What are we learning from the relative orientation between density structures and the magnetic field in molecular clouds?

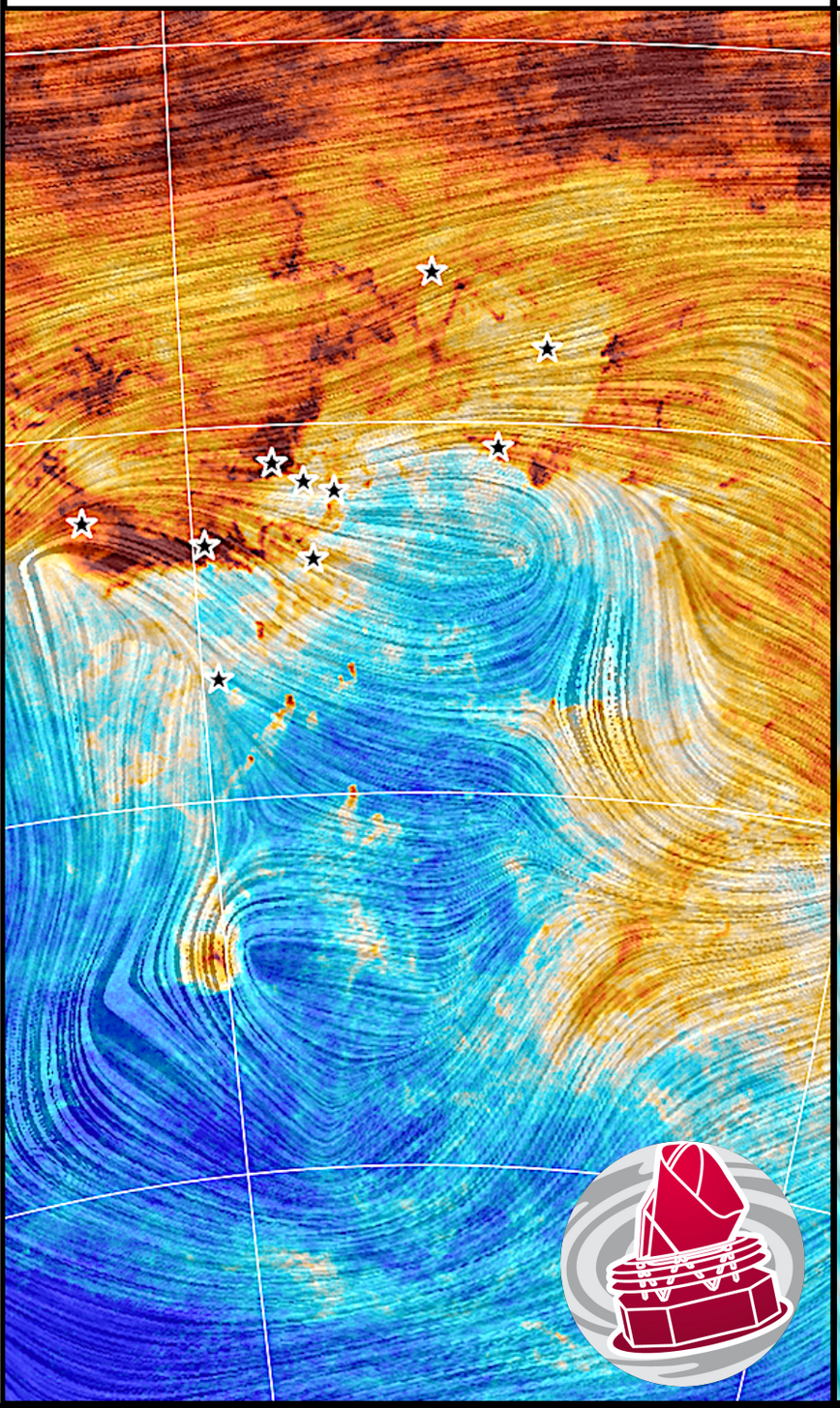
by Juan Diego Soler (MPIA, Heidelberg)

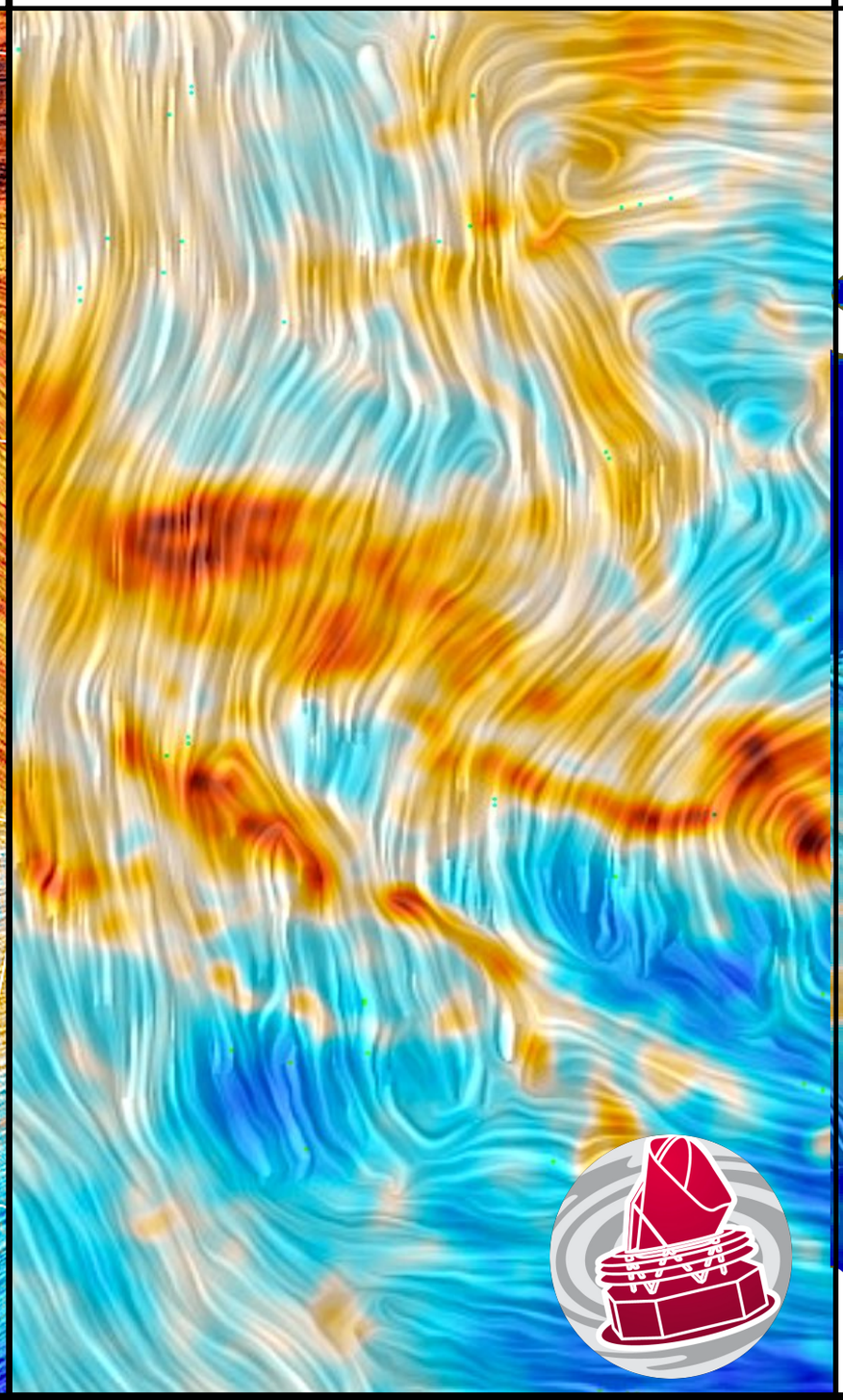
Tracing the Flow: Galactic Environments and the Formation of Massive Stars
July 2-6, 2018

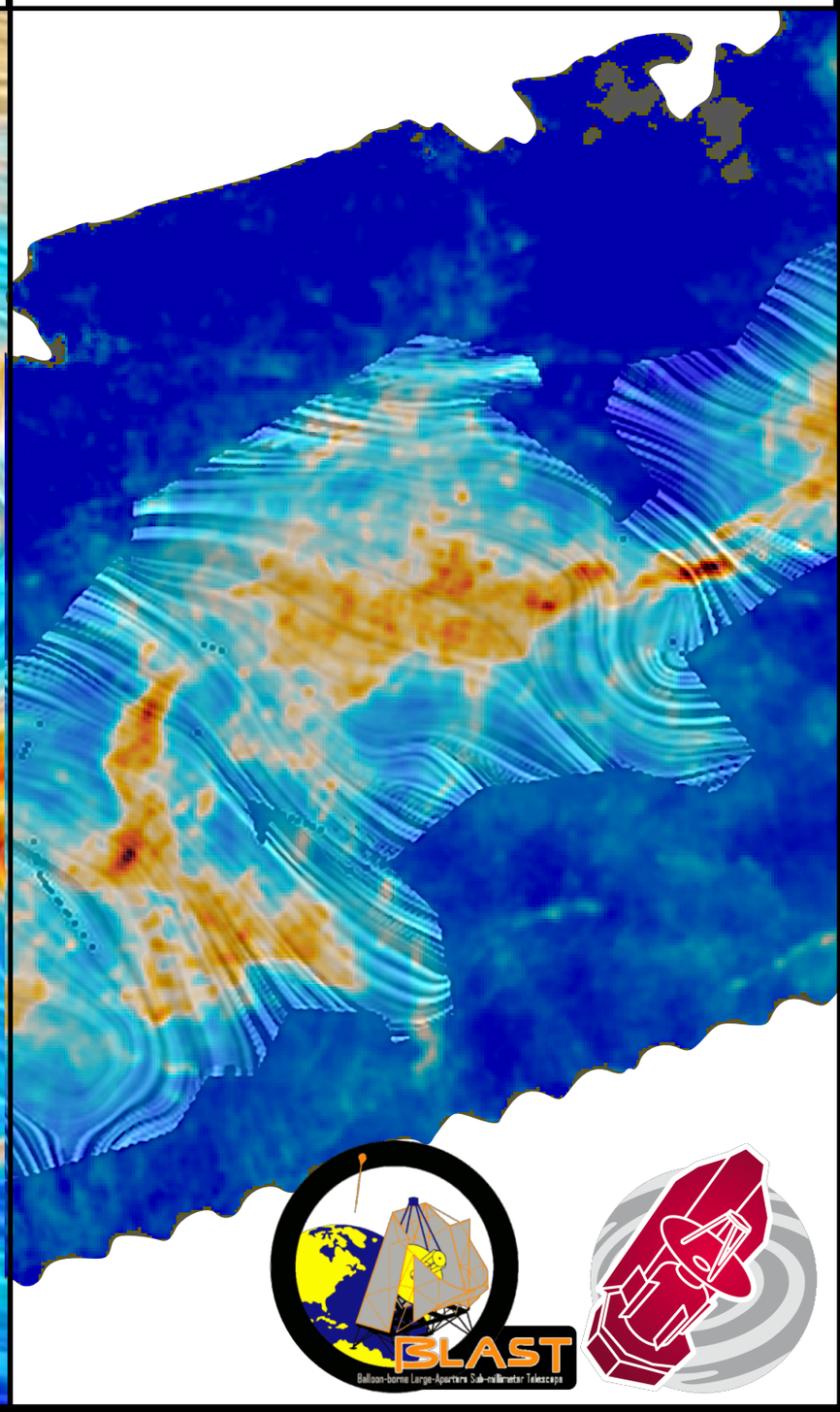
Three moments in the life of a molecular cloud

Soler J.D. & P. Hennebelle, A&A 607A (2017) 2S

Soler, Bracco, & Pon. 2017. A&A 609L (2018) 3S.	Planck intermediate results. XXXV. A&A, 586 (2016) A138	Soler and the BLASTPol Collaboration A&A 603A (2017) 64S







with the collaboration of

PLANCK
F. Boulanger, M.-A. Miville-Deschênes, P. Martin, M. Alves, D. Arzoumanian, A. Bracco, T. Ghosh, F. Levrier, E. Falgarone, K. Ferrière, and the Planck collaboration.

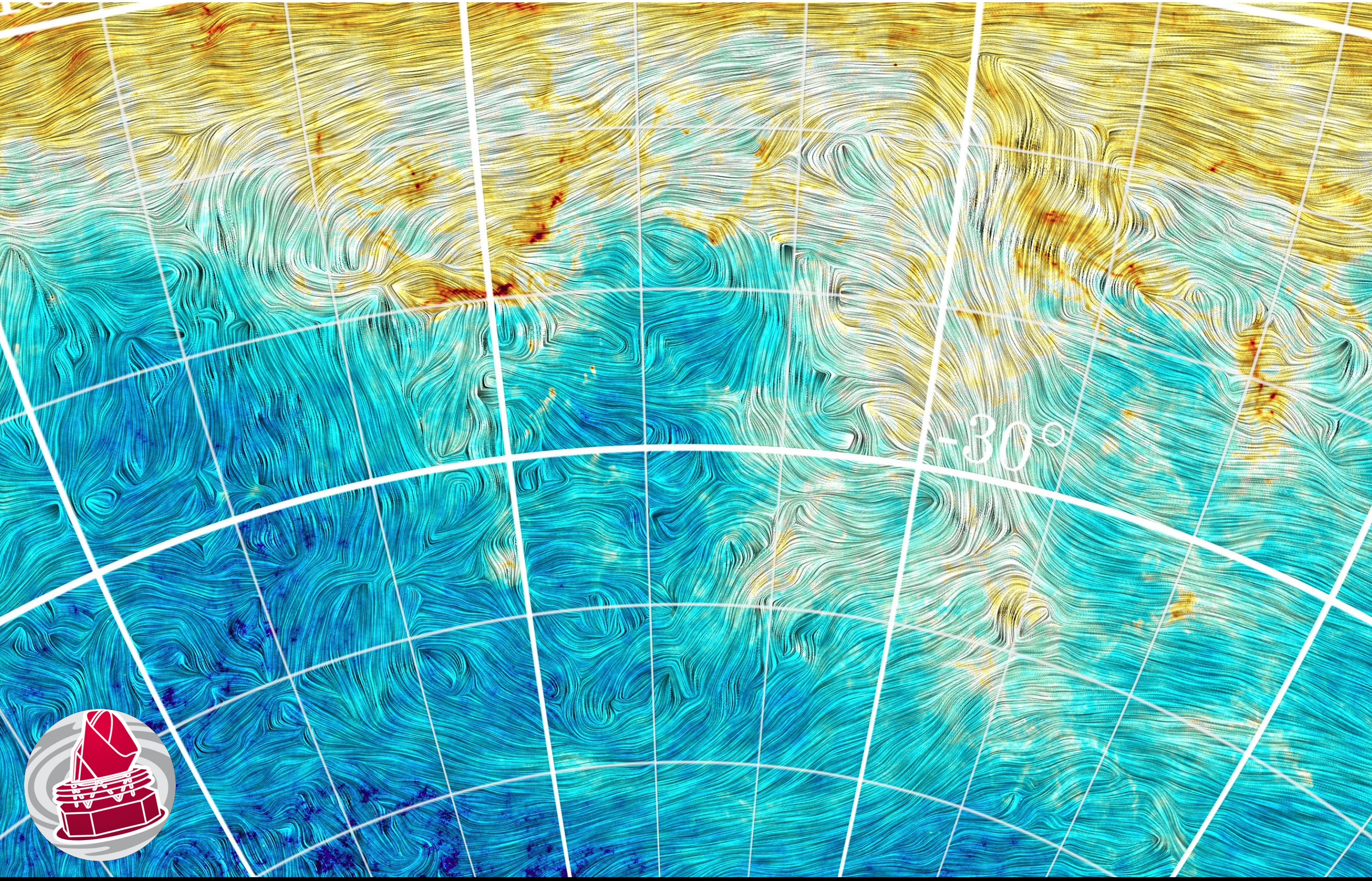
FRIGG
P. Hennebelle, S. Geen, E. Ntormousi

BLASTPol
P. Ade, E. Angilè, P. Ashton, S. Benton, M. Devlin, B. Dober, **L. Fissel**, Y. Fukui, N. Galitzki, N. Gandilo, J. Klein, Z.-Y. Li, A. Korotkov, P. Martin, T. Matthews, L. Moncelsi, B. Netterfield, G. Novak, E. Pascale, F. Poidevin, F. Santos, G. Savini, D. Scott, J.A. Shariff, N. Thomas, C. Tucker, G. Tucker, D. Ward-Thompson

THOR
H. Beuther, Y. Wang, M. Rugel, et al.

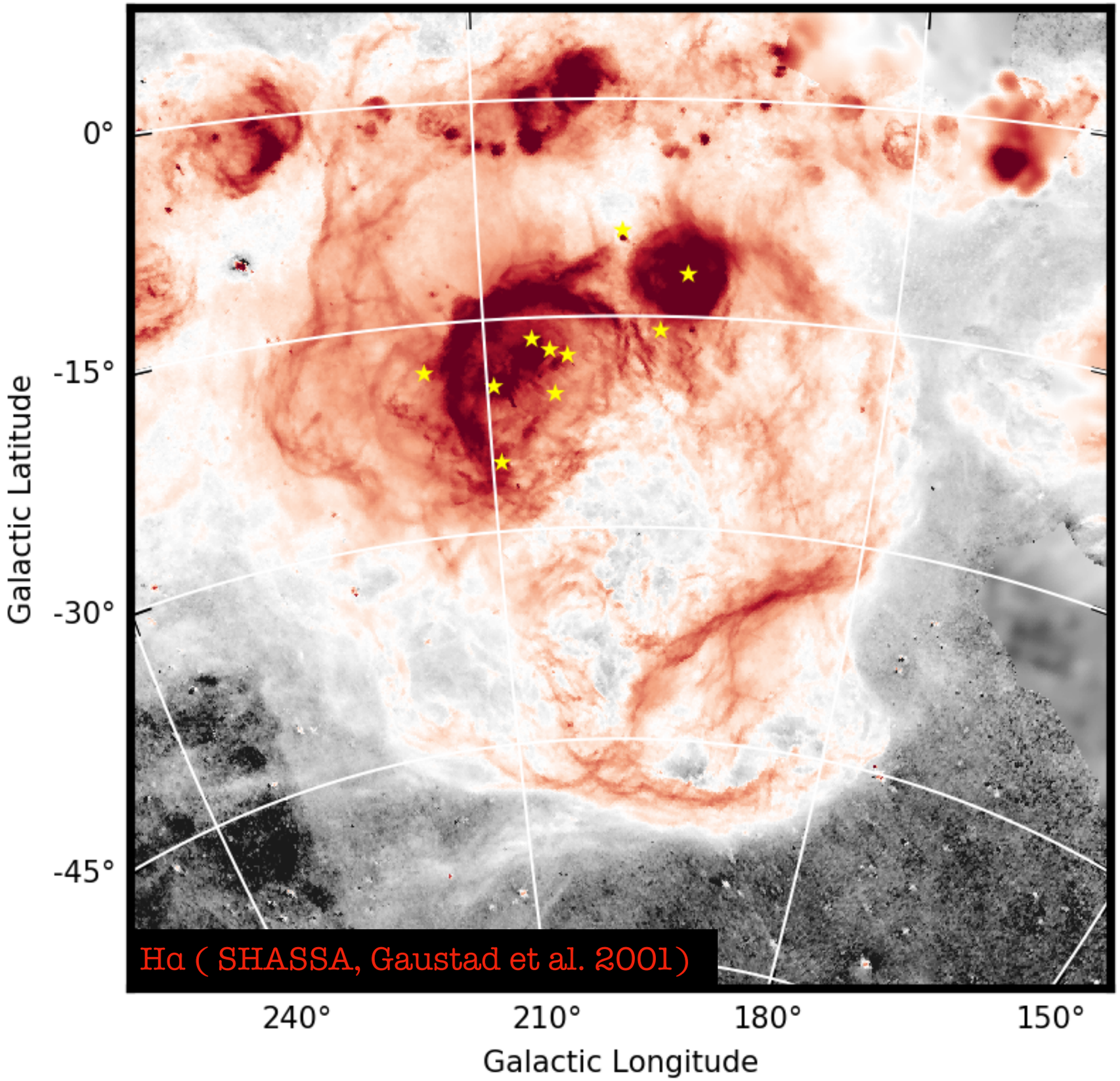
Magnetic field in the Orion-Eridanus superbubble

Soler, Bracco, & Pon, A&A 609L (2018) 3S



H-alpha towards the Orion-Eridanus superbubble

Heiles 1976; Reynolds & Ogden 1979; Heiles et al. 1999; Ochsendorf et al. 2015; Pon et al. 2016



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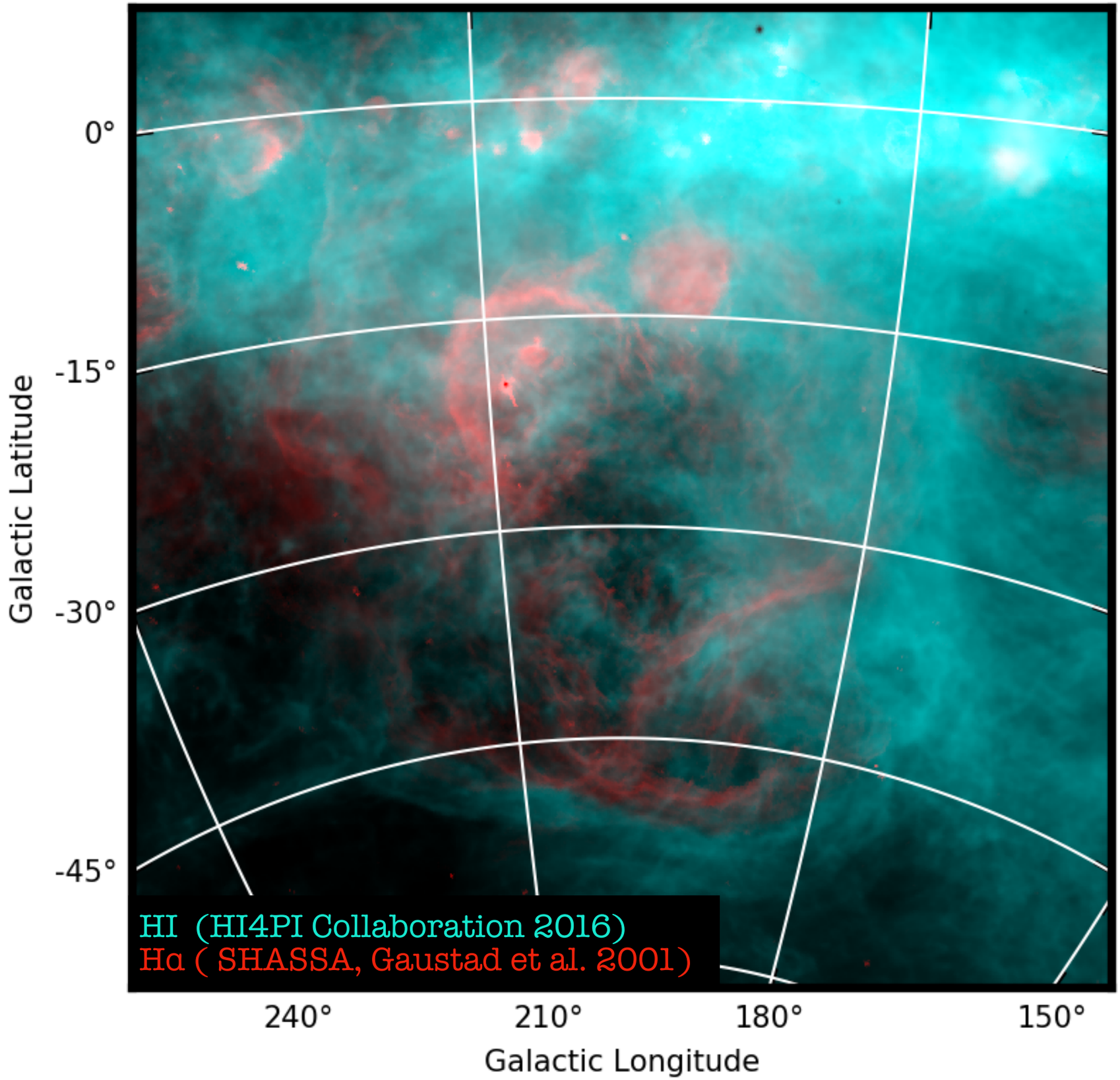

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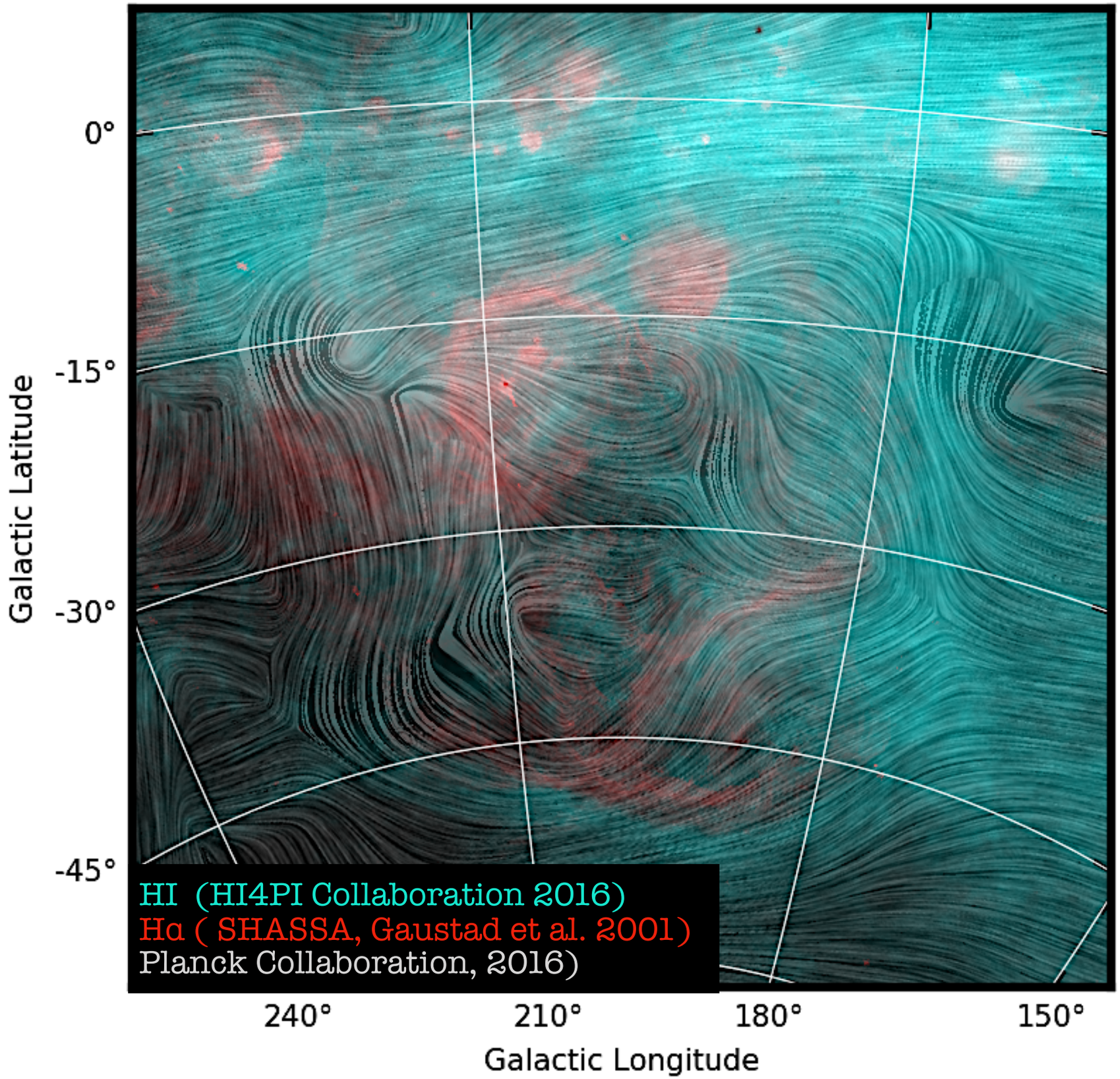

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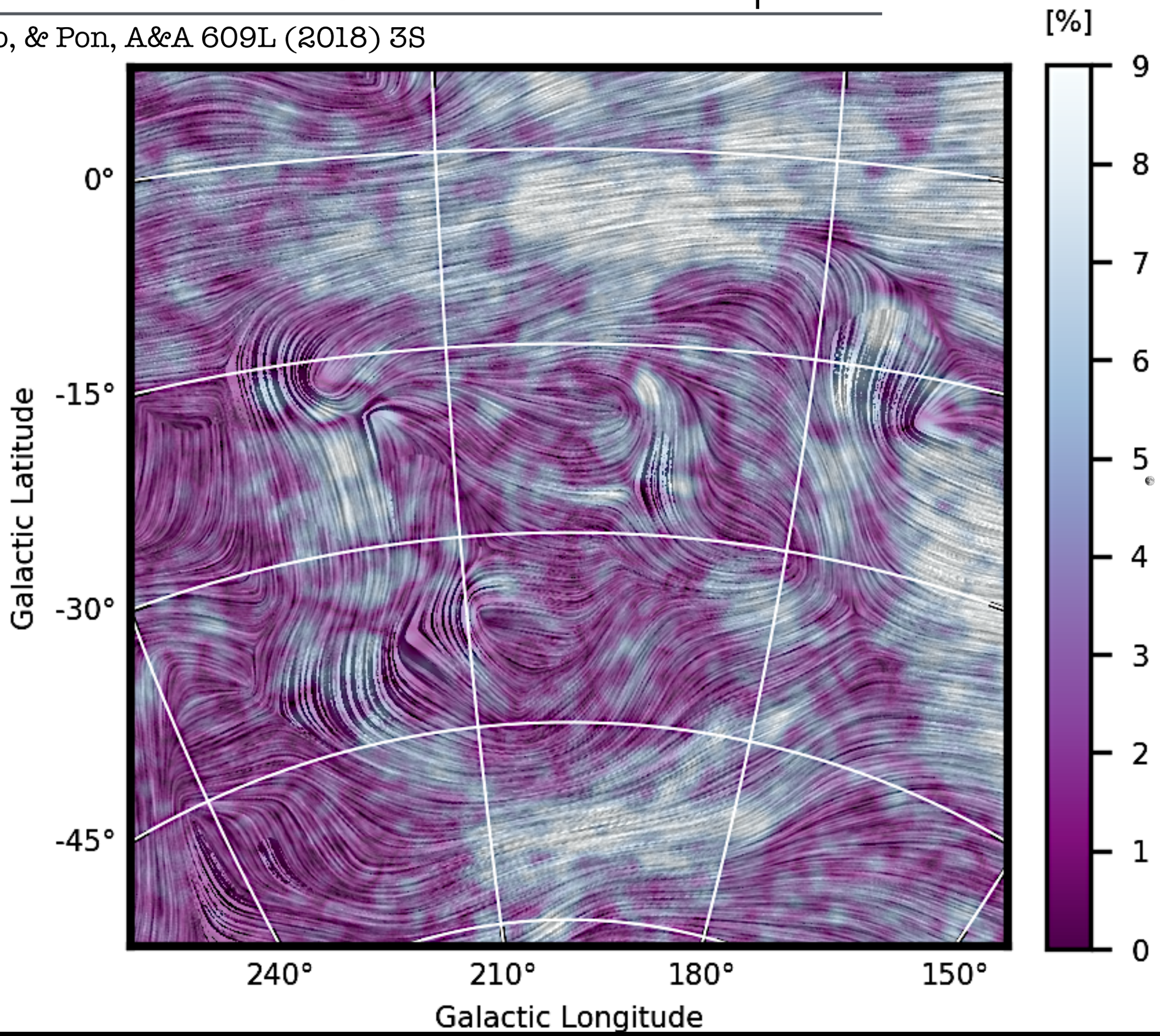
Soler, Bracco, & Pon, A&A 609L (2018) 3S



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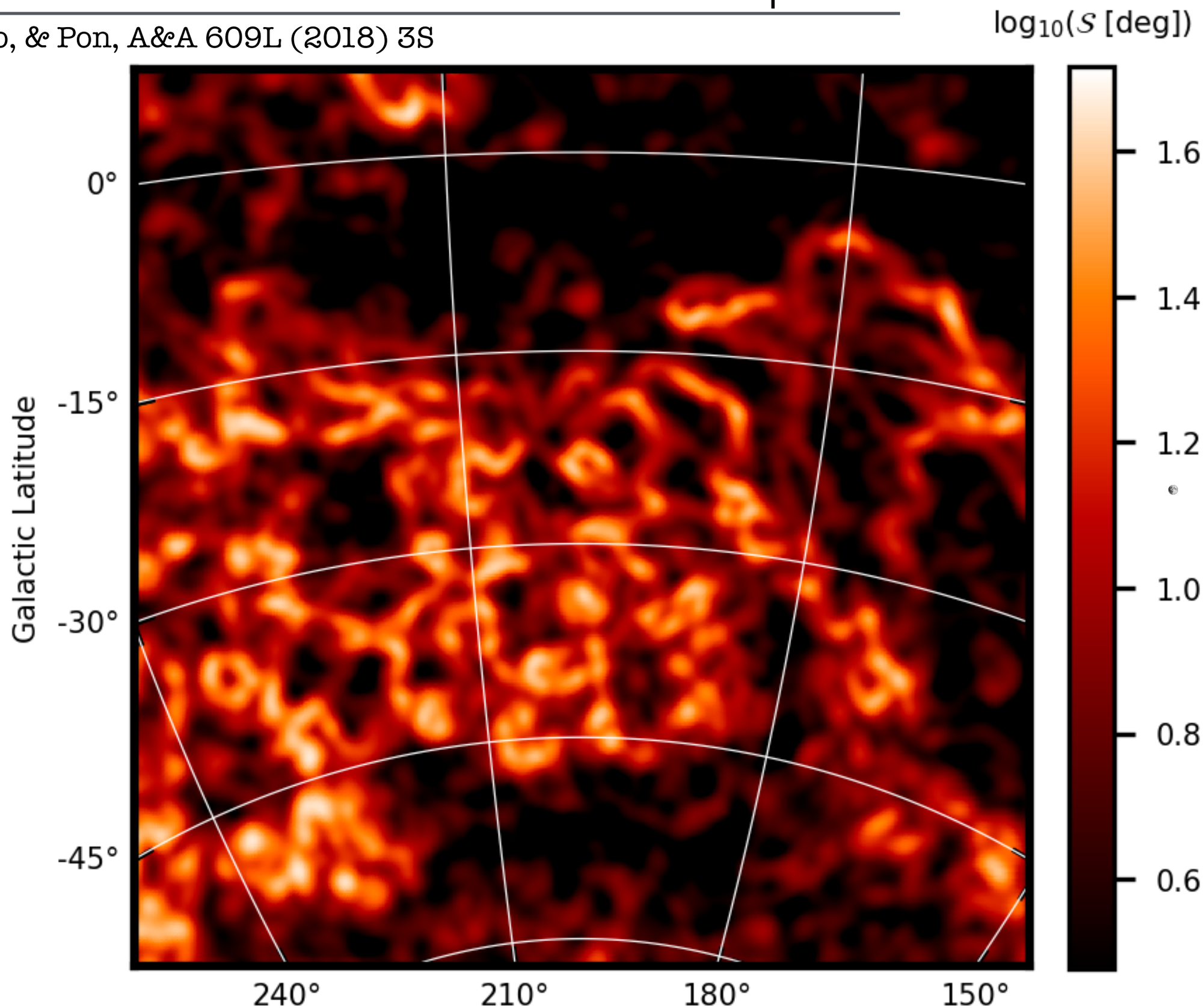
Soler, Bracco, & Pon, A&A 609L (2018) 3S



Magnetic field in the Orion-Eridanus superbubble

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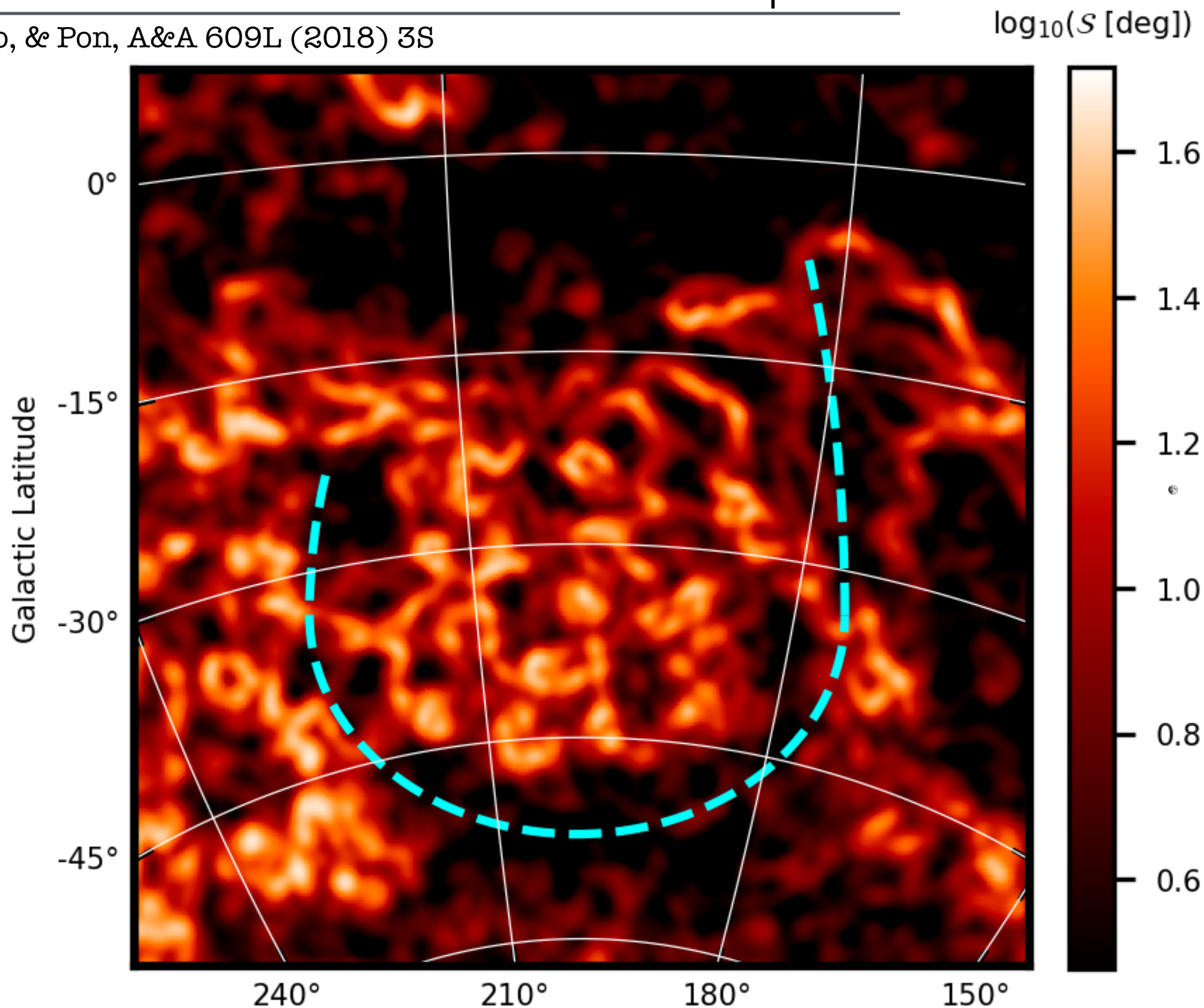

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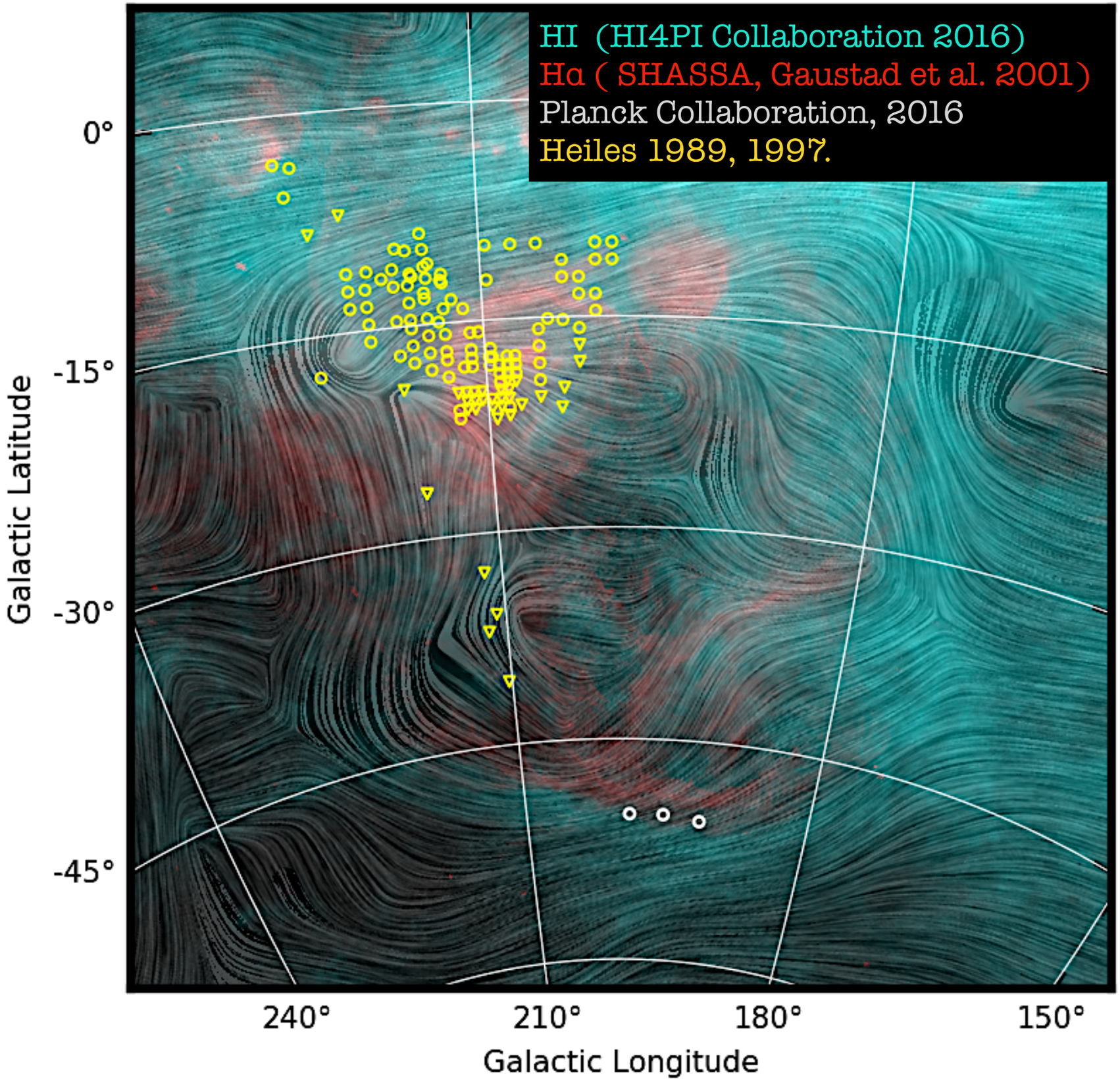
Soler, Bracco, & Pon, A&A 609L (2018) 3S



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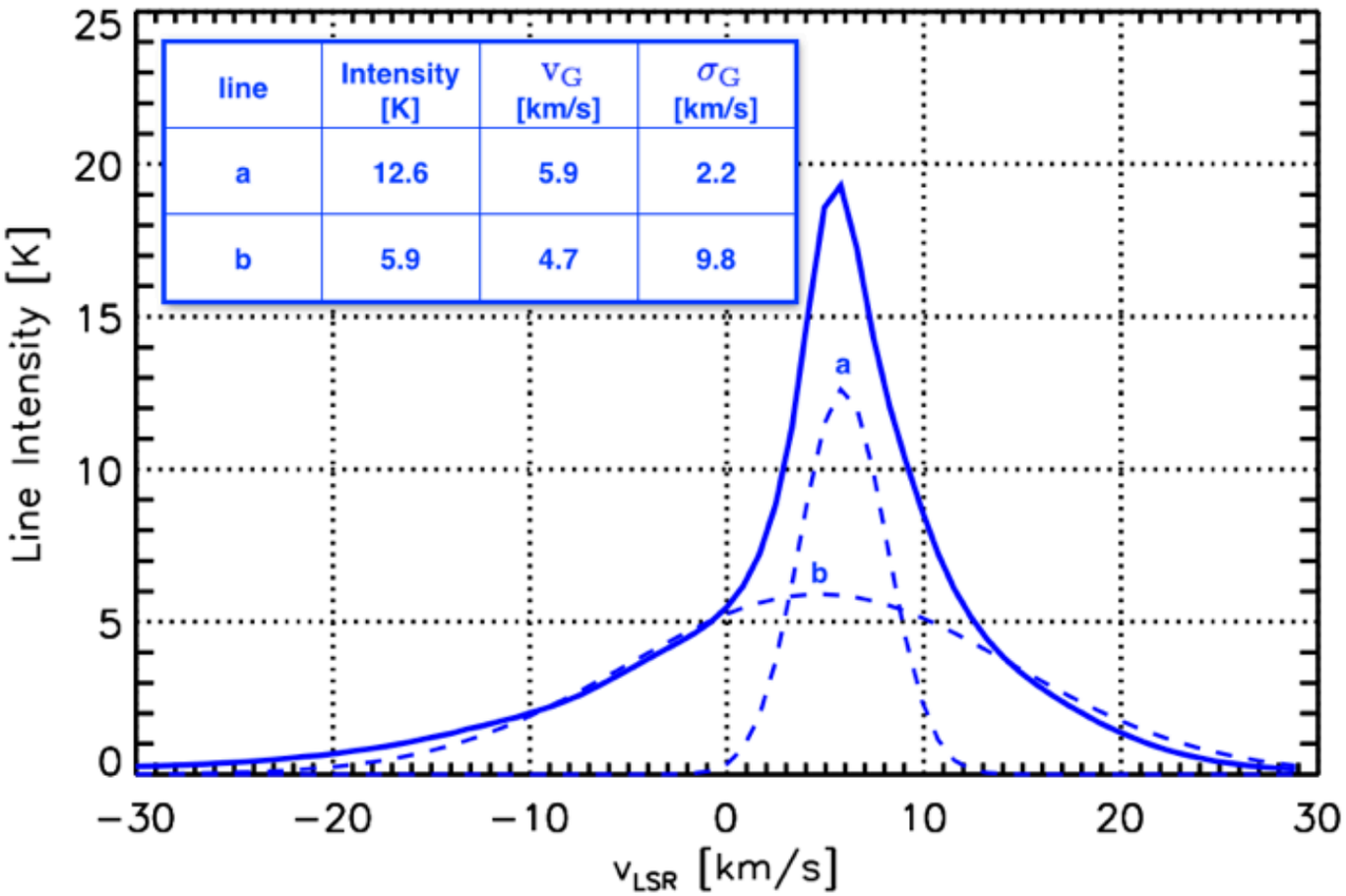


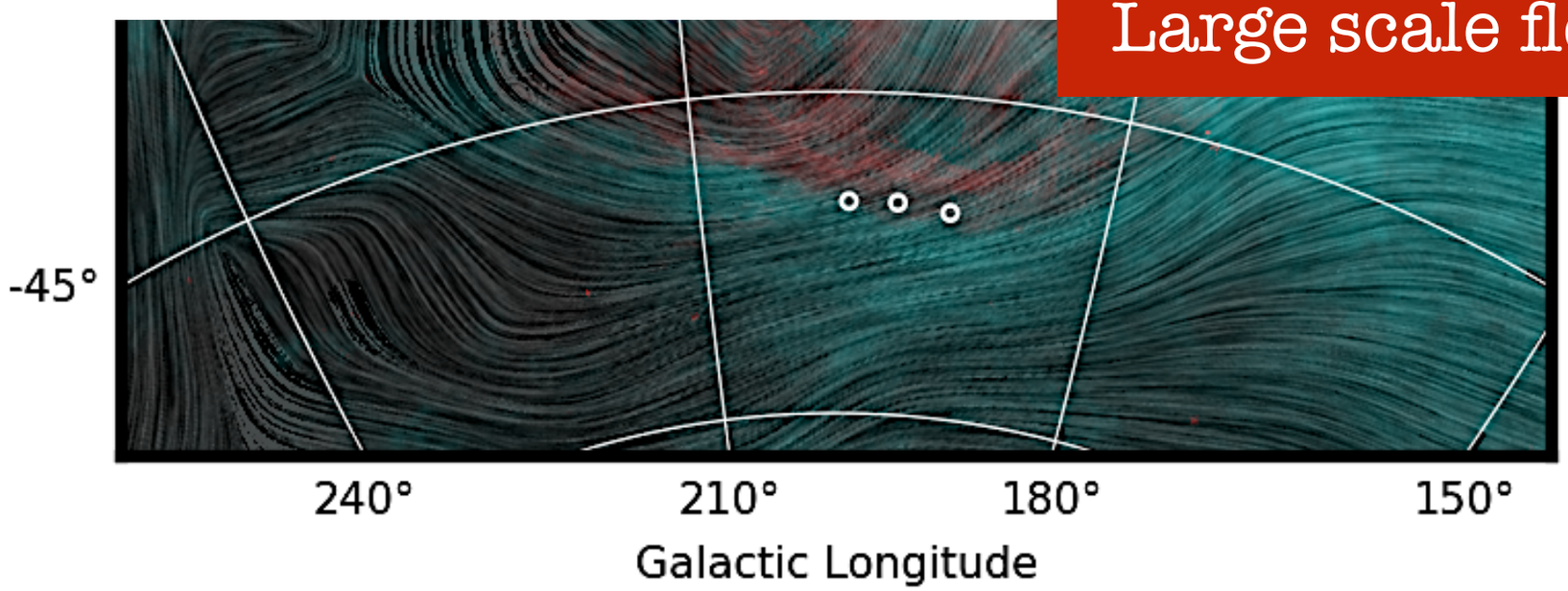
line	Intensity [K]	v_G [km/s]	σ_G [km/s]
a	12.6	5.9	2.2
b	5.9	4.7	9.8

$B_\perp^{DCF}$ [μG]	$B_\parallel^{b}$ [μG]	$v_A^{c,d}$ [km s^{-1}]
87±9	−6.6 ± 0.6	19±4
55±6	−11.8 ± 1.3	17±4
25±3	−9.5 ± 0.7	7±2

Expansion velocity 15 to 23 km s^{-1}

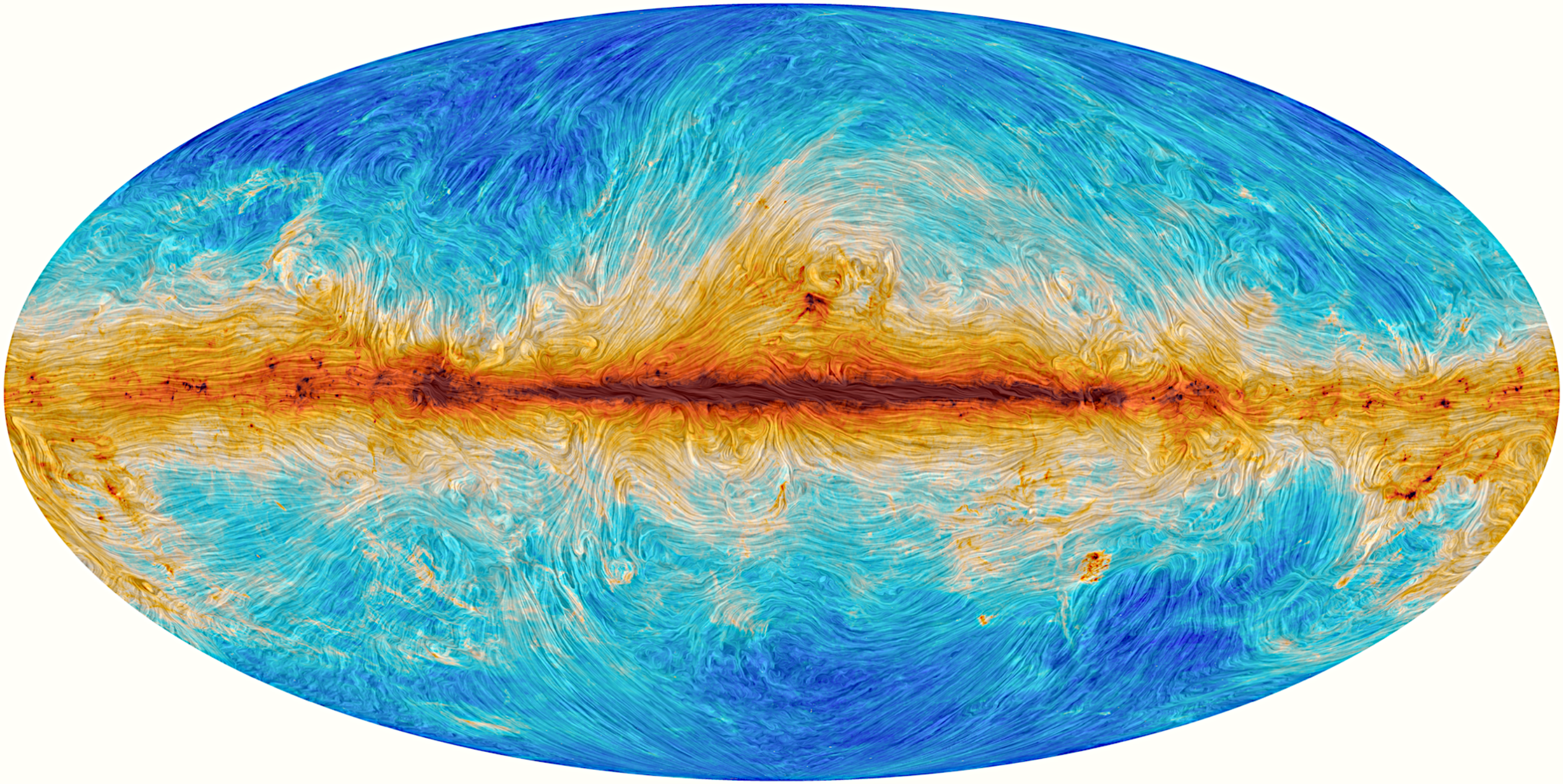
Reynolds, R. J. & Ogden, P. M. 1979, ApJ

Turbulence 😕
Magnetic fields 🙂
Large scale flow 😀



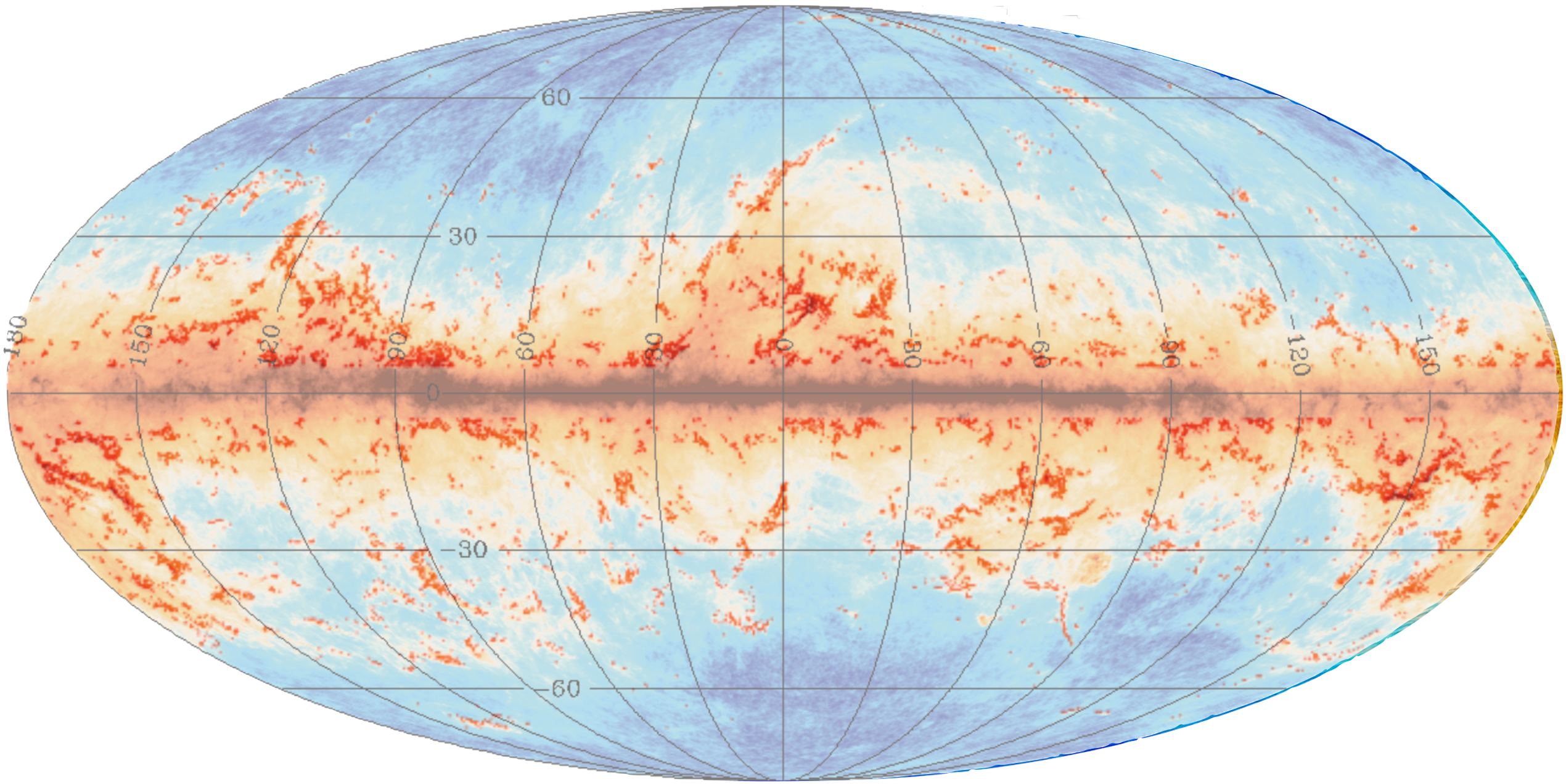
Column density and magnetic field orientation

Planck 2015 results I. A&A, 594 (2016), A1



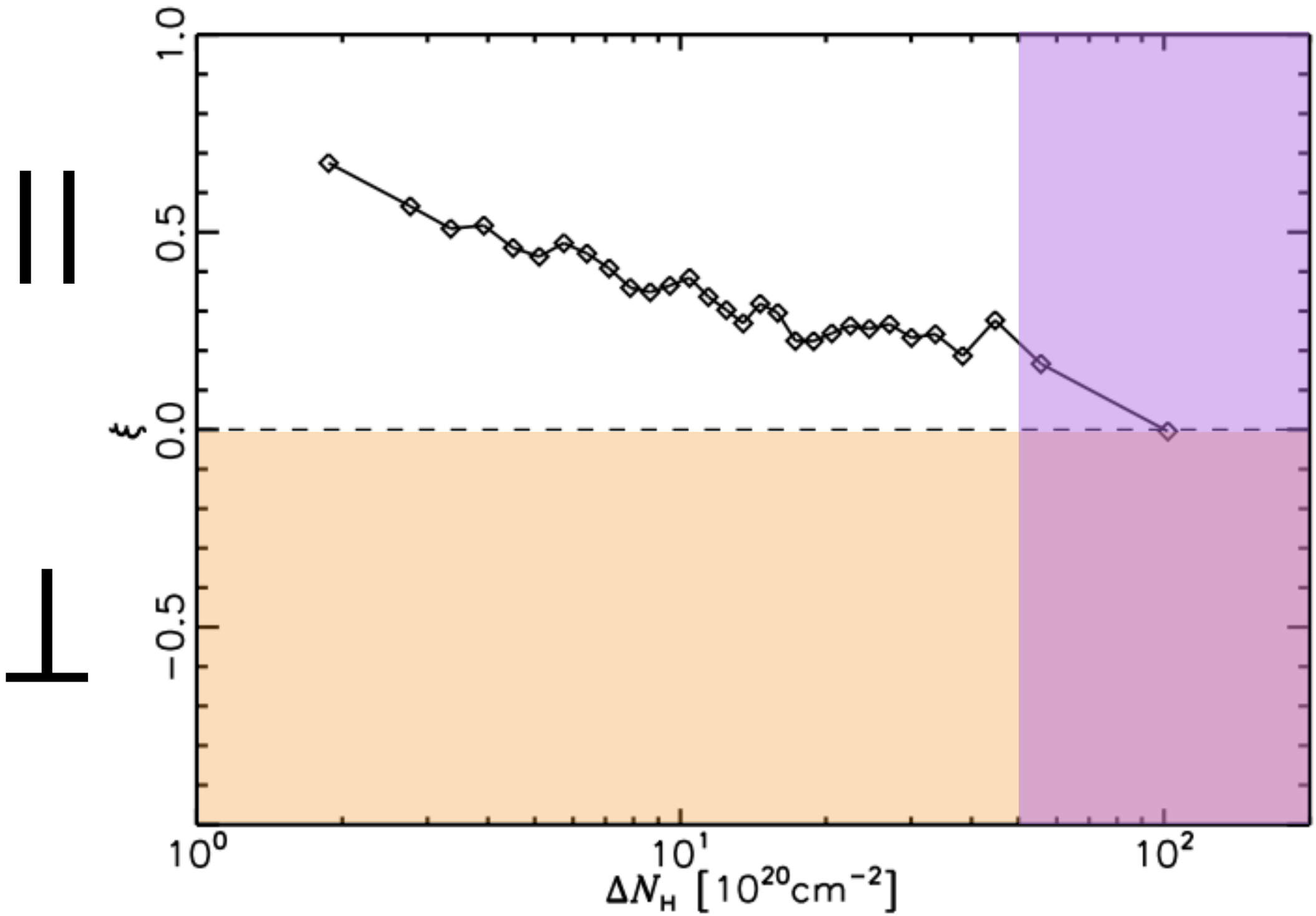
Column density and magnetic field orientation

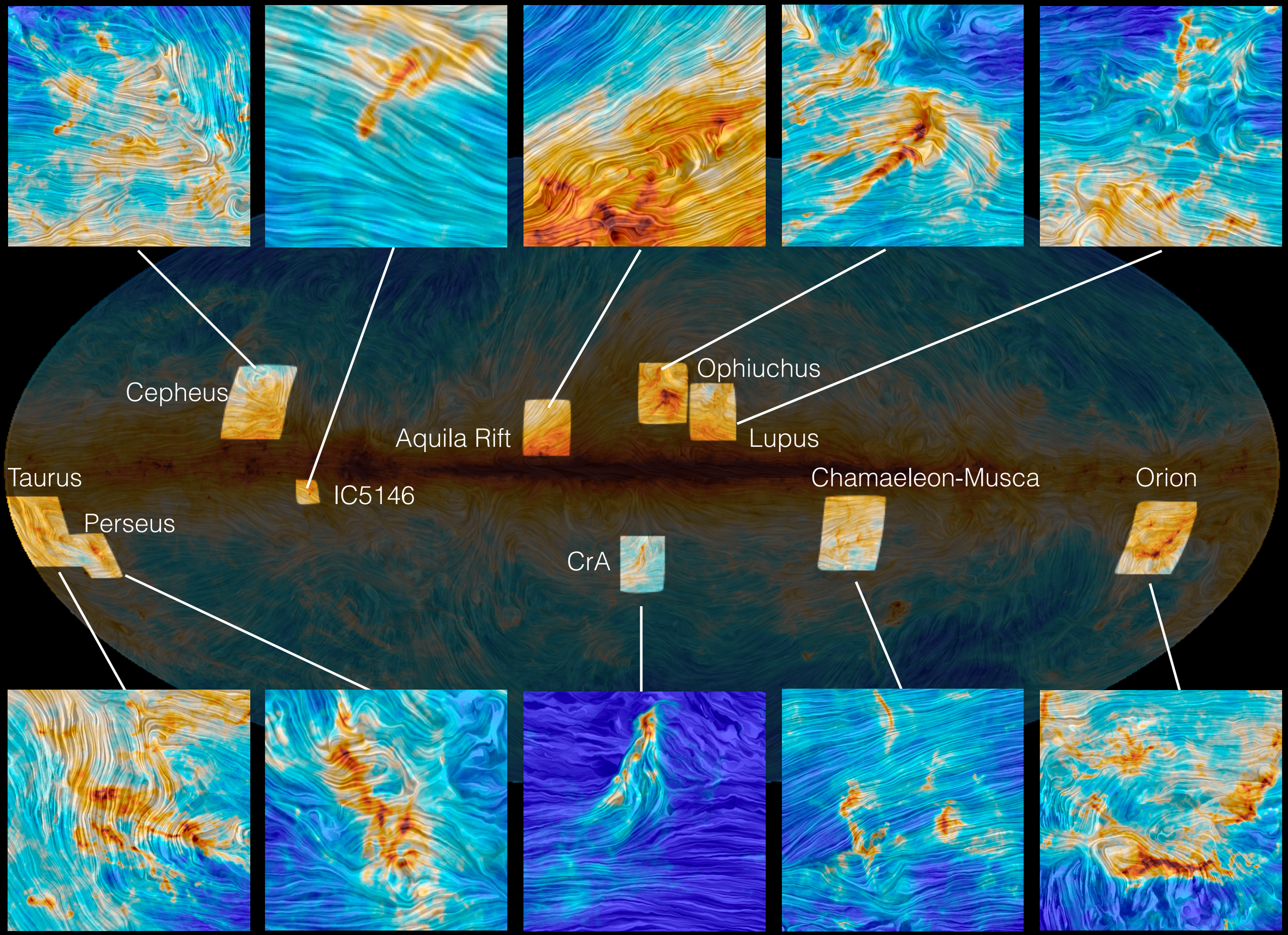
Planck XXXII. A&A, 586 (2016) A135



Relative orientation between $B_\perp$ and N_H structures

Planck XXXII. A&A, 586 (2016) A135

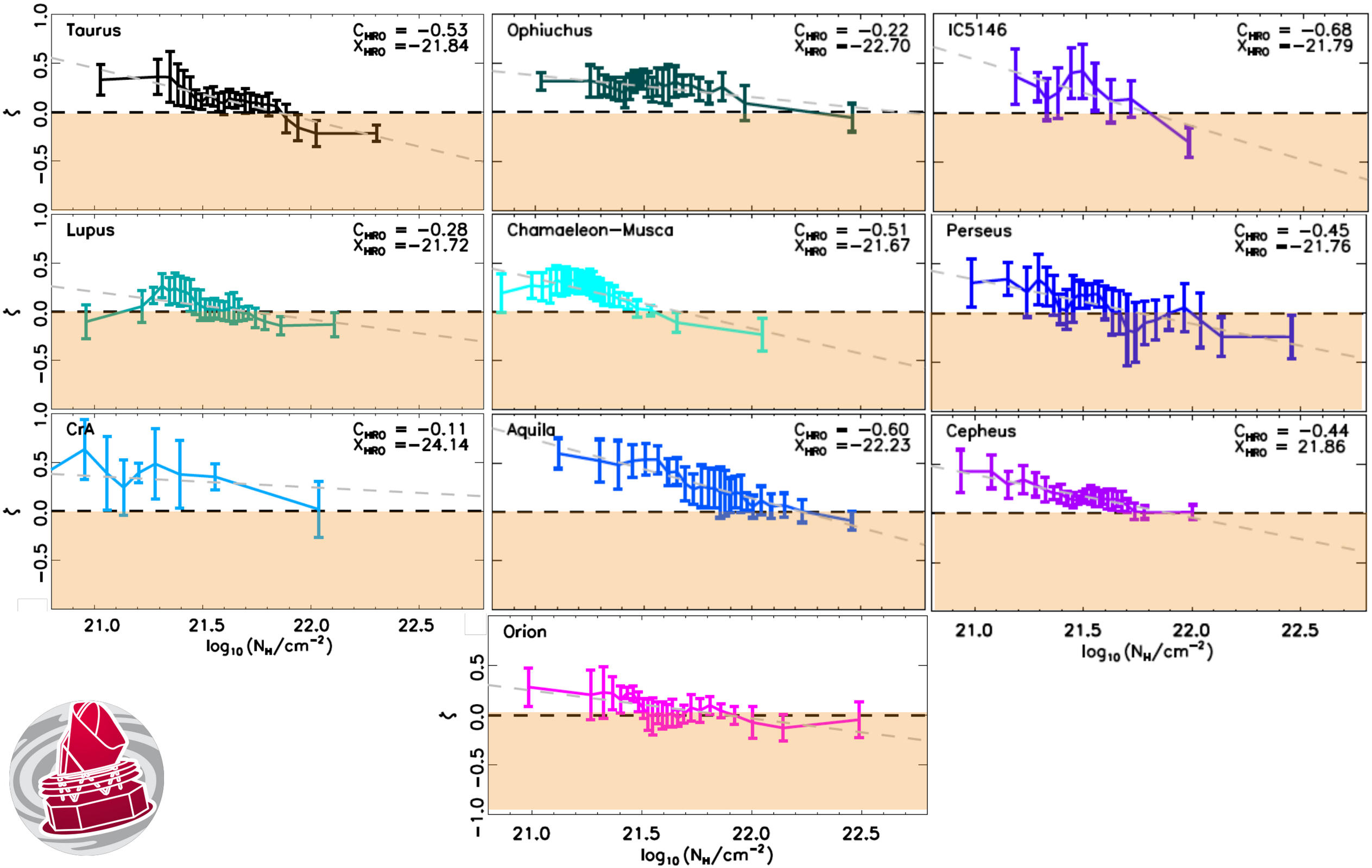




Juan D. Soler (MPIA). Tracing the Flow. July, 2018.

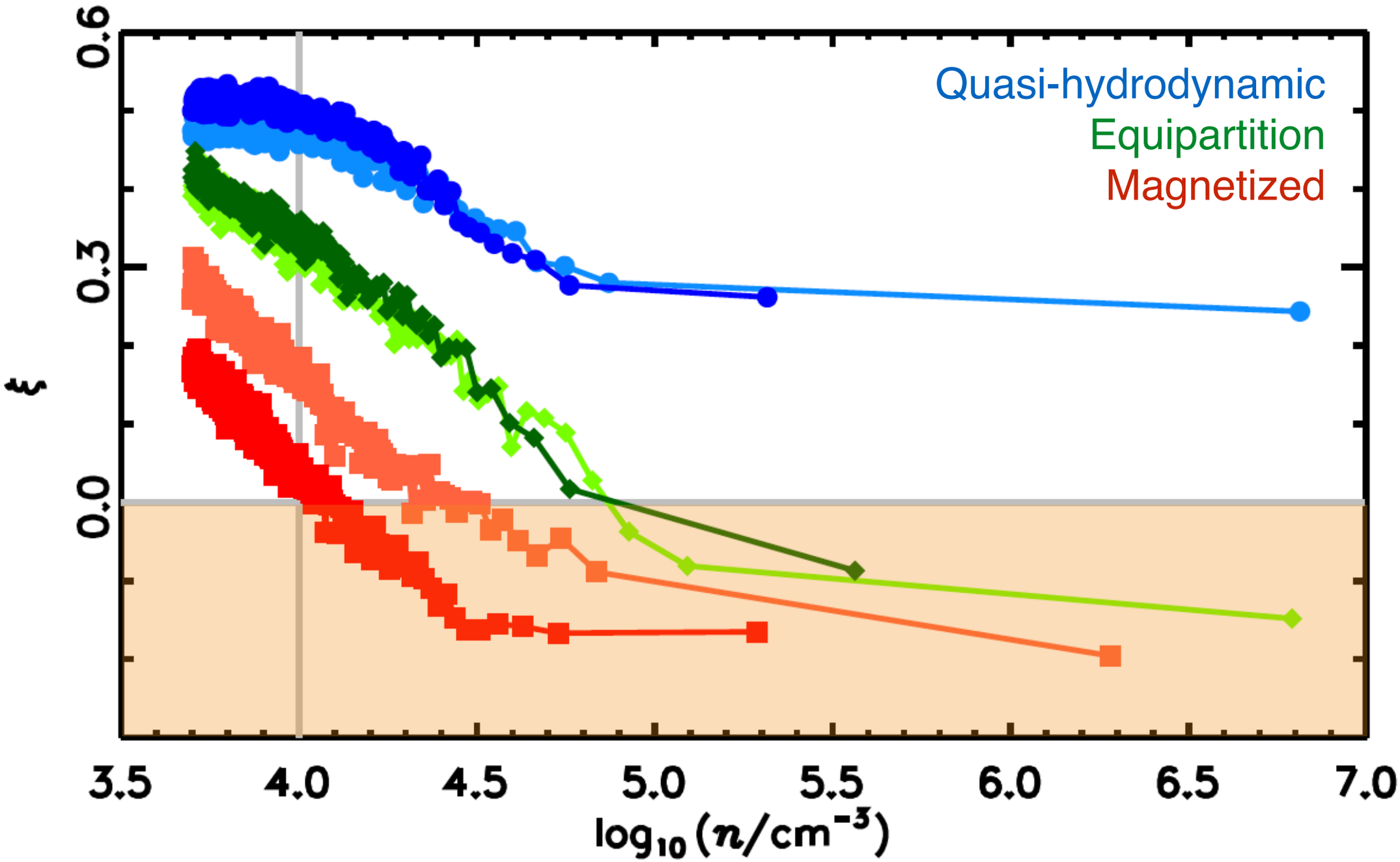
Relative Orientations

Soler, J.D., et al, ApJ. 774 (2013), 128 (HRO method)
Planck intermediate results. XXXV. A&A, 586 (2016) A138 (c.a. Juan D. Soler)



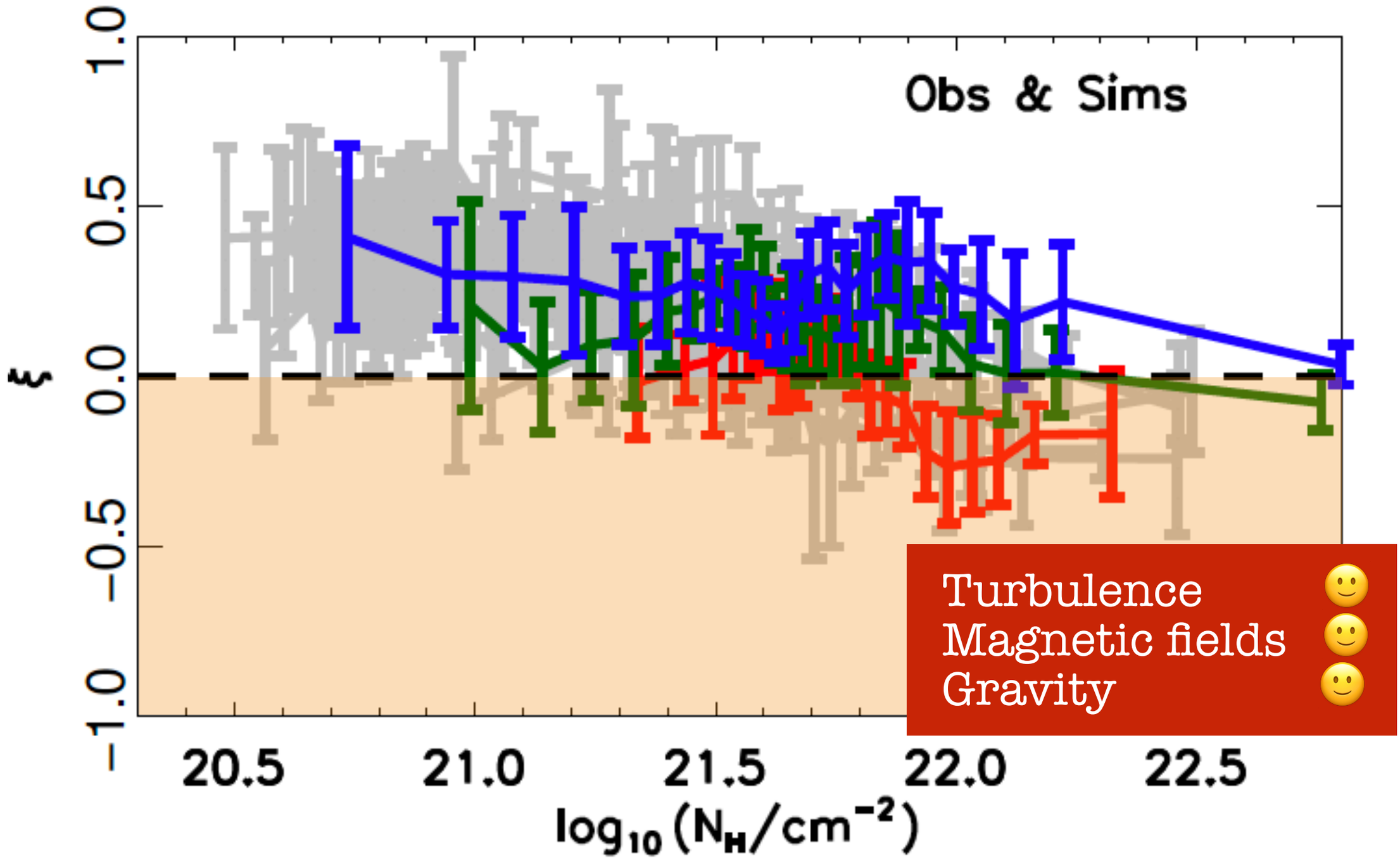
Relative orientation between N_H and $B_\perp$

Soler, J.D., et al, ApJ. 774 (2013), 128



Magnetic fields and cloud formation

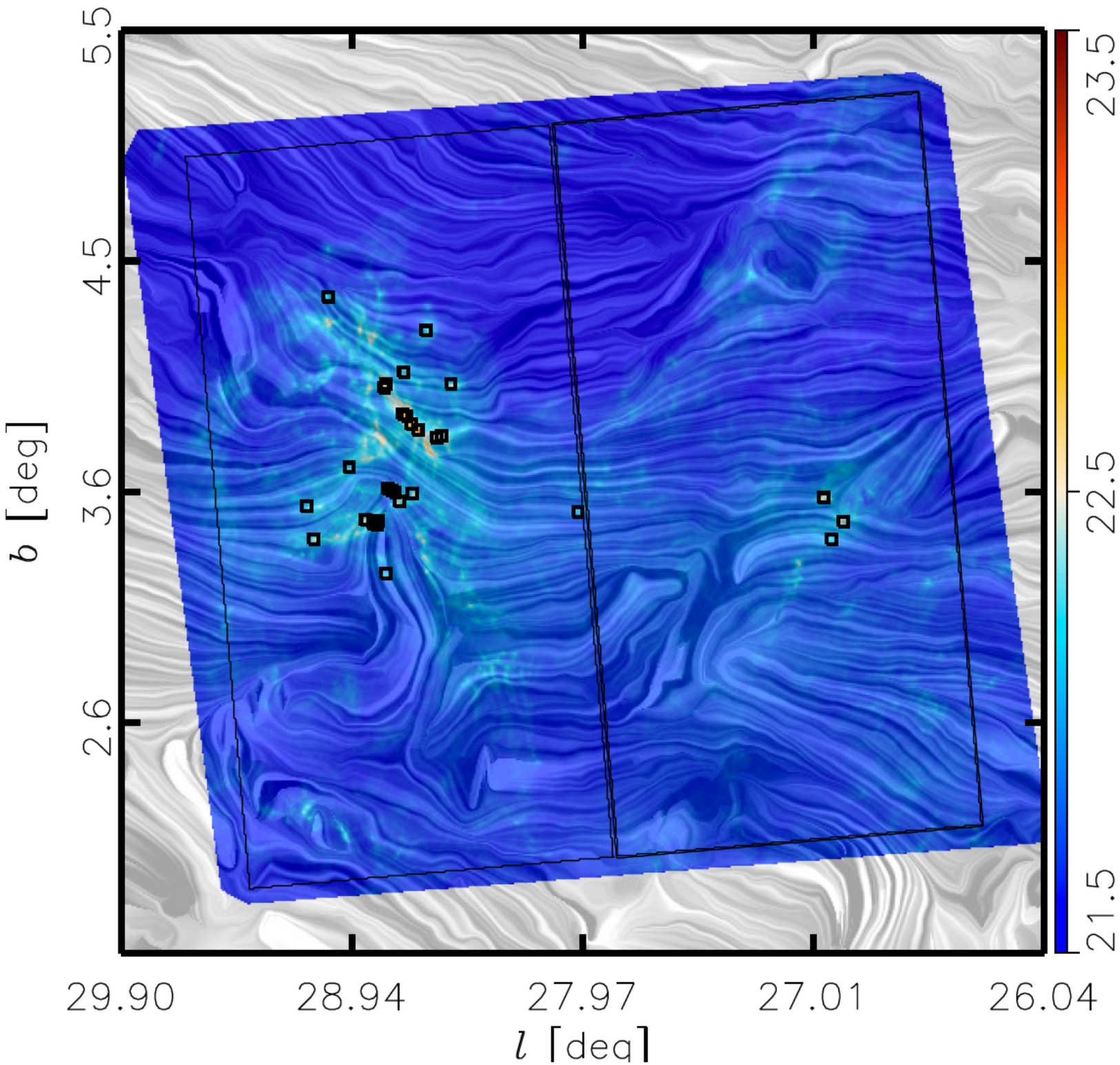
Soler, J.D., et al, ApJ. 774 (2013), 128
Planck intermediate results. XXXV. A&A, 586 (2016) A138



Turbulence 🙂
Magnetic fields 🙂
Gravity 🙂

Serpens South - Aquila Rift

Soler, J.D. and the BLASTPol Collaboration A&A 603A (2017) 64S



Serpens South - Aquila Rift

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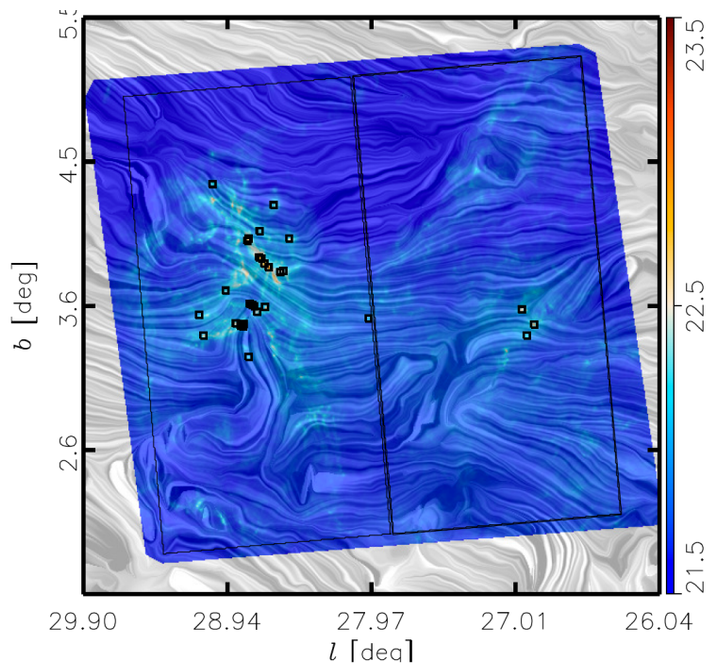

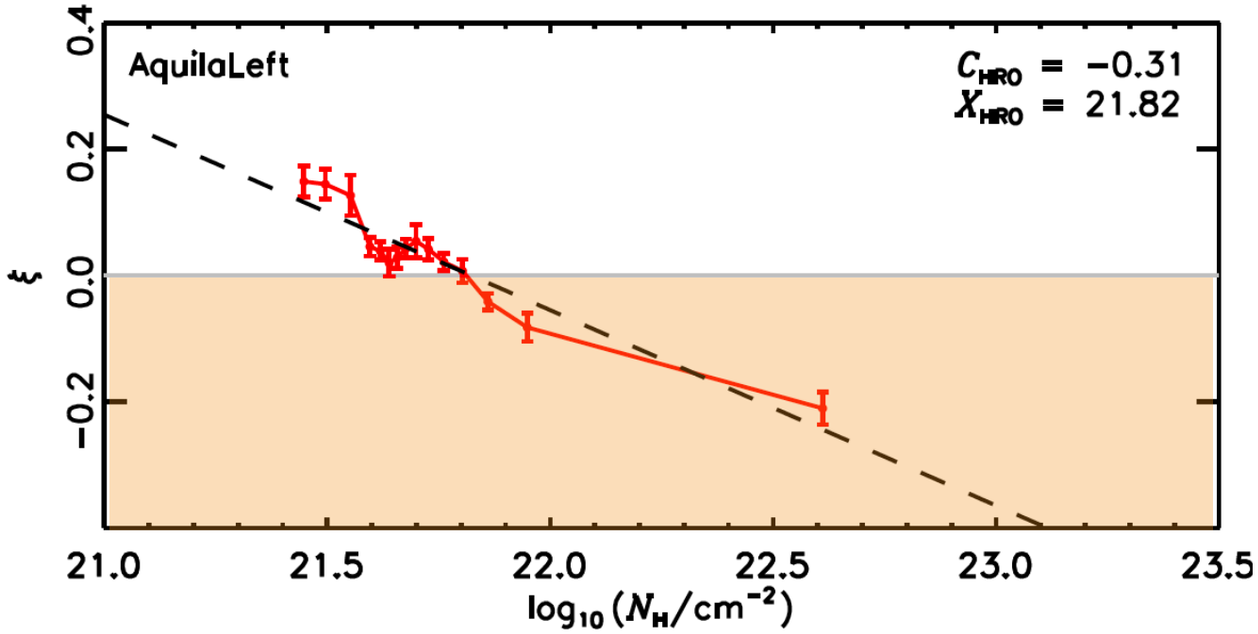

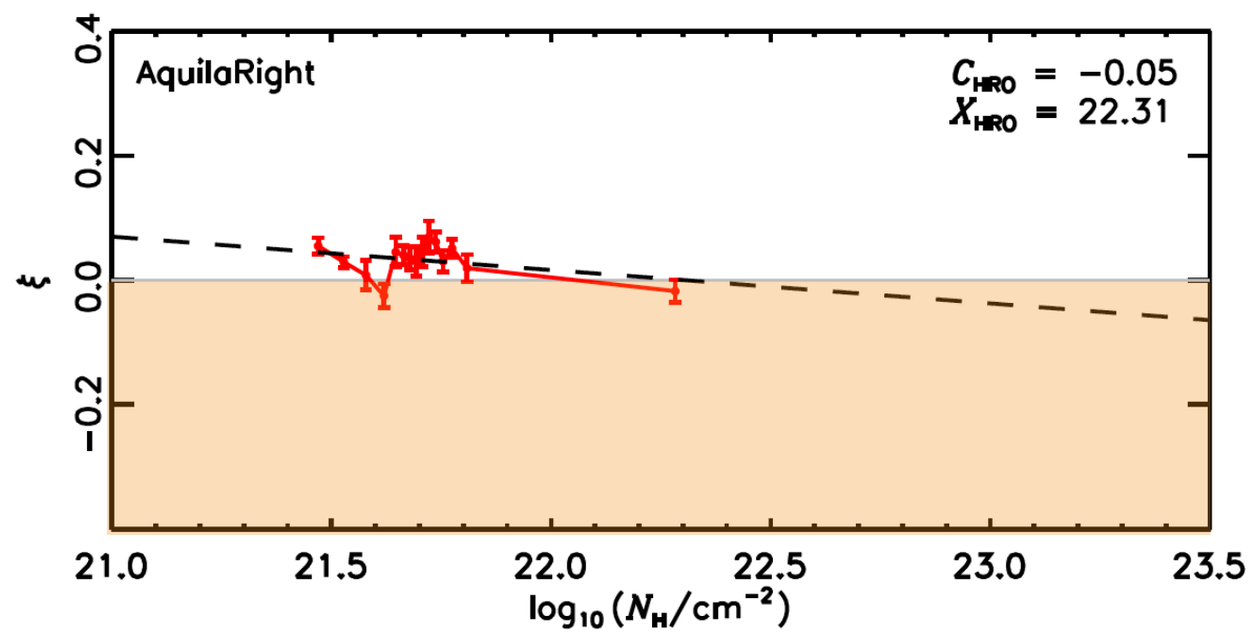

Turbulence 🙂
Magnetic fields 🙂
Gravity 😀

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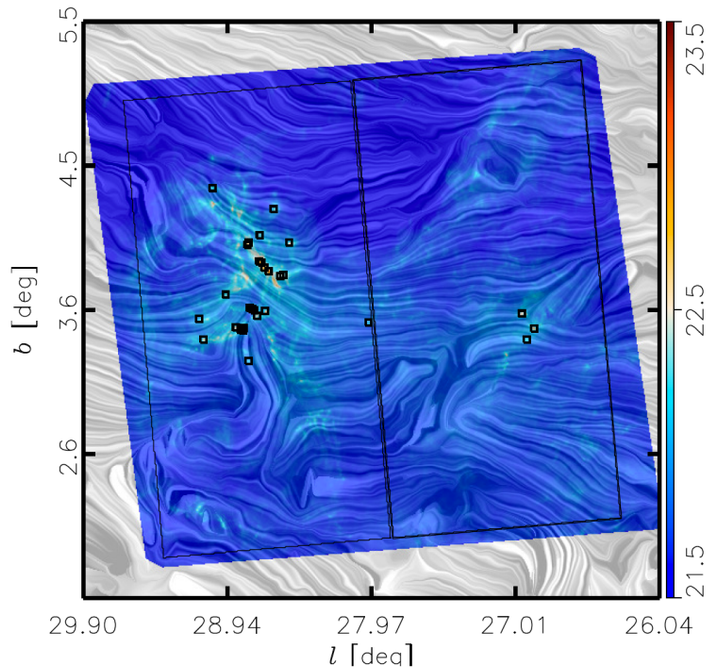
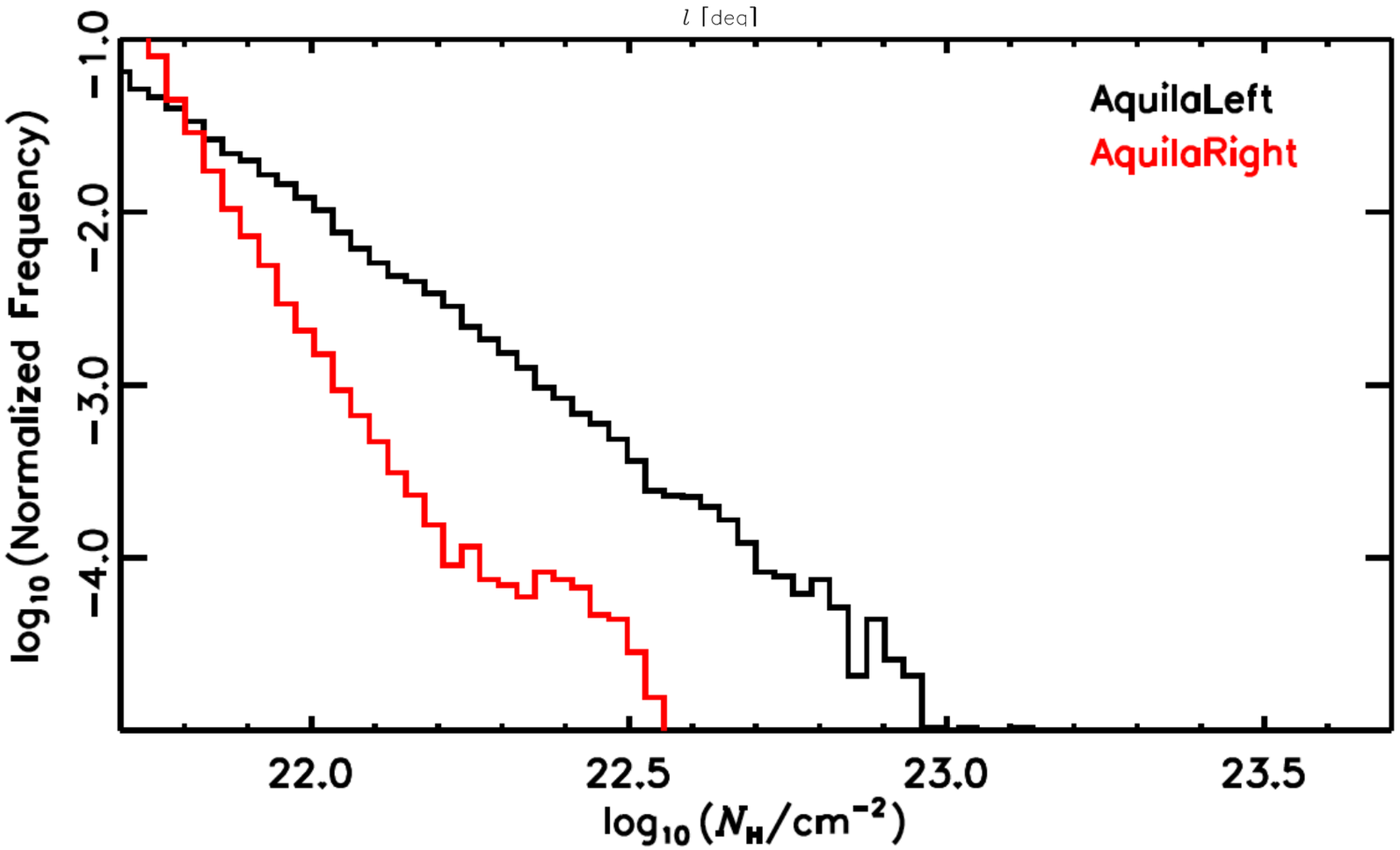
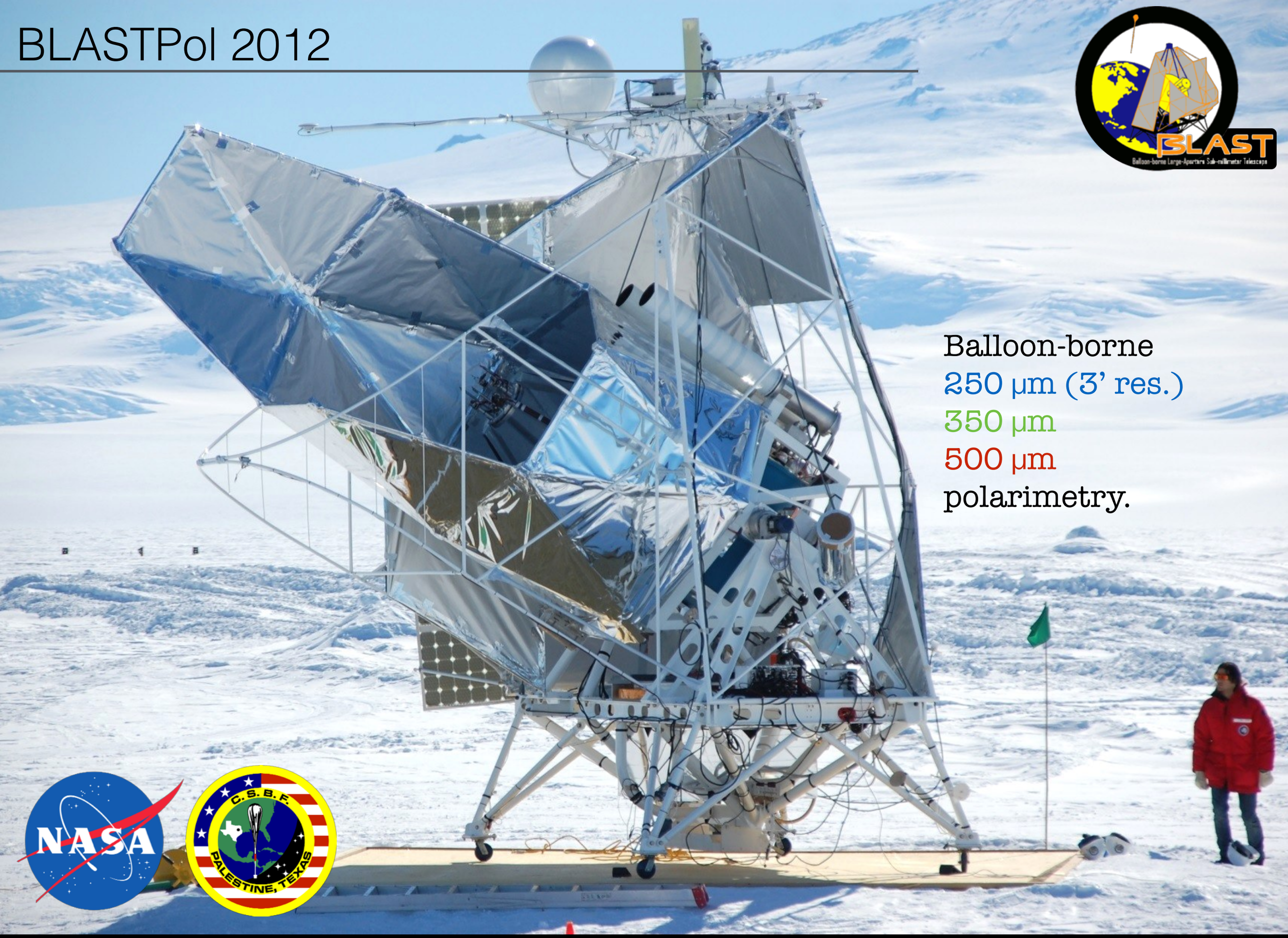




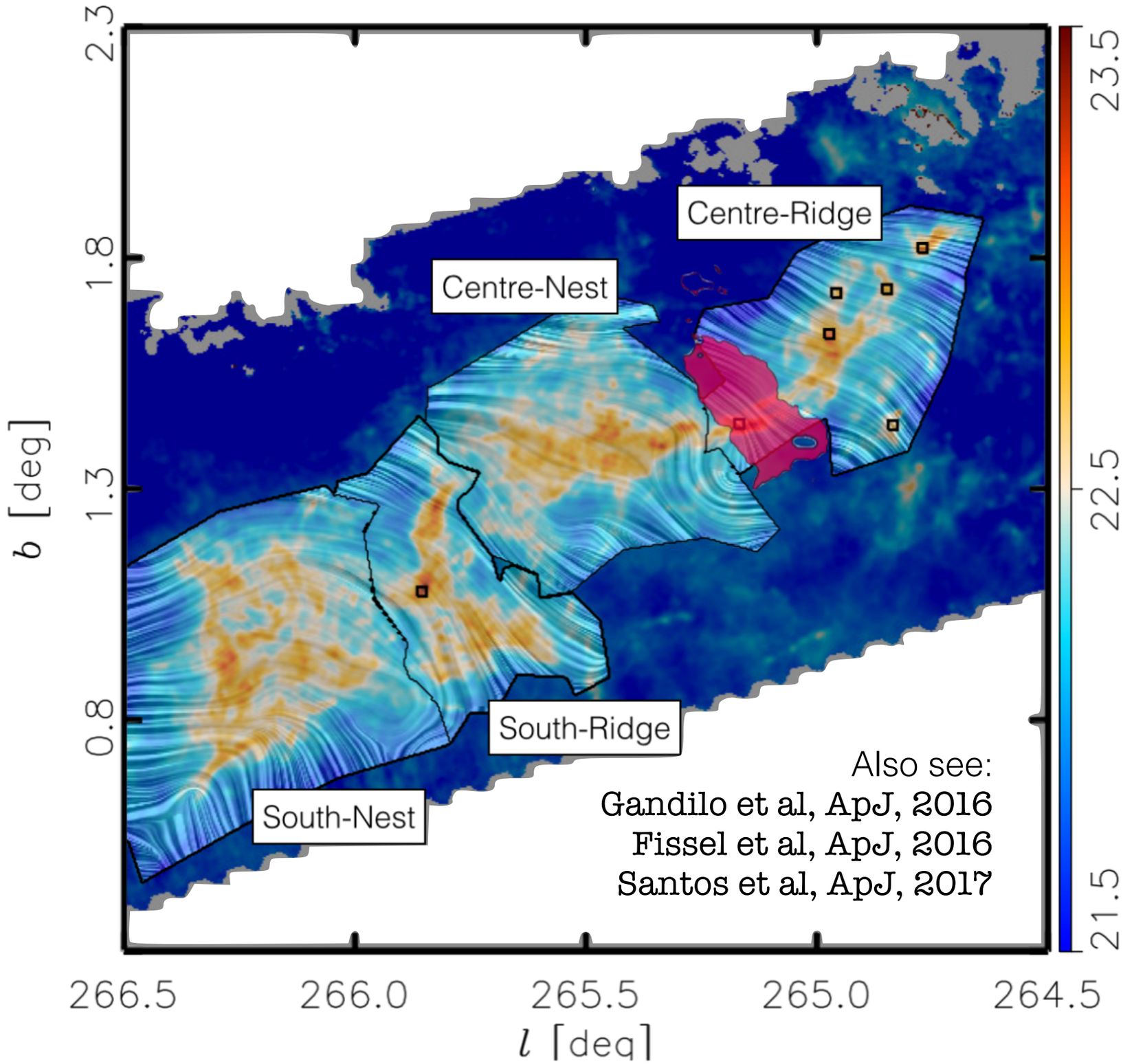
BLASTPol 2012



Balloon-borne
250 μm (3' res.)
350 μm
500 μm
polarimetry.

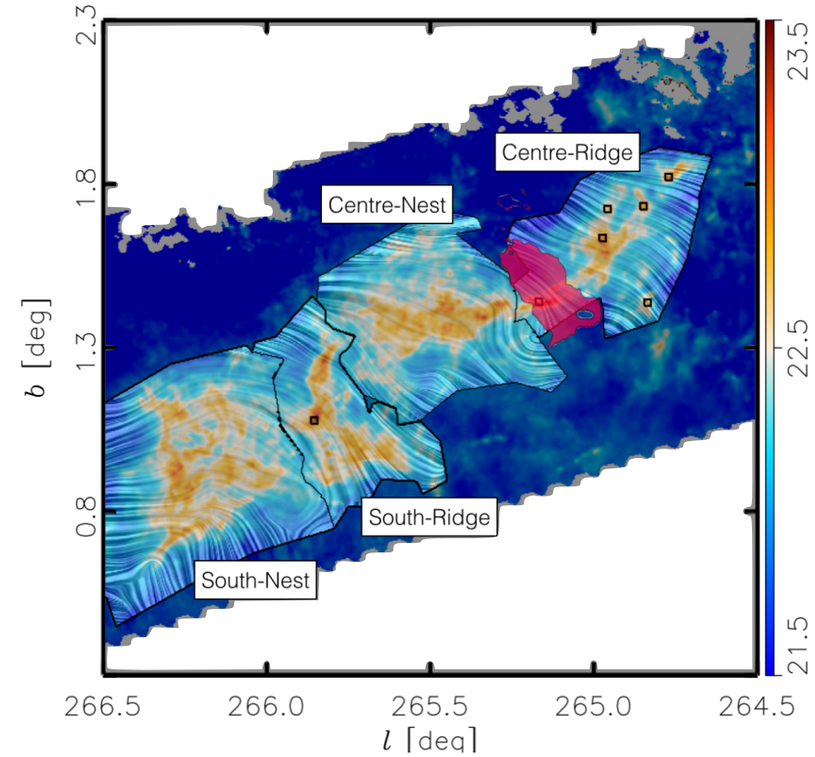
Relative Orientations

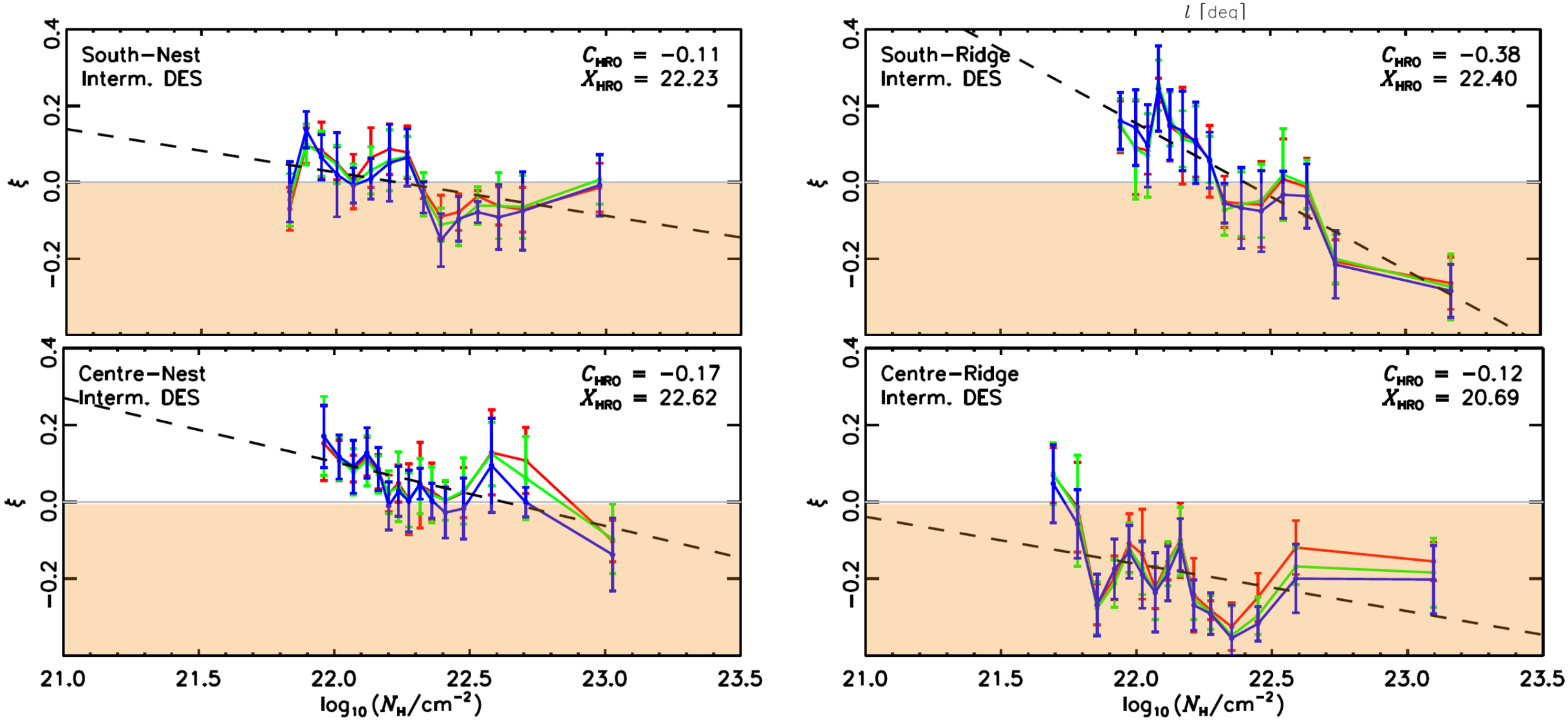
Soler, J.D. and the BLASTPol Collaboration A&A 603A (2017) 64S



Relative Orientations

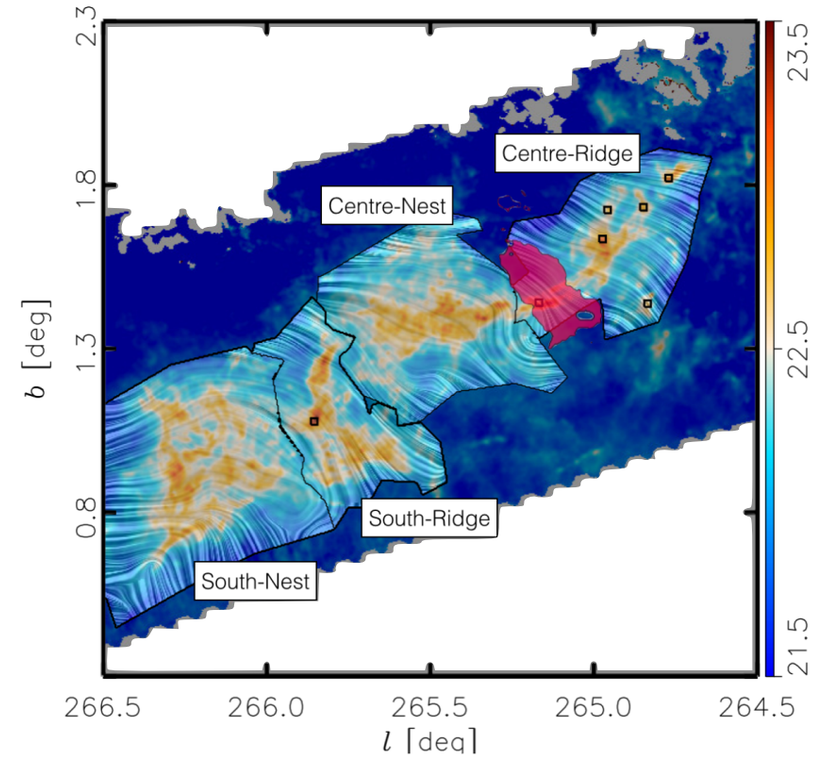
Soler, J.D. and the BLASTPol Collaboration
A&A 603A (2017) 64S

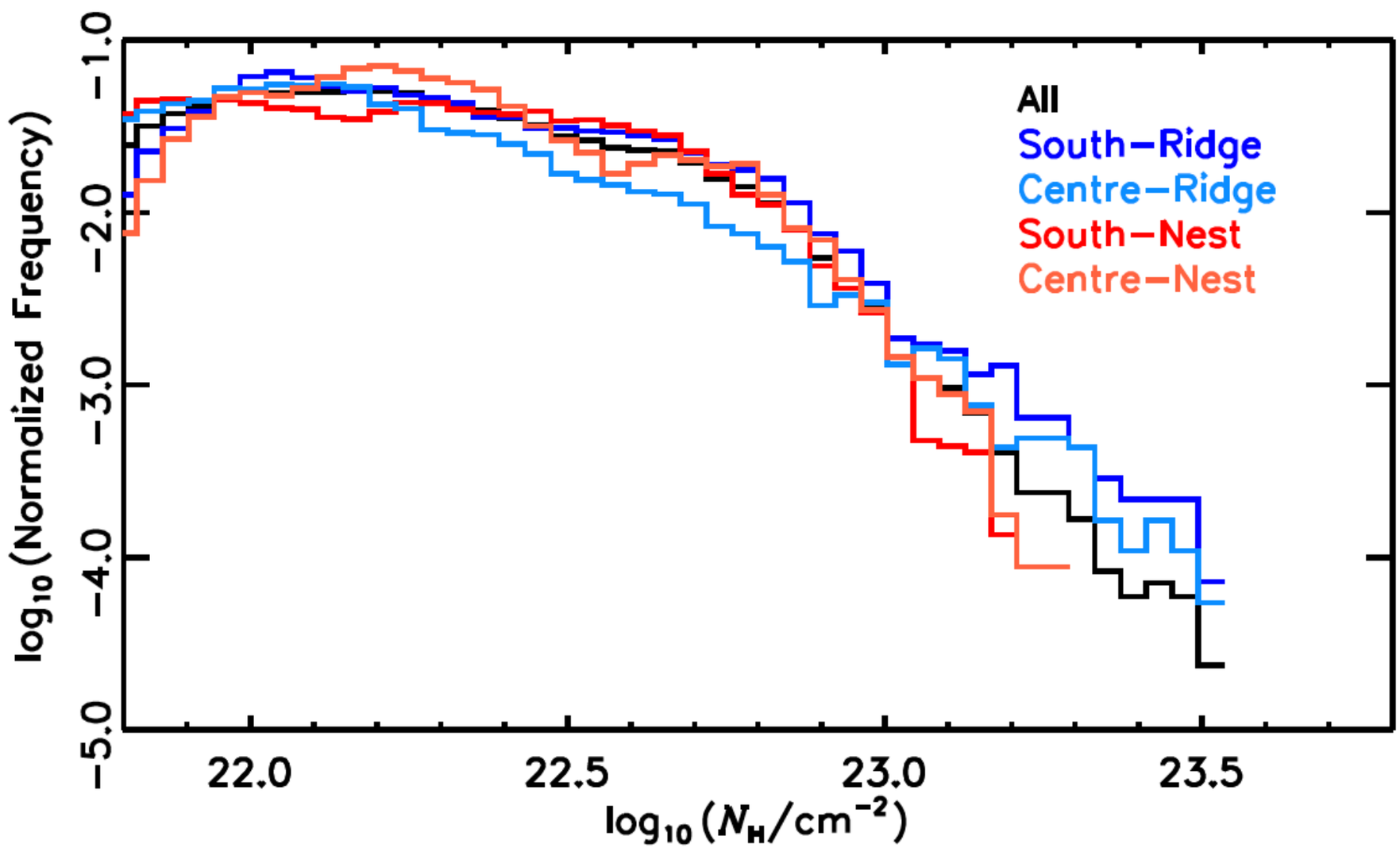




Relative Orientations

Soler, J.D. and the BLASTPol Collaboration
A&A 603A (2017) 64S

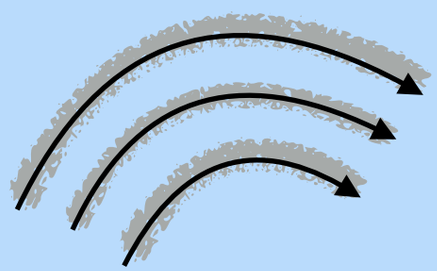




Magnetic fields and cloud formation

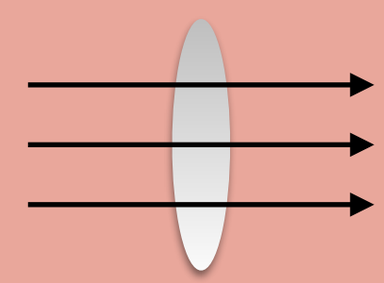
Planck intermediate results. XXXV. A&A, 586 (2016) A138

- Density structures and **B** stretched in the same direction.



Hennebelle, P., 2013
Banerjee, R., 2009
Matthaeus, W., et al. 2008

- Flows occur mainly along **B**.



Hartmann, L., et al. 2001.
Inutsuka, S., 2015
Nakamura F. & Li, Z., 2008

Relative orientation between N_H and $B_\perp$

Soler J.D. & P. Hennebelle, A&A 607A (2017) 2S

① $$\frac{d\log\rho}{dt} = -\partial_j v_j$$

② $$\frac{dB_i}{dt} = B_j(\partial_j v_i) - B_i(\partial_j v_j)$$

$$\cos\phi = \frac{\boldsymbol{\nabla}\rho\cdot\boldsymbol{B}}{|\boldsymbol{\nabla}\rho|\,|\boldsymbol{B}|}$$

Relative orientation between N_H and $B_\perp$

Soler J.D. & P. Hennebelle, A&A 607A (2017) 2S

$$r_i \equiv \frac{R_i}{(R_k R_k)^{1/2}} \qquad R_i \equiv \partial_i \log \rho$$

$$\frac{d(\cos\phi)}{dt} = \frac{\partial_i(\partial_j v_j)}{(R_k R_k)^{1/2}}[-b_i + r_i \cos\phi] + \partial_i v_j [r_i r_j - b_i b_j] \cos\phi$$

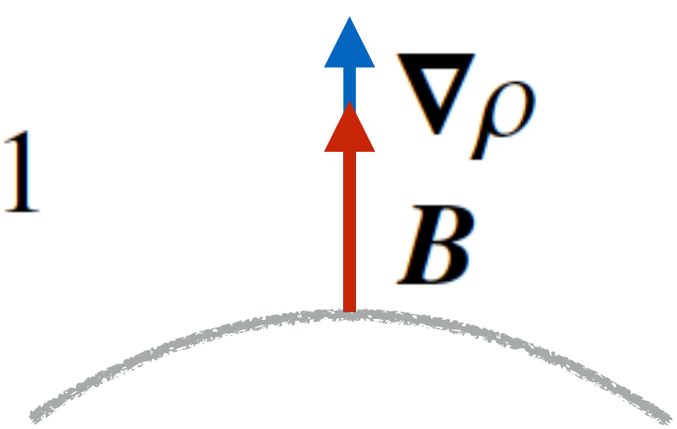
$$b_i \equiv \frac{B_i}{(B_k B_k)^{1/2}}$$

Relative orientation between N_H and $B_\perp$

Soler J.D. & P. Hennebelle, A&A 607A (2017) 2S

$$\frac{d(\cos\phi)}{dt} = \frac{\partial_i(\partial_j v_j)}{(R_k R_k)^{1/2}}[-b_i + r_i\cos\phi] + \partial_i v_j[r_i r_j - b_i b_j]\cos\phi$$

$$\cos\phi = \pm 1$$
$$r_i = \pm b_i$$



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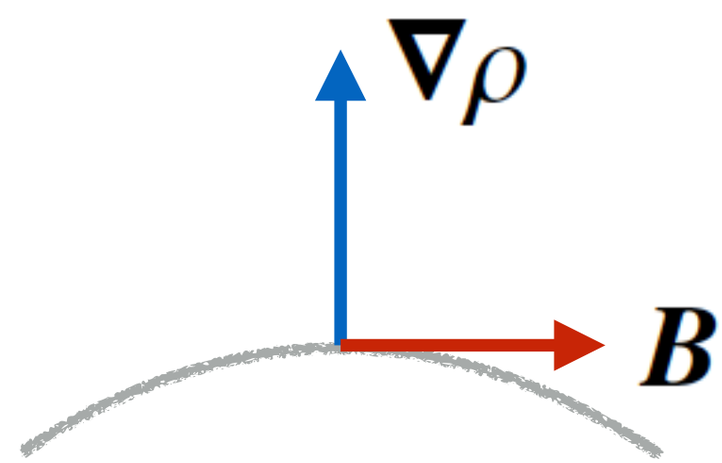
Soler J.D. & P. Hennebelle, A&A 607A (2017) 2S

$$\frac{d(\cos\phi)}{dt} = \frac{\partial_i(\partial_j v_j)}{(R_k R_k)^{1/2}}[-b_i + r_i \cos\phi] + \partial_i v_j [r_i r_j - b_i b_j] \cos\phi$$

$$\cos\phi = 0$$



Conclusions

The magnetic field matters in the formation of molecular clouds out of diffuse atomic gas.

Conclusions

@OrionEridanusSuperbubble large scale motions set the initial conditions of MC formation, including the magnetic field. **#BfieldAndSNe.**
Soler, Bracco, & Pon. A&A. 2018.

@Planck 10 nearby MCs, relative orientation between N_H and $B_\perp$: **#BfieldMattersForMCformation.**
Planck intermediate results. XXXV. A&A. 2016.

@BLASTPol Vela C: relative orientation between N_H and $B_\perp$ related to the N_H distribution **#BfieldAndPowerLawTail**.
Soler, J.D. and the BLASTPol collaboration. A&A. 2017.

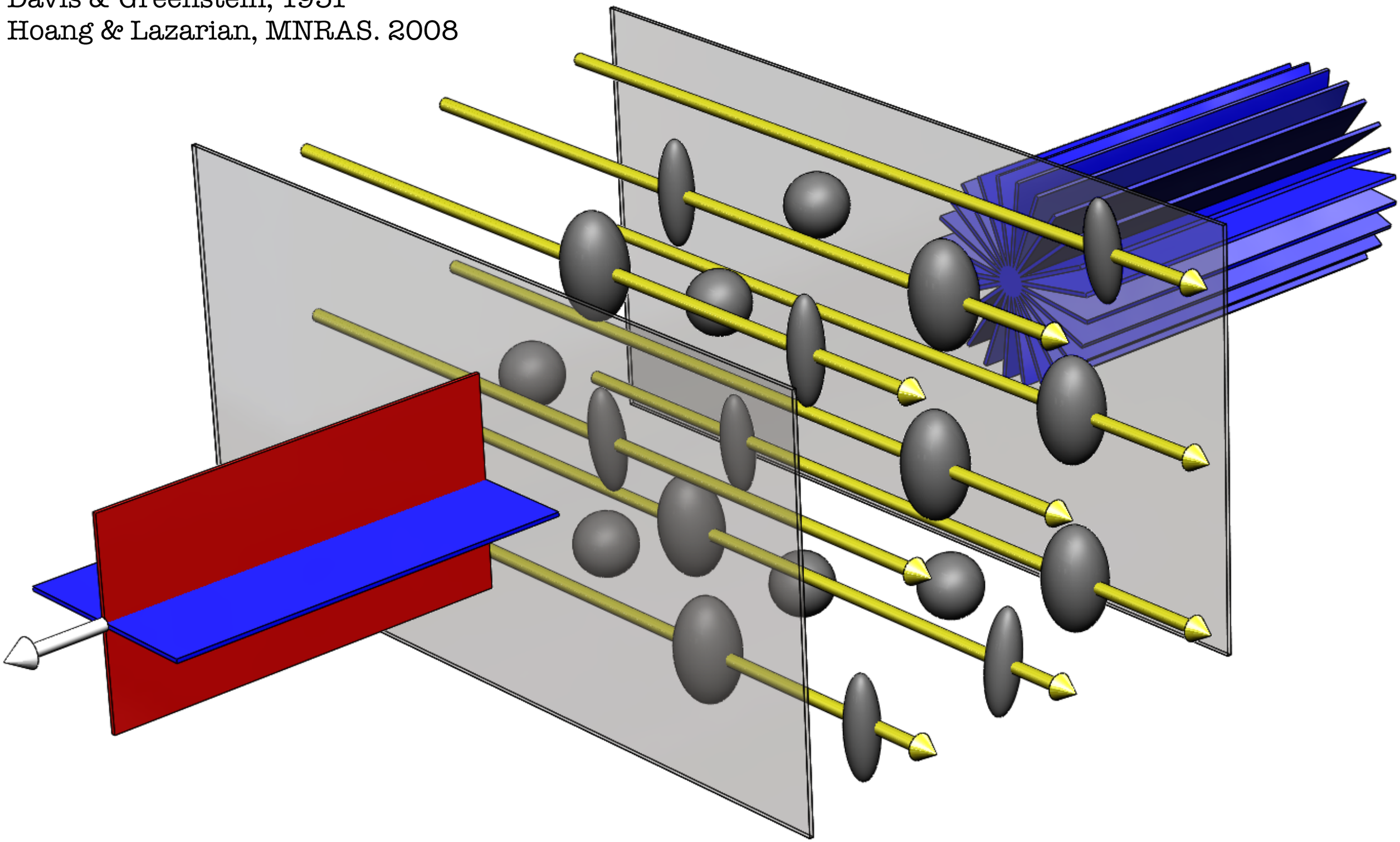
N_H and $B_\perp$ **parallel or perpendicular** are **equilibrium points** of MHD transport equations. Changes are related to velocity divergence. **#BfieldAndISMflows**. Soler J.D. & P. Hennebelle, A&A. 2017.

https://github.com/solerjuan/magnetar

Extra slides

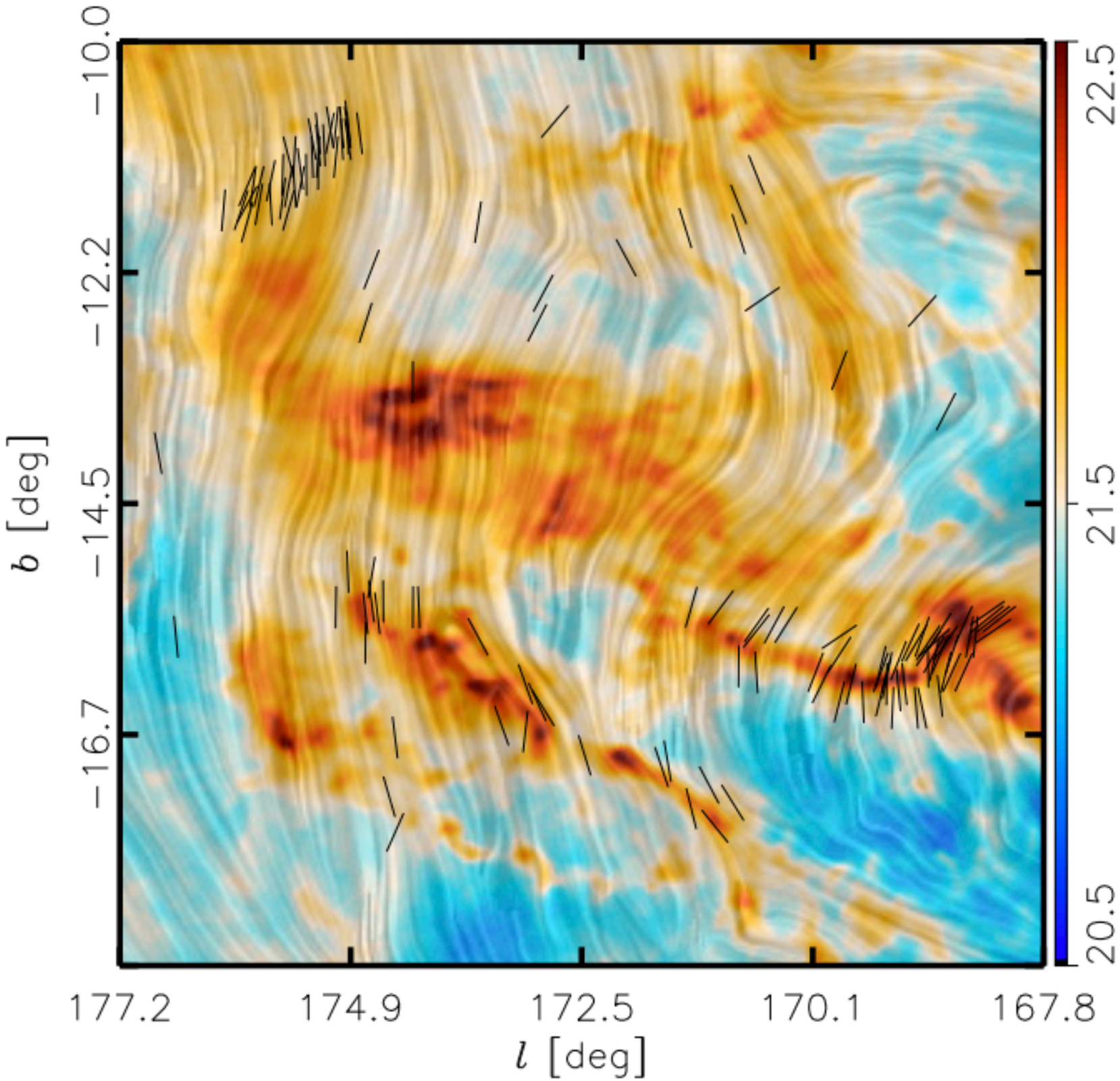
Dust polarized emission/absorption

Hall, 1949
Hiltner, 1949
Davis & Greenstein, 1951
Hoang & Lazarian, MNRAS. 2008



Comparison with starlight polarization

Soler, J.D., Alves, F., et al, 2016 A&A 596, A93 (2016)



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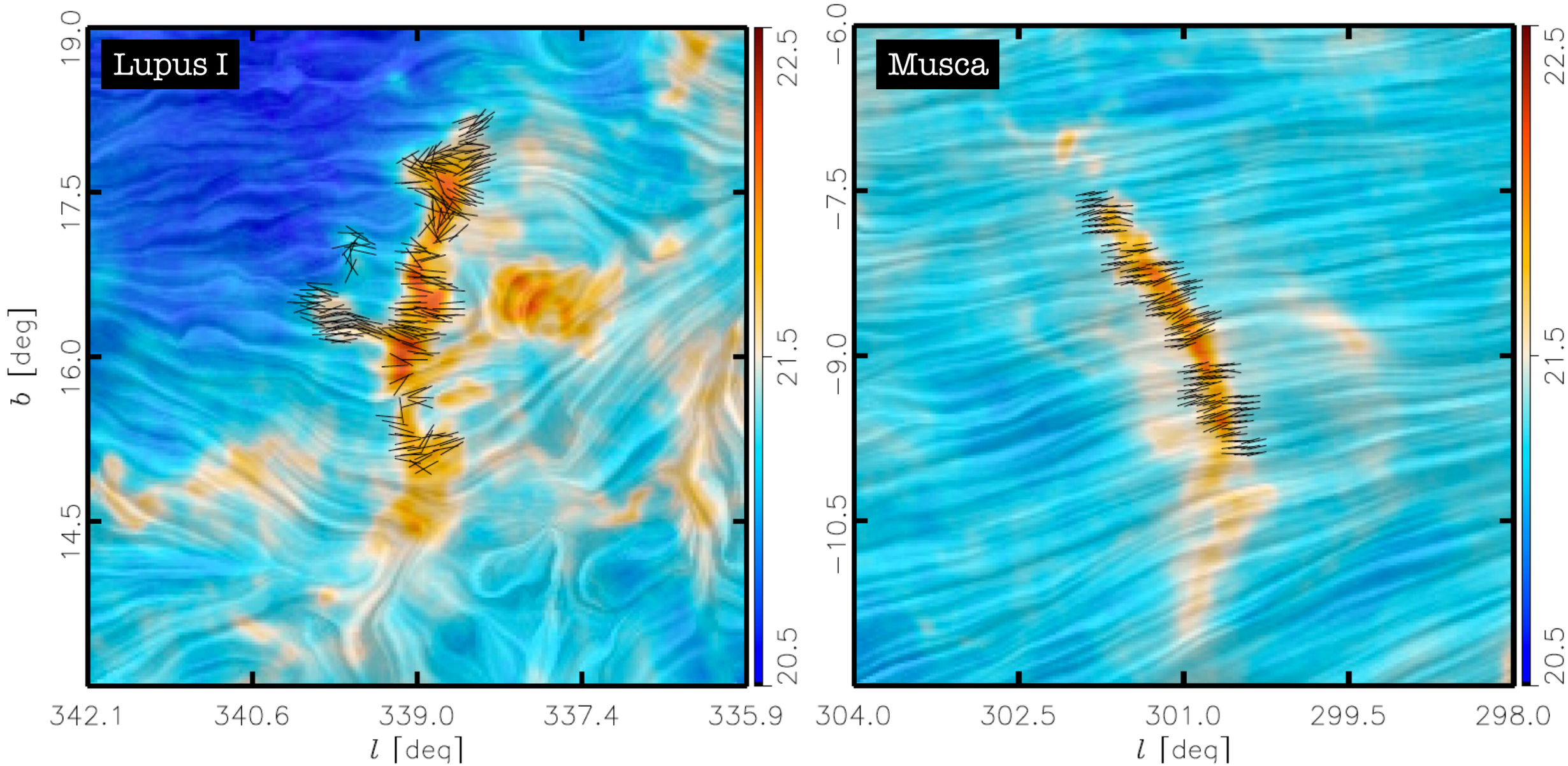
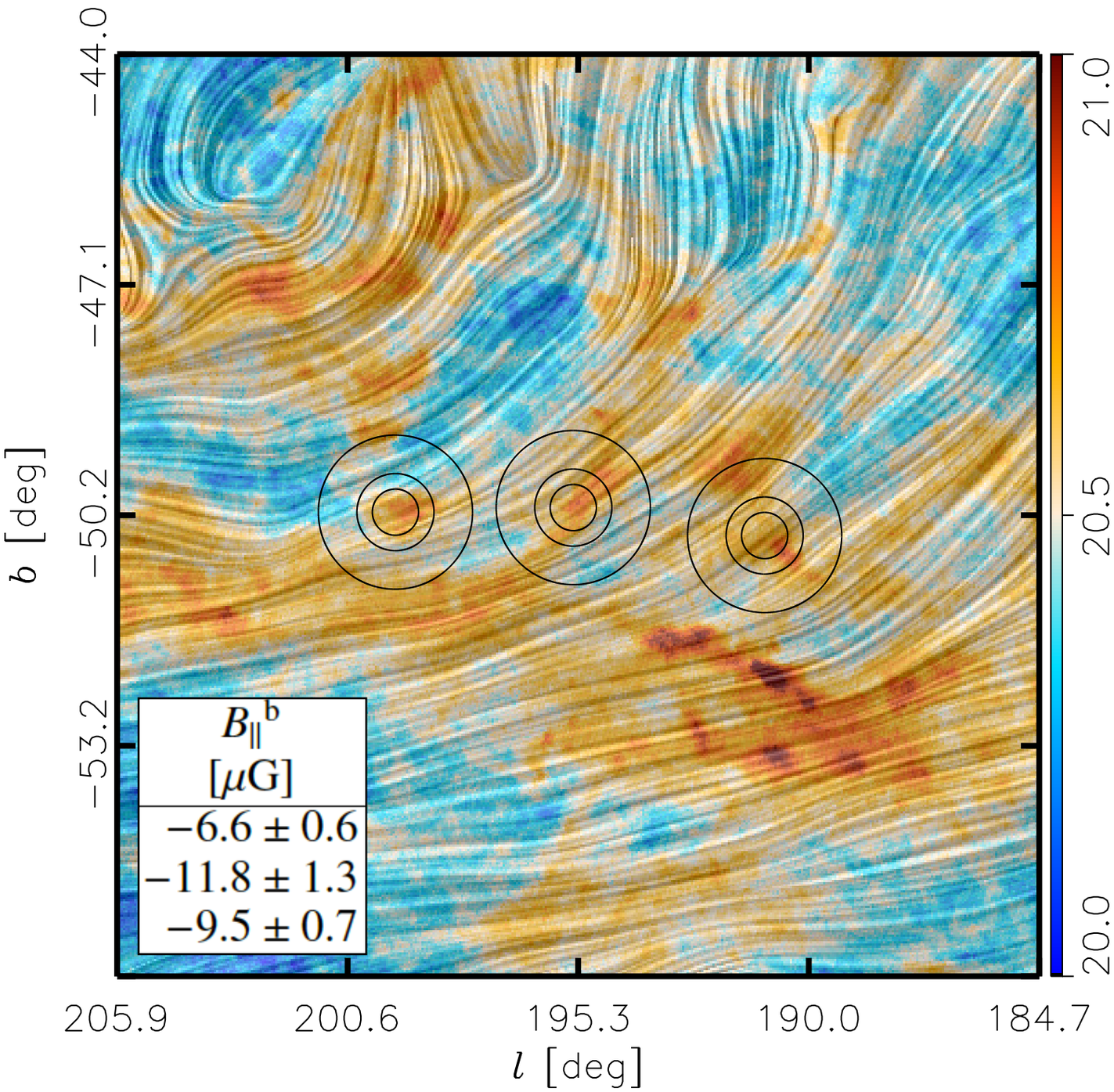
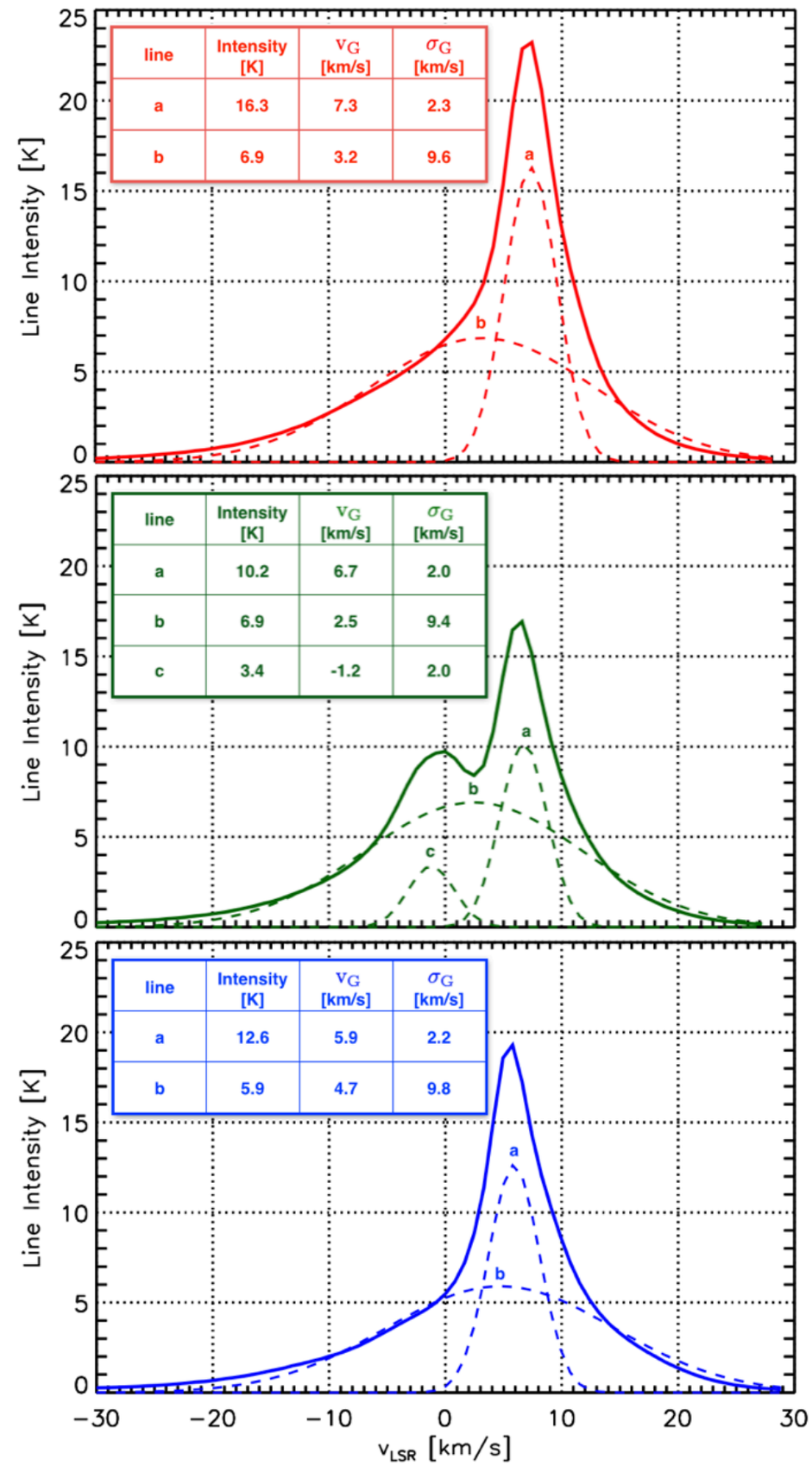


Magnetic field in the Orion-Eridanus superbubble

Soler, Bracco, & Pon. 2017. A&A in press.

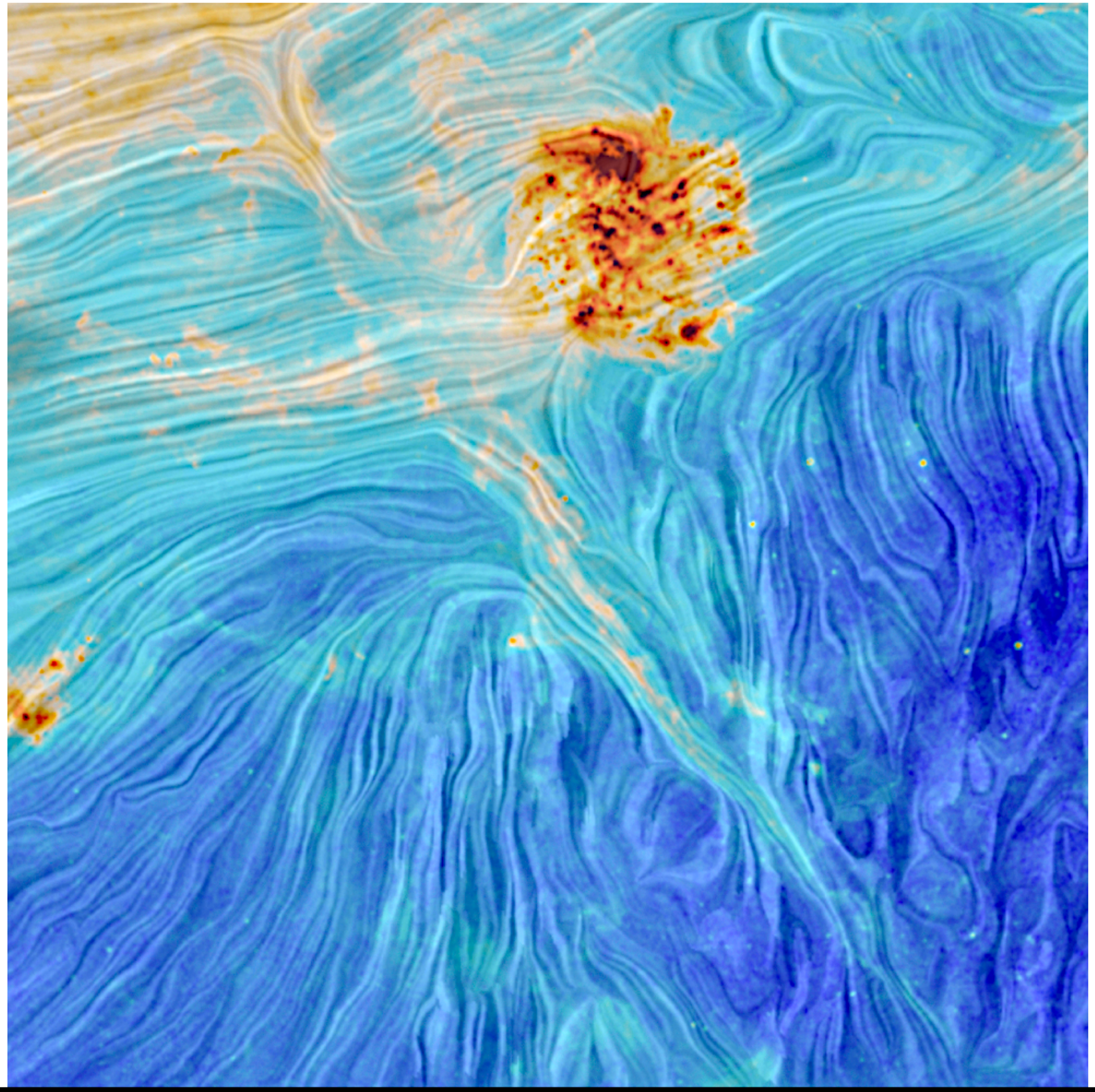


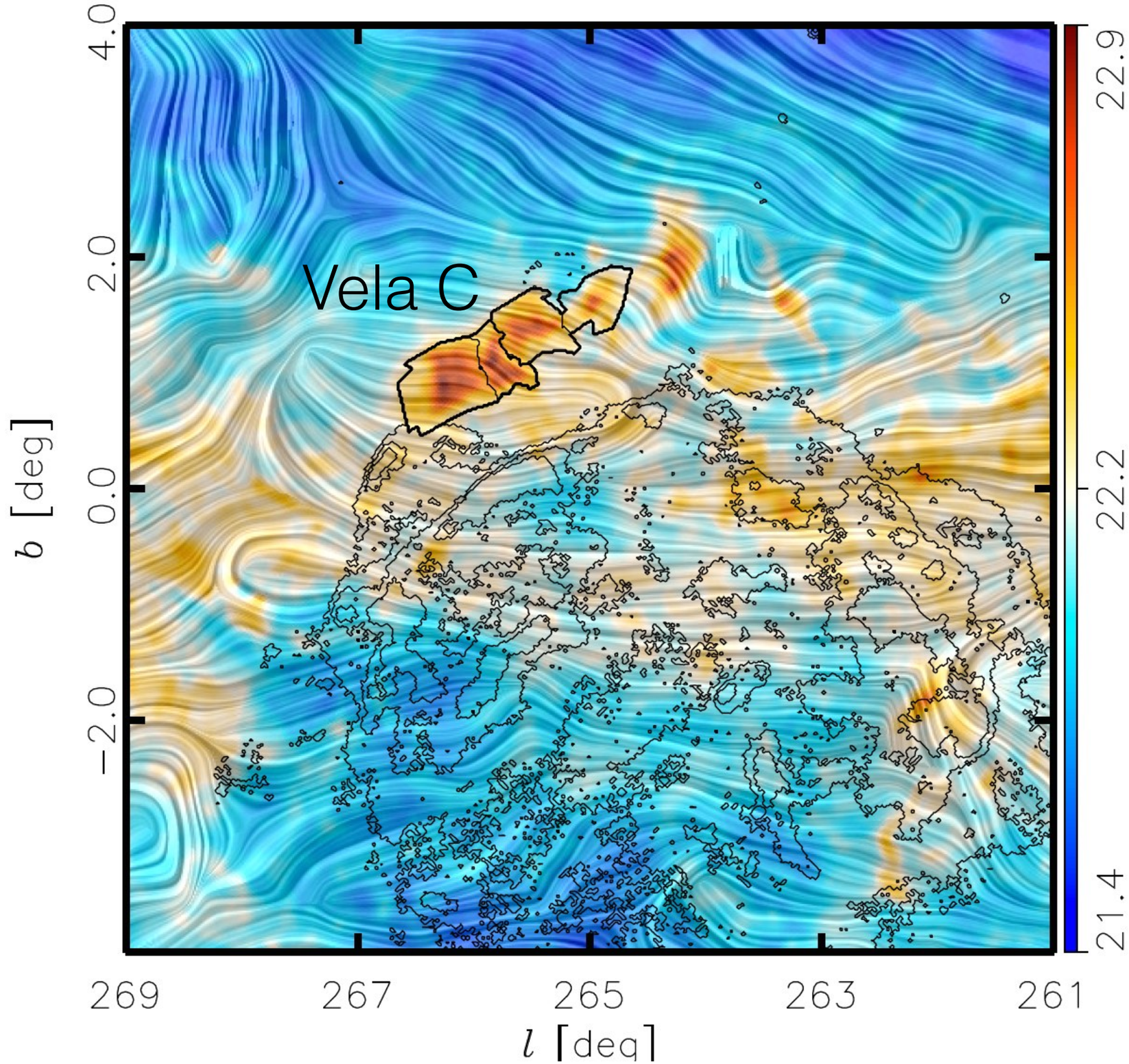


[b]Heiles, C. 1989, ApJ, 336, 808

Column density and magnetic field orientation

Planck 2015 results I. A&A, 594 (2016), A1



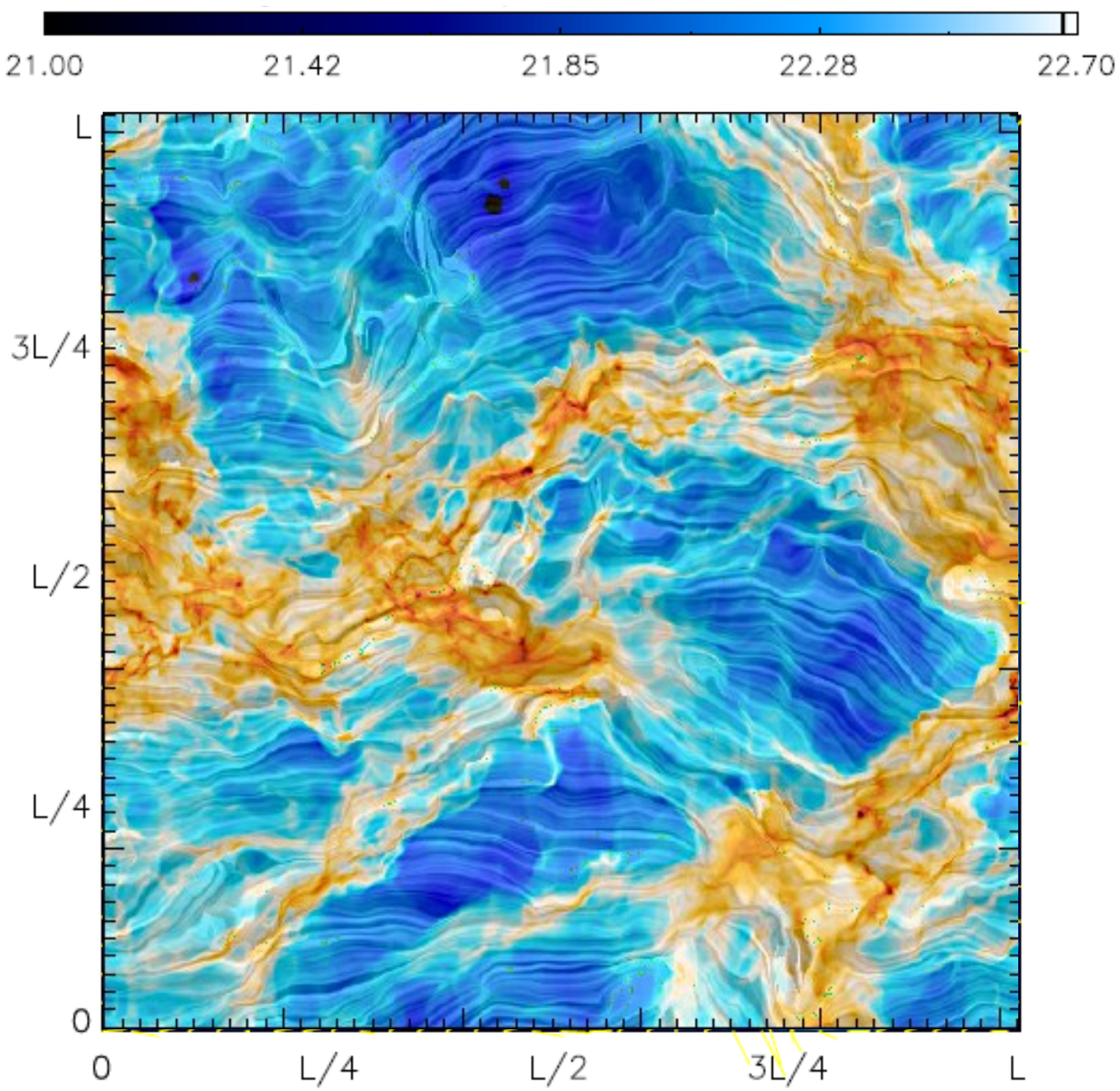


- Colors: N_H from dust optical depth - **Planck Collaboration XI**.
- Texture: $\mathbf{B}_\perp$ from Planck 353 GHz polarization.
- Contours: X-ray emission from ROSAT

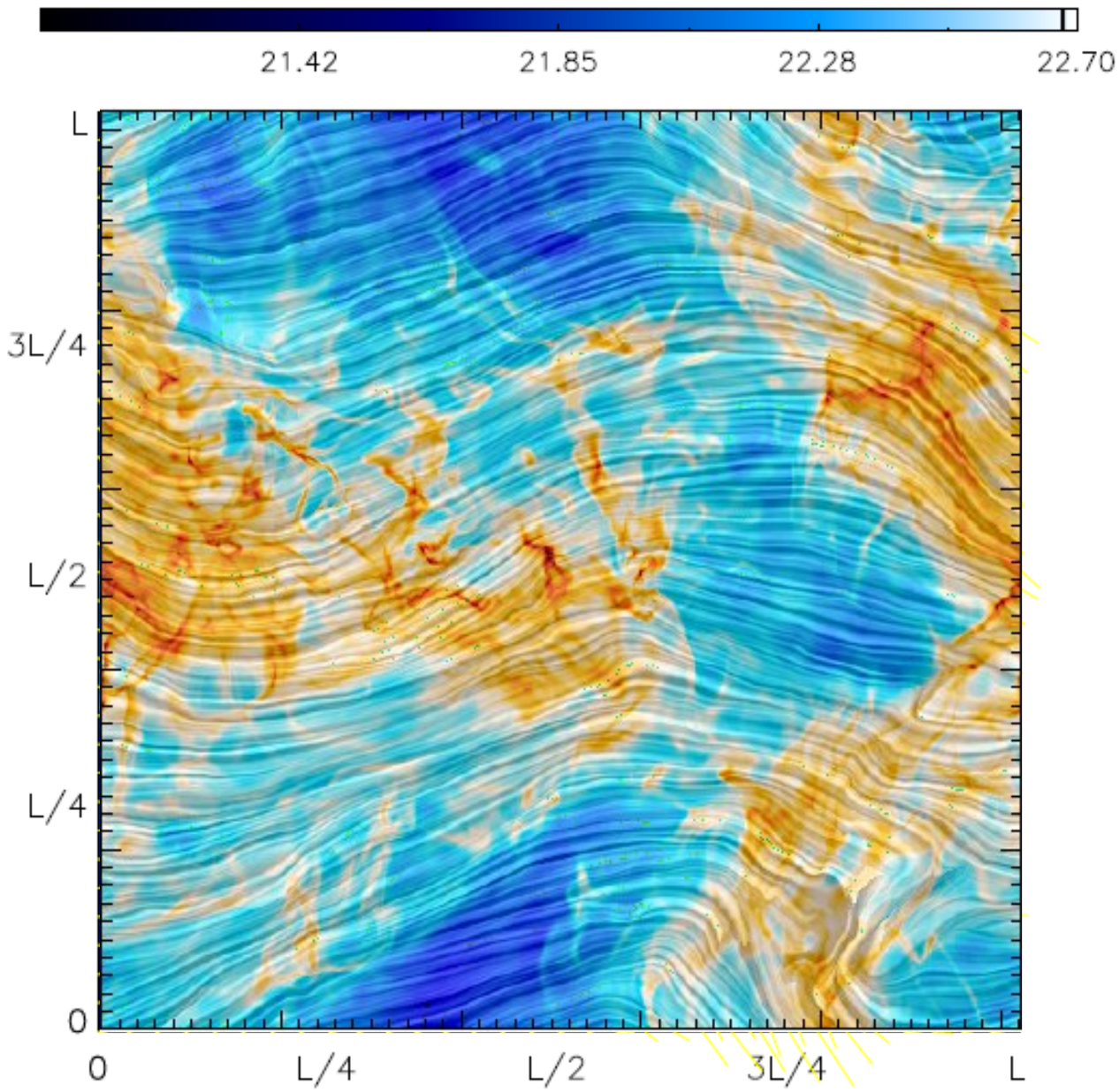
Relative Orientations

Soler, J.D., et al, ApJ. 774 (2013), 128

Weak magnetic field (β = 100.0)

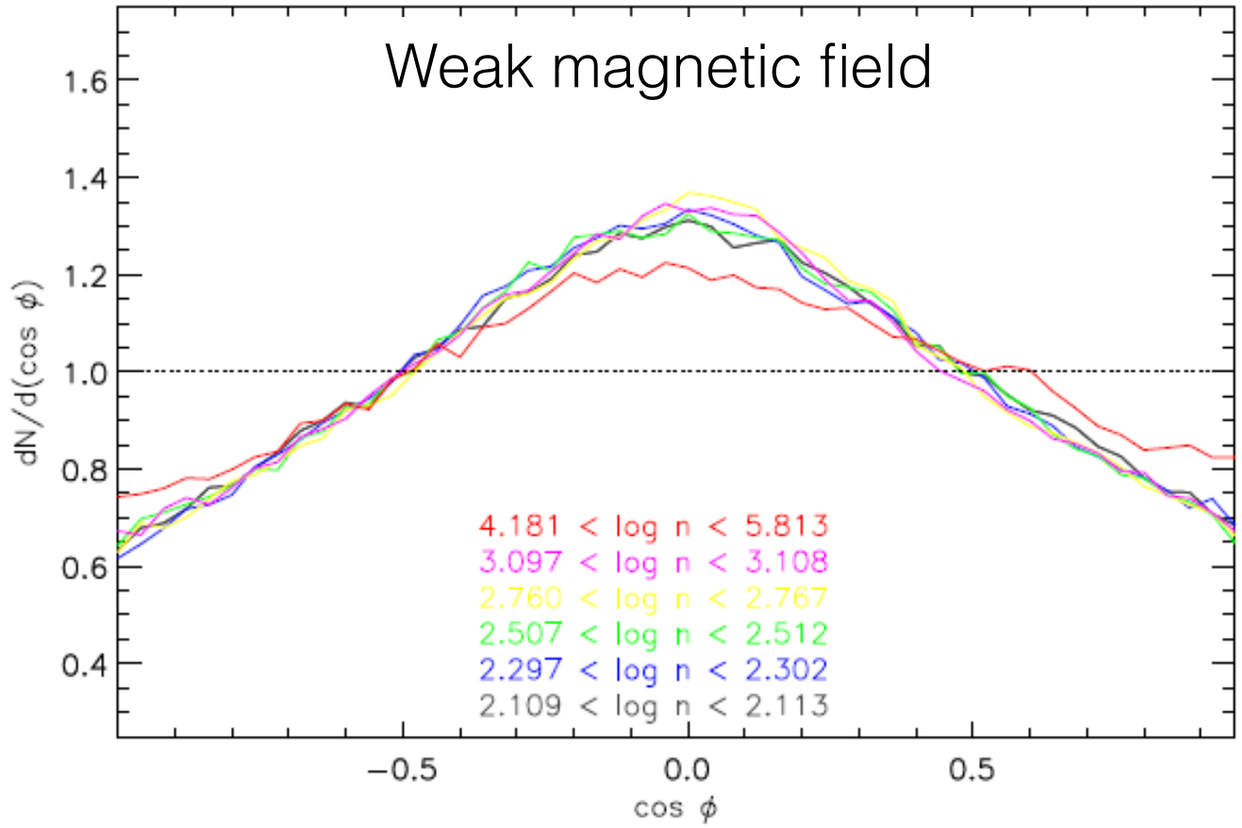


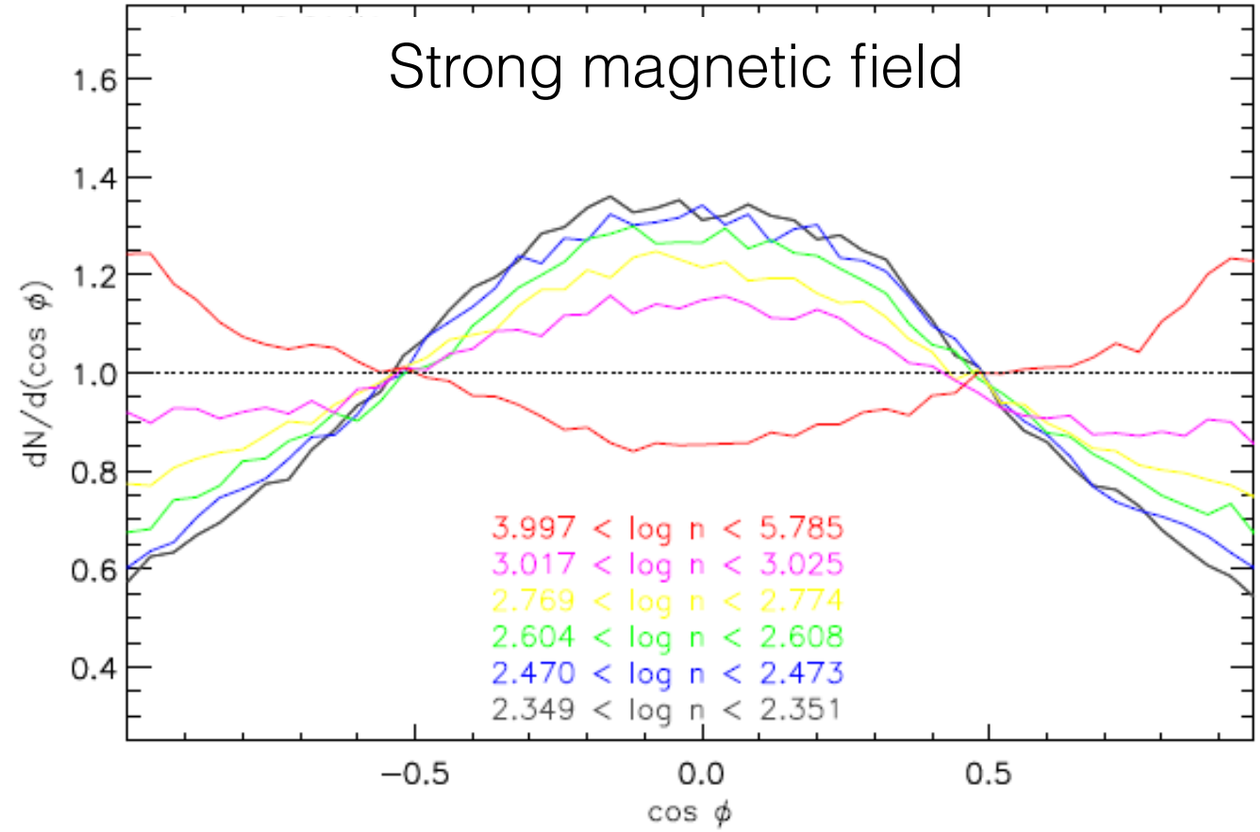
Strong magnetic field (β = 0.1)

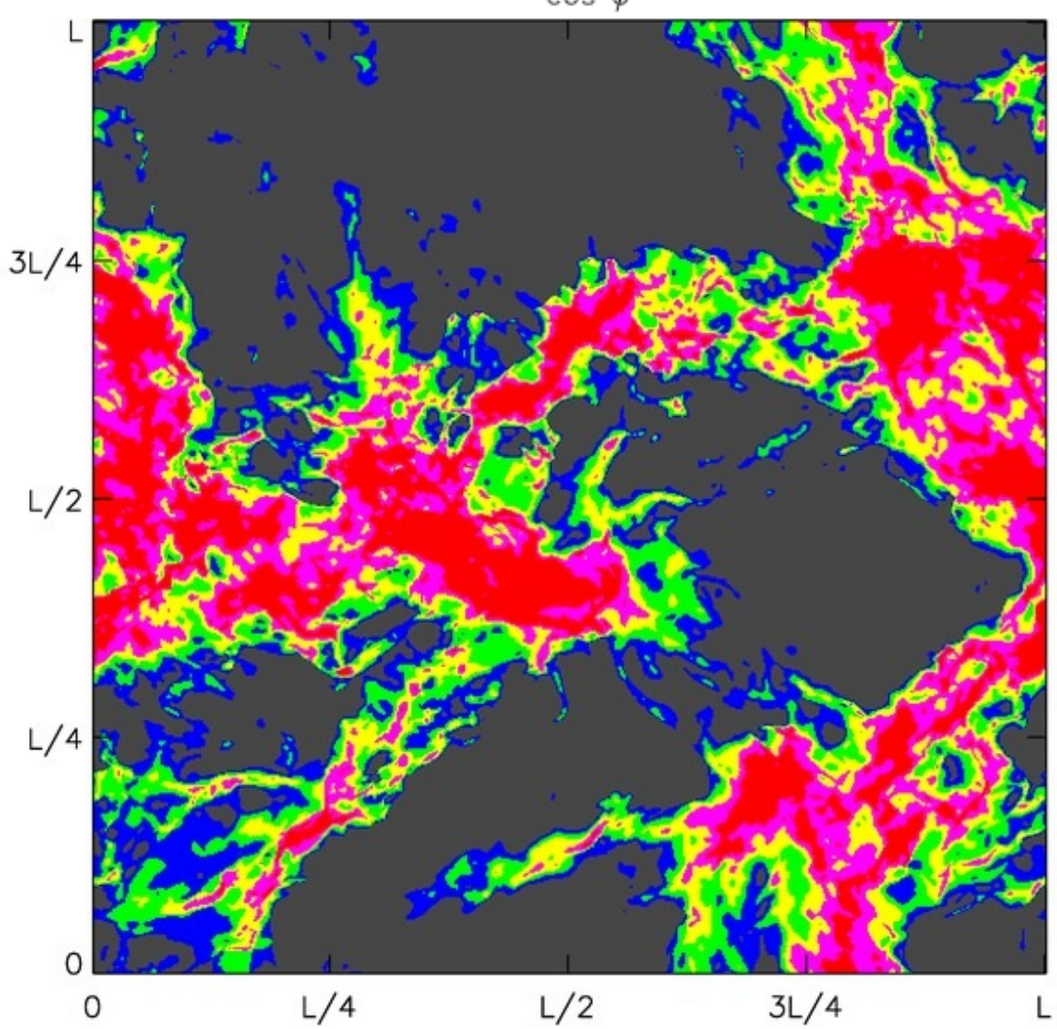


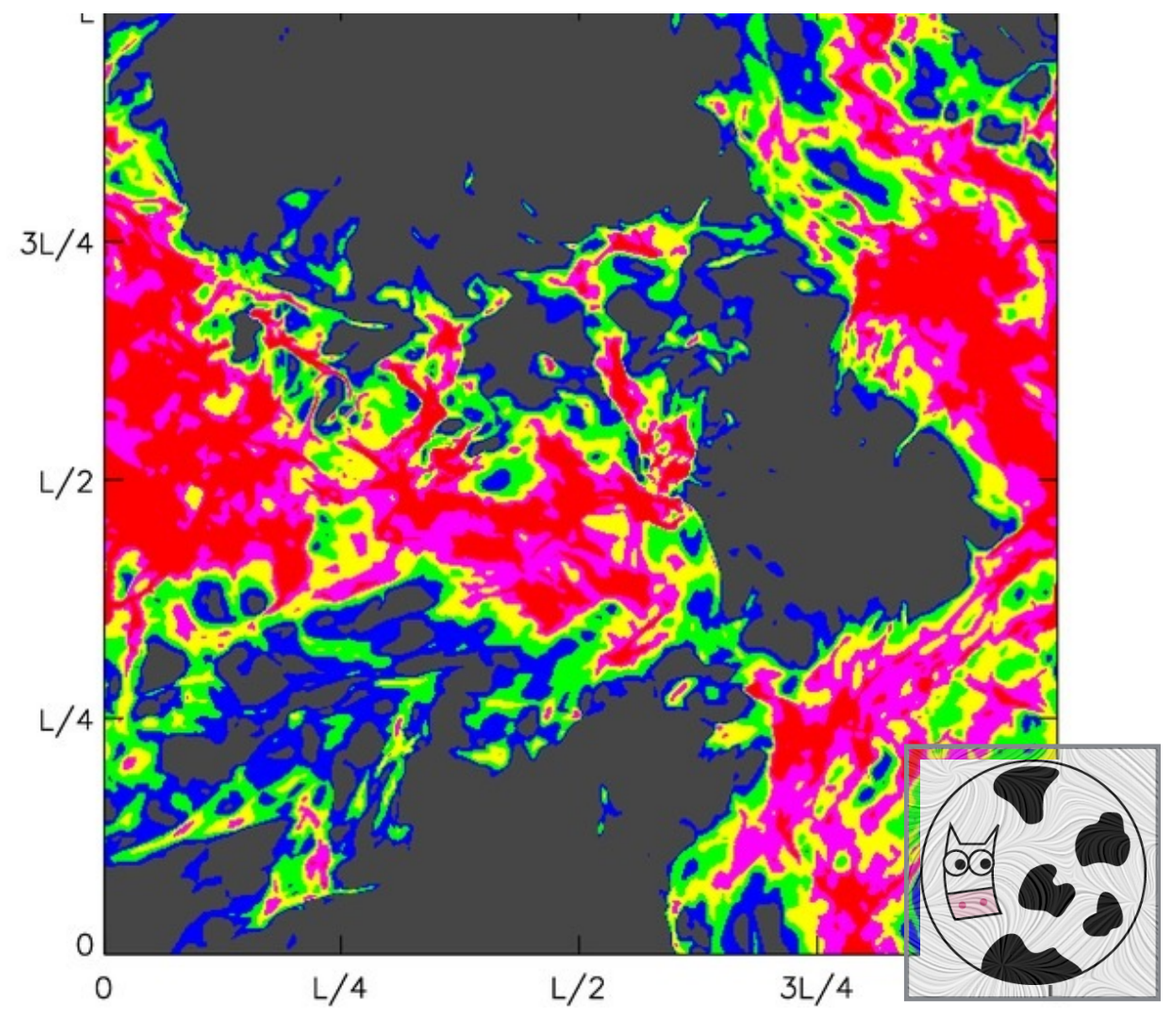
L = 4 pc (2^9 to 2^{11} resolution)
T = 11.4 K
n_0 = 536.4 cm^{-3}
$\mathscr{M}$ = 10.0 (decaying)

Simulations of MHD turbulence by P. Hennebelle


Weak magnetic field
dN/d(cos φ)
cos φ
4.181 < log n < 5.813
3.097 < log n < 3.108
2.760 < log n < 2.767
2.507 < log n < 2.512
2.297 < log n < 2.302
2.109 < log n < 2.113

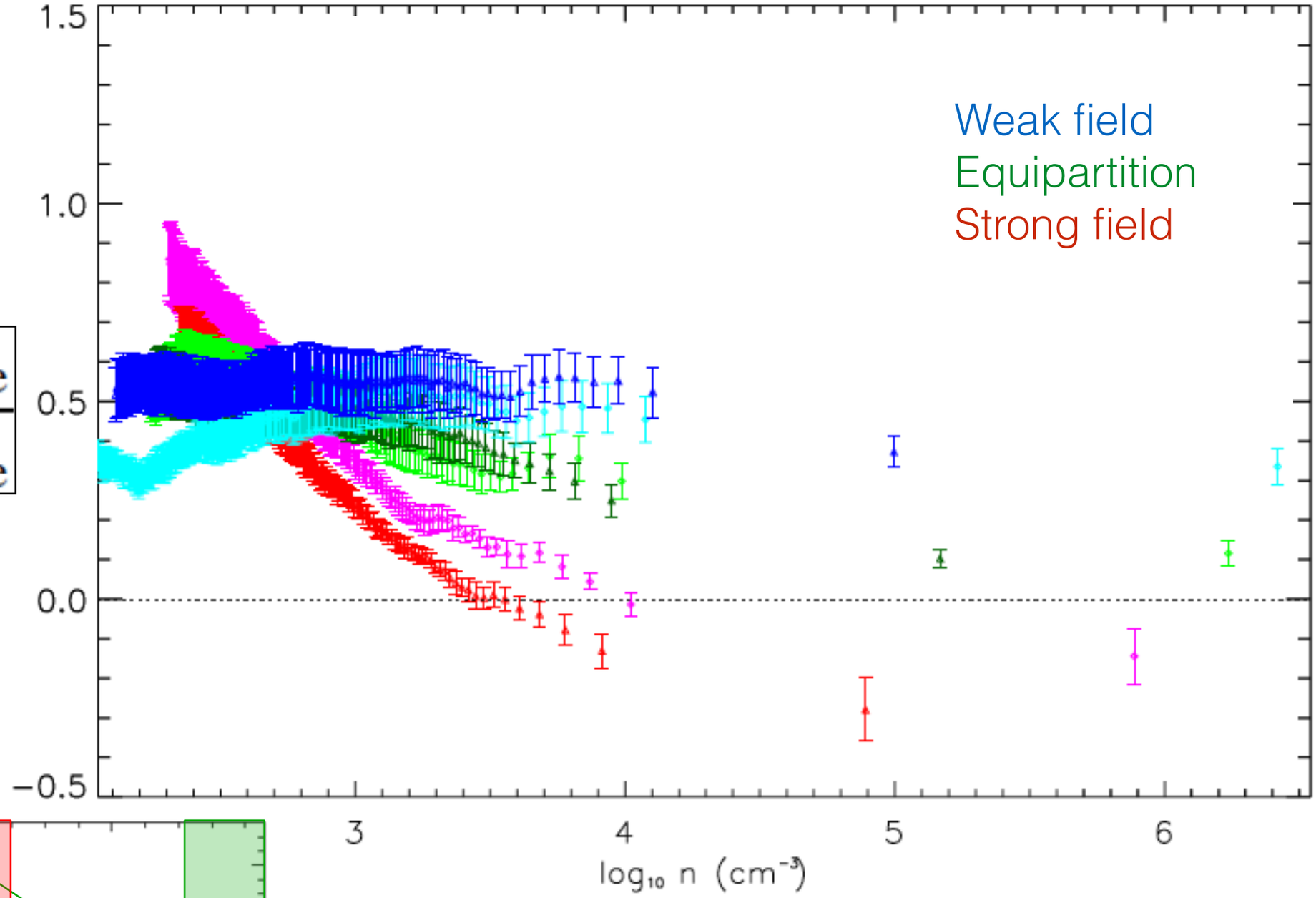

Strong magnetic field
dN/d(cos φ)
cos φ
3.997 < log n < 5.785
3.017 < log n < 3.025
2.769 < log n < 2.774
2.604 < log n < 2.608
2.470 < log n < 2.473
2.349 < log n < 2.351

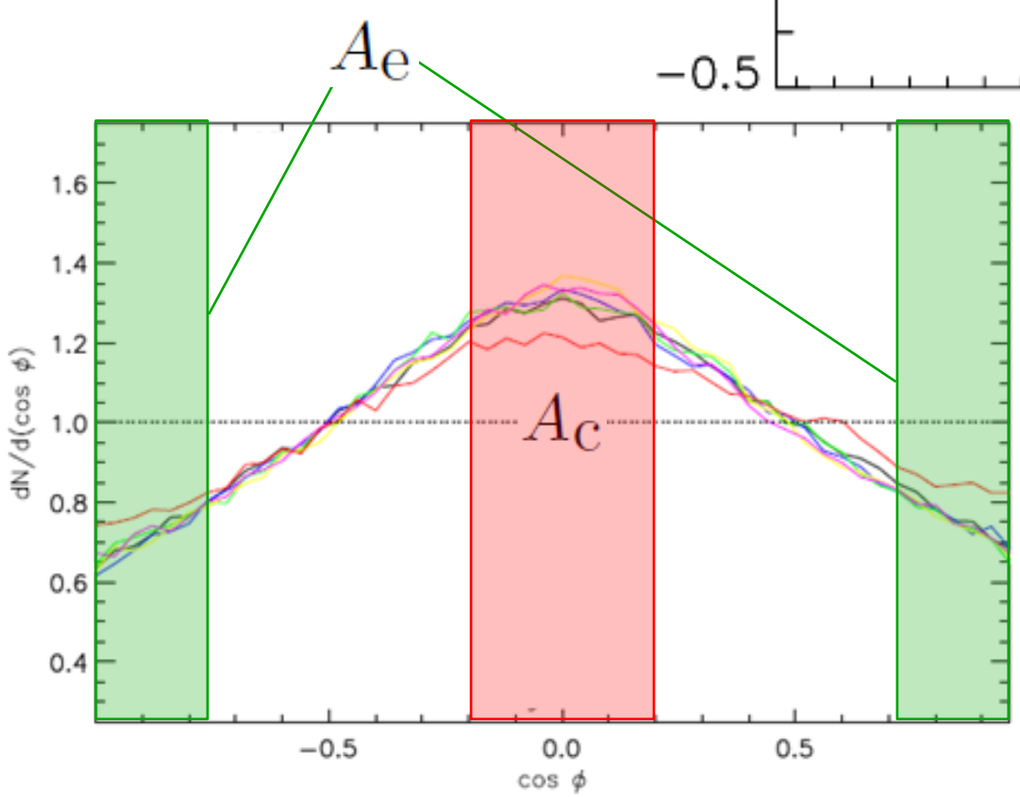

L
3L/4
L/2
L/4
0
0
L/4
L/2
3L/4
L


3L/4
L/2
L/4
0
0
L/4
L/2
3L/4

3D

$$\zeta = \frac{A_c - A_e}{A_c + A_e}$$

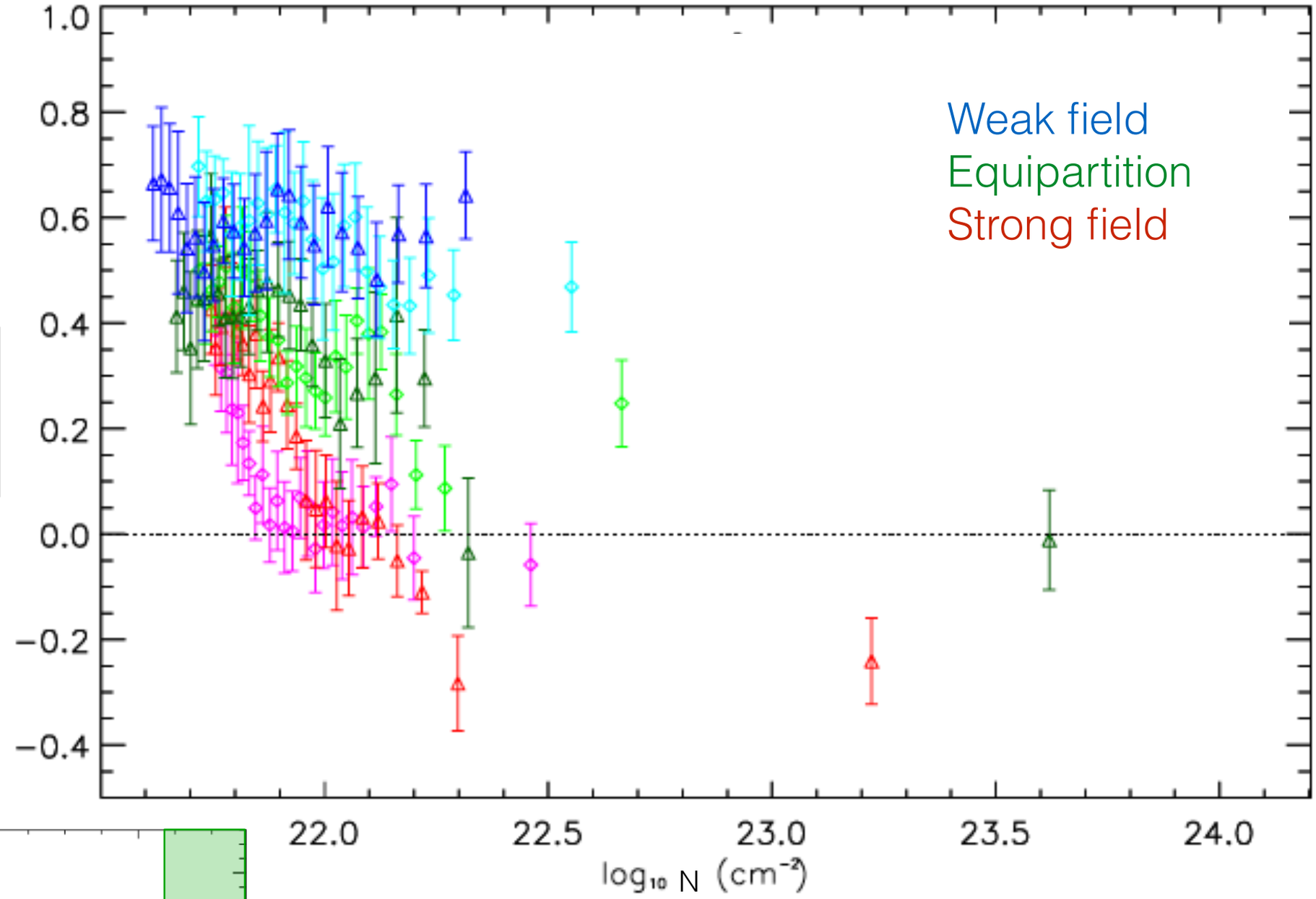


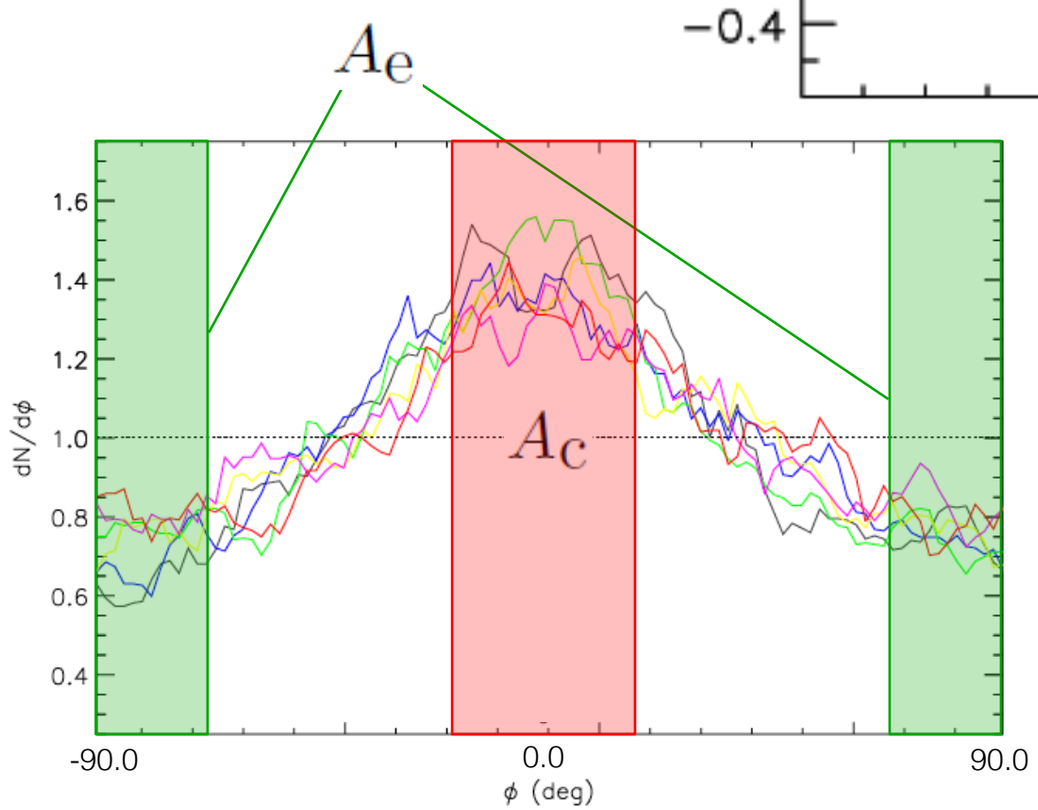


Soler, J.D., et al, ApJ. 774 (2013), 128
Soler, J.D & Hennebelle, P., 2017 A&A in press.

2D

$$\zeta = \frac{A_c - A_e}{A_c + A_e}$$

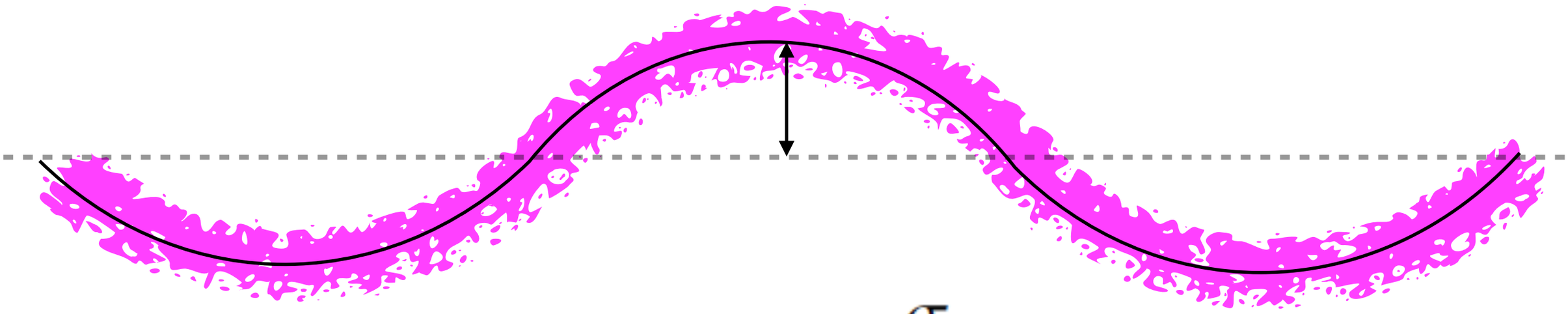




Soler, J.D., et al, ApJ. 774 (2013), 128

Davis-Chandrasekhar-Fermi method

Davis, L., 1951; Chandrasekhar, S. & Fermi, E., 1953; Hildebrand, R. et al., 2009; Houde, M., 2009



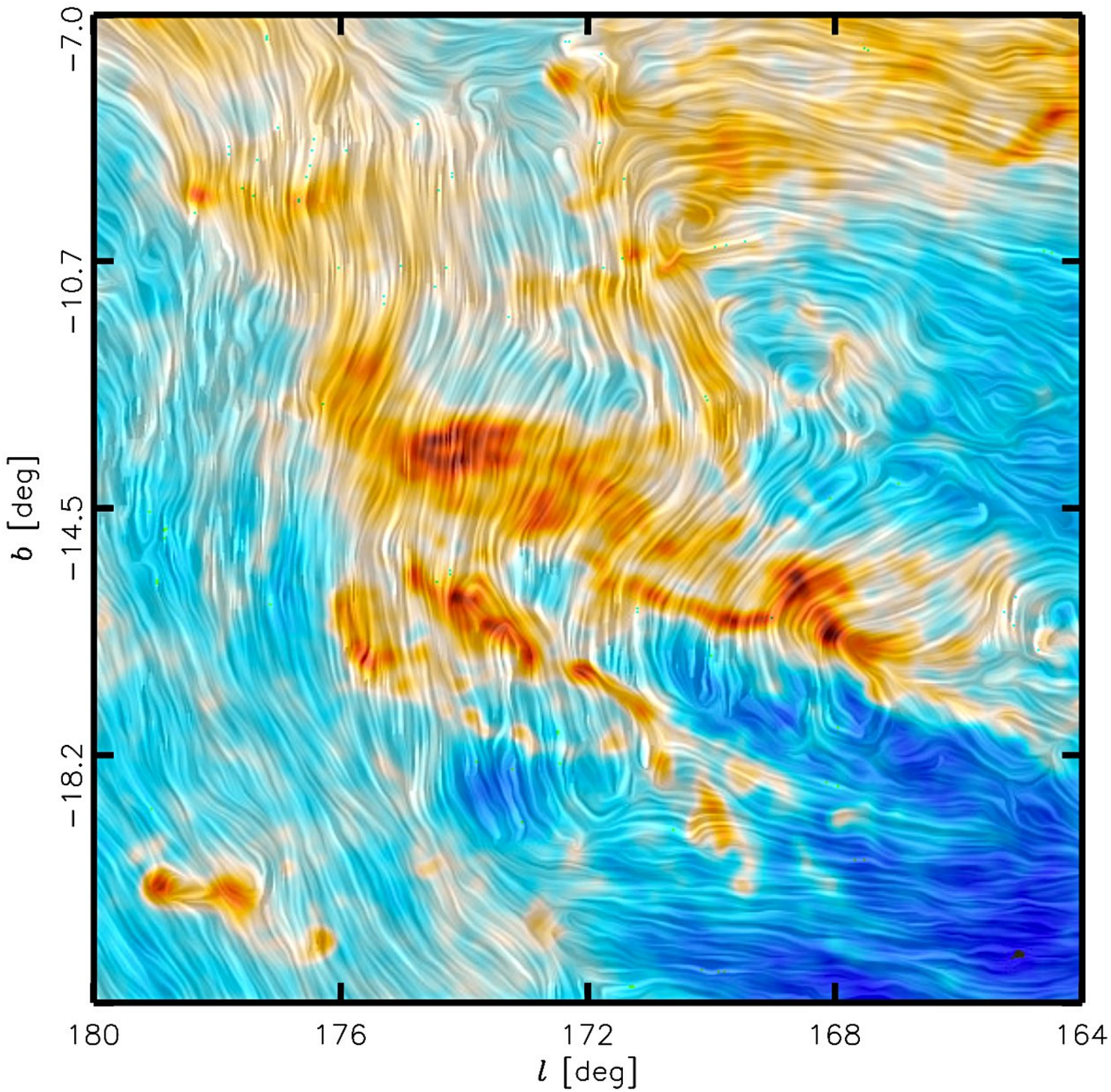
$$B_{\perp}^{\mathrm{CF}} = \sqrt{4\pi\rho}\,\frac{\sigma_{v_{\parallel}}}{S_{\psi}}$$

⚠ CAUTION

1. Magnetic field **not always** frozen into the gas.
2. N_H **is not** n
3. $\boldsymbol{B}_{\perp}$ **is not only** due to transverse incompressible Alfvén waves.
4. $\boldsymbol{v}_{\parallel}$ **depends** on molecular tracer.
5. $\boldsymbol{B}_{\perp}$ and $\boldsymbol{v}_{\parallel}$ **are not** projected in the same way.

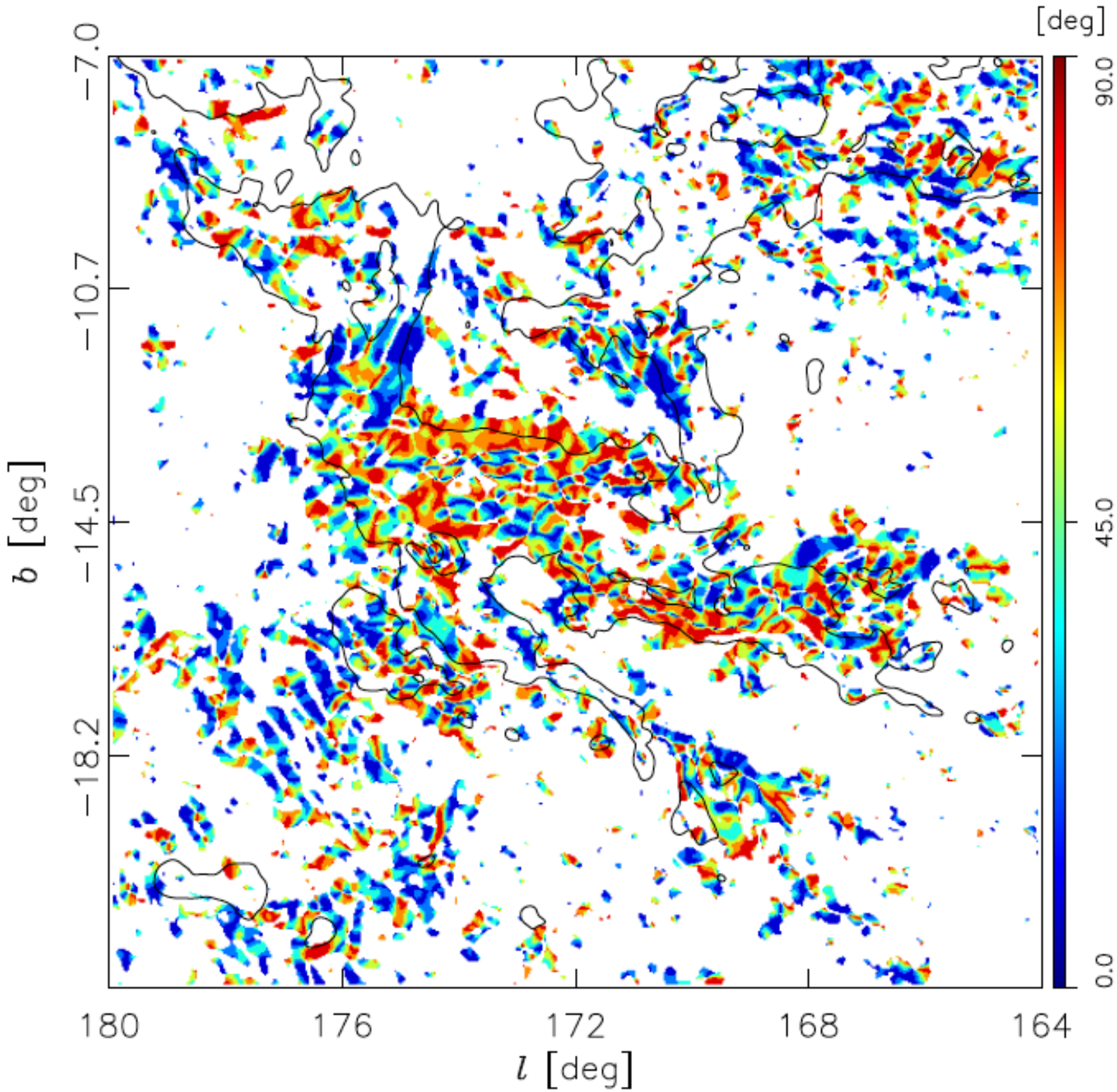
Relative Orientations

Planck intermediate results. XXXV. A&A, 586 (2016) A138 (c.a. Juan D. Soler)



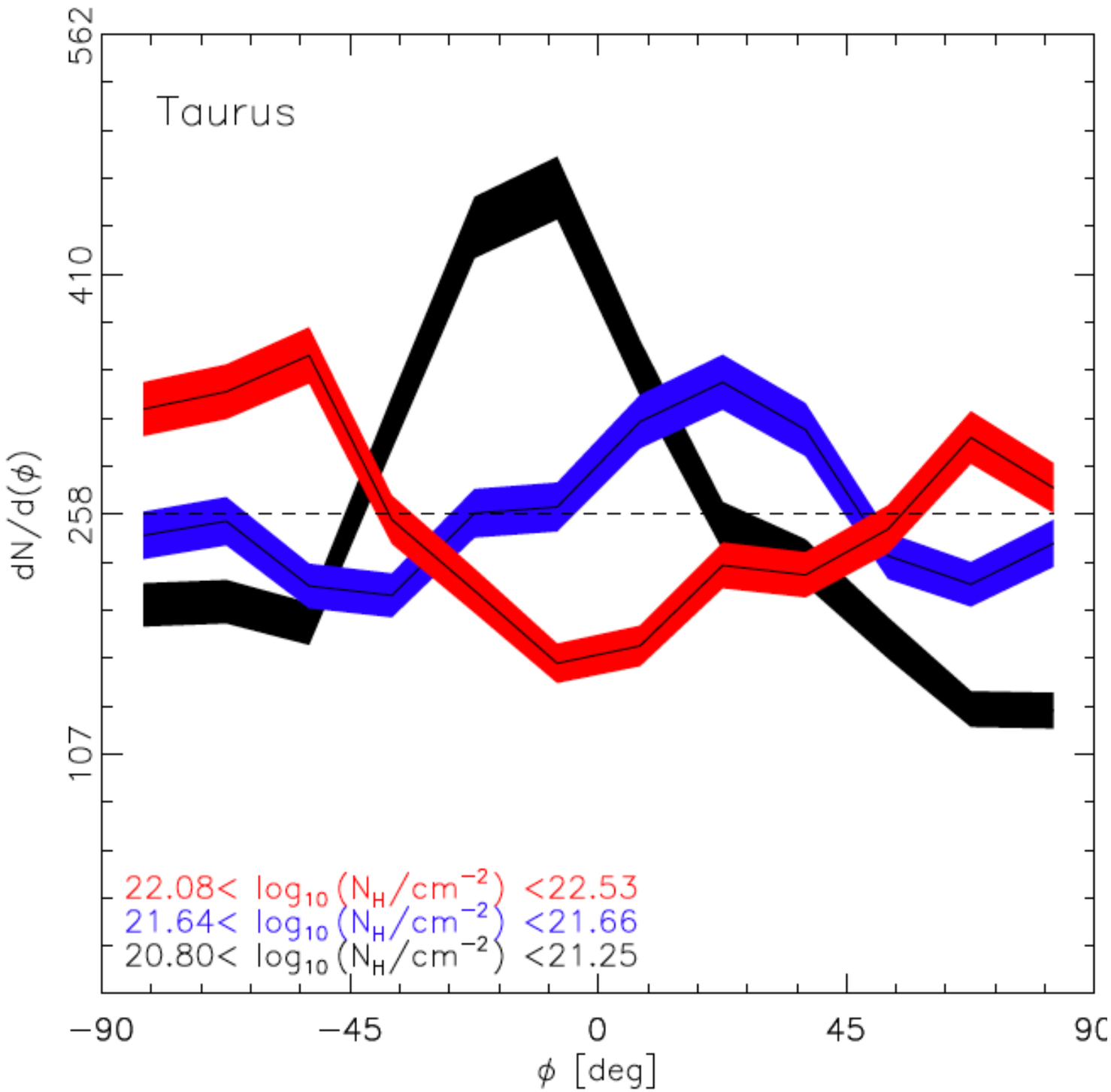
Relative Orientations

Planck intermediate results. XXXV. A&A, 586 (2016) A138 (c.a. Juan D. Soler)

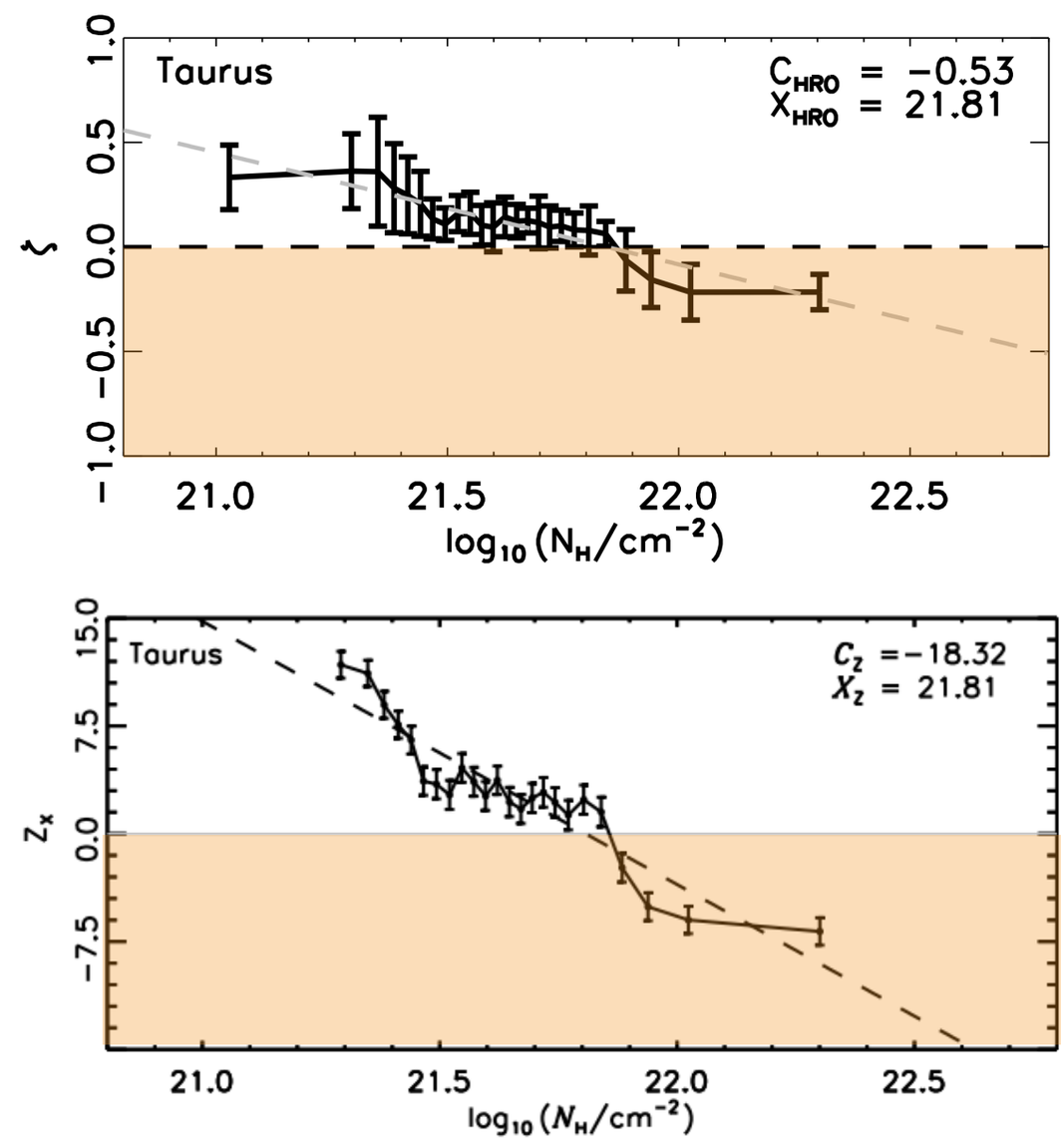


Histogram of Relative Orientations

Planck XXXV. A&A, 586 (2016) A138 (corresponding author: J.D. Soler)



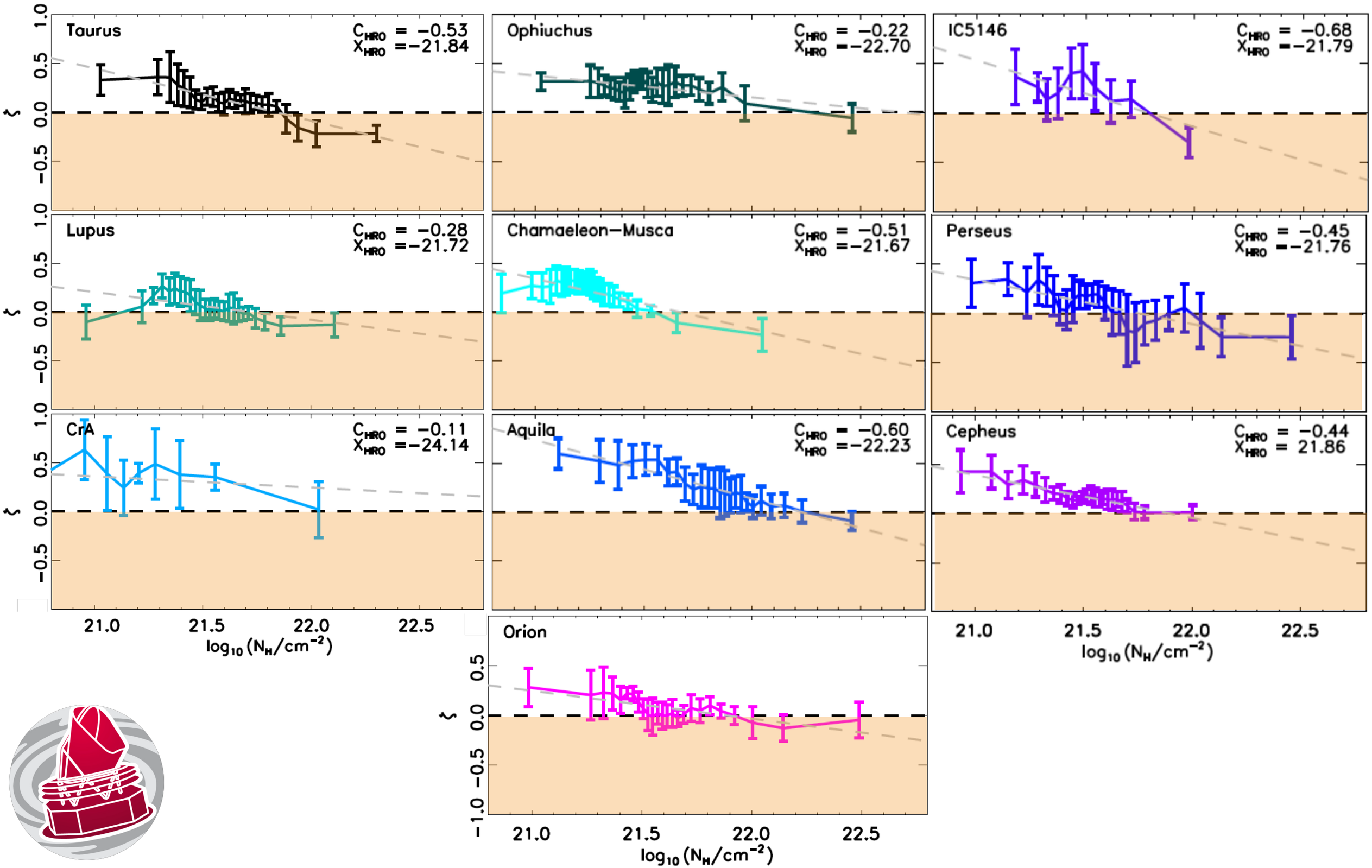
$$\zeta = \frac{A_c - A_e}{A_c + A_e}$$



Jow, D. et al (incl. JDS). A&A submitted. arXiv:1708.04063

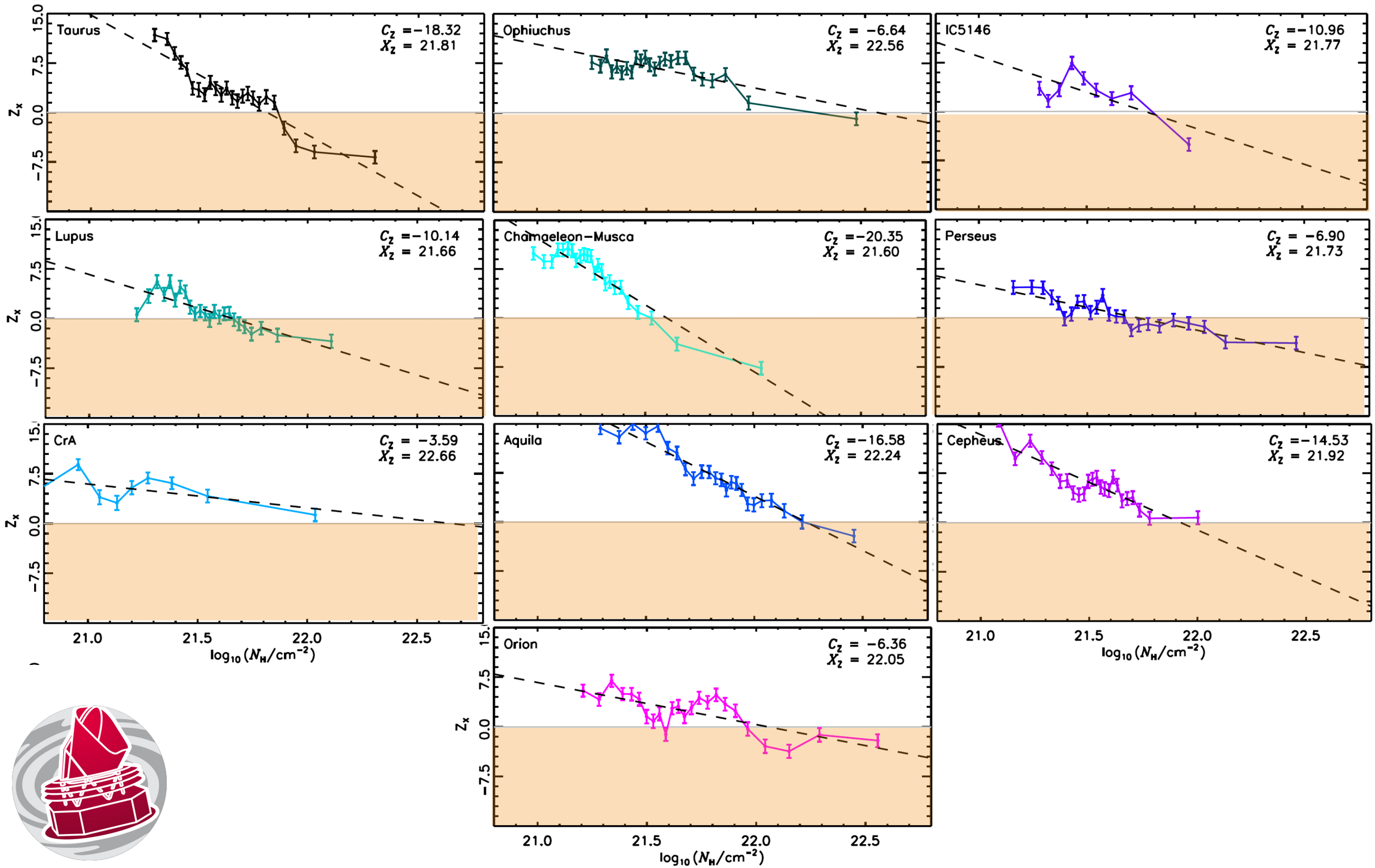
Relative Orientations

Planck intermediate results. XXXV. A&A, 586 (2016) A138 (c.a. Juan D. Soler)



The Projected Rayleigh Statistic

Jow, D., et al. (incl. J. D. Soler). MNRAS (2018) 474, p.1018-1027.



Relative Orientations

Planck XXXV. A&A, 586 (2016) A138 (corresponding author: J.D. Soler)