

4th CRISM conference – Grenoble, France

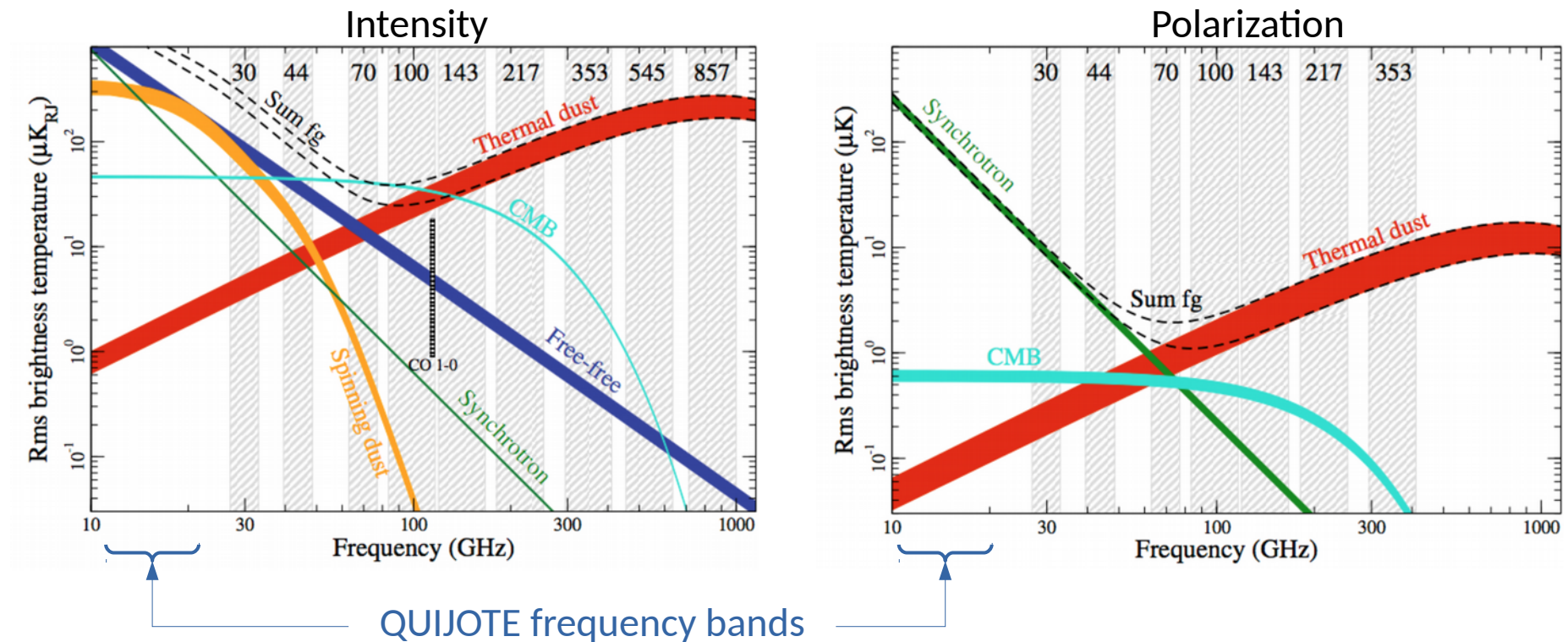
Reconstruction of the regular Galactic magnetic field from polarized emission at CMB frequencies

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‘Ultimate’ characterization of the CMB Foregrounds at radio to sub-mm wavelengths

- Add low frequency data to help the separation of the components

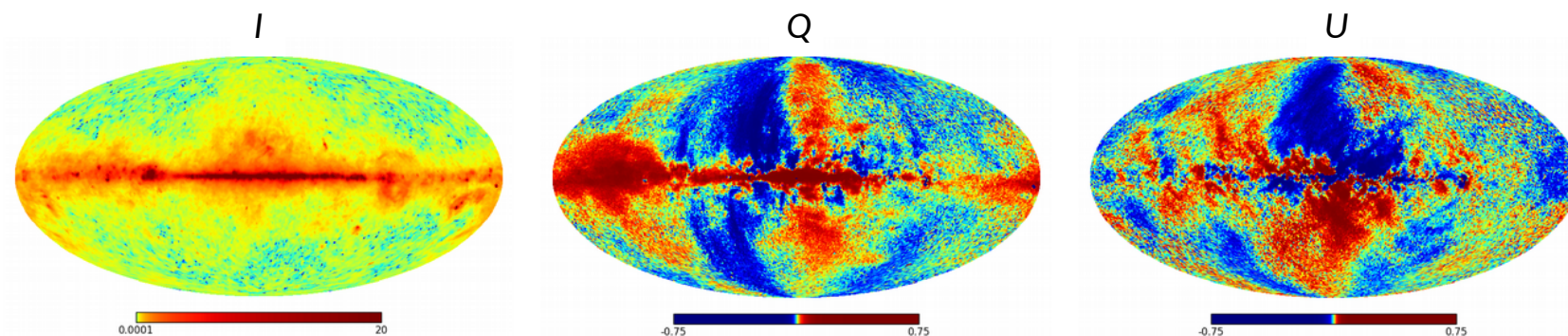


- Provide the community with tools and up-to-date models
- Forecasting limitations of component separation algorithms for the future CMB probes
- Provide the best **three-dimensional regular Galactic Magnetic field**

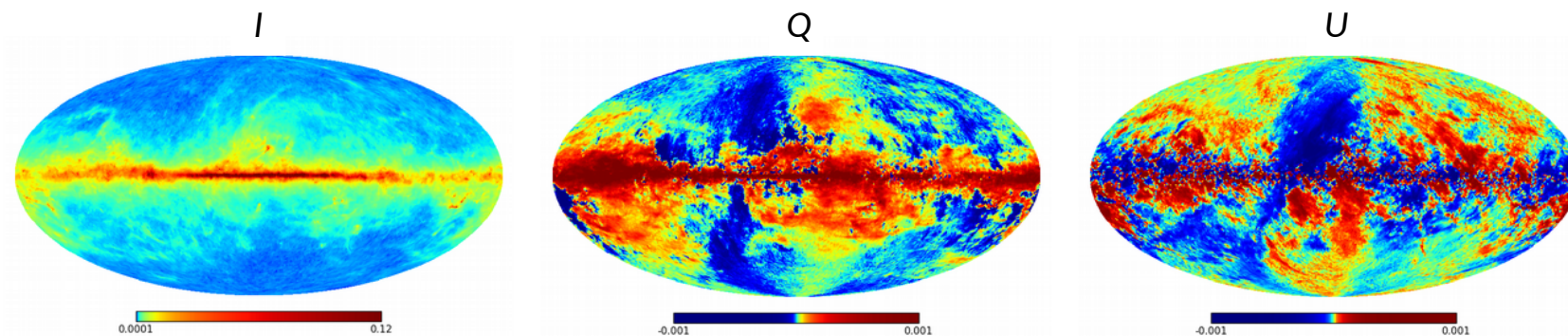
Polarized Diffuse Galactic Foregrounds and GMF

DATA: synchrotron & thermal dust

Synchrotron @ 22 GHz (WMAP)

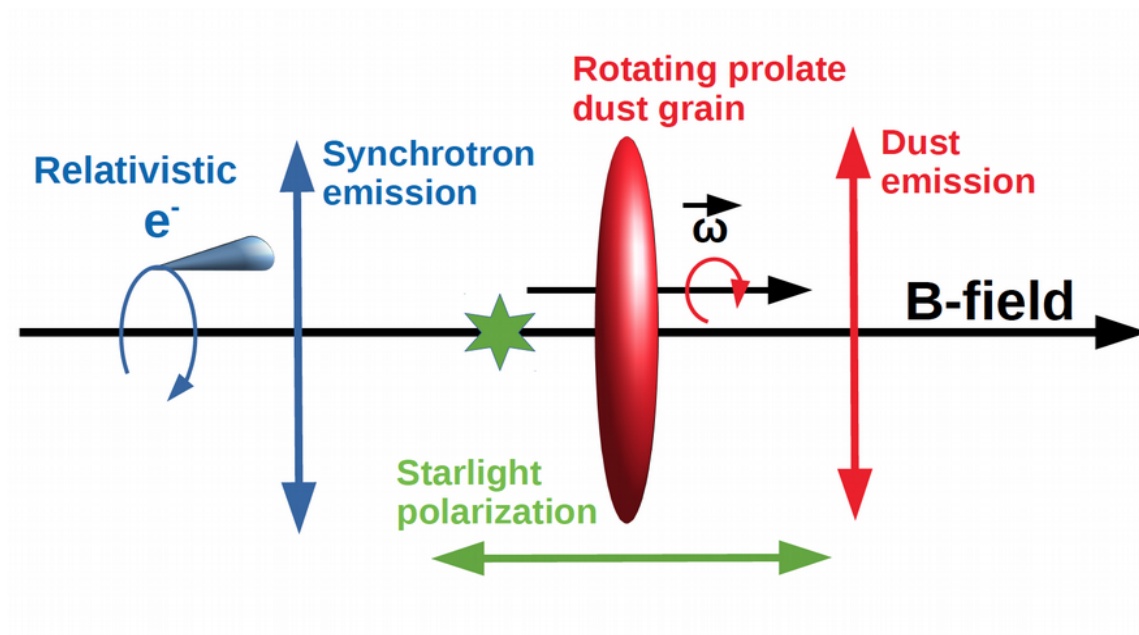


Thermal dust @ 353 GHz (*Planck*)



OBJECTIVE: extract the GMF from there

Polarized Diffuse Galactic Foregrounds and GMF



Emission modelings:

- Synchrotron: (inspired from [Rybicki & Lightman 1979])

$$I(\mathbf{n}) = \epsilon_\nu \int_0^{+\infty} dr n_e(r, \mathbf{n}) (\mathbf{B}_\perp(r, \mathbf{n})^2)^{(s+1)/4}$$

$$Q(\mathbf{n}) = \epsilon_\nu p_{sync} \int_0^{+\infty} dr n_e(r, \mathbf{n}) (\mathbf{B}_\perp(r, \mathbf{n})^2)^{(s+1)/4} \cos[2\gamma(r, \mathbf{n})]$$

$$U(\mathbf{n}) = \epsilon_\nu p_{sync} \int_0^{+\infty} dr n_e(r, \mathbf{n}) (\mathbf{B}_\perp(r, \mathbf{n})^2)^{(s+1)/4} \sin[2\gamma(r, \mathbf{n})]$$

α = inclination angle
 γ = position angle

of the GMF vectors
w.r.t. lines of sight

- Thermal dust: (inspired from [Lee & Drain 1985; Fauvet et al. 2011])

$$I(\mathbf{n}) = \epsilon_\nu \int_0^{+\infty} dr n_d(r, \mathbf{n}) \left\{ 1 + p^{\text{dust}} f_{\text{ma}} \left(\frac{2}{3} - \sin^2 \alpha(r, \mathbf{n}) \right) \right\}$$

$$Q(\mathbf{n}) = \epsilon_\nu p^{\text{dust}} f_{\text{ma}} \int_0^{+\infty} dr n_d(r, \mathbf{n}) \sin^2 \alpha(r, \mathbf{n}) \cos[2\gamma(r, \mathbf{n})]$$

$$U(\mathbf{n}) = \epsilon_\nu p^{\text{dust}} f_{\text{ma}} \int_0^{+\infty} dr n_d(r, \mathbf{n}) \sin^2 \alpha(r, \mathbf{n}) \sin[2\gamma(r, \mathbf{n})]$$

To extract GMF, considering dust is to simplify our life:

‘significant’ reduction of the number of parameters to be handled at once

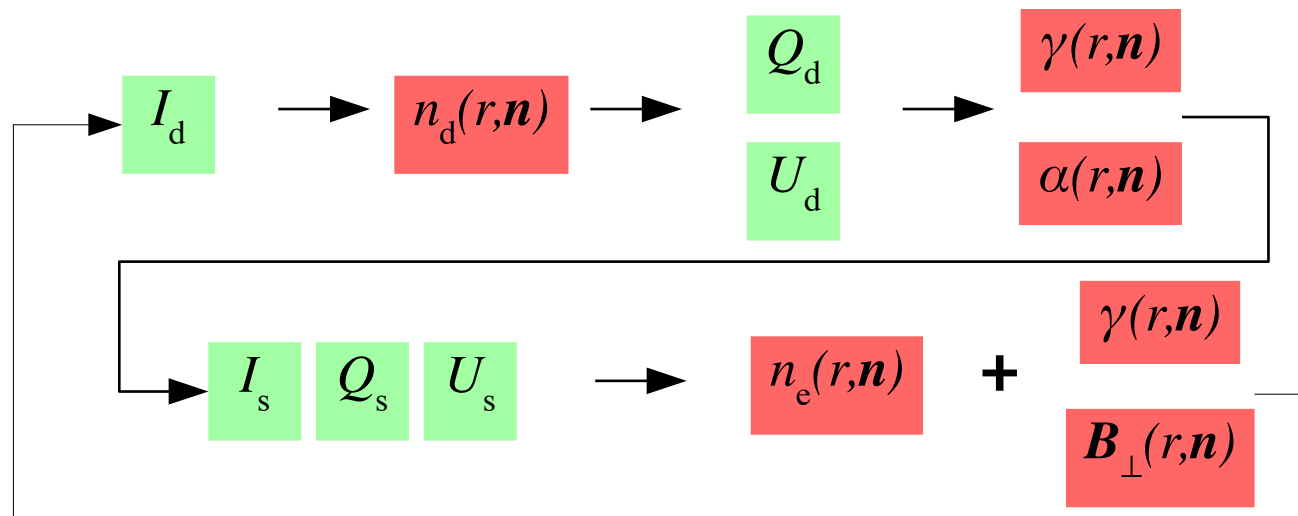
- polarized dust depends ONLY on the geometry of the GMF (not its strength)
- to first order there is the possibility to separate matter and GMF in dust modeling

→ traceability and feasibility for MCMC analysis

Polarized Diffuse Galactic Foregrounds and GMF

Reconstruction of the GMF from synchrotron and dust data?

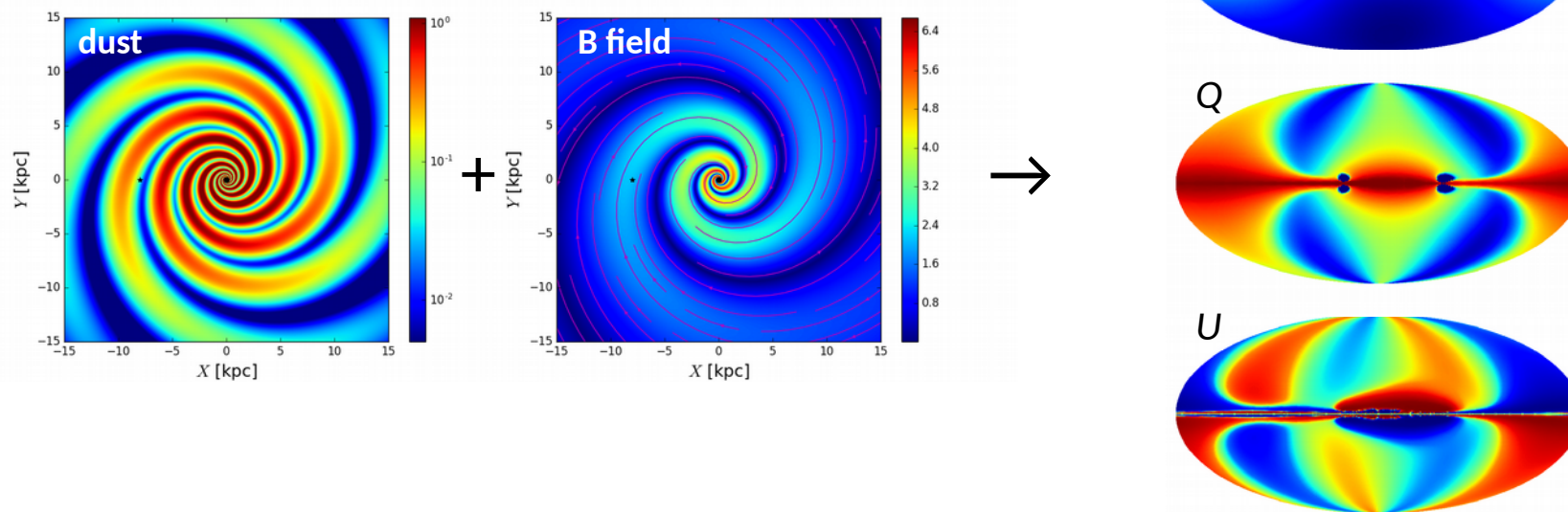
- Our approach: going step by step with sizable parametric models



Polarized Diffuse Galactic Foregrounds and GMF

APPROACH: 3-dimensional modeling of the magnetized Galaxy

- 3D models of matter content
- 3D models of GMF structure (large-scale regular part)
- Integration along the lines of sight of emission mechanism(s)



gpempy software:

- PYthon modules to simulate Galactic Polarized EMISSION (presently thermal dust & synchrotron)

Being released here: [<http://www.radioforegrounds.eu/pages/software/gmf-reconstruction.php>]

Polarized Diffuse Galactic Foregrounds and GMF



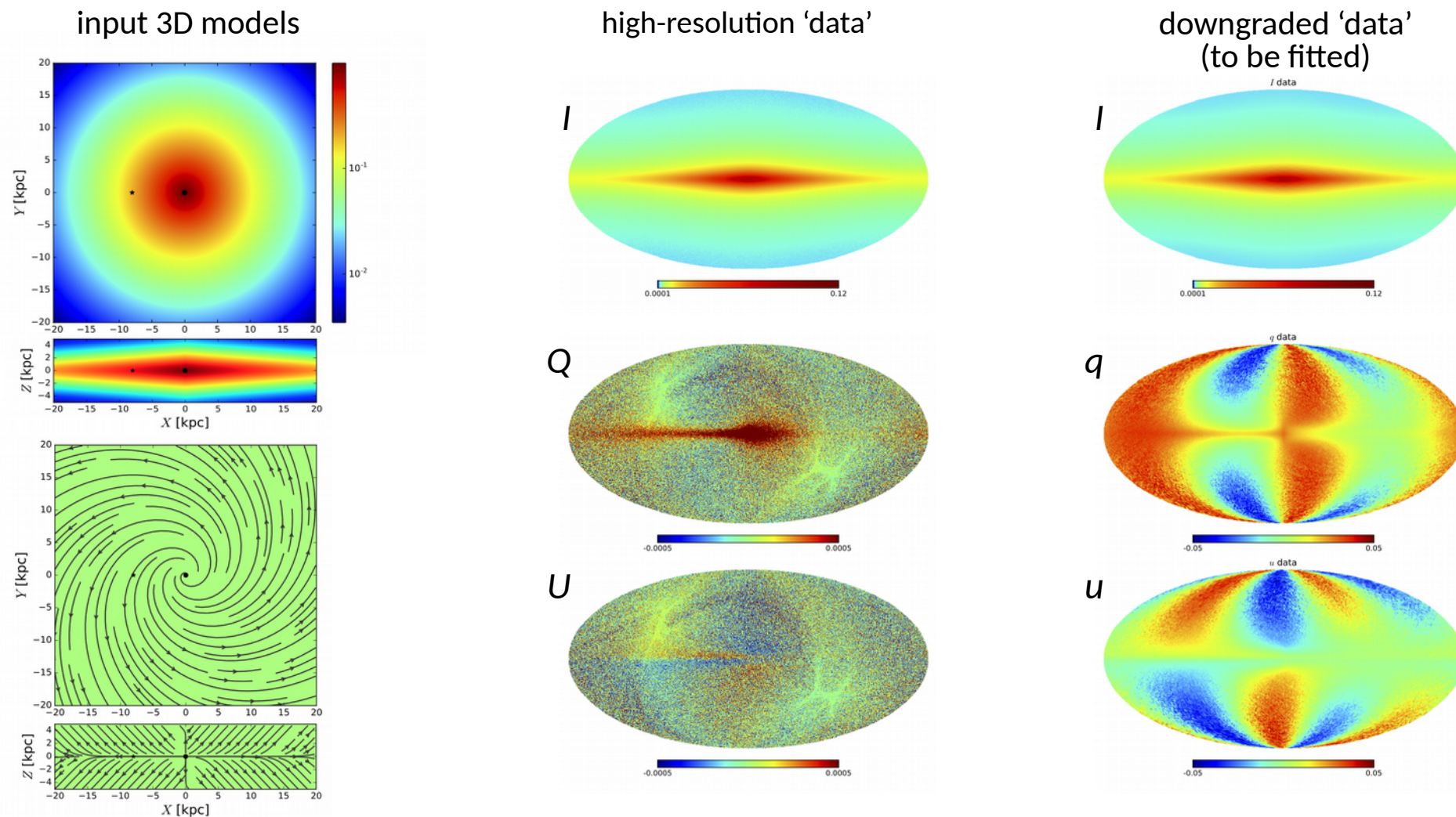
Can we really constrain the GMF from dust data?

Polarized Diffuse Galactic Foregrounds and GMF

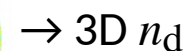
Can we really constrain the GMF from dust data?

Proof of concept using our MCMC on *mock* datasets

I. `mock_1`: n_d = exponential disk ; GMF = WMAP model [Page et al. 2007]

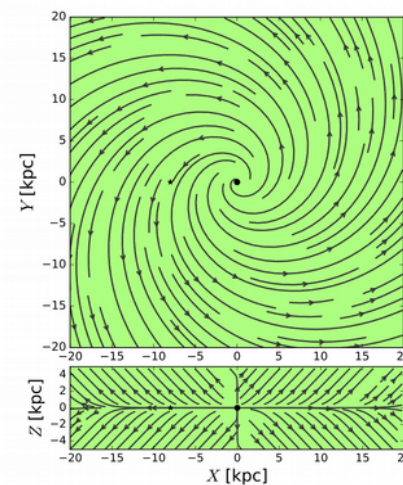
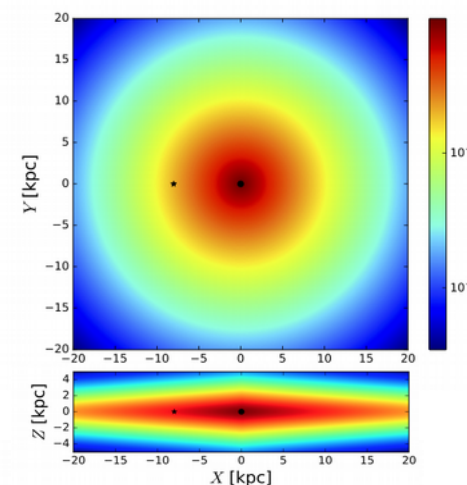


II. MCMC fits on maps



III. 3D models comparison

recovered 3D models

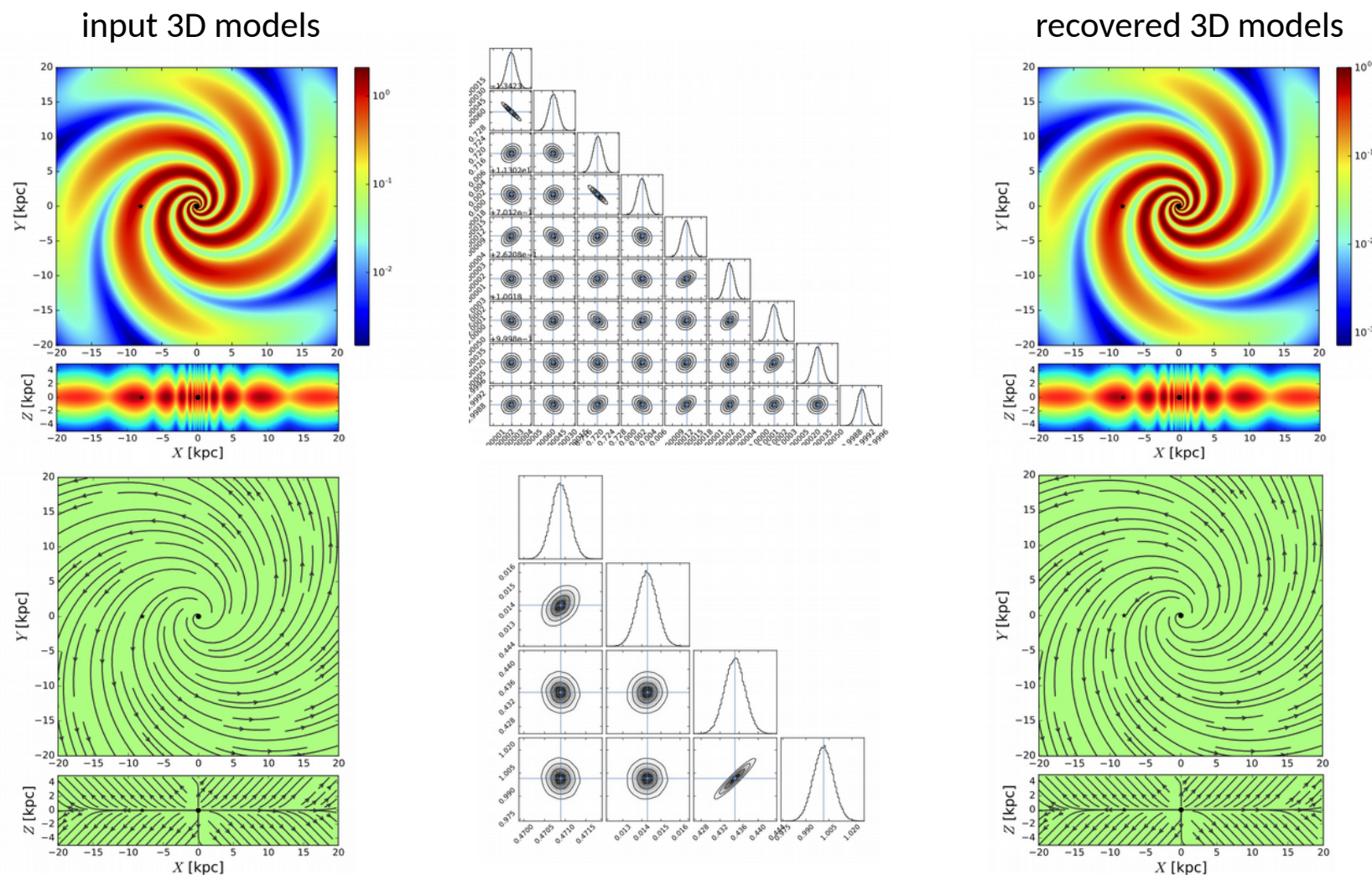


Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from dust data?

Proof of concept using our MCMC on *mock* datasets

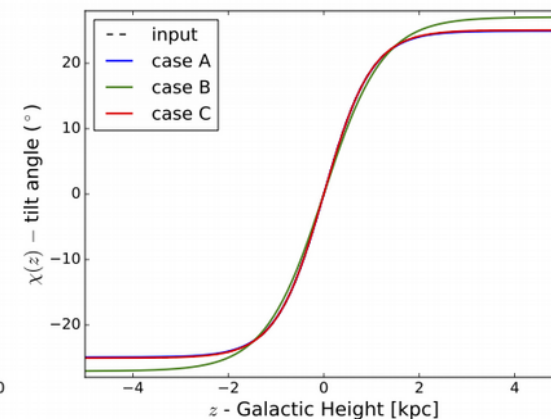
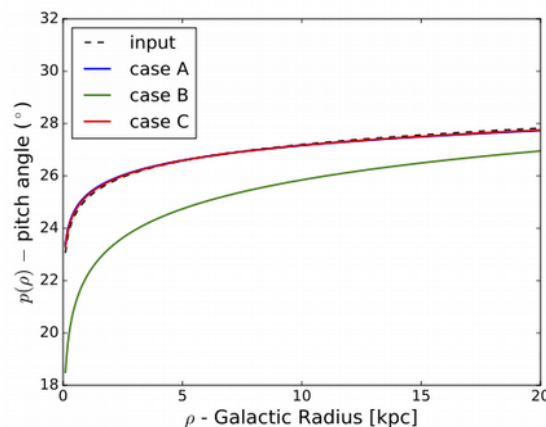
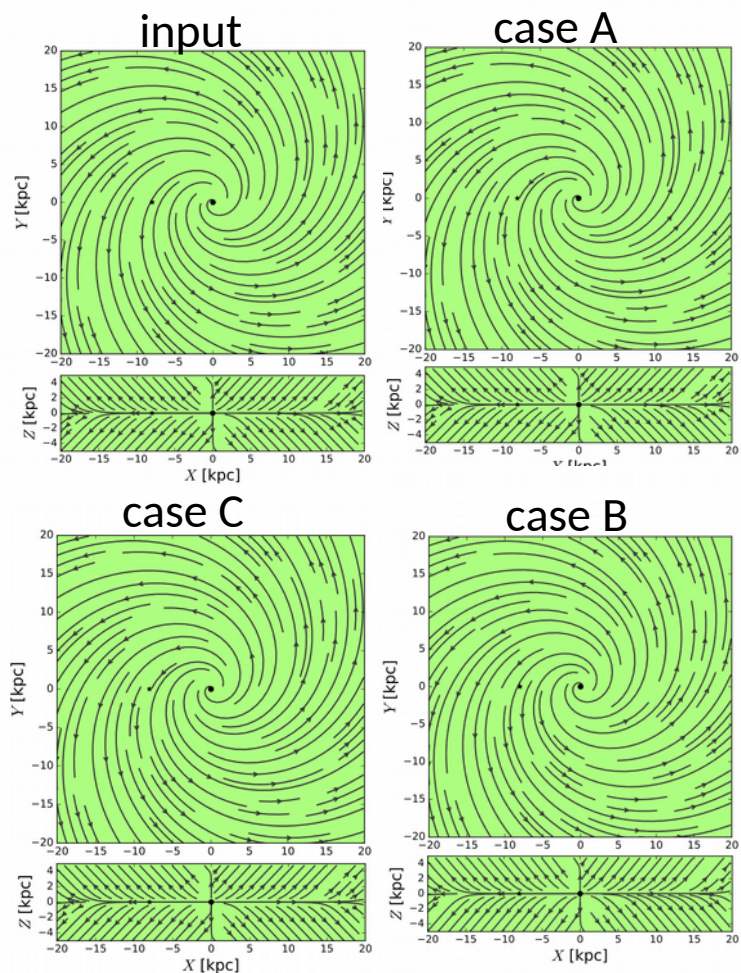
III. 3D models comparison



Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from dust data?

Proof of concept using our MCMC on *mock* datasets



≠ input-best-fit across the whole (3D) sampled space

	A	B	C
➤ Spiral pitch:	< 1°	< 4°	< 1°
➤ Out-of-plane:	< 1°	< 3°	< 1°

case A: n_d = exponential disk (ED) fitted by ED

case B: n_d = 4 spiral arms (4SA) fitted by ED

case C: n_d = 4SA fitted by 4SA

Polarized Diffuse Galactic Foregrounds and GMF



Can we really constrain the GMF from dust data?

Polarized Diffuse Galactic Foregrounds and GMF



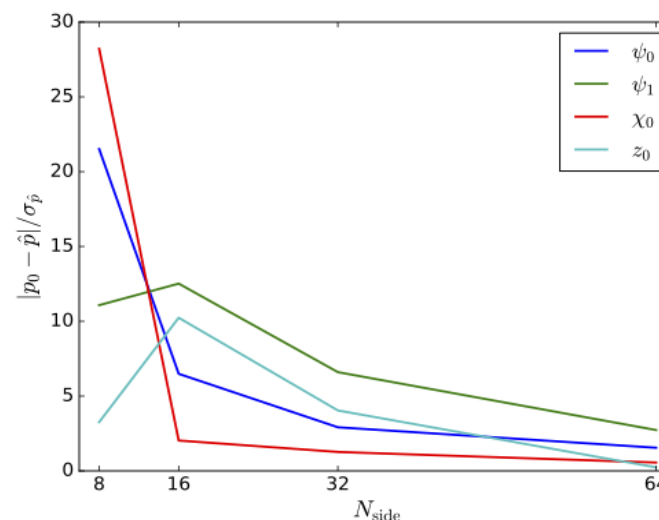
Can we really constrain the GMF from dust data?

→ Yes, we do!

Can we really constrain the GMF from dust data?

Proof of concept using our MCMC on *mock* datasets

- **Results:**
 - Excellent to fair reconstruction of the GMF geometry
 - reconstructed GMF
 - stable irrespective of the chosen n_d best-fit model
 - is expected to be better in the Galactic plane (pitch angle) than across the Galactic disk (tilt angle) in realistic cases
 - **Fits with reduced Stokes (q, u) allow us to circumvent mismodeling of n_d**
- **Technical points and systematics:**
 - Biases in parameter space due to
 - limited resolution of MCMC simulations
 - the chosen 'derived' dataset to be fitted (e.g. hyperpixel, profile, ...)
 - MCMC contours do not account for these points
 - Reduced χ^2 values become rapidly outrageous, even based on simulated data



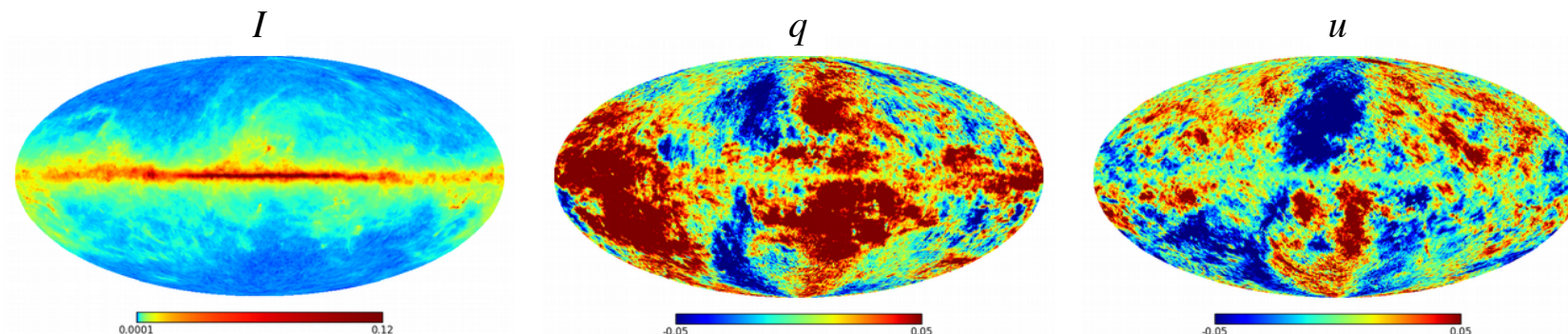
[Pelgrims, Macías-Pérez & Ruppín, (to be submitted)]

→ Yes, we do!

Polarized Diffuse Galactic Foregrounds and GMF

GMF from *real* dust data: a 'first' step forwards

- Fitted datasets: [*Planck* 353-GHz full-sky polarization maps]

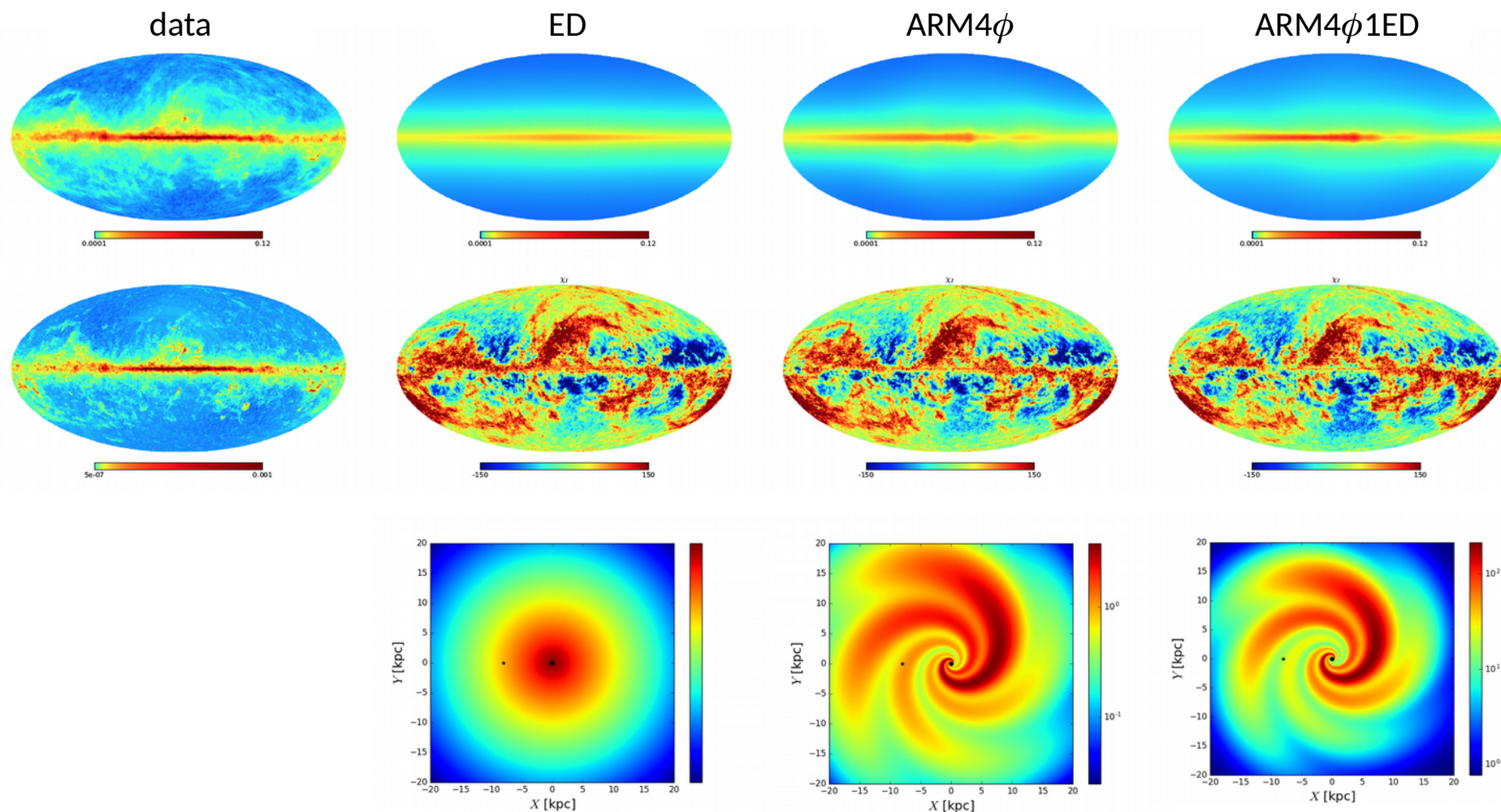


- Fitted models (at $N_{\text{side}} = 64$)
 - Dust density distribution n_d :
 - ED (exponential disk)
 - ARM4 ϕ (4 spiral arms)
 - ARM4 ϕ 1ED (4 spiral arms + exponential disk)
 - Regular and large-scale GMF: [spiral pattern + out-of-plane component]
 - ASS (axisymmetric logarithmic spiral)
 - WMAP (Page et al. model: like ASS but *not* logarithmic)
 - BSS (bi-symmetric logarithmic spiral: field strength modulation \rightarrow 2 arms)
 - QSS (quadri-symmetric logarithmic spiral: field strength modulation \rightarrow 4 arms)
 - Every n_d - GMF combinations \rightarrow 12 models of the magnetized Galaxy

Polarized Diffuse Galactic Foregrounds and GMF

GMF from dust data: [*Planck* 353-GHz full-sky maps]

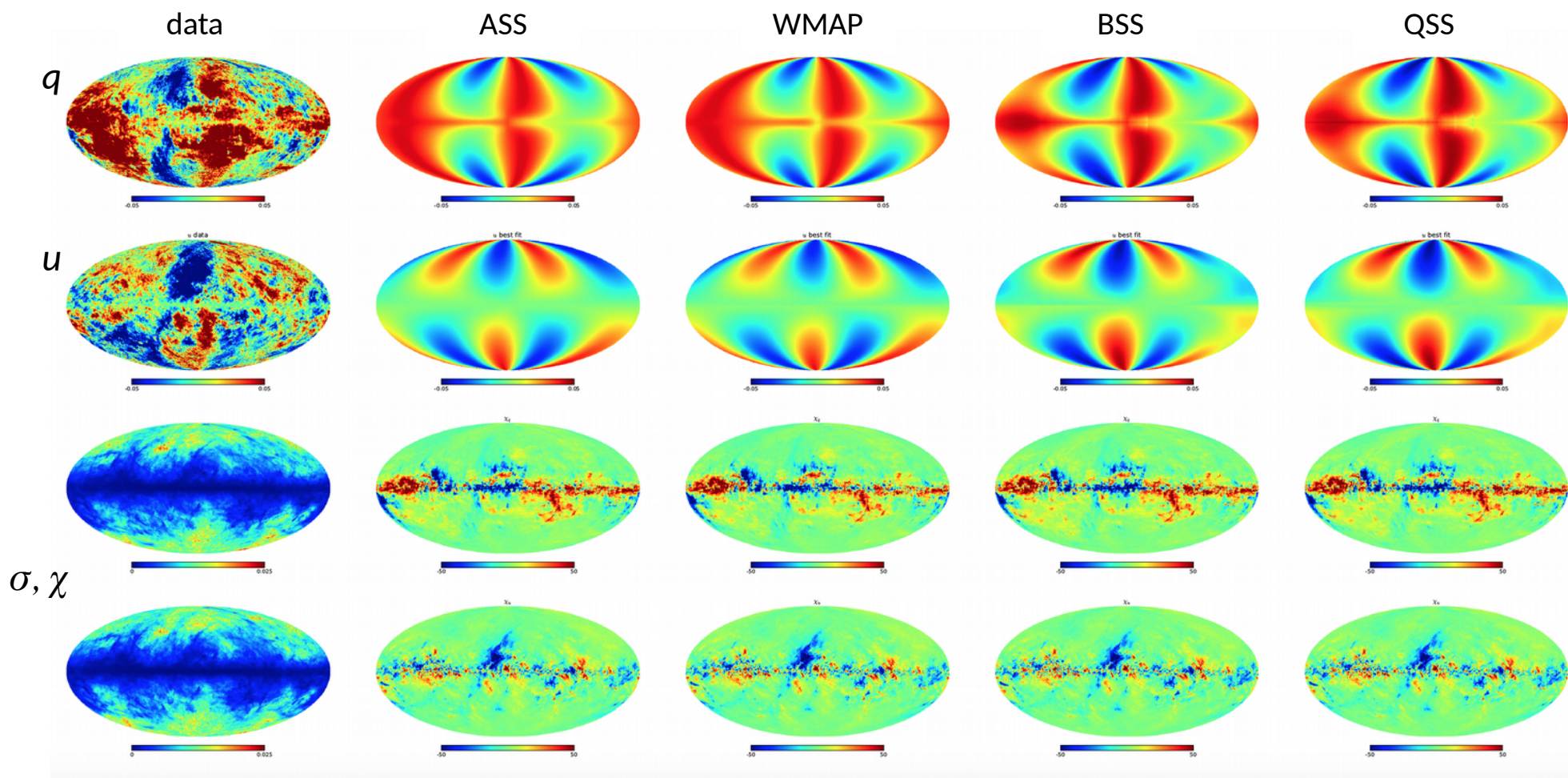
- Fit of intensity map and n_d models:



Polarized Diffuse Galactic Foregrounds and GMF

GMF from dust data: [*Planck* 353-GHz full-sky maps]

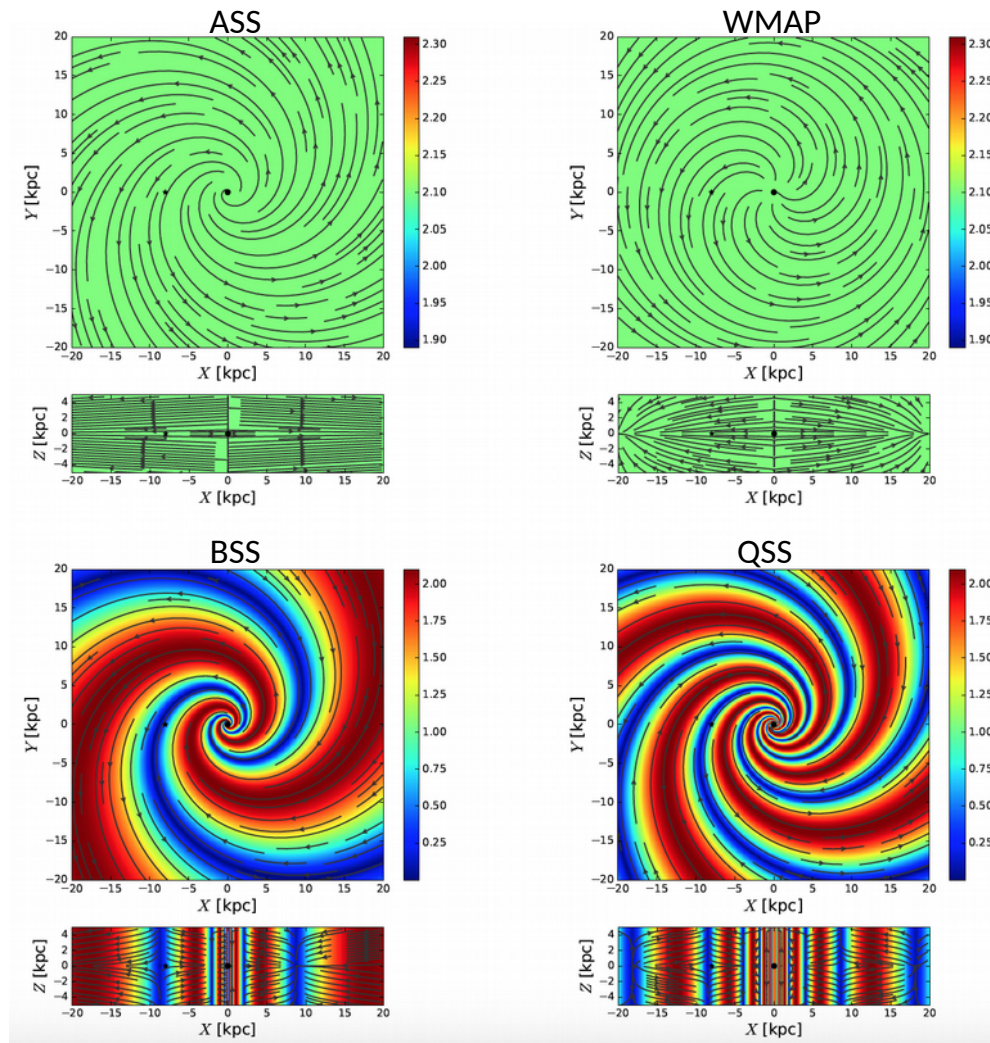
- Fit of polarization maps (q , u) and GMF models: (here with $n_d = \text{ED}$)



Polarized Diffuse Galactic Foregrounds and GMF

GMF from dust data: [*Planck* 353-GHz full-sky maps]

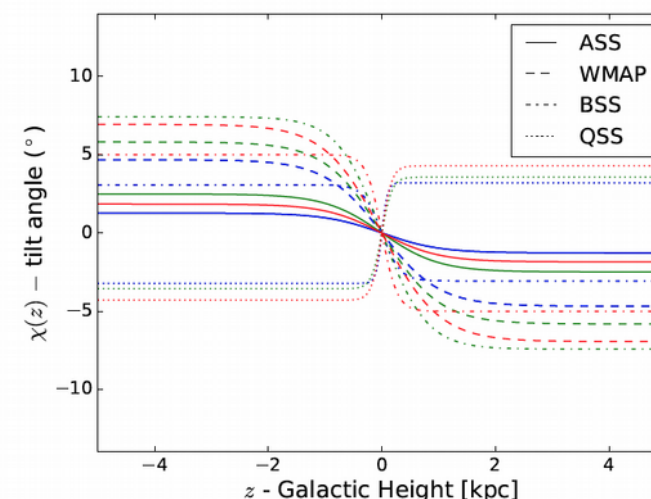
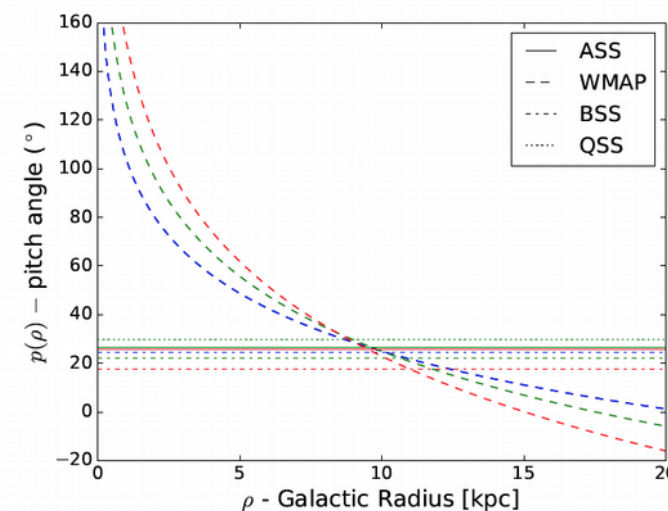
- Comparison of best-fit GMF models from (q, u) maps: (here with $n_d = \text{ED}$)



- Reconstructed GMF look similar (despite different parameterization and uninformative prior)

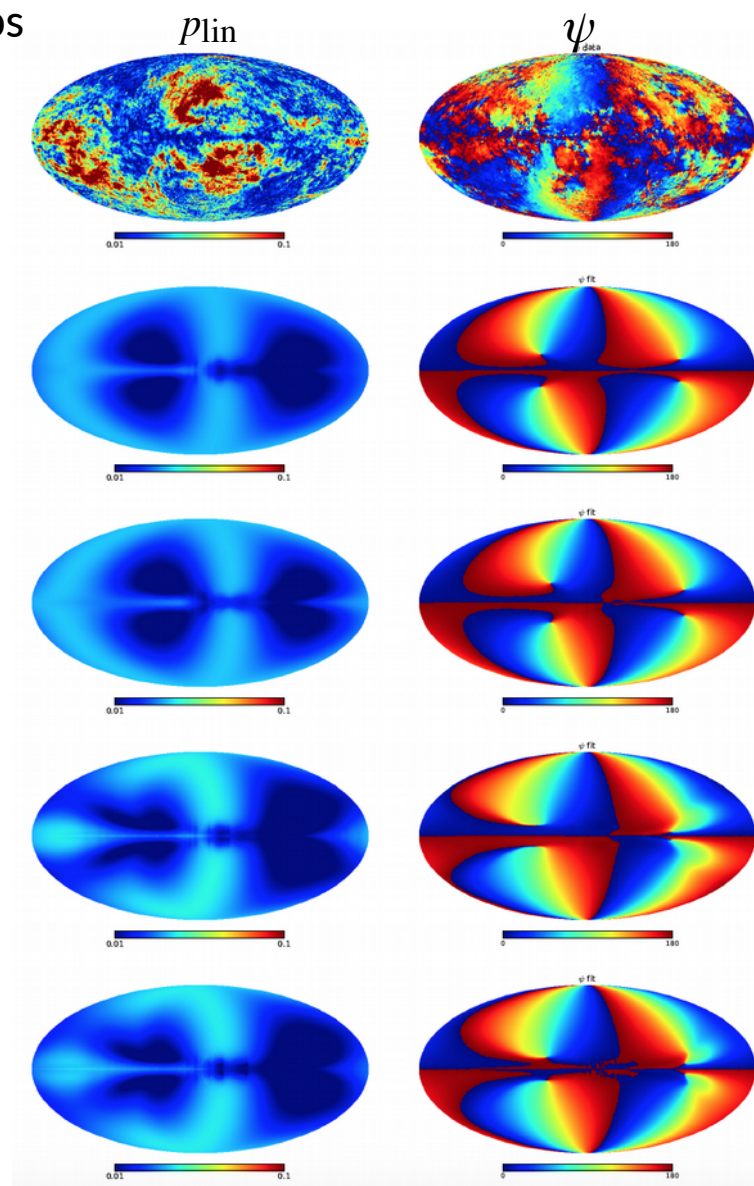
GMF from dust data: [Planck 353-GHz full-sky maps]

- Comparison of best-fit GMF models from (q, u) maps:
 - Reconstructed spiral patterns are (very) similar among reconstructions
 - pitch angle $24^\circ \pm 3^\circ$
(including a pitch of about 32° at Sun radius for WMAP model)
 - Out-of-plane component is less constrained
 - tilt angle of about $-3^\circ \pm 5^\circ$
 - seemingly none of the reconstructions shows the expected X-shape observed in radio data of other galaxies
- Robustness of GMF against leakage etc.
- Stability of GMF against adopted dust density models from I_{353} or τ_{353}



GMF from dust data: [Planck 353-GHz full-sky maps]

- Comparison of best-fit GMF models from (q, u) maps in terms of the degree of linear polarization and of the polarization position angle (deduced from the best-fits, not fitted)
- line-of-sight depolarization by integration of varying GMF orientations seen in p_{lin}
- overall agreement in ψ even if twisted and skewed
- clear offset of the models from the data either in p_{lin} or ψ
- offsets in p_{lin} and ψ are NOT spatially correlated
- should be phenomenologically exploited to refine models, together with other maps (I, Q, U)
- Highlight limitations of the models
GMF, matter density and possibly assumptions in emission modeling



Conclusion

Regular (large-scale) GMF can be constrained from polarized dust data

- Validation based on simulations
- First MCMC fits on *Planck* data (12 models: 3 n_d , 4 GMF)

There is still room for lots of improvements

- Matter density models
- GMF models
- Fitting approaches (treatment of the systematics)

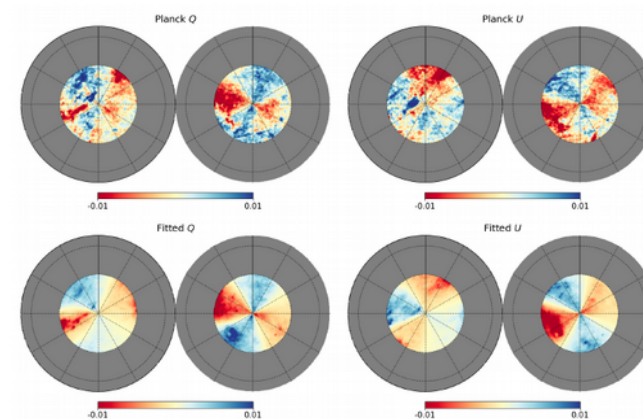
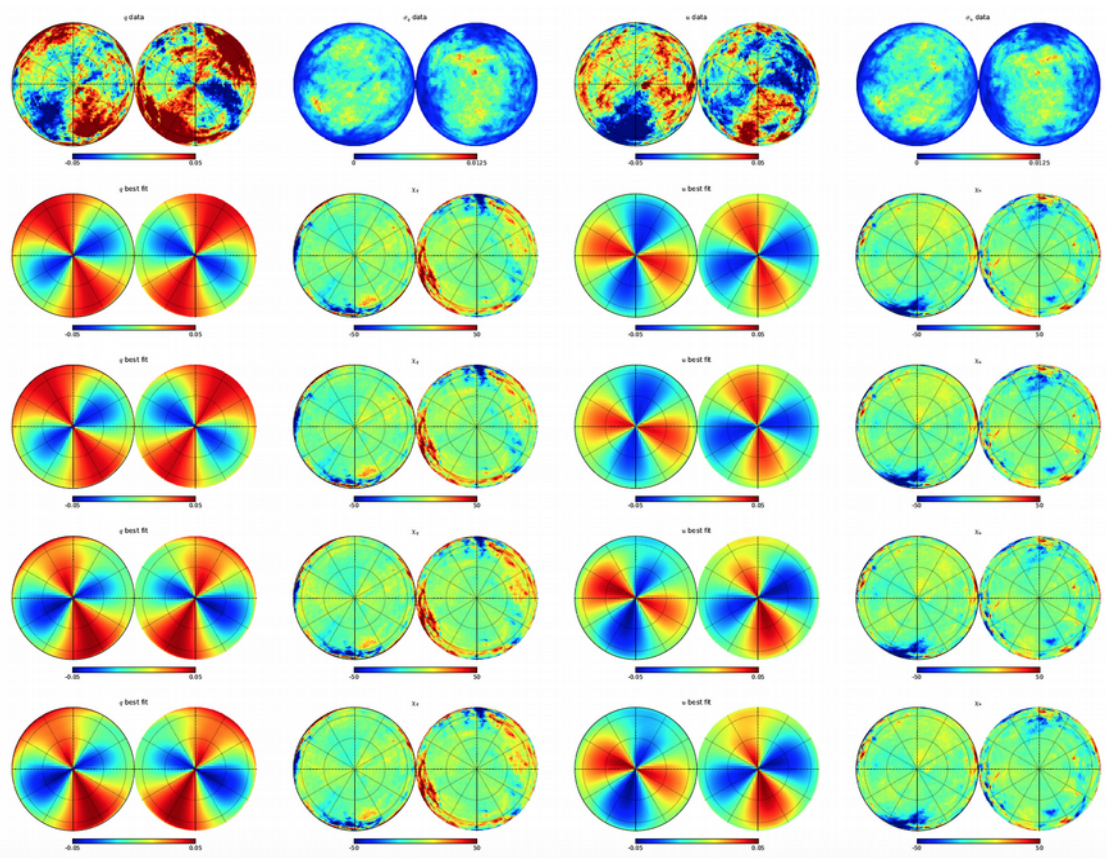
Open questions

- How do the local and the global magnetic field connect?
- How far can we go with the regular part of the field alone?

Thank you

[Pelgrims, Macías-Pérez & Ruppin, (to be submitted)]
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Polarized Diffuse Galactic Foregrounds and GMF



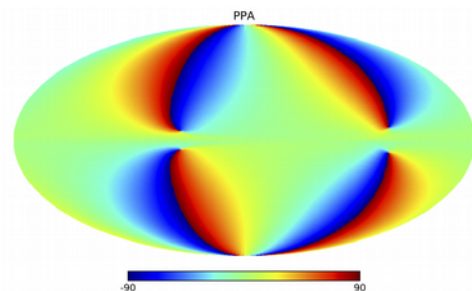
[Alves et al. 2018]

Polarized Diffuse Galactic Foregrounds and GMF

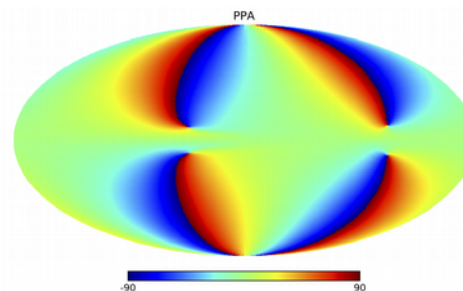
GMF from dust data: [SIMULATIONS]

- GMF reconstruction
 - Reconstructed dust polarization position angle (deduced, not fitted)

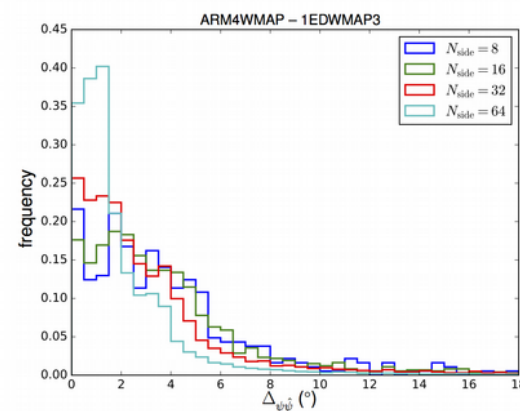
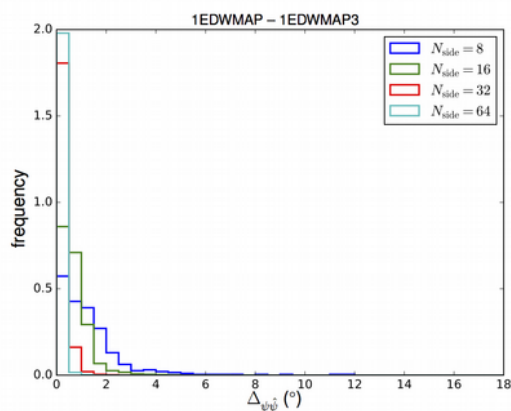
case A



case B



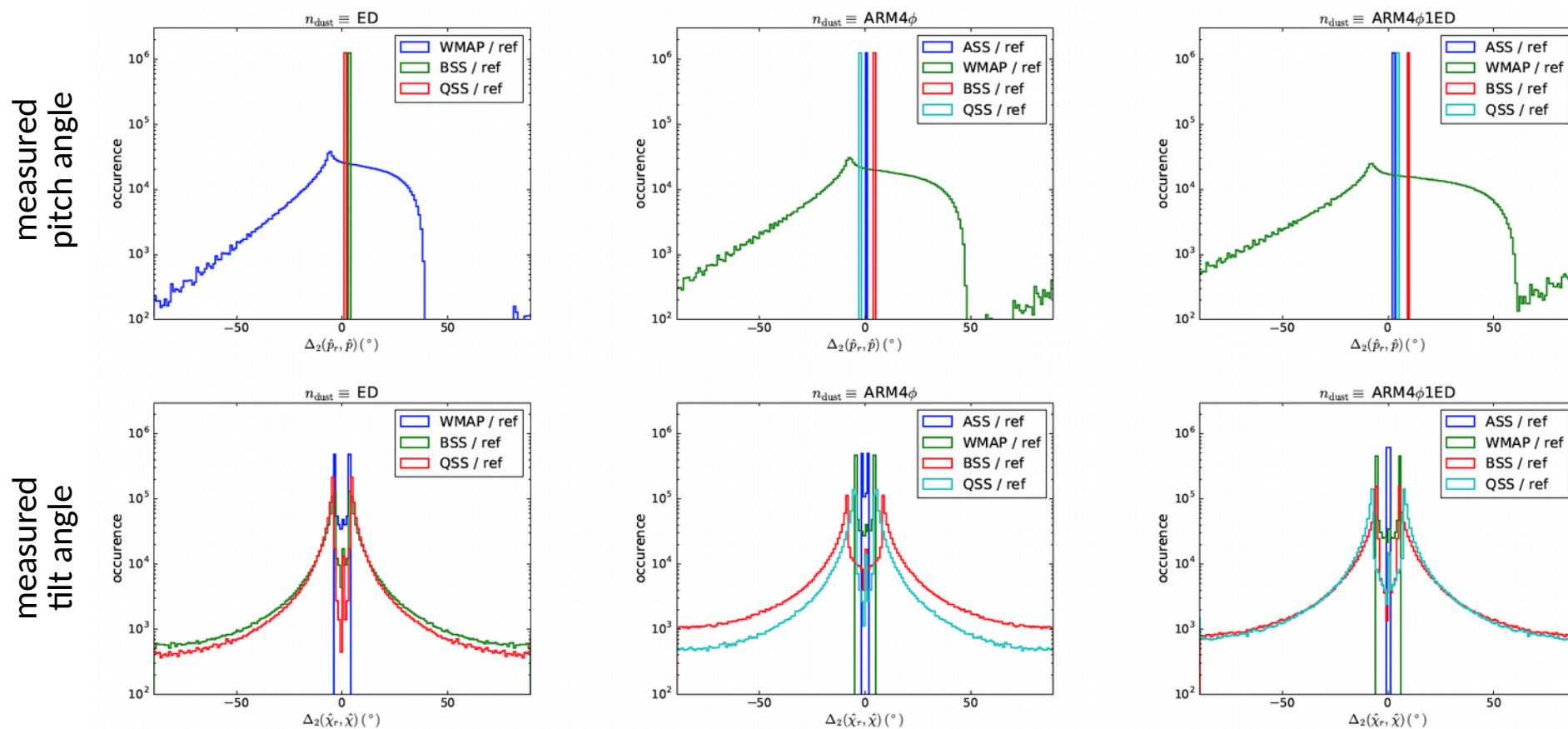
- Compared to the angle of the input model



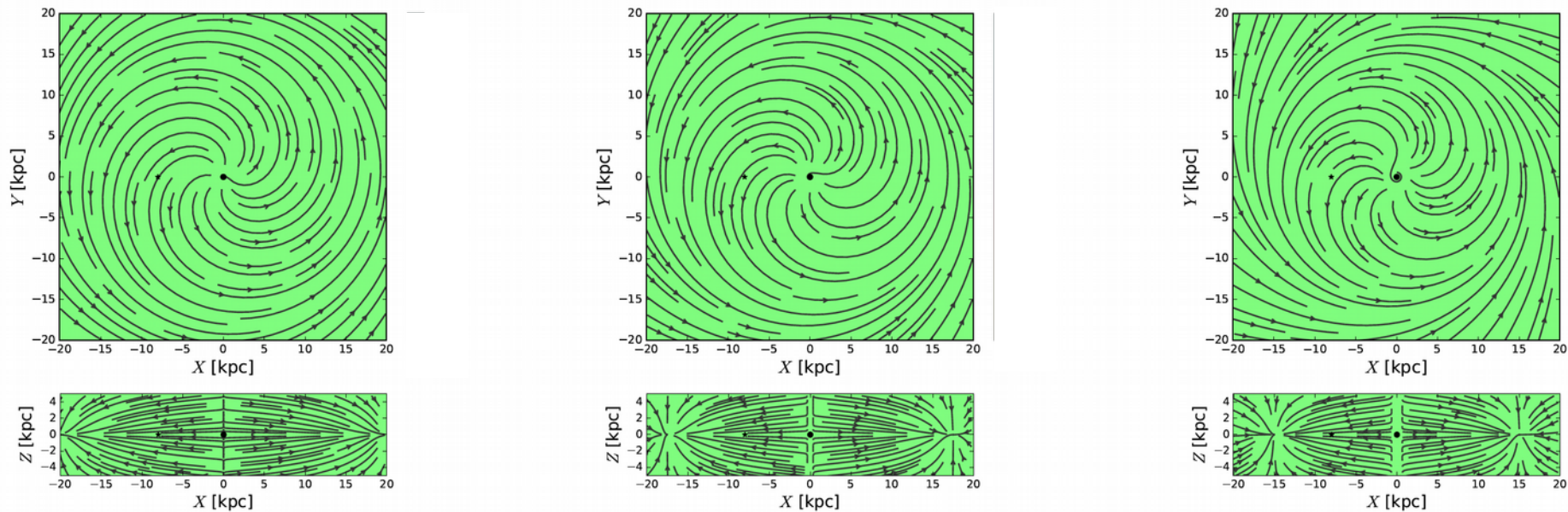
Polarized Diffuse Galactic Foregrounds and GMF

GMF from dust data: [*Planck* 353-GHz full-sky maps]

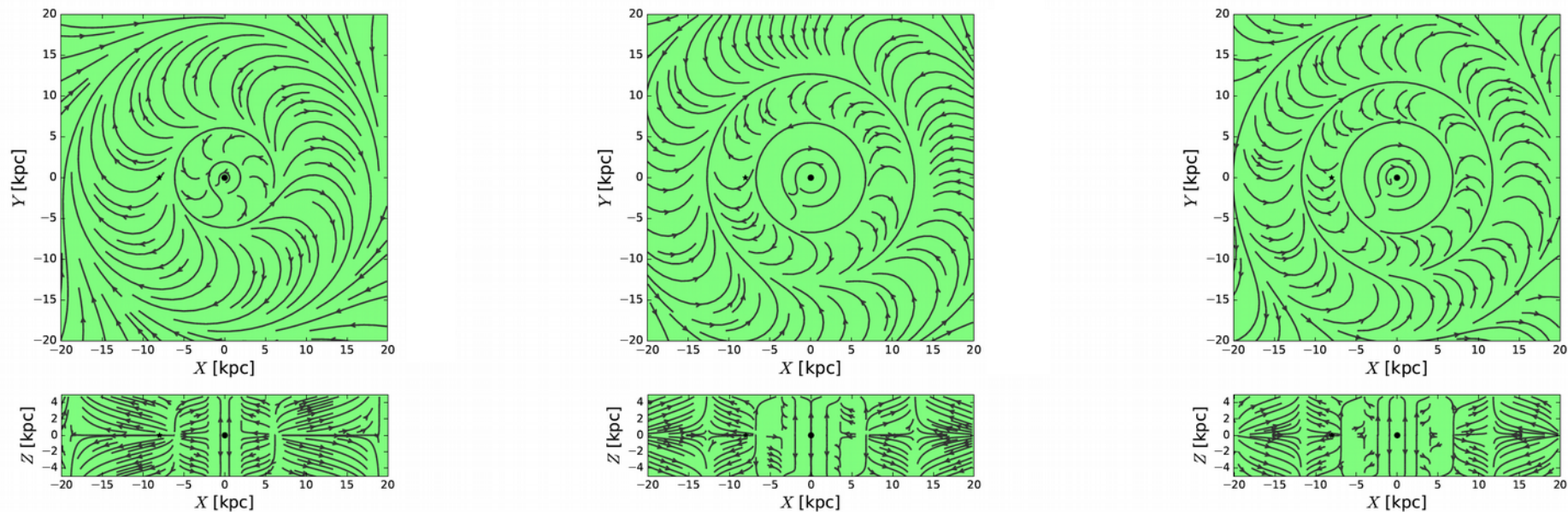
- Comparison of best-fit GMF models from (q, u) maps:
 - pitch and tilt angles at each location of the (3D) sampled space
 - comparison with the ones from ' $n_d = \text{ED} - \text{GMF} = \text{ASS}$ ' (the least evolved)



Our 'best-fit' solution for the WMAP GMF model (global minima of the χ^2)



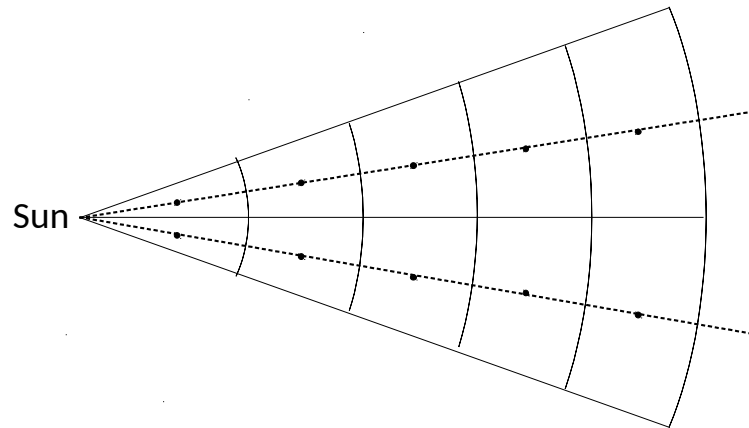
Our 'second' solution for the WMAP GMF model (local minima of the χ^2)



Polarized Diffuse Galactic Foregrounds and GMF

gpempy:

- Galactic space is sampled spherically around the Sun
 - ✓ angular sampling based on HEALPix tessellation [Górski+ 2005]
 - ✓ radial sampling = constant step
- Line-of-sight integration = sum over all (3D) cells along



- Matter density distribution evaluated at each point
- GMF vectors evaluated at each point
- the two are combined according to the relevant emission mechanism
- the mixture is then integrated to produce the map

Polarized Diffuse Galactic Foregrounds and GMF



gpempy:

GalaxyBasics

- Galactic space sampling

- Simple function for changes of coordinate system

GalacticProfile

- Numerous models of matter density distribution;
including bubbles, clouds, spiral arms, ...

- User-friendly

- e.g. allows for configuration files through dictionary facilities

BFIELD

- Numerous models of regular GMF;
including rings, spiral arms, ...

- User-friendly

- e.g. allows for configuration files through dictionary facilities

GalacticForegrounds

- Implementation of emission mechanisms

- Synchrotron and thermal dust [Lee & Drain and corrected version of Fauvet et al. 2011]

- Line-of-sight integration