Influence of the galactic magnetic field on the trajectory of UHECRs

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Contents

- Introduction
- Galactic Magnetic Fields in the universe
- Correlation test using the distribution of Arrival Direction
- Analysis results
- Estimation of the strength of GMF
- Summary

Introduction

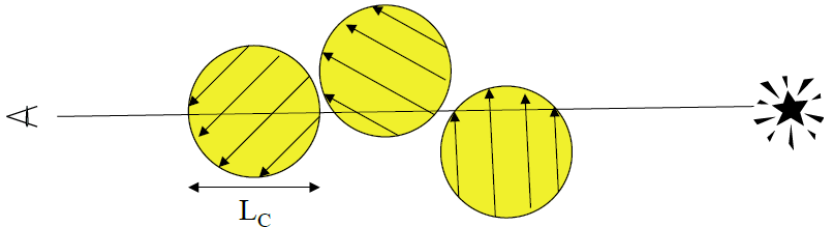
- The origin and nature of magnetic fields in our universe, is one of the outstanding problems of modern astrophysics.

- Exploration of the Galactic magnetic field (GMF) and the intergalactic magnetic field (IGMF) is listed as one of the key science projects for
  - the Square Kilometer Array (SKA)
  - Jansky Very Large Array (JVLA)
  - Murchison Widefield Array (MWA)
  - the Low Frequency Array (LOFAR)
  - the Australian SKA Pathfinder (ASKAP)
  - …

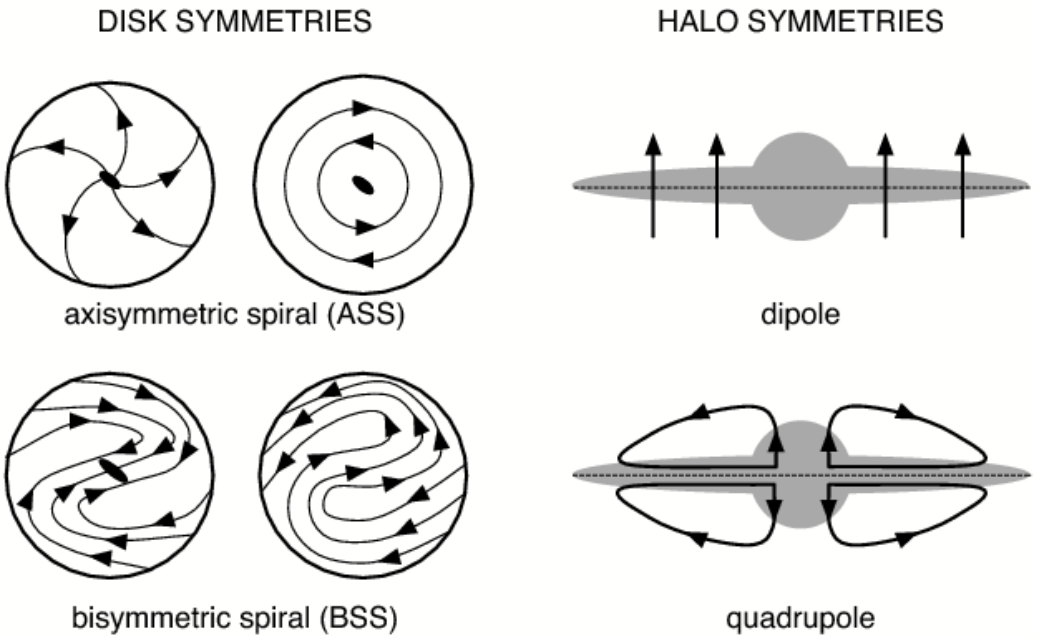
- However, the nature of the GMF and IGMF are not fully understood observationally and theoretically.

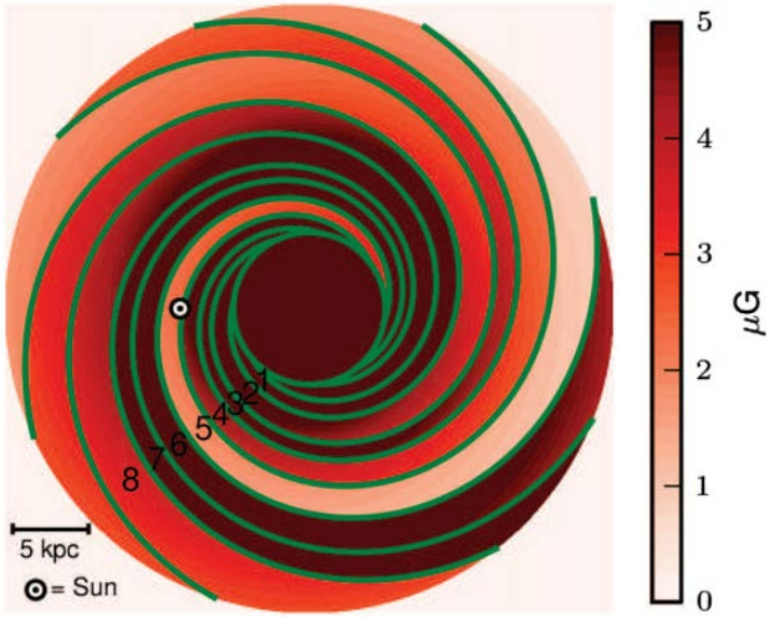
Deflection by Galactic Magnetic Field

- Galactic magnetic field
  - $B_{\rm G}\sim$ a few μG
  - $R_{\rm G}\sim 10$ kpc



- A variety Models of GMF





Brown, ASP Conf.Ser. **438,** 216 (2010)

Jansson and Farrar, ApJL **761** L11 (2012)

Strategy

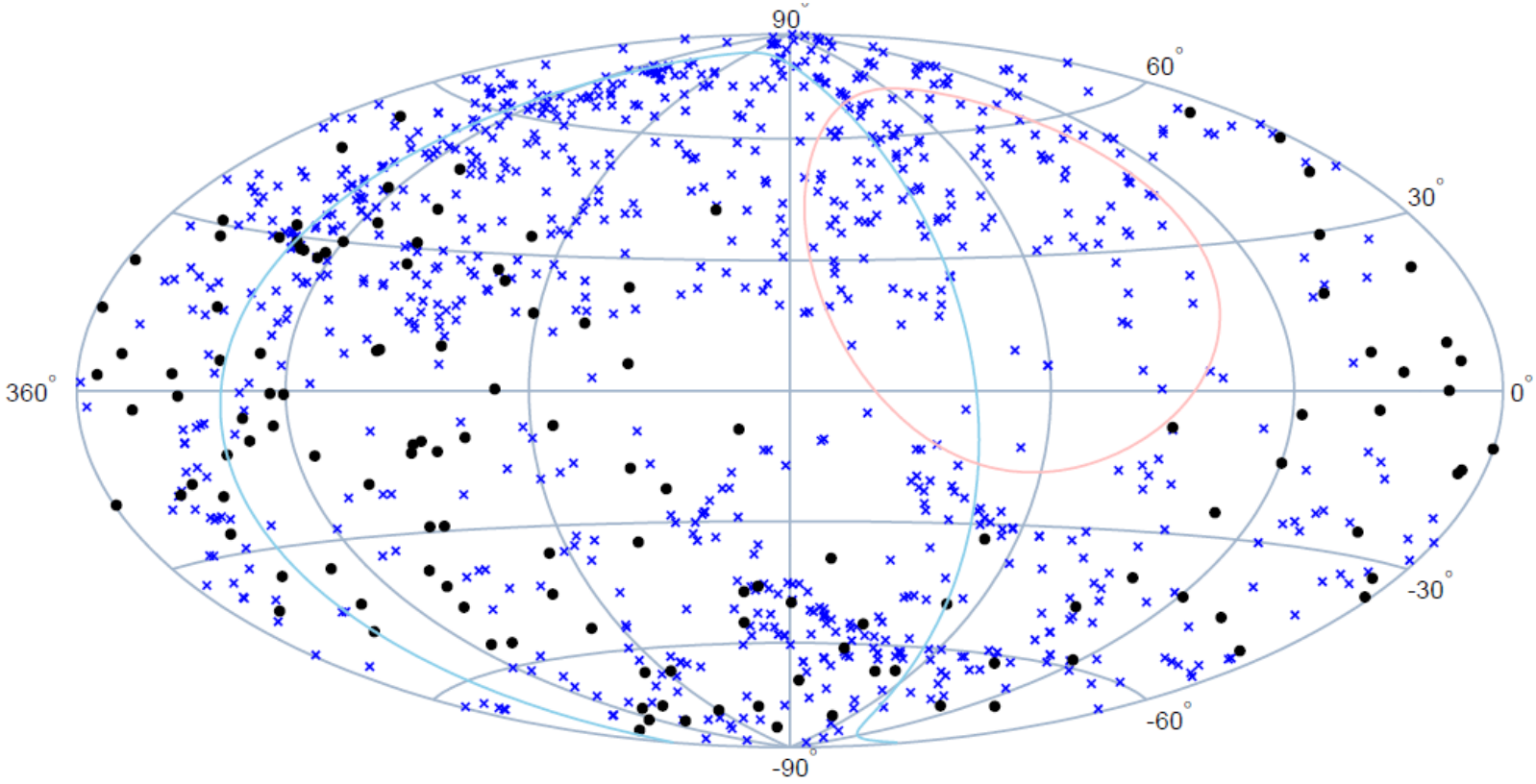
- Here, we assume that the influence of the IGMF is not significant compared to that of the GMF. If it is right, we can expect that the deflections by the GMF are mainly dependent on the galactic latitude,. since the influence of GMF on the distribution of UHECR would be imprinted in each region.
- To explore the property of GMF, we analyze the correlation between the arrival direction of UHECRs and the LSS of the universe in each region divided by the galactic latitude, *b*, we divide the regions of sky as below

	S. Galactic pole region	**Intermediate region**	**Galactic plane region**
coverage	$-90° \leq \mathrm{b} < -60°$	$-60° \leq \mathrm{b} < -30°$	$-30° \leq \mathrm{b} \leq 0°$
# of AGN	83	139	98
# of PAO	18	32	35

PAO: the data set published in 2015 ($E \geq 60$ EeV & $\theta_z \leq 80°$)

AGN: the 13th edition of VCV catalog ($\mathrm{D} \leq 100$ Mpc)

PAO-AGN in the Galactic Coordinates



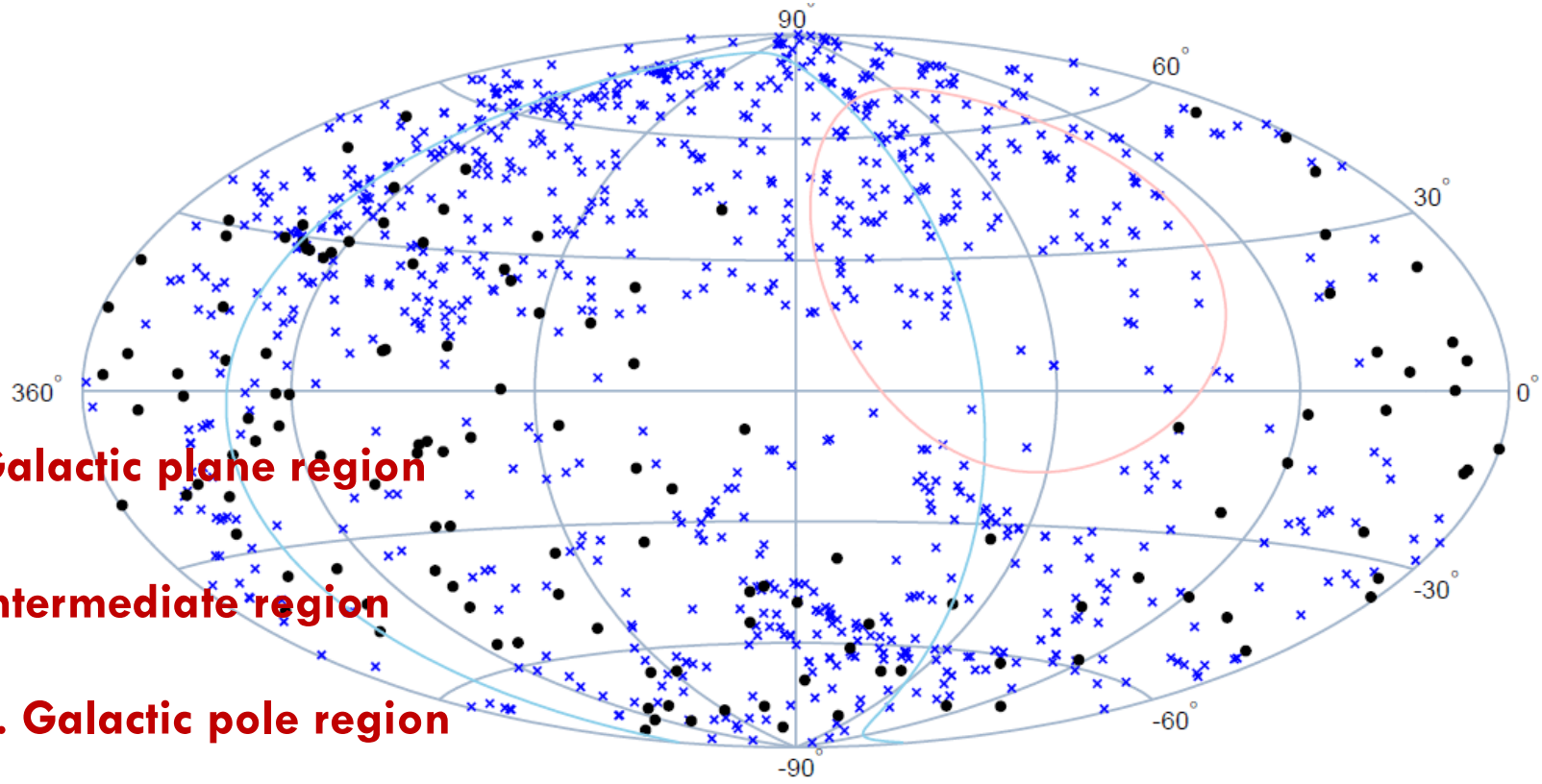
Black: 136 PAO UHECRs ($E \geq 60$ EeV)

Blue: VCV AGN ($\mathrm{D} \leq 100$ Mpc)

Pink line: Boundary of PAO exposure

Skyblue: Supergalactic plane

PAO-AGN in the Galactic Coordinates



Galactic plane region

Intermediate region

S. Galactic pole region

Black: 136 PAO UHECRs ($E \geq 60$ EeV)

Blue: VCV AGN ($\mathrm{D} \leq 100$ Mpc)

Pink line: Boundary of PAO exposure

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Simulation / Comparison methods

- UHECR flux of the source model

$$F(\hat{r}) \propto \sum_{j \in \mathrm{AGN}} \frac{L}{4\pi d_j^2} \exp[-(\theta_j(\hat{r}))/\theta_{sj})^2]$$

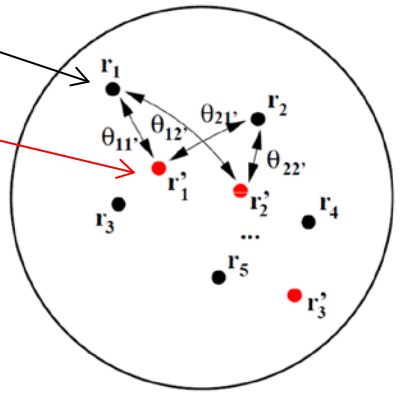
the Gaussian smearing angle

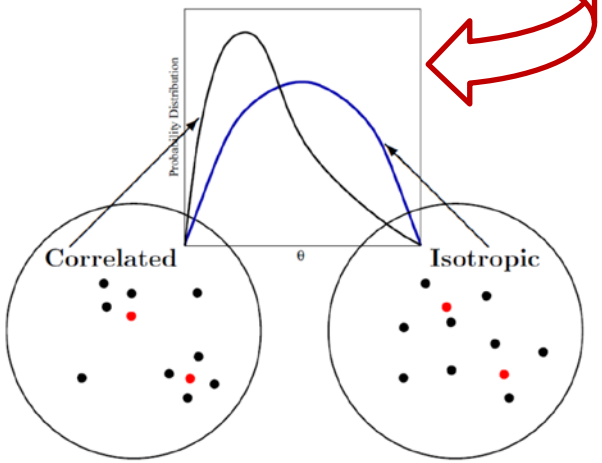
- The deflection angle of UHECRs from sources by the magnetic field in the universe is reflected in a source model by introducing the Gaussian smearing angle as a free parameter.
- To compare the observed distribution of UHECR with the expected one based on the model, we introduce a quantity defined as follows:

$$\left\{ \cos\theta_{ij'} \equiv \hat{\mathbf{r}}_i \cdot \hat{\mathbf{r}}'_j \mid i = 1, \ldots, N;\ j = 1, \ldots, M \right\}$$

Black: LSS of the universe

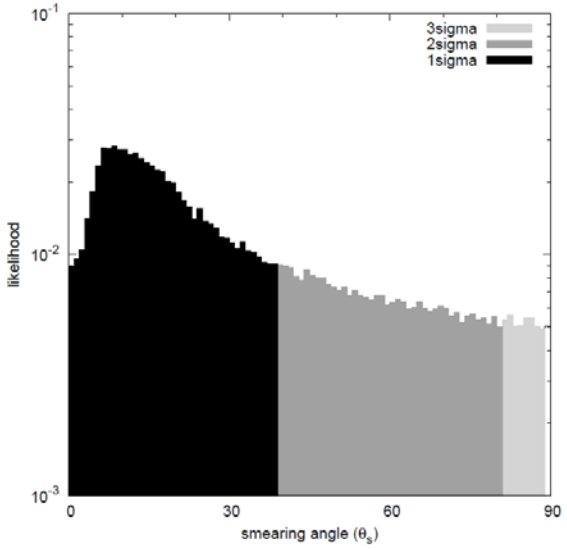
Red: UHECR events





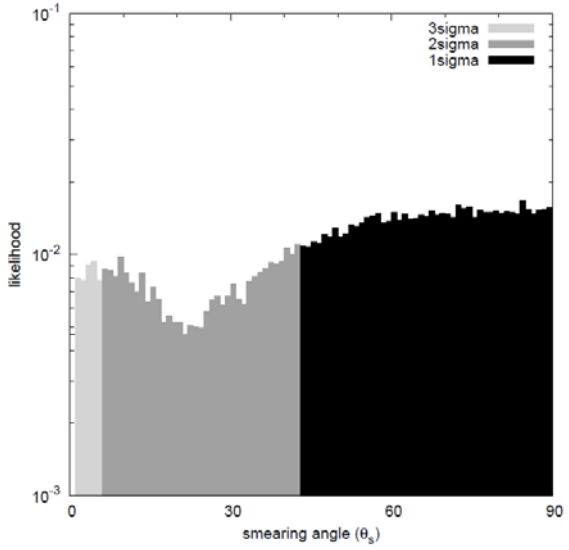
Credible interval of deflection angle (PAO)

- When $f_s = 0.7$, [Koers and Tinyakov, JCAP 04 003 (2009)]



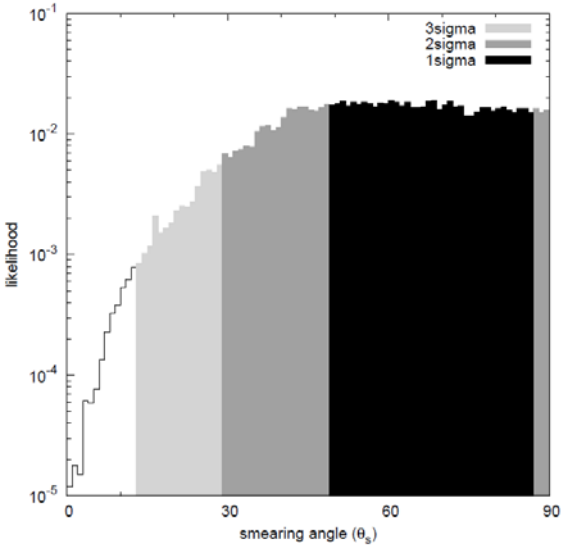
S. Galactic pole region

1sigma: $0° \leq \theta_s \leq 38°$ (19°)



Intermediate region

$42° \leq \theta_s \leq 90°$ (66°)



Galactic plane region

$47° \leq \theta_s \leq 88°$ (67.5°)

Estimation of GMF strength

- Estimation of the GMF strength by the deflection angle

$$B_{rms}\,[\mu G] = \frac{\delta_{tur}}{5.83^\circ}\left(\frac{7}{Z}\right)\left(\frac{E}{6\times10^{19}\,eV}\right)\left(\frac{10\,kpc}{D}\right)^{1/2}\left(\frac{100\,pc}{l_c}\right)^{1/2}$$

- According to PAO, the primary particles are presumed to be heavy nuclei. If we assume the composition is N ($Z = 7$) having $E = 6.0 \times 10^{19}\,eV$, the strength of GMF in each region are estimated as follows.
- Galactic plane region: $\delta_{tur} = 67.5^\circ,\ D = 10\,kpc,\ l_c = 100\,pc$

  → $B = 11.6\,\mu G$
- Intermediate region: $\delta_{tur} = 66^\circ,\ D = 7\,kpc,\ l_c = 200\,pc$

  → $B = 9.6\,\mu G$
- S. Galactic pole region: $\delta_{tur} = 19^\circ,\ D = 3\,kpc,\ l_c = 300\,pc$

  → $B = 3.4\,\mu G$

Summary

- If we adopt the primary particle of UHECR to be CNO, the estimated strength of GMF field toward the galactic magnetic field is about $10\ \mu G$, which is consistent with the observationally/theoretically known strength.
- Then, we can use this to predict the strength of GMF toward high galactic latitude which is not understood well yet.
- More data will make the estimation of GMF by using UHECR data possible more accurately.