Introduction

Analyzing POL-2 data

POL-2 850 micron maps

POL-2 sensitivity

850 μm vs. 450 μm maps

Summary

Polarization imaging: lessons learned and wishes for future instrumentation

Ray S. Furuya (U. Tokushima, Japan)

B-field and polarimetry: questions to be addressed

- *B* fields are detected via polarimetry towards any astronomical objects.
- **What is the origin of *B* fields?**

Are there primordial B fields or are they produced by astrophysical process?

B-field and polarimetry: questions to be addressed

Center of gravity can be defined

Primordial

Circumstellar ***B***

Primordial

Circumnuclear ***B***

Interstellar ***B***

Intergalactic ***B*** field

Primordial?, astrophysical process? or both?

Center of gravity cannot be defined

B field structure of a cloud: 10-pc scale down to 0.001 pc

Planck 850 μm

BISTRO 850 μm

Interstellar *B*

Circumstellar *B*

Interstellar *B*

Circumstellar *B*

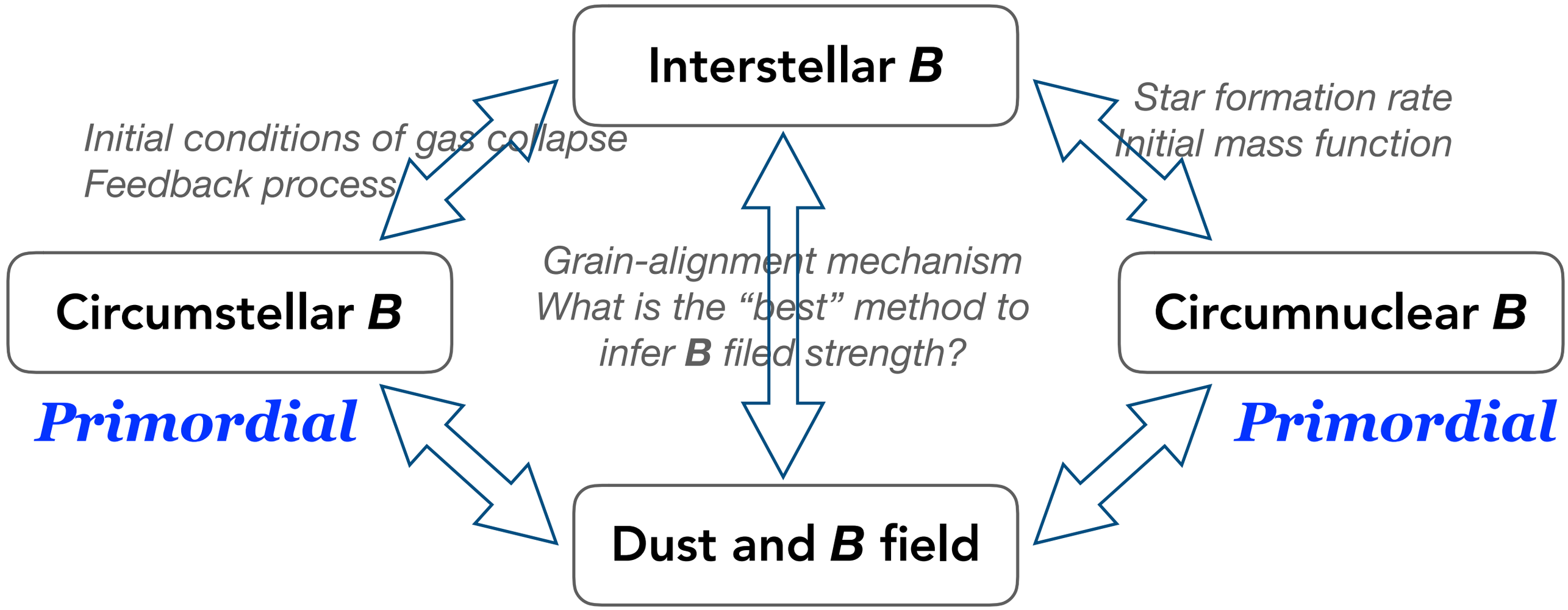
CARMA 1 mm

Planck, BISTRO data: **Y. Doi**, RSF et al. 2019, in prep.

CARMA data: Hull et al. 2014

B-field study with POL-2: questions to be addressed

Primordial?, astrophysical process? or both?



In most astrophysical process, *B* fields are passive in dynamics, however, *B* fields play significant roles in some stages.

At what *evolutionary stage*, over what *spatial scale*,

or/and over what *density range* do B field is playing key role?

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**,

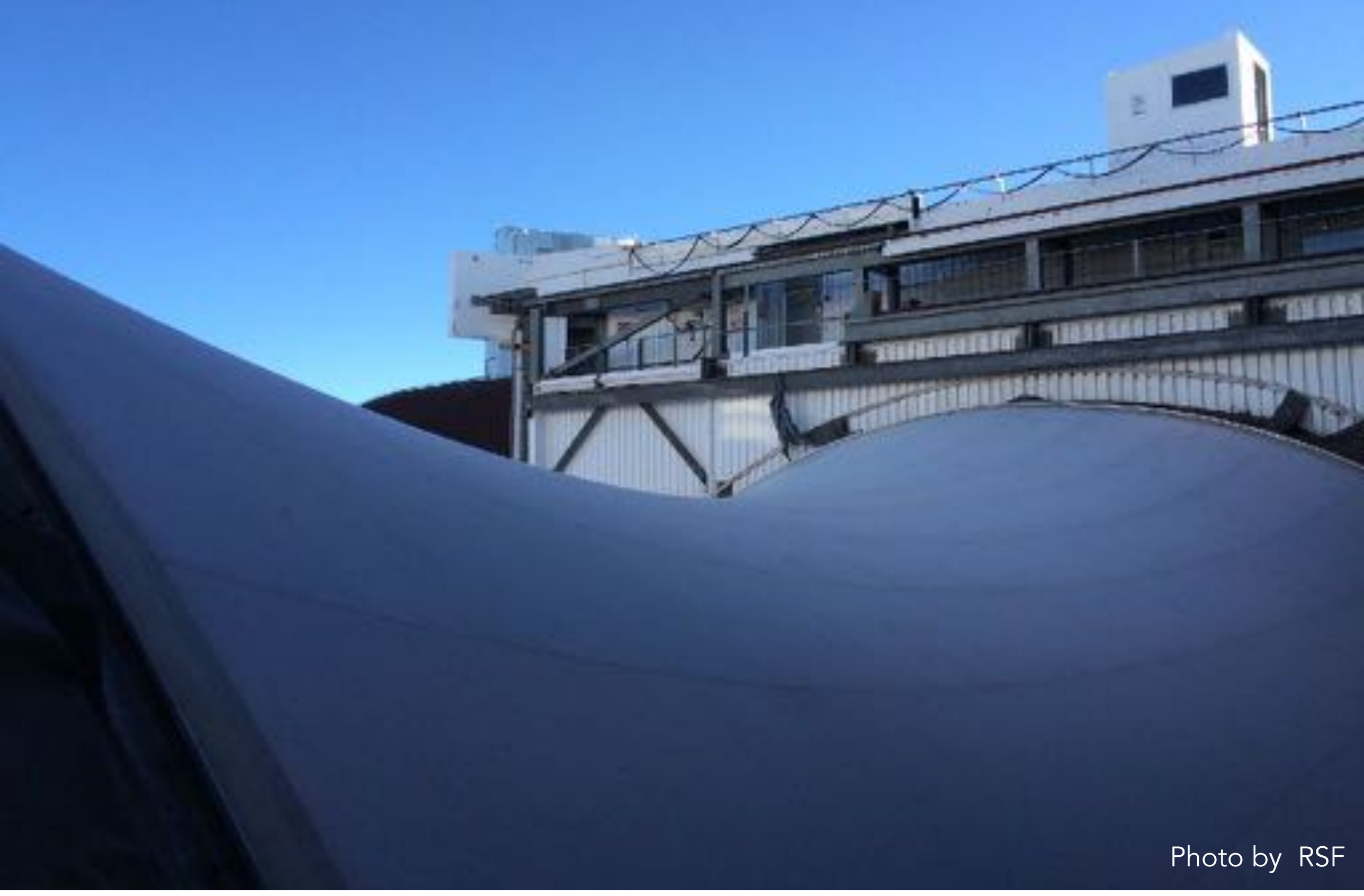
    e.g., Zeeman effect, maser, laser, Goldreich-Kylafis effect

- **Polarization caused in radiative transfer process**

  - 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

Path



Analyzing POL-2 data

Data and data reduction

- **Tried to reduce the accessible data** taken between 2015 and 2019 April
  - **450 micron** data are limited to those **taken under τ_{225}<0.04**

- **Successfully reduced,**
  - Twenty-eight 450-micron observations (including 21 BISTRO targets)
  - Forty-three 850 micron observations (including 23 BISTRO targets)

- **Data reduction**
  - Starlink 2019-02-05 version (not the faster PCA version)
  - **12** Linux machines — CPU 3 GHz 16 cores, memory = 256 Gb at **NAOJ**
  - Tried pixel sizes of 4 and 12 arcseconds
  - Data volume and required scratch area
    - Rawdata = 5.5 Tb, Starlink scratch area = 4.1 Tb for BISTRO data
    - Rawdata = 2.1 Tb, Starlink scratch area = 1.5 Tb for non-BISTRO data

I greatly appreciate ADC!!

Data reduction procedure

1. **Reduced 850 micron** data pol2map pipeline

2. **Reduced 450 micro** data using the 850 map as a reference map, yielding a **common** pixel gridding

3. Convolved 450 um data with **a single-gaussian-beam** so that the dual-band data have **the same beam size**

4. Produced

   (a) Pol. intensity (*PI*), pol. fraction (*P*), pol, angle (*PA*) maps

   (b) Vector catalogues

   (c) House keeping, e.g., verification, various images statistics

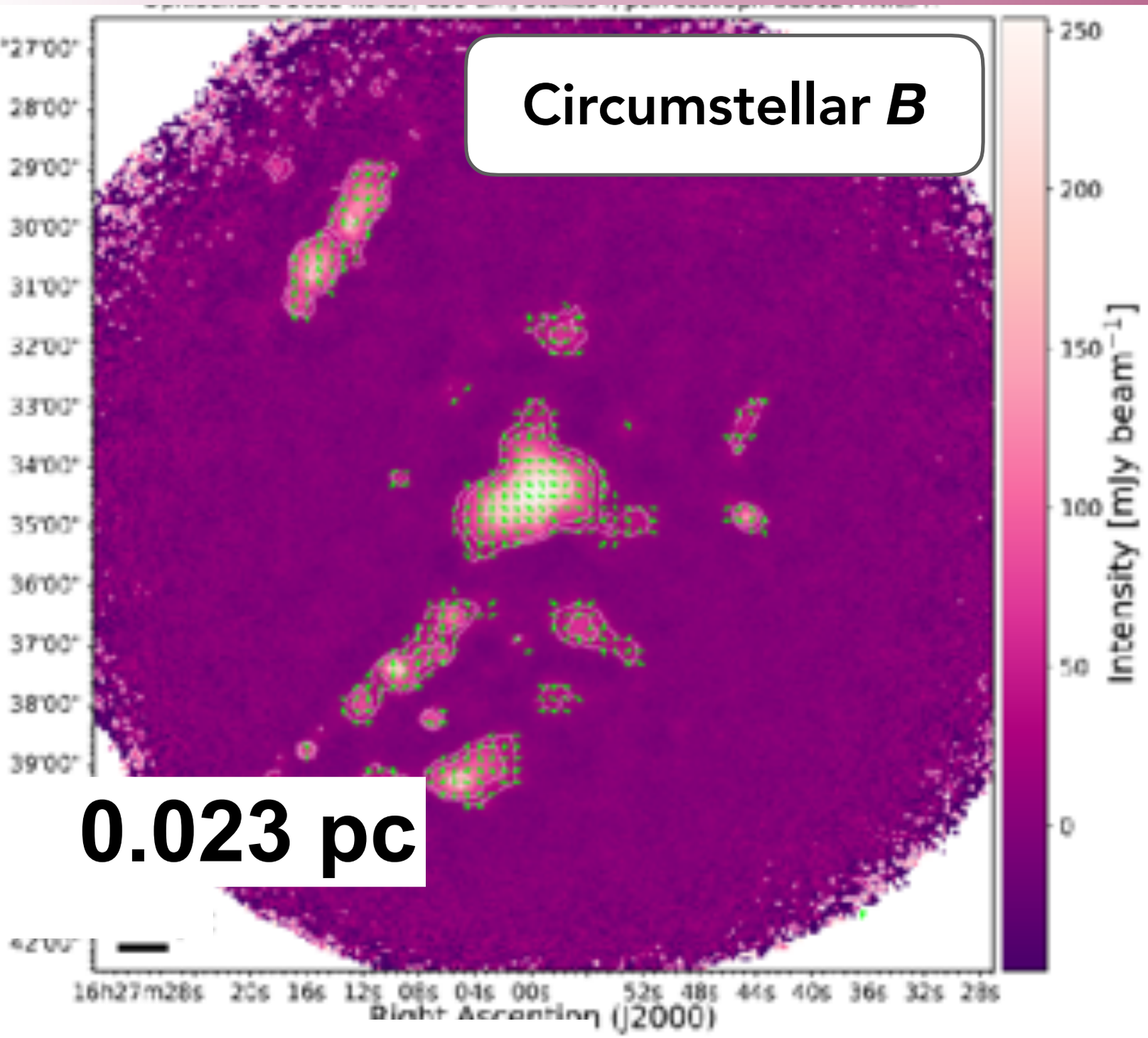
5. Vector catalog matching between the 450 and 850 data

6. Image display

Photo by RSF

POL-2 maps

What we would see with 10-times higher scan speed ?



***d* ~ 120 pc**

What are presented here?

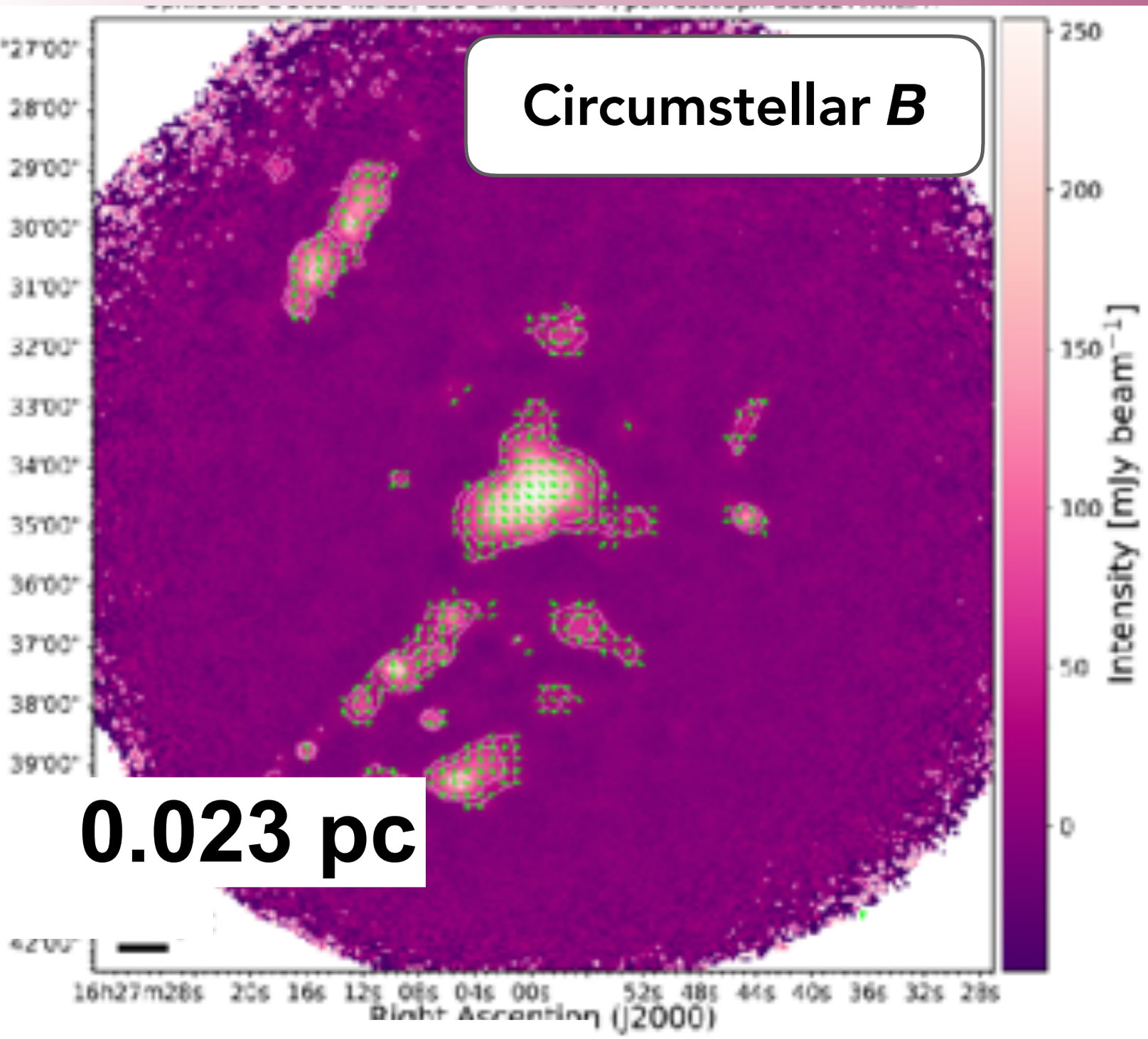
- **Data**: 850 micron
- **Image**: Stokes *I*
- **Contour**: 90% percentile of Stokes *I*
- **Vectors**: rotated 90 deg, shown w. identical length to see directions

How vectors are selected?

- A **threshold** of ***I*/Δ*I* > 10 only,** so as **not to miss intrinsically-weak** polarization

Liu, …, RSF et al. 2019, ApJ, in press.

What we would see with 10-times higher scan speed ?



Because of,

the Eq. below,

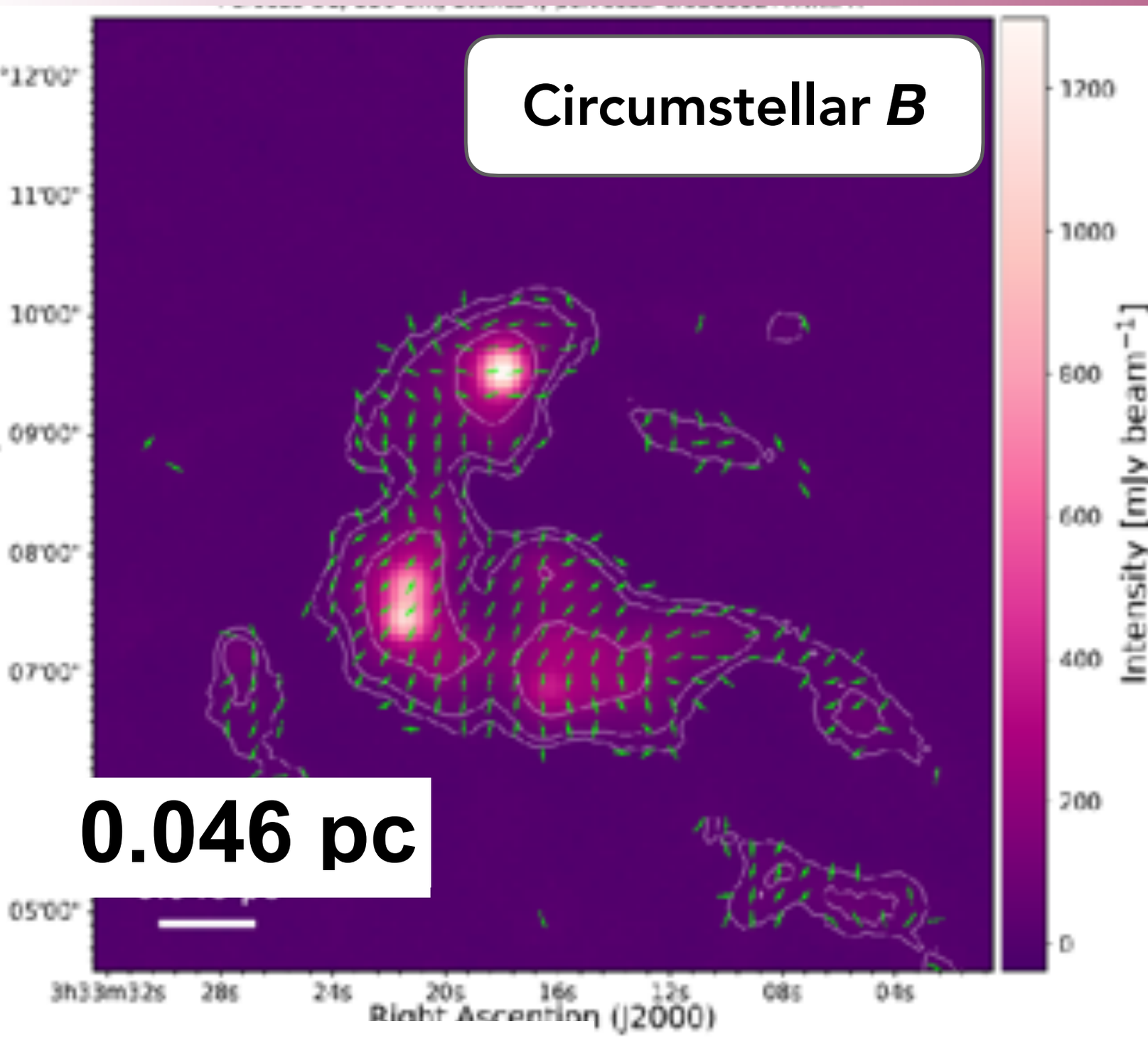
we do not see polarization structure of the **inter-core gas**, **i.e., *B*-field structure inside filaments.**

With the new camera, we would detect them toward the nearest low-mass star-forming region(s).

***d* ~ 120 pc**

$$\text{Largest detectable size [radian]} = \frac{\text{Scan velocity [radian Hz]}}{\text{Frequency cut [Hz]}}$$

What we would see with 10-times higher scan speed ?



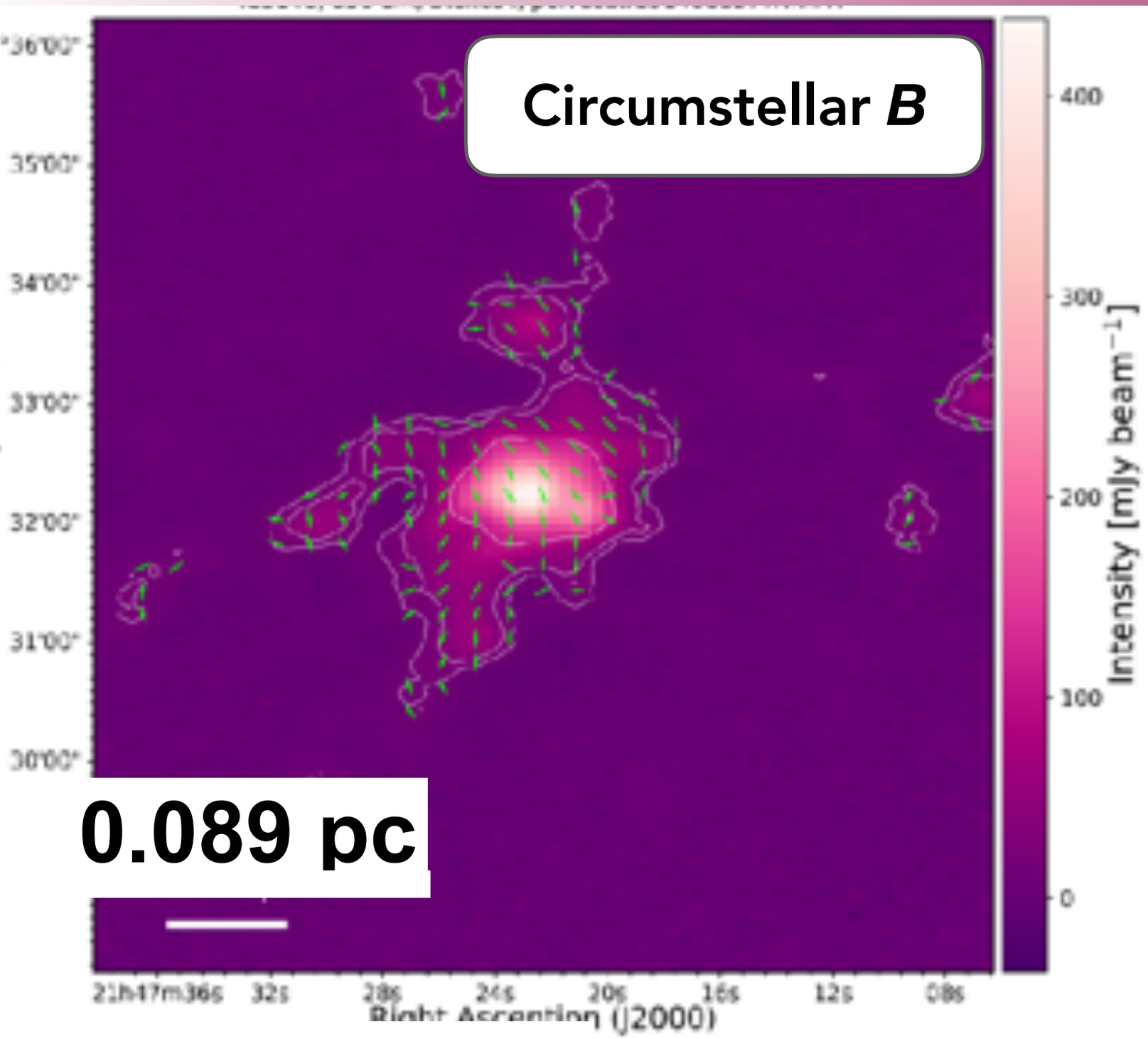
***d* ~ 230 pc**

Because we already see "**partially resolved-out**" filaments towards a few SFRs **w. POL2,** we may see their ***overall structure*** toward the nearby low-mass star-forming region(s).

With **an enhanced sensitivity**, **striations** may be detected in pol.

Coude, …, RSF et al. 2019, ApJ, in press.

What we would see with 10-times higher scan speed ?

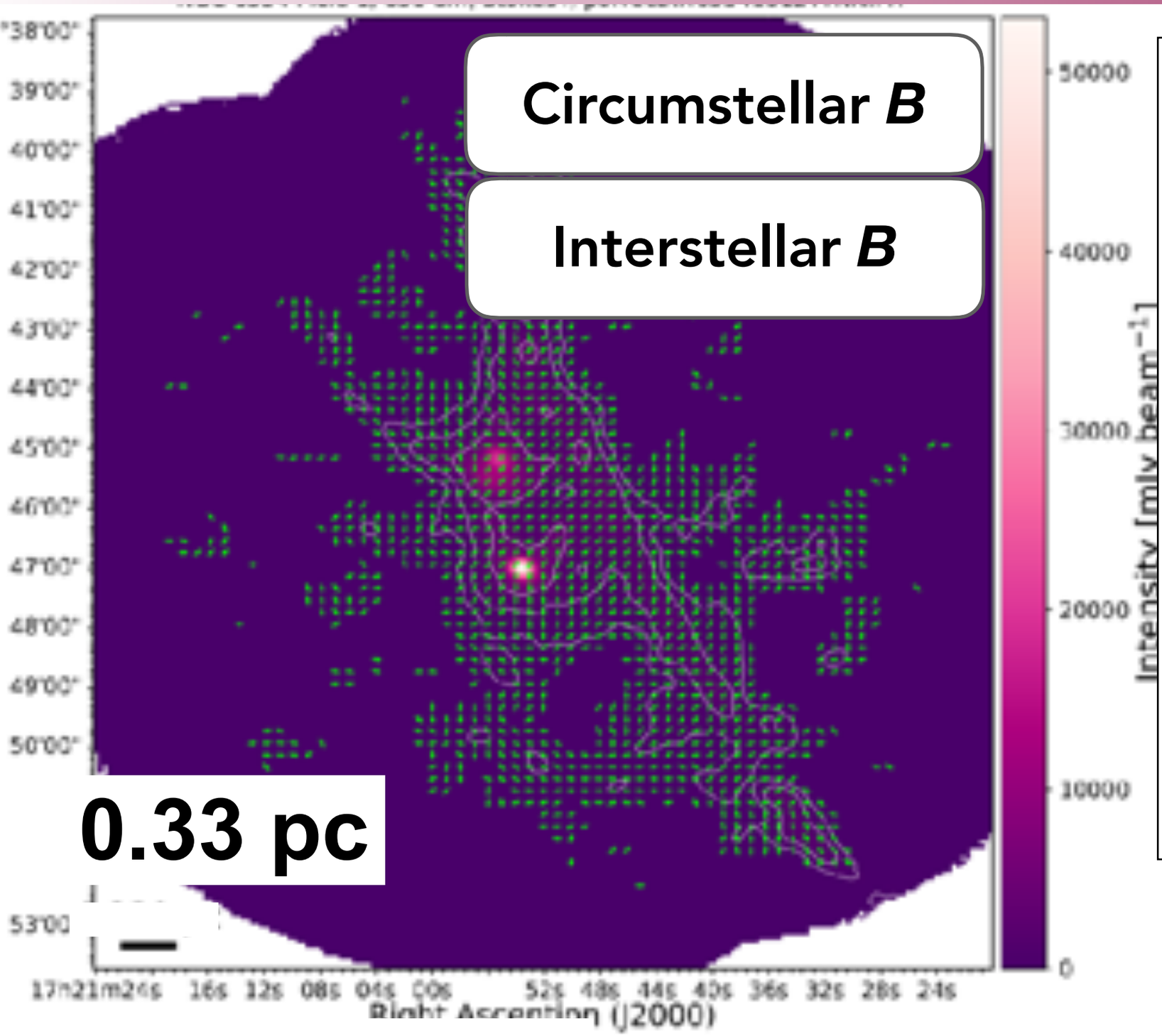


***d* ~ 460 pc**

Because we already see "**partially resolved-out" filament-and-hub structure** toward a few SFRs, we may see their ***overall structure and associated filaments/ striations*** toward the more distant star-forming region(s).

Wang, …, RSF et al. 2019, ApJ, in press.

What we would see with 10-times higher scan speed ?

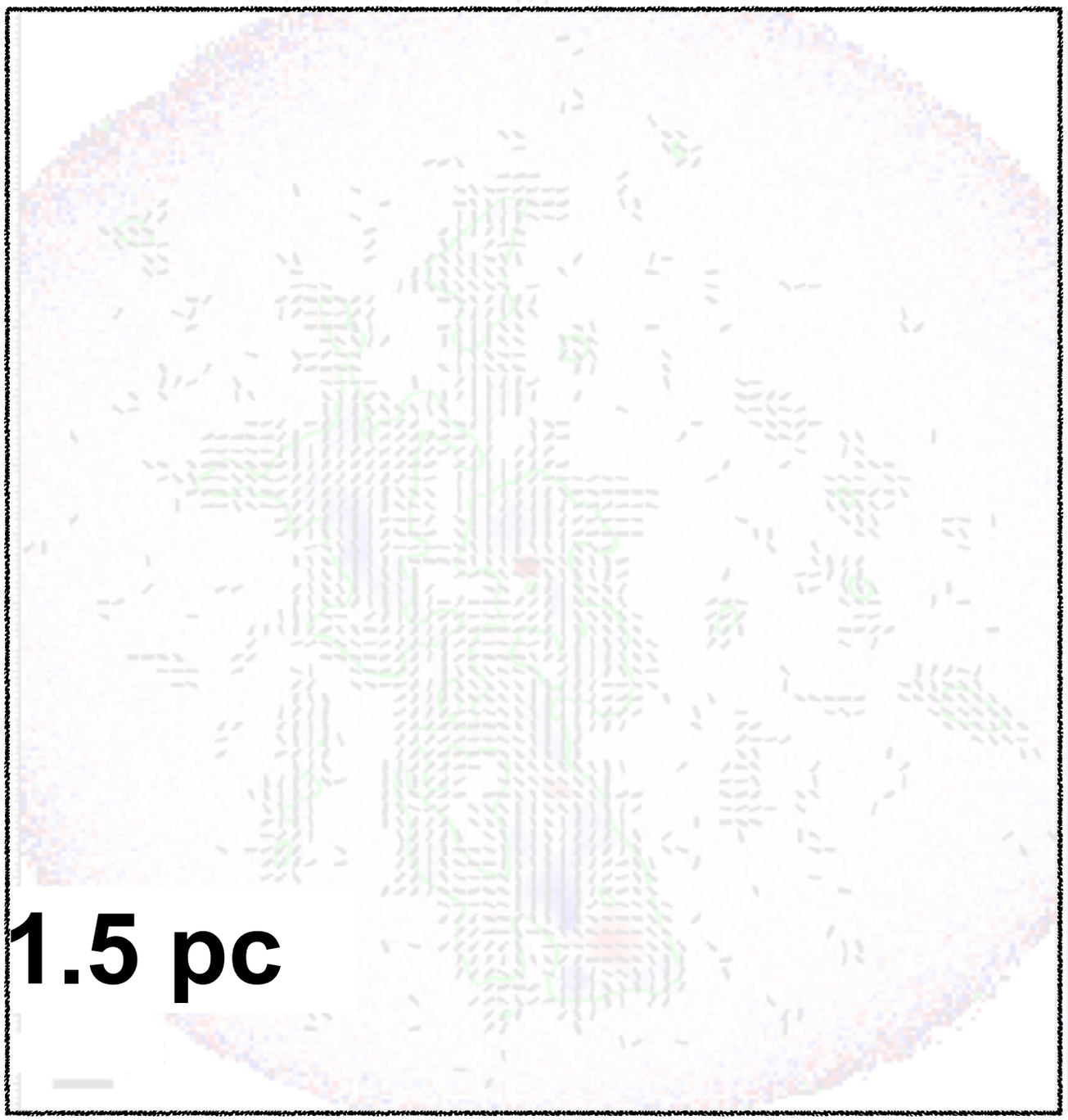


***d* ~ 1700 pc**

Because we already see "**partially resolved-out" clump-core-filament system** toward a few **massive SFRs**, we may see their ***overall structure of them*** toward the **distant high-mass** star-forming region(s) w. the new camera.

Arzoumanian, RSF et al. in prep.

POL-2 give us Stokes *Q* and *U* maps!



Circumnuclear ***B***

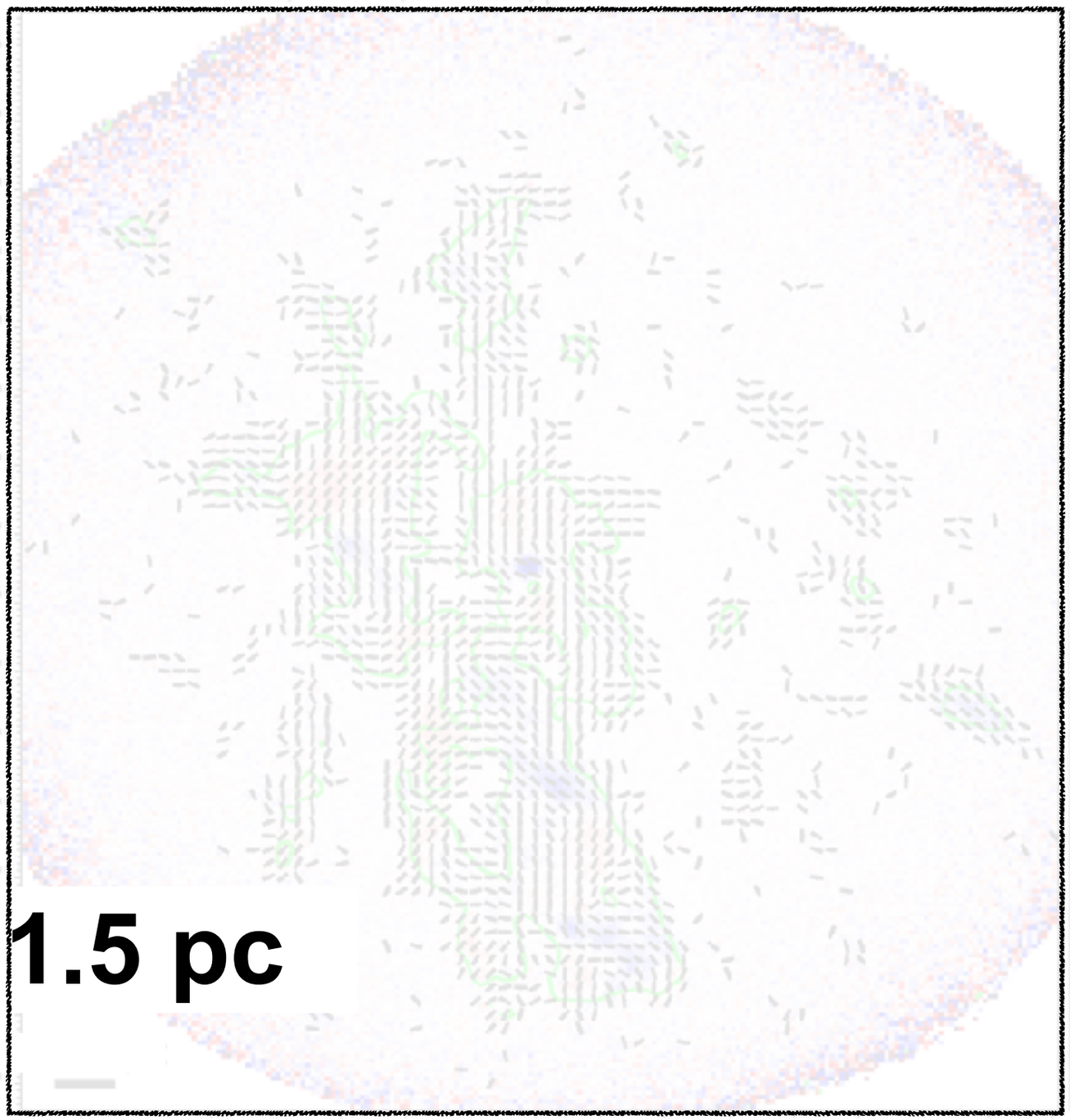
Interstellar ***B*** ?

d **~ 78600 pc**

Stokes *Q*

Project code #M17AP074.

POL-2 give us Stokes *Q* and *U* maps!



Circumnuclear *B*

Interstellar *B* ?

***d* ~ 78600 pc**

Stokes *U*

Project code #M17AP074.

Stokes *Q* and *U* yield polarized intensity, *PI* map

Sorry that I forgot to bring the PI image of the G.C. in my laptop!!

Circumnuclear *B*

Interstellar *B* ?

Polarized intensity, $PI = \sqrt{Q^2 + U^2}$, always takes positive value.

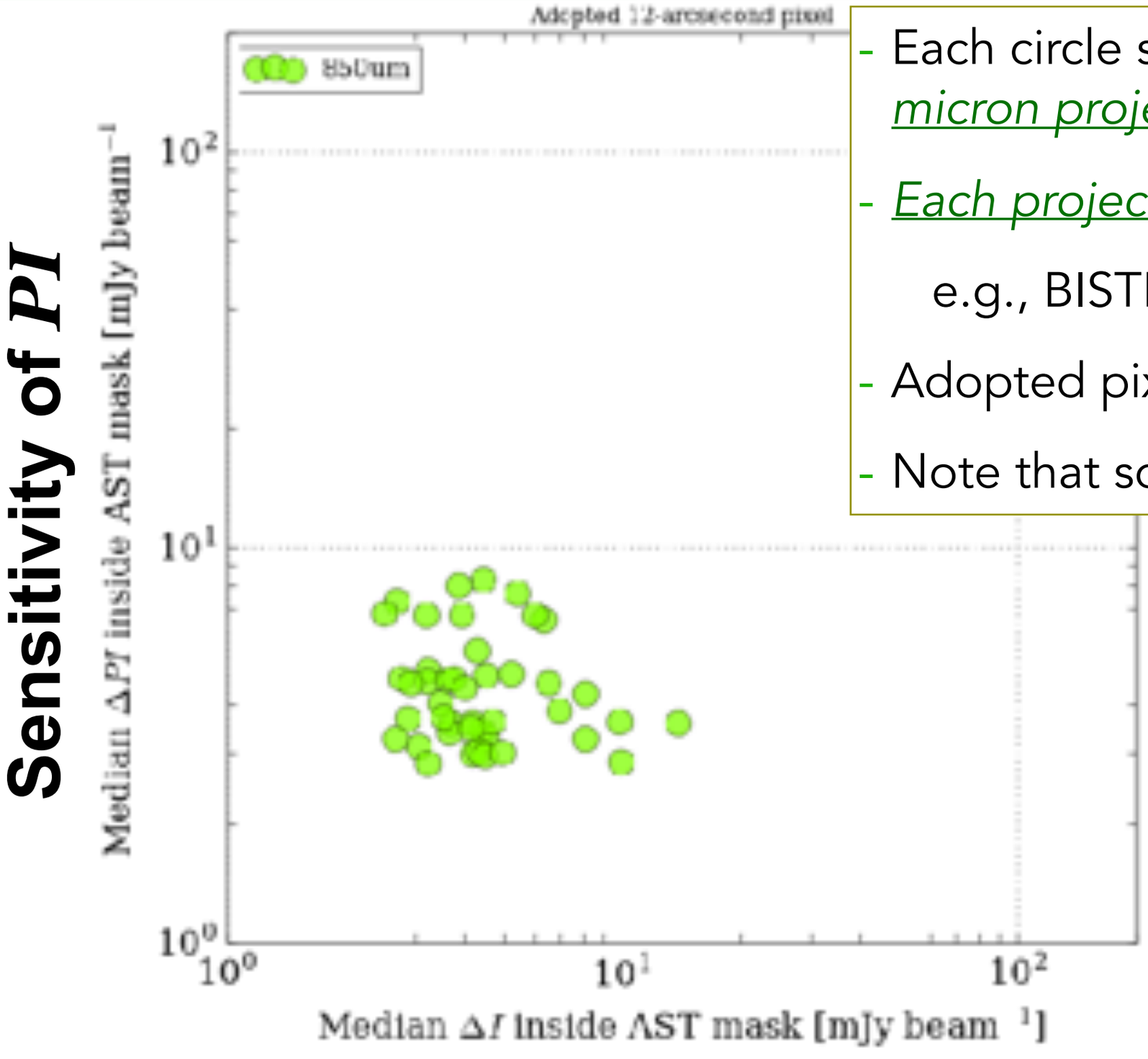
PDF of Δ*PI* : Rice distribution

Project code #M17AP074.

Photo by RSF

POL-2 sensitivity

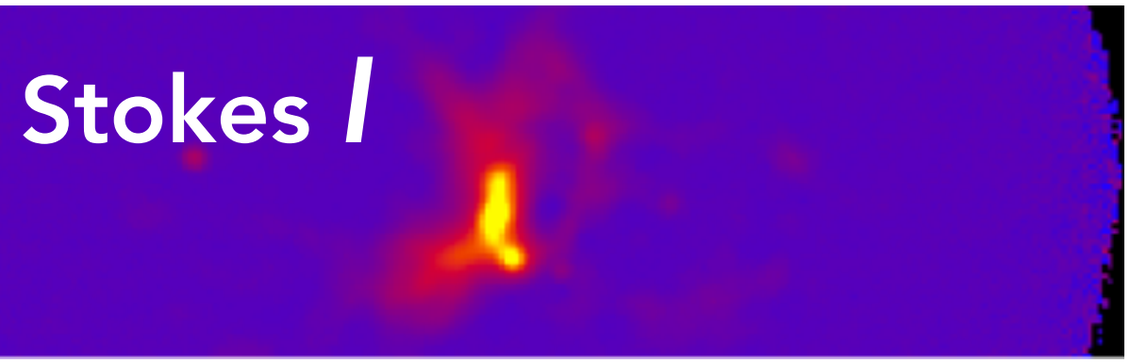
Sensitivity of POL-2 maps in Stokes *I* vs. *PI*

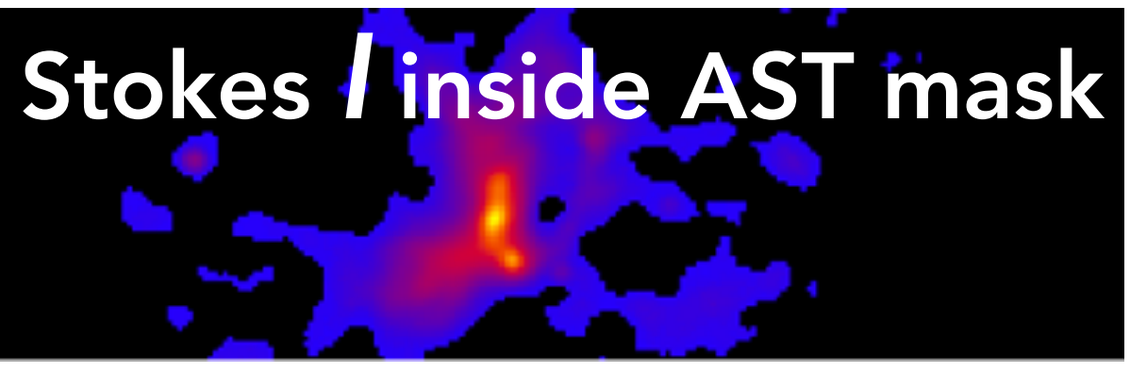


- Each circle shows sensitivity of *each 850 micron project.*
- *Each project* has T [min/obs] x n [obs]

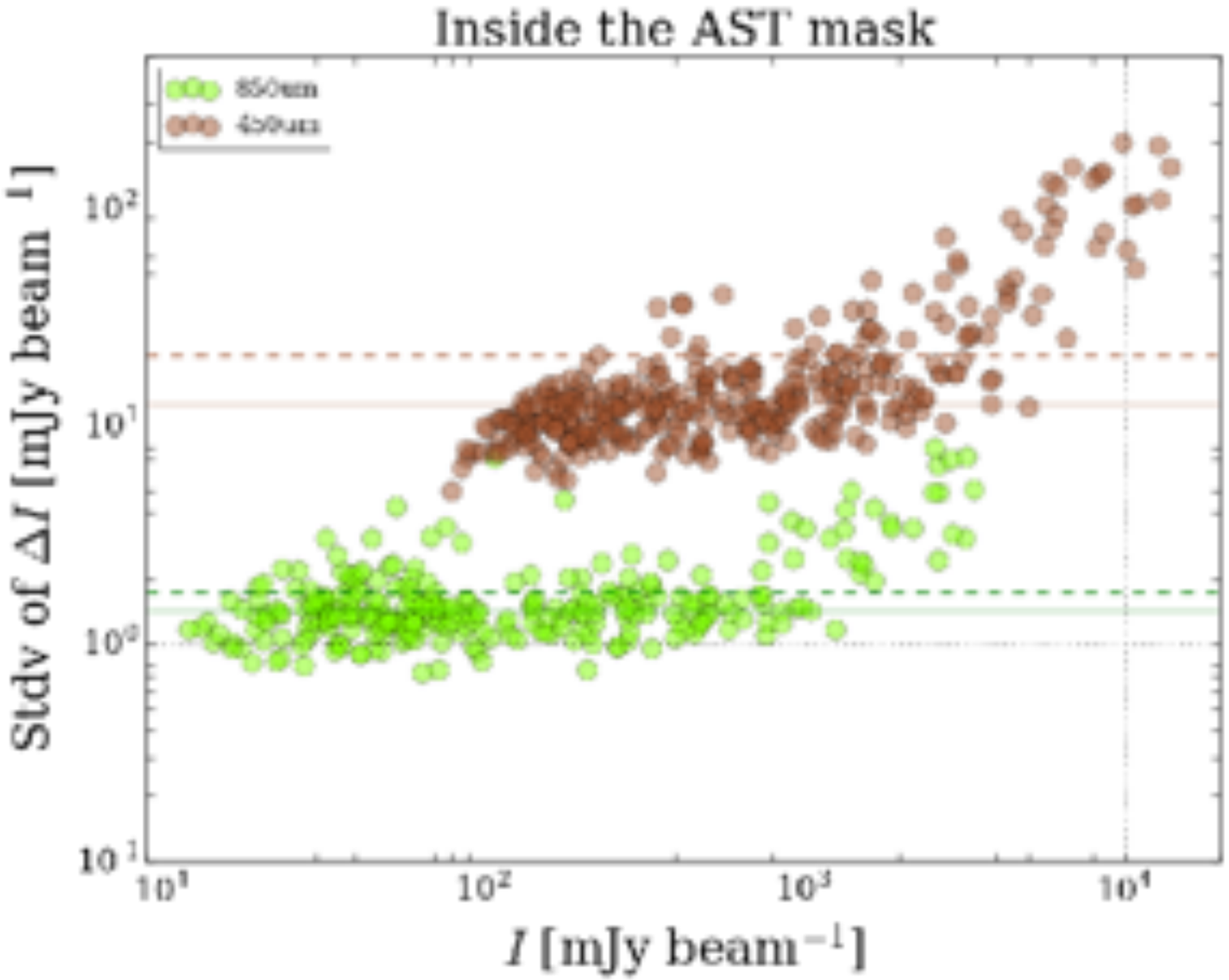
  e.g., BISTRO: 40 [min/obs] x 20 [obs].
- Adopted pixel size of 12″
- Note that some projects are still ongoing

How to get the sensitivity?

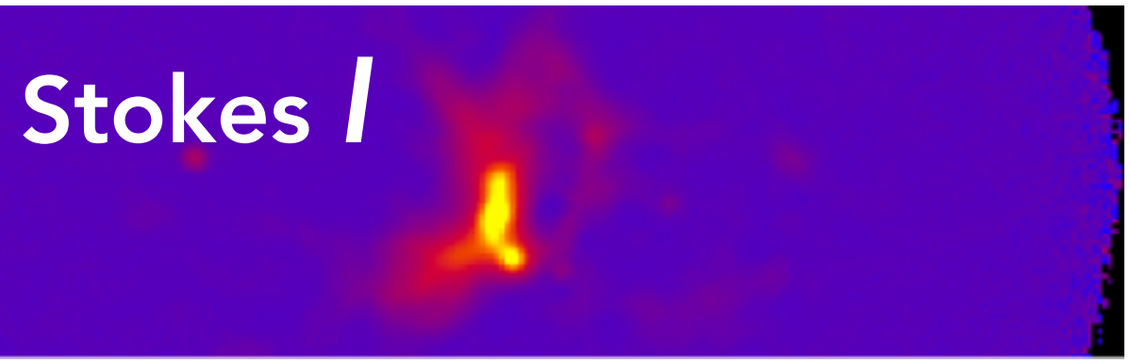


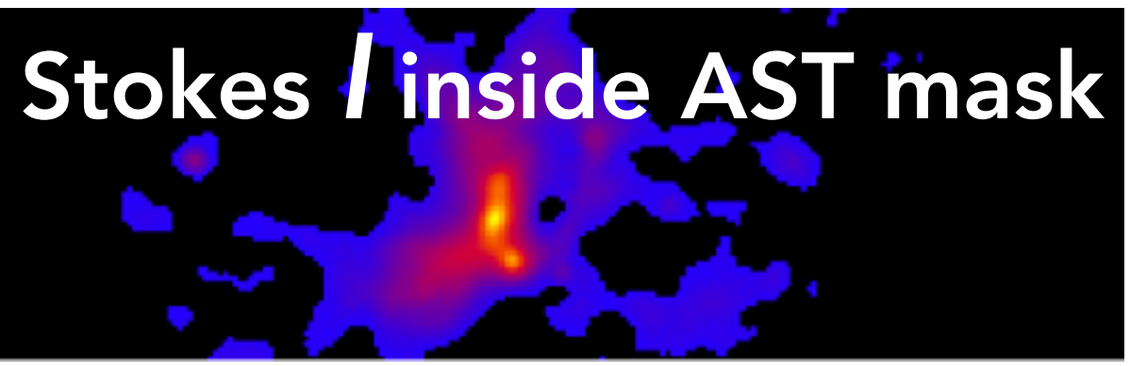


Variance of *DI* inside AST mask



How to get the sensitivity?





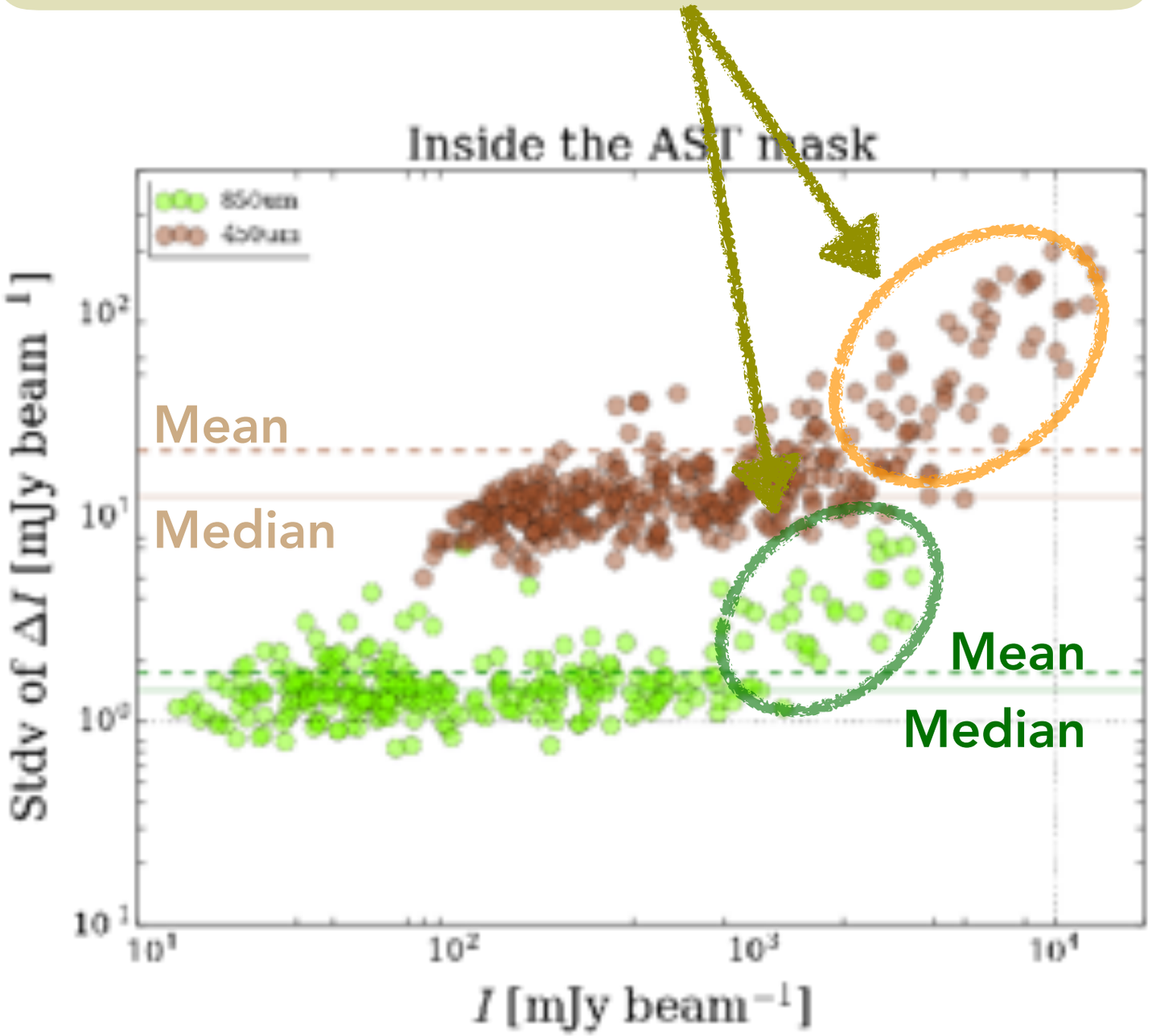
Variance of *DI* inside AST mask

Due to *e.g.*,

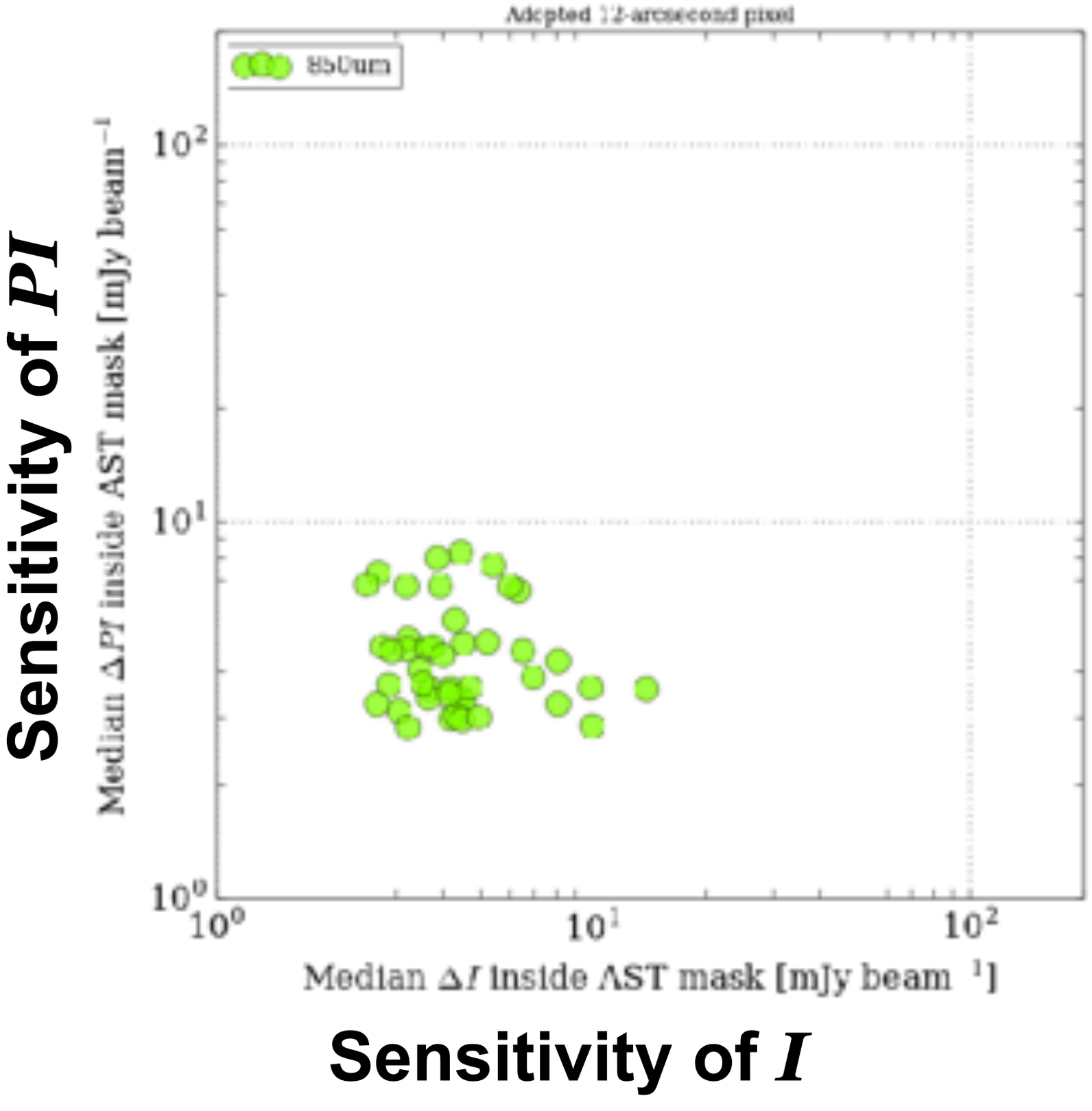
Time variation of atmospheric opacity?

Uncertainty of instrumental polarization model?

→ *Needs to monitor time variation during exposure*

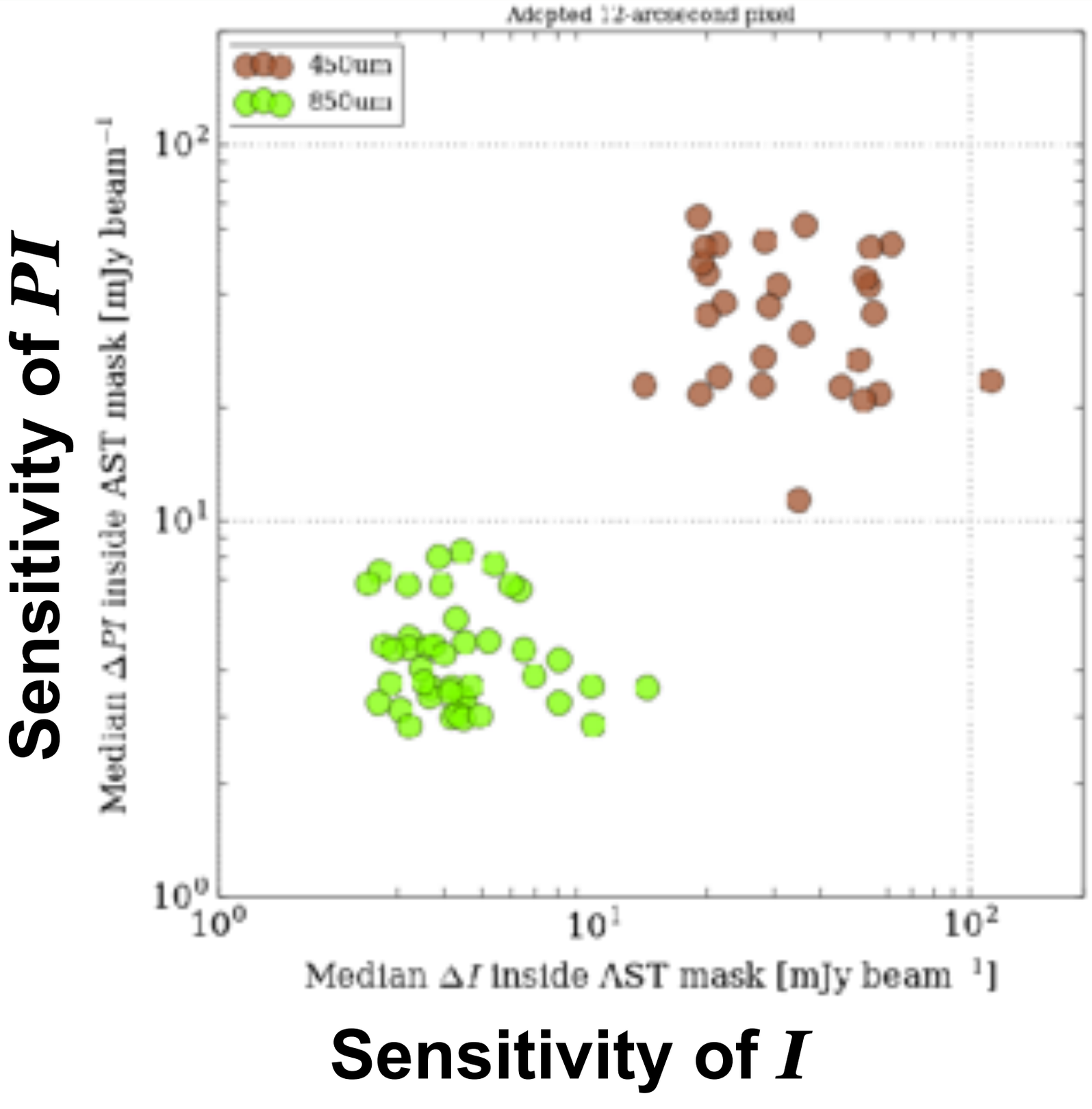


Sensitivity of POL-2 maps in Stokes *I* vs. *PI*



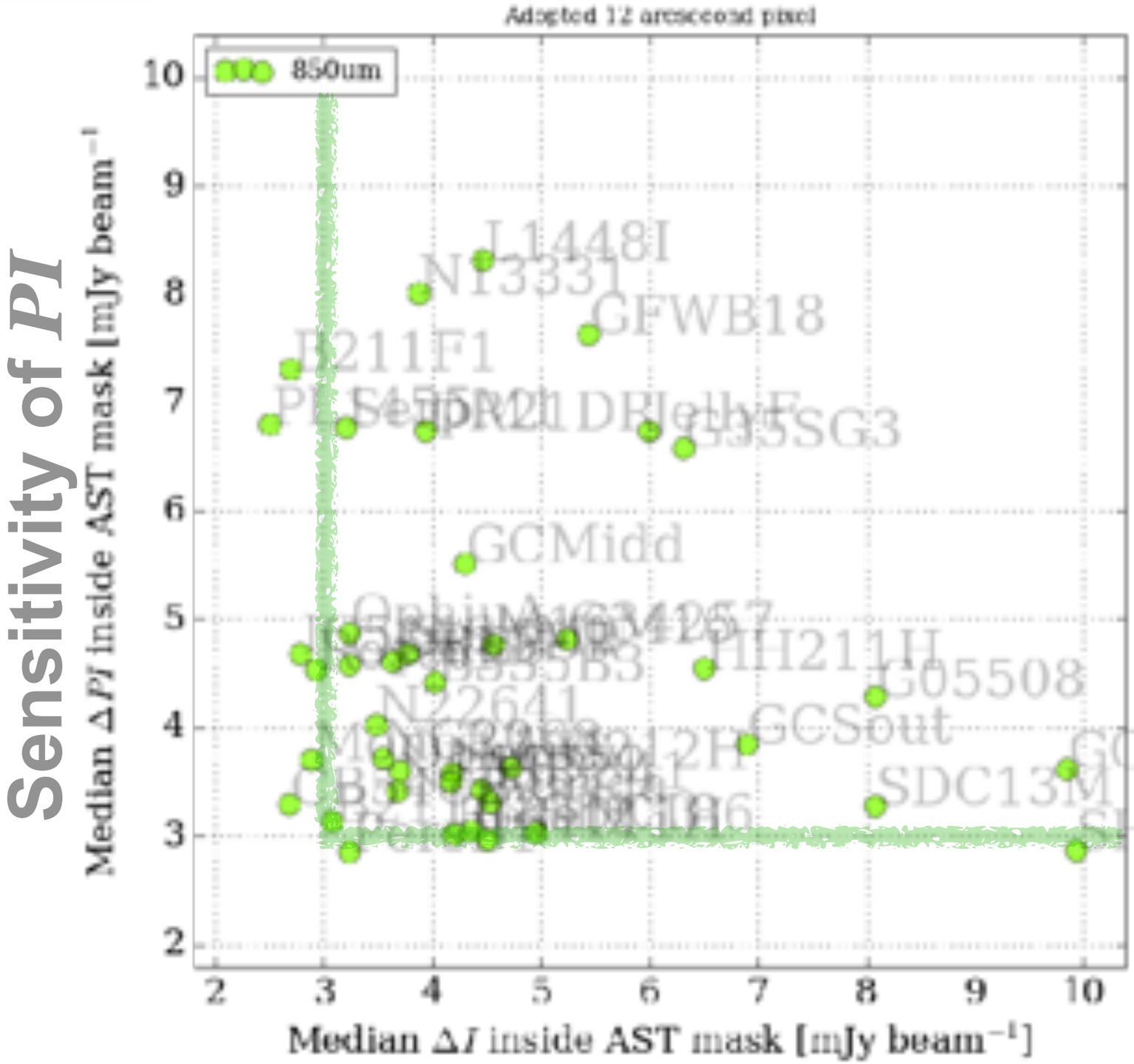
- **Green** circles show sensitivity of ***each*** *850 micron* ***project****.*
- Adopted pixel size of 12” for the dual bands
- Note that some projects are still ongoing

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



- Green and brown circles show sensitivity of ***each*** ***850*** *and* ***450 micron*** ***project****, respectively.*
- Adopted pixel size of 12" for the dual bands
- 450 micron data were convolved so that they have 14" aperture
- Note that some projects are still ongoing

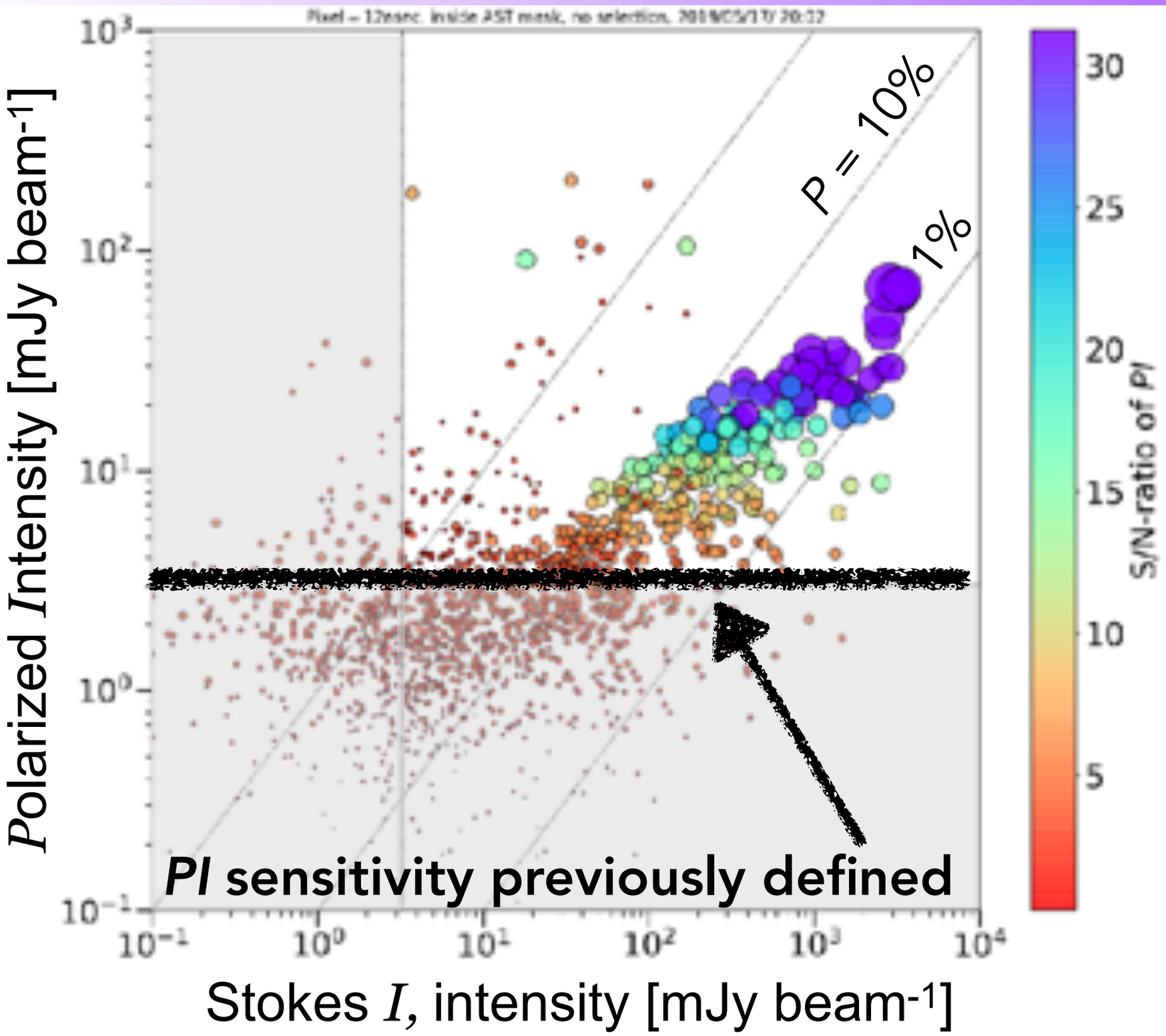
850 um sensitivity of POL-2 maps in Stokes *I* vs. *PI*



- Green circles show sensitivity of *each 850 micron project*.
- Adopted pixel size of 12″ for the dual bands
- **Note that some projects are still ongoing**

A *horizon* of 850 um POL2 image may be ~3 mJy per 14″ beam w. 12″ pixel in *I* and *PI*.

Oph A 850 μm data inside AST mask: Stokes *I* vs. *PI*



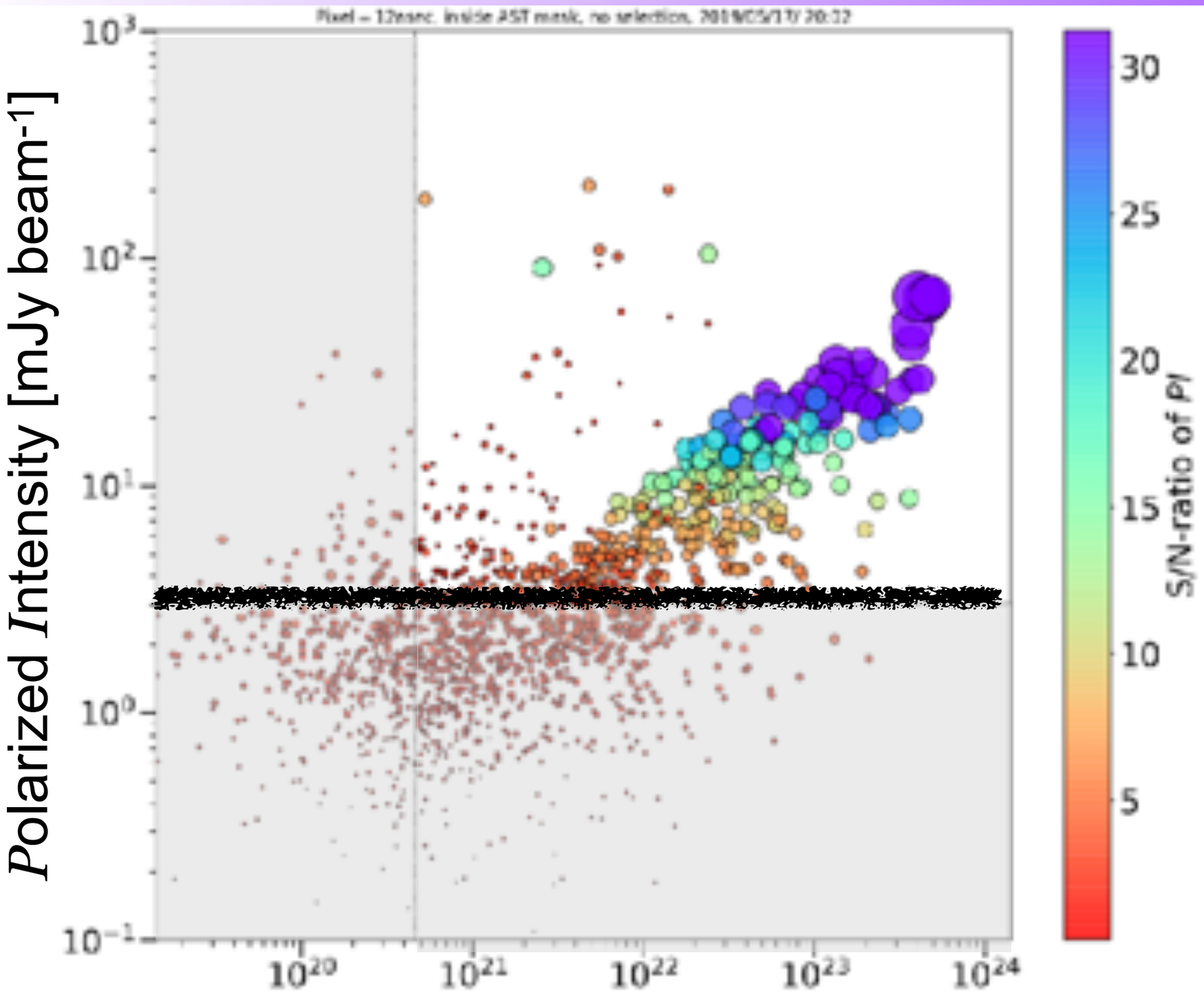
- Each circle presents measurements w. 12-arcsec pixel **inside the AST mask** of **a source**.
- All data are plotted, i.e., **no data clipping**
- Color represents S/N ratio of polarized intensity, *PI*.

Polarization fraction,

$$P = \frac{PI}{I}$$

RSF+ in prep, see J. Kwon, …, RSF et al. 2018

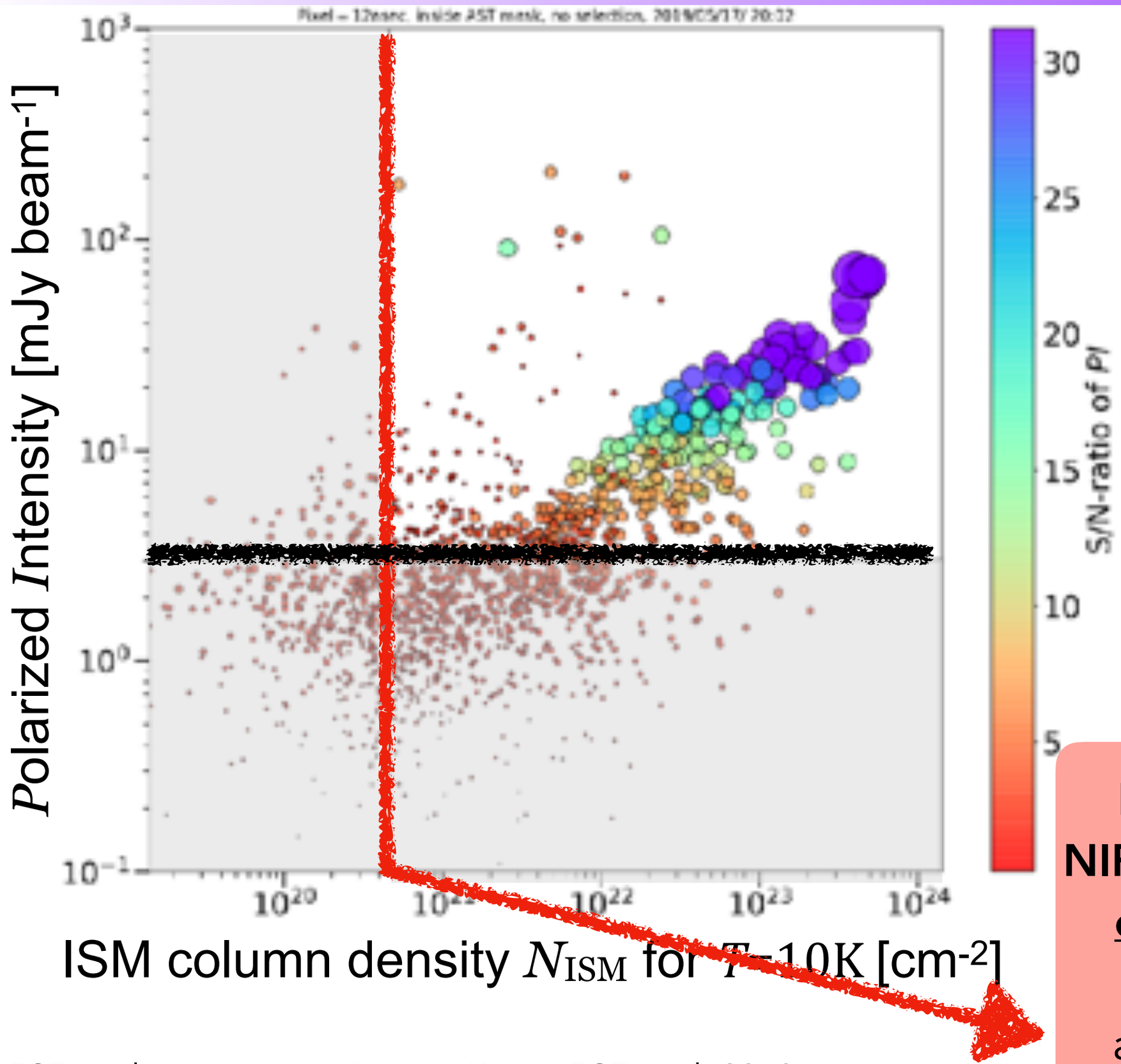
Oph A 850 μm data inside AST mask: N_{ISM} vs. *PI*



- Each circle presents measurements w. 12-arcsec pixel **inside the AST mask** of **a source**.
- All data are plotted, i.e., **no data clipping**
- Color represents S/N ratio of polarized intensity, *PI*.
- Horizontal axis is converted to $N_{\rm ISM}$ with **fiducial values** of κ and β. **No temperature distribution was considered**. So pls think the $N_{\rm ISM}$ values as **an approximation**.

RSF et al. in prep, see Jungmi Kwon, RSF et al. 2018

Oph A 850 μm data inside AST mask: N_{ISM} vs. *PI*



- Each circle presents measurements w. 12-arcsec pixel inside the AST mask of **a source**.
- All data are plotted, i.e., no data clipping
- Color represents S/N ratio of polarized intensity, *PI*.
- Horizontal axis is converted to $N_{\rm ISM}$.

DIRECT comparison w. **NIR** extinction polarimetry is **<u>currently only</u>** possible toward a few "lucky" positions.

RSF et al. in prep, see Jungmi Kwon, RSF et al. 2018

Photo by RSF

Do we really need 450 um?

Caught pol. structure even toward highest N_{ISM} regions!

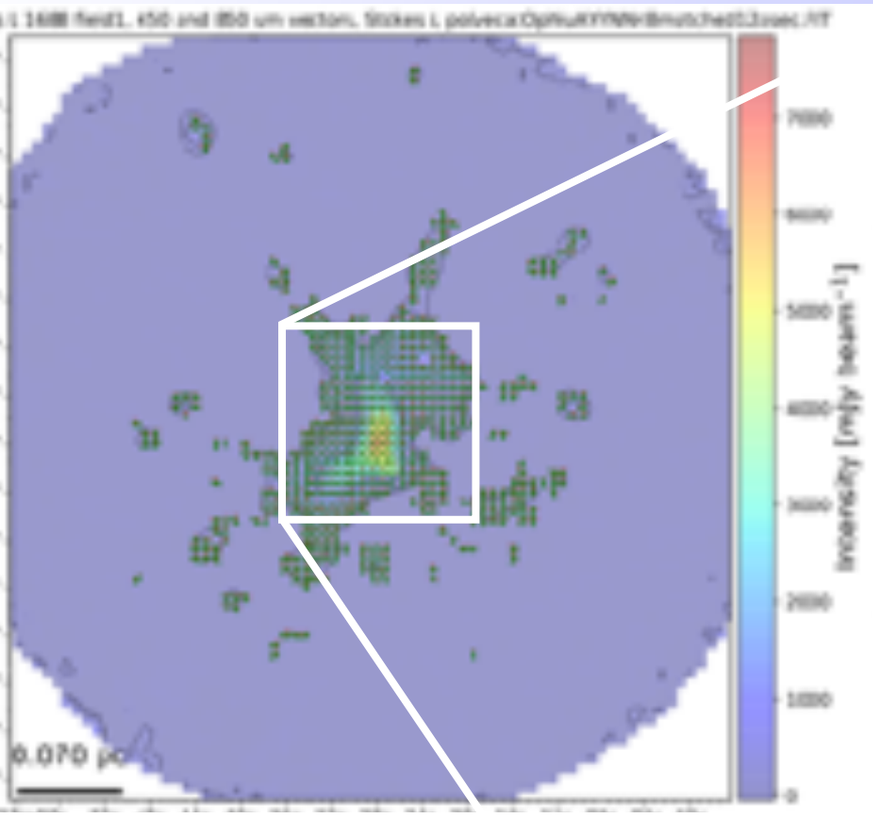
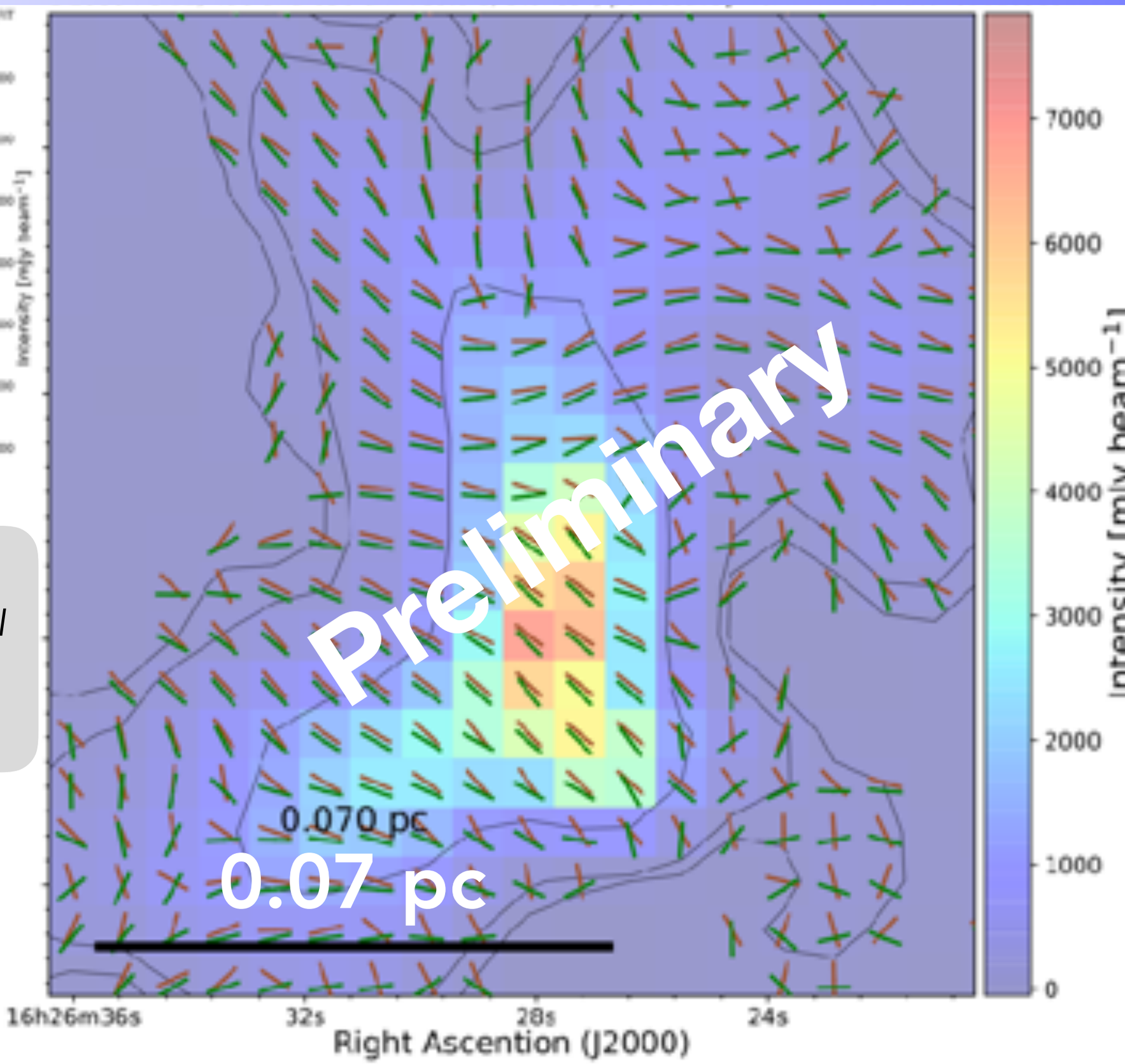


Image: 450 micron Stokes *I*
Contour: 90% percentile of *I*
Brown vectors: 450 micron
Green vectors: 850 micron



RSF et al., in prep

Caught pol. structure even toward highest N_{ISM} regions!

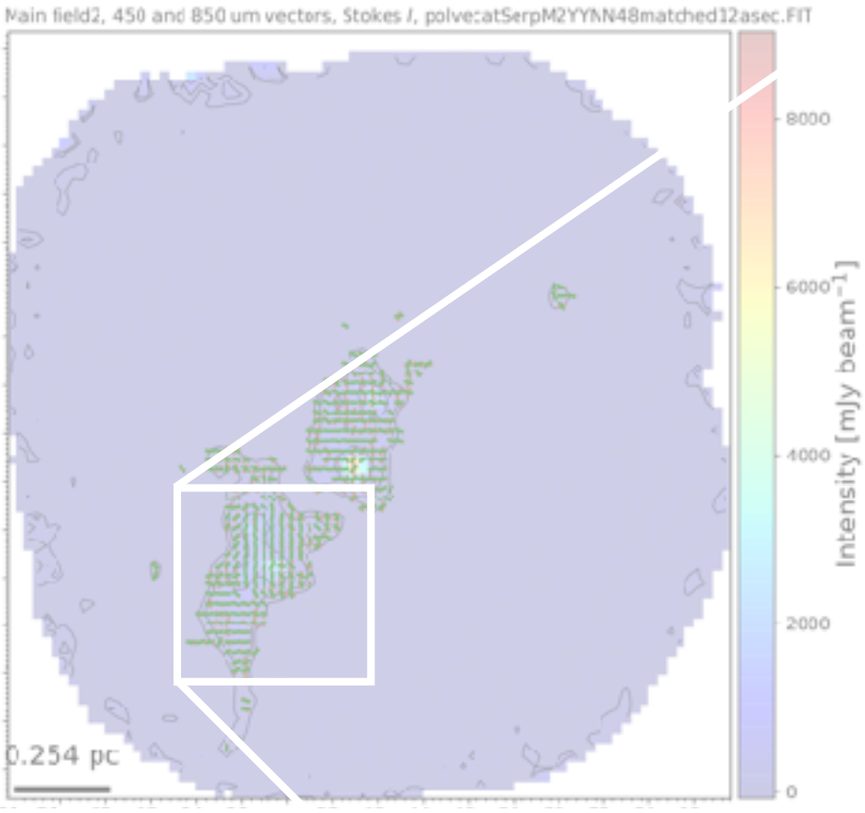


Image: 450 micron Stokes *I*
Contour: 90% percentile of *I*
Brown vectors: 450 micron
Green vectors: 850 micron

0.25 pc

W. Kwon, …, RSF et al., in prep

Caught pol. structure even toward highest N_{ISM} regions!

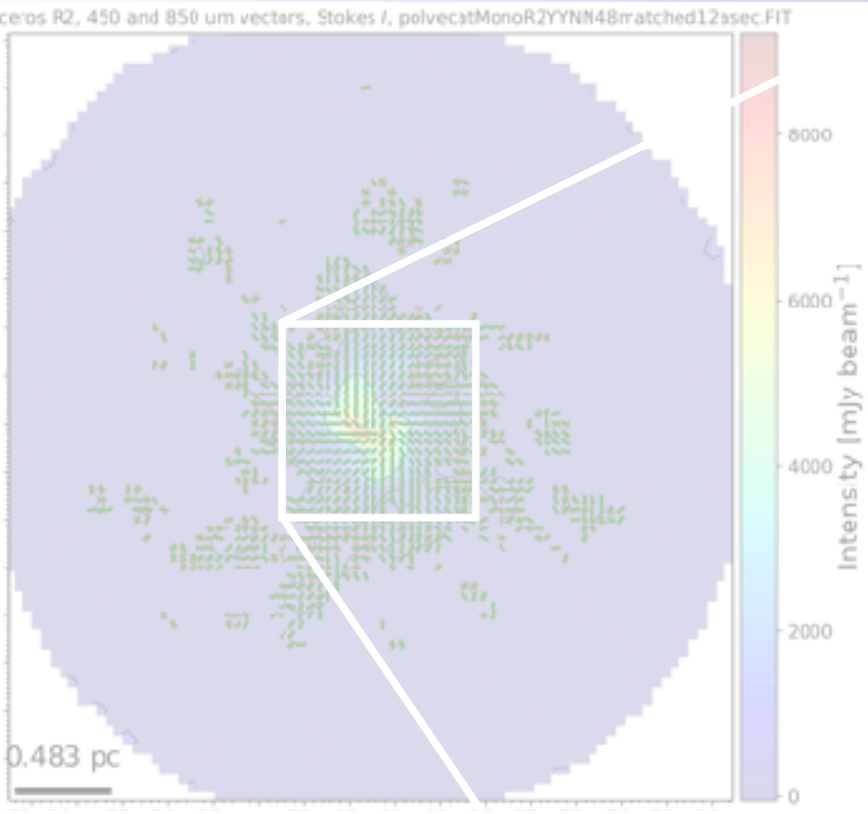


Image: 450 micron Stokes *I*
Contour: 90% percentile of *I*
Brown vectors: 450 micron
Green vectors: 850 micron

0.48 pc

J. Hwang, …, RSF et al., in prep

Caught pol. structure even toward highest N_{ISM} regions!

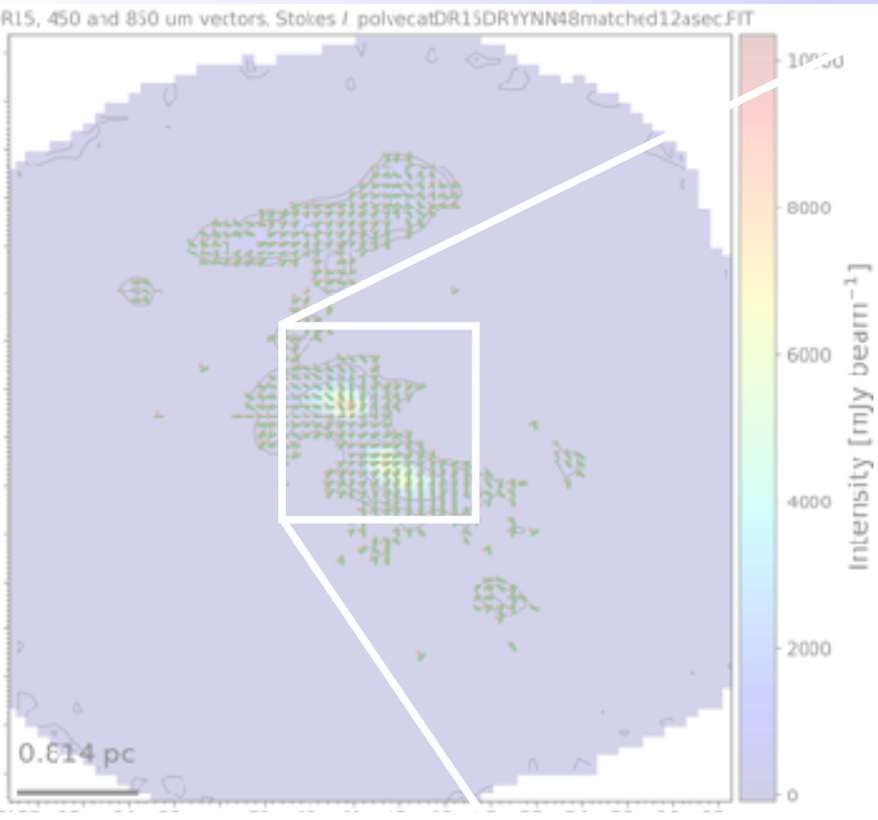


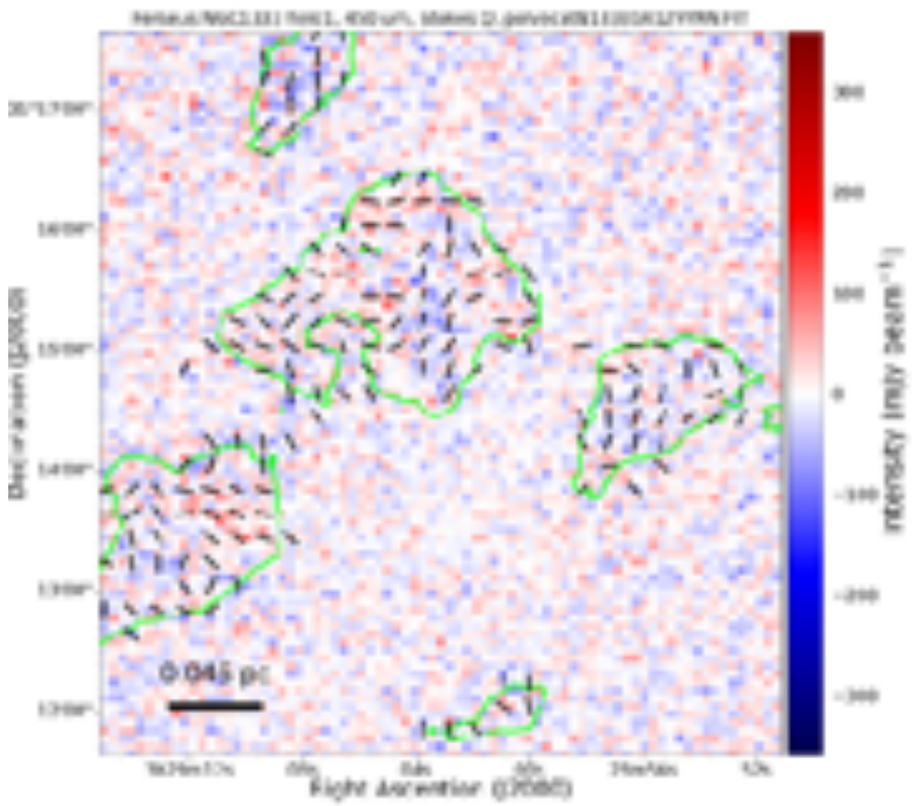
Image: 450 micron Stokes *I*
Contour: 90% percentile of *I*
Brown vectors: 450 micron
Green vectors: 850 micron

0.61 pc

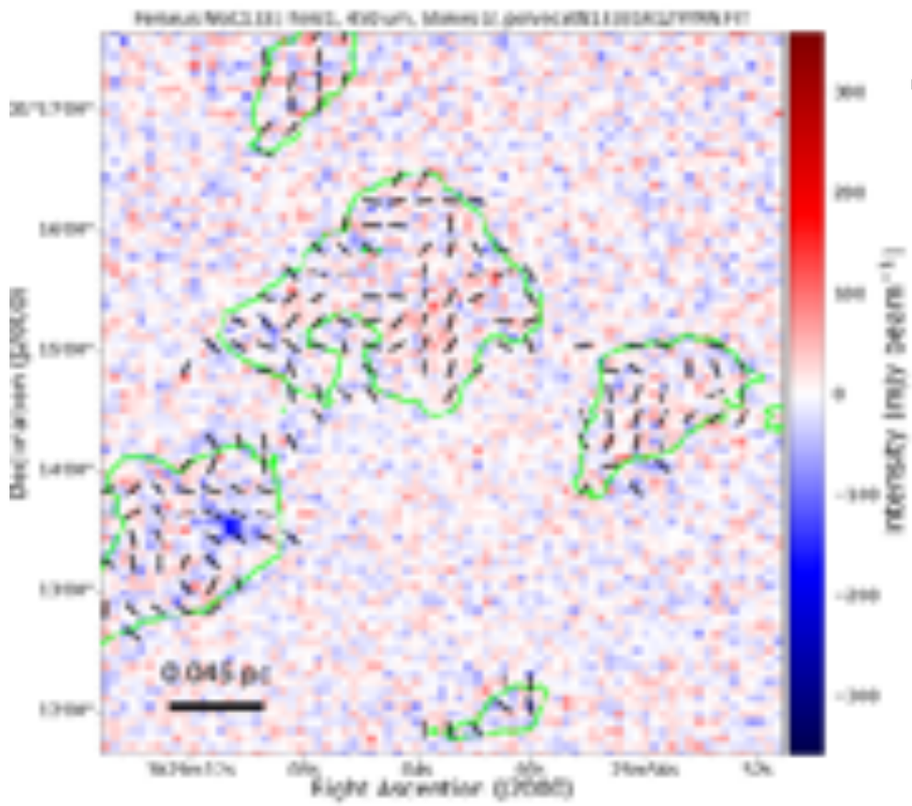
BISTRO Taiwan team, …, RSF et al., in prep

850 vs. 450 um maps: caught GK effect at 850 um?

450 *Q*

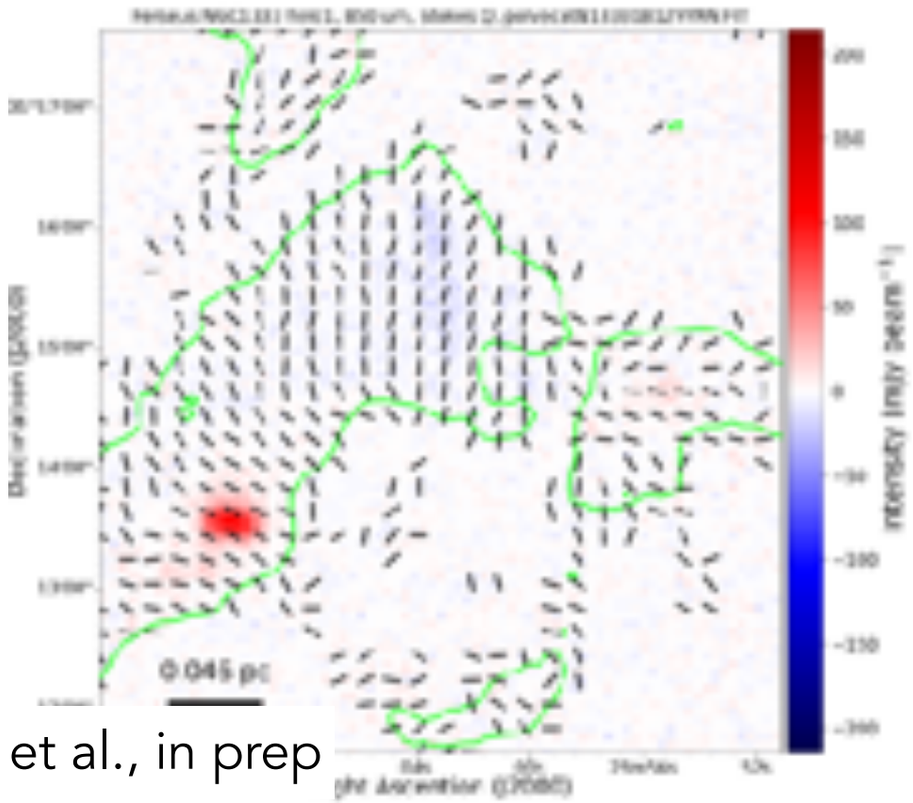


450 *U*

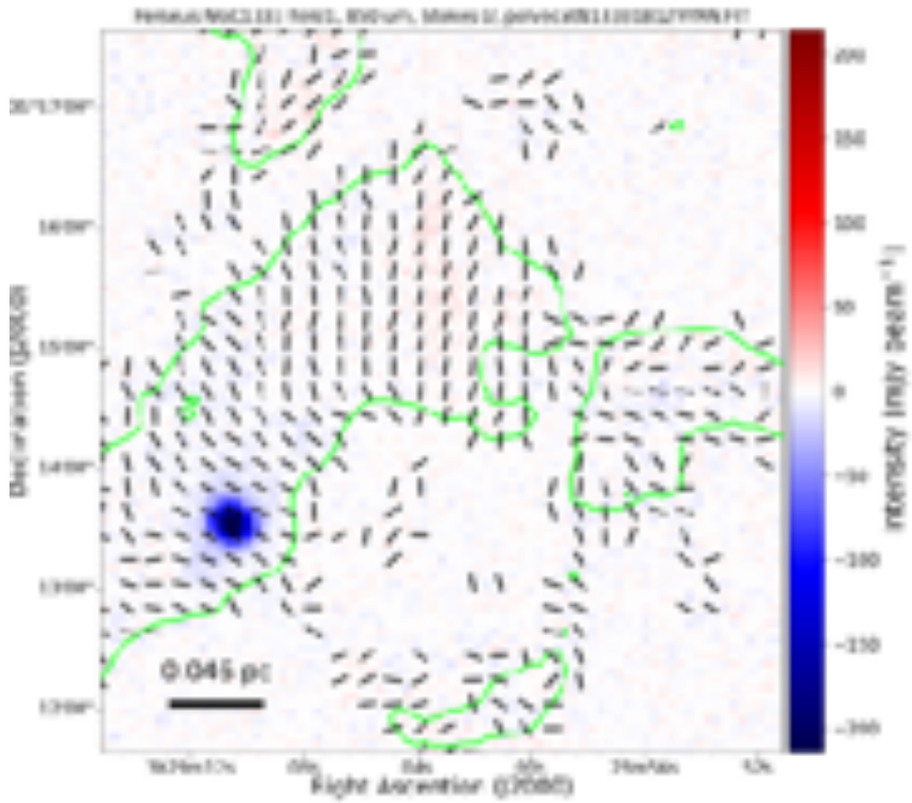


Note that ranges of the color bars do not match at the dual bands.

850 *Q*



850 *U*



Doi, …, RSF et al., in prep

The new camera is expected to link

Interstellar *B* with **Circumstellar *B***

The new camera should

- ✓ be **simple** design to get good IP correction
- ✓ be mappable **extended emission**
- ✓ be delivered to community in **timely manner**
- ✓ concentrate on **850 micron** only

Summary