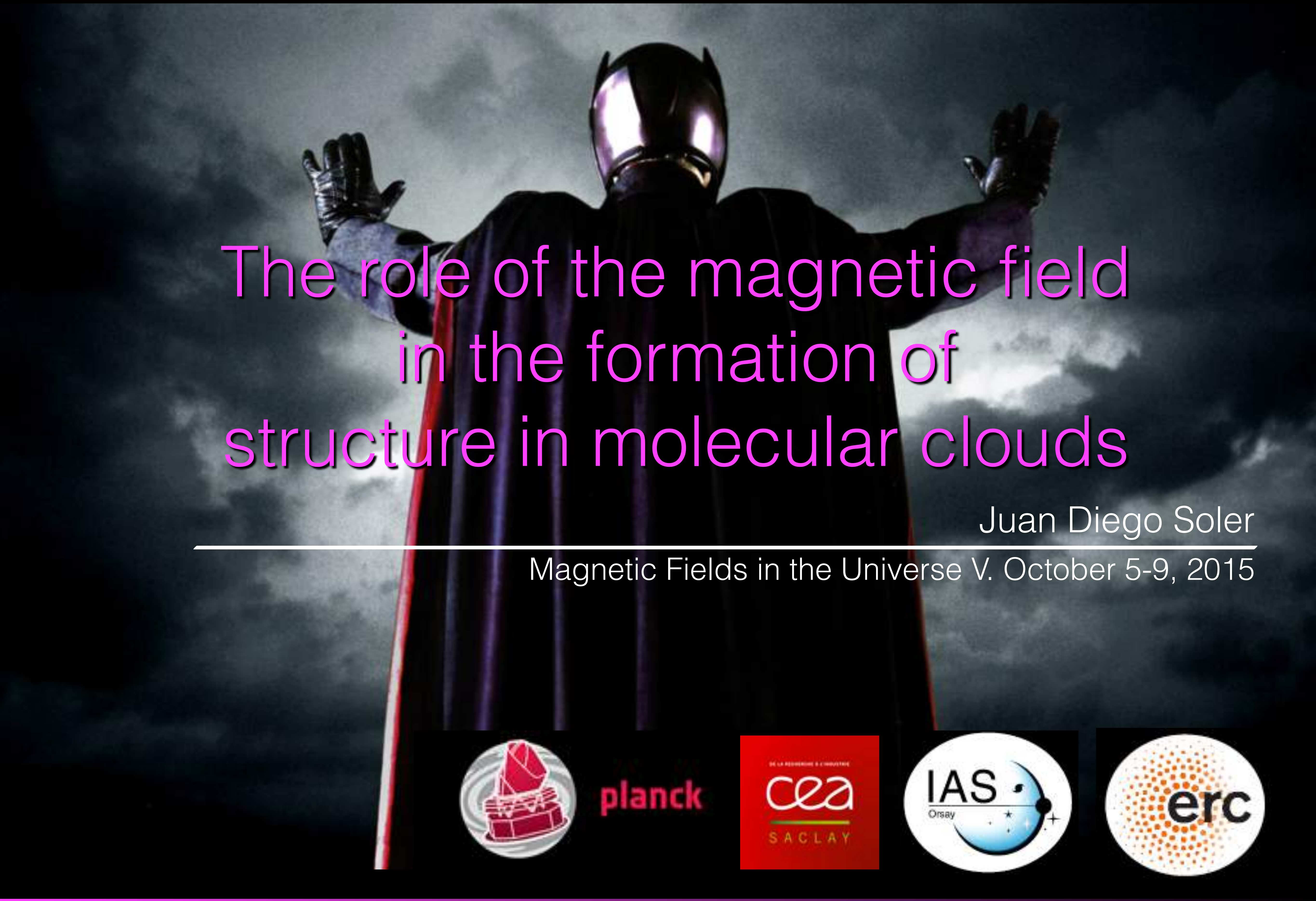


The role of the magnetic field in the formation of structure in molecular clouds

Juan Diego Soler

Magnetic Fields in the Universe V. October 5-9, 2015

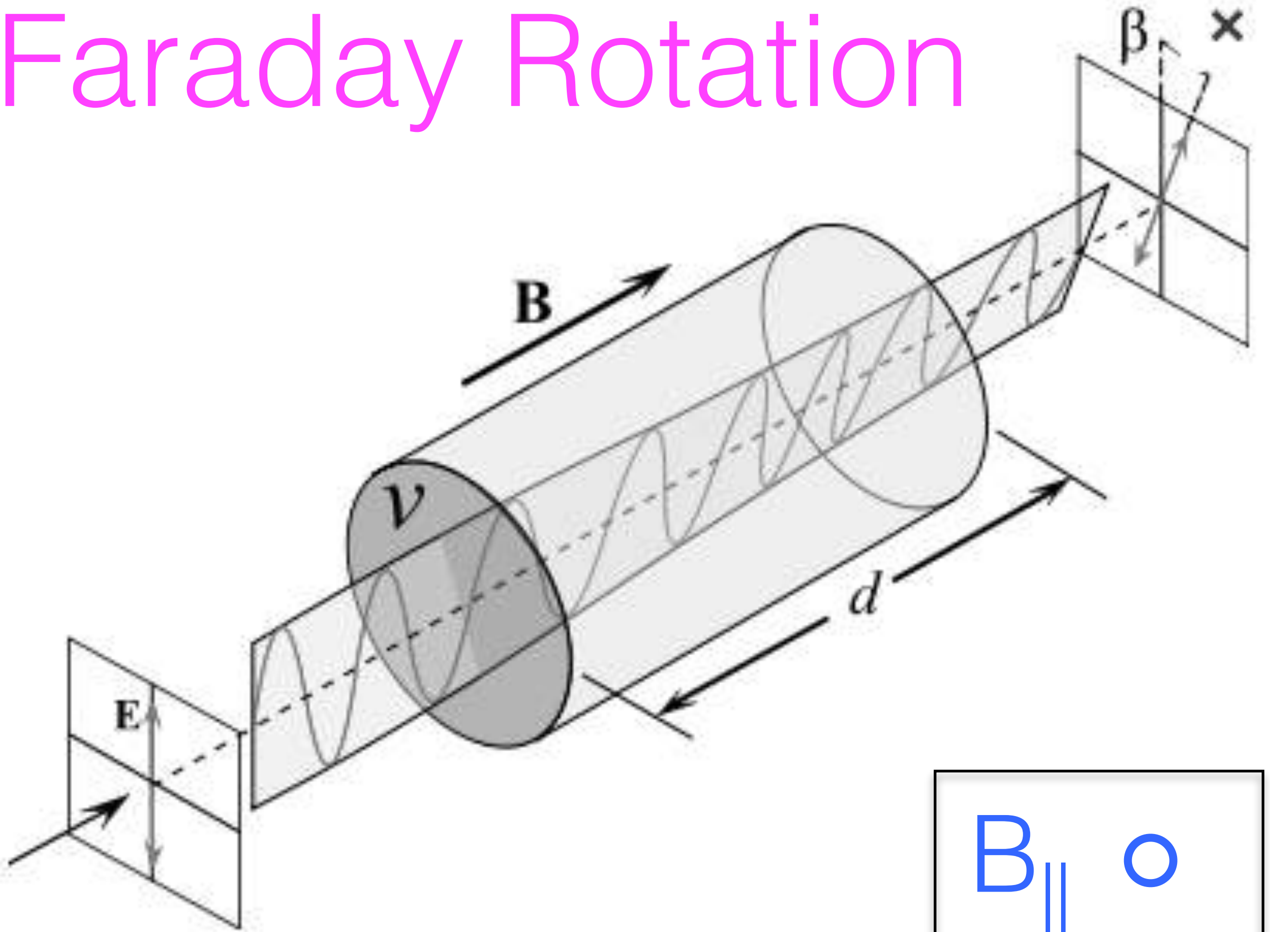
planck

cea SACLAY

IAS Orsay

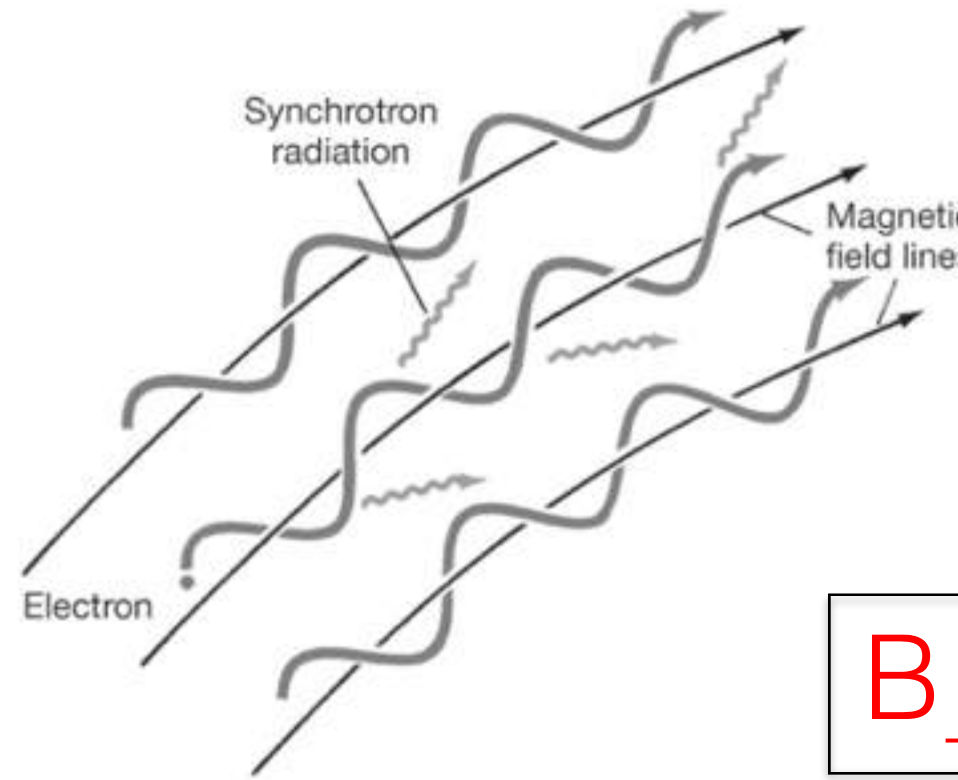
erc

Faraday Rotation



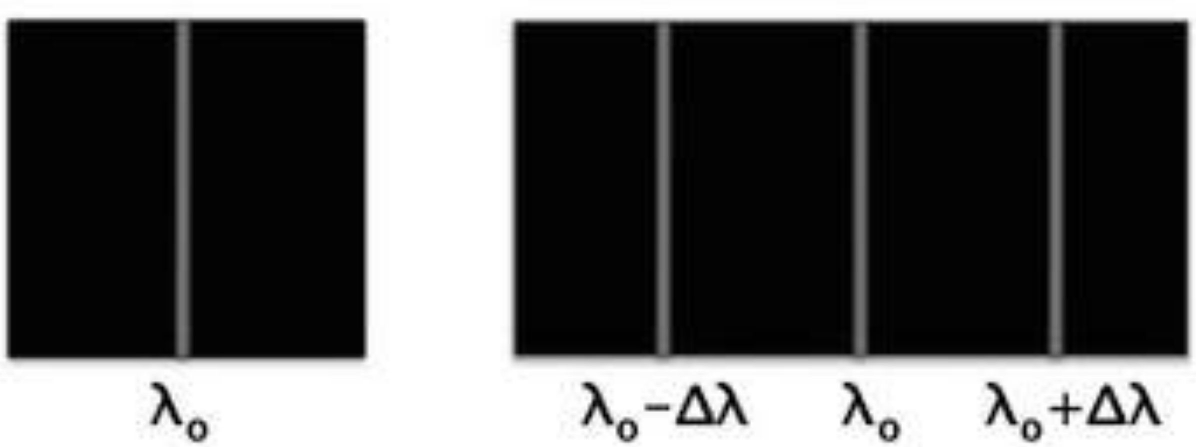
$B_{\parallel}$ ○

Synchrotron Emission



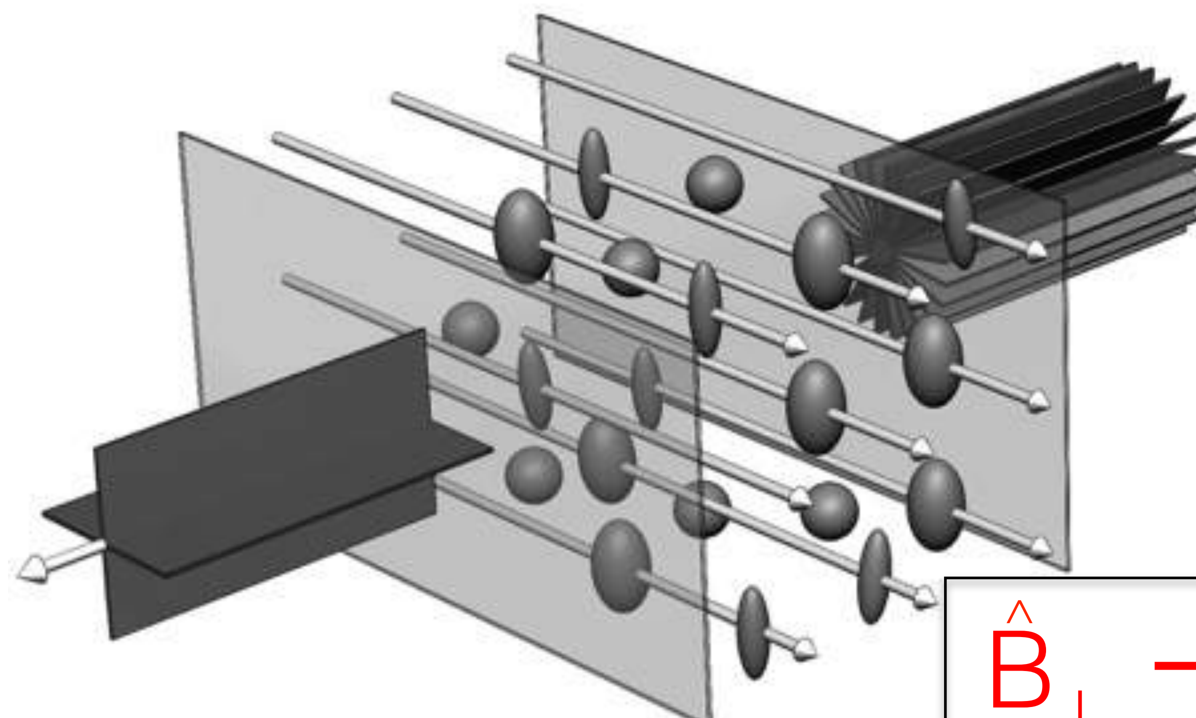
$B_{\perp}$ →

Zeeman Splitting

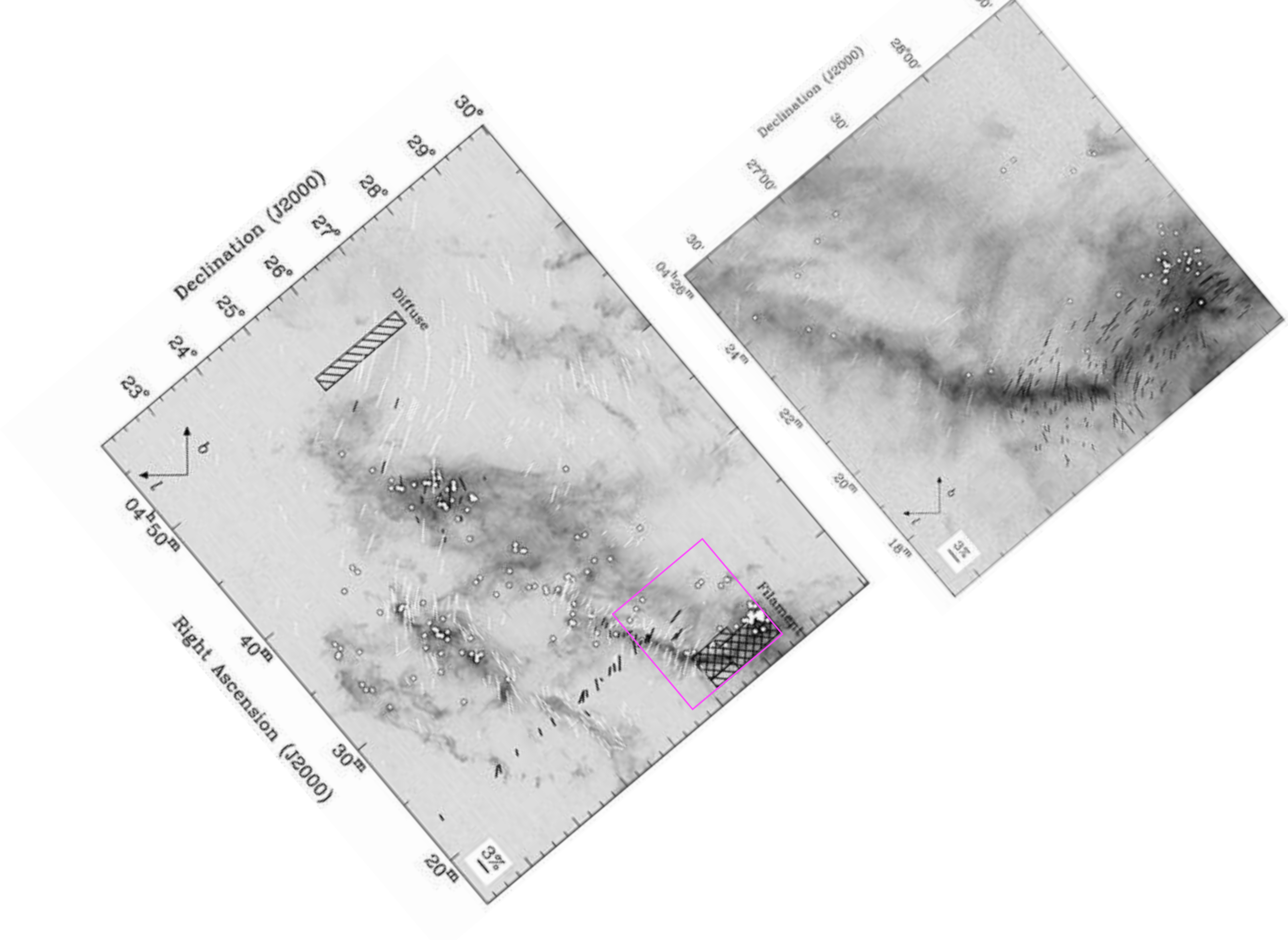


$B_{\parallel}$ ○

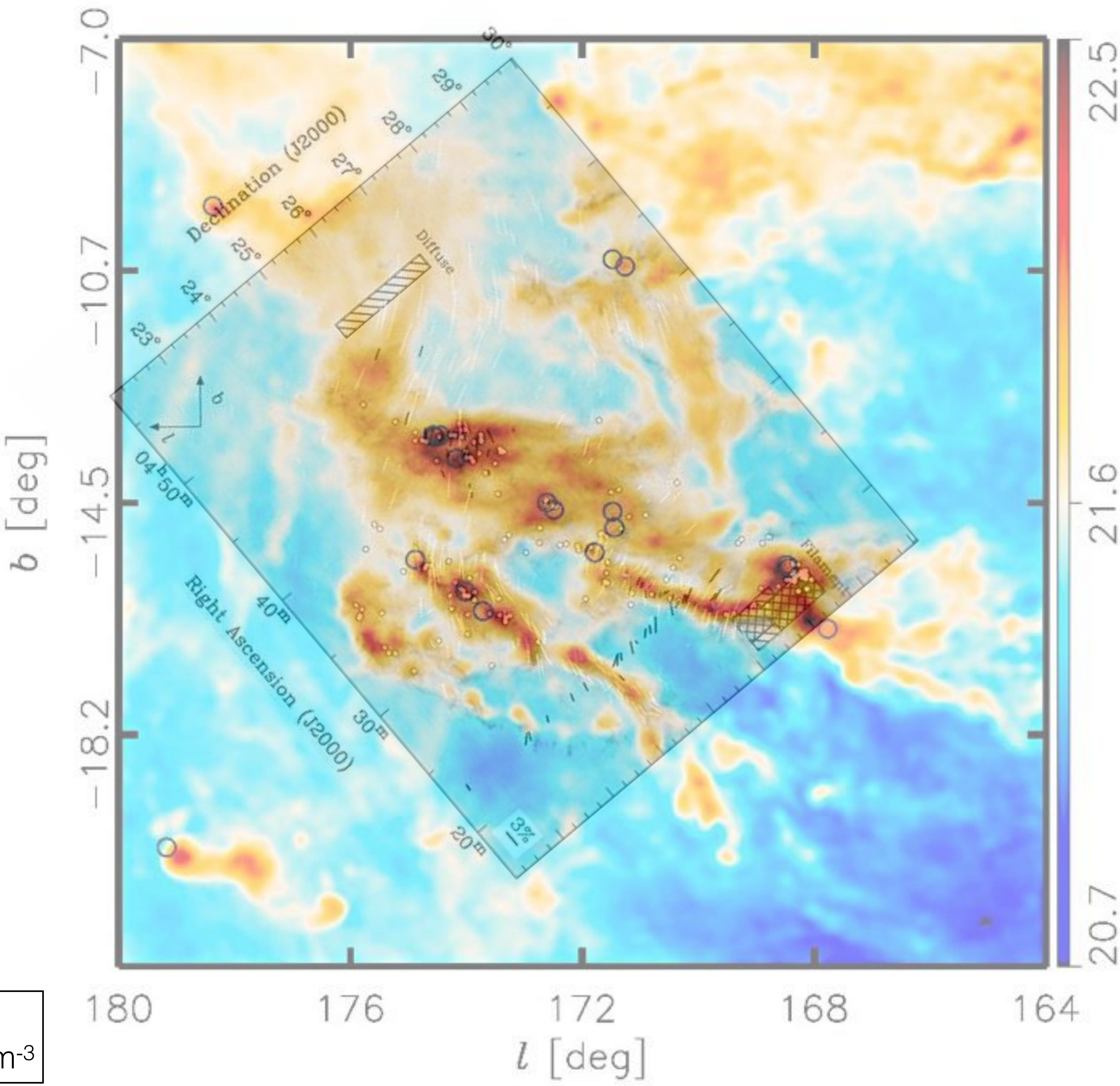
Dust polarization



$\hat{B}_{\perp}$ →

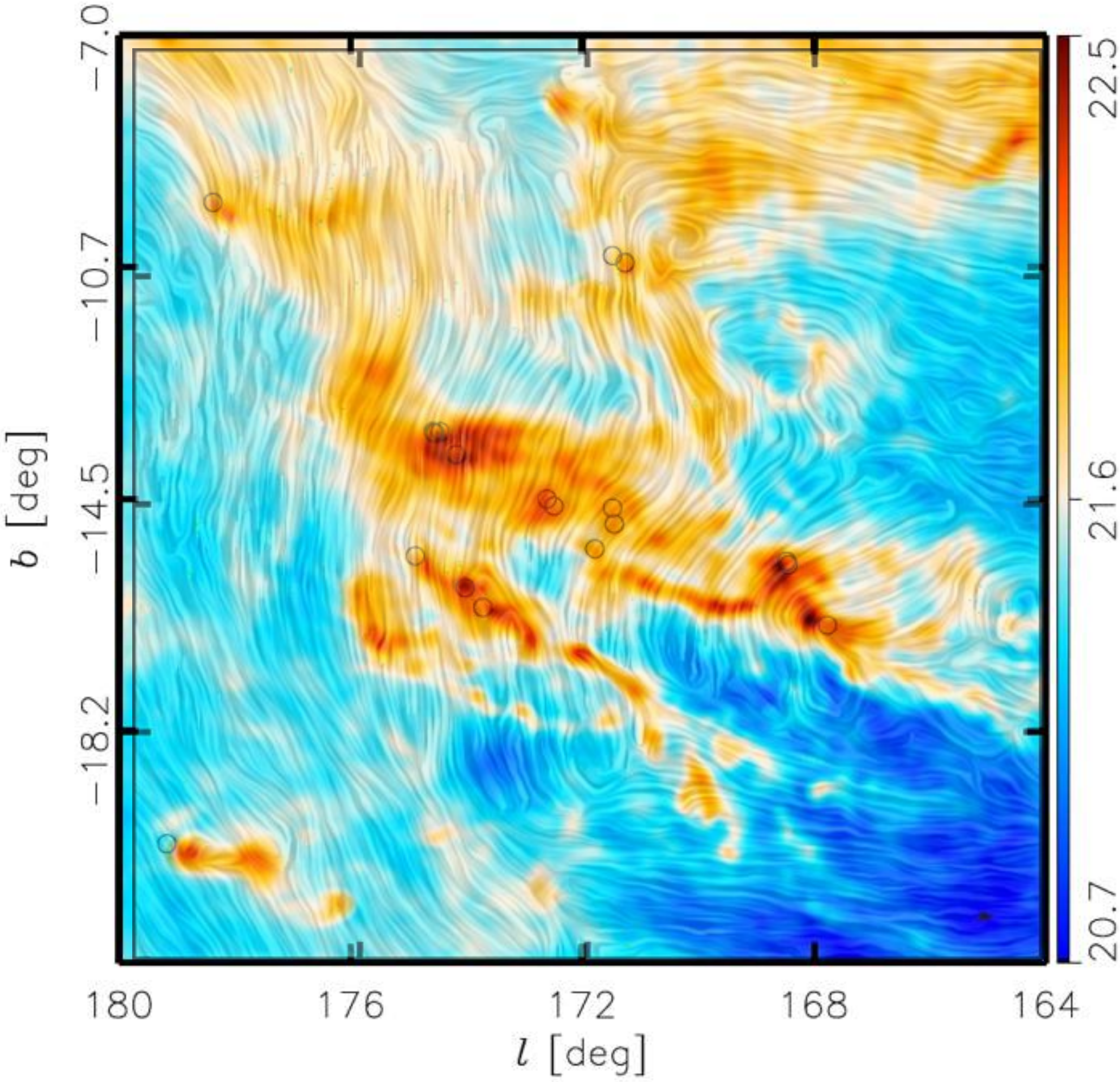


Optical and near-infrared polarization
Chapman et al., ApJ, 2011



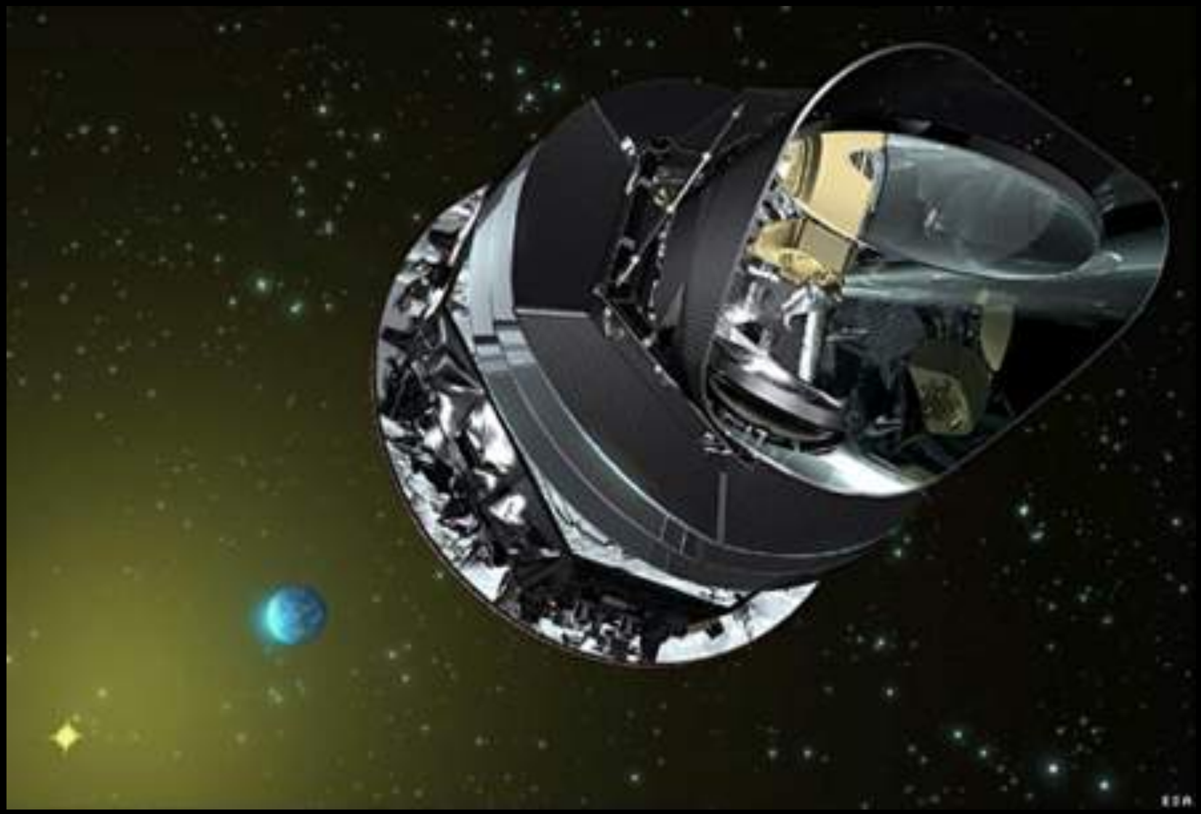
OH
10^3 to 10^4 cm^{-3}

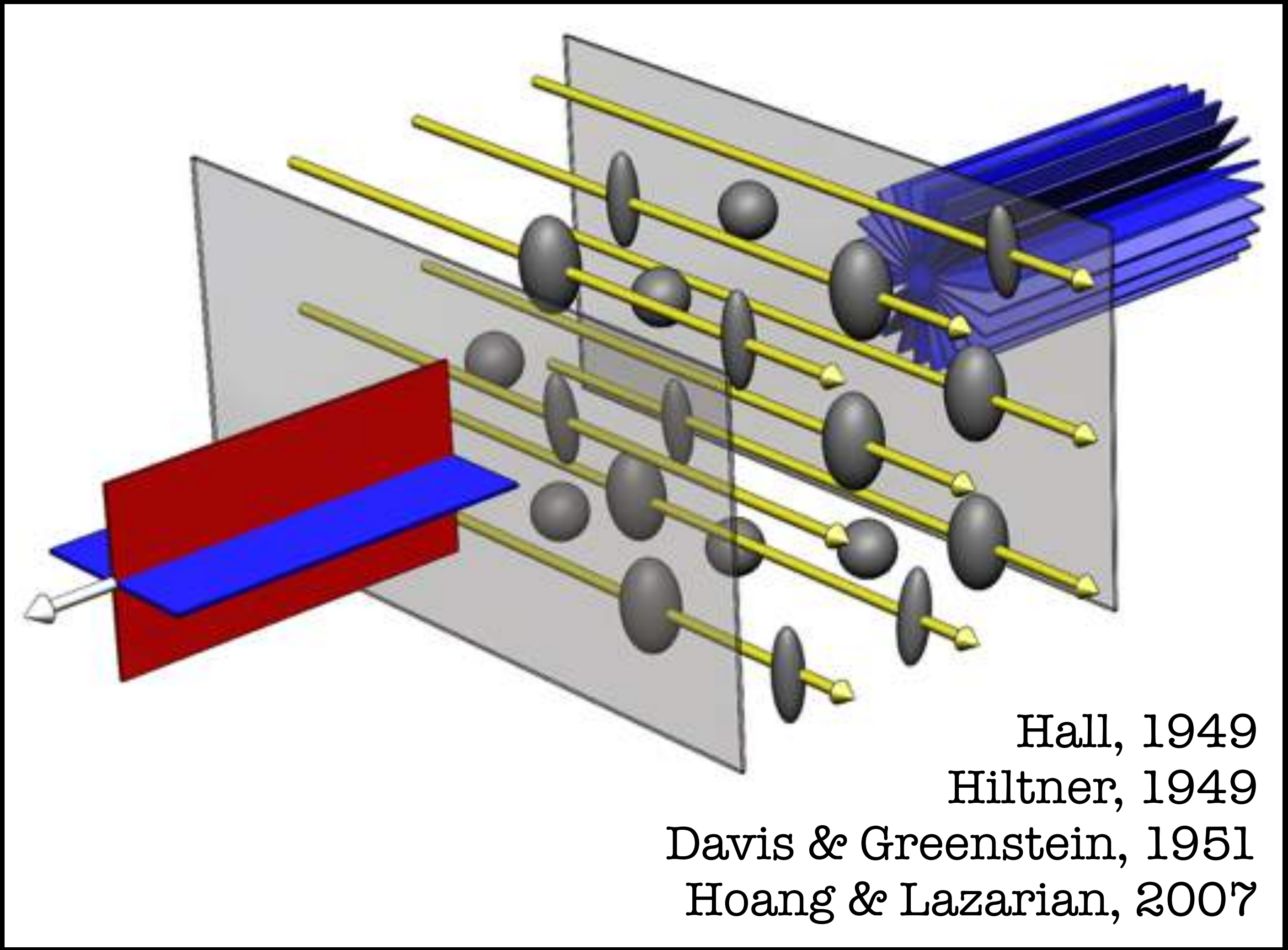
Zeeman OH observations courtesy of T. Troland



Planck intermediate results. XXXV

Dust polarized emission and the magnetic field





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Planck 2015 results. I. Overview of products and results esa

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cnes

asi
agenzia spaziale italiana

NASA

CNRS

DTU Space
National Space Institute

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Science & Technology Facilities Council

CSIC

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

HFI PLANCK

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

ioa

KICC

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

irfu

cea

saclay

CESR

CITA–ICAT

CNRS IN2P3

ipac Infrared Processing and Analysis Center

HELSINKI INSTITUTE OF PHYSICS

Imperial College London

Università degli Studi di Milano

NÉEL Institut

IPAG

ISDC

JPL

LAL

l'Observatoire

LERMA

LPSC Grenoble

MilliLab

NUI MAYNOOTH

INAF OSSERVATORIO ASTRONOMICO DI PADOVA

SAPIENZA

Science & Technology Facilities Council
Rutherford Appleton Laboratory

UBC

UC

UCSB

SISSA

US

esa

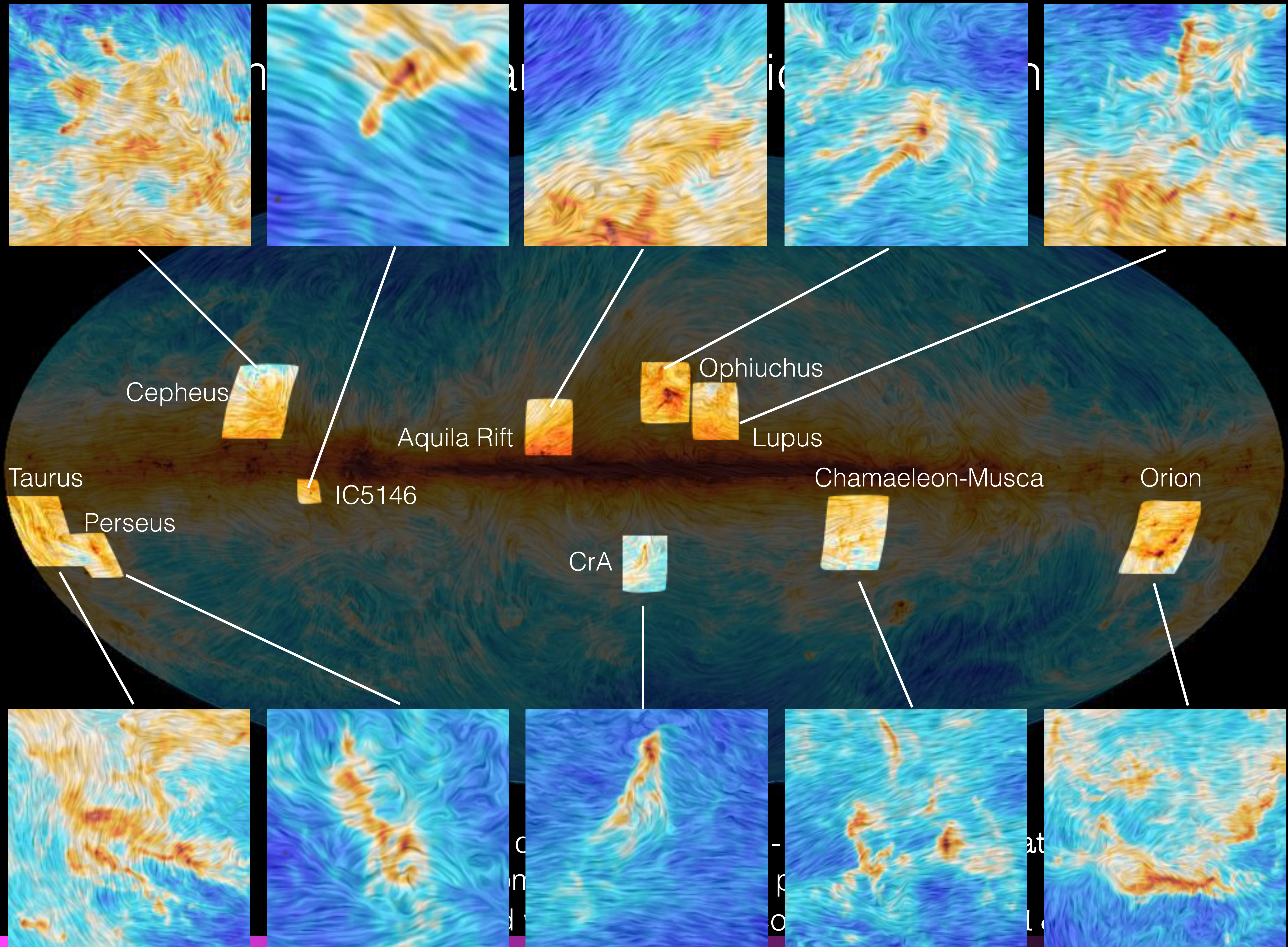
UNIVERSITY OF HELSINKI

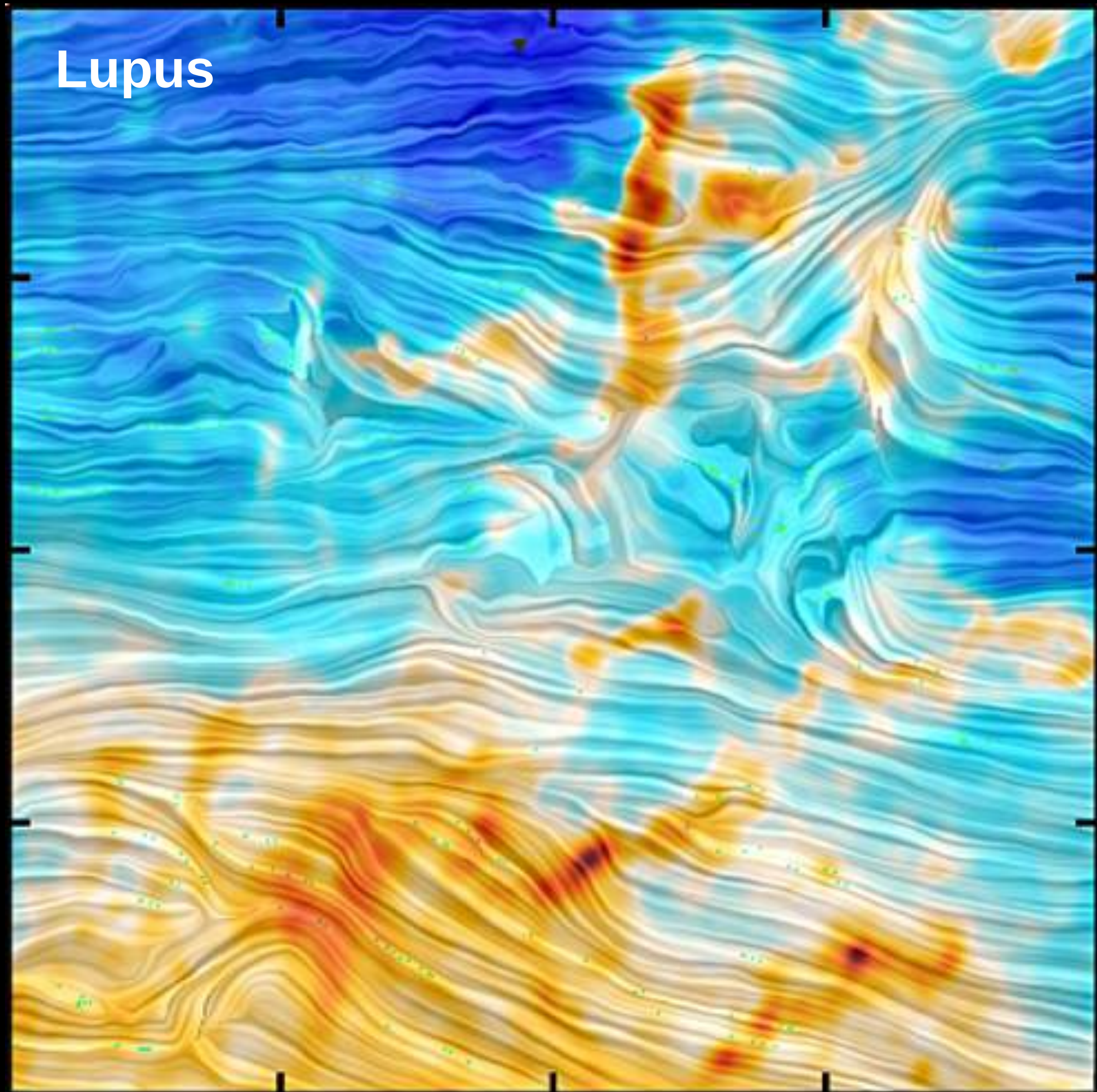
UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

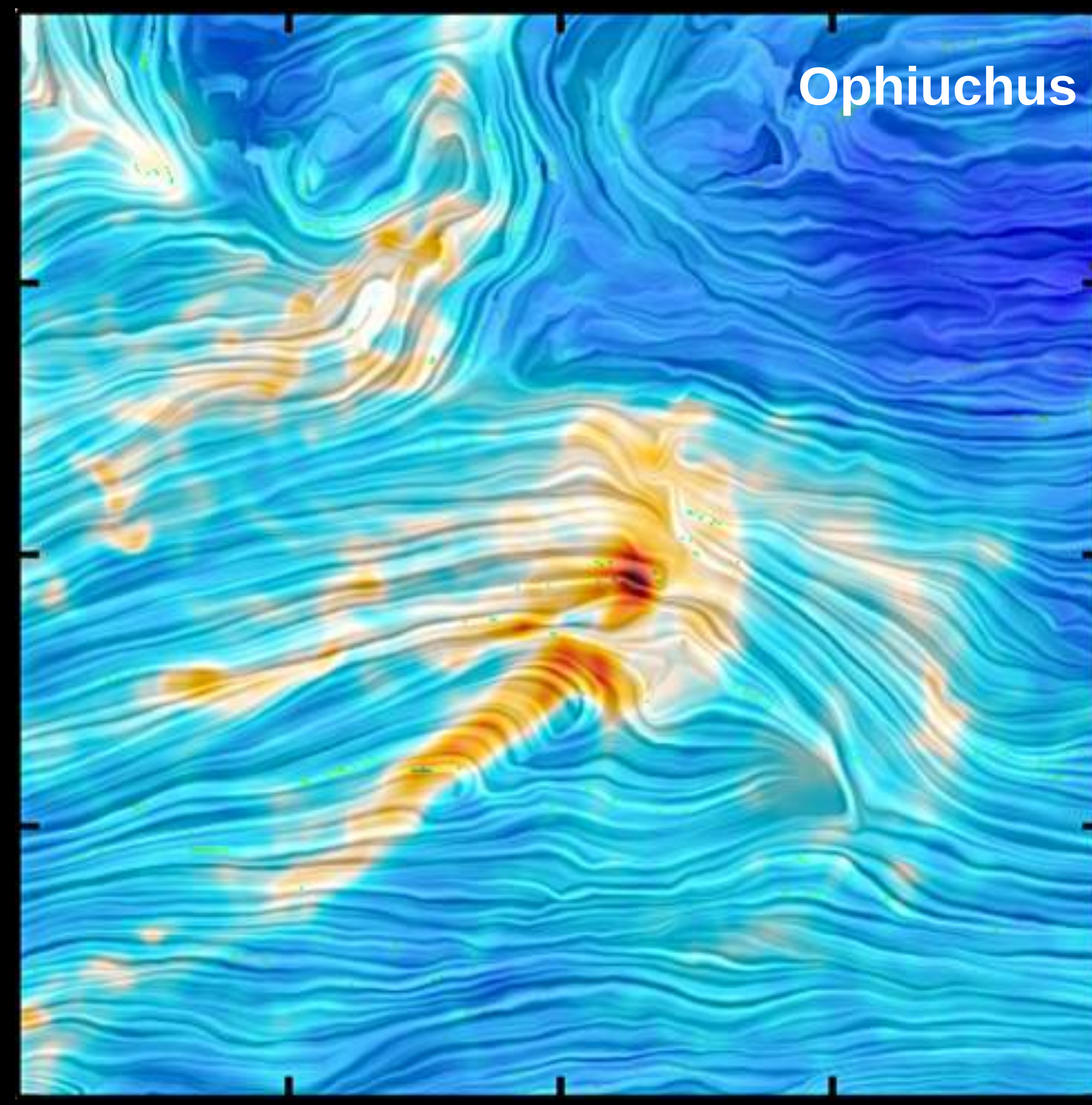
UNIVERSITÉ DE PARIS-SUD XI

asdc

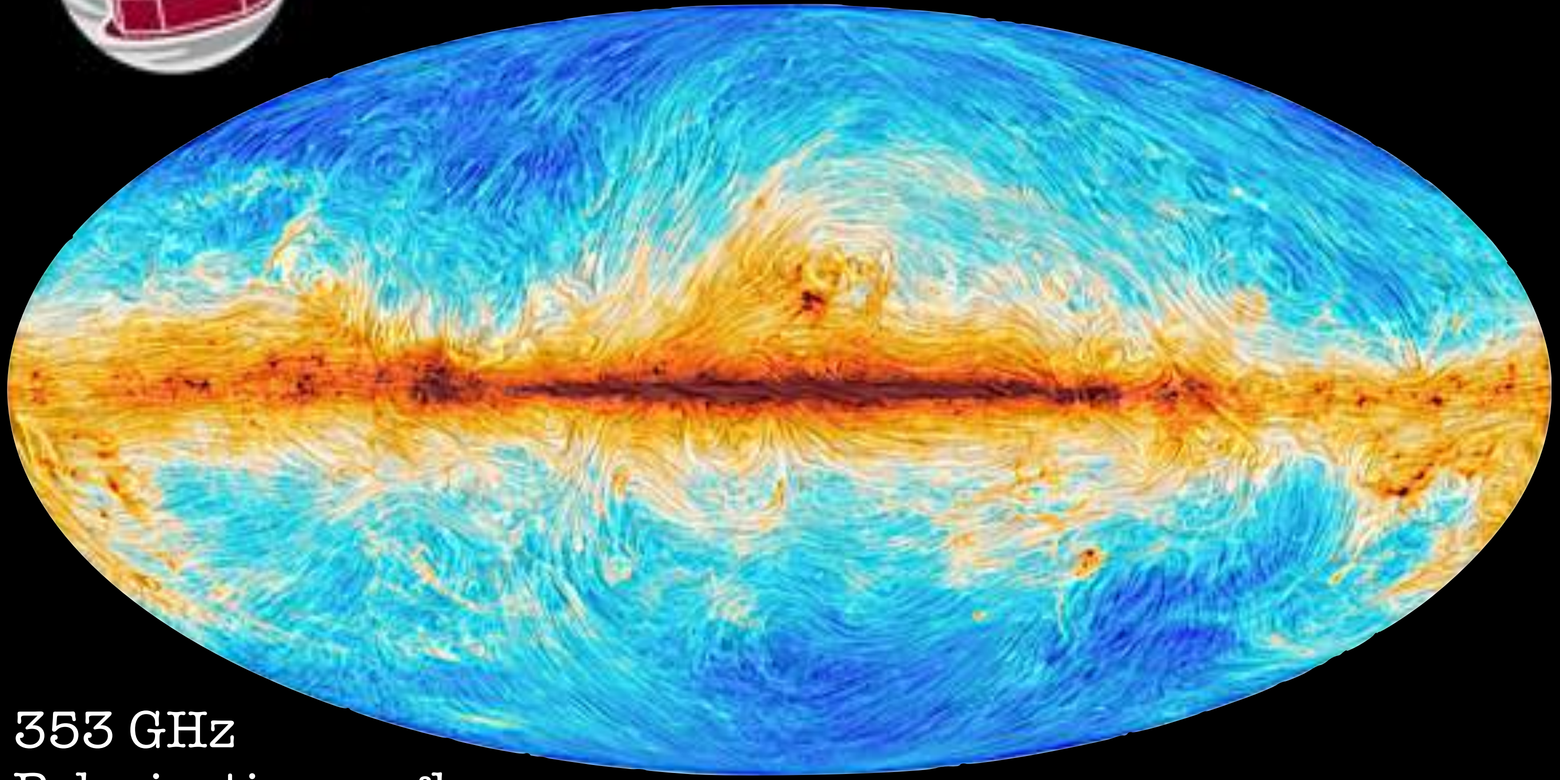

Cepheus
Aquila Rift
Ophiuchus
Lupus
Taurus
IC5146
Perseus
Chamaeleon-Musca
Orion
CrA



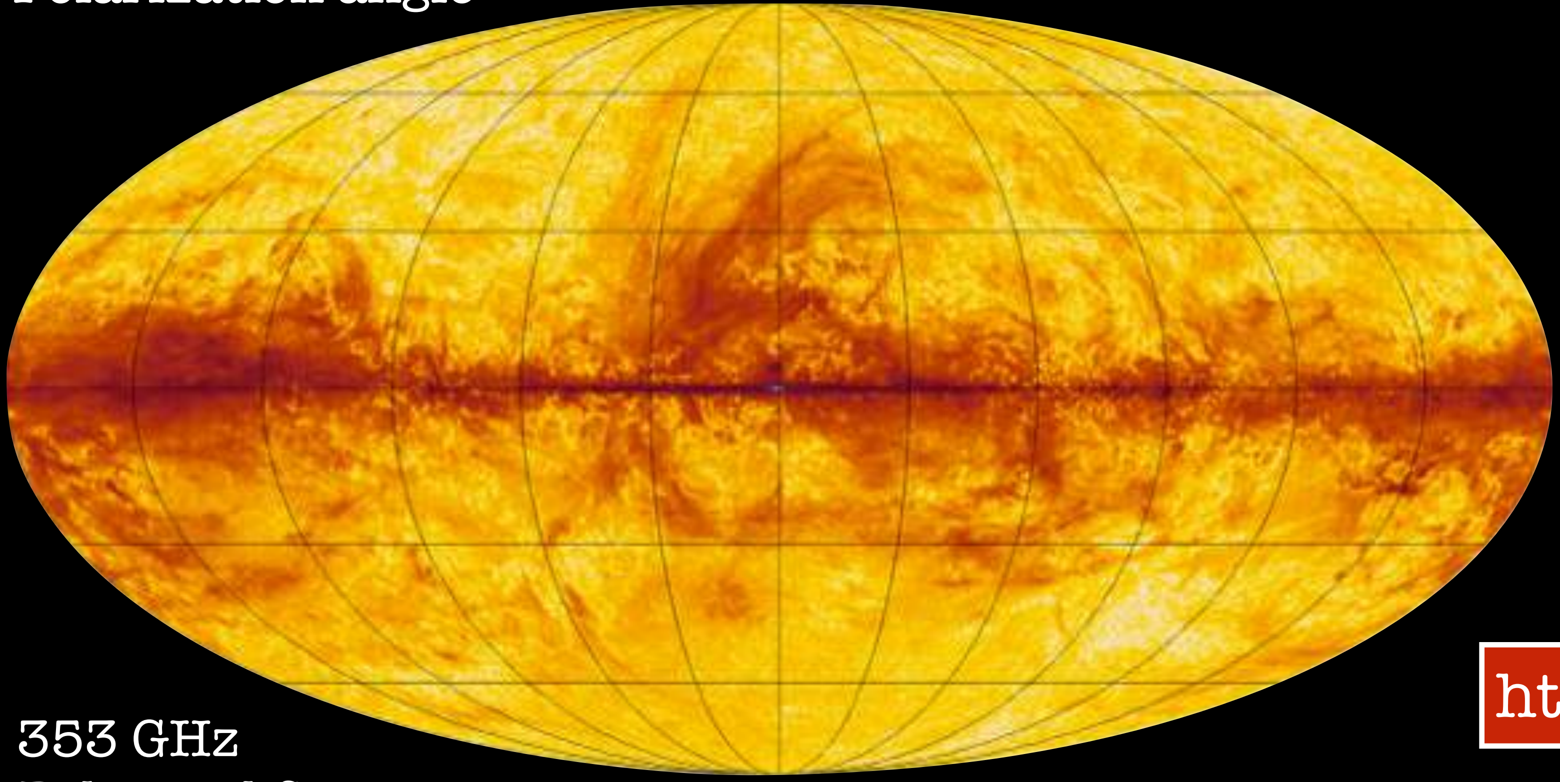
planck



Magnetic field and polarization statistics



353 GHz
Polarization angle



353 GHz
Polarized flux

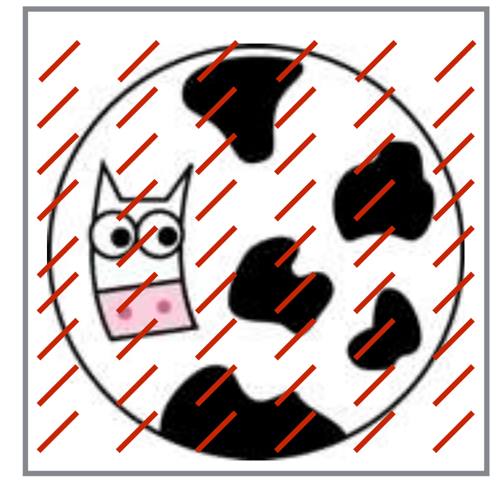
- Angle dispersion
  Planck intermediate results. XIX
- Polarized fraction
  Planck intermediate results. XX
- Power spectrum
  Planck intermediate results. XXX
- Geometric modelling
  Planck intermediate results. XXXIII
  Planck intermediate results. XXXIV
- Relative orientation
  Planck intermediate results. XXXII
  Planck intermediate results. XXXV
- Relation to E- and B-modes
  Planck intermediate results. XXXVIII

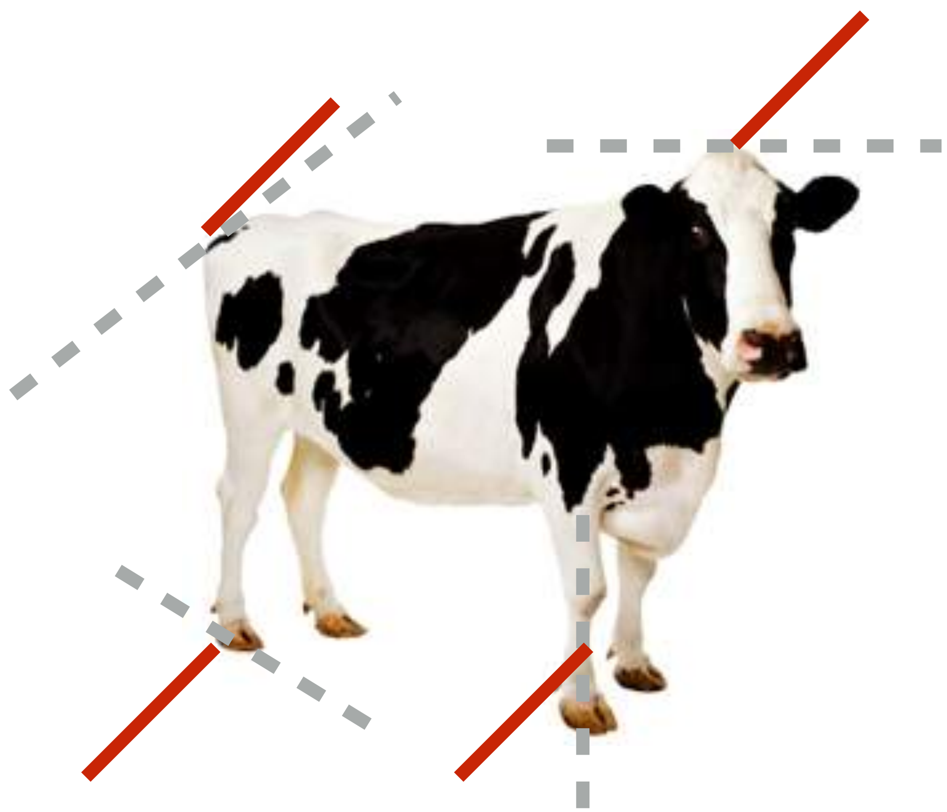
http://planckandthemagneticfield.info

Observations

Relative orientation

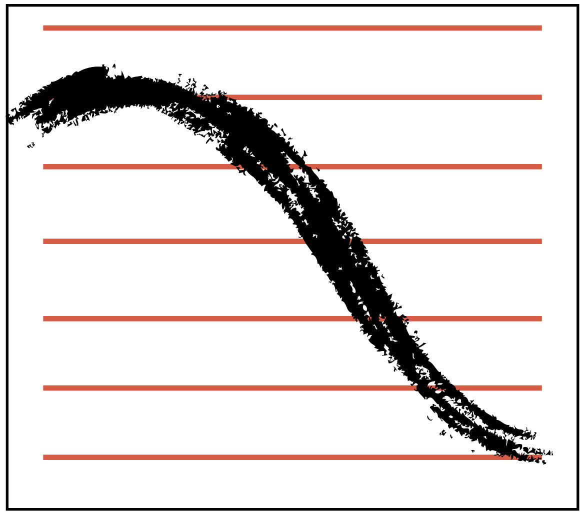
Simulations

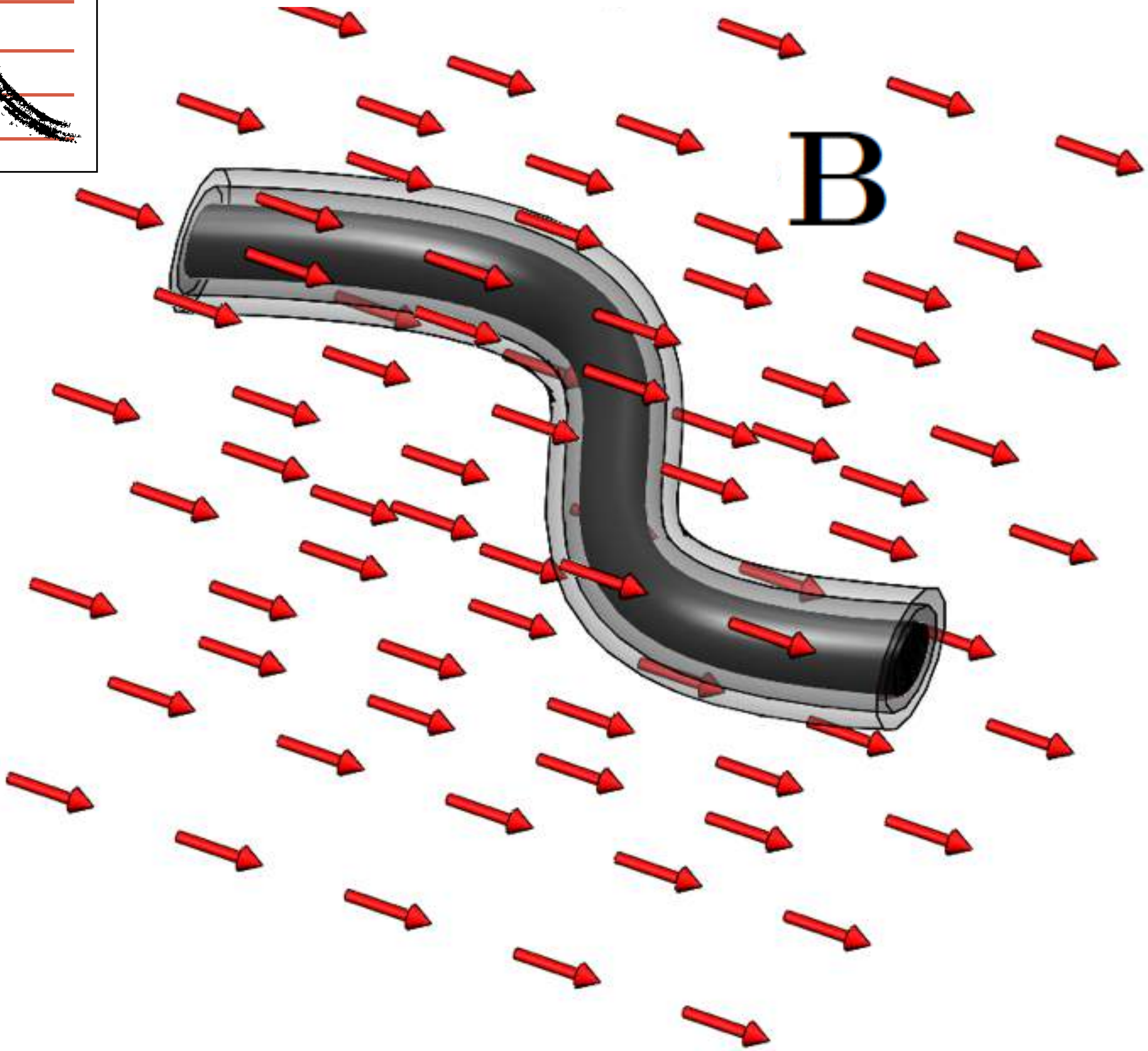




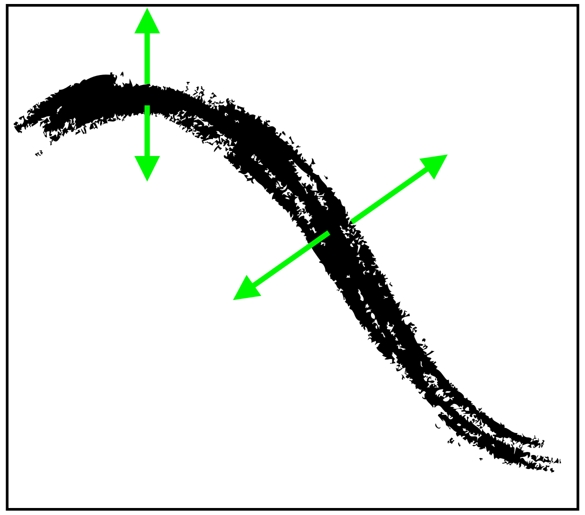
- Magnetic field
- Turbulence
- Gravity

Relative Orientations

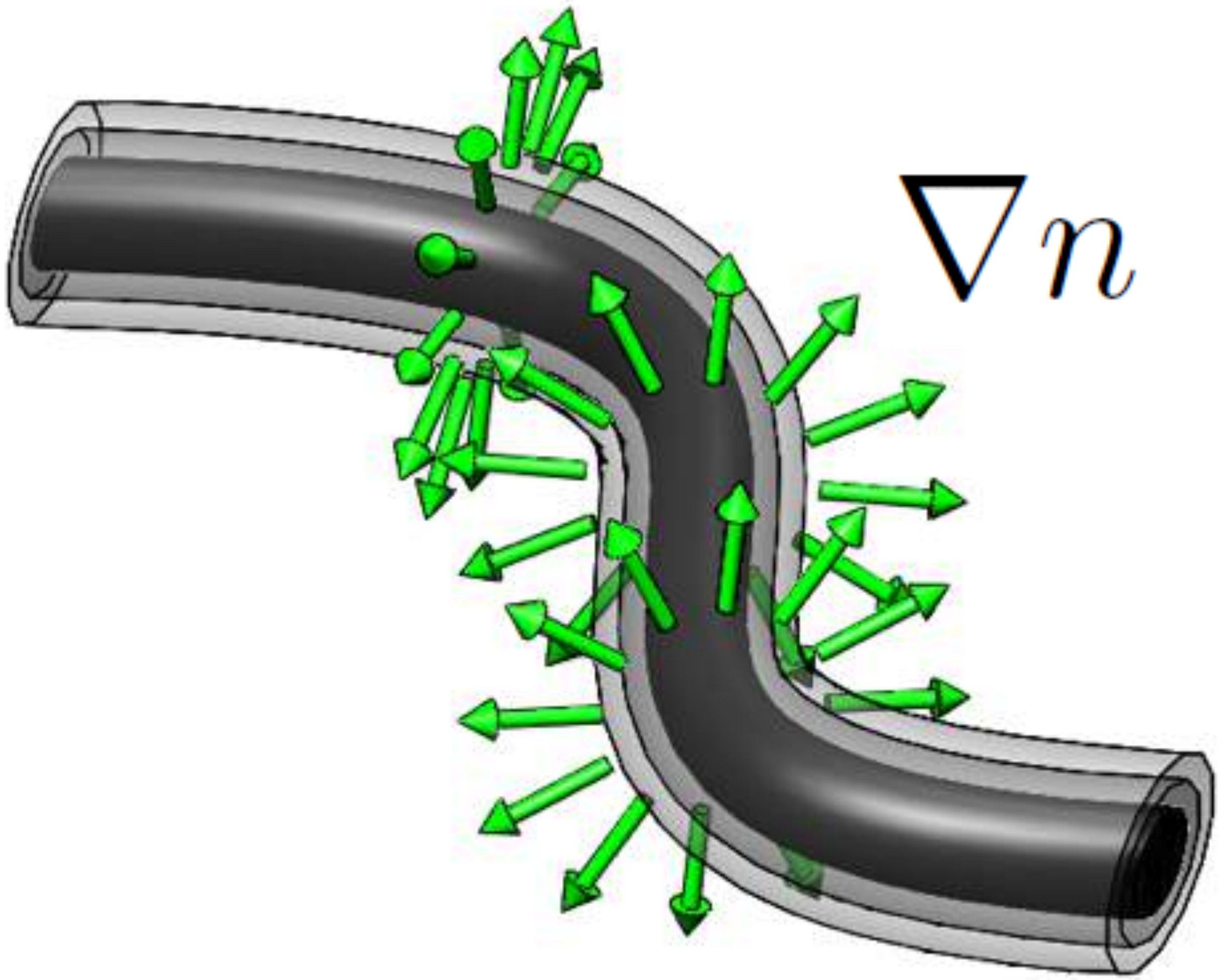




Soler et al, 2013

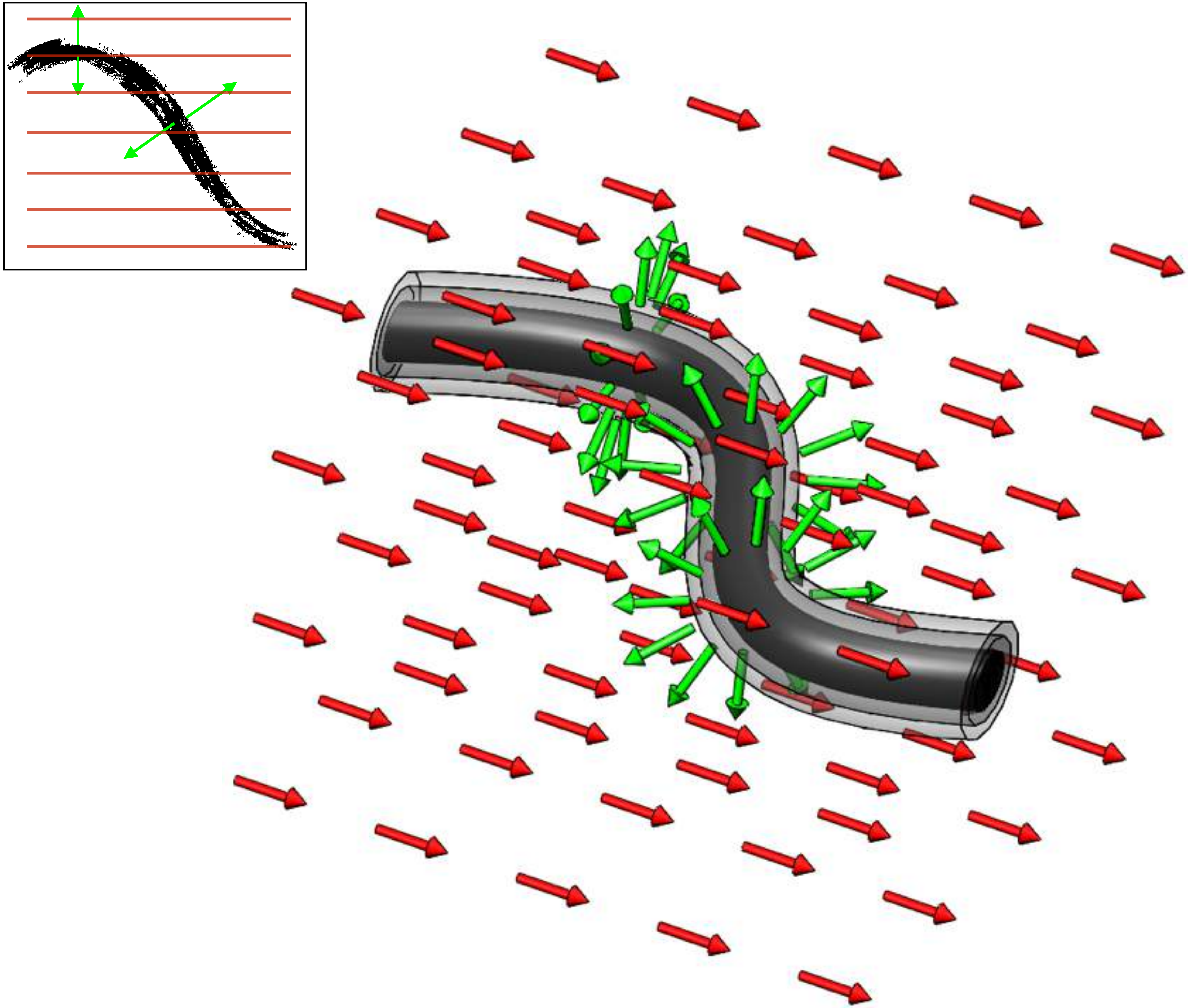


$$\nabla n = \left(\frac{\partial n}{\partial x}\right)^{(l)} \hat{x} + \left(\frac{\partial n}{\partial y}\right)^{(l)} \hat{y} + \left(\frac{\partial n}{\partial z}\right)^{(l)} \hat{z}$$

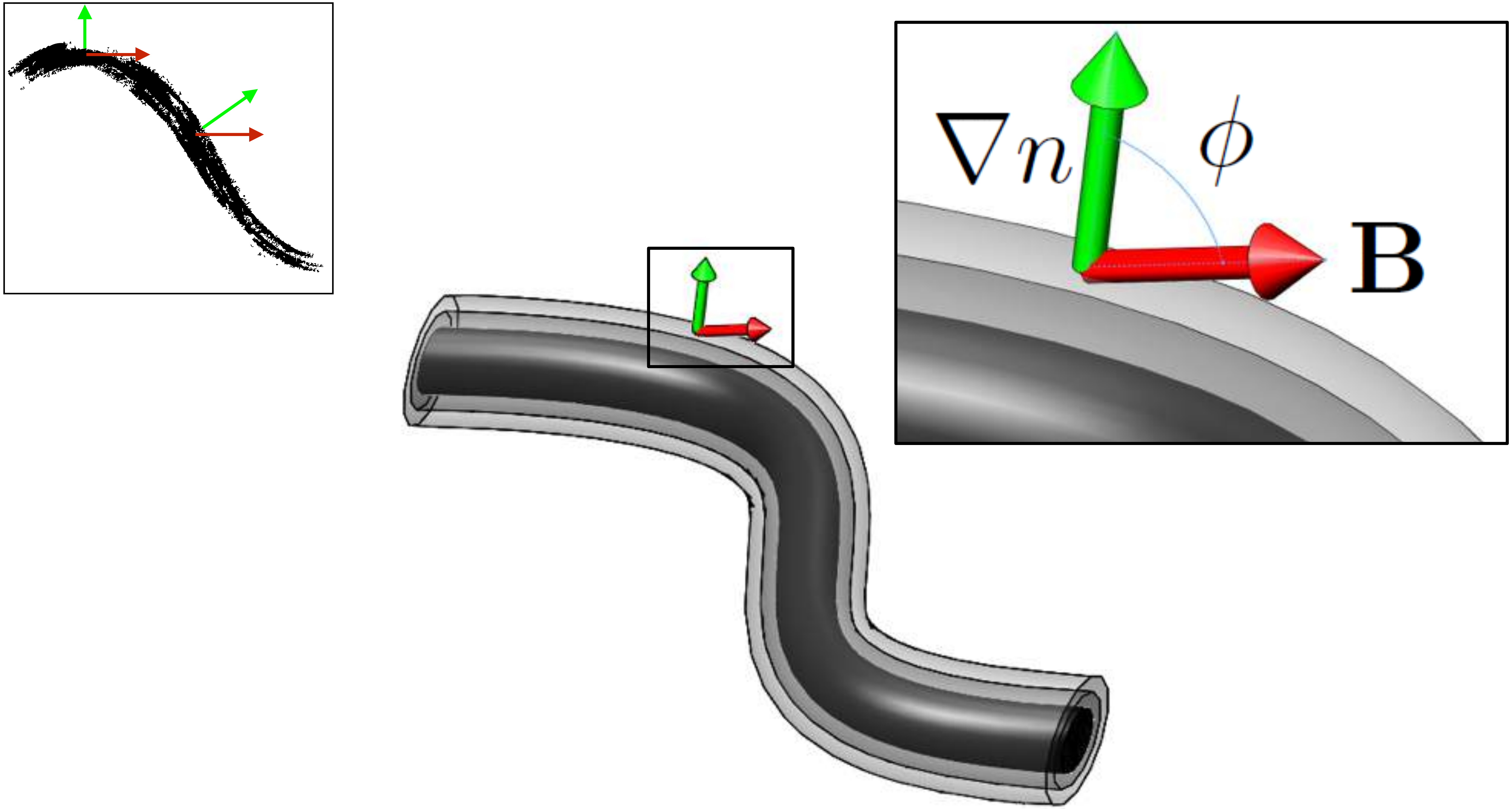


$$\left(\frac{\partial n}{\partial x}\right)^{(l)} = n(x,y) \star K^{(\partial/\partial x)}$$

Soler et al, 2013



Soler et al, 2013

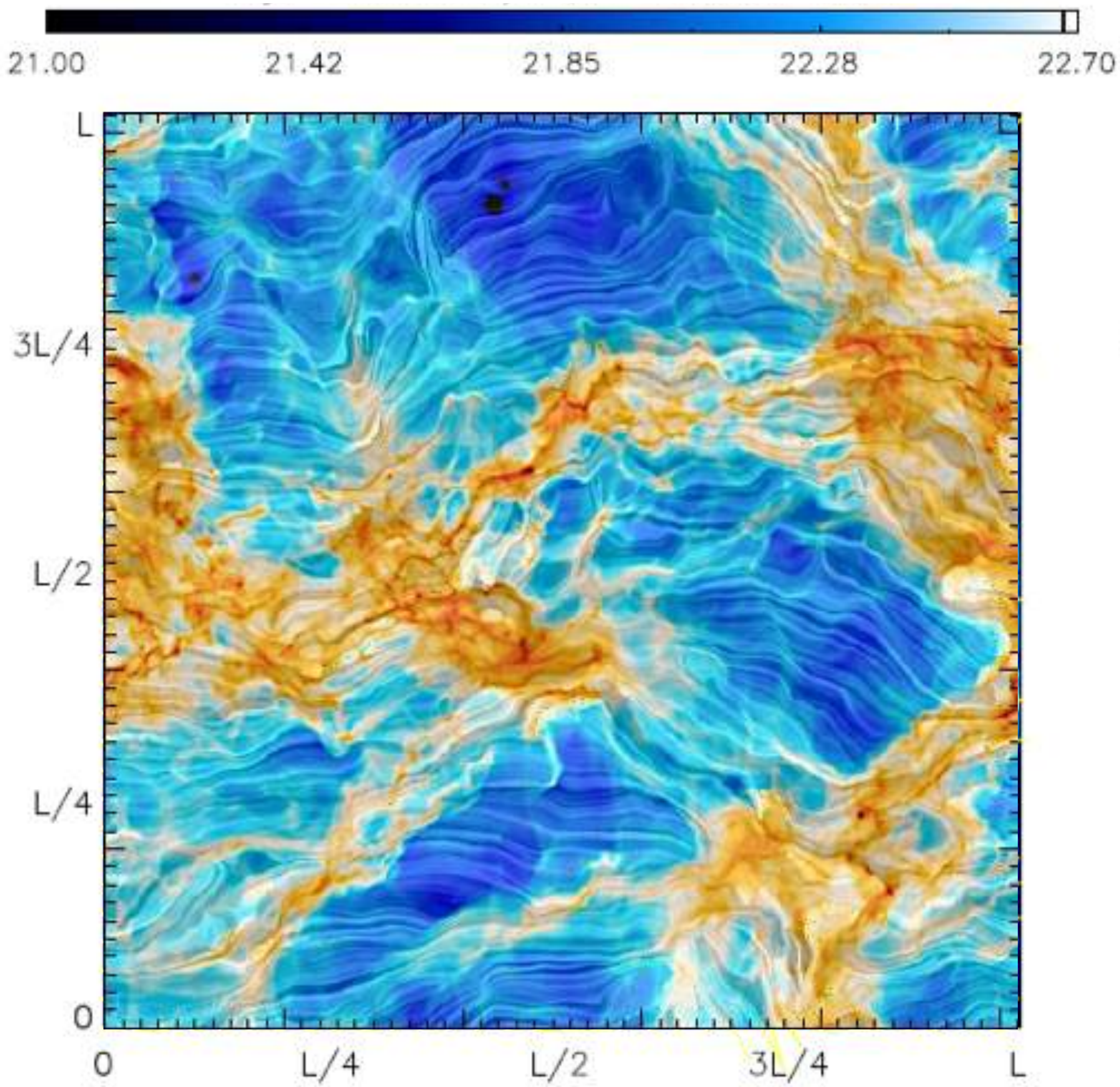


$$\phi = \arctan\left(\frac{|\mathbf{B} \times \nabla n|}{\mathbf{B} \cdot \nabla n}\right)$$

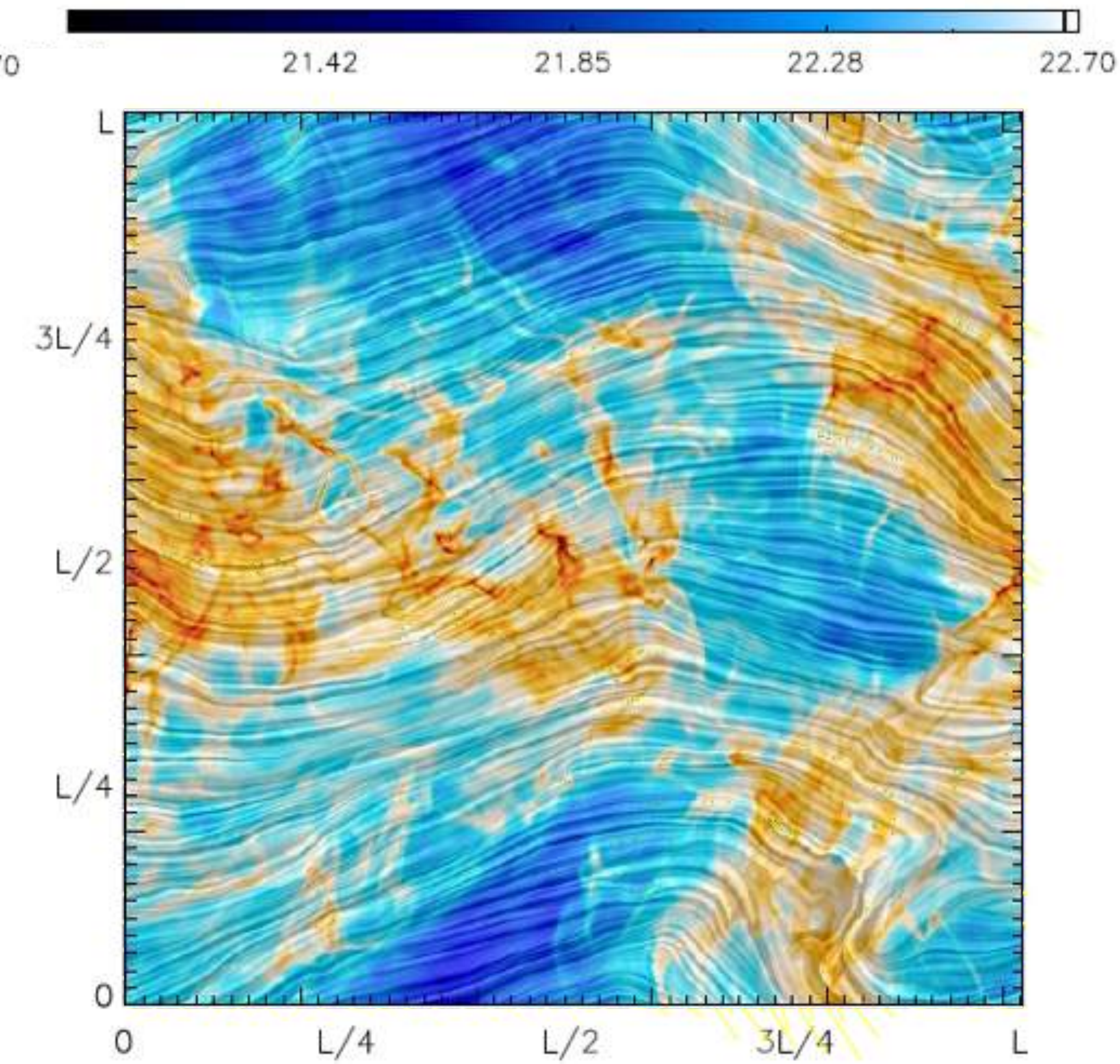
Soler et al, 2013

Histogram of Relative Orientations

Weak magnetic field (β = 100.0)

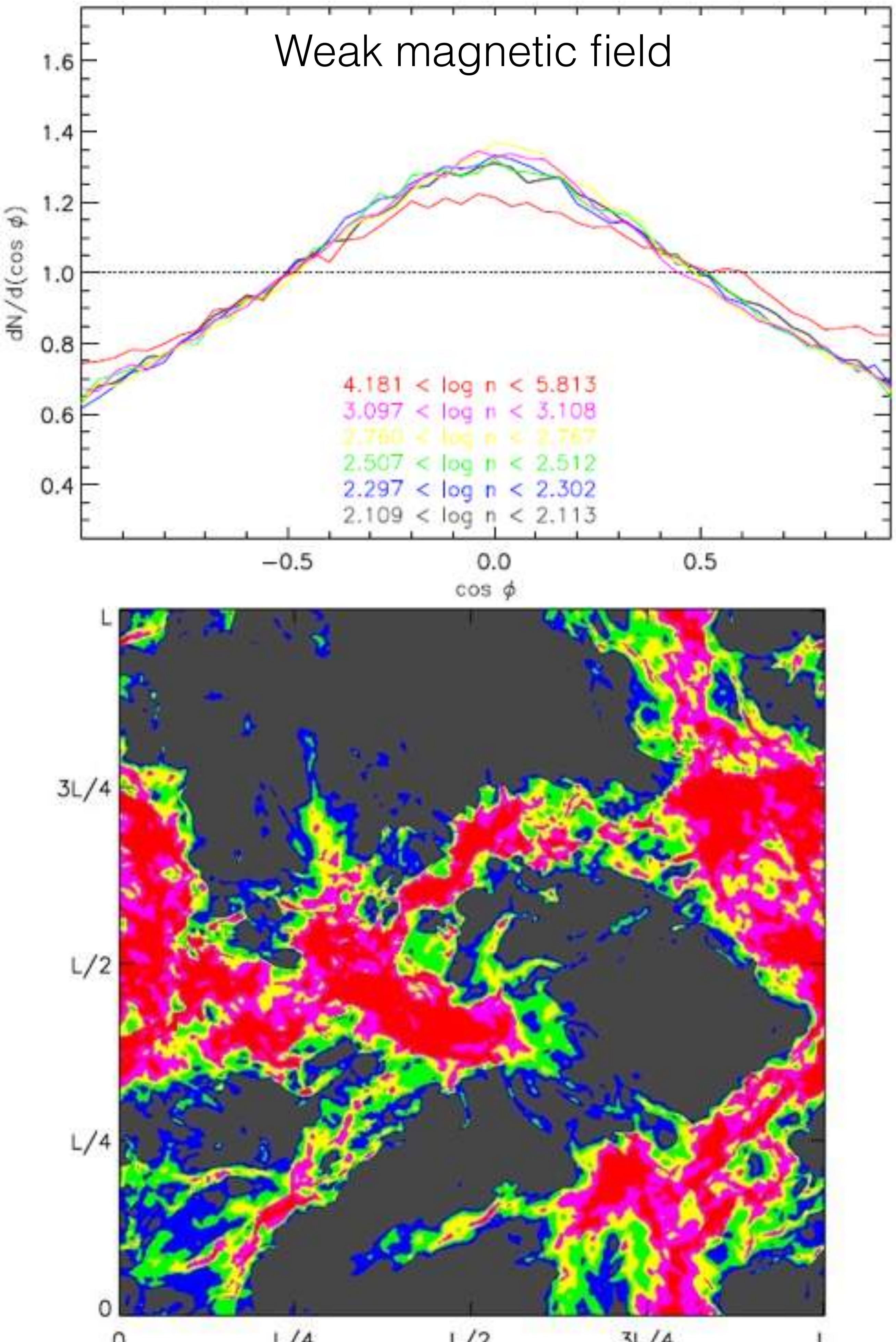


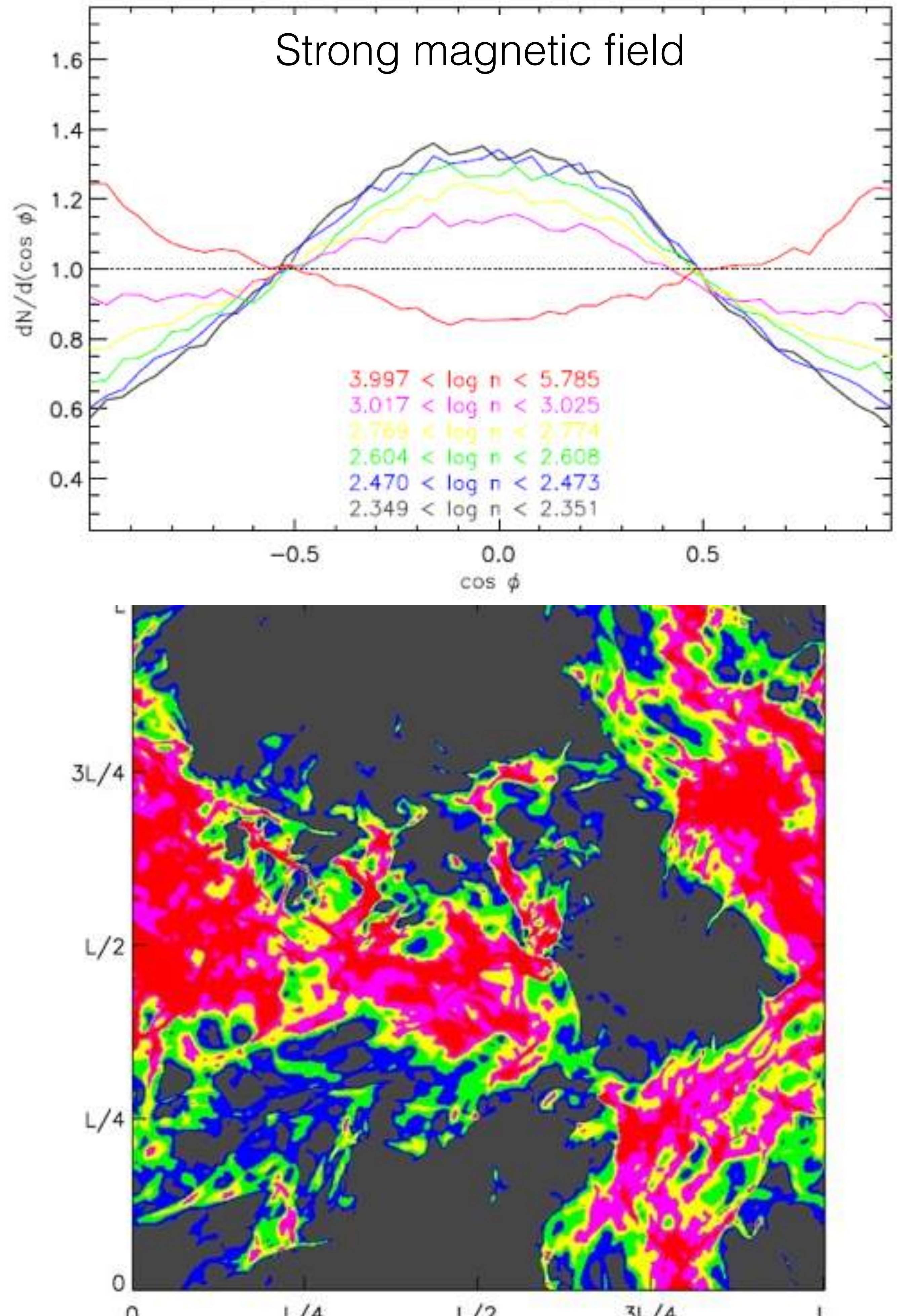
Strong magnetic field (β = 0.1)



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

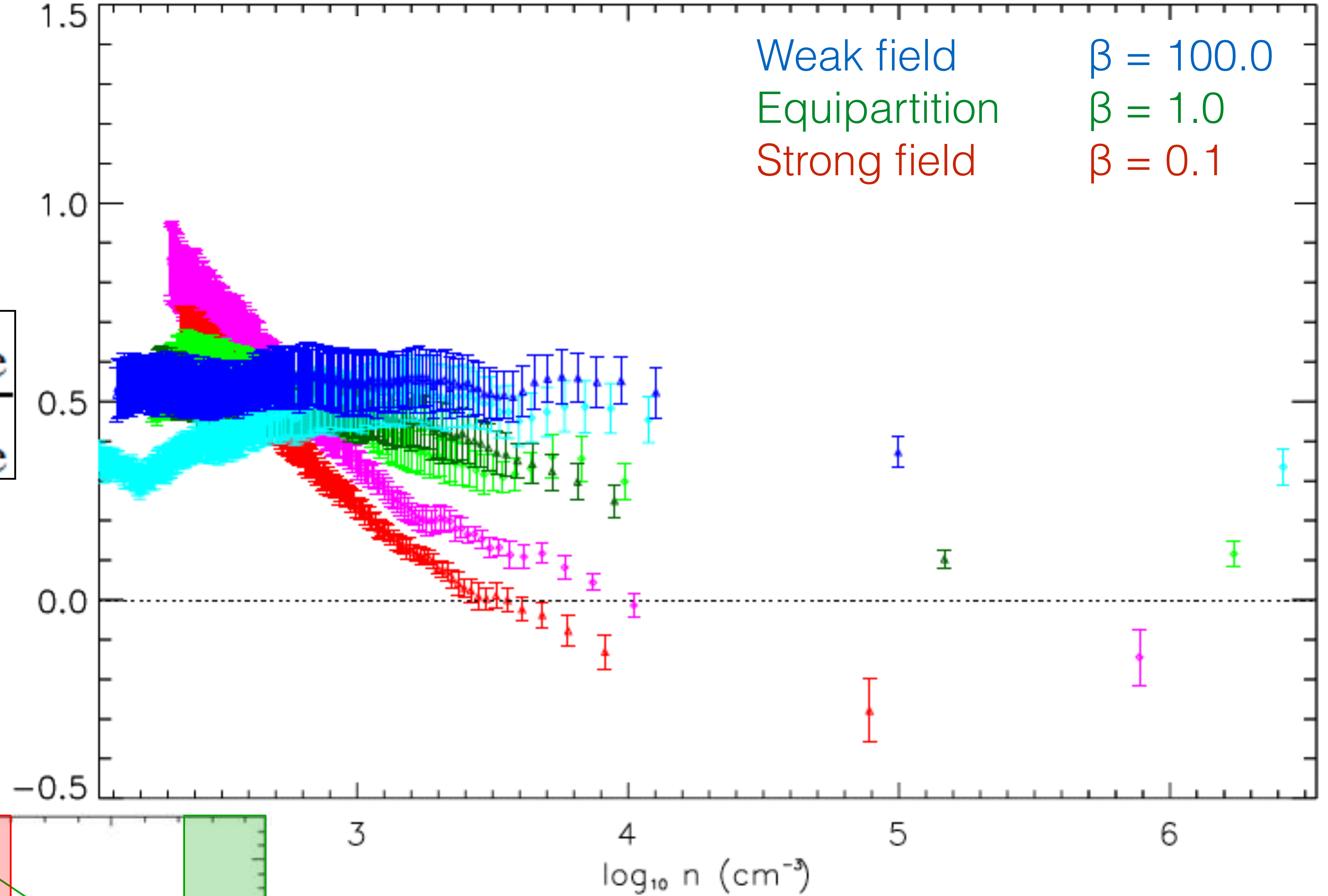
Simulations of MHD turbulence by P. Hennebelle
HRO: Soler et al, 2013

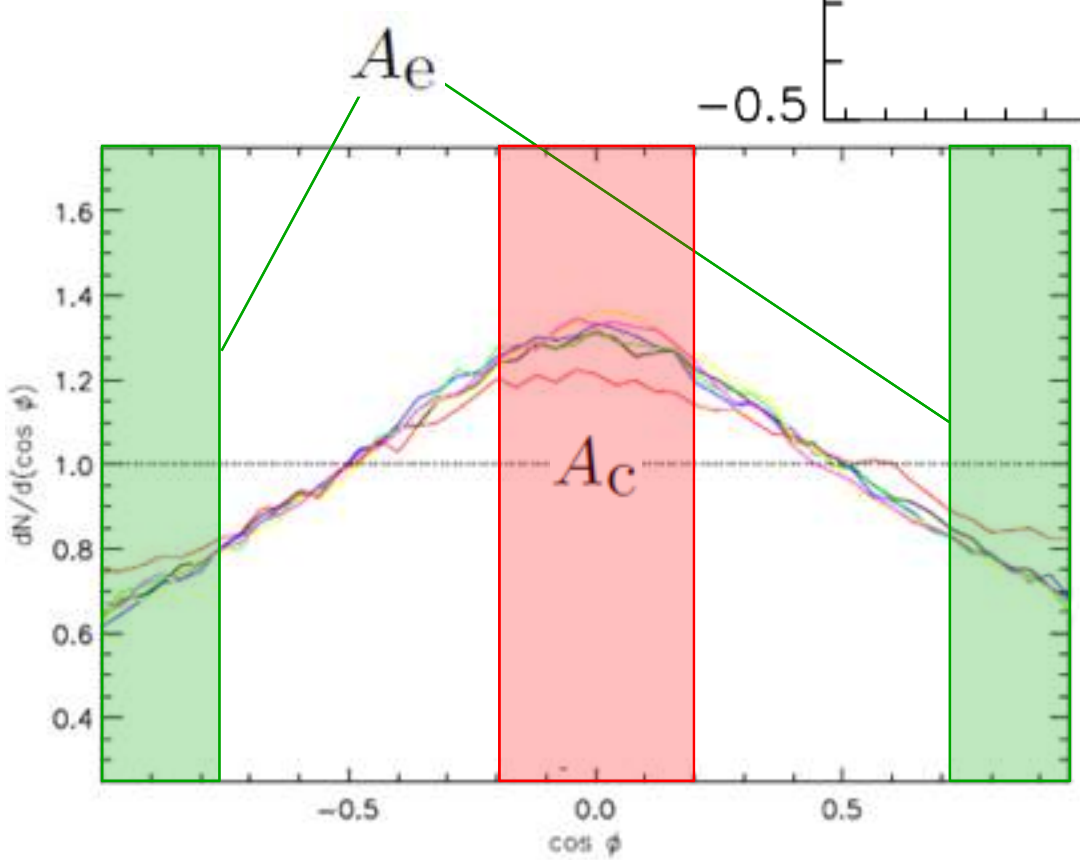

Weak magnetic field
1.6
1.4
1.2
1.0
0.8
0.6
0.4
dN/d(cos ϕ)
4.181 < log n < 5.813
3.097 < log n < 3.108
2.507 < log n < 2.512
2.297 < log n < 2.302
2.109 < log n < 2.113
−0.5
0.0
0.5
cos ϕ
L
3L/4
L/2
L/4
0
0
L/4
L/2
3L/4
L


Strong magnetic field
1.6
1.4
1.2
1.0
0.8
0.6
0.4
dN/d(cos ϕ)
3.997 < log n < 5.785
3.017 < log n < 3.025
2.604 < log n < 2.608
2.470 < log n < 2.473
2.349 < log n < 2.351
−0.5
0.0
0.5
cos ϕ
3L/4
L/2
L/4
0
0
L/4
L/2
3L/4
L

3D

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

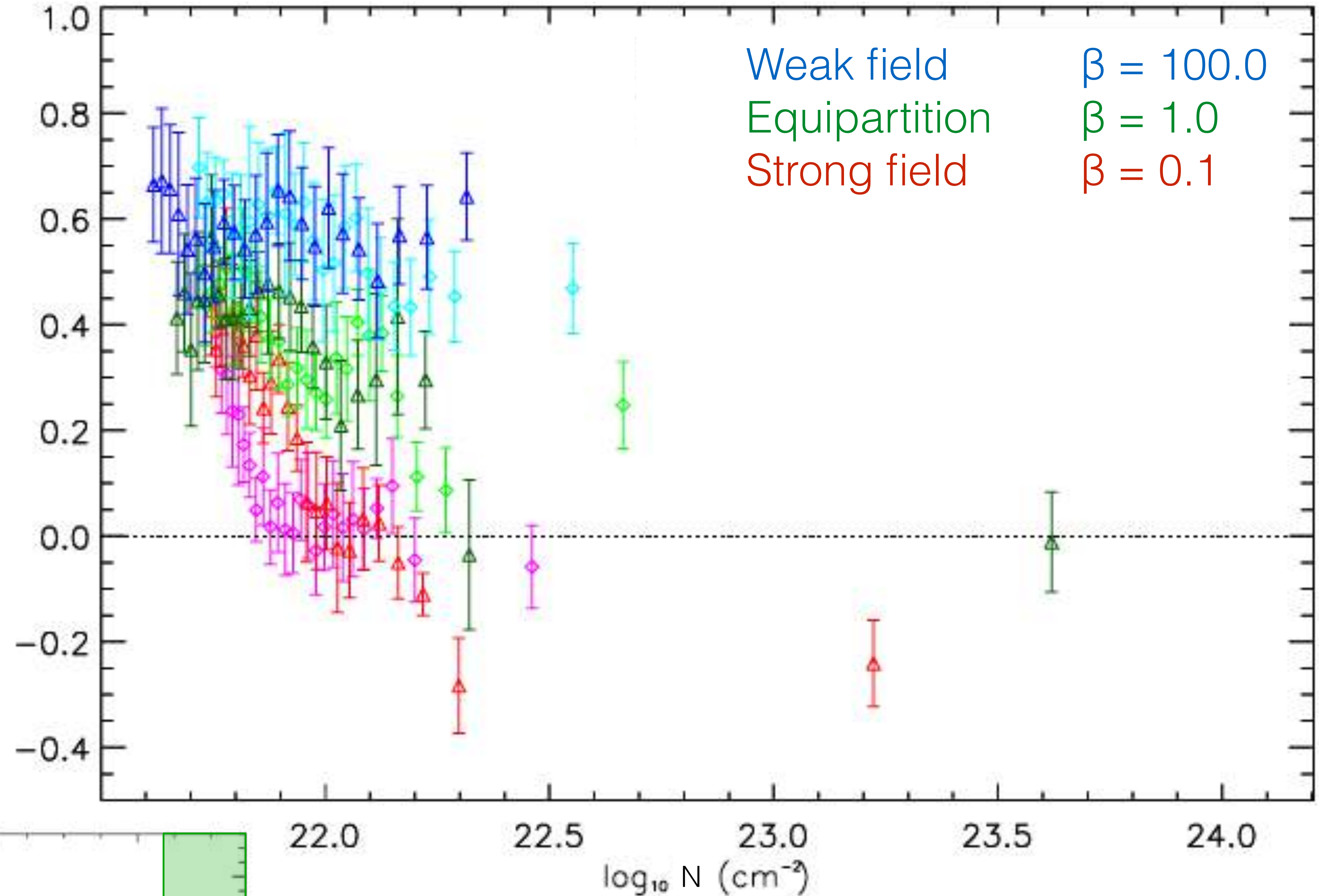


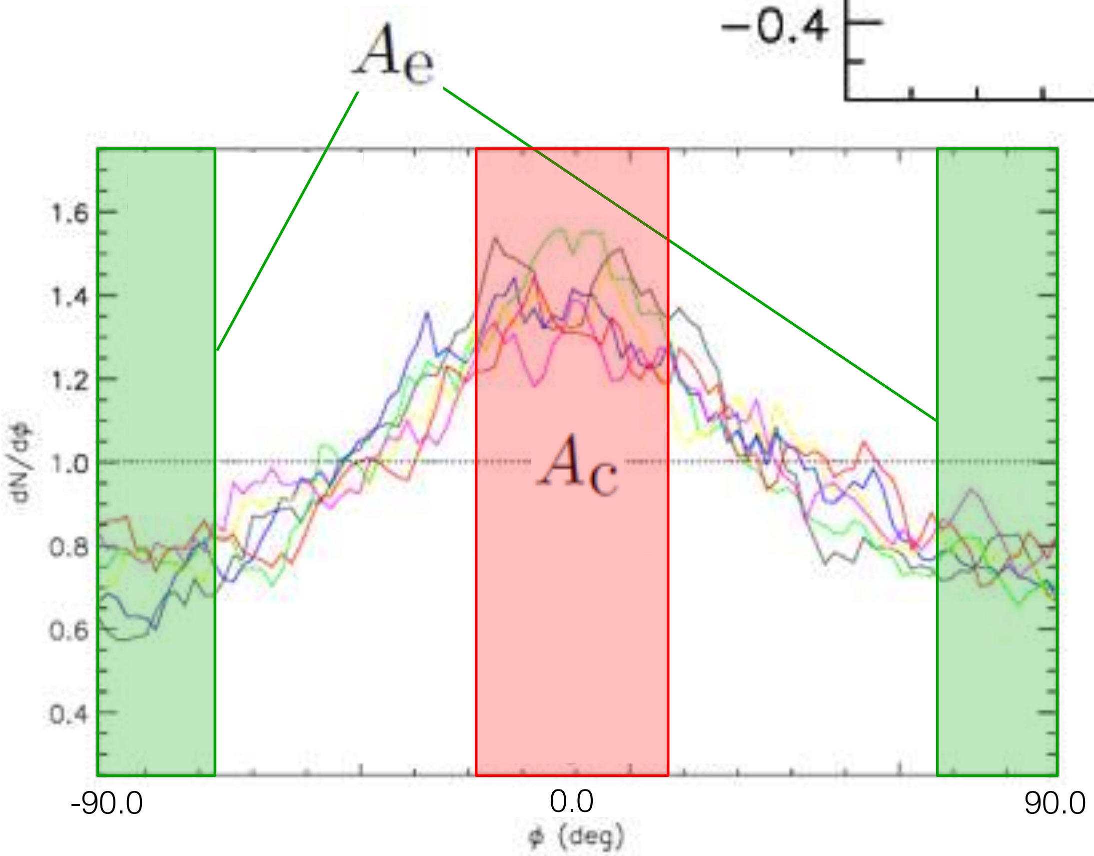


Soler et al, 2013

2D

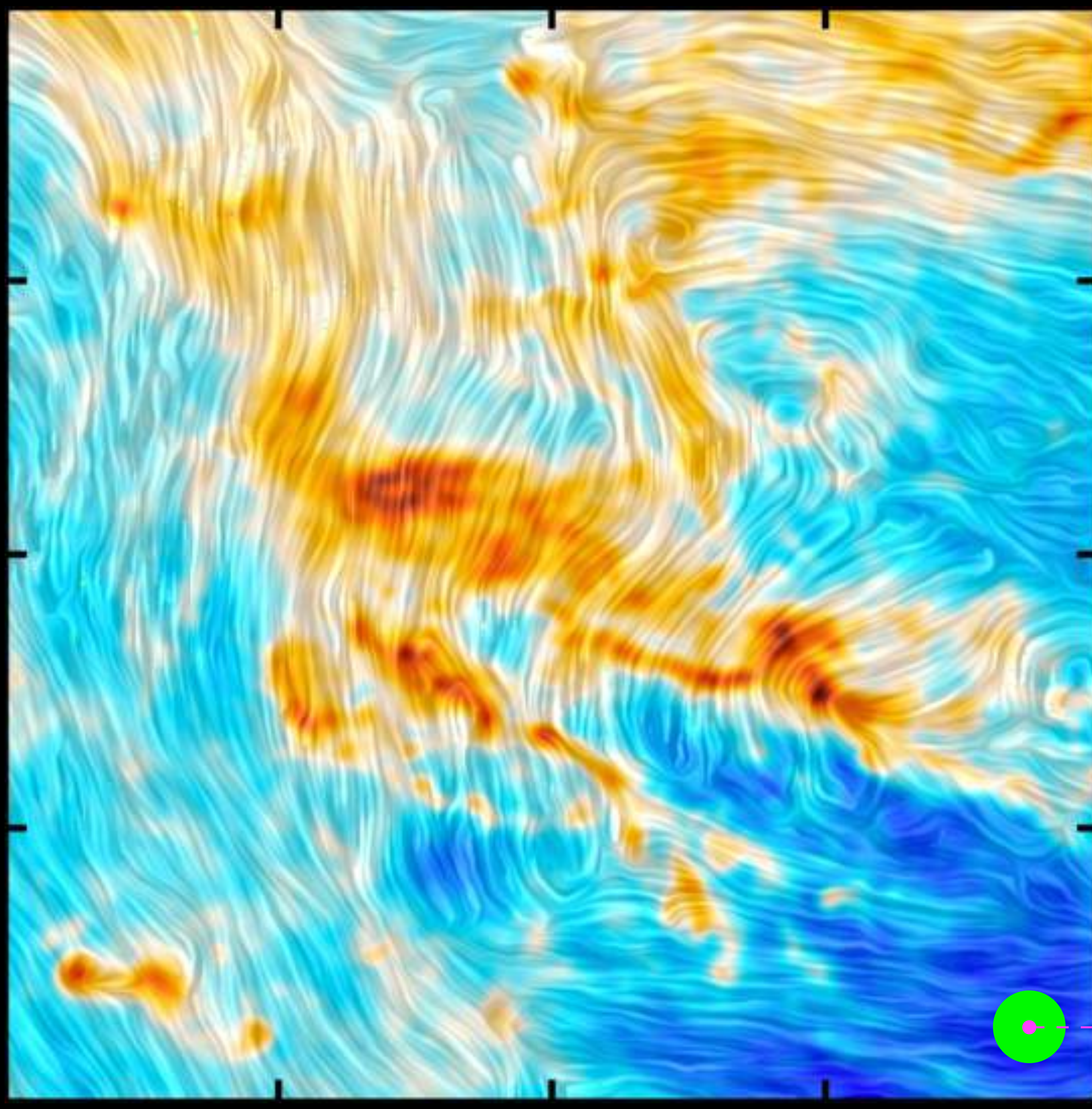
$$\zeta = \frac{A_c - A_e}{A_c + A_e}$$





Soler et al, 2013

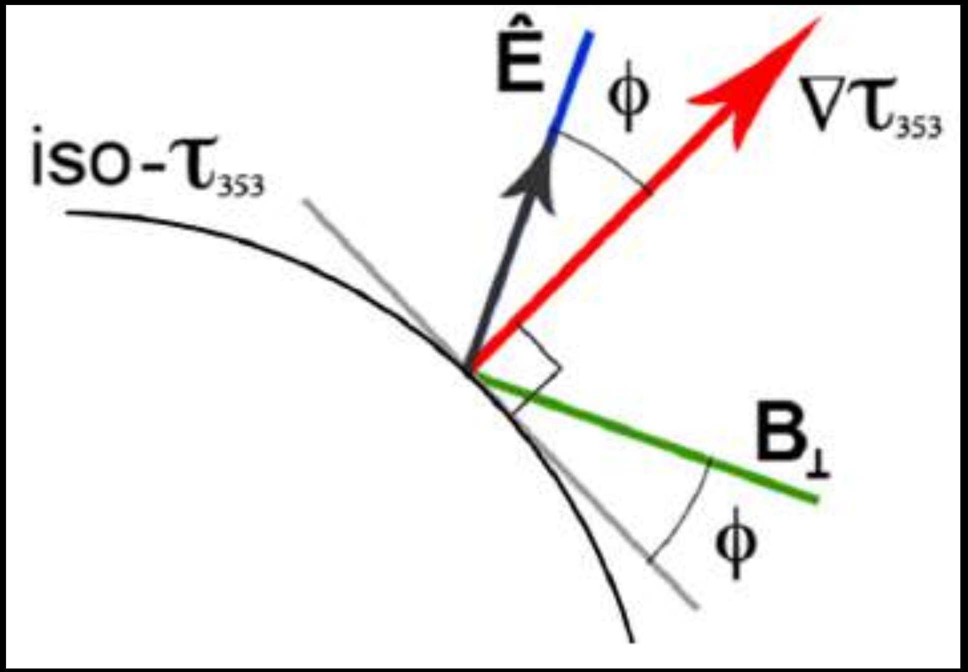
Relative Orientations



16 deg (40 pc @ d=140 pc)

Taurus region

- N_H from dust optical depth
- $\mathbf{B}_\perp$ from Planck 353 GHz pol.



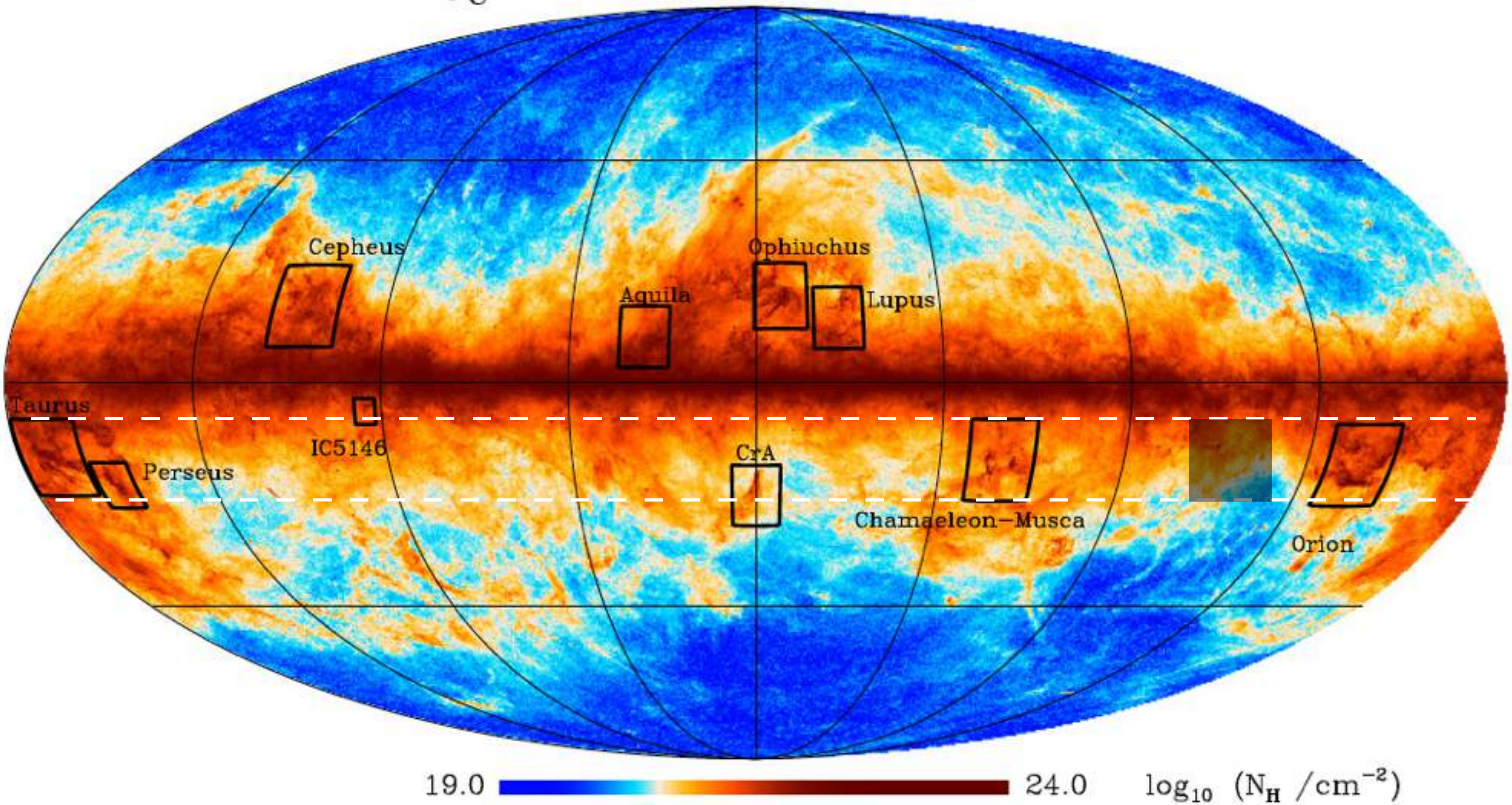
10’ FWHM (0.4 pc @ d=140 pc)

Planck intermediate results. XXXV

$$Q^{\mathrm{OBS}} = Q^{\mathrm{MC}} + Q^{\mathrm{BG}} + \delta_{\mathrm{Q}}$$

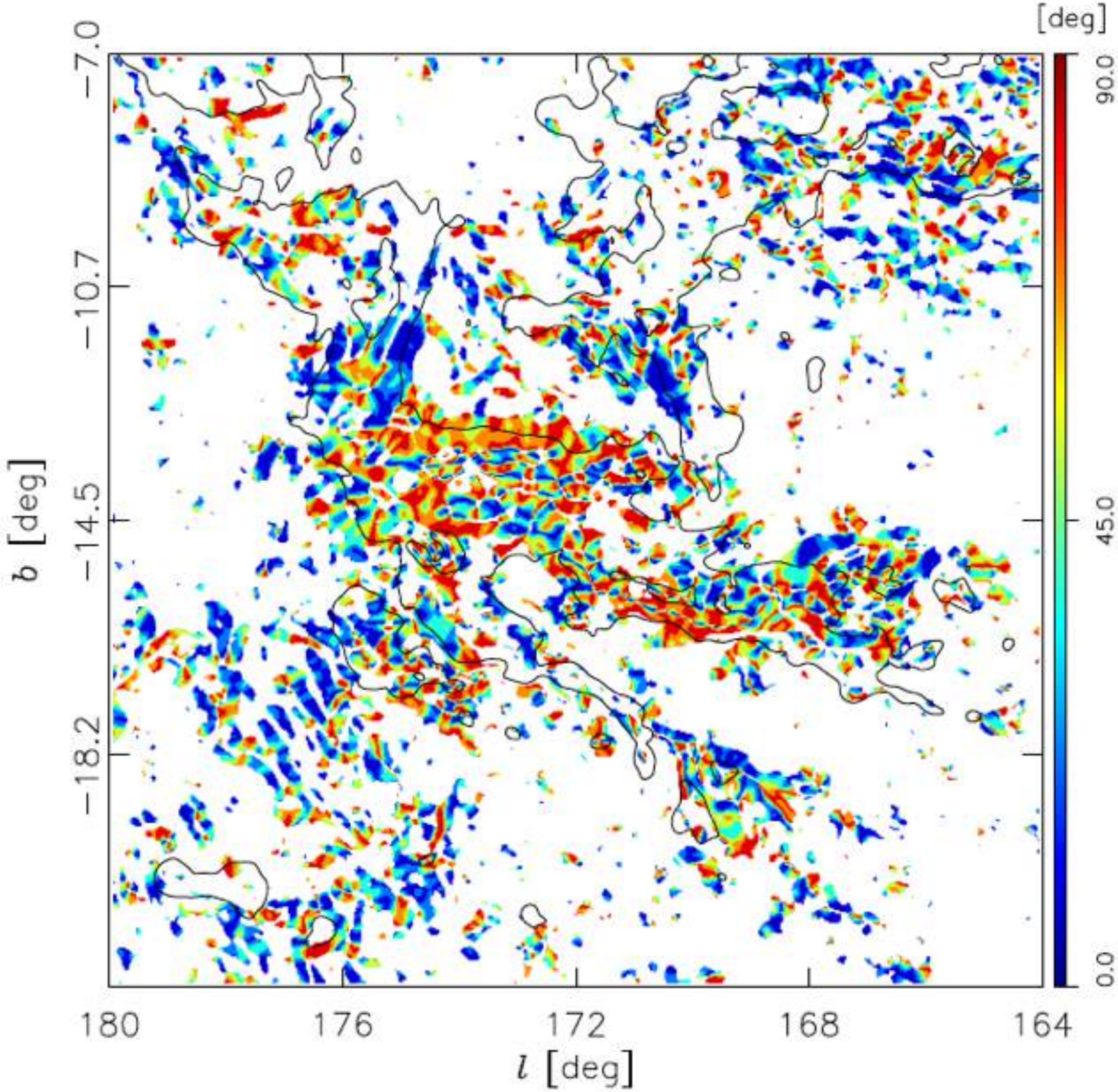
$$U^{\mathrm{OBS}} = U^{\mathrm{MC}} + U^{\mathrm{BG}} + \delta_{\mathrm{U}}$$

$$\nabla\tau_{353}^{\mathrm{OBS}} = \nabla\tau_{353}^{\mathrm{MC}} + \nabla(\tau_{353}^{\mathrm{BG}} + \delta_{\tau 353})$$



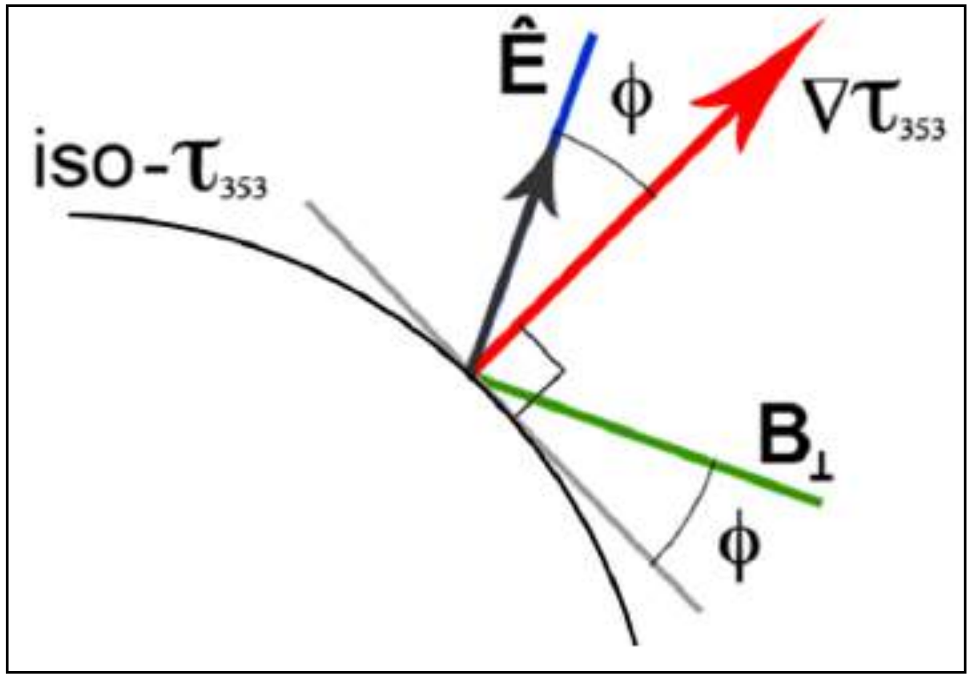
Planck intermediate results. XXXV

Relative Orientations



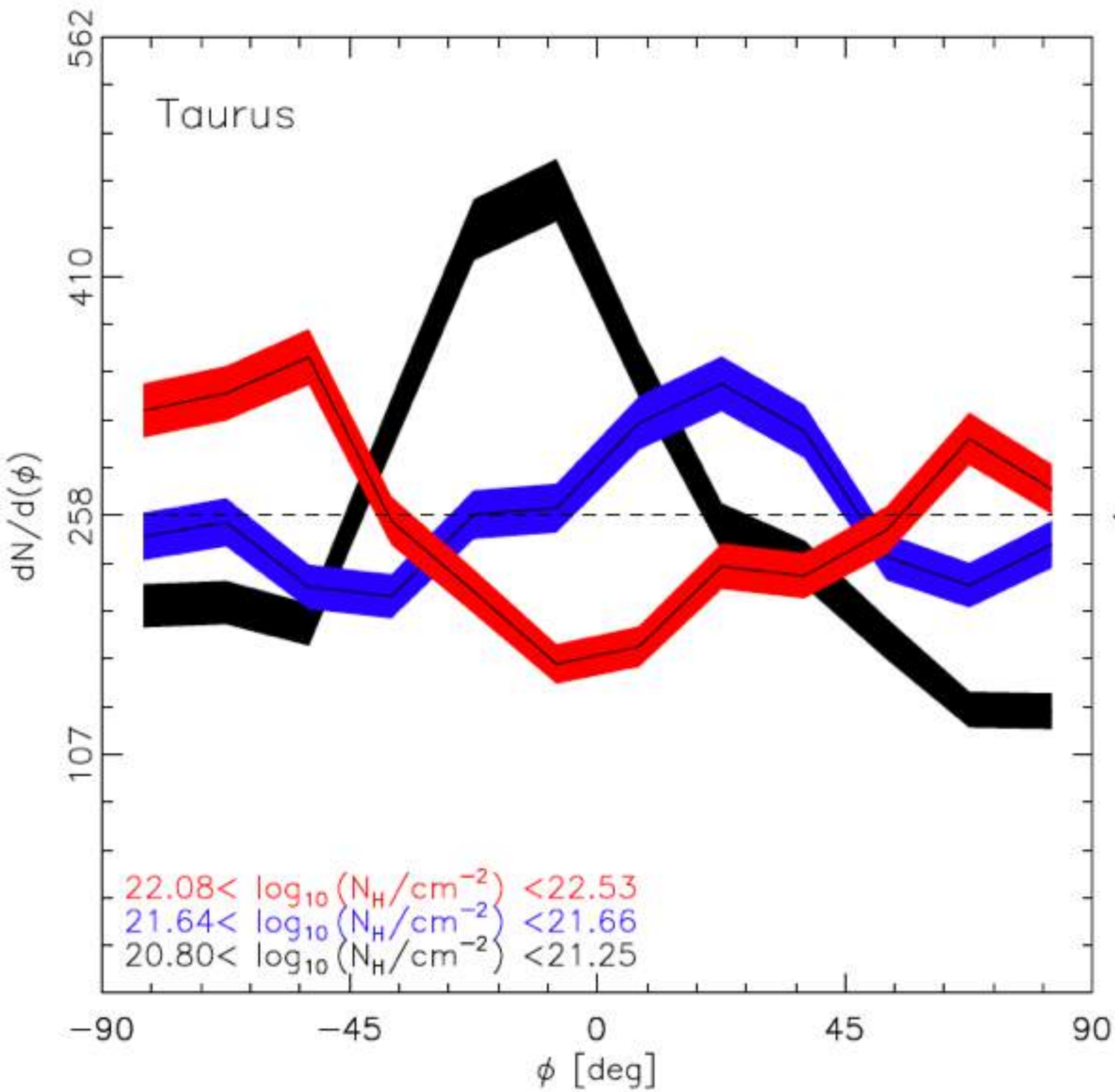
Taurus region

- Perpendicular
- Parallel

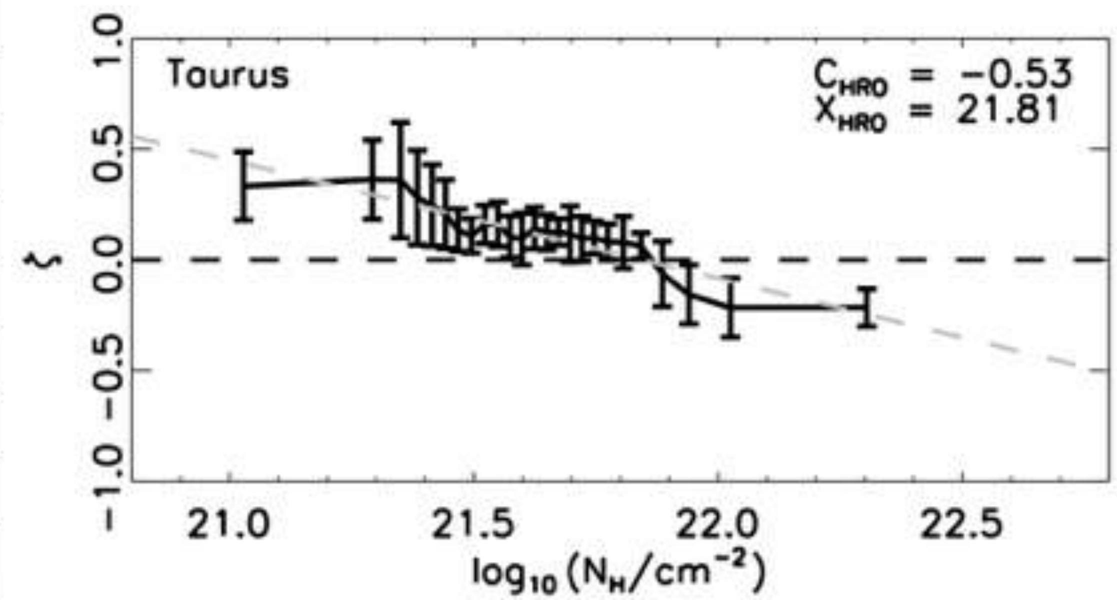


Planck intermediate results. XXXV

Histogram of Relative Orientations

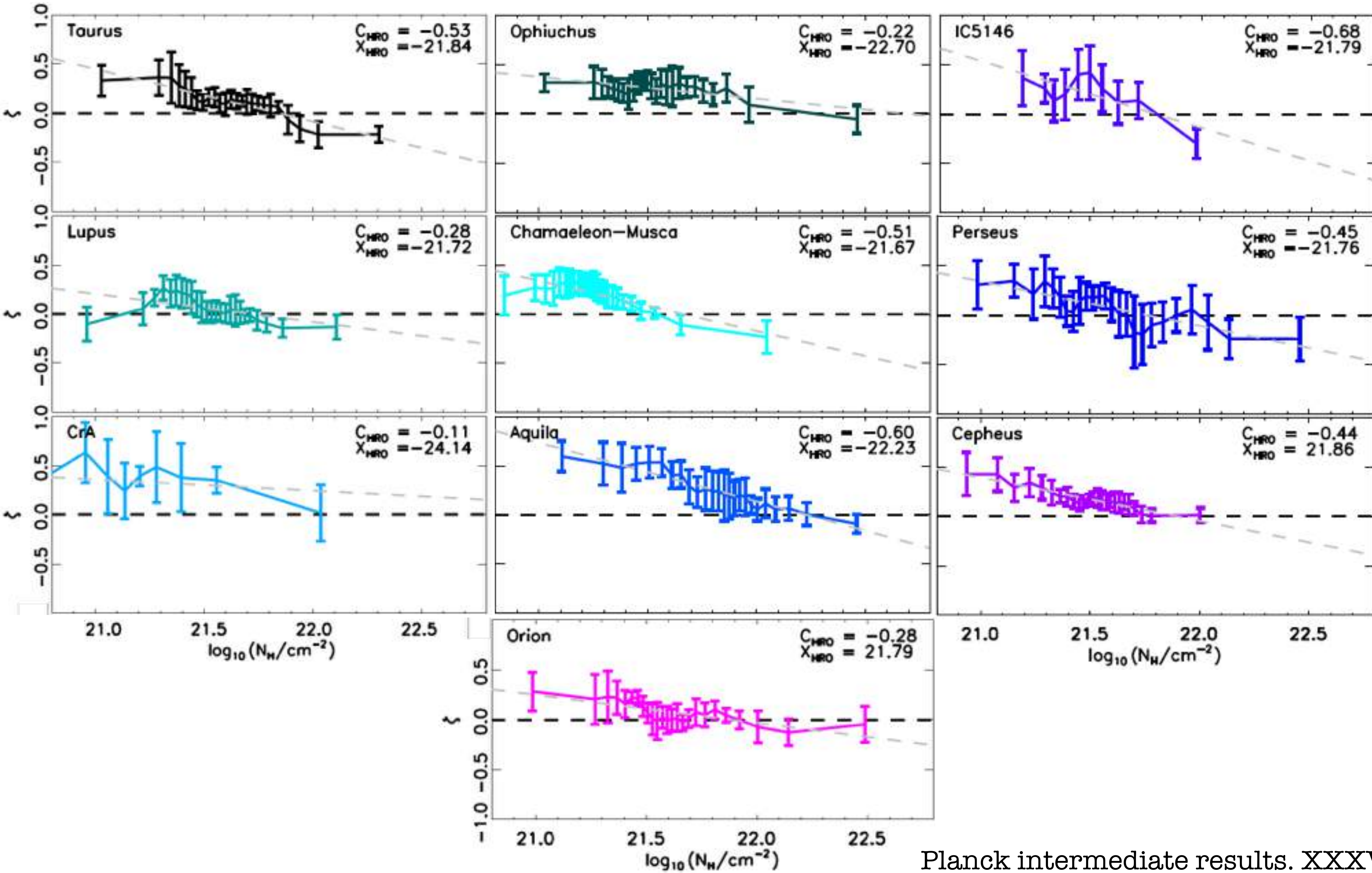


$$\zeta = \frac{A_c - A_e}{A_c + A_e}$$

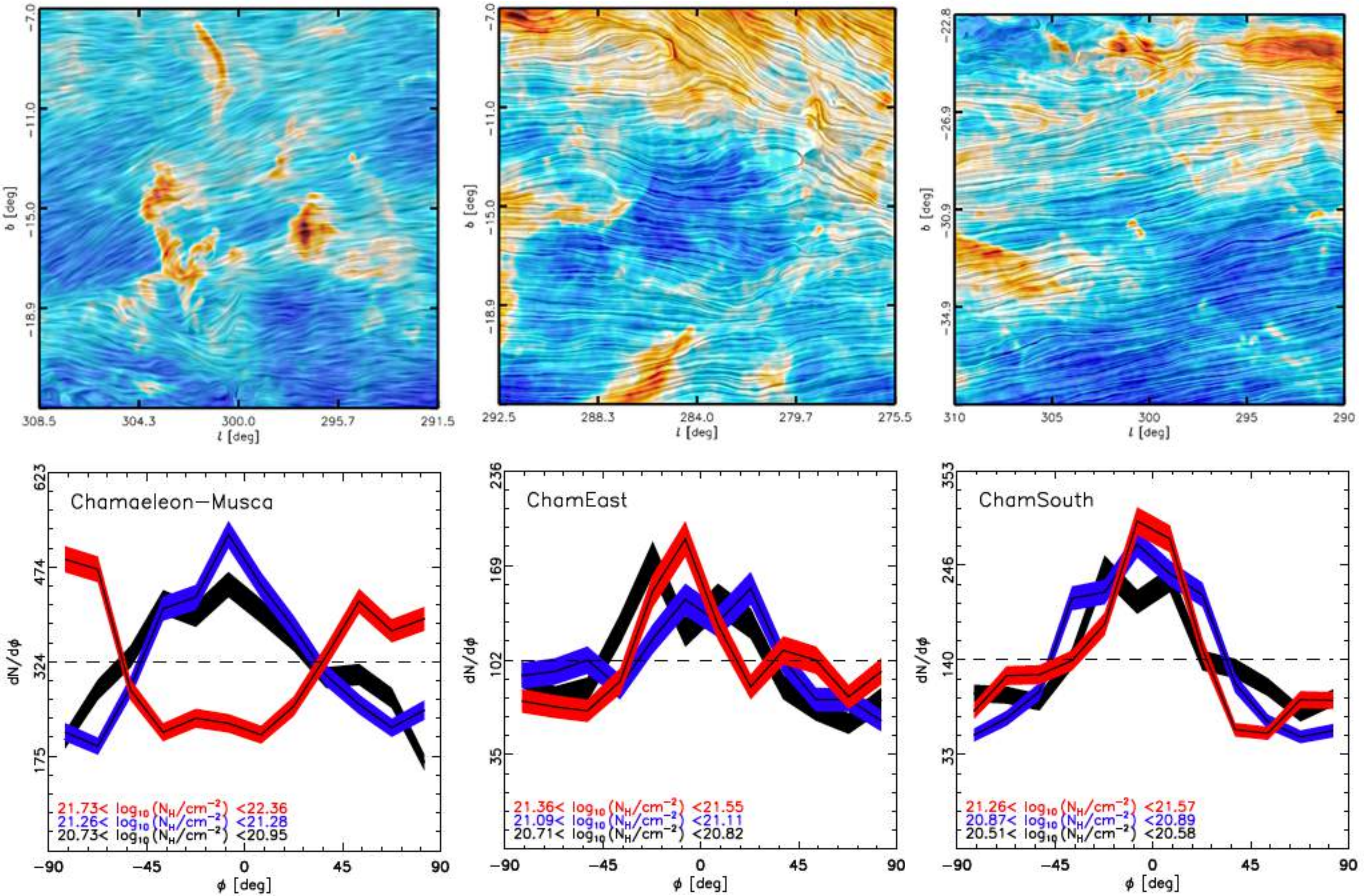


Planck intermediate results. XXXV

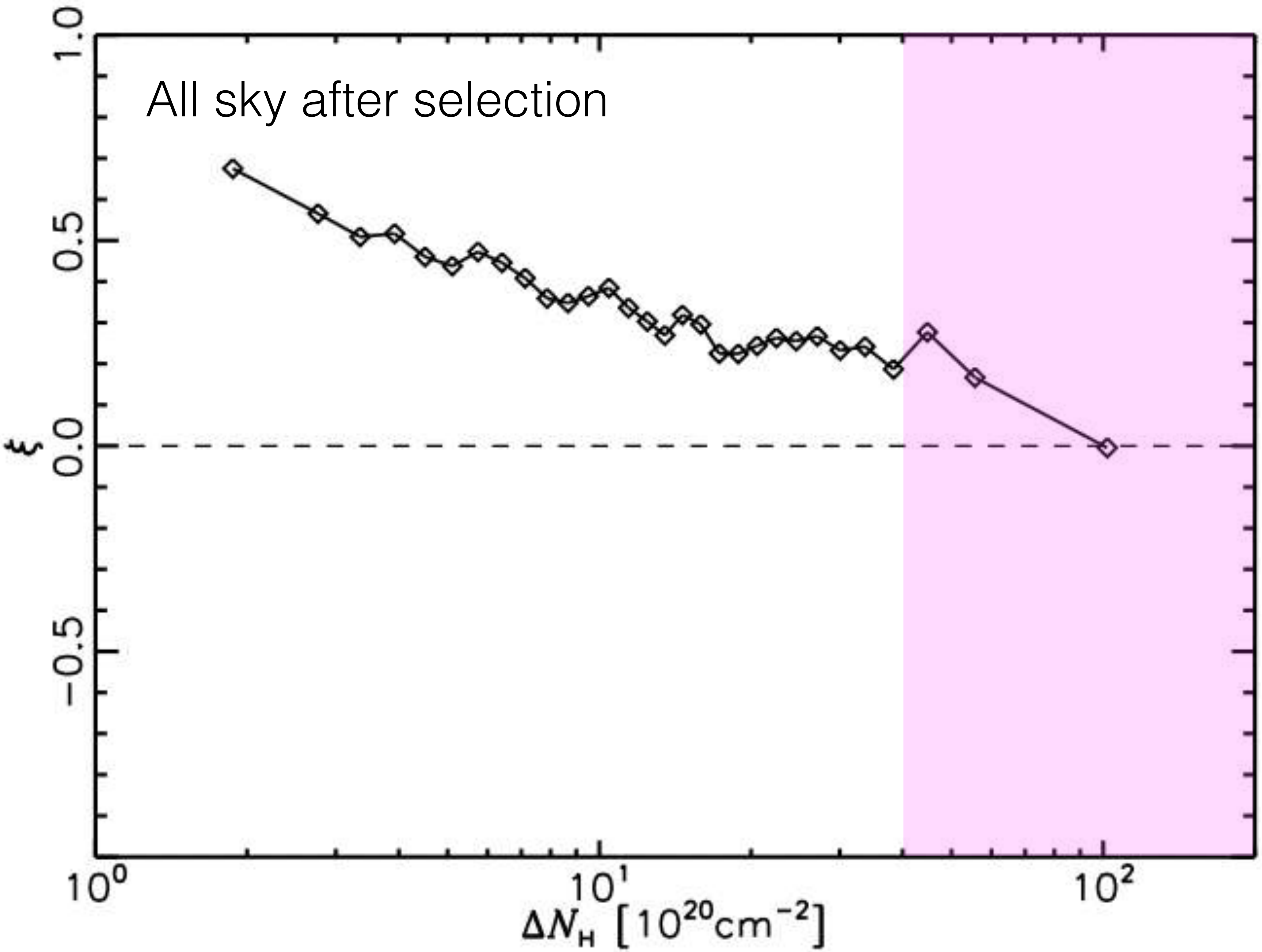
Relative Orientations



Planck intermediate results. XXXV

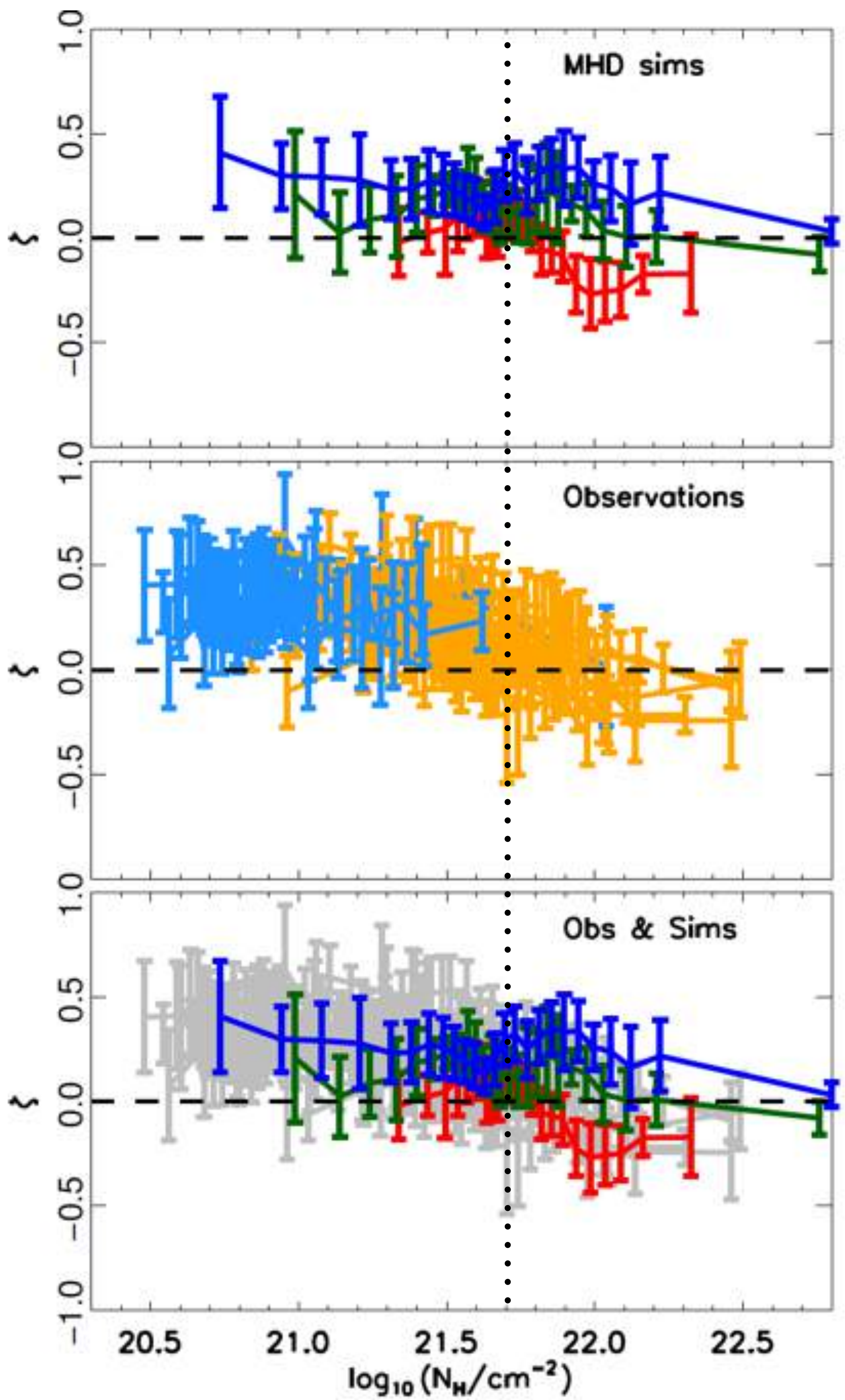

Chamaeleon−Musca
21.73< log10(NH/cm−2) <22.36
21.26< log10(NH/cm−2) <21.28
20.73< log10(NH/cm−2) <20.95
ChamEast
21.36< log10(NH/cm−2) <21.55
21.09< log10(NH/cm−2) <21.11
20.71< log10(NH/cm−2) <20.82
ChamSouth
21.26< log10(NH/cm−2) <21.57
20.87< log10(NH/cm−2) <20.89
20.51< log10(NH/cm−2) <20.58
dN/dϕ
ϕ [deg]
b [deg]
l [deg]

Relative Orientations

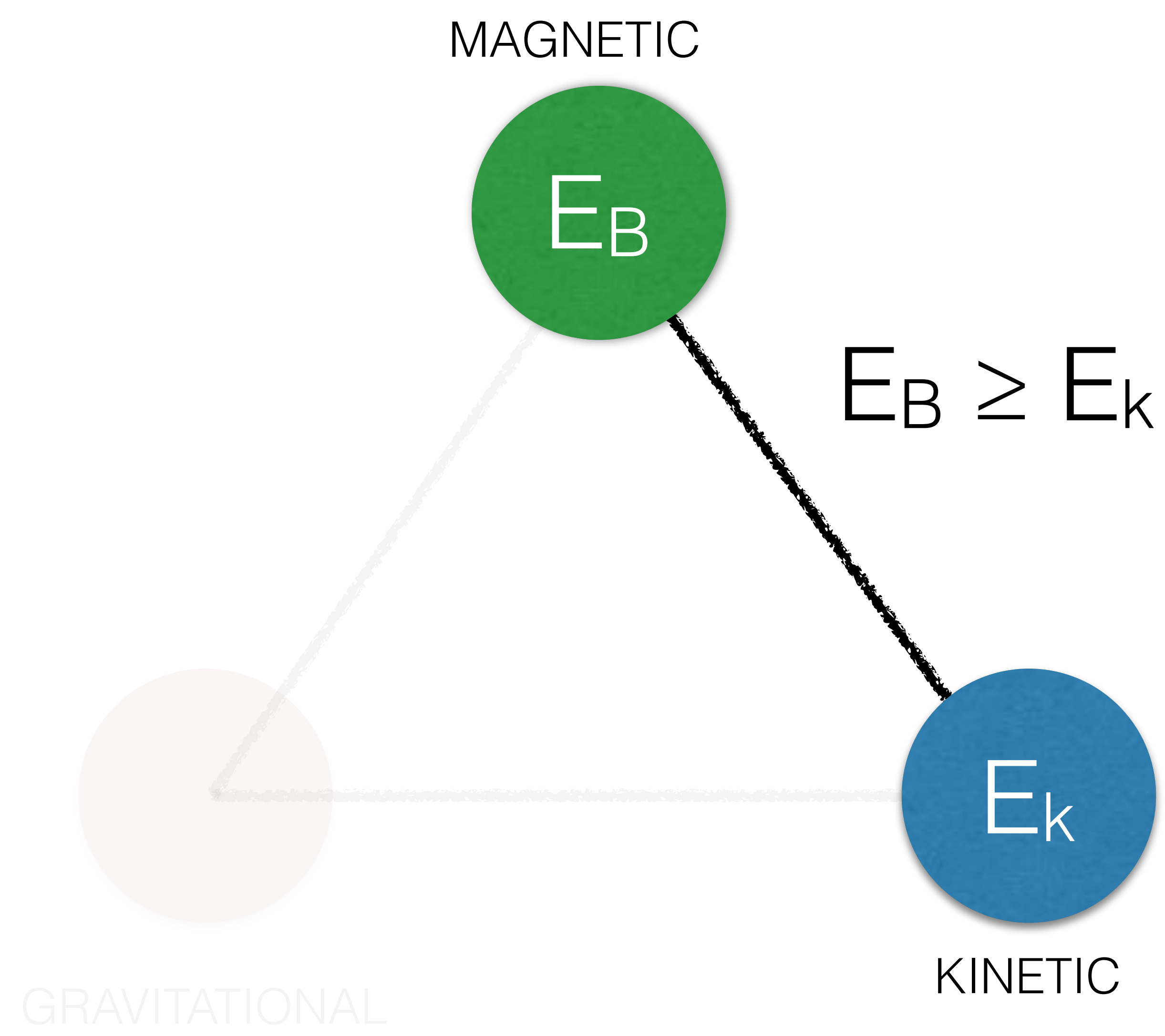


Planck intermediate results. XXXII
arXiv:1411.2271 A&A accepted

Relative Orientations



Weak field
Equipartition
Strong field

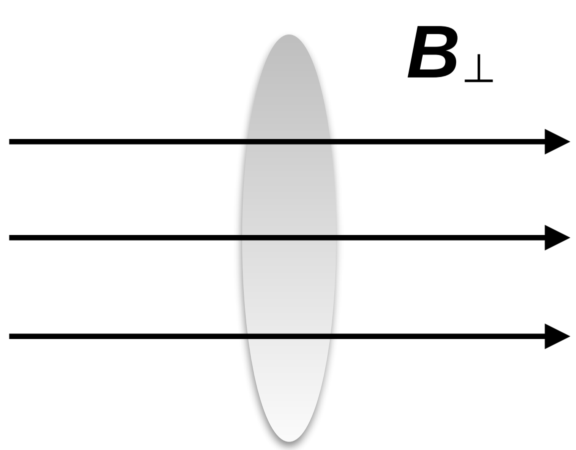


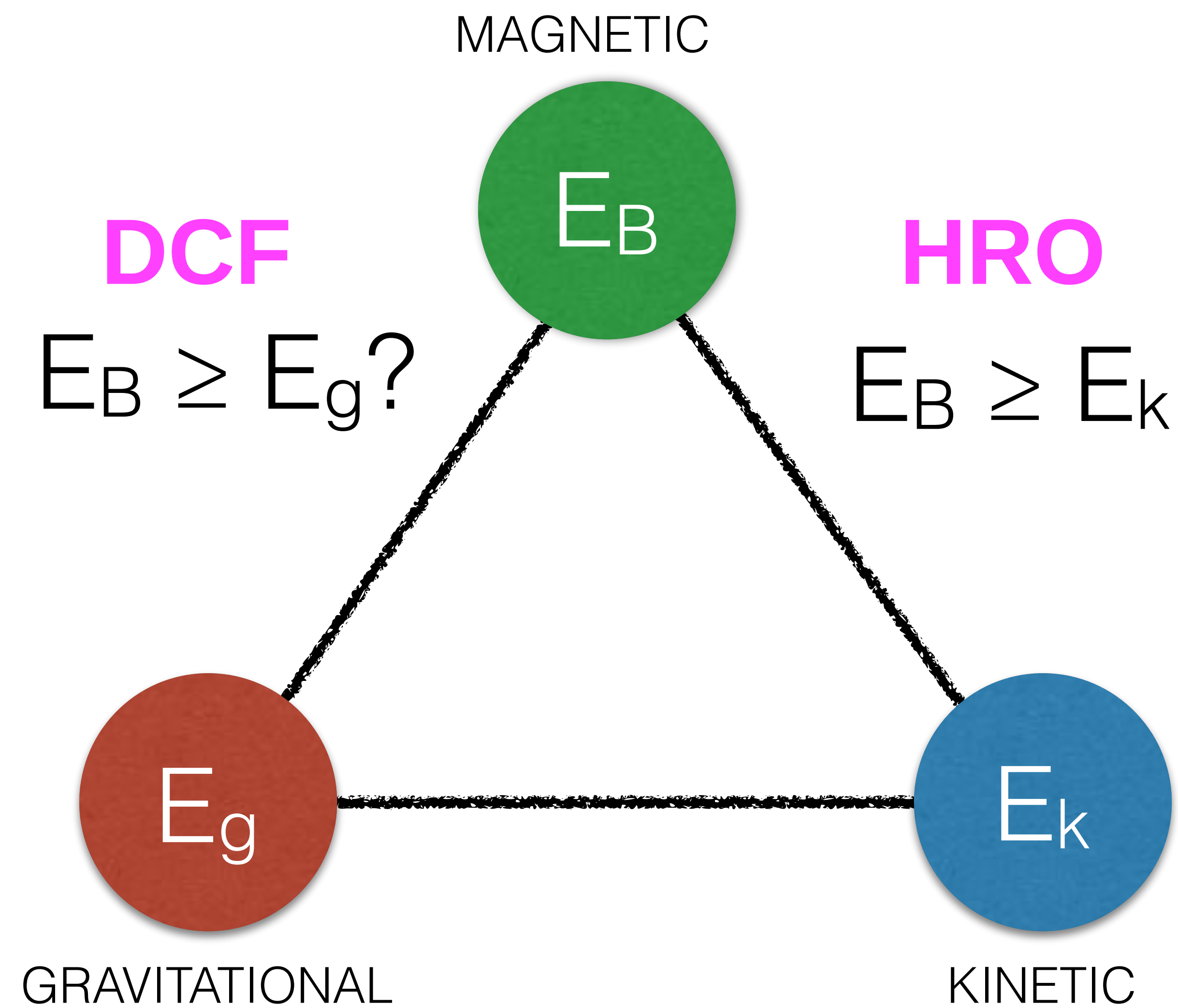
Planck intermediate results. XXXV

Magnetic fields in molecular cloud formation

What have we learned?

- Magnetic field at least in equipartition with turbulence.
- Magnetic field comparable to gravity?



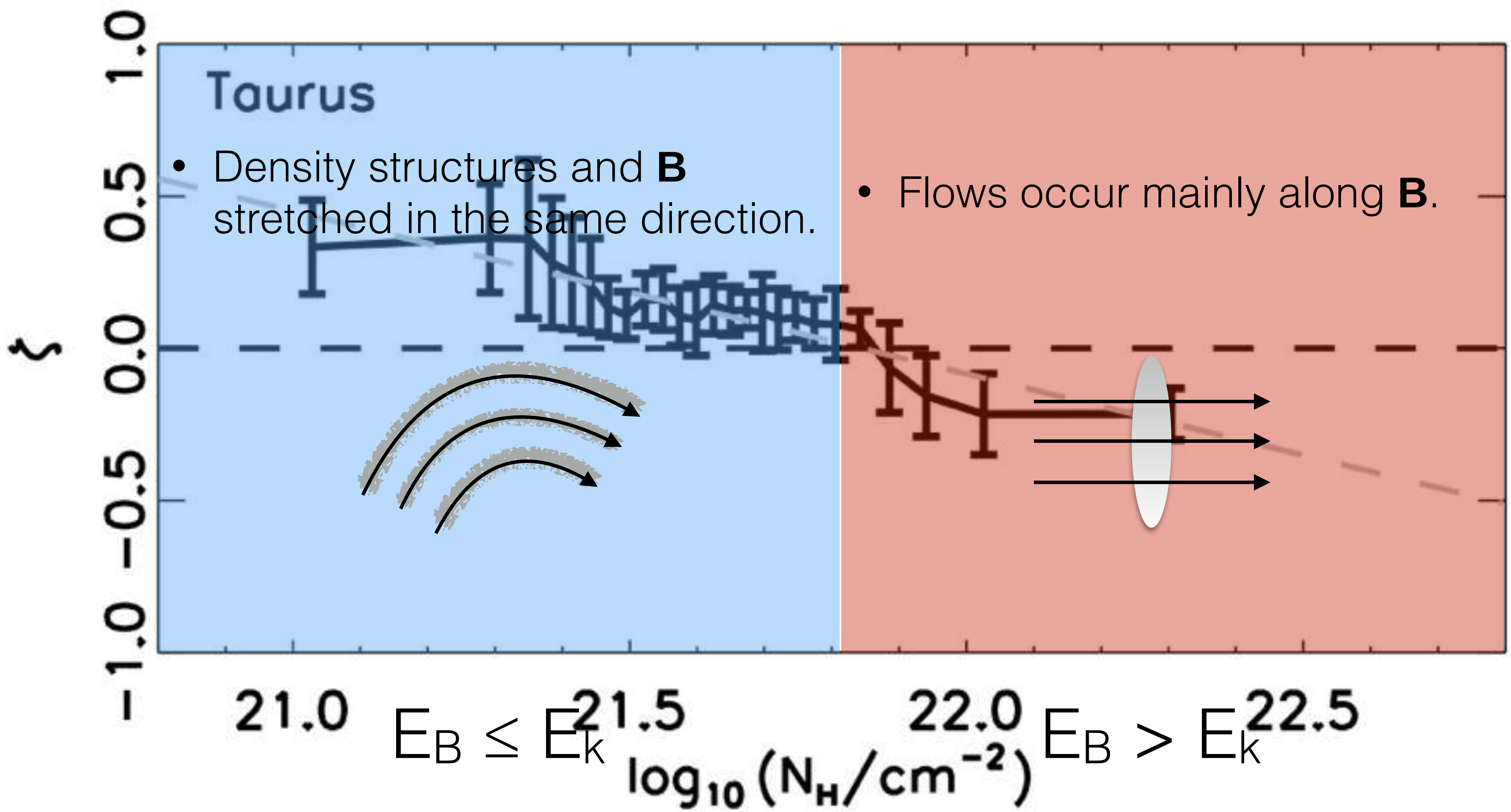


$E_g \approx E_k$

Virialized structure

Planck intermediate results. XXXV

Magnetic fields and cloud formation



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

- Flows occur mainly along **B**.

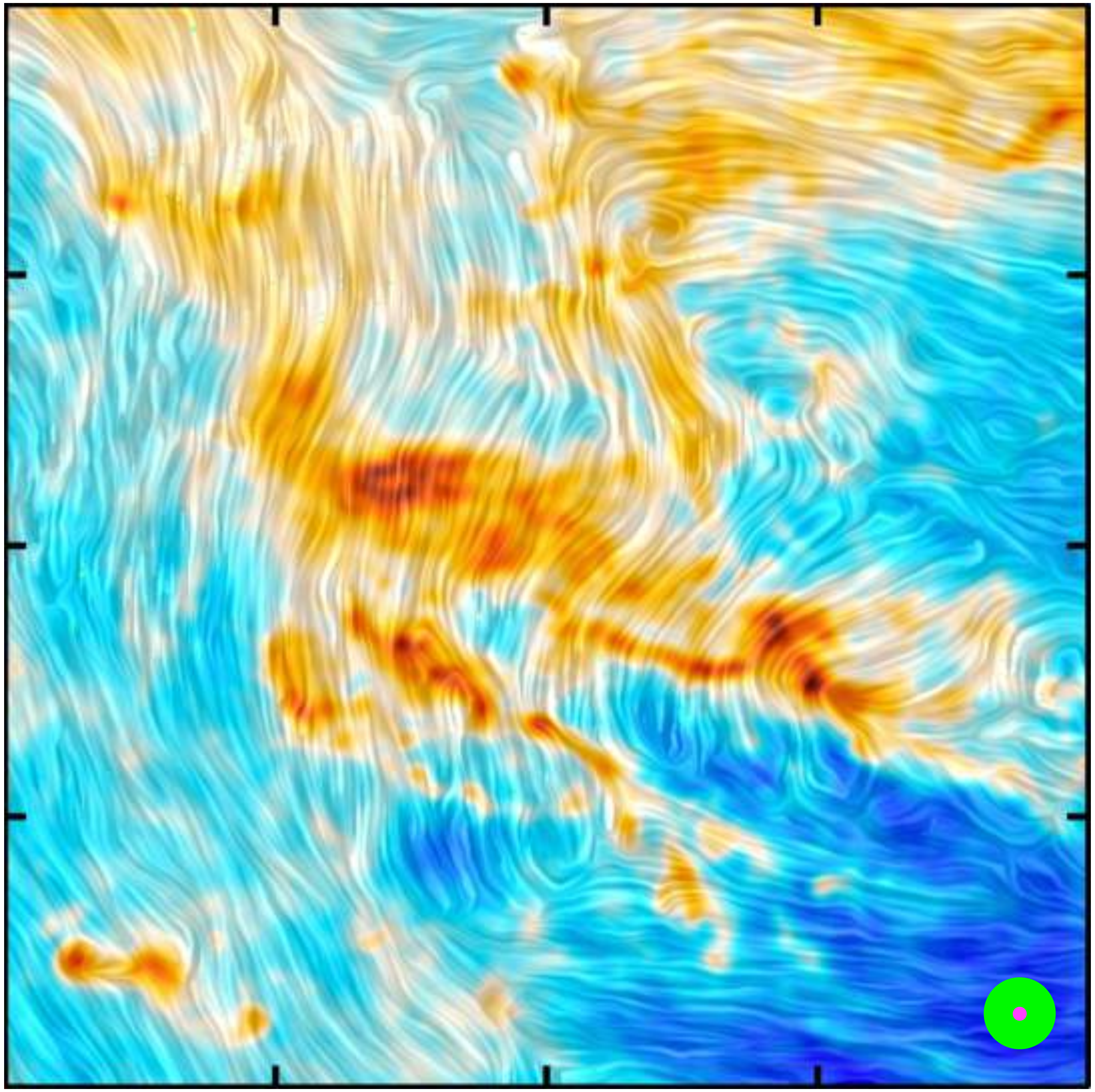
$E_B \leq E_k$

$E_B > E_k$

Planck intermediate results. XXXII
Hennebelle, P., 2013
Banerjee, R., 2009
Matthaeus, W. et al, 2008

Inutsuka, S., 2015
Nakamura F. & Li, Z., 2008

Open questions

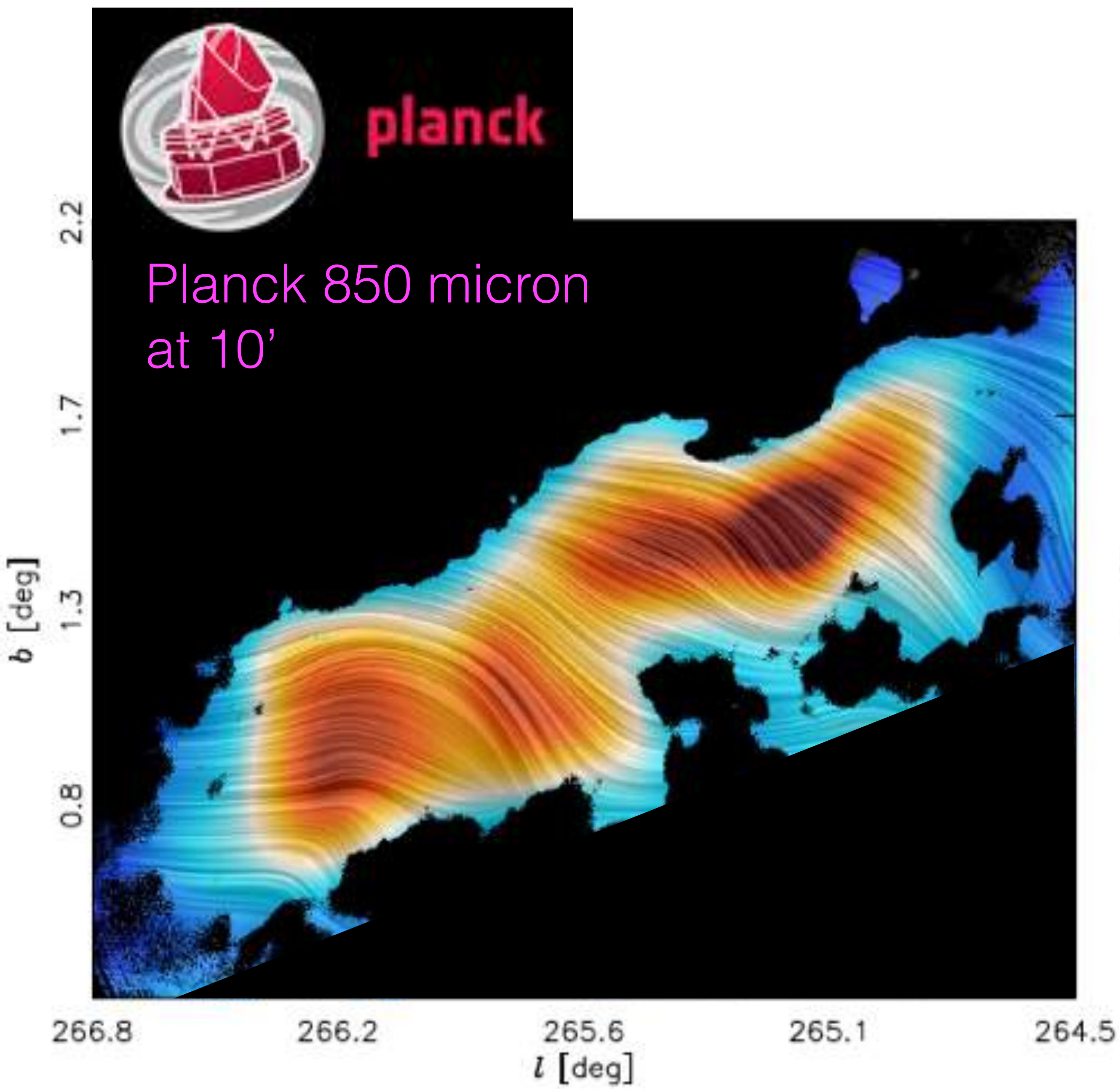


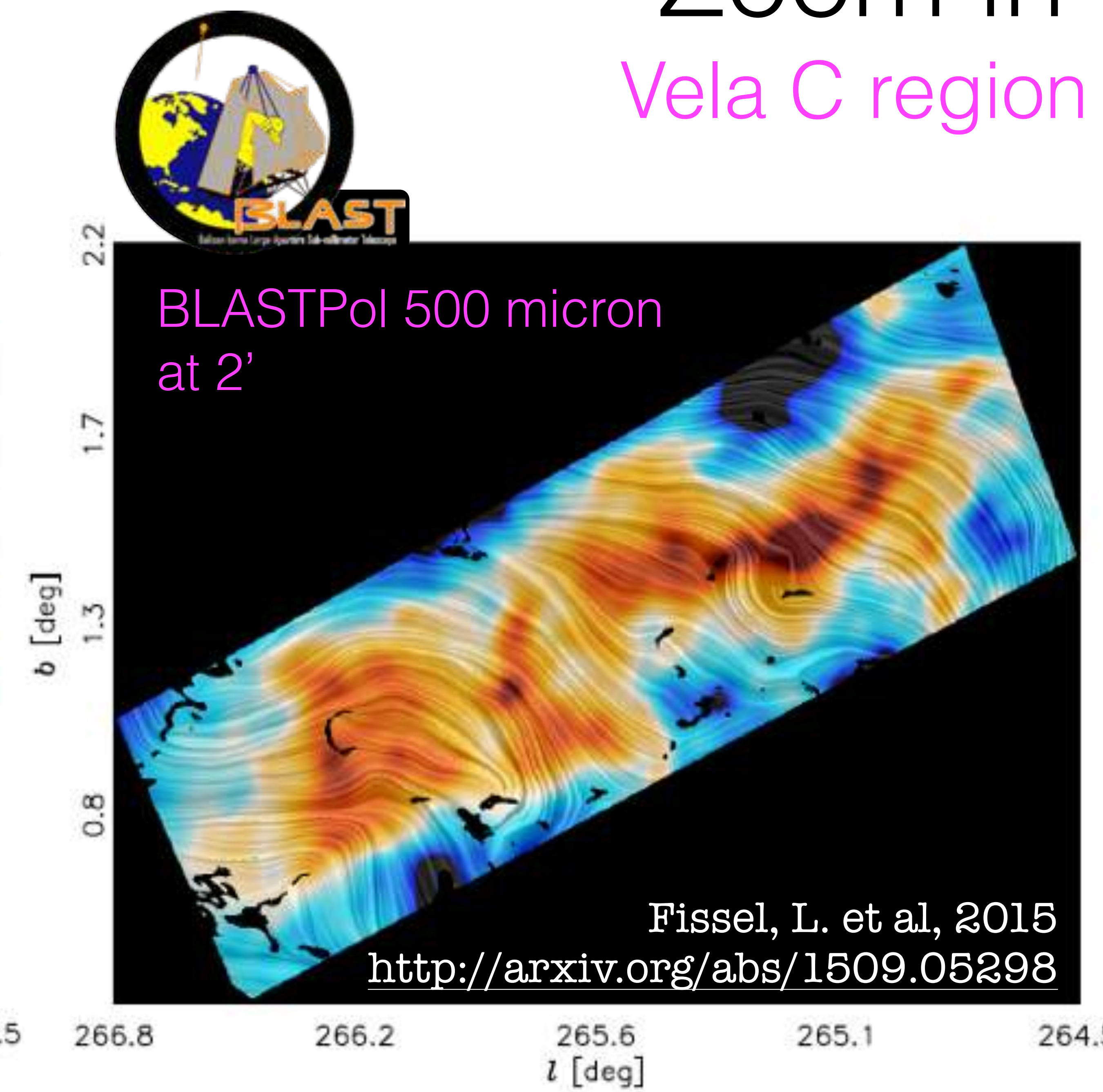
16 deg (40 pc @ d=140 pc)

- Line of sight integration
- Dust grain alignment
- Field structure at smaller scales

Zoom in

Vela C region





Gandilo, N. and BLASTPol collaboration, 2015 in preparation
Shariff, J. and BLASTPol collaboration, 2015 in preparation
Soler, J.D. and BLASTPol collaboration, 2016 in preparation

Check out poster by Laura Fissel

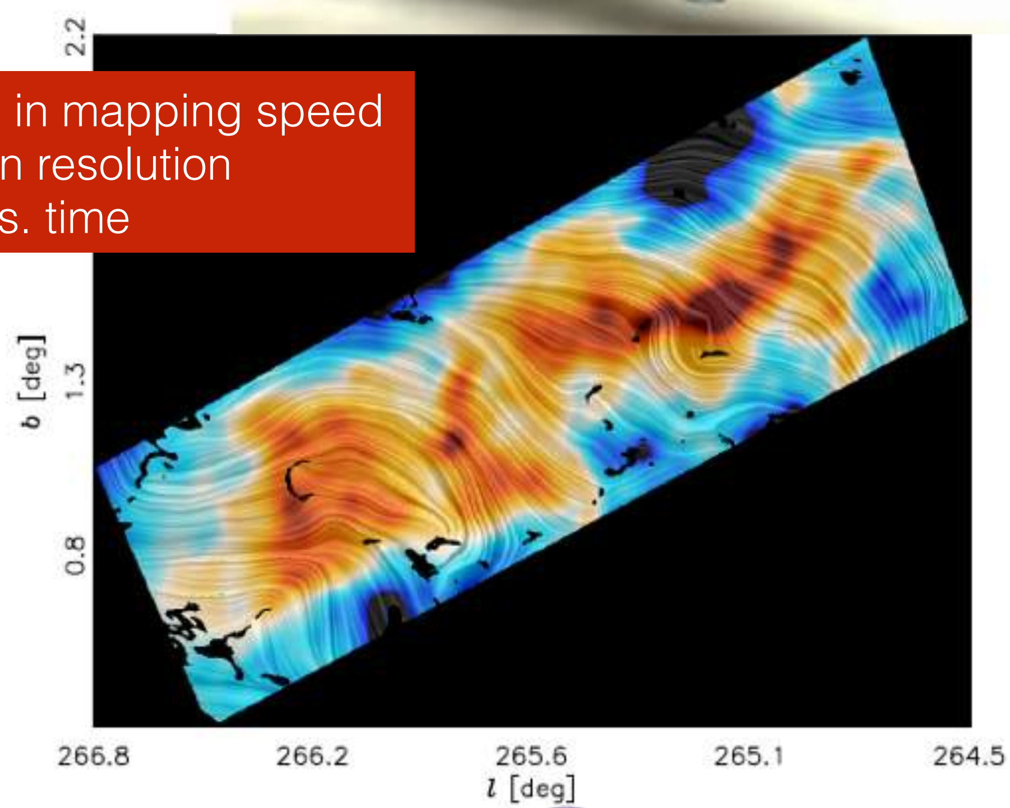
BLAST-TNG

Balloon -borne
250 µm (22'' res.)
350 µm
500 µm
polarimetry.

1000 MKID
detectors.

Flying from Antarctica
in 2017

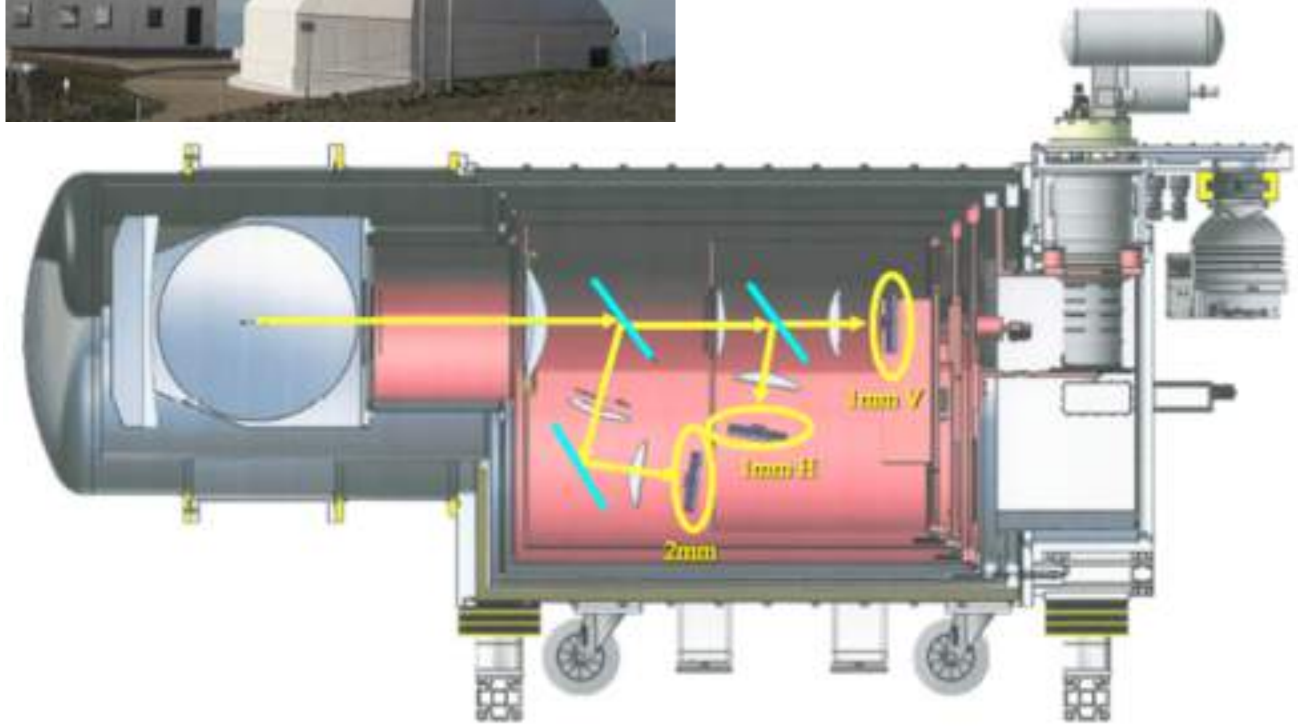
~16x increase in mapping speed
~6x increase in resolution
~3x longer obs. time



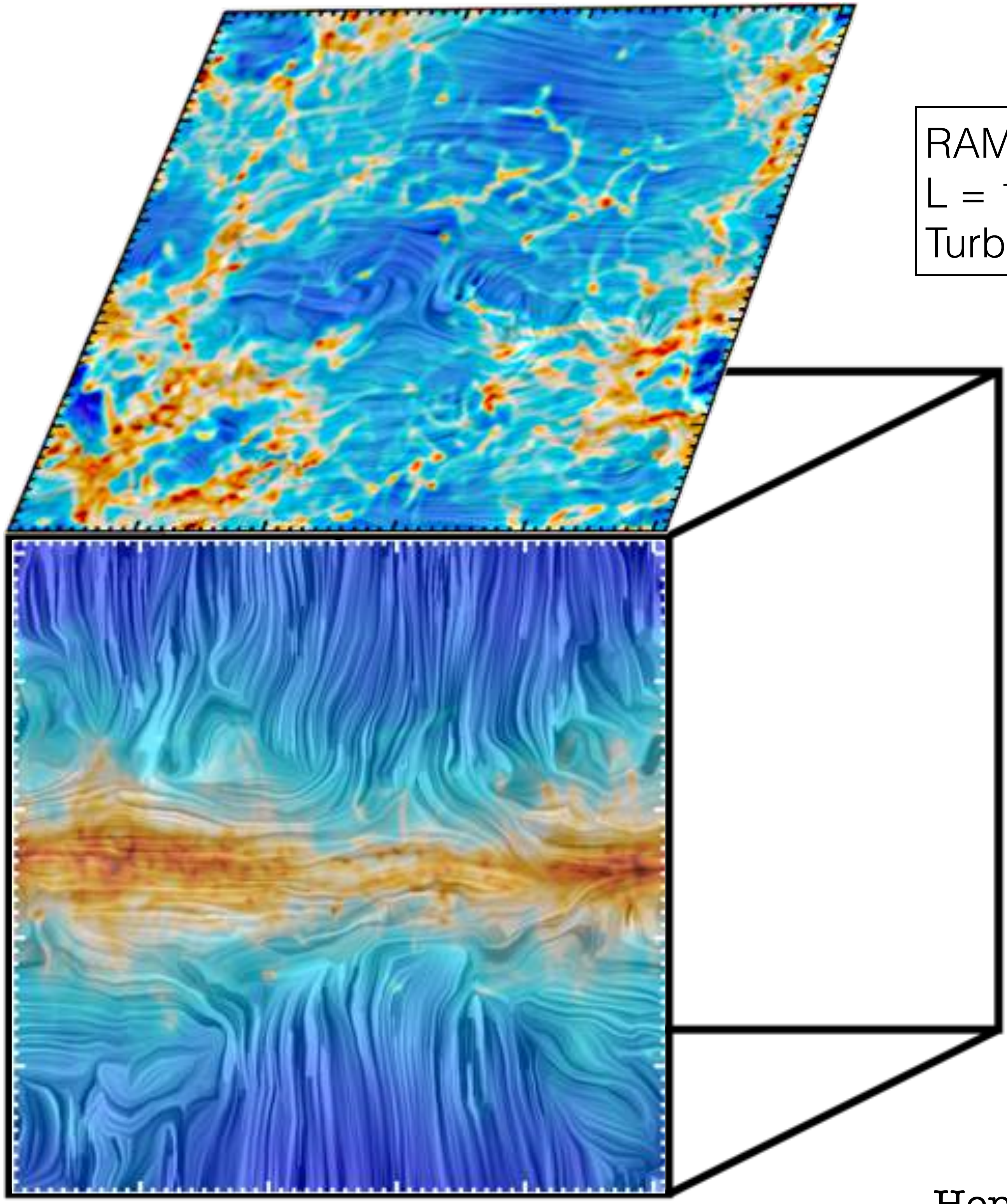
NIKA2

IRAM 30m telescope
1.2 mm (10'' res.)
polarimetry.
6.5' FoV

2x2000 MKID
detectors



Challenging observations call for challenging simulations



RAMSES simulation
L = 1 kpc (2^9 to 2^X resolution)
Turbulence driven by SNe

Hennebelle & Iffrig, 2014, 2015

Conclusions

@Planck polarization observations provide an unprecedented data set for the study of the magnetic field in molecular clouds #PlanckRocks

In 10 nearby MCs, high-N_H structures mostly perpendicular to the field. May have formed by #ConvergingFlows or #GravitationalCollapse along the field. #MagneticFieldMatters

#InDustWeTrust, but we have to improve our understanding of #DustGrainAlignment, combine #MultipleScales, and contrast the observations with #MHDSims

Visit http://planckandthemagneticfield.info

Planck intermediate results. XXXV
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