

**0.01 pc scale view of  
Polarization (Magnetic?) Fields in  
Star Forming Regions**

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on behalf of Team BISTRO-J

# Outline of talk

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1. Motivations and Goals
2. POL-2 Data
3. Property of Submm Polarized Emission
4. Structure Function Analysis
5. Inside the Cluster: Ordered or Random?
6. A Comparison with Molecular Line Data
7. Future Works
8. Summary

# BISTRO Four-fold Immediate Objectives

## [1] フィラメント内の磁場構造は？

磁気圧優勢 → 揃った磁場

乱流優勢 → ランダムな磁場

磁気乱流の散逸とフィラメントの寿命の関係性は？

## [2] フィラメント内の磁力線と非球形の分子雲コアと磁場方向の相関は？

→ 分子雲コアの初期条件と境界条件(あわせて環境条件)を観測から提示したい。

→ 環境条件の多様性が星形成の多様性の起源だろうか？

## [3] 観測からフィラメントの圧縮史を読み取り, 理論は素過程の物理を提示し,

→ **フィラメント形成史は, 環境条件の多様性の起源だろうか？**

## [4] ハブで形成されている大質量分子雲コアの磁場環境は？

→ 星団形成を伴う大質量星形成の環境条件 → 星形成の多様性の起源解明に必要

# まとめ：本研究の狙いと究極のゴール

星の質量を決めるさまざまな過程のうち、  
主に磁場によって制御されている物理過程はどれか？

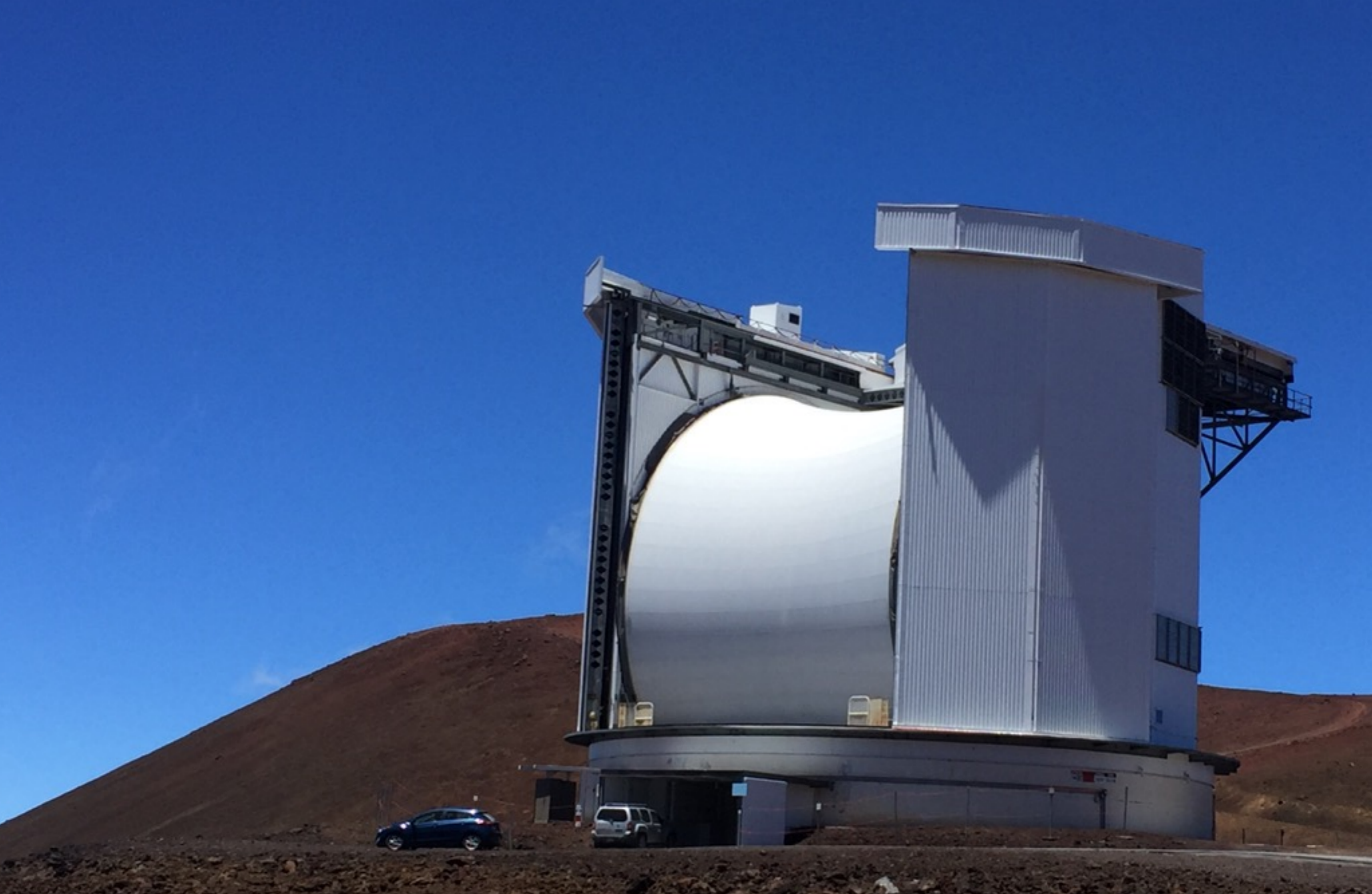
銀河系内の星の90%は星団で生まれるが、  
「孤立的 vs. 集団的星形成」と磁場の関連は？


星形成の多様性の起源である、

分子雲コアの多様性の起源に磁場はどのように関与？

\* **BISTRO** でめざすもの

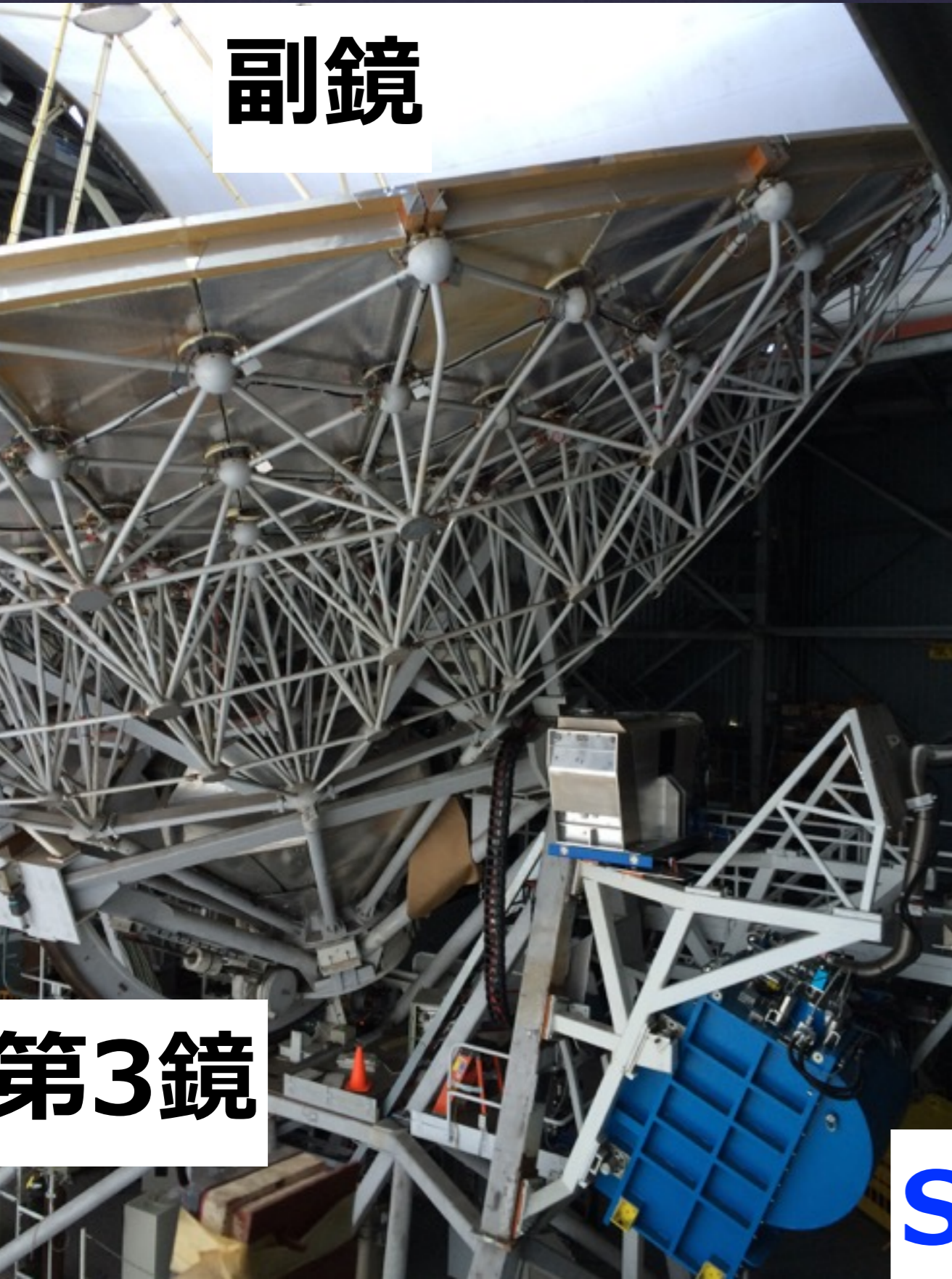
\* **BISTRO** と **ALMA** でめざすもの



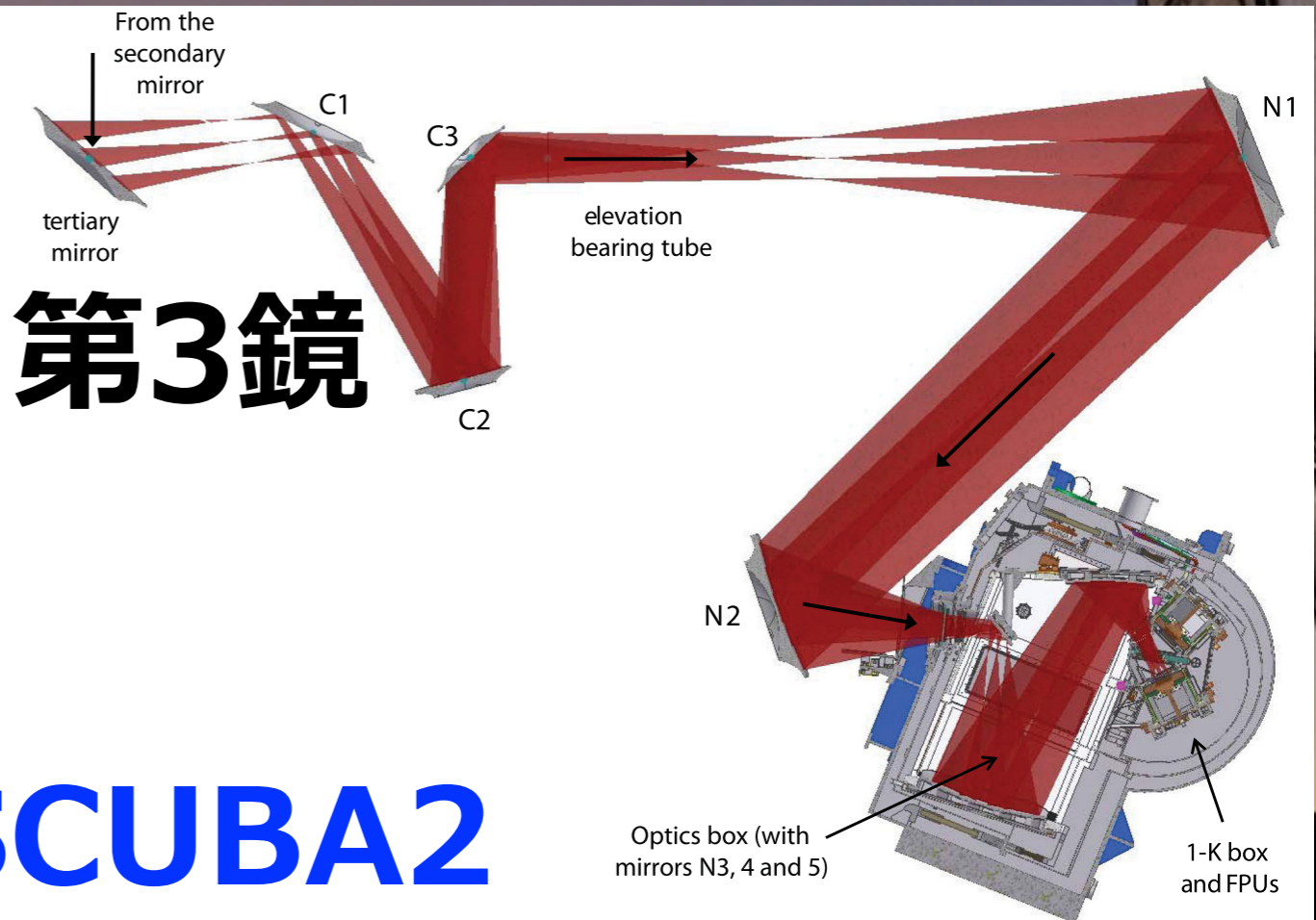
 ***POL-2 Data***

# The SCUBA2 and POL2 system on JCMT

副鏡



副鏡から

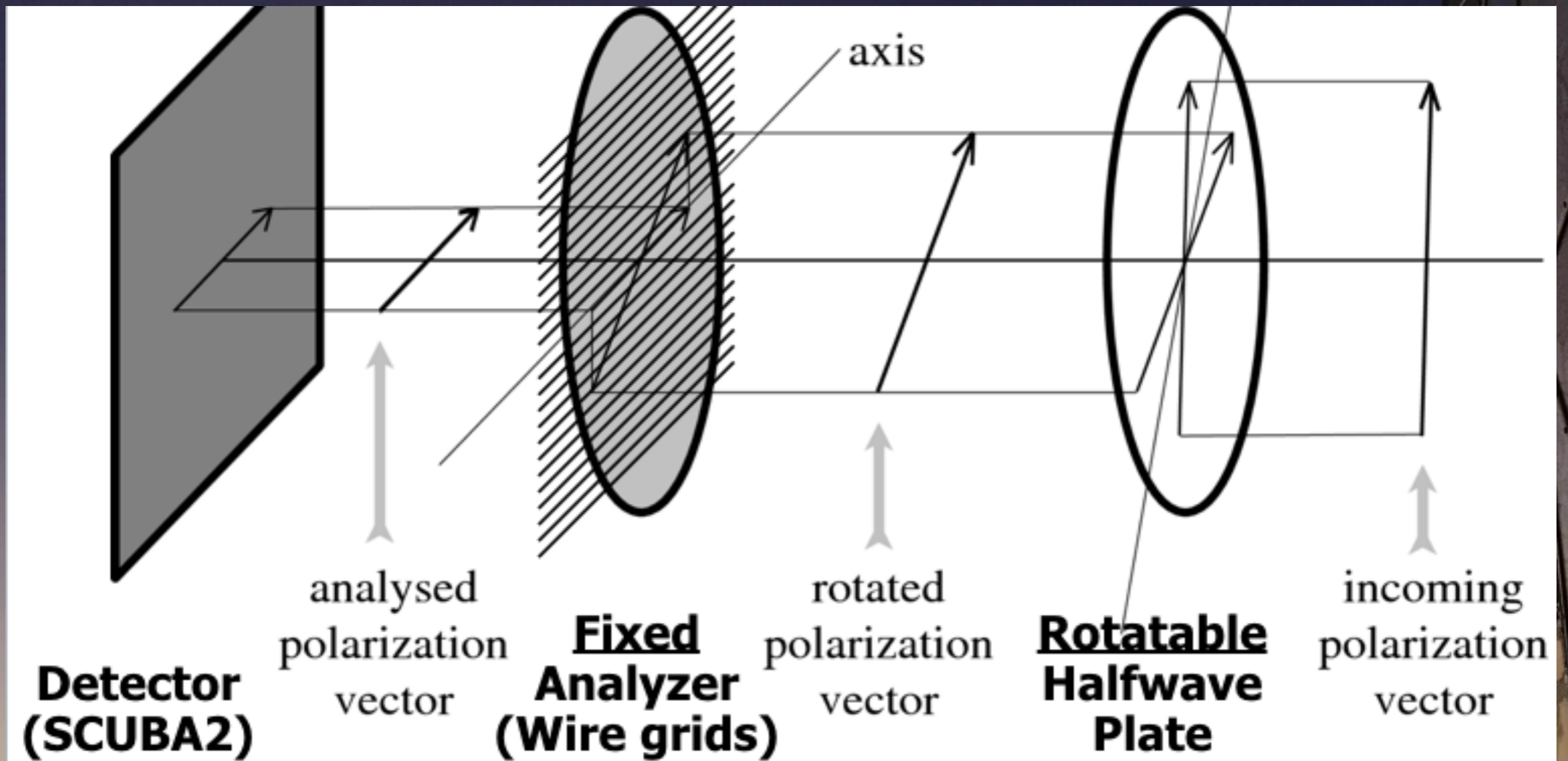


第3鏡

第3鏡

SCUBA2

# The SCUBA2 and POL2 system on JCMT

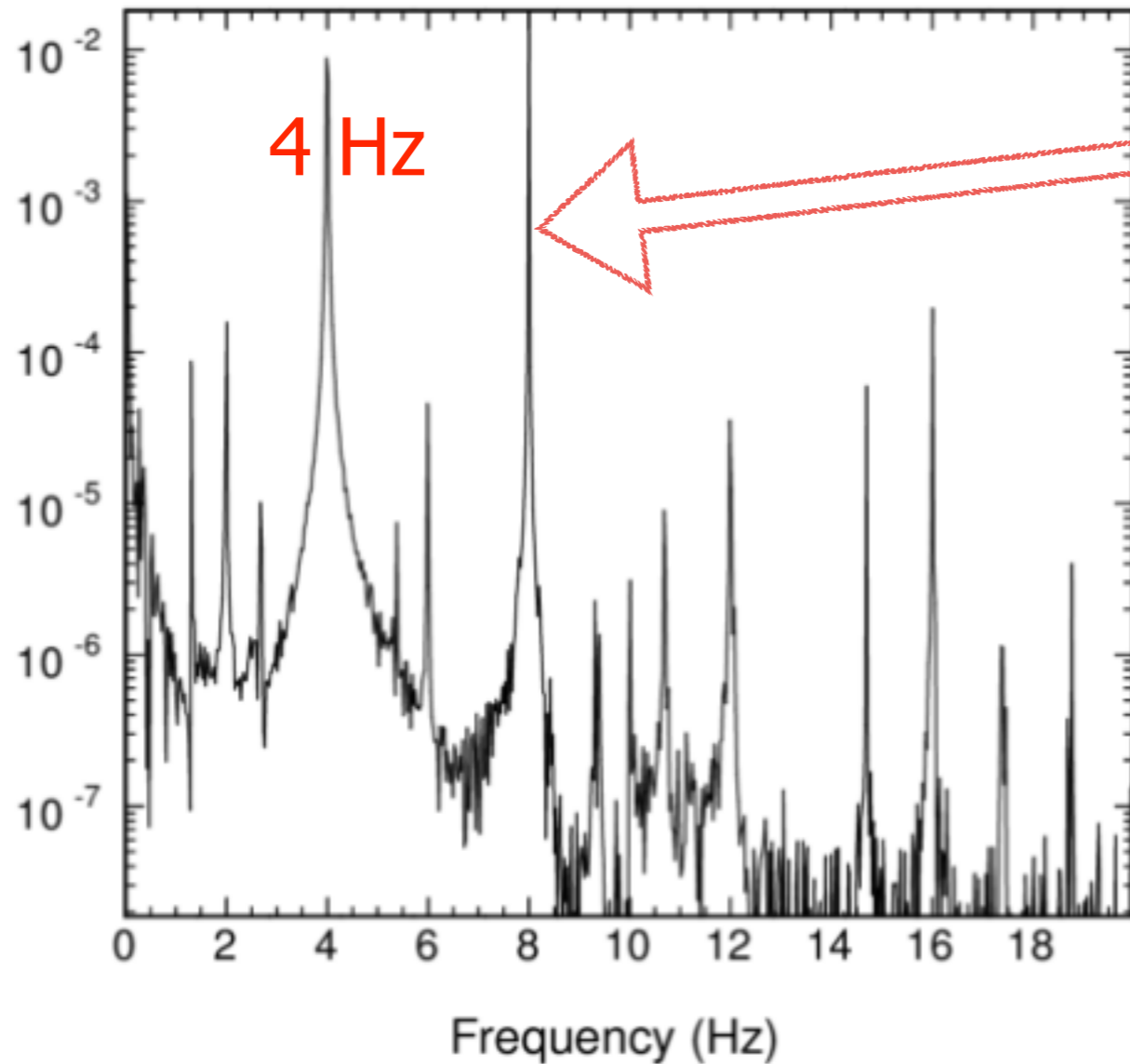


2Hz rotation;  
4 times data dumping each rotation  
→ 8 Hz sampling



# Data Reduction: Raw Data

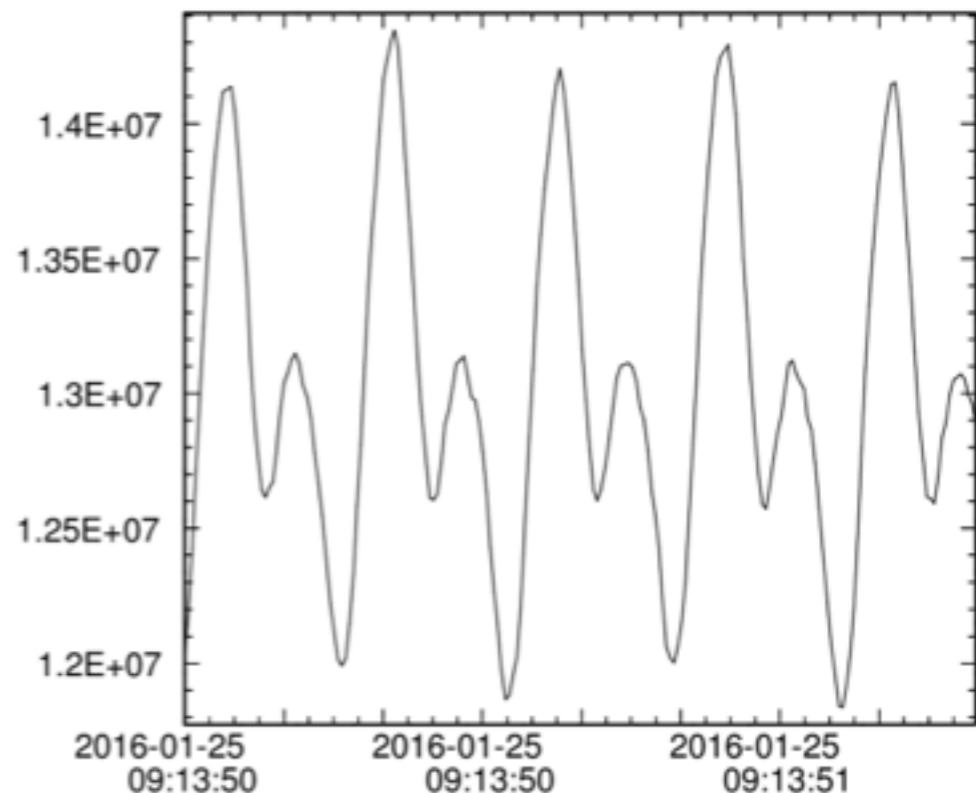
Power Spectral Density  
[(pW)<sup>2</sup>/Hz]



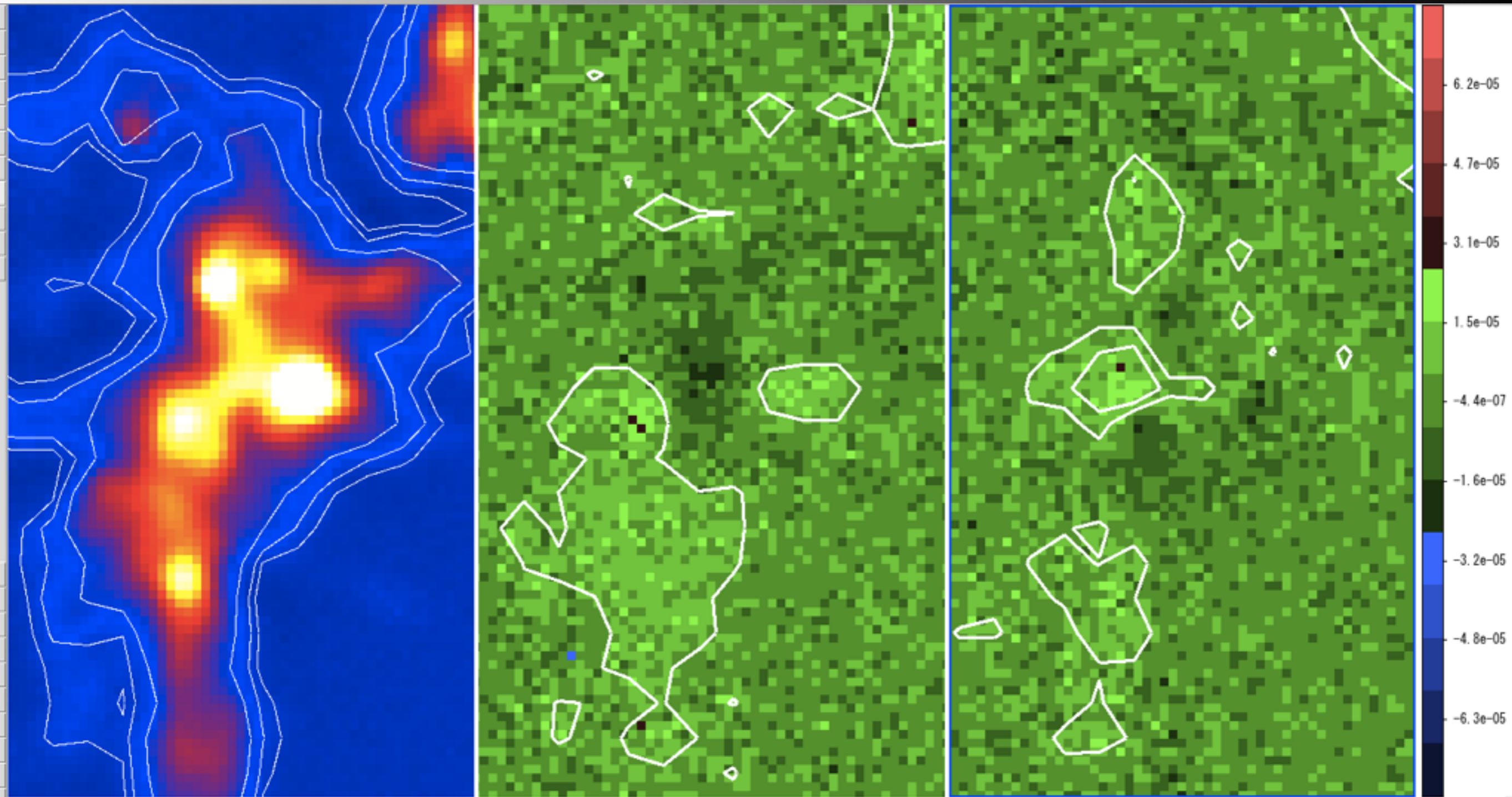
The 8 Hz signal convey  
Instrumental polarization (IP)  
plus  
**astronomical polarization**

All signals are harmonics of 2 Hz which is the spin freq. of the Half Wave Plate (HWP).  
Most of the 2 Hz harmonics: standing waves caused by HWP and the fixed analyzer.

Time stream after sky subtraction



# POL-2 Maps



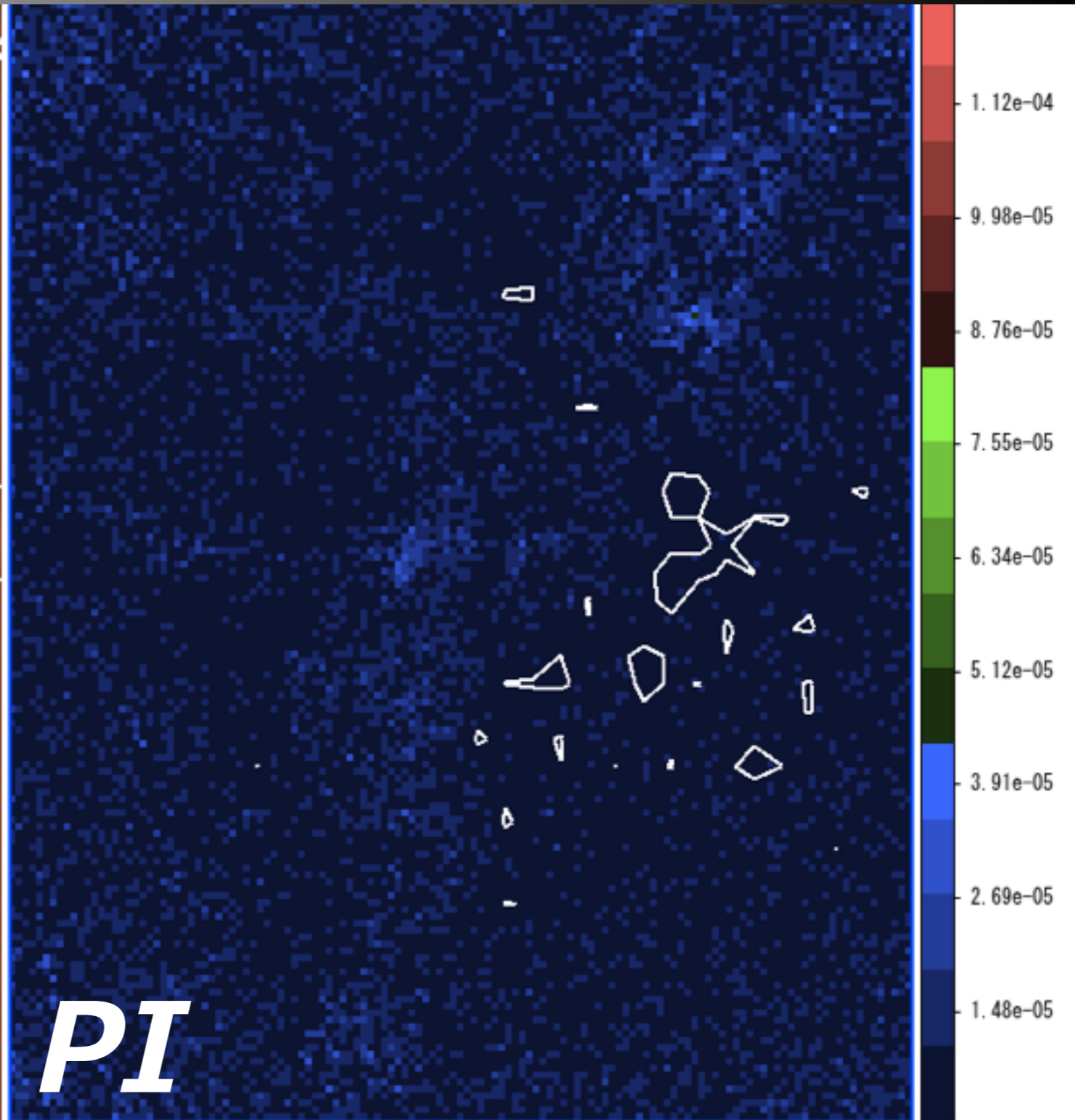
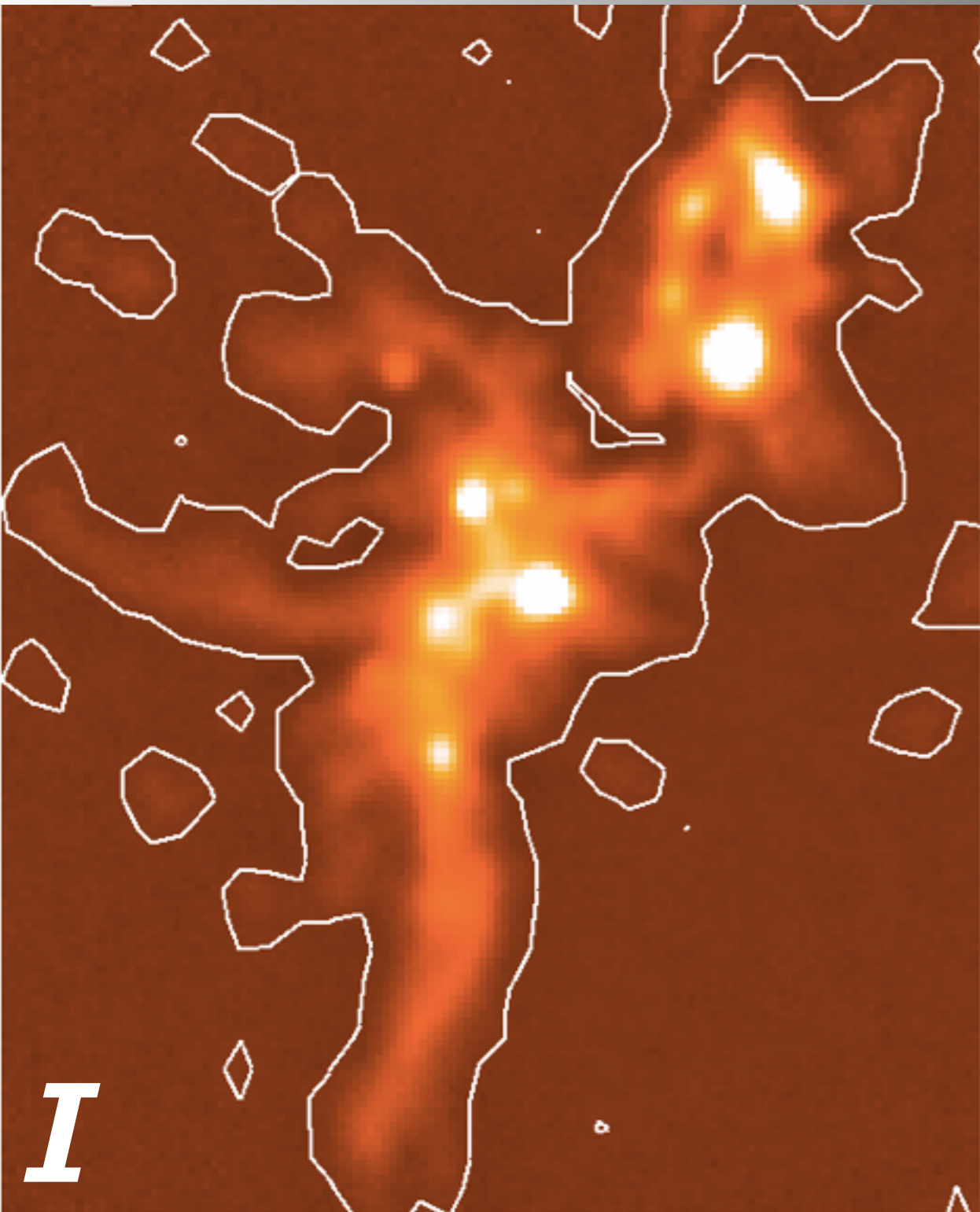
***I***

***Q***

***U***

Contours:  $16 \times 10^{-6}$ ,  $8 \times 10^{-6}$ , and  $4 \times 10^{-6}$  pw

# POL-2 Maps



Contour: 5e-6 pw

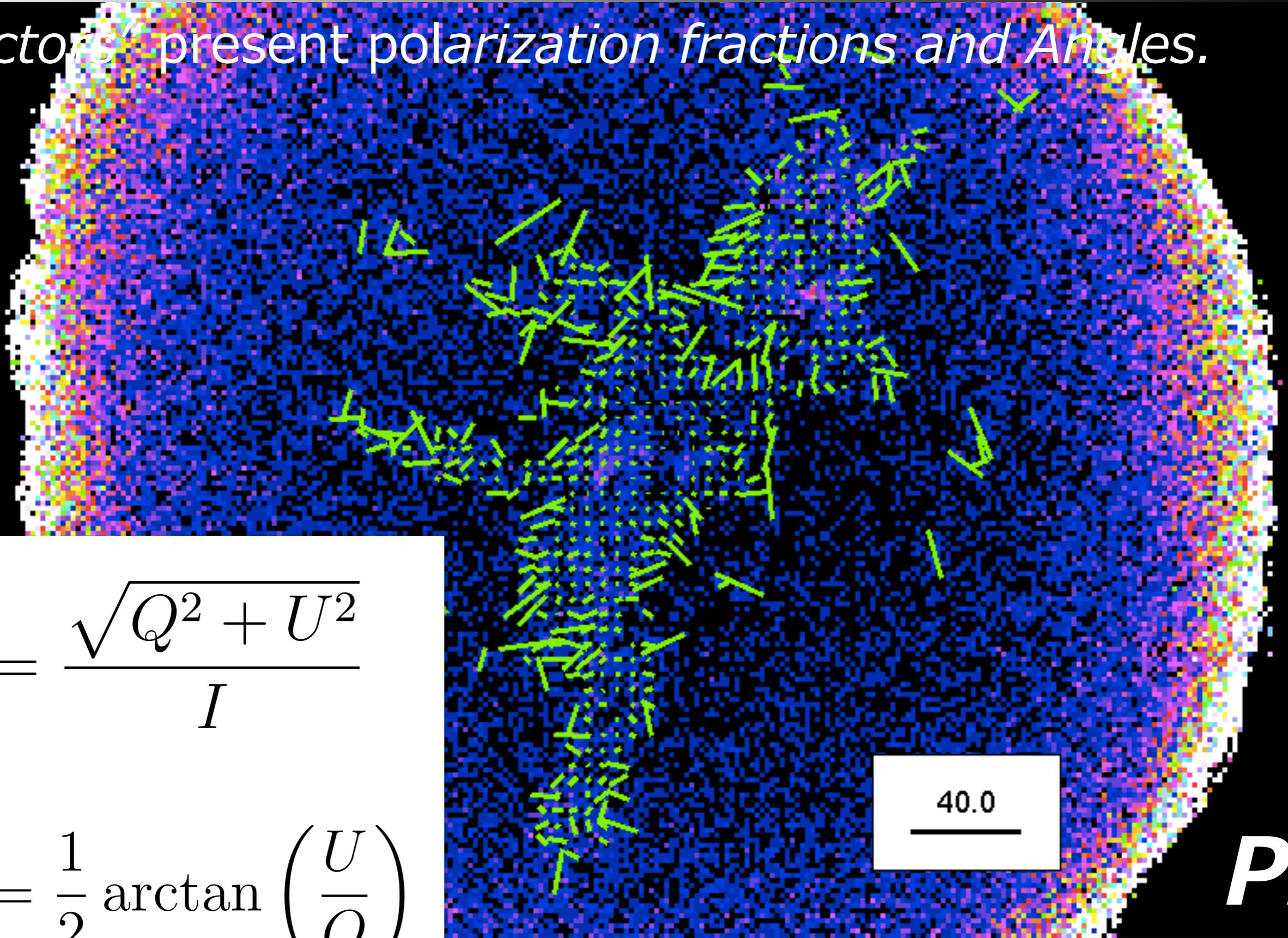
$$PI = \sqrt{Q^2 + U^2}$$

# Pol. "Vectors" on Polarized Intensity Map

"Vectors" present polarization fractions and Angles.

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)$$

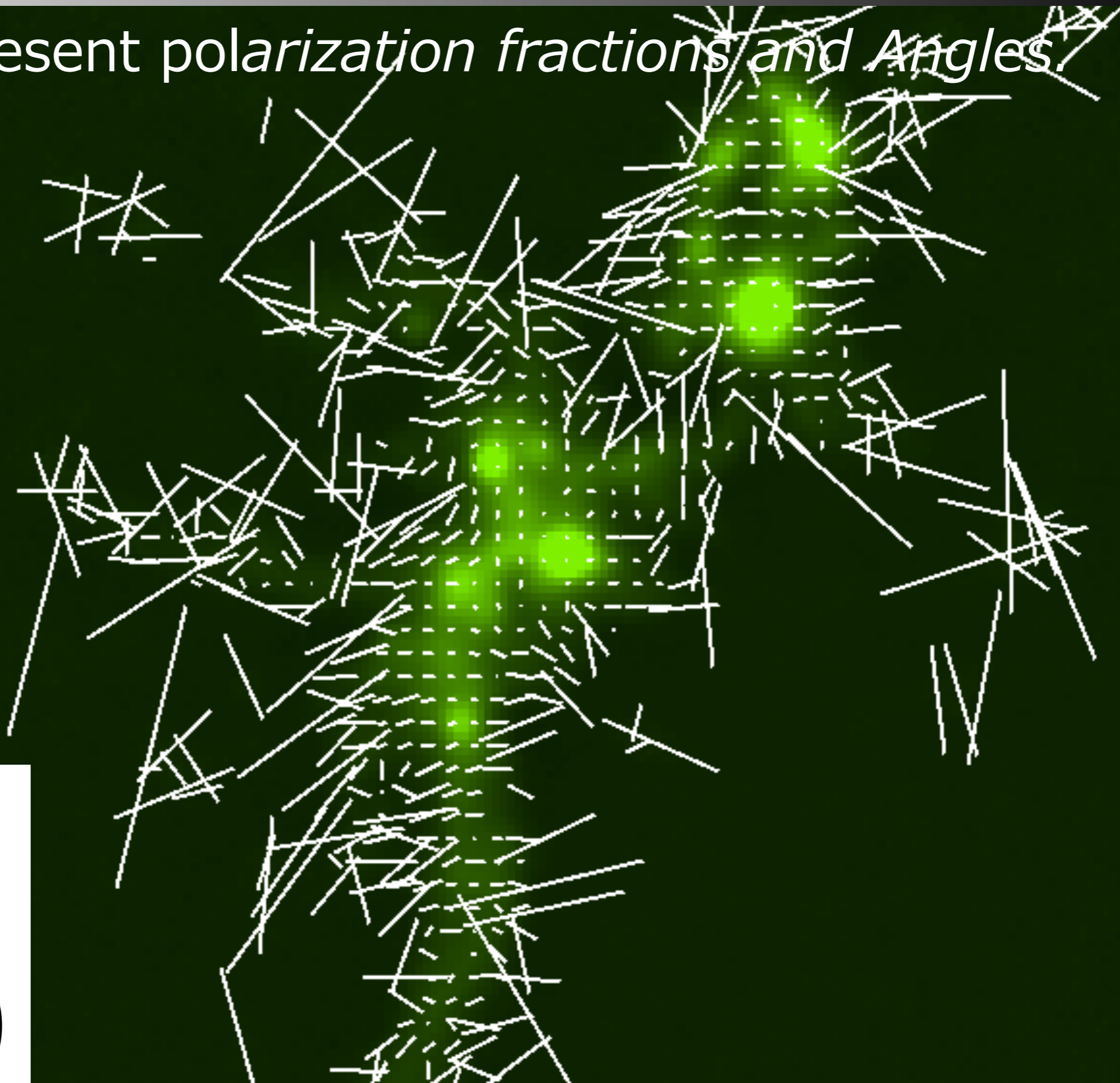


40.0

**PI**

# Displaying *Polarization fractions and Angles*

“*Vectors*” present polarization fractions and Angles.

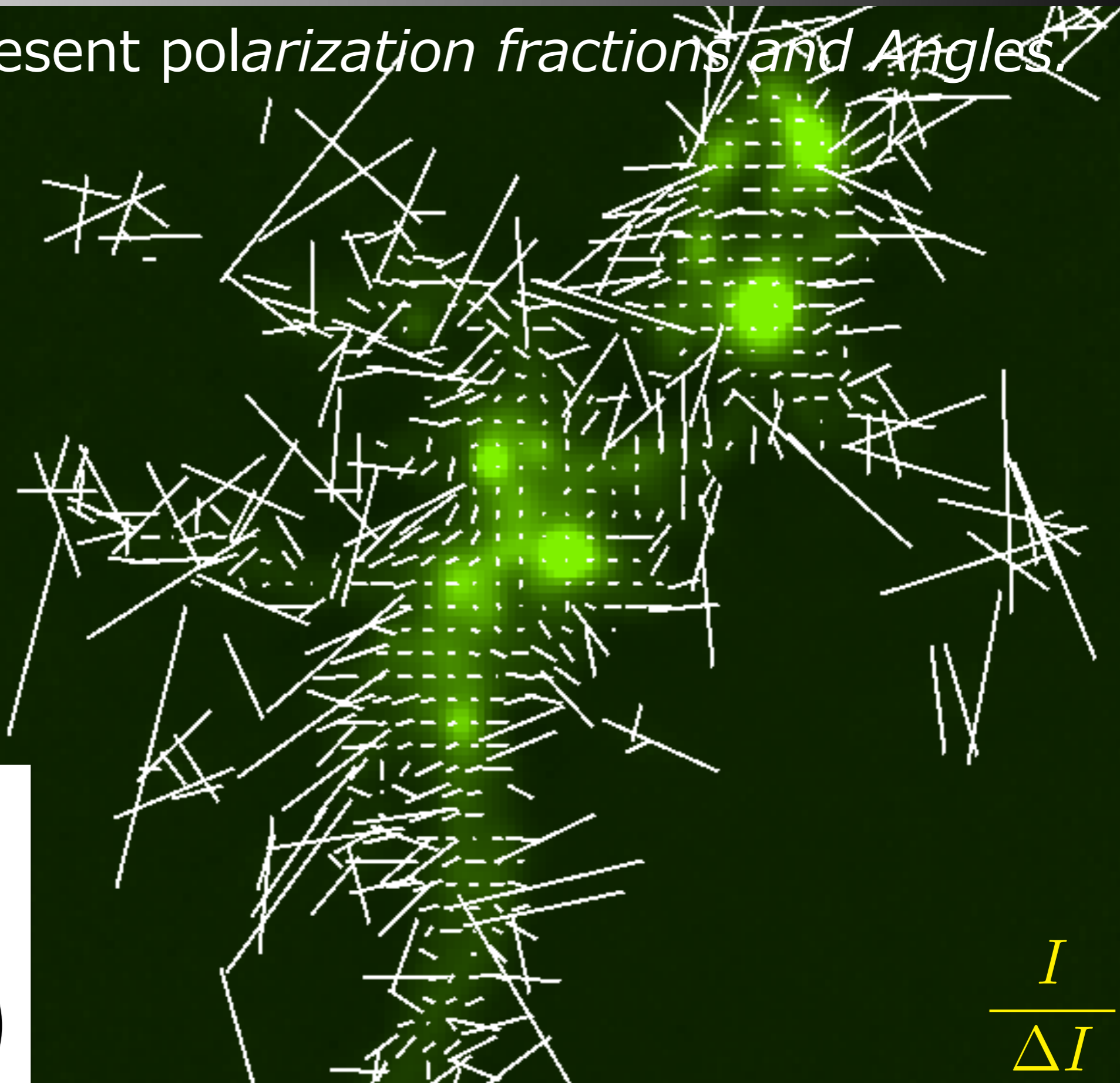


$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)$$

# Selecting Polarization "Vectors"

"Vectors" present polarization fractions and Angles.



$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)$$

$$\frac{I}{\Delta I} > 5$$

# Selecting Polarization "Vectors"

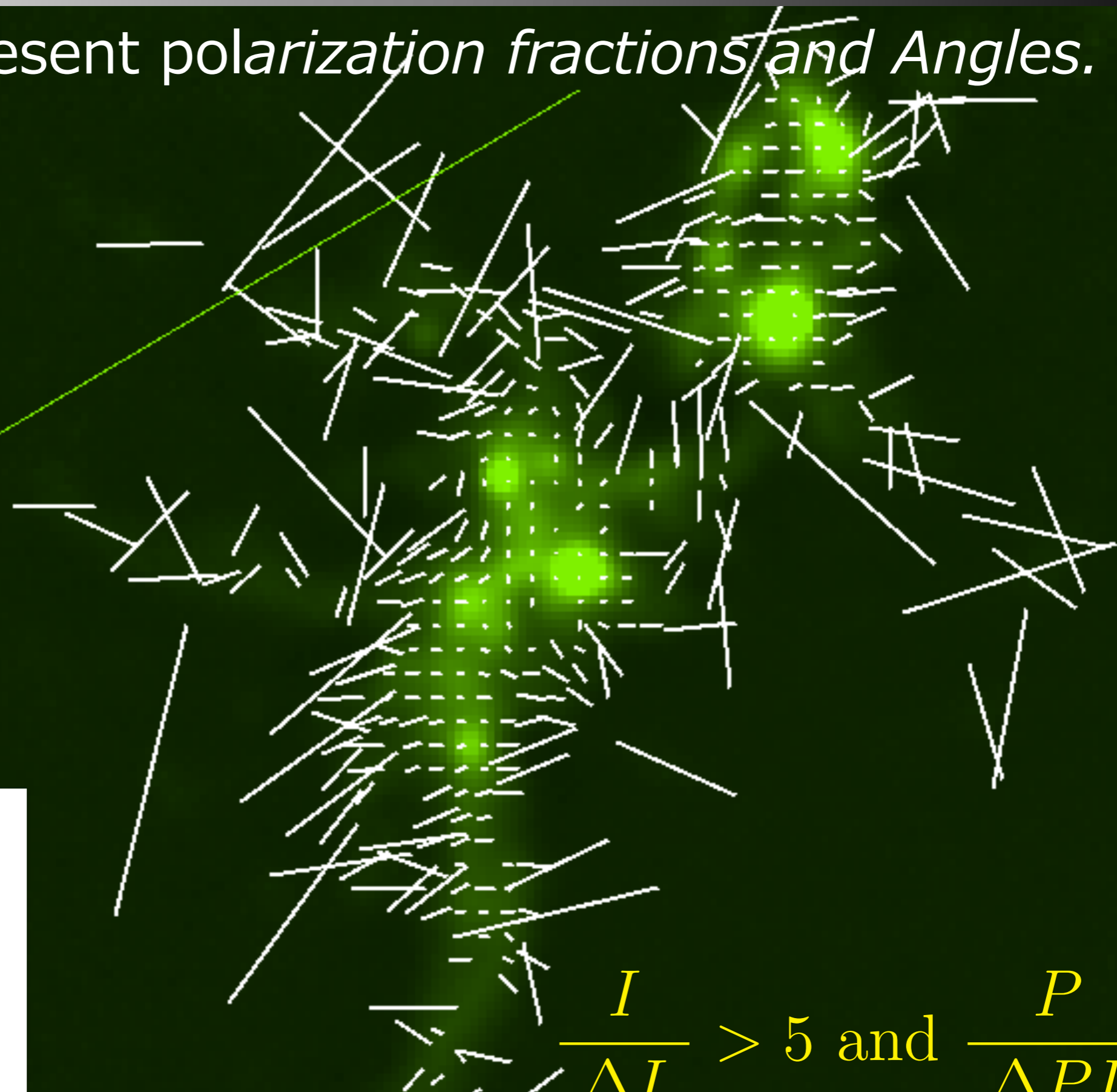
"Vectors" present polarization fractions and Angles.

133.5

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)$$

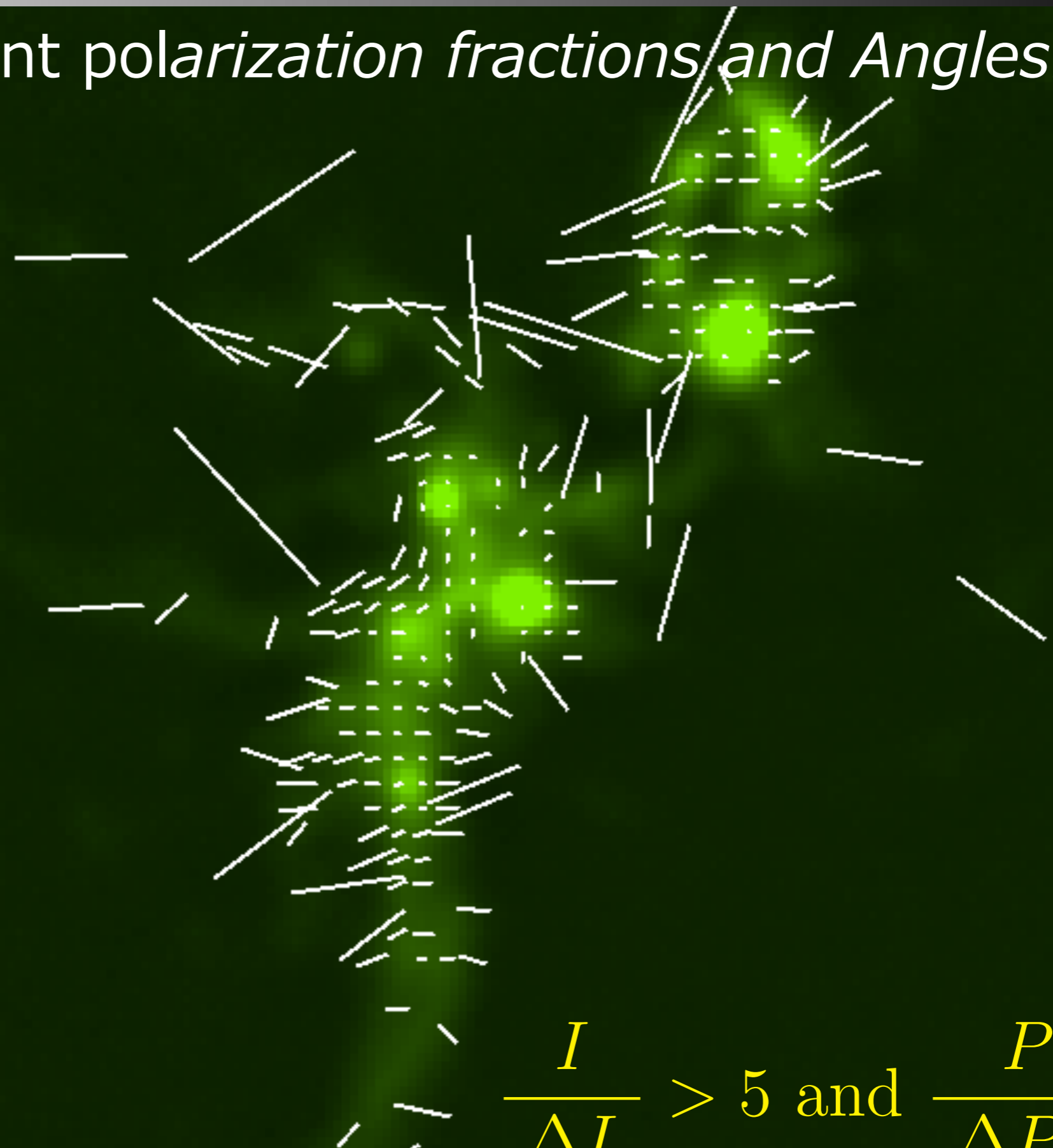
$$\frac{I}{\Delta I} > 5 \text{ and } \frac{P}{\Delta P I} > 2$$



# Selecting Polarization "Vectors"

"Vectors" present polarization fractions and Angles.

185.5



$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)$$

$$\frac{I}{\Delta I} > 5 \text{ and } \frac{P}{\Delta PI} > 3$$

# Selecting Polarization "Vectors"

*"Vectors" present polarization fractions and Angles.*

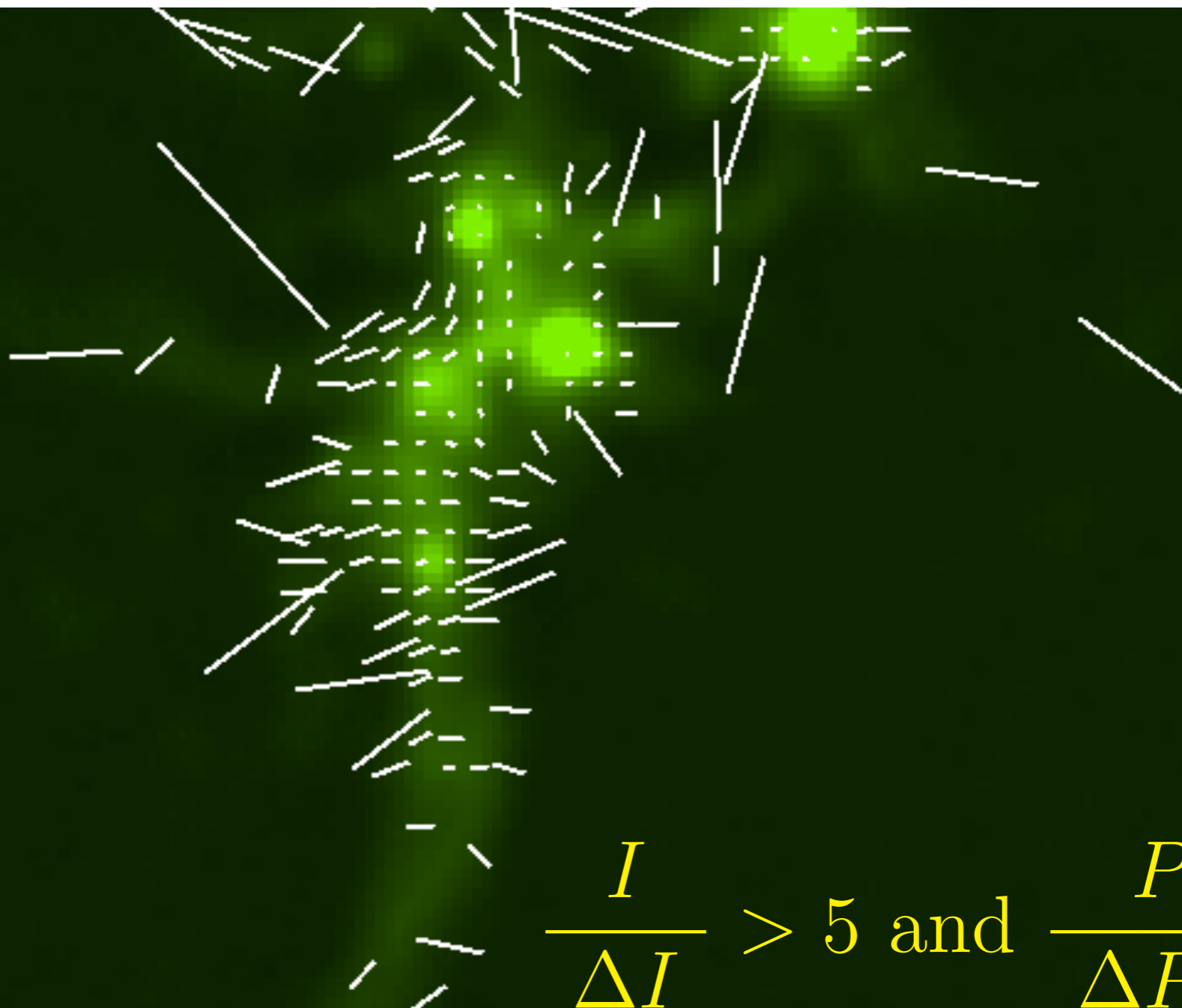
If we select vectors on the basis of S/N-ratio of  $P$ , we would miss intrinsically weakly-polarized ones.

185.5

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$

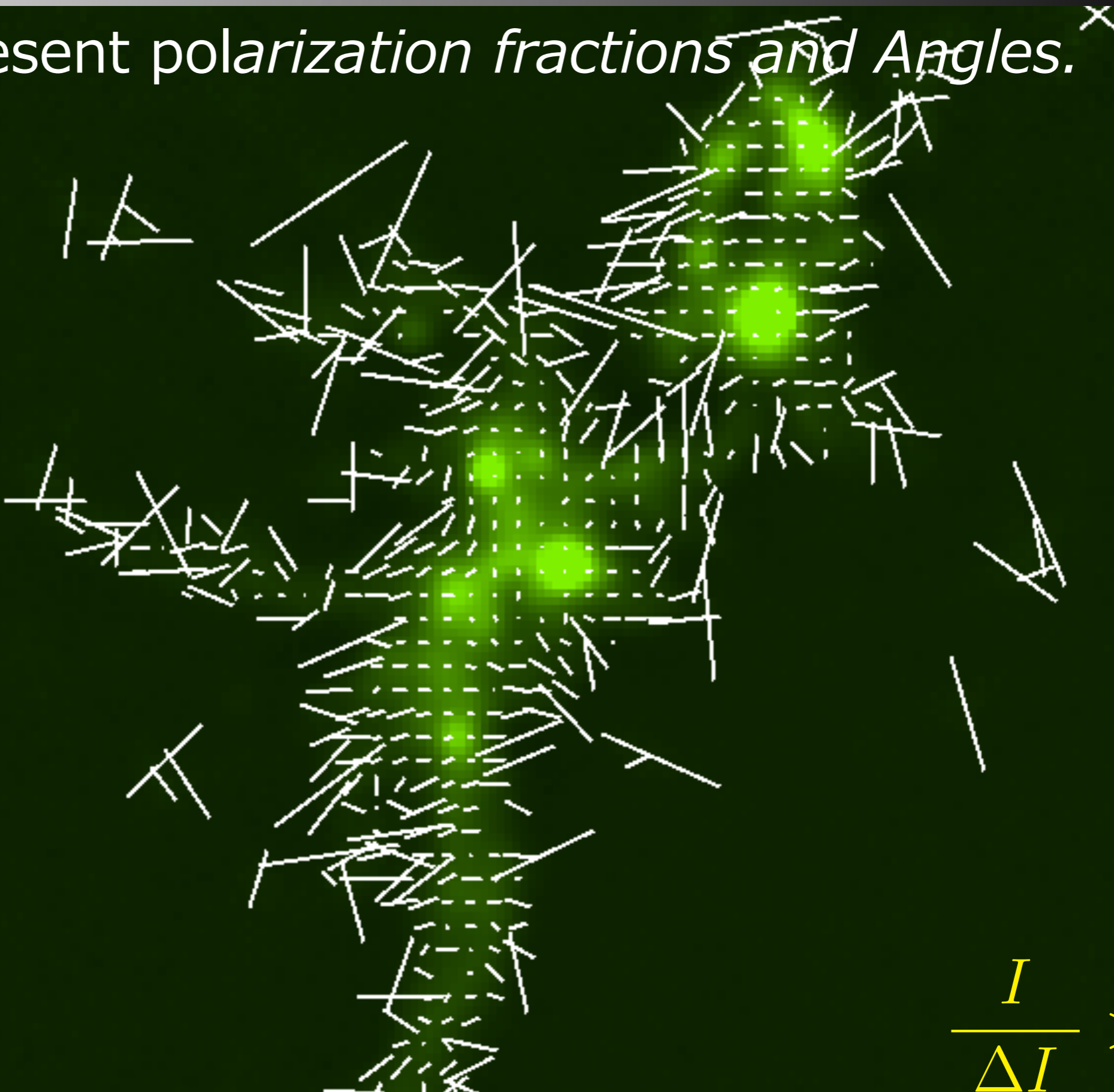
$$\chi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)$$

$$\frac{I}{\Delta I} > 5 \text{ and } \frac{P}{\Delta P I} > 3$$

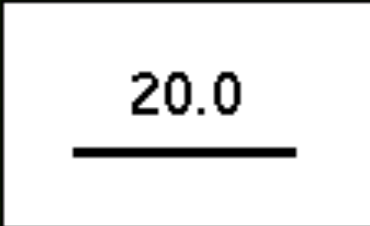


# Selecting Polarization "Vectors"

"Vectors" present polarization fractions and Angles.



74.9



$$\frac{I}{\Delta I} > 10$$



# ***POL-2 B-fields Gallery***

# POL-2 *B*-fields Gallery: Ophiucus A

0.21 pc

Kwon+,  
submitted

$$\frac{I}{\Delta I} > 10$$

# POL-2 *B*-fields Gallery: Ophiucus B

0.21 pc

Soam+,  
submitted

$$\frac{I}{\Delta I} > 10$$

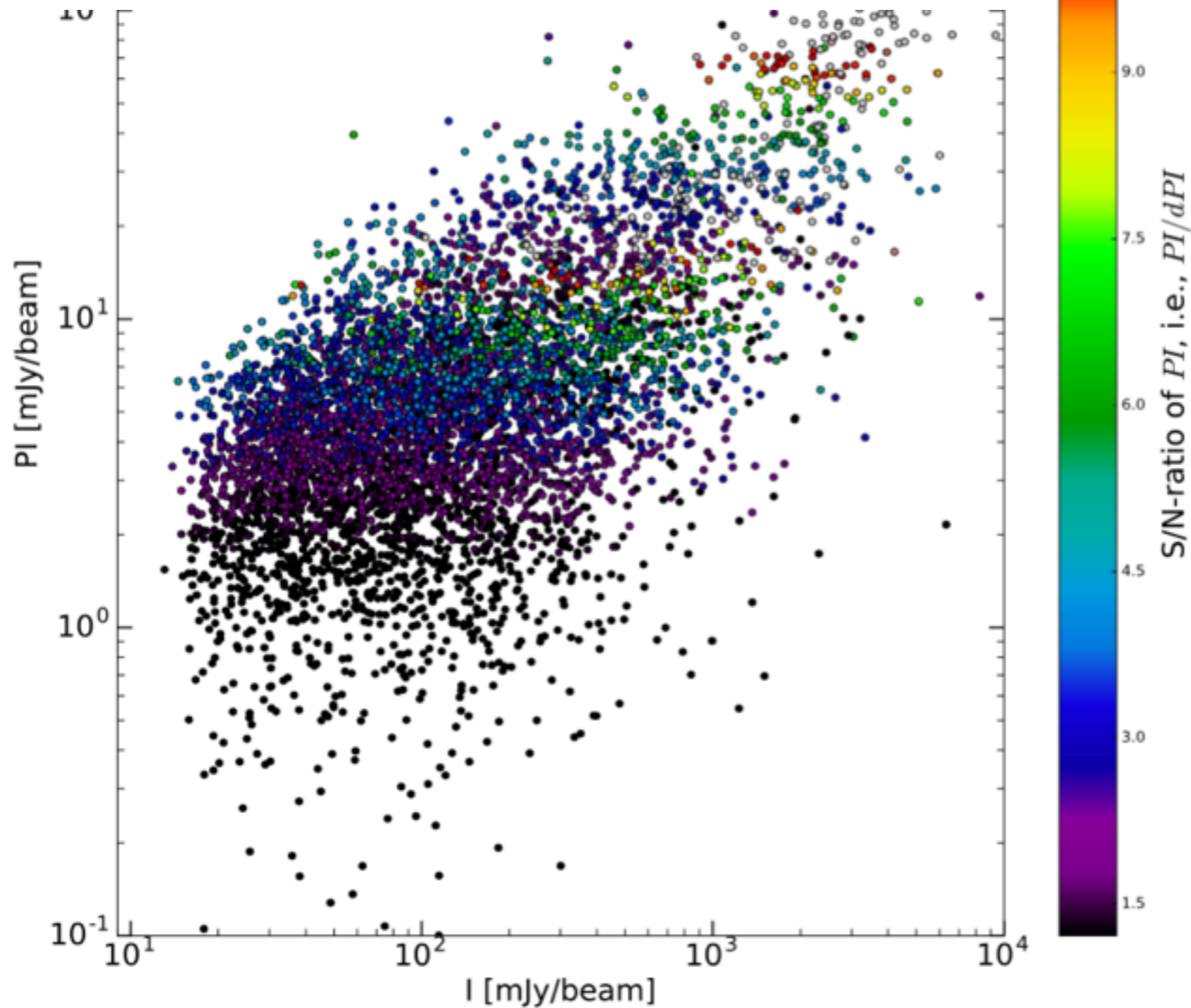


# ***Property of Submm Polarized Emission***

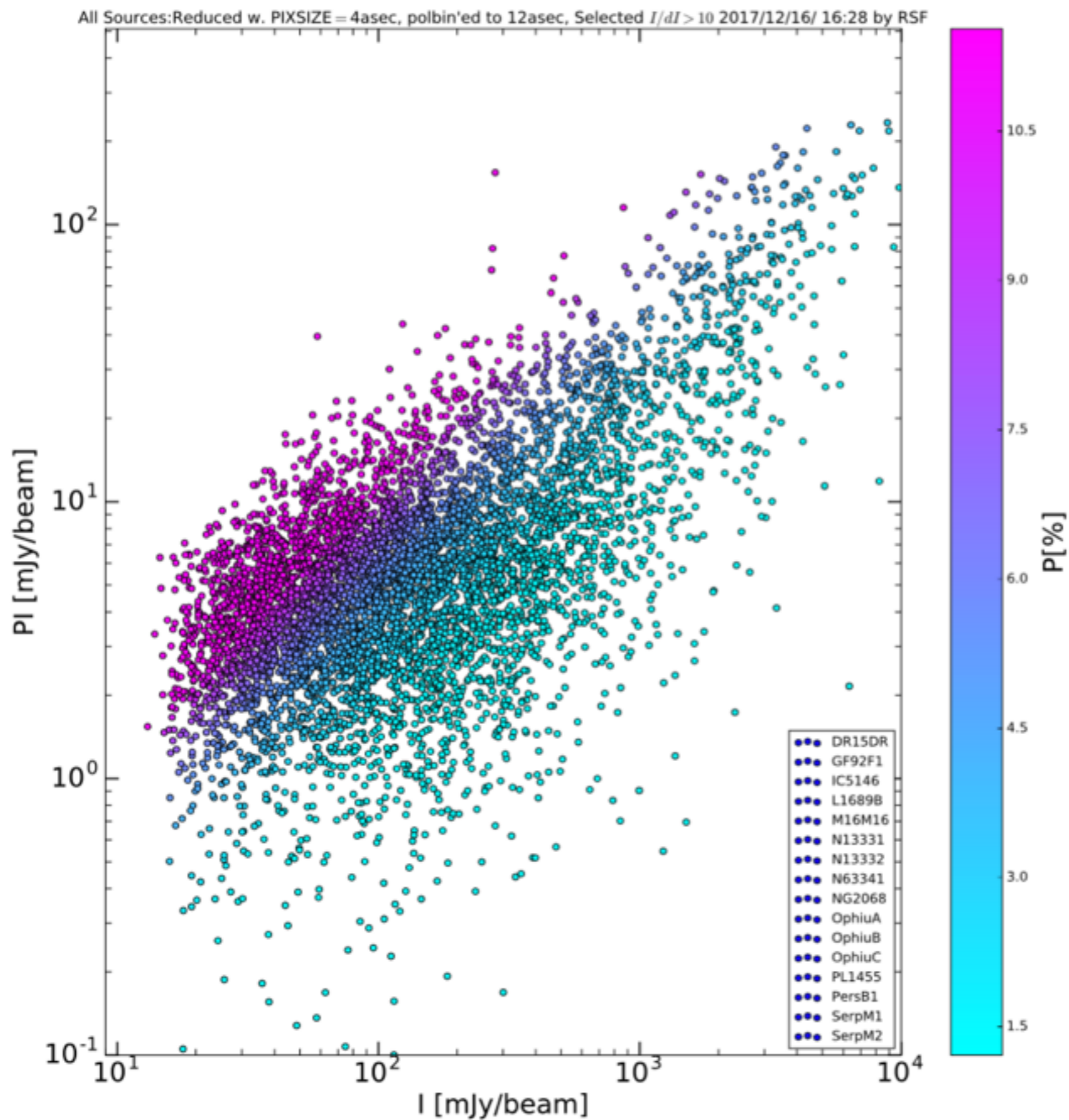
# Stokes $I$ vs. $PI$ ; Colors = $PI/dPI$

Caution MUST be used:

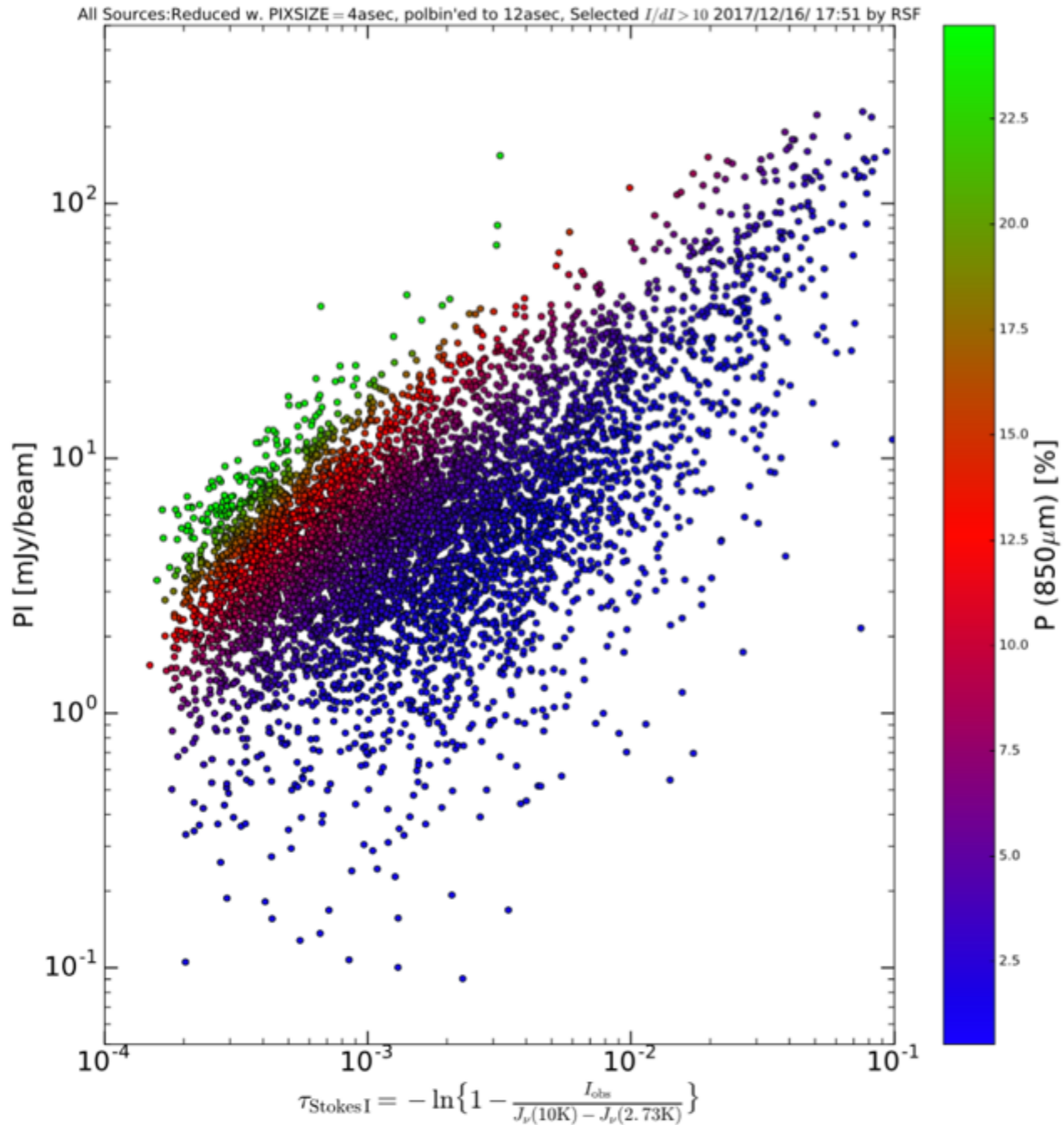
Selecting vectors based on S/N-ratio of  $P$ ,  
we would miss intrinsically weakly-polarized ones.



# Stokes $I$ vs. $PI$ ; Colors = $p$ , i.e., $PI/I$

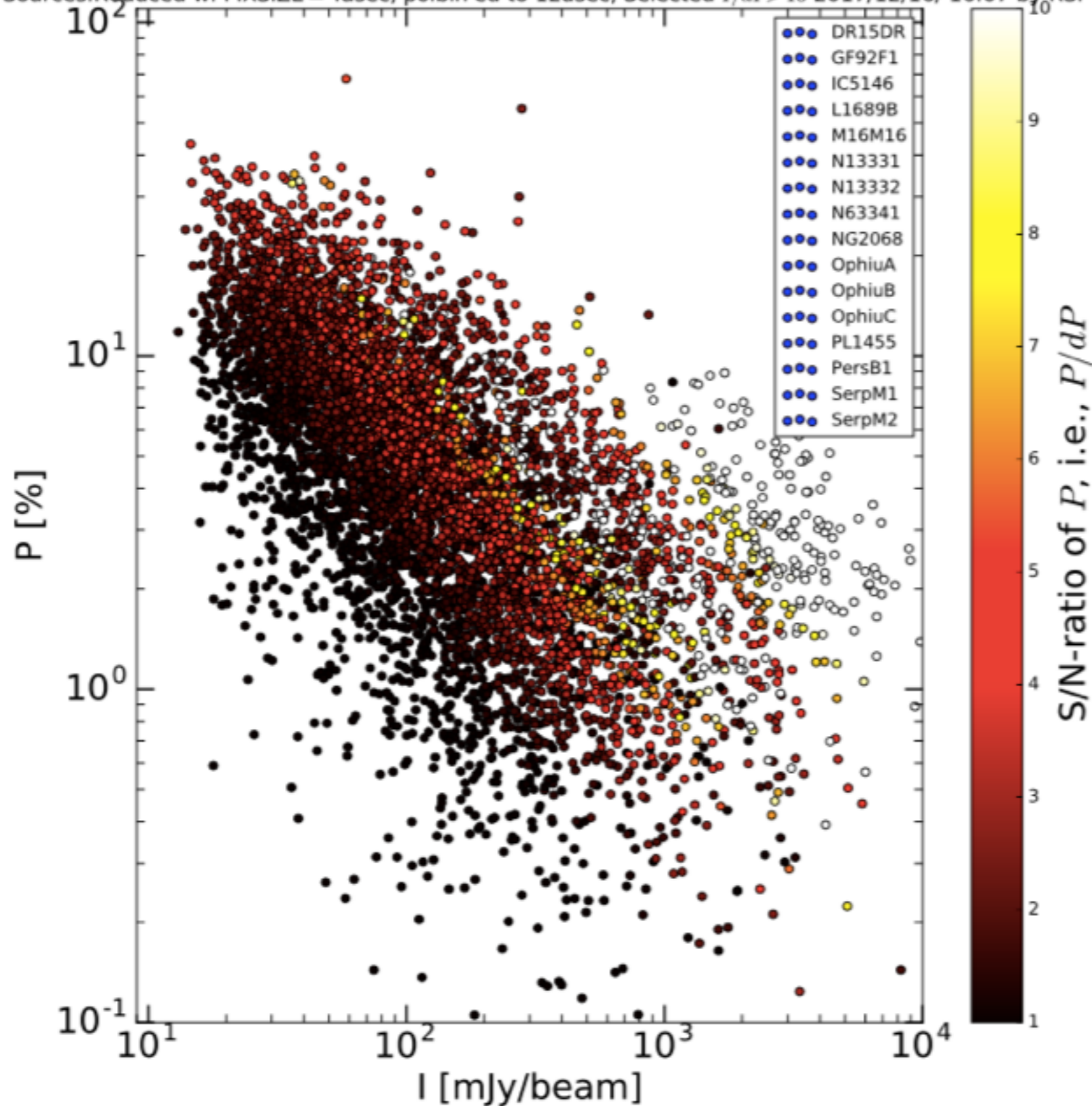


# 850 $\mu\text{m}$ $\tau$ vs. $PI$ ; Colors = $p$

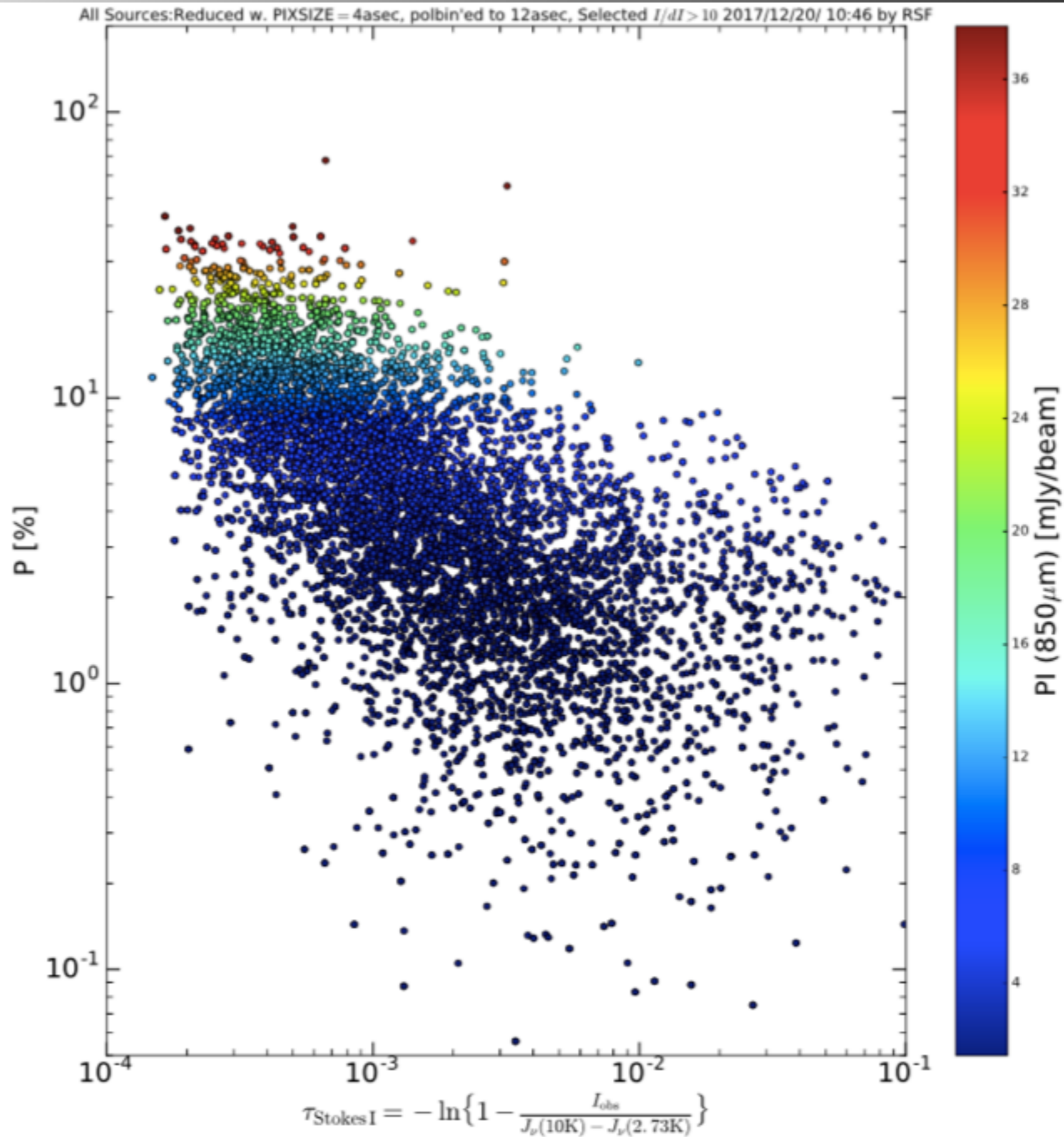


# Stokes $I$ vs. $p$ , i.e., $PI/I$ ; Colors = $P/dP$

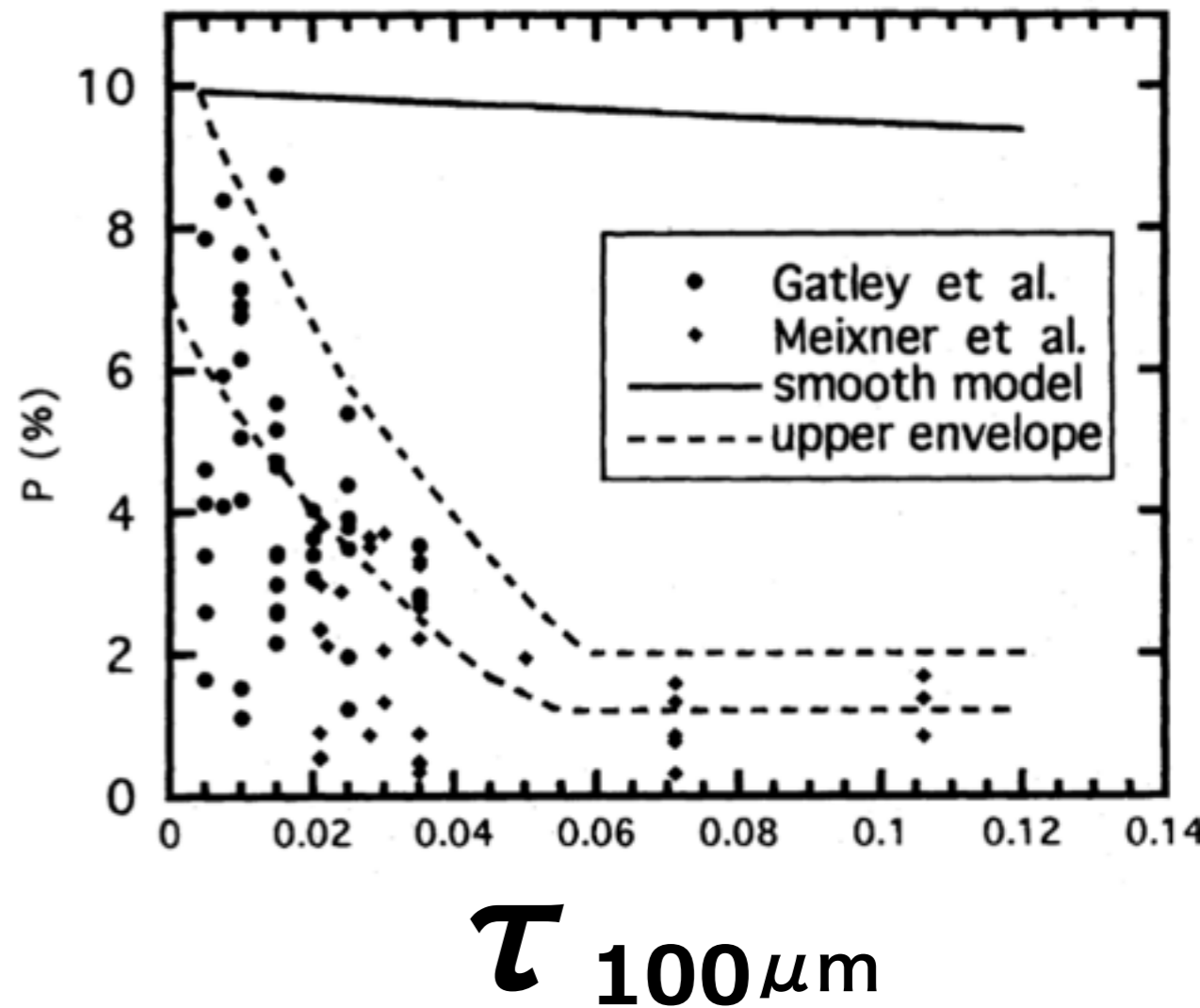
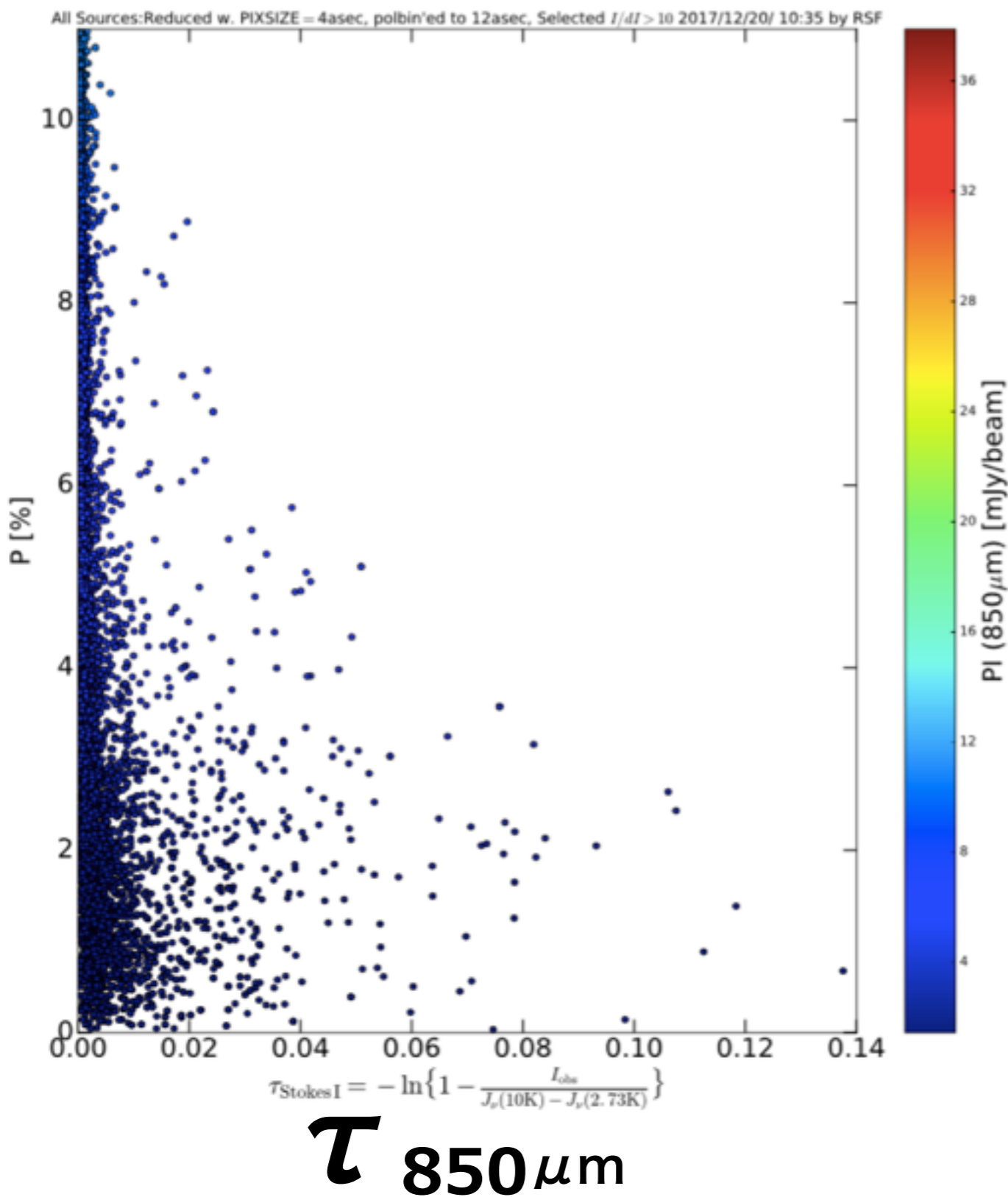
All Sources: Reduced w. PIXSIZE = 4asec, polbin'ed to 12asec, Selected  $I/dI > 10$  2017/12/16/ 16:07 by RSF



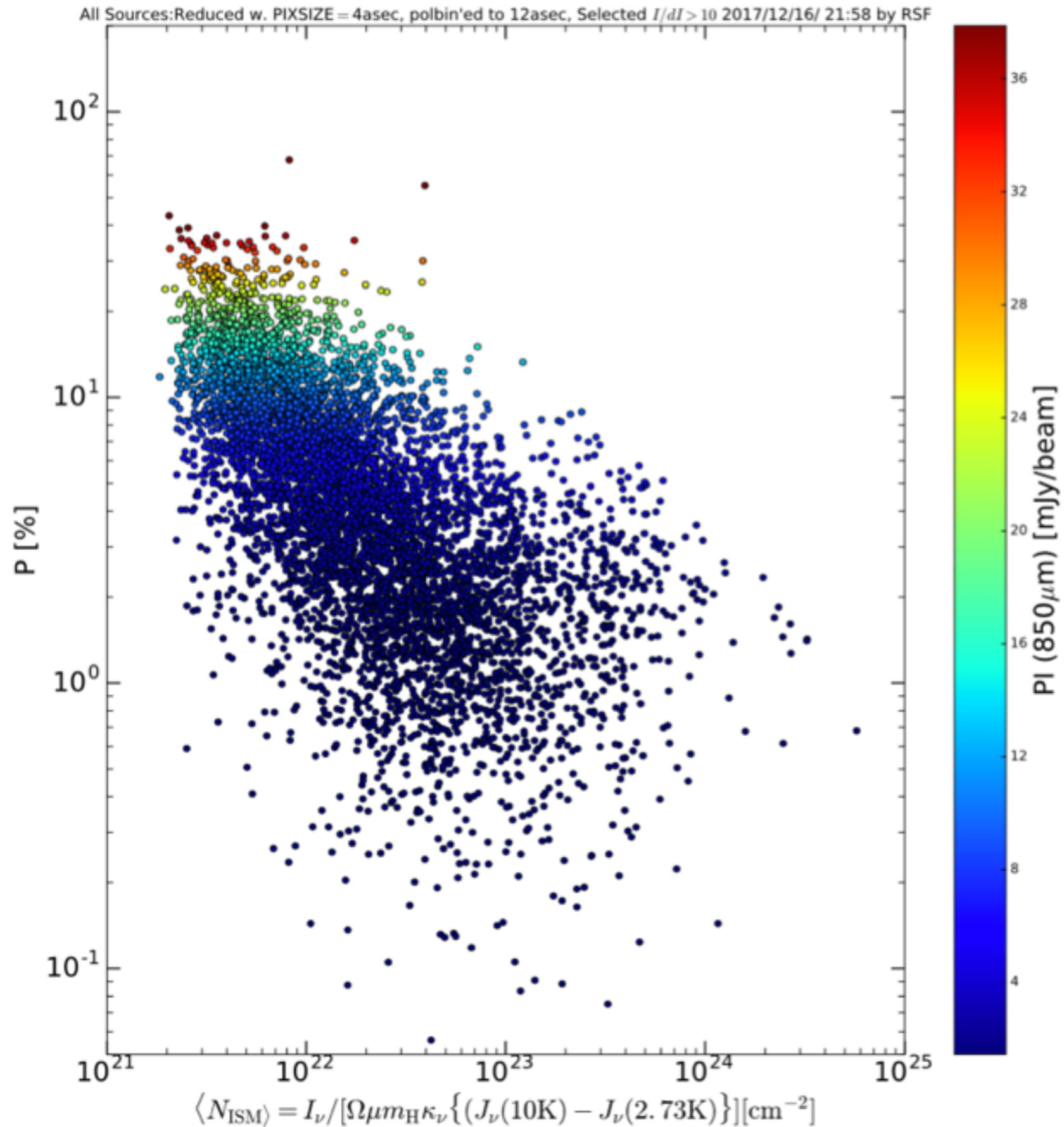
# Stokes $I$ vs. $p$ , i.e., $PI/I$ ; Colors = $P/dP$



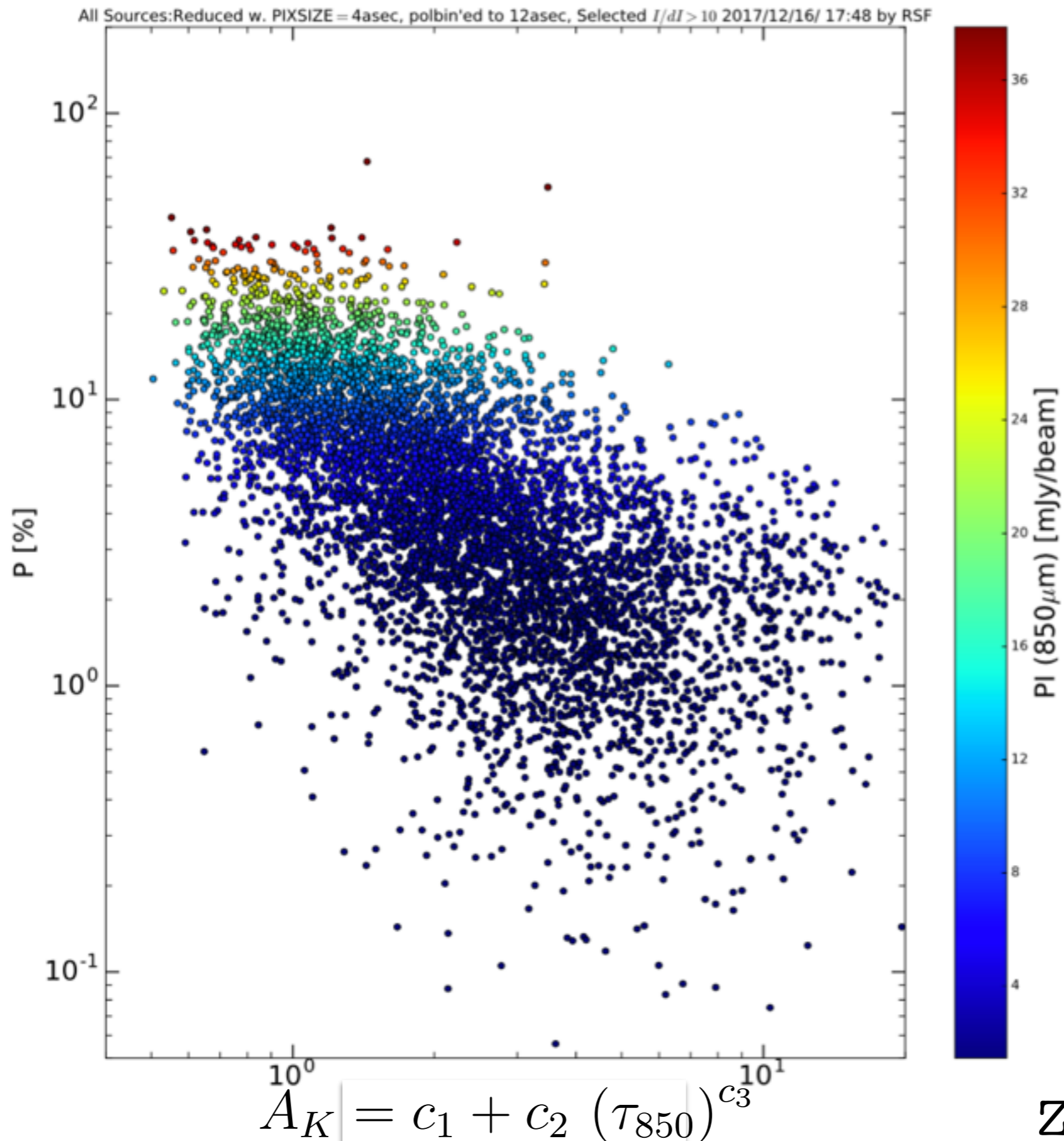
# Stokes $I$ vs. $p$ , i.e., $PI/I$ ; Colors = $P/dP$



# ISM Column Density vs. $P$ ; Colors = $PI$



# Converted $A_K$ vs. $850\mu\text{m } p$ ; Colors = $PI$





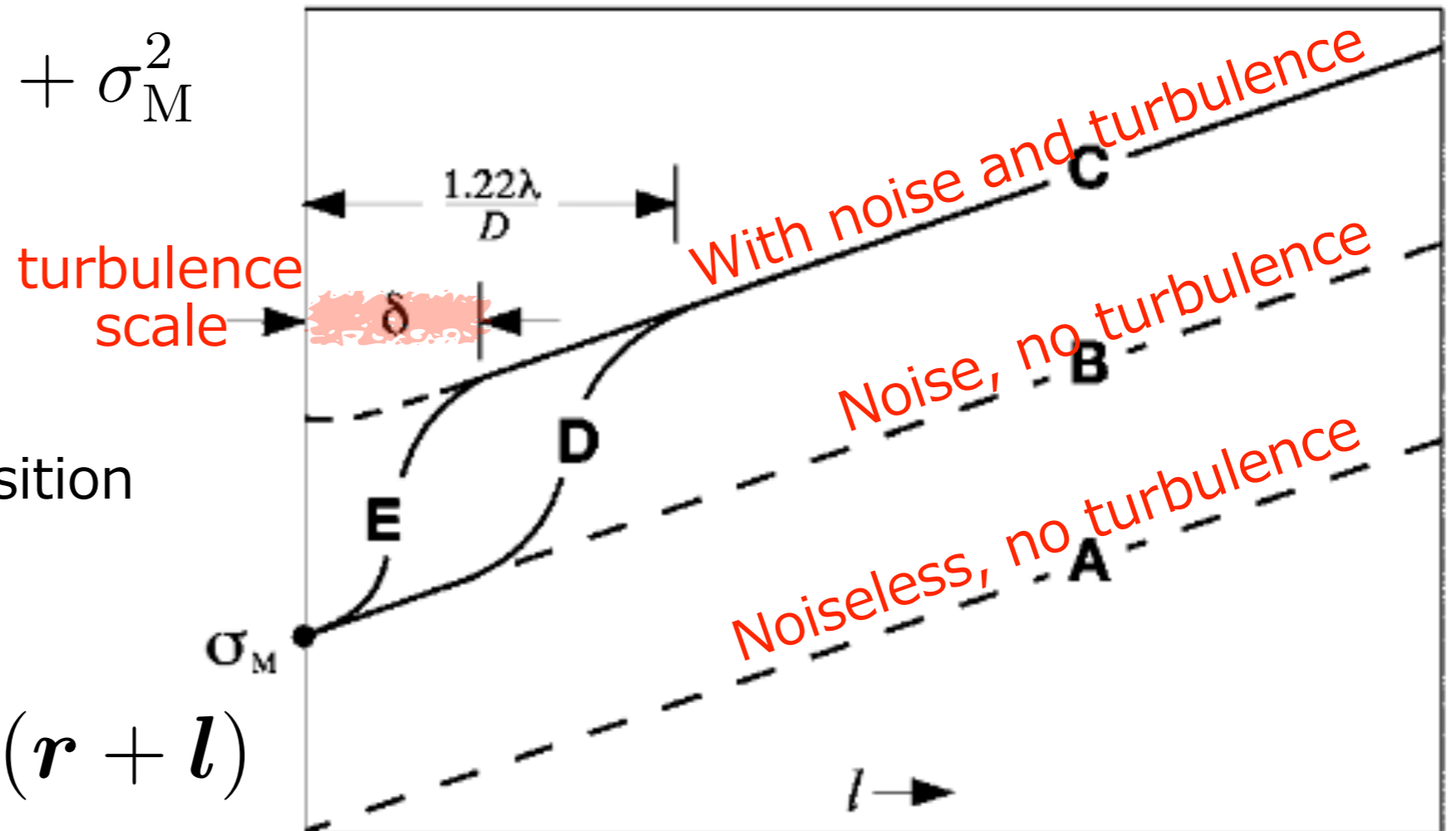
# ***Structure Function Analysis***

# Dispersion Function, a.k.a., Structure F.

$$\langle \Delta \Phi^2(l) \rangle = b^2 + m^2 l^2 + \sigma_M^2$$

Difference of measured position angles,

$$\Delta \Phi(l) \equiv \Phi(\mathbf{r}) - \Phi(\mathbf{r} + \mathbf{l})$$



Structure function, i.e., dispersion function is defined by,

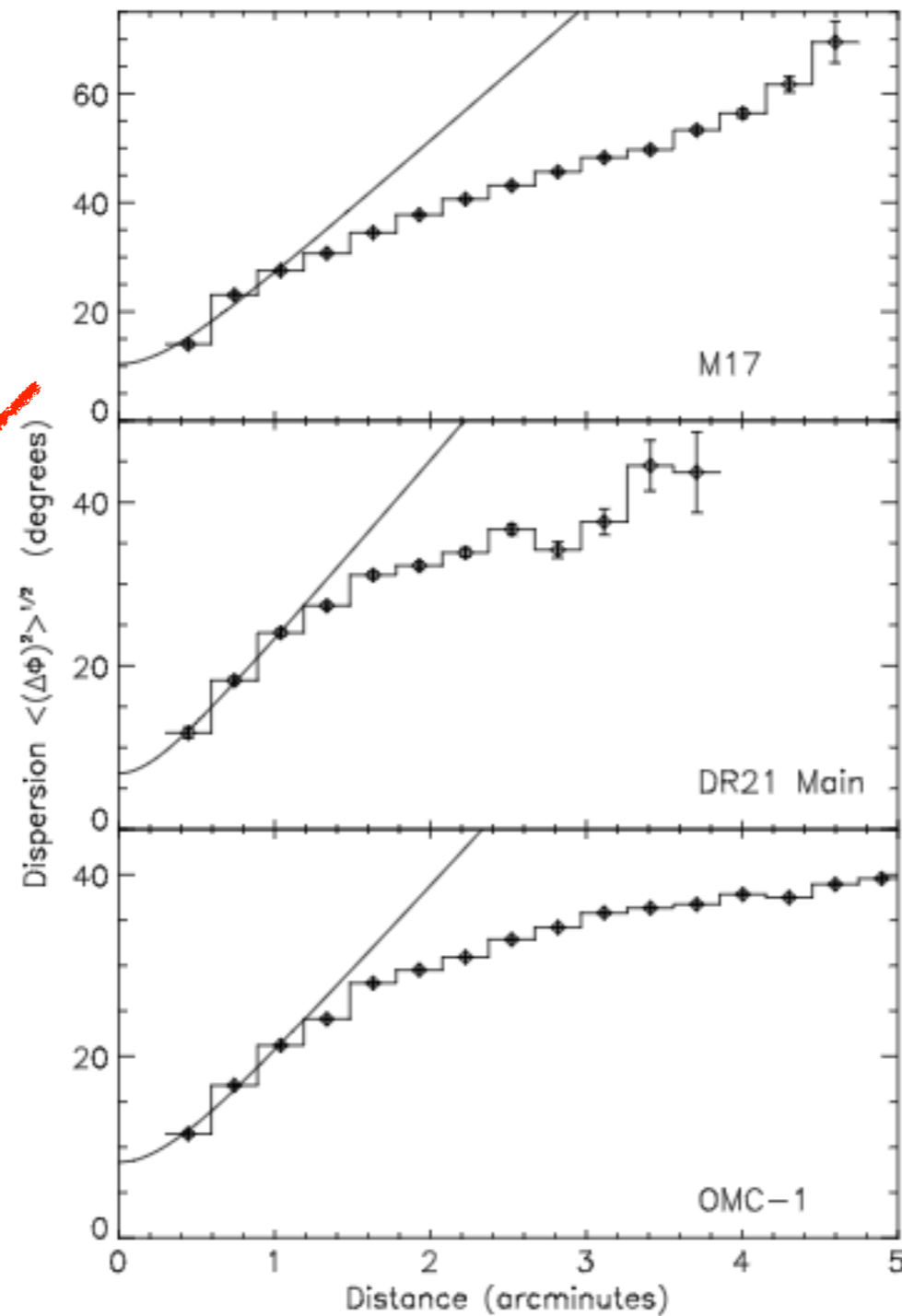
$$\langle \Delta \Phi^2(l) \rangle^{1/2} = \left[ \frac{1}{N(l)} \sum_{i=1}^{N(l)} \{ \Phi(\mathbf{r}) - \Phi(\mathbf{r} + \mathbf{l}) \}^2 \right]^{1/2}$$

# Dispersion Function, a.k.a., Structure F.

From the y intercept,

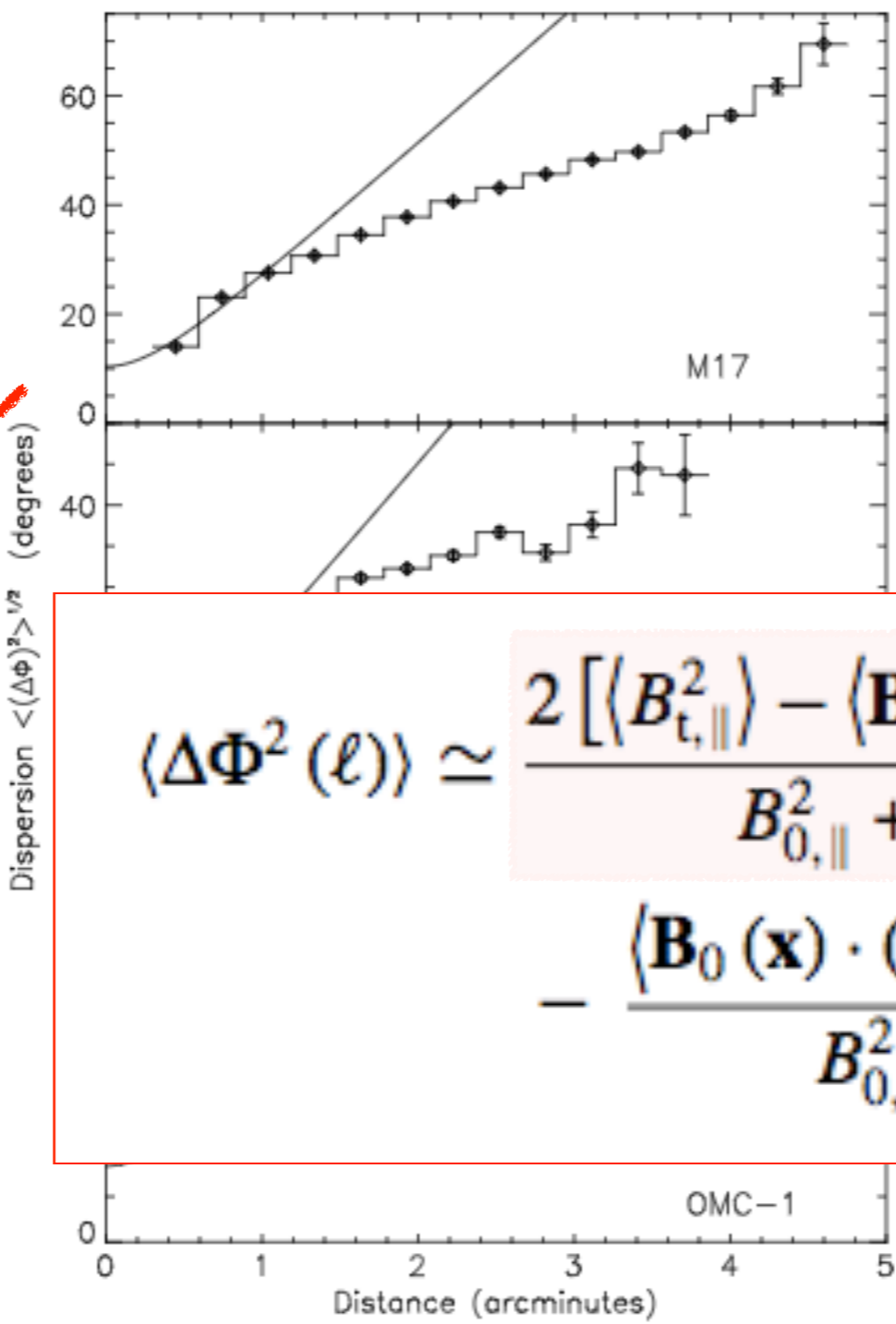
$$\frac{\langle B_{\text{turb}}^2 \rangle^{1/2}}{B_0} = \frac{b^2}{\sqrt{2 - b^2}}$$

$$\frac{\langle B_{\text{turb}}^2 \rangle^{1/2}}{B_0} \rightarrow \frac{\delta B}{B_0}$$



Object	$b^a$ (deg)	$\langle B_t^2 \rangle^{1/2} / B_0^b$	$\sigma(v)$ ( $\text{km s}^{-1}$ )	$B_0^c$ (mG)
OMC-1	$8.3 \pm 0.3$	$0.10 \pm 0.01$	1.85	3.8
M17	$10.4 \pm 0.6$	$0.13 \pm 0.01$	1.66	2.9
DR21(Main)	$6.8 \pm 1.3$	$0.08 \pm 0.02$	4.09	10.6

# Dispersion Function, a.k.a., Structure F.



From the y intercept,



$$\frac{\langle B_{\text{turb}}^2 \rangle^{1/2}}{B_0} = \frac{b^2}{\sqrt{2 - b^2}}$$

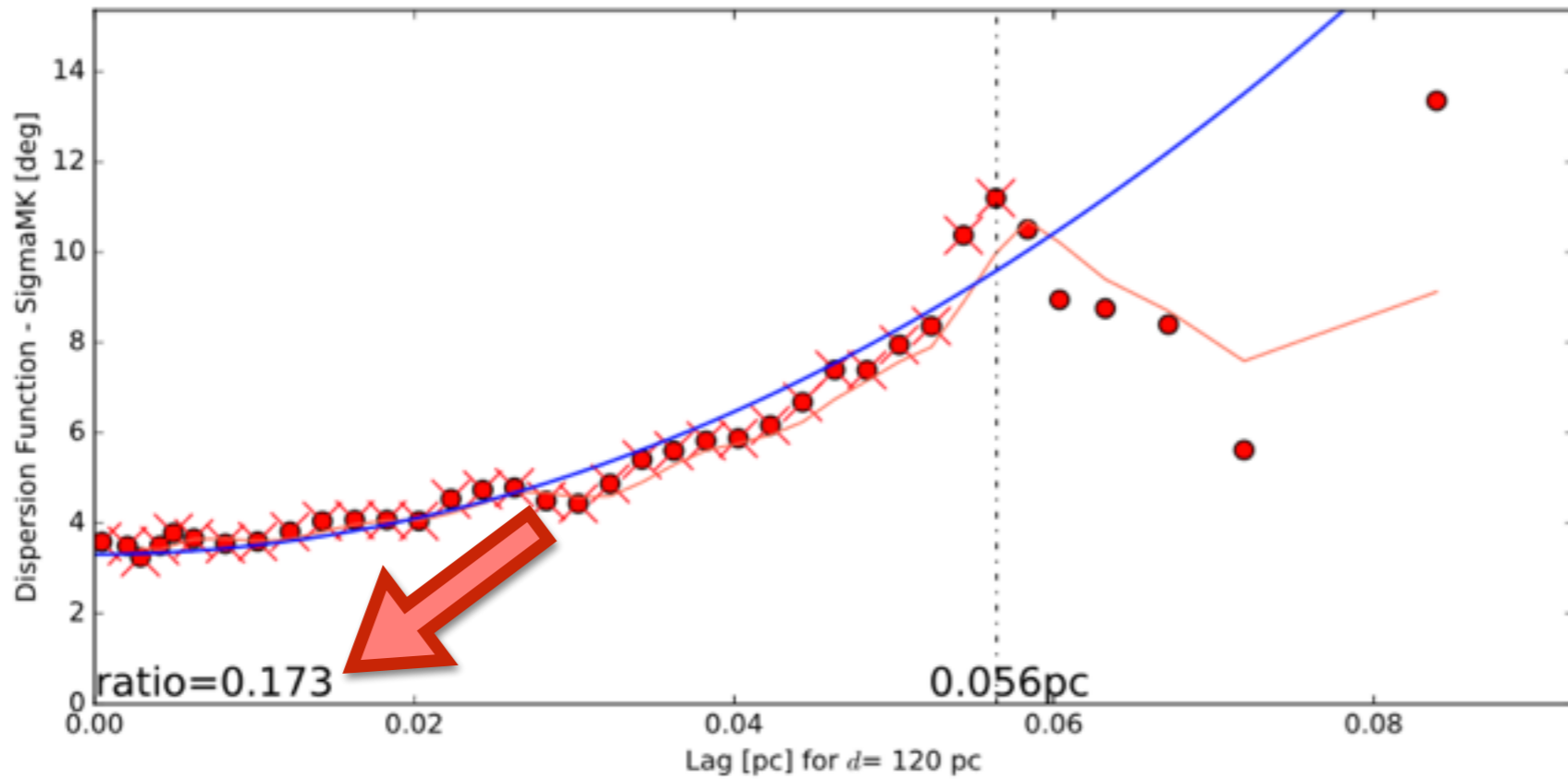
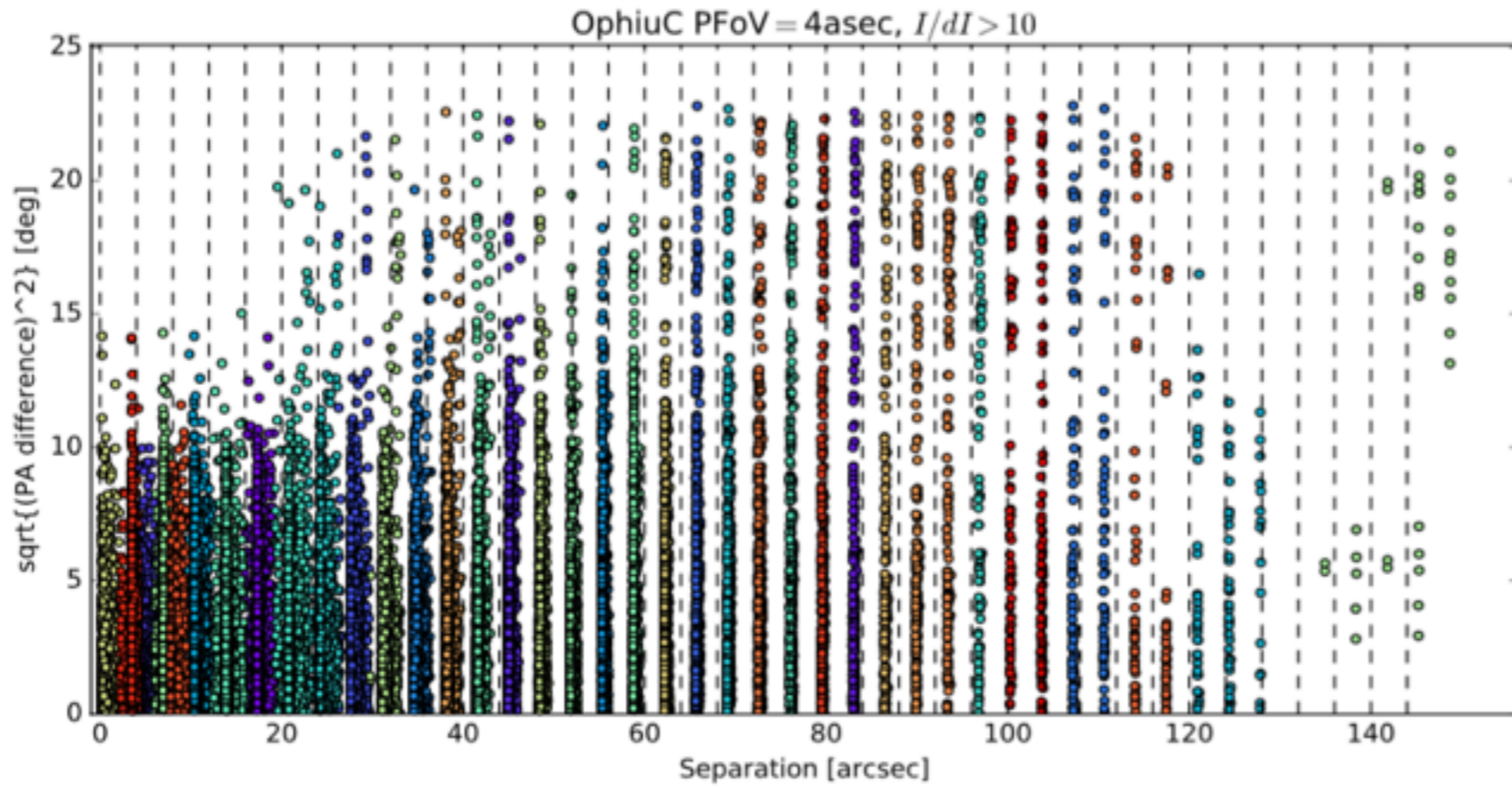
$$\frac{\langle B_{\text{turb}}^2 \rangle^{1/2}}{B_0} \rightarrow \frac{\delta B}{B_0}$$

$$\langle \Delta\Phi^2(\ell) \rangle \simeq \frac{2 [\langle B_{t,\parallel}^2 \rangle - \langle \mathbf{B}_{t,\parallel} \cdot \mathbf{B}_{t,\parallel}(\ell) \rangle]}{B_{0,\parallel}^2 + \langle B_{t,\parallel}^2 \rangle} - \frac{\langle \mathbf{B}_0(\mathbf{x}) \cdot (\mathbf{e}_\ell \cdot \nabla)^2 \mathbf{B}_0(\mathbf{x}) \rangle}{B_{0,\parallel}^2 + \langle B_{t,\parallel}^2 \rangle} \ell^2, \quad (\text{A21})$$

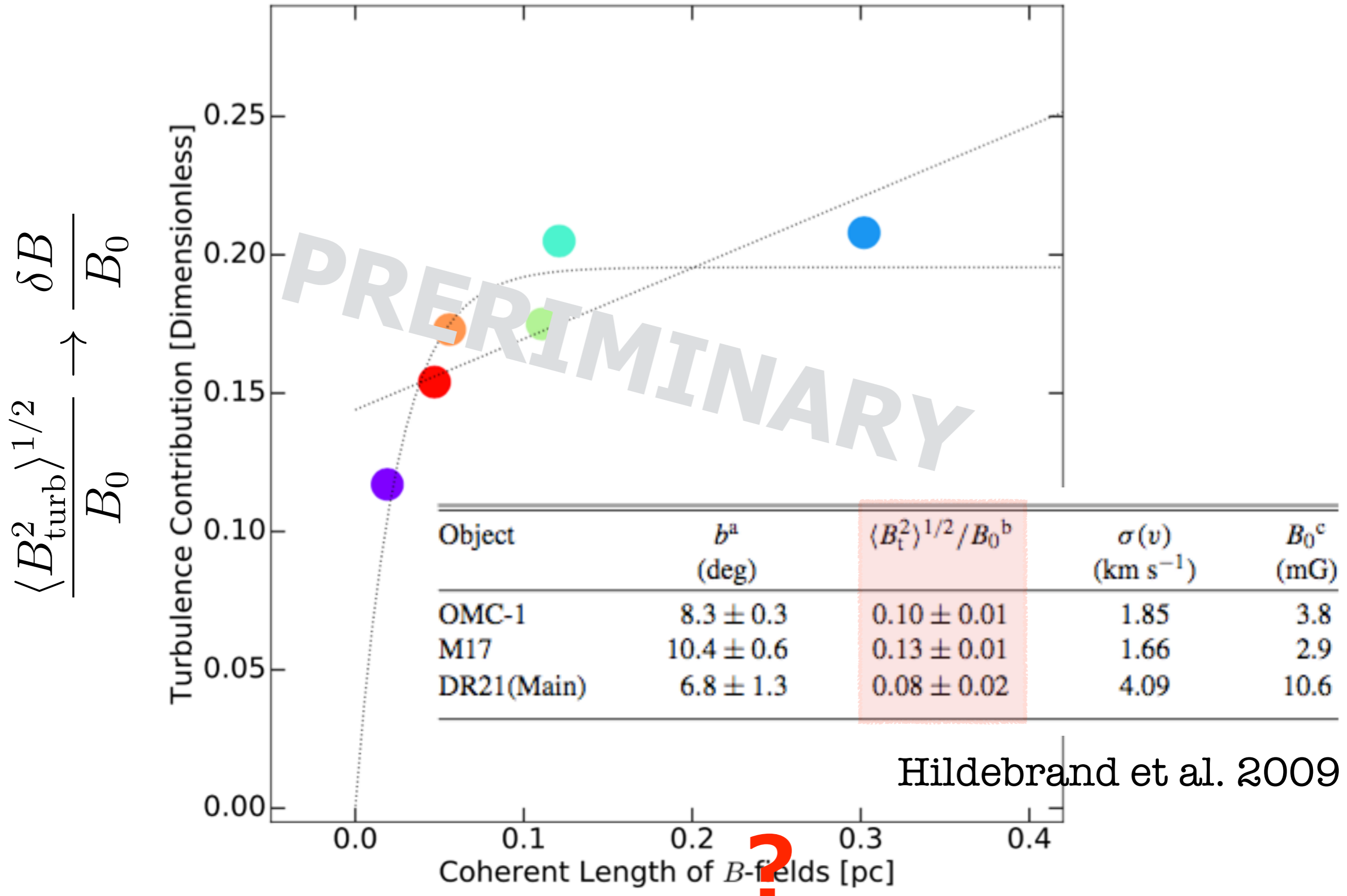
Object	$b^a$ (deg)	$\langle B_t^2 \rangle^{1/2} / B_0^b$	$\sigma(v)$ (km s <sup>-1</sup> )	$B_0^c$ (mG)
OMC-1	8.3 ± 0.3	0.10 ± 0.01	1.85	3.8
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DR21(Main)	6.8 ± 1.3	0.08 ± 0.02	4.09	10.6

# Dispersion Function, a.k.a., Structure F.

$$\langle \Delta \Phi^2(l) \rangle - \sigma_M^2(l) \simeq b^2 + m^2 l^2$$



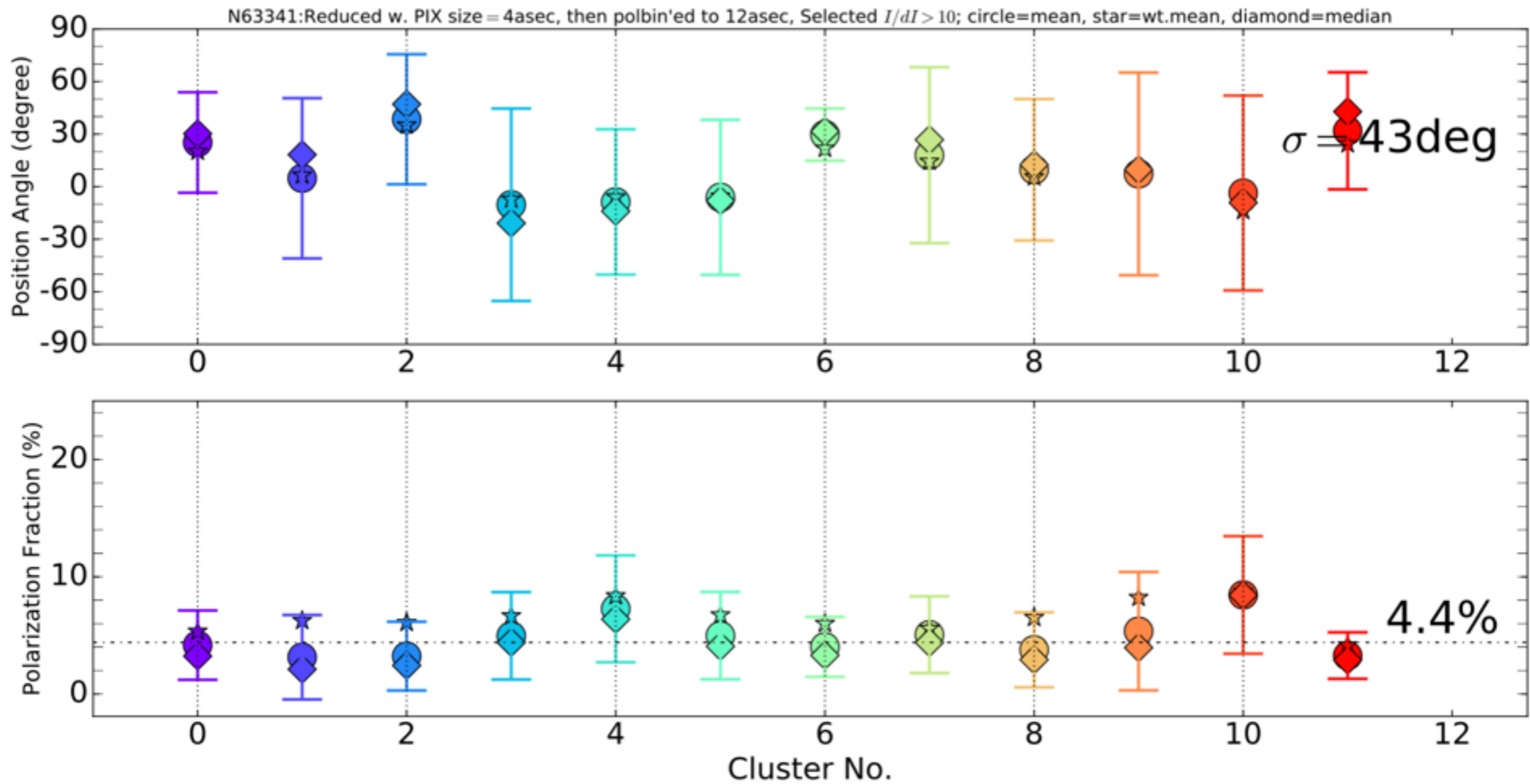
# Dispersion Function Analysis: Summary



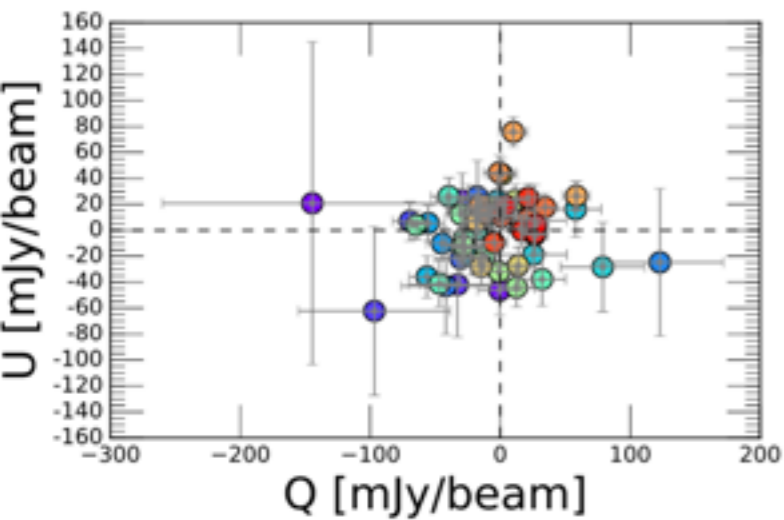


***Inside Clusters: Ordered or Random?***

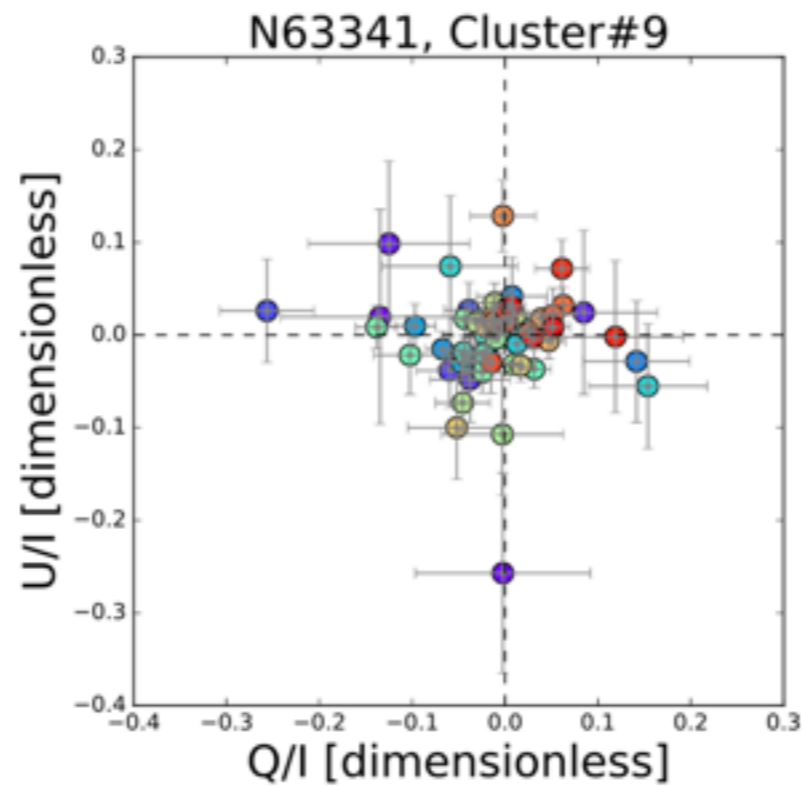
# Polarization Structure : 0.1 pc scale



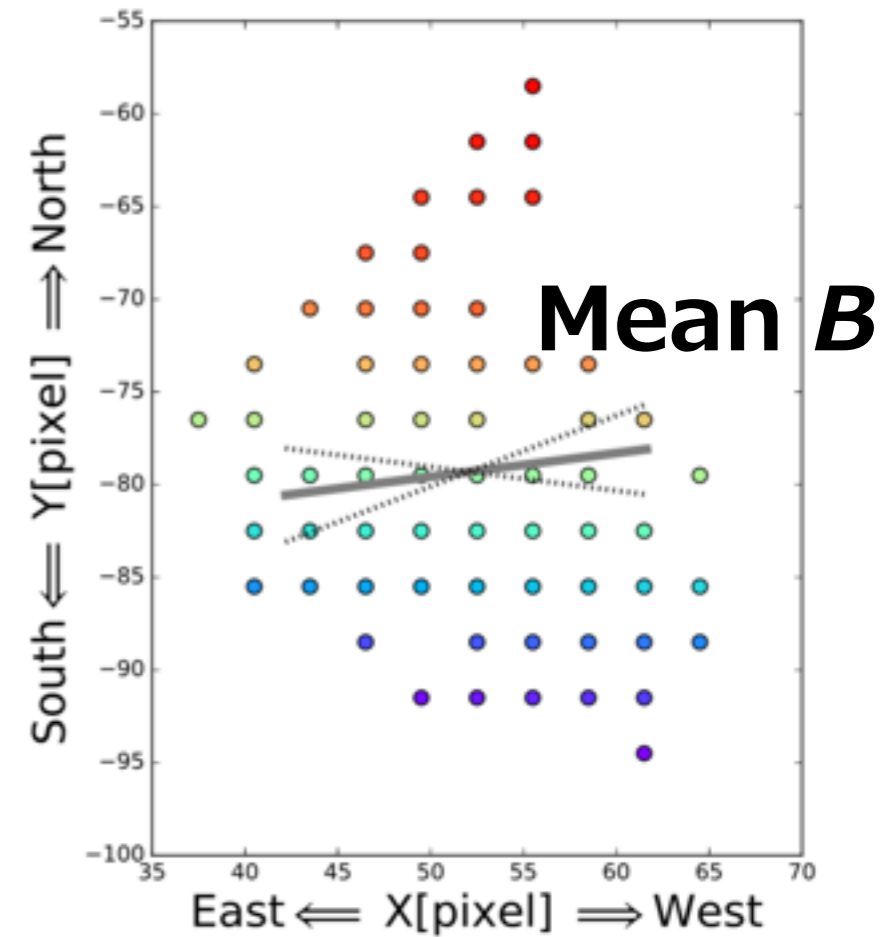
# Polarization Structure : 0.1 pc scale



$Q$  vs.  $U$



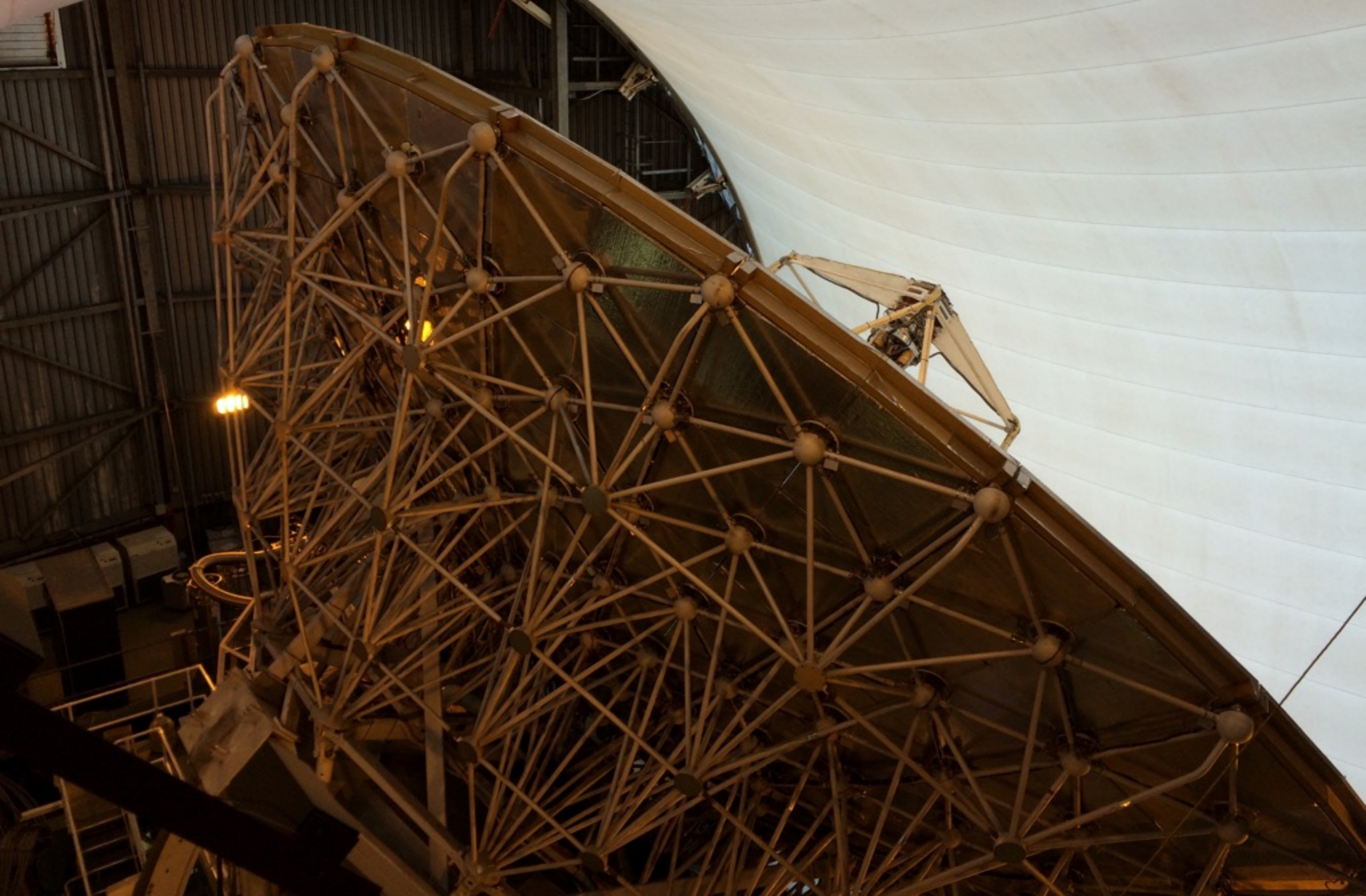
$\frac{Q}{I}$  vs.  $\frac{U}{I}$



$x$  vs.  $y$

***Single or Double?***

***90<sup>deg</sup>?***



***A Comparison w. Molecular Line Data***

# Oph A-F: *B*-fields vs. $C^{18}O$ $J=3-2$

Total Integrated  
Intensity Map

# Oph A-F: *B*-fields vs. $C^{18}O$ $J=3-2$

Centroid  
Velocity Map

# Oph A-F: *B*-fields vs. $C^{18}O$ $J=3-2$

Velocity  
Dispersion

 ***Future Works***

# 磁場込みの0.01pcスケールの新しい描像へ

2017 2018 2019 2020 2021

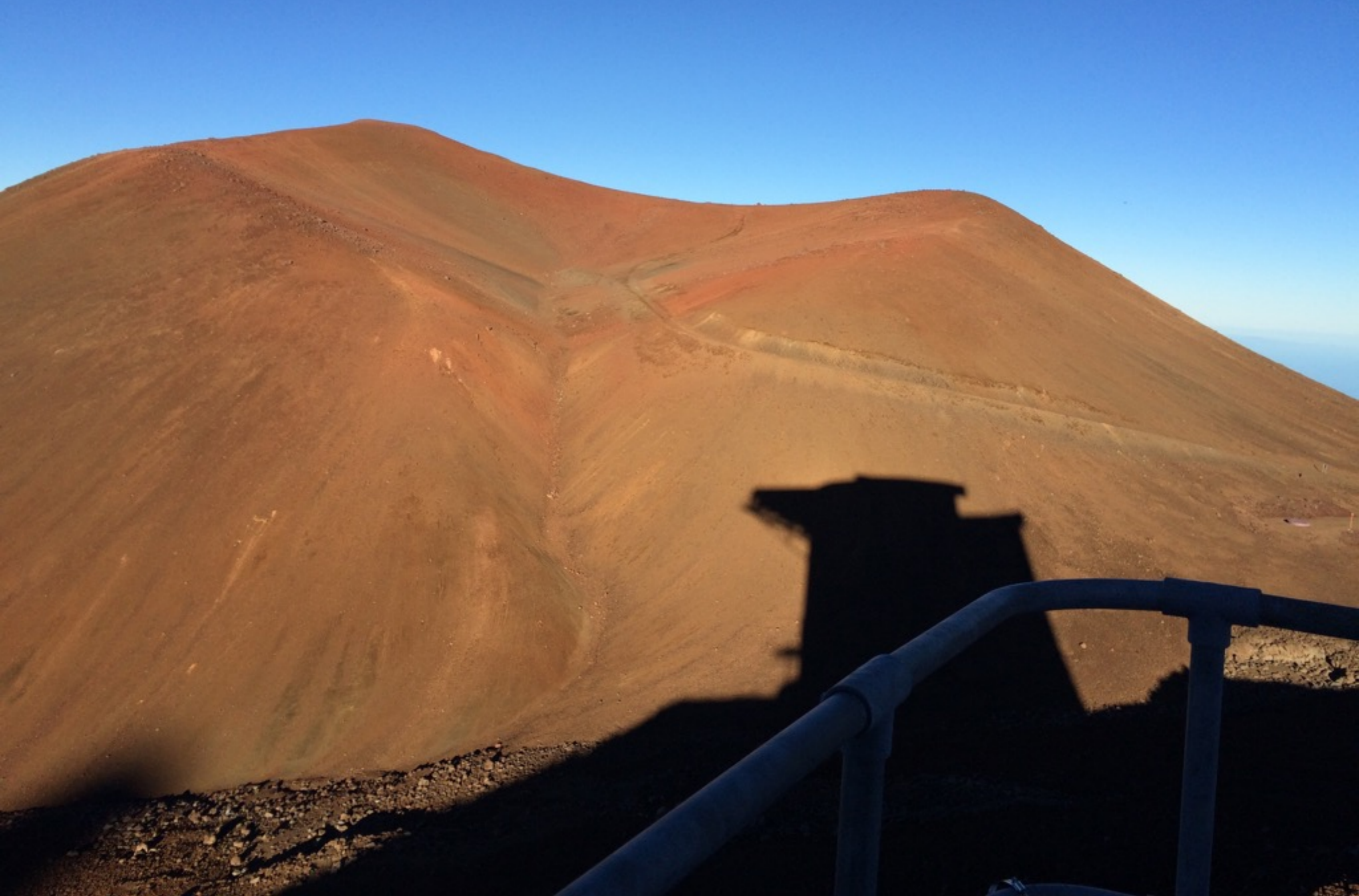
POL-2観測：**BISTRO** →

ALMA個別(パイロット)観測

→  
Cycle 5 観測    Cycle 6 提案    Cycle 7 提案

ALMAラージプログラム提案

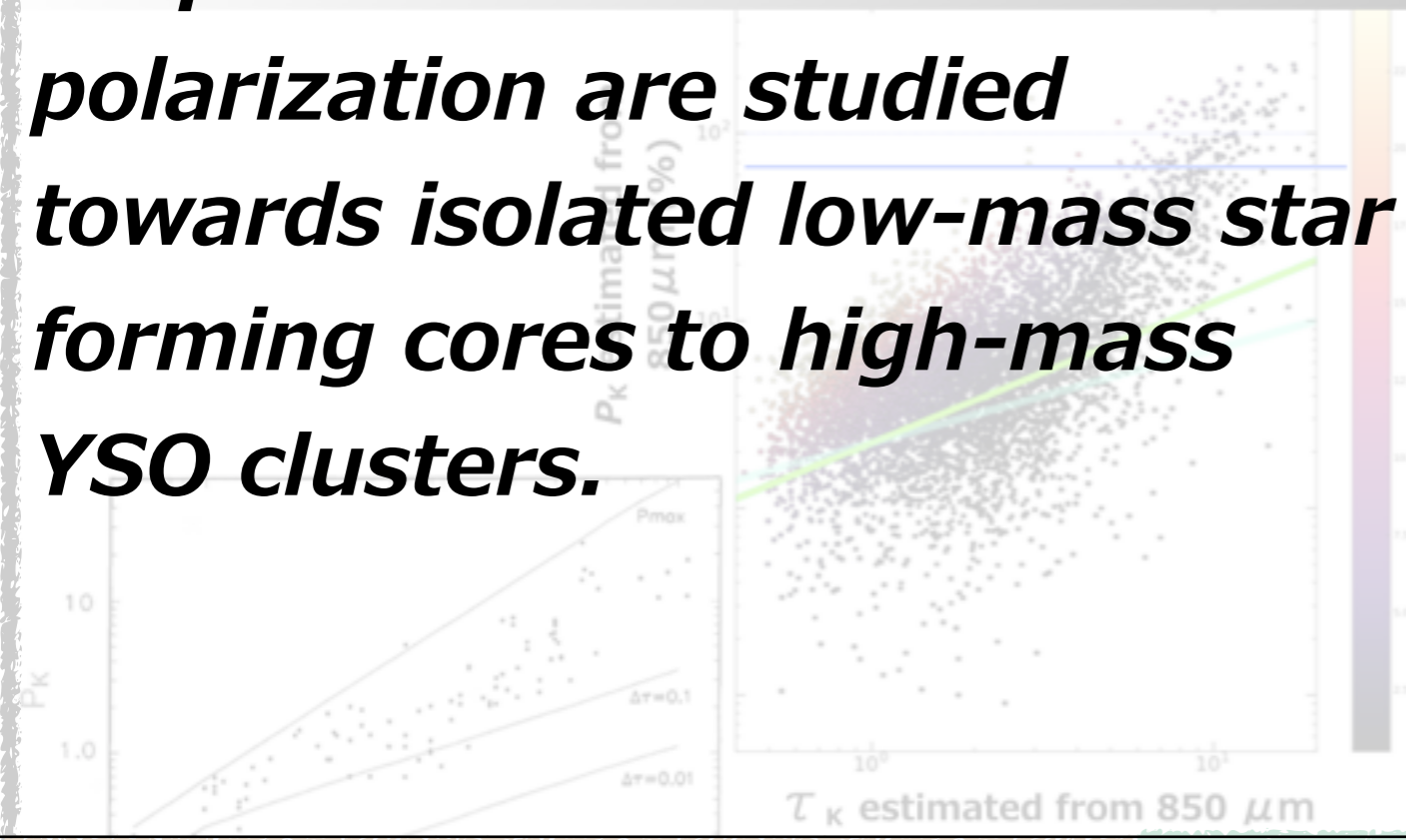




# ***Summary***

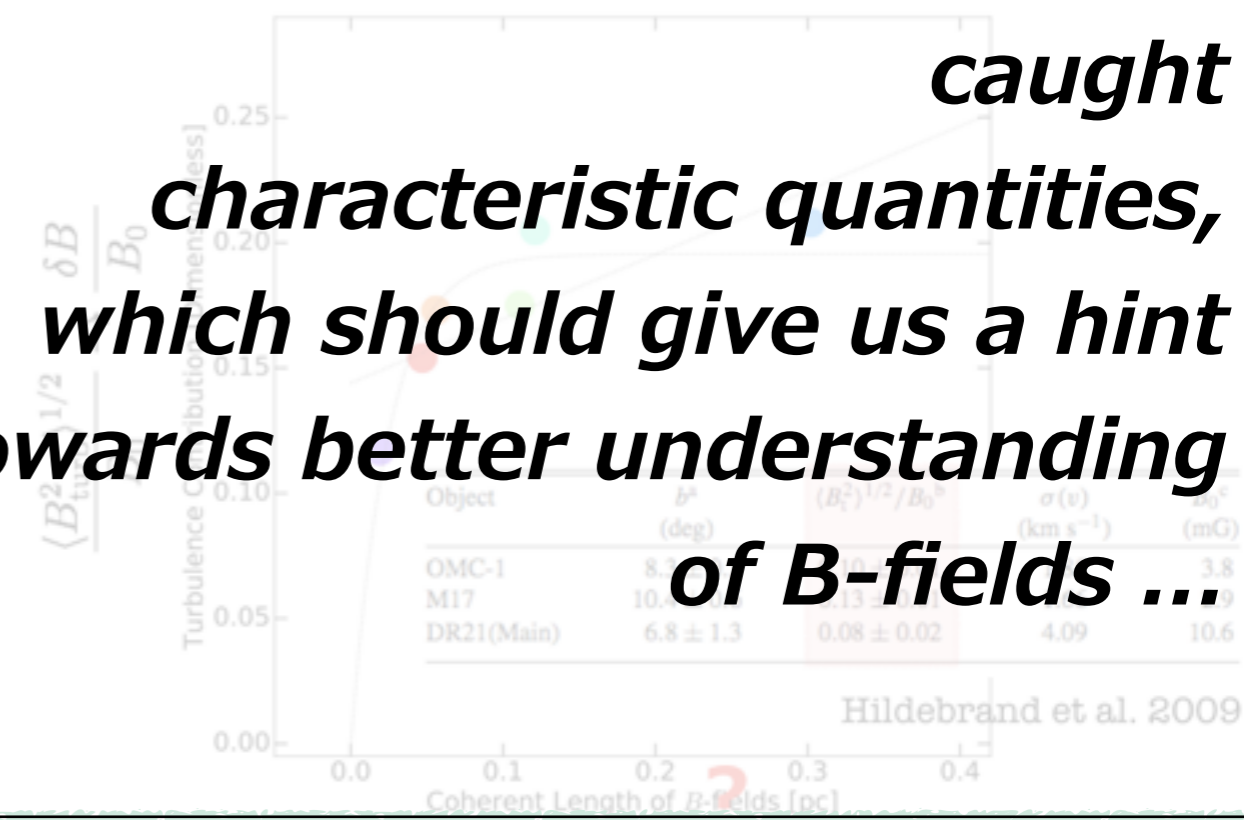
**Properties of submm  $s = 850 \mu\text{m}$ ,  $\rho$**

**polarization are studied towards isolated low-mass star forming cores to high-mass YSO clusters.**



**Structure Function Analysis**

**caught characteristic quantities, which should give us a hint towards better understanding of B-fields ...**

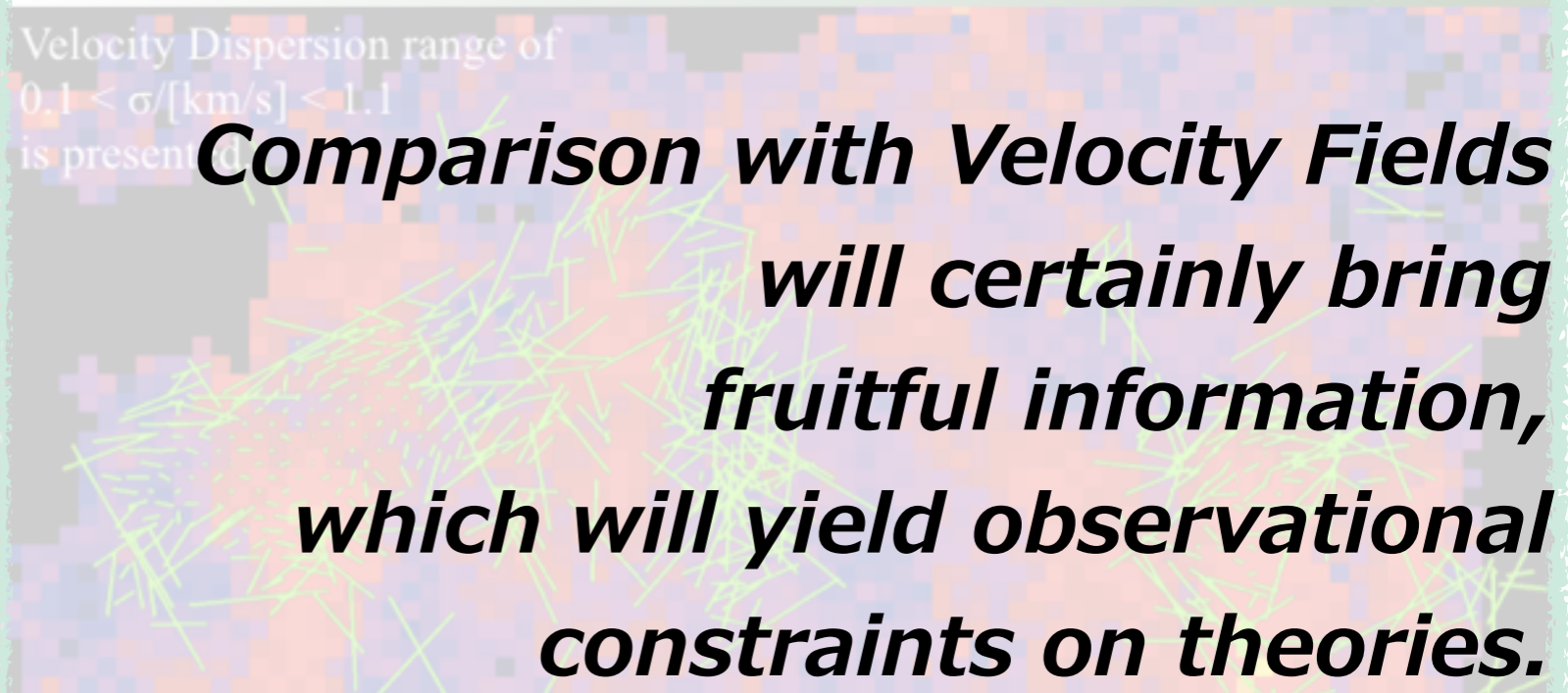


**Polarization Structure : 0.1 pc scale**



**Zooming Up Clusters:  
Ordered  
or  
Single or Random?  
Random?  
90<sup>deg</sup>?**

**Oph A-F: B-fields vs.  $\text{C}^{18}\text{O}$   $J=3-2$  Velocity Dispersion**



**Summary**