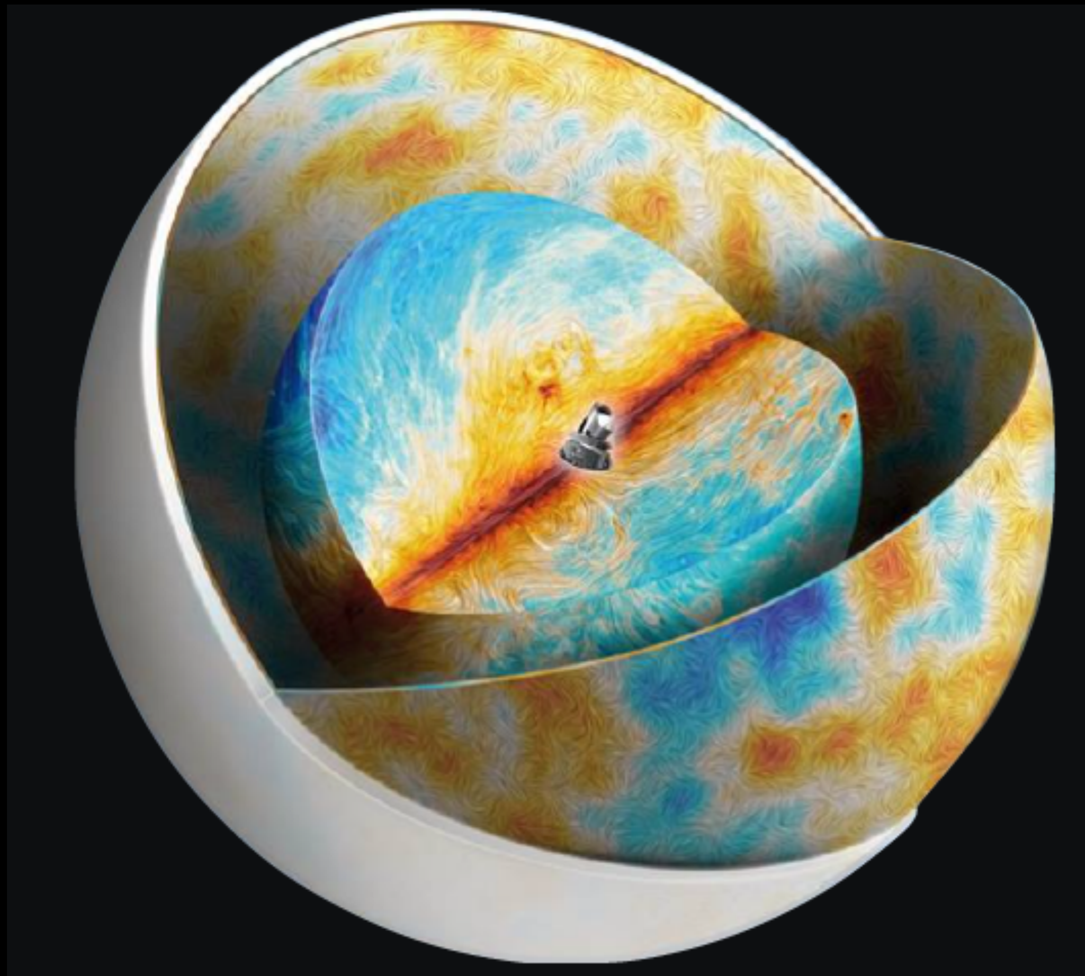
Polarized Foregrounds



François Boulanger
Ecole Normale Supérieure

- ★Lecture I: Dust emission/polarization properties (Monday, Vincent Guillet)
- ★Lecture II: The magnetized interstellar medium
- ★Lecture III: Statistical description and modeling of polarized foregrounds

Outline

- ★Broad context: cosmic magnetism
- ★Observations of interstellar magnetic fields
- ★The interplay between turbulence and magnetic fields in the interstellar medium

Magnetic fields are the hidden (*dark*) agent of baryon physics across the universe

Two outstanding questions:

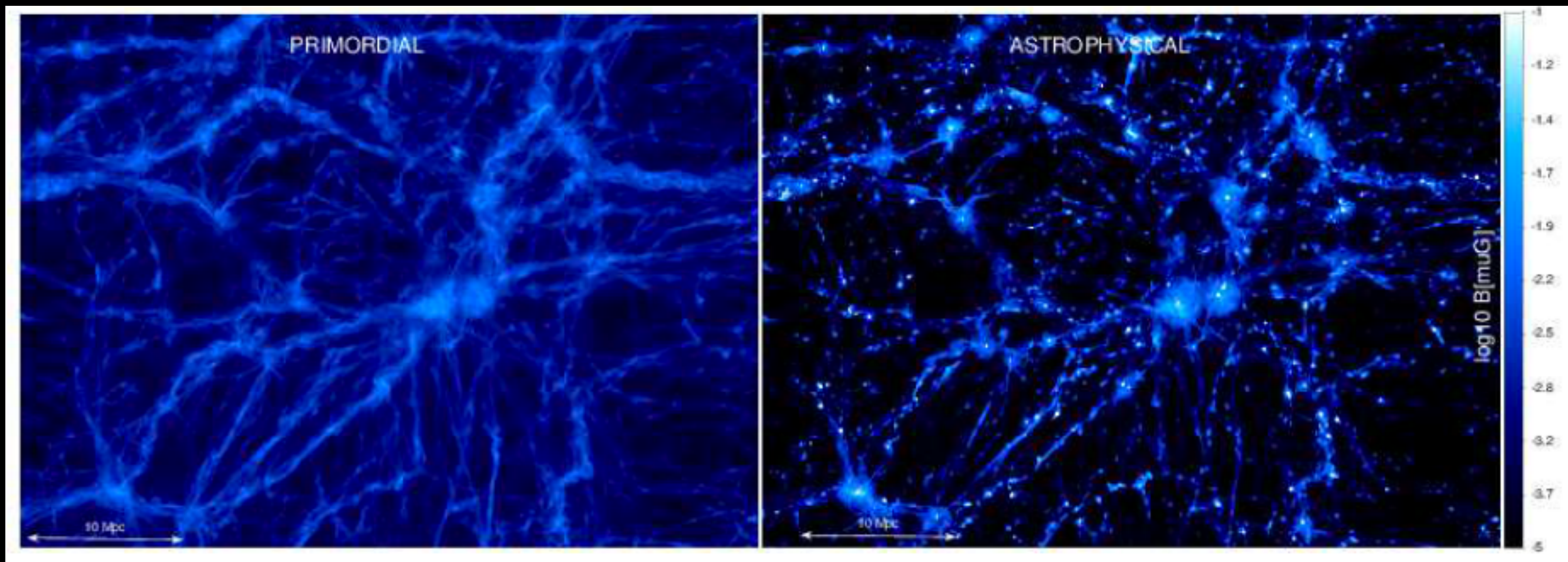
- ★ The origin of cosmic magnetic fields
- ★ Their role in the formation of galaxies, stars and planets

The Universe shows strong and coherent magnetic fields on all observed scales from proto-planetary discs to clusters.

Some processes have amplified and organized a much weaker primordial field

Seed field + Turbulent dynamo

Field diffusion from galaxies



Field strength

Cosmic web z=0.025, Vazza+16

A magnetized universe

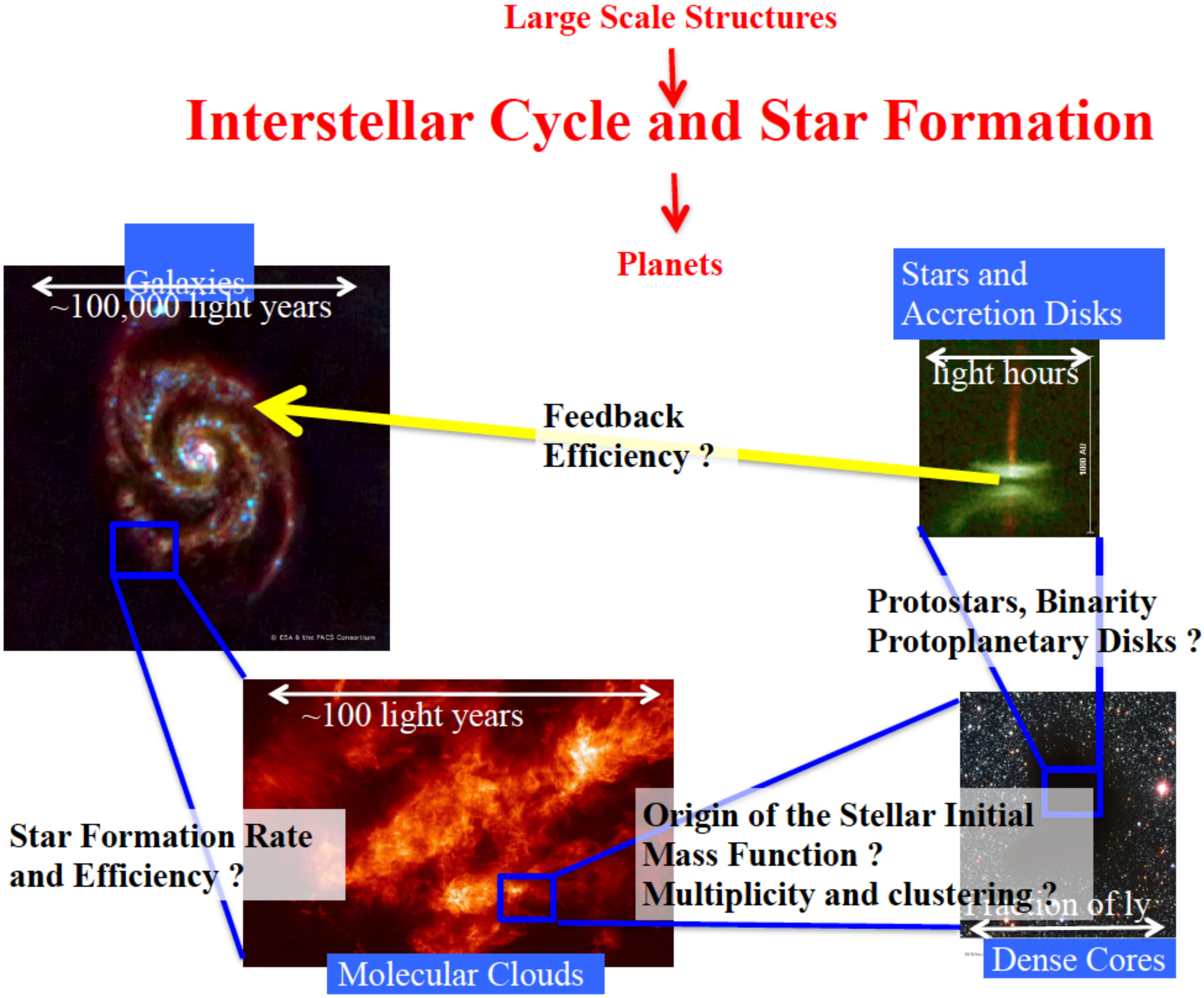
- The Universe shows strong and coherent magnetic fields on all observed scales from proto-planetary discs to clusters.
- Some processes have amplified and organized a much weaker primordial field

These processes involve physical couplings between three energy reservoirs

- Gas kinetic energy in bulk and turbulent motions
- Cosmic rays
- Magnetic fields

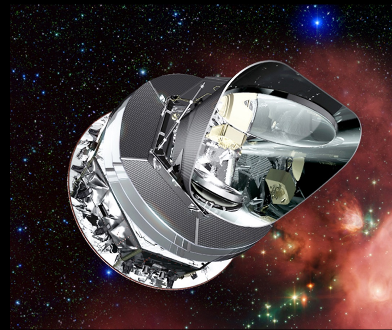
Equipartition is, on average, the expected outcome of energy exchanges.

=> Magnetic fields are expected and observed to be dynamically important.


Large Scale Structures
Interstellar Cycle and Star Formation
Planets
Galaxies
~100,000 light years
© ESA & the PACS Consortium
Stars and
Accretion Disks
light hours
1000 AU
Feedback
Efficiency ?
Protostars, Binarity
Protoplanetary Disks ?
~100 light years
Star Formation Rate
and Efficiency ?
Origin of the Stellar Initial
Mass Function ?
Multiplicity and clustering ?
Molecular Clouds
Dense Cores

Multiple observational perspectives

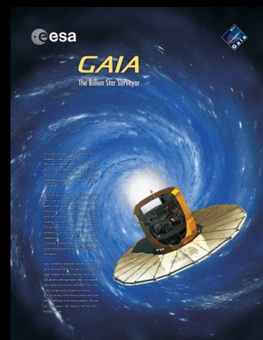
★CMB data are unique to characterize statistically interstellar turbulence: the interplay between matter and magnetic fields in interstellar space



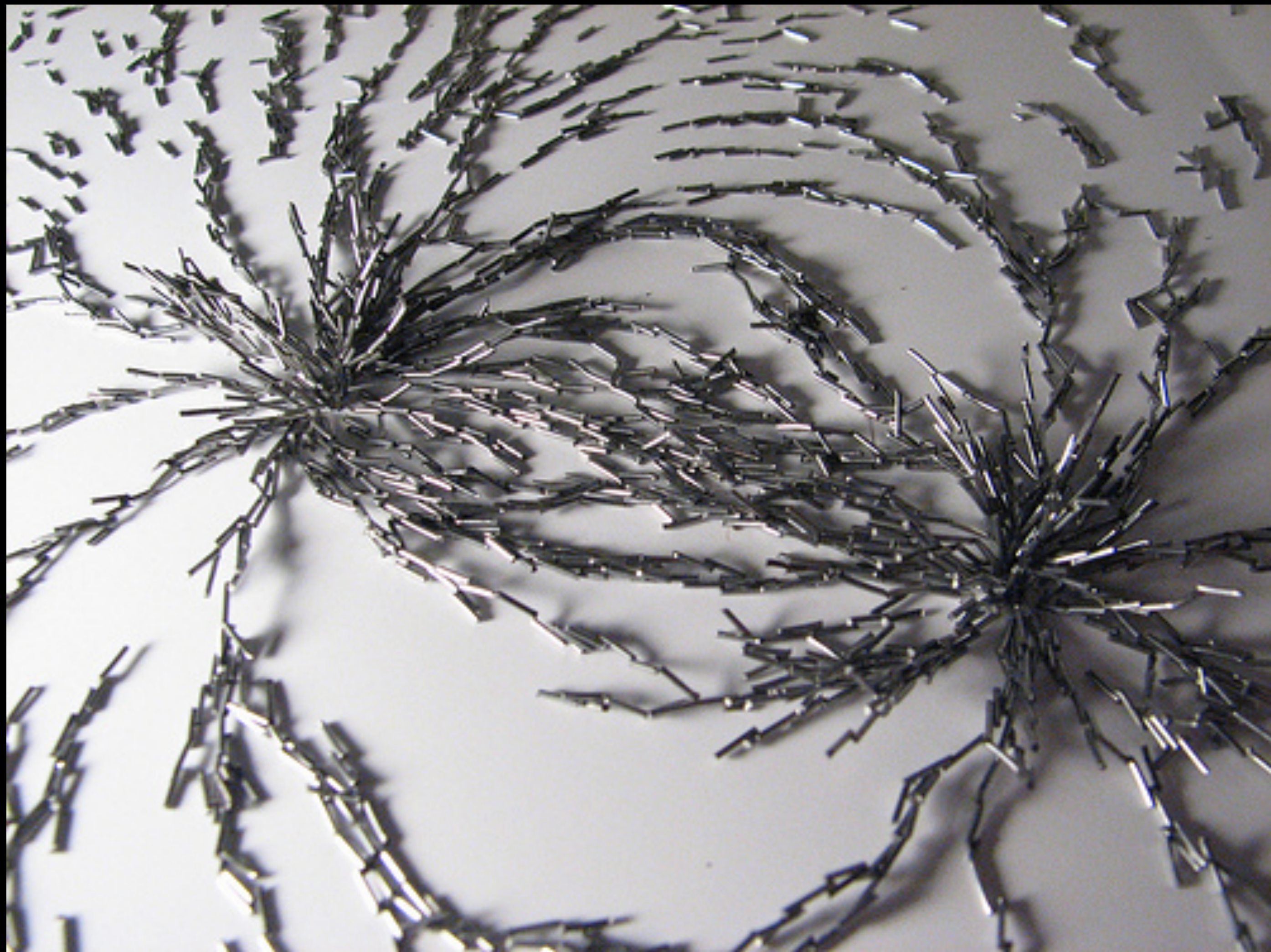
★SKA will be unique to probe magnetic fields in distant galaxies, clusters and the cosmic web.

★ALMA and NOEMA provide the angular resolution to study magnetic fields from pre-stellar cores to proto-stars and their proto-planetary disks

★GAIA astrometry should allow us to build a 3D model of the Milky Way magnetic field on Galactic scales



Interstellar magnetic fields



Turbulence

Magnetic fields

Gravity

In the diffuse ISM observations show that :

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

Gravity

Turbulence

Magnetic fields

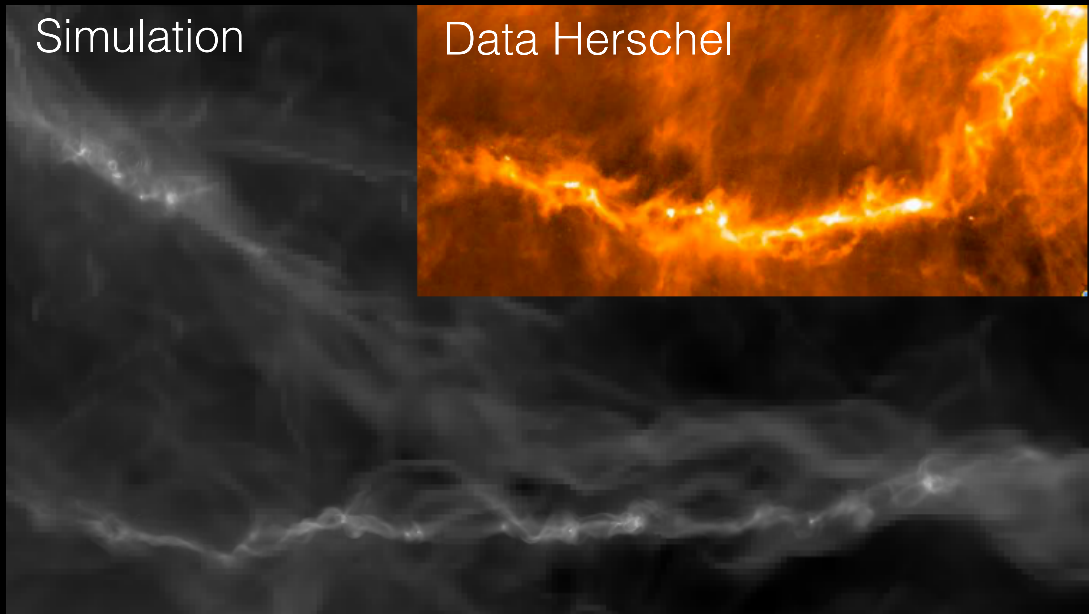
How does gravity become the local dominant force to allow for Star Formation ?

How does turbulence shape the magnetized universe ?

- ★Energy equipartition is observed between kinetic and magnetic energy over a range of scales: in galaxies, the diffuse ISM and star forming molecular clouds
- ★Turbulence creates a range of density structures in interstellar matter and locally the initial conditions for star formation
- ★Turbulence drives the mass, momentum and energy exchange among ISM phases
- ★Interstellar turbulence may not be understood without access to the structure of magnetic field, and its correlation with the density and velocity structure of the gas

How to move forward?

Numerical simulations resemble observations in terms of structures and scaling laws, but because of their limited numerical resolution, they cannot reach the very large Reynolds (10^{10}) numbers of interstellar and intergalactic gas flows.



Kritsuk+13

Synergy between observational and numerical studies is essential to make headway.

Statistical studies represent the best hope to bridge theory, simulations and observations.

Observational methods

Magnetic fields may be traced with polarization observations

- Faraday rotation

  In ionized regions

  $\rightarrow$ $B_{\parallel}$ (strength & sign)

- Synchrotron emission

  In general (CR-filled) ISM

  $\rightarrow$ $\vec{B}_{\perp}$ (strength & orientation)

- Dust polarization

  In general (dusty) ISM

  $\rightarrow$ $\vec{B}_{\perp}$ (orientation only)

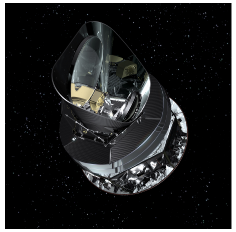
- Zeeman splitting

  In neutral (molecular & atomic) regions

  $\rightarrow$ $B_{\parallel}$ (strength & sign)

SKA SQUARE KILOMETRE ARRAY

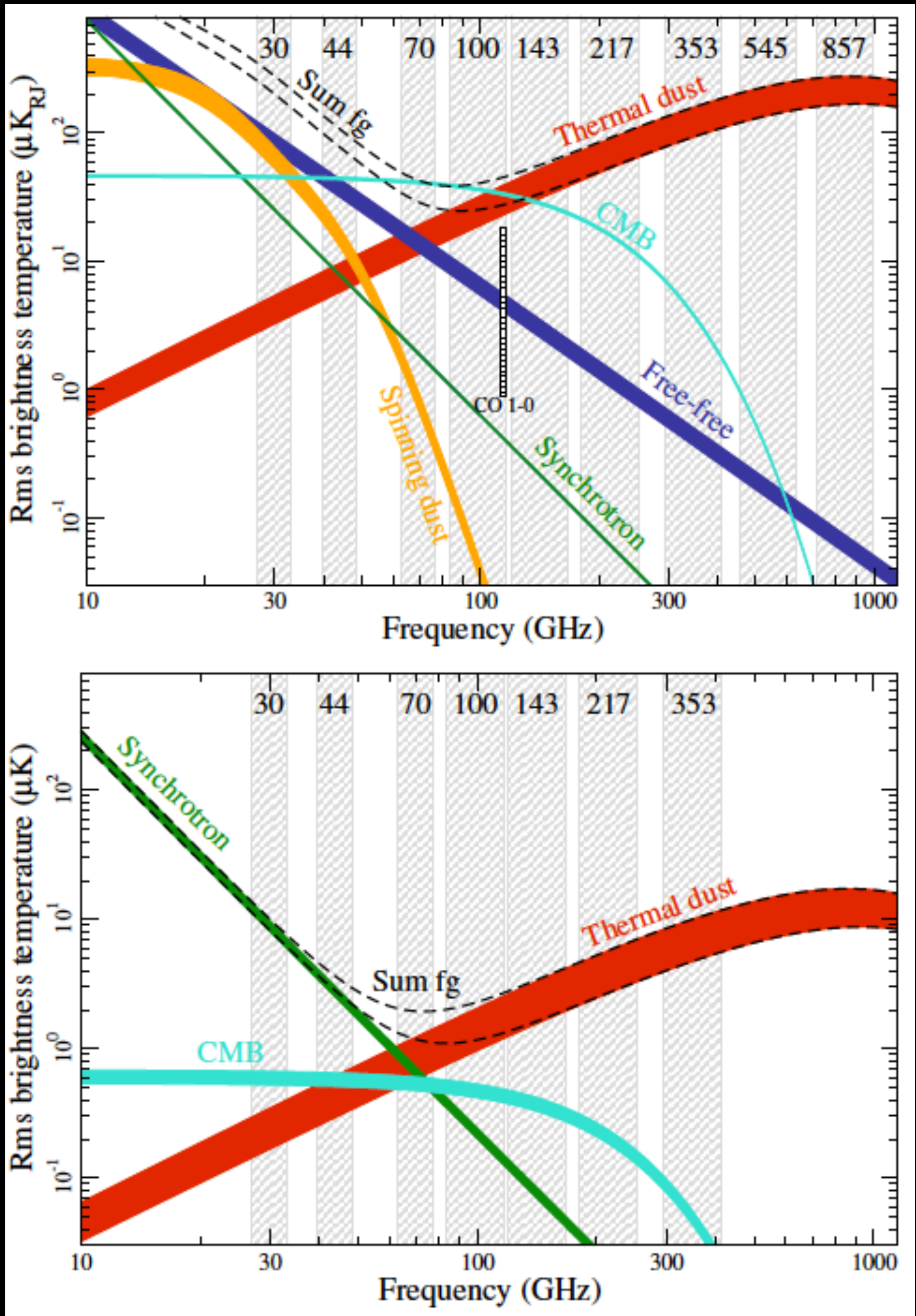
LOFAR



ALMA

x12 NOEMA project

Galactic Foregrounds



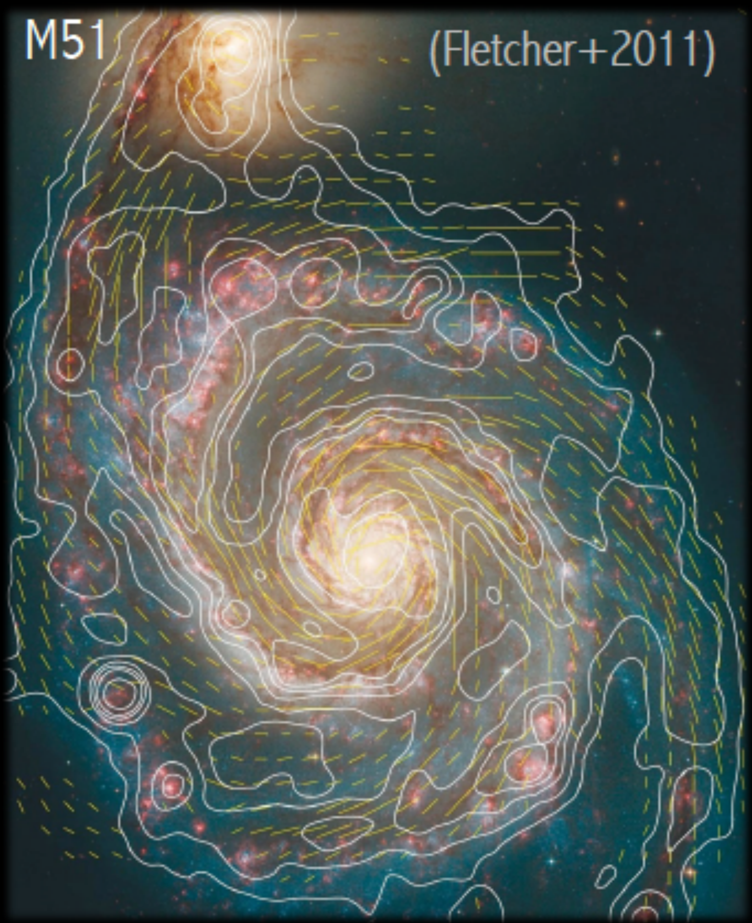
Total Intensity

Polarization

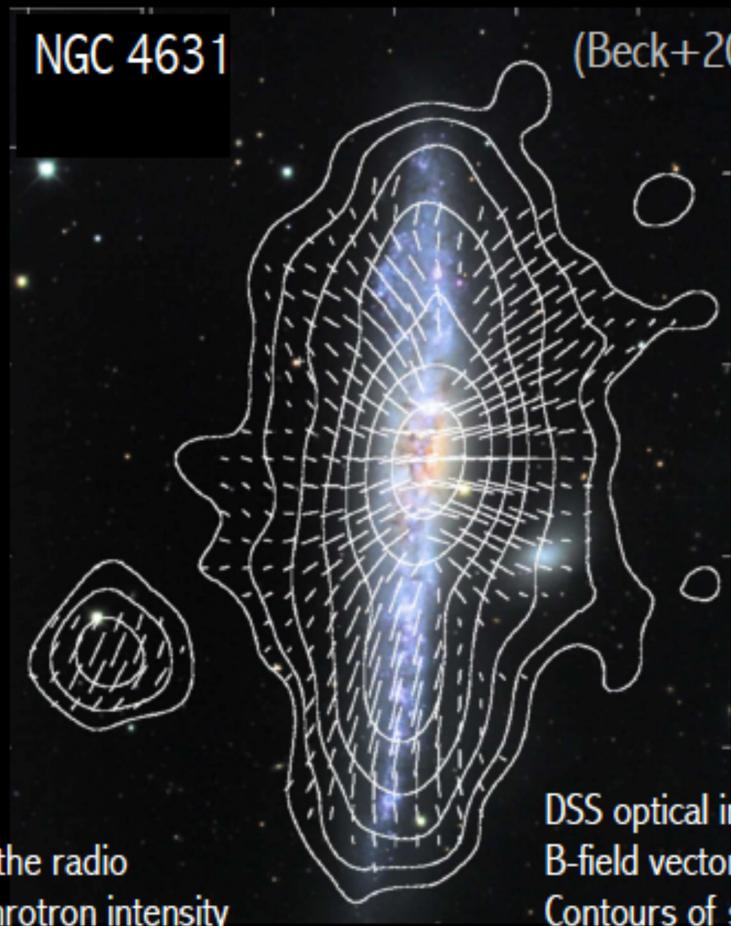
Magnetic fields at large scale in external galaxies

Tight coupling between magnetic fields gas and cosmic rays → Magnetic fields are crucial for the dynamics of galaxies

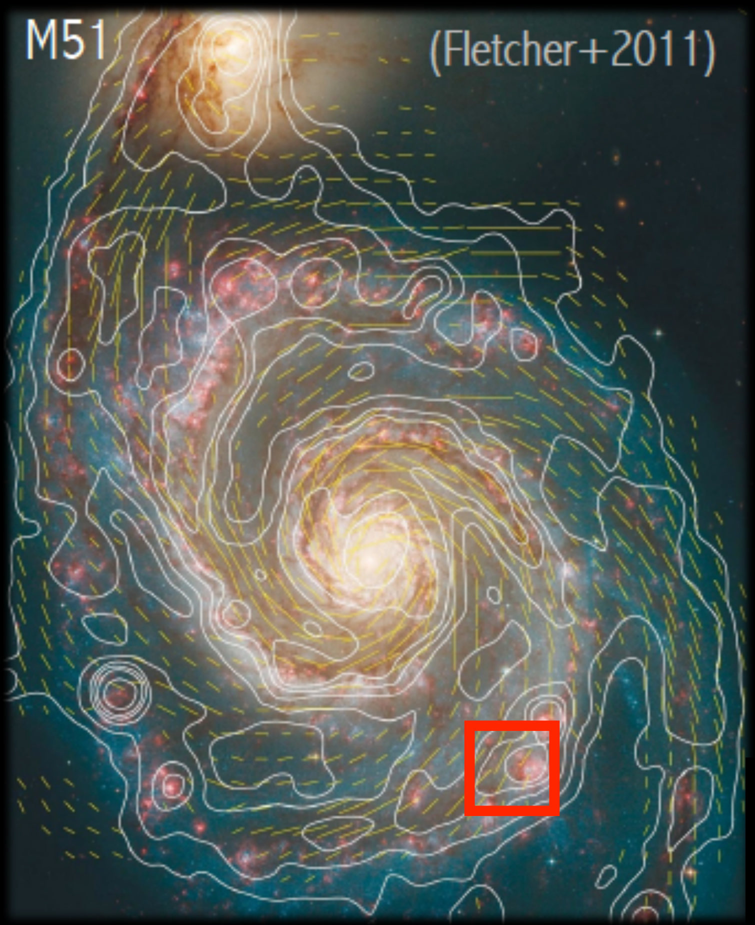
- From synchrotron polarization **ordered** B-Fields (~10 μG) are observed on galactic scales both in edge- and face-on galaxies (see Beck,2015 for a recent review)
- An important **turbulent** component of the B-field (~5 μG) results from RM measures and depolarization of synchrotron emission (Sokoloff+1998)

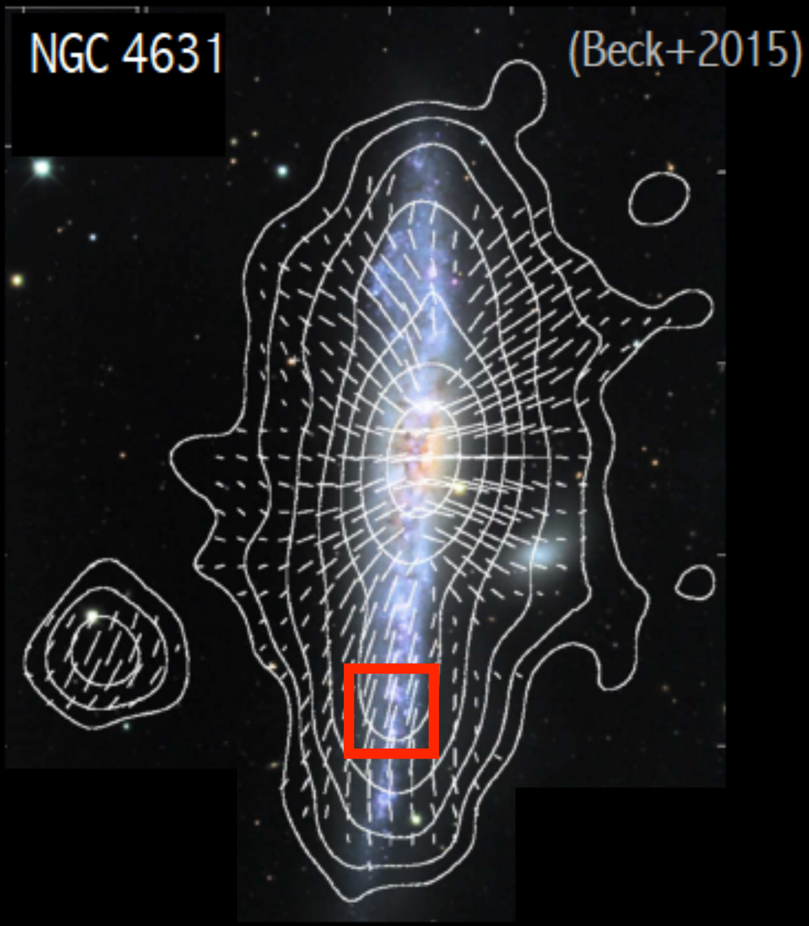


HST optical image
B-field vectors in the radio
Contours of synchrotron intensity



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



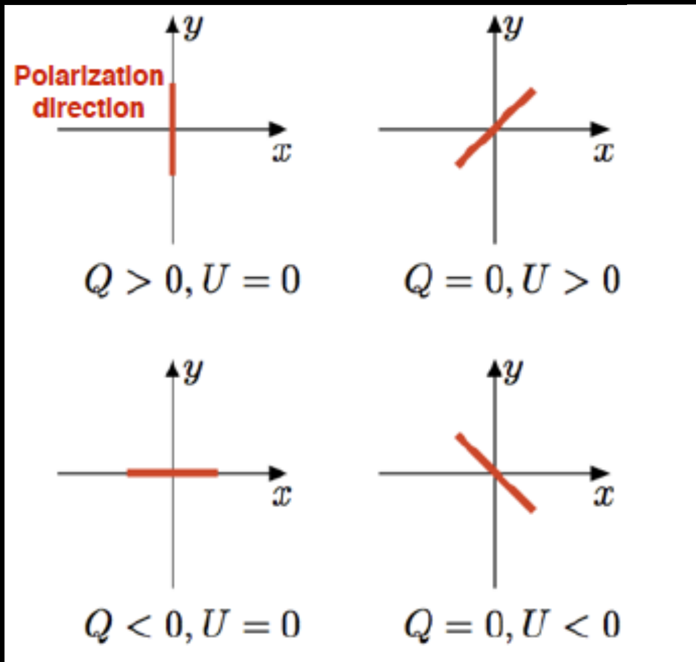


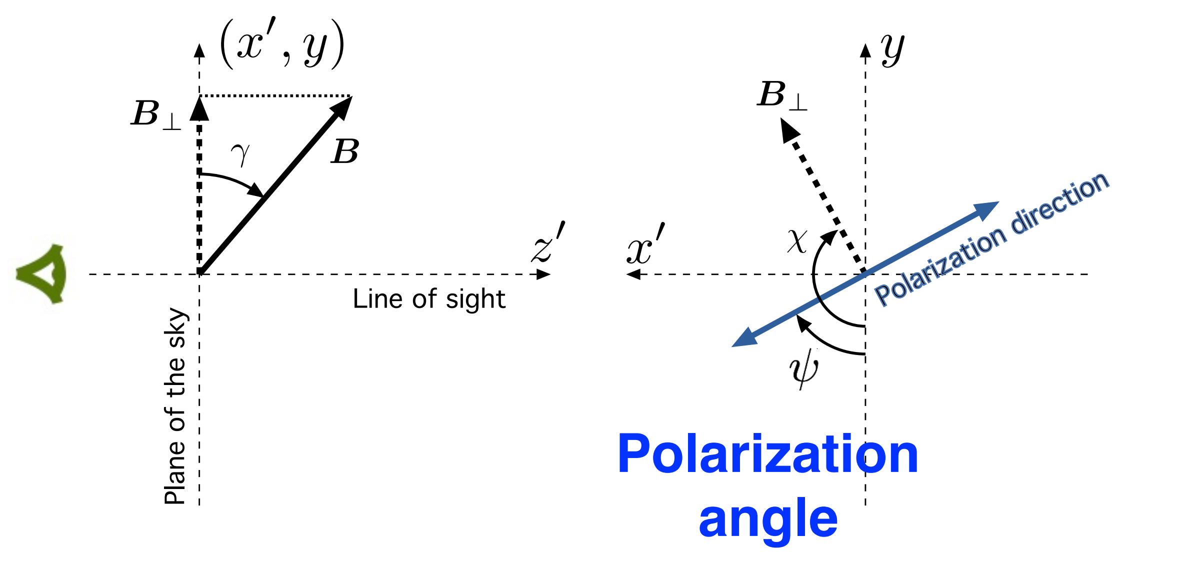
Planck dust polarization: zoom on magnetic fields with a distinct tracer

- Sub-mm dust emission traces dust mass

➡ Sub-mm dust polarization best suited to investigate the interplay between interstellar magnetic fields and matter

Stokes parameters





$$
\begin{aligned}
Q &= \int p_{\max}\, R \, cos(2\psi)\, cos^2\gamma \, dI \\
U &= -\int p_{\max}\, R \, sin(2\psi)\, cos^2\gamma \, dI
\end{aligned}
$$

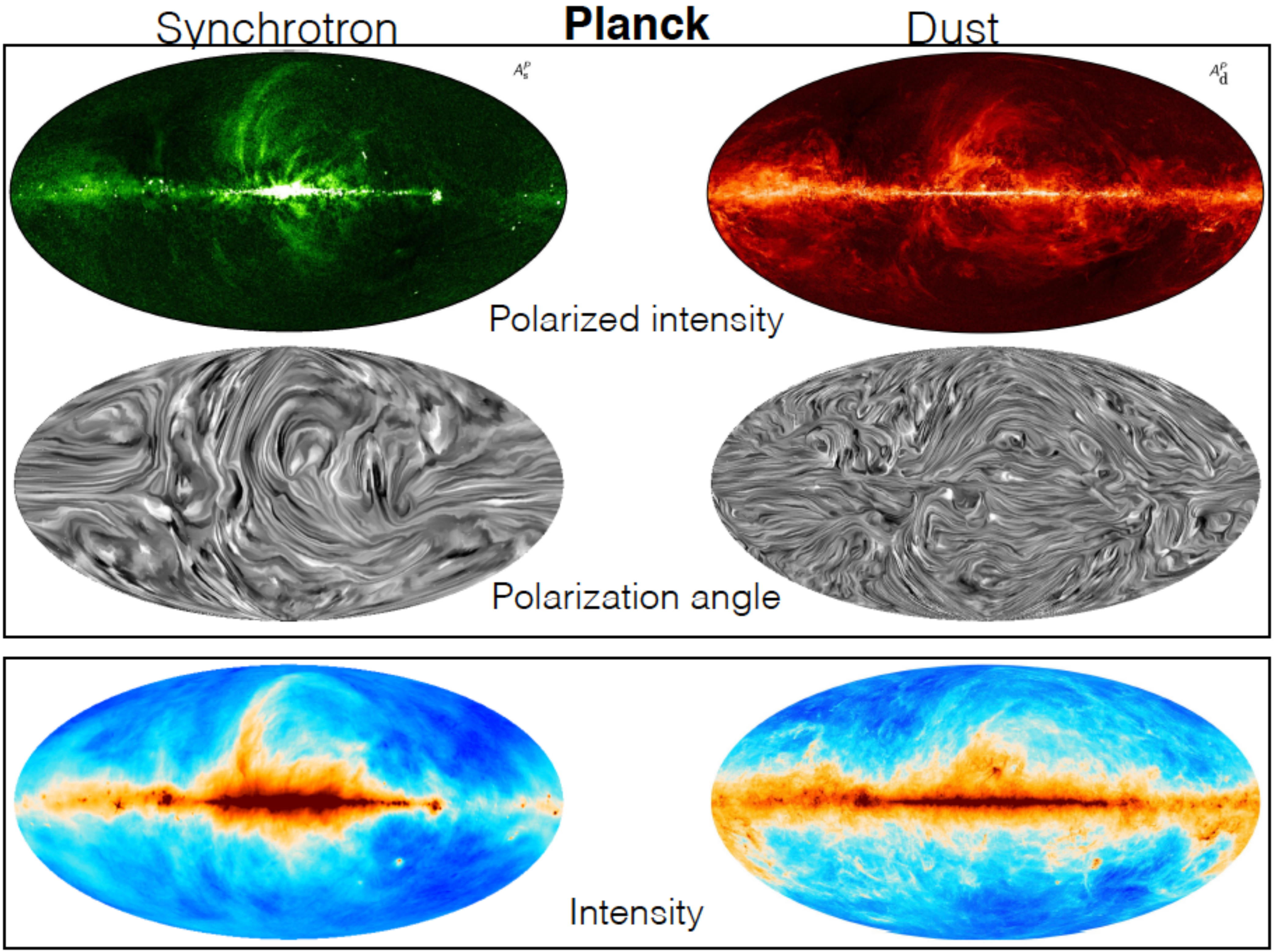
$$
\begin{aligned}
P &= (Q^2 + U^2)^{0.5} \\
p &= P/I \\
\psi &= 0.5 \arctan(-U, Q)
\end{aligned}
$$

Polarization fraction

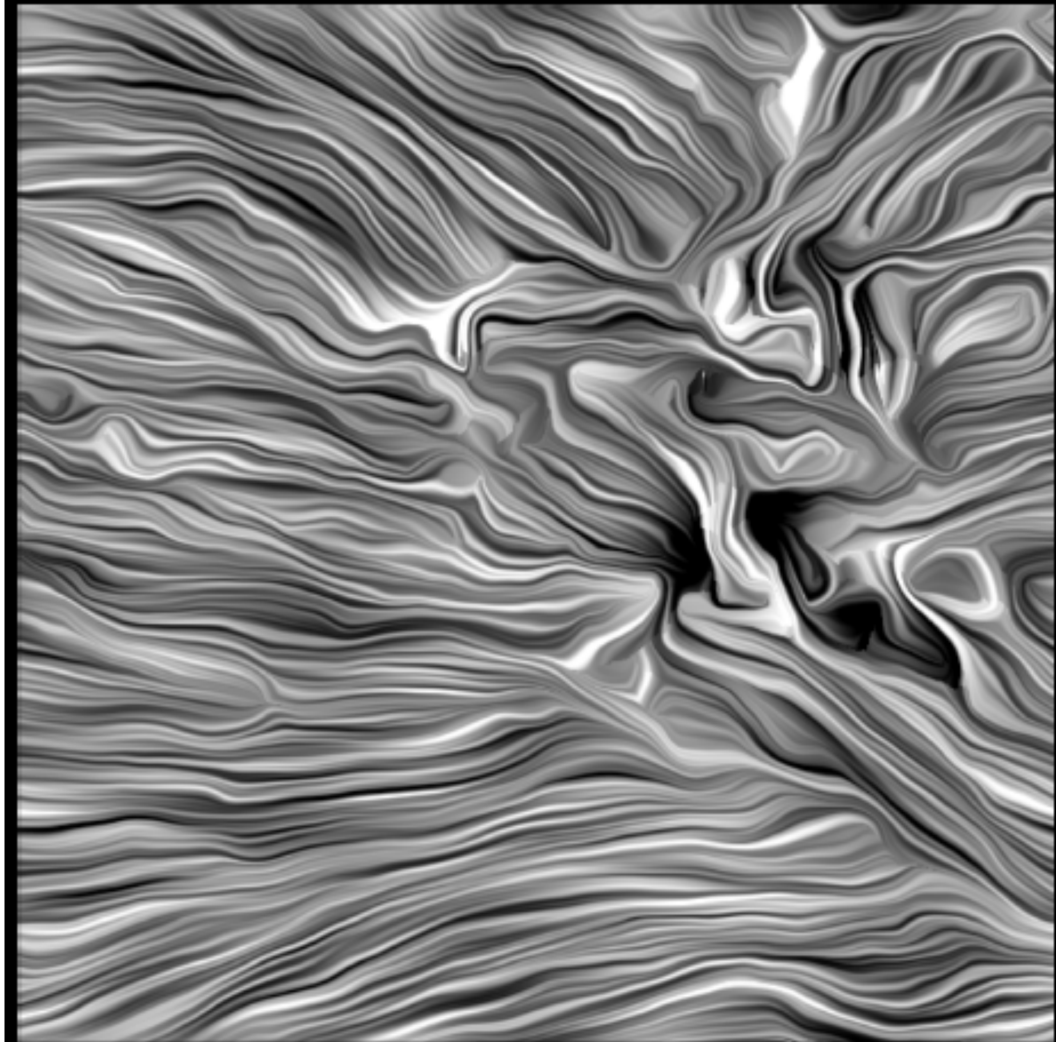
$$
\begin{aligned}
p &= p_{\max}\, R\, F\, cos^2\gamma \\
R &\text{ and } F \leq 1
\end{aligned}
$$

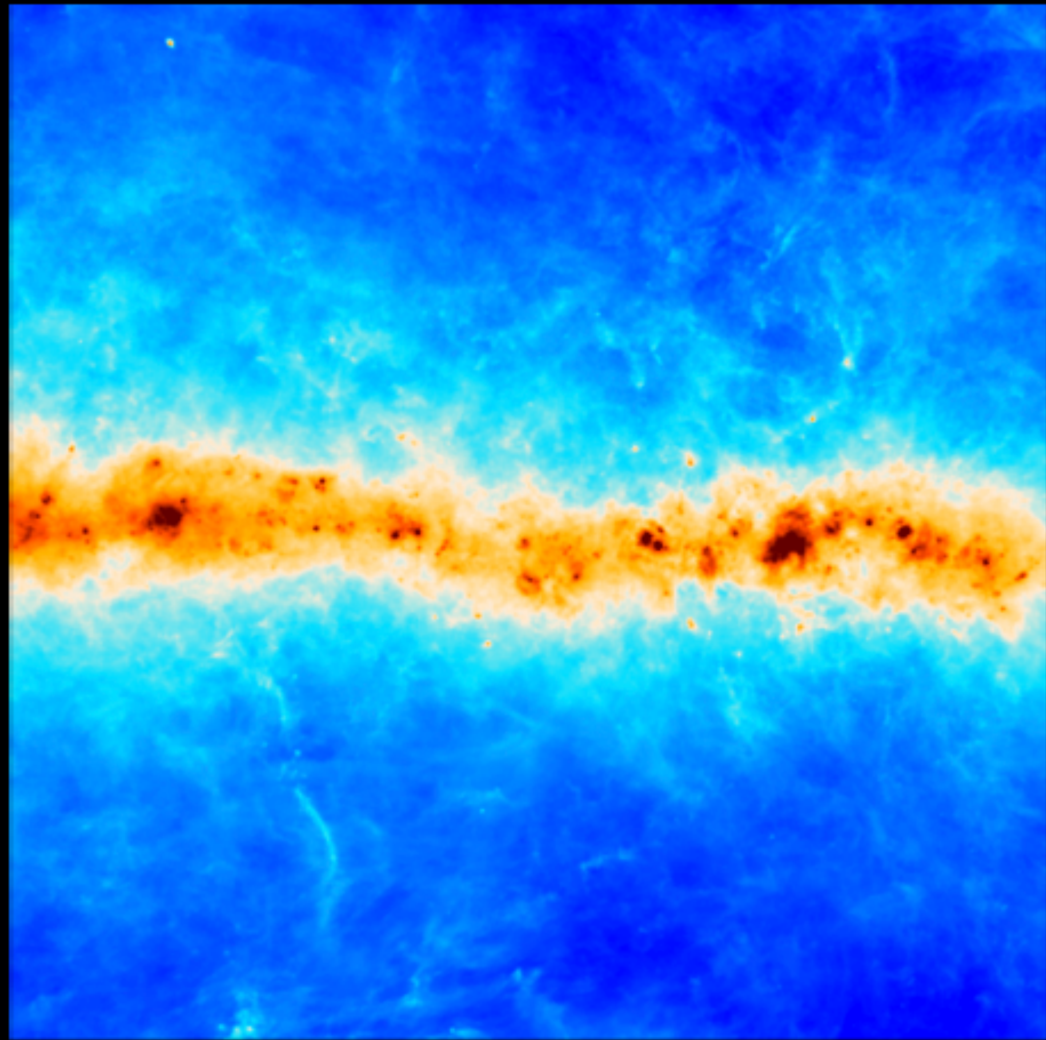
R: Rayleigh reduction factor (efficiency of grain alignment)

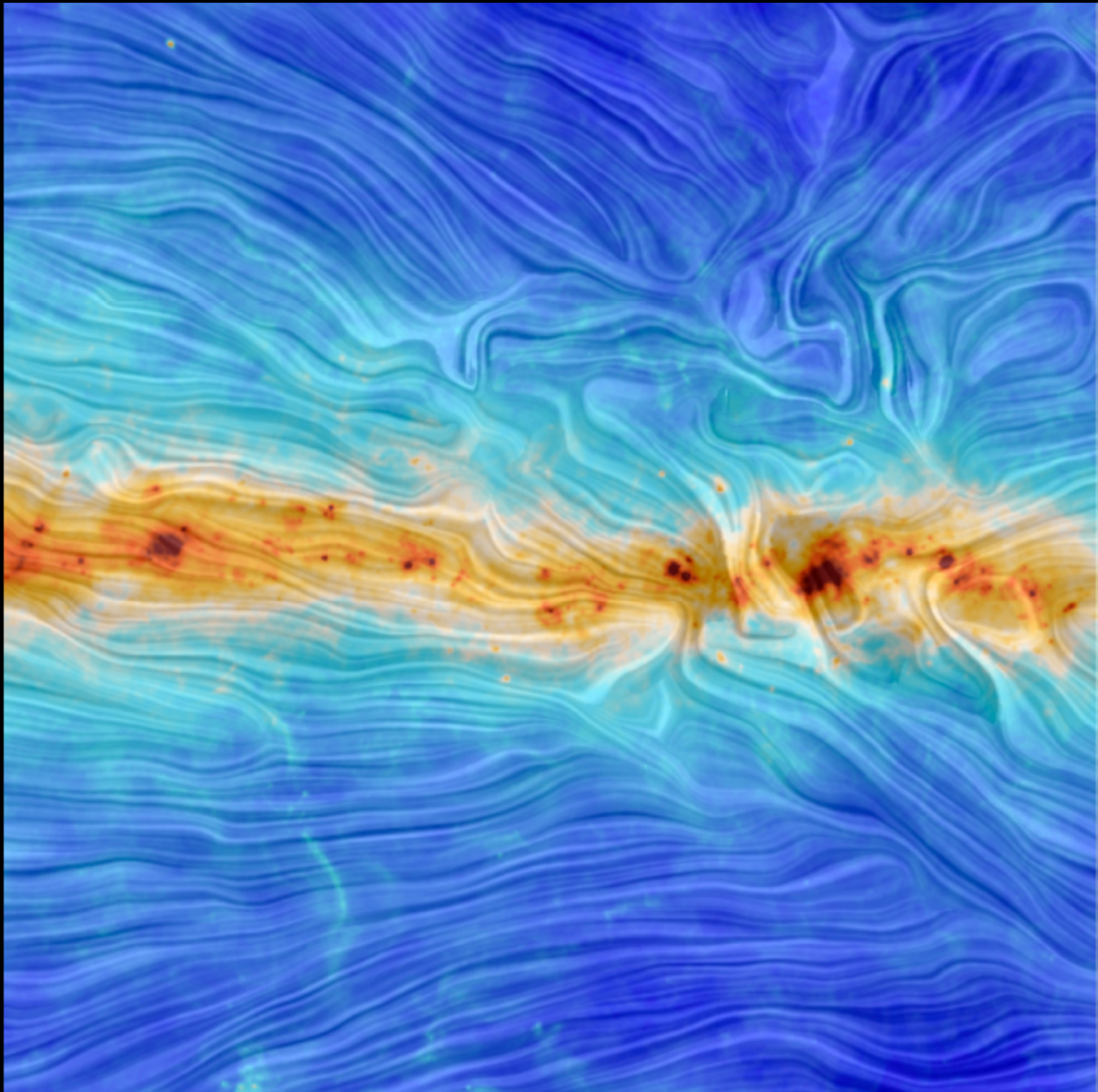
F: Depolarization factor (change of B orientation within the beam)

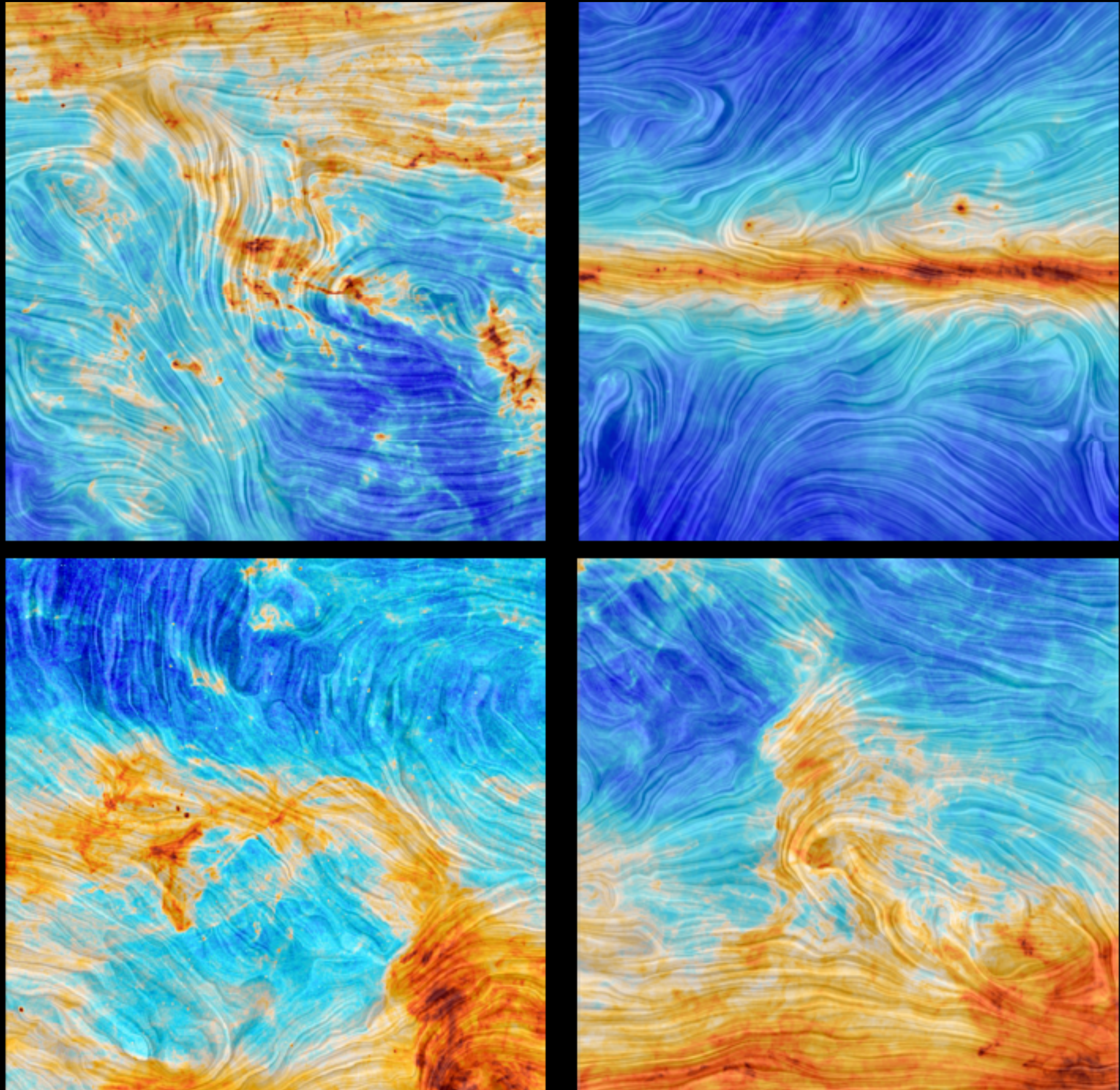

Synchrotron
Planck
Dust
Polarized intensity
Polarization angle
Intensity

Line Integral Convolution : looking at vector fields differently

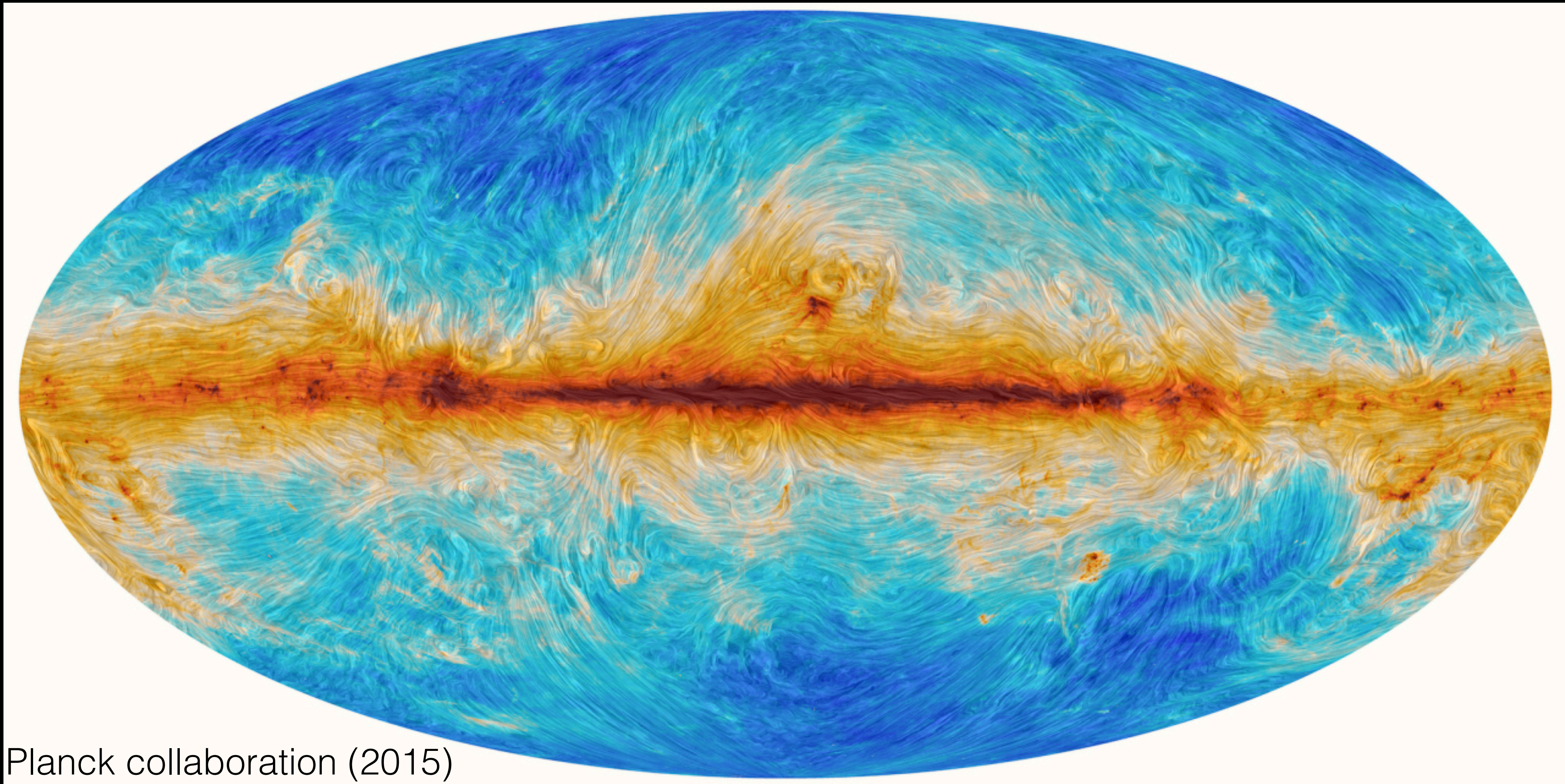








Magnetic field and ISM structure

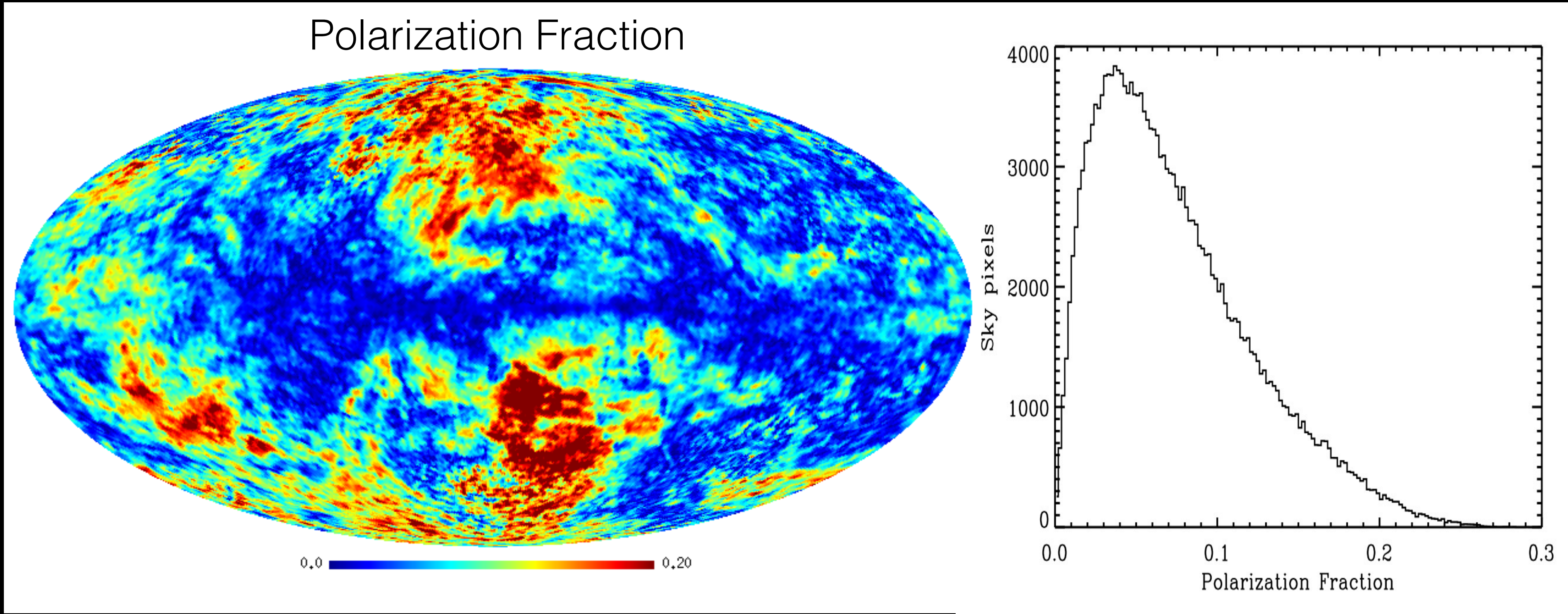


Planck collaboration (2015)

➡Huge step forward in terms of sensitivity, sky coverage and statistics

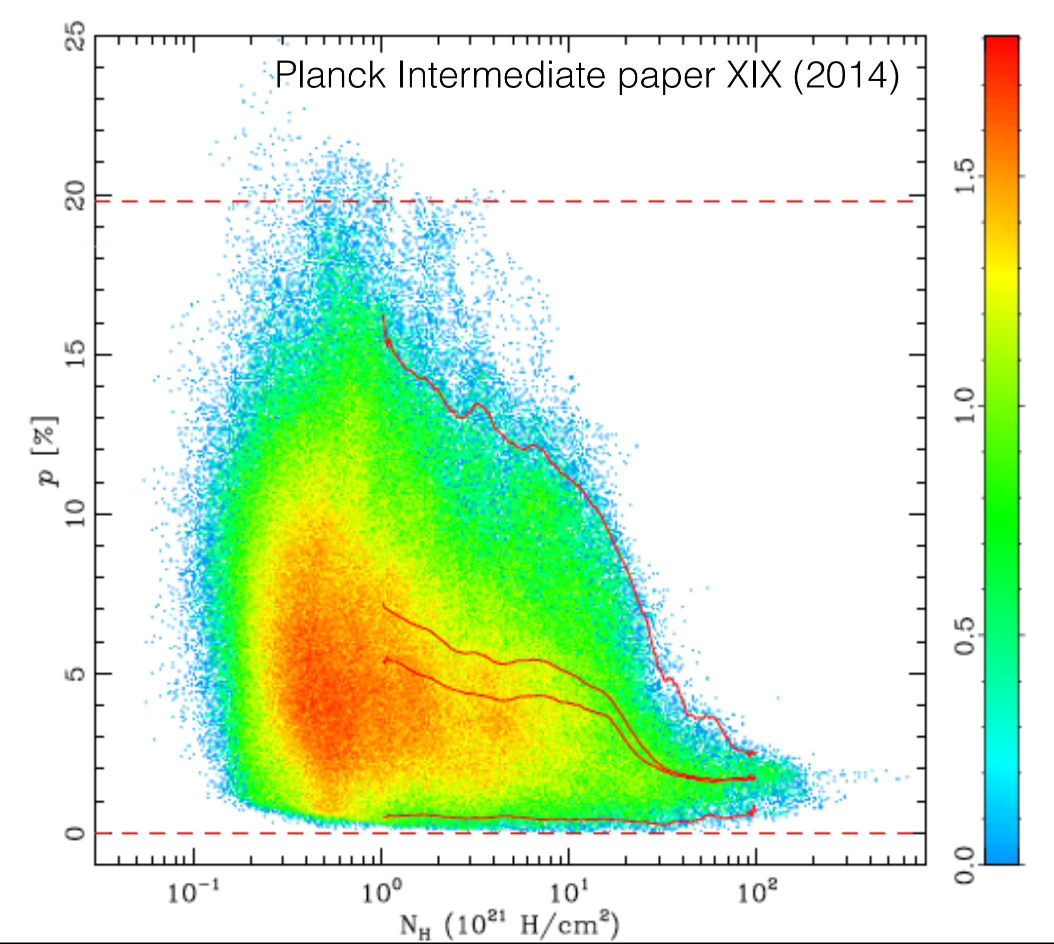
Polarization Fraction

Overview paper dust polarization by Planck collaboration (2014)



- The maximal polarization fraction is large (>20%). It is a challenge for dust models to explain such high values
- The polarization fraction shows a large scatter, which we interpret as line of sight depolarization associated with interstellar turbulence

Polarization fraction p vs NH



- Polarization fraction up to 20%.
- Large dispersion of p at all N_H, tracing changes in B-field orientation and depolarization within the beam.
- Sharp decrease of $p > 10^{22}$ H cm^{-2}. Consistent with earlier results from ground-based observations. It has been interpreted by a loss of grain alignment in the shielded interiors of clouds.

Polarization fraction

$$p = p_{\max} R\, F\, cos^2\gamma$$

$$R \quad \text{and } F \leq 1$$

p_{max}: dust properties

R: Rayleigh reduction factor (efficiency of grain alignment)

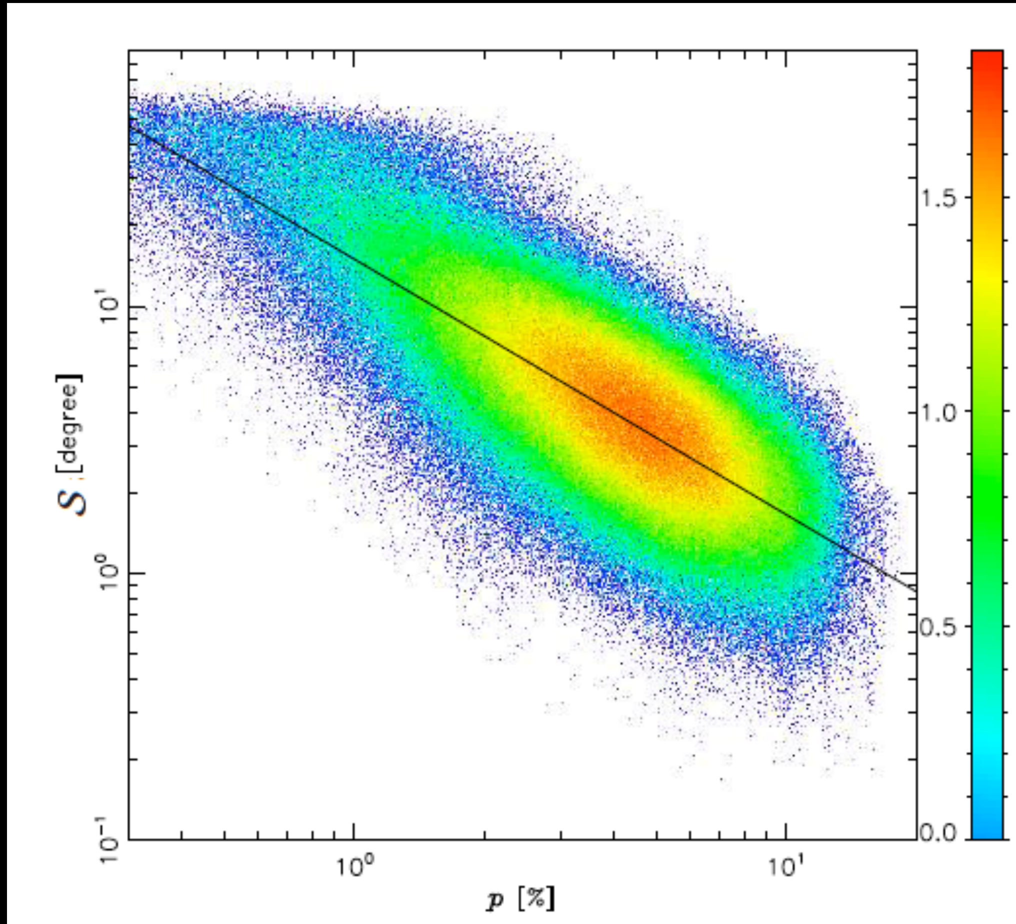
F: Depolarization factor (change of B orientation within the beam)

Depolarization from Field Structure

Dispersion of polarization angle

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

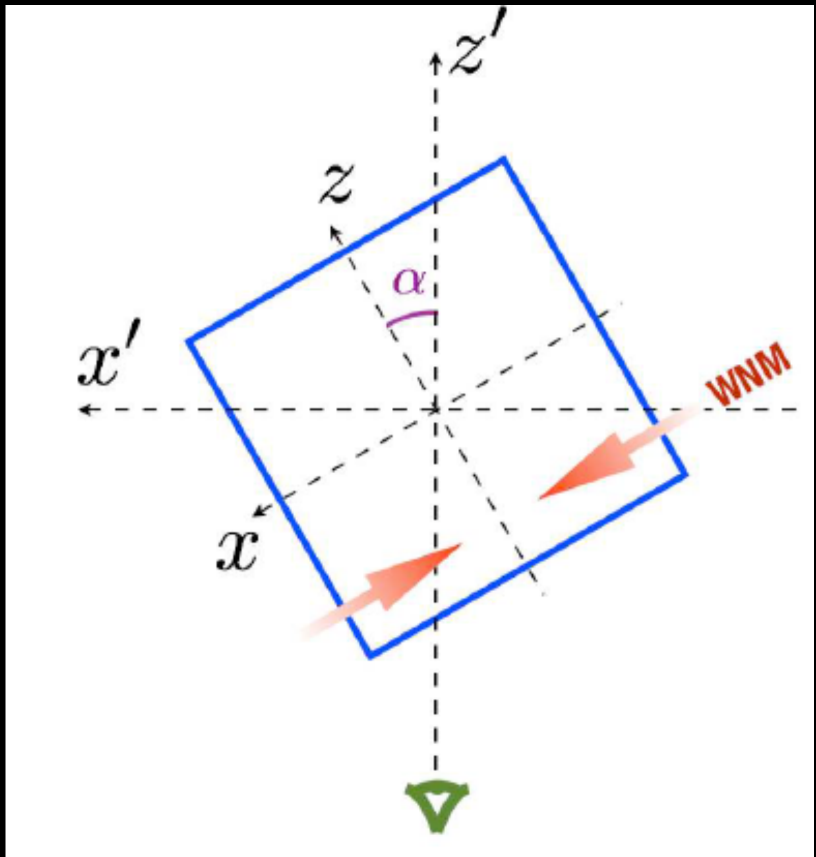
Independent of grain alignment

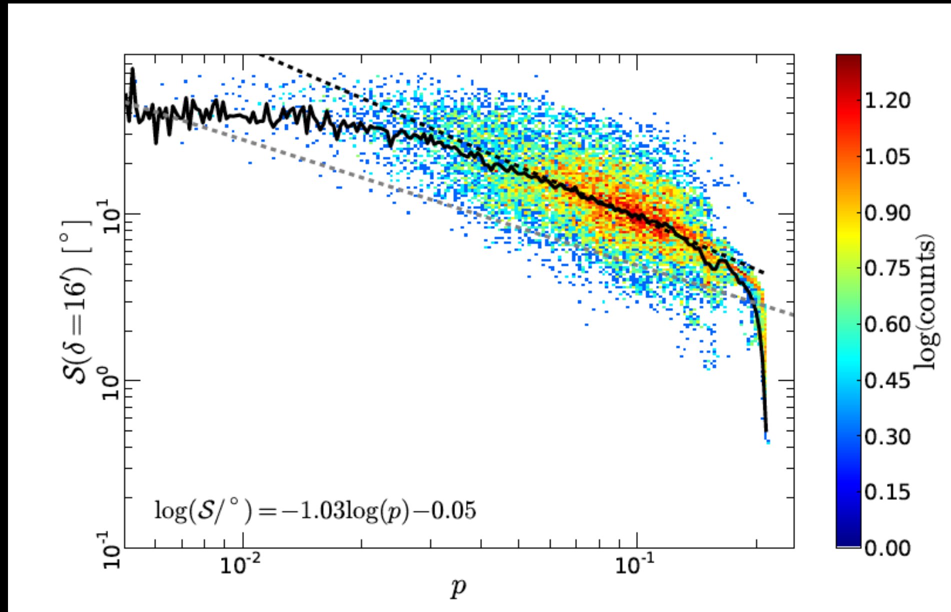


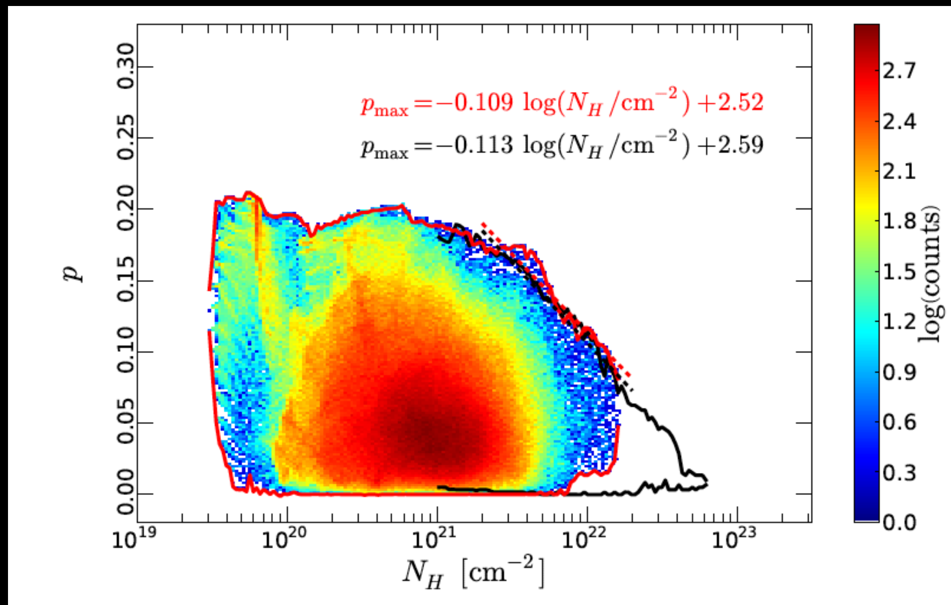
Planck Intermediate paper XIX (2014)

The Planck data suggests that depolarization in the diffuse ISM mainly results from superposition of signals with different polarization directions. Within this interpretation variations in p are primarly related to the field structure

Comparison with MHD Simulations





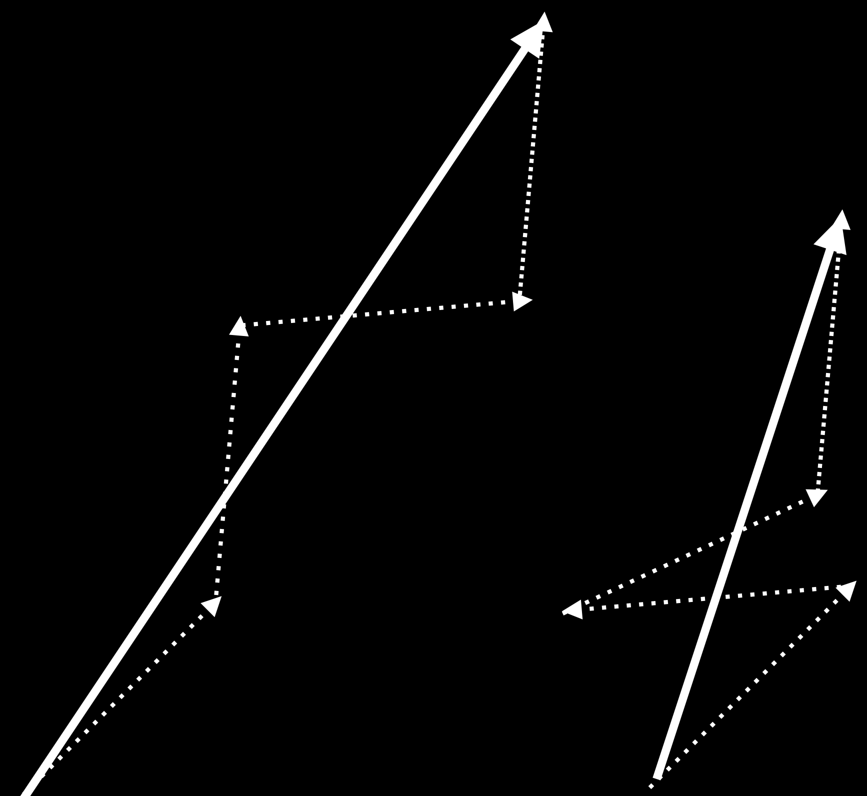


Formation of a molecular cloud at the interface of two converging flows of warm gas

PIP XX (2014)

Schematic explanation

Dust polarization may be viewed as a random walk in the Q,U plane about a mean direction



Sky pixel 1

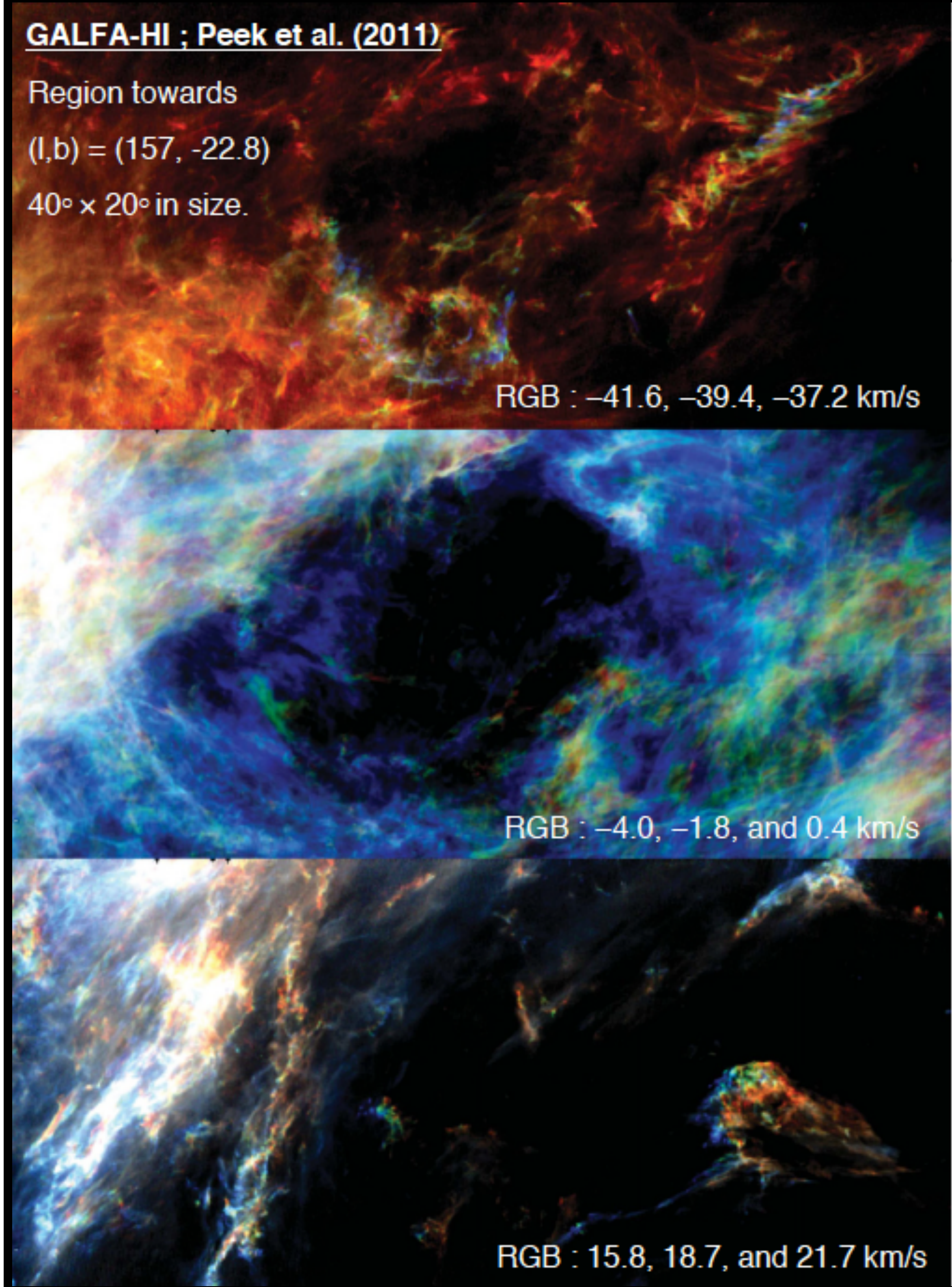
Sky pixel 2

Same I but different polarized intensity and polarization angle

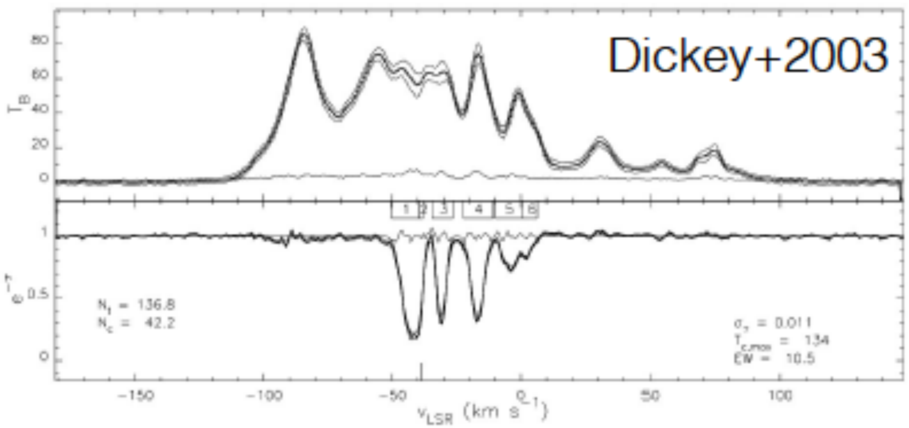
- The magnetic field orientation sets the direction of each step about a mean orientation set by its ordered component.
- Dust polarized intensity sets the length
- The large variance of p implies that the number of steps is small

➡ Multiphase structure of the ISM

➡ Correlation length of interstellar magnetic field

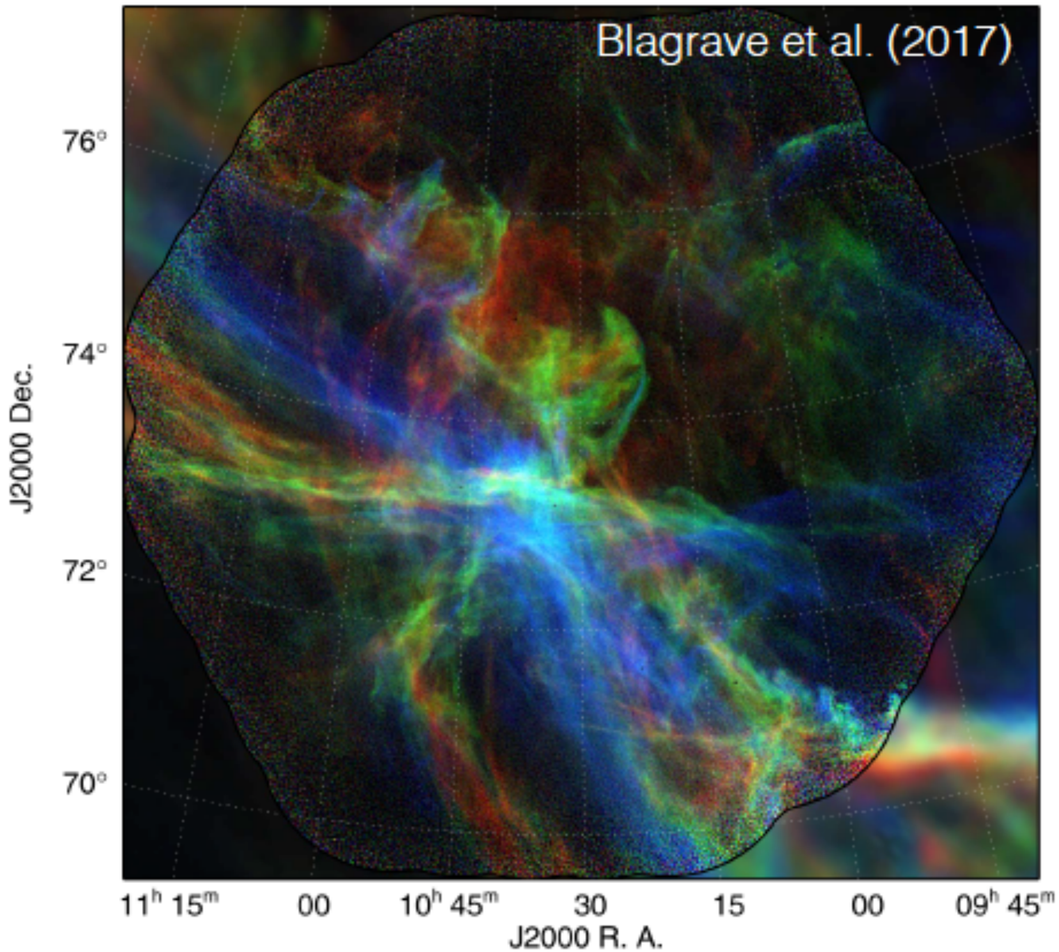


The diffuse atomic gas : the main CMB foreground

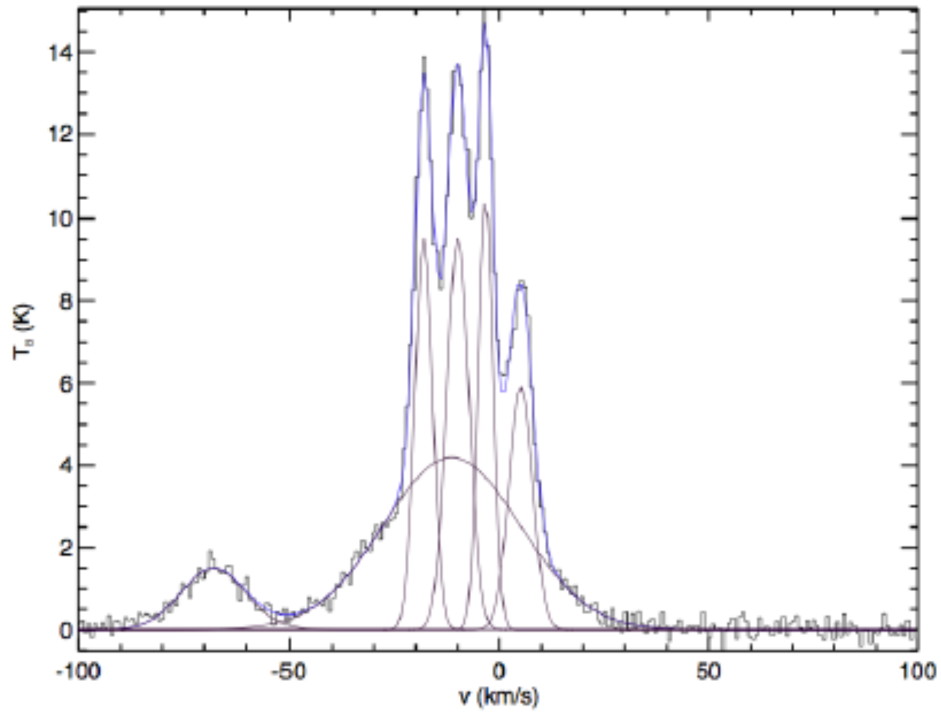


The HI

- dominates column density at high Galactic latitudes
- is a a two phase medium : CNM (40-80 K) and WNM (6000 K)
- only the CNM appears in absorption

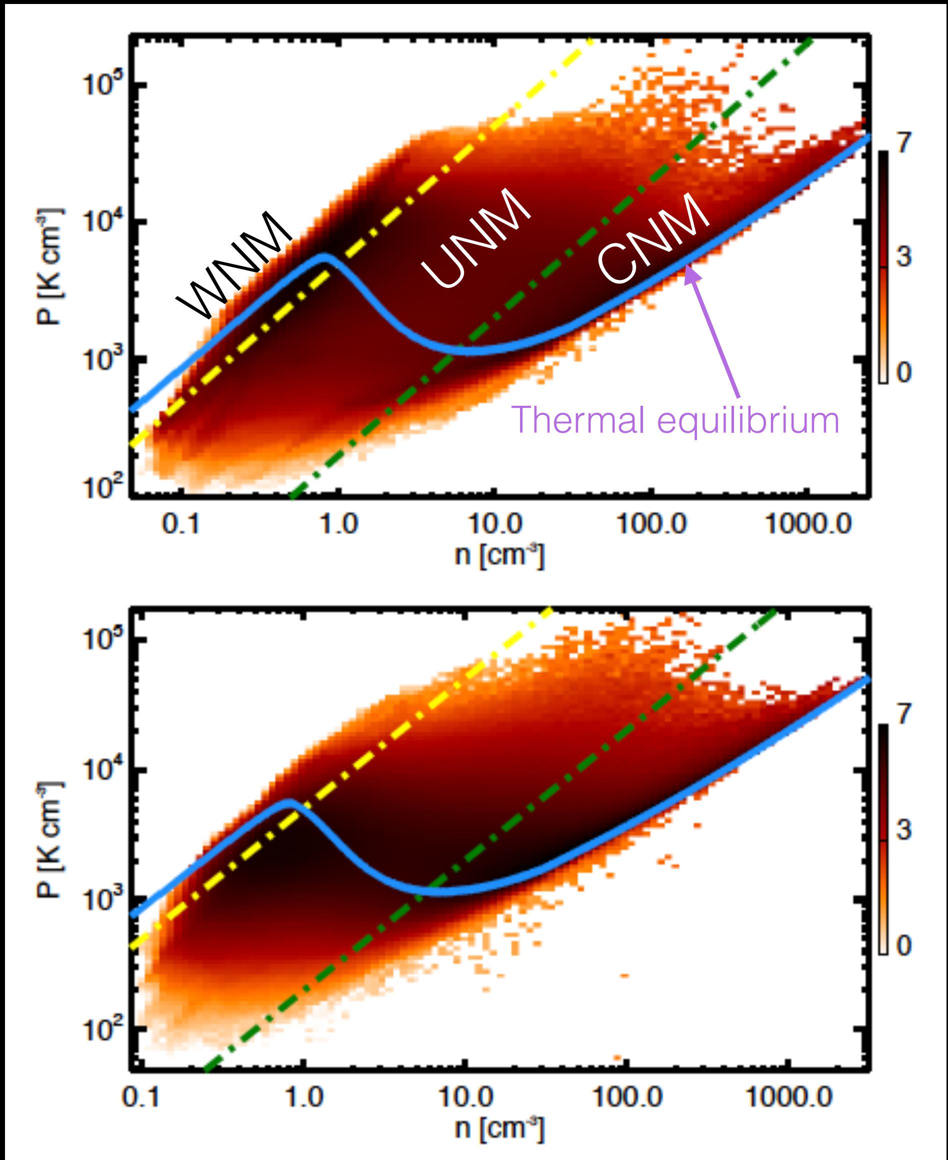


21 cm data of a diffuse cloud

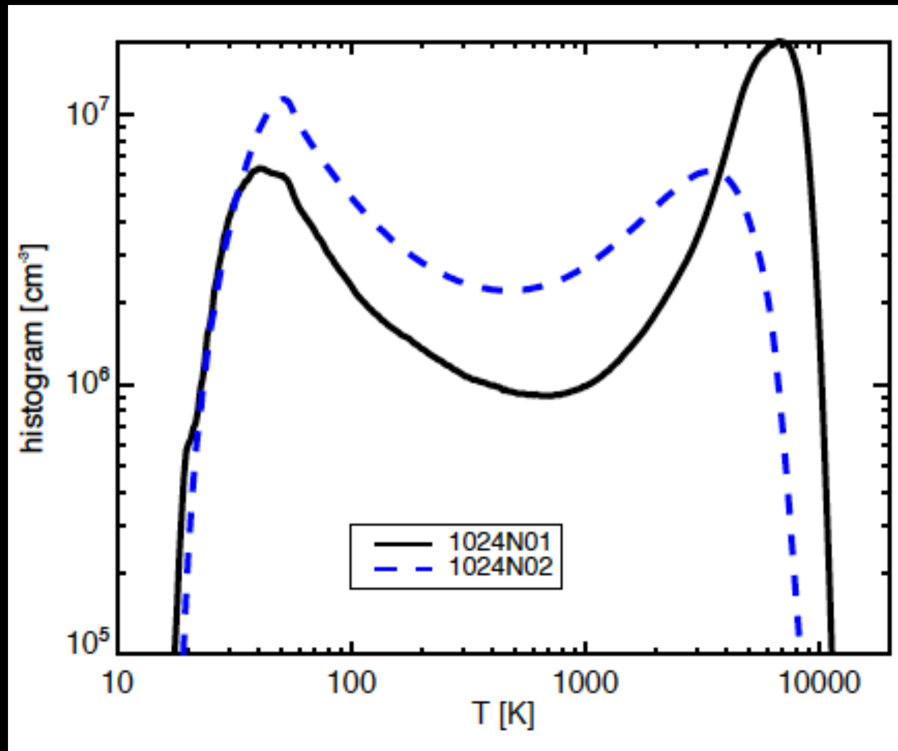


- The diffuse ISM is made of cold-dense structures with a low volume filling factor, immersed in a warm and diffuse phase.
- Its structure is extremely filamentary

Two hydro simulations with distinct initial conditions

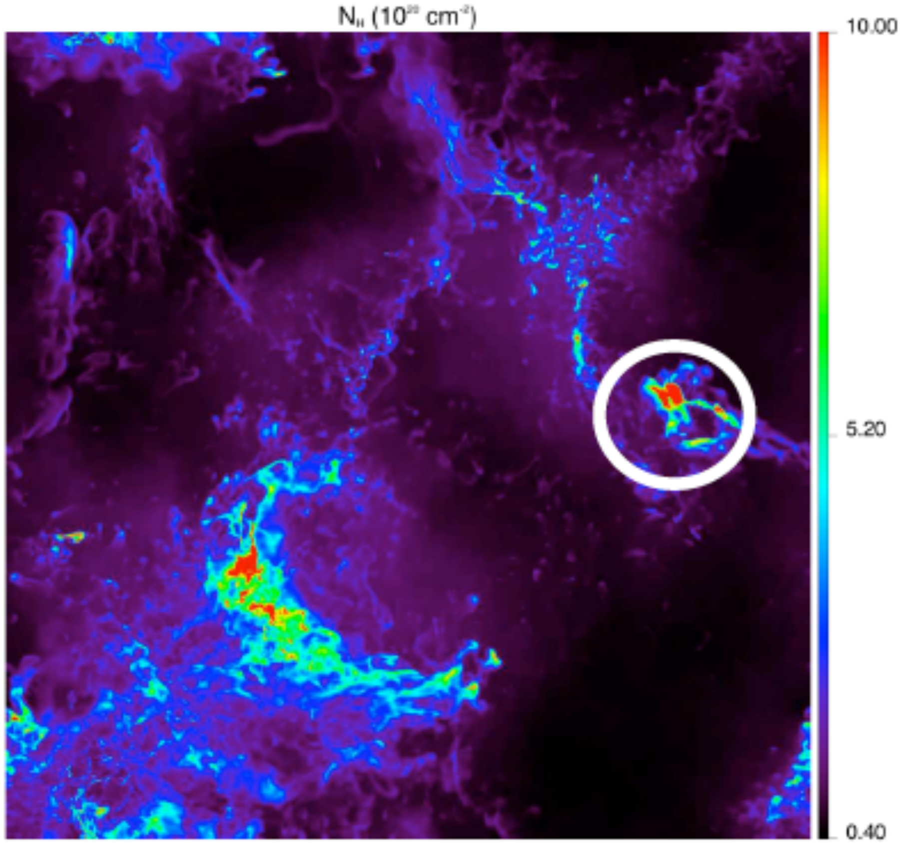


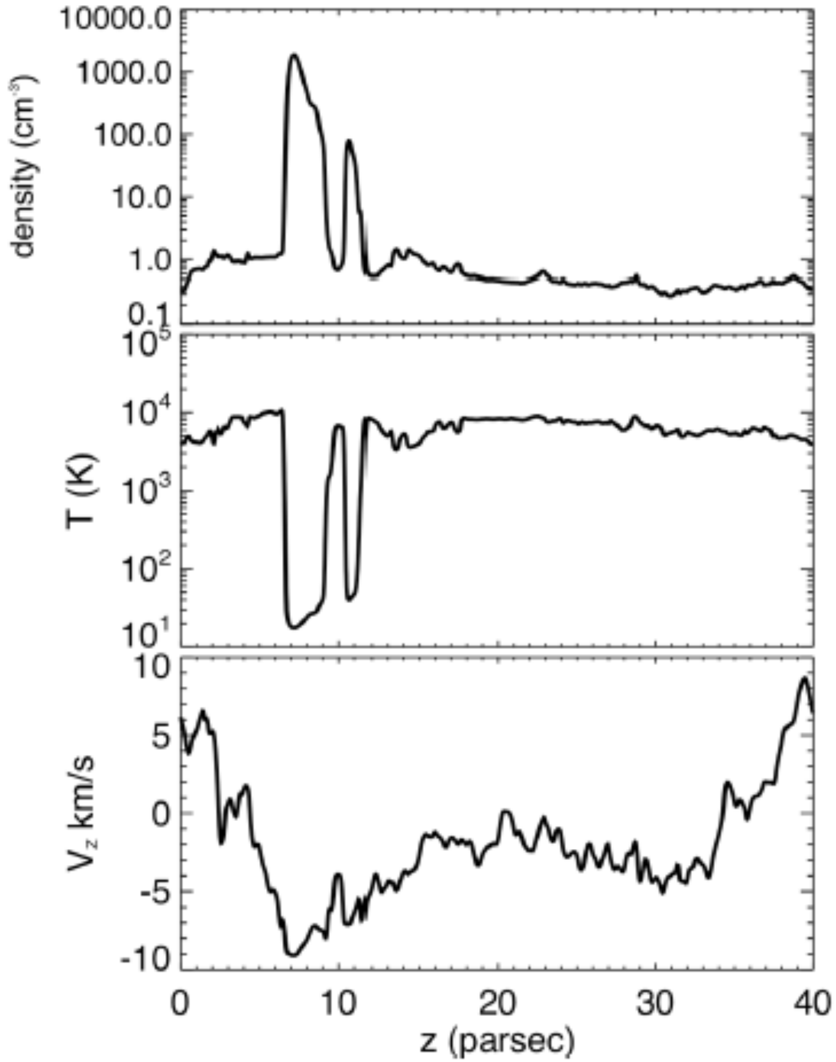
The presence of a significant gas fraction at intermediate temperatures between the two stable cold and warm phases testify of the **dynamical** nature of the **diffuse ISM structure** with $\mathbf{t_{dyn} \sim t_{cool}}$ **(WNM, a few 10^6 yrs)**



Saury+14

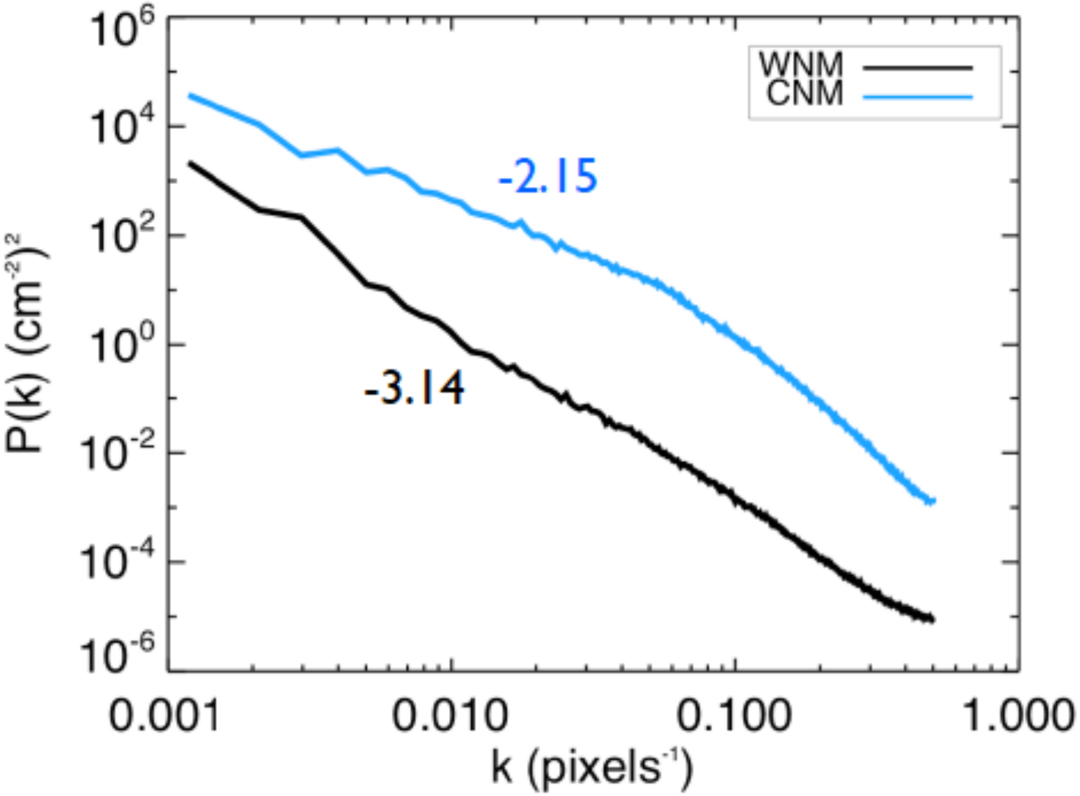
What is on the line of sight at high Galactic latitudes ?





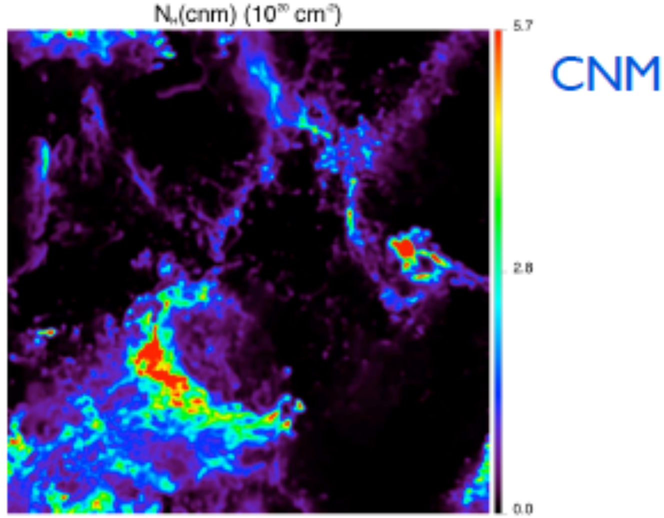
Numerical simulations of HI
Saury et al. (2014)

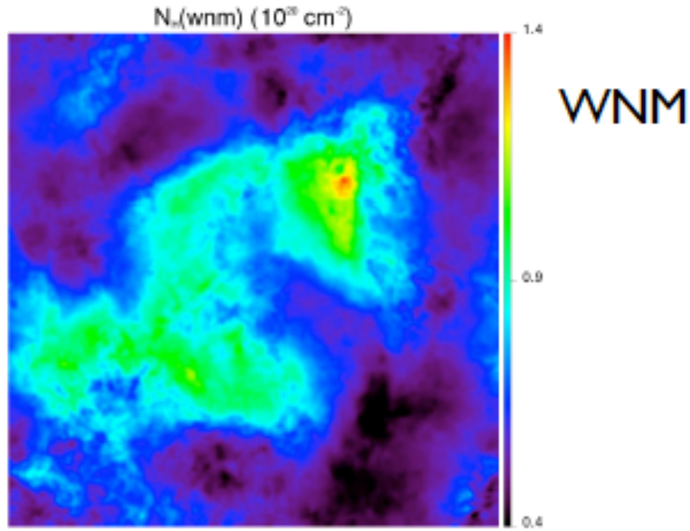
Power spectra of column density : thermally bi-stable turbulence



The CNM has more structure at small scales (flatter P(k)).

The WNM is a smoother medium that fills most of the volume.

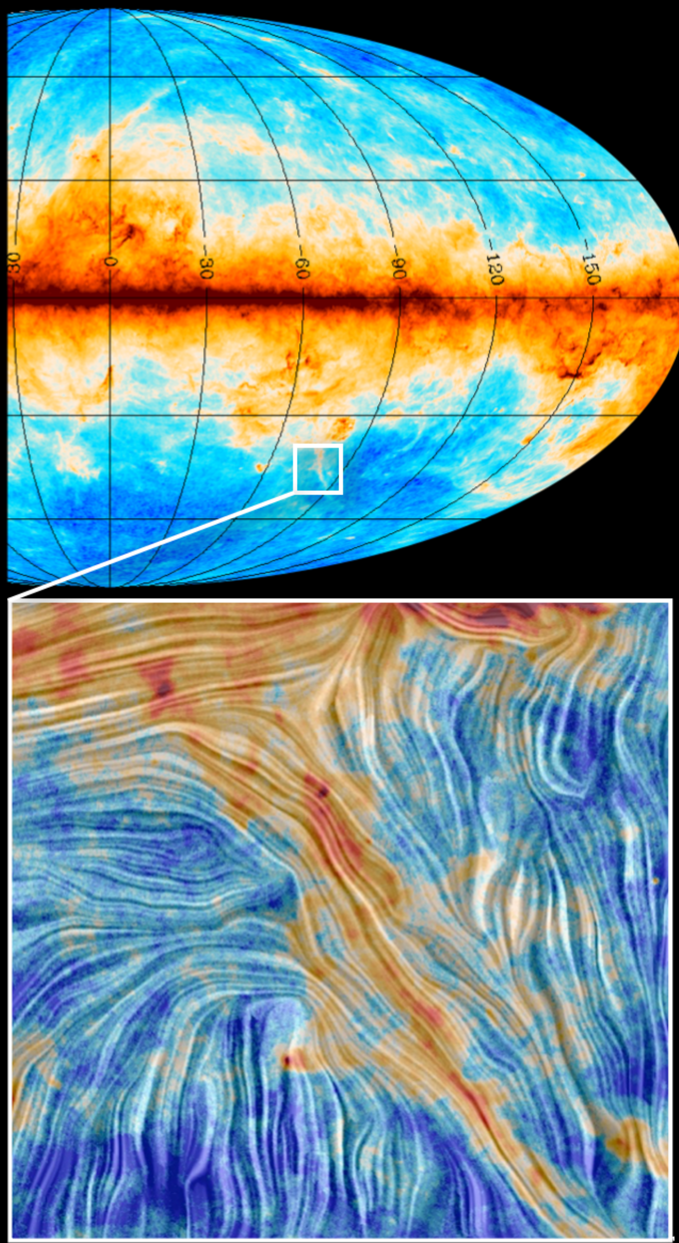




Separation of CNM and WNM based on temperature in numerical simulation
Saury et al. (2014)

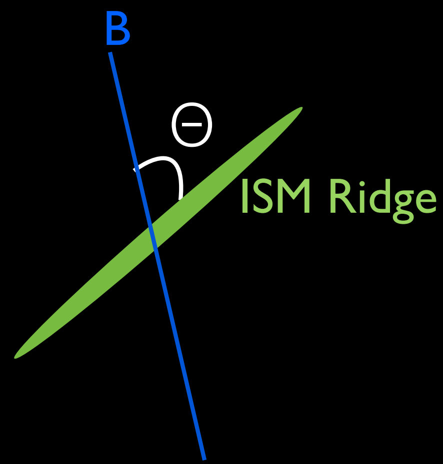
Magnetic fields and structure formation

[Planck Intermediate XXXII 2014, arXiv:1409.6728]



(*Planck* intensity 353GHz, B-field lines)

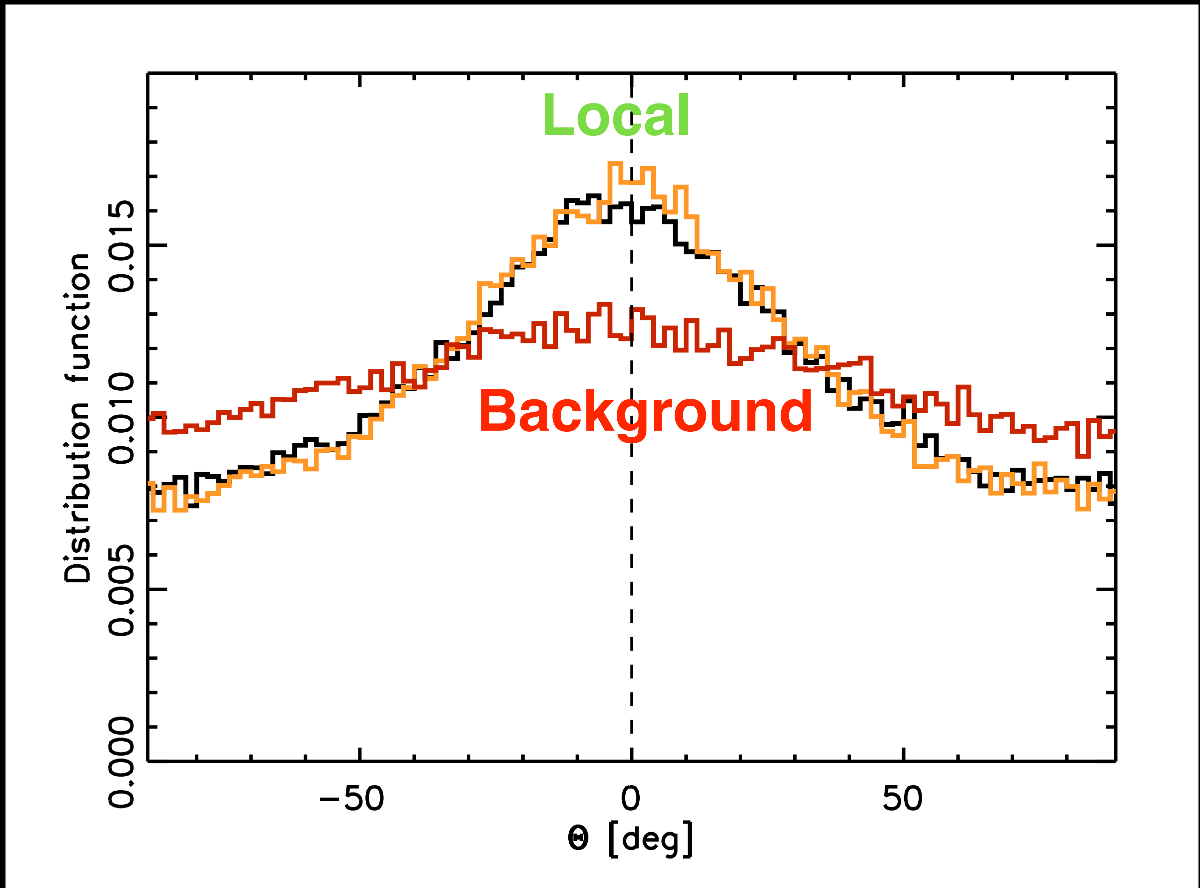
The filamentary structure of the interstellar medium

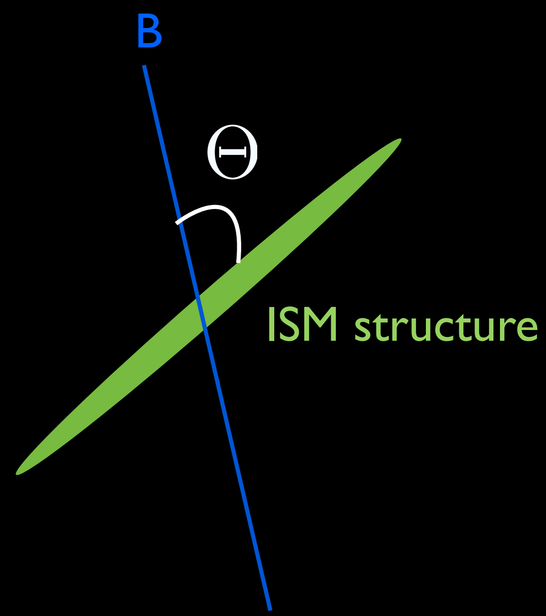


In the diffuse ISM we observe an alignment of the filamentary CNM structures with the magnetic field orientation

Matter vs Magnetic Field

[Planck Intermediate XXXII 2014, arXiv:1409.6728]
Bracco - PhD 2014, Université Paris-Sud, Orsay

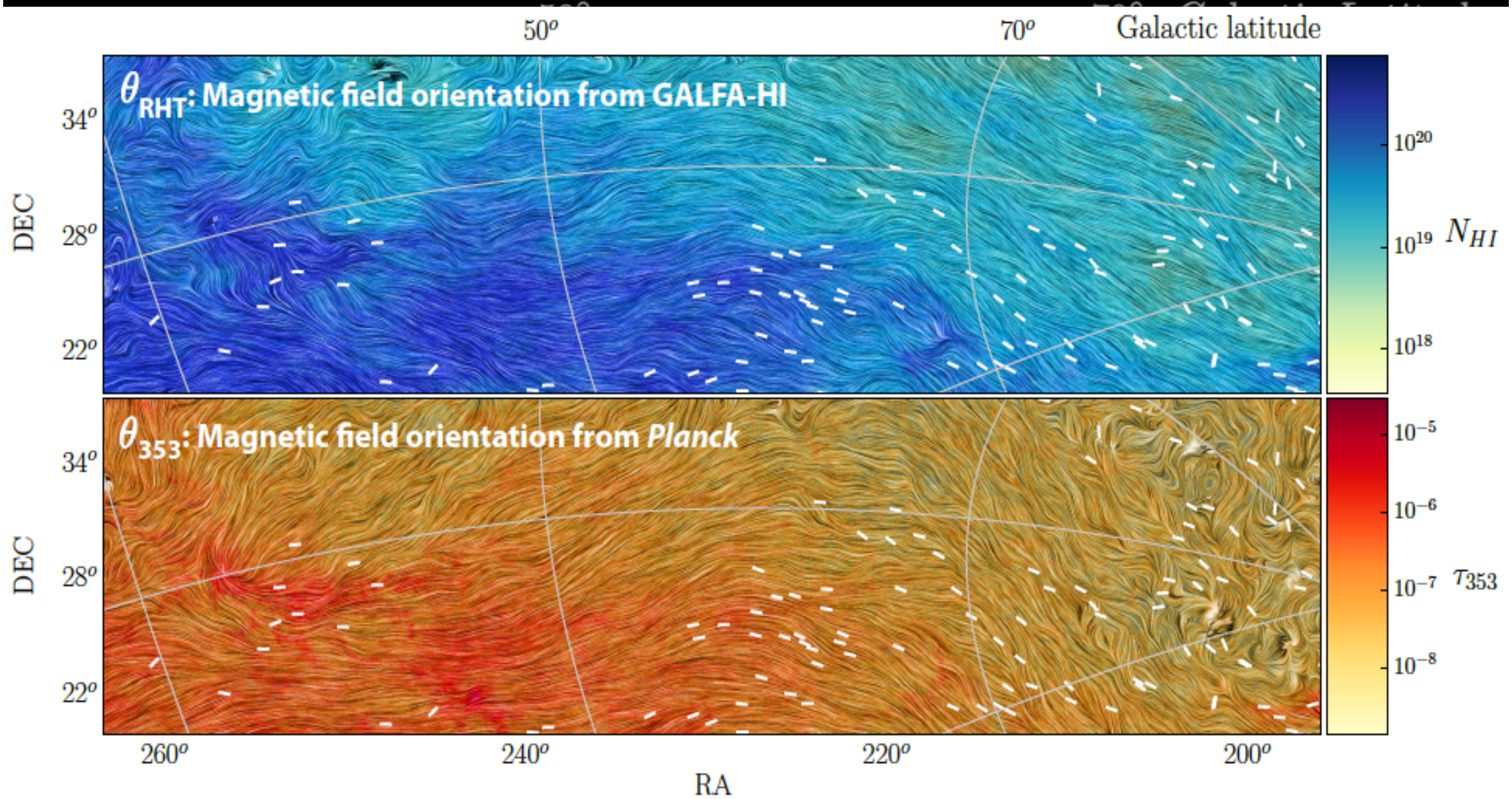




The structures tend to be aligned with the local magnetic field

Projection effects (3D to 2D) are crucial for the interpretation of the shape of the distribution

High latitude GALFA-HI structures are aligned with the Planck magnetic field orientation.

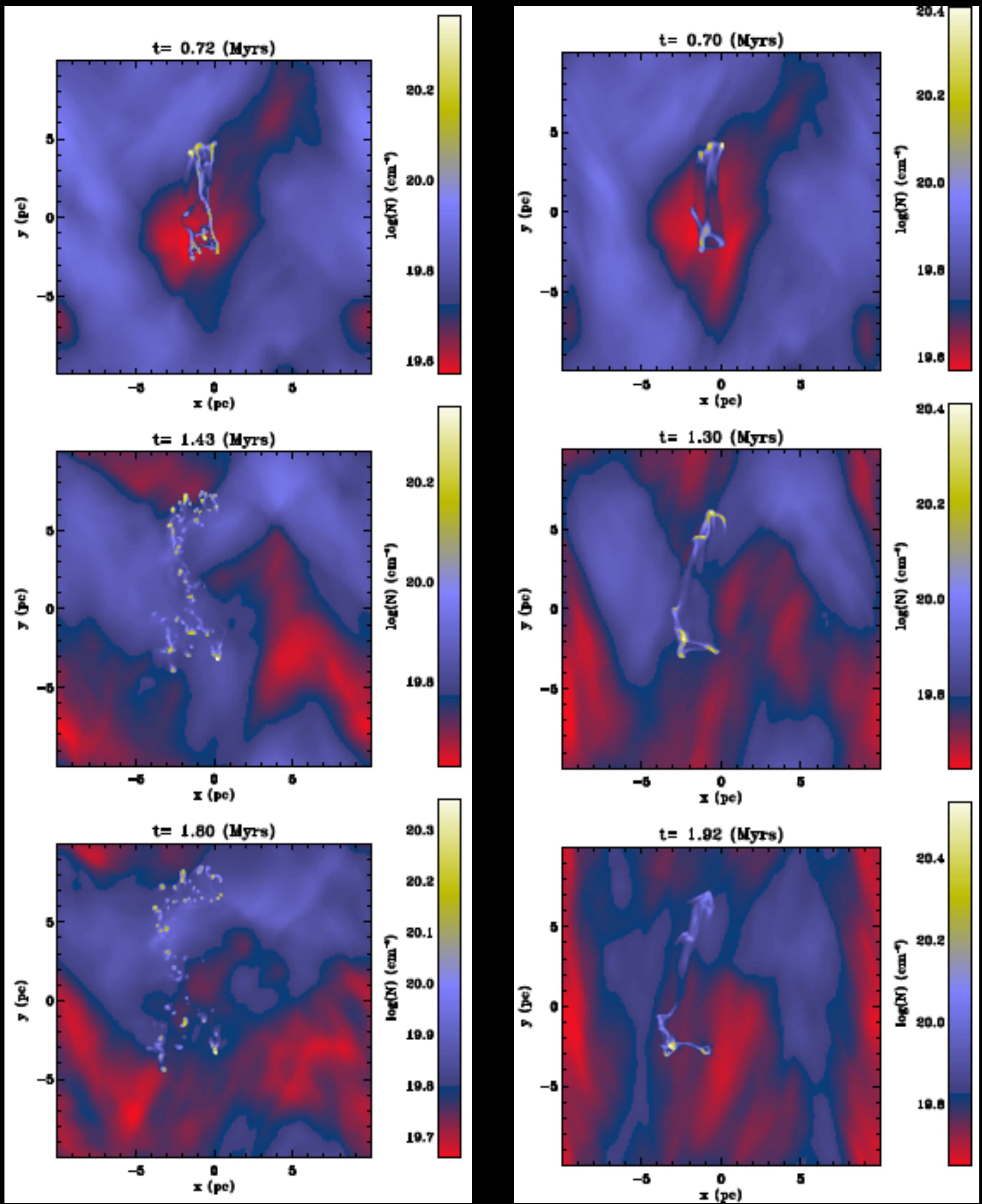


Starlight polarization: Heiles 2000

Clark+ 2015, PRL

Formation of a filament through shear

HD MHD



★In both experiments, the gas condensation is stretched into a filamentary structure by the velocity shear, but in the HD case the structure is broken up by instabilities, while in the MHD case it remains coherent.

★Filamentary structures may result from turbulent shear (rather than shocks) that stretches both CNM gas condensations and the magnetic field.

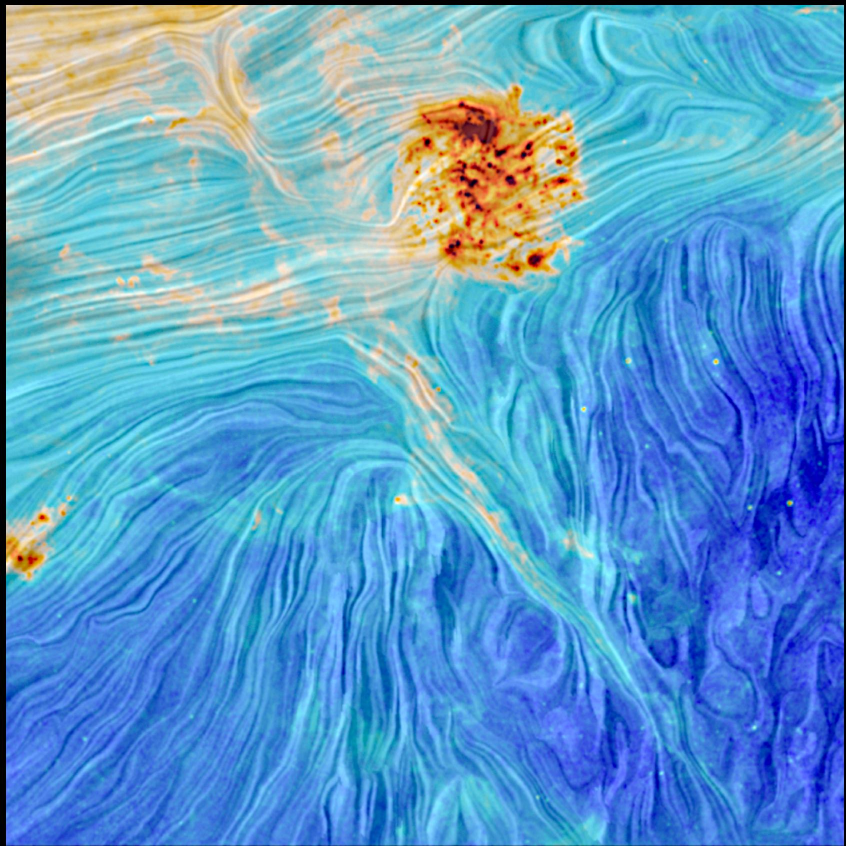
Hennebelle 2013

The interplay between gravity, magnetic fields and turbulence in the interstellar medium

Planck collaboration XXXII and XXXV (2016)

Diffuse ISM

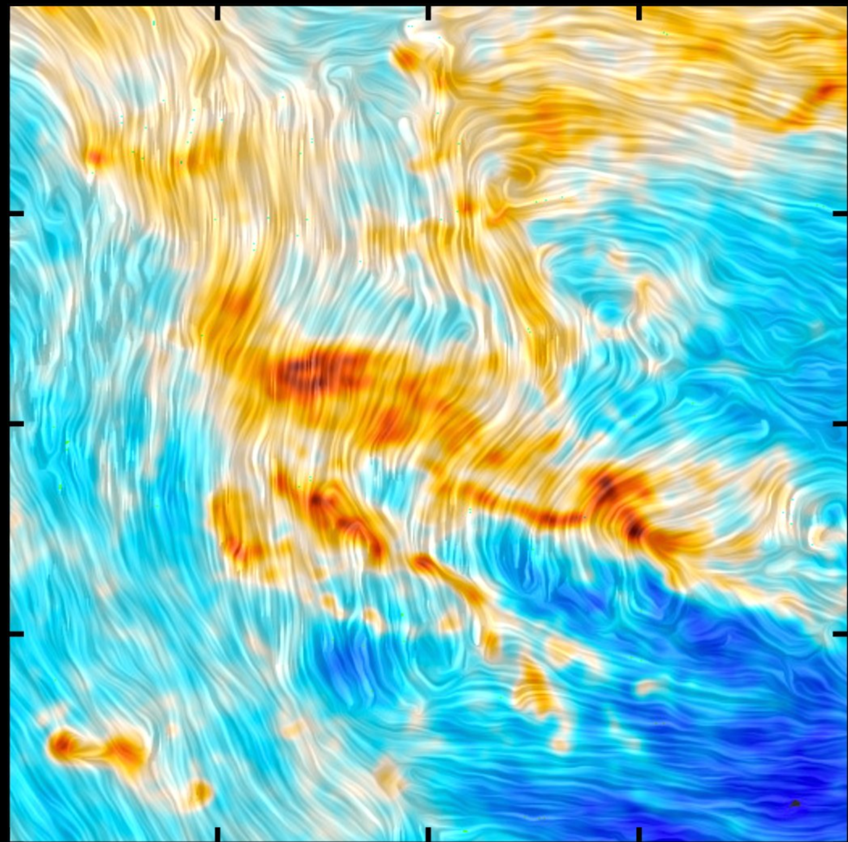
$E_{mag} \sim E_{turb} >> E_{grav}$



Matter/Magnetic field alignment

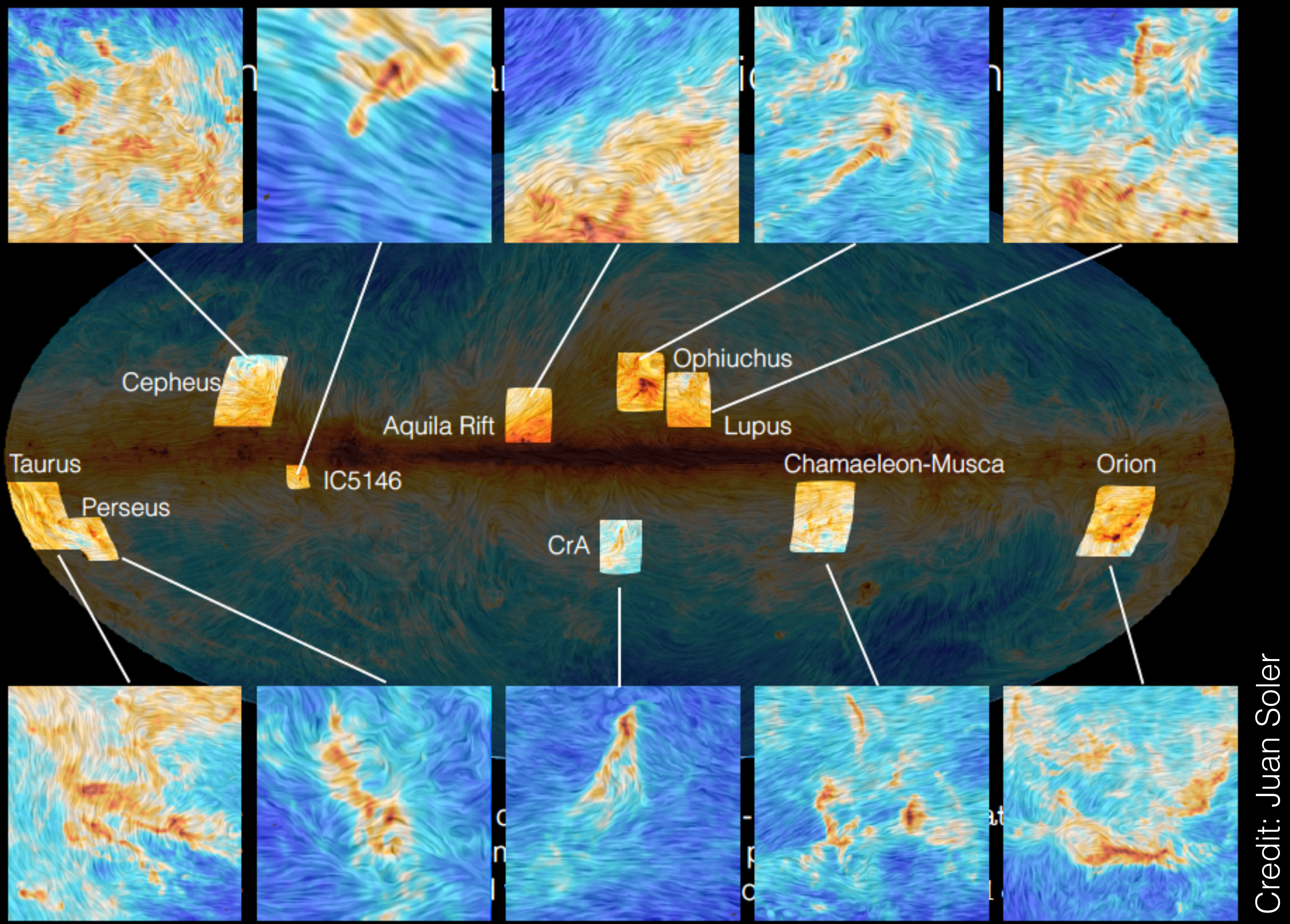
Taurus molecular cloud

$E_{mag} \sim E_{turb} \sim E_{grav}$



Magnetic field perpendicular to matter

Gould Belt's molecular clouds



- Magnetic field tends to be perpendicular to star forming filaments
- This is interpreted as a signature of formation of gravitationally bound structures for a dynamically important magnetic field.

Summary

- ★ Planck dust polarization maps reveal the imprint of interstellar magnetic fields on matter.
- ★ The data probe the field structure in the diffuse ISM and in star-forming molecular clouds, on scales relevant to the formation of their filamentary structure.
- ★ They open a new perspective on the magnetic field structure and its interplay with matter
- ★ Further advances expected from ground based microwave experiments, as well as radio (LOFAR, SKA), optical and interferometric (ALMA, NOEMA) polarization data

➡ Component separation ties the search for B-modes CMB polarization to the statistical description and modelling of Galactic polarization (next lecture tomorrow)