

Millimeter-wave Polarization of Protoplanetary Disks in the ALMA 2040 Era

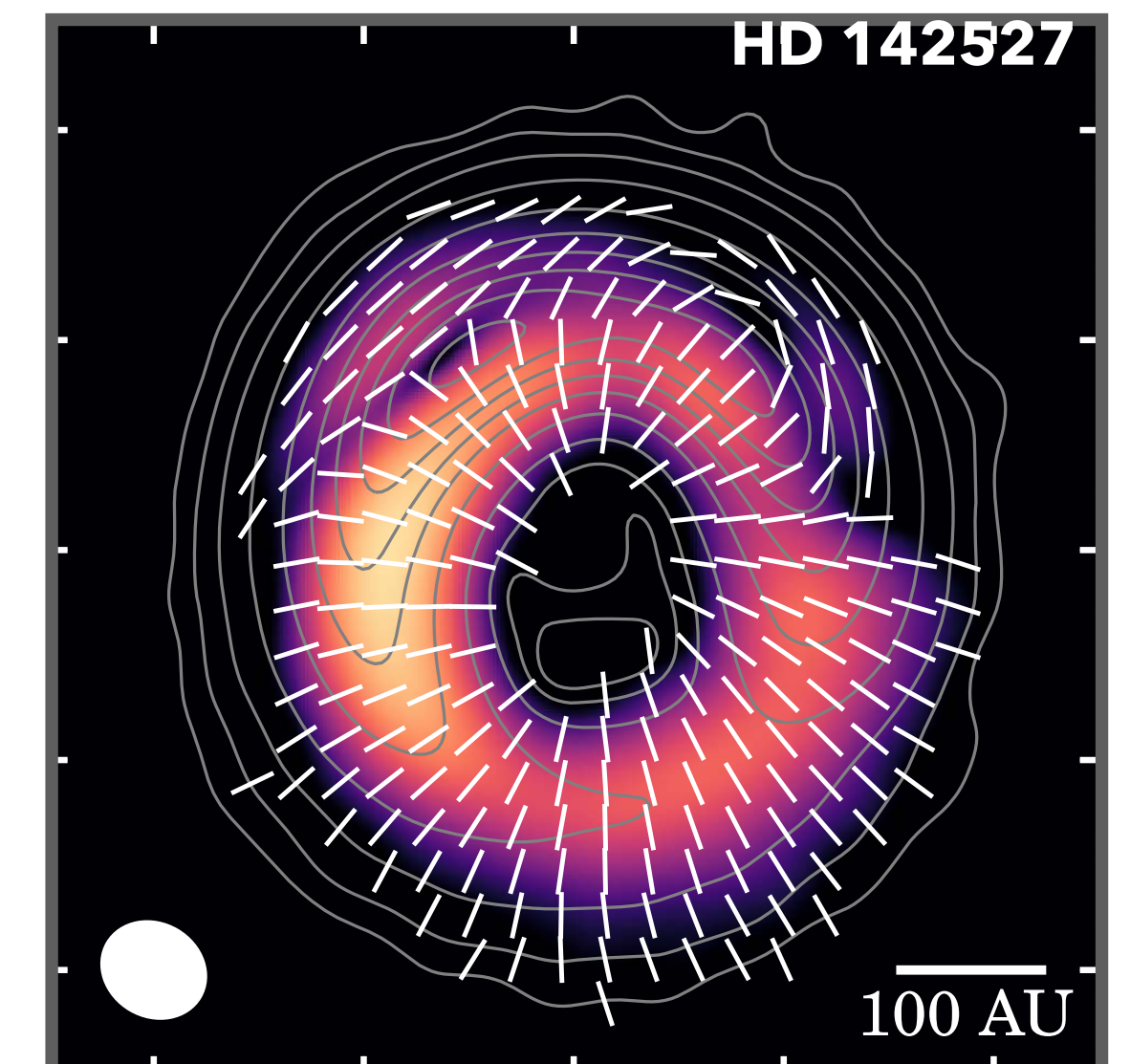
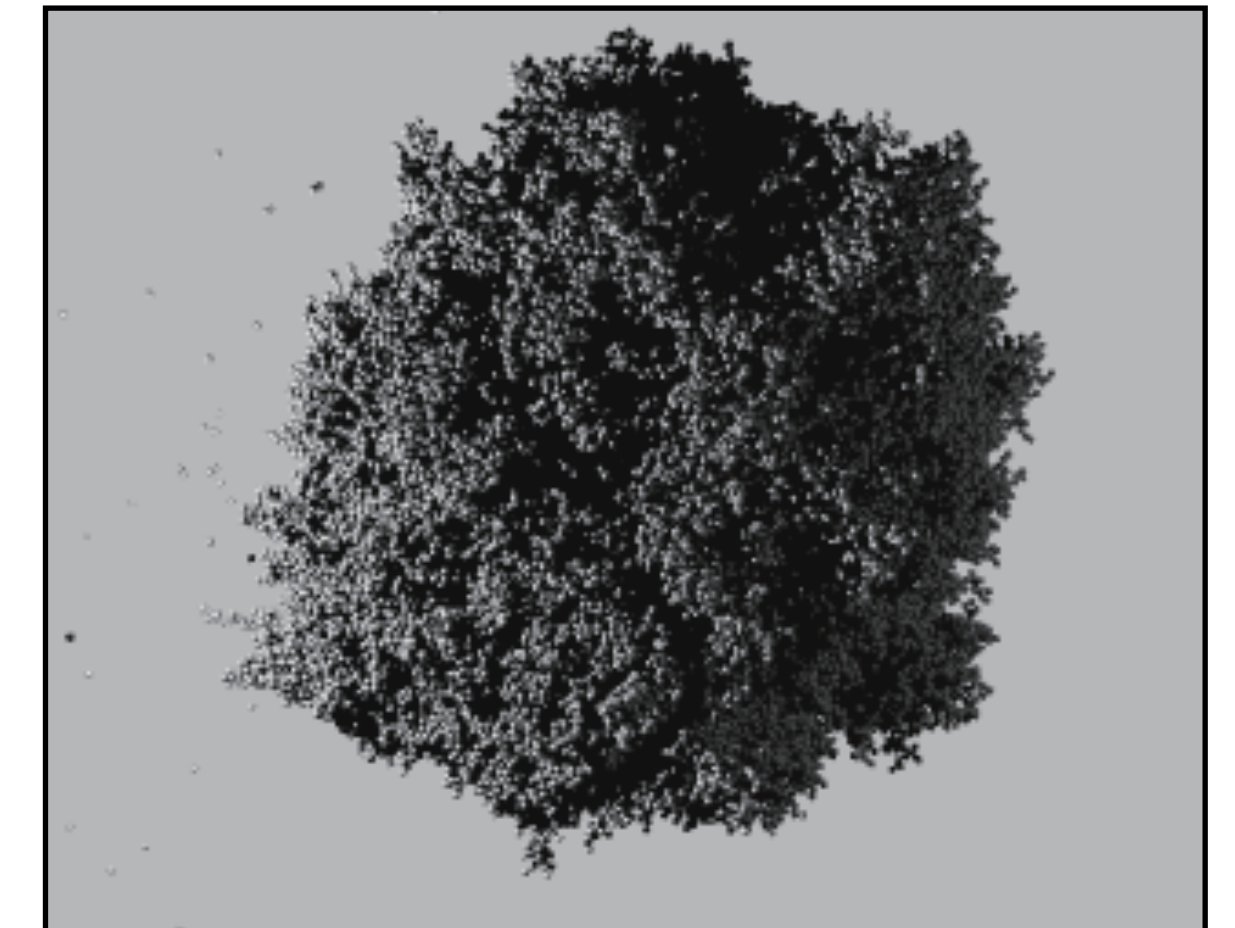
Akimasa Kataoka

National Astronomical Observatory of Japan

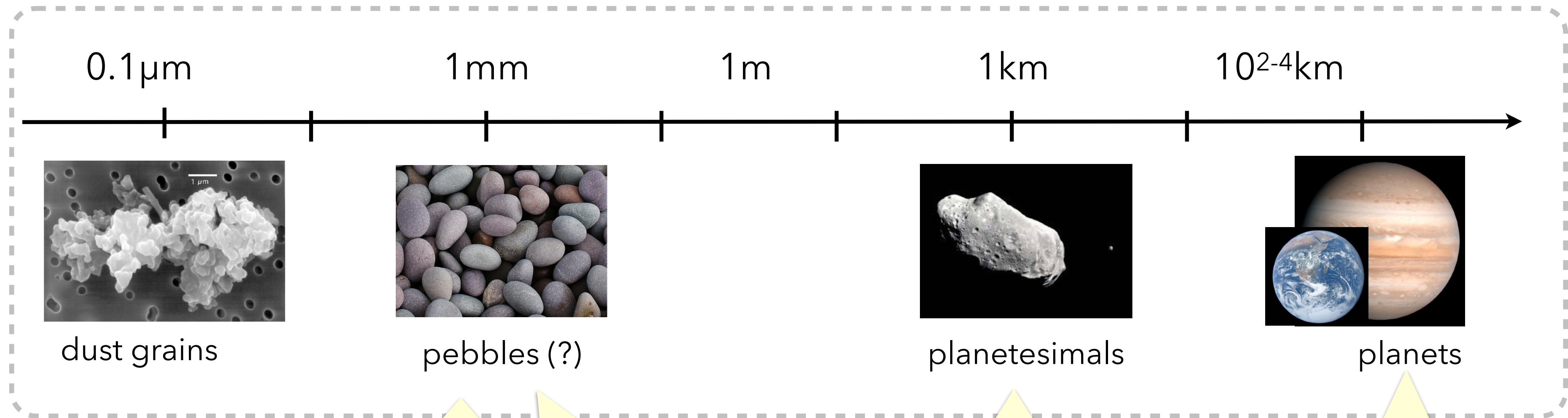
July 17th, 2026, East Asian ALMA Community Workshop

Abstract

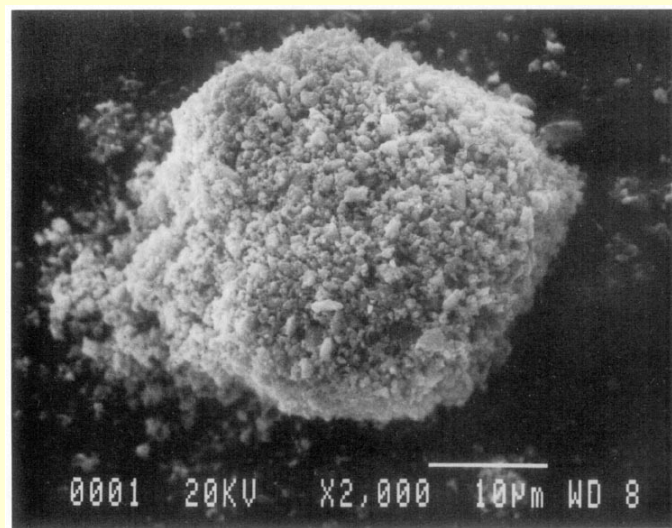
- **Science:** Microphysics of dust grains in planet formation.
- **Methods:** Linear polarization of continuum emission from protoplanetary disks.
- **Requirements:** An order-of-magnitude improvement in sensitivity without relying on broader bandwidth, full-polarization capability across all ALMA bands, and polarization calibration accurate to 0.01%.
- **EA community:** A leading role in both theoretical and observational studies of polarization and dust microphysics.



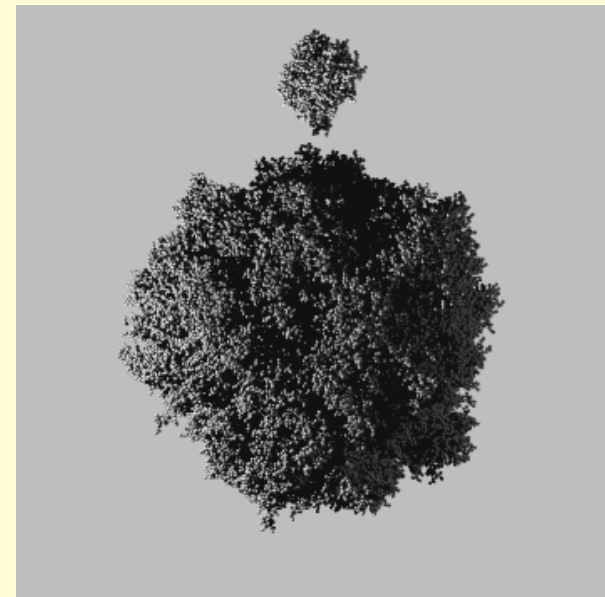
Planet formation



Numerical simulations /
Laboratory experiments

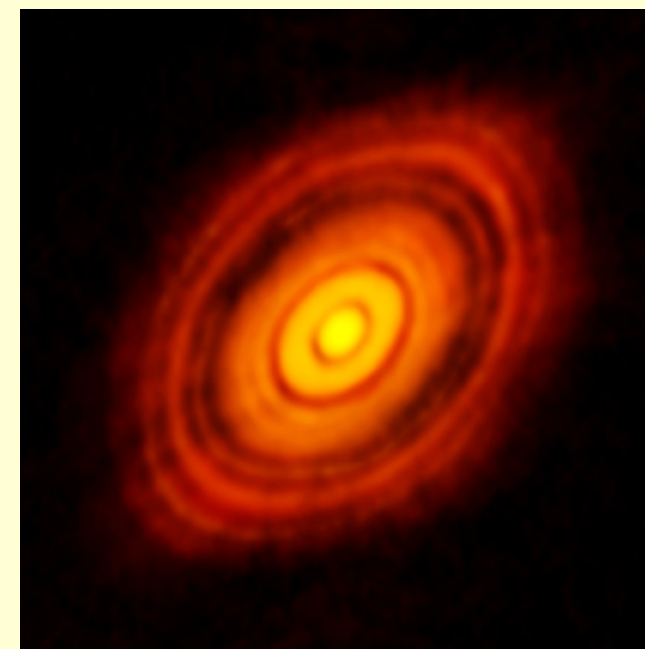


Blum & Münch 1993



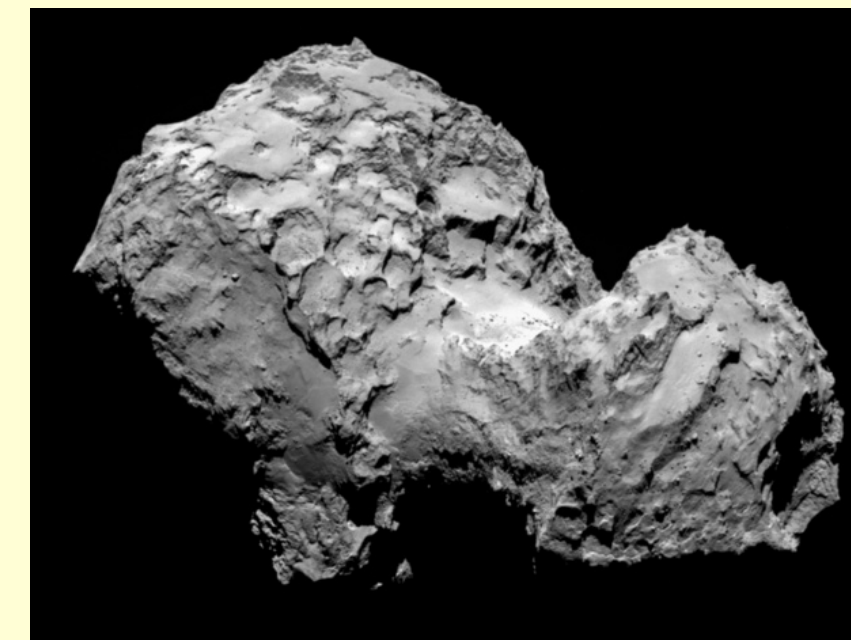
Wada et al. 2013

Astronomical
Observations



ALMA Partnership 2015

Comets

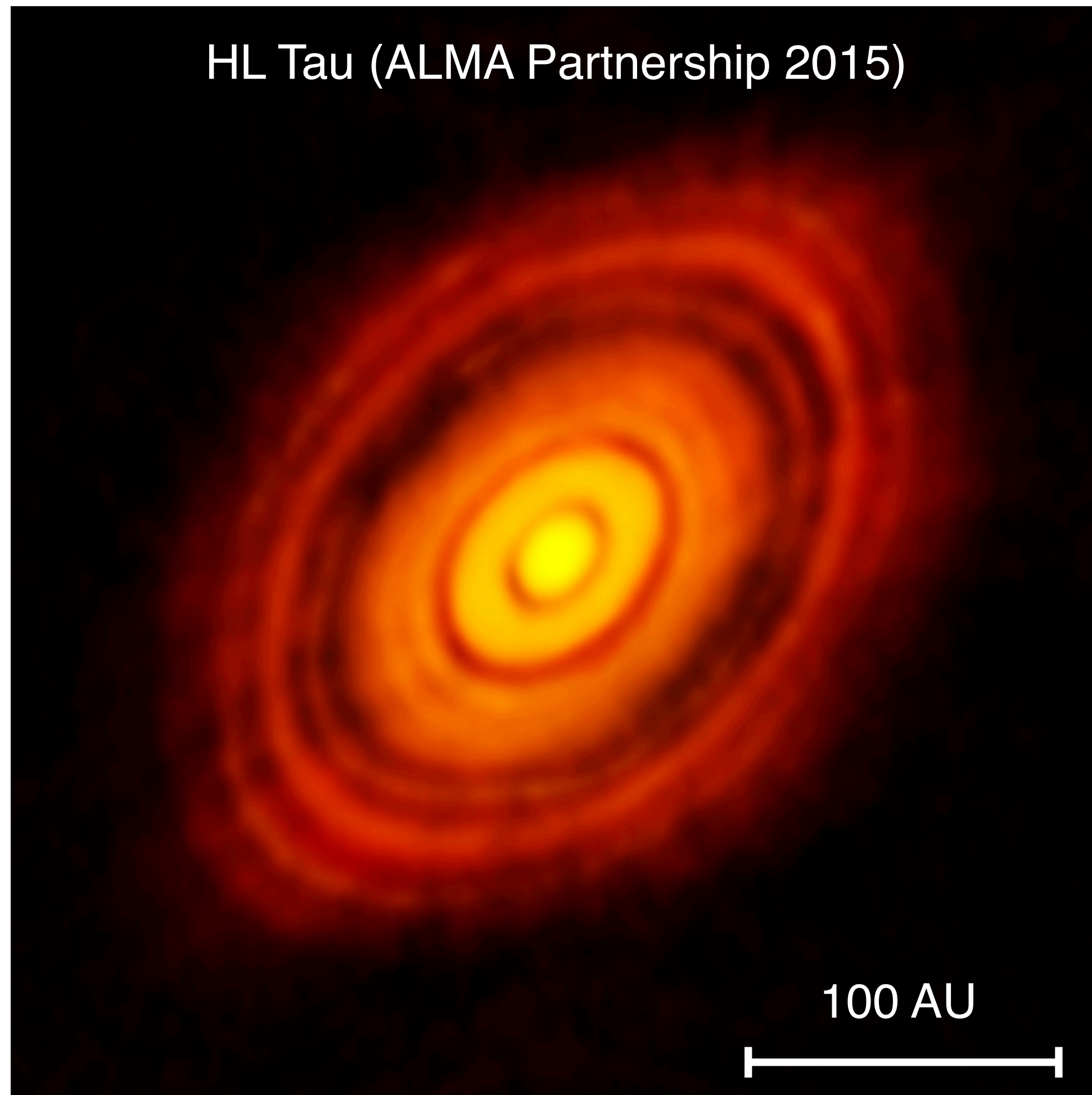


Rosetta mission

(extra)solar system



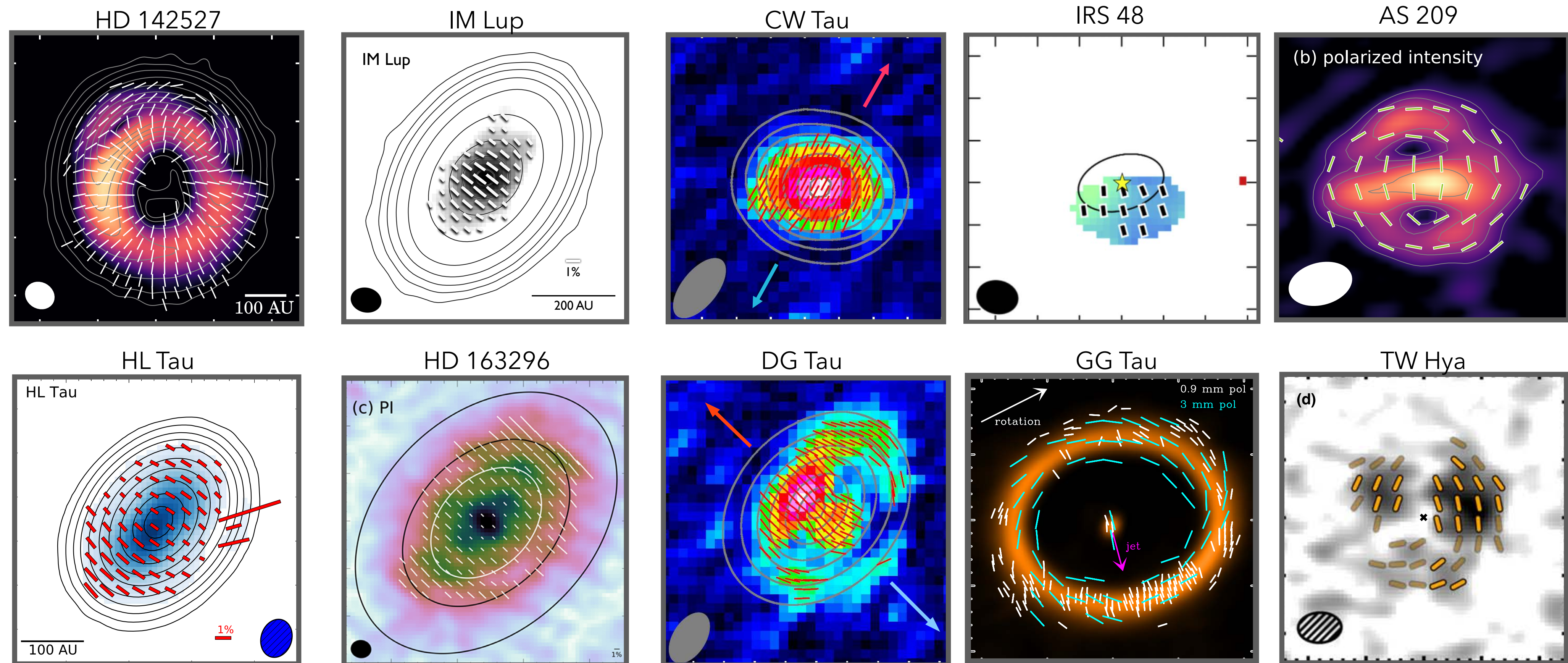
Millimeter emission of protoplanetary disks



- (Stokes I) continuum = thermal dust emission
 - Dust distribution, mass, size ...
- **Linear polarization of continuum**
 - **Dust size, porosity, shape ...**
- Molecular line emission
 - Gas mass, composition, kinematics...
- Linear/circular polarization of line emission
 - Not detected yet.

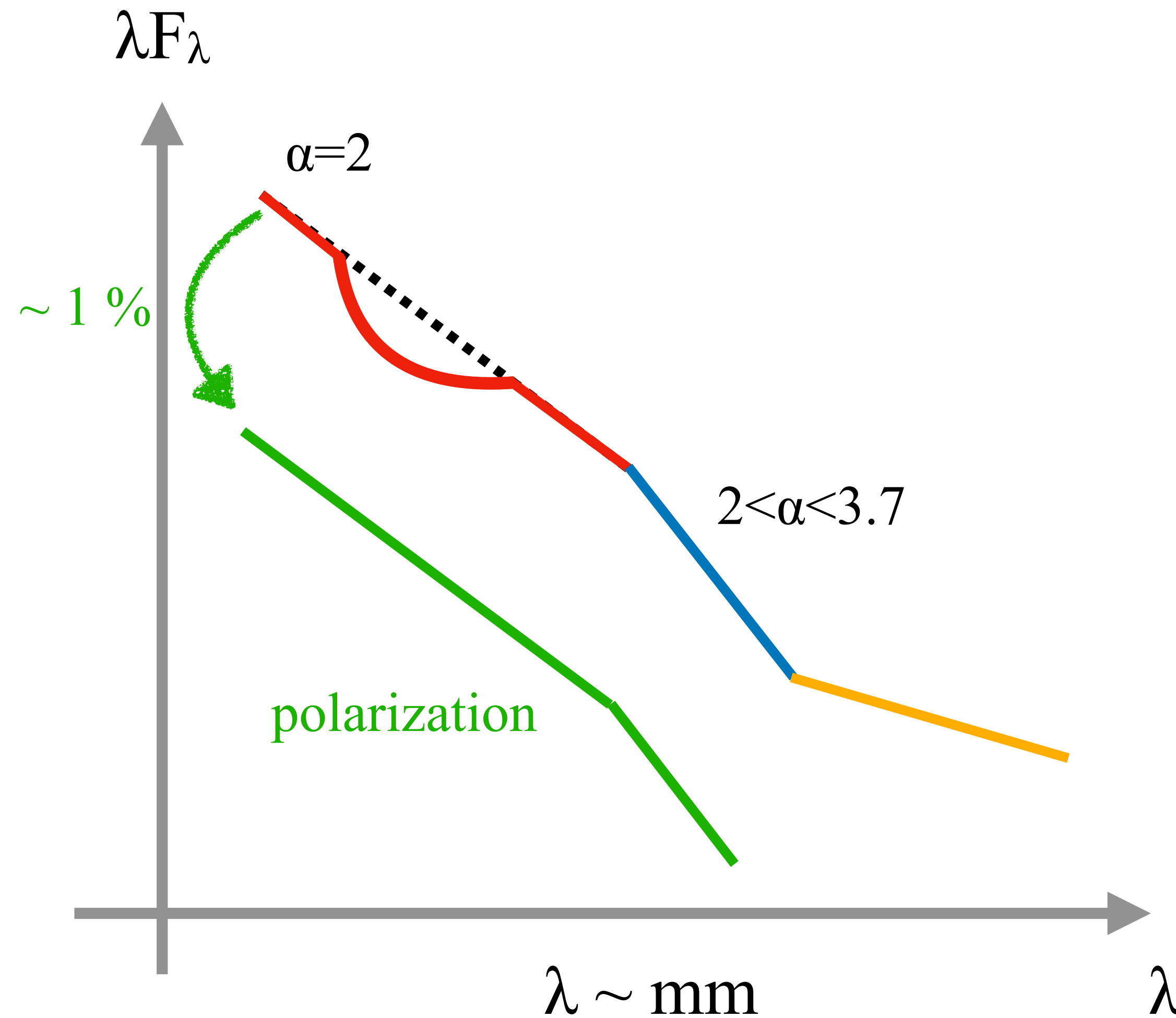
Linear polarization of disks with ALMA

Note: in pre-ALMA era, non-detection has been reported on HD 163296, TW Hya, GM Aur and DG Tau (Hughes et al. 2009, 2013) except for HL Tau (Stephens et al. 2014)



Kataoka et al. 2016, Hull et al. 2018, Bacciotti et al. 2018, Dent et al. 2019, Stephens et al. 2017, Satoshi Ohashi et al. 2020, Teague et al. 2021, Ya-Wen Tang et al. 2023, cf. Kataoka et al. 2017, Satoshi Ohashi et al. 2018, Zhe-Yu Daniel Lin et al. 2023

Why was it hard to detect continuum polarization?

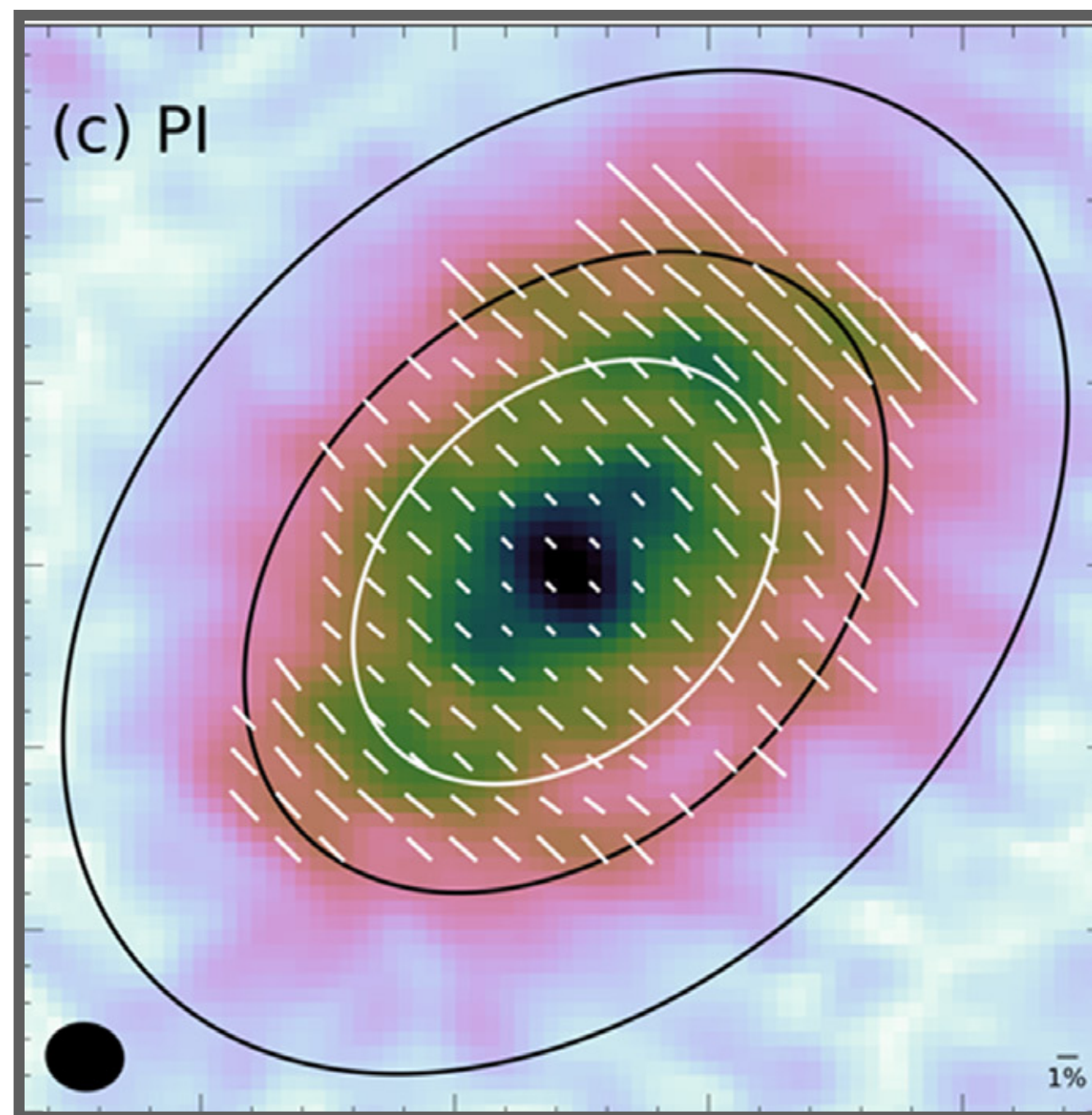


- Linear polarization of continuum is detectable but weak; $\sim 1\%$ or less of Stokes I emission
- We need high sensitivity.
- Spatial resolution especially at long wavelength (i.e., Band 3) is not high enough to resolve substructures.

Science with millimeter-wave polarization

Self-scattering

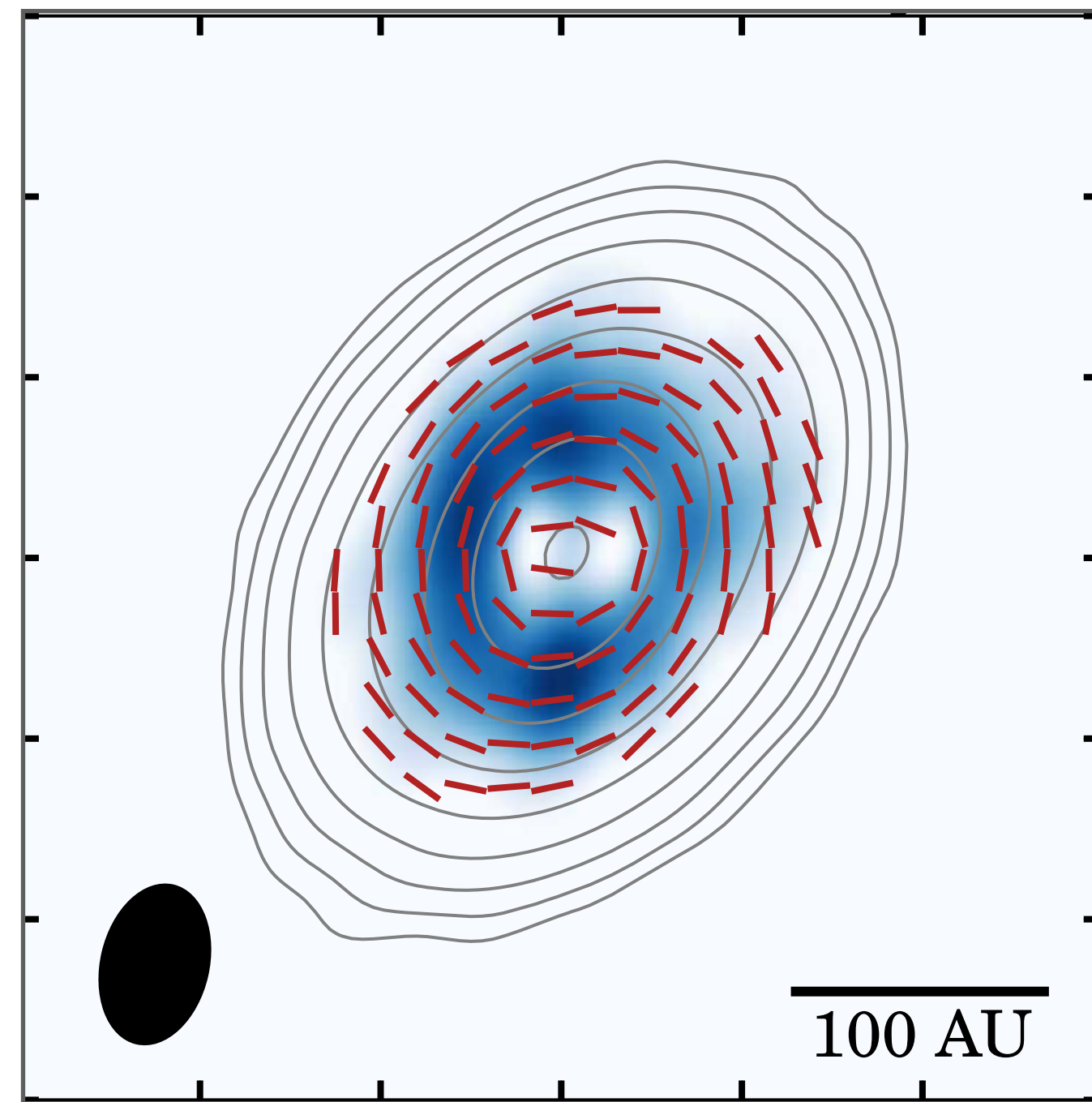
HD 163296 (0.9 mm)



Dent et al. 2019

Intrinsic

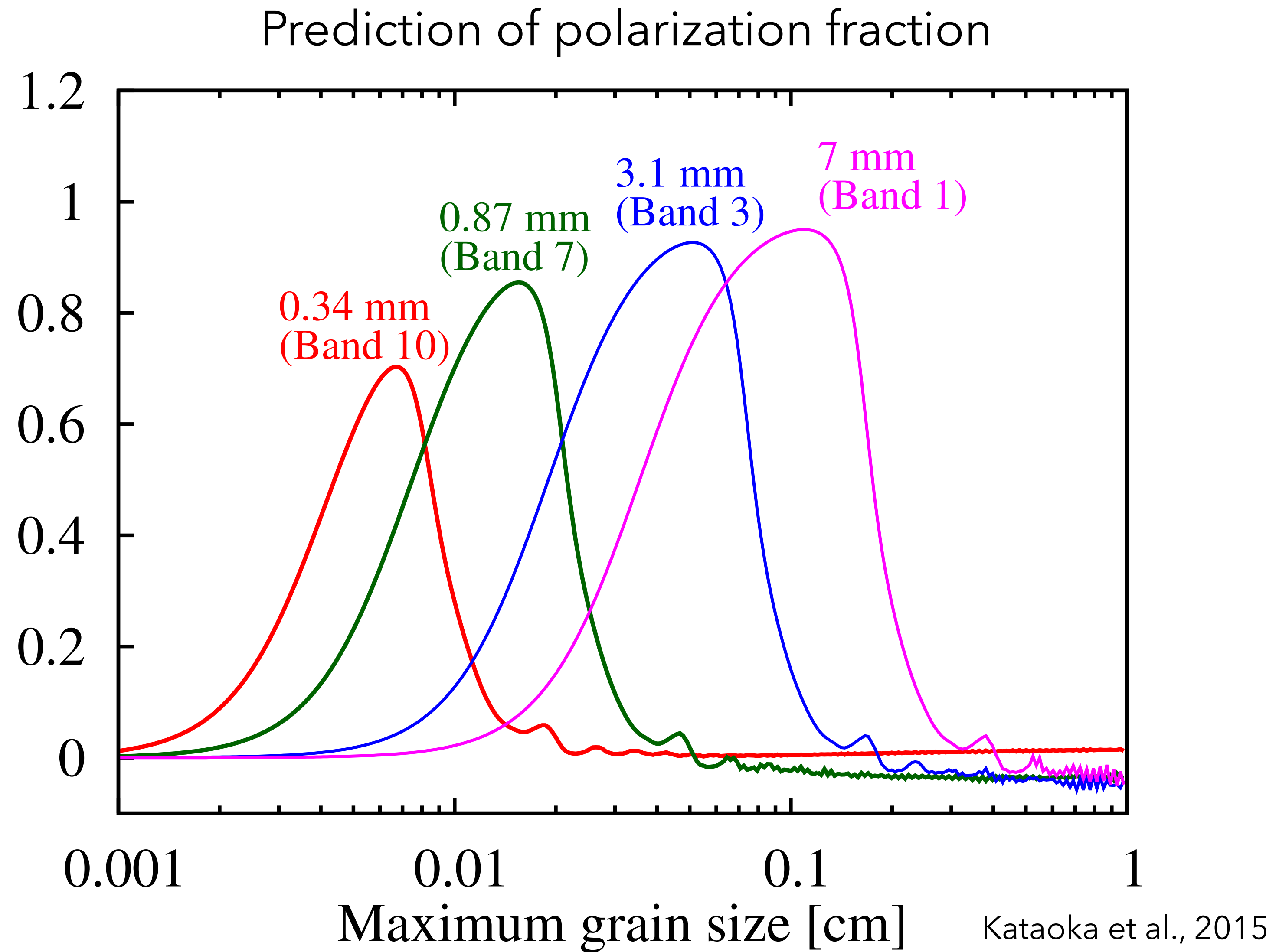
HL Tau (3 mm)



Kataoka et al. 2017

- Polarization can be decomposed into two components
- Polarization parallel to the minor axis, which is **consistent with self-scattering of thermal emission.**
- Polarization in the azimuthal direction, which is somewhat **consistent with intrinsic polarization of elongated dust grains.**

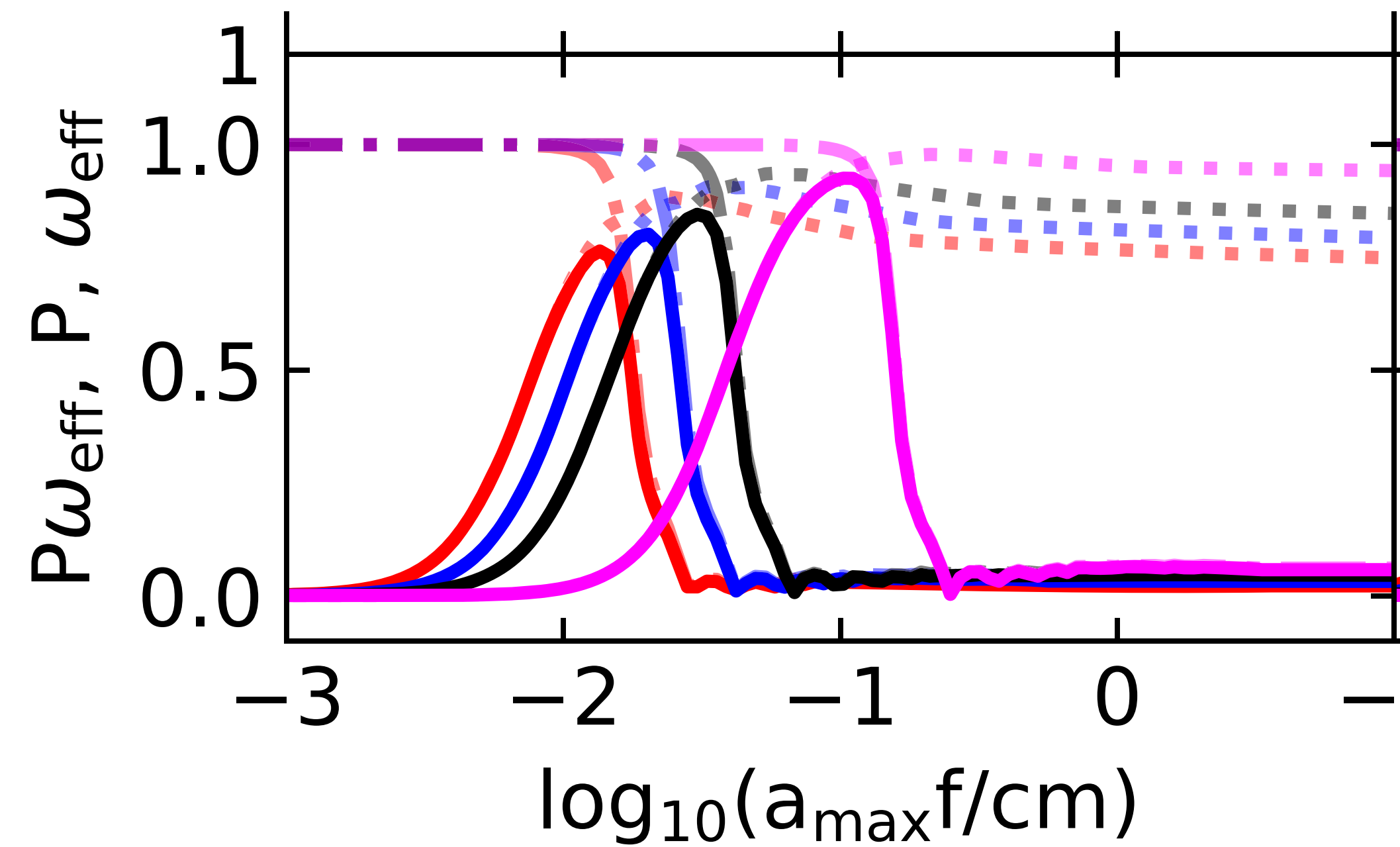
What can we learn from self-scattering?



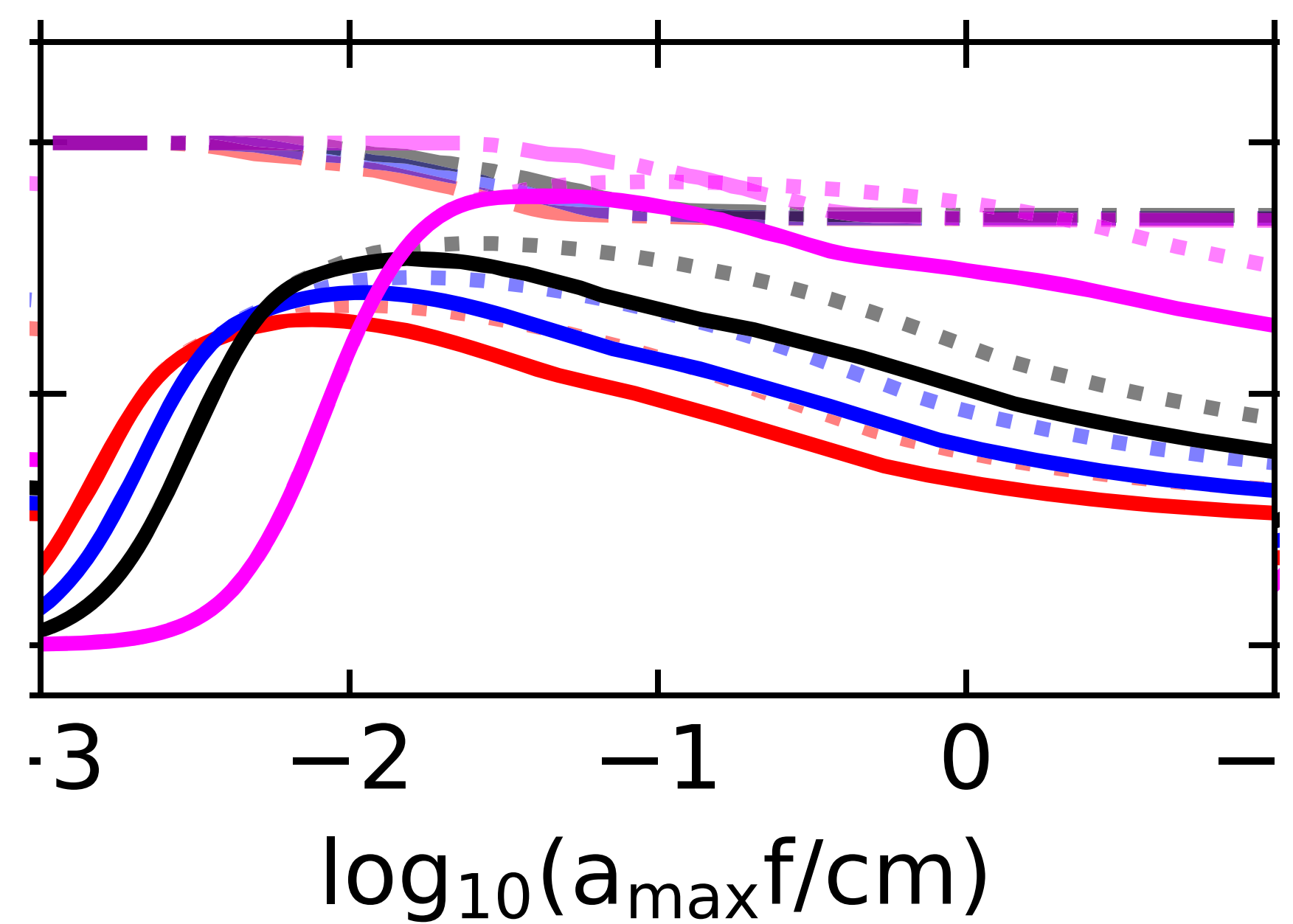
$$(\text{grain size}) \sim \lambda/2\pi$$

Compact vs. Porous

Filling factor = 1; compact

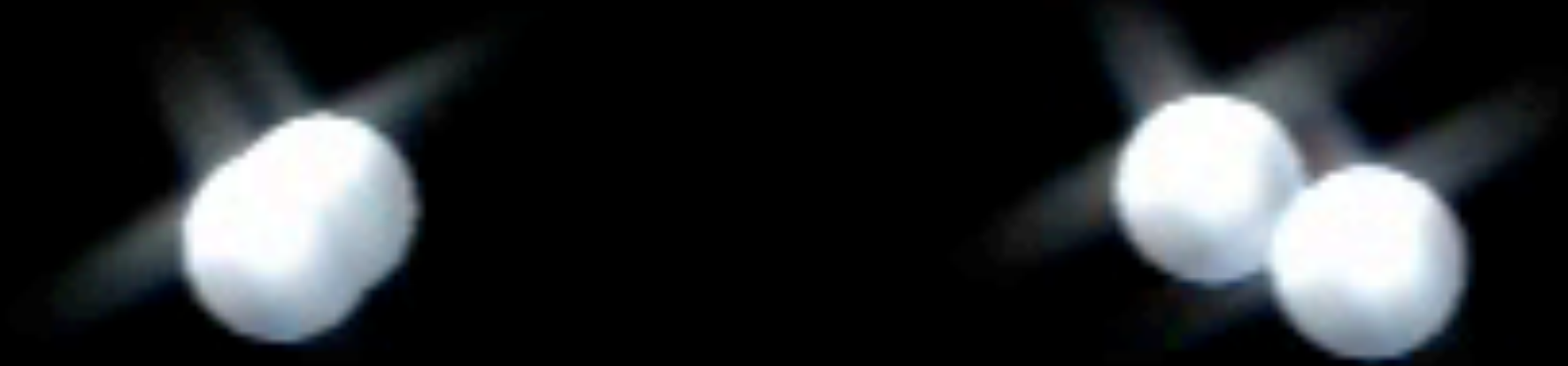


Filling factor = 0.1; porous



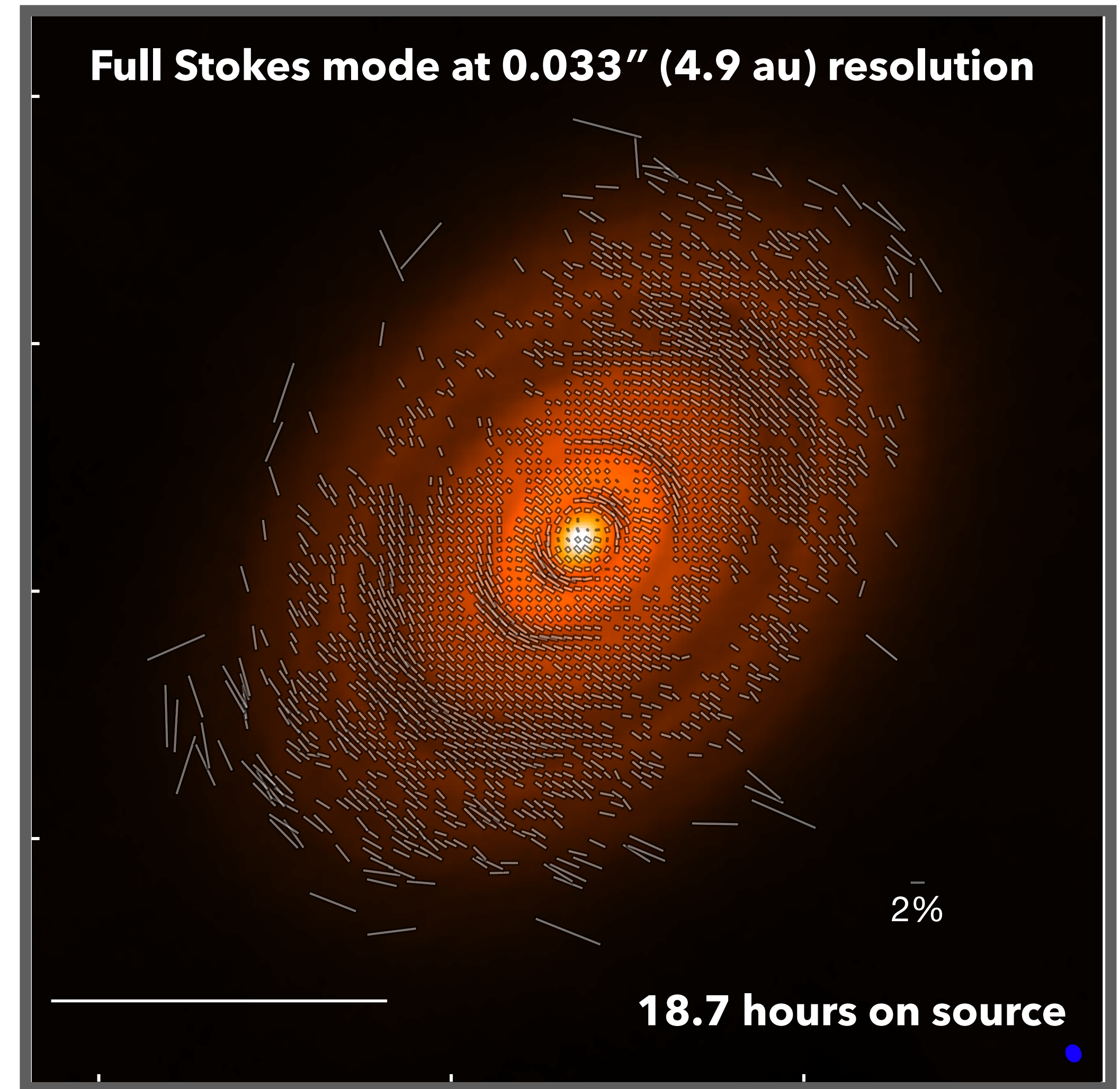
$\lambda = 0.87\text{mm}$ $\lambda = 1.29\text{mm}$
 $\lambda = 2.14\text{mm}$ $\lambda = 7.89\text{mm}$

Dust coagulation – porosity



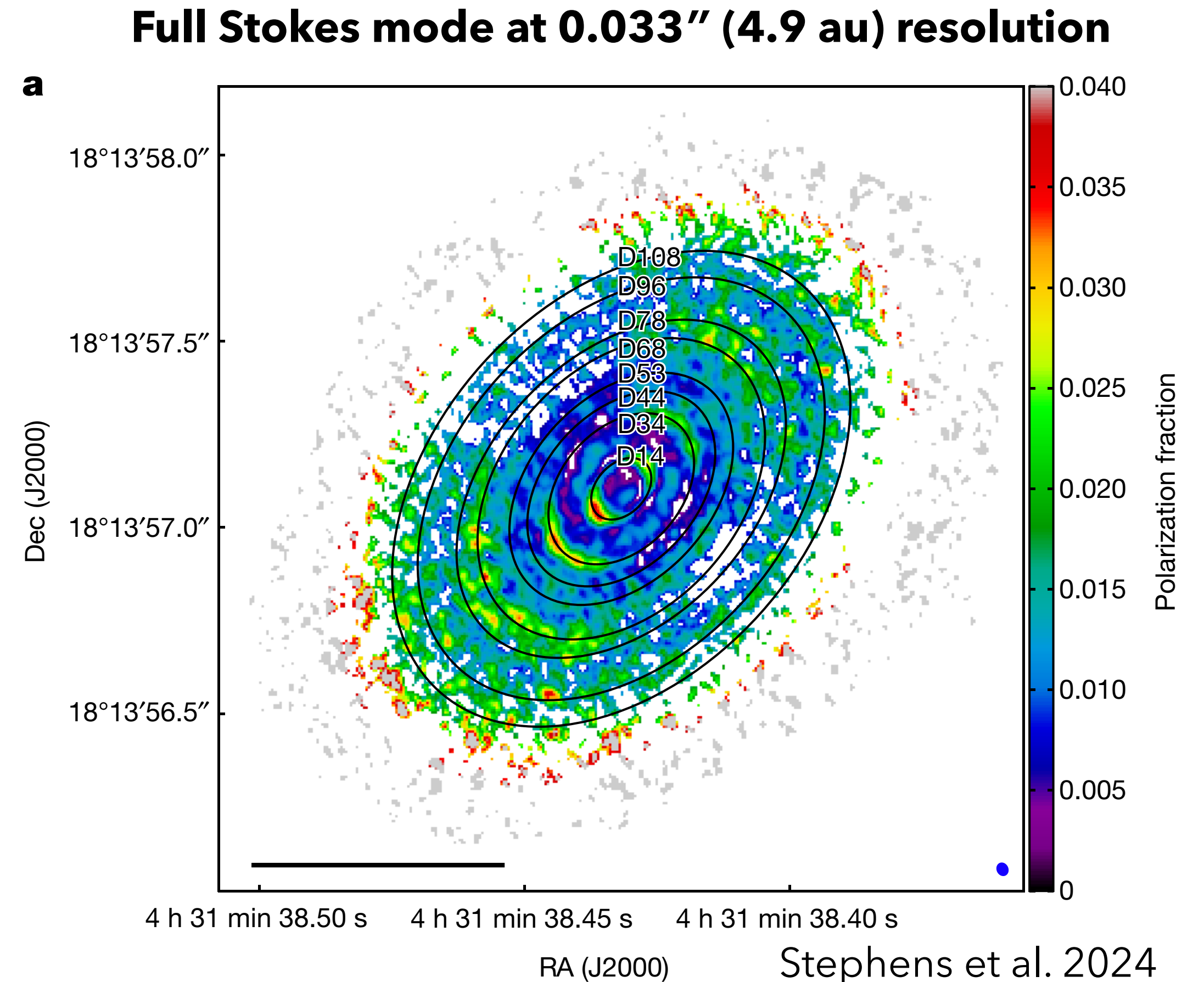
Requirements

- **(Angular resolution):** The highest resolution currently achievable with ALMA
- Sensitivity: An order-of-magnitude improvement in polarization sensitivity
- Multiband polarization: Full-polarization capability across Bands 1–10
- Polarization accuracy: Absolute accuracy at the 0.01% level
- (Circular polarization): Reliable Stokes V measurements for magnetic-field studies



Requirements

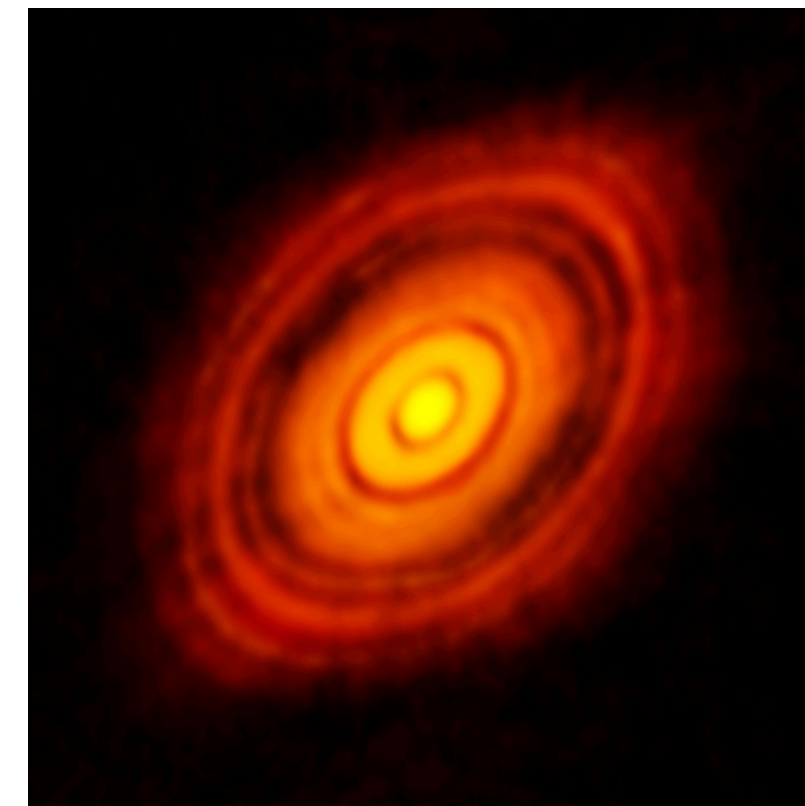
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The gaps have ~4% polarization fraction, while the rings have 0.5%

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ALMA Partnership 2015

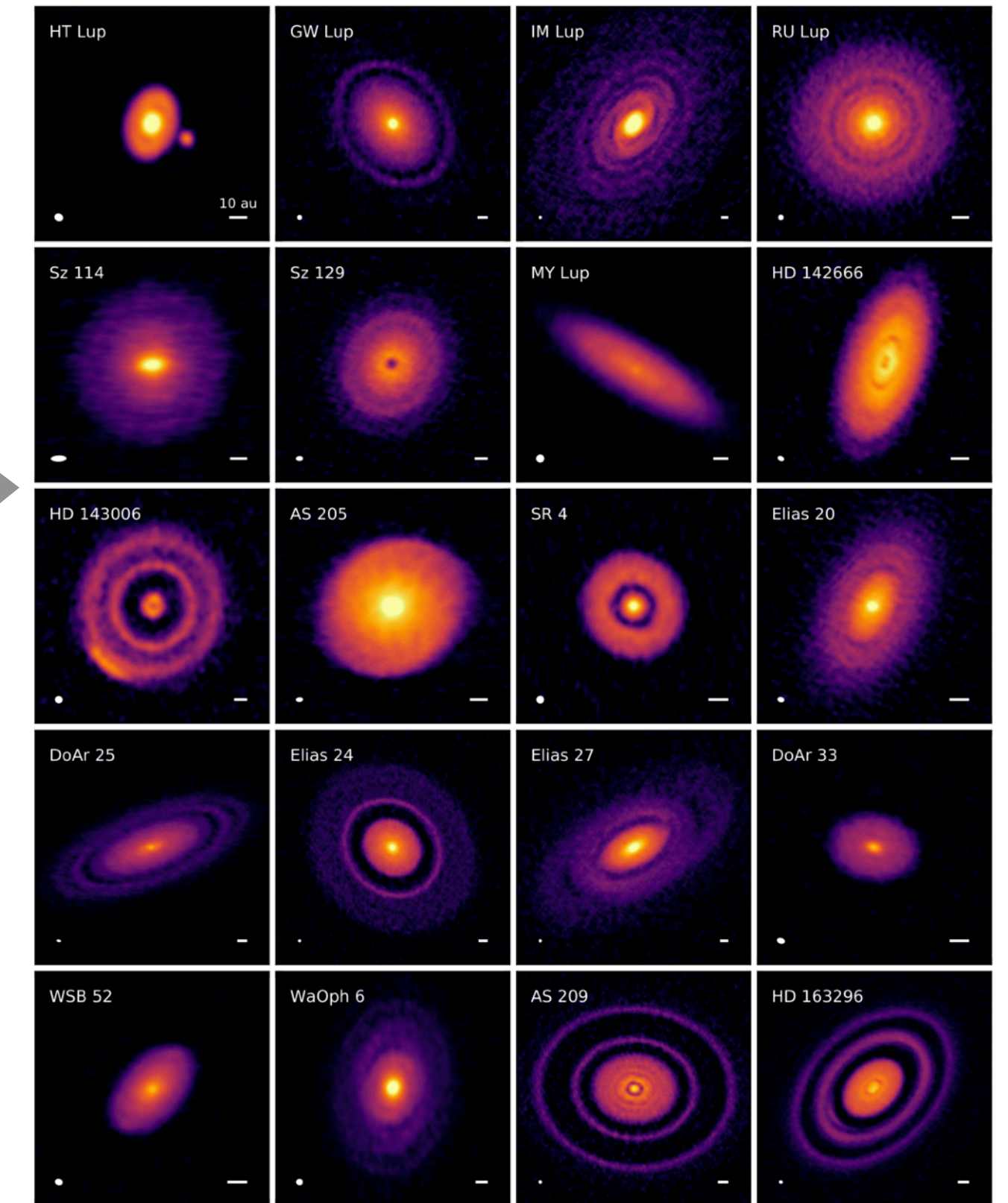
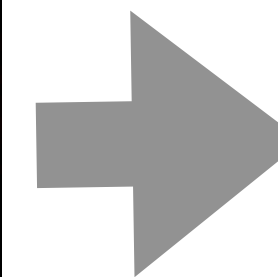


Figure 3. Gallery of 240 GHz (1.25 mm) continuum emission images for the disks in the DSHARP sample. Beam sizes and 10 au scalebars are shown in the lower left and right corners of each panel, respectively. All images are shown with an asinh stretch to reduce the dynamic range (accentuate fainter details without oversaturating the bright emission peaks). For more quantitative details regarding the image dimensions and intensity scales, see Huang et al. (2018a) and Kurtovic et al. (2018).

DSHARP; Andrews et al. 2018

Increasing targets allows us to discuss statistics

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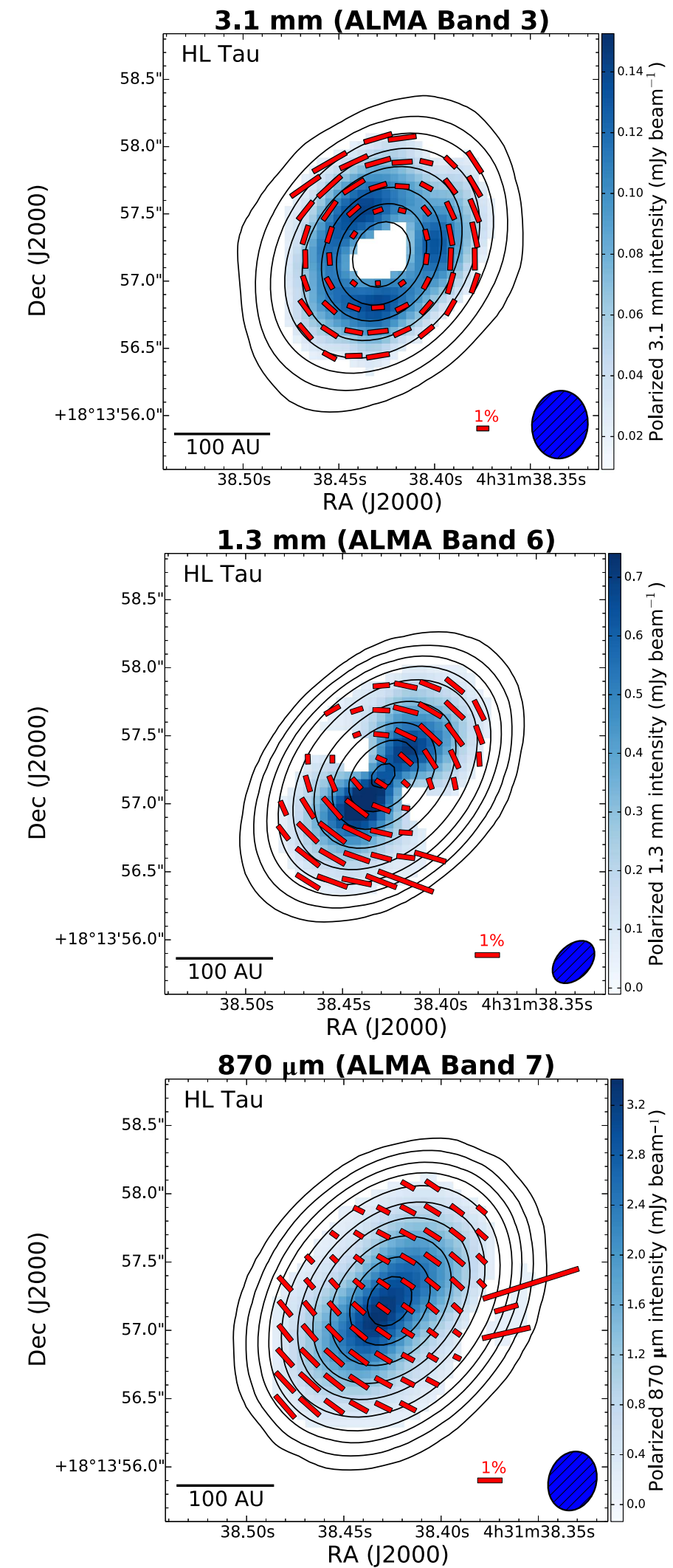
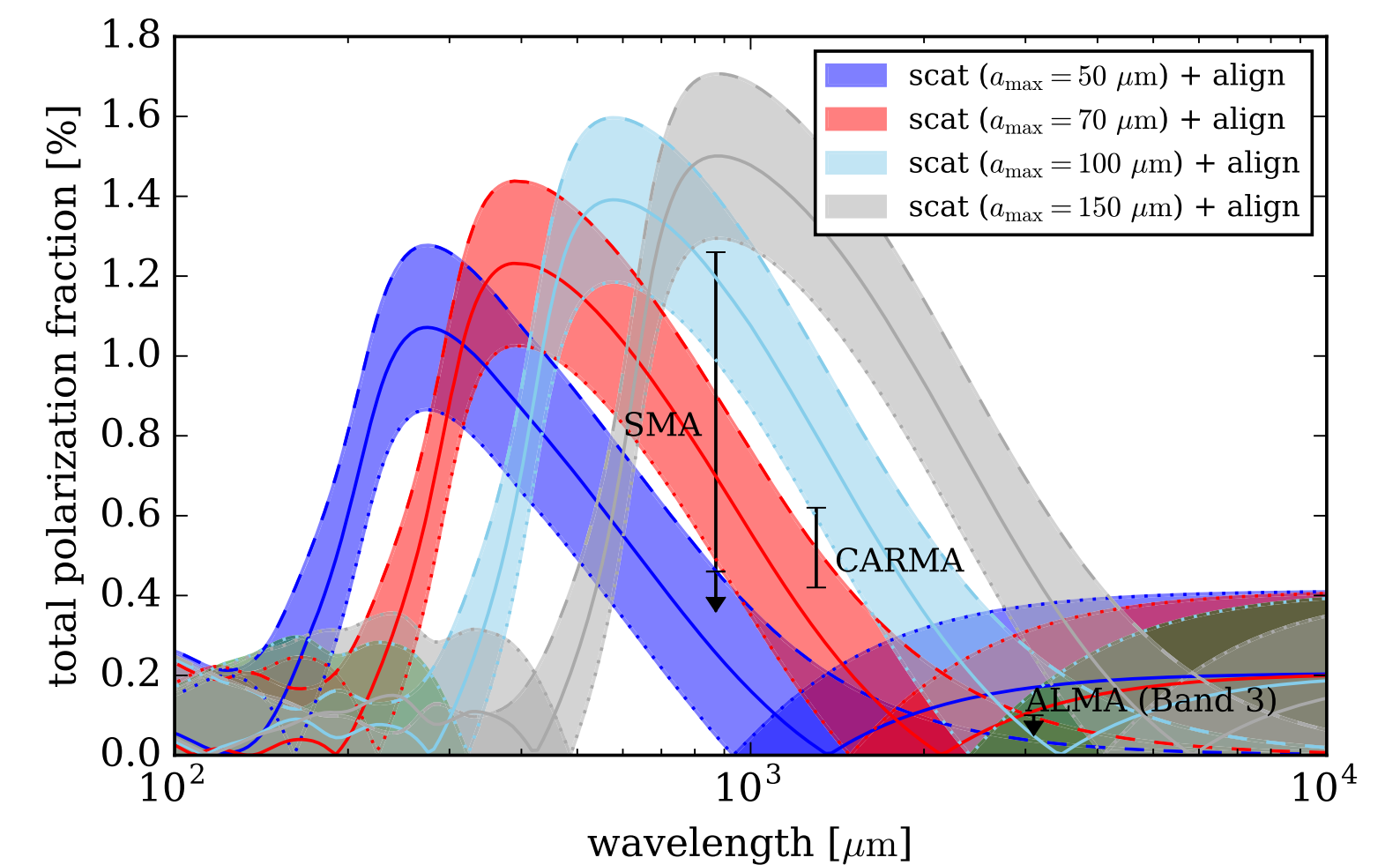


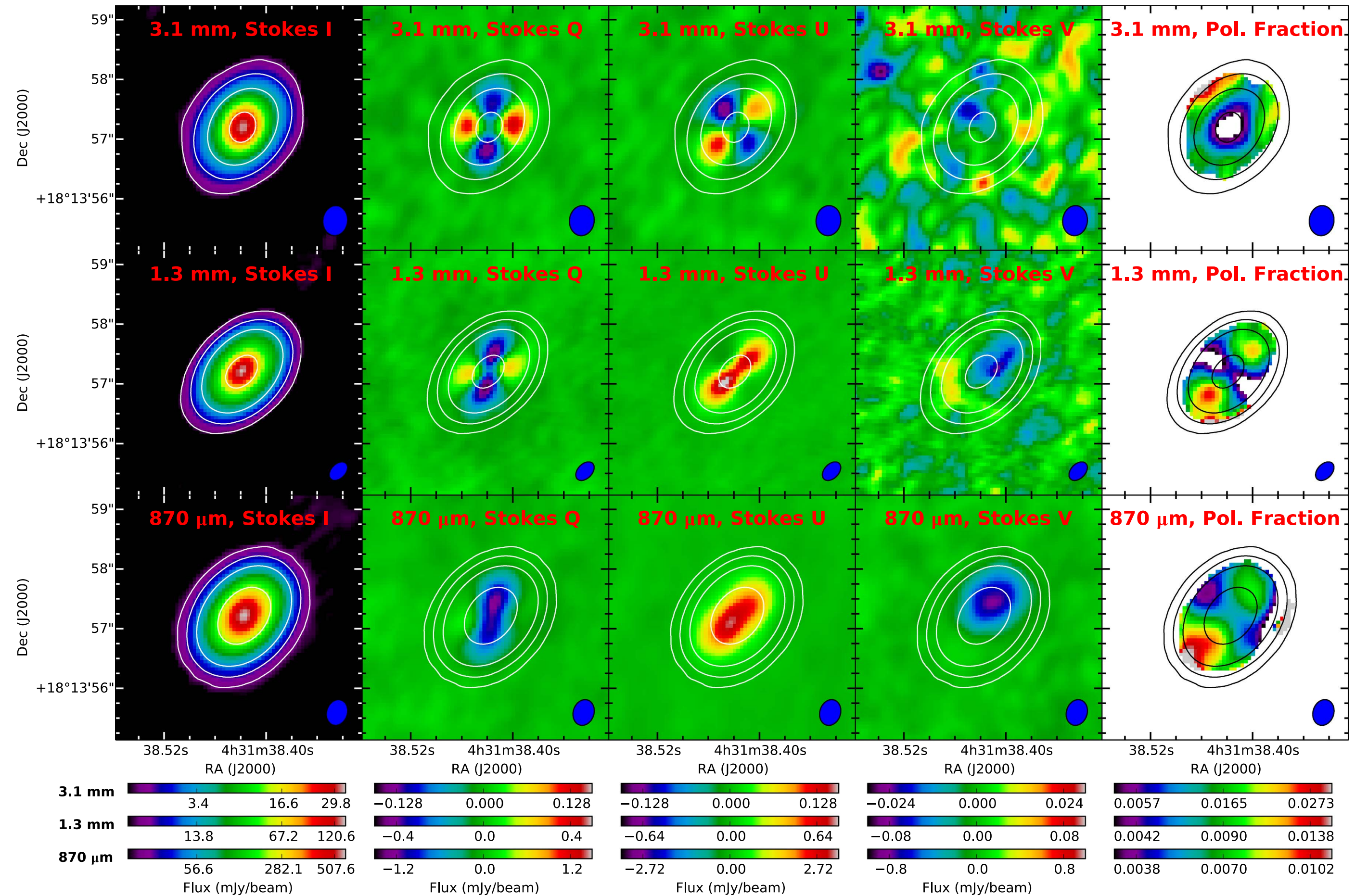
Figure 1. ALMA polarimetric observations at 3.1 mm (top, Kataoka et al. 2017), 1.3 mm (middle), and 870 μm (bottom), where the red vectors show the $>3\sigma$ polarization morphology (i.e., vectors have not been rotated). Vector lengths are linearly proportional to P . The color scale shows the polarized intensity, which is masked to only show 3σ detections. Stokes I contours in each panel are shown for $[3, 10, 25, 50, 100, 200, 325, 500, 750, 1000] \times \sigma_I$, where σ_I is 44, 154, and 460 μJy beam⁻¹ for 3.1 mm, 1.3 mm, and 870 μm, respectively.



Wavelength dependence is strong.
Wide-band upgrade may be problematic for increasing sensitivity.

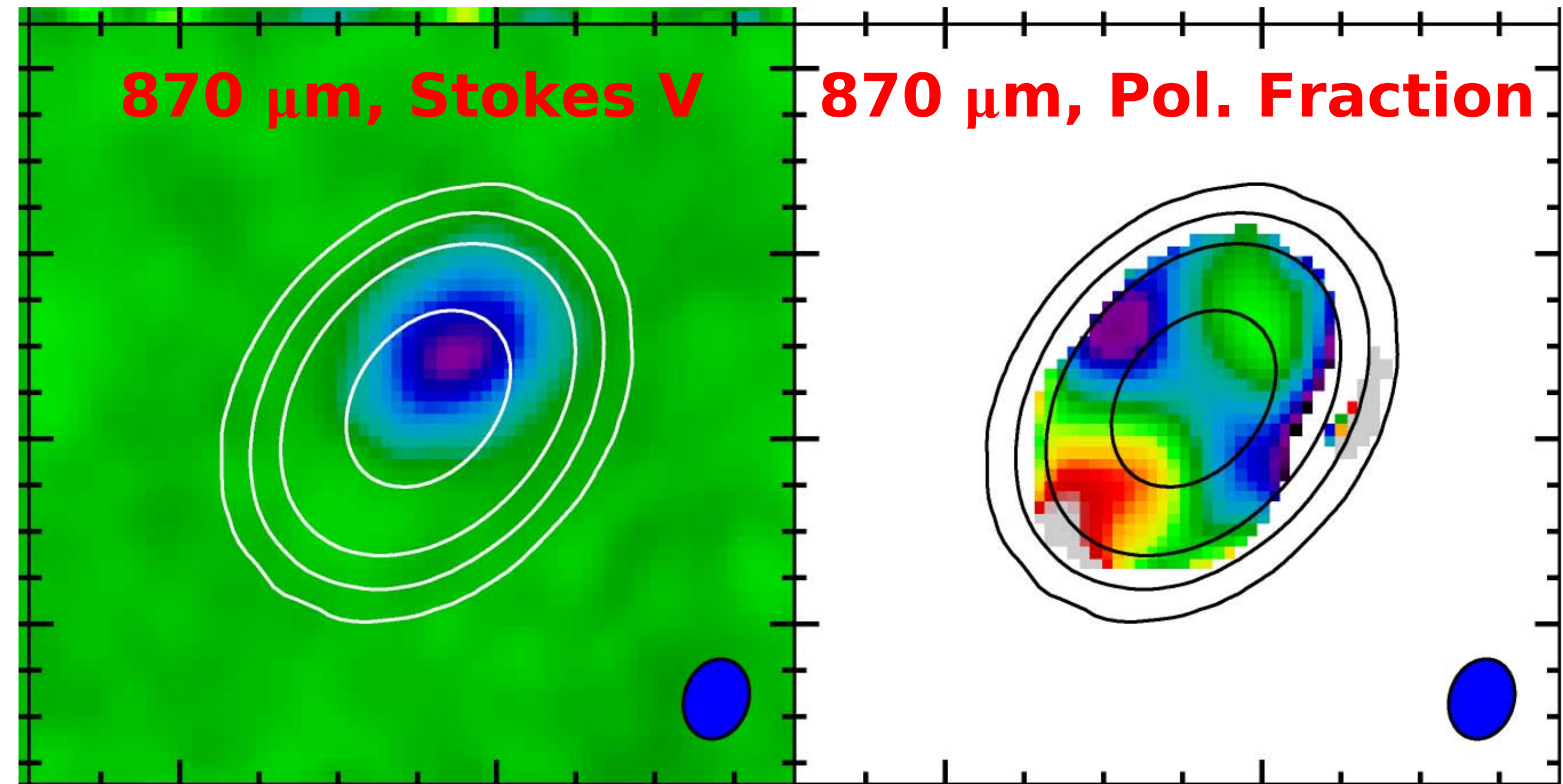
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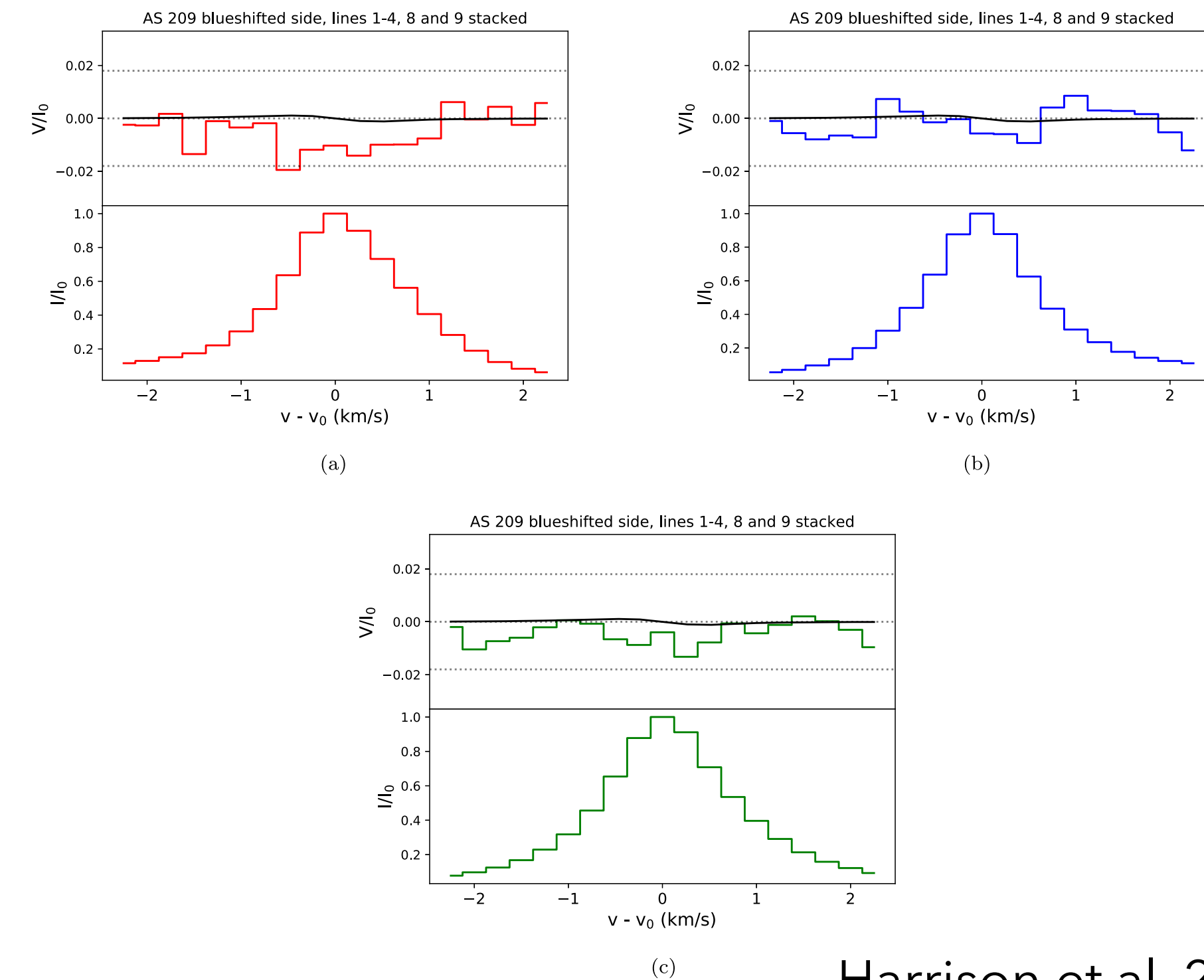
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- **(Circular polarization):** Reliable Stokes V measurements for magnetic-field studies

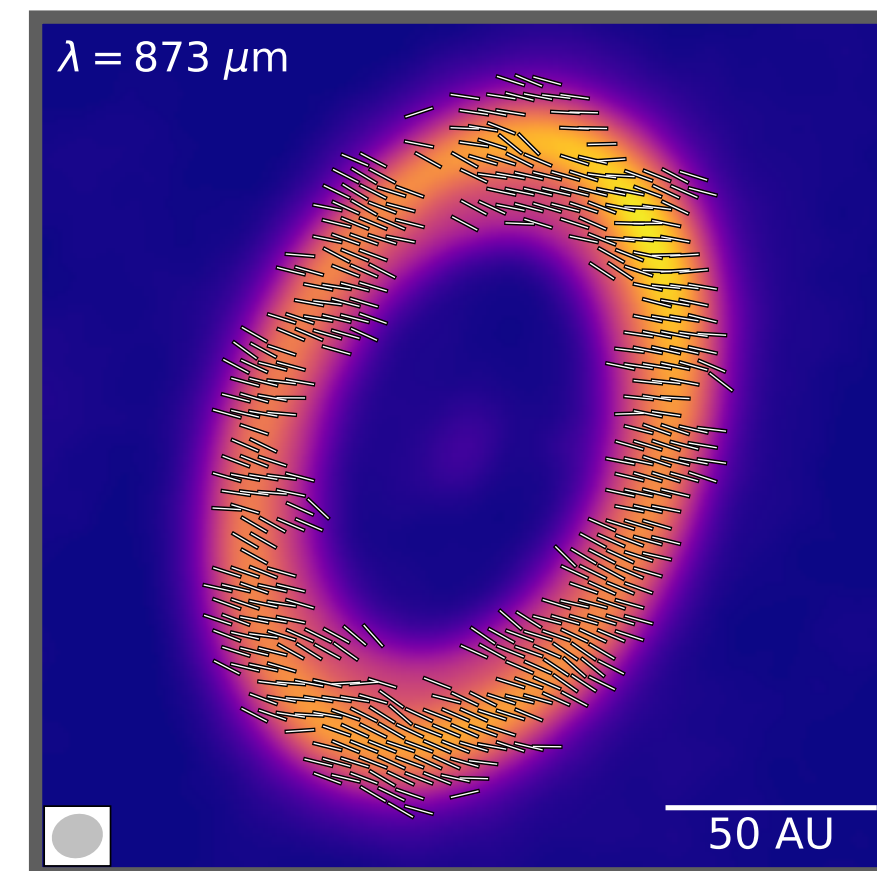


Harrison et al. 2021

Stokes V of CN line has not yet detected

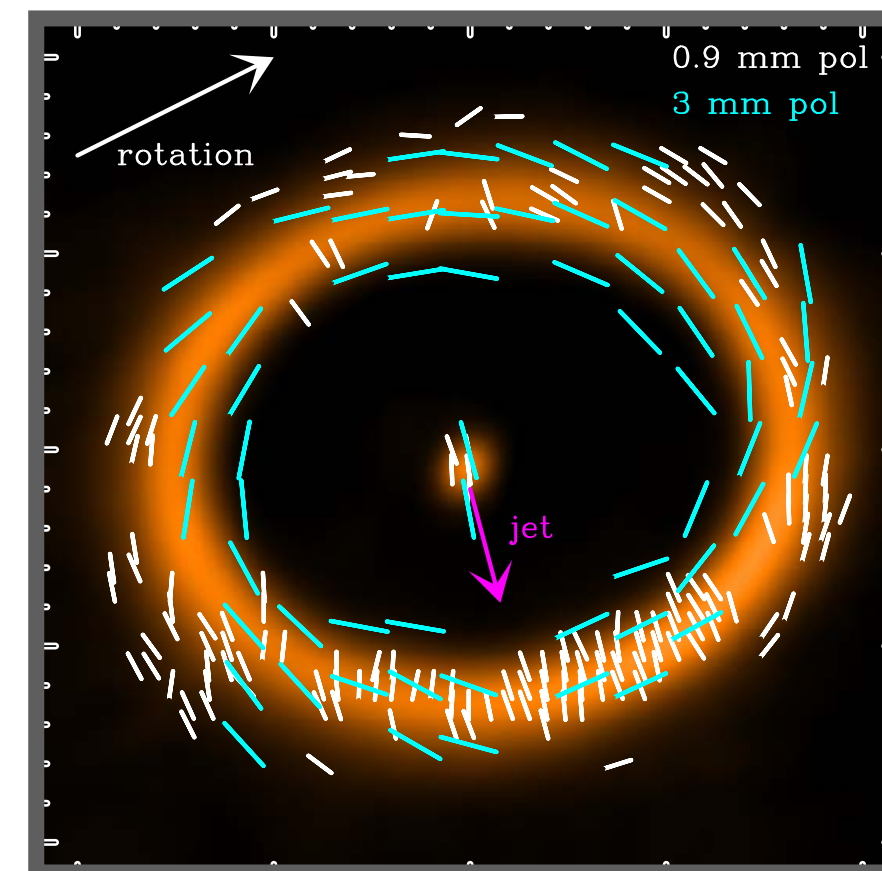
EA community - observations

PDS 70



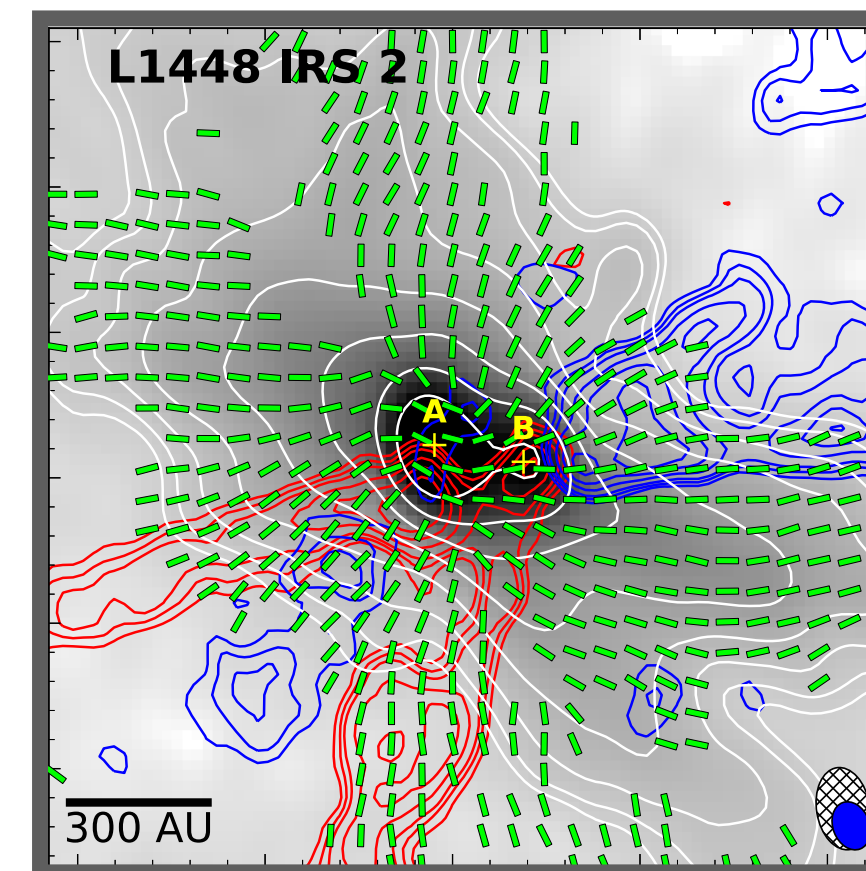
Baobab Liu et al. 2026

GG Tau



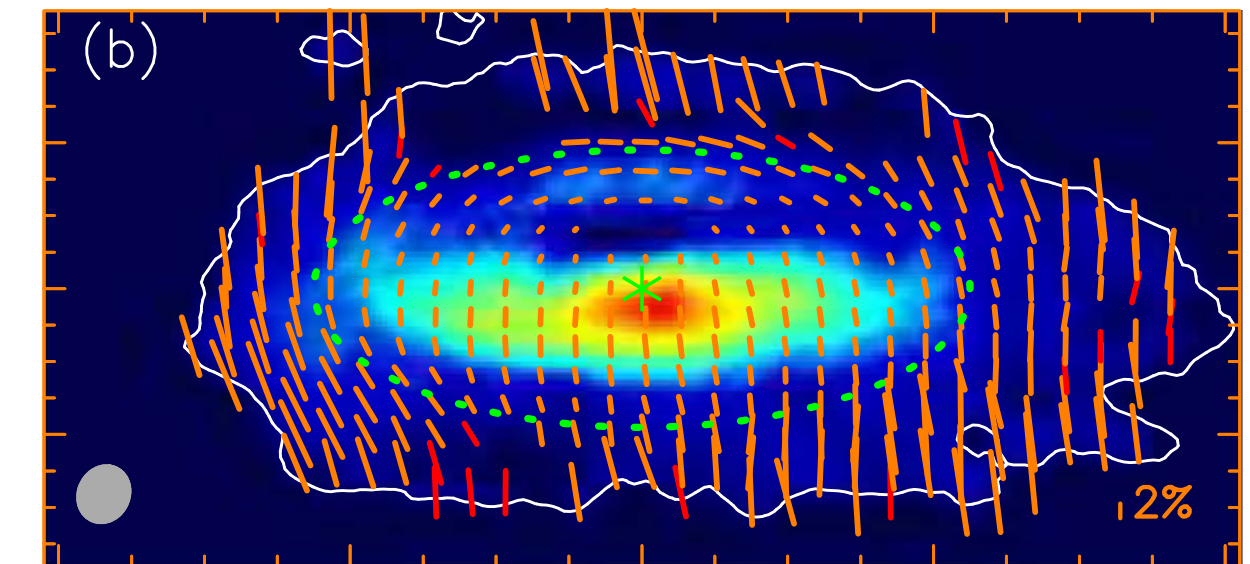
Ya-Wen Tang et al. 2023

L1448 IRS 2



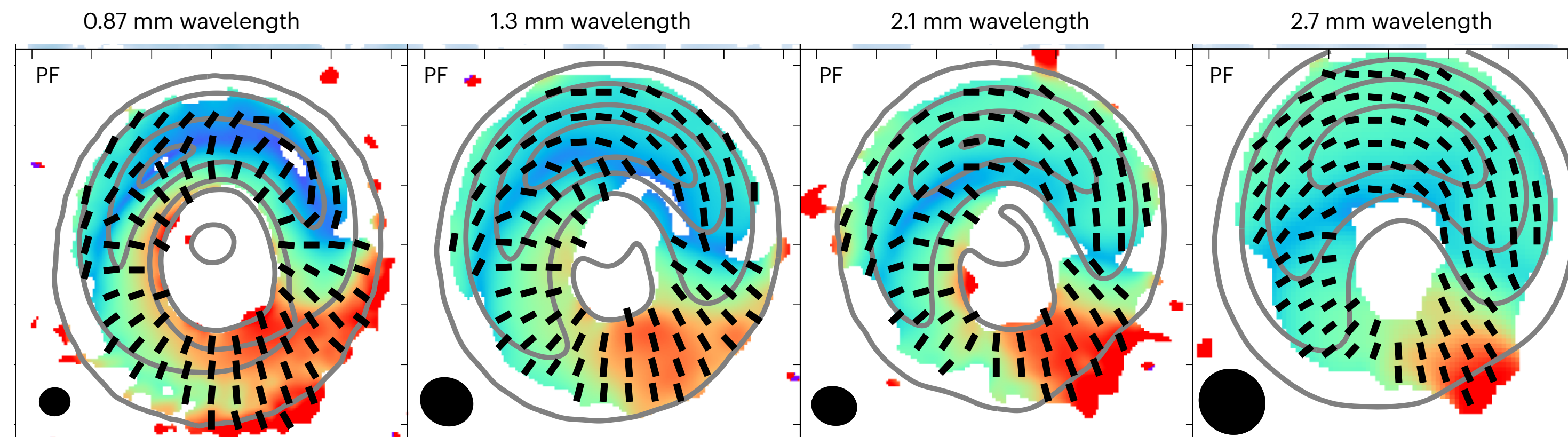
Kwon et al. 2019

HH111



Chin-Fei Lee et al. 2024

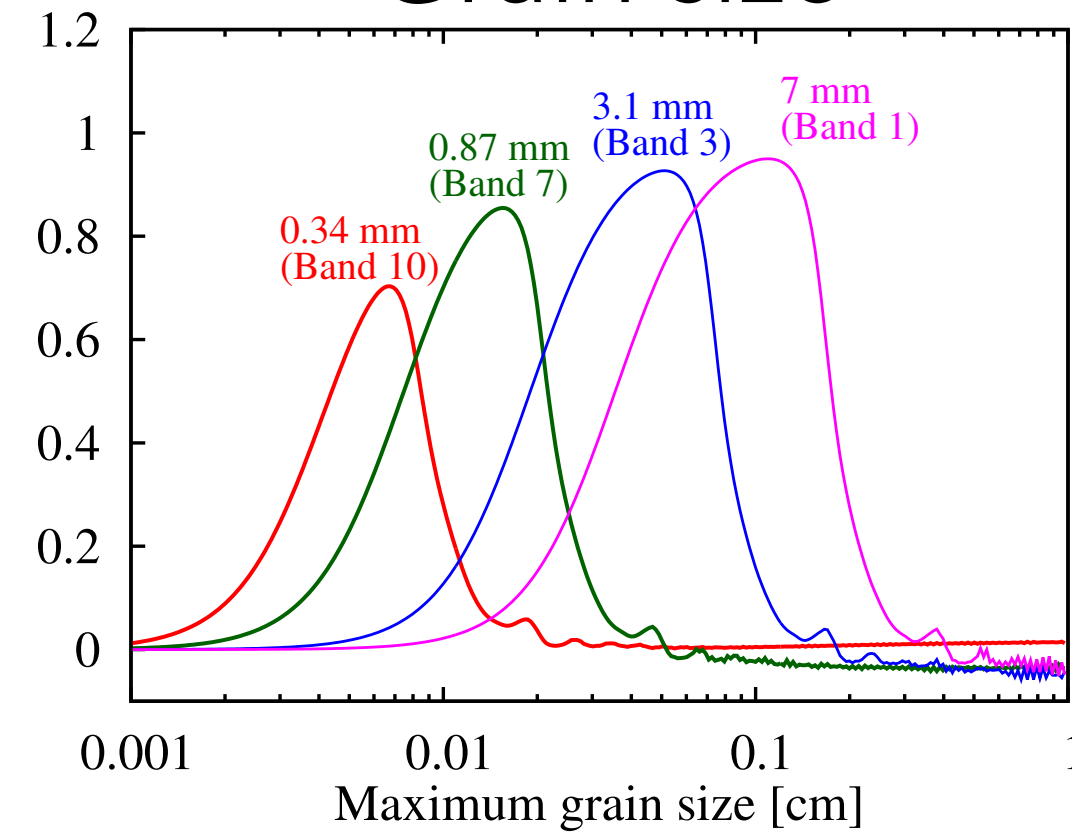
HD 142527



Satoshi Ohashi et al. 2025

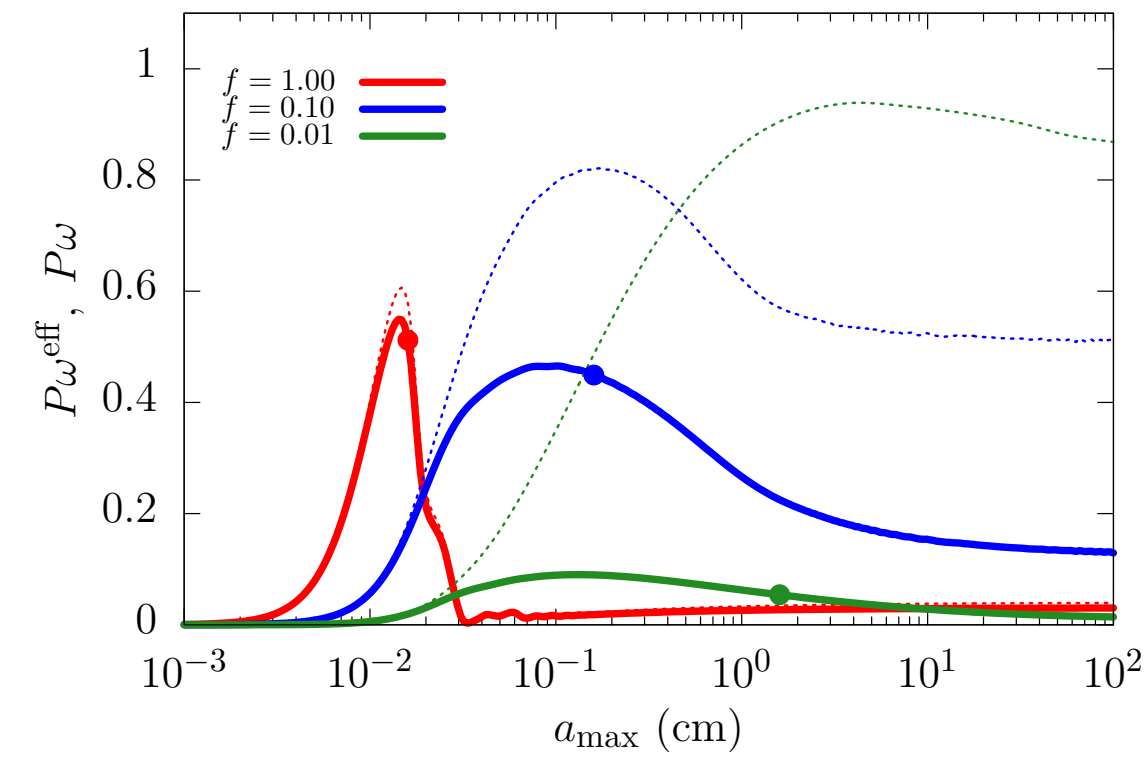
EA community - theory

Grain size

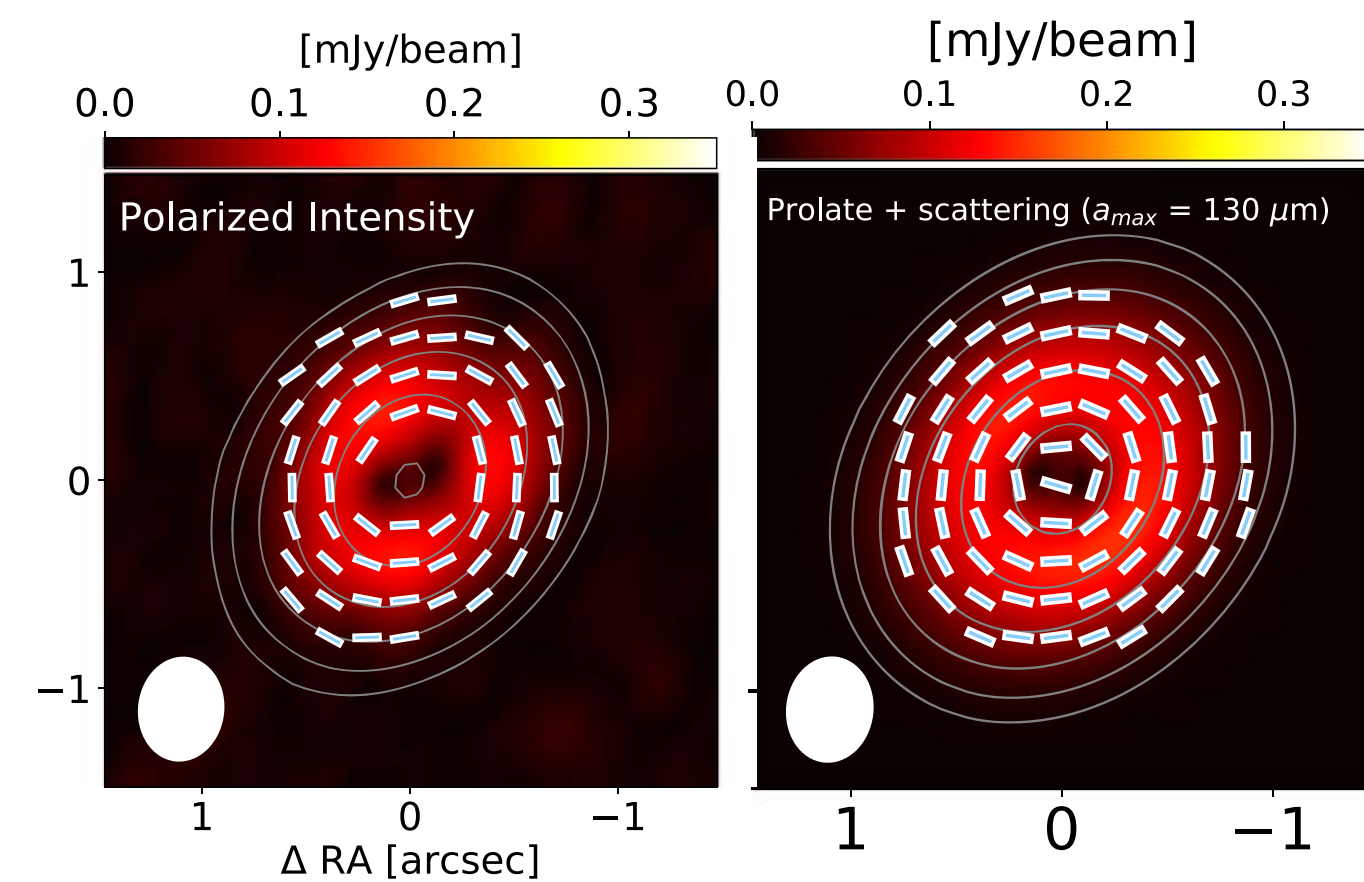


Kataoka et al., 2015

Porosity



Tazaki et al., 2019



Prolate + self-scattering

Mori and Kataoka, 2021

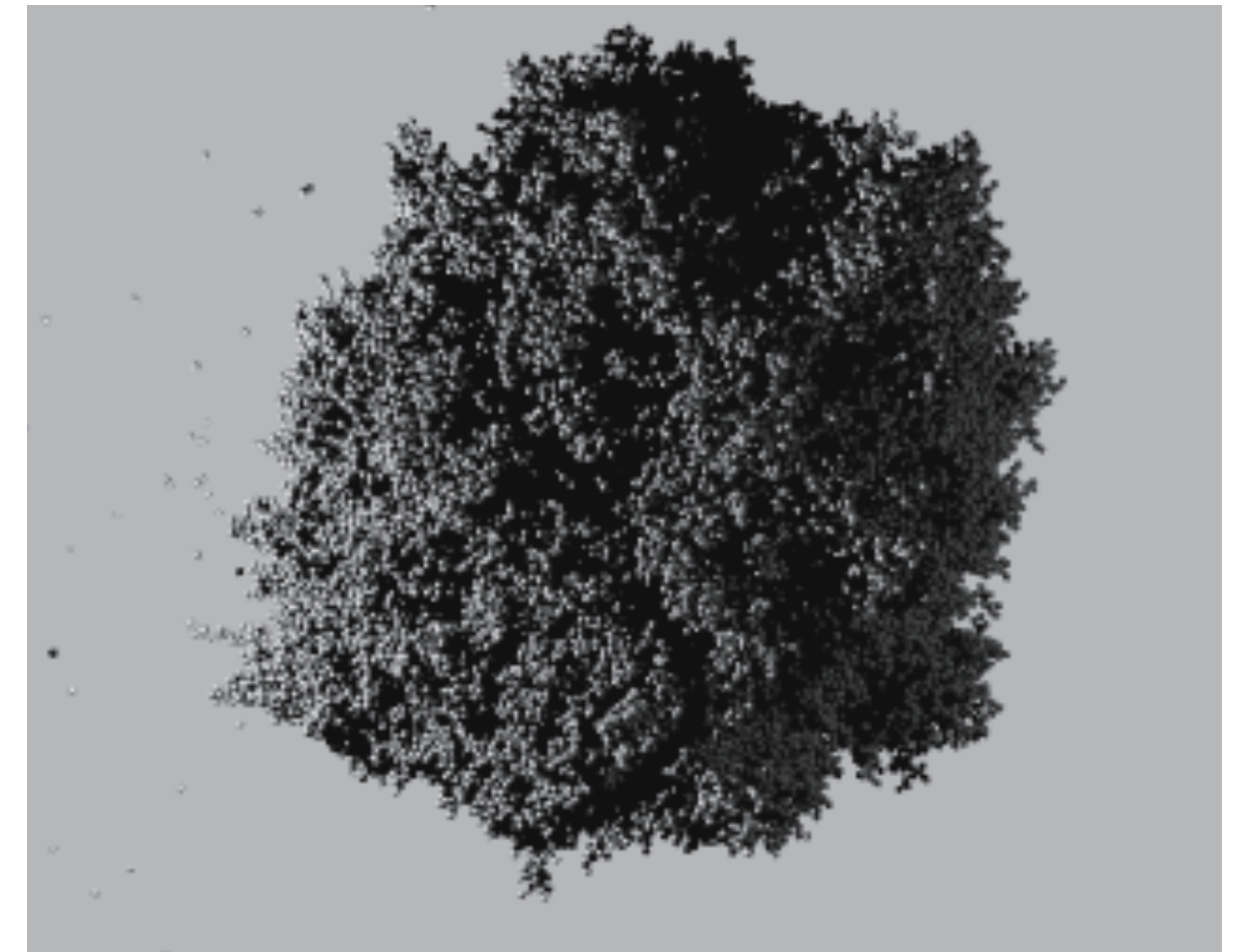
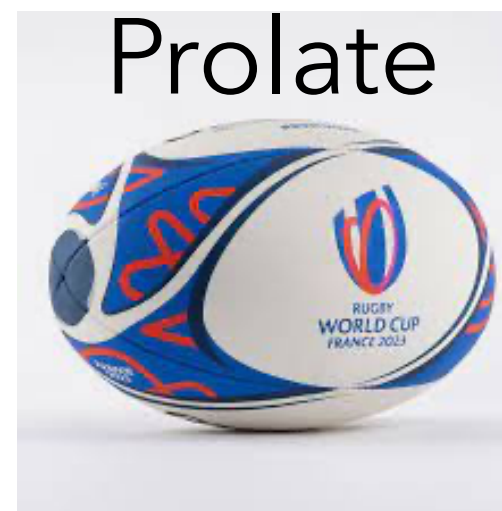
No

Oblate

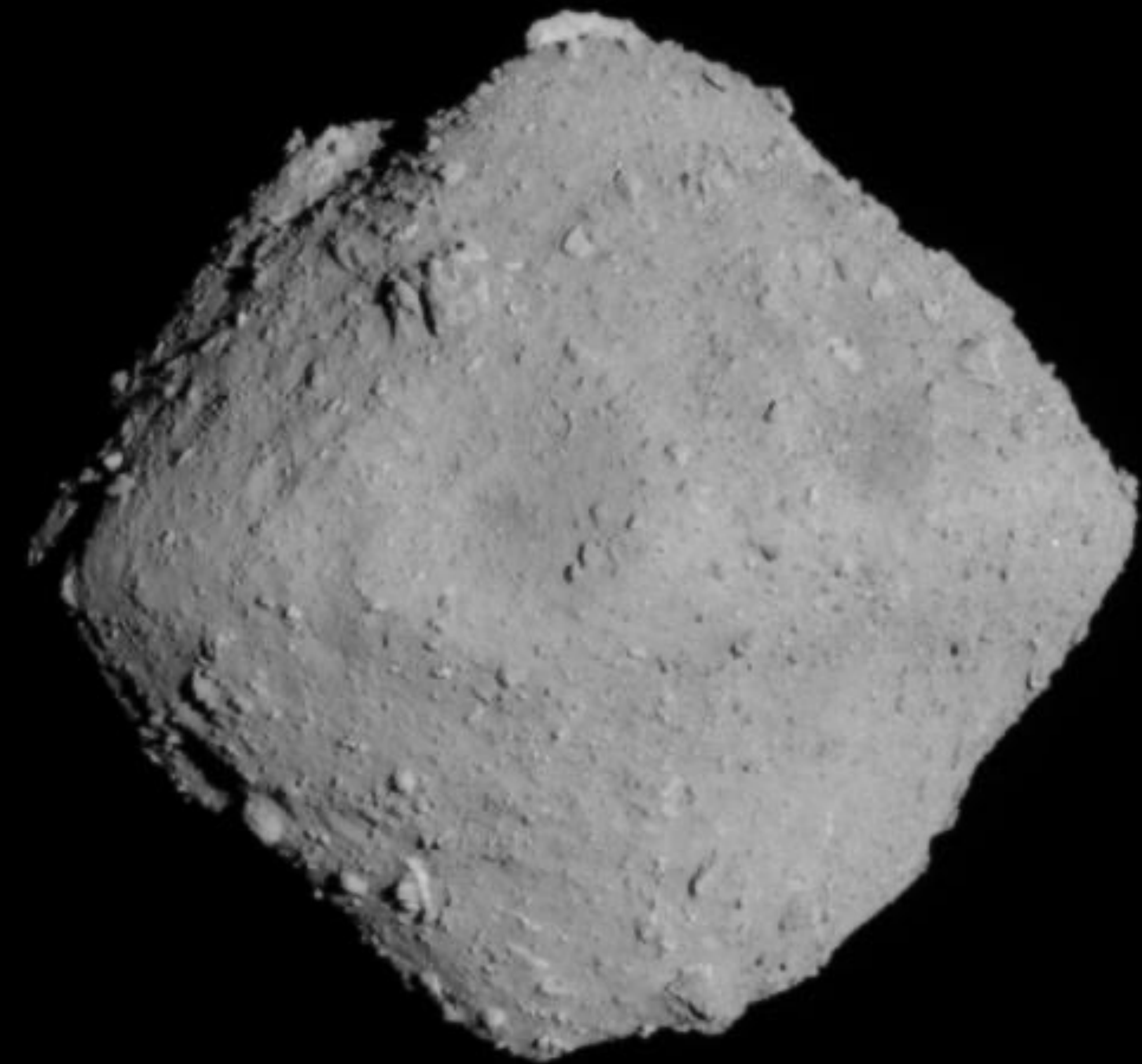


Yes

Prolate



Wada et al., 2013



018-06-30 14:13

Ryugu by Hayabusa2



67P by Rosetta

Summary

- **Millimeter-wave polarization provides a unique probe of dust microphysics**—including grain size, porosity, shape, and alignment—in planet-forming disks.
- **The observed polarization is produced by multiple mechanisms**, primarily dust self-scattering and intrinsic emission from aligned, non-spherical grains. High-resolution, multiwavelength observations are essential to disentangle them.
- **Current observations are strongly sensitivity-limited**. An order-of-magnitude improvement would enable polarization imaging of disk substructures and statistical studies across a large sample of disks.
- **ALMA 2040 should provide full-polarization capability across Bands 1-10**, while maintaining the highest angular resolution and achieving polarization calibration accuracy at the **0.01% level**.
- **The East Asian community is well positioned to lead this field**, with strong expertise in both polarization observations and theoretical modeling of dust scattering, alignment, and aggregate microphysics.