Grain Alignment and Magnetic Field at the Galactic Centre from Polarized Dust Emission

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SOFIA Tele-Talk Series

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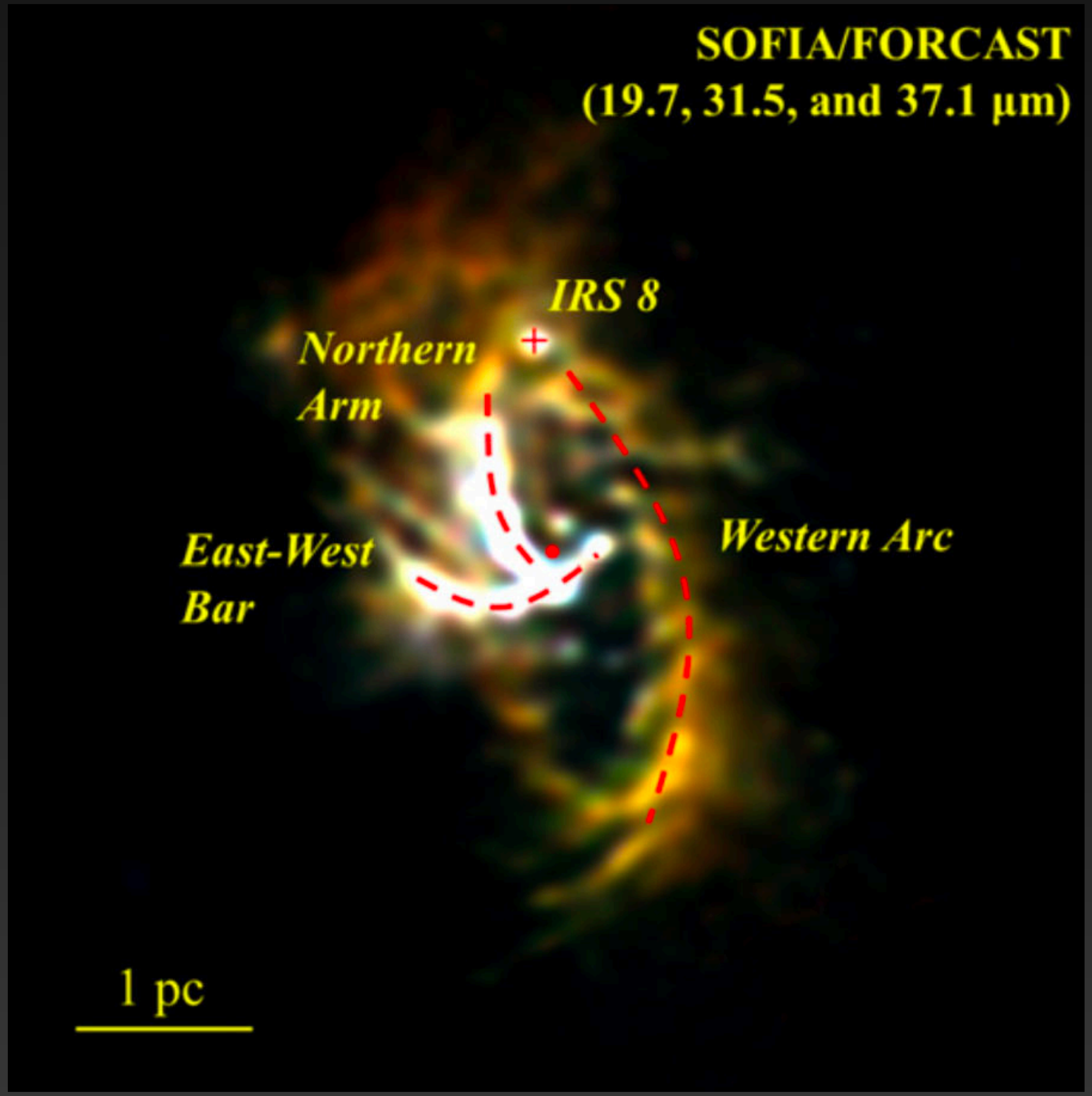
ENVIRONMENT AROUND Sgr A*

- Exotic environment
- Molecular and ionic gas streams
- Closest molecular reservoir to the Galactic Centre
- Drop in p due to change in B-field direction or other physical process?
- Role of B-field in kinematics

Also, beautiful data!

Circumnuclear Disk (CND)
Density ~ 10^5 - 10^6 cm^{-3}
B ~ 2 - 10 mG



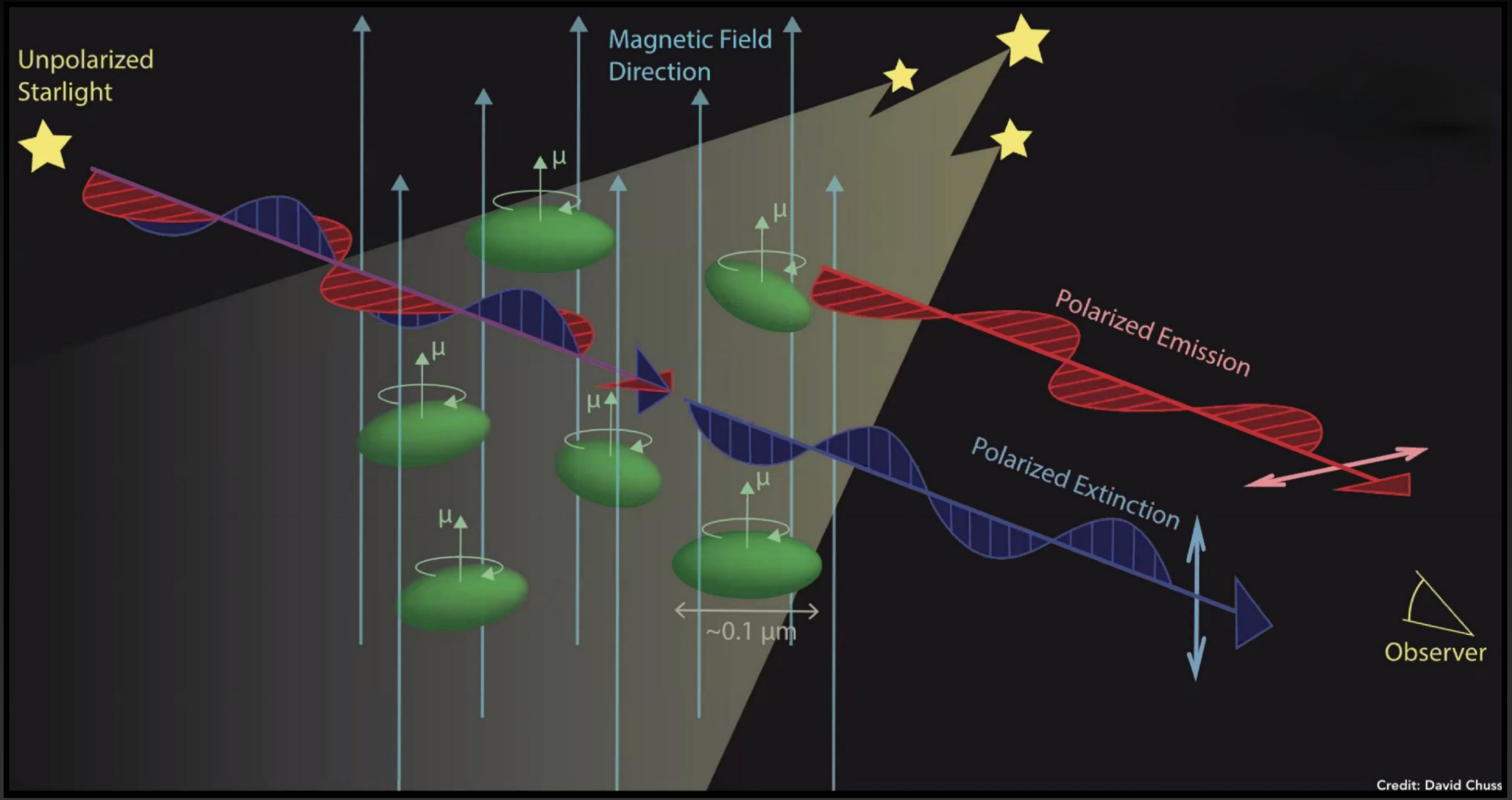
(Lau et al. 2013)

Credit: NASA/SOFIA/D. Dowell/W. Reach/L Proudfit

POLARIZATION

- ➡ Grain Elongation

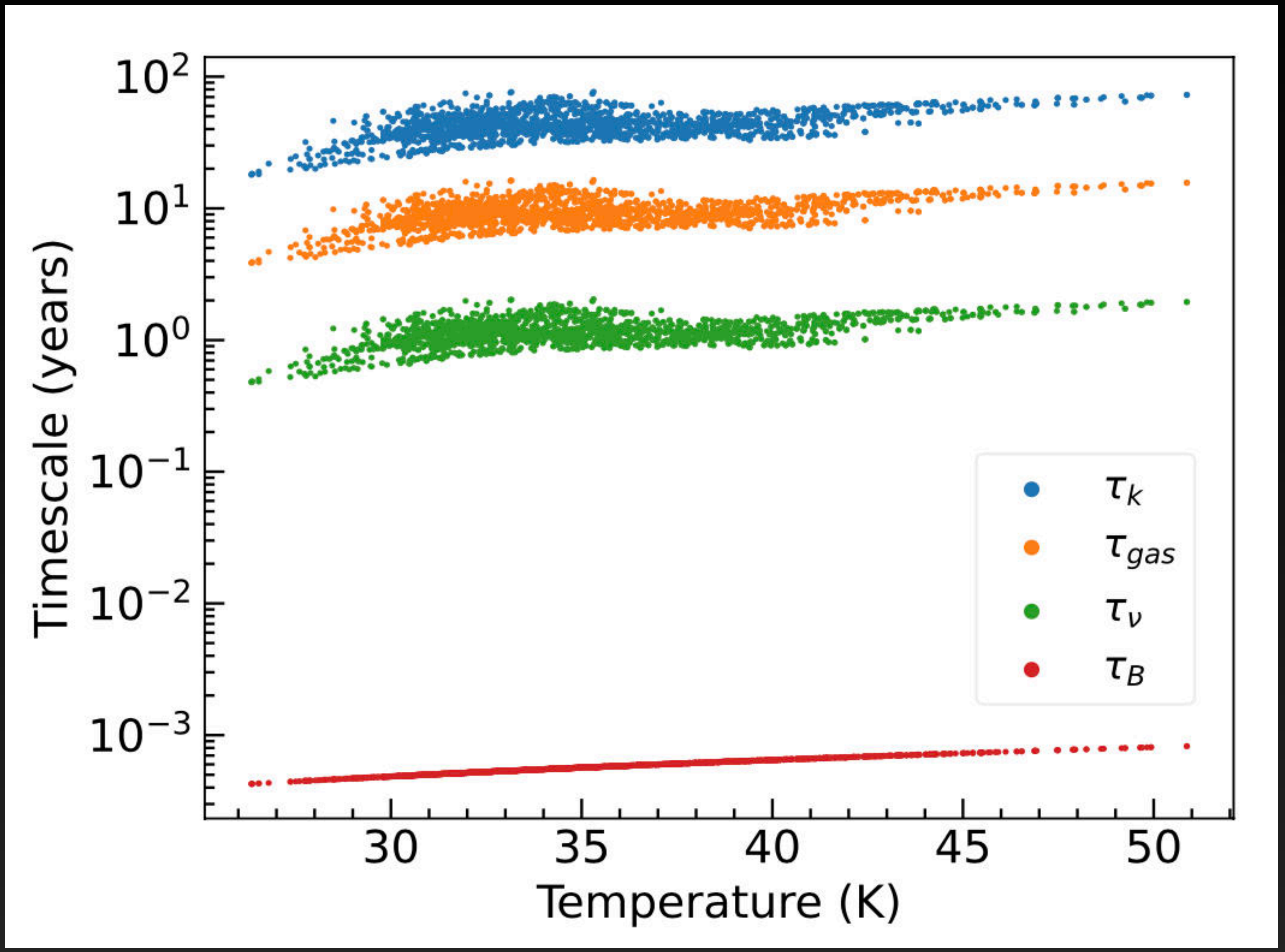
- ➡ Grain Alignment
- Internal Alignment
- External Alignment

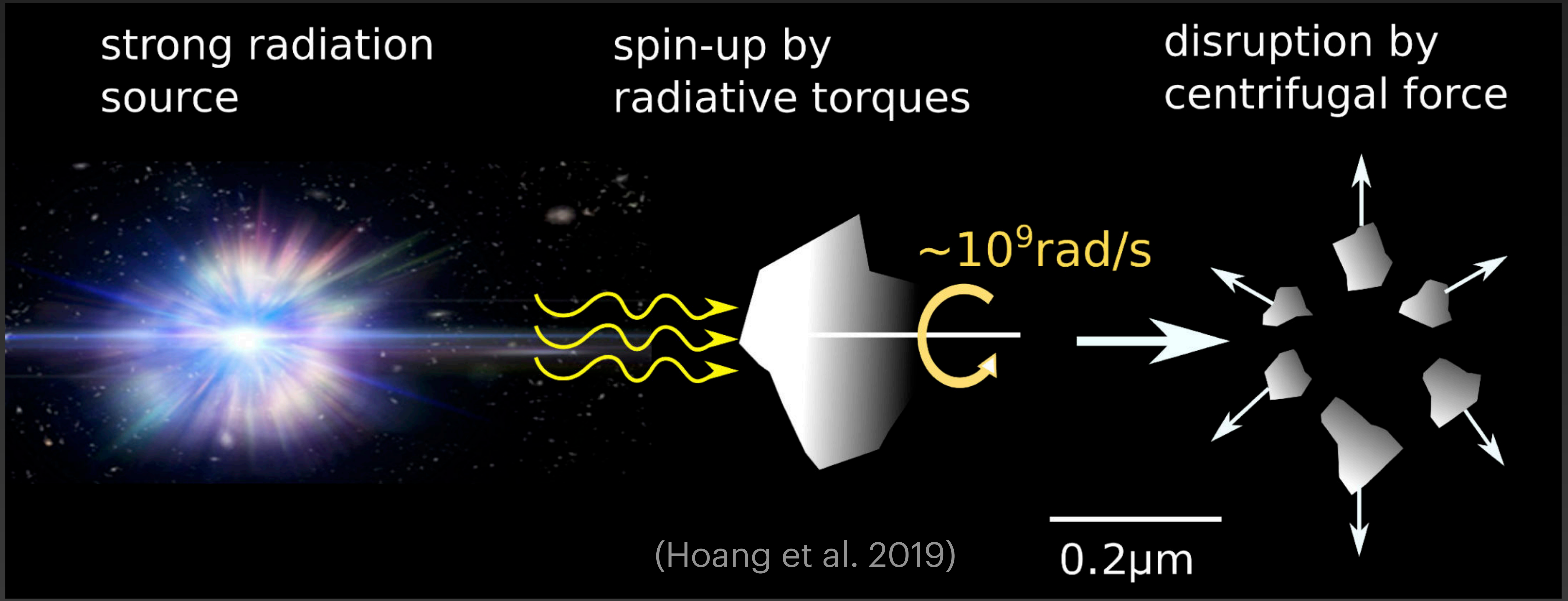


EXTERNAL ALIGNMENT

- MEchanical Torques
  (METs; Lazarian & Hoang 2007)
- RAdiative Torques
  (RATs; Dolginov & Mitrofanov 1976)
  - RAT Disruption
    (RAT-D; Hoang et al. 2019)
  - RAT + Magnetic Relaxation
    (Davis & Greenstein 1951)
    Magnetically Enhanced RAT
    (MRAT; Hoang et al. 2022)

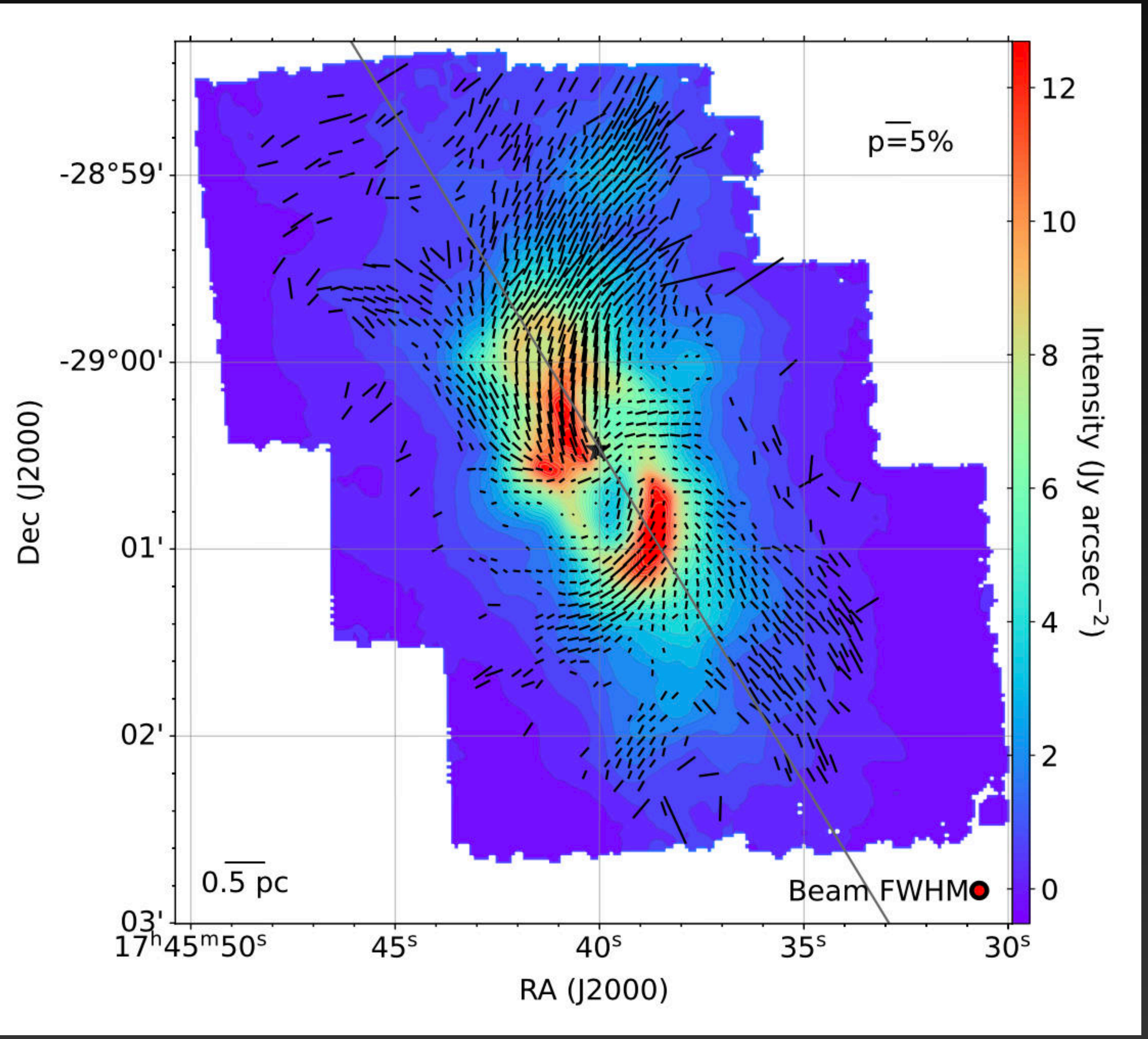
Suprathermal Rotation!



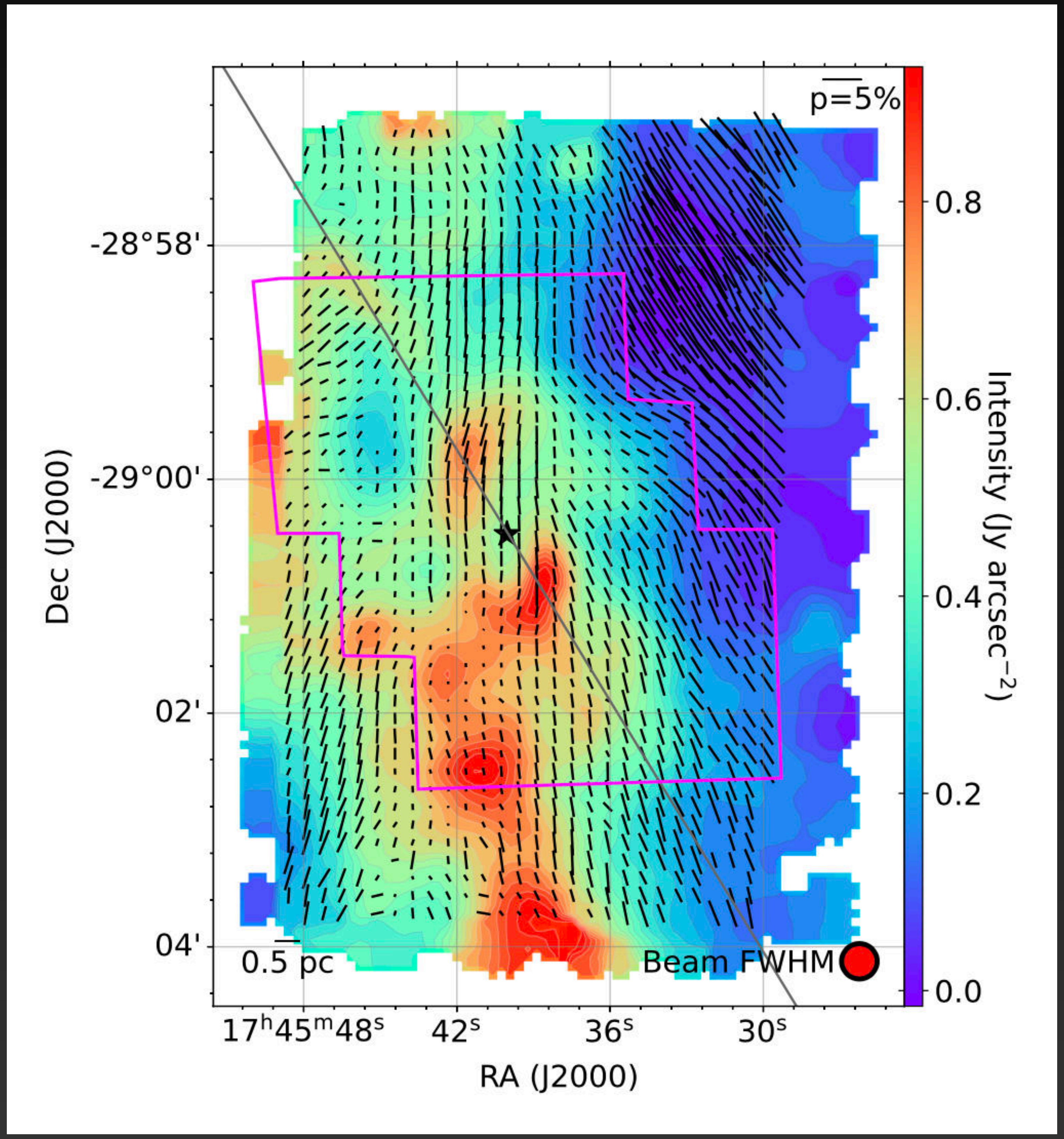


OBSERVATIONS

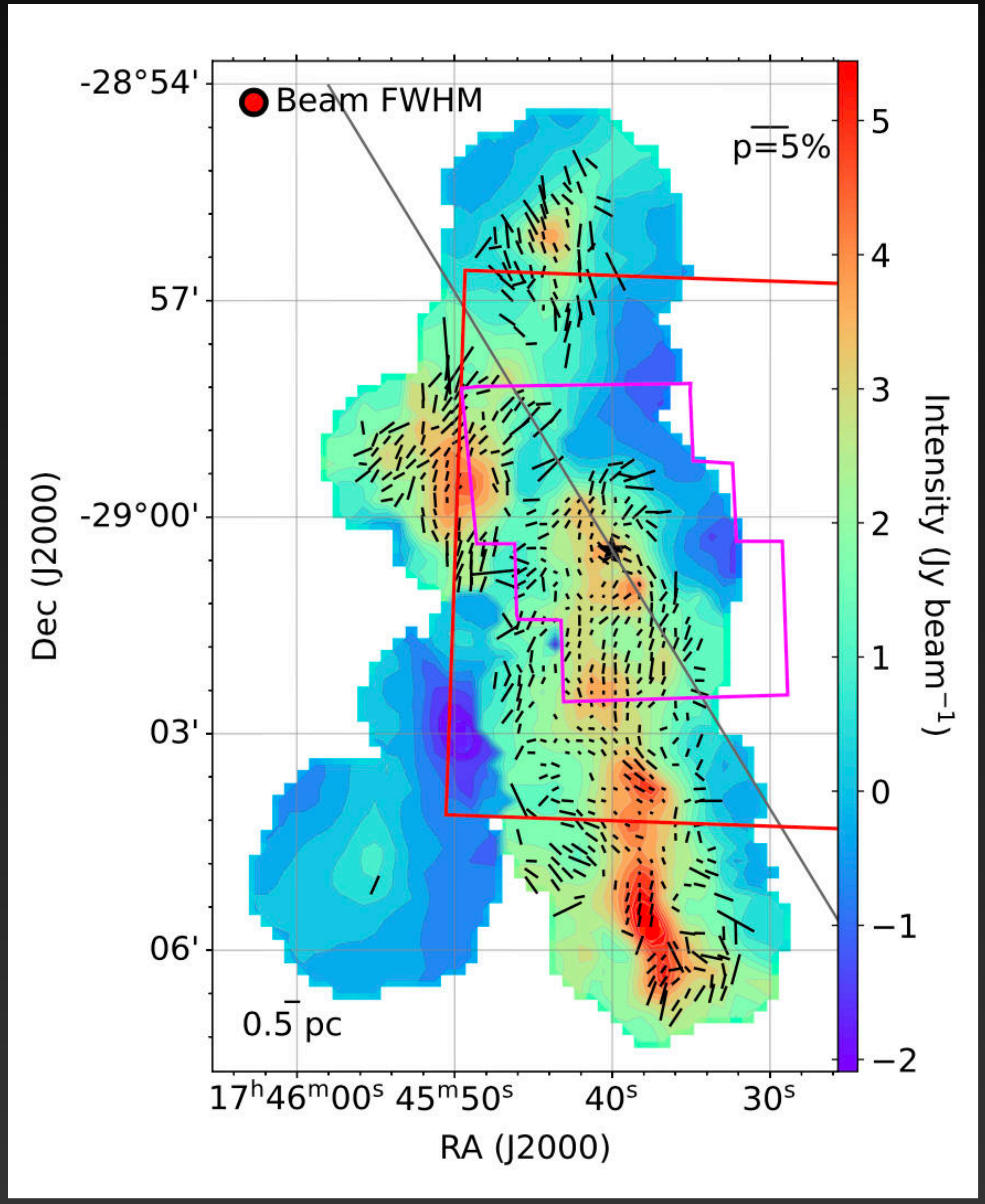
Physical scale: 0.2 - 0.8 pc with FOV: 10 - 30 pc (Beam size: 4.85′′, 18.5′′, and 20′′)



SOFIA/HAWC+ 53 μm

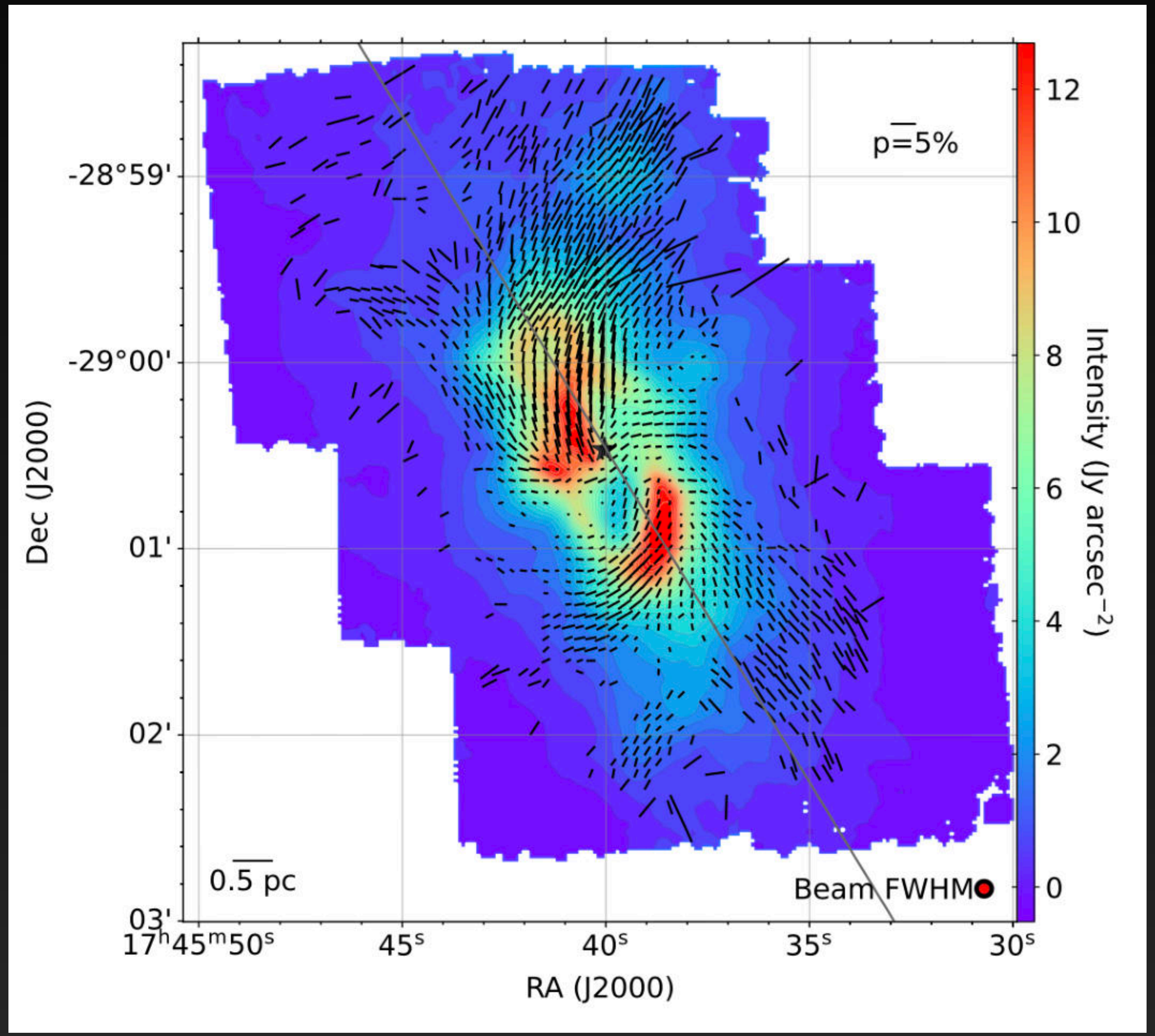


SOFIA/HAWC+ 216 μm



JCMT/SCUPOL 850 μm

B-FIELD MORPHOLOGY



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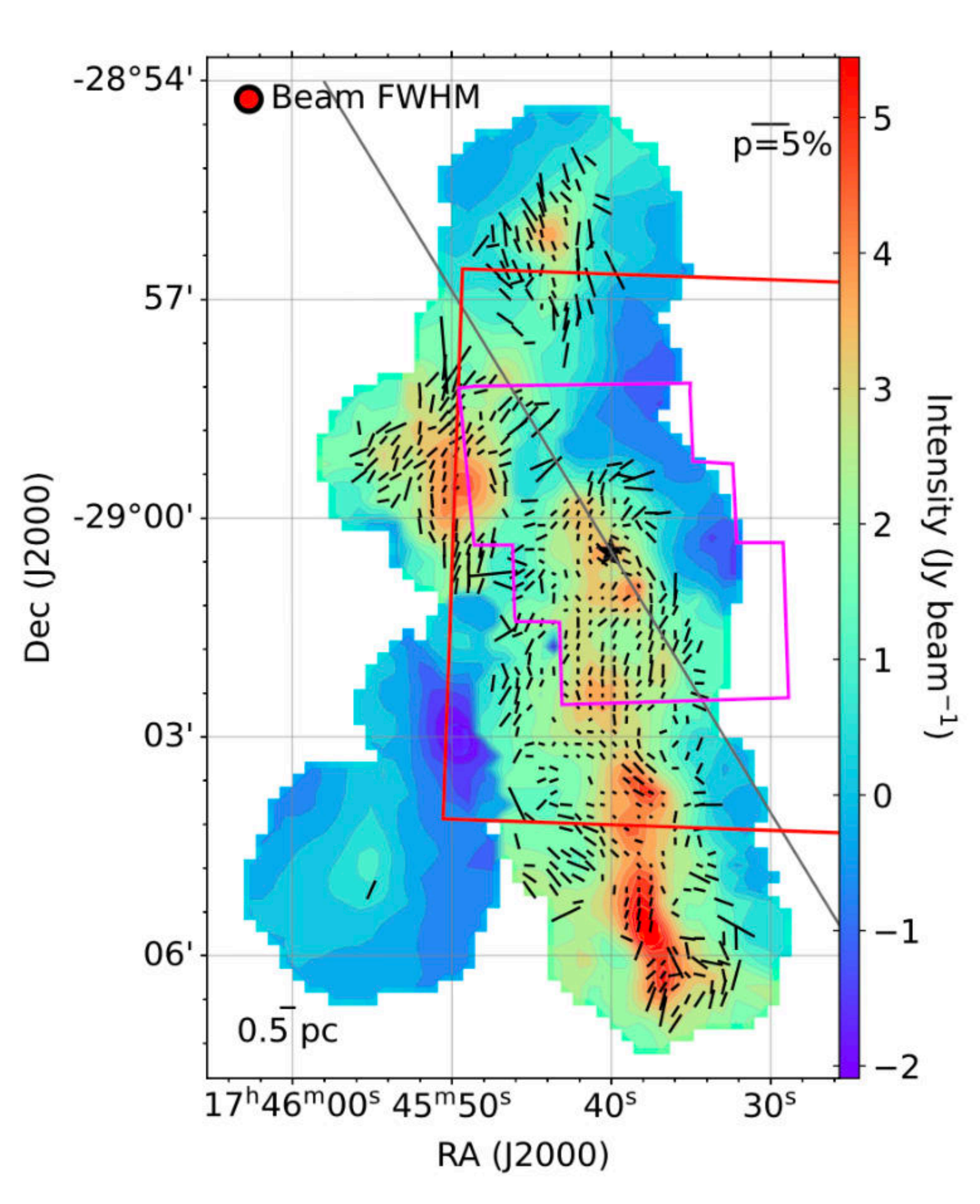
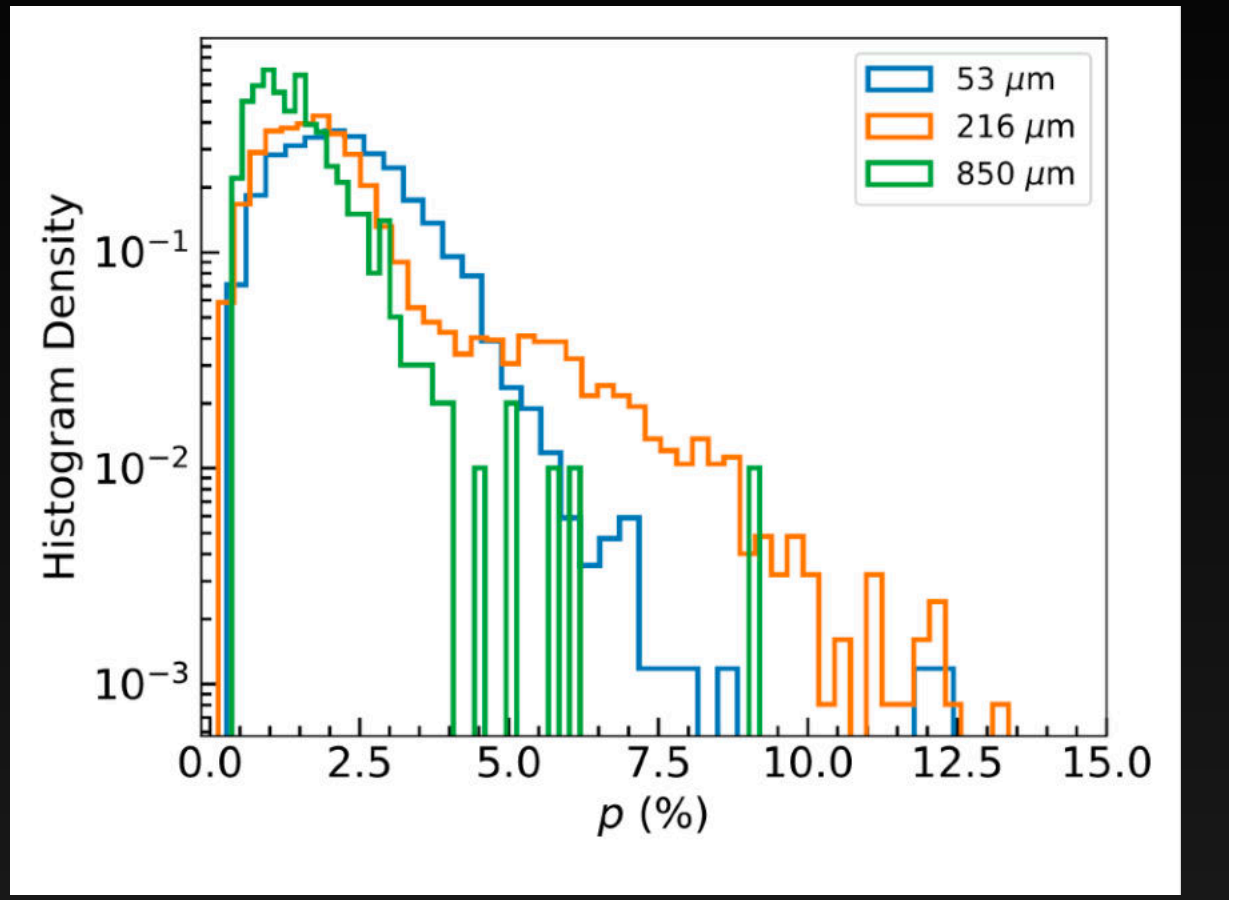
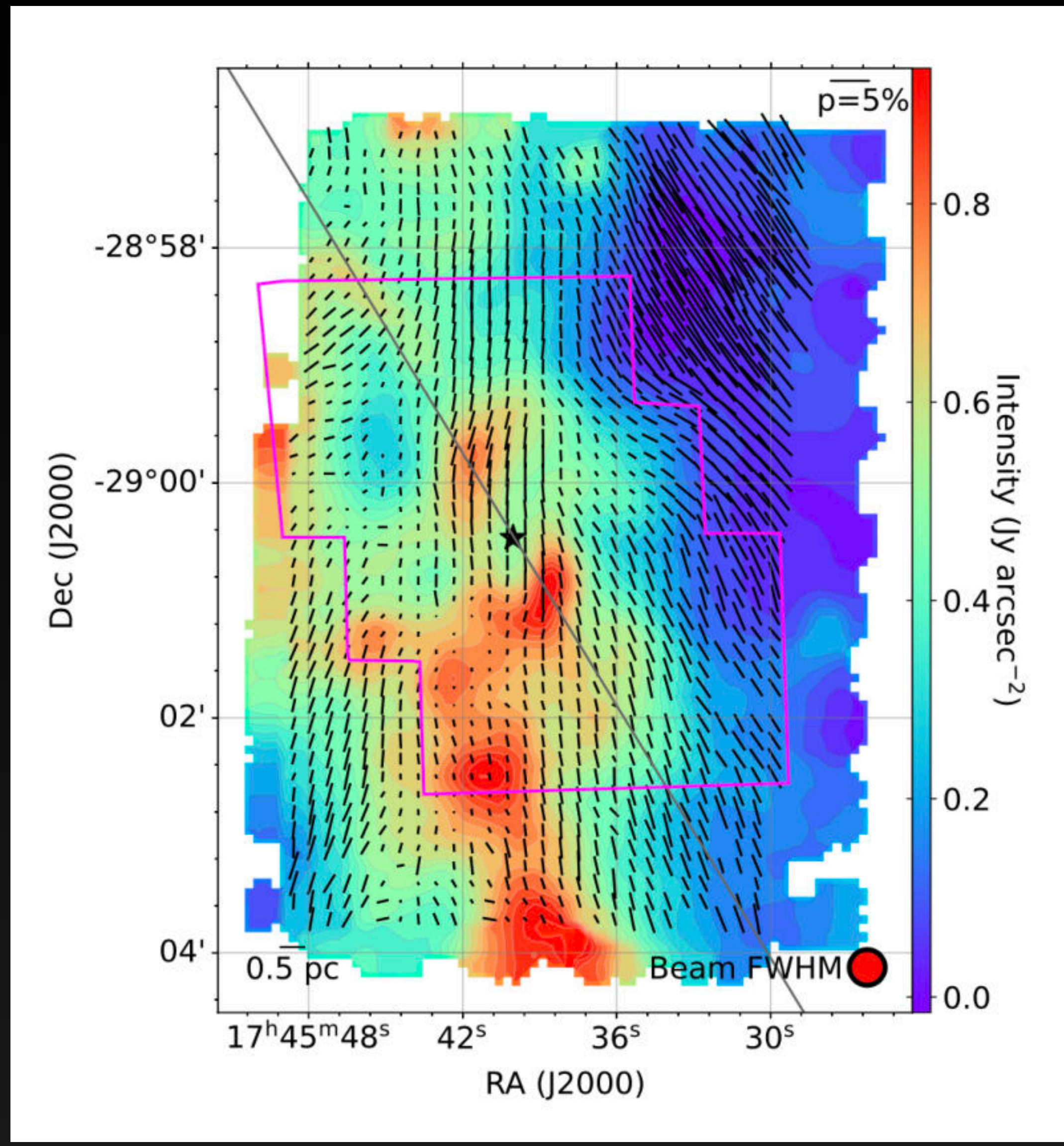


JCMT/SCUPOL 850 µm

Spiral structure in 53 µm and 850 µm



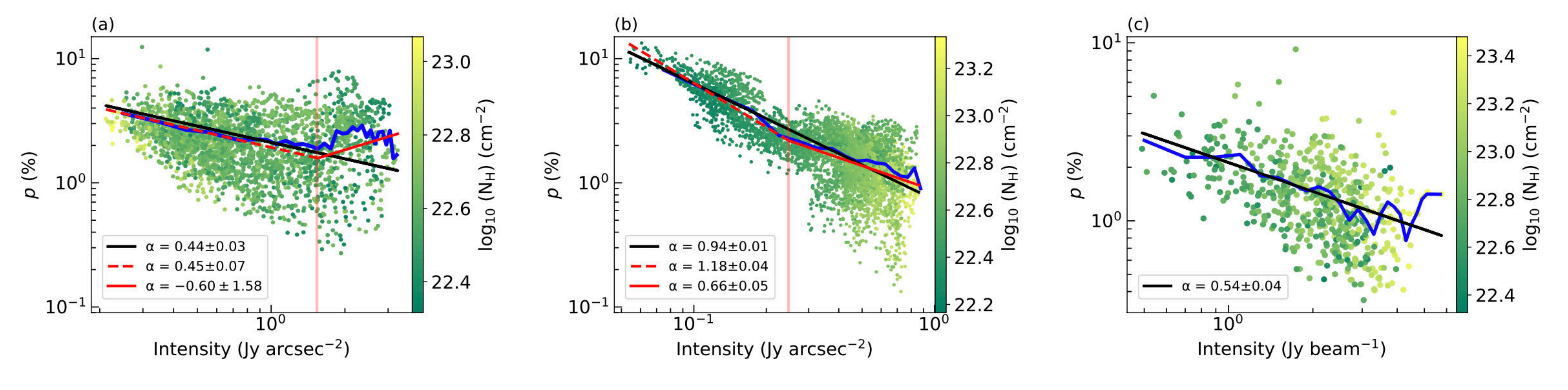


SOFIA/HAWC+ 216 µm

- Diffuse regions
  - Alignment along the Galactic plane
  - Highest polarization degree
- Maximum polarization at 216 µm
  - Above the Galactic plane

Drop in *p* due to change in field direction or grain alignment?

POLARIZATION DEGREE vs. INTENSITY



Intensity traces column density at long wavelengths

Expected Relation: $p \propto I^{-\alpha}$

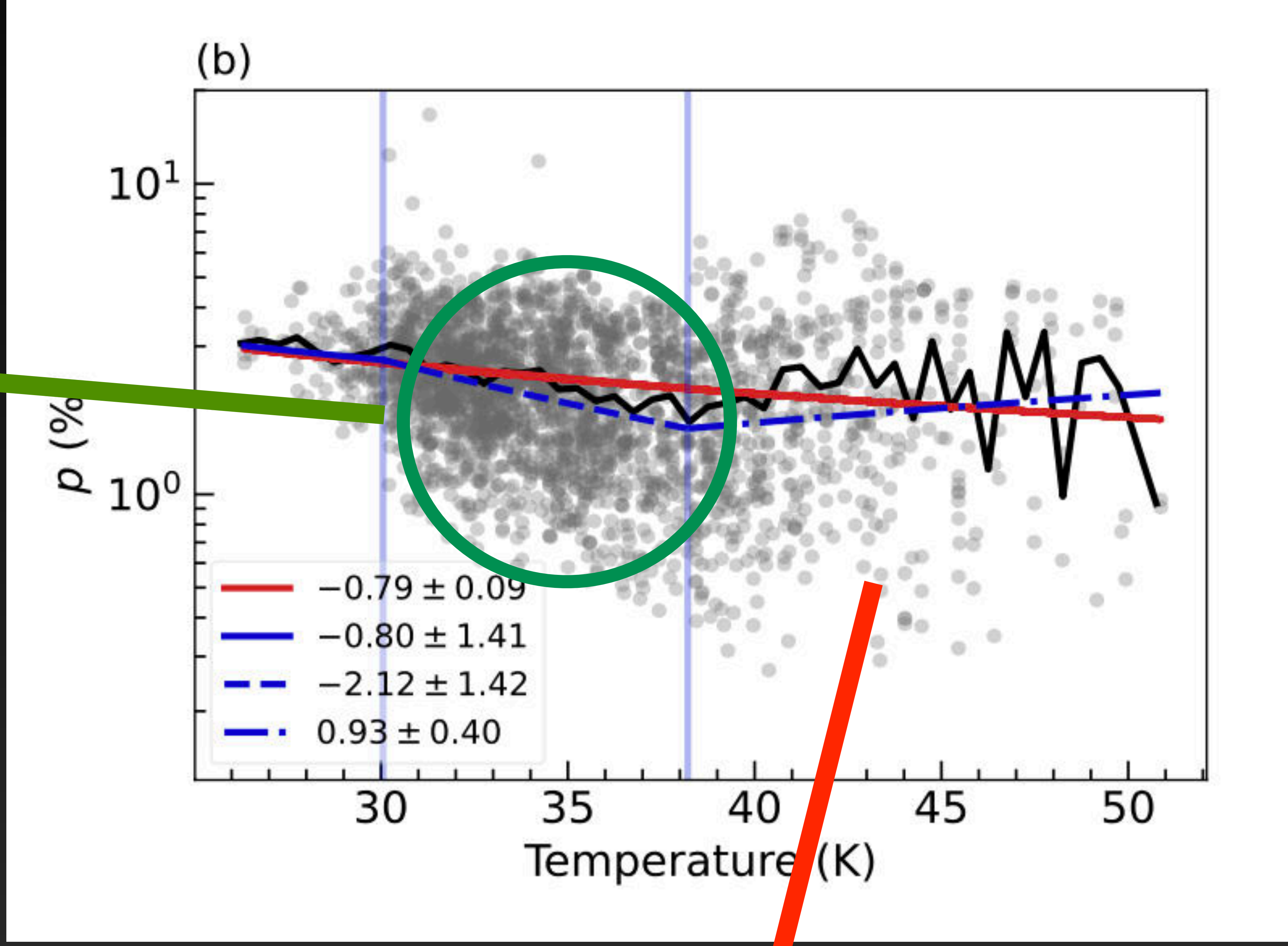
$\alpha = 0 \Rightarrow$ uniform grain alignment for all N(H)

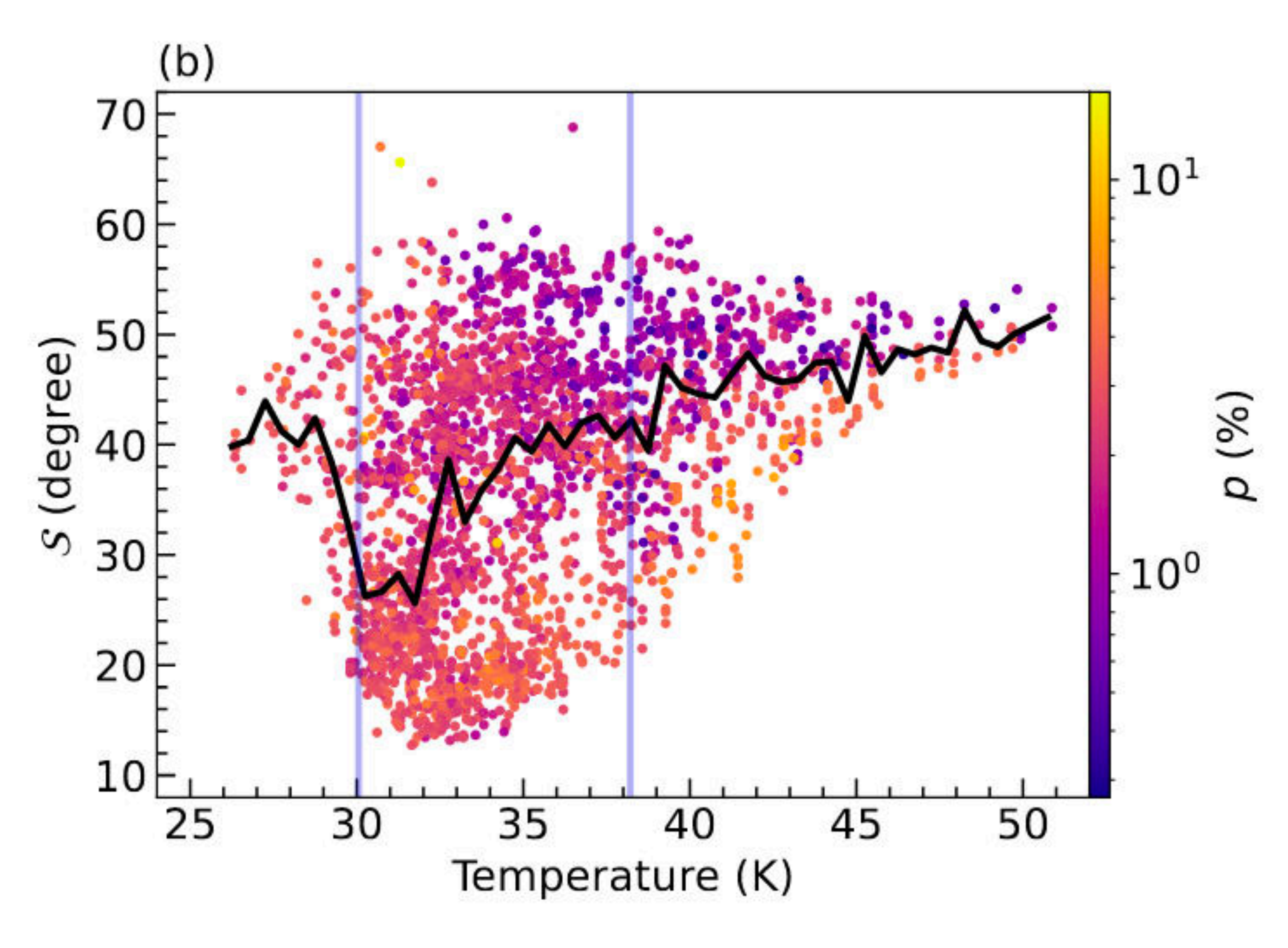
$\alpha = 1 \Rightarrow$ only grains in the outer layer are aligned

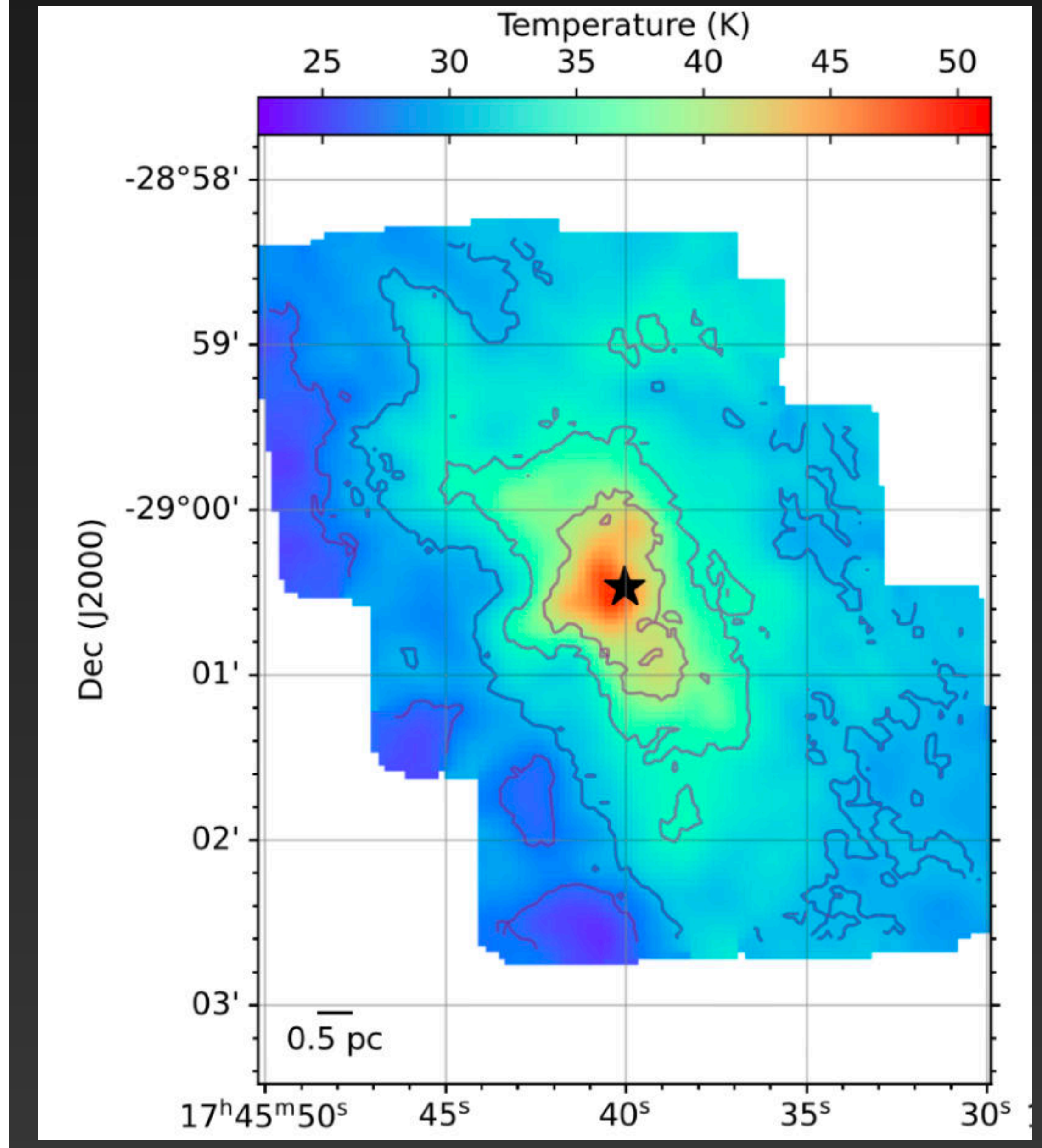
SOFIA/HAWC+ 53 μm

Polarization Angle Dispersion Function

$$\mathcal{S}(r,\delta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[\psi(r+\delta_i) - \psi(r)]^2}$$







In accordance to RAT-A Theory!

SOFIA/HAWC+ 53 μm

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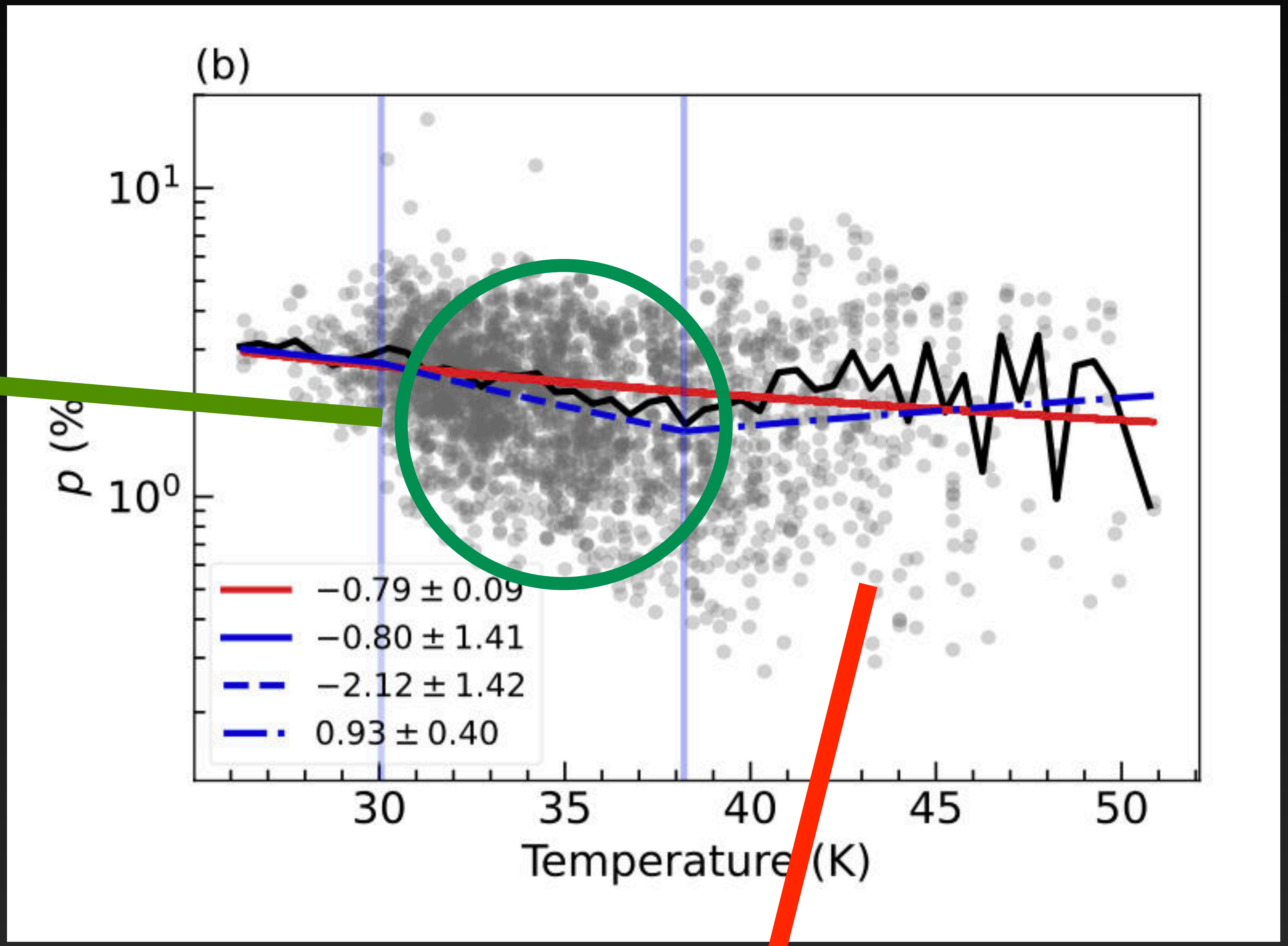
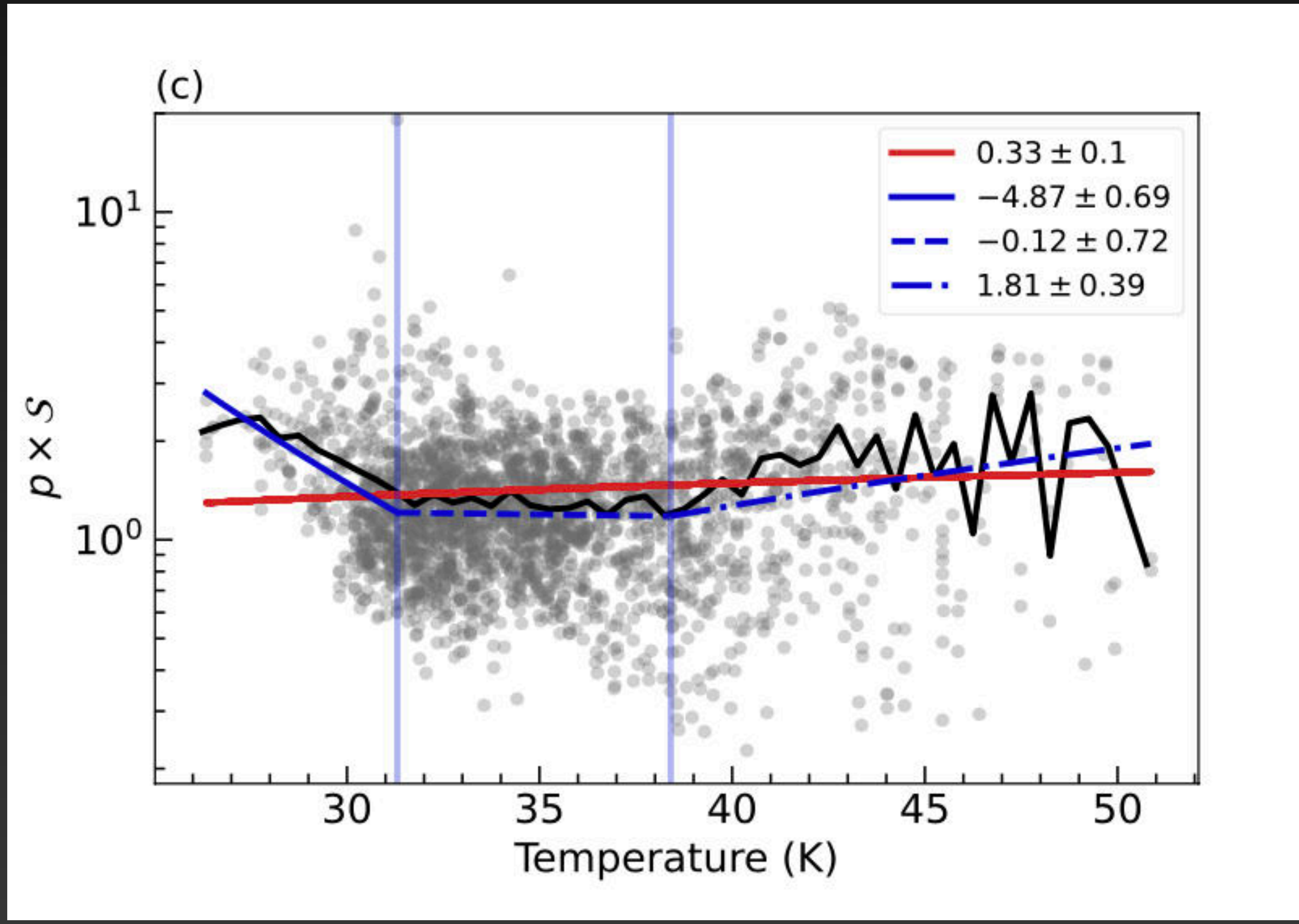
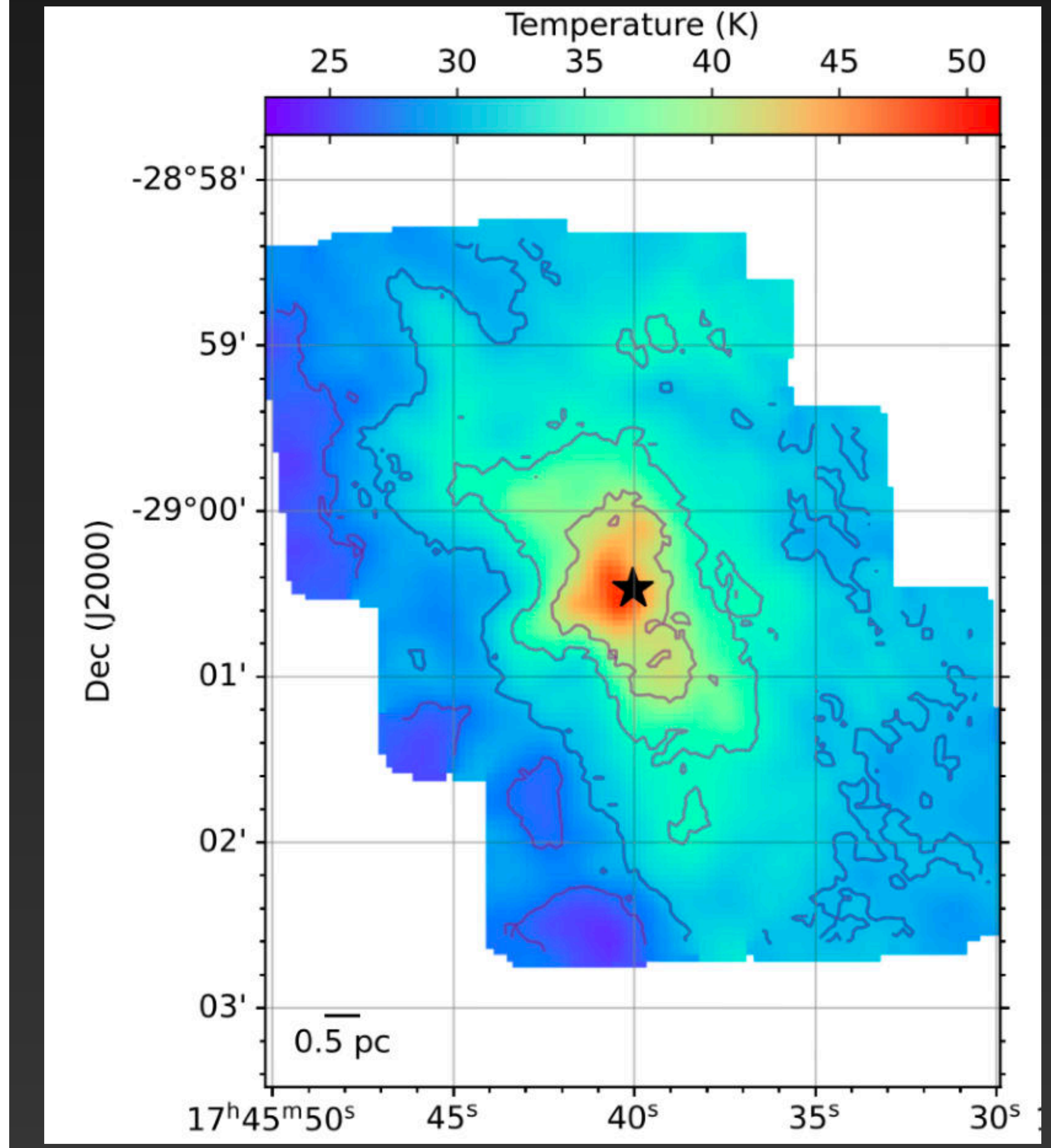


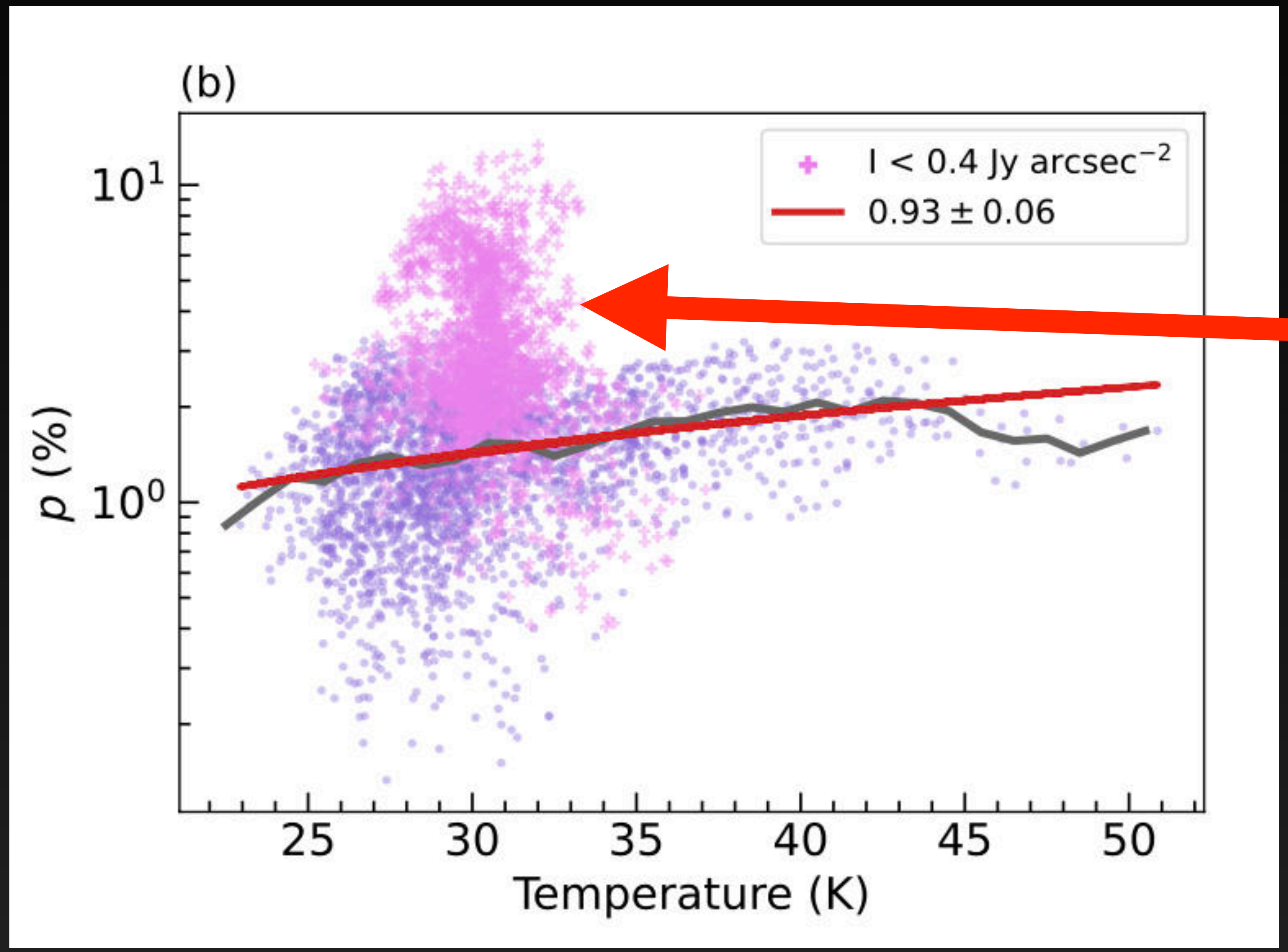


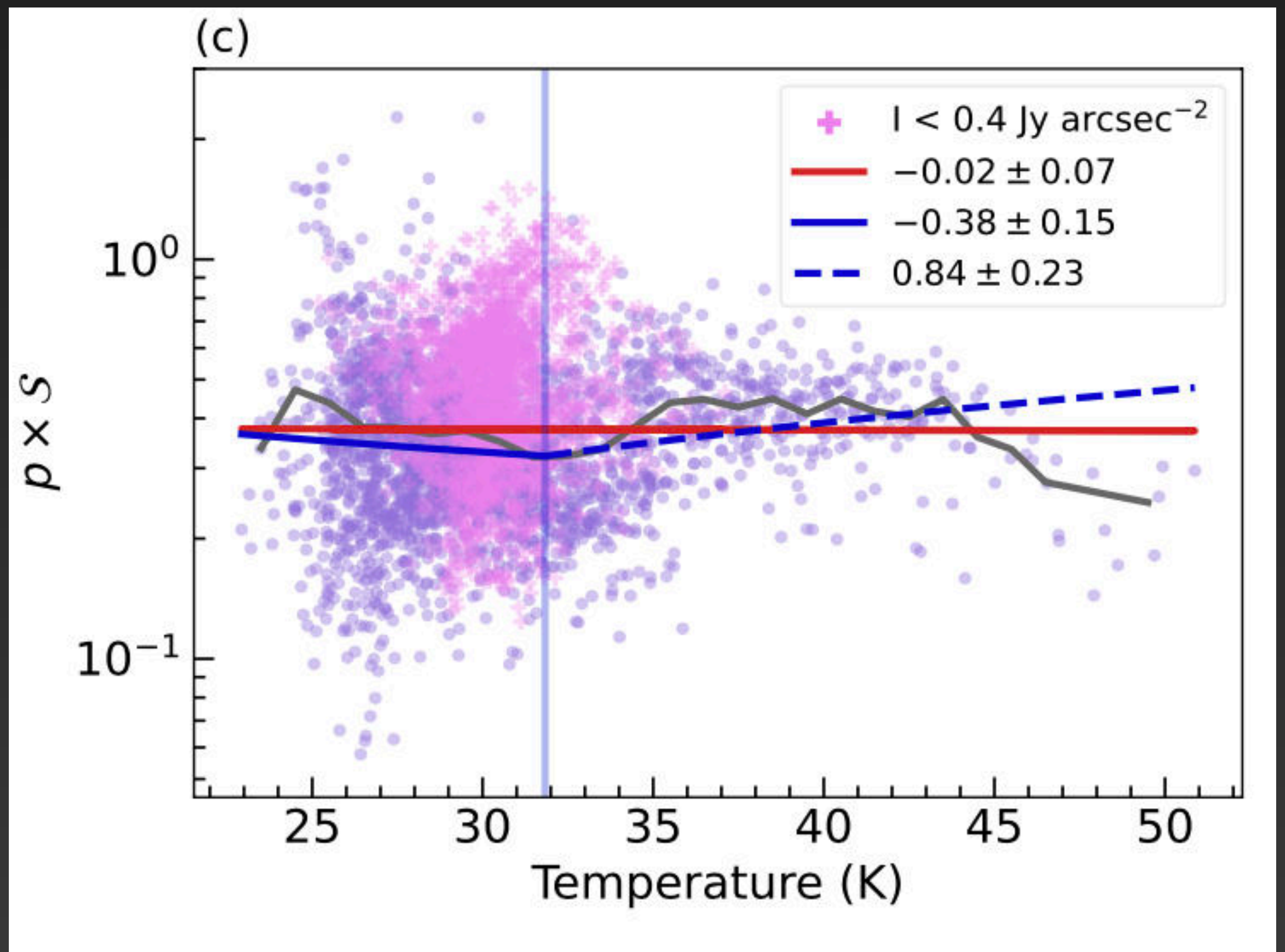


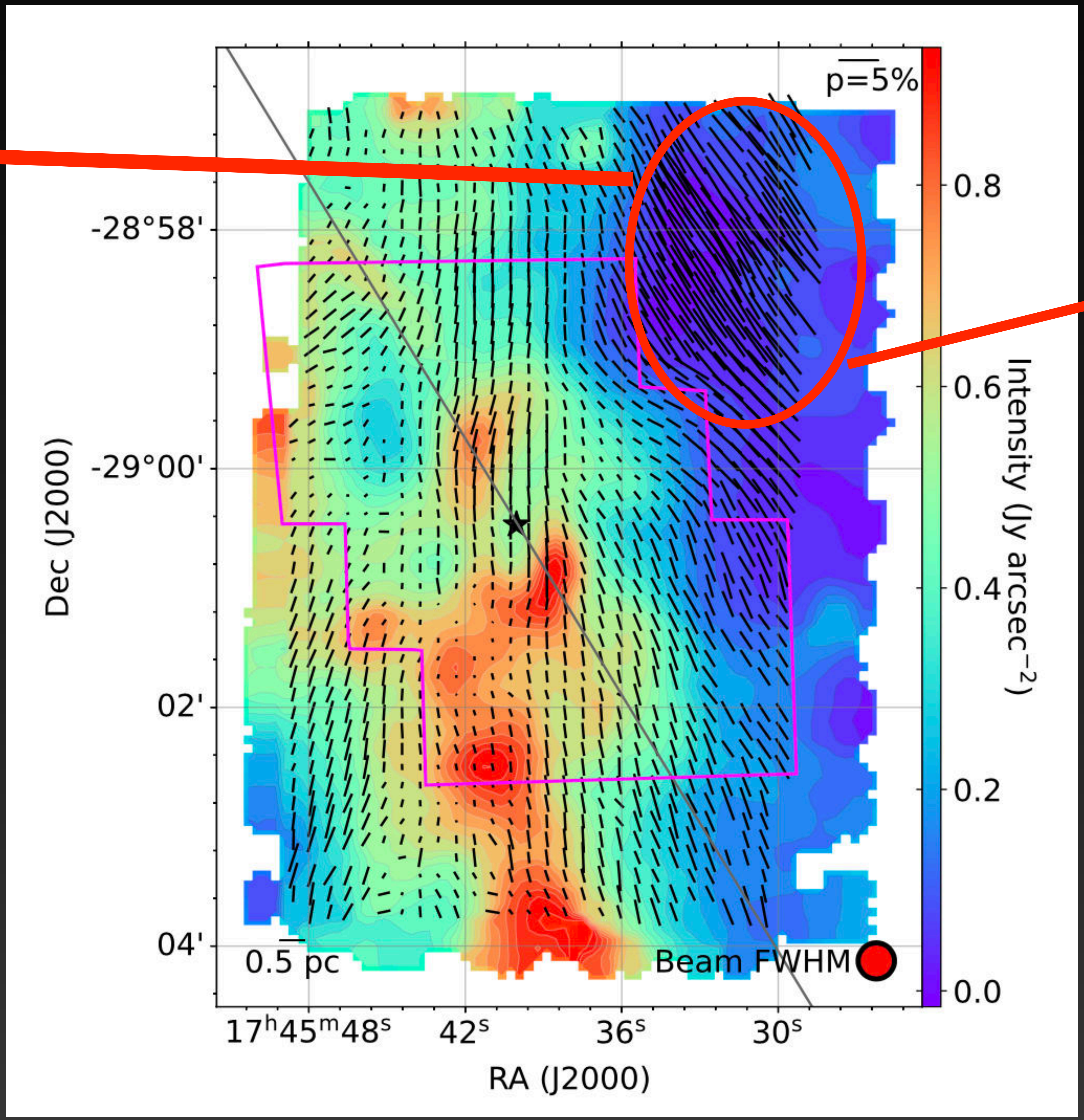
In accordance to RAT-A Theory!

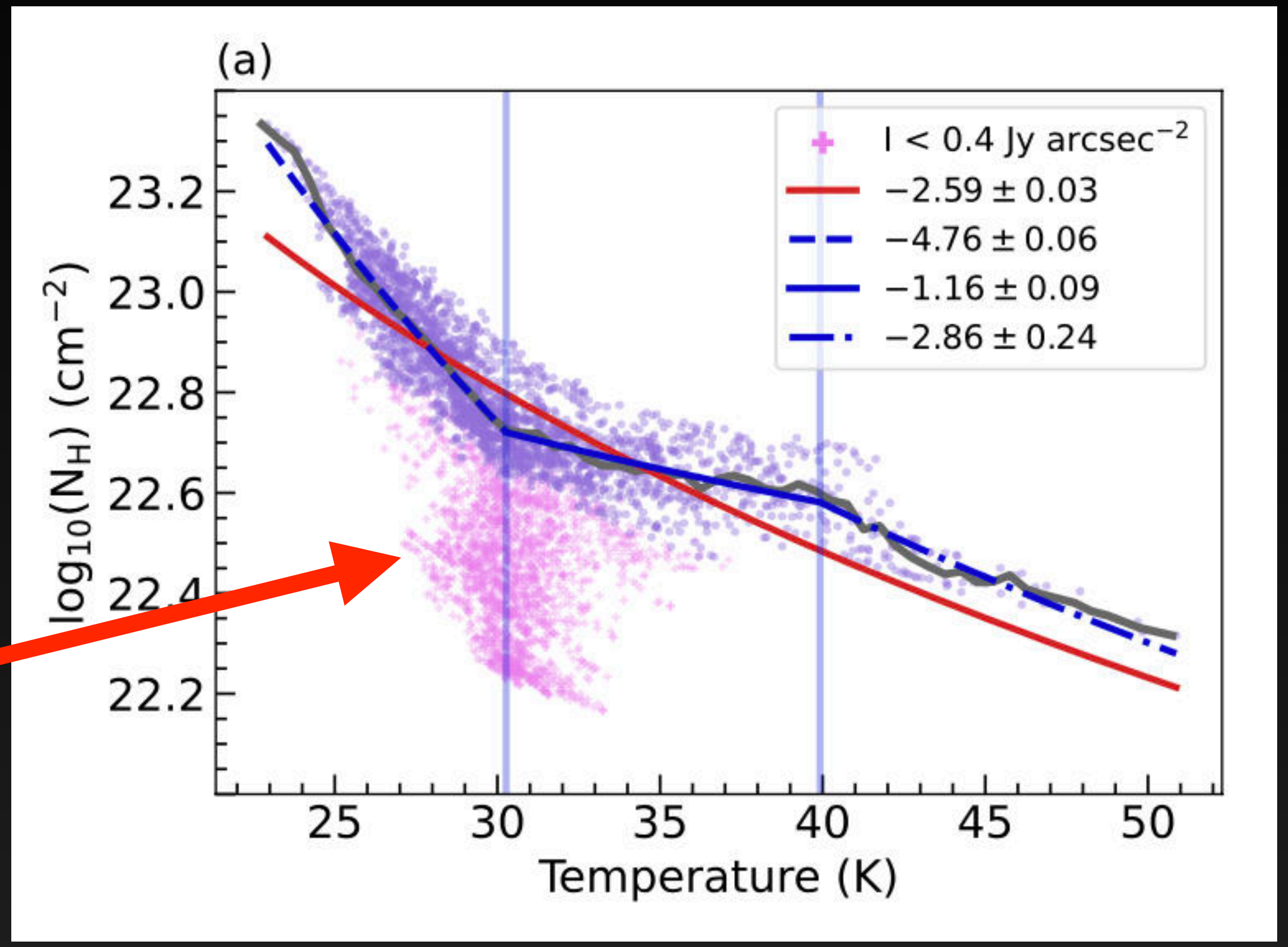
$p \times \mathcal{S}$ can trace dust grain alignment

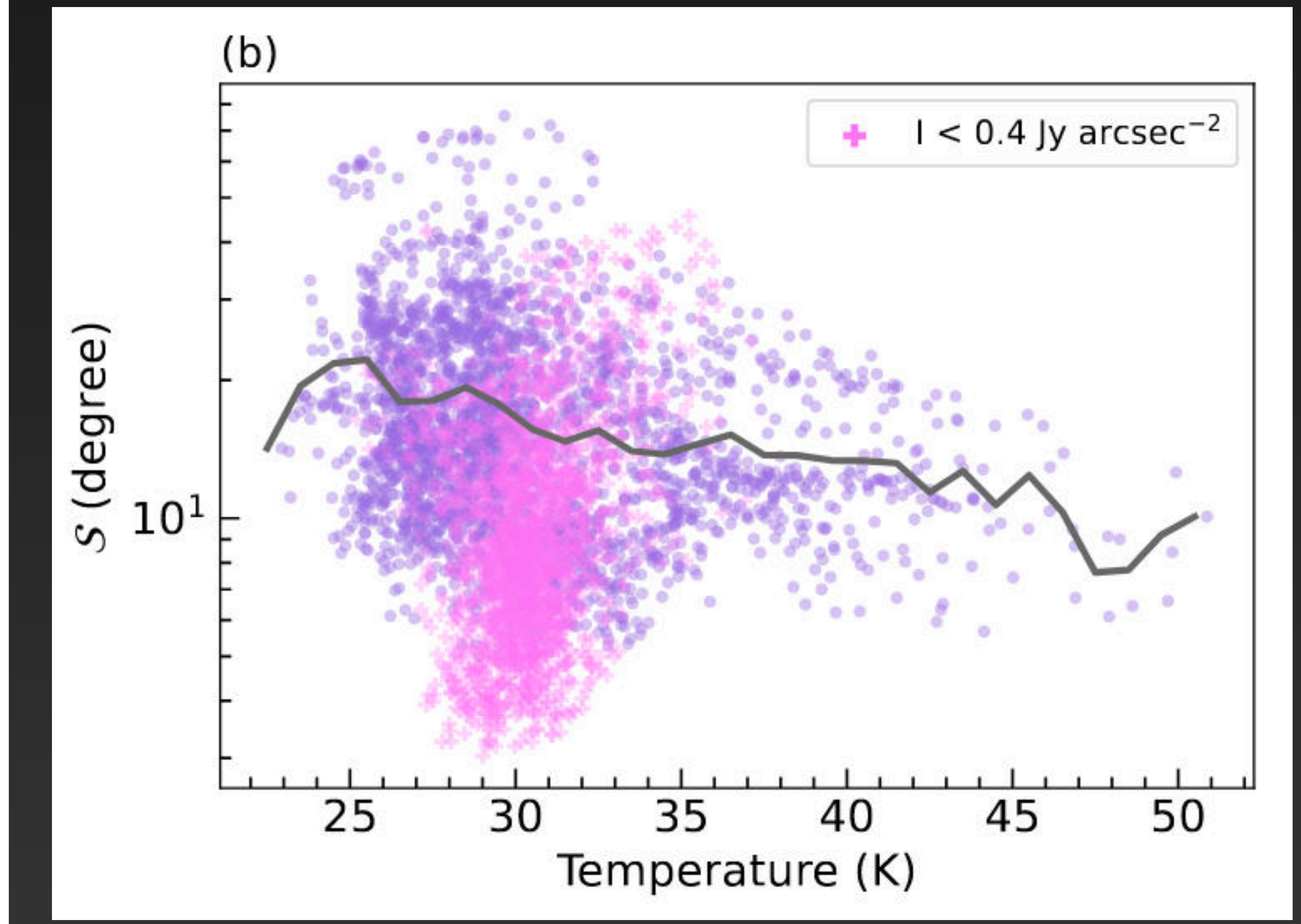
SOFIA/HAWC+ 216 µm





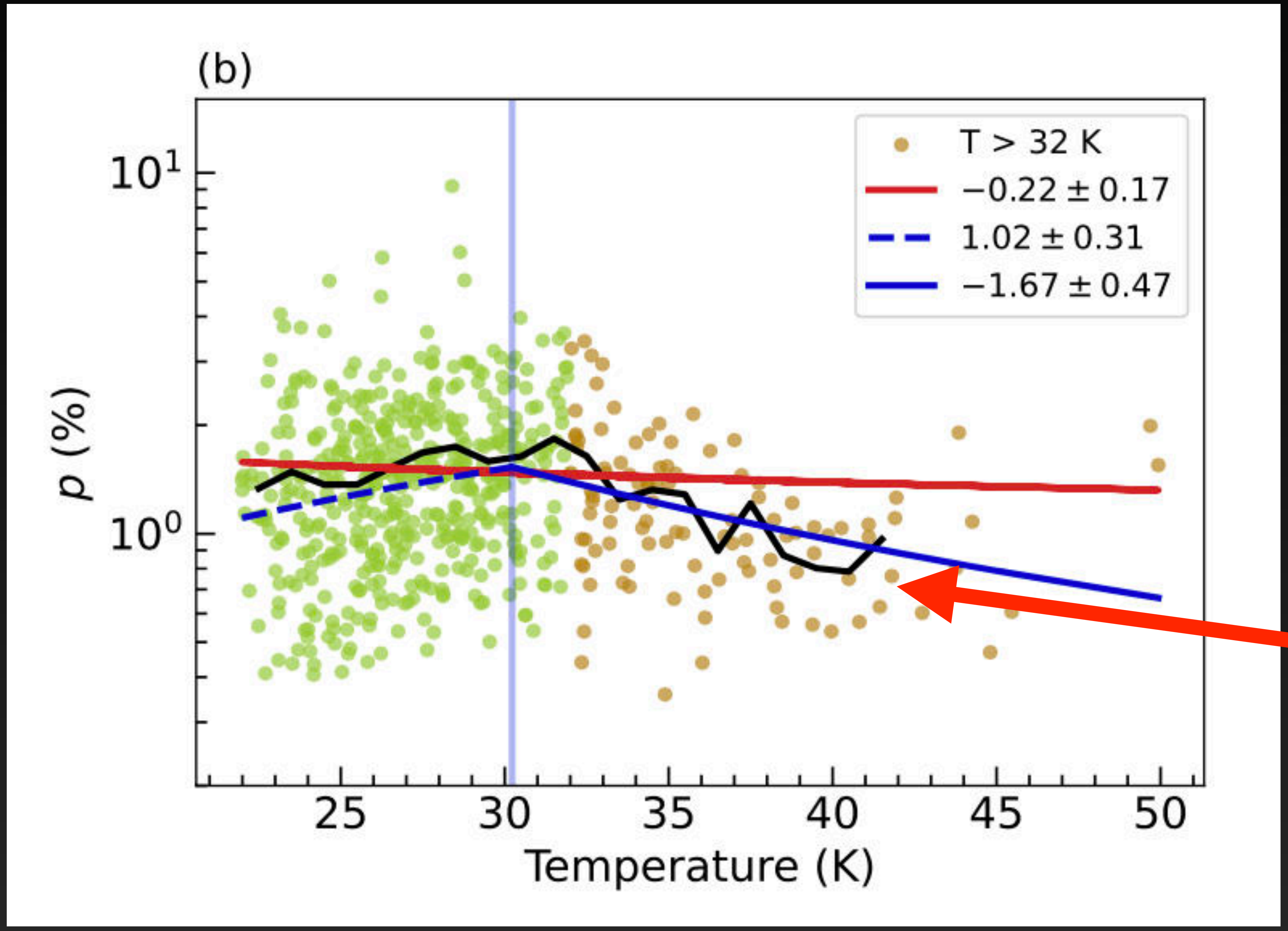


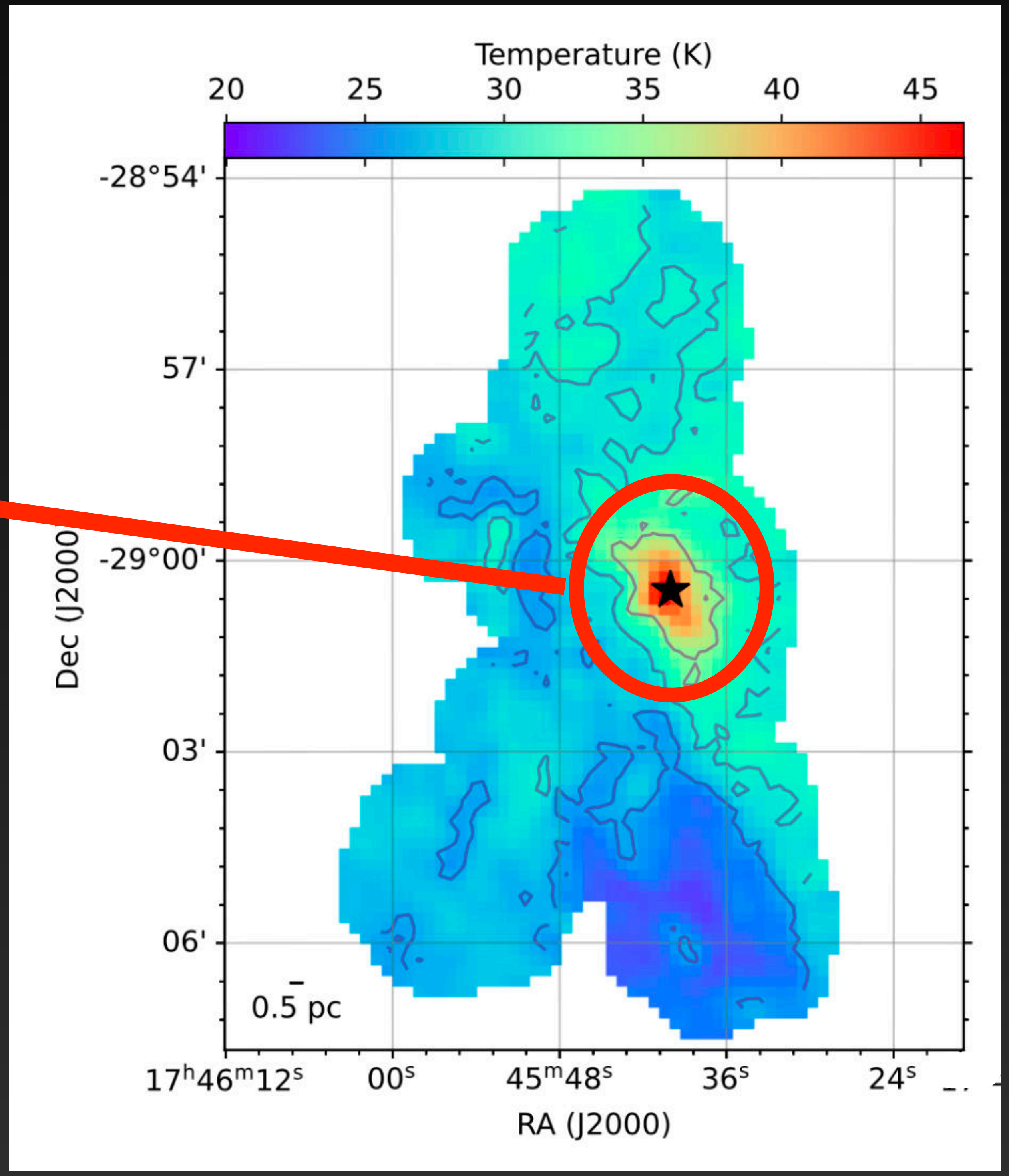




In accordance with RAT-A

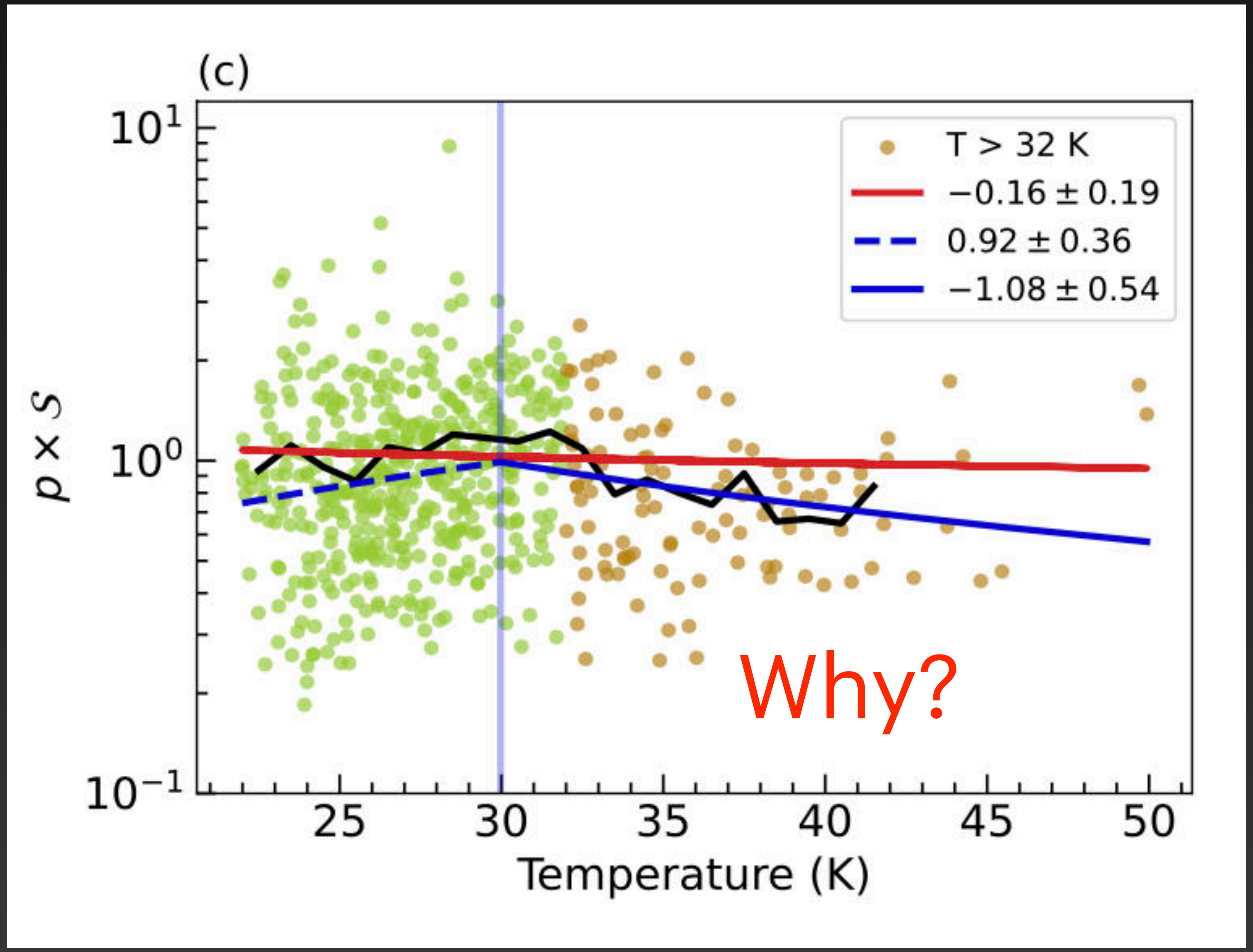
JCMT/SCUPOL 216 µm





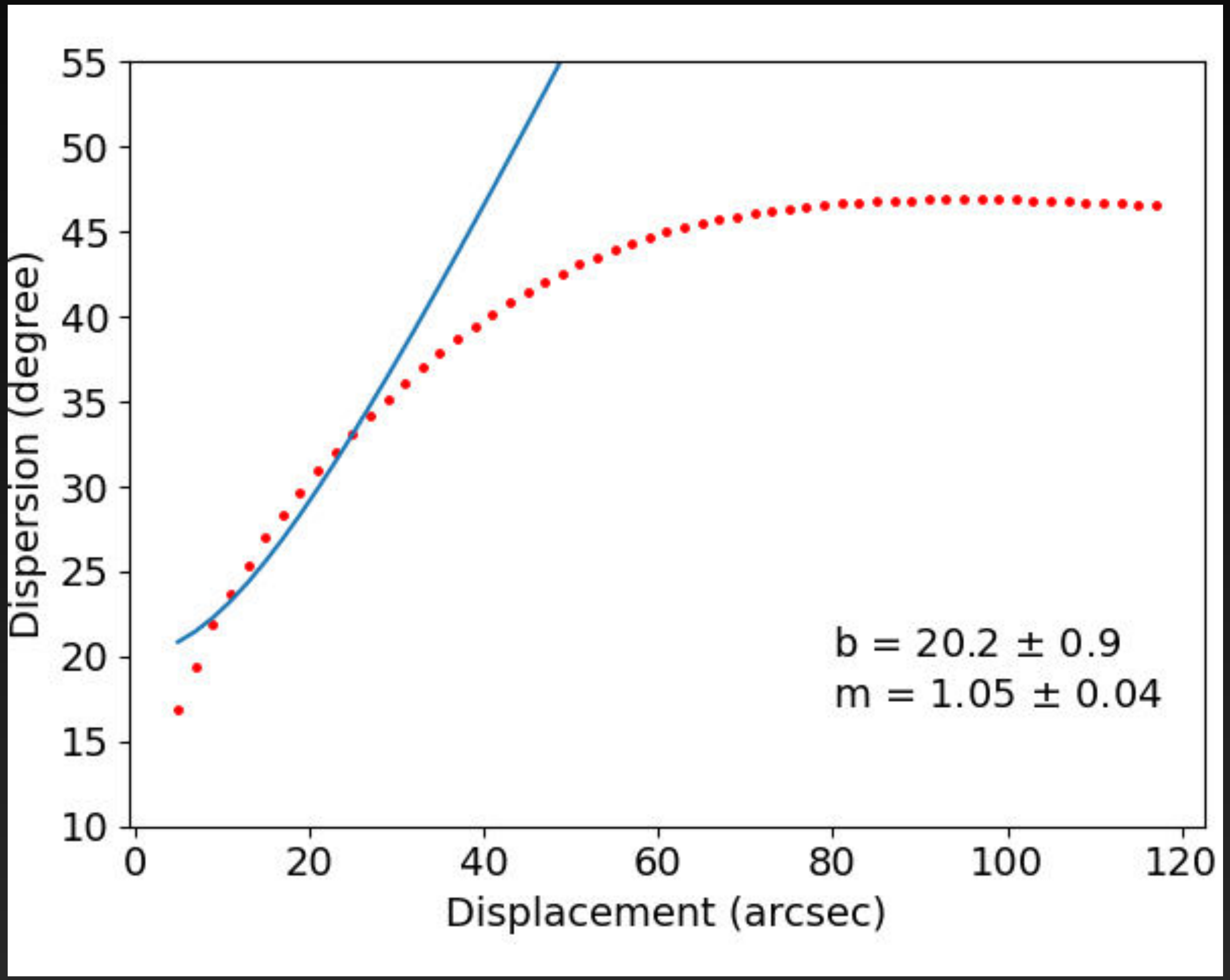
Evidence of RAT-D

850 µm also comes from large grains



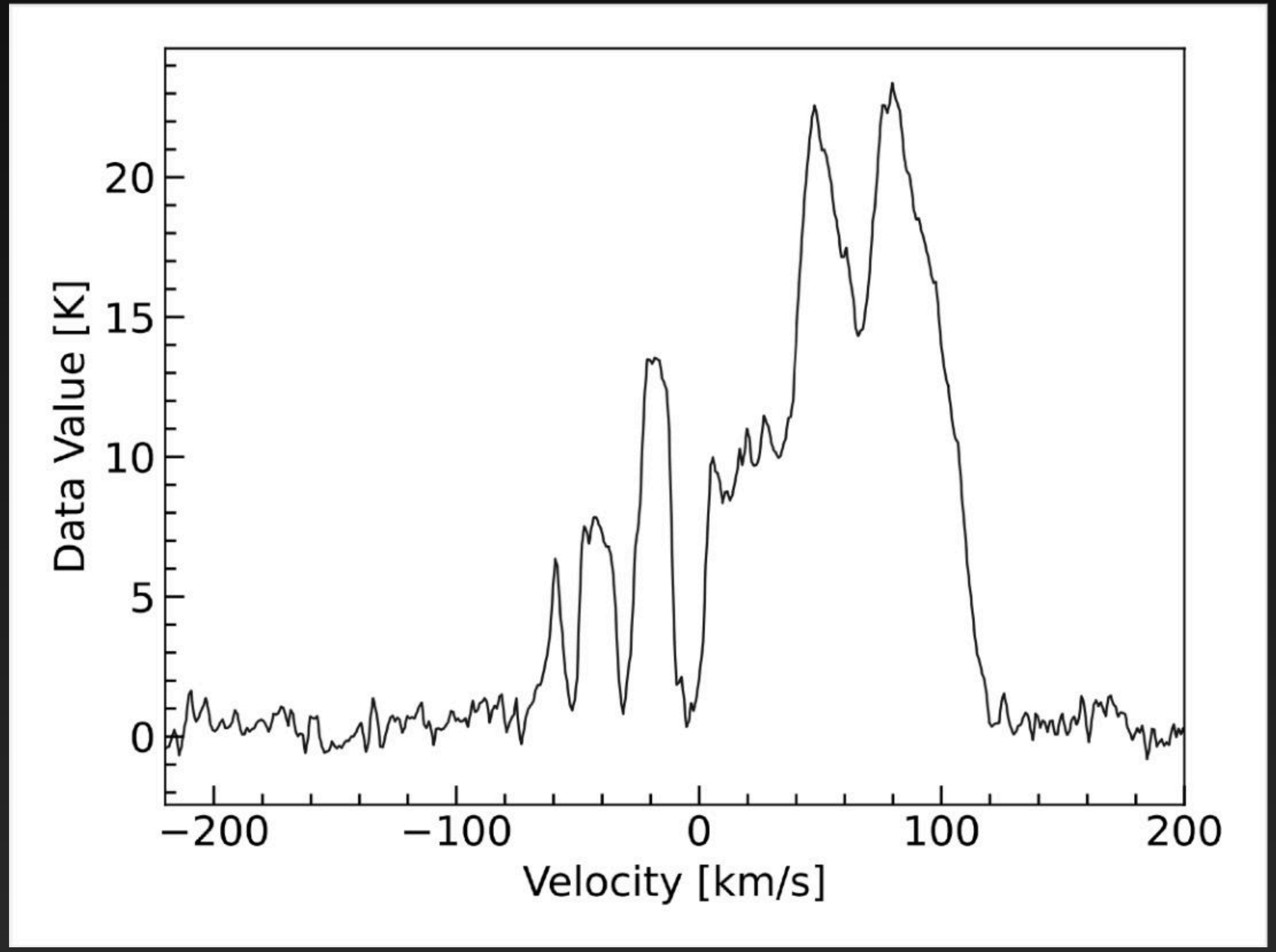
From RAT-A ⇨ *p* should increase with T_d

B-FIELD STRENGTH



$\delta\theta$ from structure function method

Velocity Dispersion Components
^{12}CO(J = 3→2) from CHIMPS2
(Eden et al. 2020)



ΔV obtained from moment 0 analysis

$$B_{\rm POS} = Q_c\sqrt{4\pi\rho}\,\frac{\sigma_v}{\sigma_\theta} \approx 9.3\sqrt{n(\mathrm{H_2})}\,\frac{\Delta \mathrm{V}}{\sigma_\theta}\ [\mu\mathrm{G}],$$

Davis-Chandrasekhar-Fermi Method
(Davis 1951; Chandrasekhar & Fermi 1953; Crutcher 2004)

Modified DCF Method:
Skalidis & Tassis (2021)

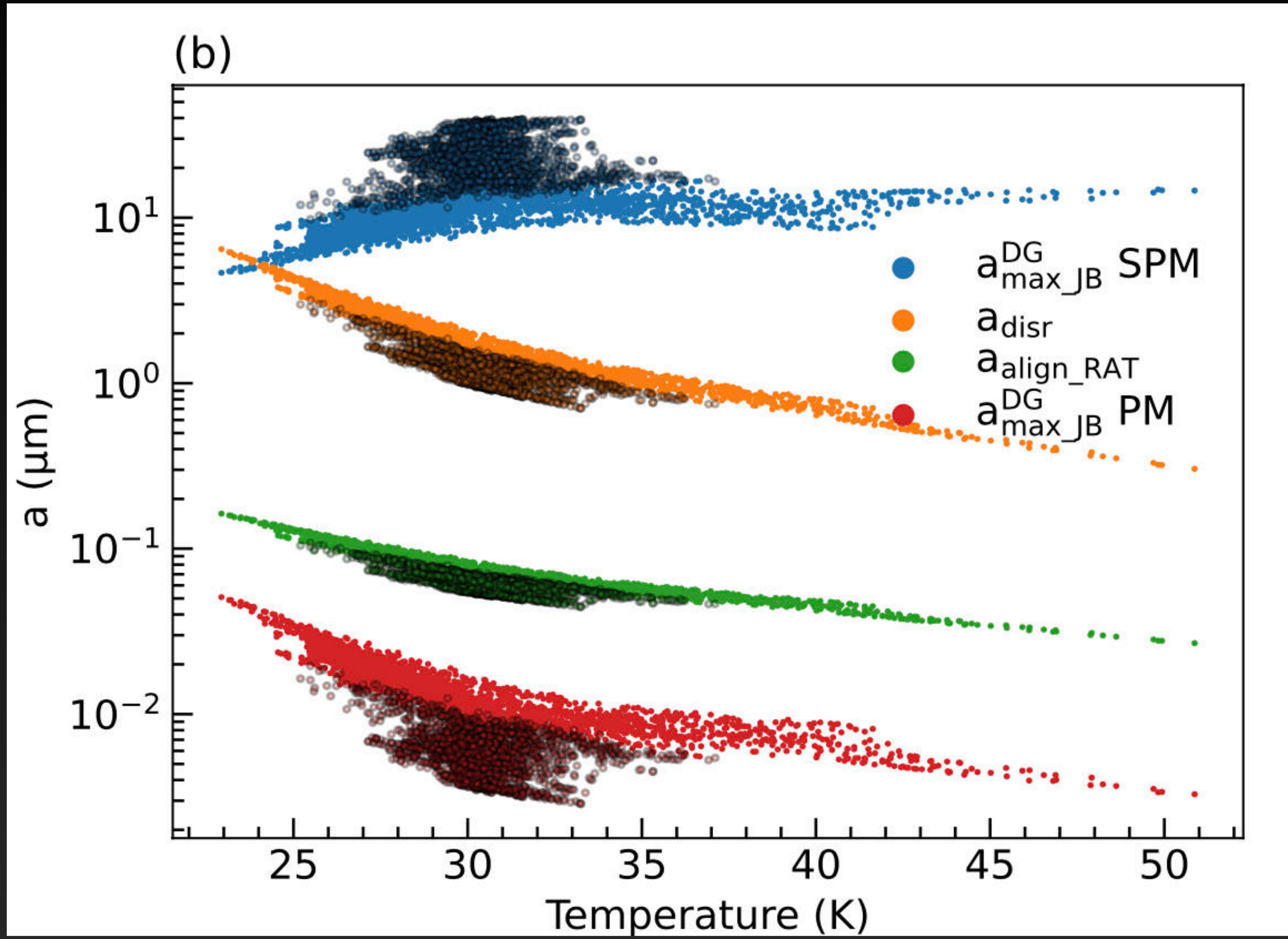
$$B_0 = \sqrt{2\pi\rho}\,\frac{\delta v}{\sqrt{\delta\theta}},$$

Preliminary Rough Estimates!

With ΔV < 9 km/s gives ~ 5 mGauss
Acceptable value from previous estimates
(2-5 mGauss)

Analytical Models of RAT

Alignment Sizes $\longrightarrow$ $a_{\mathrm{align}} \propto n_{\mathrm{H}}^{2/7} T_{\mathrm{d}}^{-12/7}$



$$\delta_{\mathrm{mag}} = \tau_{\mathrm{gas}}/\tau_{\mathrm{m}}$$

(Hoang et al. 2021, Hoang et al. 2022)

Magnetically Enhanced RAT

Paramagnetic Relaxation alone cannot lead to suprathermal rotation

$$\delta_{\rm mag} = \tau_{\rm gas}/\tau_{\rm m}$$

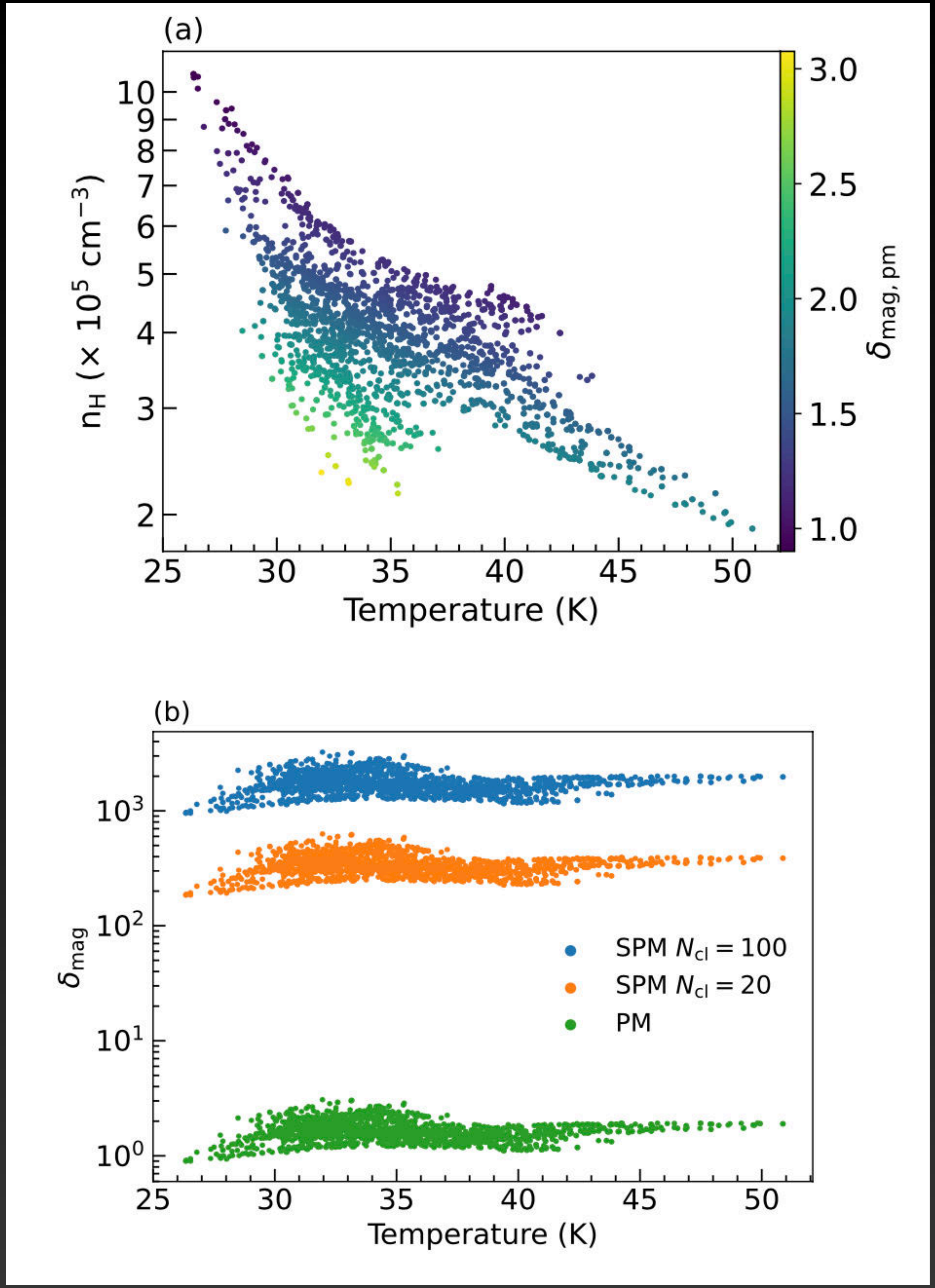
(Hoang and Lazarian 2016)

$\delta_{\rm mag} > 10 \Longrightarrow$ Perfect Alignment

$$\delta_{\rm mag,pm} \sim aB^2 n_{\rm H}^{-1} T_{\rm gas}^{-1/2}$$

$$\delta_{\rm mag,sp} \sim a^{-1} N_{\rm cl} \phi_{\rm sp} B^2 n_{\rm H}^{-1} T_{\rm d}^{-1} T_{\rm gas}^{-1/2}$$

Analytical model from Hoang et al. (2022)



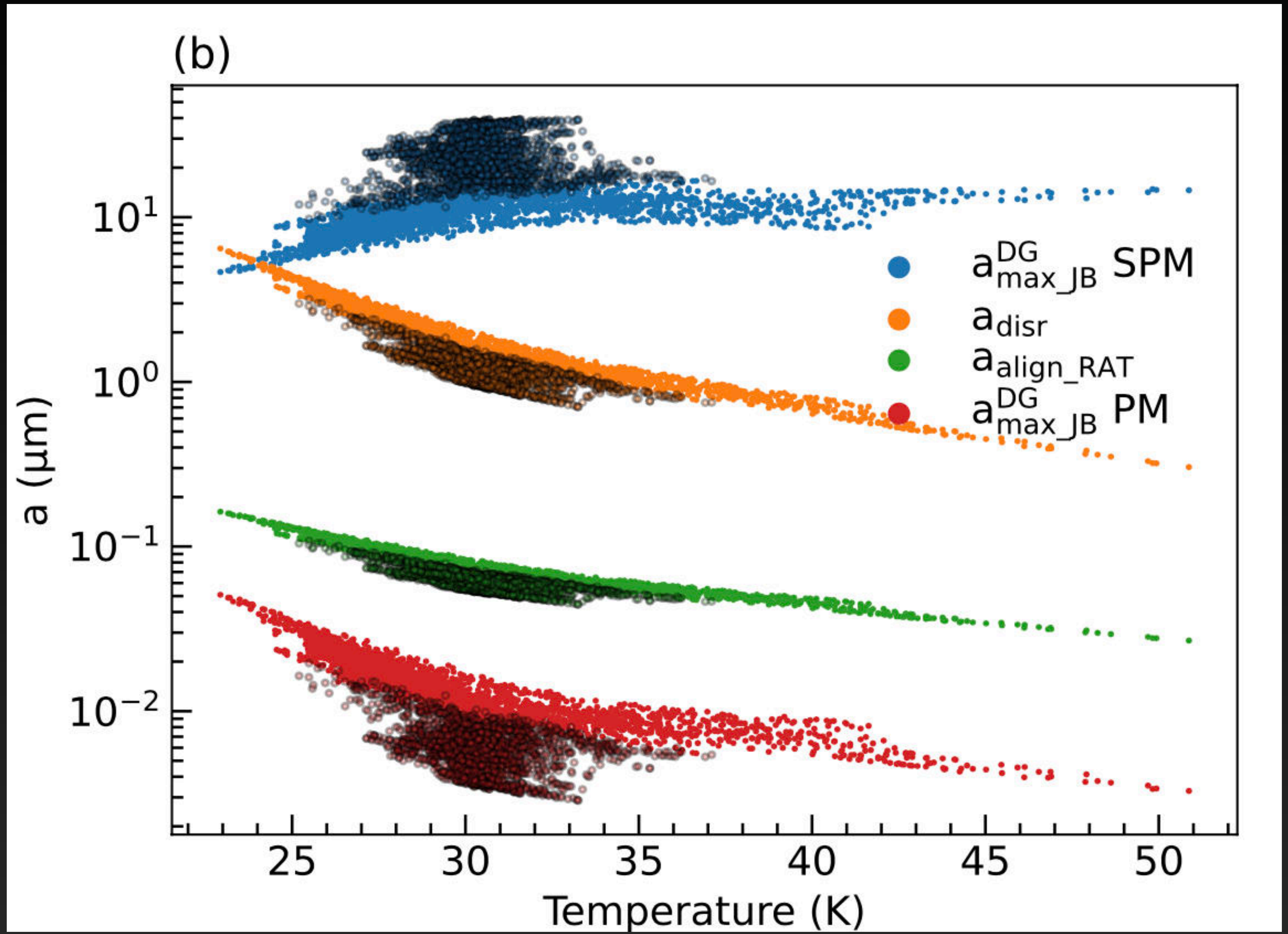
Perfect alignment for SPM Grains

Analytical Models of RAT

Alignment Sizes → $a_{\rm align} \propto n_{\rm H}^{2/7} T_{\rm d}^{-12/7}$

MRAT → $a_{\rm max\_JB}^{\rm DG} \Longleftarrow \delta_{\rm mag} > 1$

Disruption Size → $a_{\rm disr} \propto n_{\rm H}^{1/2} T_{\rm d}^{-3} S_{\rm max}^{1/4}$



$$\delta_{\rm mag} = \tau_{\rm gas}/\tau_{\rm m}$$

$$S_{\rm max} \sim 10^6 \text{ erg cm}^{-3}$$

(Hoang et al. 2021, Hoang et al. 2022)

Analytical Models of RAT

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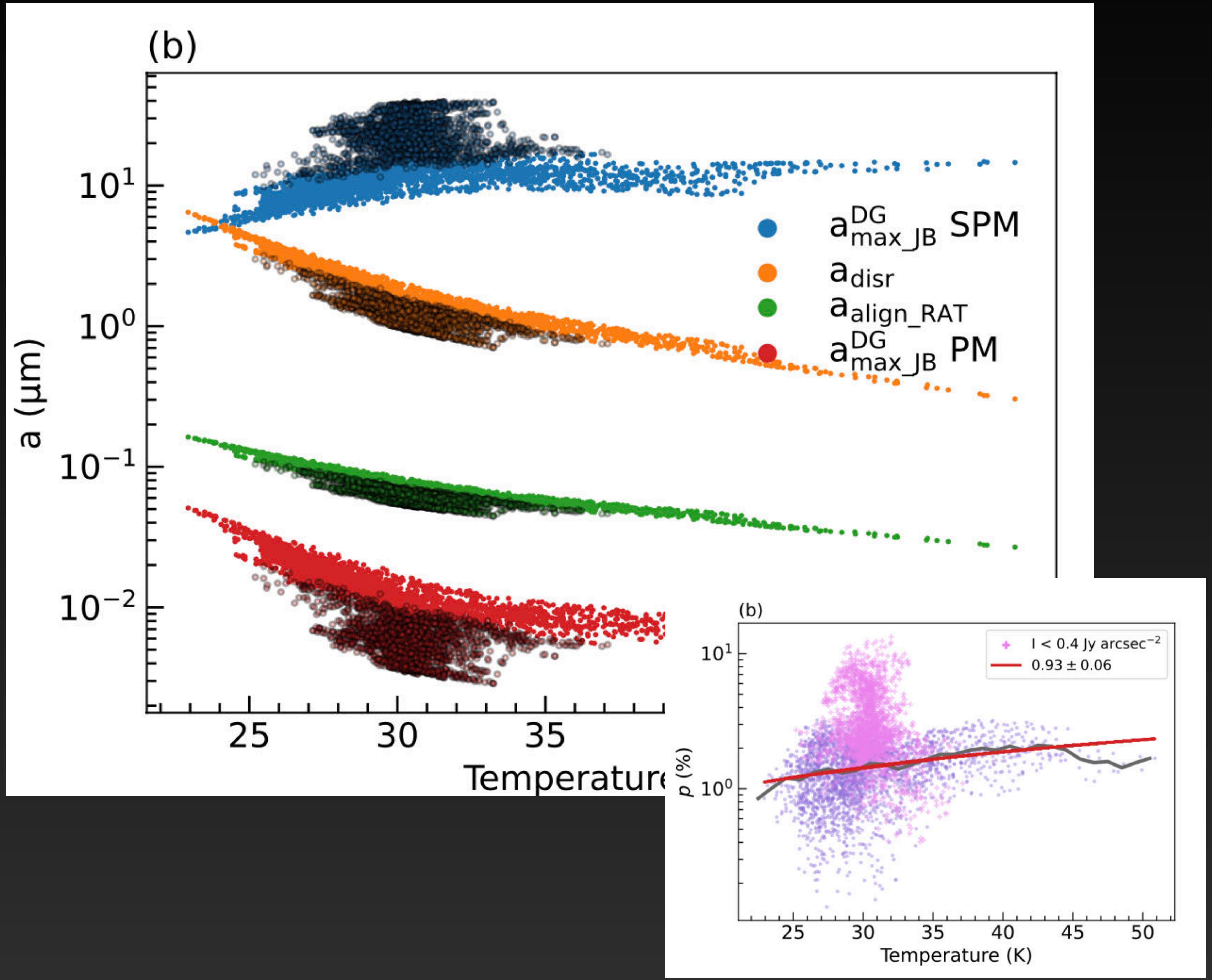
Maximum size distribution for maximum polarization



$\delta_{\rm mag} = \tau_{\rm gas}/\tau_{\rm m}$

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(Hoang et al. 2021, Hoang et al. 2022)

Analytical Models of RAT

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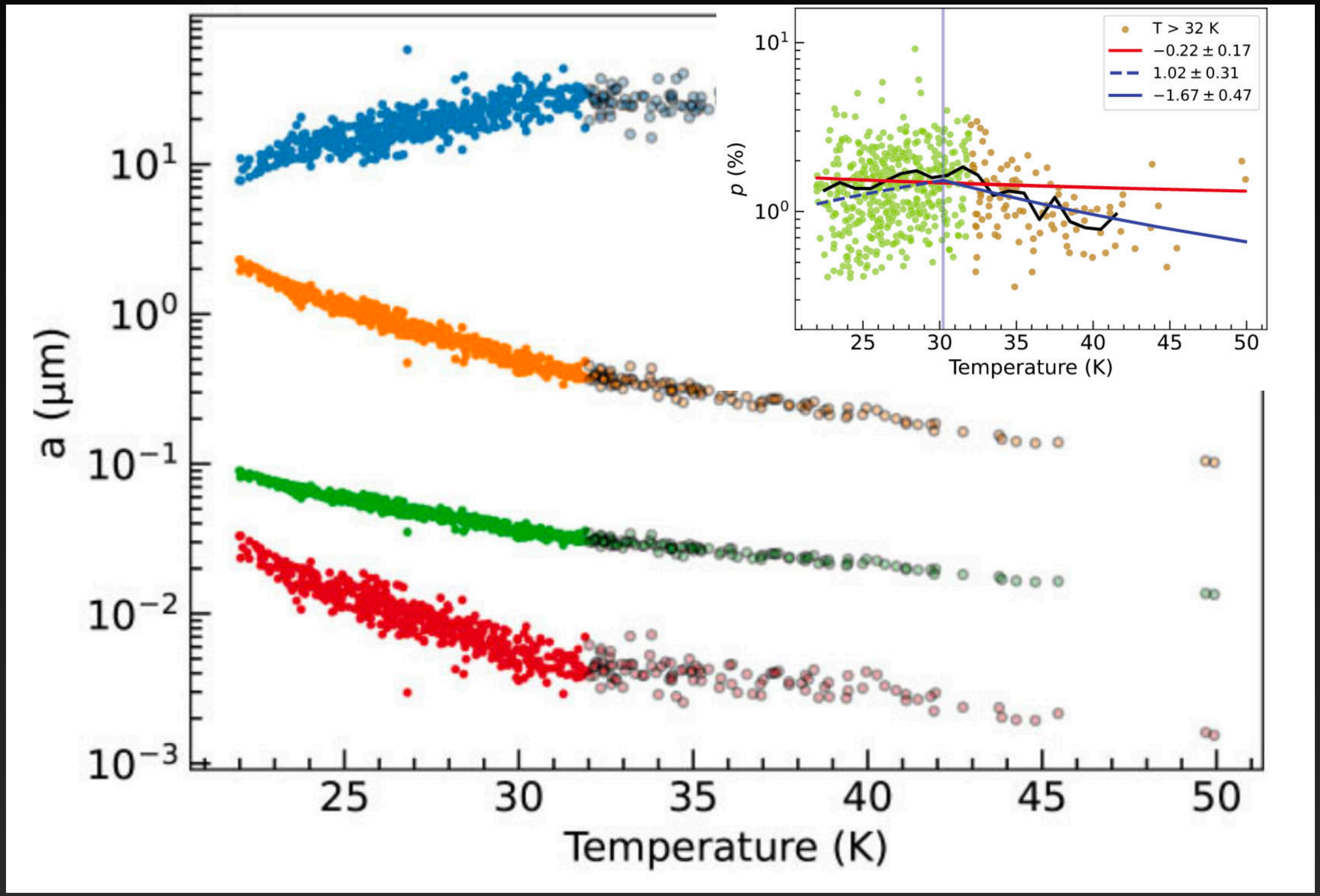


Disruption size < 1 μm
850 μm emission predominantly from large grains

$$\delta_{\rm mag} = \tau_{\rm gas}/\tau_{\rm m}$$

$$S_{\rm max} \sim 10^6 \text{ erg cm}^{-3}$$

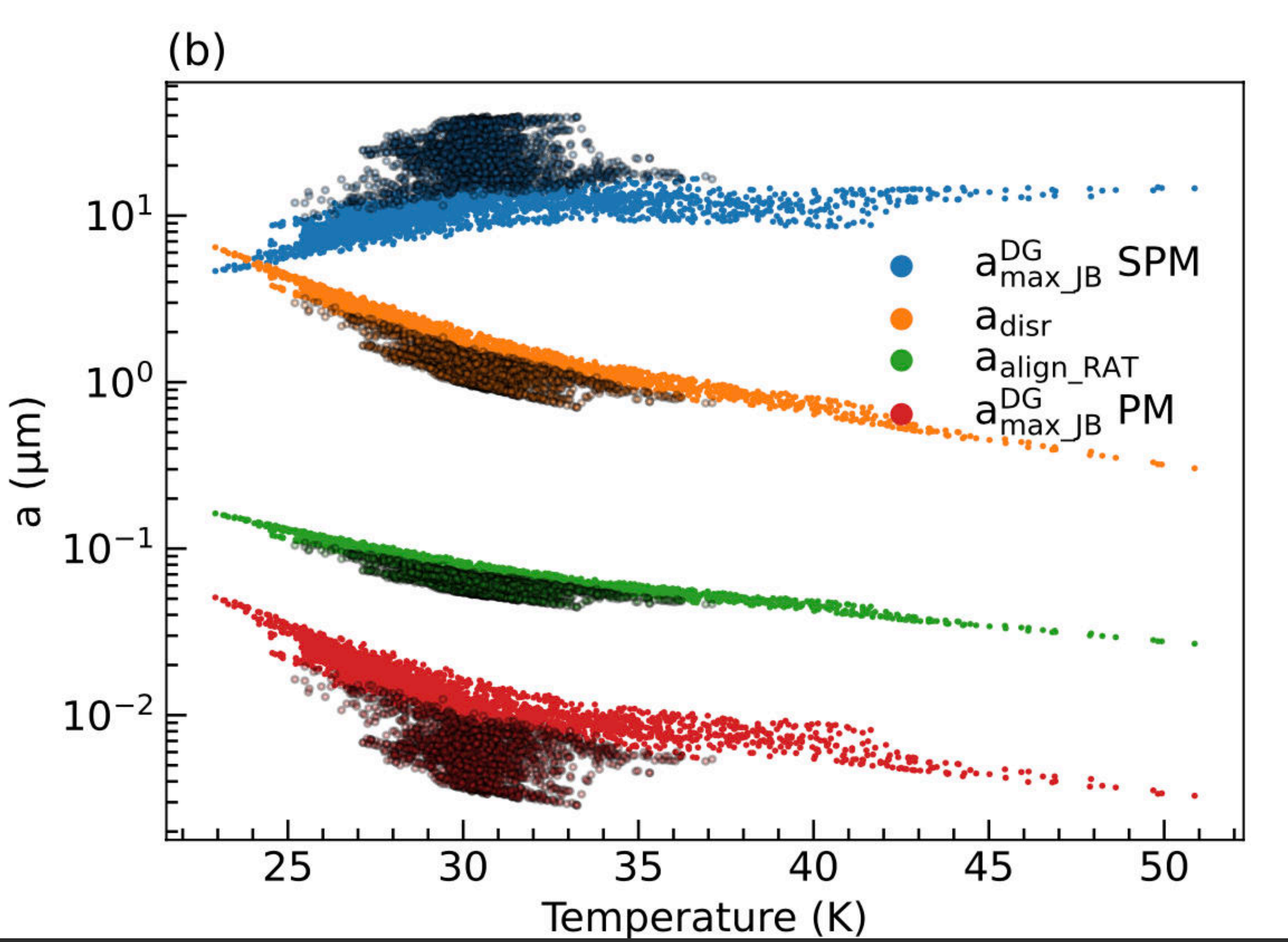
(Hoang et al. 2021, Hoang et al. 2022)

Analytical Models of RAT

- Previous studies predicted the dominant mechanism of grain alignment to be paramagnetic relaxation (eg. Aitken et al. 1986)
- Recent theories indicate that is not strong enough for observed level of polarization

Main conclusion:

RAT-A main alignment mechanism
MRAT if grains are SPM in nature



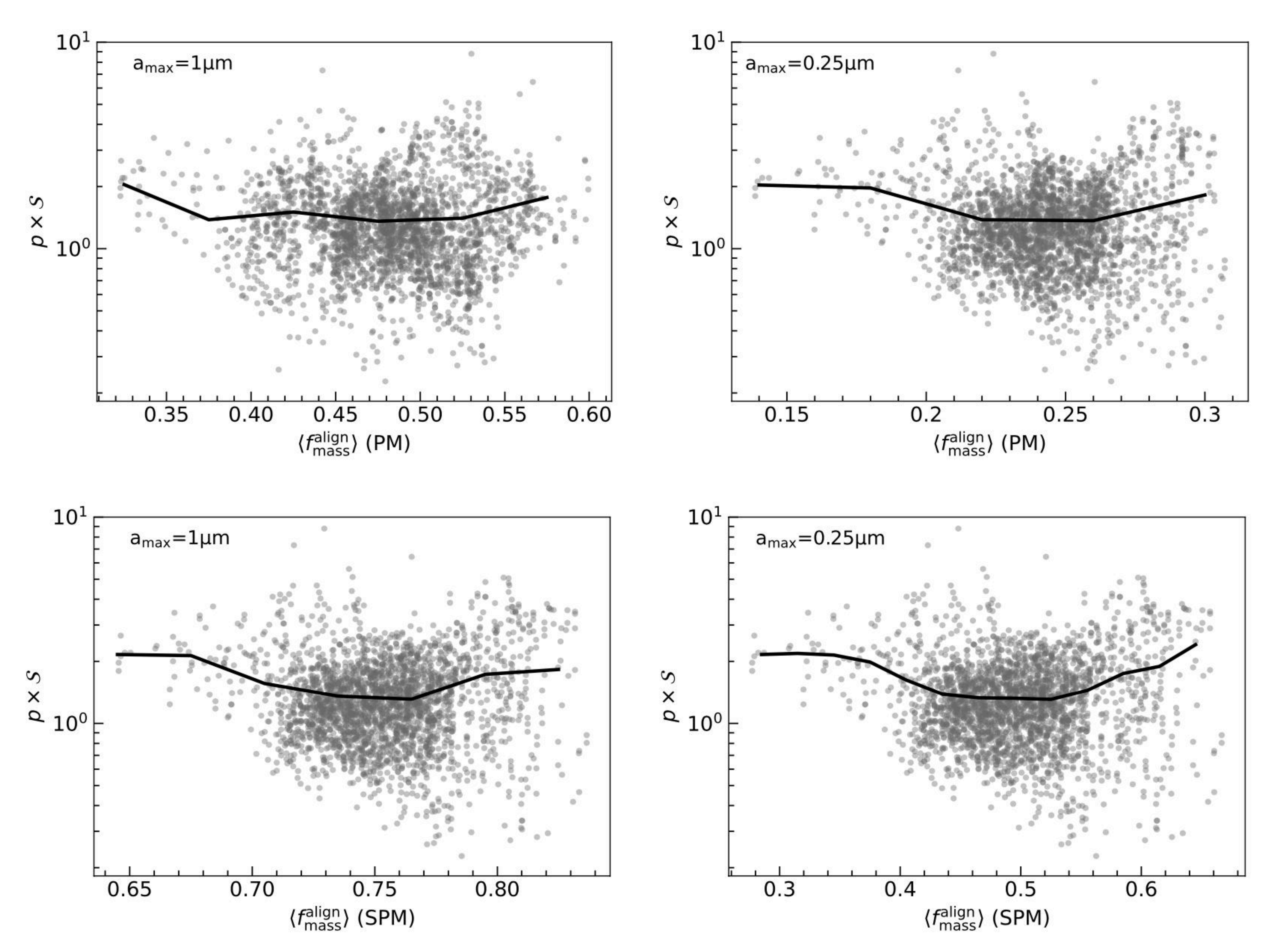
ALIGNED GRAIN MASS

$$\langle f_{\rm mass}^{\rm align} \rangle = \frac{\int_{a_{\rm align}}^{a_{\rm max}} \left(\frac{dm}{da}\right) da \times f_{\rm high-J}(a)}{\int_{a_{\rm min}}^{a_{\rm max}} \left(\frac{dm}{da}\right) da}$$

$$\frac{dm}{da} = \frac{4}{3}\pi\rho s a^3 n(a)$$

$$f_{\rm high-J}(\delta_{\rm mag}) = \begin{cases} 0.25 & \text{for } \delta_{\rm mag} < 1 \\ 0.5 & \text{for } 1 \leq \delta_{\rm mag} \leq 10 \\ 1 & \text{for } \delta_{\rm mag} > 10 \end{cases}$$

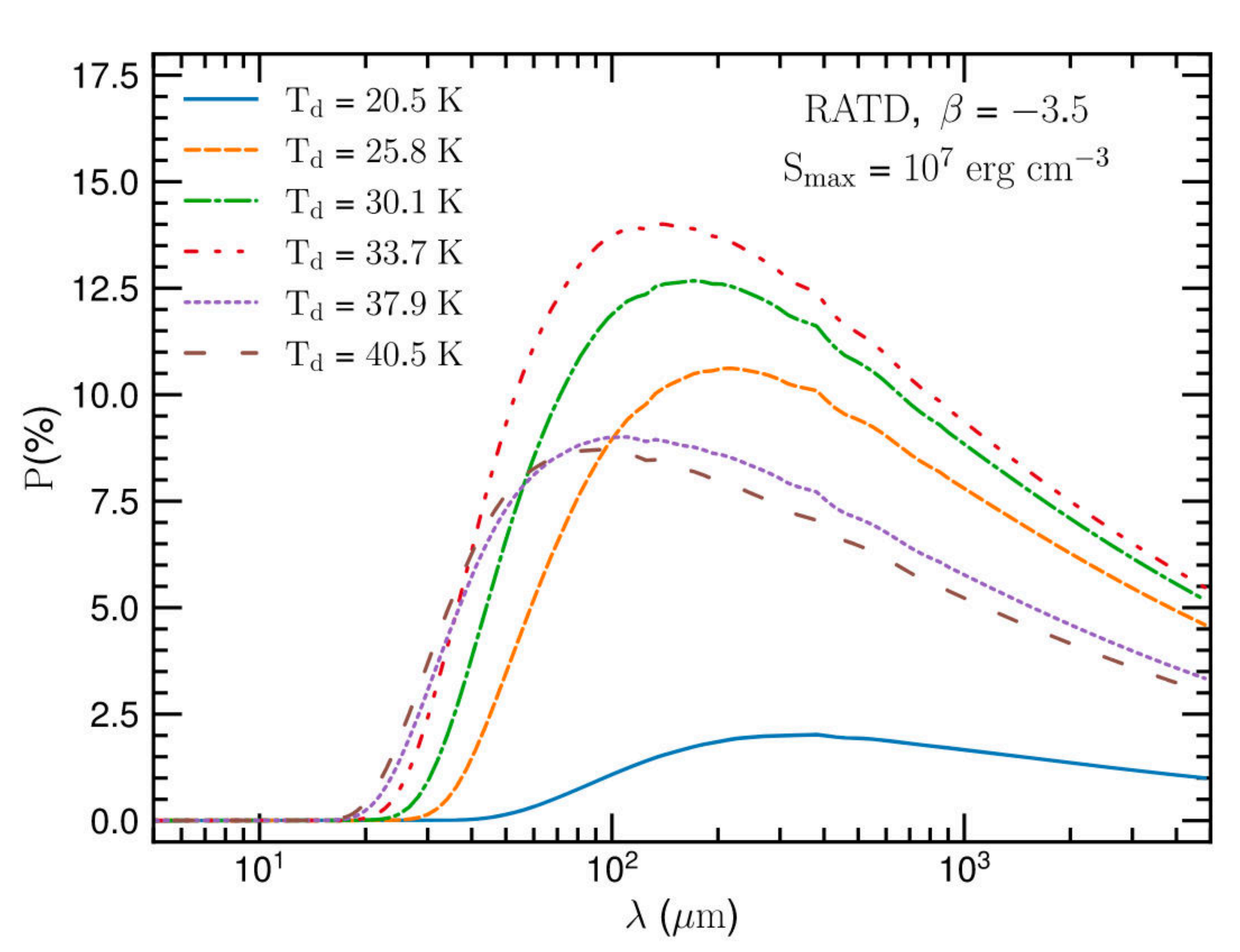
(Giang et al. 2023)

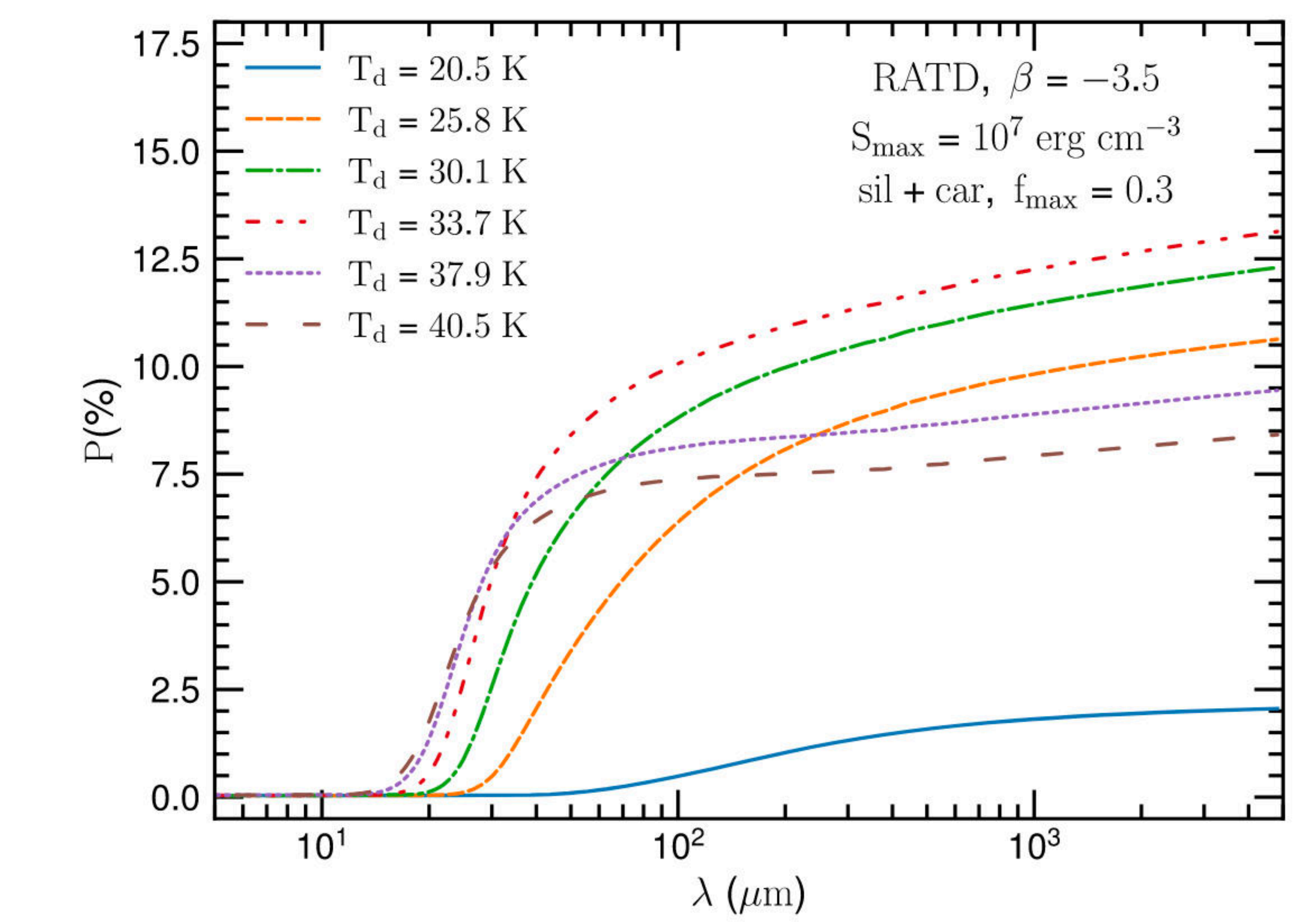


$$n(a) = \frac{dn}{da} = C n_{\rm H} a^{-3.5}$$

(Mathis et al. 1977; MRN Distribution)

GRAIN MODEL PREDICTIONS





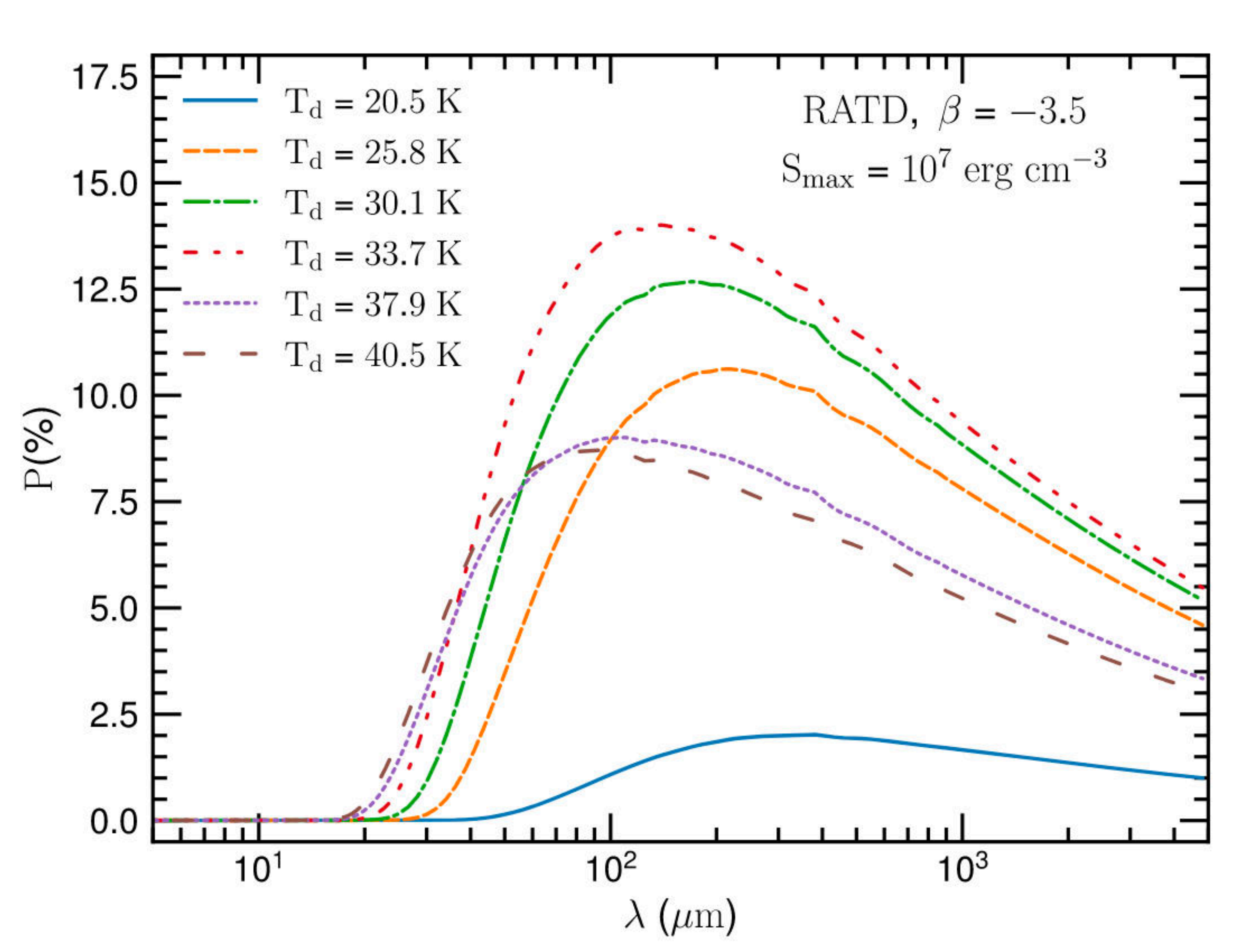
(Lee et al. 2020; Tram et al. 2021)

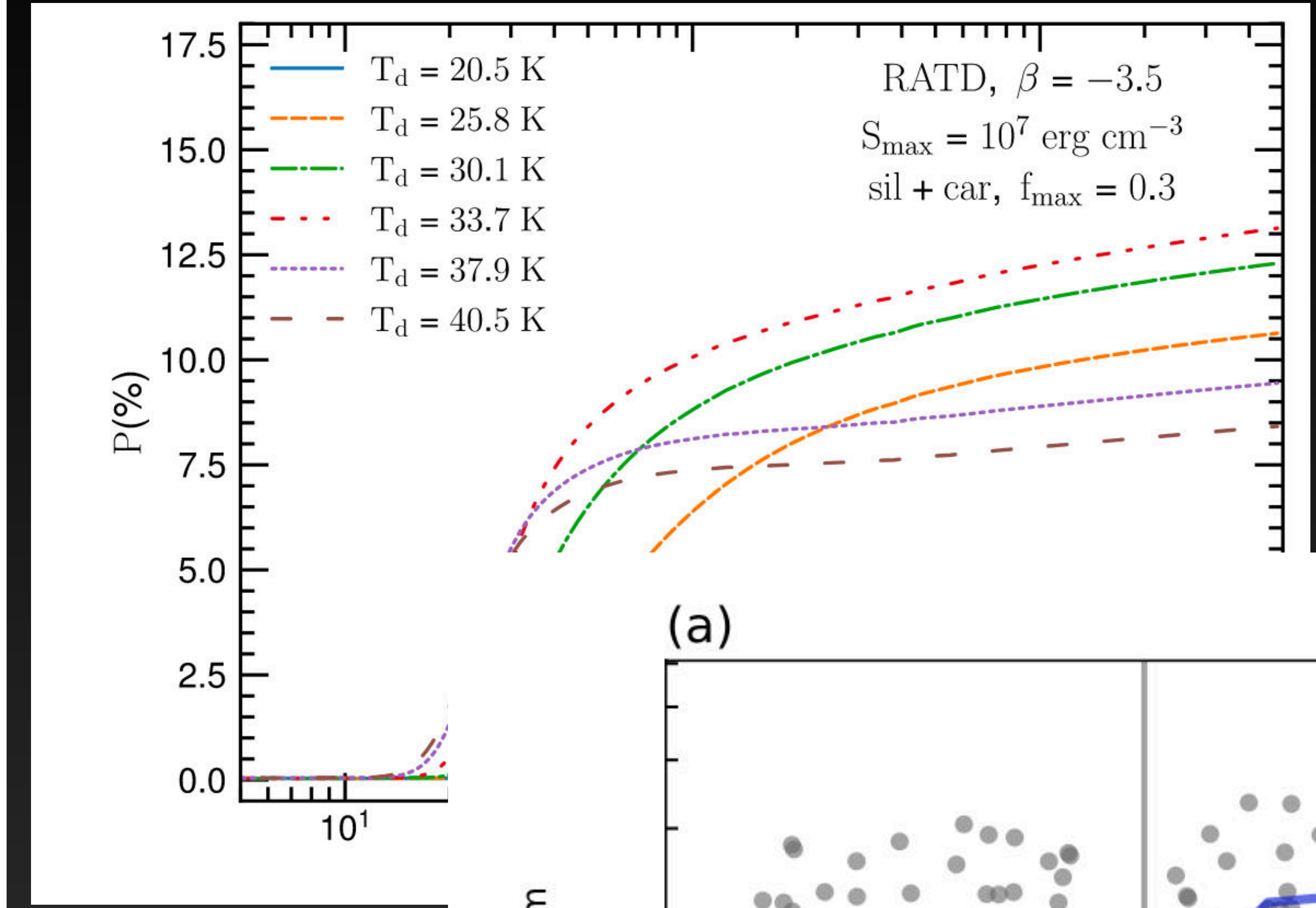
$$\frac{p_{\lambda 1}}{p_{\lambda 2}} < 1$$

Peak ~ 100 µm

$$\frac{p_{\lambda 1}}{p_{\lambda 2}} > 1$$

GRAIN MODEL PREDICTIONS





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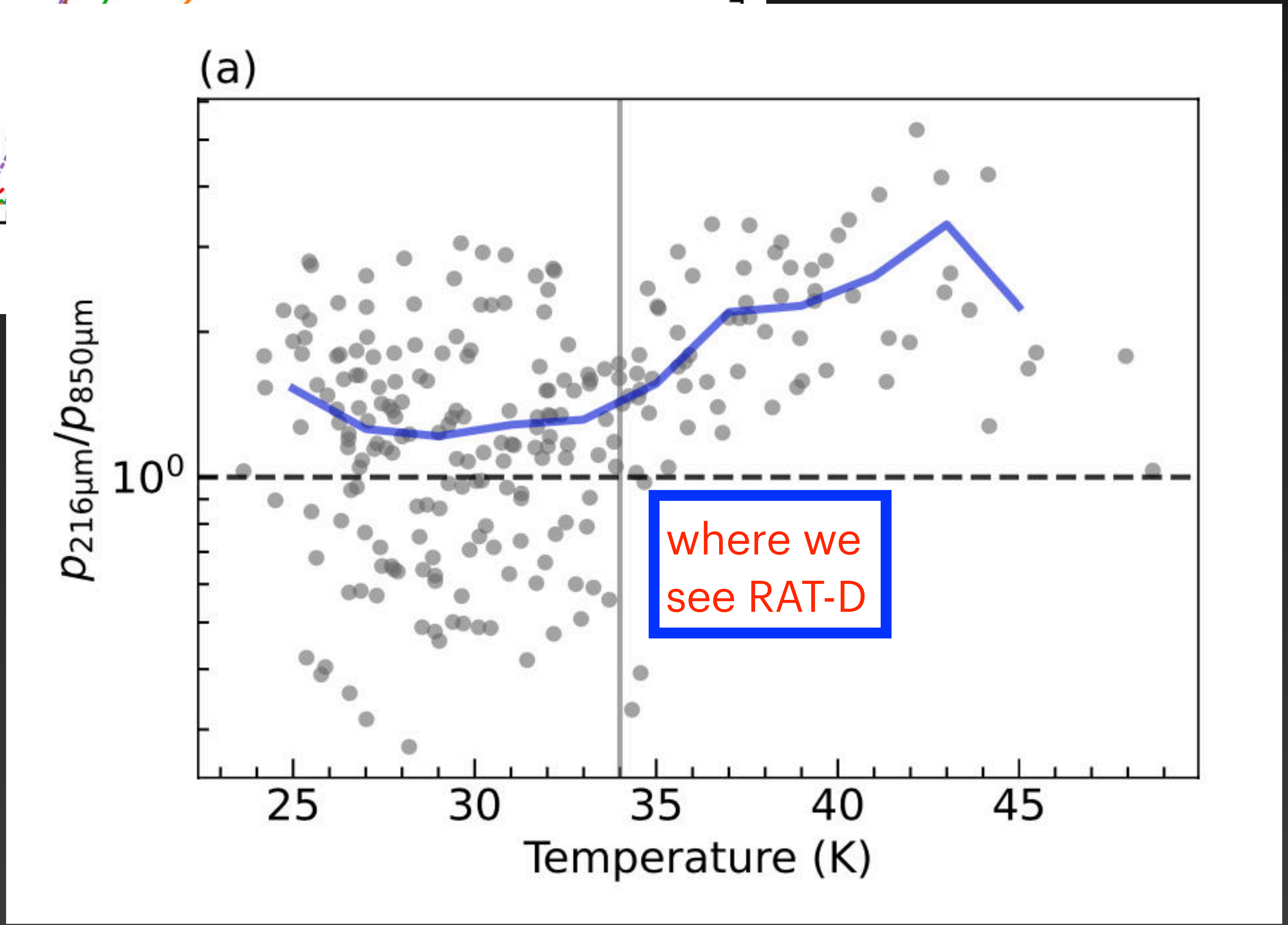


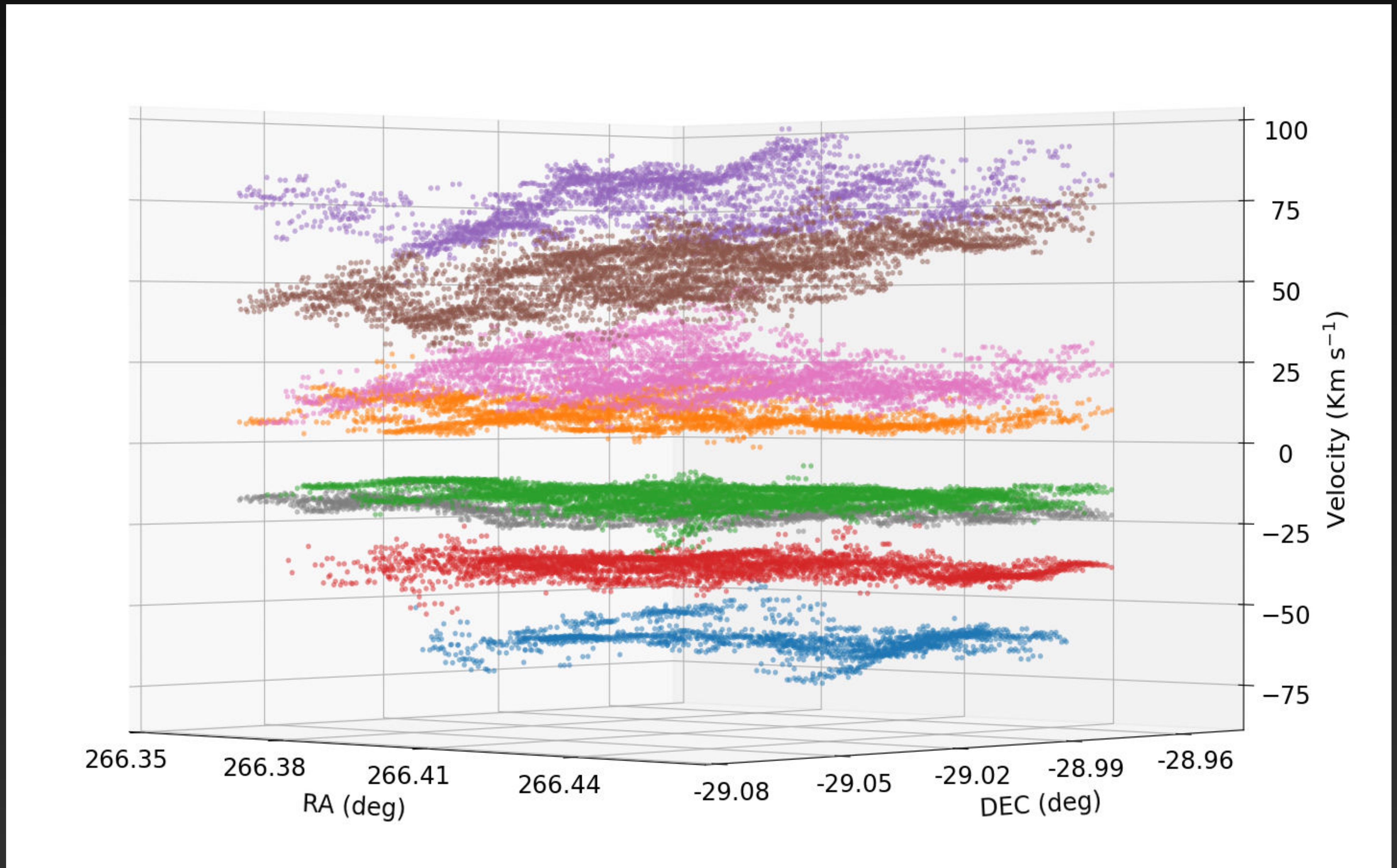
$$\frac{p_{\lambda 1}}{p_{\lambda 2}} > 1$$

Peak ~ 100 µm

$$\frac{p_{\lambda 1}}{p_{\lambda 2}} < 1$$

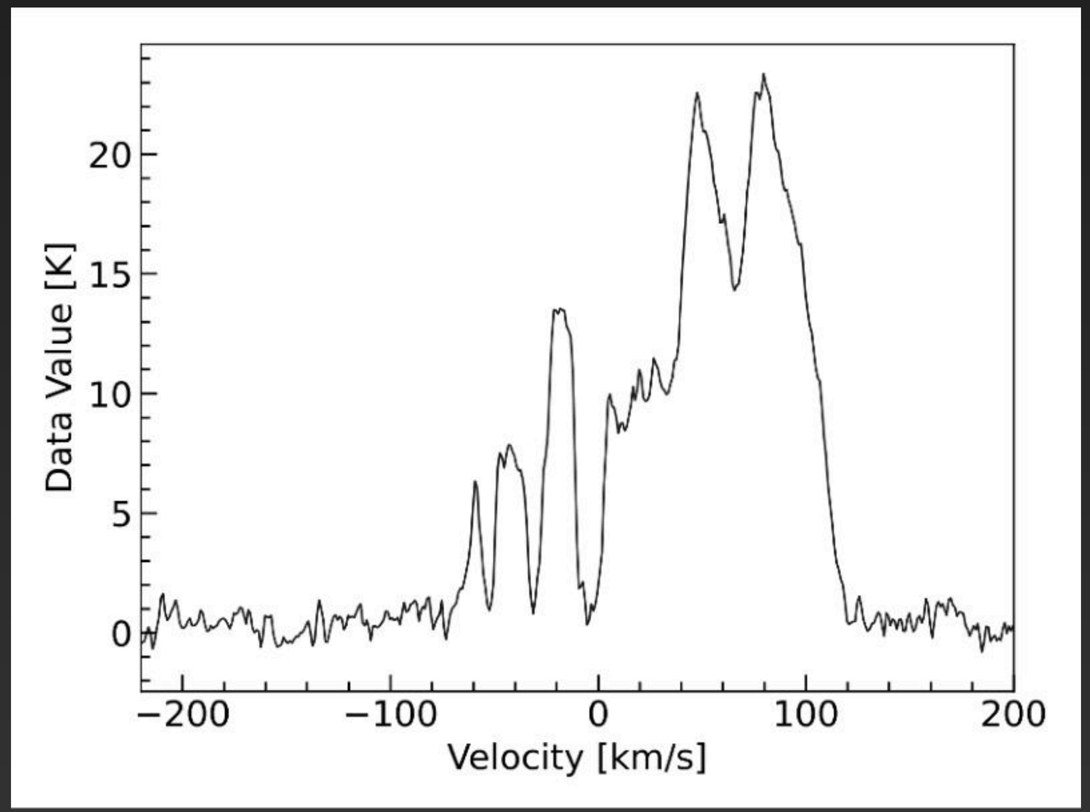
VELOCITY COMPONENTS

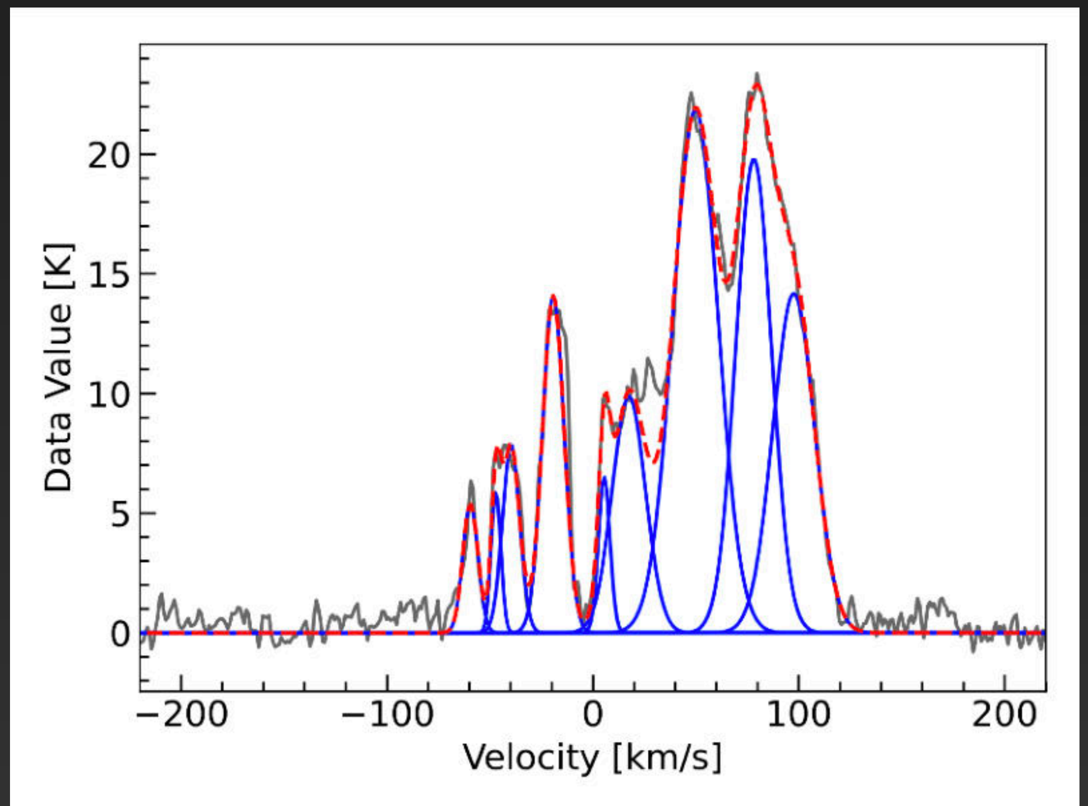
ΔV is a major source of uncertainty while using DCF method to estimate *B*-Field (Chen et al. 2022)



Agglomerative Clustering for ORganizing Nested Structures (acorns: Henshaw et al. 2016)

Semi-Automated multi-COmponent Universal Spectral-line fitting Engine (scousepy: Henshaw et al. 2016)

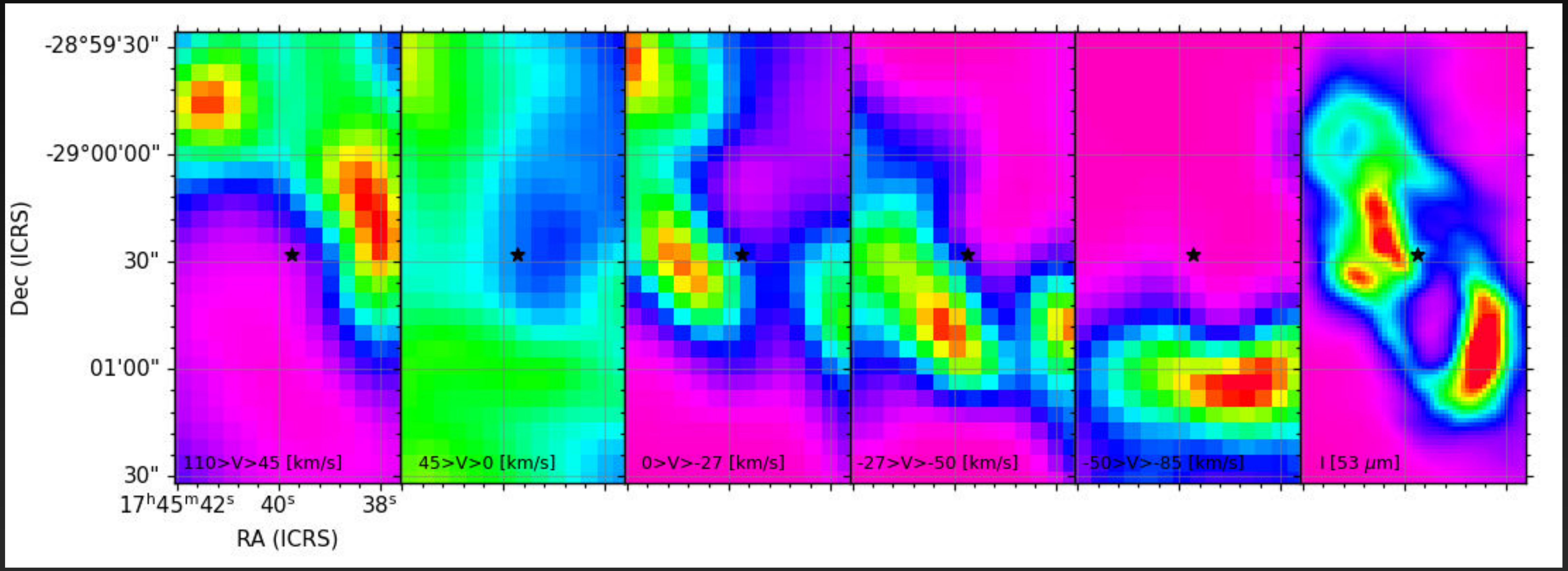


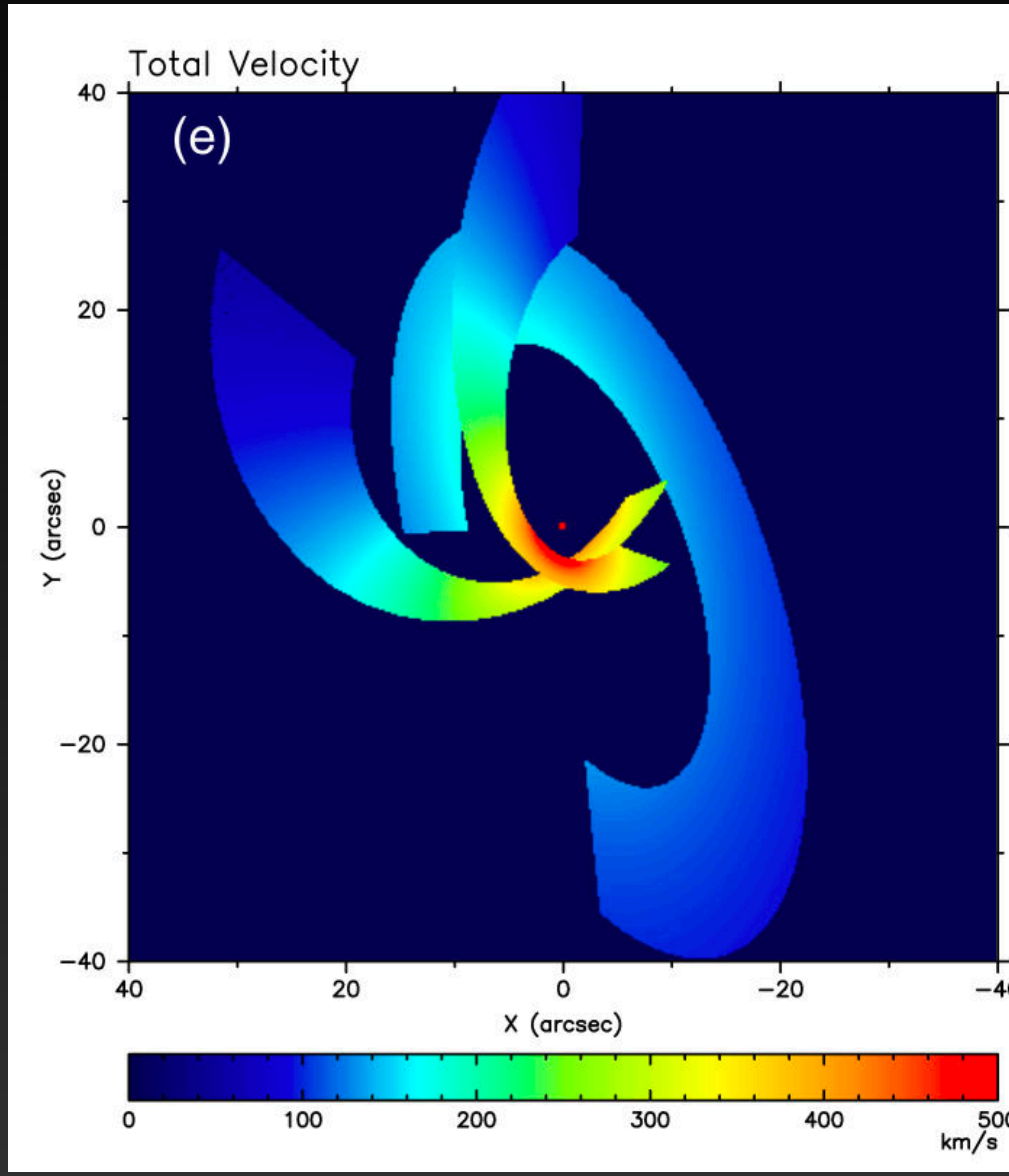


Velocity Dispersion Components $^{12}CO(J = 3 \rightarrow 2)$ from CHIMPS2 (Eden et al. 2020)

Velocity Components SOFIA 53 µm

Moment zero maps of acorns resolved components



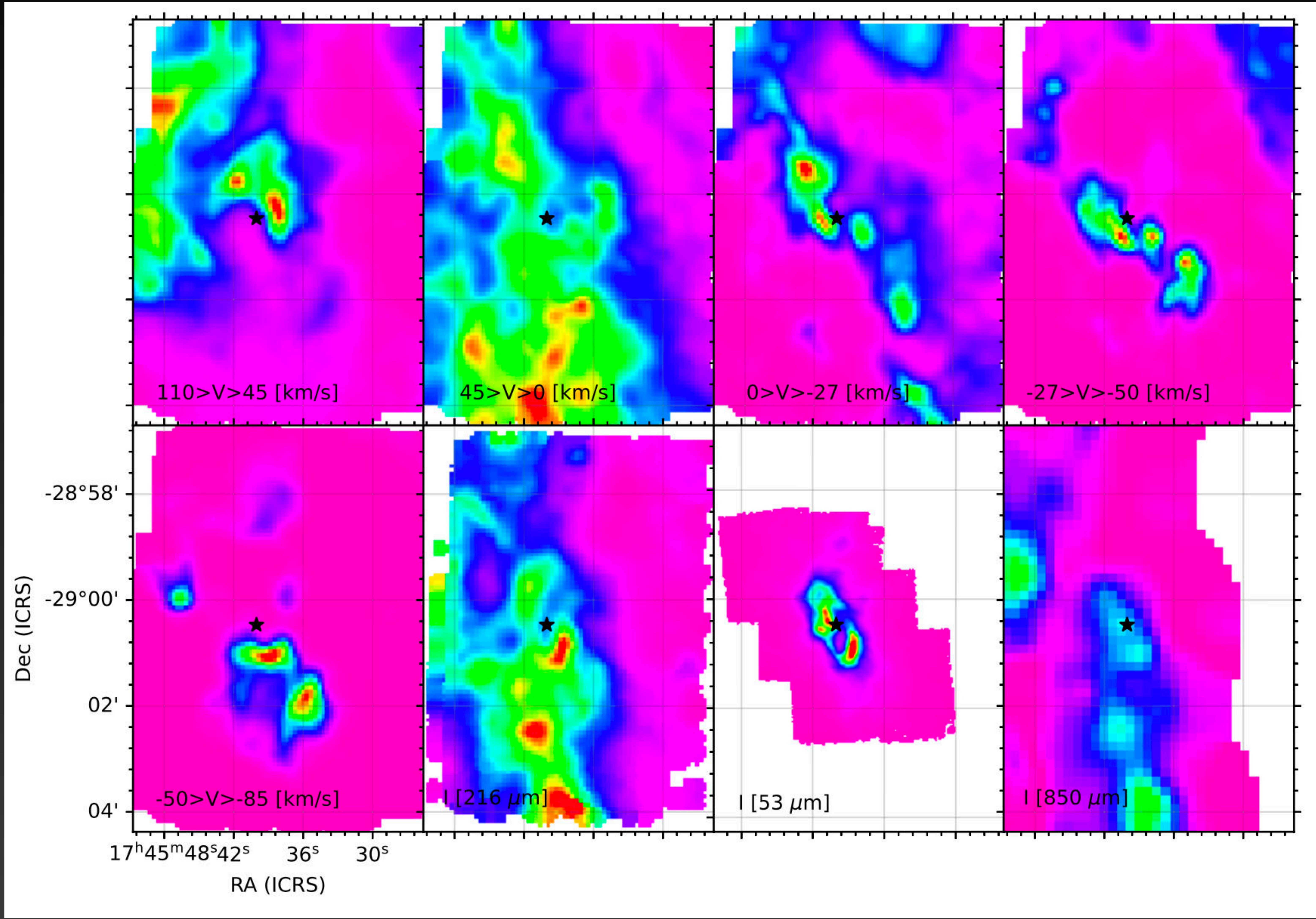


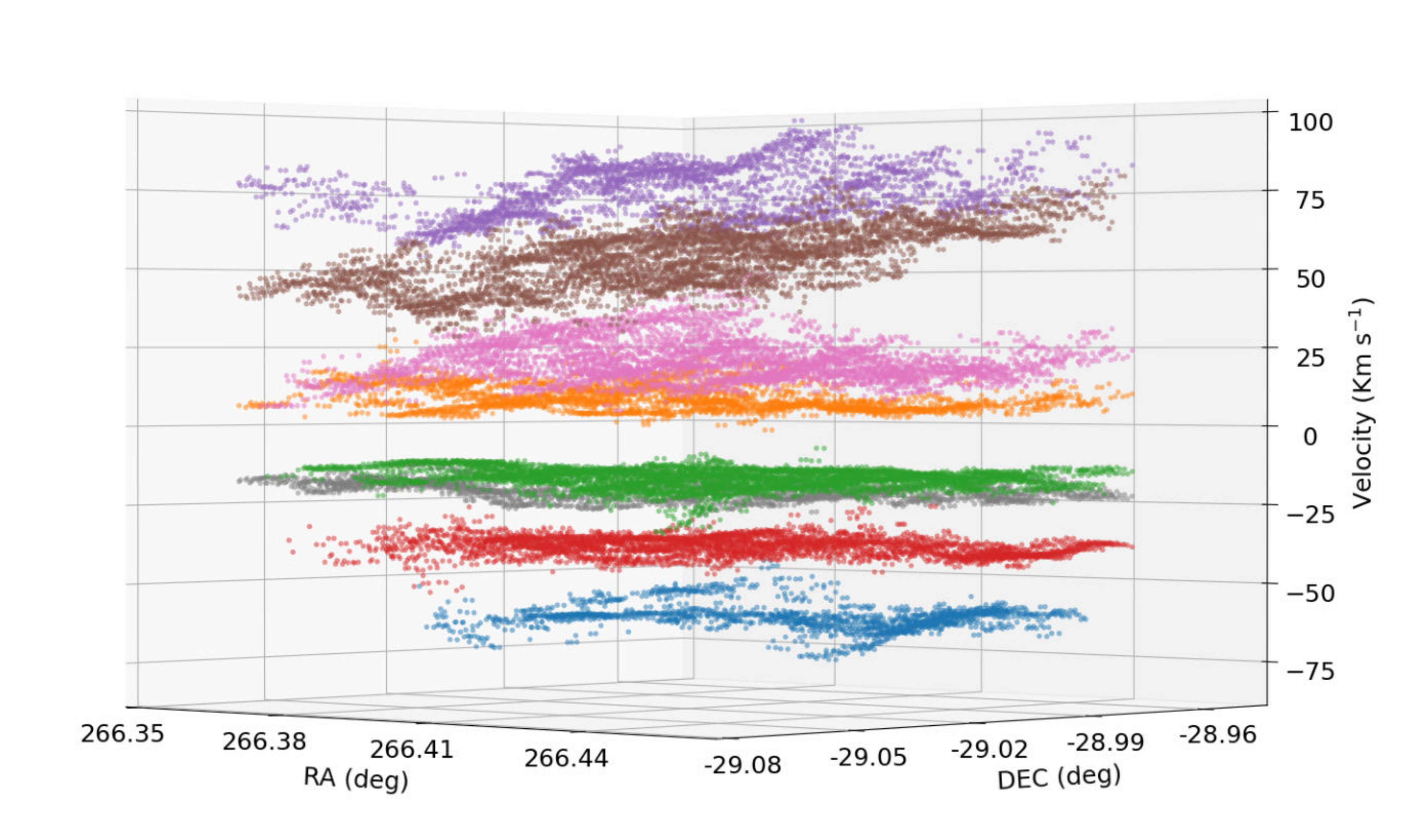
53 µm emission appears to come from 0 — 85 km/s foreground (blue shifted) velocity components

Total velocity of three streams around Sgr A* from best fit models (Zhao et al. 2009)

Velocity Components 216 μm & 850 μm

Moment zero maps of acorns resolved components





216 μm & 850 μm emission appears to be dominated by background 0 — 100 km/s (red shifted) velocity components

CONCLUSIONS

- Short wavelength polarization follows RAT-A predictions
- Evidence for RAT-D at long wavelength
- Highest polarization comes from region of high T_d, low n_H, and ordered magnetic field (low $\mathcal{S}$)
- Same region shows maximum aligned grain sizes from MRAT analytical models
- Large grains dominate alignment mass
- Polarization ratio indicates mixed population of carbon and silicate grains
- Observed polarization at different wavelengths maybe coming from different components along the line of sight

(Akshaya & Hoang 2023; MNRAS)

CURRENT WORK

- Map the magnetic field of the region
- Use the resolved components and study how they effect the observed field strength and morphology
- Velocity Gradient technique to compare field morphologies at different wavelengths with different components
- Compare field morphologies across density scales
- Study how the magnetic field plays a role in the kinematics of the CND

Thank you!