Non-thermal radiation due to cosmic ray transport in **the magnetic halo of the Milky Way**

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https://www.nature.com/articles/s41550-024-02362-0

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Article | Published: 23 September 2024

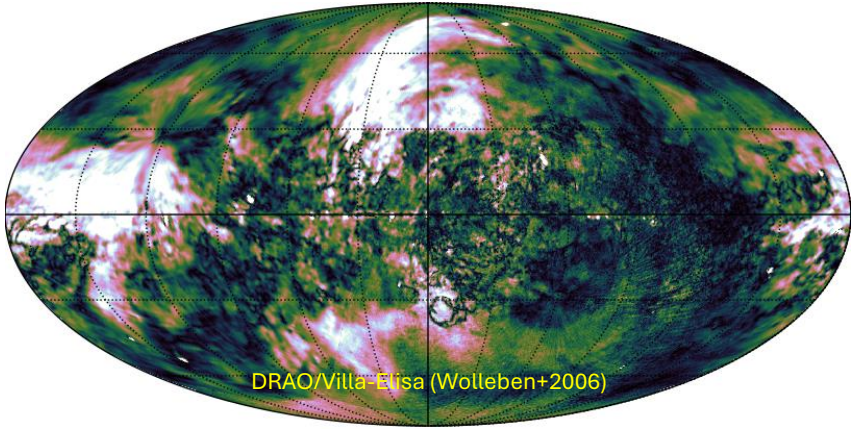
A magnetized Galactic halo from inner Galaxy outflows

He-Shou Zhang, Gabriele Ponti, Ettore Carretti, Ruo-Yu Liu, Mark R. Morris, Marijke Haverkorn, Nicola Locatelli, Xueying Zheng, Felix Aharonian, Hai-Ming Zhang, Yi Zhang, Giovanni Stel, Andrew Strong, Michael C. H. Yeung & Andrea Merloni

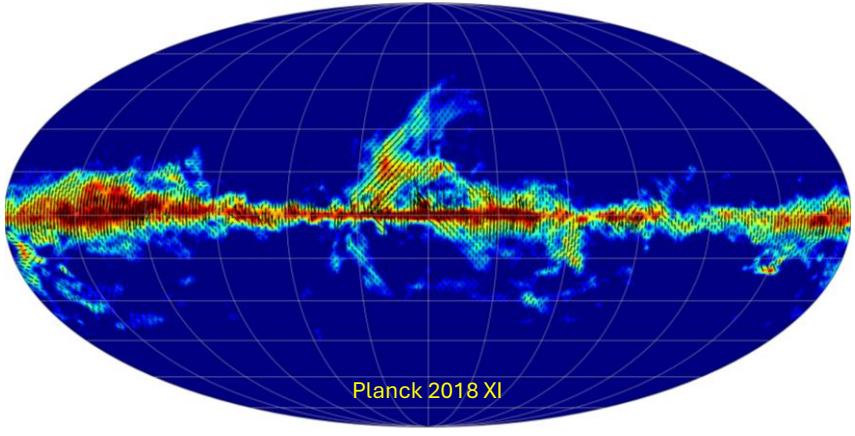
Nature Astronomy (2024) | Cite this article

1. Large scale structures

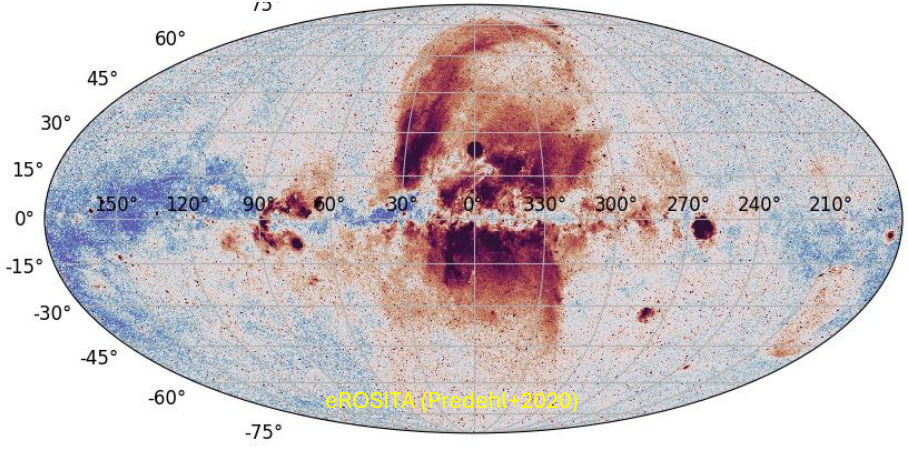
Radio sky (1.4GHz)



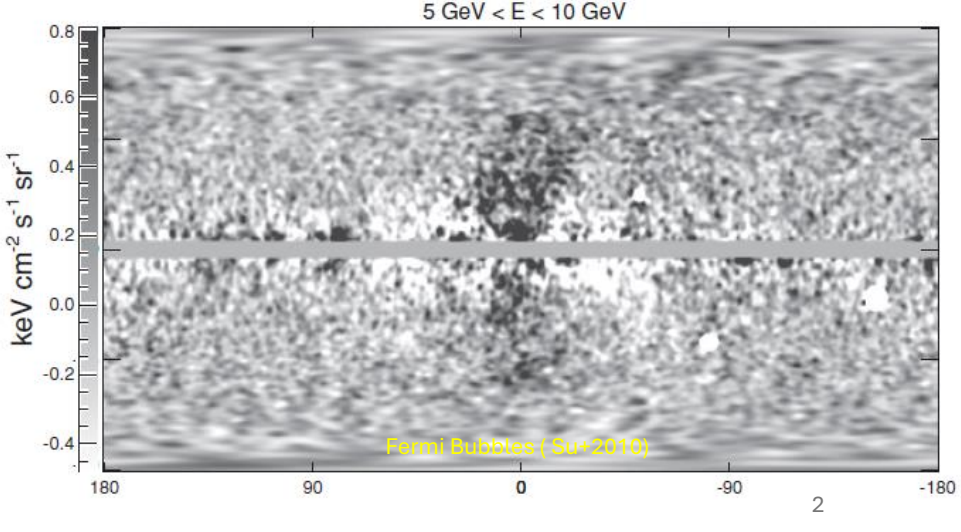
Dust sky (353 GHz)



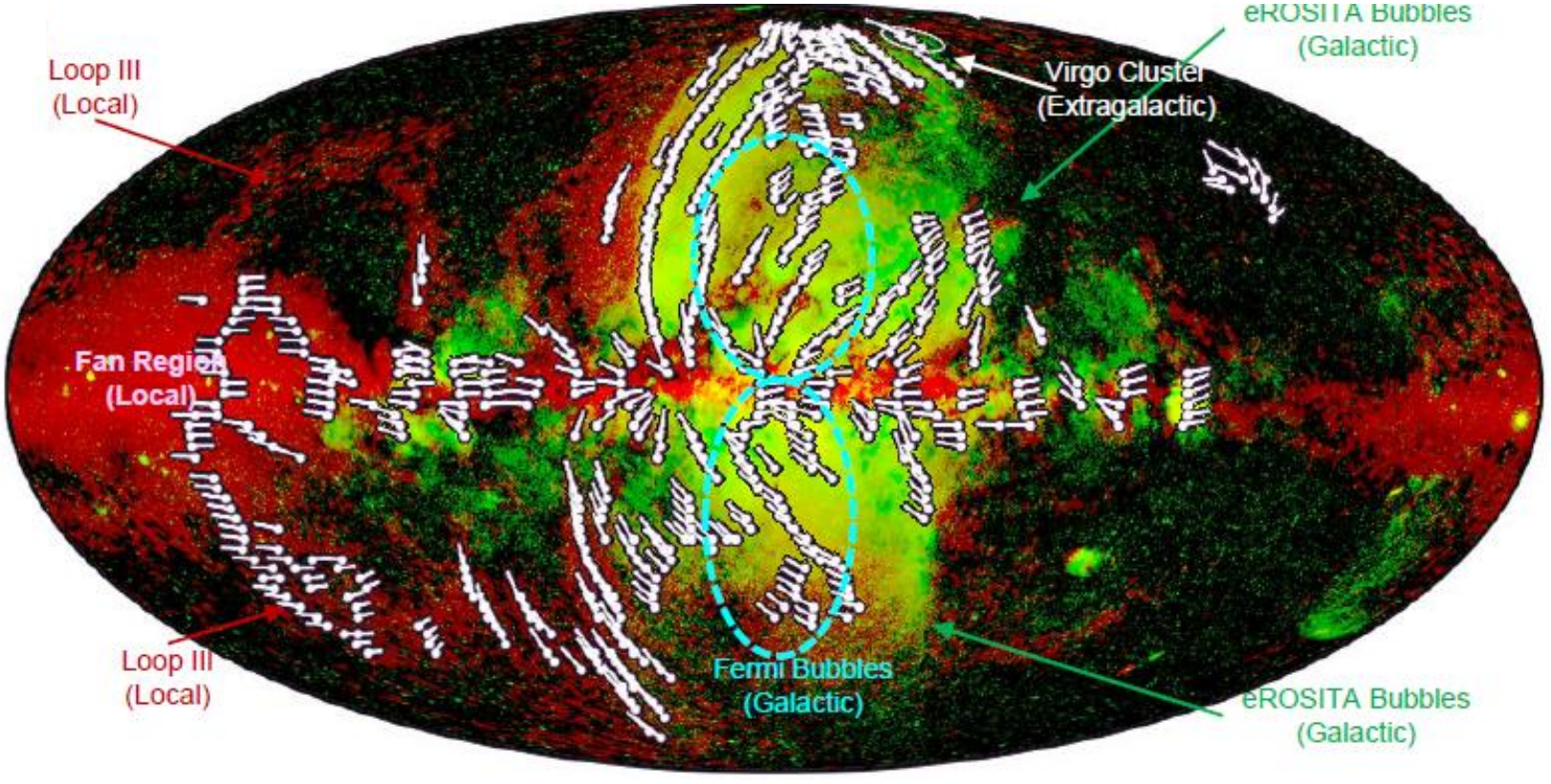
X-ray sky (eROSITA Bubbles, 0.6-1.0 keV)



gamma-ray sky (Fermi Bubbles)



2. The Magnetic ridges vs the eROSITA Bubbles



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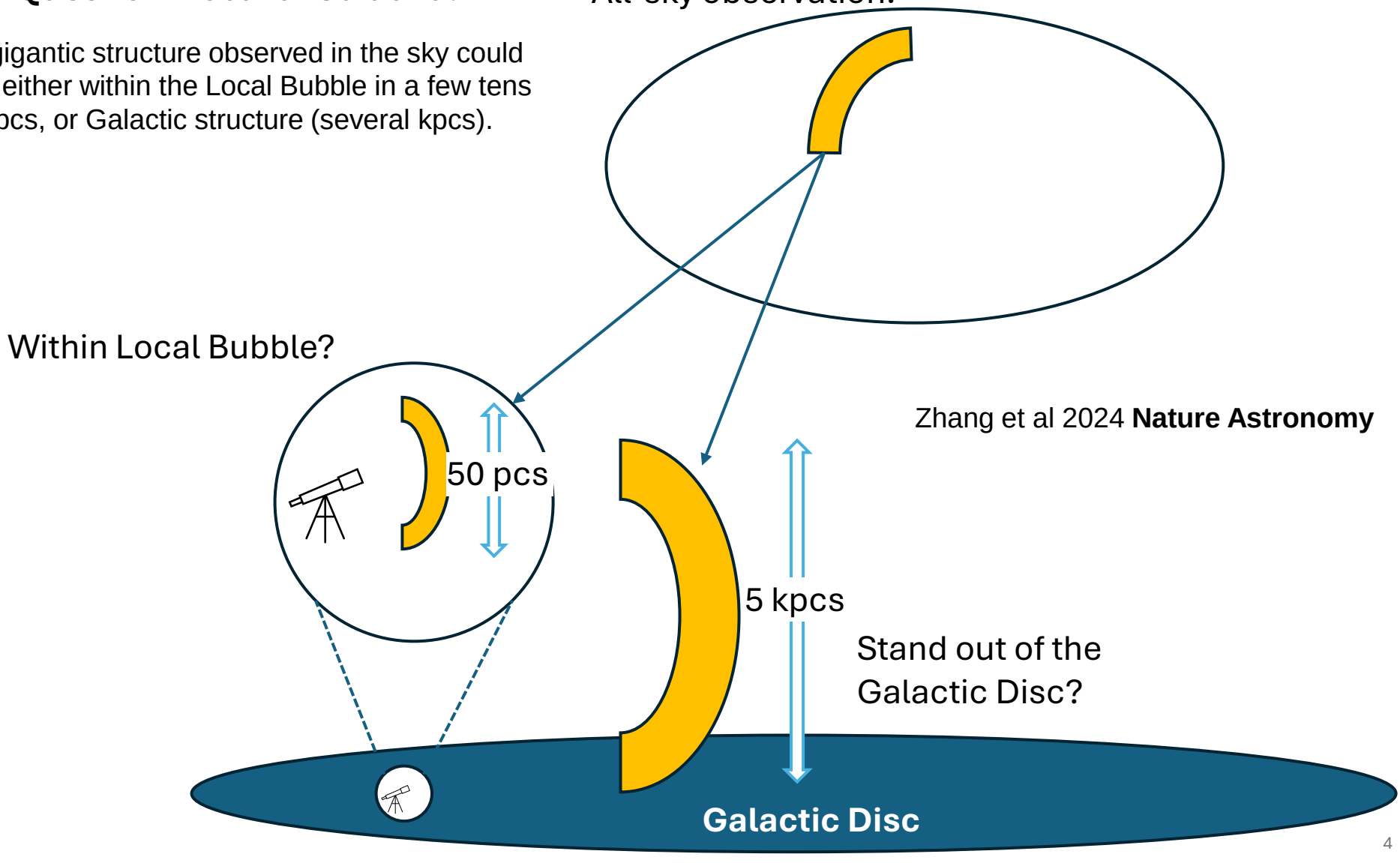
White bars: magnetic field (23 GHz)
Green: 0.6-1.0 keV X-ray

Within Local Spiral Arm, or beyond the Galactic Disc?

3. Question: Local or Galactic?

A gigantic structure observed in the sky could be either within the Local Bubble in a few tens of pcs, or Galactic structure (several kpcs).



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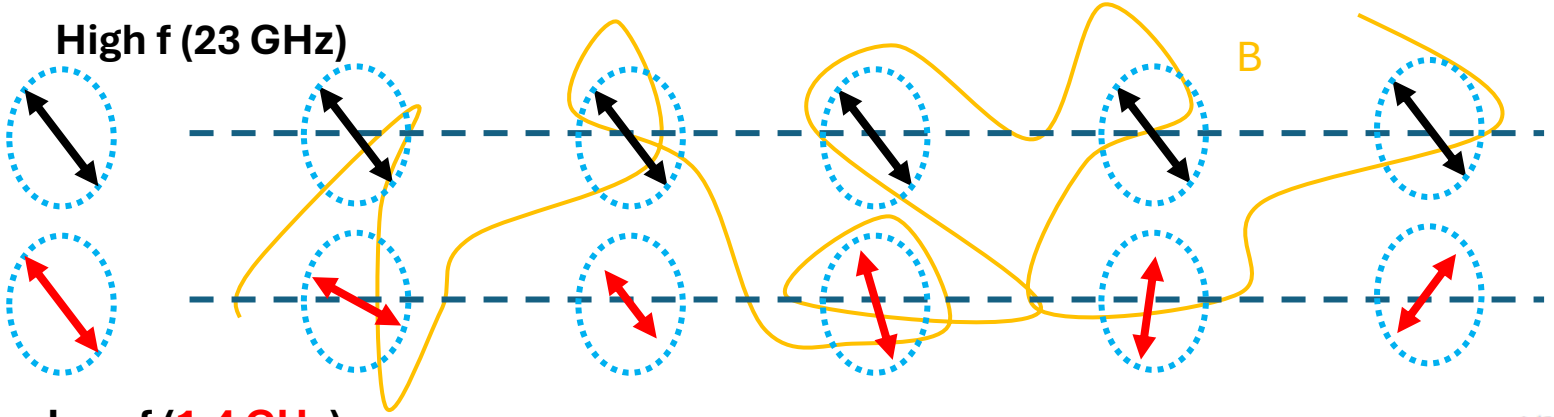
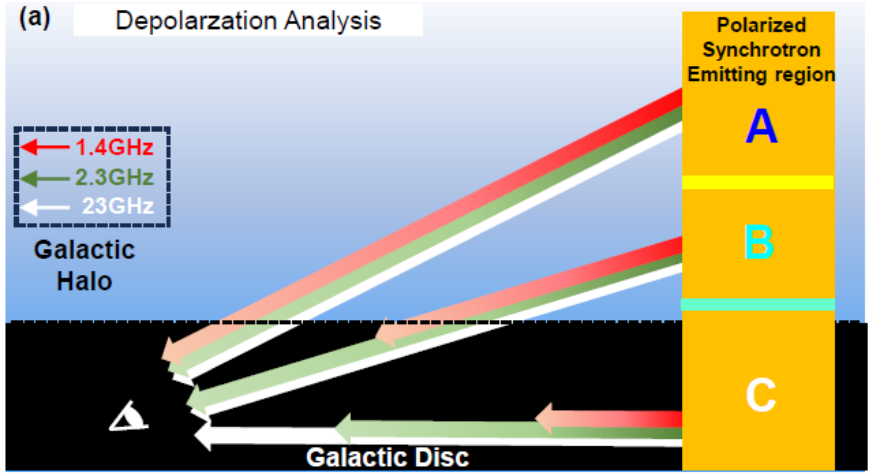
3. **Question**: Local or Galactic?

Faraday Rotation Depolarization

Polarized signal from synchrotron will be Faraday rotated, Signals depolarized in turbulent foreground.





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Rotation measure: $\sigma_{RM} = 0.81\,\sigma_{B\parallel}\,n_e\,d\,N_{||}^{1/2}$

Dispersion angle: $\Delta\Phi = \sigma_{RM}\lambda^2$

The Galactic Disc will **imprint on the synchrotron structure!**

Lower frequency signal
(longer wavelengths)

More disc imprint

3. Question: Local or Galactic?

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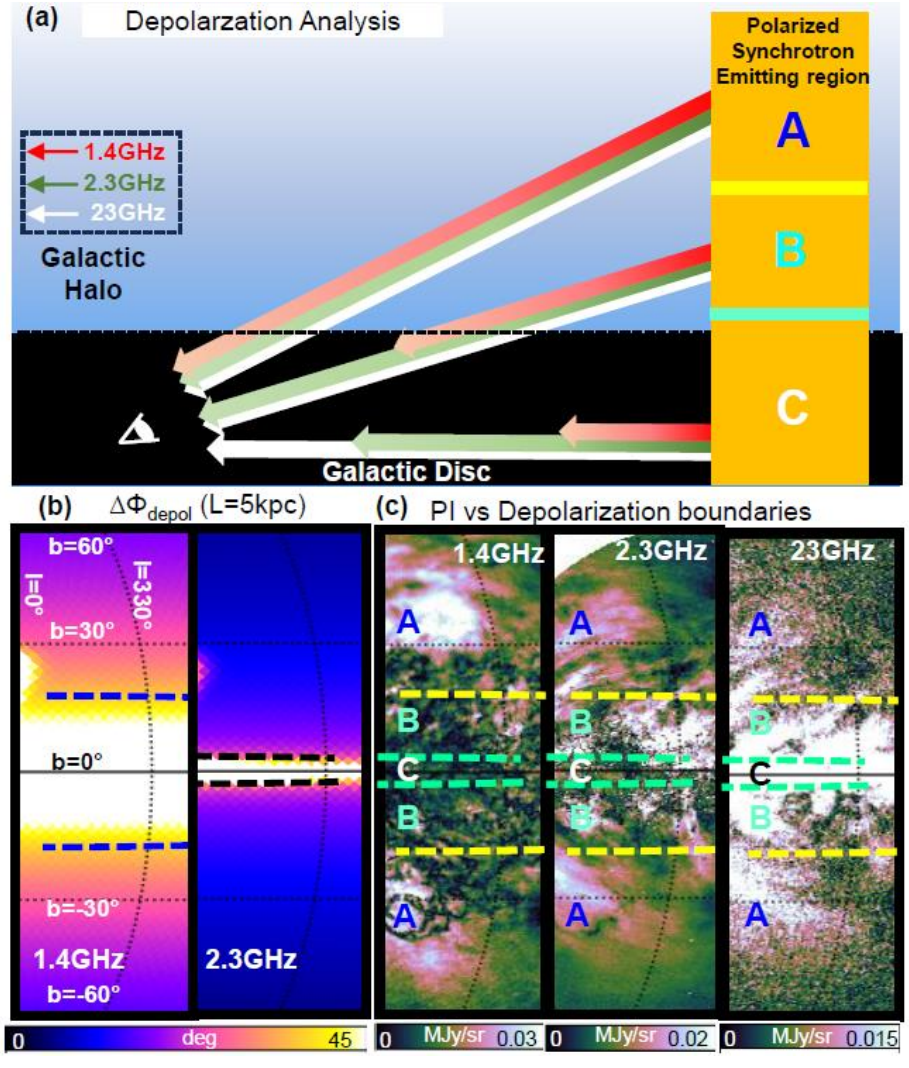

Distance measurements with Faraday Rotation Depolarization

Lower frequency signal

More disc imprint

Depolarization screen at 5kpc anti-correlated with the observed polarized synchrotron emission.

3. Question: Local or Galactic?

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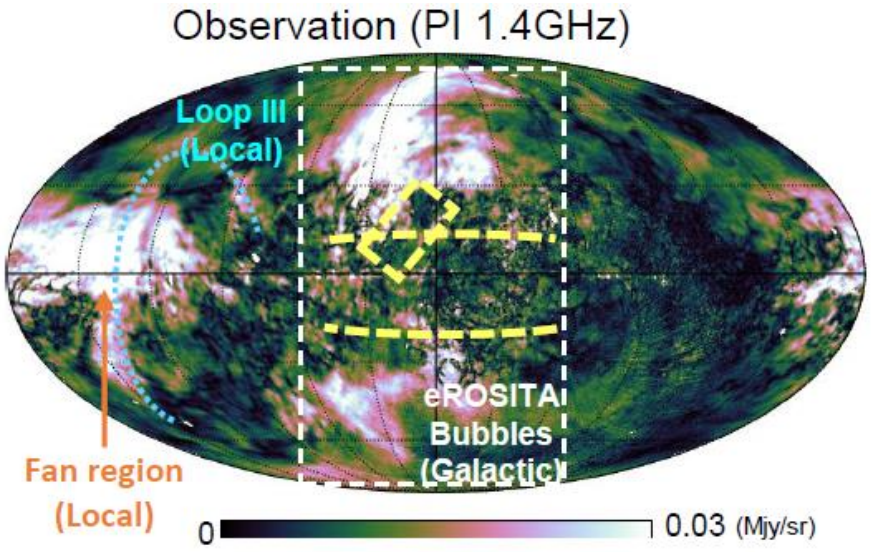
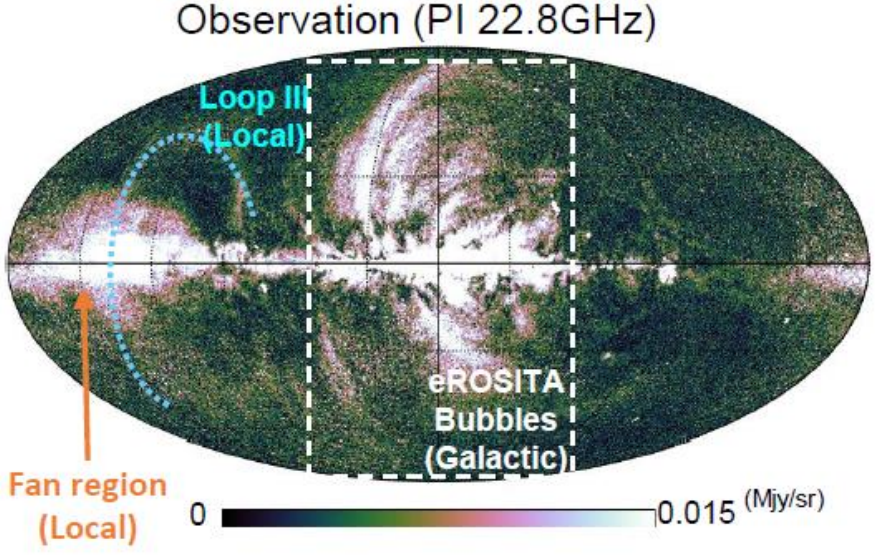
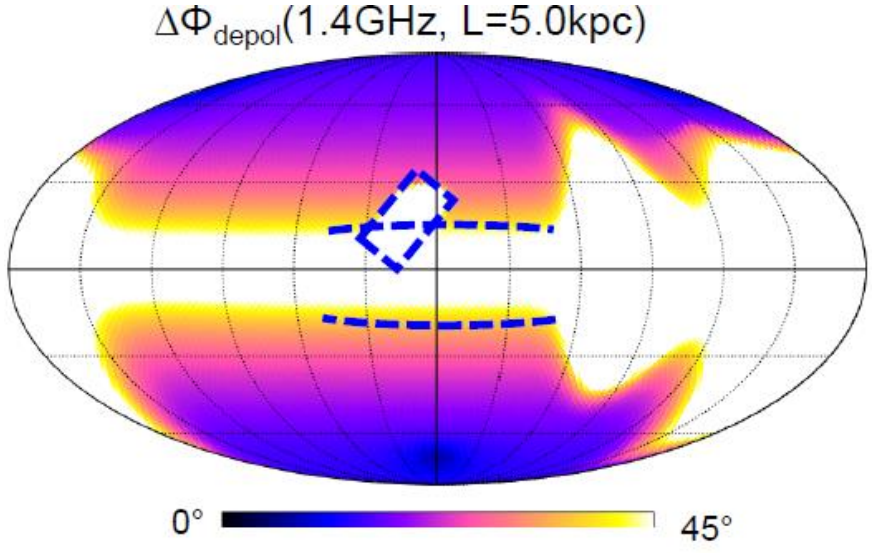




Faraday Rotation depolarization screen

Local: in front of the screen

Galactic: behind the screen



3. Question: Local or Galactic?
Answer: Galactic X-ray halo

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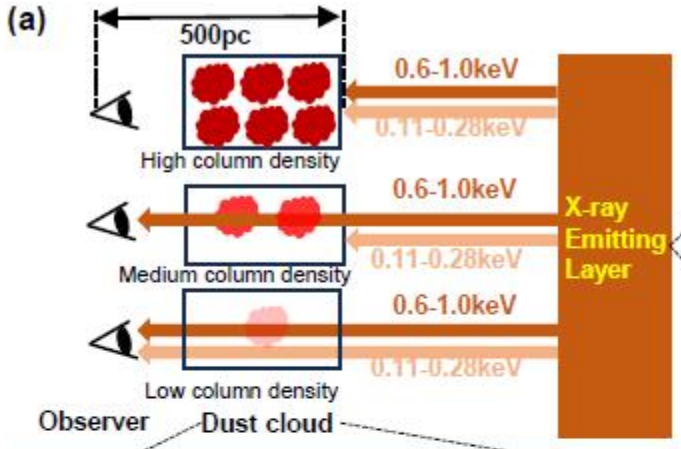
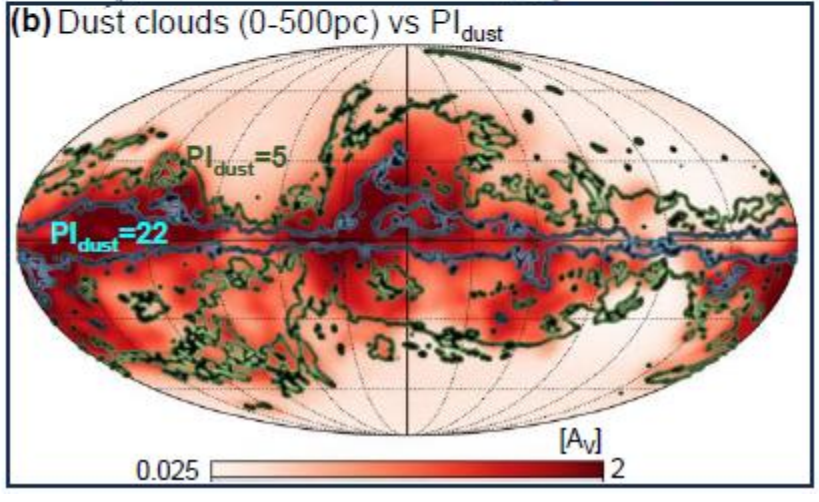
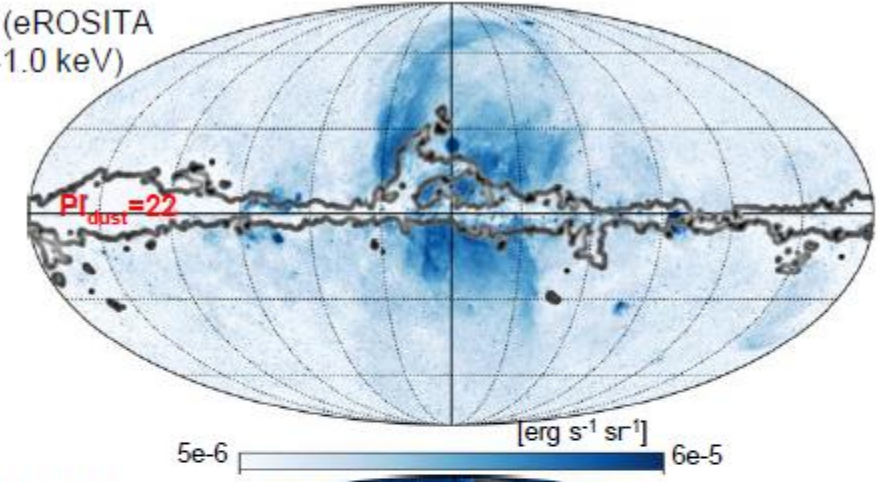
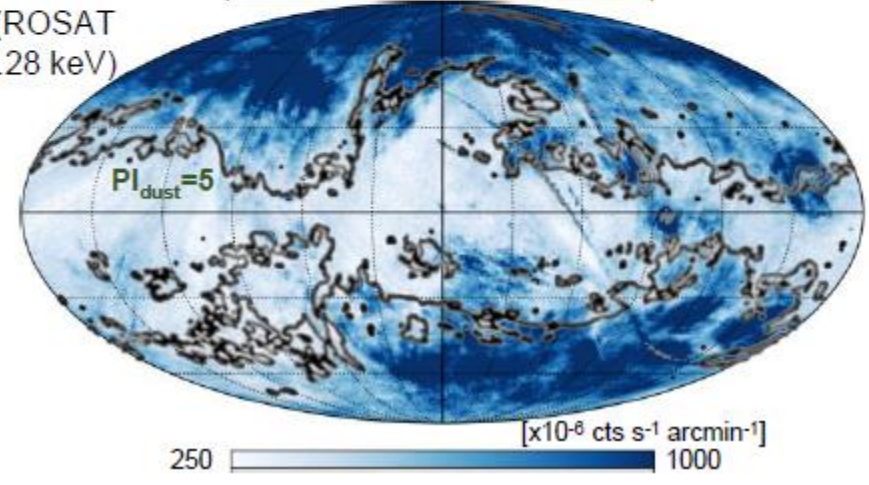


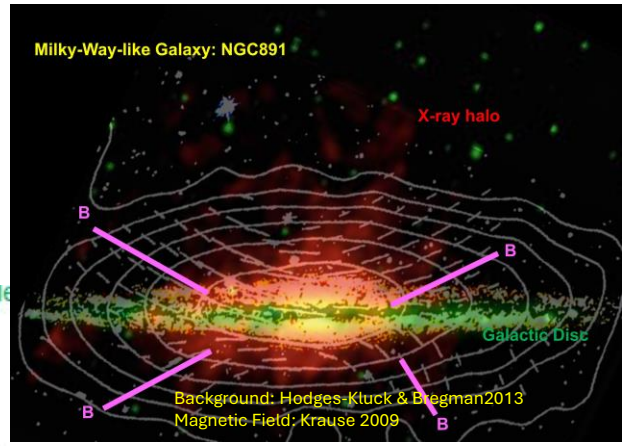




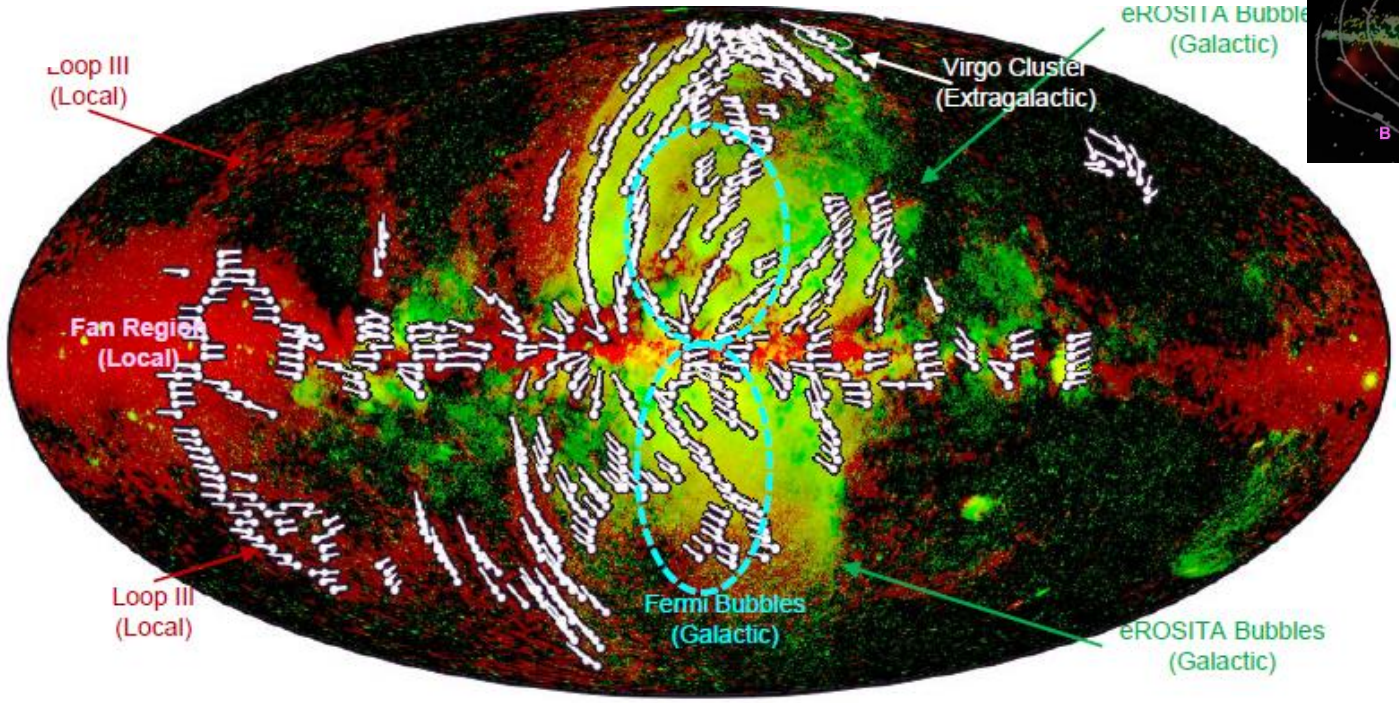


The eROSITA Bubbles - out of the Galactic plane!

4. Magnetic and X-ray emitting halo



The Milky Way



Beyond the Galactic Disc, Coherent ridges in the central +60°>l>-60°.

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4. Gamma-ray counterpart of the magnetic halo

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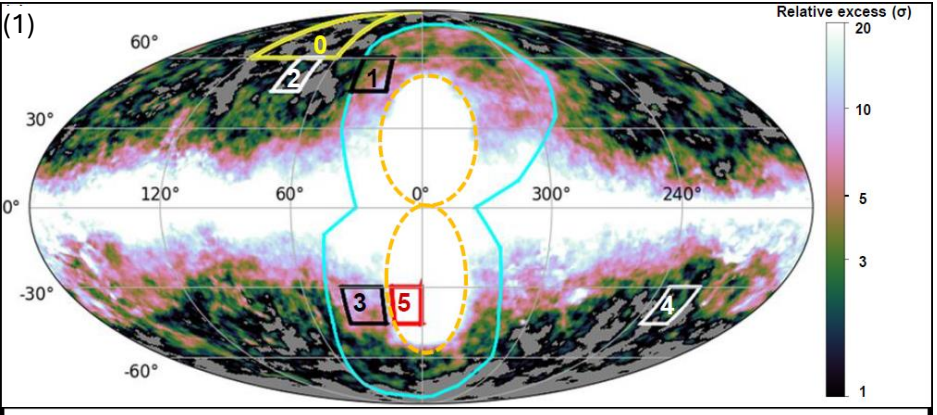
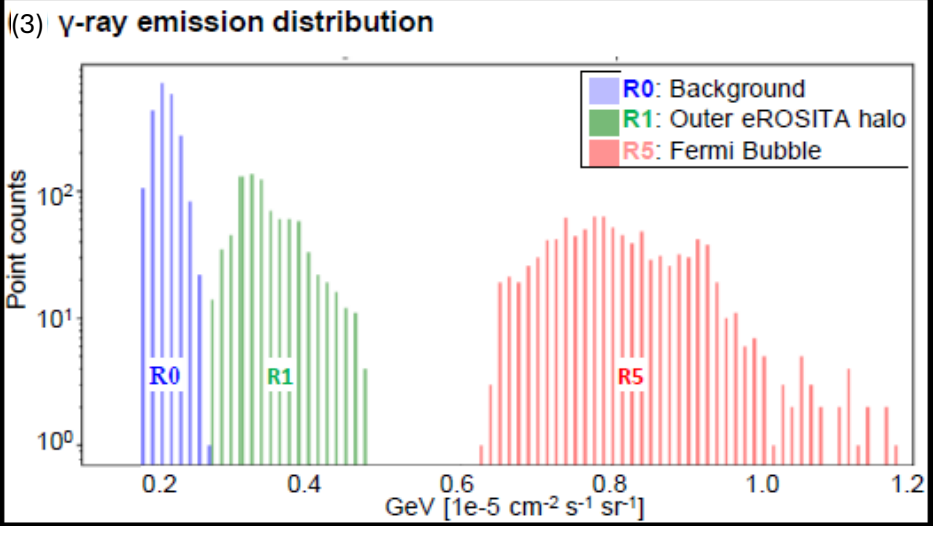
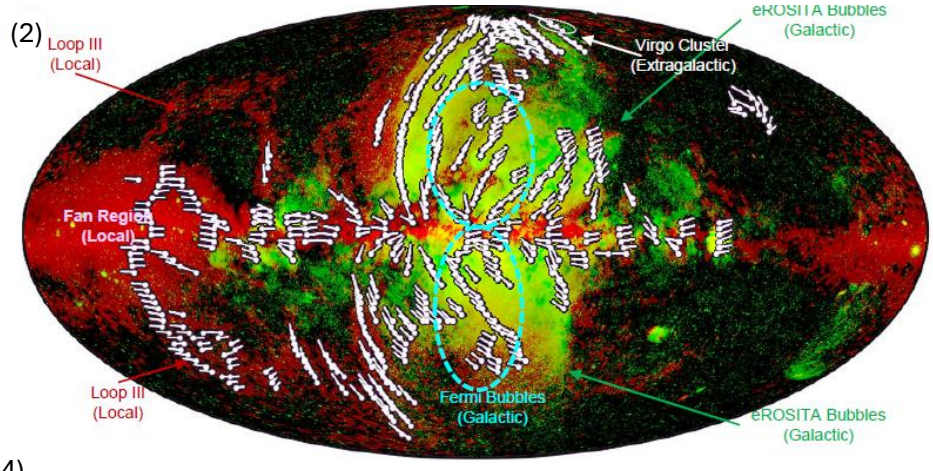
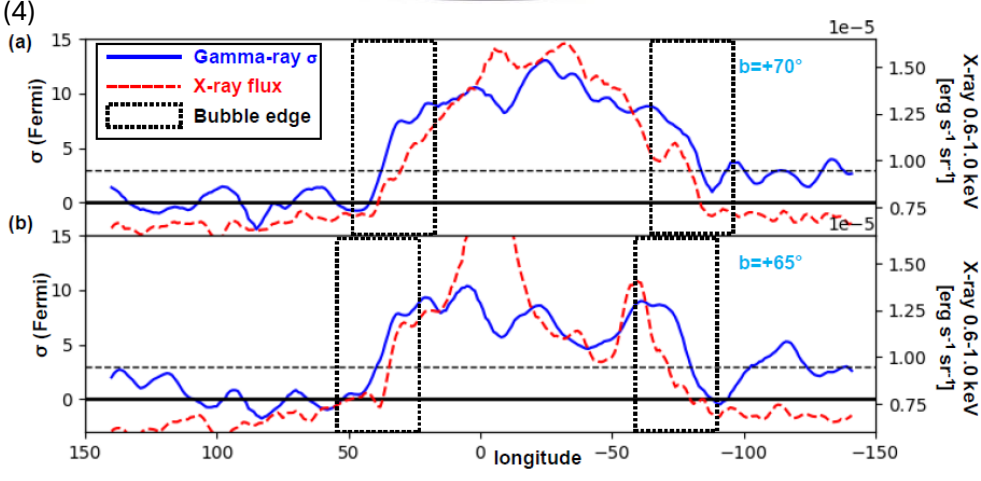


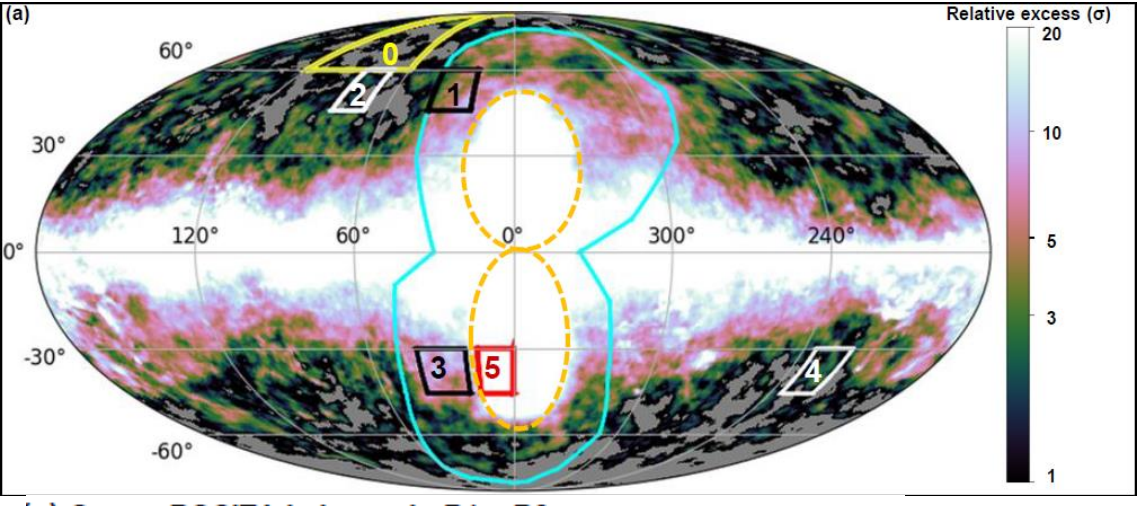






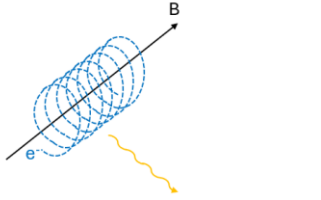
A gamma-diffuse halo (see 1), with magnetic ridges enhanced at the edges (see 2), independent of the background or Fermi Bubbles (see 3), and similar morphology to the eROSITA Bubbles (see 4)

5. Magnetic field strength measurements



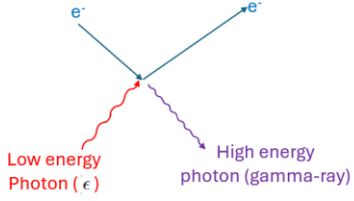
Magnetic field strength diagnostic from multi-messenger approach

- Synchrotron:
  Relativistic electrons radiate when gyrating around the magnetic field



$$E_{\rm syn} = 10^{-4}(E_e/40{\rm GeV})^2(B/1\mu{\rm G})\,{\rm eV}.$$

- Inverse Compton (IC):
  Relativistic electrons scatters low energy photons to gamma-ray



$$E_{\rm IC} \approx 3(E_e/40\,{\rm GeV})^2(\epsilon/0.4{\rm eV})\,{\rm GeV}$$

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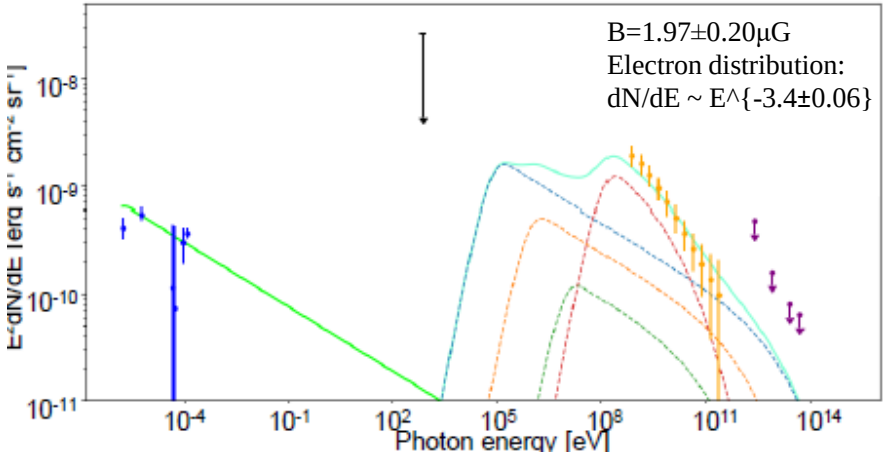
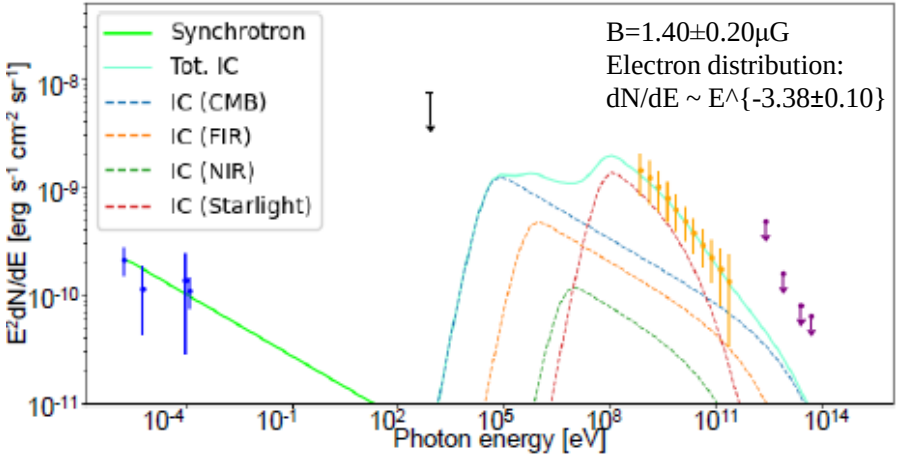
(c) Outer eROSITA halo north: R1 – R2

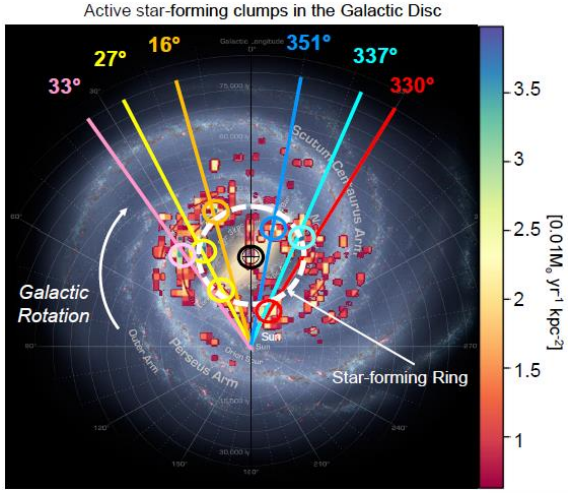


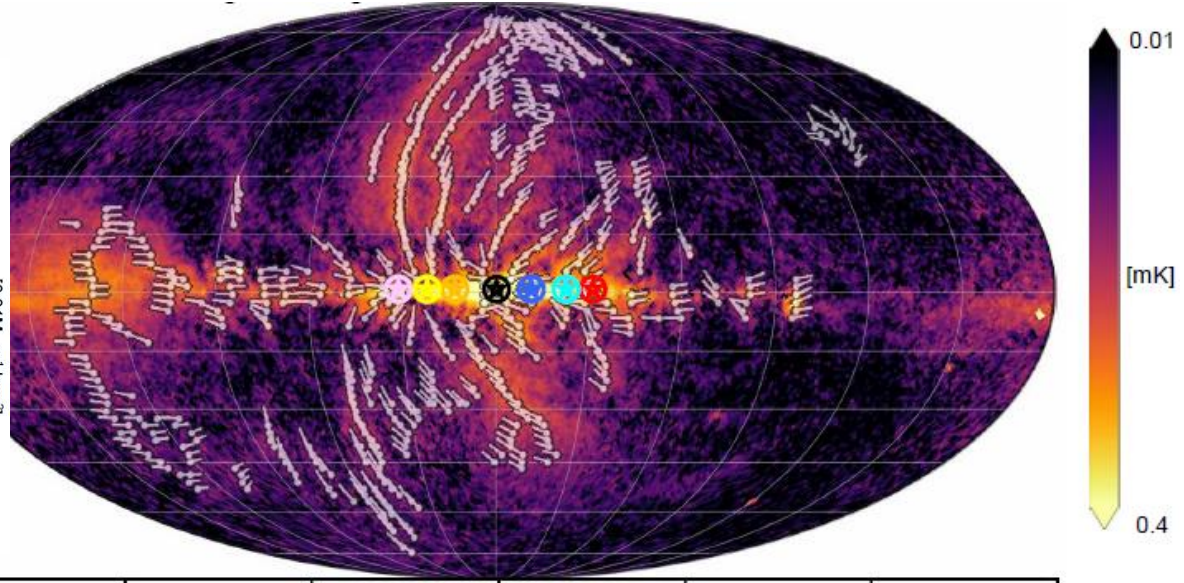
(d) Outer eROSITA halo south: R3 – R4

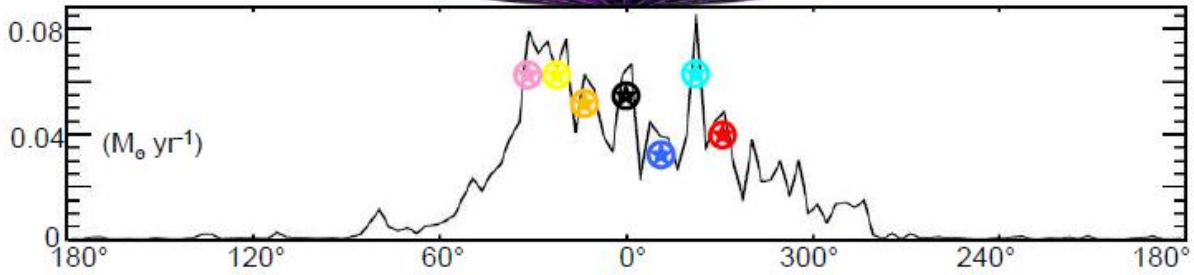


North-South non-thermal symmetry: **similar magnetic field, similar electron index, plasma-beta around 10**!

6. Magnetic Ridges in the halo vs Star Formation in the disc







Footpoints of the Magnetic ridges for Fermi Bubbles and eROSITA Bubbles are different:

Fermi Bubbles to the GC;

eROSITA Bubbles to a few kpcs from the GC!

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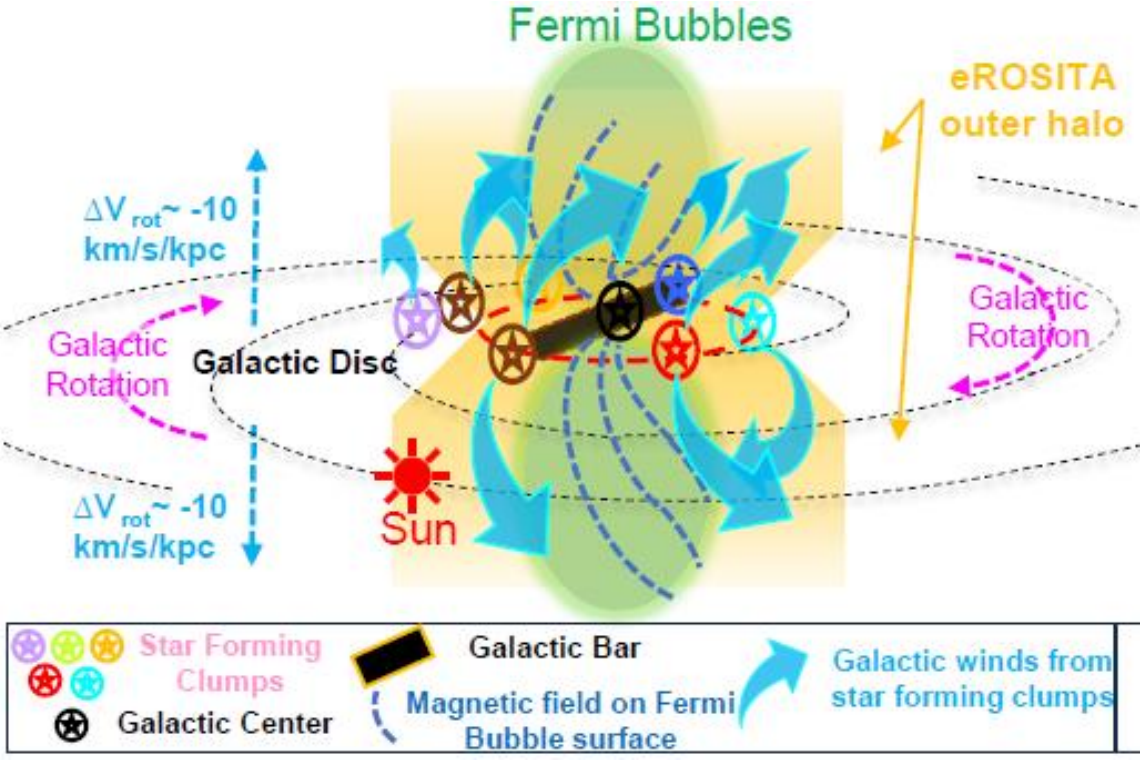
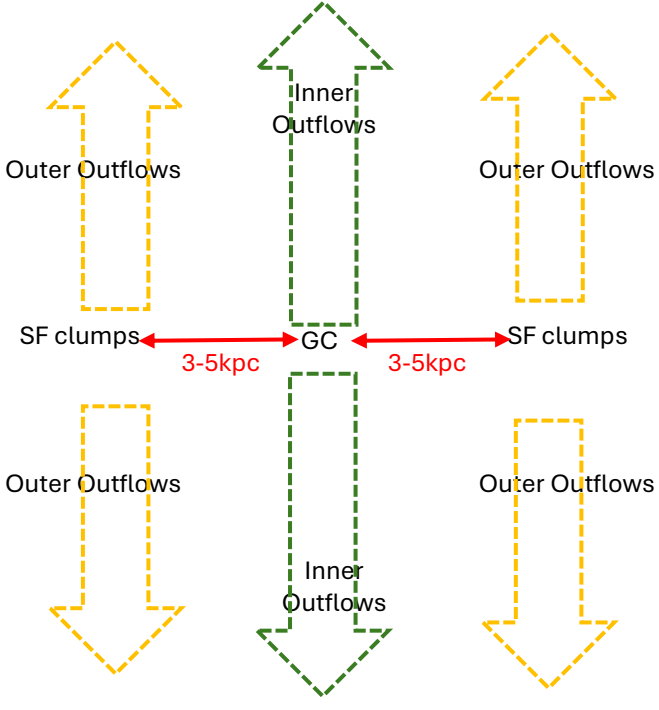
7. Magnetic halo and Galactic Outflows





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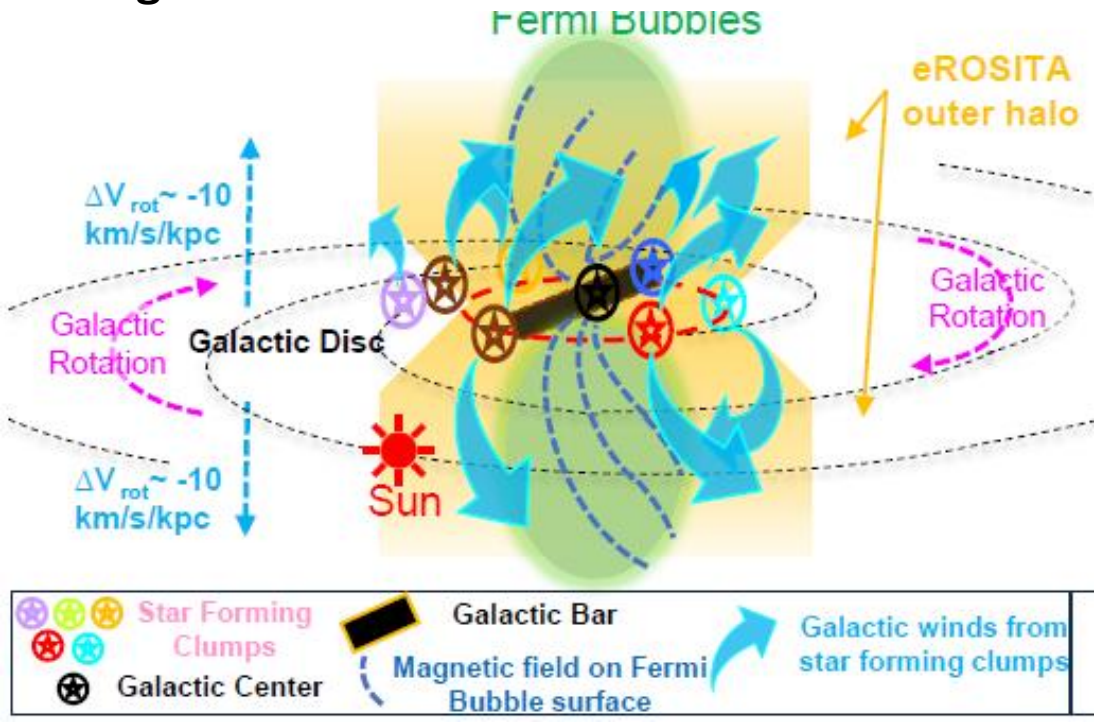

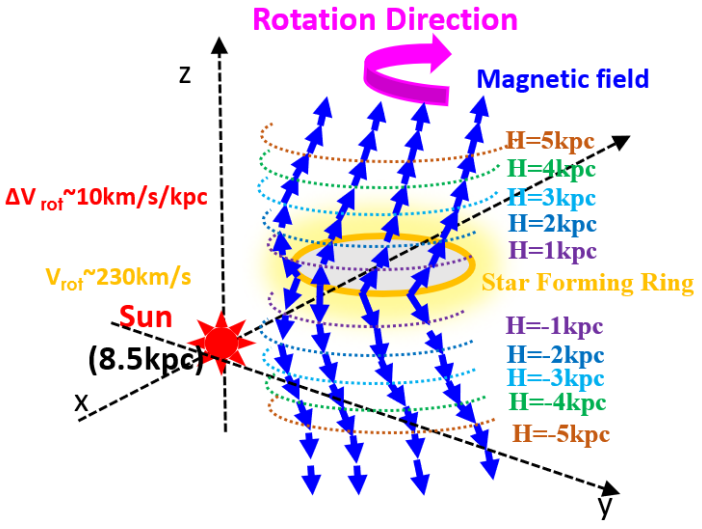

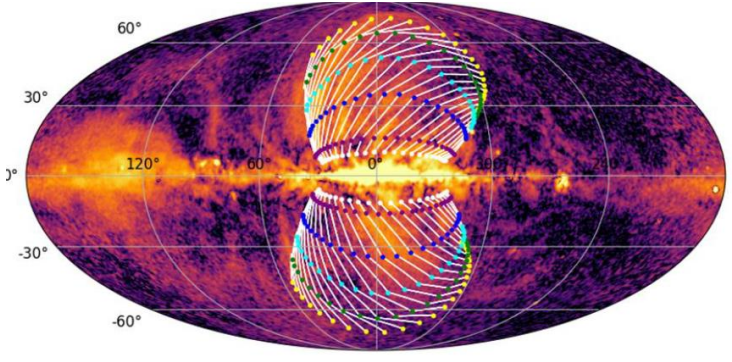

Magnetic field lines in the halo trace the Galactic outflows!

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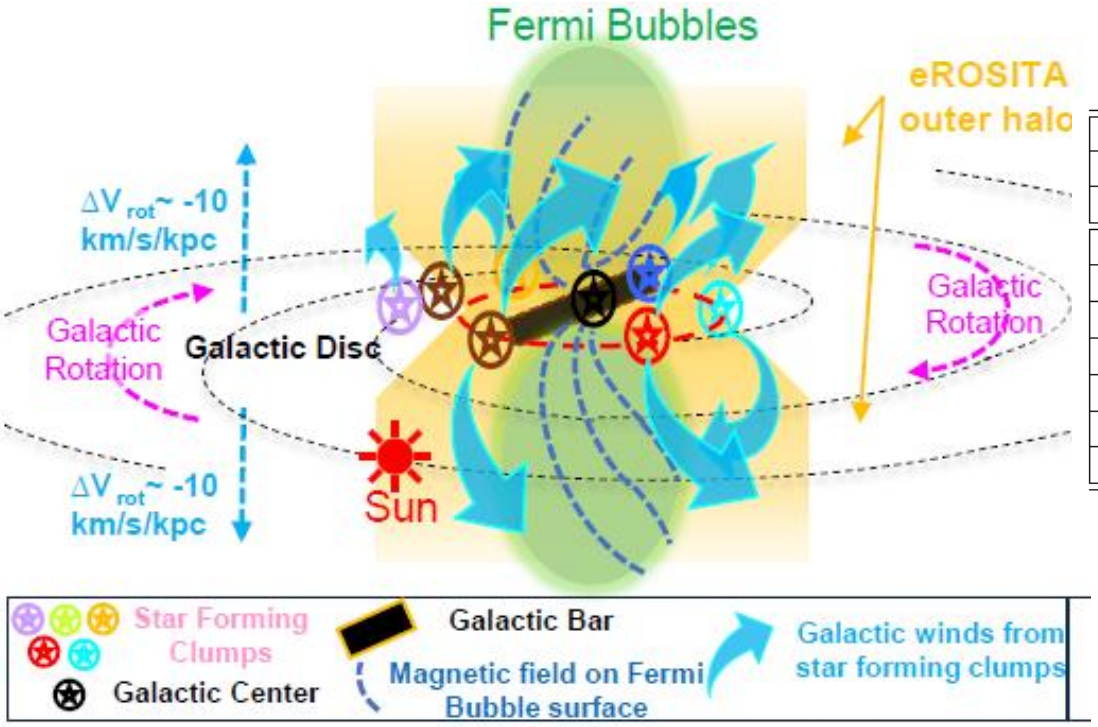
7. Magnetic halo and Galactic Outflows



Assumptions						
H_{sys} [kpc]	4		7		10	
t_{dyn} [yrs]	10^8	10^9	10^8	10^9	10^8	10^9
Results						
E_{therm} [$\times 10^{55}$ erg]	5.9		10		14	
E_B [$\times 10^{55}$ erg]	1.5		3.3		5.3	
E_{tot} [$\times 10^{55}$ erg]	8.6		15		21	
$\dot{E}_{inj}$ [$\times 10^{40}$ erg/s]	2.7	1.4	4.7	2.5	6.6	3.5
χ_{inj} [%]	8.5	4.5	14.6	7.7	20.5	10.8
$\dot{M}_{inj}$ [$M_\odot$/yr]	0.54	0.28	0.92	0.49	1.3	0.68

The SNR rate in the 3-5 kpc star-forming ring is around 1 per century: $\dot{E}_{SFR} \simeq 3.2 \times 10^{41}$ erg/s.

1. The outer outflows can be powered by the 3-5 kpc star-forming ring by a few to 20% of their mechanical energy from SNe;
2. The mass injection rate required around 0.3 ~ 1.3 Solar mass / year.

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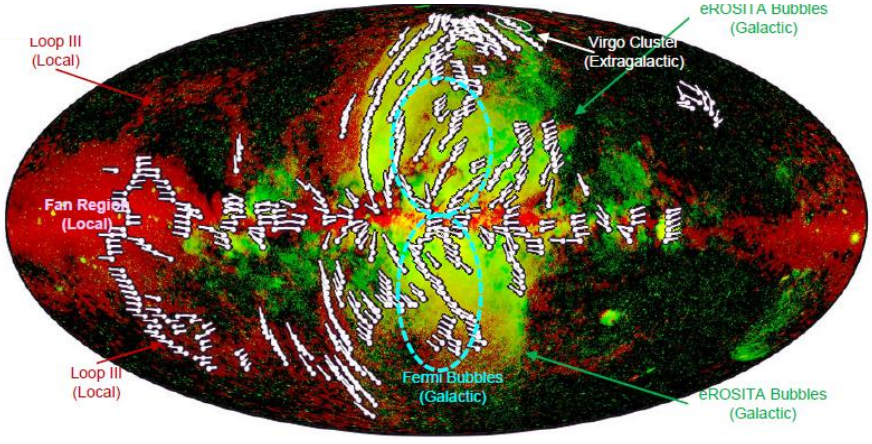
Summary

1. The Milky Way has inner outflows from GC (Fermi Bubbles) and outer outflows from the star forming clumps (eROSITA Bubbles, footpoints span several kpc).
2. The magnetic field is coherent and highly anisotropic in the Galactic halo, tracing the Galactic outflows.



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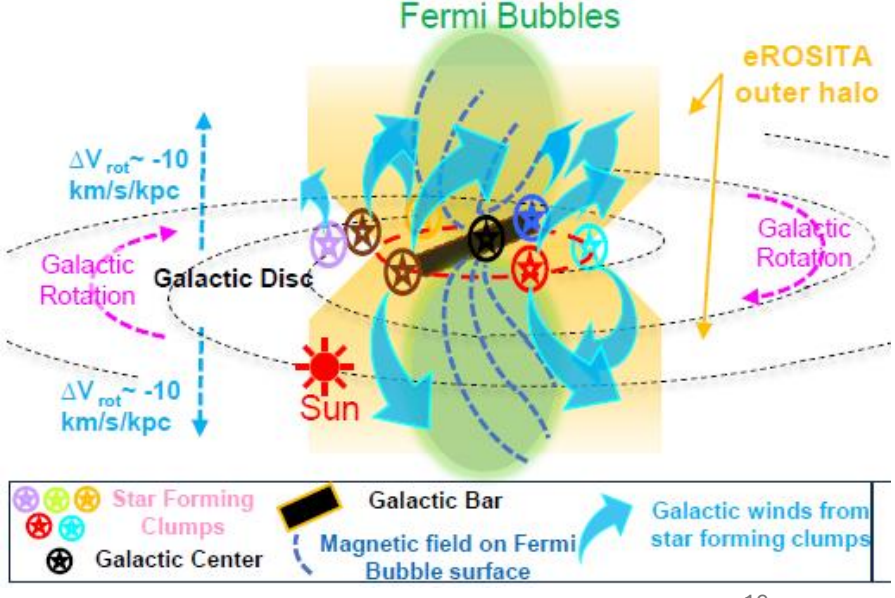
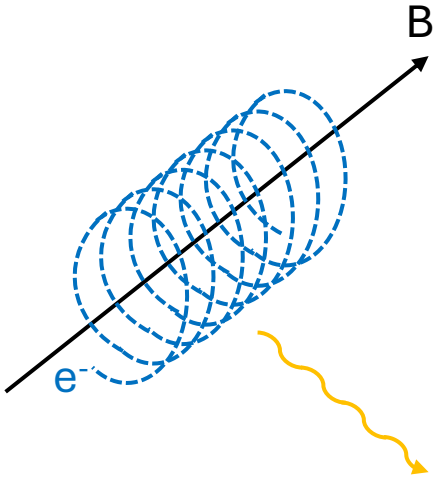
https://www.nature.com/articles/s41550-024-02362-0



Magnetic field strength diagnostic from multi-messenger approach

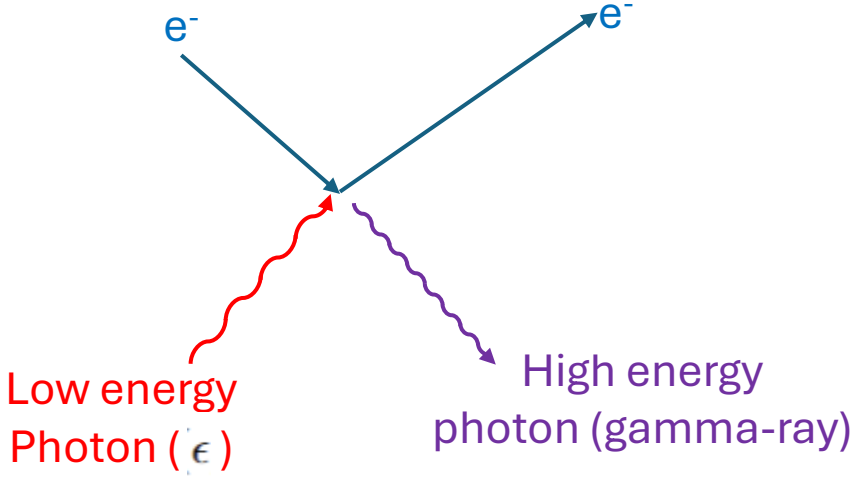
- Synchrotron:
  Relativistic electrons radiate when gyrating around the magnetic field



Radio Synchrotron light

$$E_{\rm syn} = 10^{-4}(E_e/40{\rm GeV})^2(B/1\mu{\rm G})\,{\rm eV}.$$

- Inverse Compton (IC):
  Relativistic electrons scatters low energy photons to gamma-ray

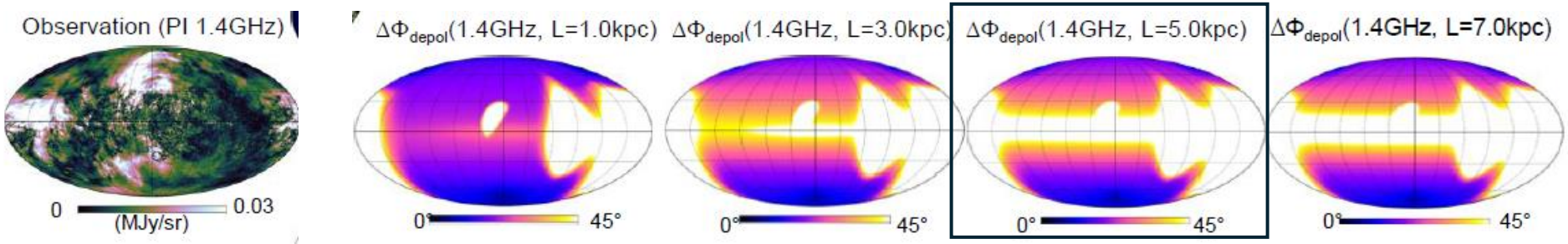


$$E_{\rm IC} \approx 3(E_e/40\,{\rm GeV})^2(\epsilon/0.4{\rm eV})\,{\rm GeV}.$$

ISRF+CMB

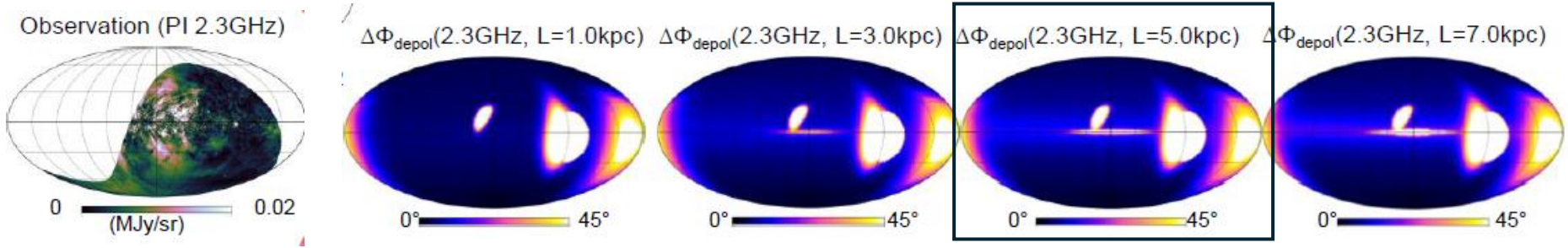
3. Question: Local or Galactic?

Depolarization screen at different distances



Depolarization screen at 5kpc anti-correlated with the observed polarized synchrotron emission.

These magnetic ridges are several kpc scales stemming out of the Galactic plane.



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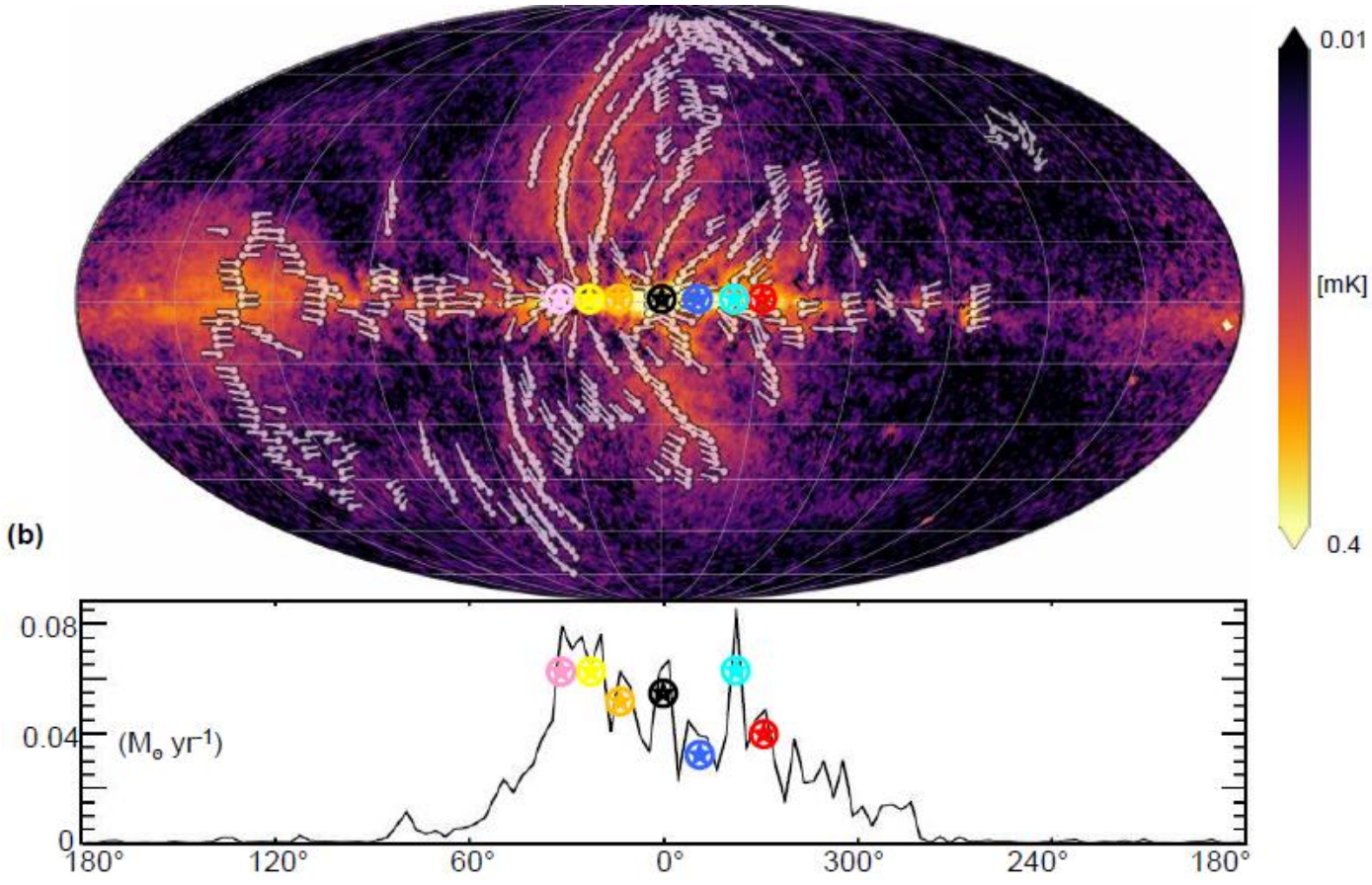
6. Magnetic Ridges in the halo vs Star Formation in the disc



1. Magnetic ridges are not all connected to the Galactic Center, but rather to some of the active star-forming points in the Galactic disc.

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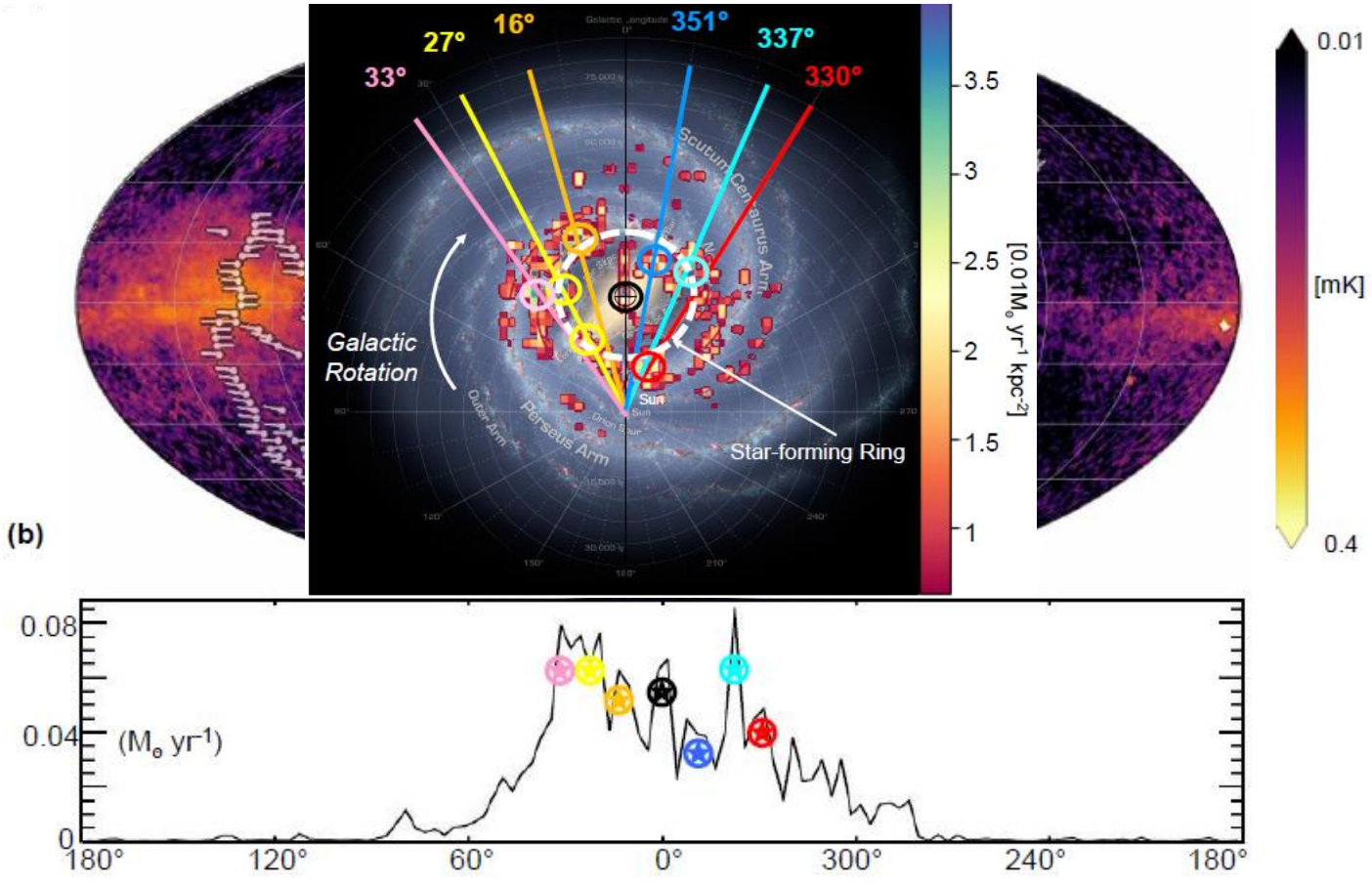
6. Magnetic Ridges in the halo vs Star Formation in the disc



1. Magnetic ridges are not all connected to the Galactic Center, but rather to some of the active star-forming points in the Galactic disc.
2. These active star-forming points are connected to the clumps in the disc with high specific star-forming rate 3-5 kpc from the Galactic Center (known as “star-forming ring”, see e.g. Elia+2022).

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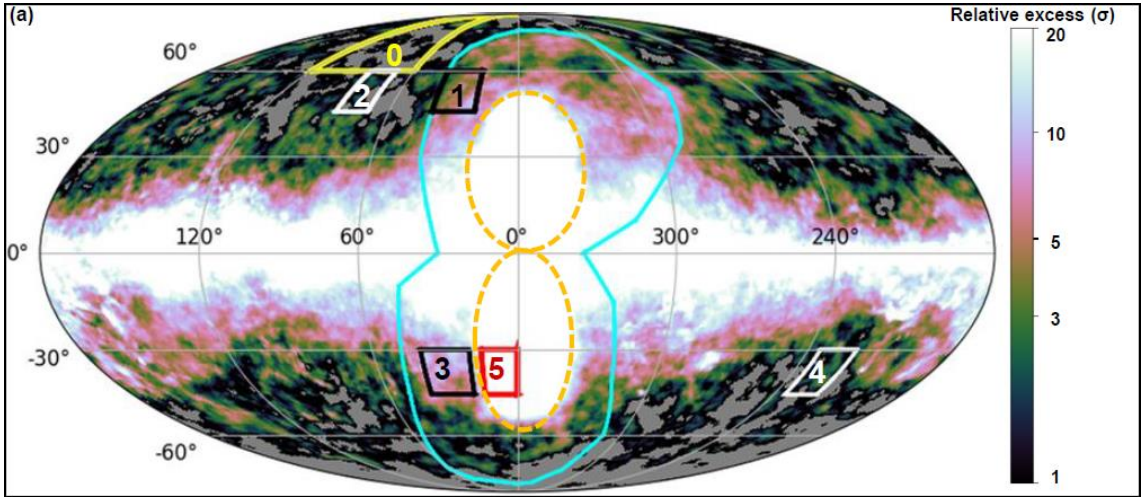

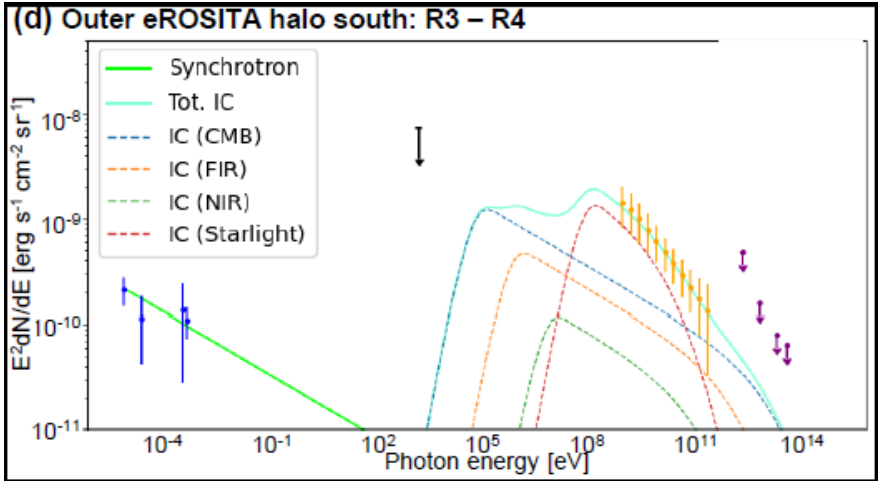

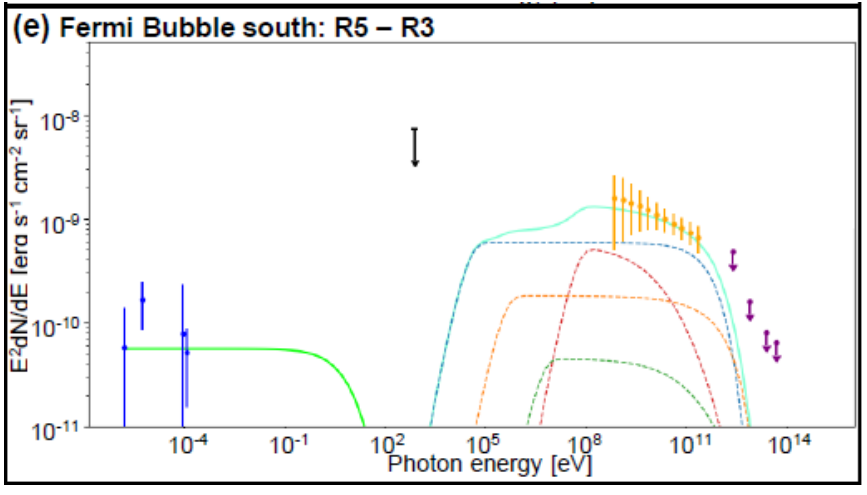

Radio and gamma-ray fluxes in the outer region (left) is not lower than the inner region (right) at the same Galactic latitude. This indicates the injection from the Fermi Bubbles are not enough to explain all the emission in the outer region (between boundaries of Fermi Bubbles and eROSITA Bubbles).

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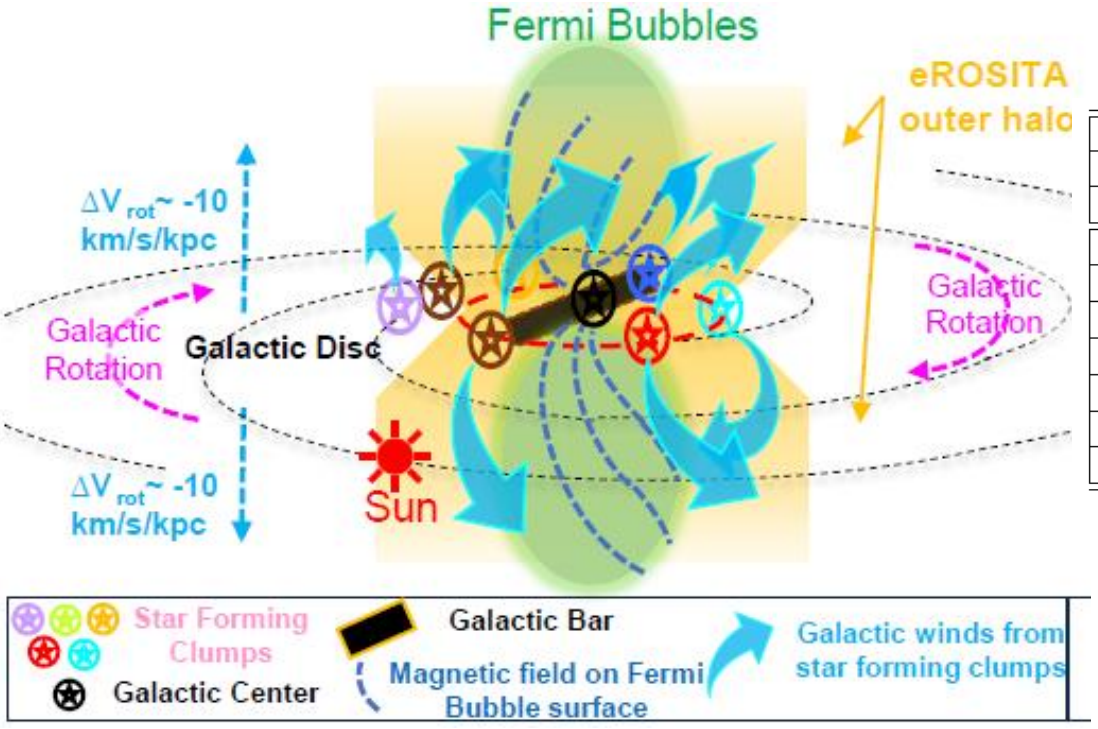
7. Magnetic halo and Galactic Outflows



Assumptions						
H_{sys} [kpc]	4		7		10	
t_{dyn} [yrs]	10^8	10^9	10^8	10^9	10^8	10^9
Results						
E_{therm} [$\times 10^{55}$ erg]	5.9		10		14	
E_B [$\times 10^{55}$ erg]	1.5		3.3		5.3	
E_{tot} [$\times 10^{55}$ erg]	8.6		15		21	
$\dot{E}_{inj}$ [$\times 10^{40}$ erg/s]	2.7	1.4	4.7	2.5	6.6	3.5
χ_{inj} [%]	8.5	4.5	14.6	7.7	20.5	10.8
$\dot{M}_{inj}$ [$M_\odot$/yr]	0.54	0.28	0.92	0.49	1.3	0.68

The SNR rate in the 3-5 kpc star-forming ring is around 1 per century: $\dot{E}_{SFR} \simeq 3.2 \times 10^{41}$ erg/s.

1. Fermi Bubble footpoints: Galactic Center/ eROSITA Bubbles footpoints: several kpcs
2. Inner outflows connect to the GC; Outer outflows connect to active star forming clumps
3. Tilt result from galactic rotation
4. Magnetic fields in the halo are filamented, tracing the outflows

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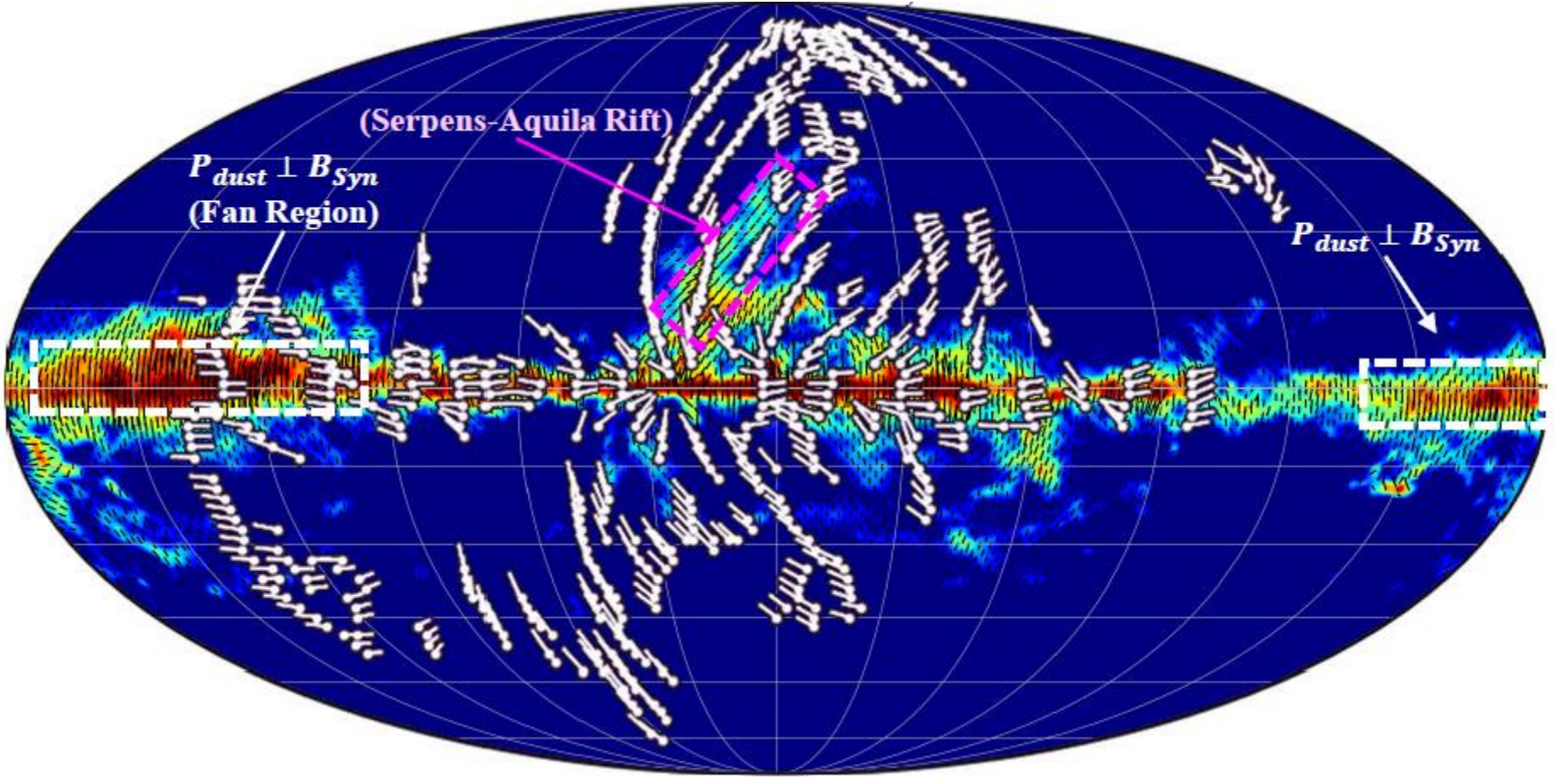
Polarized E-vector from dust emission vs magnetic ridges from synchrotron



There is no counterpart for the polarized dust emission (mainly local, see Maconi+2023) with the magnetic ridges in the Galactic halo.

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3D geometry of the eROSITA Bubbles

Does “eROSITA Bubbles” observed in 2D sky indicate a pair of 3D Bubbles?

No necessarily!
Because of the projection effect, the observed morphology can result from different emitting structures.

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