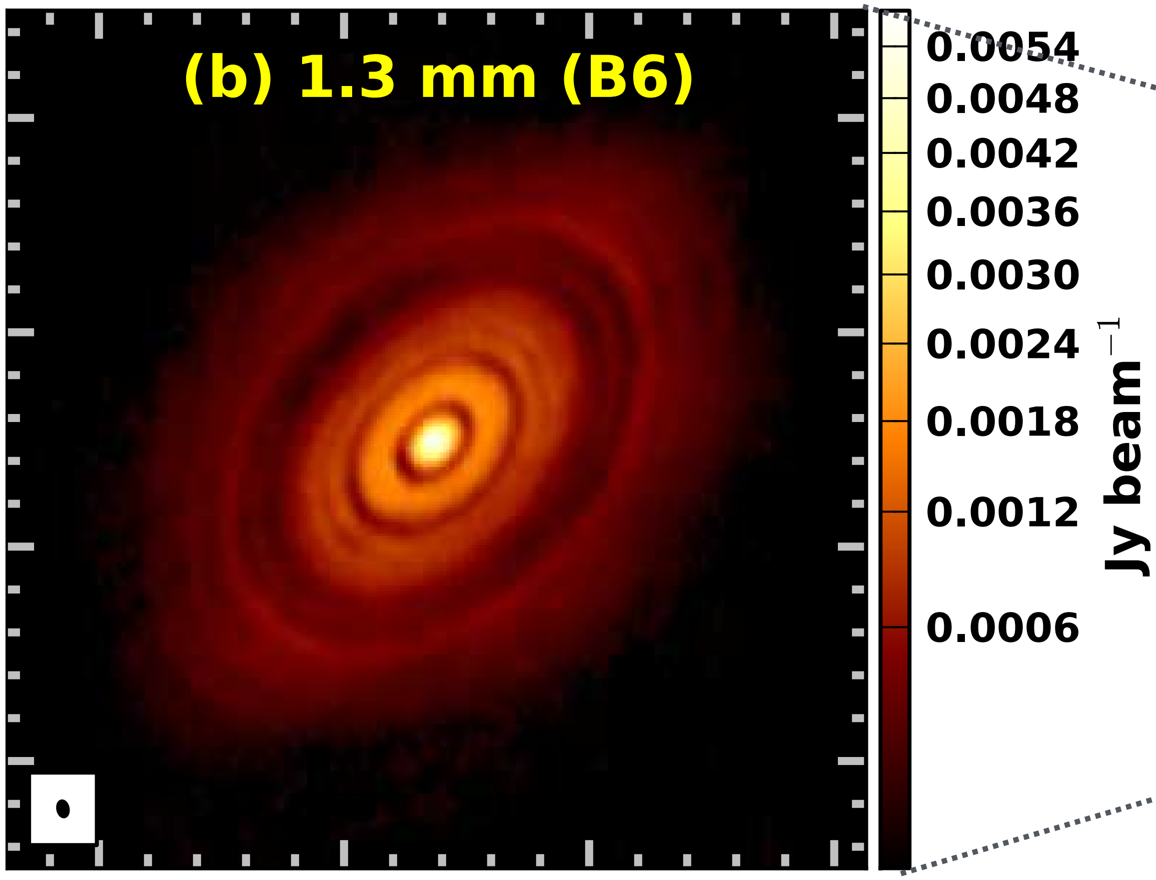
Test the theory with observations!



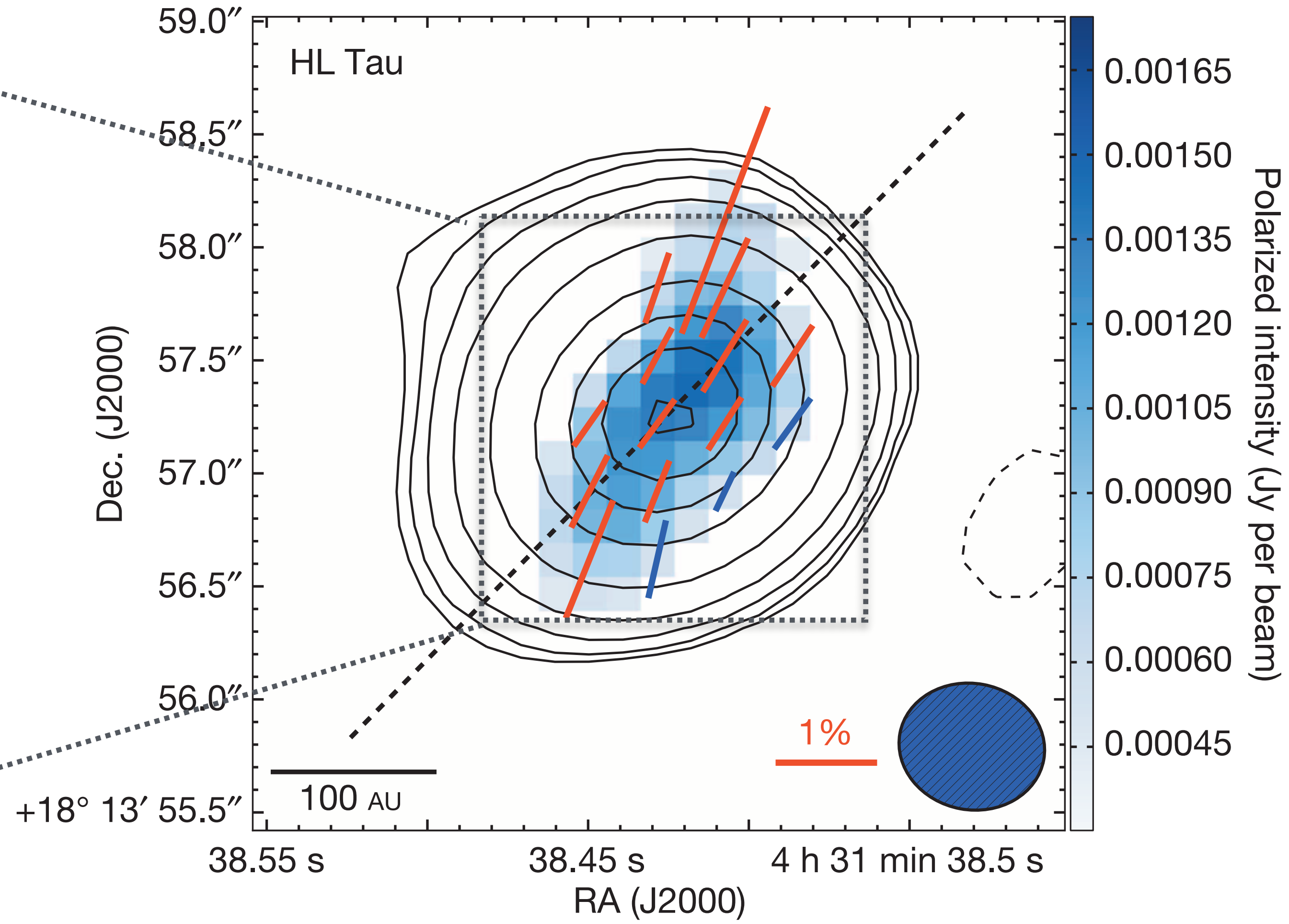
observations of mm-wave polarization: are they due to dust scattering or alignment?

Case study : HL Tau

ALMA, continuum



CARMA & SMA, polarization



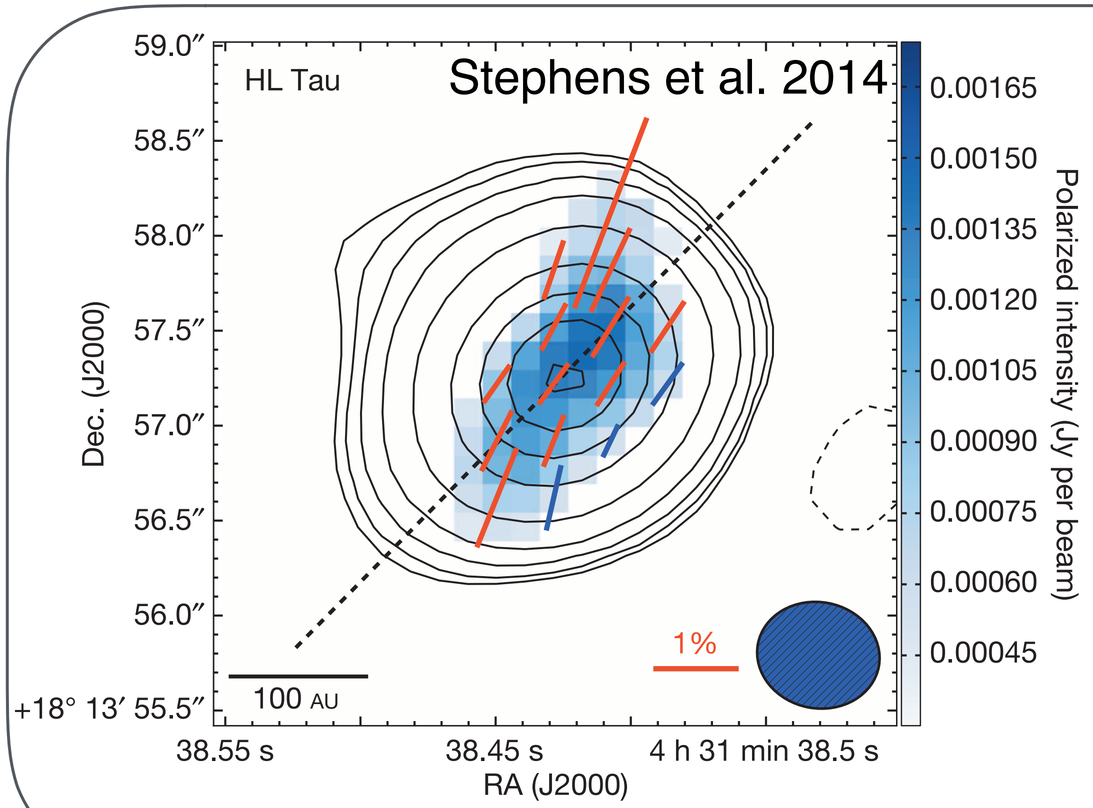
red : polarization vectors rotated by 90°

ALMA partnership 2015

Stephens et al. 2014

- HL Tau - multiple-ring structure revealed by ALMA.
- spectral index is ~2 in the inner part: optically thick?
- The net polarization at mm wave is ~ 0.9 %.

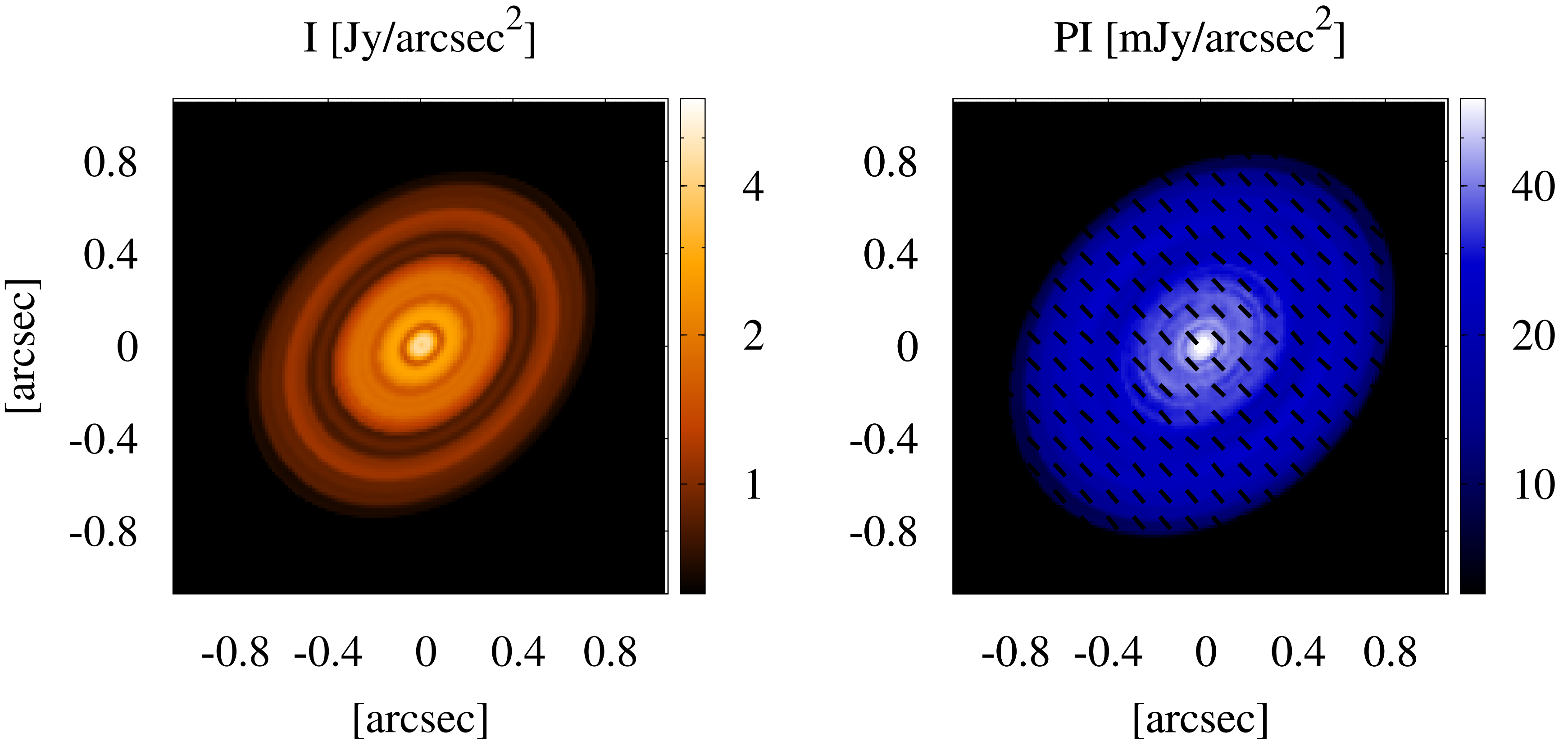
Case study : HL Tau



red : polarization vectors rotated by 90°

B-field

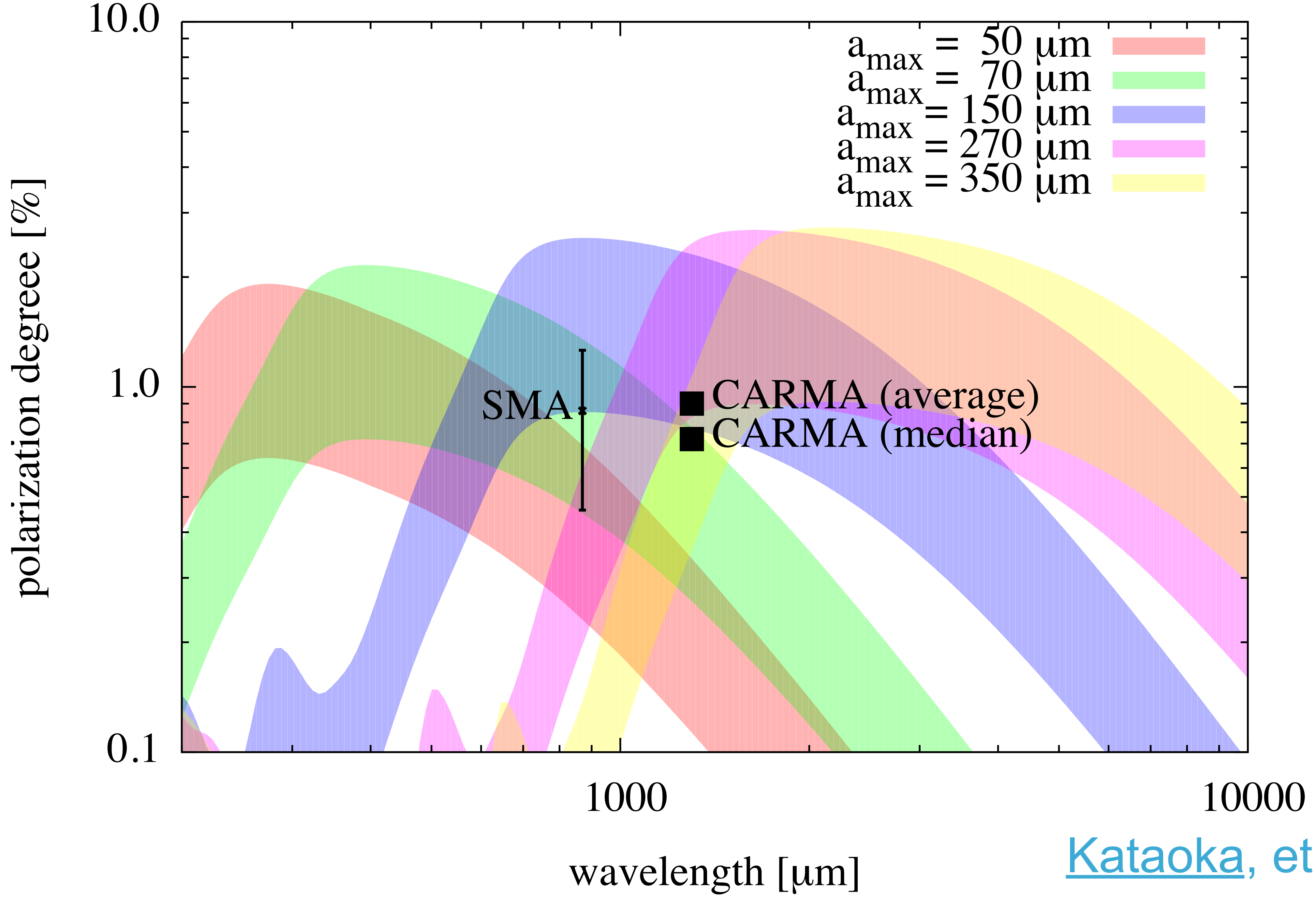
E-field (polarization vectors)



The polarization signature is well explained by the self-scattering

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

Case study : HL Tau

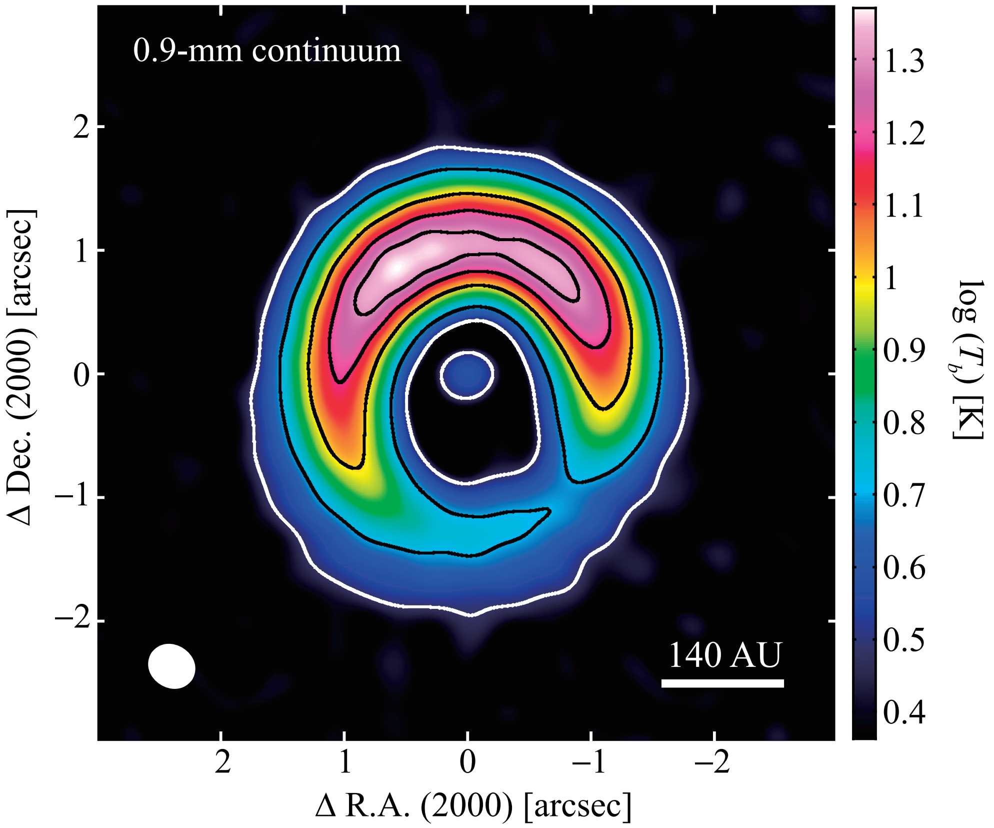


Kataoka, et al., 2016a

Constraints on grain size: $70\ \mu m < a_{max} < 270\ \mu m$

Case study of HD 142527

Anisotropies **grain size**



Fukagawa et al. 2013

× ? = polarization observation

- Mstar~2Msun, ~ 5 Myr old
- Lopsided dust continuum distribution

Cycle 3 observations

ALMA Band 7
target : HD 142527
mode : full polarization
beam size :0.51" x 0.44" (compact configuration)
data was taken on March 11, 2016

ALMA Observations

noise level:

σ_I = 185 μJy beam^{-1}

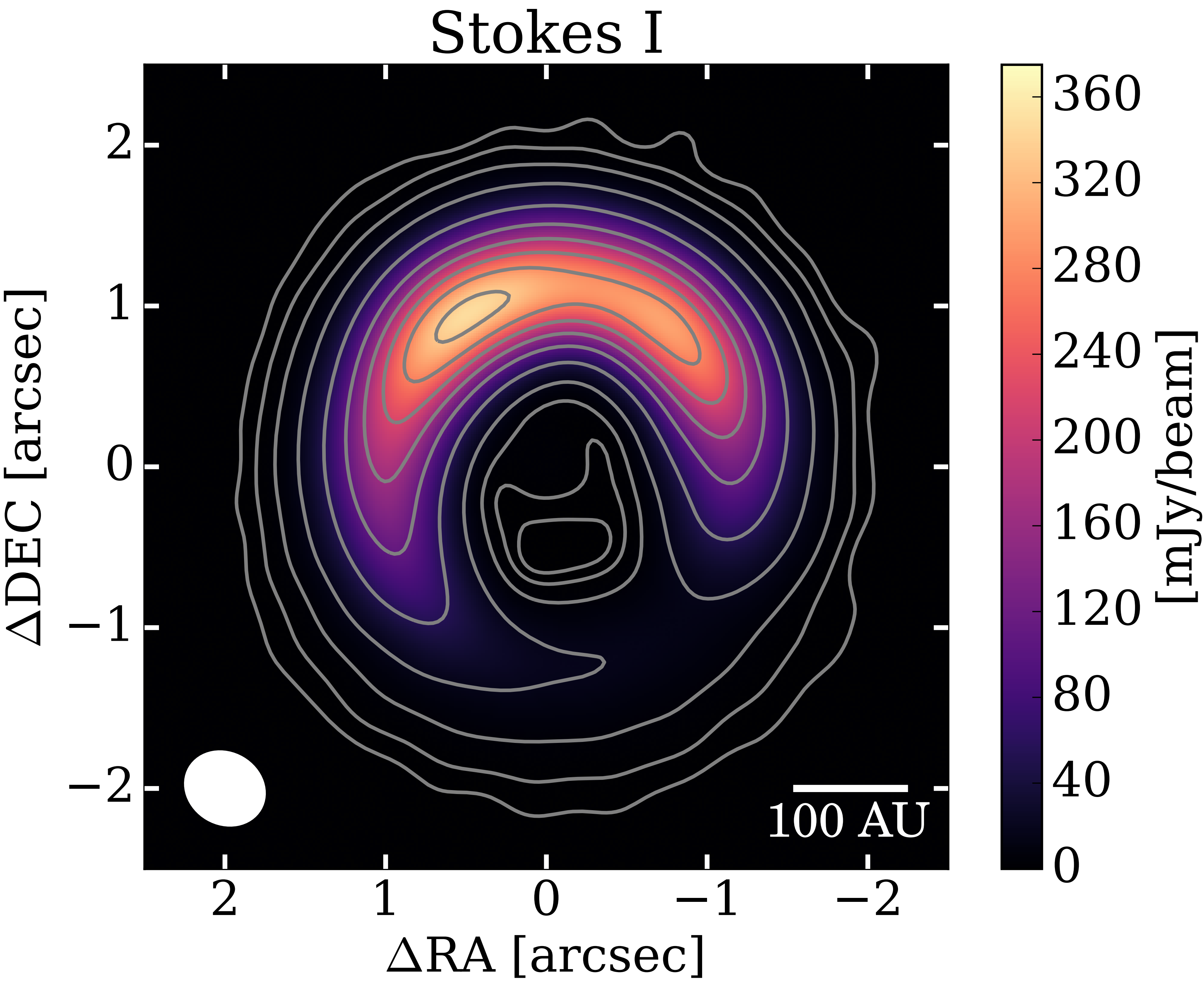
contours:

(3, 10, 30, 50, 100, 300, 600, 900, 1200, 1500, 1800) × σ_I

peak:

340 mJy/beam (=1838σ_I)

- Confirmed the previous observations (e.g., Casassus et al. 2013, Fukagwa et al. 2013)



Kataoka, et al., 2016b

ALMA Polarization Observations

noise level:

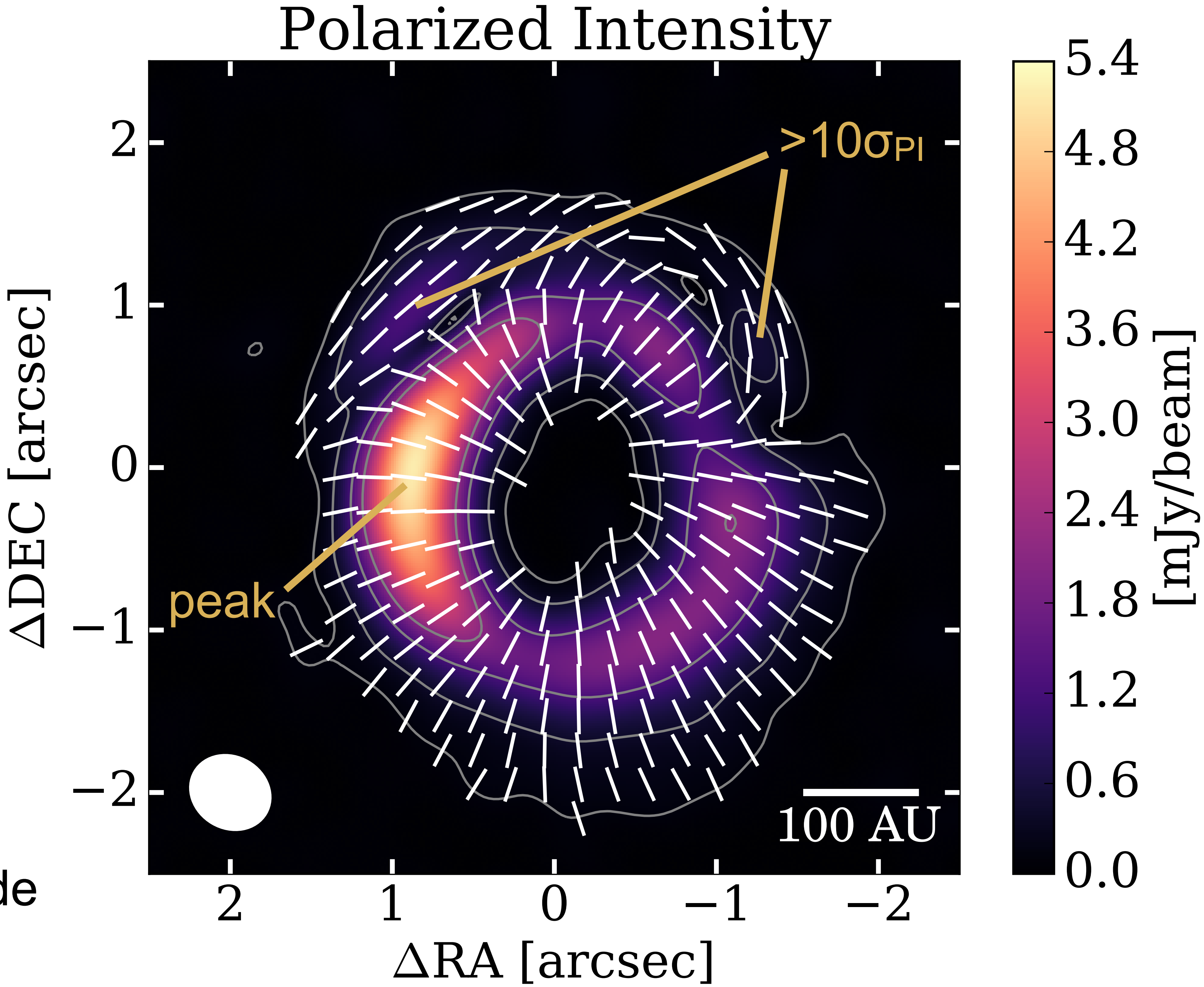
σ_{PI} = 42.8 μJy beam^{-1}

contours:

(3, 10, 30, 50, 100) × σ_{PI}

peak:

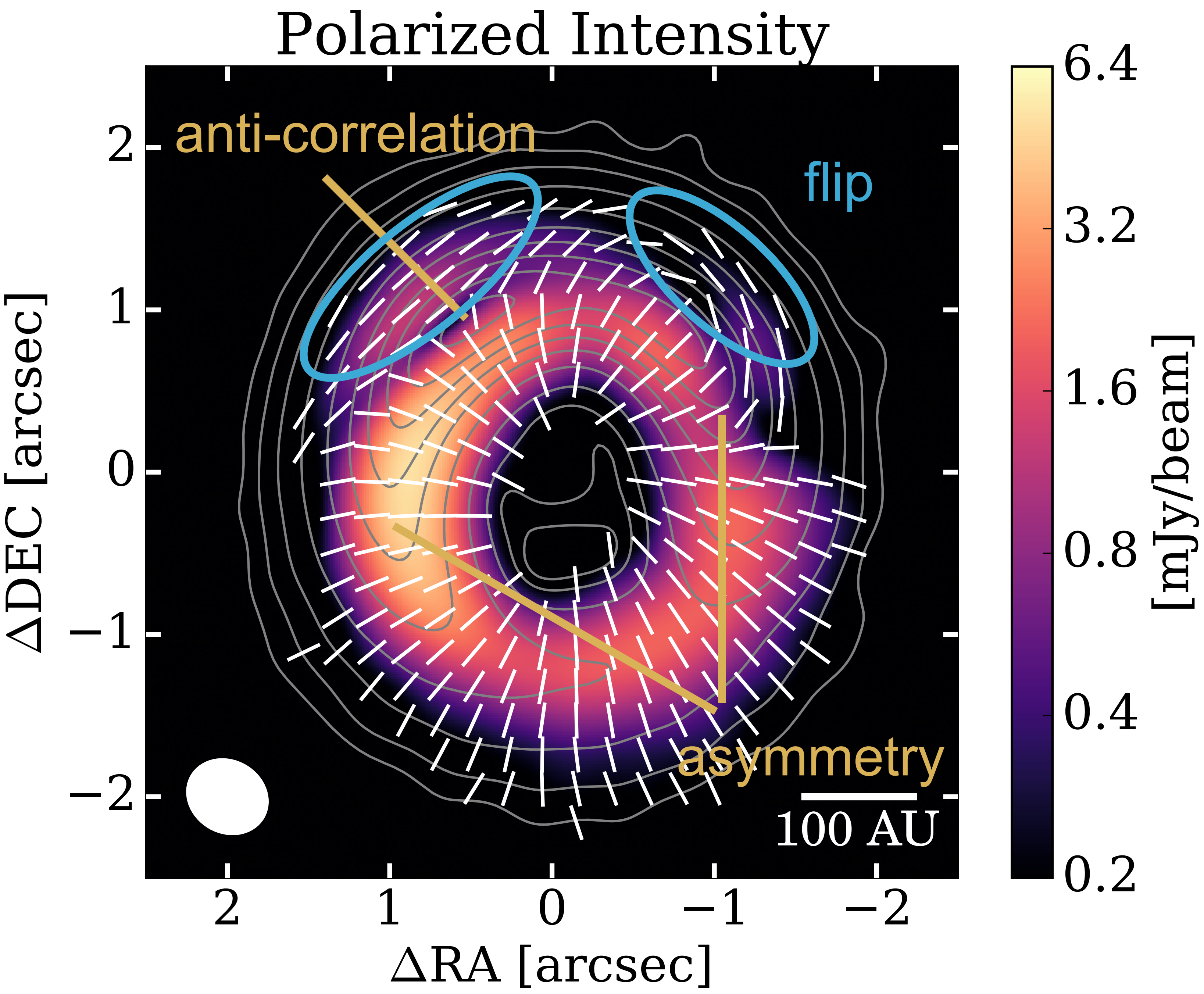
5.22 mJy/beam (=122σ_{PI})



- Polarization vectors' orientation is radial inside and azimuthal outside (north)

Kataoka, et al., 2016b

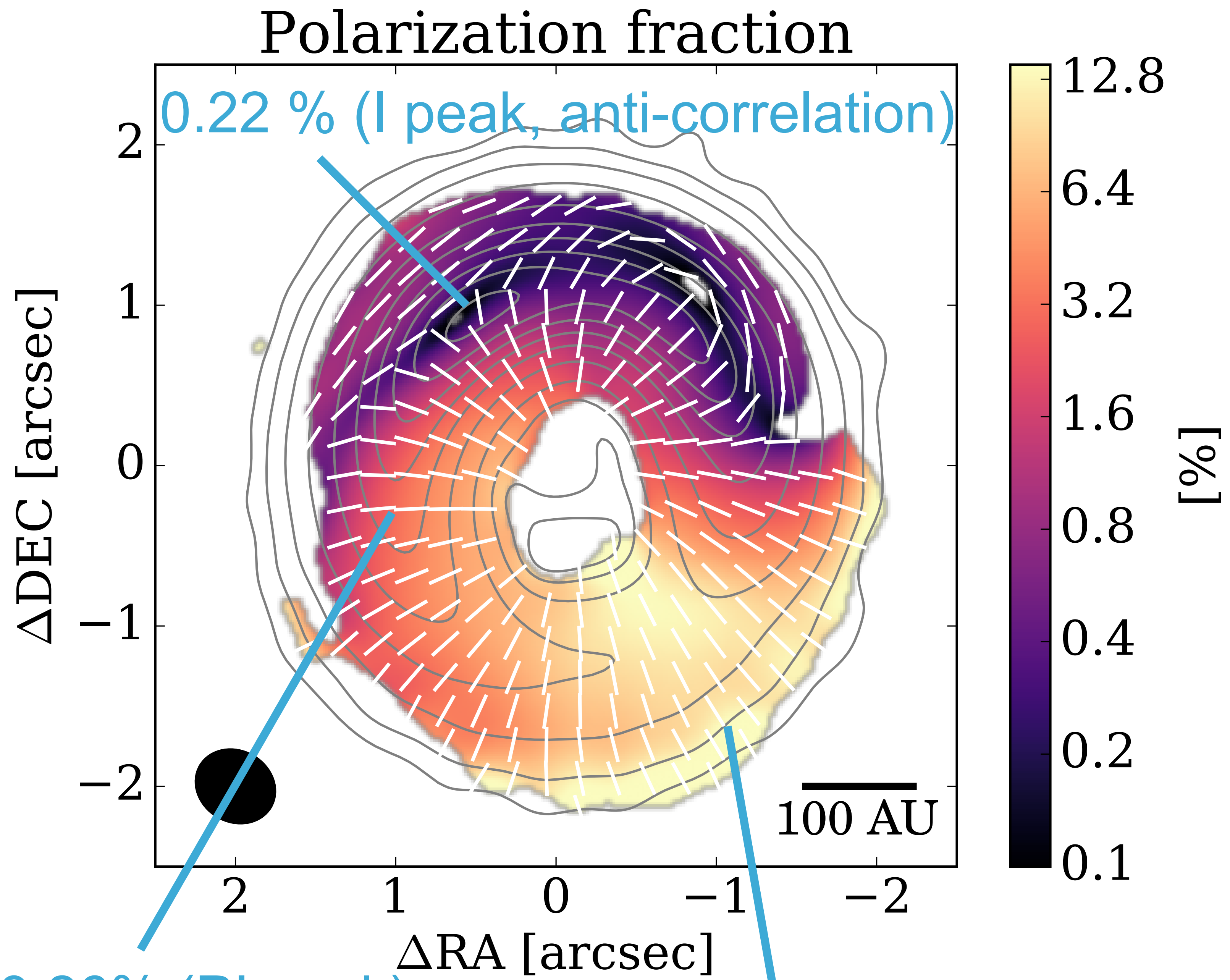
ALMA Polarization Observations



- Flip of polarization vectors
  - Change of the direction of radiative flux - evidence of the self-scattering (Kataoka et al. 2015)
- Anti-correlation between I and PI at the I peak.
  - expected from the optical depth effects (Kataoka et al. 2015)
- Asymmetry in PI between head and tail of the vortex?

Kataoka, et al., 2016b

ALMA Polarization Observations



0.22 % (I peak, anti-correlation)

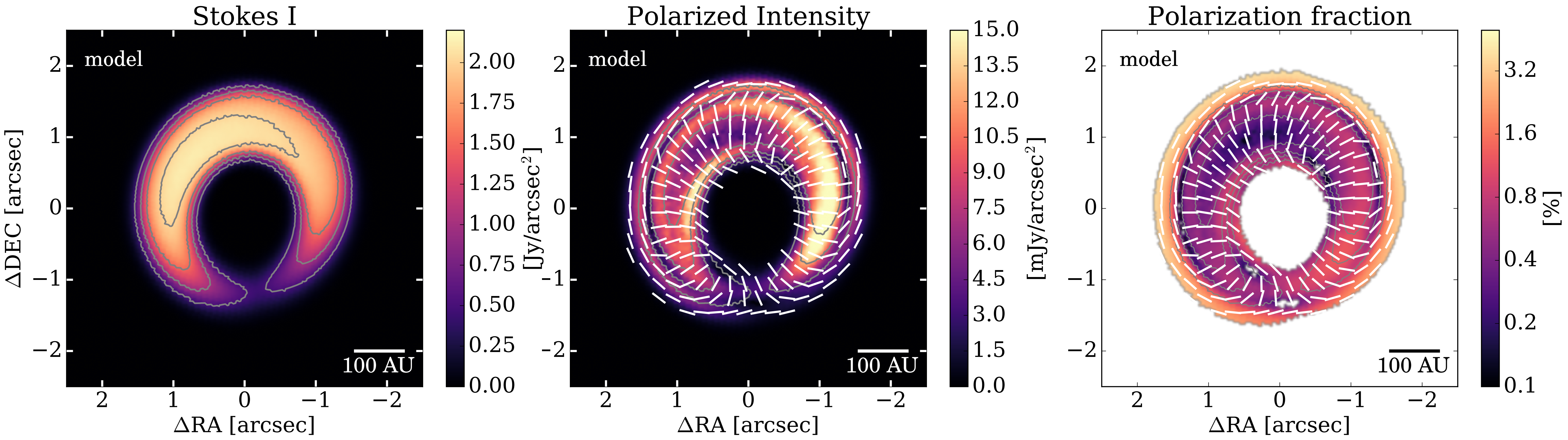
3.26% (PI peak)

high percentage: 13.9 %

- High percentage
  - high polarization fraction (13.9%) is not expected from the self scattering (~<5 %)
  - It could be due to the resolving-out effects

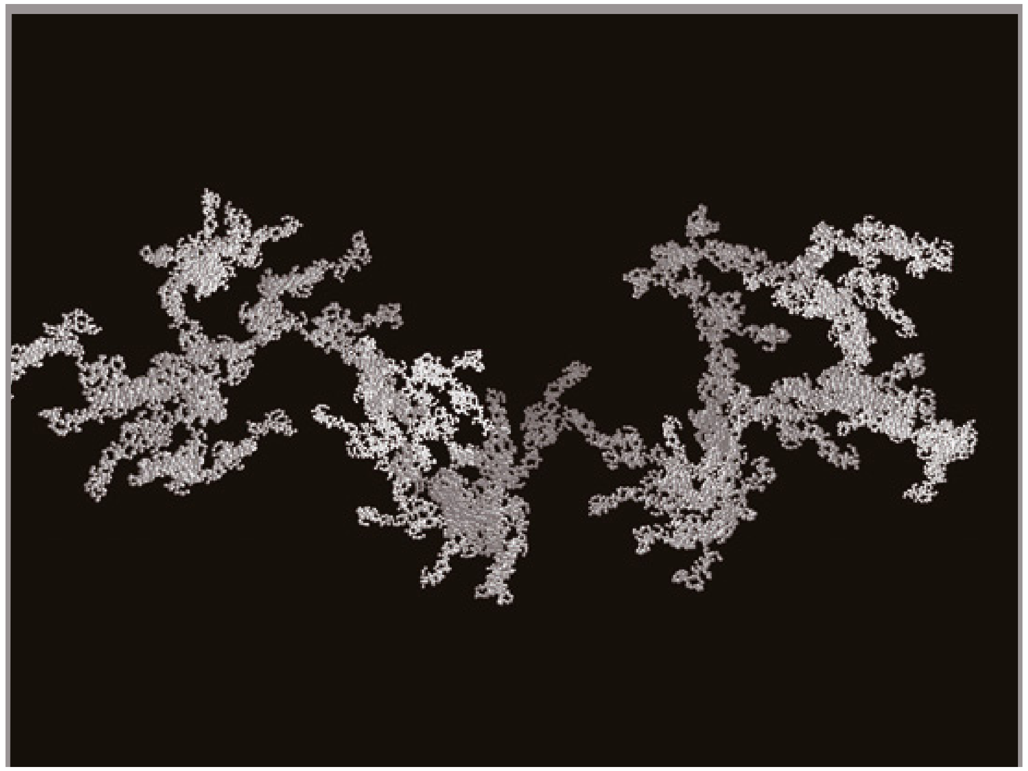
[Kataoka](), et al., 2016b

Model calculations



- The self-scattering model explains the flip of the polarization vectors' orientation, the anti-correlation between I and PI.
- However, it cannot explain the observed asymmetry in PI and high polarization percentage.

[Kataoka](), et al., 2016b



Future directions

Future directions

Anisotropies of radiation field at the observed wavelengths. (Predictable from Stokes I continuum)

×

Grain size
(Measurable)

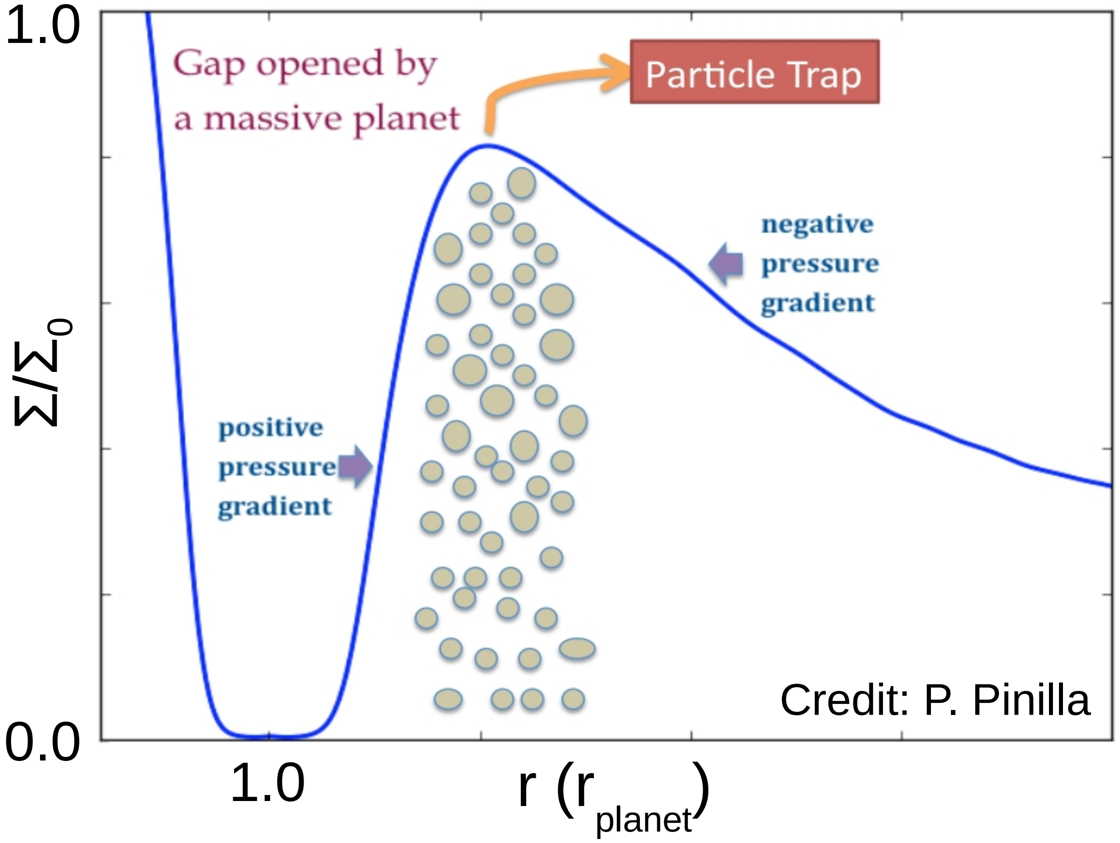
=

Polarization

Dust coagulation, fragmentation, and migration theory gives us the grain size distribution in a disk.

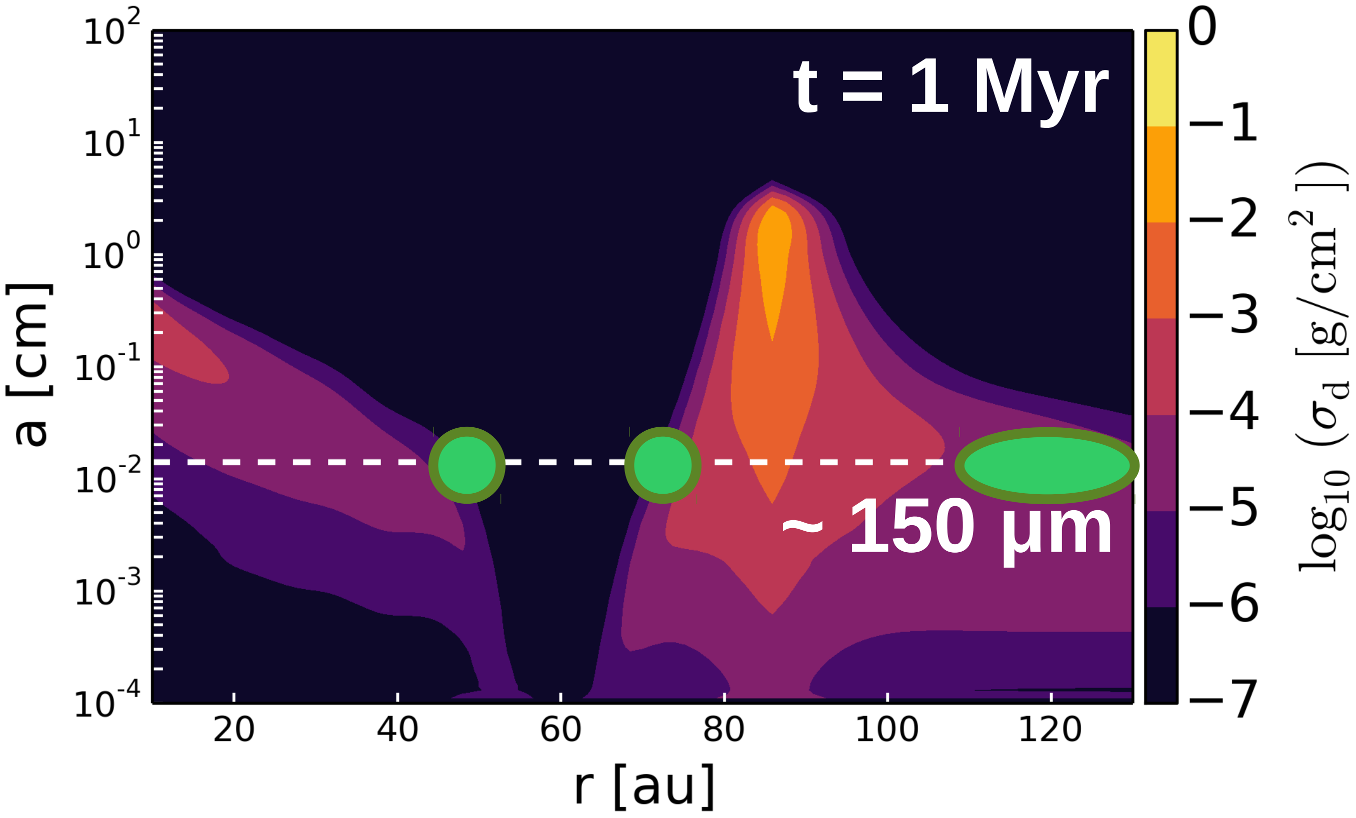
Synthetic Observations

Dust trap by a planet



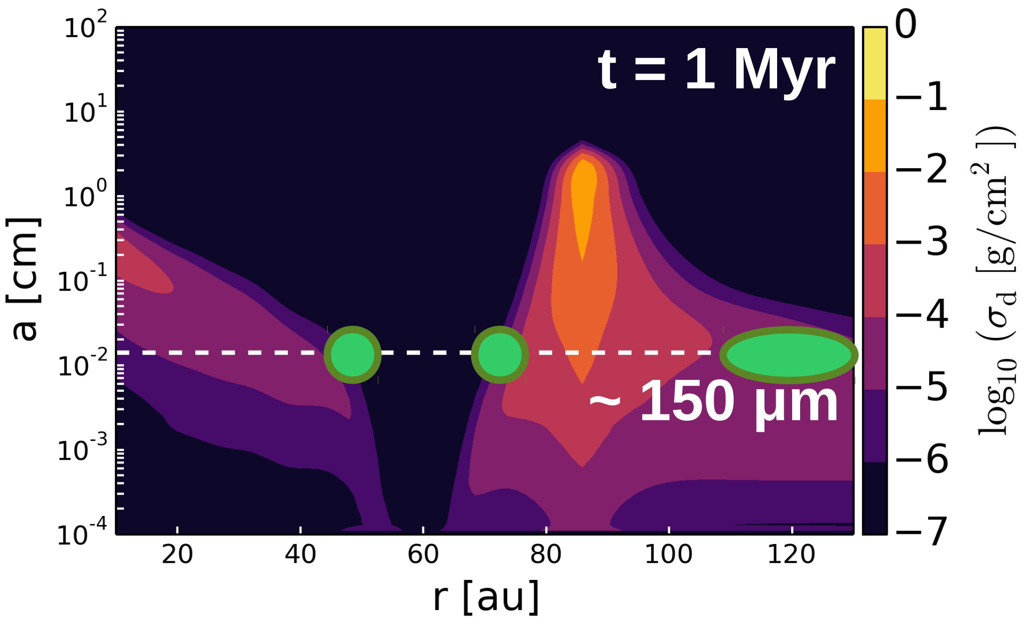
cf) Pinilla et al. 2012

Grain size distribution

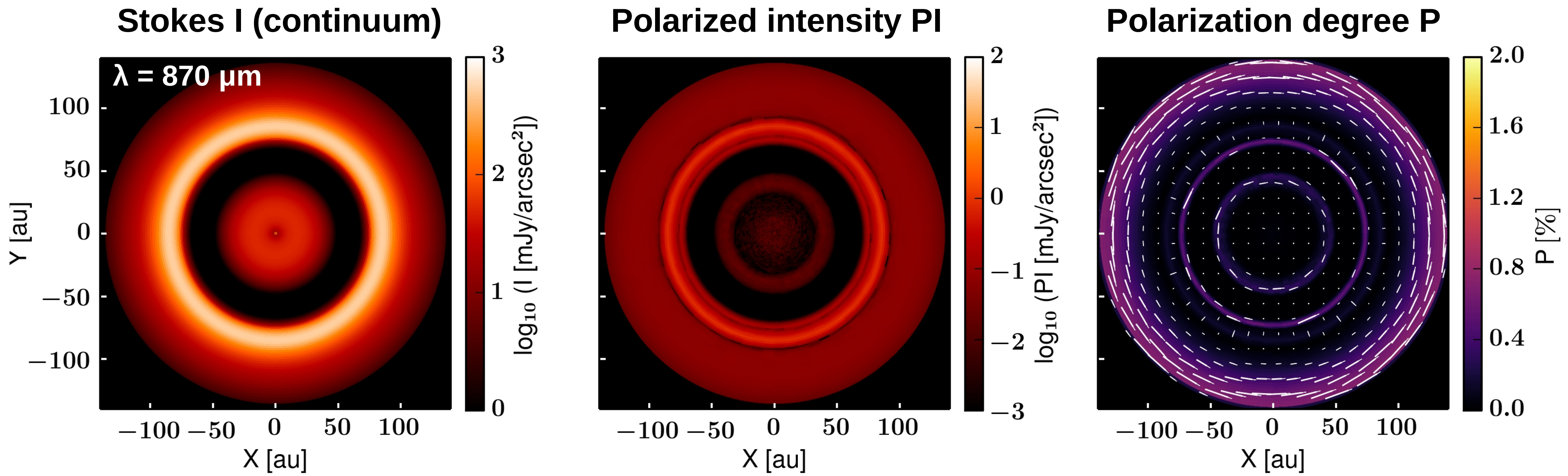


Pohl, Kataoka, et al., 2016

Synthetic Observations

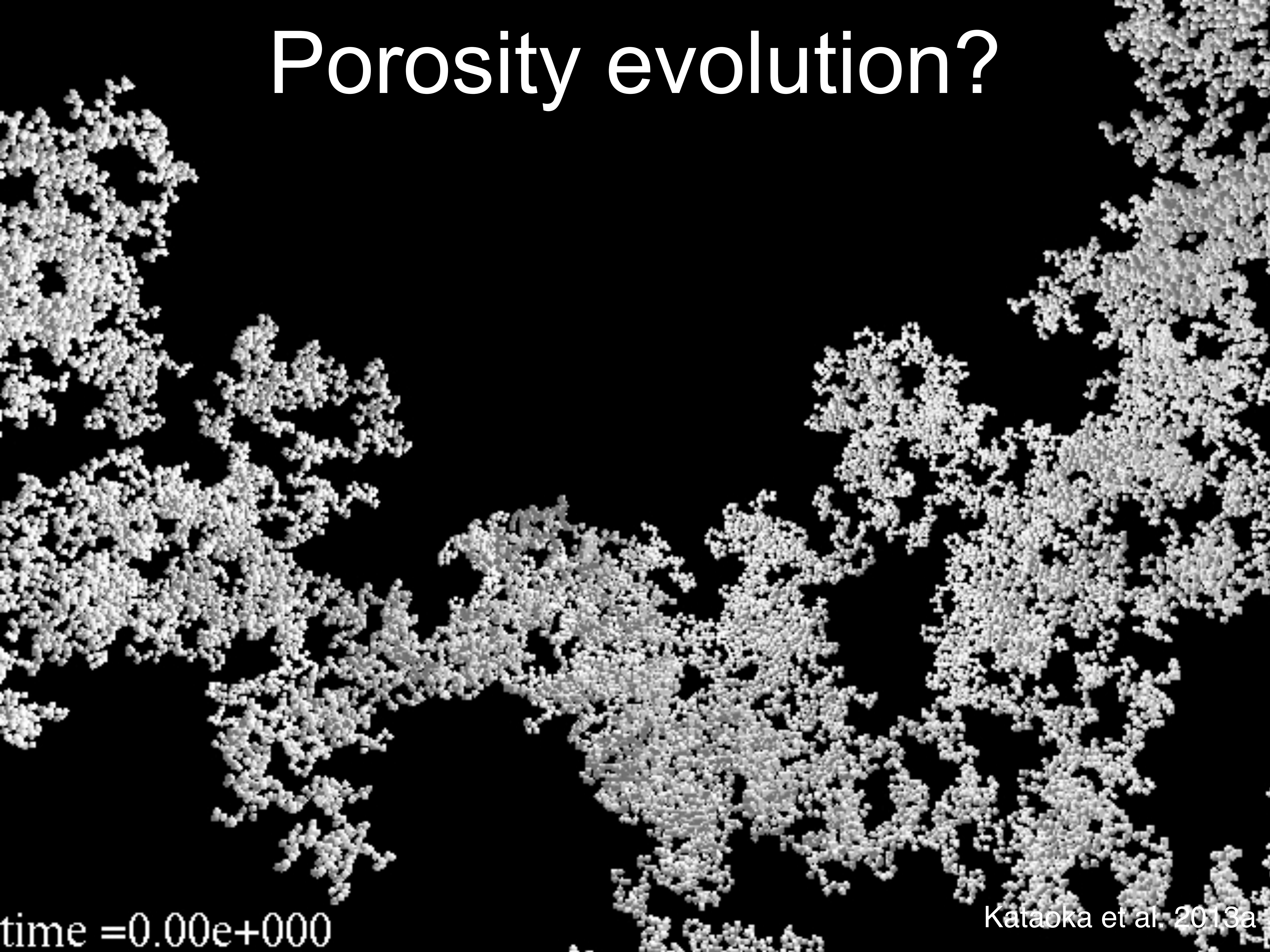


- Polarization is emitted only from locations where a_{max} = 150μm (λ=870 μm)
- In a disk with a planet, three polarization rings are expected.



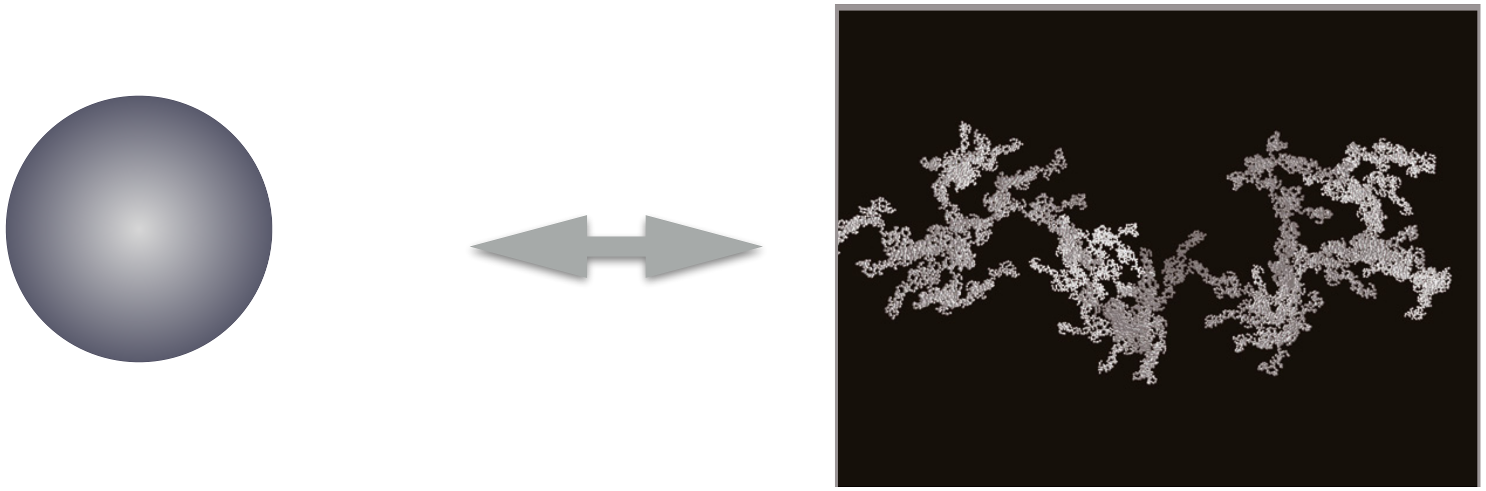
Pohl, Kataoka, et al., 2016

Porosity evolution?



Kataoka et al. 2013a

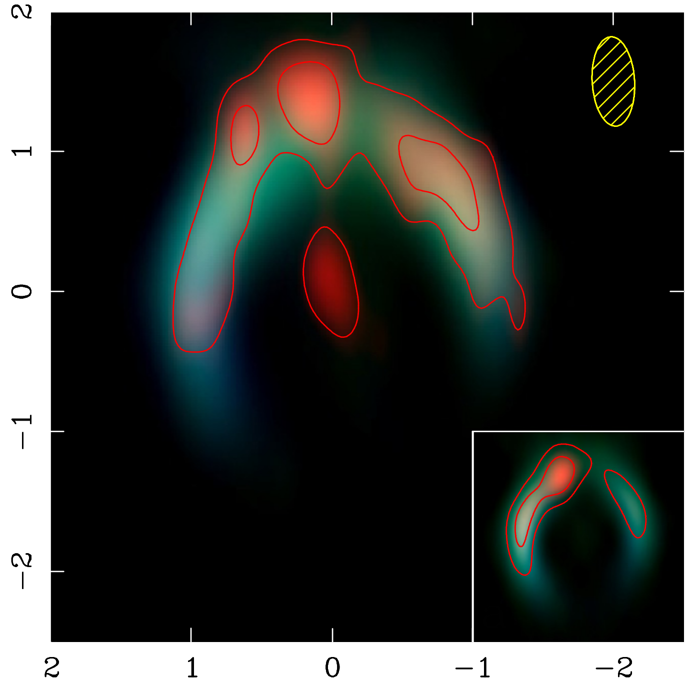
Measuring the porosity?



We cannot distinguish them in absorption opacity

- absorption opacity (spectral index)
  - Grain size (*af*) should be 1 mm or larger
- scattering opacity (mm-wave polarization)
  - Grain size should be ~150 μm (=λ/2π) if they are compact

red: ATCA, 9 mm
green: ALMA Band 7
blue: ALMA Band 9



Casassus et al. 2015

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 modeled the polarization of HL Tau
  - The observed feature is well explained by the self-scattering.
  - The maximum grain size is constrained to be ~150 μm

(Kataoka et al. 2016a, ApJ)

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

(Kataoka et al. 2016b, ApJL)