$$E_{Mag} \approx E_{Tur} \gg R_{grav}$$

Studying magnetic fields toward M17 cloud using dust polarization taken with SOFIA/HAWC+

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Aims

Magnetic fields in the plane-of-sky (B_{POS}) of M17 using SOFIA/HAWC+ polarimetric data at 154 μm.

Method

Davis-Chandrasekhar-Fermi (DCF) analytical technique for dust polarization tracing B_{POS}.

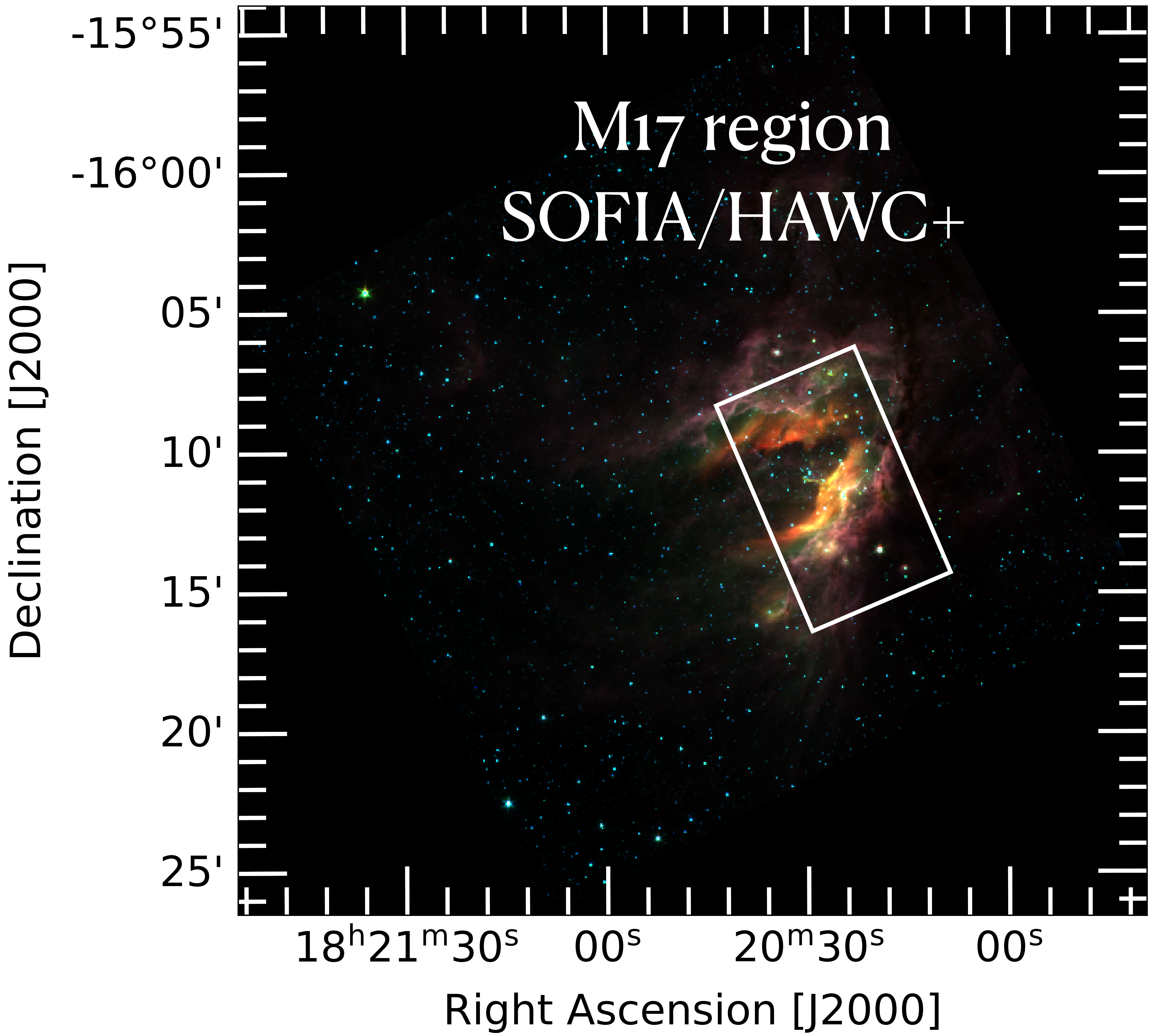
Result

★ Strong magnetic fields (B_{POS} = 326 and 839 μG in lower- and higher-density regions, respectively).

★ Magnetic fields dominate turbulences (i.e. M_A =0.02-0.004): Well-aligned magnetic field morphology.

★ The subcritical values of mass-to-magnetic flux ratio (i.e. λ=0.21-0.55): Low star formation rate in M17.

★ Dust emission, grain alignment and rotation disruption by radiative torques (RATs).



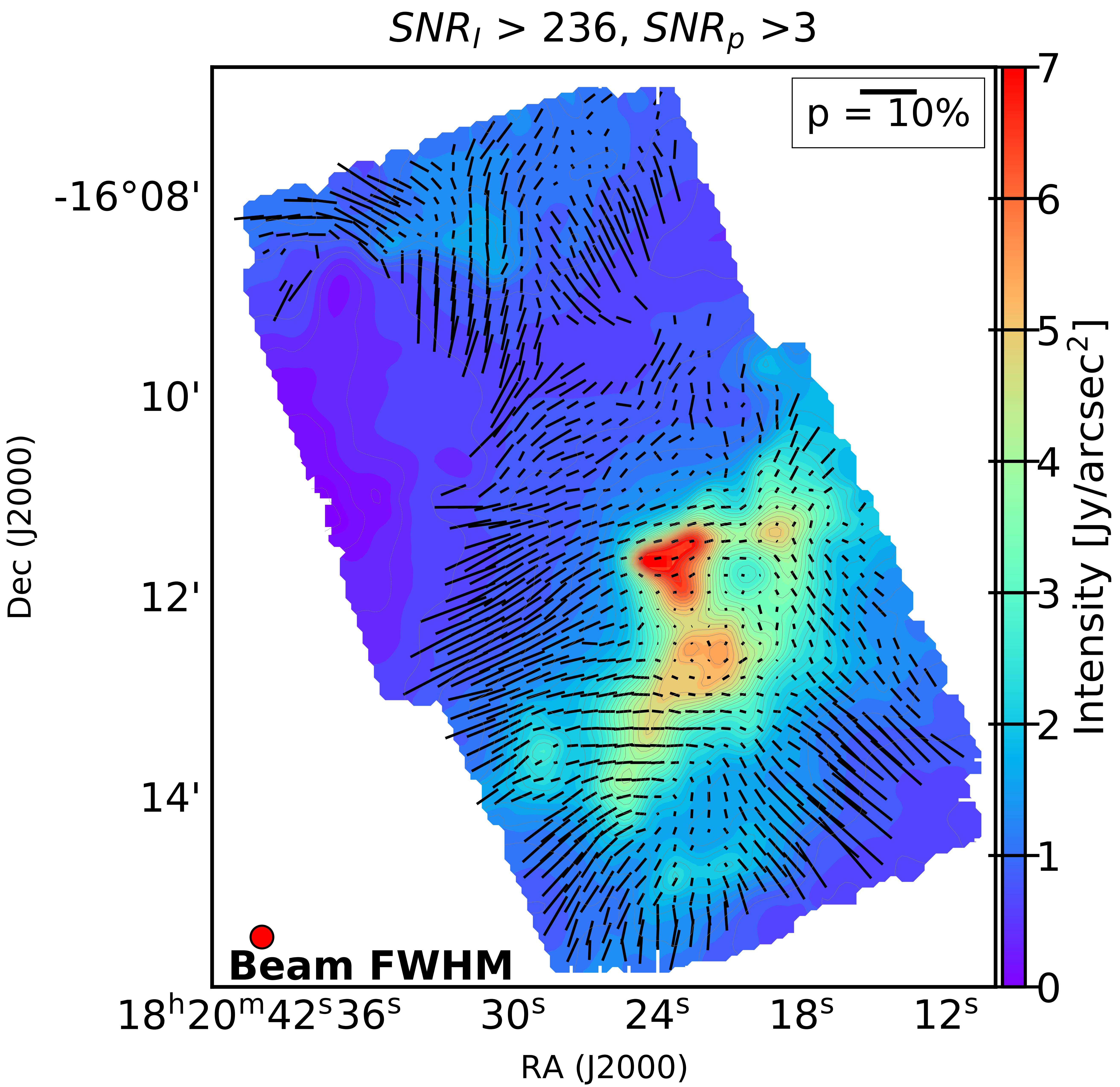
Spitzer data: (R = 8 μm, G = 4.5 μm, and B = 3.6 μm)

SOFIA/HAWC+ Polarization data

- Quality cut:
  - $SNR_I > 236$ (0.6 % polarization errors).
  - $SNR_p > 3$

- The polarization angles are rotated 90° to derive B-fields orientation.

(Gordon et al. 2018)



Magnetic Fields in the plane of sky - B_{POS}

- ★ Dust polarization is a tracer of magnetic fields.
- ★ DCF technique estimates B-fields in the plane of sky B_{POS} base on three main parameters: σ_θ, σ_ν, $n(H_2)$.

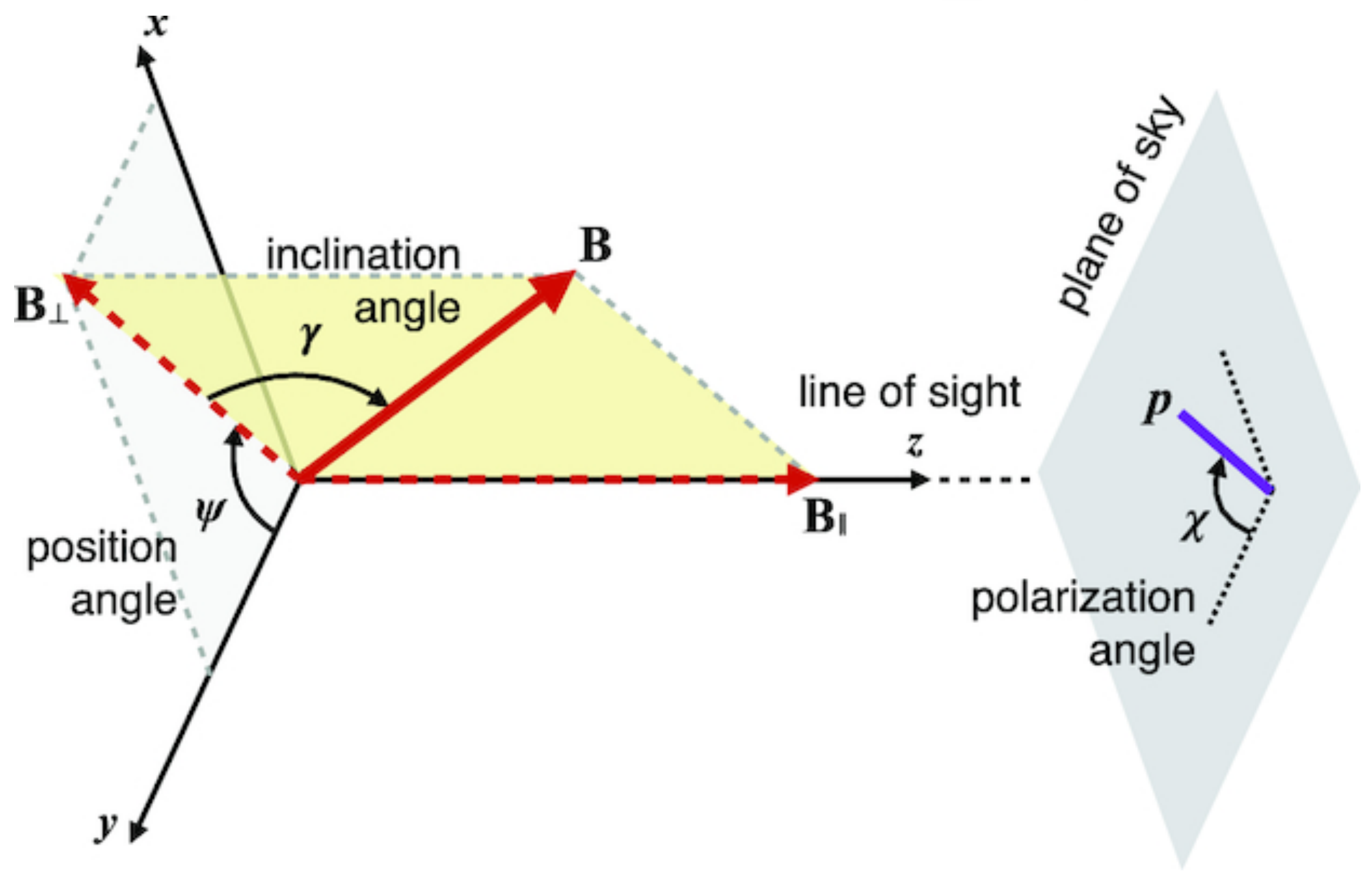
$$\Delta V = 2.355\sigma_\nu$$

Gas number density

Velocity dispersion

$$B_{POS} = 9.3\sqrt{n(H_2)}\frac{\Delta V}{\sigma_\theta}\ [\mu G]\,.$$

Dust polarization angle dispersion



(Davis 1951; Chandrasekhar & Fermi 1953)

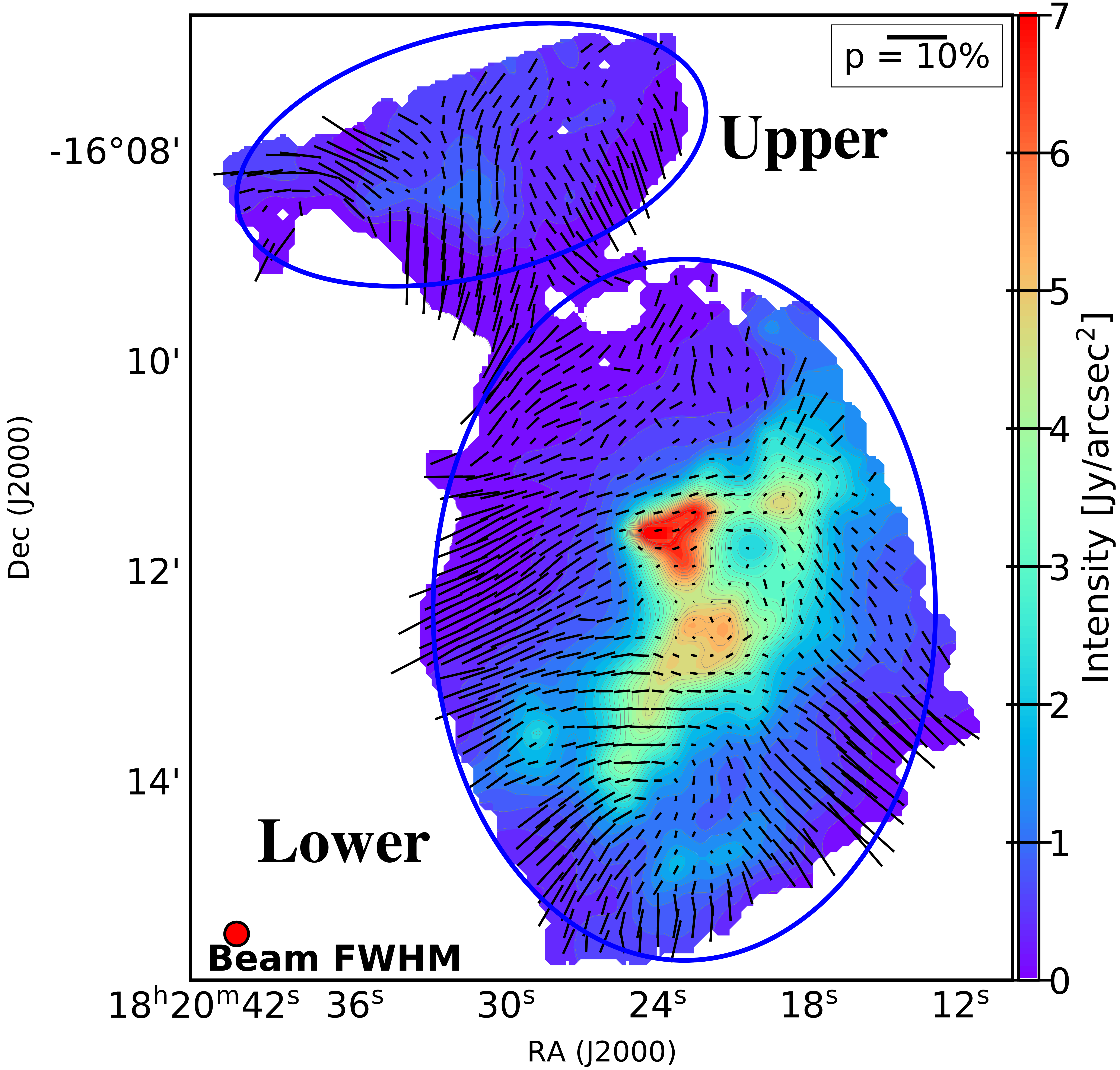
Gas number density $n(H_2)$

- Assuming a spherical volume of molecular clumps.

- Radius of the center region:

  R_{eff} upper: 68.955”
  R_{eff} lower: 119.78”

Number density (cm^{-3})	Upper region	Lower region
n_{H_2}	6.84×10^3	2.94×10^4



Technique from:
(Lee et al. 2012); (Li, D. L. et al. 2014); (Ngoc et al. 2020); (Jeffrey and Yancy 2015).

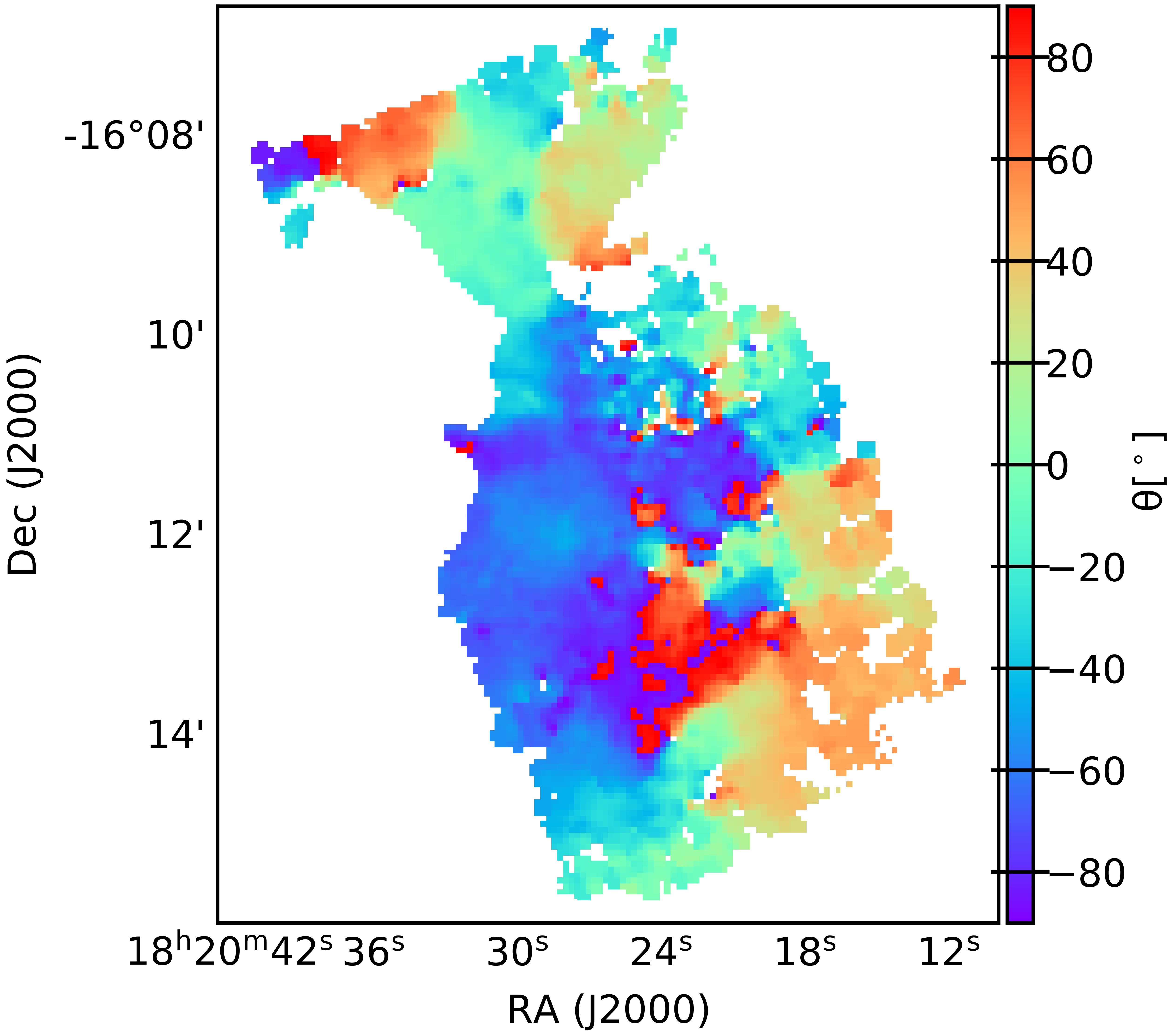
Davis-Chandrasekhar-Fermi (DCF) technique

Magnetic fields in the plane-of-sky

$$\Delta V = 2.355\sigma_{\nu}$$

$$B_{POS} = 9.3\sqrt{n(H_2)}\frac{\Delta V}{\sigma_\theta}\ [\mu G]\,.$$

Dust polarization angle dispersion



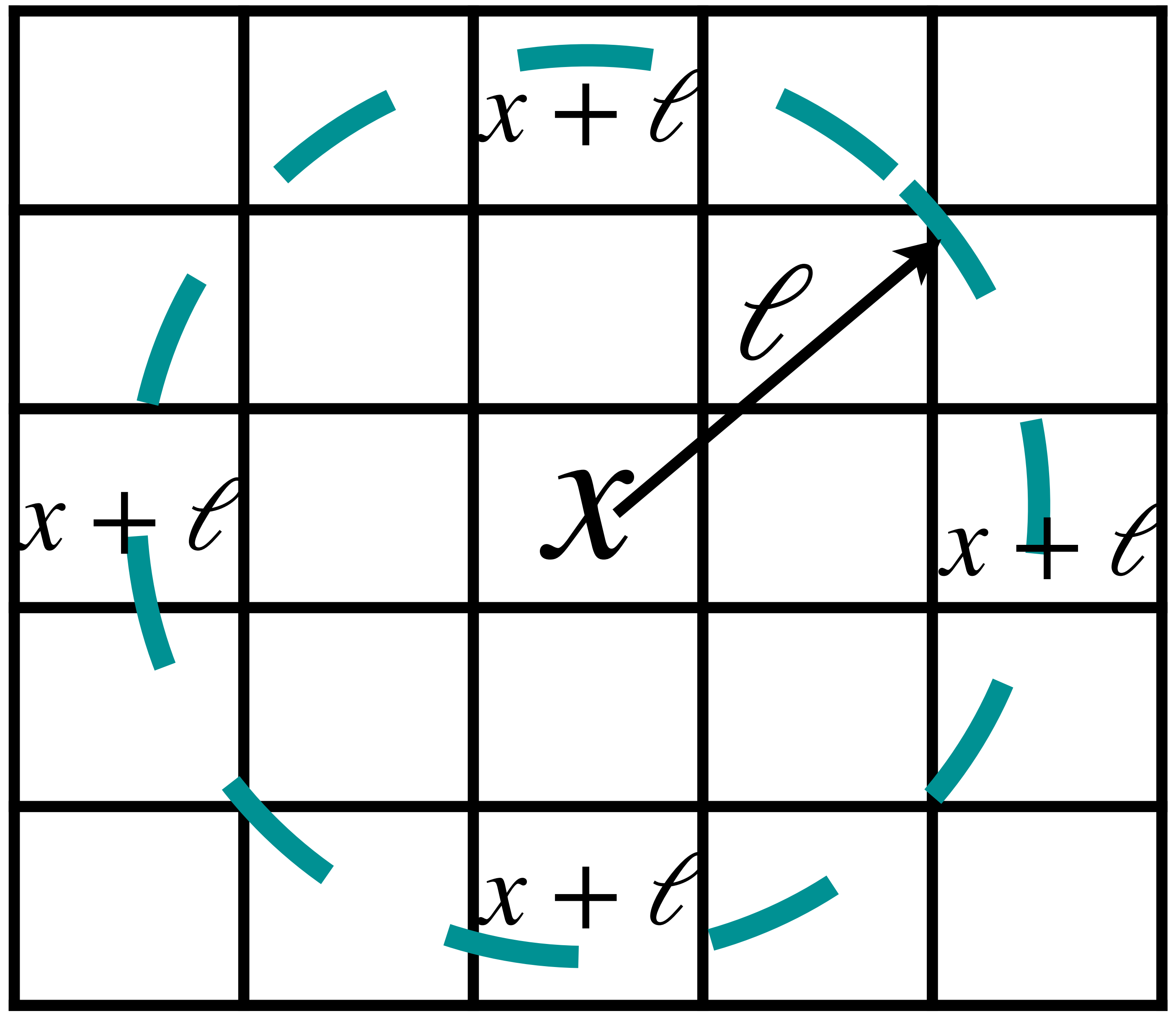
(Davis 1951; Chandrasekhar & Fermi 1953)

Polarization angle dispersion σ_θ

Structure function (Two-point correlation function)

$$\langle \Delta\theta(\ell) \rangle^{1/2} = \left\{ \frac{1}{N(\ell)} \sum_{i=1}^{N(\ell)} \left[\theta(\mathbf{x}) - \theta(\mathbf{x} + \boldsymbol{\ell}) \right]^2 \right\}^{1/2}.$$

2D Image



- $N(\ell)$: Number of pairs of pixel.
- x: Pixel location.
- $x + \ell$: Pixel at distance ℓ
- Note that: $\Delta\theta(\ell) = |\theta(x) - \theta(x + \ell)|$ is in range of [0,90°].

Hildebrand et al. (2009)

Polarization angle dispersion σ_θ

- Taylor expansion

$$\langle \Delta\theta^2(\ell) \rangle \approx a^2\ell^2 + b^2$$

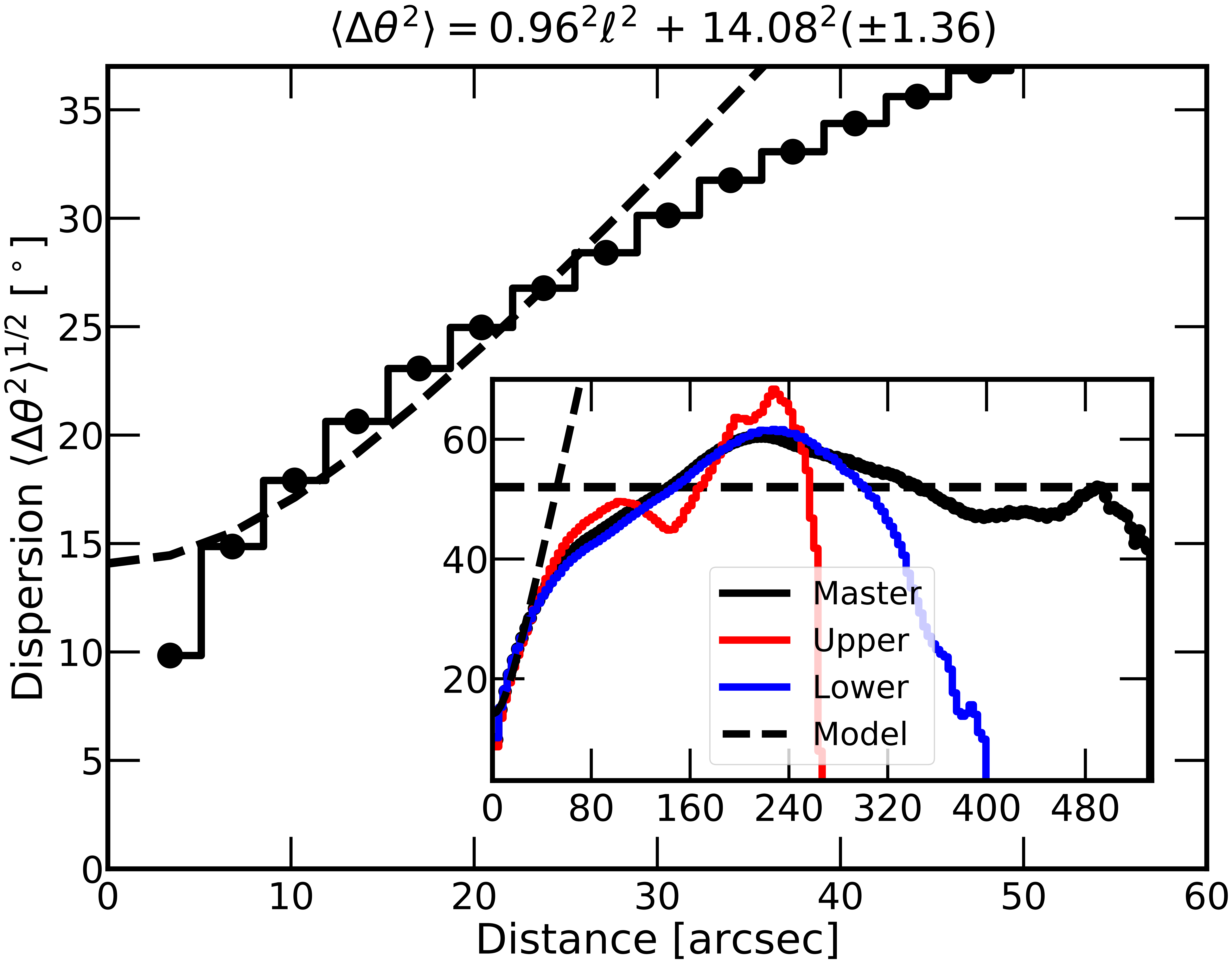
a: The large-scale variations of the B-field.

b: The ratio of the turbulent and uniformity of the magnetic field

- The fitted model for a distance of 8 pixels ~ 2 beam sizes.

$$\sigma_\theta = b/\sqrt{2}$$

$$= 9.958 \pm 0.96 \ [\mathrm{deg}]$$



Davis-Chandrasekhar-Fermi (DCF) technique

$$\Delta V = 2.355\sigma_\nu$$

Velocity dispersion

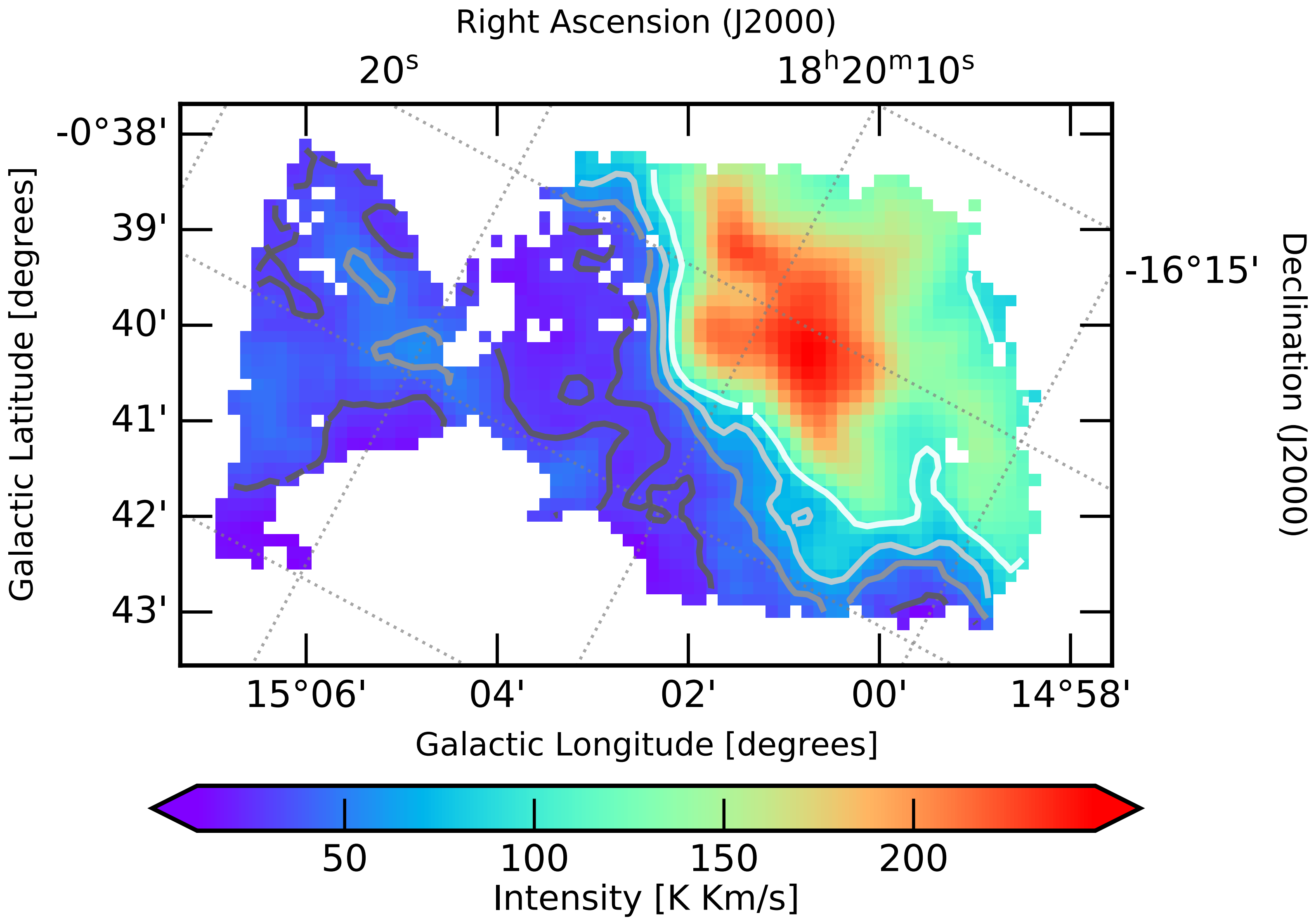
Magnetic fields in the plane-of-sky

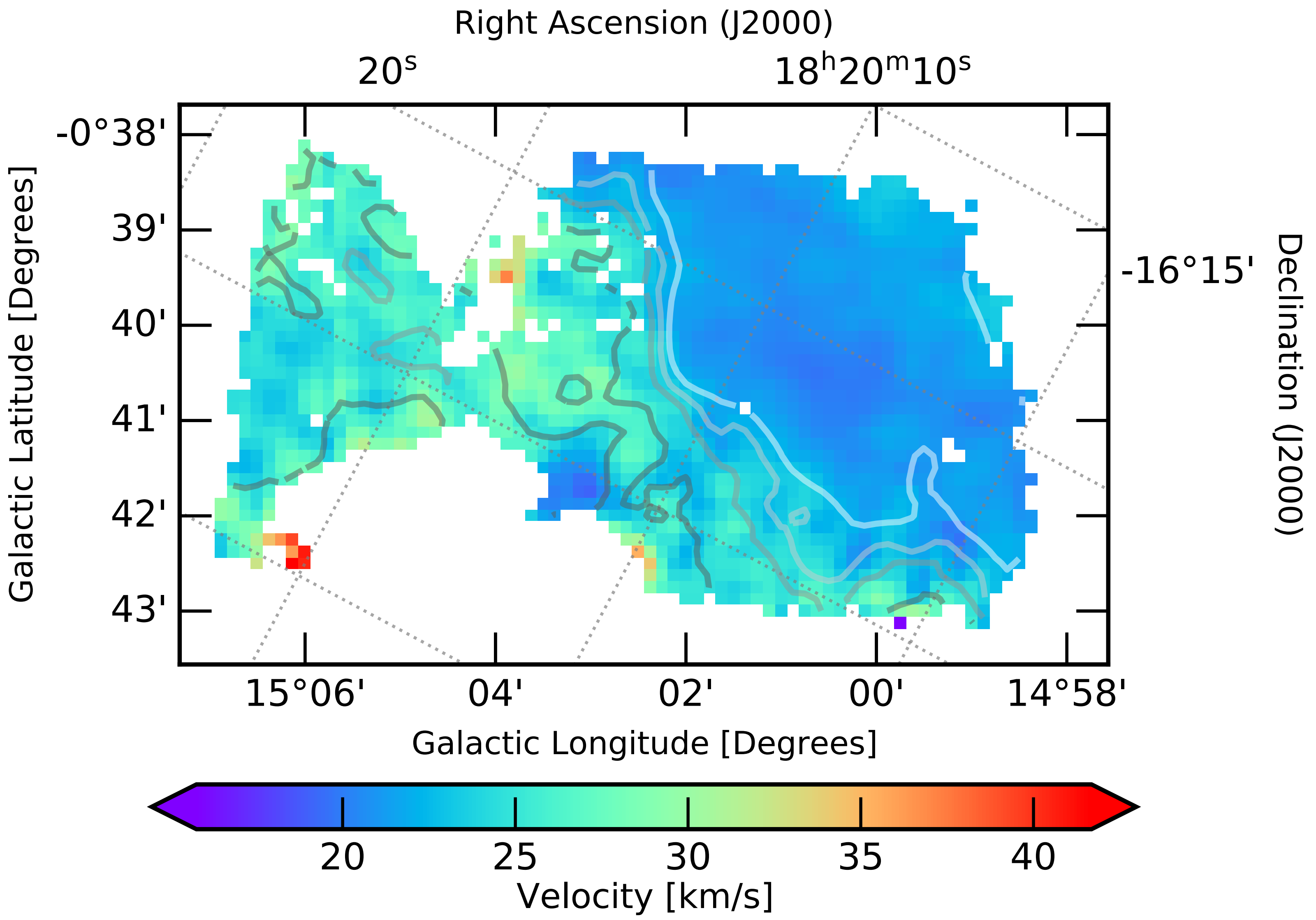
$$B_{POS} = 9.3\sqrt{n(H_2)}\frac{\Delta V}{\sigma_\theta}\ [\mu G]\,.$$

(Davis 1951; Chandrasekhar & Fermi 1953)

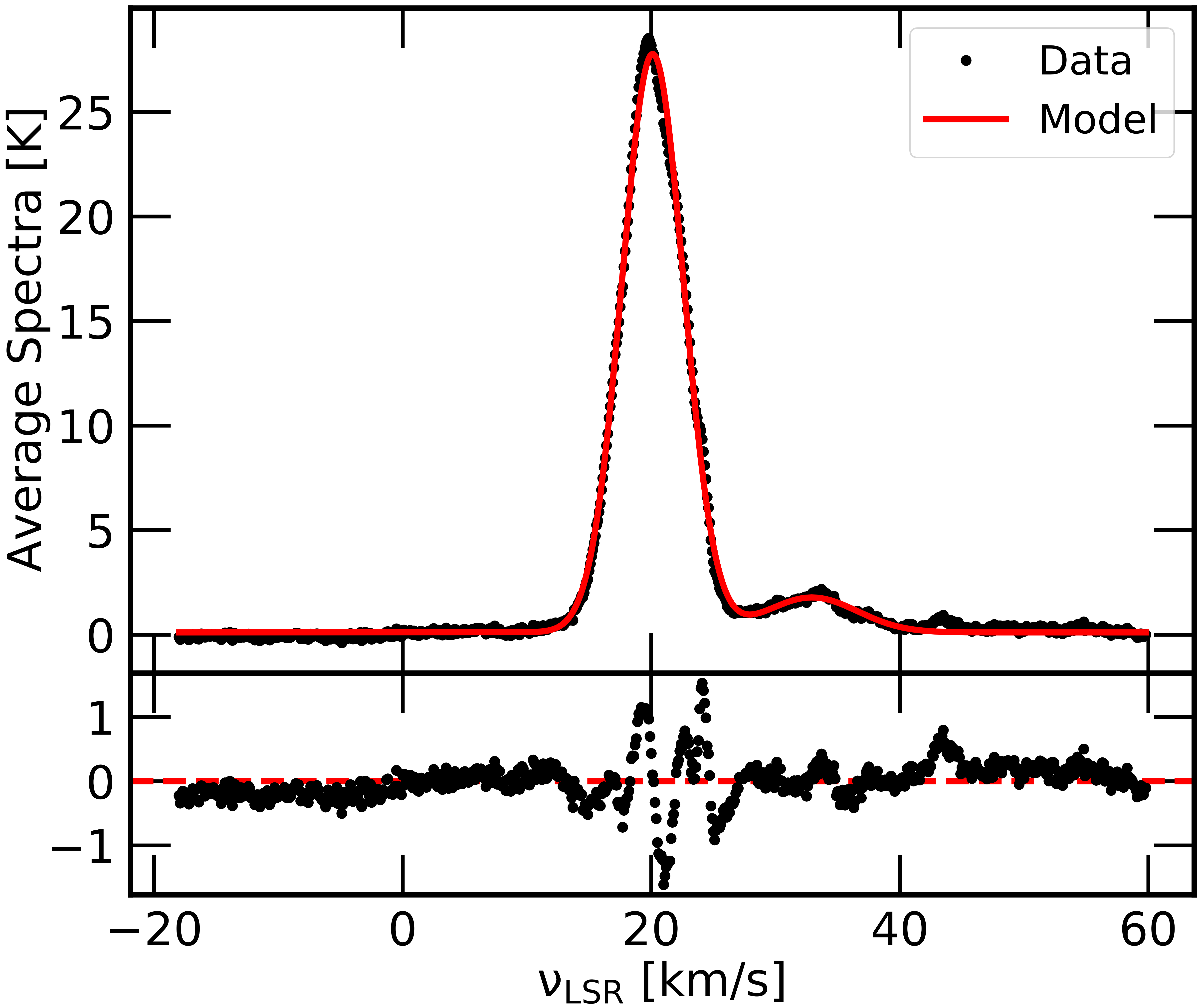
Velocity Dispersion σ_ν

The ^{13}CO $(J = 1 \rightarrow 0)$ data cube is archived from Nobeyama 45 m telescope *Nakamura et al (2019)*, the pixel size is 8.5”.





$$y = 1.672e^{-\frac{(x-32.925)^2}{2(3.665)^2}} + 27.655e^{-\frac{(x-20.113)^2}{2(2.483)^2}} + 0.114$$

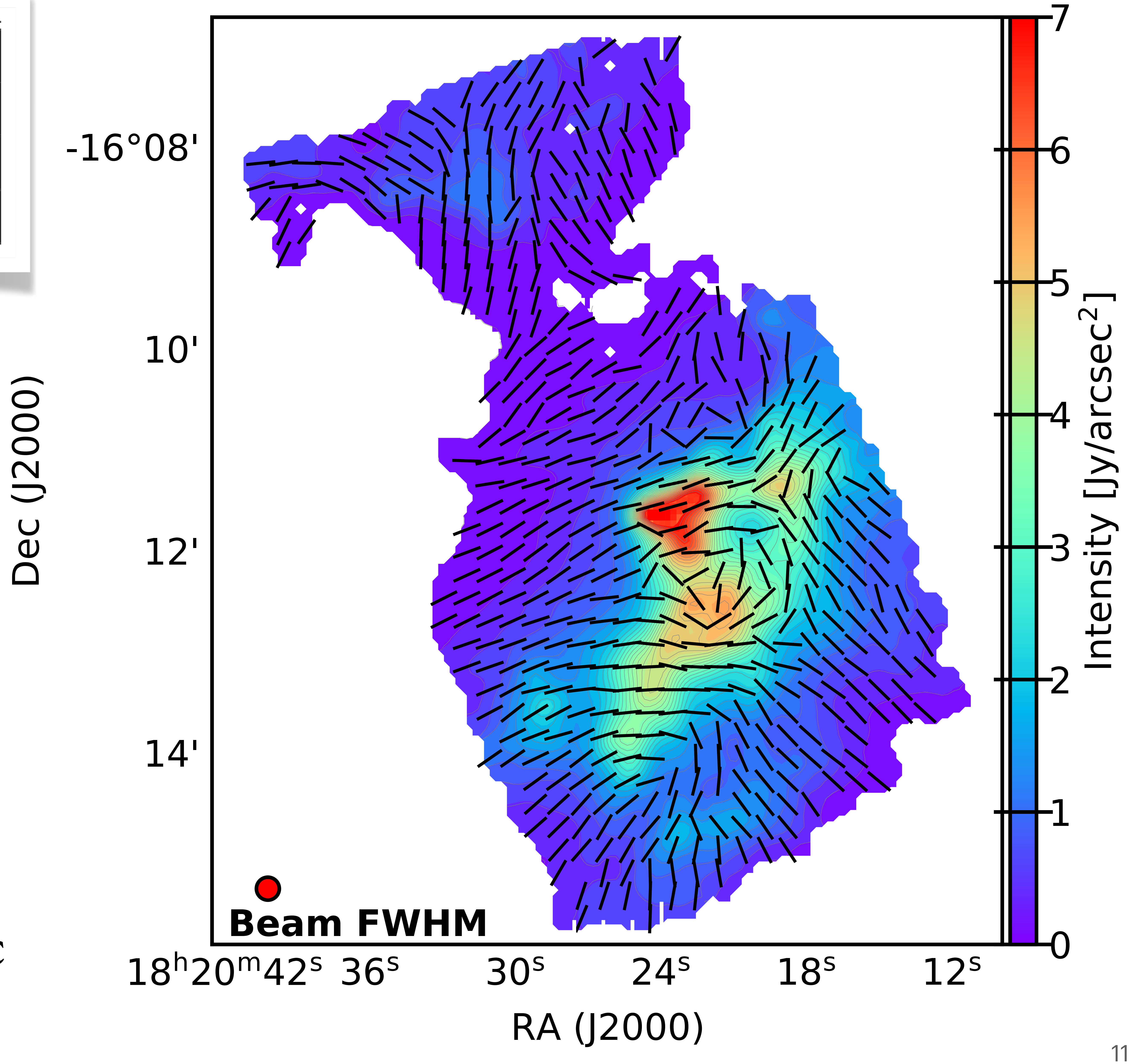


- The average velocity map is peak at ~ 20 $\mathrm{kms^{-1}}$.
- Non-thermal velocity dispersion: $\sigma_v \approx 2.296\ \mathrm{kms^{-1}}$.

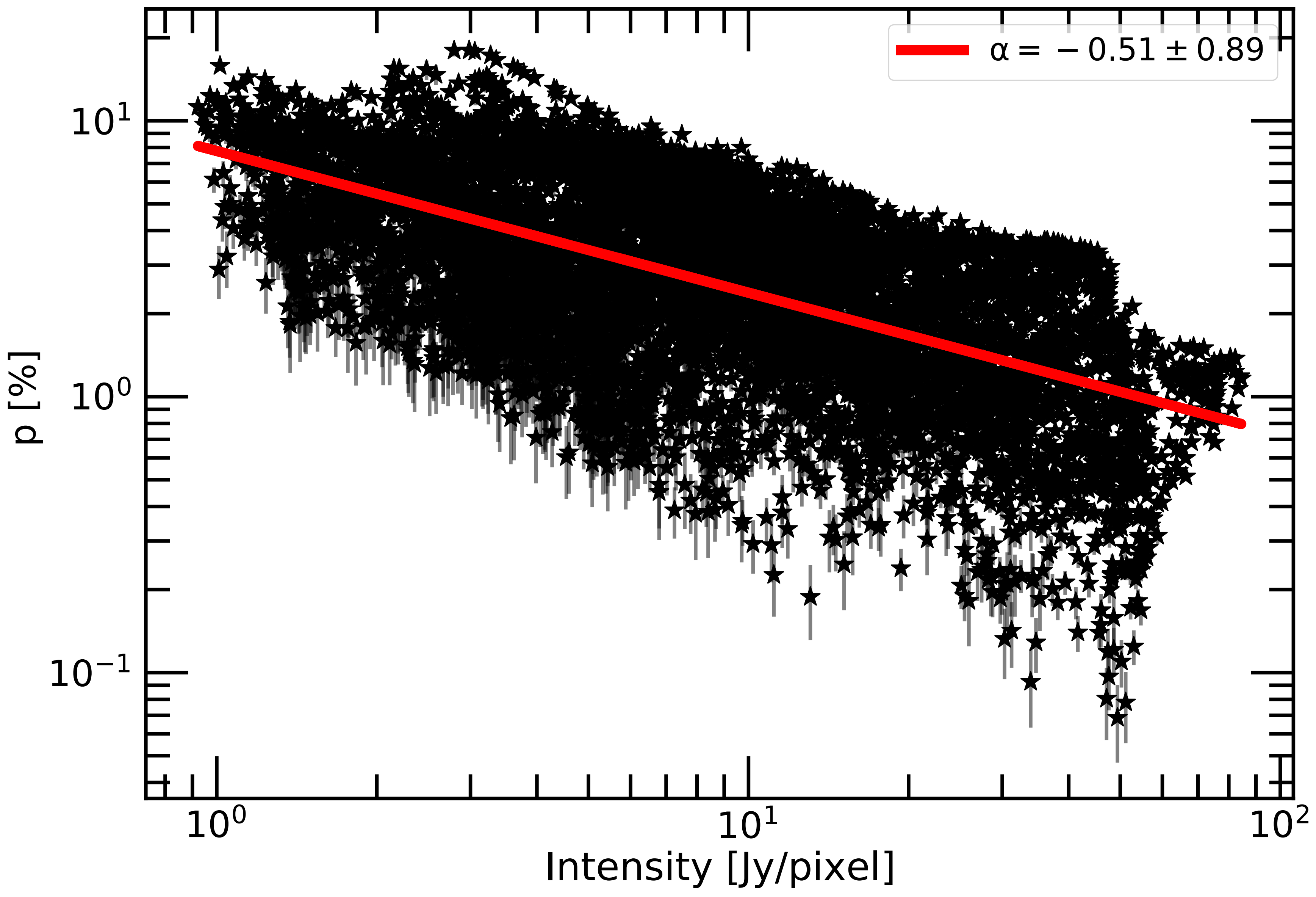
B-fields strength estimation

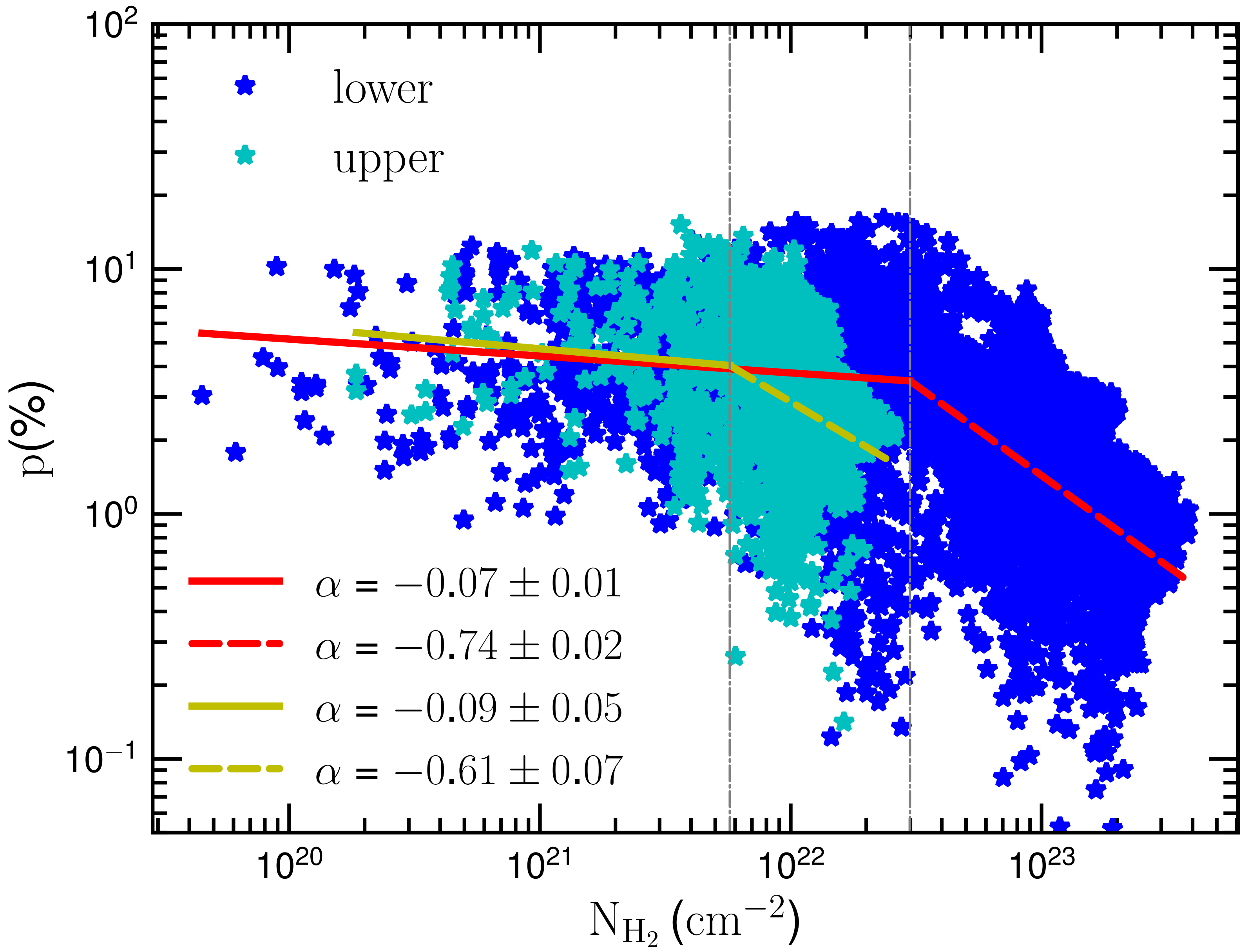
Region	B_{POS} [μG]	Mach number M_A	Mass-to-flux λ
Upper	326.735 ± 33.62	0.02	0.212 ± 0.098
Lower	839.380 ± 79.8	0.004	0.553 ± 0.5897

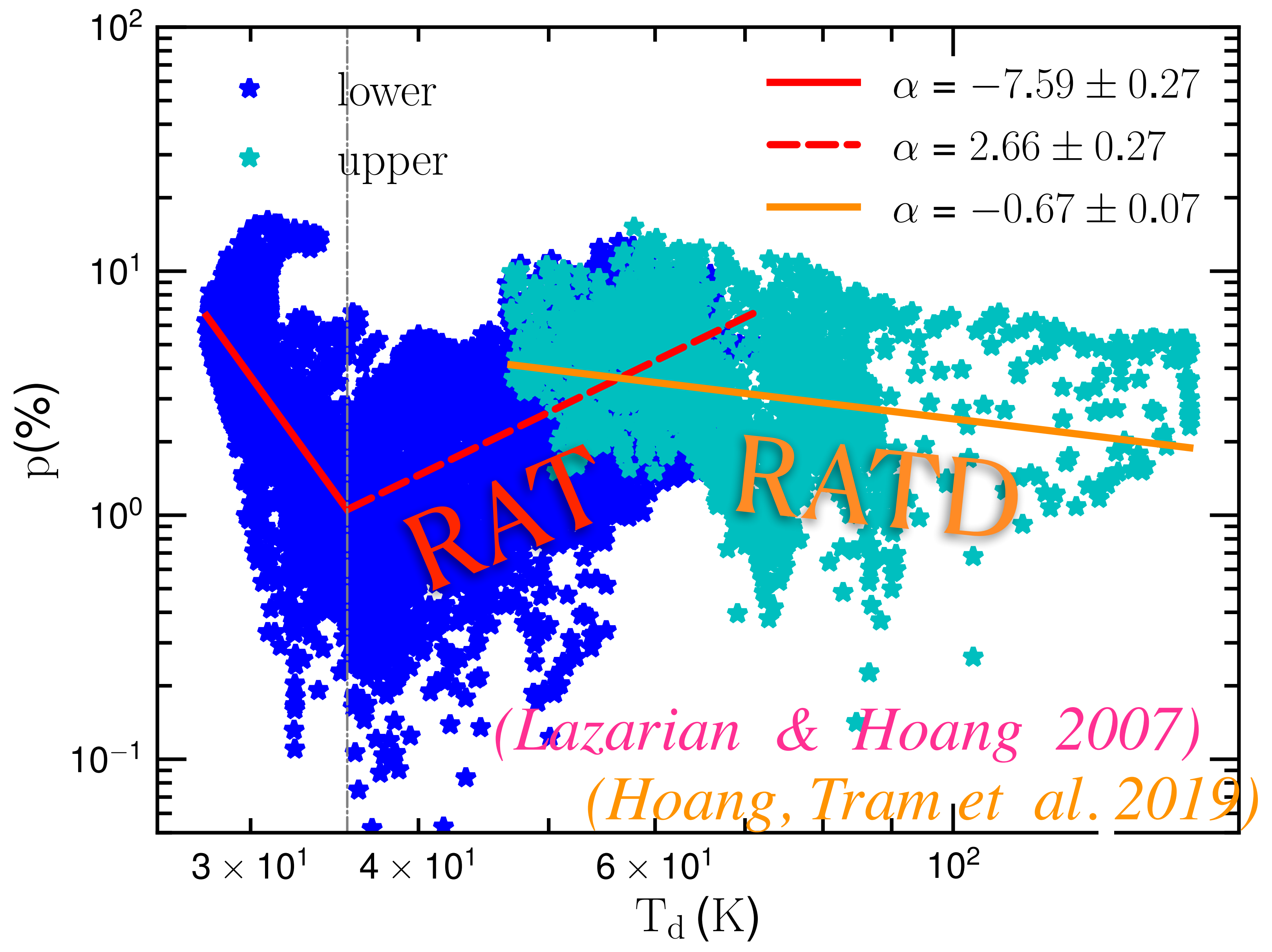
- ★ Strong magnetic fields supportably counteract gravitational collapse.
- ★ The Sub-Alfvénic $M_A \ll 1$, magnetic fields dominate turbulences: Well-aligned magnetic field morphology.
- ★ Mass-to-flux ratio $\lambda < 1$: Low star formation rate in M17.
- ★ The result is compatible with studies:
  - *Brogan et al. (1999)*: Zeeman effect, B_{LOS}~ -450-550 μG.
  - *Pellegrini et al. (2007)* reported strong magnetic fields peaking at 600 μG.



Grain alignment and distribution by RATs







⋆**p vs I:** The polarization degree p(%) decreases with increasing in the intensity I.

⋆**p vs** N_{H_2}**:** p gradually decreases when moving from a lower-density to a higher-density gas.

⋆**p vs Td:**

- Lower: Radiative Torques (RATs): Irregular grain alignment => Increment of dust polarization with the dust temperature Td.
- Upper: High dust temperature induces fast rotations, resulting in the disruption of grains into small fragments (RATD) => Decrease of dust polarization with Td.

Summary

★We estimate a strong magnetic fields in the M17 regions using SOFIA/HAWC+ polarimetric data at 154 μm . B-fields support against gravitational collapse.

★The Sub-Alfvénic Mach numbers, magnetic fields dominate turbulences: Well-aligned magnetic field morphology.

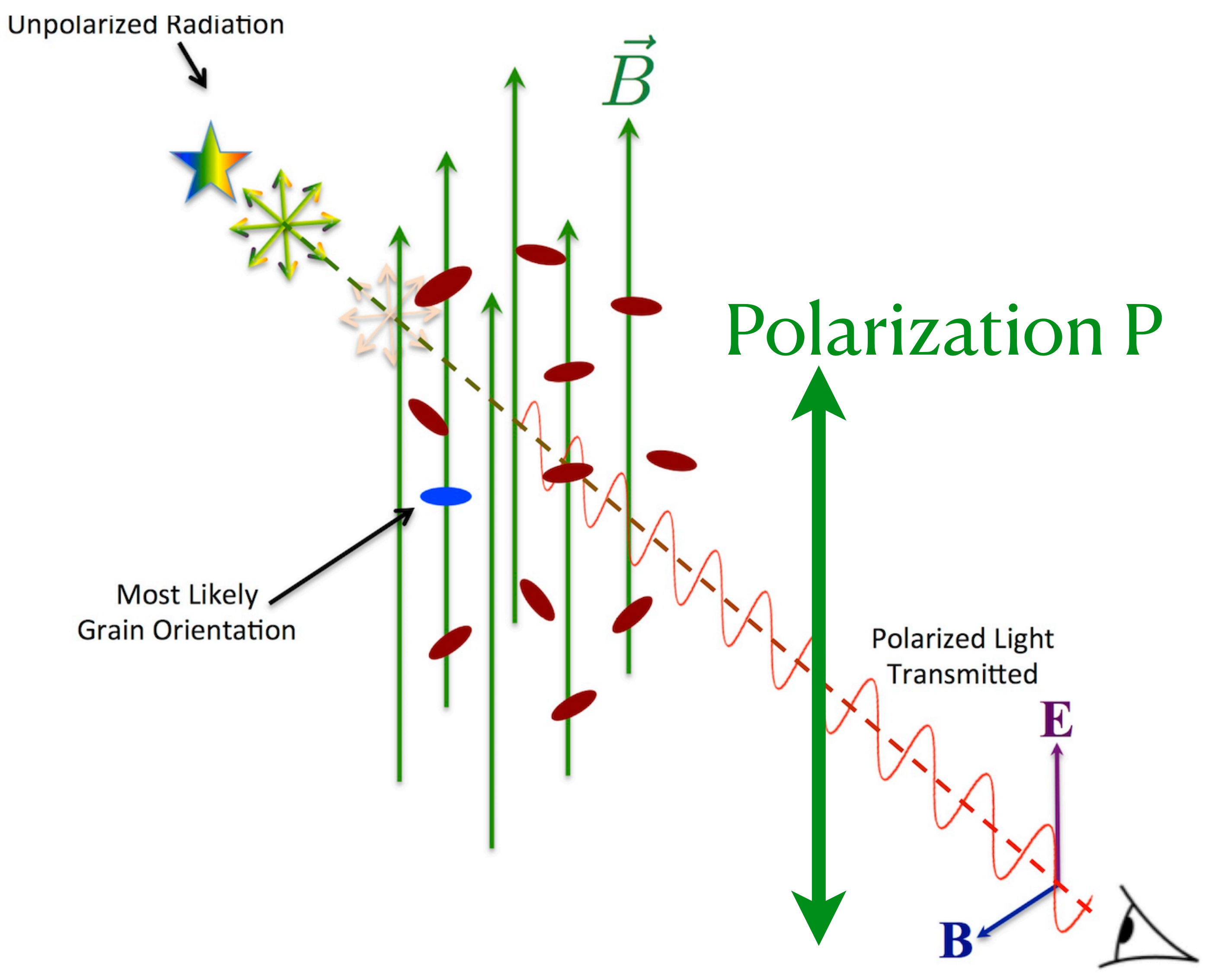
★The sub-critical values of mass-to-flux ratio $\lambda < 1$. => Low star formation rate in M17?

★Evidence of RAT and RATD models.

Thank you!

Magnetic Fields and the Structure of the Filamentary Interstellar Medium

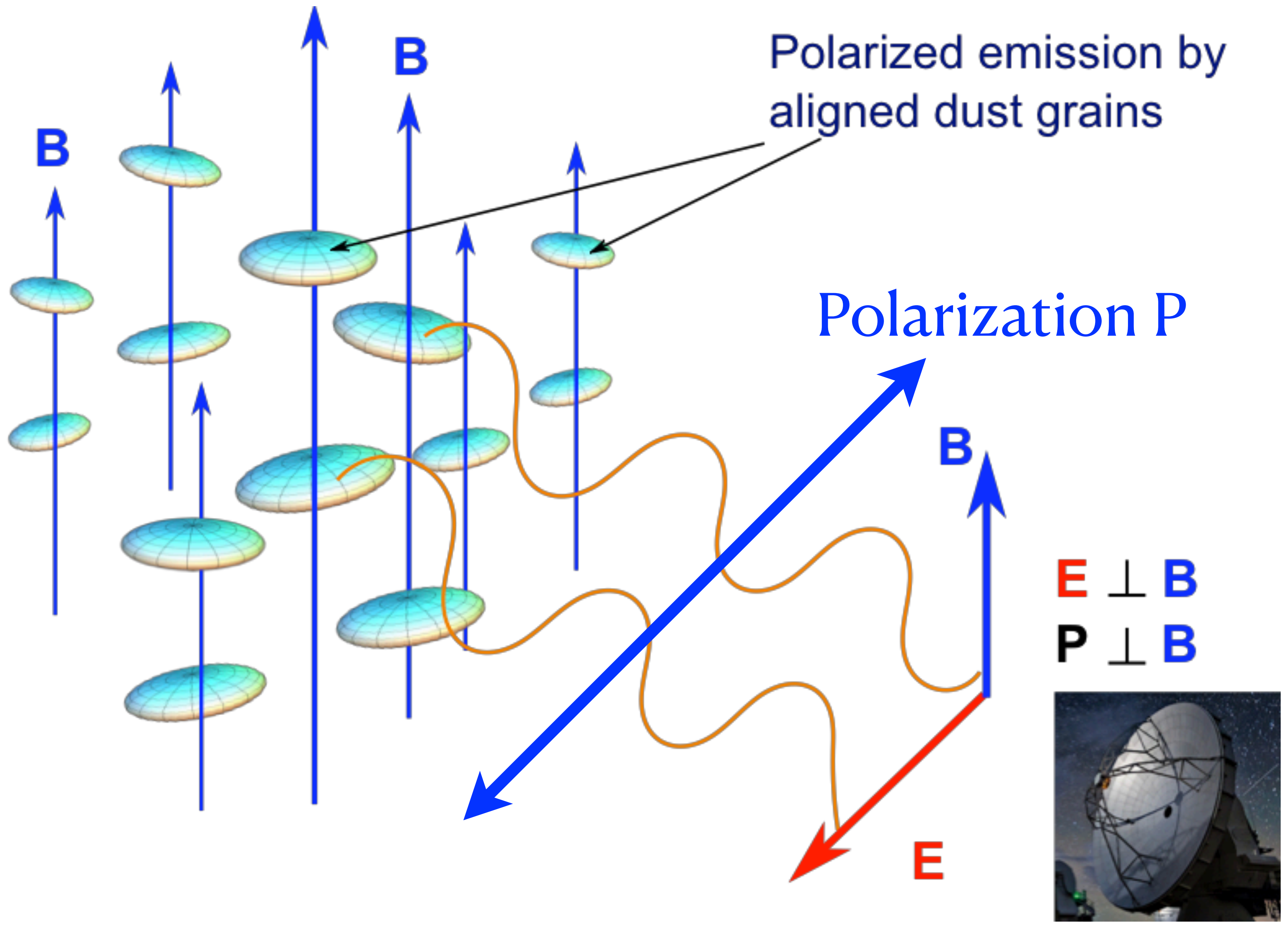
Dust polarization

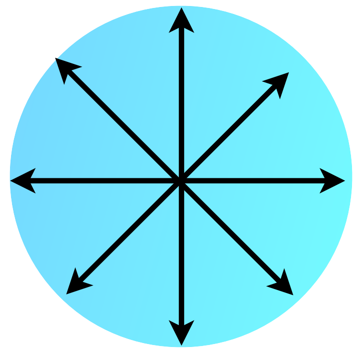
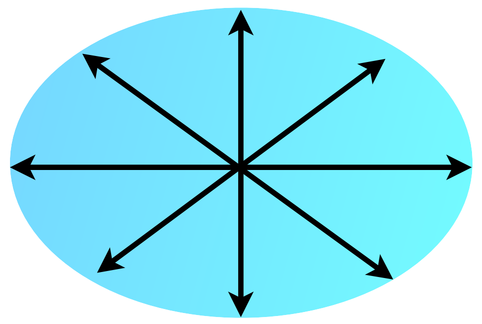
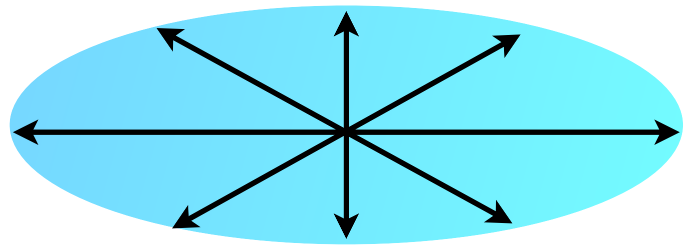


- Optical/NIR: Dust absorbed starlight
  => Polarization P is parallel with magnetic fields (B-fields)

- IR/sub-mm: Thermal dust emission
  => Polarization is perpendicular with B-fields.

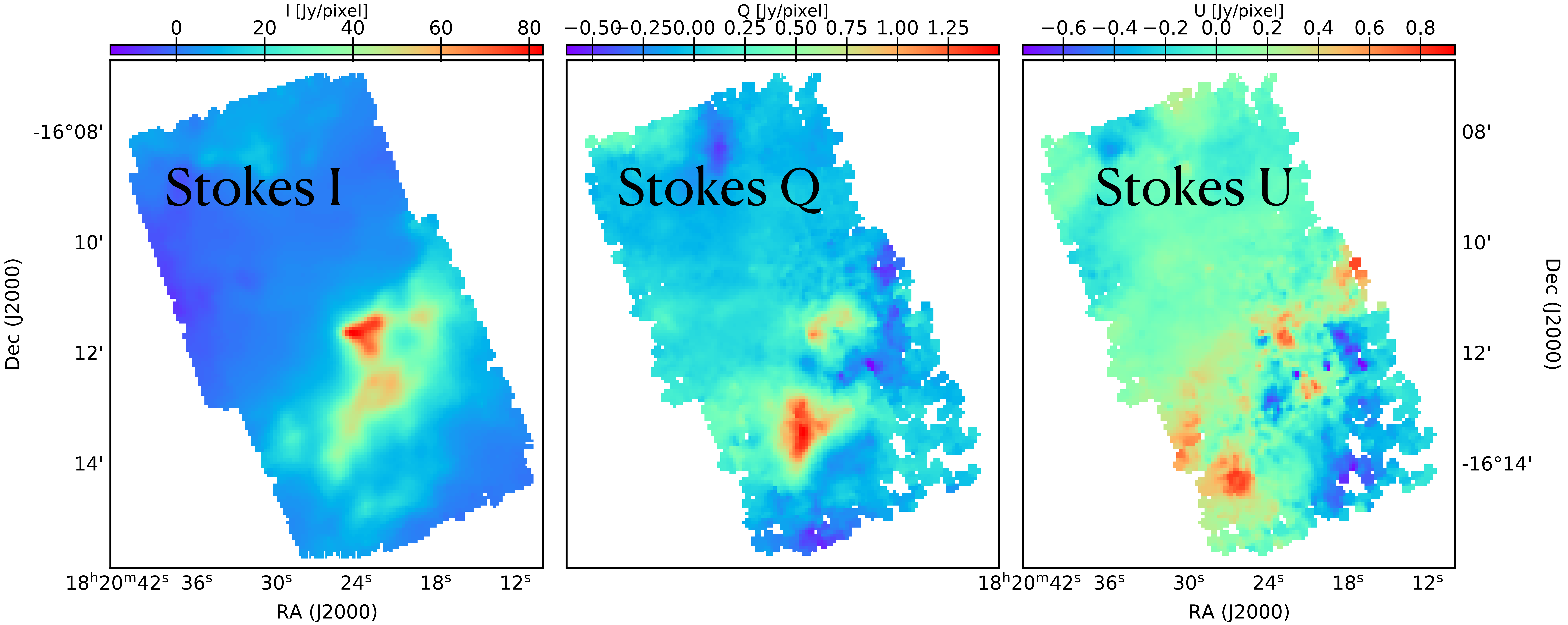
- Dust polarization depends on grain alignment degree & grain elongation.



- Unpolarized
- Small P
- Large P

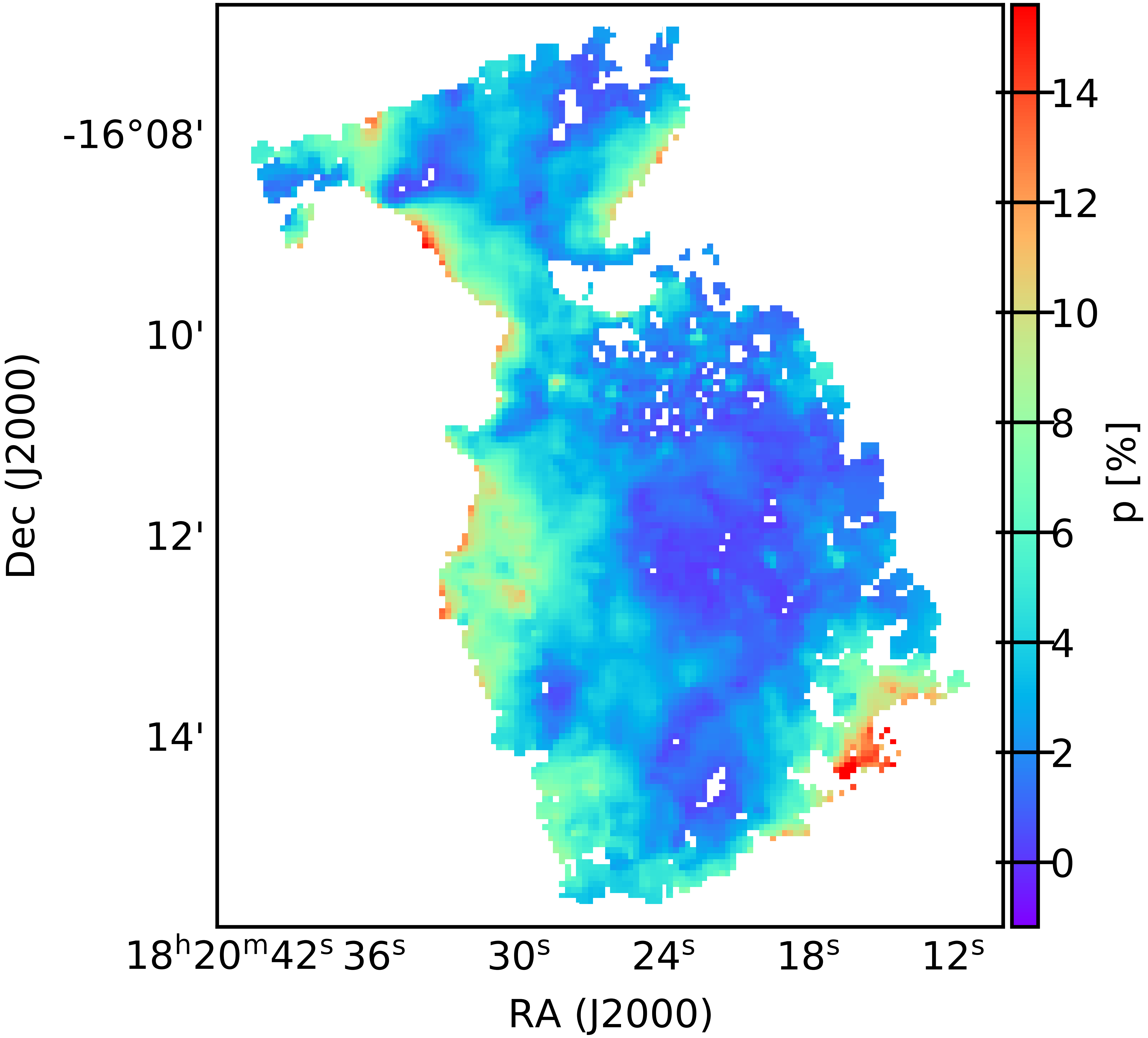
SOFIA/HAWC+ Polarization data

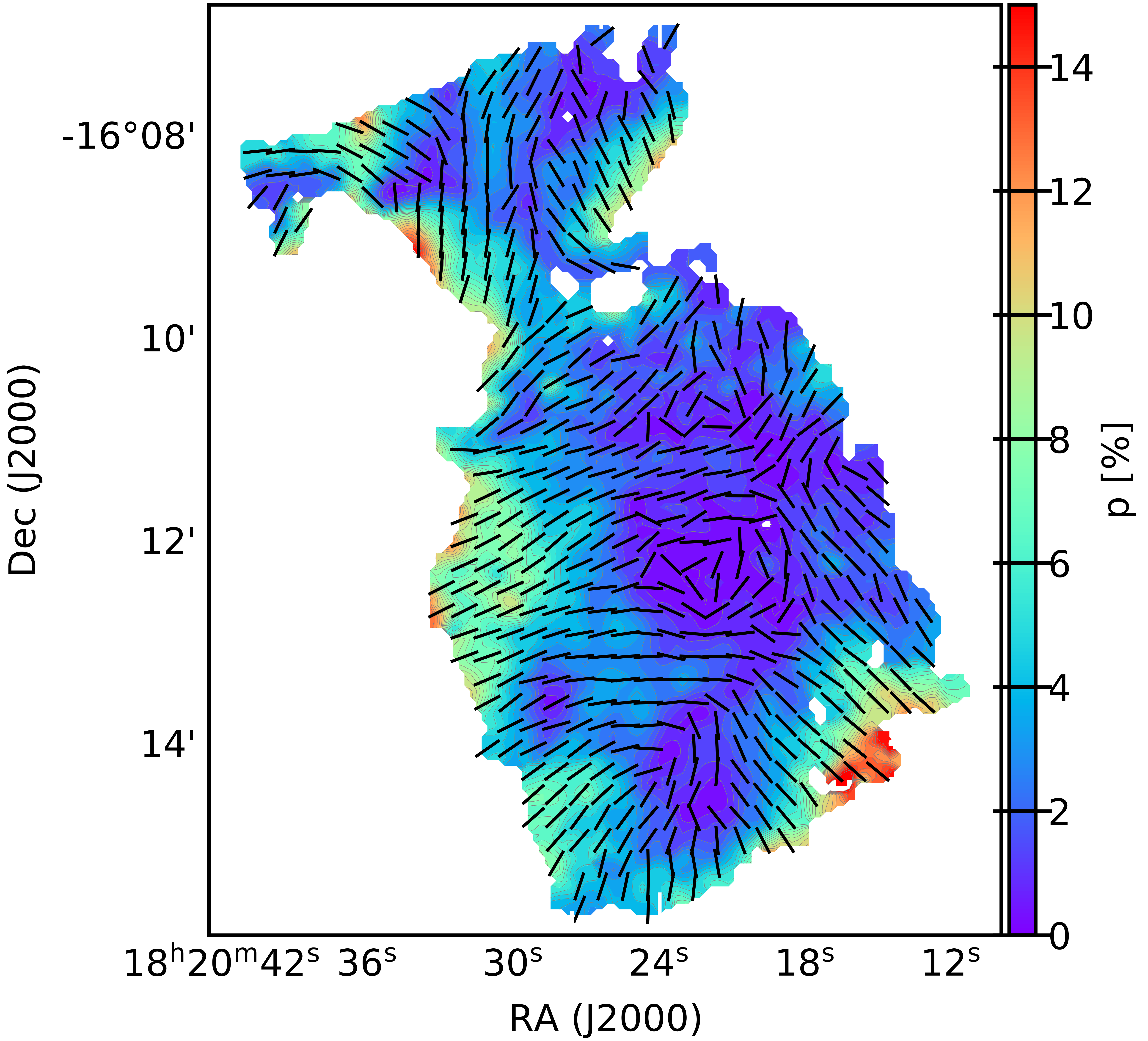


- Dust observation at wavelength = 154 μm.
- Beam size = 13.6".
- Pixel scale on maps = 3.4".

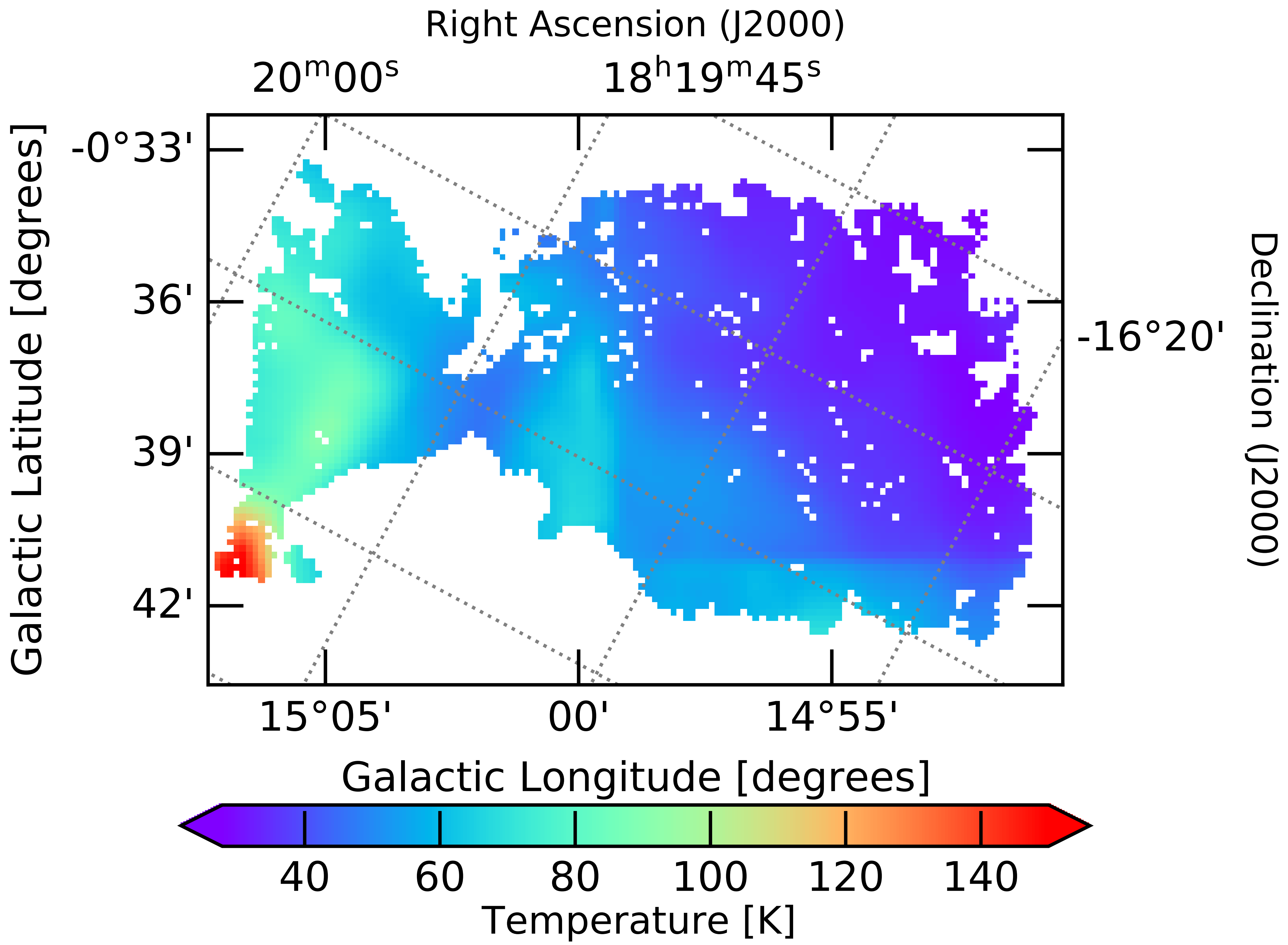
(Temi et al. 2018; Harper et al. 2018a).

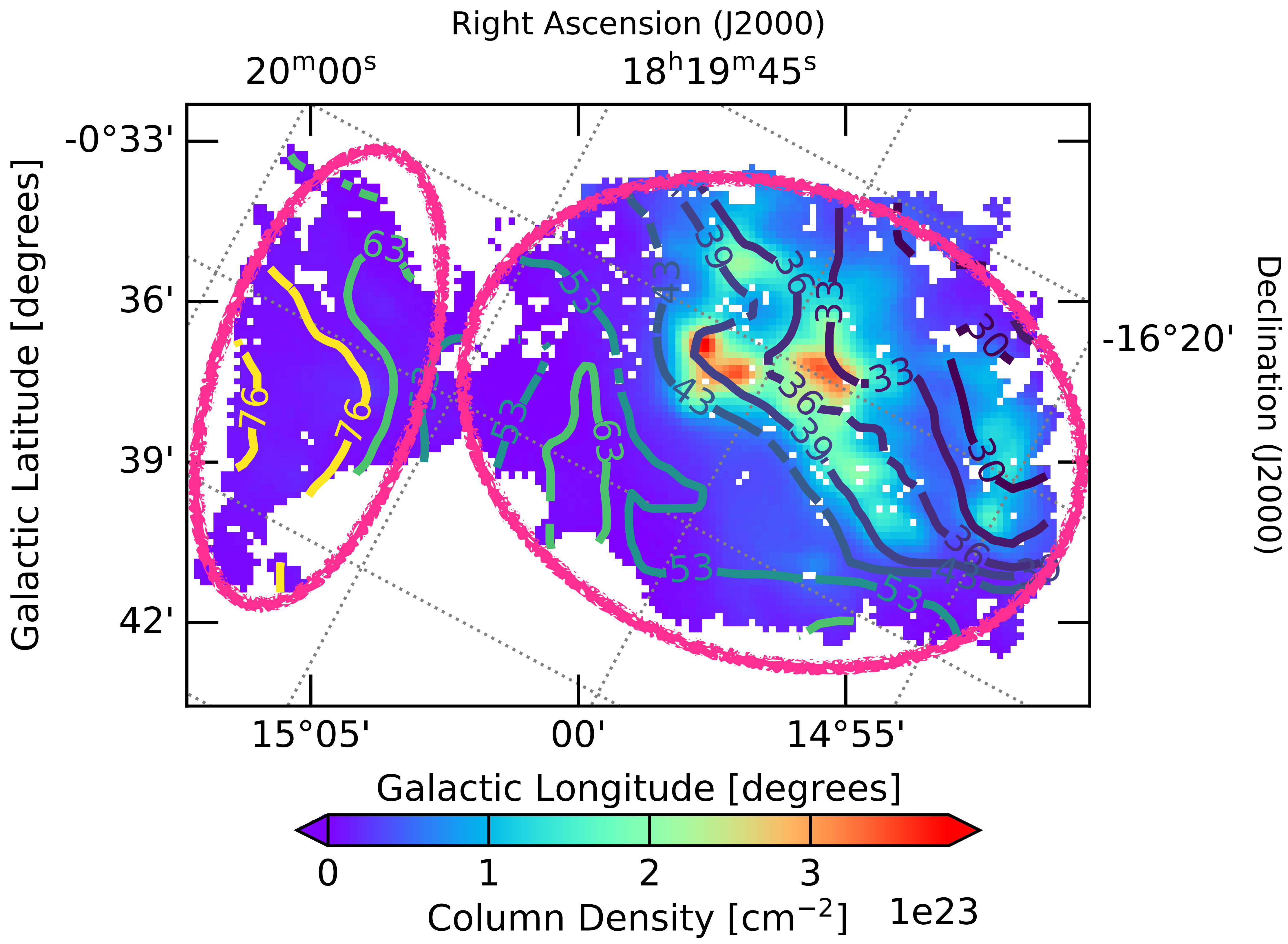
p, and morphology maps





Number density $n(H_2)$





Number density:

$$n_{H_2} = \frac{3\beta N_{H_2}(D\Delta)^2}{4\pi R^3}$$

- Abundance of He, factor: $\beta = 1.39$
- $N_{H_2,total}$: Total column density
- Distance D = 1.98 kpc
- Pixel size $\Delta = 3.4''$
- Radius of the center region: $R = \sqrt{ab/2}$

Number density (cm^{-3})	**upper map**	**lower map**
n_{H_2}	$6.84 \times 10^3 \pm 2.25$	$2.94 \times 10^4 \pm 6.77$

SOFIA/HAWC+ Polarization data