THE MAGNETIZED AND MULTIPHASE ISM AS SEEN BY PLANCK

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esa-Planck Consortium

Outline

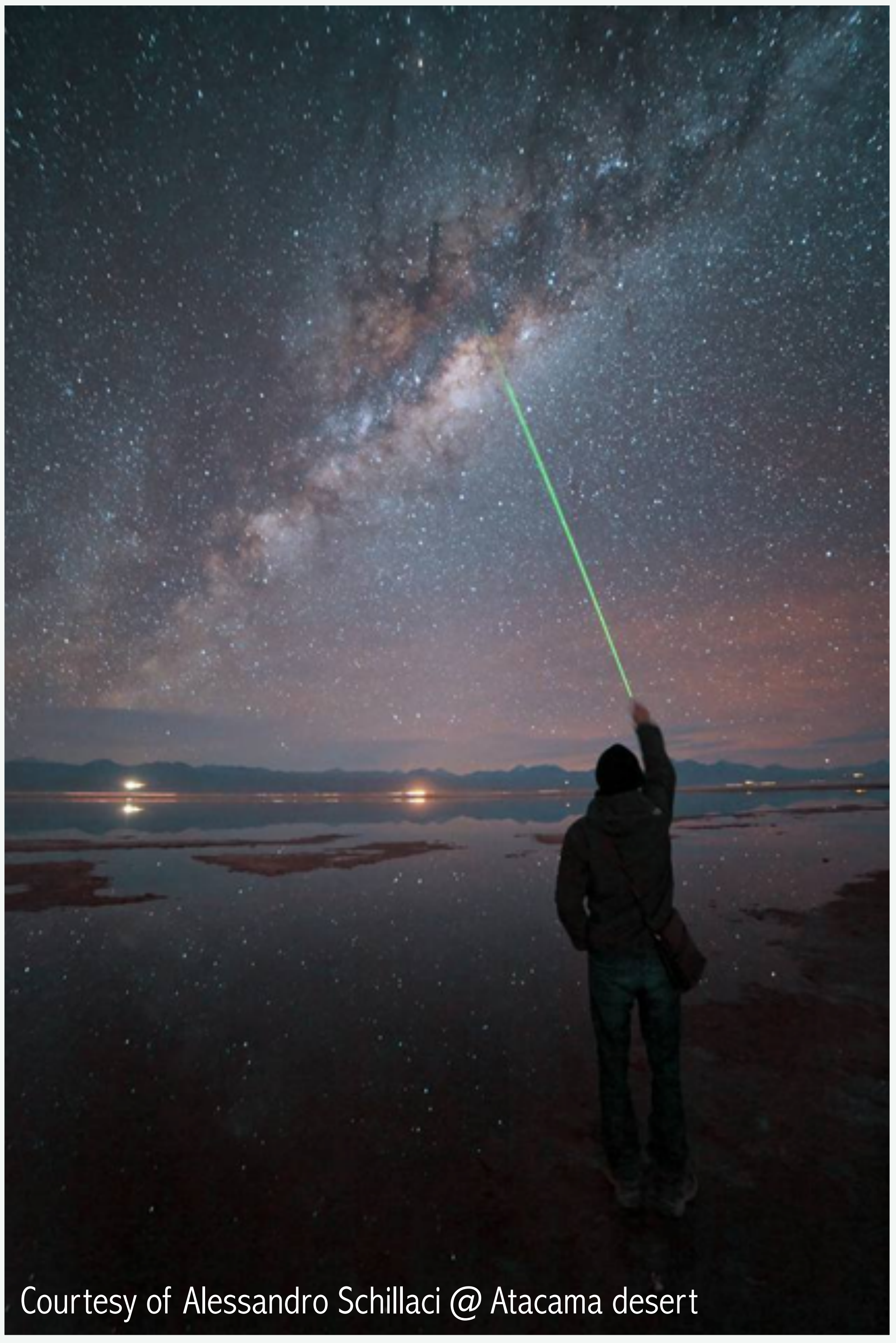
- A short ride through the multiphase interstellar medium (ISM)

- Key questions (for me) in the study of the ISM : how do magnetic fields fit into the picture?

- How do we measure interstellar magnetic fields and where do we stand?

- The breakthrough of the Planck satellite : results and challenges in three steps

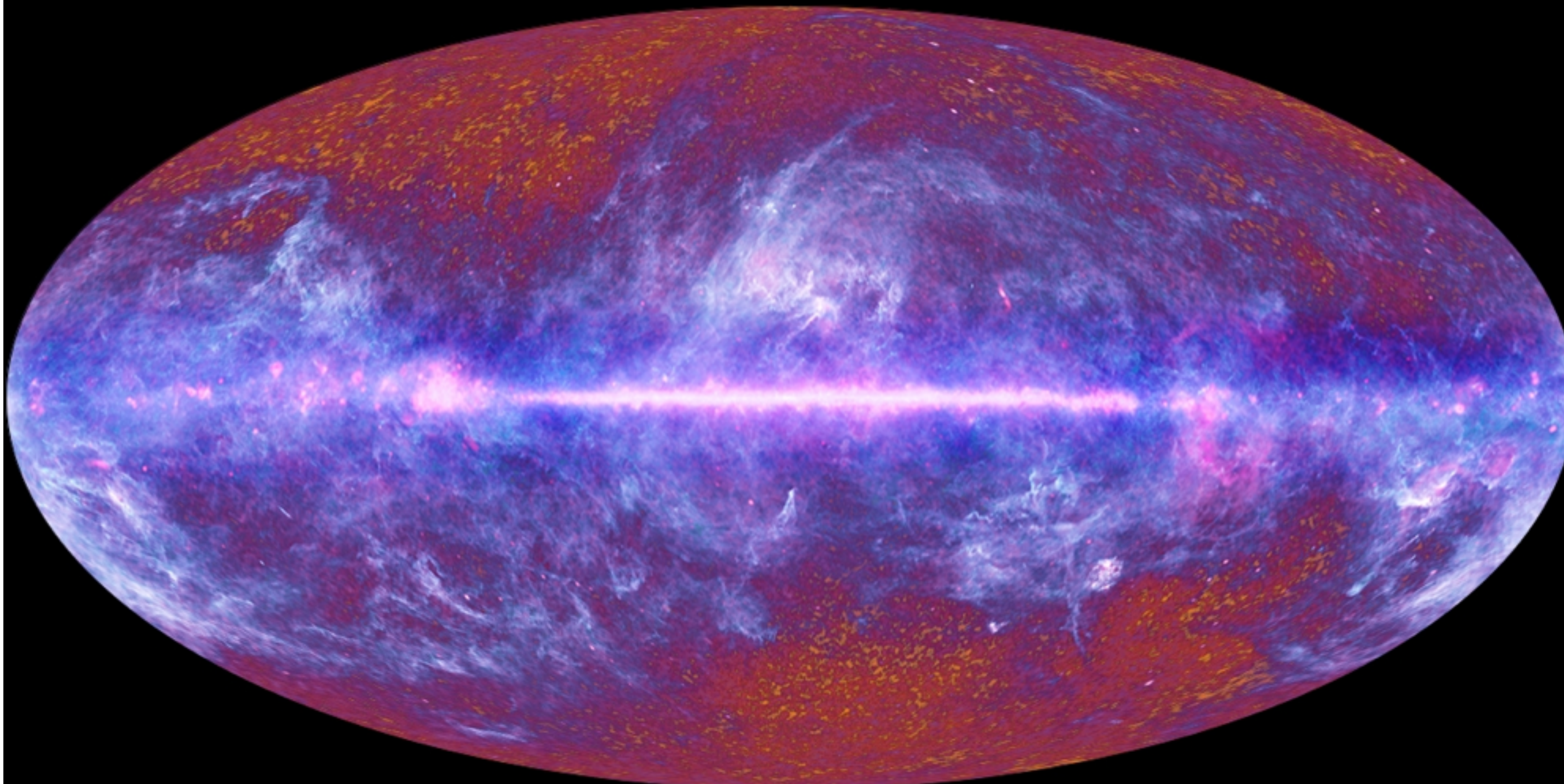
A look into the outer space: the interstellar medium (ISM)



Courtesy of Alessandro Schillaci @ Atacama desert

A look into the outer space: the interstellar medium (ISM)

Total intensity of Planck at sub-mm, mm wavelengths (Planck 2013 results. I)



Neutral gas (~99% of ISM mass) (atomic & molecular)
Dust (~1% of ISM mass) (Draine+2007)

For dust modeling
see Jones+2013,2015,2017
review Draine 2003

A look into the outer space: the multiphase ISM

The cycle of matter in the ISM

[see book Tielens (2005)]

Hot ionized medium (HIM) T~10^6 K ; n ~ 10^-2 cm^-3

Warm ionized medium (WIM) T~5x10^3 K ; n ~ 0.5 cm^-3

Warm neutral medium (WNM) T~5x10^3 K ; n ~ 0.5^-2 cm^-3

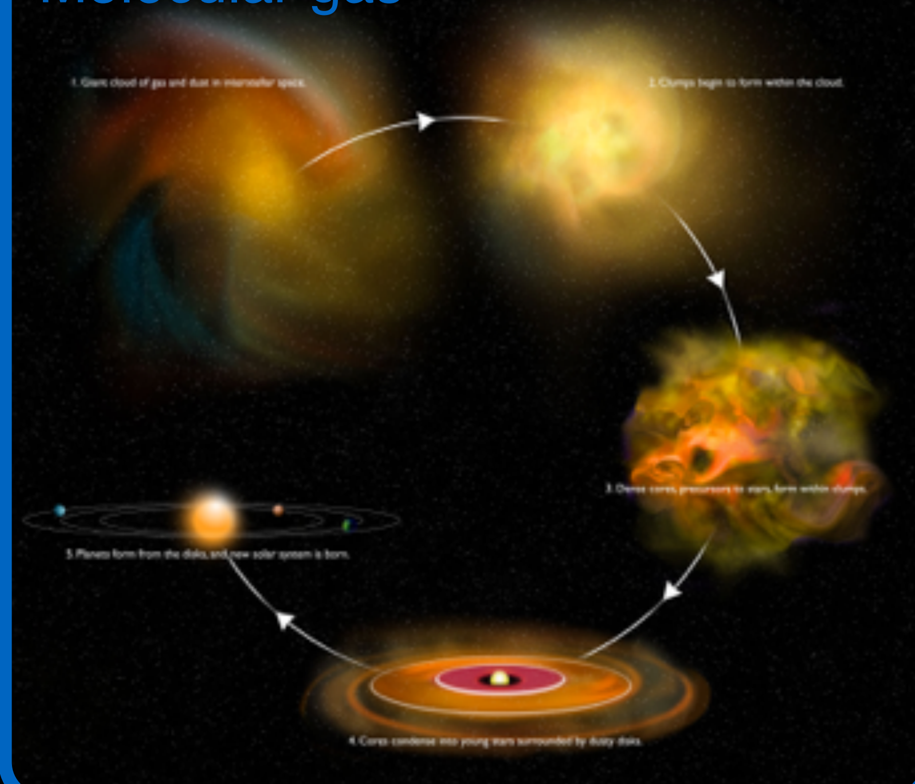
Cold neutral medium (CNM) T~10^2 K ; n ~ 10^2 cm^-3

Molecules T~few tens of K ; n ~ 10^3 cm^-3

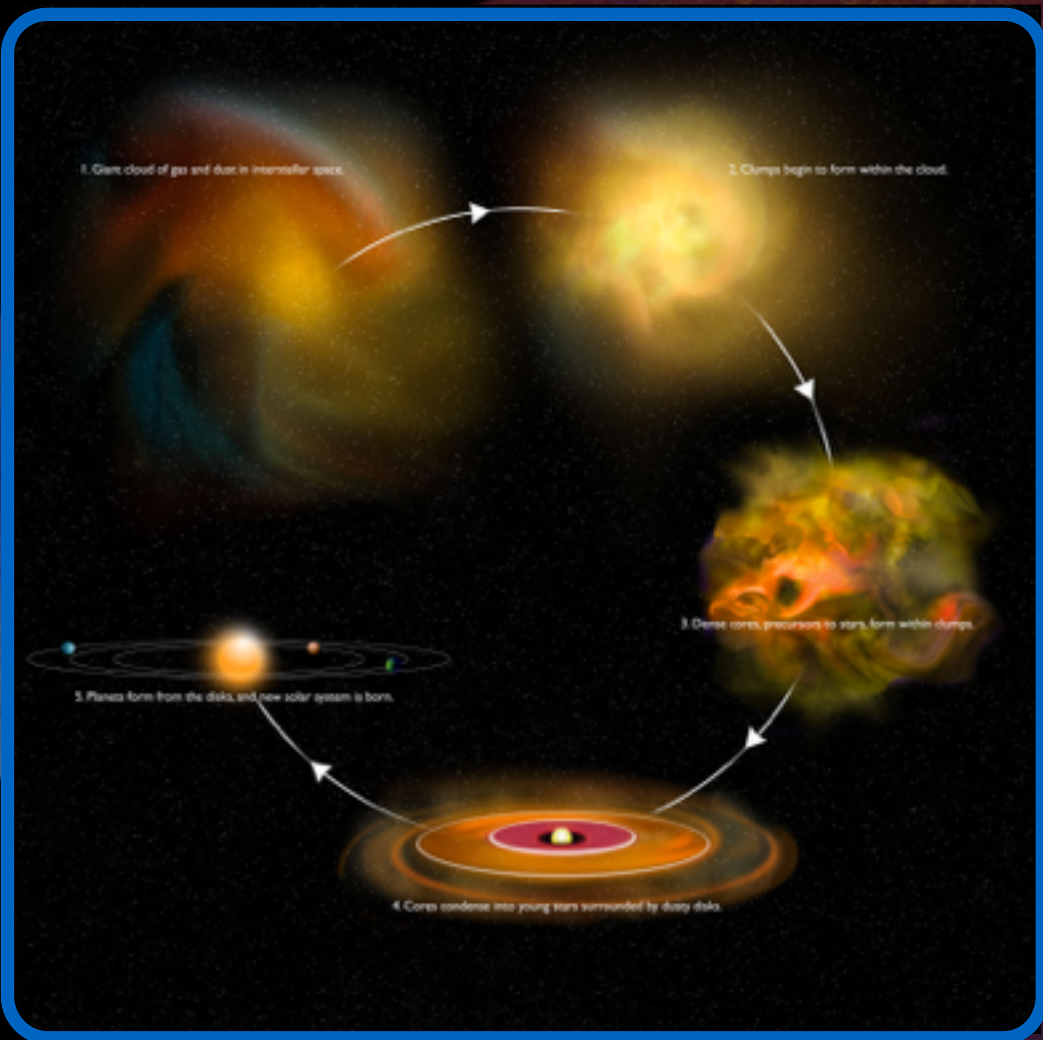
Dust grains

Feedback

Molecular gas



Interstellar medium and star formation: an outstanding problem



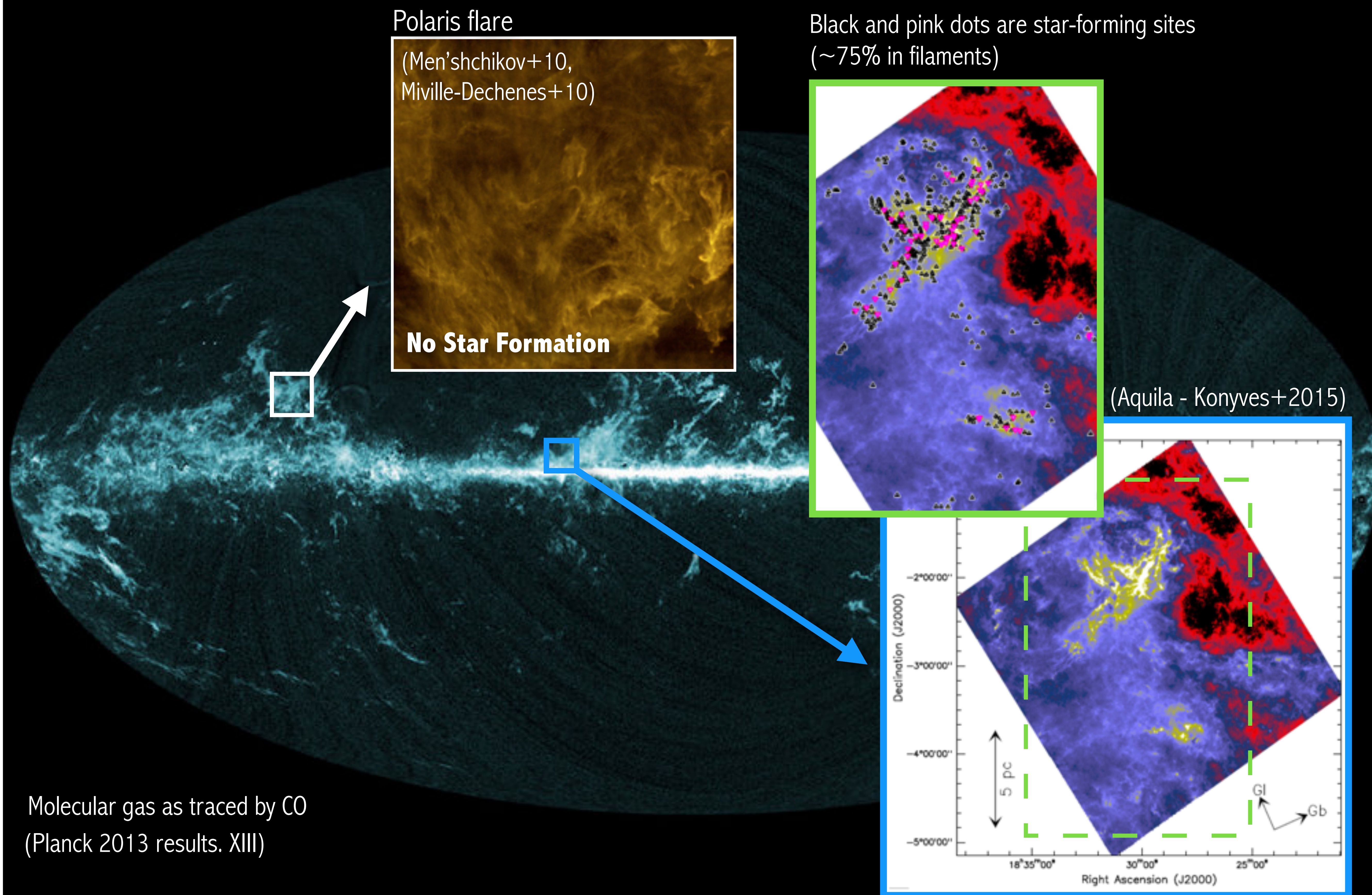
Disk of the Milky Way has 10^9 M_sun of molecular gas
(Williams & McKee 1997)
If only gravity:

Free-fall time of giant clouds with masses of 10^6 M_sun and n~100/1000 cm^-3 ($1/\sqrt{nG}$) of ~ 4 Myr

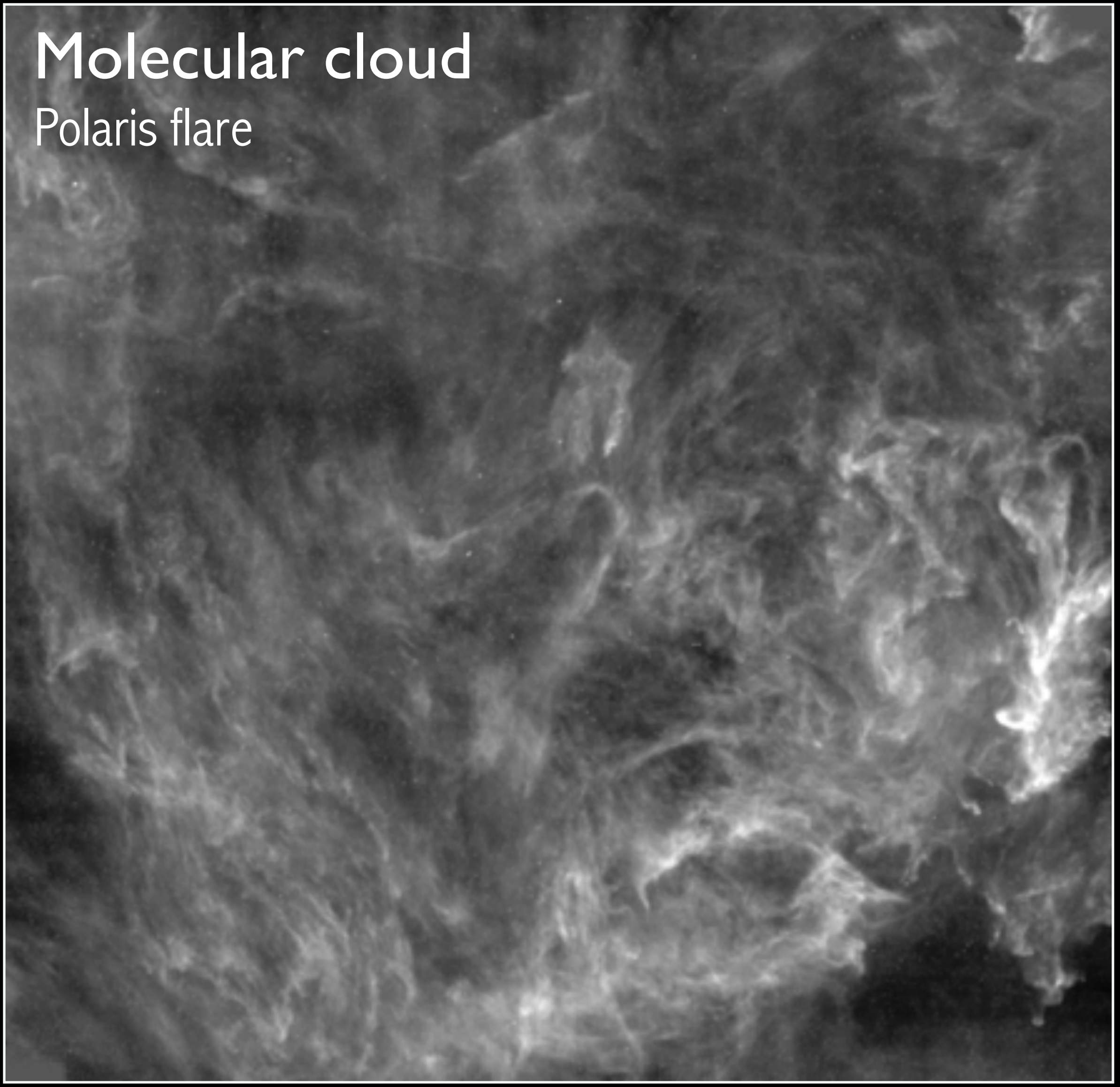
Star-forming rate of ~250 M_sun/yr
(Krumholz et al. 2005)

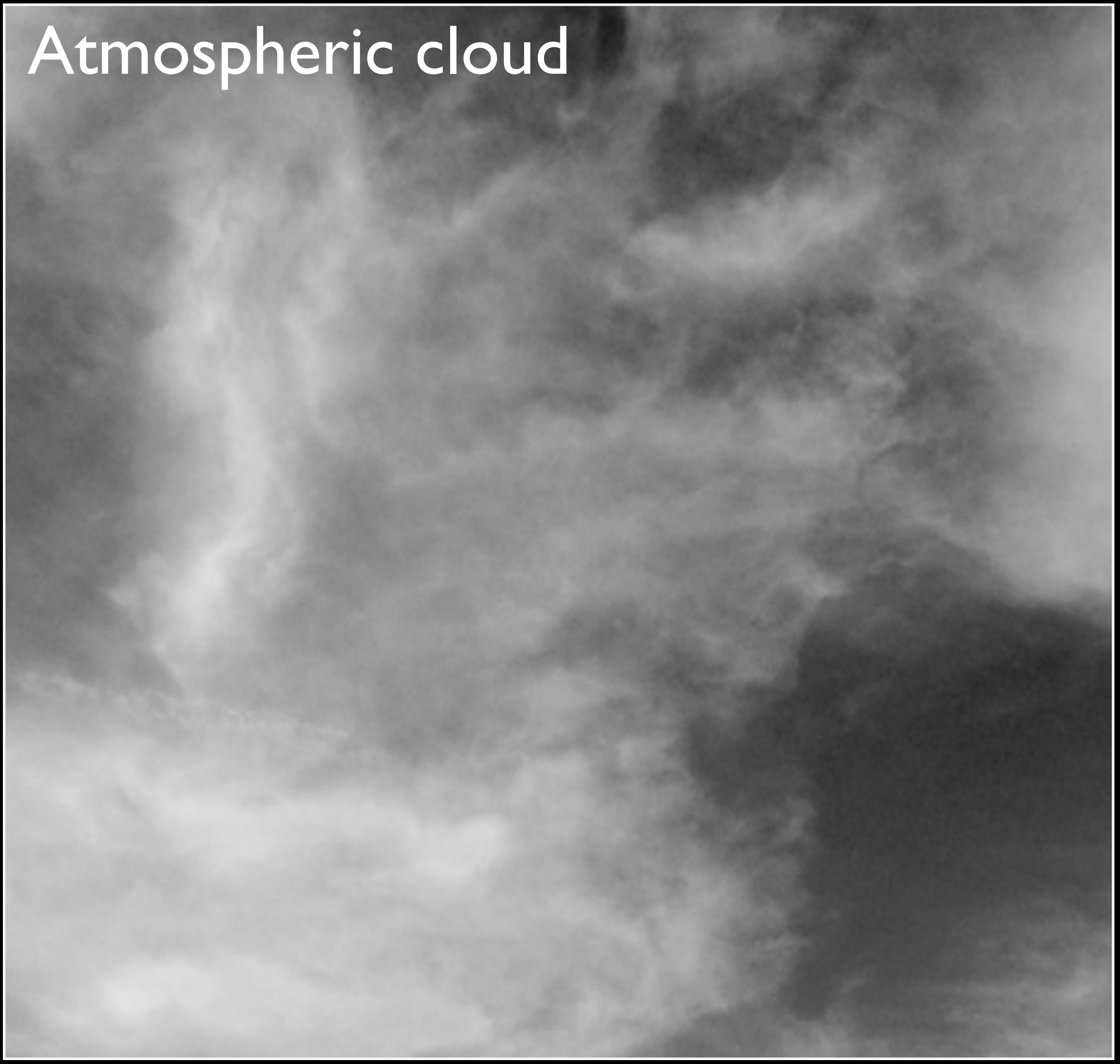
The observed is only ~3 M_sun/yr
(Zuckerman & Evans 1974; McKee & Williams 1997)

A closer look at star formation regions: molecular clouds

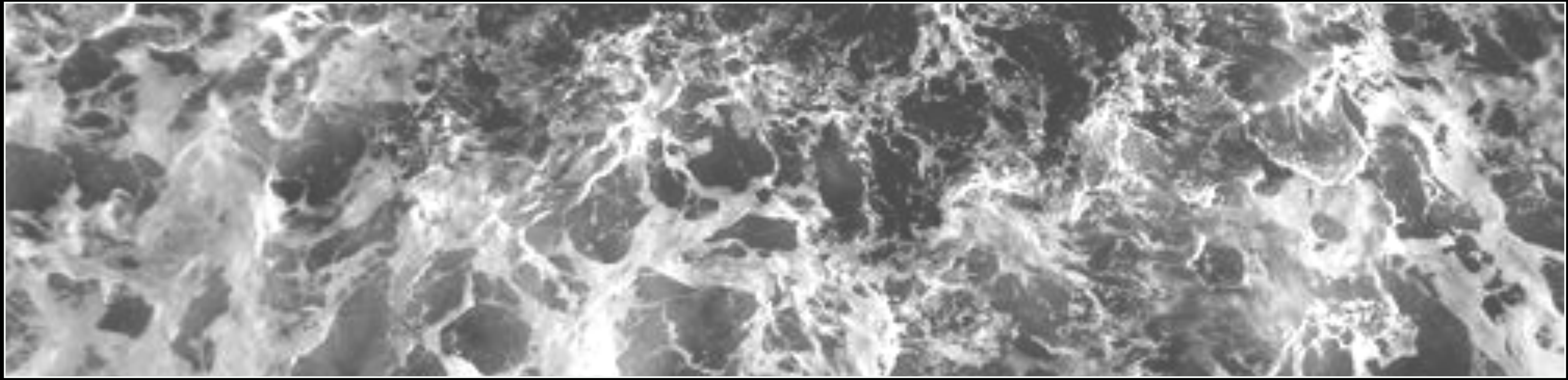


Find the difference

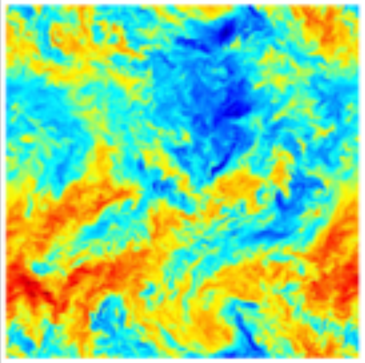




Water



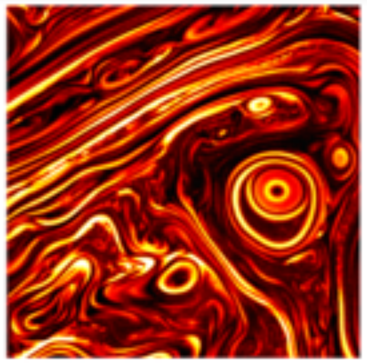
Some hints about turbulence



Vorticity (JHU)

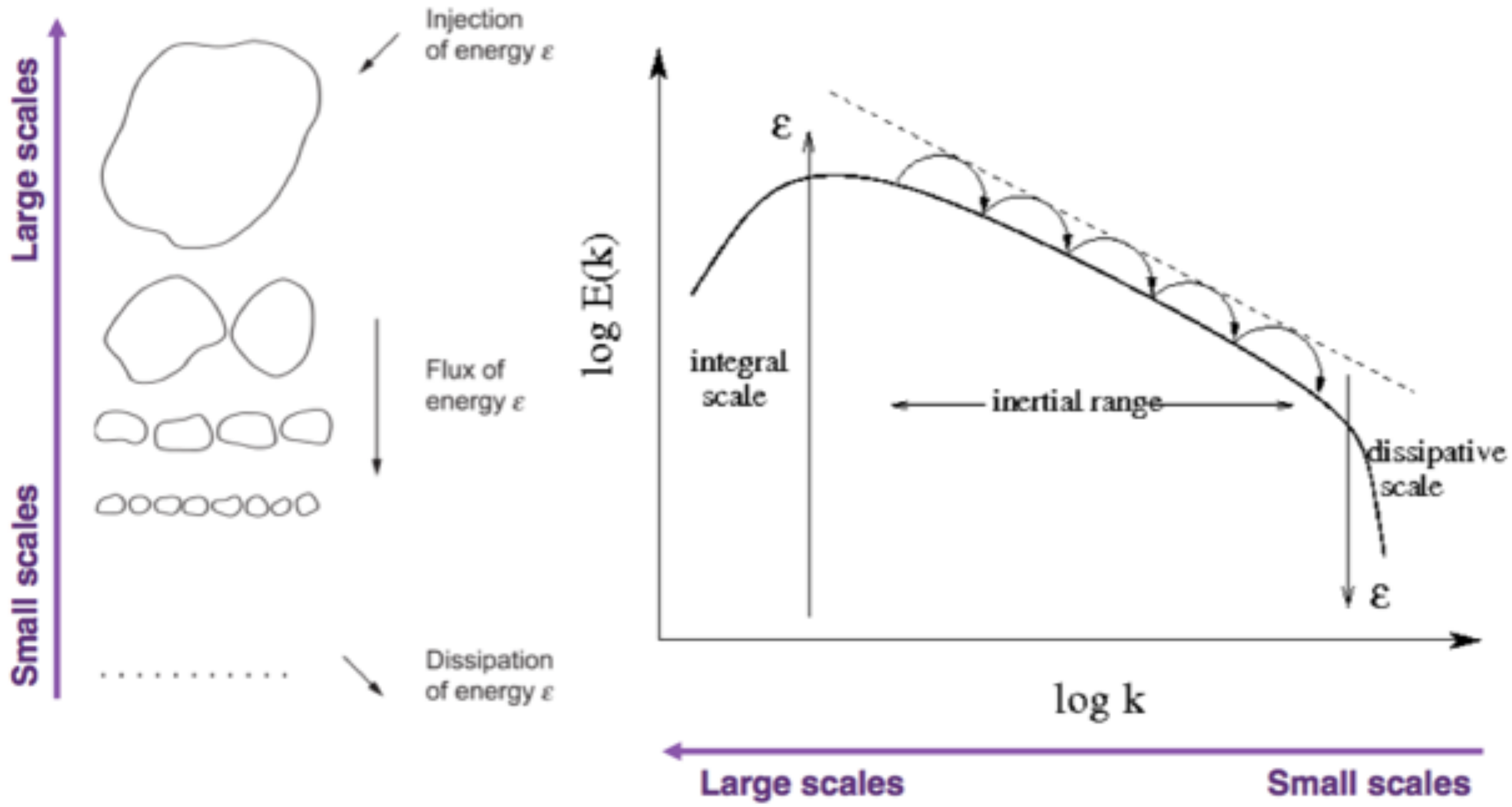
Turbulence

« Big whirls have little whirls
that feed on their velocity,
and little whirls have lesser whirls
and so on to viscosity. »
Lewis Fry Richardson (1920)



Current (UCSD, Berkeley Lab)

- Kolmogorov's K41 theory : incompressible, homogeneous, isotropic cascade of energy
- Scaling laws and self-similarity



Energy spectrum

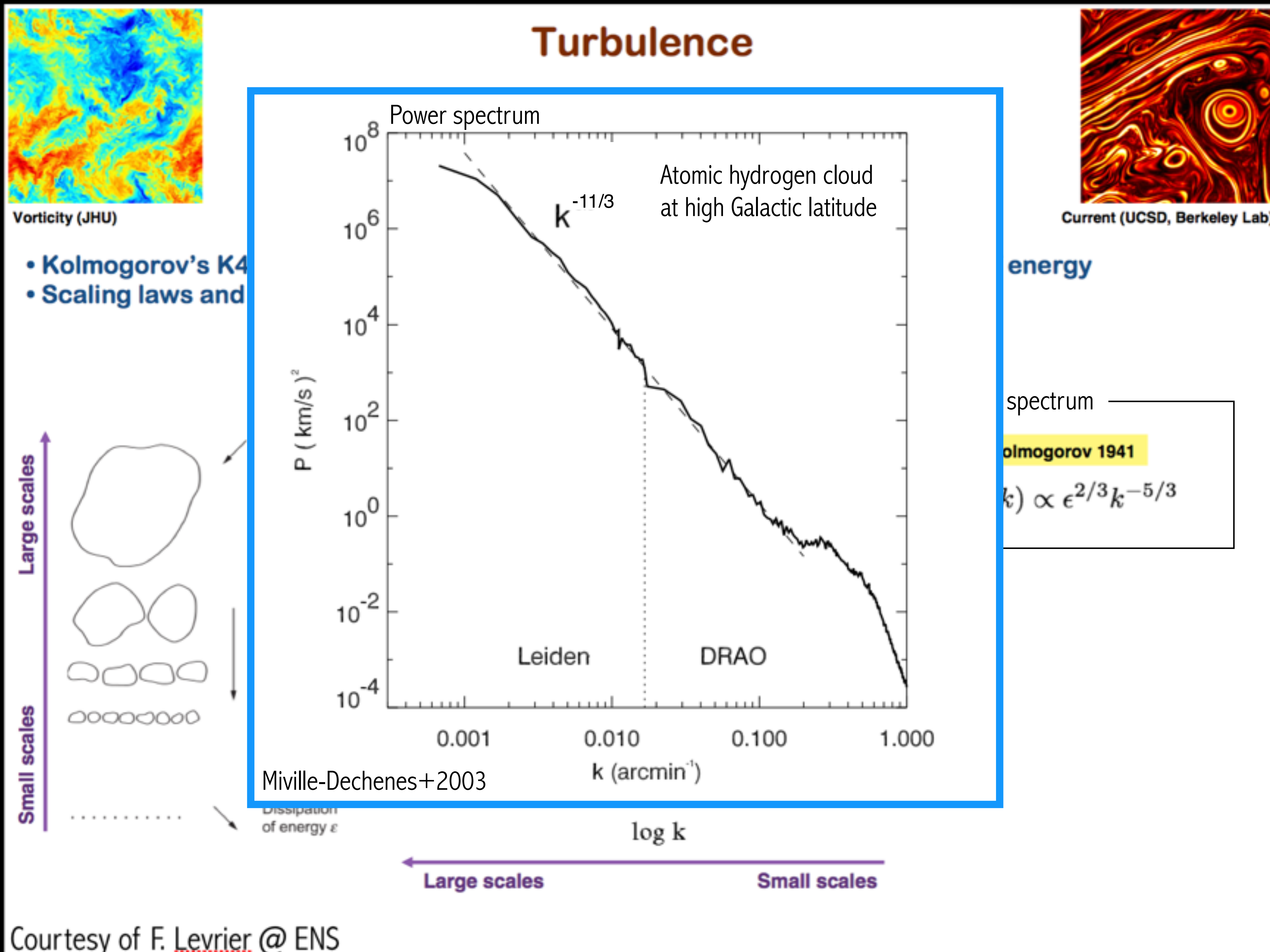
Kolmogorov 1941

$$P_v(k) \propto \epsilon^{2/3} k^{-5/3}$$

$$(P_k \propto k^{-\frac{11}{3}})$$

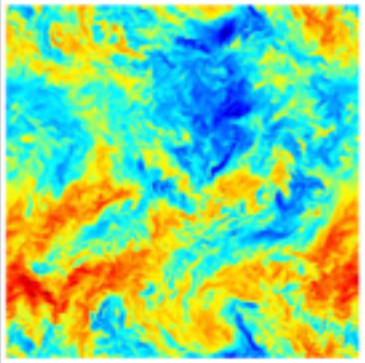
Courtesy of F. Levrier @ ENS

Some hints about turbulence



Some hints about turbulence

Turbulence



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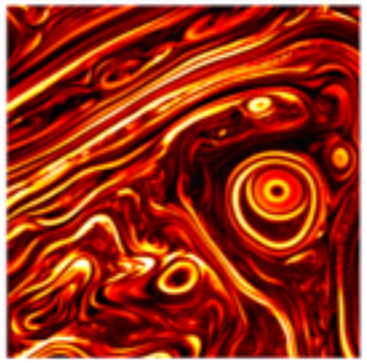
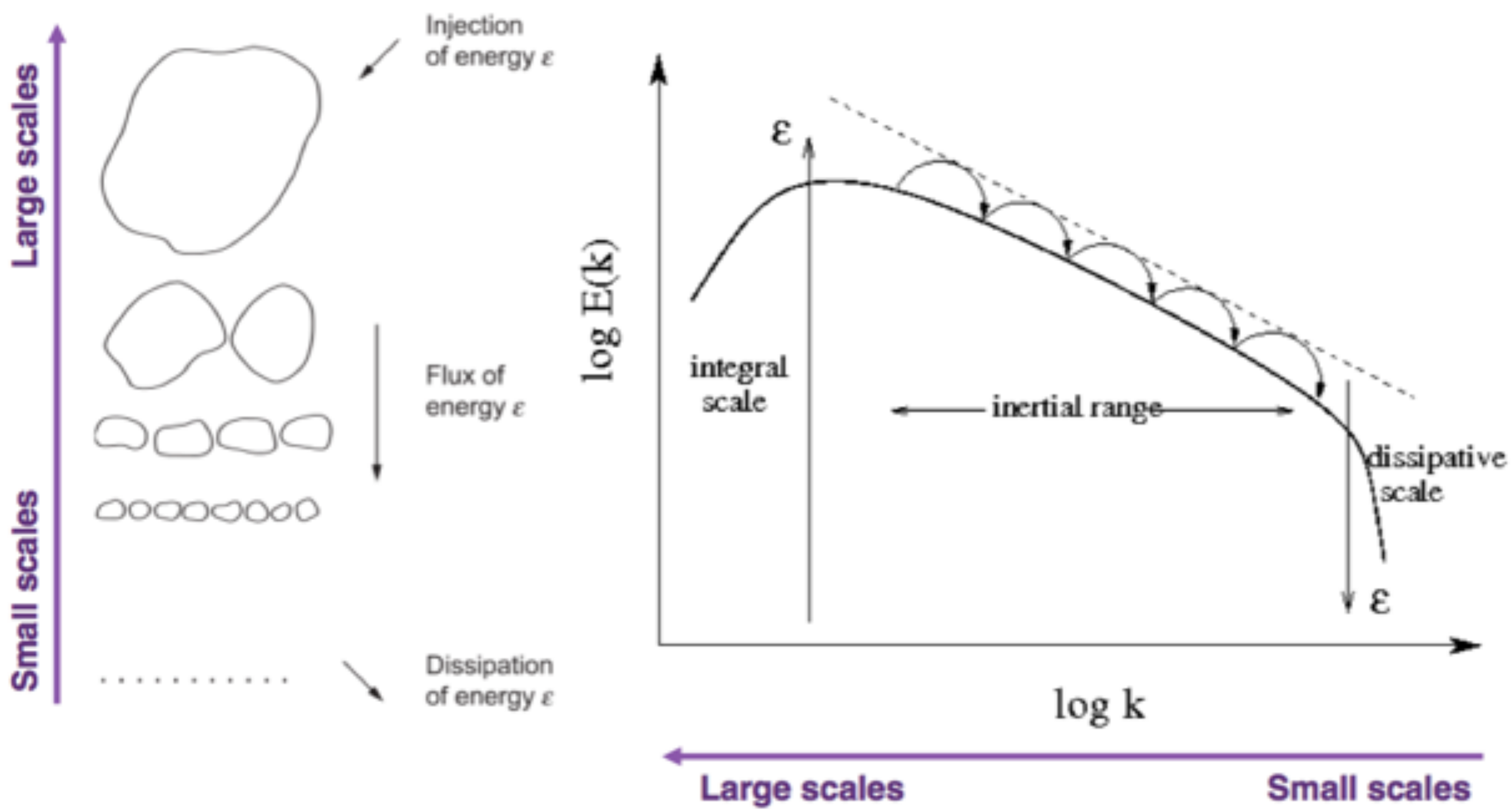


Current (UCSD, Berkeley Lab)

- Kolmogorov's K41 theory : incompressible, homogeneous, isotropic cascade of energy
- Scaling laws and self-similarity

- Modification of scaling laws from compressibility and magnetic fields (MHD turbulence)



Energy spectrum

Kolmogorov 1941

$$P_v(k) \propto \epsilon^{2/3} k^{-5/3}$$

Iroshnikov 1964, Kraichnan 1965

$$P_v(k) \propto (\epsilon v_A)^{1/2} k^{-3/2}$$

Sridhar & Goldreich 1994, 1995

$$P_{v_\perp}(k) \propto k_\perp^{-5/3}$$

Kowal & Lazarian 2007

$$P_{\rho^{1/3} v}(k) \propto k^{-5/3}$$

Courtesy of F. Levrier @ ENS

Interstellar magnetic fields : magnetohydrodynamical approach

Table 1 Properties of phases (Heiles & Haverkorn 2012)

Property	CNM	WNM	WIM	WPIM[a]	HIM	HIM Erid[b]
$\frac{P_{th}}{k}$ (cm^{-3} K)	4000	4000	4000	2000	10000	50000
T (K)	50	6000	8000	7000	1.5×10^6	1.5×10^6
n_{Hn} (cm^{-3})	80	0.7	0.25	0.2	0.0034	0.015
$\frac{n_e}{n_{Hn}}$	2×10^{-4}	1×10^{-3}	1	$\frac{1}{2}$	1	1
$N_{typ,Hn,20}$	0.5	1	0.08	0.06	0.01	0.06
$N_{typ,e,20}$	1×10^{-4}	1×10^{-3}	0.08	0.03	0.01	0.06
$N_{\perp,Hn,20}$	1.5	1.5	1.0	?	0.1	–
$N_{\perp,e,20}$	3×10^{-4}	1.5×10^{-3}	1.0	?	0.1	–

- In the molecular phase the ionization fraction can go down to ~1E-6/-7 (Padovani+2011)

"In view of the **infinite conductivity,** every motion (perpendicular to the field) of the liquid in relation to the lines of force is forbidden because it would give infinite eddy currents. **Thus the matter of the liquid is "fastened" to the lines of force**…" (Alfven 1942)

- Through ions-neutrals collisions the **magnetic field** becomes dynamically important **(frozen into matter)**

$$\vec{F}_{mag} = \underbrace{\frac{1}{4\pi}(\vec{B}\cdot\vec{\nabla})\vec{B}}_{\text{magnetic tension}} - \underbrace{\vec{\nabla}\left(\frac{B^2}{8\pi}\right)}_{\text{magnetic pressure}}$$

The dynamics of the interstellar medium

The formation of structures in the ISM depends on the interplay of:

Gravity

Turbulent motions

Magnetic fields

In the diffuse ISM atomic hydrogen observations and Zeeman measurements show:

$$E_{\rm grav}(\frac{M^2}{R}) << E_{\rm turb}(M\delta v_{\rm gas}^2) \approx E_{\rm mag}(B^2)$$

(Heiles & Troland 2005)

How does gravity become the dominant force to form structures and stars?

A closer look at interstellar magnetic fields

A) Magnetic fields in the interstellar medium are weak…

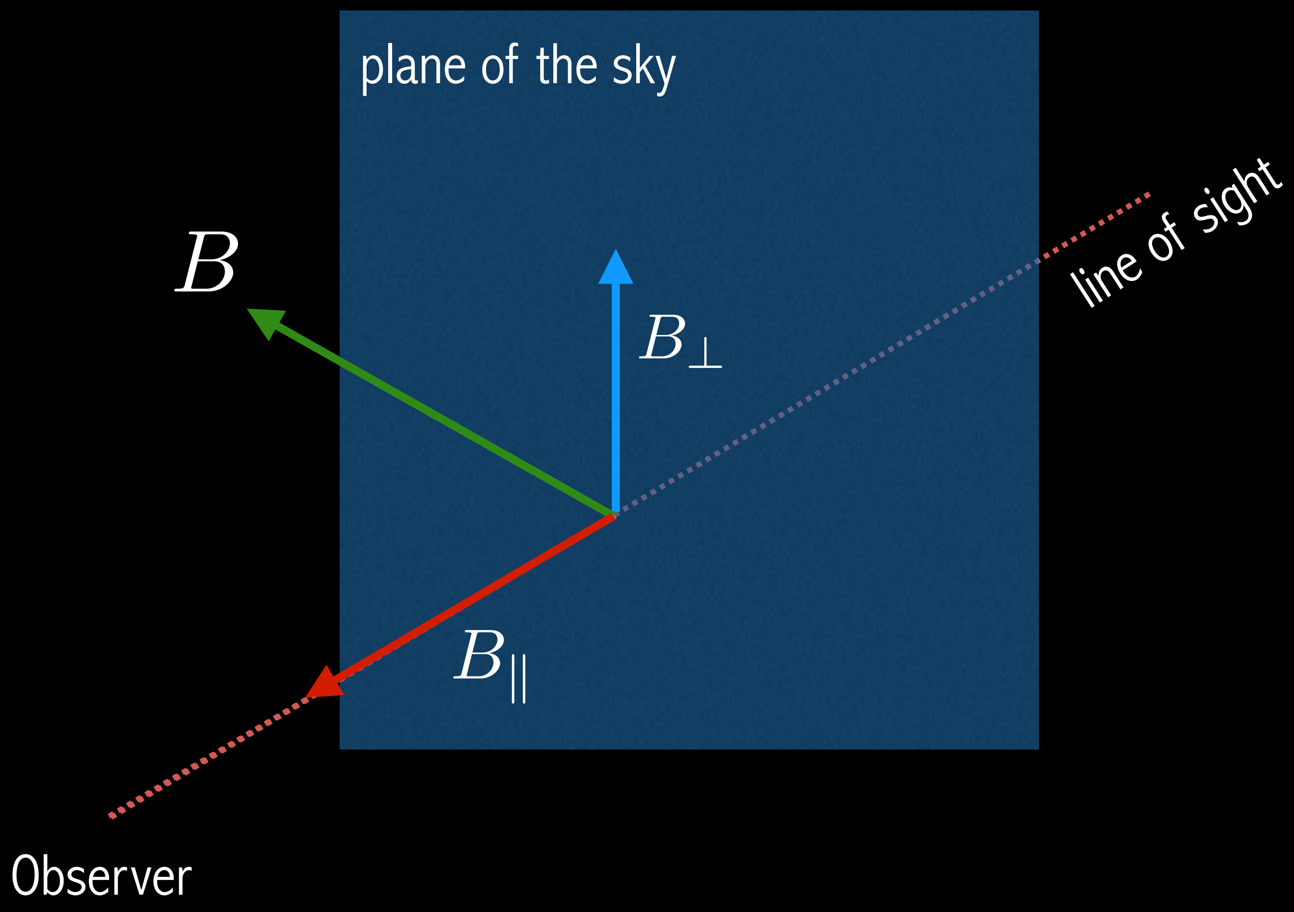
	Magnetic field strength [G]
"Seeds" fields in the early Universe	$10^{-30} - 10^{-20}$
Intergalactic gas	$(1 - 10) \times 10^{-9}$
Intracluster gas	$(0.1 - 1) \times 10^{-6}$
Human brain	$(1 - 100) \times 10^{-6}$
Interstellar gas	$< 1 \times 10^{-3}$
Center of the Milky Way	$< 10 \times 10^{-3}$
Earth magnetic field	$\sim 500 \times 10^{-3}$
Refrigerator magnet	~ 50
Magnetic resonance imaging	$(15 - 30) \times 10^{3}$
Normal star (HD 215441)	34×10^{3}
White dwarf (PG J1847-0130)	10^{6}
Strongest pulsed magnetic field (with explosive) in laboratory (VNIIEF, Russia)	28×10^{6}
Magnetar (SGR 1806-20)	$10^{15} - 10^{16}$

A closer look at interstellar magnetic fields

B) hard task: characterizing a vectorial field. Projection effects are crucial !

Artistic view of magnetic fields

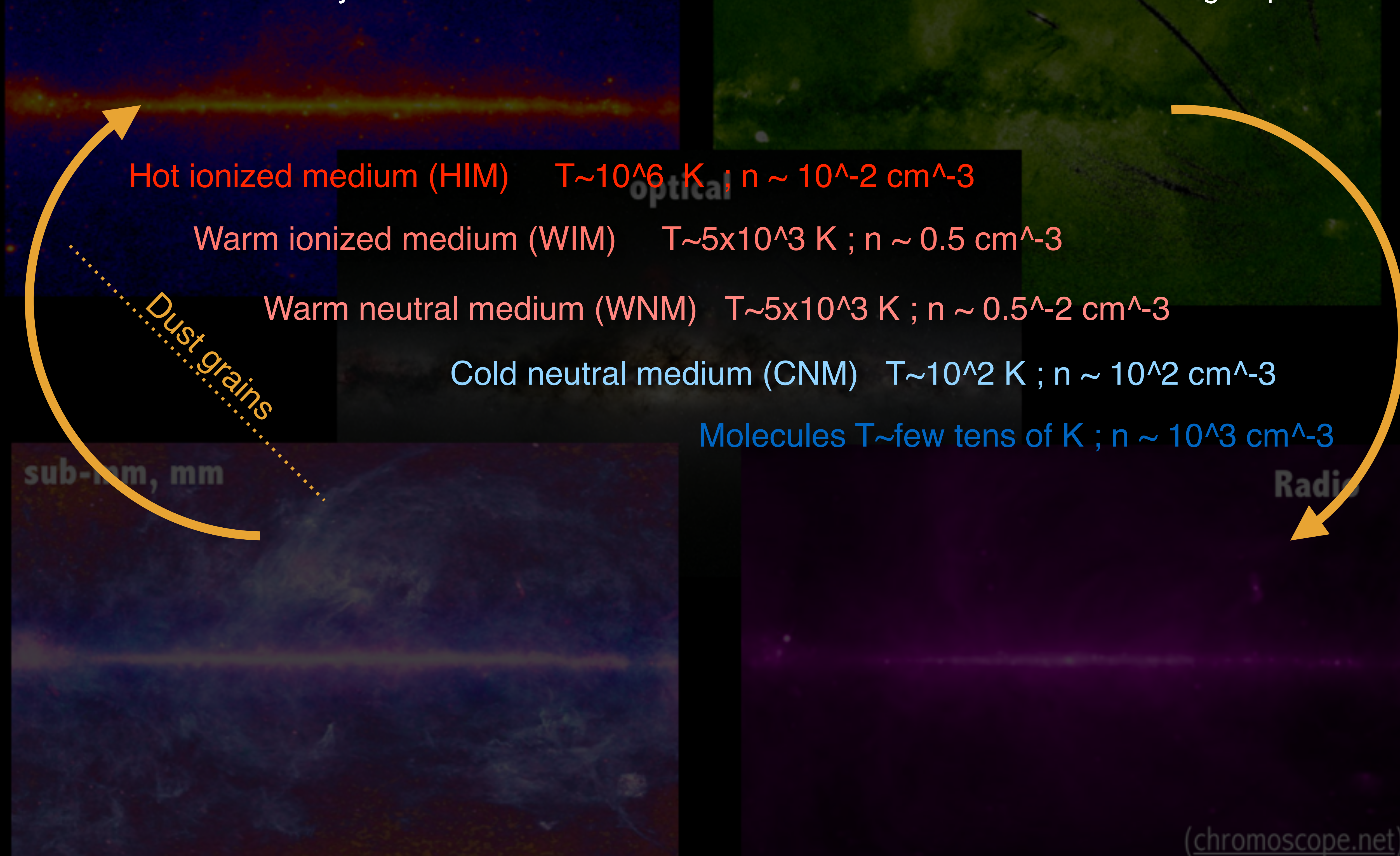
Panagiotis "Takis" Vassilakis



A closer look at interstellar magnetic fields

C) No direct measurement of the magnetic field!

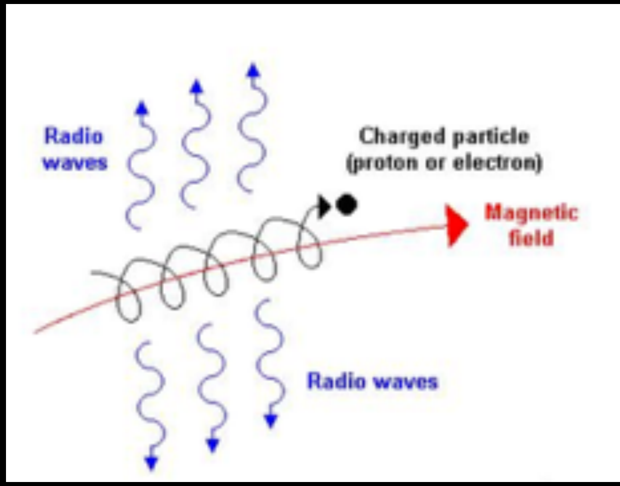
Observations must rely on its interaction with interstellar matter in the different gas phases!



How to measure interstellar magnetic fields

Synchrotron emission and polarization

Hot ionized medium



Orientation of $B_\perp$

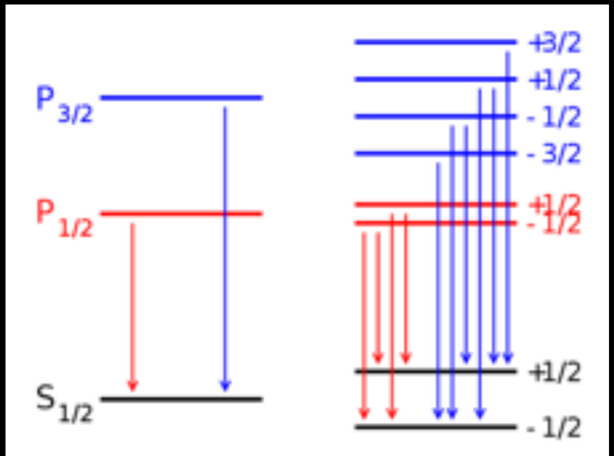
strength of B

Zeeman effect

(measure of circular polarization)

Cold neutral medium

Molecules



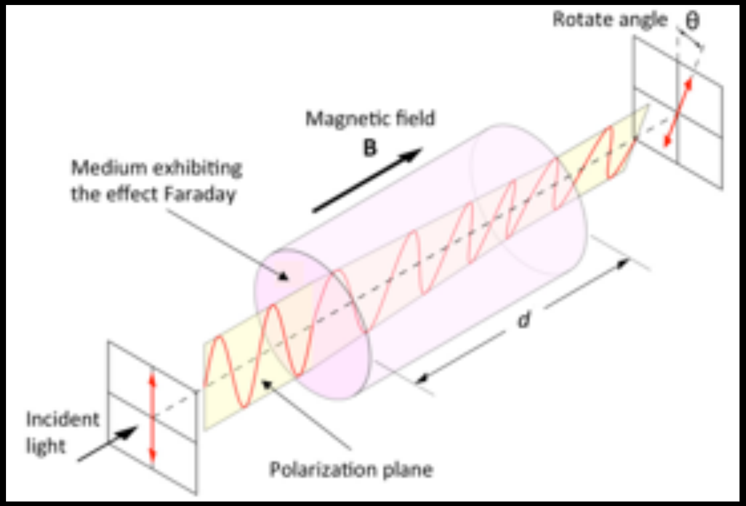
Direction/ strength of $B_{||}$

Faraday rotation

(rotation of polarization plane)

Warm ionized medium

Direction/ strength of $B_{||}$

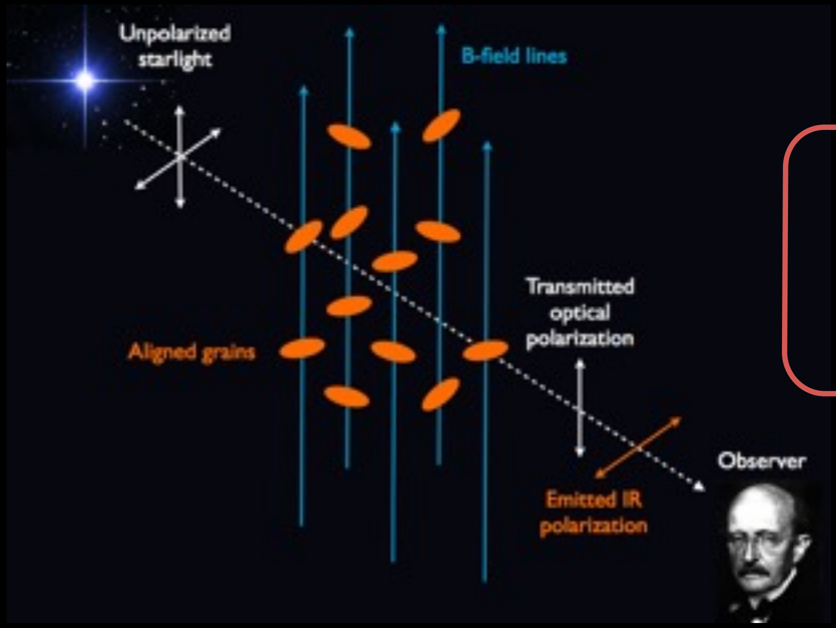


Interstellar dust polarization

Warm neutral medium

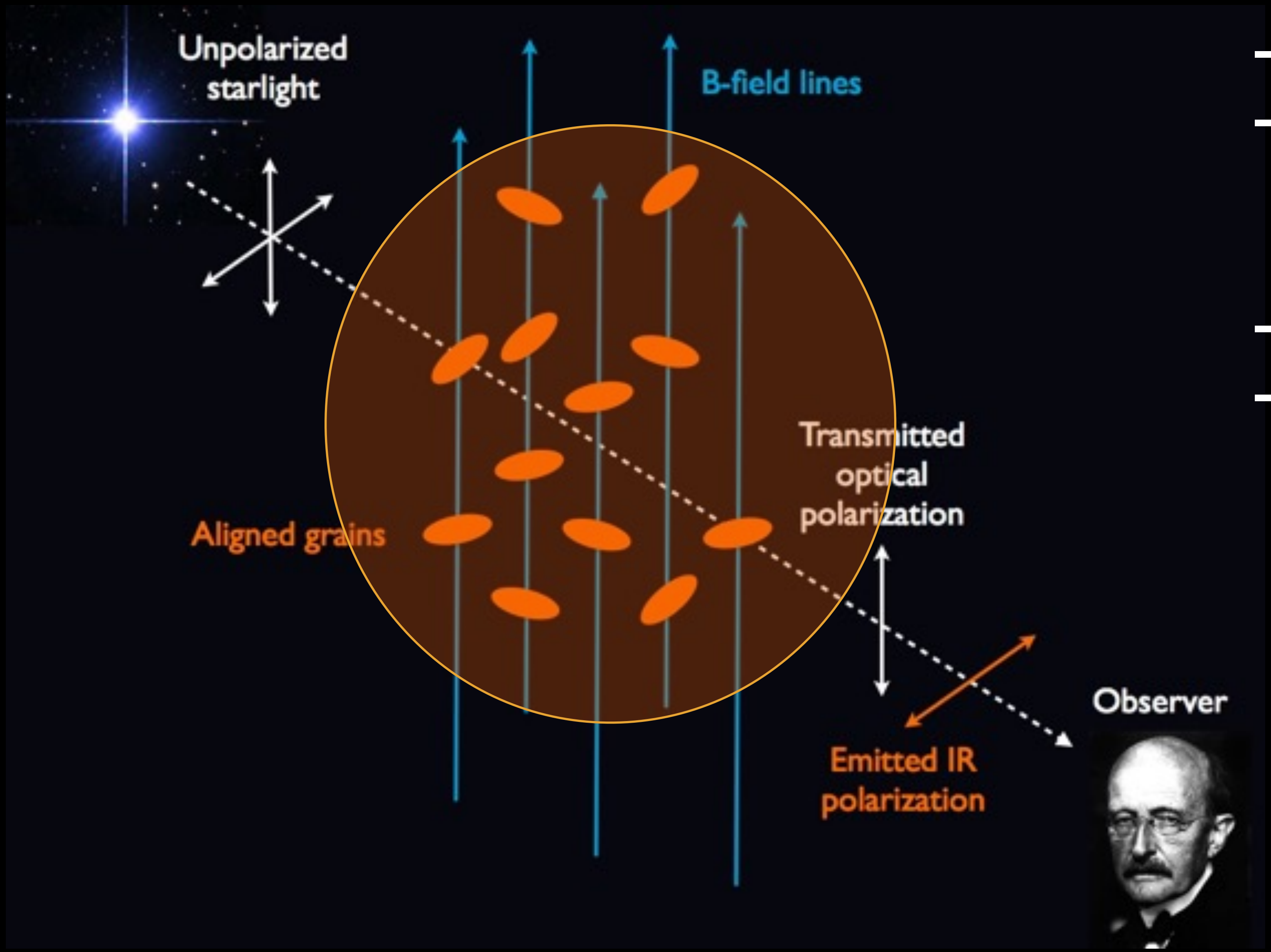
Cold neutral medium

Molecules



Orientation of $B_\perp$

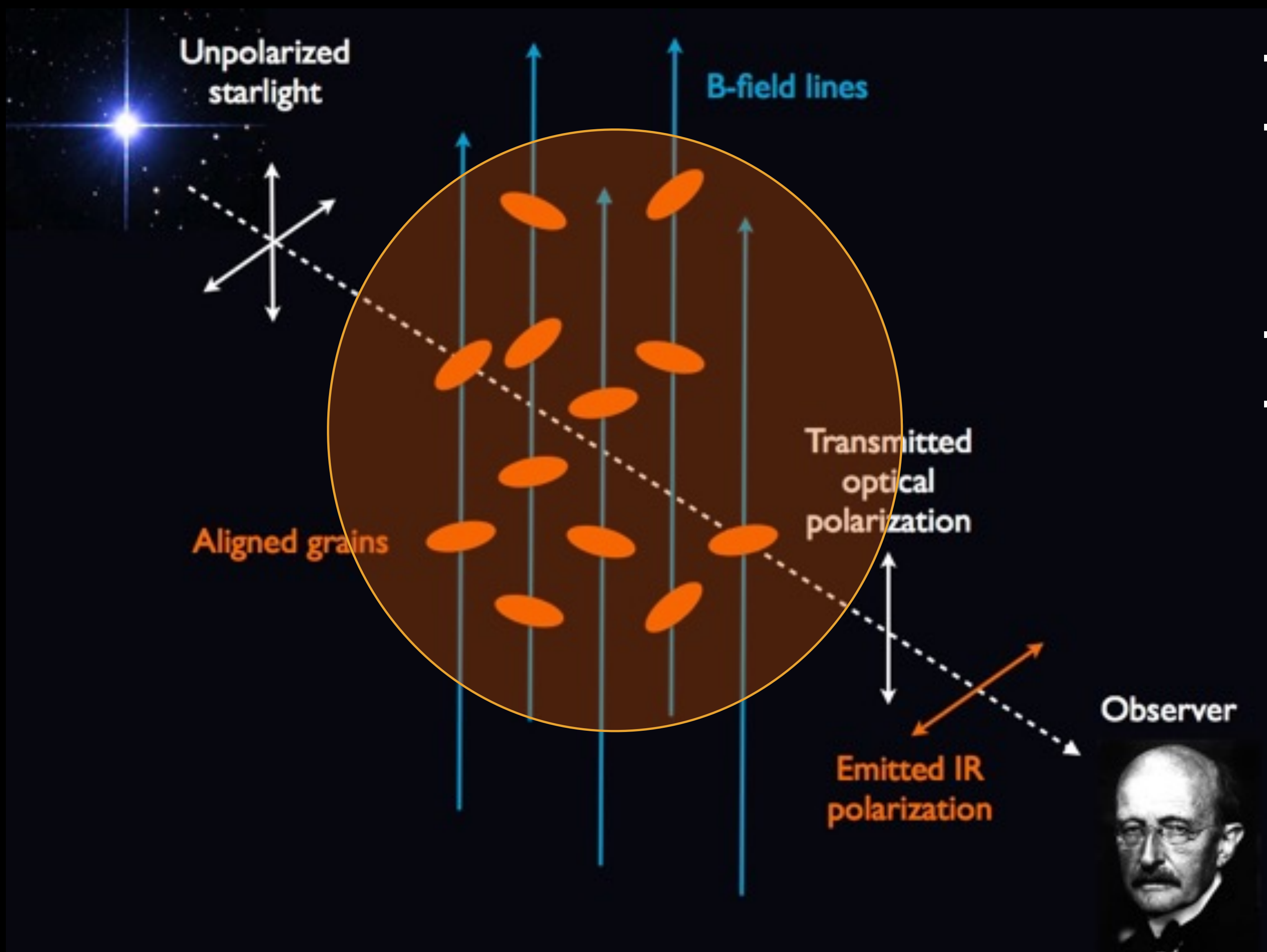
A closer look at dust polarization



- Dust grains are compasses in the sky
- They super-thermally spin around the ambient magnetic field lines (radiative torques - Draine 1996, Lazarian 2015)
- They emit linearly polarized light
- The polarization is maximal when the magnetic field is perpendicular to the line of sight, vice-versa:

On average null polarization

A closer look at dust polarization



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On average null polarization

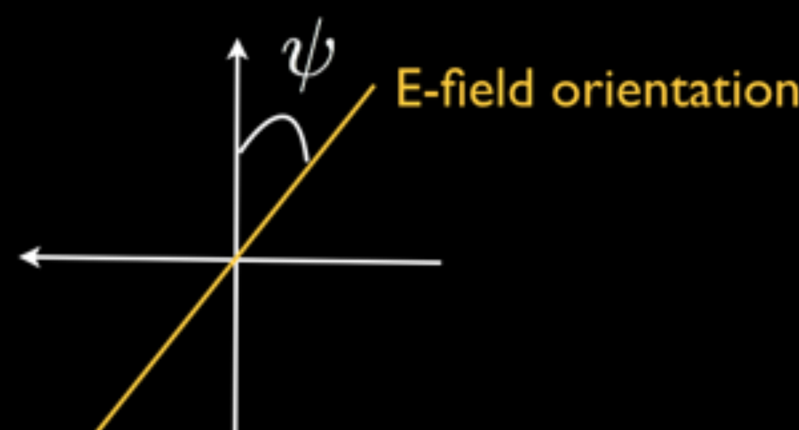
Stokes parameters for linear polarization

I is the total intensity

P is the polarized intensity

$Q = P \cos 2\psi$

$U = P \sin 2\psi$



Observables:

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\psi = \frac{1}{2} \tan^{-1}(U/Q)$$

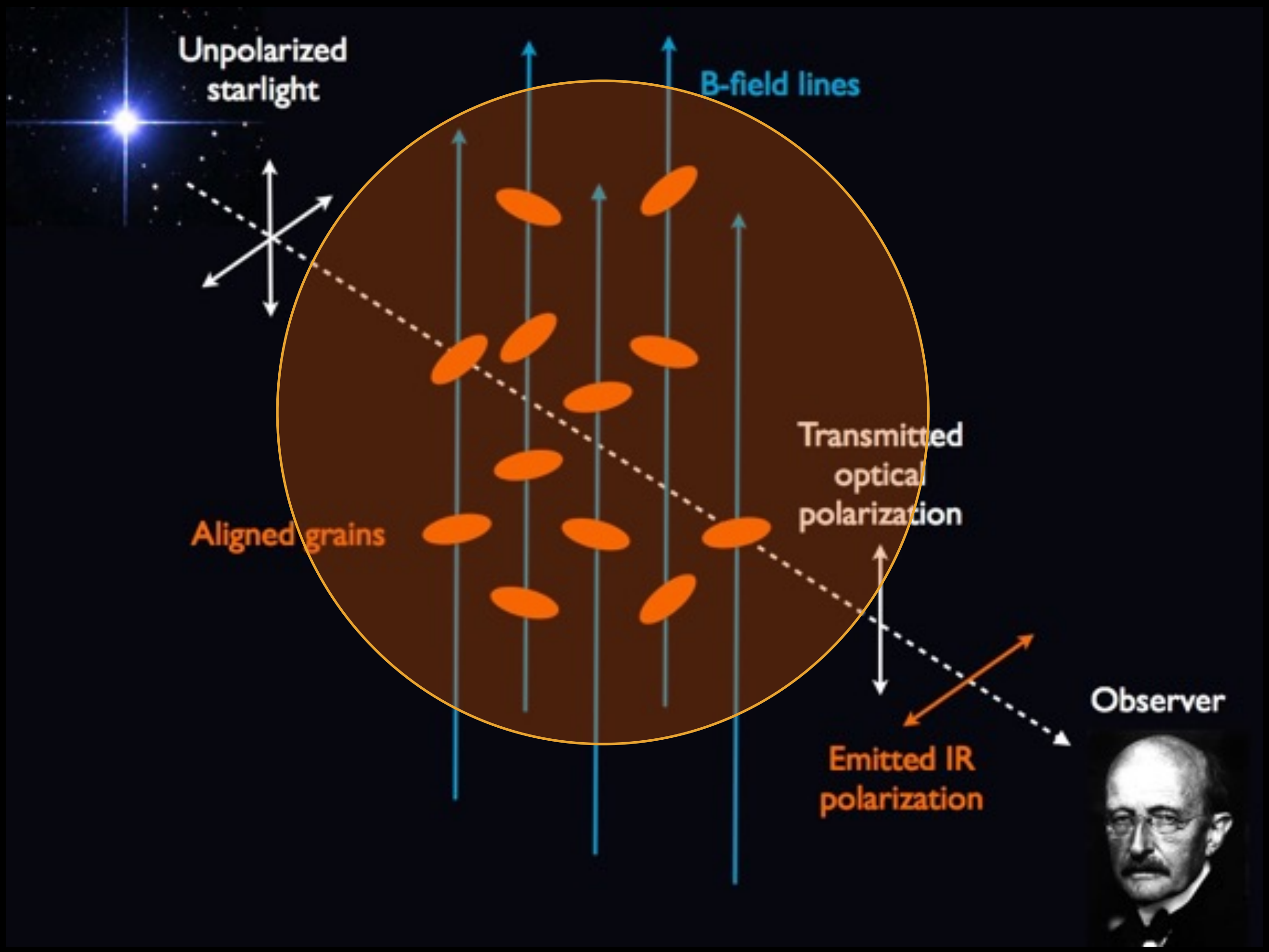
A closer look at dust polarization

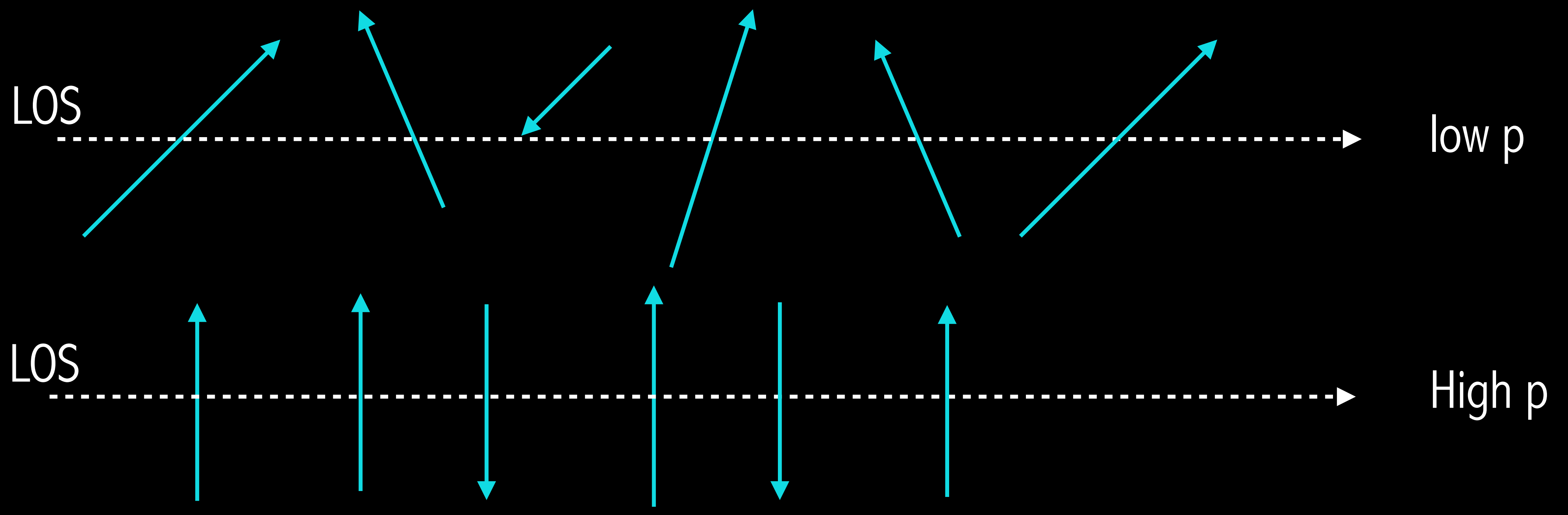
parallel/perpendicular orientation with respect to $B_\perp$

$$\psi = \frac{1}{2}\tan^{-1}(U/Q)$$

$$p = \frac{\sqrt{Q^2+U^2}}{I}$$

The polarization fraction depends on :
- dust properties
- structure of the magnetic field
- turbulence along the LOS generate low p



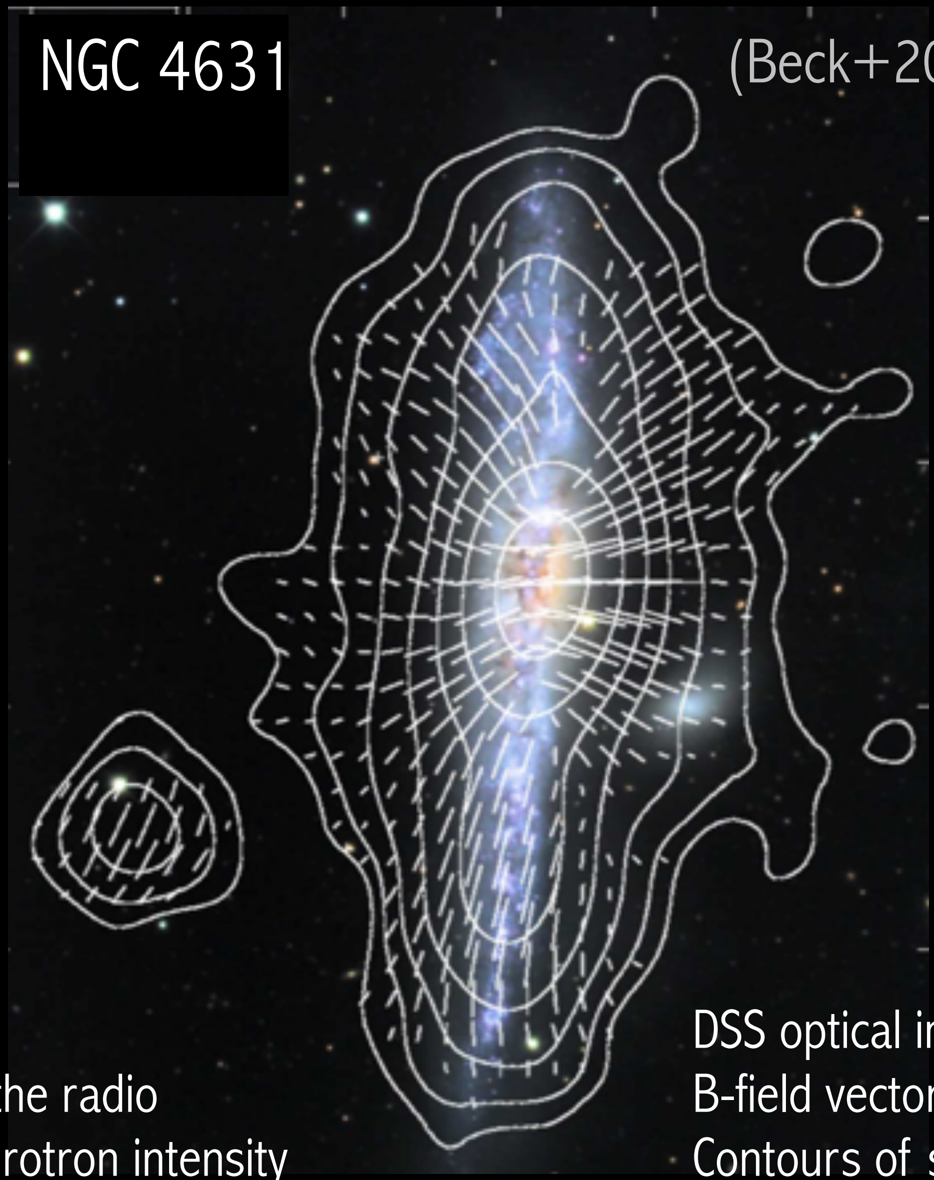


Where do we stand?

$$\vec{B} = \vec{B}_{\rm ord} + \vec{B}_{\rm turb}$$

- From synchrotron polarization **ordered** B-Fields ($\sim 10\,\mu$G) are observed on galactic scales both in edge- and face-on galaxies (see Beck 2015 for a recent review)
- An important **turbulent** component of the B-field ($\sim 5\,\mu$G) results from RM measures and depolarization of synchrotron emission (Sokoloff+1998)

HST optical image
B-field vectors in the radio
Contours of synchrotron intensity



DSS optical image
B-field vectors in the radio
Contours of synch. intensity

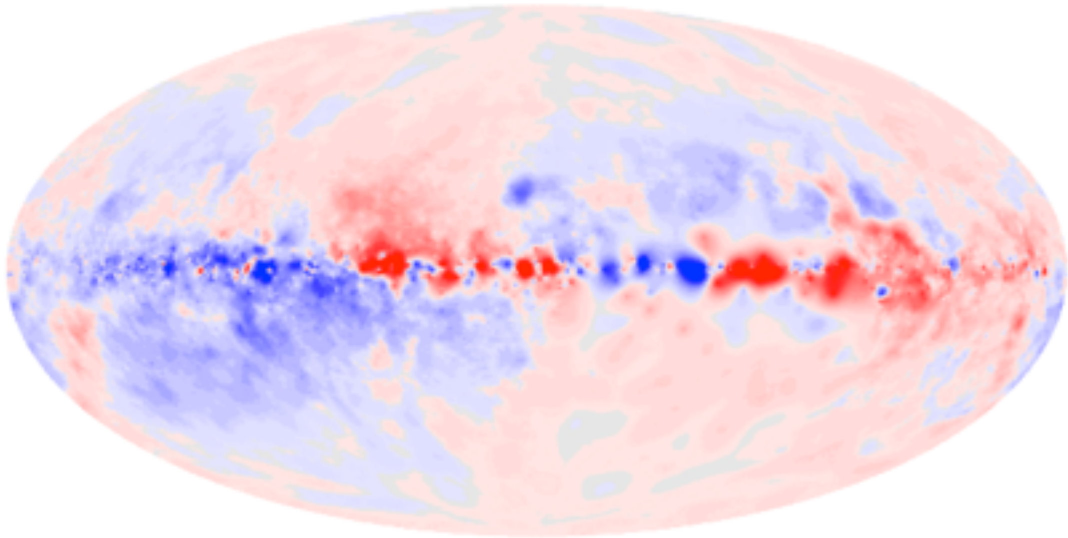
Where do we stand?

$$\Delta\beta = RM\,\lambda^2$$

$$\boxed{RM = C\int n_e B_{\parallel}\, dl}$$

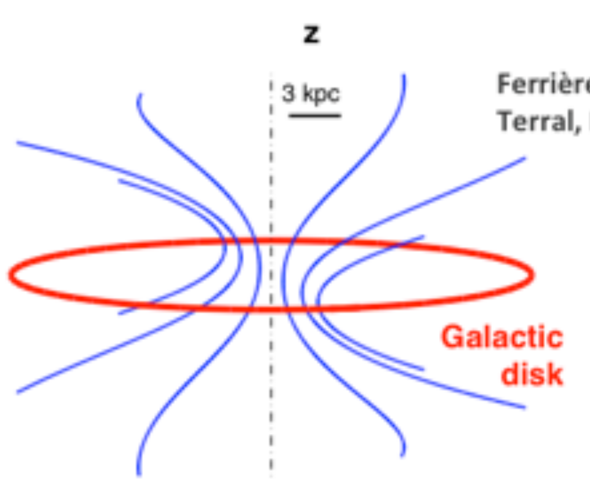
Faraday rotation of point sources

RMs of EGRS (Extra Galactic Radio Sources)

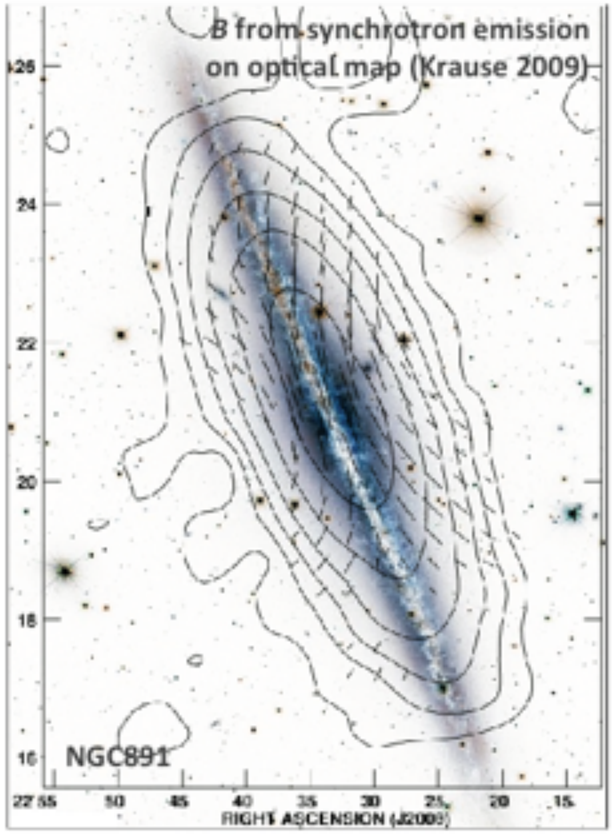


Taylor et al. (2009); Oppermann et al. (2015)

→ In the halo, $\vec{B}_{reg}$:
has **horizontal & vertical components**
is **antisymmetric** wrt midplane $|\ell| < 90°$
is **symmetric** wrt midplane $|\ell| > 90°$



Ferrière & Terral (2014)
Terral, PhD Thesis (2016)



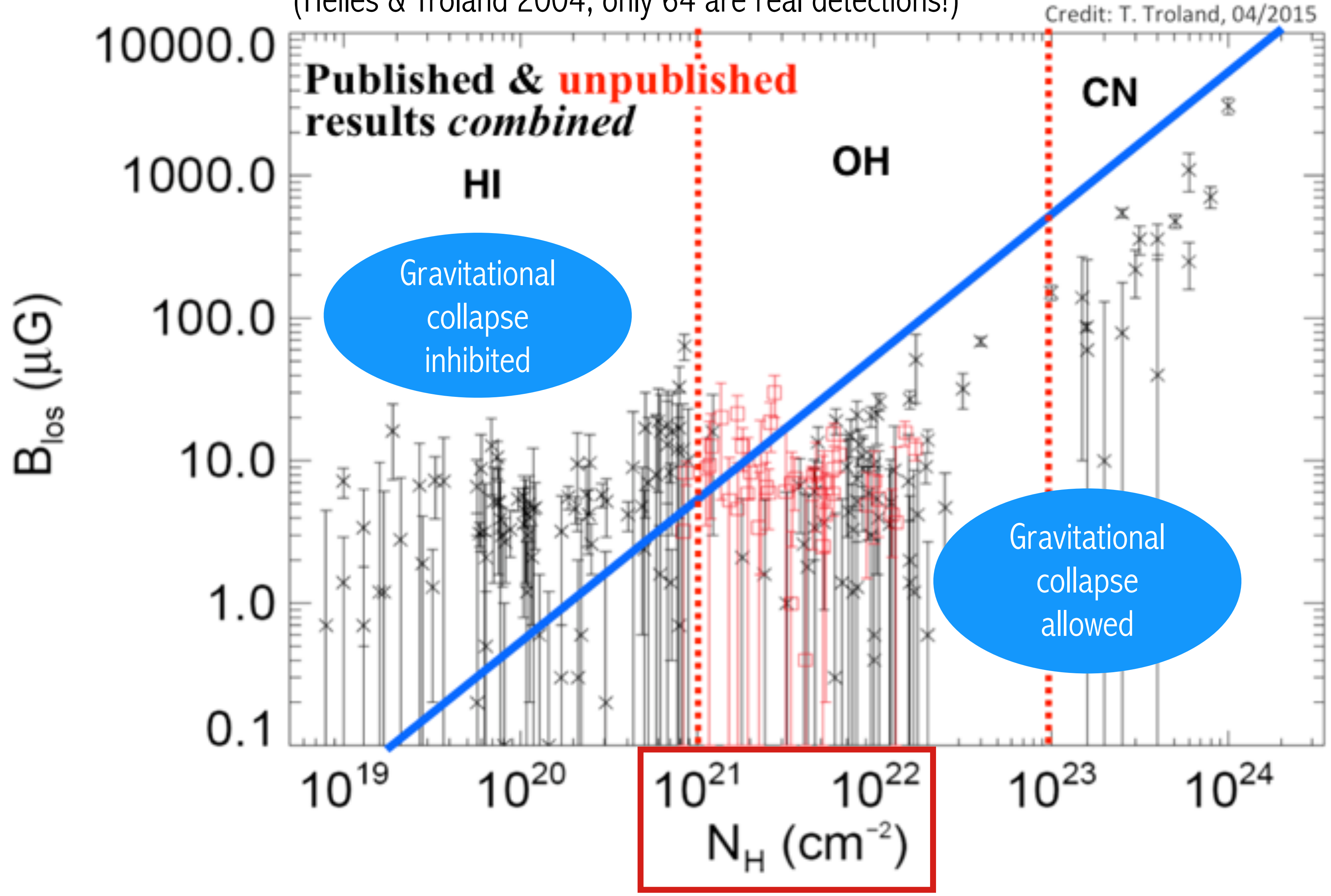
→ Is the **halo bisymmetric (X-shape)** or **axisymmetric (parallel to the plane)**?

Courtesy of M. I. R. Alves @ IRAP

Where do we stand?

Zeeman splitting

(Heiles & Troland 2004, only 64 are real detections!)



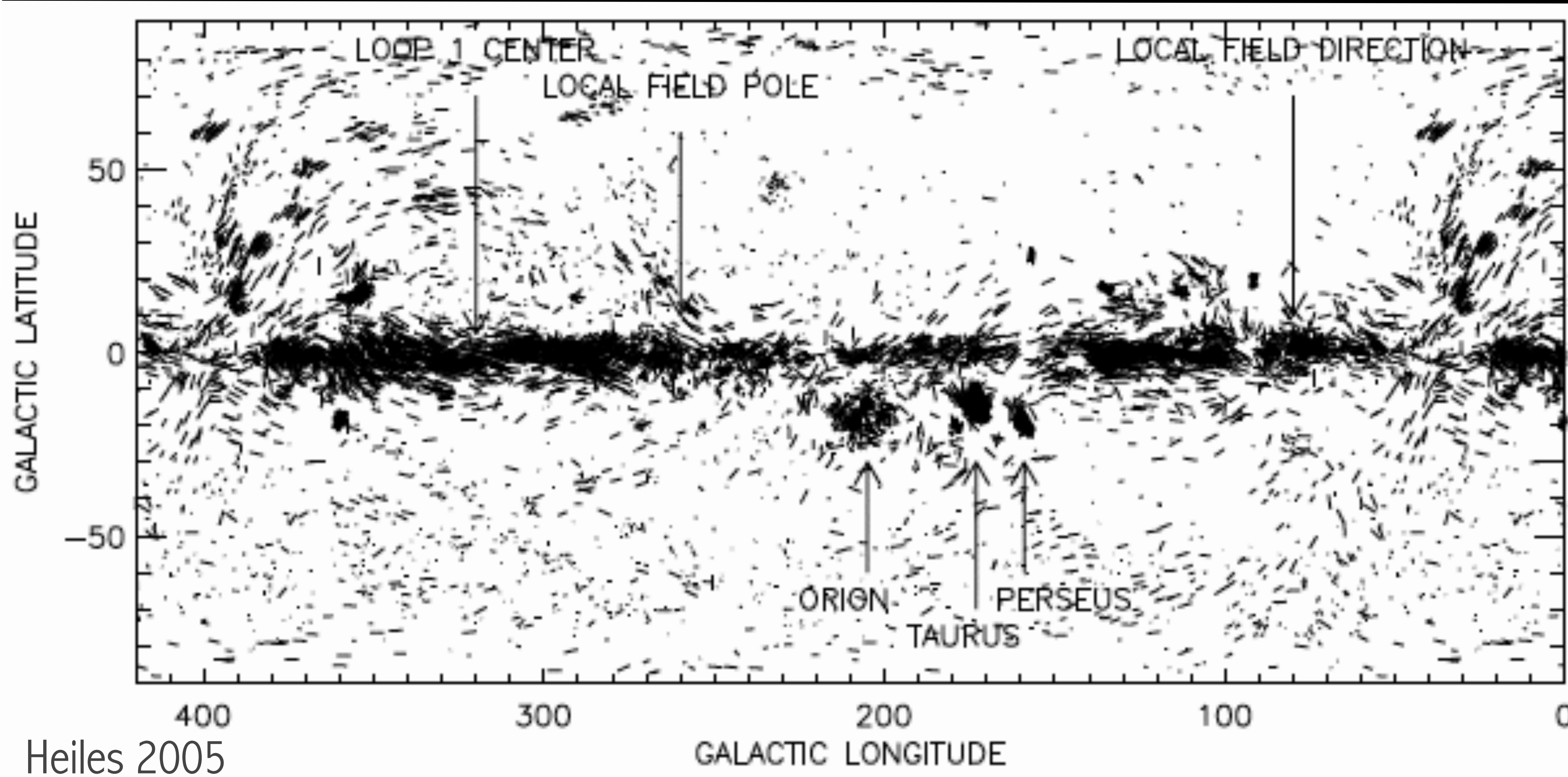
→ In atomic clouds: B ~ a few µG

→ In molecular clouds: B ~ (10 – 1000) µG

(see also Crutcher+2010)

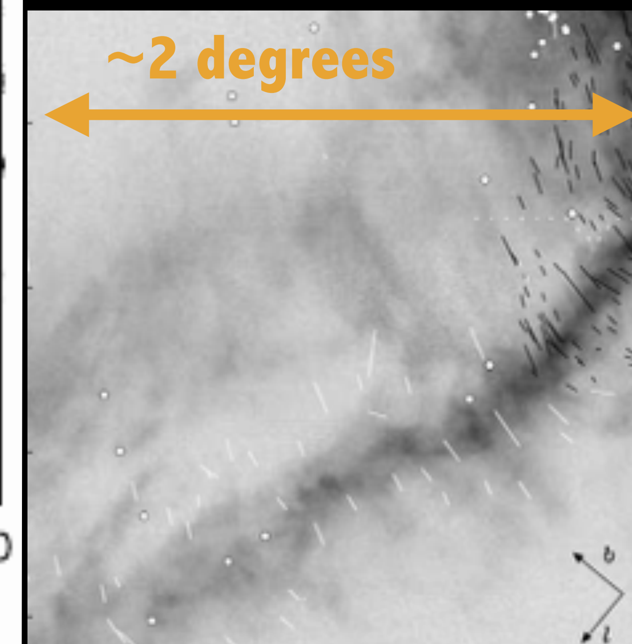
Courtesy of M. I. R. Alves @ IRAP

The magnetic field structure in our Galaxy

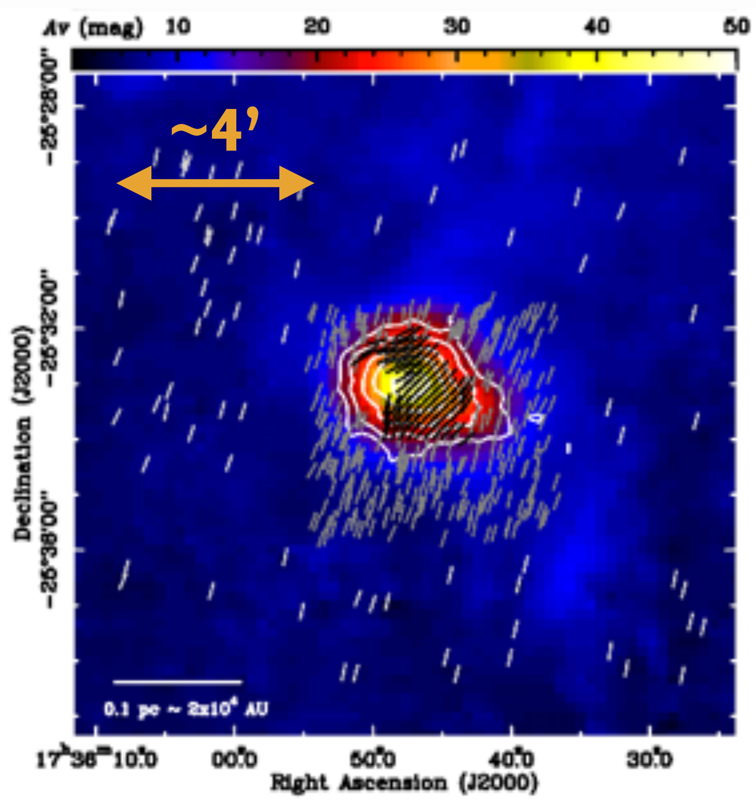


Heiles 2005

- Stellar polarimetry point-like measures constrained by extinction along the line of sight



Chapman et al. 2011



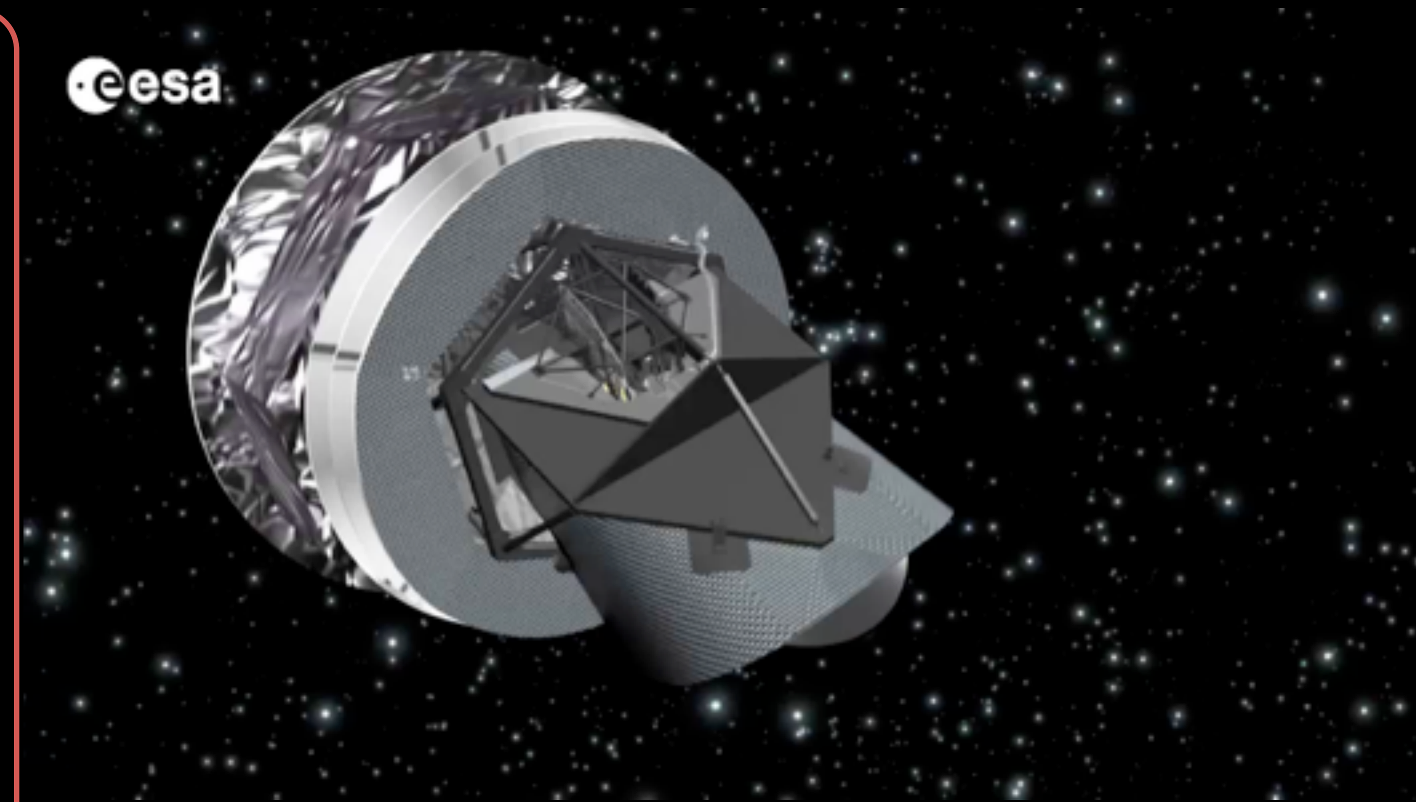
- Balloon-borne and ground-based experiments targeted objects in emission at high resolution in the Milky Way

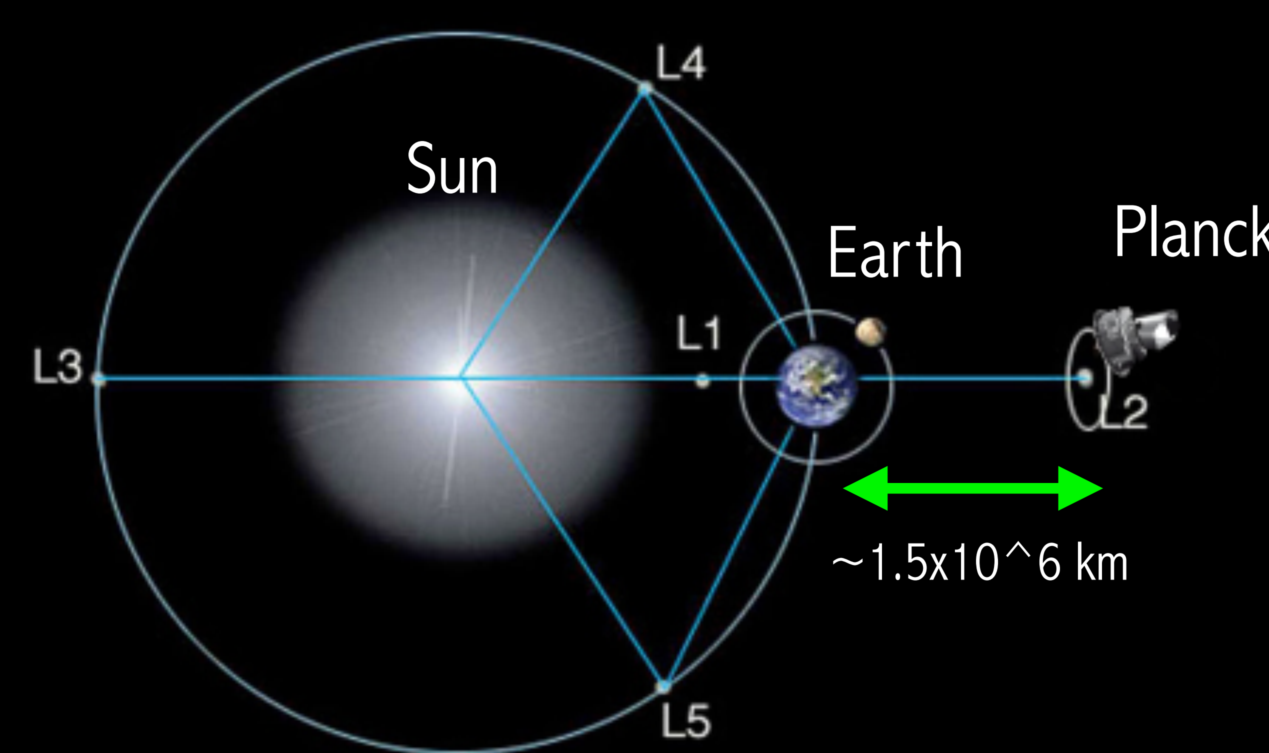
- Link between the large scales and small scales
- No statistical conclusions from observations (Goodman+95, Li+13, Clark+14, ...)

Alves+14

The dusty and polarized interstellar medium with Planck

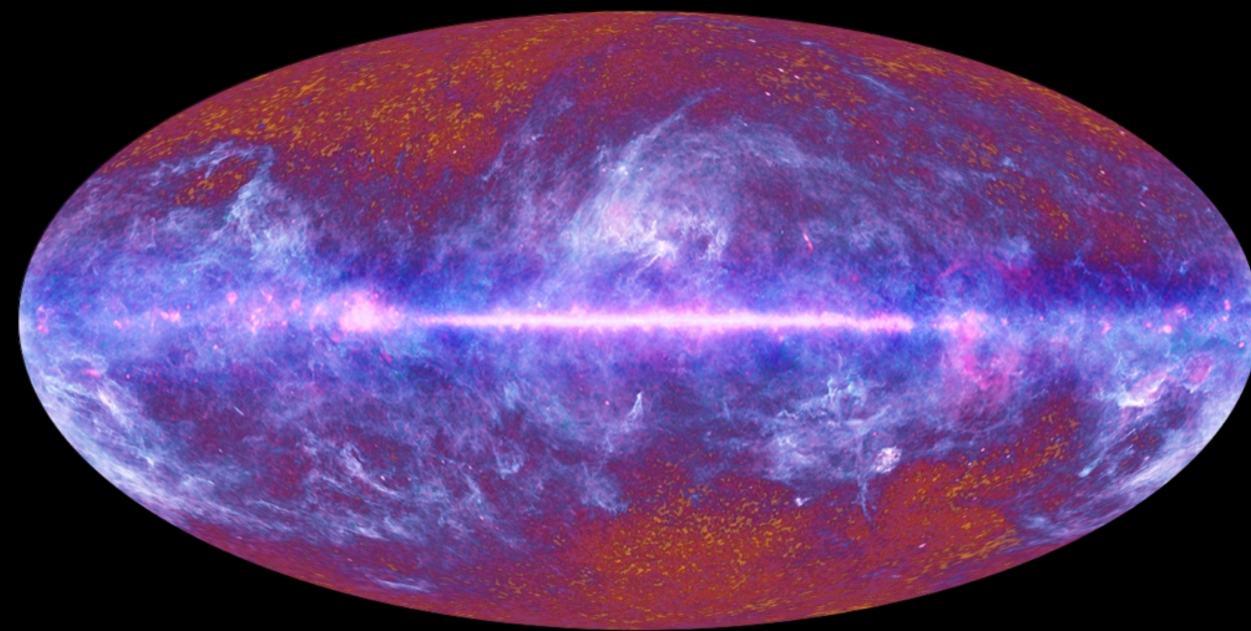
- 3rd generation satellite to study CMB anisotropies in intensity and polarization
- Need of studying foregrounds
- High and Low Frequency Instruments, from the radio to the mm range.
- All-sky survey at 9 frequencies. Polarization data for the 7 lowest frequencies, also at **sub-mm and mm wavelengths!**
- Five HFI full-sky surveys with different scanning strategies. Redundancy is key to identify and correct for systematics
- End of HFI Cryogen in January 2012.
- New insights for Galactic science at 850μm

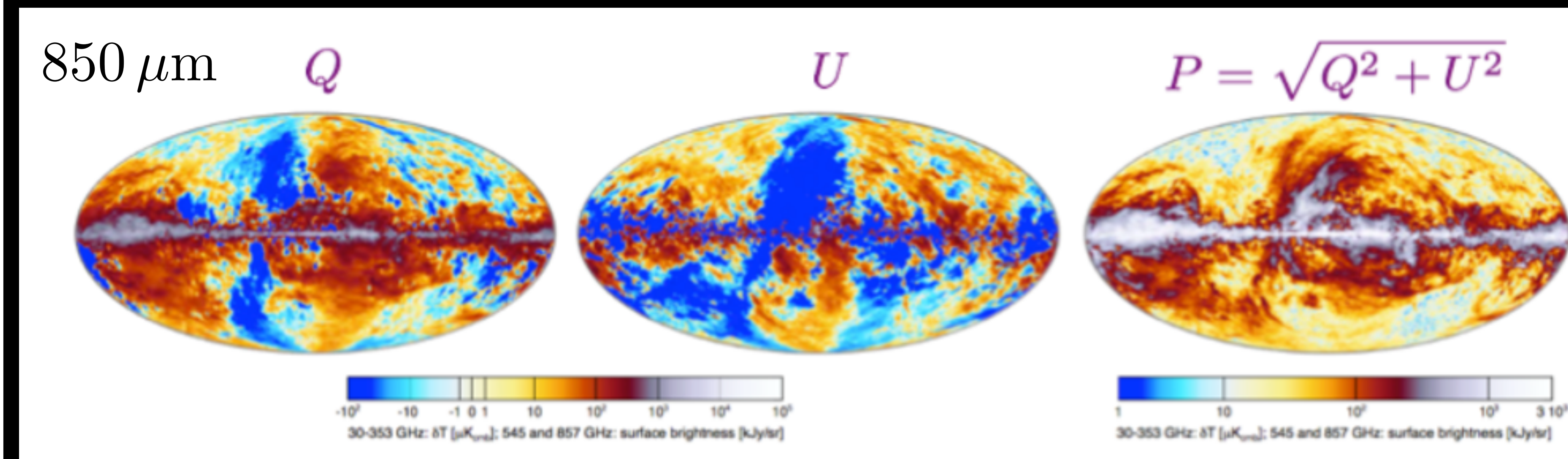




The dusty and polarized interstellar medium with Planck

Total intensity of Planck at sub-mm, mm wavelengths (Planck 2013 results. I)



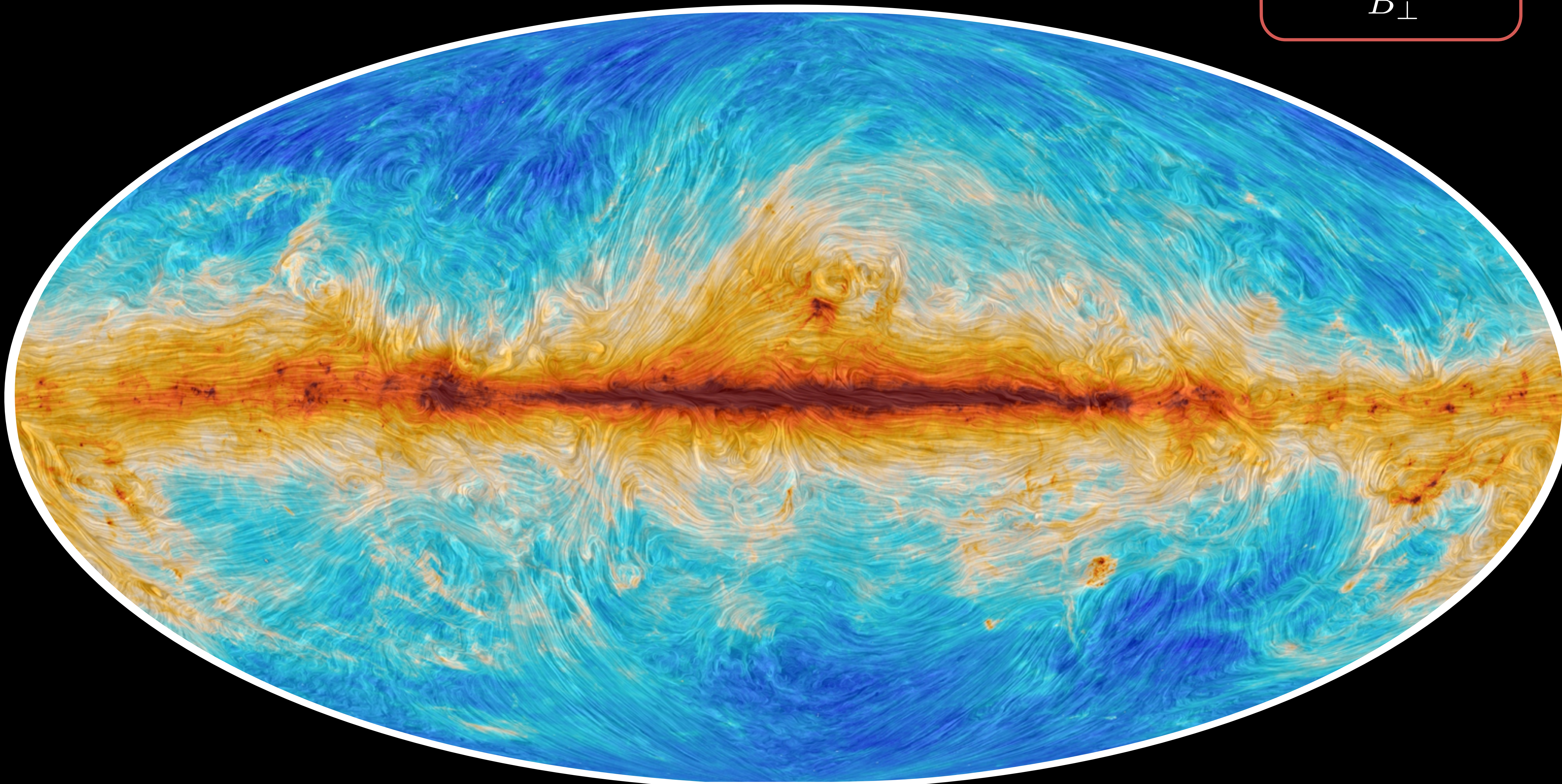


The sky looks different in polarization !

The magnetic field orientation from dust polarization with Planck

Galactic emission at 353 GHz (or 850 um) (Planck 2013 results. I)
with drapery tracing magnetic field lines (LIC)

Orientation of
$B_\perp$



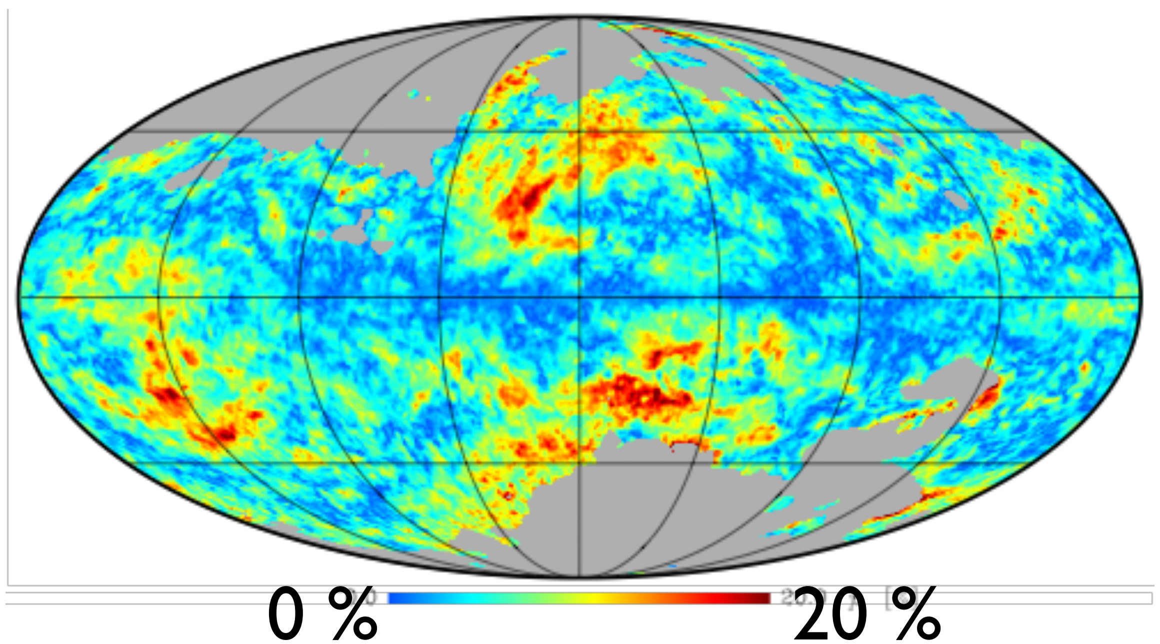
Properties of large-scale thermal dust polarization

- Low polarization fractions in the Galactic Plane and some highly polarized regions
- Thin filamentary structures of low polarization with no material counterpart

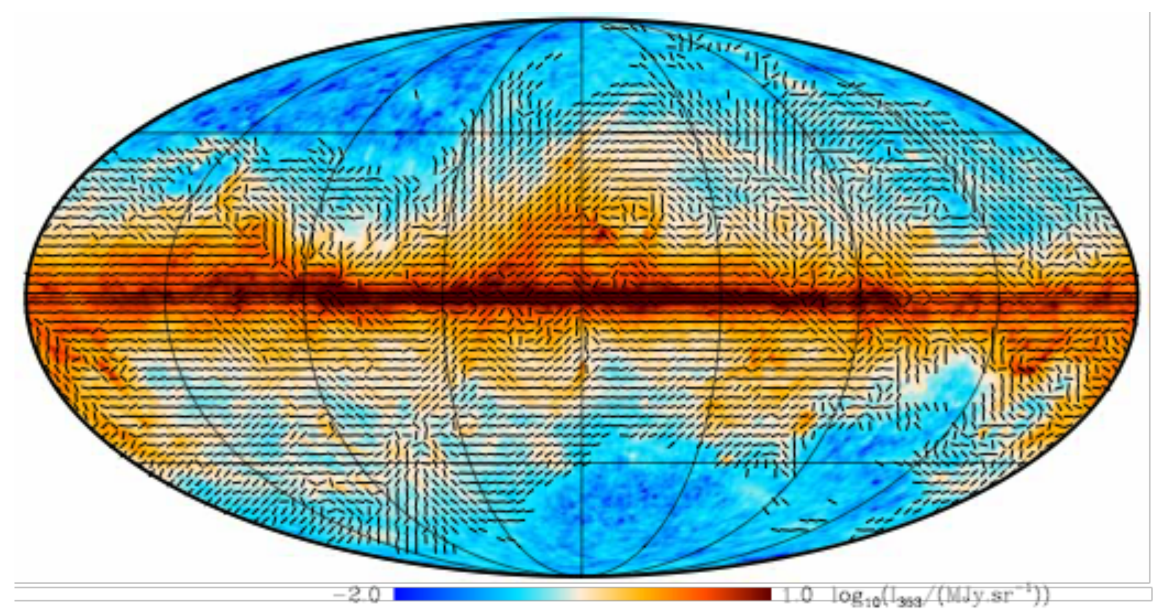
High polarization fraction due to ordered B-field patterns but …

(Grey mask due to residual systematic effects in the data)

Polarization fraction $p = \frac{P}{I}$



Polarization angle $\psi = \frac{1}{2}\mathrm{atan}(U, Q)$



Update in early 2017…

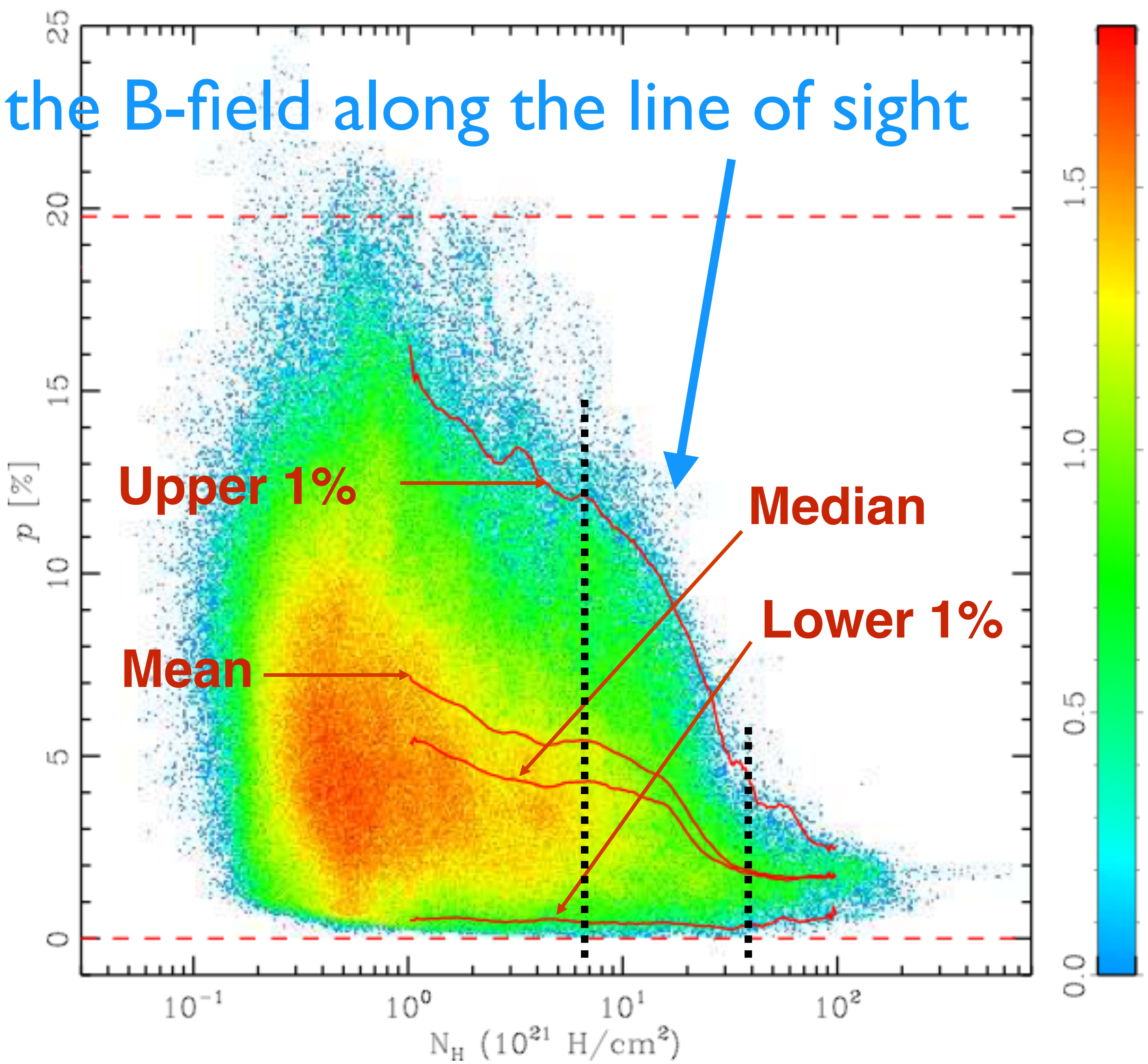
Planck Collaboration Int. XIX (2015)

… strong depolarization across the sky!

Some of the main Planck results on Galactic magnetic fields

Polarization fraction vs. column density

- Intrinsic dust polarization at least of order 20%
- Decrease of the maximum polarization fraction with increasing column density



column of dust along the line of sight

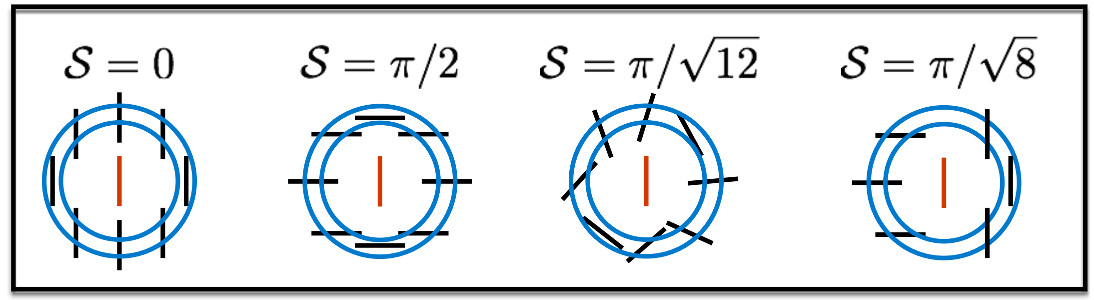
Planck Collaboration Int. XIX (2015)

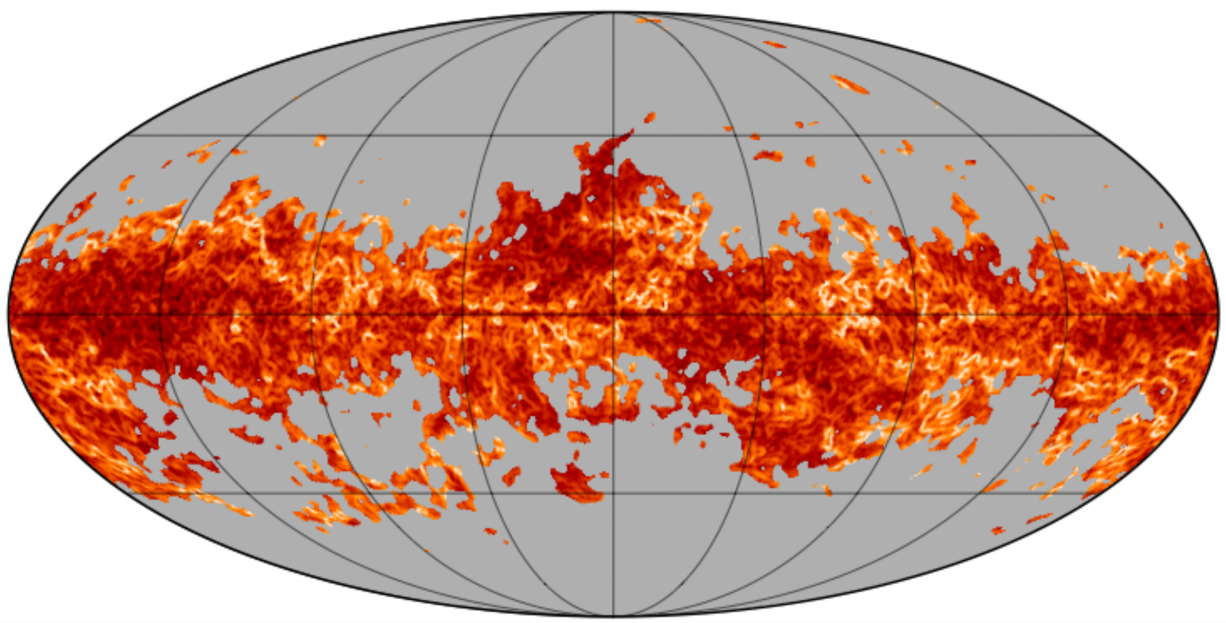
Some of the main Planck results on Galactic magnetic fields

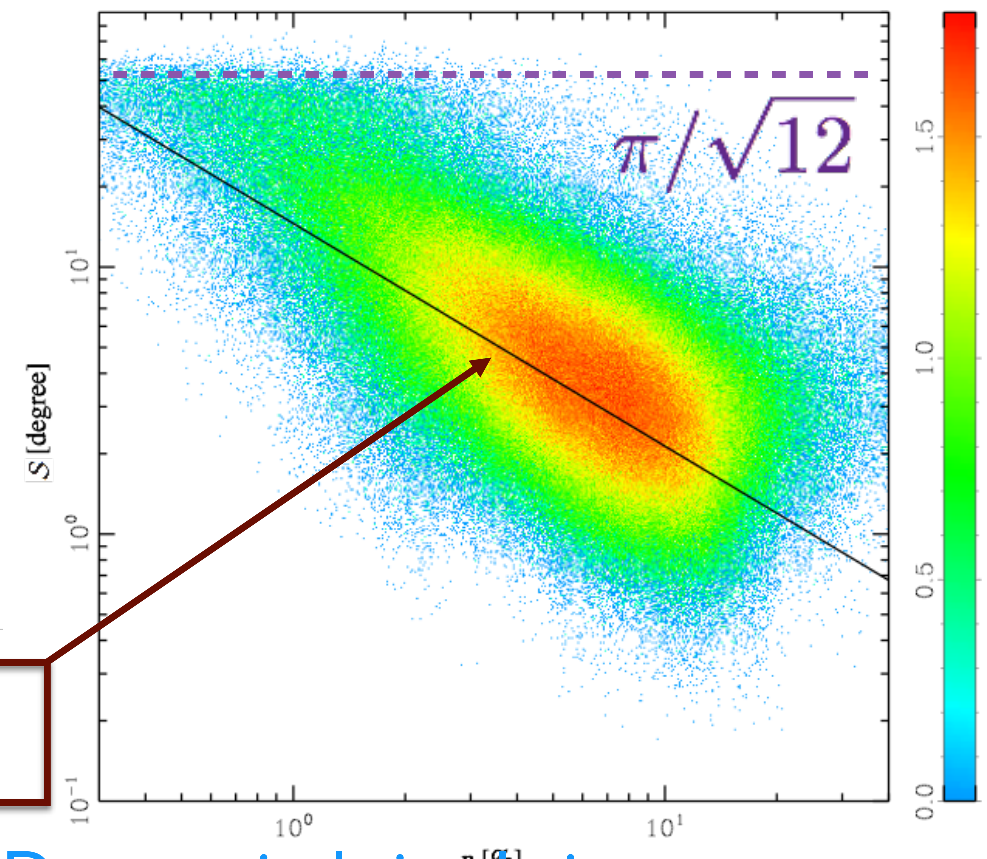
Spatial structure of the polarization angle map

Polarization angle dispersion function

$$\mathcal{S}(\boldsymbol{r},\delta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\psi(\boldsymbol{r}+\boldsymbol{\delta}_i)-\psi(\boldsymbol{r})\right]^2}$$







$$\log(\mathcal{S}/\,\mathrm{deg}) = -0.834\log p - 0.504$$

Have a look at Planck int. results XX on MHD numerical simulations

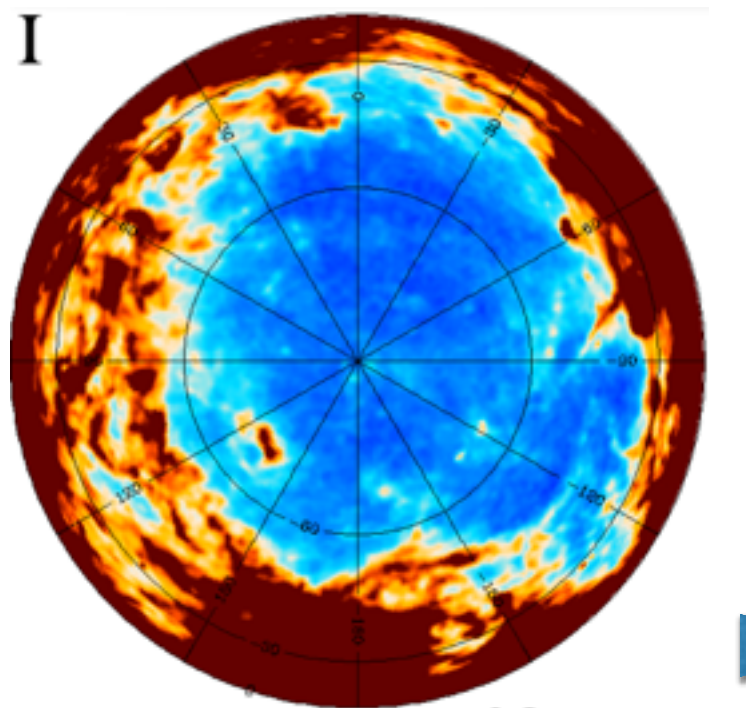
- Strongly anti-correlated with the polarization fraction
- Low polarization fractions found where the polarization angle direction changes abruptly
- Increased lag δ flattens the anti-correlation

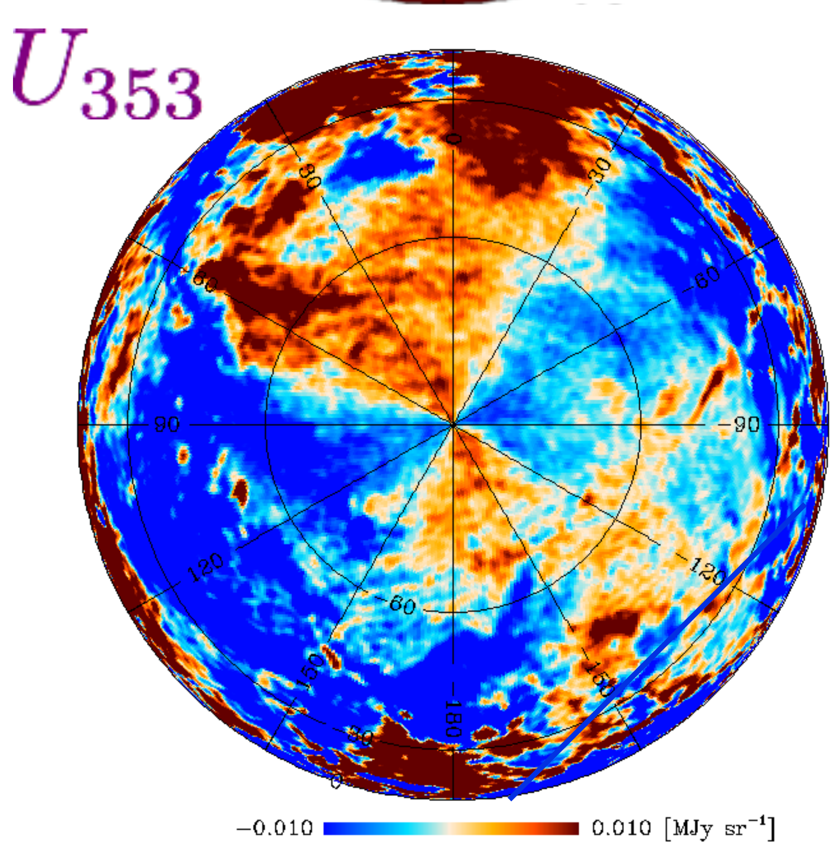
Planck Collaboration Int. XIX (2015)

Important turbulent component of the magnetic field!

Some of the main Planck results on Galactic magnetic fields

A Gaussian model of the polarized sky





Warm neutral medium

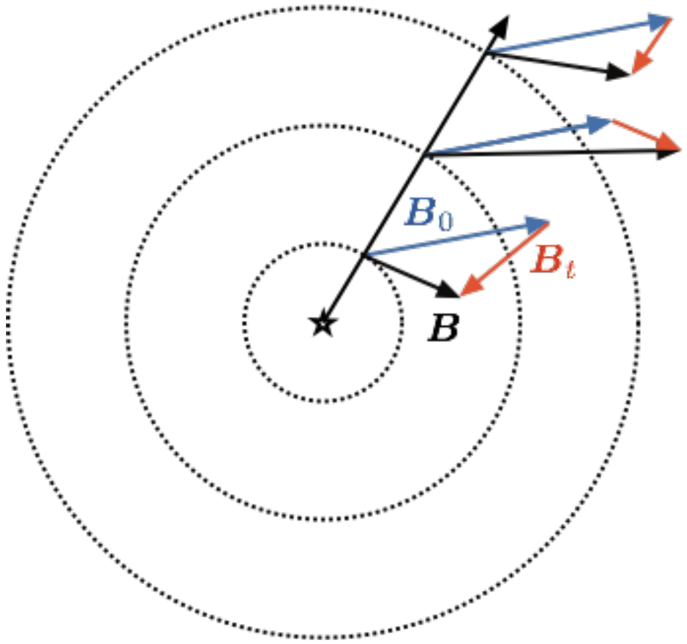
Magnetic field $\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}_t$

Uniform field Turbulent field

Planck Collaboration Int. XXXII, XLIV (2016)

A Gaussian model of the polarized sky

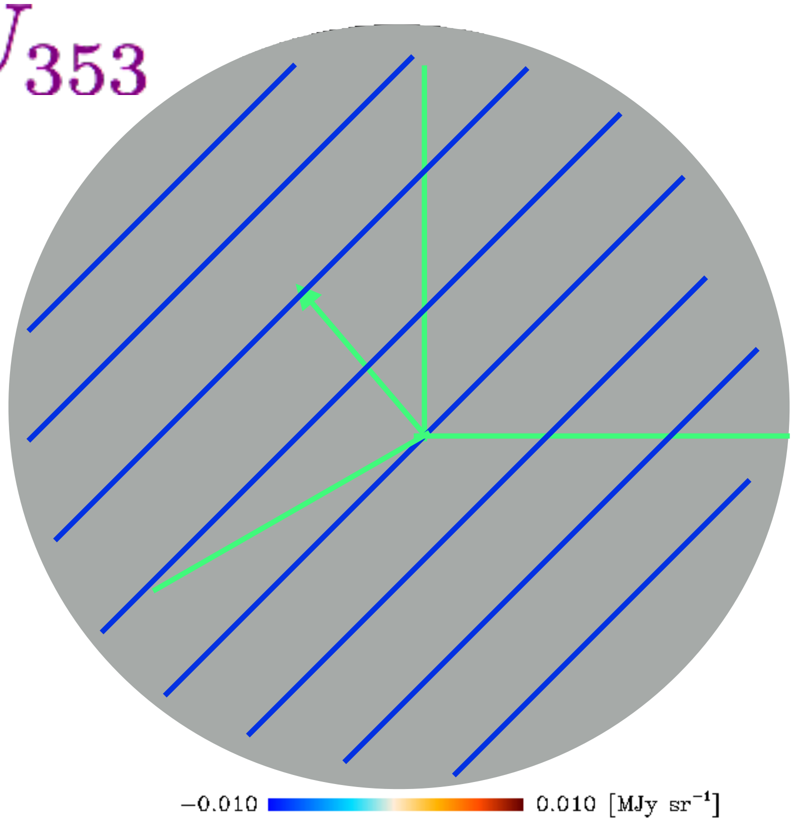
Warm neutral medium



Magnetic field $B = B_0 + B_t$

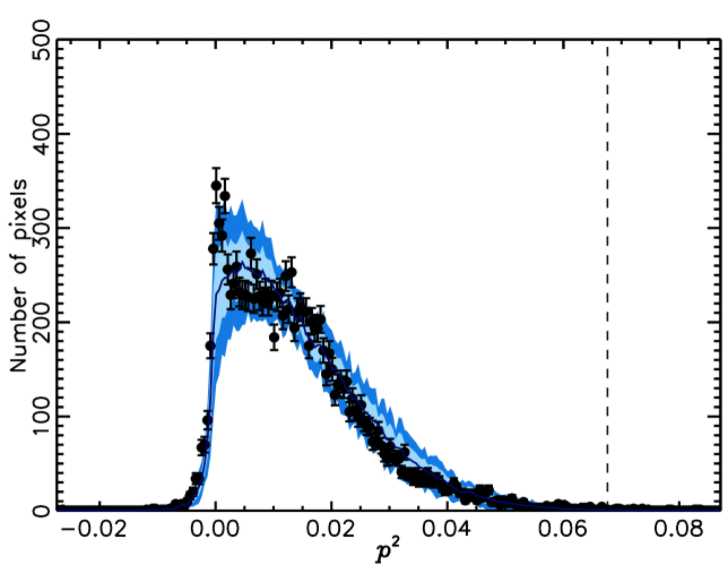
Uniform field | Turbulent field

- A superposition of variously polarized layers (turbulent cells ?)
- Turbulent field : 3D Gaussian random variable
- Analysis of the Southern Galactic cap

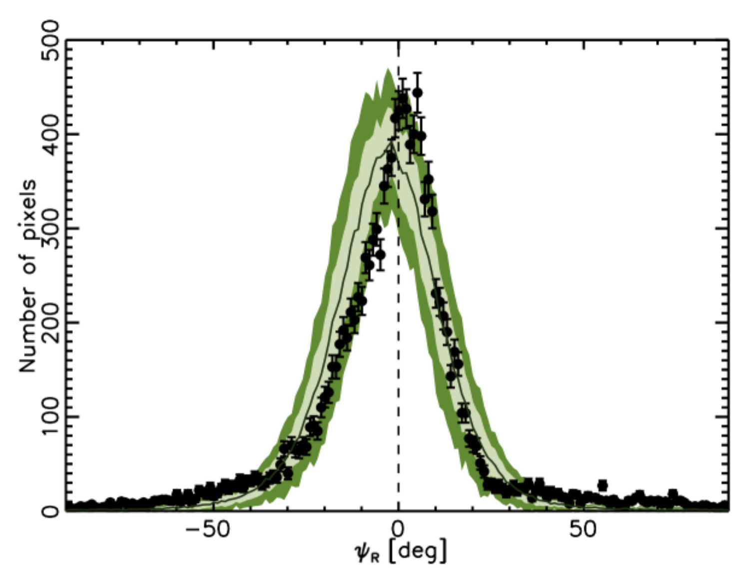


- Spatial power spectrum unconstrained $C_\ell \propto \ell^{\alpha_M}$
- Direction of the large-scale field $(l_0, b_0) = (70 \pm 5°, 24 \pm 5°)$
- Turbulent-to-mean ratio $f_M = 0.9 \pm 0.1$
- Number of layers $N = 7 \pm 2$
- Intrinsic polarization fraction $p_0 = 26 \pm 3\%$

<u>Observations (black dots) vs. Simulations (colored regions)</u>



Polarization fraction



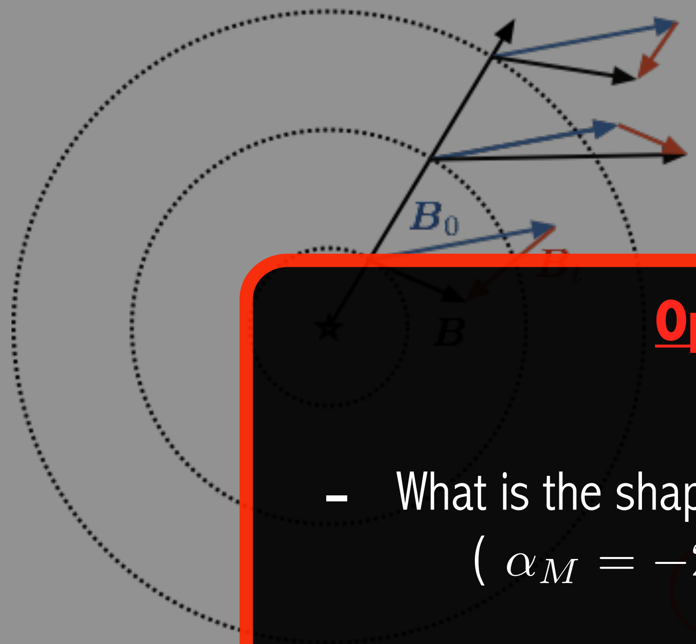
Polarization angle relative to the large-scale field

Planck Collaboration Int. XXXII, XLIV (2016)

Some of the main Planck results on Galactic magnetic fields

A Gaussian model of the polarized sky

Warm neutral medium



Magnetic field $B = B_0 + B_t$

Uniform field — Turbulent field

- A superposition of variously polarized layers (turbulent cells ?)
- Turbulent field : 3D Gaussian random variable

Open questions and challenges

- What is the shape and the meaning of the "turbulent" power spectrum ? ($\alpha_M = -2.5 \pm 0.1$, Vansyngel+2016, Ghosh+2016)
- What is the role of the multiphase ISM? (Ghosh+2016)

- Spatial power spectrum unconstrained $C_\ell \propto \ell^{\alpha_M}$
- Direction of the large-scale field $= (70 \pm 5°, 24 \pm 5°)$
- Turbulent-to-mean ratio $f_M = 0.9 \pm 0.1$
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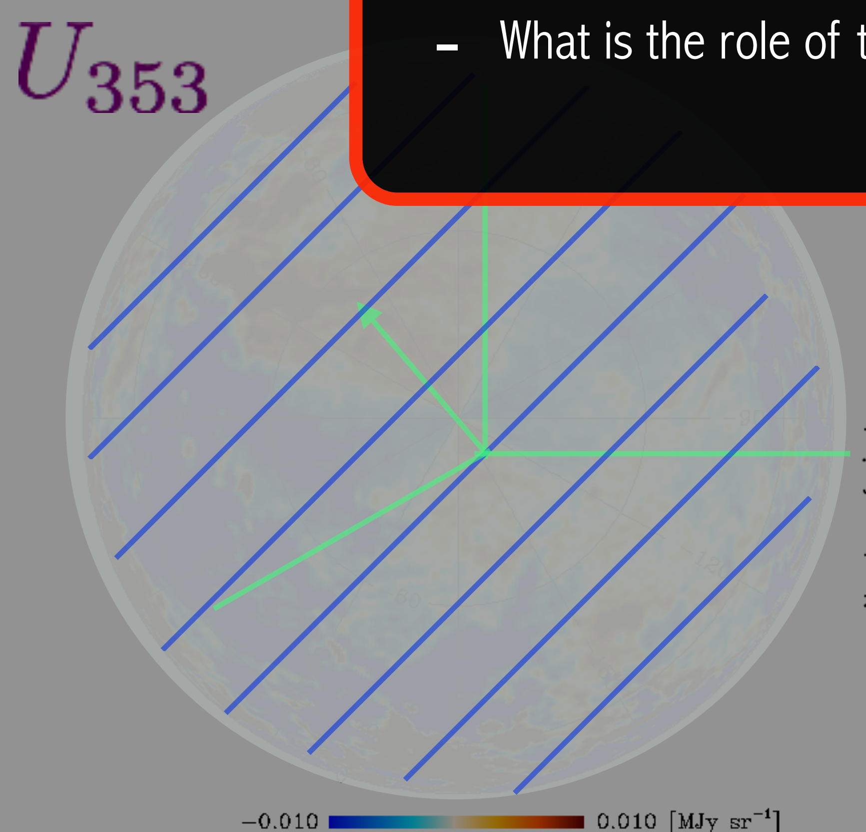
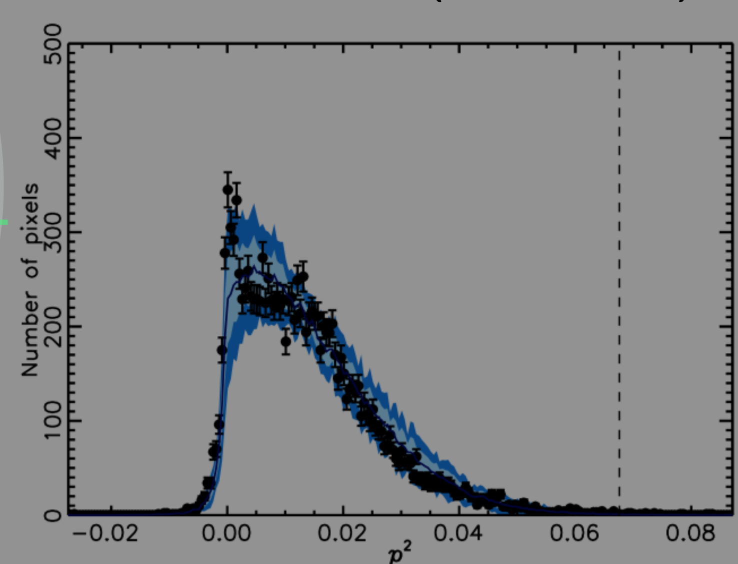
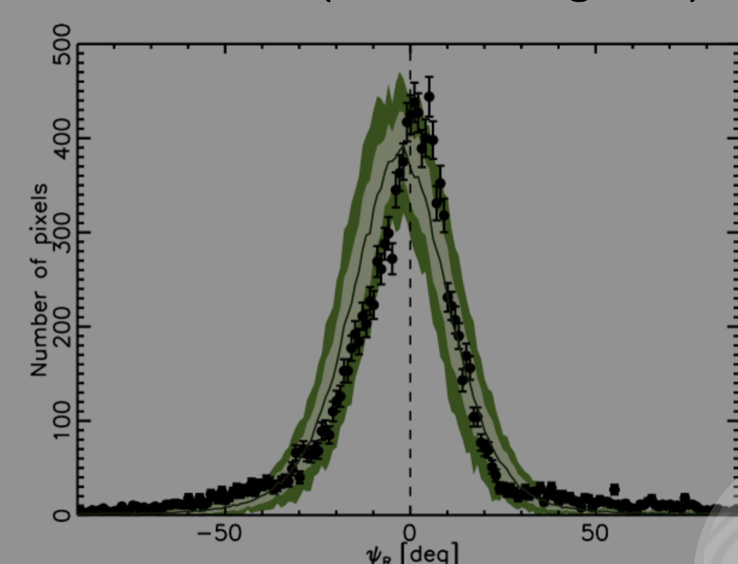


Observations (black dots) vs. Simulations (colored regions)



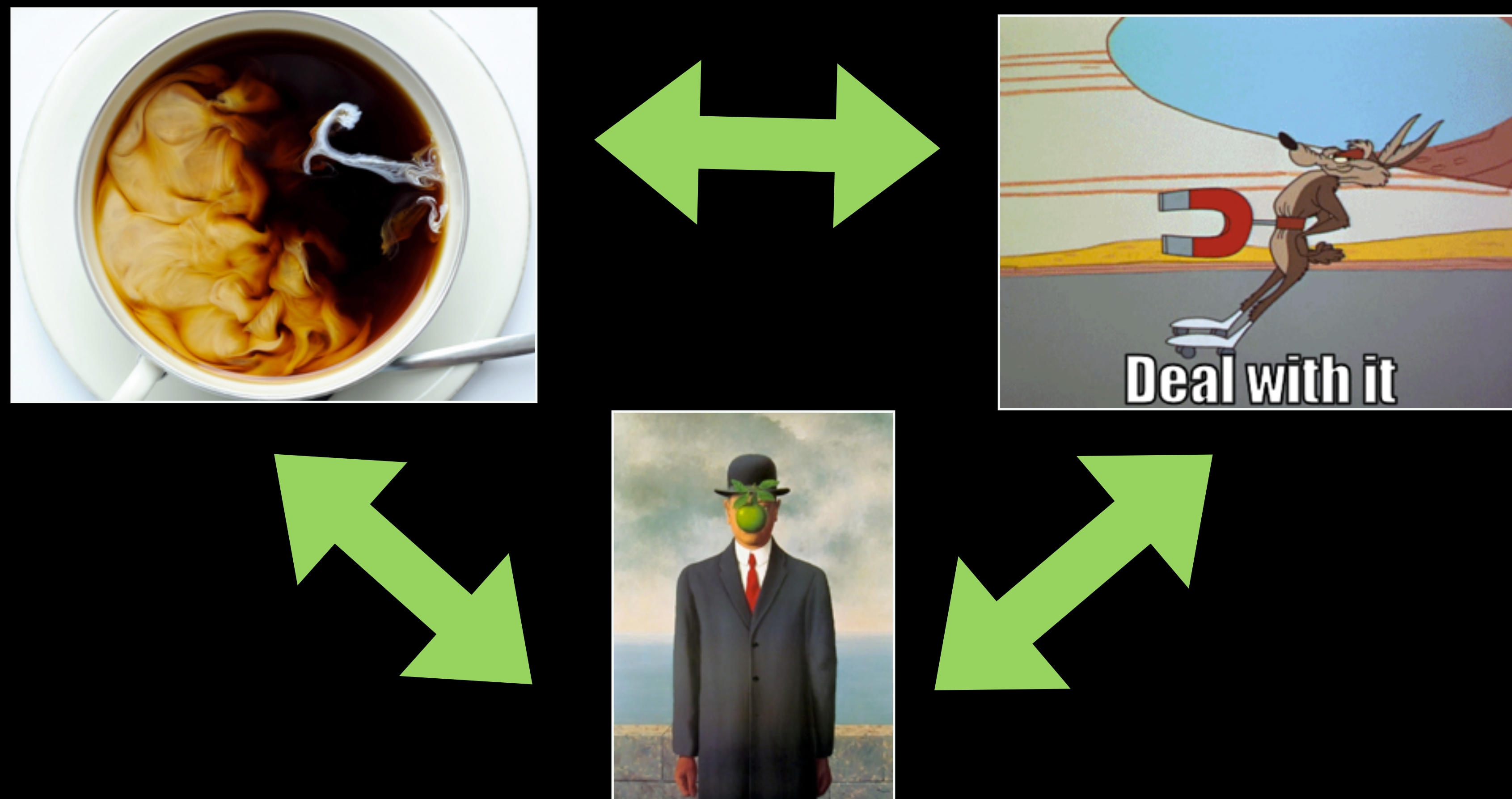
Polarization fraction



Polarization angle relative to the large-scale field

Planck Collaboration Int. XXXII, XLIV (2016)

Toward dense structures in the ISM: part B

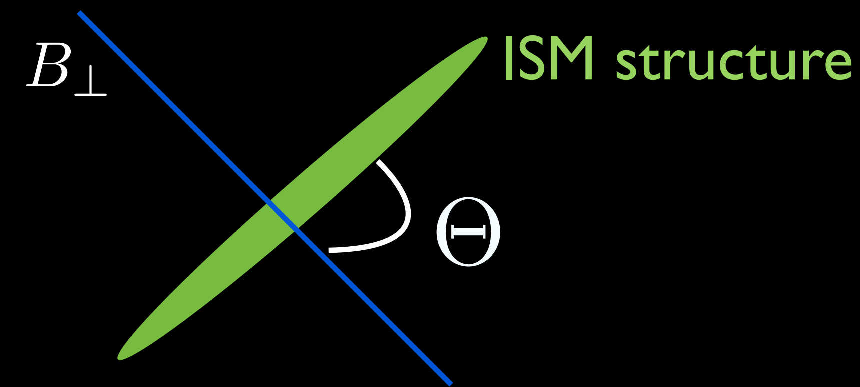


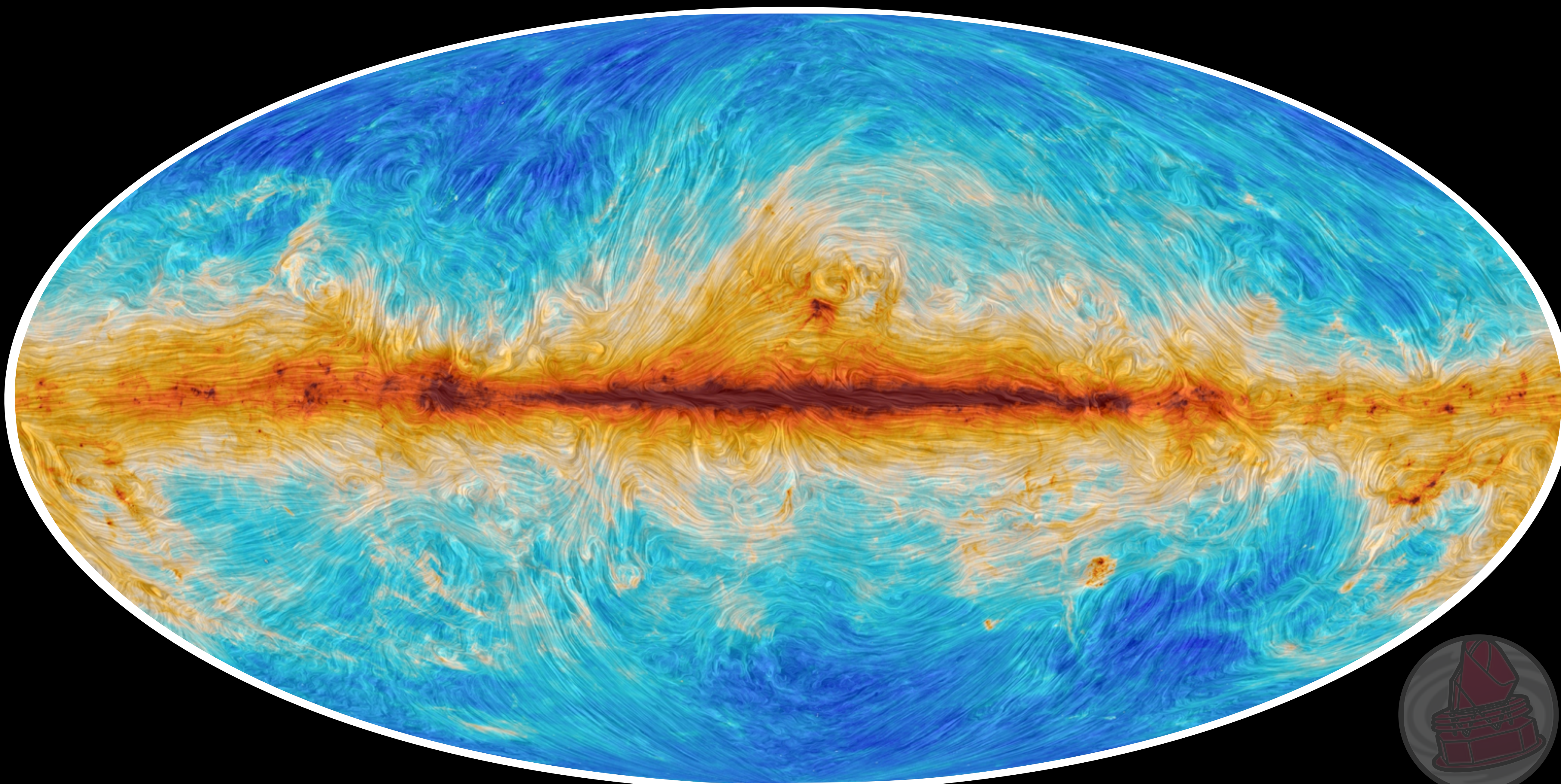
Dynamical alignment of gas velocity and magnetic field contributes to gather matter along field lines without corresponding increase of magnetic flux (Brandenburg+13)

Study of the relative orientation between the B-field structure and that of matter

(**Dense**: Goodman+90,95; Li+13. **Diffuse**: Clark+14,15)

Histogram of relative orientation (HRO) (Planck int. results XXXII)

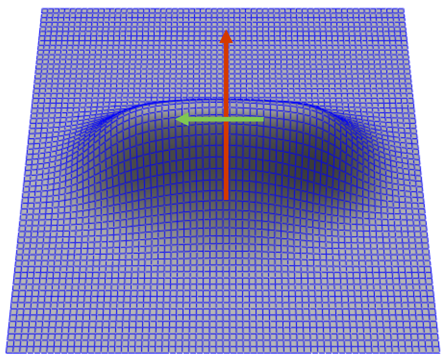




Magnetic field orientation with respect to structures of matter

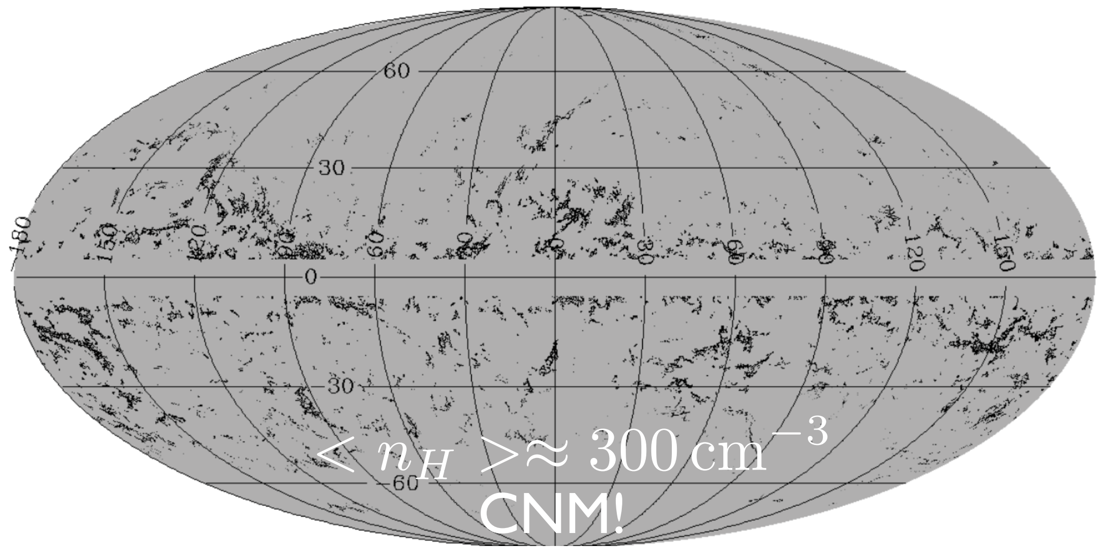
- At intermediate and high Galactic latitudes, using the eigenvalues and eigenvectors of the Hessian
- Relative angle between filaments and magnetic field shows preferred alignment

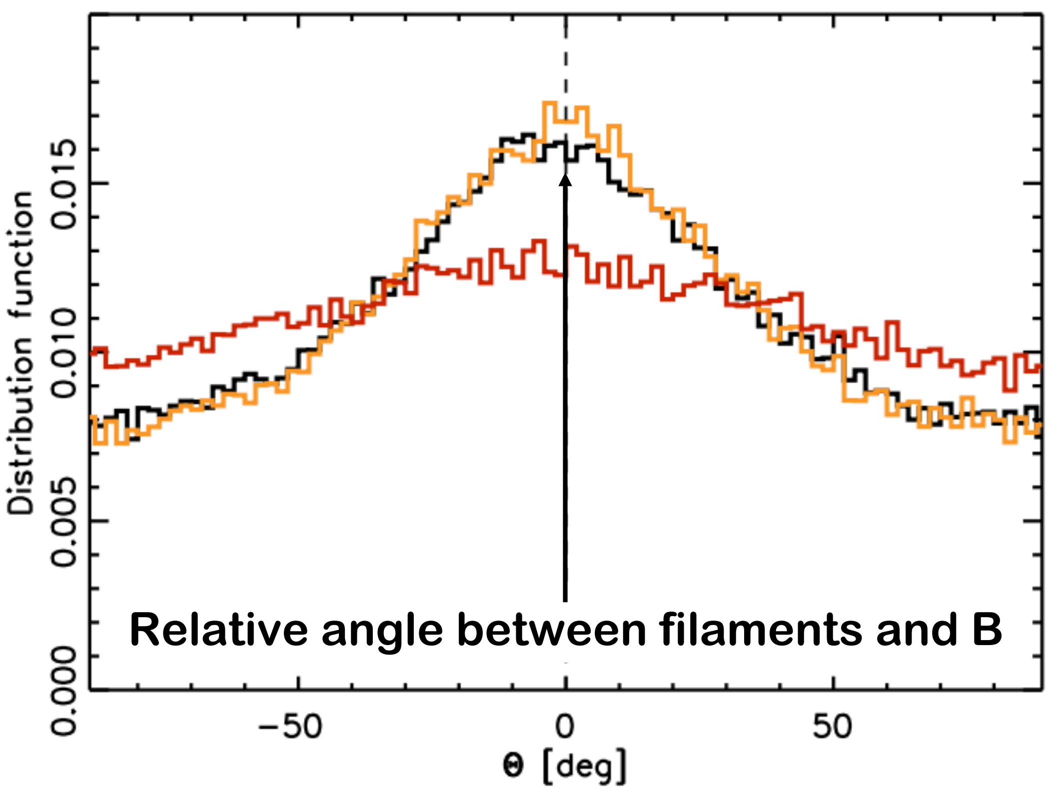
$$\mathbf{H} = \begin{bmatrix} \partial^2_{xx} D_{353} & \partial^2_{xy} D_{353} \\ \partial^2_{xy} D_{353} & \partial^2_{yy} D_{353} \end{bmatrix}$$

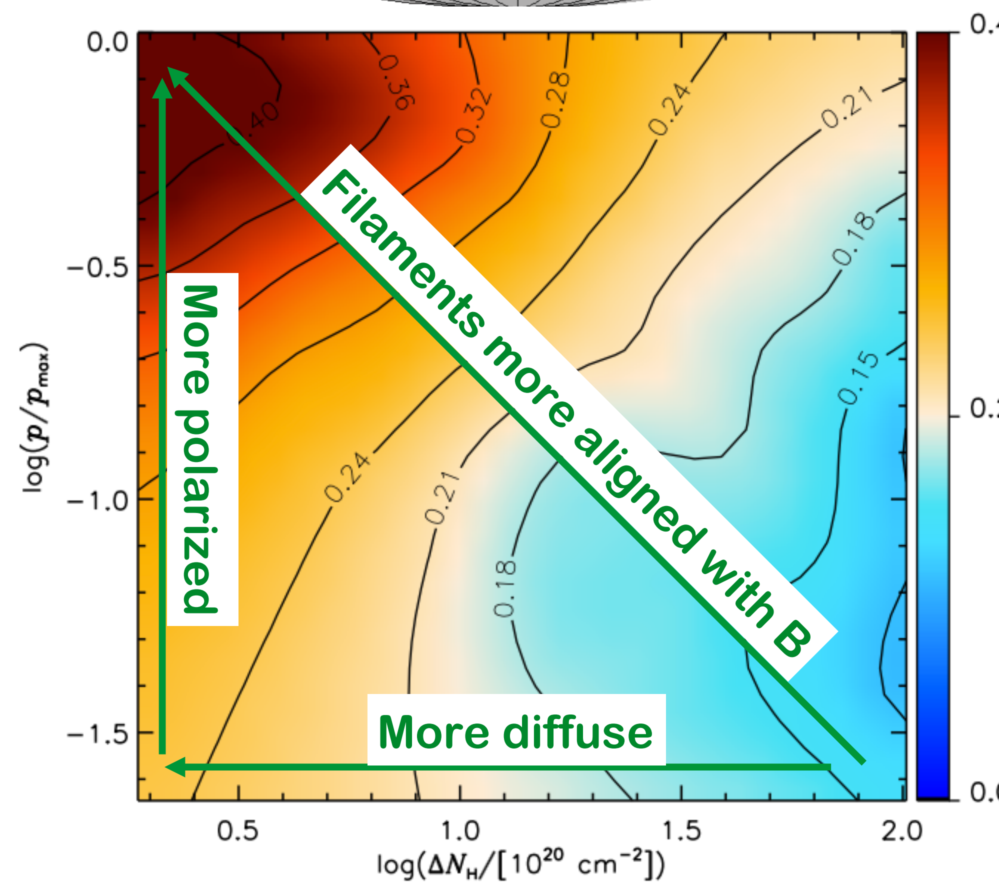


$$\boxed{\langle p \rangle = 12 \pm 1\%}$$

Map of the most negative eigenvalue







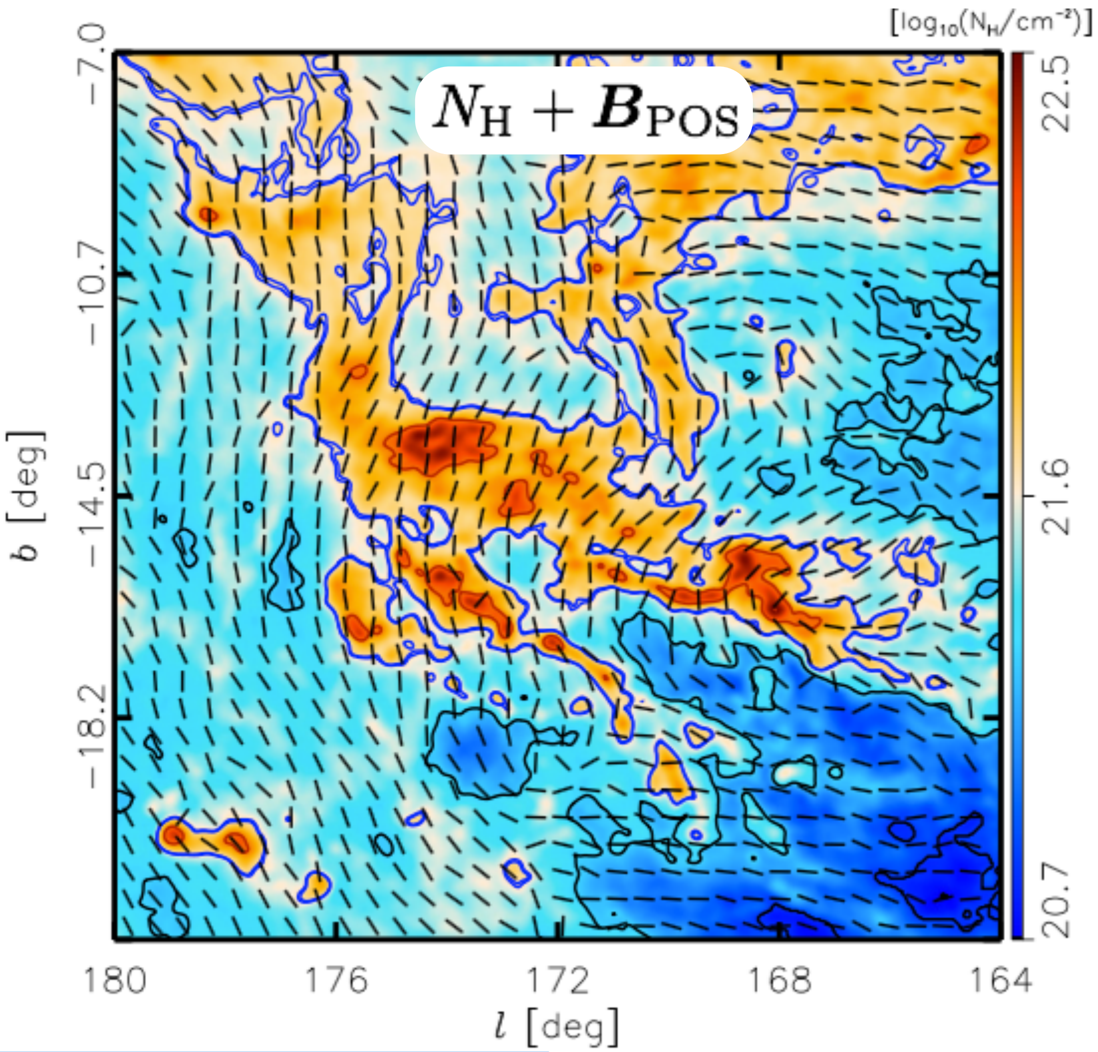
Planck Collaboration Int. XXXII (2016)

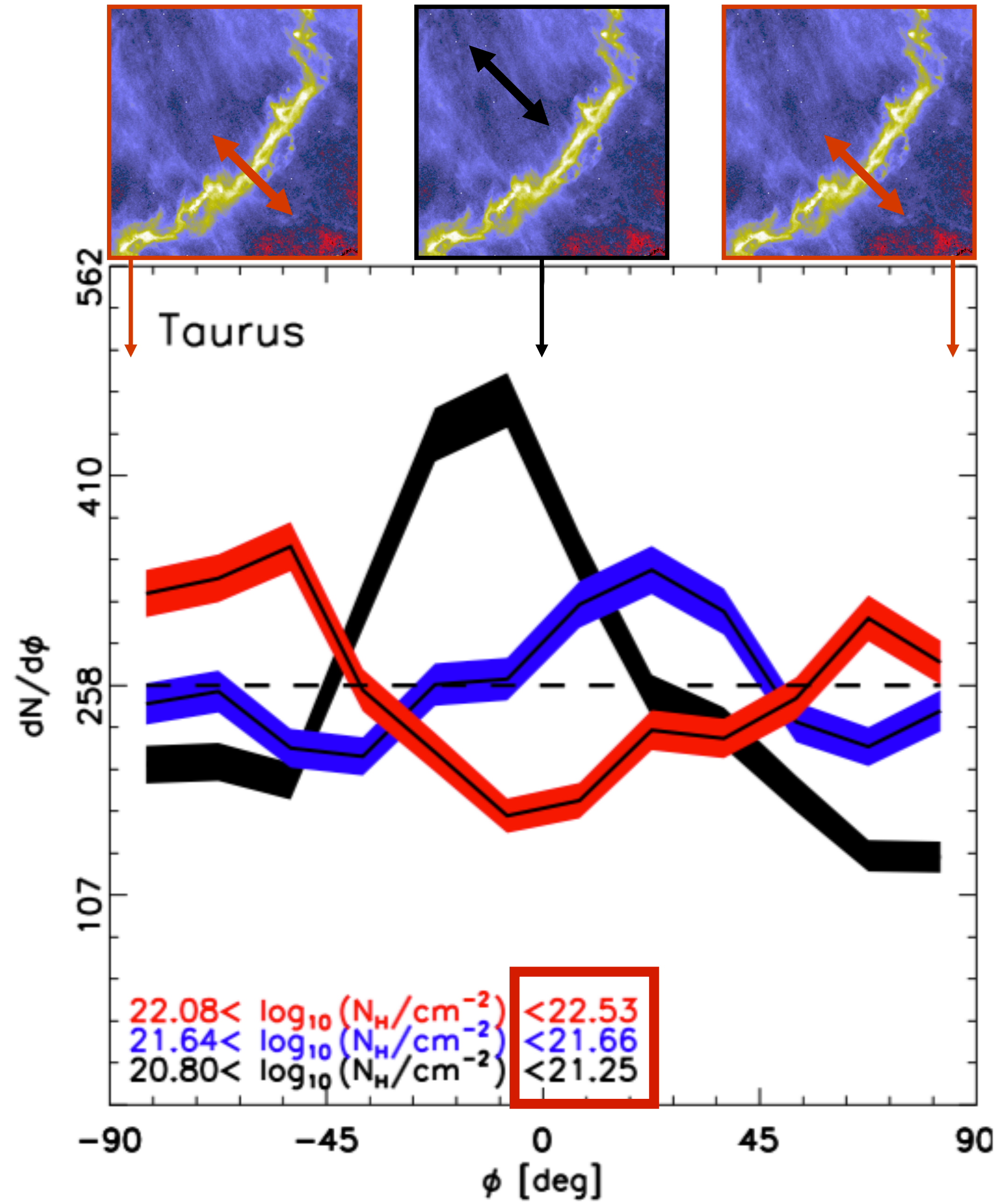
Some of the main Planck results on Galactic magnetic fields

Magnetic field orientation with respect to structures of matter

- In nearby molecular clouds, using the Histogram of Relative Orientations (HRO) Soler et al. (2013)
- Change of relative orientation as column density increases
- Consistent with sub- and trans-Alfvénic simulations of MHD turbulence (strong magnetic field)
- Estimates of B from the Davis-Chandrasekhar-Fermi method Chandrasekhar & Fermi (1953), Hildebrand et al. (2009)

$$\boxed{B_{\rm POS} \sim 10 - 50\,\mu{\rm G}}$$



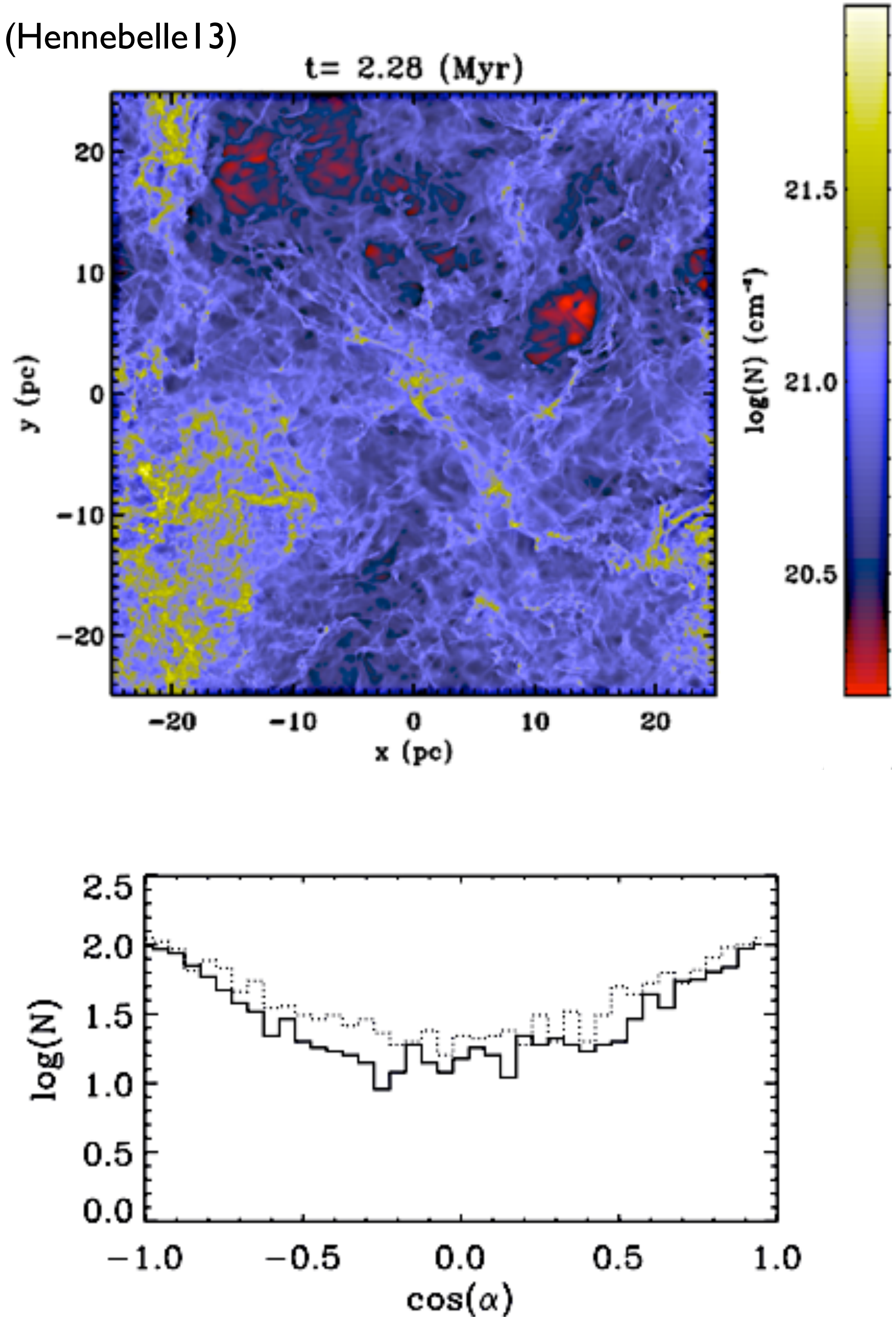


Planck Collaboration Int. XXXV (2016)

See analytical interpretation by Soler & Hennebelle 2017

MHD simulations : diffuse ISM

(Hennebelle13)



Strain Vs main axis of the filaments

- Two-phase medium
- Decaying turbulence (super-sonic and trans-Alfvenic)

$$E_{grav} << E_{turb} \approx E_{mag}$$

Filamentary structures result mainly from stretch induced by turbulence in the diffuse ISM

This can account for the preferred alignment between B-field and matter

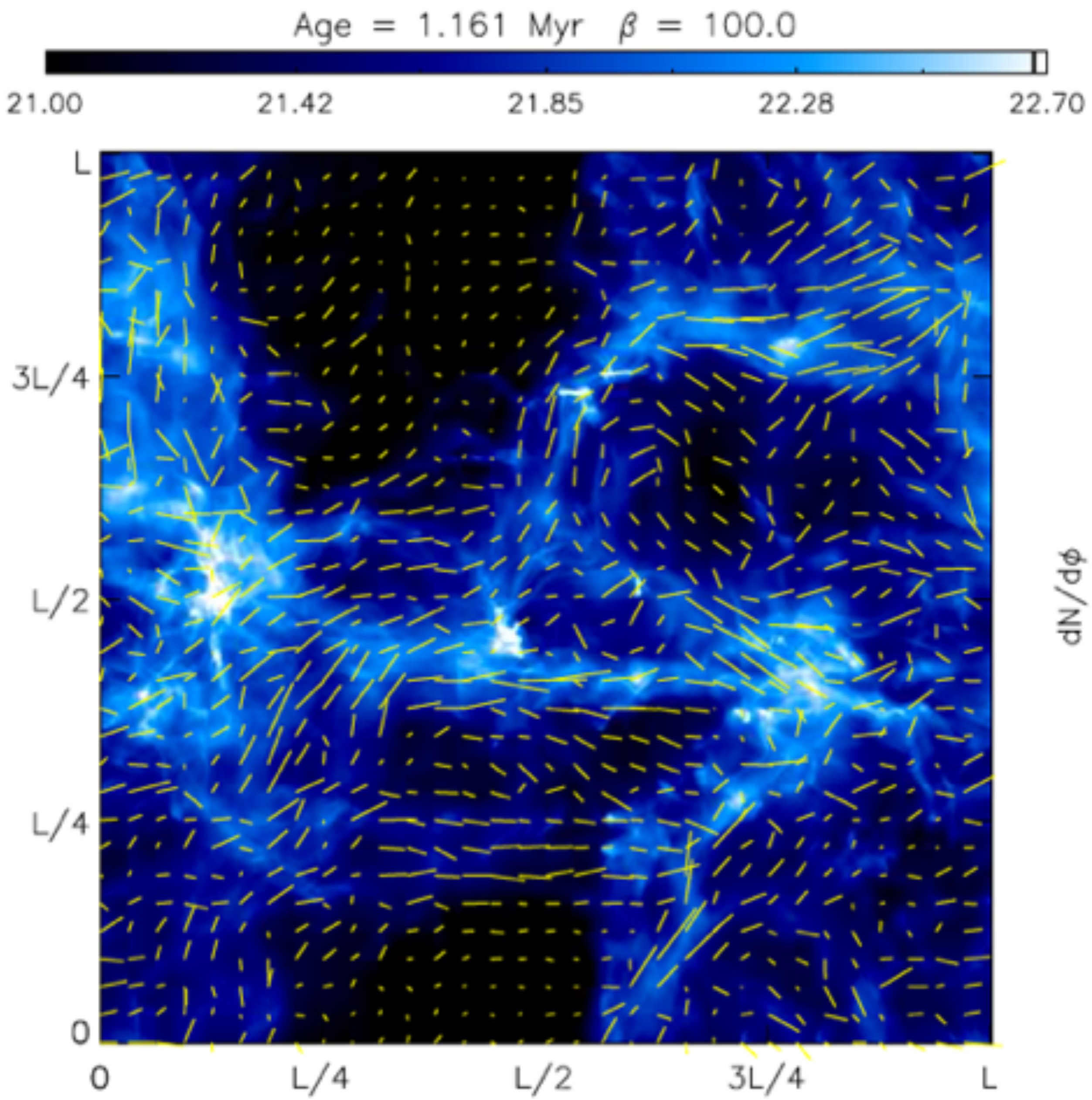
See also Inoue & Inutsuka 2016 for the formation of HI fibers (Clark+2014)

MHD simulations : molecular clouds

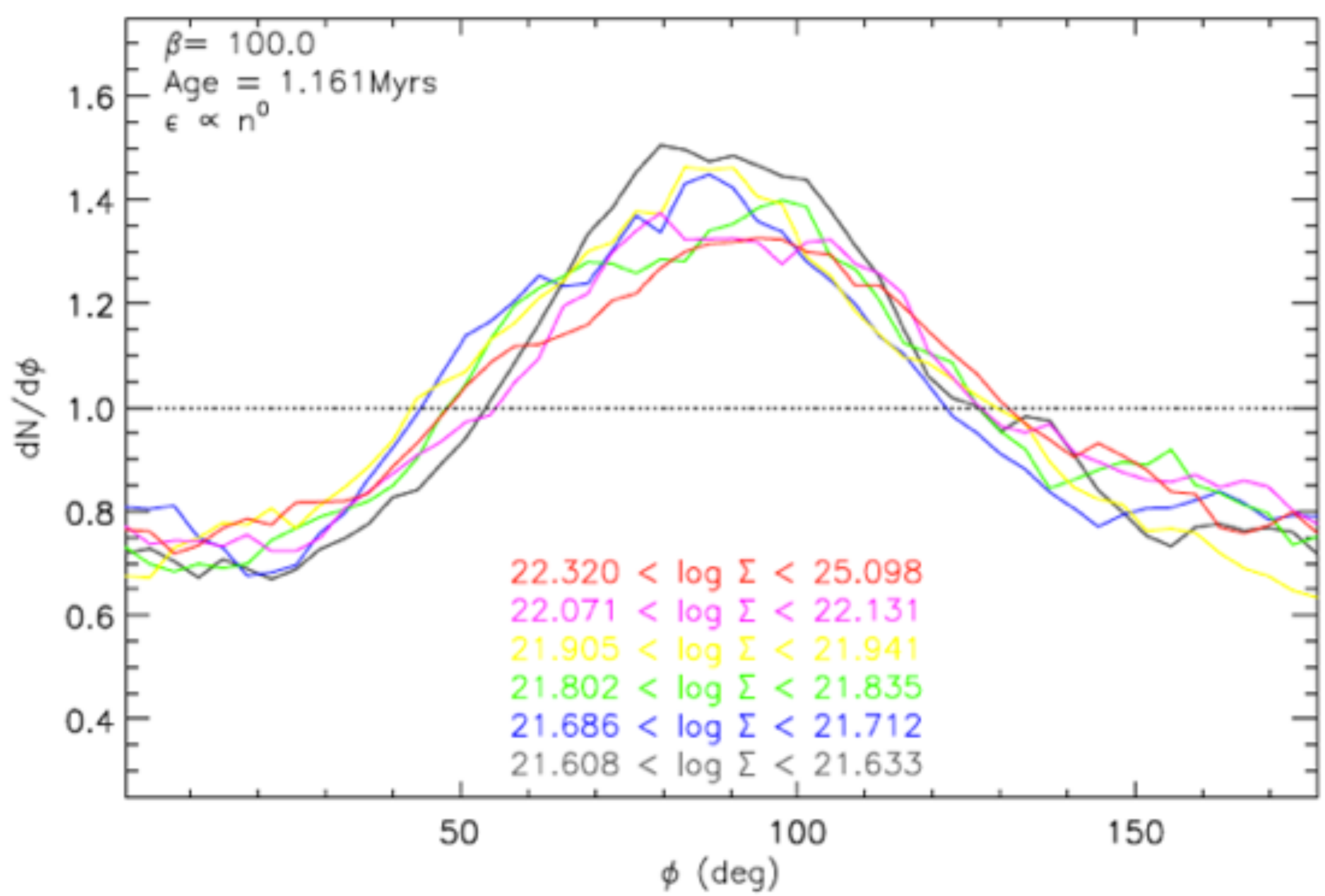
Soler+13 (similar initial conditions of Taurus, including gravity, decaying turbulence, isothermal)

$$E_{grav} \approx E_{turb} > E_{mag}$$

super-Alfvenic turbulence



Binning in column density

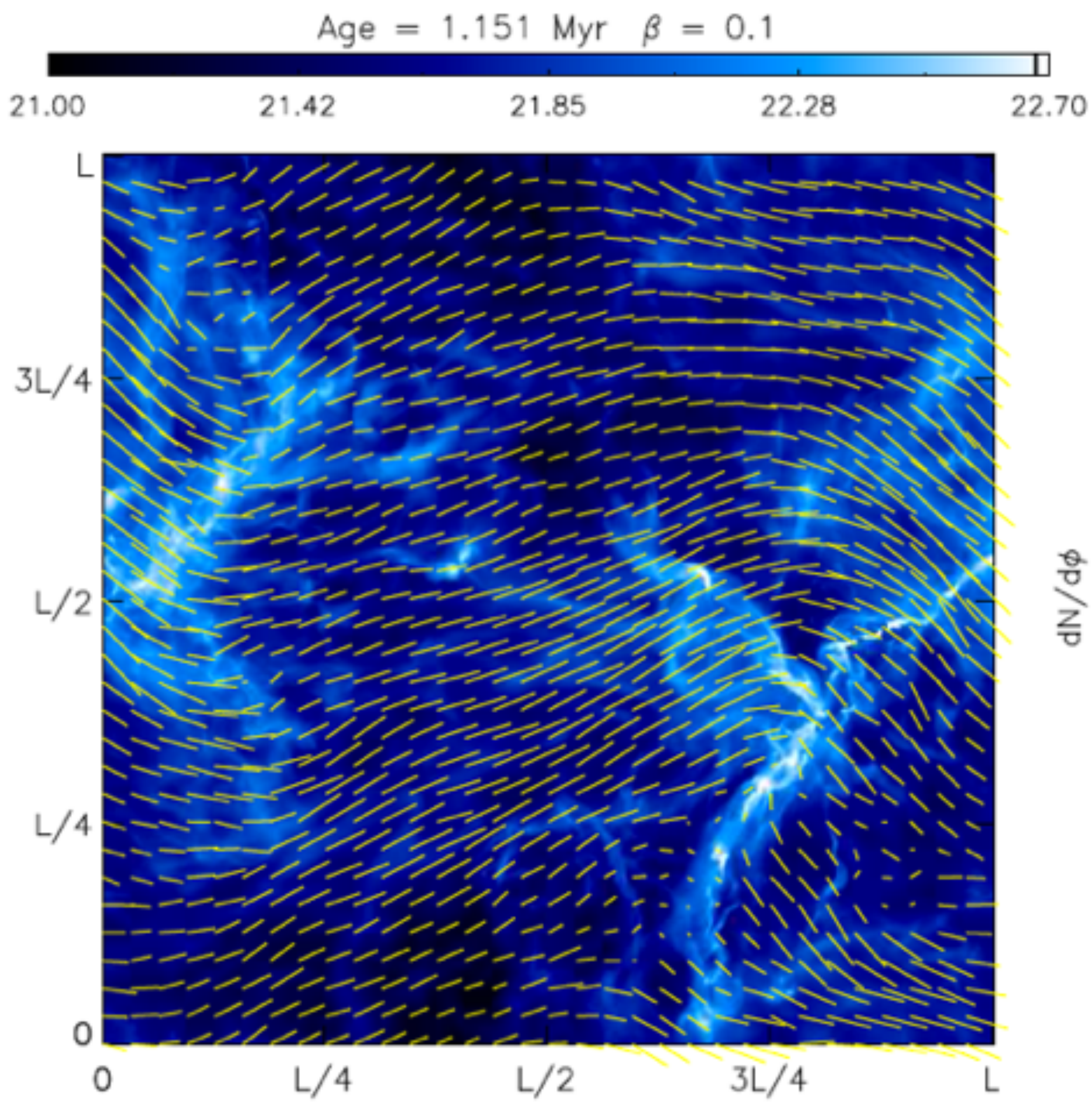


MHD simulations : molecular clouds

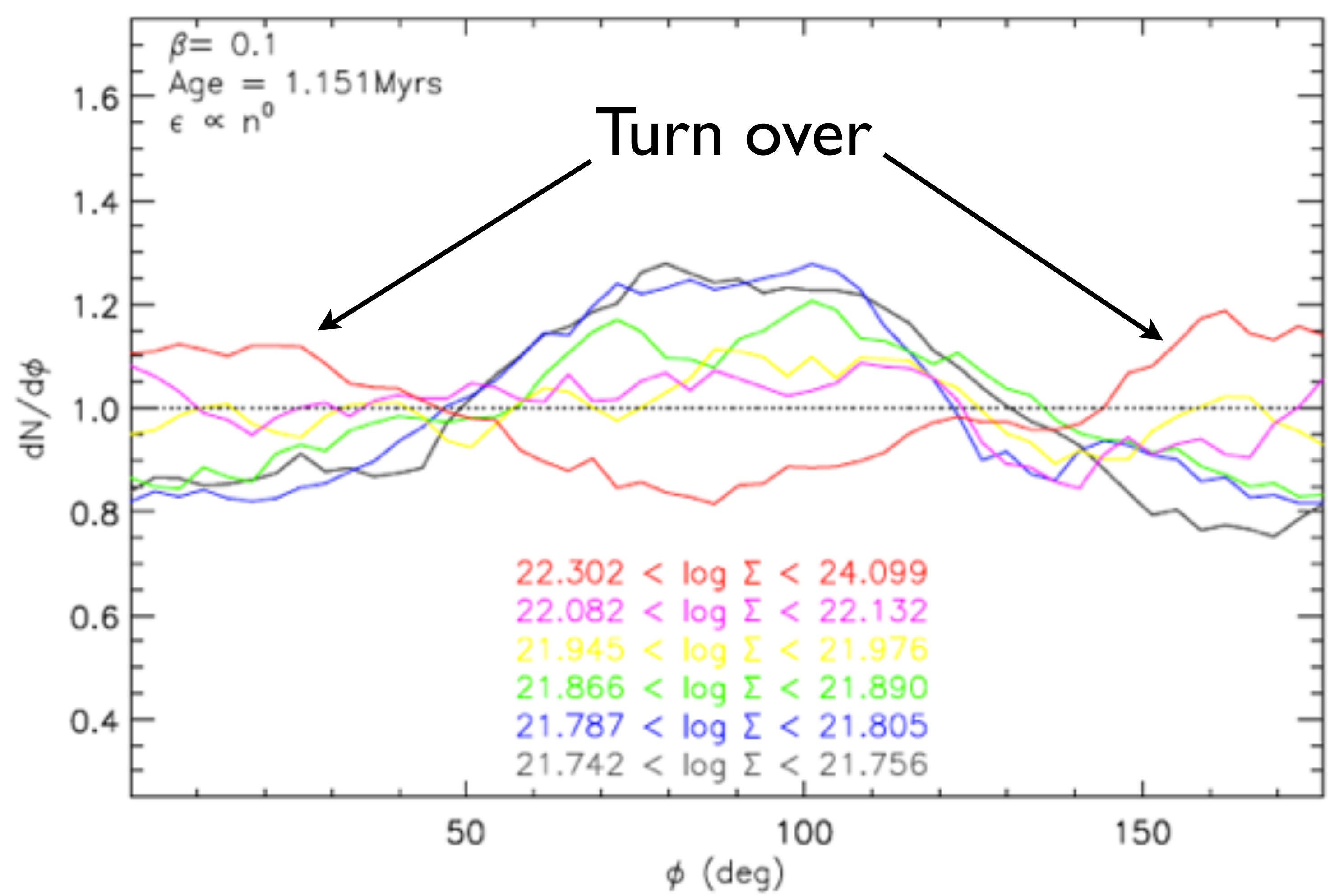
Soler+13 (similar initial conditions of Taurus, including gravity, decaying turbulence, isothermal)

$$E_{grav} \approx E_{turb} < E_{mag}$$

sub-Alfvenic turbulence

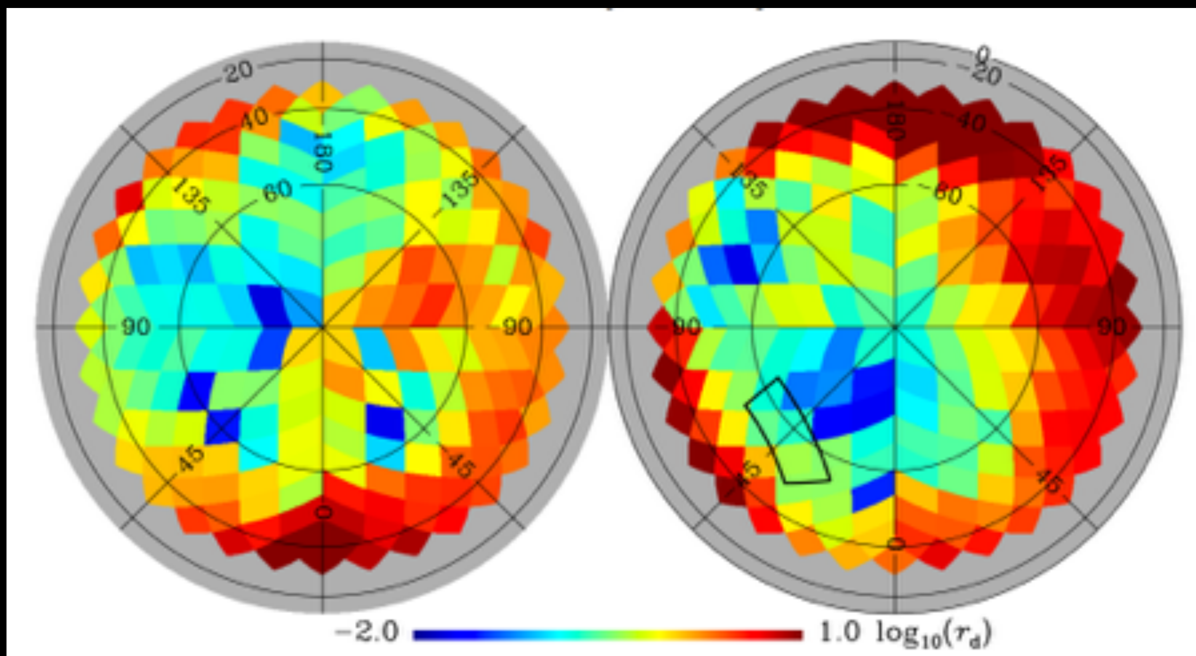


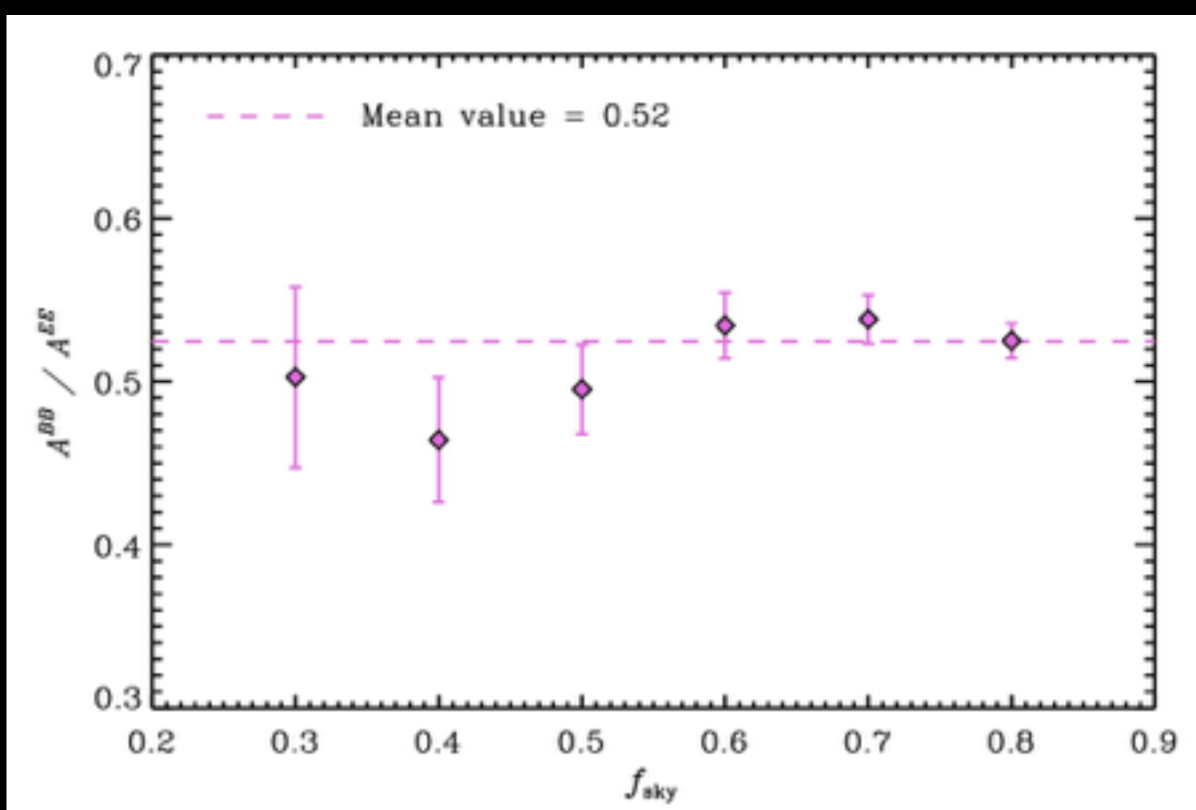
Binning in column density



A bridge between cosmology and ISM

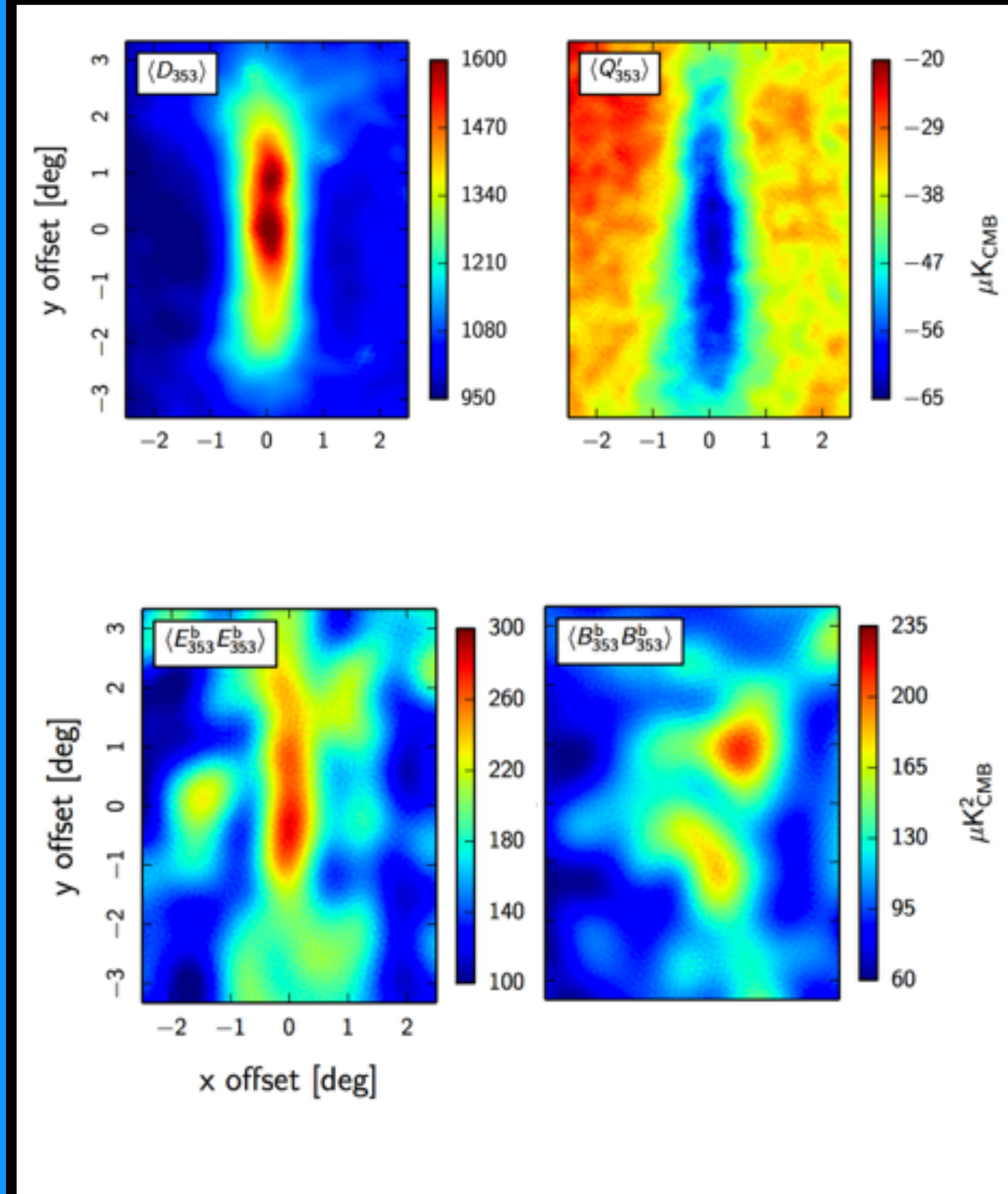
Dust contamination of B modes to cosmological parameters across the south Galactic hemisphere





(Planck int. Results. XXX. 2015)

Stacked properties of 260 filaments at intermediate and high Galactic latitude



(Planck int. Results. XXXVIII. 2016) (Planck 2015 results. X)

A bridge between cosmology and ISM

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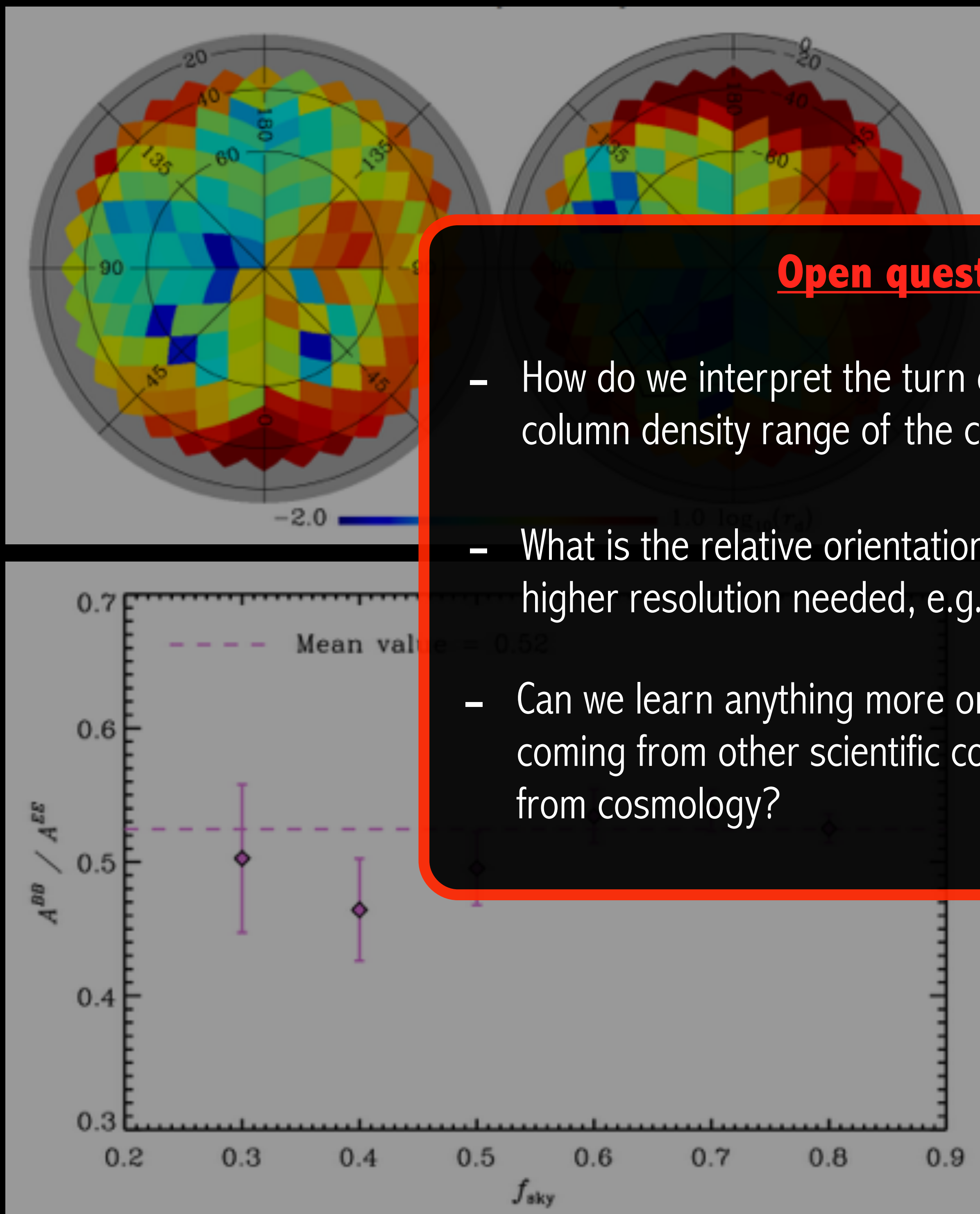

(Planck int. Results. XXX. 2015)

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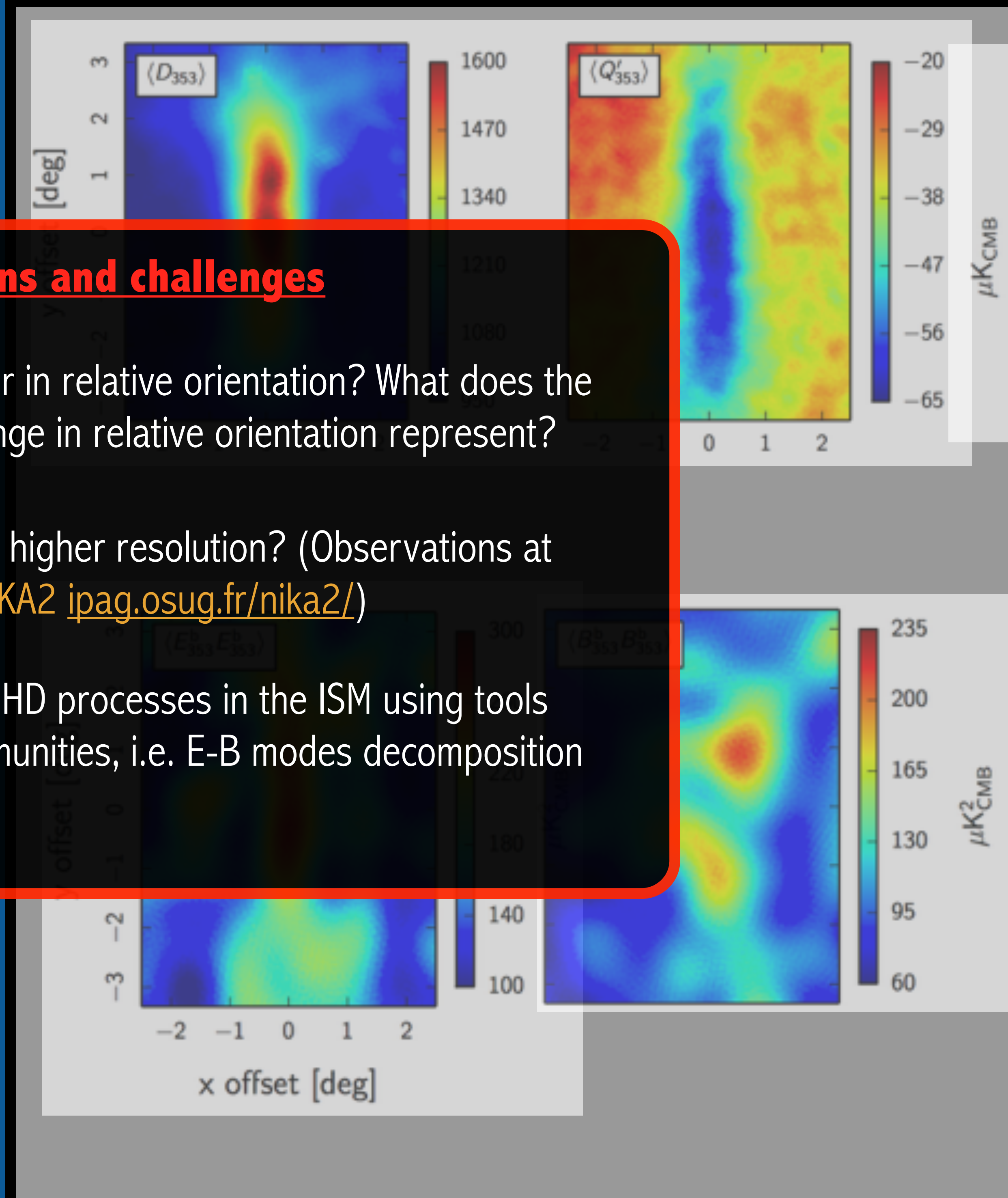


(Planck int. Results. XXXVIII. 2016) (Planck 2015 results. X)

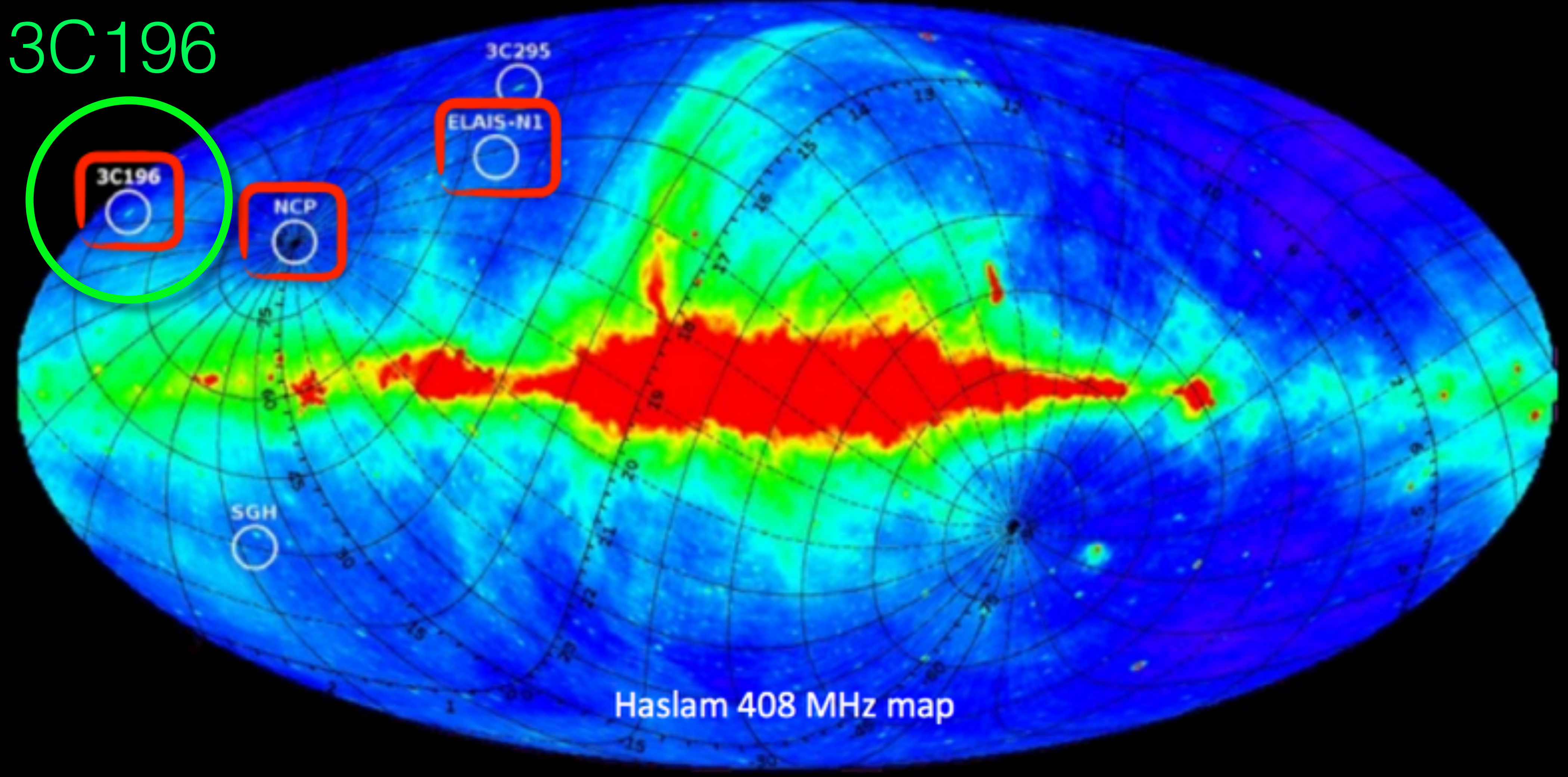
Open questions and challenges

- How do we interpret the turn over in relative orientation? What does the column density range of the change in relative orientation represent?
- What is the relative orientation at higher resolution? (Observations at higher resolution needed, e.g. NIKA2 ipag.osug.fr/nika2/)
- Can we learn anything more on MHD processes in the ISM using tools coming from other scientific communities, i.e. E-B modes decomposition from cosmology?

Magnetic fields and the multiphase ISM: part C

LOFAR - HBA observations

- 115 - 175 MHz, 0.2 MHz
- baselines 10-800λ, 3 arcmin resolution, 25 deg²
- RM synthesis: $\Delta\Phi \cong 1$ rad/m²

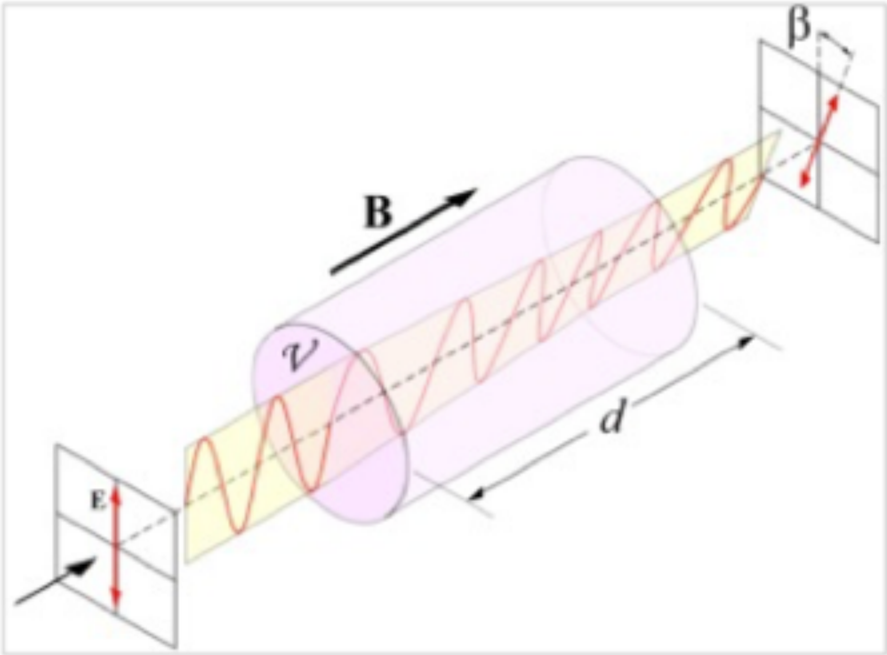


Faraday tomography: physical concept

- Faraday rotation of a background source

$$\Delta\beta = RM\,\lambda^2$$

$$RM = C\int_0^L n_e B_{\parallel}\, dl \qquad \text{(rotation measure)}$$

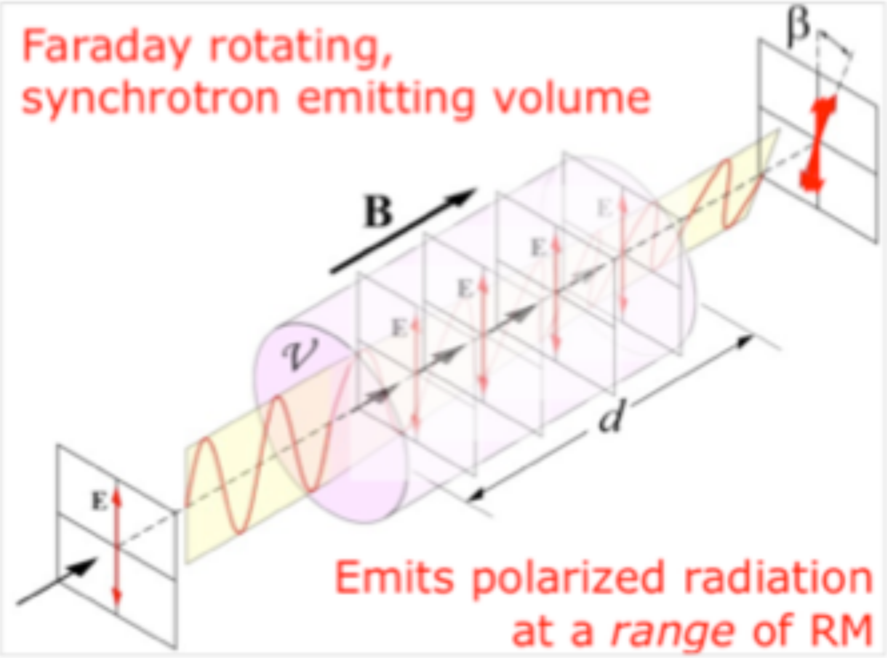


- Faraday rotation of a diffuse synchrotron emission

$$\Phi = C\int_0^z n_e B_{\parallel}\, dl \qquad \text{(Faraday depth)}$$

$$P(\lambda^2) = \int F(\Phi) e^{2i\Phi\lambda^2}\, d\Phi$$

Fourier transform $\boxed{P(\lambda^2) \rightarrow F(\Phi)}$



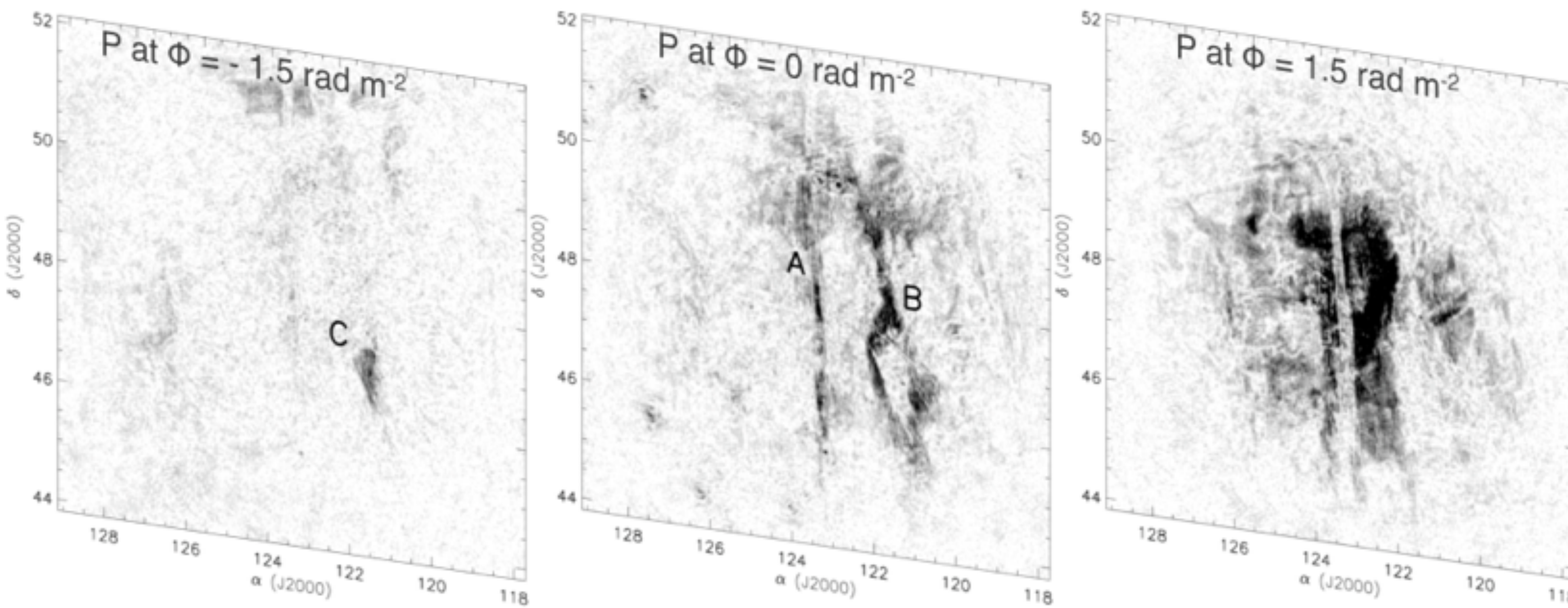
Credit: G. Heald

Magnetic fields and the multiphase ISM

Slices in a Faraday depth cube

A high Galactic latitude region observed with **LOFAR** (high band array)

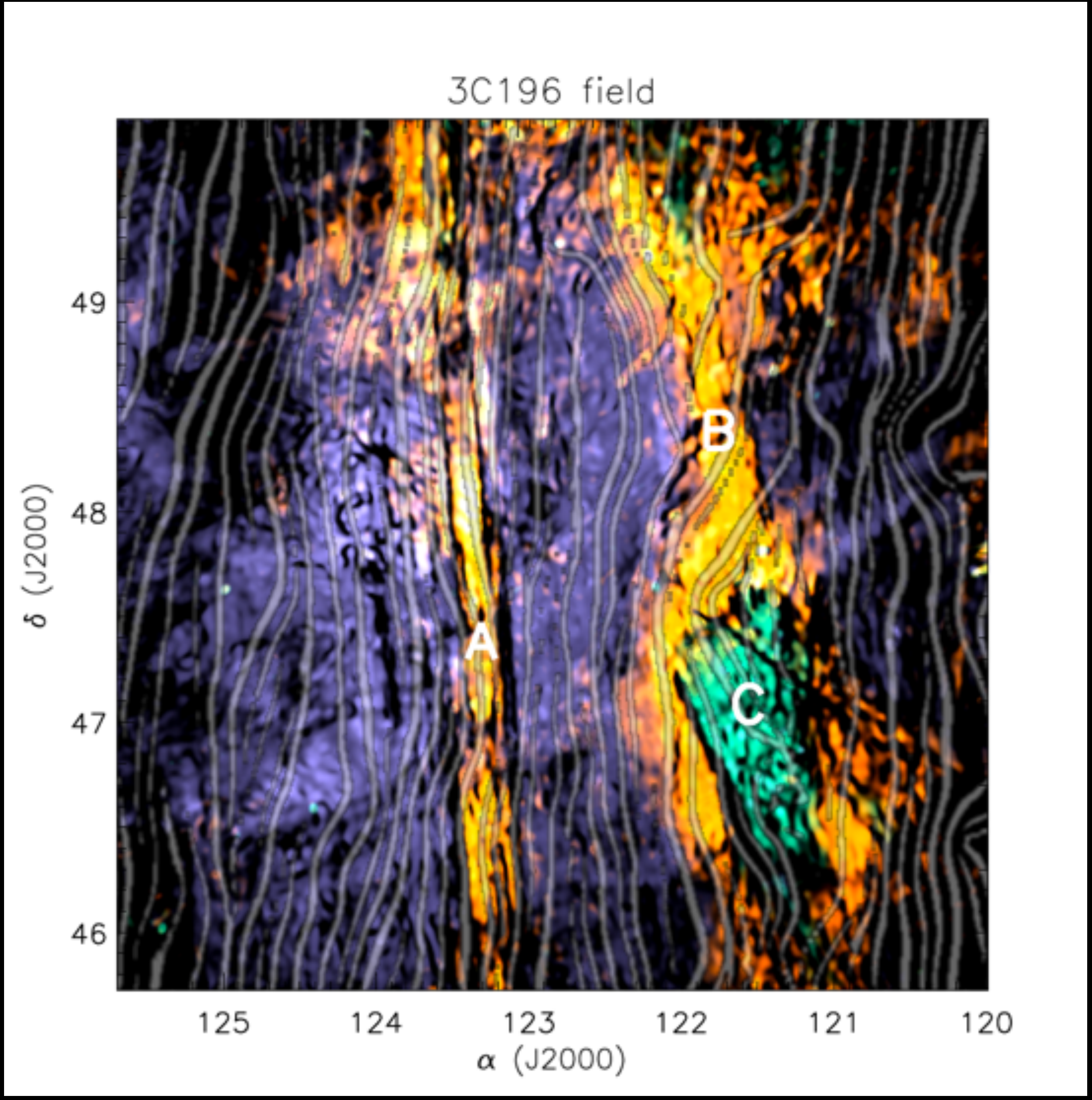
Polarized intensity at 3 different Faraday depths



Jelić et al. (2015)

Magnetic fields and the multiphase ISM

Planck B-field lines and LOFAR data



Zaroubi et al. 2015

It is worth to notice:

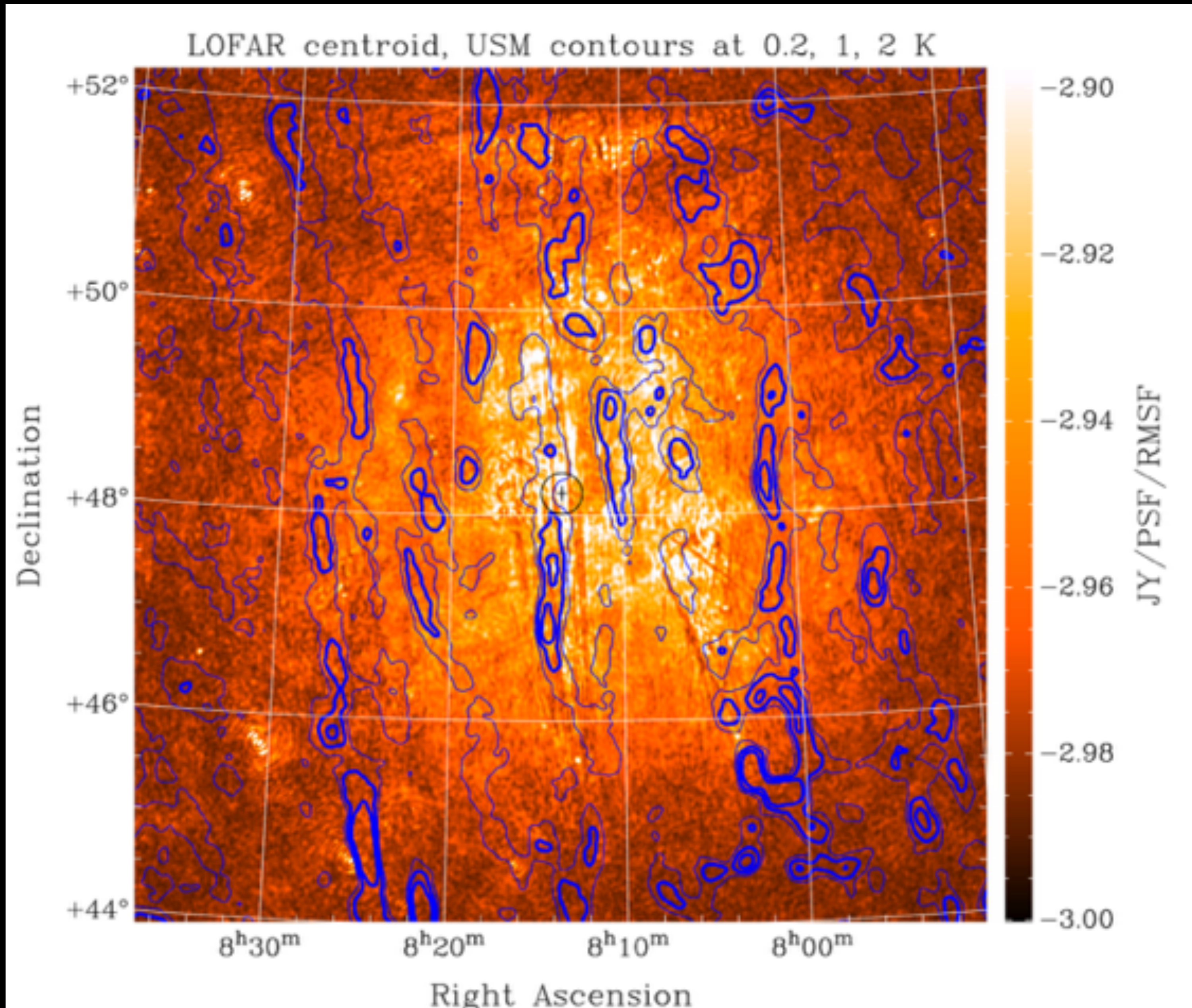
1) The sharpest gradients are observed to be perpendicular to the field orientation inferred from dust polarization ($B_\perp$)

2) Variations in LOFAR data coincide with the bending of the field lines ($B_\perp$)

3) Only the magnetic field structure ($B_{||}$) can change the sign of LOFAR data

Magnetic fields and the multiphase ISM

LOFAR data and EBHIS-HI contours



Kalberla et al. 2016

It is worth to notice:

1) The sharpest gradients are observed to be perpendicular to the field orientation inferred from dust polarization ($B_\perp$)

2) Variations in LOFAR data coincide with the bending of the field lines ($B_\perp$)

3) Only the magnetic field structure ($B_{||}$) can change the sign of LOFAR data

What are we seeing?

Witnessing phase transition in the magnetized WIM?

Wrapping up with Planck

1) The magnetic field structure in key to interpret the sky in dust polarization (cosmologists are also figuring it out…) (i.e., Ghosh+2017, Vansyngel+2017)

2) The turbulent component of the field is in equipartition with the ordered one both in the diffuse and in the dense neutral medium

3) Magnetic fields are correlated with the density structure of the ISM and important for the dynamical evolution of molecular clouds

4) We are now approaching a new era to study interstellar magnetic fields thanks to the breakthrough in resolution and sensitivity of new experiments (i.e., Planck, LOFAR, the upcoming SKA) and capture the complexity of the multiphase ISM

For further information check the following page:

www.planckandthemagneticfield.info

Contact information: **andrea.bracco@cea.fr**