The Milky Way magnetic halo, the Local Bubble and UHECR deflections

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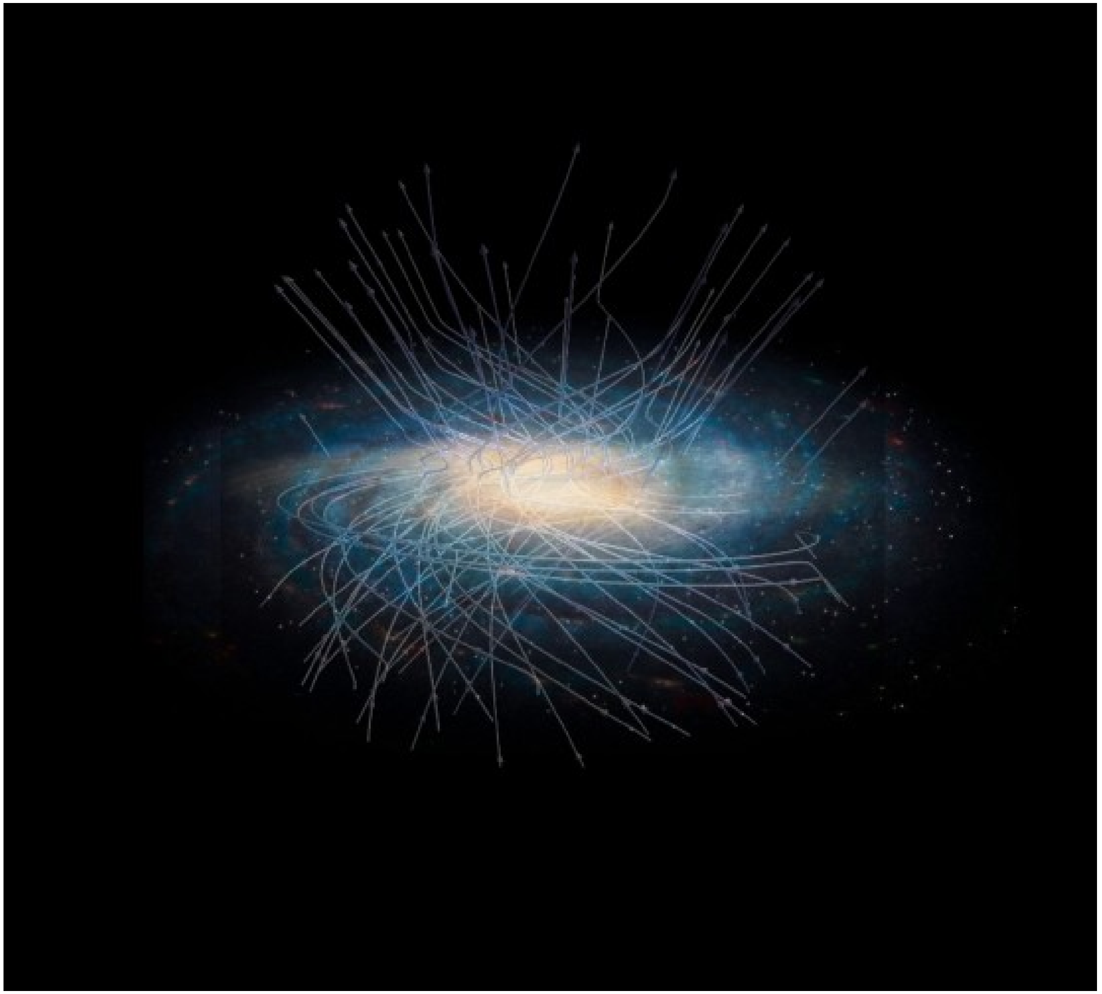
in collaboration with Dmitri Semikoz and Peter Tinyakov, arXiv:2407.02148

Overview:

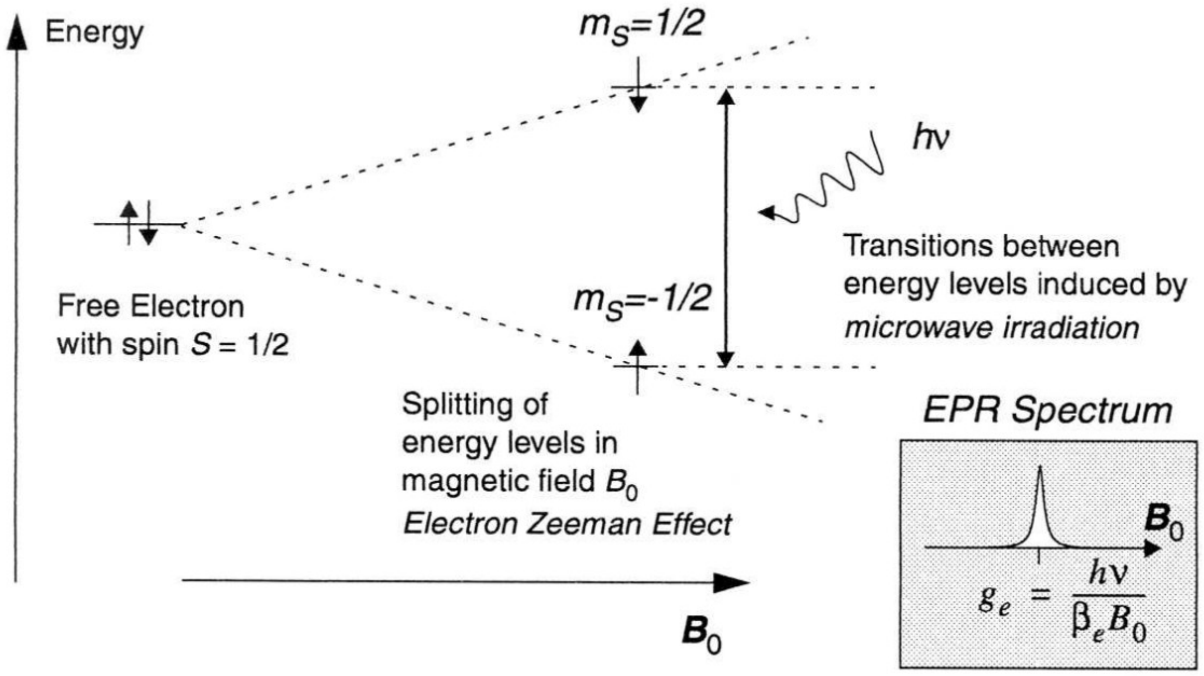
- What is Galactic magnetic field (GMF) ?
- Observables
- Magnetic field of other galaxies
- Existing models
- Our model

GMF and Galactic processes



- GMF affects star formation
- Important for cosmic ray propagation
- UHECR deflections, we still don't know the sources
- Cosmic ray leptons and dust emission – background for CMB measurements
- GMF origin? Dynamo?

How to measure GMF: **Zeeman Splitting**



POSITIVE DETERMINATION OF AN INTERSTELLAR MAGNETIC FIELD BY MEASUREMENT OF THE ZEEMAN SPLITTING OF THE 21-cm HYDROGEN LINE

G. L. Verschuur
National Radio Astronomy Observatory,* Green Bank, West Virginia
(Received 17 July 1968)

Fields of the order of 2×10^{-5} G exist in the Perseus spiral arm in the direction of the radio source Cassiopeia A.

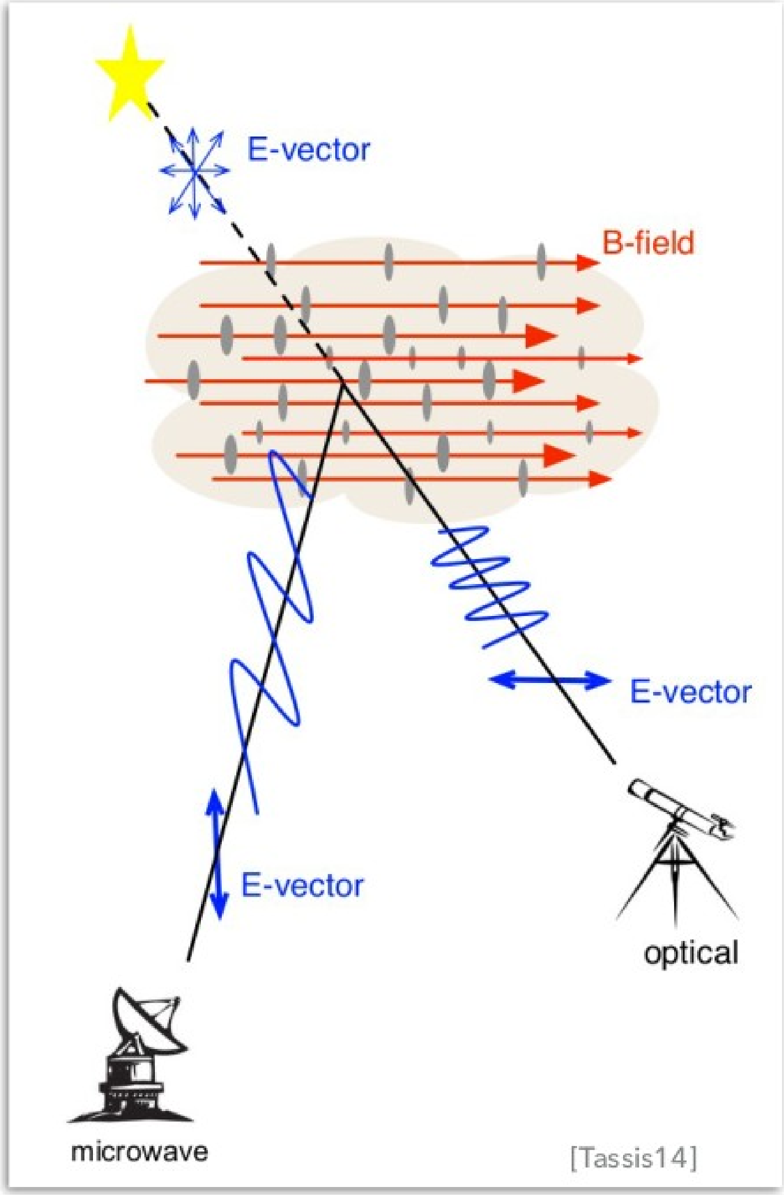
How to heasure GMF: **using Galactic dust**

Starlight reaches us after having traveled through the magnetized, dusty Inter-stellar Medium (ISM). On its journey, starlight interacts with the interstellar dust. Part of the light becomes absorbed by the dust grains.

Because the grains are asymmetric and elongated, they preferentially absorb light along their long axis. This causes the light to become polarized along the short axis of the grain.

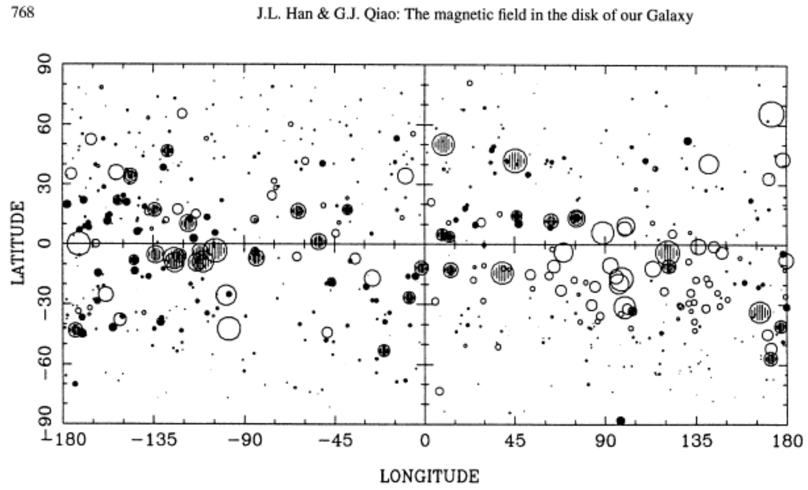
As dust grains are aligned with their short axis along the direction of the local magnetic field, the starlight's polarization is also parallel to the magnetic field.

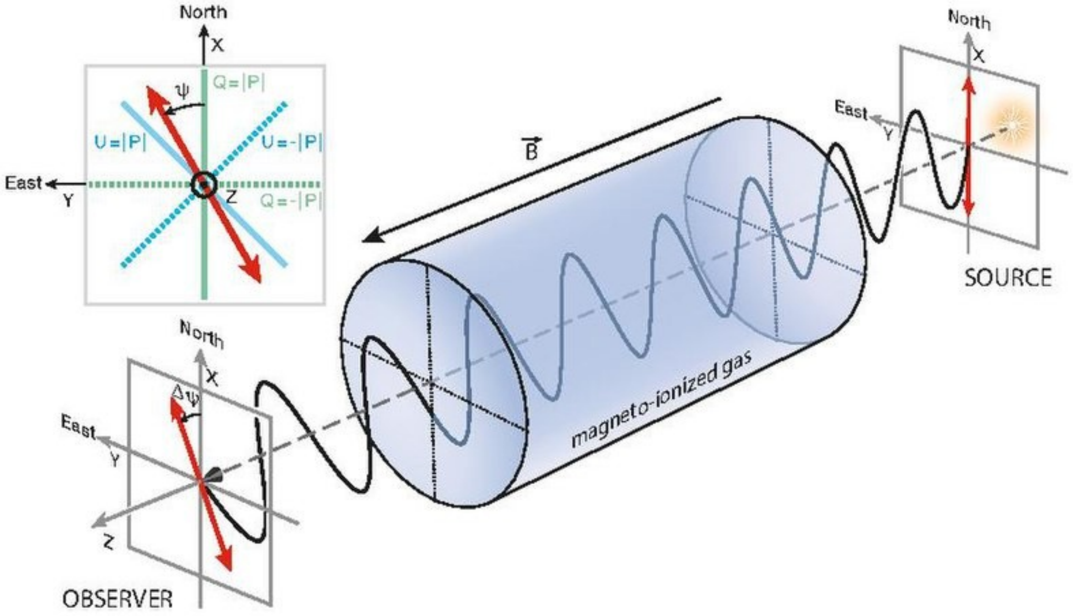
Historically first measurement of the GMF, Hiltner(1949), Hall(1949)



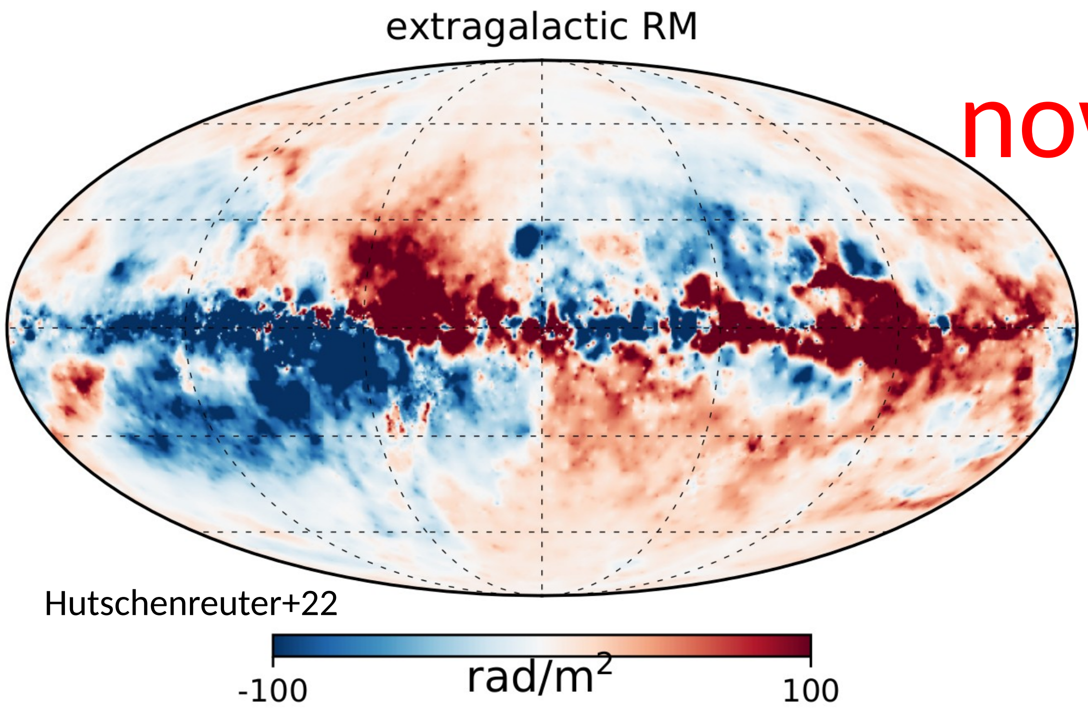
Data: extragalactic Faraday rotation measures (RM)

1994





now

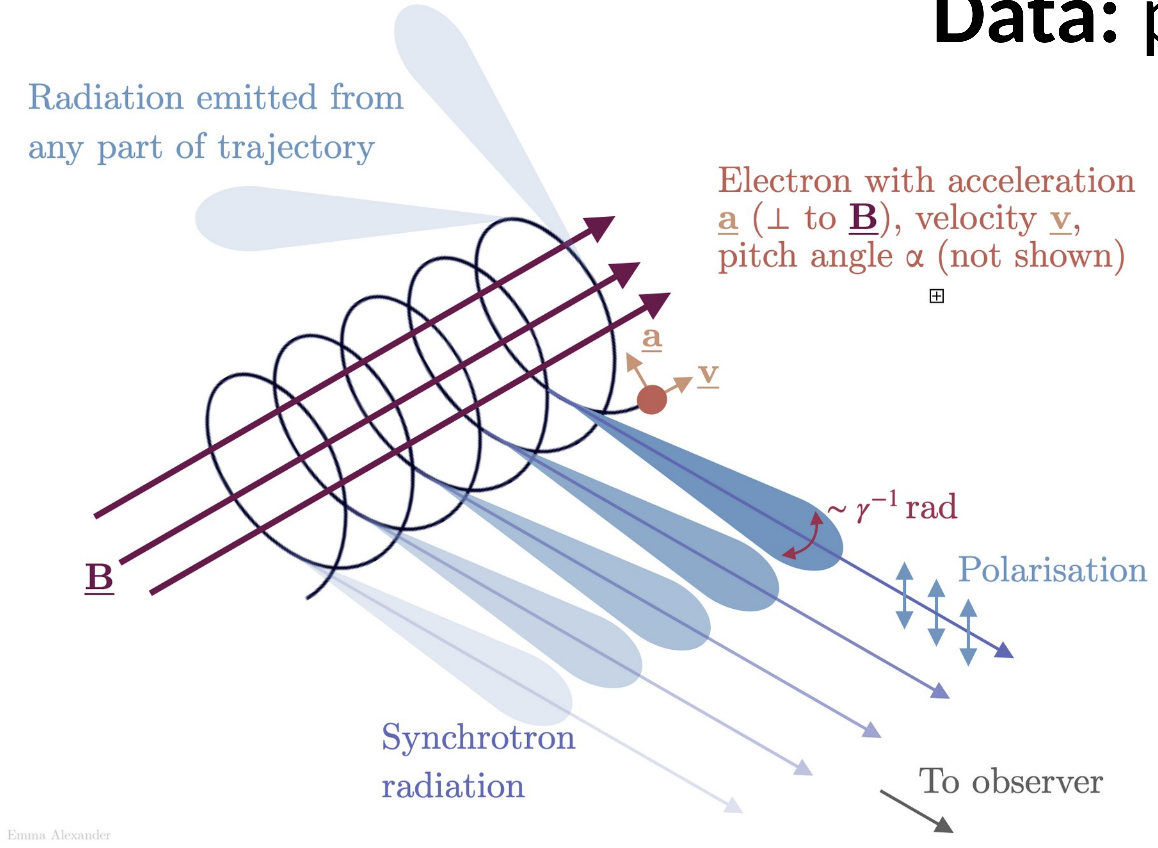


RM traces B field component parallel to LOS

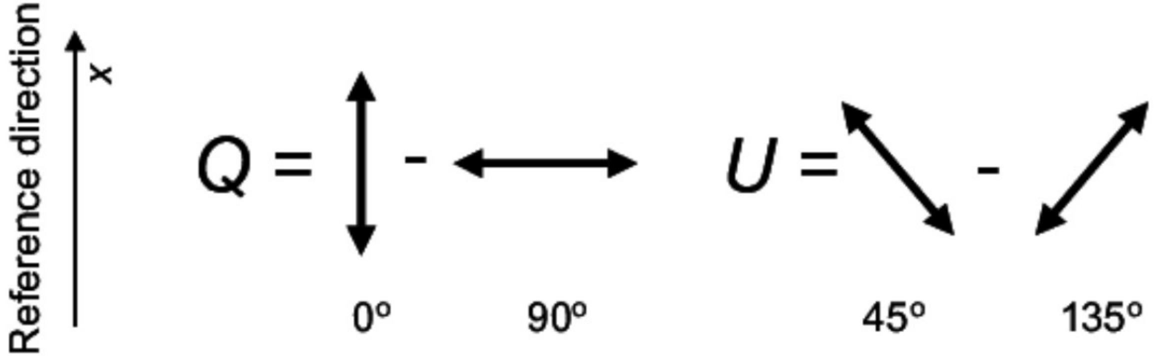
Brown – MF pointing towards us

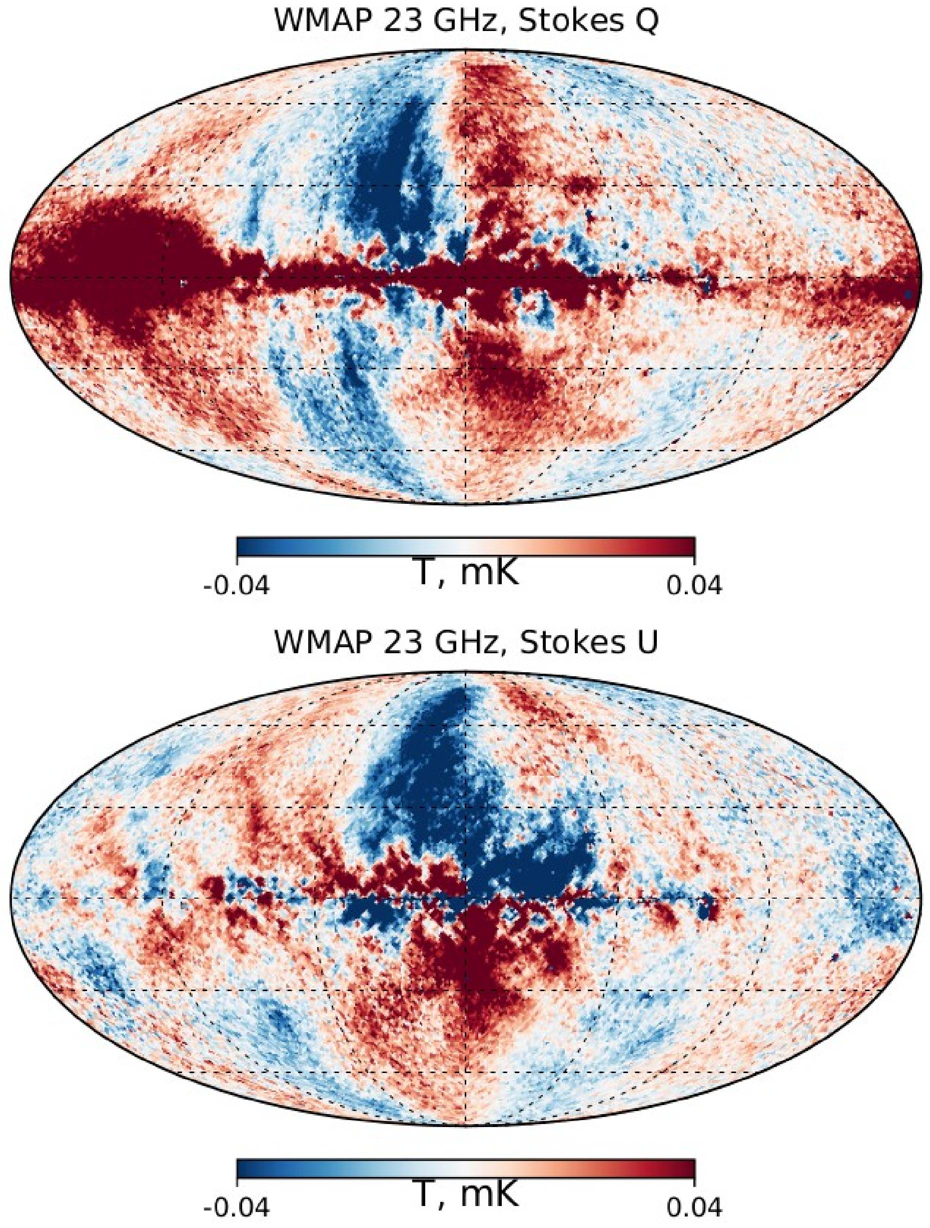
Blue – MF pointing away from us

Data: polarized synchrotron skymaps



Stokes parameters





Summary of observables

- Zeemam splitting – only for exeptional places

- Polarized Dust Emission – limited to thin disk (<200 pc), gives only direction but not strength, perfect for reconstruction local field

- Rotation Measures – cover full sky, thermal electron distribution should be known

$$\mathrm{RM} \approx 0.812 \int_0^l \left[\frac{n_e(s)}{\mathrm{cm}^{-3}}\right]\left[\frac{B_{||}(s)}{10^{-6}\,\mathrm{G}}\right]\left[\frac{\mathrm{d}s}{\mathrm{pc}}\right] \quad \mathrm{rad/m^2}$$

- Polarized synchrotron – full sky, cosmic ray electron distribution should be known

External galaxies

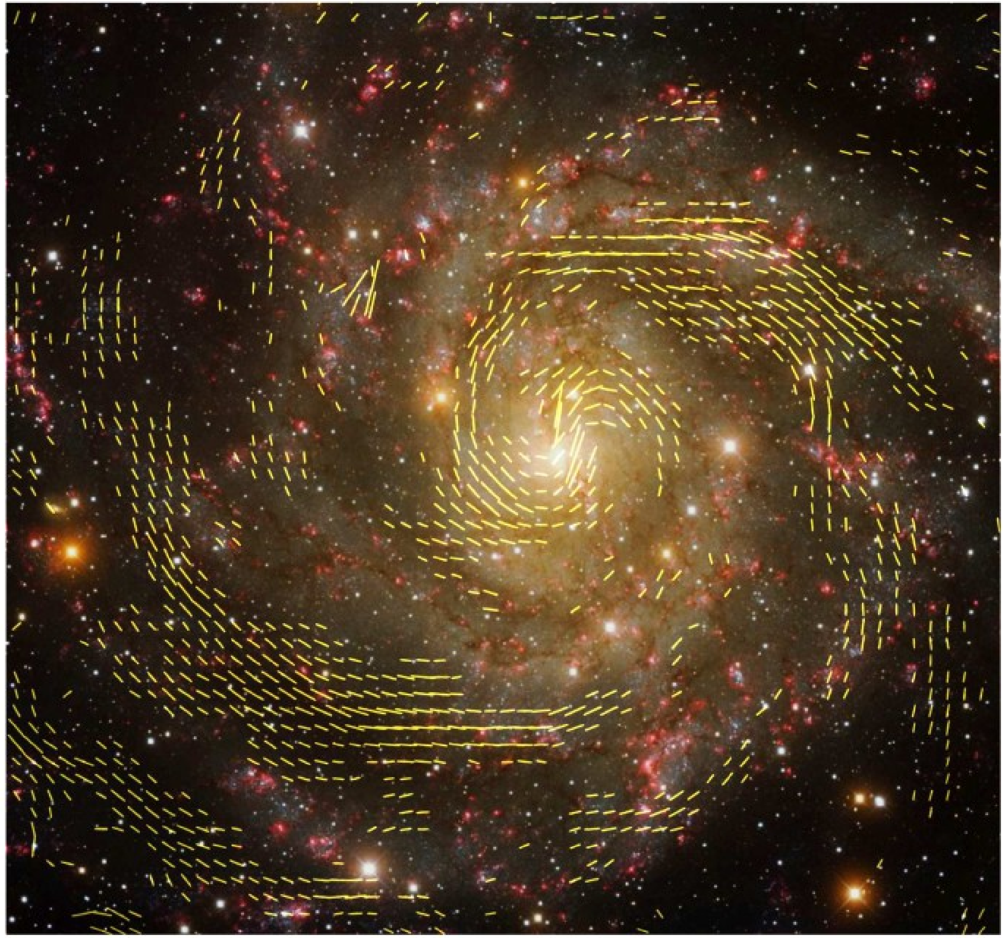
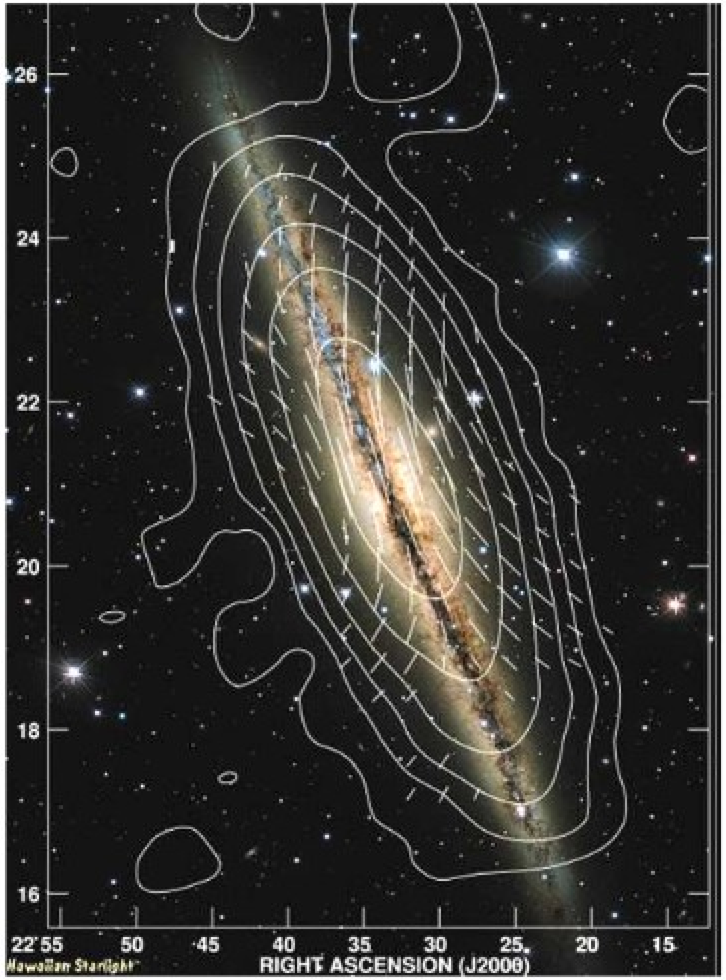


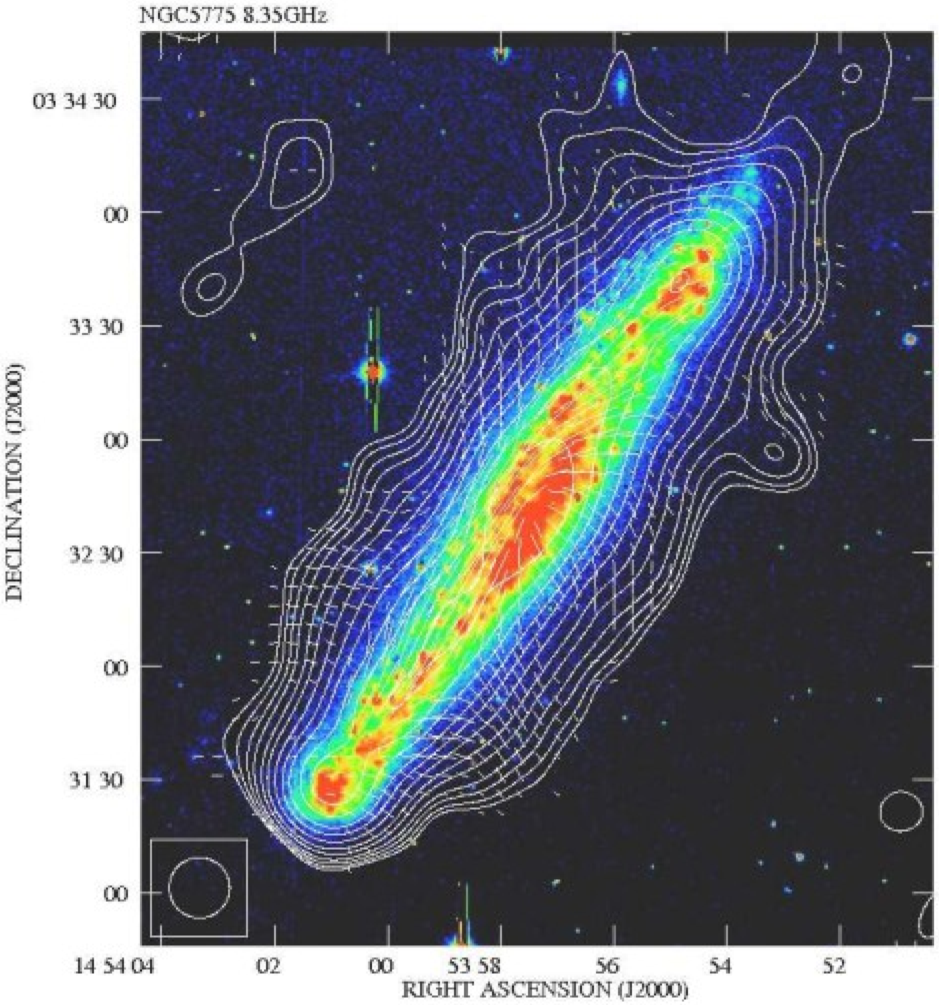
Fig. 6 Polarization B–vectors of IC 342, combined from observations at 6 cm wavelength with the VLA and Effelsberg telescopes and smoothed to 25″ resolution (from Beck (2015)), overlaid on a colour image from the Kitt Peak Observatory (credit: T.A. Rector, University of Alaska Anchorage, and H. Schweiker, WIYN and NOAO/AURA/NSF). A region of 16′ × 16′ (about 16 × 16 kpc) is shown. (Copyright: MPIfR Bonn)

IC 342

In a first approximation magnetic field is aligned with the spiral arms

External galaxies: edge on view



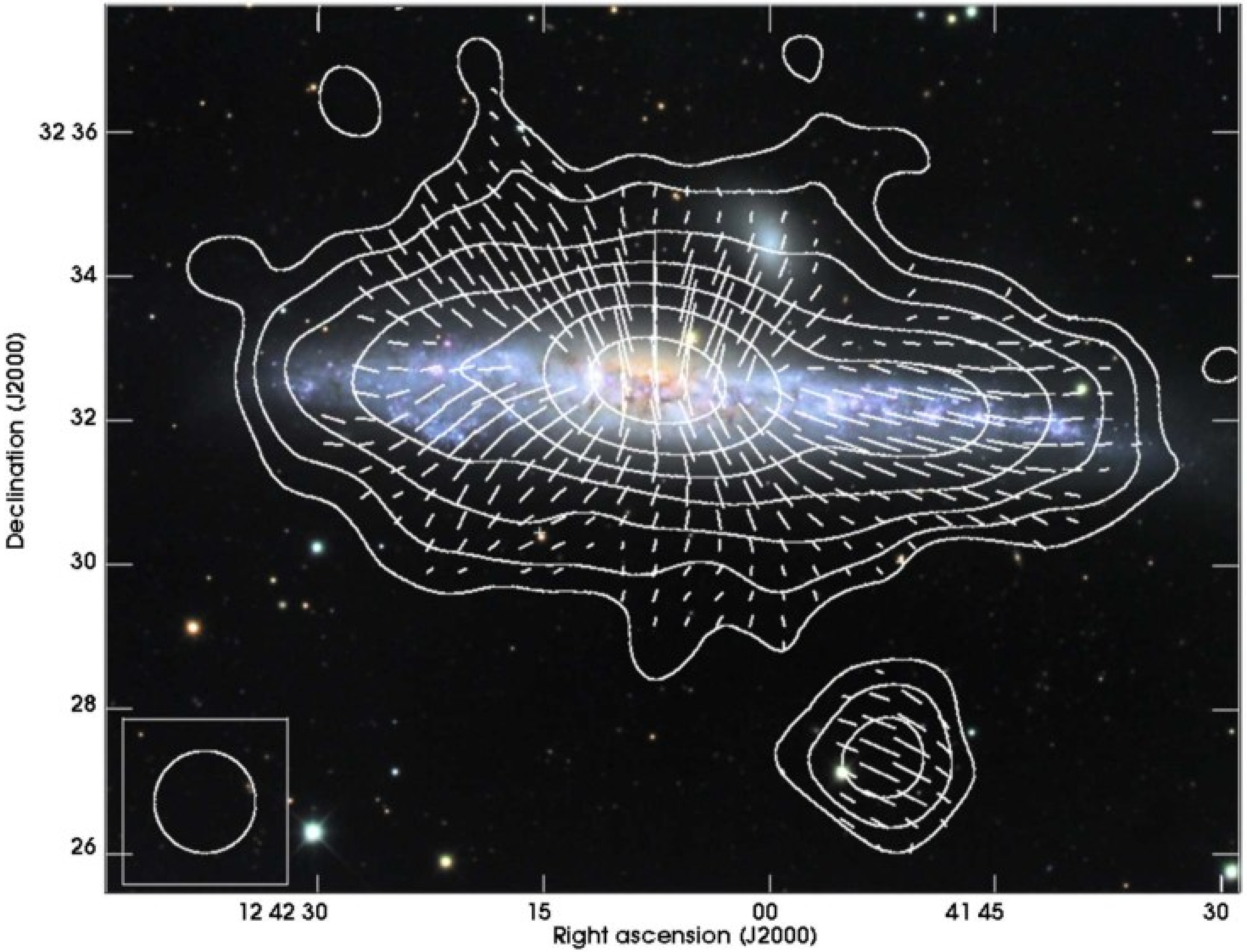


Out of the plane field = X-field

NGC 891

NGC 5775

External galaxies: edge on view

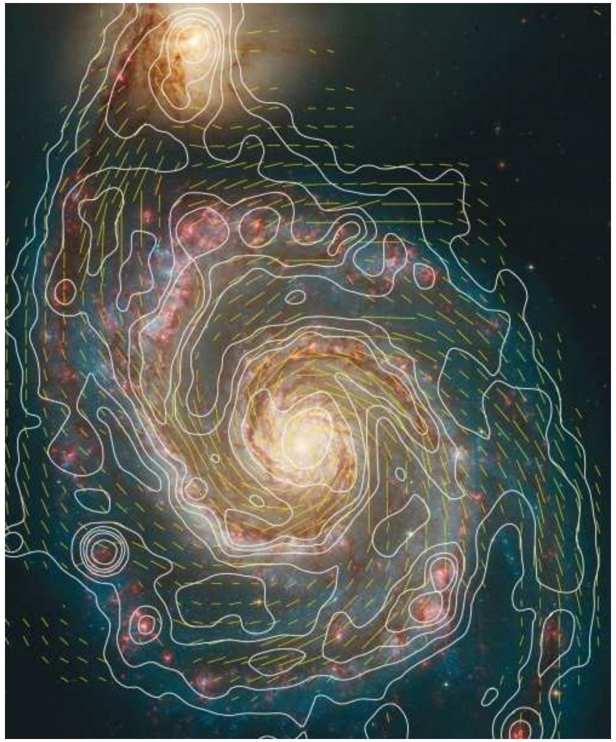


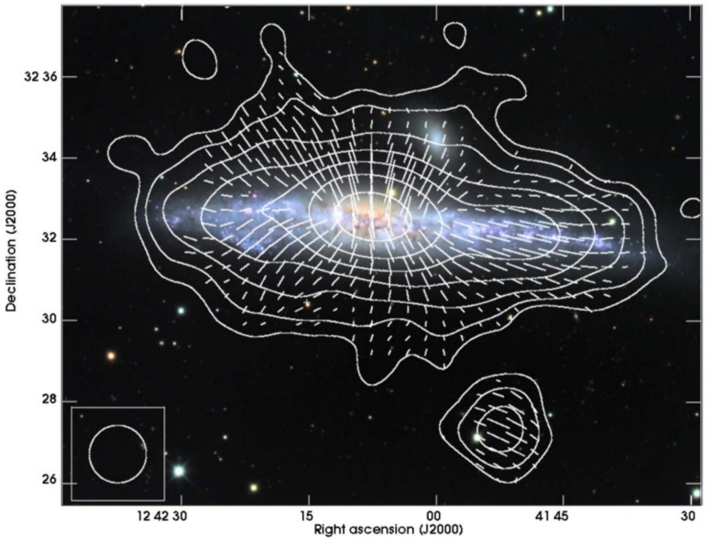
NGC 4631

Another example of an X-field

External galaxies: summary

- Turbulent and ordered B field can be identified in external galaxies
- Ordered field has several components: disk field, halo field, X-field
- We focus on the ordered field and assume that our Galaxy has the same components





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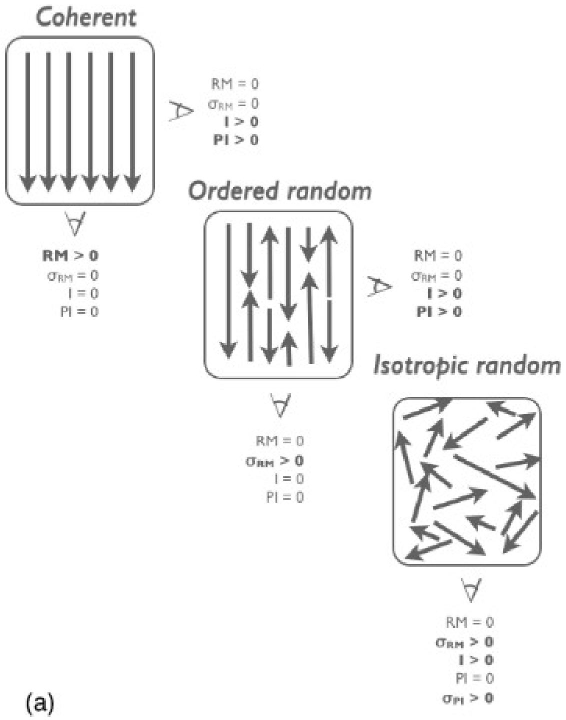
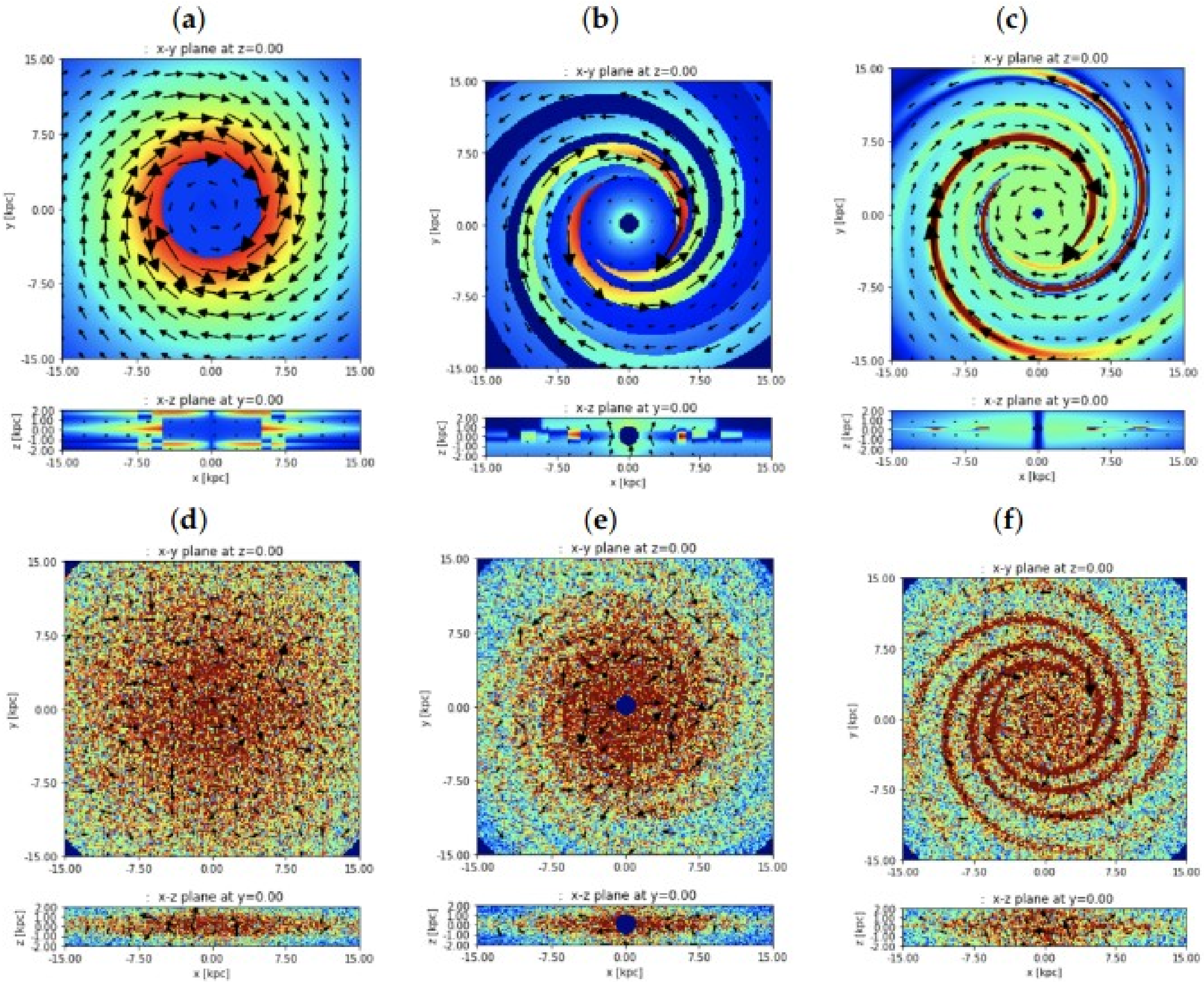
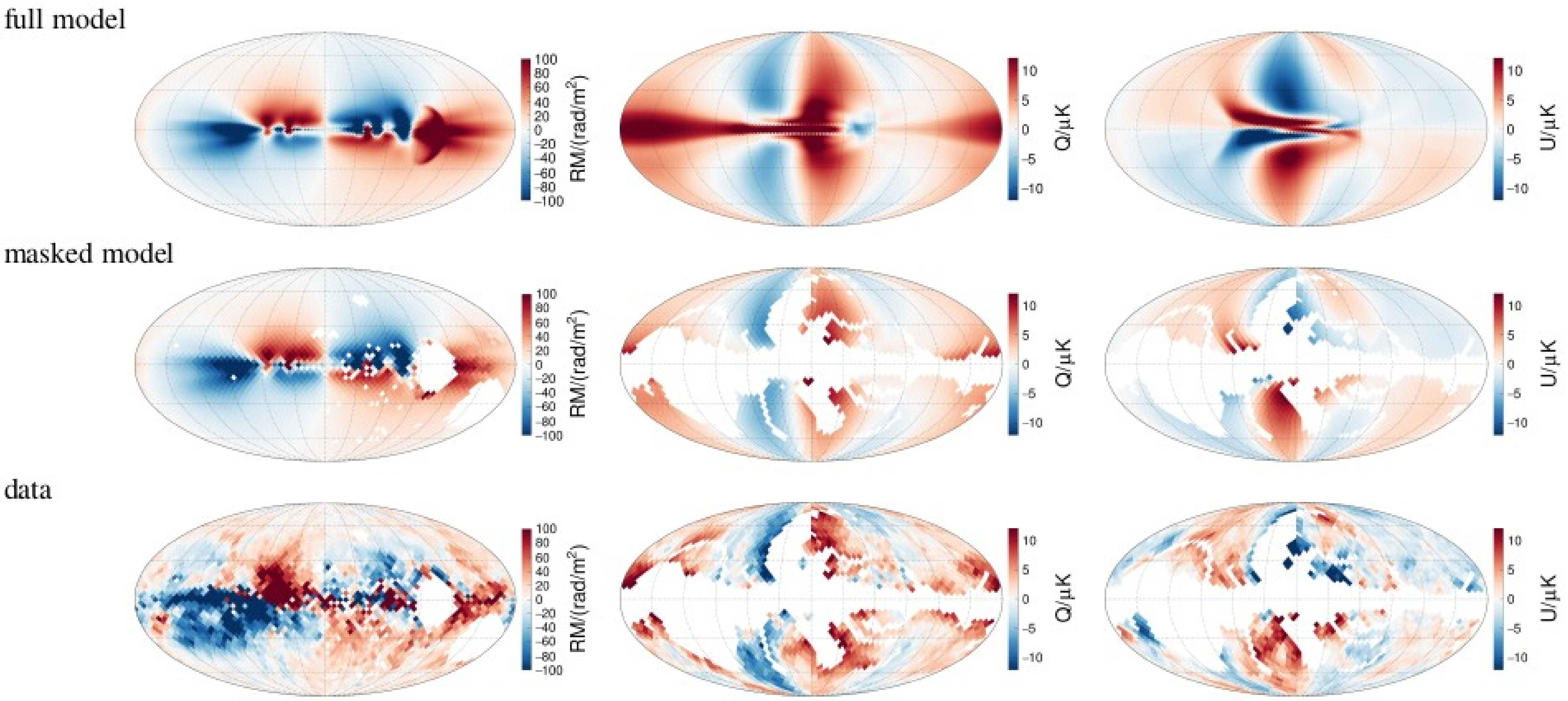


Jaffe+10

Previous models



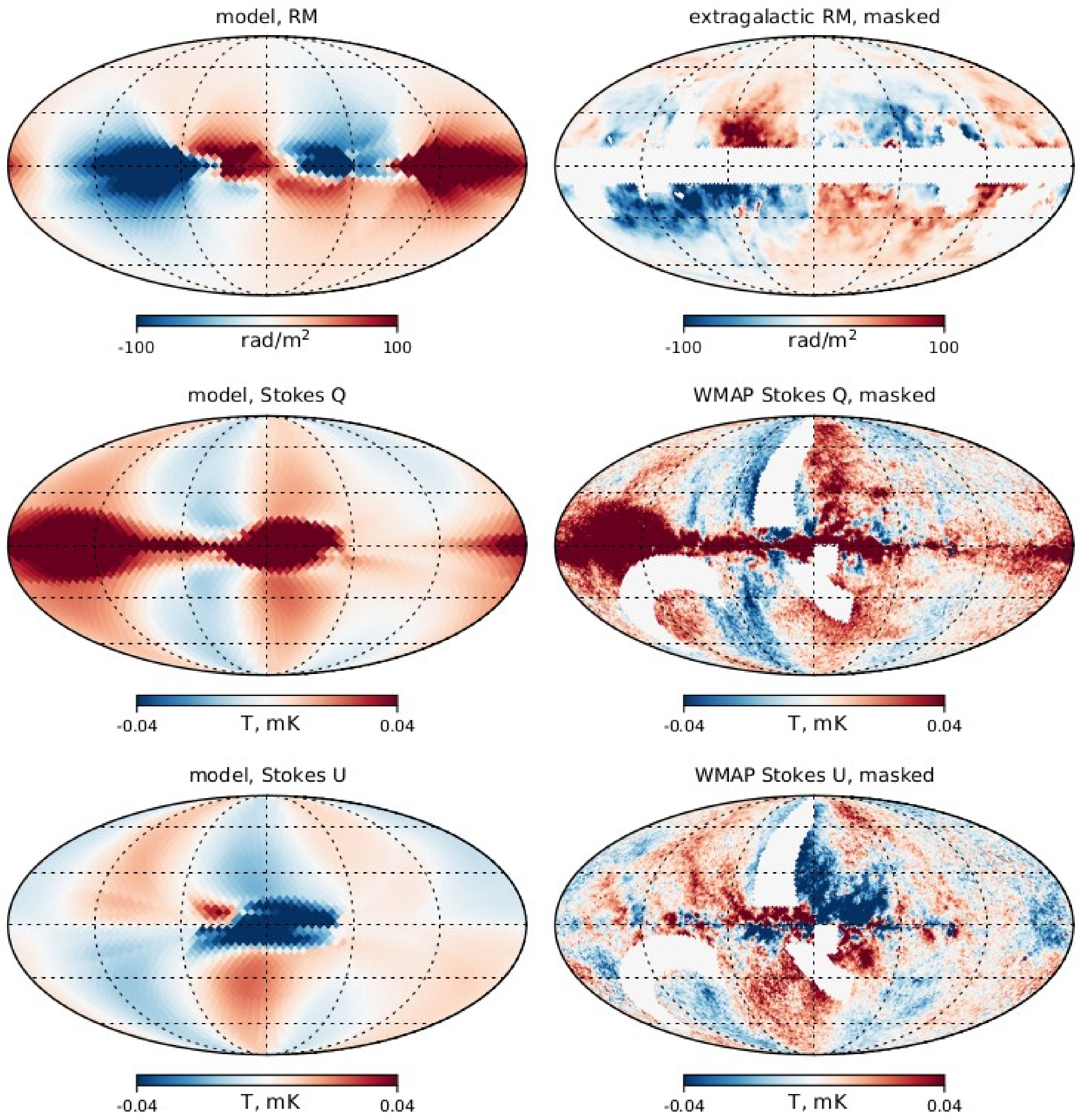
Collection of GMF models **UF23**



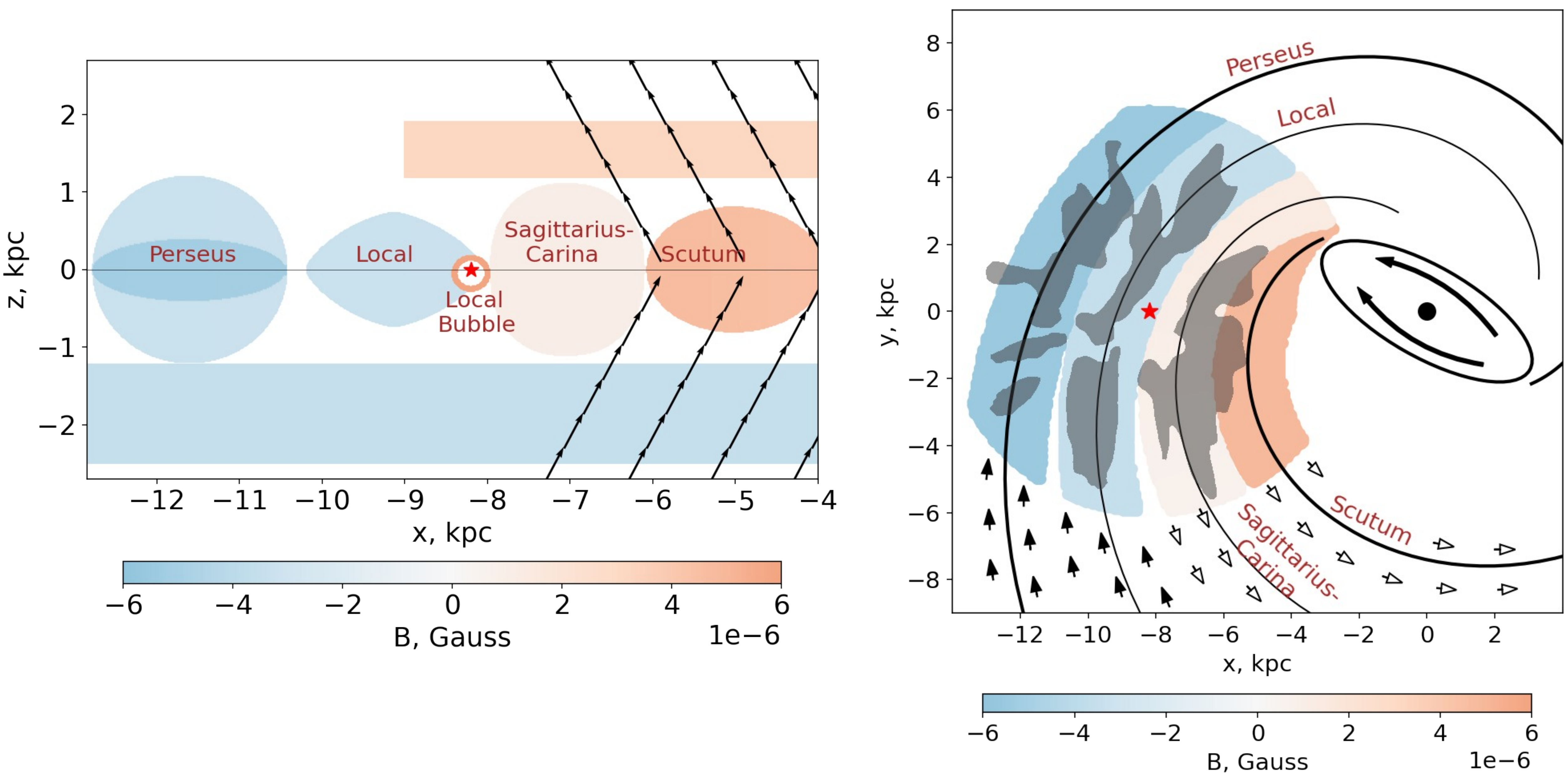
Unger&Farrar 2023

Why do we need a new GMF model?

- Previous models do not converge to the same values
- Different statistical approaches to the data
- Large portions of the sky masked out
- Do we need “striation” = order-random field
- Pitch angle of the disk field?
- Self-consistent modelling of GMF and cosmic rays



Our new model



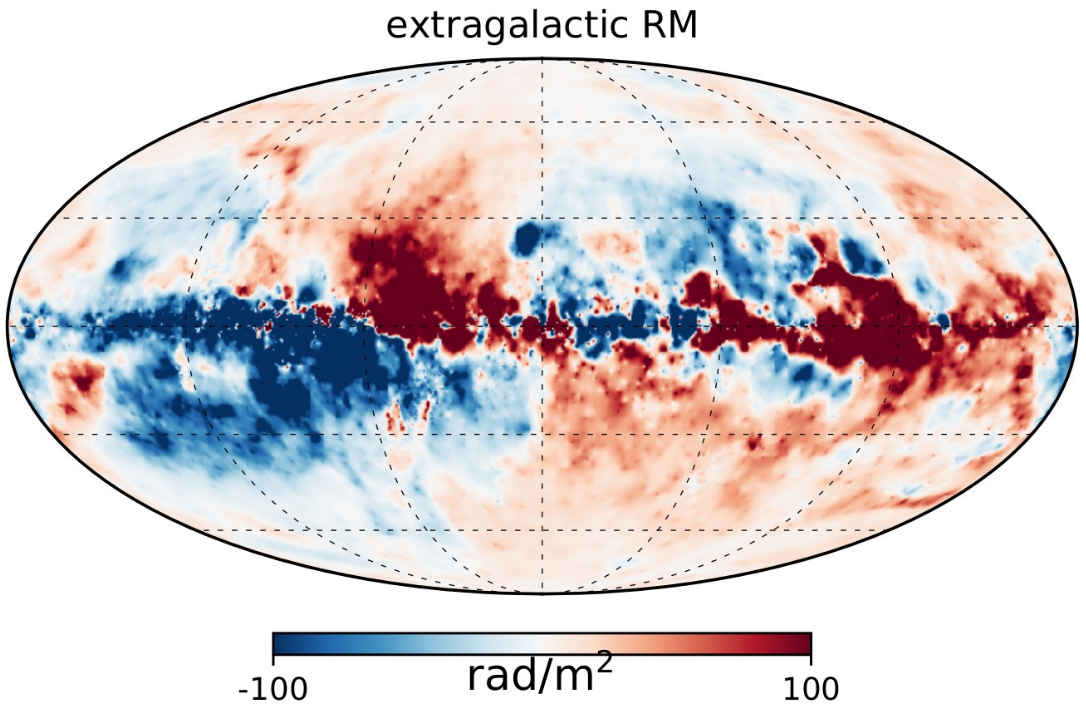
Perseus
Local
Local Bubble
Sagittarius-Carina
Scutum
z, kpc
x, kpc
B, Gauss
1e−6
y, kpc

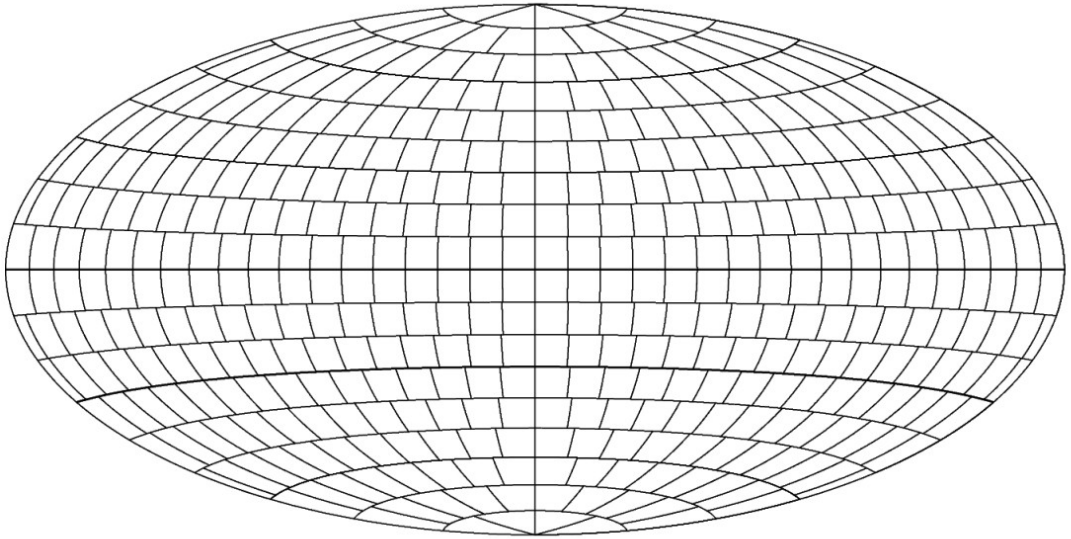
Main new features of our model

- Better treatement of statistical errorbars
- The grand-design of the model fits Gaia observations of spiral arms – larger pitch angle of 20 deg
- Fan Region is explained naturally as a part of the large-scale field
- Local Bubble is taken into account – striation is not needed

1) Bins errorbars

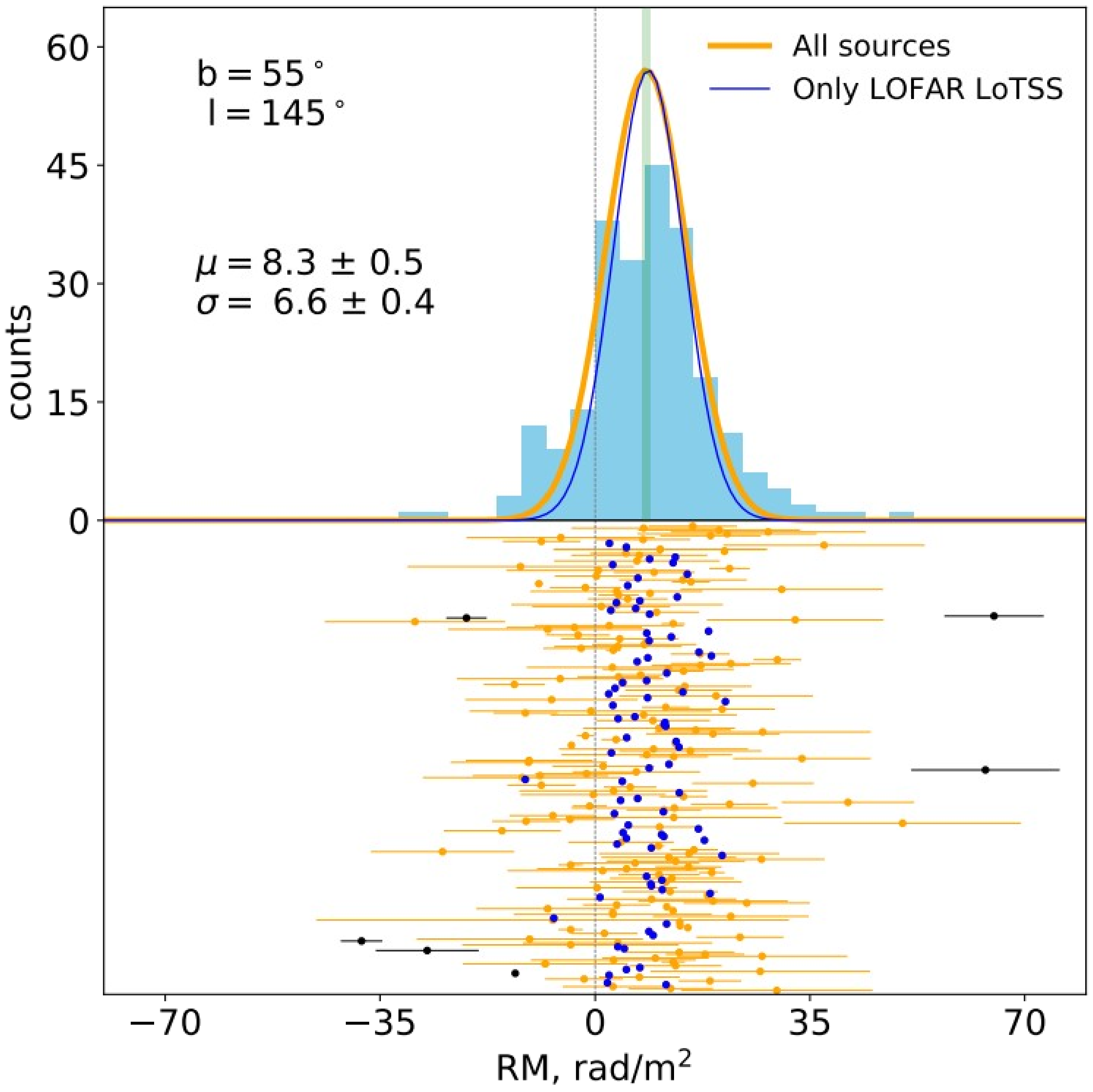
Estimation of data bins errorbars

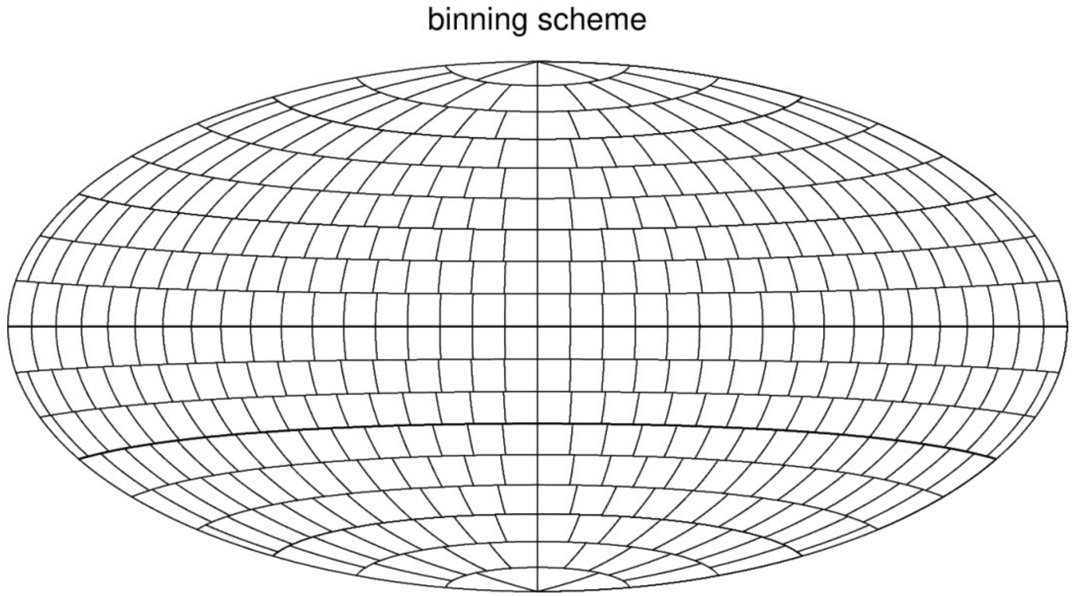




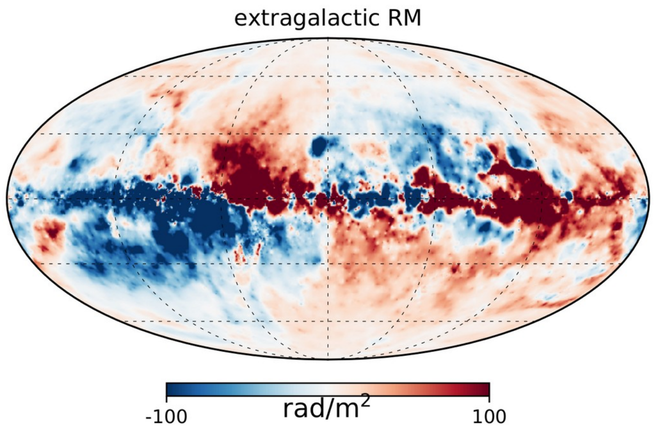
- We are interested in global GMF structure – small details are not important

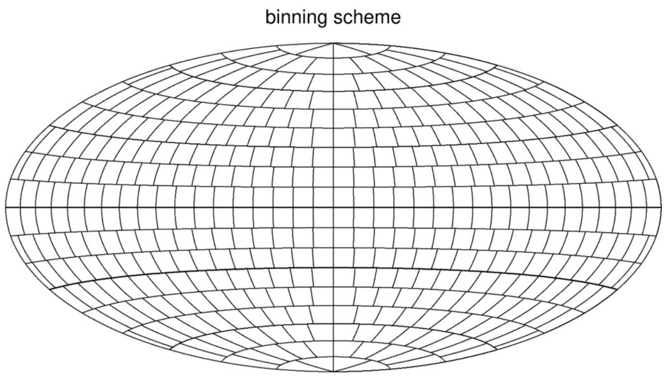
Estimation of data bins errorbars: **example of the RM bin**

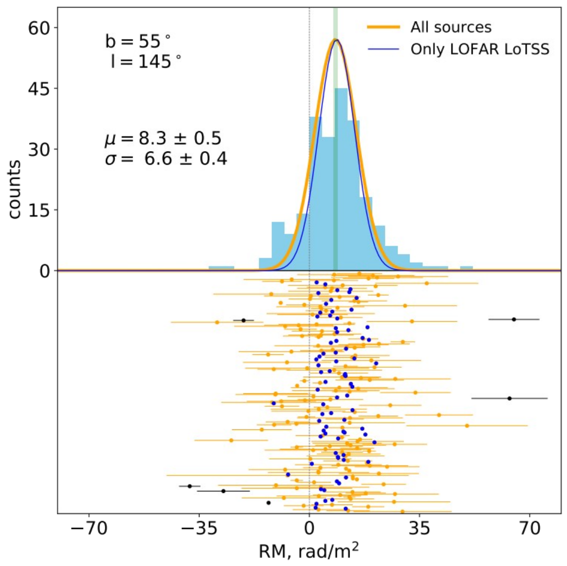


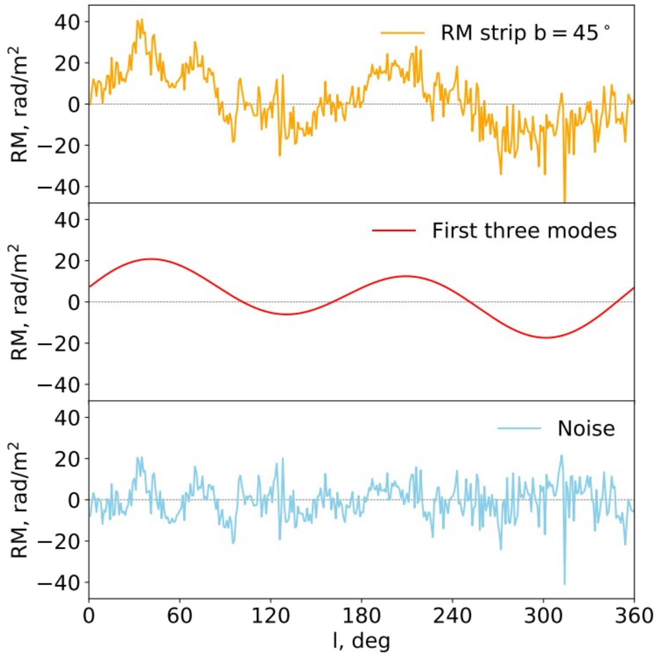


Estimation of data bins errorbars









- We are interested in global GMF structure – small details are not important

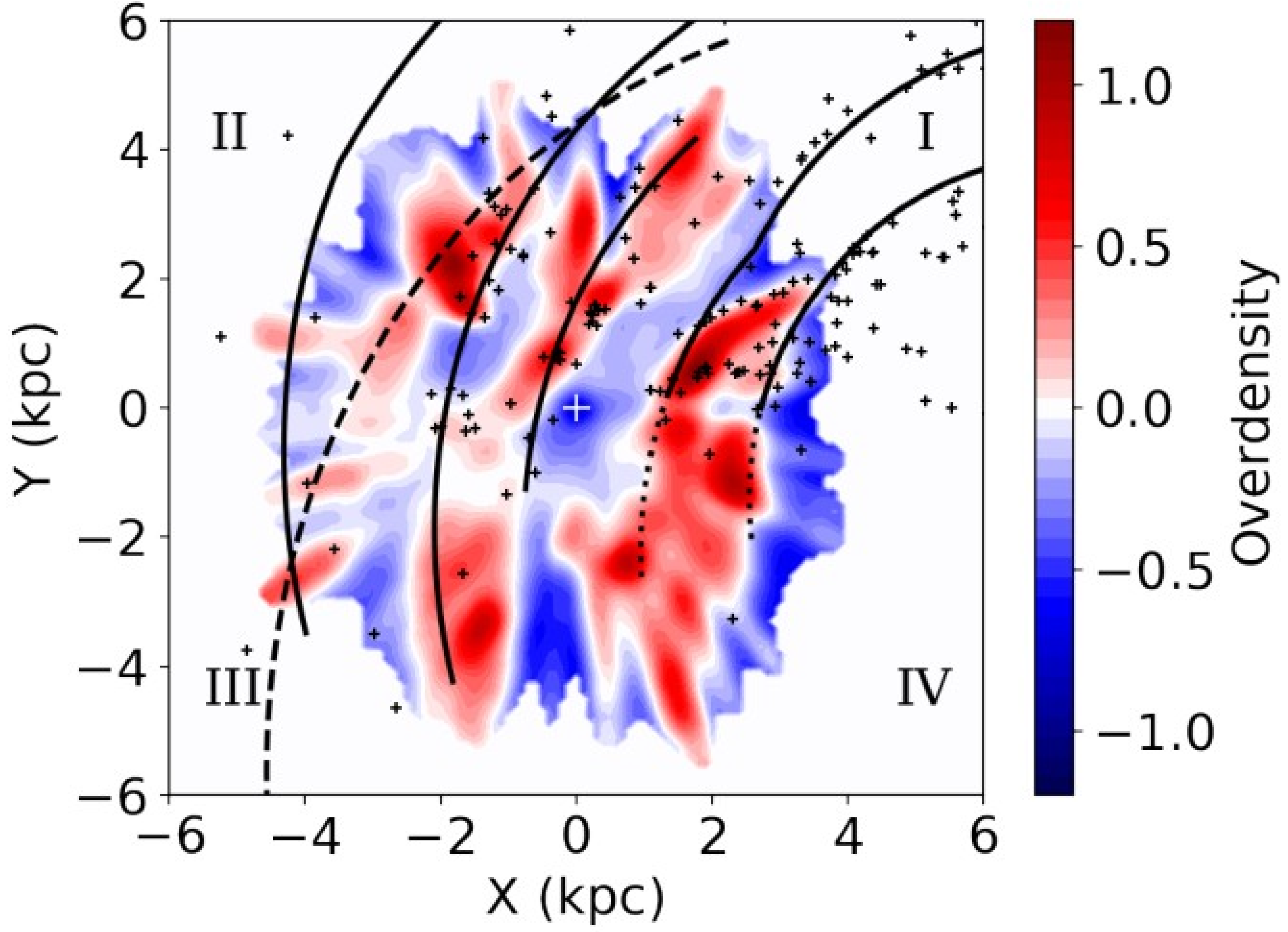
- Errors assignment procedure based on Fourier analysis

$$\sigma_{\mathrm{L}}^2 = 2\sum_{k_0}^{\infty} \mathrm{sinc}^2\left(\frac{kL}{2}\right) S_k$$

- Better treatement of errorbars – better sensitivity to the data

2) Pitch angle

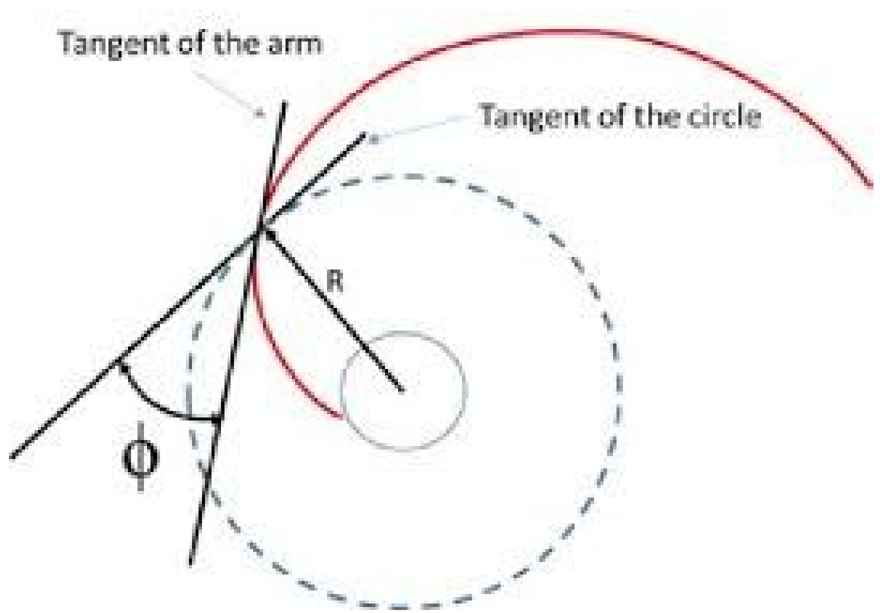
Pitch angle



Gaia spiral arm segments,
Poggio+21

According to GAIA DR3 data the spiral arms are more inclined than previously thought

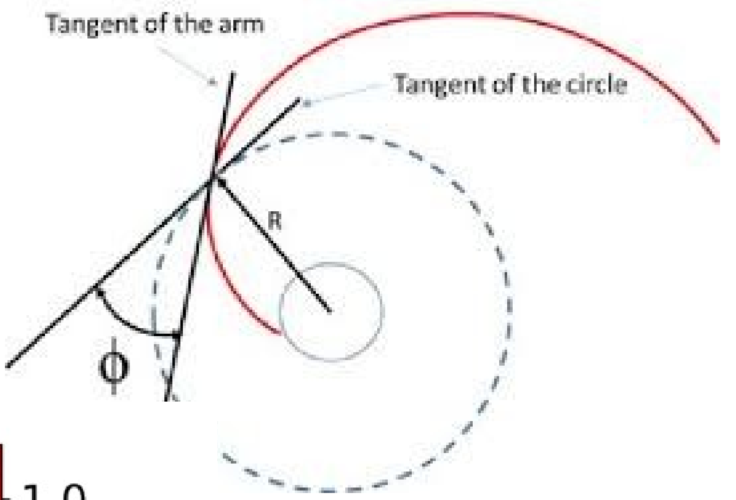
Pitch angle ~ 20 deg
In earlier studies pitch ~ 10 deg



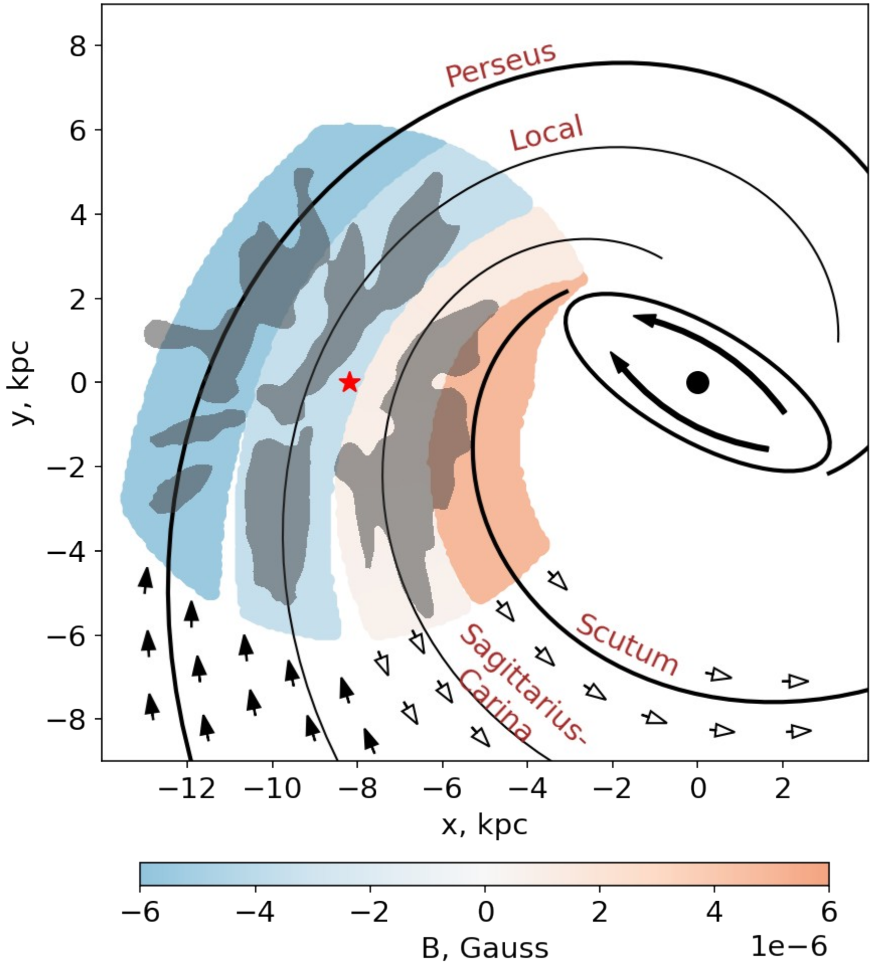
Pitch angle

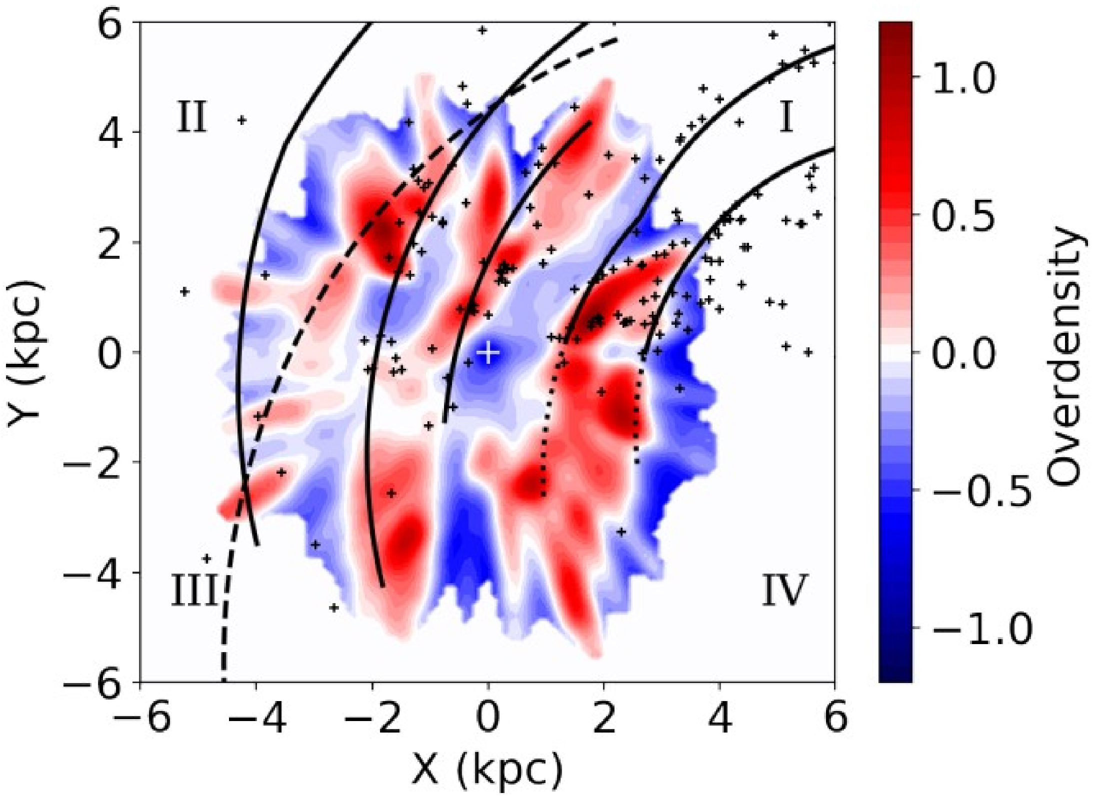
According to GAIA DR3 data the spiral arms are more inclined than previously thought

Our and Gaia pitch angle ~ 20 deg
In earlier studies pitch angle ~ 10 deg



Our model

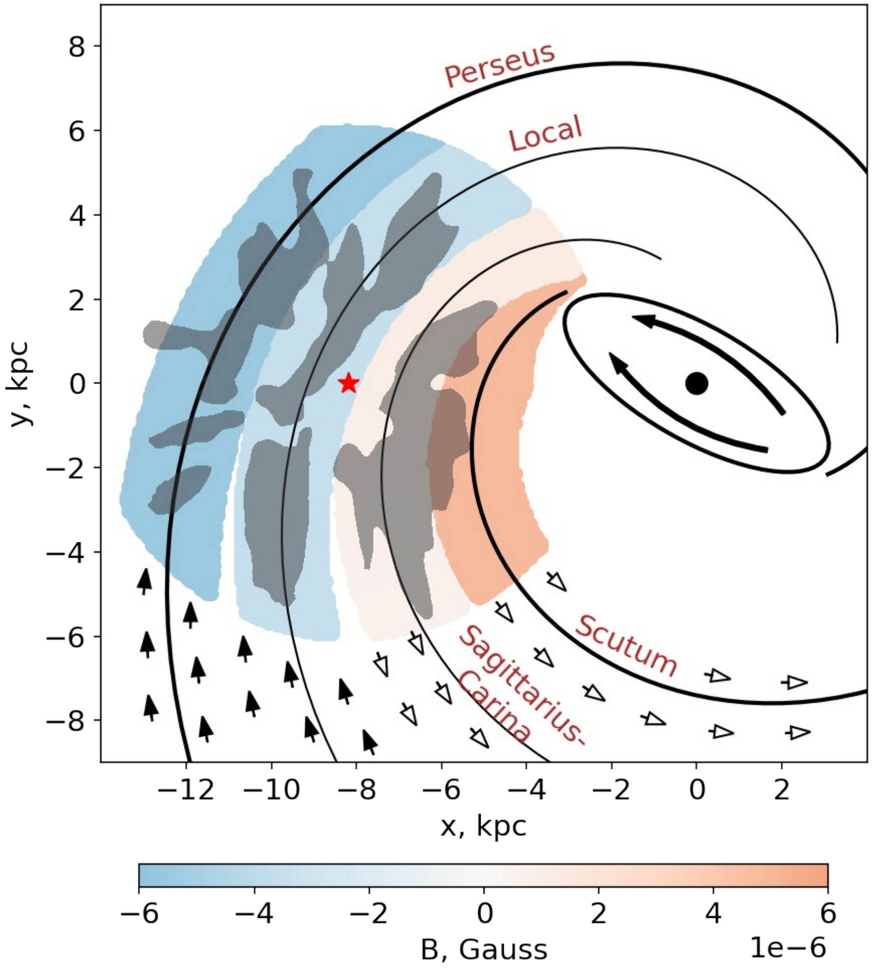




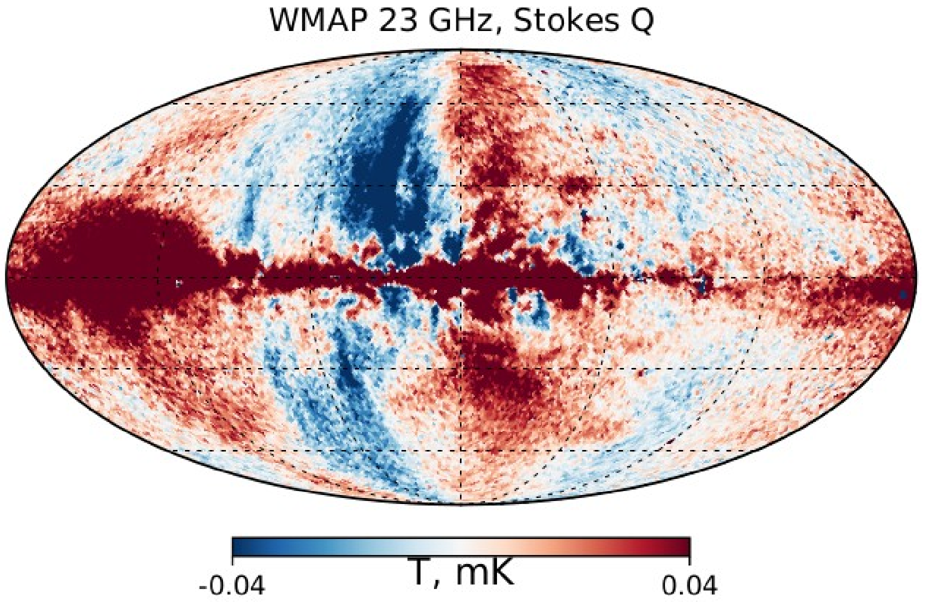
Gaia spiral arm segments, Poggio+21

3) Fan Region

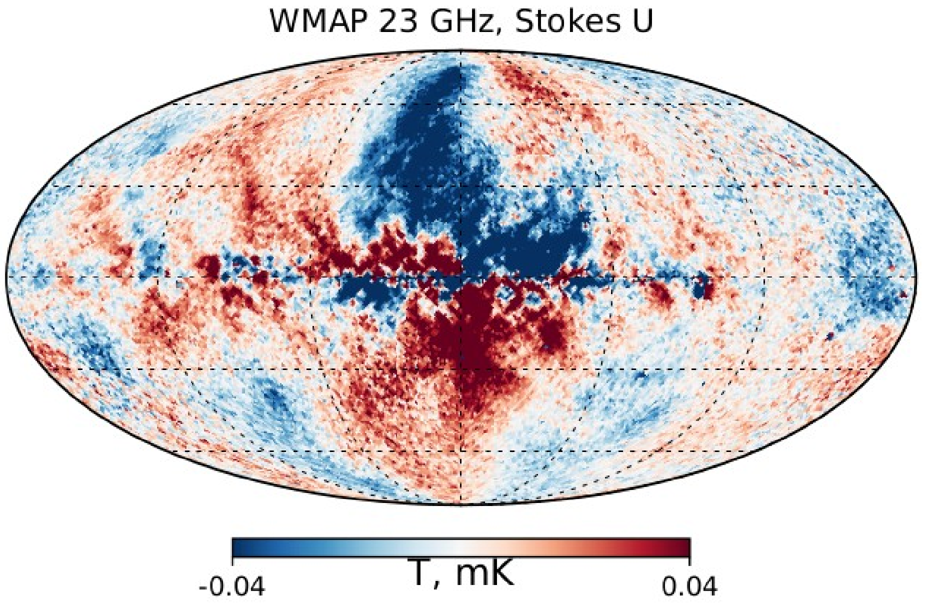
Fan Region



Perseus
Local
Sagittarius-
Carina
Scutum
y, kpc
x, kpc
8
6
4
2
0
−2
−4
−6
−8
−12
−10
−8
−6
−4
−2
0
2
−6
−4
−2
0
2
4
6
B, Gauss
1e−6



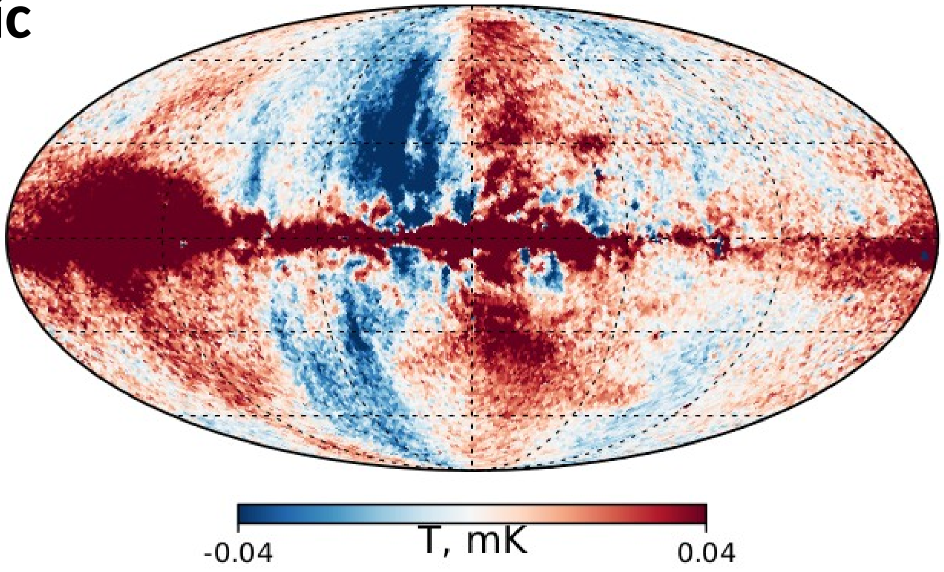
WMAP 23 GHz, Stokes Q
-0.04
T, mK
0.04

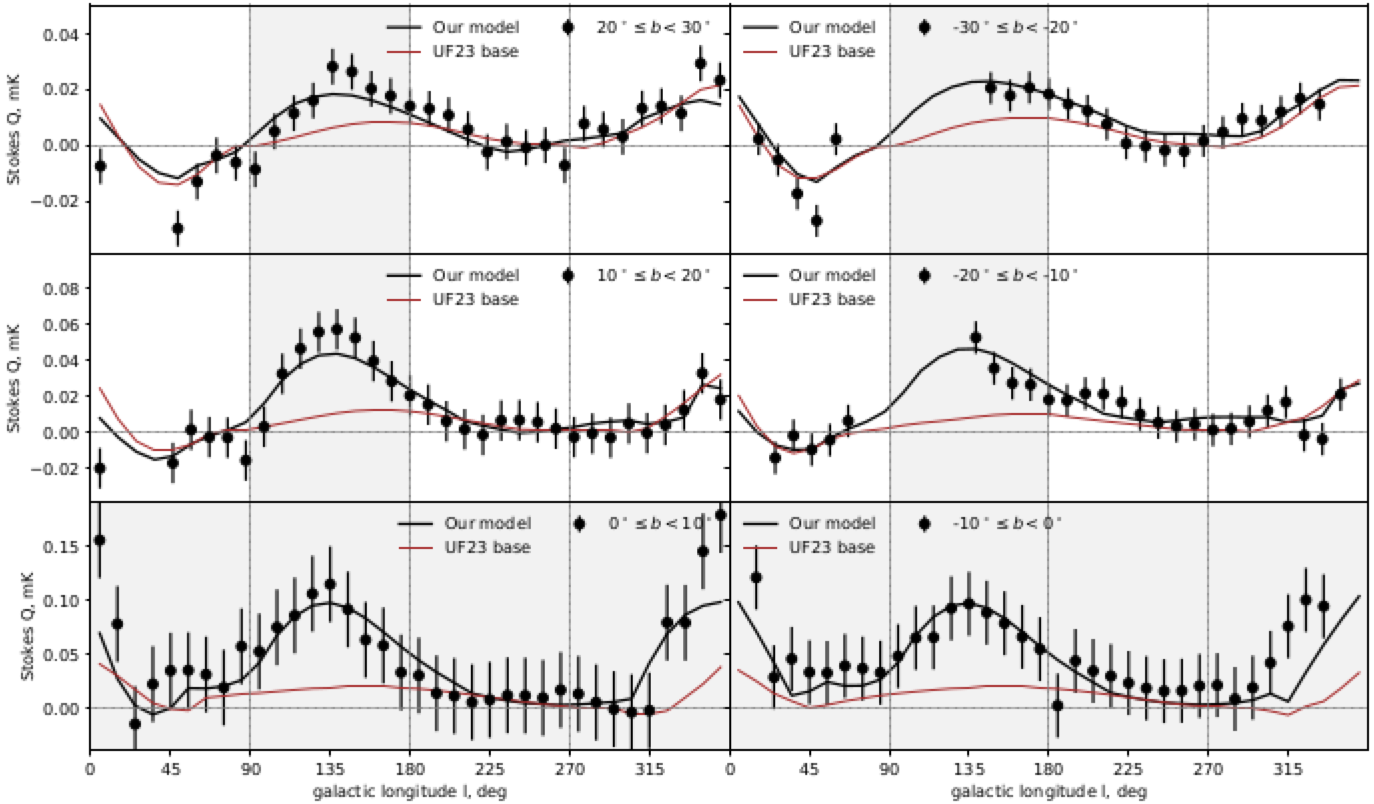


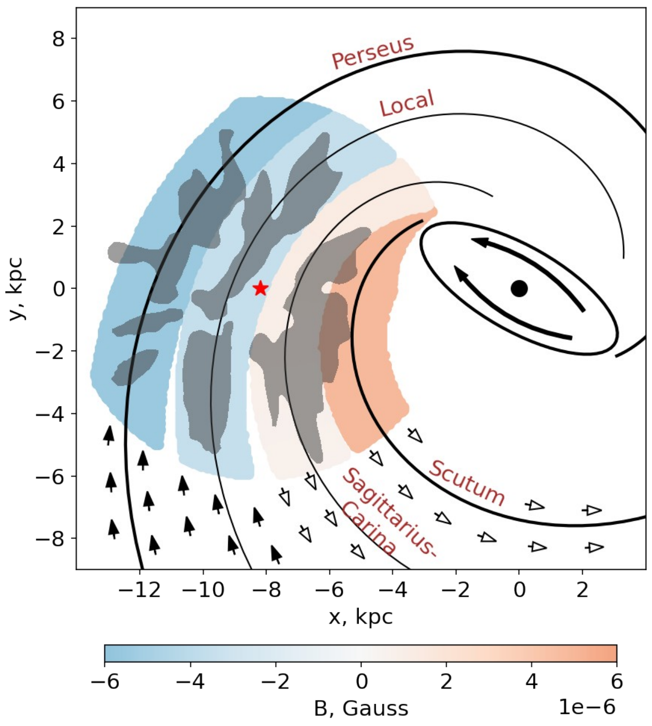
WMAP 23 GHz, Stokes U
-0.04
T, mK
0.04

Fan Region – bright red spot in Stokes Q near the Galactic plane at 90 < l < 180 deg

Hill+17: >30% of the Fan Region emission originates beyond 2 kpc from the Sun – part of the large-scale GMF

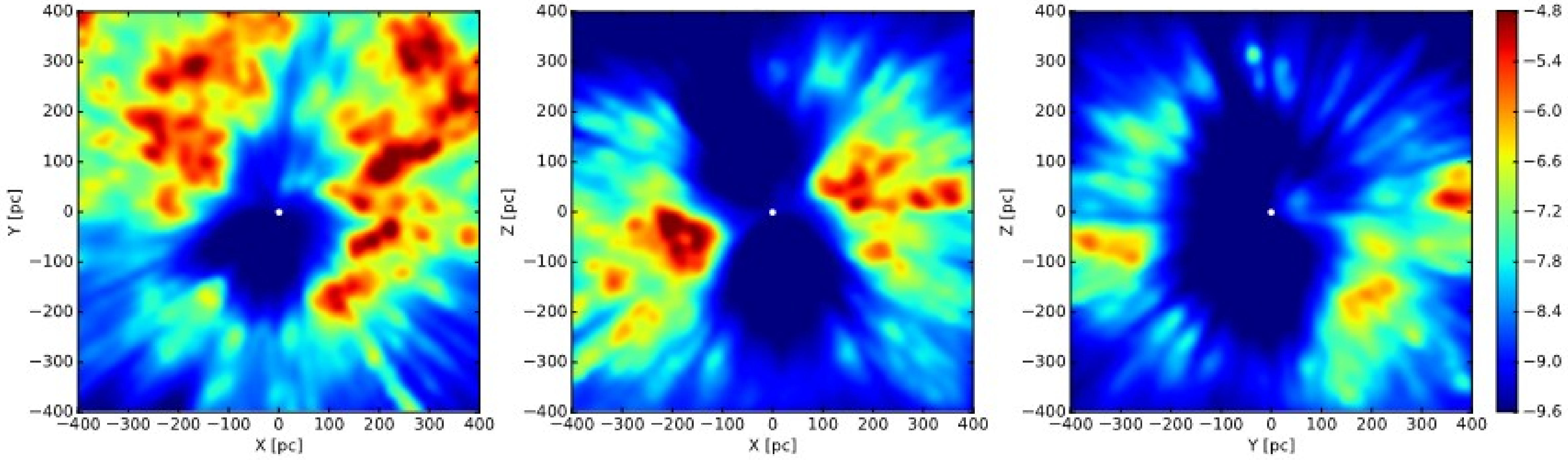






4) Local Bubble

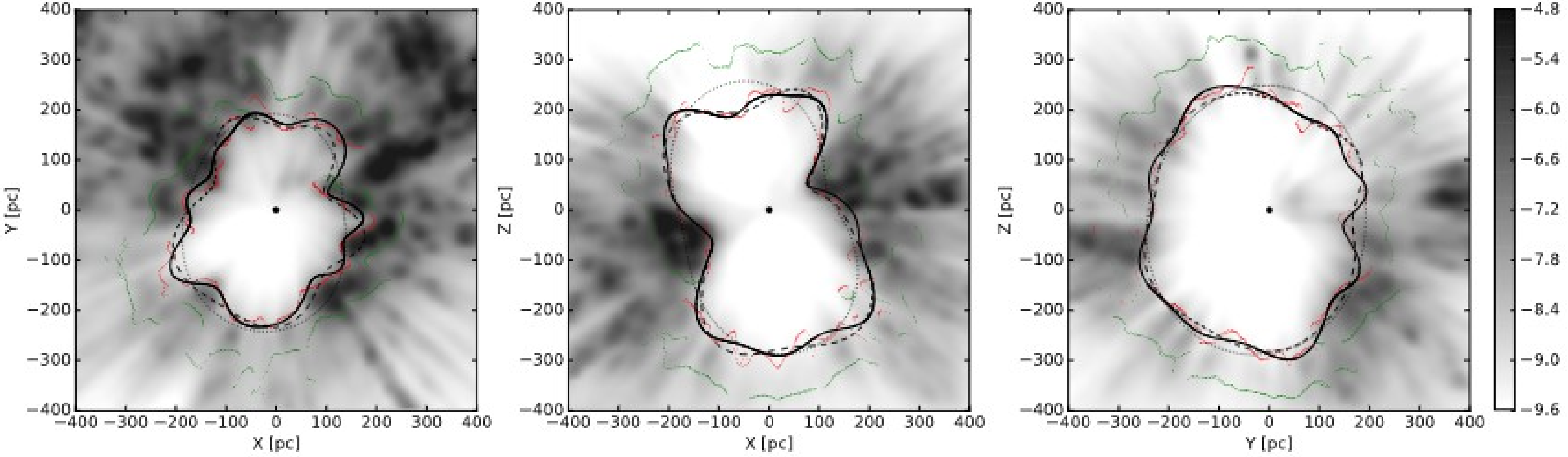
Local Bubble: extinction maps



Z axis is perpendicular to the Galactic plane
Bubble radius ~ 200 pc

Pelgrims+19

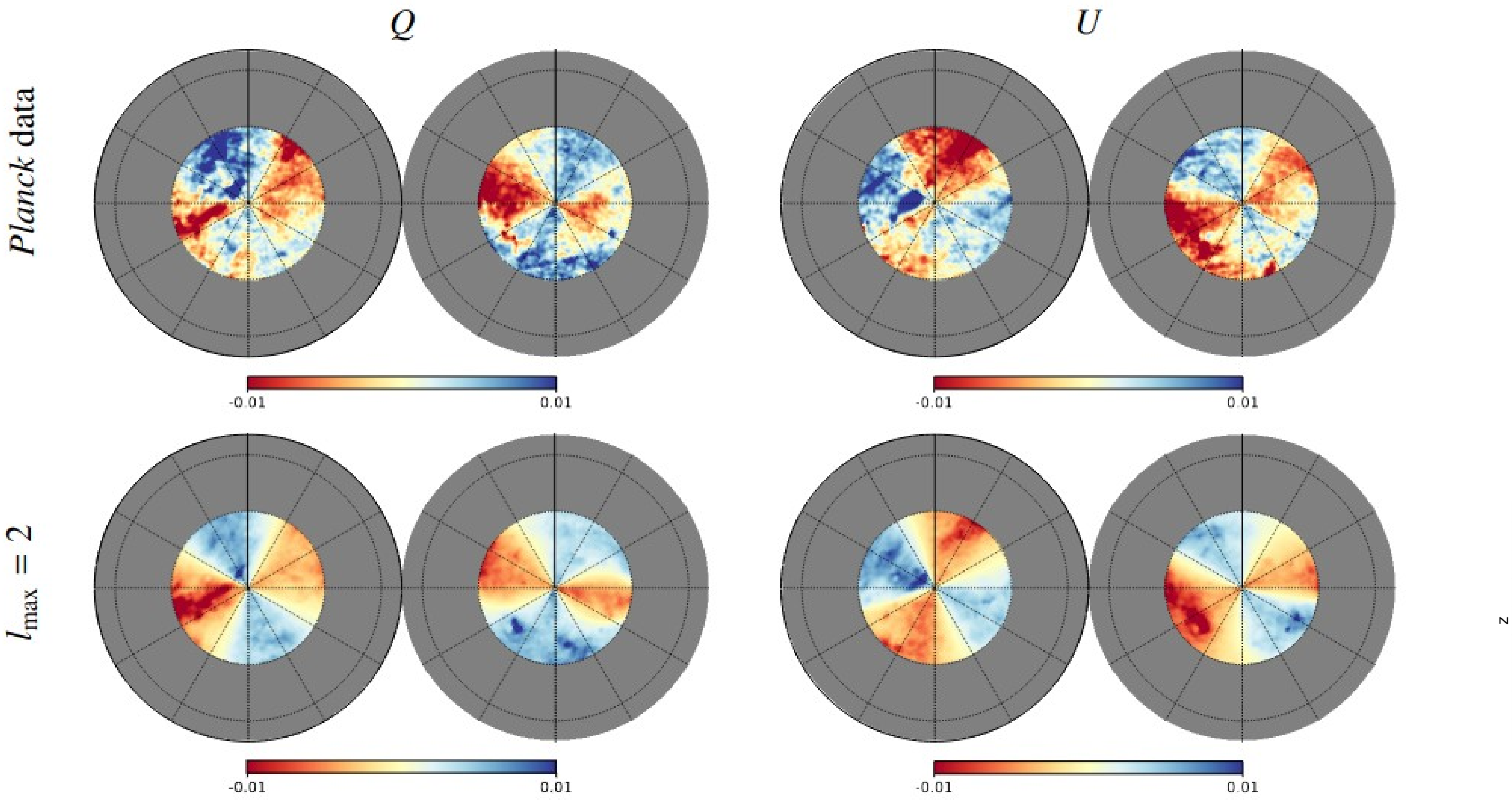
Local Bubble: shape of the wall

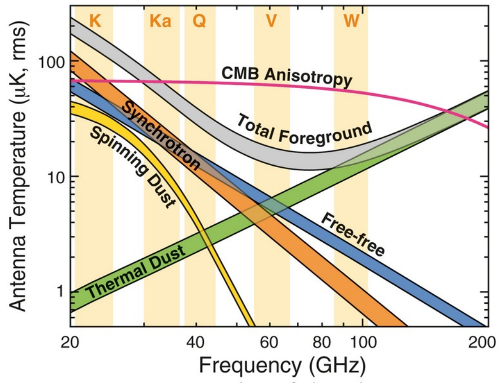


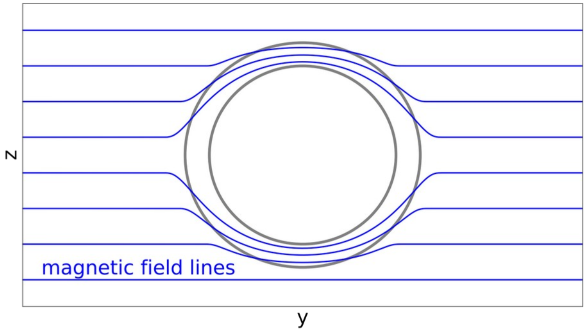
Z axis is perpendicular to the Galactic plane

Pelgrims+19

Local Bubble and Planck 353 GHz



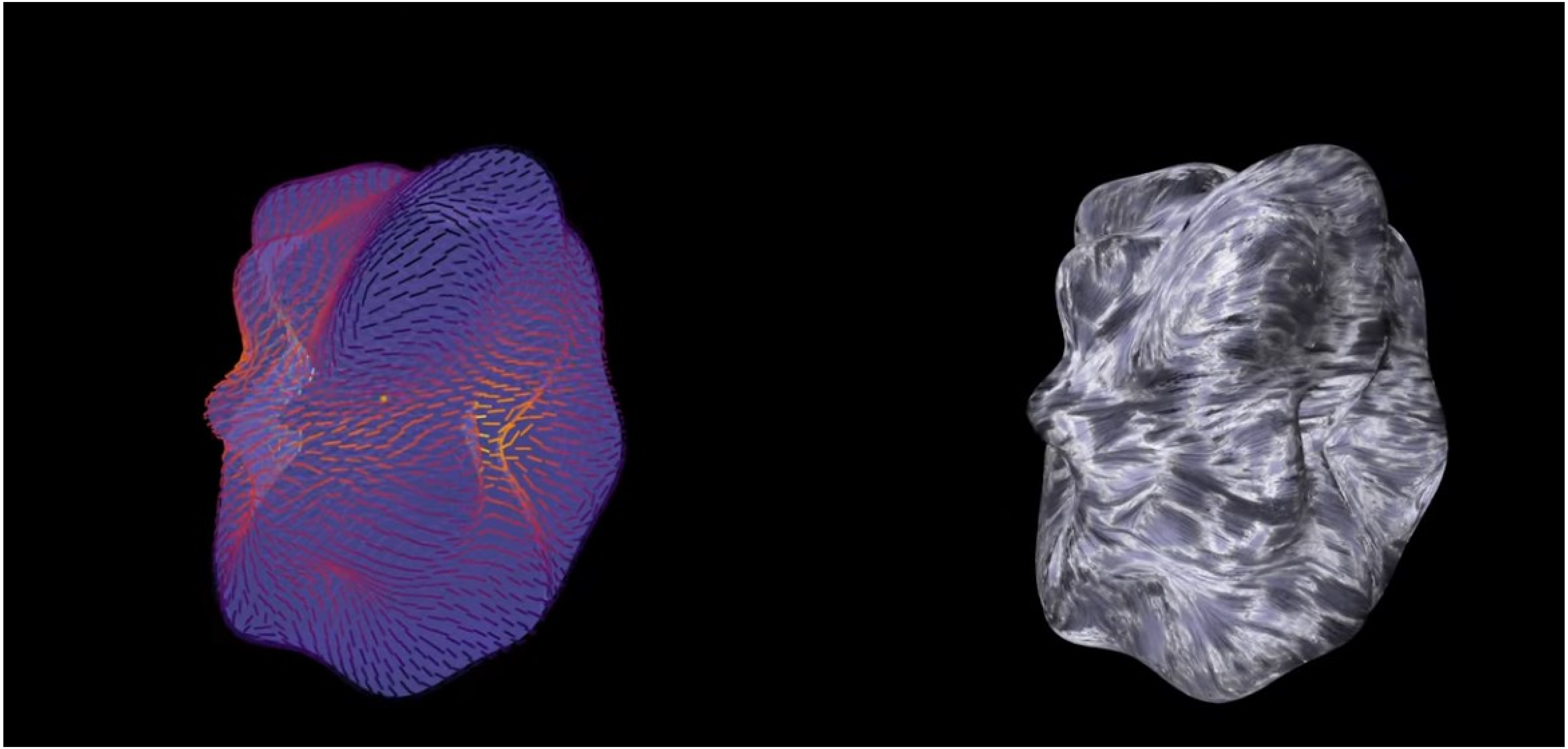




Pelgrims+19

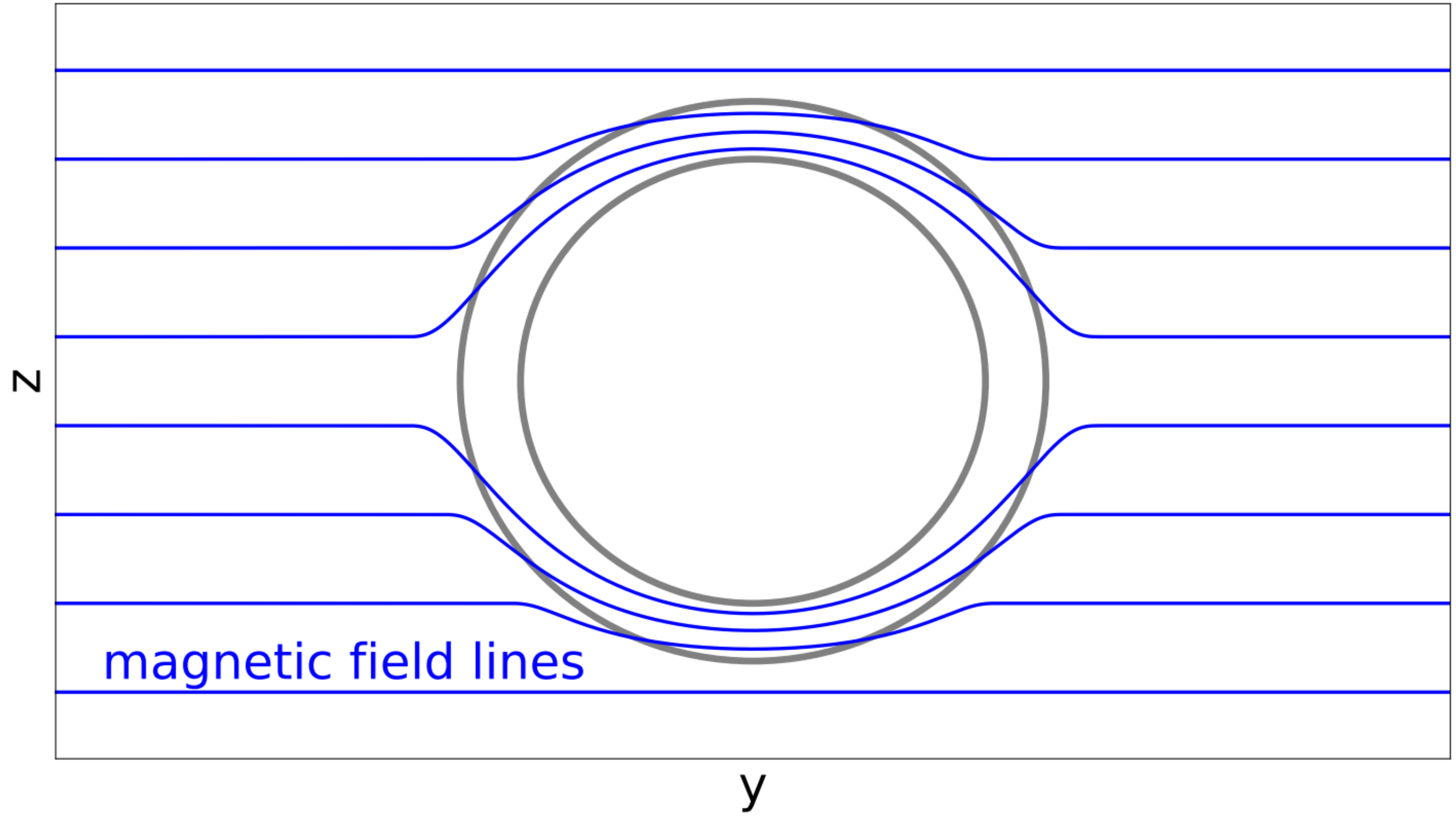
At the polar caps emission is dominated by the Local Bubble

Local Bubble: magnetic field on the wall



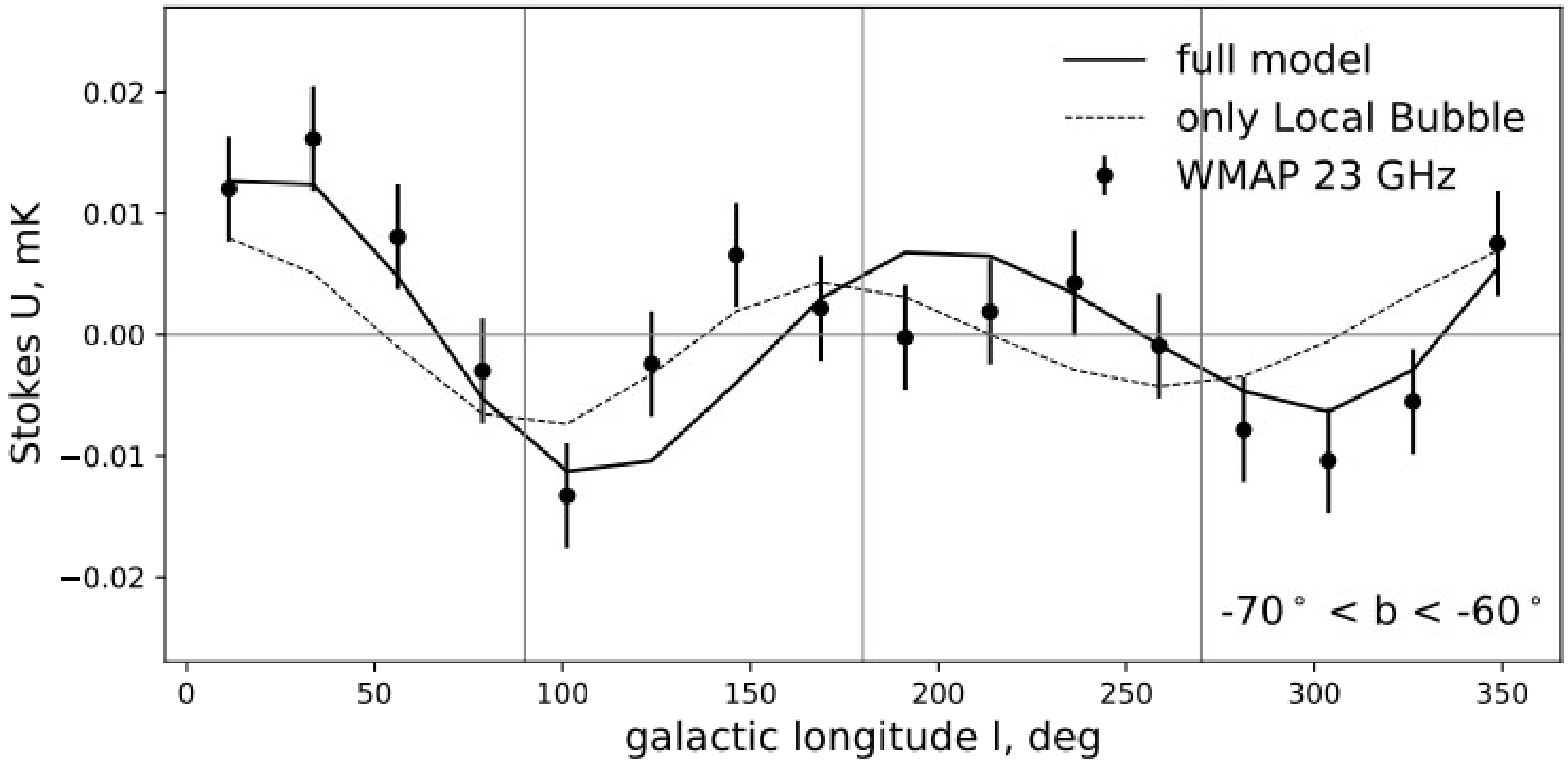
O'Neill+20

Local Bubble: toy model

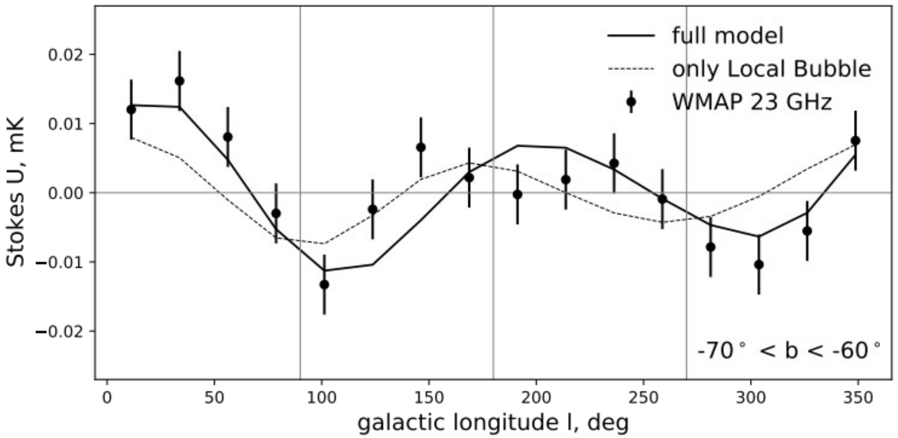


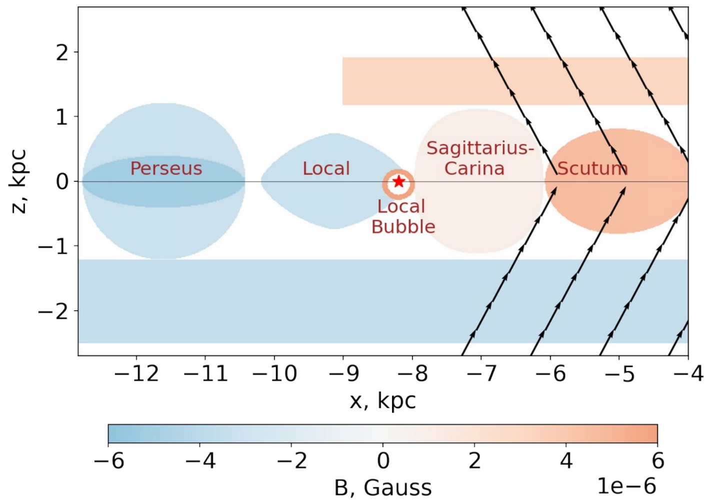
1) Pre-compressed field strength is the same as in the Local arm
2) The field is tangential to the bubble wall

Local Bubble: missing part of the synchrotron emission?

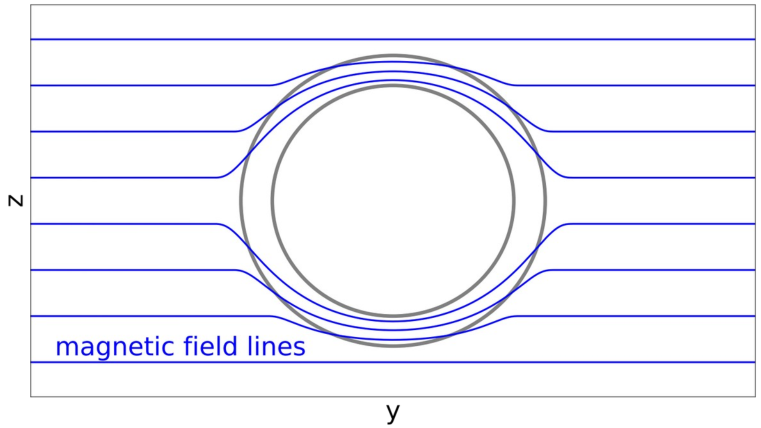


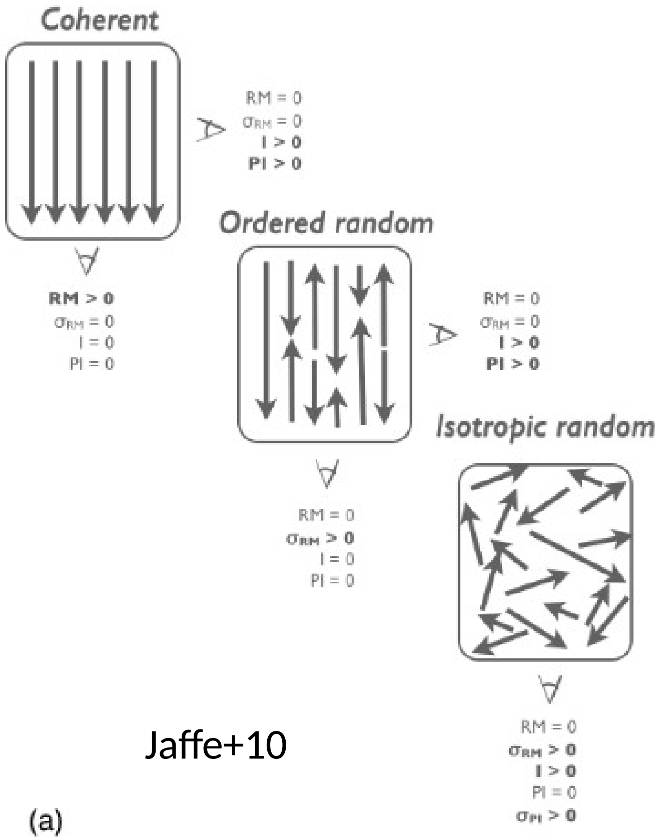
Local Bubble: missing part of the synchrotron emission?





PI(Local Bubble) ~ PI(Halo)



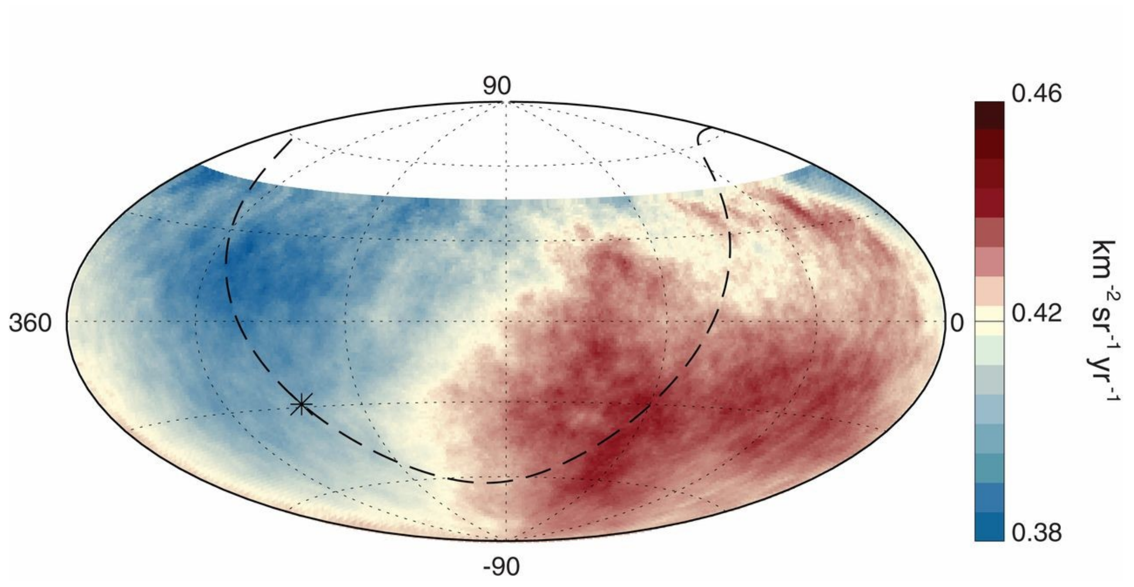


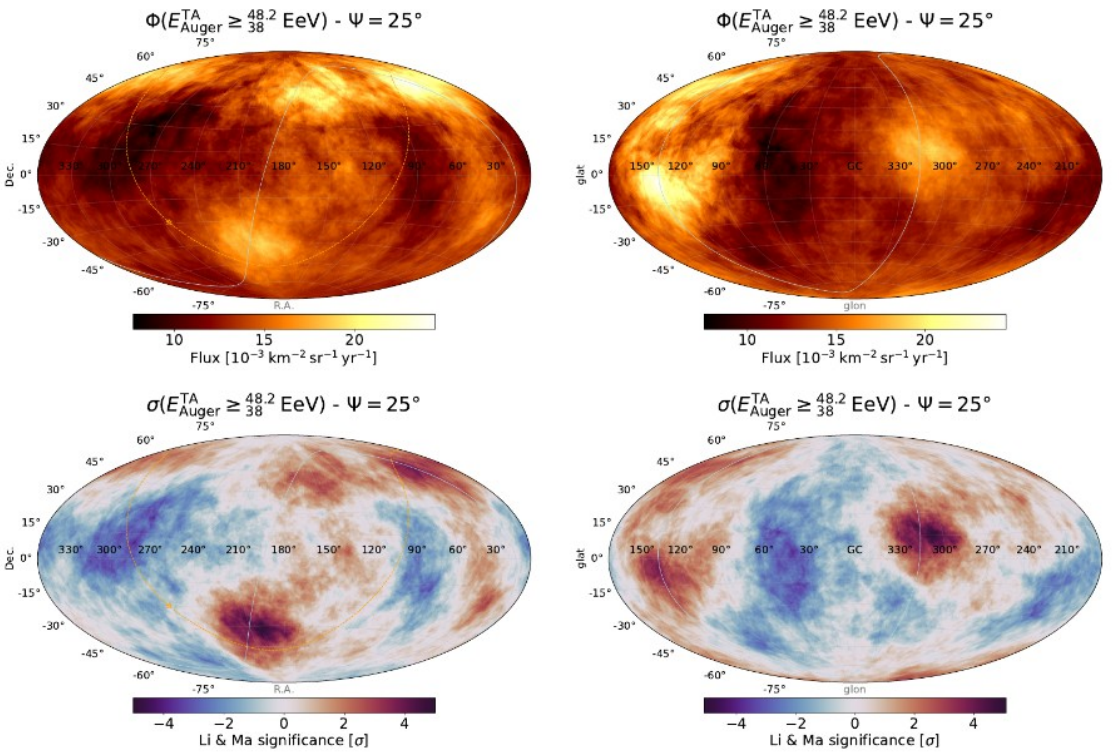
Jaffe+10

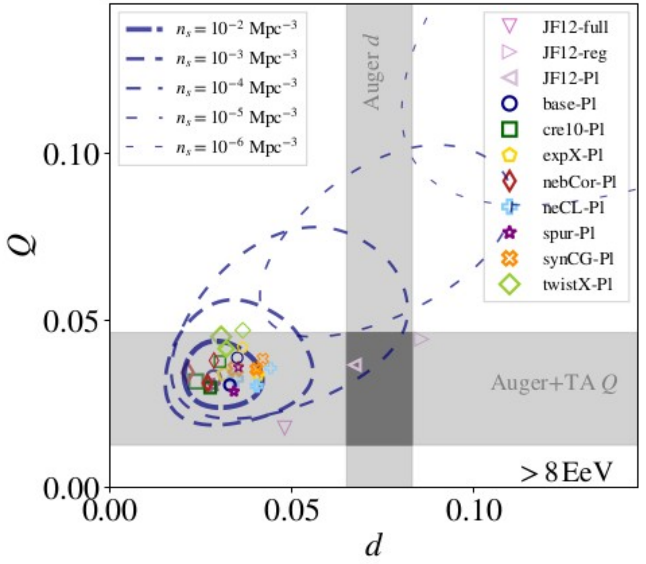
(a)

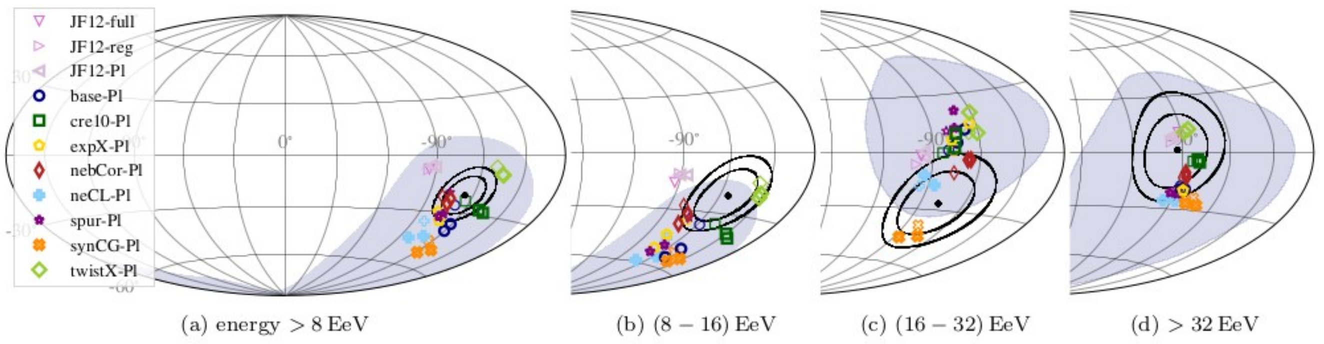
Taking into account the polarized synchrotron emission of the Local Bubble at 23 GHz, we found that striated fields (ordered random) are not needed. Local Bubble produces the missing part of the synchrotron brightness. Also it improves RM modeling and so prefered by the fit (compared to striated field which only improves synchrotron)

UHECR anisotropies



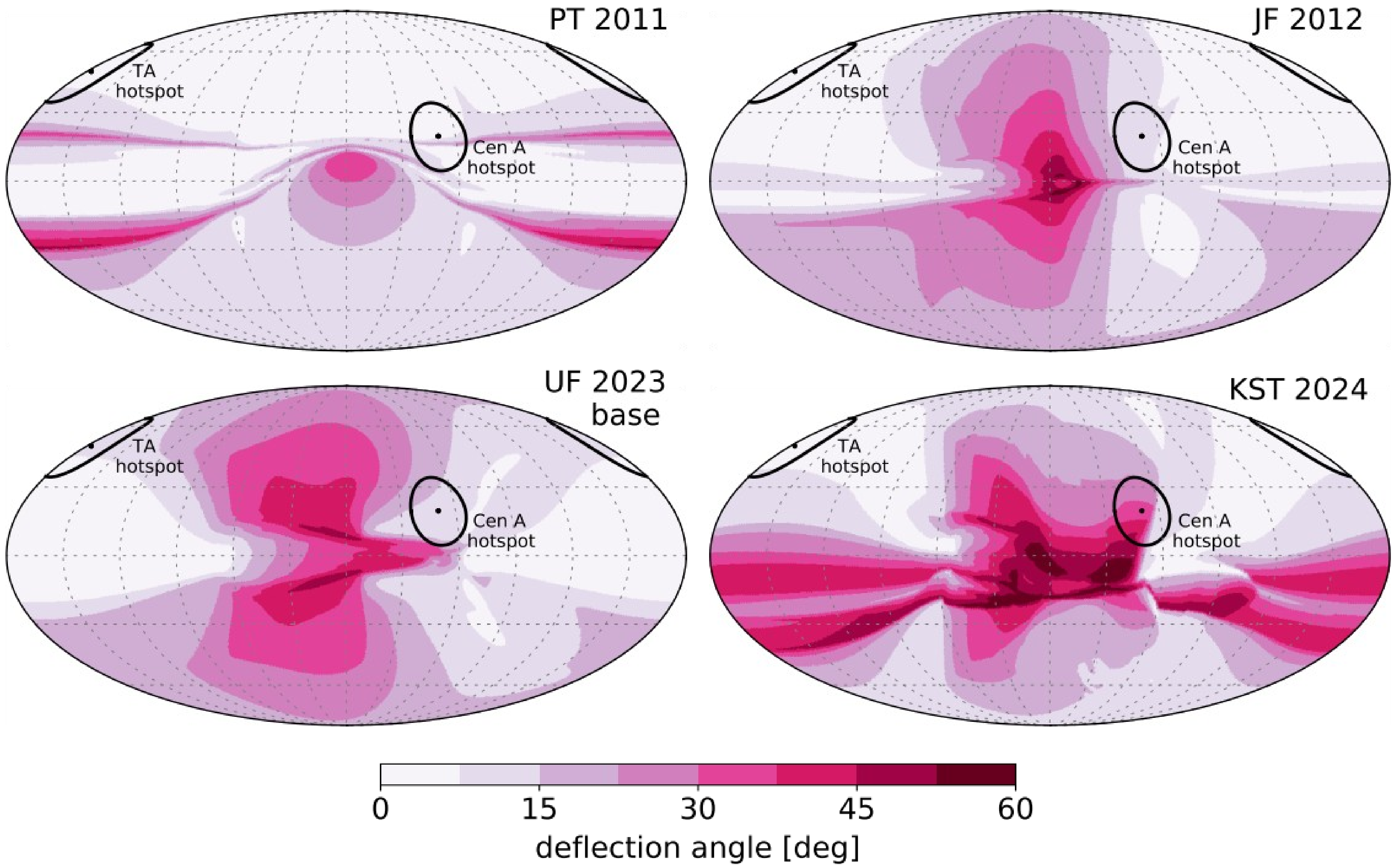






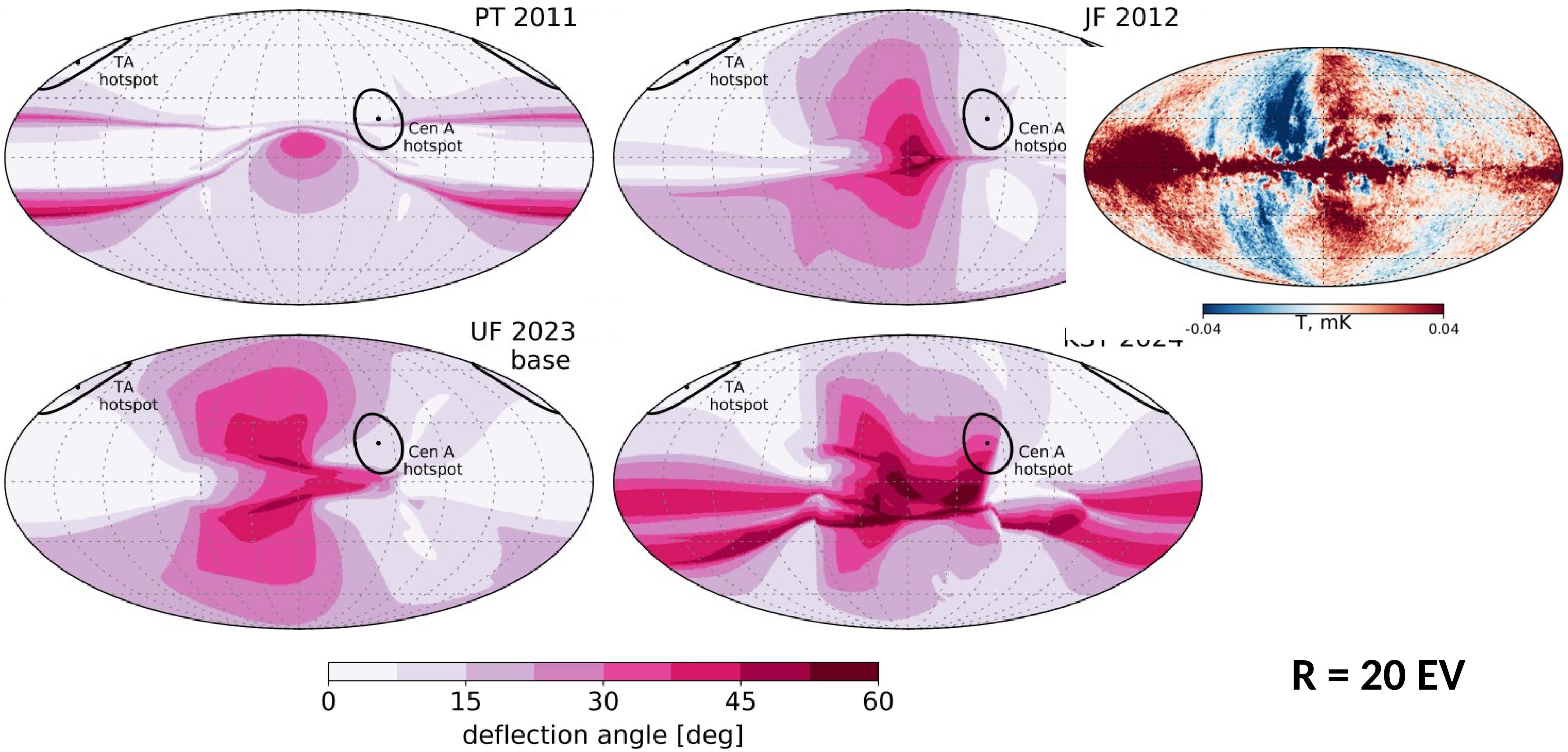
Bister, Farrar, Unger 2024

UHECR Deflections at 20 EV: model comparison



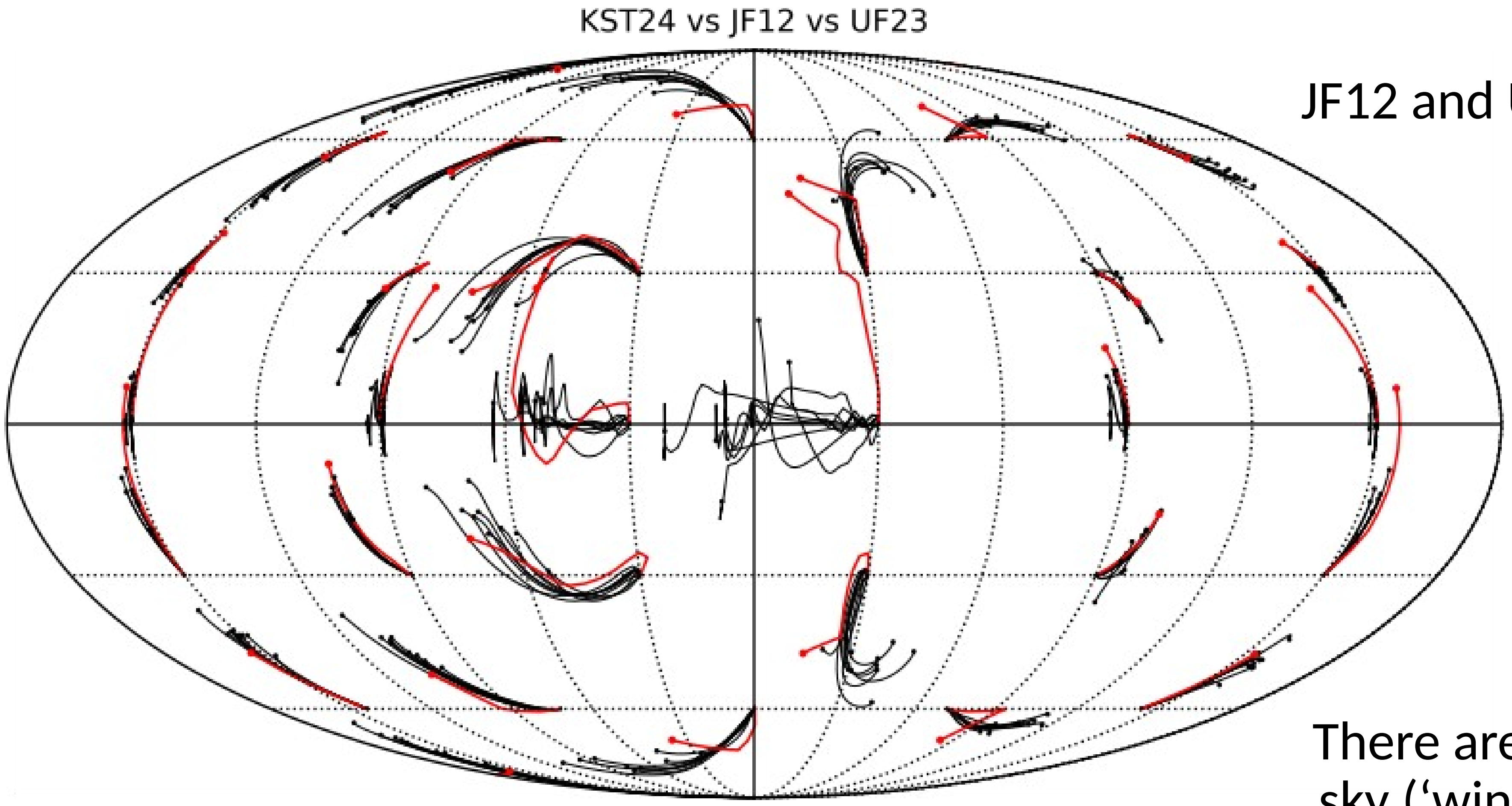
R = 20 EV

UHECR Deflections at 20 EV: model comparison



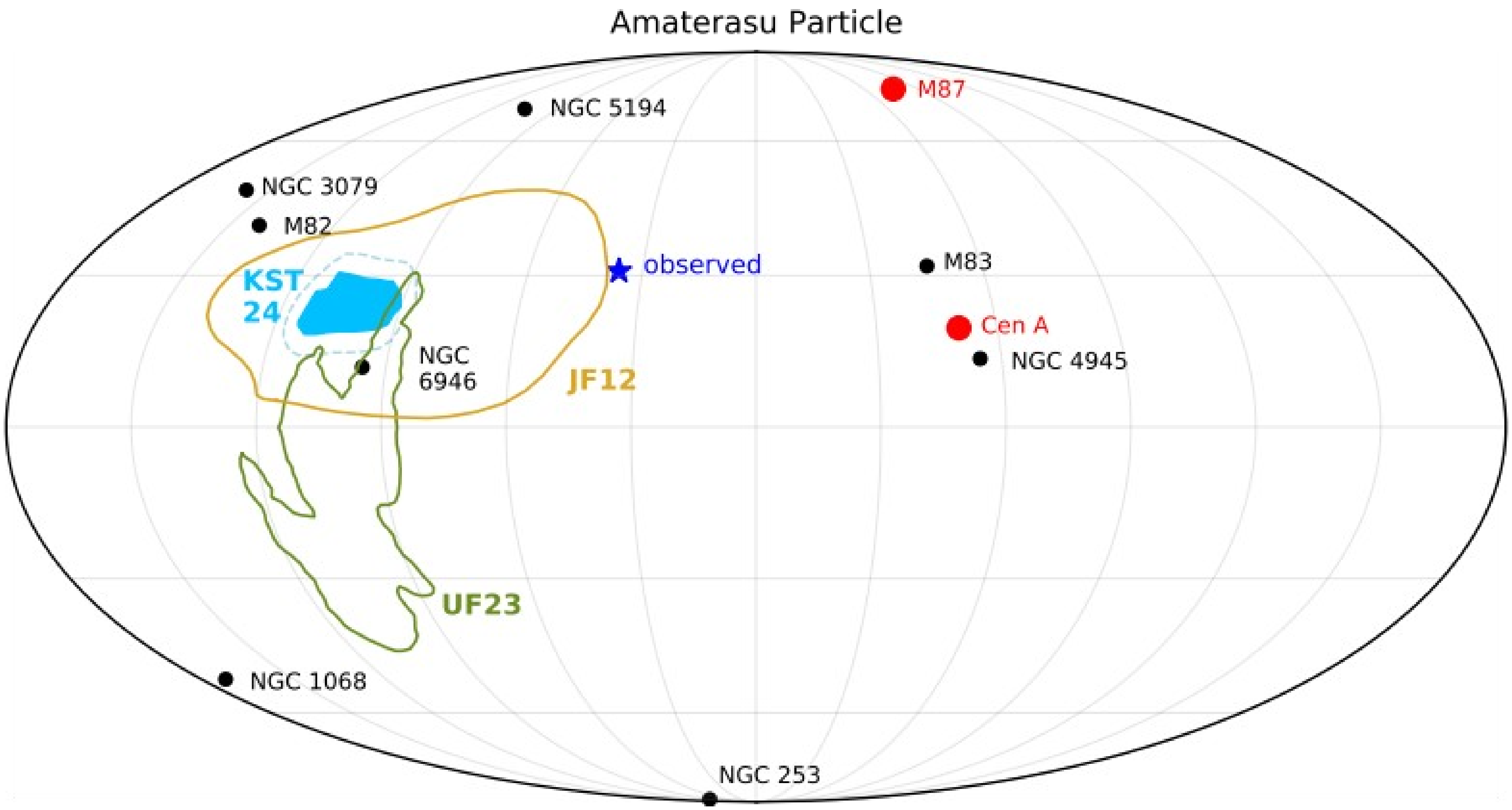
R = 20 EV

UHECR Deflections at 20 EV: model comparison



KST24 – red
JF12 and UF23 collection - black

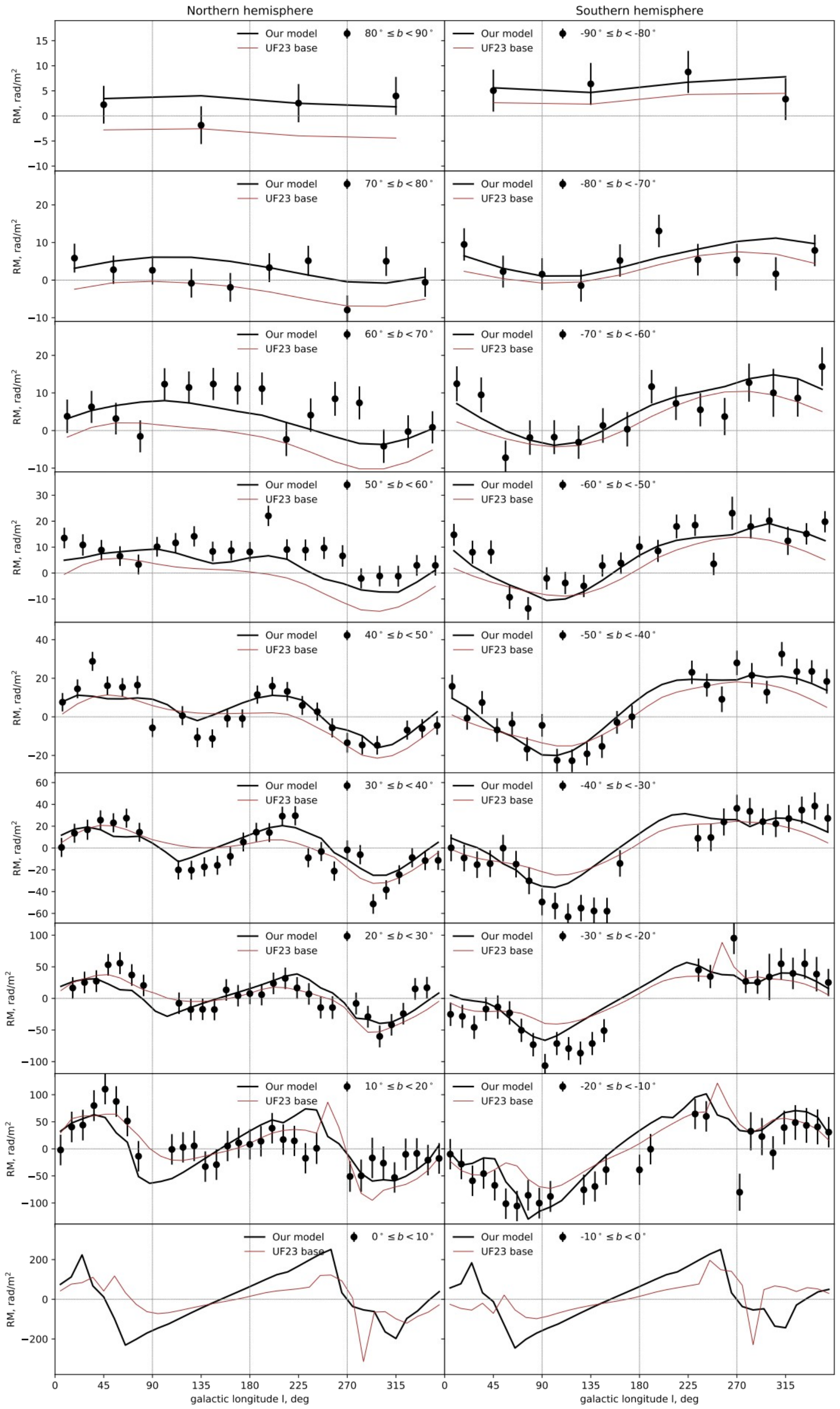
There are stable regions in the sky ('windows') where UHECR deflections are similar across all models


Amaterasu Particle
M87
NGC 5194
NGC 3079
M82
observed
M83
KST 24
Cen A
NGC 6946
NGC 4945
JF12
UF23
NGC 1068
NGC 253

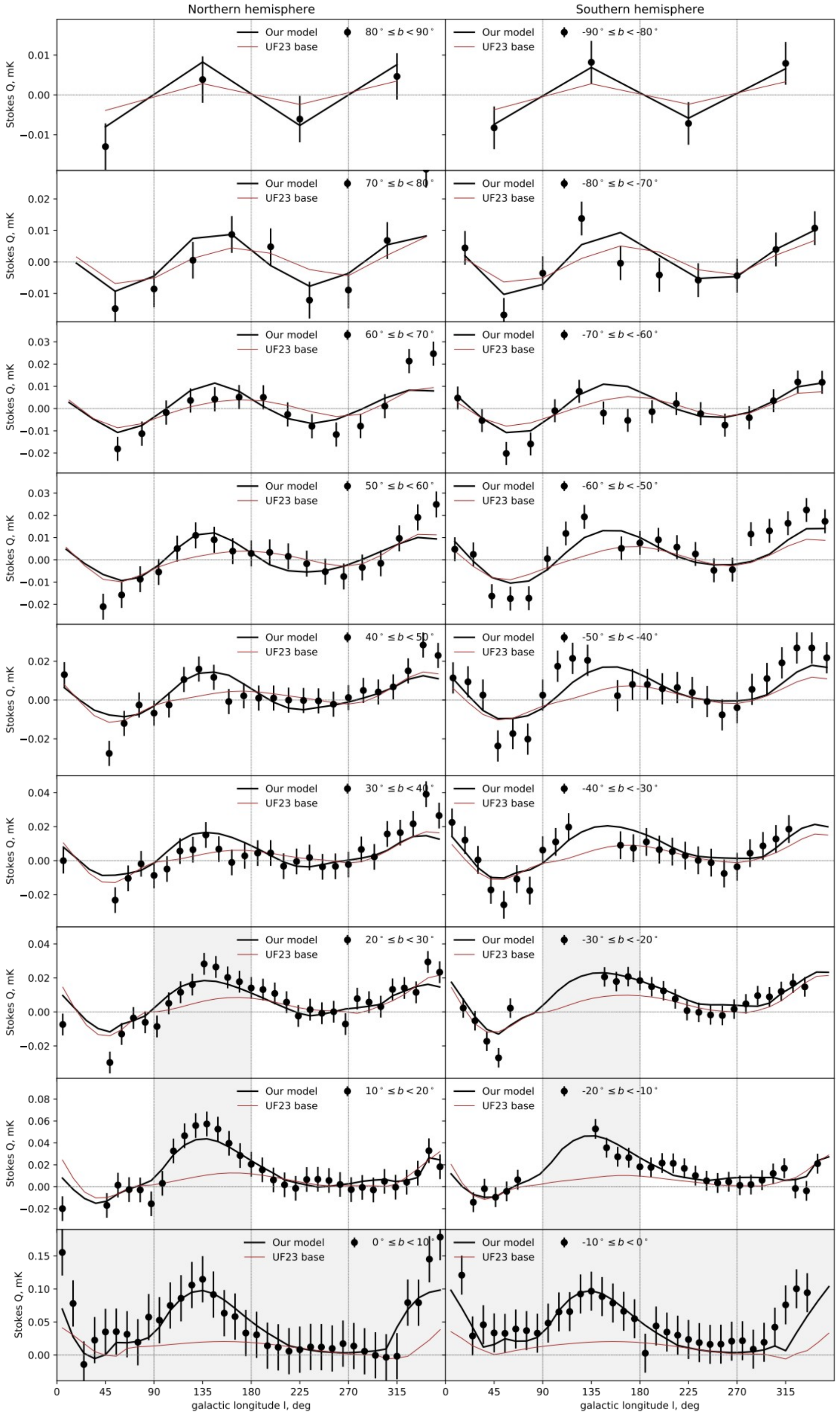
Conclusions

- We developed new statistical procedure that allow us to treat all datasets on the same footing
- We pitch angle of the disk field was found to be 20 deg in agreement with Gaia data
- The Fan Region is naturally incorporated into the large-scale structure of the GMF
- Local Bubble is taken into account – no striated fields needed
- There are regions in the sky there JF12, UF23 and KST24 predict similar small deflections - ‘windows’

Thank you for your attention!



Northern hemisphere
Southern hemisphere
Our model
UF23 base
80° ≤ b < 90°
-90° ≤ b < -80°
70° ≤ b < 80°
-80° ≤ b < -70°
60° ≤ b < 70°
-70° ≤ b < -60°
50° ≤ b < 60°
-60° ≤ b < -50°
40° ≤ b < 50°
-50° ≤ b < -40°
30° ≤ b < 40°
-40° ≤ b < -30°
20° ≤ b < 30°
-30° ≤ b < -20°
10° ≤ b < 20°
-20° ≤ b < -10°
0° ≤ b < 10°
-10° ≤ b < 0°
RM, rad/m²
galactic longitude l, deg



Northern hemisphere
Southern hemisphere
Our model
UF23 base
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-90° ≤ b < -80°
70° ≤ b < 80°
-80° ≤ b < -70°
60° ≤ b < 70°
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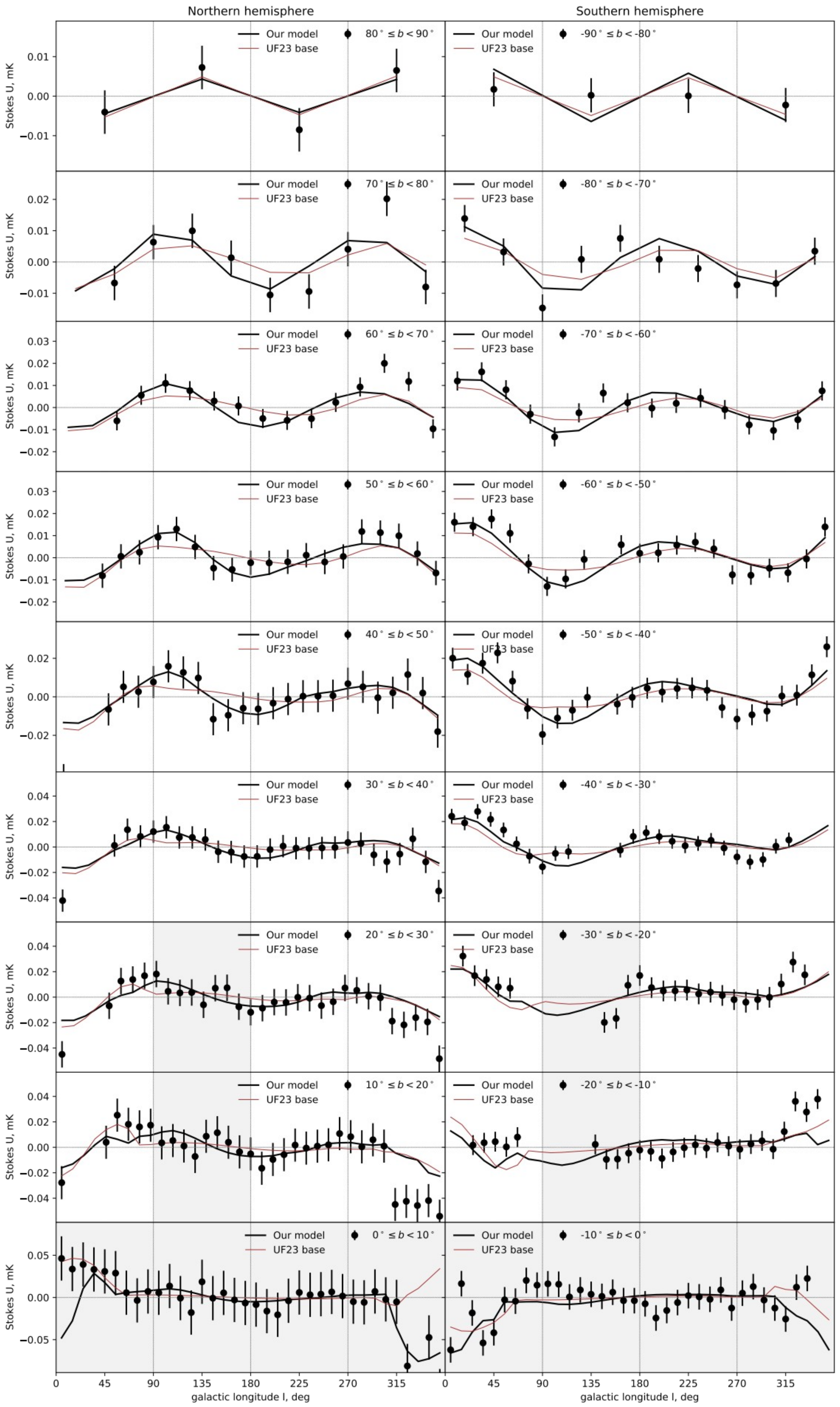
-50° ≤ b < -40°
30° ≤ b < 40°
-40° ≤ b < -30°
20° ≤ b < 30°
-30° ≤ b < -20°
10° ≤ b < 20°
-20° ≤ b < -10°
0° ≤ b < 10°
-10° ≤ b < 0°
Stokes Q, mK
galactic longitude l, deg


Northern hemisphere
Southern hemisphere
Our model
UF23 base
80° ≤ b < 90°
70° ≤ b < 80°
60° ≤ b < 70°
50° ≤ b < 60°
40° ≤ b < 50°
30° ≤ b < 40°
20° ≤ b < 30°
10° ≤ b < 20°
0° ≤ b < 10°
-90° ≤ b < -80°
-80° ≤ b < -70°
-70° ≤ b < -60°
-60° ≤ b < -50°
-50° ≤ b < -40°
-40° ≤ b < -30°
-30° ≤ b < -20°
-20° ≤ b < -10°
-10° ≤ b < 0°
Stokes U, mK
galactic longitude l, deg