CR PROPAGATION AND MAGNETIC FIELDS

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Outline

1. Propagation of CR in Magnetic Fields
2. Extragalactic fields
3. Galactic field
4. Summary

Outline

Deflections in magnetic fields

- In the relativistic limit, deflections only depend on rigidity Z/E
- Regular field

$$\theta \sim 0.52^\circ \, Z \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{R}{1\mathrm{kpc}}\right) \left(\frac{B_\perp}{10^{-6}\mathrm{G}}\right)$$

- Random field

$$\theta \sim 1.8^\circ \, Z \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{l_c R}{50\mathrm{Mpc}^2}\right)^{1/2} \left(\frac{B}{10^{-9}\mathrm{G}}\right)$$

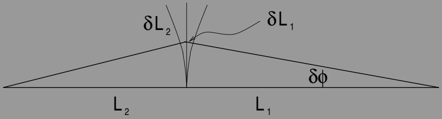
- $\Longrightarrow$Need to understand magnetic fields

Time delays

- Deflections imply time delays

$$\frac{\delta L}{L} = \frac{1}{2}(\delta\phi)^2 \frac{L_1}{L_2}$$

Take $\delta\phi = 2^\circ$,



$$L_1 = 1\ \mathrm{kpc} \quad \rightarrow \quad \Delta t = 2\ \mathrm{yr}$$
$$L = 50\ \mathrm{Mpc} \quad \rightarrow \quad \Delta t = 10^5\ \mathrm{yr}$$

- Transient sources are seen as steady

Outline

Extragalactic fields

- Outside of galaxies, fields have only been measured in some galaxy clusters. Large values $O(\mu G)$ were found in cluster cores, coherent over distances of order of core size.
- These fields are irrelevant for deflections (but still produce time delays!) since angular size of cluster cores as seen from Earth is small.

- Fields in filaments and sheets are not known, only theoretical estimates exist. Likely also irrelevant for deflections, *unless we are inside a filament ourselves*.

- Fields in voids are not measured either, but are constrained from observations.

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Fields in voids: upper bounds

- Strongest bounds come from Faraday rotation measures

Pshirkov, PT, Urban, PRL 116 (2016) 191302

- Polarized light passing through magnetized medium containing density of free electrons n_e changes polarization direction by the angle proportional to (wavelength)^2. The coefficient is called rotation measure (RM); specifically,

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2} \int n_e(l) B_{||}(l)\, dl$$

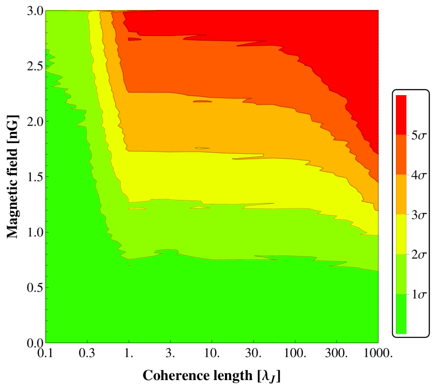
Note:

(i) only parallel component of B enters

(ii) electron density is required to estimate B

Fields in voids: upper bounds

- The NVSS catalog contains $\sim 40\,000$ RMs of extragalactic sources.
- In the presence of extra-galactic MFs the rotation measures are expected to systematically grow with redshift. Observations do not demonstrate such growth. $\Longrightarrow$ constraints on MF



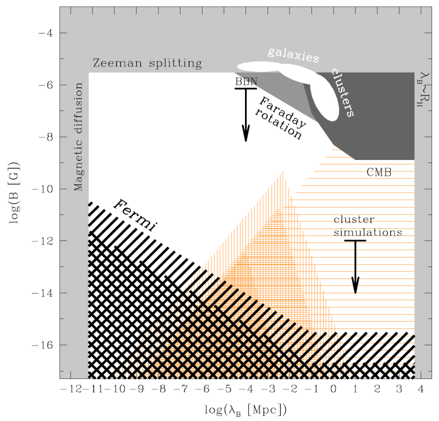
Extragalactic fields: lower bound

- Interestingly, there exists also a lower bound

  Neronov, Vovk, Science 328(2010)73

$$B \geq 3 \times 10^{-16}\mathrm{G}$$

- This bound comes from non-observation of cascade photons in the spectra of TeV gamma-ray sources. This non-observation is explained by the deflection of cascading e^{+}, e^{-} in the extragalactic magnetic field, hence lower bound.

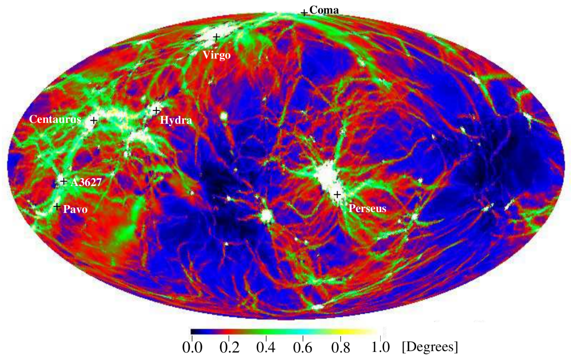


Numerical simulations

- Some insight may come from simulations:

  Dolag, Grasso, Springel, Tkachev 2003;
  Sigl, Miniati, Enslin 2004

  (contradict each other!)



$E = 4 \times 10^{19}$ eV

- Fields in voids: $\sim 10^{-12}$ G
  Fields in filaments: $\sim 10^{-10}$ G

Outline

Coherent Galactic field

- Galactic field is usually considered as consisting of two components:
  - Regular component. Coherent over scales $\gtrsim 1$ kpc. Origin is not really understood; probably dynamo mechanism (?).
  - Turbulent component. Larger strength but smaller coherence length. Originates from supernova explosions and other local processes.
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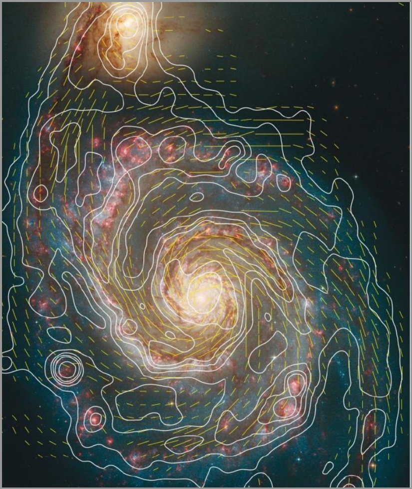
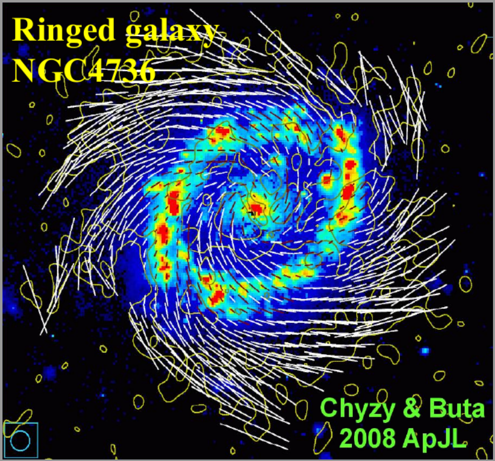
Coherent Galactic field

- Is coherent magnetic field observed in other galaxies?





Coherent Galactic field

- Is coherent magnetic field present in the Milky way?
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Taylor, Stil and Sunstrum, 2009, ApJ, 702, 1230

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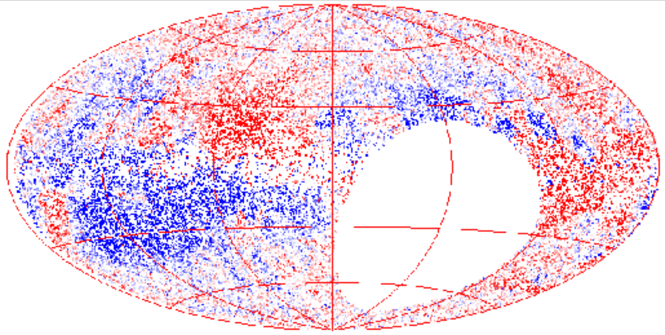


Taylor, Stil and Sunstrum, 2009, ApJ, 702, 1230

Coherent Galactic field

- Pulsar Faraday rotation measures:

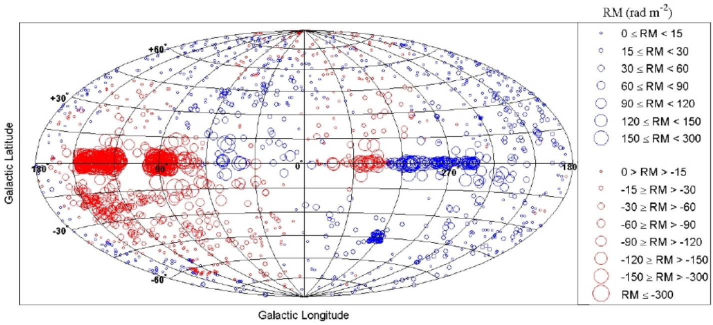


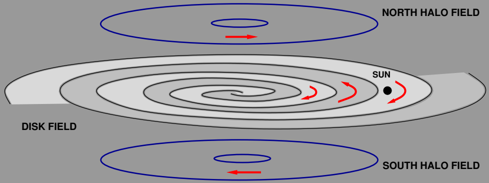
Fig. 1.— An all-sky equal-area Aitoff RM plot of the smoothed RM's from our 2257-source compilation of extragalactic source RM's. The smoothing method is described in the text.

Kronberg, Newton-McGee' 2009

Coherent Galactic field

- The RM data can be reasonably well fitted by a model containing both disk and halo components

Pshirkov, P.T., Kronberg, Newton-McGee, 2011 ApJ 738 192



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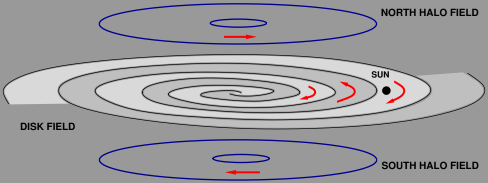
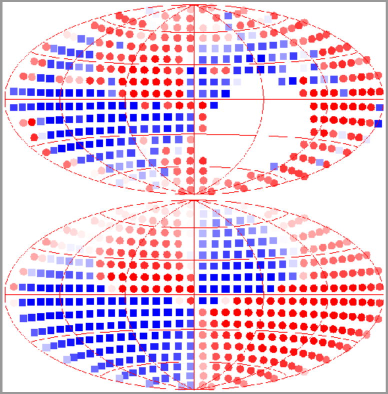
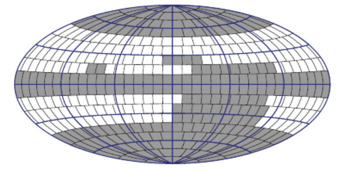
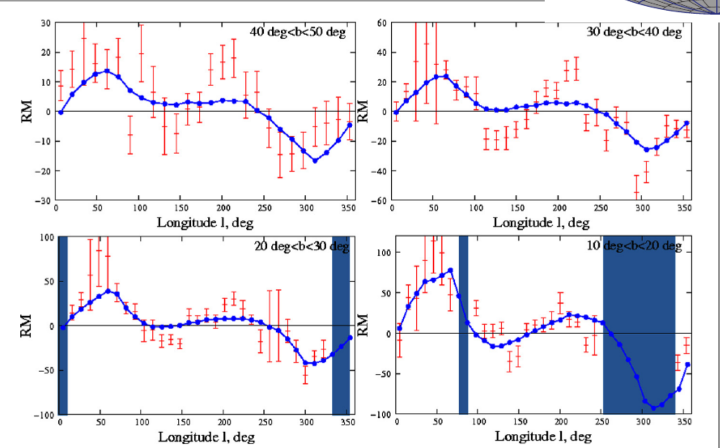




Coherent Galactic field

- Model vs. observations





Coherent Galactic field

Basic model parameters:

- Magnitude of disk field around the Earth: 2μG
- Pitch: -5°
- Thickness of the disk: 1 kpc
- Magnitude of the halo: 4μG
- Height of the halo above disk: 1.3 kpc
- Typical uncertainties: $\sim 30\%$

JF model

A more elaborate model of Galactic MF

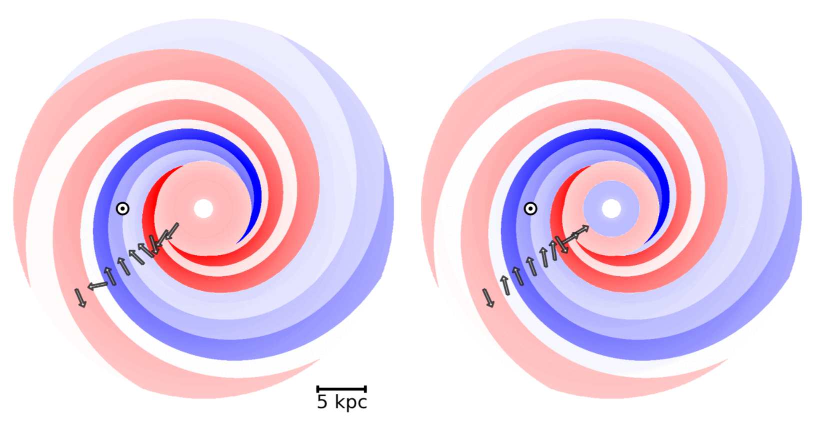
Jansson, Farrar, Astrophys.J. 757 (2012) 14

New ingredients:

- Inclusion of WMAP polarization data. *[Note however: this adds one more unknown, the relativistic electron density.]*
- More detailed Galactic arm structure (more realistic?)
- Additional X-shaped component as inspired by observations of other galaxies

JF model

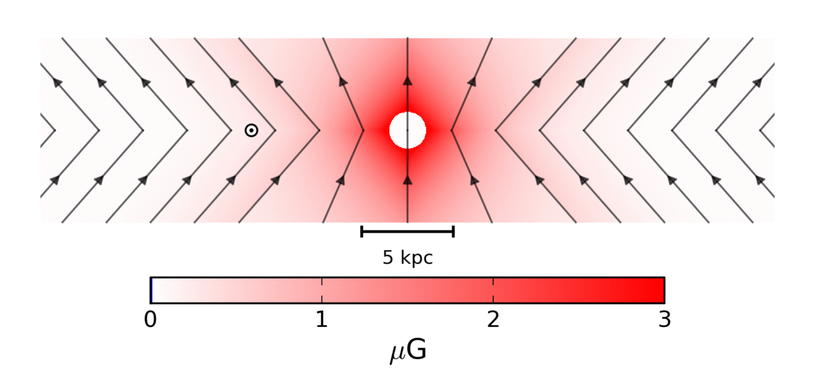
Galactic arms structure:



Slices at $\pm$10 pc parallel to the Galactic plane

JF model

Additional X-shaped component:



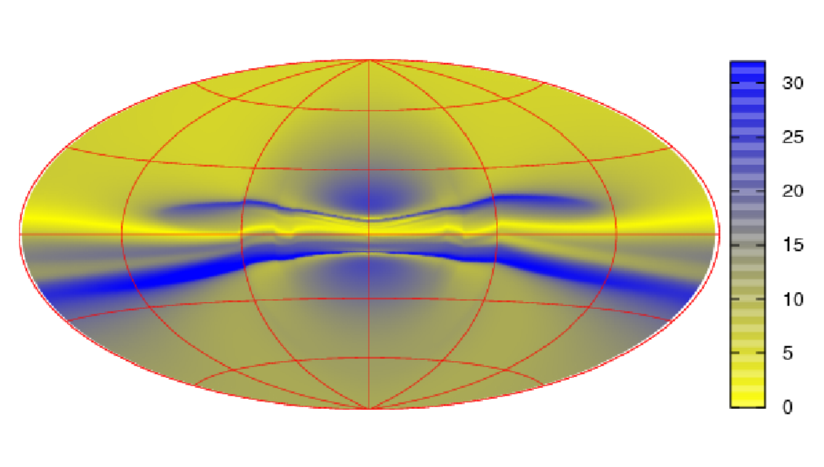
Cut perpendicular to GP.

JF model

- Similar magnitude of field in two models, but different structure (notably, the X-shaped field)
- $\Longrightarrow$ similar magnitude, but different pattern of deflections

Deflections: PT2011

$E = 4 \times 10^{19}$ eV, protons



Deflections: JF2012

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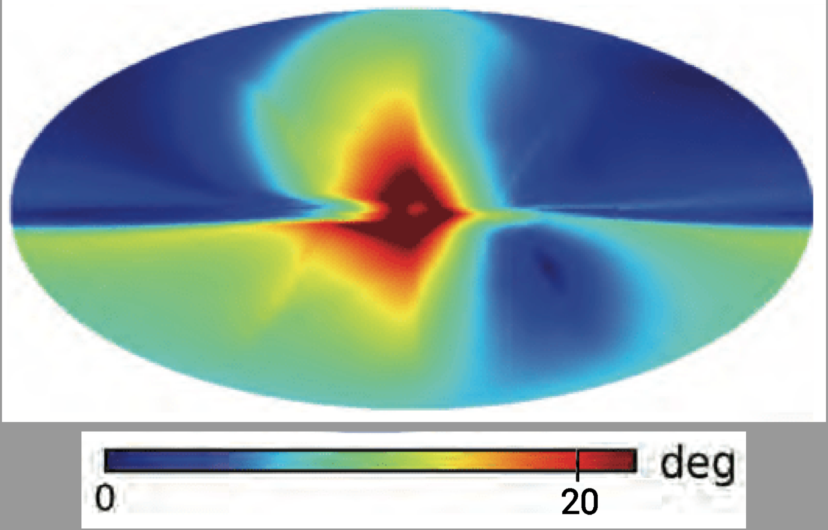
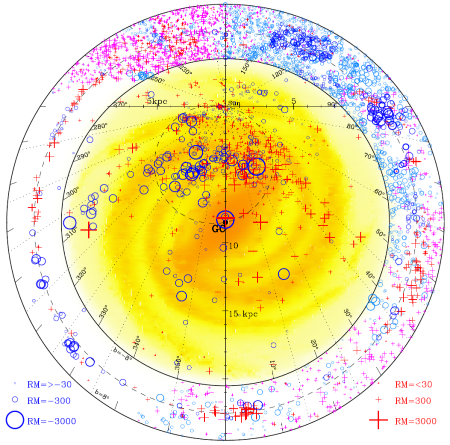


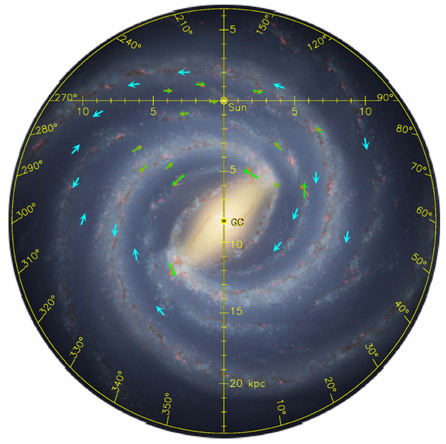
MF from pulsar data

MG in the Galactic disk can be inferred from pulsar RMs.

Han et al, MNRAS 486(2019)4275

Han et al, ApJS 234(2018)11

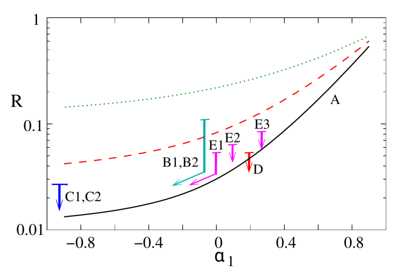


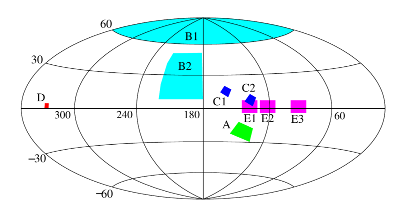


Random component

- MF has been measured in detail in small selected patches on the sky. One may convert these measurements into CR deflections.

PT, Tkachev, Astropart.Phys. 24 (2005) 32-43



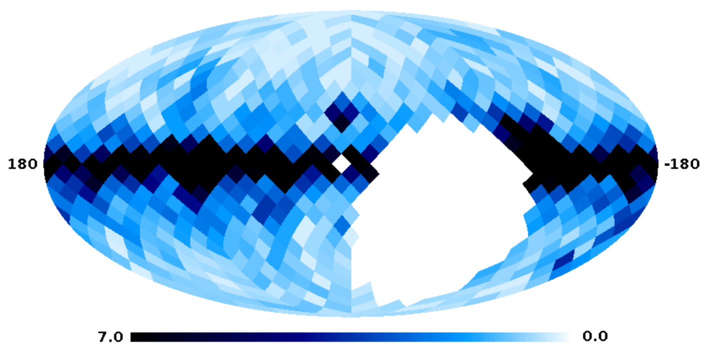


- Conclusion: in all cases deflections in the random field is smaller than that in the regular field by the factor $R \sim 0.3 - 0.03$.

Random component

- Altermantively, one may relate variation of the RM in a small patch directly to random CR deflections. NVSS catalog of RMs gives then the sky map of random deflections.

Pshirkov, PT, Urban, MNRAS 436 (2013) 2326



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Summary

- ... uncertainties, uncertainties, uncertainties ...
- Deflections in the extragalactic MF are likely to be small.
  Caveat: we may live inside a filament of the large-scale structure where fields can reach $10^{-8} - 10^{-7}$ G with the correlation length $\mathcal{O}$(Mpc).
  Then deflections may be large.
- Deflections of protons in GMF are dominated by the regular field and may be of the order $2 - 6^{\circ}$ at energy $E = 10^{20}$ eV depending on the direction
- $\Longrightarrow$Charge-particle astronomy may be possible only at highest energies, and only if UHECR are protons

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