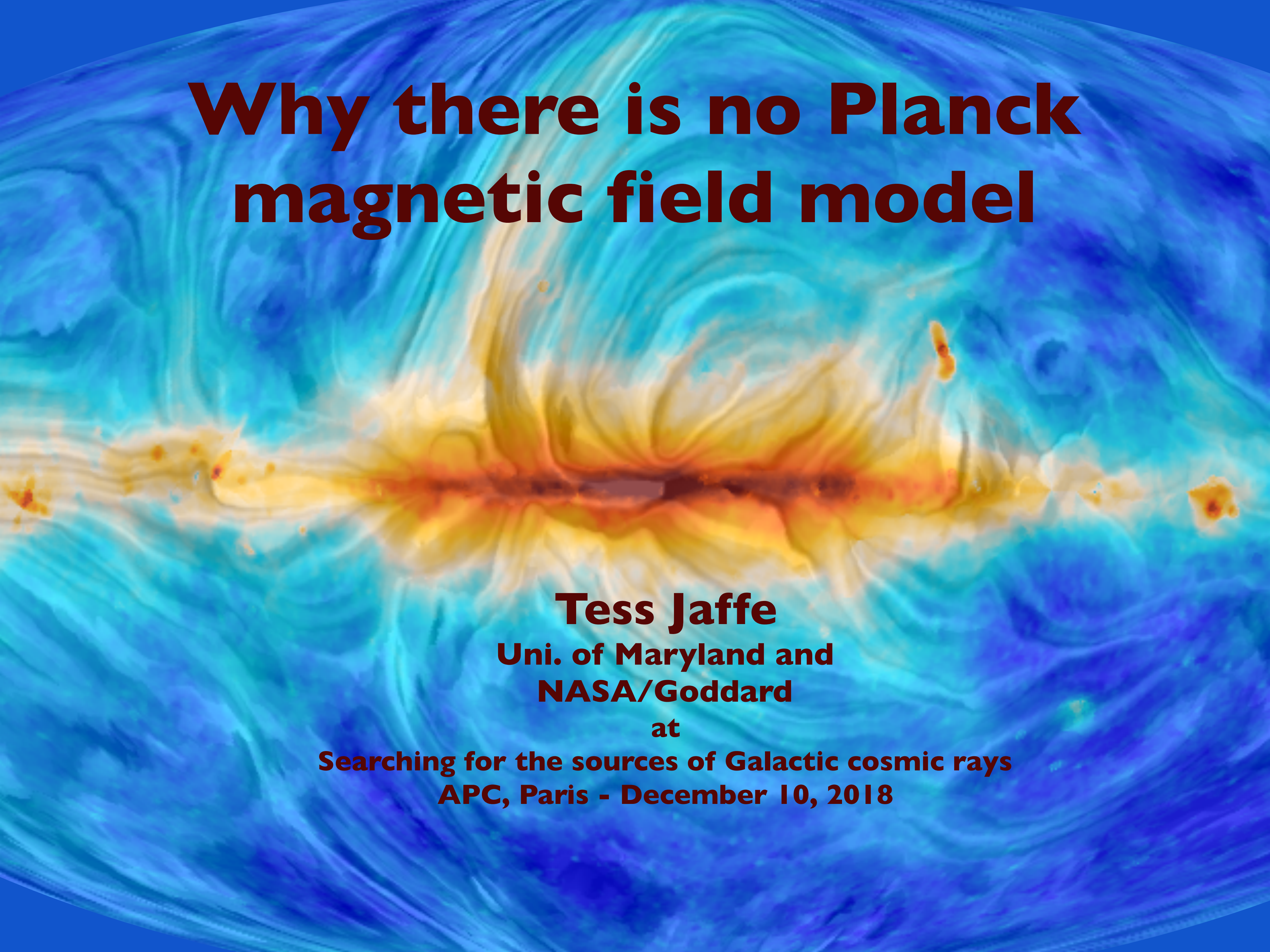


Why there is no Planck magnetic field model

Tess Jaffe
Uni. of Maryland and
NASA/Goddard

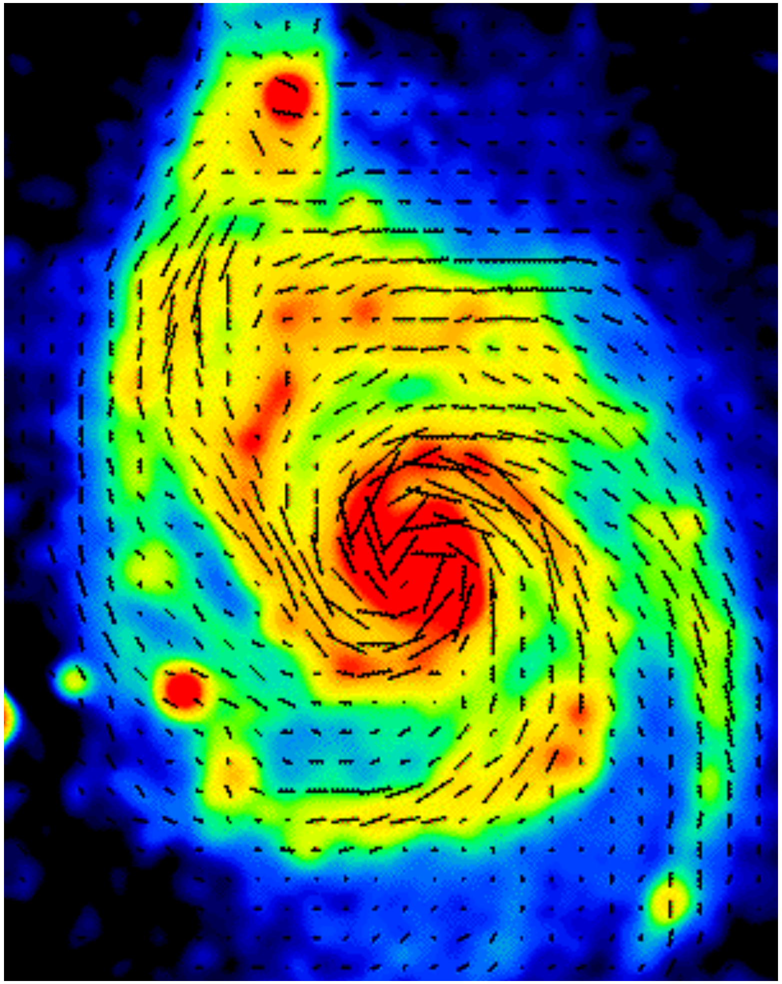
at
Searching for the sources of Galactic cosmic rays
APC, Paris - December 10, 2018

Why are magnetic fields important?

- They are everywhere.
- They play key roles in:
  - galaxy formation and evolution;
  - hydrostatic balance in the ISM;
  - **cosmic ray** propagation**;**
  - **turbulence** in both the ISM and the IGM;
  - supernova remnant expansion**;**
  - molecular cloud collapse;
  - star formation;
  - deflection of ultra-high energy cosmic rays (UHECRs);
  - ....
- They generate **foregrounds** for CMB and 21cm background.

External galaxies: one example

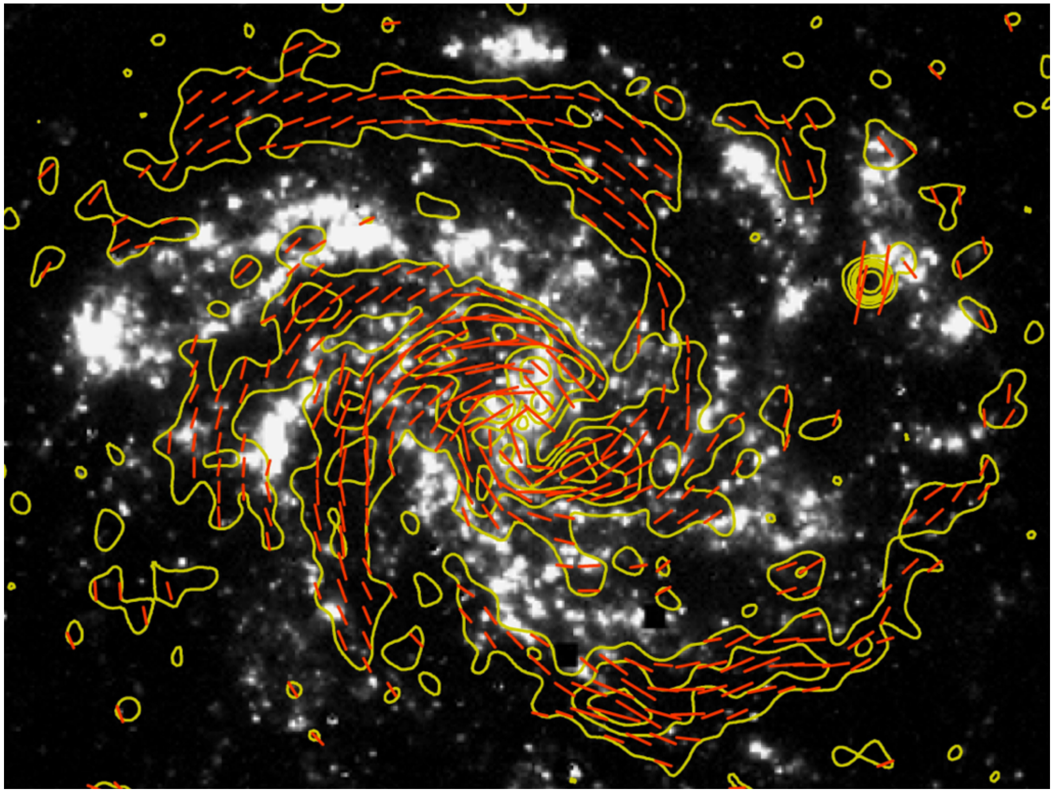
M51 6cm total intensity + magnetic field (VLA+Effelsberg)



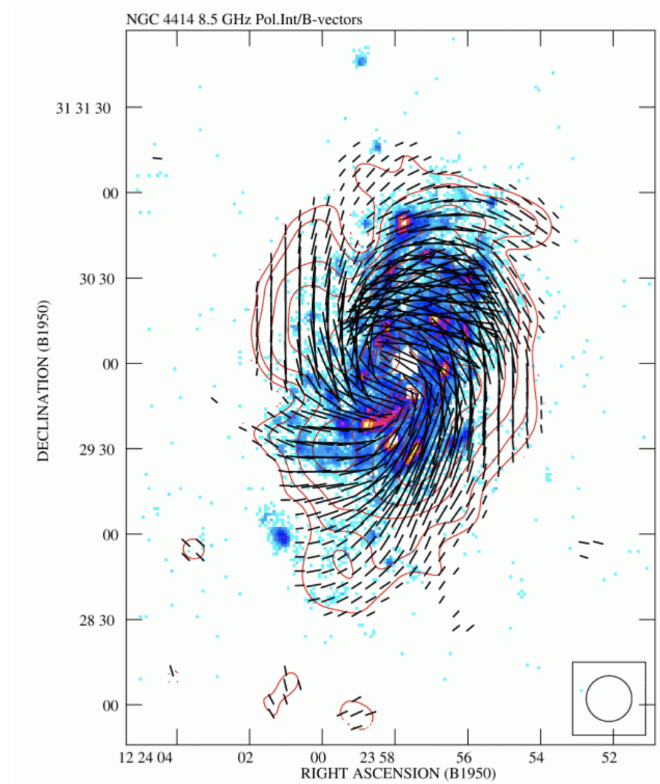
- First order: magnetic fields aligned with matter spiral structure. Can't be coincidental.
- But not always.
- Unfortunately, we cannot see our own galaxy like this.
- Furthermore, in an external galaxy, we cannot see the direction, but only its orientation.

Note that plots of polarization vectors are often rotated 90deg to show B-field direction

External galaxies: other examples



NGC6946 6cm PI over Hα (Copyright R. Beck, MPIfR)

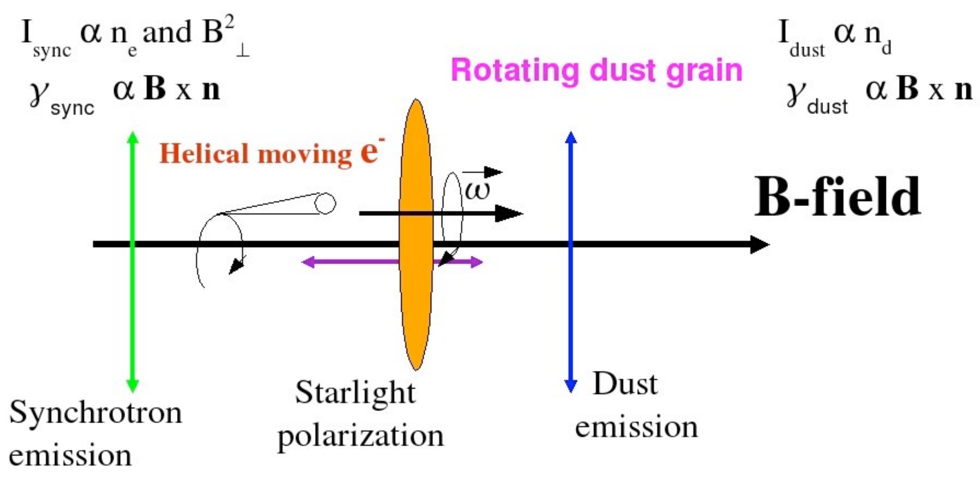


(Soida et al. 2002)

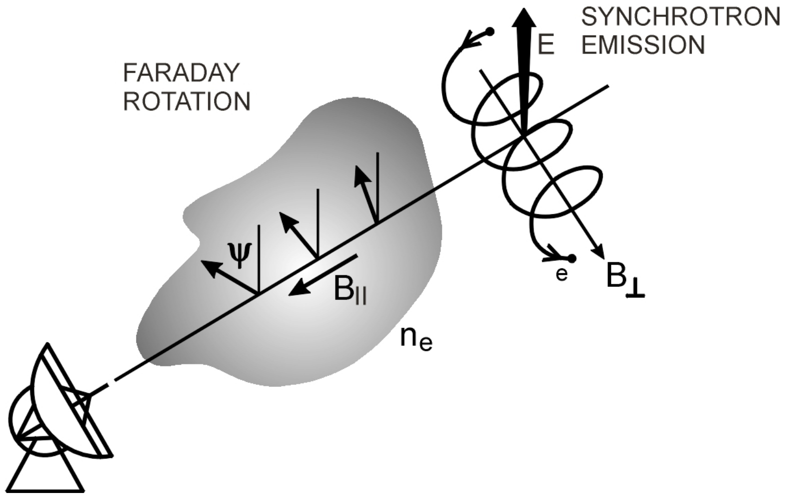
A variety of morphologies observed, and we cannot assume a relationship with other matter tracers.

Physics of the observables

- Synchrotron emission: $I(\nu) \propto \int_{LOS} n_{CRE} B_{\perp}^2 dl$ i.e. traces component ***perpendicular*** to LOS
- Faraday rotation measure: $RM \propto \int_{LOS} n_e B_{\parallel} dl$ i.e. traces component ***parallel*** to LOS
- Thermal (vibrational) dust emission: **?** traces component ***perpendicular*** to LOS but depends on dust environment, grain sizes and shapes, alignment mechanisms....
- Starlight polarization: ***perpendicular*** component, ***3D*** with star distances.
- Zeeman splitting, masers, etc....

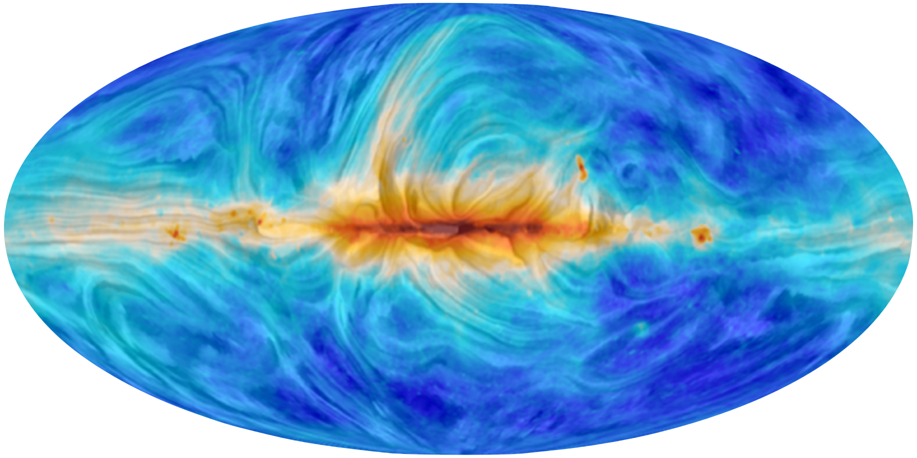


(Courtesy J.F. Macías-Pérez)

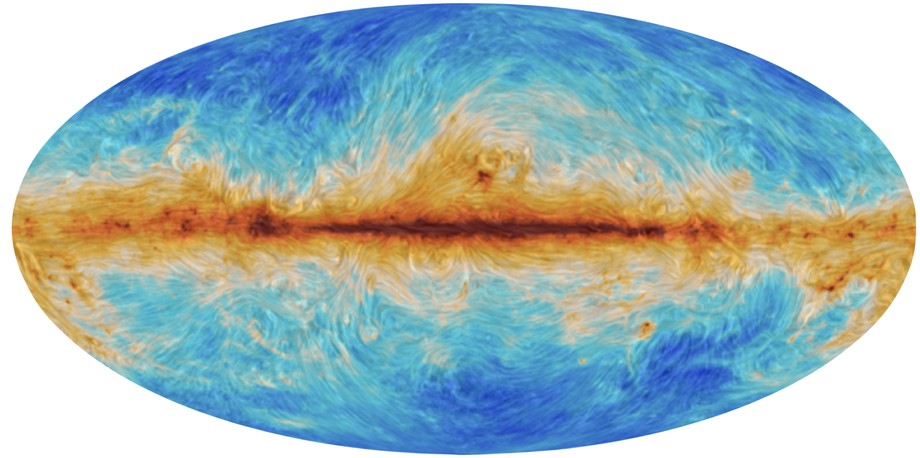


(Courtesy R. Wielebinski)

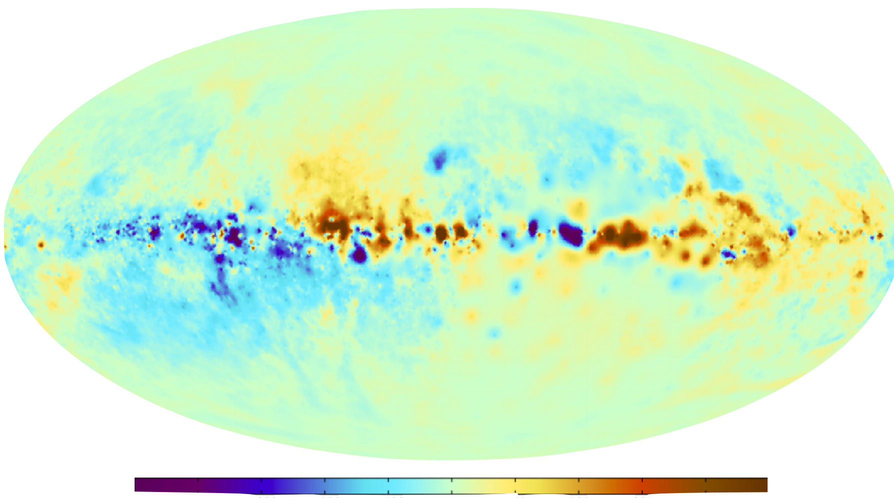
Data



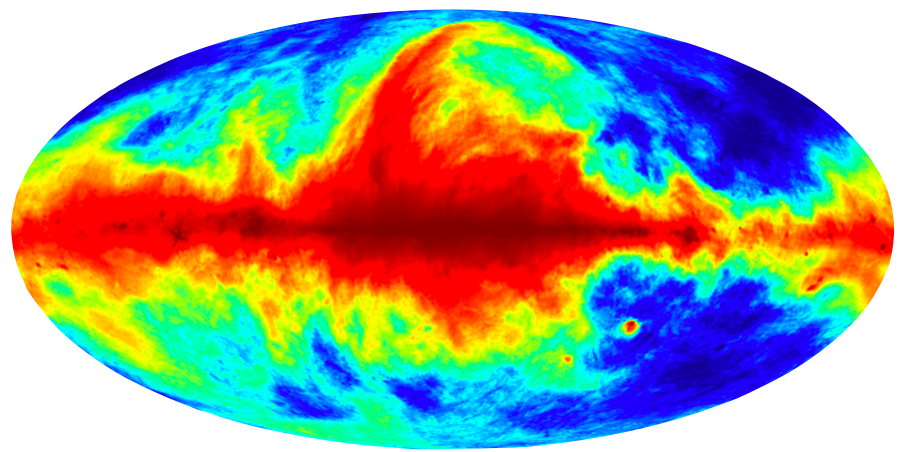
30 GHz polarized synchrotron (ESA, Planck Collaboration)



353 GHz polarized dust (ESA, Planck Collaboration)

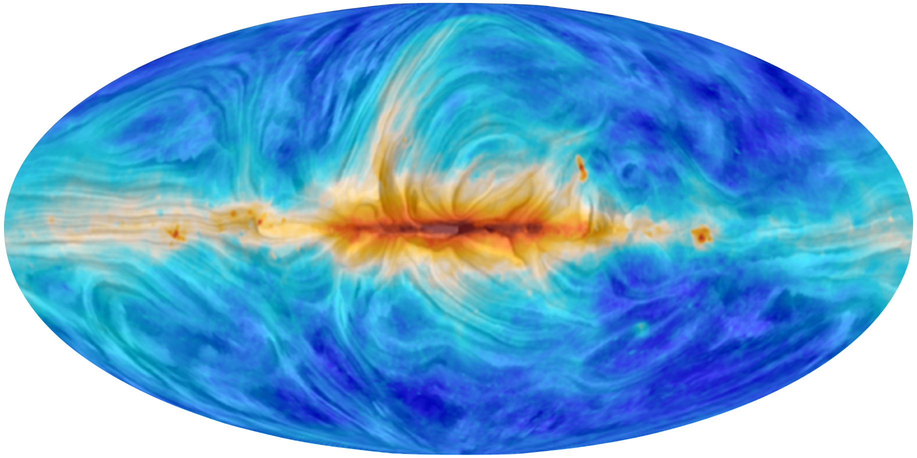


Faraday depth (rad/m^2)
(Oppermann et al. 2012)

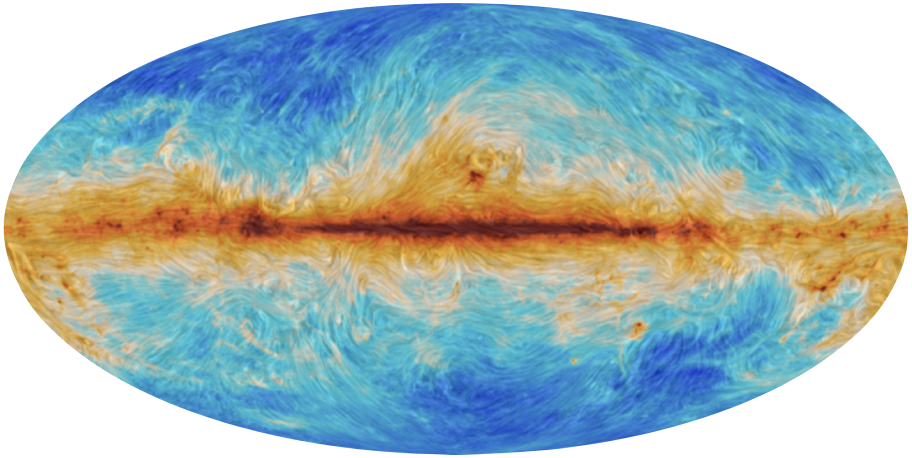


408 MHz total intensity emission (Haslam et al. 1982 and Remazeilles et al. 2014)

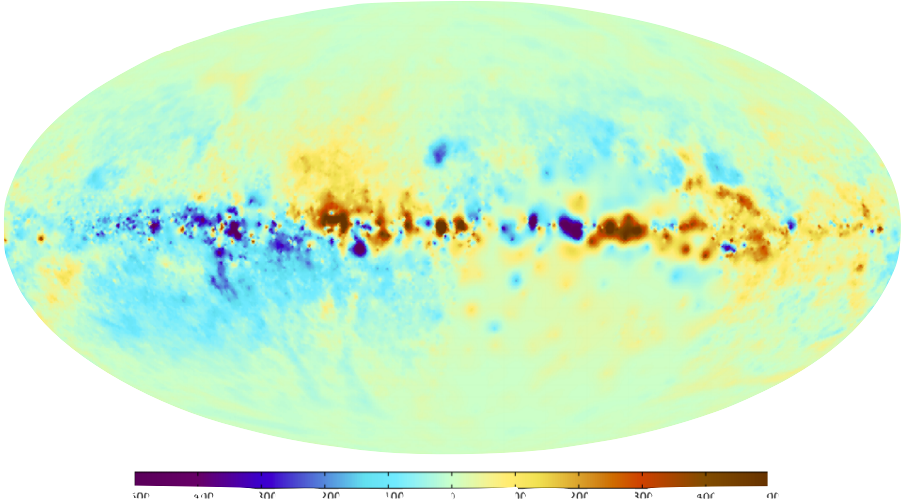
Data



30 GHz polarized synchrotron (ESA, Planck Collaboration)

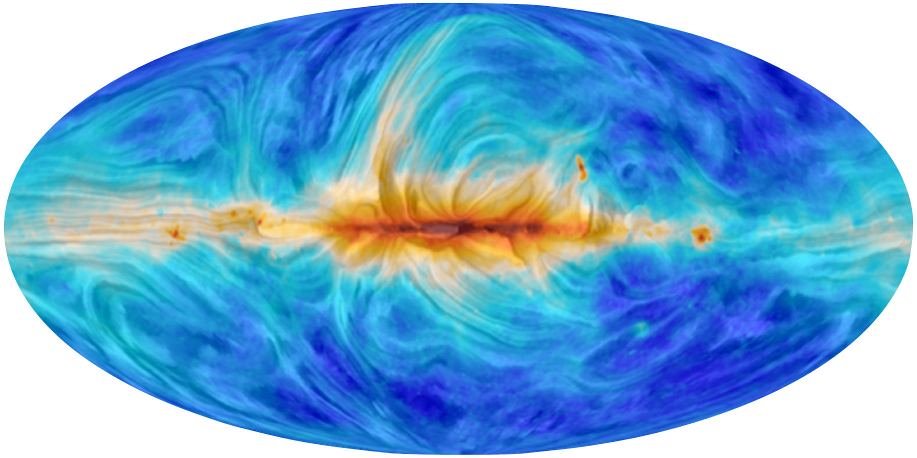


353 GHz polarized dust (ESA, Planck Collaboration)



Faraday depth (rad/m^2)
(Oppermann et al. 2012)

Data



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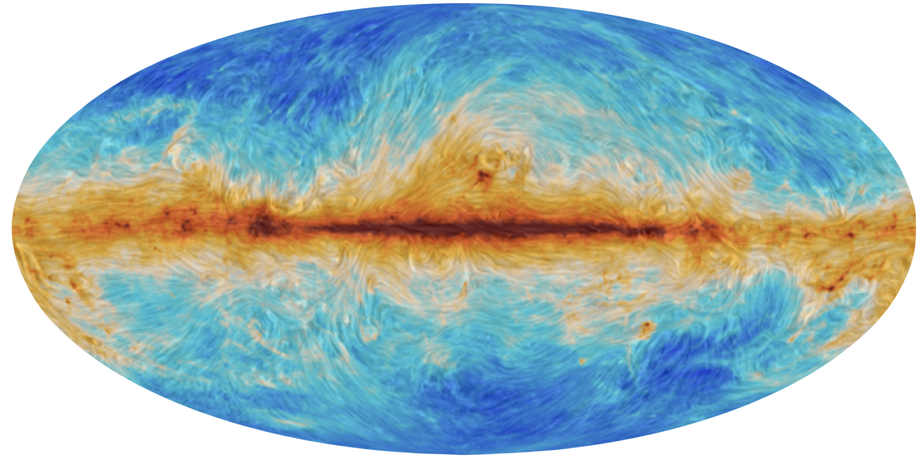
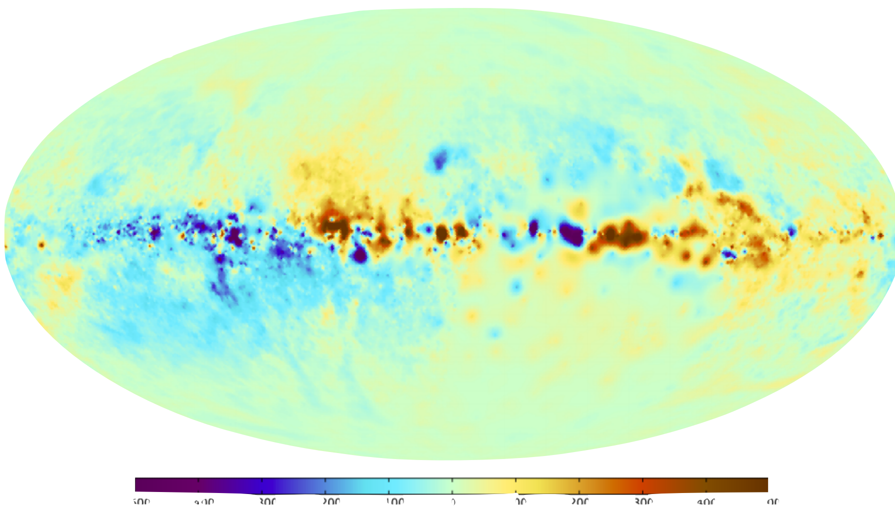
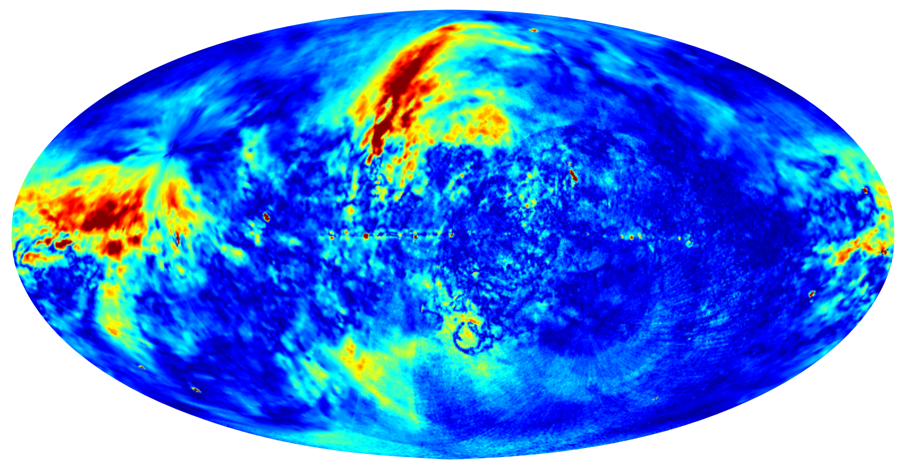


353 GHz polarized dust (ESA, Planck Collaboration)

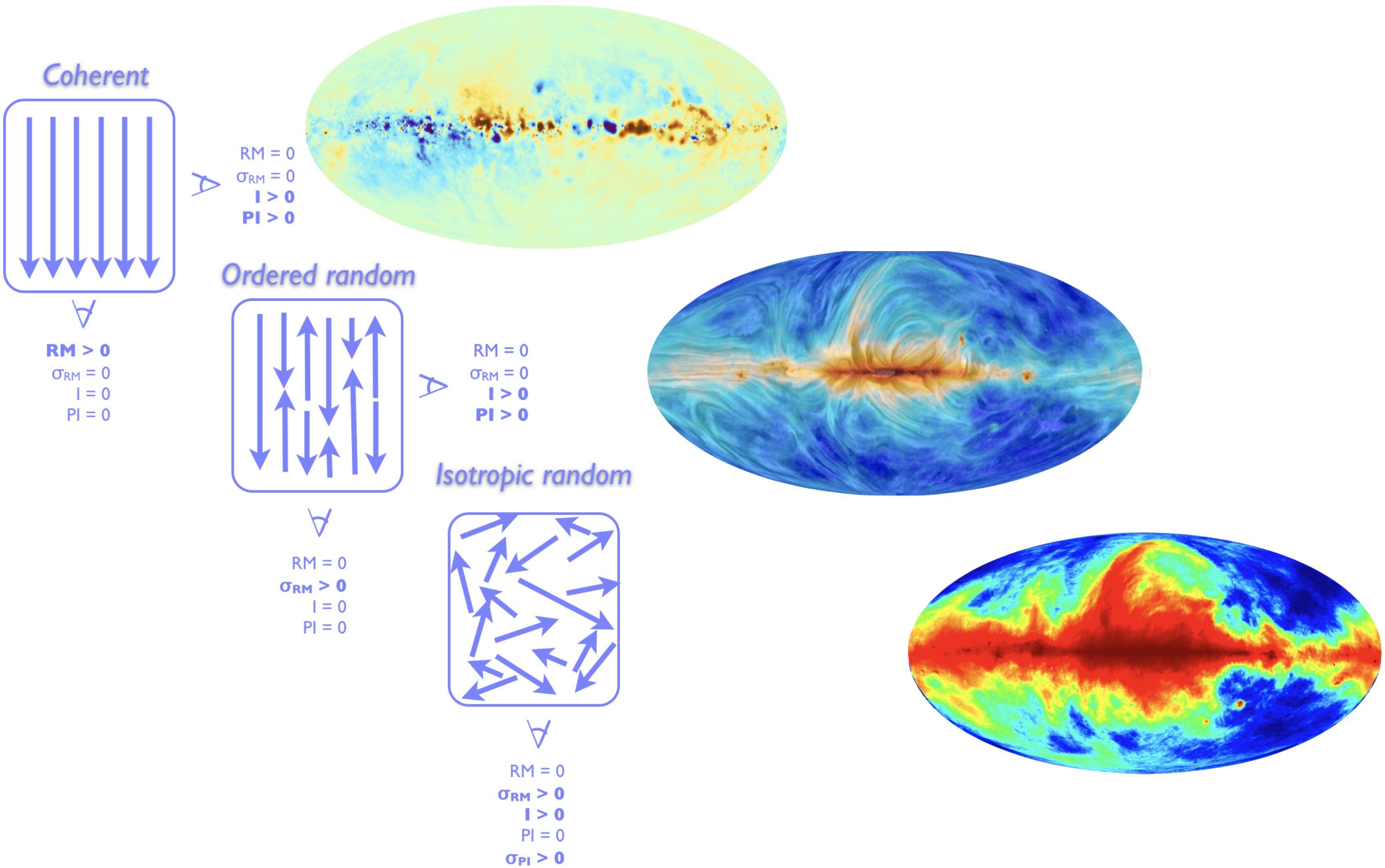


Faraday depth (rad/m^2)
(Oppermann et al. 2012)

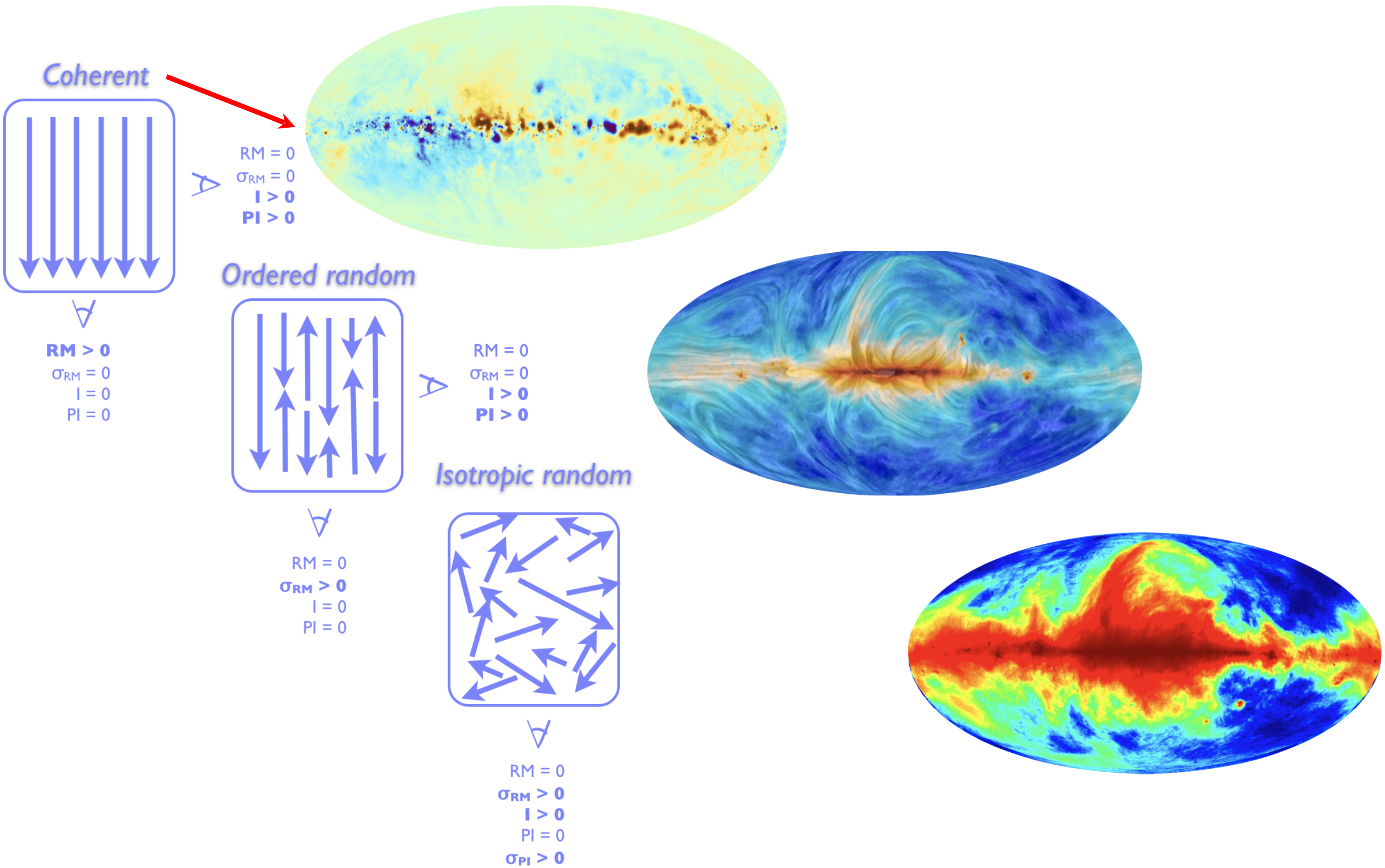


1.4 GHz polarized synchrotron (Reich 1982, Wolleben et al. 2006, Testori et al. 2008)

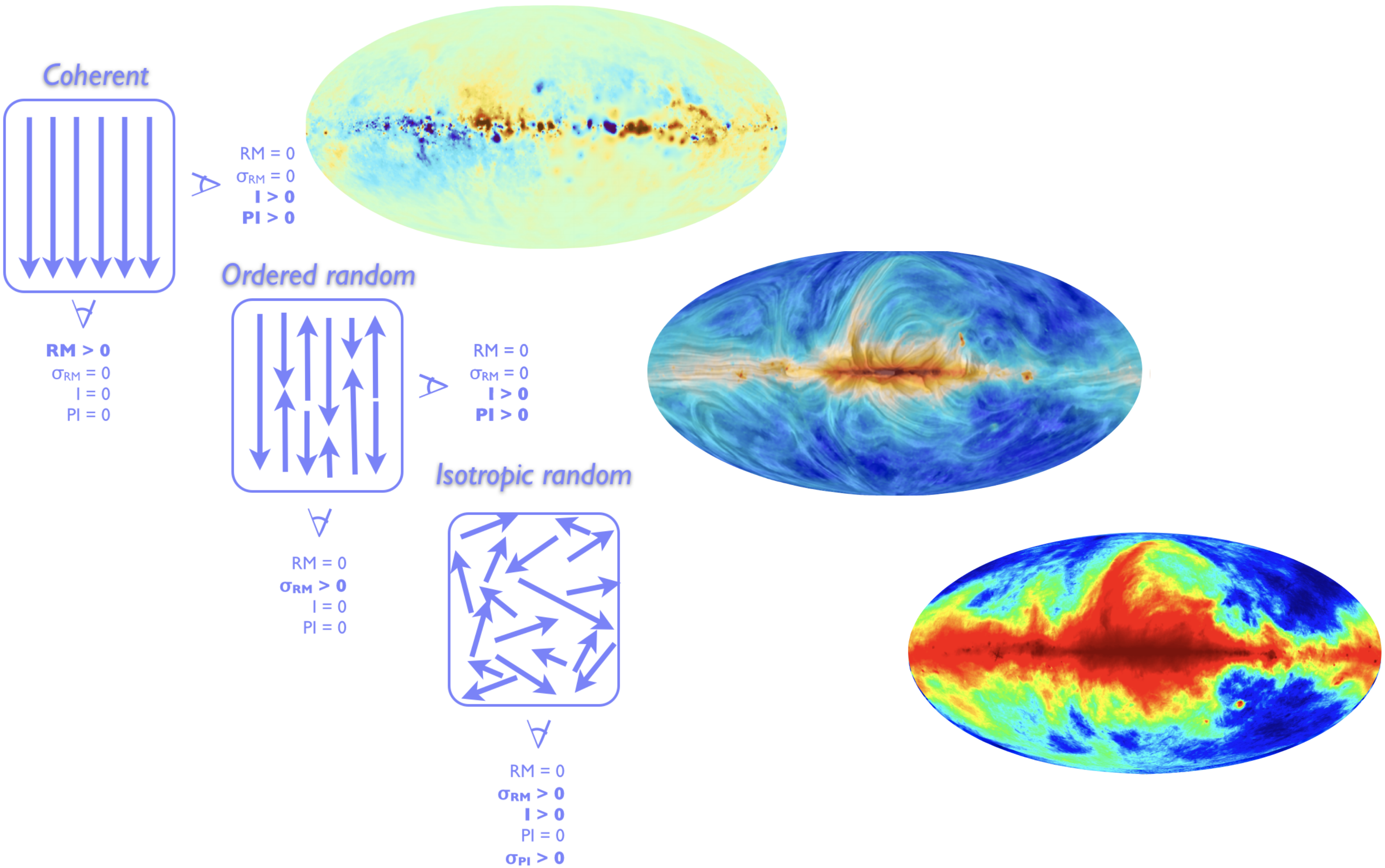
Components of the GMF



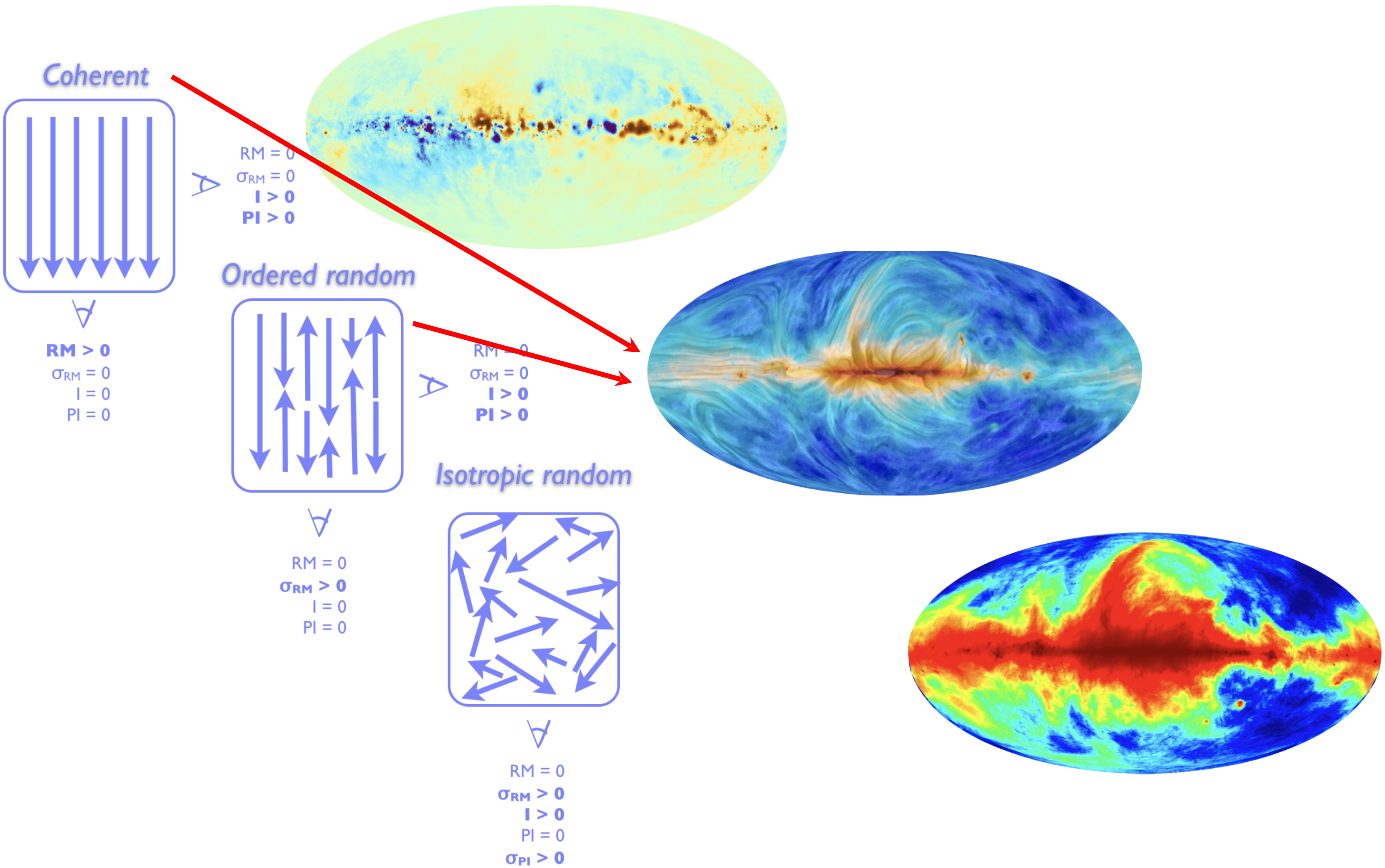
Components of the GMF



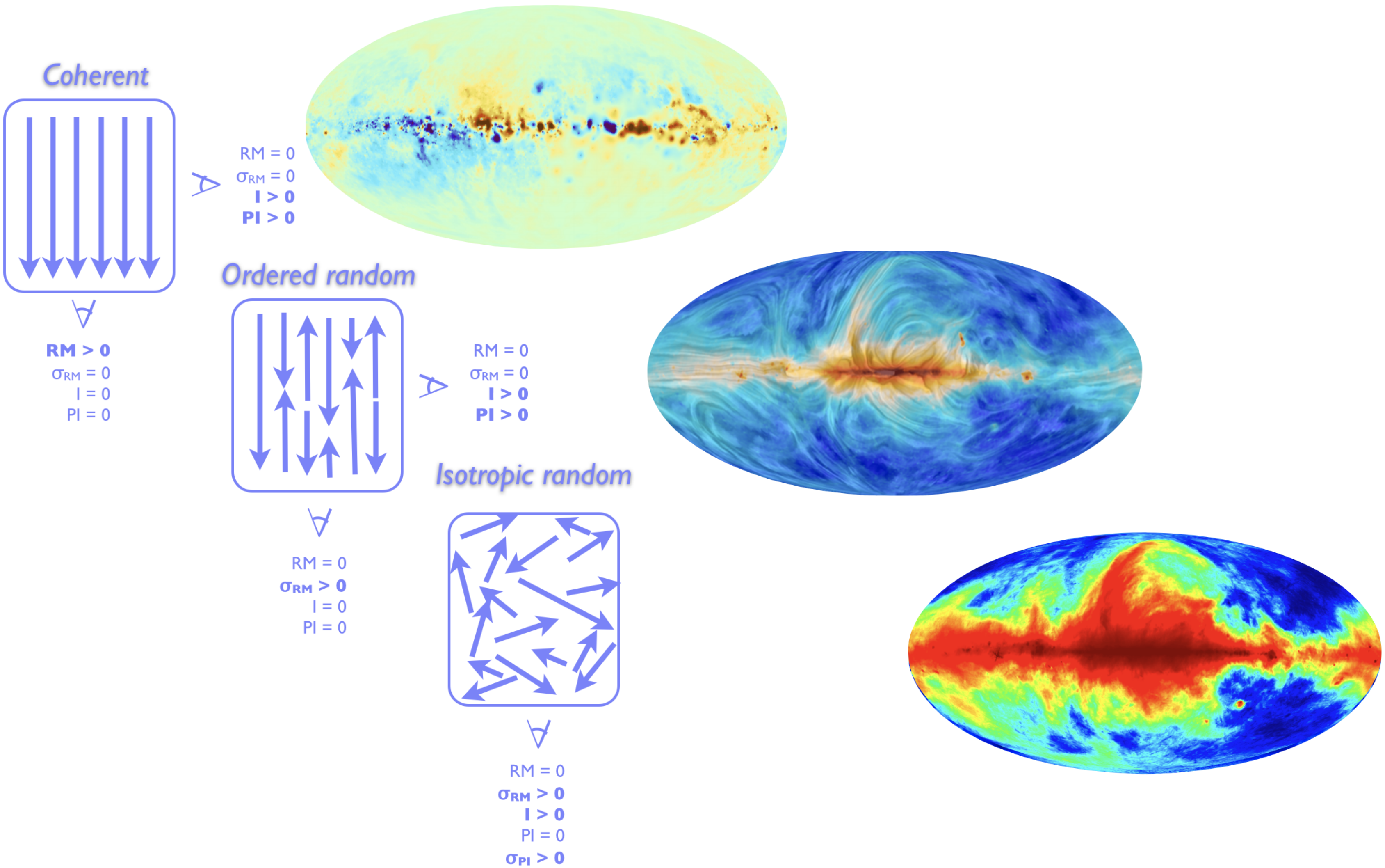
Components of the GMF



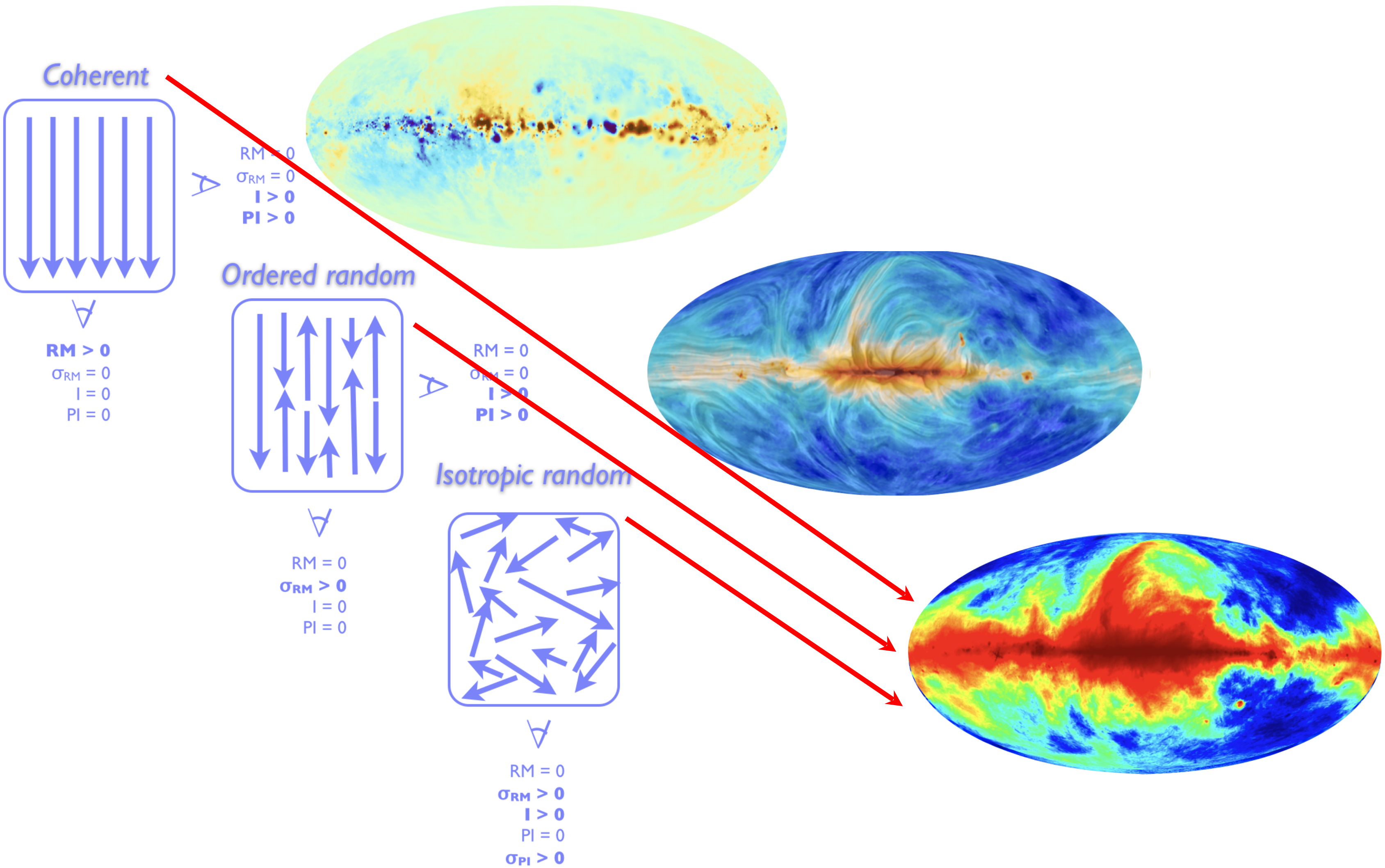
Components of the GMF



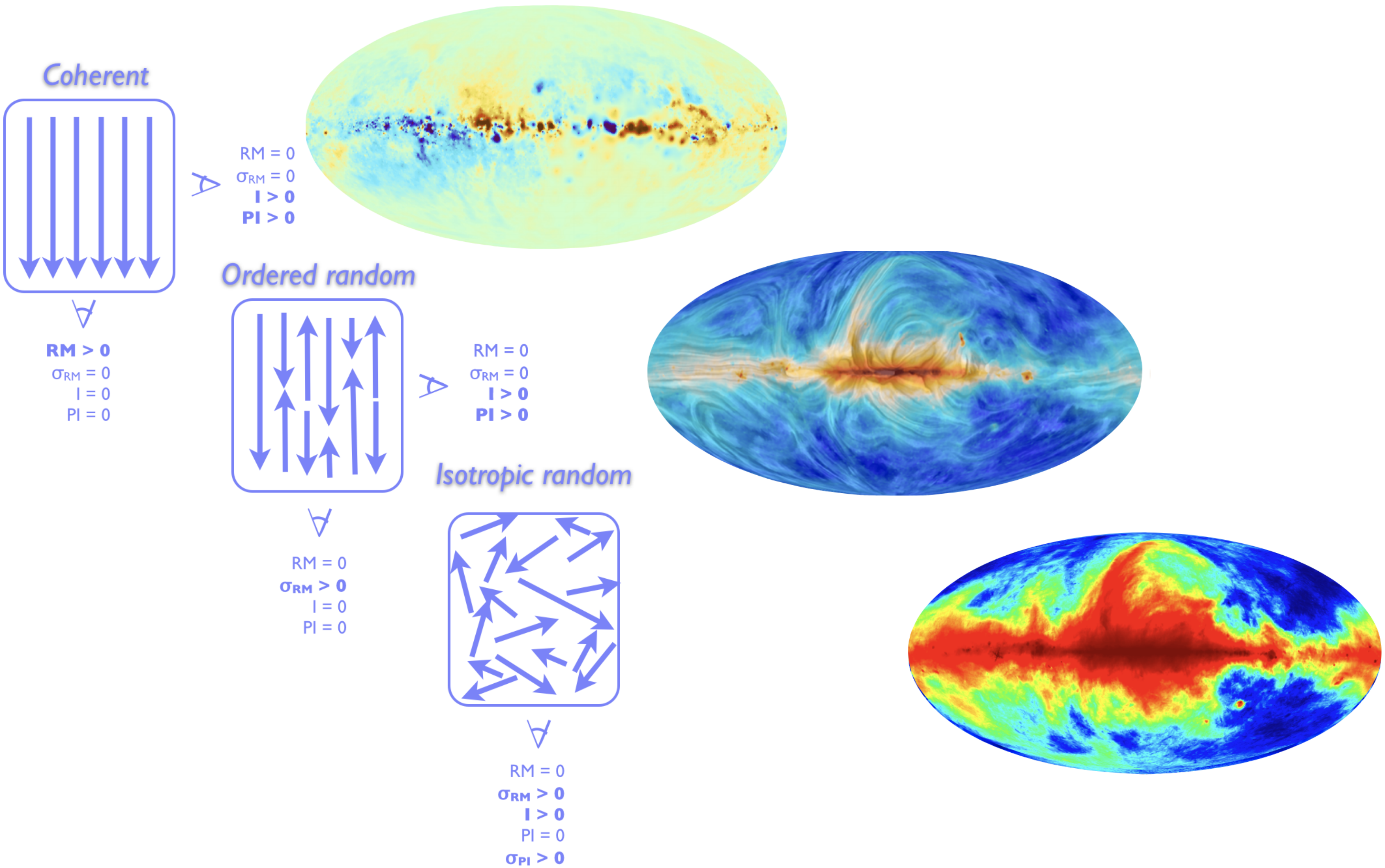
Components of the GMF



Components of the GMF



Components of the GMF

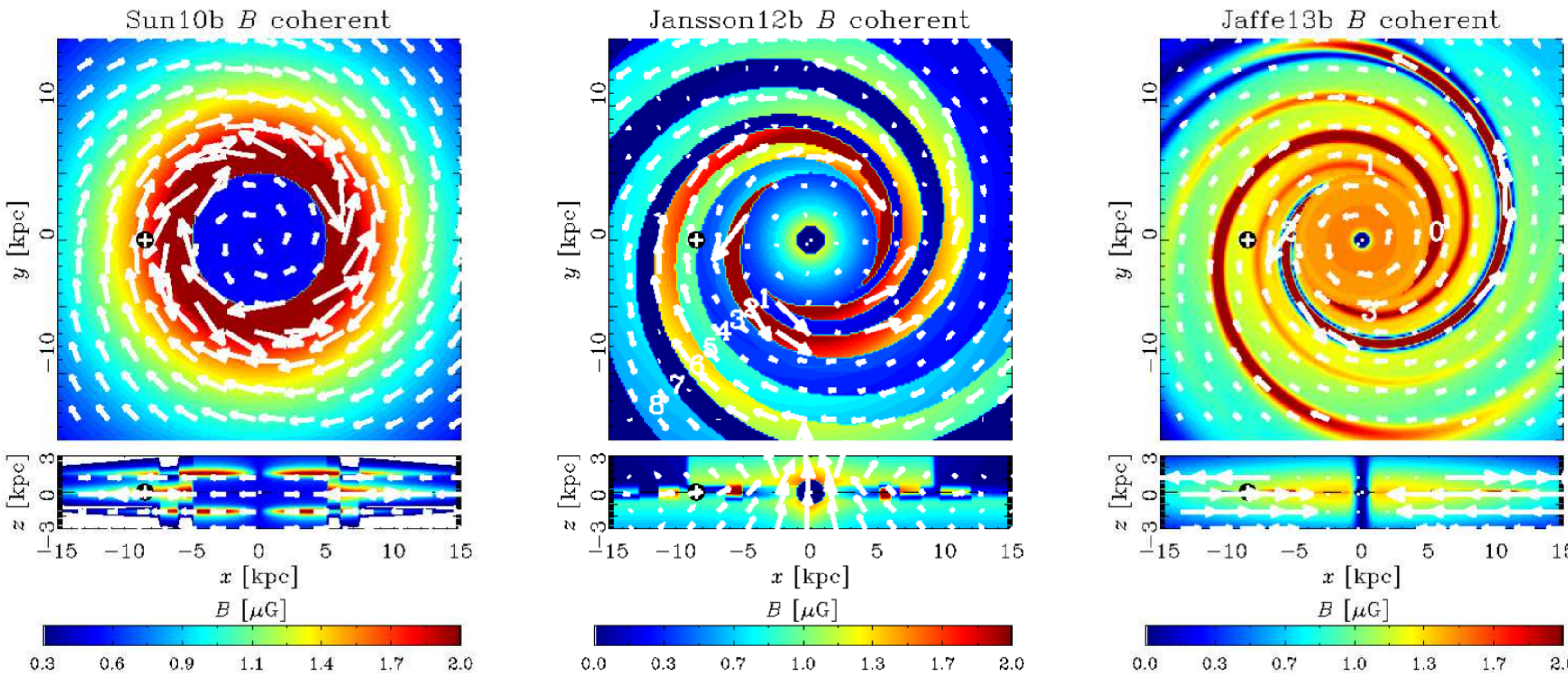


A few of the problems with the state of the art

- Very different models all roughly match the same(ish) observables.
  - *(degeneracies all over the place)*
- None is very connected to physics.
  - *(this can be done better now)*
- A Bayesian model comparison has not been done.
  - *(this is hard but do-able now)*
- And don’t even ask about the treatment of the turbulence.
  - *(this is annoying and needs thought)*
- Planck Planck Intermediate Results XLII (2016, “PIPXLII”) showed why all previous fits (including mine) are wrong.

A few of the problems with the state of the art

- Very different models all roughly match the same(ish) observables.

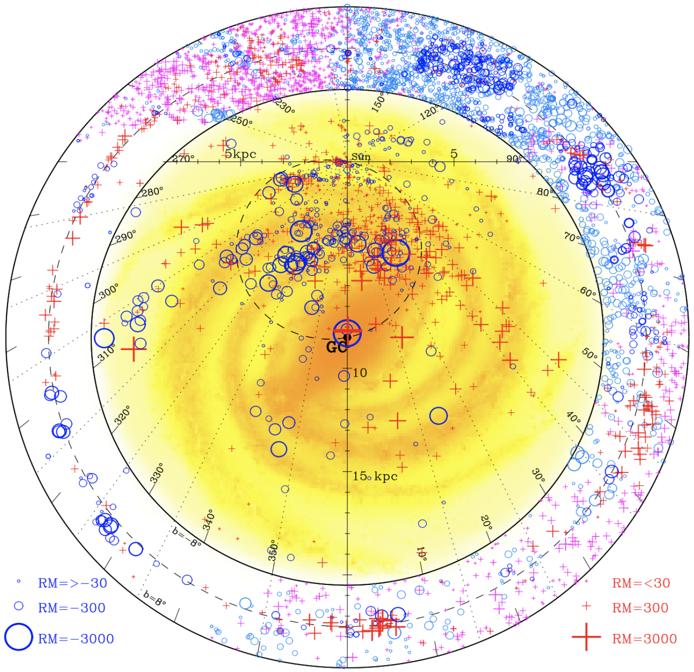


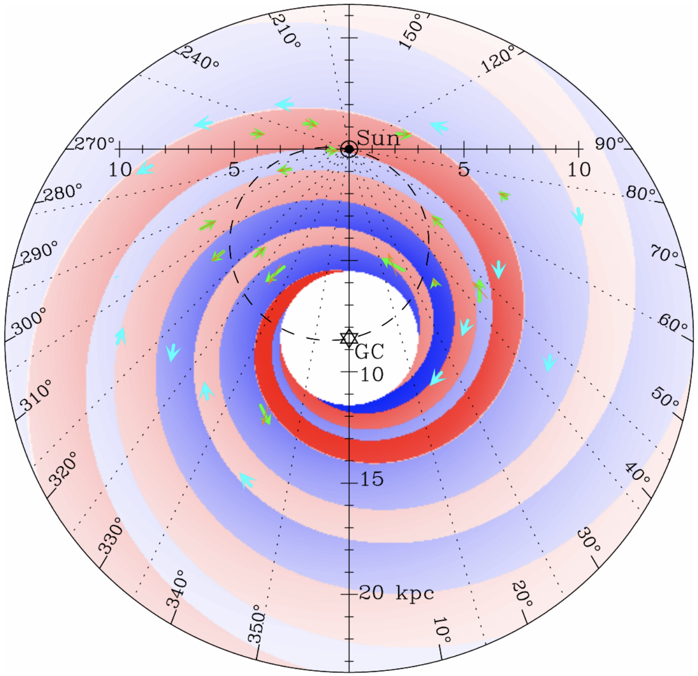
(PIPXLII)

- **Insufficient distance information:** current sampling of Galactic pulsars leaves significant uncertainty as to where the coherent field features lie along the LOS.
- **Uncertain CR spatial distribution**: likewise, few 3D tracers of CR density and therefore synchrotron emissivity is degenerate between CRs and **B**.
- **Uncertain CR spectral distribution**: introduces a degeneracy between field components due to combination of varying spectrum and Faraday effects.

Field reversals: where?

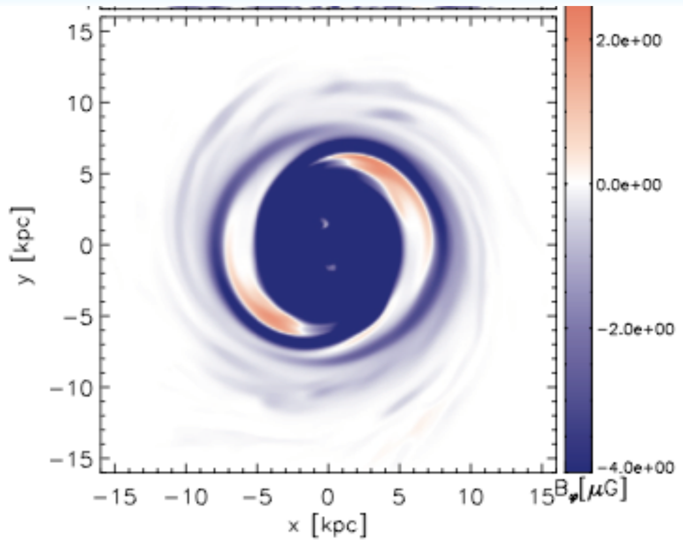
- With RMs, can study direction of field (from RM mean) and amount of turbulence along LOS (from RM variance).
- Pulsar distance estimates probe along LOS, while extra-galactic sources give better sampling and probe full disk.
- But uncertainties in thermal electron distribution as well as related pulsar distance determinations.
- The only certainty is that there are puzzling reversals.





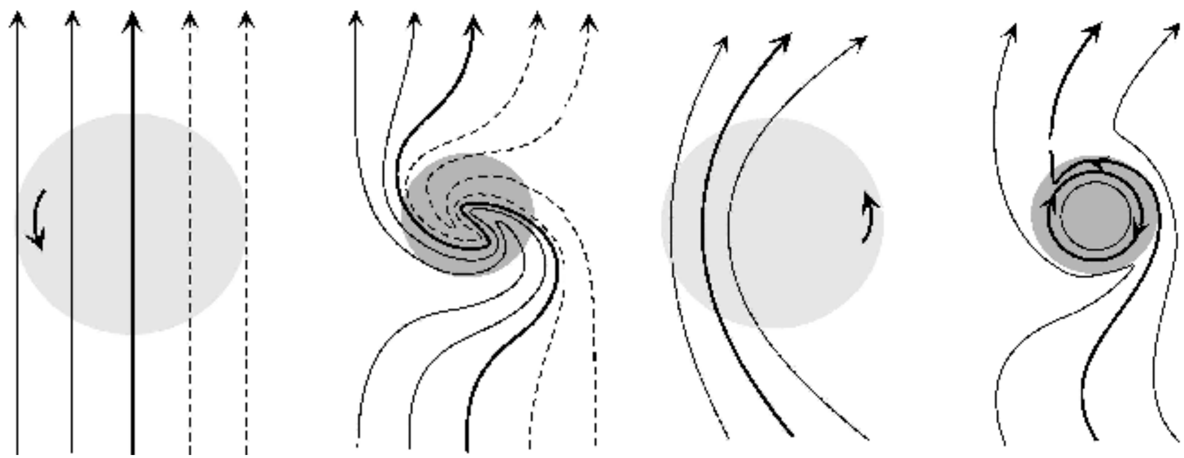
Left: galactic pulsars and extragalactic radio sources and their RMs. Right: a model of alternating arm and inter-arm reversals. (Han et al. 2017)

Field reversals?



Example of numerical simulation of field generated by CR-driven dynamo in barred spiral (Kulpa-Dybeł et al. 2011)

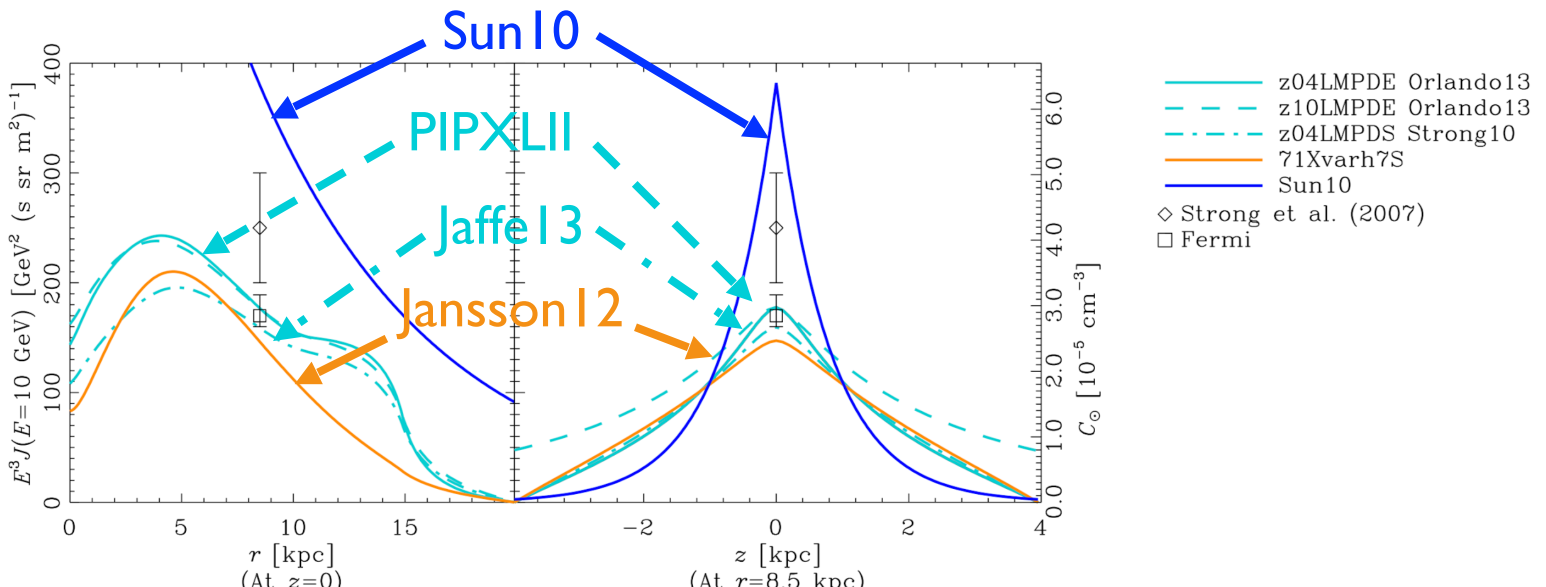
- Reversals => dynamos or primordial?
- Need a more detailed understanding of where the fields are reversed, i.e. more Galactic pulsar RMs.



Examples of formation of bisymmetric spiral (BSS, left) or ring reversal (right) from primordial field (Sofue et al. 2010)

CR spatial distribution?

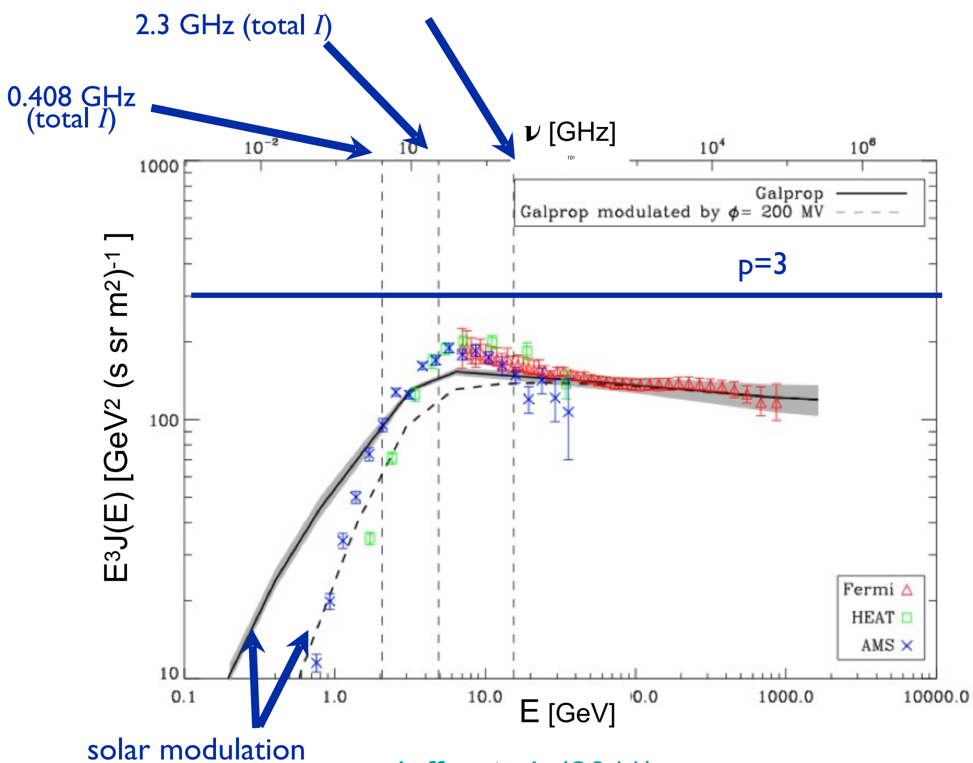
- Most of these differences are due to the source distribution.



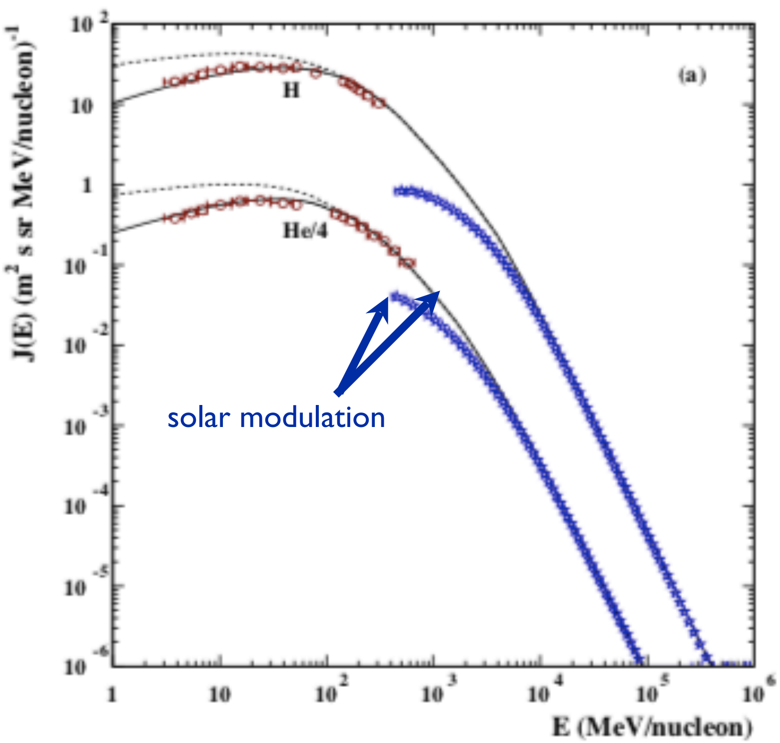
(PIPXLII)

CR spectral distribution?

GMF <=> n_cr(E)
(each has the potential to constrain the other)



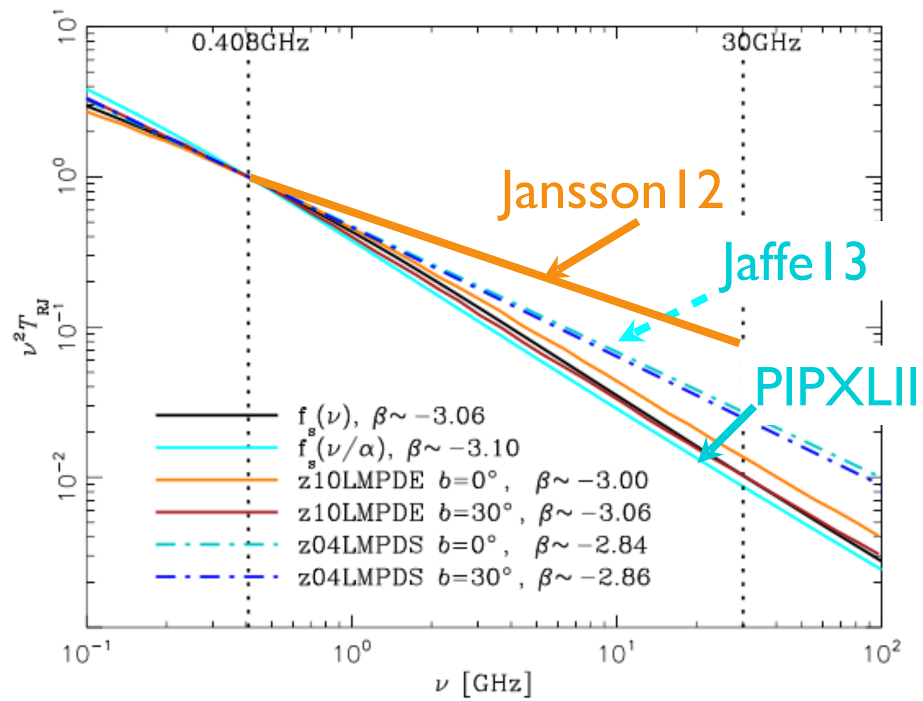
Jaffe et al. (2011)
(See also Strong, Orlando, & Jaffe 2011)



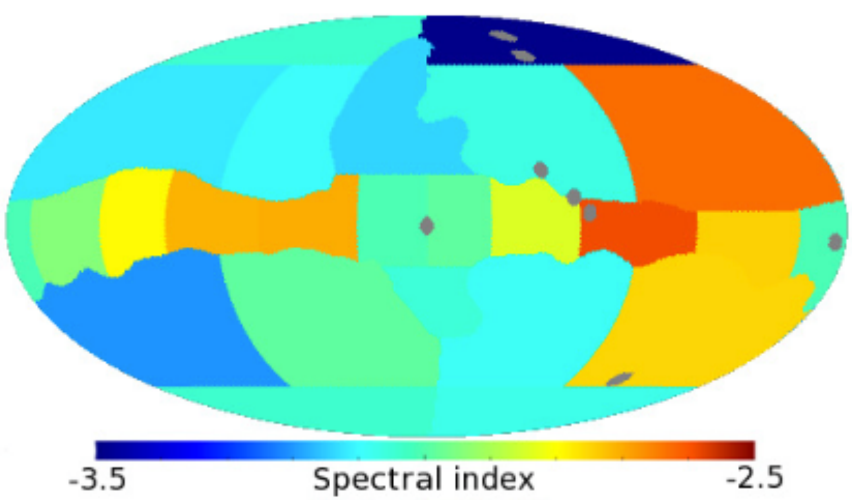
Protons measured by Voyager 1 (red) and AMS (blue)
Tatischeff & Gabici (2018)

Synchrotron spectral distribution?

- Planck PIP XLII based on Commander component separation
  - based on z10LMPDE
  - spectral template from a 'representative' high-latitude pixel
  - a fitted spectral shift, α



(PIPXLII)



(in the microwave bands)
Fuskeland et al. (2014)

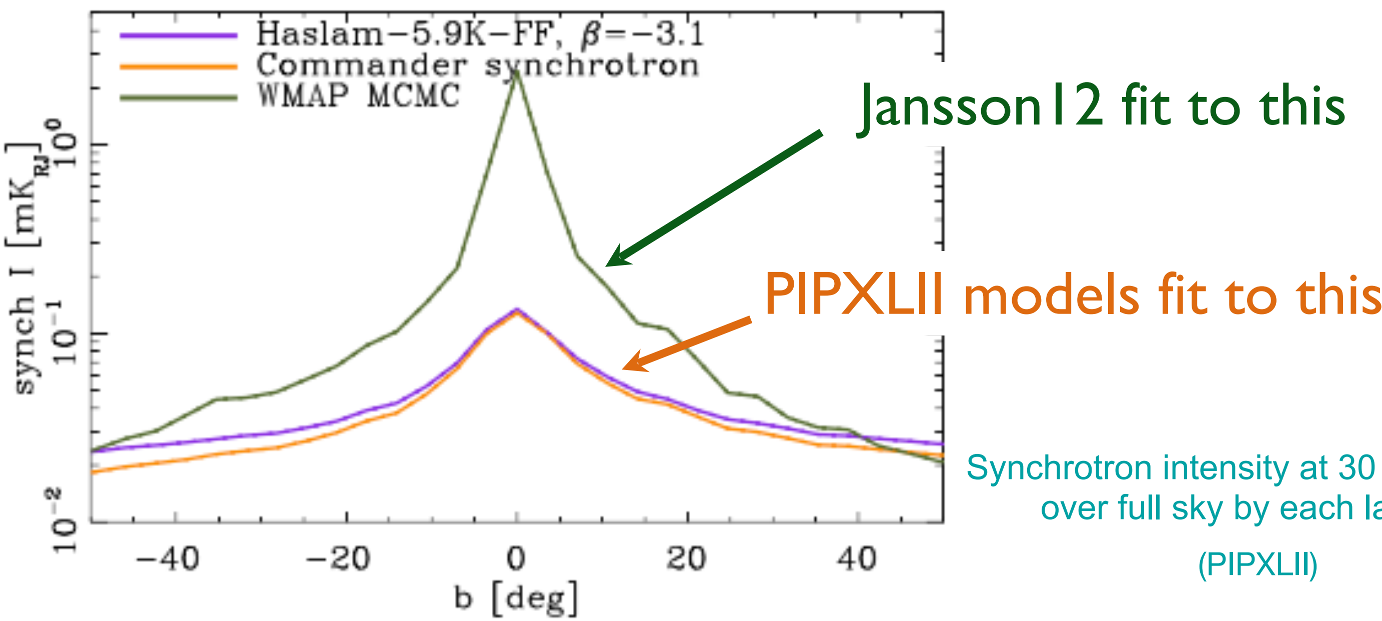
- Note: none of these models predict the amount of hardening toward the plane that is observed.

The component separation problem

- The synchrotron spectrum varies:
  - spatially, steepening by $\Delta\beta$~0.14-0.2 from low (β~-2.9) to high (β~-3.1) latitudes (Fuskeland et al. 2014, QUIET Collaboration 2015)
  - as a function of frequency, steepening by $\Delta\beta$~0.2 from radio (β~-2.7) to the microwave (β~-2.9) in the plane (Planck PIP XXIII 2015)
- Planck Commander assumes constant GALPROP-based spectrum with effective β=-3.1 from 0.408 to 30 GHz, i.e. assumes everywhere a spectrum that is only typical of the high-frequency and high-latitude regimes.
- *WMAP* MCMC used by JF12 assumes no AME and is likely significantly contaminated, thus the very flat β_{eff}~-2.6.

Impact on the fitting

- A difference in the synchrotron spectral index of Δβ~0.2 from 408MHz to 30GHz implies a difference in synchrotron intensity of **a factor of four**!
    - JF12 (β~-2.6) overestimates synchrotron total intensity and therefore the random magnetic field components.
    - The Planck Commander solution (β~-3.1) likely underestimates them.
    - The Jaffe13 β~-2.85 is (coincidentally) right in the middle.

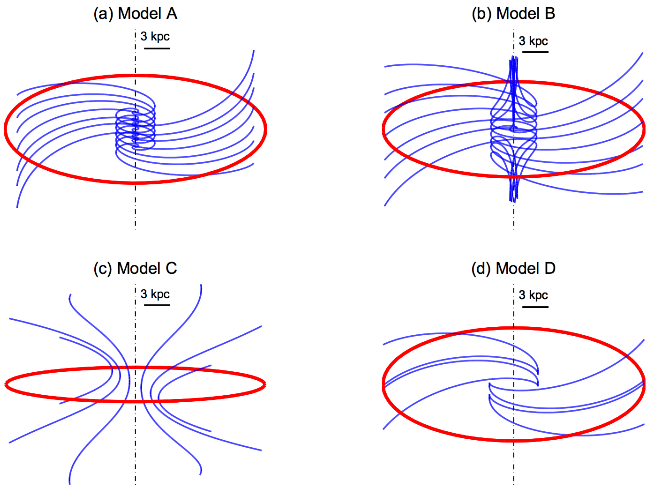


Synchrotron intensity at 30 GHz averaged over full sky by each latitude bin

(PIPXLII)

A few of the problems with the state of the art

- **None is very connected to physics.**
  - ➢ Ferrière and Terral (2014) and Shukurov et al. (2018) have made a good start:



Analytically derived x-shaped field models
Ferrière & Terral (2014)
Terral & Ferrière (2017)

(See also Unger and Farrar 2017)

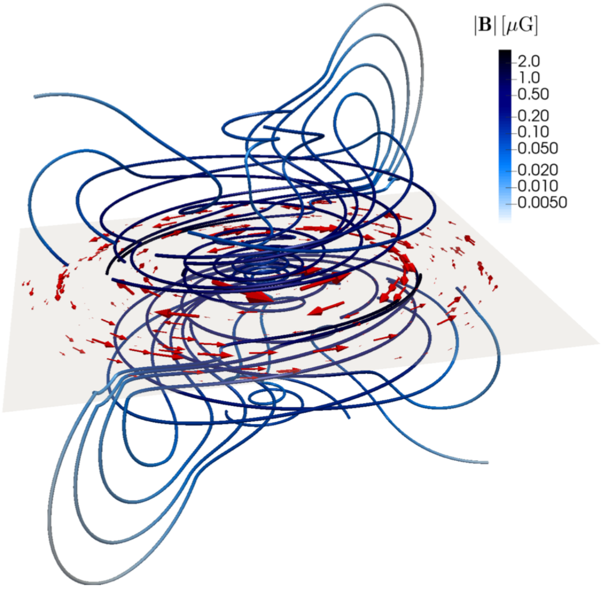


Figure 11. Three-dimensional rendering of a symmetric (quadrupolar) halo field solution combined with a quadrupolar disc field with two reversals at $s = 7\,\mathrm{kpc}$ and $12\,\mathrm{kpc}$. The domain is a $(17\,\mathrm{kpc})^3$ box. The field lines were seeded uniformly along a diagonal through the box. The arrows show the magnetic field at points randomly sampled within the slice of thickness $2.5\,\mathrm{kpc}$ around the galactic mid-plane (which is indicated by the semi-transparent surface) and are scaled according to the magnitude of the magnetic field.

Shukurov et al. (2018)

A few of the problems with the state of the art

- **A Bayesian model comparison has not been done.**

➢ Unger and Farrar (2017) have made a good start:

Uncertainties in the Magnetic Field of the Milky Way Michael Unger

id	disk model	toroidal model	poloidal model	thermal electrons	cosmic-ray electrons	synchrotron data product	misc.	χ^2/ndf
Parametric models								
a	JF	JF	JF	NE2001	GP_{JF}	WMAP7	-	1.10
b	JF	JF	FTC	NE2001	GP_{JF}	WMAP7	-	1.09
c	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP7	-	1.11
d	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP7	warp	1.11
e	UF	JFsym	FTC	NE2001	GP_{JF}	WMAP7	-	1.09
f	UF	UFa		NE2001	GP_{JF}	WMAP7	-	1.14
g	UF	UFb		NE2001	GP_{JF}	WMAP7	-	1.09
Synchrotron products								
h	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP9base	-	$1.22^{\dagger}$
i	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP9sdc	-	$1.24^{\dagger}$
j	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP9fs	-	$1.11^{\dagger}$
k	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP9fss	-	$1.22^{\dagger}$
l	JF	JFsym	FTC	NE2001	GP_{JF}	Planck15	-	$0.78^{\dagger}$
Thermal electrons								
m	JF	JFsym	FTC	YMW17	GP_{JF}	WMAP7	-	1.21
n	UF	JFsym	FTC	YMW17	GP_{JF}	WMAP7	-	1.14
o	JF	JF	FTC	NE2001	GP_{JF}	WMAP7	$\kappa = -1$	1.05^{*}
p	JF	JF	FTC	NE2001	GP_{JF}	WMAP7	$\kappa = +1$	1.05^{*}
q	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP7	HIM	1.12
Cosmic-ray electrons								
r	JF	JFsym	FTC	NE2001	O13a	WMAP7	-	1.13
s	JF	JFsym	FTC	NE2001	O13b	WMAP7	-	1.12
t	JF	JFsym	FTC	NE2001	S10	WMAP7	-	1.13

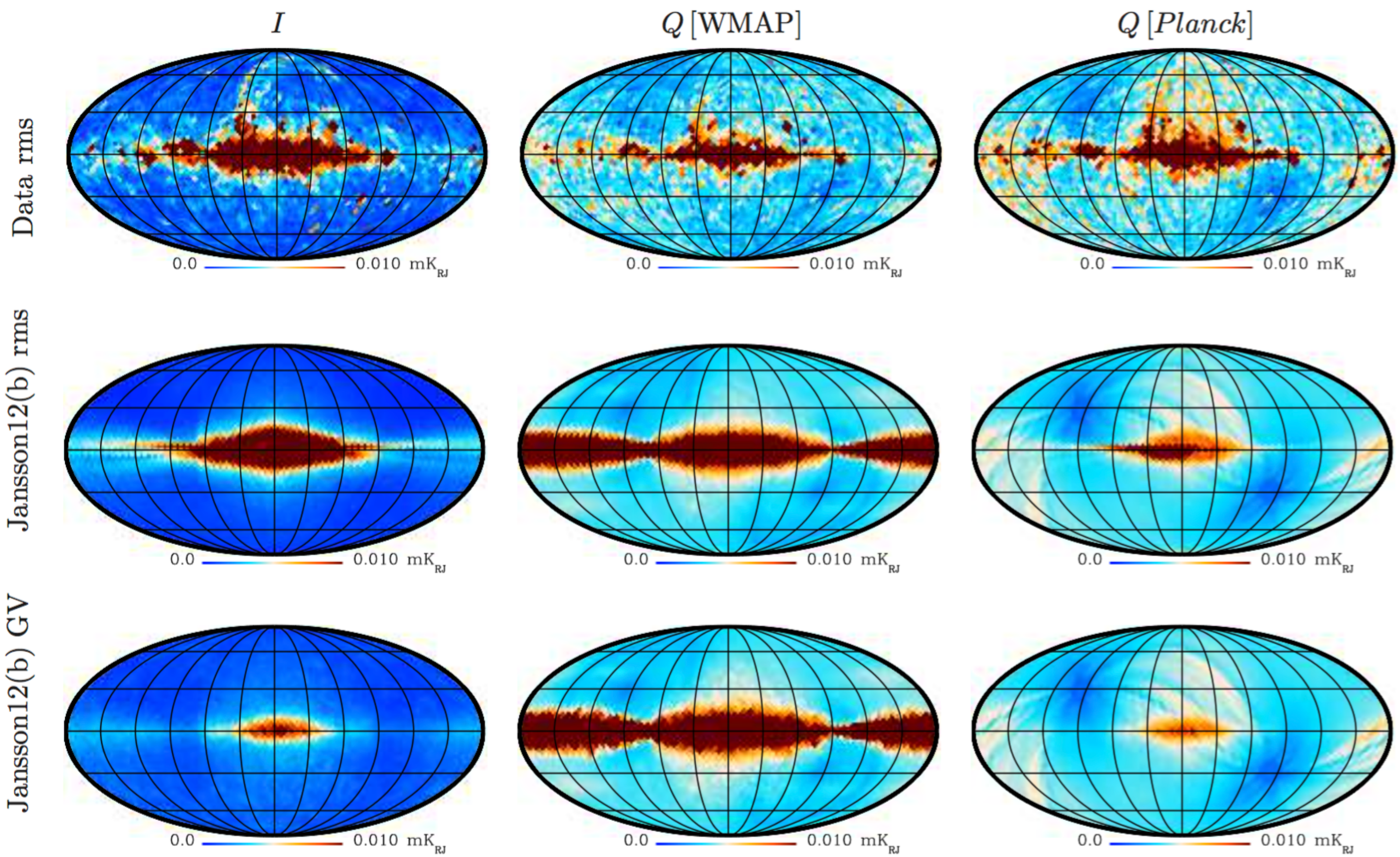
Table 1: Summary of model variations investigated in this paper. The original JF12 model corresponds to the first row (model a) and the reference model is given in the third row (model 3). The goodness of fit for describing the RM, Q and U data is given in the last column with the exception for the combined fits of coherent and random field (marked with a *), where the χ^2 also includes the contribution from the total intensity I. The χ^2s of the fits with different synchrotron data products (marked with a †) used different weights in the fits derived from these products.

Unger and Farrar (2017)

“galactic variance” as an observable

- **And don’t even ask about the treatment of the turbulence.**

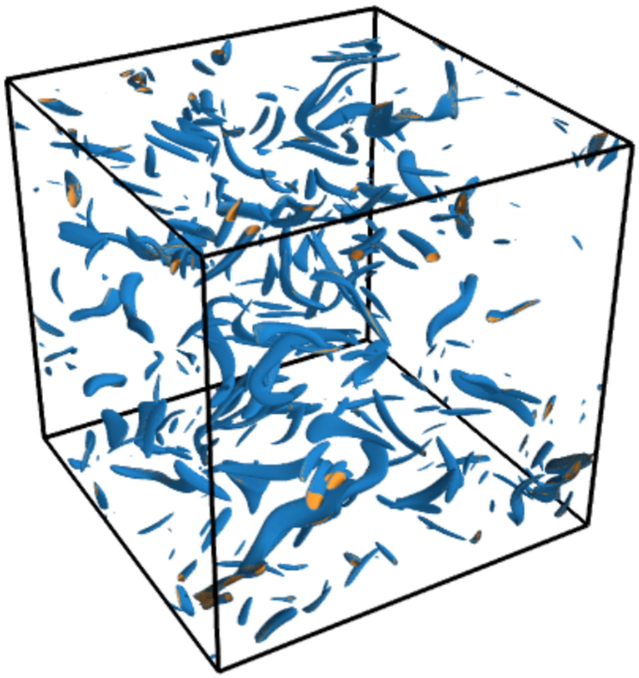
RMS: averaging high-res pixels into a low-res pixel in one realization or dataset
GV: (“galactic variance”) averaging each pixel among an ensemble of realizations of a model

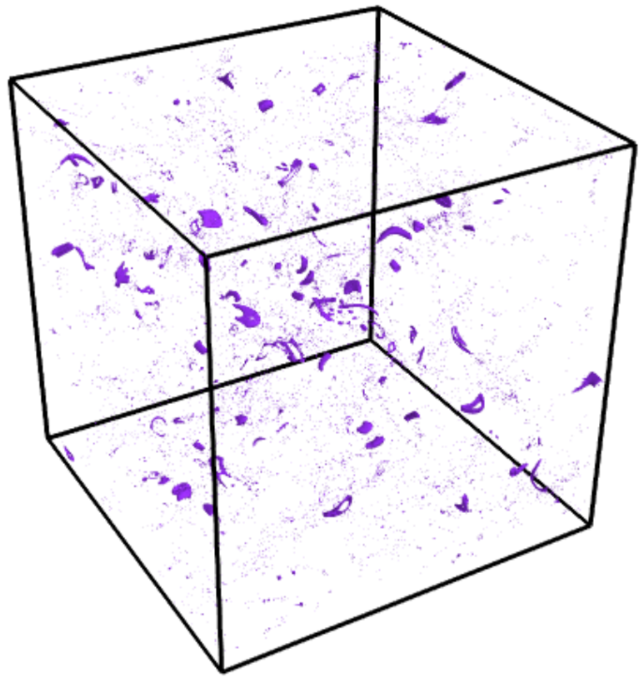


(PIPXLII)

Real turbulence?

- **And don't even ask about the treatment of the turbulence.**





Isosurfaces of the strength of a random magnetic field *B (left)* and CR number density (*right*) produced by the fluctuation dynamo

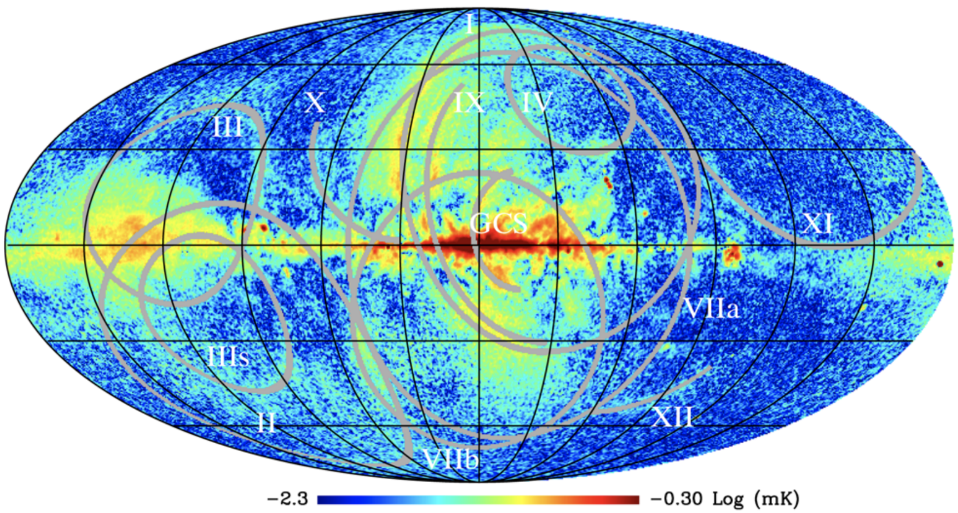
(Seta et al. 2018)

A few of the problems with the state of the art

- Very different models all roughly match the same(ish) observables.
- None is very connected to physics.
- A Bayesian model comparison has not been done.
- And don’t even ask about the treatment of the turbulence.
- **Planck Planck Intermediate Results XLII (2016, PIPXLII) showed why all previous fits (including mine) are wrong.**

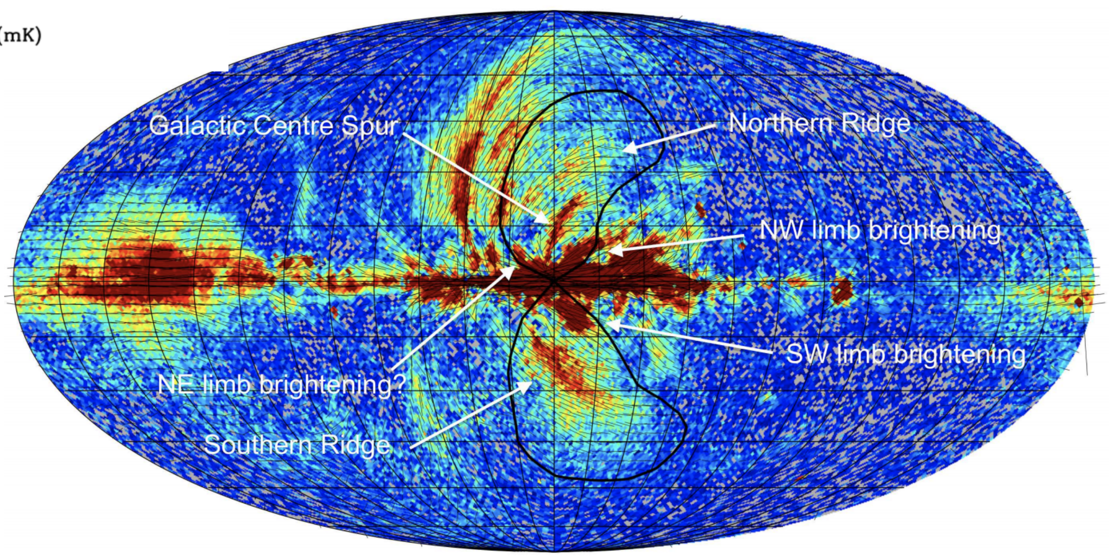
Loops, spurs, and super bubbles?

- Most are local. All?
- *And how do they impact global GMF fits?*

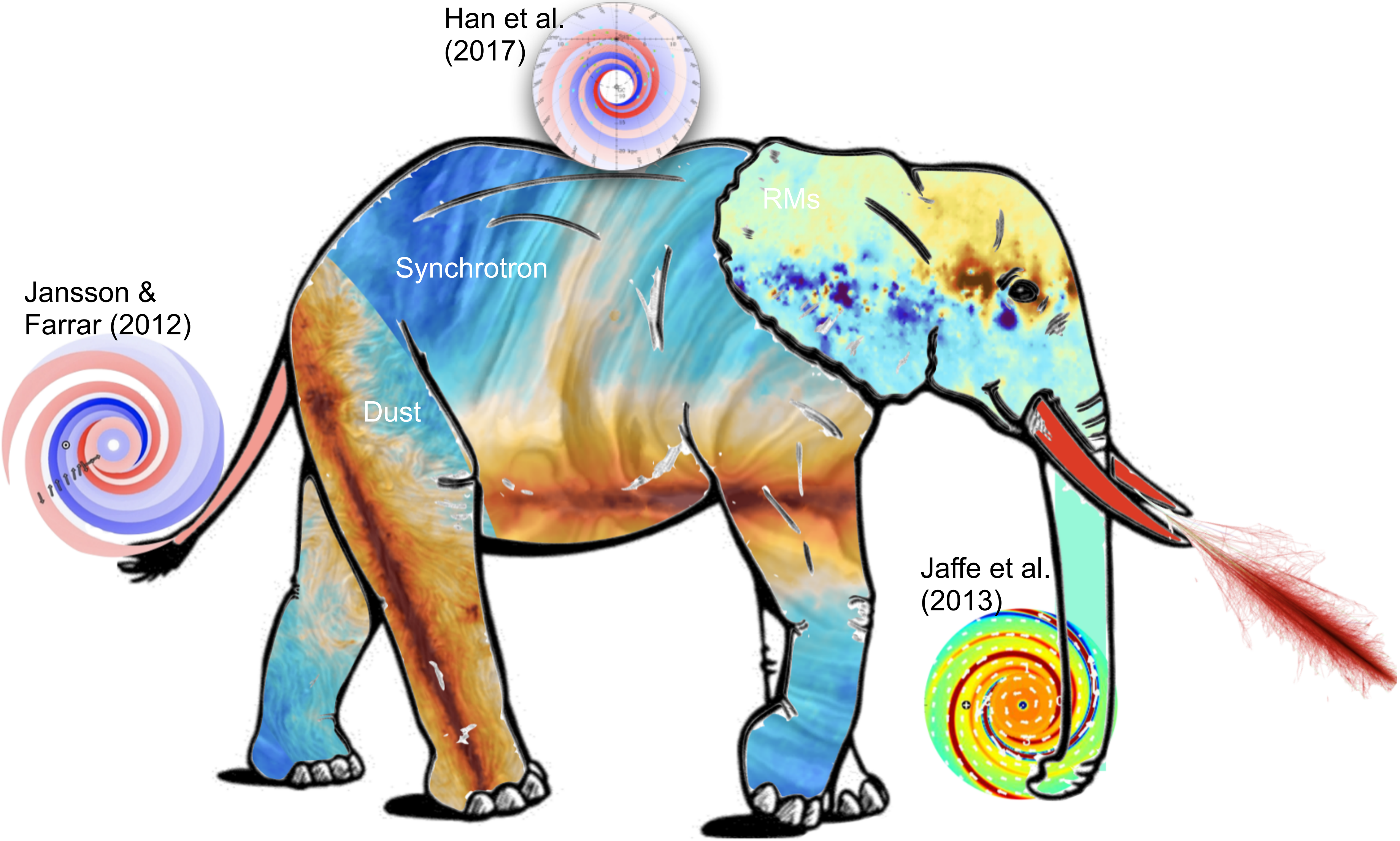


Vidal et al. (2015)

Carretti et al. (2013)



The proverbial elephant



"If we knew the GMF, we could then use X to constrain Y.
Likewise, if we knew Y, we could use X to constrain the GMF."

Another observable: CR anisotropies?

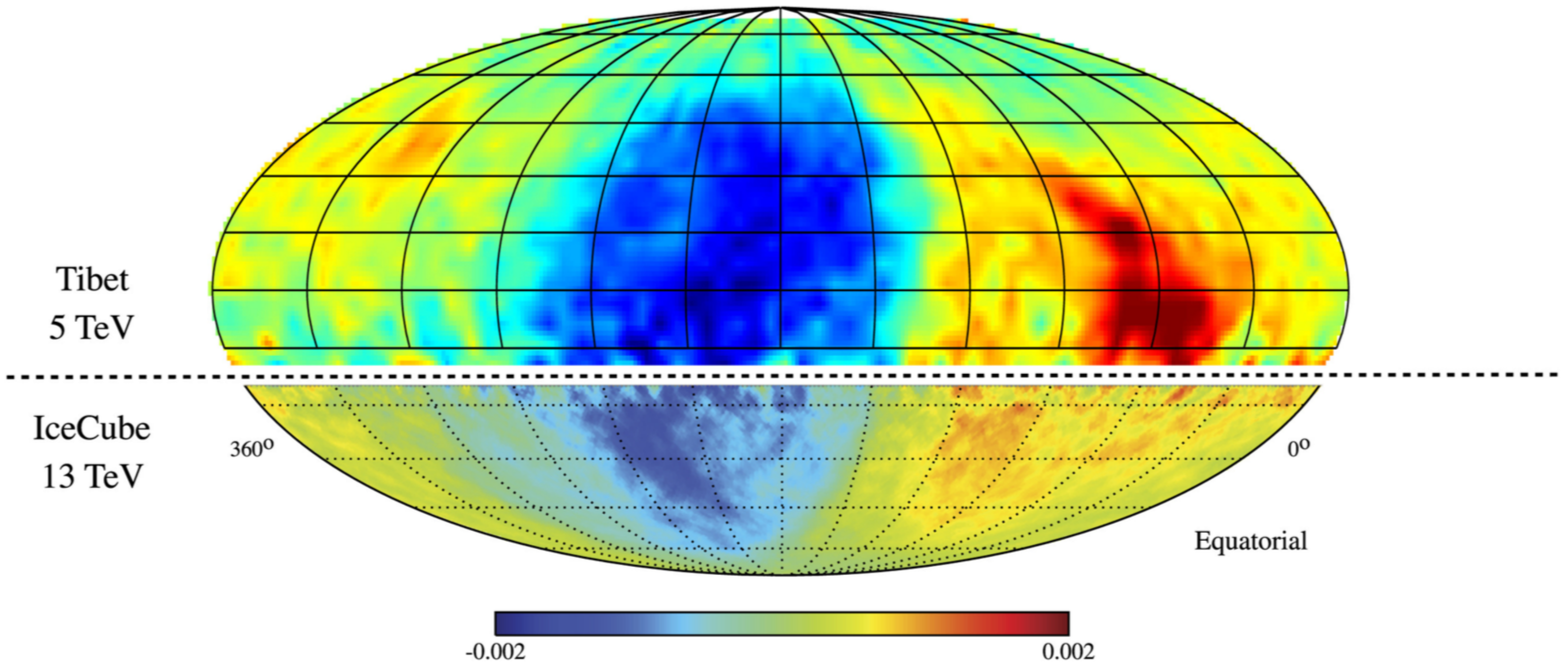
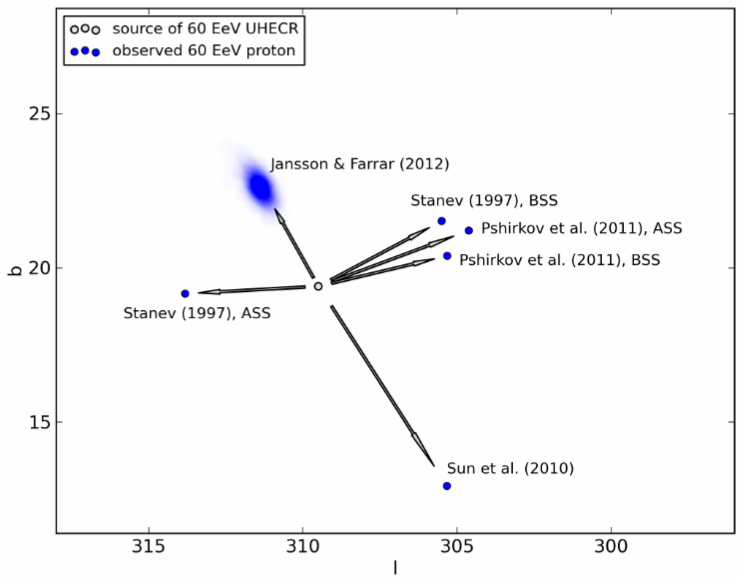


Figure 2. Combined cosmic ray anisotropy of the Tibet-AS and IceCube experiments in the equatorial coordinate system. Image credit and detailed information: M. Ahlers and P. Mertsch [30].

Another observable: UHECRs

- Charged UHECRs deflected in B.
  - Need to know B to find sources. *Or:*
- If you know the sources, you can infer B from the UHECRs.



UHECR sources and B-field models
(Farrar et al., JCAP 01, 023 , 2013)

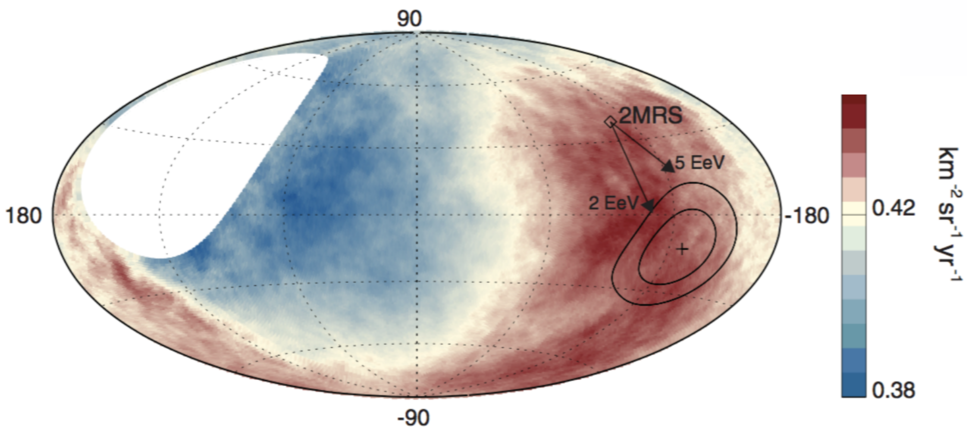


Figure 8. Sky map in galactic coordinates showing the cosmic ray flux as measured by the Pierre Auger Observatory for $E > 8$ EeV smoothed with a 45° top-hat function. The Galactic centre is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected for the JF12 GMF model on particles with $E/Z = 2$ or 5 EeV. Image credit: Pierre Auger Collaboration [149].

What don't we know?

(The known unknowns.)

- Where, how, and why do the fields reverse and what does it tell us about Galactic dynamos?
- To what degree does the coherent field orientation follow the material spiral structure and why?
- What is the morphology of the 'halo' field component, e.g., is it x-shaped, with what scale height, with what (anti-)symmetry?
- What is the physical origin of the anisotropy in the turbulence, e.g., shocks or differential rotation?
- To what degree is the polarized emission measured (either synchrotron or dust) on the full sky affected by local structures like the NPS?
- ...