MAGNETIC FIELDS IN STAR-FORMING CLOUDS

a review by

Juan Diego Soler (MPIA, Heidelberg)

IAU Focus Meeting FM4: Magnetic fields along the star-formation sequence

August 30-31, 2018

$50 \lesssim n_H \lesssim 10^4$ cm^{-3}

$0.1 \lesssim L \lesssim 50$ pc

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biased and brief review by

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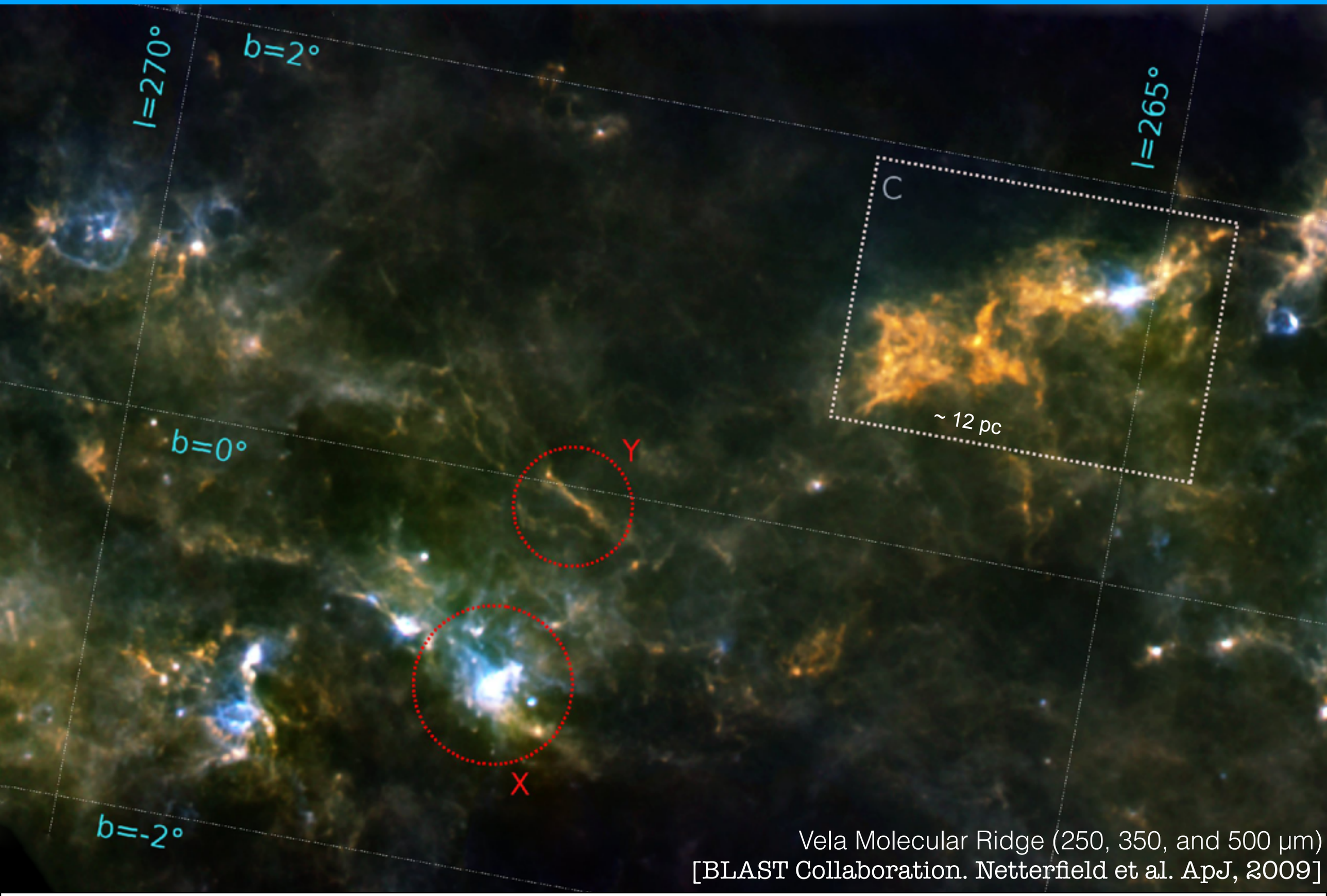
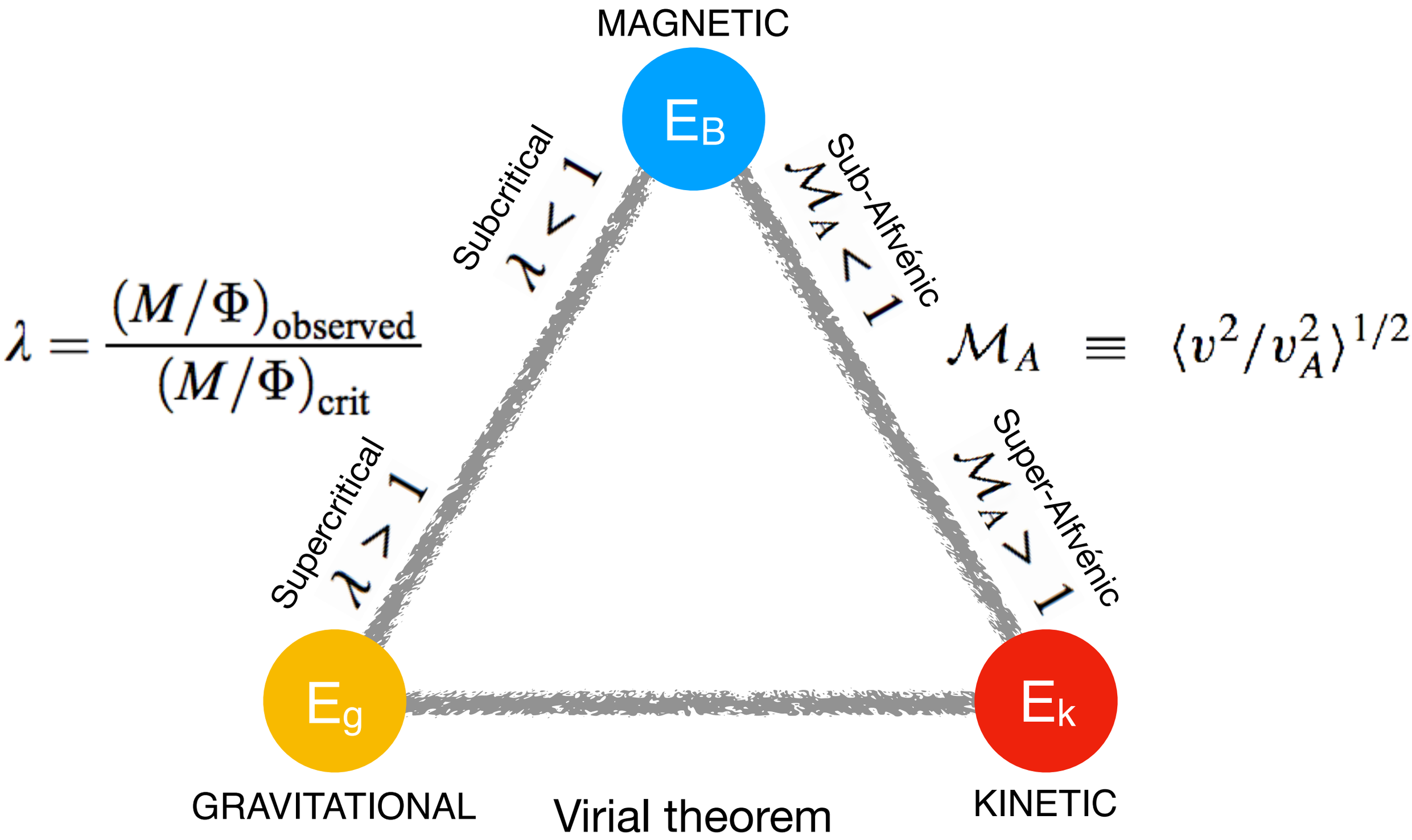
Why does the magnetic field matter for star-forming clouds?



Vela Molecular Ridge (250, 350, and 500 μm)
[BLAST Collaboration. Netterfield et al. ApJ, 2009]

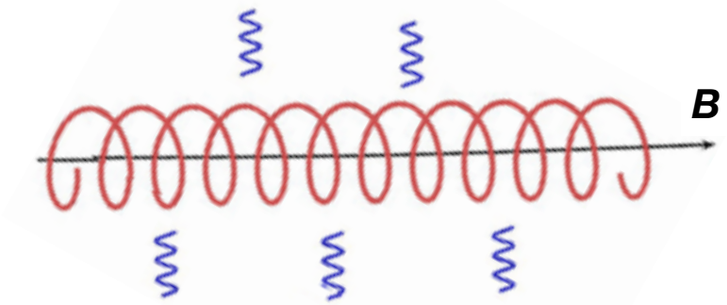
We want to measure *B*!

Nakano, T. & Nakamura, T., 1978; Crutcher, R.M., et al., 2004; McKee, C. & Zweibel, E.G., 1995

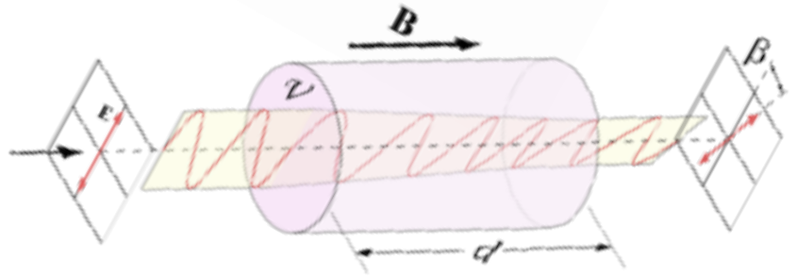


Measuring the magnetic field in the interstellar medium

1. Synchroton polarization

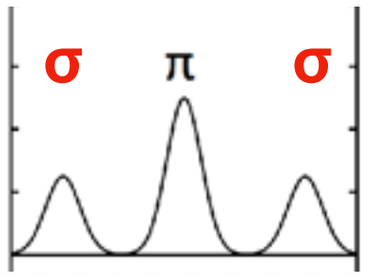


2. Faraday rotation

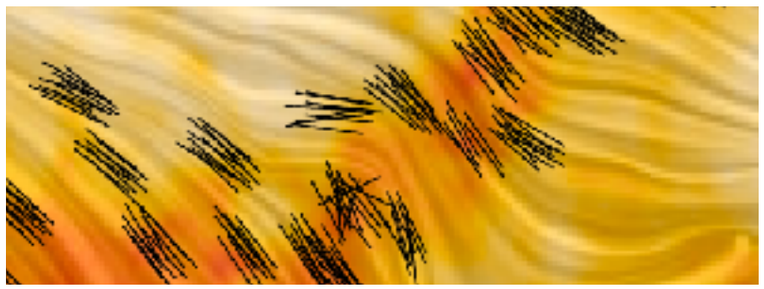


3. Zeeman splitting

4. Goldreich-Kylafis effect

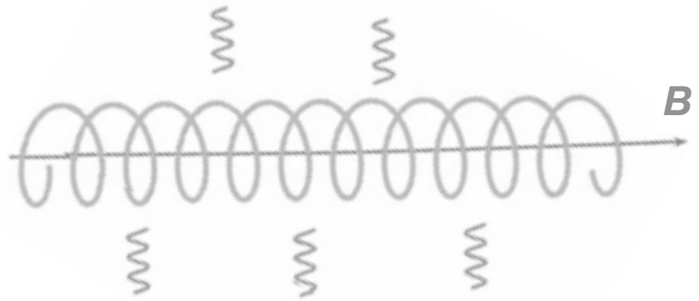


5. Dust polarized absorption/emission



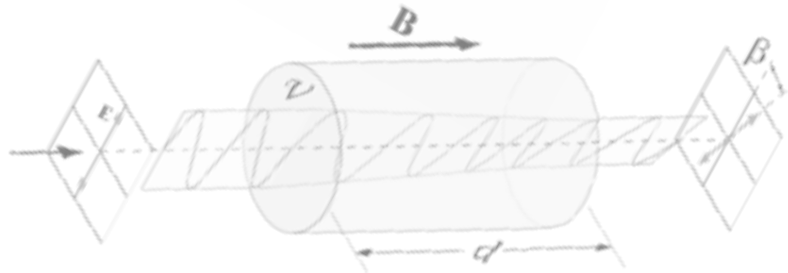
Measuring the magnetic field in star forming clouds

1. Synchroton polarization



2. Faraday rotation

*see talk by M. Tahani 14:10- 30AUG



3. Zeeman splitting

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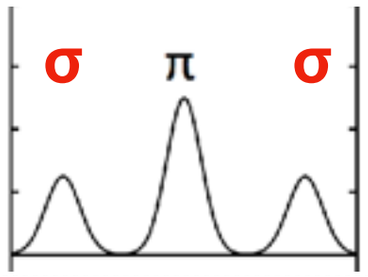

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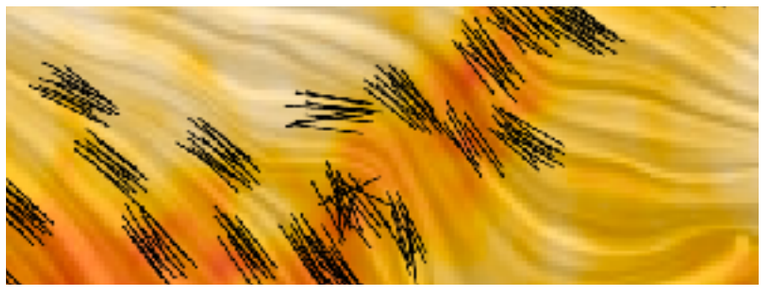
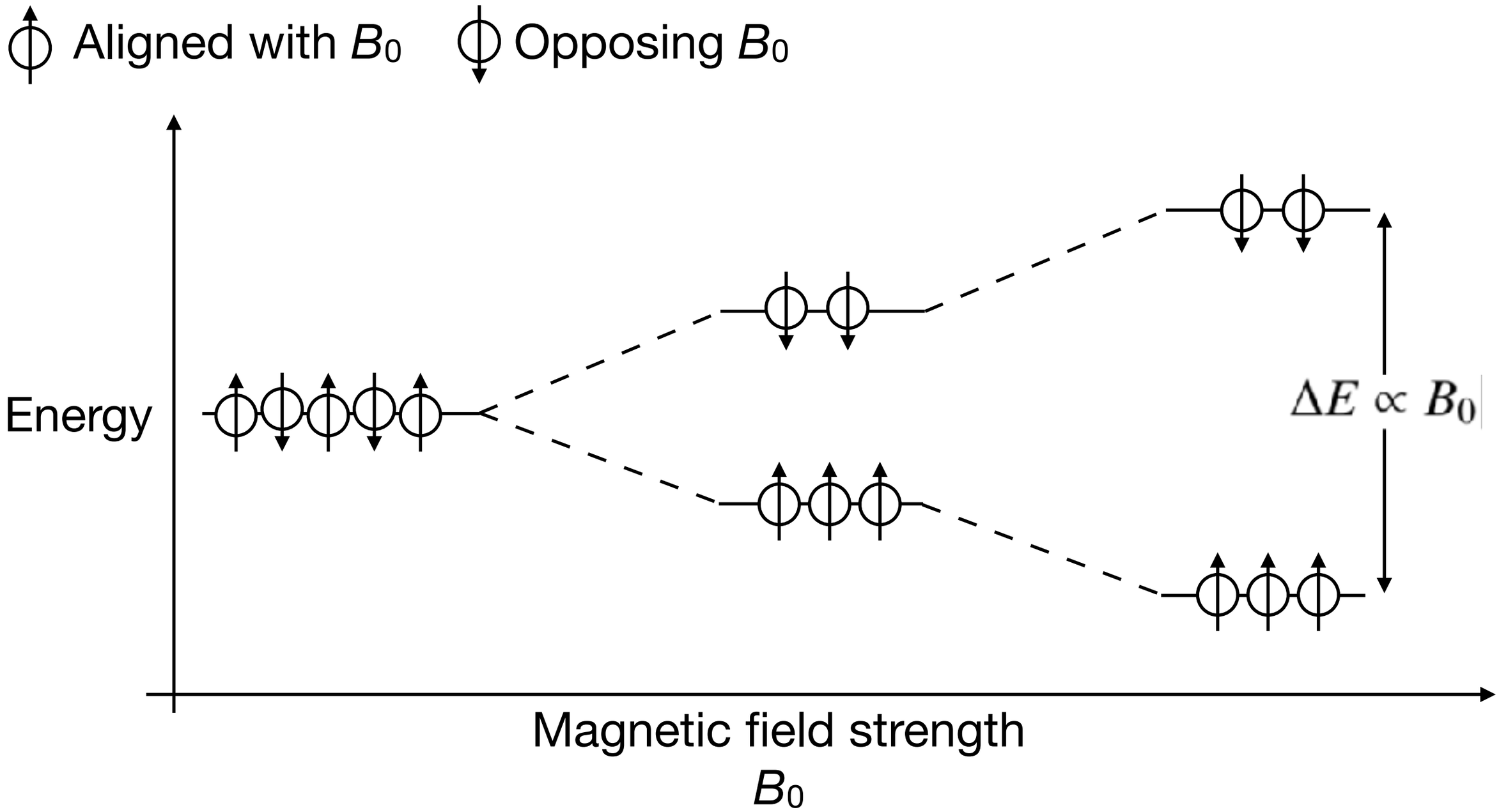


Zeeman splitting

Kamerlingh Onnes (1922)

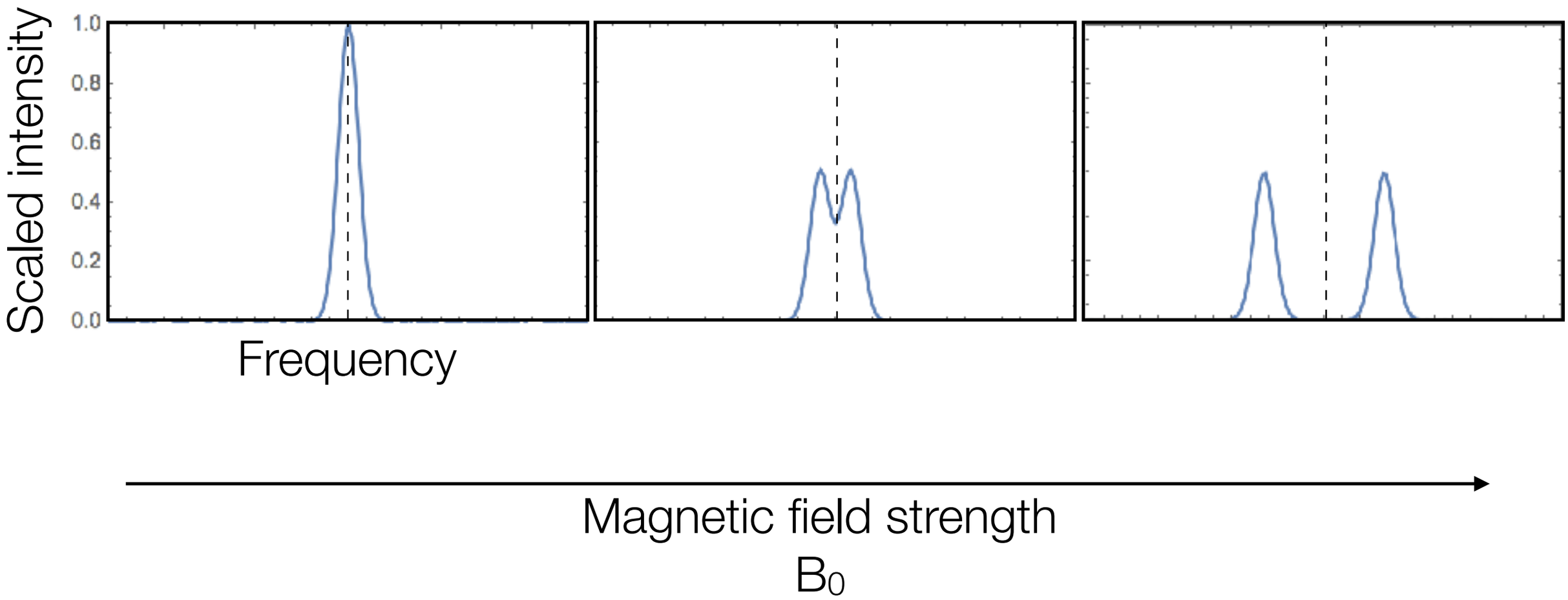
Zeeman splitting

Zeeman, P., ApJ, 5, 332Z (1897)



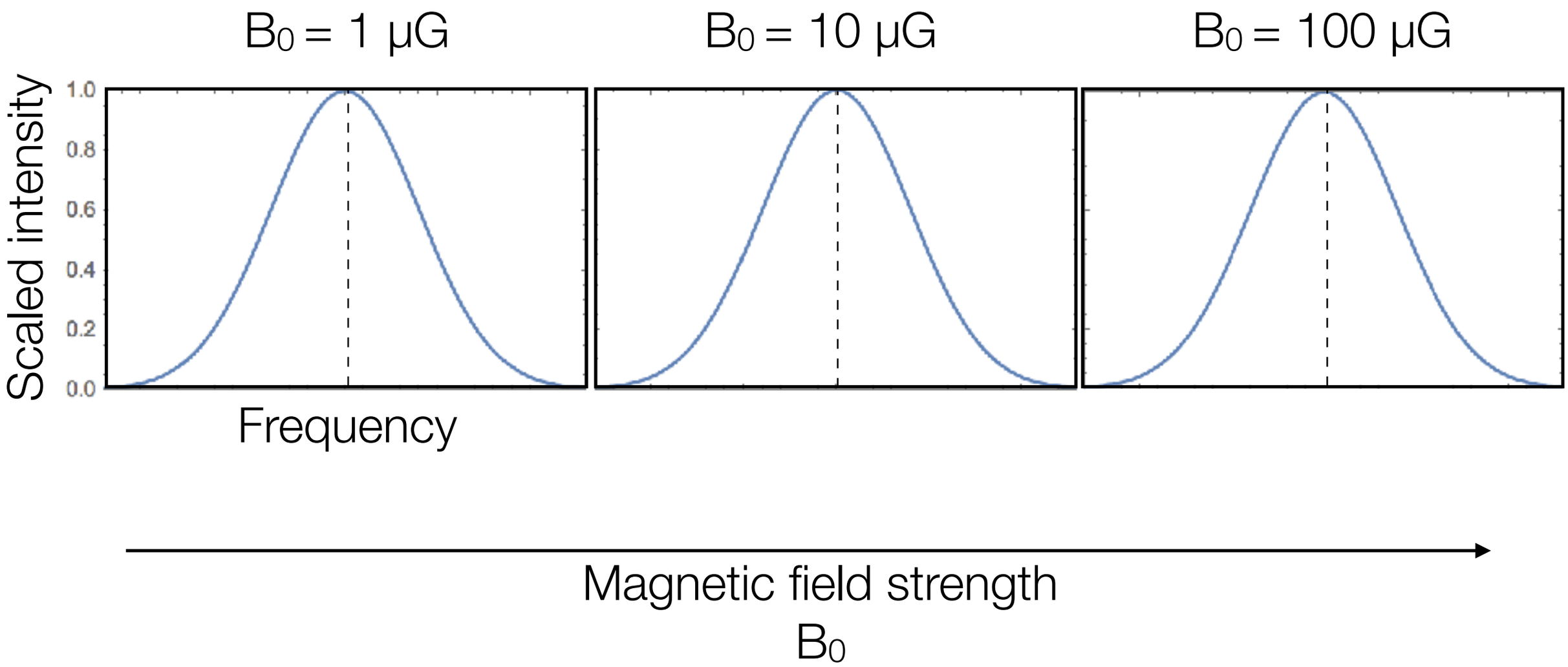
Zeeman splitting

Demonstrations by L. Woolsey (2013)



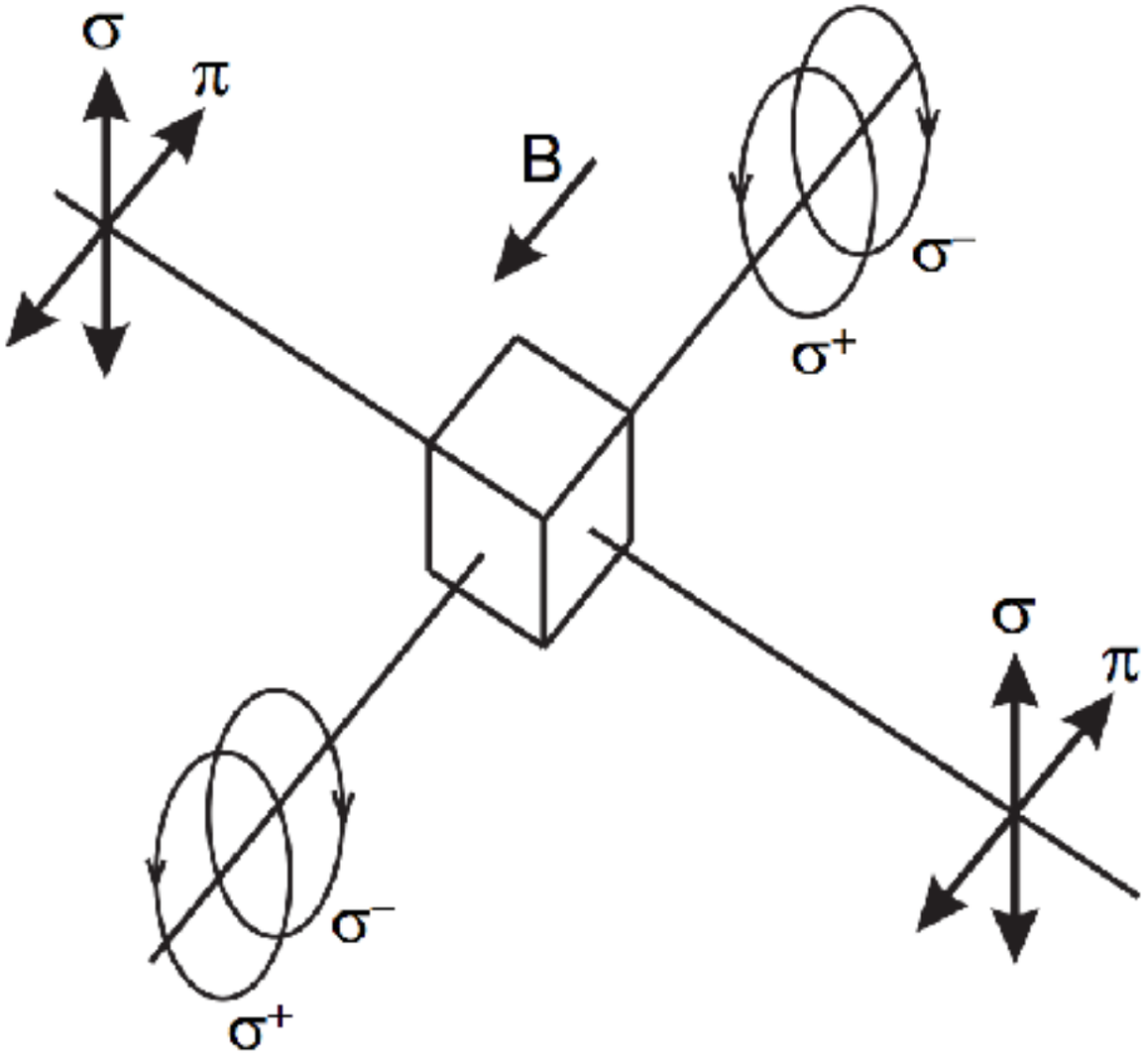
Zeeman splitting in the interstellar medium

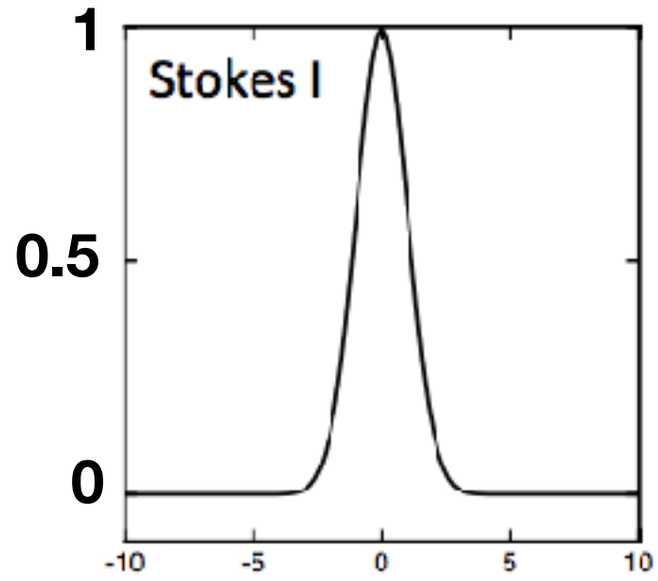
Bolton, J.G. & Wild, J.P. ApJ 125 (1957) 296B
Demonstrations by L. Woolsey (2013)

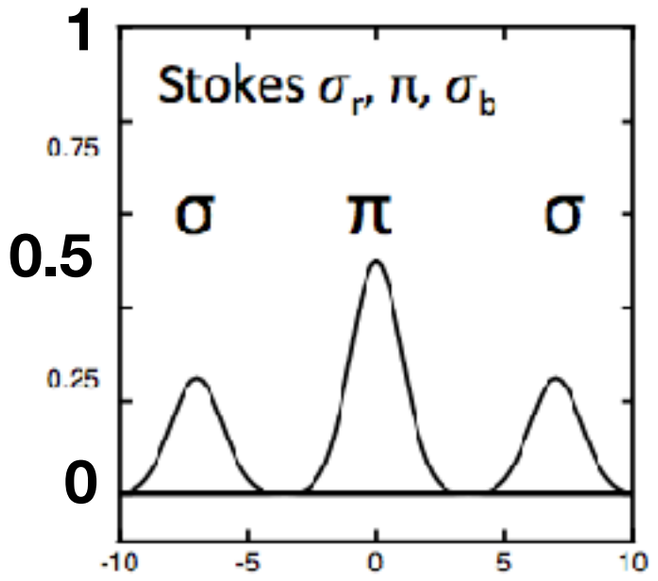


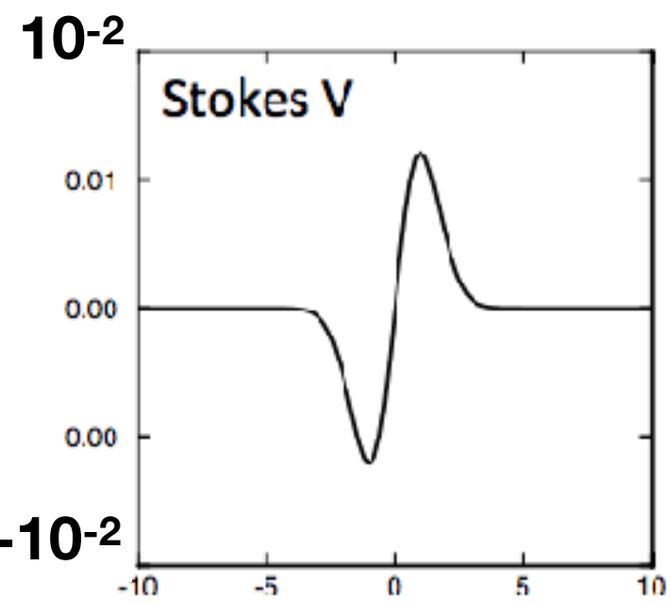
Zeeman splitting in the interstellar medium

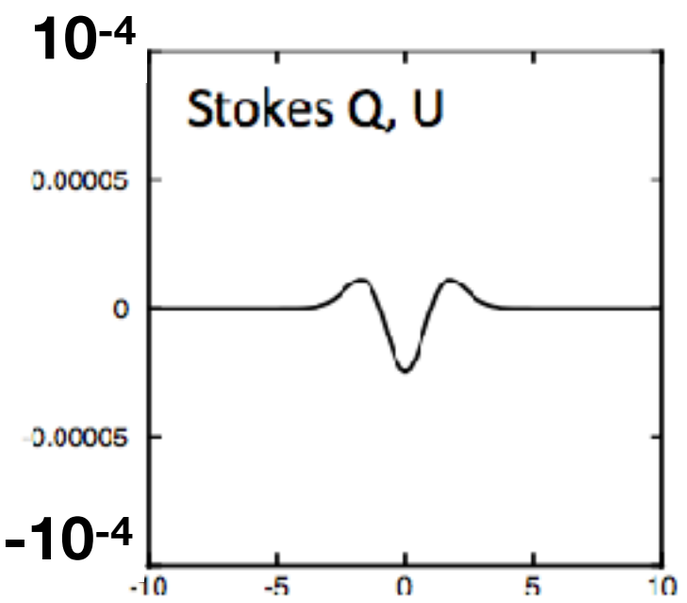
Bolton, J.G. & Wild, J.P. ApJ 125 (1957) 296B
Heiles, C., et al. Protostars and Planets III (1993)







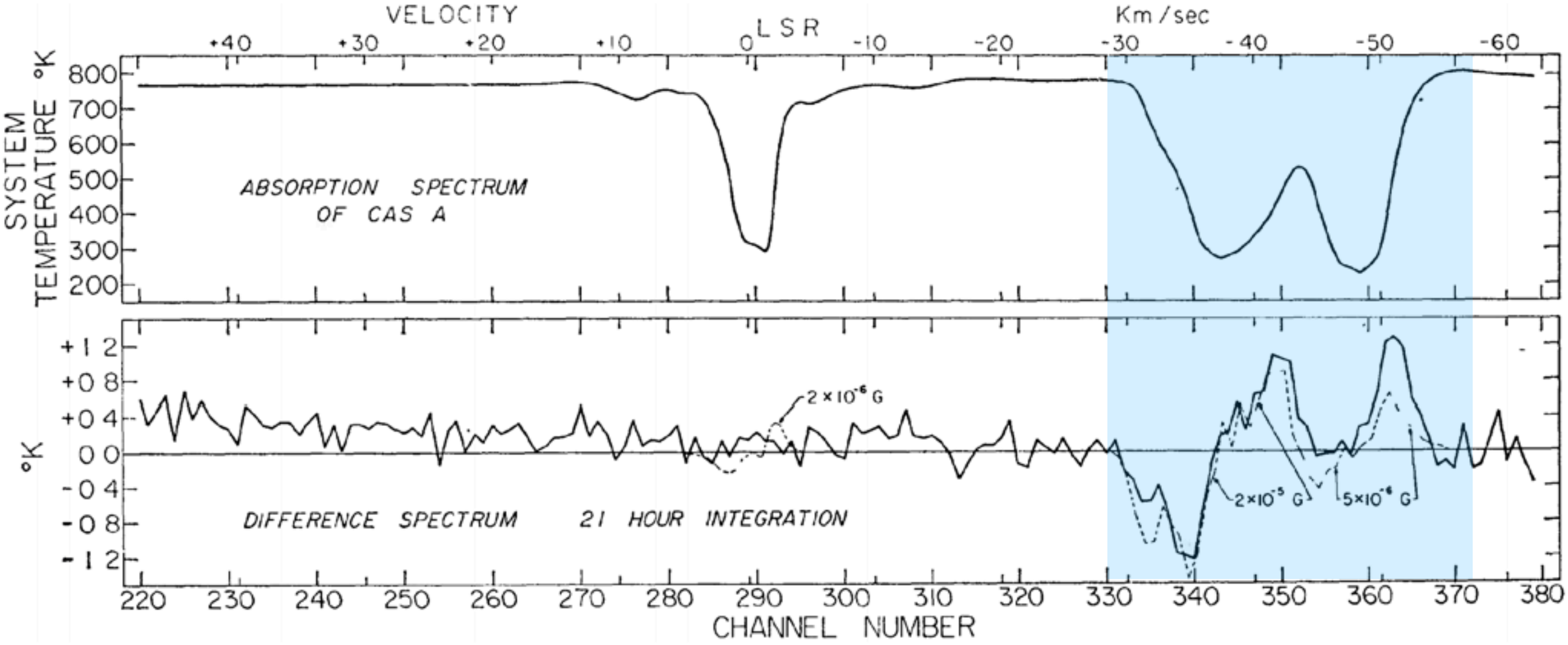




Zeeman splitting in the interstellar medium

Verschuur, G.L. PhRvL. 21 (1968) 775V
Verschuur, G.L. ApJ. 156 (1969) 861V

$B_0 \sim 5 - 20\ \mu G$



Zeeman splitting in the interstellar medium

Crutcher, R.M., et al. ApJ 725, 446C (2010)

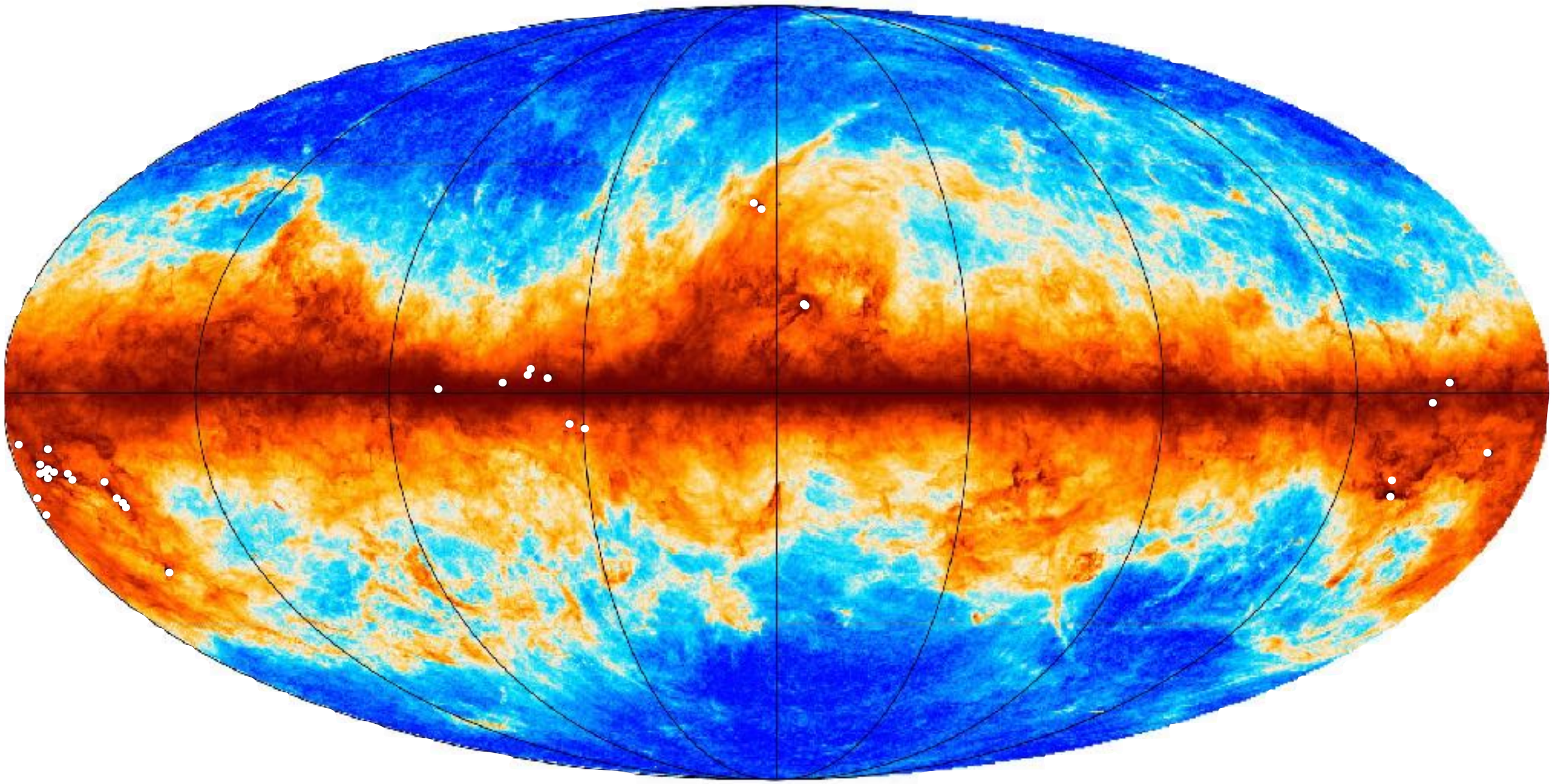
Species	Wavelength	n_H sampled
HI	21 cm	10^1 - 10^2 cm^{-3}
OH	18 cm	10^3 - 10^4 cm^{-3}
CN	2.6 mm (N=1→0) 1.3 mm (N=2→1)	10^5 - 10^7 cm^{-3}

and masers (OH, H_2O, CH_3OH).

Review: Vlemmings, W.H.T., IAU Symposium, Vol. 242, p. 37-46 (2007)
See talk by D. Dall'Olio 10:30- 31AUG

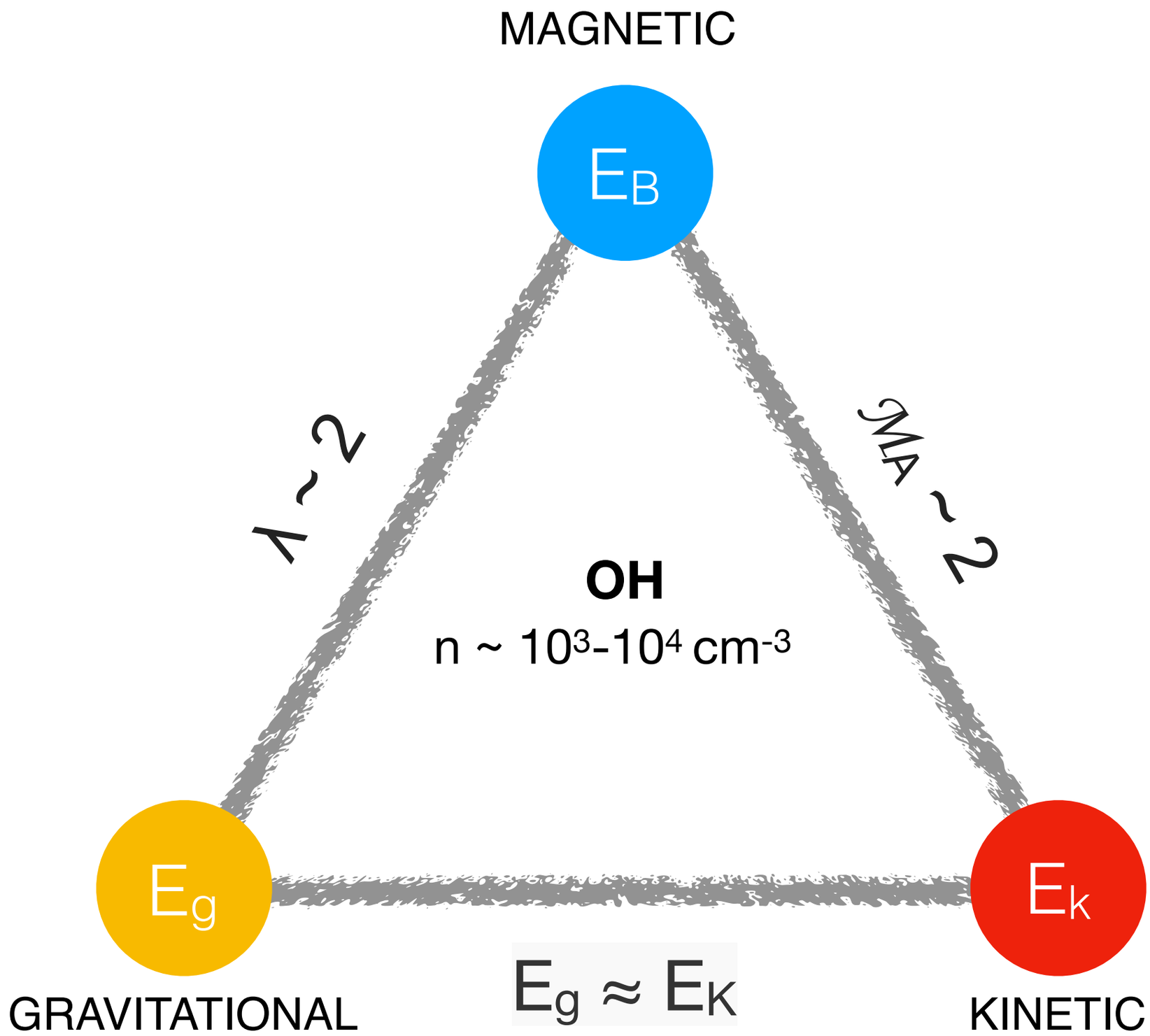
OH Zeeman splitting in emission (500 hours of observations)

Troland, T.H. & Crutcher R.M. ApJ 680, 457C (2008)



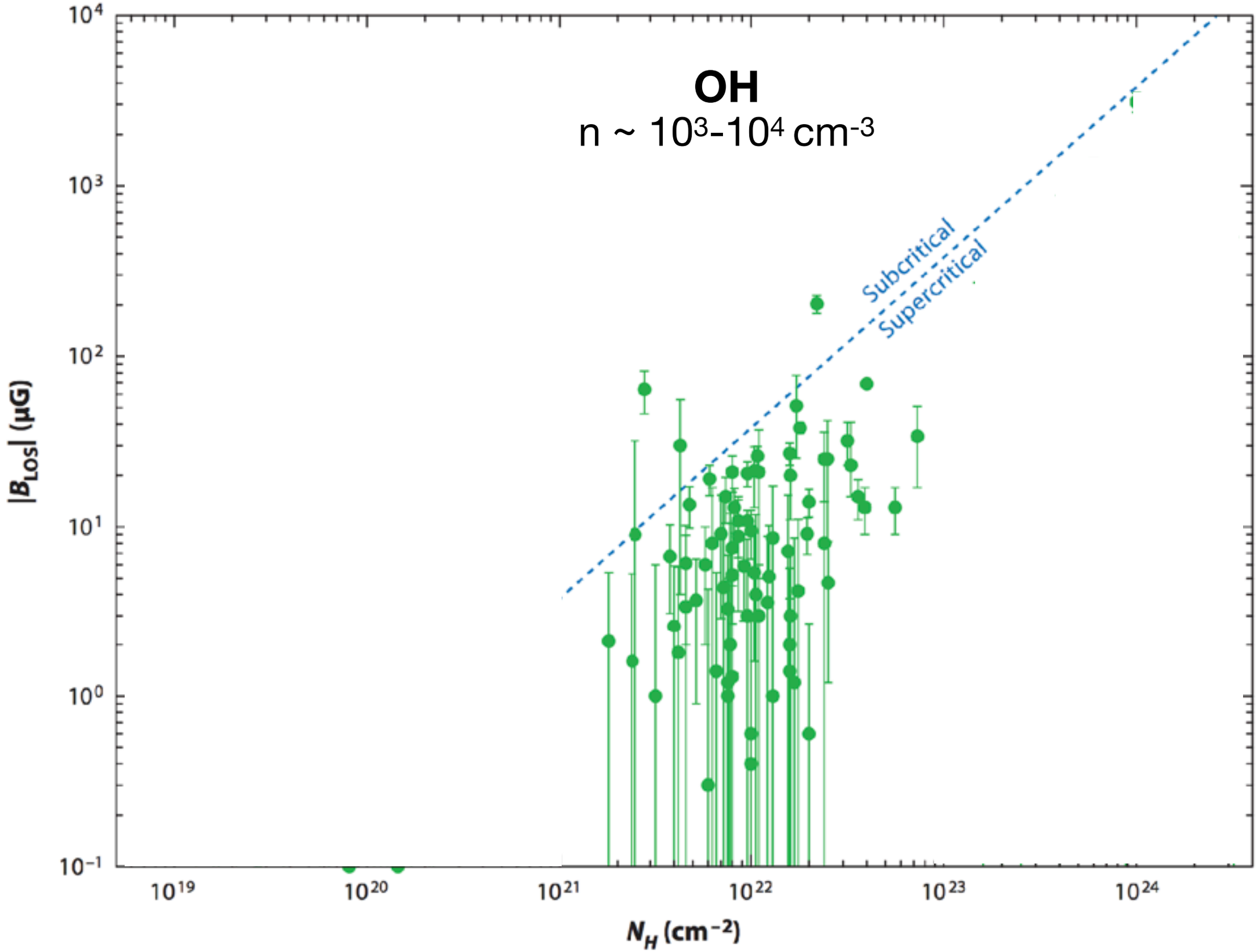
OH Zeeman splitting

Troland, T.H. & Crutcher R.M. ApJ 680, 457C (2008)



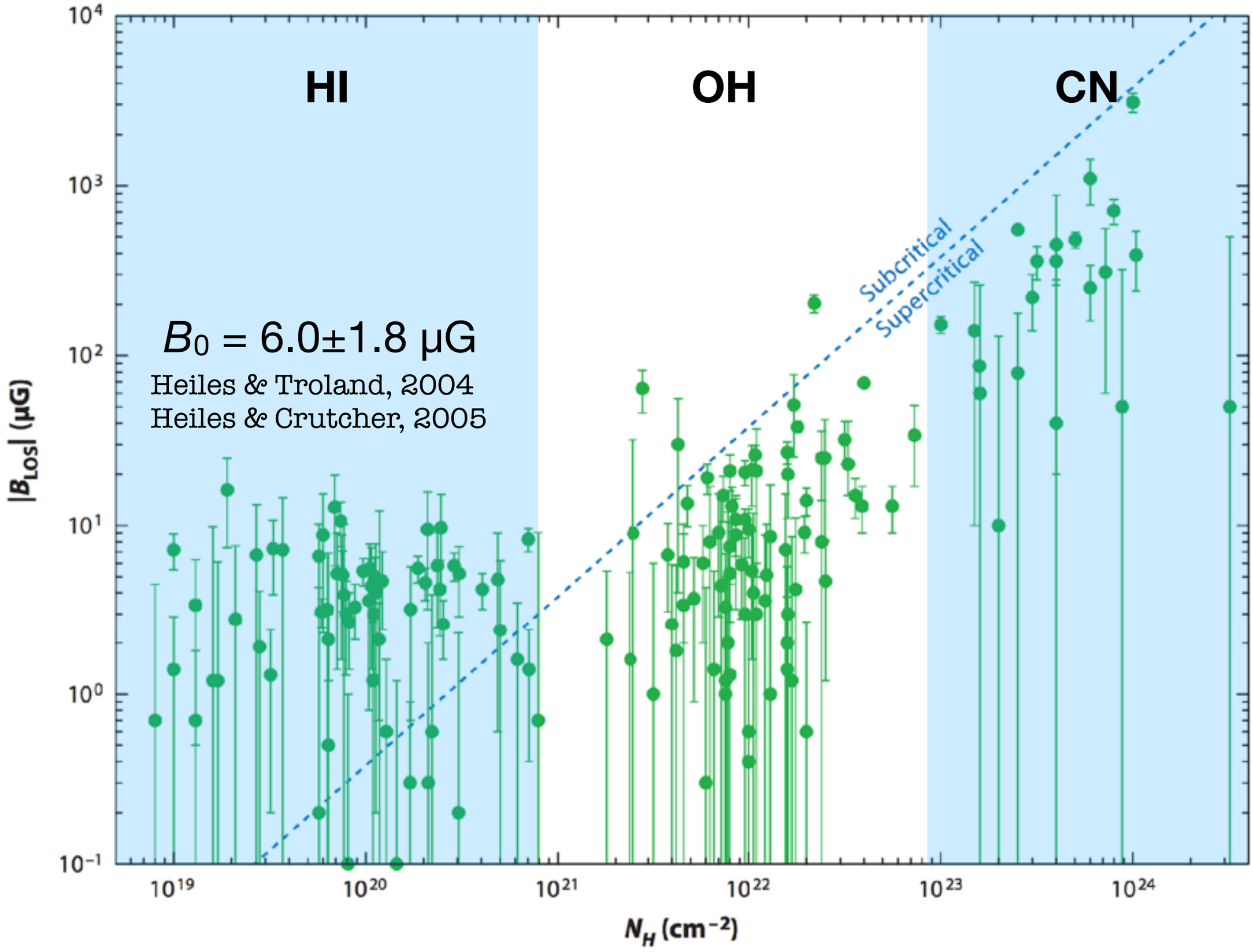
OH Zeeman splitting

Crutcher, R.M., 1999; Troland, T.H. & Crutcher R.M., 2008; Bourke, T., et al. 2008



Zeeman splitting in the interstellar medium

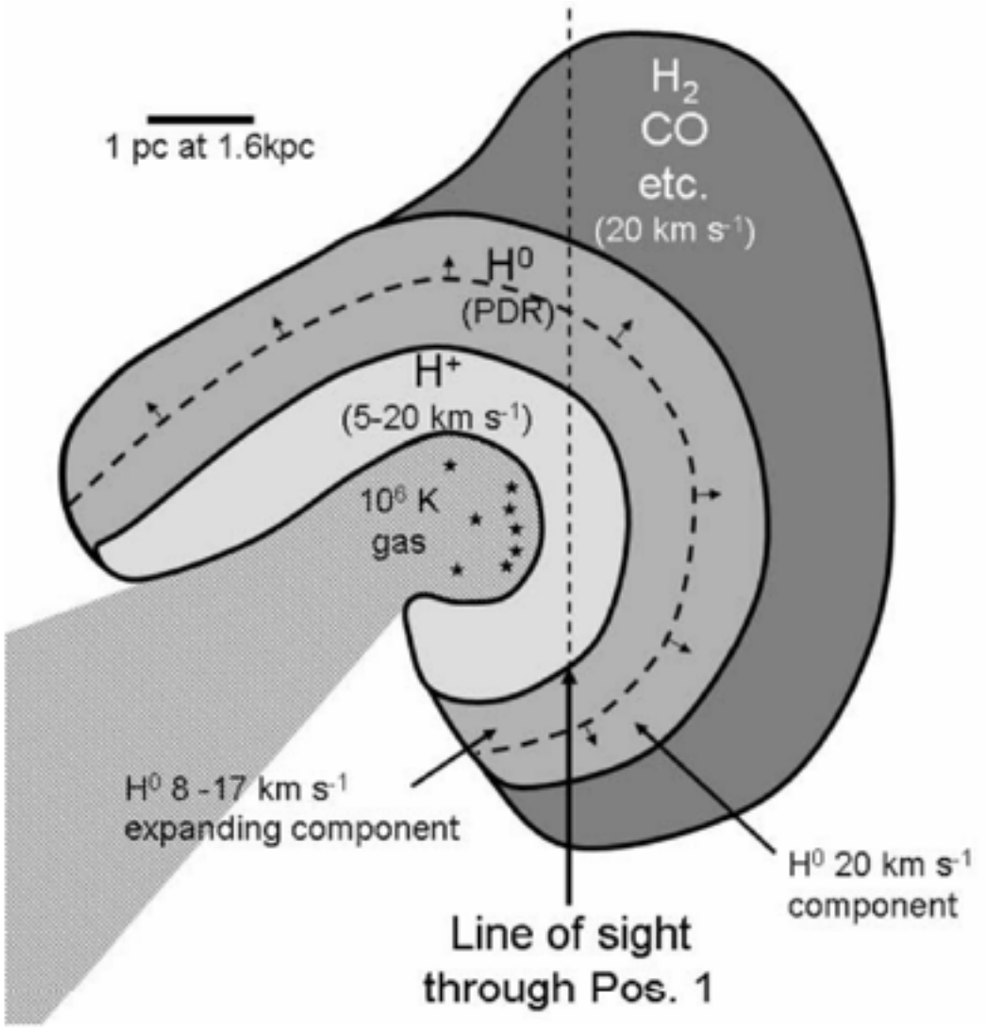
Crutcher, R.M., et al. ApJ 725, 446C (2010); Crutcher, R.M., et al. ApJ 725, 446C (2010)

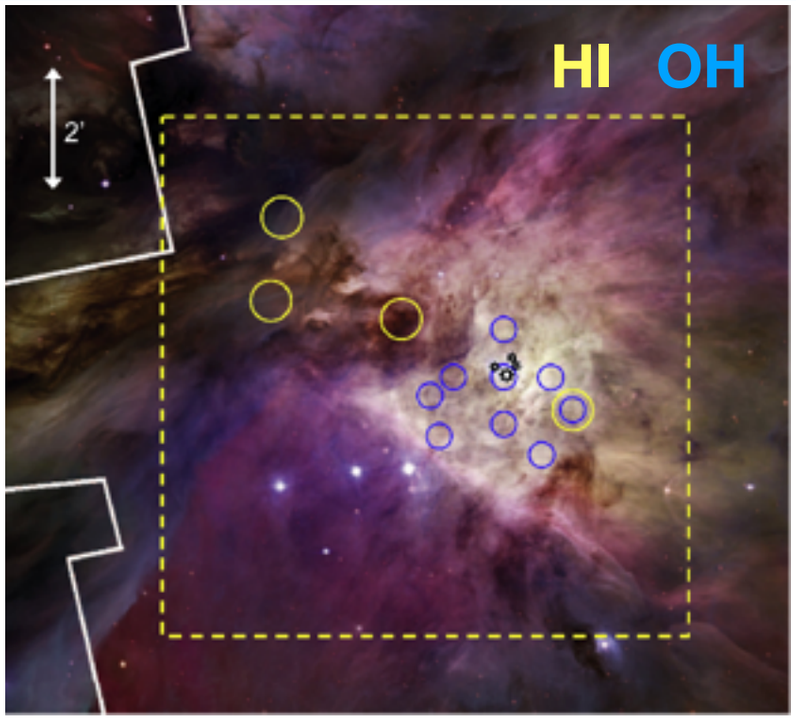


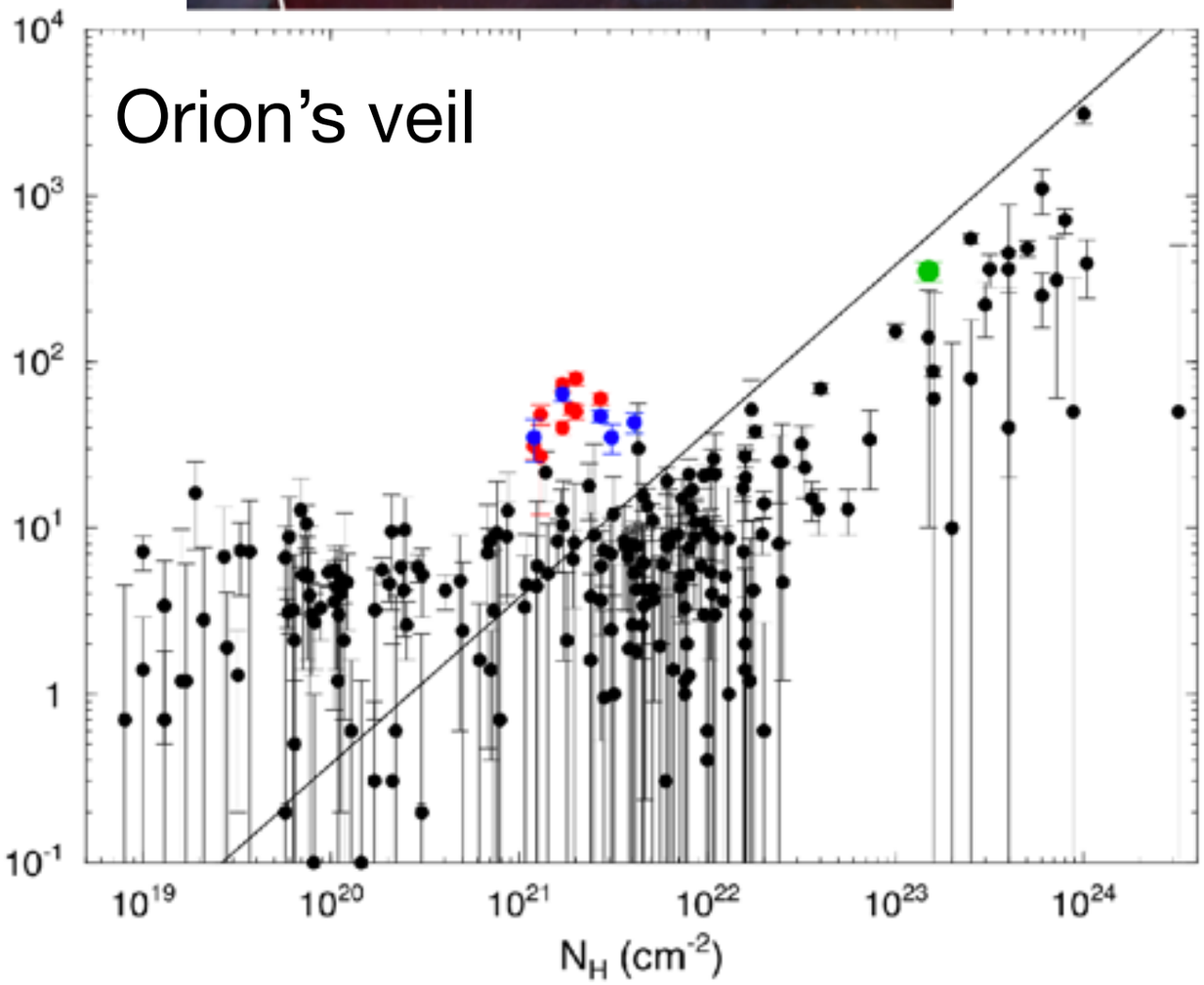
Magnetically supported photodissociation regions (PDRs)

Pellegrini, E., et al. ApJ 658 (2007) 1119P
Troland, T.H. et al. ApJ 825 (2016) 2T

Schematic view of PDR







Goldreich-Kylafis effect

Image: 2001: A Space Odyssey. Warner Bros.

Goldreich-Kylafis effect

Goldreich, P. & Kylafis, N.D., ApJ, 243, 75G (1981)

Linear polarization of molecular line emission

It happens if:

1. **Radiative** dominates collisional excitation.
2. Local **anisotropy** in line optical depths
   OR **anisotropy** in radiation field.
3. Line optical depth, **τ~1**.

Result:

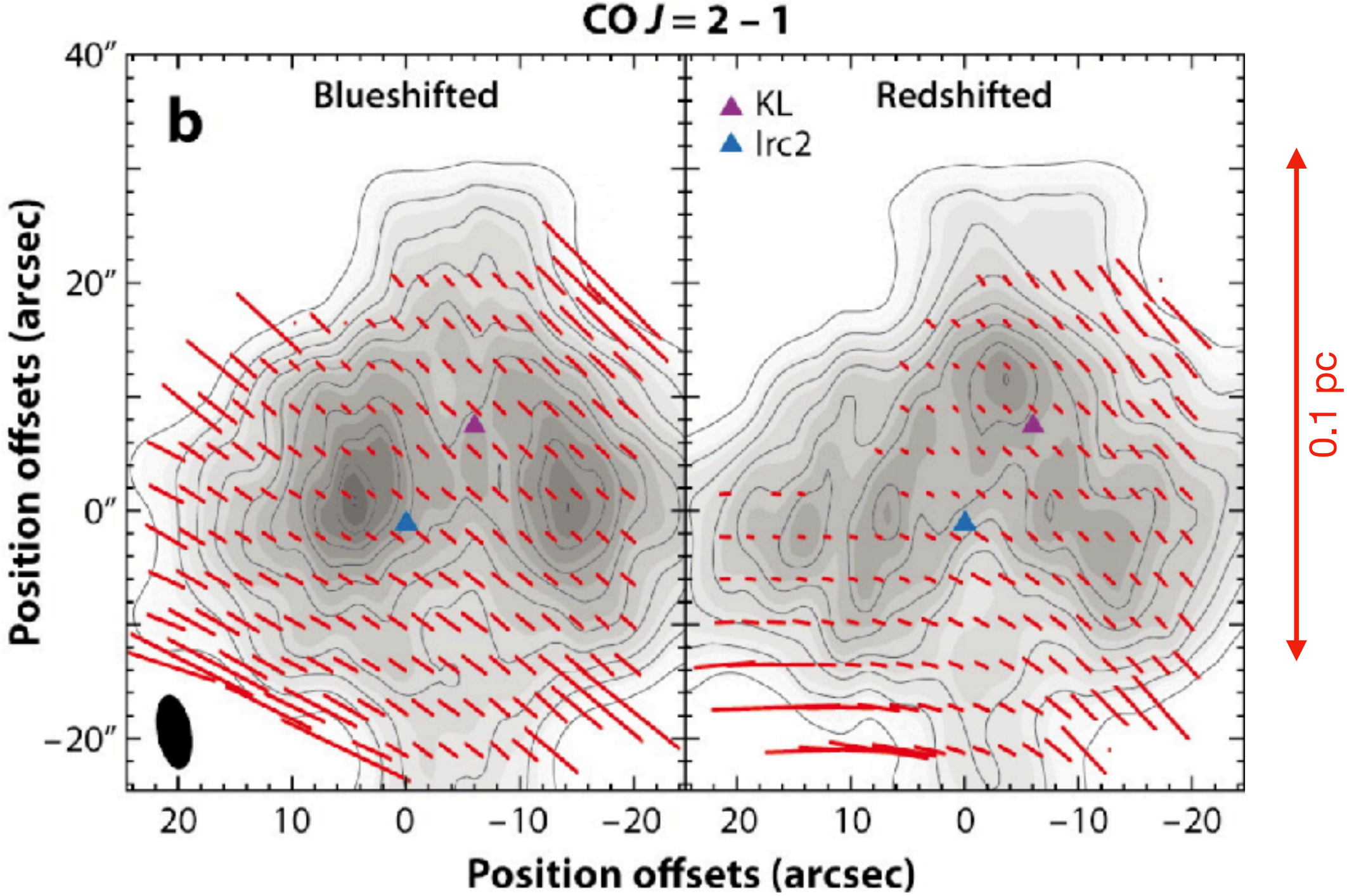
- Non-LTE population of magnetic sublevels.
- Linearly polarized spectral lines.
- Linear polarization is **∥ or ⊥ to $B_\perp$**.

see poster by G.H.M. Bertrang
M. Chamma

Goldreich-Kylafis effect (CO J = 2→1 towards Orion KL/IRc2)

Girart, J.M., et al. Ap&SS 292, 119-125 (2004)
Crutcher, R.M. Annu. Rev. Astron. Astrophys. 50:29-63 (2012)

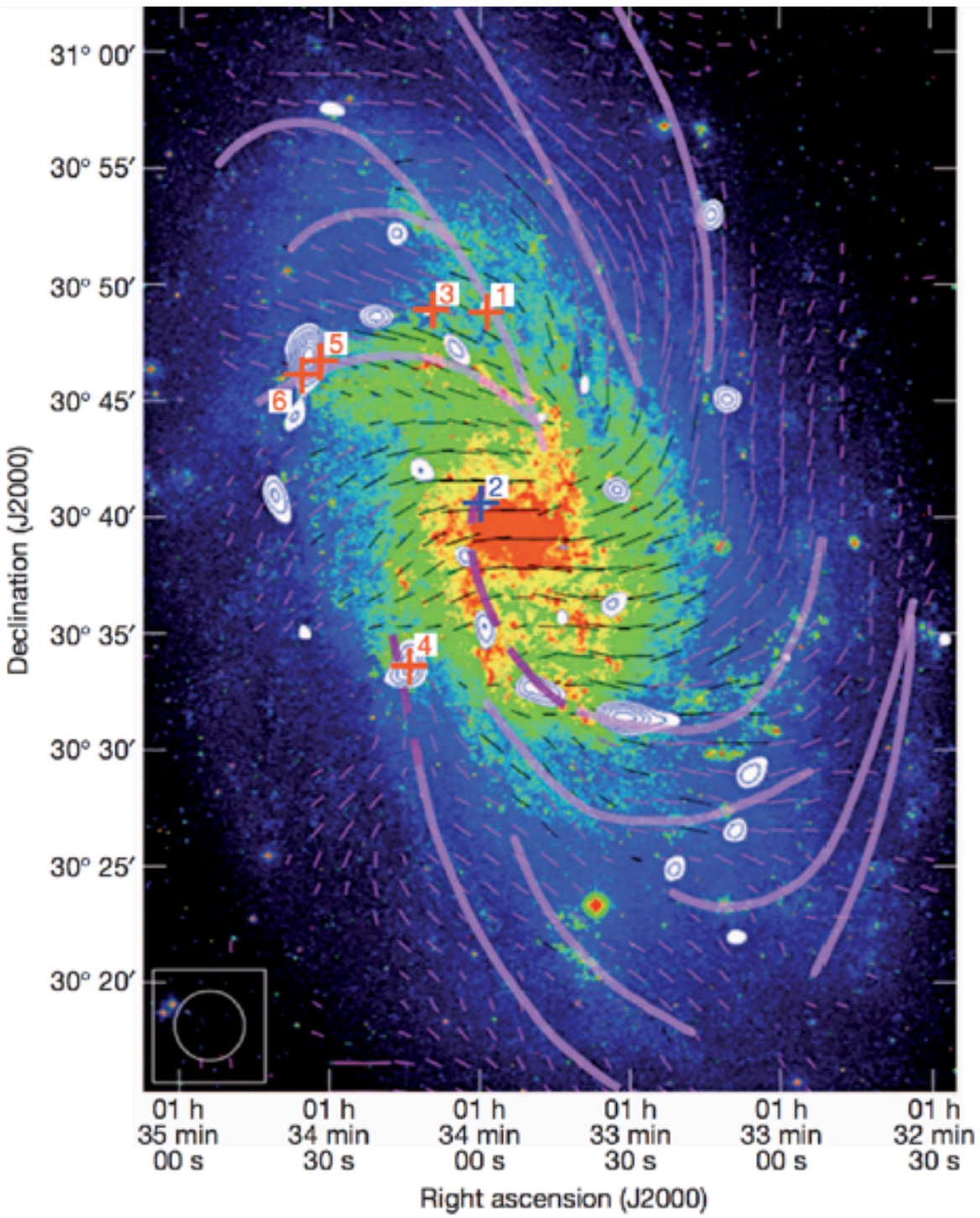
JCMT+ BIMA



MCs and M33 magnetic field (d = 900 kpc)

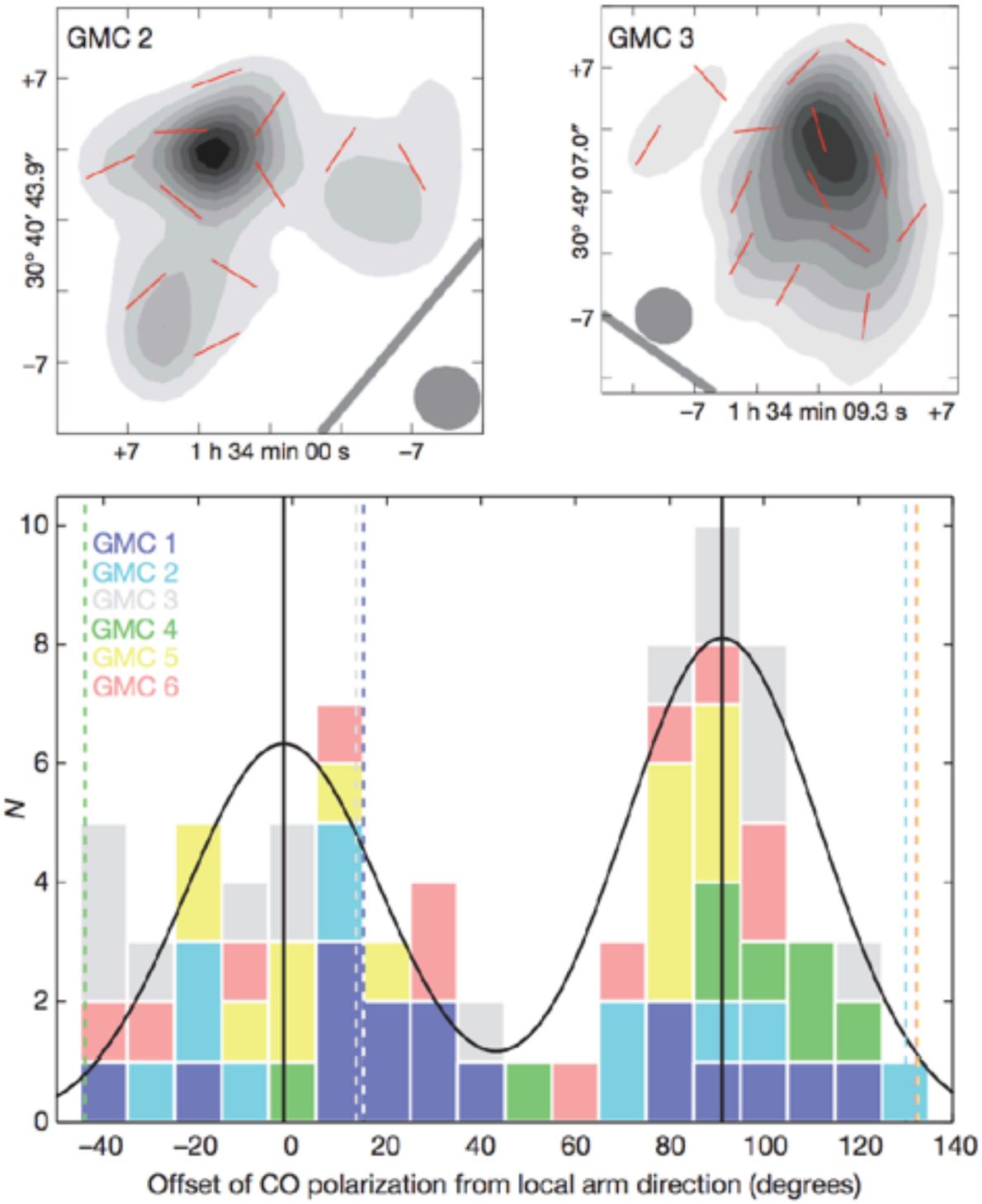
Li, H.-B. & Henning, Th. Nature 479 (2011) 499L

M33 3.6-cm synch. polarization



CO J=2–1

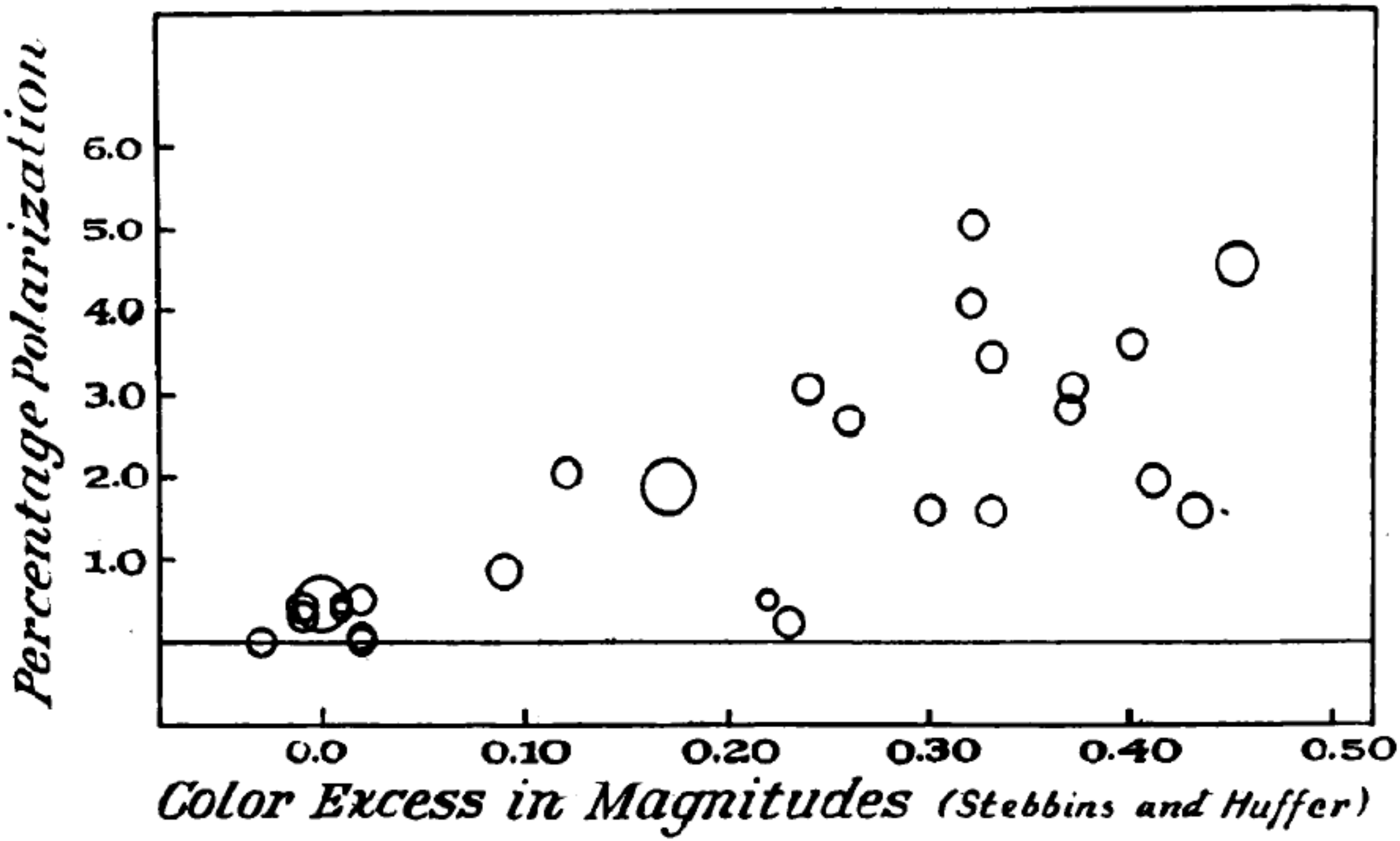
SMA



Starlight polarization

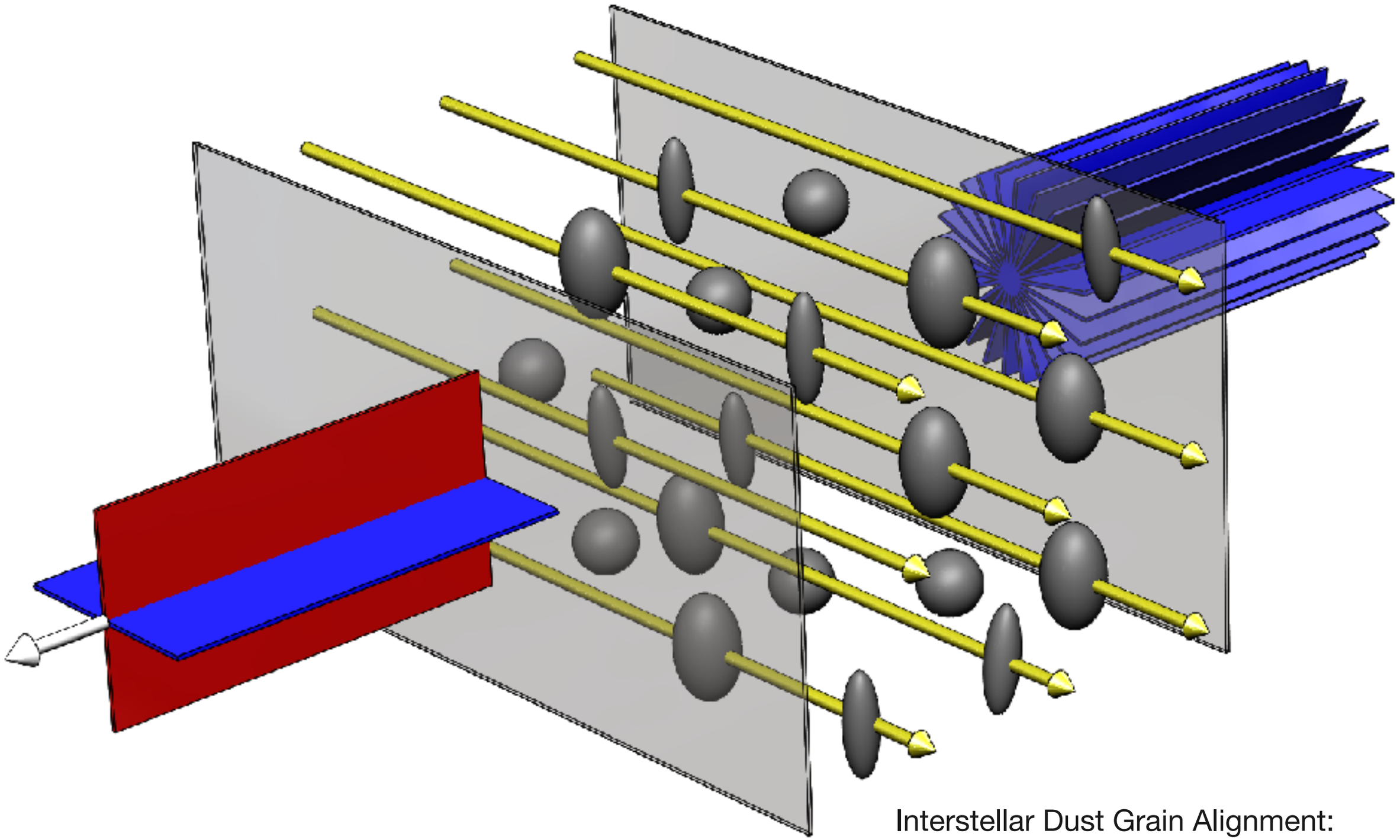
Starlight polarization (28 stars)

Hall, J.S., Science, 109, 166 (1949)
Hiltner, W.A., Science, 109, 165H (1949)



Starlight polarization

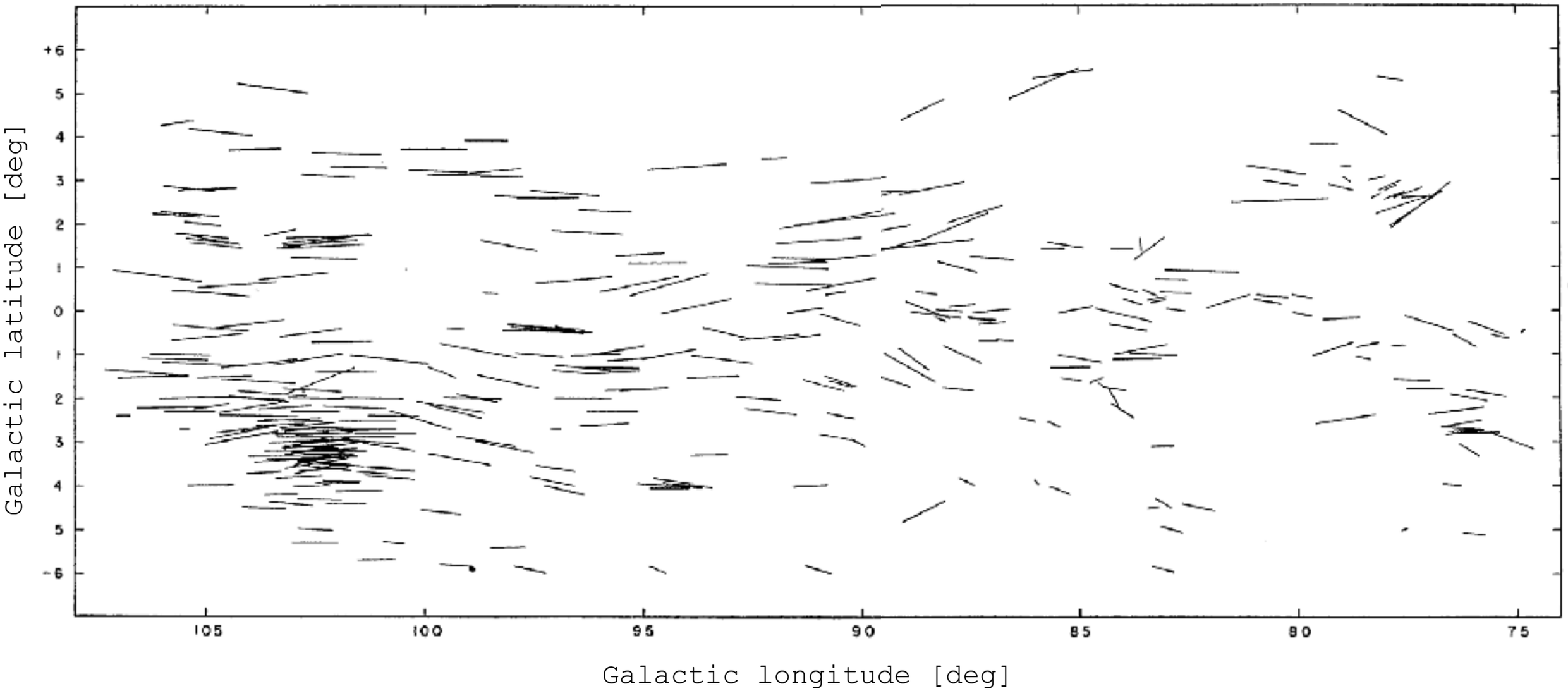
Davis, L. & Greenstein, J.L. ApJ 114 (1951) 206D



Interstellar Dust Grain Alignment:
see talk by B.G. Anderson 9:30 - 30AUG

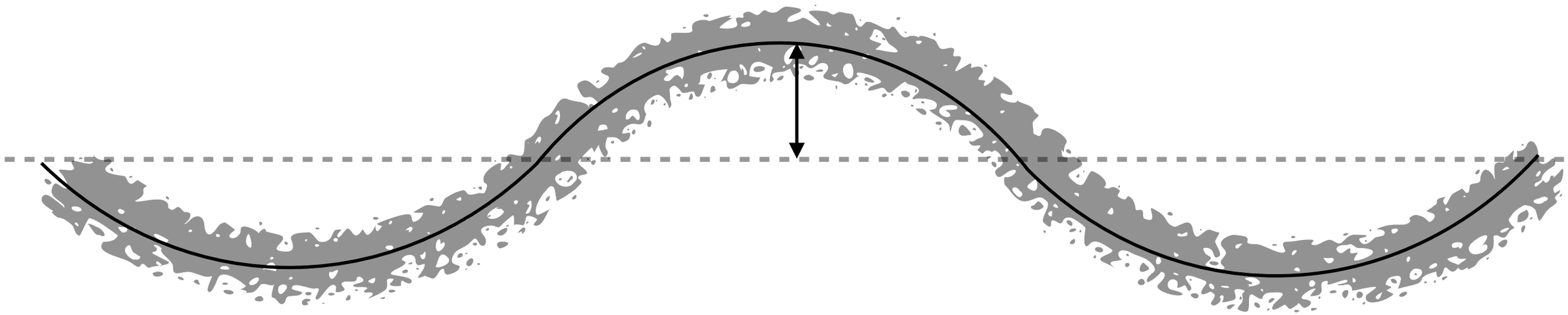
Starlight polarization (841 stars)

Hiltner, W.A., ApJ, 114, 241 (1951)



Davis-Chandrasekhar-Fermi method

Davis, L. Phys. Rev. 81 (1951) 890
Chandrasekhar, S. & Fermi, E. ApJ 118 (1953) 113

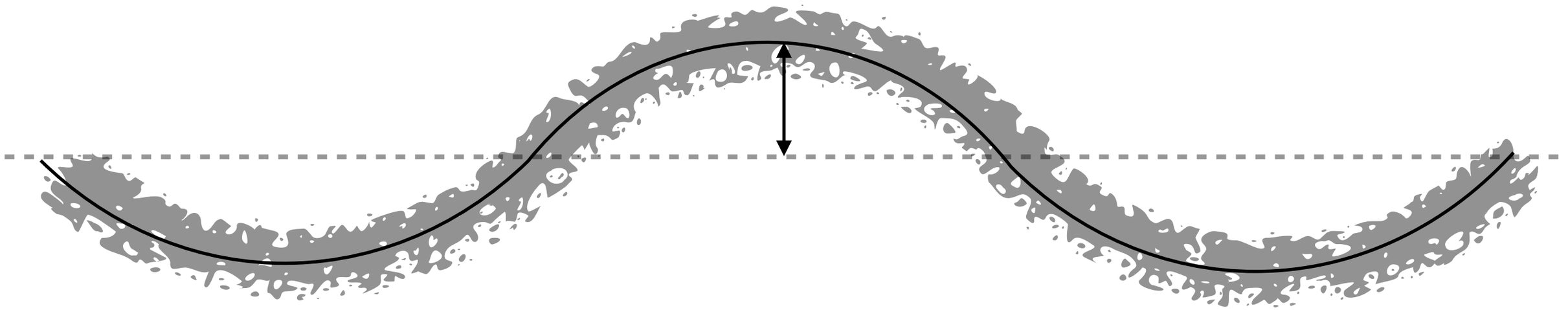


$$B_{\perp}^{\mathrm{CF}} = \sqrt{4\pi\rho}\frac{\sigma_{v_{\parallel}}}{S_{\psi}}$$

$$B_0 = 7.2 \times 10^{-6} \text{ gauss}$$

Davis-Chandrasekhar-Fermi method

Davis, L. Phys. Rev. 81 (1951) 890
Chandrasekhar, S. & Fermi, E. ApJ 118 (1953) 113



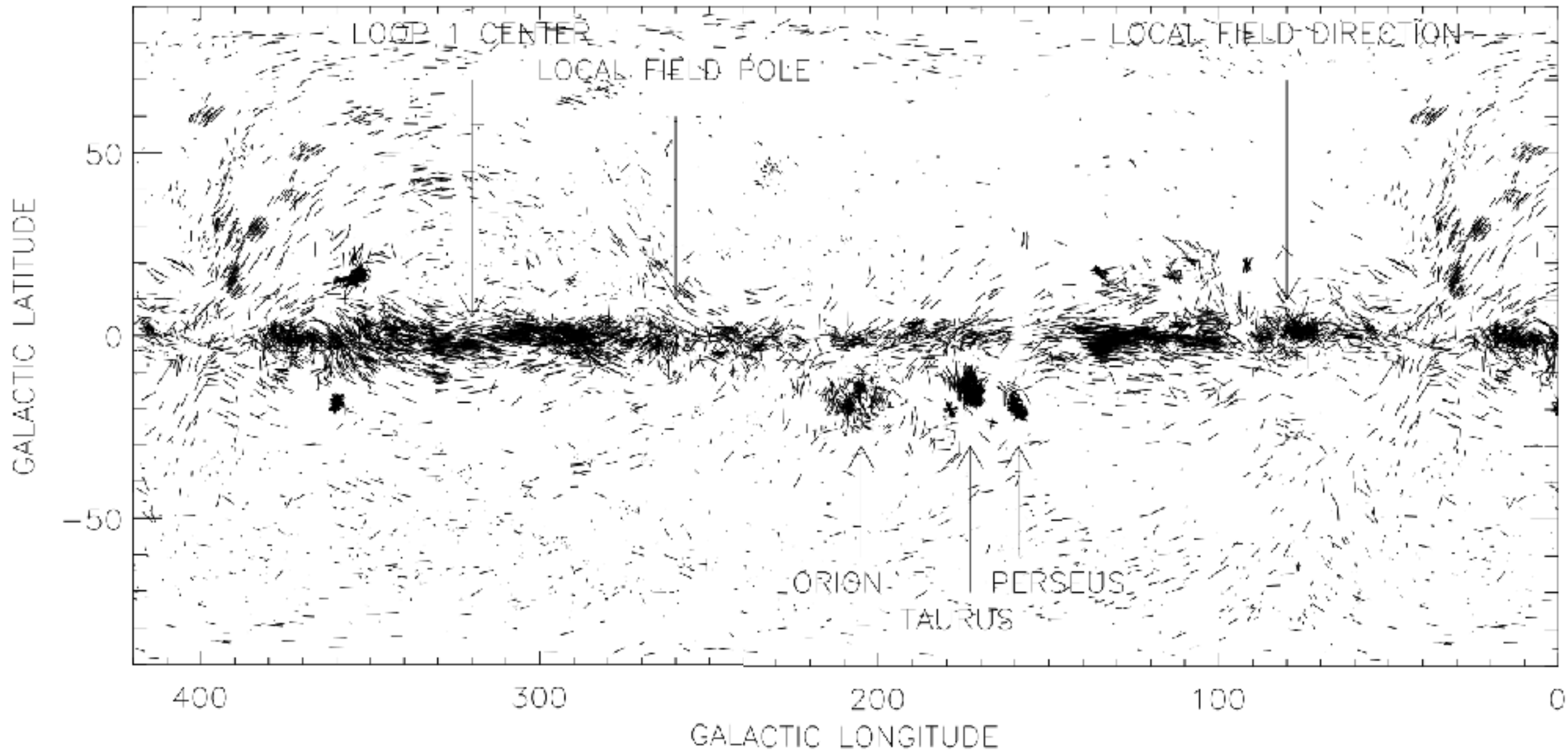
$$B_{\perp}^{\mathrm{CF}} = \sqrt{4\pi\rho}\frac{\sigma_{v_{\parallel}}}{S_{\psi}}$$

⚠ CAUTION ⚠ CAUTION ⚠ CAUTION ⚠ CAUTION ⚠ CA

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

Starlight polarization (9286 stars)

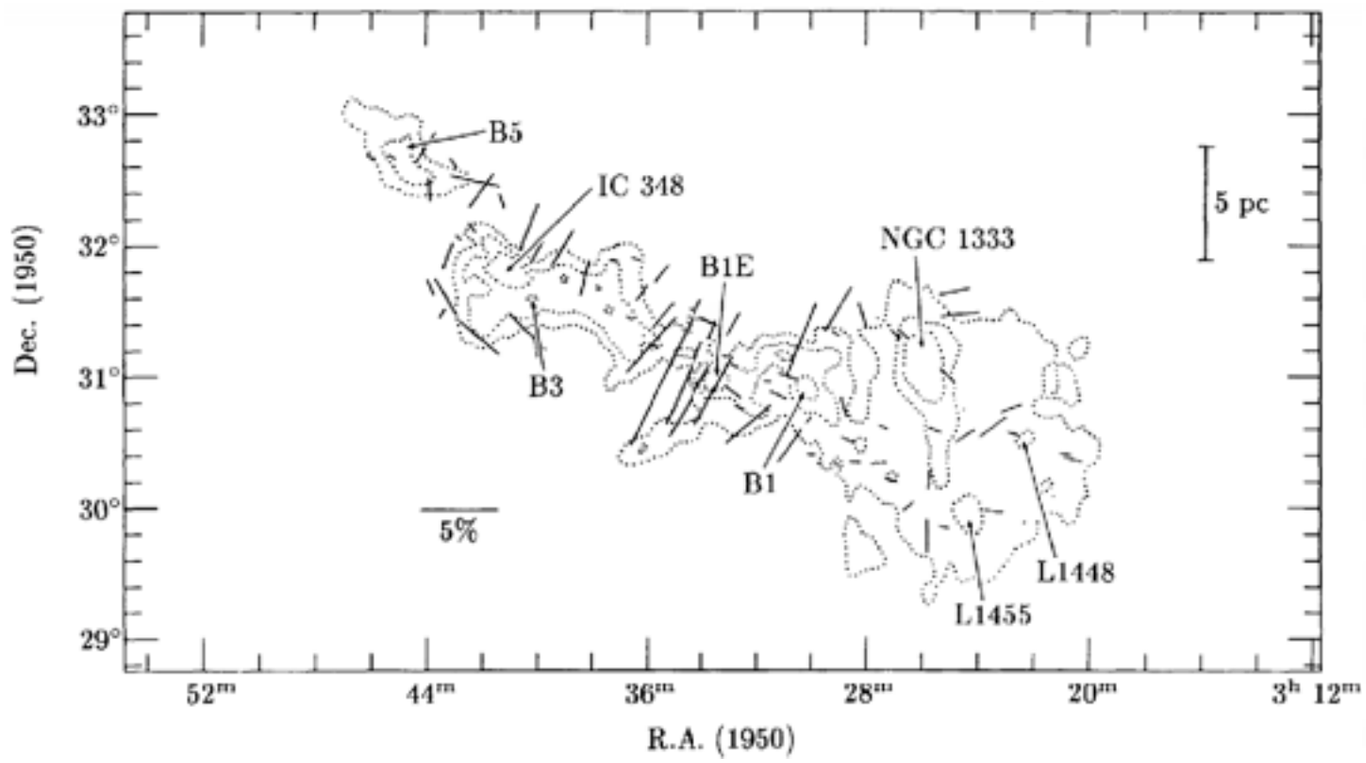
Mathewson, D.S. & Ford, V.L., MmRAS. 74 (1970) 139M – 1800 stars
Heiles, C. AJ. 119 (2000) 923H – 9286 stars



Starlight polarization (15 dark clouds)

Goodman, A.A., et al. ApJ 353 (1990) 363
Myers, P.C. & Goodman, A.A. ApJ 373 (1991) 509M
Li, H.-B., et al. MNRAS 436 (2013) 3707L

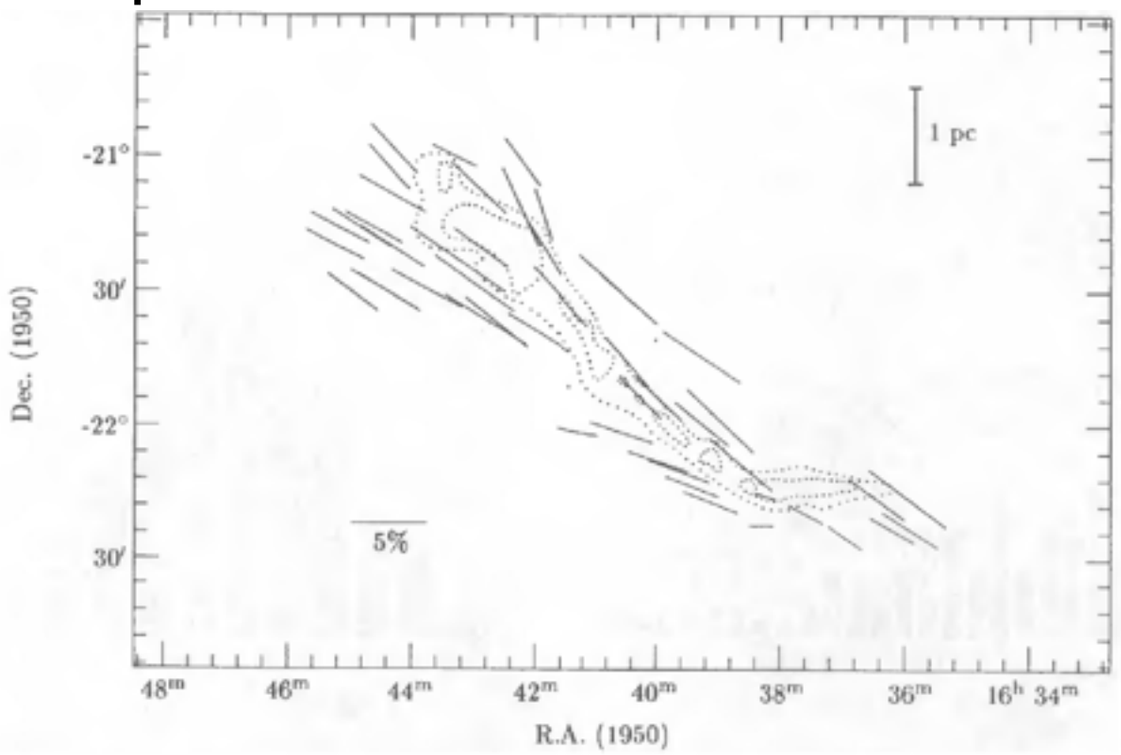
Perseus dark cloud complex



Myers, P.C. ApJ 700 (2009) 1609M

Hub-filaments

Ophiuchus L1755 dark cloud

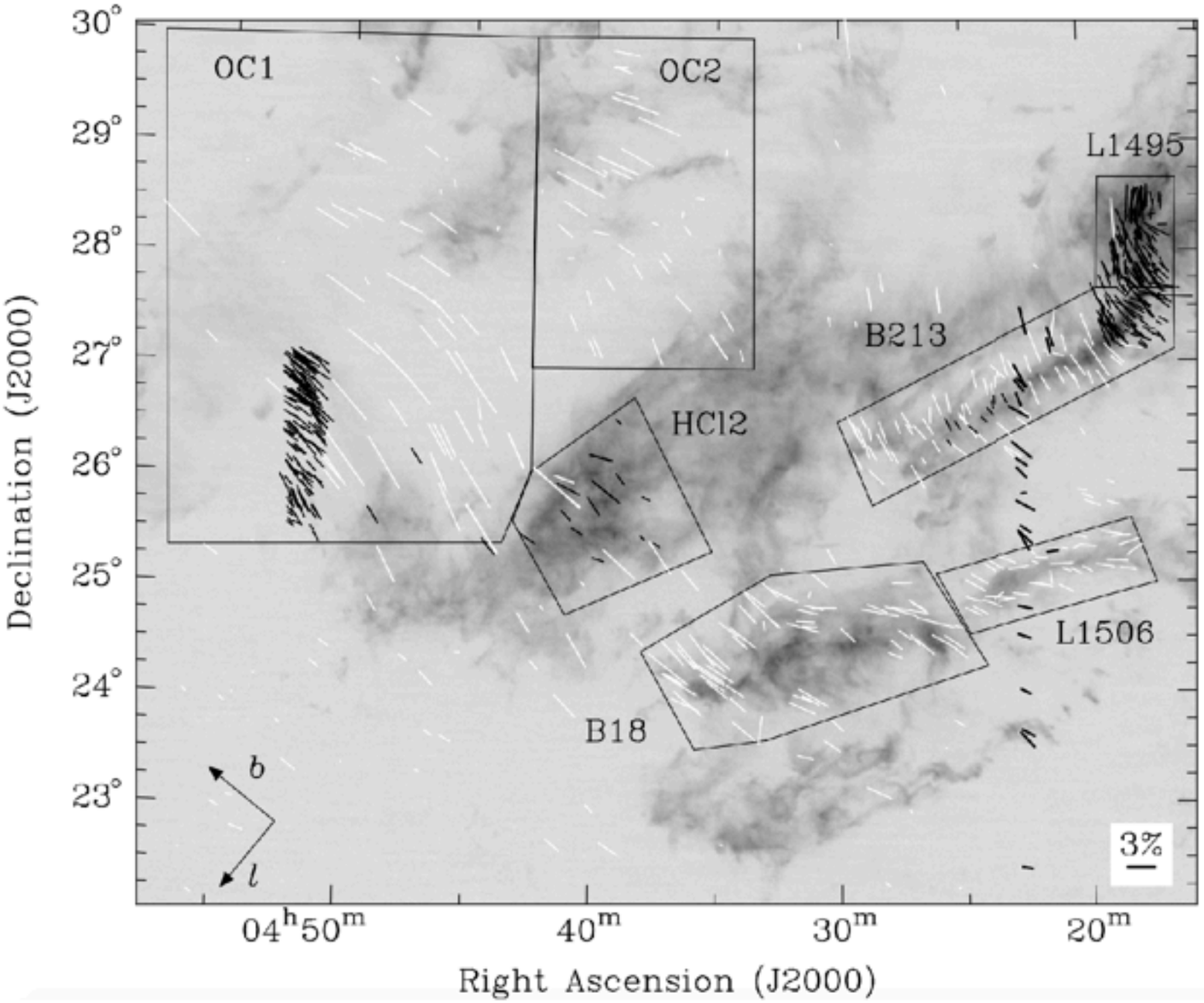


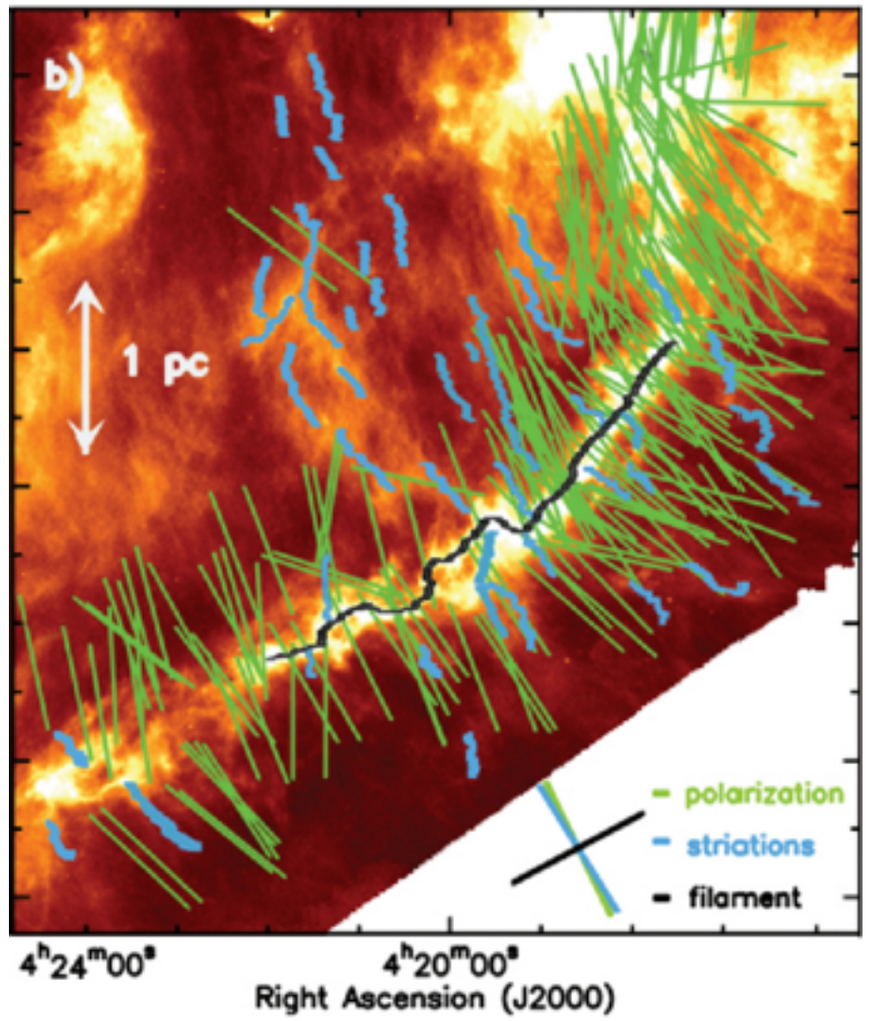
Magnetic field and filaments

Chapman, N.L., et al. ApJ 741 (2011) 21C

Palmeirim, P., et al. A&A 550A (2013) 38P

Taurus





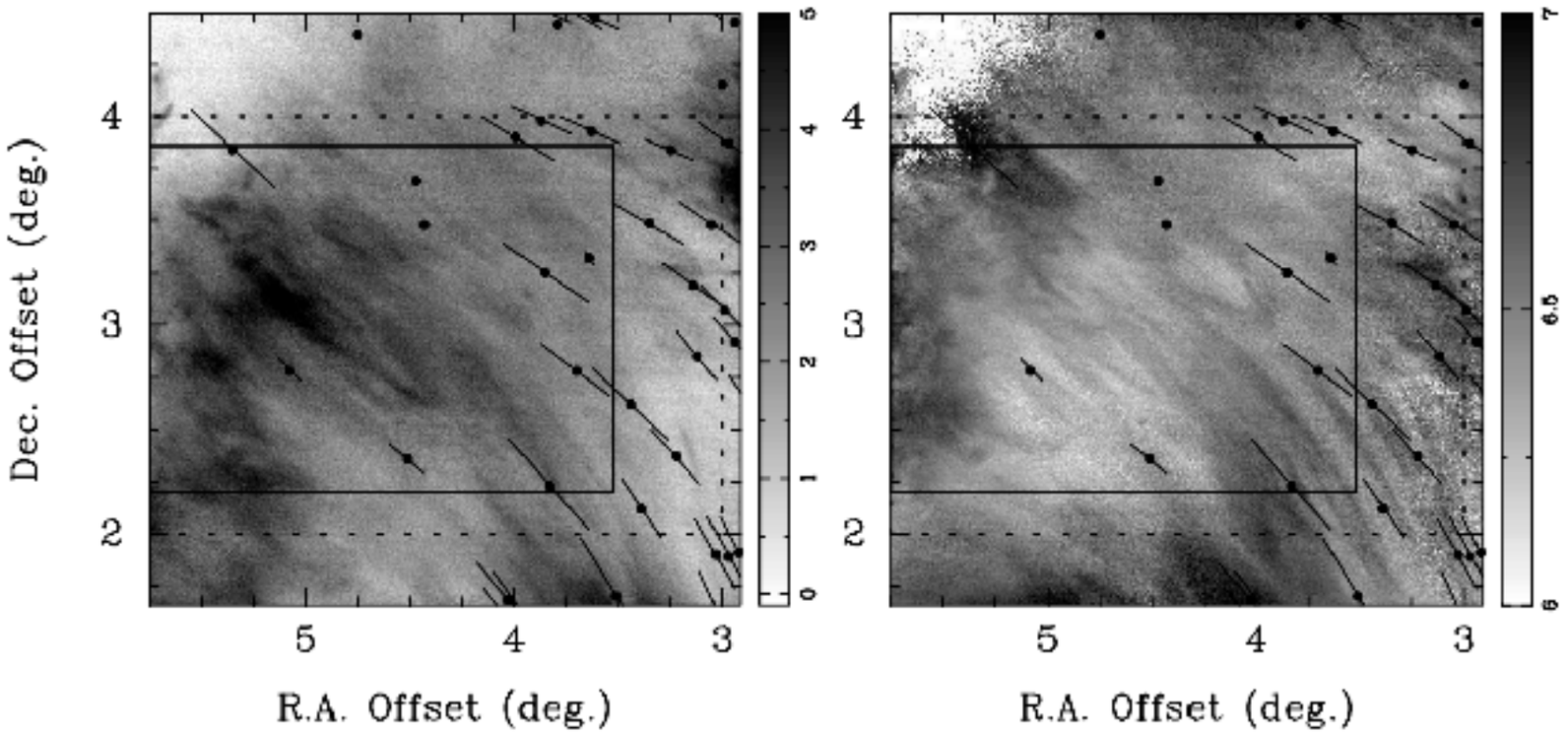
See also:

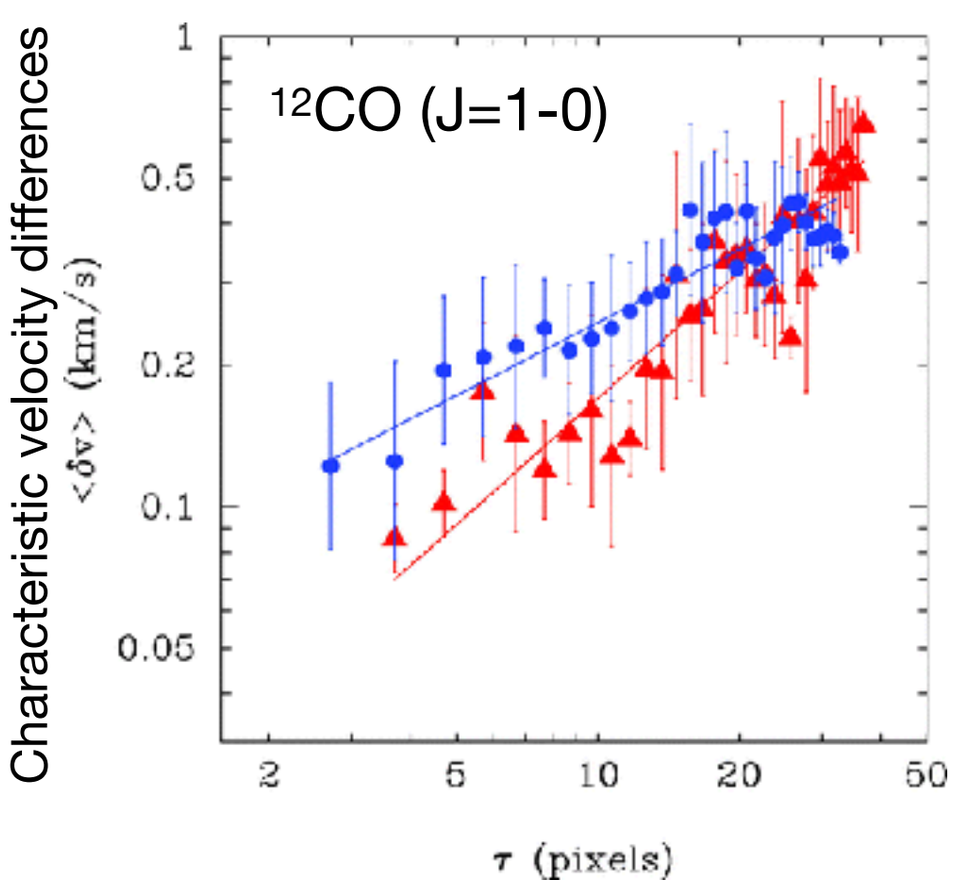
Sugitani, K., et al., 2011

Pereyra, A. & Magalhães, A.M., 2004

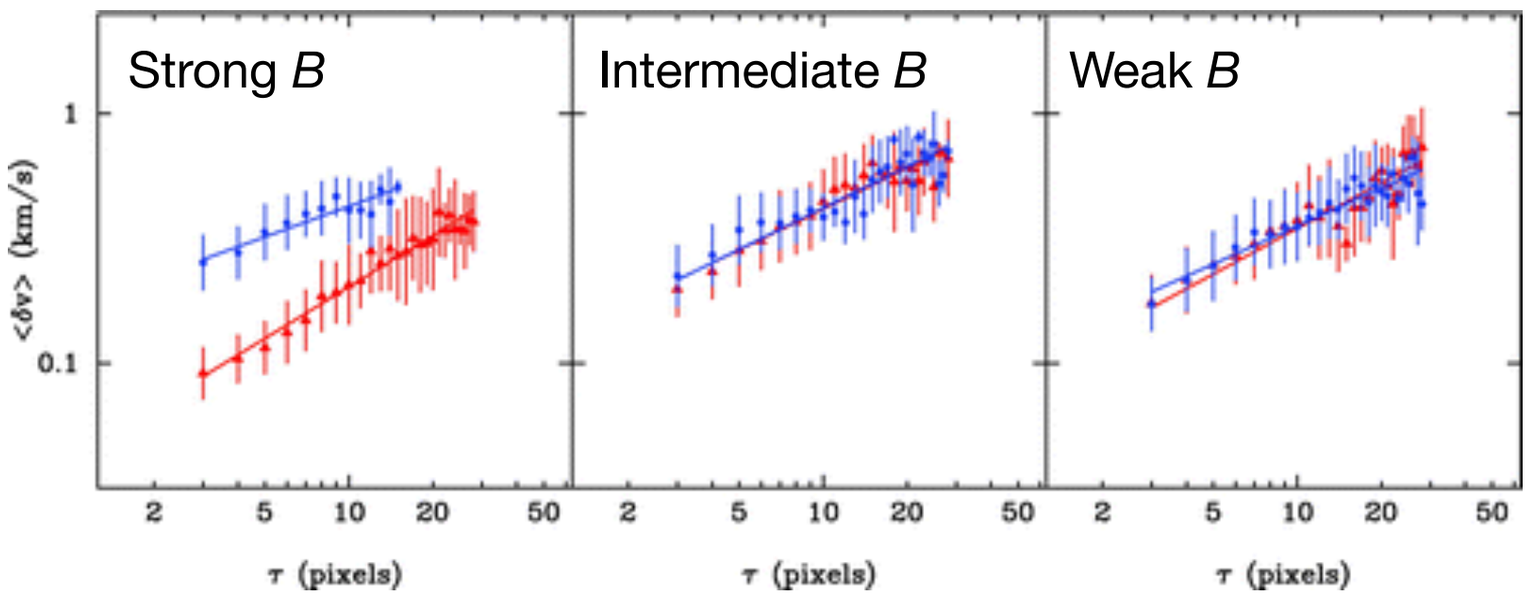
Magnetically aligned velocity anisotropy (Taurus)

Heyer, M., et al. ApJ 680 (2008) 420; Heyer, M., et al. MNRAS 461 (2016) 3918H





Numerical models



Dust polarized emission

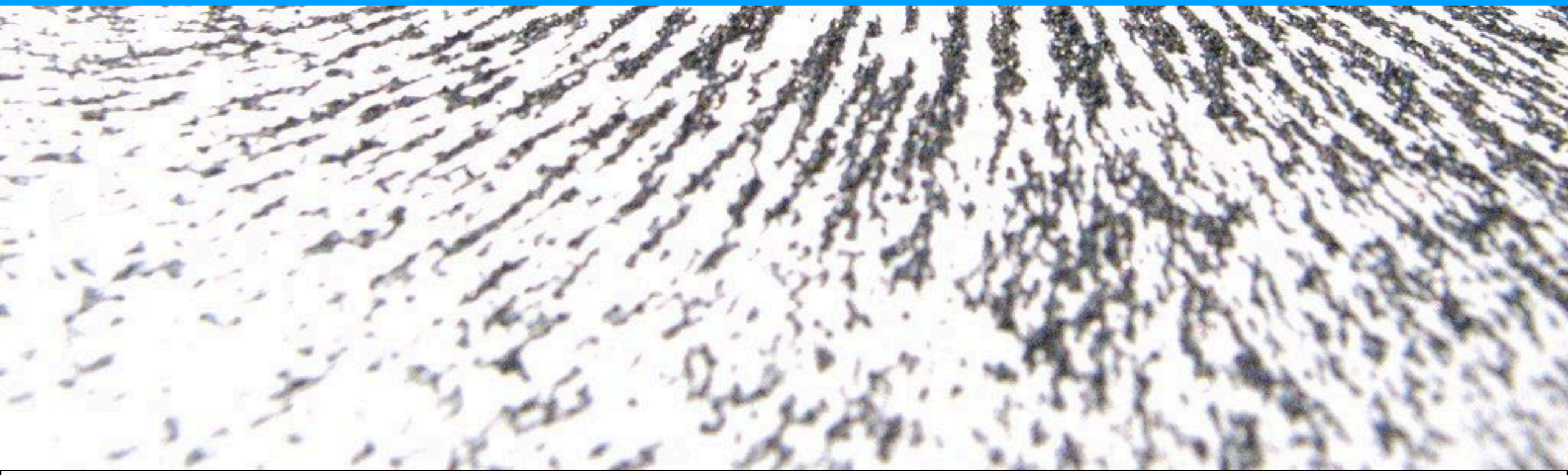
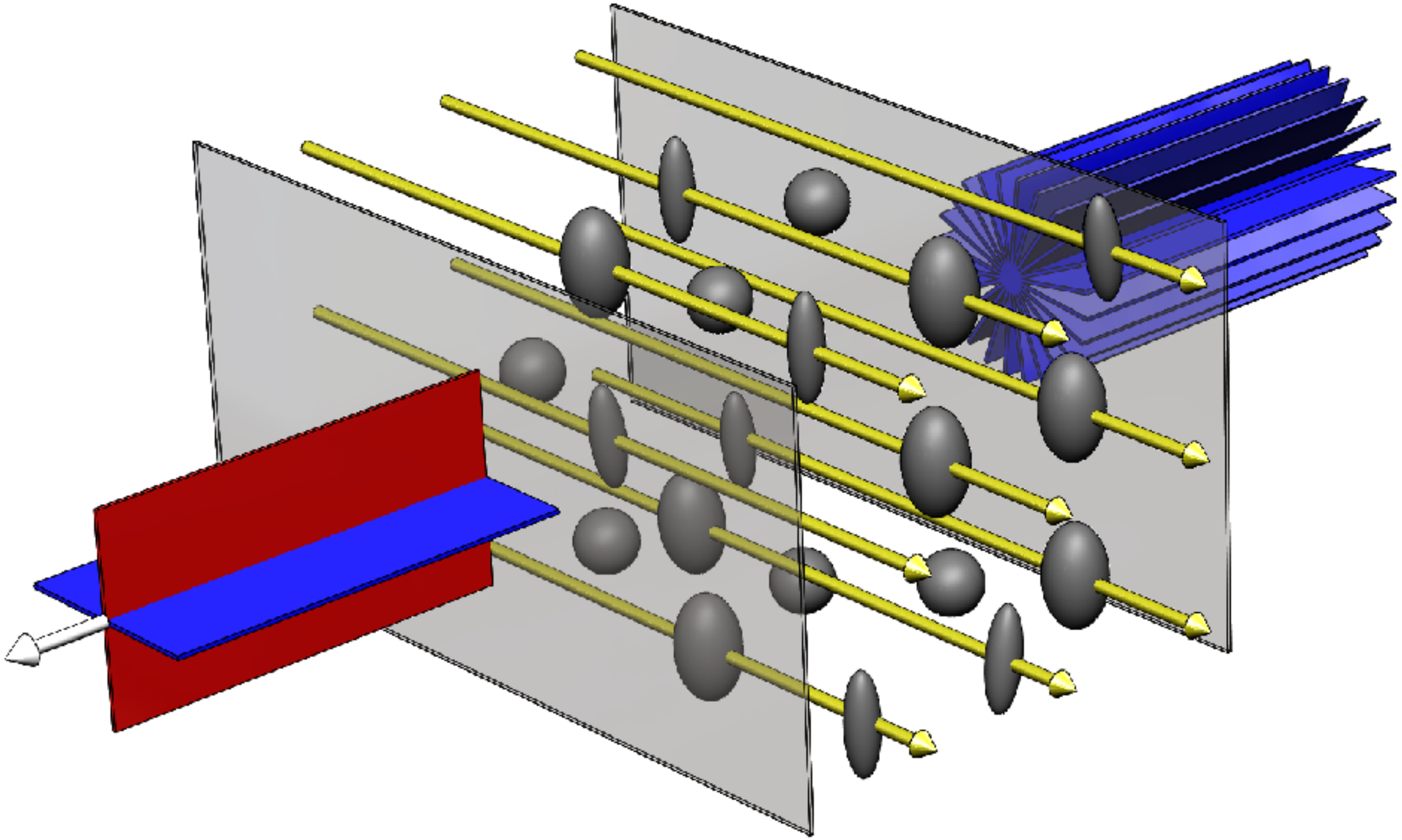


Image: Windell Oskay

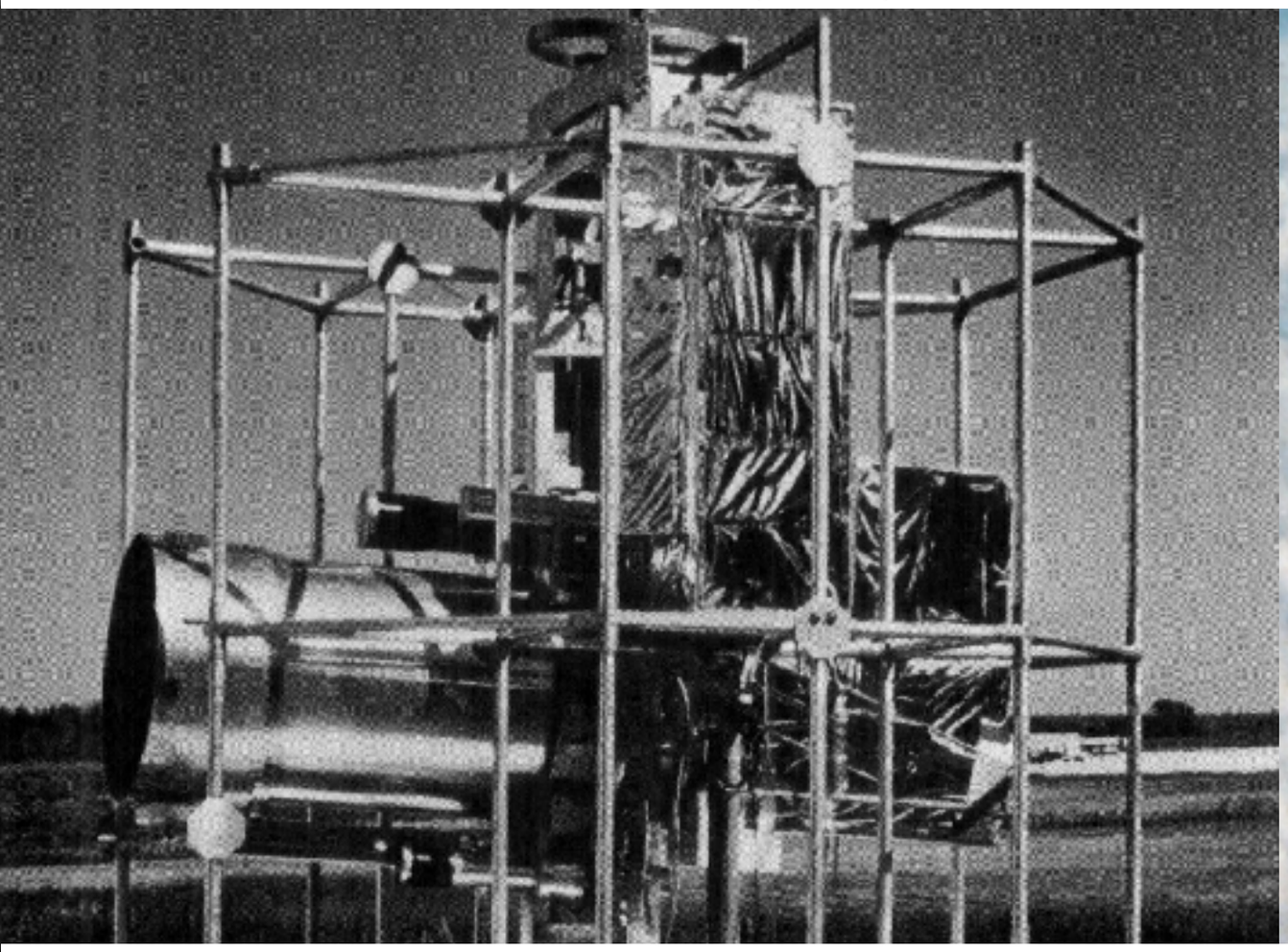
Dust polarized thermal emission

Stone, W. ApJ. 144 (1966) 318S
Hildebrand, R.H. QJRAS 29(1988) 327H



Far-infrared 70 μm polarization

Cudlip, W., et al, MNRAS, 200 (1982) 1169C



Messier 42 (Orion Nebula)

2.2 ± 0.4 per cent polarization at 16° ± 8°

Submillimeter (270 μm) pol.

Hildebrand, R.H. et al, ApJ, 284L (1984) 51H

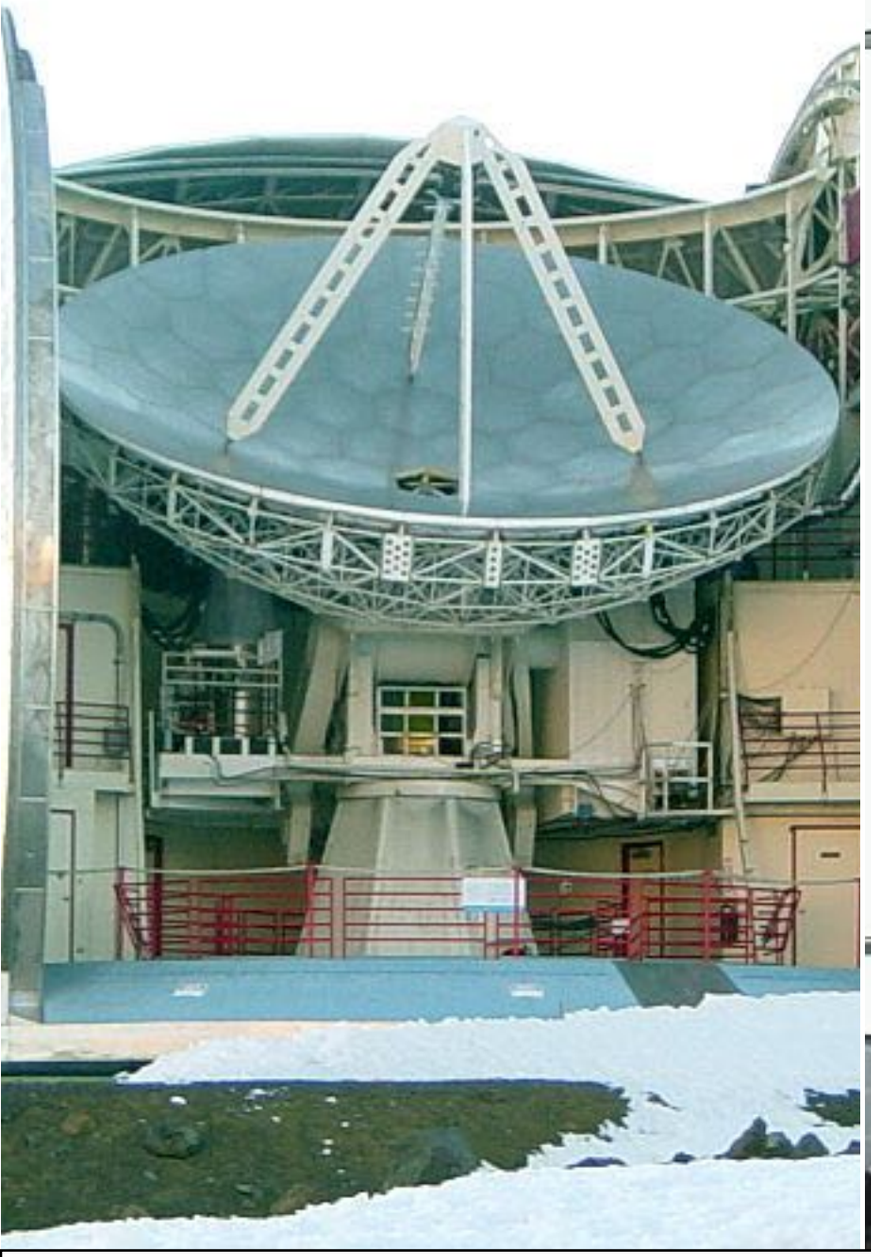
Orion Kleinmann-Low nebula

$P = (1.7 \pm 0.5)\%$ at $\phi = 27° \pm 7°$

$P = (1.7 \pm 0.4)\%$ at $\phi = 23° \pm 7°$

CSO

(1995-2005)
Hertz - 350 μm @ 20”
(2005-2015)
SHARP - 350 μm @ 9”
450 μm @ 11”



JCMT (EAO)

(1995-2005)
SCUBA - 850 μm @ 20”
(2011-)
POL-2 - 850 μm @ 14.3”
450 μm @ 9.8”

Viper 2-meter telescope

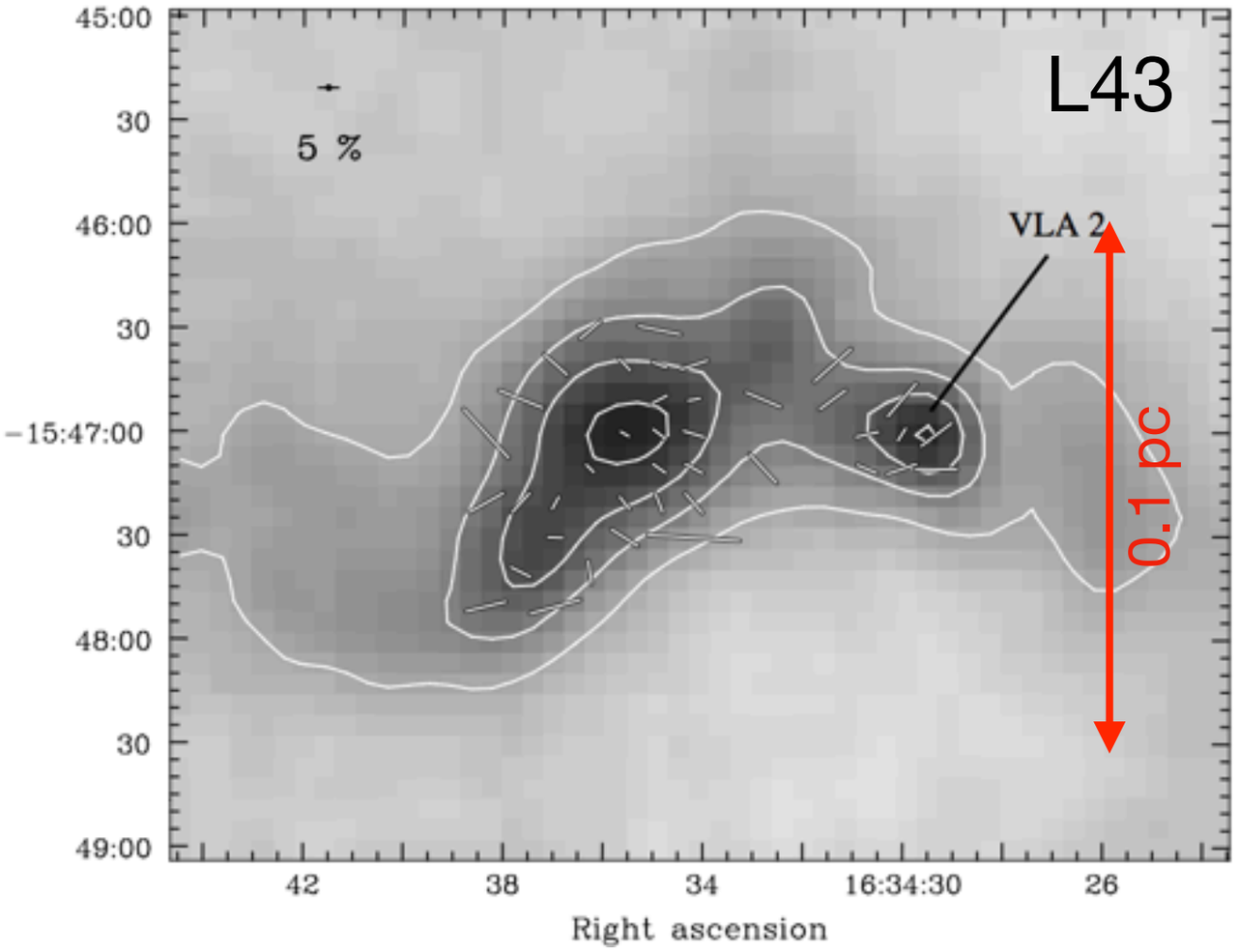
(1998 - 2004)
SPARO - 450 μm @ 4’

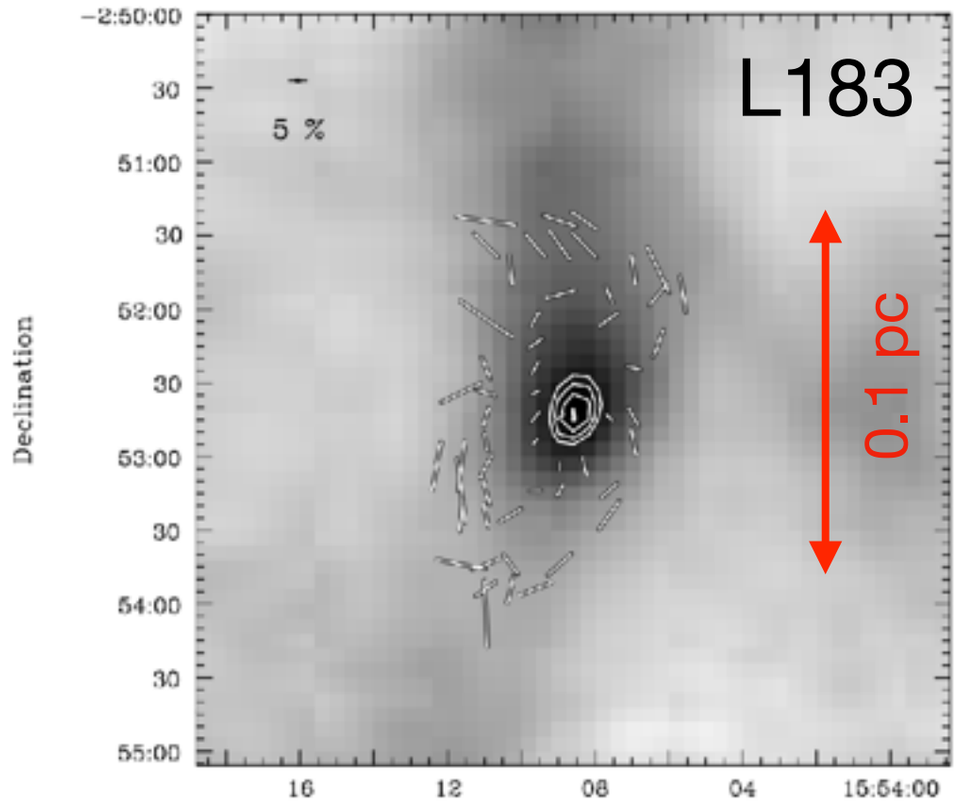
850 μm Polarimetry with SCUBA (48 star-forming regions)

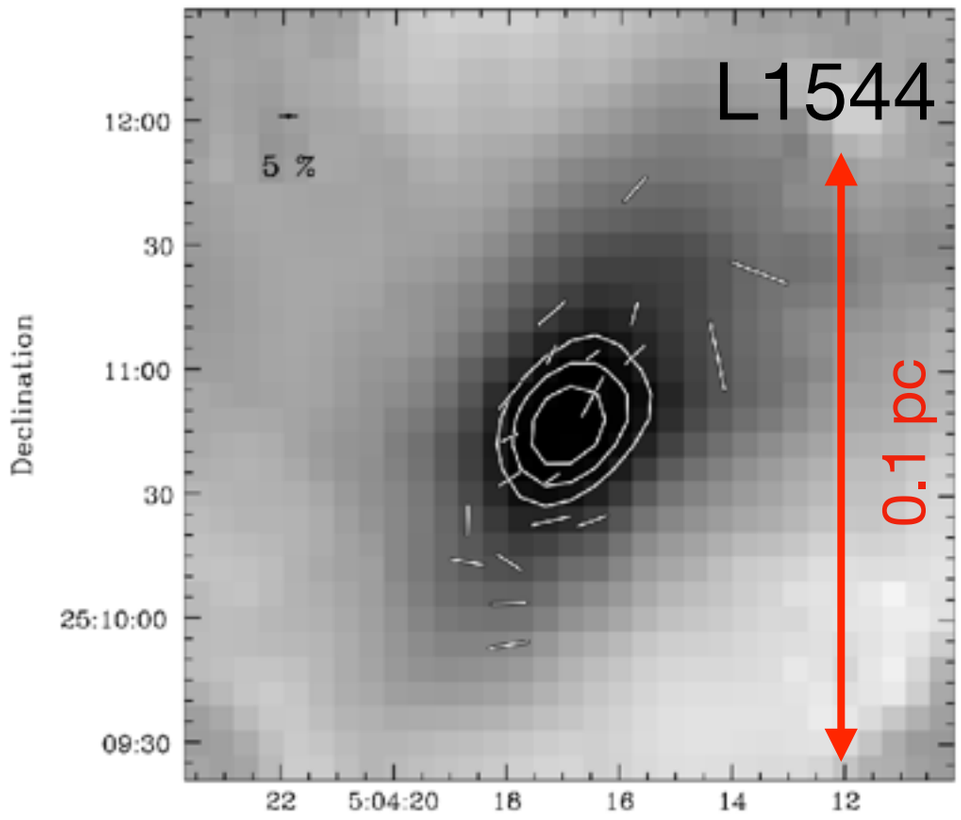
Crutcher, R.M. et al, ApJ 600 (2004) 279C

$n \sim 10^4\ cm^{-3}$

$80\ \mu G < B_{DCF} < 160\ \mu G$
$0.6\ (1.9) < \lambda < 0.9\ (2.6)$

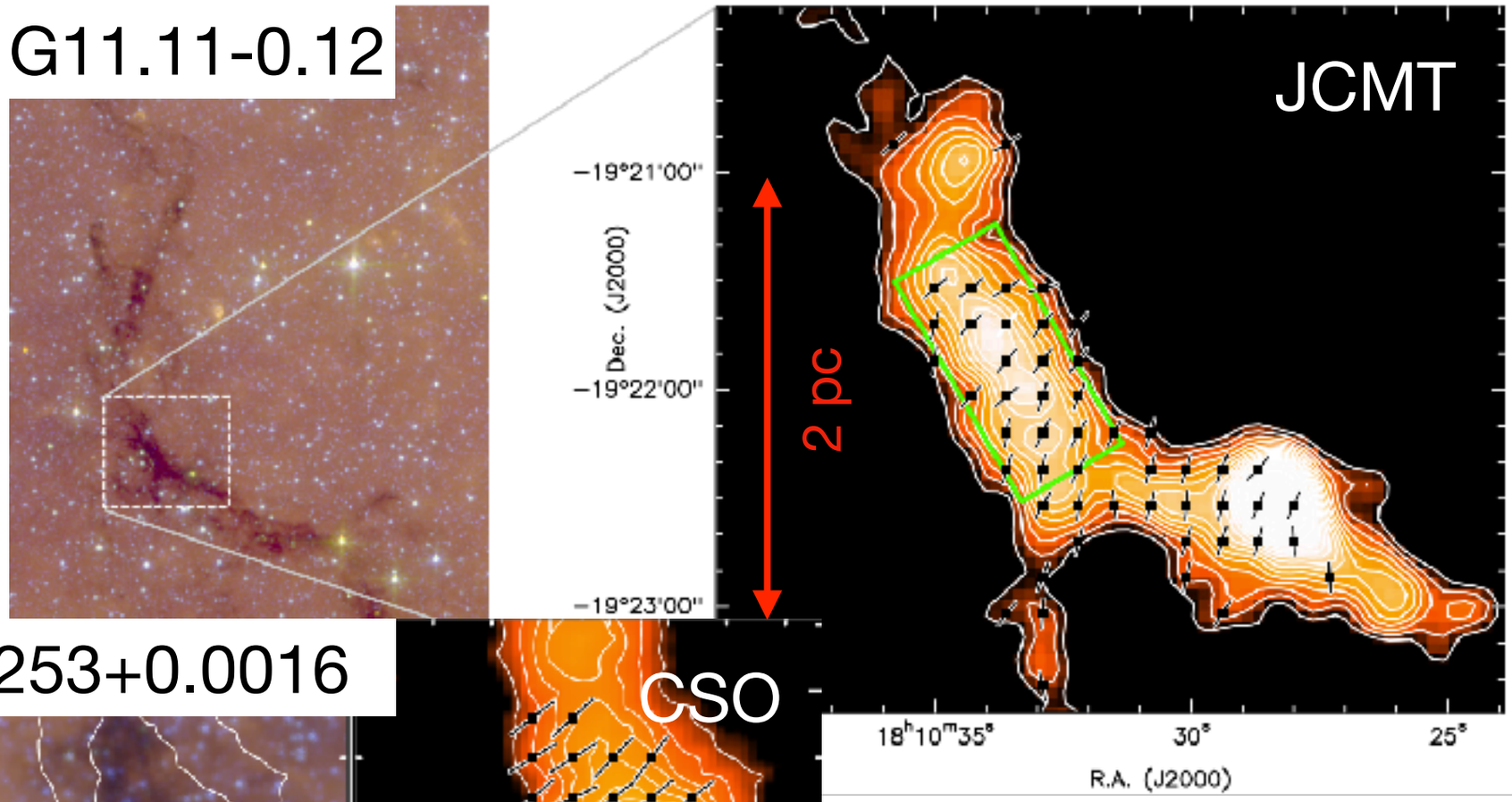


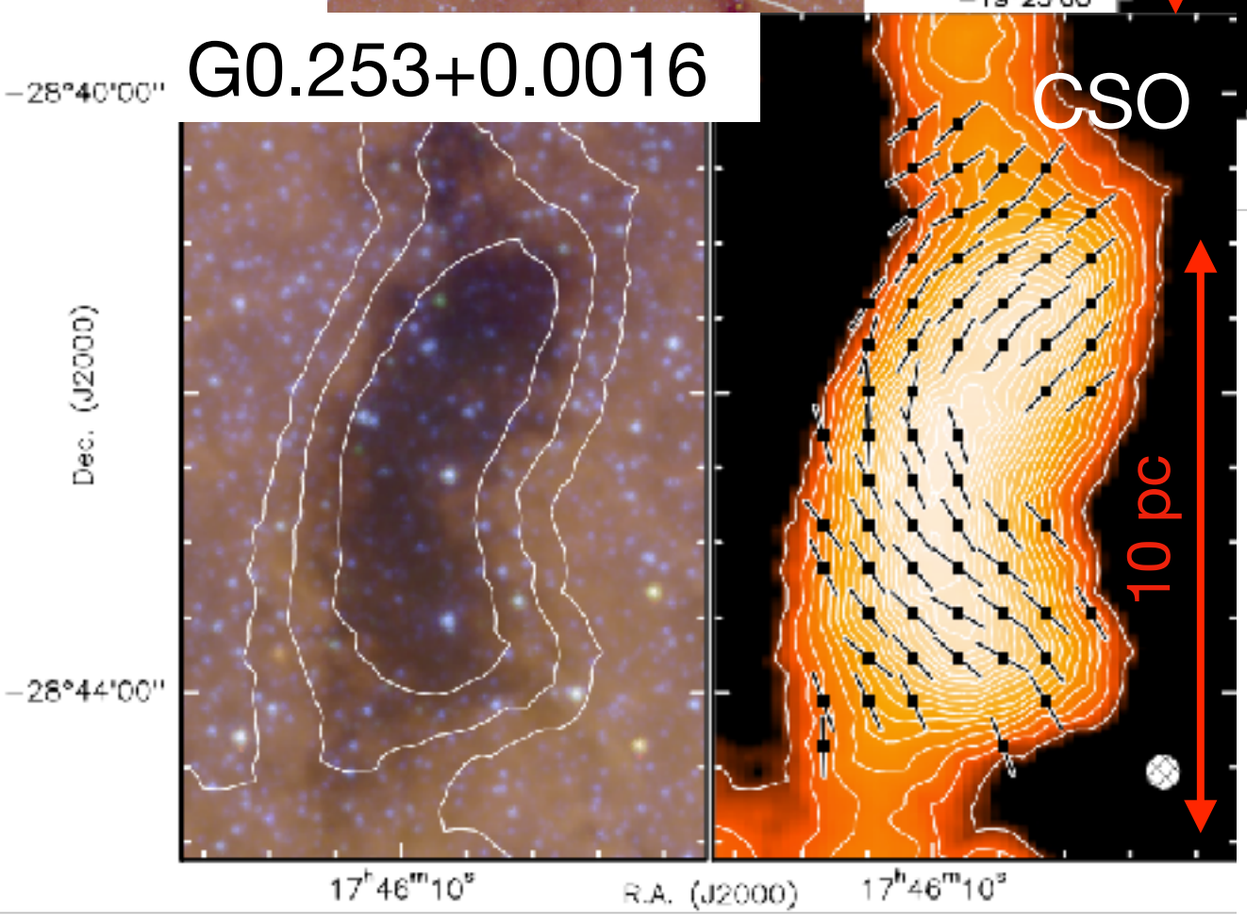




Magnetic fields in high-mass infrared dark clouds (d > 3.6kpc)

Pillai, T., Kauffmann, J., et al. ApJ 799 (2015) 74P





$n \sim 10^4\ cm^{-3}$

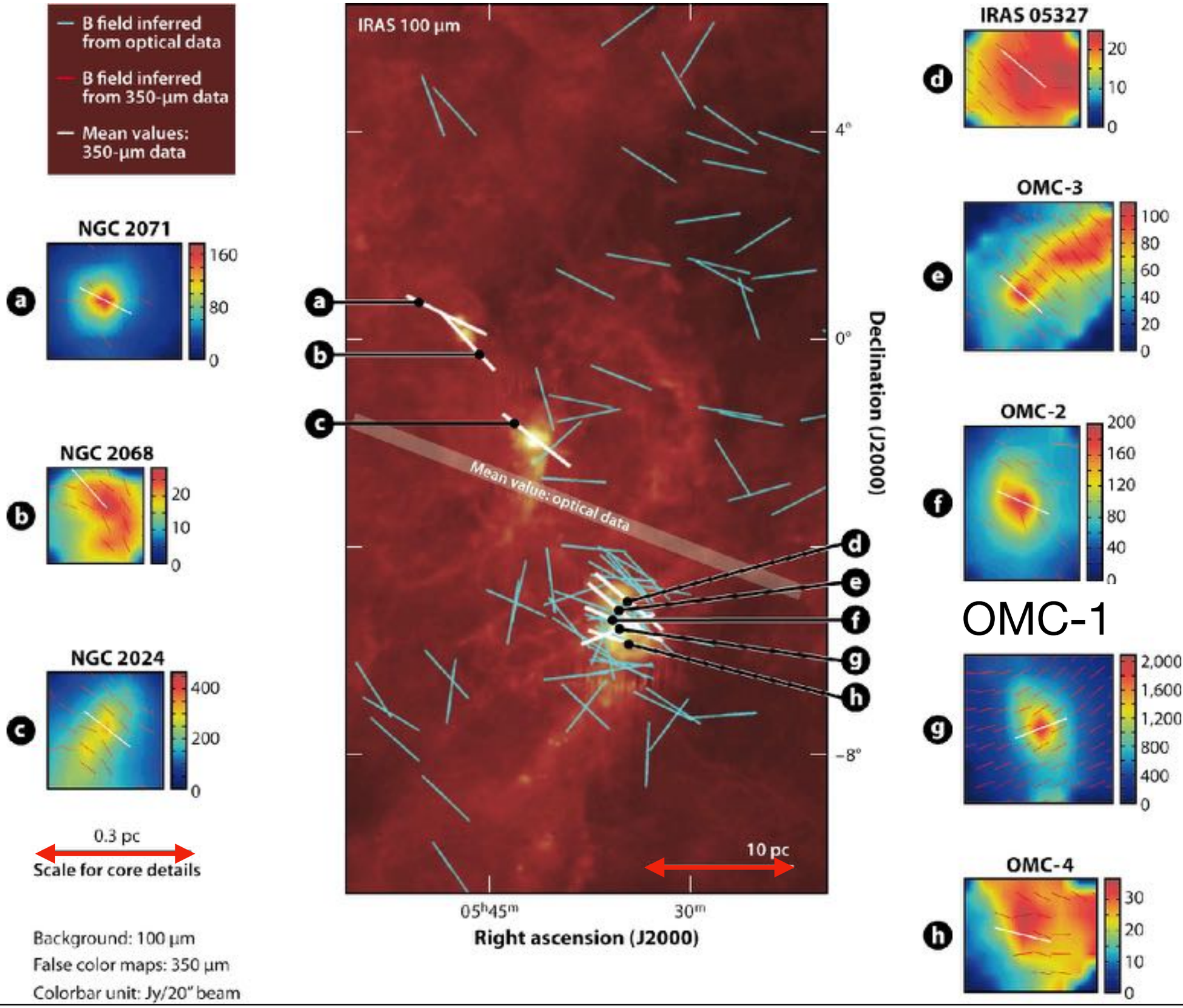
B_{DCF}* (μG)	$\mathcal{M}_A$	λ
$>267 \pm 26\,\vert^{437}_{163}$	$< 0.8 \pm 0.1\,\vert^{1.2}_{0.5}$	$<1.1 \pm 0.1\,\vert^{2.1}_{0.6}$
$5432 \pm 525\,\vert^{8908}_{3312}$	$0.4 \pm 0.1\,\vert^{0.7}_{0.3}$	$0.6 \pm 0.1\,\vert^{1.1}_{0.3}$

*Houde, M. et al. 2009

MC's B Anchoring B in dense clumps?

Li, H.-B. et al, ApJ 704 (2009) 891L

*see talk by Q. Zhang 9:20 31AUG

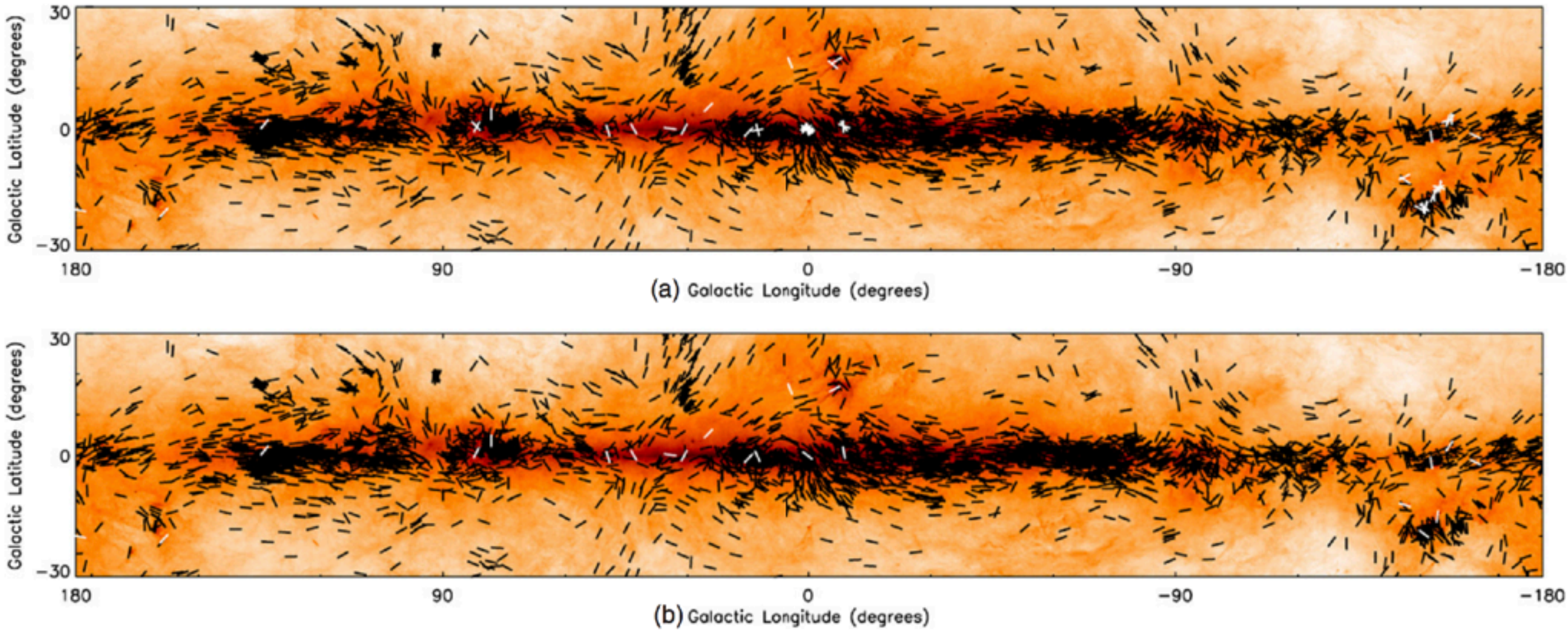


Galactic *B* Anchoring *B* in MCs?

Stephens, I., et al. ApJ 728 (2011) 99S

CSO-Hertz

52 Hertz sources

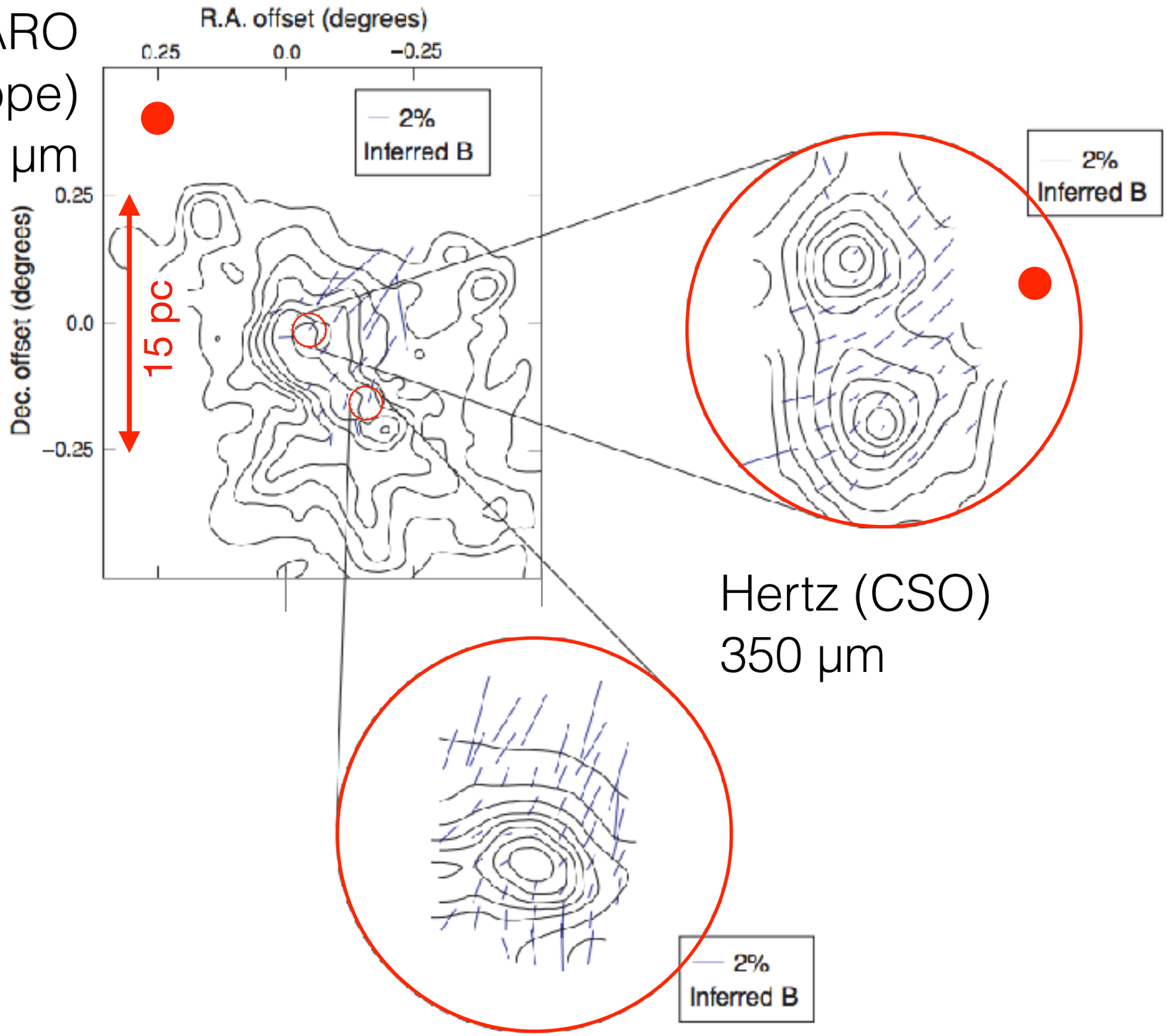


22 associations of sources

Magnetic Fields in giant molecular cloud NGC6334

Novak, G.; Dotson, J. L.; Li, H., ApJ, 695, 1362N (2009)

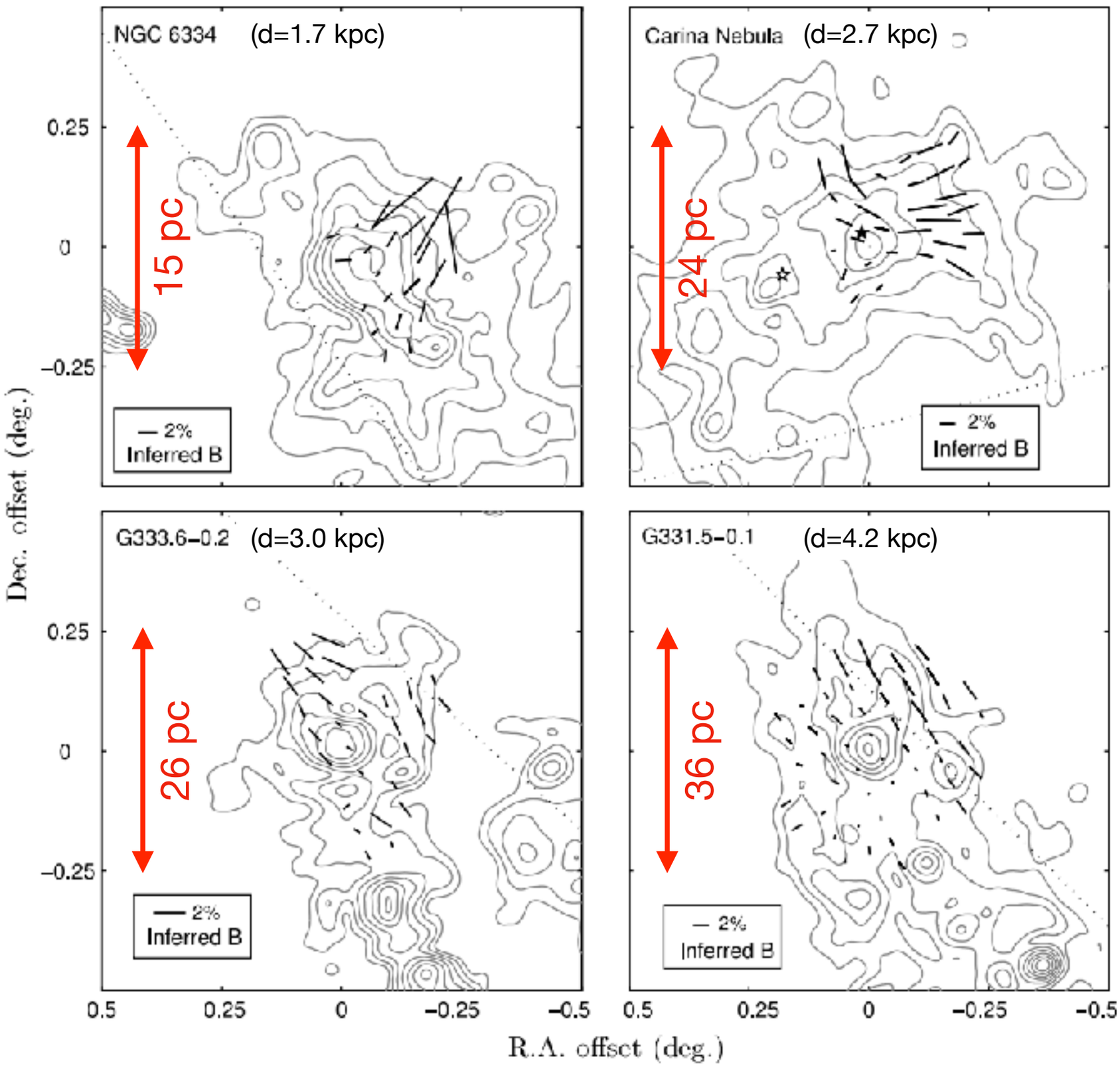
SPARO
(Viper telescope)
450 μm



Hertz (CSO)
350 μm

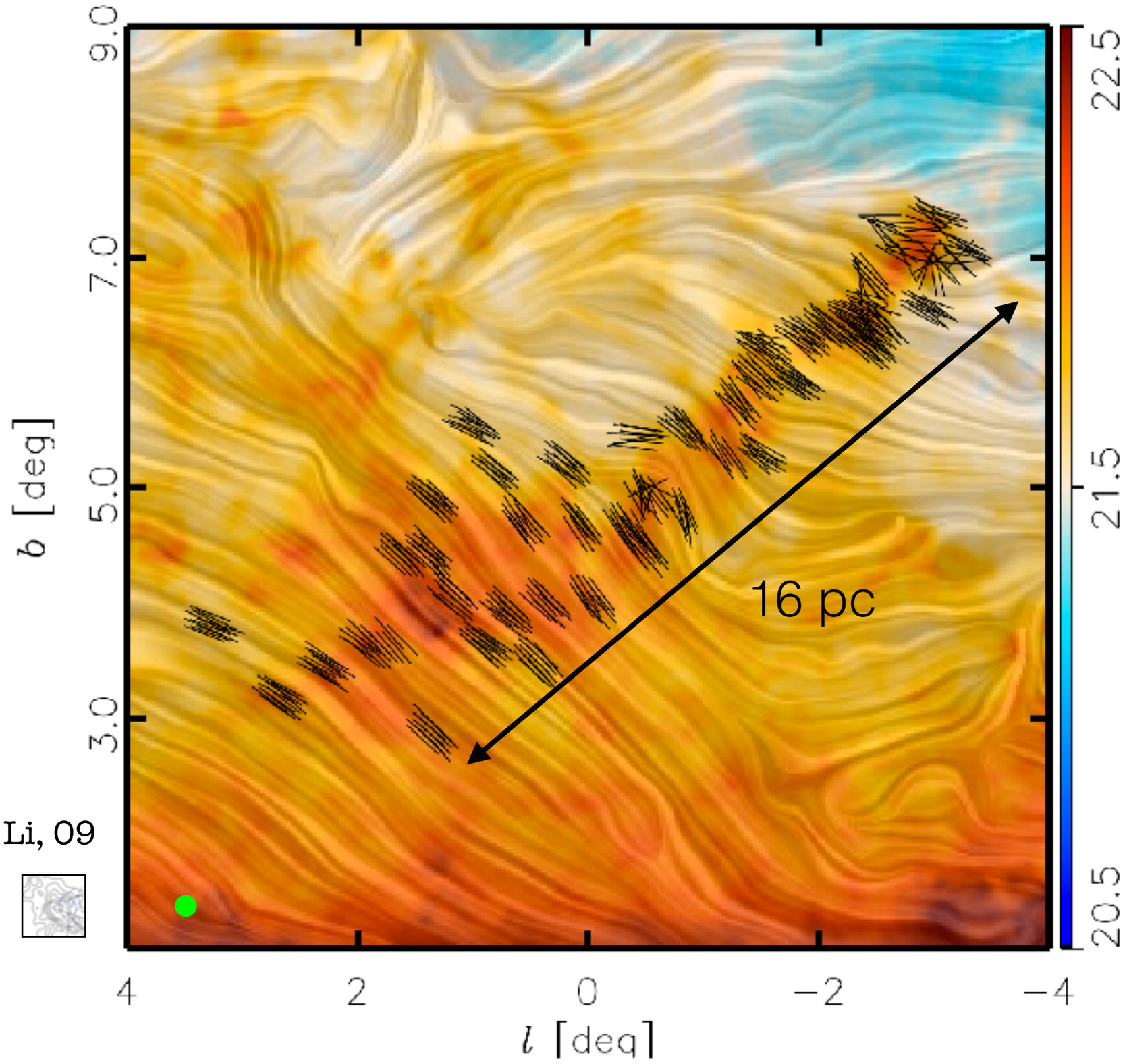
450 μm Polarimetry from SPARO (4 Giant Molecular Clouds)

Li, H.-B. et al, ApJ 648 (2006) 340L



Magnetic fields in nearby molecular clouds (Pipe Nebula)

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



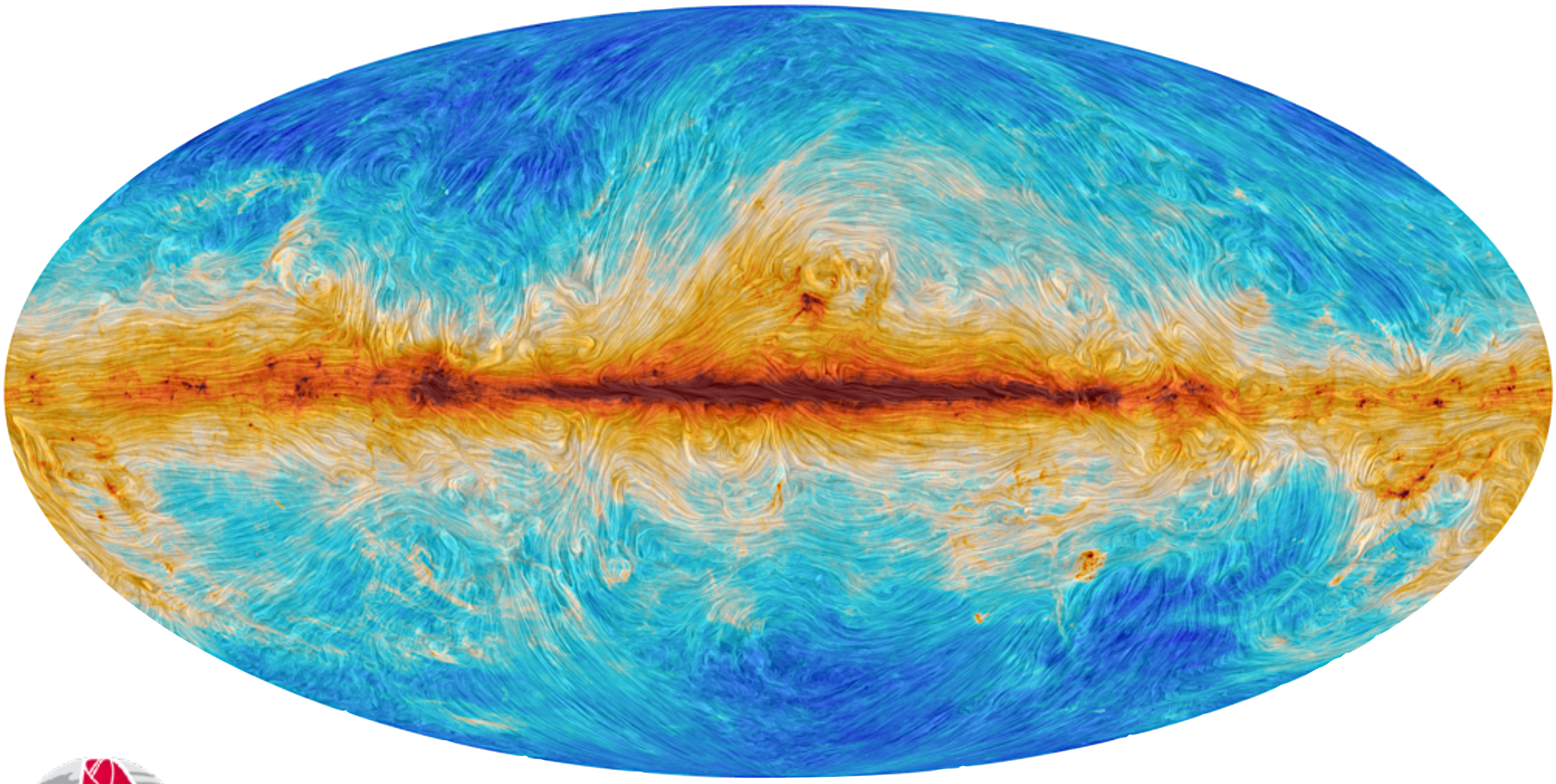
Novak, Dotson & Li, 09
GMC NGC 6334
450μm

ESA's Planck mission

HFI - 353 GHz (850 μm) @ 5'

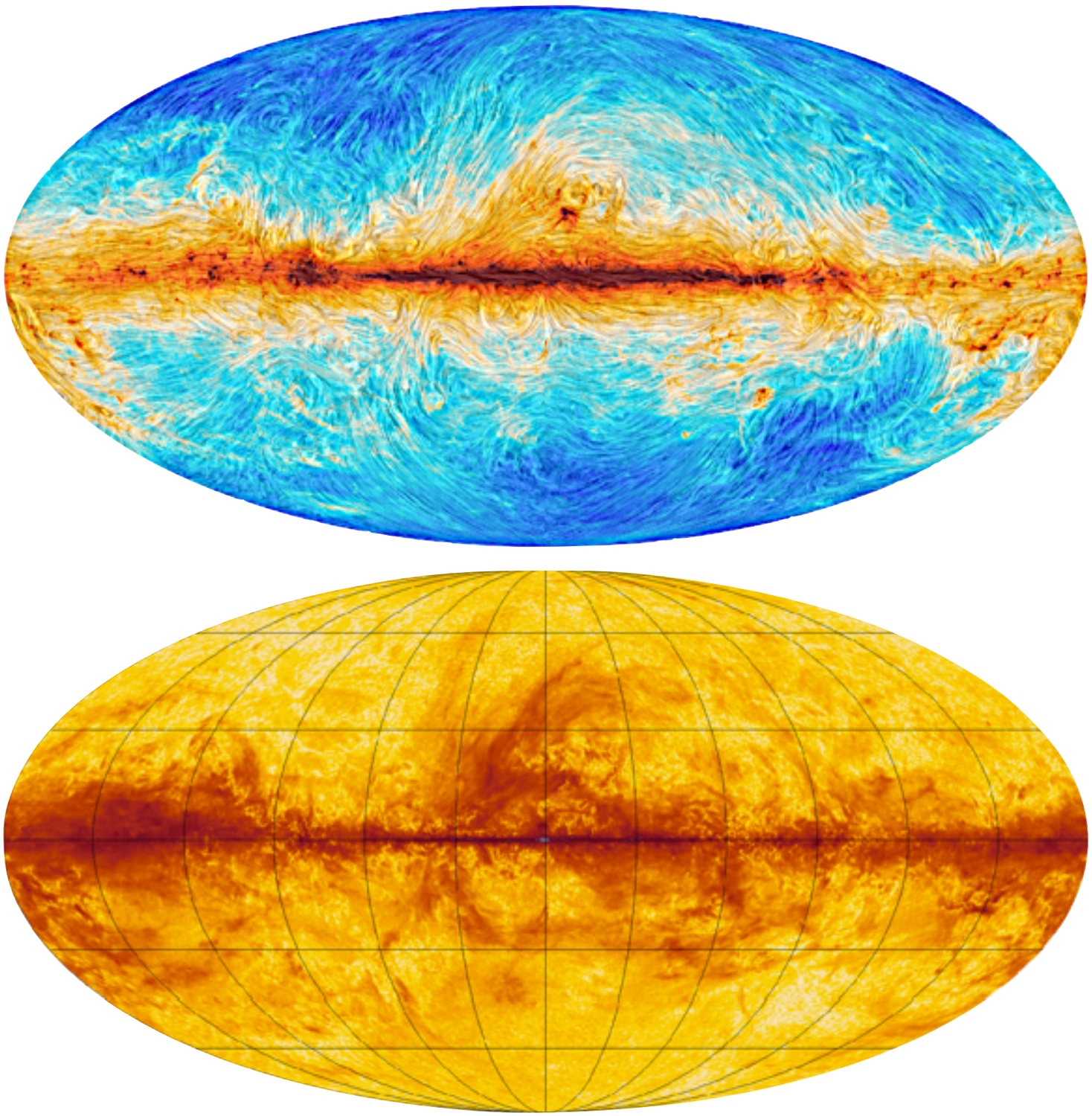
Magnetic field orientation derived from Planck 353 GHz

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



Magnetic field studies based on Planck 353 GHz

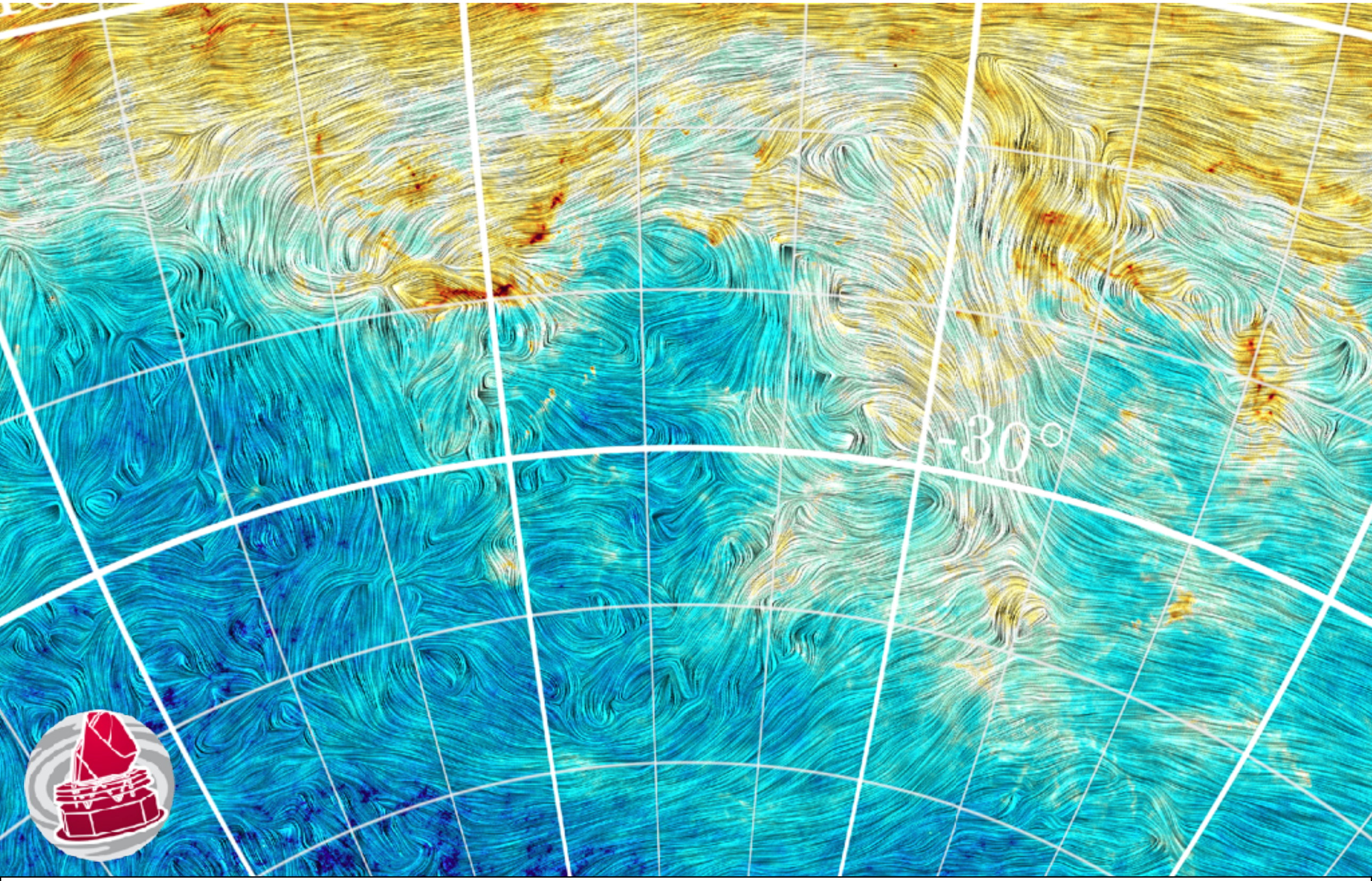
Planck 2015 results I. A&A, 594 (2016), A1



- Angle dispersion
  Planck XIX (2015)
- Comparison to starlight pol.
  Planck XXI (2015)
- Polarized fraction
  Planck XX (2015)
- Power spectrum
  Planck XXX (2016)
- Geometric modelling
  Planck XXXIII (2016)
  Planck XXXIV (2016)
- Relative orientation
  Planck XXXII (2016)
  Planck XXXV (2016)
- Relation to E- and B-modes
  Planck XXXVIII (2016)
- Dust grain alignment
  Planck XII (2018)

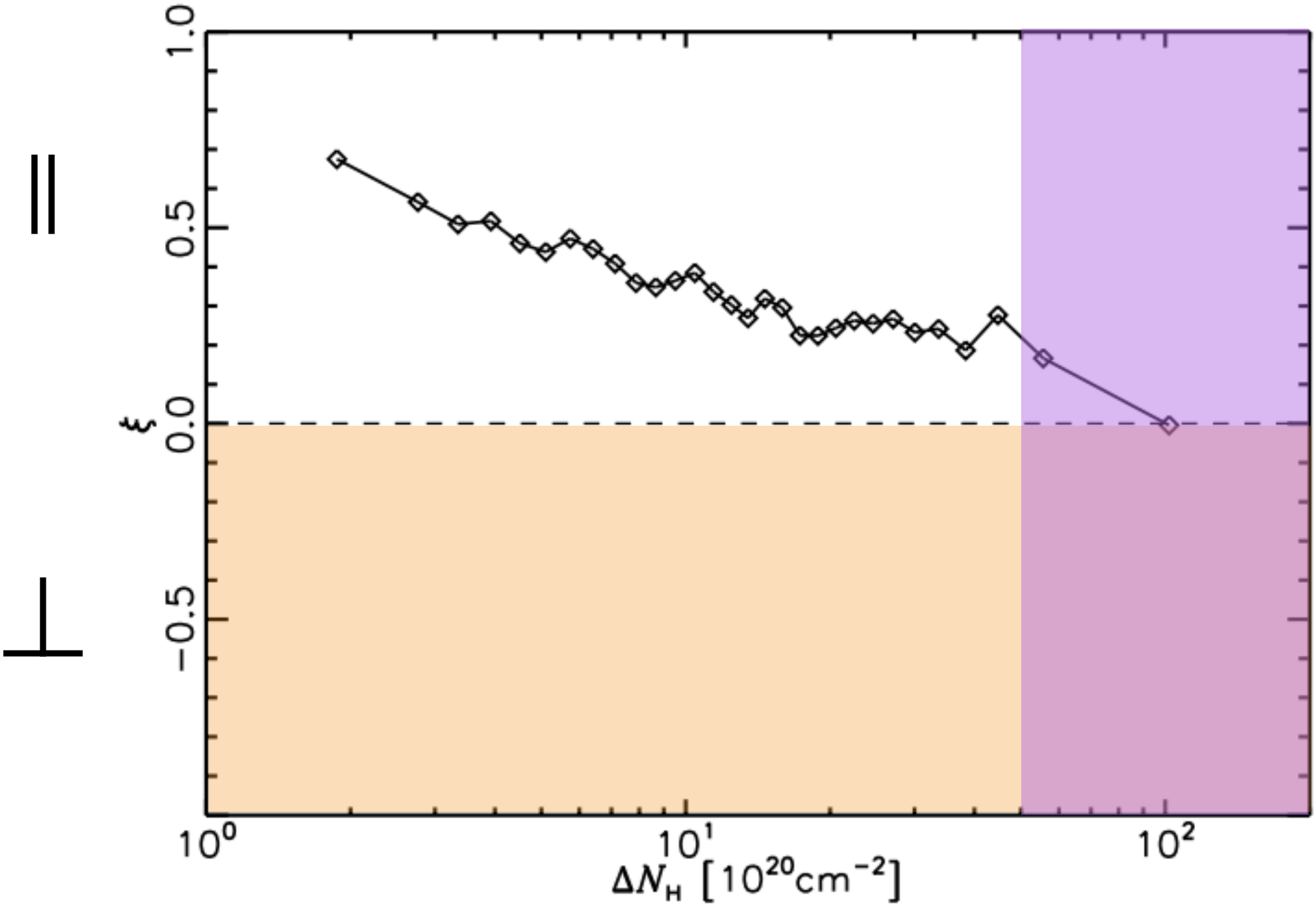
Magnetic field orientation derived from Planck 353 GHz

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



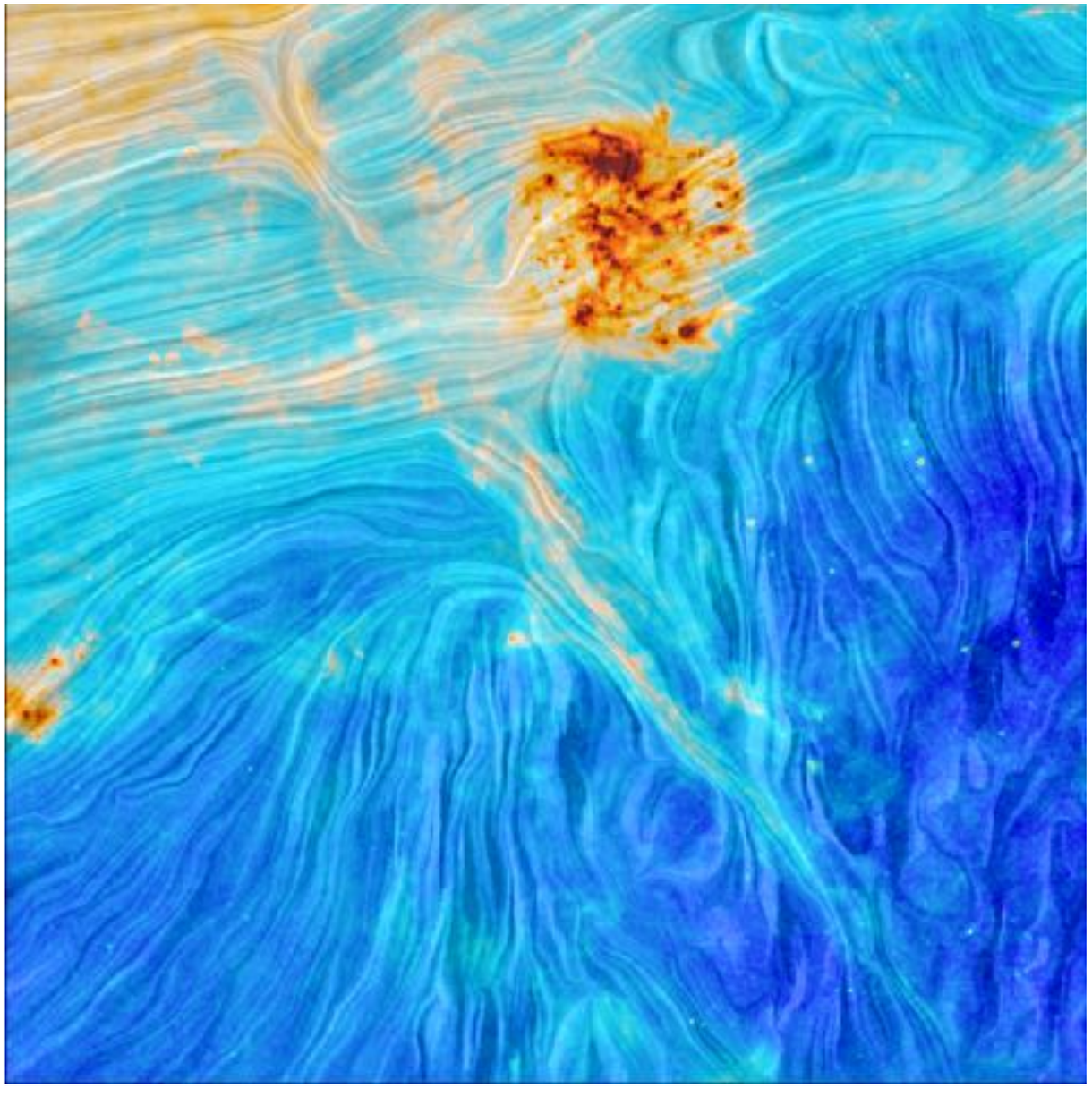
Relative orientation between N_H and $B_\perp$ (all sky)

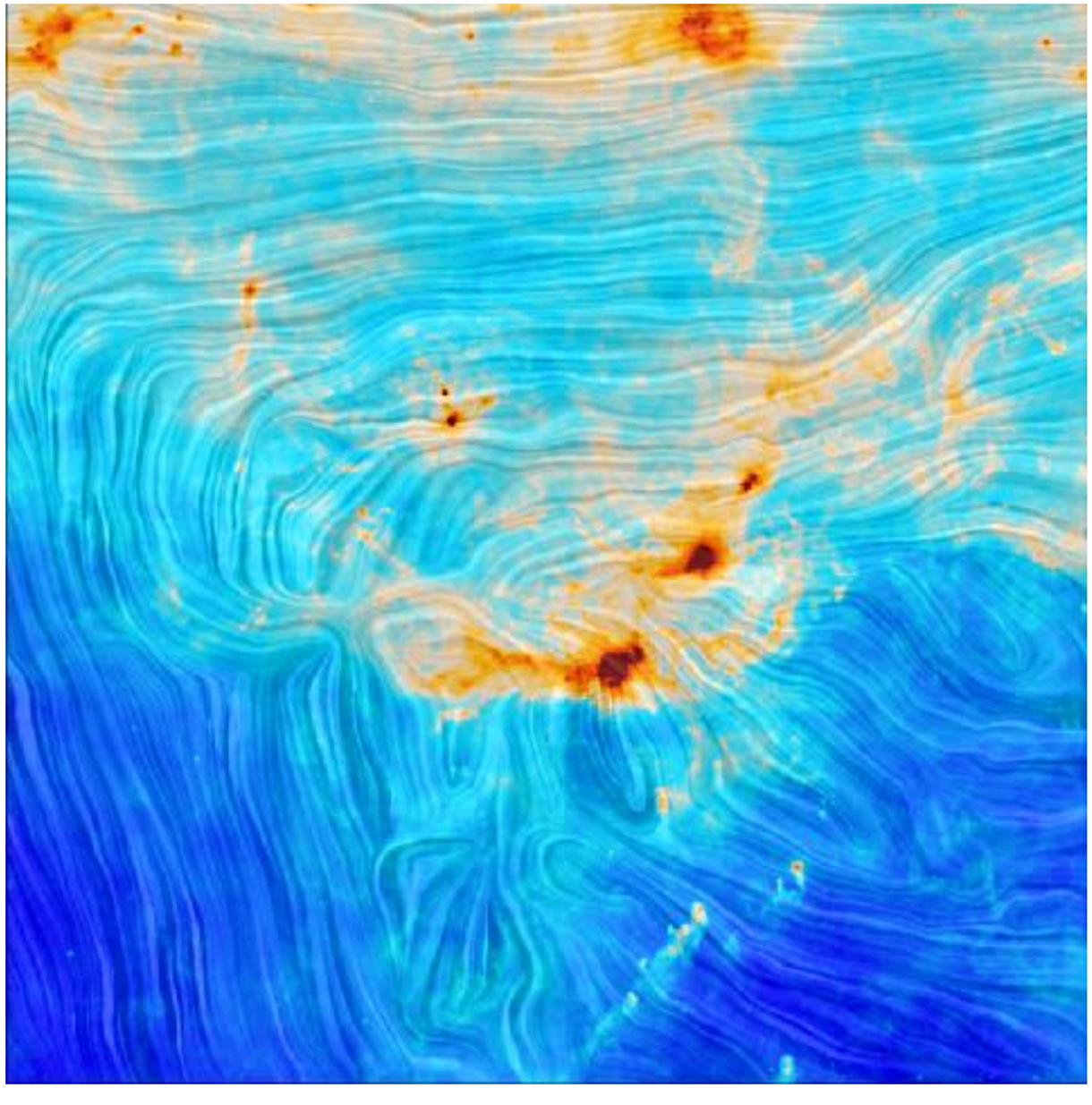
Planck intermediate results. XXXII (Bracco, A. et al.). A&A, 586 (2016) A138

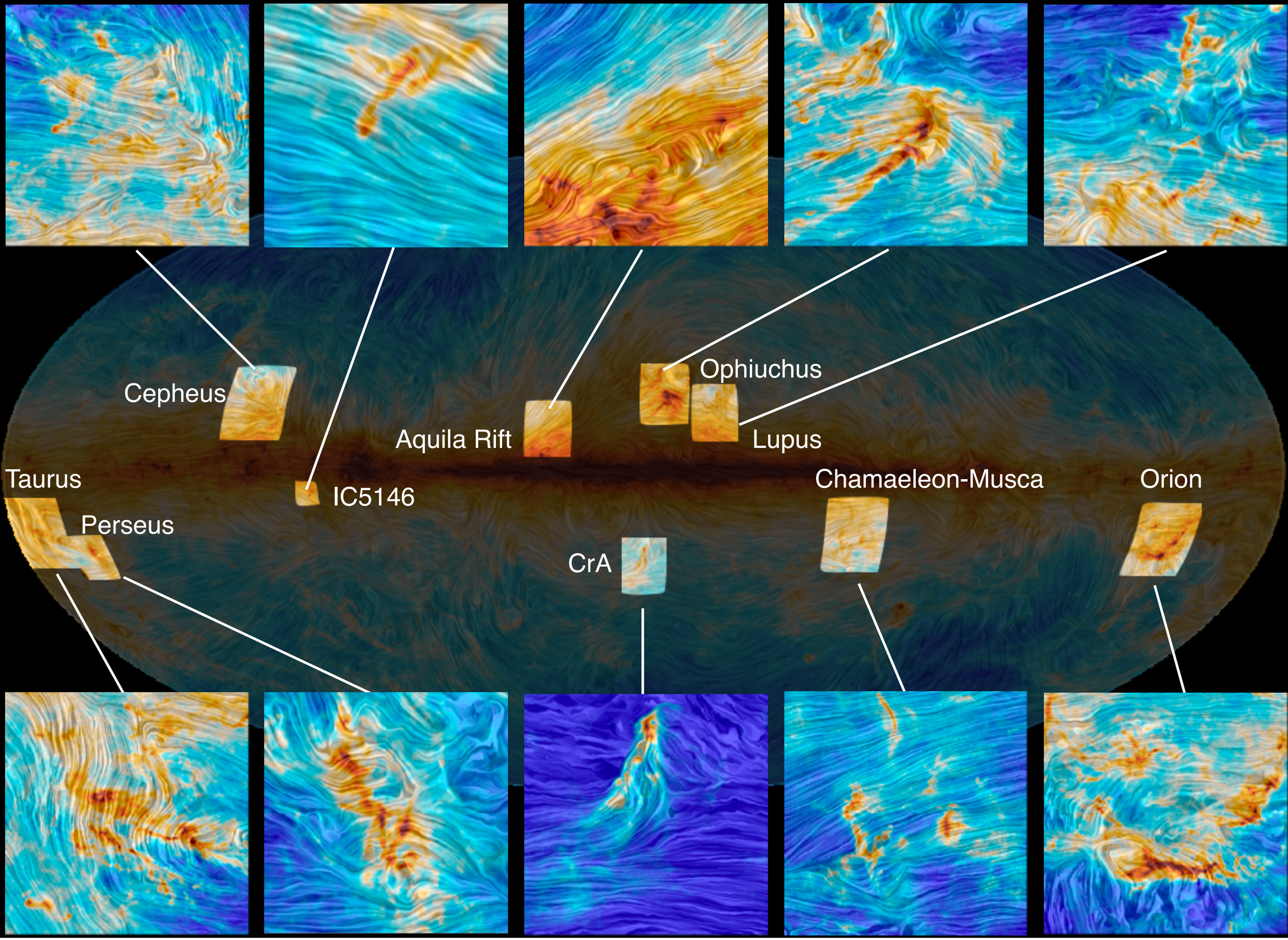


Magnetic field orientation derived from Planck 353 GHz

ESA/Planck Collaboration







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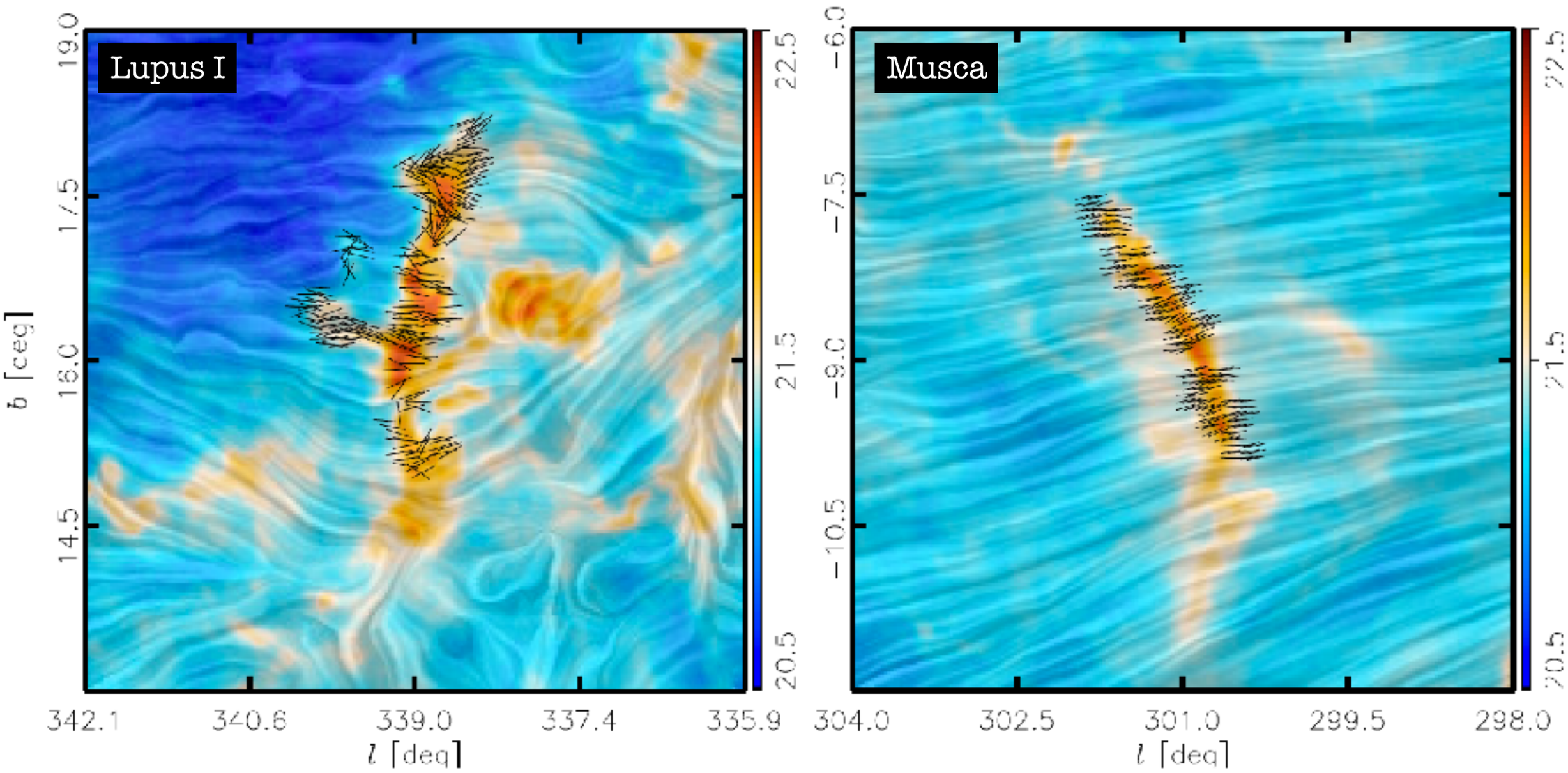
Planck: magnetic field from submm and starlight polarization

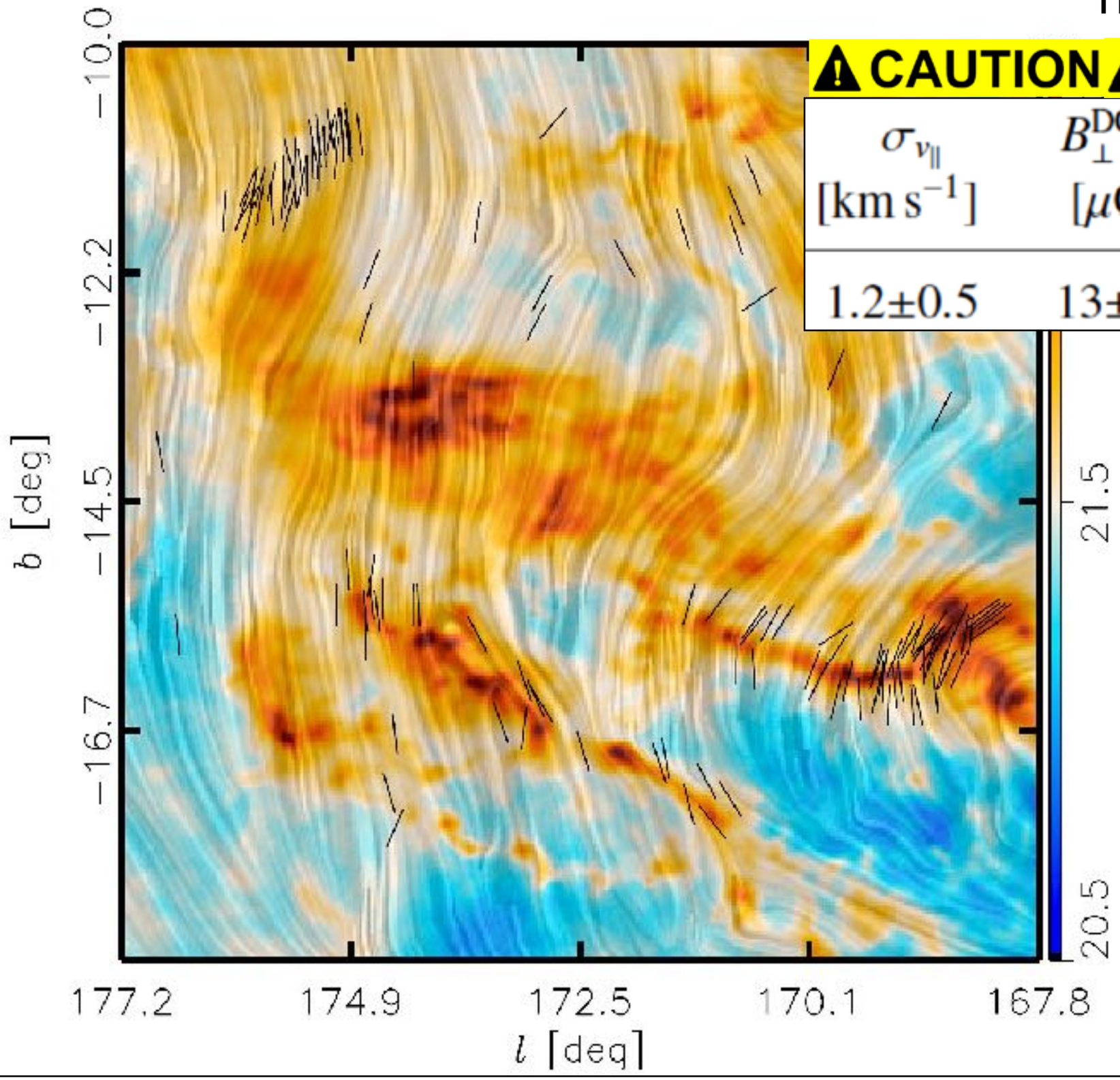
Soler, J.D., Alves, F., et al, 2016 A&A 596, A93 (2016)



Relative orientation between N_H and $B_\perp$ (Taurus MC d = 150 pc)

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

$n \sim 10^2\ cm^{-3}$

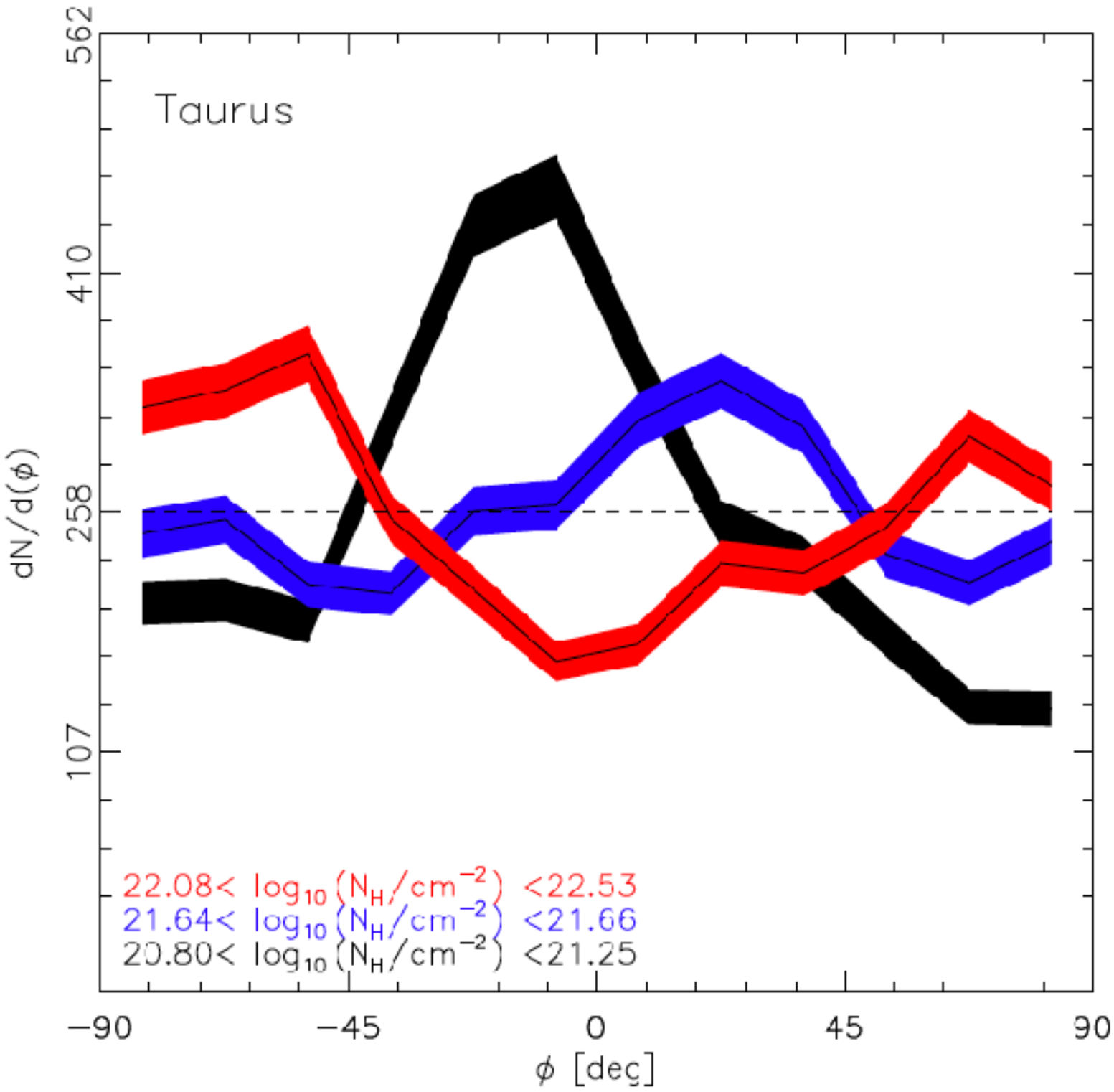


⚠ CAUTION ⚠ CAUTION

$\sigma_{v_\parallel}$ [km s^{-1}]	$B_\perp^{DCF}$ [μG]	λ_{obs}^{DCF}
1.2±0.5	13±5	0.4±0.4

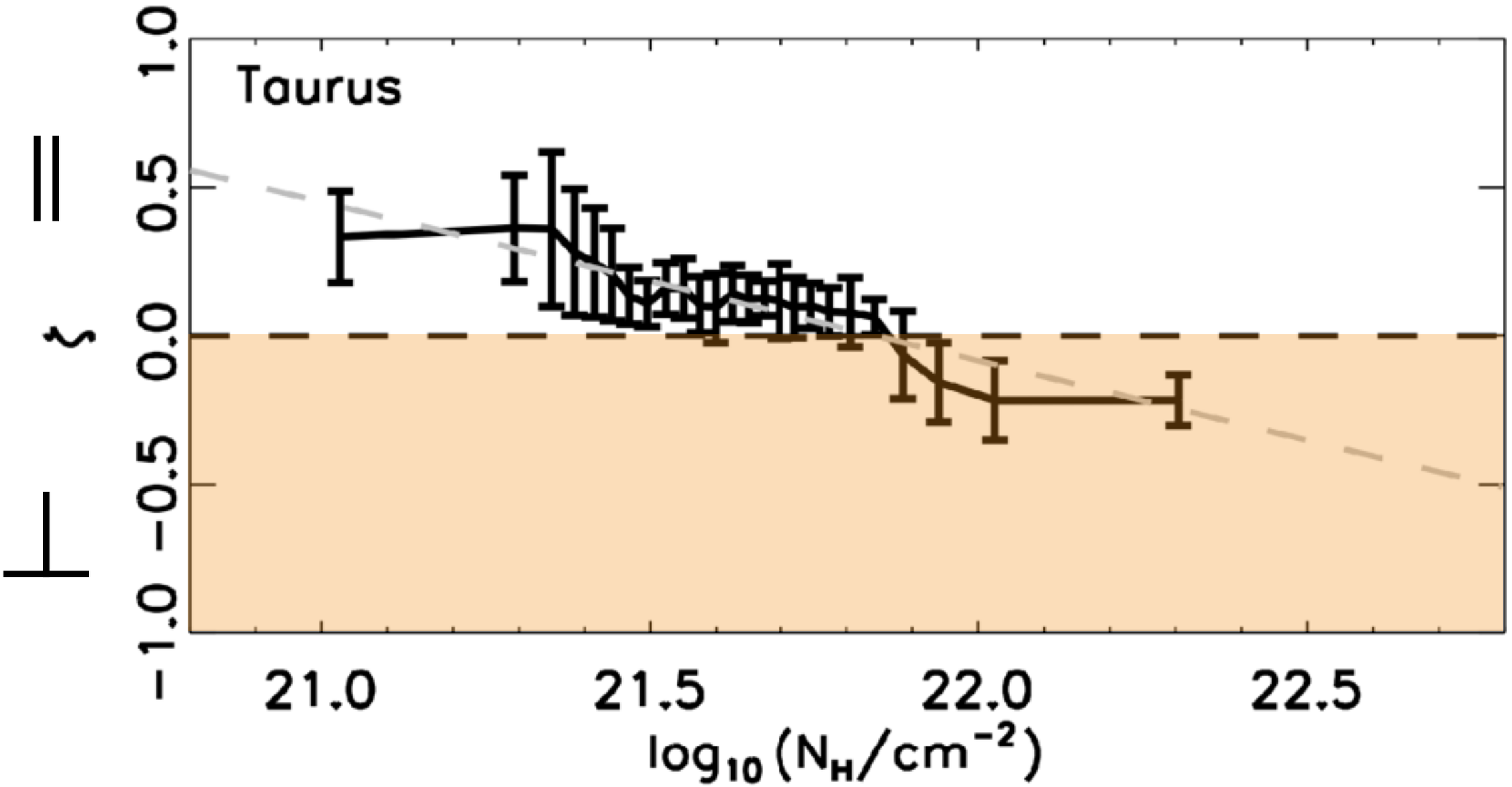
Relative orientation between N_H and $B_\perp$ (Taurus MC d = 150 pc)

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



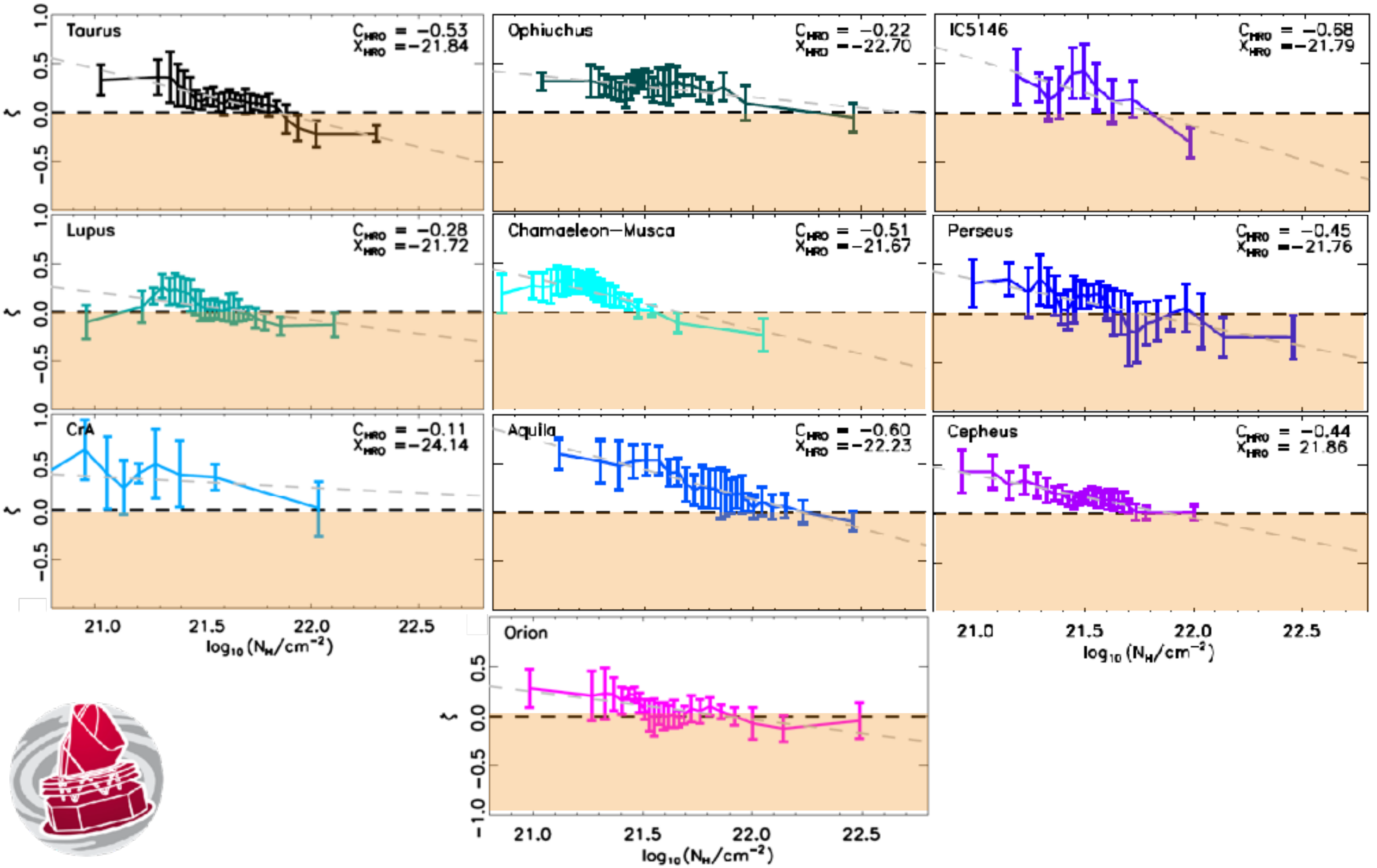
Relative orientation between N_H and $B_\perp$ (Taurus MC d = 150 pc)

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



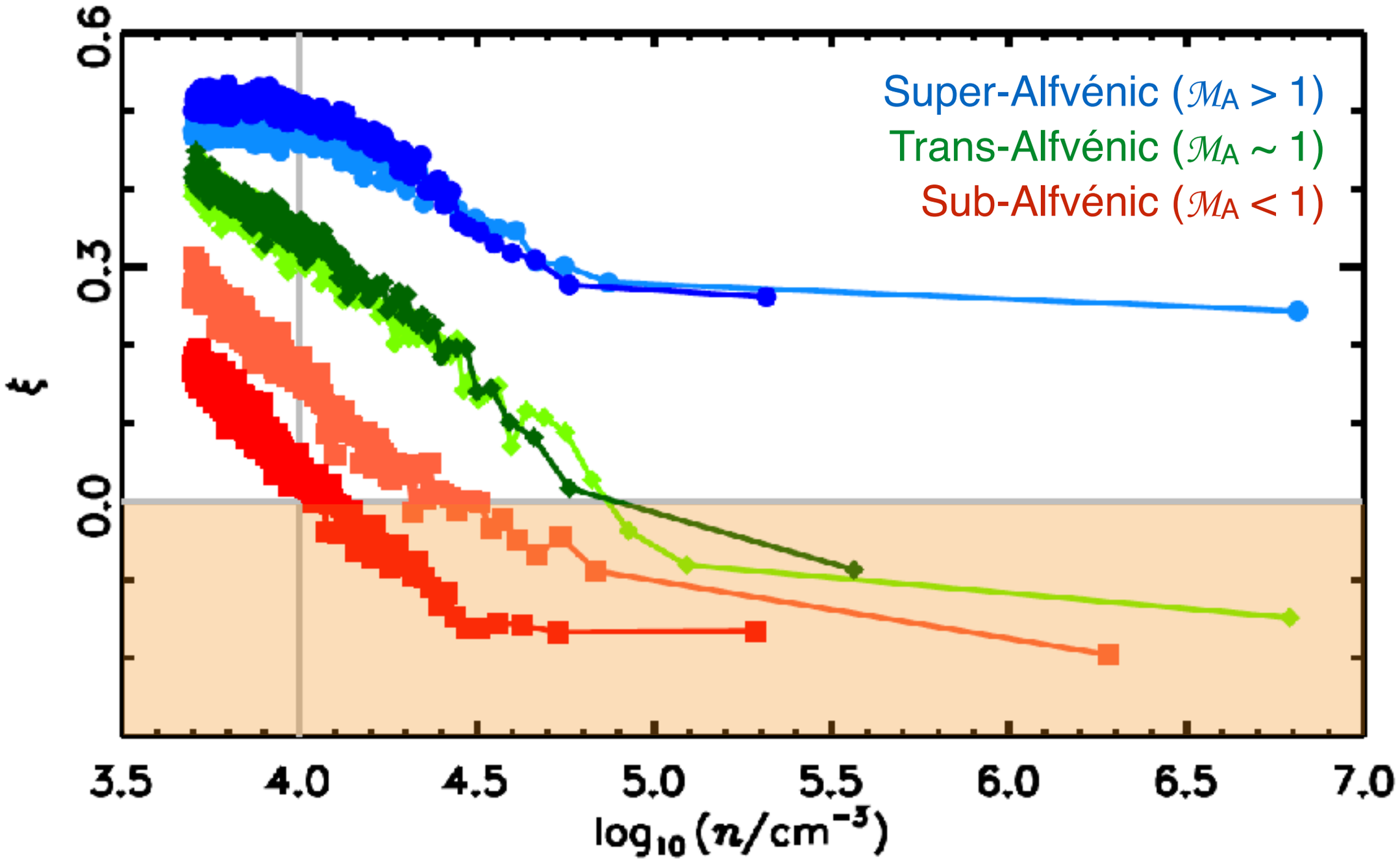
Relative orientation between N_H and $B_\perp$ (10 MCs @ d < 450 pc)

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



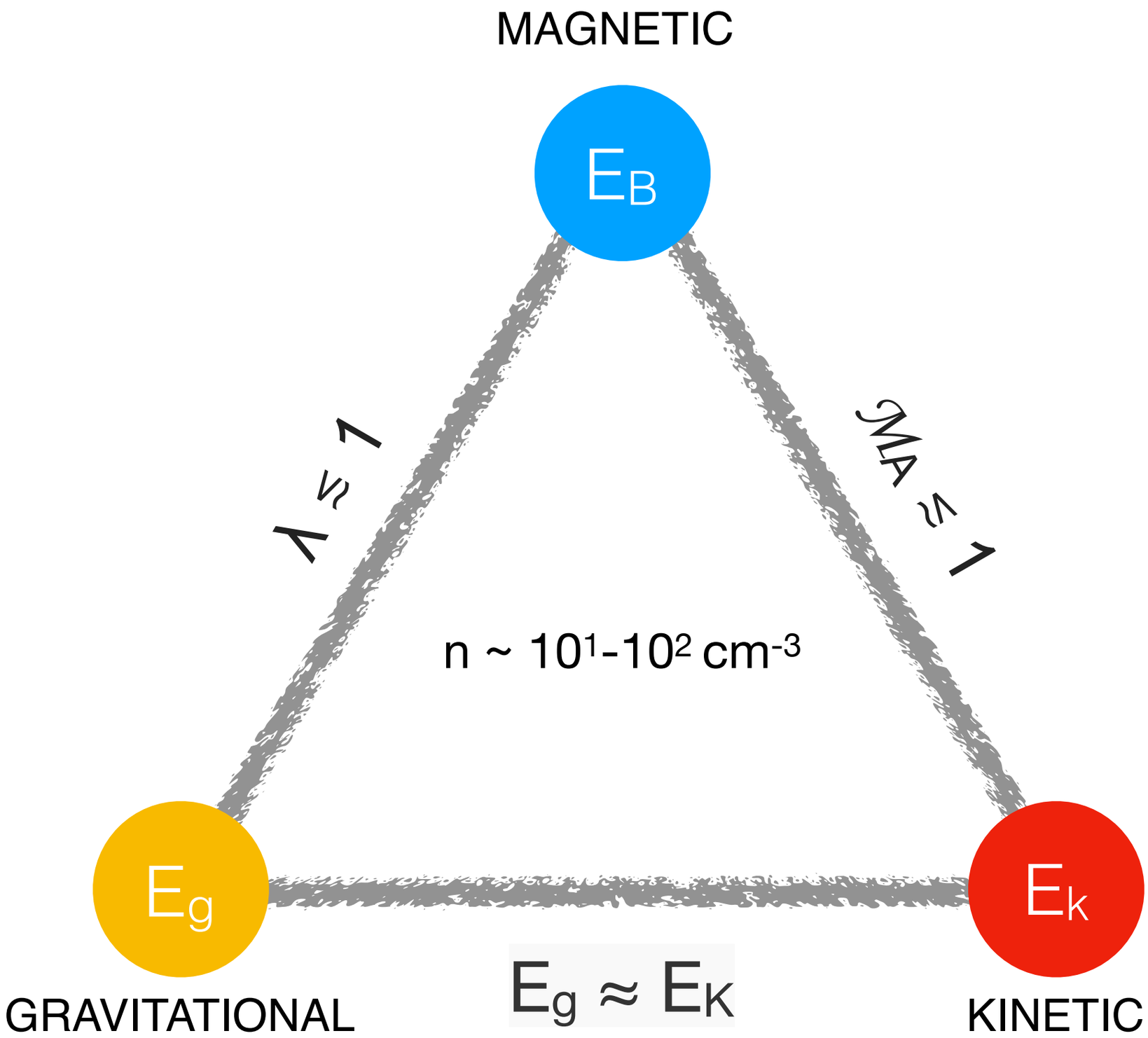
Relative orientation between N_H and $B_\perp$

Soler, J.D., et al. ApJ. 774 (2013), 128
Soler, J.D. & Hennebelle, P. A&A 607A (2017) 2S



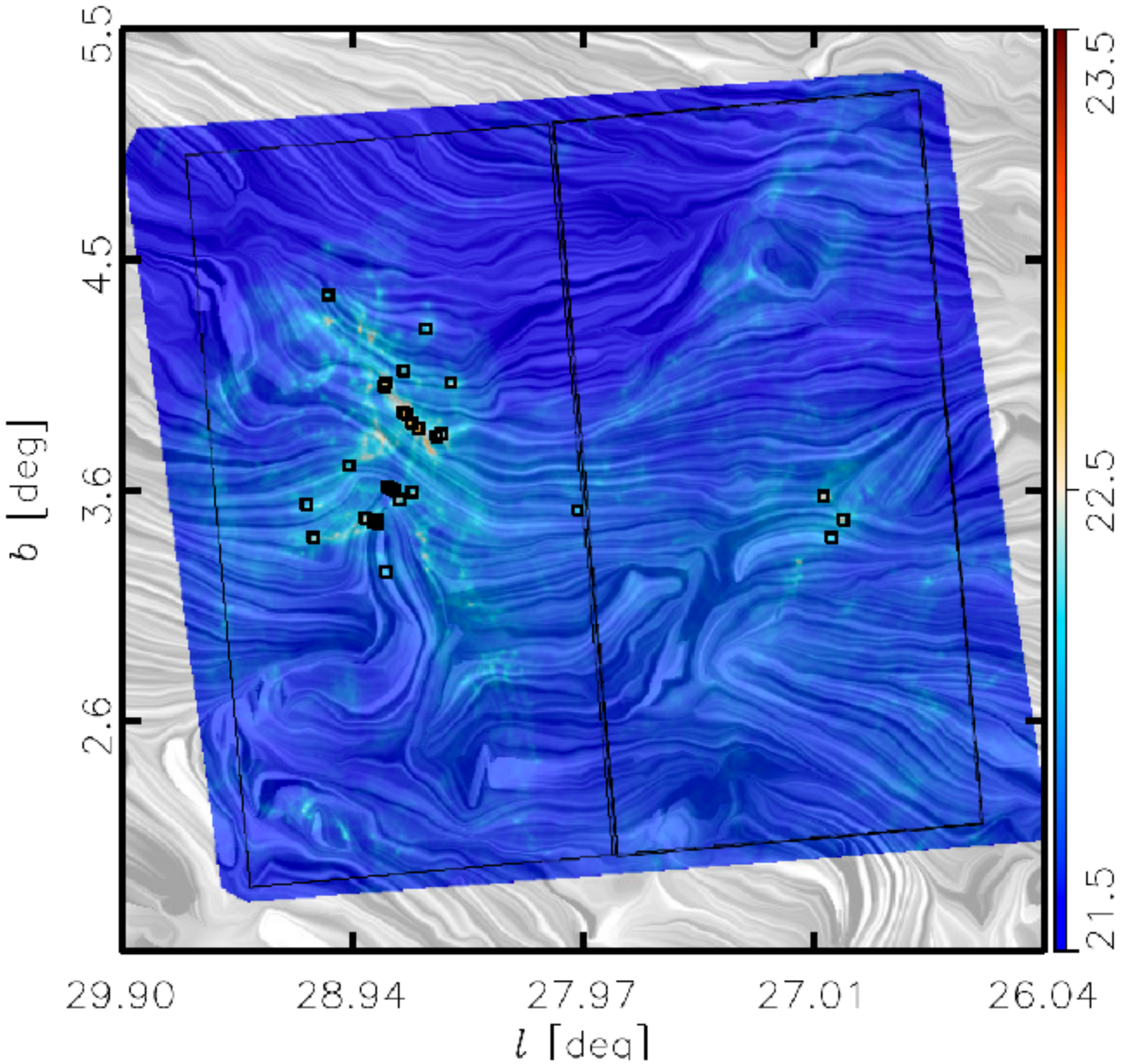
Towards nearby MCs (scales 10 and 0.2 pc)

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



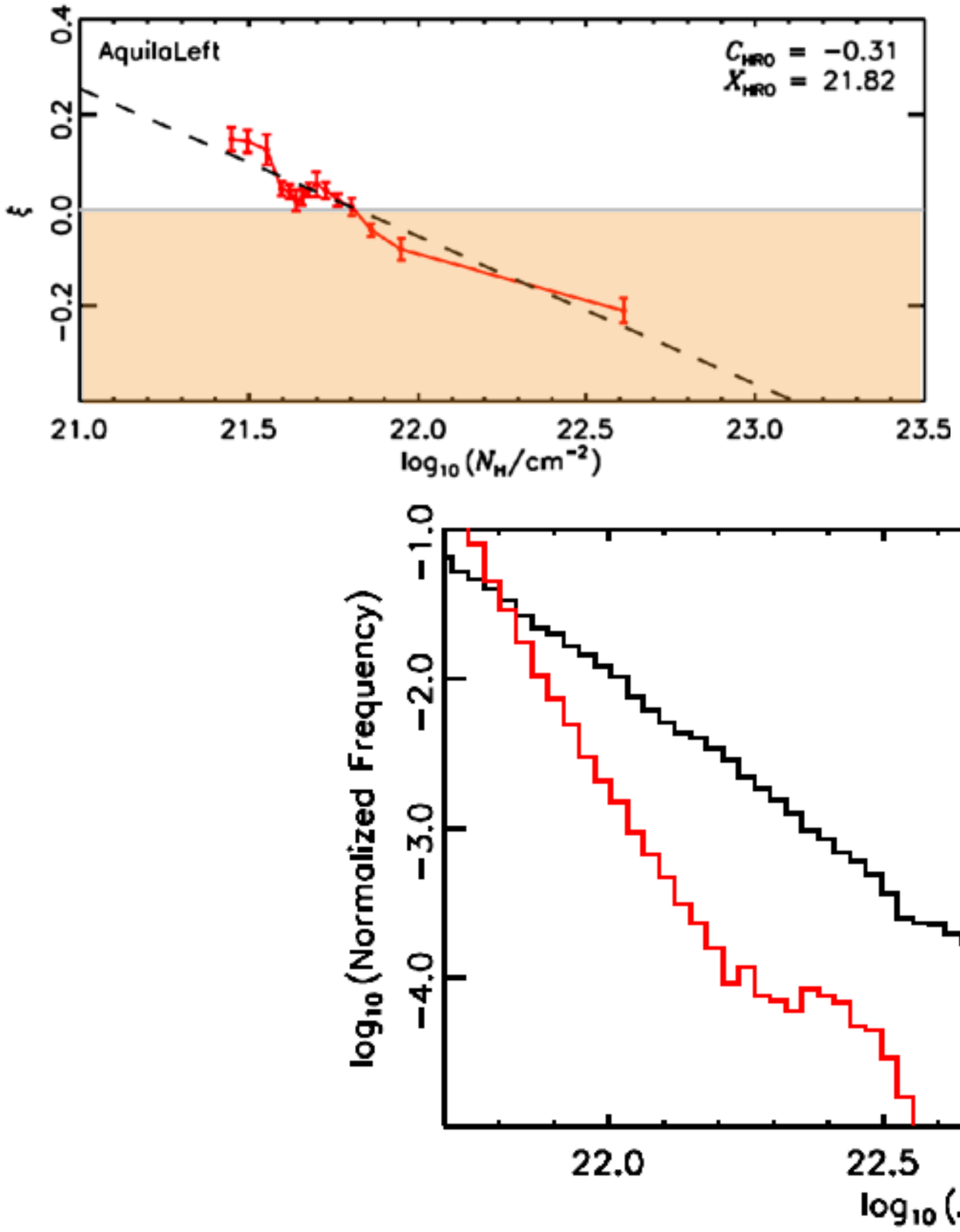
Relative orientation between N_H and $B_\perp$ towards Serpens South

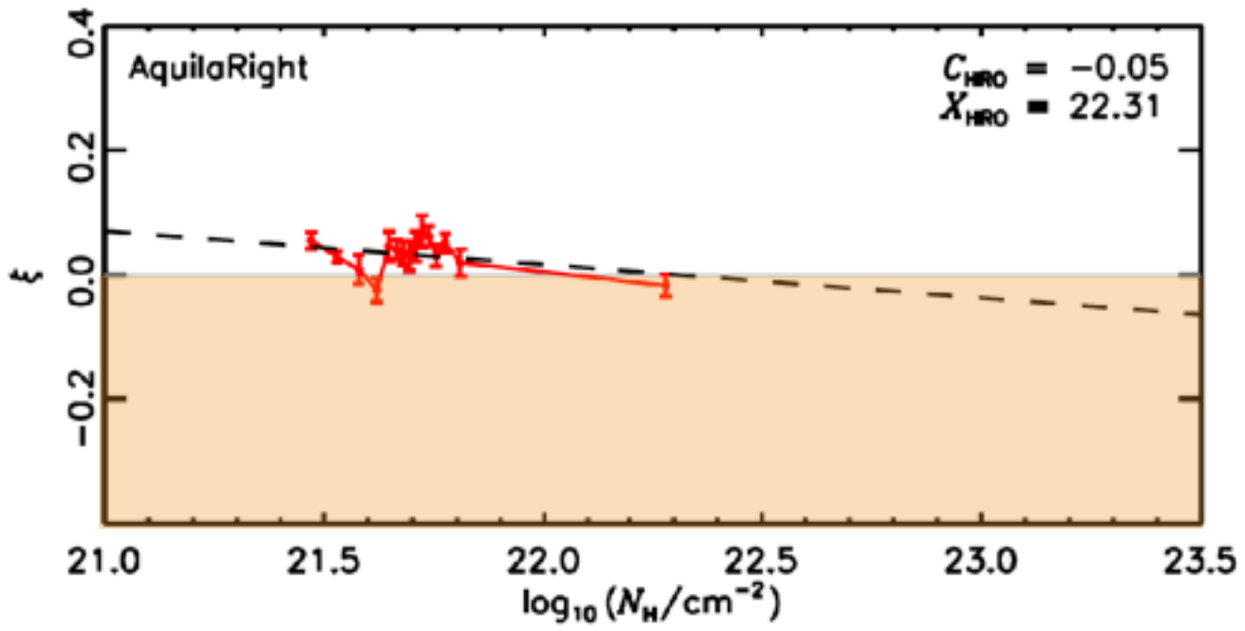
Soler, J.D. and the BLASTPol Collaboration A&A 603A (2017) 64S



Relative orientation between N_H and $B_\perp$ towards Serpens South

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





BLASTPol

BLASTPol - 250 μm @ 3’
350 μm
500 μm

JCMT (EAO)

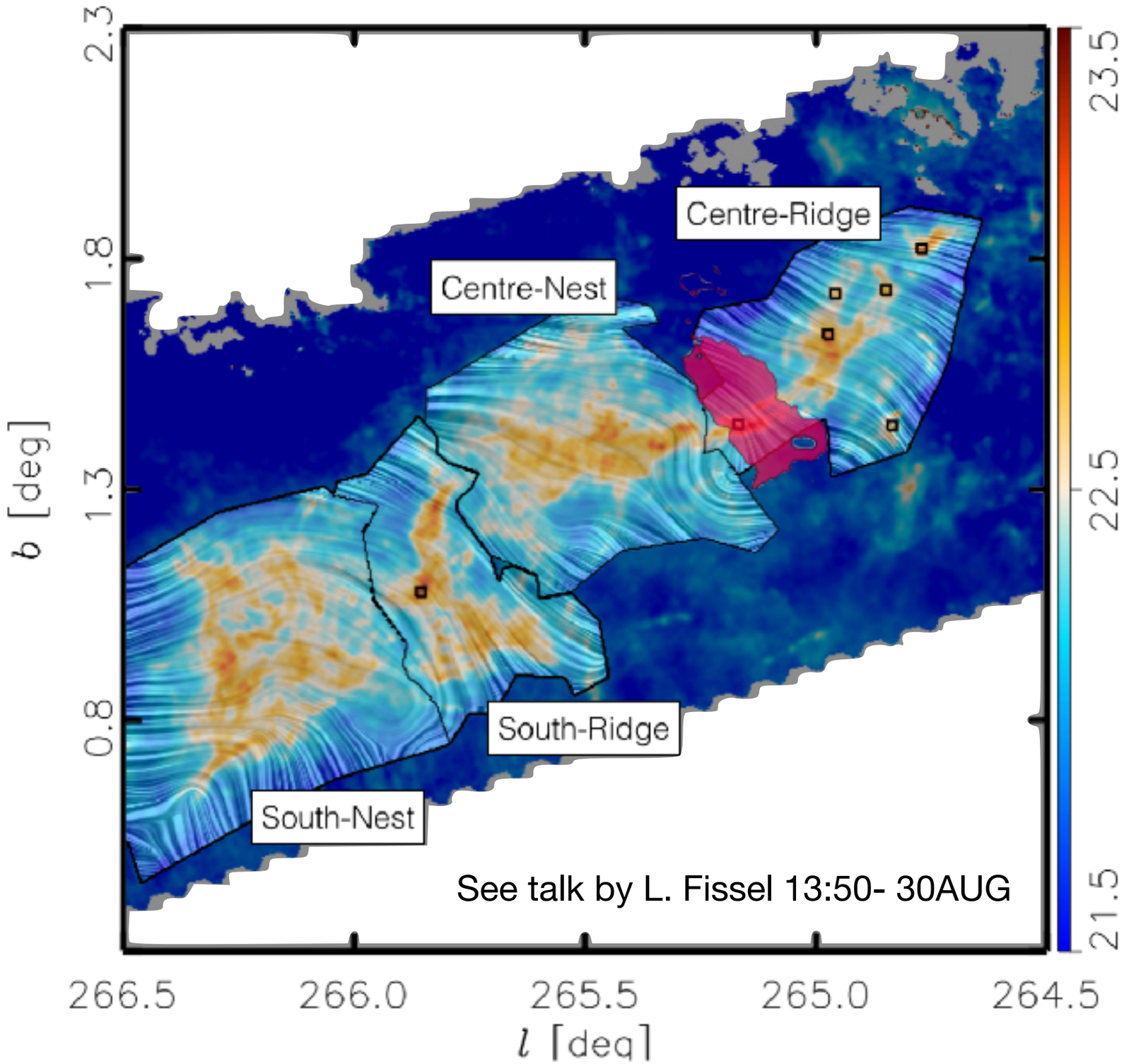
POL-2 - 850 μm @ 14.3”
450 μm @ 9.8”

SOFIA

HAWC+ 5 bands
50 μm @5” to
240 μm @20”

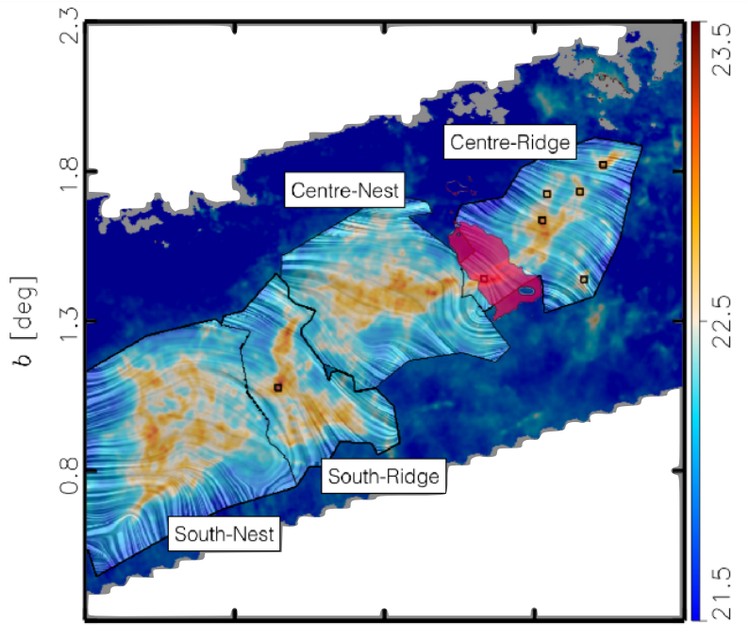
Magnetic field towards the Vela C molecular cloud (d = 700pc)

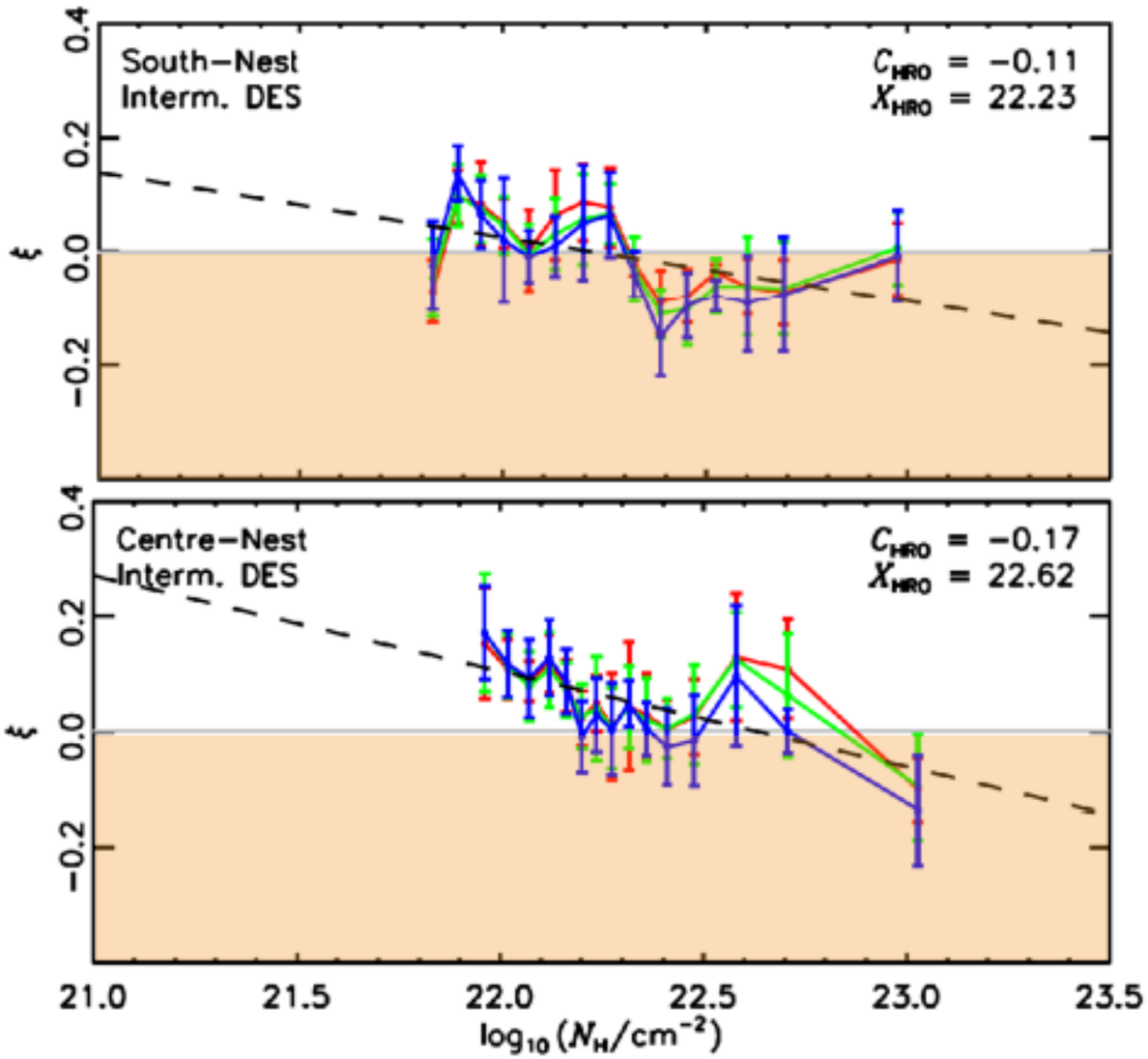
Soler, J.D., et al. A&A 603A (2017) 64S
Santos, F., et al. ApJ 837 (2016) 161S
Fissel, L.M. et al. ApJ 824 (2016) 134F

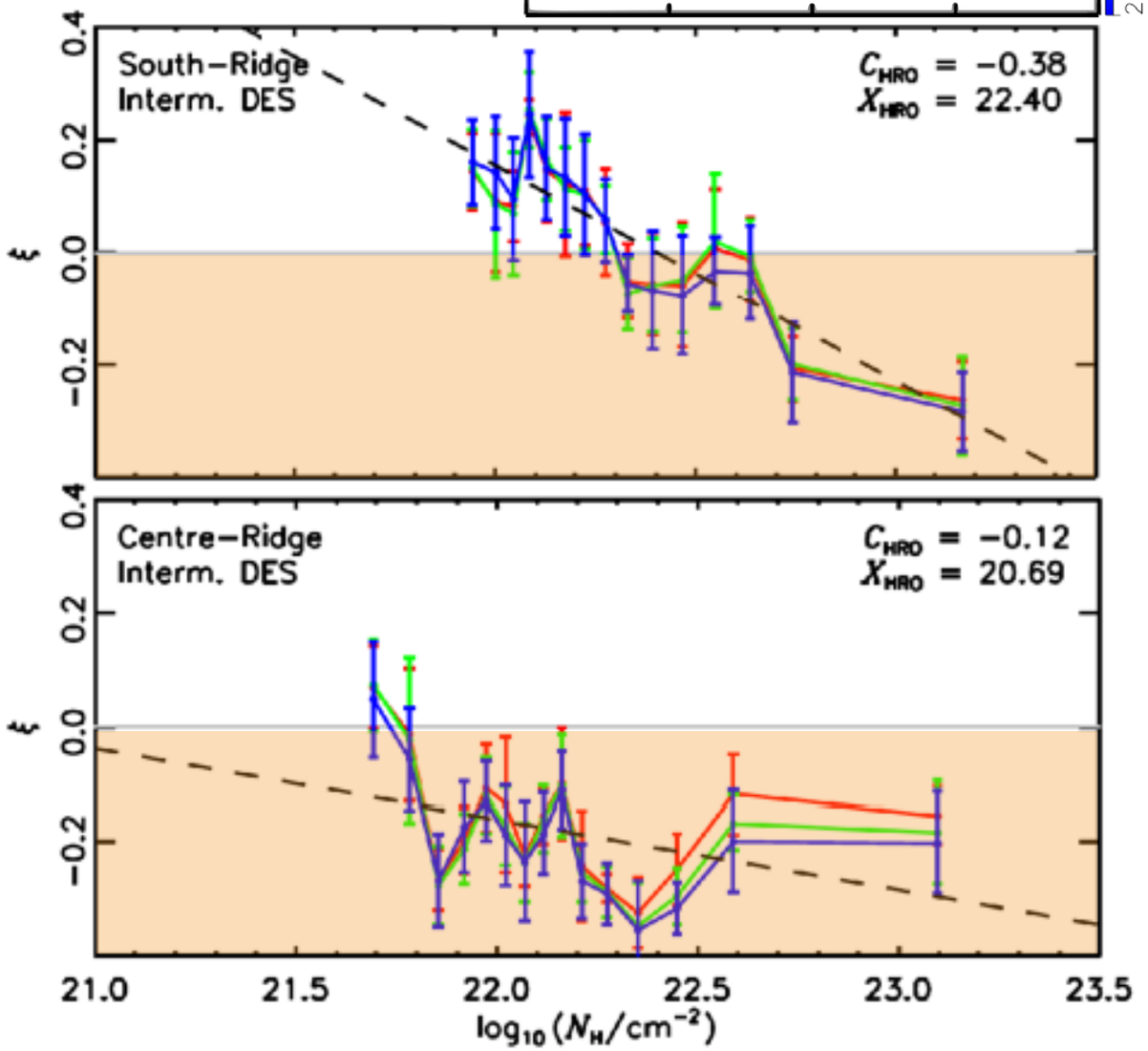


Magnetic field towards the Vela C molecular cloud (d = 700pc)

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

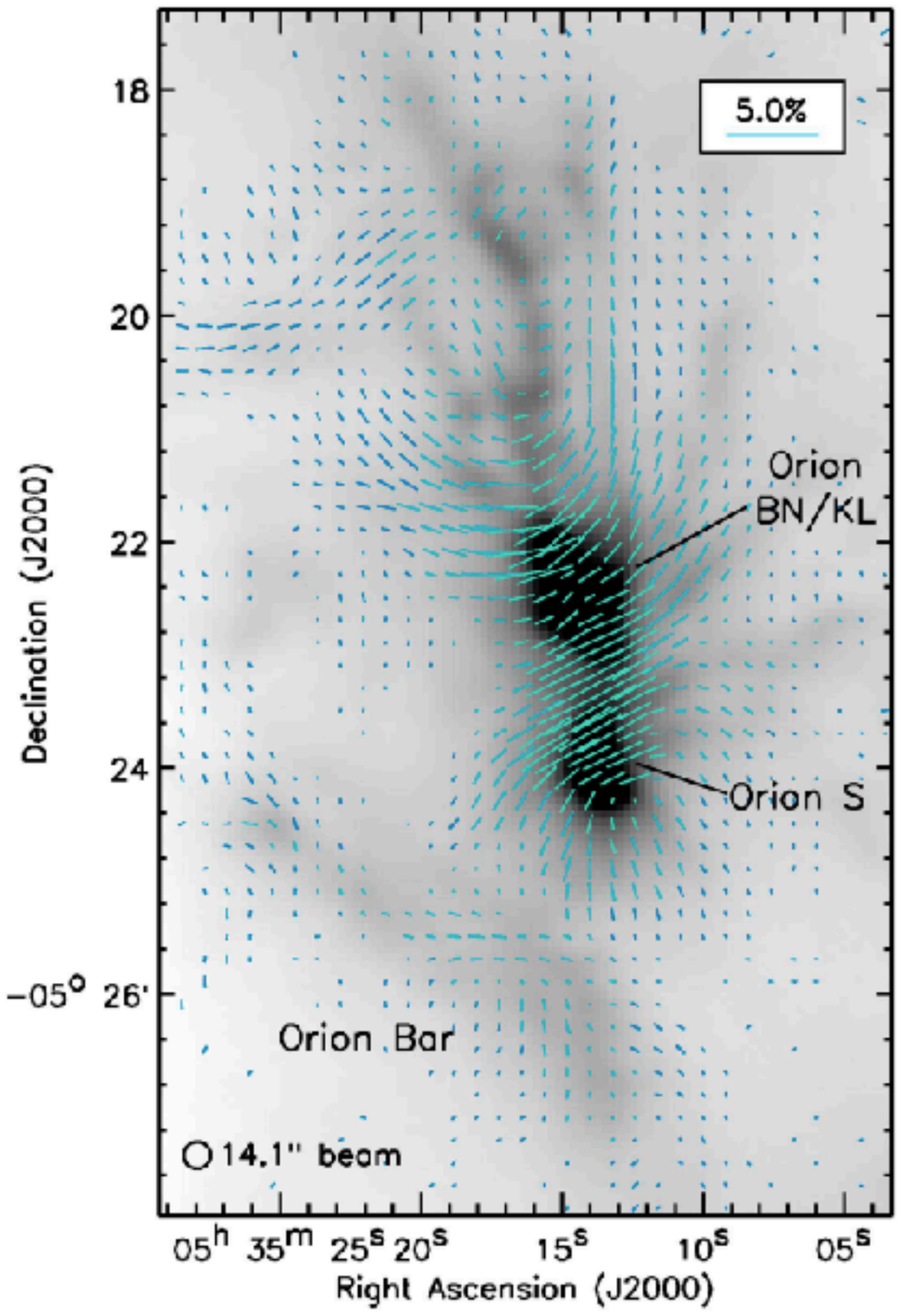




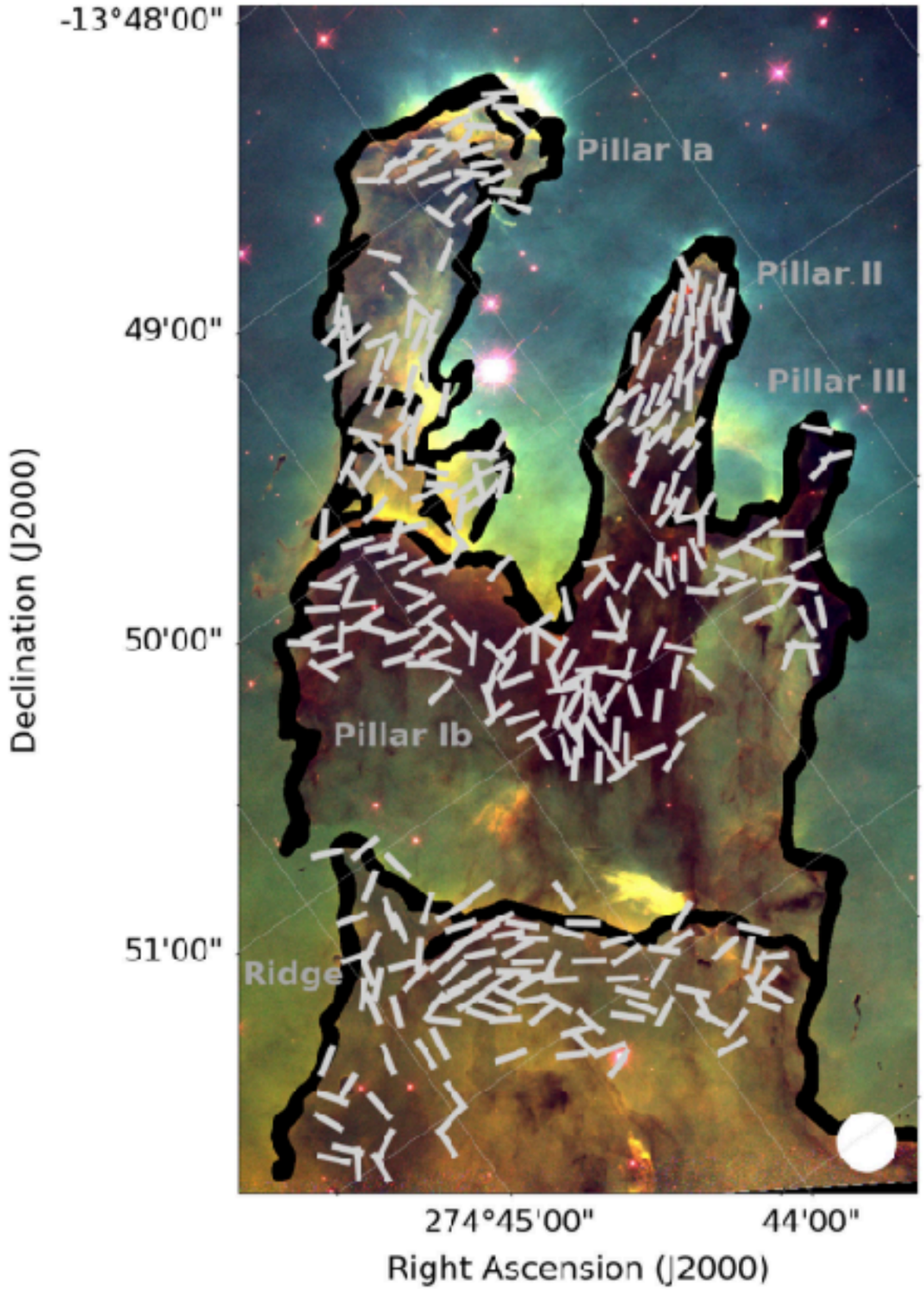


B-fields In Star-forming Region Observations (BISTRO) survey

Ward-Thompson, D., et al. ApJ, 842 (2017) 66W
Pattle, K., et al. ApJ, 846 (2017) 112P



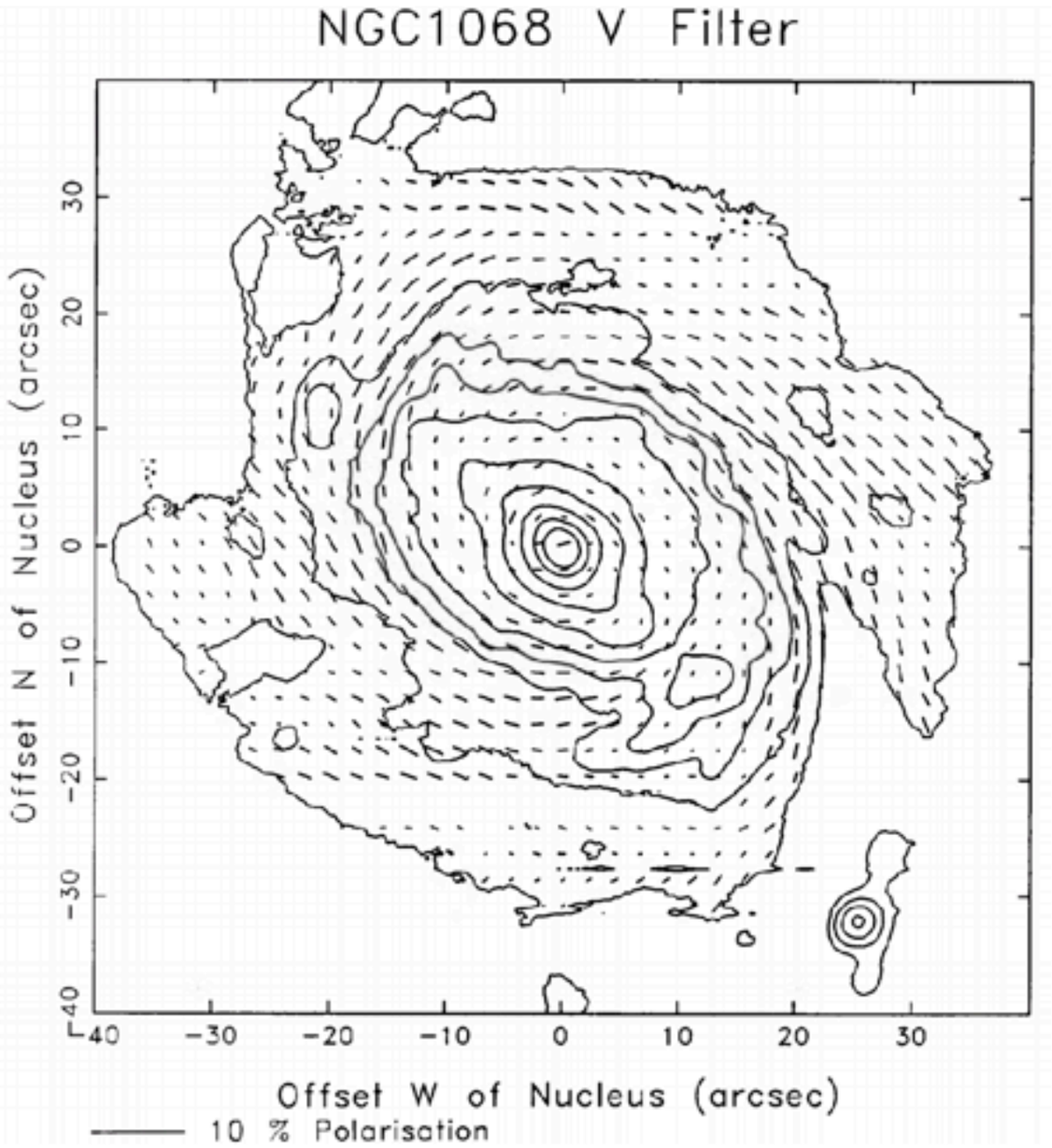
Pattle, K., et al. ApJ.860L (2018) 6P

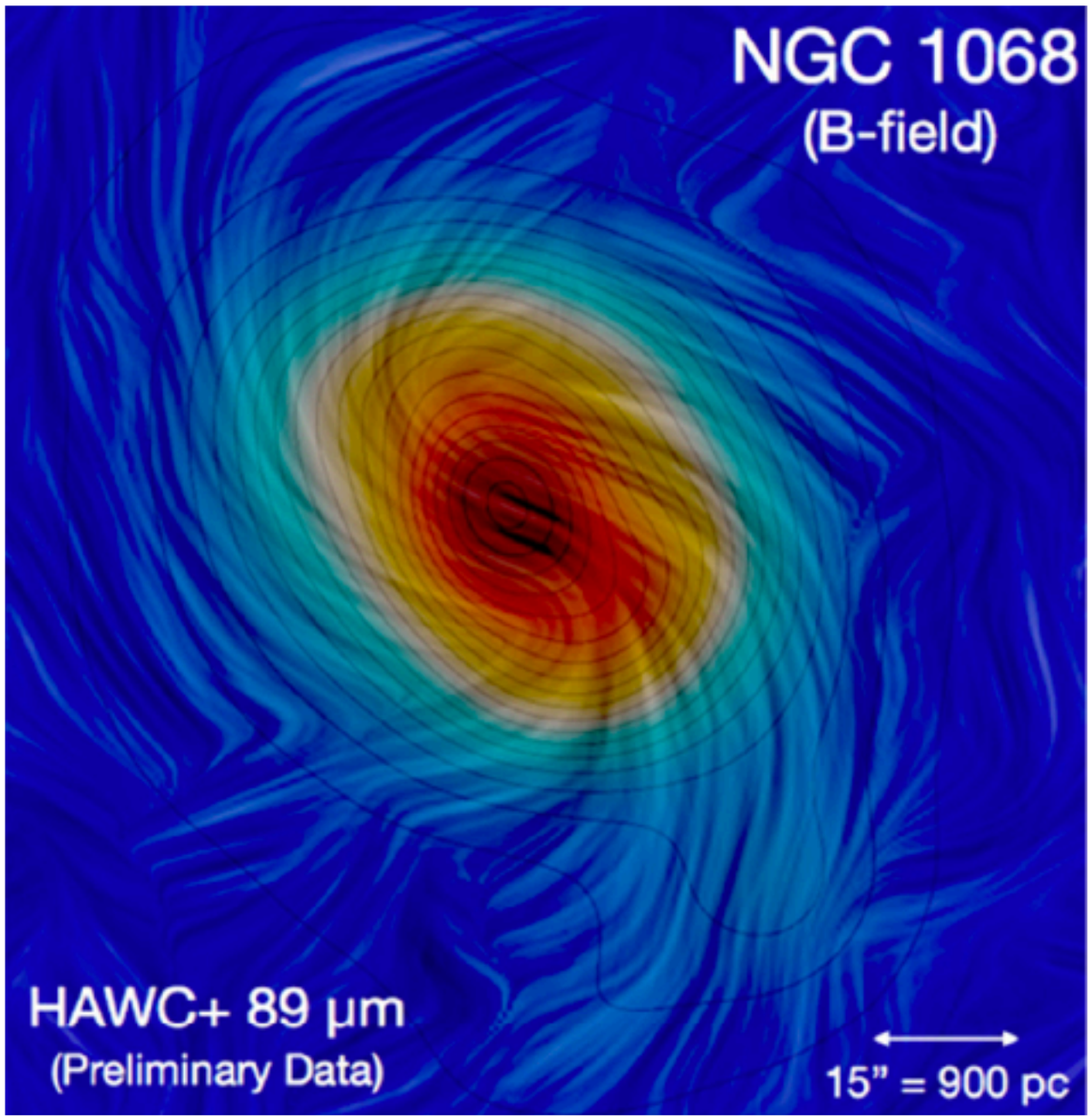


Optical polarization

Scarrott, S.M, et al., A&A, 249P (1991) 16S

Fendt, Ch., Beck,R. & Neininger, A&A, 26A (1998) 335





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Juan Diego Soler
@juandiegosoler

1

B affects flows in the diffuse ISM, but is it anchoring MCs?

Uncertain with respect to Galactic B

Undefined towards nearby clouds

Juan Diego Soler
@juandiegosoler

1

B affects flows in the diffuse ISM, but is it anchoring MCs?

Uncertain with respect to Galactic B

Undefined towards nearby clouds

2

Something is happening at $N_H \approx 10^{21.7}$ cm^{-3}

Zeeman-derived B scaling with n_H

Relative orientation between B and N_H

Empirical SF threshold

Lada et al. (2010); Heiderman et al. (2010)

Photodissociation shielding (HI to H_2 transition)

Krumholz et al. (2008,2009); Sternberg et al. 2014

Log-normal to power law N_H PDF

Kainulainen et al. (2009); Froebrich & Rowles. (2010)

Juan Diego Soler
@juandiegosoler

1. B affects flows in the diffuse ISM, but is it anchoring MCs?
   Uncertain with respect to Galactic B
   Undefined towards nearby clouds

2. Something is happening at $N_H \approx 10^{21.7}$ cm^{-3}
   Zeeman-derived B scaling with n_H
   Relative orientation between B and N_H

3. B influences the evolution of MCs
   Feedback: magnetic pillars and magnetic bubbles
   Fragmentation and “filamentation”

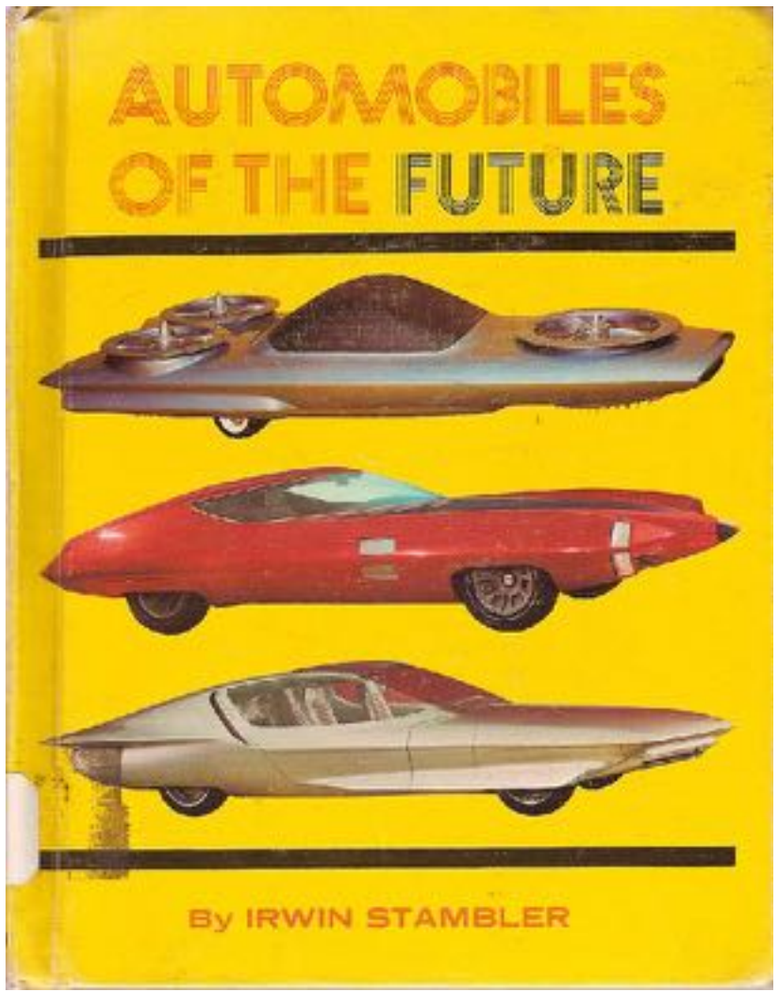
The near future

Epilogue

"... the larger one's ignorance, the stronger the magnetic field."
— Lodewijk Woltjer. Nordwijk Symposium, 1966

Epilogue

"... the larger one's ignorance, the stronger the magnetic field."
— Lodewijk Woltjer. Nordwijk Symposium, 1966



Welcome to magnetic 2018!