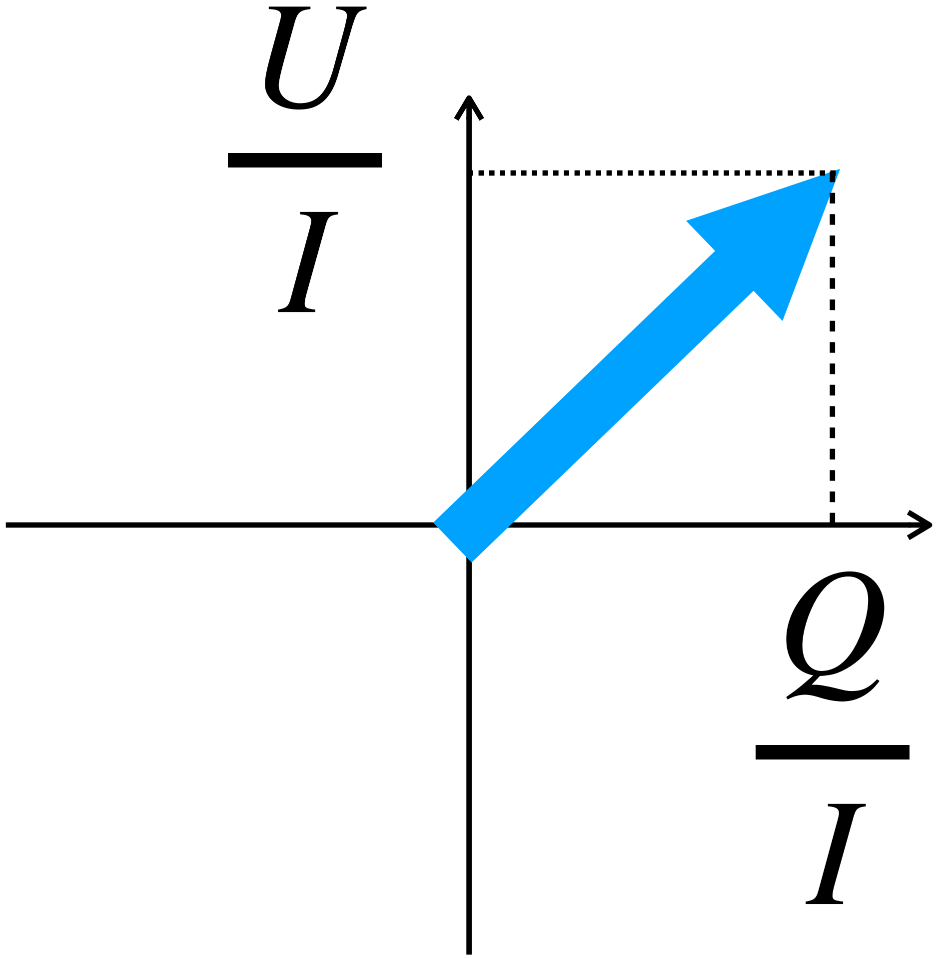
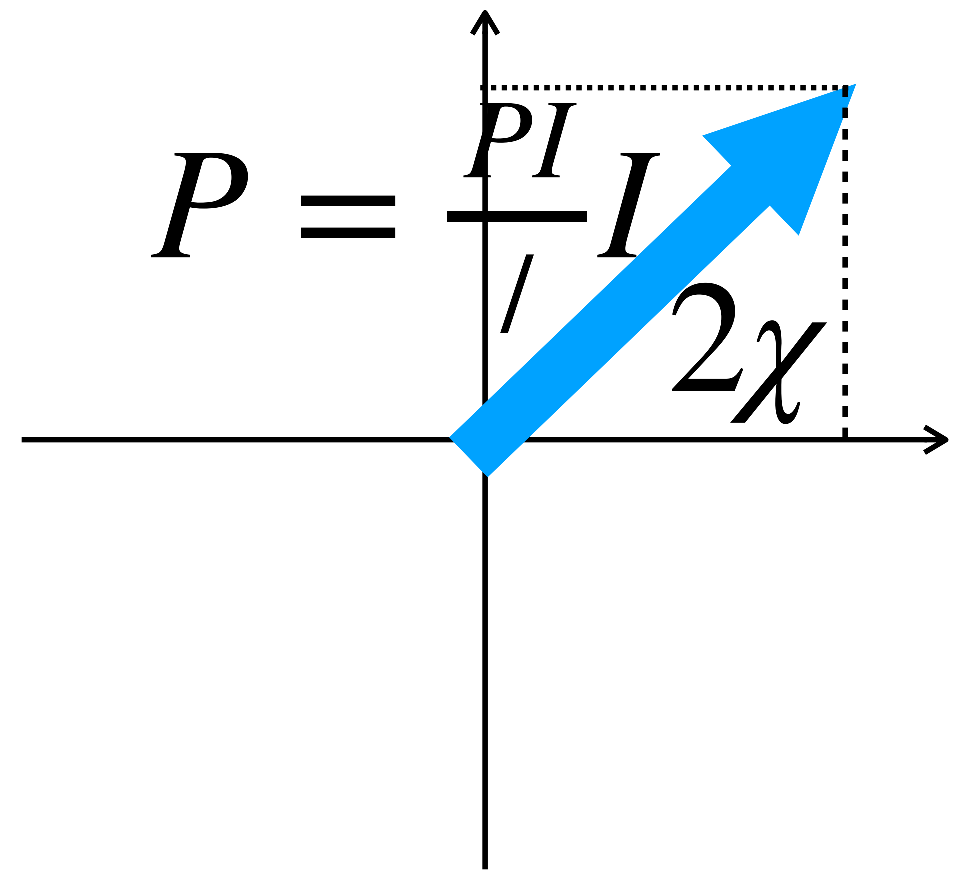
Comments to talks by Derek and Kate





Stokes I, Q, U

Cartesian coordinate

Pol. I, ang., frac.

Porlar coordinate

Noise

Positive and negative values

Normal distribution

Noise

Positive values only

Pol. ang.: von-Mises-Fisher dist.
Pol. frac.: Nakagami-Rice dist.
仲上(1940)-ライス(1945)分布

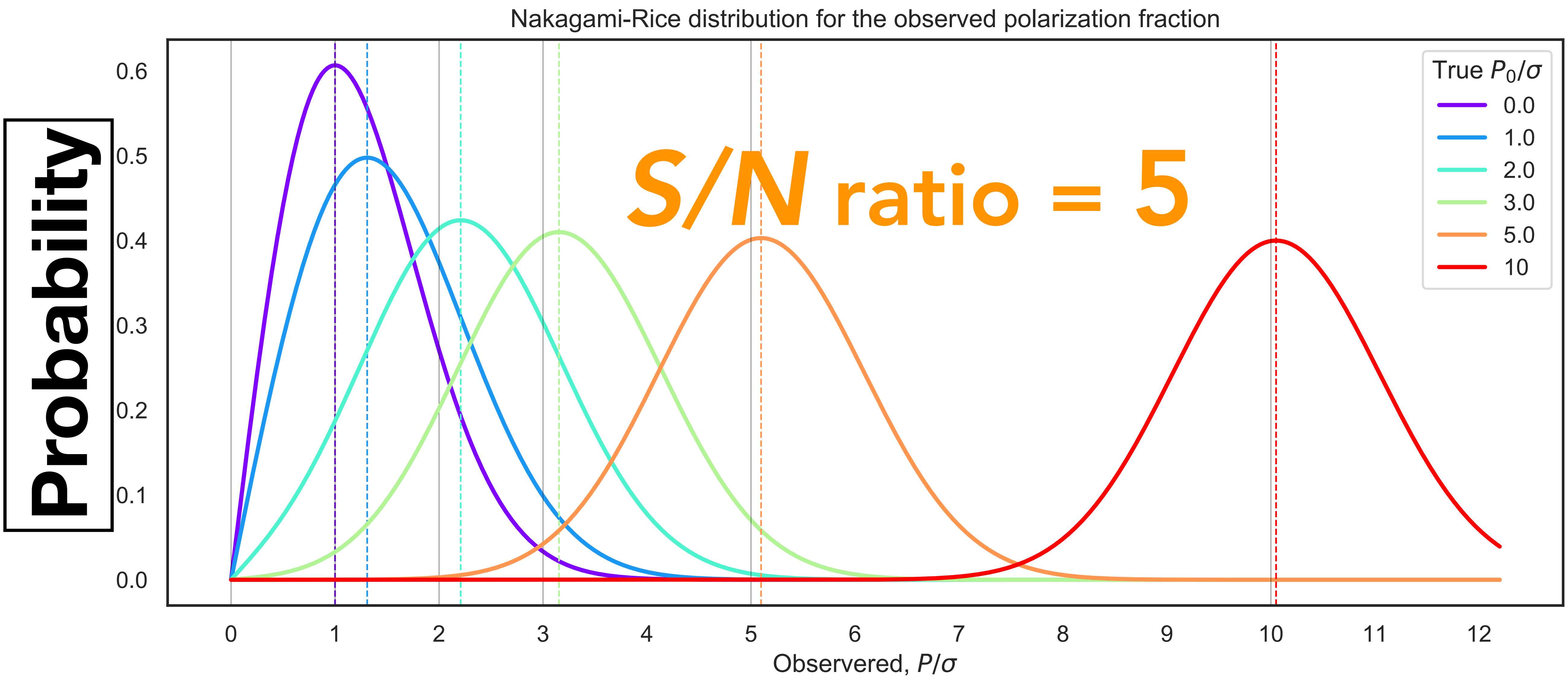


Figure 2. 仲上-Rice 分布. 色は真の偏波率の … 観測された S/N 比で, 細い黒の縦線は真の偏波率の S/N 比を示す. S/N 比が低い場合, …

Observed S/N ratio

Polarimetry | Interferometer

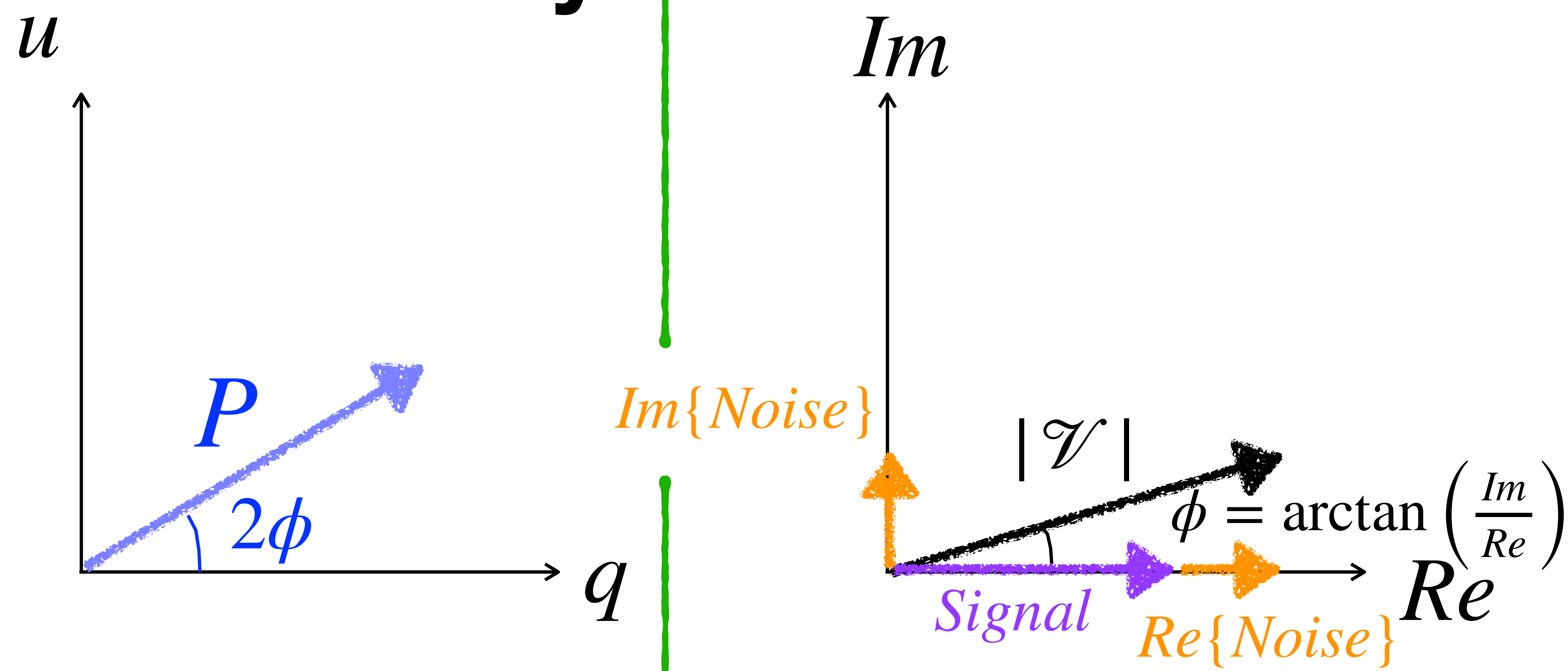


Figure 7. 偏波の記述 (左) と干渉計複素ヴィジビリティの記述 (右) の背後にある数学は共通である.

Noise PDF

Pol. ang.: von-Mises-Fisher dist.

Pol. frac.: Nakagami-Rice dist.

仲上(1940)-ライス(1945)分布

Noise PDF

Visibility phase: von-Mises-Fisher dist.

Visibility amplitude: Nakagami-Rice dist.

仲上(1940)-ライス(1945)分布

..., should look at the phase rather than amplitude. The difference between the phase distribution for the values of S/ΔS equal to 0 and 1 is much more obvious than the difference between the associated amplitude distributions.

p.132, "Sensitivity" by P. C. Crane & P. J. Napier in "Synthesis imaging radio astronomy" (1989)

polarization angle

…, should look at the phase rather than

polarization fraction

amplitude. The difference between the phase distribution for the values of S/ΔS equal to 0 and 1 is much more obvious than the difference between the associated amplitude distributions.

p.132, "Sensitivity" by P. C. Crane & P. J. Napier in "Synthesis imaging radio astronomy" (1989)

A first comparison between 850 and 450 micron dust polarization images toward high-density star-forming gas in Ophiuchu A

Ray S. Furuya
with a collaboration of BISTRO Consortium

Team BISTRO-J is supported by 262 individuals

Outline of talk

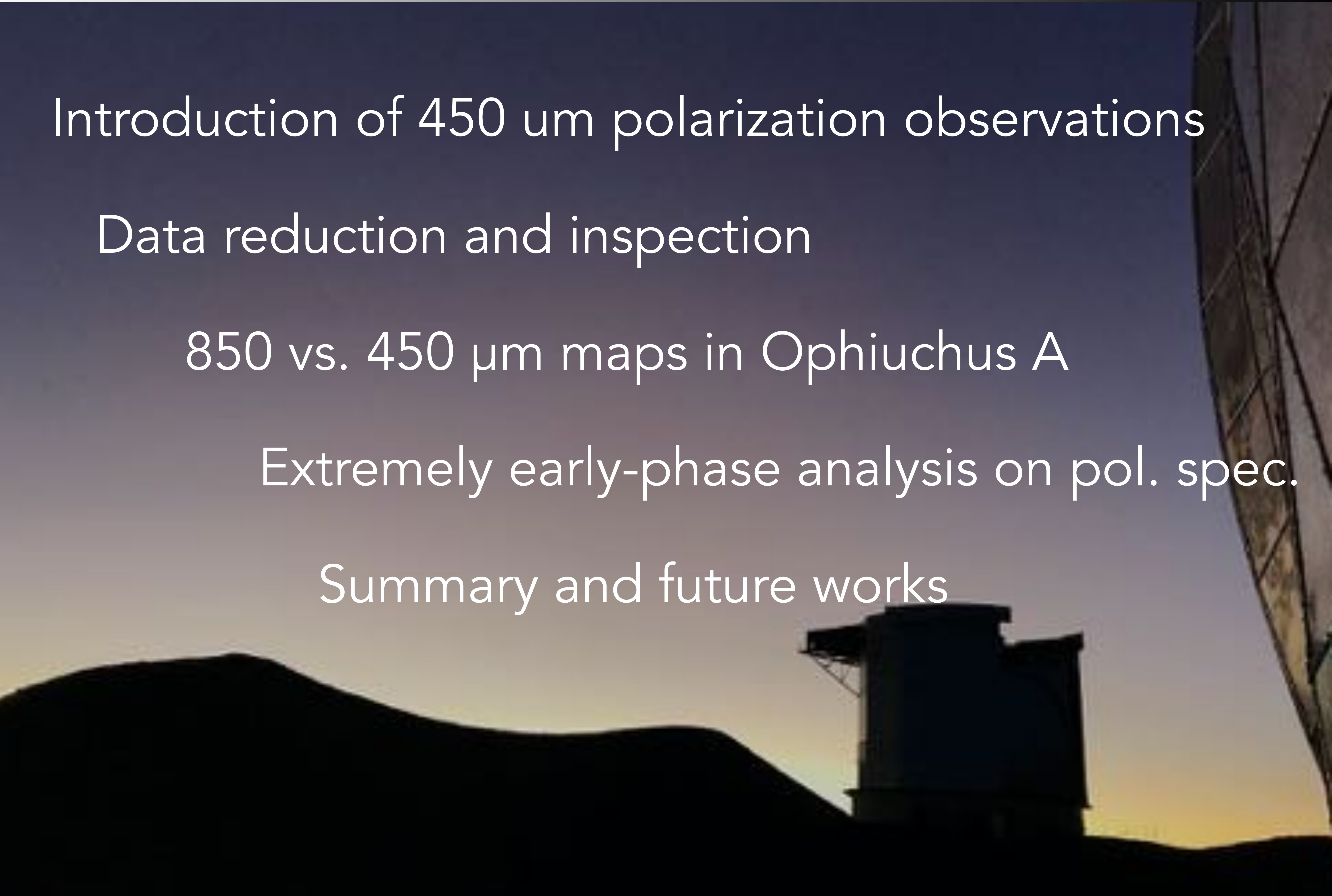
Introduction of 450 um polarization observations

Data reduction and inspection

850 vs. 450 µm maps in Ophiuchus A

Extremely early-phase analysis on pol. spec.

Summary and future works



What does polarimetry tell us?

- Intrinsic polarization of the emitter

Objects

  - **Anisotropy of directions of charged-particles' motions**

    e.g., thermal emission from aligned dust, synchrotron radiation

  - **Absorption or emission in molecules and atoms,**

    e.g., Zeeman effect, maser, laser, Goldreich-Kylafis effect

- **Polarization caused in radiative transfer process**

Path

  - Liner polarization by scattering and reflection
  - Circular polarization by multiple scattering
  - Linear polarization by selective absorption and/or scattering,

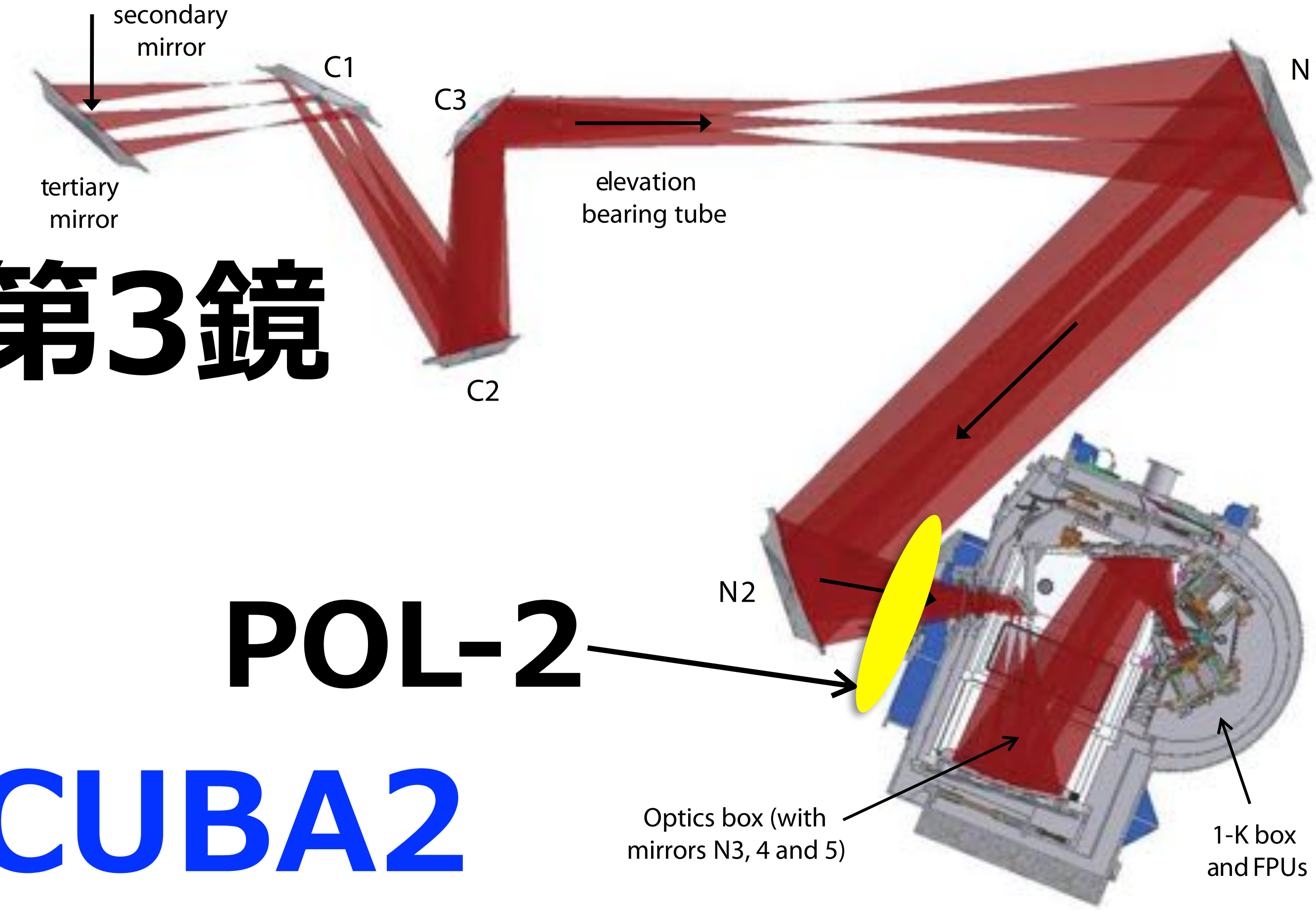
    e.g., absorption and scattering by aligned dust

  - Faraday rotation
  - Instrumental polarization (IP) caused by telescope system

POL-2 + SCUBA2 on JCMT

Holland et al. 2013

ray from subreflector

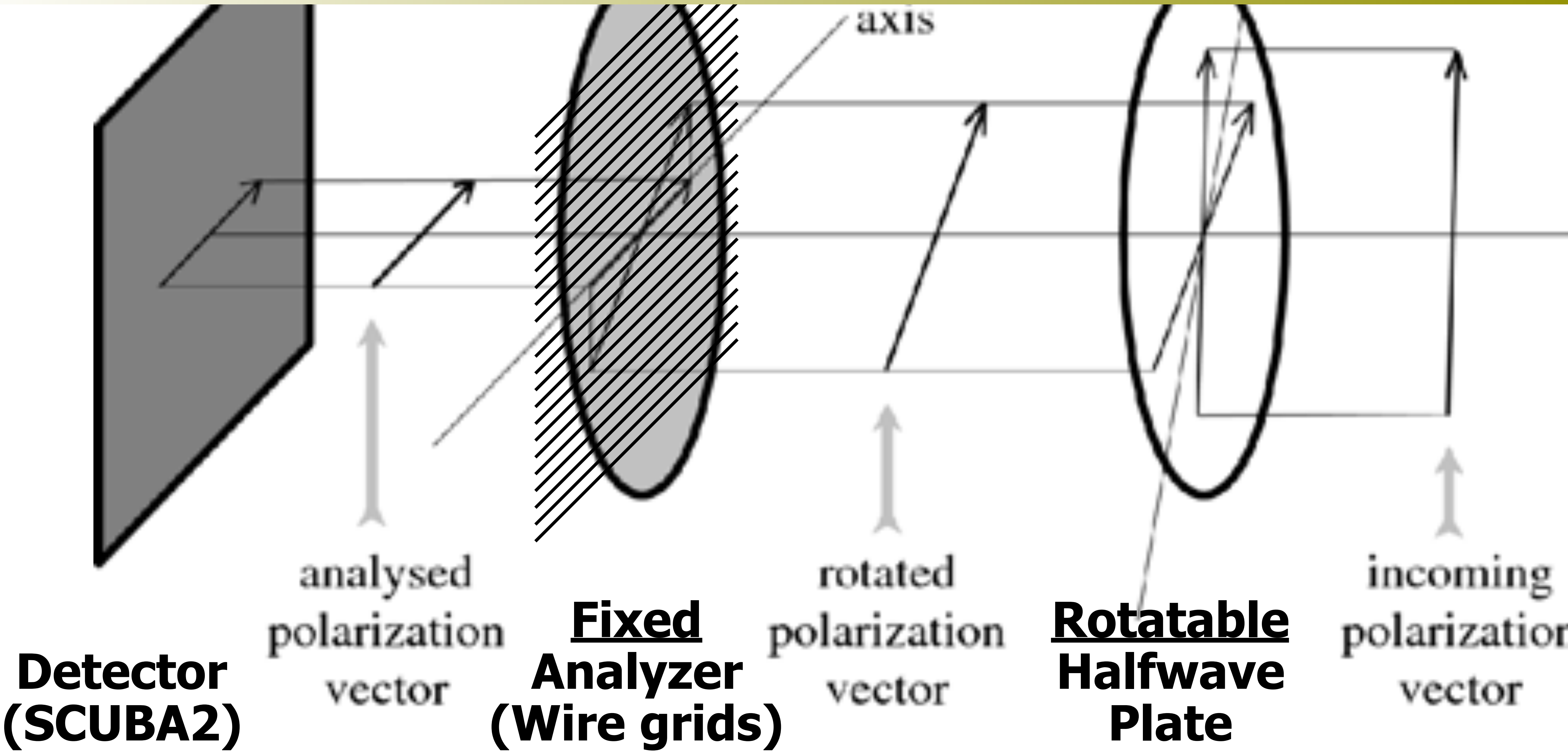


第3鏡

POL-2

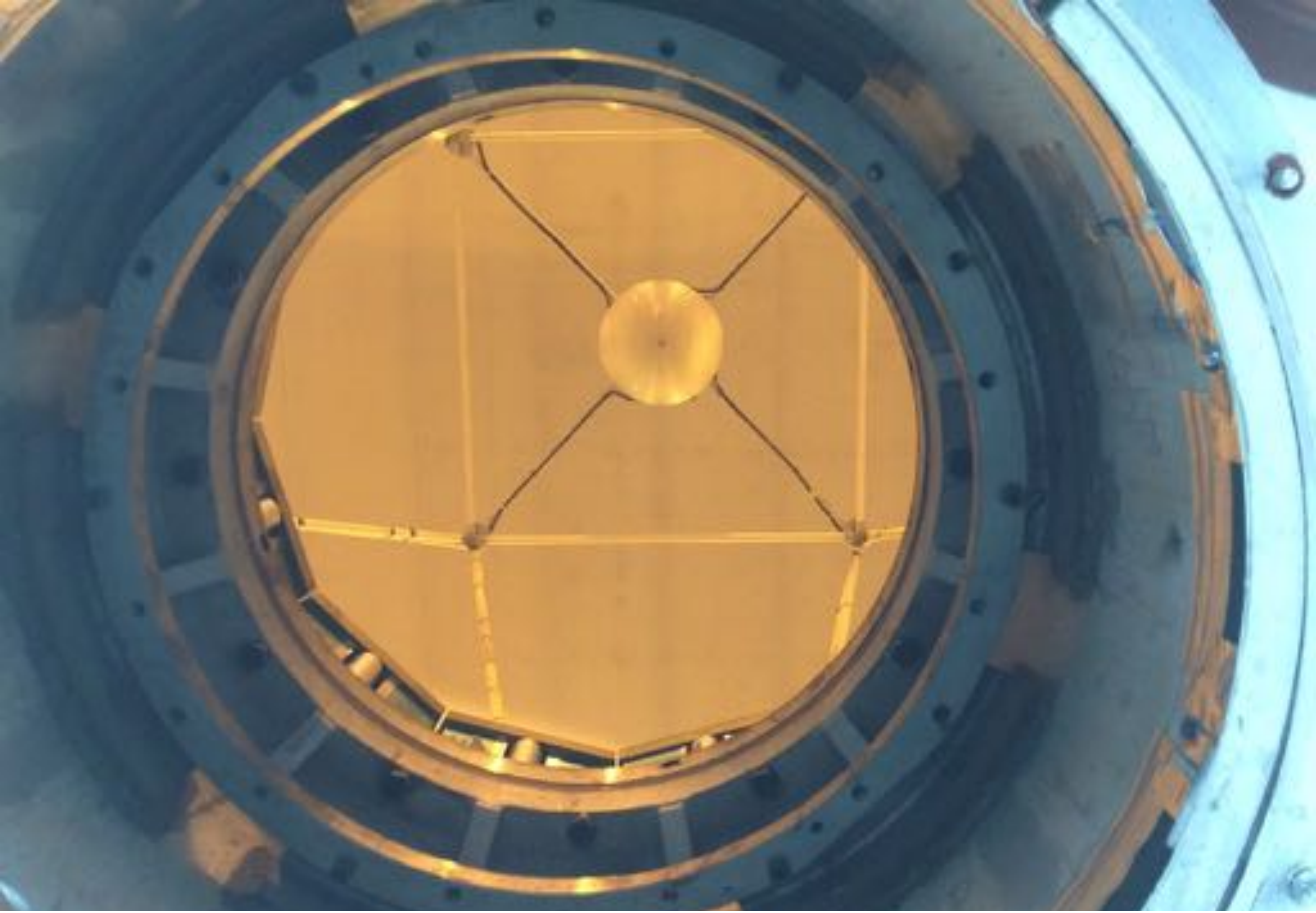
SCUBA2

POL-2: Single Beam Imaging Polarimeter



2Hz rotation;
4 times data dumping each rotation
→ 8 Hz sampling

cf. SCUBA-2 only, 180 Hz sampling



the GoreTex dome cover seen from the Cassegrain focus

Main source of Instrumental Polarization (IP)

What does polarimetry tell us?

Objects

- Intrinsic polarization of the emitter
  - **Anisotropy of directions of charged-particles' motions**

    e.g., thermal emission from aligned dust, synchrotron radiation
  - **Absorption or emission in molecules and atoms,**

    e.g., Zeeman effect, maser, laser, Goldreich-Kylafis effect

Path

- **Polarization caused in radiative transfer process**
  - Liner polarization by scattering and reflection
  - Circular polarization by multiple scattering
  - Linear polarization by selective absorption and/or scattering,

    e.g., absorption and scattering by aligned dust
  - Faraday rotation
  - **Instrumental polarization (IP) caused by telescope system**

Observations and data reduction

Telescope and instruments

- James Clerk Maxwell Telescope (JCMT) 15m
- 2016 April — May
- Polarimeter, POL-2 (rotating half-wave plate plus wire-grid analyzer) plus detector, SCUBA-2
- Observed wavelength of 450 and 850 micron simultaneously, yielding angular resolutions of 8" at 450 um and 14" at 850 um
- The 850 micron data are published in Kwon, J., et al. 2018 ApJ 859, 4.

Data reduction and analysis

450 micron data reduction

- Selected data with atmospheric ***tau_{225}* < 0.04**
- Reduced "*pol2map*" pipeline w. ver.3 **Instrumental Polarization (IP) model released 2019 August 7th**; **Utilized November 1st. v. of Starlin**
- Obtained Stokes *I*, *Q*, and *U* maps with a pixel size of 4"

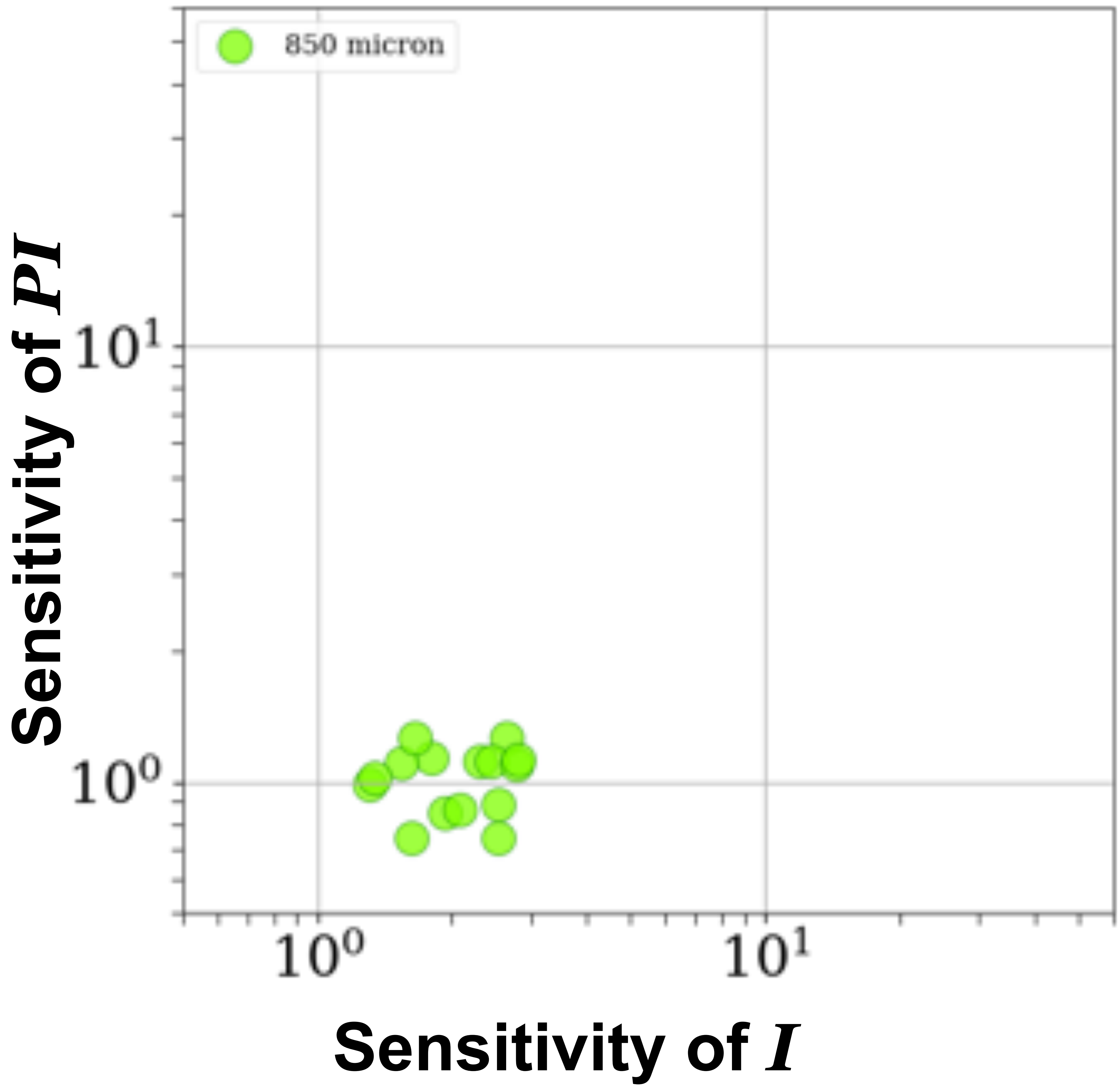
450 micron data analysis

- Residual of sinusoidal fitting to the time-series data are tracked, and stored as variance of Stokes *I*, *Q*, and *U* images
- **Convolved a Gaussian beam** so that the dual-band *I*, *Q*, and *U* **image and their variance images have the identical 14" beam**
- **Produced "vector catalog"** from the convolved images with debiasing
- **Matched the 450 and 850 micron "vector"** catalogs to make point-by-point comparison

Data inspection

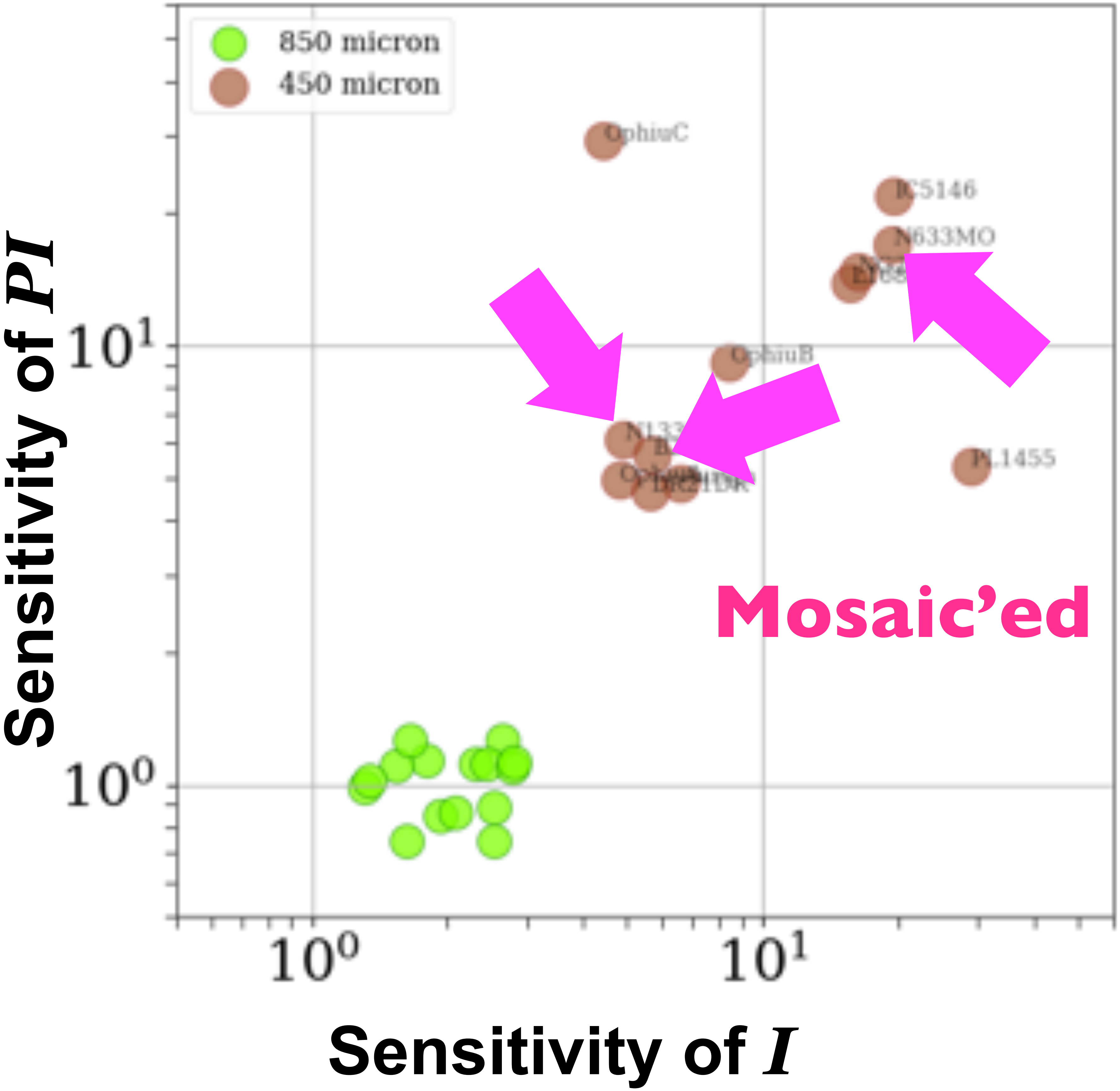
Sensitivity comparison of BISTRO data

Sensitivity of POL-2 maps in Stokes *I* vs. *PI*



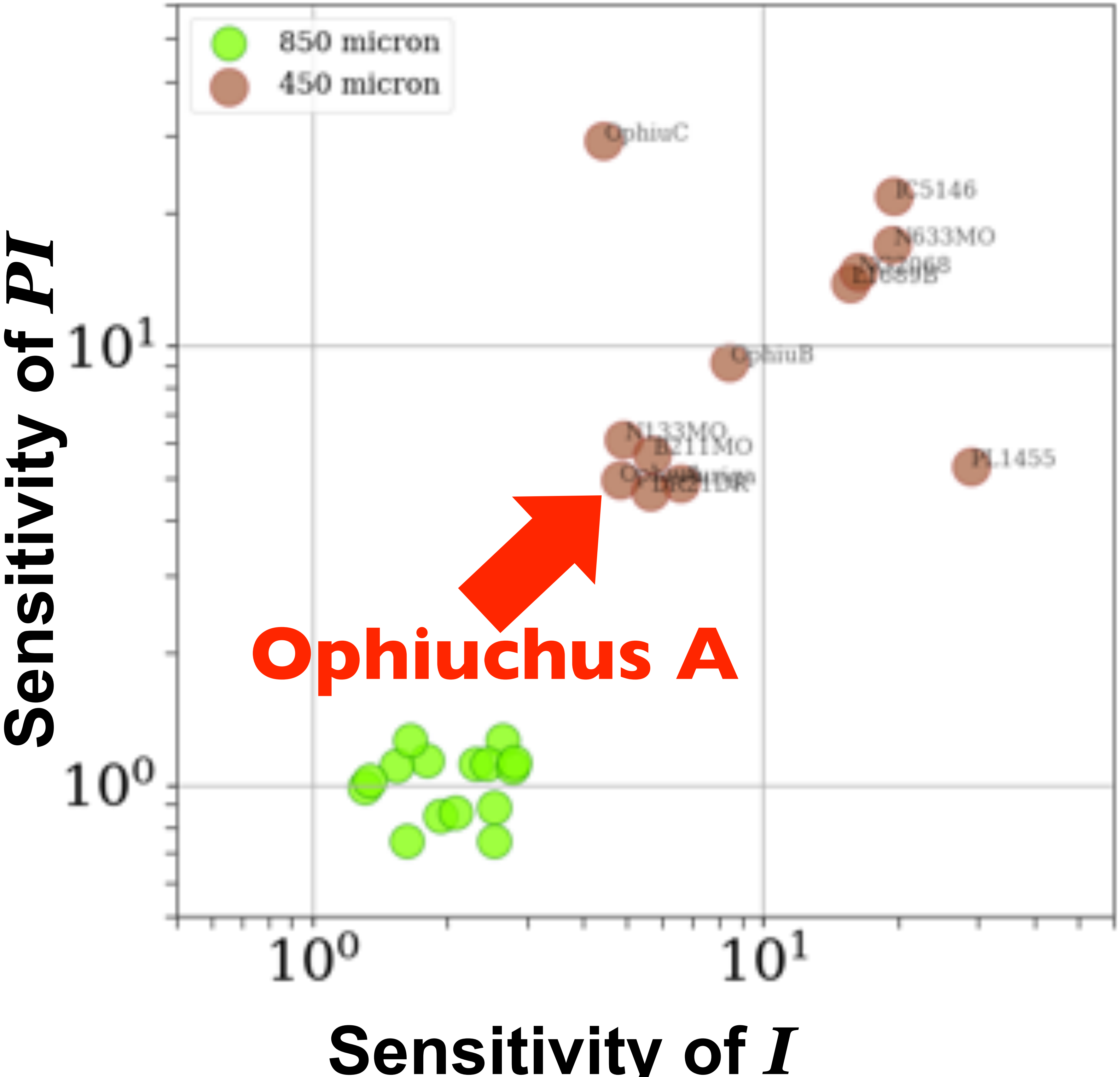
- Green and brown circles show *850 and 450 micron sensitivity, respectively.*
- 450 micron data were convolved so that they have 14" aperture
- Note that some projects are still ongoing

Sensitivity of POL-2 maps in Stokes *I* vs. *PI*



- Green and brown circles show *850 and 450 micron sensitivity, respectively.*
- 450 micron data were convolved so that they have 14" aperture
- Note that some projects are still ongoing

Sensitivity of POL-2 maps in Stokes *I* vs. *PI*

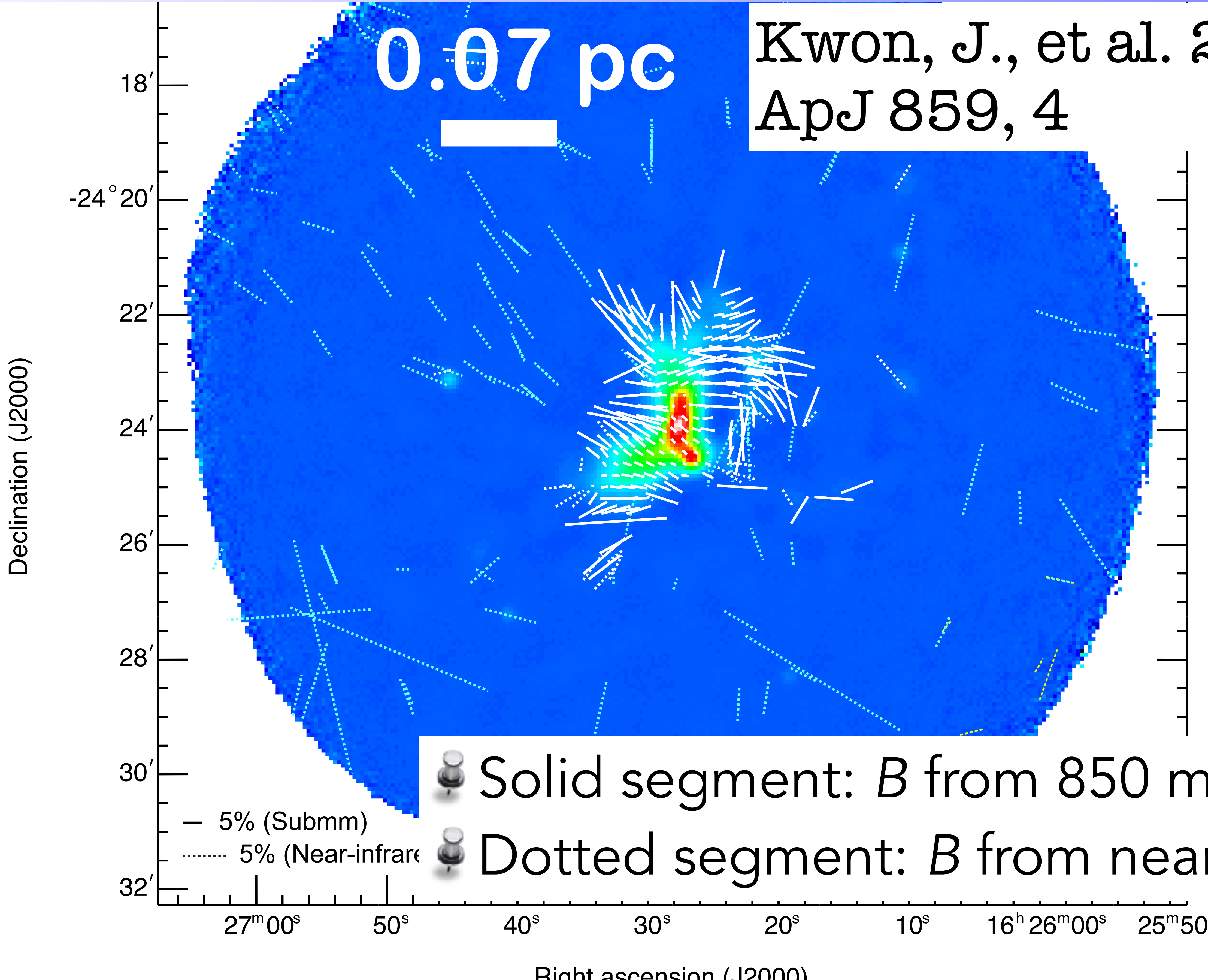


- Green and brown circles show *850 and 450 micron sensitivity, respectively.*
- 450 micron data were convolved so that they have 14” aperture
- Note that some projects are still ongoing

Data inspection

Ophiuchus A

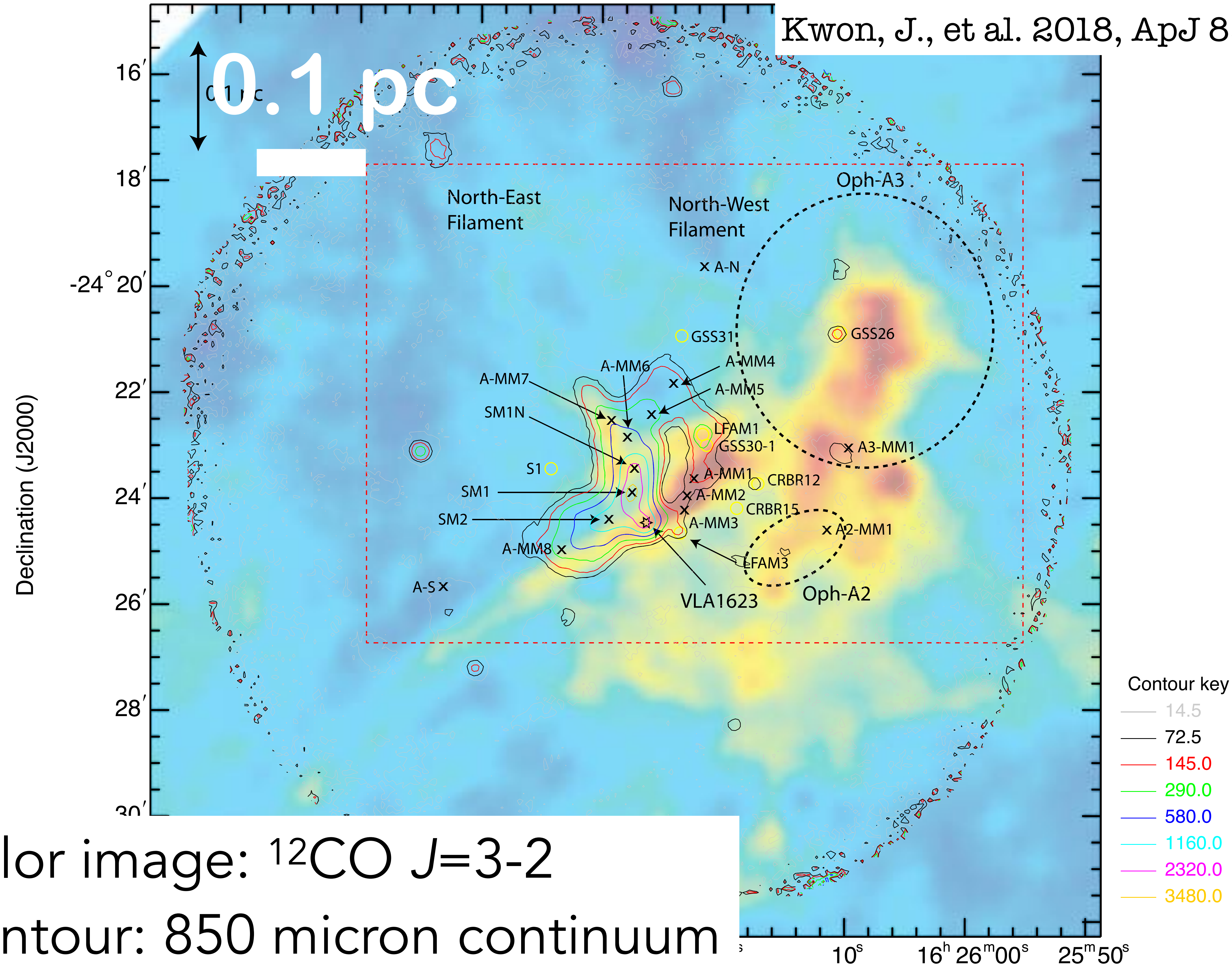
Ophiuchus A star-forming region



Kwon, J., et al. 2018, ApJ 859, 4

- Solid segment: *B* from 850 micron
- Dotted segment: *B* from near IR

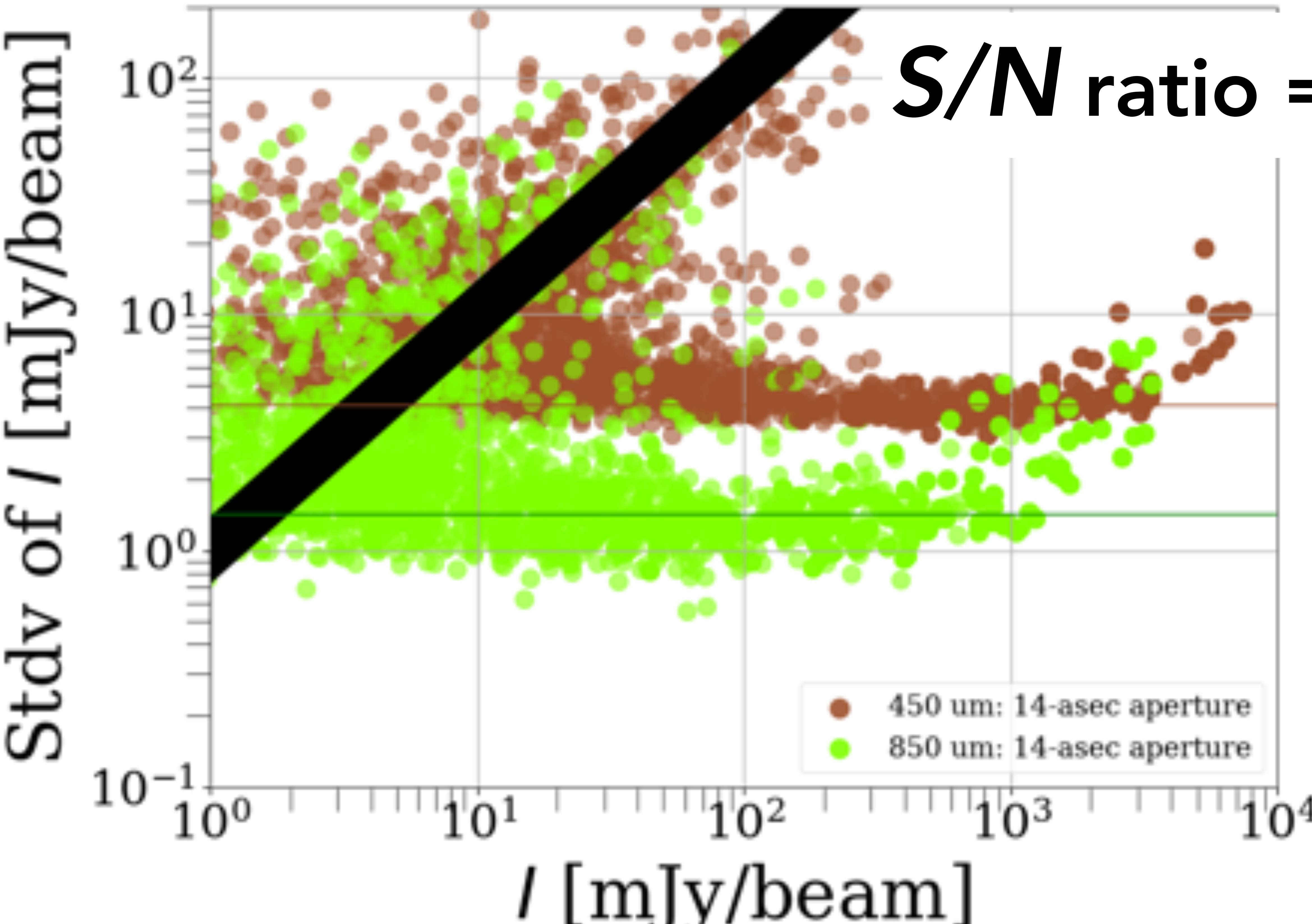
Ophiuchus A star-forming region



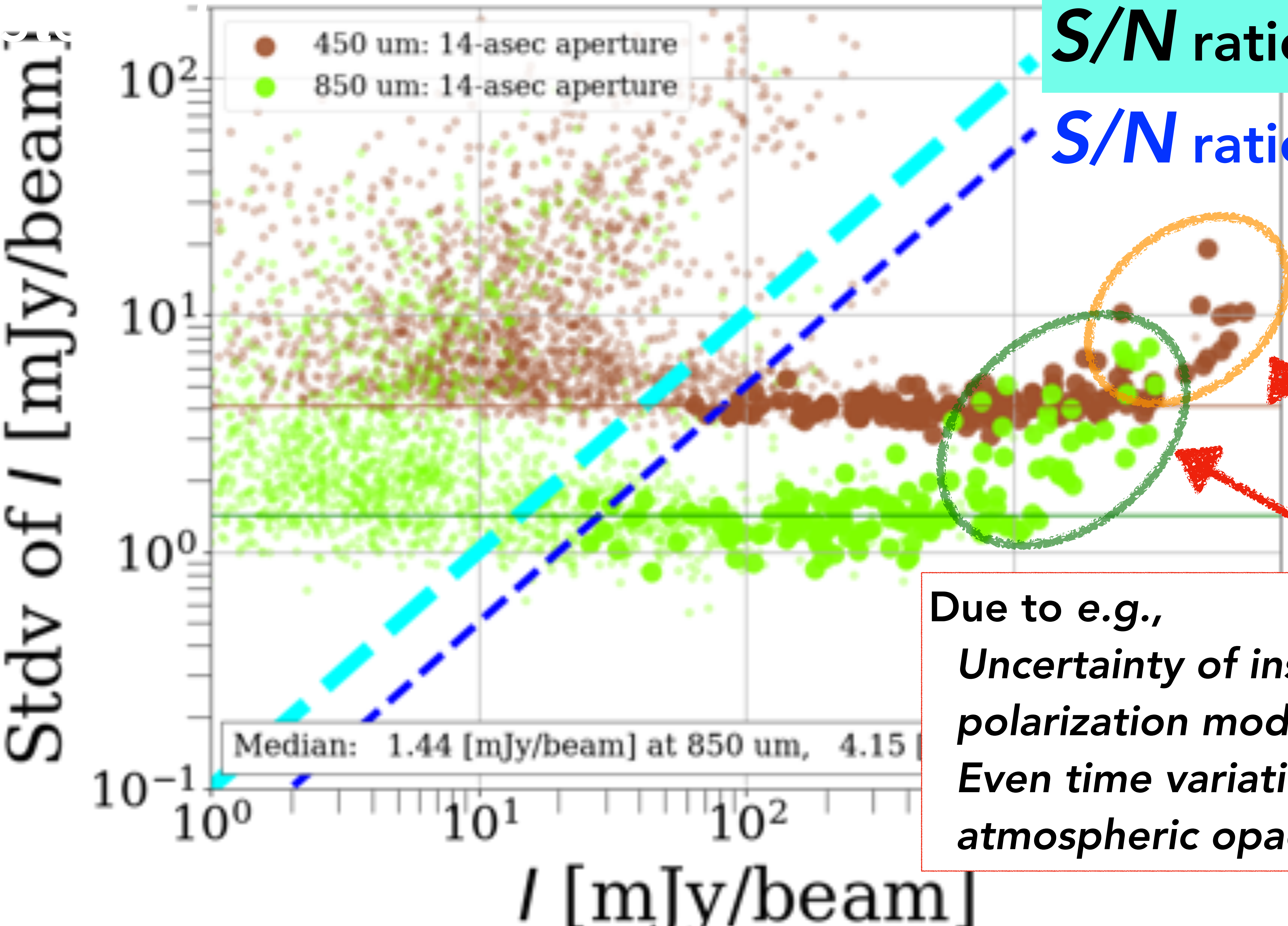
Kwon, J., et al. 2018, ApJ 859, 4

- Color image: ^{12}CO J=3-2
- Contour: 850 micron continuum

Data Inspection: Ophiuchus A, Stokes I



Data Inspection: Ophiuchus A, Stokes I



S/N ratio = 10

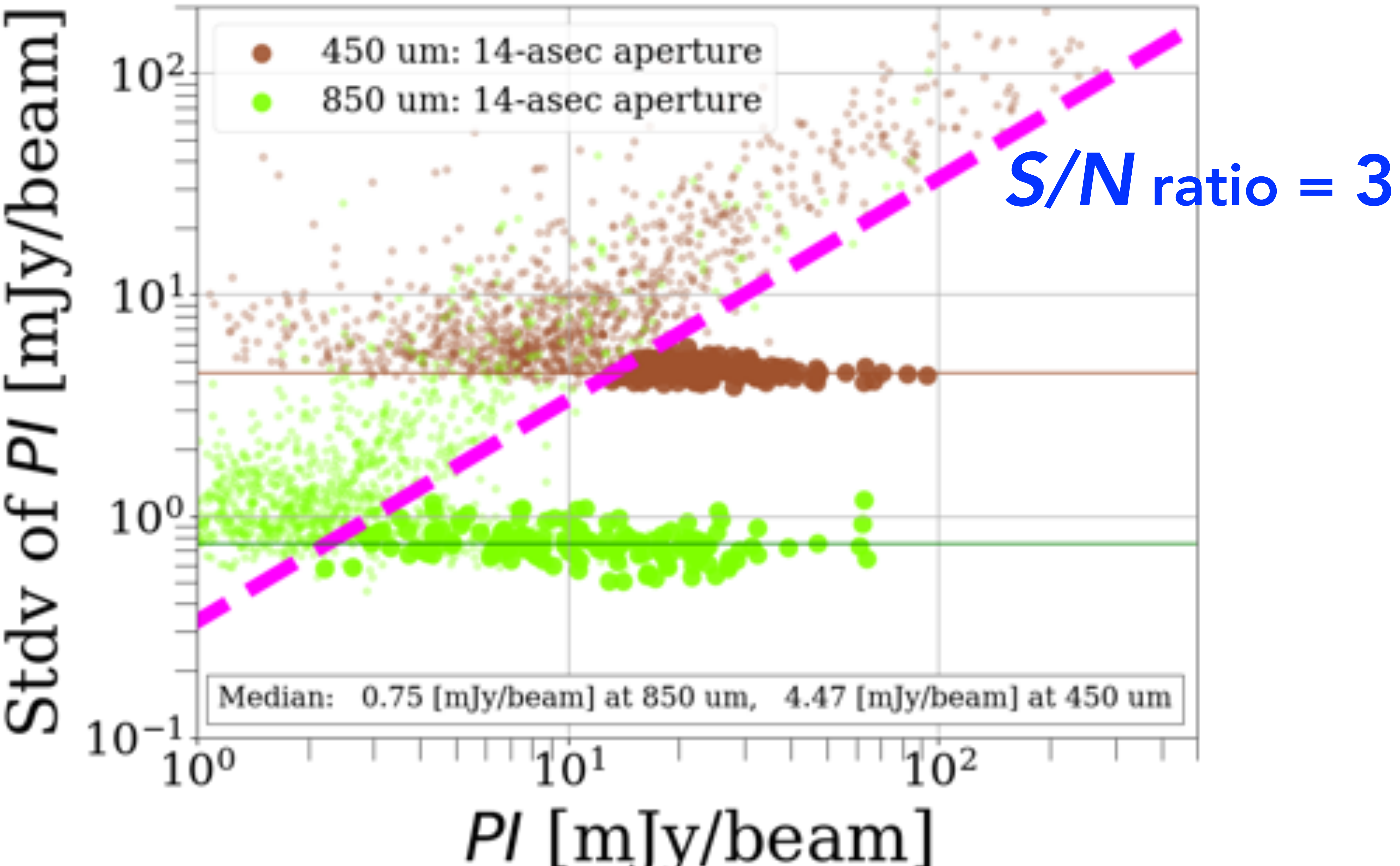
S/N ratio = 20

Due to *e.g.*,

Uncertainty of instrumental polarization model?

Even time variation of atmospheric opacity?

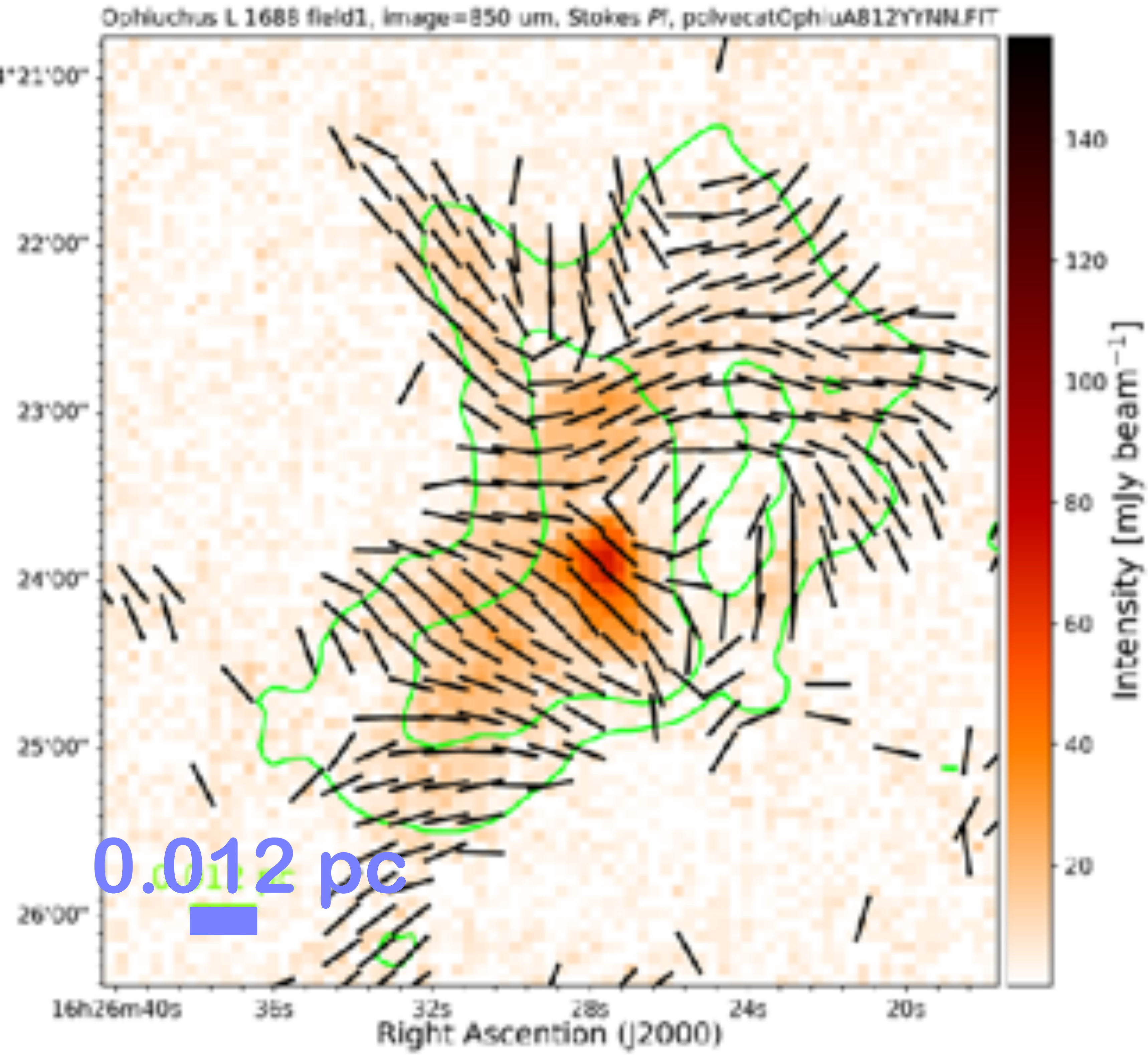
Data Inspection: Polarized Intensity, PI



Results

Maps

B-fields traced by 850 micron observations



What are presented here?

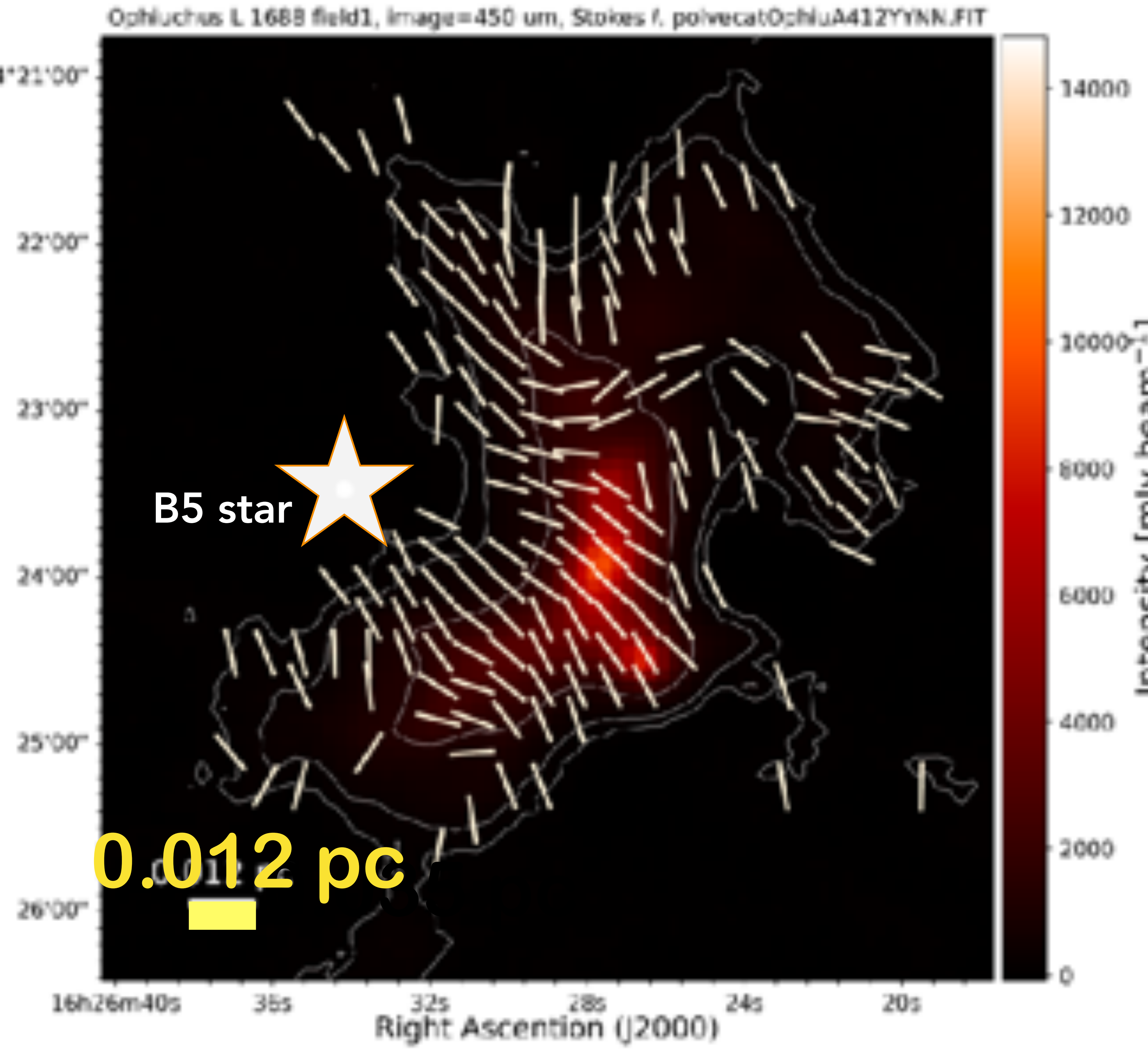
- **Color image**: Polarized intensity, *PI w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- **"Vectors"**: rotated 90 deg to see *B* field directions
- **"Vectors"** are shown with identical length to see directions

How vectors are selected?

- A **threshold** of ***I/ΔI* > 10 and *PI/ΔPI* > 3** so as **not to miss intrinsically-weak** polarization

the image = 850 micron Polarized Intensity, $PI = \sqrt{Q^2 + U^2}$

B-fields traced by 450 micron observations



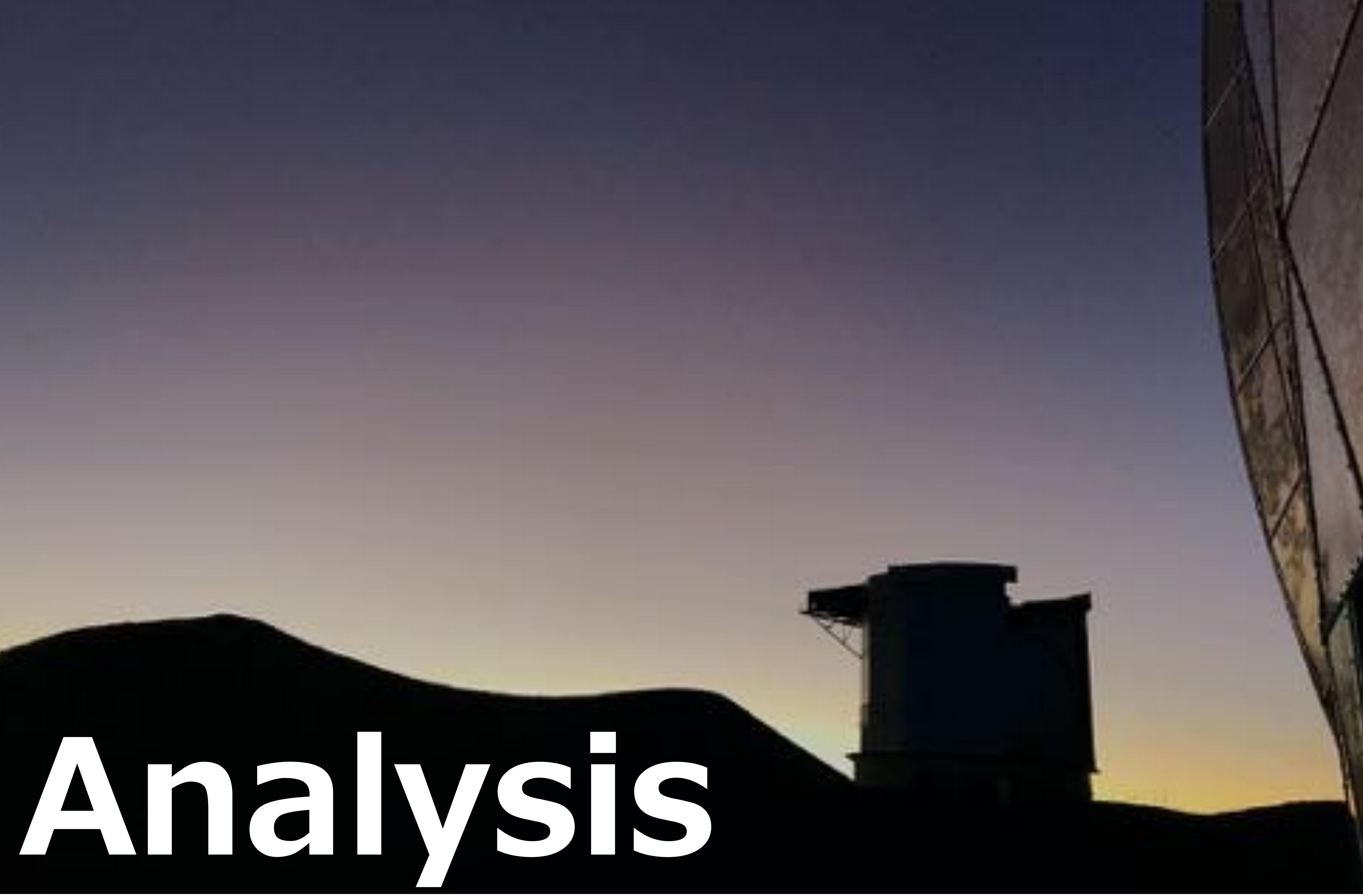
What are presented here?

- **Color image**: Stokes *I* intensity *w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- **"Vectors"**: rotated 90 $^{\text{deg}}$ to see *B* field directions
- **"Vectors"** are shown with identical length to see directions

How vectors are selected?

- A **threshold** of ***I/ΔI* > 10 and *PI/ΔPI* > 3** so as **not to miss intrinsically-weak** polarization

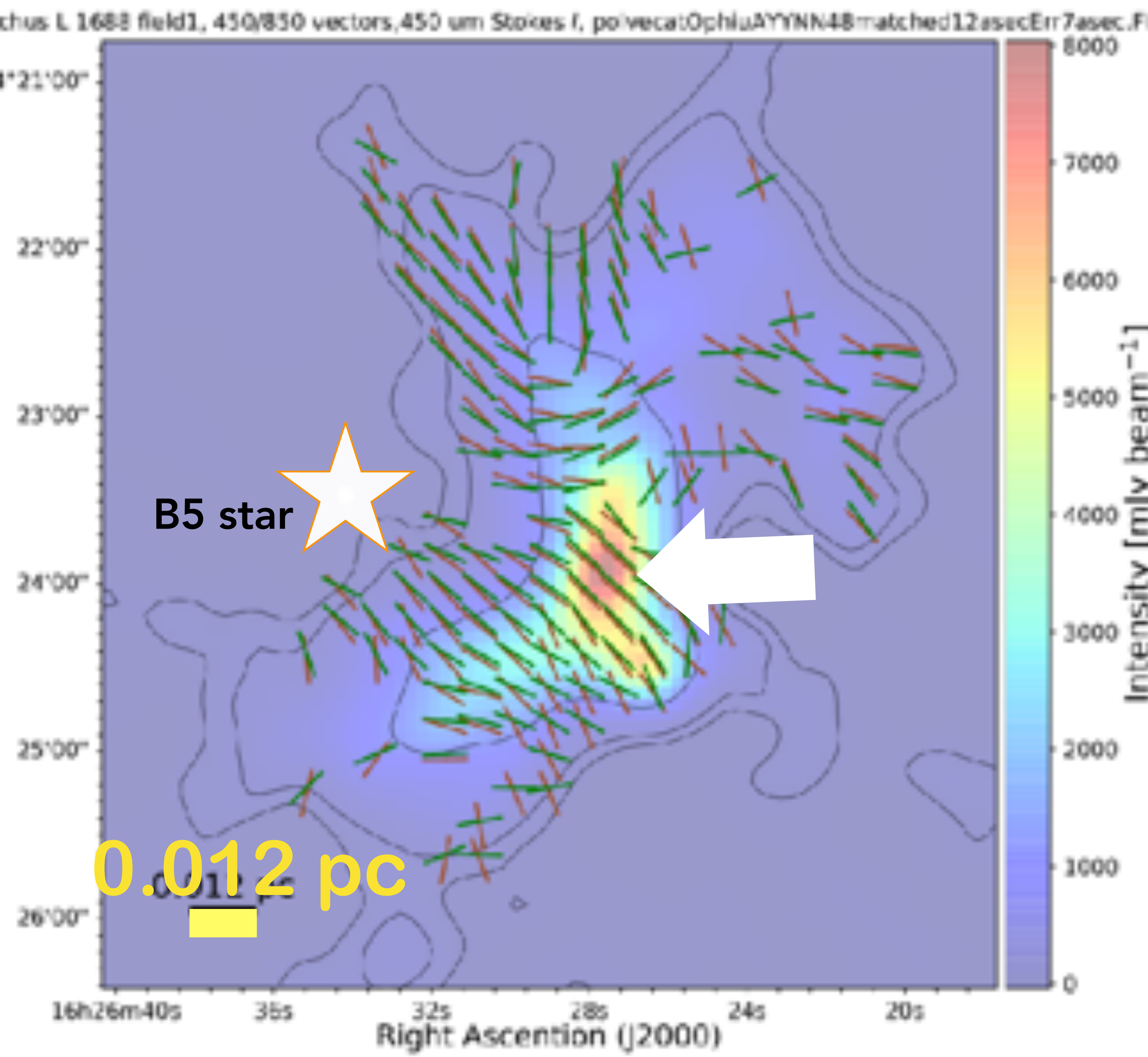
the image = 450 micron Stokes *I* intensity



Analysis

Polarization angles observed at the dual-bands

B-fields traced by 450 um vs. 850 um



What are presented here?

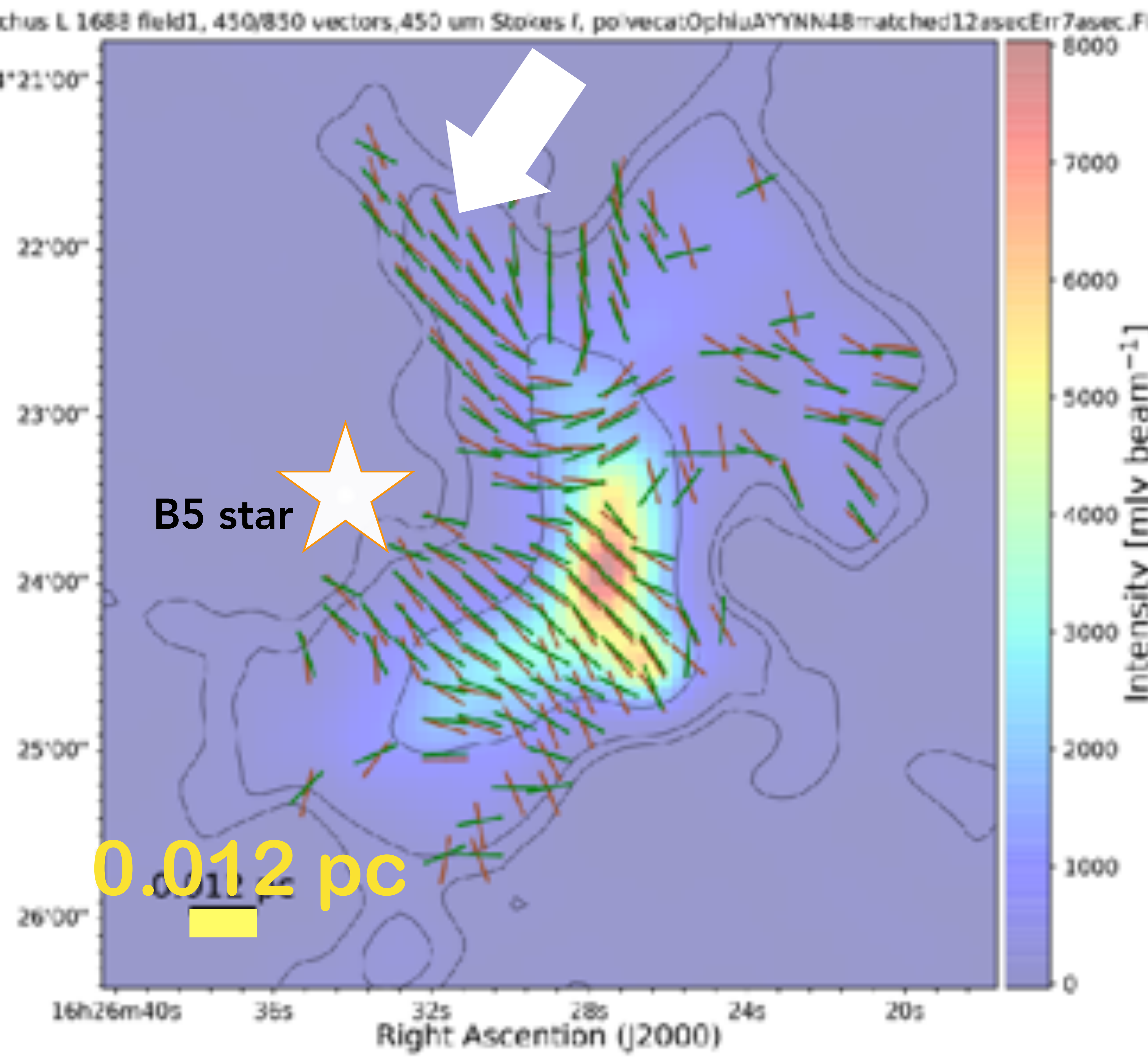
- **Color image**: 450 um Stokes *I* intensity *w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- **"Vectors"**: rotated 90 deg to see *B* field directions
- **"Vectors"** are shown with identical length, **Green: 850 mic, Brown: 450 mic**

How vectors are selected?

- A **threshold** of ***I/ΔI* > 10 and *PI/ΔPI* > 3** so as **not to miss intrinsically-weak** polarization

Well-aligned *B*-fields at the peak and periphery ⇨ IP model is reasonable

B-fields traced by 450 um vs. 850 um



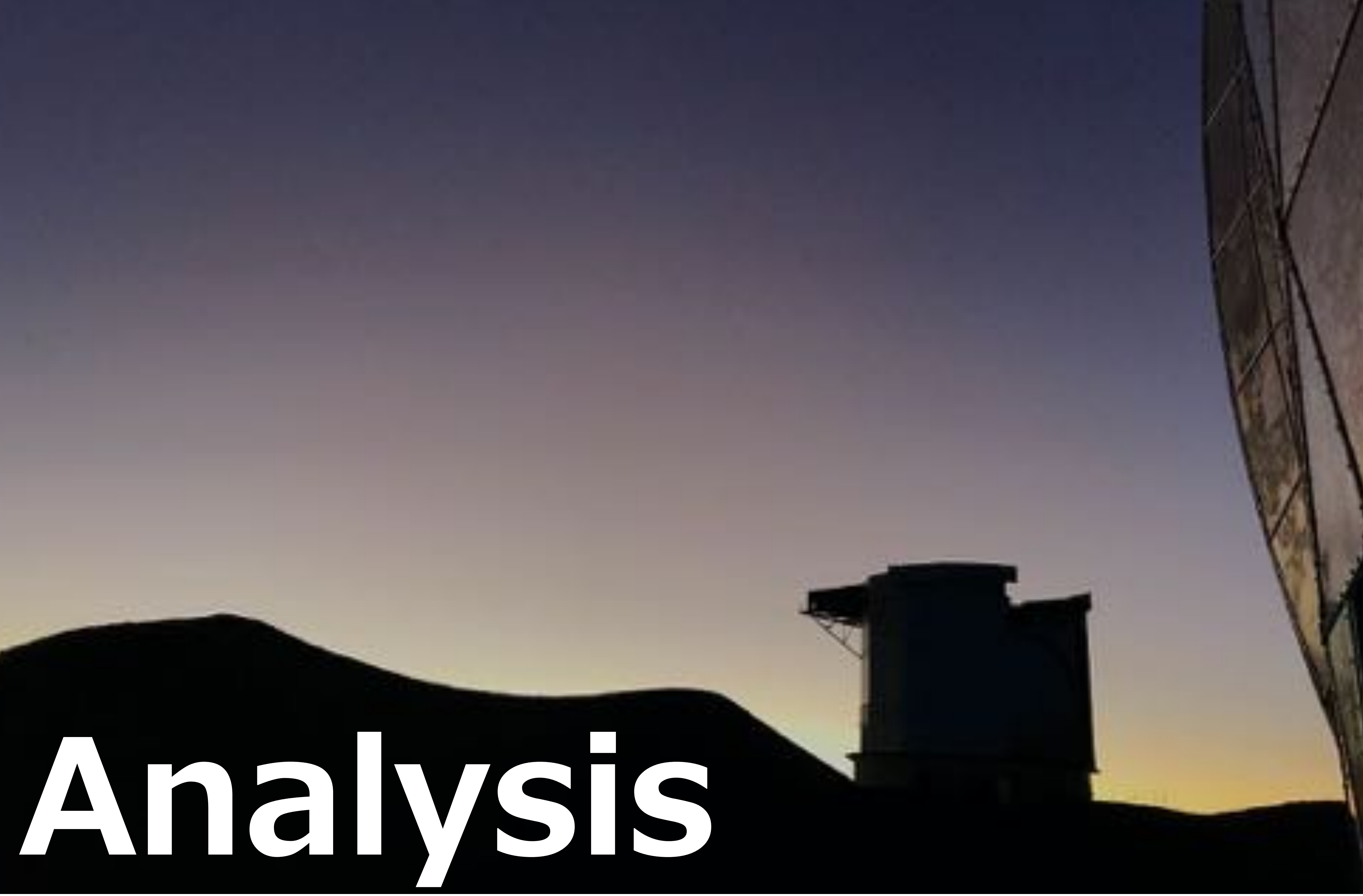
What are presented here?

- **Color image**: 450 um Stokes *I* intensity *w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- **"Vectors"**: rotated 90 deg to see *B* field directions
- **"Vectors"** are shown with identical length, **Green: 850 mic, Brown: 450 mic**

How vectors are selected?

- A **threshold** of ***I/ΔI* > 10 and *PI/ΔPI* > 3** so as **not to miss intrinsically-weak** polarization

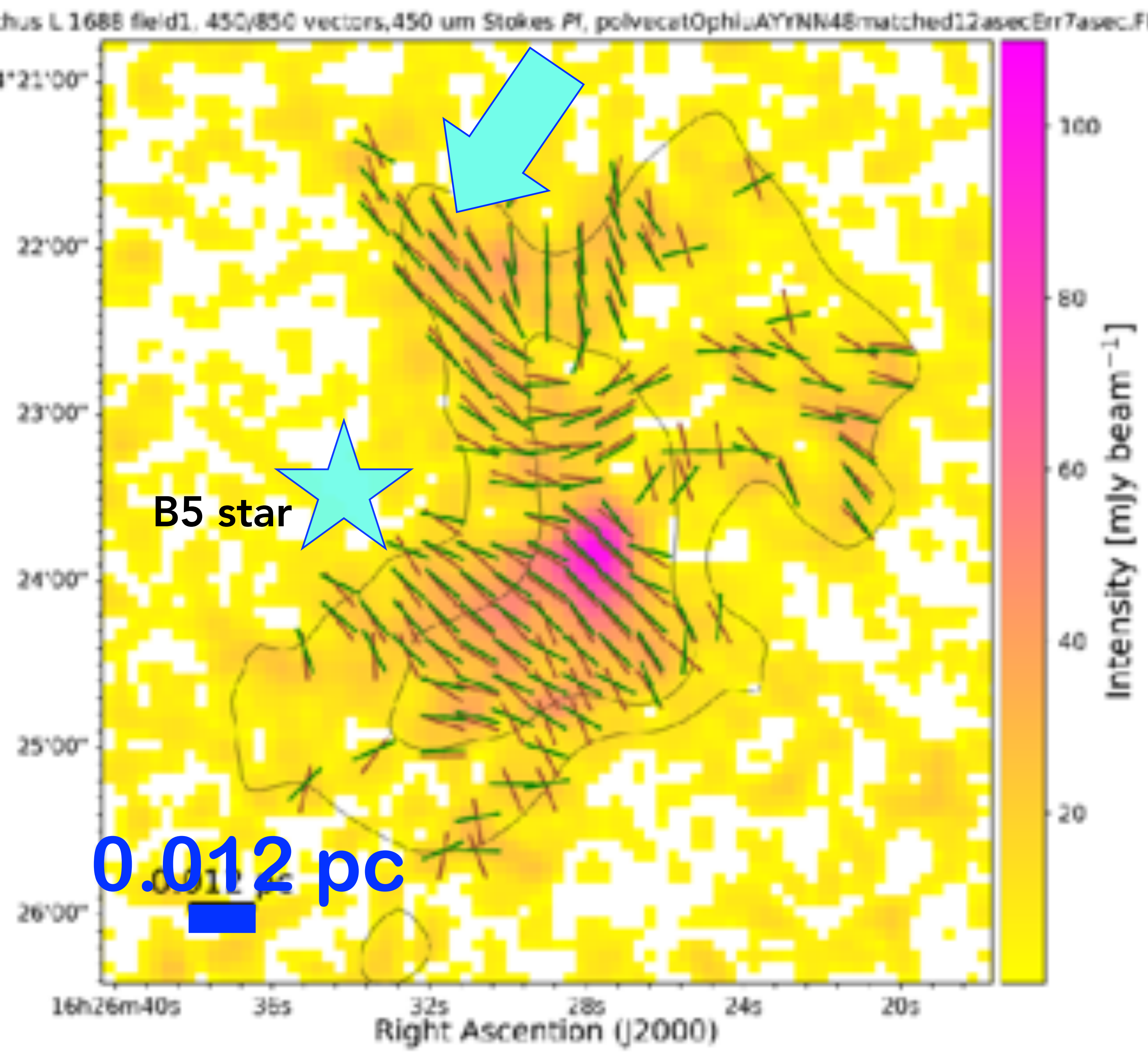
- Well-aligned *B*-fields at the peak and periphery ⇨ IP model is reasonable
- Coherent and incoherent patterns are identified in each band.



Analysis

Polarization angles observed at the dual-bands

B-fields traced by 450 um vs. 850 um



What are presented here?

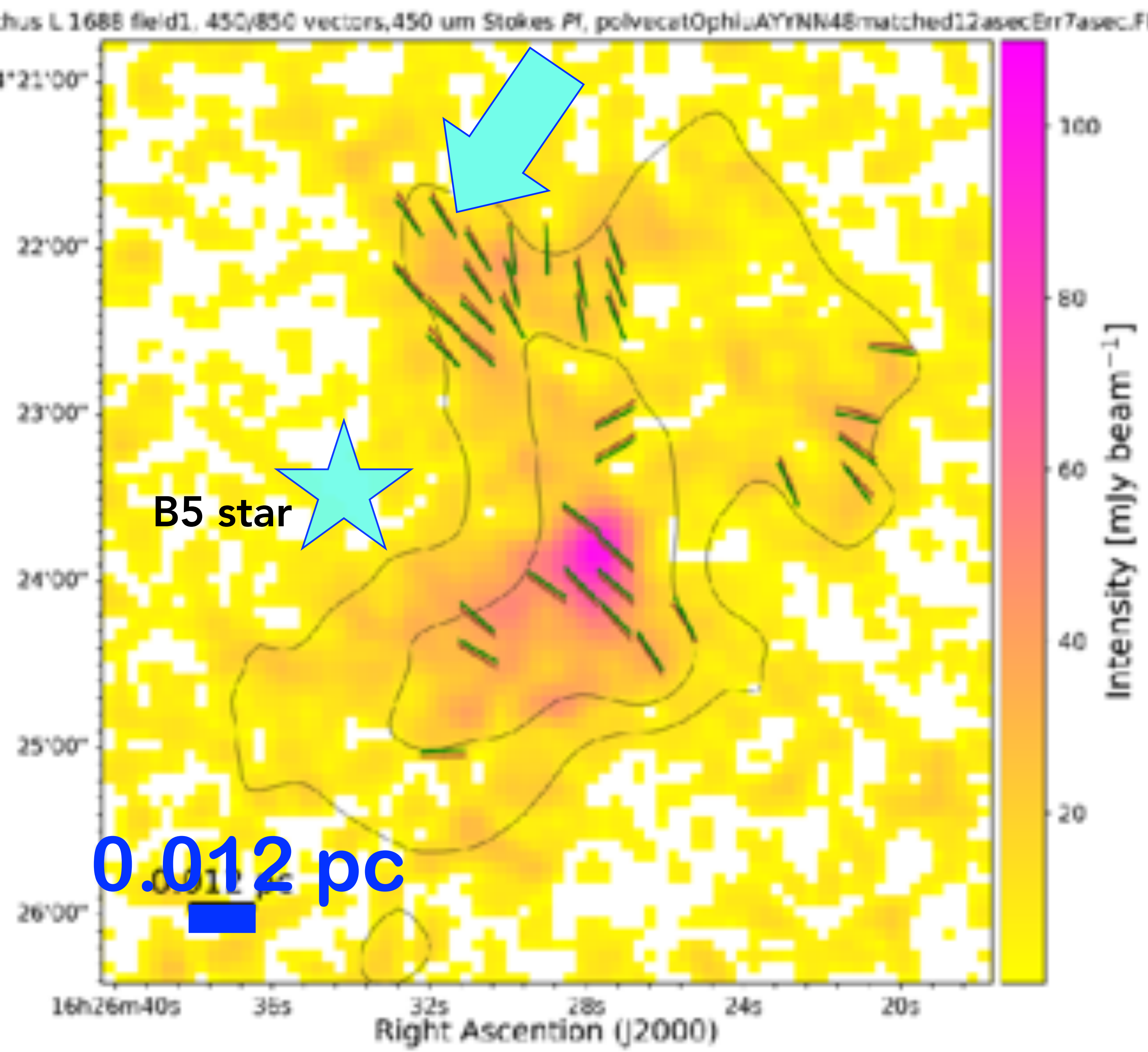
- **Color image**: 450 um polarized intensity, *PI*, *w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- "**Vectors**": rotated 90 deg to see *B* field directions
- "**Vectors**" are shown with identical length, **Green: 850 mic, Brown: 450 mic**

How vectors are selected?

- A **threshold** of ***I/ΔI*** **> 10 and *PI/ΔPI* > 3** so as **not to miss intrinsically-weak** polarization

the image = 450 micron Polarized intensity, $PI = \sqrt{Q^2 + U^2}$

B-fields traced by 450 um vs. 850 um



What are presented here?

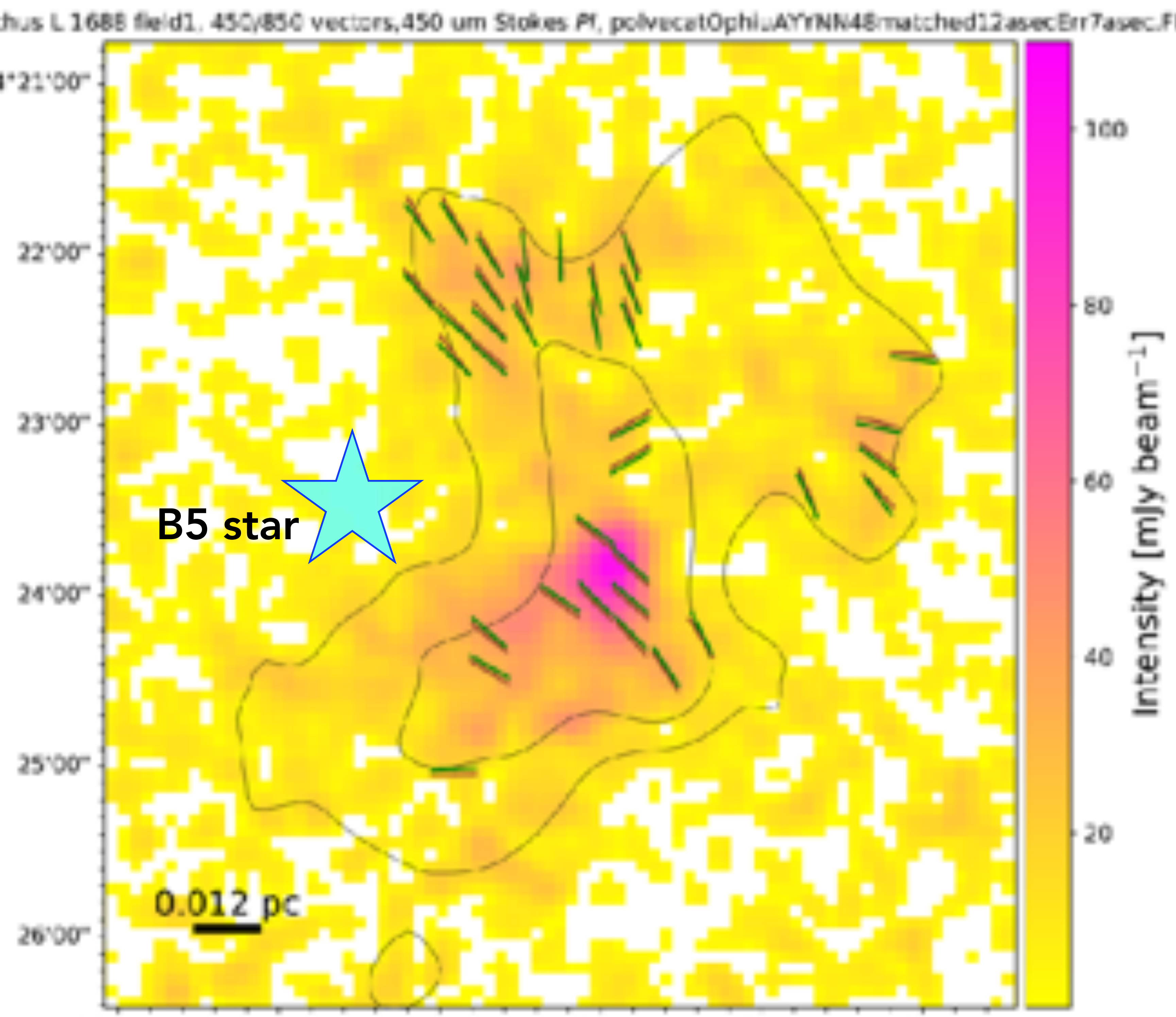
- **Color image**: 450 um polarized intensity, *PI*, *w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- "**Vectors**": rotated 90 deg to see *B* field directions
- "**Vectors**" are shown with identical length, **Green: 850 mic, Brown: 450 mic**

How vectors are selected?

- A **threshold** of ***I/ΔI* > 10 and *PI/ΔPI* > 3** so as **not to miss intrinsically-weak** polarization

the image = 450 micron Polarized intensity, $PI = \sqrt{Q^2 + U^2}$

B-fields traced by 450 um vs. 850 um



What are presented here?

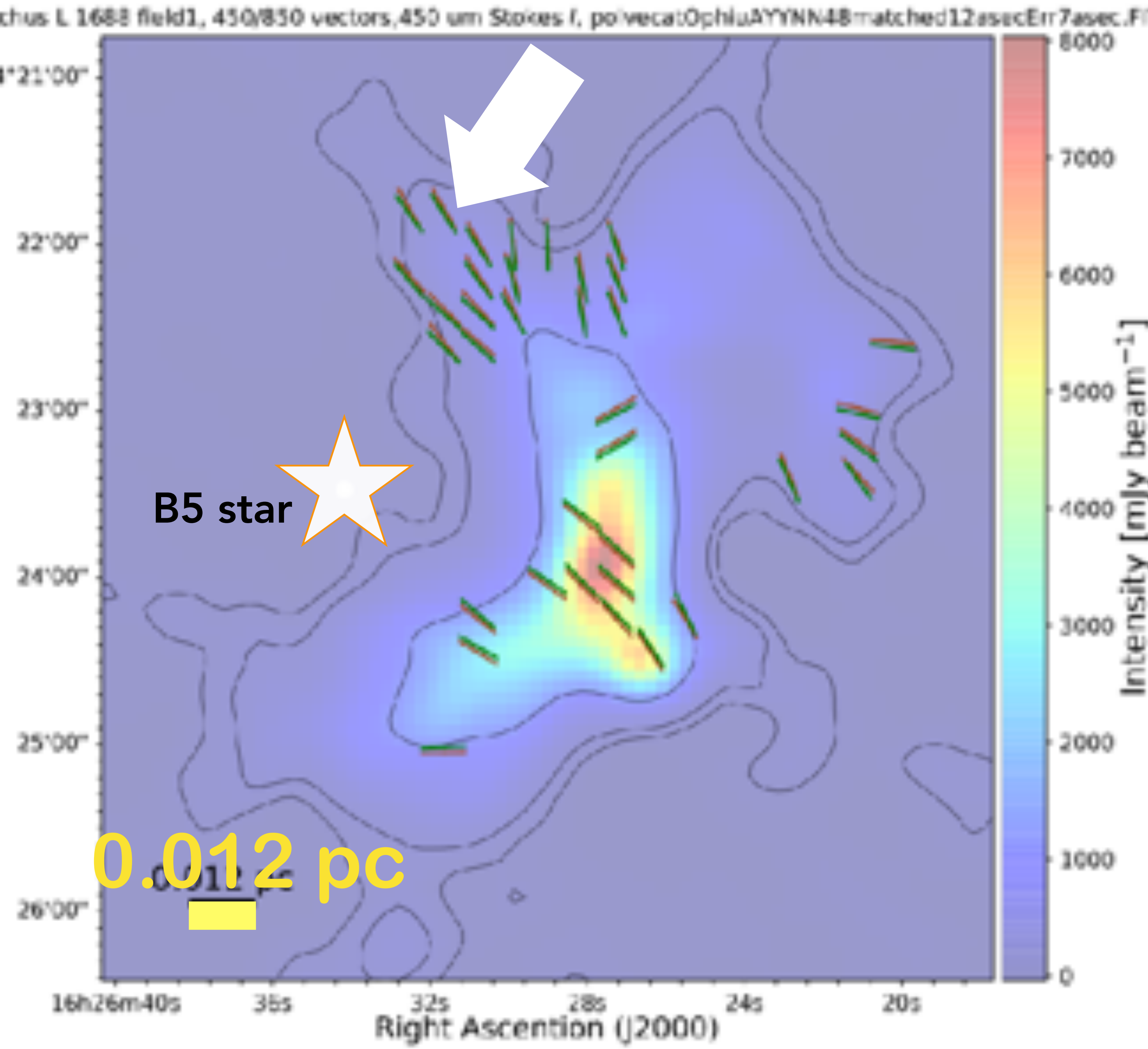
- **Color image**: 450 um polarized intensity, *PI*, *w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- **"Vectors"**: rotated 90 ^{deg} to see *B* field directions
- **"Vectors"** are shown with identical length, **Green: 850 mic, Brown: 450 mic**

How vectors are selected?

- A **threshold** of ***I/ΔI* > 10 and *PI/ΔPI* > 3** so as **not to miss intrinsically-weak** polarization

Excluding non-parallel vectors ⇨ Excluding line of sight where dual bands tracing different temperature gas

B-fields traced by 450 um vs. 850 um



What are presented here?

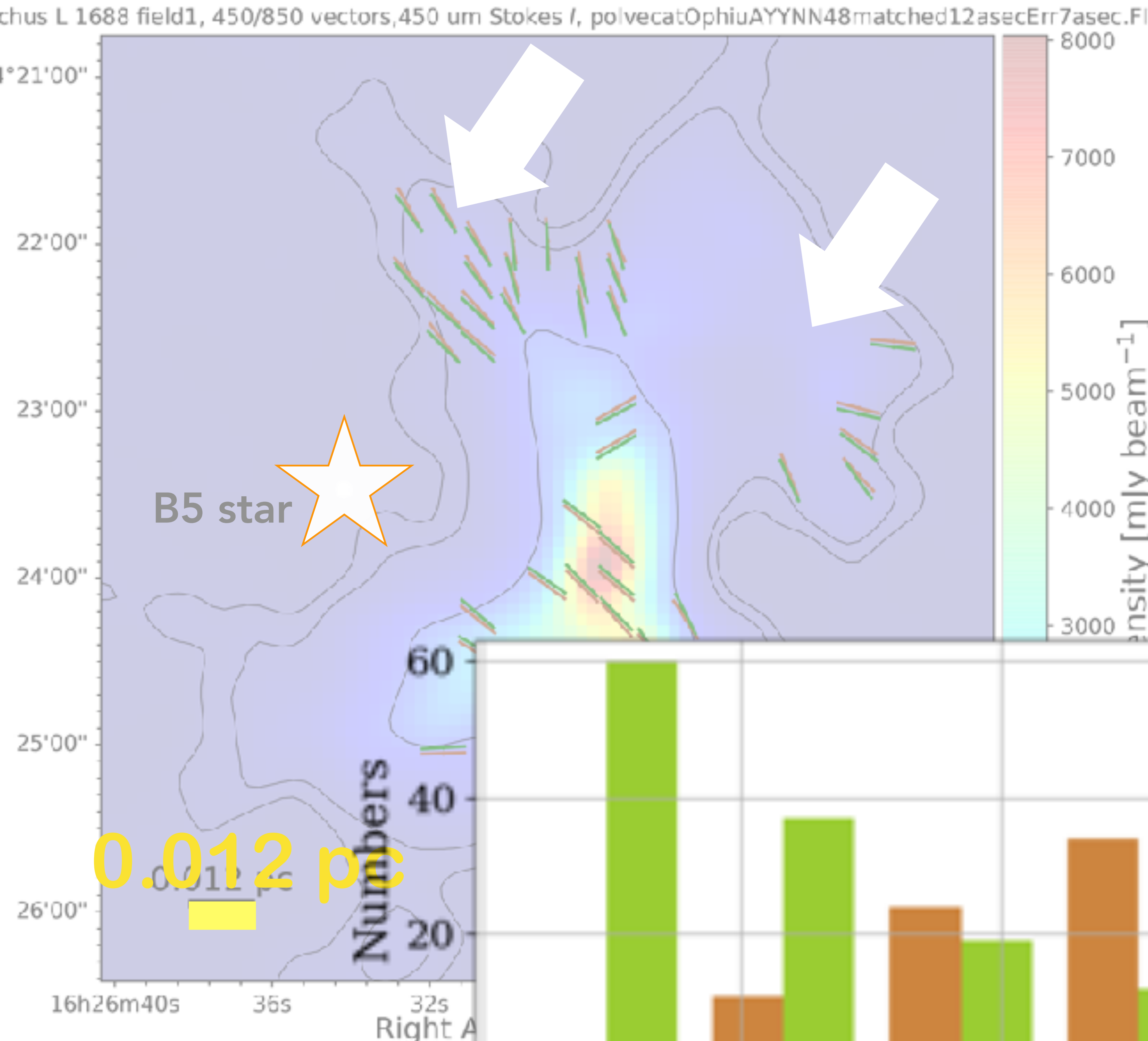
- **Color image**: 450 um Stokes *I* intensity *w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- **"Vectors"**: rotated 90 deg to see *B* field directions
- **"Vectors"** are shown with identical length, **Green: 850 mic, Brown: 450 mic**

How vectors are selected?

- A **threshold** of ***I/ΔI* > 10 and *PI/ΔPI* > 3** so as **not to miss intrinsically-weak** polarization

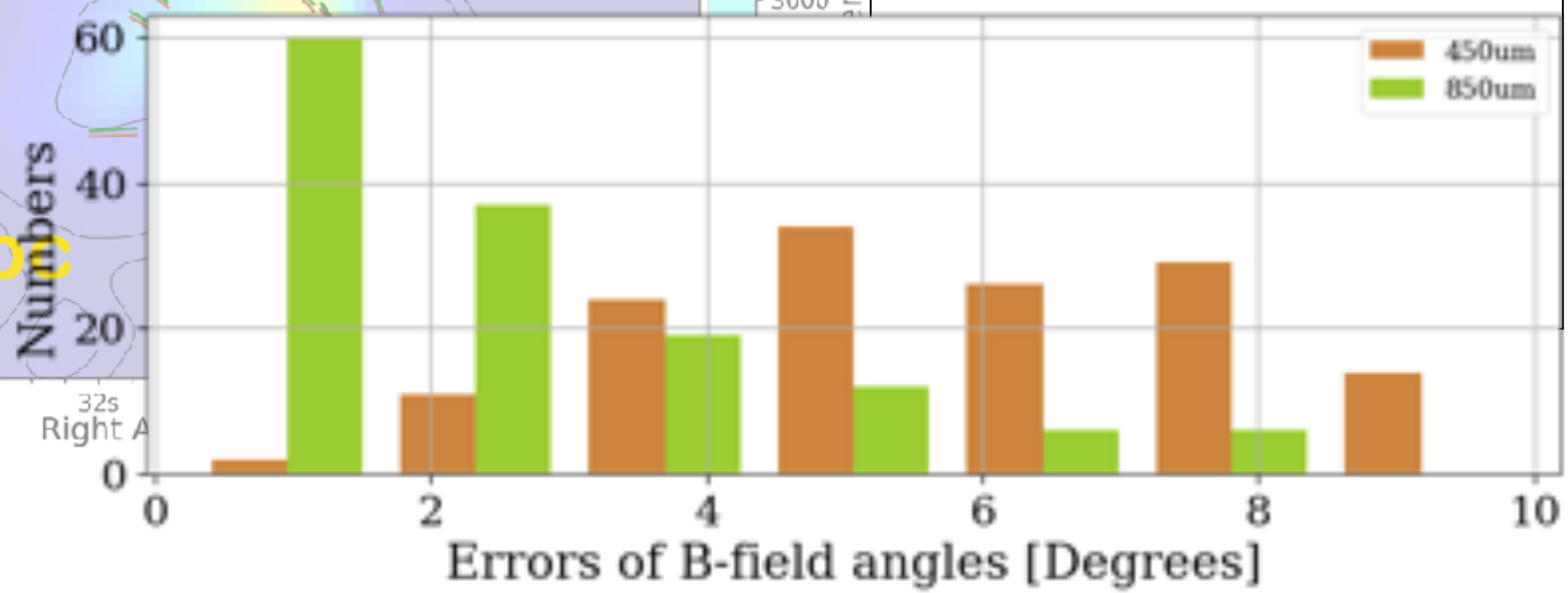
the image = 450 micron Stokes *I* intensity

B-fields traced by 450 um vs. 850 um

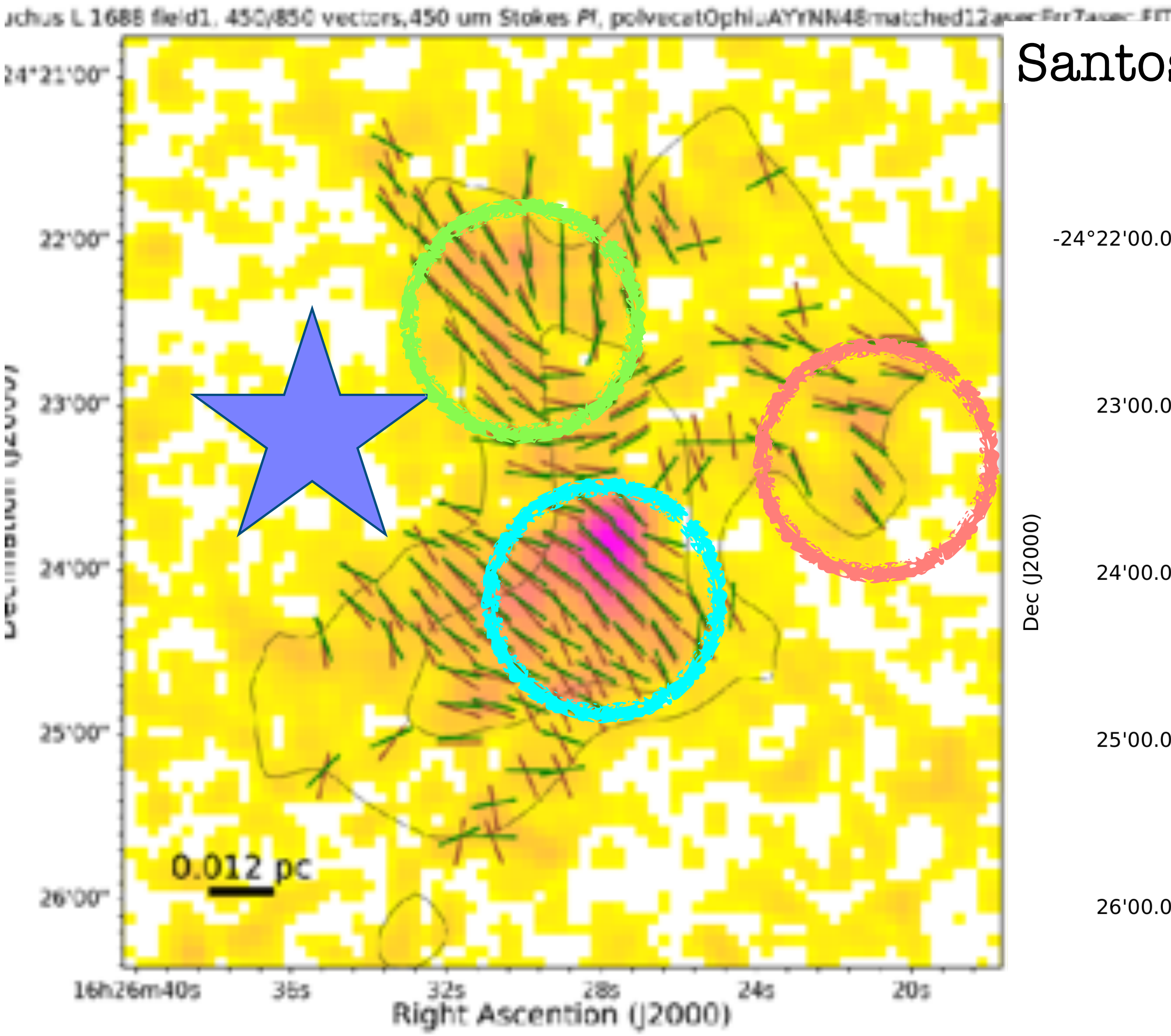


What are presented here?

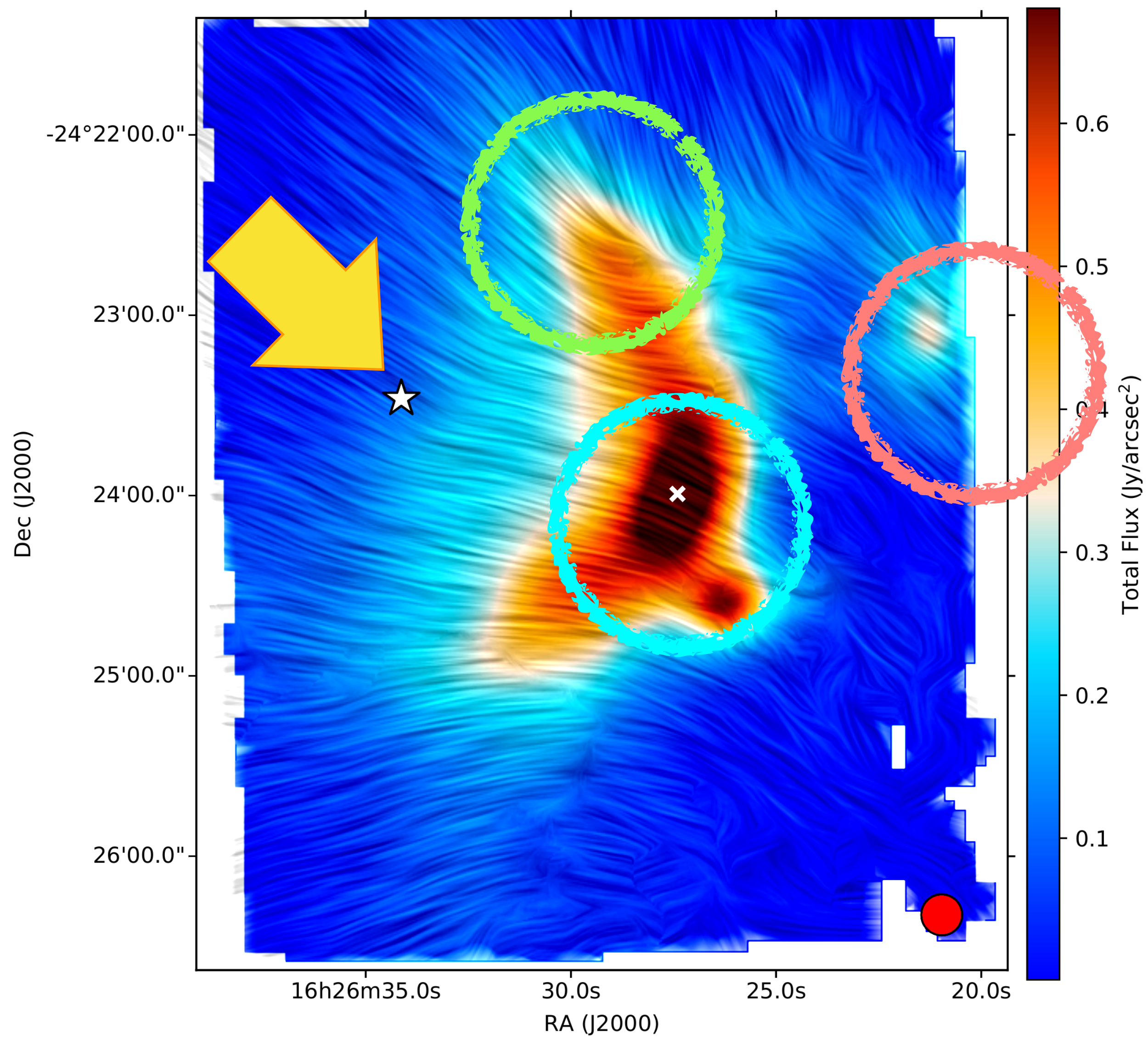
- **Color image**: 450 um Stokes *I* intensity *w. pixel size =12"*
- **Contour**: 90, 95, 99% percentile of Stokes *I*
- **"Vectors"**: rotated 90 $^{\text{deg}}$ to see *B* field directions
- **"Vectors"** are shown with identical length, **Green: 850 mic, Brown: 450 mic**



Comparison with SOFIA's 89 and 154 micron results



Santos et al. 2019, ApJ September 10 issue



BISTRO 450 micron

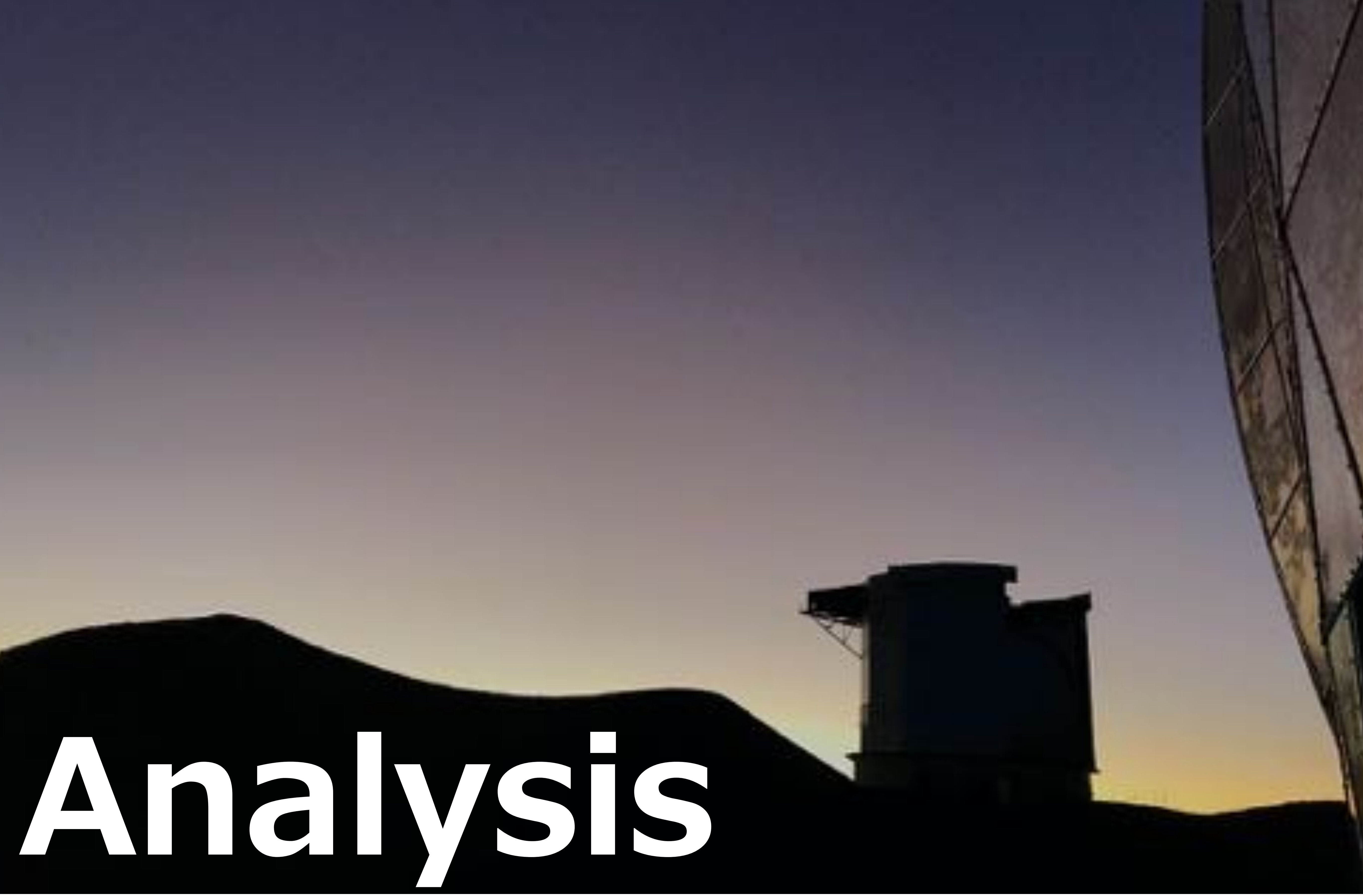
effective beam size~8″

SOFIA 154 micron

beam size = 13.6″

Well-polarized in low-density and well-illuminated cloud's periphery

Less-polarized in high-density and less-illuminated cloud's peak



Analysis

Polarization fractions and pol. spectral index

P observed in submm emission polarimetry

$$P_\nu = p_{\text{dust},\nu} \cdot R_\nu \cdot F_\nu \cdot \cos^2\gamma$$

$p_{\text{dust},\nu}$: **Dust properties — size, shape, composition**

Voshchinnikov & Hirashita 2014

R_ν : **Grain alignment efficiency w.r.t. local *B* fields**

Goodman 1992; Whittet et al. 2008; Hoang & Lazarian 2014

F_ν : **Depolarization from 2 (or multi-) layers along l.o.s.**

e.g., $F = \frac{P}{P_1 + P_2}$ where $P^2 = P_1^2 + P_2^2 + 2P_1P_2cos2\Delta\psi$ for 2 layers

Myers & Goodman 1991; Jones et al.1992, 2015; *Planck* 2015 XX, 2016 XXXIIII

$\cos^2\gamma$: ***B*-field geometry (where γ is w.r.t. p.o.s.)**

Planck 2015 XX, 2016 XXXIIII

P observed in submm emission polarimetry

$$P_\nu = p_{\mathrm{dust},\nu} \cdot R_\nu \cdot F_\nu \cdot \cos^2\gamma$$

$p_{\mathrm{dust},\nu}$: **Dust properties — size, shape, composition**

Voshchinnikov & Hirashita 2014

R_ν : **Grain alignment efficiency w.r.t. local *B* fields**

Goodman 1992; Whittet et al. 2008; Hoang & Lazarian 2014

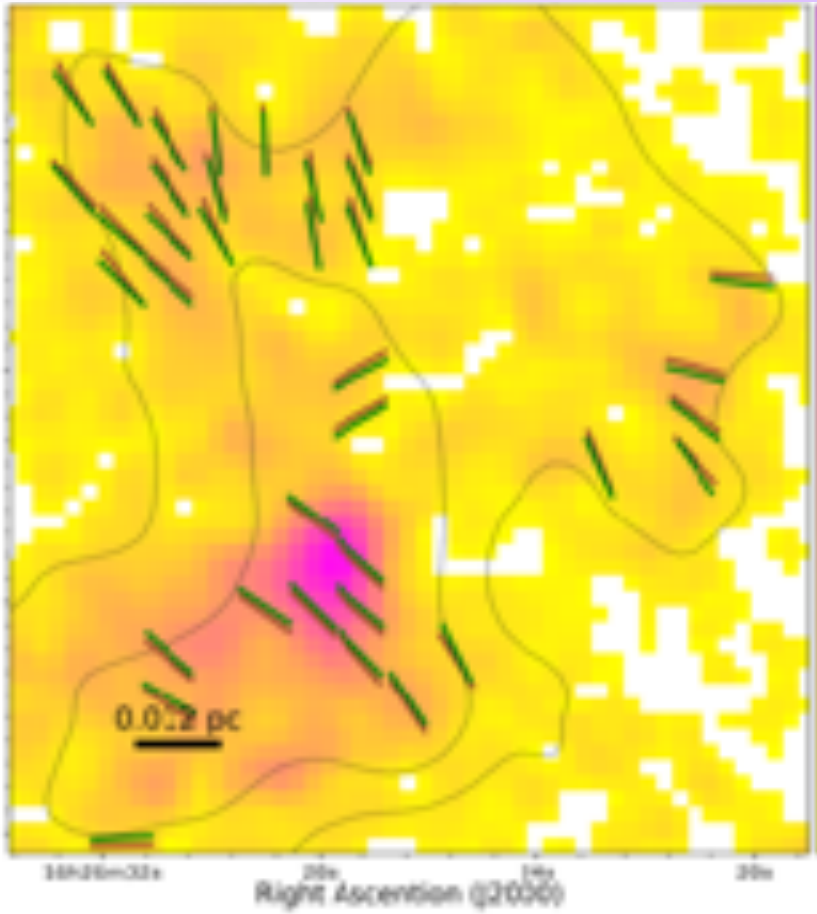
F_ν : **Depolarization from 2 (or multi-) layers along l.o.s.**

e.g., $F = \frac{P}{P_1 + P_2}$ where $P^2 = P_1^2 + P_2^2 + 2P_1P_2cos2\Delta\psi$ for 2 layers

Myers & Goodman 1991; Jones et al.1992, 2015; *Planck* 2015 XX, 2016 XXXIIII

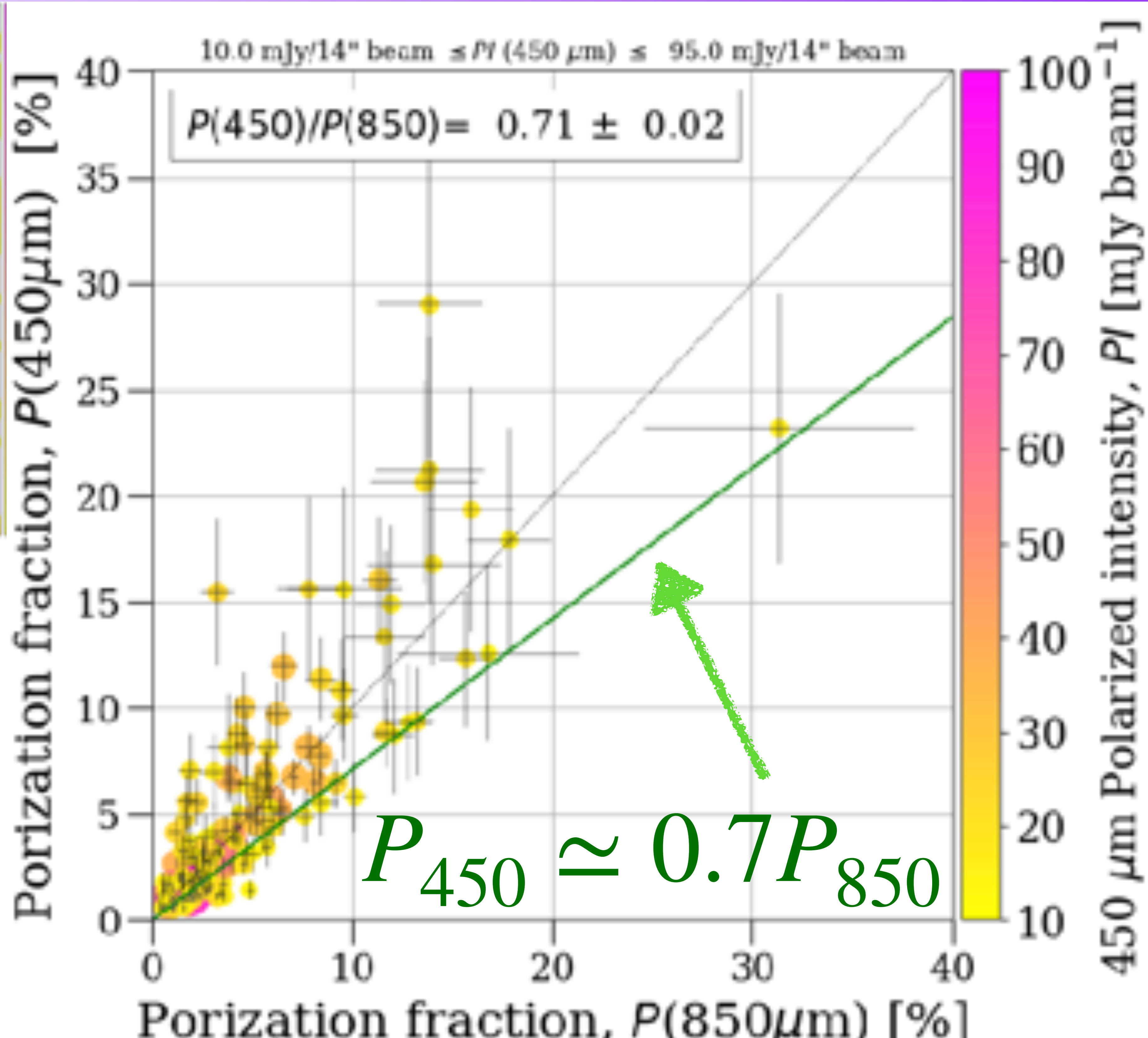
Excluding non-parallel vectors ⇨ Excluding line of sight where dual bands tracing different temperature gas

450 um polarization fraction vs. 850 um p.f.

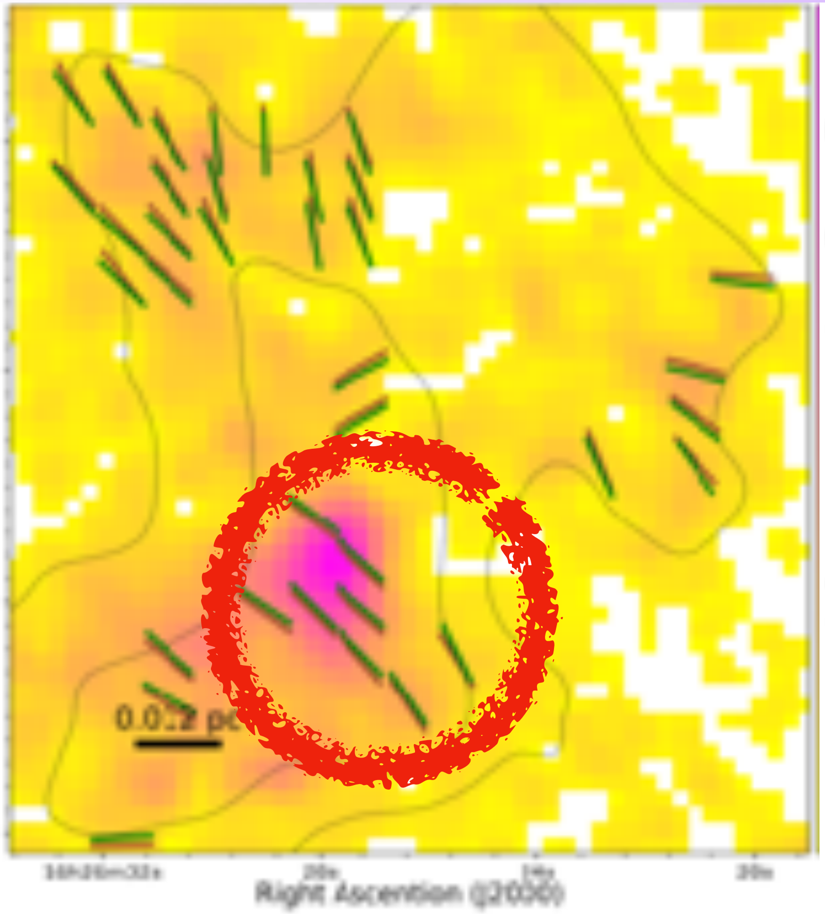


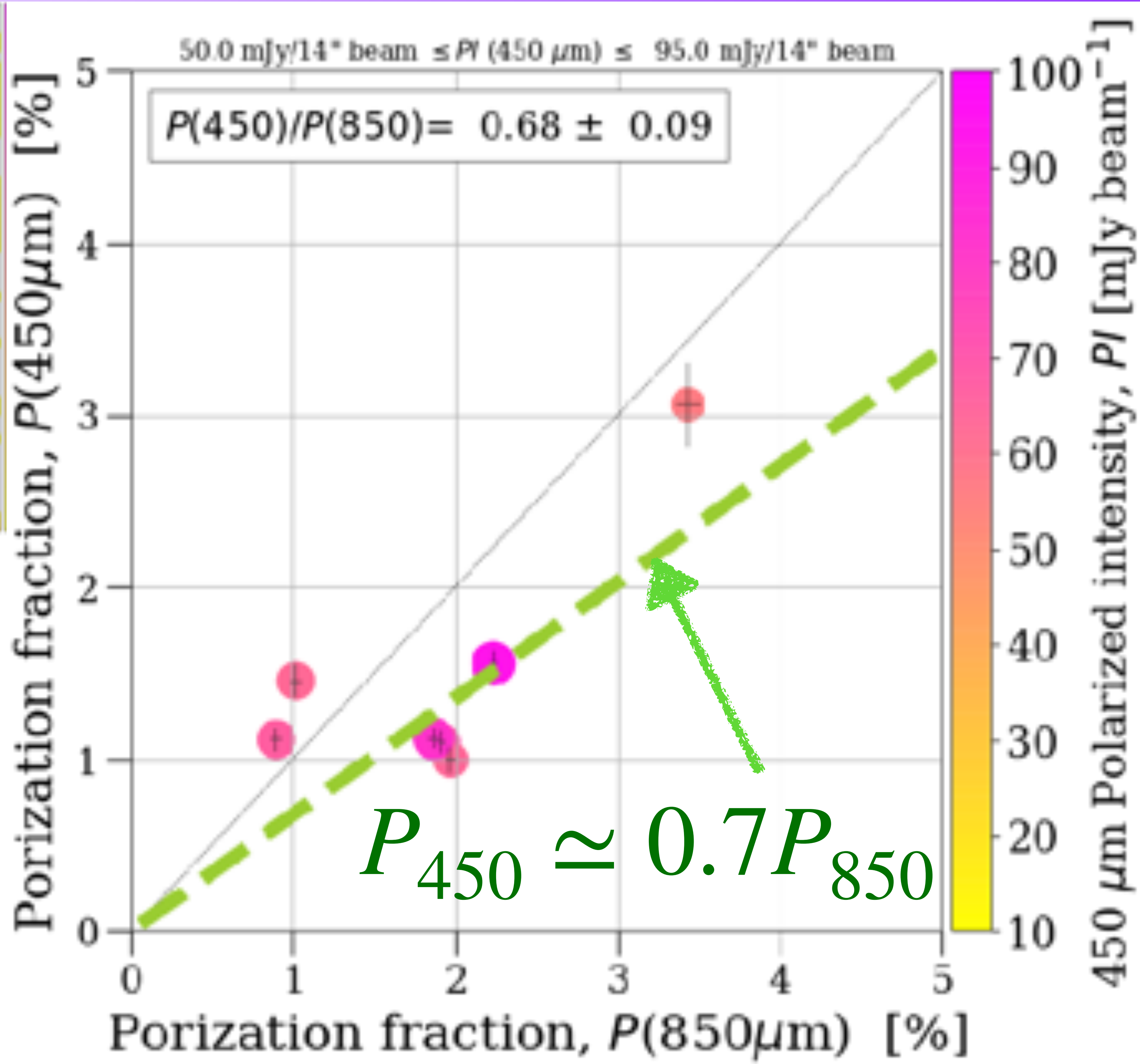
How vectors are selected?

- $I/\Delta I > 10$ and $PI/\Delta PI > 3$, and vectors whose directions agree within errors



450 um polarization fraction vs. 850 um p.f.

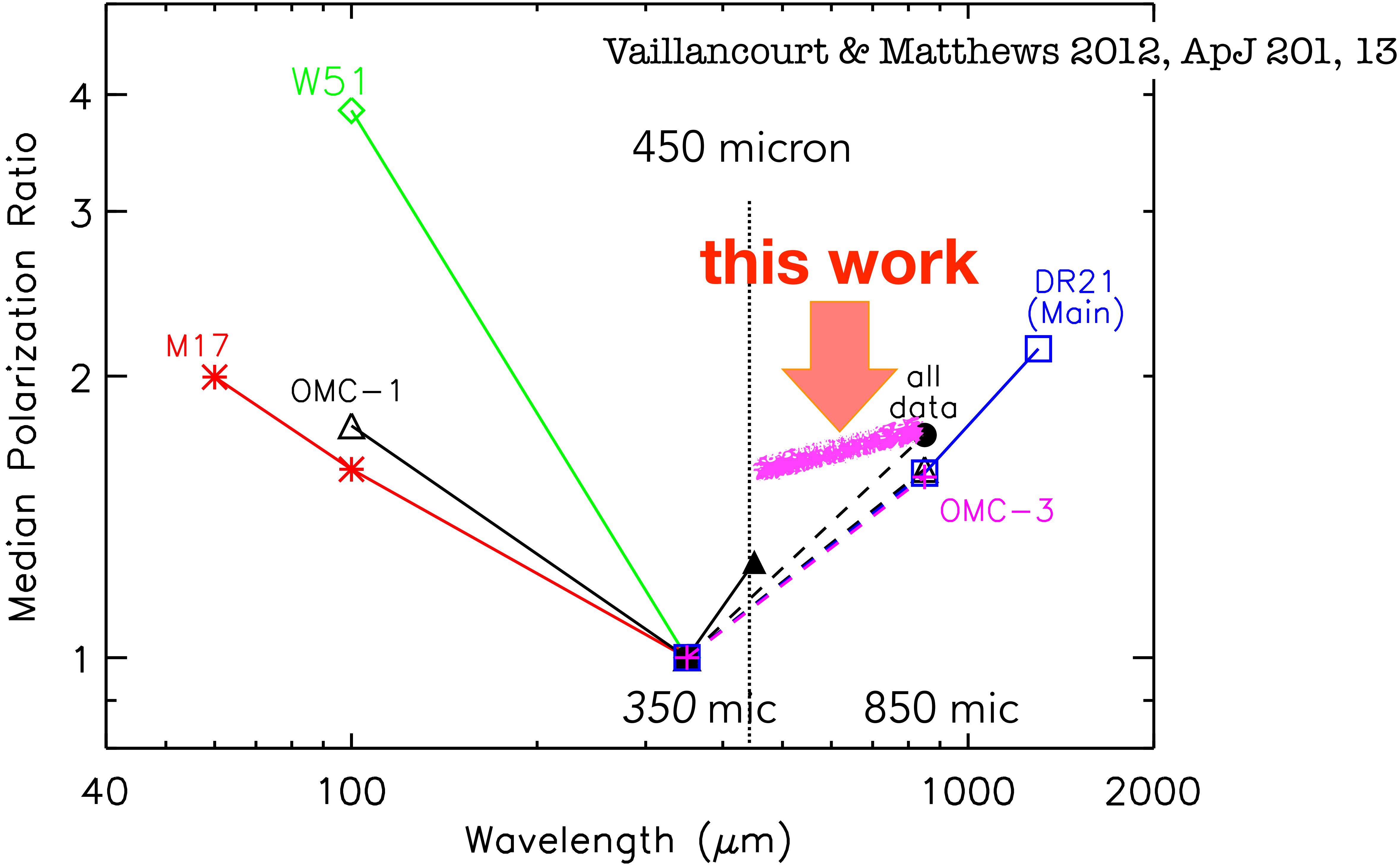




How vectors are selected?

- $I/\Delta I > 10$ and $PI/\Delta PI > 3$, and vectors whose directions agree within errors

Polarization spectra



BISTRO measurements toward Ophiuchus A reconciles with VM2012,
but shallower than their results. ***Could be flat in cloud's periphery?***

Summary and future works

450 micron observations: methodology

- The 3rd generation instrumental Polarization (IP) model of the telescope is verified via scientific analysis
- The new capability allows to explore *B*-field structure towards the innermost dense regions with an angular resolution of 7″

First look of Ophiuchus A 450 micron data

- **Polarization Angles:** Caught the *B*-field structure down to ~1e3 AU scale — corresponding to N~1e24 cm^{-2} region —- which maintains coherency from the pc-scale one.
- **Polarization Fractions:** Observed polarization properties may be explained w. Radiative Alignment Torque paradigm. But, "What causes the anti-correlation between P and N?" and "What is a general pol. spectrum?" may be studied using pol. spectra(um).