CMB foregrounds for B-mode studies
Tenerife – Spain, October 15-18, 2018

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

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Polarized Diffuse Galactic Foregrounds and GMF

Why to model the polarized diffuse Galactic sky

→ how far do we understand the data

Rationals:

Galactic science

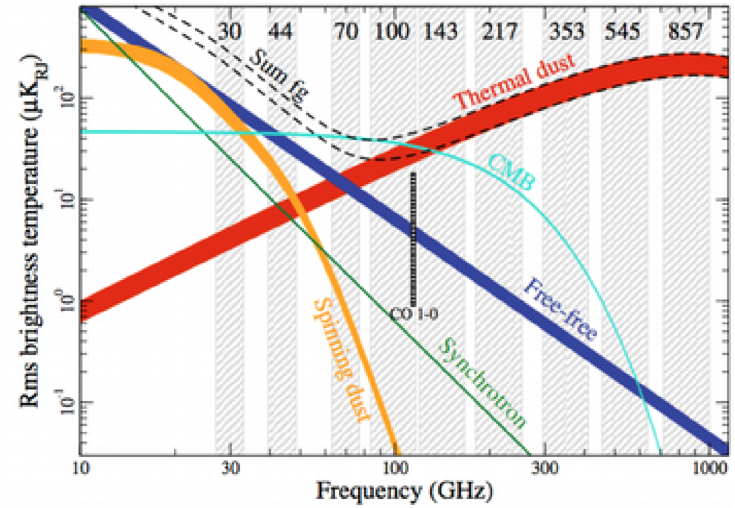
- Constraints on the different components of the magnetized interstellar medium
  - matter content (dust, relativistic electron, ...)
  - magnetic field

CMB science

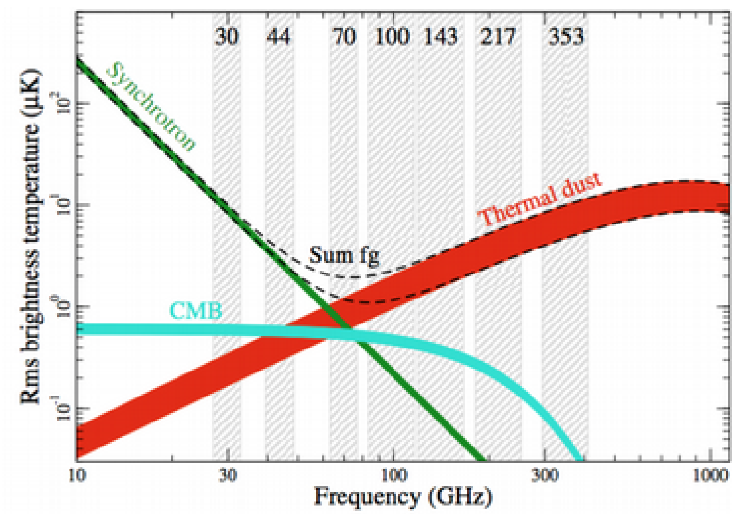
- Realistic models of Galactic foregrounds
- Provide realistic simulations to test and train component separation methods

Objective of this work:

- Constrain GMF models
- Provide up-to-date three-dimensional regular Galactic Magnetic Field



Intensity



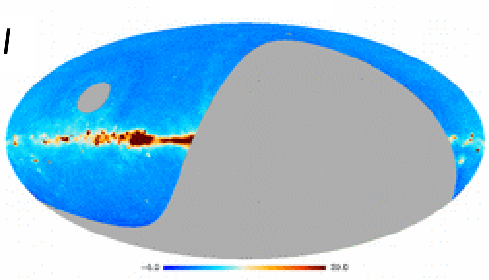
Polarization

Polarized Diffuse Galactic Foregrounds and GMF

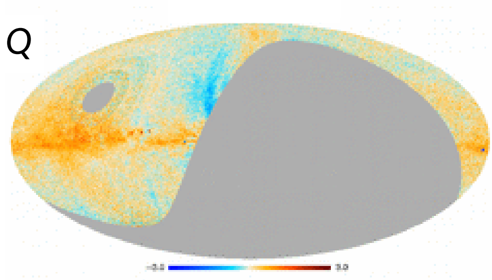
DATA: synchrotron & thermal dust

Synchrotron @ 11 GHz (*QUIJOTE*, Courtesy of the QUIJOTE collaboration)

I



Q



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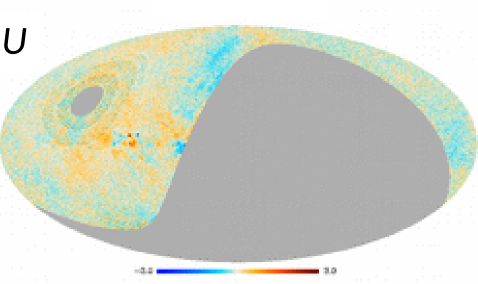
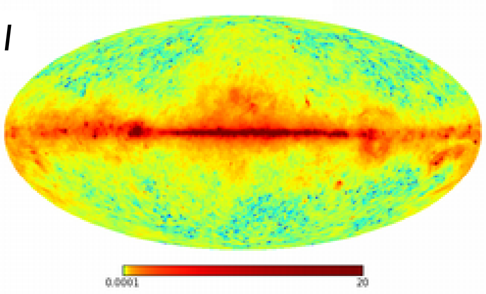


Synchrotron @ 22 GHz (*WMAP*)

I



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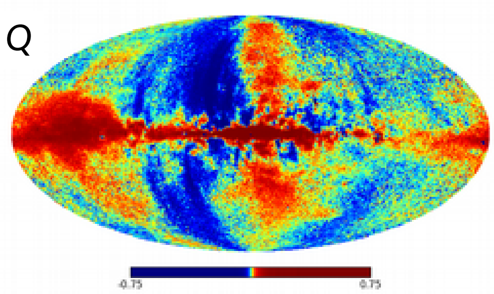

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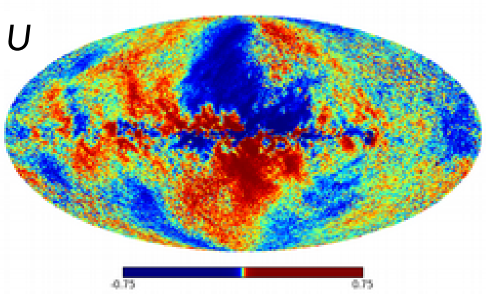
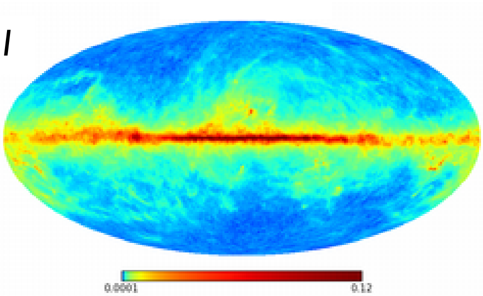


Thermal dust @ 353 GHz (*Planck*)

I



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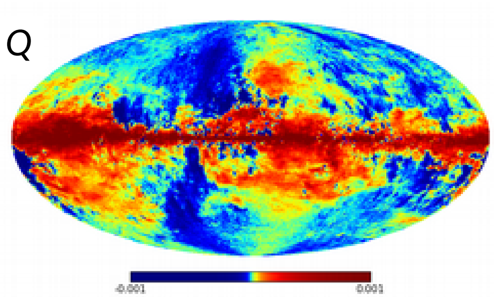

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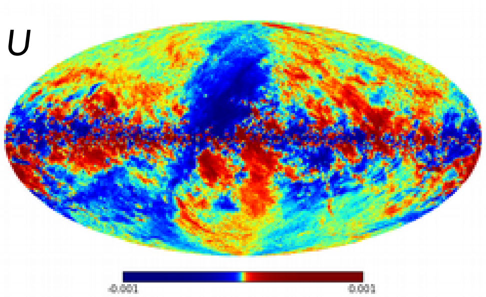
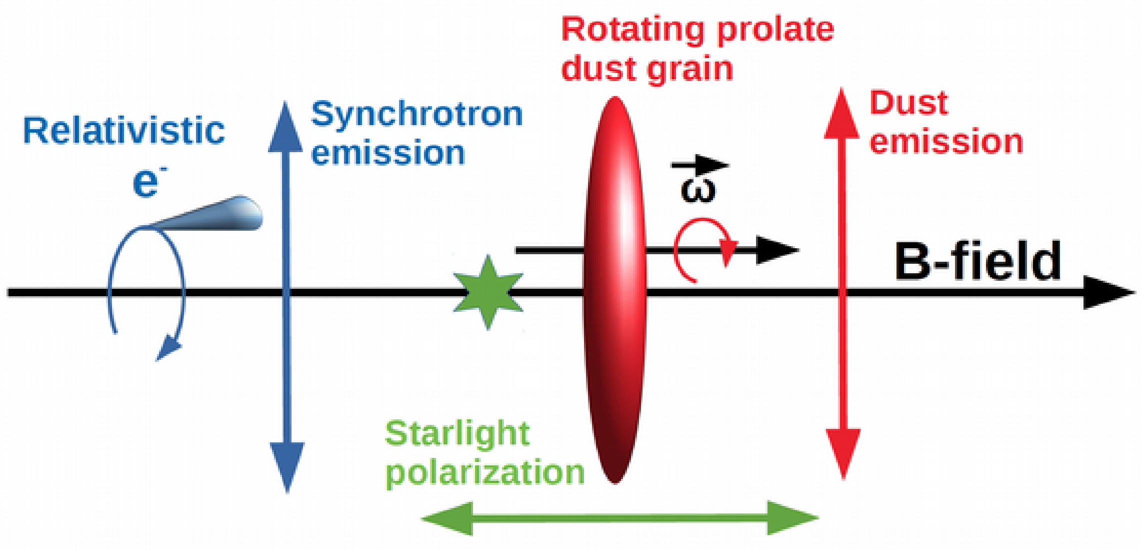


OBJECTIVE: extract the GMF from there

Polarized Diffuse Galactic Foregrounds and GMF



Polarized Diffuse Galactic Foregrounds and GMF

Emission modelings:

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

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

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

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

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])

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

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

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

To extract GMF, dust simplifies our life:

- 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

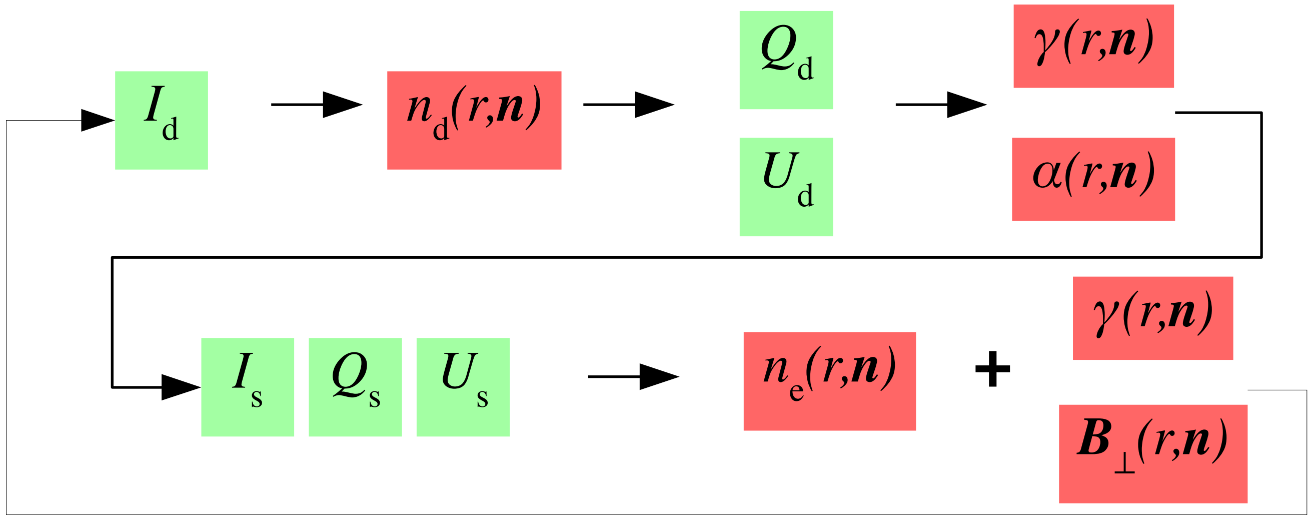
→ 'significant' reduction of the number of parameters to be handled at once

→ traceability and feasibility for MCMC analysis

Polarized Diffuse Galactic Foregrounds and GMF

Reconstruction of the GMF from synchrotron and thermal dust polarization?

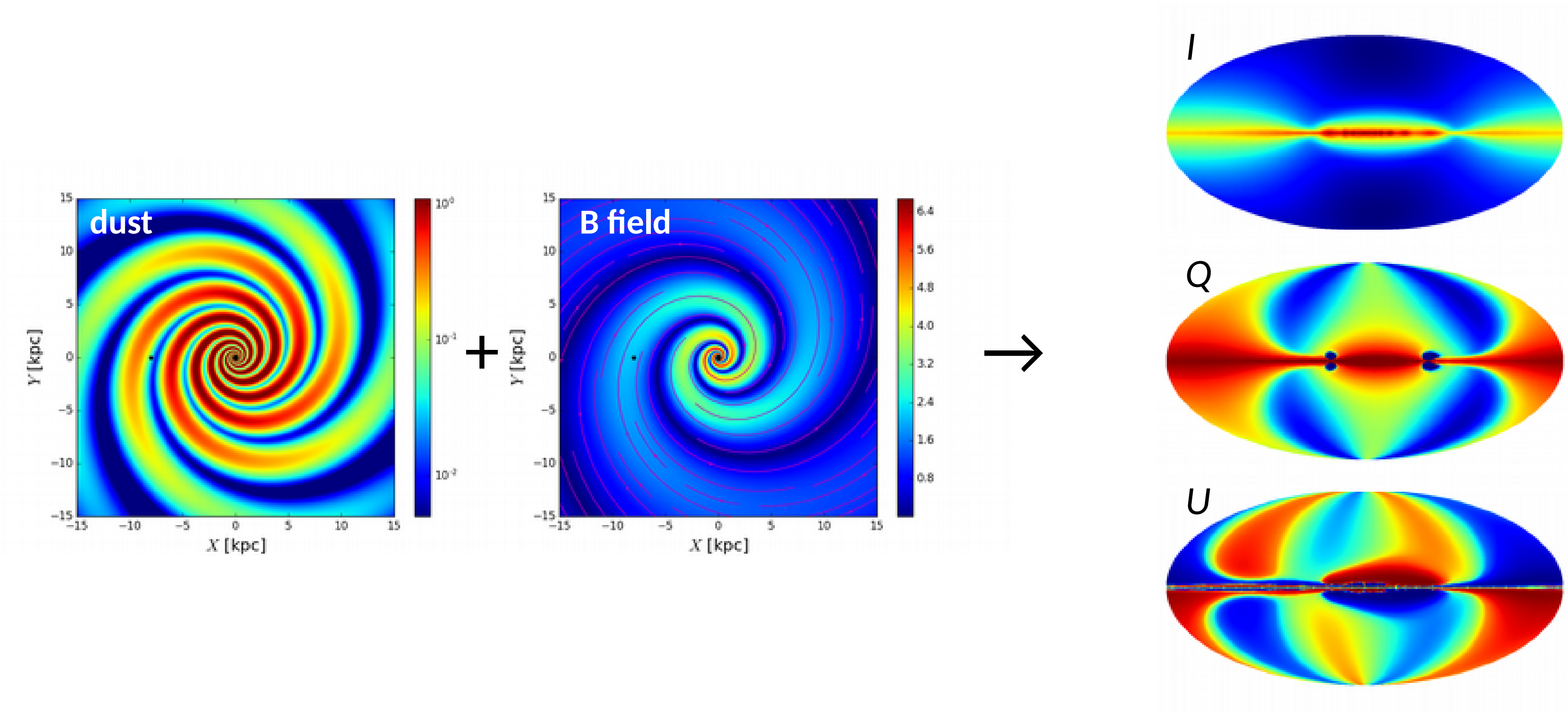
- Our approach: going step by step with sizable parametric models



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 thermal dust polarization data?

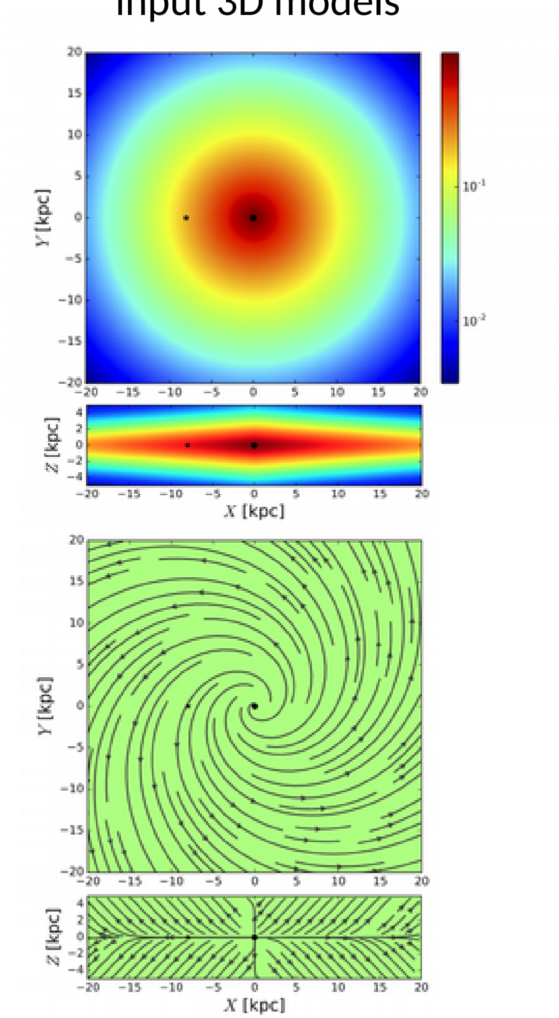
Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from thermal dust polarization data?

Proof of concept using our MCMC on *mock* datasets

I. `mock_1`: n_{d} = exponential disk ; GMF = WMAP model [Page et al. 2007]

input 3D models

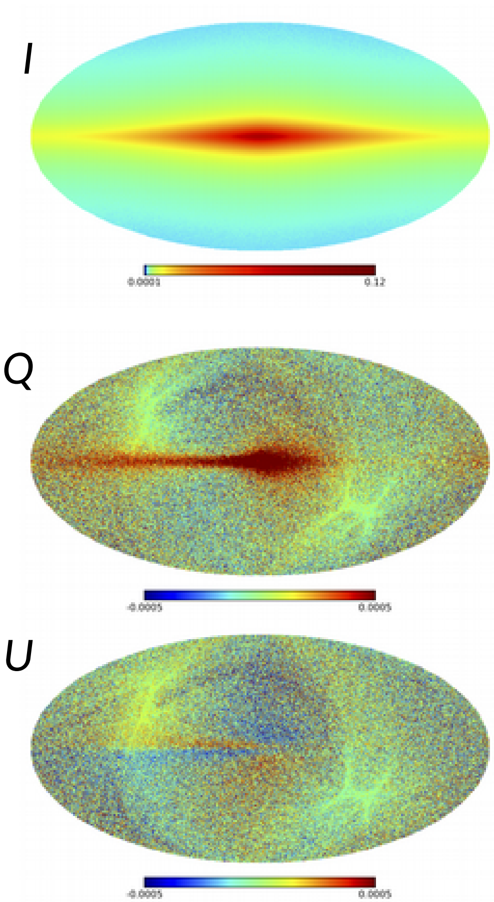


high-resolution ‘data’

I

Q

U

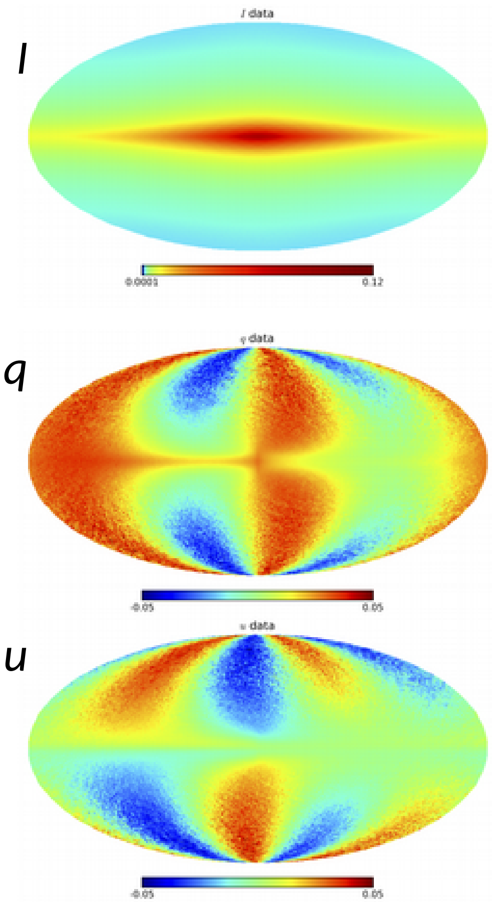


downgraded ‘data’
(to be fitted)

I

q

u

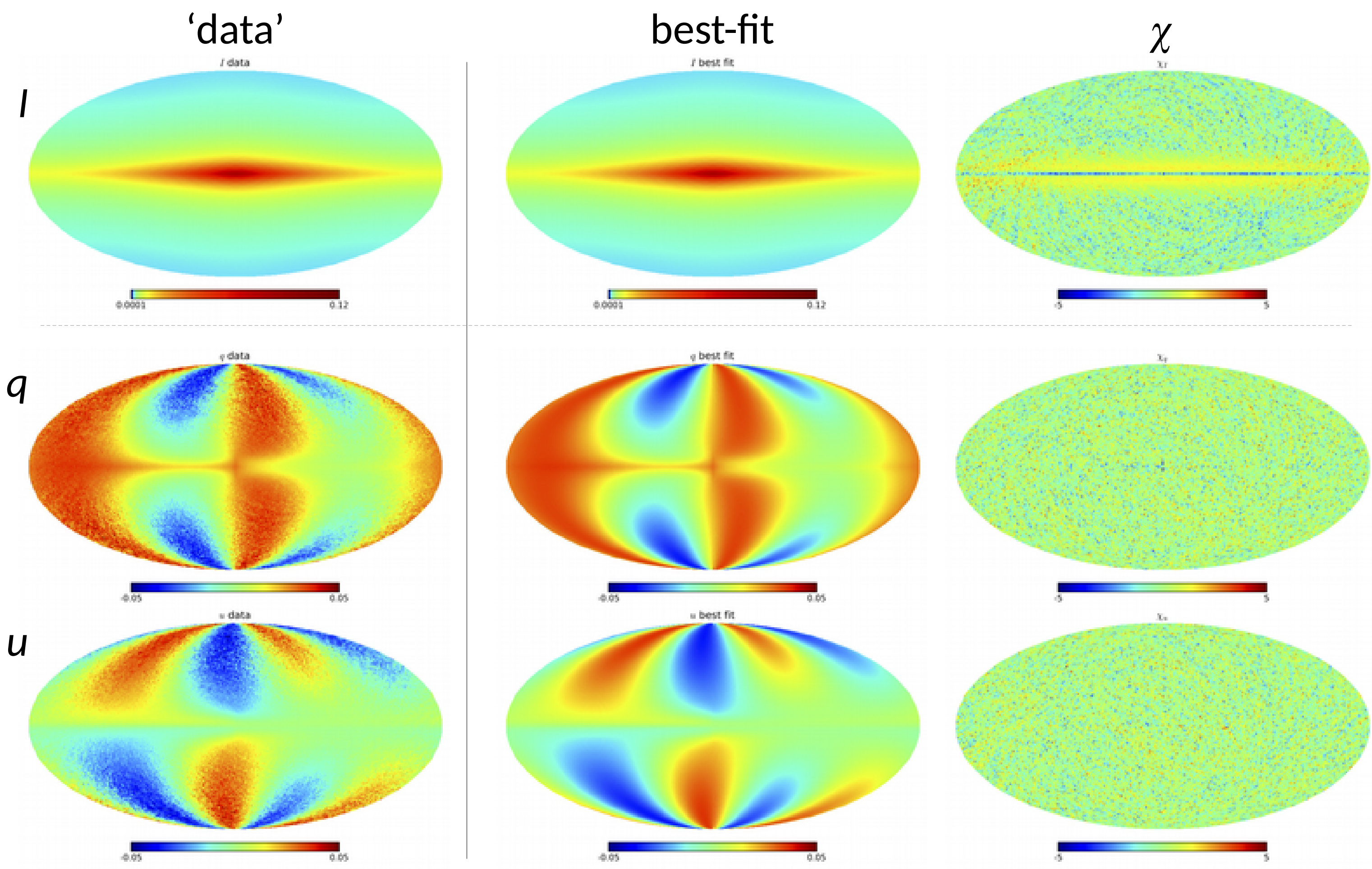


Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from thermal dust polarization data?

Proof of concept using our MCMC on *mock* datasets

II. MCMC fits on maps



→ 3D n_d

→ 3D GMF

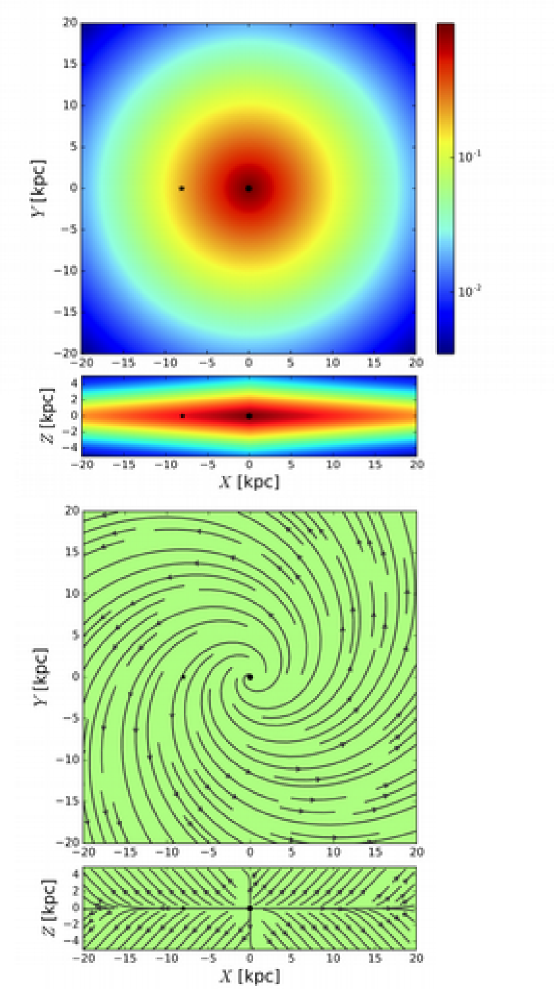
Polarized Diffuse Galactic Foregrounds and GMF

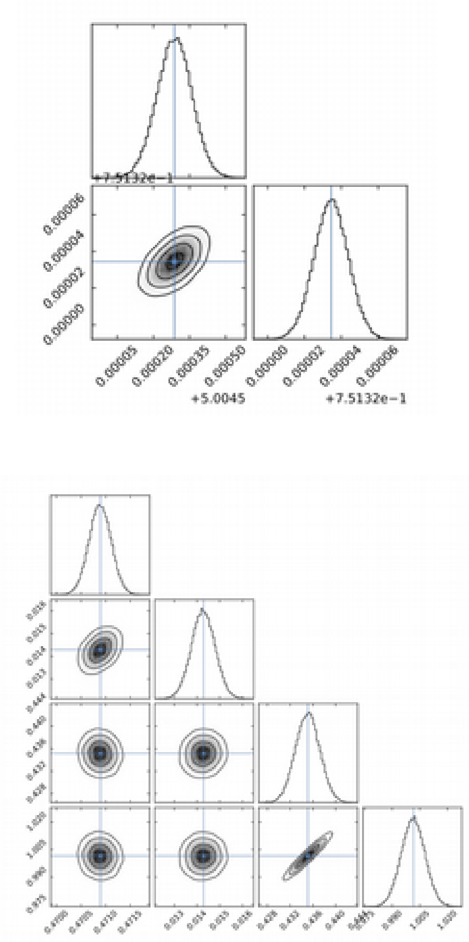
Can we really constrain the GMF from thermal dust polarization data?

Proof of concept using our MCMC on *mock* datasets

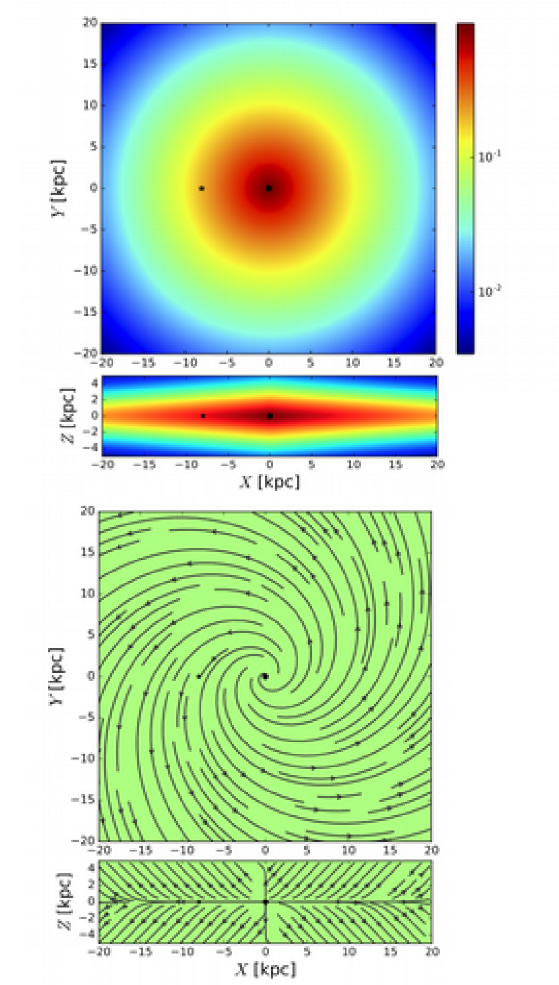
III. 3D models comparison

input 3D models





recovered 3D models



Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from thermal dust polarization data?

Proof of concept using our MCMC on *mock* datasets

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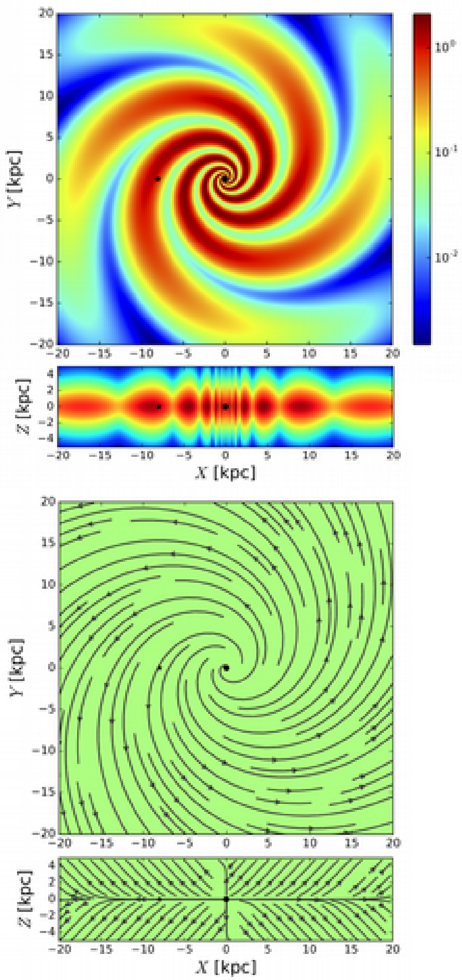
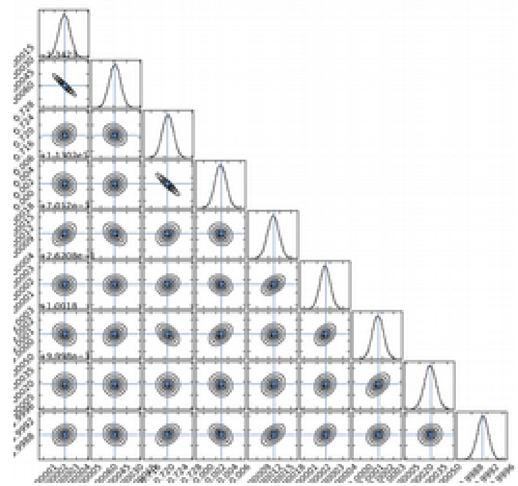
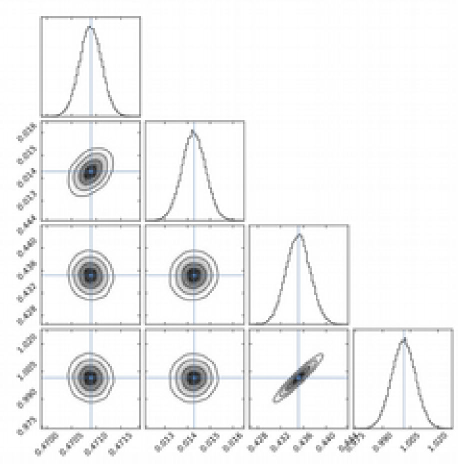
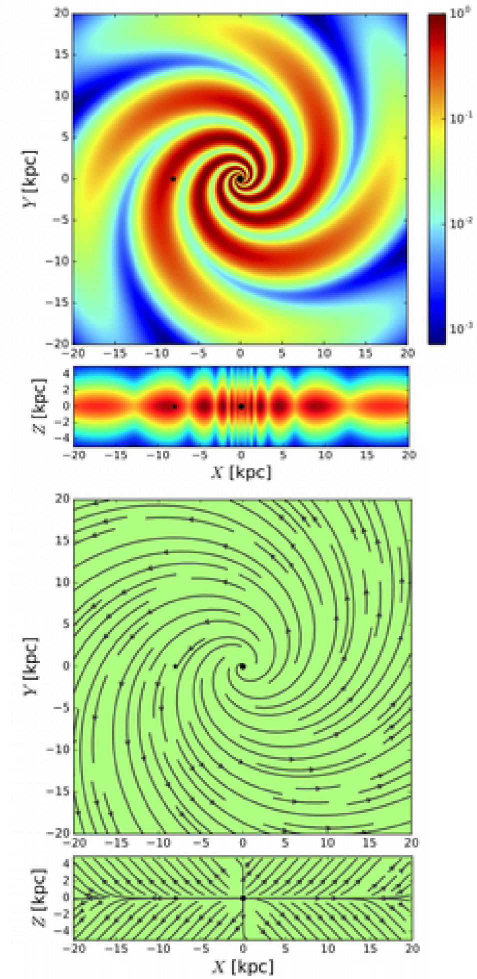
input 3D models







recovered 3D models



Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from thermal dust polarization data?

Proof of concept using our MCMC on *mock* datasets

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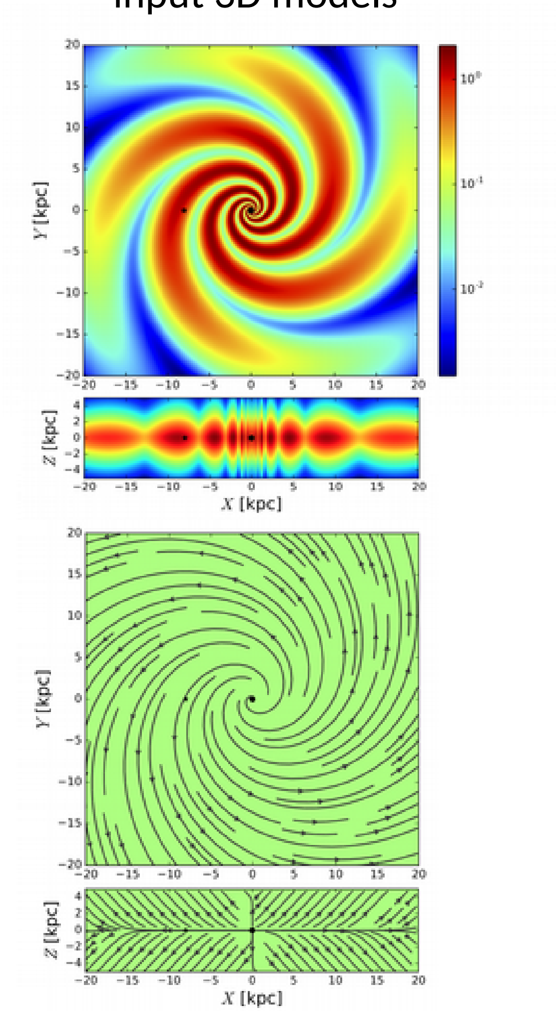
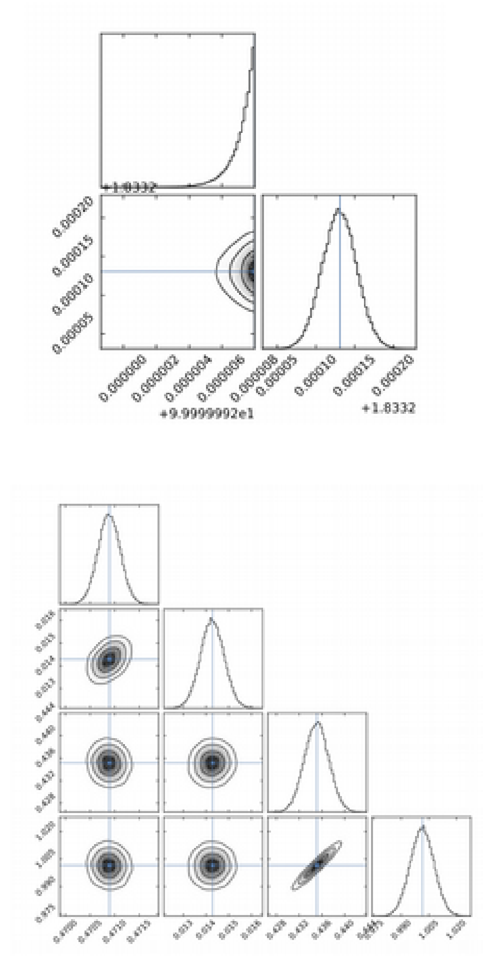
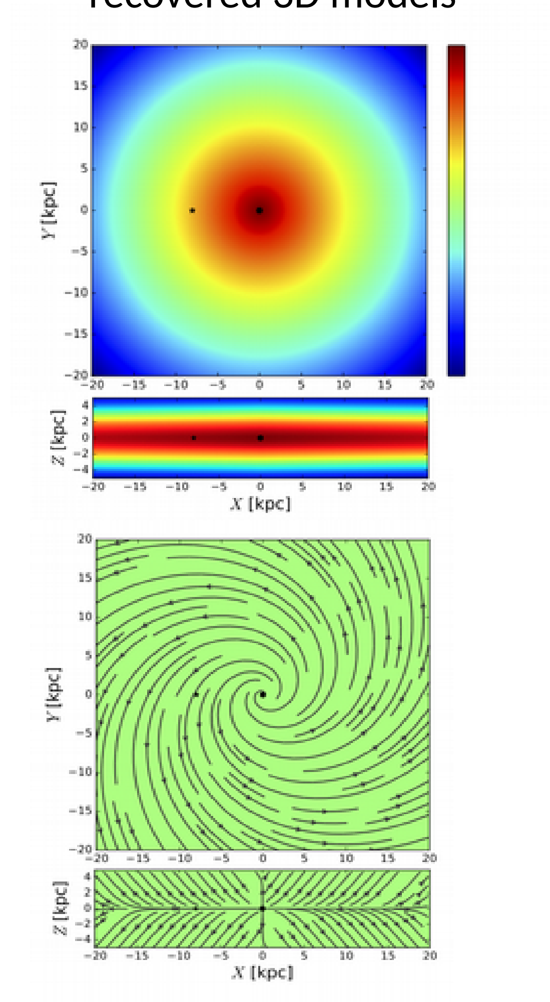
input 3D models





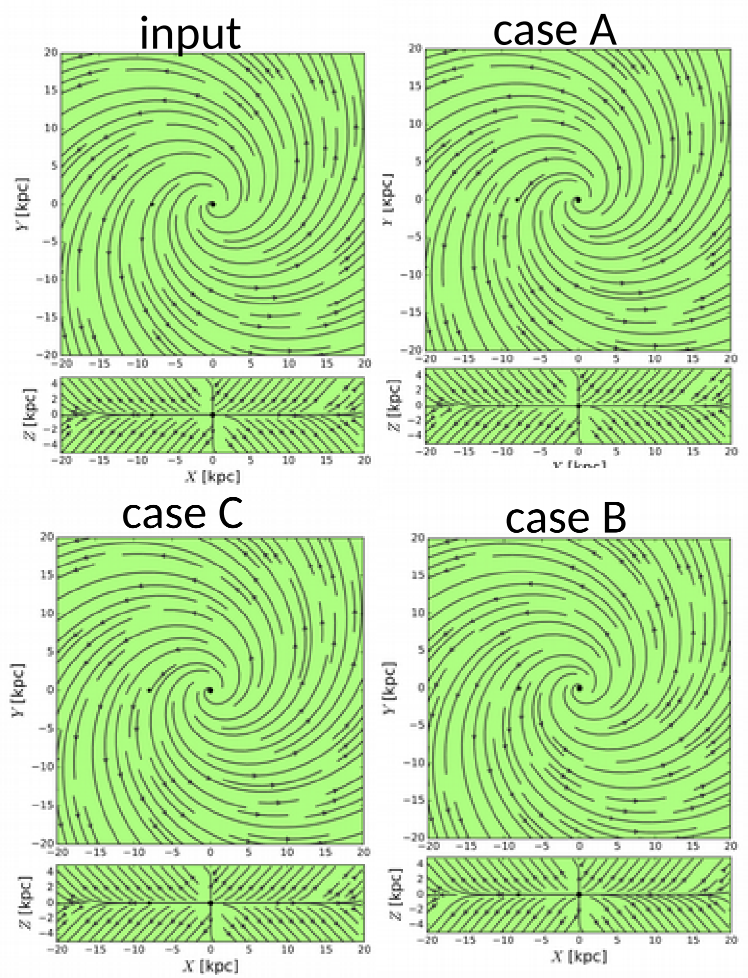
recovered 3D models



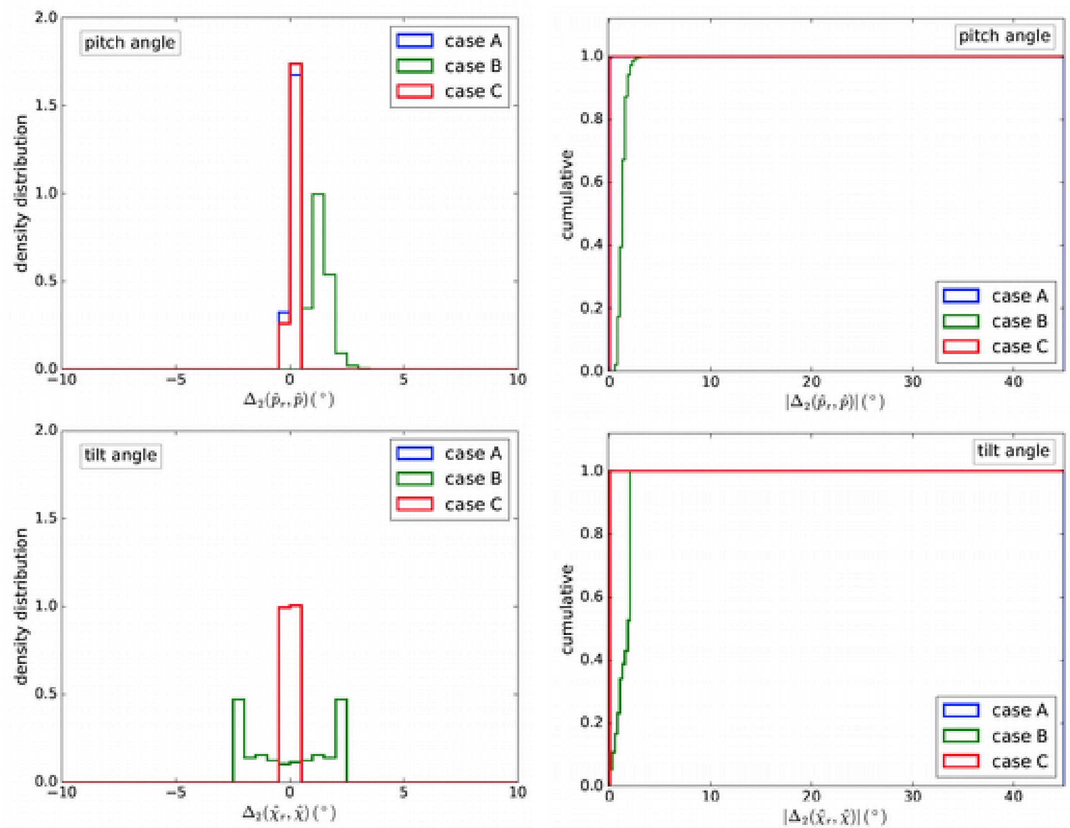
Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from thermal dust polarization data?

Proof of concept using our MCMC on *mock* datasets



≠ angles within the whole (3D) sampled space



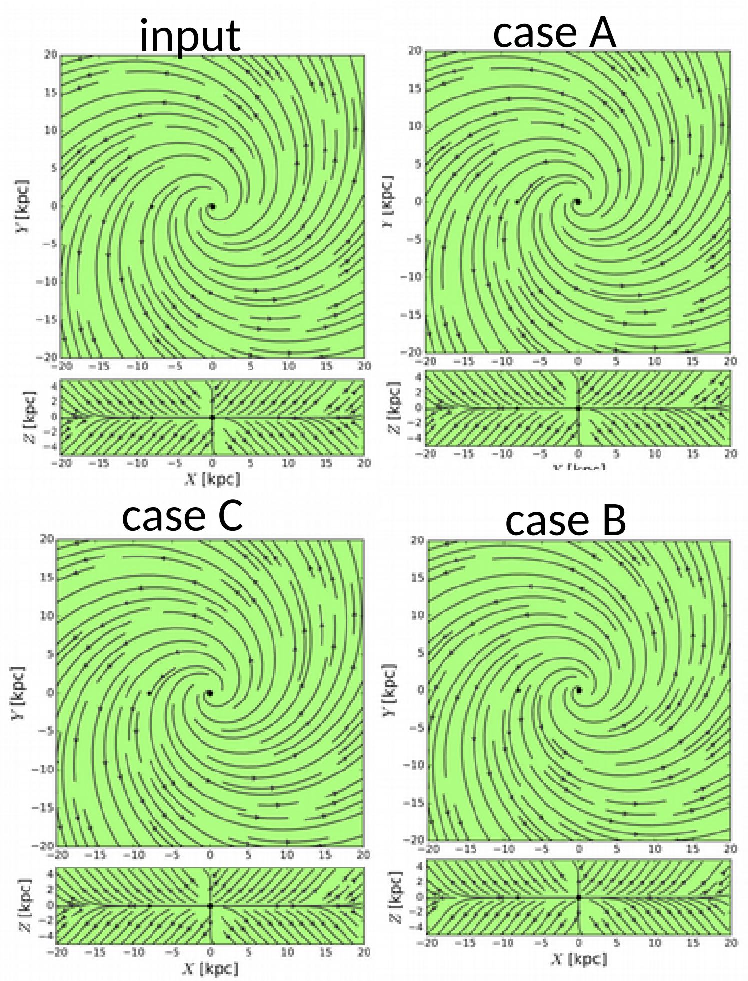
case A: n_d = exponential disk (ED) fitted by ED
case B: n_d = 4 spiral arms (4SA) fitted by ED
case C: n_d = 4SA fitted by 4SA

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

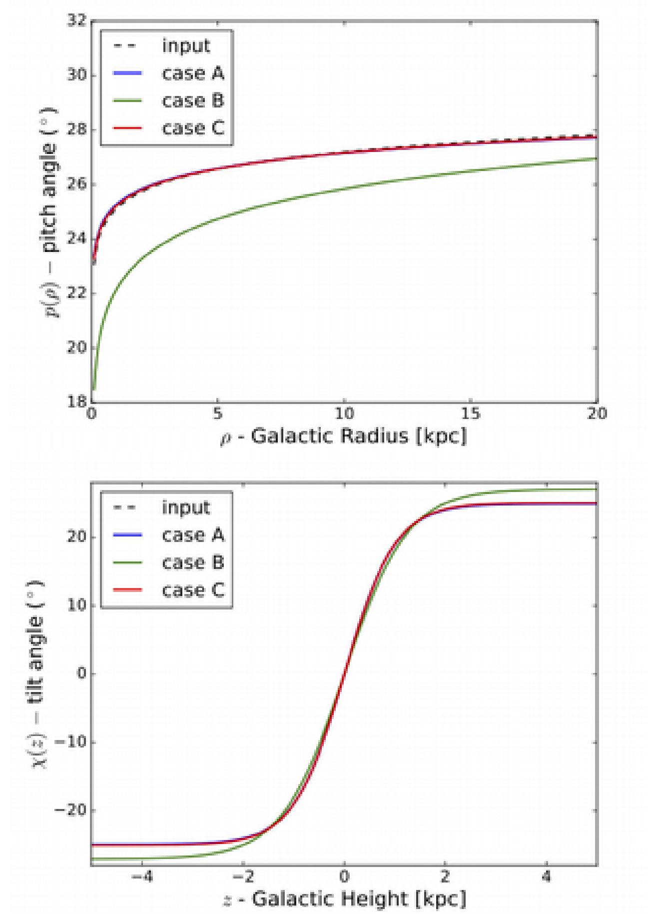
Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from thermal dust polarization data?

Proof of concept using our MCMC on *mock* datasets



Parametric forms of pitch and out-of-plane

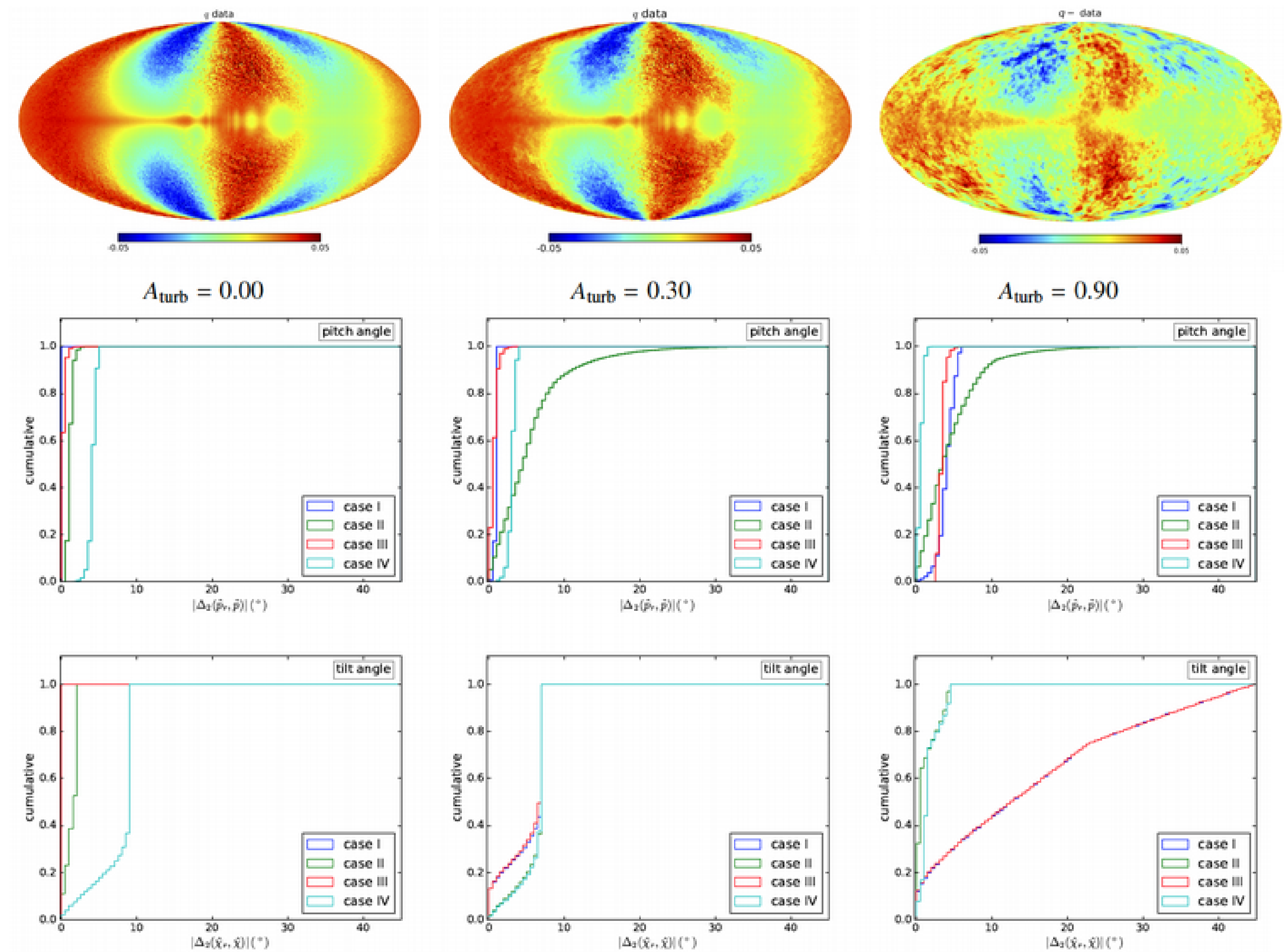


case A: $n_{\rm d}$ = exponential disk (ED) fitted by ED
case B: $n_{\rm d}$ = 4 spiral arms (4SA) fitted by ED
case C: $n_{\rm d}$ = 4SA fitted by 4SA

Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from thermal dust polarization data?

Inclusion of turbulence into the GMF in the 'data' to be fitted



4 reconstructions tested:

	$n_{\rm d}$	gmf
input:	4SA	WMAP
case I:	4SA	WMAP
case II:	ED	WMAP
case III:	4SA	ASS
case IV:	ED	ASS

≠ pitch angles < 10° for 80% of the space in all cases

≠ tilt angles worse but still …

Polarized Diffuse Galactic Foregrounds and GMF

Can we really constrain the GMF from thermal dust polarization data?

Proof of concept using our MCMC on *mock* datasets

[Pelgrims, Macías-Pérez & Ruppin, A&A *submitted*]

- Results:
  - Excellent to fair reconstruction of the GMF geometrical structure
  - reconstructed GMF
    - stable irrespective of the chosen $n_{\rm d}$ 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 $n_{\rm d}$
    - to propagate properly the uncertainties
  - The regular GMF part can be 'fairly' constrained when turbulence is added to the data

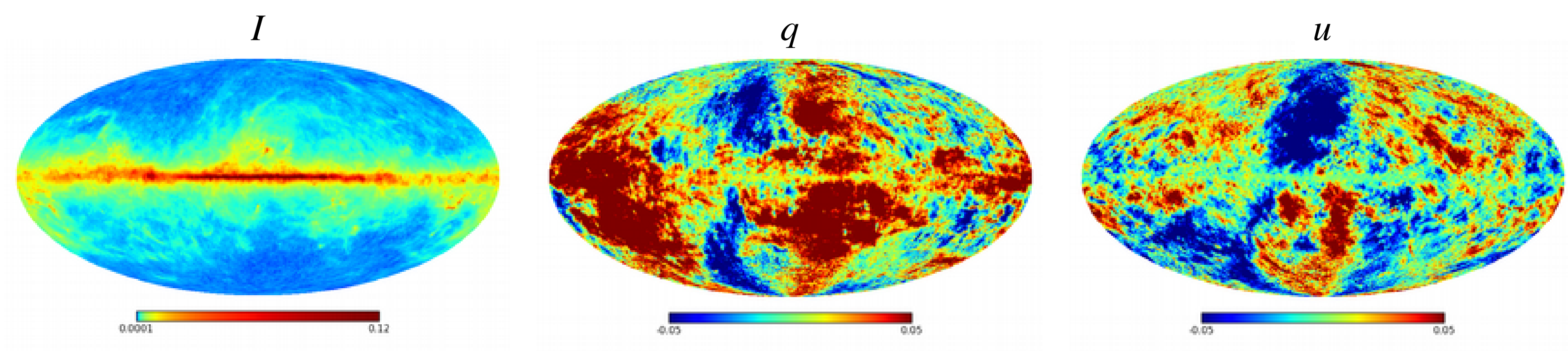
- Highlight of technical points and systematics:
  - Biases in parameter space due to
    - limited resolution of MCMC simulations
  - MCMC contours do not account for these points
  - Reduced χ^2 values become rapidly outrageous, even based on simulated data

→ Yes, we can!
(based on simulations ...)

Polarized Diffuse Galactic Foregrounds and GMF

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

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

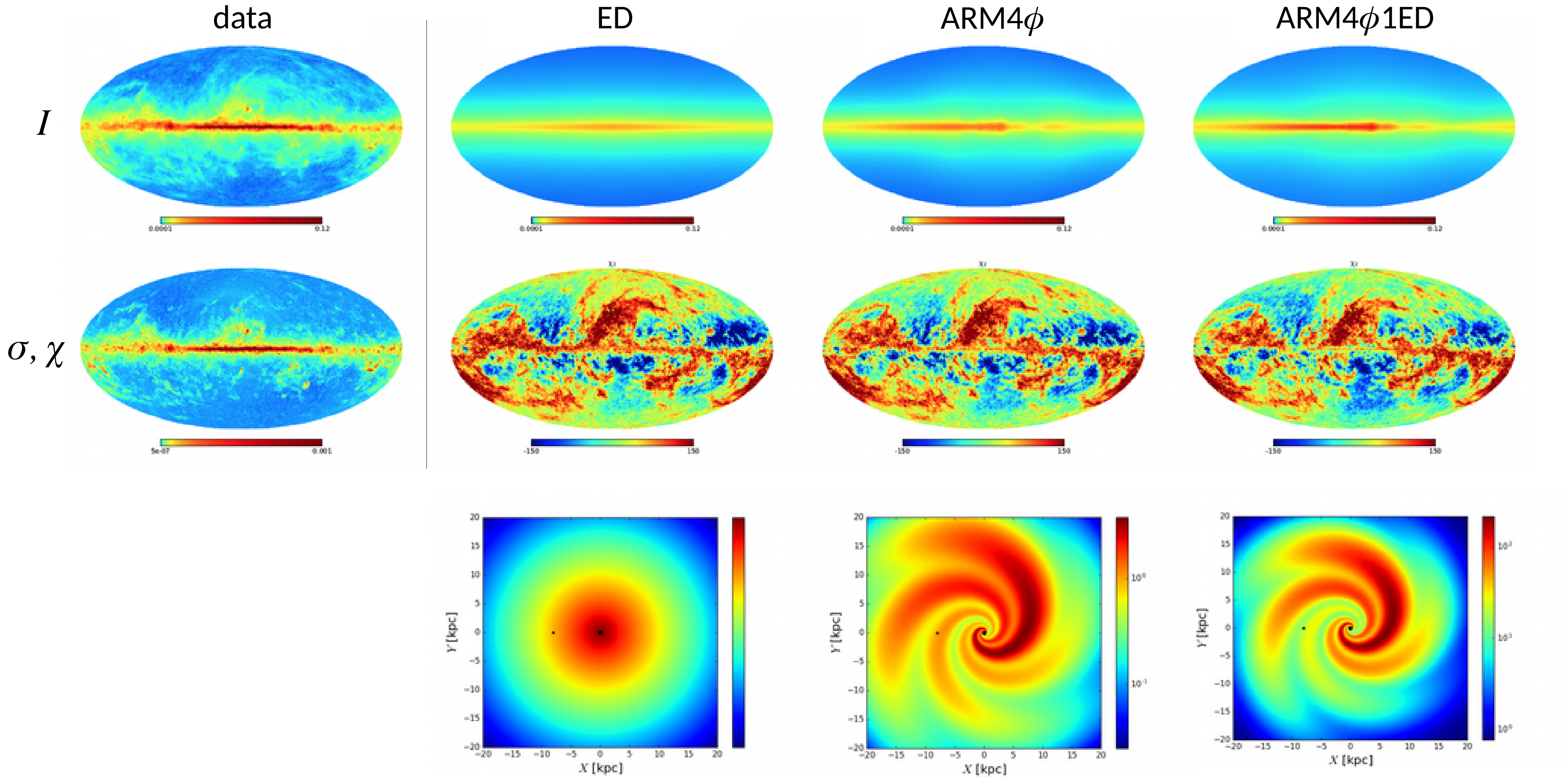


- Fitted models (at N_{side} = 64)
  - Dust density distribution n_{d}:
    - ED (exponential disk)
    - ARM4ϕ (4 spiral arms)
    - ARM4ϕ1ED (4 spiral arms + exponential disk)
  - Regular and large-scale GMF: [spiral pattern + out-of-plane component]
    - ASS (axisymmetric logarithmic spiral)
    - WMAP (Page et al. model: like ASS but *not* logarithmic)
    - BSS (bi-symmetric logarithmic spiral: field strength modulation → 2 arms)
    - QSS (quadri-symmetric logarithmic spiral: field strength modulation → 4 arms)
  - Every n_{d} – GMF combinations → 12 models of the magnetized Galaxy

Polarized Diffuse Galactic Foregrounds and GMF

GMF from *Planck* 353-GHz full-sky polarization maps

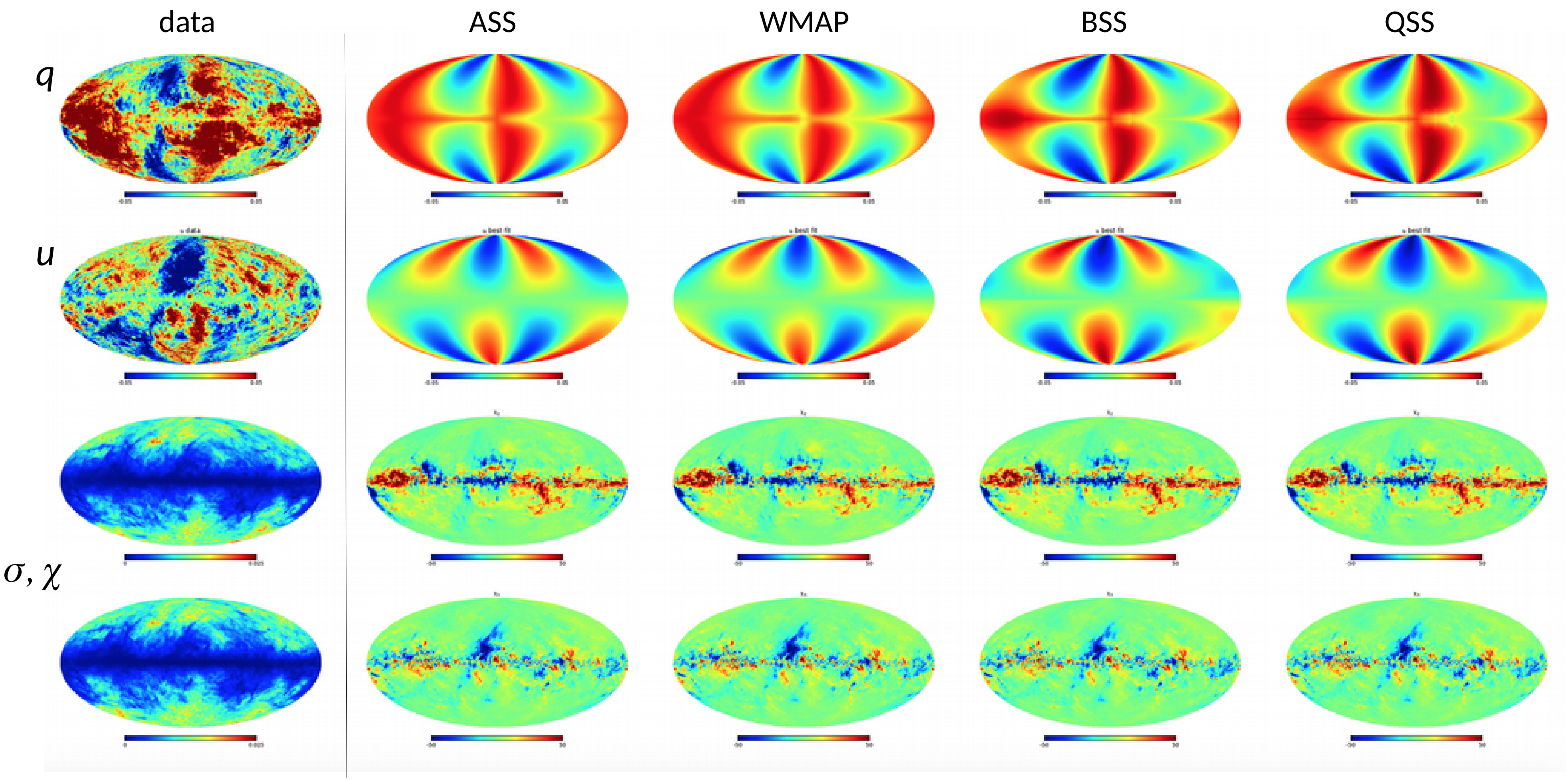
- Fit of intensity map and n_{d} models:



Polarized Diffuse Galactic Foregrounds and GMF

GMF from *Planck* 353-GHz full-sky polarization maps

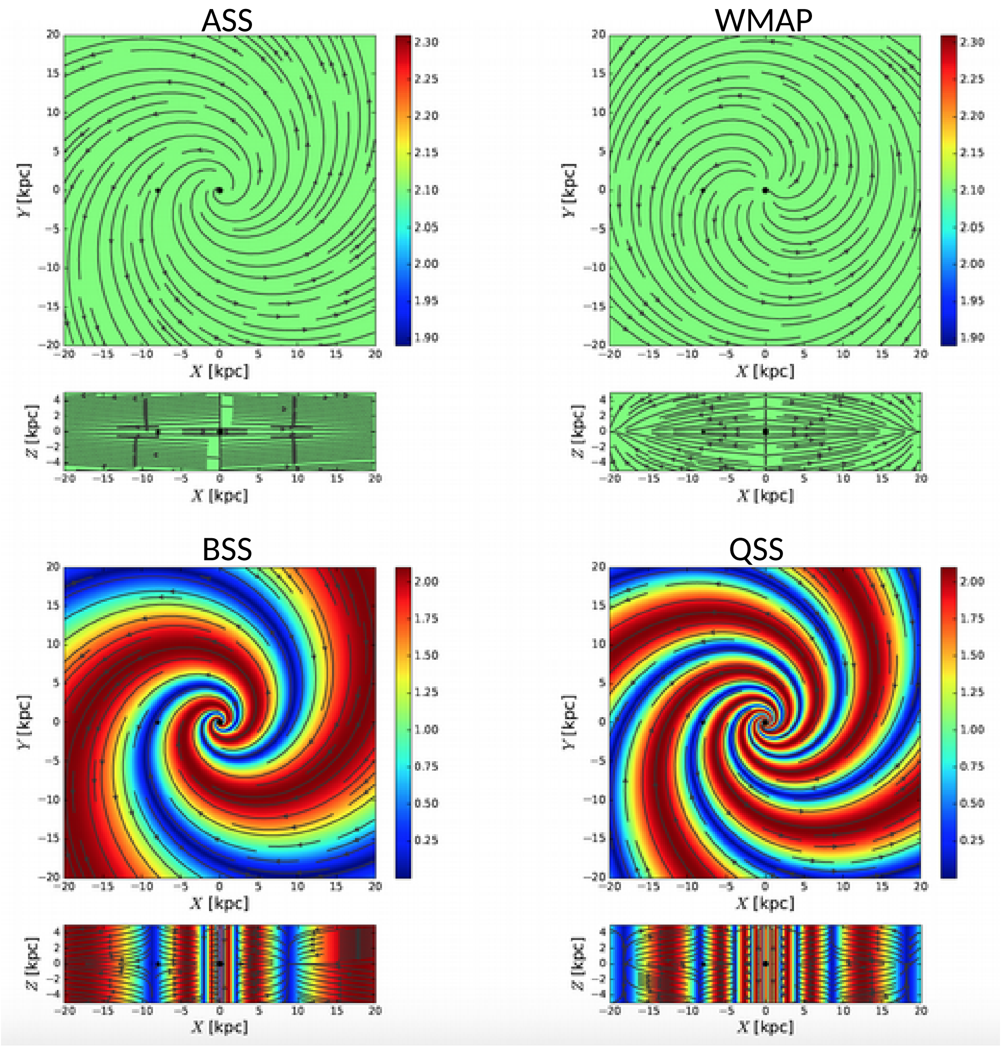
- Fit of polarization maps (q, u) and GMF models: (here with n_{d} = ED)



Polarized Diffuse Galactic Foregrounds and GMF

GMF from *Planck* 353-GHz full-sky polarization maps

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

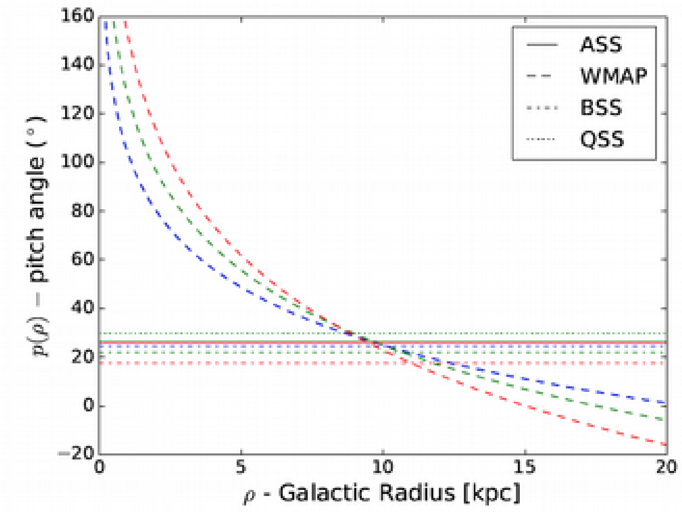


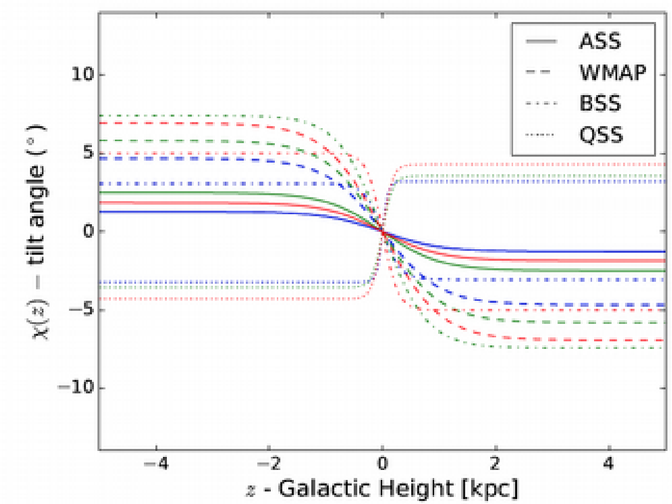
- Reconstructed GMF look similar (despite different parameterization and uninformative prior)

Polarized Diffuse Galactic Foregrounds and GMF

GMF from *Planck* 353-GHz full-sky polarization maps

- Comparison of best-fit GMF models from (q, u) maps:
  - Reconstructed spiral patterns are (very) similar among reconstructions
    - pitch angle 24° ± 3° at Sun radius (including outliers)
  - Out-of-plane component is less constrained
    - tilt angle of about -3° ± 5°
    - 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}

Note: turbulence has not been modeled here!

Polarized Diffuse Galactic Foregrounds and GMF

GMF from *Planck* 353-GHz full-sky polarization maps

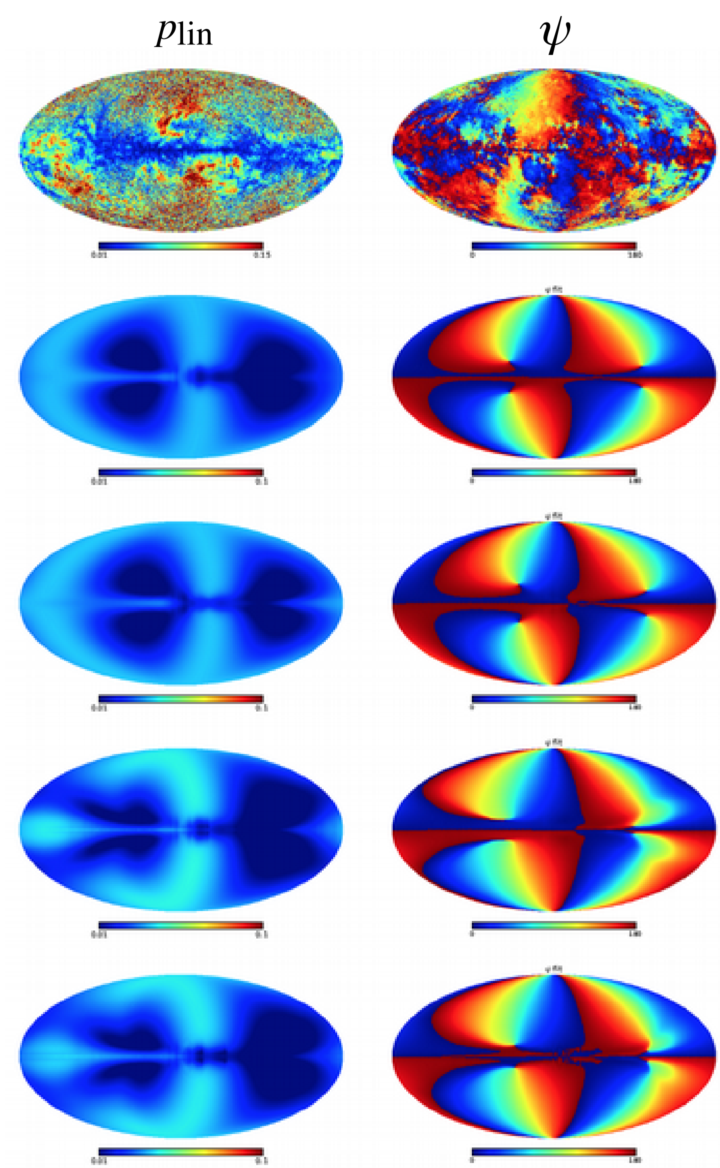
- Comparison of best-fit GMF models from (q, u) maps in terms of the degree of linear polarization and of the polarization position angle
  (deduced from the best-fits, not fitted)

  - line-of-sight depolarization by integration of varying GMF orientations seen in $p_{\rm lin}$
  - overall agreement in ψ
    even if twisted and skewed

  - clear residuals between models and data either in $p_{\rm lin}$ or ψ
  - residuals in $p_{\rm lin}$ and ψ are seemingly 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 thermal dust polarization data

- Validation based on ‘realistic’ simulations
- First MCMC fits on *Planck* 353-GHz polarization data (12 models: 3 n_{d}, 4 GMF)

There is still room for improvements

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

before (?) including a description of the turbulence

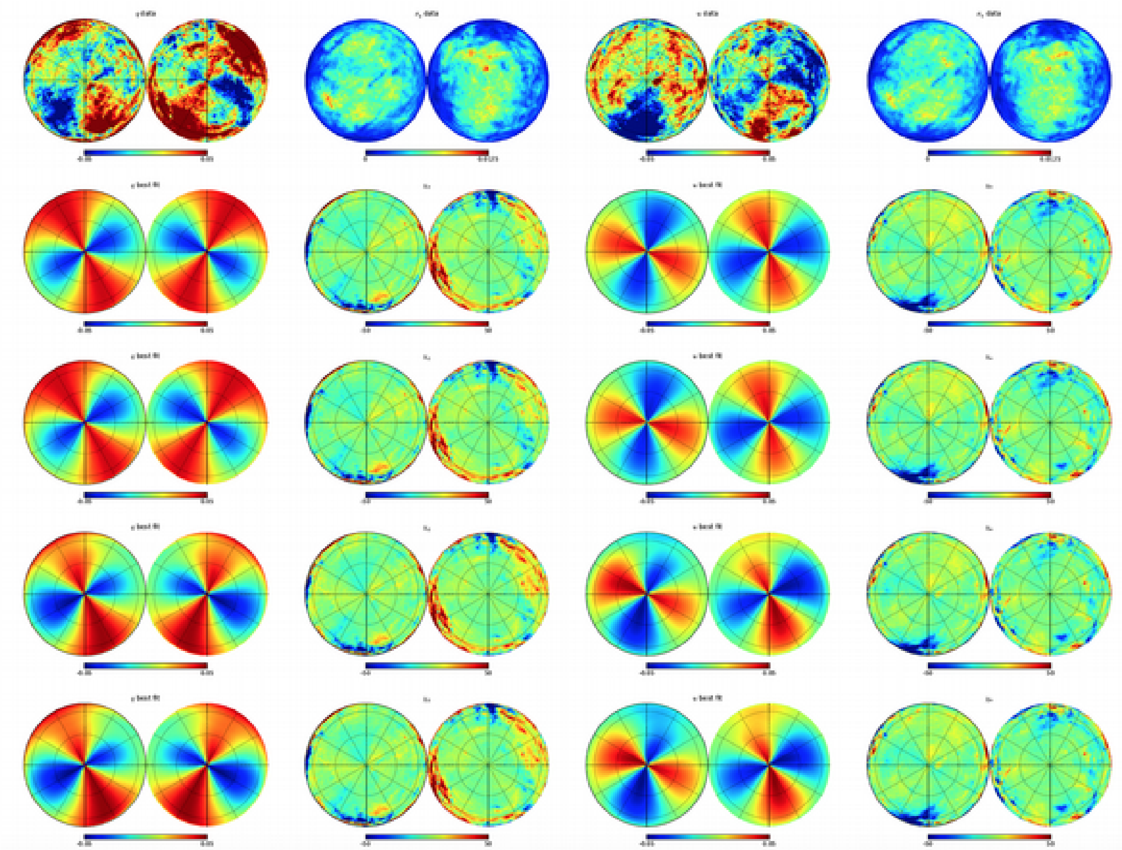
Open questions

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

Thank you

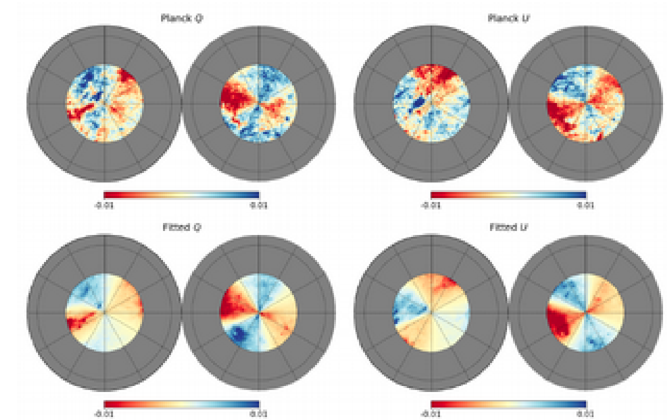
[Pelgrims, Macías-Pérez & Ruppin, A&A *submitted* – arXiv:1807.10515]
[Pelgrims & Macías-Pérez, A&A *submitted* – arXiv:1807.10516]

Polarized Diffuse Galactic Foregrounds and GMF



?

Galactic caps to constrain local magnetized structures



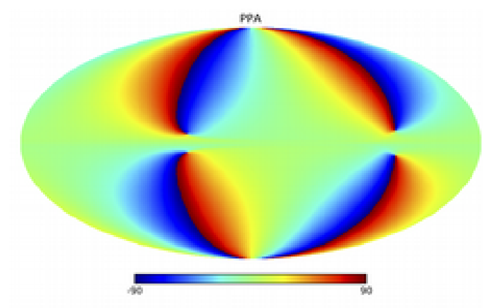
[Alves et al. 2018]

Polarized Diffuse Galactic Foregrounds and GMF

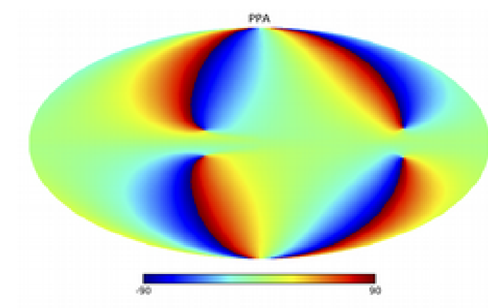
GMF from dust data: [SIMULATIONS]

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

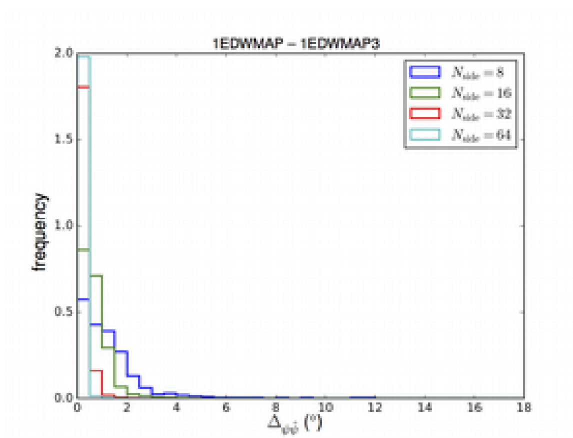
case A

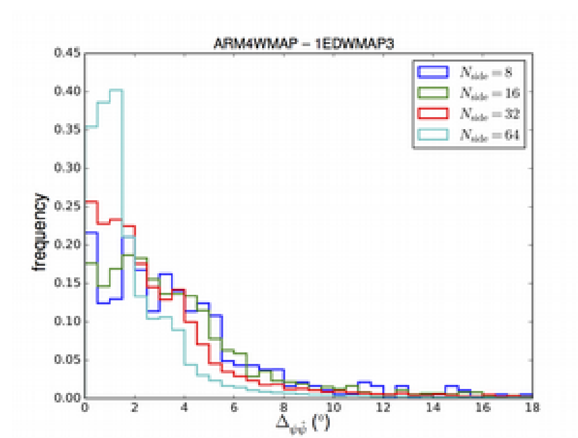


case B



  - Compared to the angle of the input model





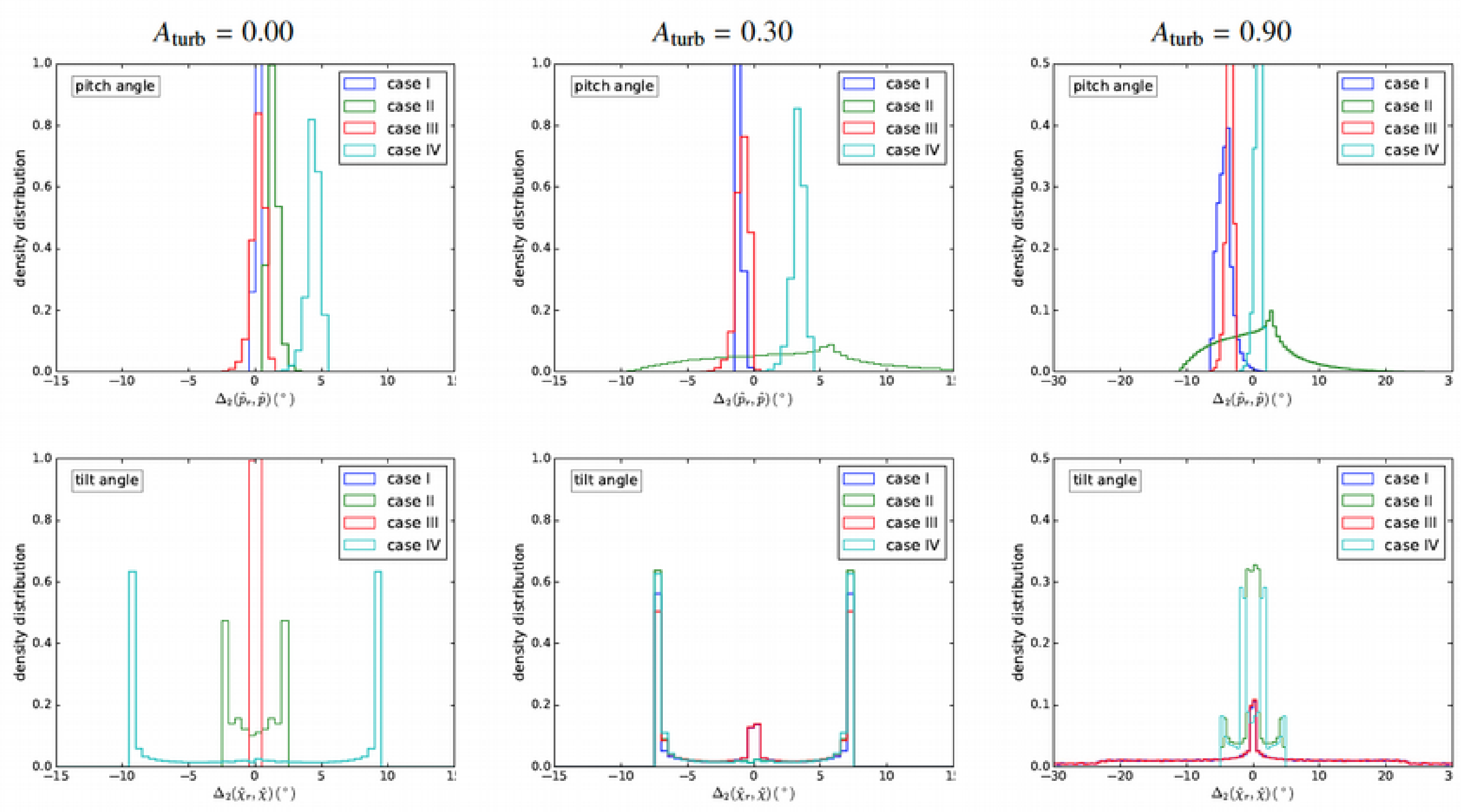
Polarized Diffuse Galactic Foregrounds and GMF

Simulations

- 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 input model (n_{d}: 4SA – gmf: WMAP)

pitch angle

tilt angle



Polarized Diffuse Galactic Foregrounds and GMF

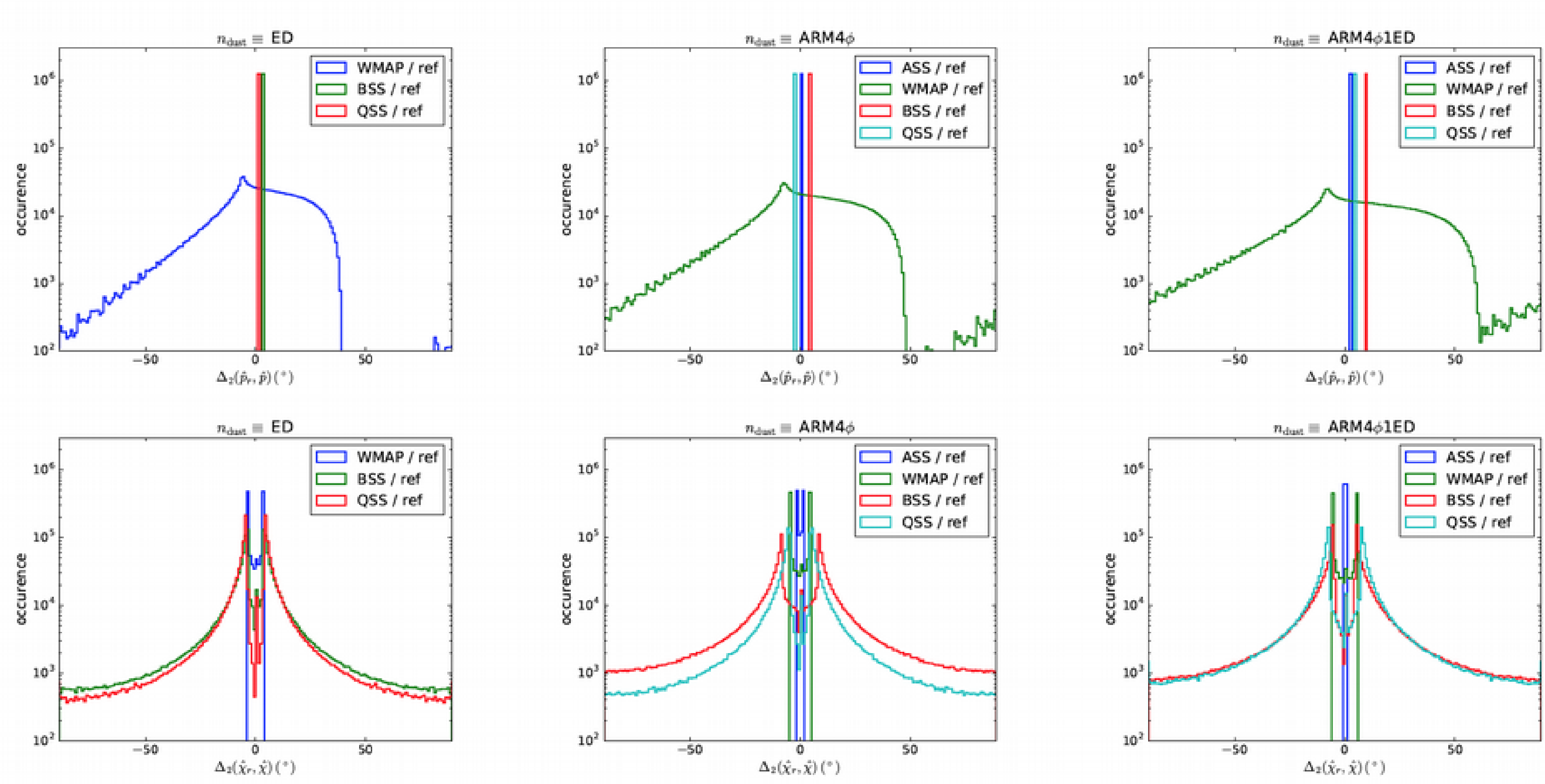
RADIO FOREGROUNDS

GMF from *Planck* 353-GHz full-sky polarization 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 '$n_{\rm d}$ = ED – GMF = ASS' (the least evolved)

measured pitch angle

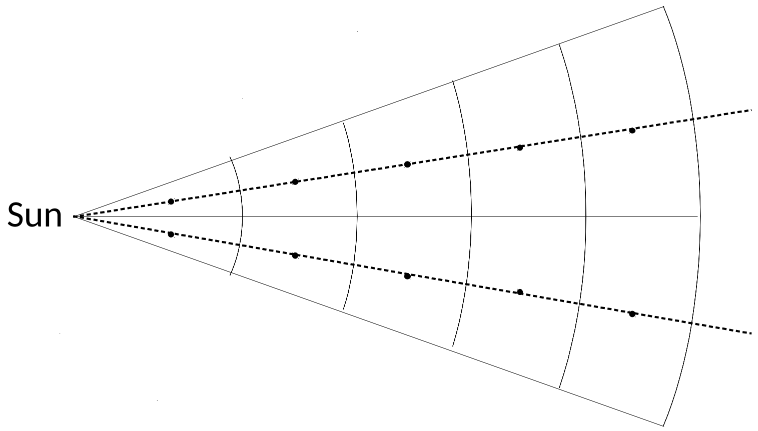
measured tilt angle



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