Does the Local Bubble bias Galactic magnetic field models used to backtrack UHECRs?

Vincent Pelgrims

MSCA fellow @ IIHE
Université Libre de Bruxelles, Auger group

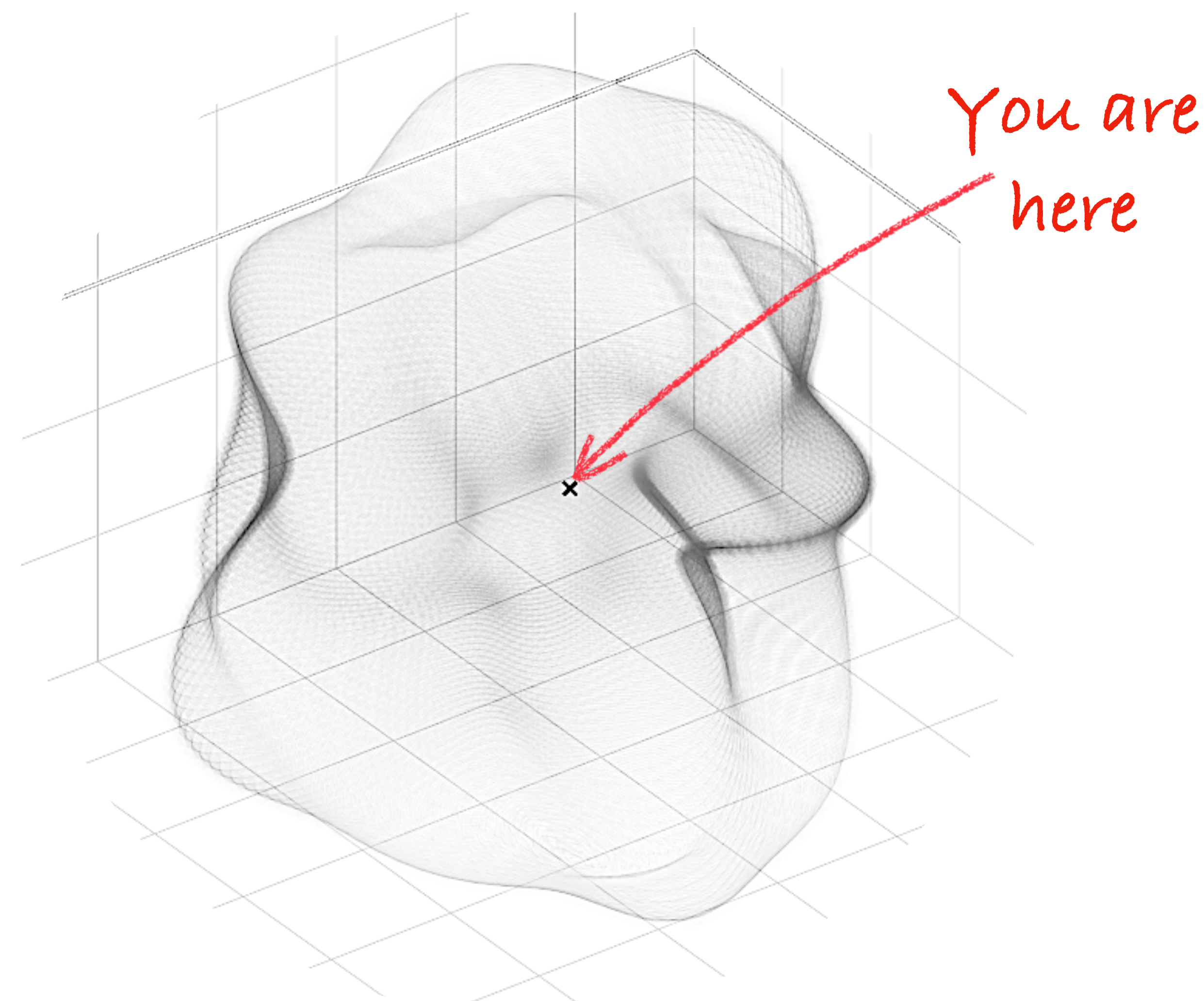
Marie Skłodowska-Curie Actions

UNIVERSITÉ LIBRE DE BRUXELLES

BRUXELLES BRUSSEL

Outline

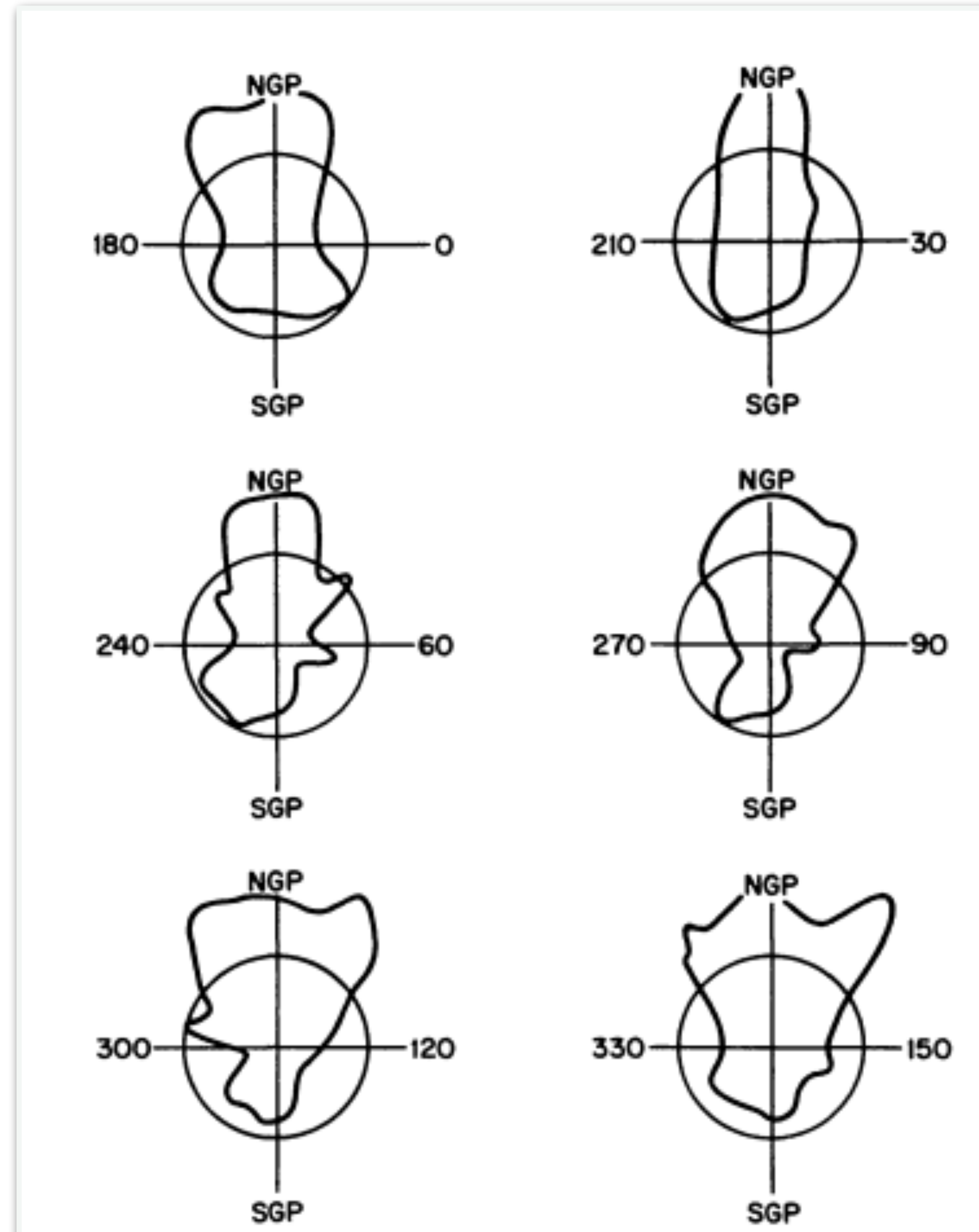
- ★ The Local Bubble
- ★ Magnetic field in the thick shell of bubbles
  - Application to the Local Bubble and potential effects for GMF modeling
- ★ The promises of starlight-polarization-based tomography



The Local Bubble — early observations and first evidence (< 80's)

- ★ The Local InterStellar Medium shows *unusual* characteristics:
  - Very low gas density ($n_{\mathrm{H_I}} \lesssim 0.1\,\mathrm{cm}^{-3}$)
  - diffuse soft X-ray background at ~0.25 keV
  - Anti-correlation between N_H and background X-ray emission

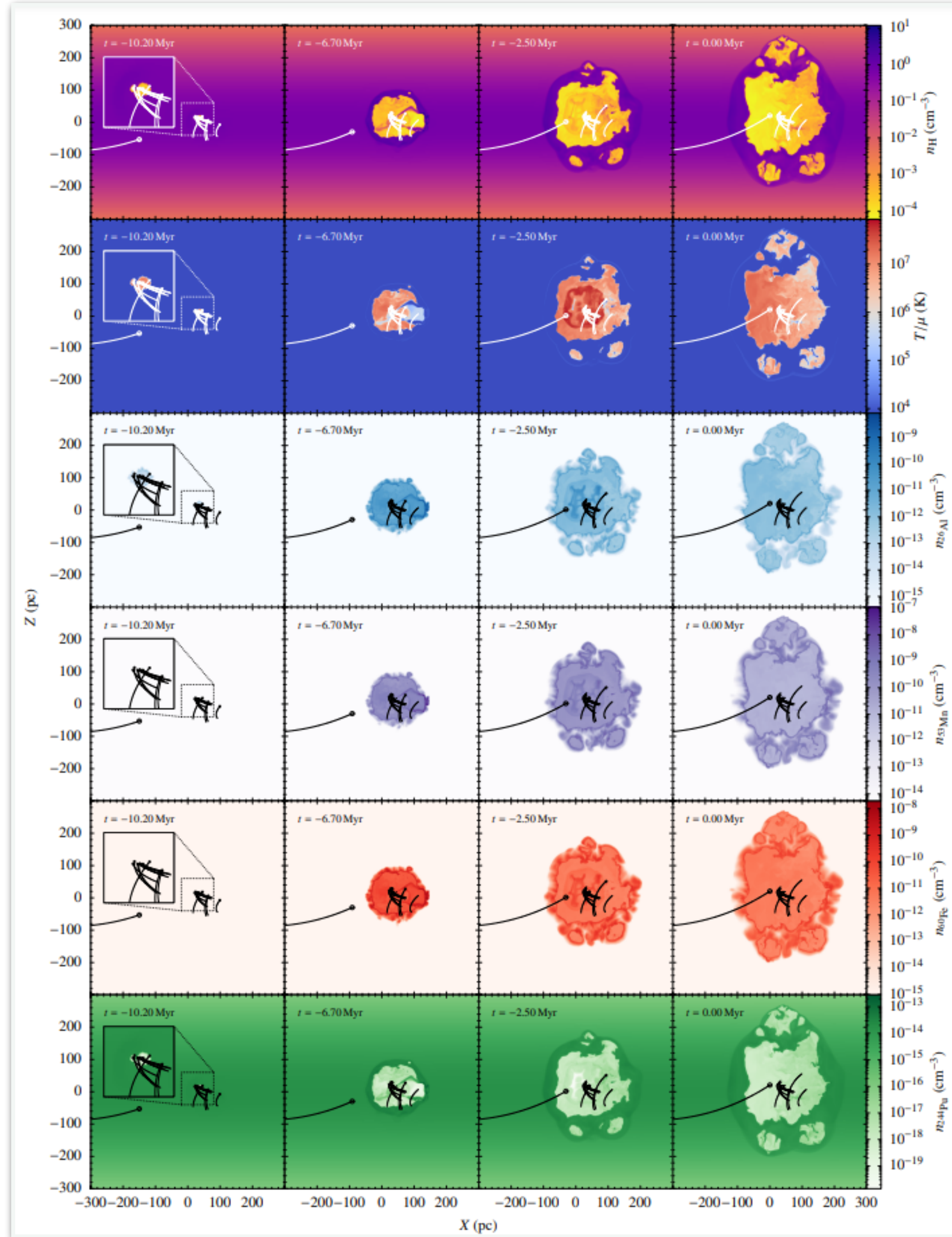
- ★ [Cox & Reynolds 1987]:
  - The LB as a local cavity filled with hot plasma with $T \approx 10^6\,\mathrm{K}$, possibly surrounded by a shell of gas
  - Presumably the result of one or more supernovae explosions



Contours for $N_\mathrm{H} \lesssim 10^{19}\,\mathrm{cm}^{-2}$ [Cox&Reynolds1987]

The Local Bubble — current evidence I

- ★ Radioactive isotopes (^{60}Fe, …) from supernovae found in Earth's crust layers
  - ‣ identification of SN progenitors
  - ‣ and time evolution modeling
- ★ [Schulreich+2023]: consistent picture
  - ‣ 14 SNe (13 in Sco-Cen star complex)
  - ‣ The Solar system entered the LB ~ 4.6Myr ago
  - ‣ Peak in isotope corresponds to closed approach w/ progenitors 2-3 Myr ago (peak in isotope

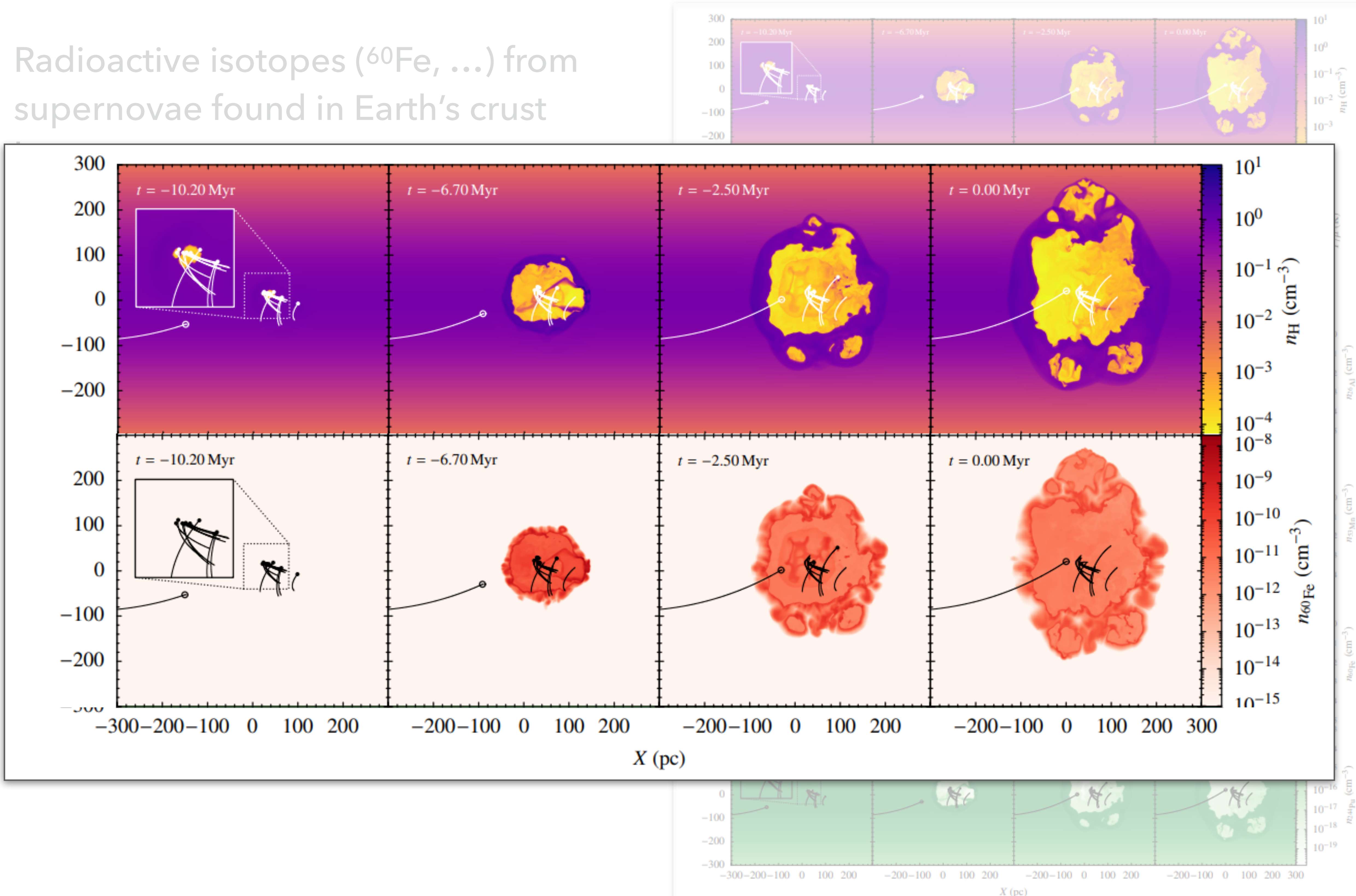


[Schulreich+2023]

The Local Bubble — current evidence I

★ Radioactive isotopes (^{60}Fe, …) from supernovae found in Earth's crust

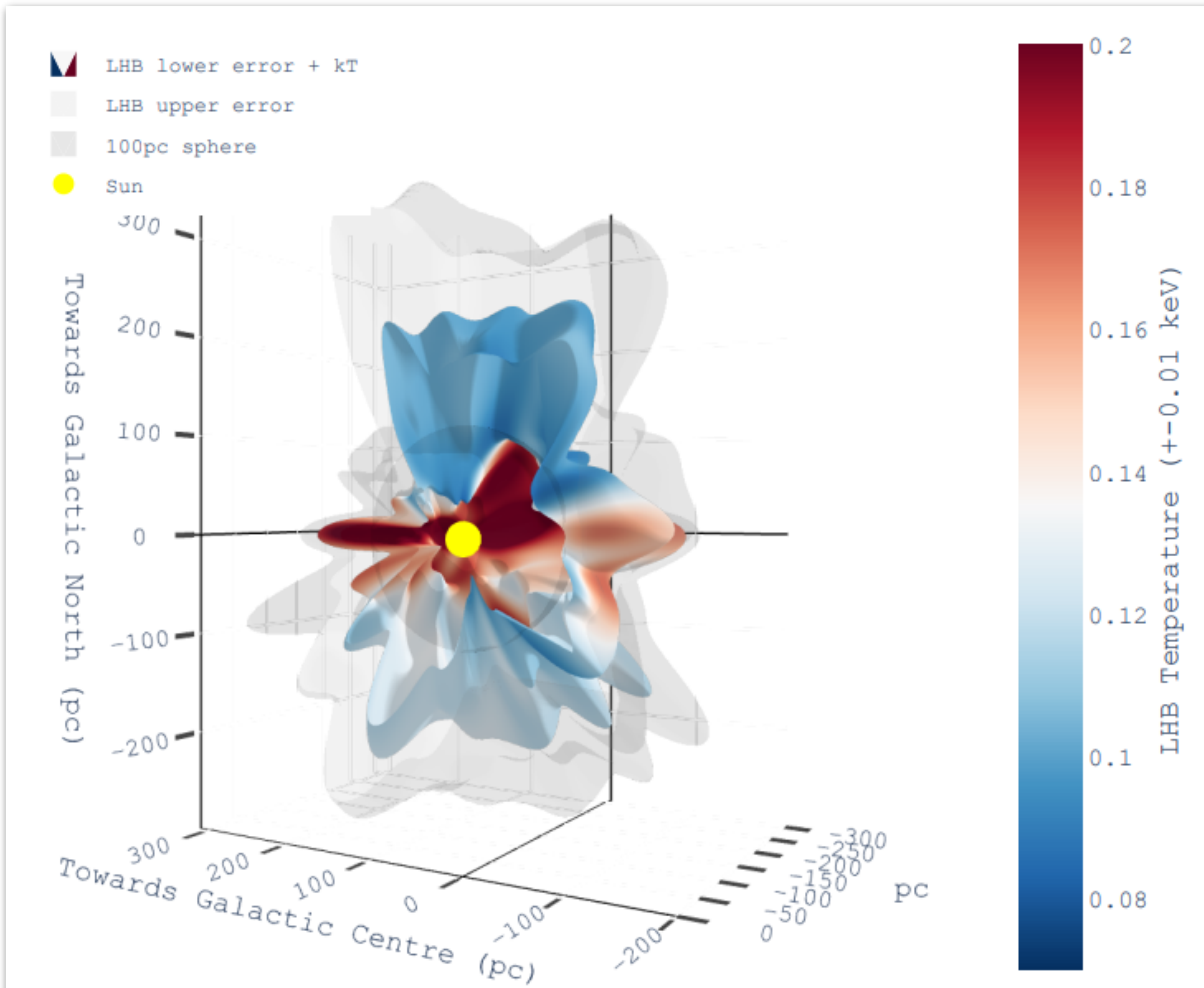
★



[Schulreich+2023]

The Local Bubble — current evidence II

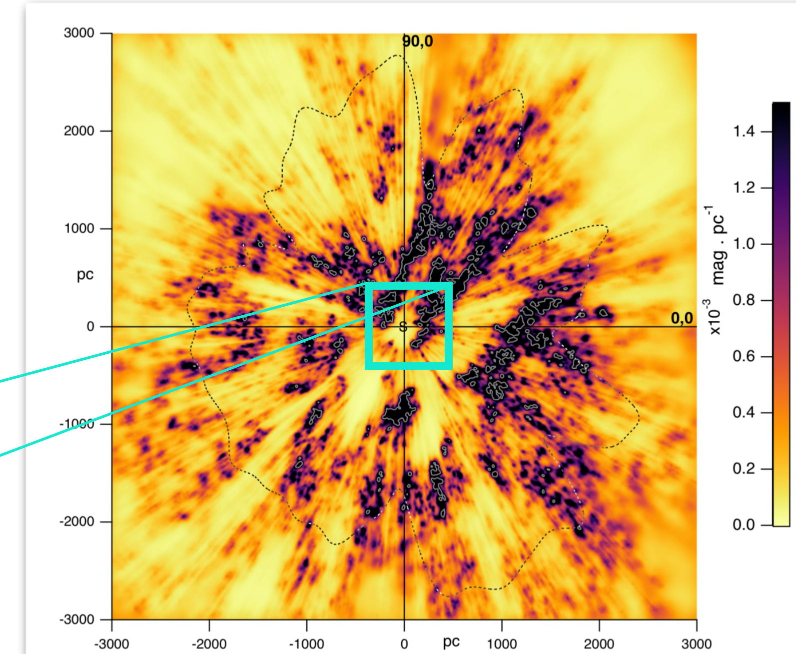
★ Local Hot Bubble well characterized, after removing heliospheric contribution to SXRB (ROSAT+DXL [Liu+2017] ; SRG/eROSITA [Yeung+2024])



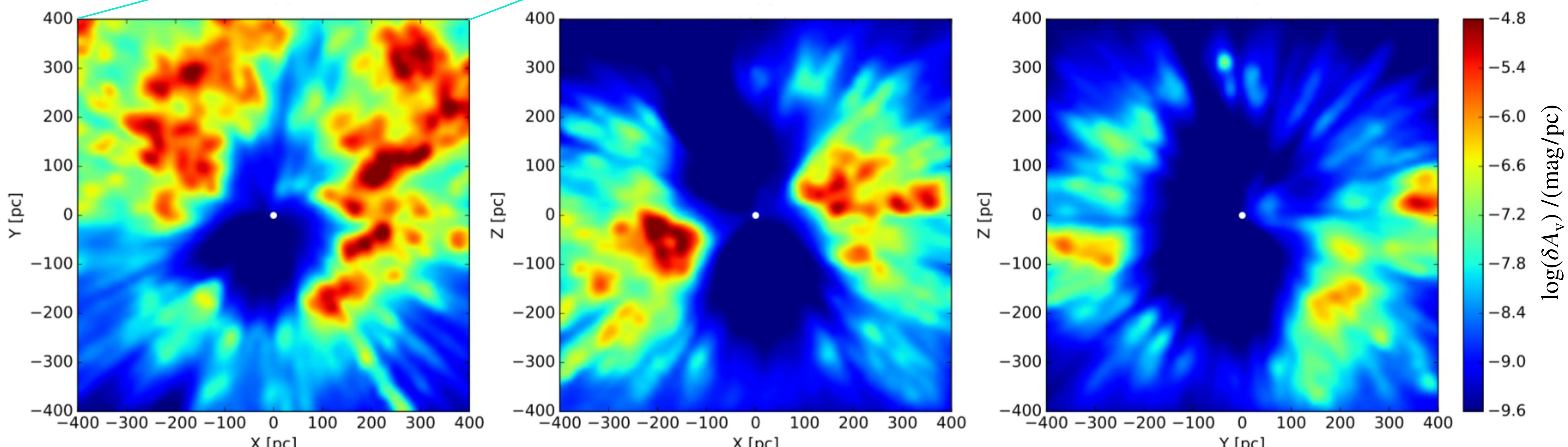
3D structure of LHB in western Galactic hemisphere from kT_{HLB} assuming constant electron density [Yeung+2024]

The Local Bubble — current evidence III

★ Cavity and shell well seen in 3D maps of dust density



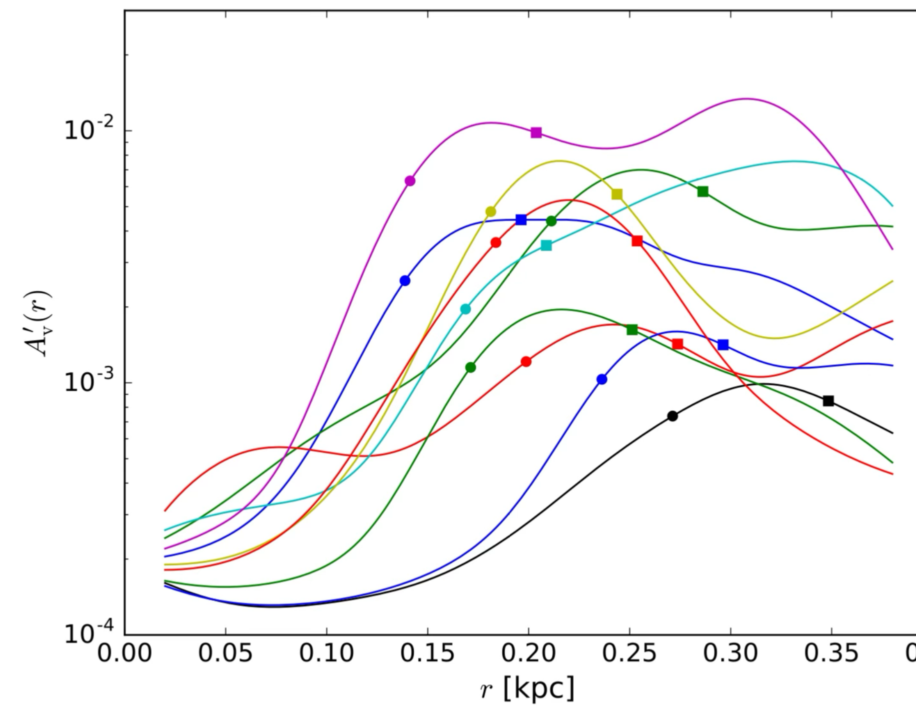
[Lallement+2019]



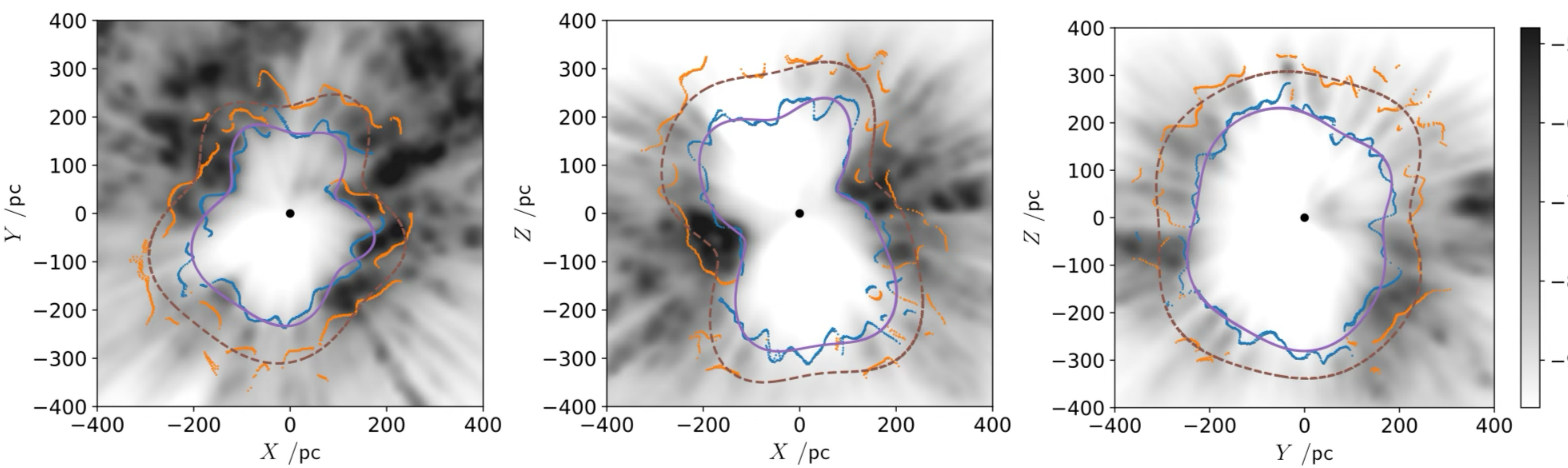
[V.P+2020]

The Local Bubble — its shell shape from 3D dust maps

- ★ [V.P+20; V.P+24] extraction of inner and outer surfaces of the dusty shell
  - ▸ first (inner) and second (outer) inflection points of radial density profiles
  - ▸ modeling surfaces through spherical harmonic decomposition



[V.P+2020]

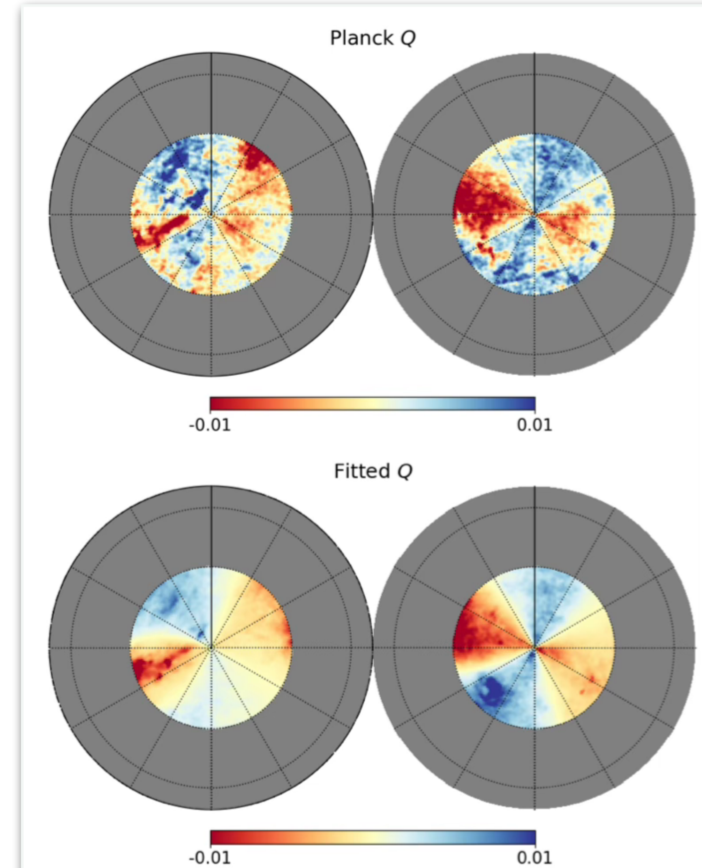


[V.P+2024]

The Local Bubble — a magnetic veil to our Galaxy?

★ [Alves+2018]:

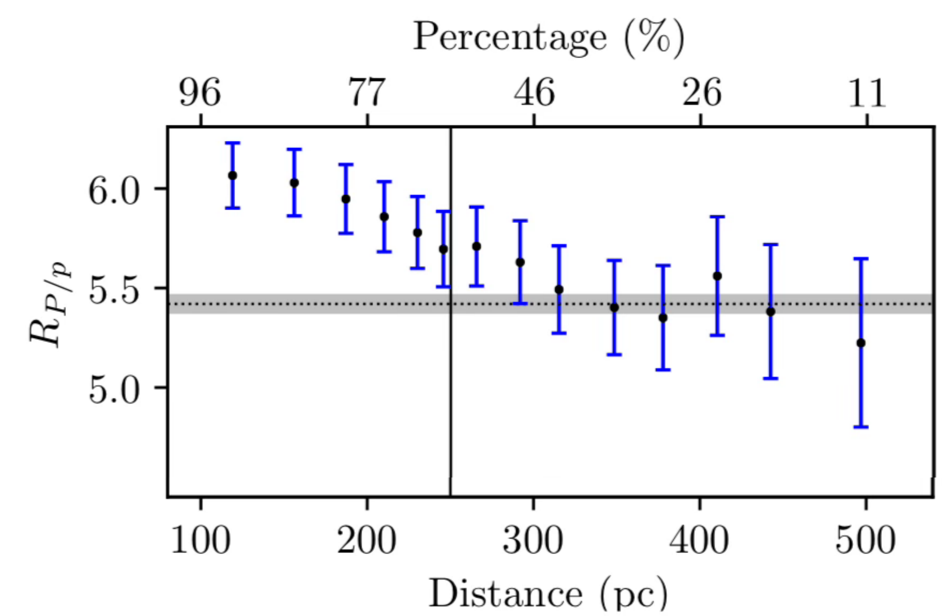
- if the LB results from SN explosions, the magnetic field should be imprinted because of flux-freezing and swept-up matter
- derived an analytical model for B in the thin shell of the LB
- used it to model the dust polarized emission in the polar caps assuming the LB is a spheroid



[Alves+2018]

★ [Skalidis&V.P+2019]:

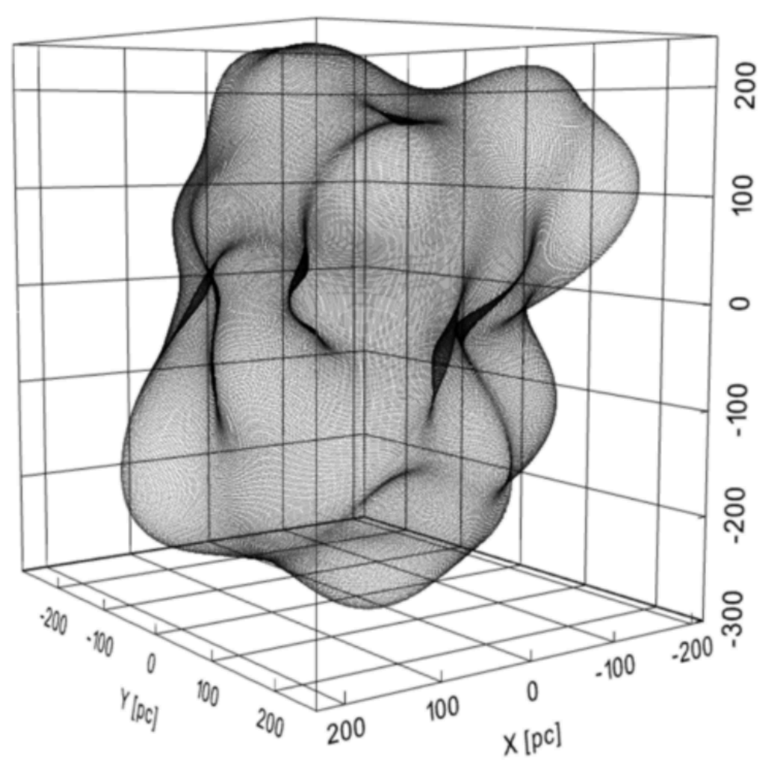
- comparison of dust in emission and absorption (stars with known distance)
- at high-$|b|$ the dust polarized emission (353-GHz) originates from a dusty magnetized region within 200-300 pc from the Sun

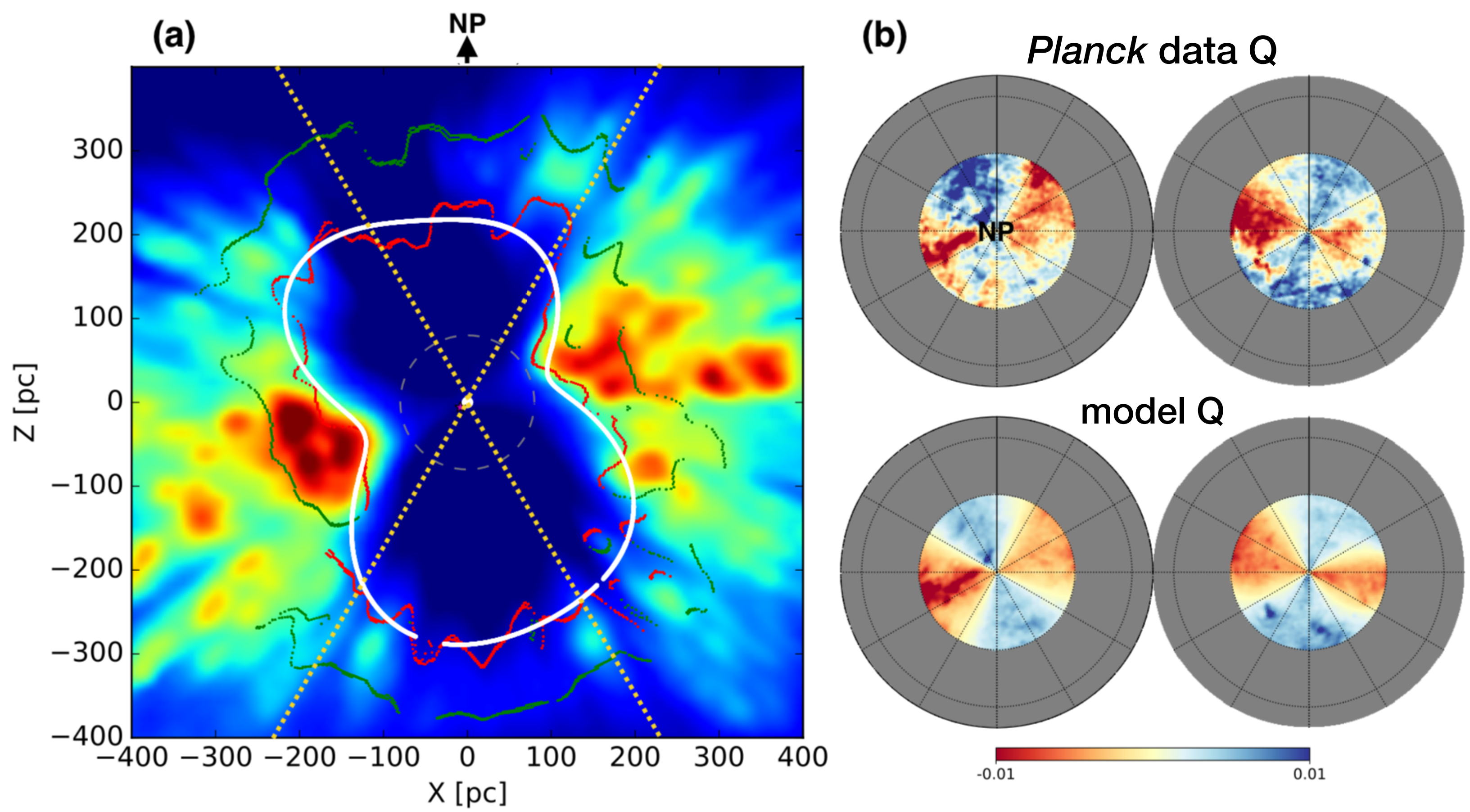


[Skalidis&VP 2019]

The Local Bubble — a magnetic veil to our Galaxy?

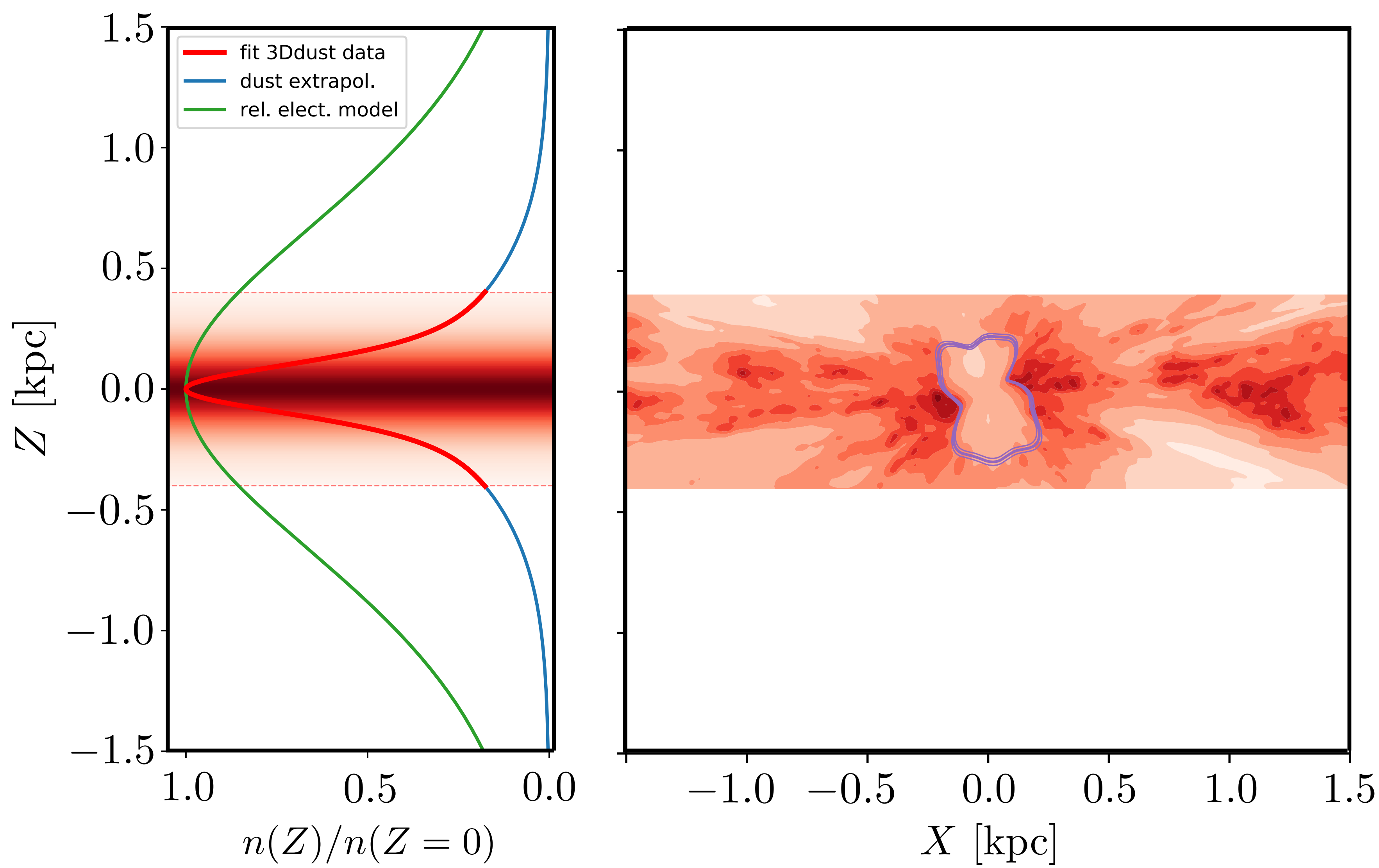
★ [V.P+2020]:
- update of [Alves+2018] using the realistic shape of the inner surface of the LB from 3D dust data
- magnetic field in the thin shell of the LB
- constraints on $\mathbf{B}^0$ and explosion center, (not $|\mathbf{B}^0|$)
- realistic shape improves the fit on dust polarized emission (uniform, spheroid LB, ...)





The Local Bubble — a magnetic veil to our Galaxy?

- ★ 3D density distribution of dust and CRE are very different
  - There is little chance that, in synchrotron, the polarization signal from the Local Bubble shell be dominant anywhere on the sky …
  - but…

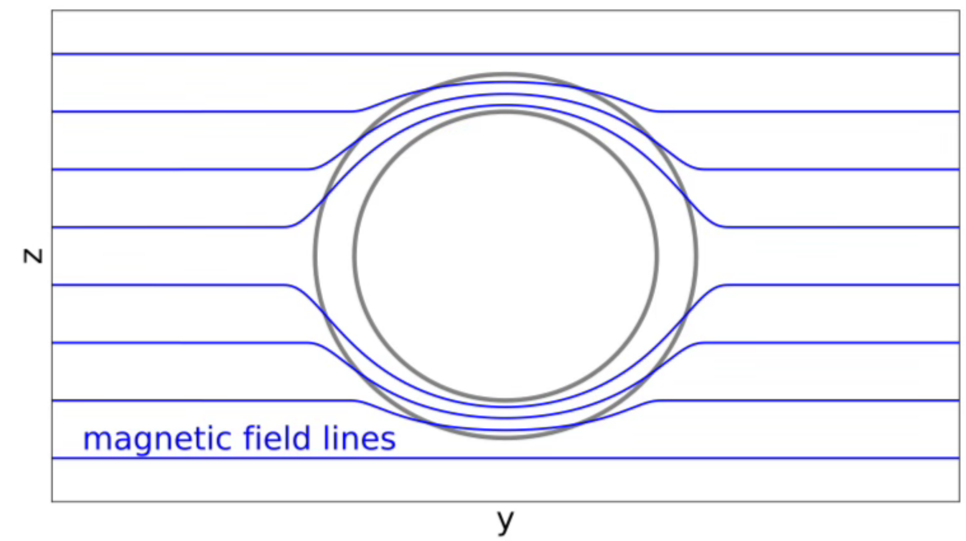


The Local Bubble — a magnetic veil to our Galaxy?

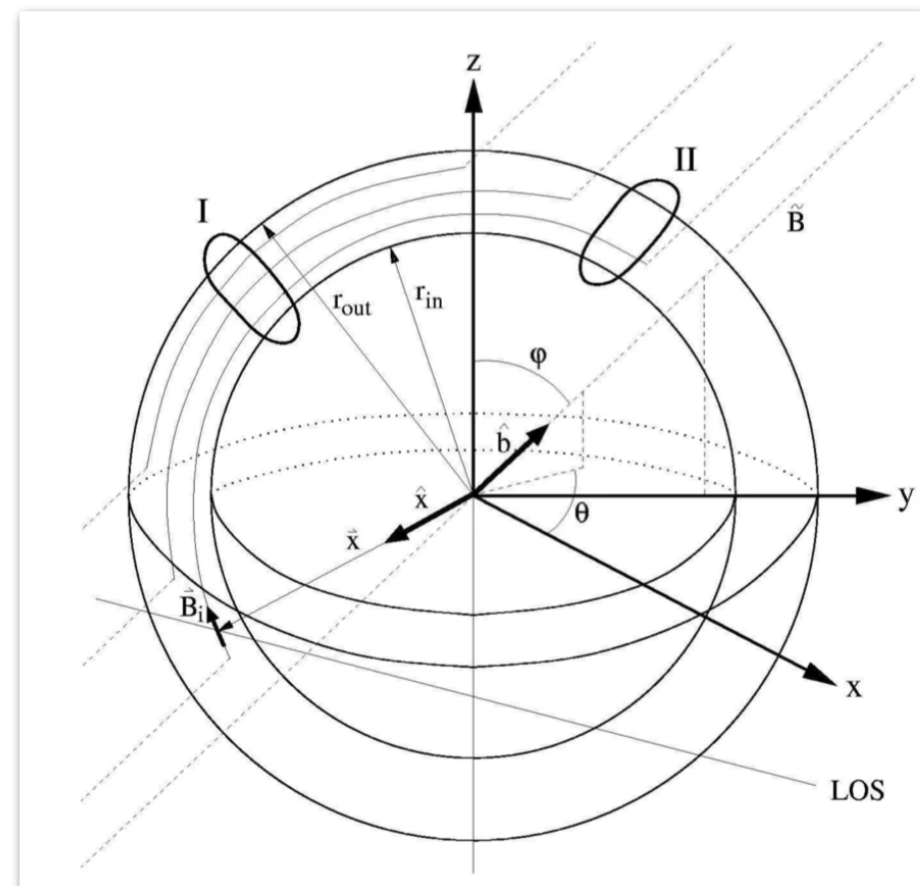
- ★ [Korochkin+2024] added a spherical bubble to large-scale components of the regular GMF
  - fitted the synchrotron and RM data

- ★ They found that the LB may contribute substantially to the polarized intensity but not so much in Faraday RM
- ★ possibly no need of striated random field

◉ **but**:
  - bubble assumed to be spherical
  - $\mathbf{B}$ constructed from geometrical arguments



[Korochkin+2024]



[Wolleben+2007]

The Local Bubble — a magnetic veil to our Galaxy?

- ★ Can we have a divergence-free model for $\mathbf{B}$ in the shell of any thick bubble?
- ★ What is the impact of the (highly) irregular shape of the LB shell on $\mathbf{B}$ and predictions for synchrotron Q and U and Faraday RM?

Astronomy & Astrophysics manuscript no. main
November 12, 2024

[arXiv:2411.06277]

An analytical model for the magnetic field in the thick shell of (super-) bubbles

V. Pelgrims[1,⋆], M. Unger[2,3], I. C. Mariş[1]

Magnetic field in the thick shell of bubbles

- ⋆ A divergence-free model for $\mathbf{B}$ in the shell of any thick bubble?
  - Consider bubbles to result from single SN explosion which swept away *radially* matter and B field lines

- ⋆ Starting from induction equation (without diffusion):

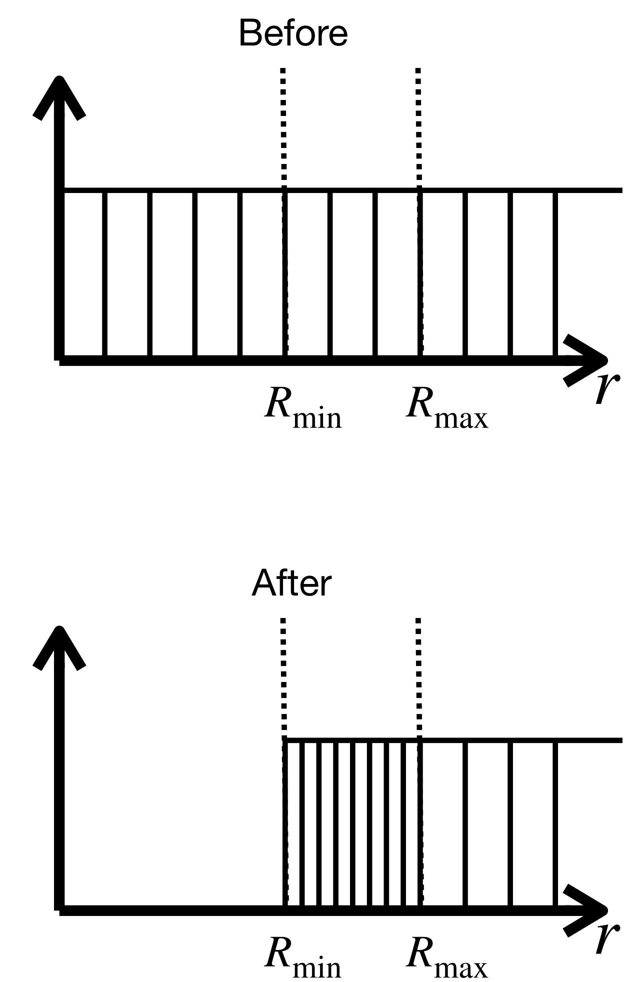
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

and solving everything in spherical coordinates centered on the SN explosion:

$$\begin{cases} B_r = \left(\frac{r^0}{r}\right)^2 B_r^0 + \frac{r^0}{r} \nabla_t \Lambda \cdot \mathbf{B}_t^0 \\ B_\theta = \frac{r^0}{r} \frac{\partial r^0}{\partial r} B_\theta^0 \\ B_\phi = \frac{r^0}{r} \frac{\partial r^0}{\partial r} B_\phi^0 \end{cases}$$

where Λ is the displacement of a particle initially at r^0 and currently at r and

$$\mathbf{r}^0 = r^0(r, \theta, \phi)\, \mathbf{e}_r = \mathbf{r} - \mathbf{\Lambda} \ .$$

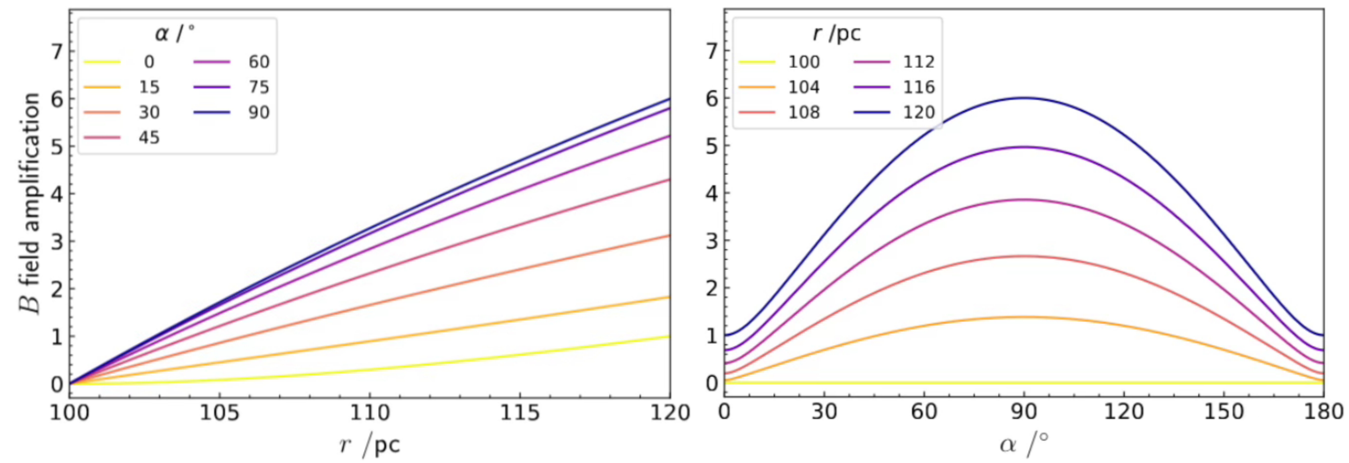


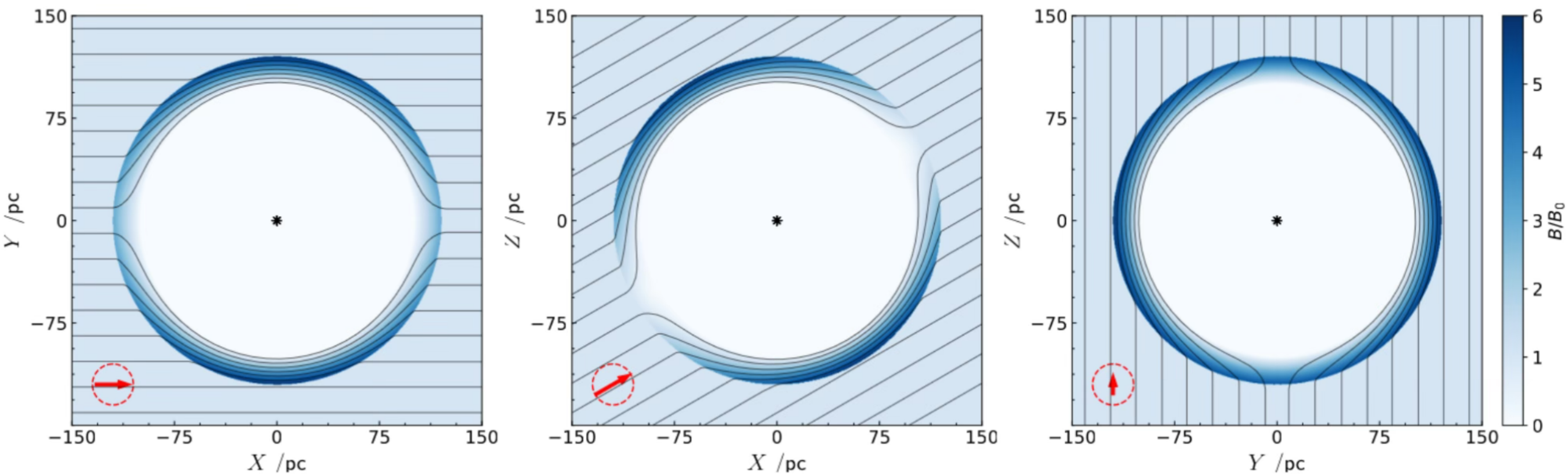
Magnetic field in the thick shell of bubbles

- ★ The case of a spherical bubble with centered explosion center; linear displacement field and assuming R_{min} and R_{max} can be determined:

  Amplification ratio:

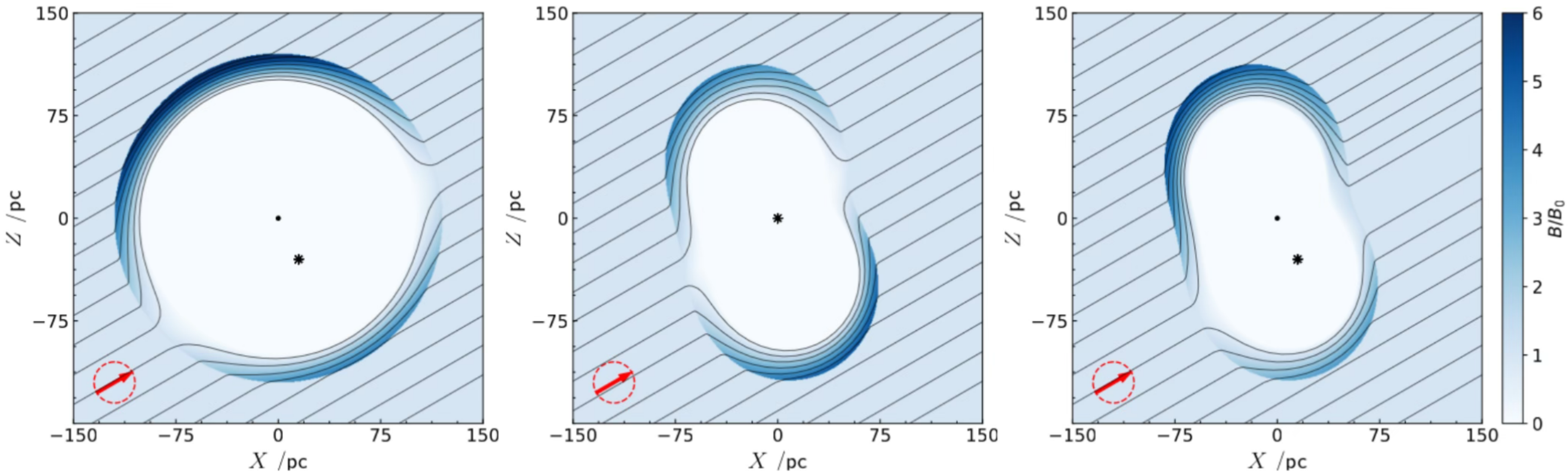
$$\left(\frac{B}{B^0}\right)^2 = \left(\frac{r - R_{\mathrm{m}}}{r}\right)^2 \left(\frac{R_{\mathrm{M}}}{R_{\mathrm{M}} - R_{\mathrm{m}}}\right)^4 \times \left(\sin^2\alpha + \cos^2\alpha \left(\frac{r - R_{\mathrm{m}}}{r}\right)^2\right)$$





Magnetic field in the thick shell of bubbles

★ Moving around the explosion center and irregular shell's shape:



★ Properties of our analytical model for $\mathbf{B}$ in the thick shell bubble:

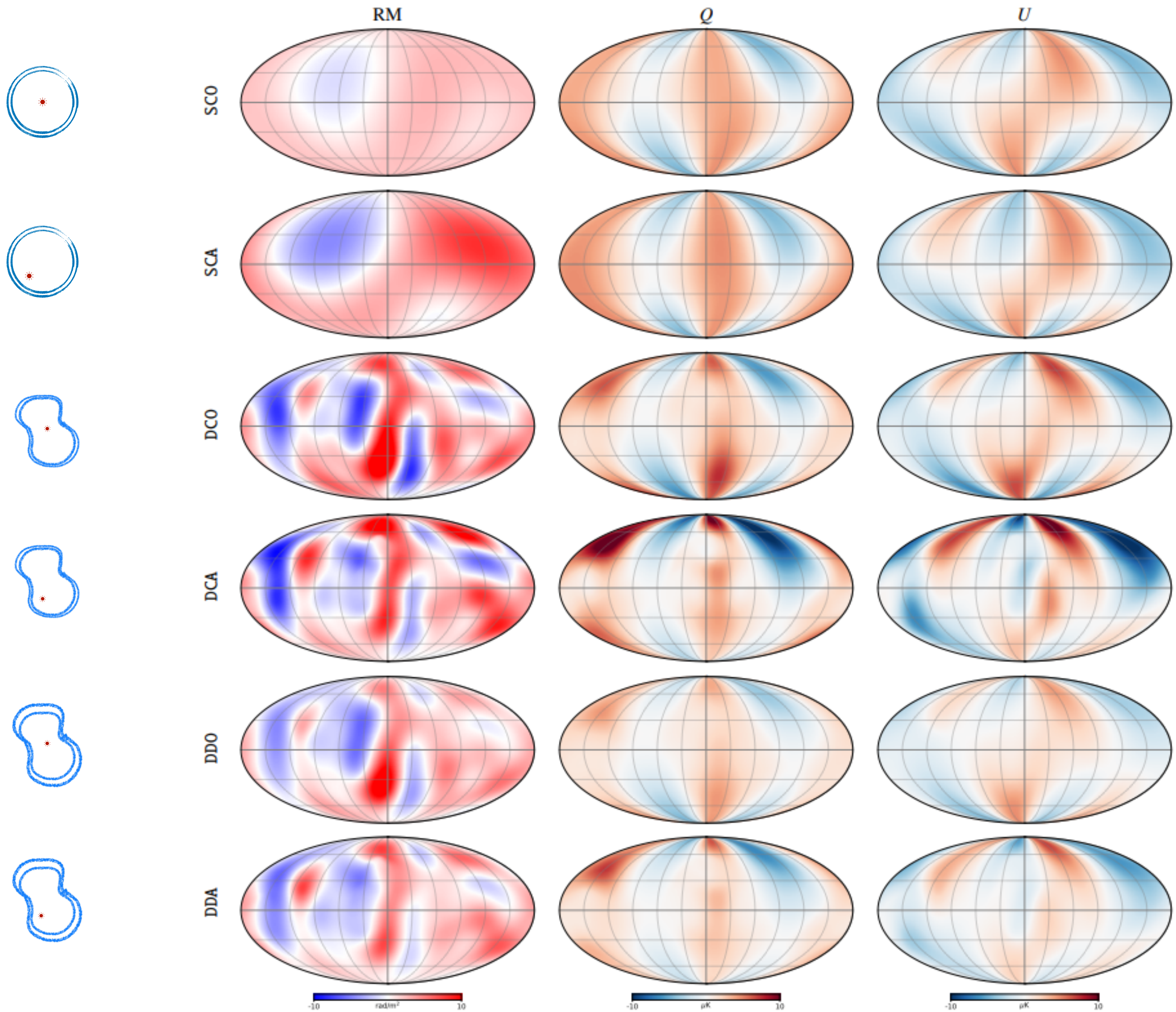
- ✓ Divergence free
- ✓ Conserve magnetic flux before >< after explosion
- ✓ Can be used to model $\mathbf{B}$ in shells with any (closed) geometry
- ✓ The explosion center can be move around in the bubble

Magnetic field in the thick shell of bubbles — the LB case

- ★ Application to the case of the LB and predictions for synchrotron Q and U and Faraday RM
- ★ Free parameters of the model:
  - Initial (uniform) magnetic field: strength and direction
  - Center of explosion
  - Inner and outer surface of the shell
  - CRE density (synchrotron), thermal electron density (RM)

- ★ Our choice:
  - Inner and outer surface of the bubble; 3D shapes from [V.P+2020]:
    1. Sphere fitted to 3D shape + thickness of 35 pc (inspired from [Yao+2017])
    2. 'Actual' smoothed 3D shape
  - Explosion center:
    1. Center of the sphere
    2. Adopting constraints from [V.P+2020]
  - Initial magnetic field
    - Direction constrained from [V.P+2020]
    - Amplitude of 3 μG
  - uniform CRE density given by [Unger & Farrar 2024]; unperturbed by SN explosion
  - uniform thermal electrons given by [Unger & Farrar 2024] ; perturbed by SN explosion

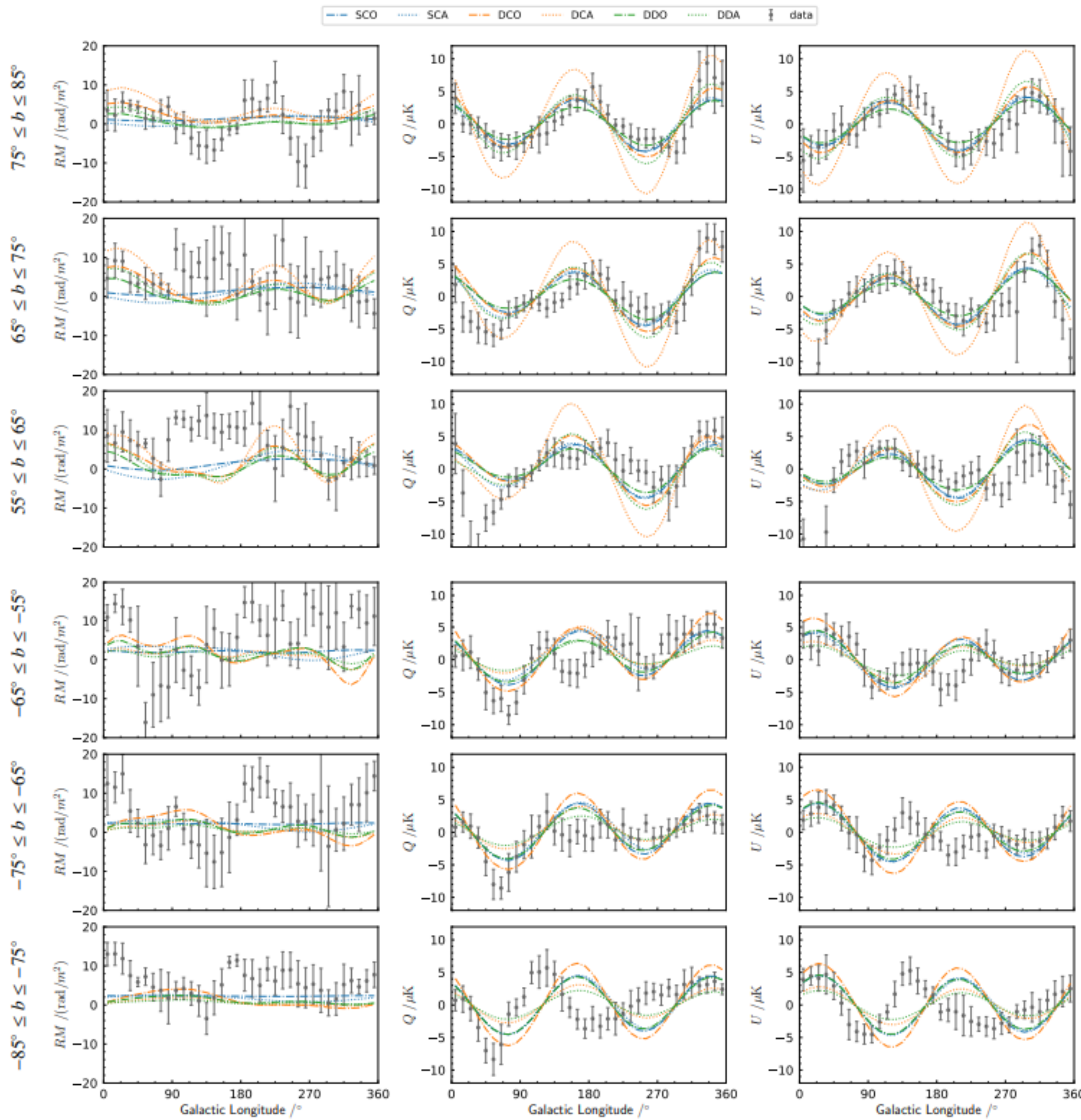
Magnetic field in the thick shell of bubbles — the LB case



Magnetic field in the thick shell of bubbles — the LB case

- ★ Comparison of models and models with data in longitude profiles for fixed latitude stripes:
- ★ Thick shell of the LB, with chosen parameters, lead to right phase and amplitude of the signal for synchrotron Q and U
- ★ The contribution to the RM is small on average

This is **not** a fit to the data !!!



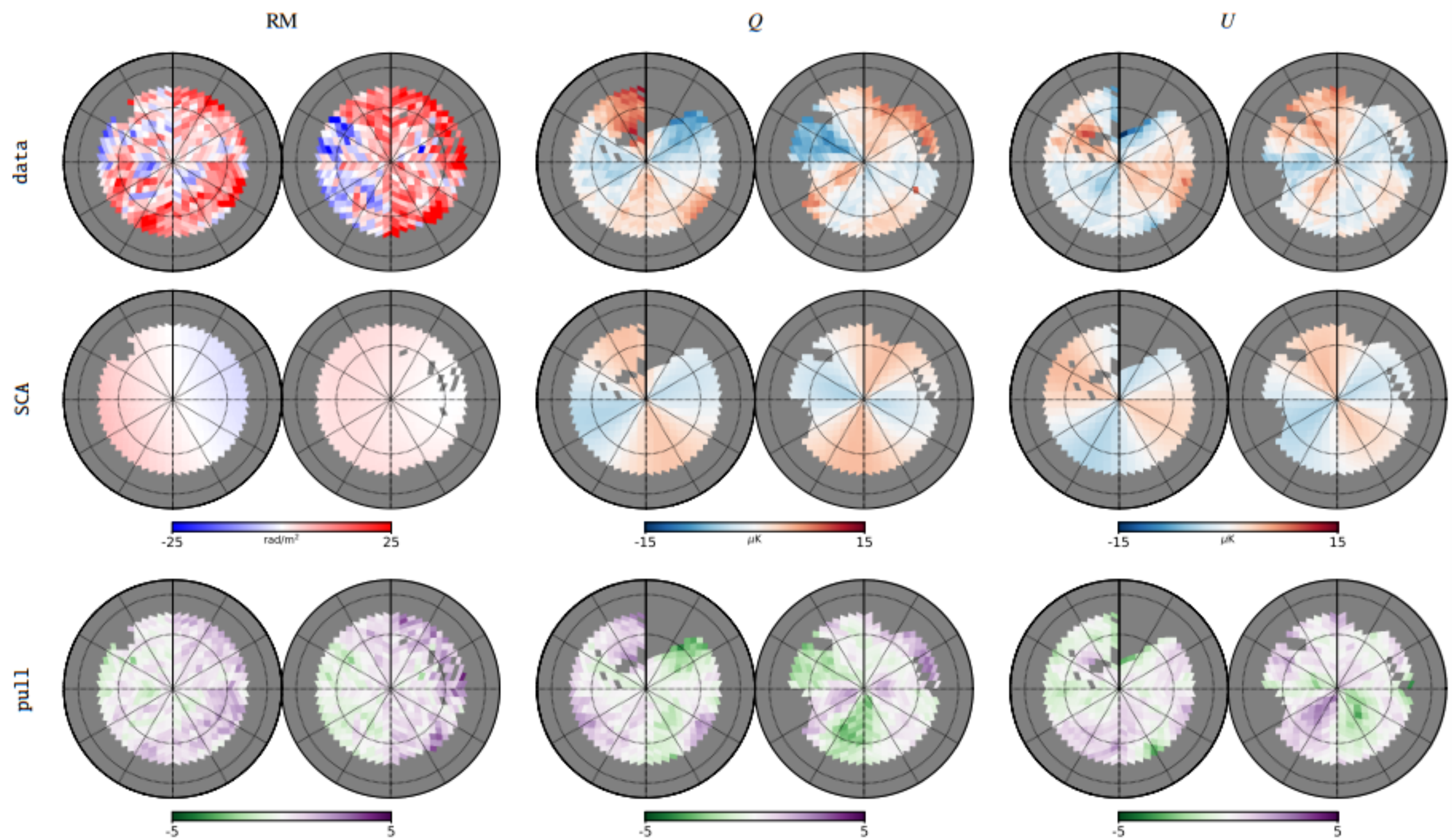
Magnetic field in the thick shell of bubbles — the LB case

- ★ Comparison of models and models with data in longitude profiles for fix…
- ★ Th… wi… lea… am… for…
- ★ Th… RM…

This is **not** a fit to the data !!!

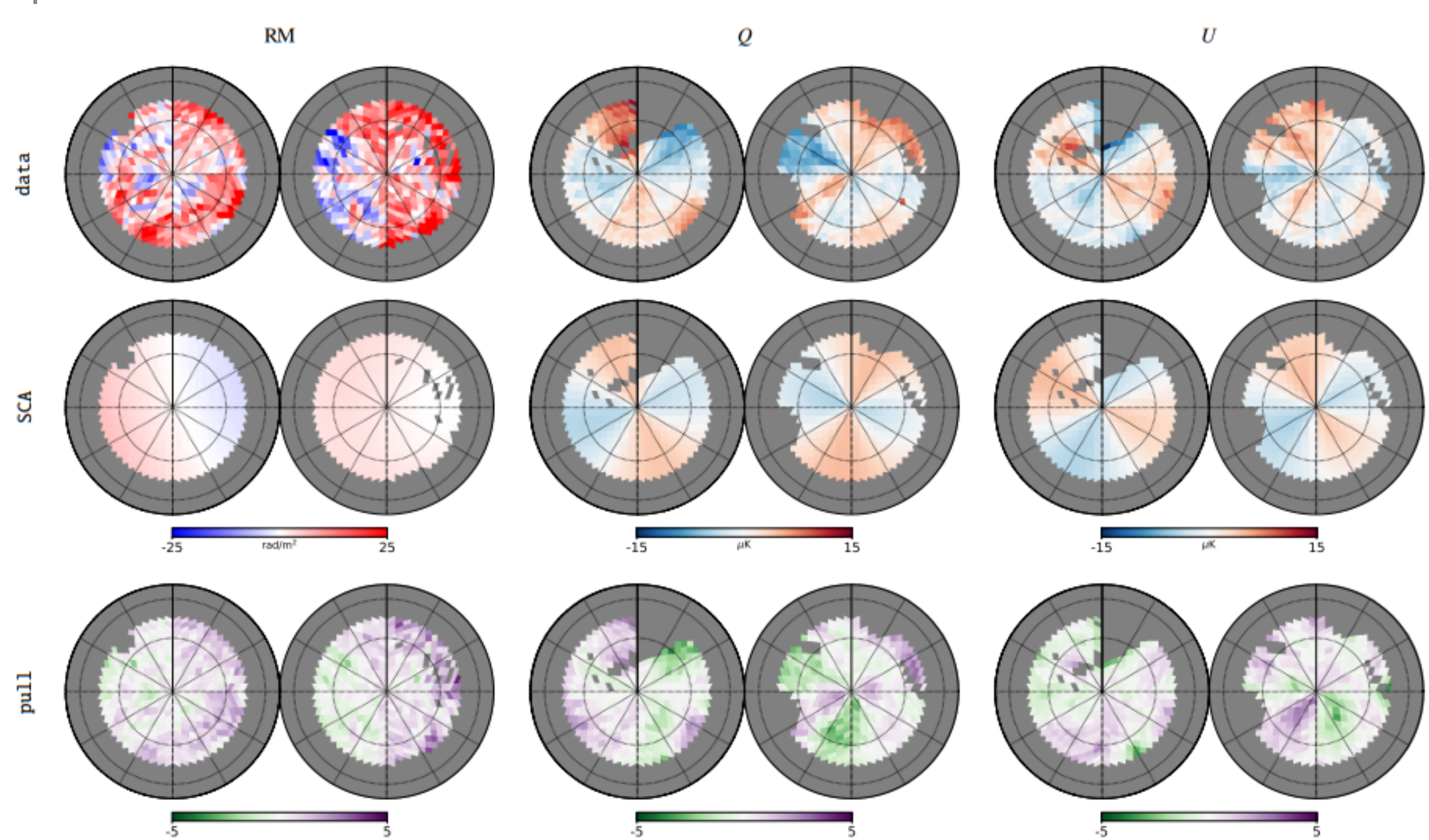
Magnetic field in the thick shell of bubbles — the LB case

★ Comparison of SCA model with data



Magnetic field in the thick shell of bubbles — the LB case

★ Comparison of SCA model with data



★ The residuals (in Q and U) clearly show structured patterns

- other components are needed even at high $|b|$: large-scale + radio loops?

Magnetic field in the thick shell of bubbles — summary

- ★ The thick, magnetized shell of the Local Bubble might be an important foreground to take into account to model the large-scale GMF (see Alexander Korochkin's talk)

- ★ We derived the equations for $\mathbf{B}$ in any bubble shell, with irregular shape and free explosion center's position
  - best suited to model $\mathbf{B}$ in the shell of the Local Bubble
    - can make a significant fraction of the signal at high Galactic latitudes
    - impact on large-scale GMF modeling in progress (see Michael Unger's talk)
  - could be used to model radio loops, instead of masking

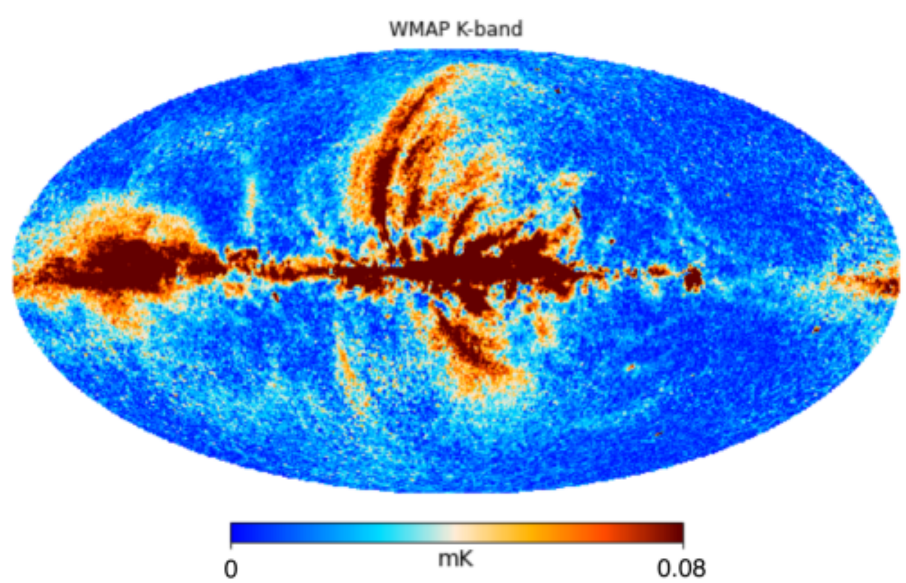
Magnetic field in the thick shell of bubbles — summary

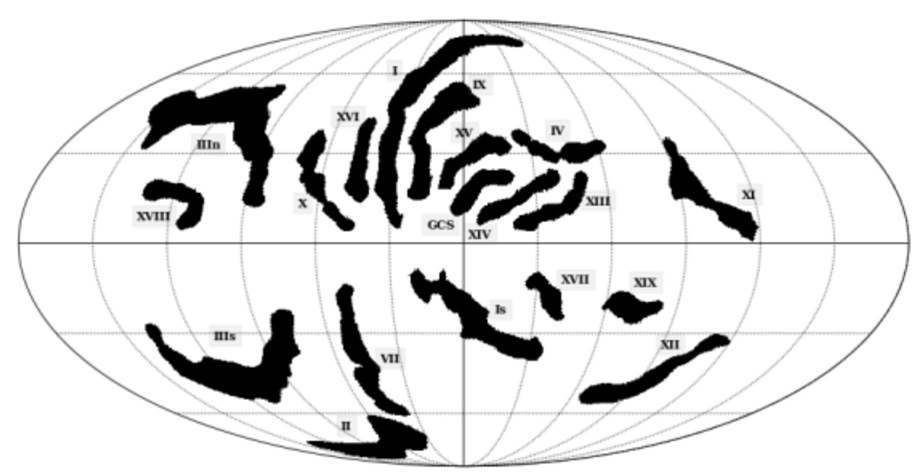
★ The thick, magnetized shell of the Local Bubble might be an important foreground to take into account to model the large-scale GMF (see Alexander Korochkin's talk)

★ We derived the equations for $\mathbf{B}$ in any bubble shell, with irregular shape and free explosion center's position

- best suited to model $\mathbf{B}$ in the shell of the Local Bubble
  - can make a significant fraction of the signal at high Galactic latitudes
  - impact on large-scale GMF modeling in progress (see Michael Unger's talk)
- could be used to model radio loops, instead of masking

★ Will we ever solve degeneracies caused by line-of-sight integration and foreground effects?

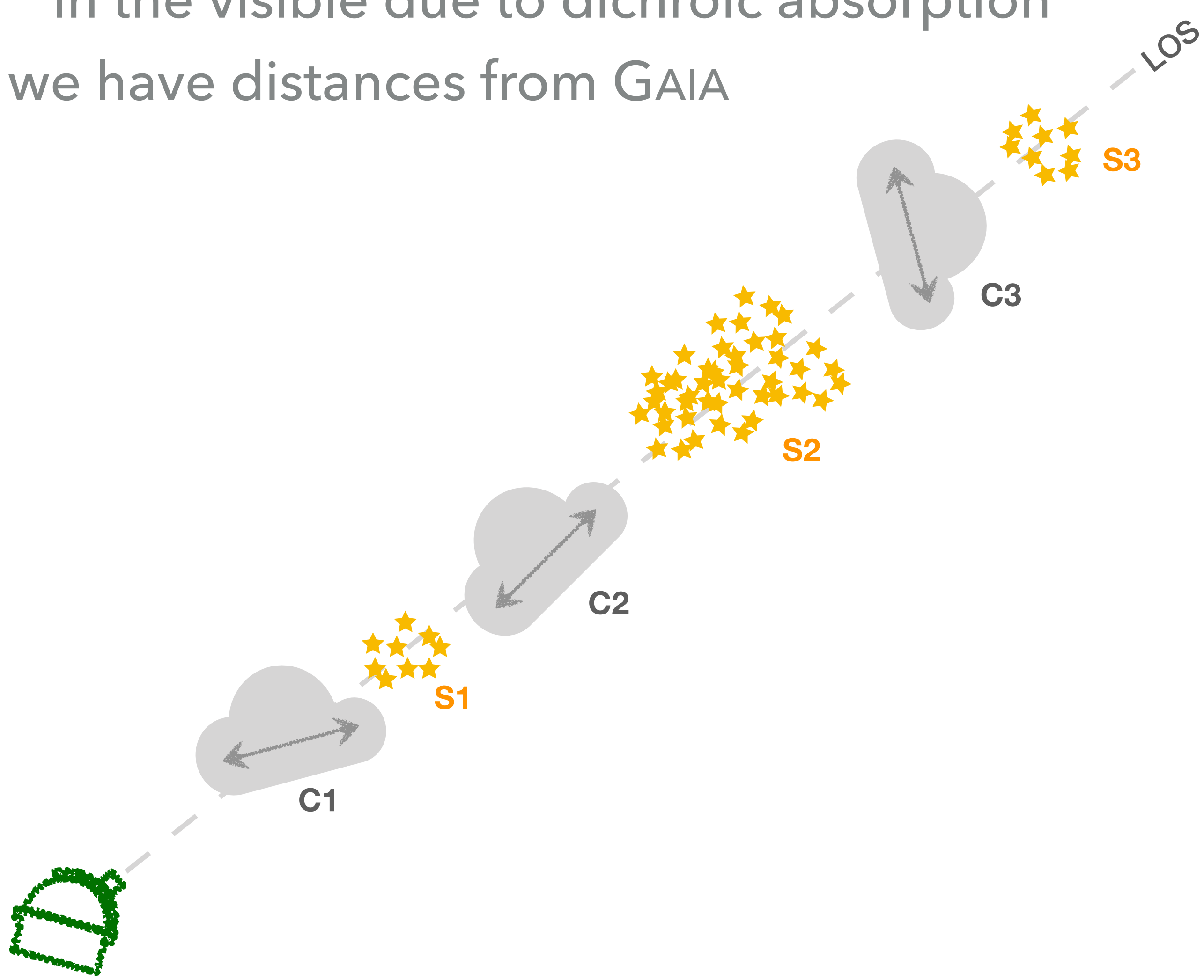


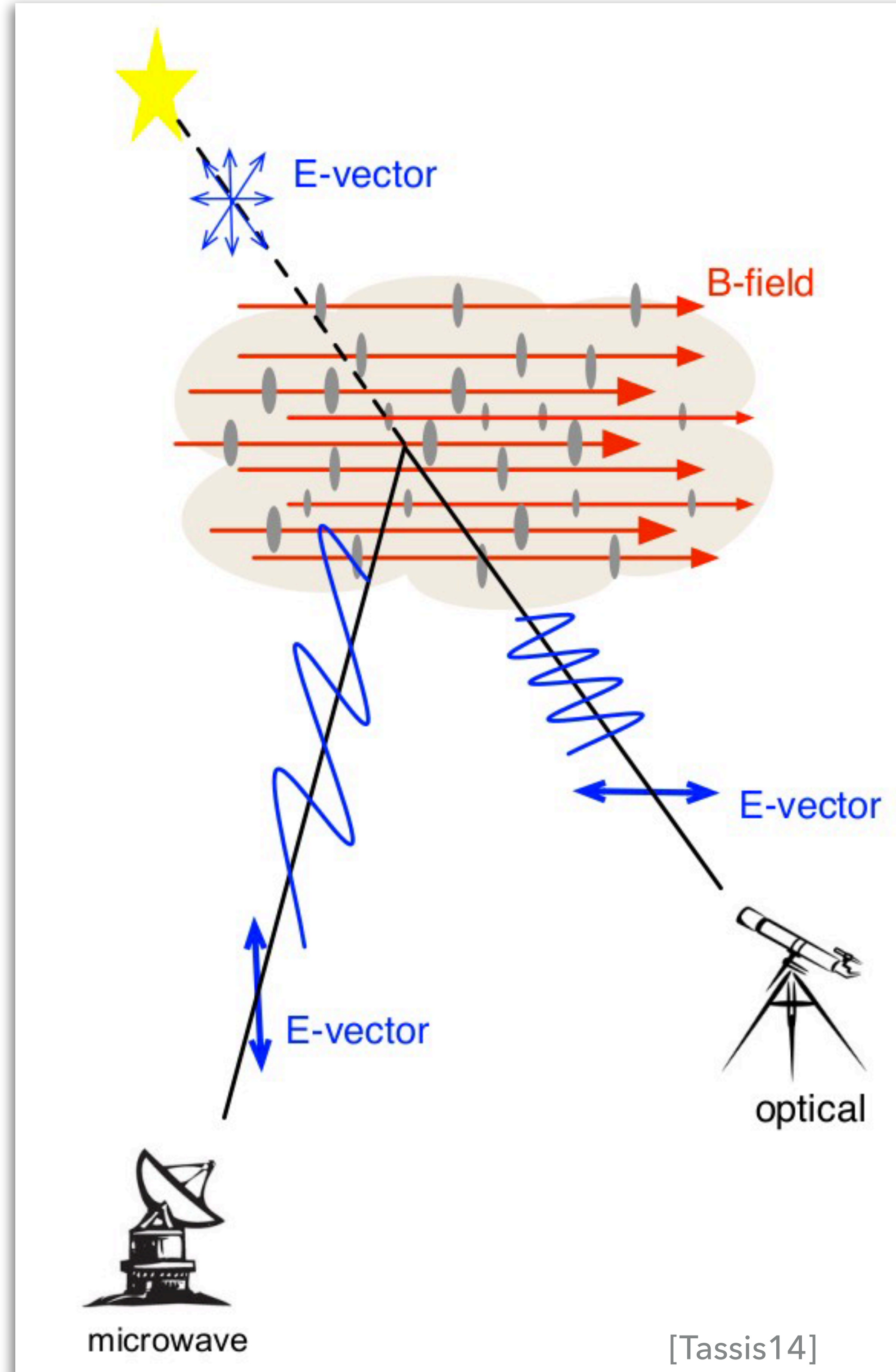


[Martire+ 2023]

The promises of starlight-polarization-based tomography

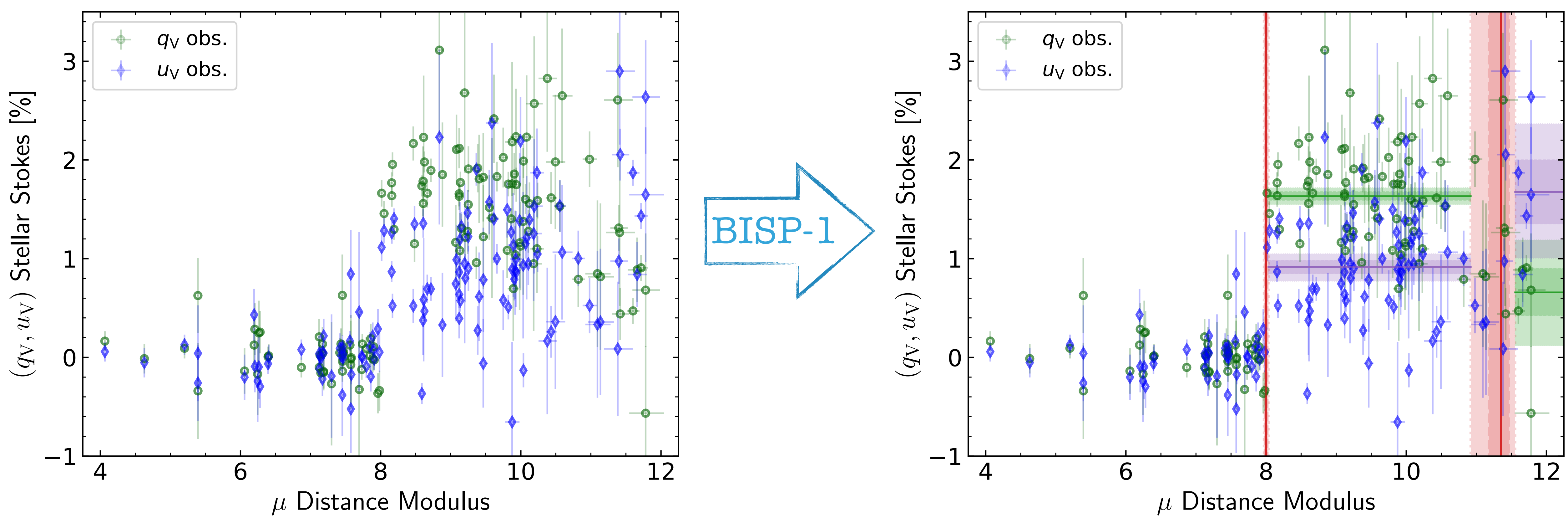
- ★ A way forward to model the GMF
- ★ spherical dust grains in the magnetized interstellar medium
  - ▸ emit polarized light in the sub-mm (foreground to the CMB / inflation)
  - ▸ induce a net polarization to incoming light in the visible due to dichroic absorption
- ★ we have distances from GAIA





The promises of starlight-polarization-based tomography

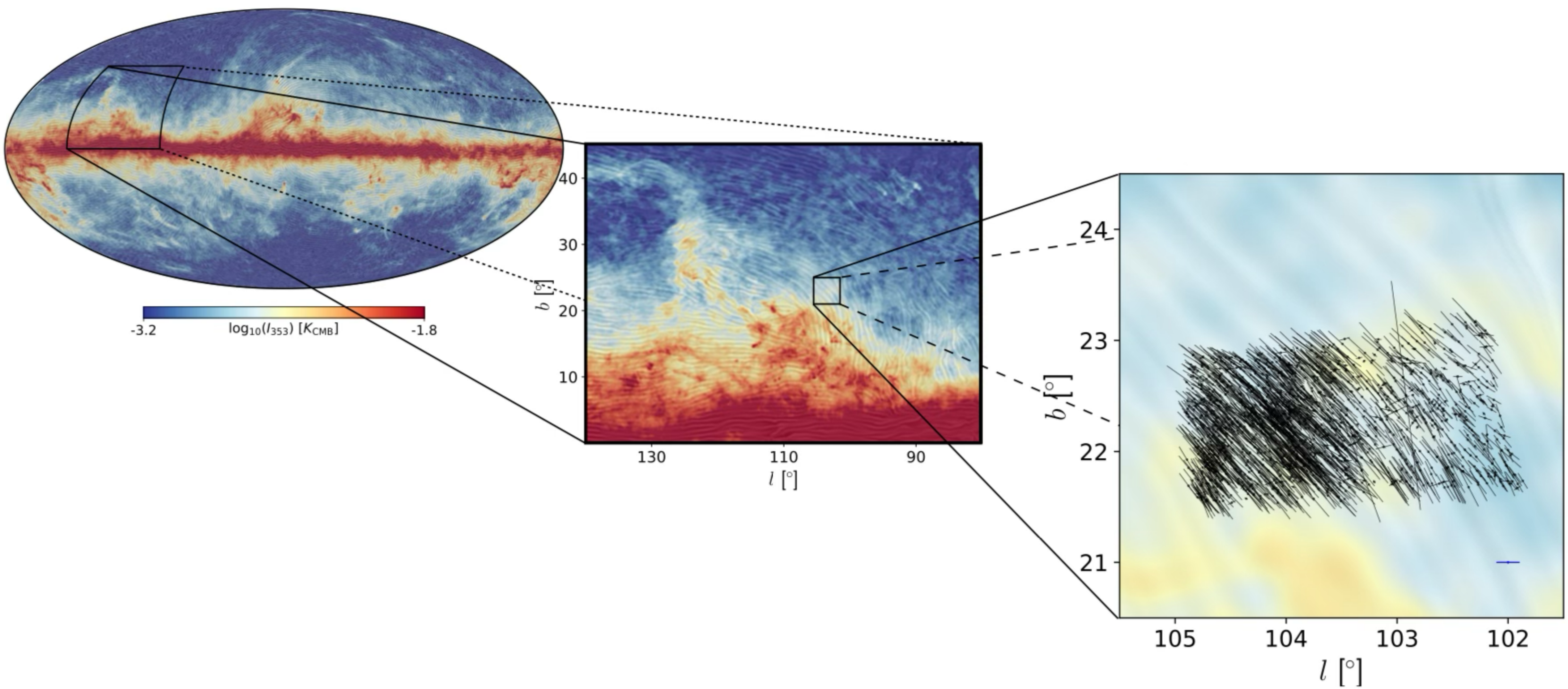
- ★ [V.P+2023]: BISP-1: Bayesian Inference of Starlight Polarization in 1D
- ★ Bayesian method to retrieve the number of clouds, their distances, and their polarization properties from stellar data on polarization and distance only
- ★ Likelihood that accounts for
  - parallax uncertainties
  - polarization uncertainties
  - intrinsic scatter from ISM turbulence



The promises of starlight-polarization-based tomography

★ [V.P+2024]: BISP-1 in 3D inversion pipeline

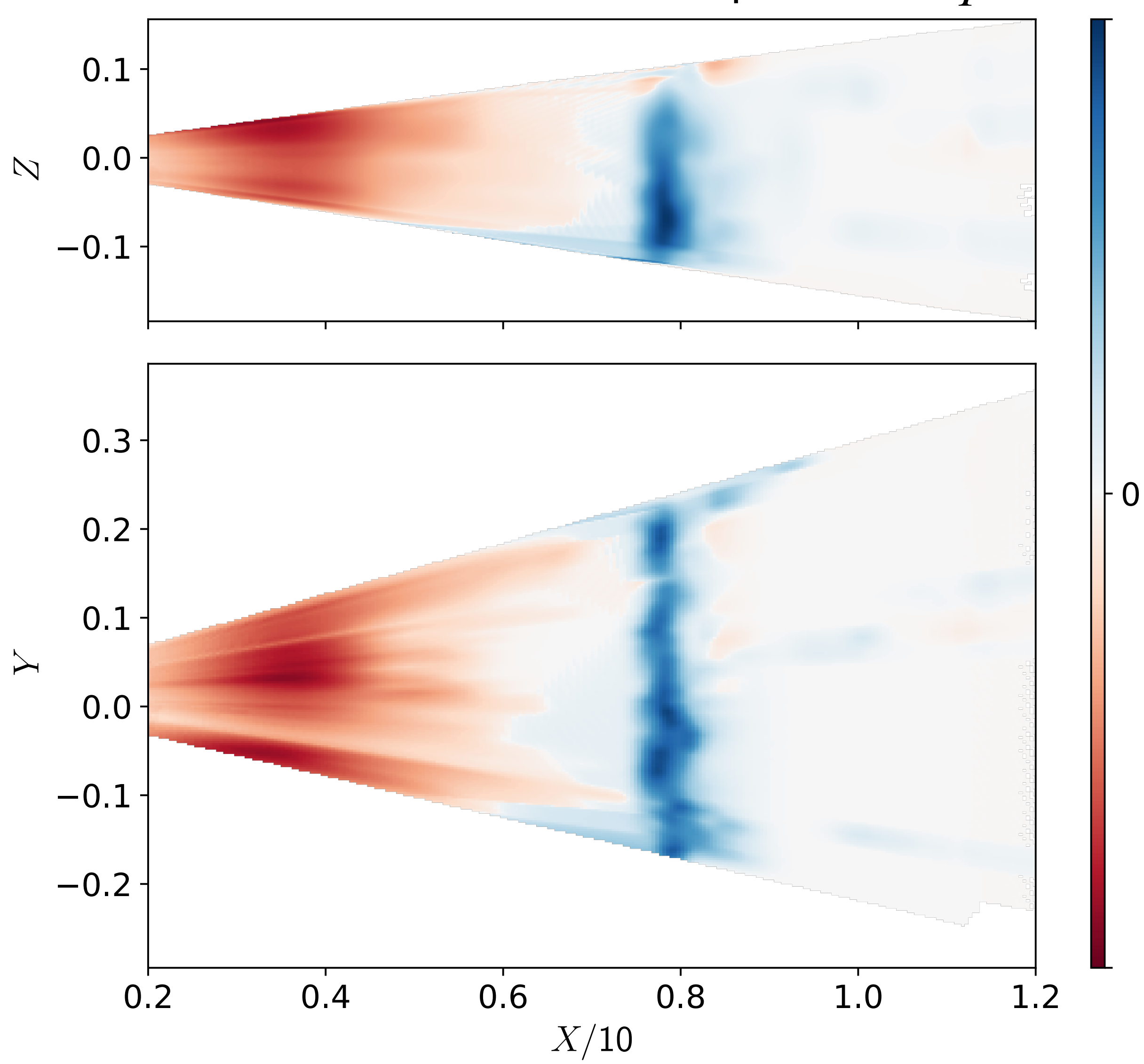
⟶ demonstration using the PASIPHAE-pathfinding survey (~4 sq.deg.)



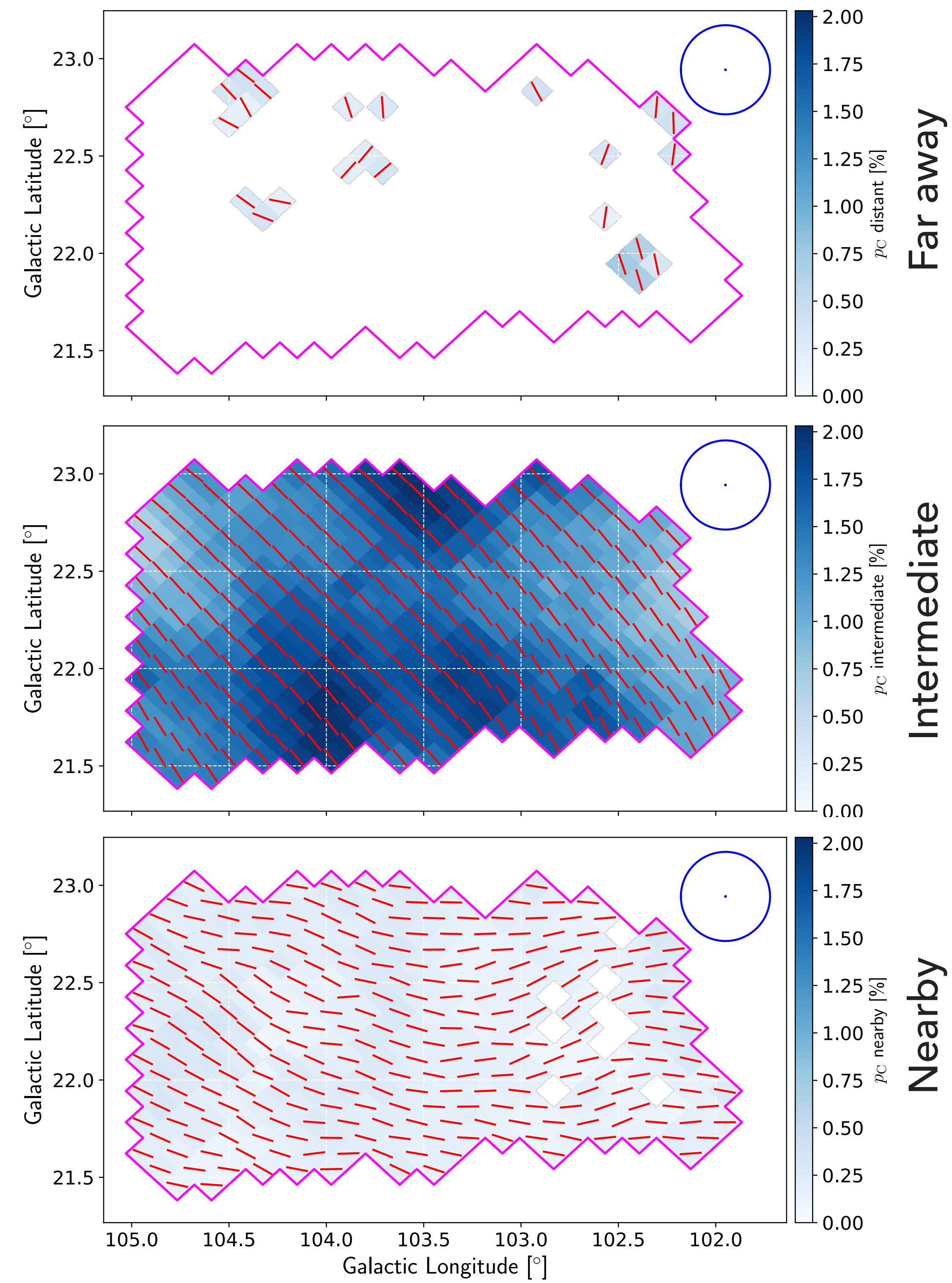
The promises of starlight-polarization-based tomography

★ Found several dust clouds and measured the plane-of-sky component of the Galactic magnetic field which permeates them

Plane projections
differentials of the Stokes parameter q

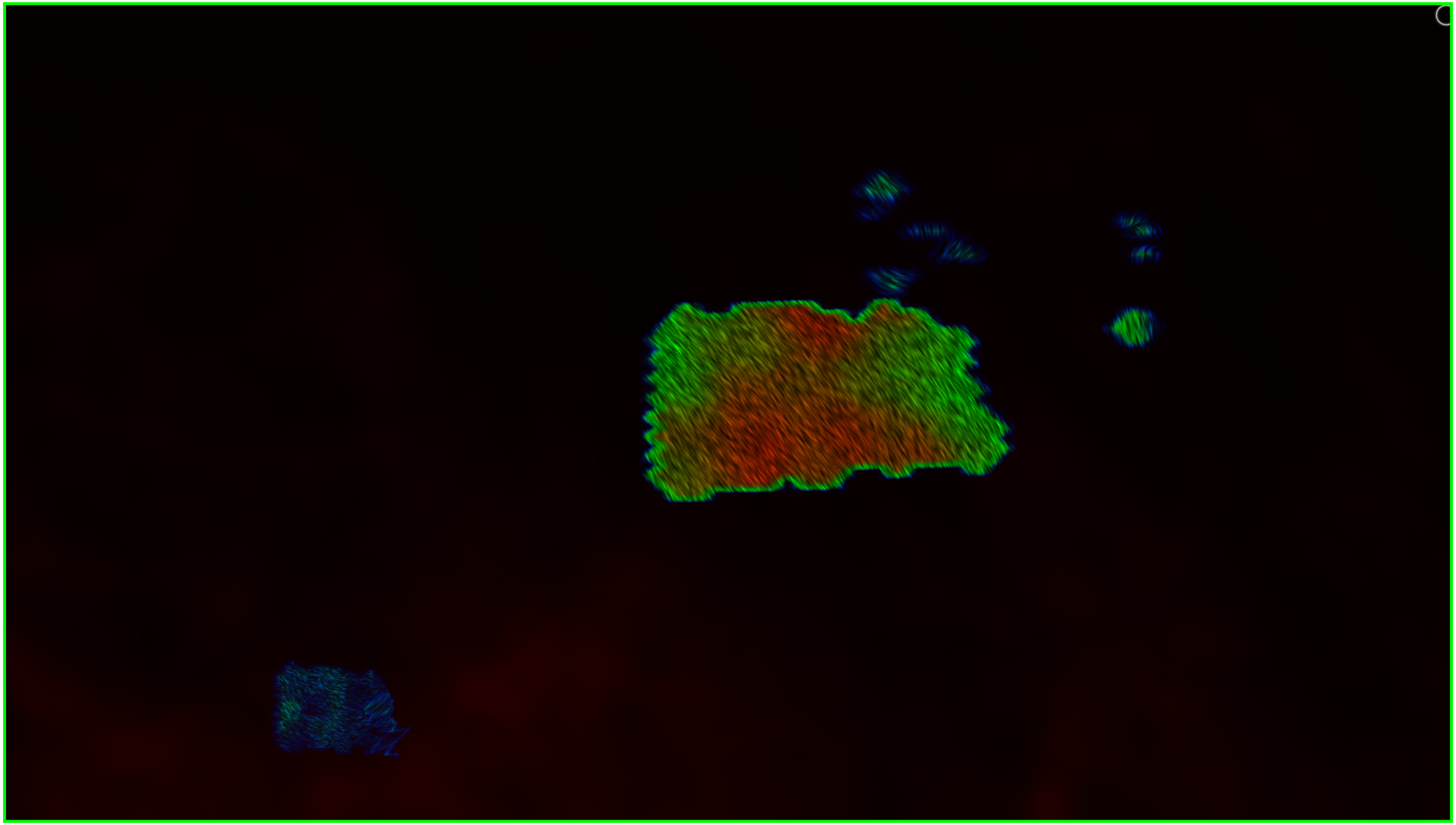


Clouds’ polarization degree and angle



The promises of starlight-polarization-based tomography

★ Visualization within ASTERION [video: https://www.youtube.com/watch?v=dB_6J1zhmPI]

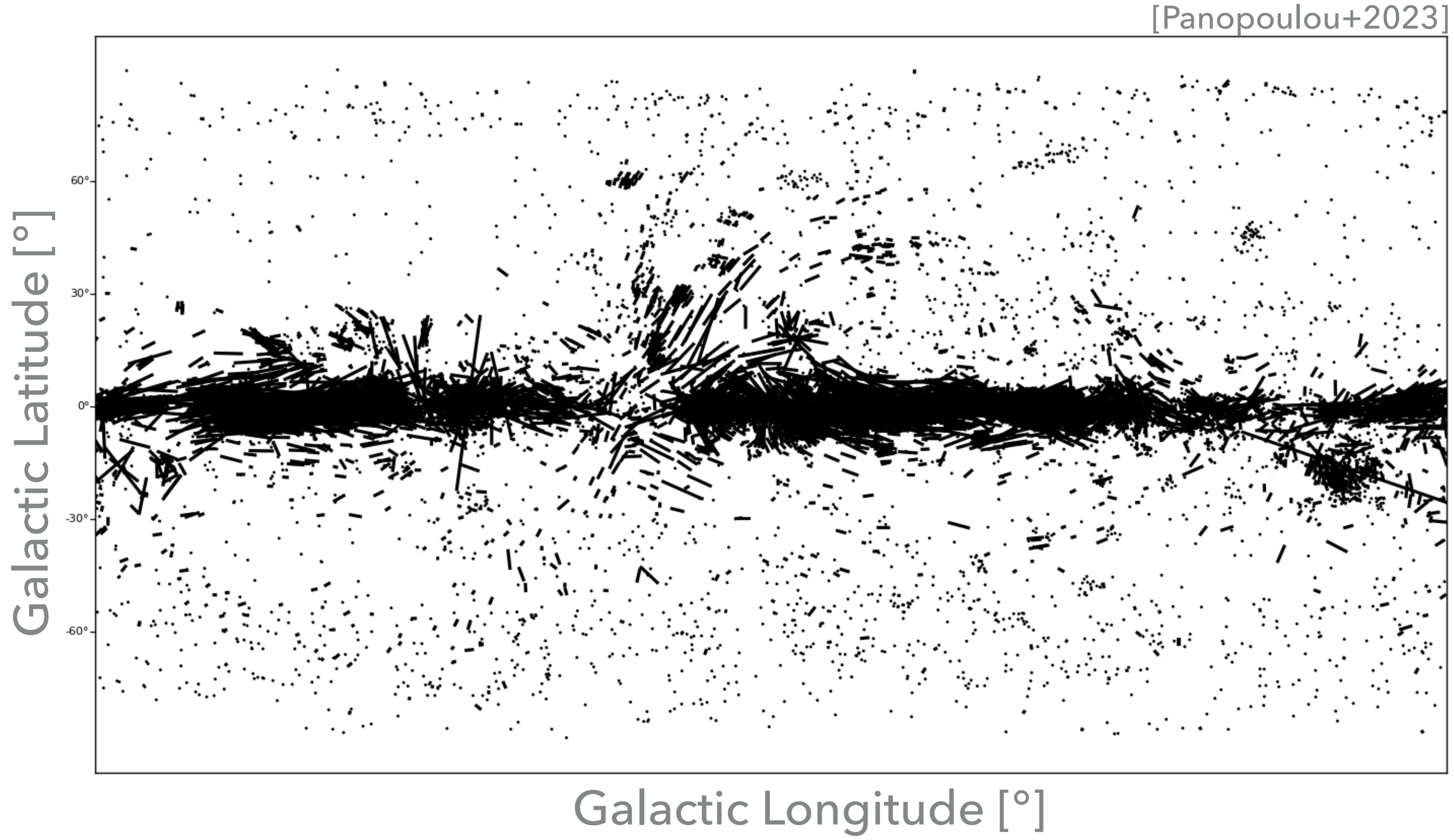


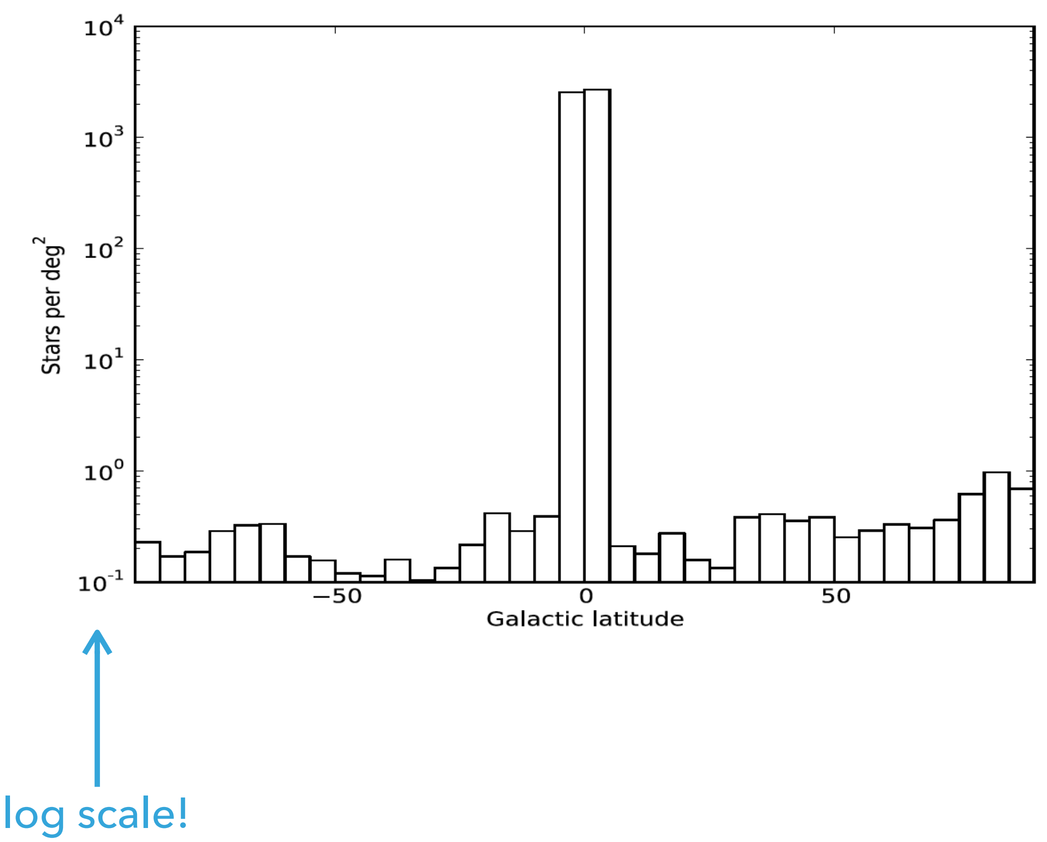
The promises of starlight-polarization-based tomography

★ 3D mapping for large volume of the Milky Way requires large data sample

- cannot be done with current data set: < 1 star per square degree at high latitude

[Panopoulou+2023]

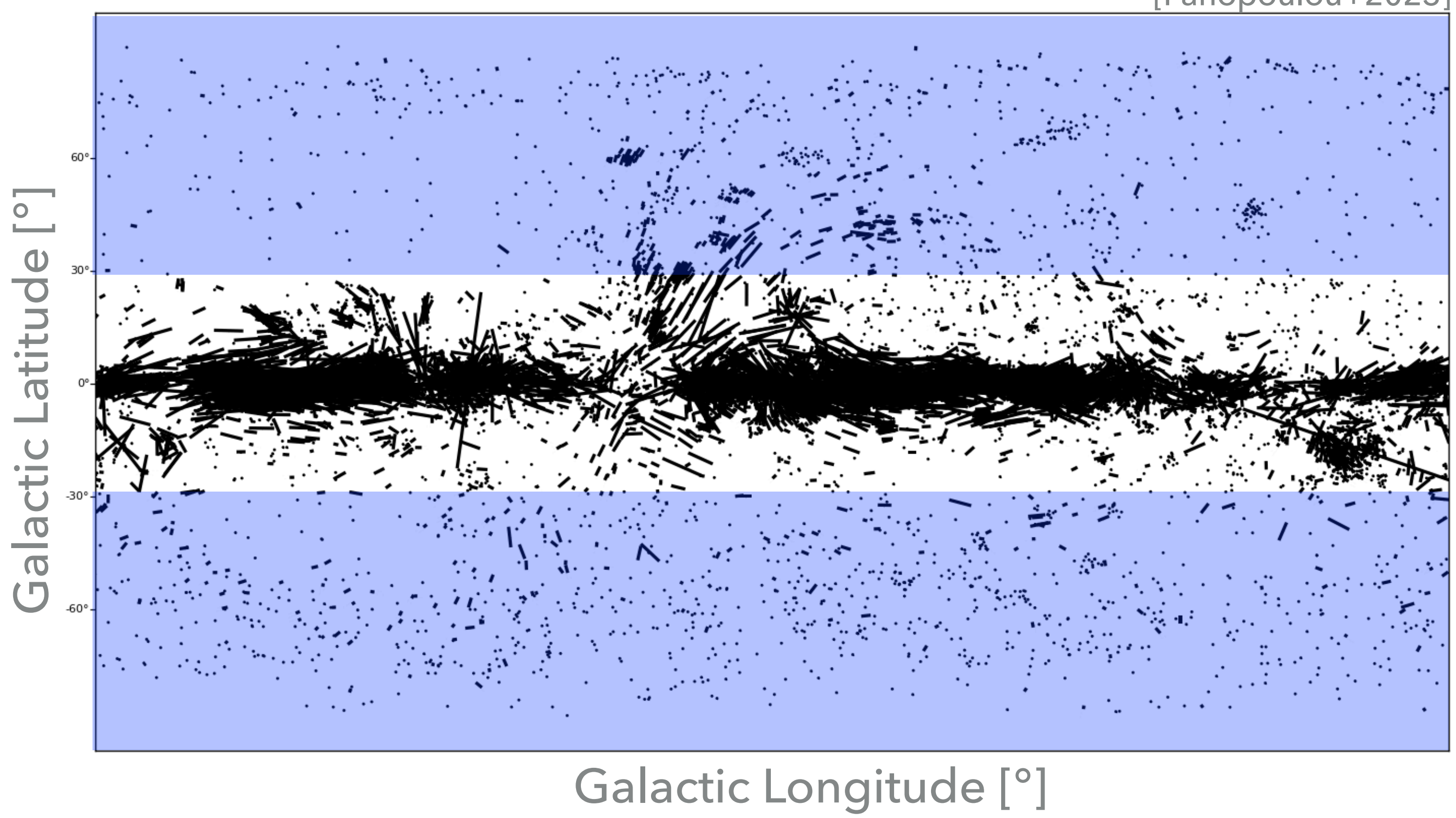


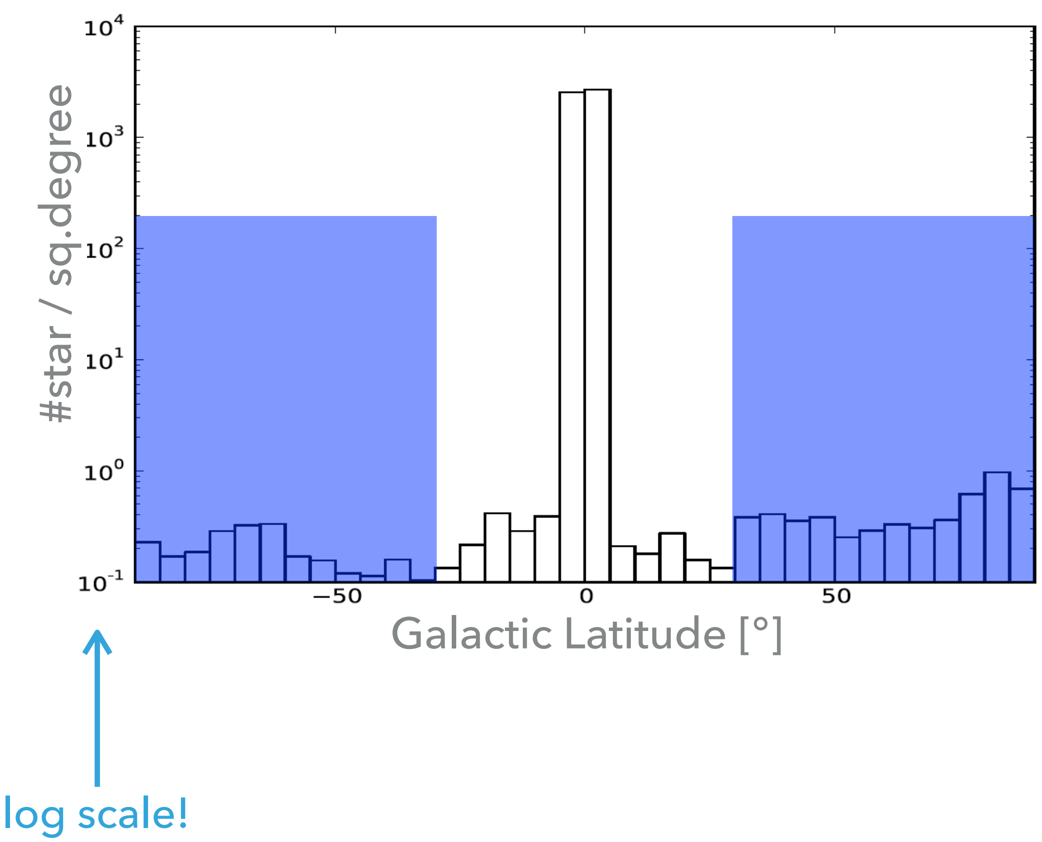


The promises of starlight-polarization-based tomography

- ★ 3D mapping for large volume of the Milky Way requires large data sample
  - ✓ about to change thanks to forthcoming surveys: PASIPHAE, South-Pol, SGMAP, VSTpol
  - ✤ PASIPHAE on sky next January! Survey plan: 4M stars with $\sigma_p \lesssim 0.1\,\%$

[Panopoulou+2023]



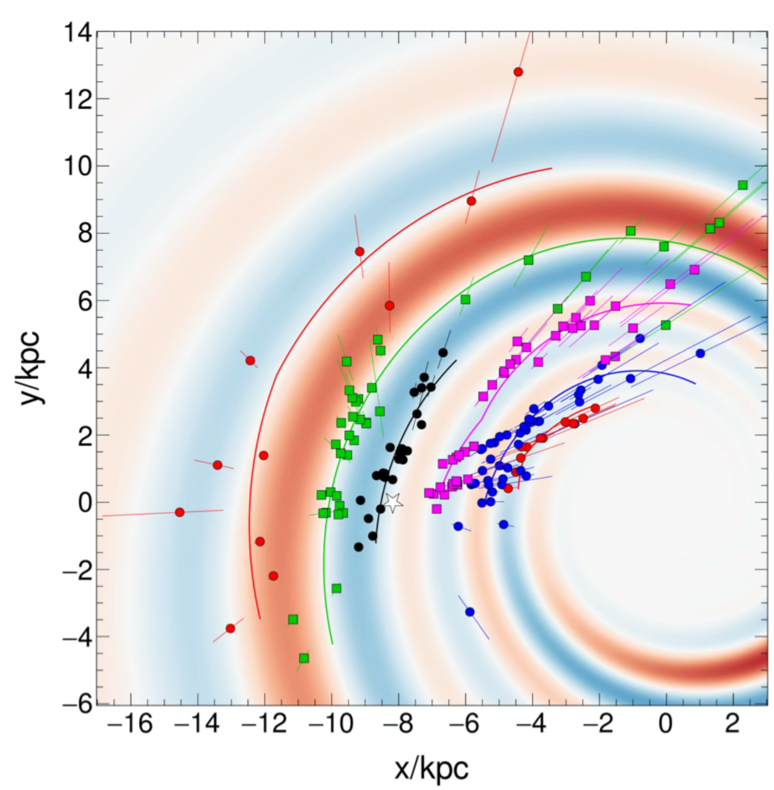


The promises of starlight-polarization-based tomography

★ 3D map of the plane-of-sky component of the GMF in dusty regions
- up to 1 or 2 kpc from the Sun

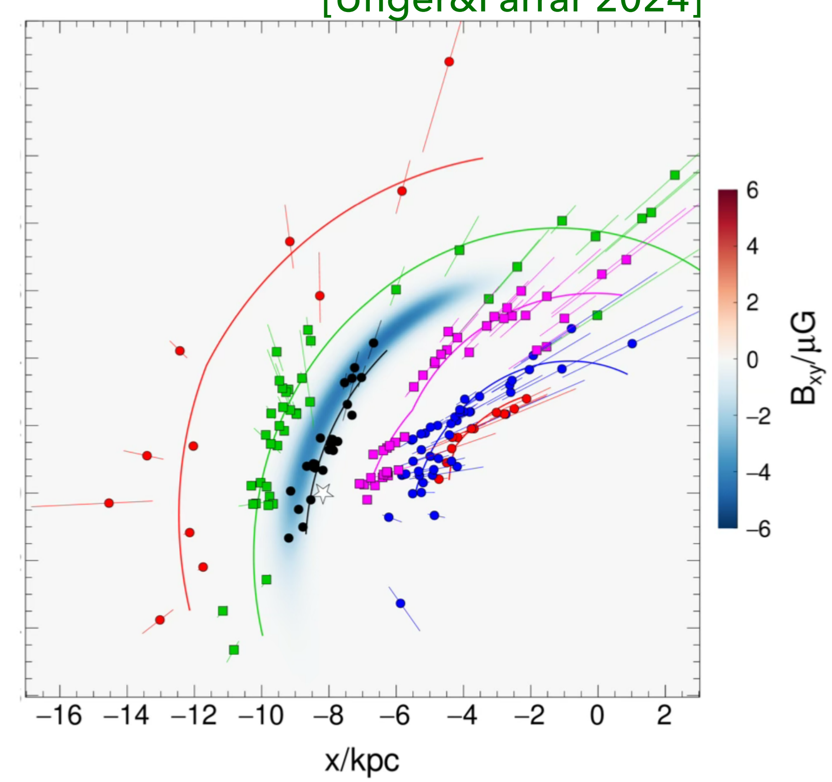
★ accurate model for the dust polarized emission,
the most significant limitation to study the primordial Universe (inflation)
based on the Cosmic Microwave Background polarization

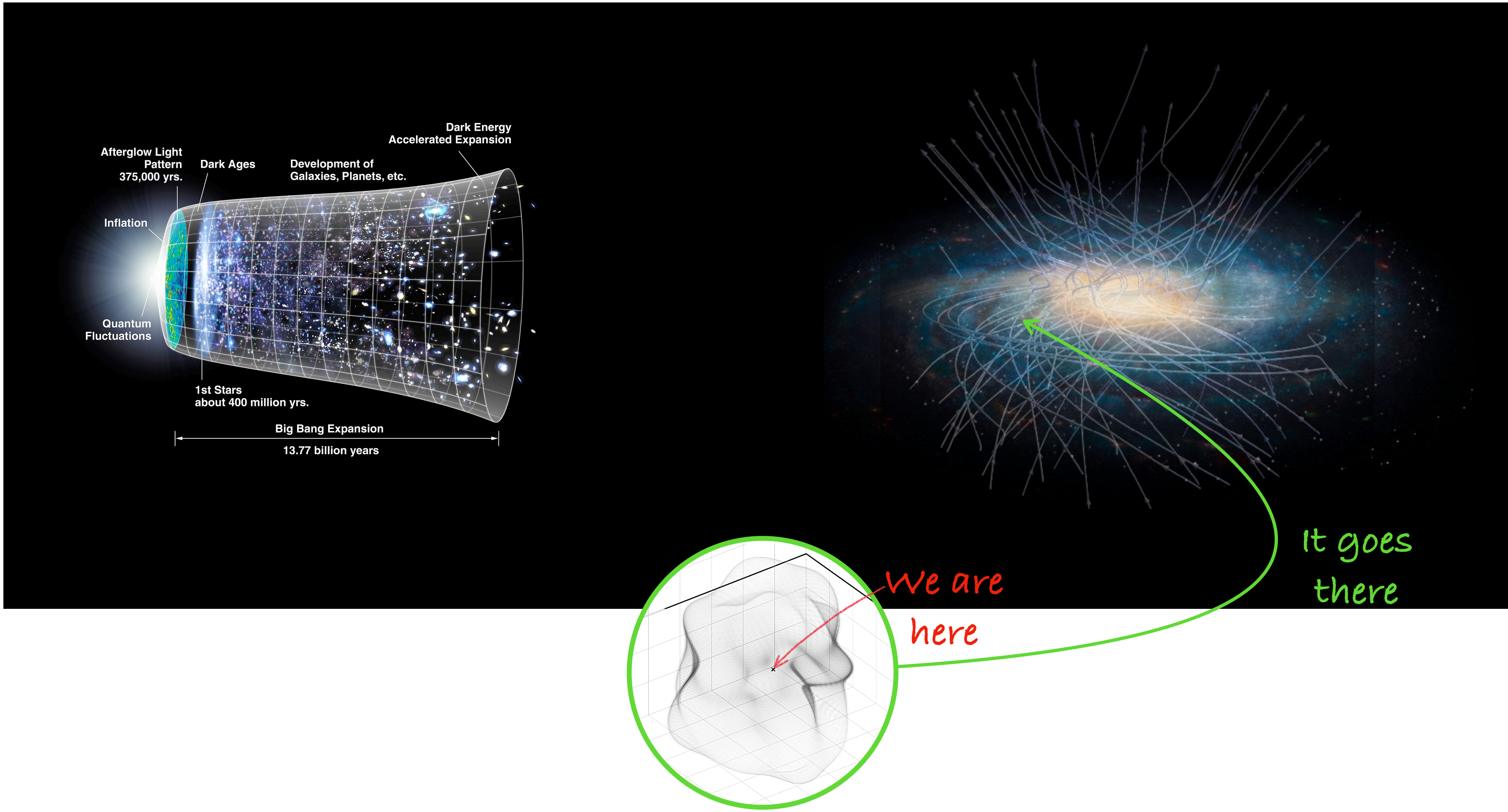
★ Local measurements of the orientation of $\mathbf{B}_{\rm POS}$ and constraints on its amplitude
$\longrightarrow$ Breaking line-of-sight degeneracy in 3D parametric modeling



$\longleftarrow ? \longrightarrow$

[Unger&Farrar 2024]




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
We are
here
It goes
there

— Thanks —

Bckp: Magnetic field in the thick shell of bubbles — the LB case

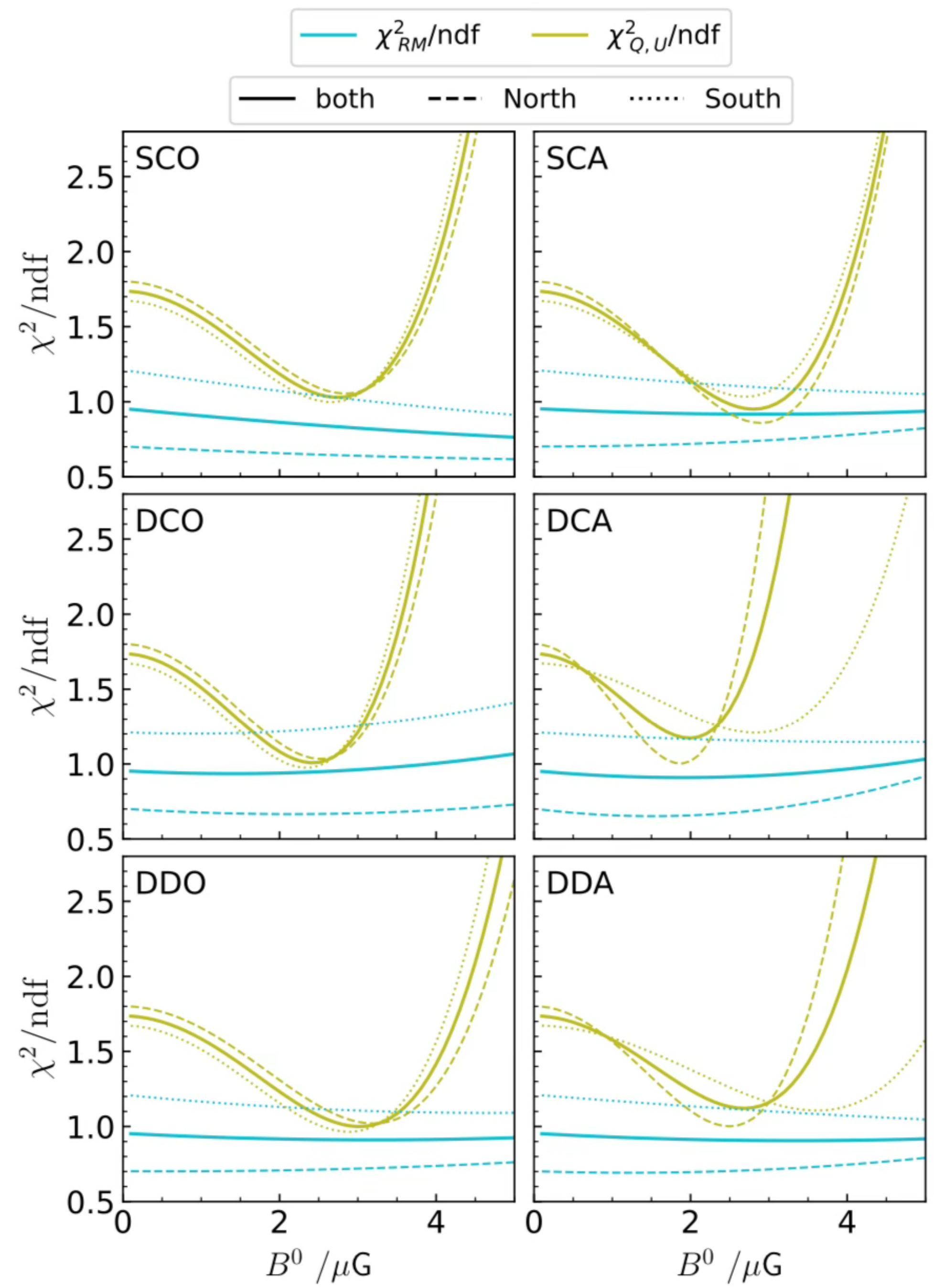
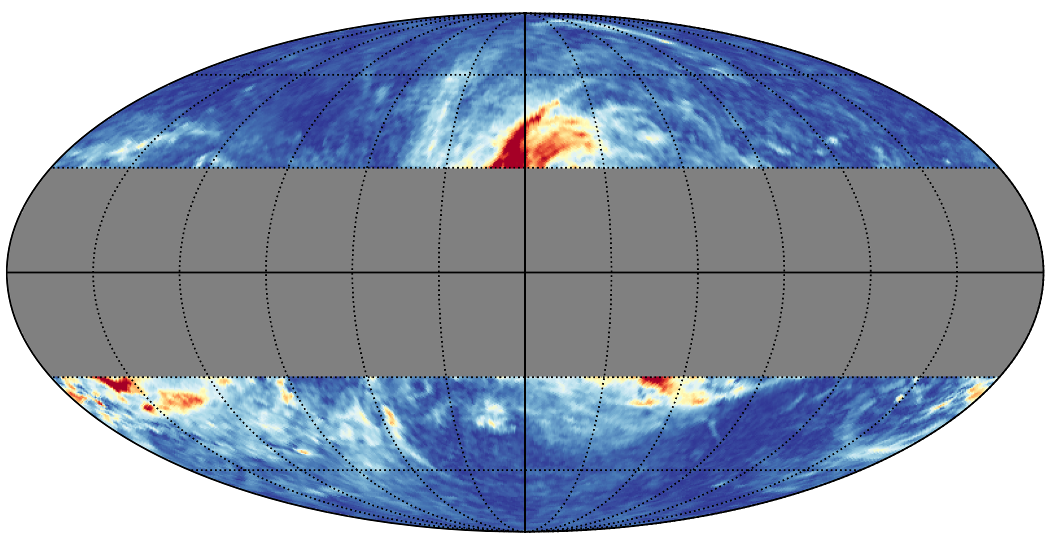
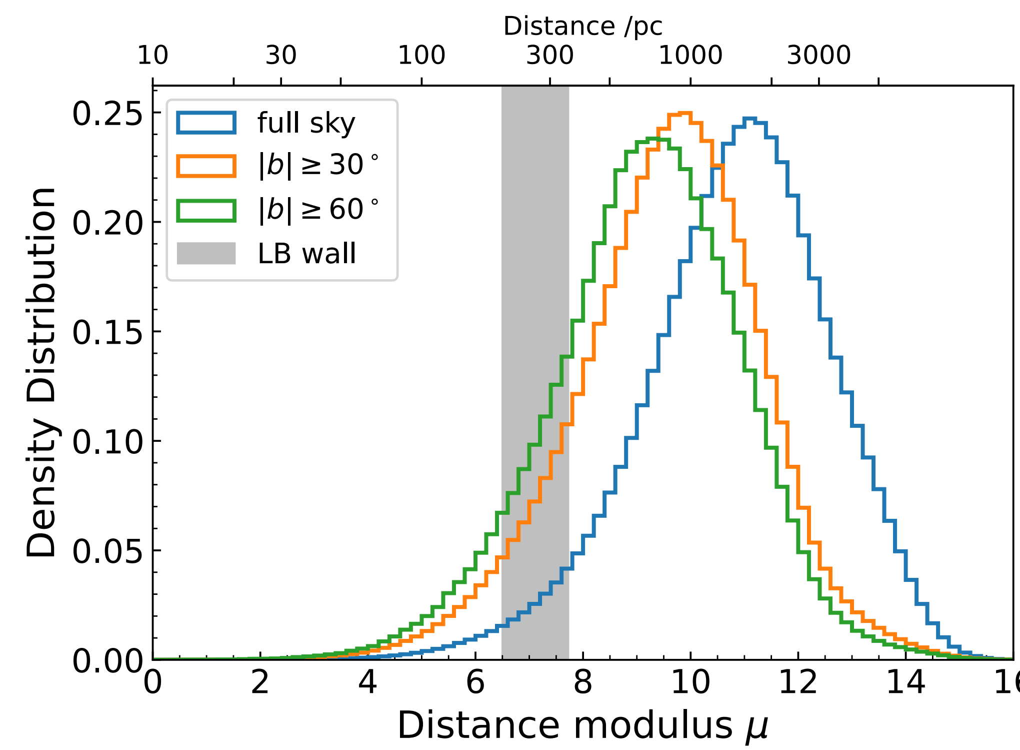


Fig. 7: Contribution to the reduced χ^2 of the different observables as a function of the strength of the initial magnetic field for the six scenarios. The contribution from Q and U are combined. The contributions from the northern and southern hemispheres are also shown with dashed and dotted lines, respectively.

Bckp: The promises of starlight-polarization-based tomography

PASIPHAE target





Density of GAIA stars with Rmag < 16