SOFIA Tele-Talk Series

April 1, 2020

UNVEILING THE MAGNETIC PROPERTIES OF A PROTOSTELLAR CORE WITH SOFIA

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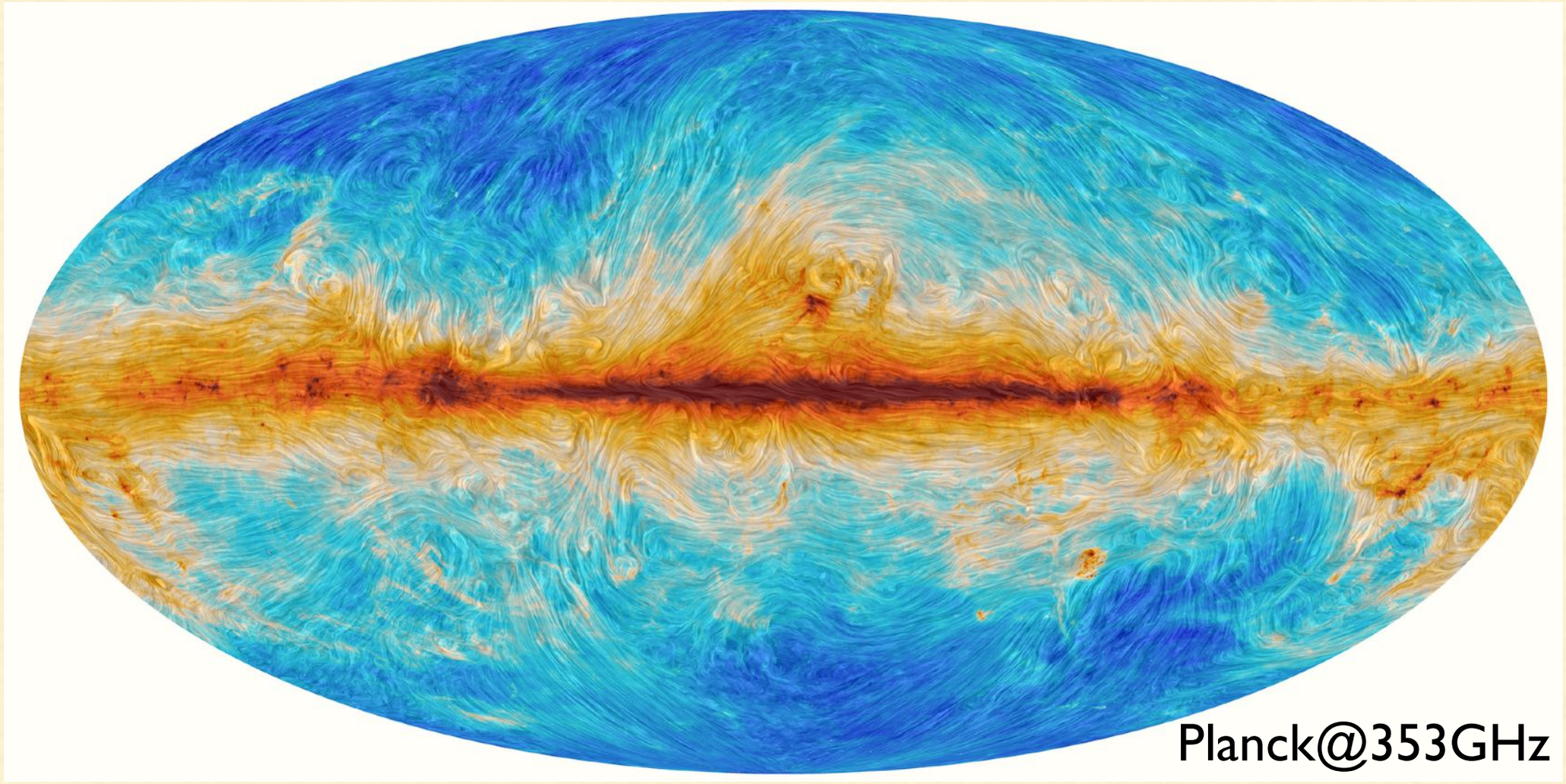
Collaborators: F. O. Alves, F. Santos, P. Caselli

THE CONTEXT: STAR FORMATION

An interplay among several forces, among which:

- **B-fields**
- **Turbulence**

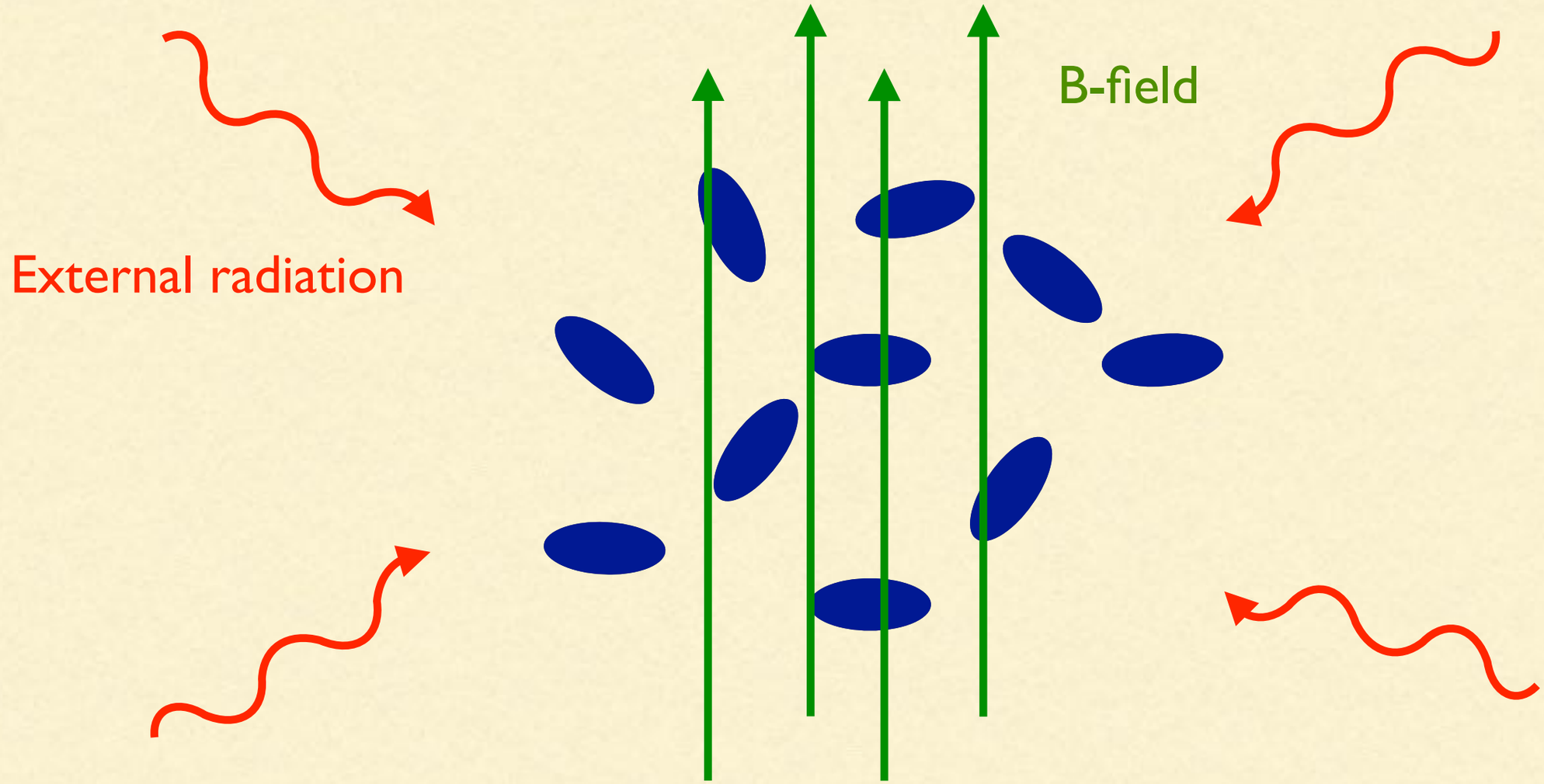


Planck@353GHz

HOW TO OBSERVE B-FIELDS IN THE ISM

Key concept:

Dust alignment via radiative torque (RAT)

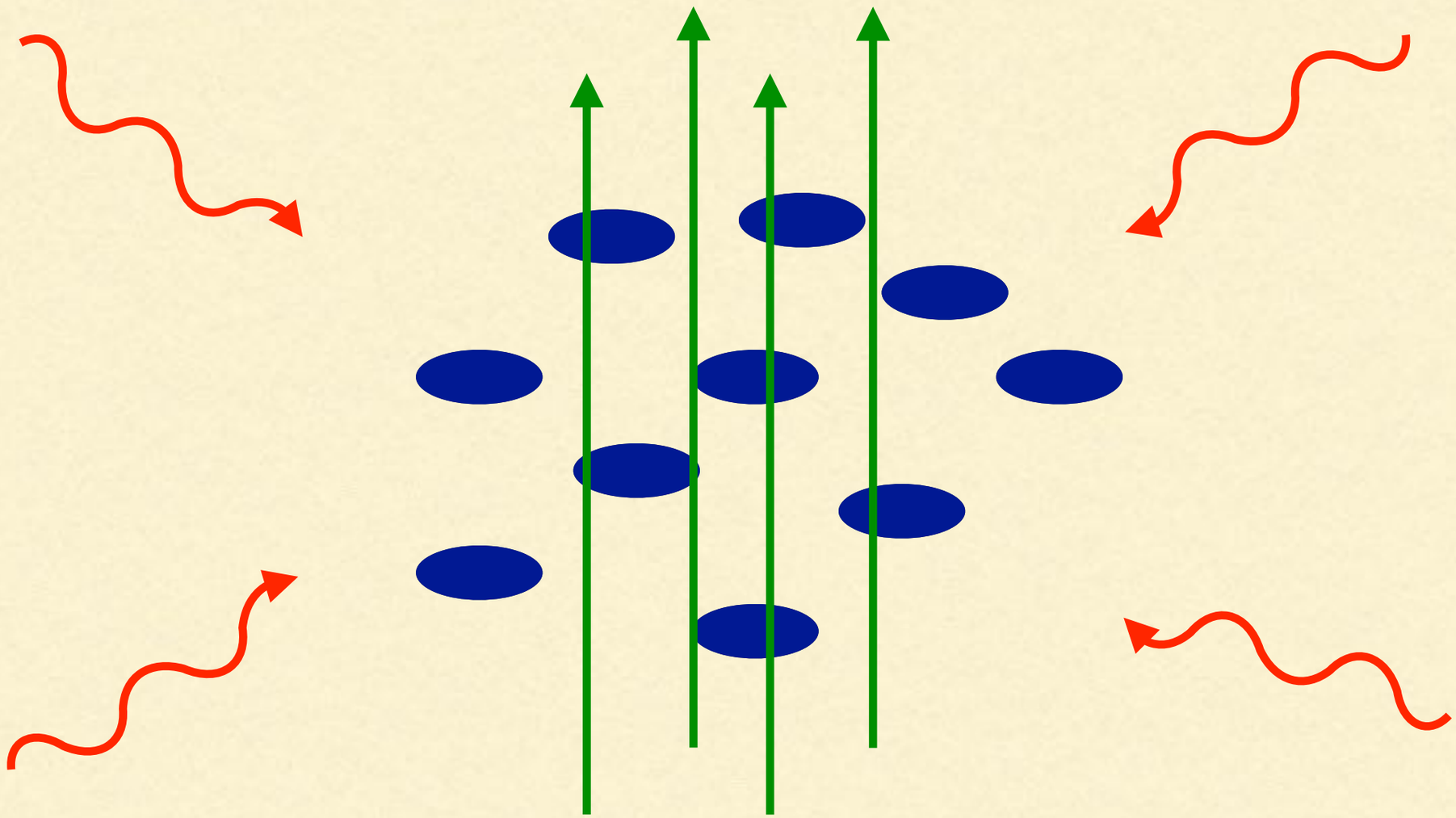


Lazarian & Hoang (2007)

HOW TO OBSERVE B-FIELDS IN THE ISM

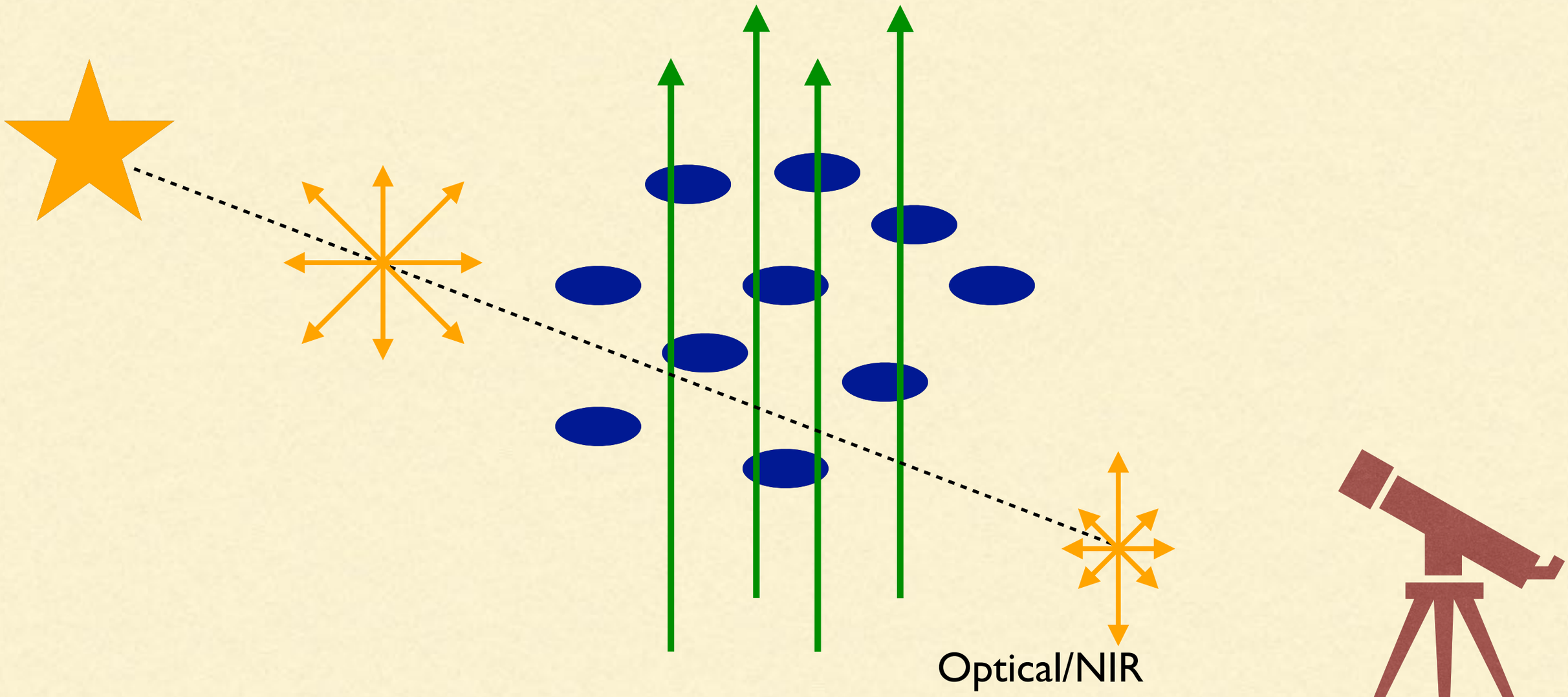
Key concept:

Dust alignment via radiative torque (RAT)



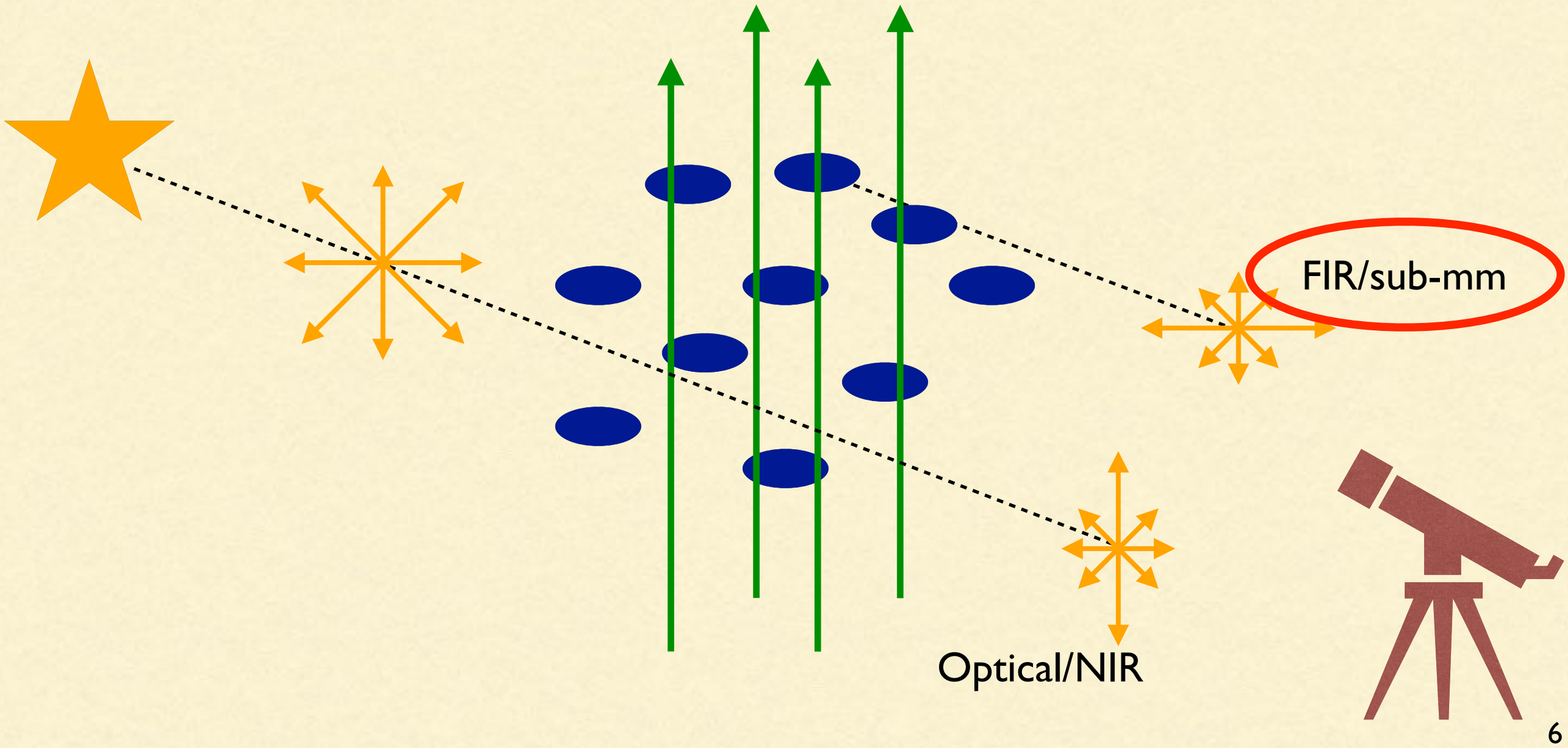
HOW TO OBSERVE B-FIELDS IN THE ISM

Polarisation both in absorption and emission

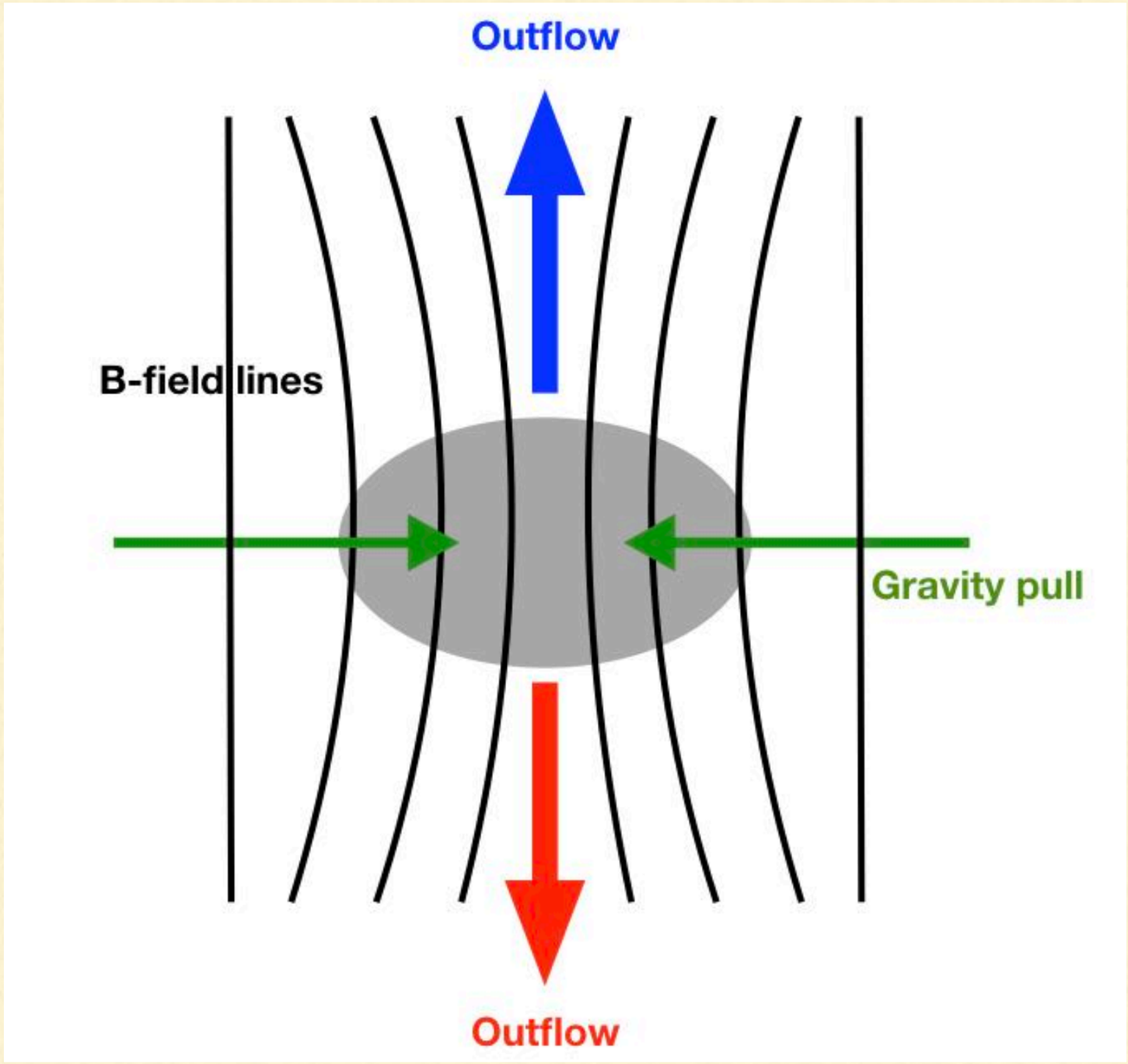


HOW TO OBSERVE B-FIELDS IN THE ISM

Polarisation both in absorption and emission

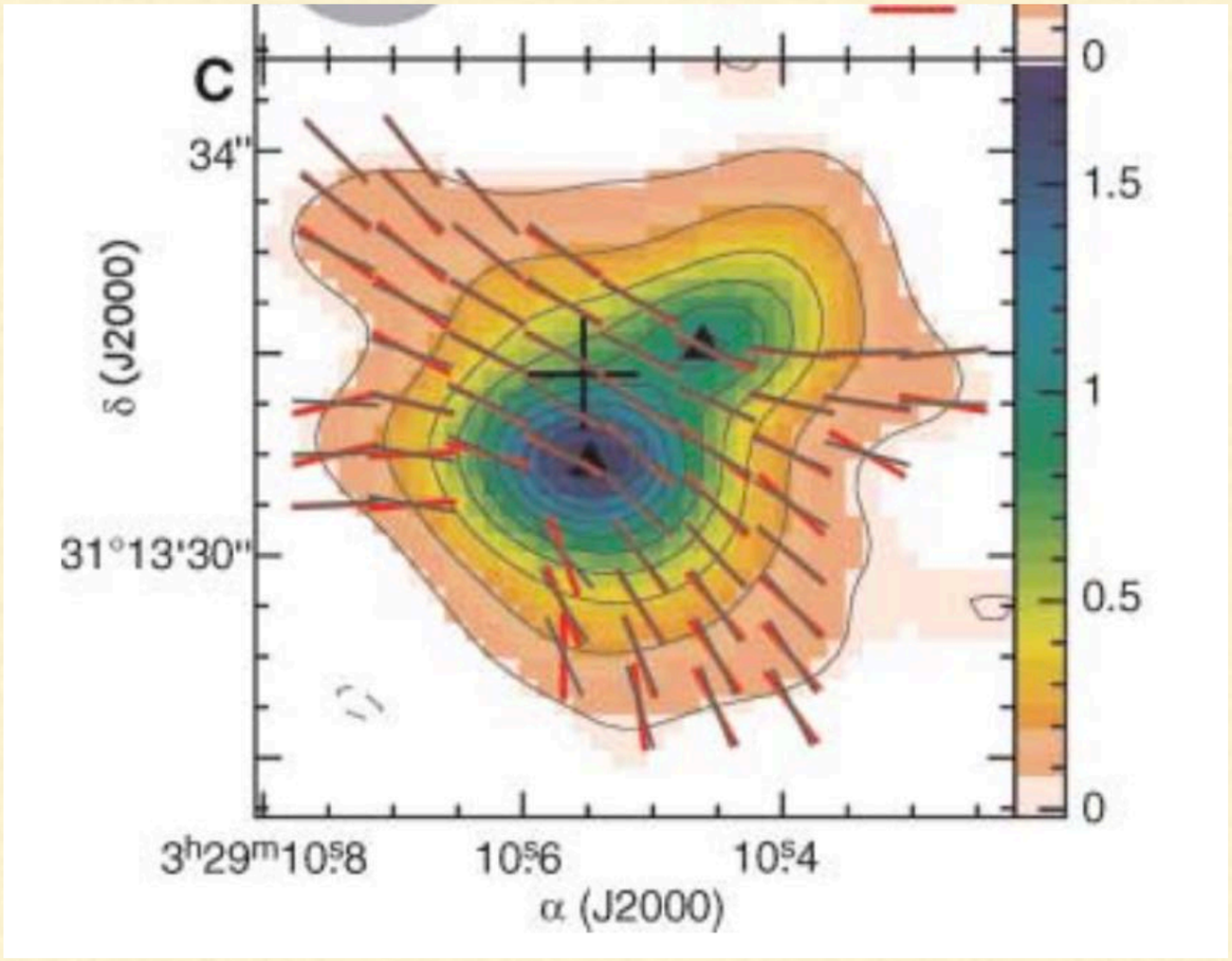


B-FIELDS IN PROTOSTARS: THEORY

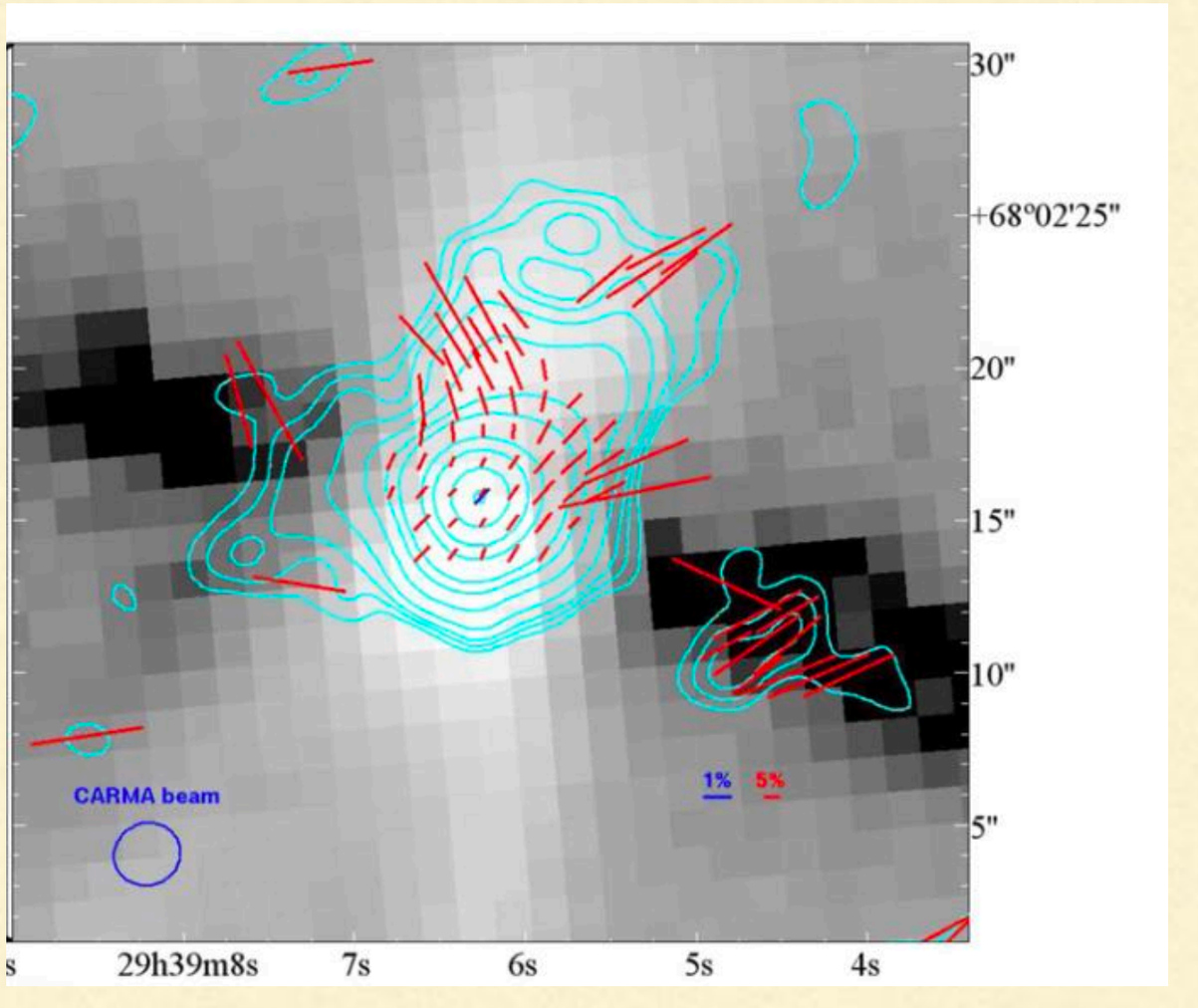


Mouschovias+(1991), Shu+(1994), Basu+(2009),…

B-FIELDS IN PROTOSTARS: OBSERVATIONS

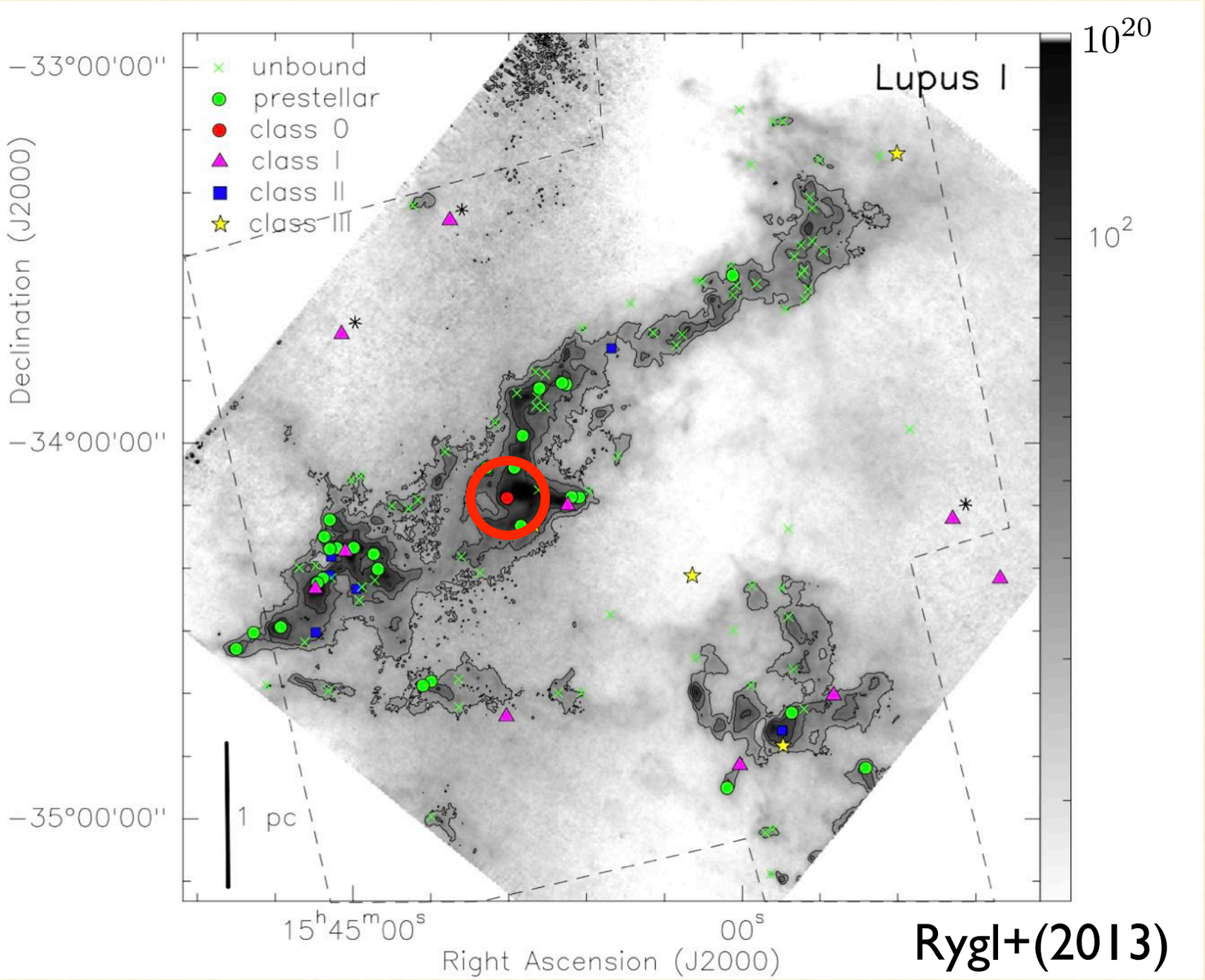


IRAS 4A in NGC1333 (Girart+2006)



L1157-mm1 (Stephens+2013)

THE SOURCE: LUPUS I

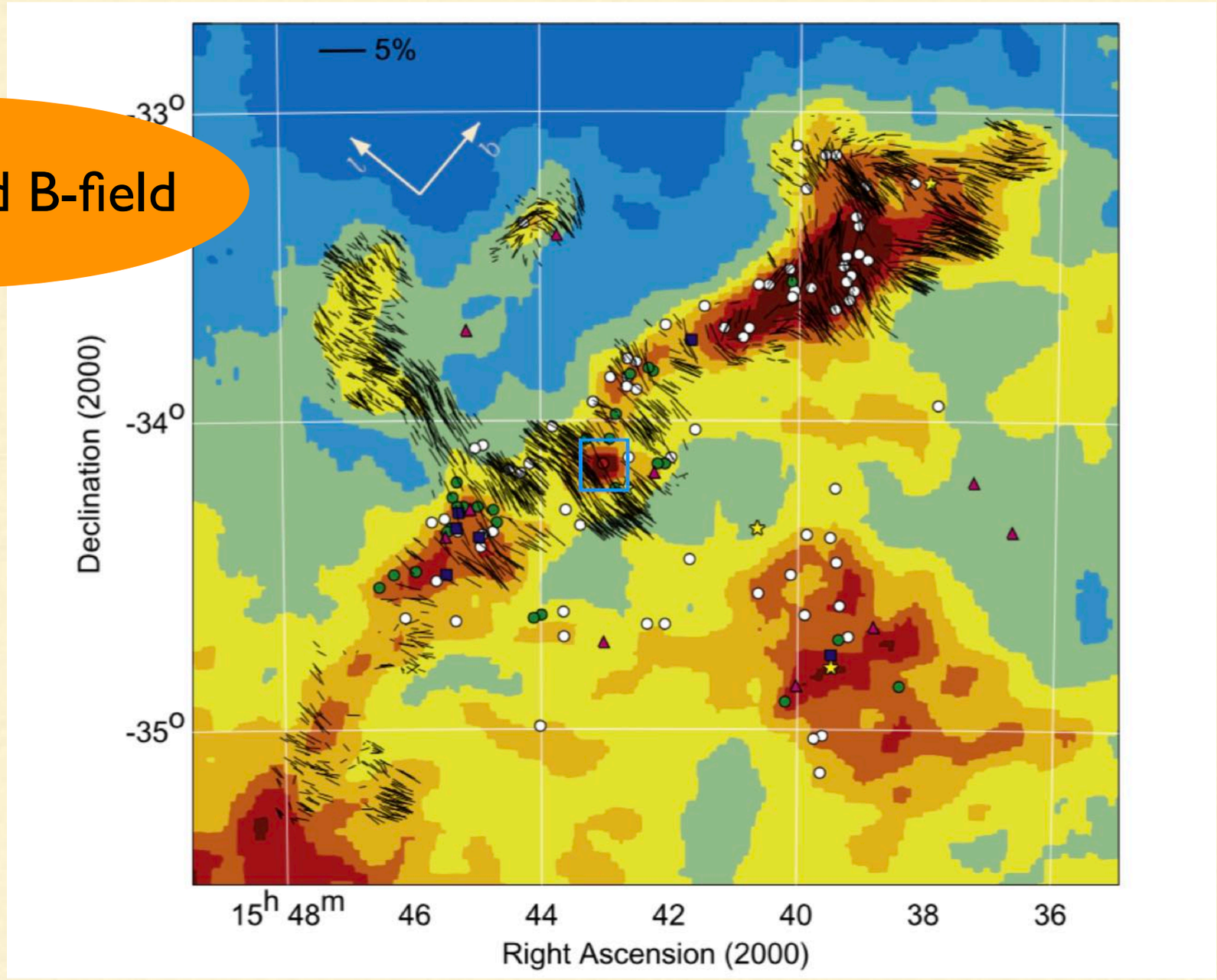


Rygl+(2013)

- The less evolved cloud of the Lupus complex
- A nearby (d~150 pc) and young star forming regions

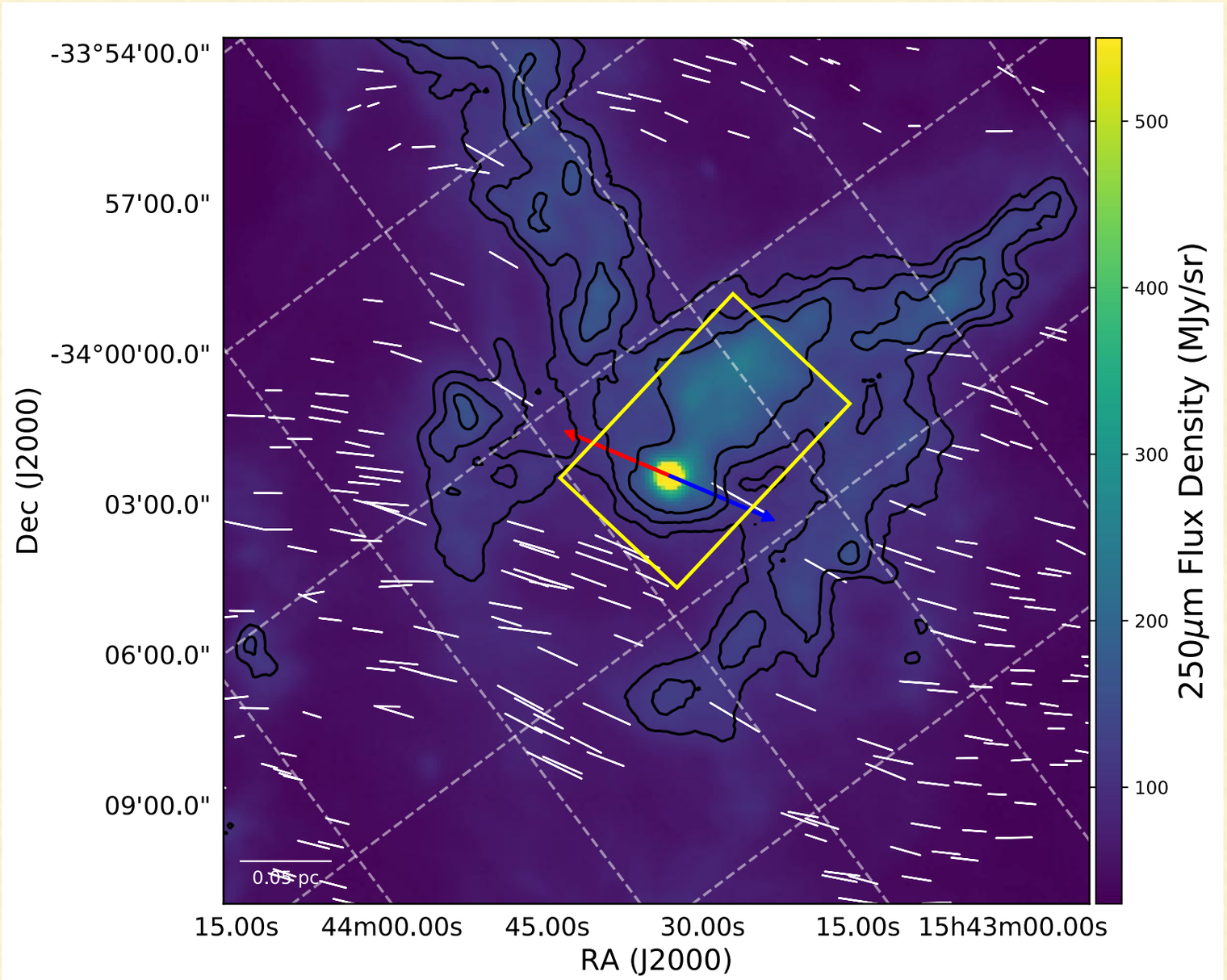
THE SOURCE: LUPUS I

Very ordered B-field



IRAS 100μm map with overlaying optical polarization (R-band) vectors (Franco&Alves, 2015)

THE SOURCE: IRAS15398



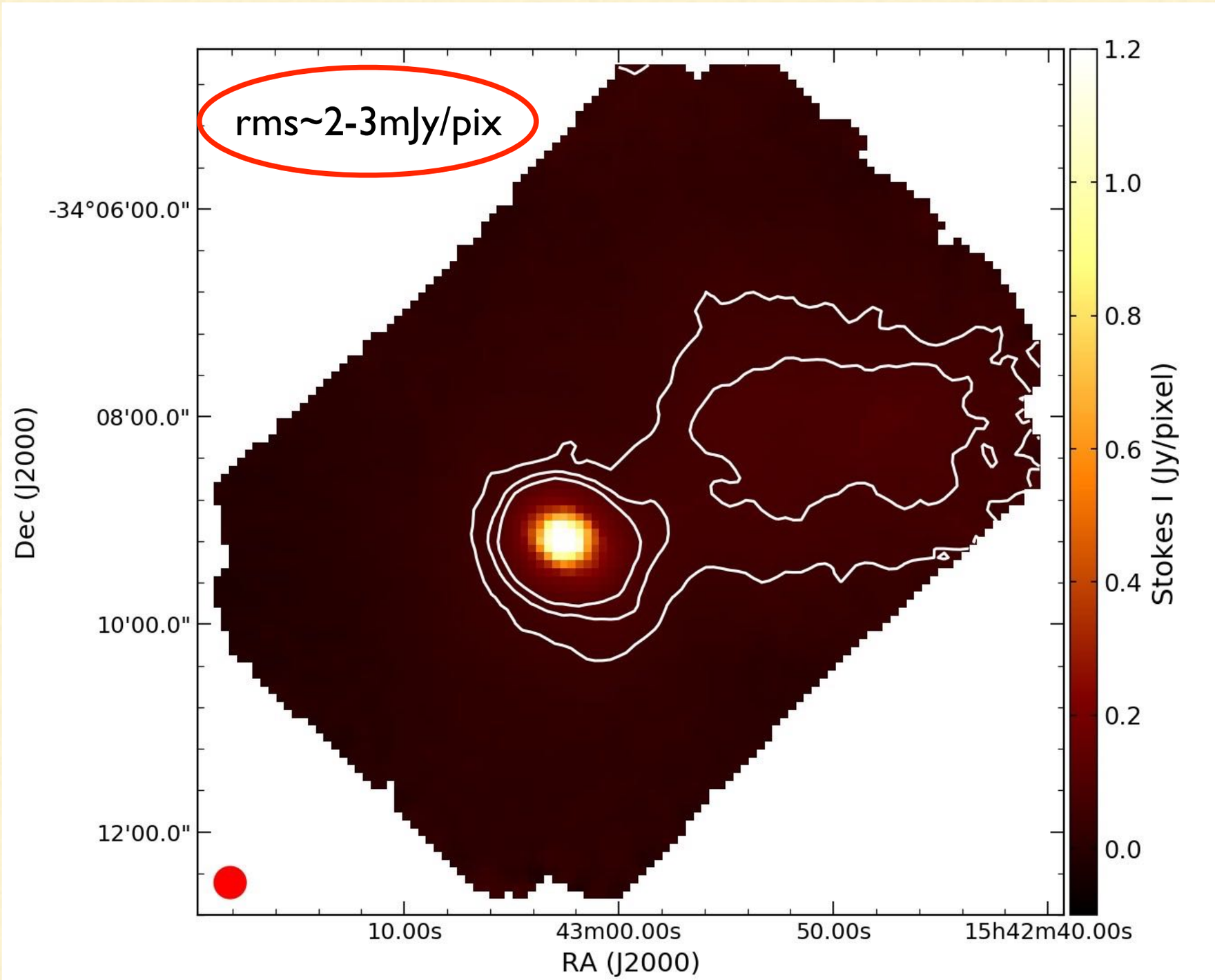
- A young class 0 object
- Driving a bipolar outflow

We want to investigate the magnetic field properties in early stages of star formation

OBSERVATIONS

- We used the HAWC+ instrument in band E (214μm)
- The nominal FoV corresponds to 0.22x0.28 pc
- We ask for 5σ detection of 5% polarization (rms~0.5mJy/pix)
- The final integration time is ~2.5 h

A FIRST LOOK TO THE DATA



χ^2 ANALYSIS OF THE DATA

Credit: Dr. Fabio Santos

- Used to test the reproducibility of the dataset and the consistency of the uncertainties

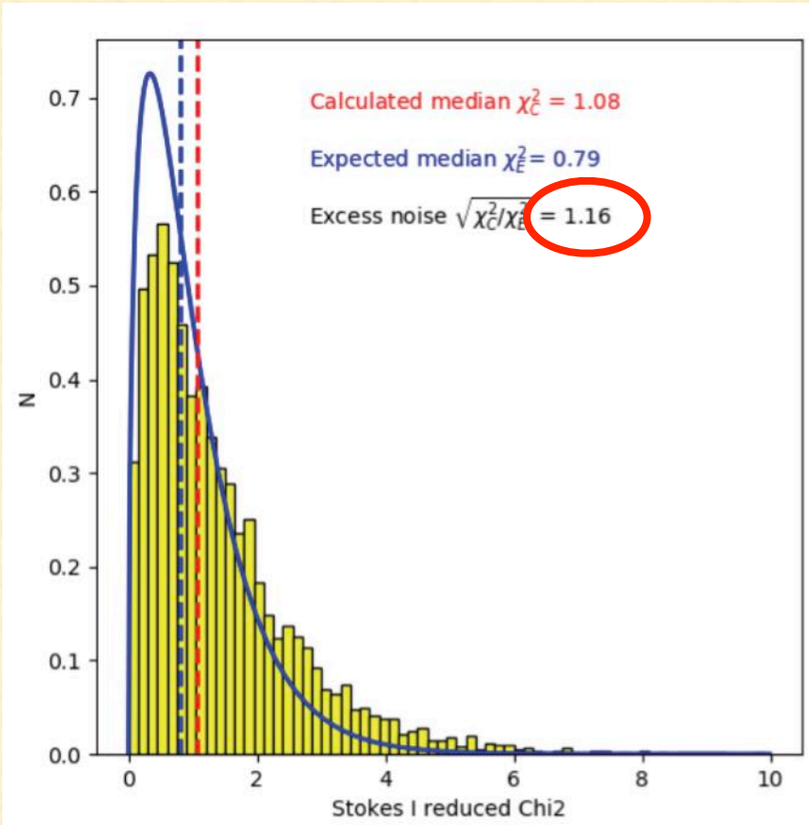
- The available files are divided according to individual dither sets (~4 files per bin)

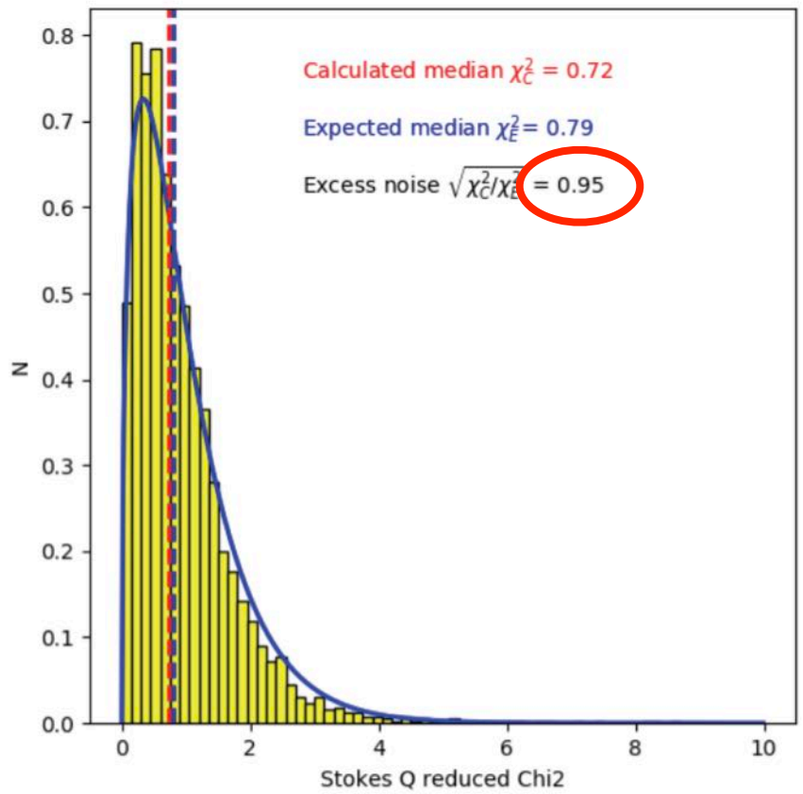
- Observations in each bin are merged separately

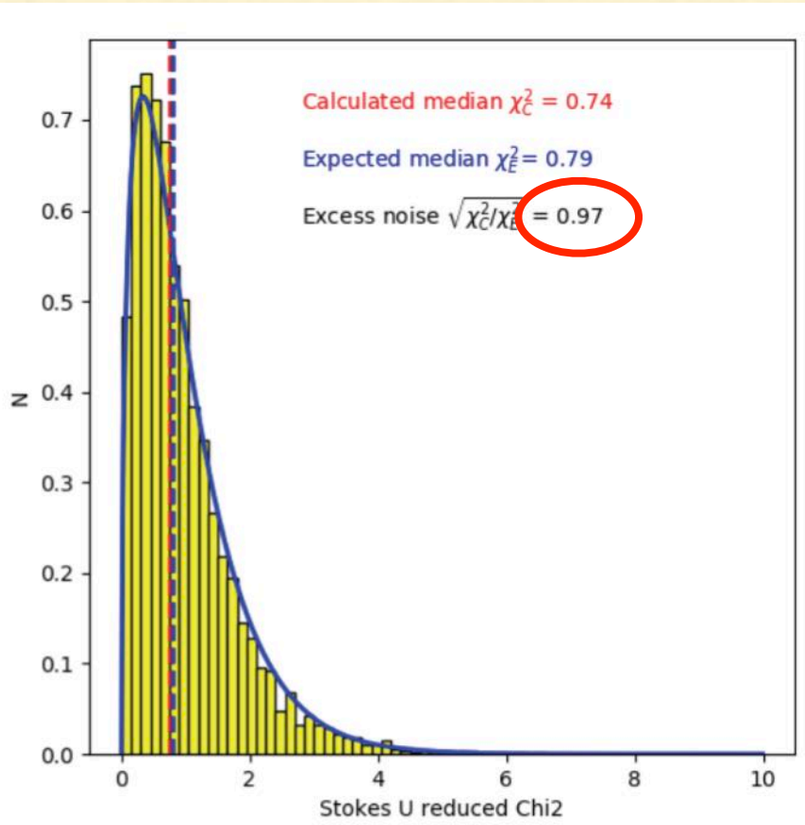
- The file containing all the observations merged together is the reference for the χ^2

- χ^2 maps are produced for each Stokes parameter

χ^2 ANALYSIS: RESULTS

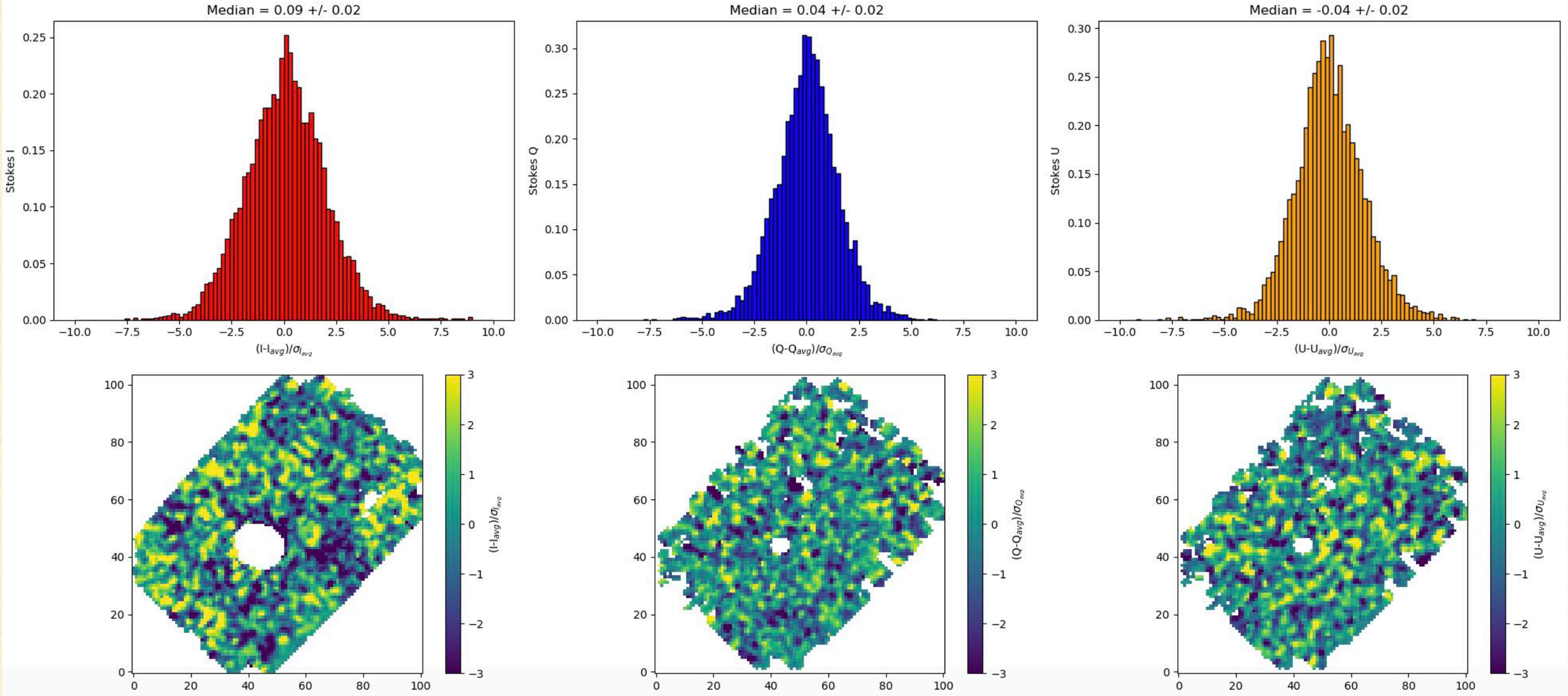






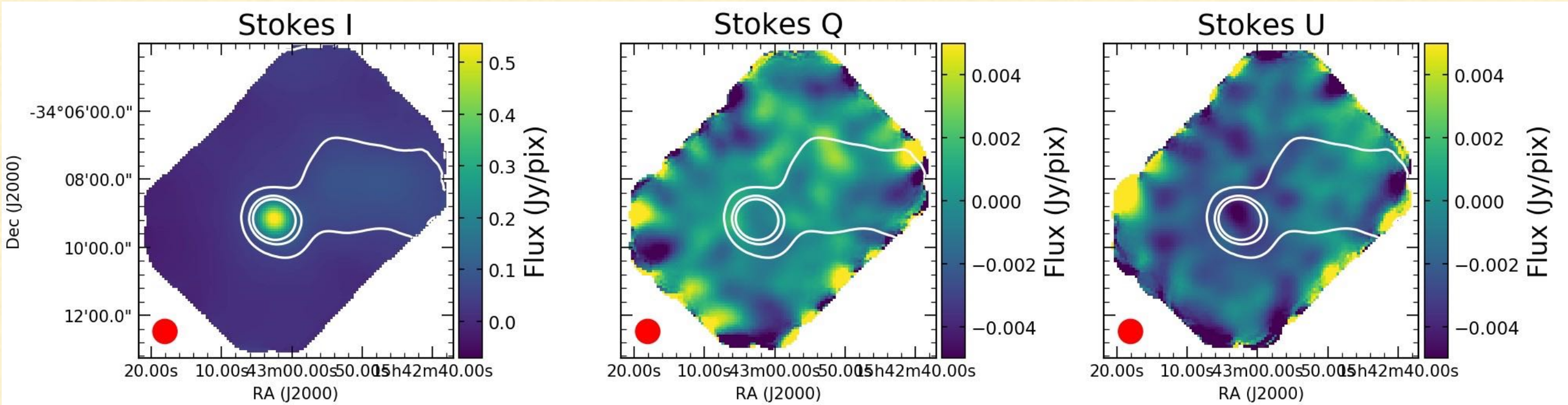
χ^2 ANALYSIS: RESIDUALS

Bin 1



THE STOKES PARAMETERS

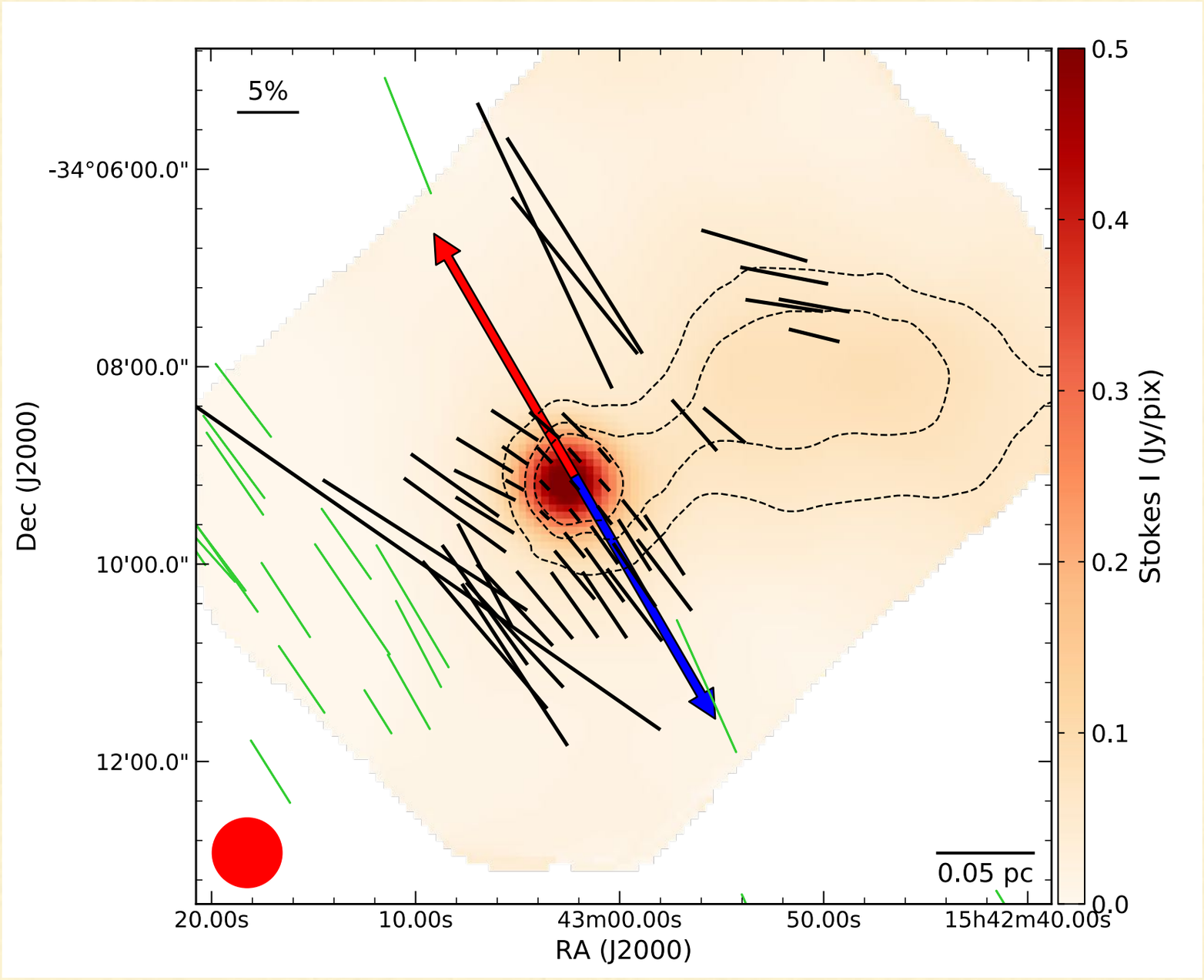
We smoothed to 42” of resolution



$$P_{\rm pol} = \frac{\sqrt{Q^2 + U^2}}{I}$$

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

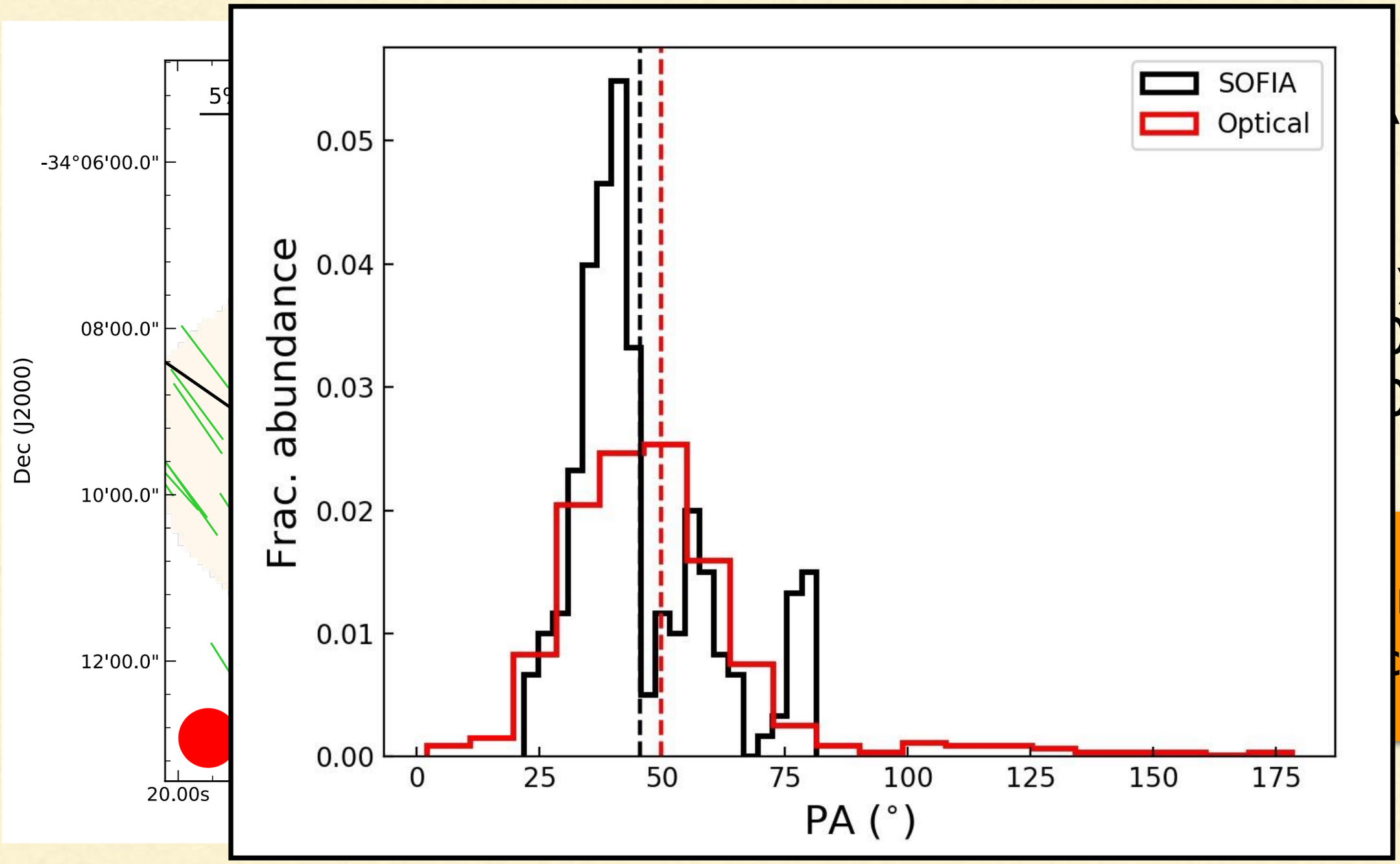
MAGNETIC FIELD DIRECTION



- Black: SOFIA vectors, Green: optical vectors
- We show only vectors with P(%) < 0.50, SNR > 3.0

B-field vectors are aligned with the optical ones

MAGNETIC FIELD DIRECTION



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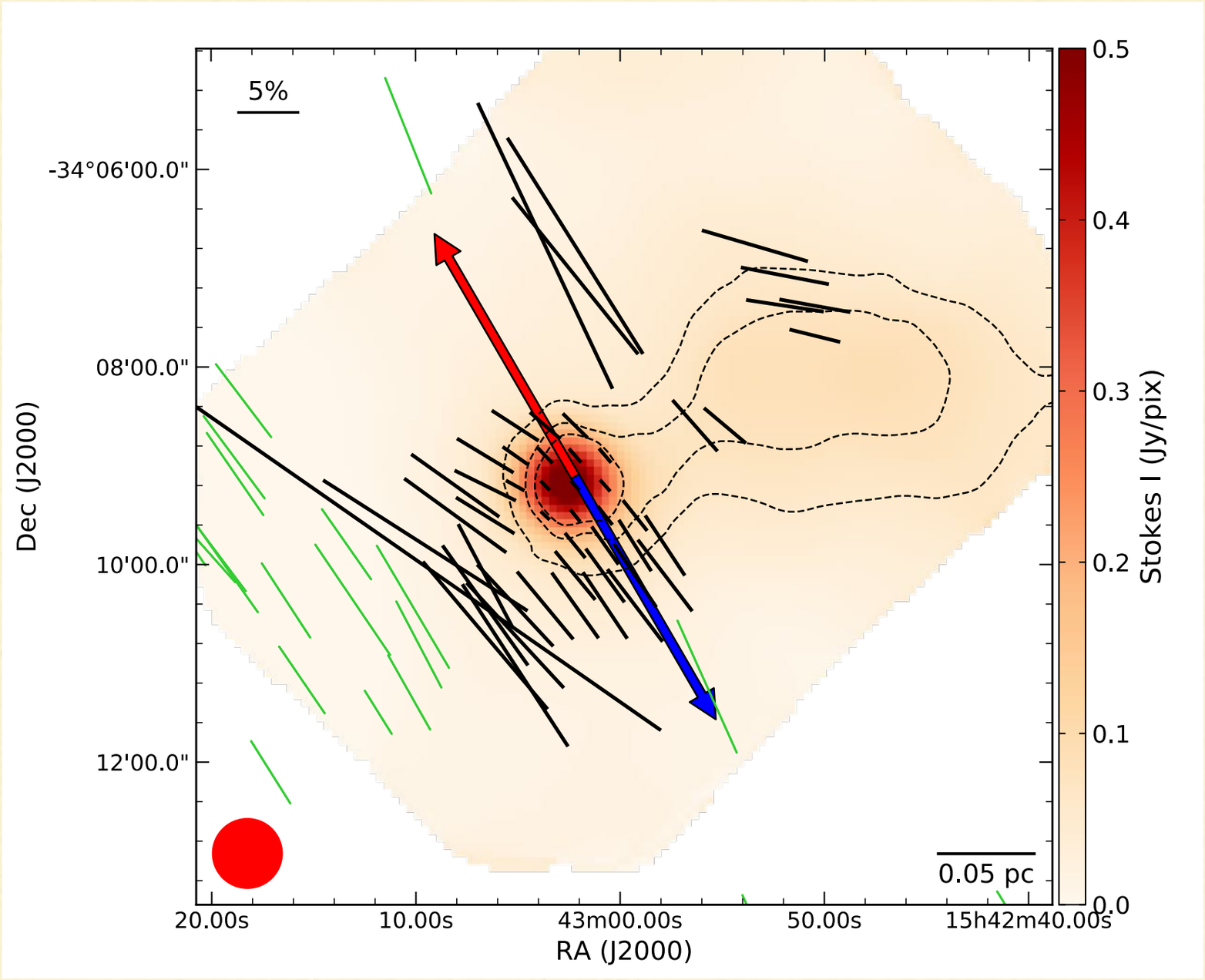
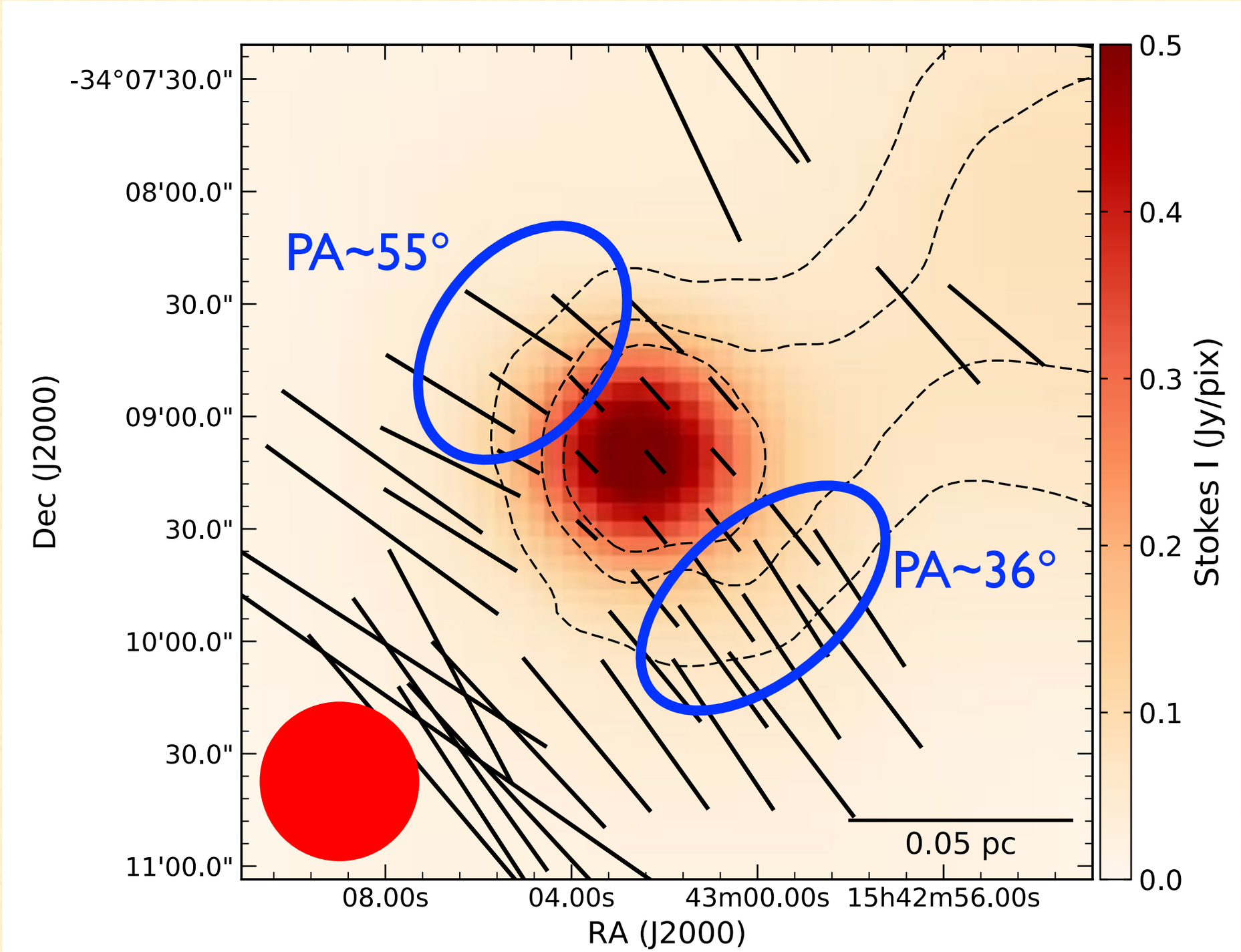
MAGNETIC FIELD DIRECTION



- Outflows PA=35° (Bjerkeli + 2016)

B-field is aligned with the outflow direction

THE HOURGLASS SHAPE



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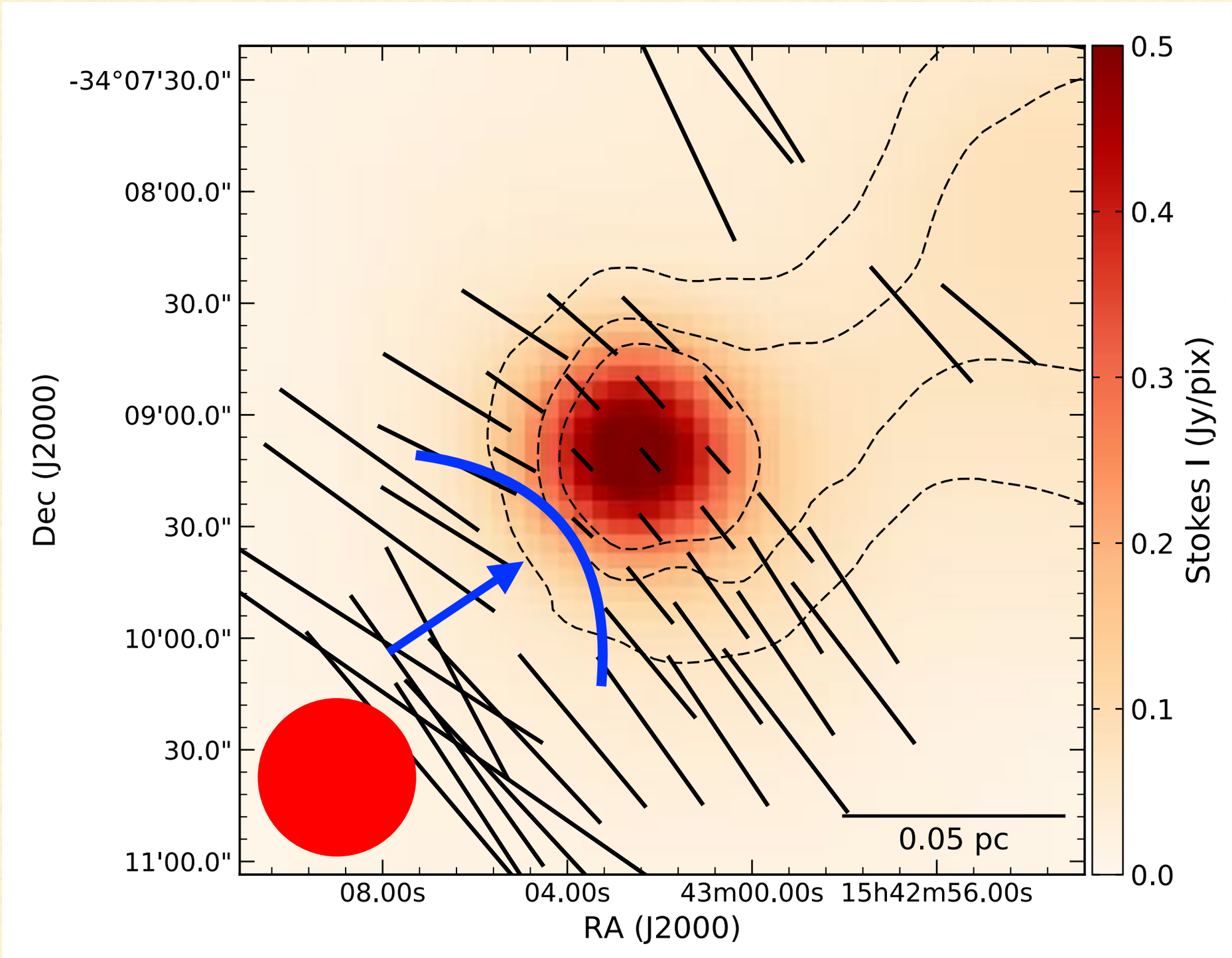

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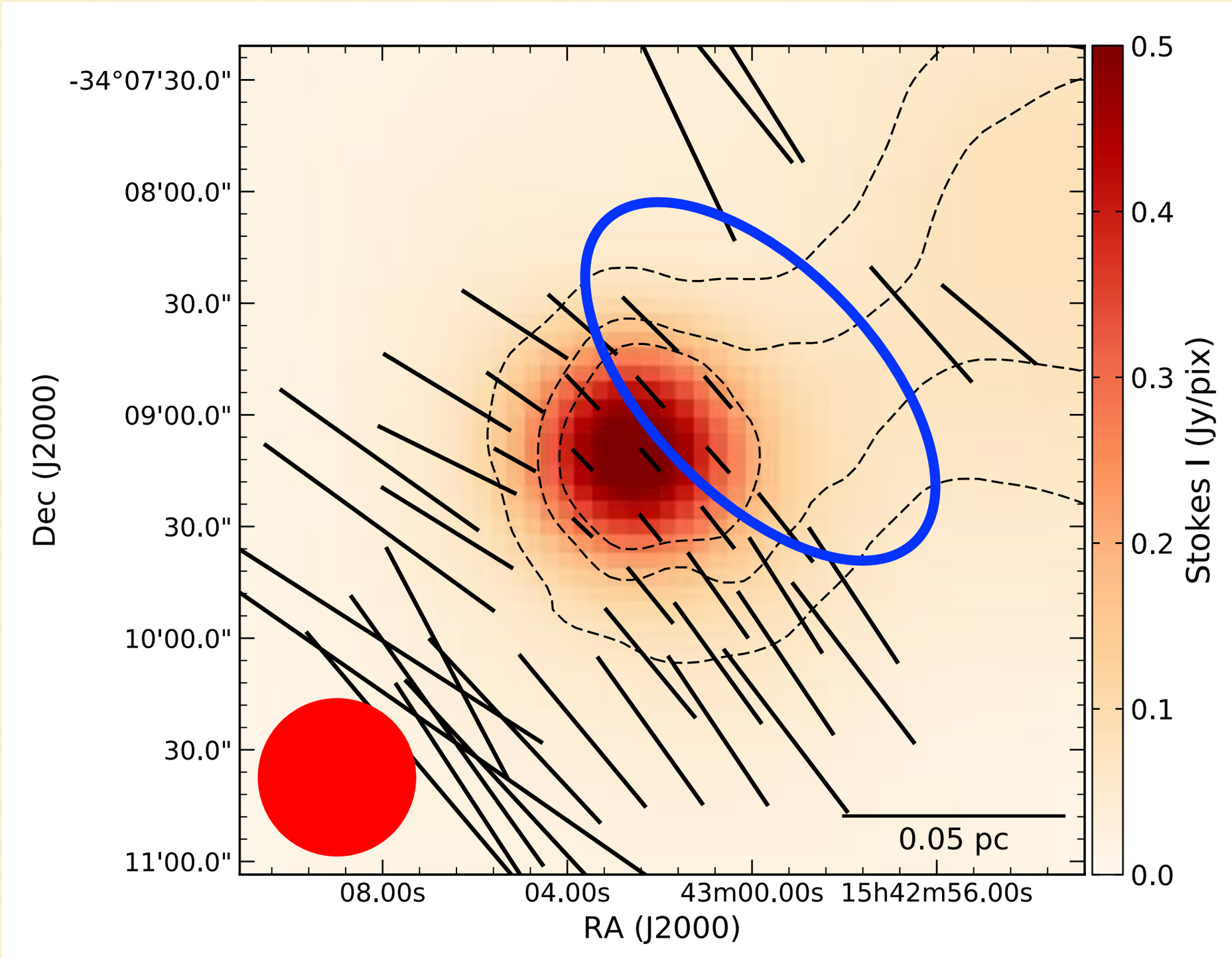
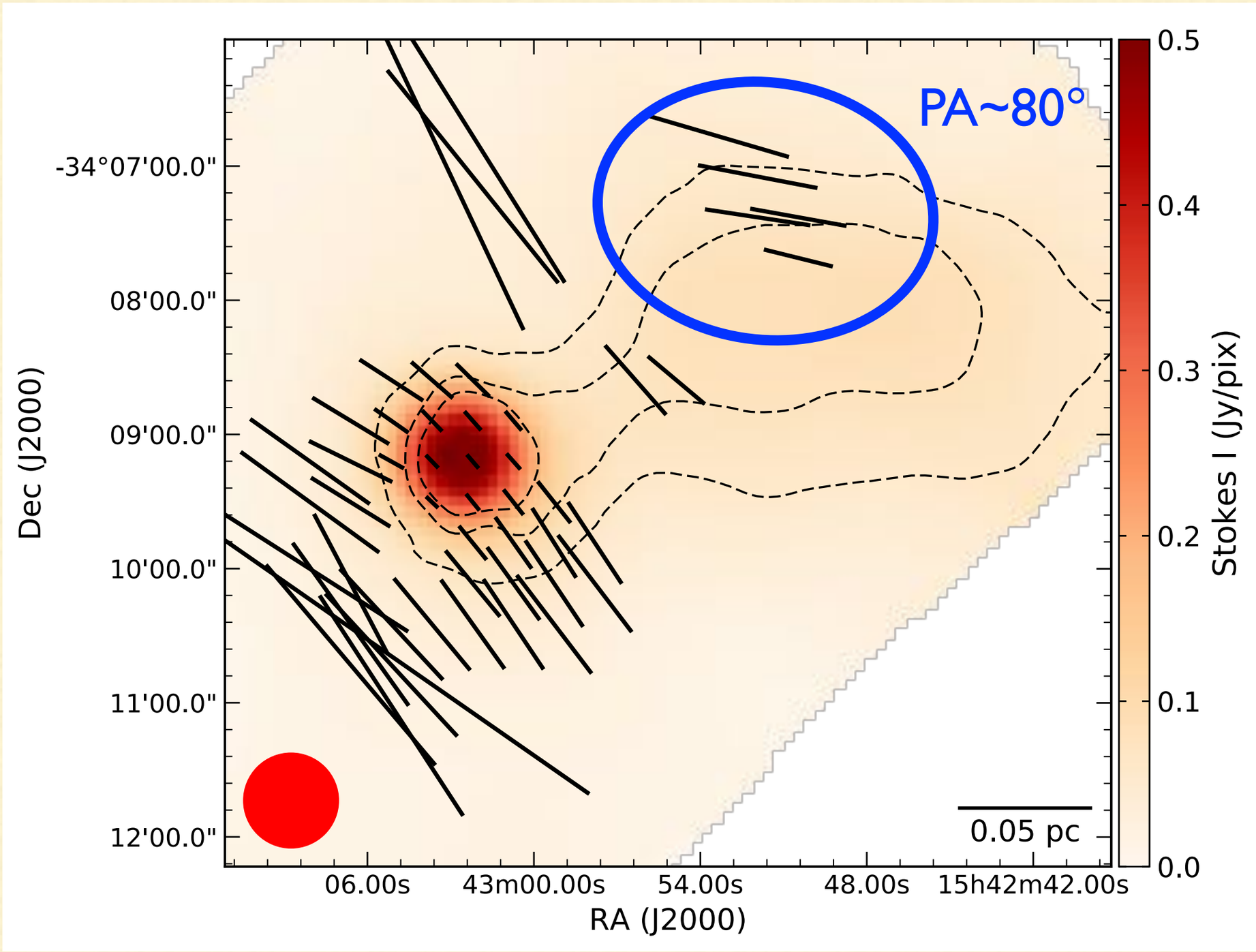
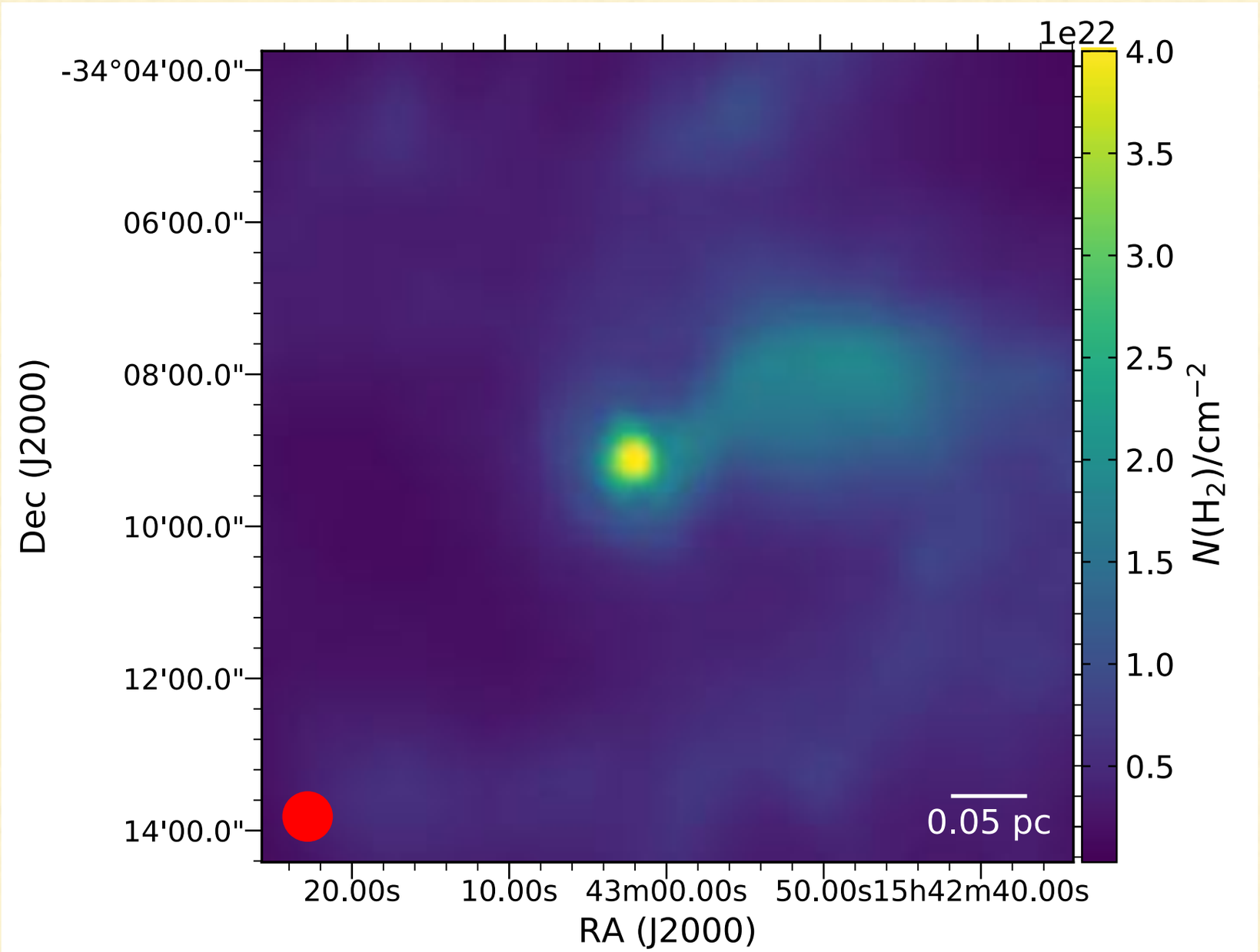


THE FILAMENT STRUCTURE

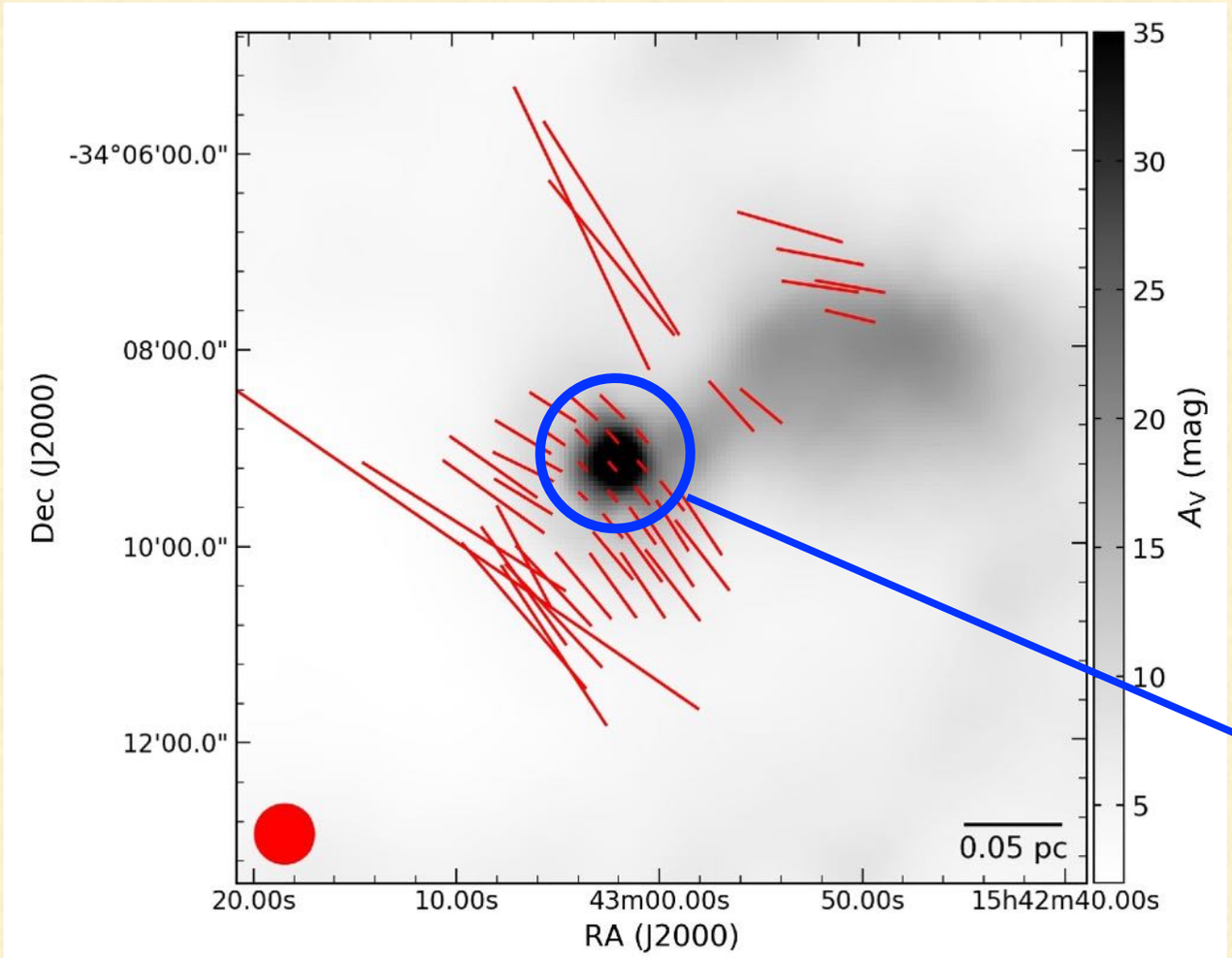


THE H_2 COLUMN DENSITY



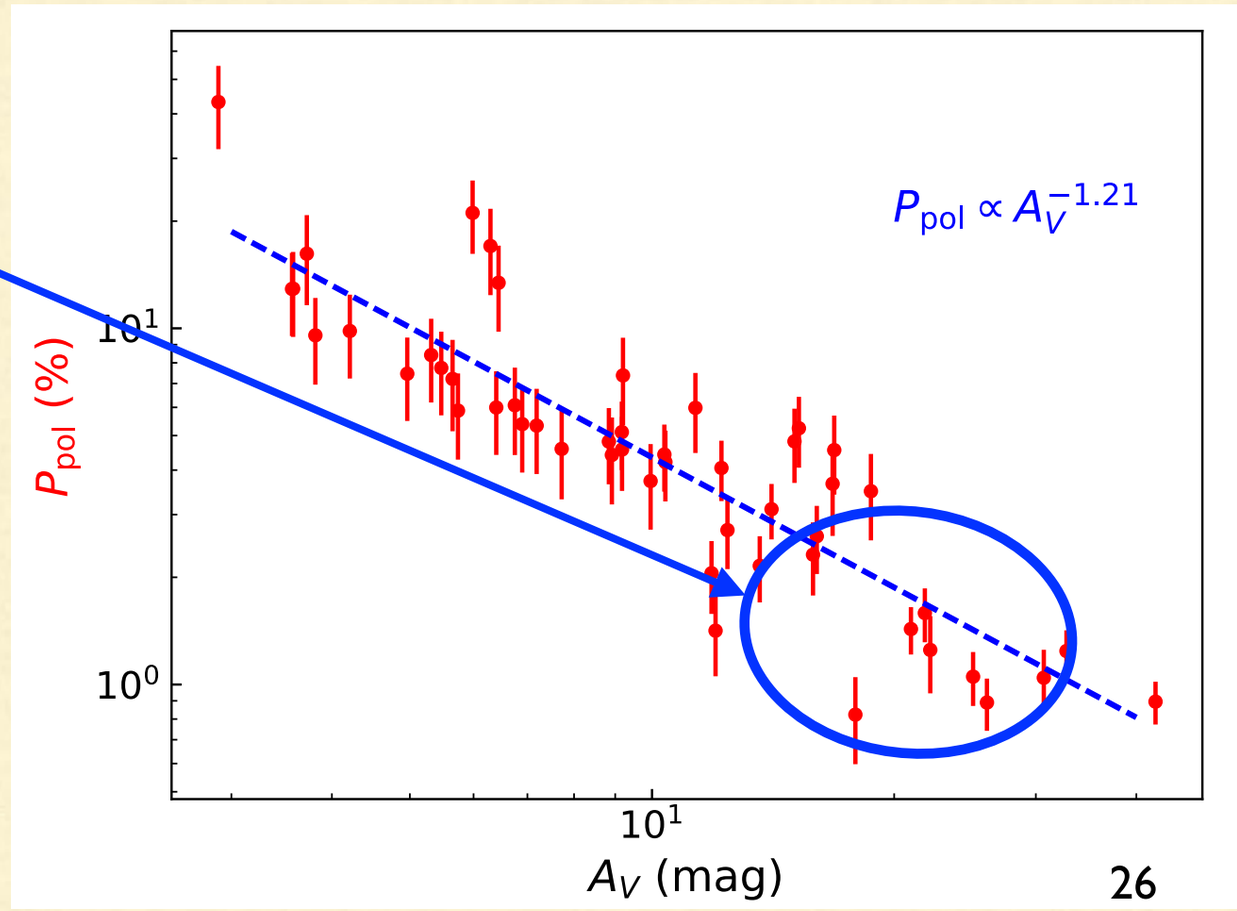
- Gould Belt Survey data (André+2010)

THE P% VS A_V CORRELATION



Possible explanations:

- Geometric smearing
- Grain-growth
- Radiation field attenuation

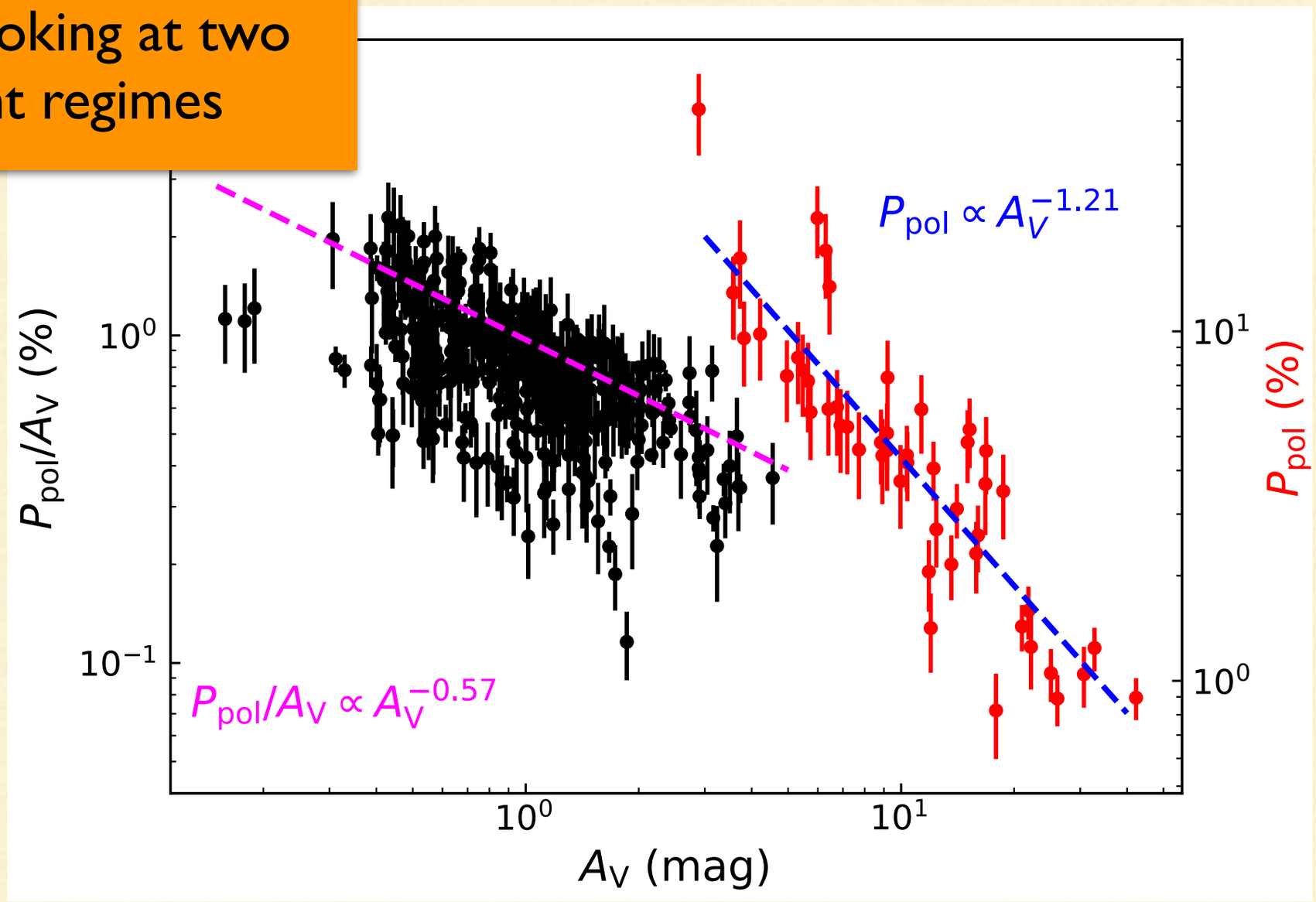


$$A_V = N(H_2)/9.4\,10^{20},\ \text{Bohlin+(1978)}$$

THE P% VS A_V CORRELATION

Optical vs FIR data

We are looking at two different regimes



ADF ANALYSIS

Autocorrelation function of the position angles

Distance

Turbulence coherent length

$$\langle \Delta\Phi^2(l) \rangle = 2\sqrt{2\pi} \left(\frac{B_\mathrm{t}}{B_0} \right)^2 \frac{\delta^3}{(\delta^2 + 2W^2)\,\Delta'} \left[1 - \exp\left(-\frac{l^2}{2\,(\delta^2 + 2W^2)} \right) \right] + m^2 l^2$$

Key parameter!

Effective thickness

Beam size

Hildebrand+(2009), Houde+(2009)

ADF ANALYSIS

Data divided in 9 distance bins

$$\langle \Delta\Phi^2(l) \rangle = 2\sqrt{2\pi} \left(\frac{B_\mathrm{t}}{B_0} \right)^2 \frac{\delta^3}{(\delta^2 + 2W^2)\,\Delta'} \left[1 - \exp\left(-\frac{l^2}{2\,(\delta^2 + 2W^2)} \right) \right] + m^2 l^2$$

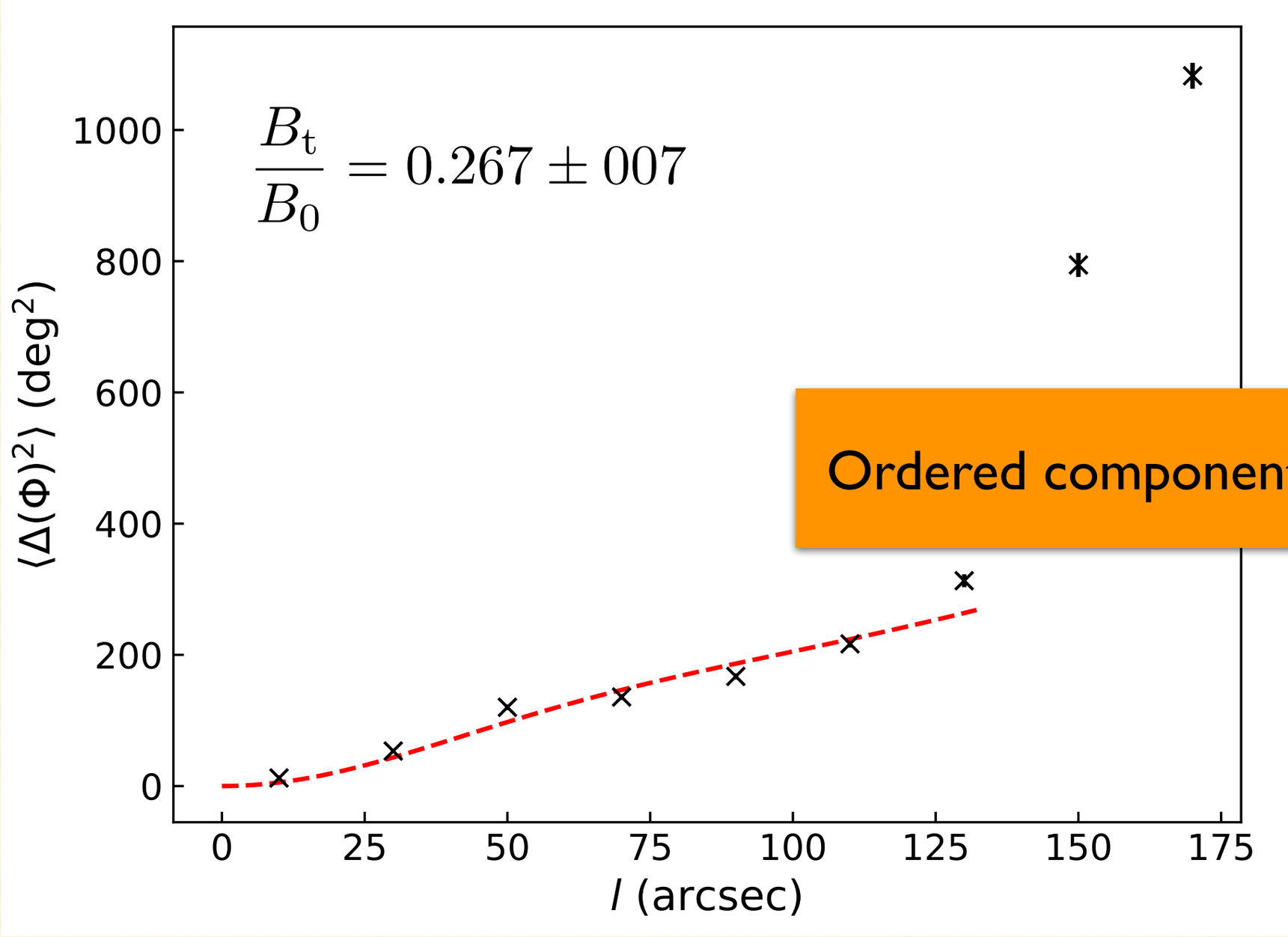
Assumptions:

$$\delta = 20\mathrm{mpc}$$

$$\Delta' = 0.1\mathrm{pc}$$

e.g. Houde+(2009),
Frau+(2014), Coudé+(2019)

ADF ANALYSIS: RESULTS



Ordered component prevails

THE FIELD STRENGTH

Modified Chandrasekhar-Fermi analysis

$$B_{\rm pos} = \sqrt{4\pi\mu m_{\rm H} n_{\rm H_2}}\,\frac{\sigma_V}{\delta\phi}$$

σ_V: $0.17\,\mathrm{km\,s^{-1}}$ — Benedettini+(2012)

$n_{\rm H_2}$: $2.6\times10^{4}\,\mathrm{cm^{-3}}$

$\delta\phi$: $\frac{B_{\rm t}}{B_0}$

$$B_{\rm pos} = 78\,\mu\mathrm{G}$$

Crutcher+(2004)

MASS-TO-FLUX PARAMETER

It indicates the dynamical state of the core

$$\lambda = \frac{(M/\Phi)_{\rm obs}}{(M/\Phi)_{\rm crit}} = 7.6 \times 10^{-21} \frac{N({\rm H_2})}{B_{\rm pos}} = 0.95$$

The core is transcritical

Crutcher+(2004)

CONCLUSIONS

- A possible first detection of the hourglass shape from SOFIA/HAWC+ in the low-mass regime

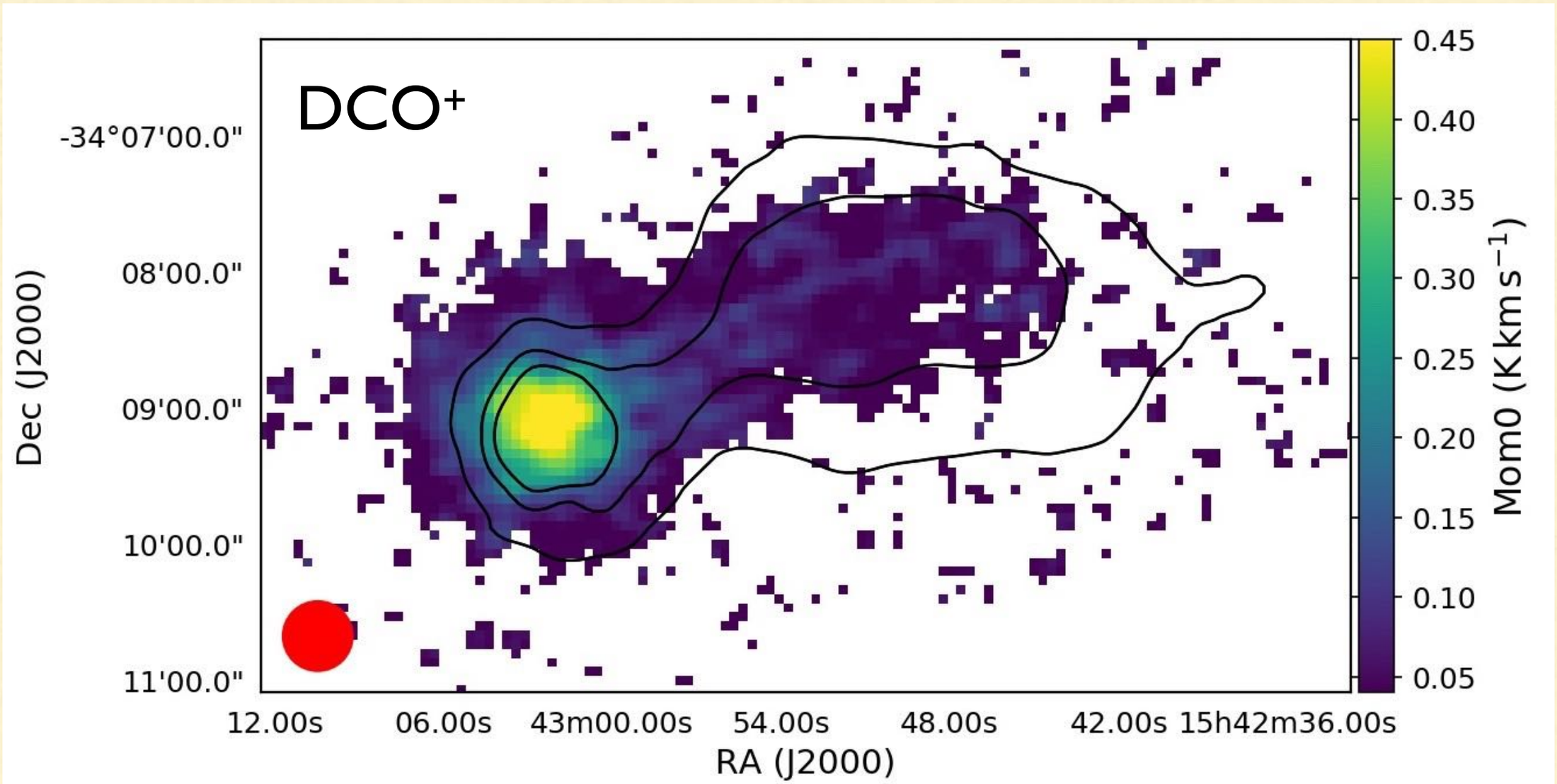
- An ordered magnetic field, stronger than the turbulent component

- The core is in a transcritical state (consistent with presence of protostar)

ON-GOING WORK

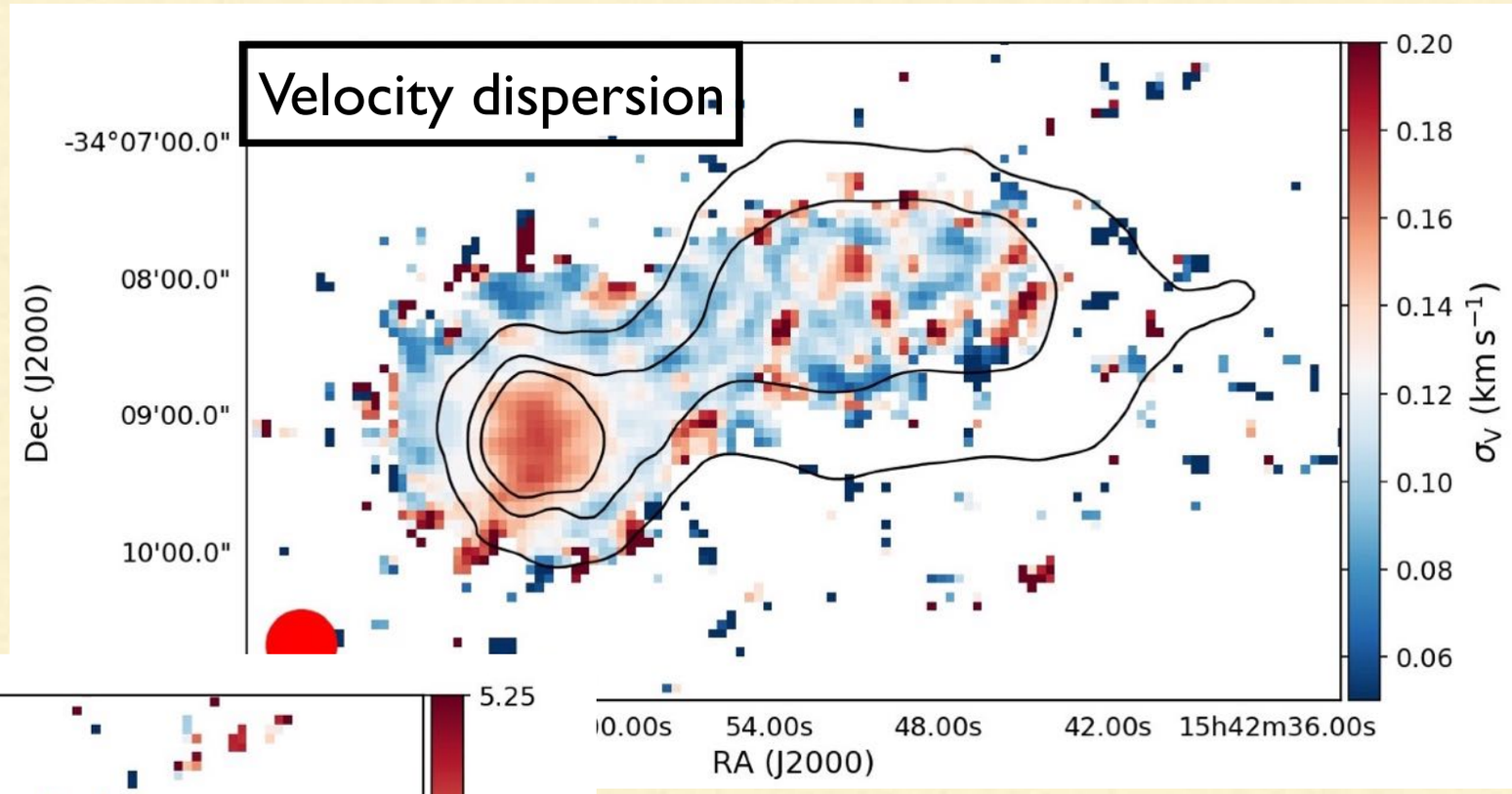
APEX proposal on lines: $C^{18}O$ and DCO^+

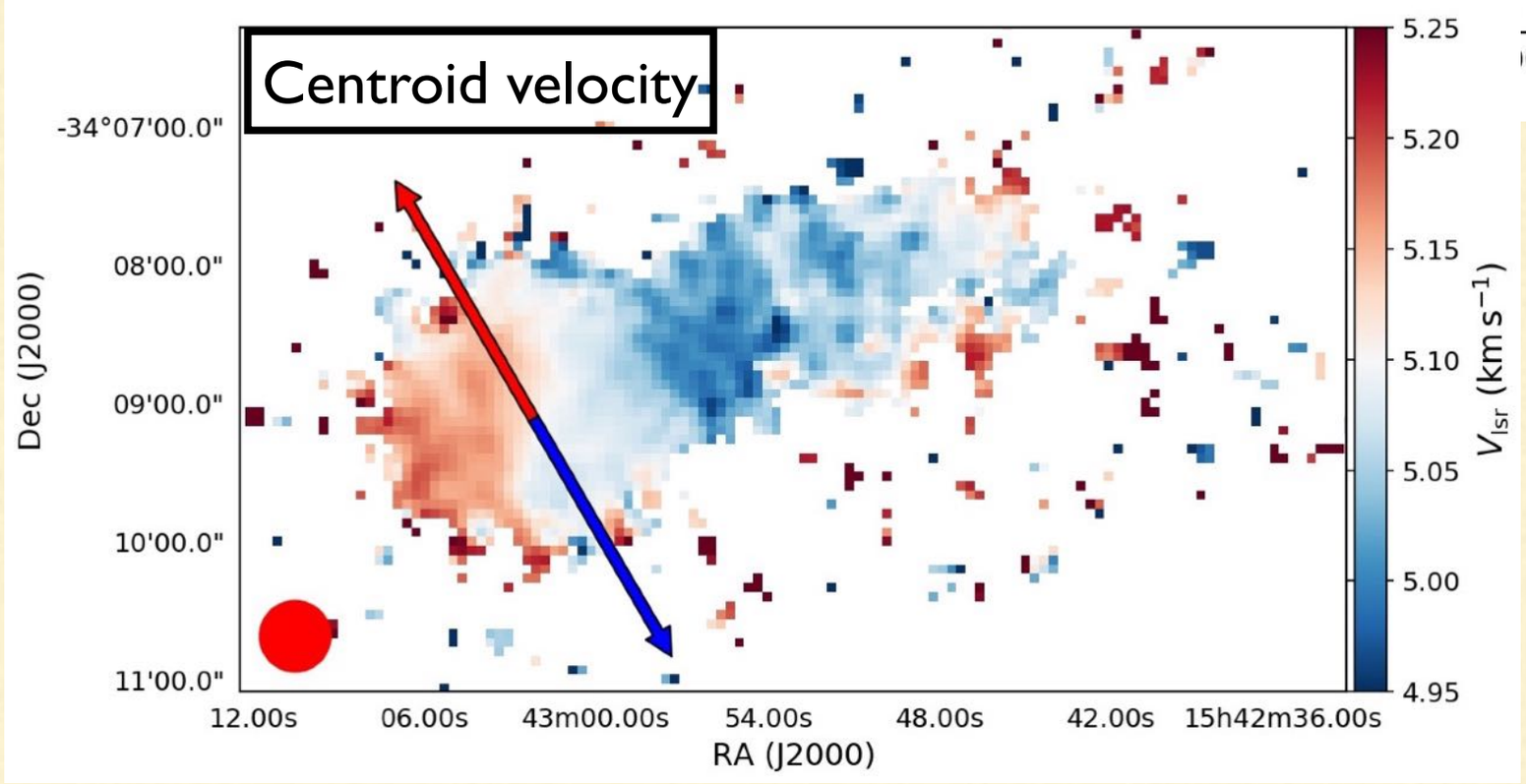
Goal: relation between kinematics and B fields



APEX DATA

DCO^+ data





FUTURE PROJECTS

- ALMA proposal to trace the envelope-scale magnetic field
- Possible new SOFIA proposal at different wavelength

THANKS FOR THE ATTENTION!

…Questions??