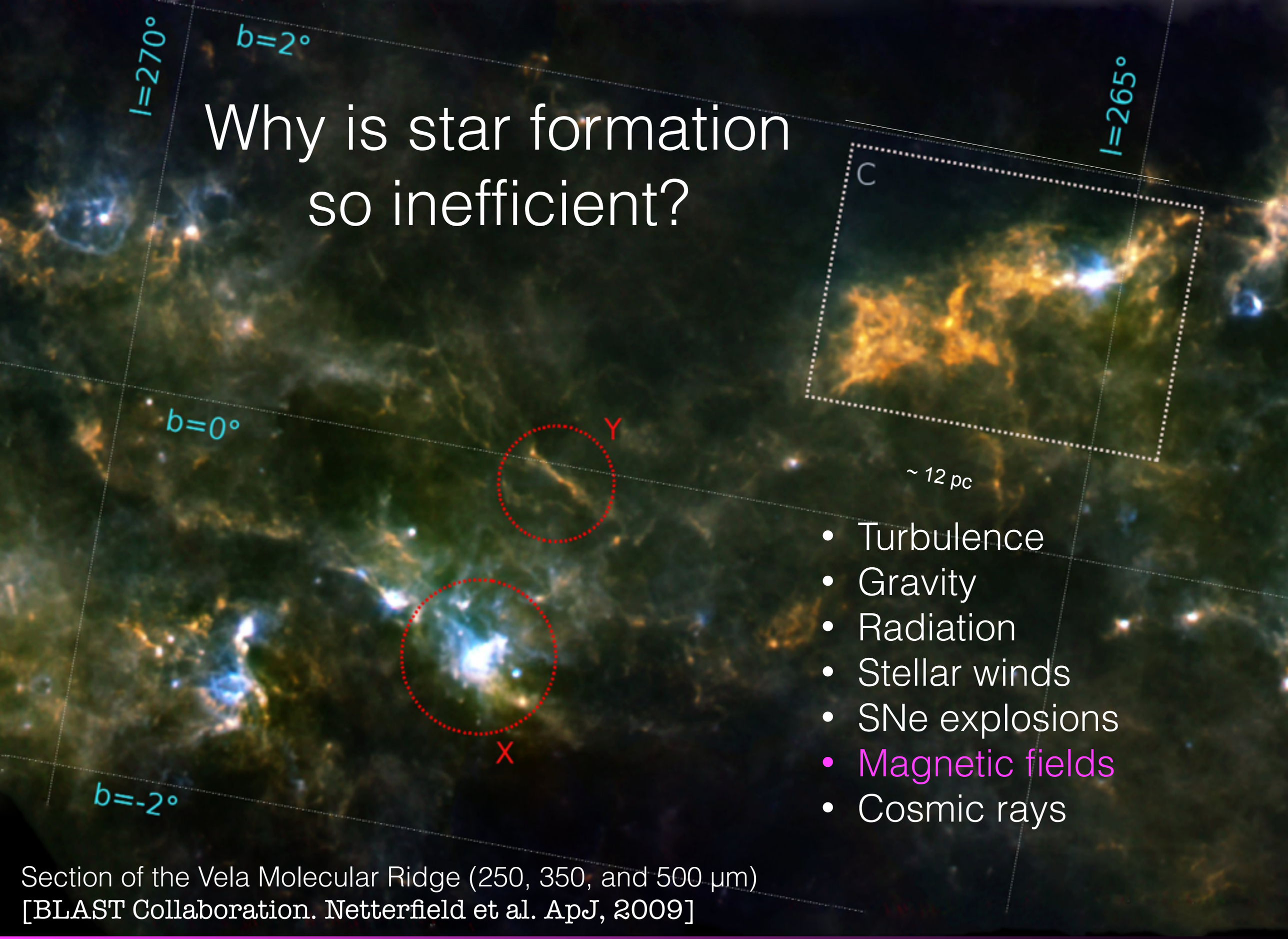
Magneto is (not) a hero

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

Juan Diego Soler (Room 224)

CEA/Saclay. January 4, 2016

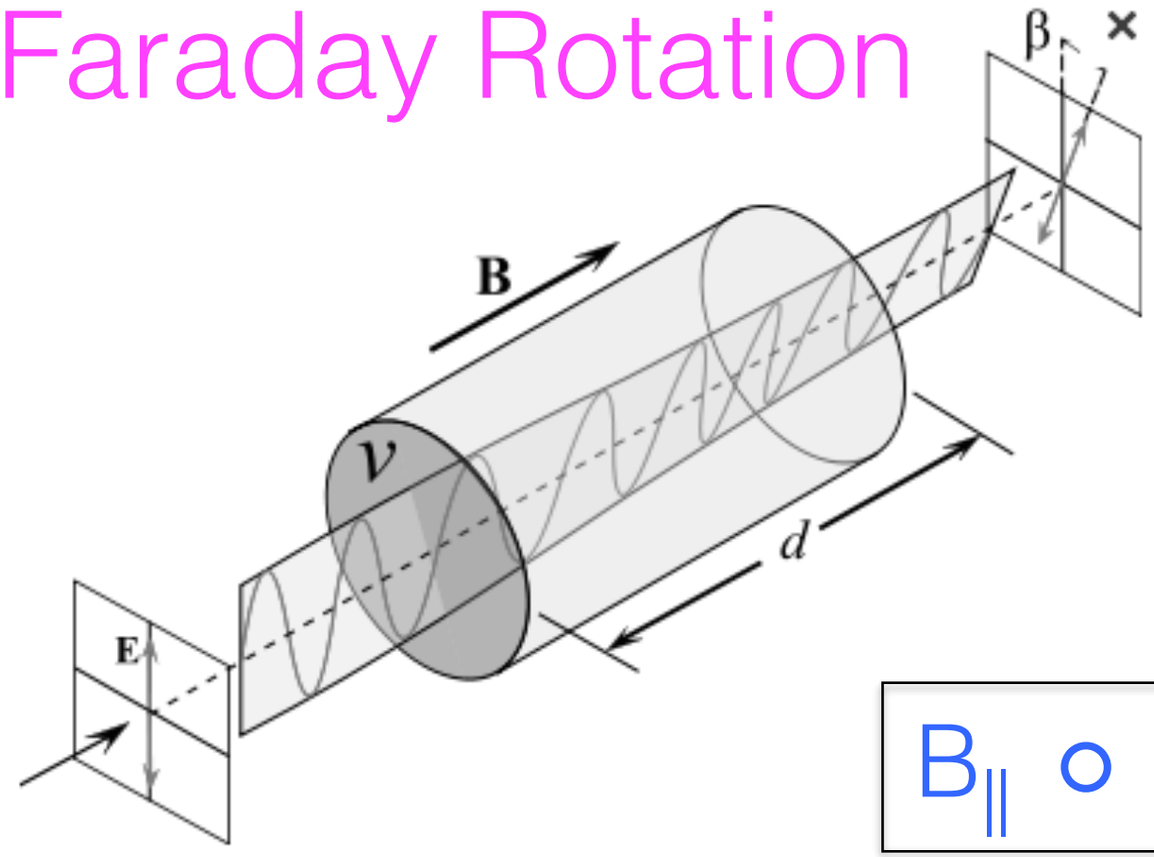
Why is star formation so inefficient?



- Turbulence
- Gravity
- Radiation
- Stellar winds
- SNe explosions
- Magnetic fields
- Cosmic rays

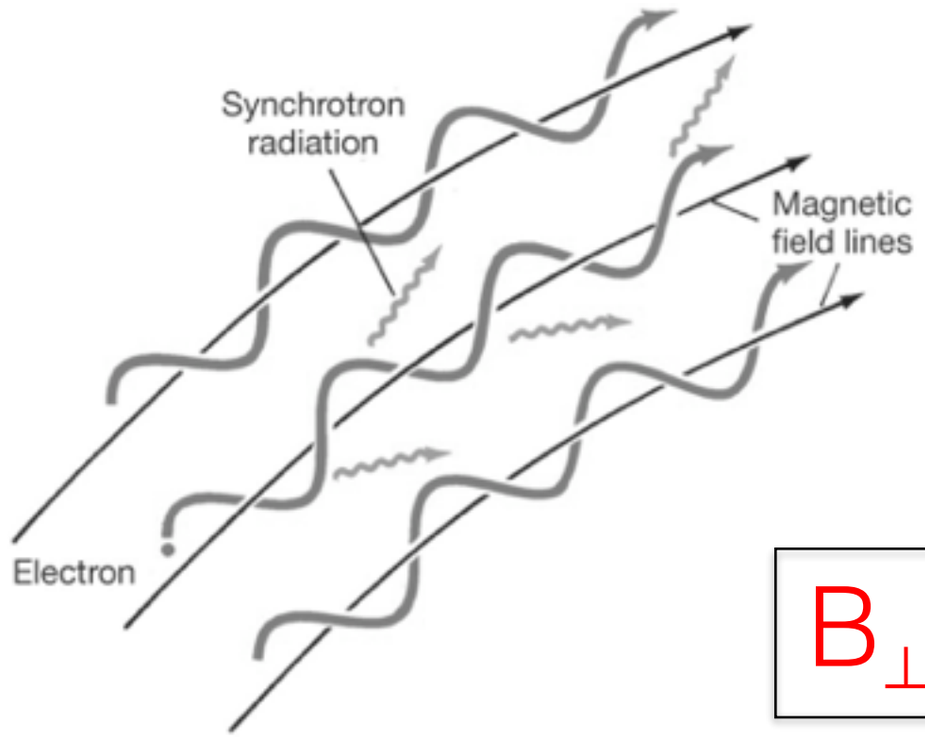
Section of the Vela Molecular Ridge (250, 350, and 500 μm)
[BLAST Collaboration. Netterfield et al. ApJ, 2009]

Faraday Rotation



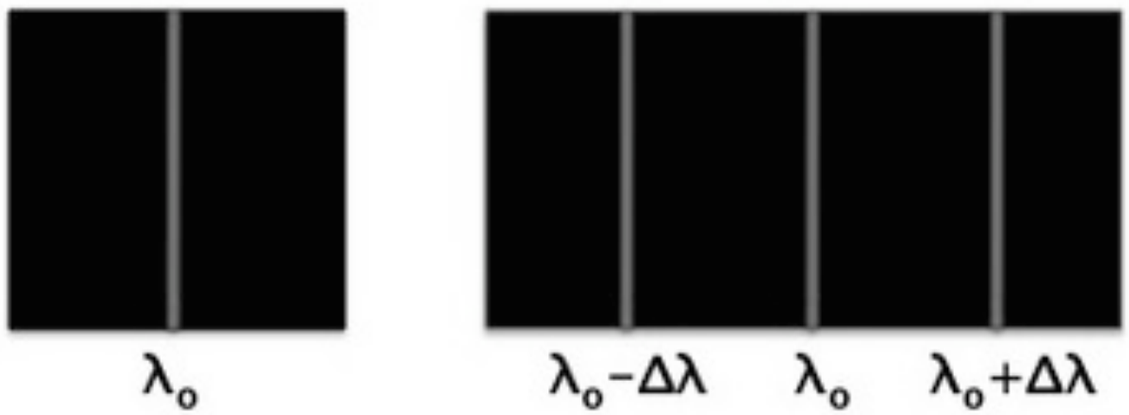
$B_{\parallel}$ ○

Synchrotron Emission



$B_{\perp}$ →

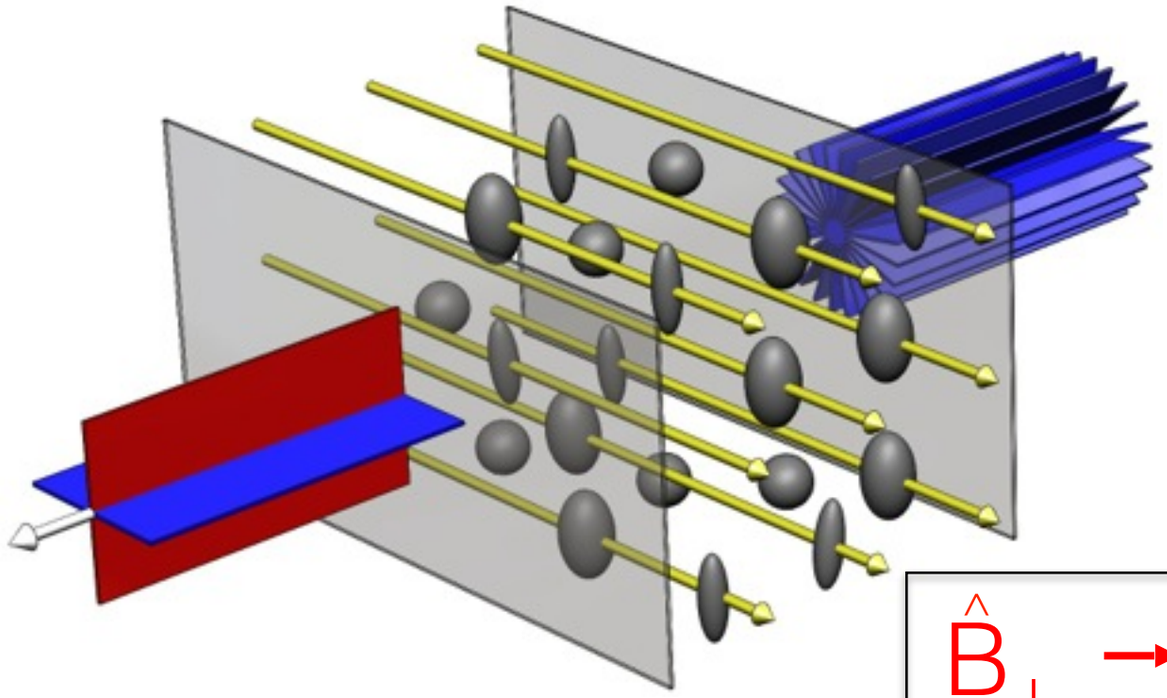
Zeeman Splitting



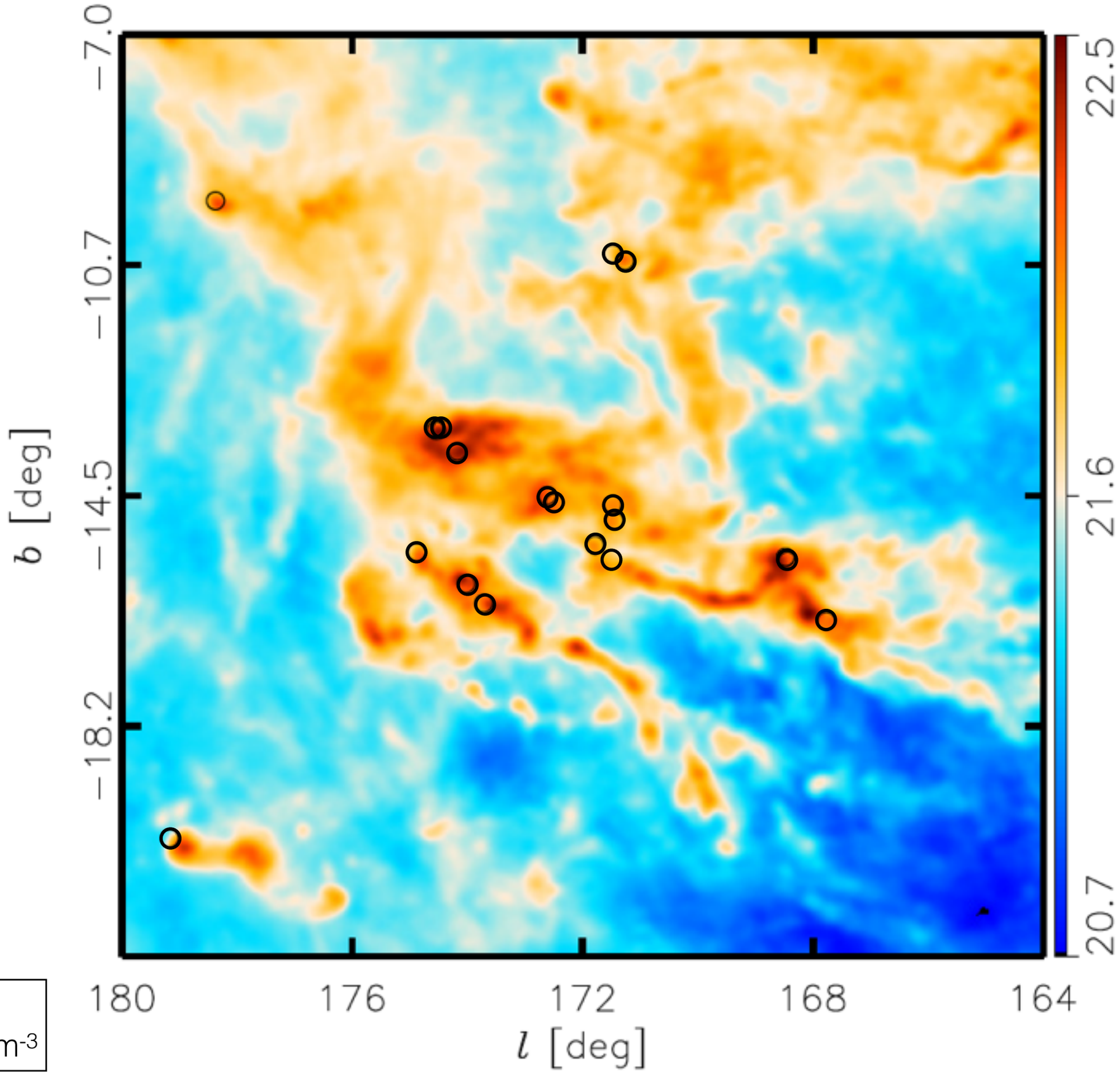
Species	Wavelength	n(H) traced
H I	21-cm	$10^1 – 10^2$ cm^{-3}
OH	18-cm	$10^3 – 10^4$ cm^{-3}
CN	3 mm	$10^5 – 10^6$ cm^{-3}

$B_{\parallel}$ ○

Dust polarization

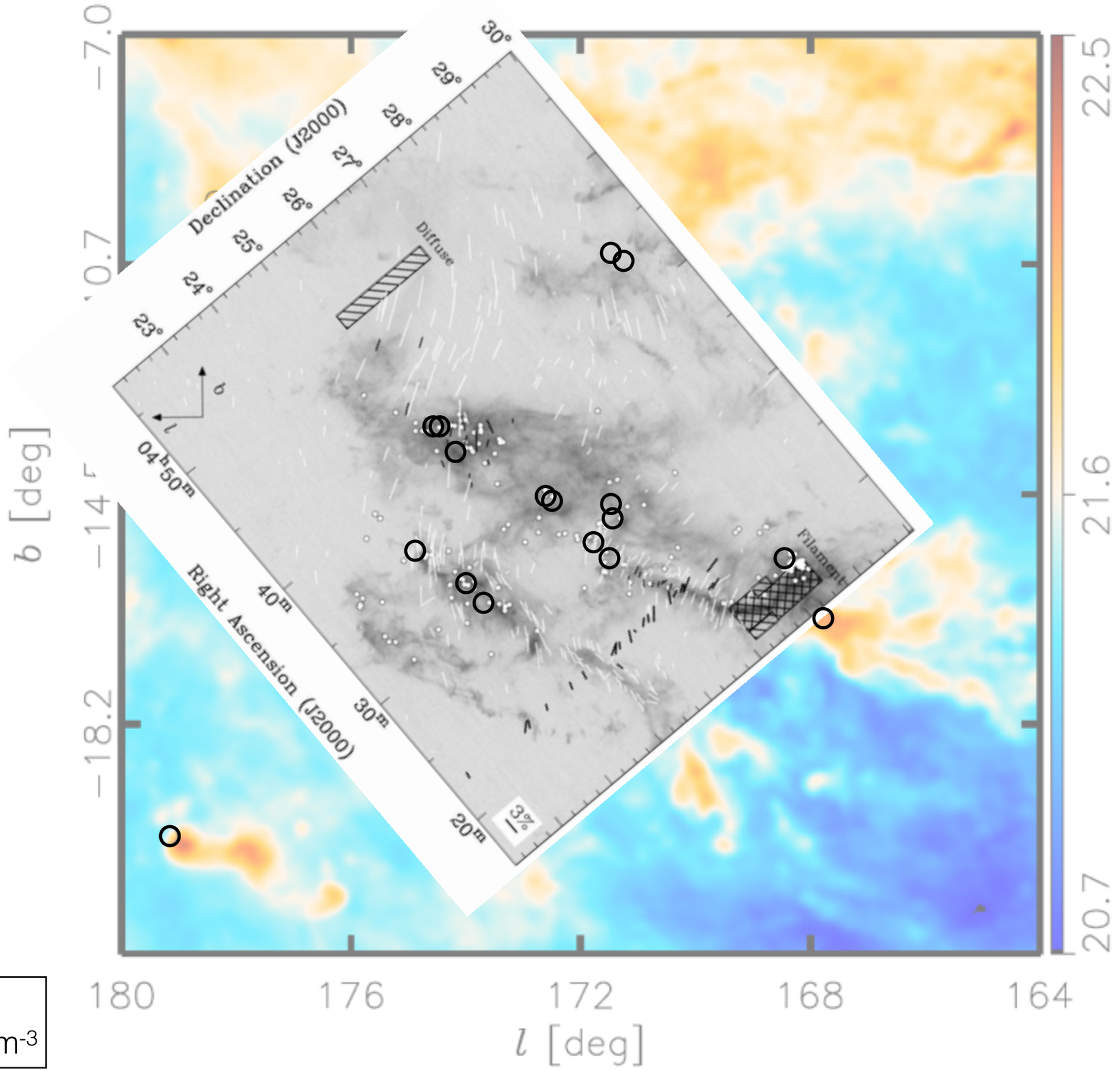


$\hat{B}_{\perp}$ →



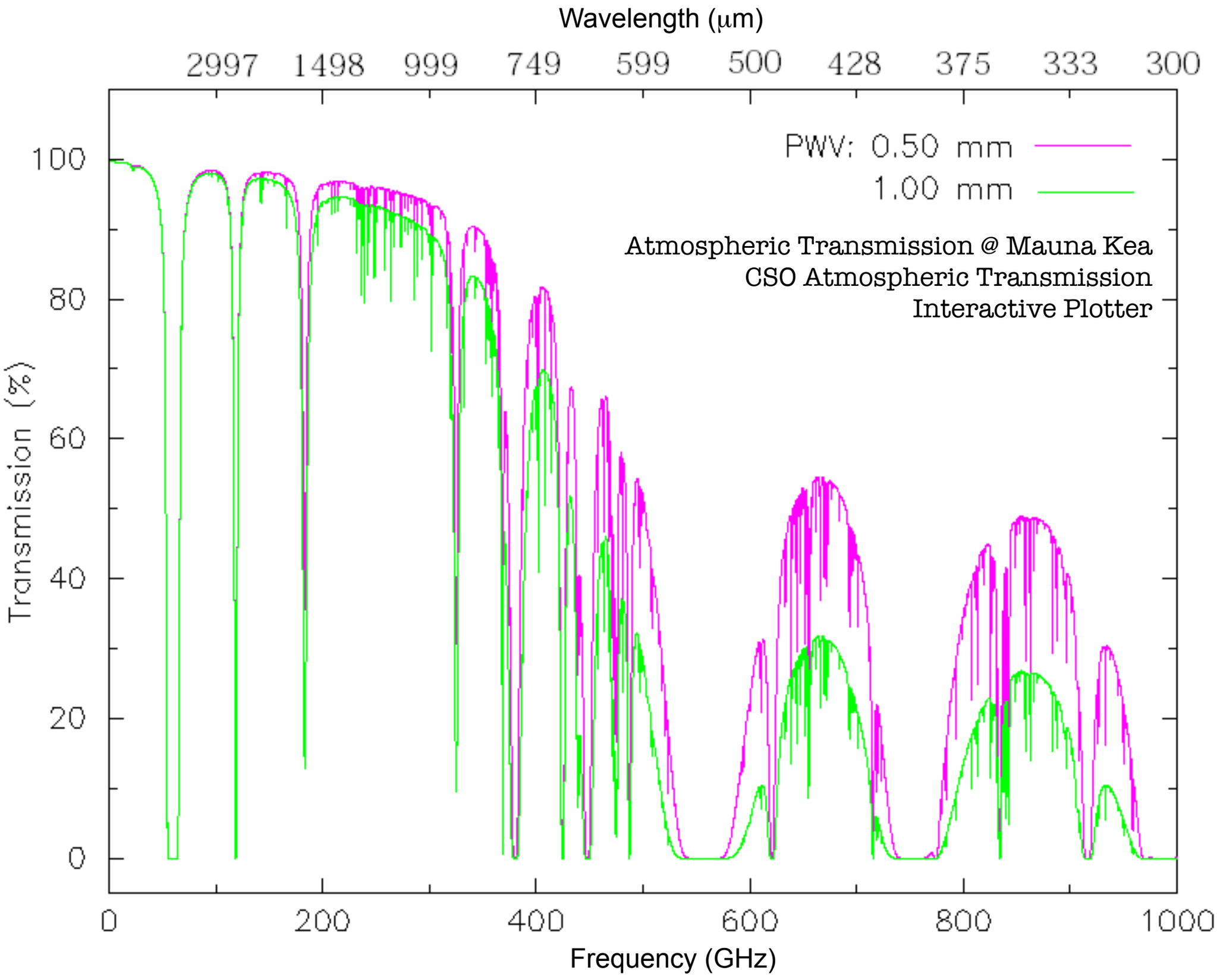
OH
10^3 to 10^4 cm^{-3}

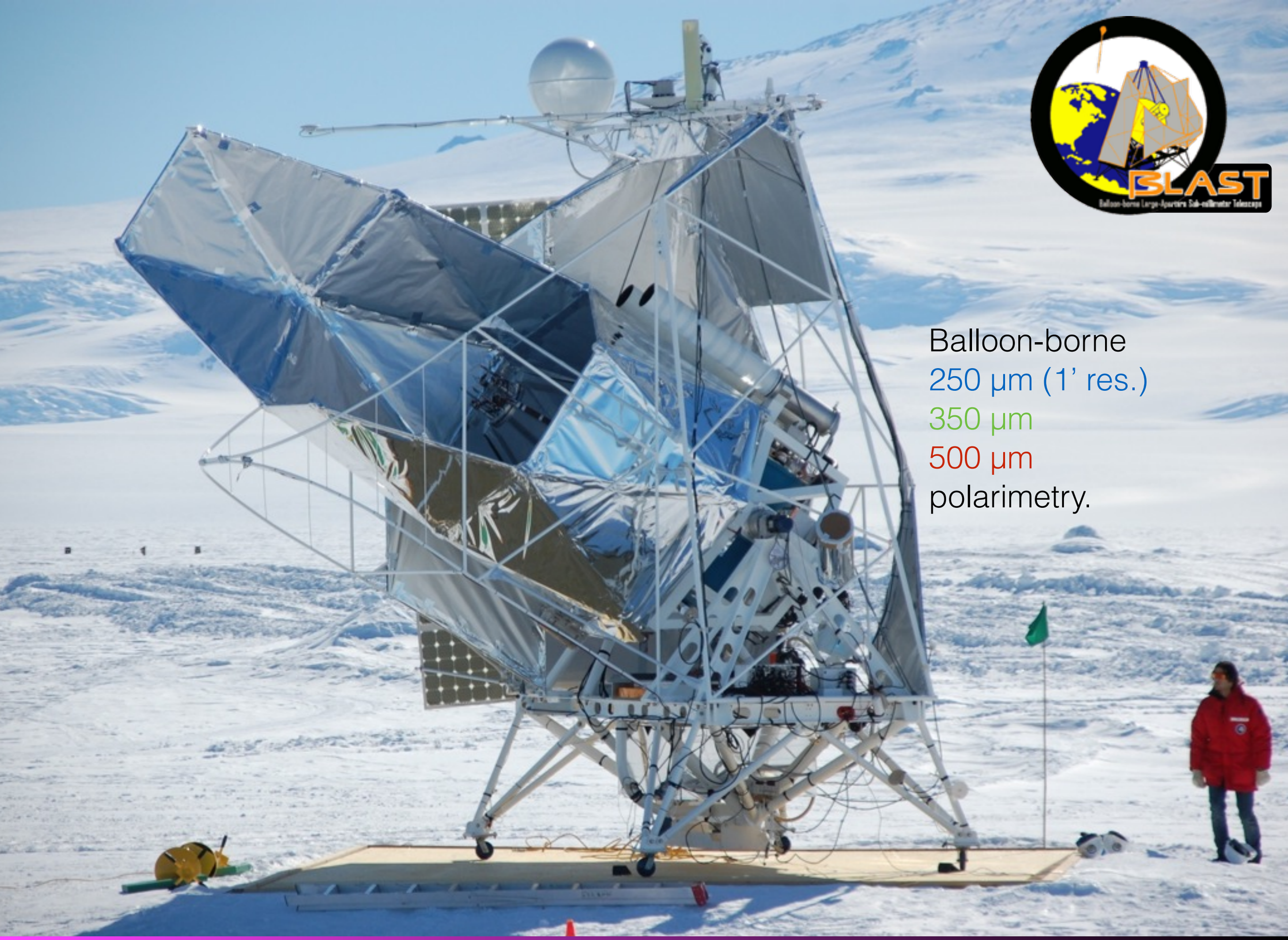
Zeeman OH observations courtesy of T. Troland



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

Zeeman OH observations courtesy of T. Troland


Wavelength (μm)
2997
1498
999
749
599
500
428
375
333
300
PWV: 0.50 mm
1.00 mm
Atmospheric Transmission @ Mauna Kea
CSO Atmospheric Transmission
Interactive Plotter
Transmission (%)
100
80
60
40
20
0
0
200
400
600
800
1000
Frequency (GHz)


BLAST
Balloon-borne
250 μm (1’ res.)
350 μm
500 μm
polarimetry.

B-modes, jobs, and a chicken in every pot

Winter: Scheduled first flight
Palestine, TX

Spring: Scheduled first flight
Alice Springs, Australia

2008	2009	2010	2011	2012	2013	2014	2015

BICEP1 ends

Planck launch

BICEP2 begins

First cryogenic run
Princeton, NJ

BLASTPol first flight
McMurdo, Antarctica

Spider integration
Palestine, TX

BLASTPol first flight
McMurdo, Antarctica

US Congress
budget sequestration

Spider first flight
McMurdo, Antarctica

2008	2009	2010	2011	2012	2013	2014	2015

BICEP1 ends

Planck launch

BICEP2 begins

BICEP2
ends

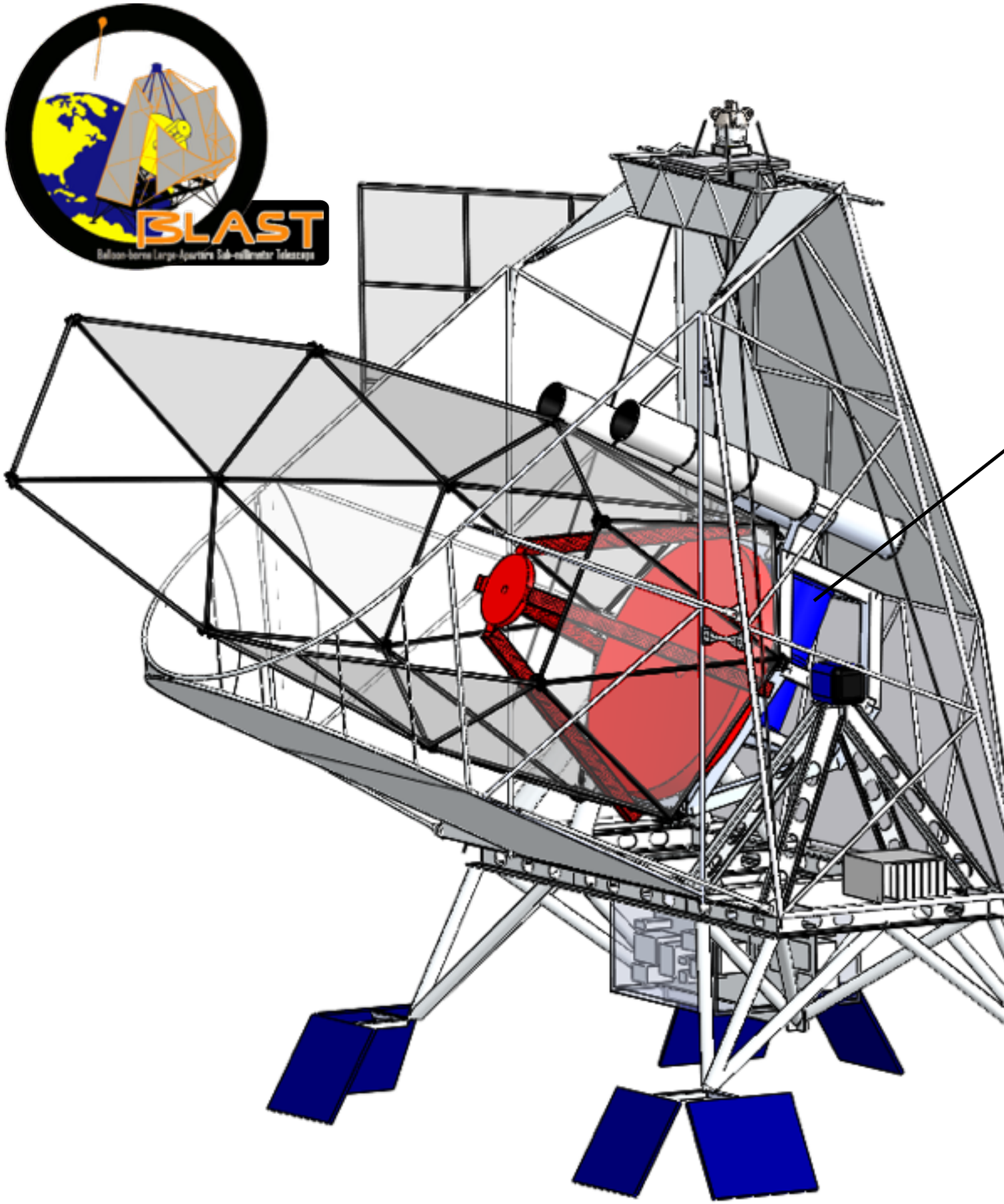
Planck runs out of ^{3}He

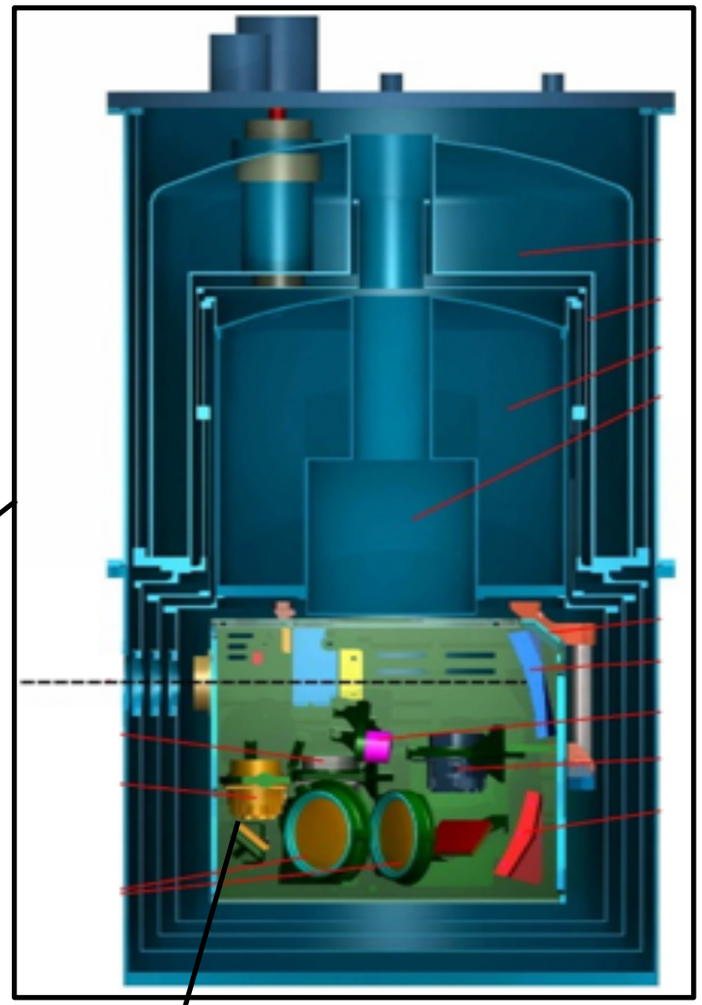
BICEP2
preprint

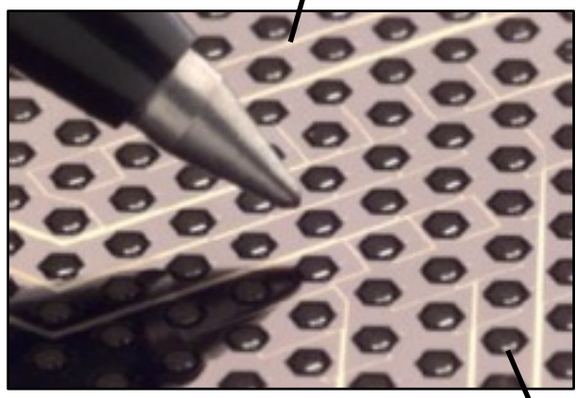
Planck XXX
preprint

B2/Planck MOU

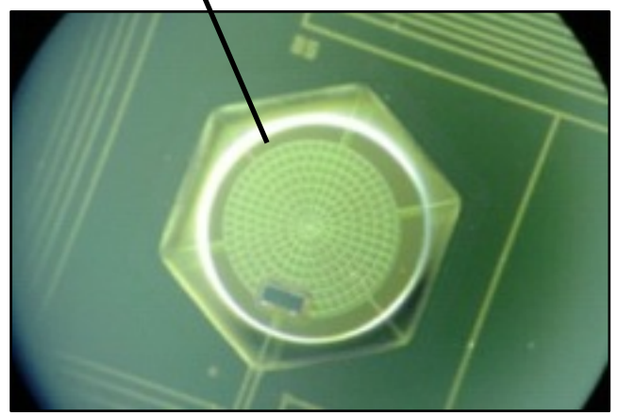
McMurdo, Antarctica. December 27, 2010





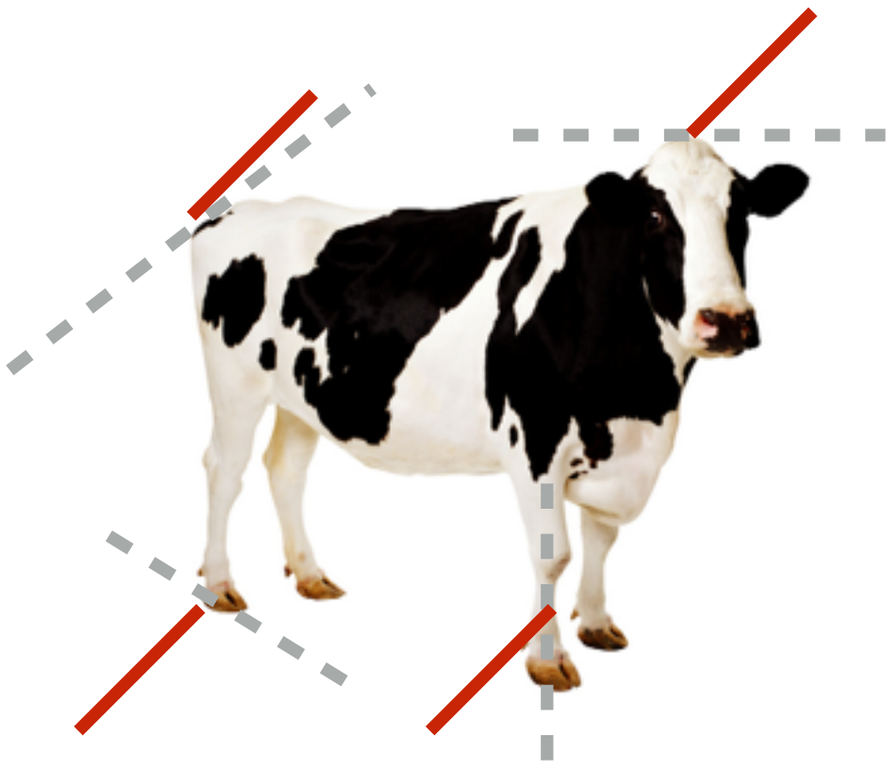


250 μm
350 μm
500 μm

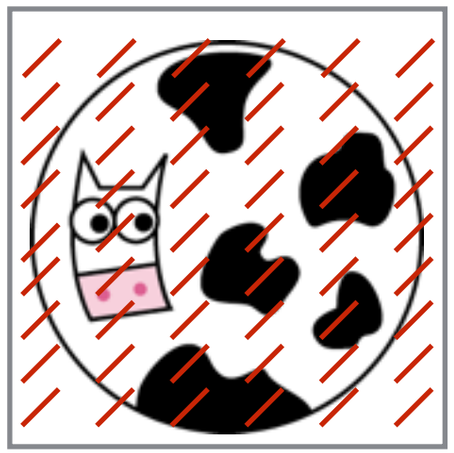


Observations

Relative orientation



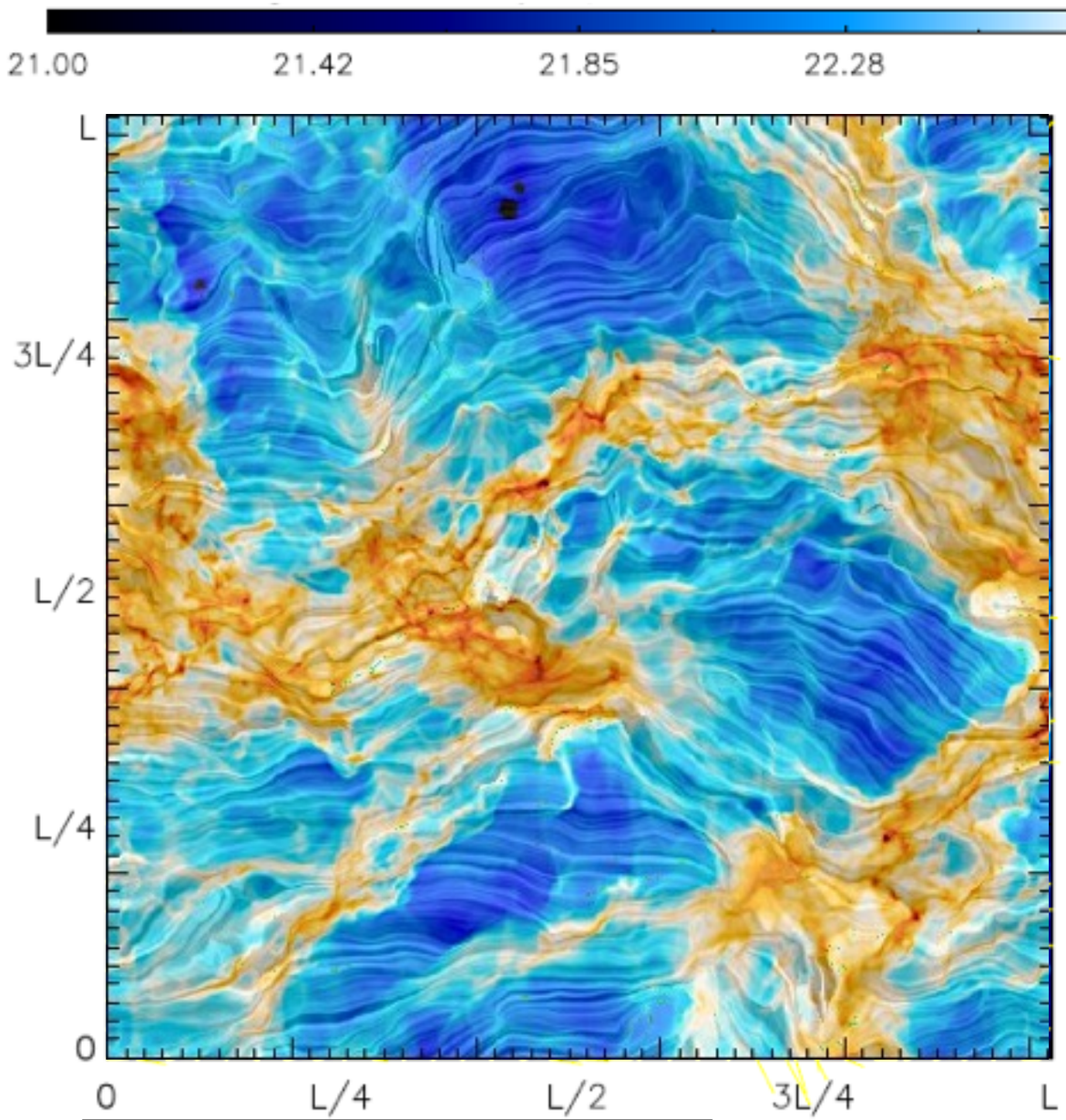
Simulations



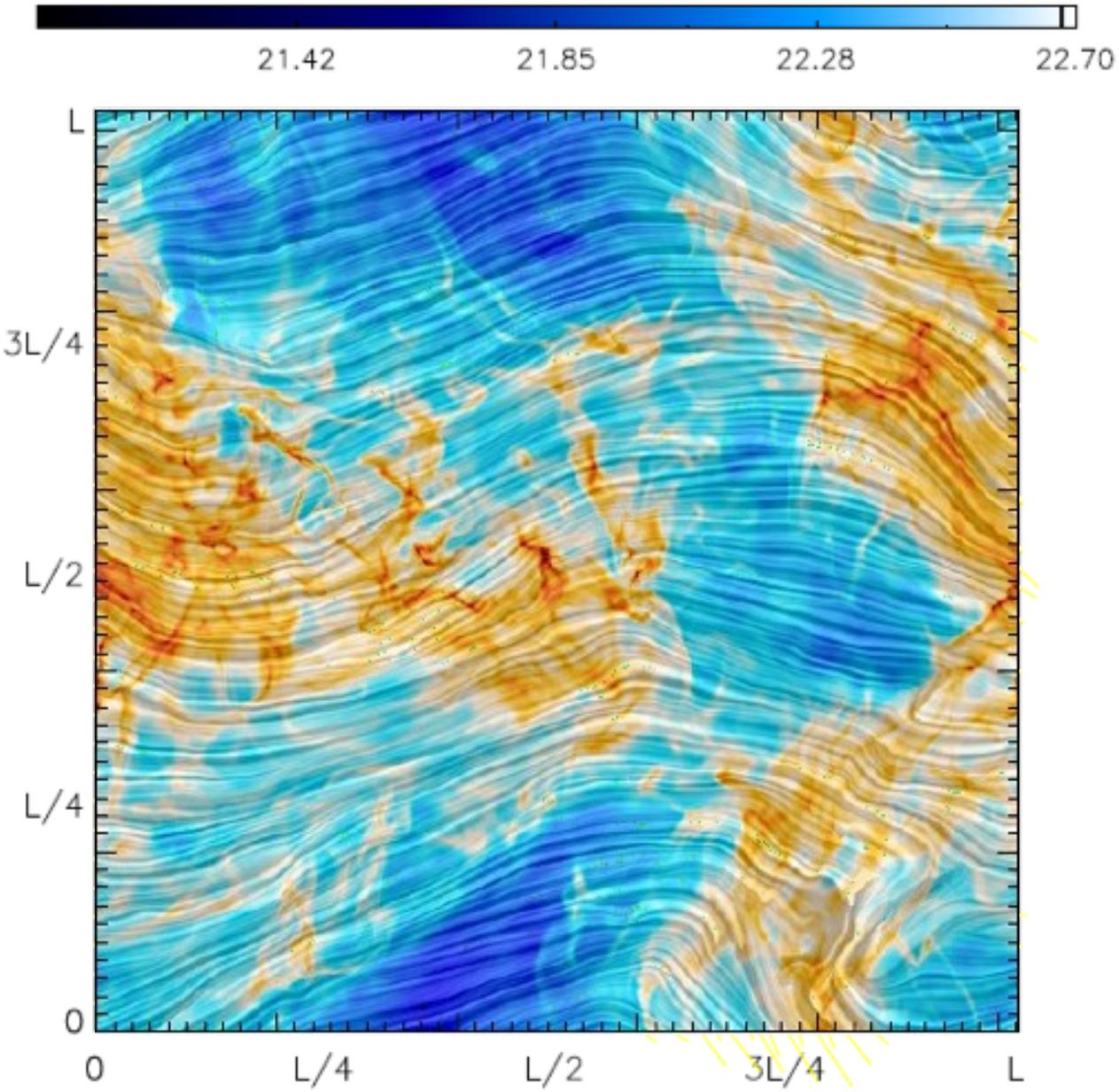
- Magnetic field
- Turbulence
- Gravity

Histogram of Relative Orientations

Weak magnetic field (β = 100.0)



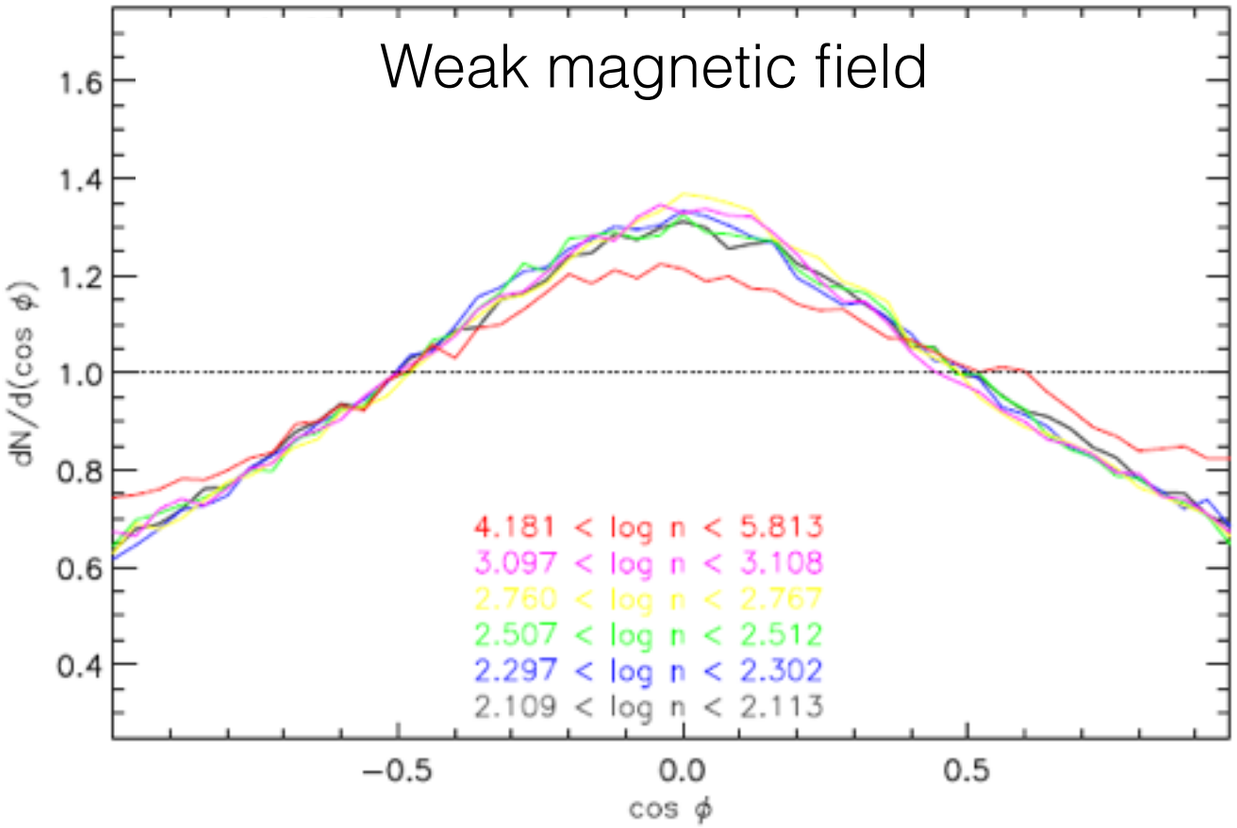
Strong magnetic field (β = 0.1)



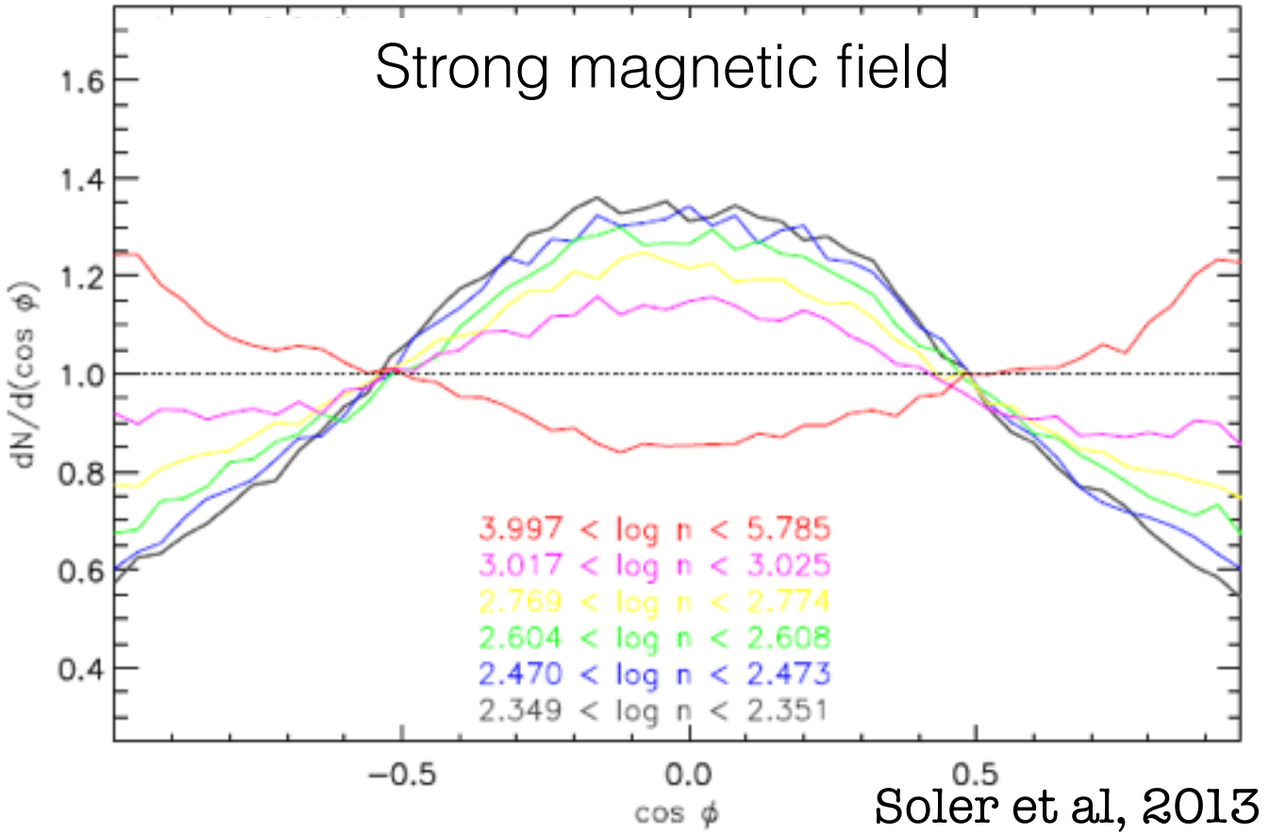
L = 4 pc (2^9 to 2^{11} resolution)
T = 11. 4 K
n_0 = 536.4 cm^{-3}
$\mathscr{M}$ = 10.0 (decaying)

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

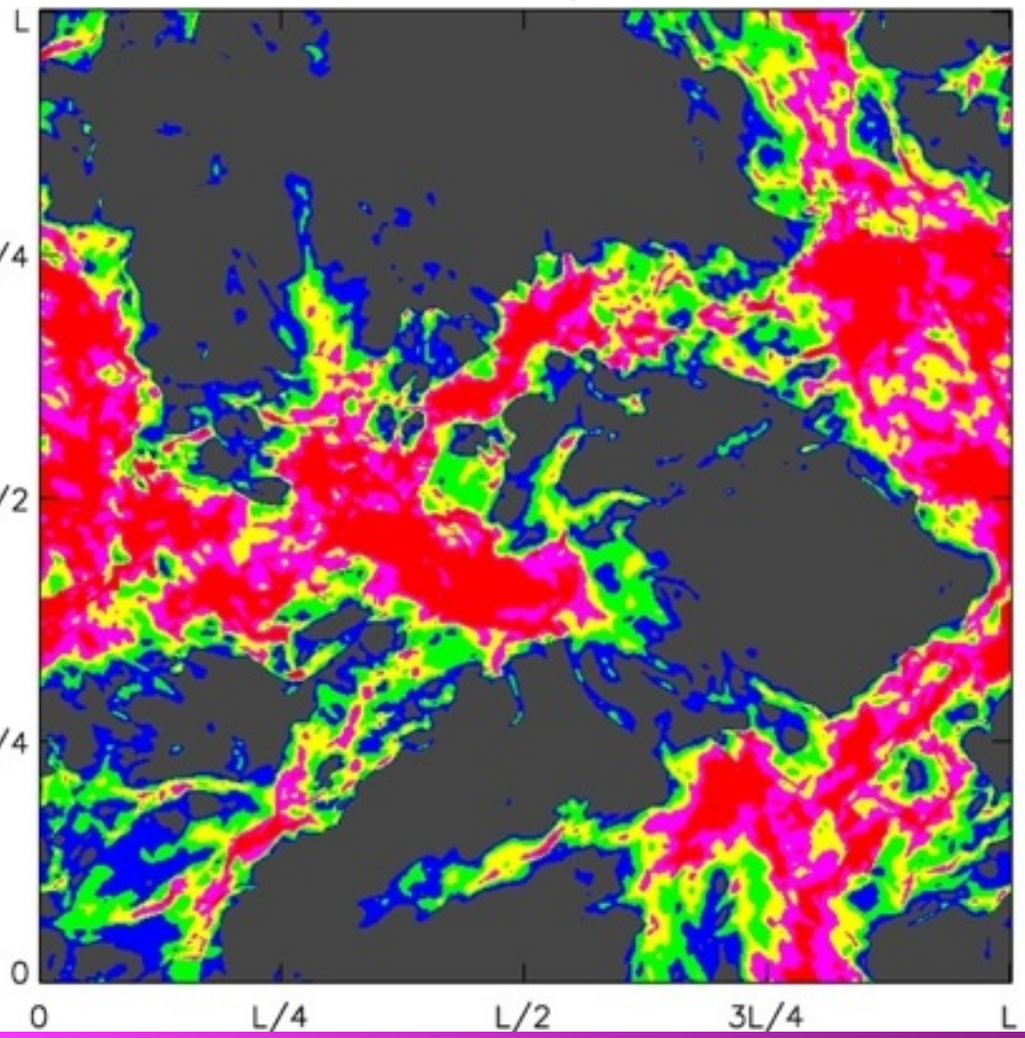
Weak magnetic field

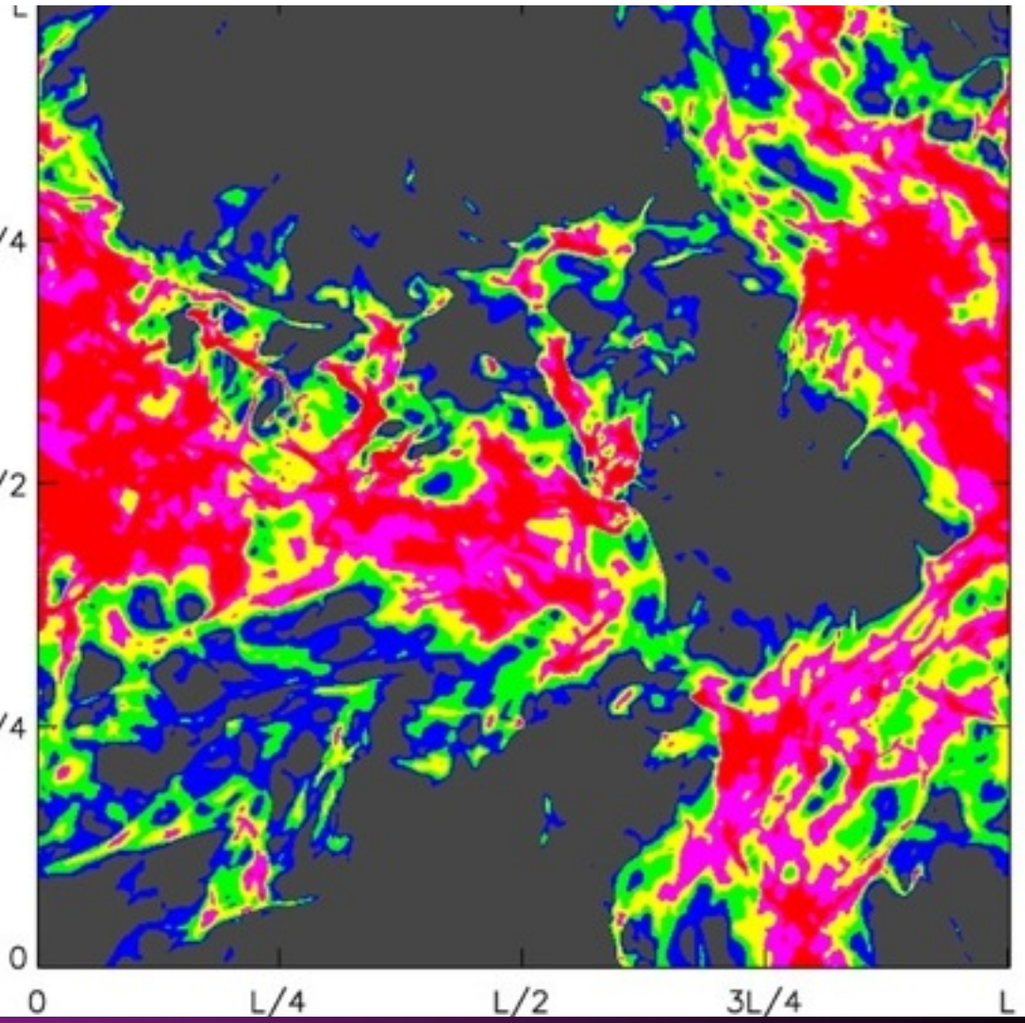


Strong magnetic field

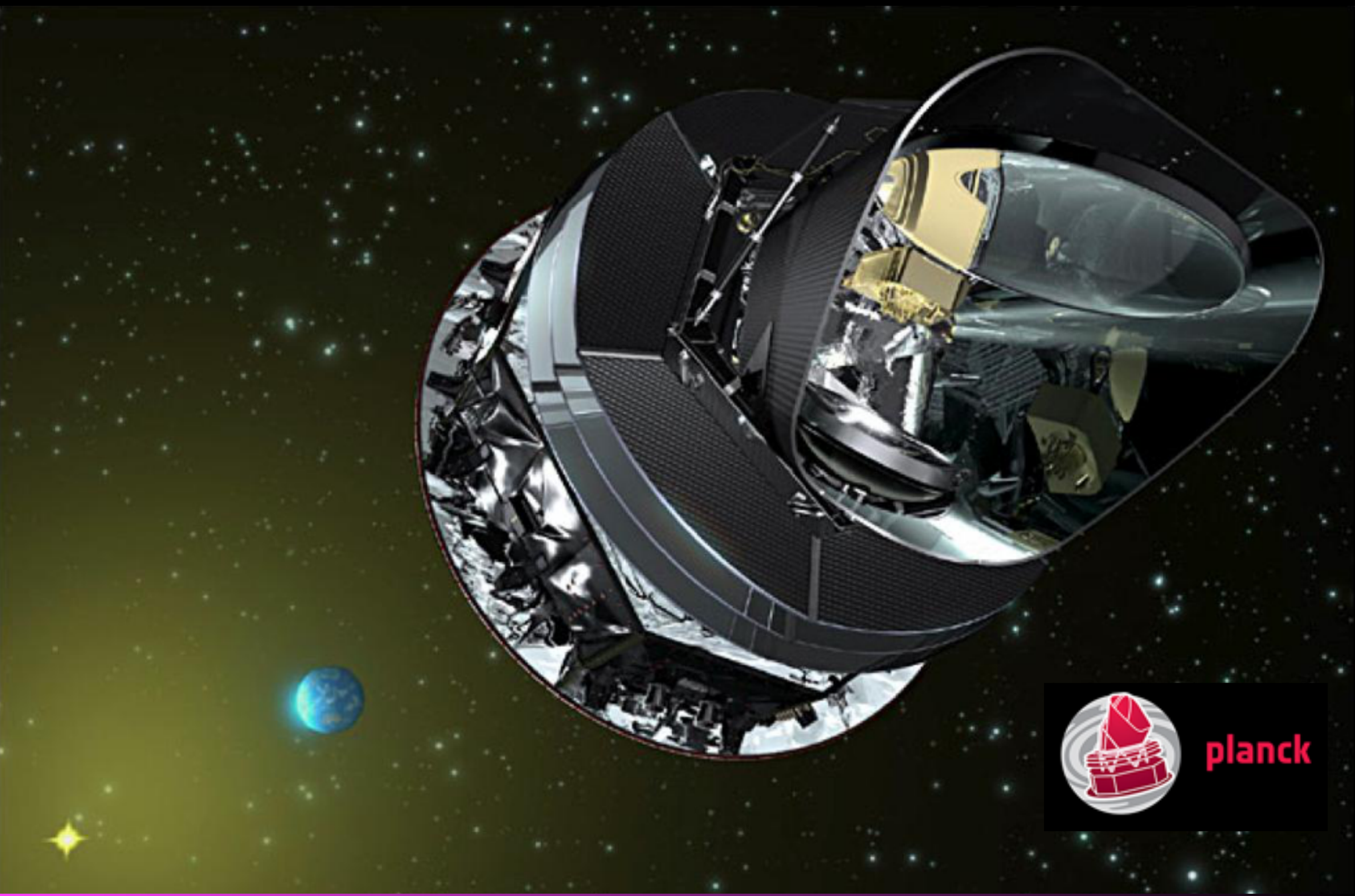


Soler et al, 2013





Juan D. Soler (CEA/Saclay). Jan. 2016


planck

esa

planck

cnes

agenzia spaziale italiana

HFI PLANCK

PLANCK LFI

NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

CSIC

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

IAS orsay

IAP

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

CSA ASC

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

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

Aalto University

ioa

KICC Kavli Institute for Cosmology Cambridge

Cavendish Astrophysics

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

irfu
saclay

cea

CESR

CITA–ICAT

cnrs IN2P3 Les deux infinis

ipac Infrared Processing and Analysis Center

HELSINKI INSTITUTE OF PHYSICS

IFCA

Imperial College London

UNIVERSITÀ DEGLI STUDI DI MILANO

NÉEL institut

IPAG

ISDC

JPL

LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

l'Observatoire de Paris LERMA

LPSC Grenoble

MilliLab

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF OSSERVATORIO ASTRONOMICO DI PADOVA

SAPIENZA Università di Roma

Science & Technology Facilities Council
Rutherford Appleton Laboratory

UBC

UC UNIVERSIDAD DE CANTABRIA

UCSB

SISSA

ALMA

ESO

US University of Sussex

esa

UNIVERSITY OF HELSINKI

UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

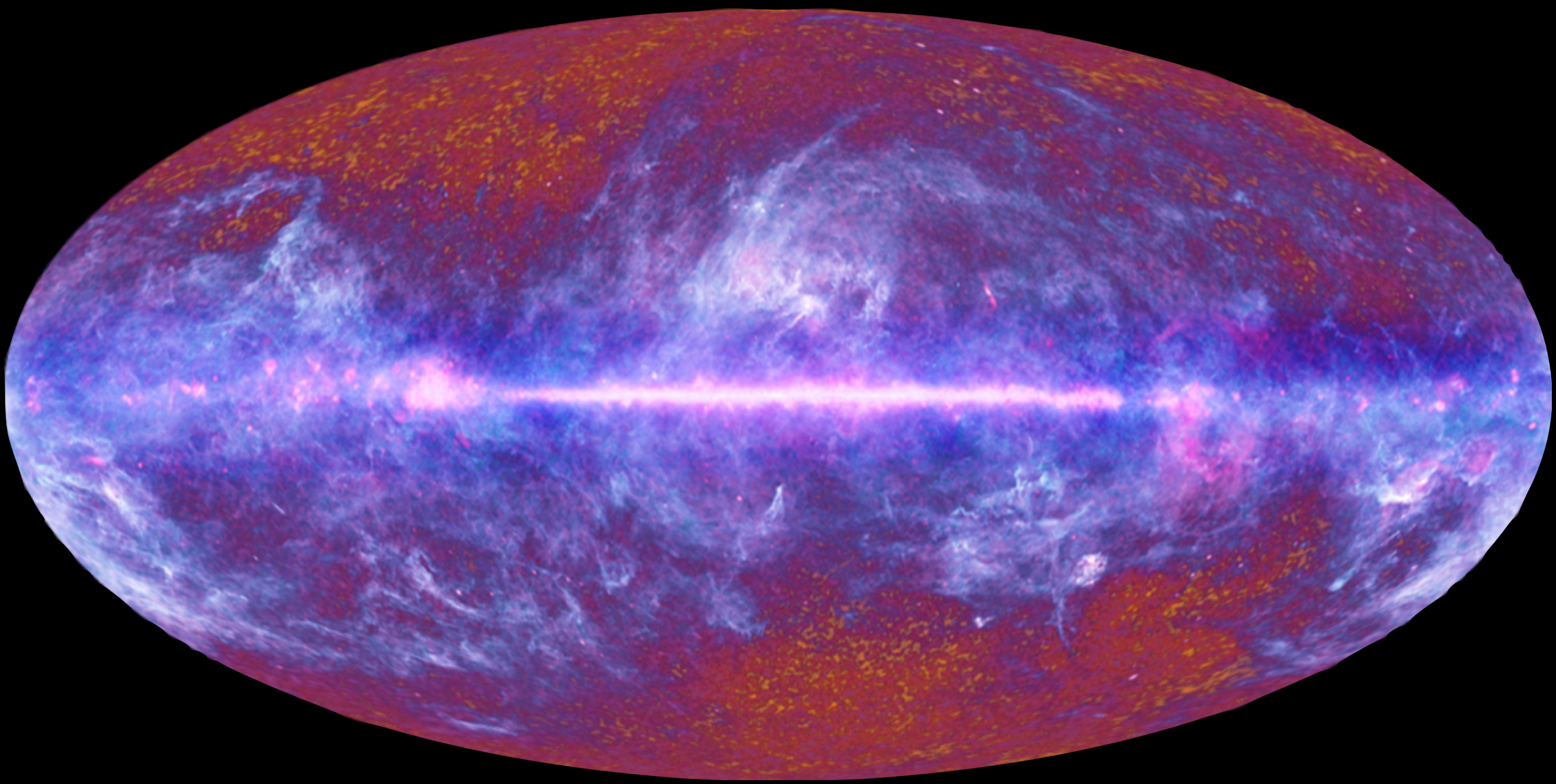
UNIVERSITÉ DE PARIS-SUD XI

asdc

Juan D. Soler (CEA/Saclay). Jan. 2016

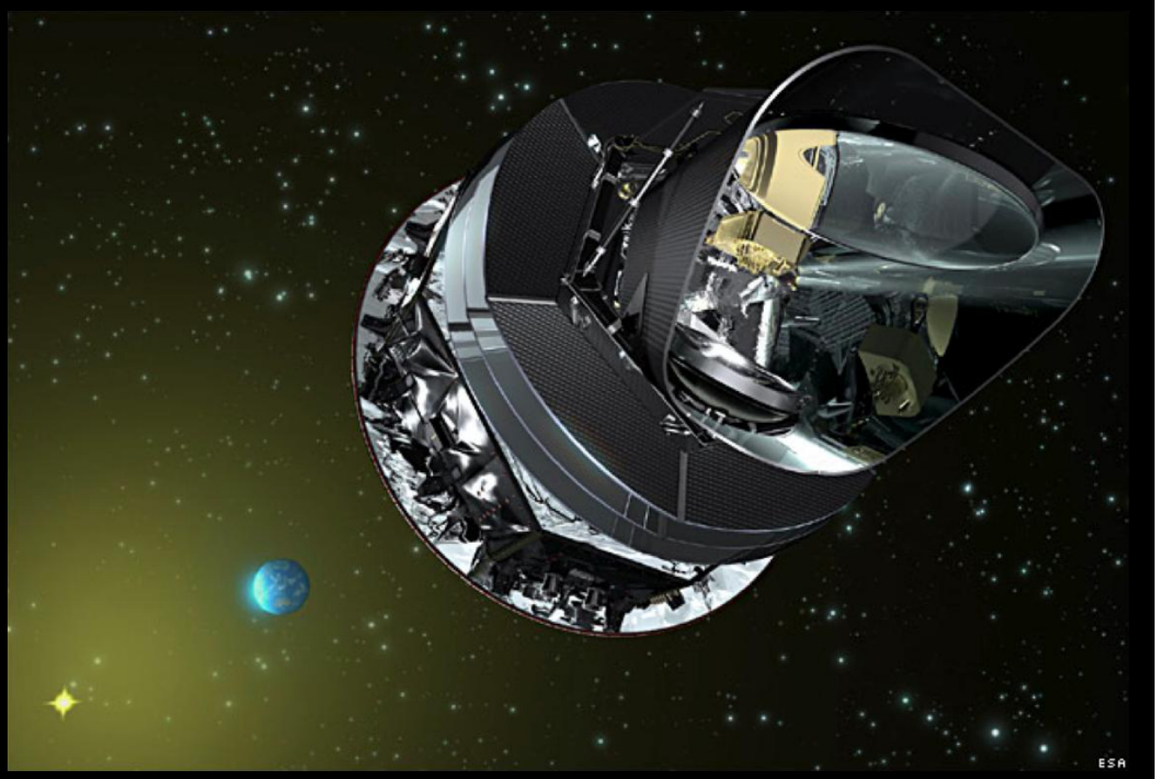
The foreground emission

30 GHz 40 GHz 70 GHz 100 GHz 143 GHz 217 GHz 353 GHz 545 GHz 857 GHz

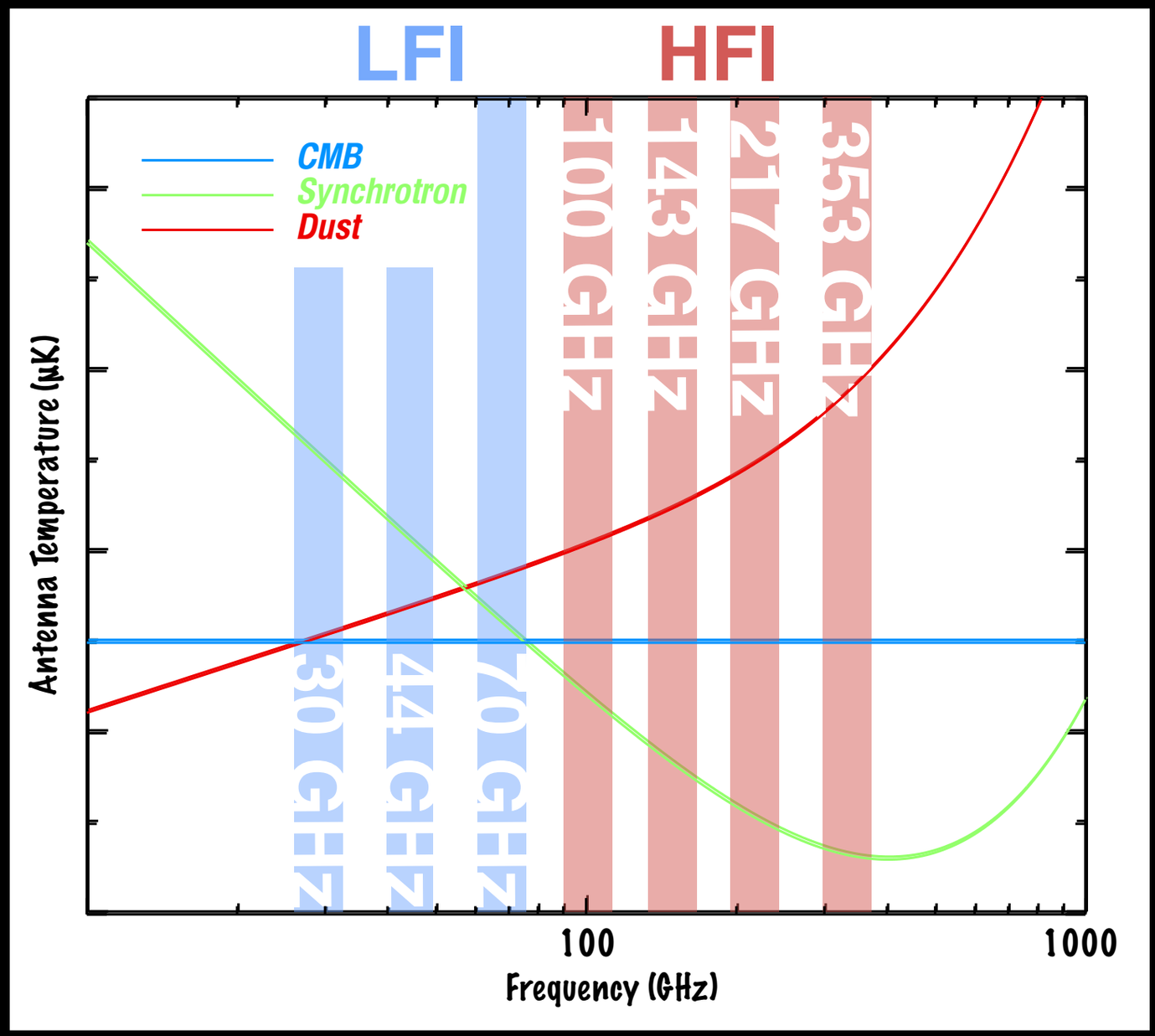


[Planck Collaboration 2011]

The polarized sky as seen by Planck

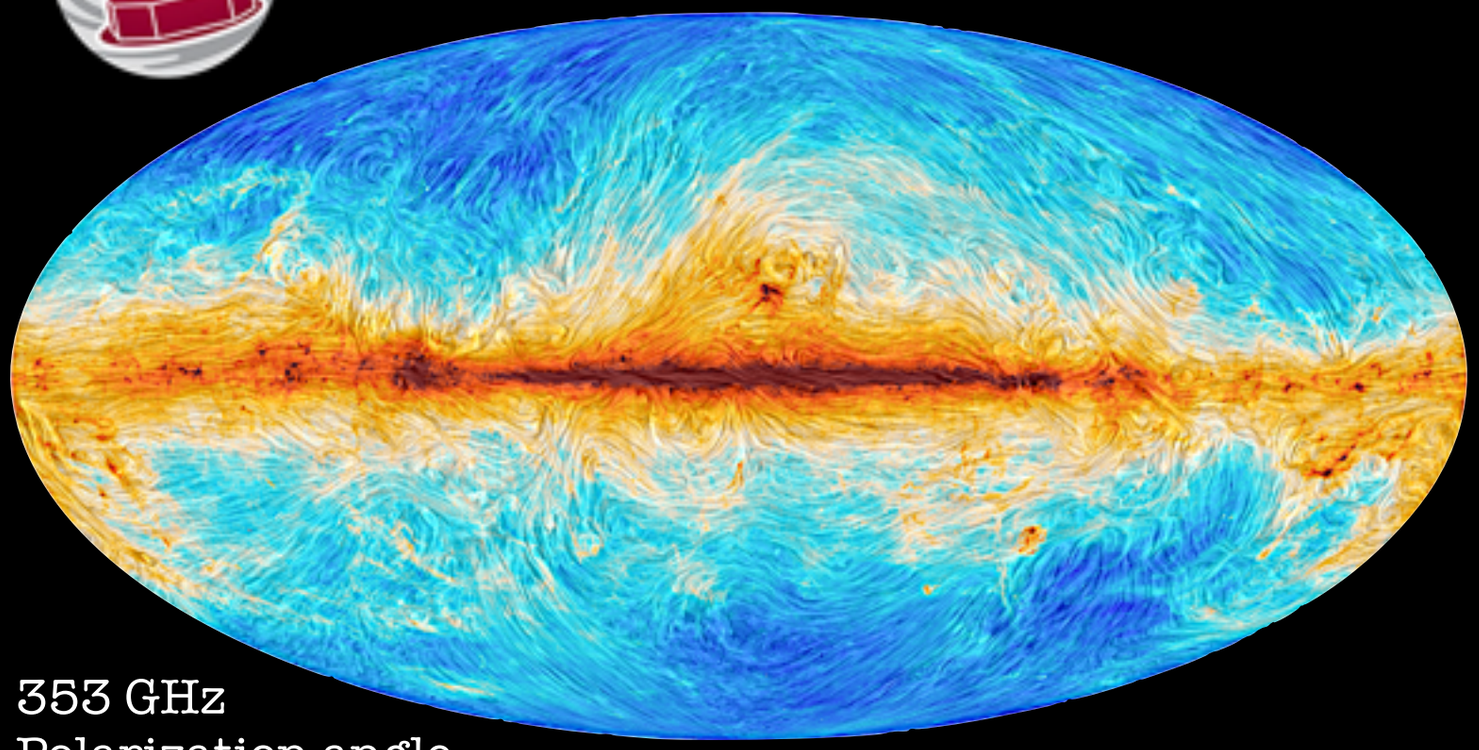


planck

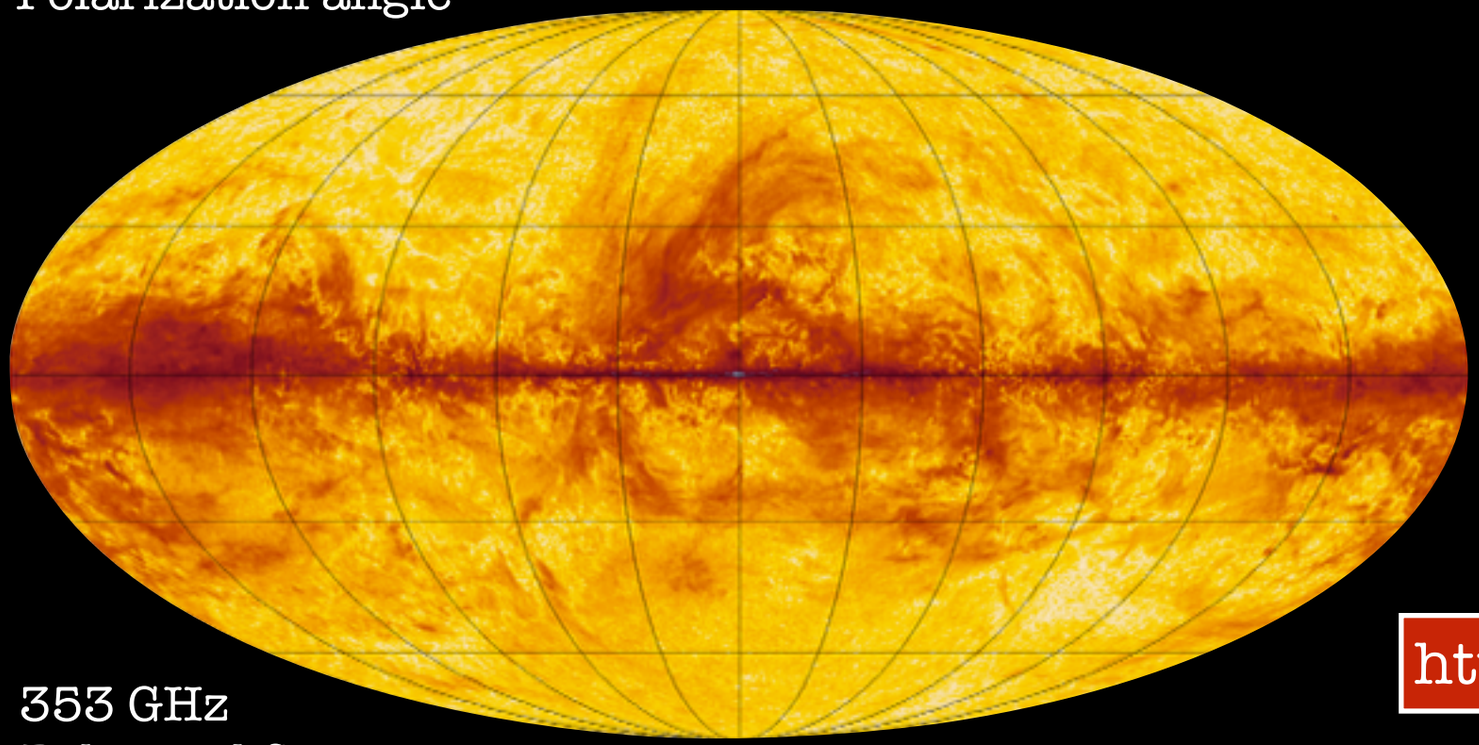


Planck 2015 results. I. Overview of products and results

Magnetic field and polarization statistics



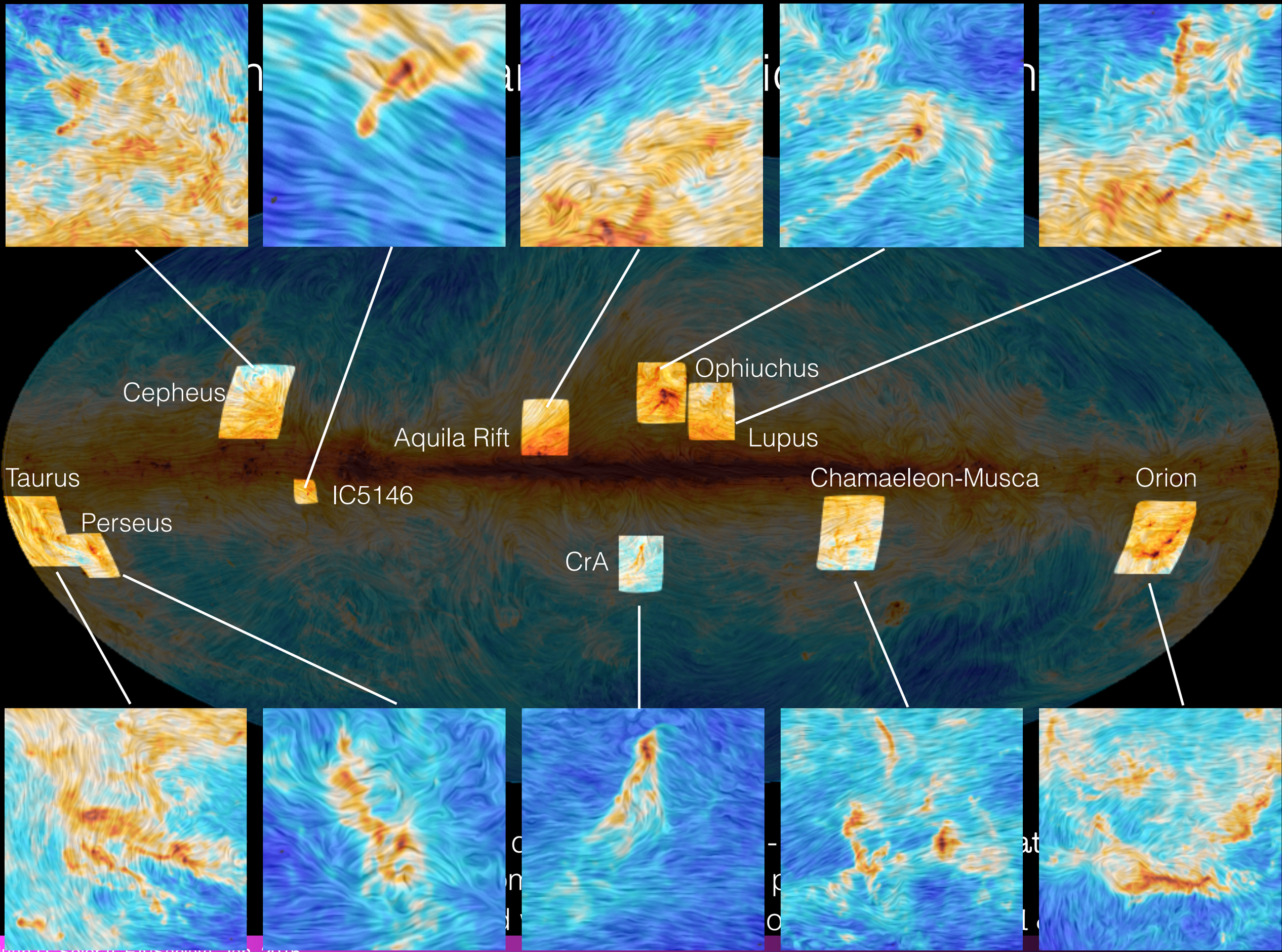
353 GHz
Polarization angle



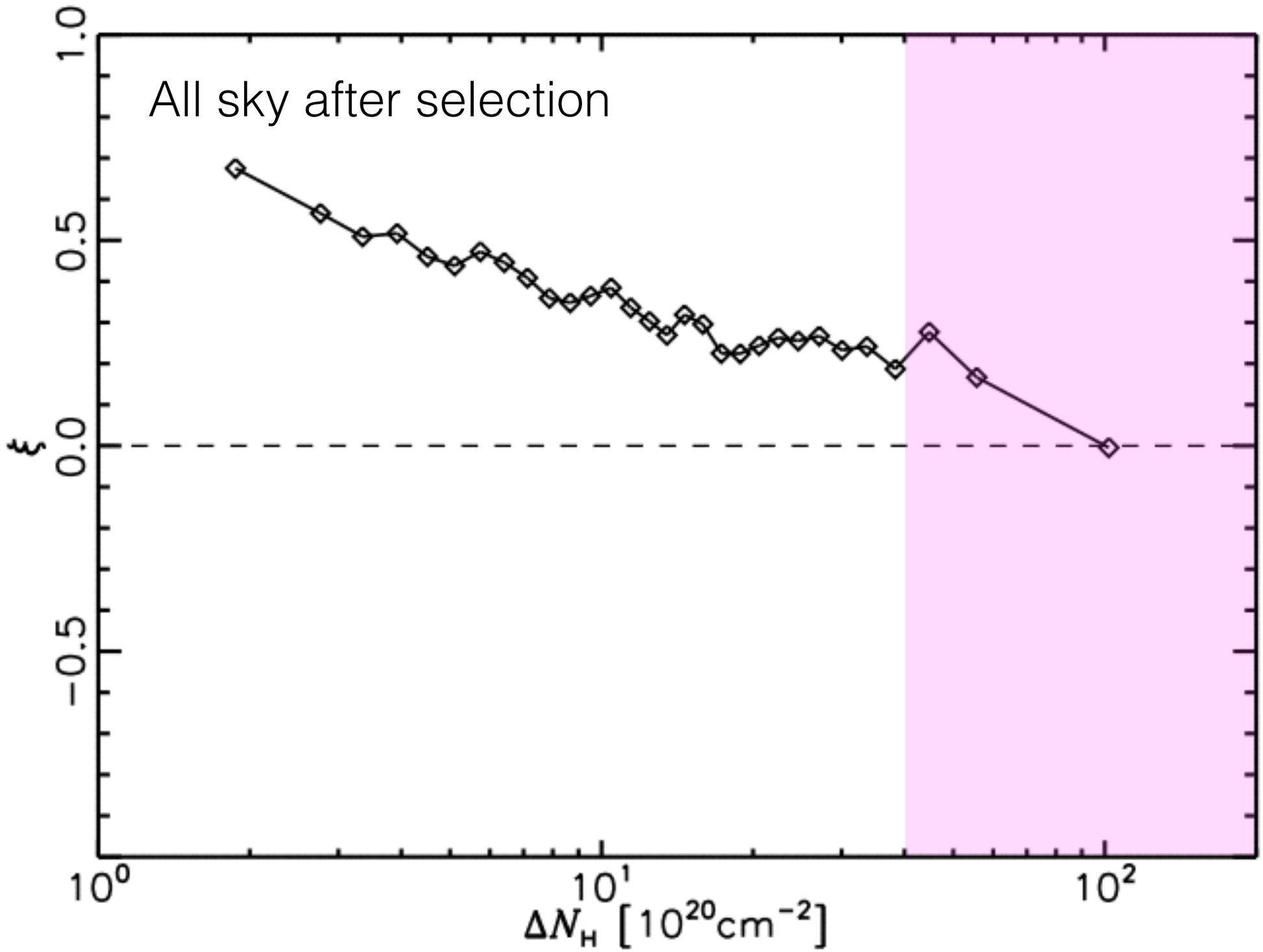
353 GHz
Polarized flux

- 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

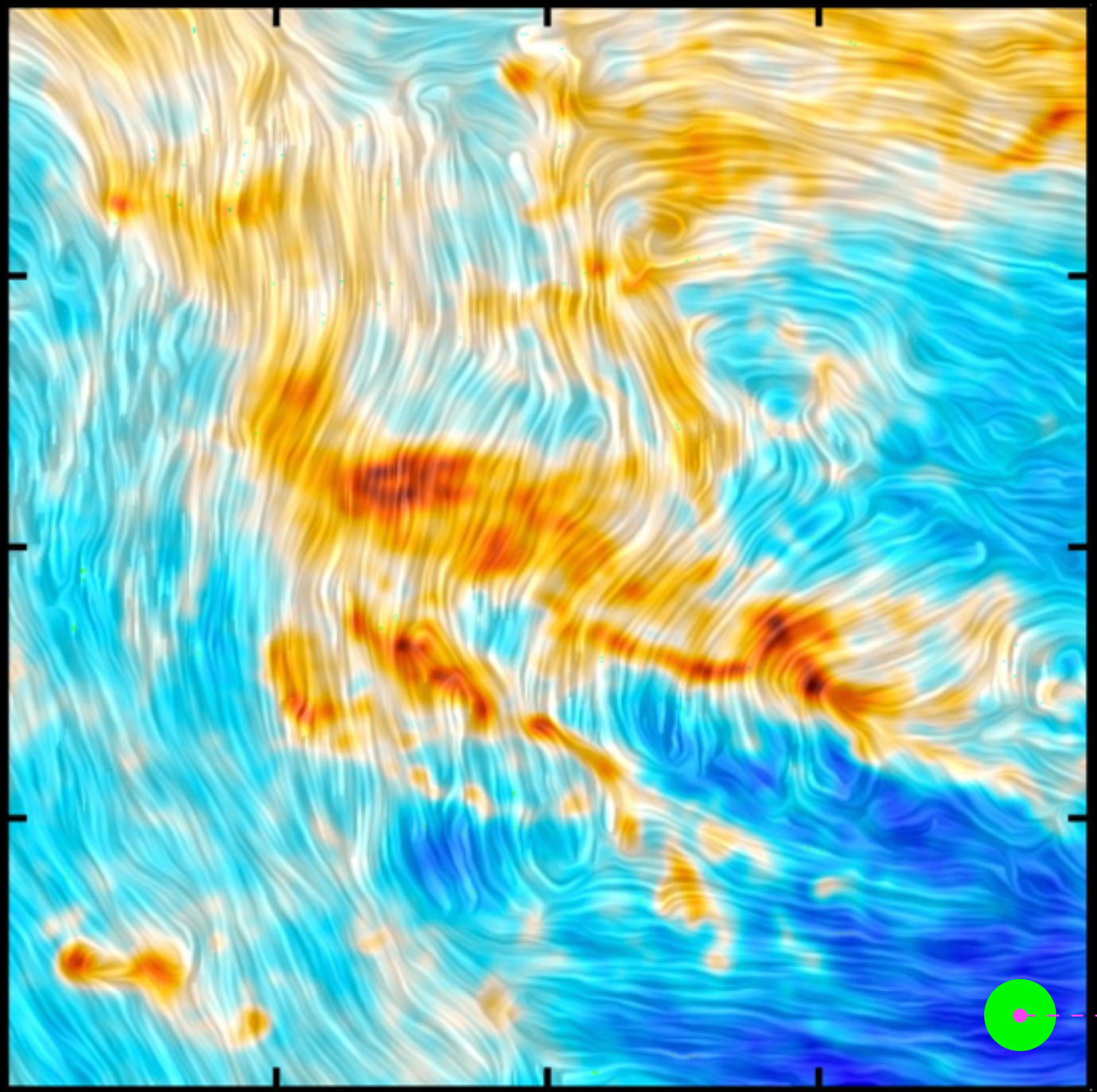

Cepheus
Aquila Rift
Ophiuchus
Lupus
Taurus
IC5146
Perseus
CrA
Chamaeleon-Musca
Orion

Relative Orientations



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

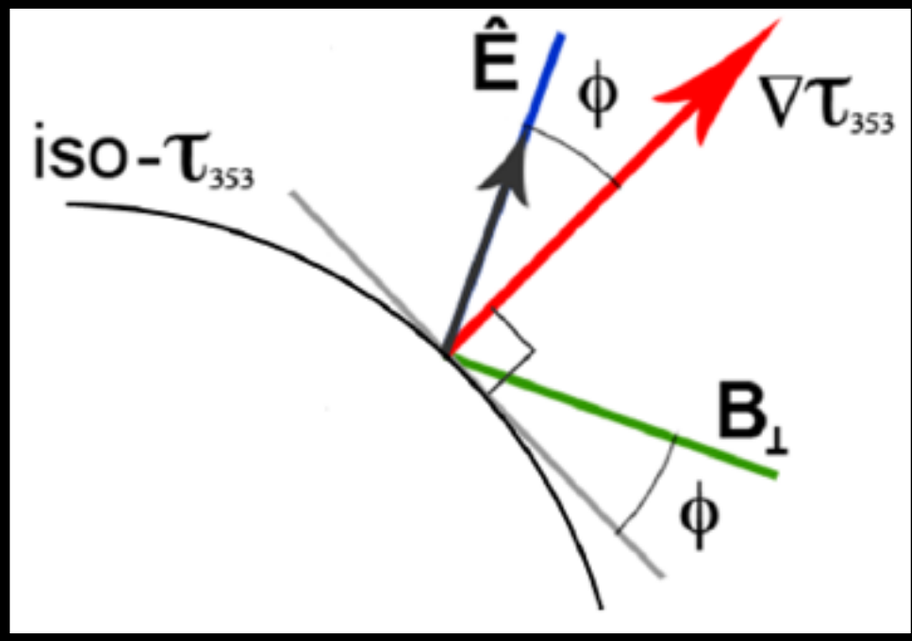
Relative Orientations



16 deg (40 pc @ d=140 pc)

Taurus region

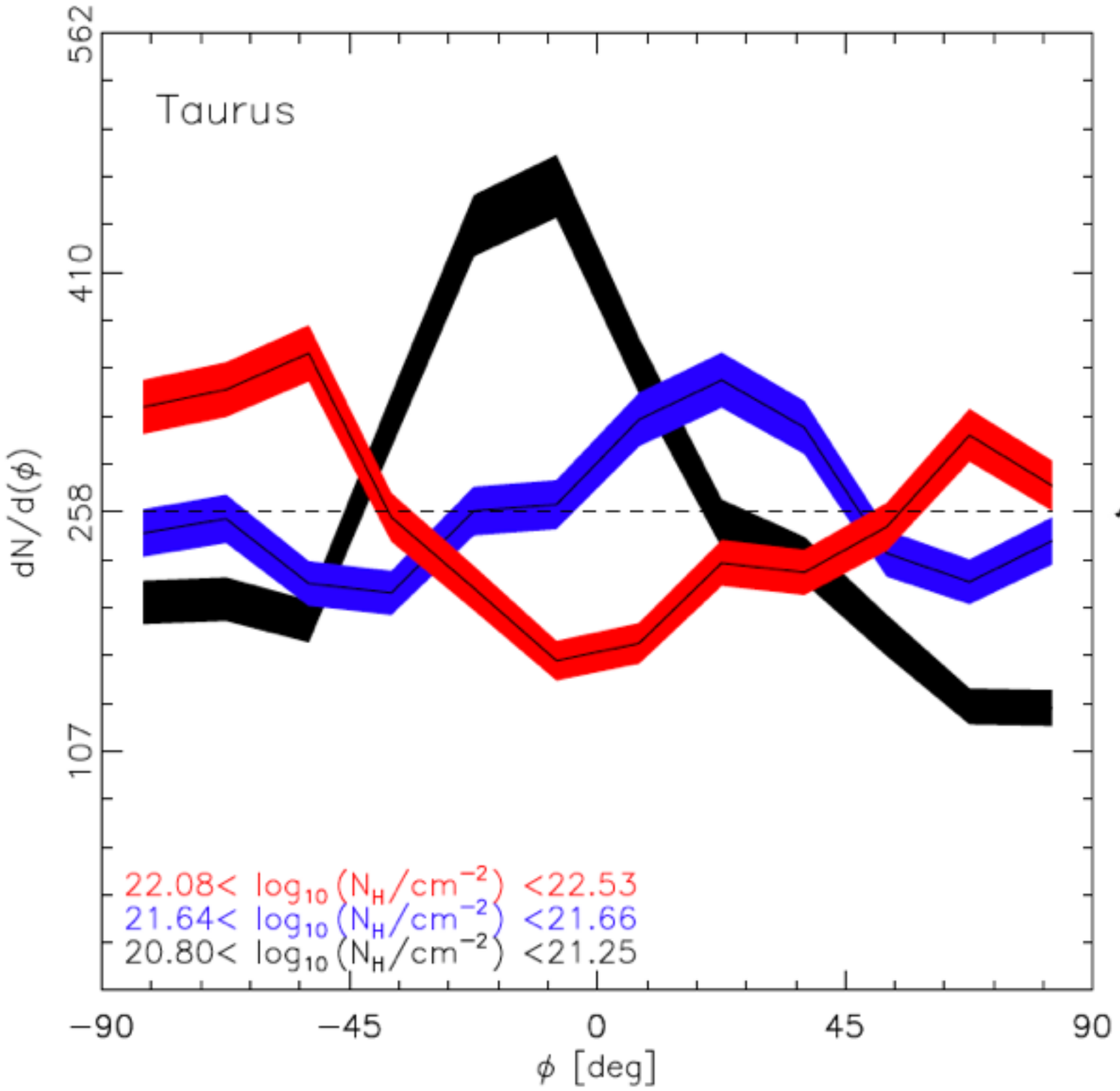
- N_H from dust optical depth
- $\mathbf{B}_\perp$ from Planck 353 GHz pol.



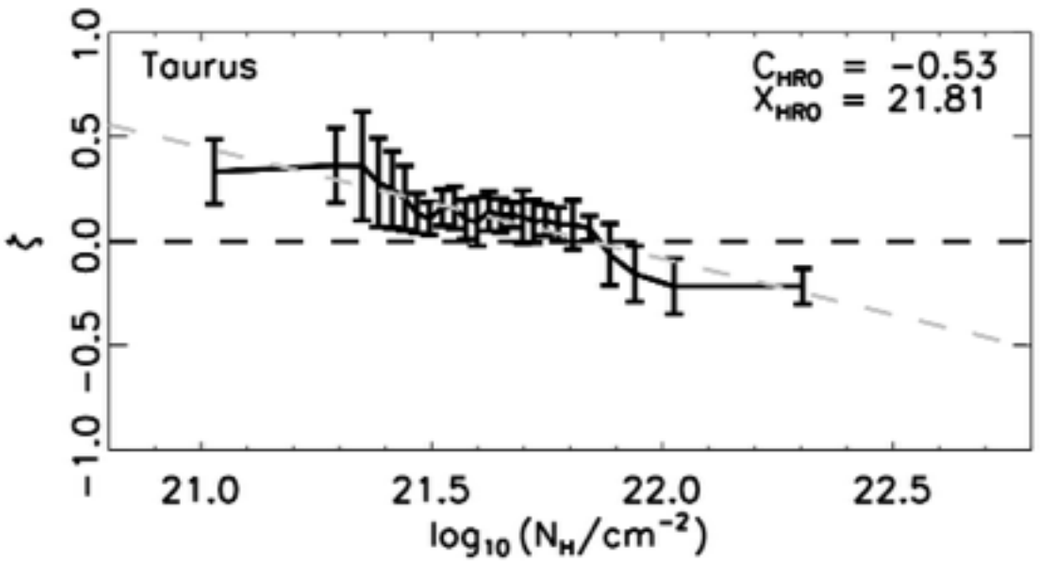
10’ FWHM (0.4 pc @ d=140 pc)

Planck intermediate results. XXXV

Histogram of Relative Orientations

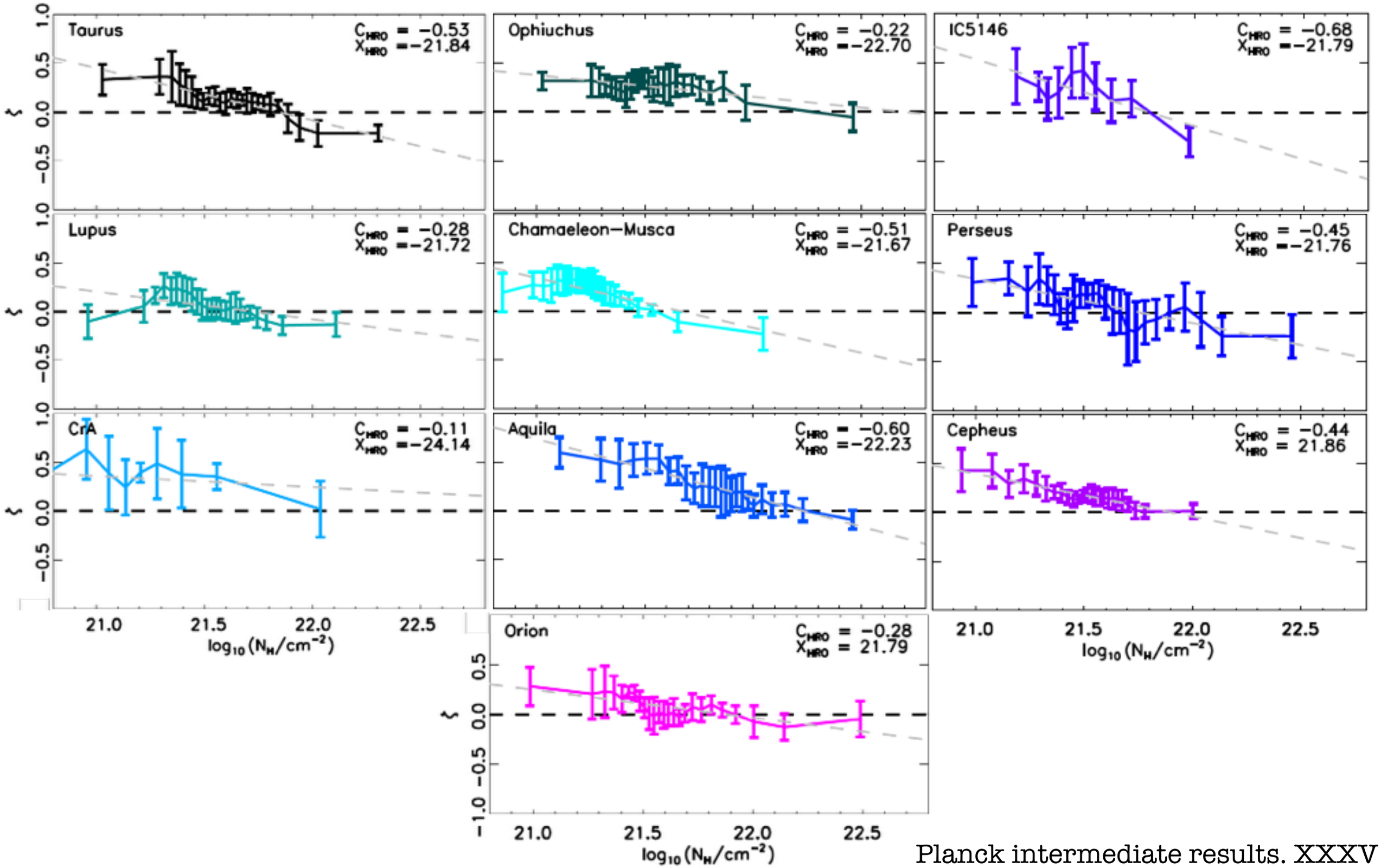


$$\zeta = \frac{A_c - A_e}{A_c + A_e}$$



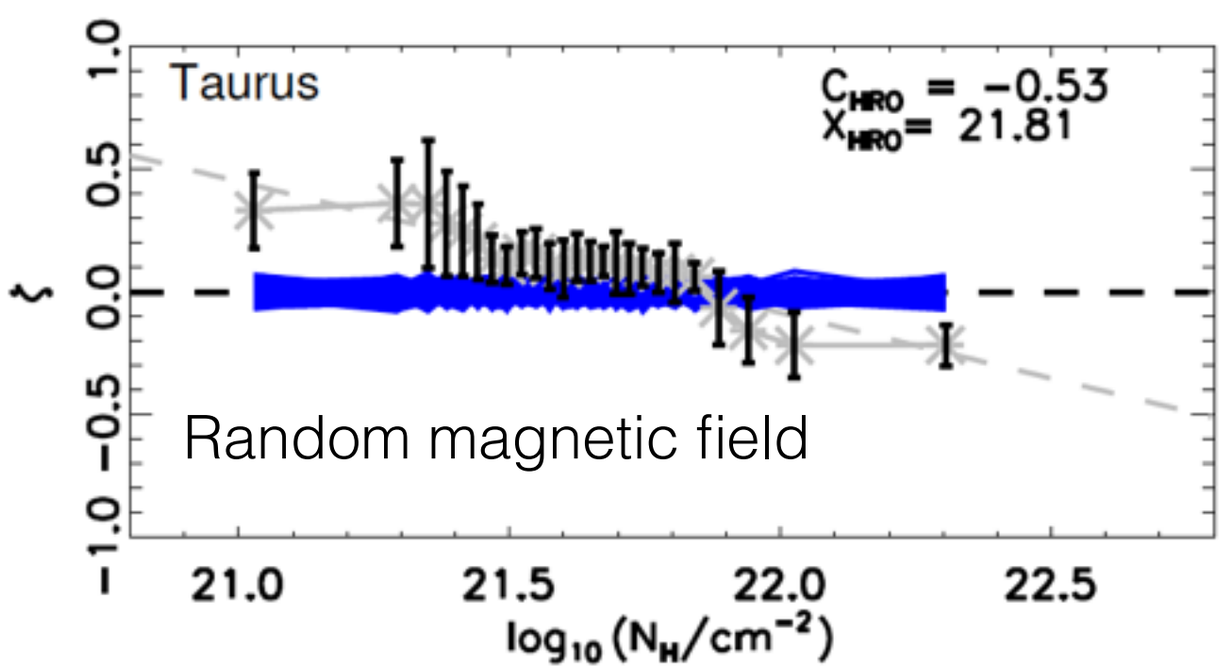
Planck intermediate results. XXXV

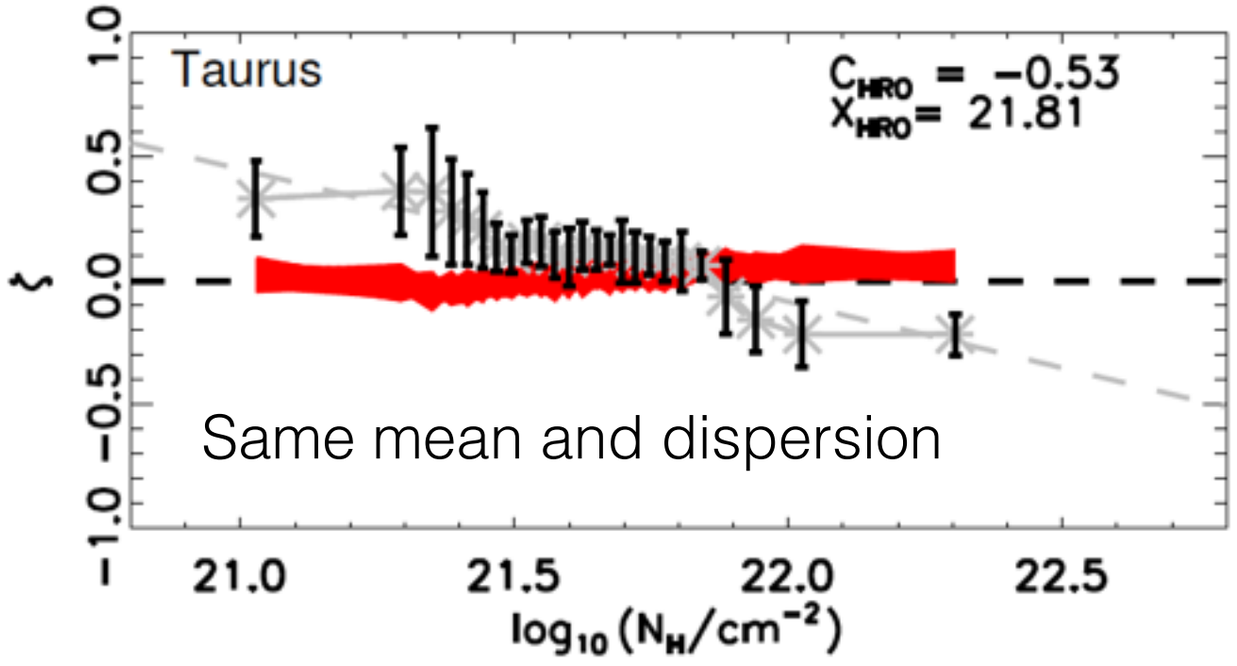
Relative Orientations

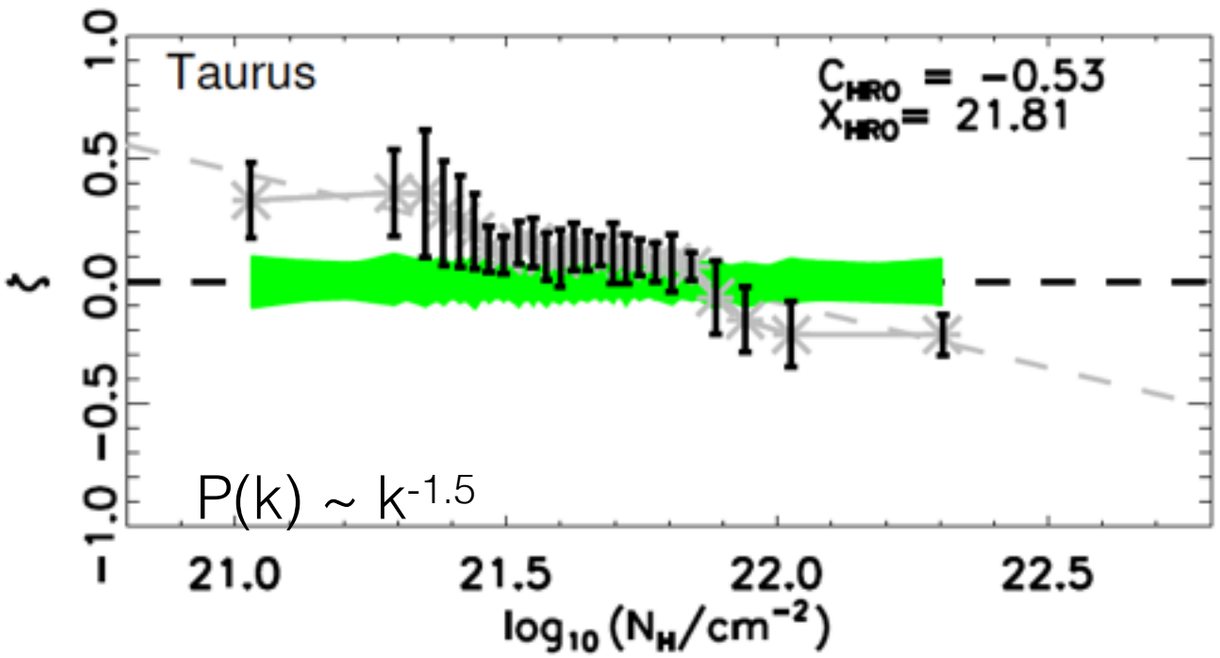


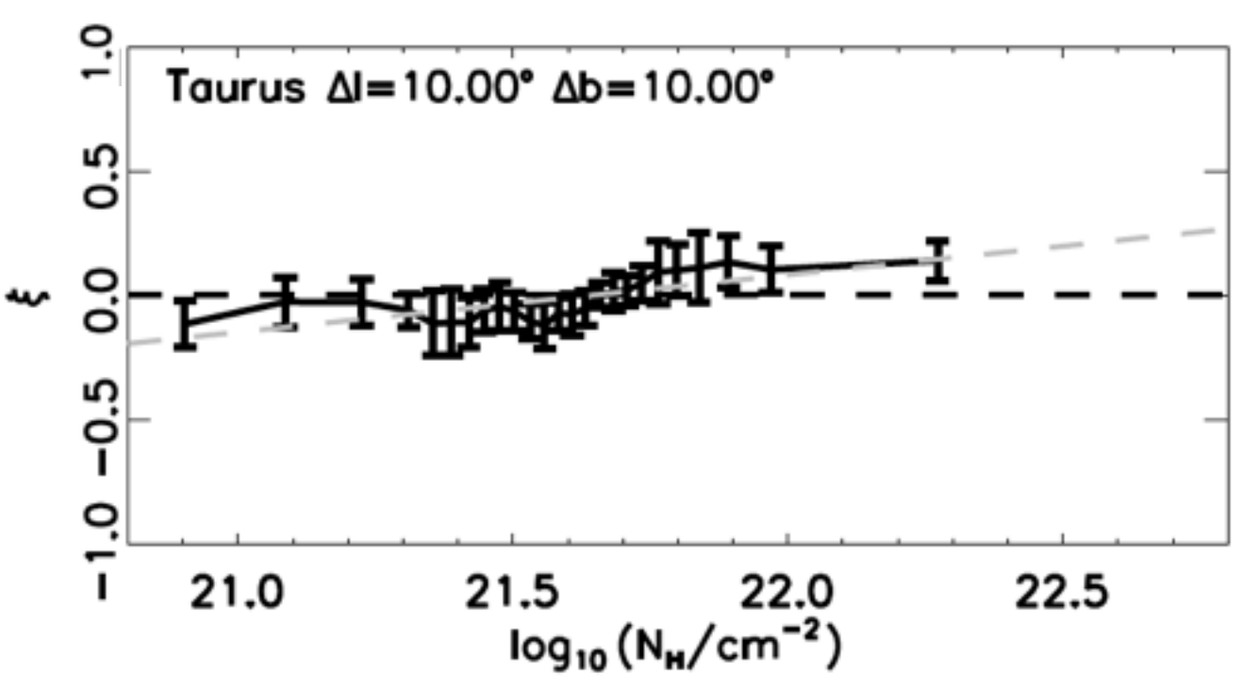
Planck intermediate results. XXXV

Statistical Significance of Relative Orientations

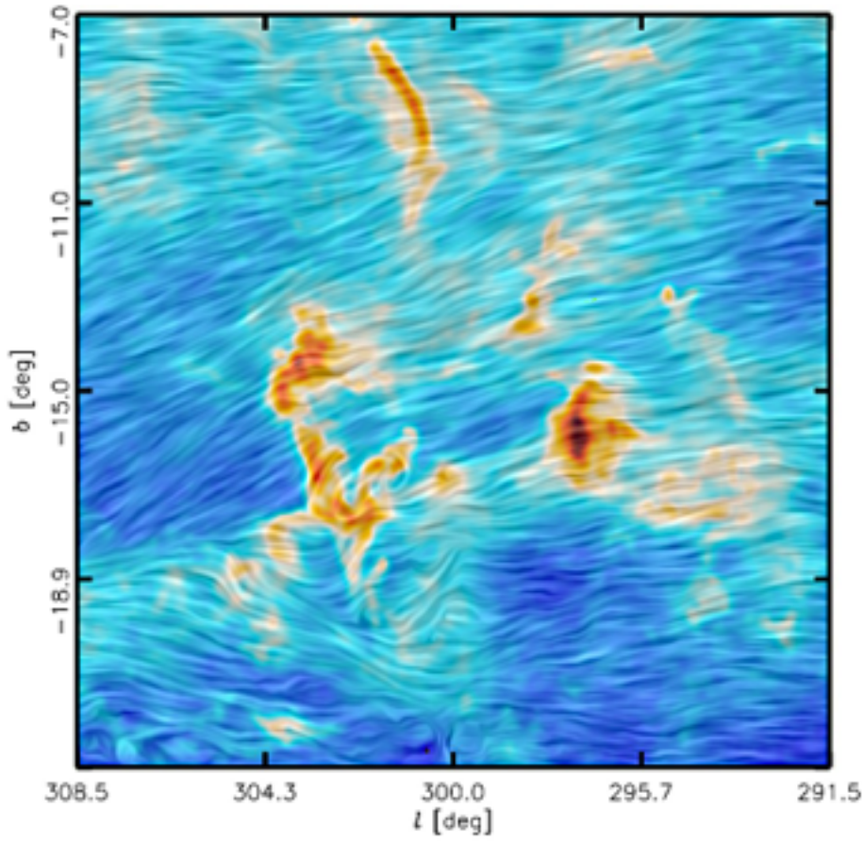


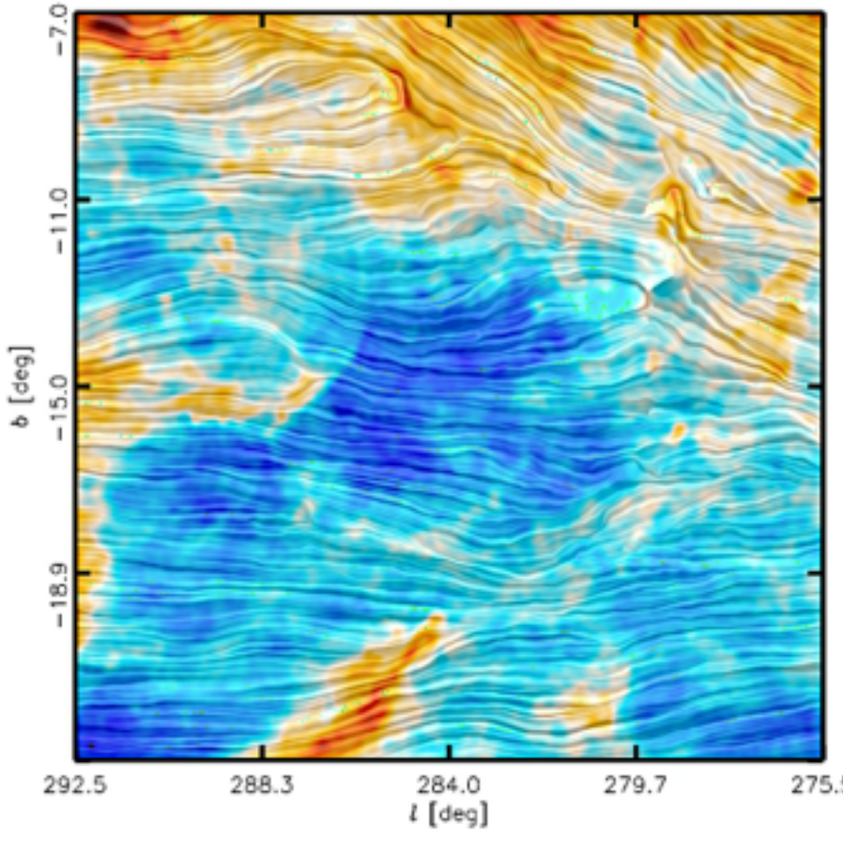


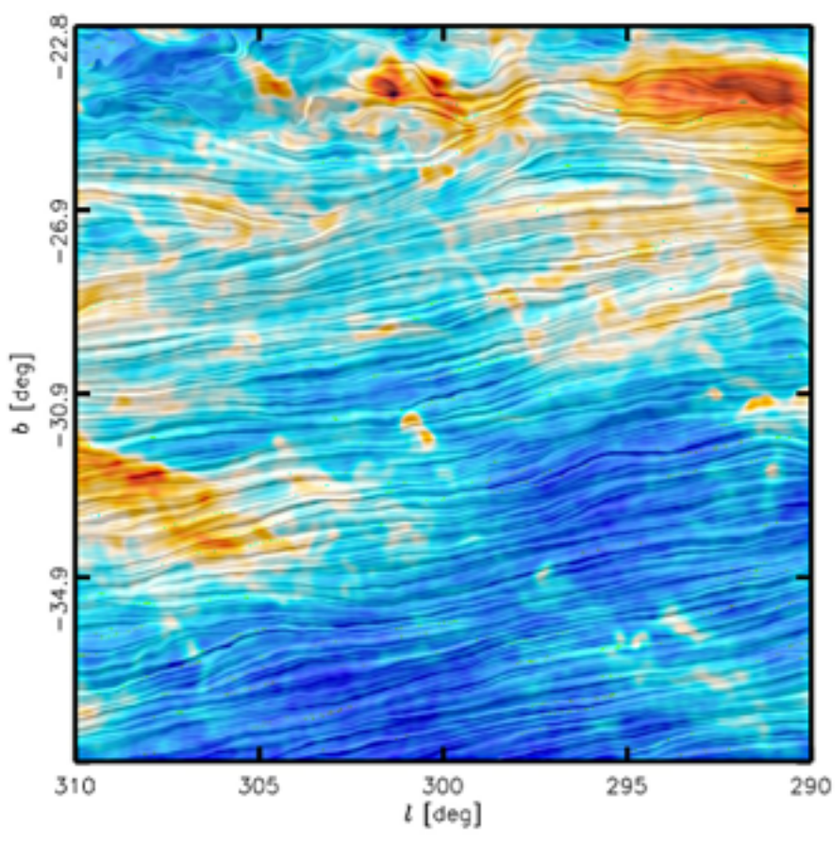


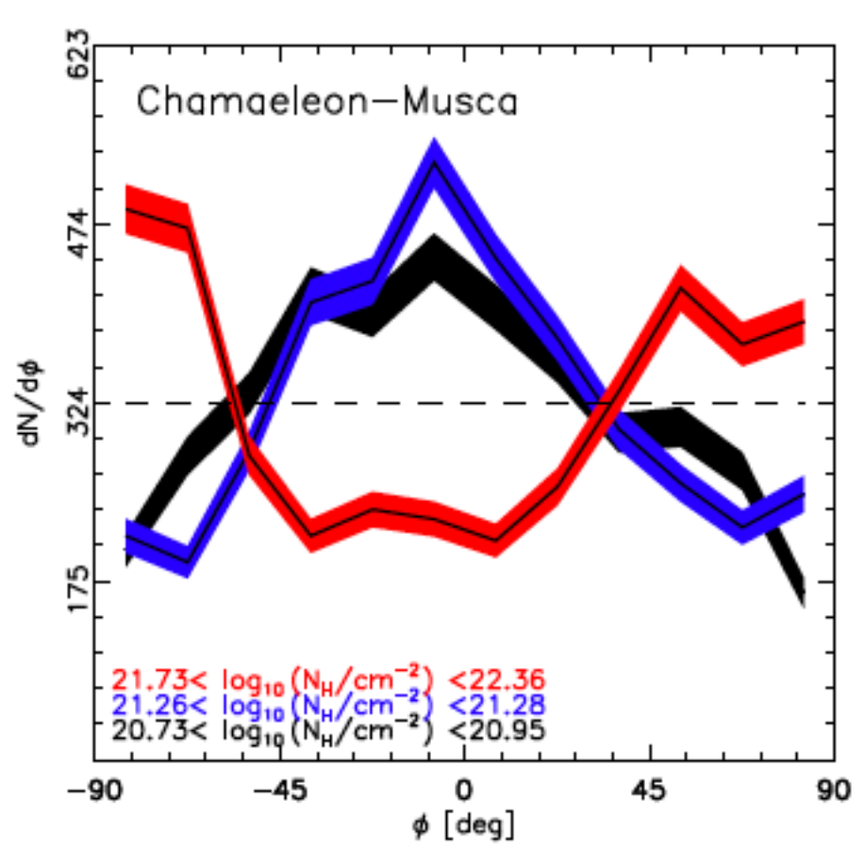


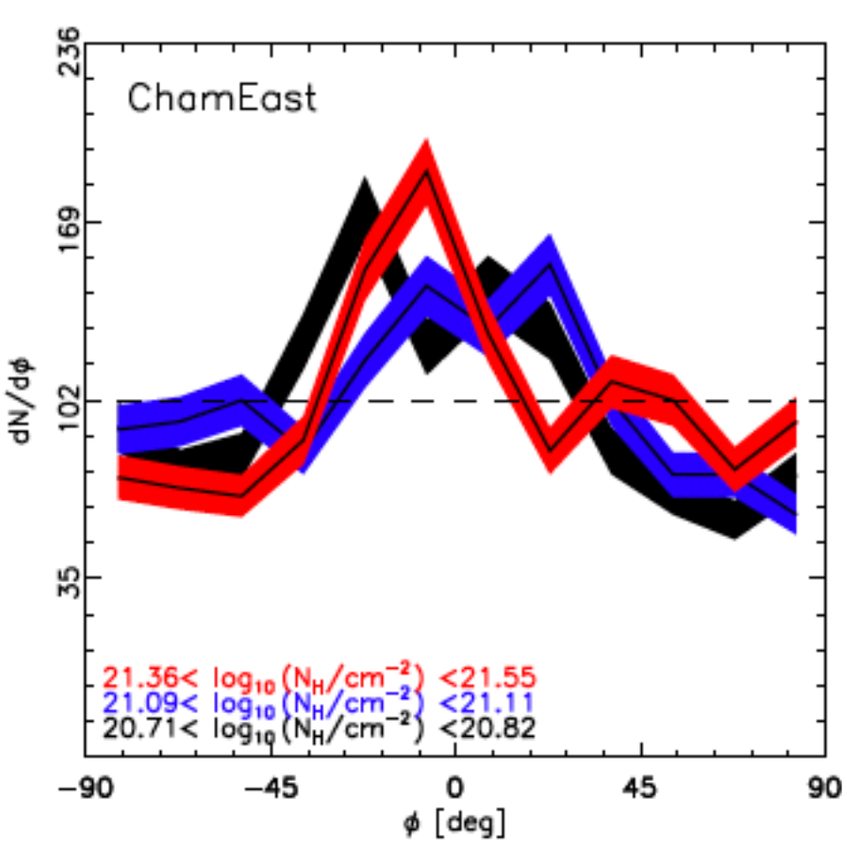
Planck intermediate results. XXXV

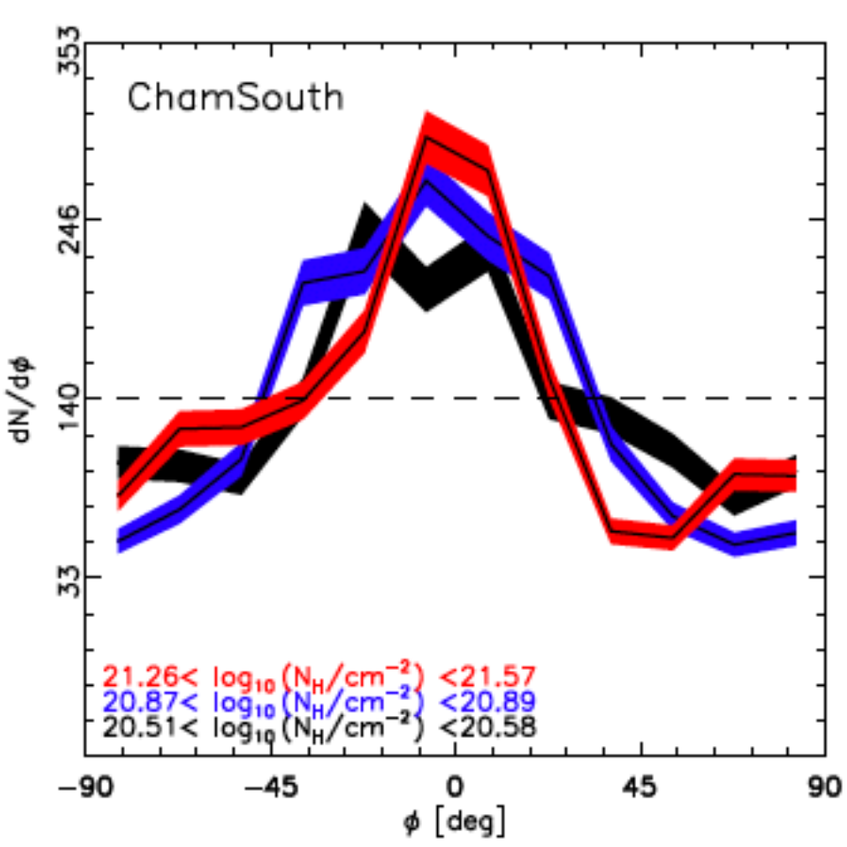

b [deg]
−7.0
−11.0
−15.0
−18.9
308.5
304.3
300.0
295.7
291.5
l [deg]


b [deg]
−7.0
−11.0
−15.0
−18.9
292.5
288.3
284.0
279.7
275.5
l [deg]

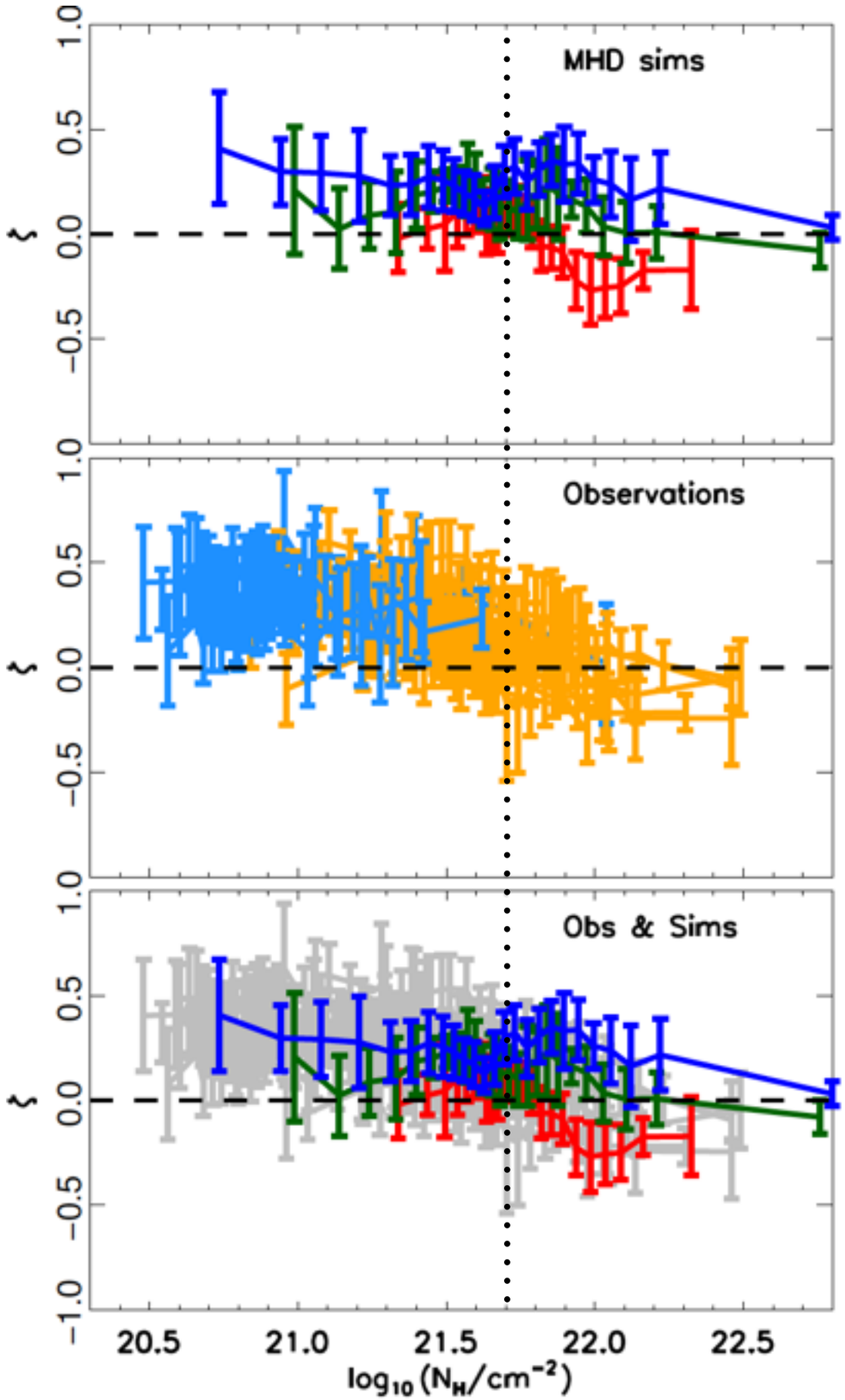

b [deg]
−22.8
−26.9
−30.9
−34.9
310
305
300
295
290
l [deg]


Chamaeleon−Musca
dN/dϕ
623
474
324
175
21.73< log10(NH/cm−2) <22.36
21.26< log10(NH/cm−2) <21.28
20.73< log10(NH/cm−2) <20.95
−90
−45
0
45
90
ϕ [deg]

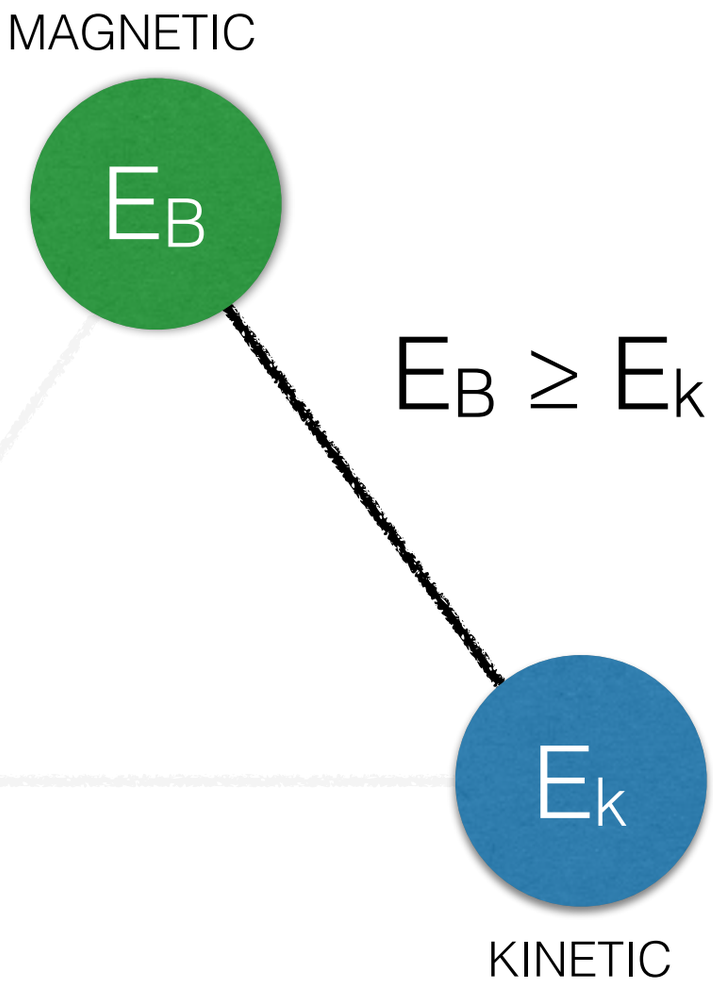

ChamEast
dN/dϕ
236
169
102
35
21.36< log10(NH/cm−2) <21.55
21.09< log10(NH/cm−2) <21.11
20.71< log10(NH/cm−2) <20.82
−90
−45
0
45
90
ϕ [deg]


ChamSouth
dN/dϕ
353
246
140
33
21.26< log10(NH/cm−2) <21.57
20.87< log10(NH/cm−2) <20.89
20.51< log10(NH/cm−2) <20.58
−90
−45
0
45
90
ϕ [deg]

Relative Orientations



Weak field
Equipartition
Strong field

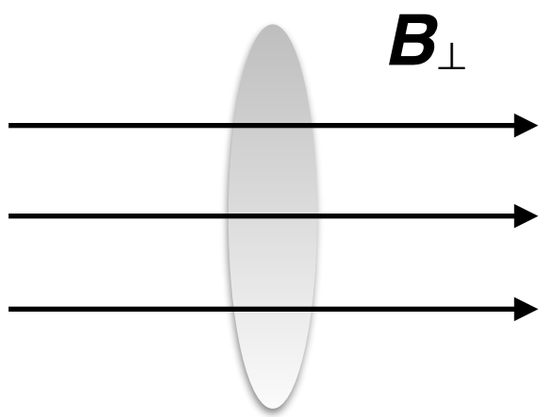


Planck intermediate results. XXXV

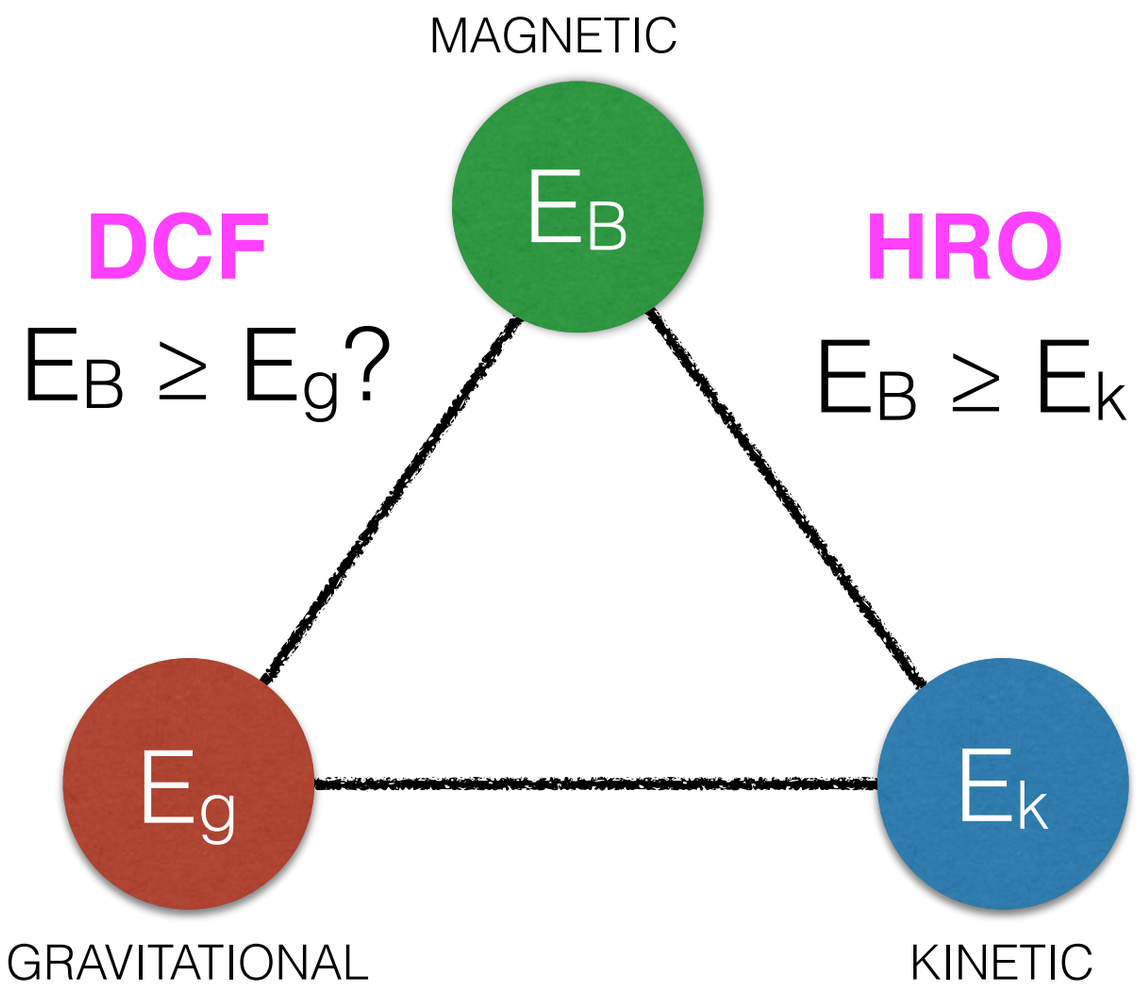
Magnetic fields in molecular cloud formation

What have we learned?

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



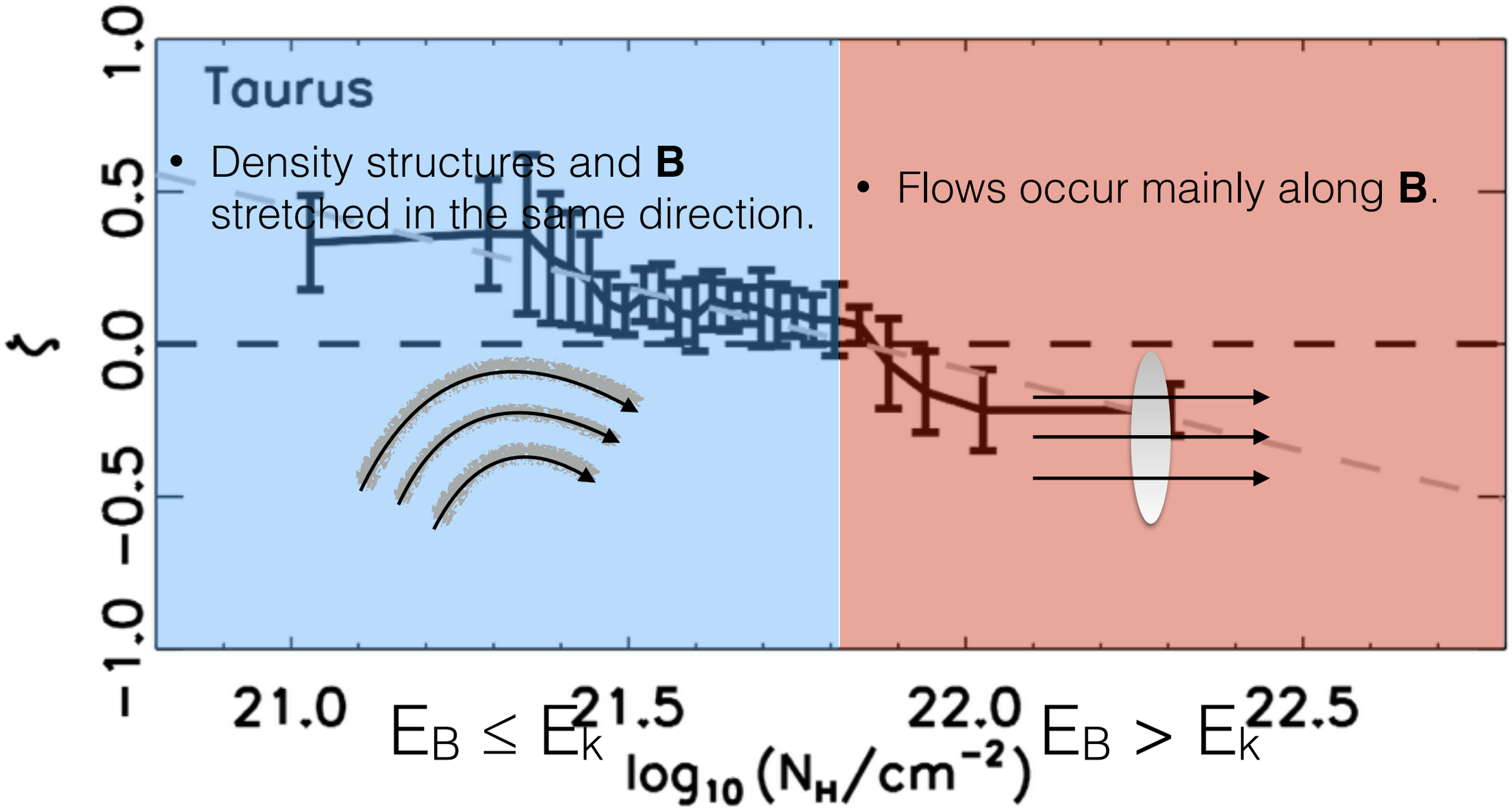
Planck intermediate results. XXXV



$E_g \approx E_k$

Virialized structure

Magnetic fields and cloud formation

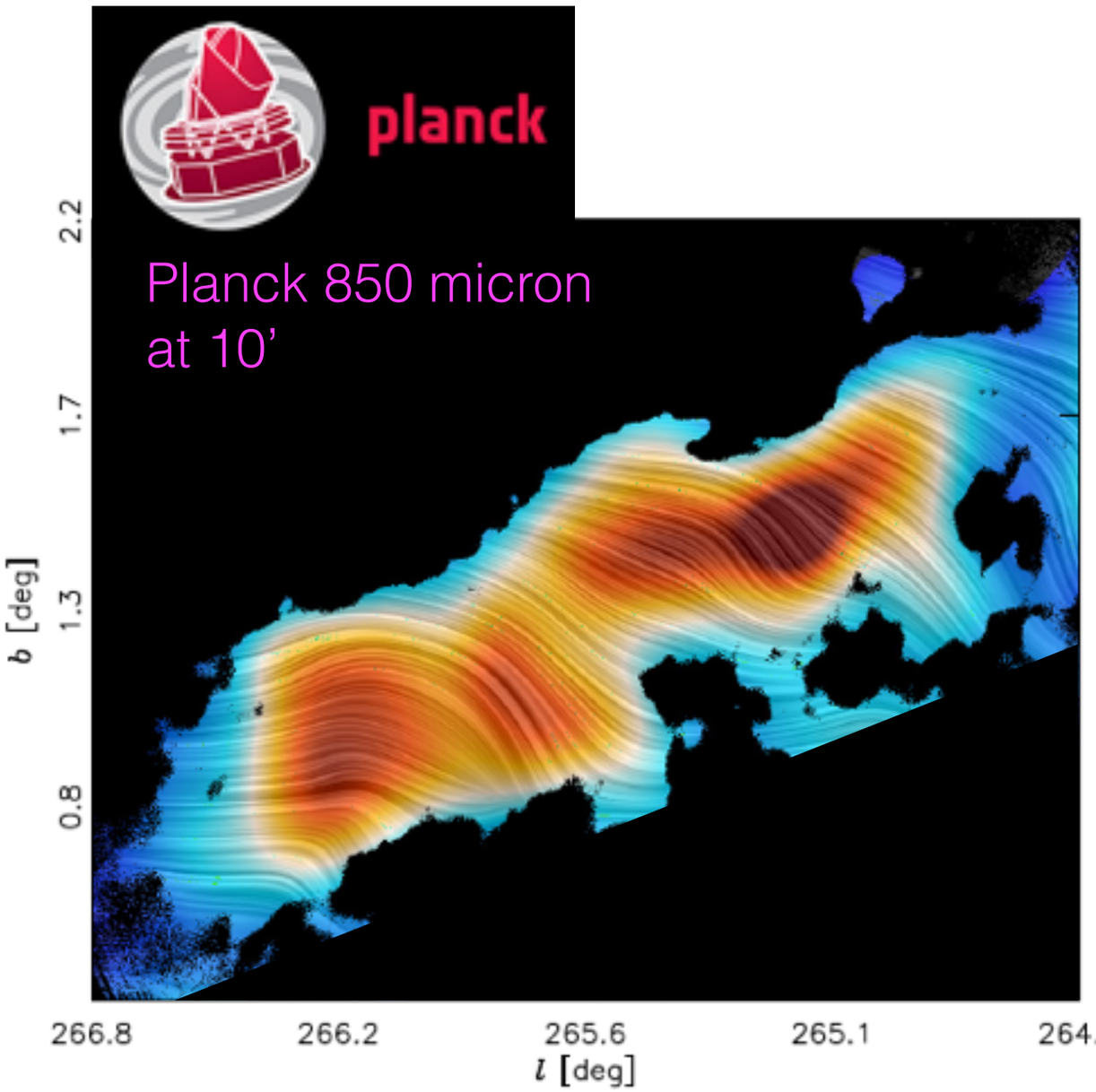


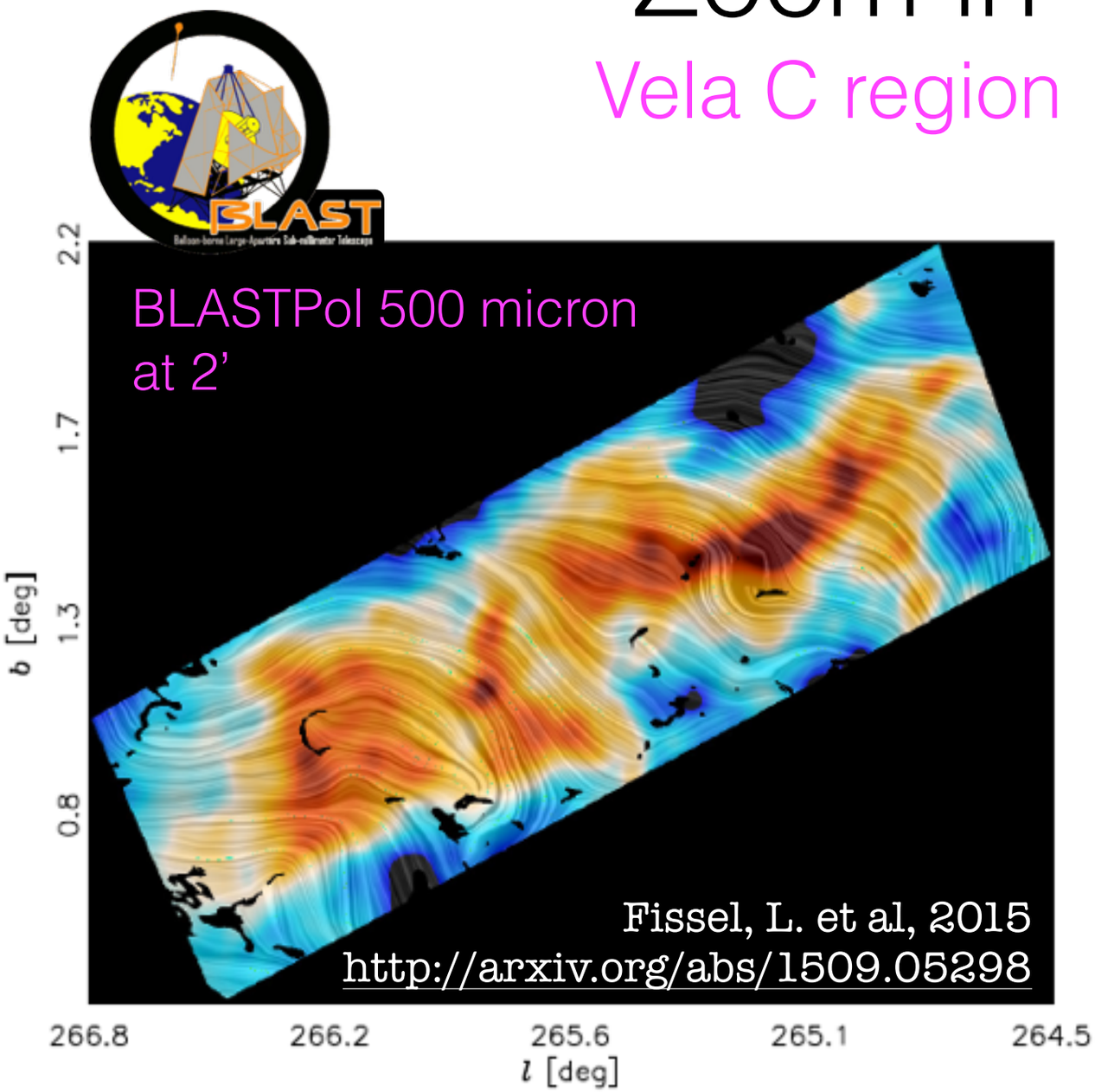
Planck intermediate results. XXXII
Hennebelle, P., 2013
Banerjee, R., 2009
Matthaeus, W. et al, 2008

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

Zoom in

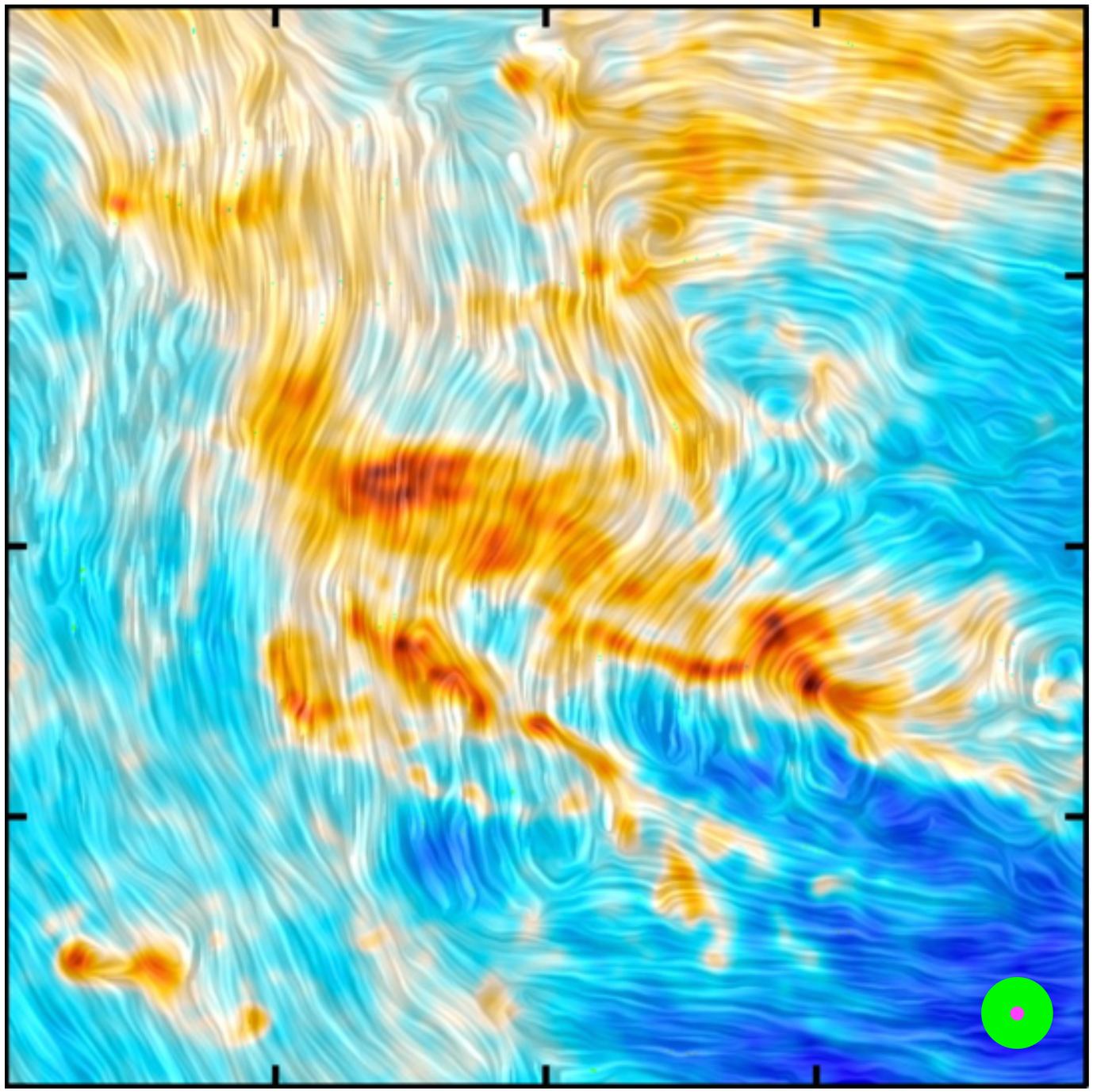
Vela C region





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

Open questions



16 deg (40 pc @ d=140 pc)

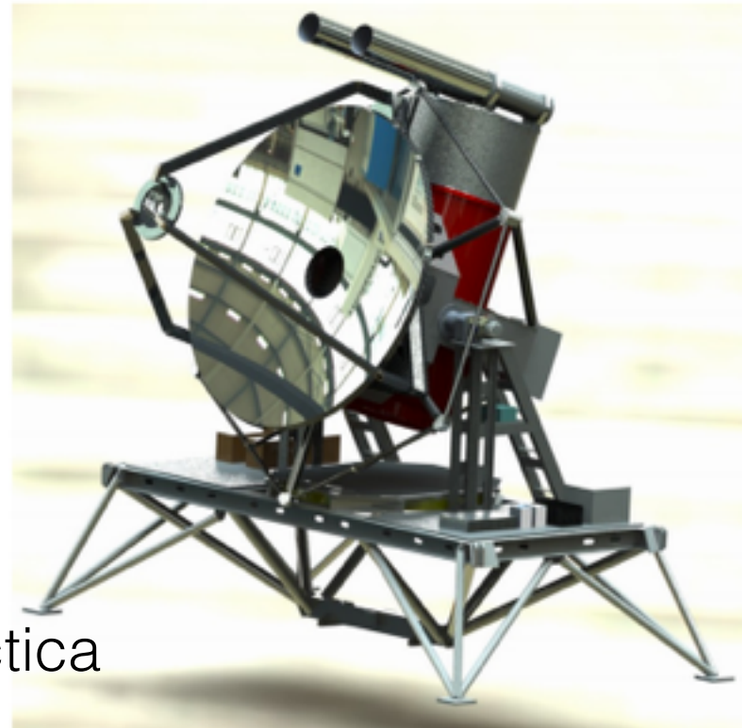
- Line of sight integration
- Dust grain alignment
- Field structure at smaller scales

BLAST-TNG

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

1000 MKIDs

Flying from Antarctica
in 2017



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

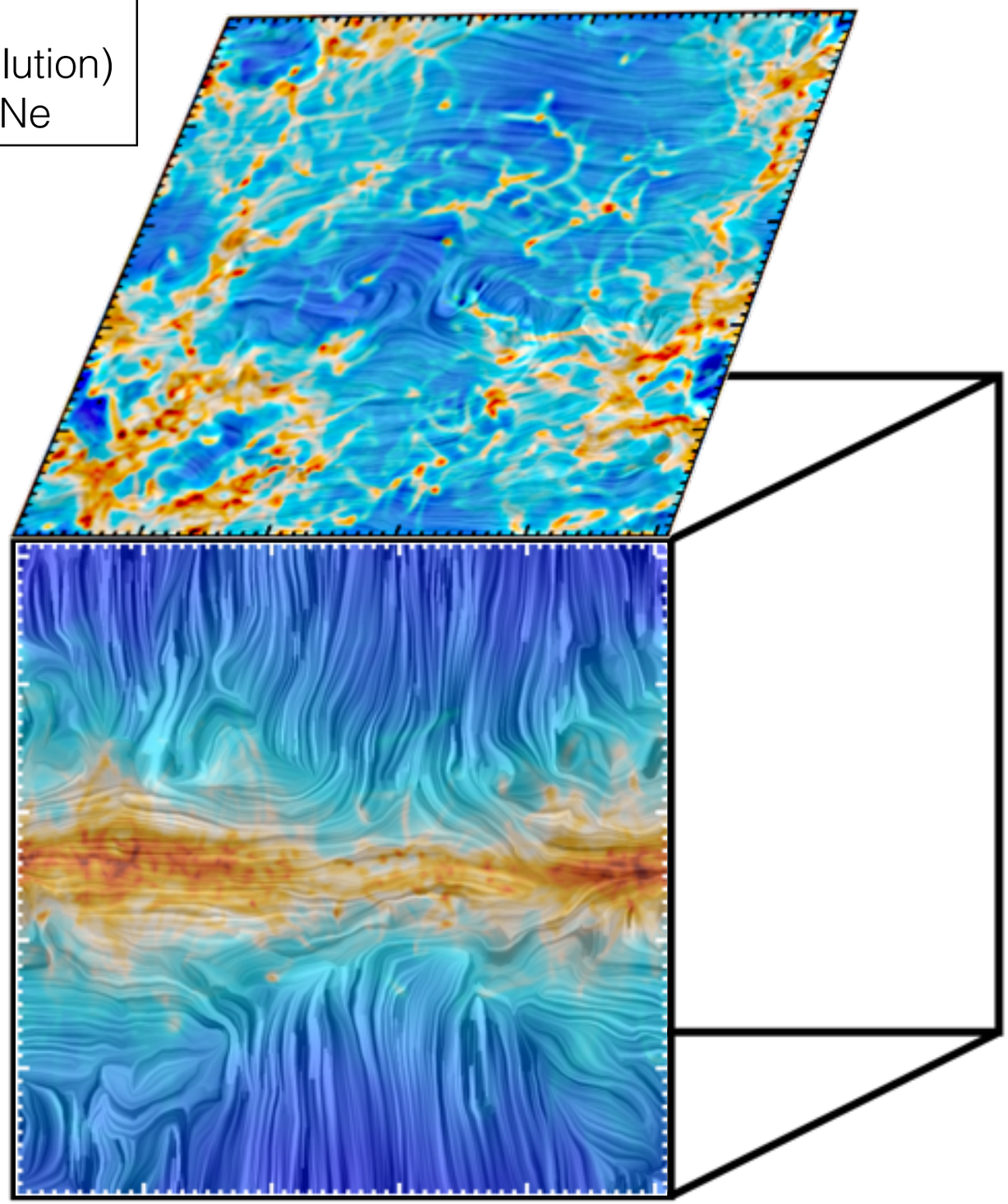
NIKA2

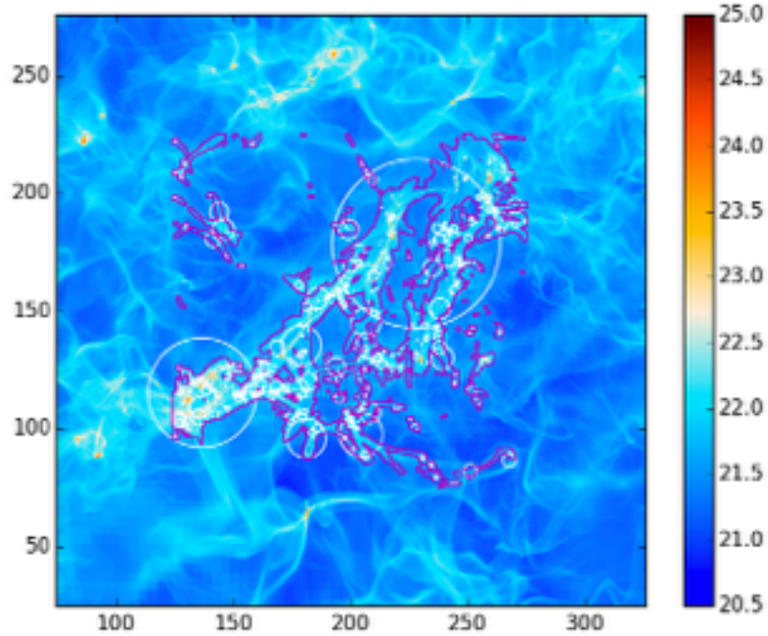
IRAM 30m telescope
1.2 mm (10'' res.)
polarimetry.
6.5' FoV

2x2000 MKID

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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arXiv:1502.04123 A&A accepted