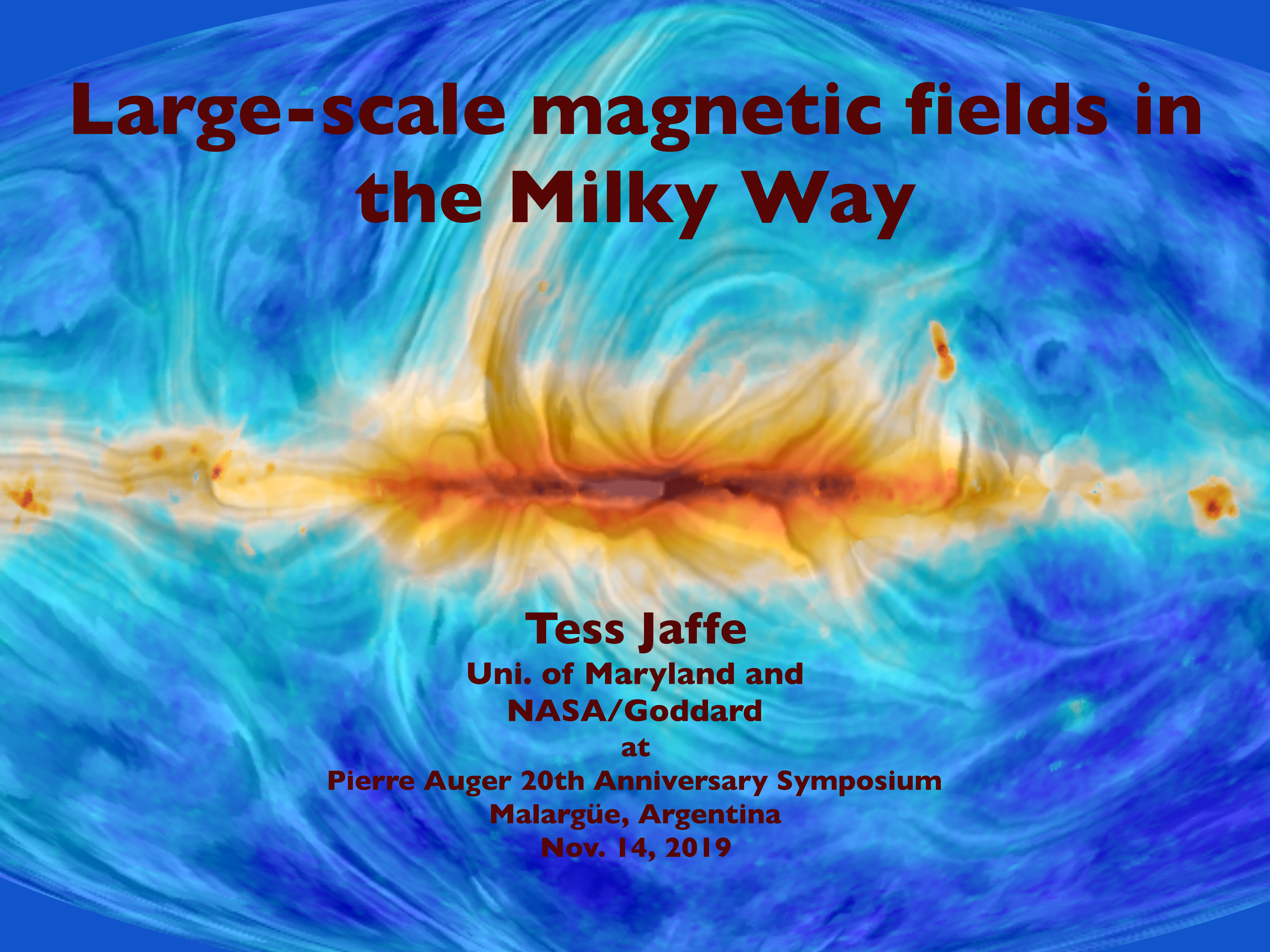


Large-scale magnetic fields in the Milky Way

Tess Jaffe
Uni. of Maryland and NASA/Goddard

at
Pierre Auger 20th Anniversary Symposium
Malargüe, Argentina
Nov. 14, 2019

Why am I here?

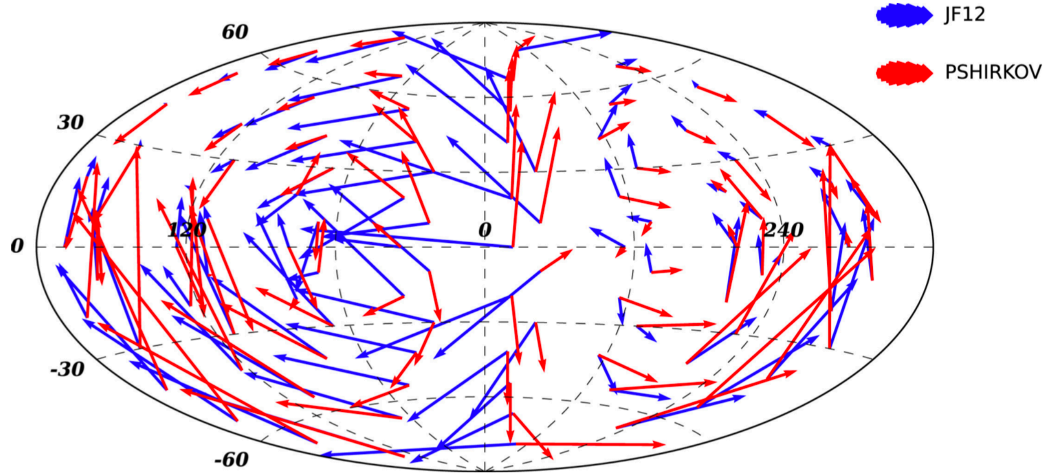
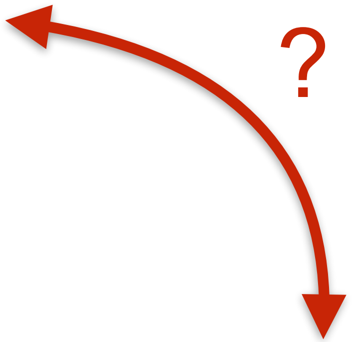


Figure 13. Comparison of deflection angles of UHECRs with rigidity $E/eZ = 10\,\text{EV}$ predicted by two published models of the GMF: Pshirkov et al. [200] and Jansson & Farrar (JF12) [71]. Image credit: S. Mollarach and E. Roulet [145].



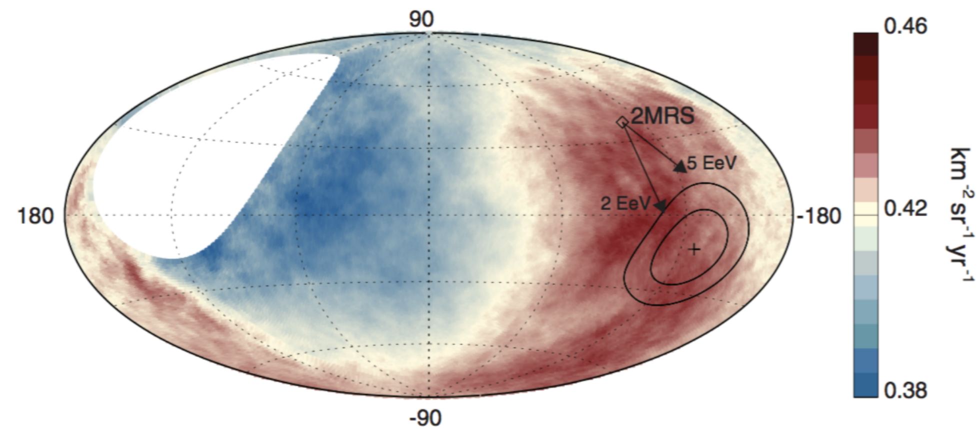
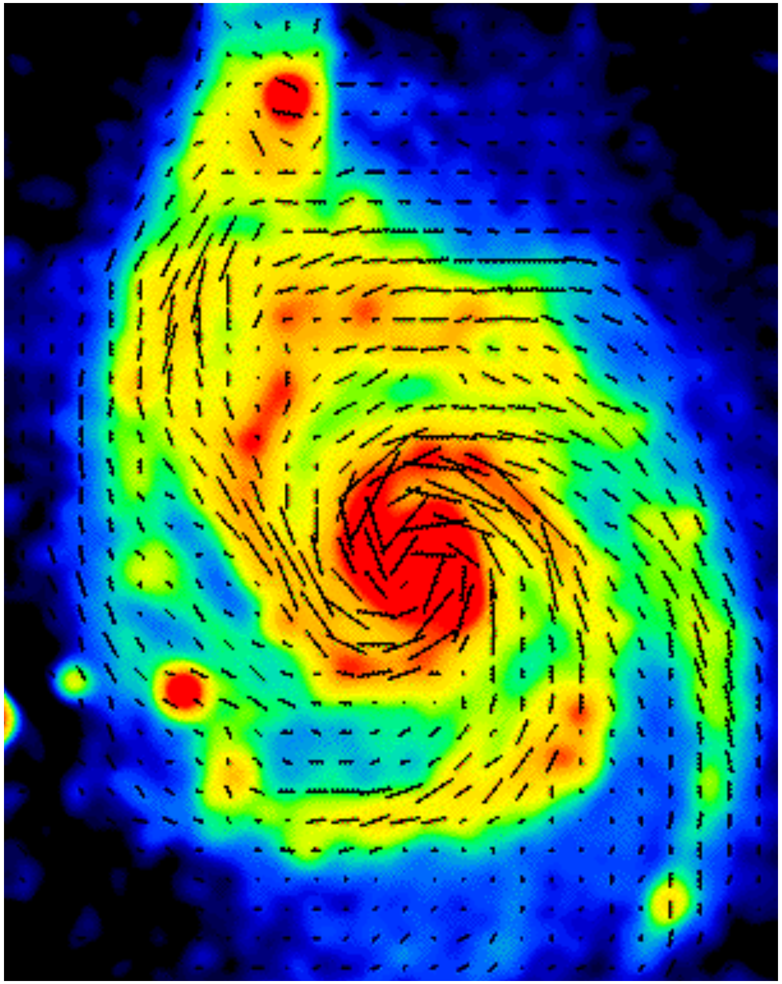


Figure 8. Sky map in galactic coordinates showing the cosmic ray flux as measured by the Pierre Auger Observatory for $E > 8\,\text{EeV}$ smoothed with a 45° top-hat function. The Galactic centre is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% 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 $5\,\text{EeV}$. Image credit: Pierre Auger Collaboration [149].

Pierre Auger Collaboration, 2017, *Science*, 357, 6357, p1266

External galaxies: one example

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

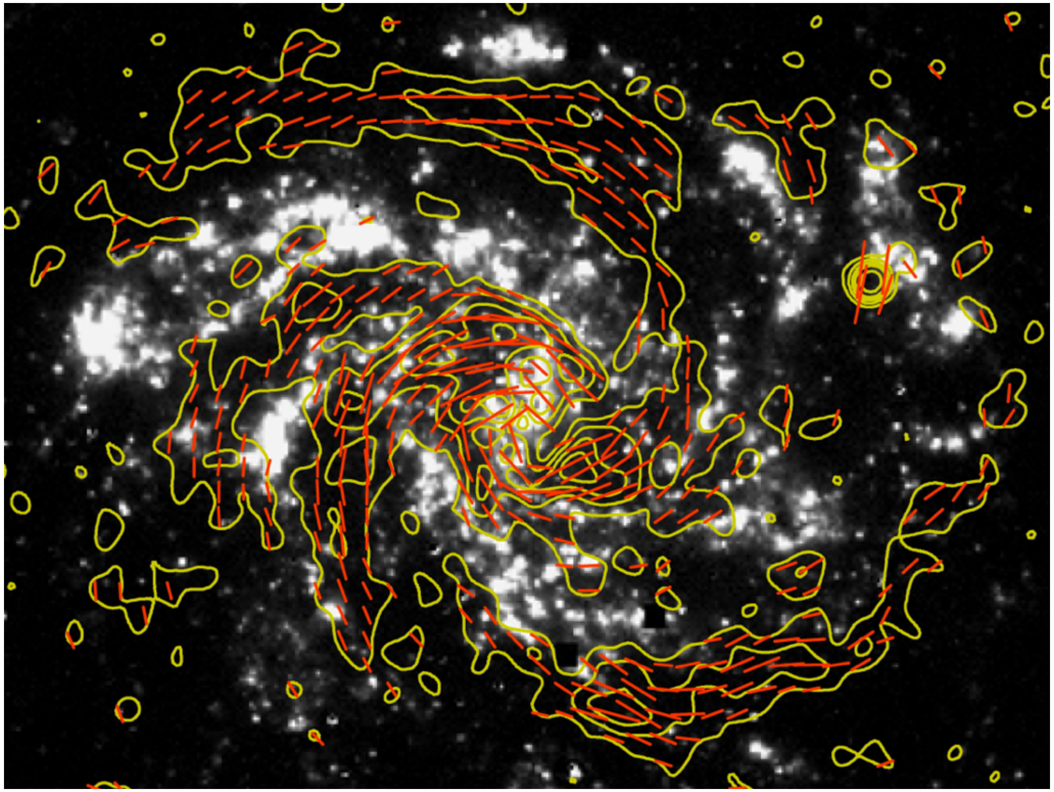


(Obligatory M51 image)

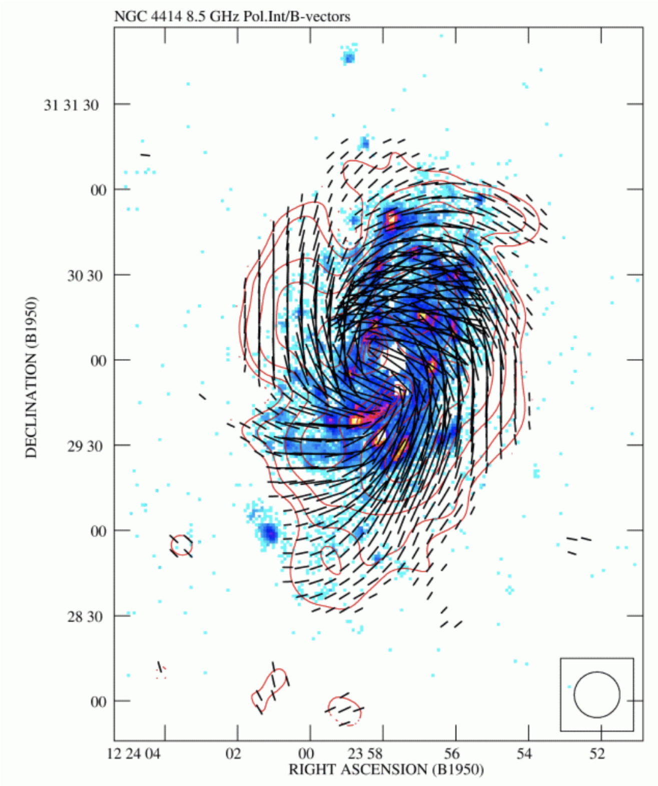
- First order: magnetic fields aligned with matter spiral structure. Can't be coincidental.
- Unfortunately, we cannot see our own galaxy like this.
- And it's a lot more complicated than this picture.

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

External galaxies: other examples



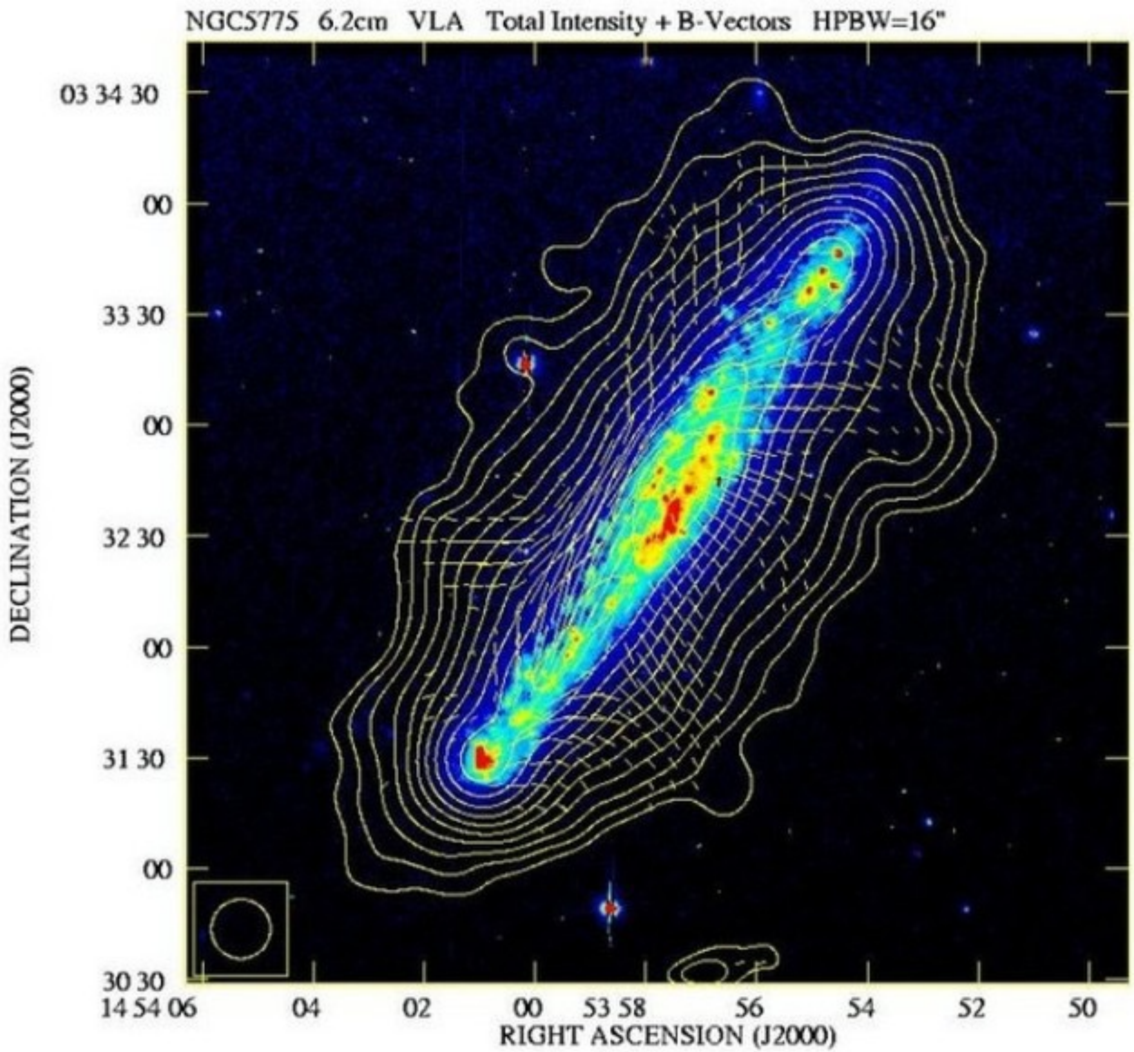
NGC6946 6cm PI over Hα (Copyright R. Beck, MPIfR)



(Soida et al. 2002)

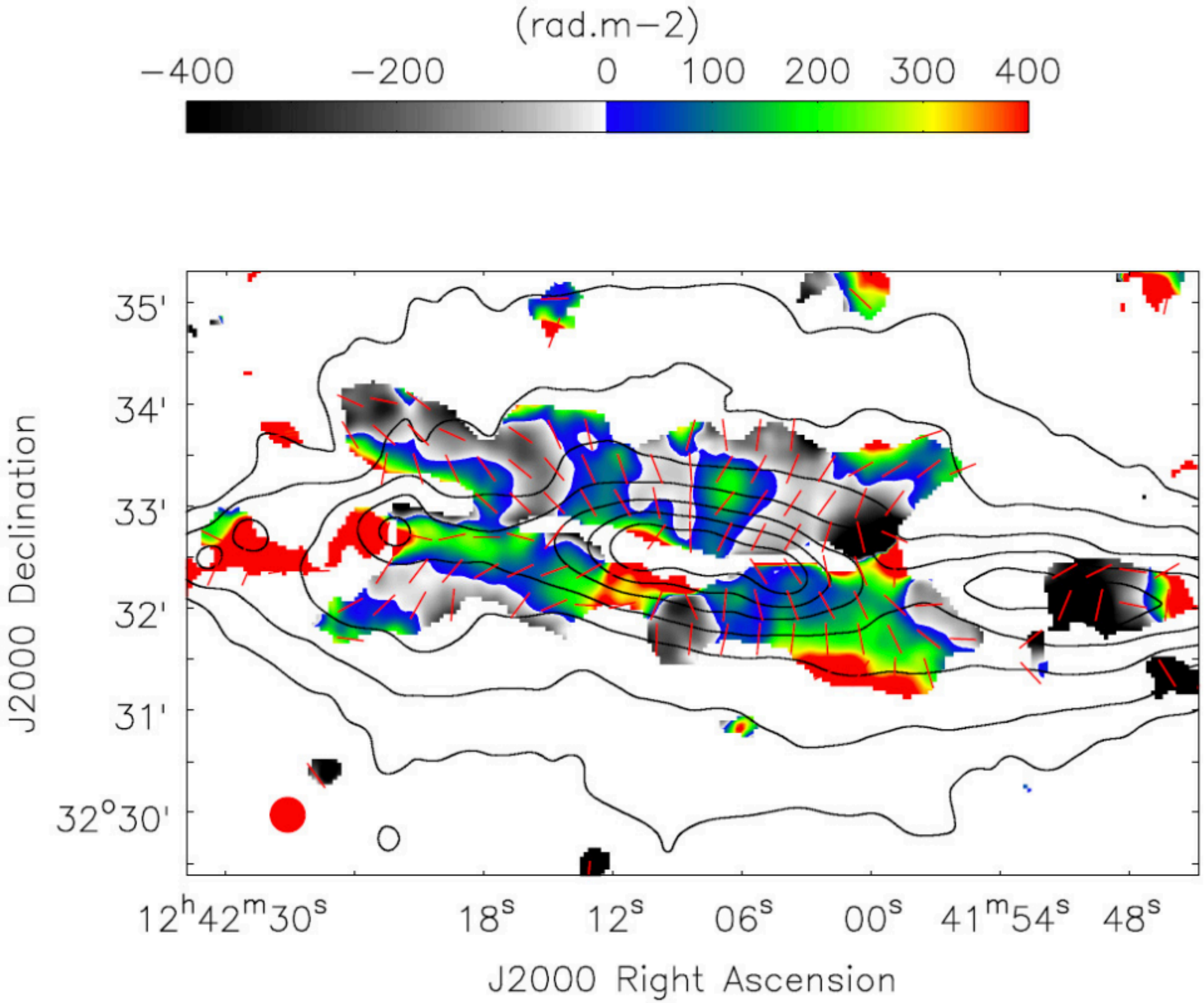
A variety of morphologies observed, and we cannot assume a relationship with other matter tracers.

External galaxies: vertical field



External galaxies: vertical field

"magnetic ropes"?



Mora-Partiarroyo et al., *A&A*, 2019, CHANG-ES XV: Large-scale magnetic fields in the halo of NGC 4631

External galaxies: halo transition(s)?

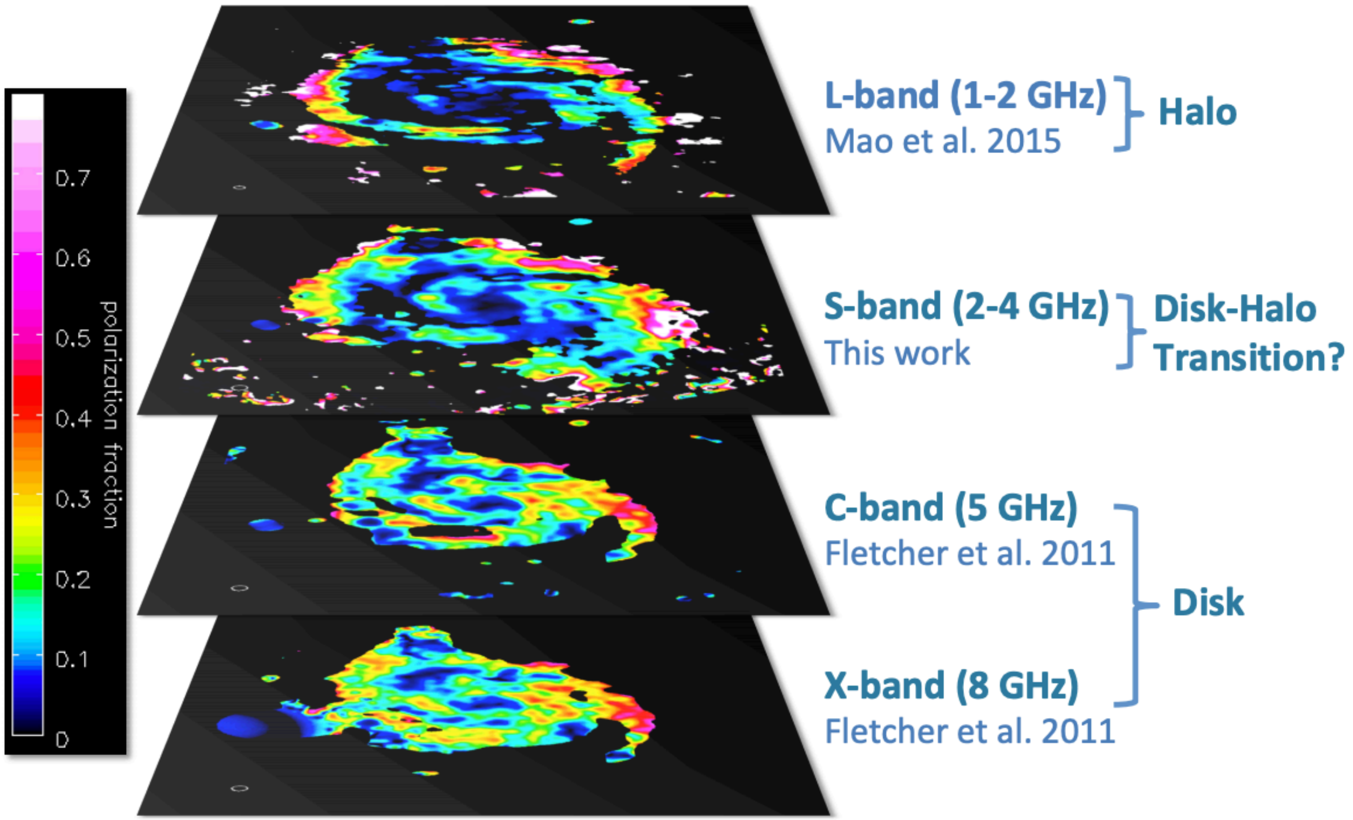


Figure 1. Observed degree of polarization of M51 at different frequencies. All images have the same color scale and are smoothed to the same resolution of 15 arcsec (which corresponds to about 550 pc at the distance of M51). Note that the total intensity images used to calculate the degree of polarization were not corrected for thermal emission.

Kierdorf et al. (2018)

Particularly the axi- versus bi-symmetric spirals seen at different heights,

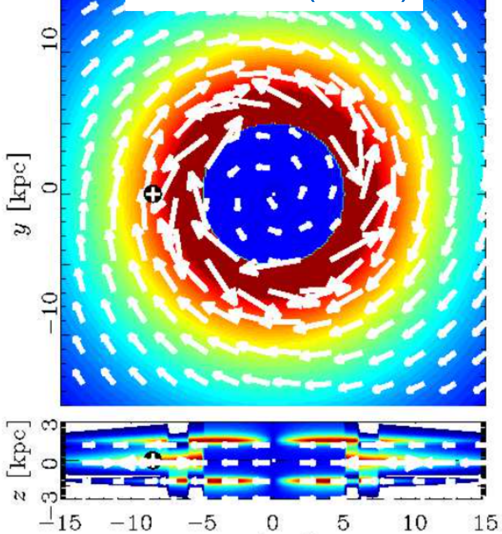
Milky Way

- So where are we in the Milky Way?
- We have all these possible complexities.
- Challenges:
  - We are in the disk and looking through it.
  - Unique challenge of projection onto full-sky.
- Advantages:
  - More 3D info.
  - Better spatial resolution.

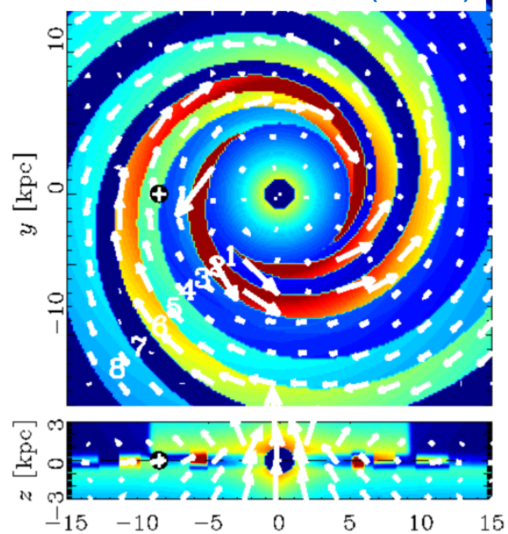
The state of the art

- Very different morphologies can roughly match the same(ish) observables.

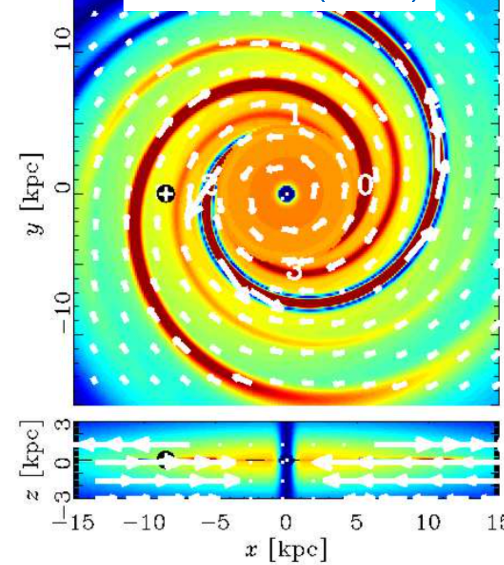
Sun et al. (2010)



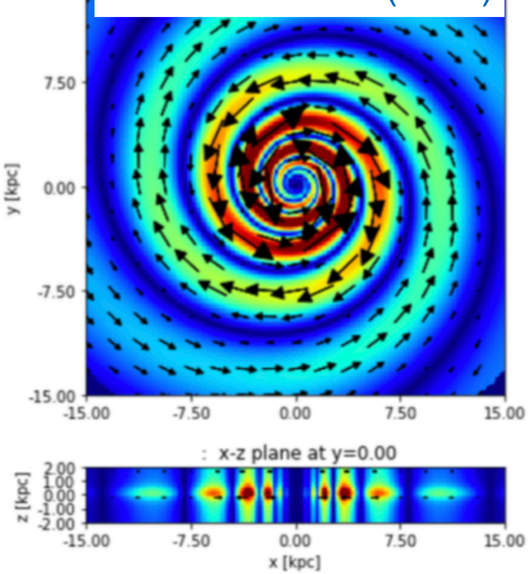
Jansson & Farrar (2012)



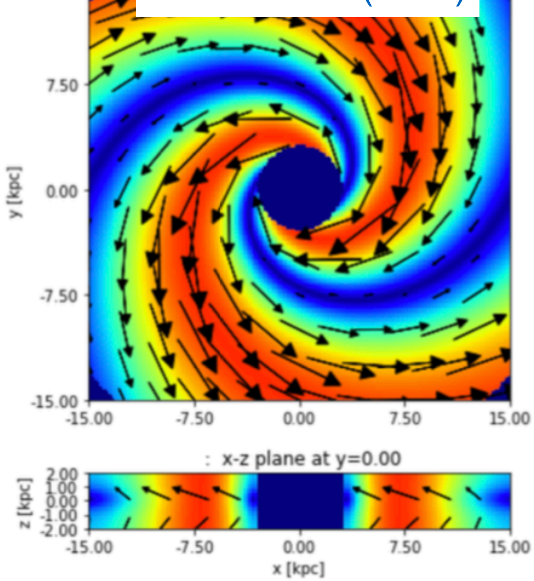
Jaffe et al. (2013)



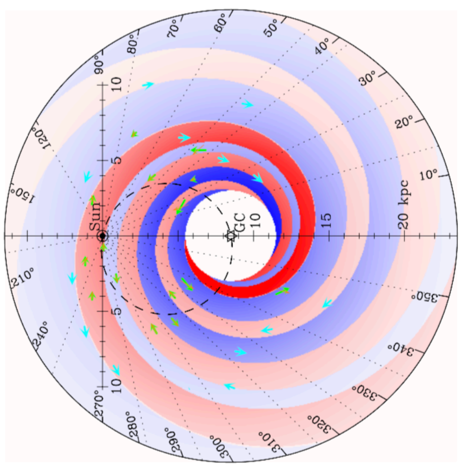
Kachelreiß et al. (2007)



Fauvet et al. (2011)

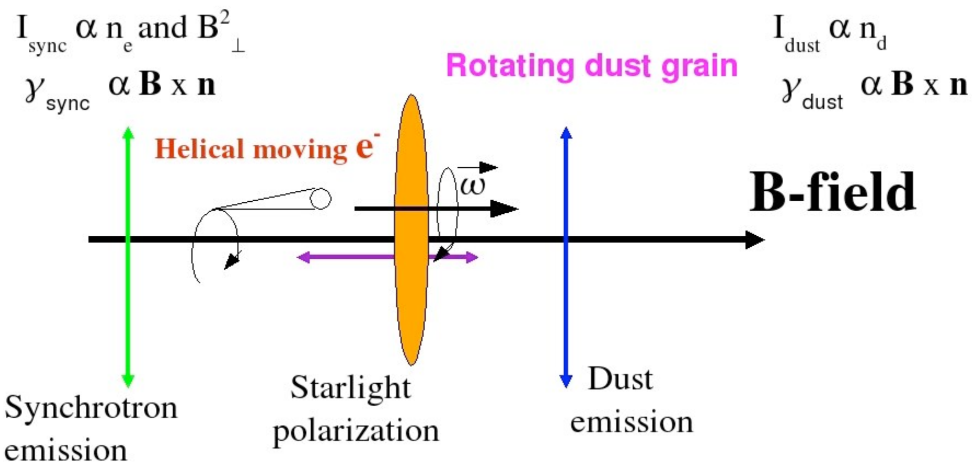


Han et al. (2017)

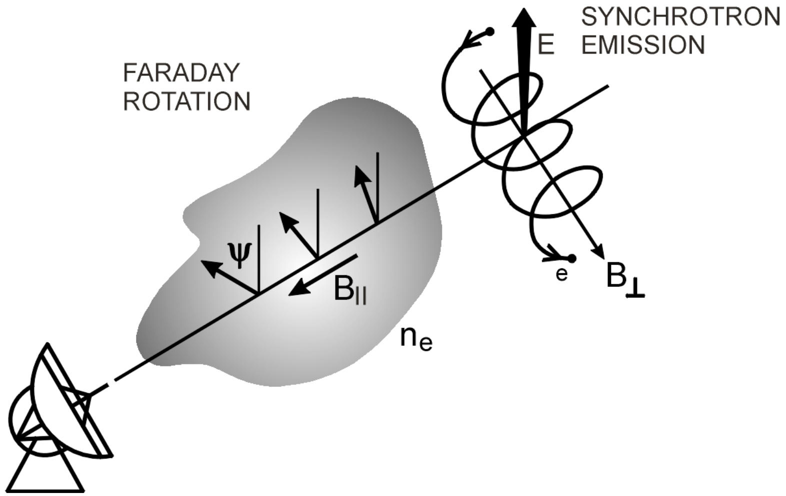


Physics of the observables

- 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, **3D** with pulsar distances
- 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….

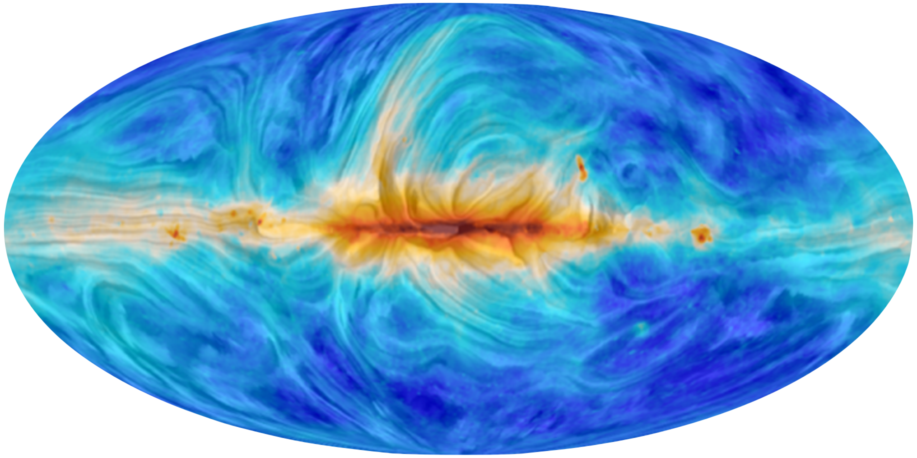


(Courtesy J.F. Macías-Pérez)

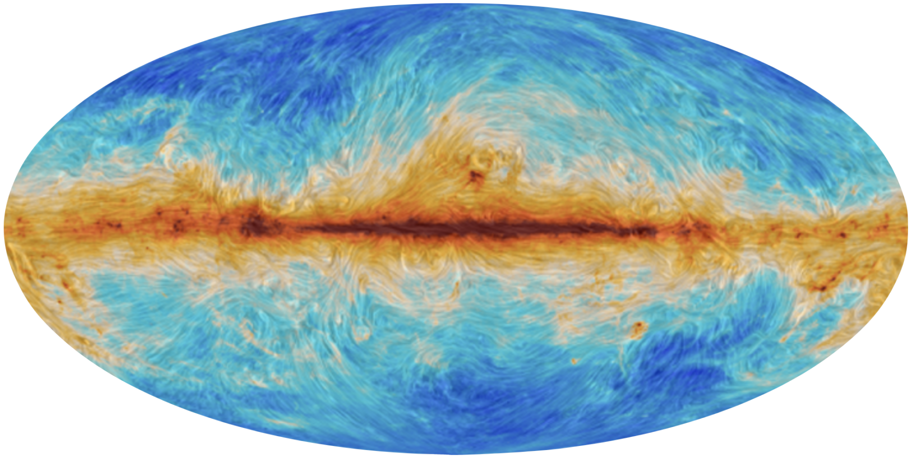


(Courtesy R. Wielebinski)

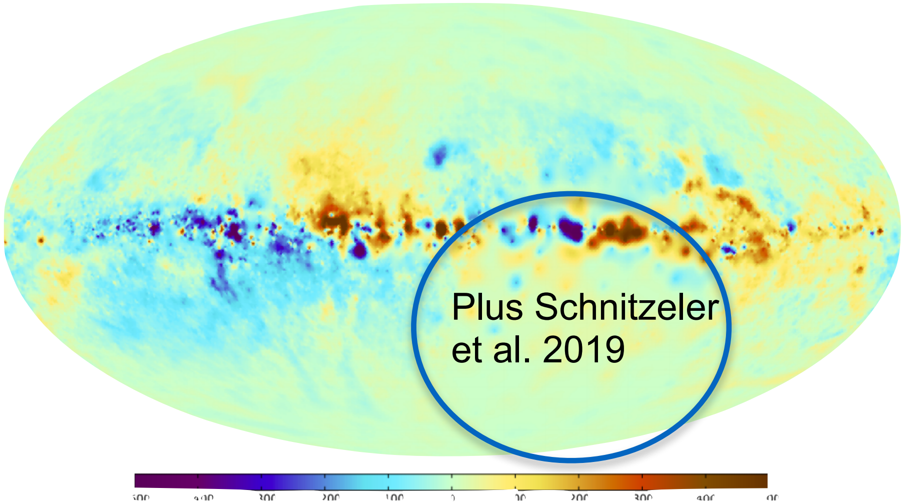
Data



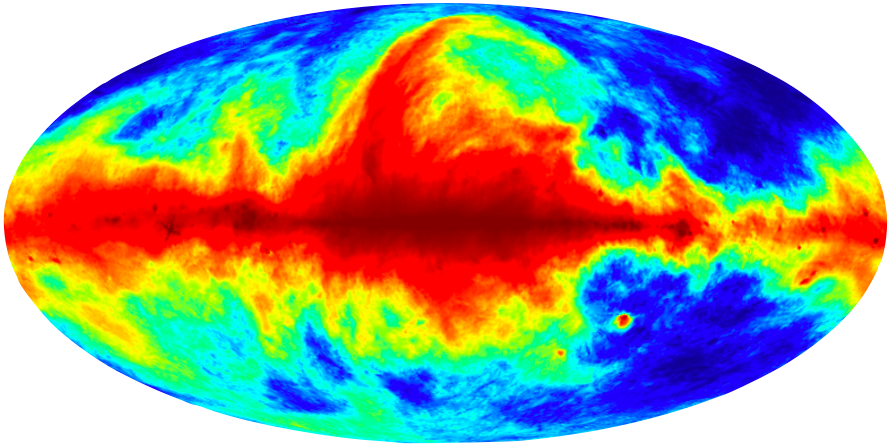
30 GHz polarized synchrotron (ESA, Planck Collaboration)



353 GHz polarized dust (ESA, Planck Collaboration)

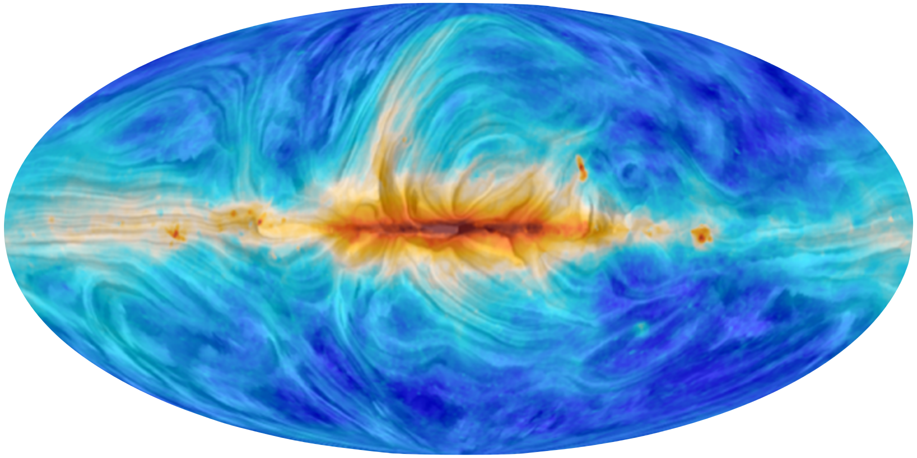


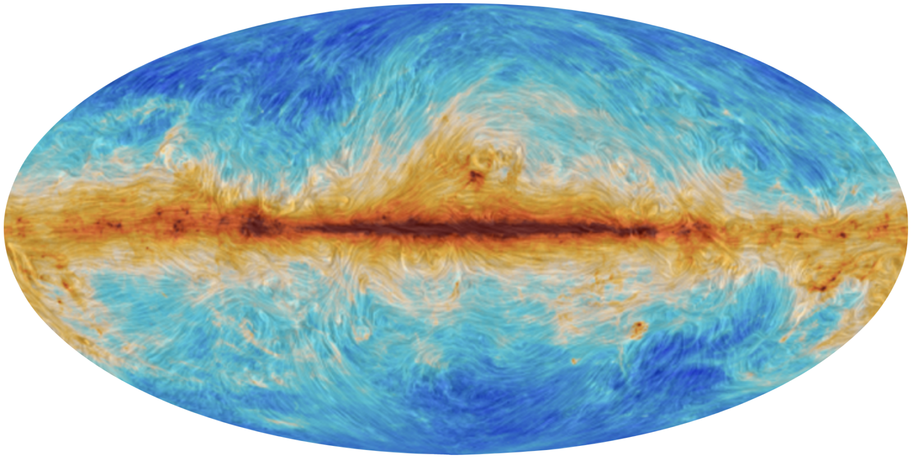
Faraday depth (rad/m^2)
(Oppermann et al. 2012)



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

Data

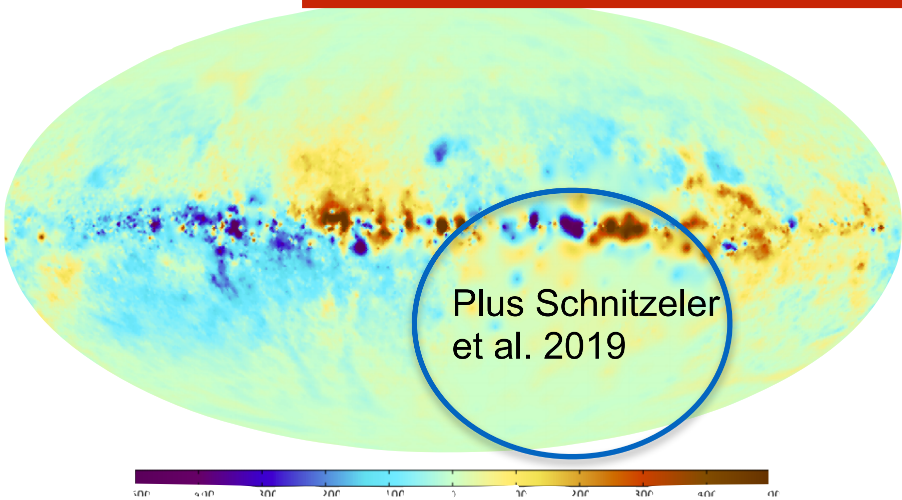




30 GHz polarized

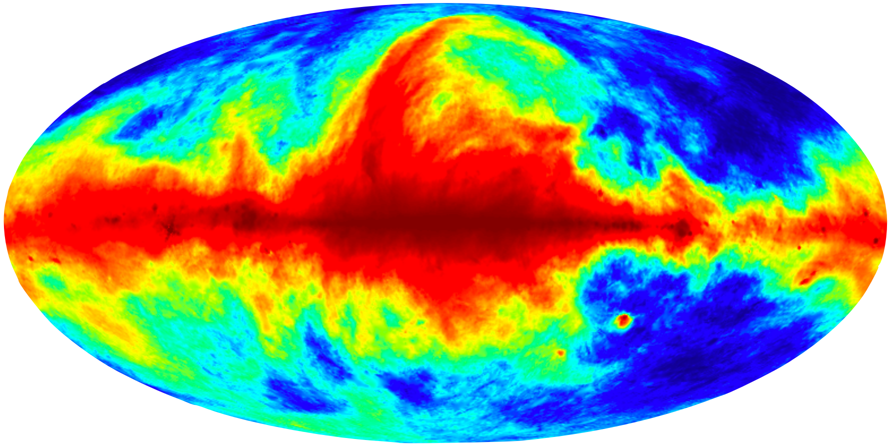
Unique challenges to full-sky analysis due to projection and beam!

ation)



Plus Schnitzeler et al. 2019

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



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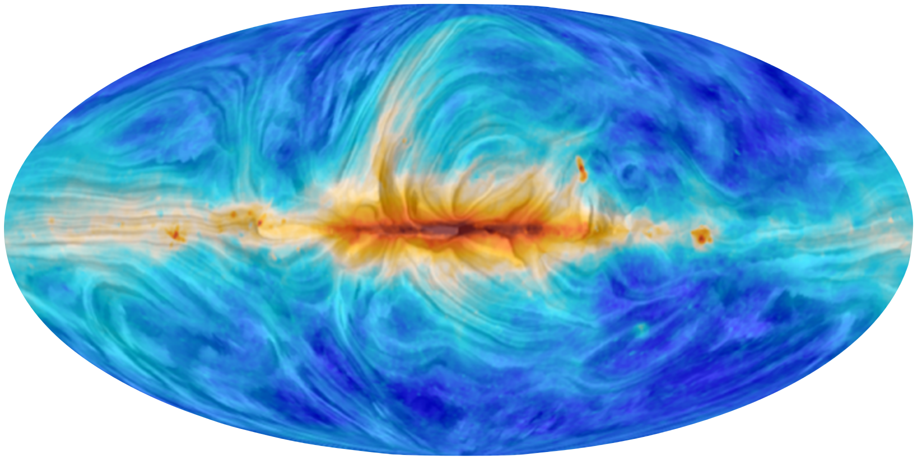
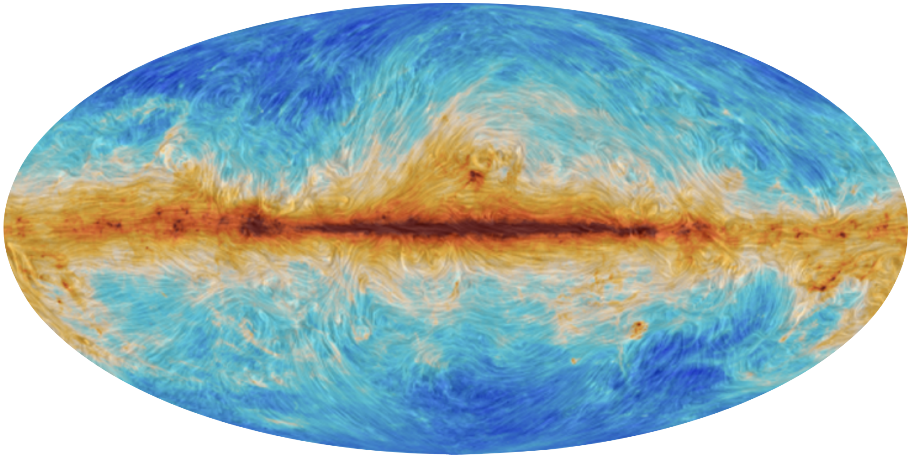
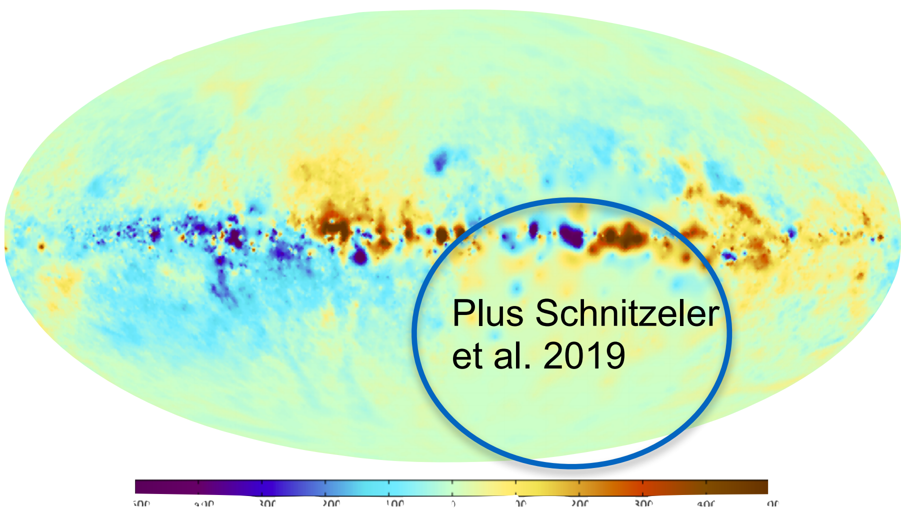


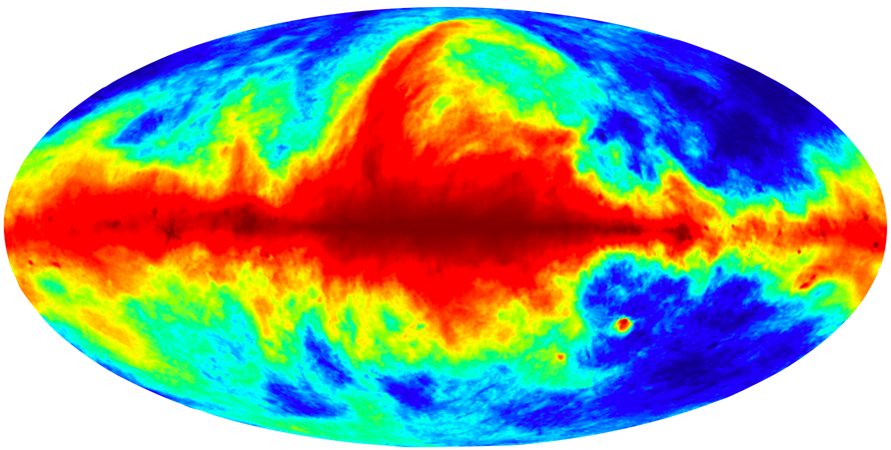
30 GHz polarized synchrotron (ESA, Planck Collaboration)



353 GHz polarized dust (ESA, Planck Collaboration)



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



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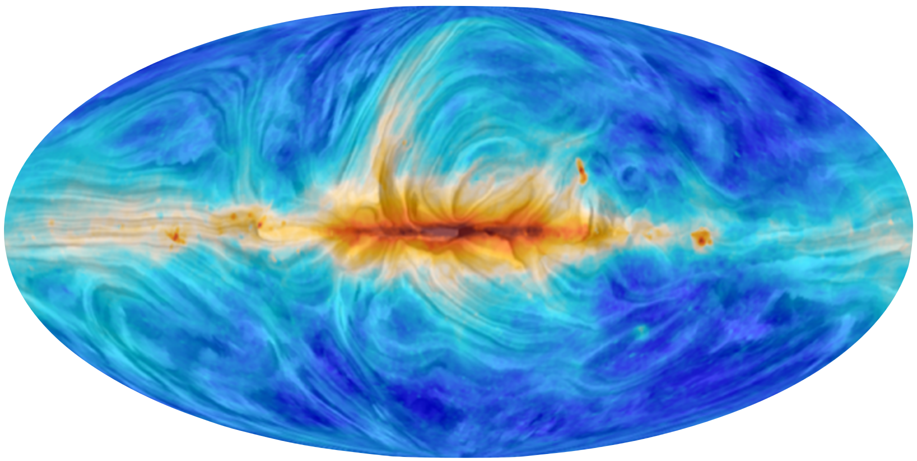
Data



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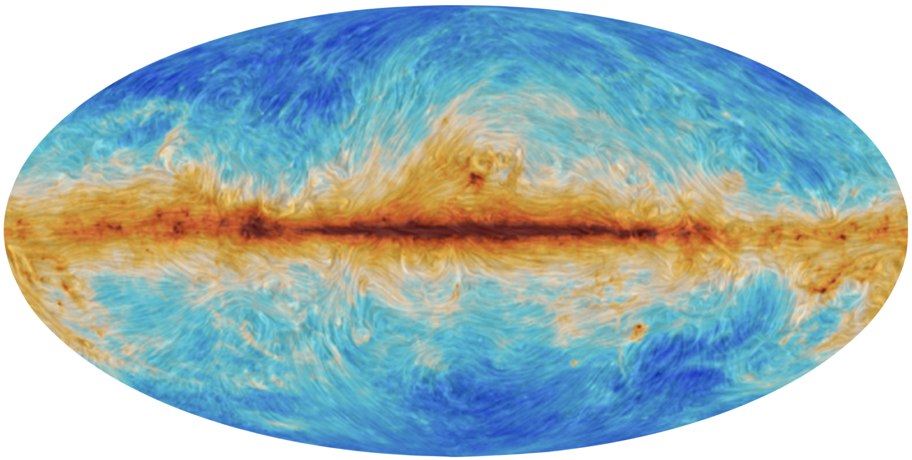
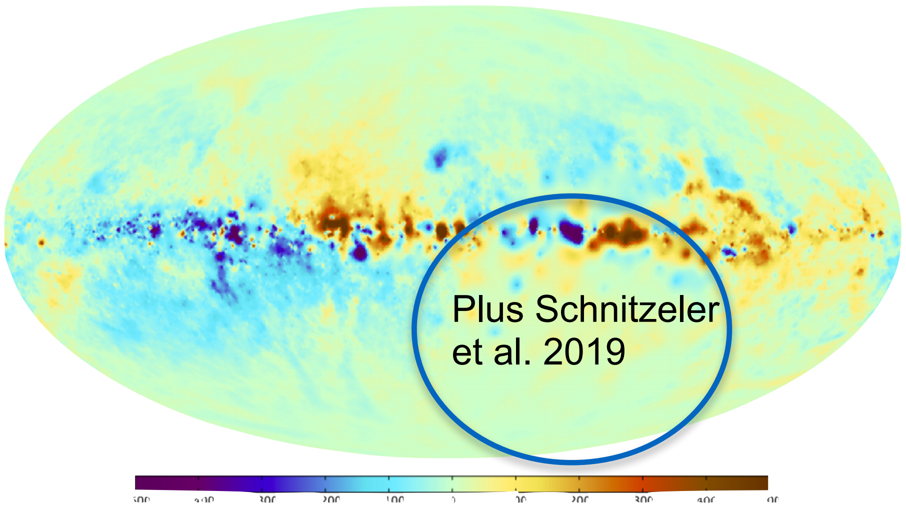


353 GHz polarized dust (ESA, Planck Collaboration)



Faraday depth (rad/m^2)
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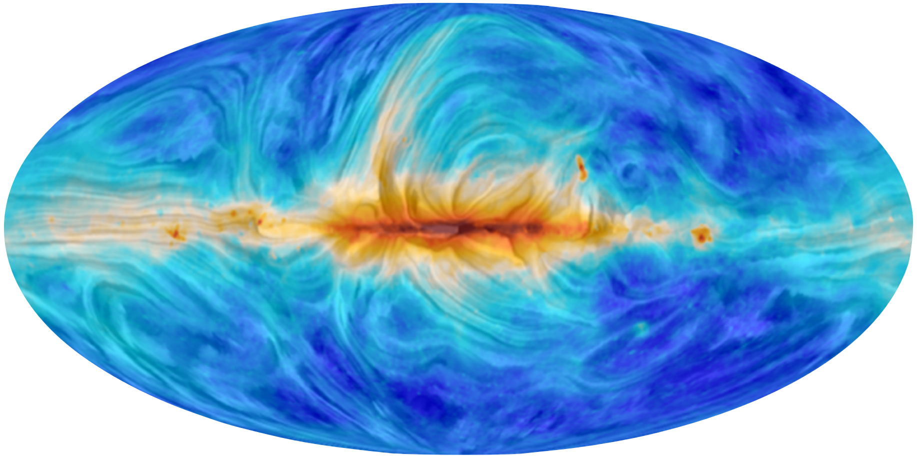
Data



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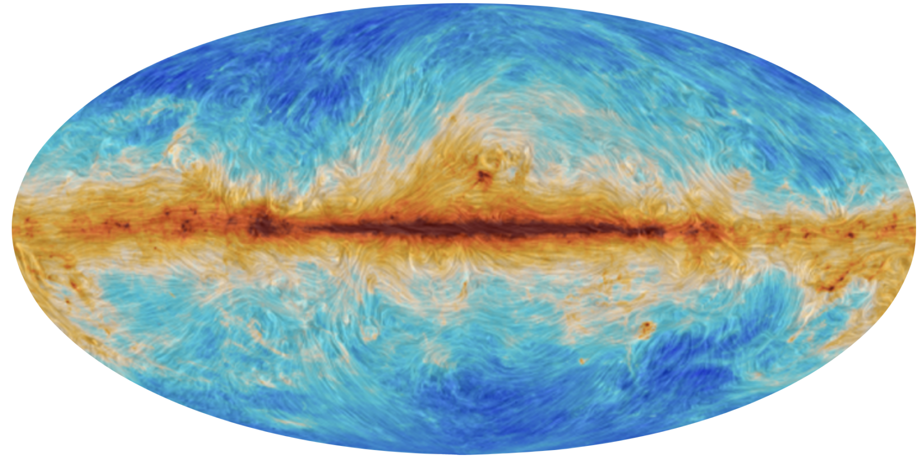
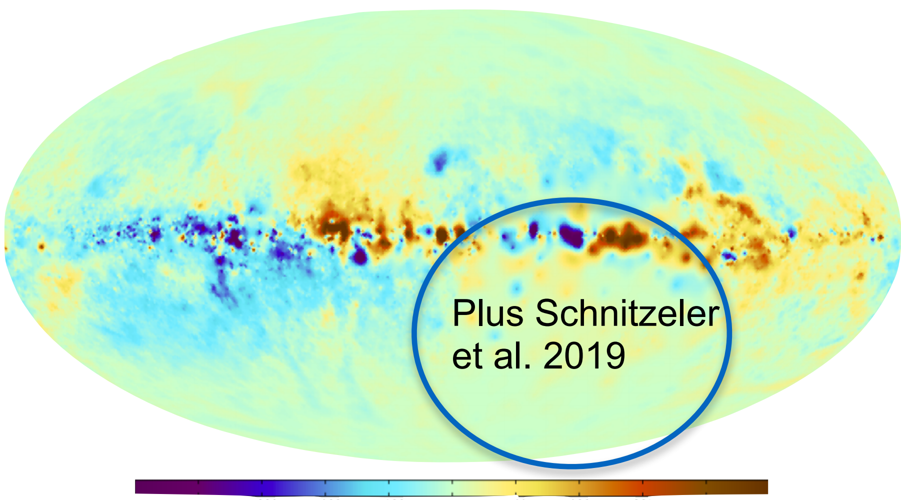
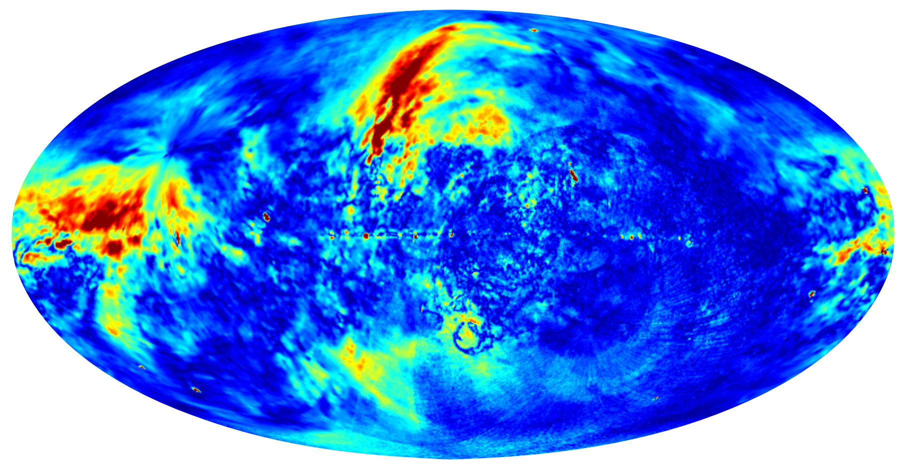


353 GHz polarized dust (ESA, Planck Collaboration)

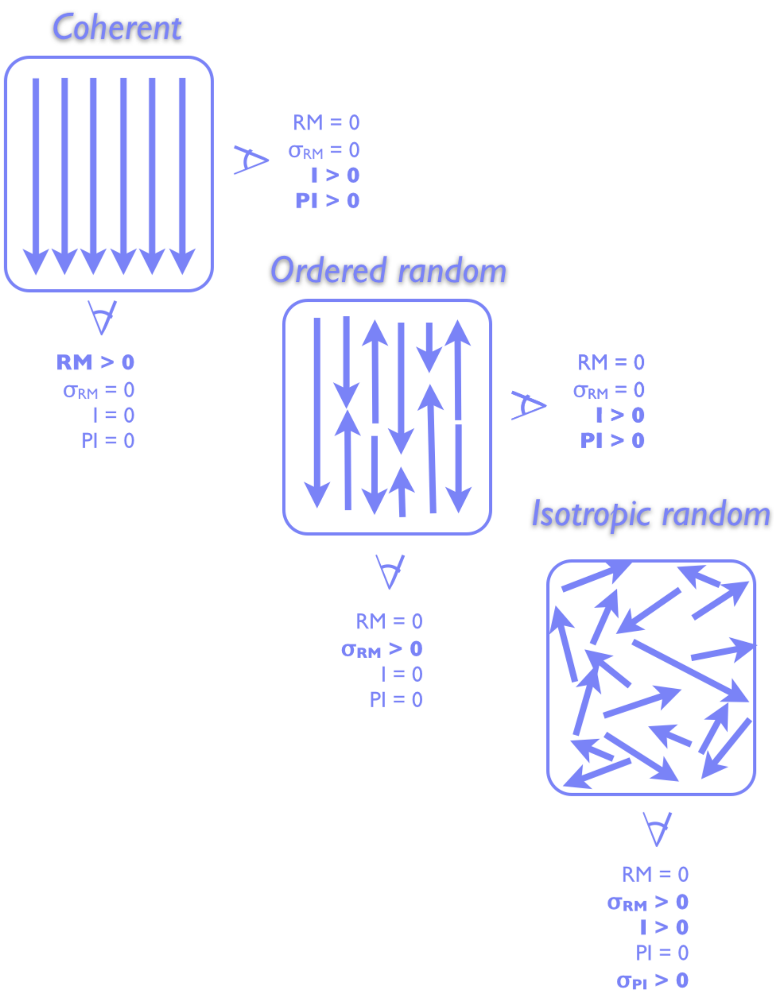


Faraday depth (rad/m²)
(Oppermann et al. 2012)

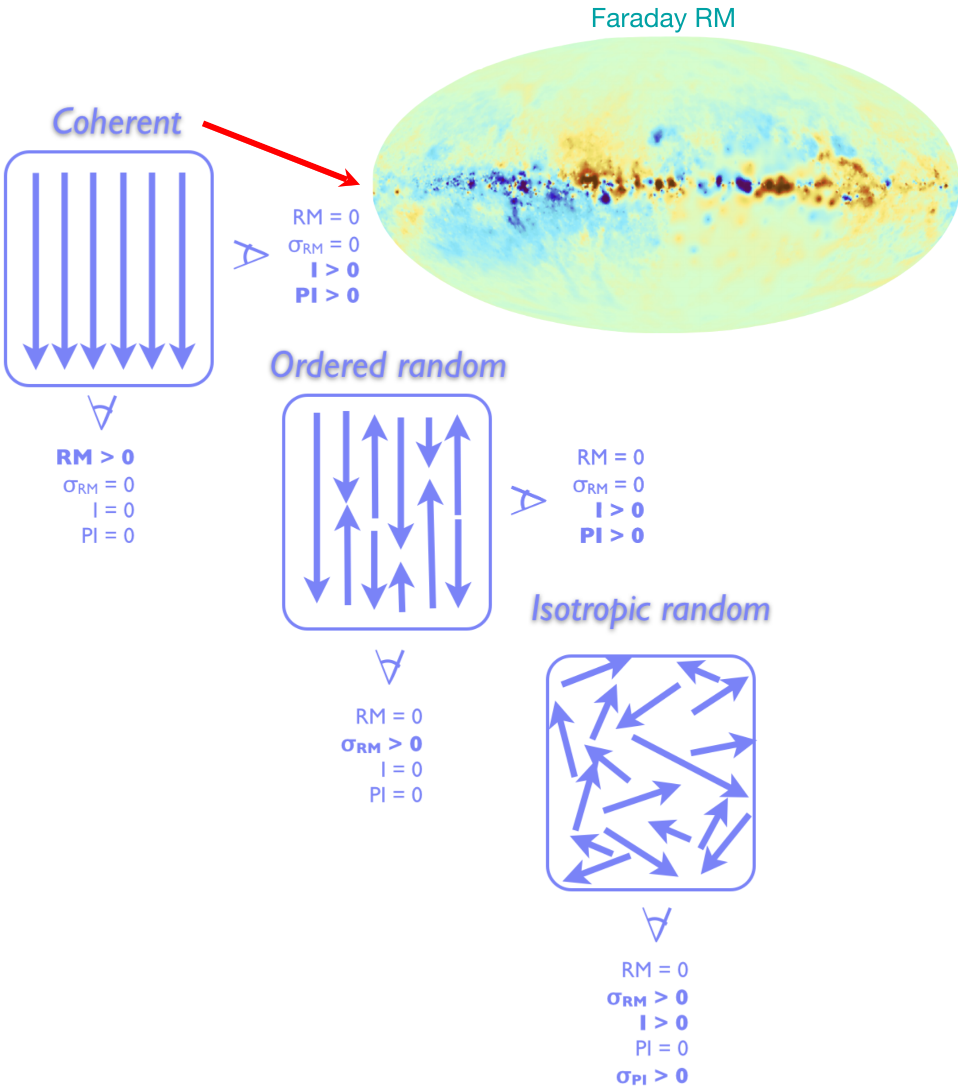


1.4 GHz polarized synchrotron (Reich 1982, Wolleben et al. 2006, Testori et al. 2008)

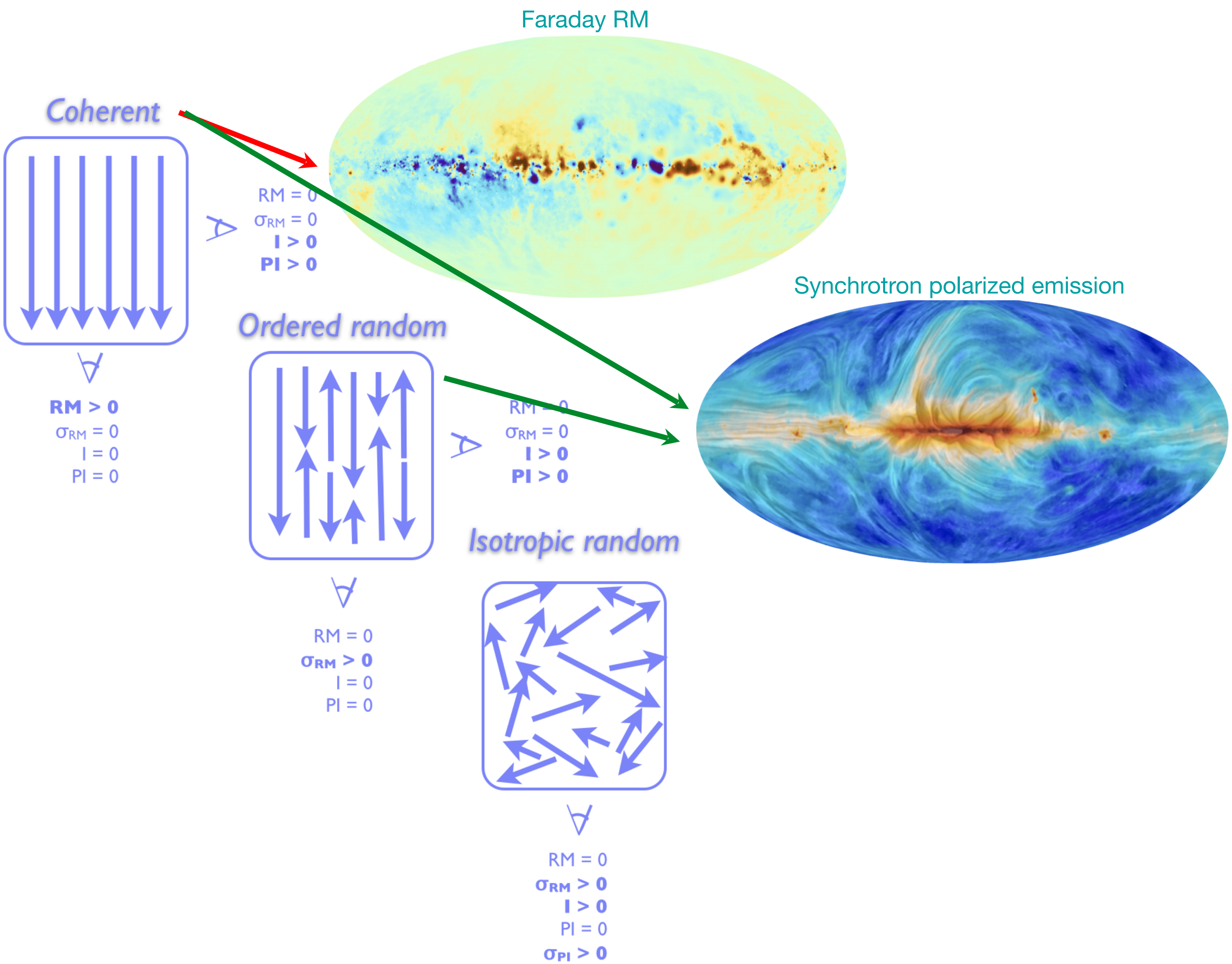
Components of the GMF



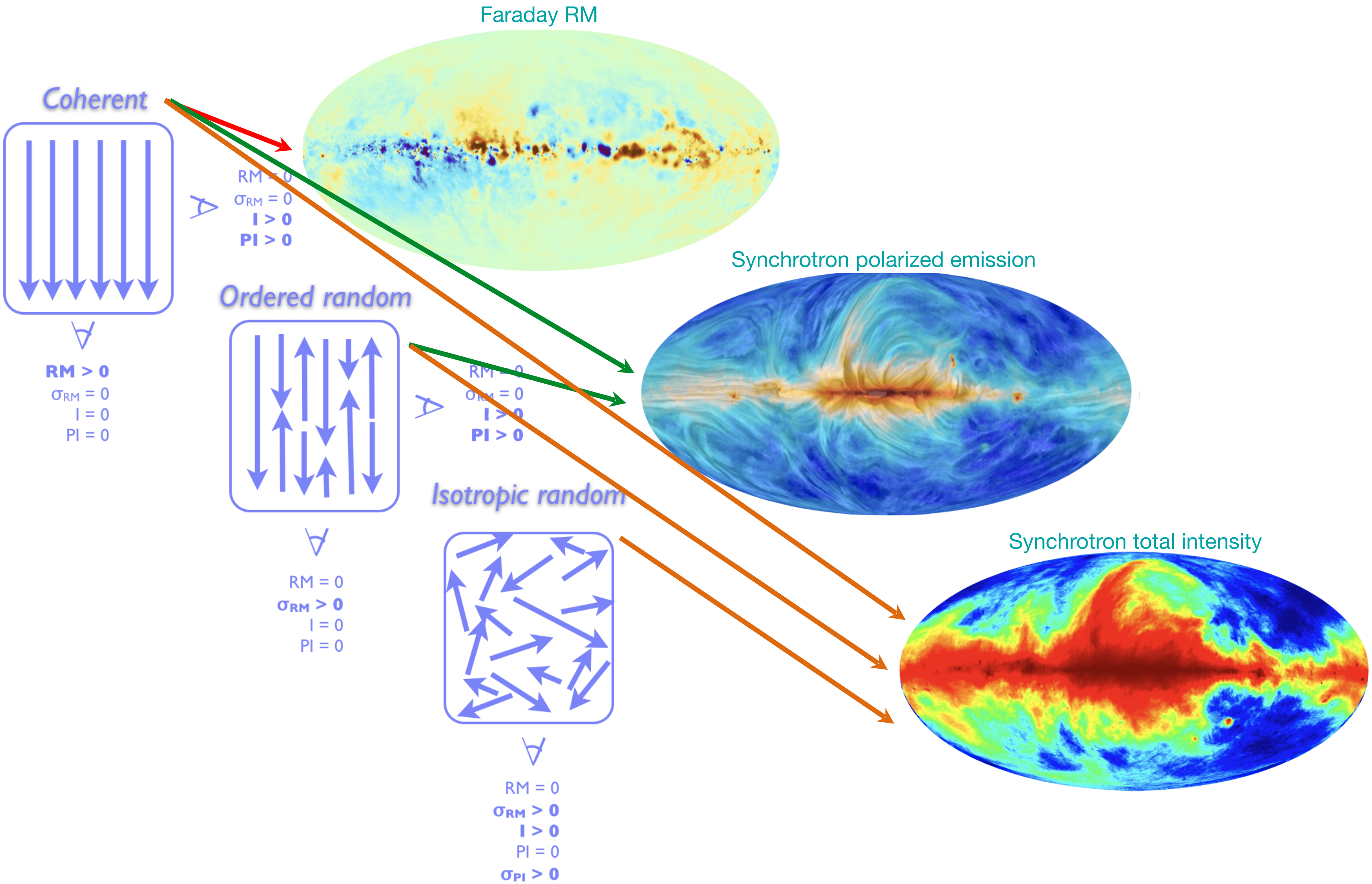
Components of the GMF



Components of the GMF



Components of the GMF



A few of the problems with the state of the art

- **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.

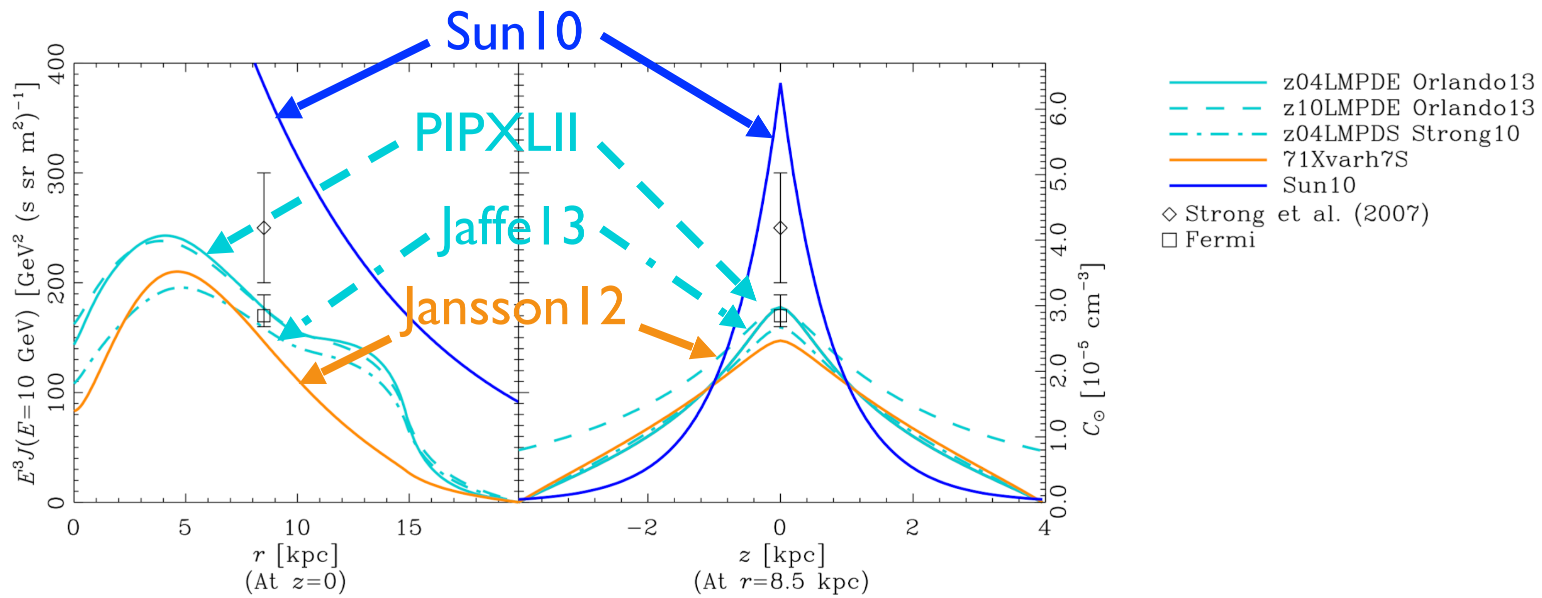
Planck Planck Intermediate Results XLII (2016, “PIPXLII”) showed why all previous fits (including mine) are wrong.

Morphological components

- Axisymmetric spiral disks
  - Thick and thin? Pitch angles? How far up do CRs and B go?
- Magnetic arms
  - Variations in ordering? Relation with material?
- Reversals
  - Regions? Arms? Annuli?
- Vertical (poloidal) field
  - Pitch? Disk-halo transition? X-shaped? Reversed ropes?
- Turbulence
  - Progress on small-scales. Impact of simplistic modeling on large scales?
  - Plus many of the above questions independent for random fields!

Galactic (low-energy) CR spatial distribution?

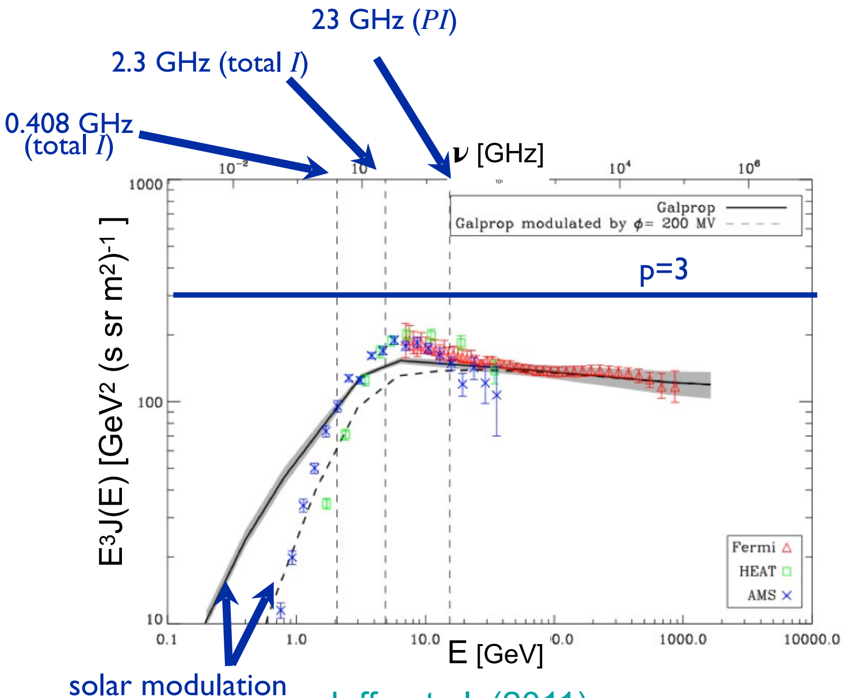
- Halos observed out to z~10 or 15 kpc!



(PIPXLII)

Galactic (low-energy) 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)

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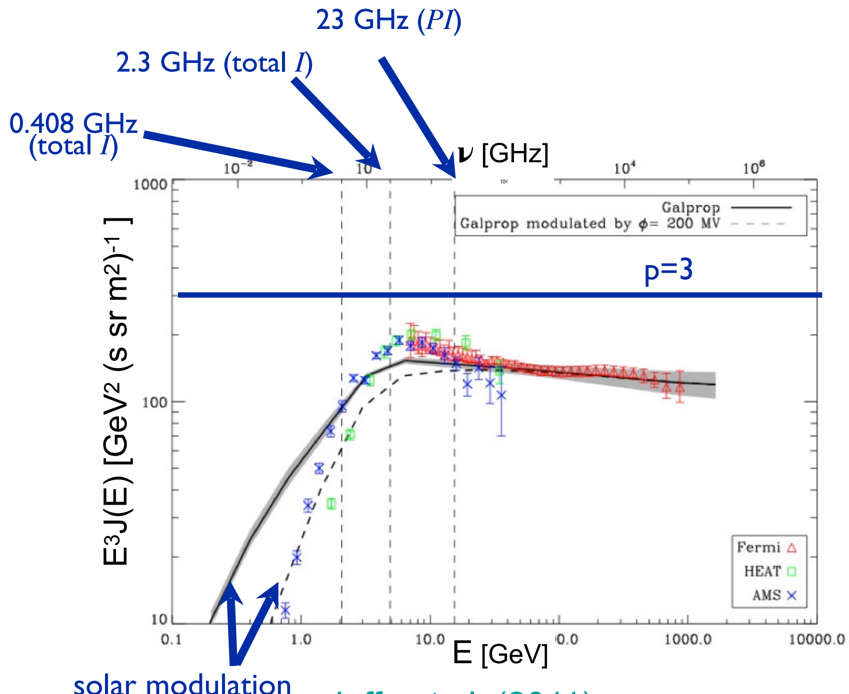

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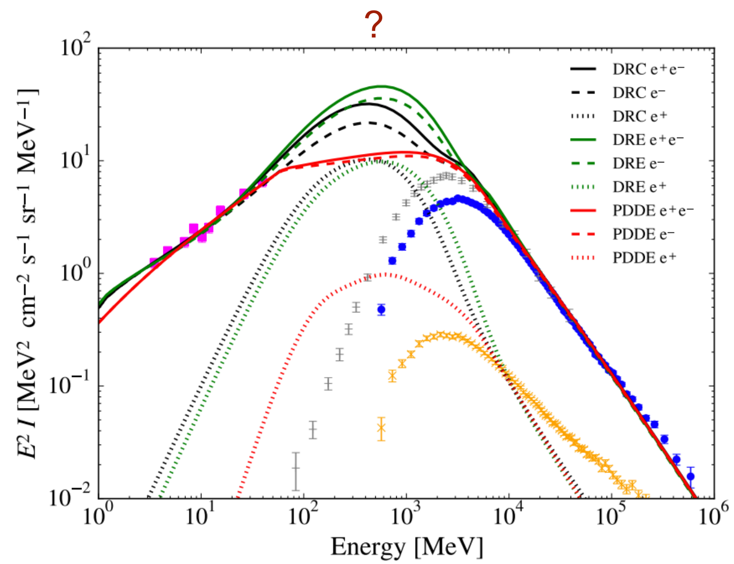

Figure 2. Propagated interstellar spectra of the three baseline models DRE (green line), DRC (black line), and PDDE (red line) for positrons (dotted lines), electrons only (dashed lines), and all-electrons (solid lines) compared with data: orange crosses: AMS-02 positrons (Aguilar et al. 2014); blue points: AMS-02 electrons (Aguilar et al. 2014); grey dashes: PAMELA electrons (Adriani et al. 2015); magenta squares: *Voyager 1* all-electrons (Cummings et al. 2016).

Orlando (2018)

Galactic (low-energy) CR spectral distribution?

GMF <=> n_cr(E)
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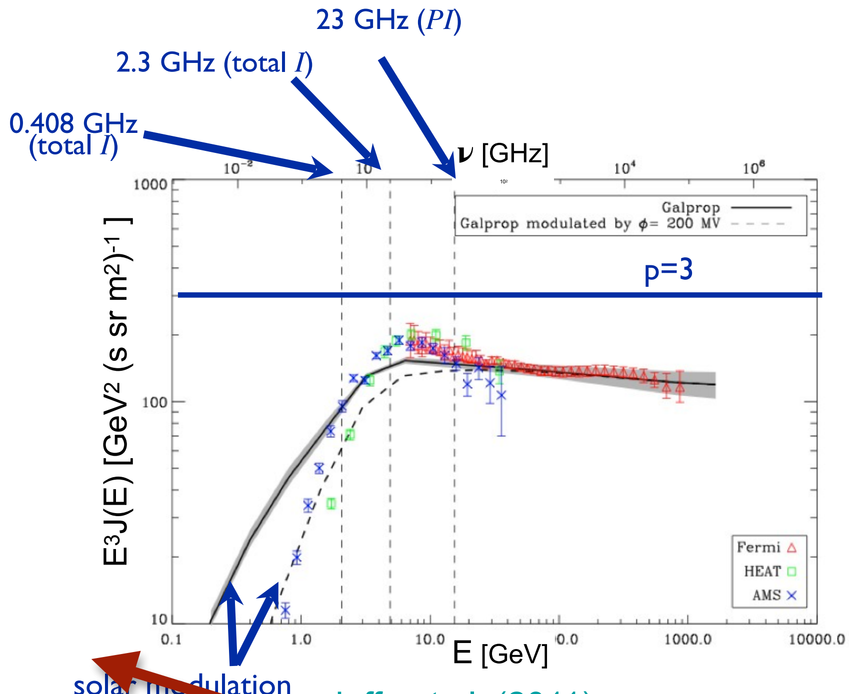

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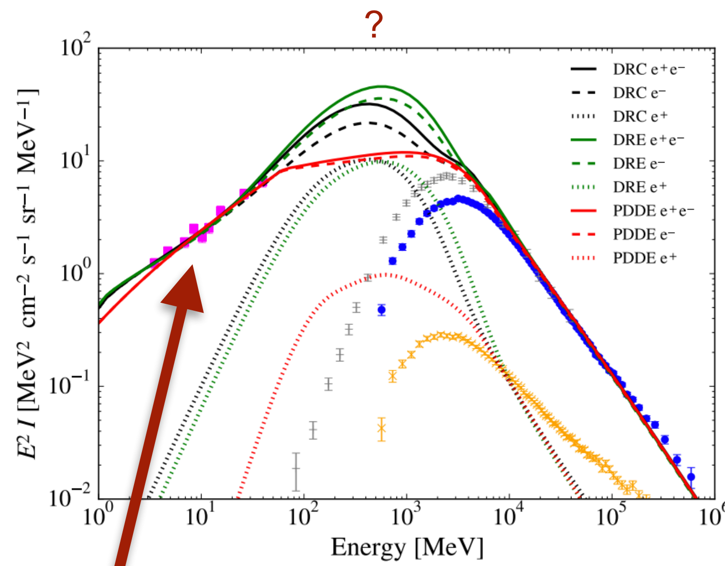

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Orlando (2018)

Voyager!

Another view of the state of the art

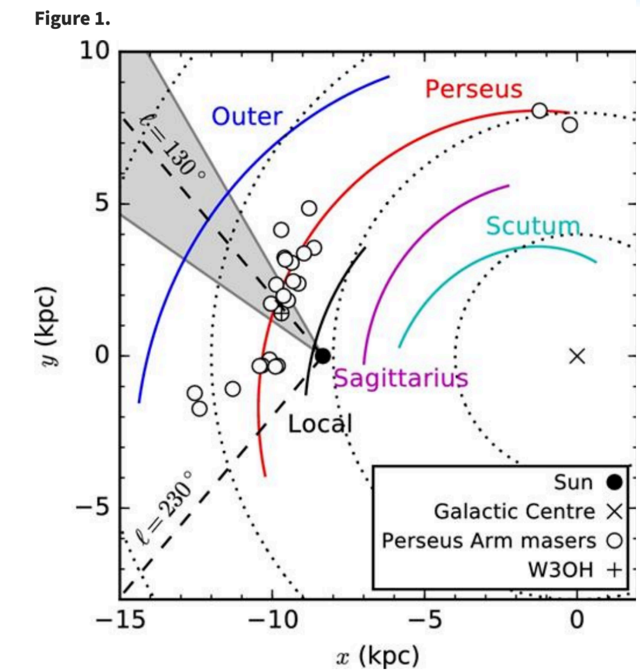
- ➢ Unger and Farrar (2017) have made a good start at comparing the different models:

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

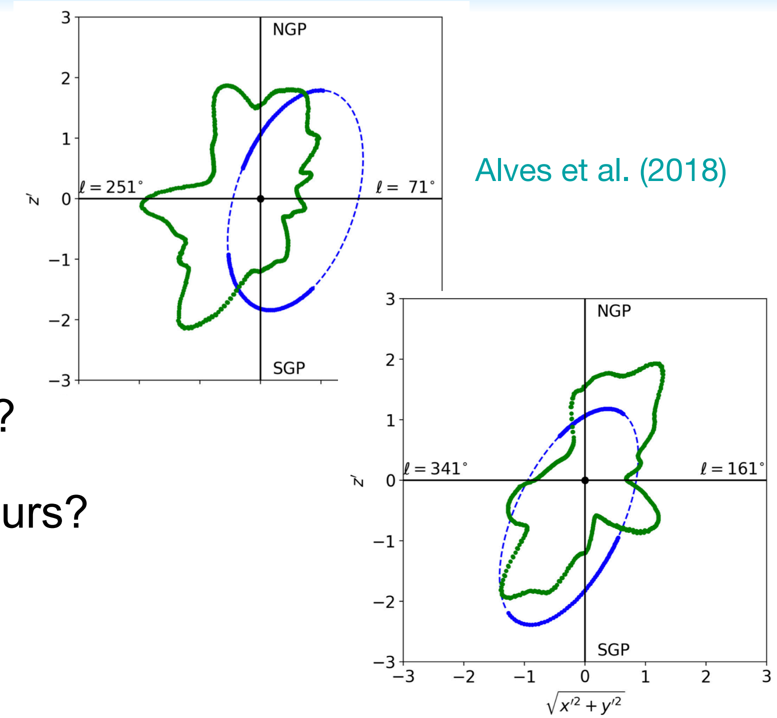
Table 1: Summary of model variations investigated in this paper. The original JF12 model corresponds to the first row (model a) and the reference model is given in the third row (model 3). The goodness of fit for describing the RM, Q and U data is given in the last column with the exception for the combined 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)

How do local features affect fitting?

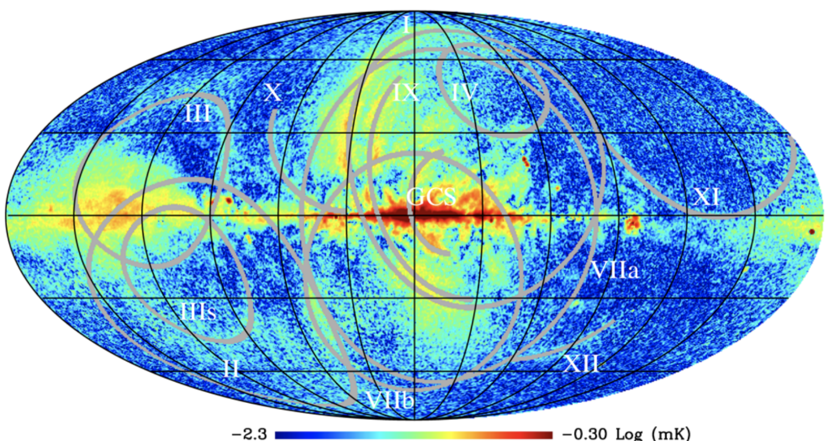


Hill et al. (2015)

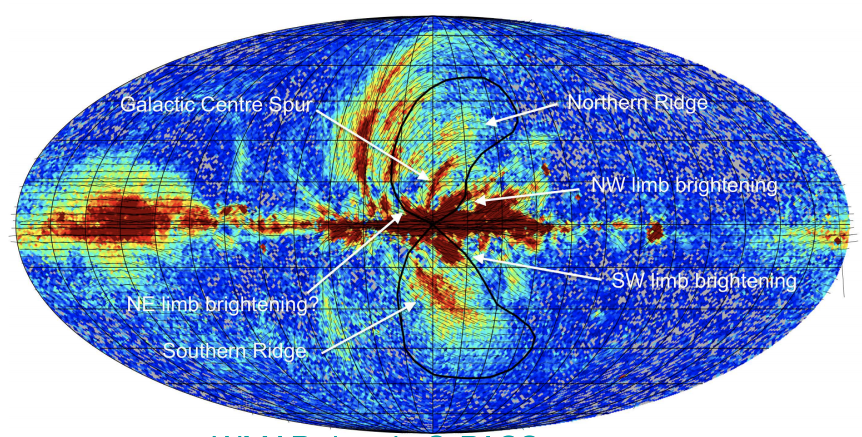


Alves et al. (2018)

- Fan?
- Local Bubble?
- Loops and spurs?



WMAP data in Vidal et al. (2015)



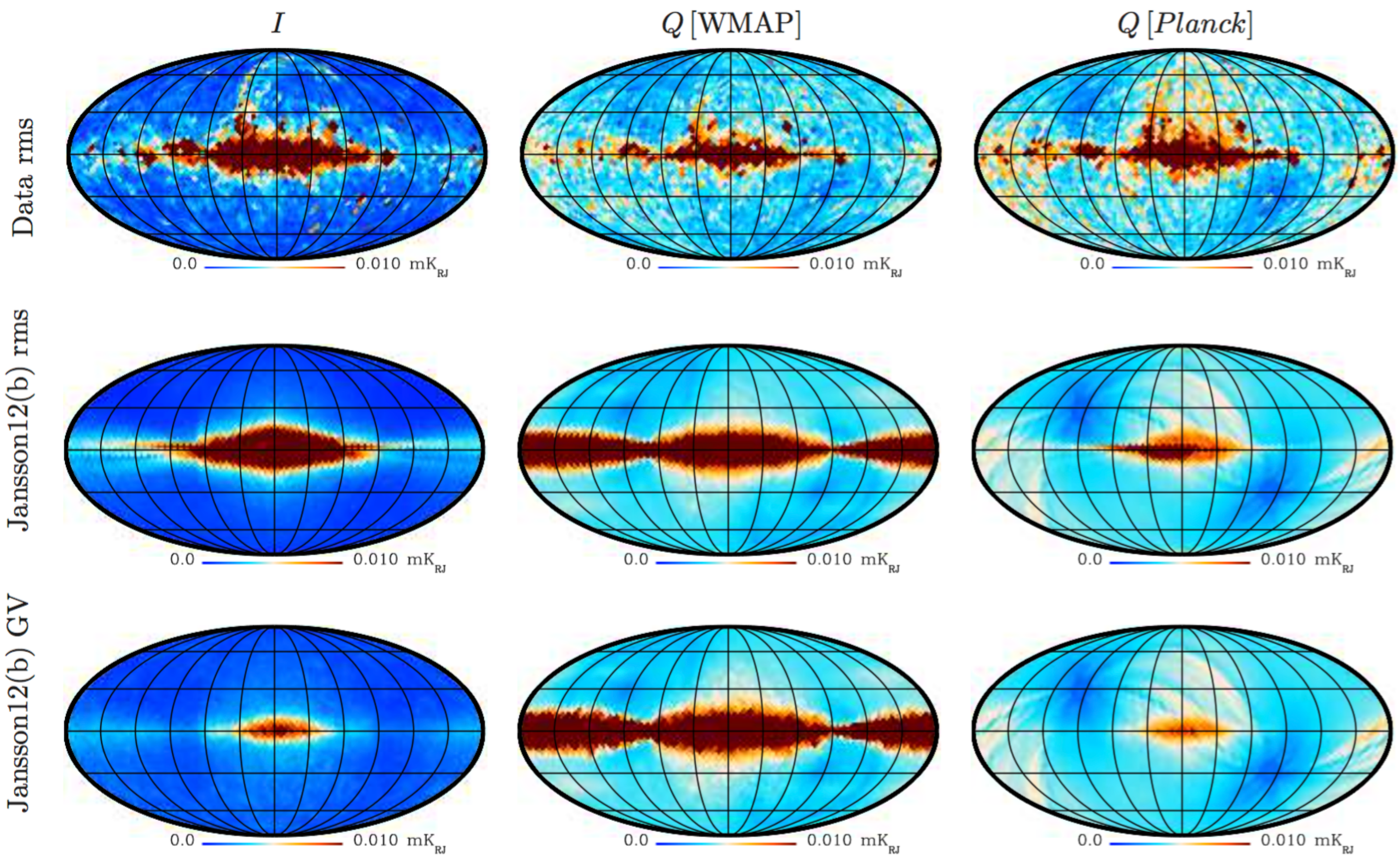
WMAP data in S-PASS paper Carretti et al. (2013)

Enough with the problems.
How about some new tools!

- New analyses of existing observables.
- New observables.
- New theoretical work.
- New collaborations.

New analyses of existing observables: "galactic variance" as an observable

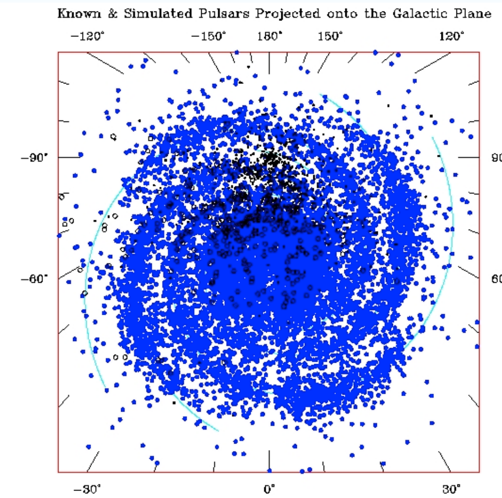
RMS: averaging high-res pixels into a low-res pixel in one realization or dataset
GV: ("galactic variance") averaging each pixel among an ensemble of realizations of a model



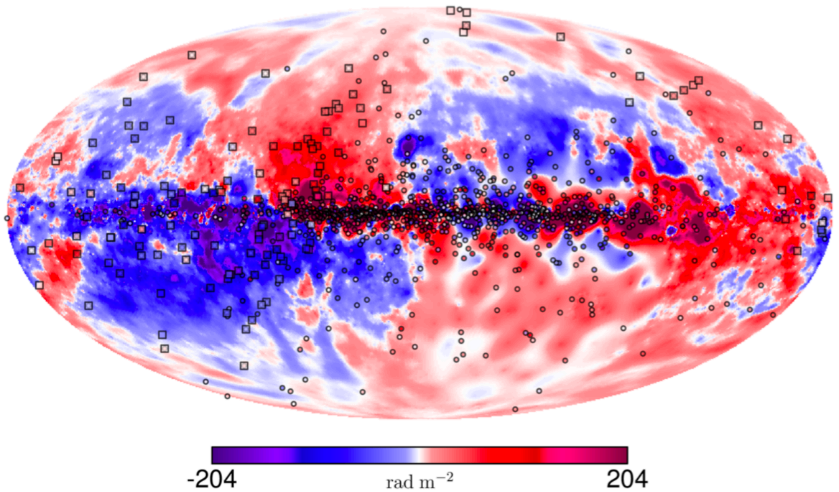
(PIPXLII)

More data!

- C-Band All Sky Survey (C-BASS) full sky, full Stokes, at 5 GHz. Important for CMB component separation, **synchrotron spectral studies**, and turbulent field modeling, etc.
- Voyager and AMEGO (medium energy gamma-rays) again for **cosmic-ray spectral studies**.
- GALFACTS polarization survey at 1.4GHz from Arecibo. An order of magnitude more extragalactic RM sources as well as diffuse polarized emission for RM synthesis..
- Low Frequency ARray (LOFAR) to model fields in Galactic halo, particularly where fields weak, ionized gas tenuous.
- Pilot, PIXIE, LiteBird, etc. for post-Planck microwave and sub-millimeter polarization
- Gaia for dust distribution via extinction.
- ASKAP and SKA!
- Zeeman splitting from, e.g., MAGMO.



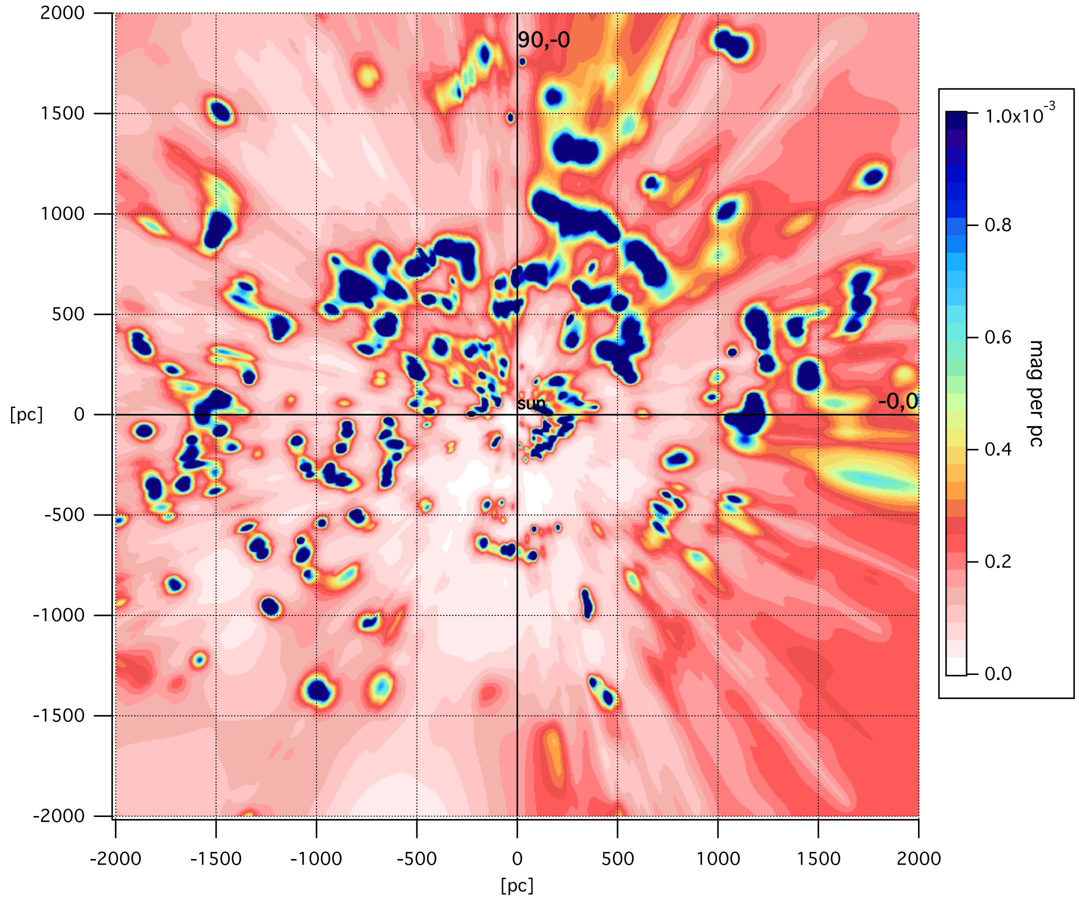
SKA simulation (J. Cordes)



Sobey et al. 2019

3D local: dust extinction

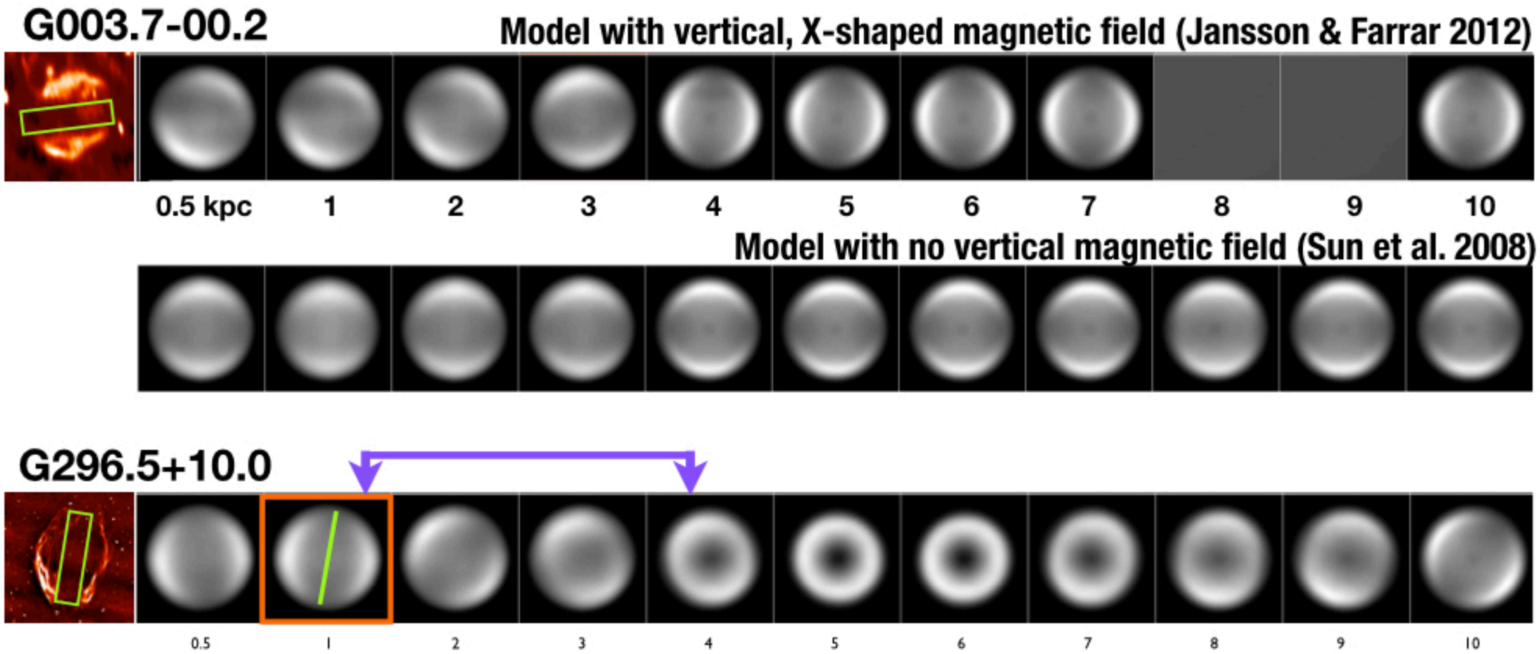
Very powerful in combination with Planck polarized dust emission

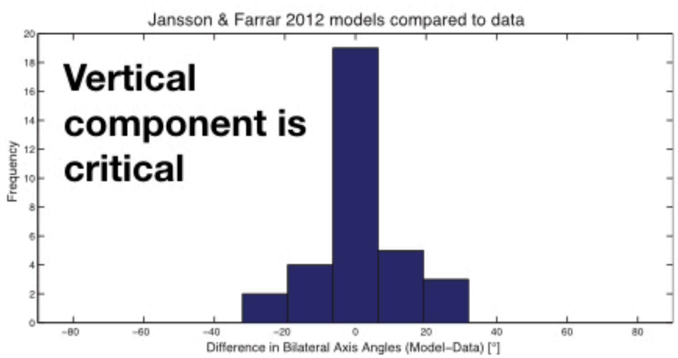


3D dust distribution from stellar reddening
(Lallemont et al. 2018)

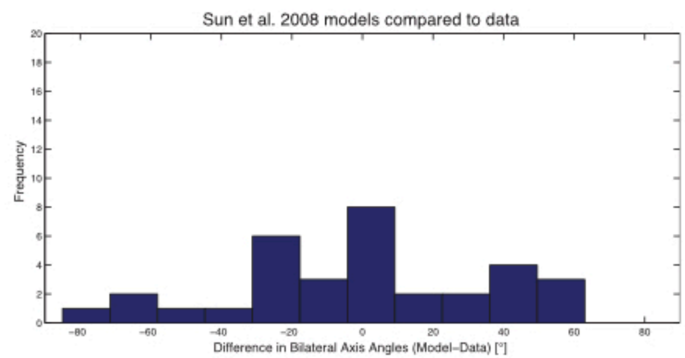
3D Galactic: Supernova remnant morphology

J. West et al. (2016)





Galactic magnetic field model with an **X-shaped halo component**

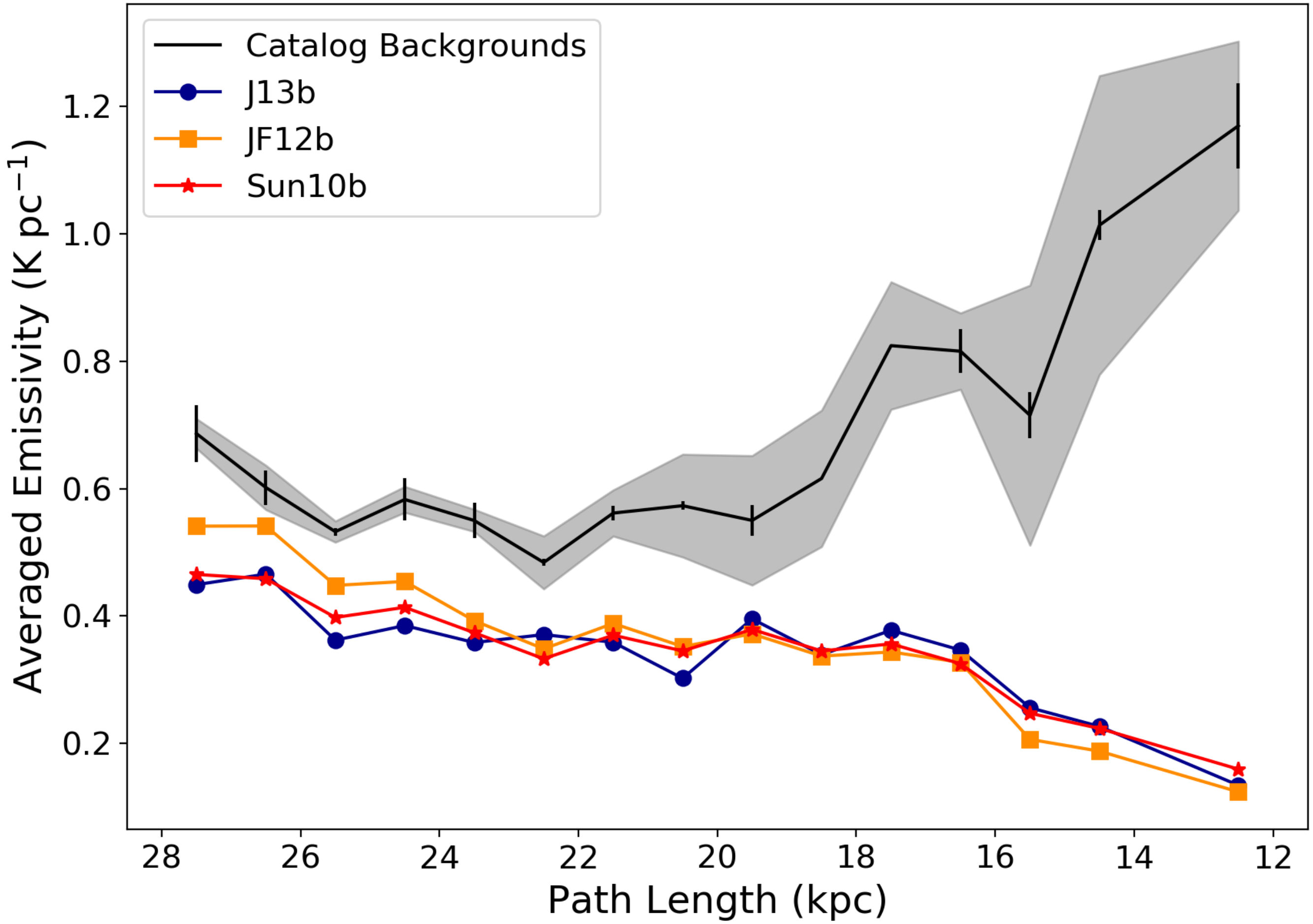


Galactic Field model with **no vertical component** (toroidal halo component only)

West+ 2016

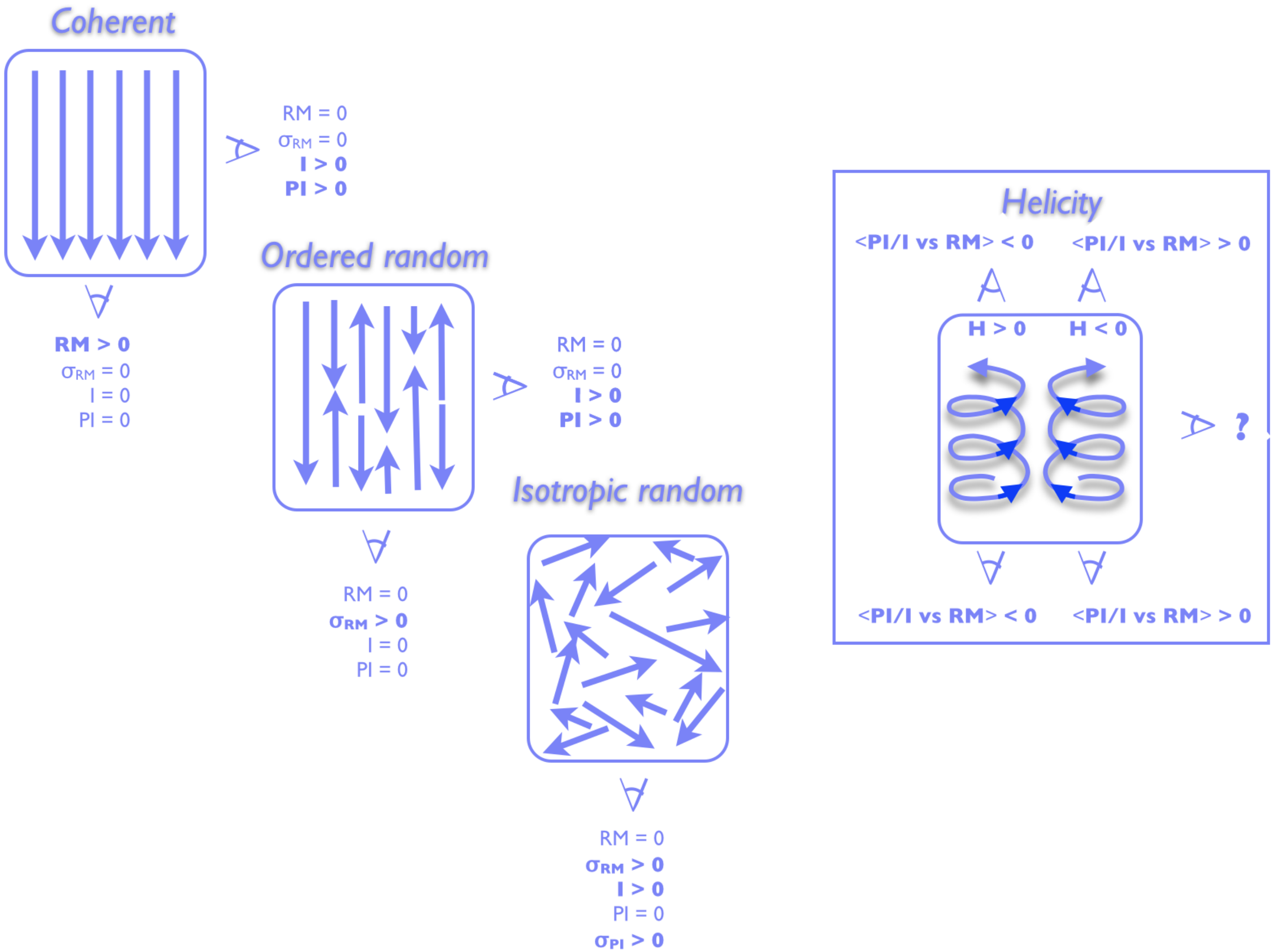
3D Galactic: Synchrotron absorption

HII regions at low (MHz) radio frequencies

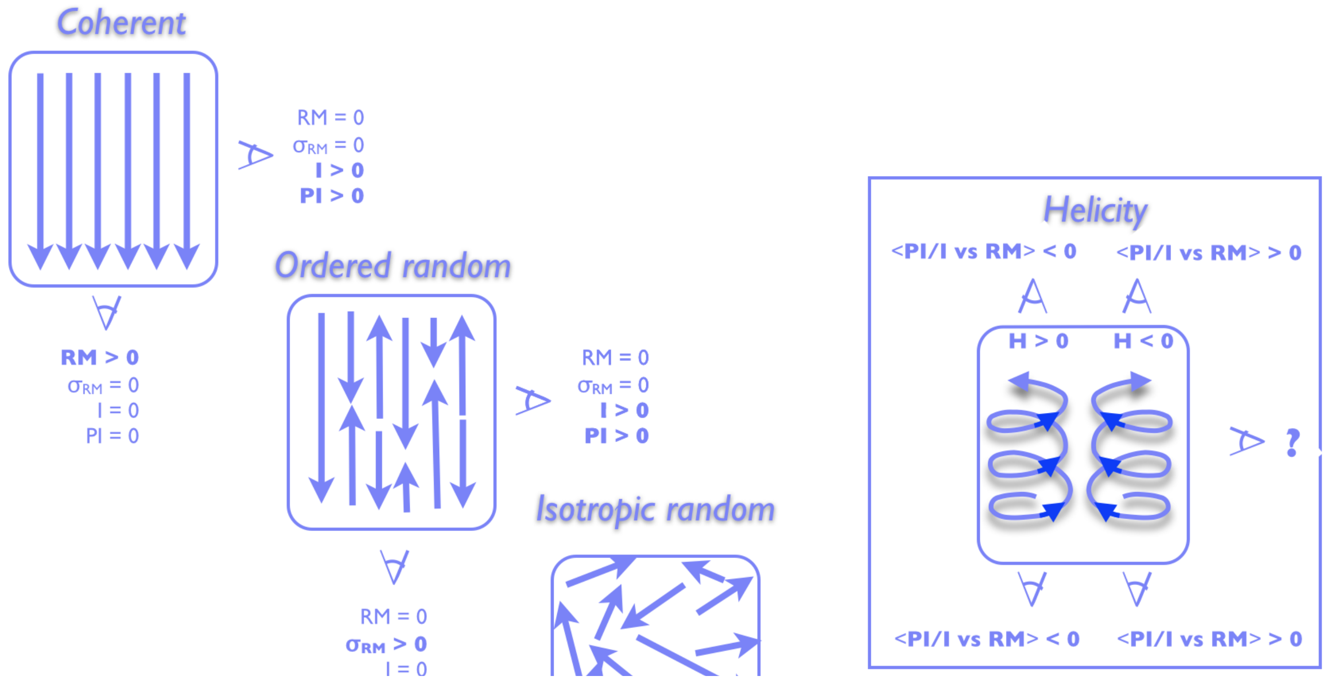


Polderman, Haverkorn, and Jaffe (*submitted*)

Helicity? Small scales.



Helicity? Small scales.



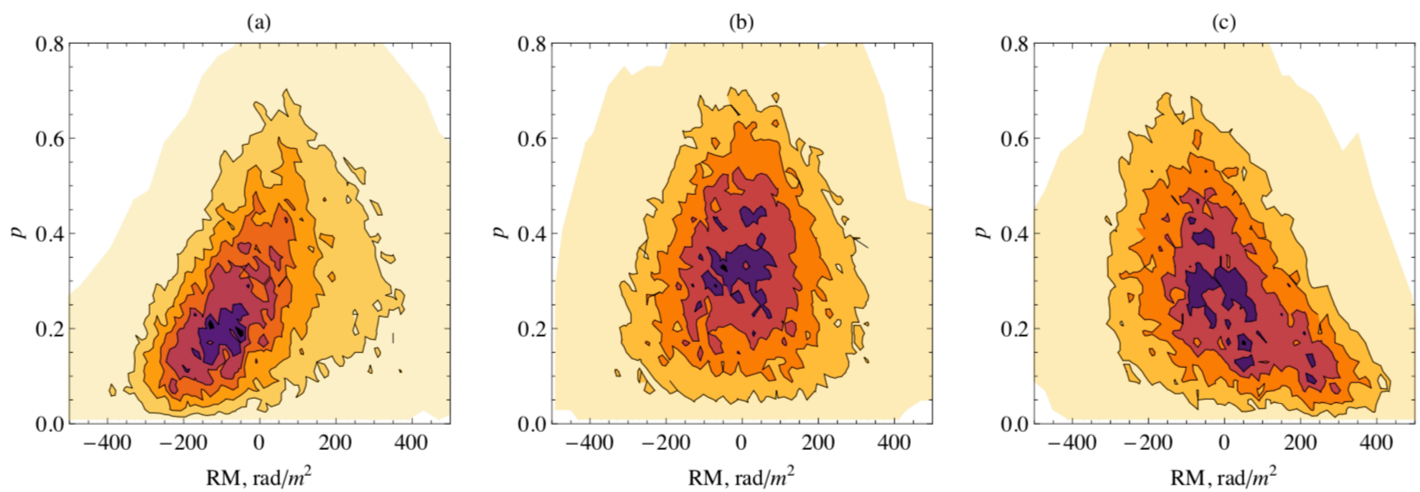
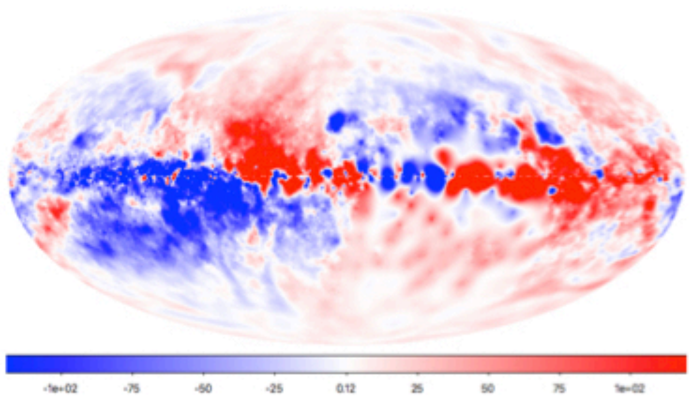
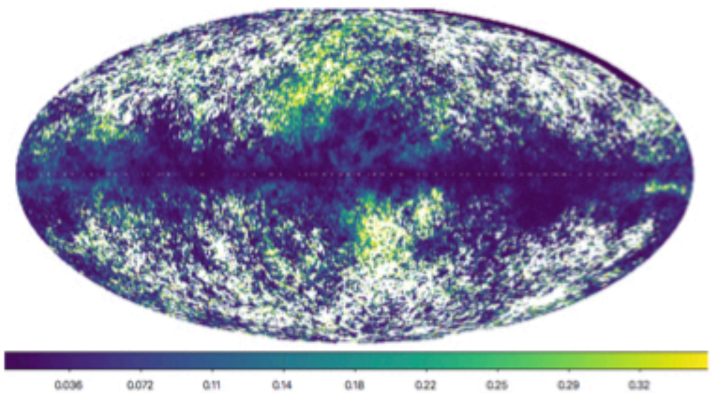


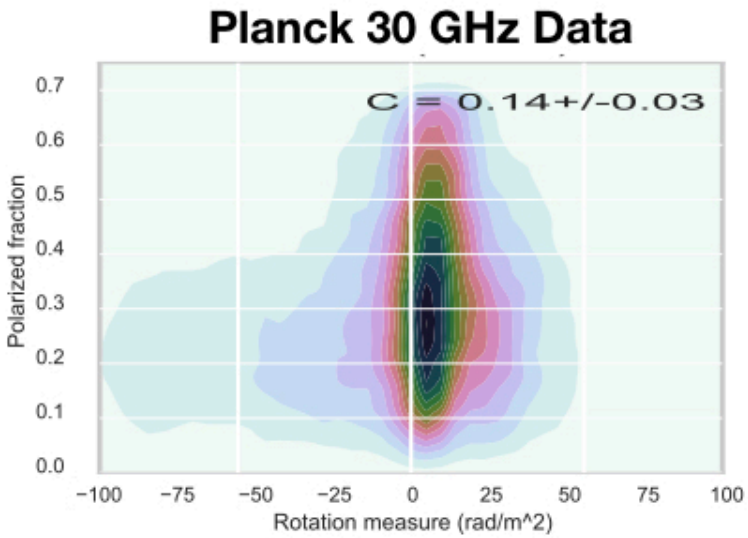
Fig.3. Joint probability distribution of pair RM and p for three levels of magnetic helicity : (a) positive, (b) zero-order, (c) negative

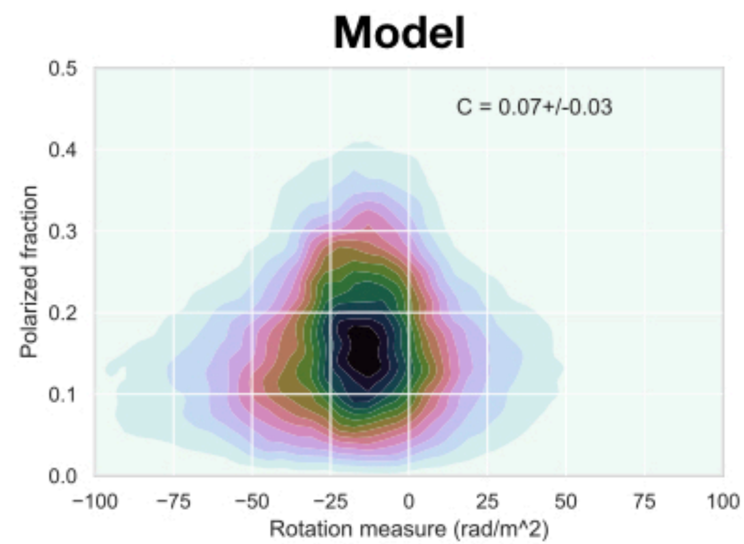
Volegova & Stepanov (2010)

Helicity? Large scales



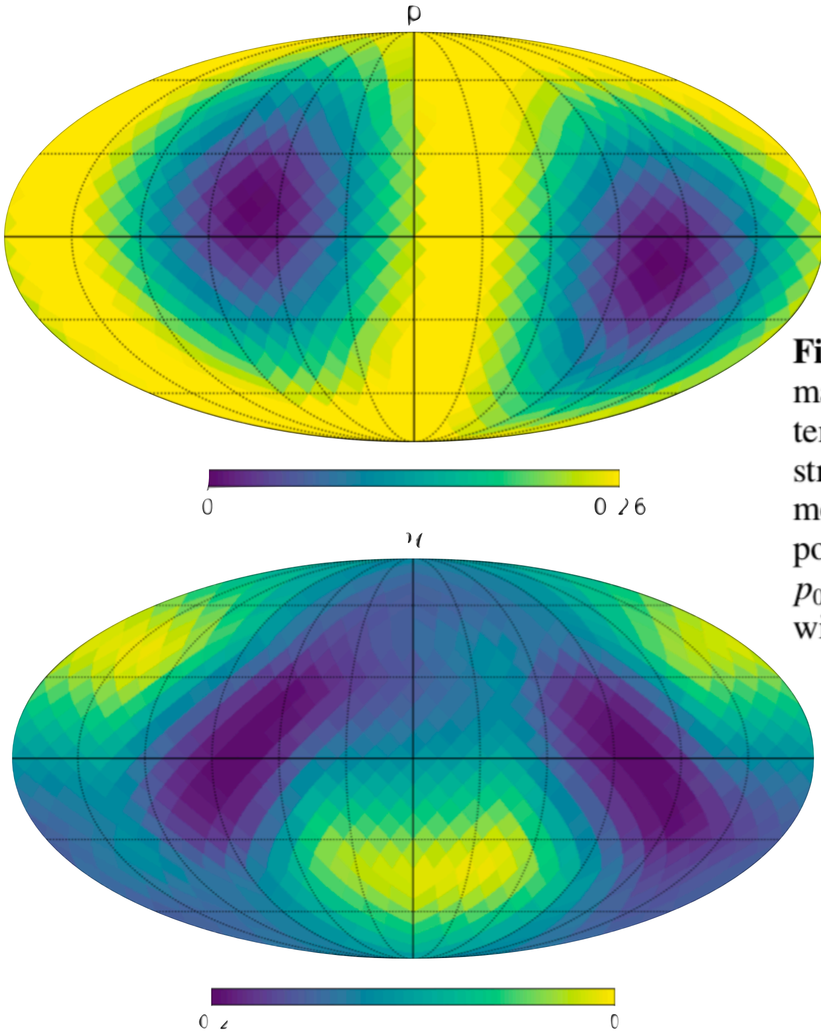






J. West, in prep

Helicity? Large scales

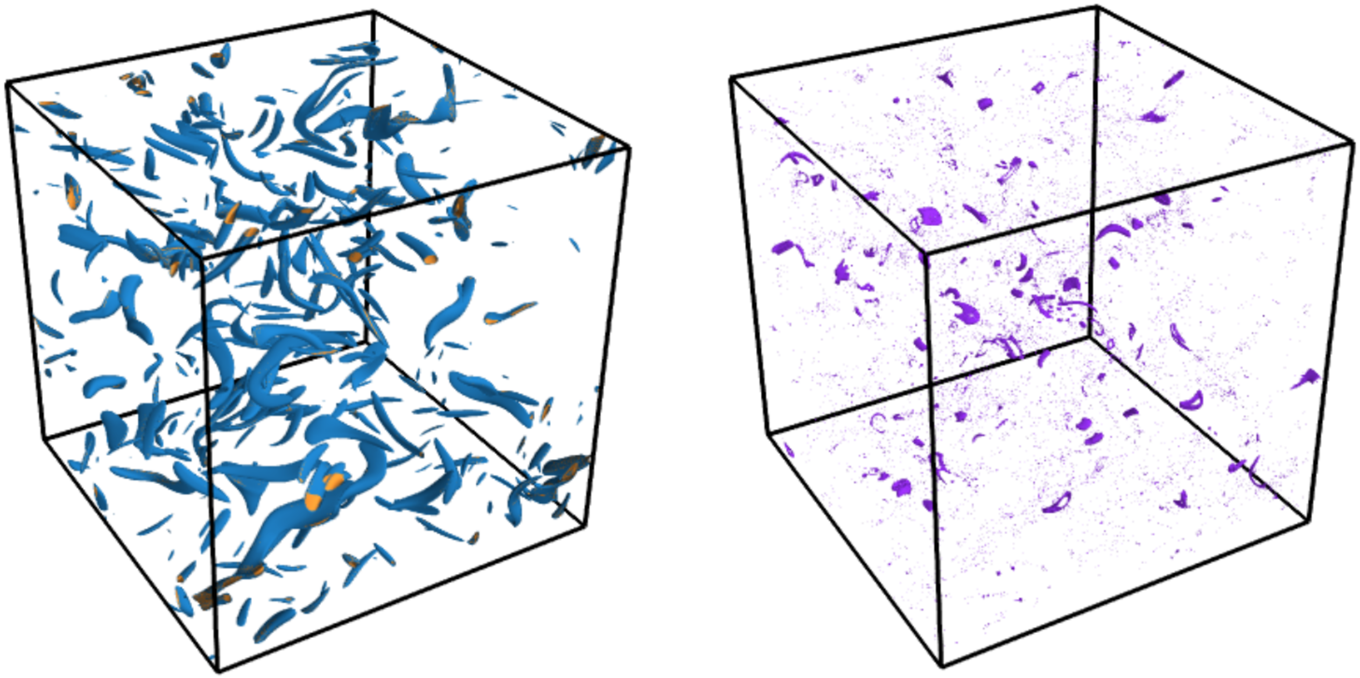


Bracco et al. (2018)

Fig. 5. Mollweide projections of the polarization fraction, p, and magnetic-helicity column, $\mathcal{H}$, produced placing the observer at the center of the filamentary structure described in Sect. 3.2 so to emulate the structure of the Galactic arm in the solar neighborhood. For this specific model, both the direction of the local arm and that of the poloidal component of the magnetic field is $[l_0^G, b_0^G] = [70°, +10°]$, $\alpha_b = -20\%$, and $p_0 = 26\%$. A Galactic coordinate grid centered in [l,b] = [0°,0°] and with steps of 30° is superposed.

Real turbulence?

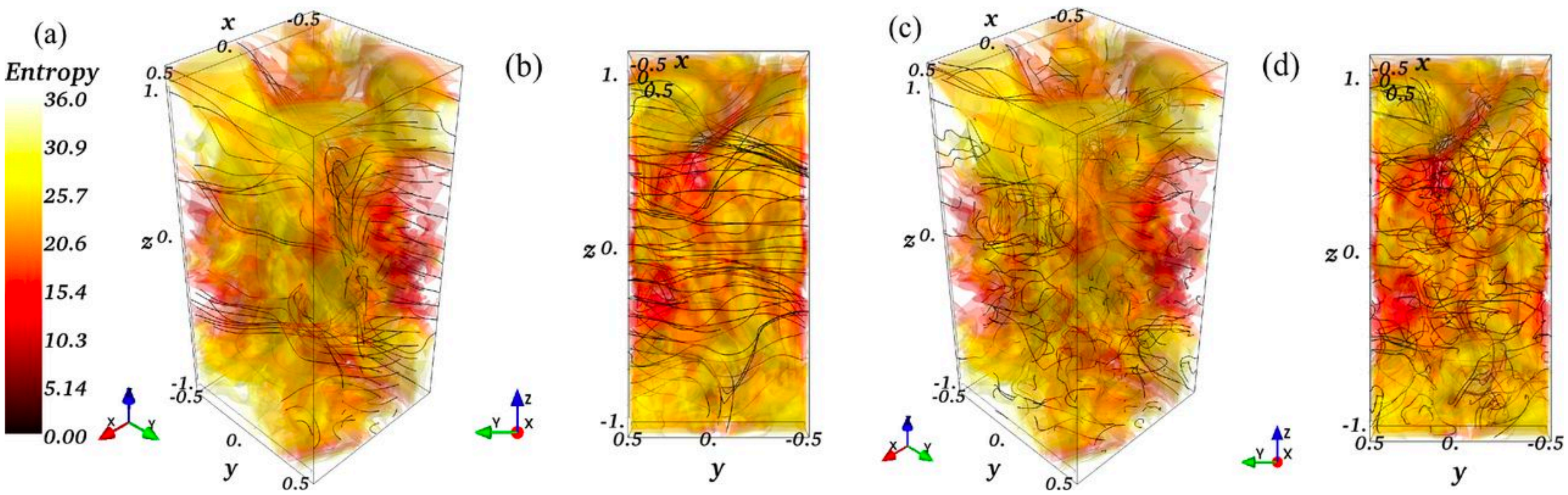
- CR propagation in a turbulent magnetic field
  - How does correlation affect large-scale modeling?



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)

Real turbulence?

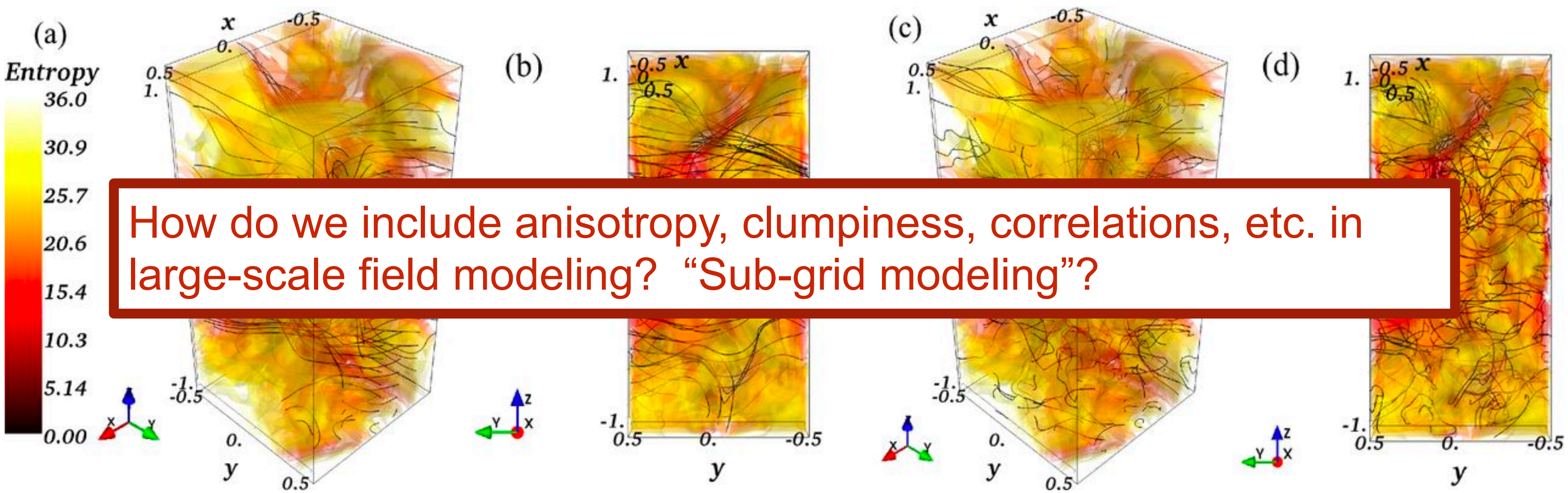
- Define "mean" versus "fluctuating" magnetic field
  - How to model both?



Field lines of "mean" field (a,b) or "fluctuating"/"random" (c,d) magnetic fields in MHD simulations of SNR-driven turbulence (Evirgen et al. 2017)

Real turbulence?

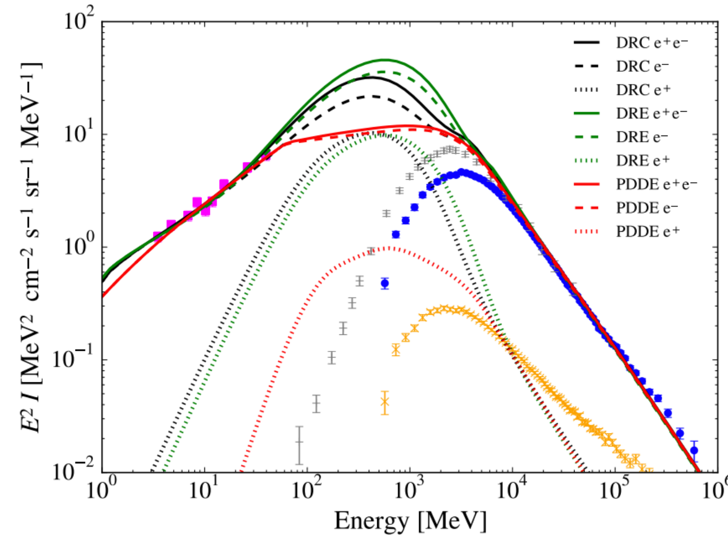
- Define "mean" versus "fluctuating" magnetic field
  - How to model both?



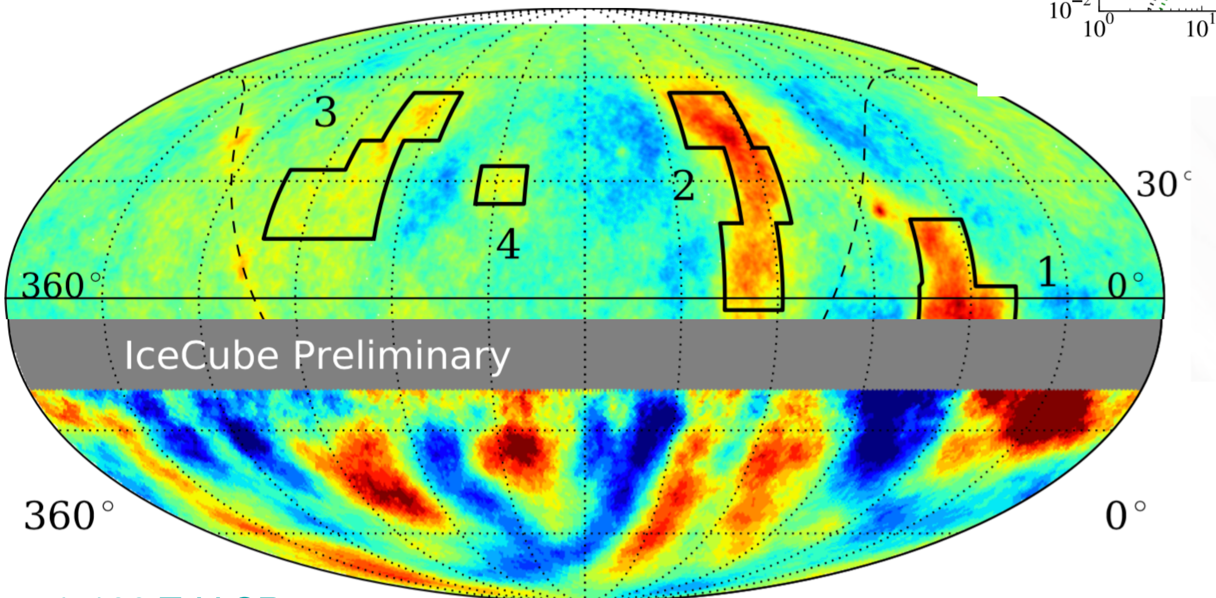
How do we include anisotropy, clumpiness, correlations, etc. in large-scale field modeling? "Sub-grid modeling"?

Field lines of "mean" field (a,b) or "fluctuating"/"random" (c,d) magnetic fields in MHD simulations of SNR-driven turbulence (Evirgen et al. 2017)

Galactic CR tracers:
spectra and arrival directions give different information



Orlando (2018)



1-100 TeV CRs
Northern: **ARGO-YBJ** from Bartoli et al. (2013).
Southern: **IceCube** from Desiati et al. (2013)

Why am I here?

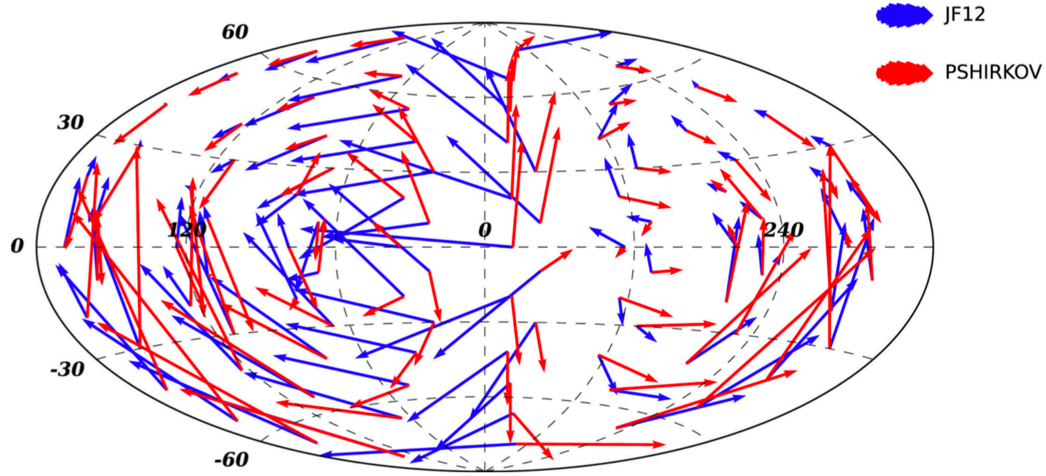


Figure 13. Comparison of deflection angles of UHECRs with rigidity $E/eZ = 10\,\mathrm{EV}$ predicted by two published models of the GMF: Pshirkov et al. [200] and Jansson & Farrar (JF12) [71]. Image credit: S. Mollarach and E. Roulet [145].

?

- 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.
  - Statistically?

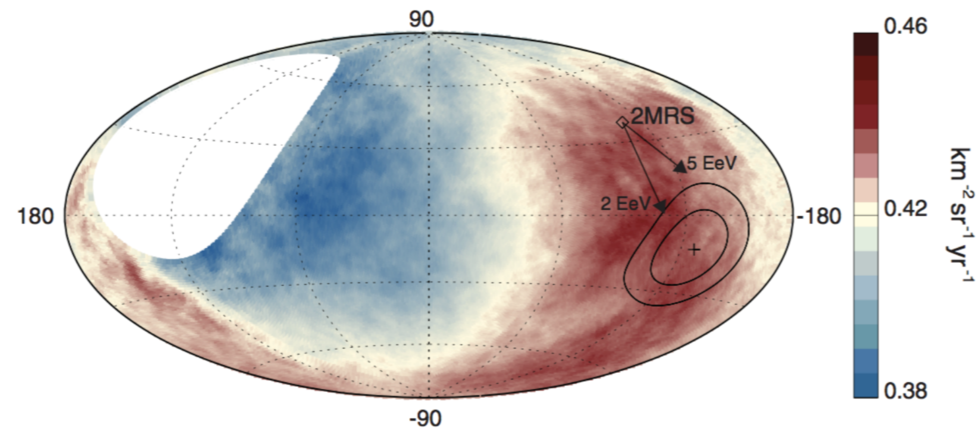
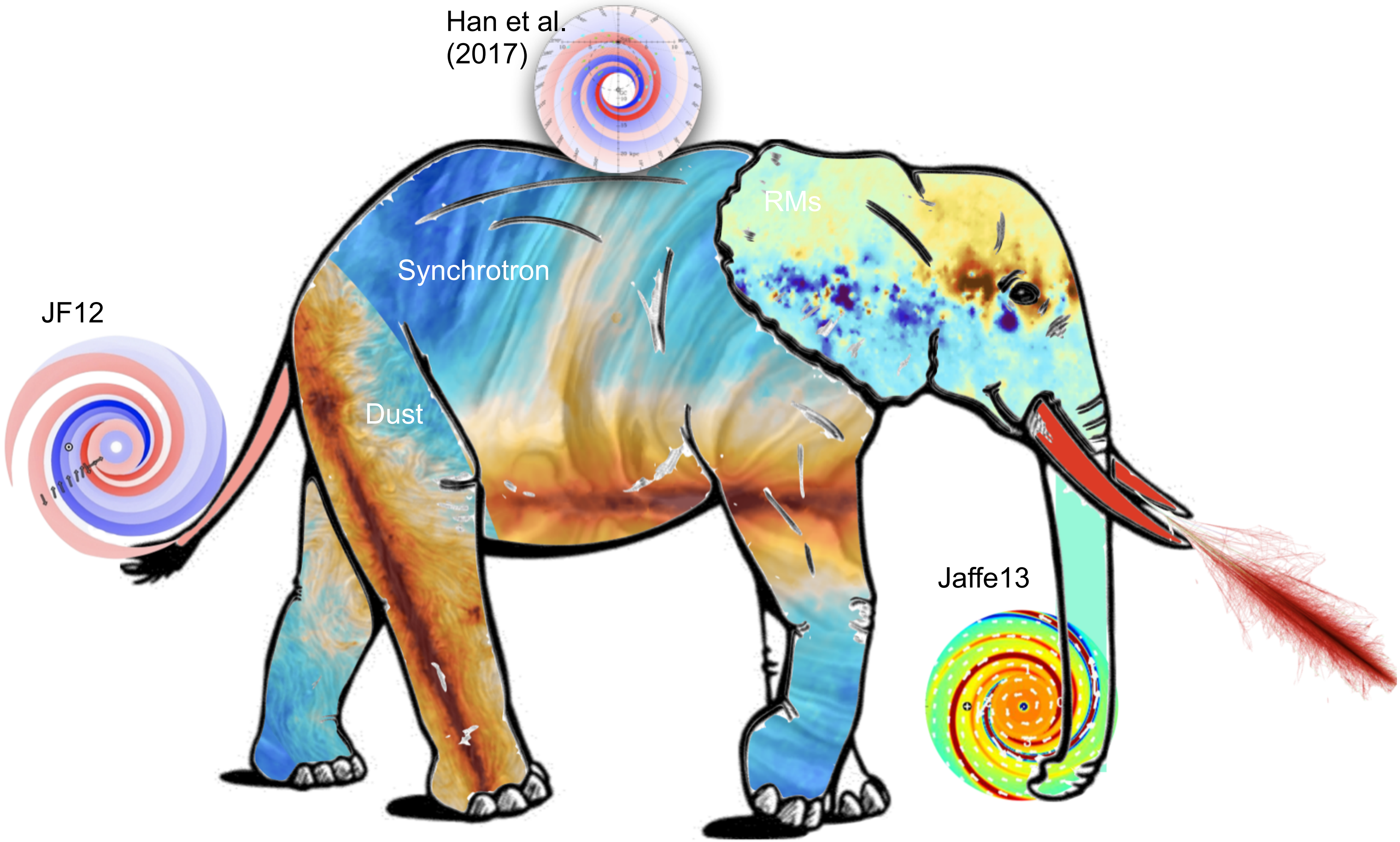


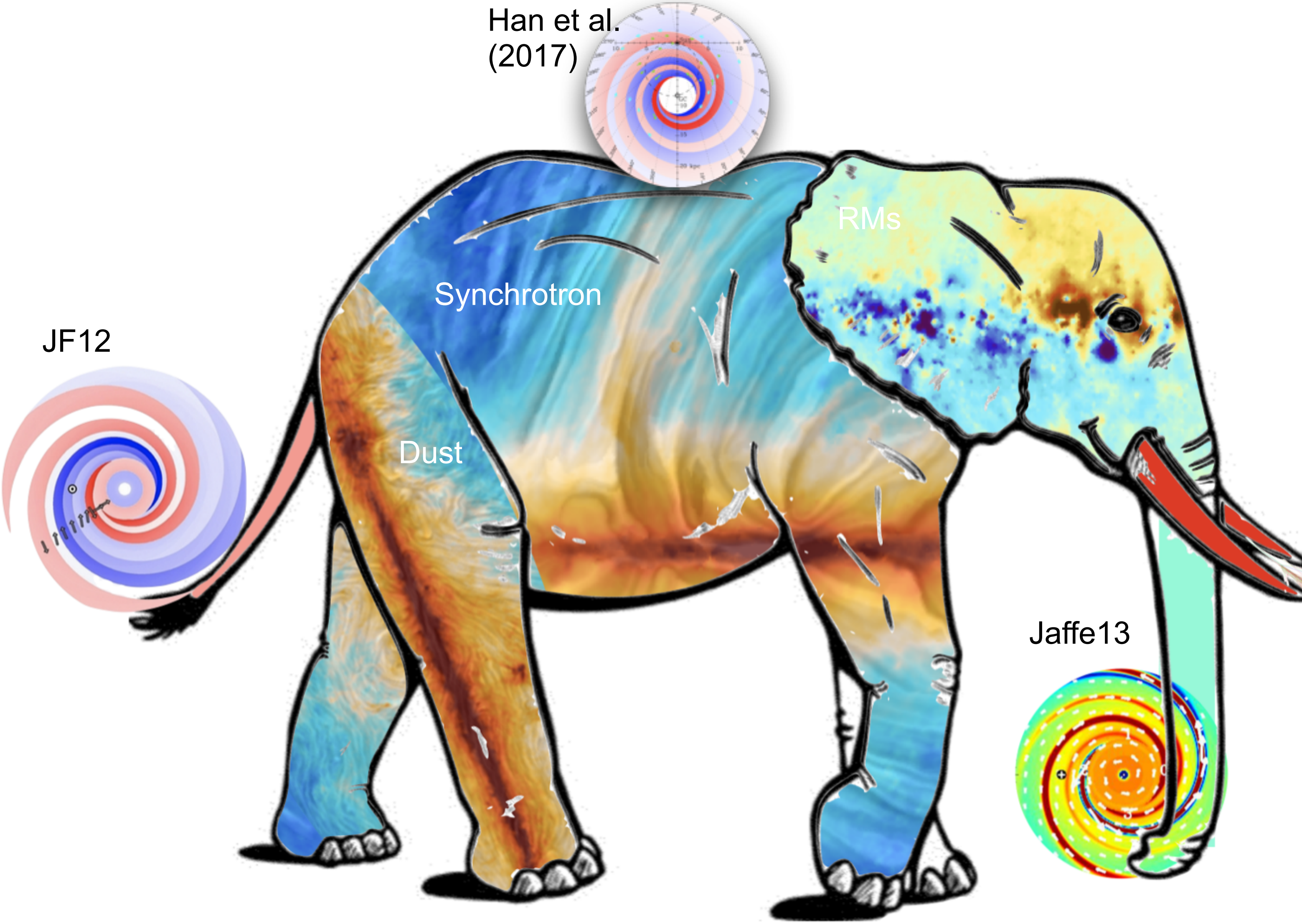
Figure 8. Sky map in galactic coordinates showing the cosmic ray flux as measured by the Pierre Auger Observatory for $E > 8\,\mathrm{EeV}$ smoothed with a 45° top-hat function. The Galactic centre is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% 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 $5\,\mathrm{EeV}$. Image credit: Pierre Auger Collaboration [149].

Pierre Auger Collaboration, 2017, *Science*, 357, 6357, p1266

The proverbial elephant



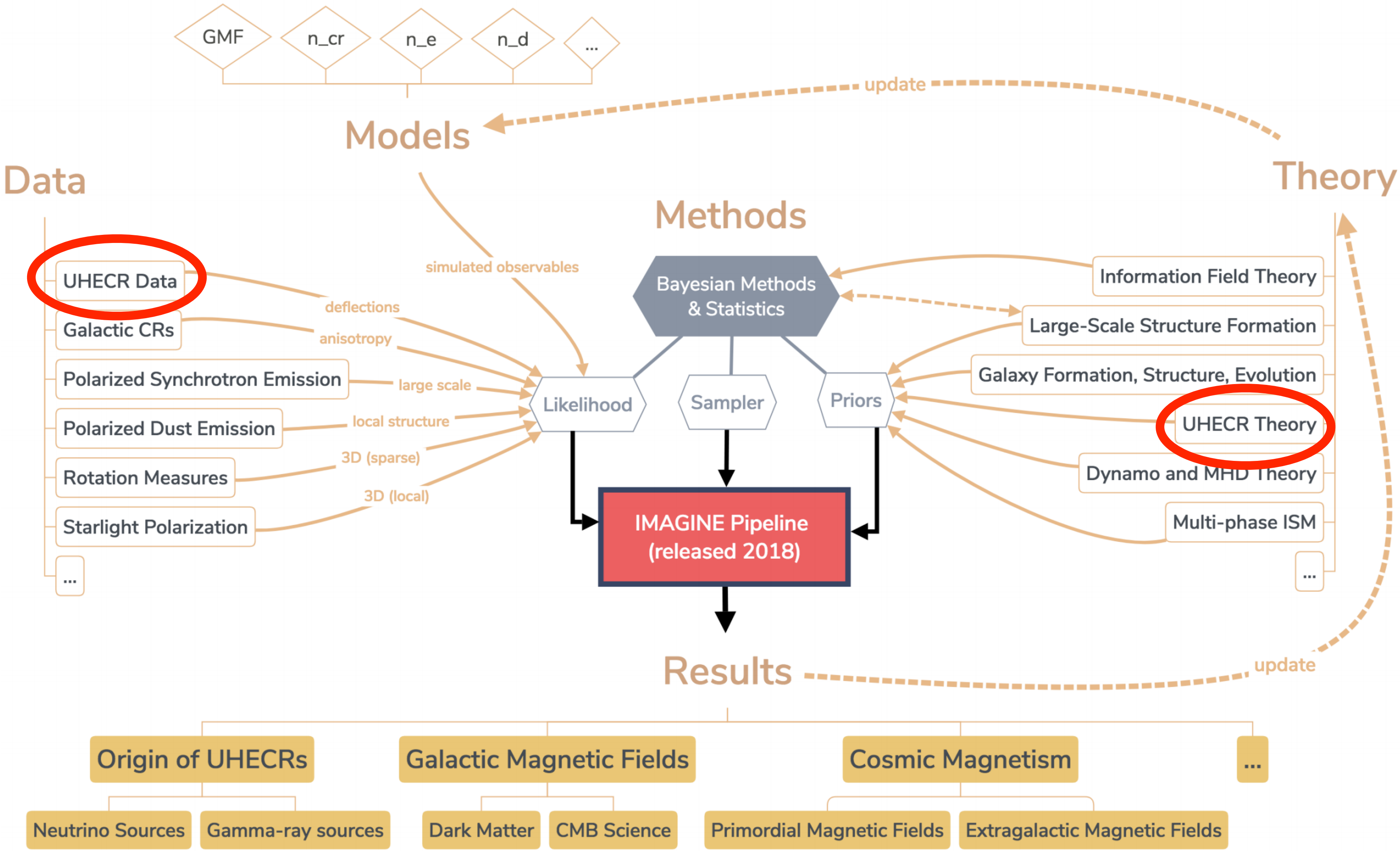
The proverbial elephant



PIERRE
AUGER
OBSERVATORY

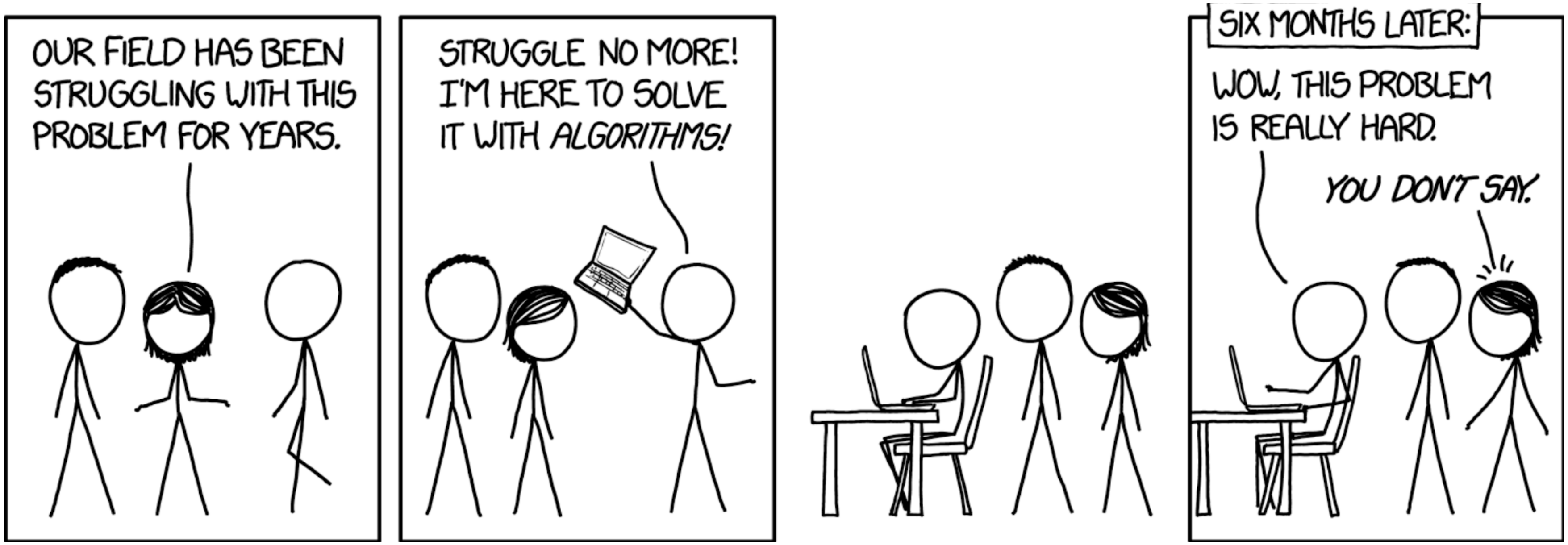
IMAGINE: the Interstellar MAGnetic field INference Engine

White Paper: Boulanger et al. (2018) https://arxiv.org/abs/1805.02496
Demonstration paper: Steininger et al. (2018), https://arxiv.org/abs/1801.04341)



Caveat

- IMAGINE isn't a silver bullet. This is still a complicated problem. But IMAGINE gives us a framework for putting the many different pieces together.



Randall Munroe, XKCD (https://xkcd.com/1831/)