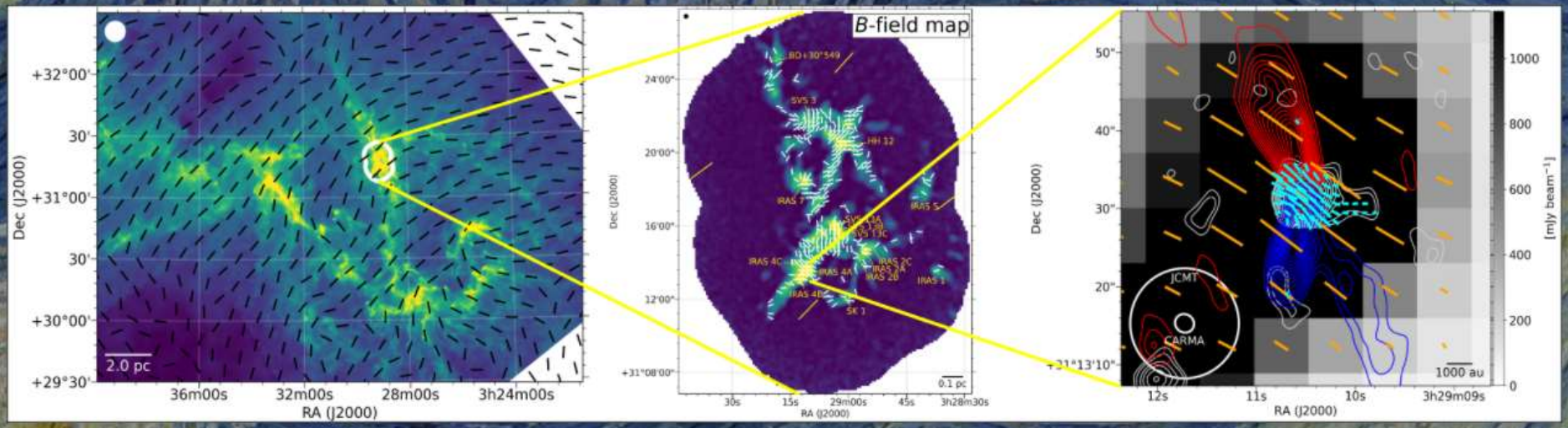
Multi-scale magnetic field structure *in* and *around* the Perseus molecular cloud

Planck
10pc~1pc

JCMT
1pc~0.01pc

Interefrometer
0.01pc~



Yasuo Doi and the BISTRO team

Contents

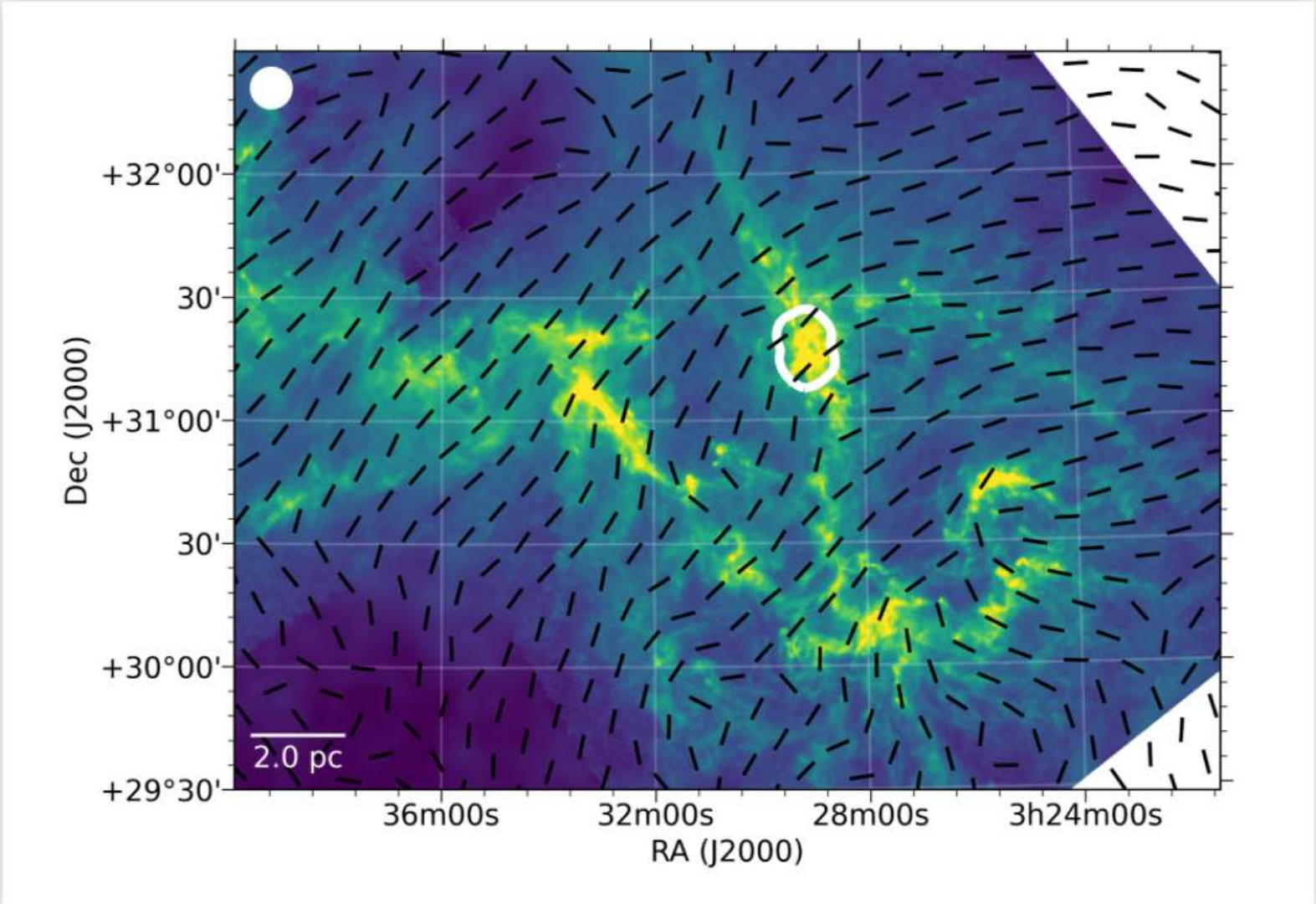
1. Magnetic field structure in the Perseus molecular cloud of 10 pc ~ 0.01 pc scale (Doi et al., 2020, *ApJ*, 899, 28)
   - < 1 pc scale magnetic field tightly associated to molecular cloud filaments
   - Distribution is perpendicular to the filaments
   - The magnetic field should be bent at the time of the filament formation, and then keep its structure continuous down to the < 0.01 pc scale.
   - $\ll 0.01$ pc ($\ll 1000$ au) scale magnetic field is affected by YSO formation

Contents

2. Magnetic field **around** the Perseus molecular cloud traced by optical polarimetry
   - optical polarimetry with *Gaia* distances can reveal the 3D *B*-field structure around Perseus and Taurus
   - optical polarimetry show *excellent* agreement with Planck magnetic field
     - NO small scale structures below Planck beam!?

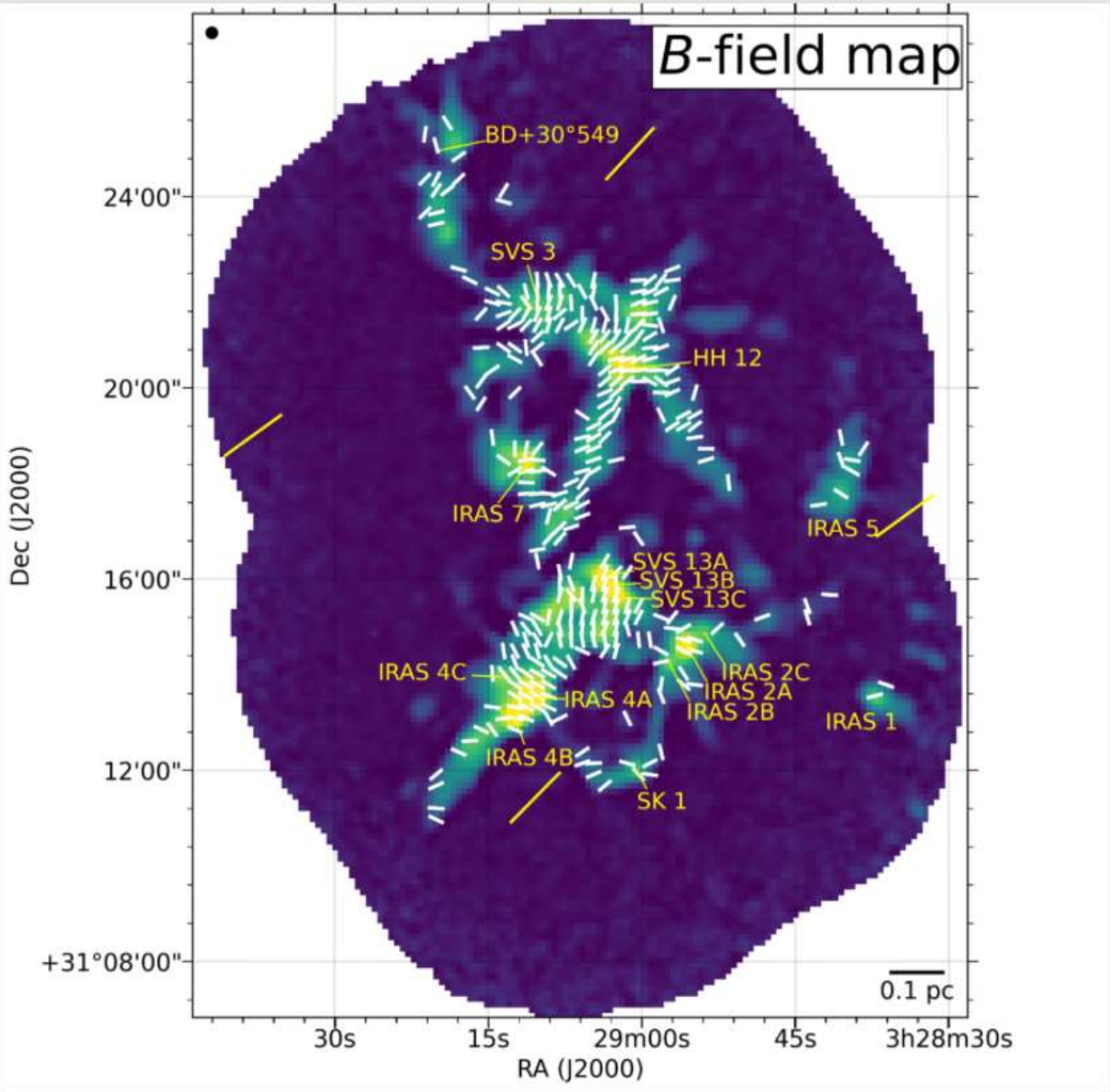
Large-scale magnetic field over Perseus

Smooth *B*-field observed by Planck (resolution $\sim$ 1 pc)



Herschel dust τ (Zari+2016) + Planck *B*-field (Planck+2018)

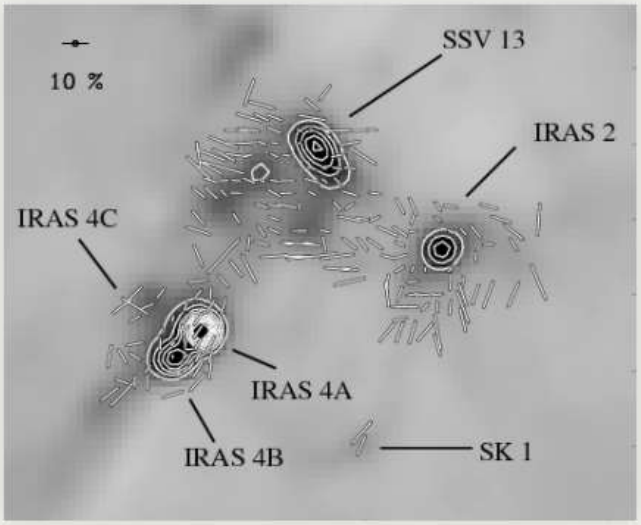
B-field in NGC 1333 obs. by BISTRO



JCMT SCUBA-2/POL-2 (Doi *et al.* 2020)

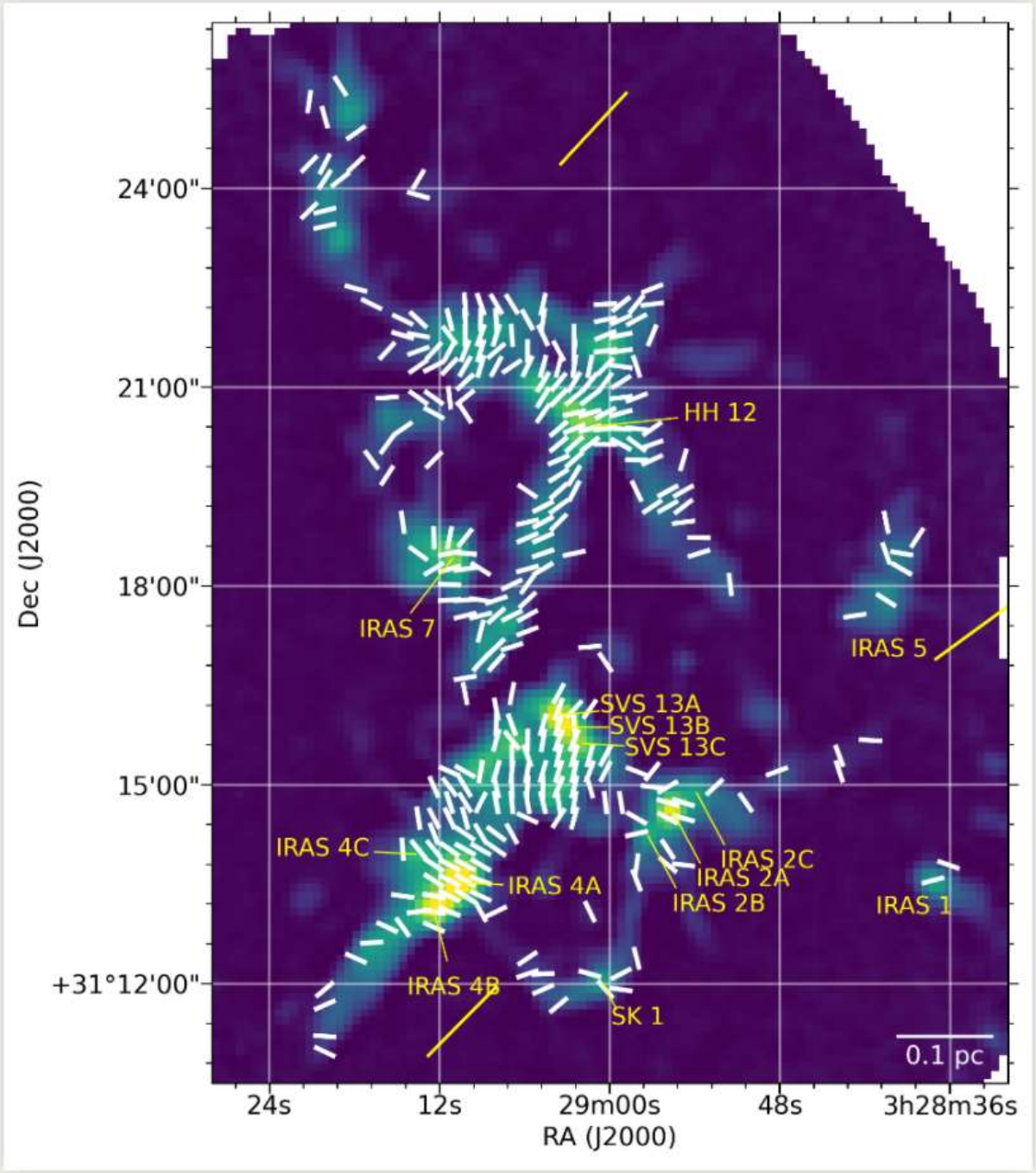
- Resolution ~ 0.02 pc
- Massive filaments ($\geq 50 M_\odot / \mathrm{pc}$)
- *B*-field for the whole region/ in filaments

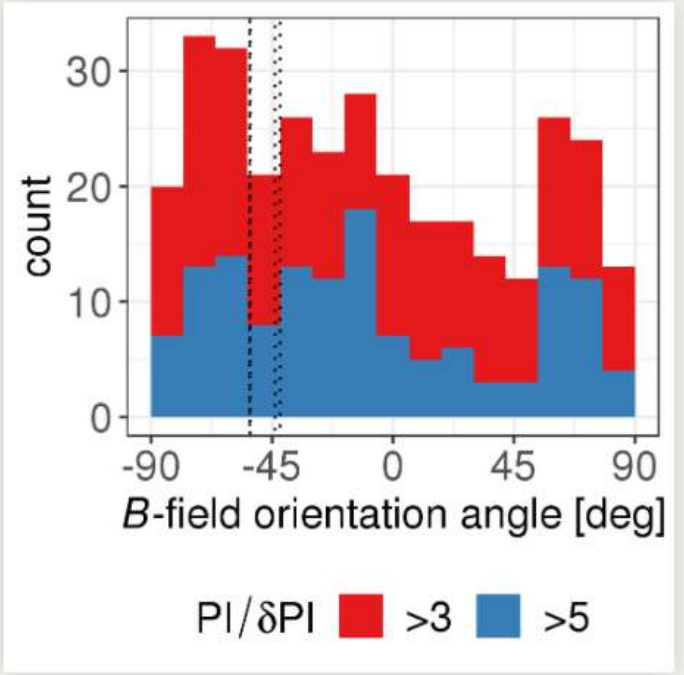
JCMT SCUPOL



(Chrysostomou *et al.* 2004)

BISTRO *B* pos. angle

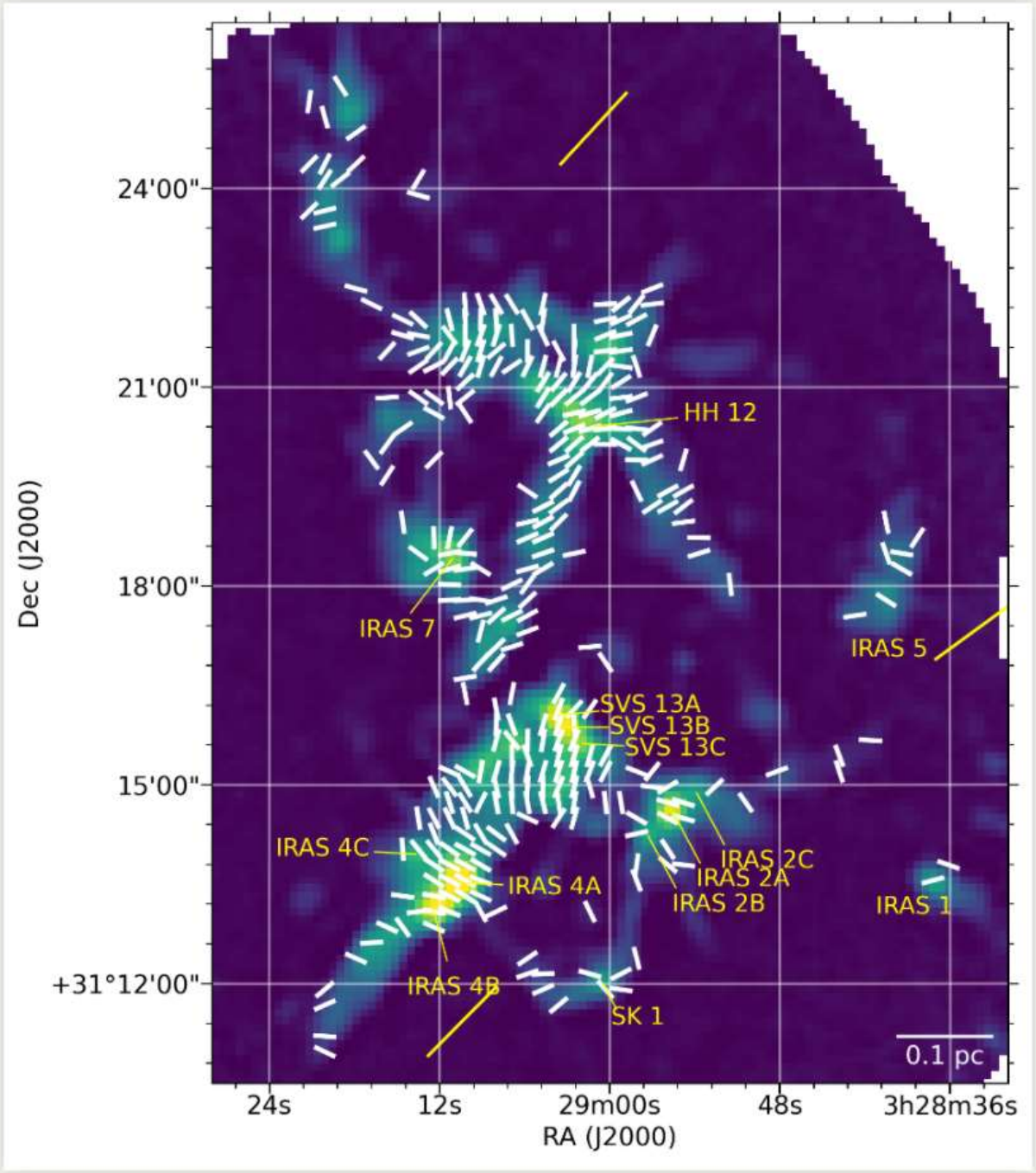


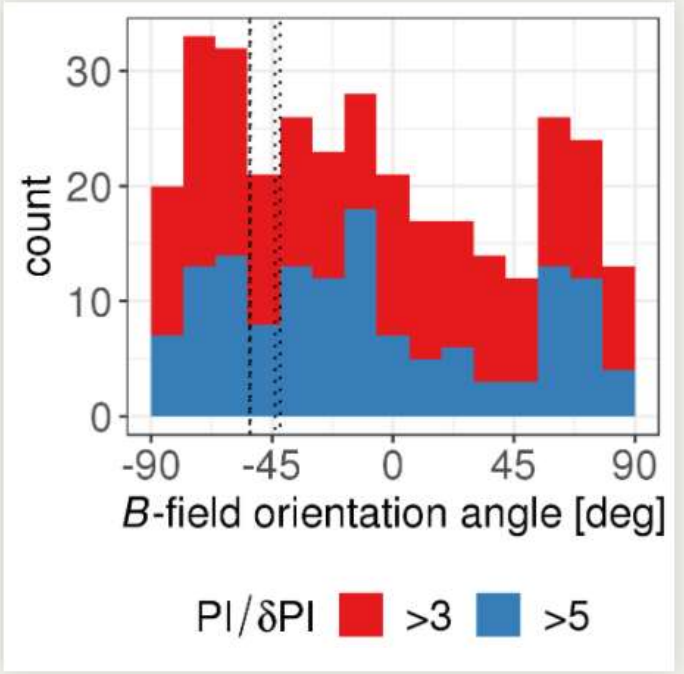


- Planck $-48^\circ \pm 6^\circ$
- JCMT $-46^\circ \pm 58^\circ$

1: $<$ 1pc scale:
B-field is **random!!**

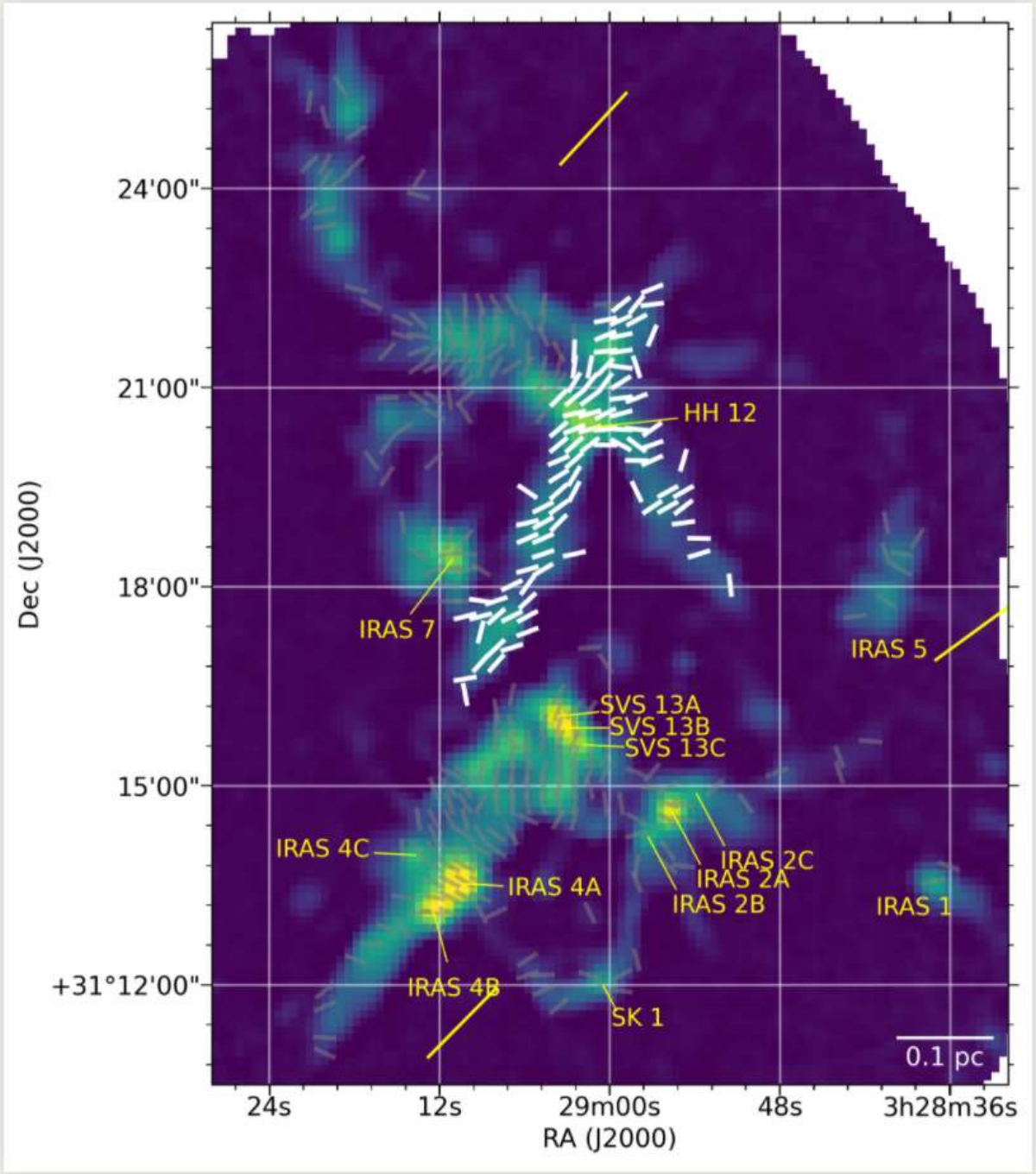
BISTRO *B* pos. angle

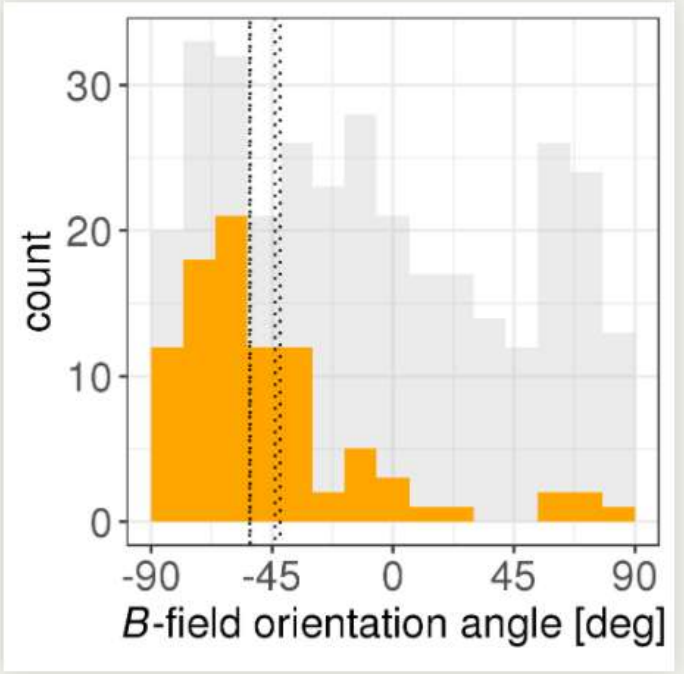




2: *B*-field aligns with each filament at different offset angles

BISTRO *B* pos. angle





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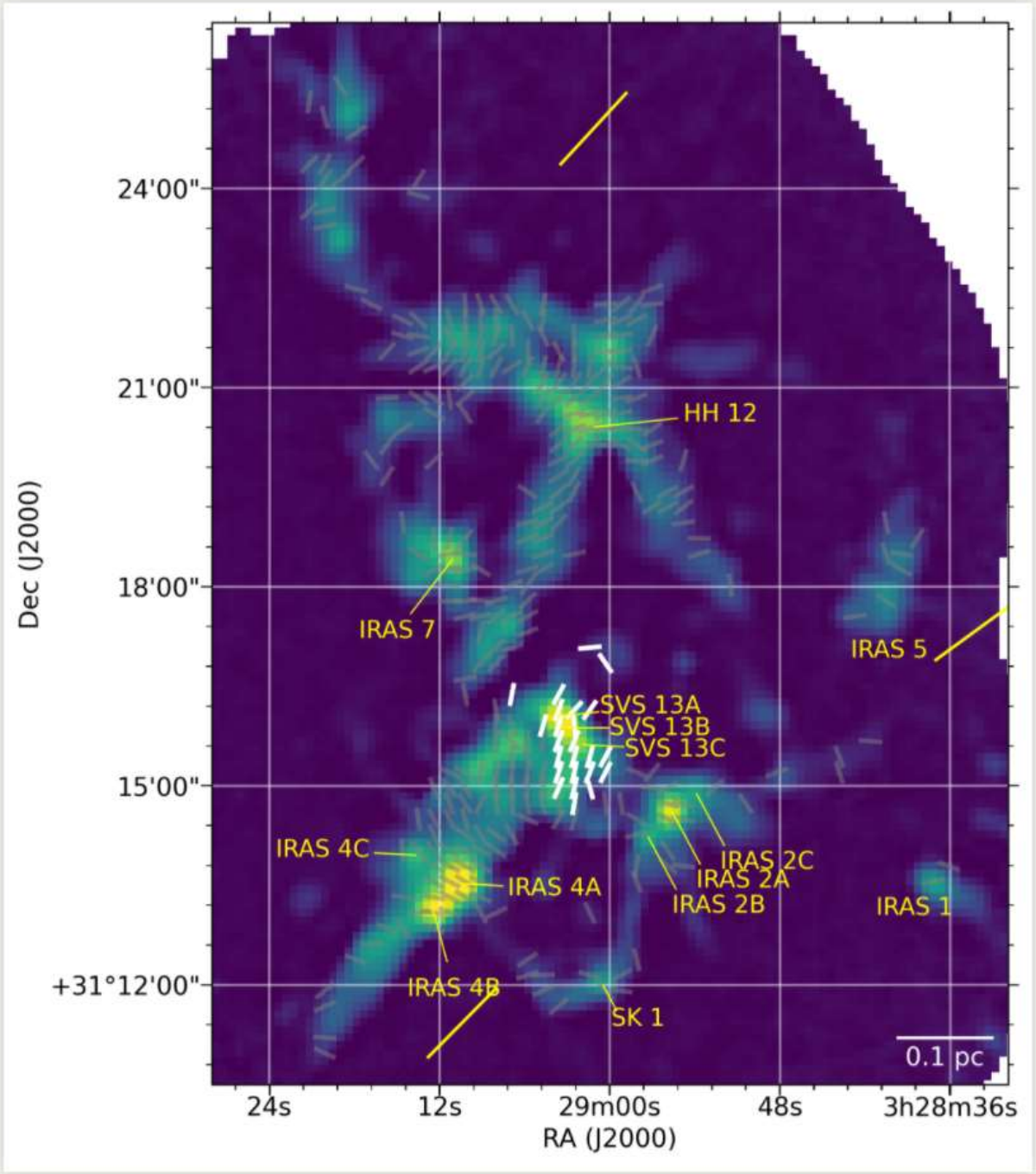

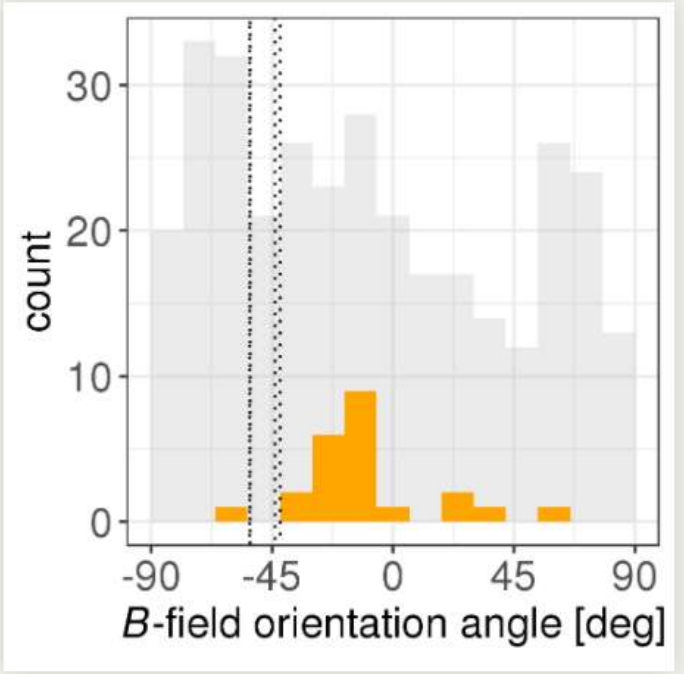

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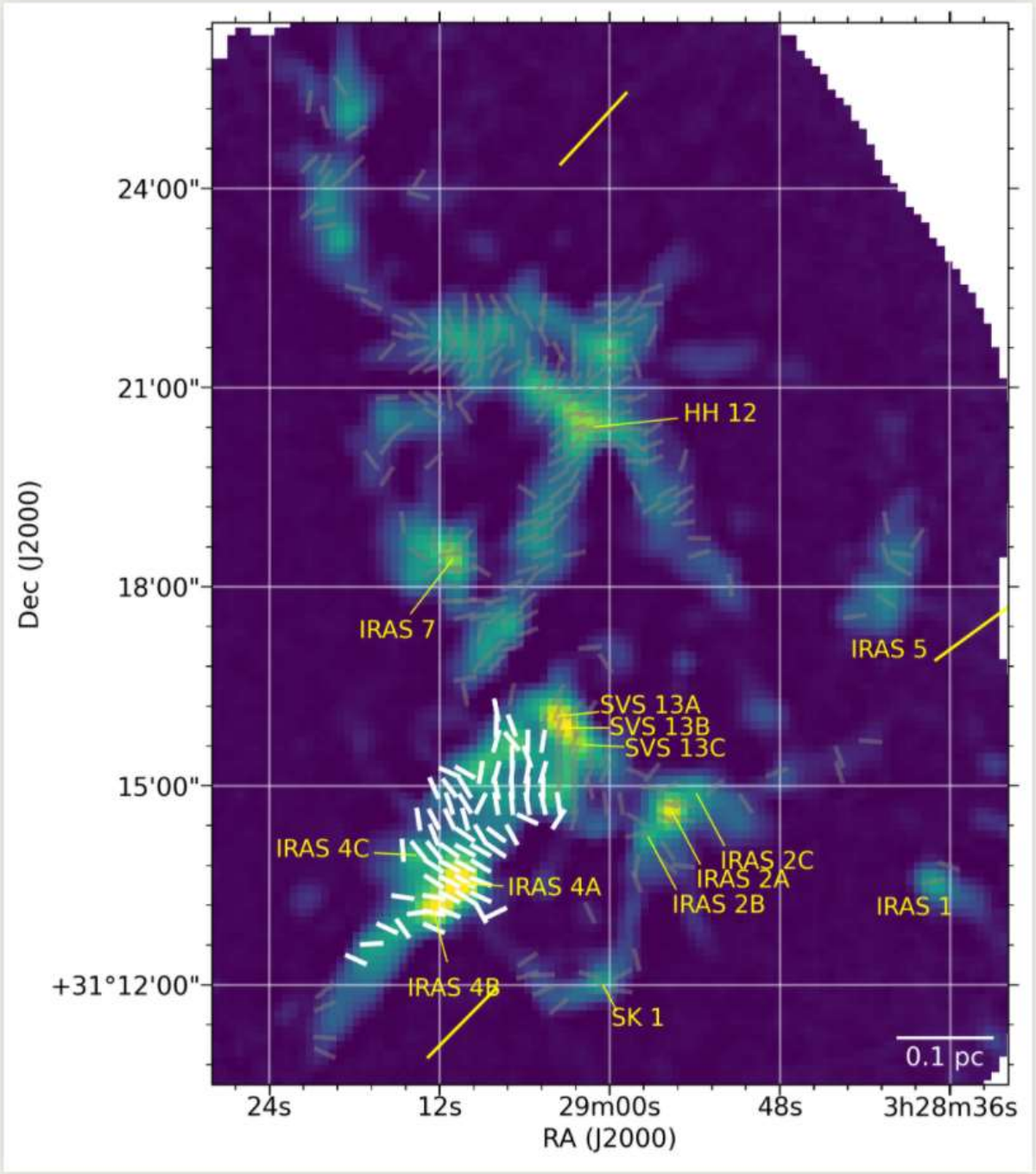
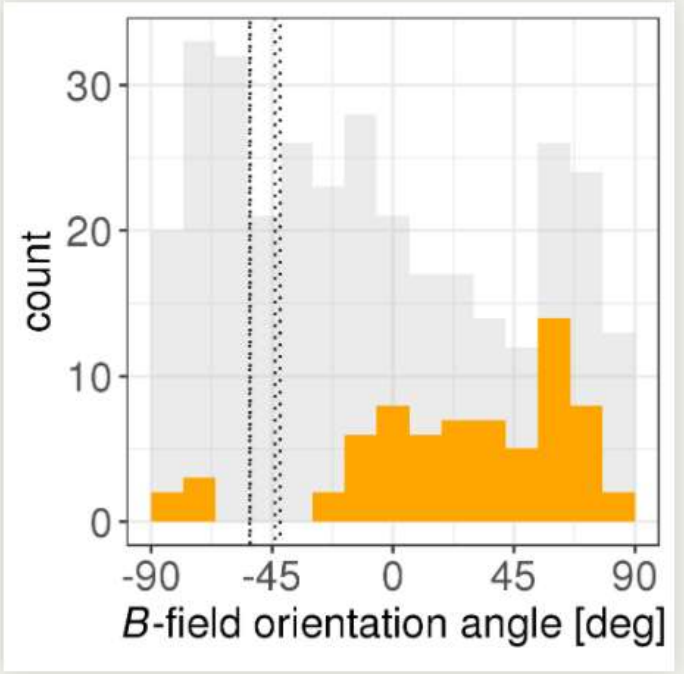


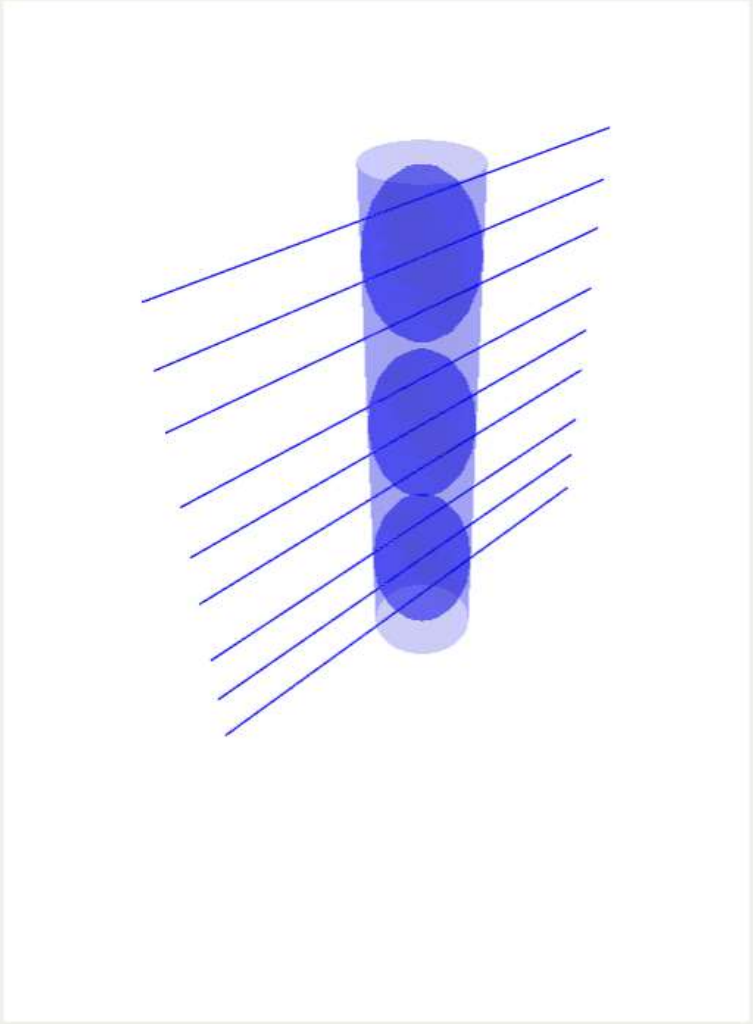


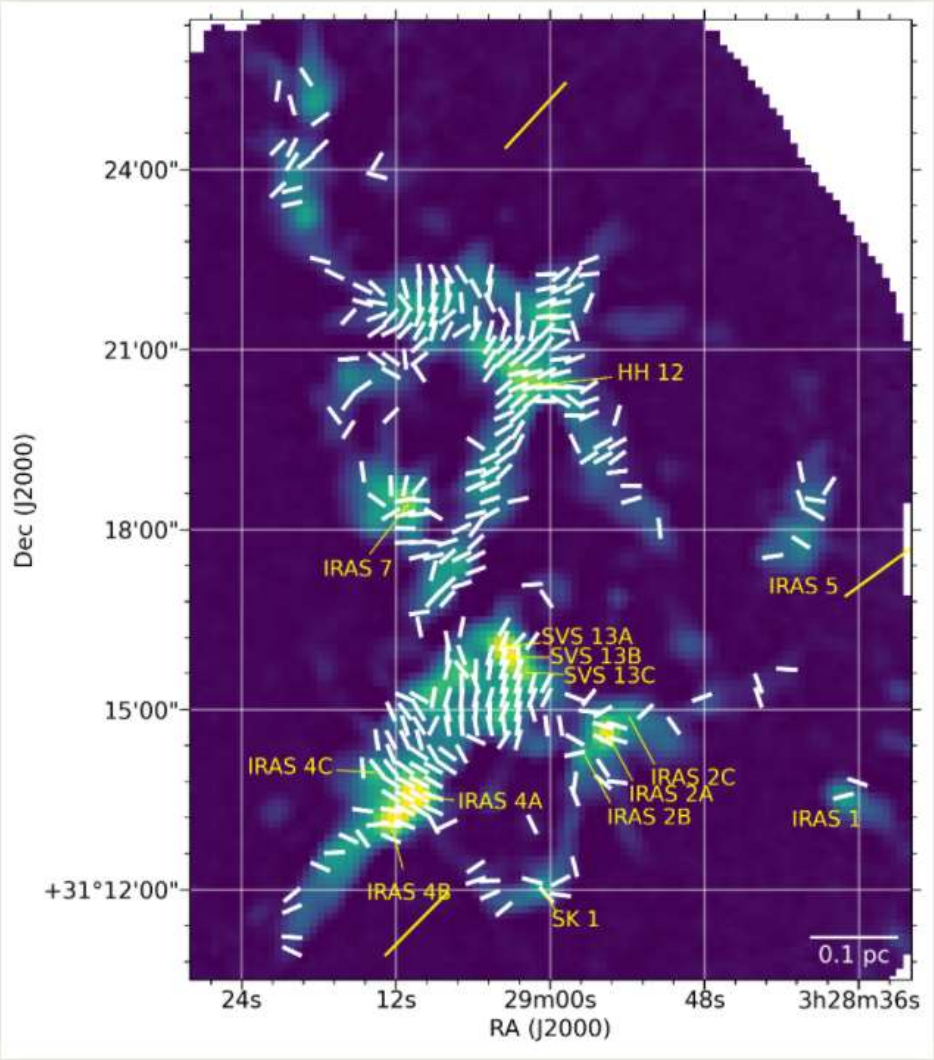
2: *B*-field aligns with each filament at different offset angles

B-field alignment to filaments

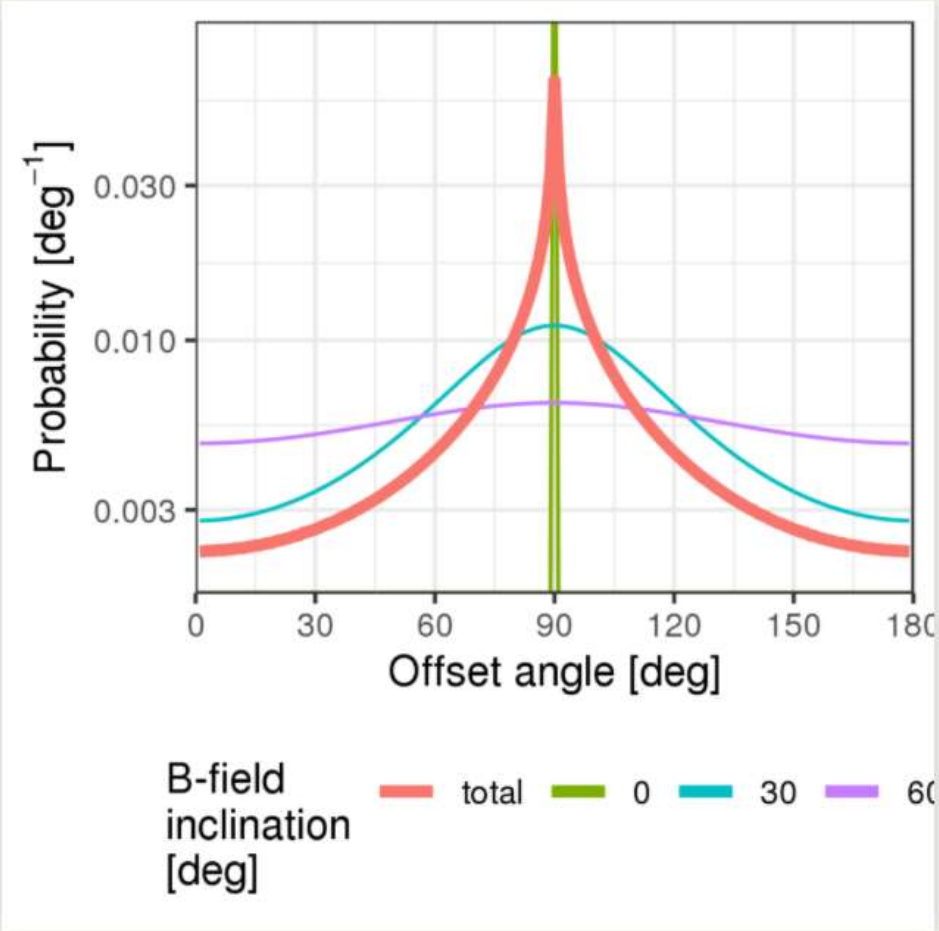
3: 3D geometry of filaments and the magnetic field (Tomisaka 2015)

- Combination of simple structure can create complex geometry



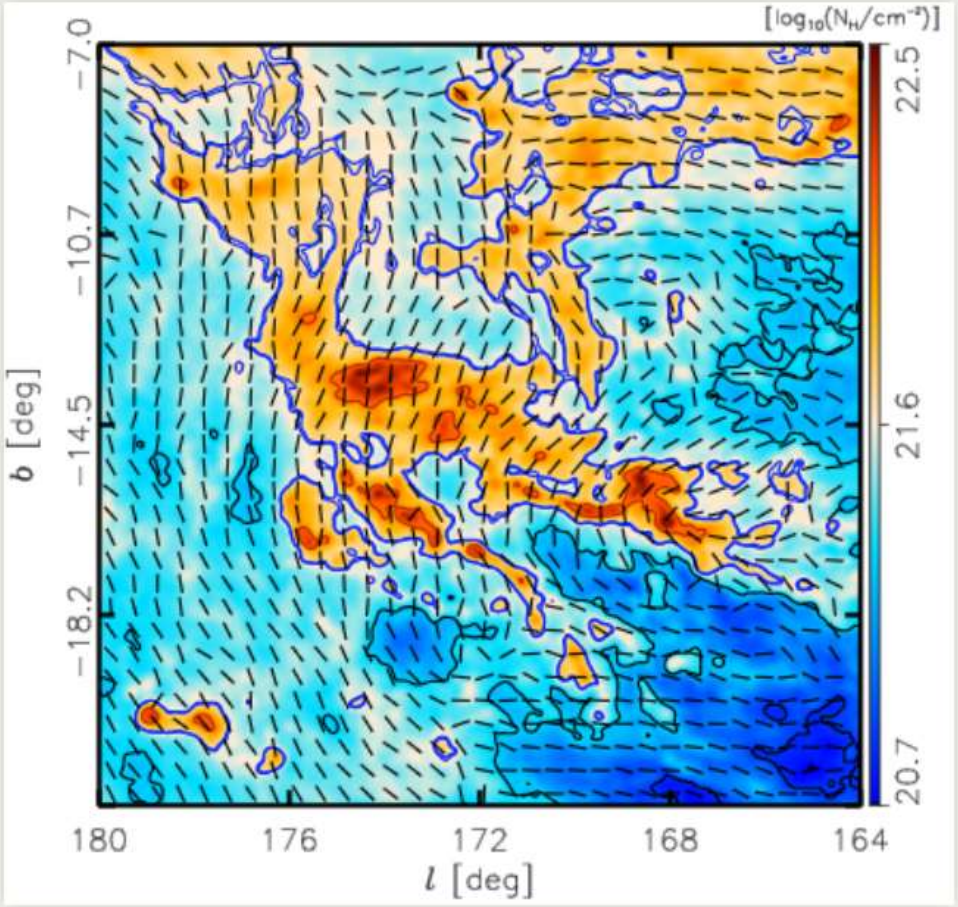


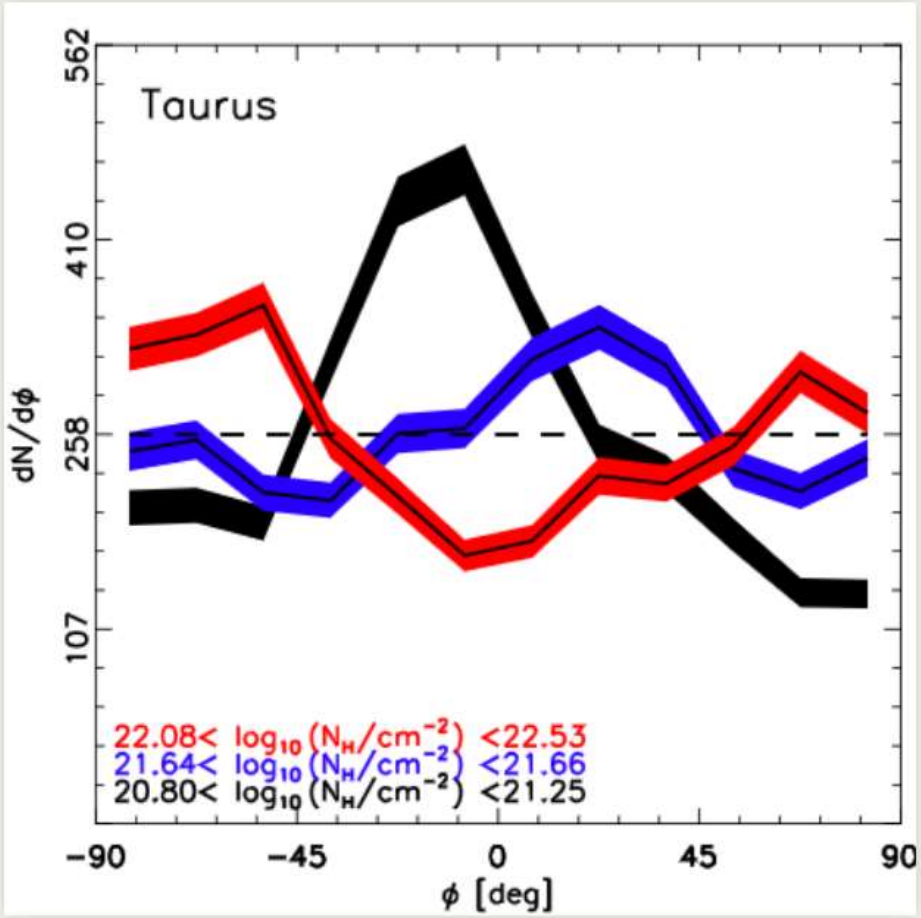
Projected offset angle between the magnetic field and the filament



Tend to be vertical -- consistent with Planck

Filamets alignment with B-field as seen by Planck



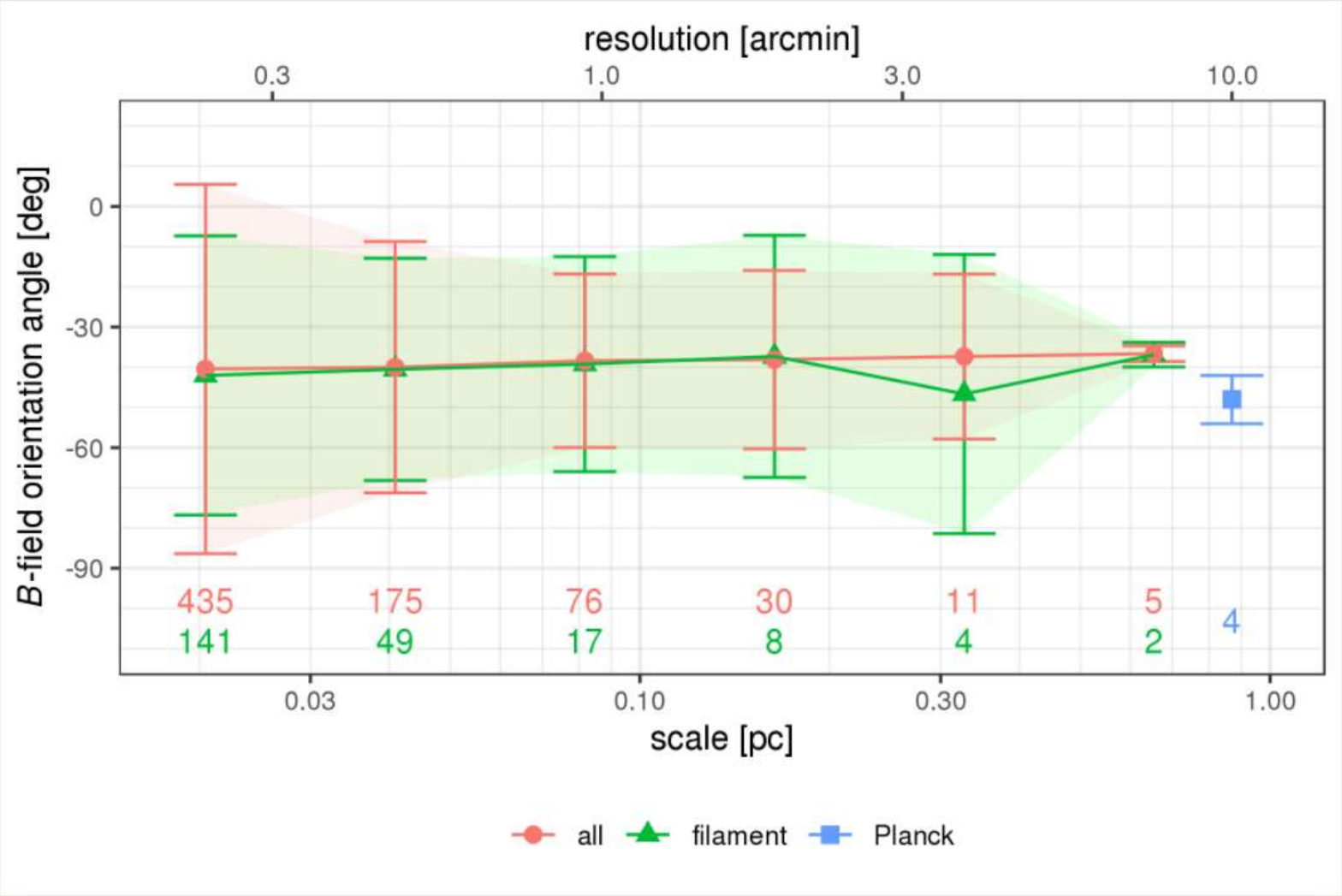


(Planck Collaboration+ 2016, A&A, 586, A138)

Scale dependence of *B*-field angle var.

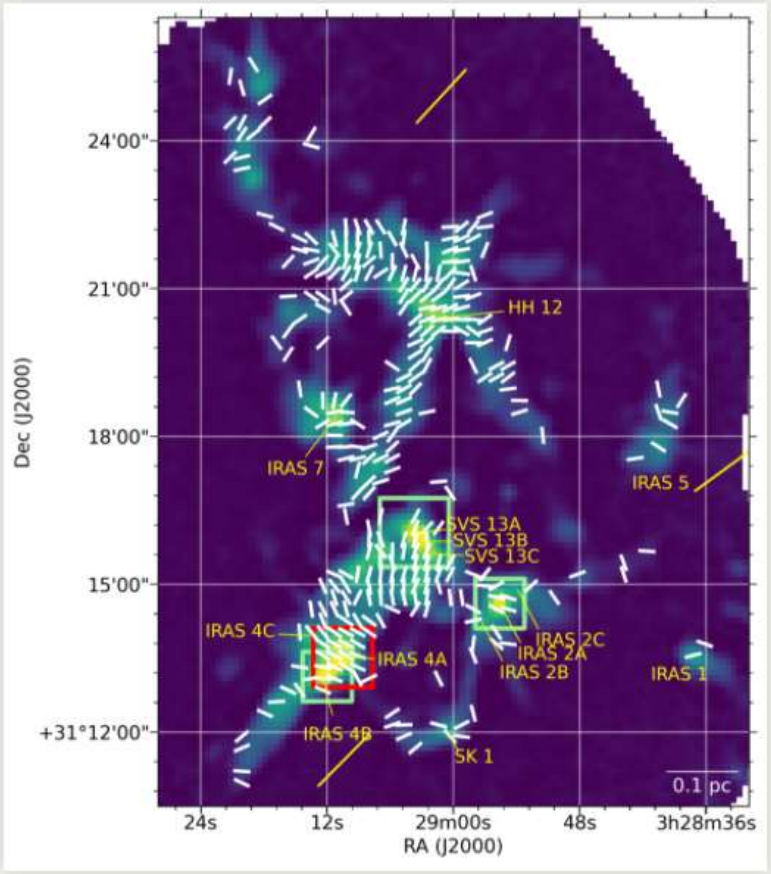
- Increases at ~ 0.3 pc & constant on smaller scales

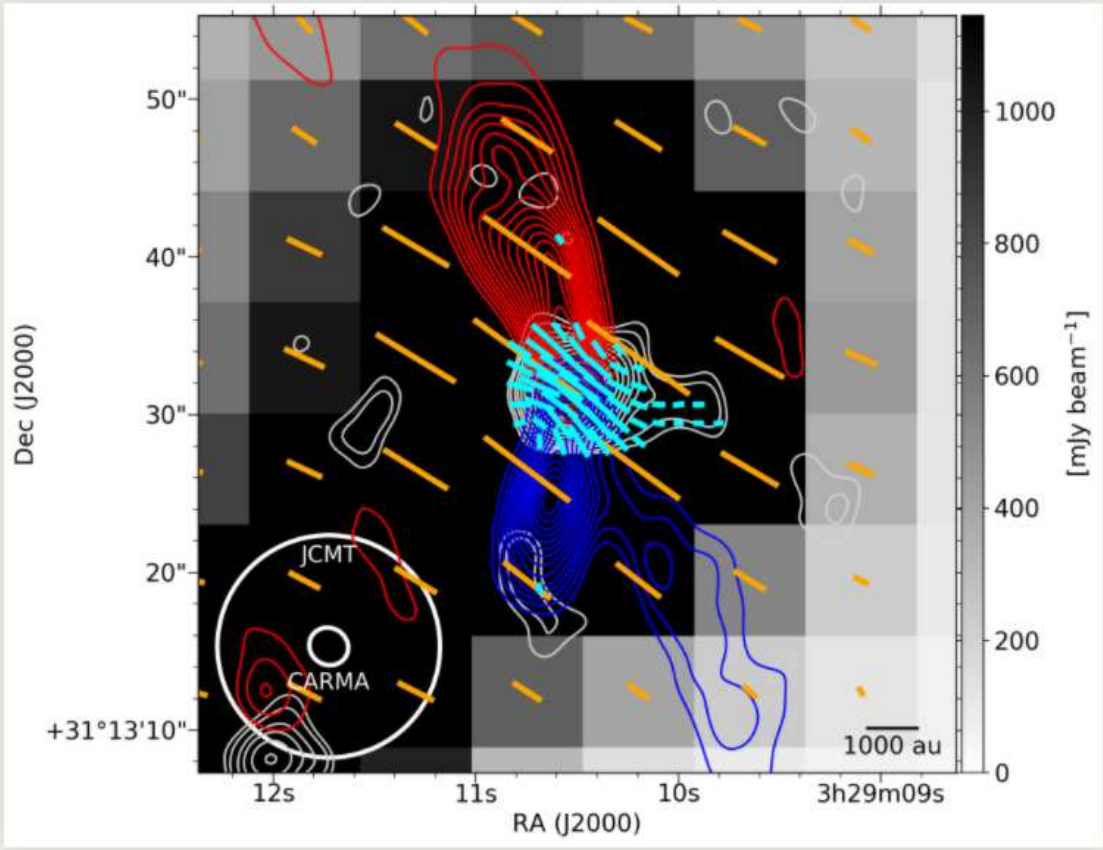
4: *B*-field structure change due to filament formation



BISTRO vs. interferometric obs. (Hull+2014)

5. *B*-field structure is consistent down to < 0.01 pc or 1000 au





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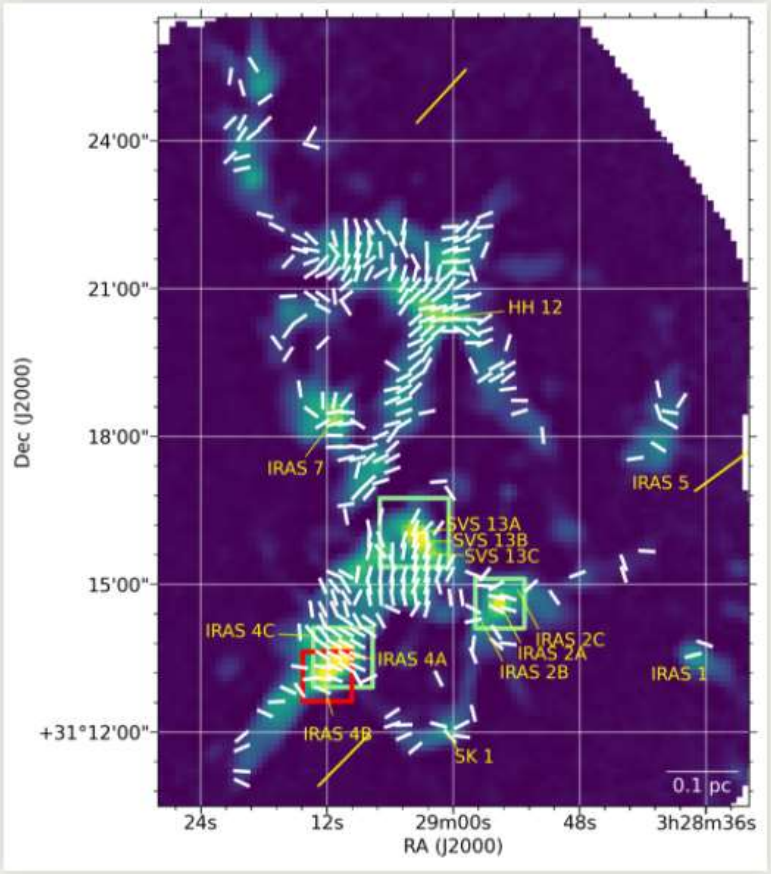

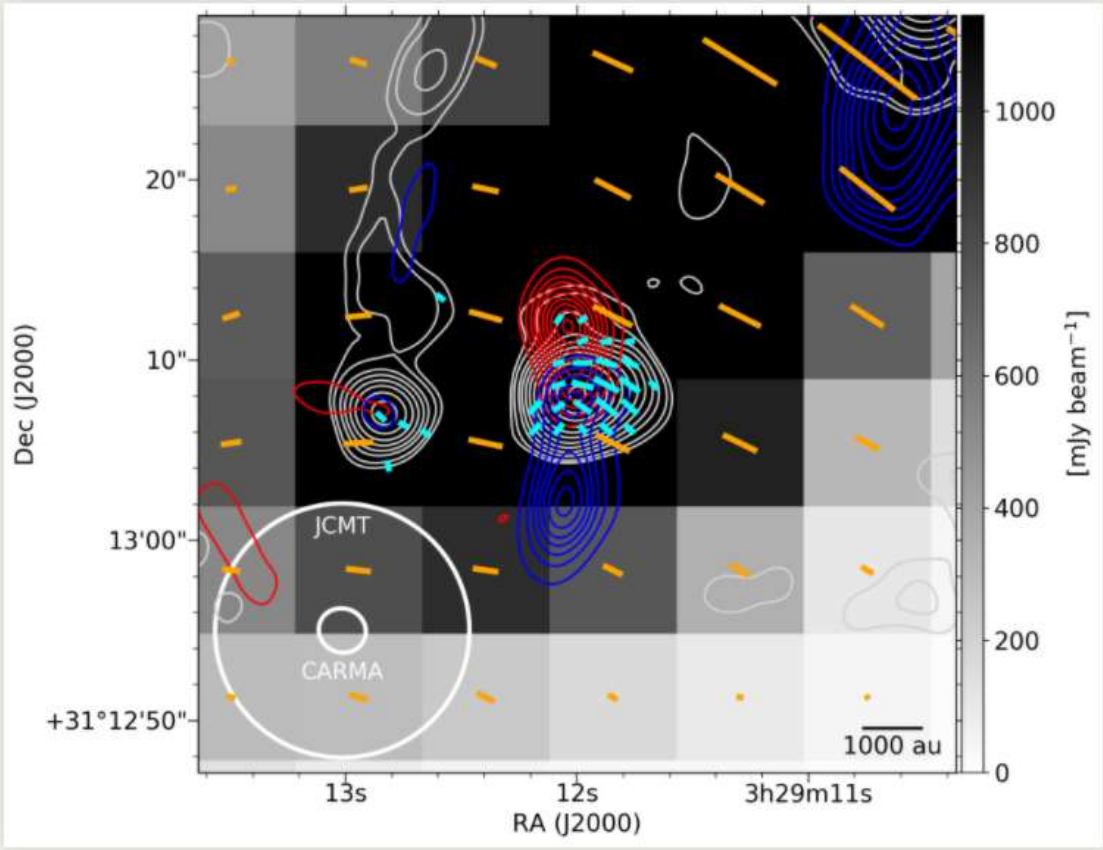

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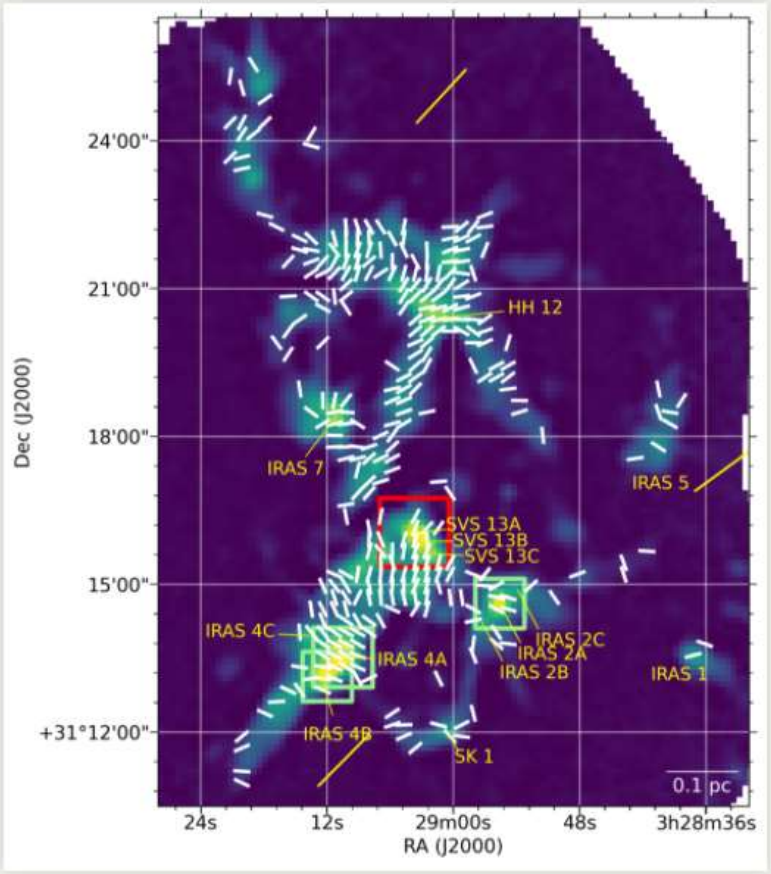

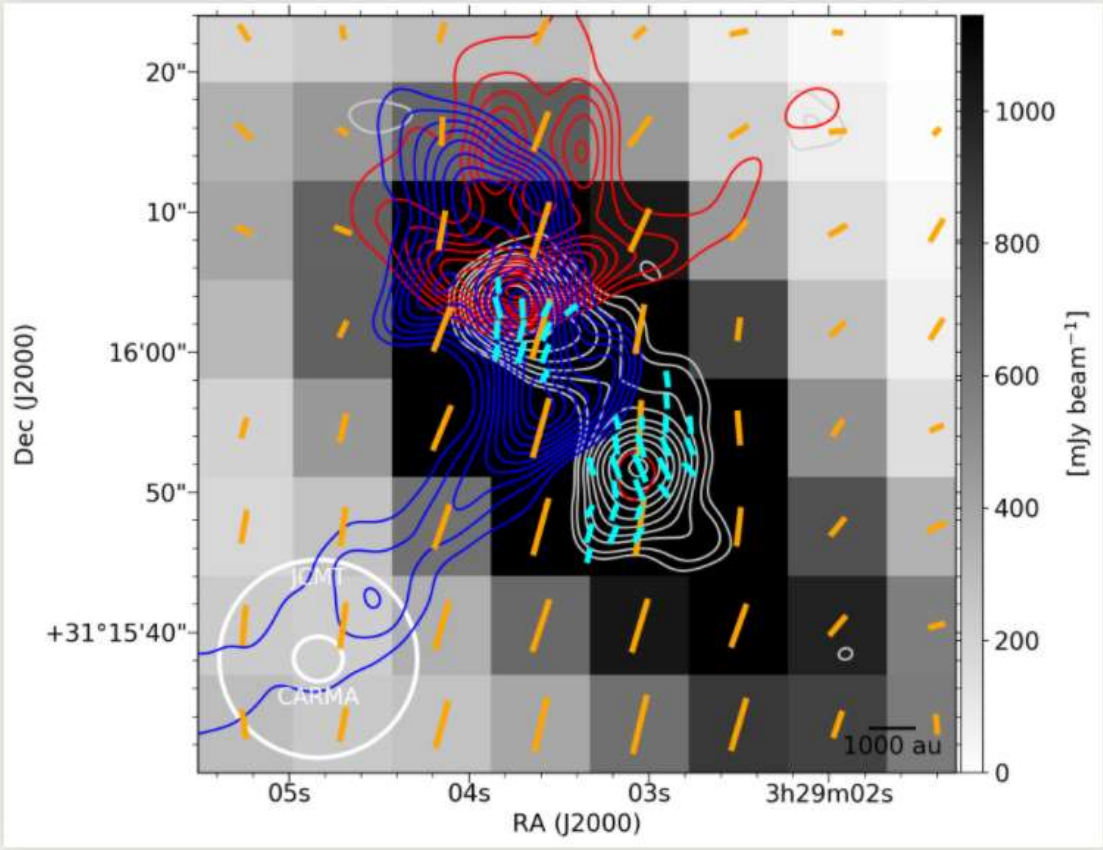

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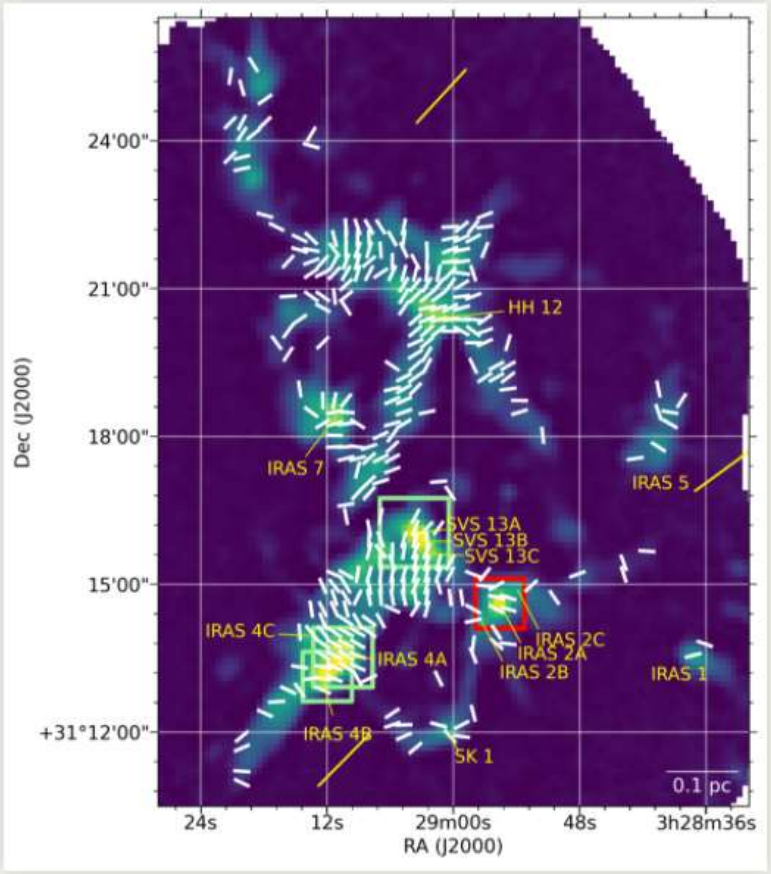
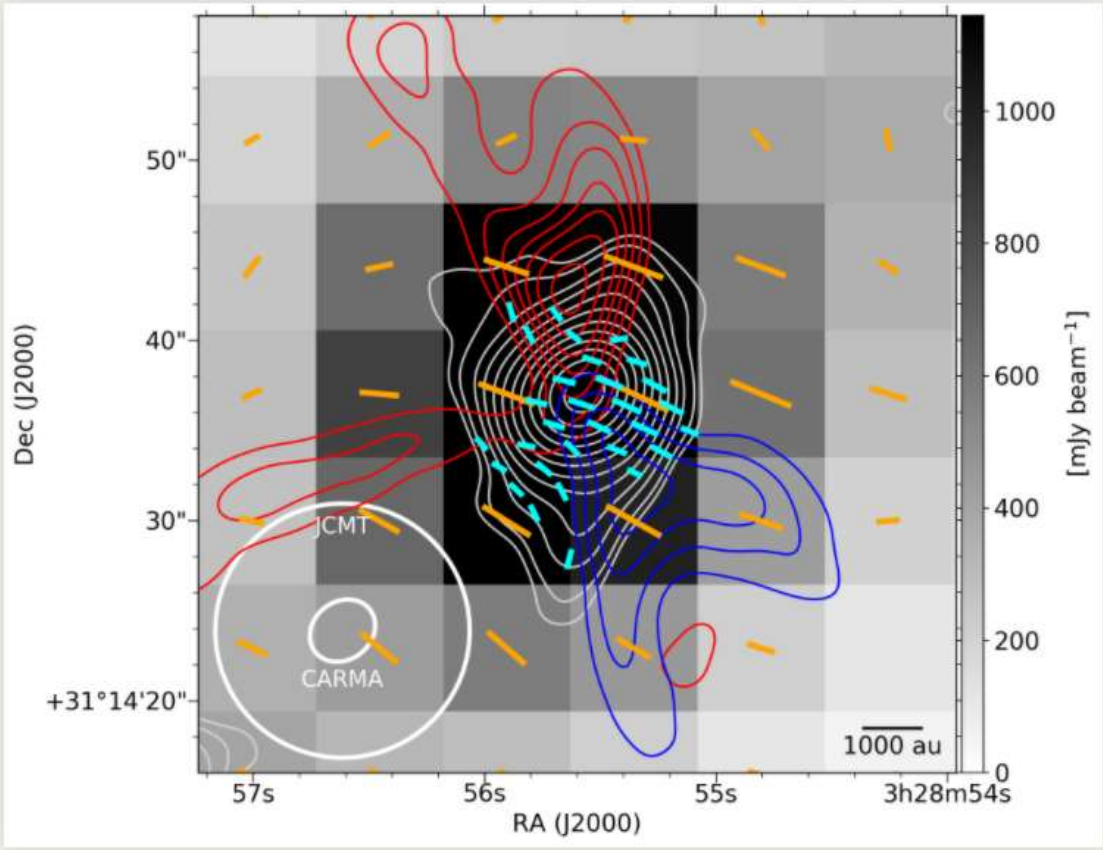
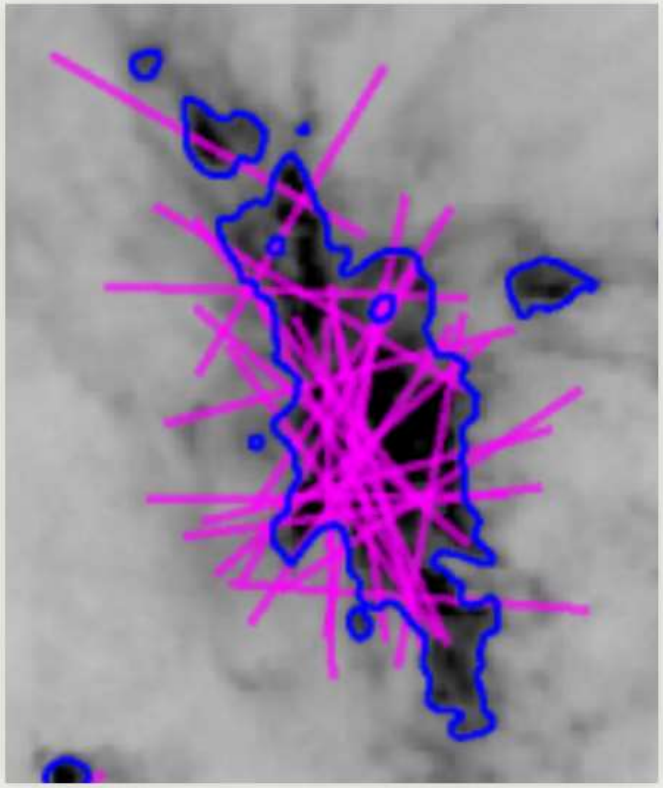




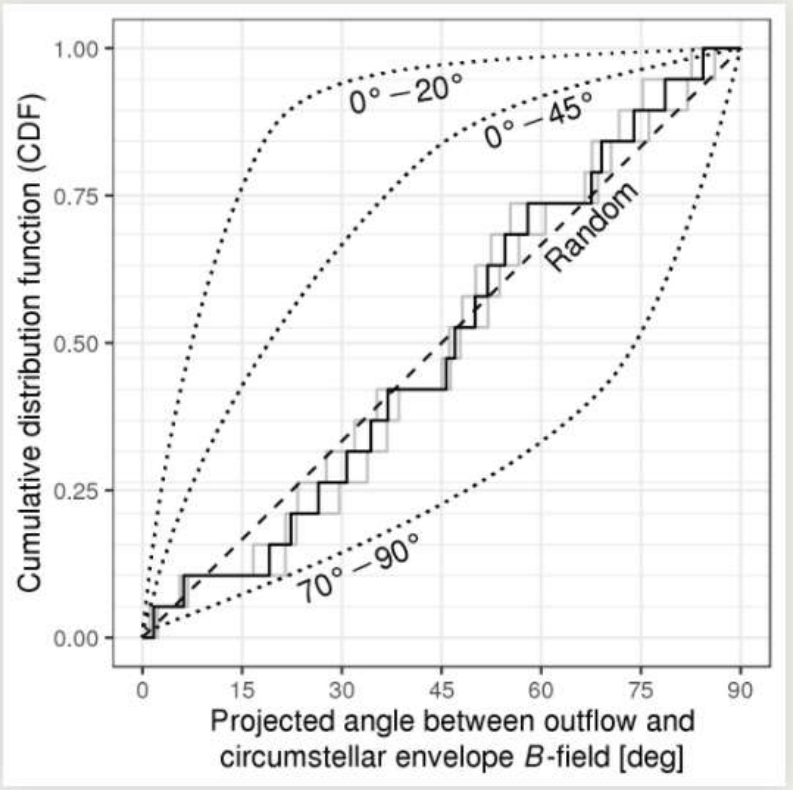
BISTRO vs. CO molecular outflows

- NO correlation between BISTRO *B*-field and the CO outflow direction (*cf.* interferometric obs.)

6. A significant change in the position angle at $\ll 1000$ au



Direction of CO molecular outflows
(Stephens+2017)



Summary of the first half of the talk

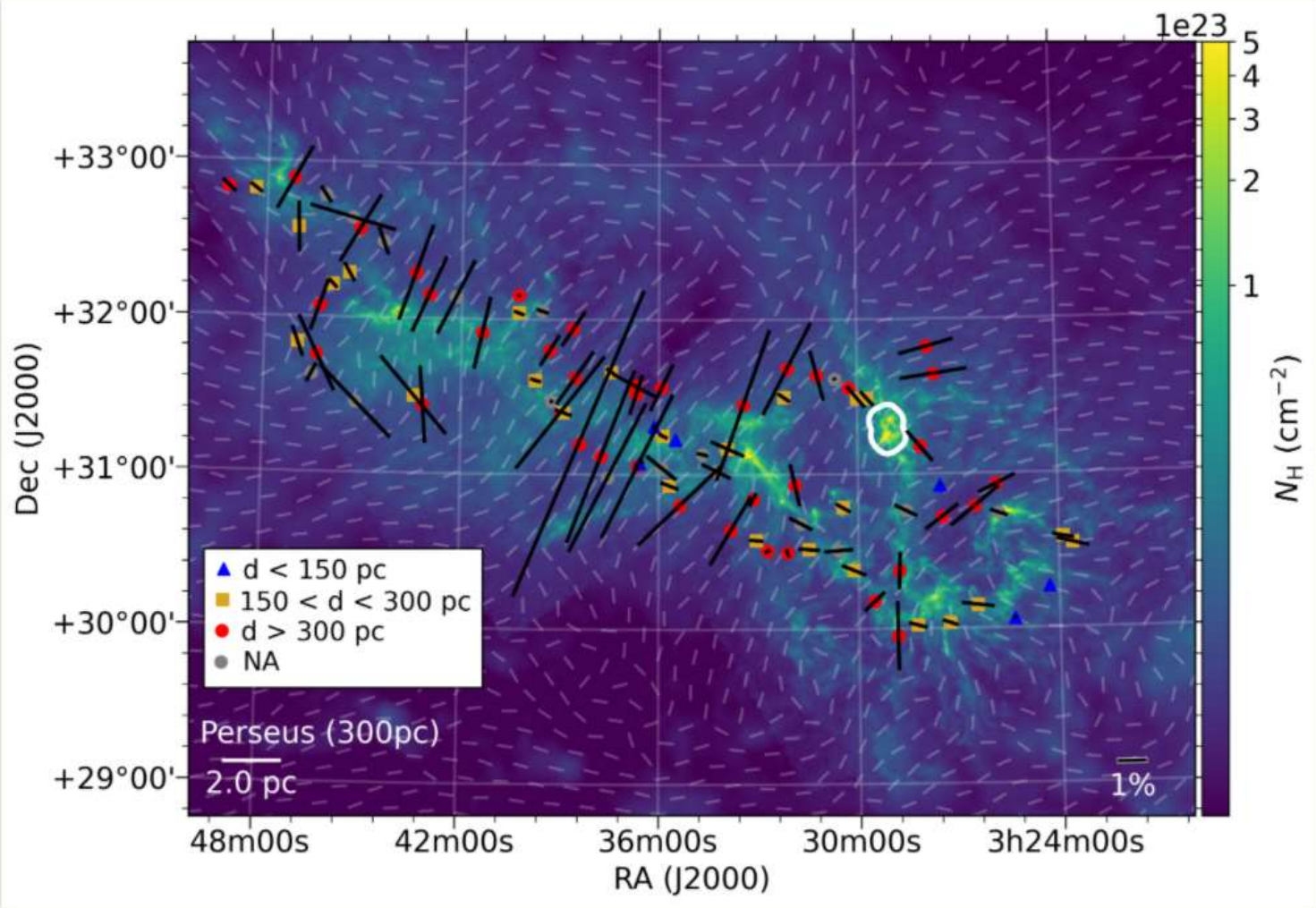
Magnetic field structure in dense molecular clouds

- < 1 pc : Magnetic field structure is changed (most probably) due to filament formation
- 1 pc ~ 0.01 pc : Maintains its distribution perpendicular to filament
- $\ll 0.01$ pc : the YSO rotation axis does not match the larger-scale magnetic field orientation

See **Doi et al., 2020, *ApJ*, 899, 28** for more information.

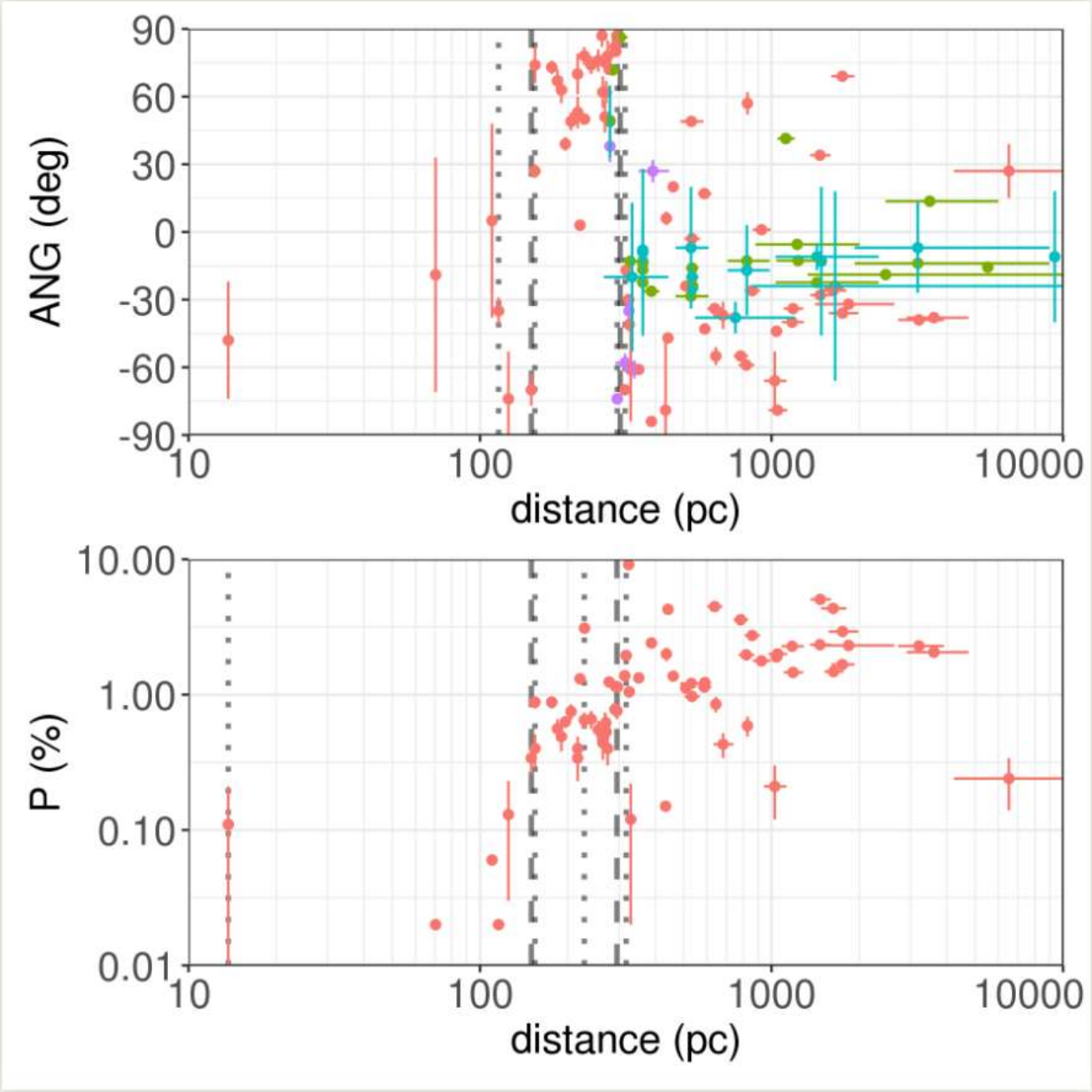
B-field 'around' the molecular cloud

- sub-mm polarimetry: $N_H \gtrsim 10^{24}\ (\mathrm{cm}^{-2})$
- Optical/NIR polarimetry: $N_H \lesssim 10^{22}\ (\mathrm{cm}^{-2})$ + high spatial resolution



Goodman et al. (1990)

Stellar distances (obs. by *Gaia*)

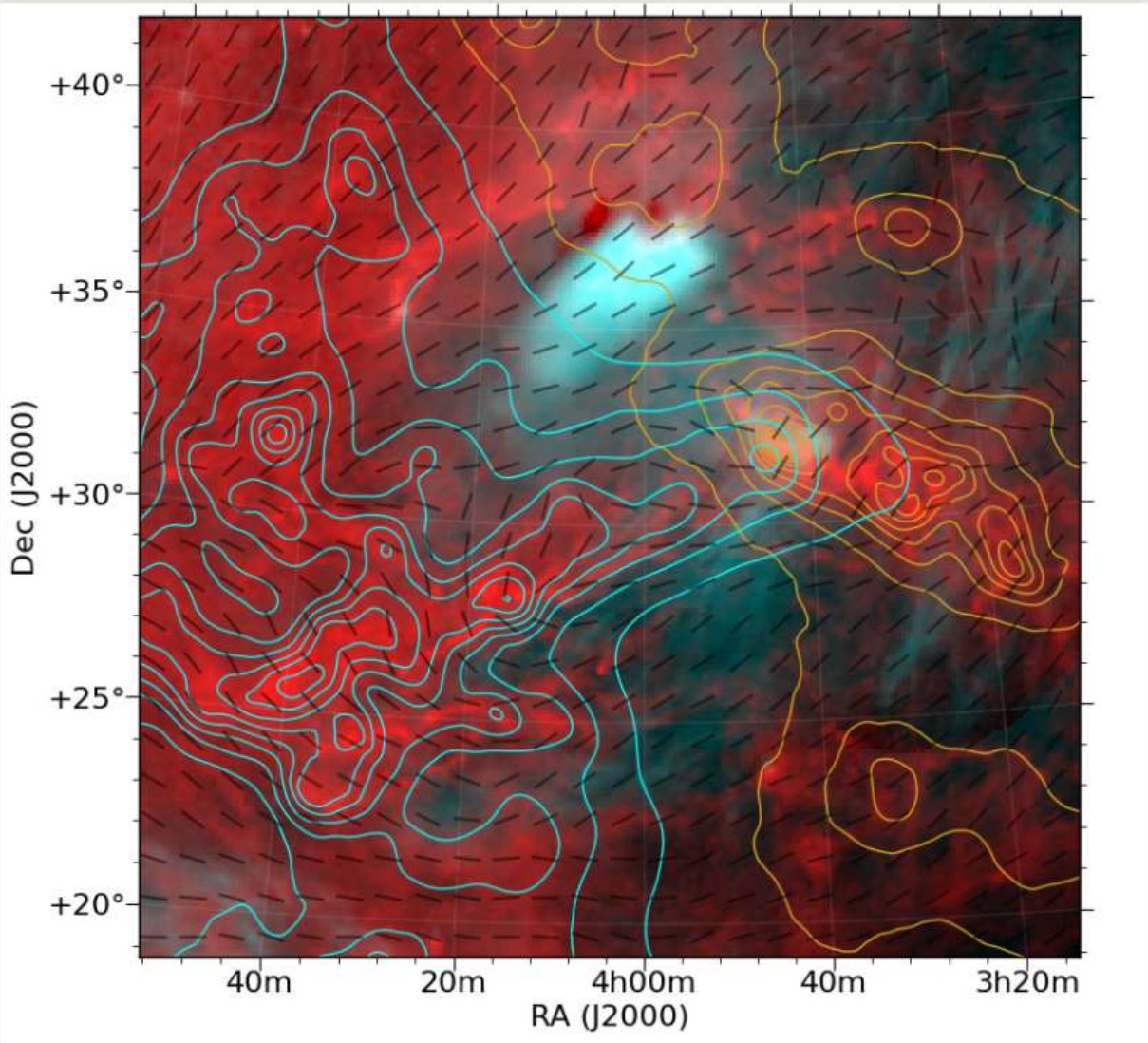


breakpoints

- ANG
  - 150^{+4}_{-34} (pc)
  - 303^{+12}_{-7} (pc)
- P
  - 150^{+4}_{-136} (pc)
  - 295^{+22}_{-67} (pc)

Opt. (Goodman+1990)
R (Alves+2011)
J (Alves+2011)
K (Tamura+1988)

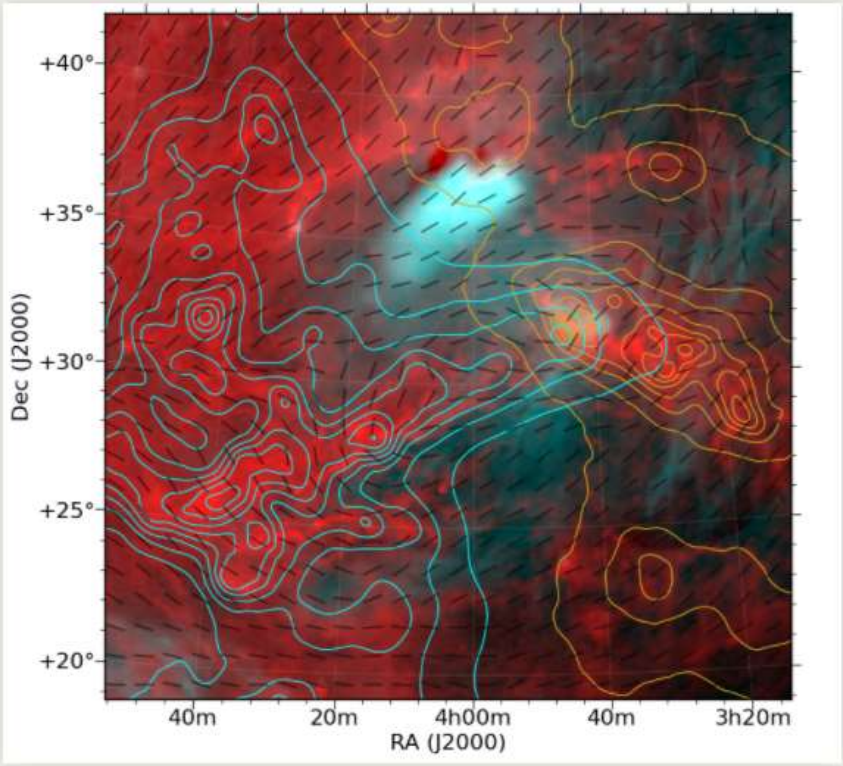
Two-layer absorption by Perseus (300 pc) and Taurus (150 pc)



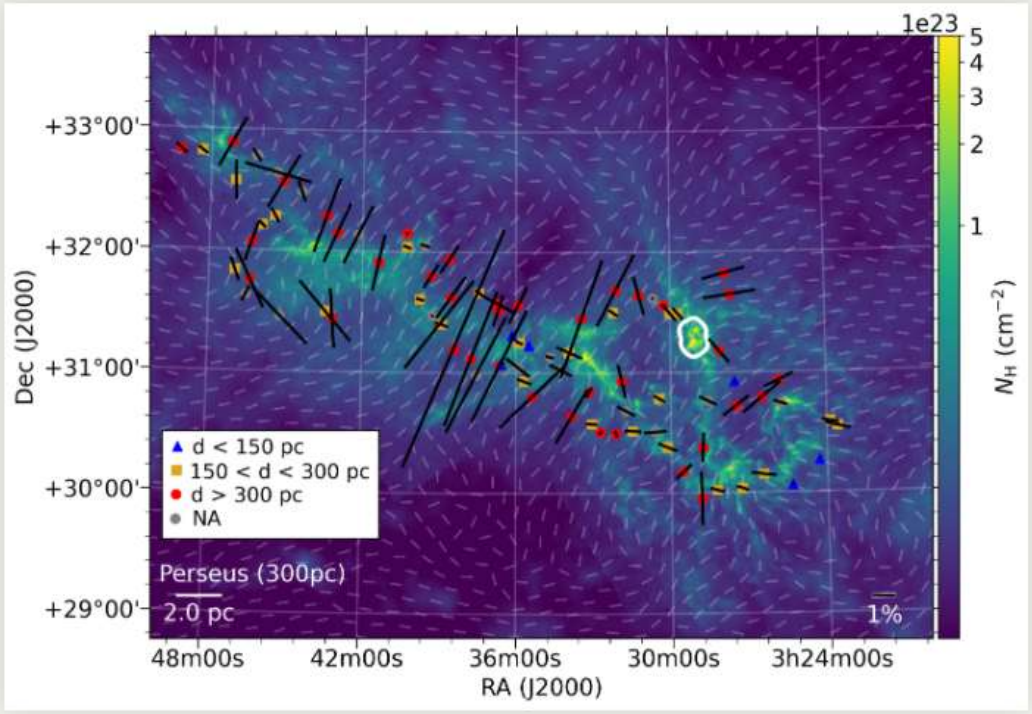
3D dust mup
(Leike et al. 2018)

- Cyan contours:
  100--200 pc
- Orange contours:
  250--350 pc
  - Red color:
    Planck 850 μm
  - Cyan color: Hα

Two layers of perpendicularly different *B*-fields

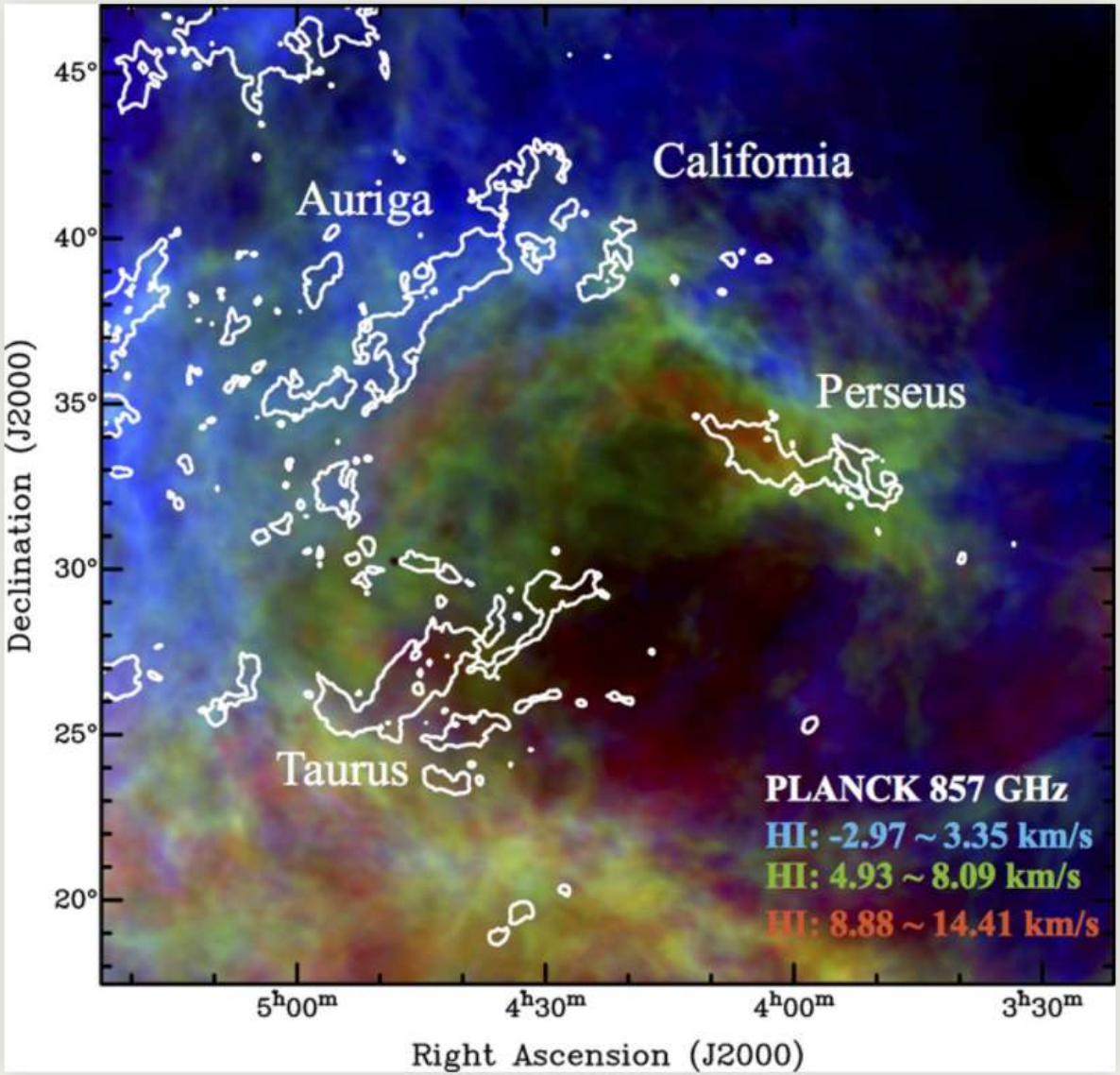


Doi+ in prep.



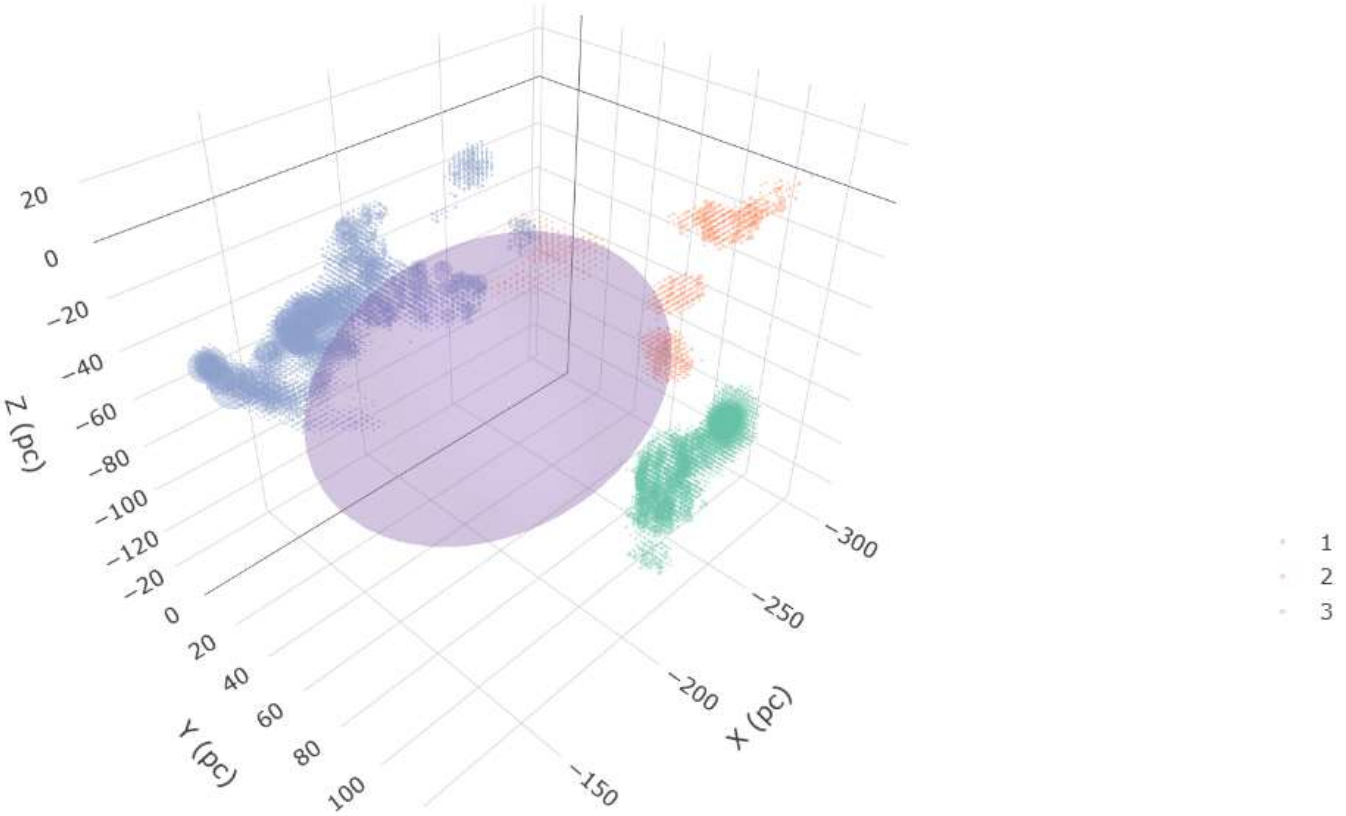
Goodman et al. (1990)

Per OB2 bubble?

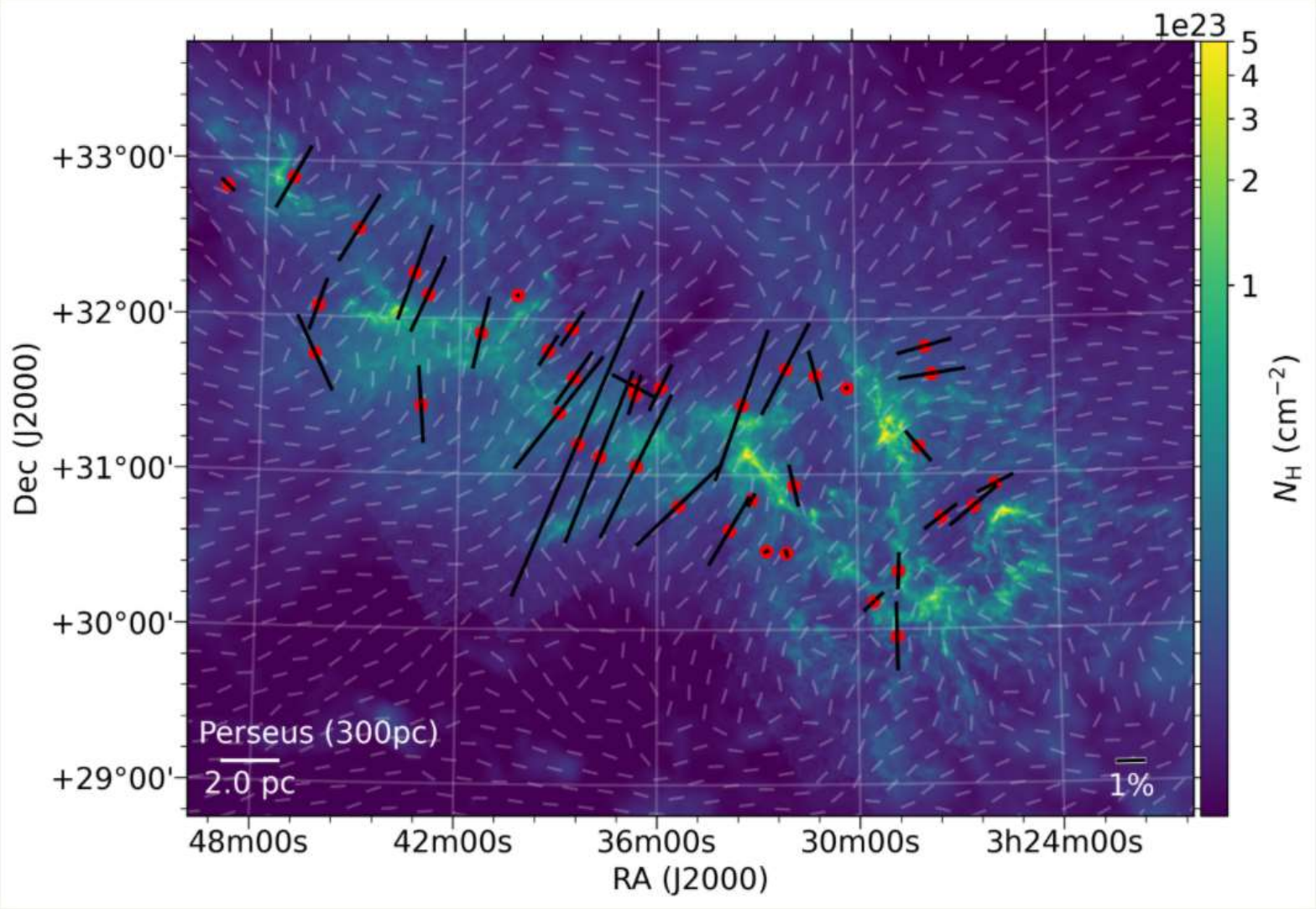


Shimajiri et al. (2019)

B-field at the frontside and the backside of the dust "cavity"



Good Correlation between Opt. polarization and Planck *B*-field



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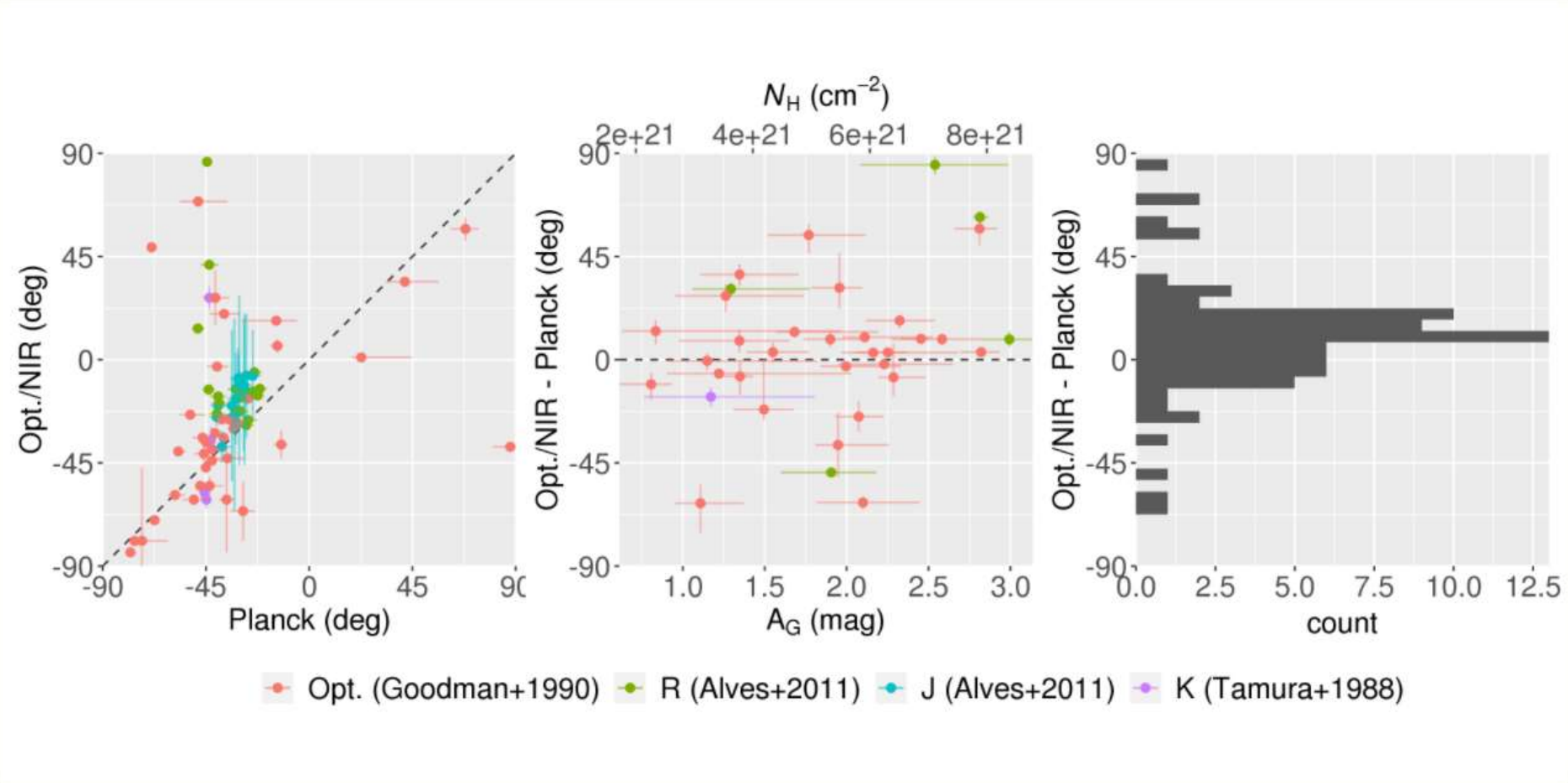
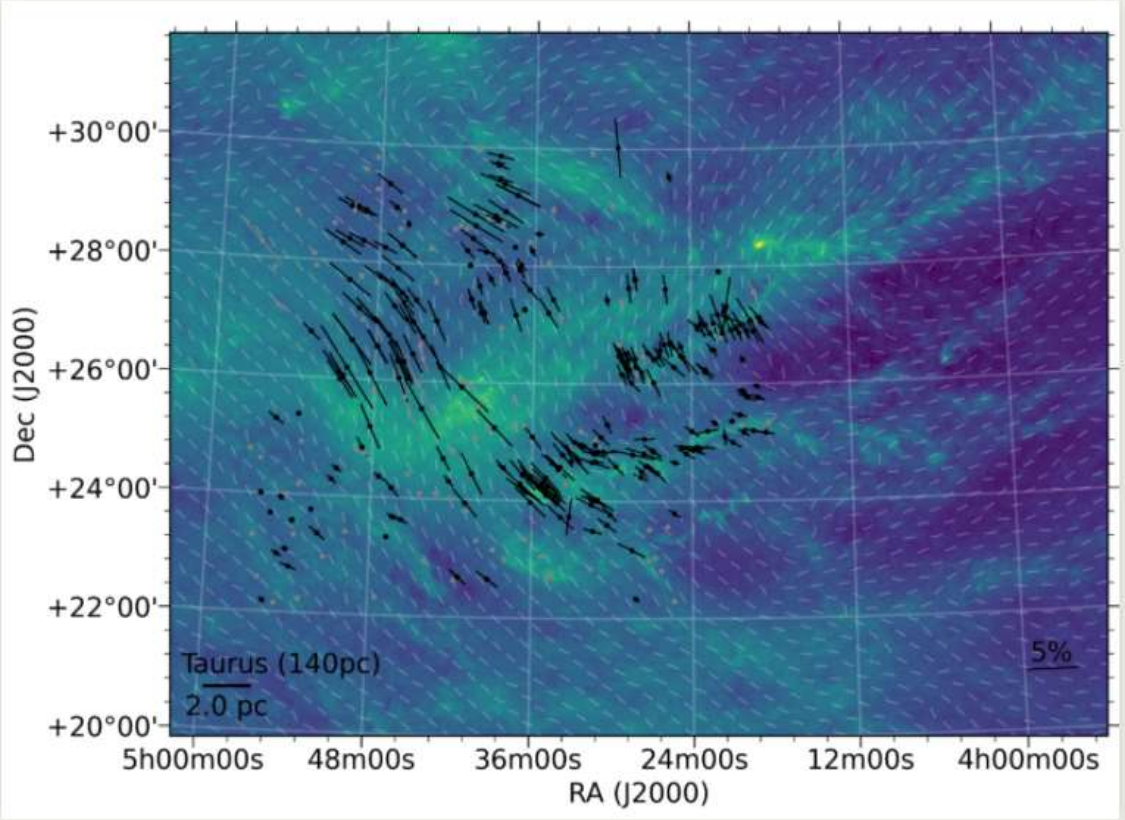
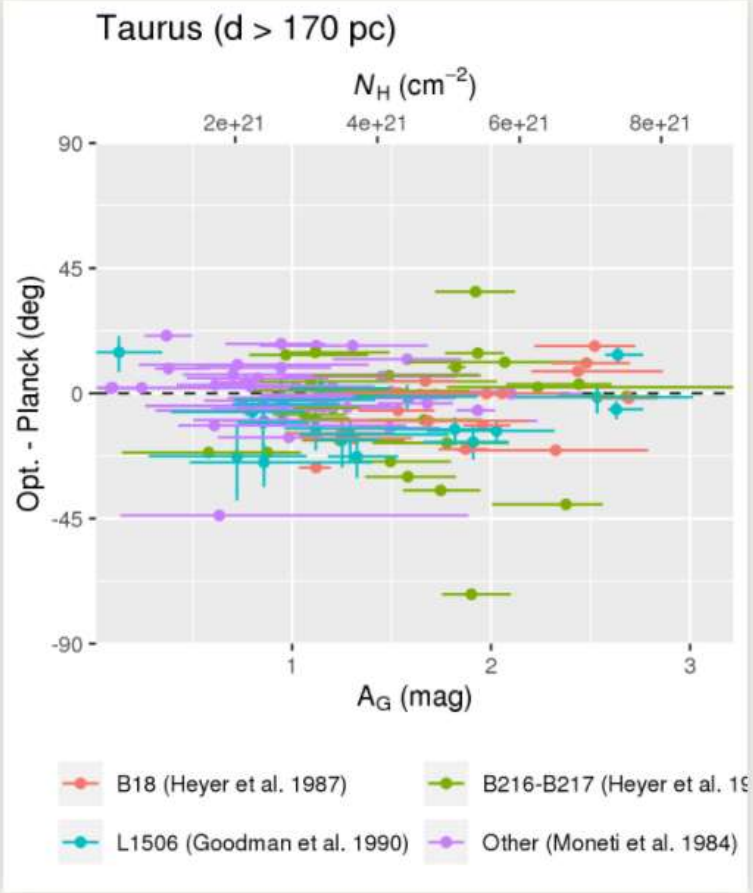
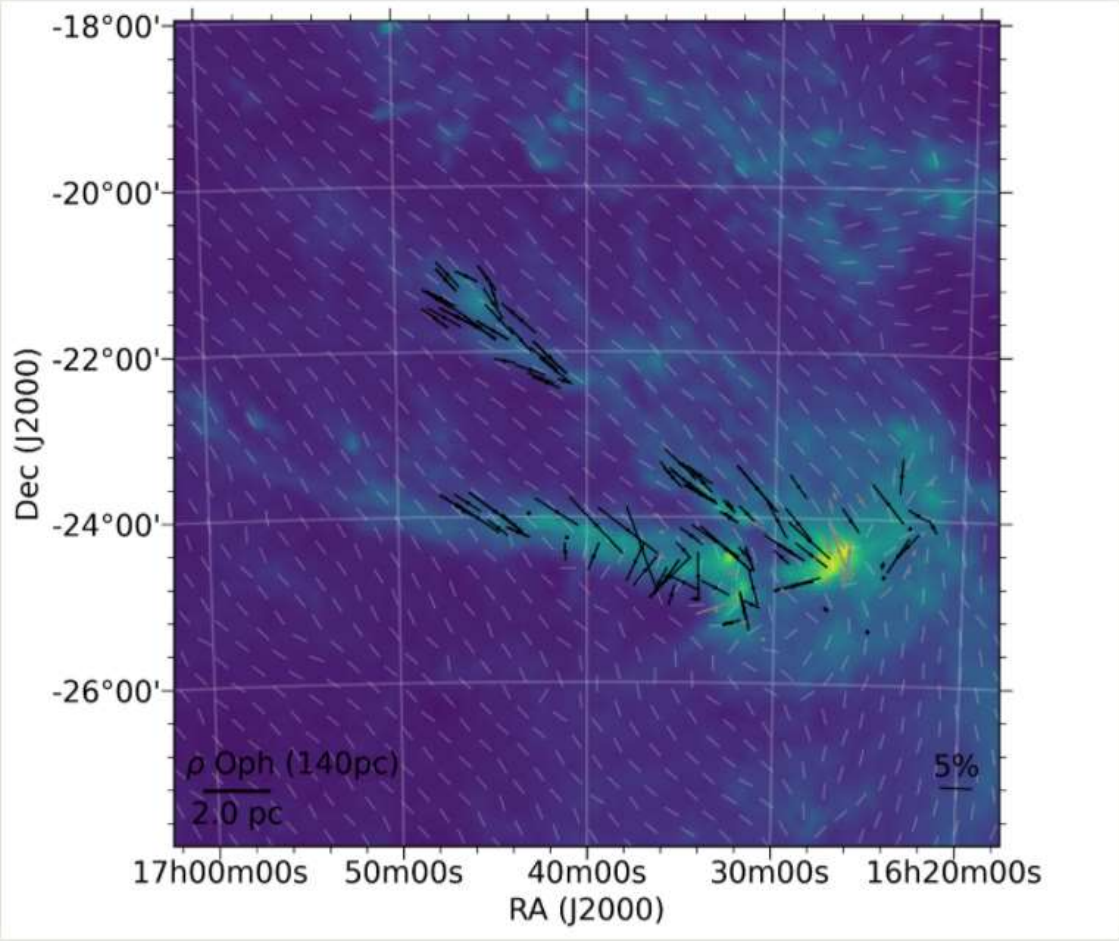


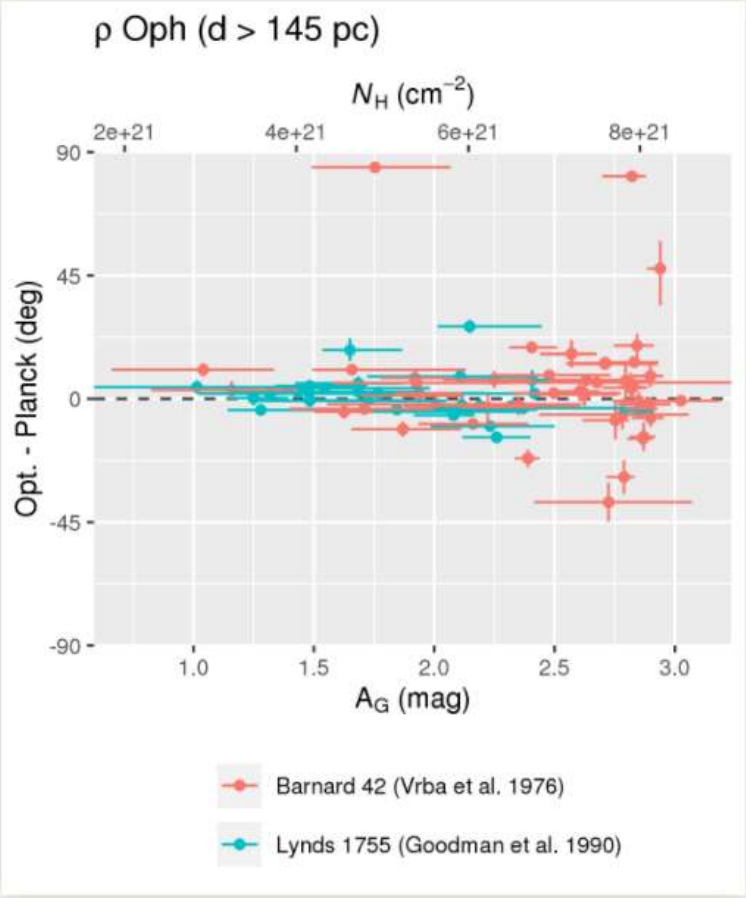
Good correlation in Taurus





Good correlation in ρ Oph



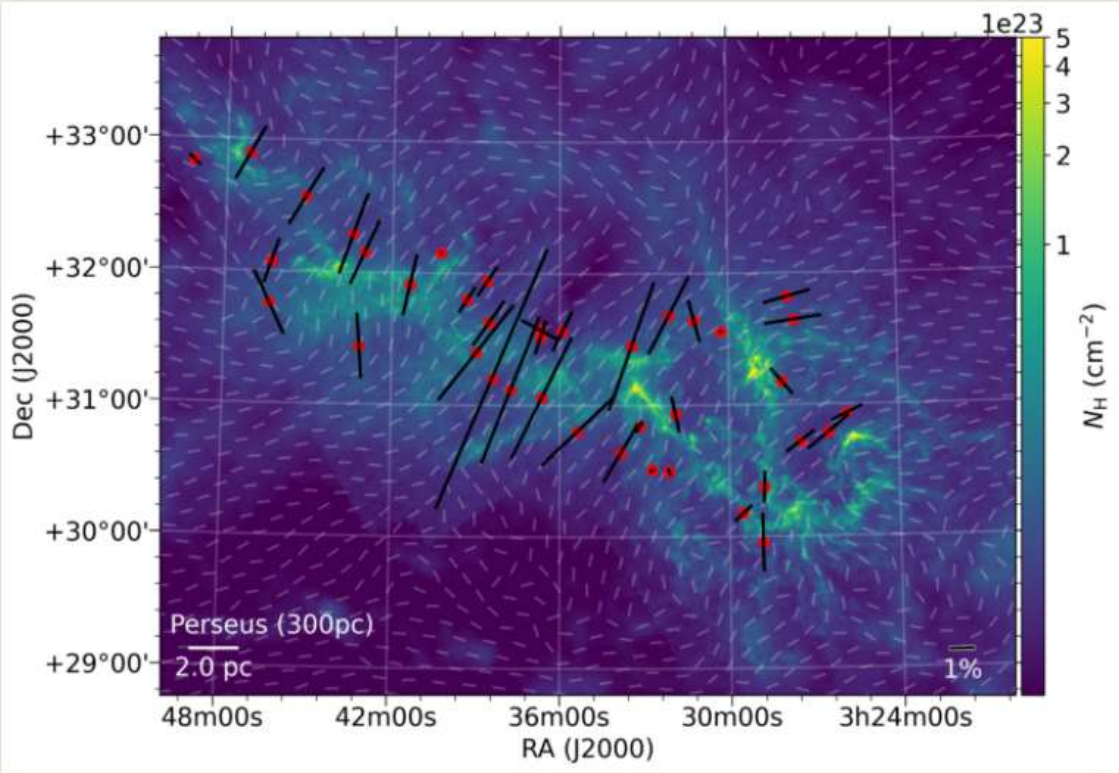


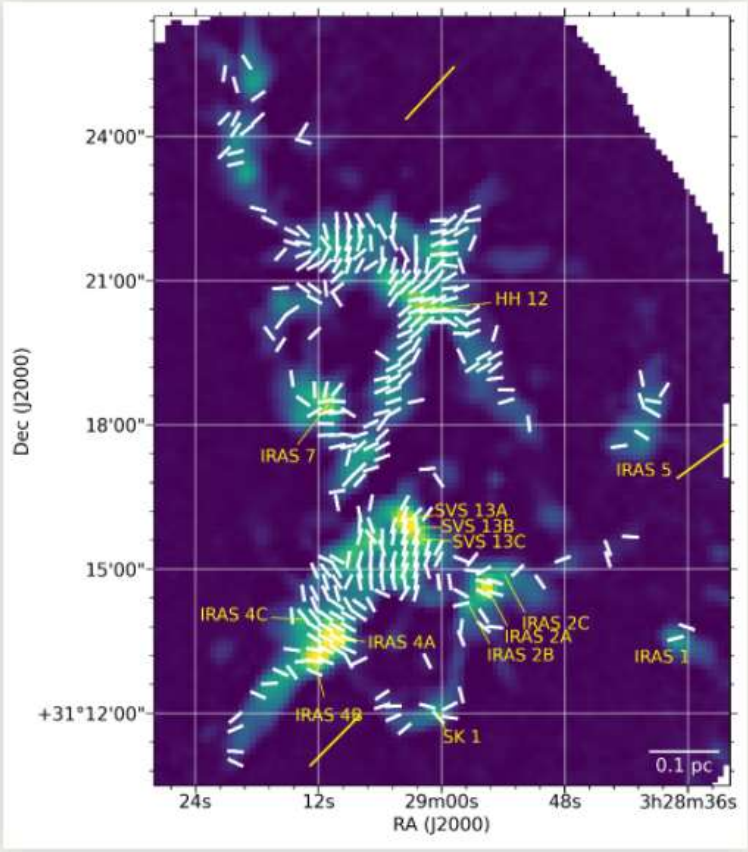
No small scale structures!?

Stellar polarimetry is aligned with Planck *B*-field.

→ **NO small scale structures** below 1 pc (Planck resolution)!?

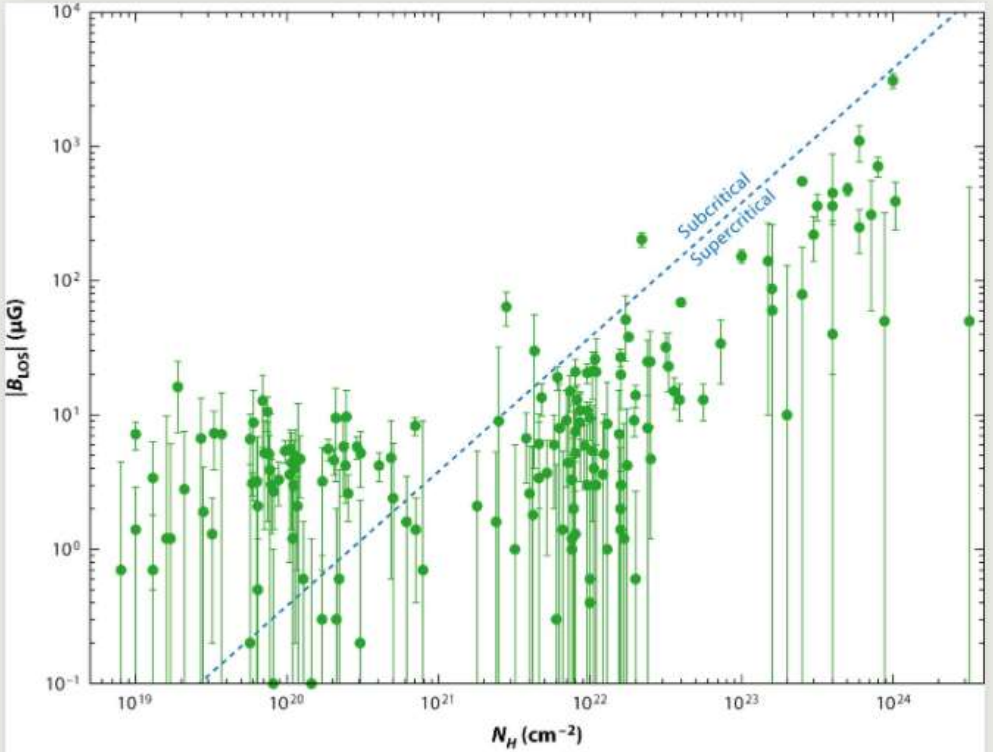
cf. B-field structure is locally (< 1 pc) perpendicular to ISM filaments





ISM B-field Evolution : a Working Hypothesis

- $N_{\rm H} \lesssim 10^{22}\ ({\rm cm}^{-2})$: no small scale structures $\lesssim 1$ pc
- $N_{\rm H} \sim 10^{23}\ ({\rm cm}^{-2})$: <u>formation site of filaments!!</u>
- $N_{\rm H} \gtrsim 10^{24}\ ({\rm cm}^{-2})$: perpendicular to local filaments



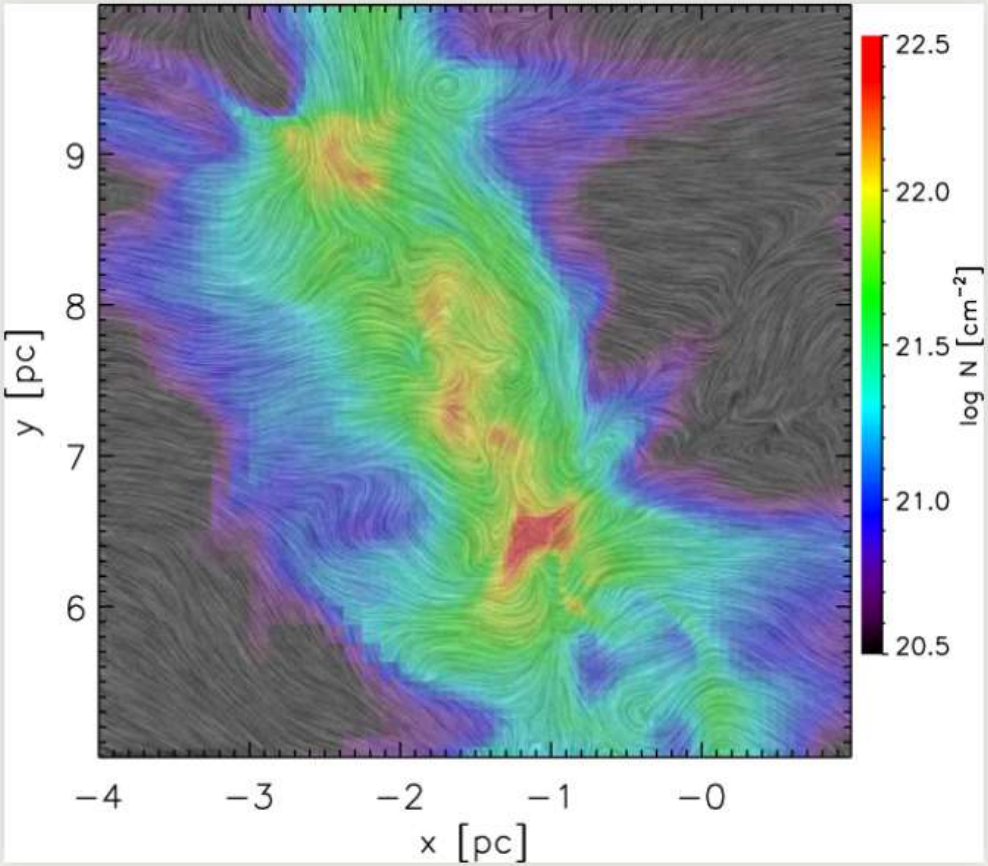
Crutcher RM. 2012.
Annu. Rev. Astron. Astrophys. 50:29–63

ISM B-field Evolution : a Working Hypothesis

- $N_{\rm H} \lesssim 10^{22}\ ({\rm cm}^{-2})$: no small scale structures $\lesssim 1$ pc
- $N_{\rm H} \sim 10^{23}\ ({\rm cm}^{-2})$: formation site of filaments!!
  - however, lack of observations...
- $N_{\rm H} \gtrsim 10^{24}\ ({\rm cm}^{-2})$: perpendicular to local filaments
- SOFIA, stellar pol., balloons...
  - can fill the obs. gap around $N_{\rm H} \sim 10^{23}\ ({\rm cm}^{-2})$!?

GMC formation history (to be) traced by Planck B-field

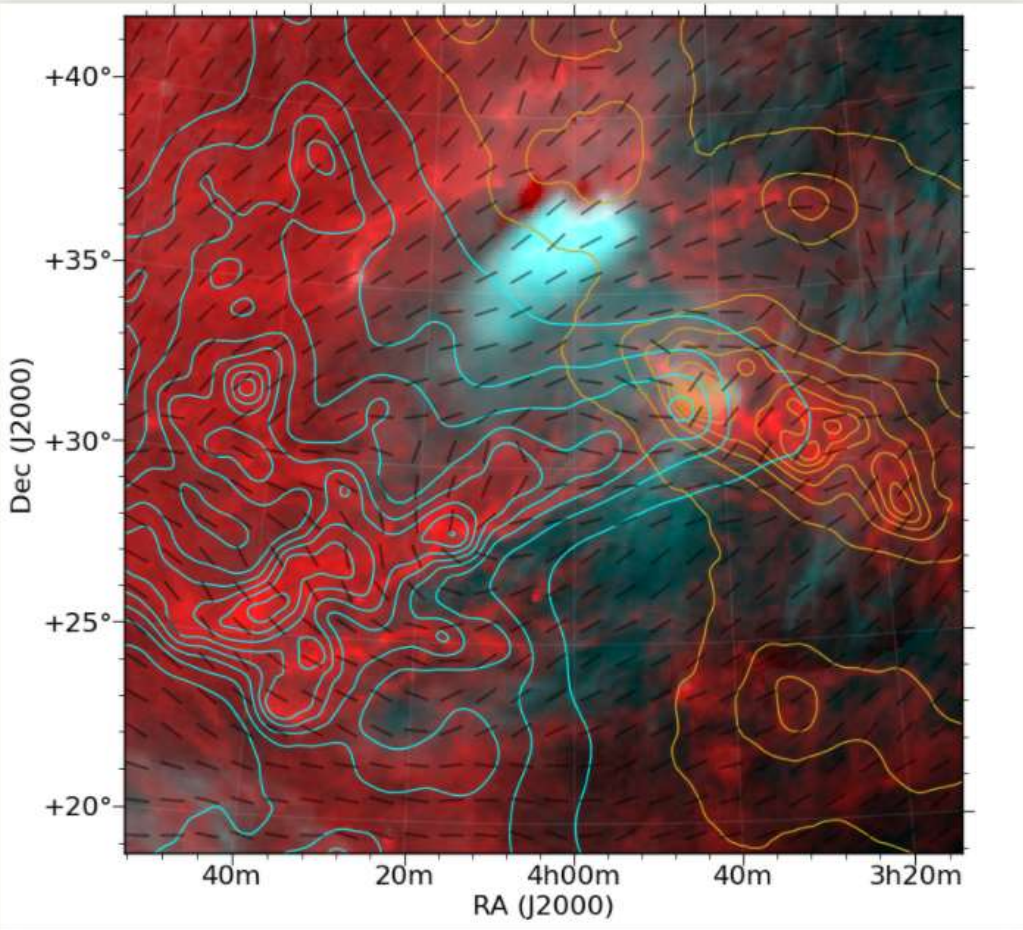
- multiple ISM compression histories should be imprinted in the B-field structure around the GMC

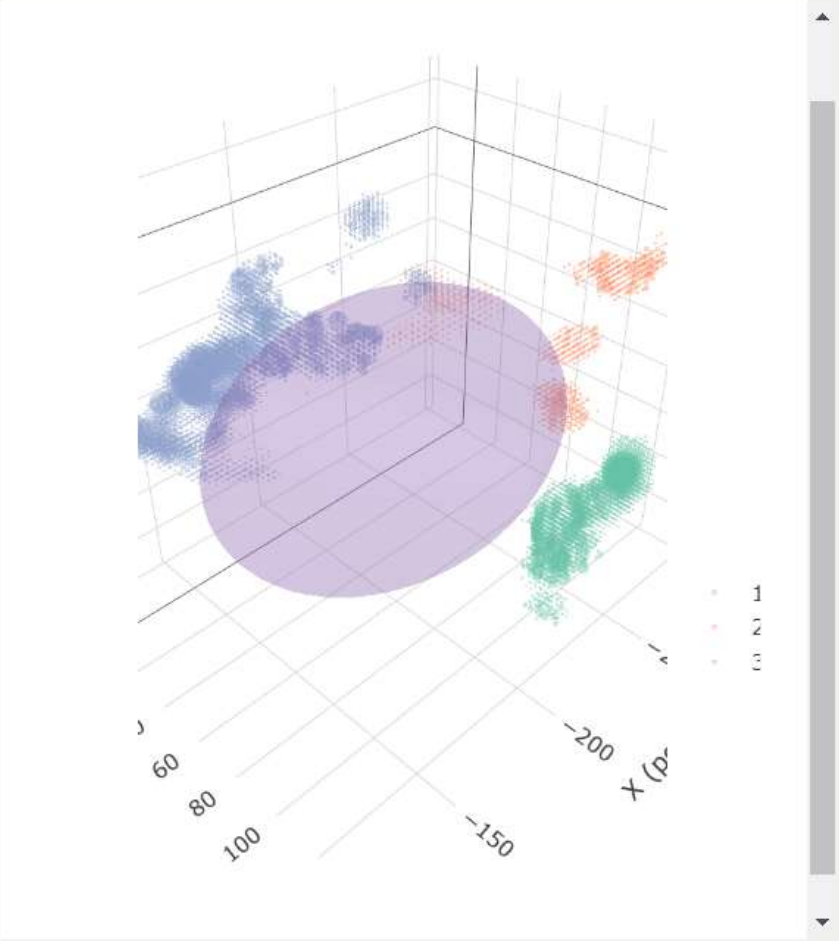


Gómez+2018

Disentangle the 3D *B*-field structure

- combination of Gaia & stellar pol. is a useful tool





Doi+ in prep.

ISM B-field Evolution : a Working Hypothesis

- $N_{\rm H} \lesssim 10^{22}\ ({\rm cm}^{-2})$: no small scale structures $\lesssim 1$ pc
- $N_{\rm H} \sim 10^{23}\ ({\rm cm}^{-2})$: formation site of filaments!!
- $N_{\rm H} \gtrsim 10^{24}\ ({\rm cm}^{-2})$: perpendicular to local filaments

Possible Observations/Analyses

- GMC formation history traced by Planck B-field
- 3D structure traced by Gaia & stellar pol.
- Filling the obs. gap around
  $N_{\rm H} = 10^{22} \sim 10^{23}\ ({\rm cm}^{-2})$
  - SOFIA, stellar pol., balloons...