The coherent magnetic field of the Milky Way halo

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Motivation

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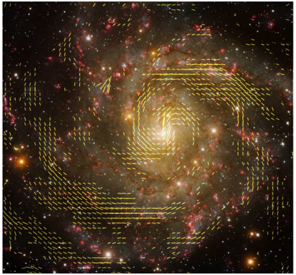
Conclusions

Motivation

- Magnetic fields play important role in the Galaxy
  - CR tarnsport and energy distribution
  - formation of galactic winds and outflows
  - formation of turbulence
- Galactic MF exist on all scales from pc to kpc
- Coherent MF of the Milky Way is crucial for finding sources of UHECR

Observations of other galaxies reveal large-scale coherent MF:



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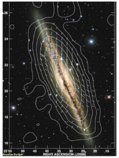
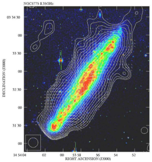


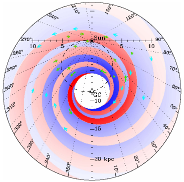


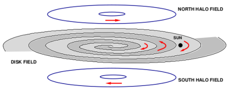
NGC891, NGC5775

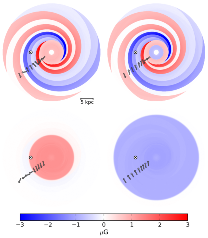
Previous phenomenological models :

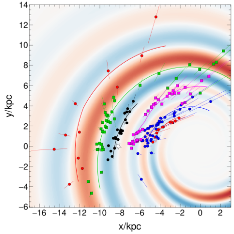
Previous models based on varous data sets:

- *Pre-NVSS:* Han et al. 1997; PT & Tkachev 2002; Beck 2001
- *NVSS:* Pshirkov et al 2011 (PT11)
- *NVSS+WMAP:* Jansson & Farrar 2012 (JF12); Han et al. 2018; Xu & Han 2019; Shaw et al. 2022; Unger & Farrar 2023 (UF23); Xu & Han 2024.









Why do we need a new model?

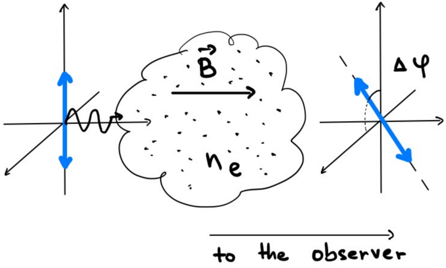
- new improved data
- shortcomings of previous models
- new structures: Local Bubble and Fan Region

Magnetic field tracers

- Fraday rotation: extragalactic sources
  - $\sim$ 59 k sources; cover whole sky
  - integrated over the line of sight
- Fraday rotation: pulsars
  - concentrated in the Galactic plane
  - have distance information
- Synchrotron emission of relativistic electrons
  - high resolution all-sky maps (WMAP and Planck)
  - integrated over the line of sight
- Starlight polarization by dust
  - dust is concentrated in the thin disk of $\sim$ 200 pc
- Zeeman splitting
  - no directional inforamtion

Data used in this analysis: **extragalactic Fraday rotations** & **synchrotron polarization maps**
[both are line-of-sight integrals]

Faraday rotation



- Rotation of the polarization plane $\Delta\phi$ of a wave propagating through the ionized gas is proportional to λ^2

$$\mathbf{RM} = \frac{\Delta\phi}{\lambda^2} = \frac{e^3}{2\pi m_e^2} \int n_e \mathbf{B}_{||} dl$$

$$= 0.81 \frac{\text{rad}}{\text{m}^2} \int n_e \mathbf{B}_{||} dl \cdot \frac{\text{cm}^3}{\mu\text{G pc}}$$

- depends on the parallel component $\mathbf{B}_{||}$.
- requires density of free electrons n_e
- positive for $\mathbf{B}_{||}$ pointing towards the observer

Faraday rotation data

- We use most recent compilation of $\sim$ **59** k *extragalactic* RMs available in *CIRADA consolidated catalog version v1.2.0* of which the core is the NRAO VLA Sky Survey (NVSS)
- Cover almost uniformly the whole sky with mean density $\sim 1.5/\text{degree}^2$.
- Galactic pulsars are *not included* in our analysis

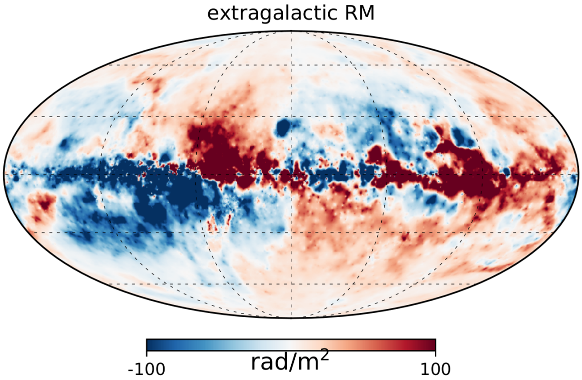
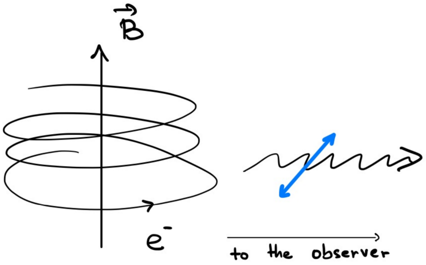


Fig: Hutschenreuter'22

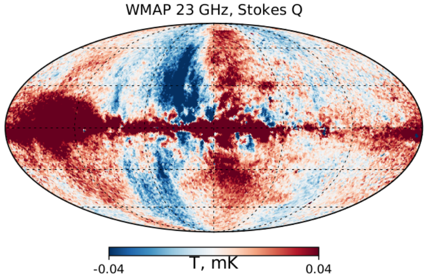
Synchrotron emission

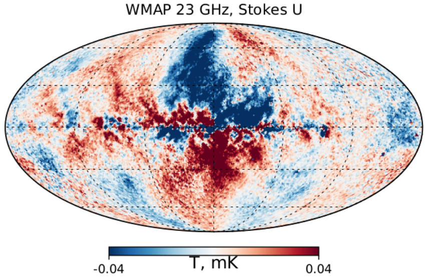


- Total synchrotron intensity is proportional to $\mathbf{B}^2$,
$$I \propto \frac{e^4}{m^2}\mathbf{B}^2\left(\frac{E}{m}\right)^2$$
- sensitive to the perpendicular component $\mathbf{B}_\perp$
- *insensitive* to the sign of $\mathbf{B}_\perp$
- proportional to the density of *relativistic electrons*
- linearly polarized in the direction perpendicular to $\mathbf{B}_\perp$

Synchrotron data

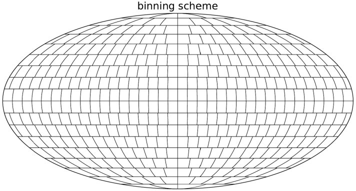
- We use the final 9-year WMAP polarization sky maps at 23 GHz
- Planck and WMAP are very similar
  (for the study of their systematic differences see Cosmoglobe project [Watts et al. 2023)])
- Stokes parameters:





Data preparation

- **Cleaning:** iteratively remove 3σ outliers until converged
- **Binning:** $10^\circ \times 10^\circ$ bins each containing ~ 100 RM measures on average

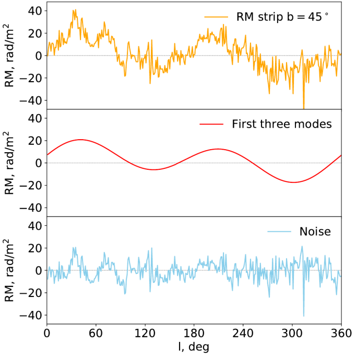


- **Masking:**
  - RM: mask the Galactic plane $\pm 10^\circ$ and some known local anomalies; 26% of the sky masked in total
  - Synchrotron: remove a few local anomalies, 11% of the sky masked

- **Error estimation:** Use variations of the data in the constant latitude strip to estimate variation in the bin of size L:

$$\sigma^2(L) = 2 \sum_{k=3} \mathrm{sinc}^2\left(\frac{kL}{2}\right) S_k$$

Example: latitude $b = 45^\circ$



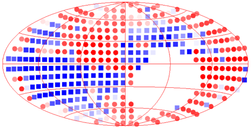
Main model components

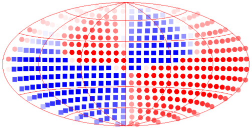
(1) **Thick disk**

- inspired by observations of other galaxies face-on
- consists of spiral arms with adjustable positions, thickness ($\sim 1 - 2$ kpc) and field magnitude

(2) **Toroidal halo**

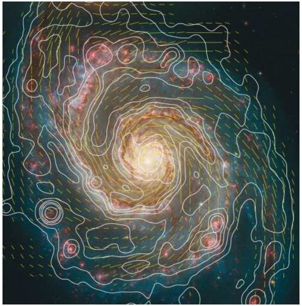
- independent North and South components
- inspired by symmetry, and by previous models (PT11)

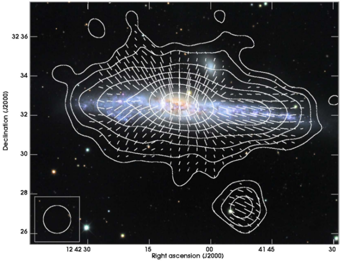




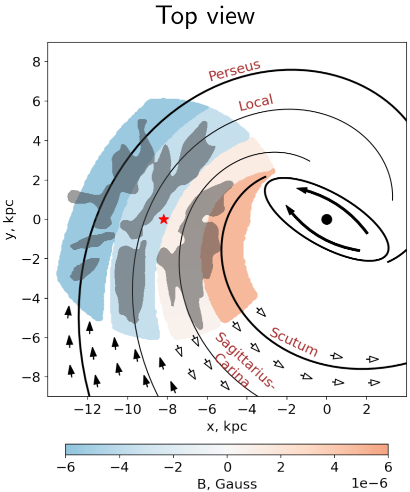
(3) **X-shape field**

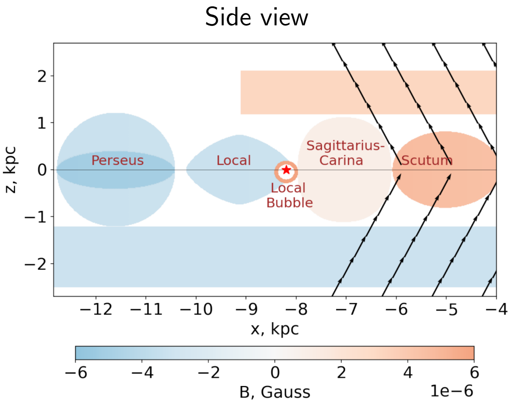
- necessary to fit synchrotron data (JF12)
- inspired by observations of other galaxies edge-on





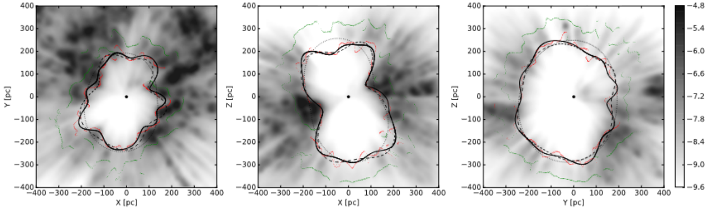
Main model components





New feature 1: Local Bubble

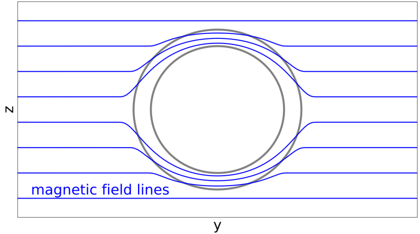
Local Bubble is a cavity in the dust distribution surrounding Sun, created by recent supernova



Pelgrims'19

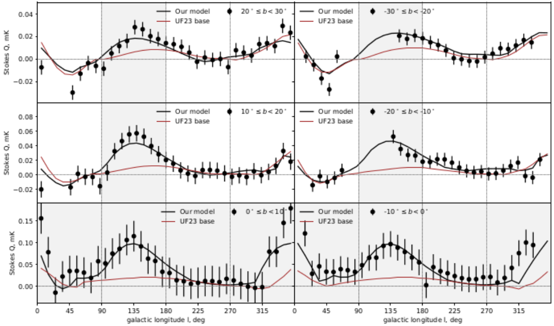
- Three main components still do not fit the data well: when normalized to RM they underproduce synchrotron at high latitudes
- Previously this problem was solved by assuming striation
- Instead we add the Local Bubble
- We play on the fact that synchrotron is quadratic in B, while RM are linear

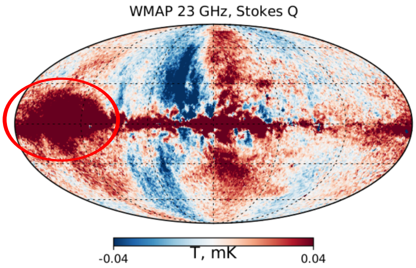
Simple model of the Local Bubble:

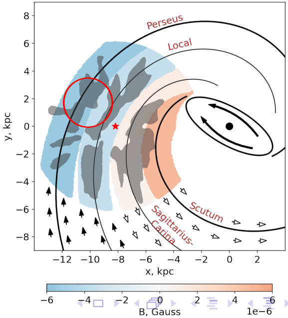


New feature 2: Fan Region

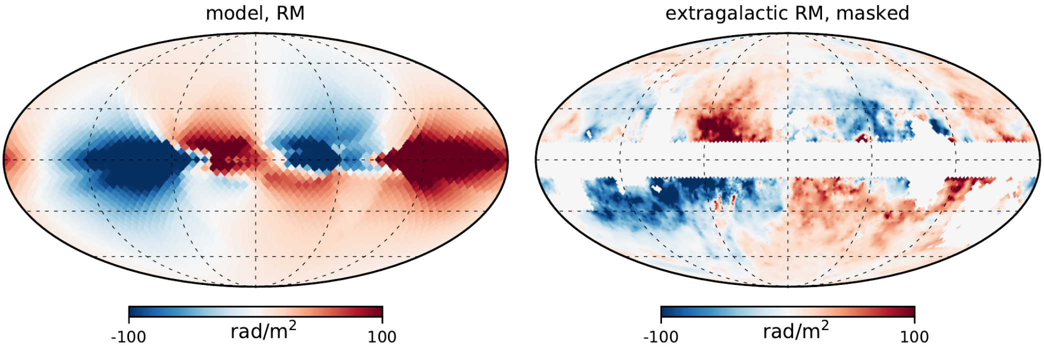
This is a bright region around the GP at $\sim 90^\circ < l <\sim 180^\circ$.
Hill'17: $> 30\%$ of the Fan Region emission originates from beyond 2 kpc $\Longrightarrow$ must be a part of a large-scale GMF



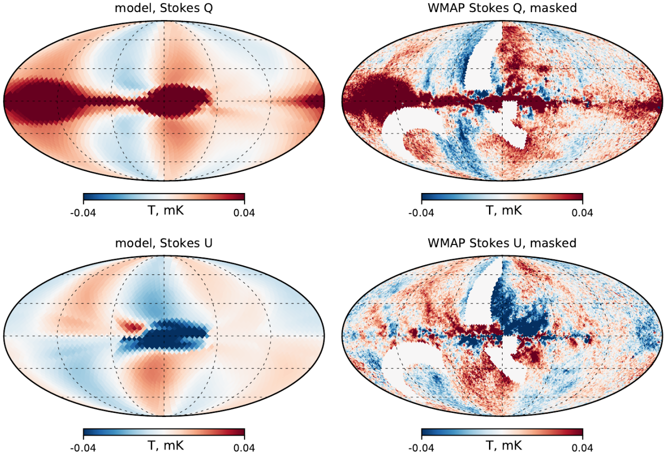




Results of the fit: RM



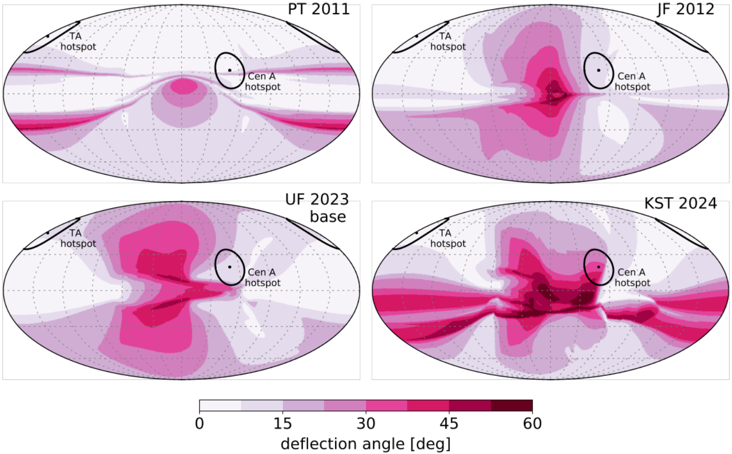
Results of the fit: Stokes Q and U



Global fit:

	χ^2	n.d.f.	χ^2/ndf
RM	544	283	1.92
Q	385	348	1.11
U	482	348	1.38
total	**1411**	**1037**	**1.36**

Comparison with previous models: UHECR defelctions



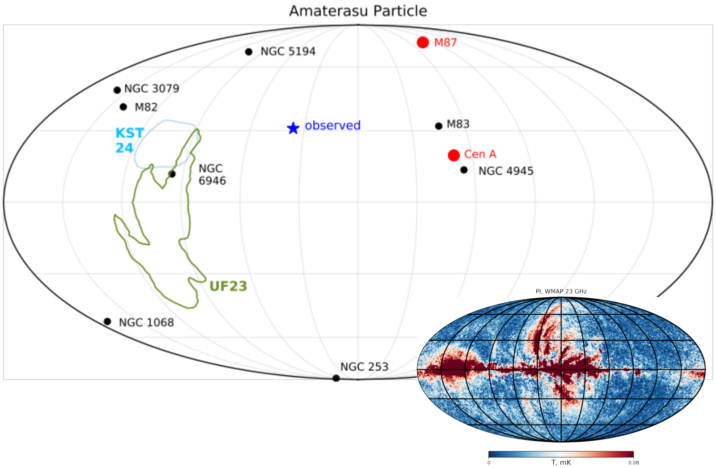
Deflections of an UHECR particle of rigidity $R = \frac{E}{Z} = 2 \times 10^{19}$ eV in several regular GMF models. Random field is not included

Note: Local Bubble does not contribute much to the deflections, while the Fan Region does contribute very significantly $\Longrightarrow$ its accurate modeling is crucial

Comparison with previous models: Amaterasu

Backtracking of the Amaterasu particle of energy 244 EeV assuming an iron nuclei.

- Only regular field is taken into account
- Blue: our model + 1σ uncertainty of energy + 1σ uncertainties of fitting parameters
- Green: collection of 8 models of UF23 with their uncertainties + 1σ uncertainty of energy
- Caveat: overlaps with Loop I



Conclusions and outlook

- We have a good idea about the overall magnitude of the coherent GMF
- This however is not sufficient to reliably calculate the UHECR deflections and determine source positions with a reasonable accuracy
- Present analysis may be refined by fitting together the GMF and relativistic electron density, but large uncertinties will remain becaue of degeneracies
- $\Longrightarrow$ new data involving distance information must be added to lift these degeneracies
  - Galactic pulsar RMs
  - RM + synchrotron measurements at many wavelengths ("magnetic tomography") [Wolleben'19,21]