A magnetized halo from inner Galaxy outflows

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Based on **Zhang et al, Nature Astronomy 8, 1416-1428 (2024)**

https://ui.adsabs.harvard.edu/abs/2024NatAs...8.1416Z/abstract

Cooperators: Gabriele Ponti, Ettore Carretti, Ruo-Yu Liu, Mark Morris, Marijke Haverkorn, Nicola Locatelli, Xueying Zheng, Felix Aharonian, Hai-Ming Zhang, Yi Zhang, Giovanni Stel, A. Strong, M. Yeung, A. Merloni

QR code to our paper

"X-riStMAs" under PNRR from MUIR funded by NextGenerationEU

(**X-r**ay **i**n **St**udying the **M**ultiphase **As**trophysics)

INAF ISTITUTO NAZIONALE DI ASTROFISICA

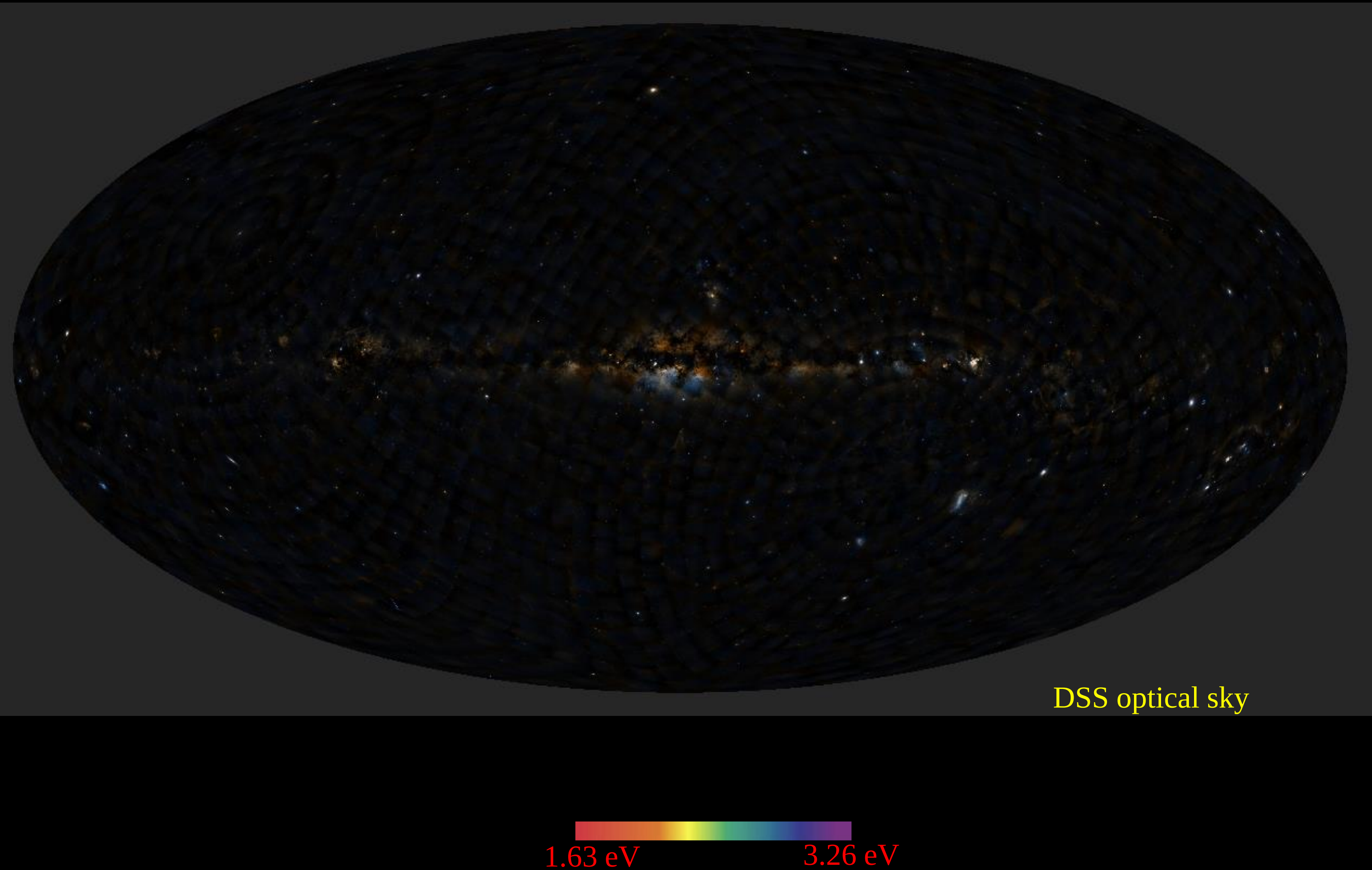
OSSERVATORIO ASTRONOMICO DI BRERA

MUR Ministero dell'Università e della Ricerca

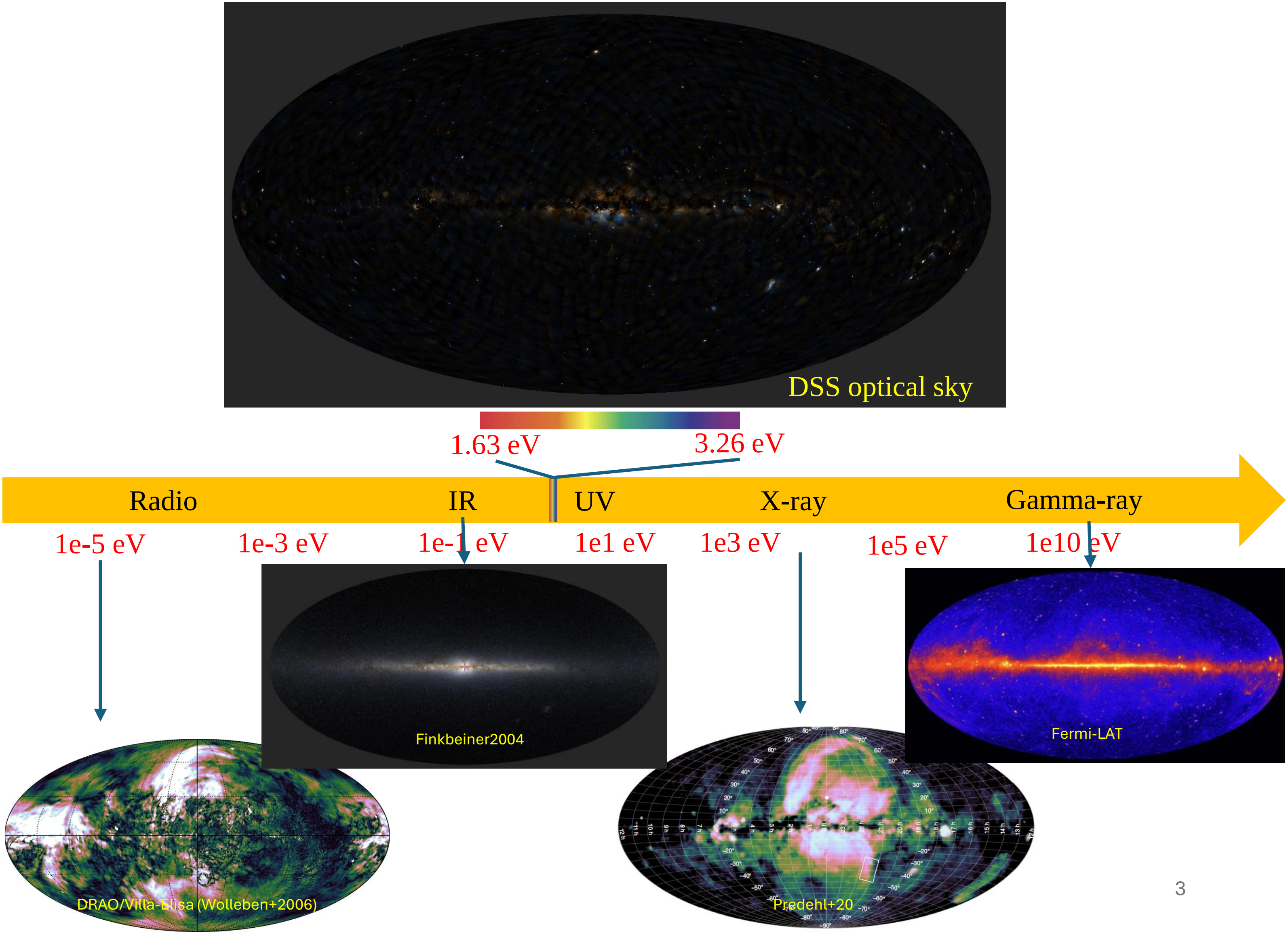
NEXT GEN EU

PNRR

0. The Optical sky

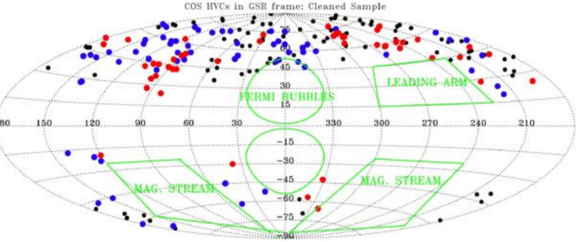


1. The era of multi-wavelength observations



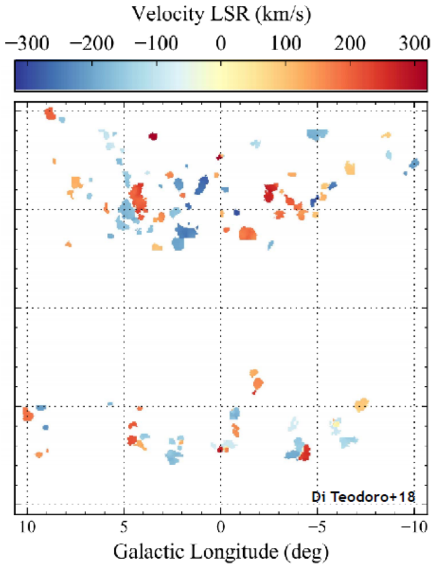
If we look beyond the Galactic disc: Multi-phase CGM

- Neutral and Ionized gas from absorption lines of QSOs

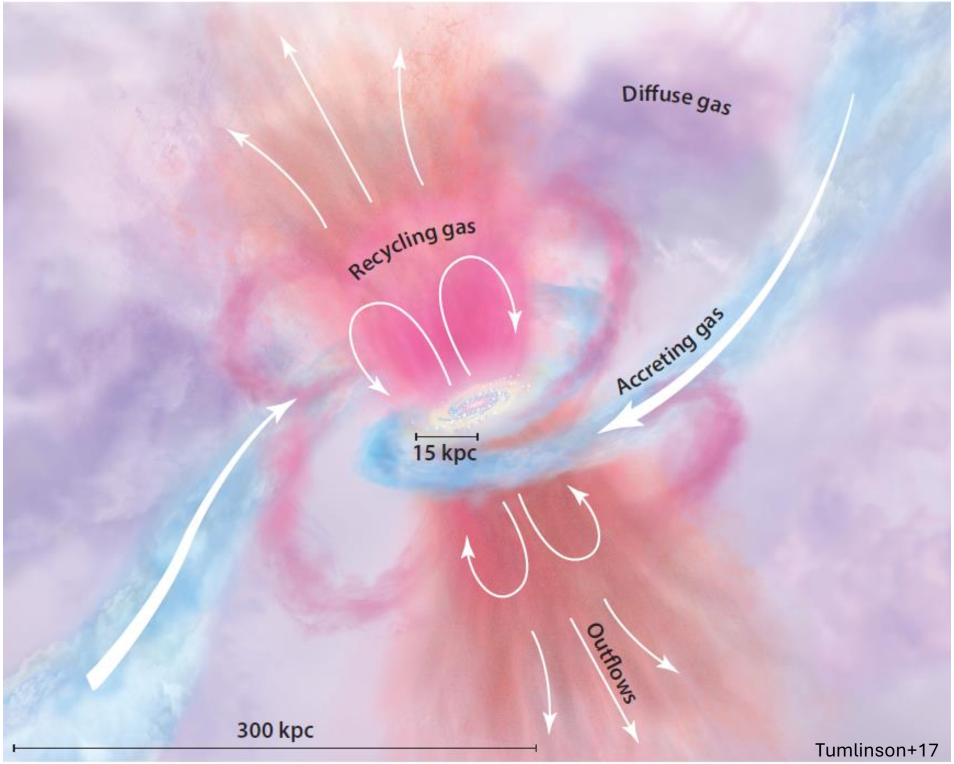


Richter+17, Fox+19

- Molecule emission lines



McClure-Griffith+13; Di Teodoro+18;+20; Lockman+20

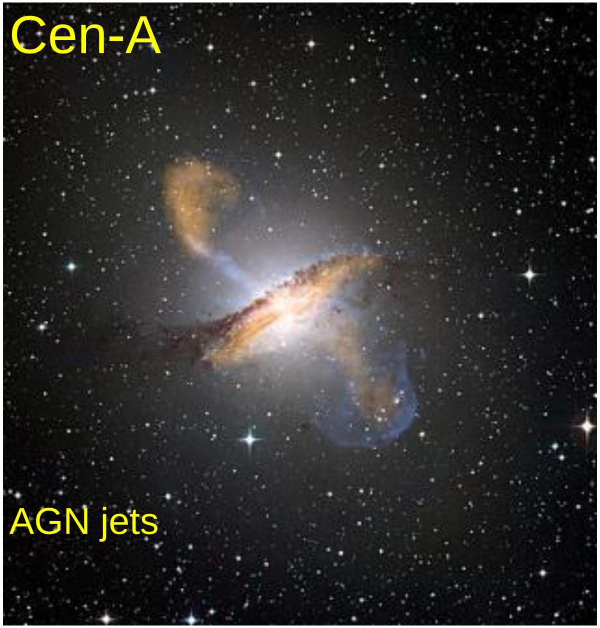


Tumlinson+17

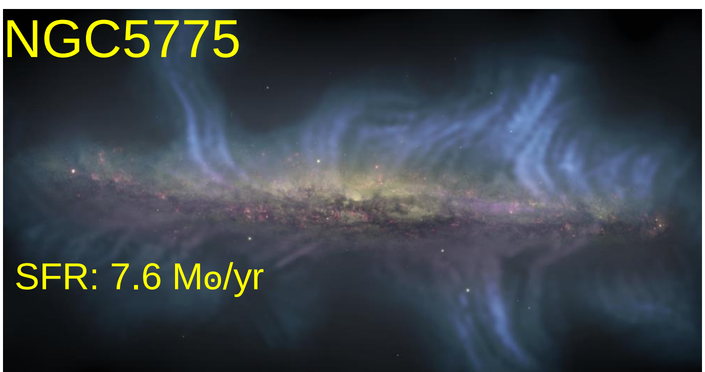
- Magnetic field (from radio continuum)
- Hot plasma (X-ray, but current instruments are not enough to resolve velocity)
- Cosmic rays (gamma-ray)

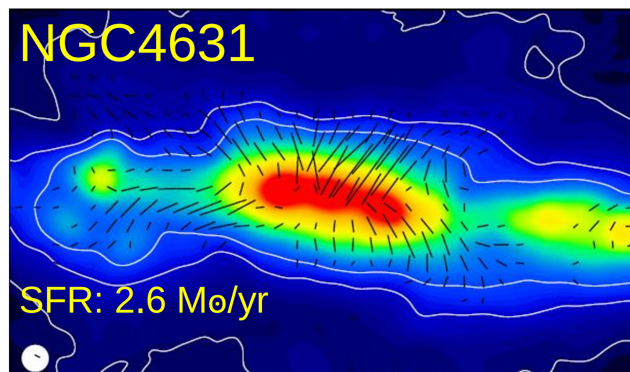
Galactic outflows from other galaxies

For review:
Thompson&Heckman24,
Sarkar24,Krause+2020



Magnetic halo



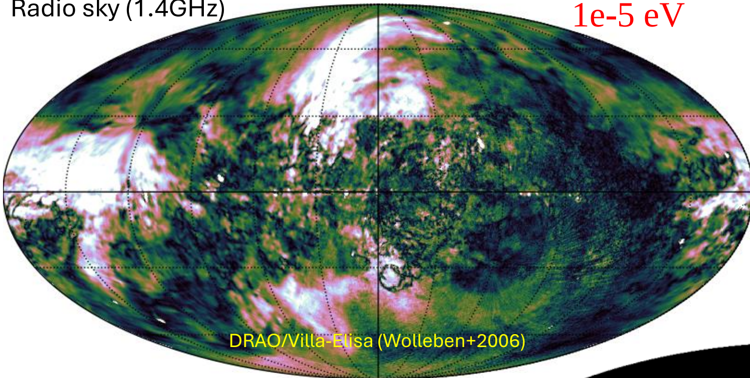


1. The era of multi-wavelength observations

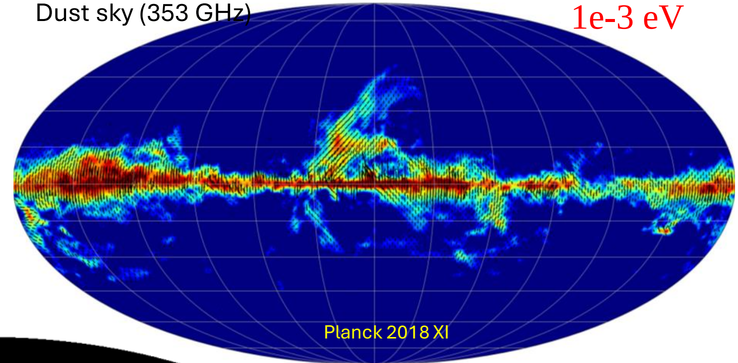
For Our Milky Way:

Large scale structures in the all-sky maps in **continuum emission**

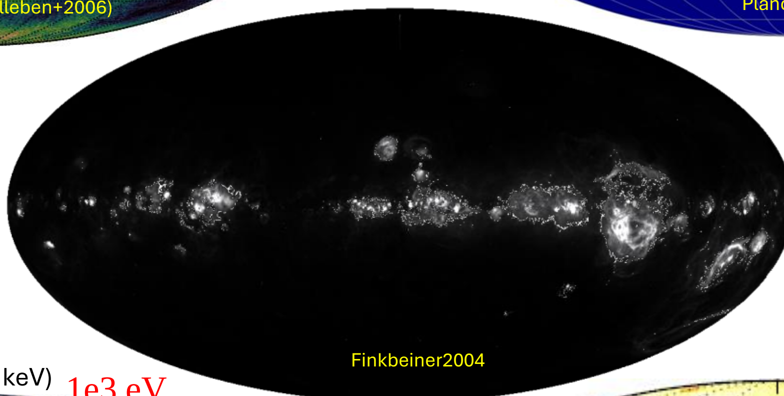
Radio sky (1.4GHz) 1e-5 eV



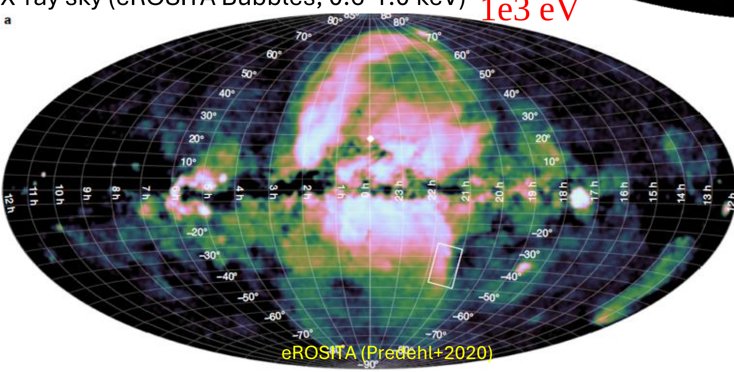
Dust sky (353 GHz) 1e-3 eV



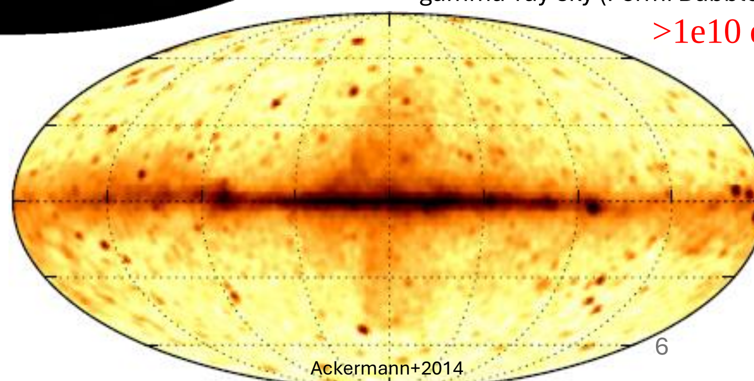
H-alpha sky (457THz) 1.9 eV



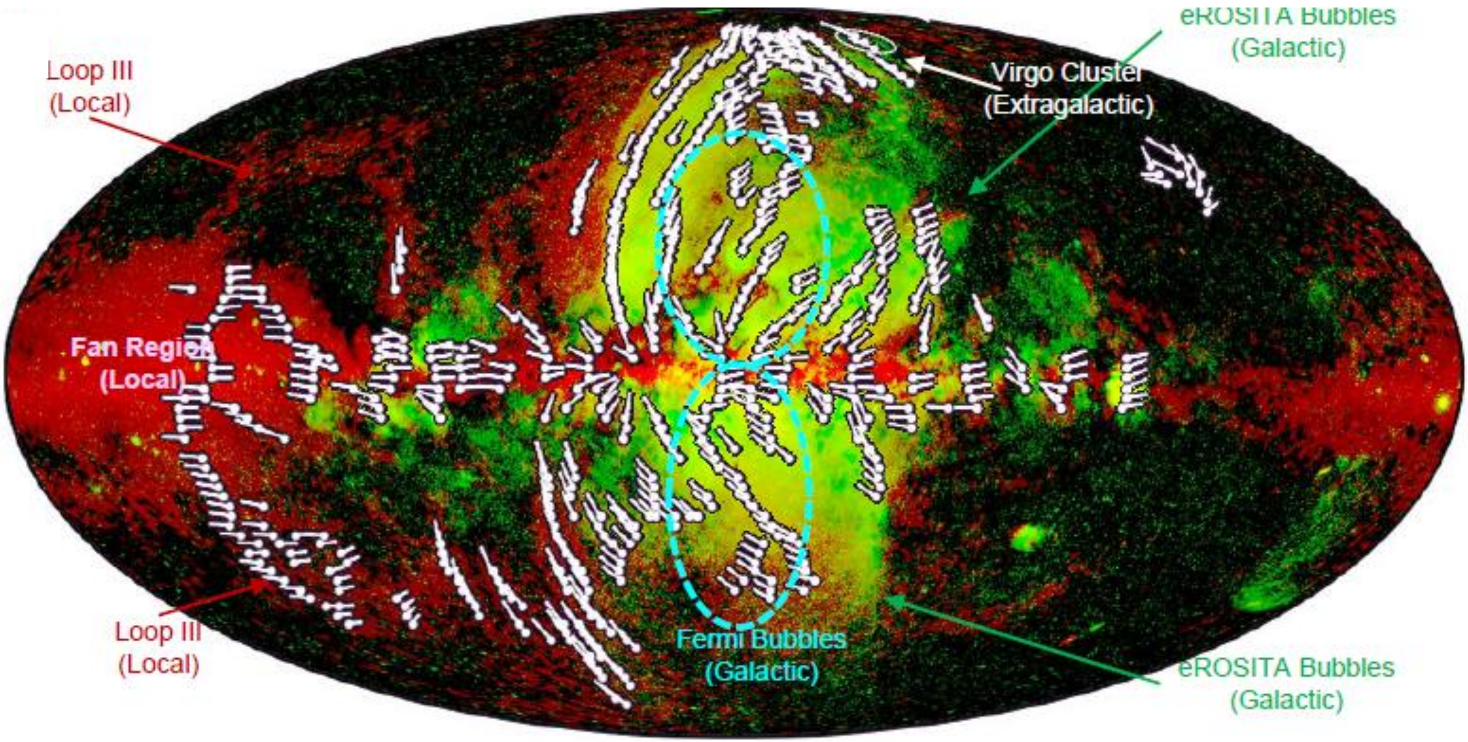
X-ray sky (eROSITA Bubbles, 0.6-1.0 keV) 1e3 eV



gamma-ray sky (Fermi Bubbles) >1e10 eV



2. The Multi-wavelength Large structures



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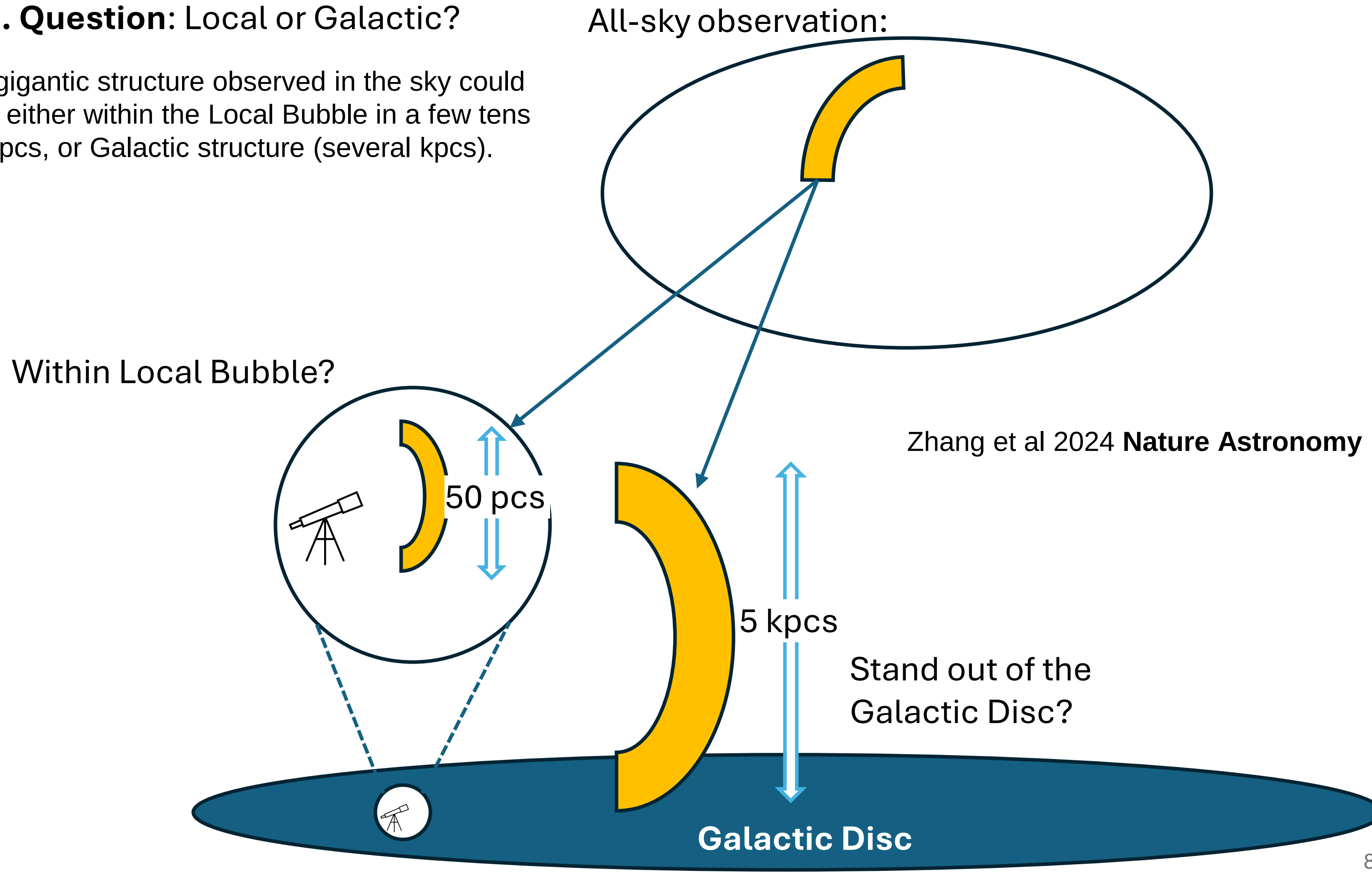
White bars: magnetic field (23 GHz)
Green: 0.6-1.0 keV X-ray

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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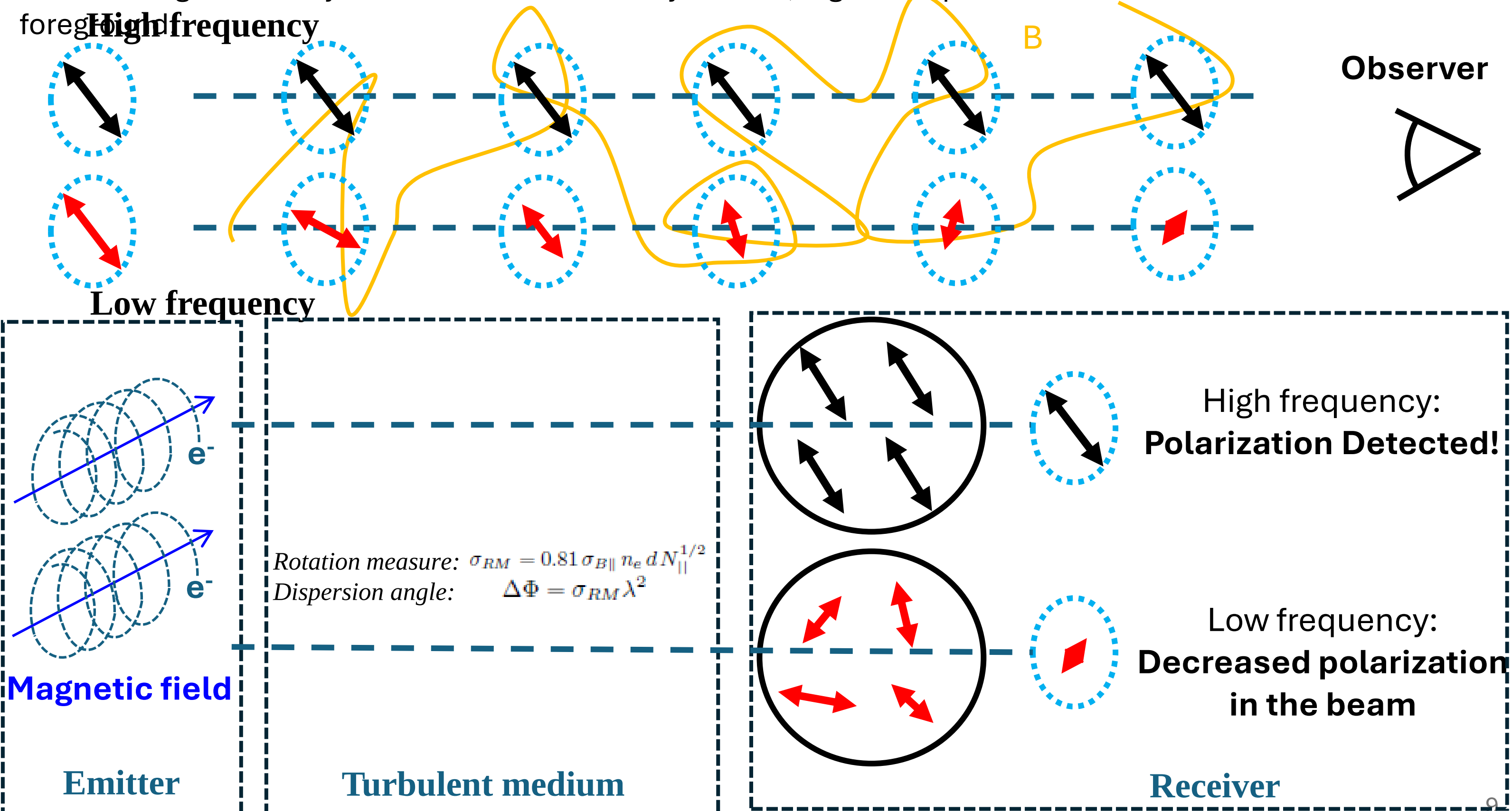
3. Question: Local or Galactic?

Faraday Rotation Depolarization

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



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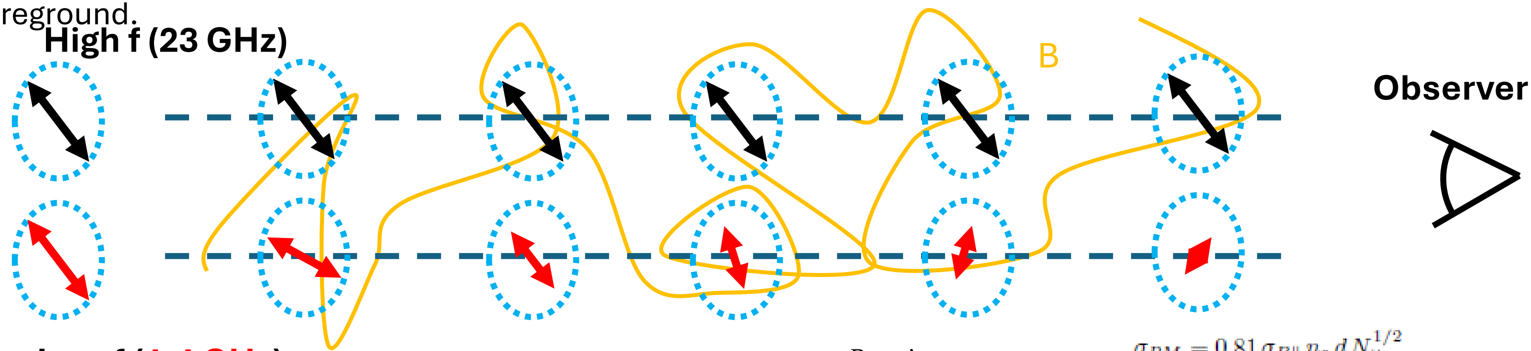
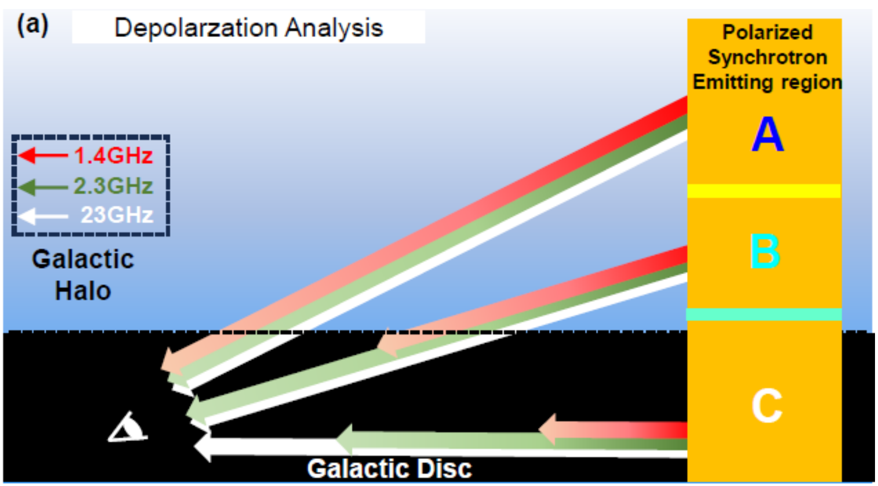


$$f_{\text{depol}} = \frac{1 - \exp(-S)}{S}, \; S \equiv 2\sigma^2_{\text{RM}}\lambda^4$$ [Burn66, Sokoloff98]

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

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

LOS Integrations: $\sigma^2_{\text{RM}} = \int_L^O (0.81 B_{\|}(l,b,L))^2 \, d\, n_e^2(l,b,L)\delta\mathbf{L}$



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Ne: YMW16, Locatelli+24
B: Sun+10, JF12, JF12_Planck (Planck2018XLII)

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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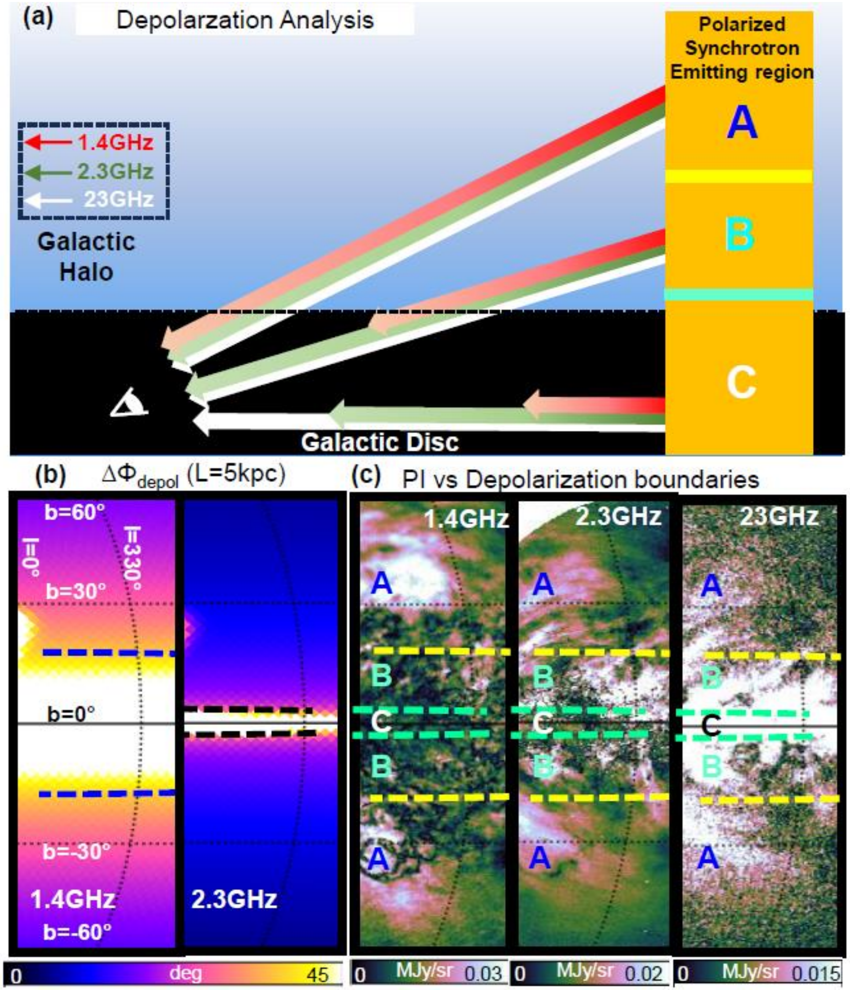


Distance measurements with Faraday Rotation Depolarization

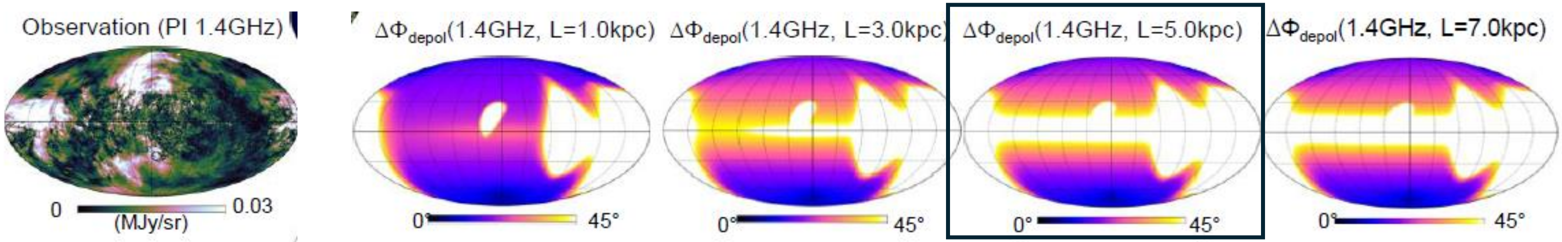
Lower frequency signal

More disc imprint

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

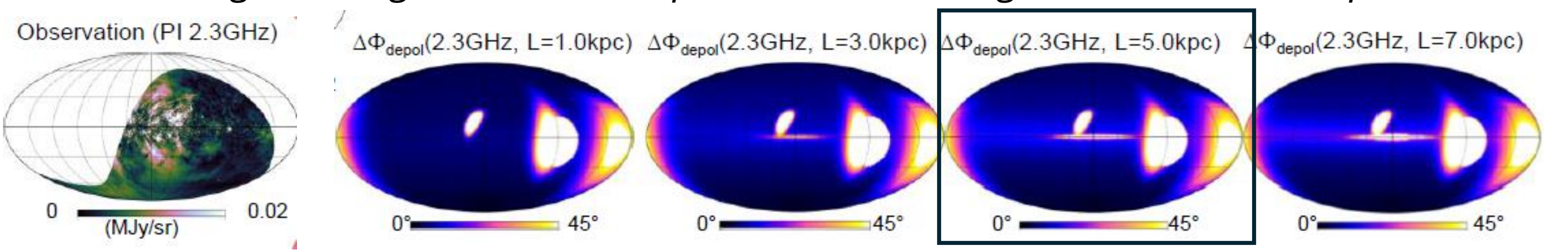
3. Question: Local or Galactic?

Depolarization screen at different distances



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

<u>These magnetic ridges are several kpc scales stemming out of the Galactic plane</u>.



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3. Question: Local or Galactic?

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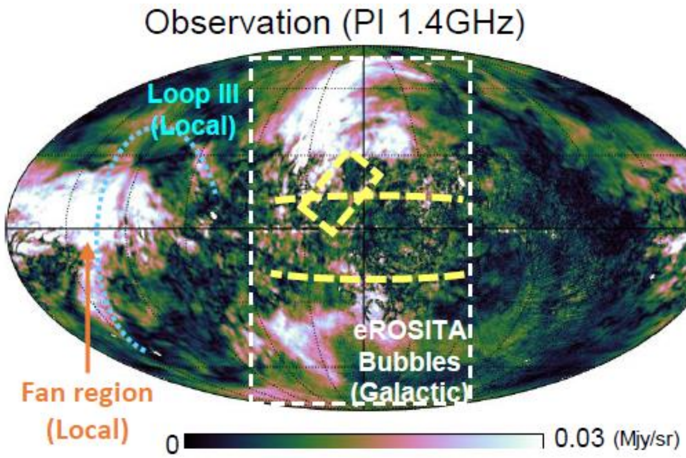
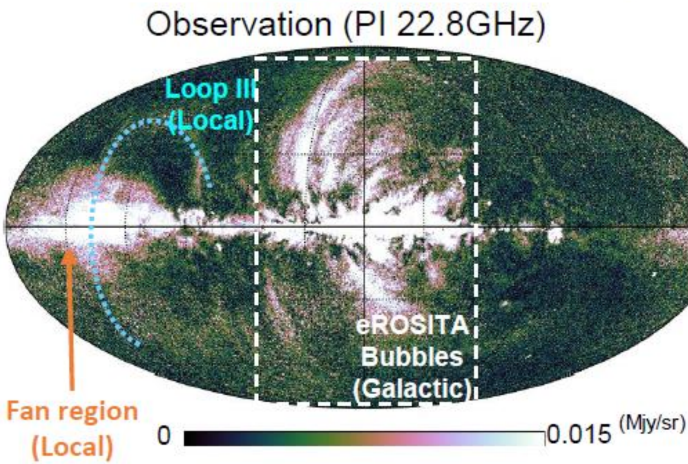
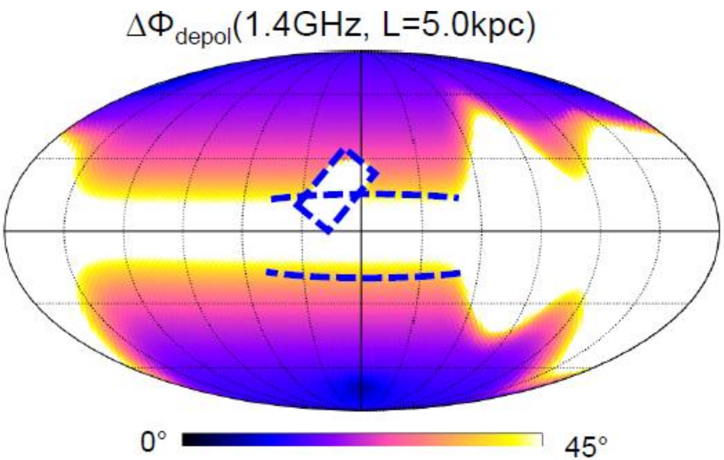




Faraday Rotation depolarization screen

Local: in front of the screen

Galactic: behind the screen



3. Question: Local or Galactic?

Answer: Galactic X-ray halo

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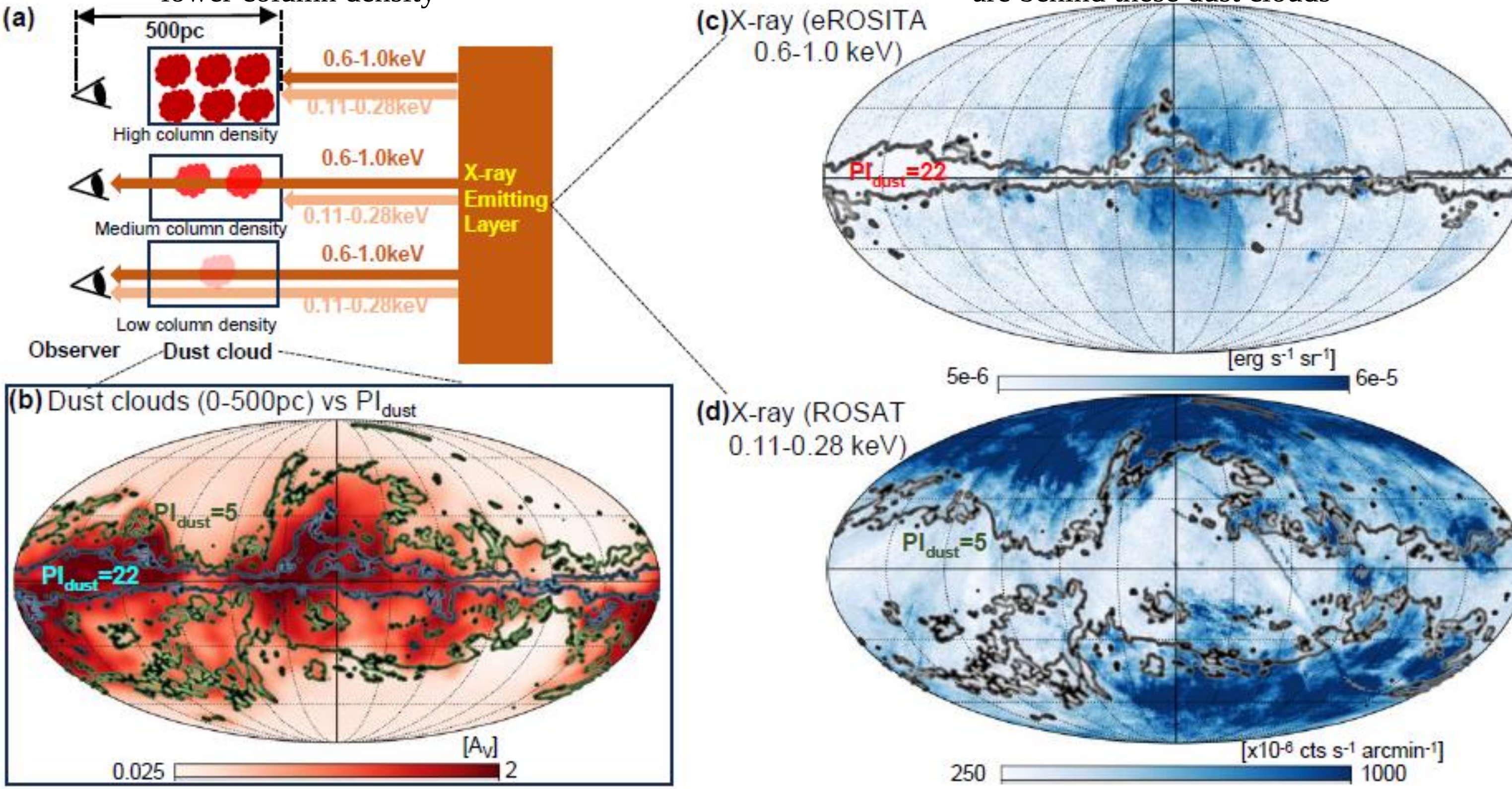
(a): Soft X-ray absorbed by dust with lower column density

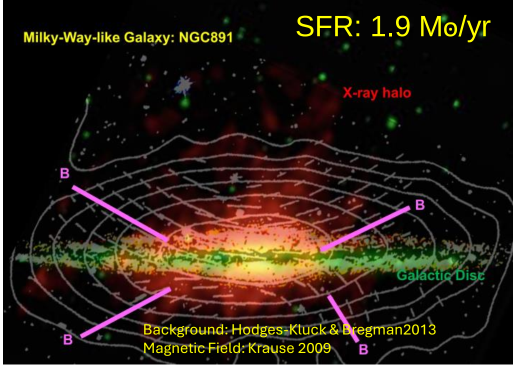
(c,d): these X-ray emitting structures are behind these dust clouds



(b): Polarized dust emissions are mainly from local dust in the Galactic disc

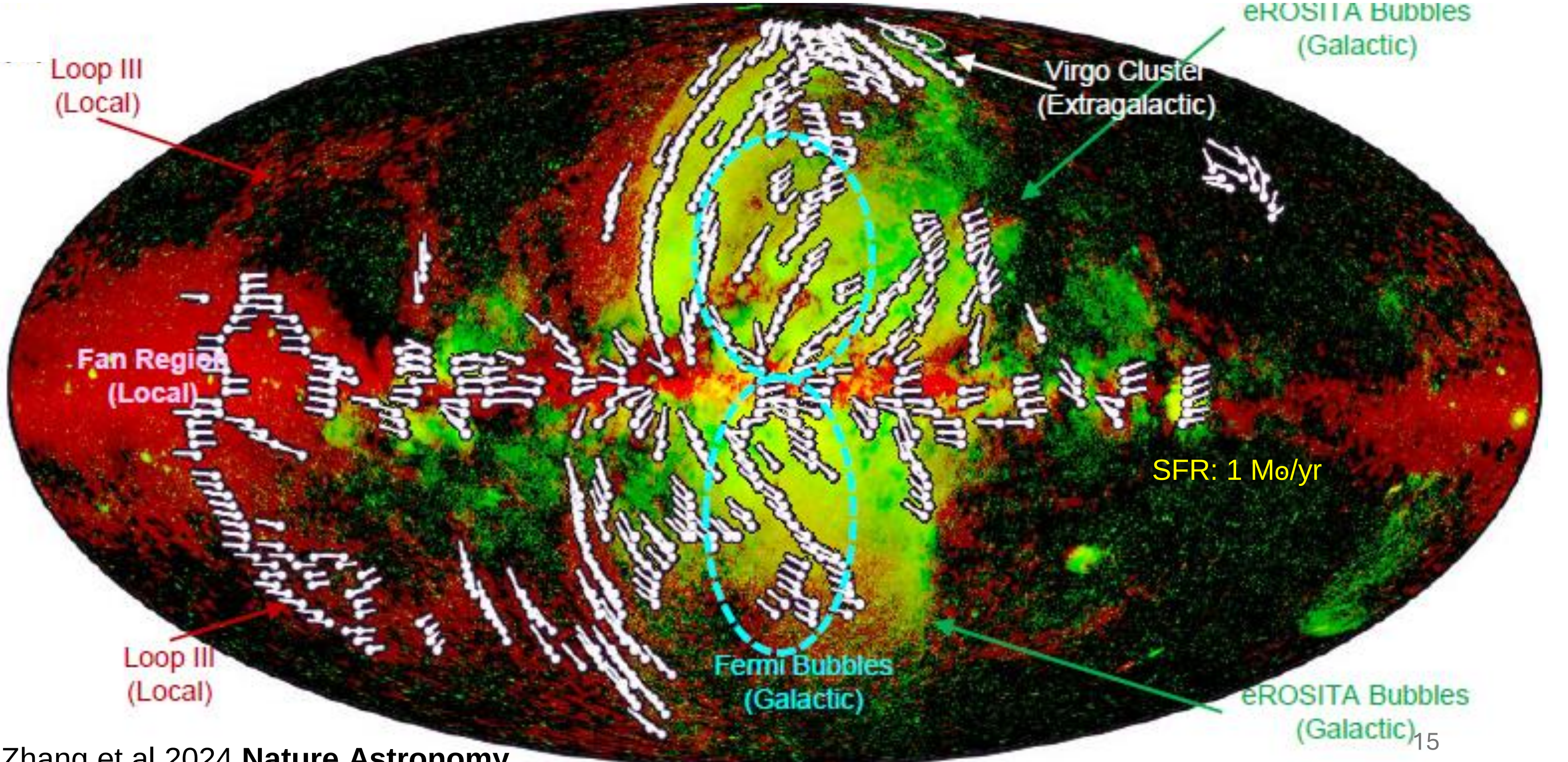
The bulk of the X-ray emission eROSITA Bubbles - out of the Galactic plane!

Magnetic and X-ray emitting galactic halo: The Milky Way vs other galaxies



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

The Milky Way



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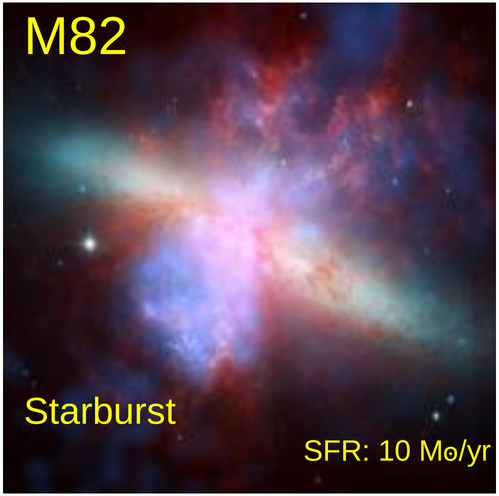
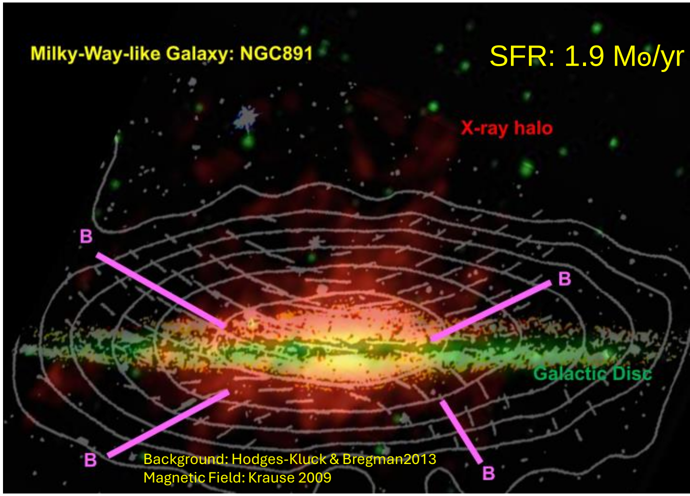
Magnetized halo from other galaxies





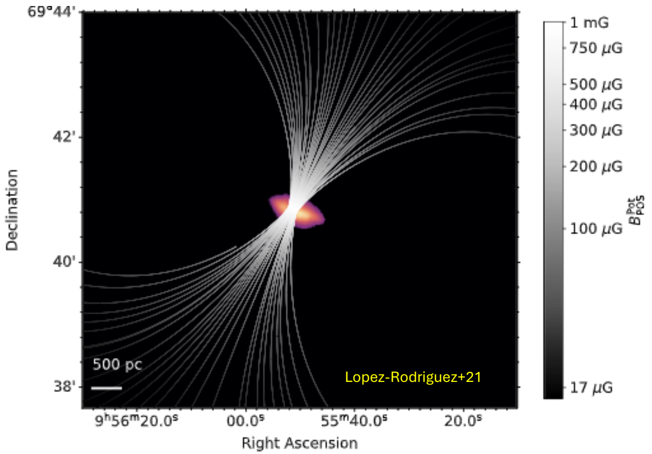
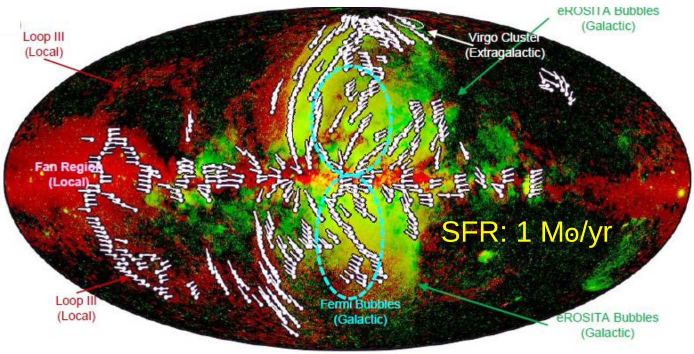


Figure 6. Potential magnetic field lines of M82 inferred using the 53 μm polarimetric observations with HAWC+/SOFIA. The potential magnetic field is calculated by extrapolation of the magnetic field at the galaxy's plane. Magnetic field lines are visualized in a field of view (FOV) $\sim$7.2 kpc^2 centered at M82. The potential field strength is larger in the bulk of the galaxy in good agreement with the 2D map of M82 in Figure 4.



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4. Gamma-ray counterpart of the magnetic halo

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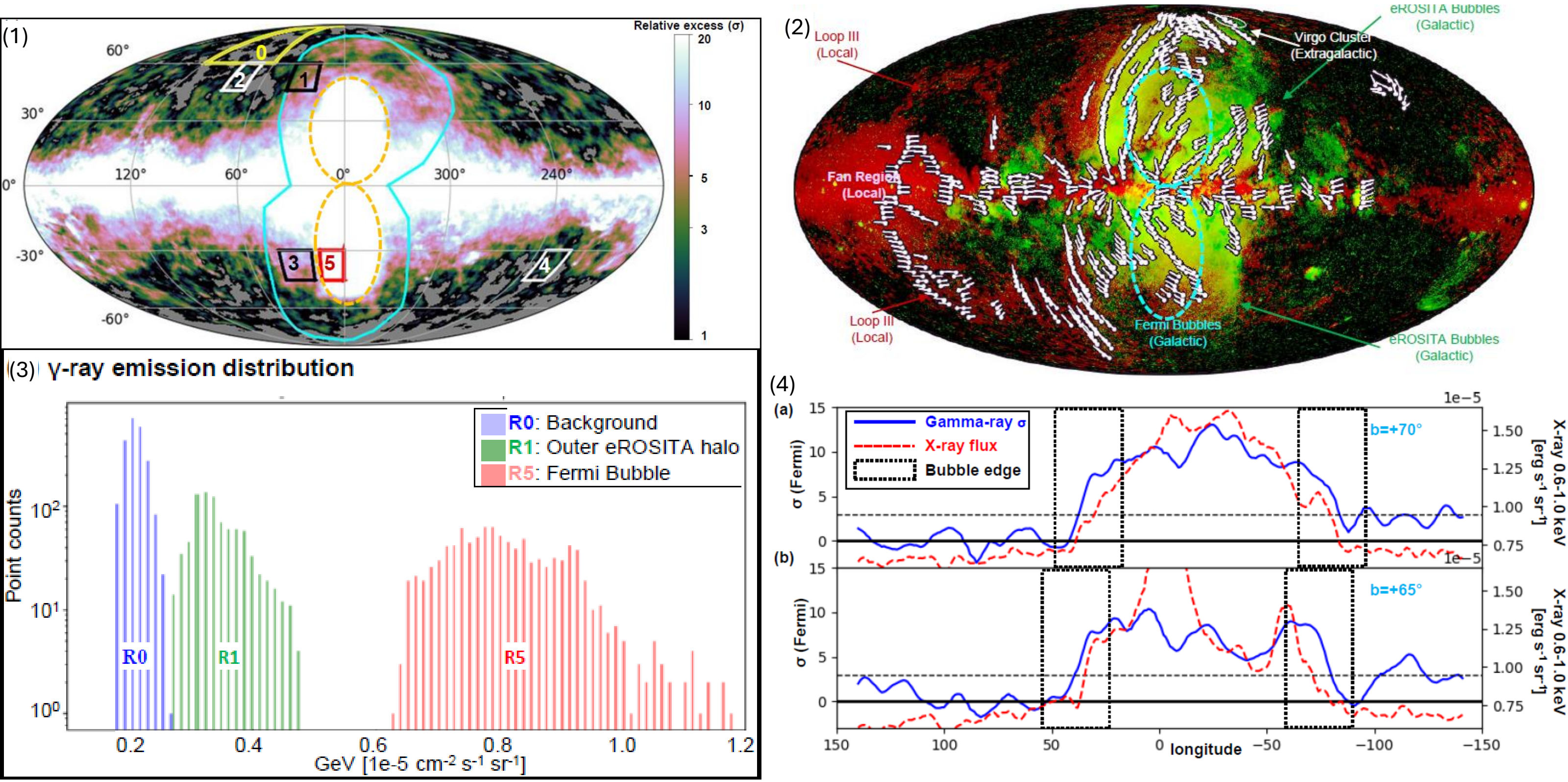

A gamma-diffuse halo (see 1, data from Scheel-Platz+23), with magnetic ridges enhanced at the edges (see 2), independent of the background or Fermi Bubbles (see 3), and similar morphology to the eROSITA Bubbles (see 4)

4. Gamma-ray counterpart of the magnetic halo

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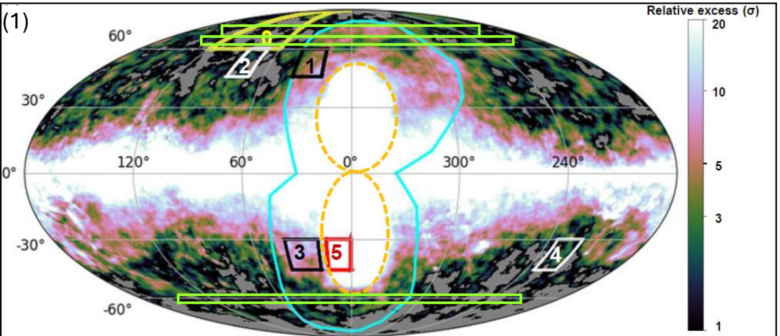
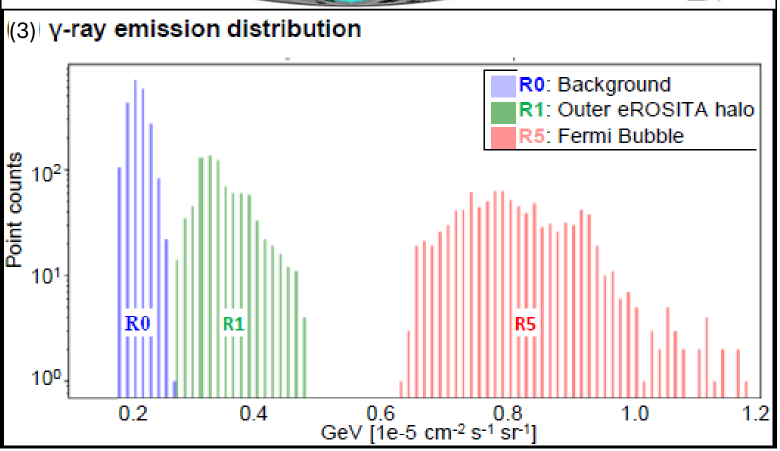
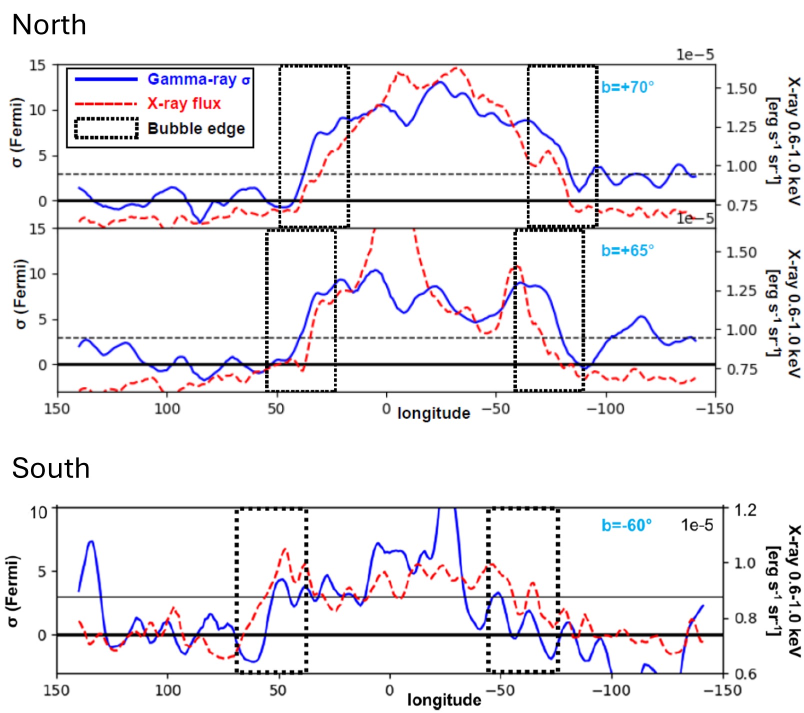




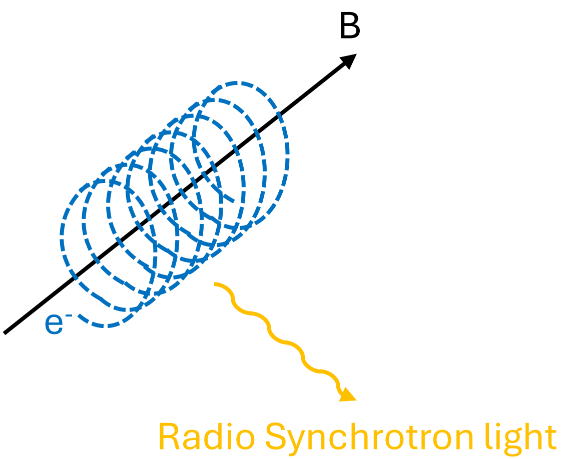


The outer gamma-diffuse halo is independent of the background or Fermi Bubbles (see 3), and similar morphology to the eROSITA Bubbles (see right)

Magnetic field strength diagnostic from multi-messenger approach

- Synchrotron:

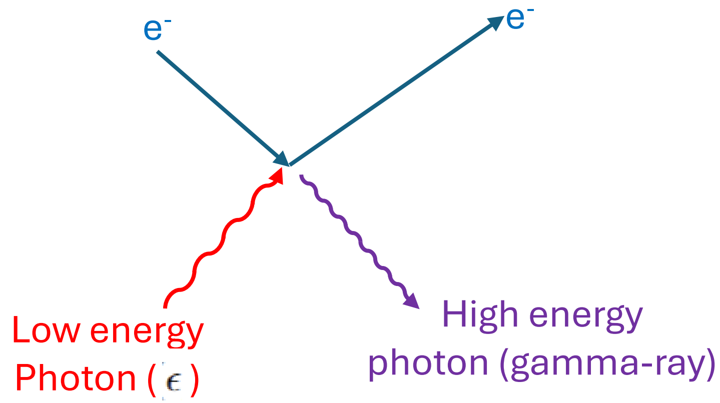
  Relativistic electrons radiate when gyrating around the magnetic field



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

- Inverse Compton (IC):

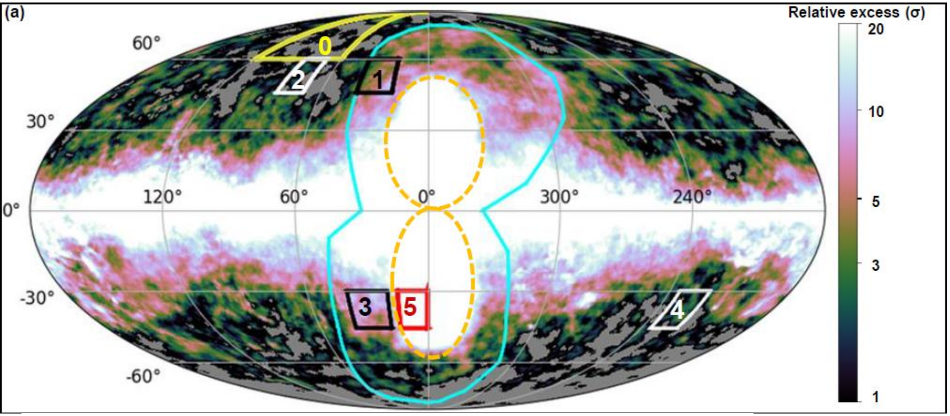
  Relativistic electrons scatters low energy photons to gamma-ray



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

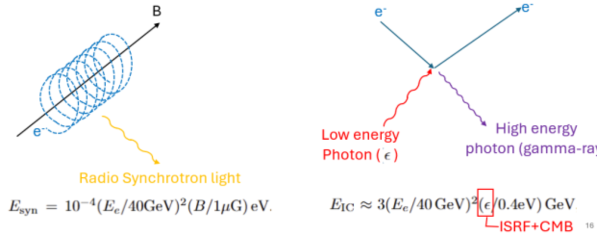
ISRF+CMB

5. Magnetic field strength measurements



Magnetic field strength diagnostic from multi-messenger approach

- Synchrotron: Relativistic electrons radiate when gyrating around the magnetic field
- Inverse Compton (IC): Relativistic electrons scatters low energy photons to gamma-ray



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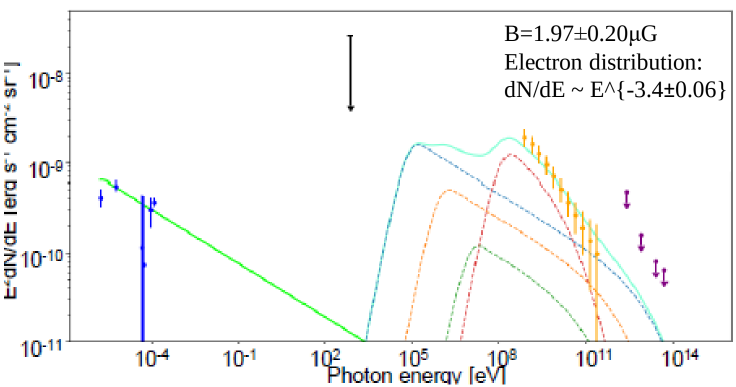
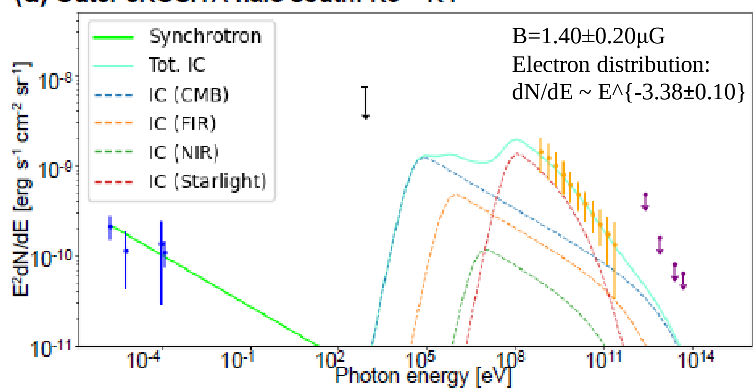
(c) Outer eROSITA halo north: R1 – R2



(d) Outer eROSITA halo south: R3 – R4



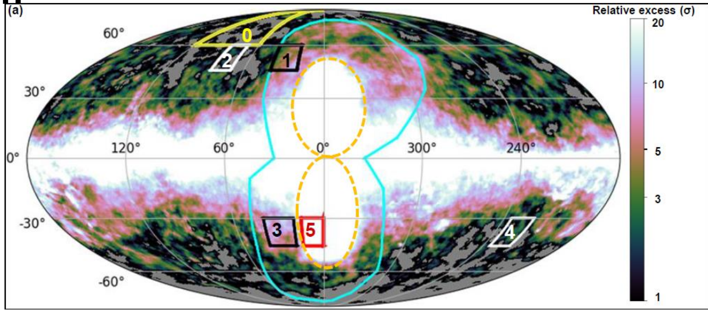
North-South non-thermal symmetry:

1) **similar magnetic field strength,**
2) **symmetric magnetic direction to the Galactic disc,**
3) **similar electron index,**
4) **plasma-beta around 10**!

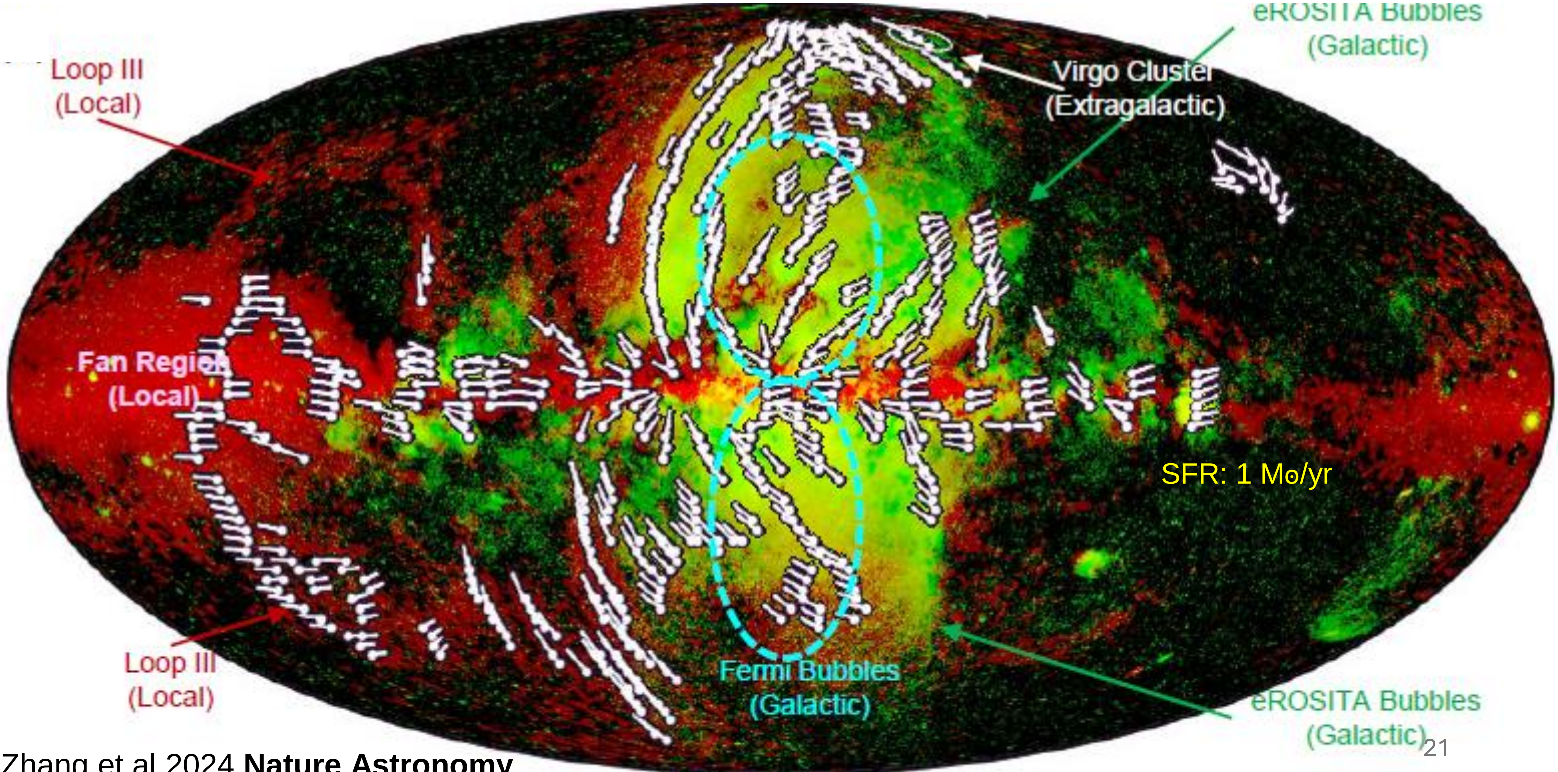
6. Magnetic and X-ray emitting galactic halo: Origin

(**Fermi Bubbles** related)
Inner ridges → GC

(**eROSITA Bubbles** related)
Outer ridges → ~30° away from GC in the disc



The Milky Way



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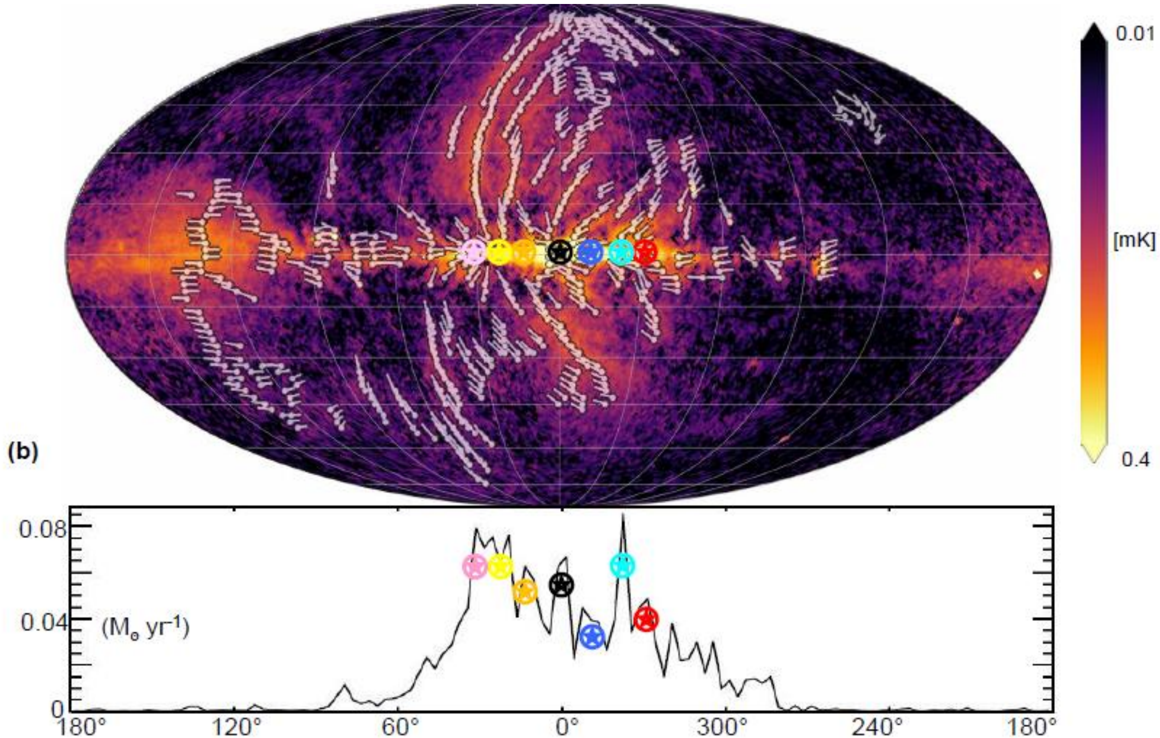
6. Magnetic and X-ray emitting galactic halo: Origin

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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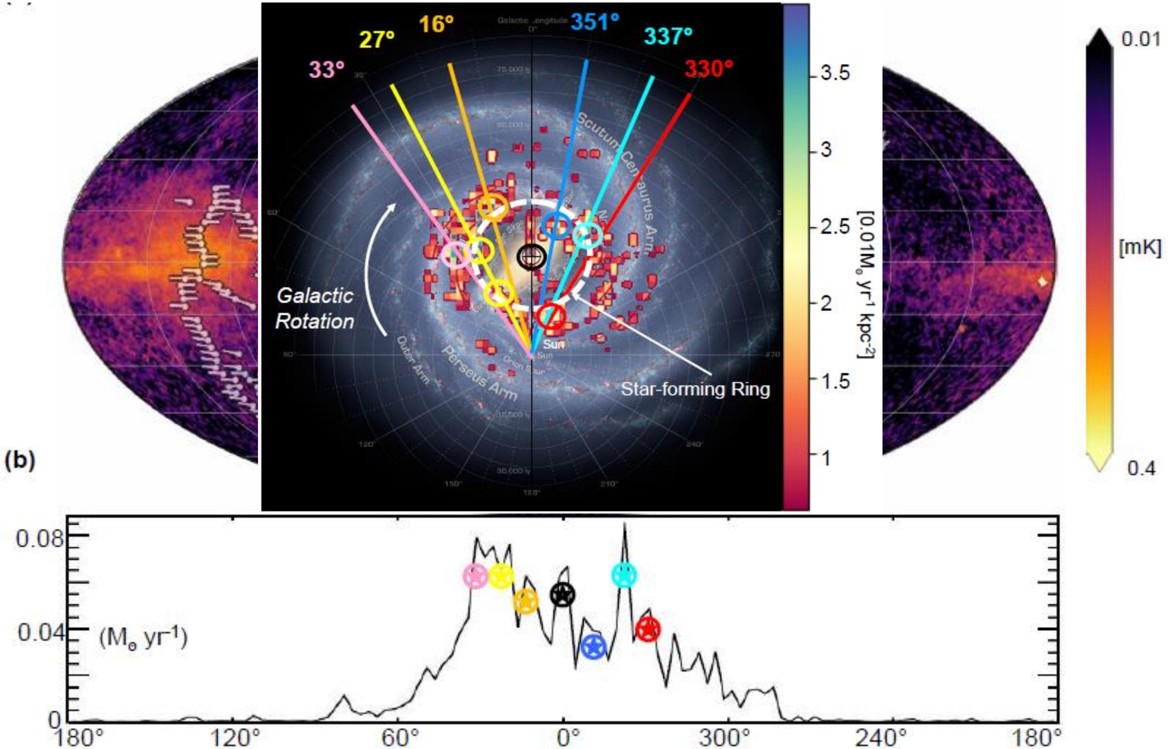
6. Magnetic and X-ray emitting galactic halo: Origin

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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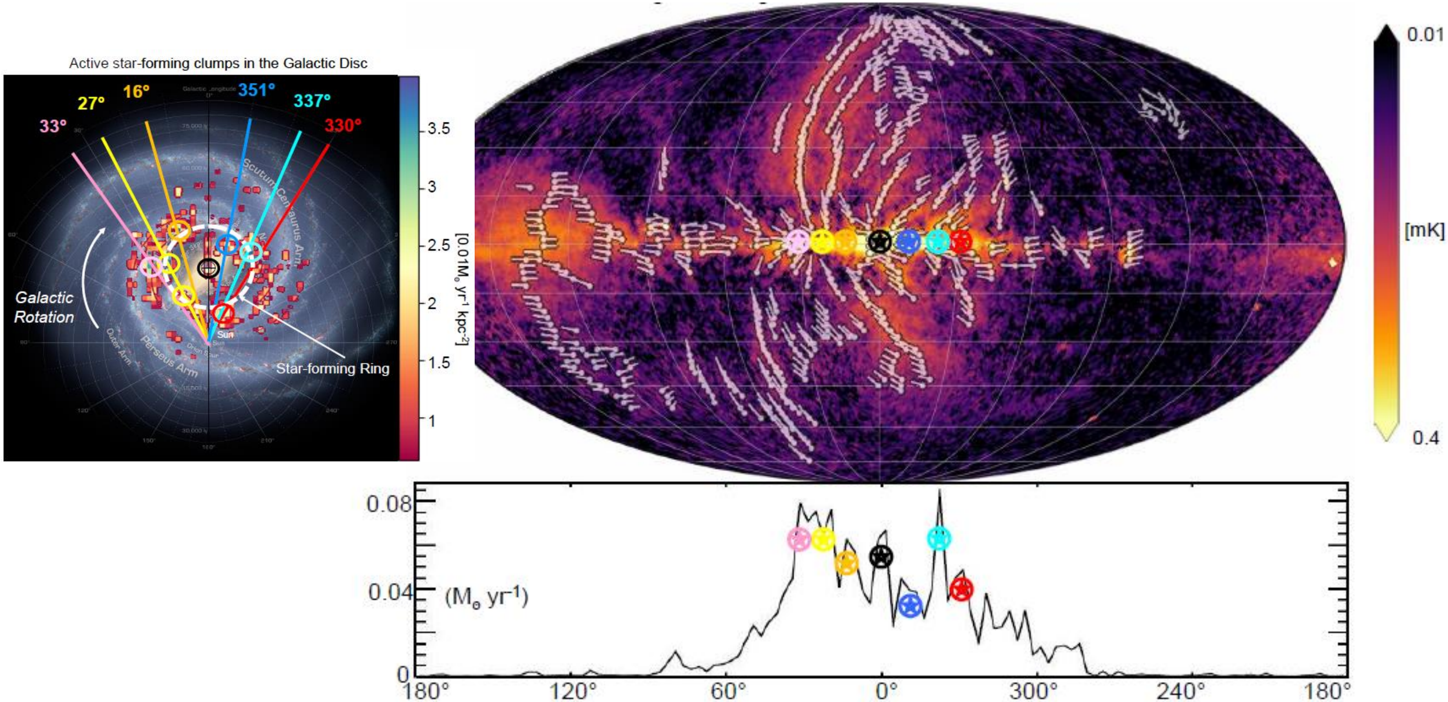
6. Magnetic and X-ray emitting galactic halo: Origin

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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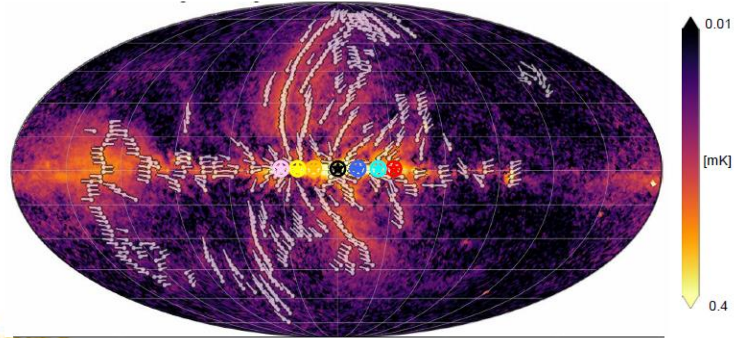
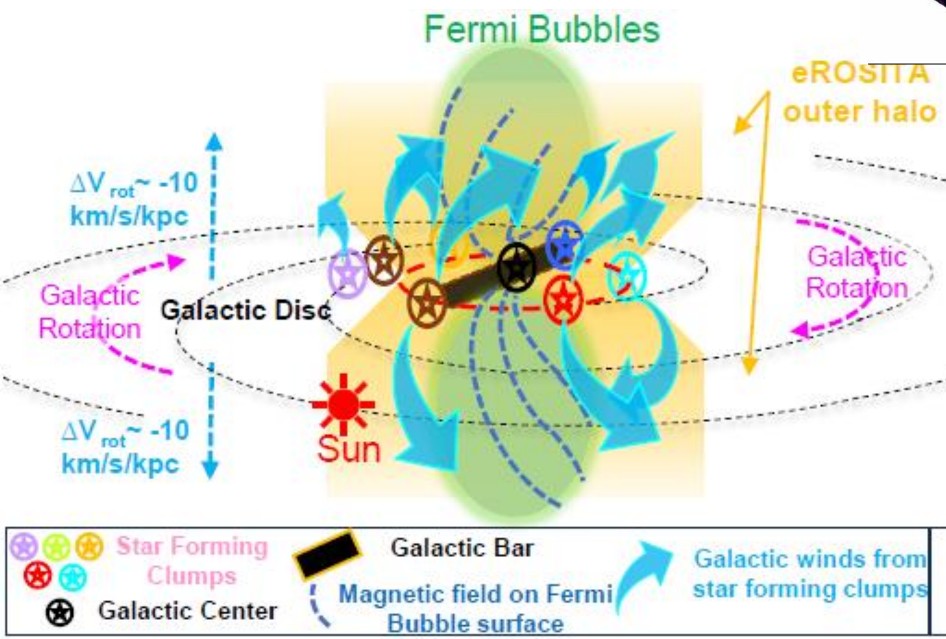
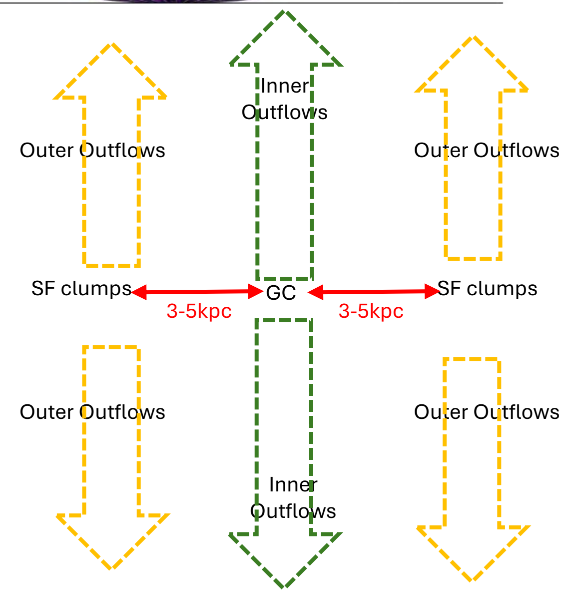
7. Magnetic halo and Galactic Outflows







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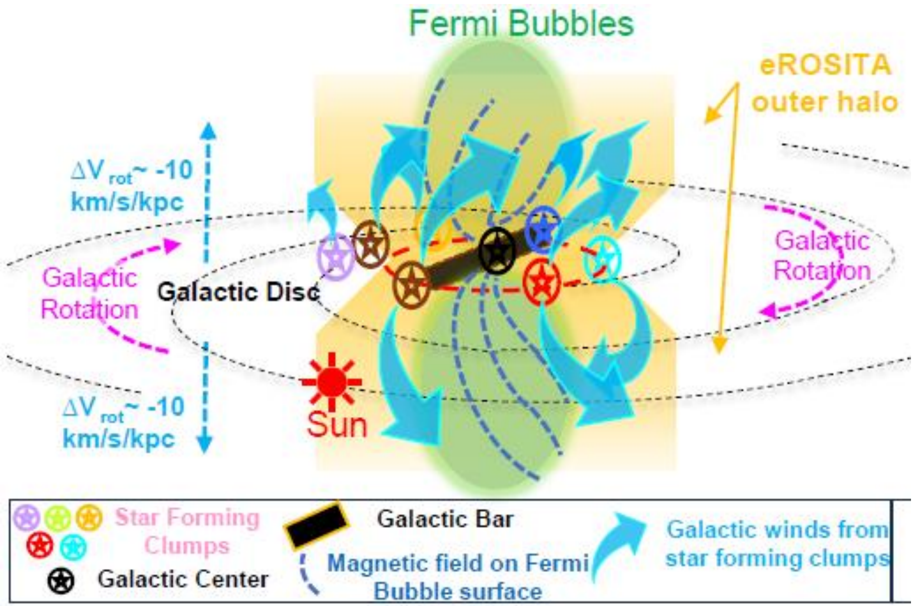
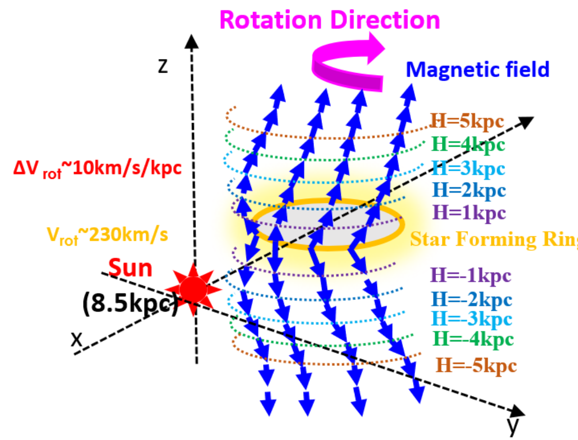
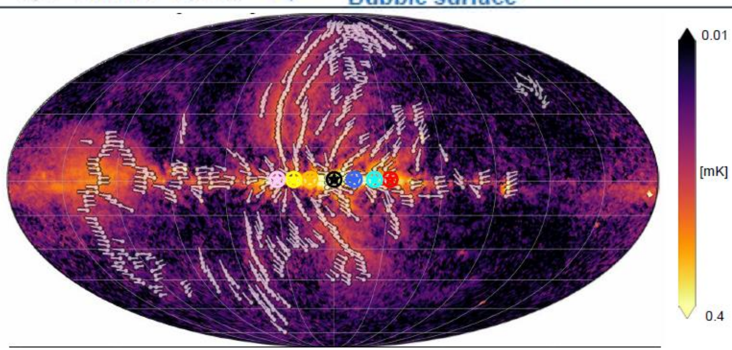
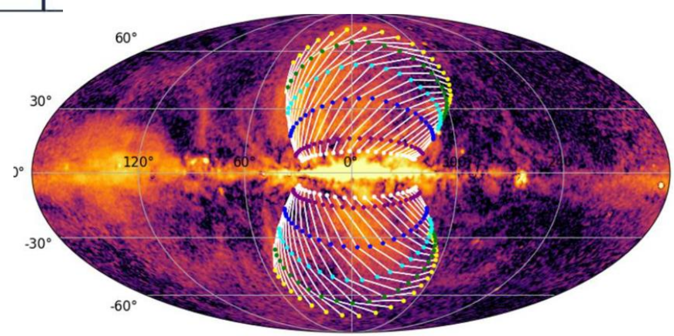
7. Magnetic halo and Galactic Outflows









Magnetic field lines in the halo trace the Galactic outflows!

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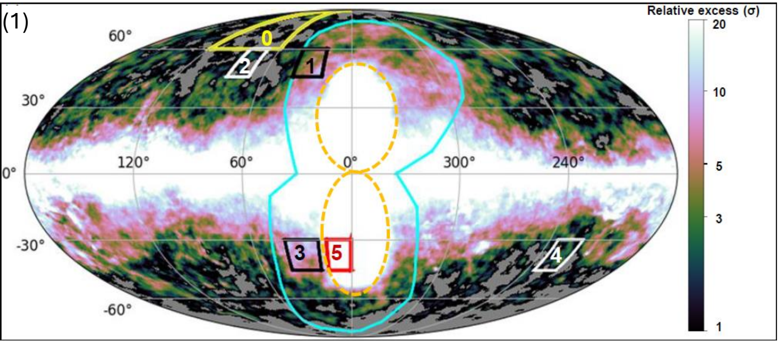
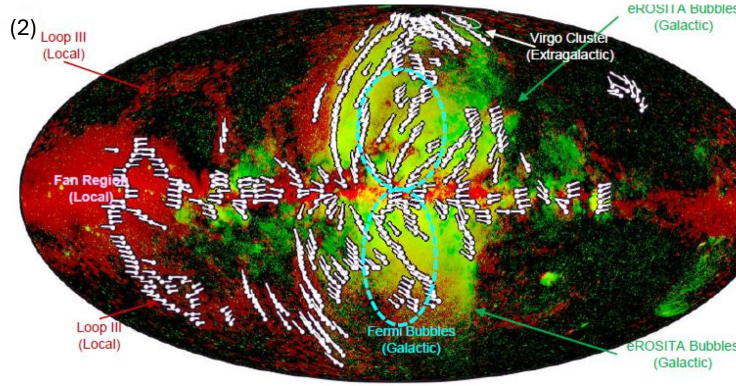
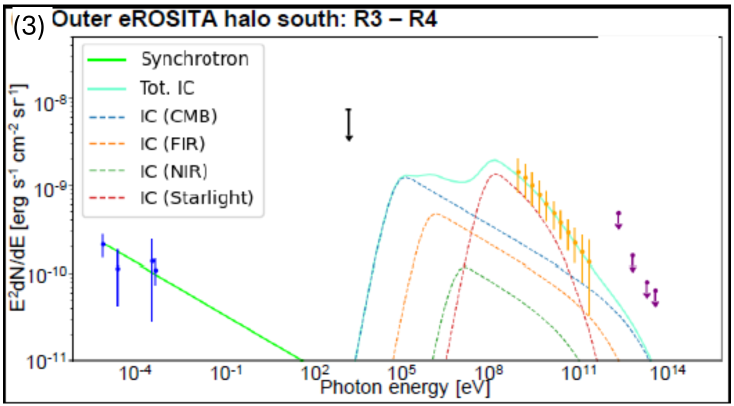
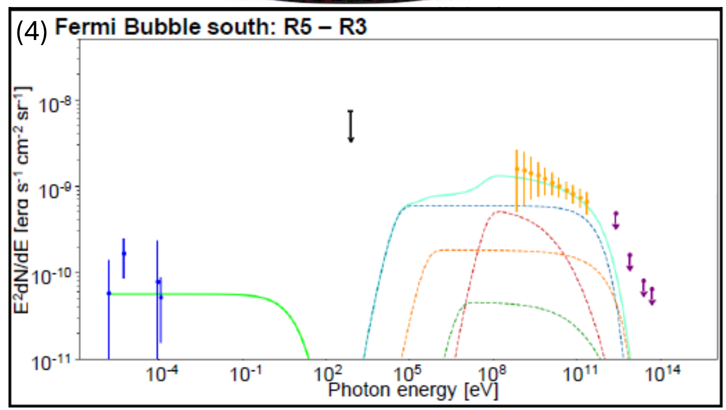
7. Magnetic halo and Galactic Outflows

SED for the Inner and Outer outflows of the Milky Way









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)**.

The very soft index in the outer outflows indicates that **the gamma-ray extended outer halo is unlikely to be hadronic origin**!

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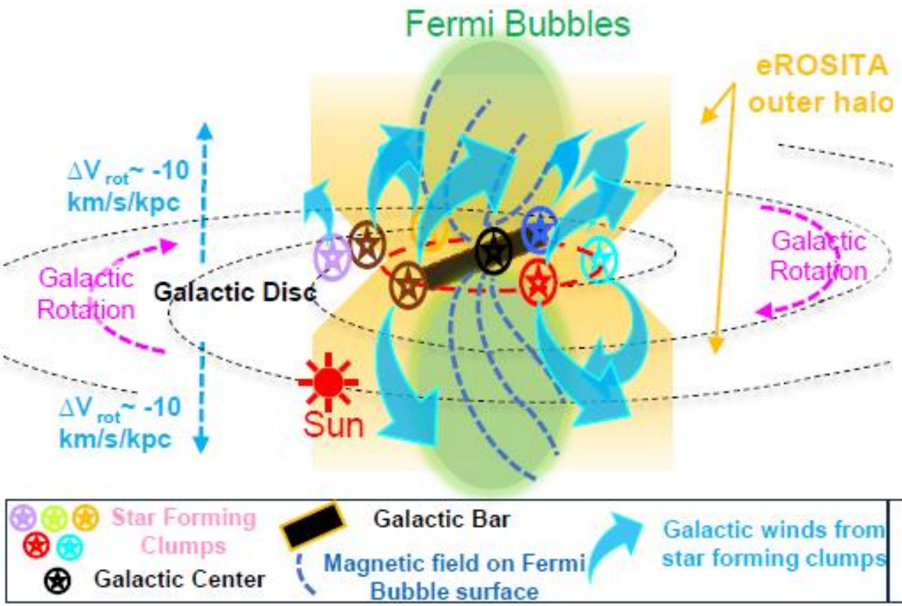
7. Magnetic halo and Galactic Outflows



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} [$\times10^{55}$ erg]	5.9		10		14	
E_B [$\times10^{55}$ erg]	1.5		3.3		5.3	
E_{tot} [$\times10^{55}$ erg]	8.6		15		21	
$\dot{E}_{inj}$ [$\times10^{40}$ 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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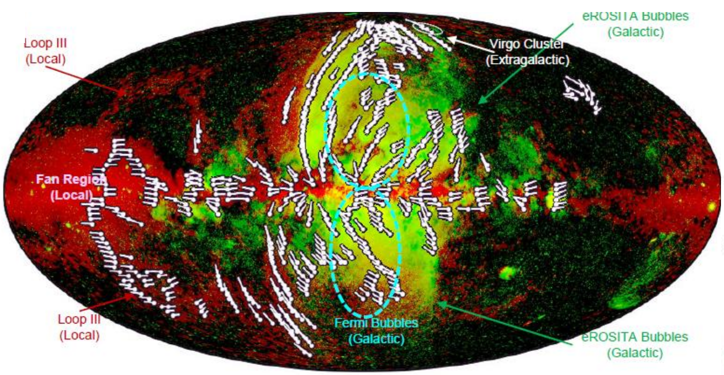
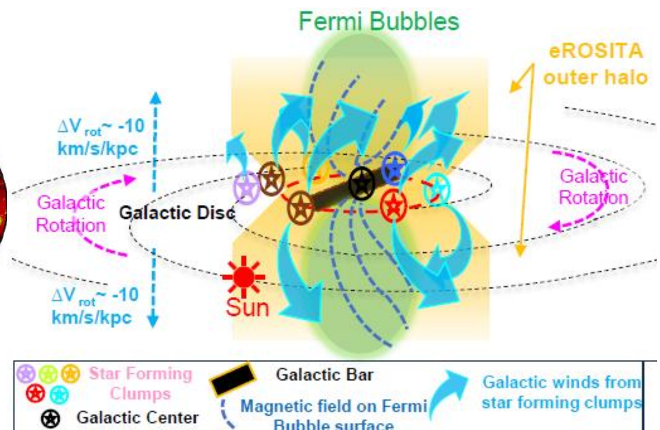
A few remarks

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 X-ray eROSITA Bubbles are hot plasma in the Galactic halo standing kpc scales above and below the Galactic disc, showing non-thermal emitting in radio (by synchrotron) and gamma-ray (by Inverse Compton) counterparts.
3. The coherent and highly anisotropic magnetic fields are identified in the Galactic halo, tracing the Galactic outflows.
4. Stellar feedback plays important role in the Galaxy feedback.

Further Questions in next slides!





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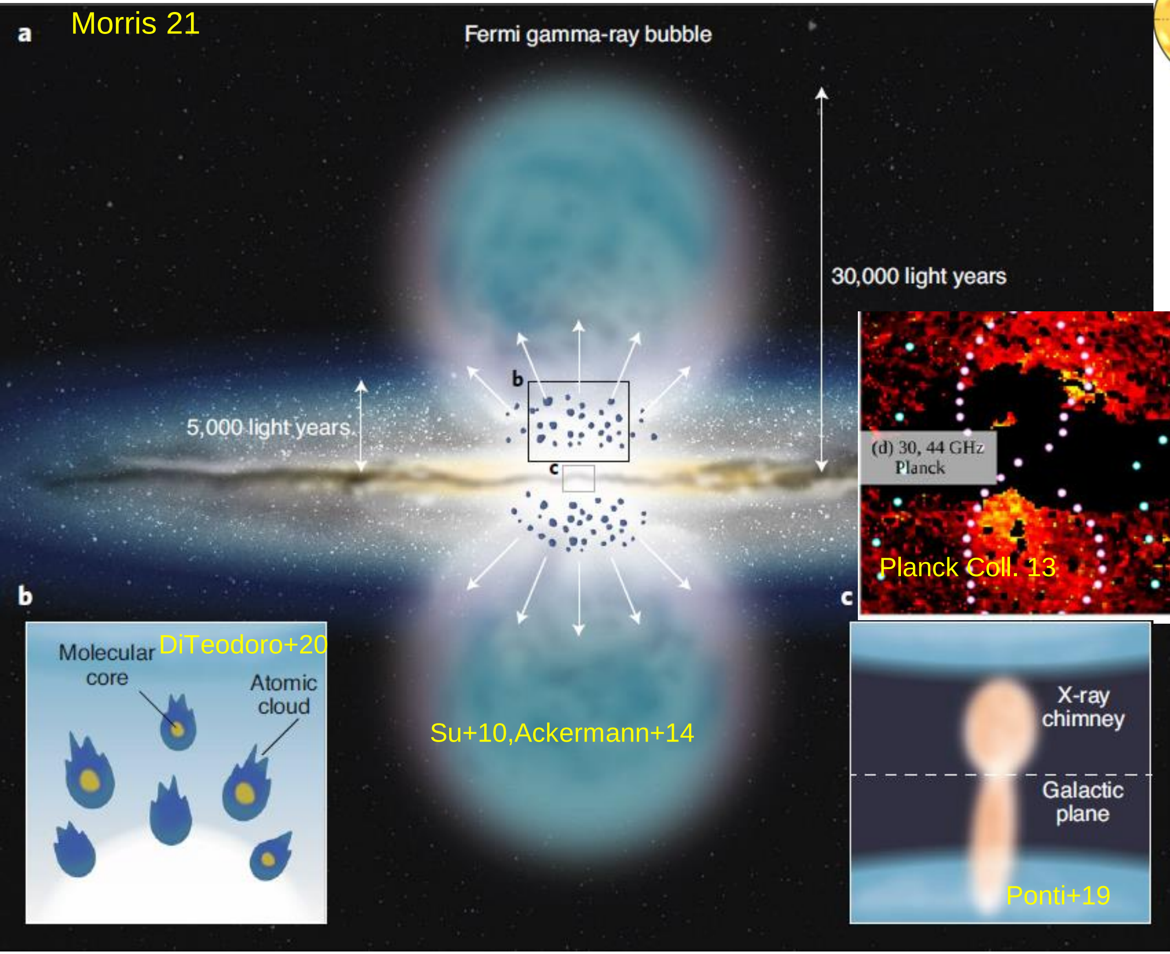
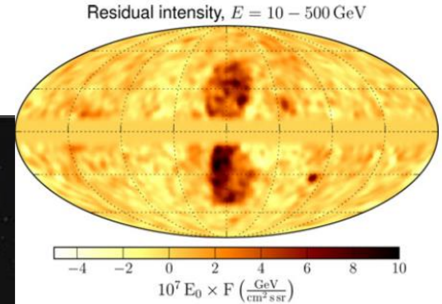
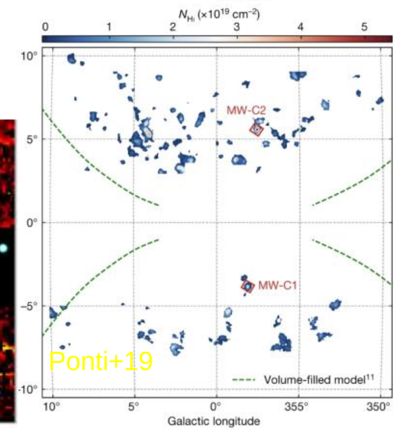
https://ui.adsabs.harvard.edu/abs/2024NatAs...8.1416Z/abstract

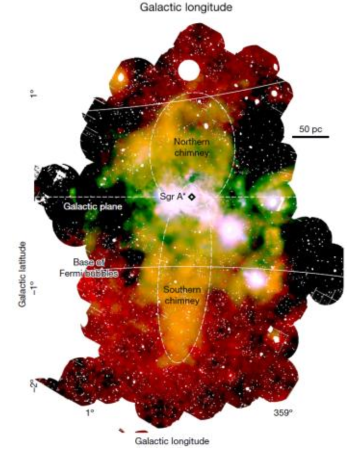
8. Some questions related to the eROSITA Bubbles

Elephant in the room: ***<u>Fermi Bubbles</u>***?





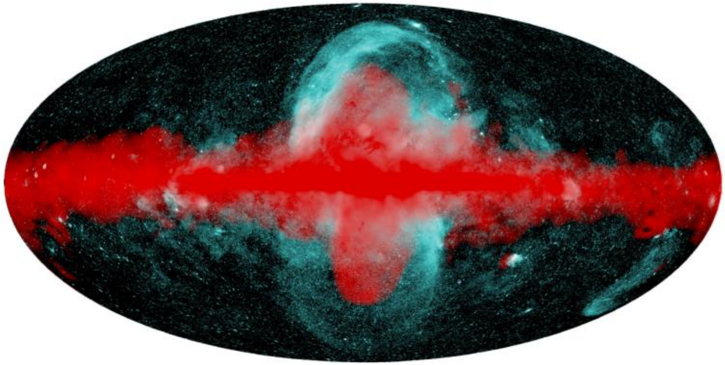


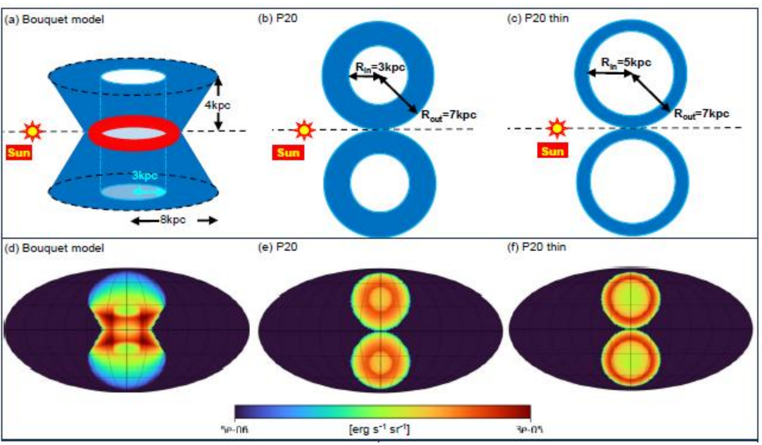


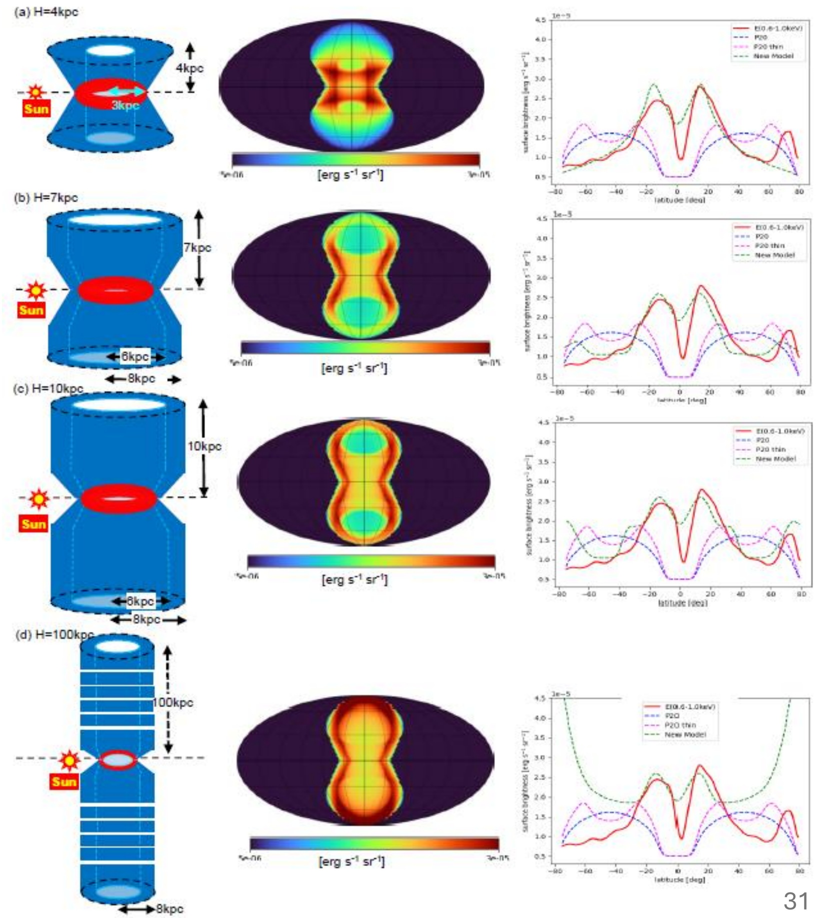
8. Some questions related to the eROSITA Bubbles

Are the eROSITA Bubbles really **Bubbles**?

No necessarily!







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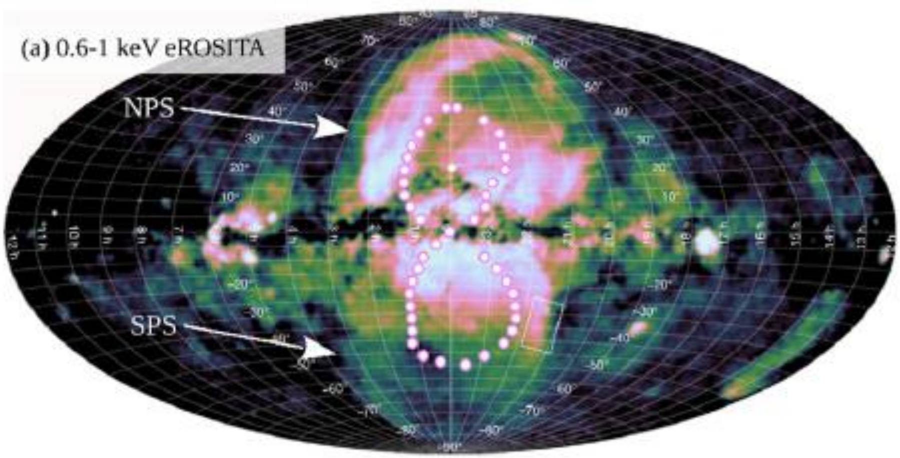
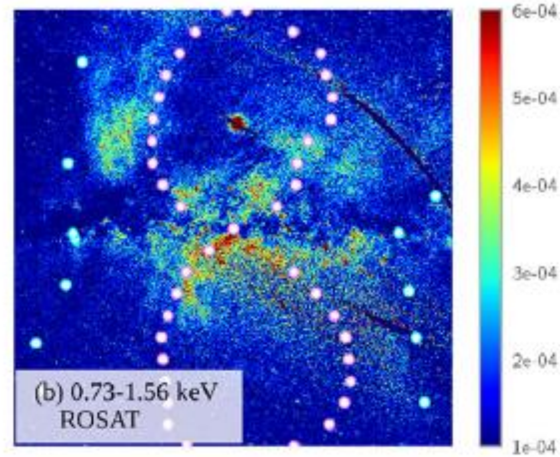
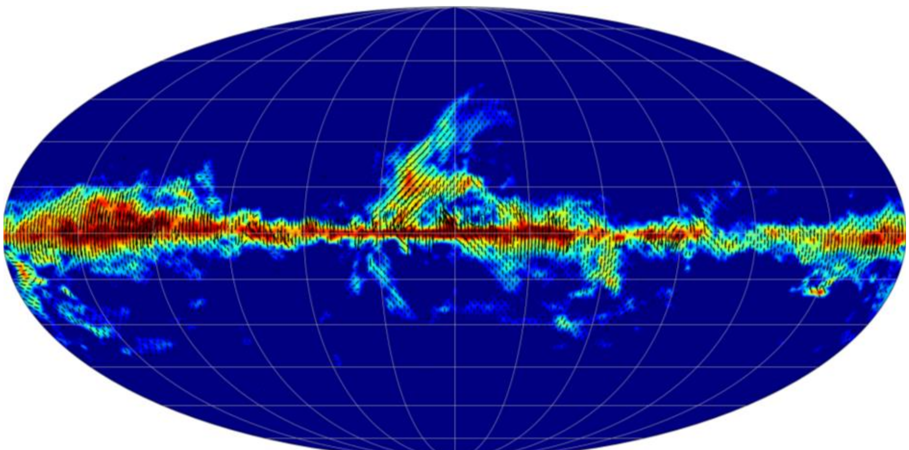
Ask me why eROSITA Bubbles caps over the Fermi Bubbles?

8. Some questions related to the eROSITA Bubbles

NPS caps over Fermi Bubbles indicates a shock front?



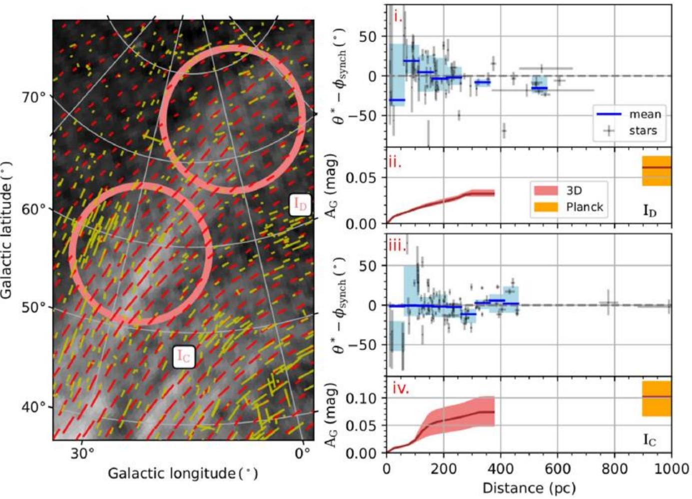




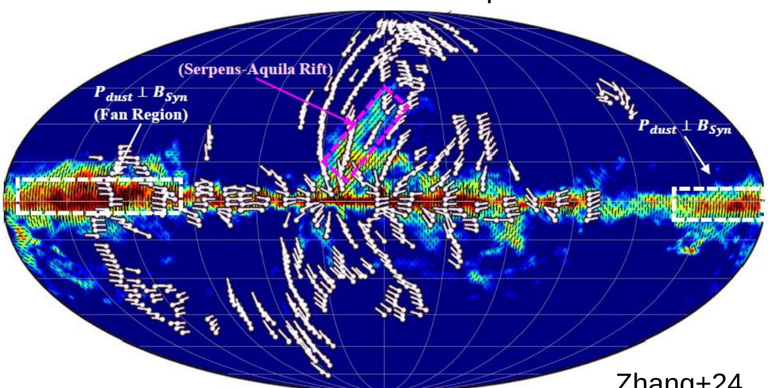
Not necessary! Because the enhancement in the upper cap can result from dust absorption!

8. Some questions related to the eROSITA Bubbles

Local Contribution from the cap of the North Polar Spur



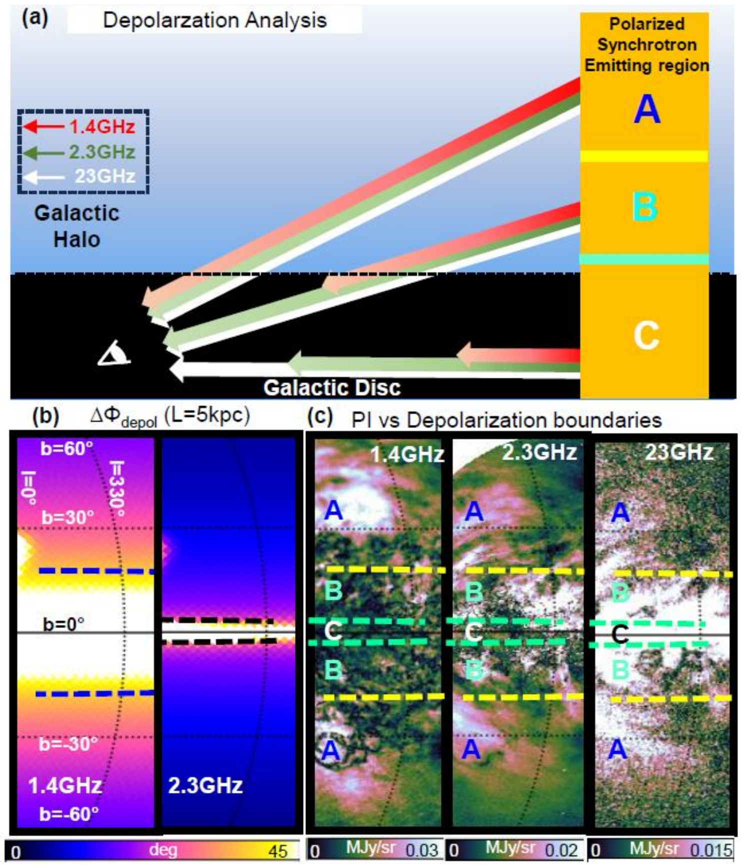
Panopoulou+21



Zhang+24

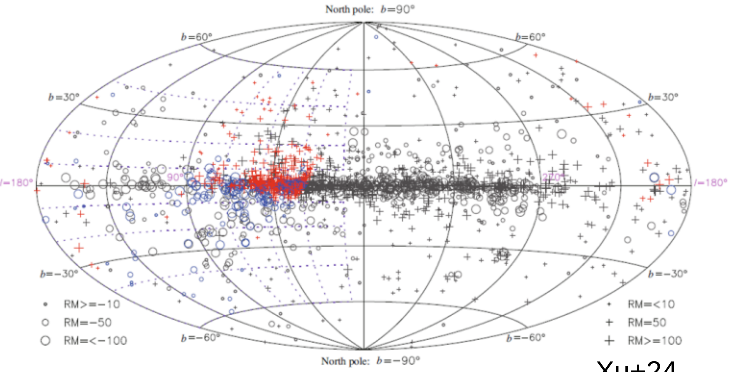
There are dust E-vectors with lower polarization intensity that are parallel to the vicinity of the cap of eROSITA Bubbles.

Doesn't influence our conclusion that the bulk of ***the polarized ridges and the X-ray emitting eROSITA Bubbles are several-kpc scale Galactic*** *structures!*

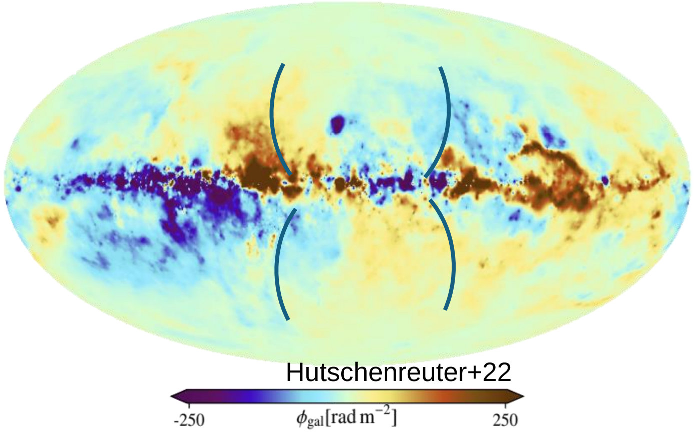


Other magnetic halo measurements

Faraday rotation measured halo

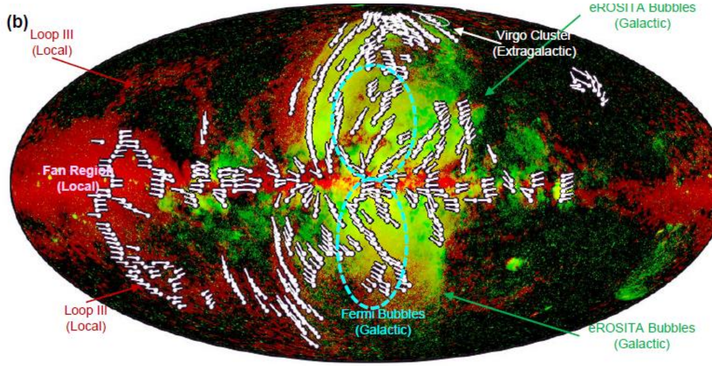


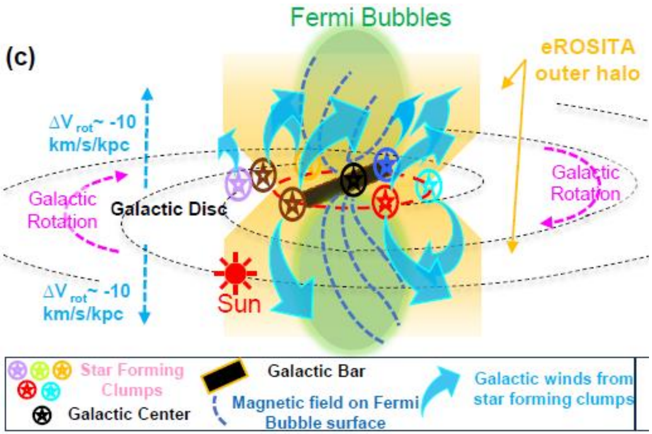
Xu+24



Hutschenreuter+22

Galactic outflow related halo





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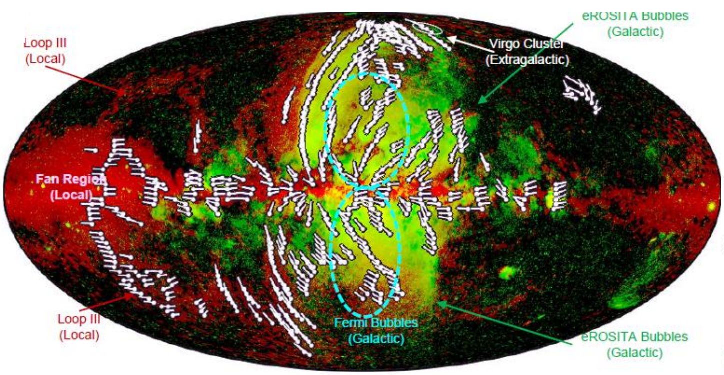
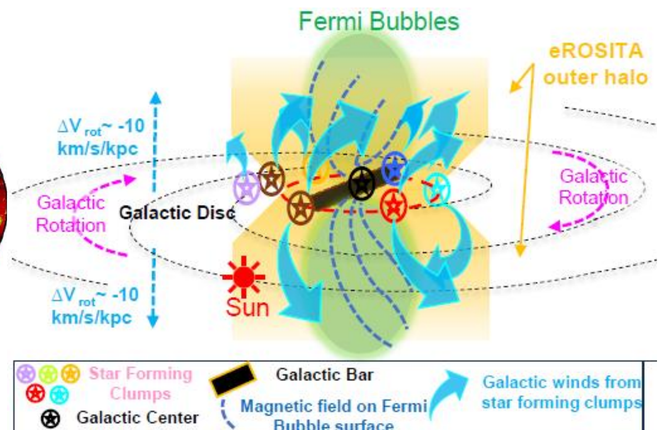
Results from different measurements are complimentary!

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 X-ray eROSITA Bubbles are hot plasma in the Galactic halo standing kpc scales above and below the Galactic disc, showing non-thermal emitting in radio (by synchrotron) and gamma-ray (by Inverse Compton) counterparts.
3. The coherent and highly anisotropic magnetic fields are identified in the Galactic halo, tracing the Galactic outflows.
4. Stellar feedback plays important role in the Galaxy feedback.
5. ***Future modelling for CR propagation in the Milky Way and Galaxy evolution should consider the new multi-wavelength measurements!***





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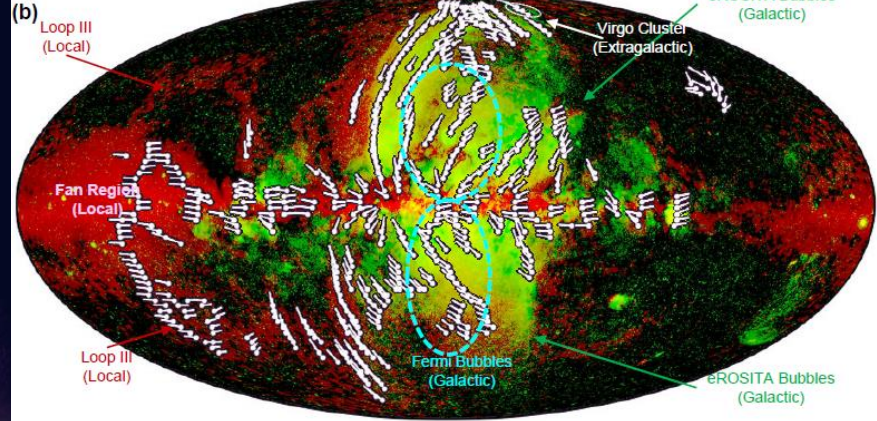
https://ui.adsabs.harvard.edu/abs/2024NatAs...8.1416Z/abstract

Art impression:
Magnetic halo of our Milky Way

Thank You!

Paint by Xiangyuan Li



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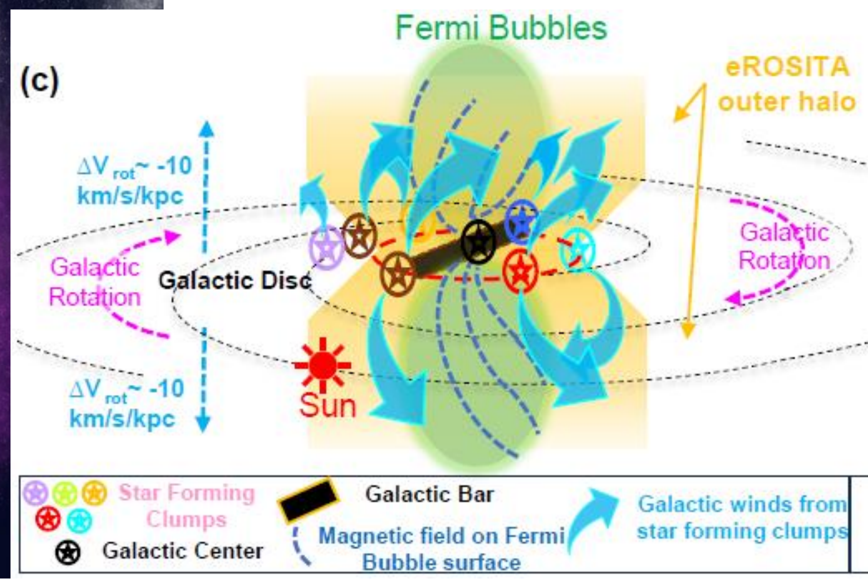
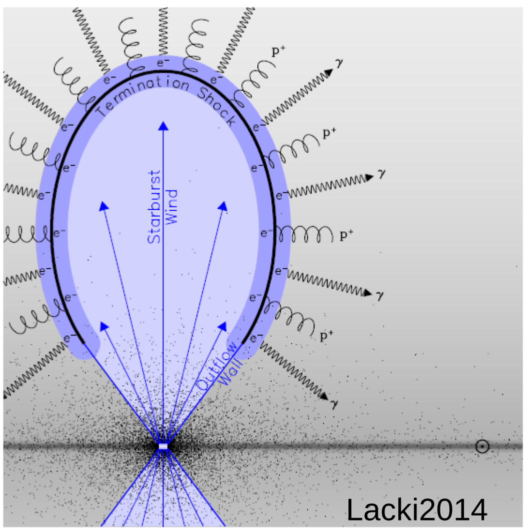


Understanding of the Fermi Bubbles

- Modelling re-examination is needed to study the Observations

Previous models:

- CMZ as sources or SMBH?
- Possibility to explain both inner and outer outflows?



Lacki2014

Figure 1. Sketch of the CMZ and its wind termination shock with respect to the Galaxy. CR e^- and p^+ are accelerated at the shock; leptonic emission appears as the radio and γ-ray bubbles.

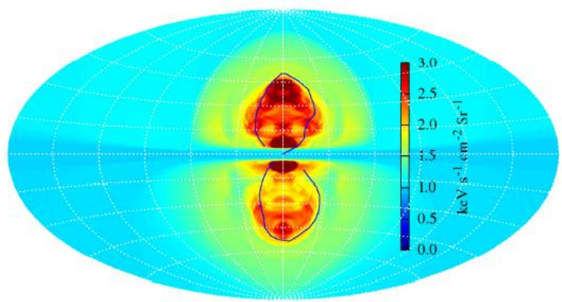
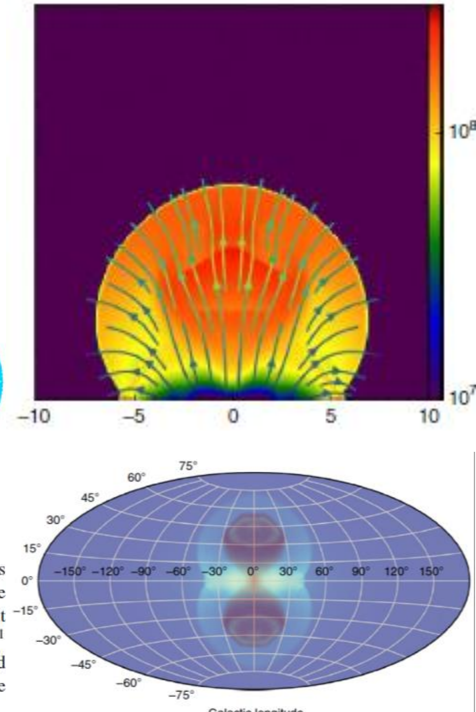


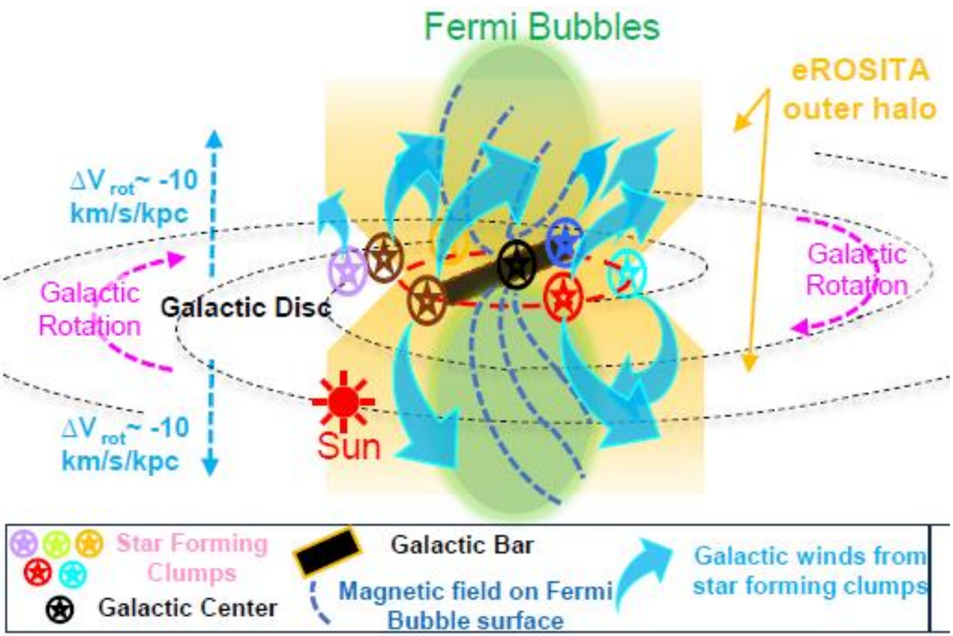
Figure 4. A γ-ray sky map at 5 GeV generated at $t_{age} = 28$ Myr. The shapes and sizes of north and south FBs are consistent with the observed FBs (blue solid lines). A clear shock structure is seen in the Northern hemisphere but not in the southern part. A constant background/foreground of 1 keV s^{-1} cm^{-2} Sr^{-1} (Su et al. 2010) is added in order to account for the observed diffuse emission. Also, regions with $|z| \leq 700$ pc are not included in the map in order to avoid any disc emission.

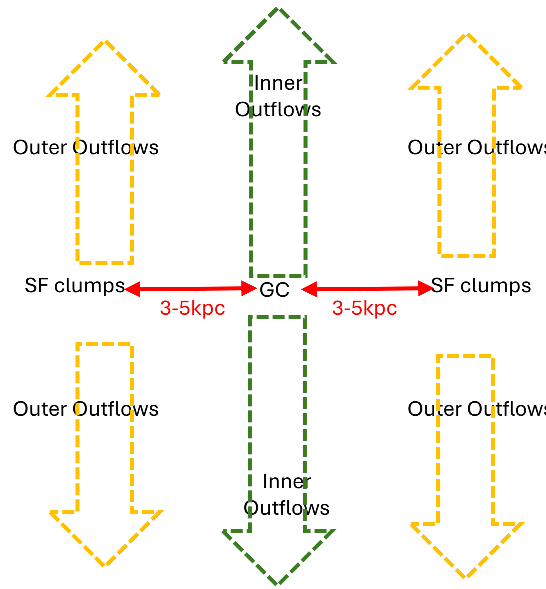
Sarkar2019



Yang+2022

Galactic Outflows Geometry





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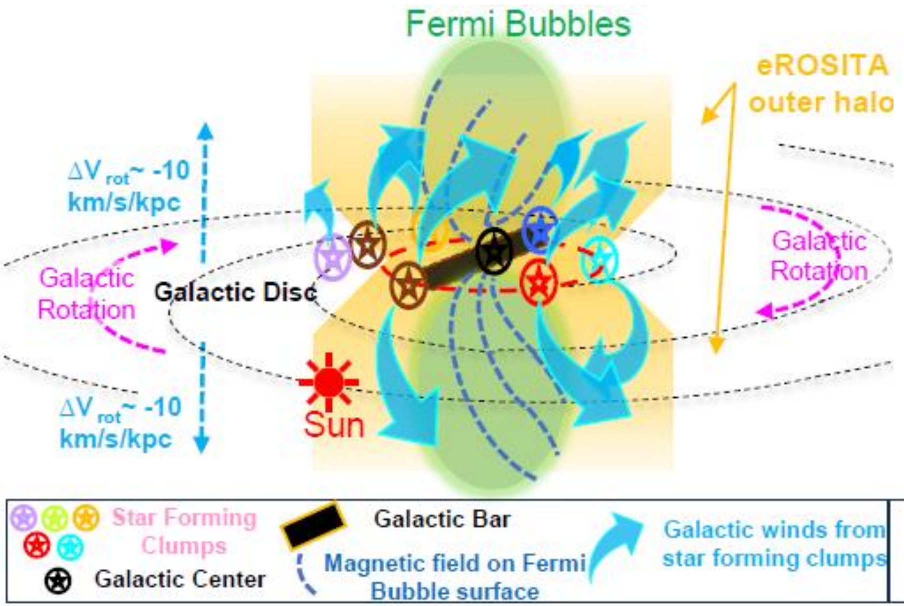
7. Magnetic halo and Galactic Outflows



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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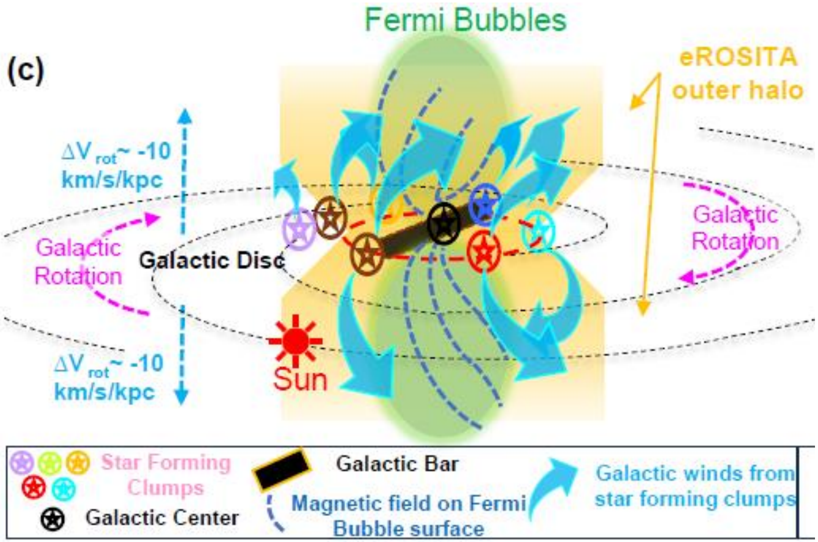
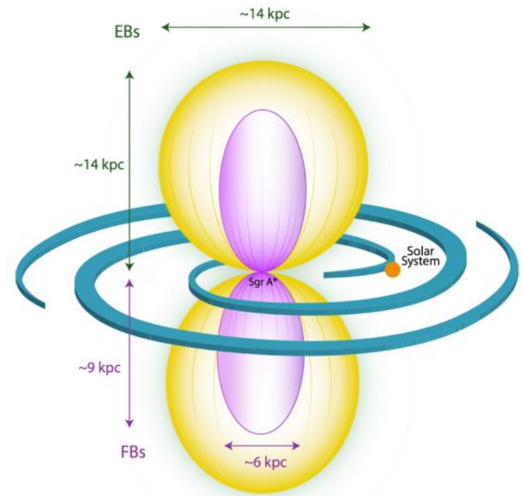
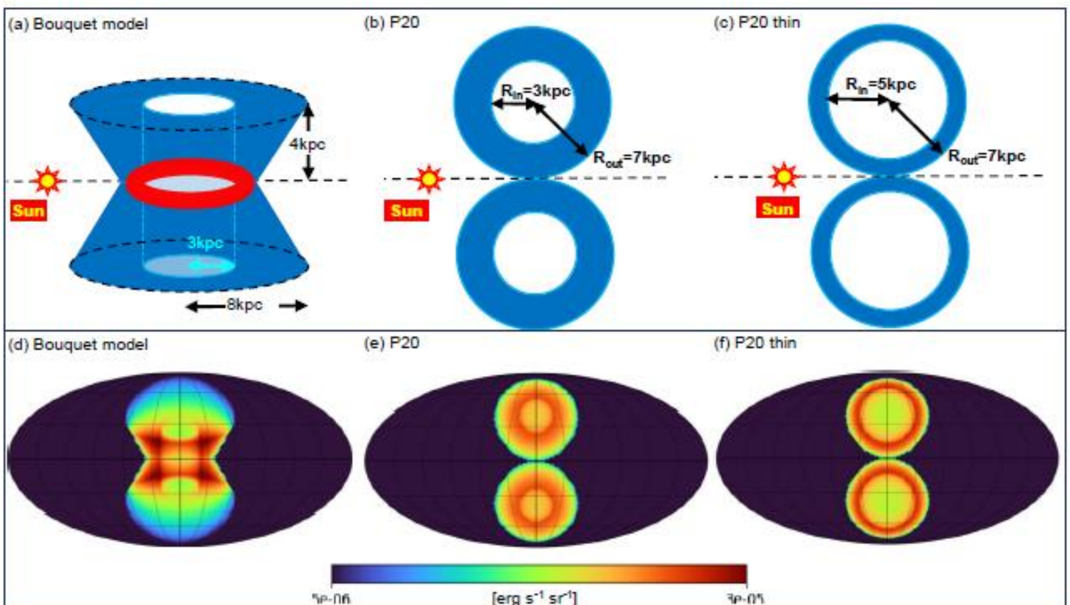


(c)
Fermi Bubbles
eROSITA
outer halo
ΔV rot ~ -10
km/s/kpc
Galactic
Rotation
Galactic Disc
Galactic
Rotation
ΔV rot ~ -10
km/s/kpc
Sun
Star Forming
Clumps
Galactic Center
Galactic Bar
Magnetic field on Fermi
Bubble surface
Galactic winds from
star forming clumps



EBs
~14 kpc
~14 kpc
Solar
System
Sgr A*
~9 kpc
FBs
~6 kpc



(a) Bouquet model
4kpc
Sun
3kpc
8kpc
(b) P20
R_{in}=3kpc
R_{out}=7kpc
Sun
(c) P20 thin
R_{in}=5kpc
R_{out}=7kpc
Sun
(d) Bouquet model
(e) P20
(f) P20 thin
[erg s^{-1} sr^{-1}]

4. Gamma-ray counterpart of the magnetic halo

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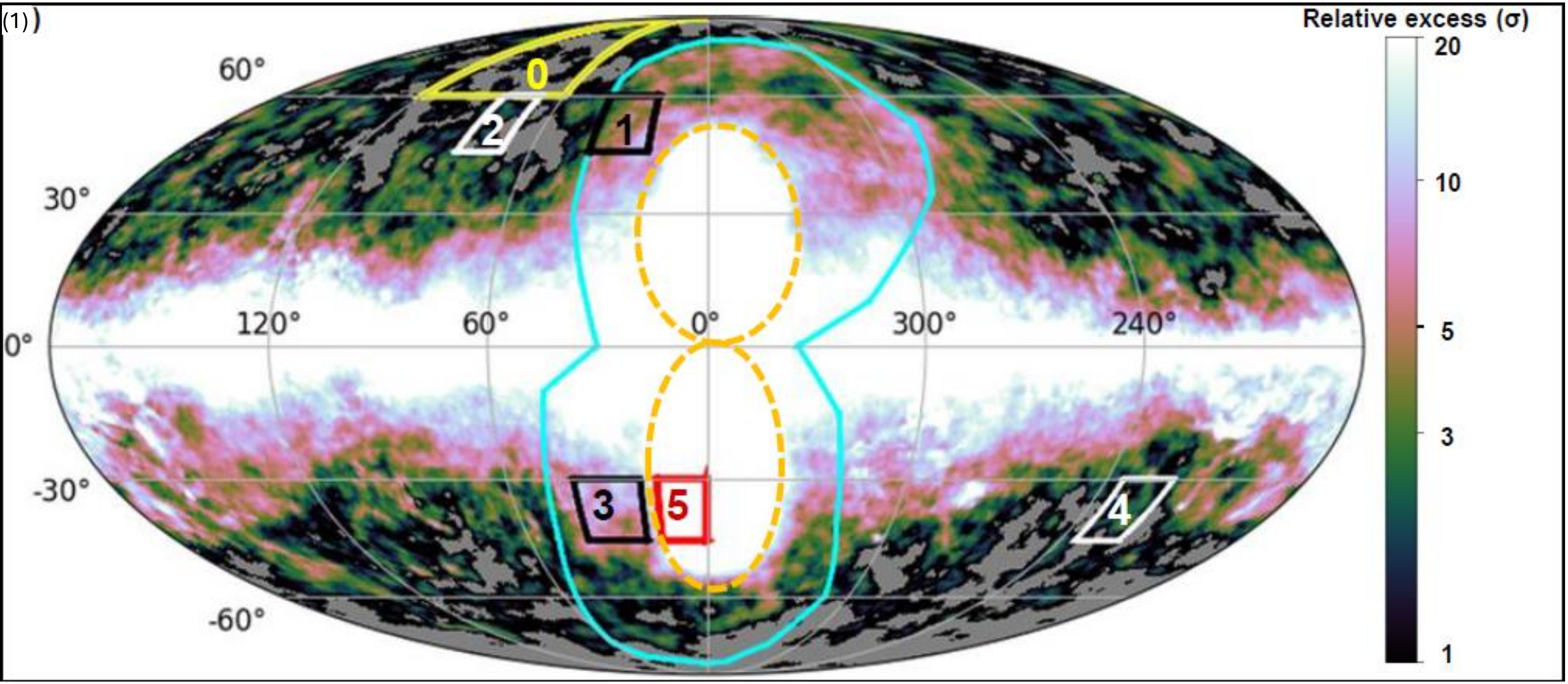
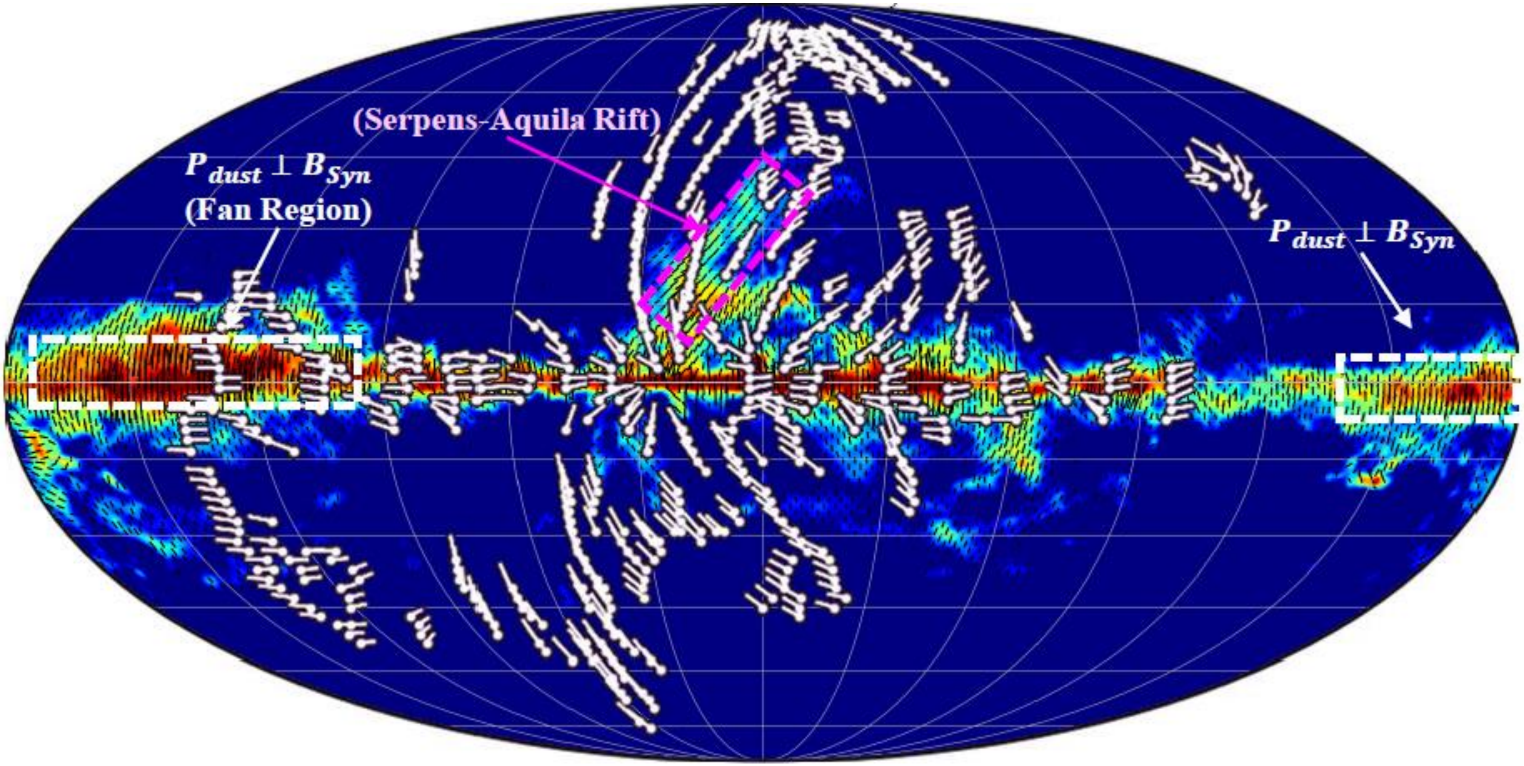


A gamma-diffuse halo shows similar morphology to the eROSITA Bubbles

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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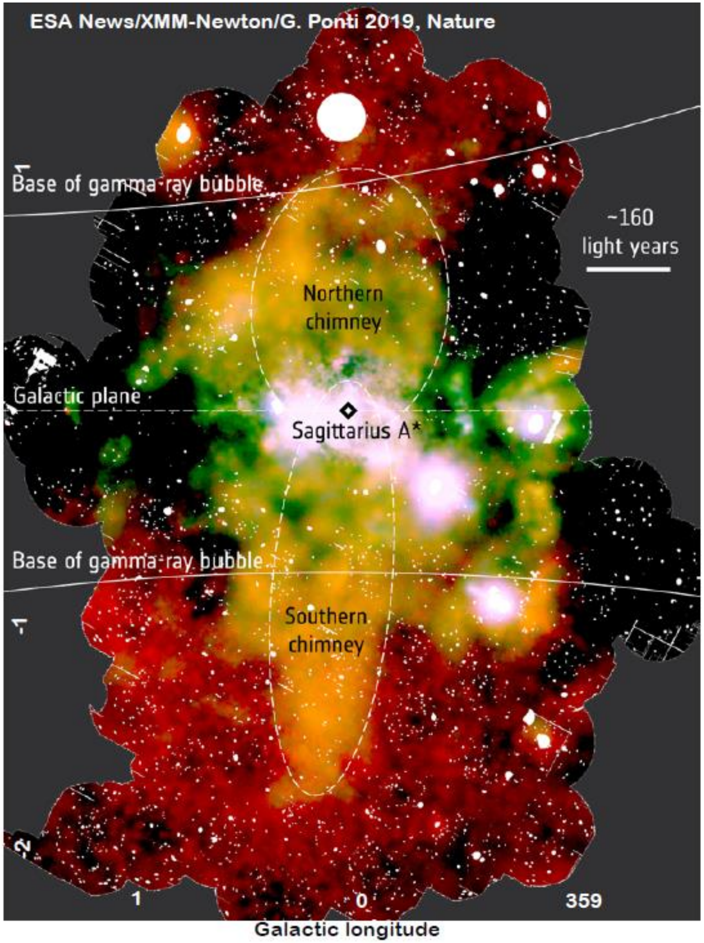
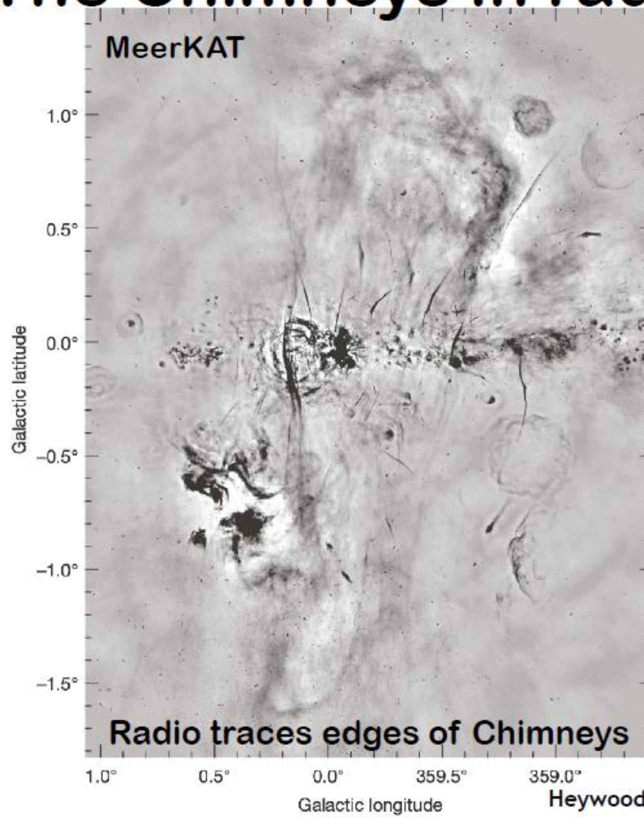
The Chimneys in radio





Heywood +19, Nature

Outflow has radio counterpart

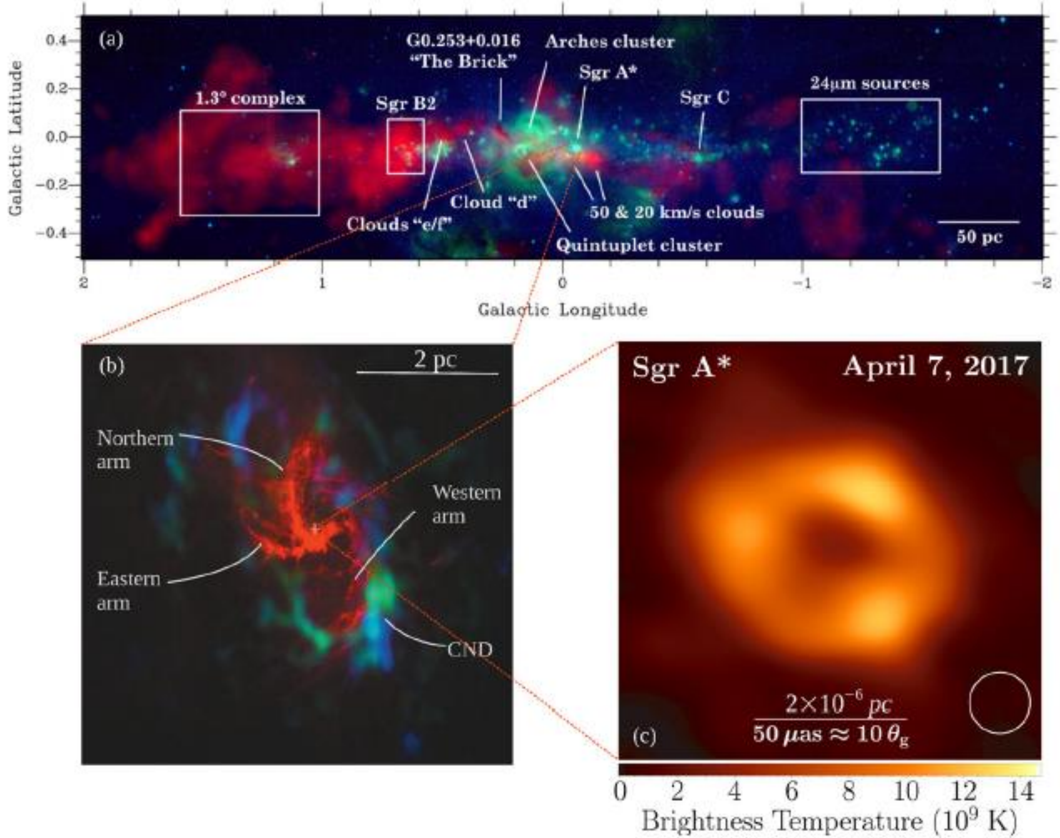
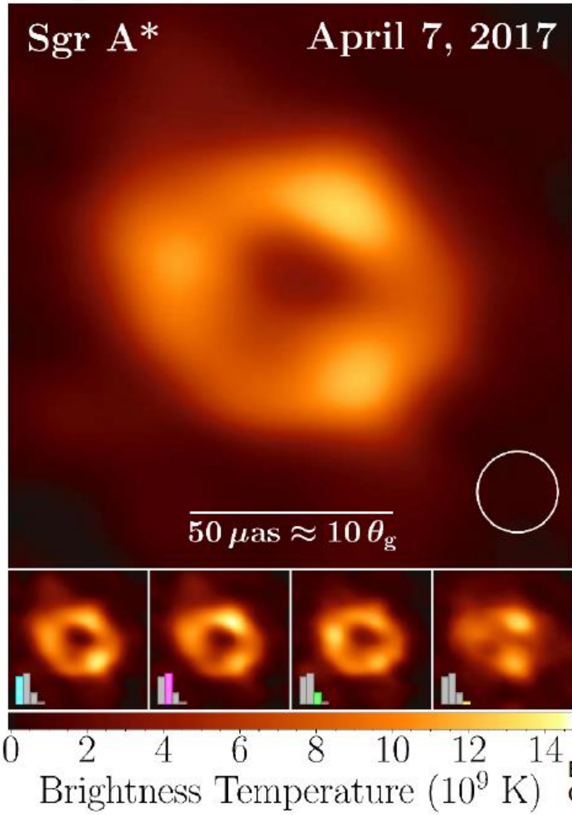


Fig. 8 Galactic center at different scales. **a** ($1^\circ \approx 150$ pc): multi-wavelength emission from the central molecular zone. The red shows NH_3 emission and represents dense ($\gtrsim 10^3$ cm^{-3}) gas. The green and blue shows the 21.3 μm and 8.28 μm emission, respectively, and represent the PAH emission from cloud edges, young stellar objects, and evolved stars. The image is adapted from Kruijssen et al. (2014). **b** Interstellar matter in the central few pc of Sgr A* (adapted from Genzel et al. 2010) showing the circum-nuclear disk (CND) in green and blue (HCN emission), and the ionized streams in red (6 cm radio continuum emission). The location of the Sgr A* is marked with a '+' sign. **c** Event Horizon Telescope observation of the accretion disk around the Sgr A* at 1.3 mm (adapted from EHT Collaboration et al. 2022b). Here, $\theta_g = GM_{\rm bh}/c^2 D$) is the gravitational radius of the central SMBH with mass $M_{\rm bh}$, and D is the distance from Earth. The white circle shows the beam size used for the image reconstruction

Sgr A* is face on: How can the outflow be real?

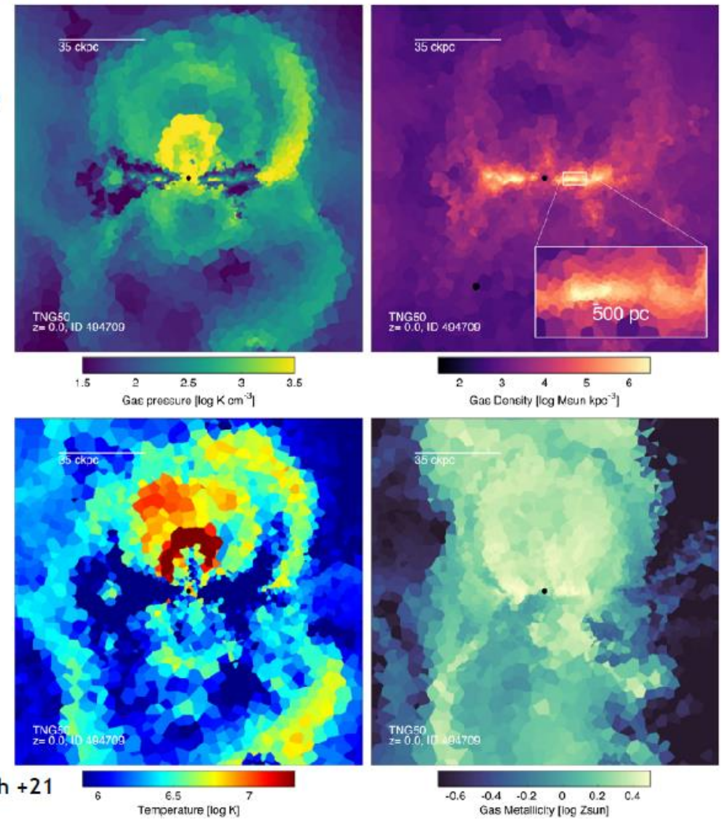


EHT Collab. 22
Gravity Collab. 18

Cosmological simulation of Milky Way-like galaxy with randomly oriented AGN outflow inflate eROSITA-like bubbles on large scales

Pillepich +21;
But see Mondal+22;
Yang+22 Sarkar+23

But orientation maintained on small scales



Pillepich +21