Image composed by Jörg P. Rachen for ISSI International Team 323, Bern 2014/15,

IMAGINE

the interstellar magnetic field inference engine

https://arxiv.org/abs/1805.02496

Co-PIs:	François Boulanger	IAS, Paris	*Planck*, polarized dust
	Torsten Enßlin	**MPA, Munich**	**Information Theory, CR and B-field theory**
	Marije Haverkorn	Radboud U., Nijmegen	Radio astronomy, B-fields, turbulence
	Jörg Hörandel	Radboud U., Nijmegen	CR observations, radio emission
	Tess Jaffe	NASA/GSFC	*Planck*, B-field modeling, numerical simulation
	Jens Jasche	TUM, Munich	IFT, Bayesian methods, theory
	Jörg Rachen	Radboud U., Nijmegen	UHECRs, Bayesian methods
	Anvar Shukurov	Newcastle U	Theory of CRs, B-fields, turbulence.

Members:	Andrew Fletcher , Philipp Girichides, Michael Kachelreiß, Christoph Pfrommer, Luis Rodrigues, Beatrice Ruiz Granados, Günter Sigl, Theo Steininger, Ajen van Vliet, Jiaxin Wang. . . .

Image composed by Jörg P. Rachen for ISSI International Team 323, Bern 2014/15,

IMAGINE

the interstellar magnetic field inference engine

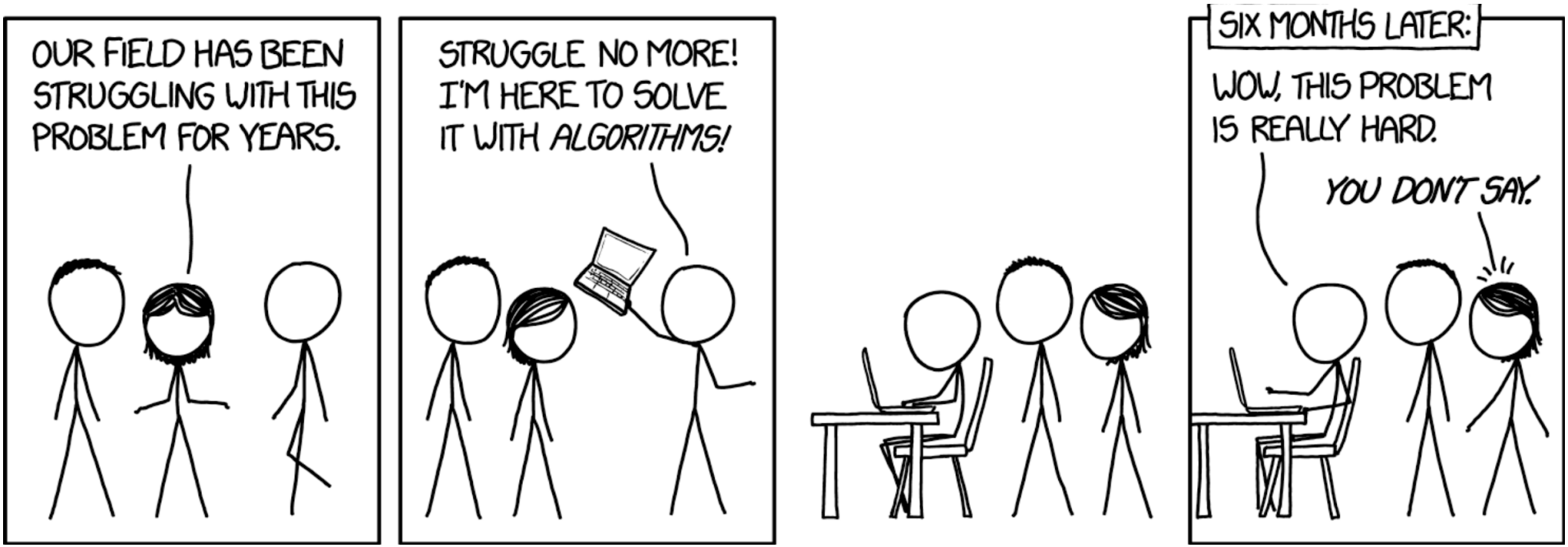
https://arxiv.org/abs/1805.02496

IMAGINE: a consortium & a pipeline

- open collaboration
- open data
- open source code

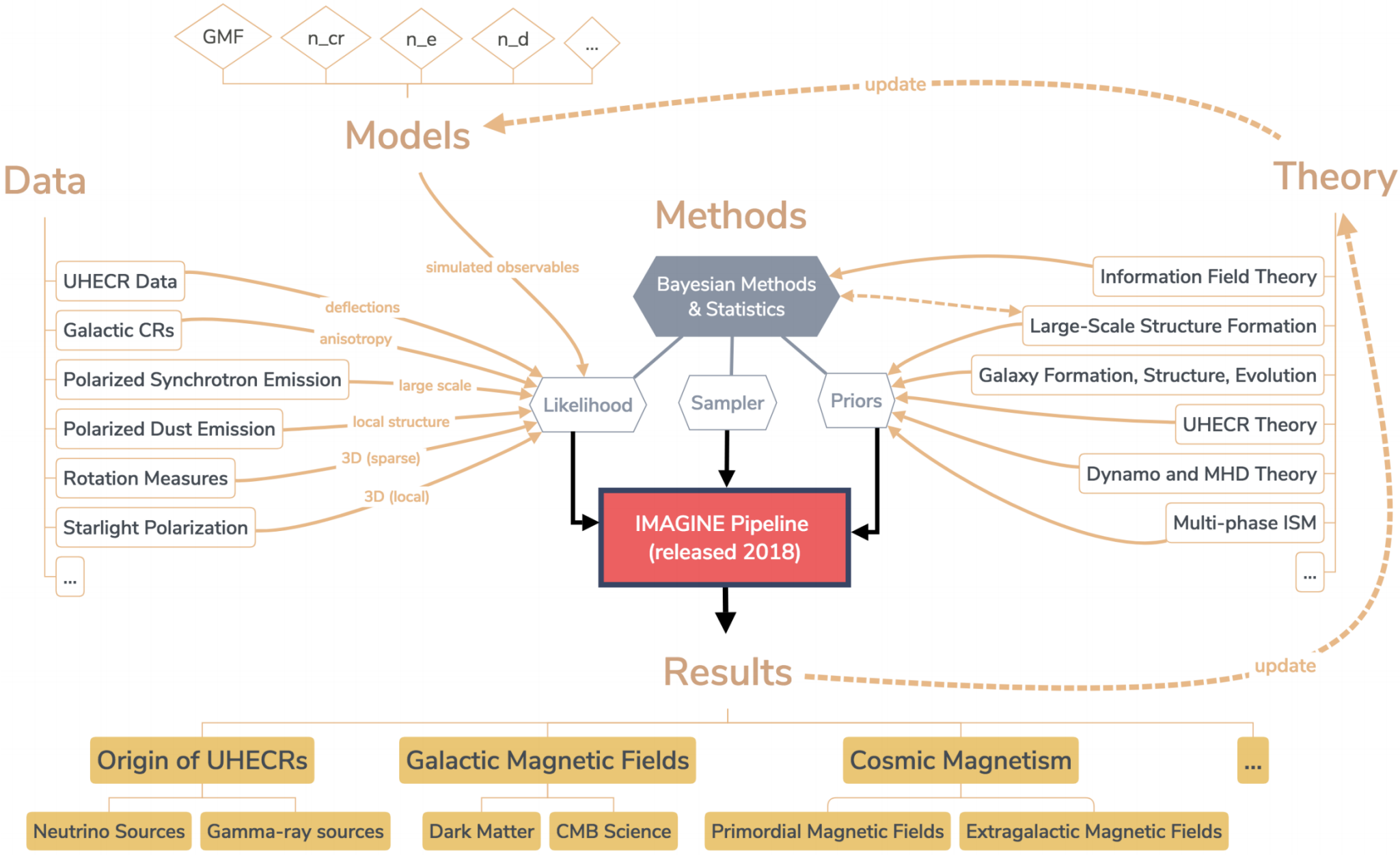
→ testable & reproducible results

IMAGINE ALGORITHM

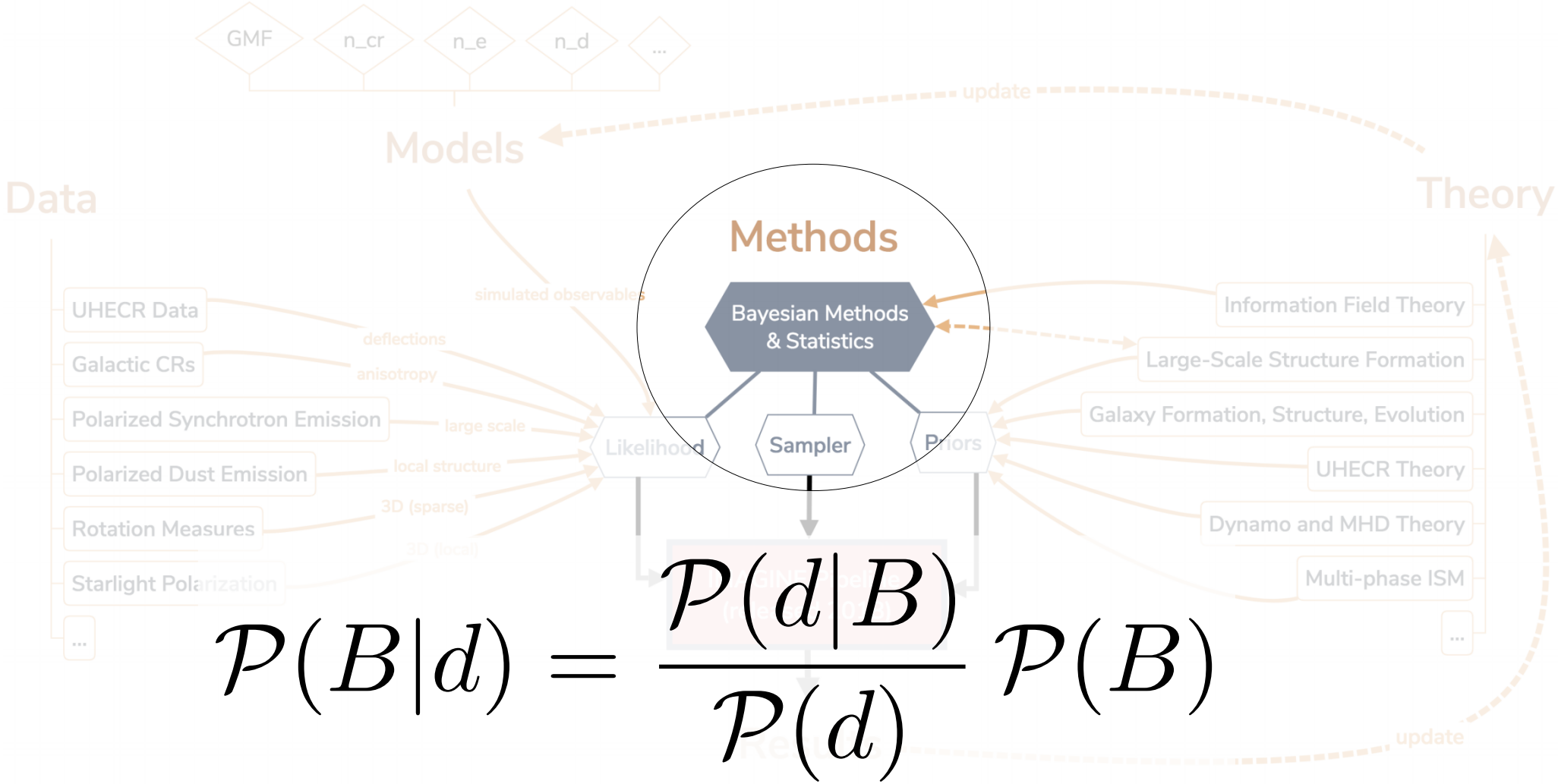


Randall Munroe, XKCD (https://xkcd.com/1831/)

IMAGINE overview



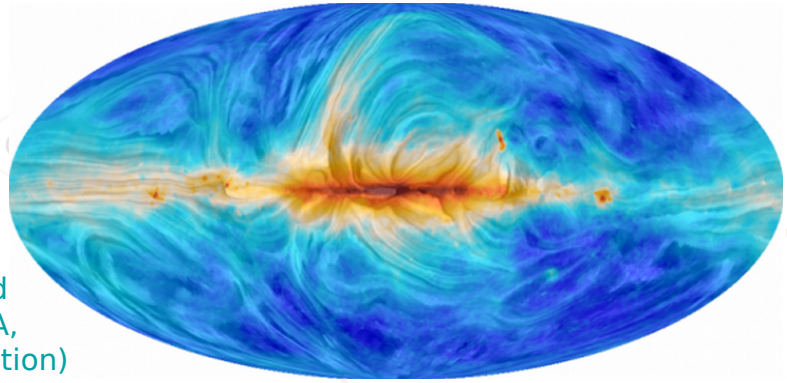
Bayesian Inference



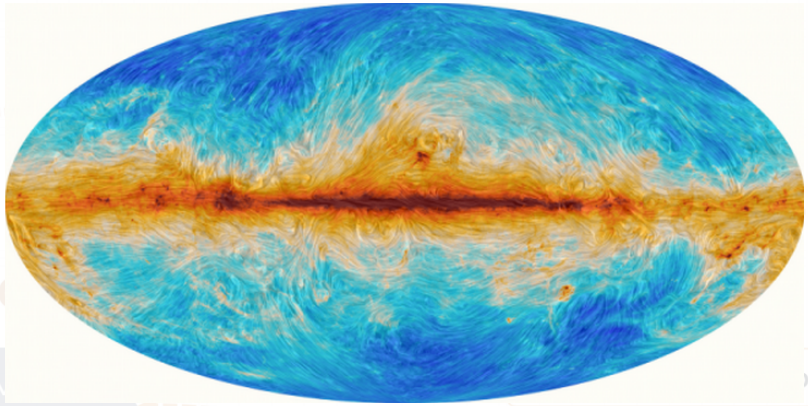
$$\mathcal{P}(B|d) = \frac{\mathcal{P}(d|B)}{\mathcal{P}(d)}\,\mathcal{P}(B)$$

posterior knowledge ← data experience ← prior knowledge

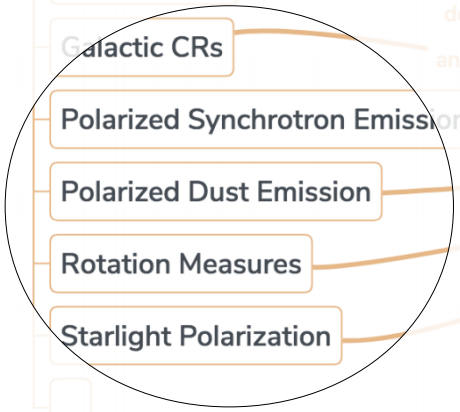
Magnetic Field Tracers

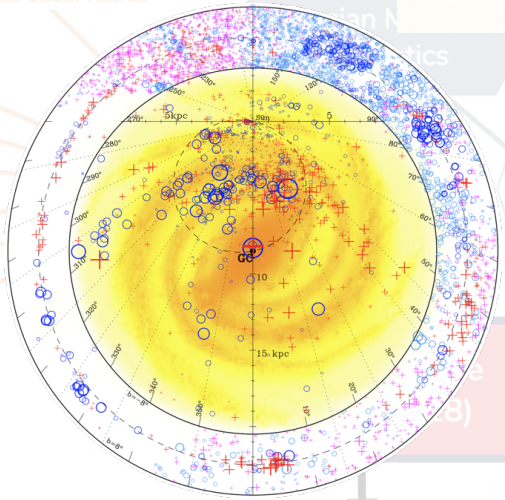


30 GHz polarized synchrotron (ESA, Planck Collaboration)

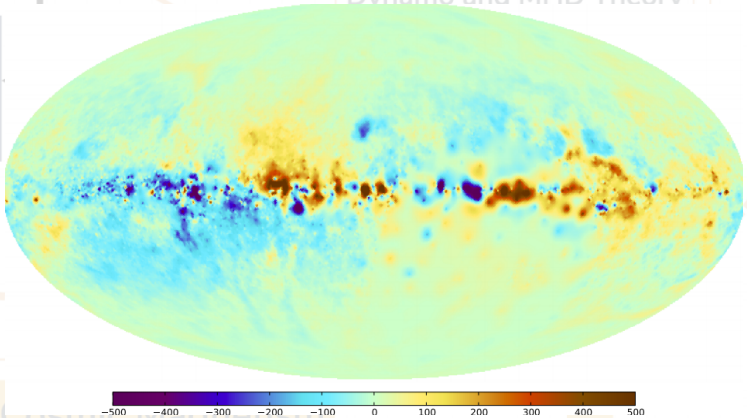


353 GHz polarized dust (ESA, Planck Collaboration)

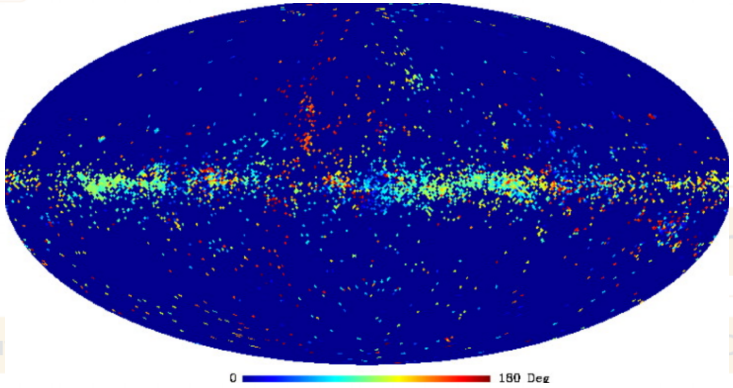




Galactic and extra-galactic RMs (Han et al. 2017)

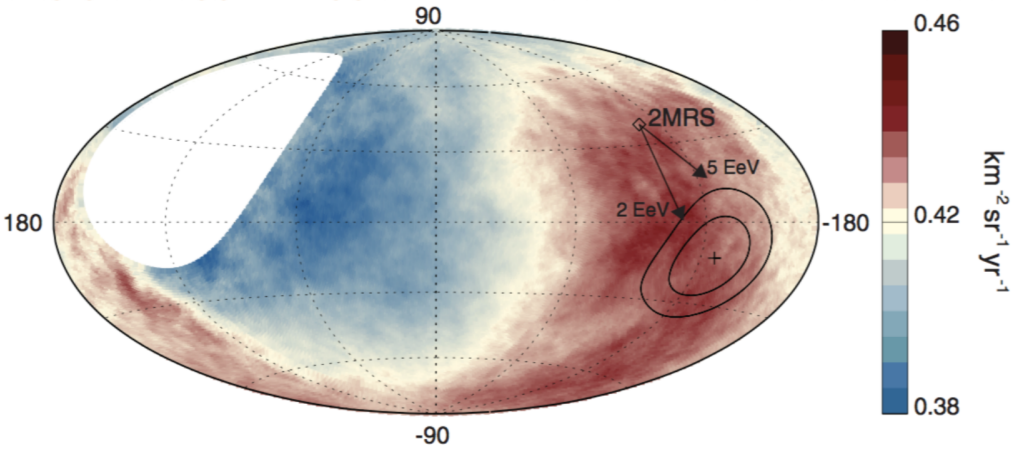


Faradaydepth (rad/m²) (Oppermann et al. 2012)



Starlight polarization (Fosalba et al. 2002)

Cosmic Rays



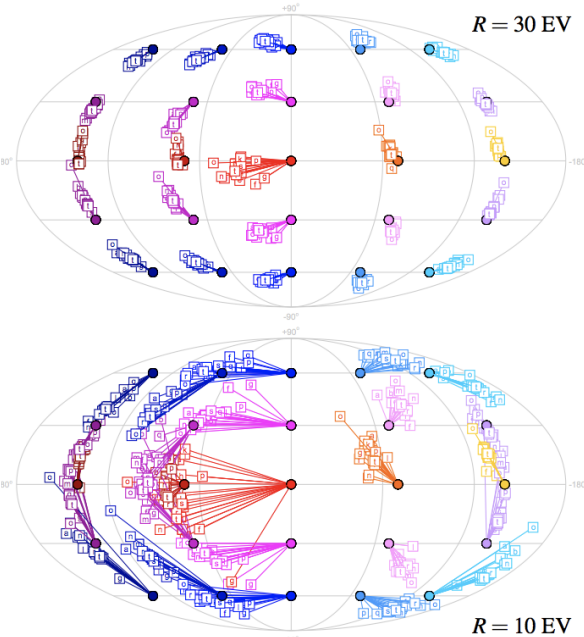


Figure 8. Sky map in galactic coordinates showing the cosmic ray flux as measured by the Pierre Auger Observatory for $E > 8$ EeV smoothed with a 45° top-hat function. The Galactic centre is at the origin. The

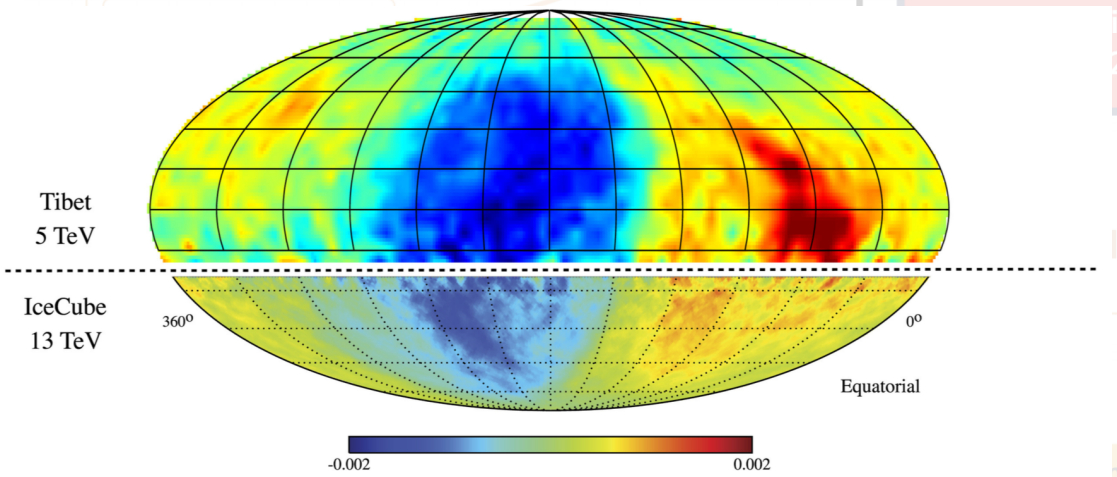
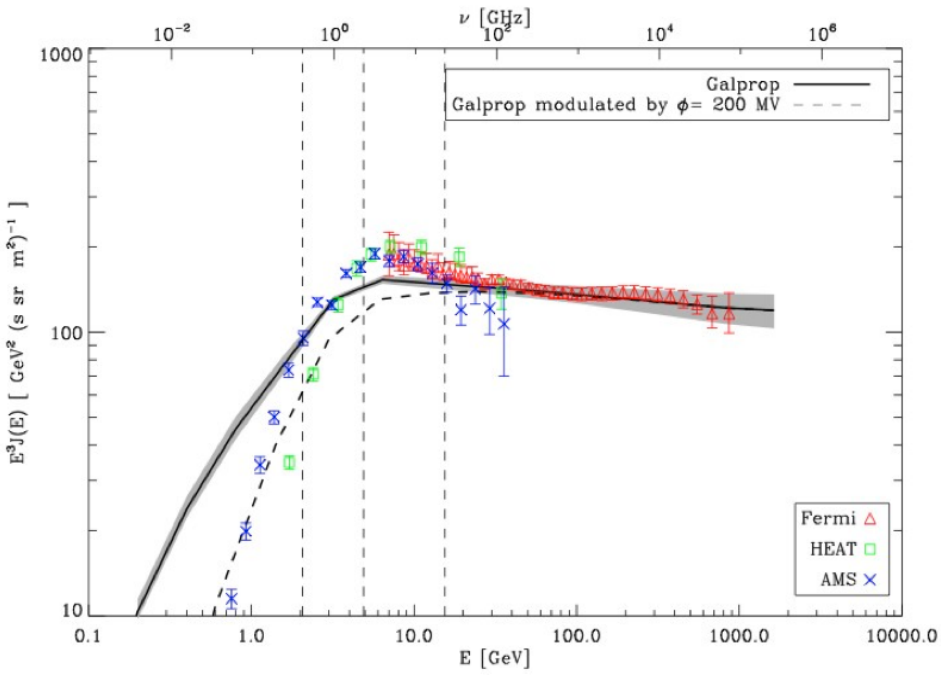
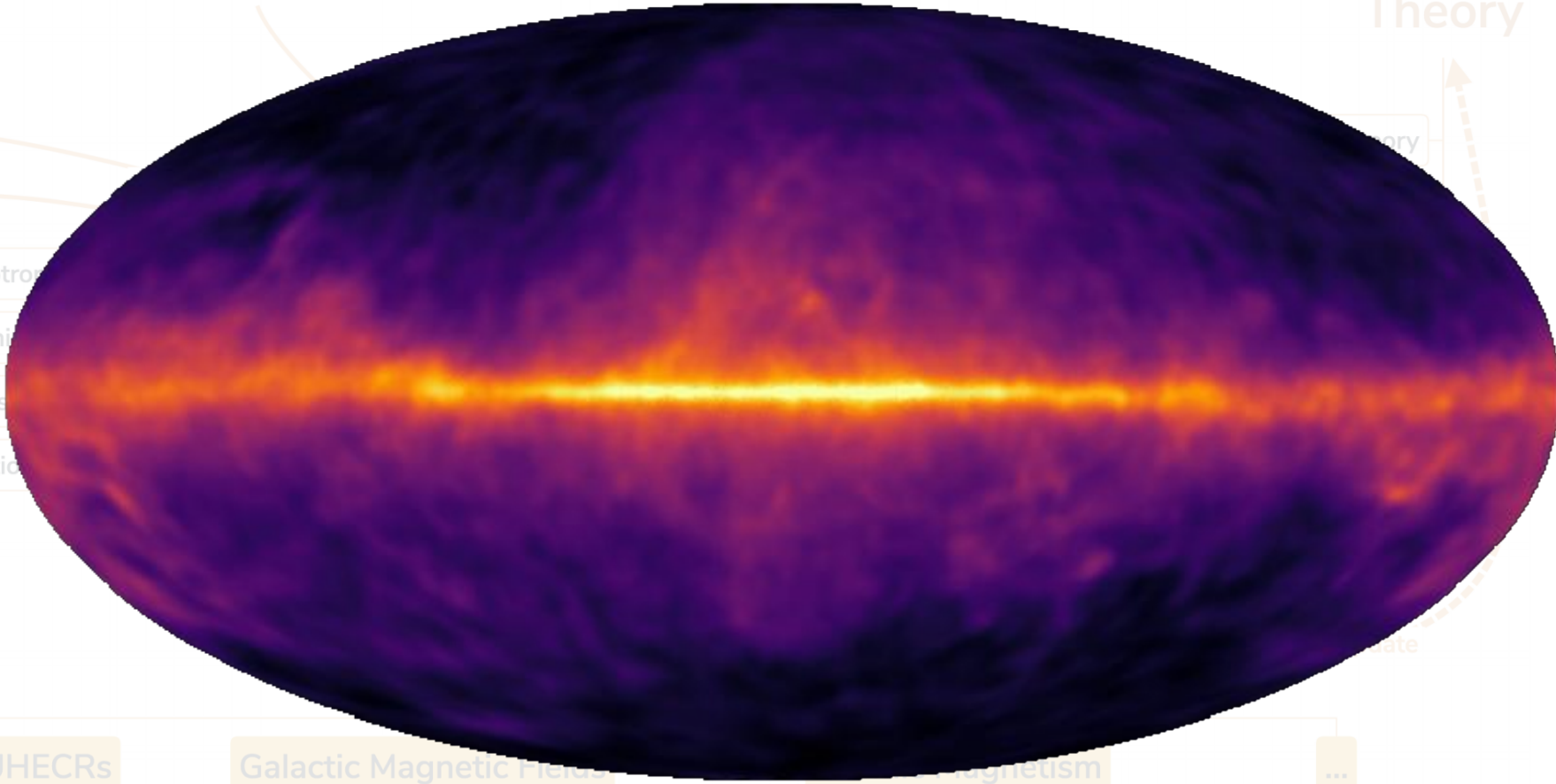


Figure 2. Combined cosmic ray anisotropy of the Tibet-AS and IceCube experiments in the equatorial coordinate system. Image credit and detailed information: M. Ahlers and P. Mertsch [30].



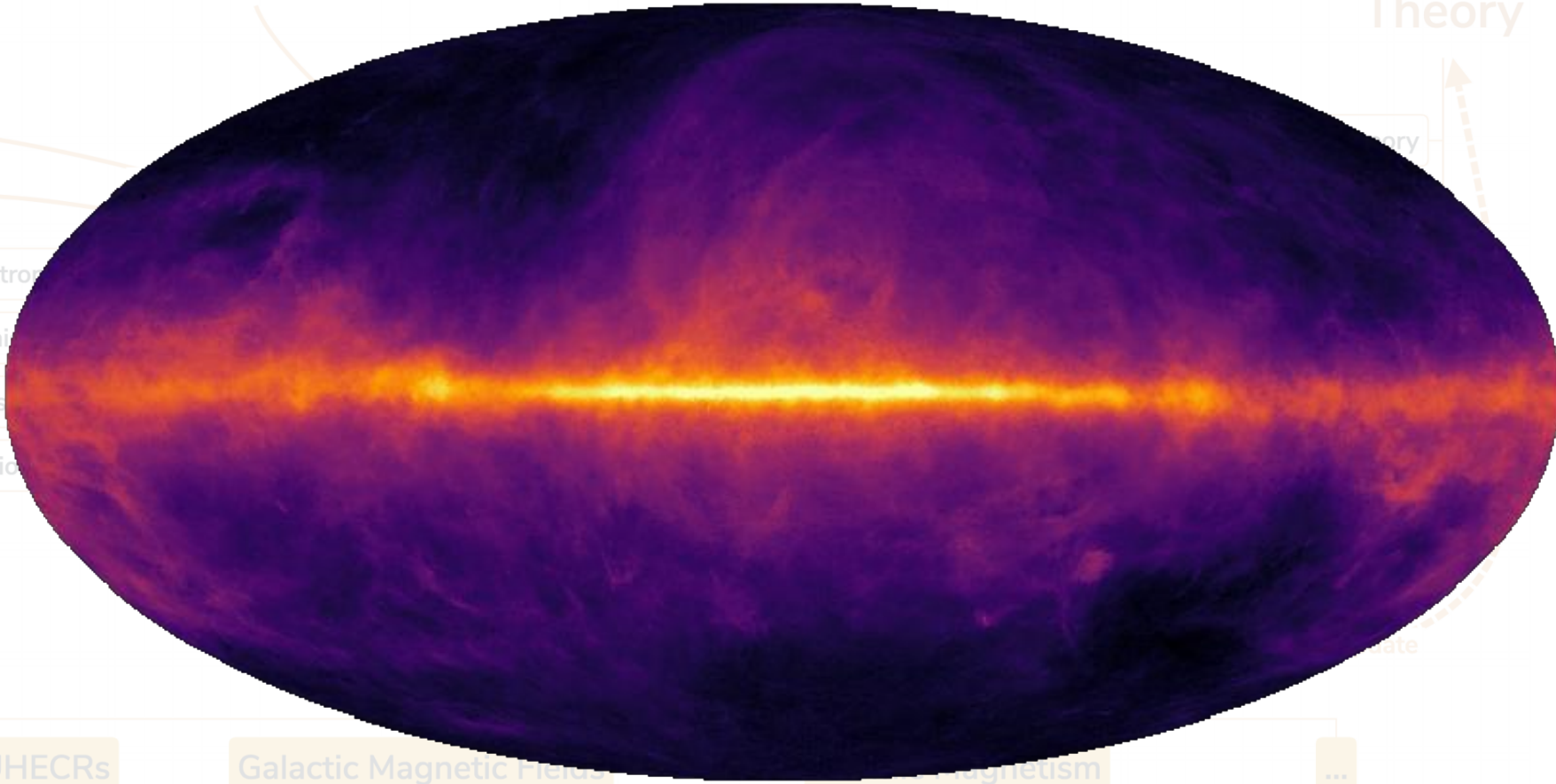
Gamma Rays

Selig et al (2014)

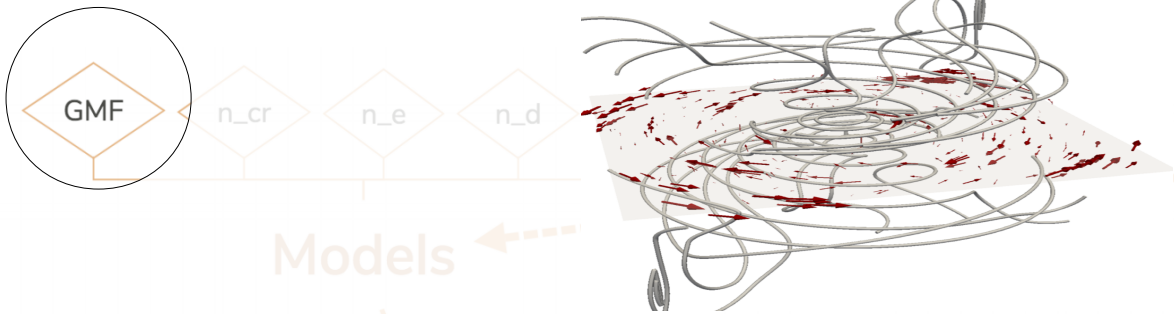


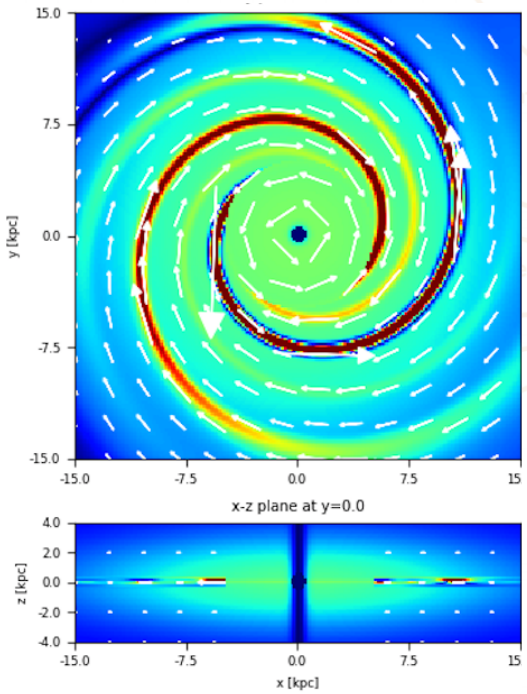
Gamma Rays

Ancla Müller et al (2018)

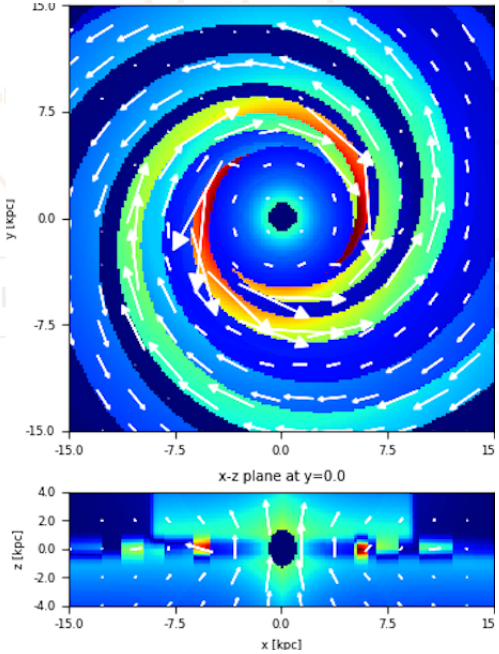


Galactic Magnetic Field

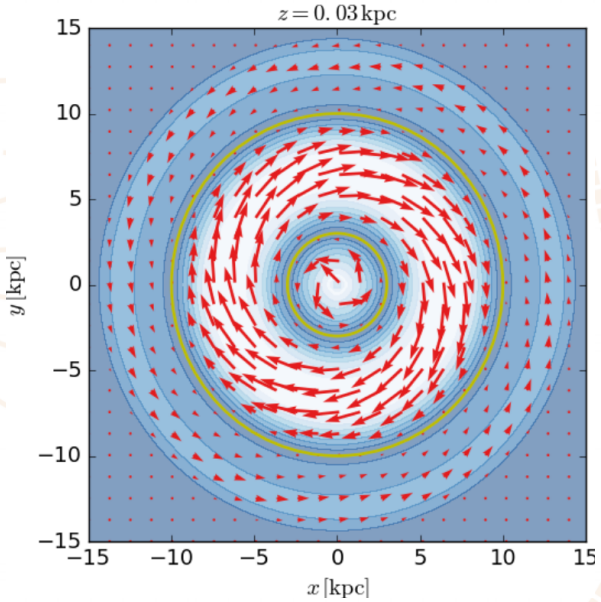




Jaffe et al. 2010,2011,2013)



Jansson & Farrar (2012a,b)



Theoretical GMF model
(courtesy L. Rodrigues)

Origin of UHECRs
Galactic Magnetic Fields
Cosmic Magnetism
...
Neutrino Sources
Gamma-ray sources
Dark Matter
CMB Science
Primordial Magnetic Fields
Extragalactic Magnetic Fields

Galactic Cosmic Rays

Orlando (2018)

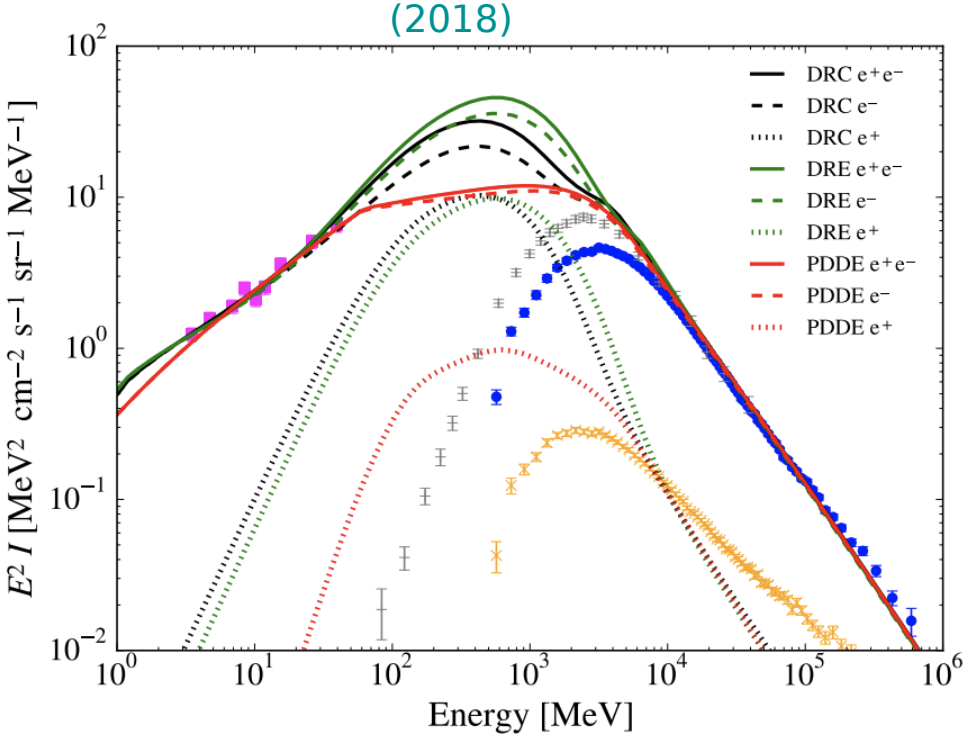
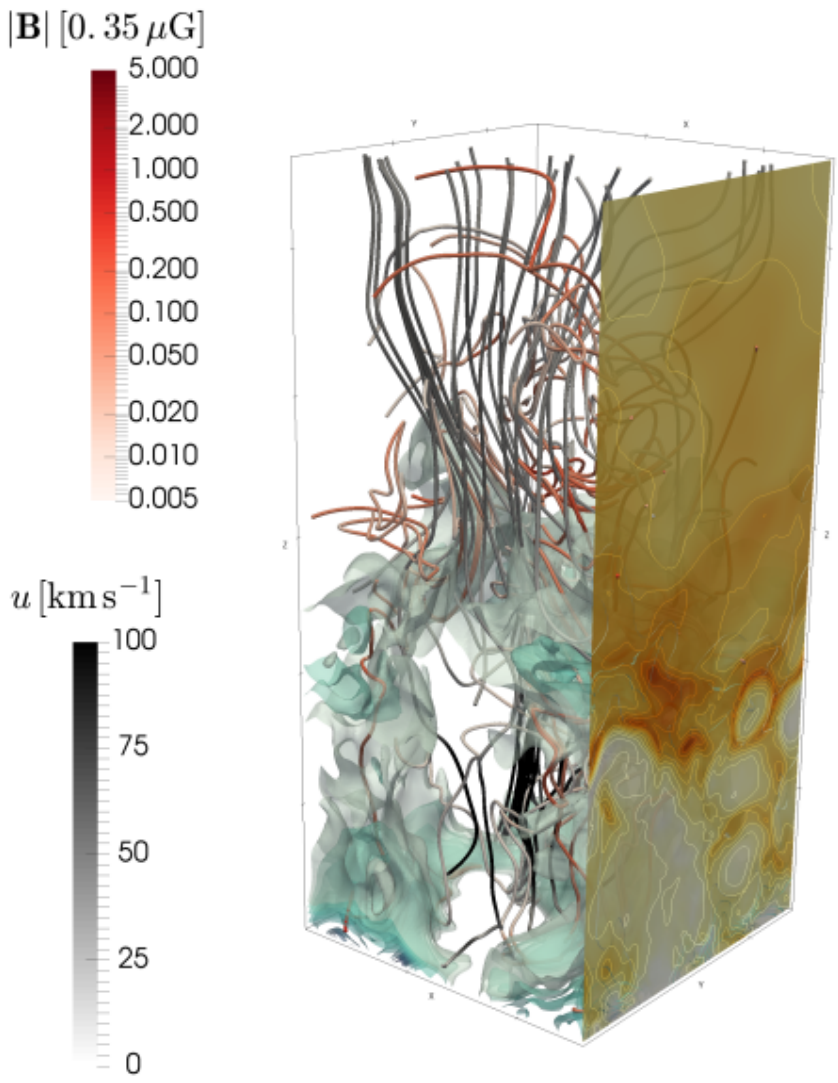
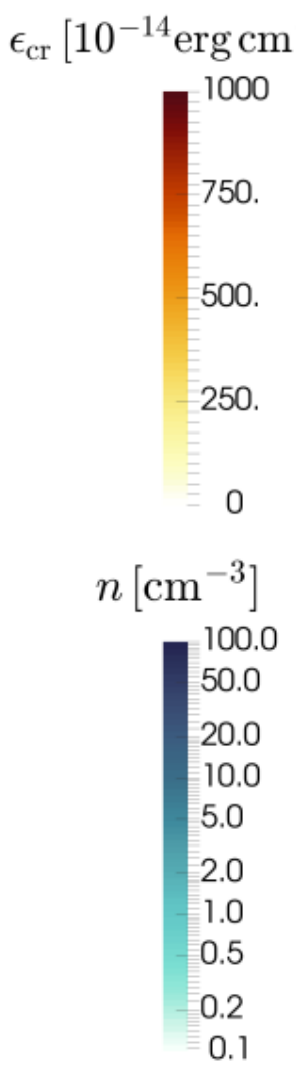
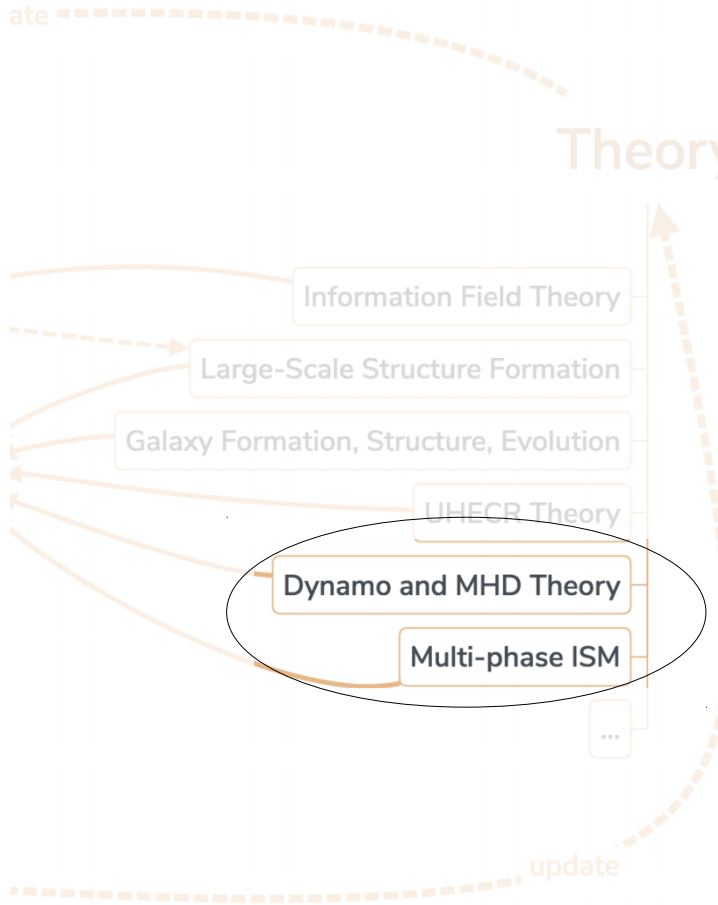


Figure 2. Propagated interstellar spectra of the three baseline models DRE (green line), DRC (black line), and PDDE (red line) for positrons (dotted lines), electrons only (dashed lines), and all-electrons (solid lines) compared with data: orange crosses: AMS-02 positrons (Aguilar et al. 2014); blue 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).

Turbulent ISM



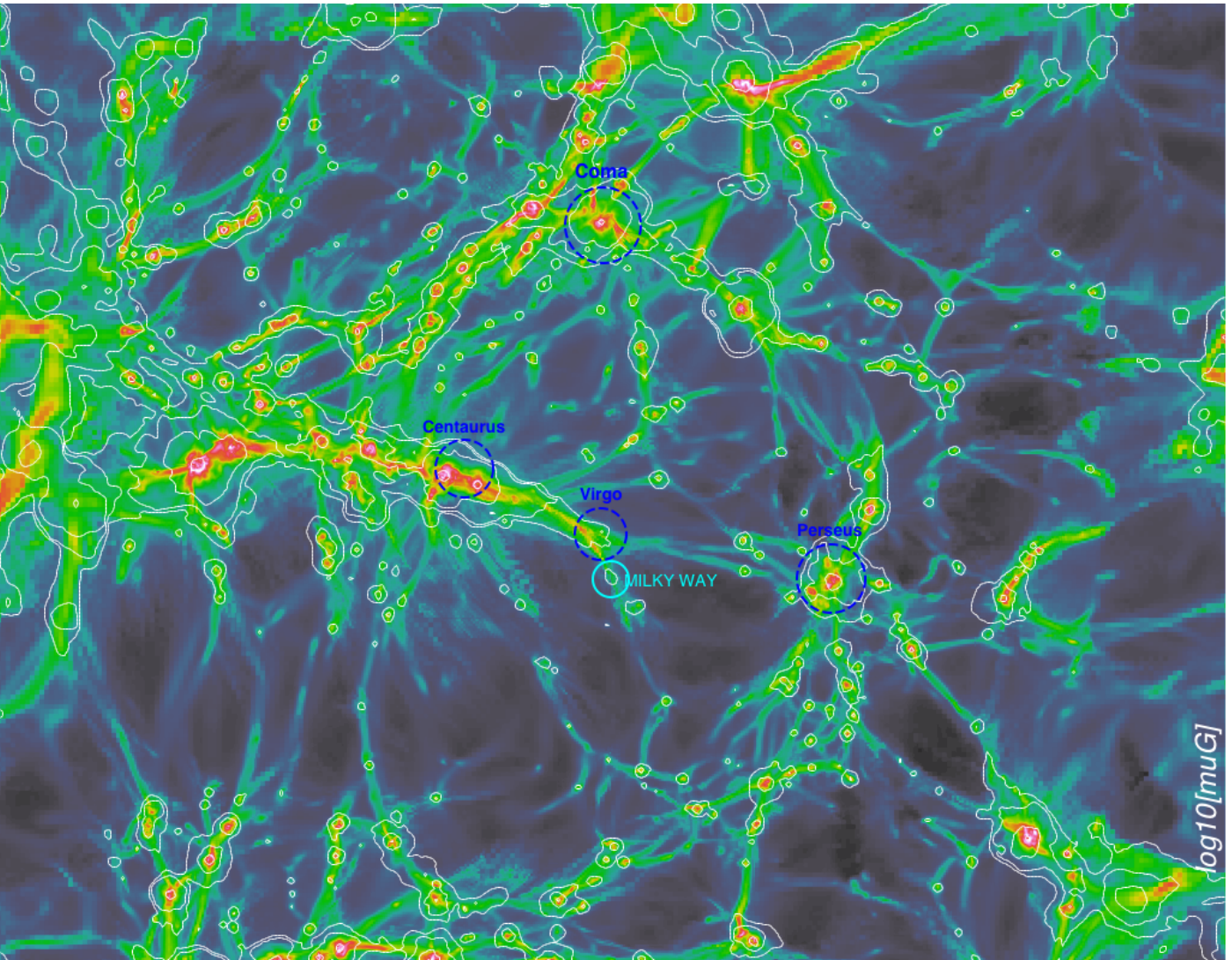




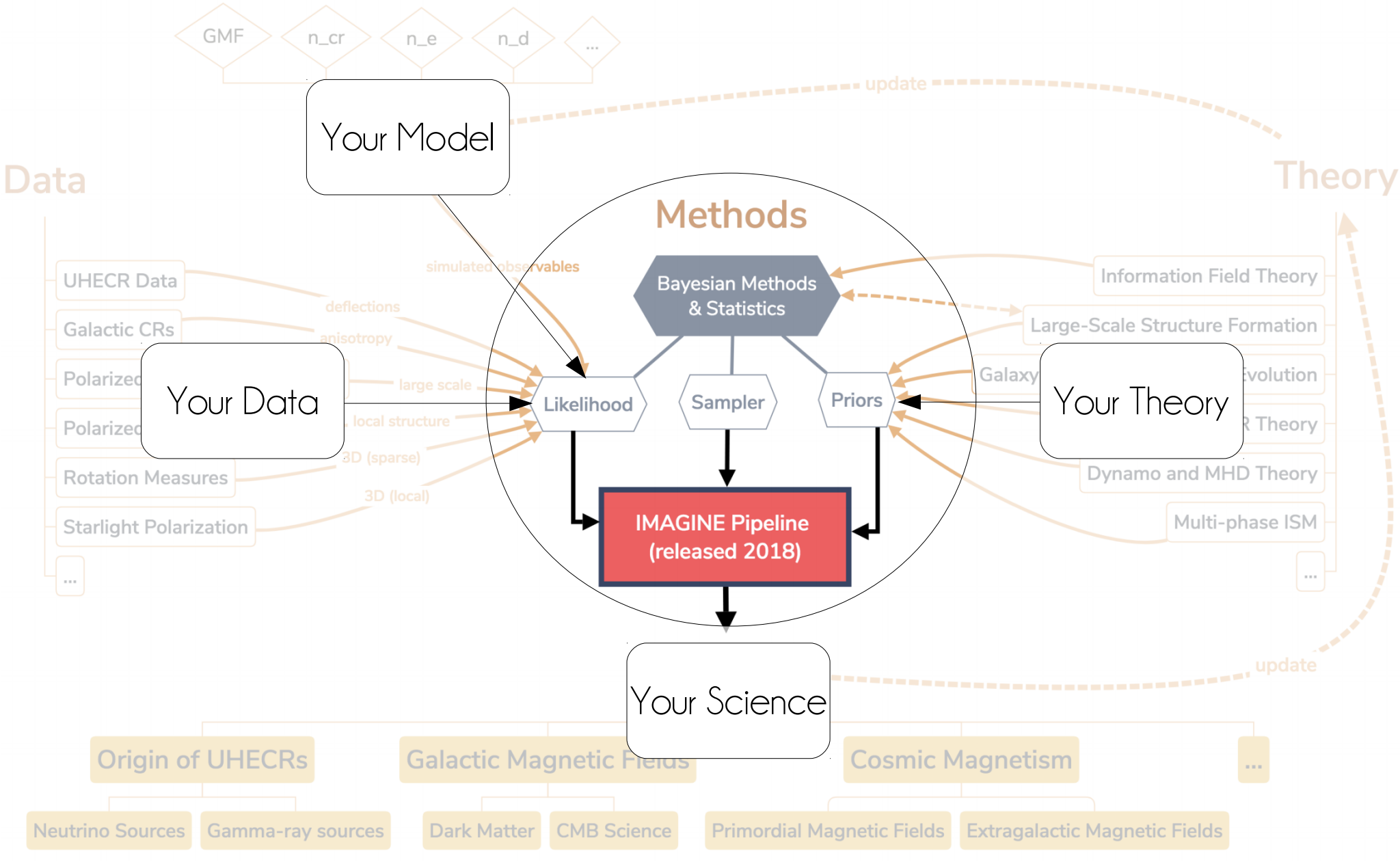
Origin of UHECRs | Galactic Magnetic Fields | Cosmic Magnetism | ...

Neutrino Sources | Gamma-ray sources | Dark Matter | CMB Science | Primordial Magnetic Fields | Extragalactic Magnetic Fields

Intergalactic Magnetism

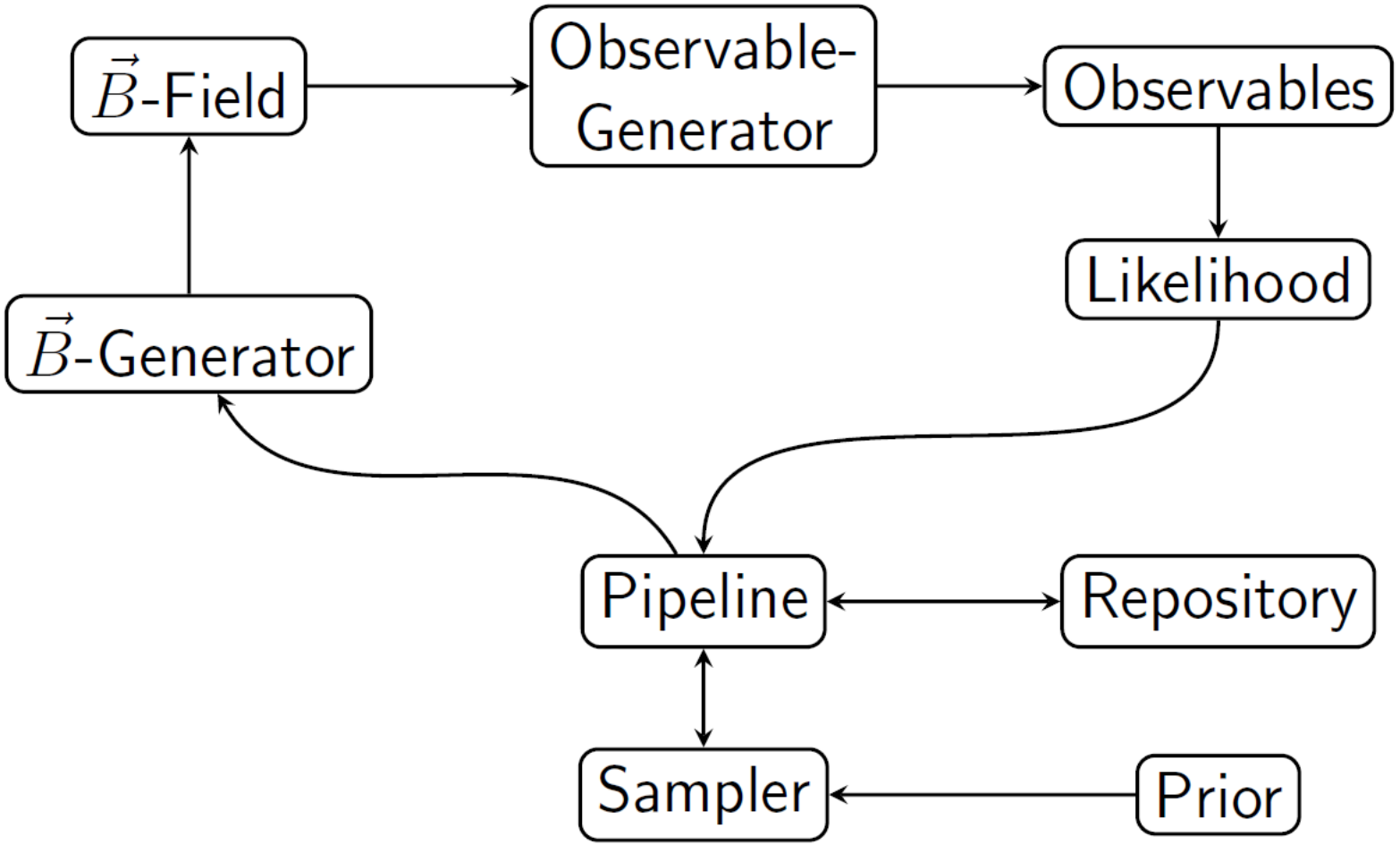


Modular Engine



IMAGINE ALGORITHM

Theo Steininger et al (2018)
arXiv:1801.04341



IMAGINE ALGORITHM

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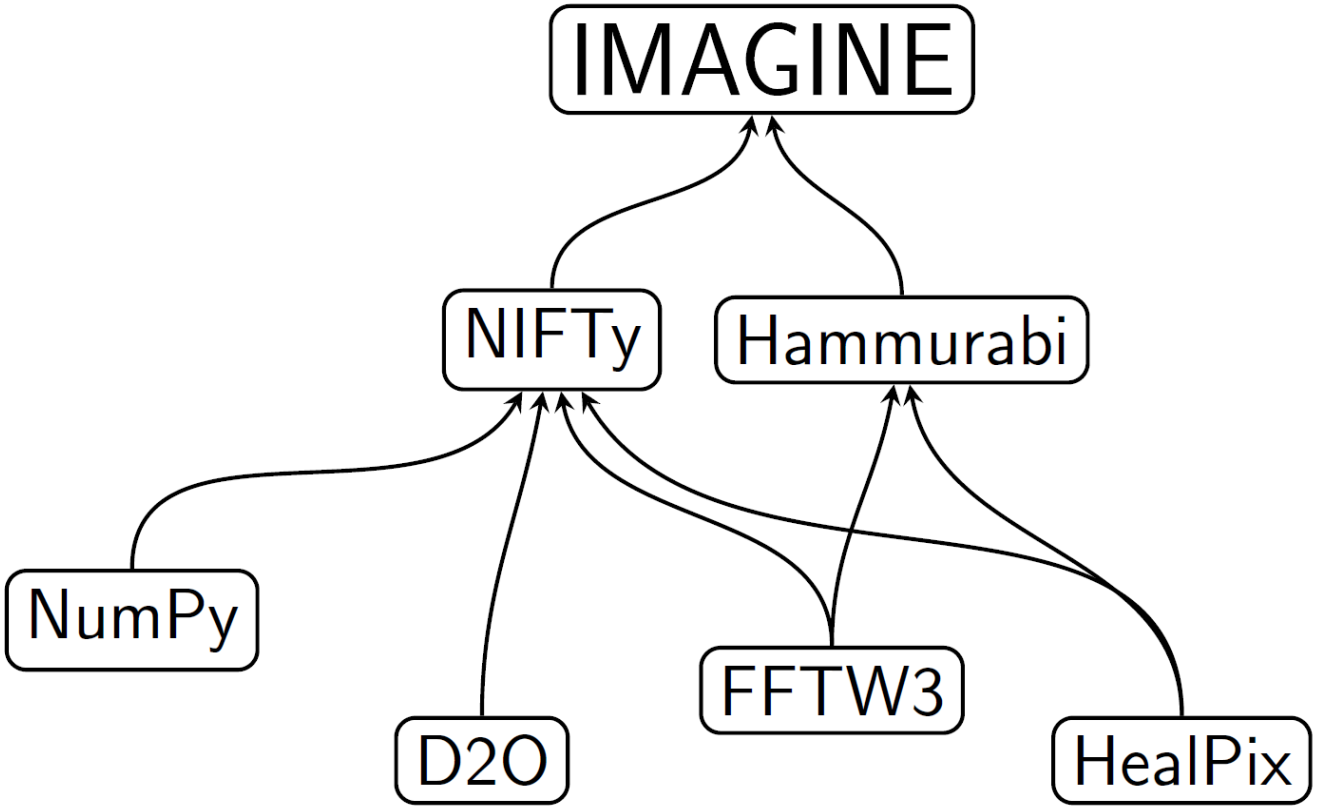
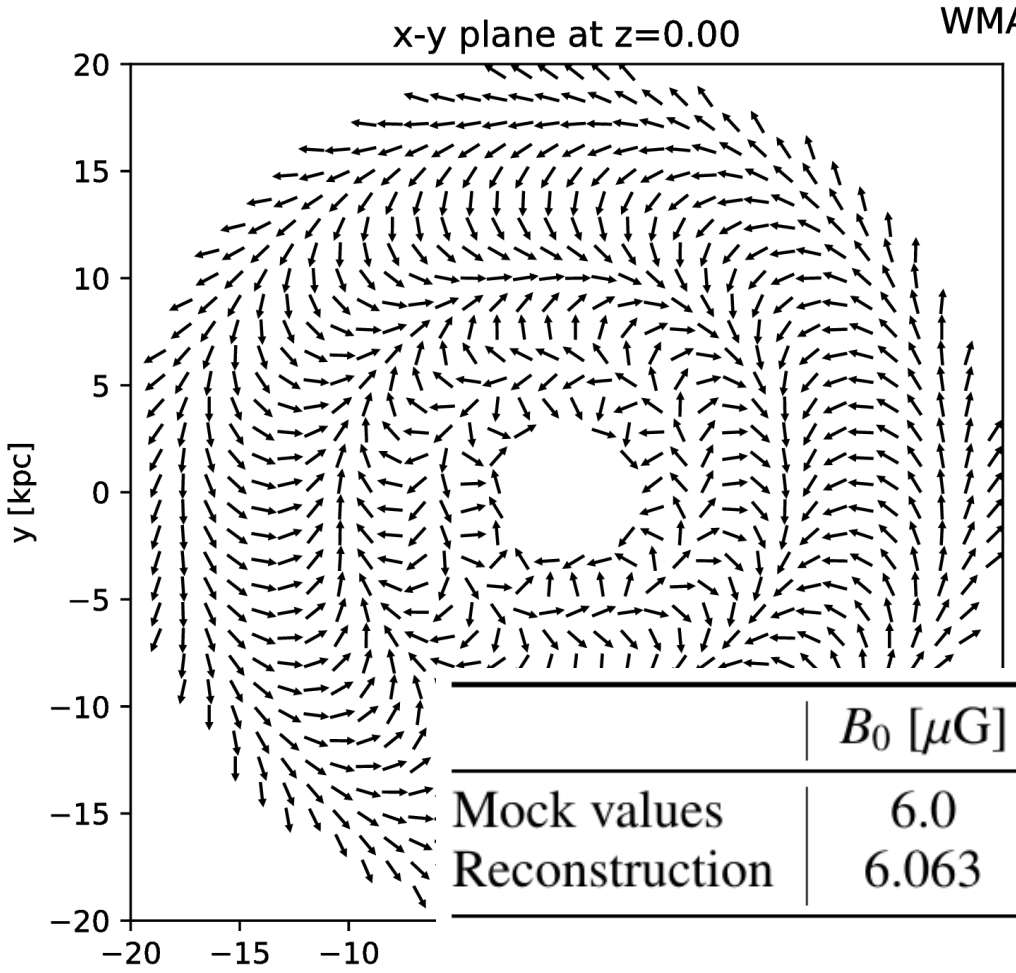


WMAP Model

Theo Steininger et al (2018)
arXiv:1801.04341



$$
\begin{aligned}
B_0 &= 6.00 \in [0.3, 11.7]\ \mu\mathrm{G} \\
\chi_0 &= 25.0 \in [1.0, 49.0]^\circ \\
\psi_0 &= 27.0 \in [6.0, 48.0]^\circ \\
\psi_1 &= 7.95 \in [0, 15.9]^\circ \\
\tau &= 2.00 \in [0.2, 3.8]\ \mu\mathrm{G} \\
\alpha &= 1.7 \in [0.2, 3.2]
\end{aligned}
$$

	B_0 [μG]	ψ_0 [°]	ψ_1 [°]	χ_0 [°]	τ [μG]	α
Mock values	6.0	27.0	7.95	25.0	2.0	1.7
Reconstruction	6.063	26.86	8.38	23.9	2.11	1.698

$$\boldsymbol{B}(r, \phi, z) = B_0 \left[\sin(\psi)\cos(\chi)\hat{\boldsymbol{r}} + \cos(\psi)\cos(\chi)\hat{\boldsymbol{\phi}} + \sin(\chi)\hat{\boldsymbol{z}} \right] ,$$

$$\psi = \psi_0 + \psi_1 \ln\left(\frac{r}{R_0}\right) ,$$

$$\chi = \chi_0 \tanh\left(\frac{z}{z_0}\right) ,$$

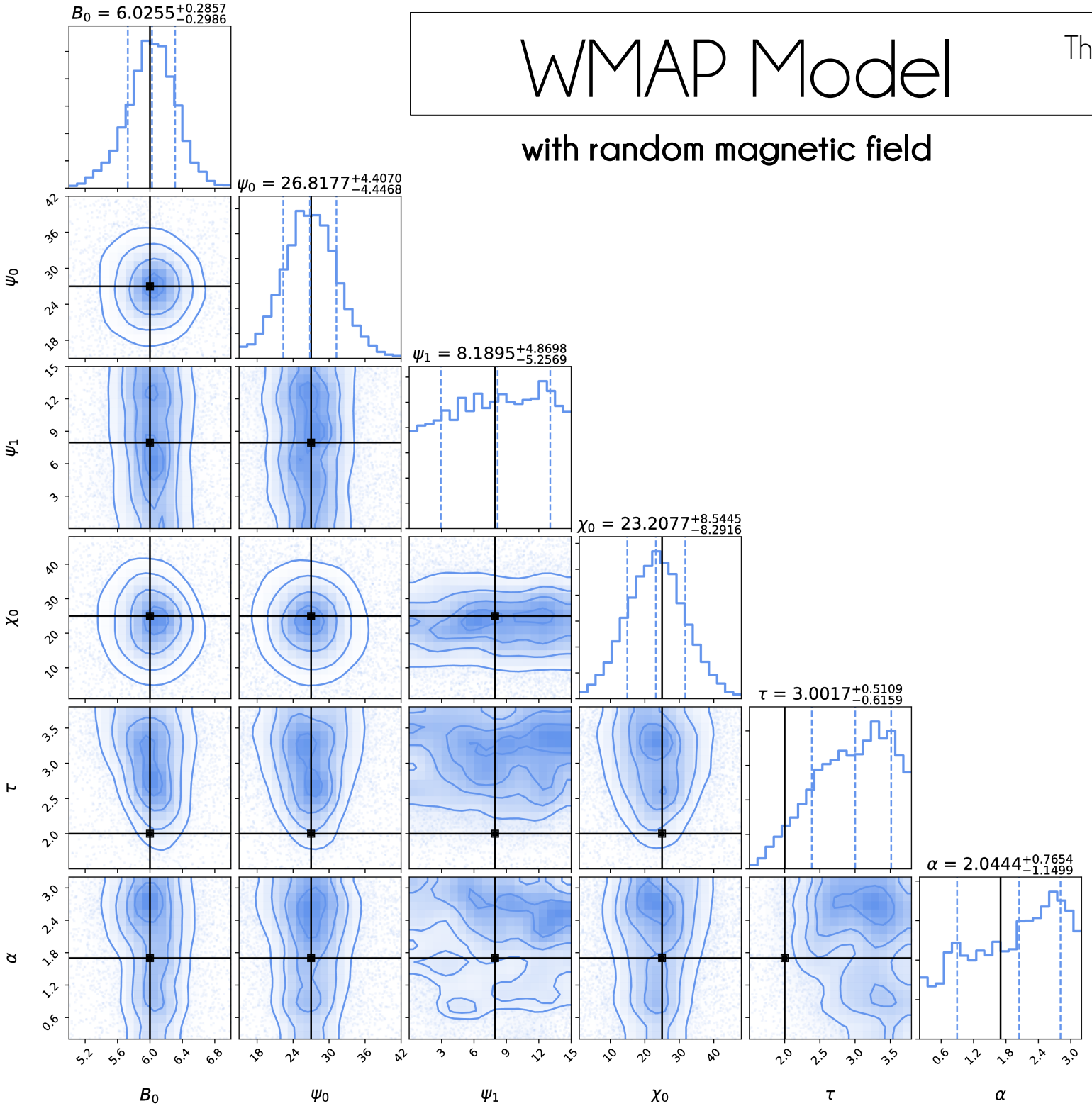
Radom magnetic field with profile, being solenoidal, from Gaussian process with spatial power spectrum

→ Galactic variance is fully taken into account!

WMAP Model

Theo Steininger et al (2018)
arXiv:1801.04341

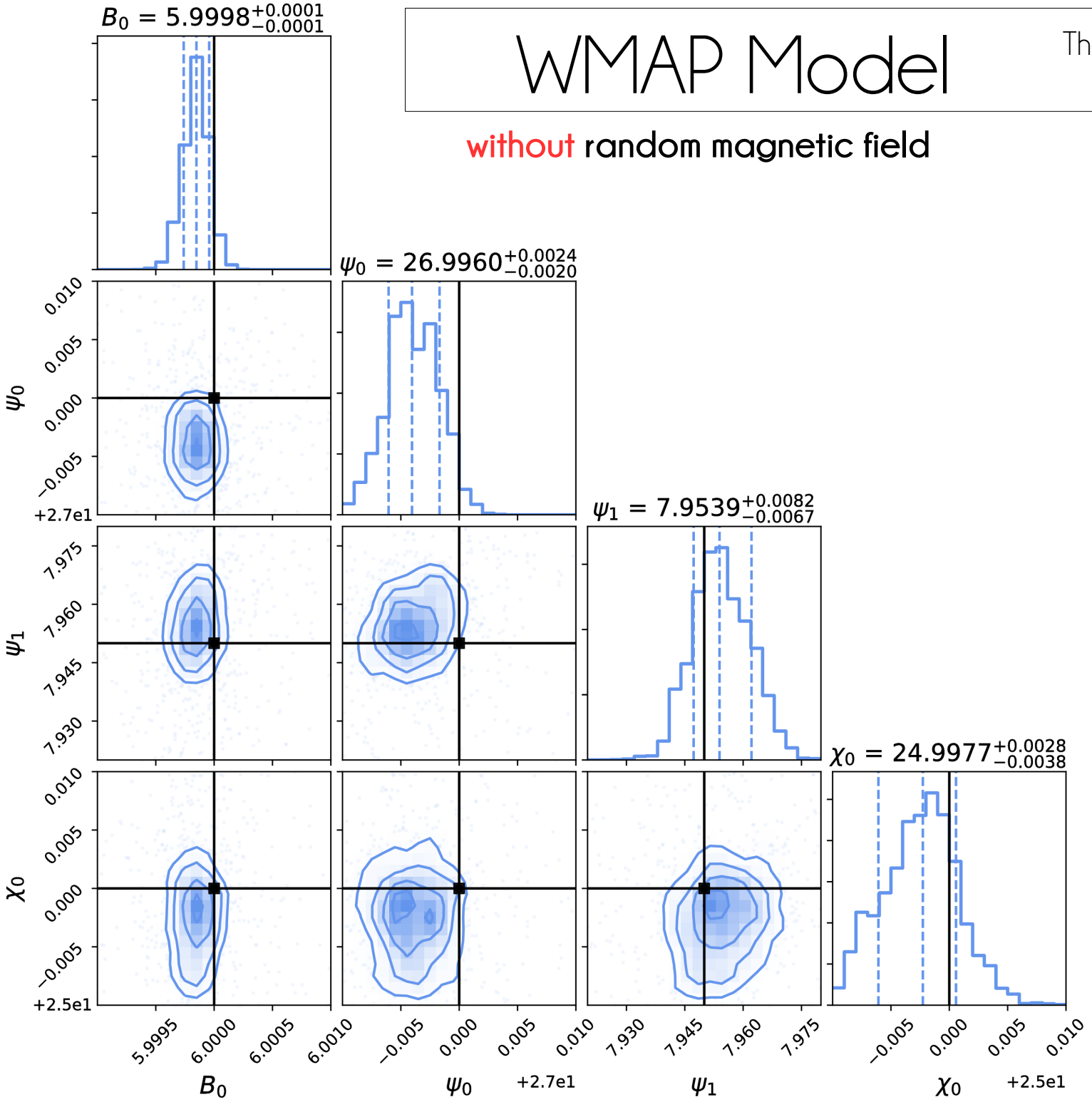
with random magnetic field



WMAP Model

Theo Steininger et al (2018)
arXiv:1801.04341

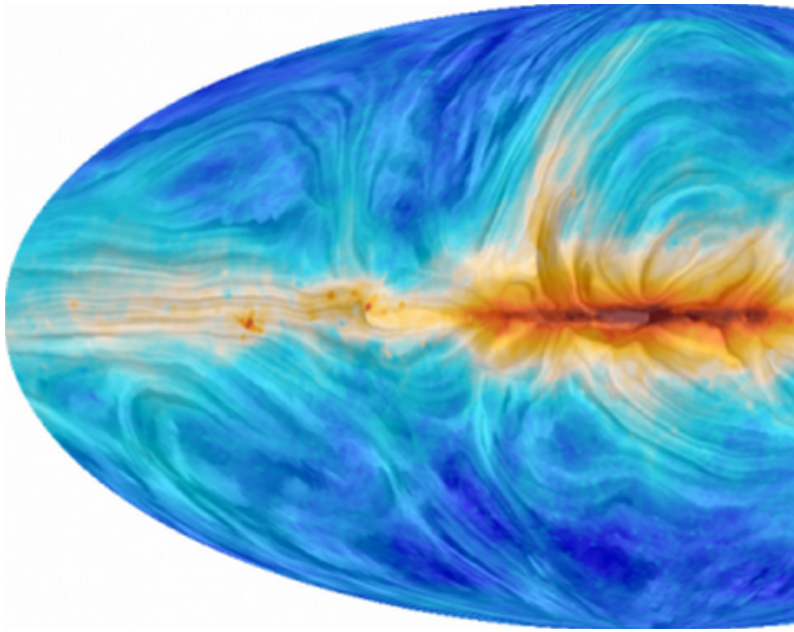
without random magnetic field

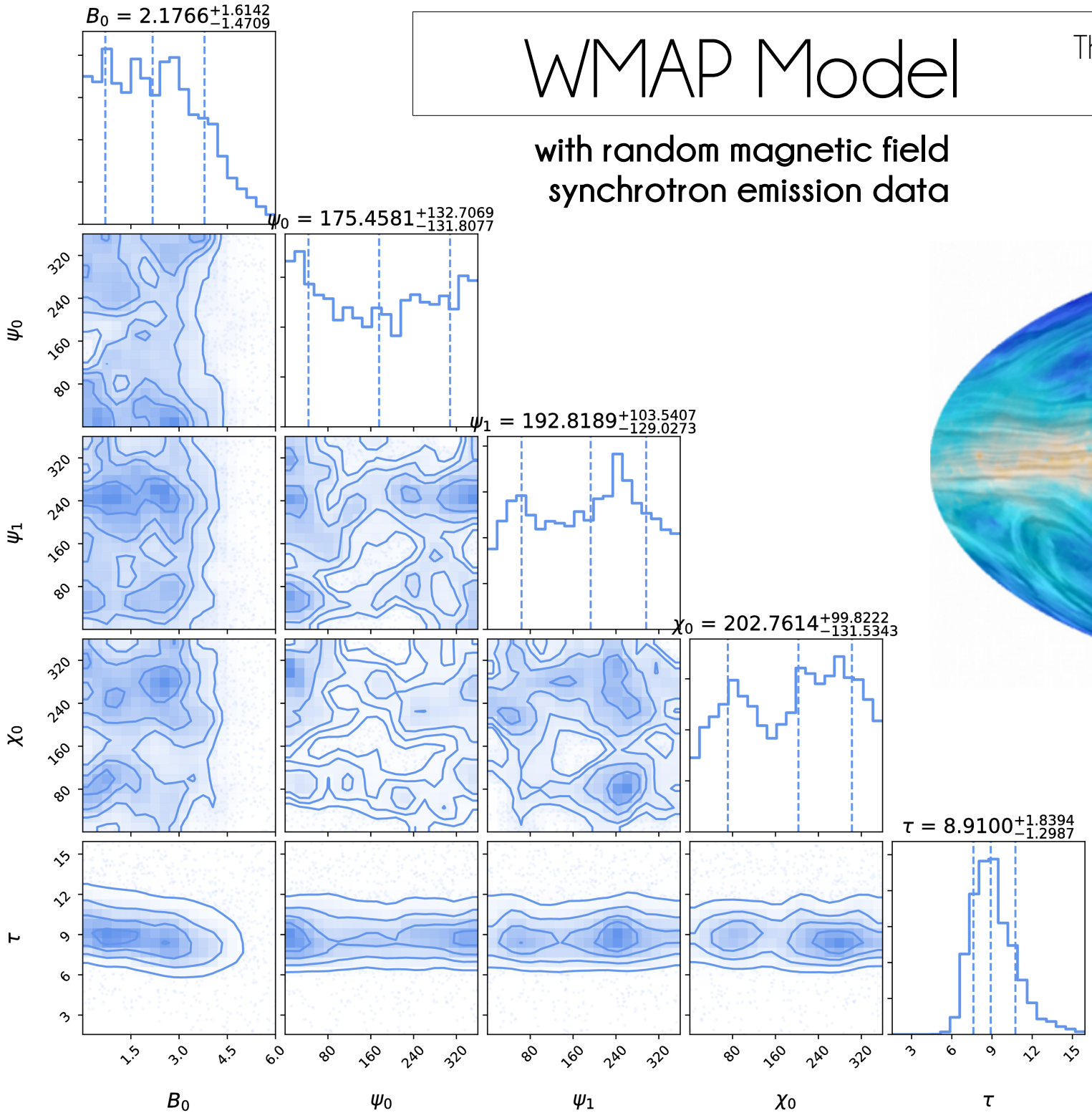


WMAP Model

Theo Steininger et al (2018)
arXiv:1801.04341

with random magnetic field
synchrotron emission data

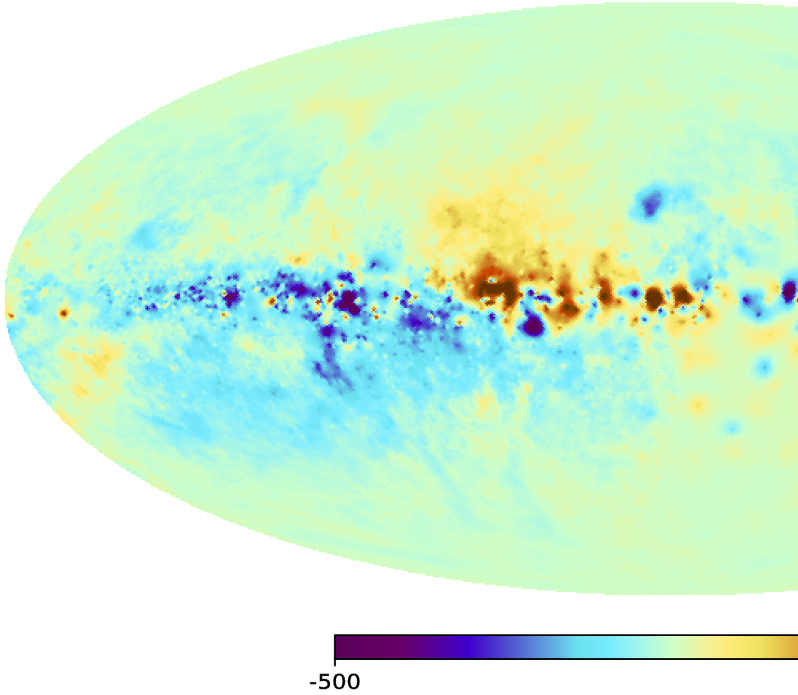


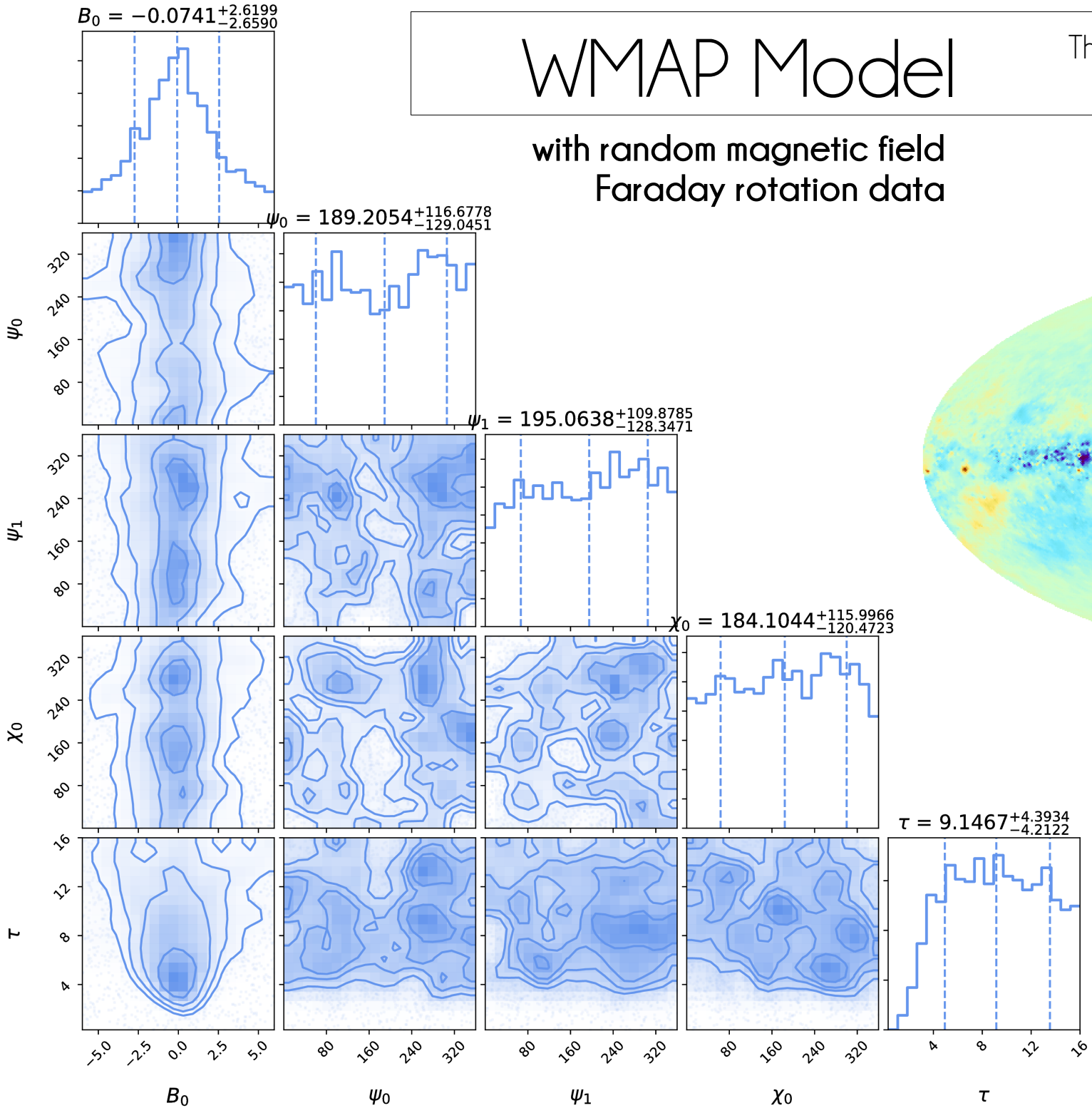


WMAP Model

Theo Steininger et al (2018)
arXiv:1801.04341

with random magnetic field
Faraday rotation data





Galactic Tomography

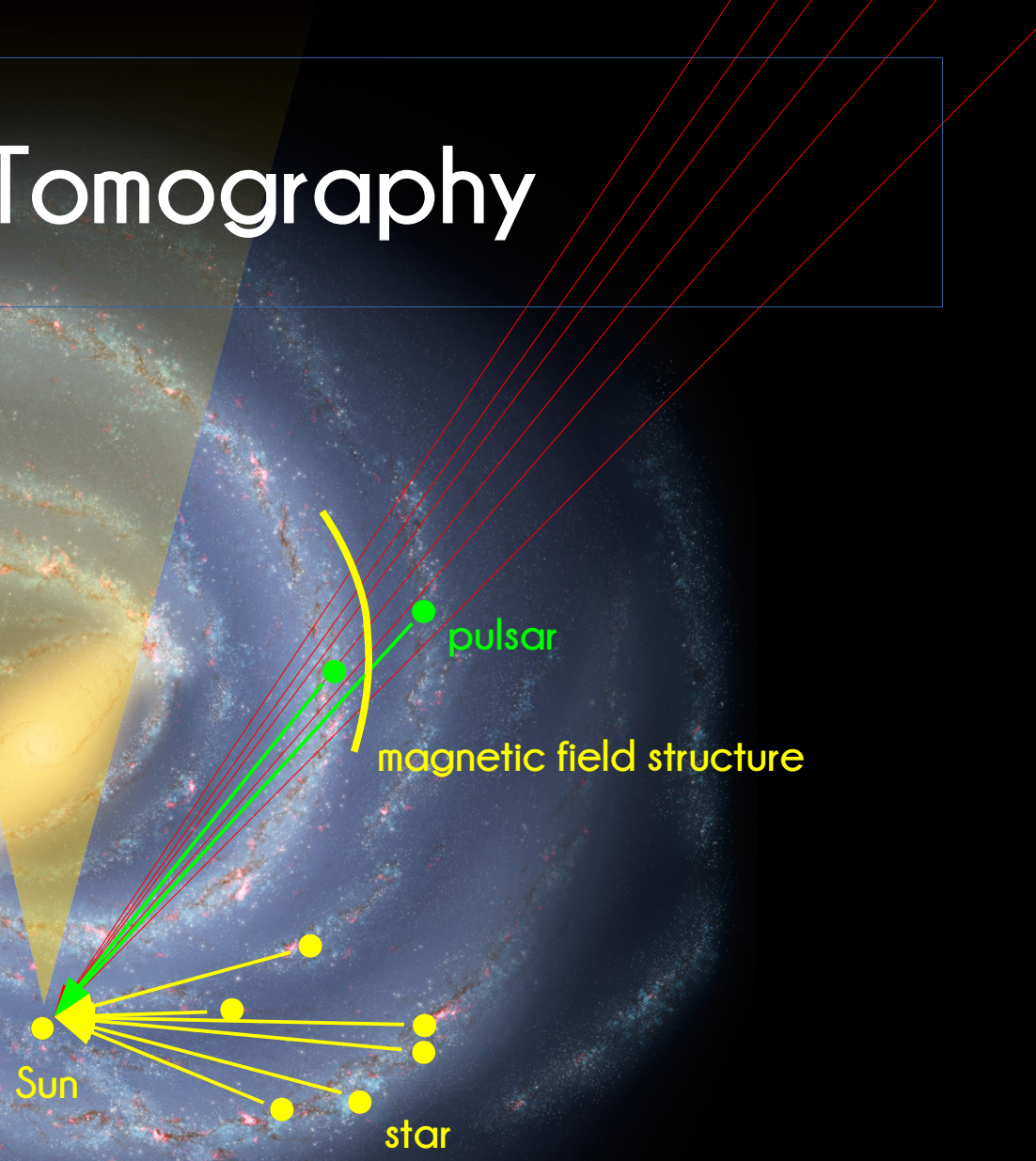
Pulsars:
Dispersion Measure → electron density
Rotation Measure → magnetic field x el. dens.
Scintillation Measure → el. dens. x turbulence

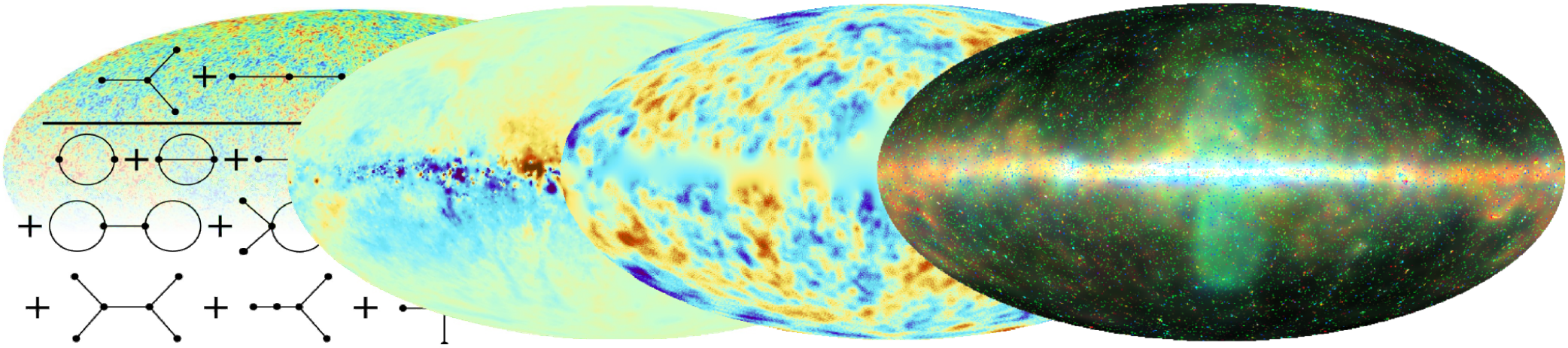
Extragalactic sources:
Rotation Measure → magnetic field x el. dens.
Ultra High Energy Cosmic Rays → mag. fields

Stars:
Dust reddening → dust density & properties
Positions → stellar density & radiation field
Kinematics → gravitational potential

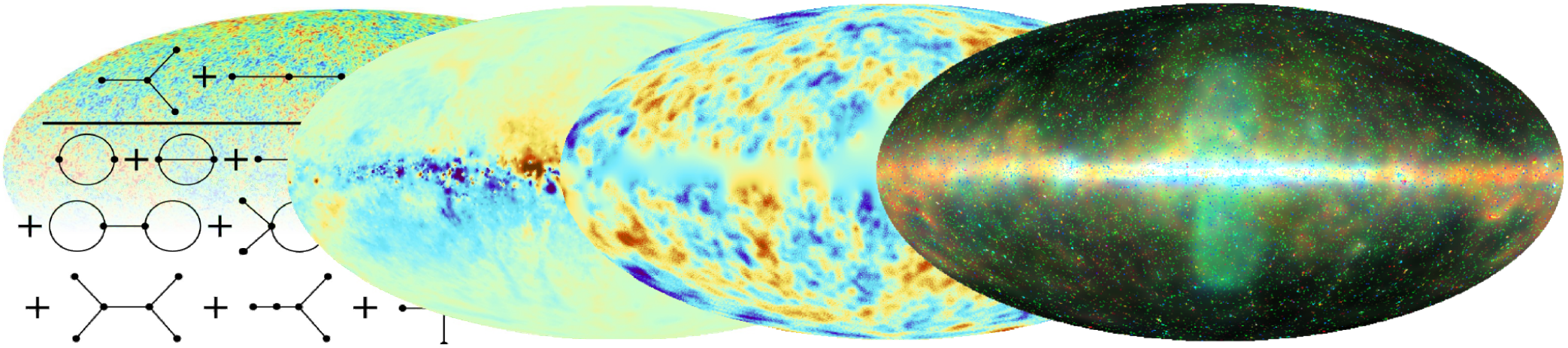
Emission Processes:
Dust emission → dust density & radiation field
Synchrotron → relativistic el. x mag. Fields
Bremsstrahlung → thermal, rel. el. x gas density
Inverse Compton → rel. el. x radiation field
Hadronic interactions → rel. nuclei x gas density
Lines (21 cm, CO, ...) → gas density & kinematics

Other information sources:
Correlation structures (auto- & cross-correlations)
Approximate symmetries
Physical laws
Empirical laws
...





Information field theory



Information theory for fields

Conclusions

IMAGINE
a framework, a consortium, & a pipeline
for Galactic (magnetic) field inference

so far
parametric model fitting
including non-parametric random magnetic fields

Galactic tomography
is the way to go
requires information theory for fields
→ Information Field Theory (stay tuned)