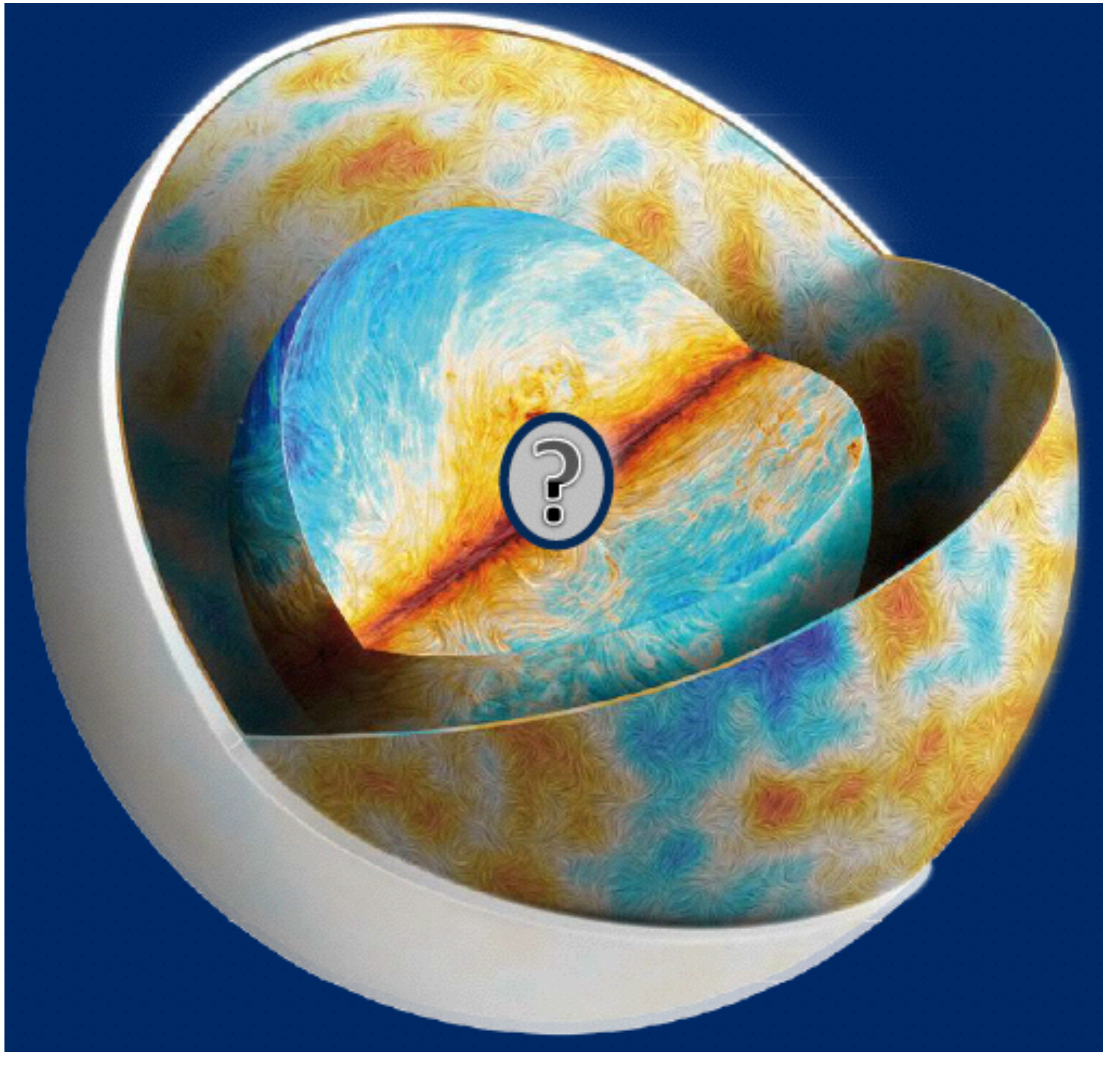
Foregrounds



F. Boulanger
Institut d'Astrophysique Spatiale

Towards the European Coordination of a CMB Program - September 2016

Part I: Foregrounds Science

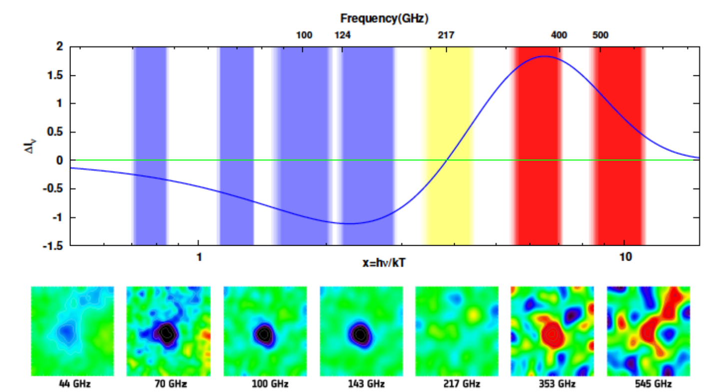
Part II: Complexity of polarized Foregrounds

Part I

Foregrounds Science

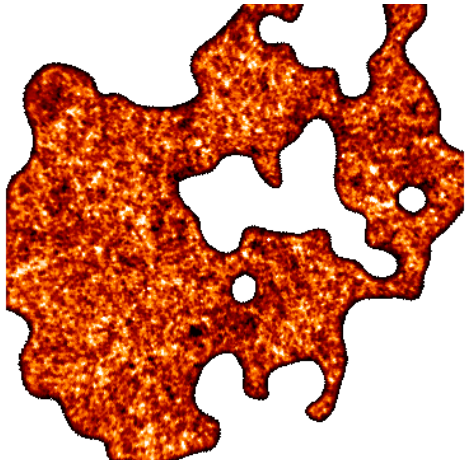
★Galaxy clusters & Hot Baryons

- SZ effect (thermal and kinetic)



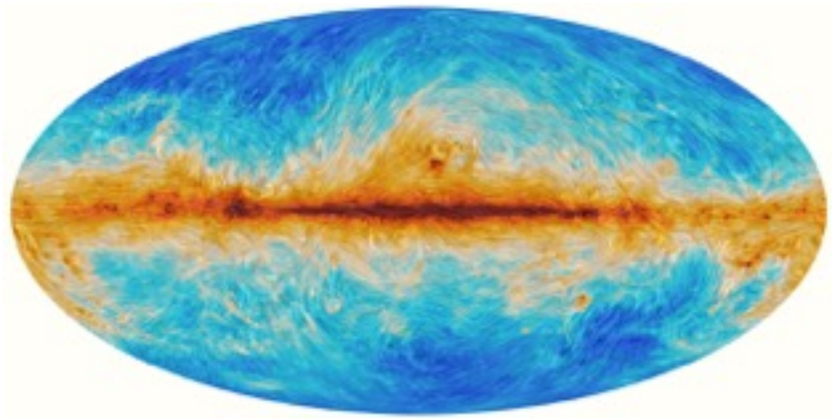
★Star formation and galaxy evolution

- The cosmic IR background (CIB)



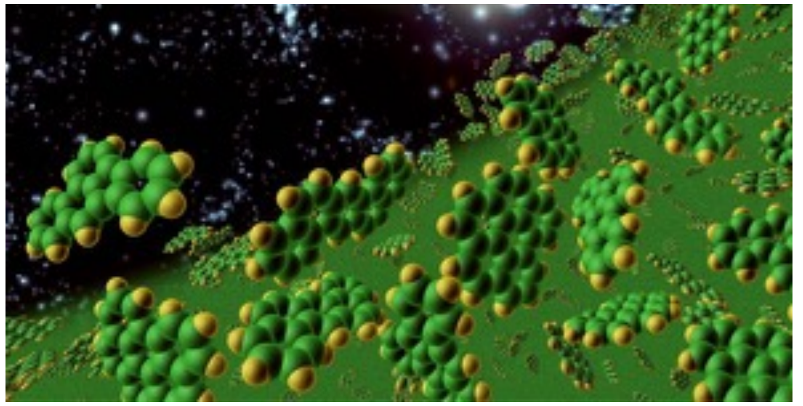
★Cosmic magnetism

- Dust and synchrotron polarization



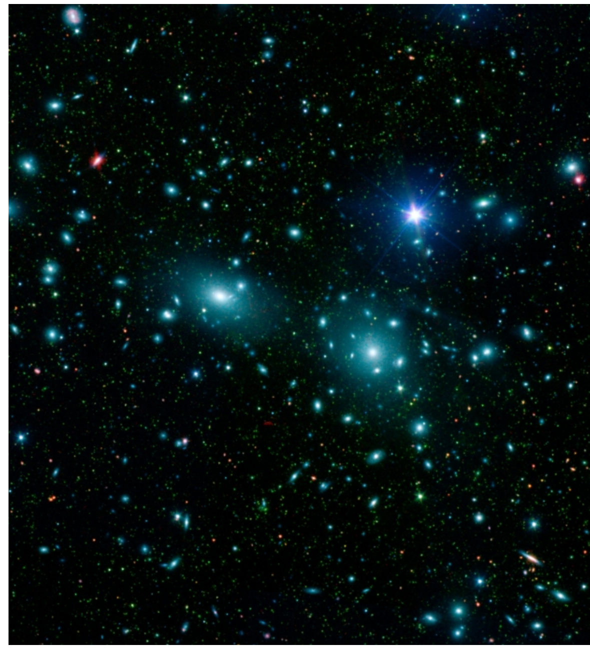
★Interstellar dust

- Spectral energy distribution of dust emission

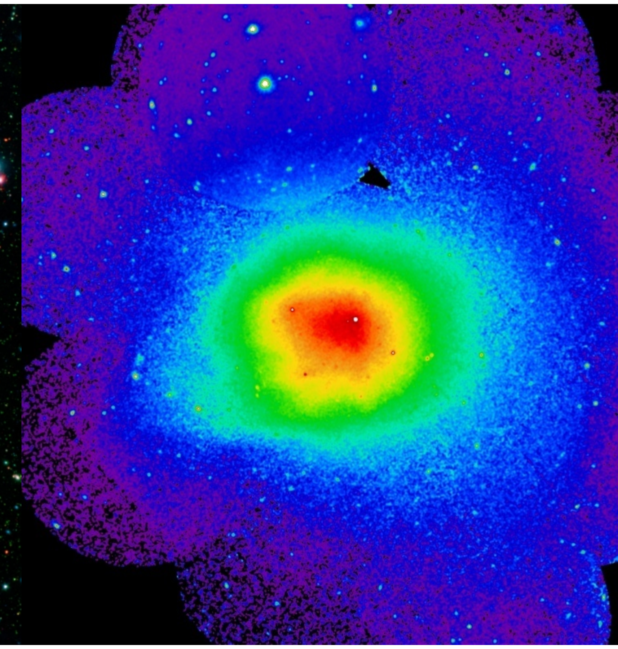


Galaxy clusters

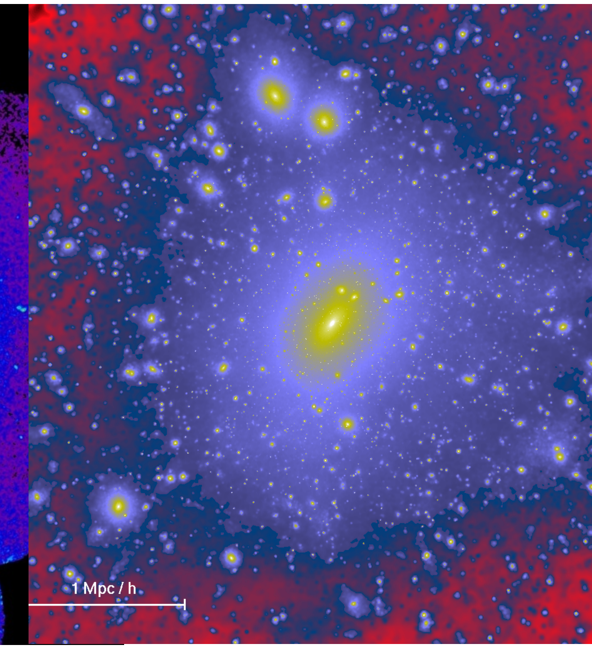
- Largest bound structures in the universe
- Cosmic probes
- SZ observations are complementary to X-ray and optical studies



Stars

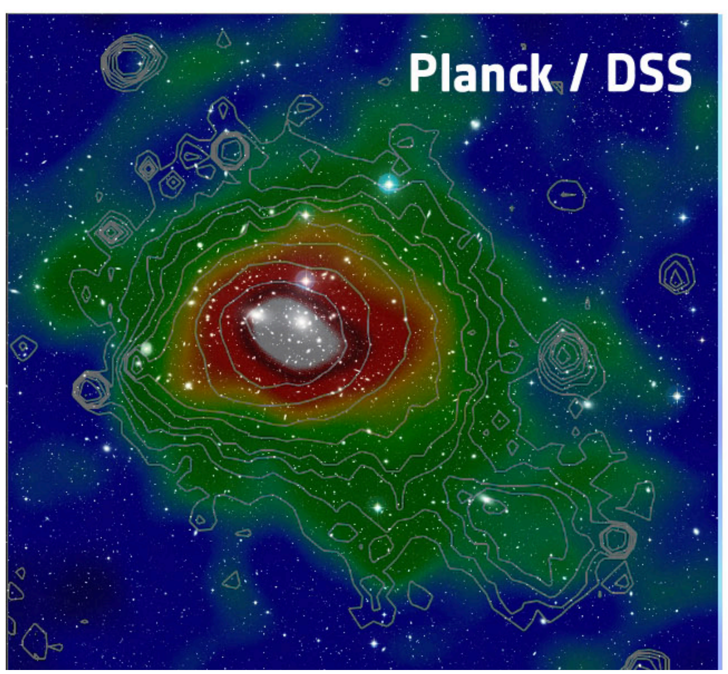


Hot plasma



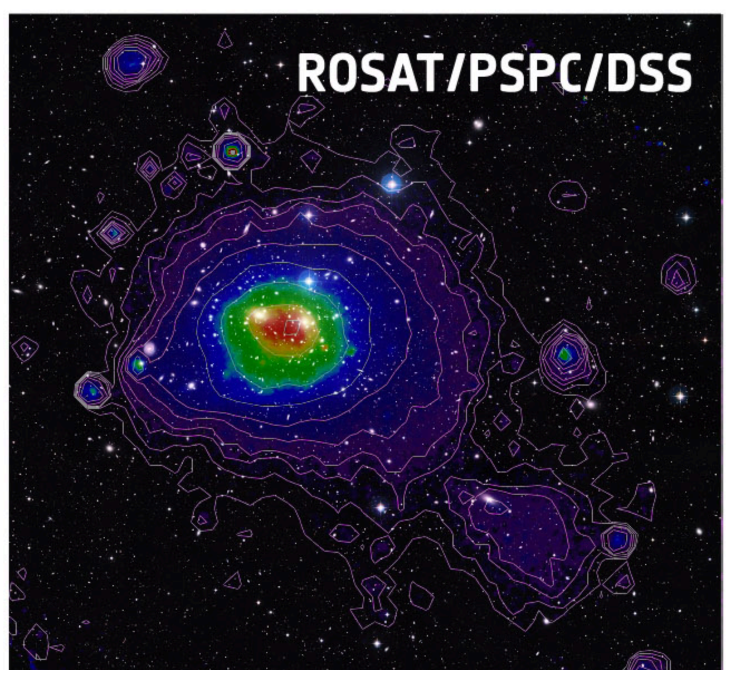
Dark matter

SZ (Planck) + Stars (DSS)

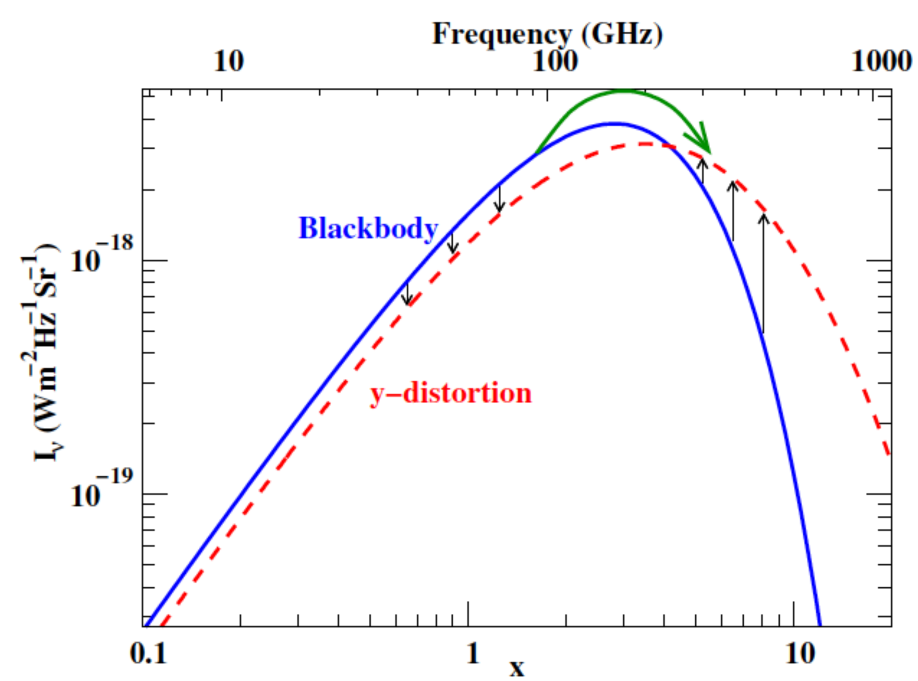


Coma Cluster

X-ray (ROSAT) + Stars



SZ signal (y-distortion)



Known clusters (ROSAT+SPT+Planck)

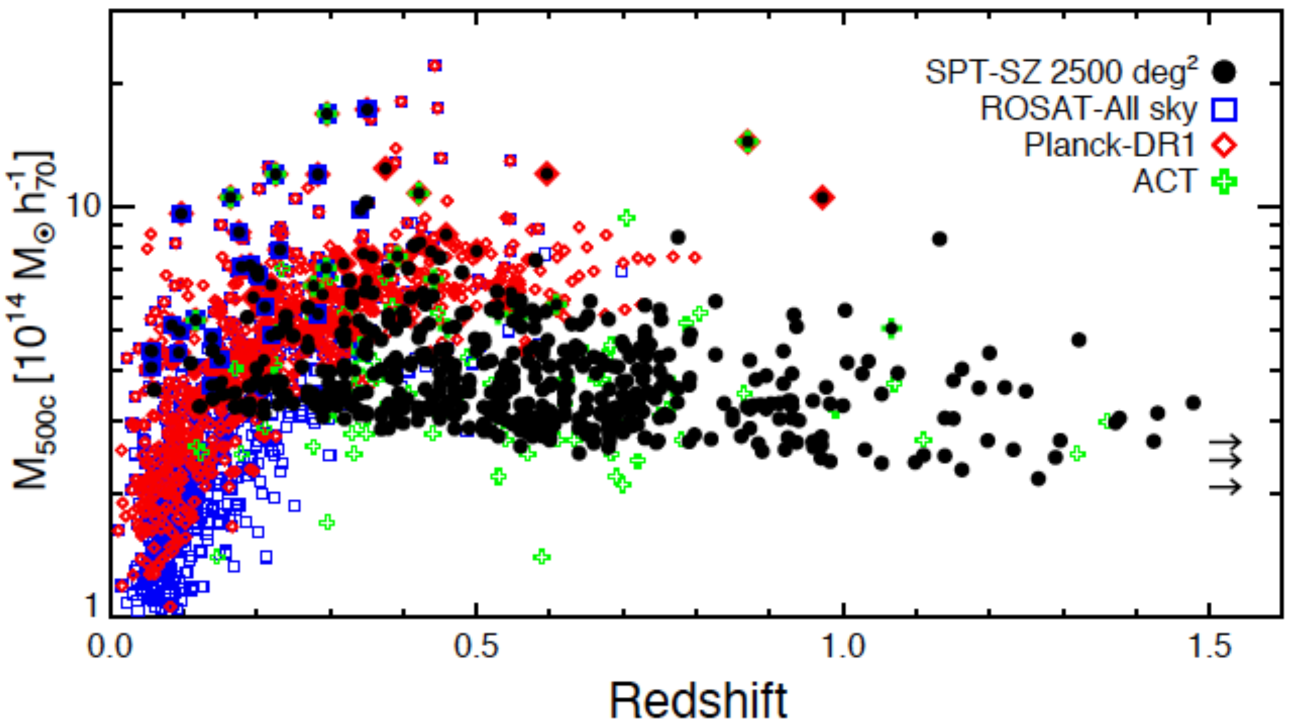
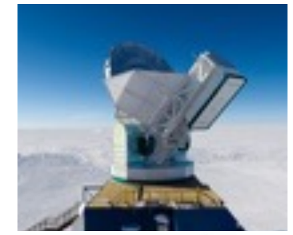
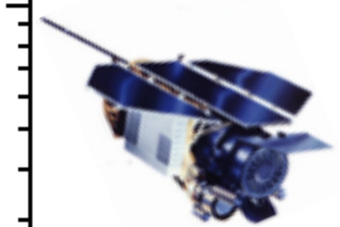
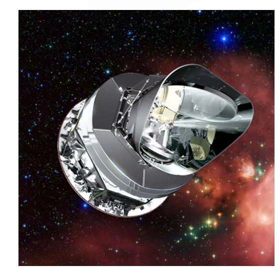


Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850

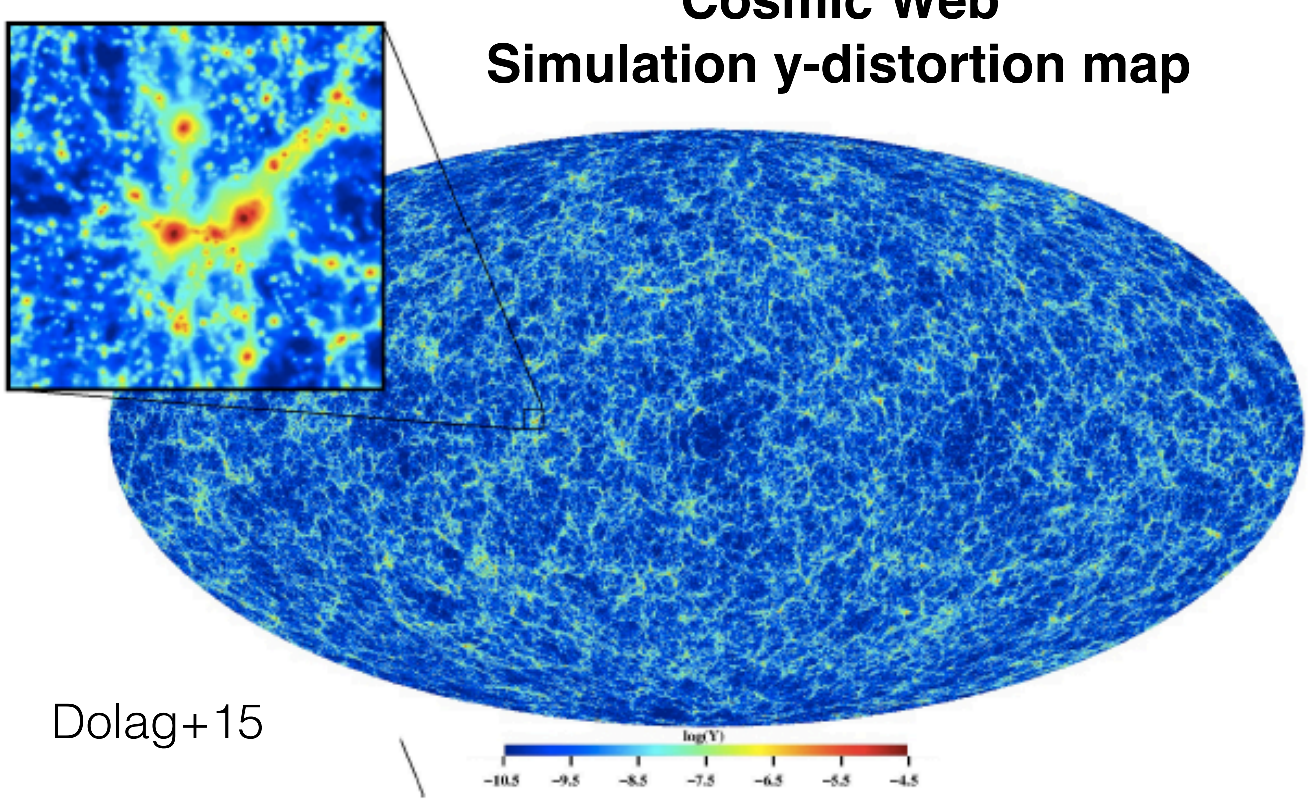






- Many more clusters to be discovered with future X-ray mission (eRosita) and CMB experiments
- Optimal outcome of SZ detection for arcminute angular resolution

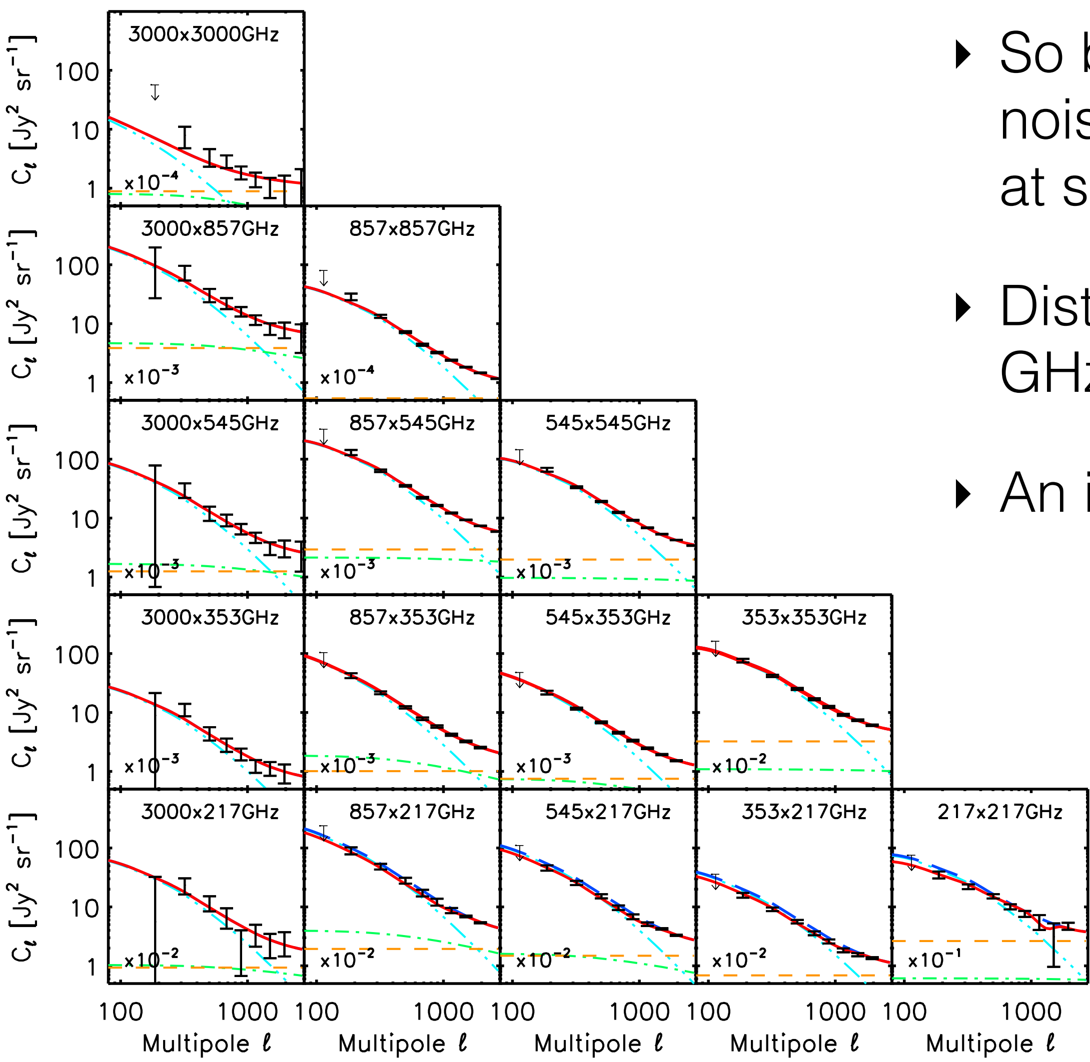
Cosmic Web
Simulation y-distortion map



Dolag+15

- Total SZ effect from Cosmic Web may be measured by PIXIE
- Kinetic-SZ effect measurements to probe cosmic velocities

CIB anisotropies



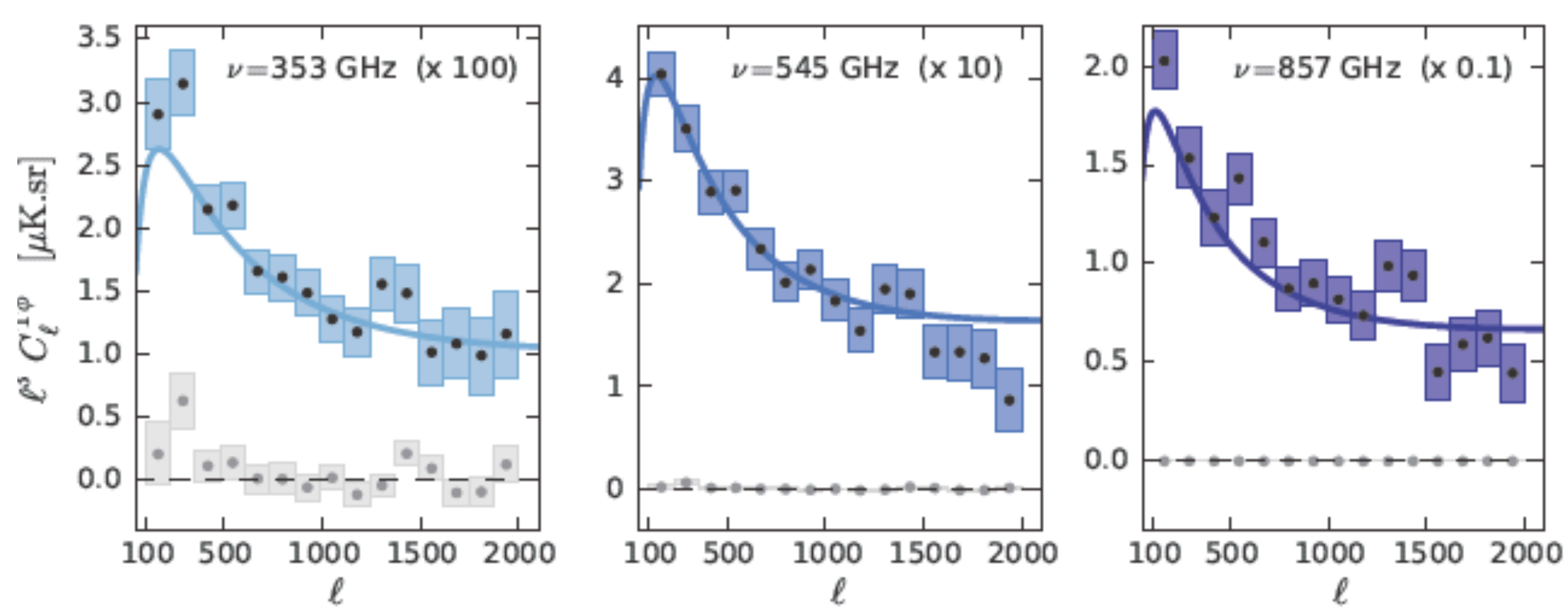
Planck Results XXX, 2013

- So bright (δI/I~10-15%) that they represent (together with the shot noise) the main foreground contaminant to CMB temperature maps at small scales.
- Distinct frequency-redshift dependance (from 3000 GHz to 100 GHz) probe a large span of redshifts (0.5<z<4)
- An important tracer of large-scale structures

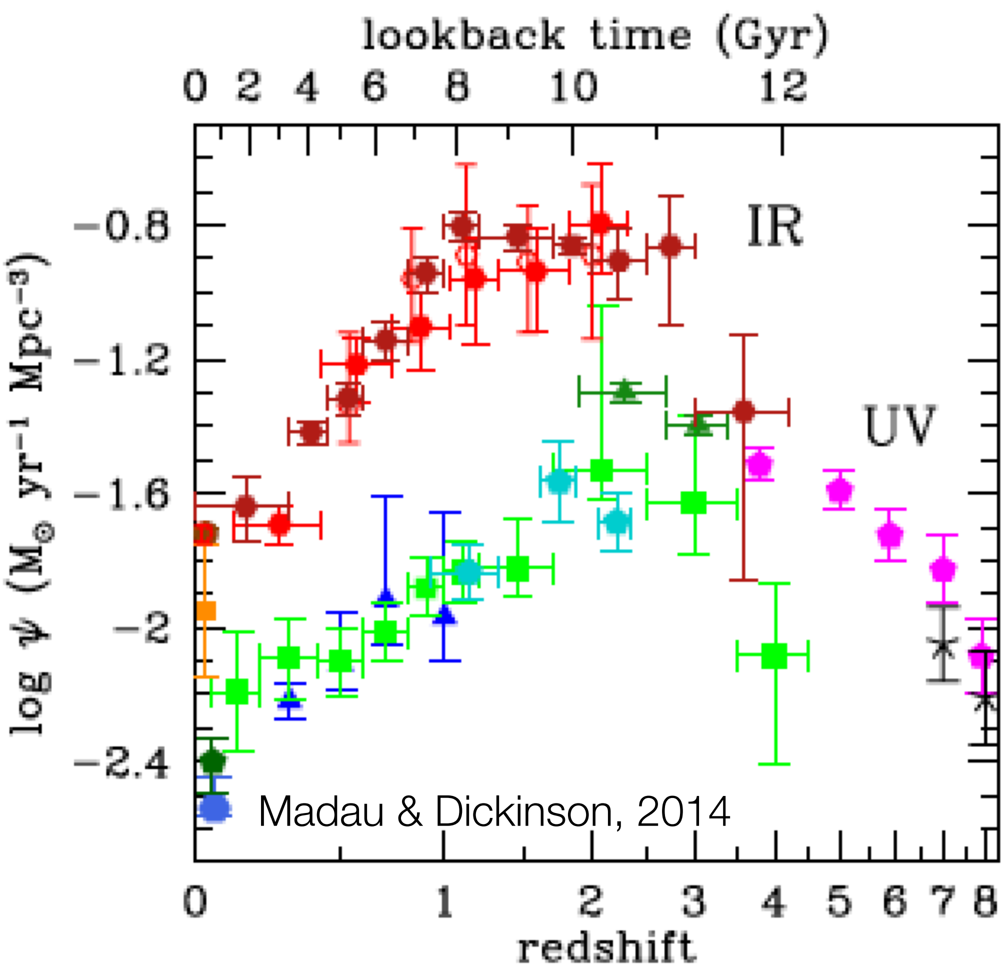
➡The physical processes governing the star formation and galaxy evolution

➡The cosmology of baryons: clustering properties of dusty, star-forming galaxies

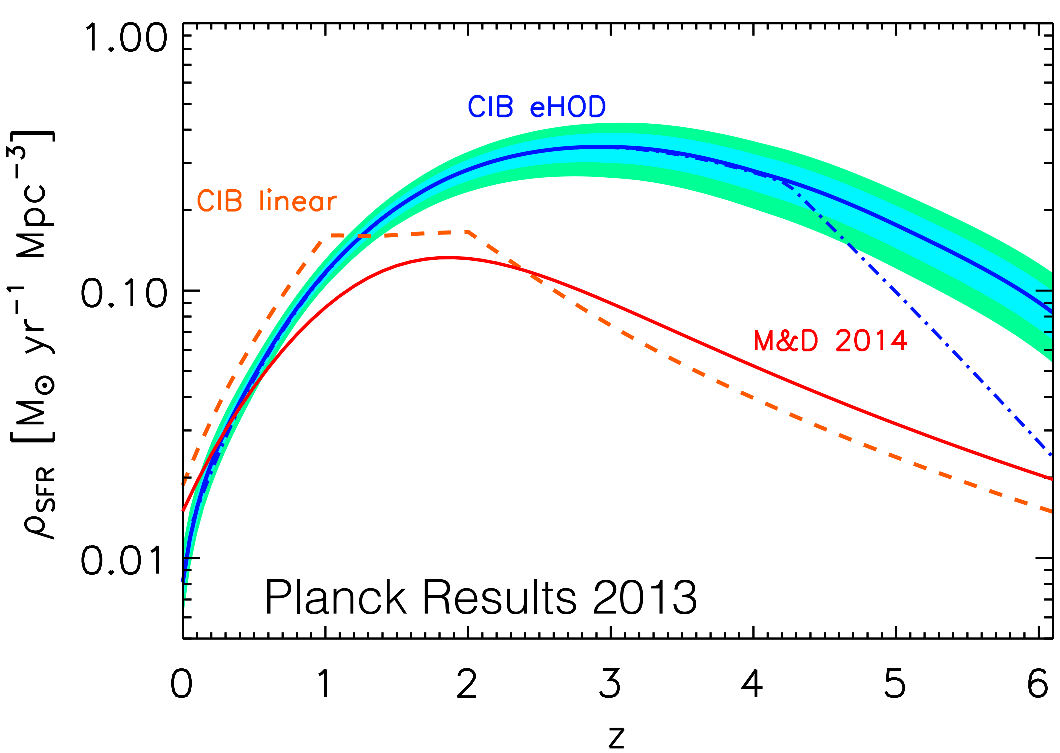
Correlation with lensing from dark matter
Planck Collaboration XVIII 2013



Cosmic Star Formation Rate Density



From source counts



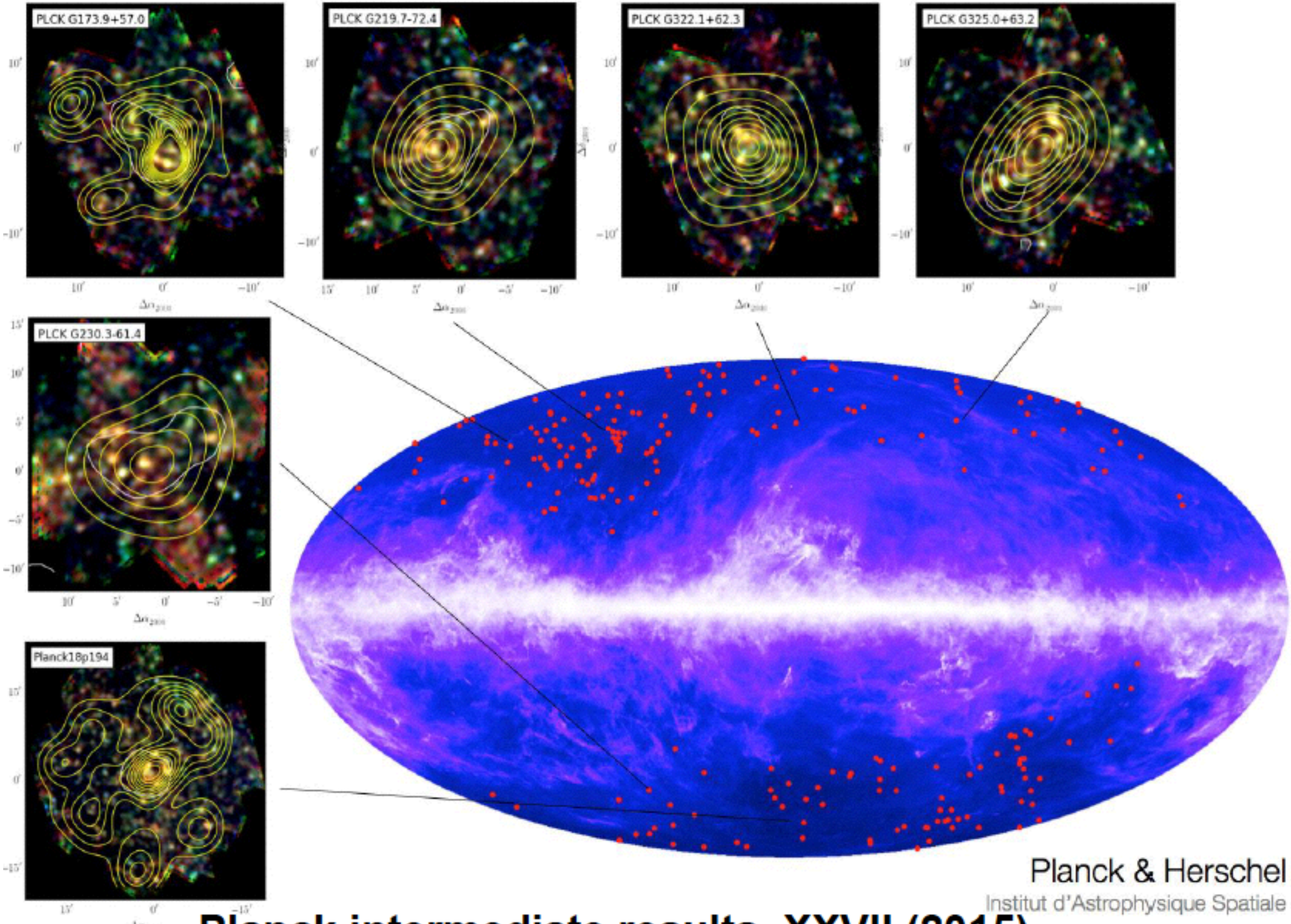
From CIB model

CIB anisotropies are not the best tool to understand the physics of galaxy formation due to model degeneracies (SEDs, luminosity functions, redshift distribution)

More to be learned from spectroscopic surveys (intensity mapping and detection of sources)

Future perspectives:

- CIB mean spectrum from PIXIE => global energy bugdet
- CO and CII intensity mapping from PIXIE => gas in galaxies up to z~7
- Lensed high-z sources from ground-based high-resolution & large-area CMB maps : Physics of dusty galaxies in the early Universe



Planck intermediate results. XXVII (2015)

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

Two outstanding questions:

- ★The origin of cosmic magnetic fields (seed field and dynamo amplification)
- ★Their role in the formation of galaxies, stars and planets

The structure of magnetic fields may be traced with polarization observations from the cosmic web to planets

A broad research field

Cosmic magnetism is a highlighted research field of several large observatories

★SKA and its precursors: Synchrotron, Faraday rotation and Zeeman spectroscopy

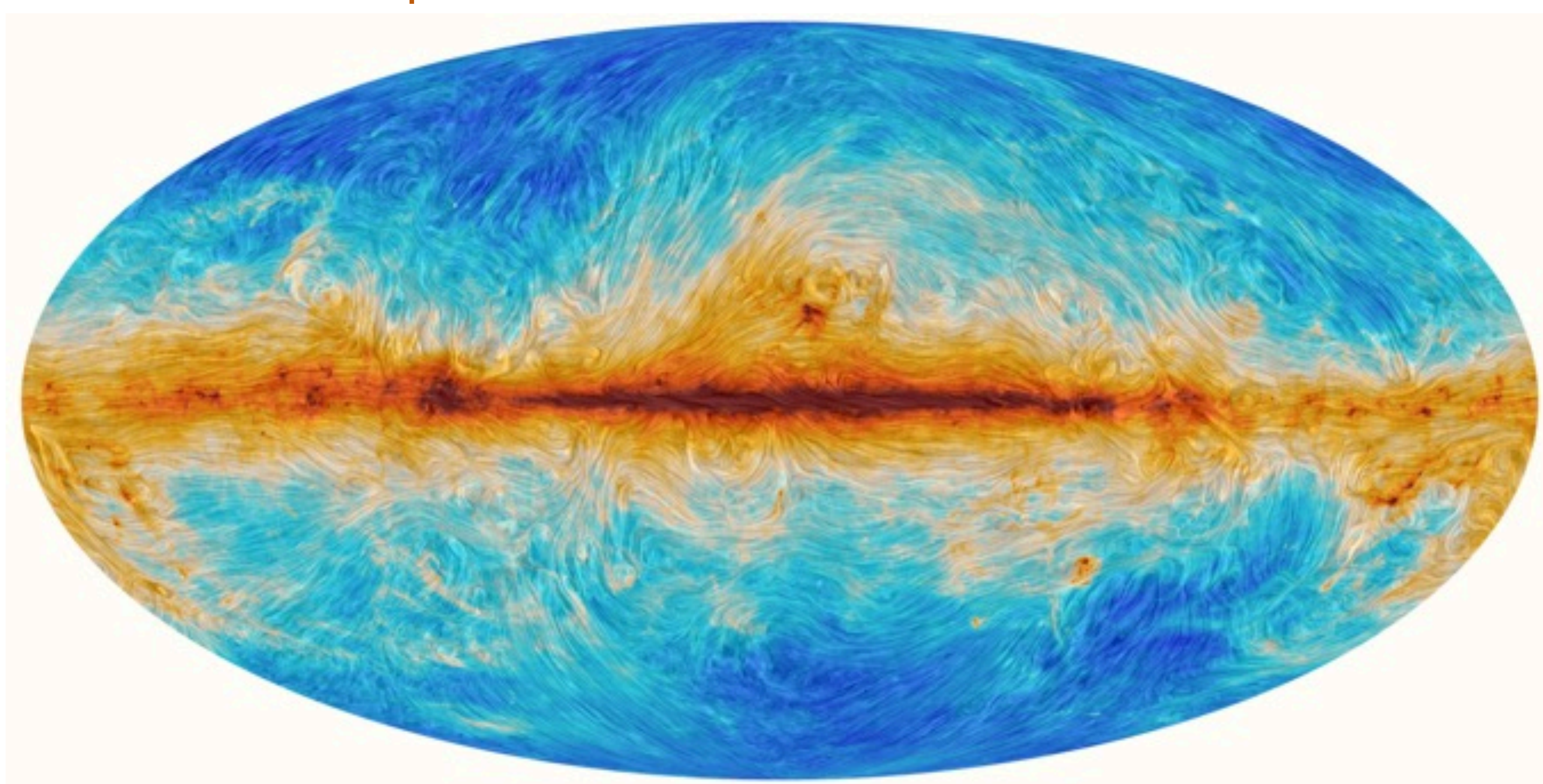
★ALMA and NOEMA(IRAM) interferometers: Dust polarization and Zeeman spectroscopy

★Stellar polarization surveys + GAIA : Tomography of Galactic dust polarization

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

It implies a set of ubiquitous processes that have amplified and organized a much weaker seed field

A CMB space experiment like CORE will have a unique capability to characterize statistically interstellar turbulence: the interplay between matter and magnetic fields in cosmic space

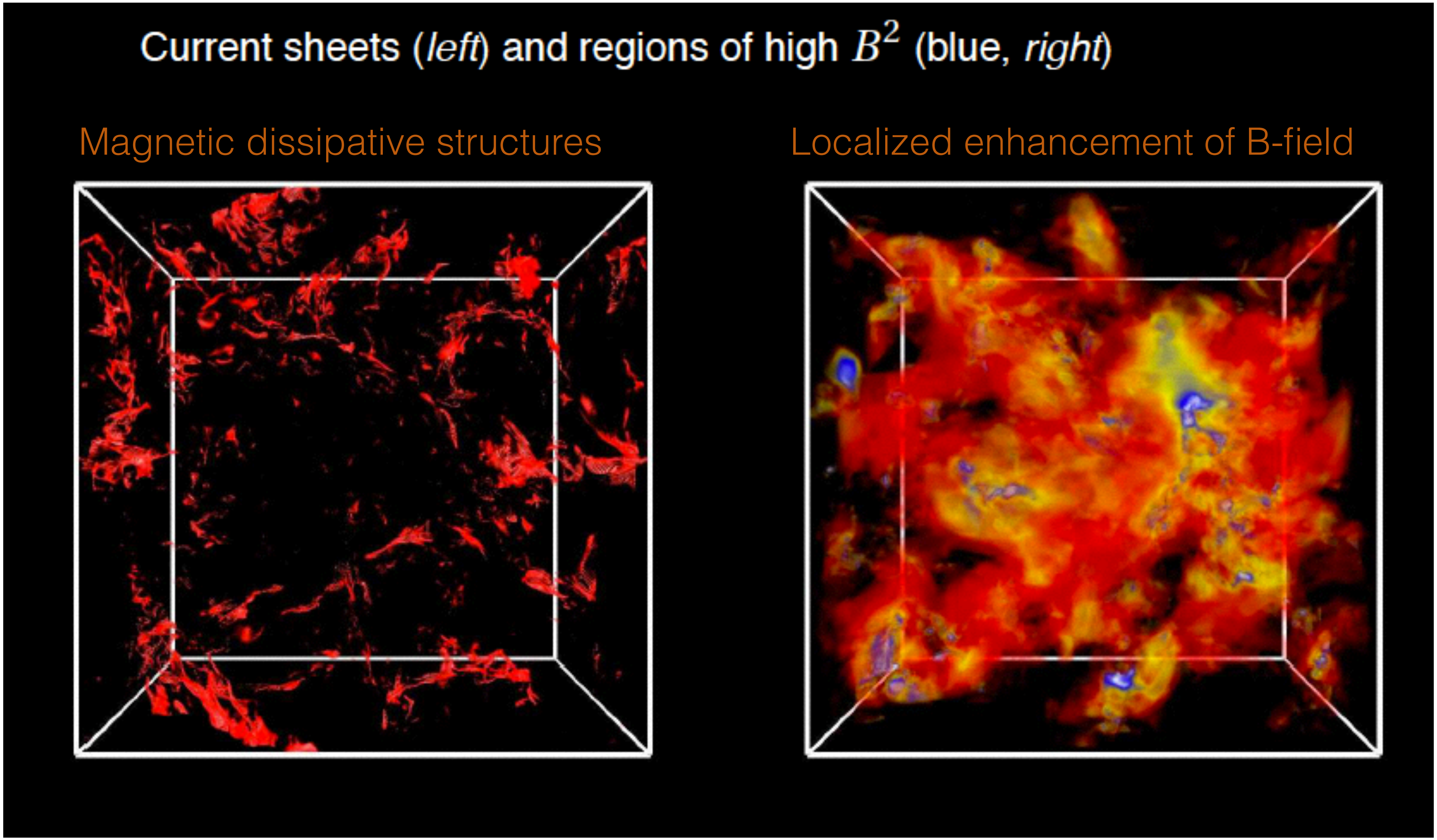


Planck collaboration 2015

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
- ★ The structure of the B-field is also key to model cosmic-ray diffusion and acceleration

Magnetic structures



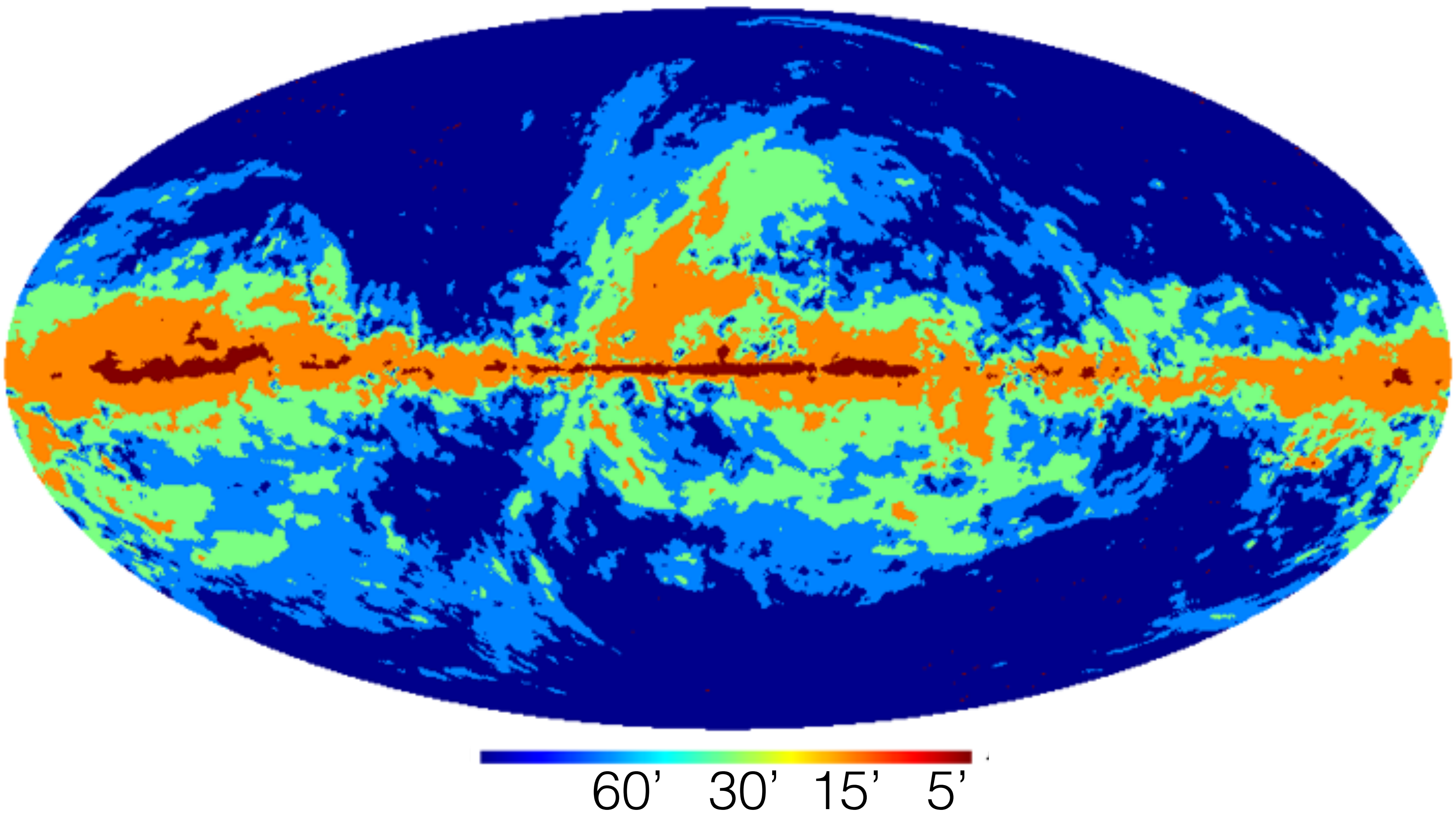
Kritsuk+10

Non-Gaussian excursions => High statistics required

Overcoming Planck limits

Angular scale where EE dust power = Planck noise

Based on power spectra in Planck
intermediate XXX 2014, arXiv 1409.5738



➡ The gain in sensitivity and angular resolution of CORE will increase the data statistics by a factor of 10^3.

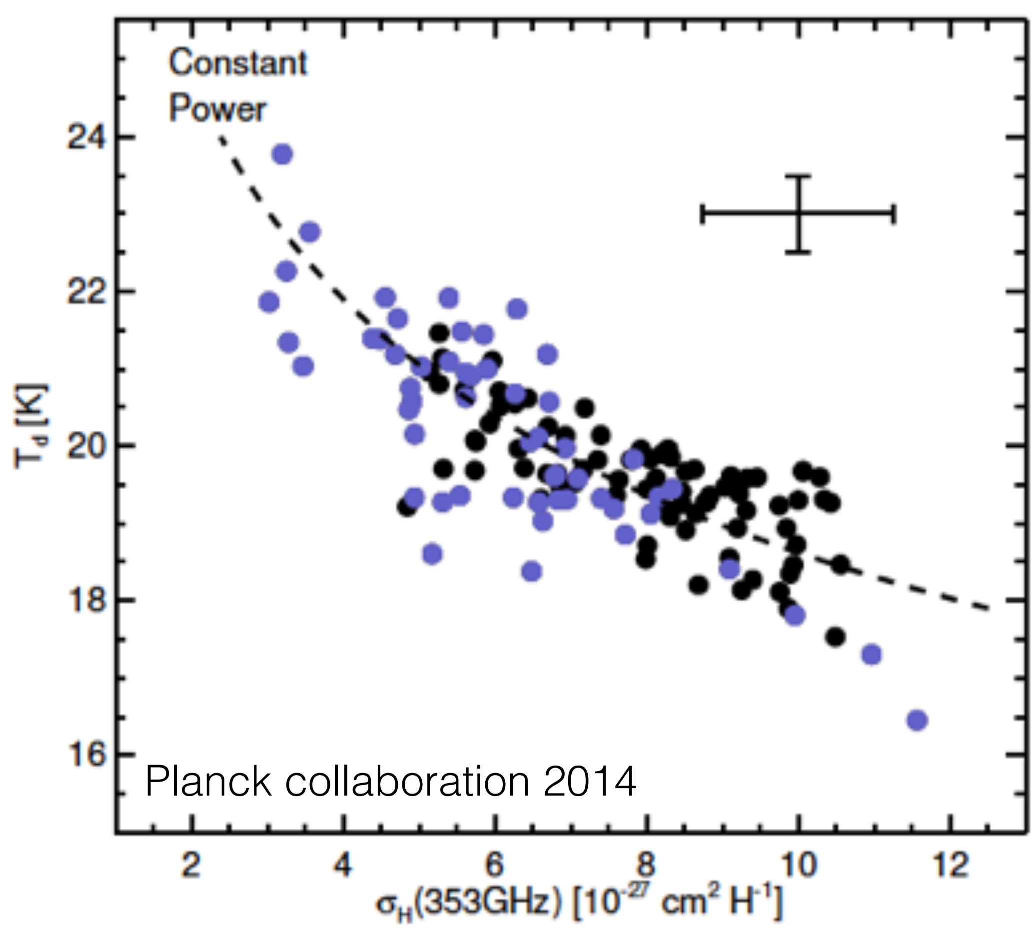
➡ CORE statistics will be comparable to that of the SKA grid of Faraday rotation measures

Interstellar dust is an ubiquitous actor in the universe from high redshift galaxies to star forming clouds

Interstellar dust is not *Star Dust.*

Its composition reflects interstellar processes that contribute to break and re-build grains over time-scales much shorter than the injection of new dust by stars.

What are the relevant processes?

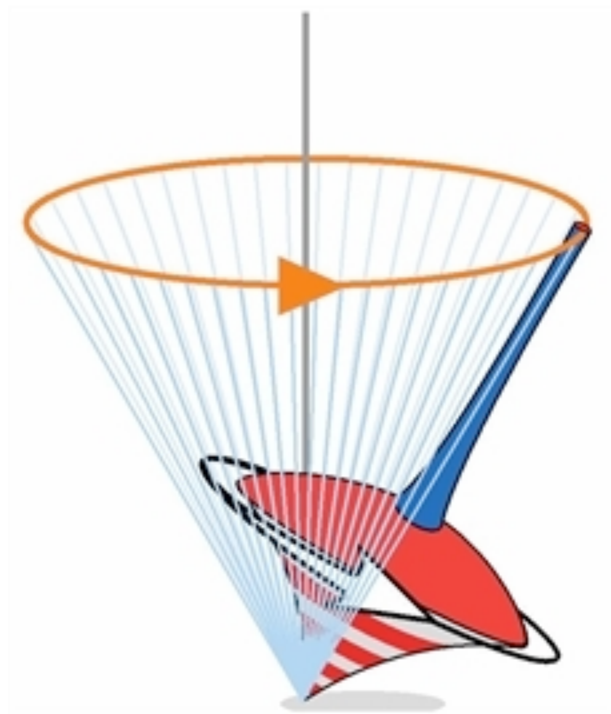


Planck has provided evidence for evolution of dust composition within the diffuse ISM

More to be learned on relevant processes from sub-mm/microwave imaging of the dusty sky

The Physics of dust grains alignment

- Interstellar grains spin like tops around their axis of maximal inertia.
- Their rotation axis precesses around the magnetic field lines.
- Dissipation of precession energy leads to alignment with the field. Alignment may be associated with paramagnetic relaxation (Davis-Greenstein 1951) and/or radiative torques (Lazarian & Hoang 2007). Other processes (e.g. H_2 formation) may contribute.



Where in the ISM and with what efficiency are the grains aligned ?

Are very small dust particles aligned (polarization of AME) ?

Part I

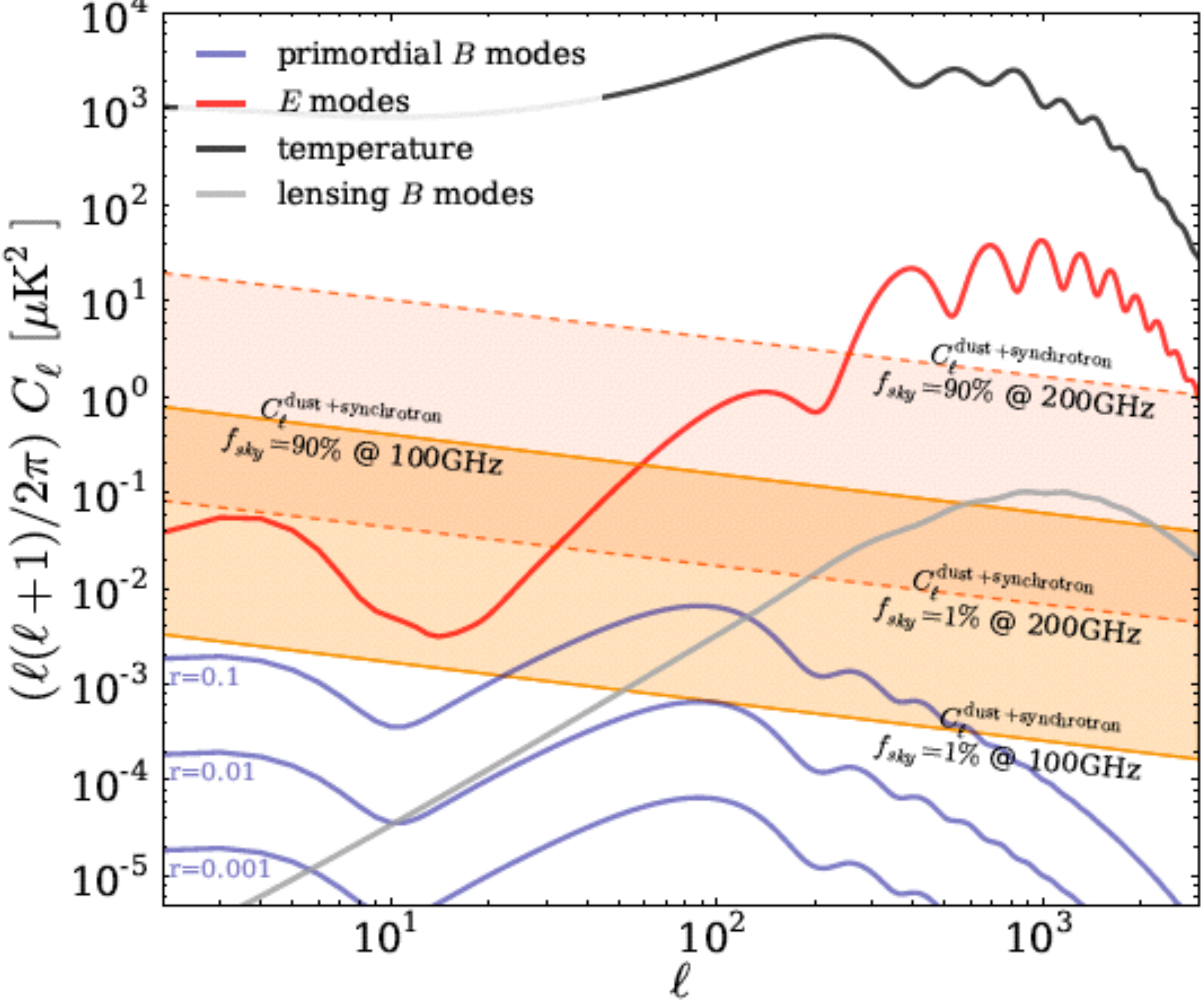
- ★Planck has shown that diverse ancillary science may be addressed with CMB data
- ★CMB data provide unique information, complementary to data obtained with other observatories
- ★This will continue to be true for future CMB experiments.

- ★Much of the ancillary science (dust polarization, SZ from clusters, extragalactic sources) calls for arc minute resolution, all-sky, imaging in the sub-mm.
- ★CORE will boost by very large factors the limited statistics of current studies opening new discovery space.

Illustrated for the separation of CMB primordial B-modes from dust polarization.

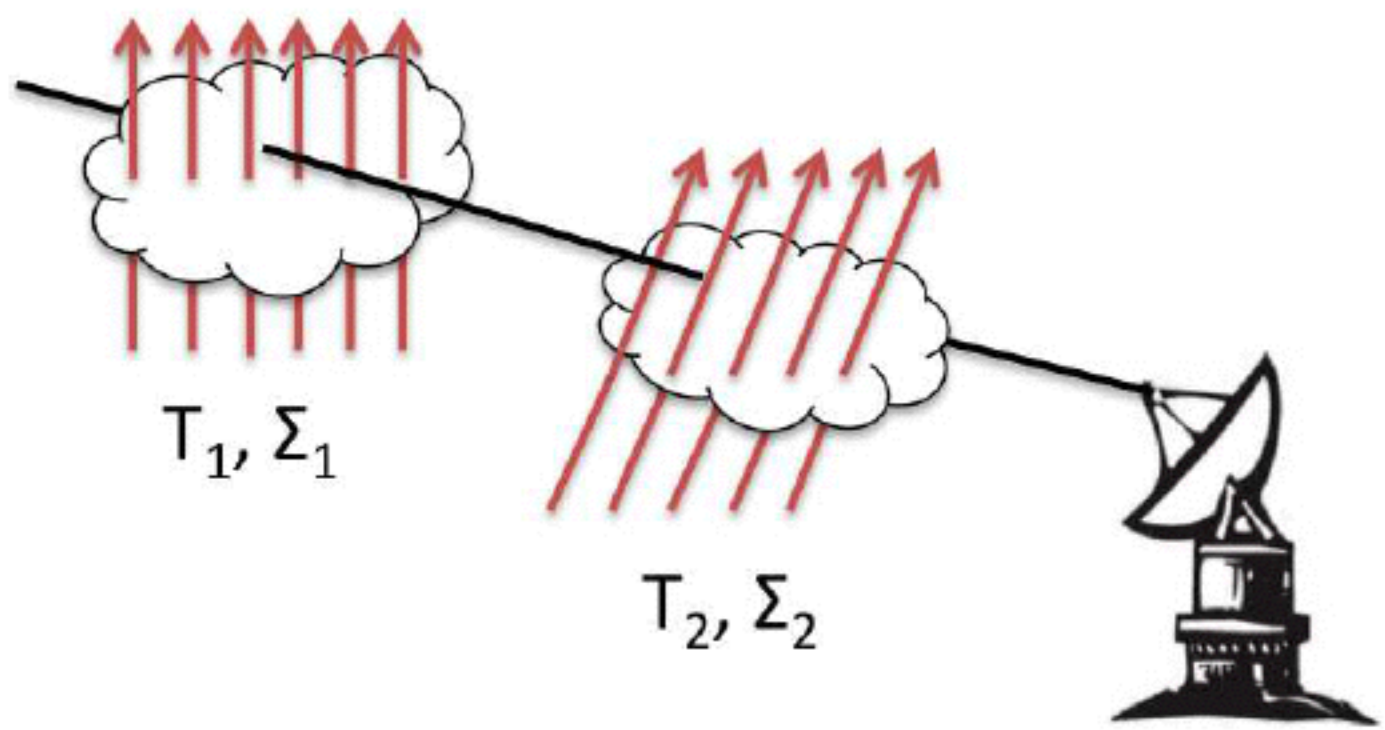
Similar complexity expected for synchrotron polarization.

The search for CMB spectral distortions will also face foregrounds complexity but current studies are less advanced than for B-modes.



primordial B modes
E modes
temperature
lensing B modes
$C_\ell^{\rm dust+synchrotron}$
f_{sky}=90% @ 200GHz
$C_\ell^{\rm dust+synchrotron}$
f_{sky}=90% @ 100GHz
$C_\ell^{\rm dust+synchrotron}$
f_{sky}=1% @ 200GHz
$C_\ell^{\rm dust+synchrotron}$
f_{sky}=1% @ 100GHz
r=0.1
r=0.01
r=0.001
$(\ell(\ell+1)/2\pi)\ C_\ell\ [\mu K^2]$
ℓ

Interplay with dust emission properties



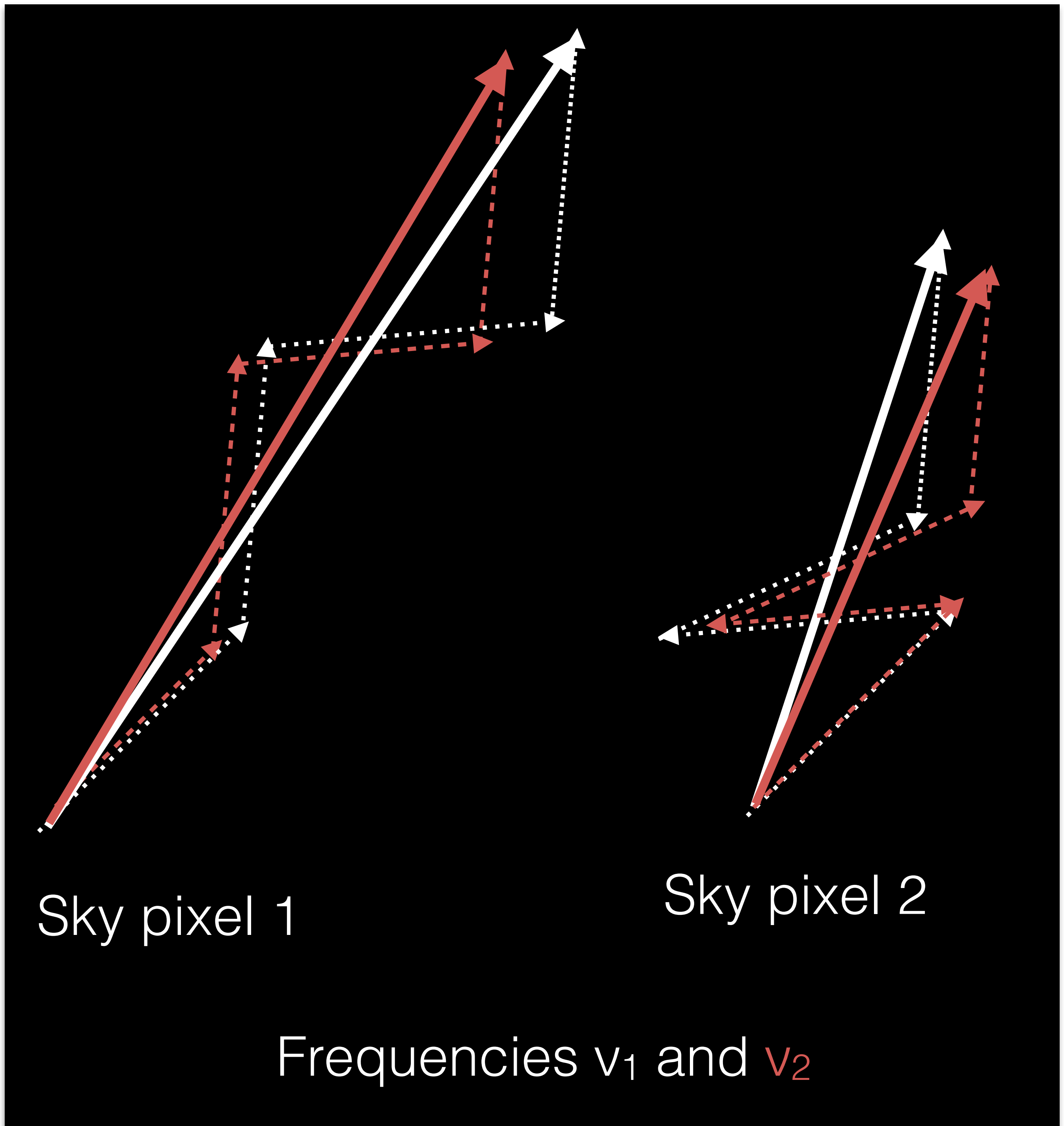
Tassis & Pavlidou 2015, MNRAS

The interplay between magnetic field structure and dust emission properties generates spectral decorrelation

Dust polarization maps at high frequency do not simply scale to CMB frequencies

Schematic explanation

Two sky pixels with the same I_{Dust} but different polarized intensity and polarization angle



Dust polarization may be viewed as a random walk in the Q,U plane with a small number of steps

- The magnetic field orientation sets the direction of the step
- Dust polarized intensity sets the length
- Decorrelation of the dust polarization signal between frequencies results from the correlation between the magnetic field, ISM structure and dust polarization properties.

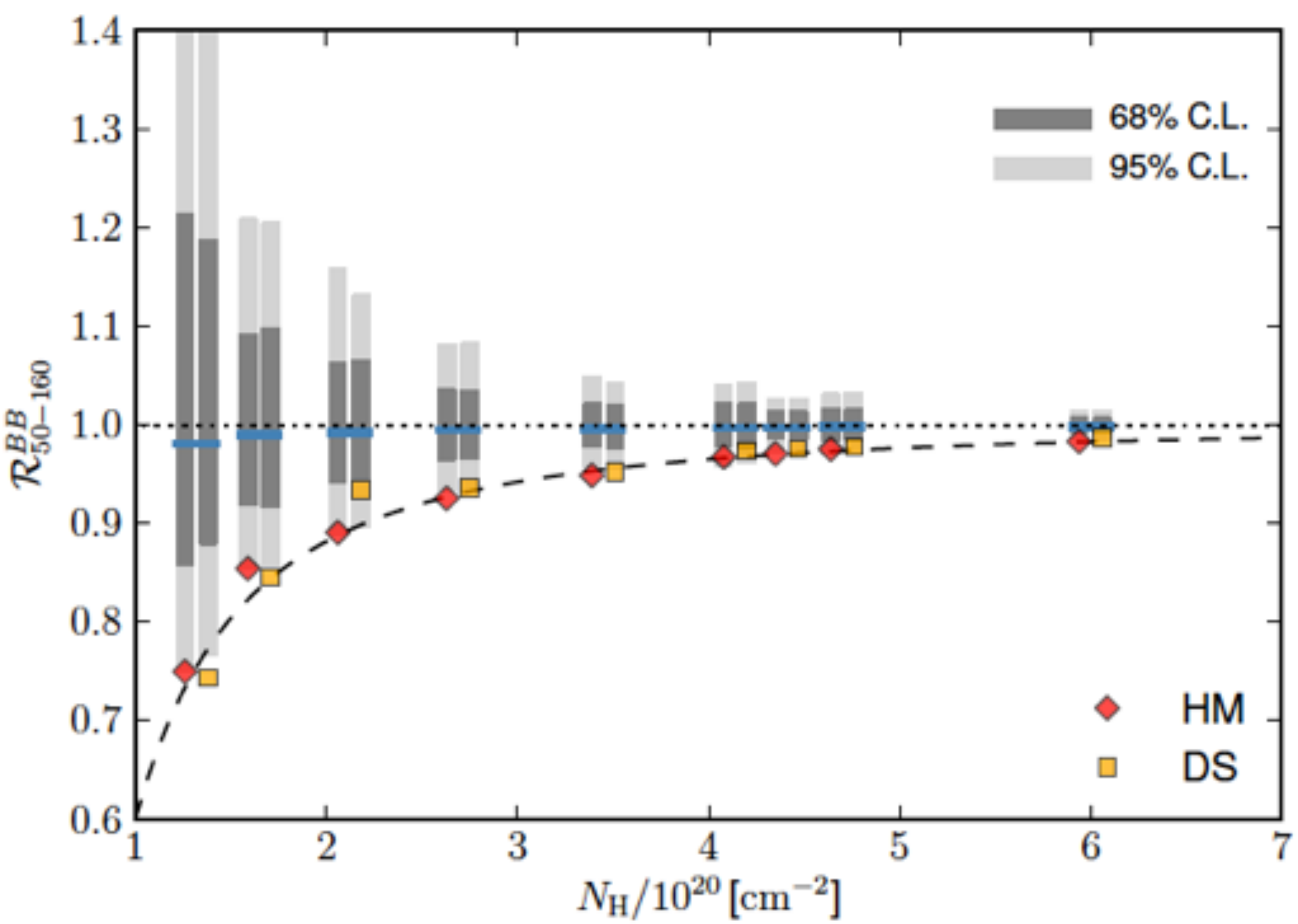
Both the polarized intensity and polarization angle change with frequency.

Decorrelation is a non-linear effect that modifies the frequency dependence of dust polarization.

Planck measurements

Correlation ratio between 217 and 353 GHz maps

$$\mathcal{R}_\ell^{XX} \equiv \frac{C_\ell^{XX}(353\times 217)}{\sqrt{C_\ell^{XX}(353\times 353)\,C_\ell^{XX}(217\times 217)}}$$



Planck Int. Res. L., 2016, arXiv:1606.07335

- Correlation ratio measured for several sky regions (f_{sky} =0.2 to 0.8) with BB cross-spectra using different data subsets
- Confidence estimated with Gaussian sky simulations
- Systematics tested comparing results for different data combinations
- The effect is (marginally) detected in all regions. The confidence of combined results is more than 99%.
- Indication that the decorrelation increases towards low column density sky area.

- ★Component separation is **a BIG challenge**.
- ★We have in-hand tools to reach the level of residuals required for the detection of a tensor-to-scalar ratio **r** down to $\boldsymbol{\sigma}$~ 0.01.
- ★For higher precision determination of **r** or the detection at lower values of r, the situation is less clear. It is certainly more uncertain to rely only on the current knowledge of Galactic emission, the complexity of which has become apparent with Planck observations
- ★The uncertainty from component separation will become an increasingly dominant part of the error budget. An accurate propagation of those uncertainties must be a priority in order to give realistic limits and eventually claim a detection of the B-mode signal with confidence.
- ★This requirement mandates a continuing effort on foreground simulations and astrophysical modelling.