Correlation studies between ultra-high energy cosmic rays and Fermi gamma-ray sources

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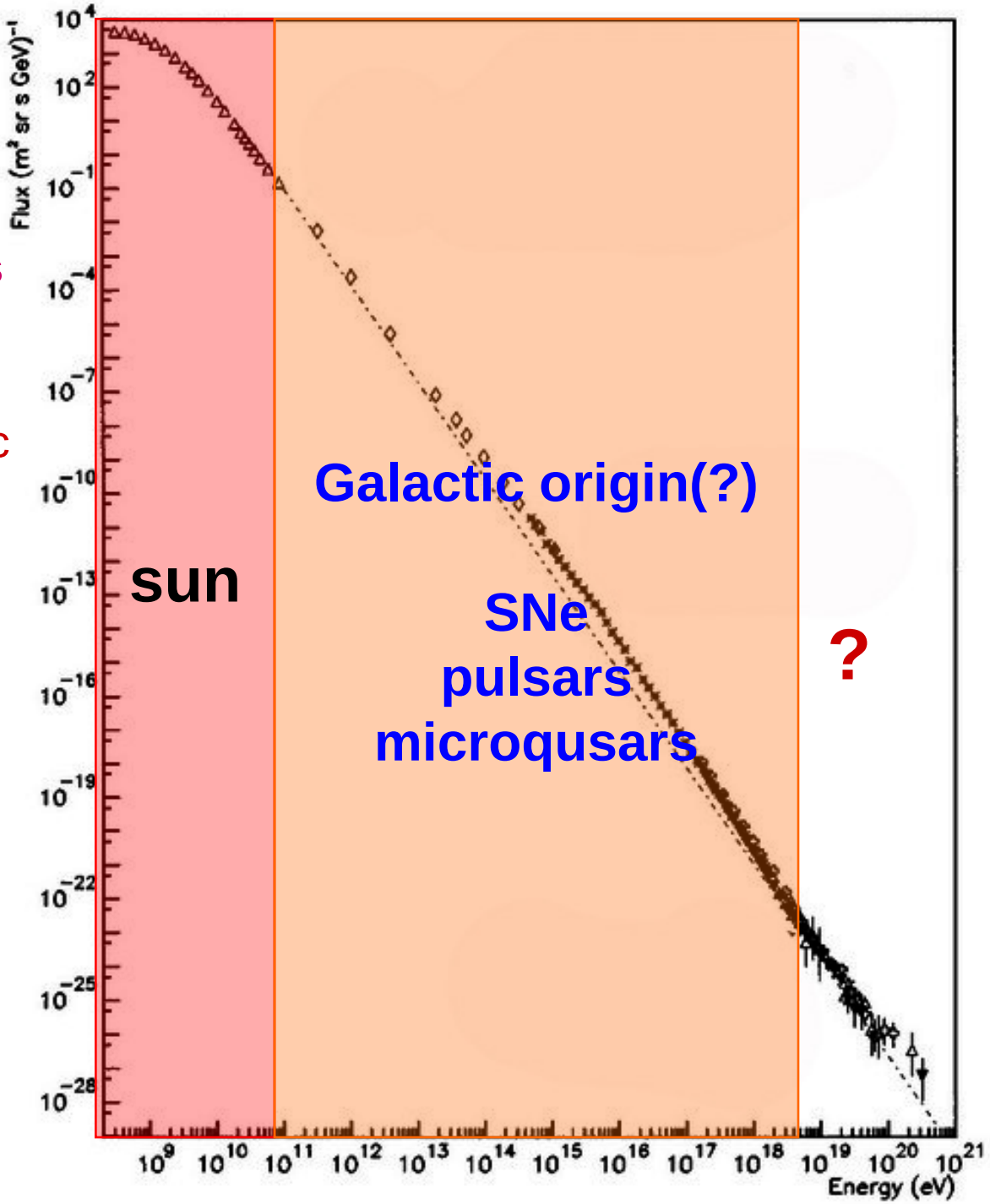
Spectra of cosmic rays

Ultra-high energy cosmic rays (UHECRs) (above 10^{19} eV)

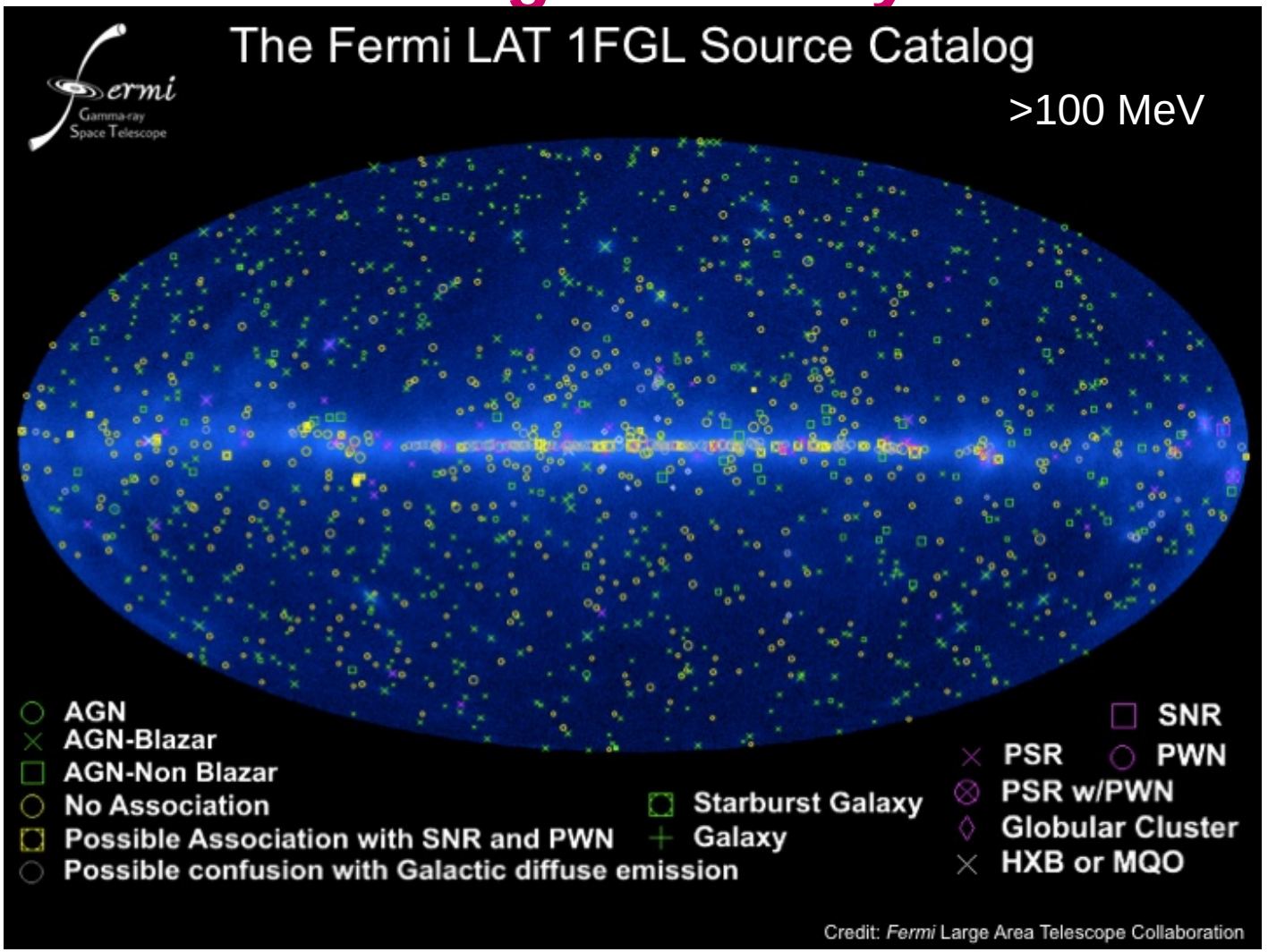
Possible extra-galactic origins:
AGN
GRB
…



We aim to do

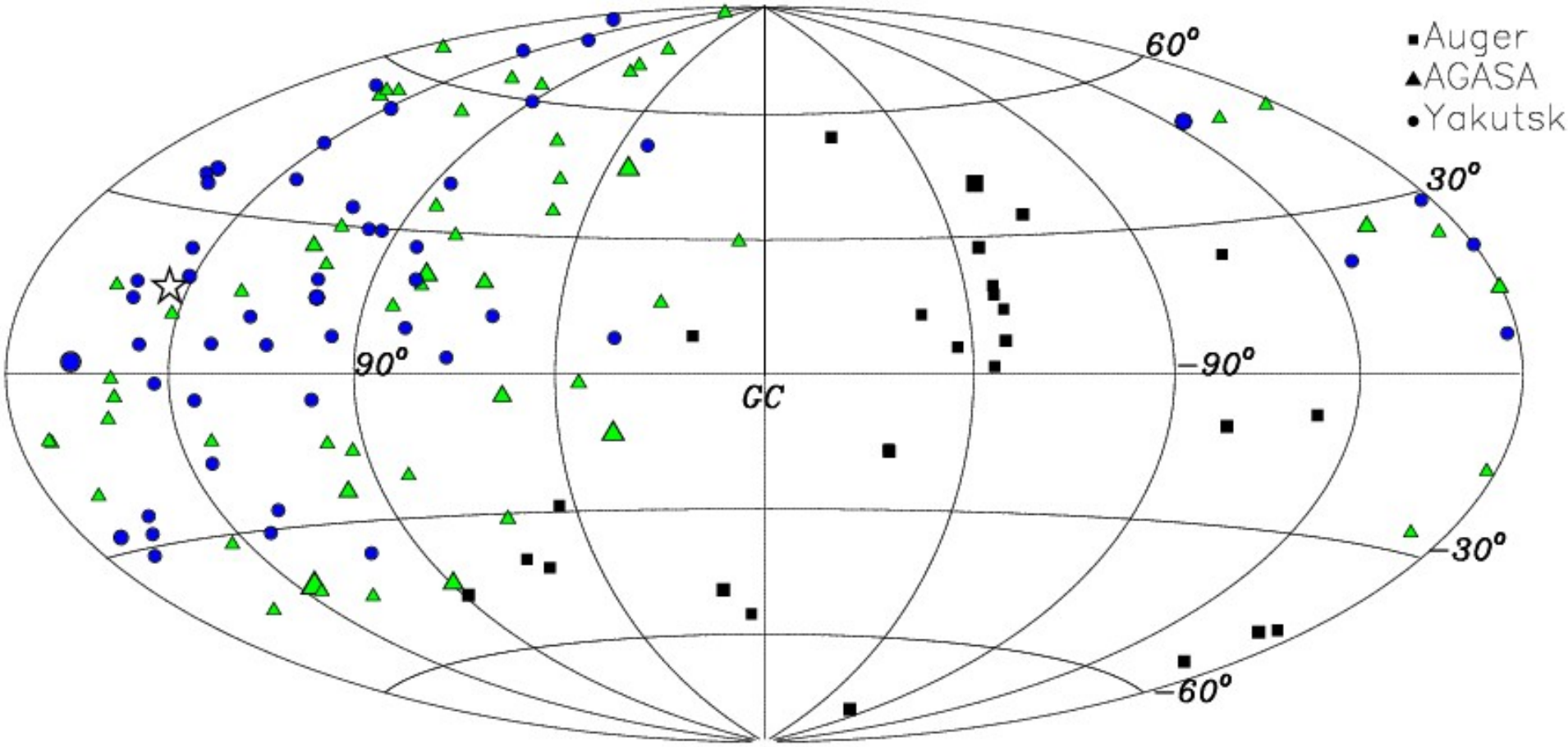
- Correlation between UHECRs and gamma-ray sources? - connection among the highest-energy phenomena in the Universe
- The deflection effects of the Galactic magnetic fields (GMF) on arriving directions of UHECRs and the effects on correlation studies

Fermi/LAT gamma-ray sources



1451 sources (EGRET 270): 690 AGNs; 630 un-id sources

UHECR Events

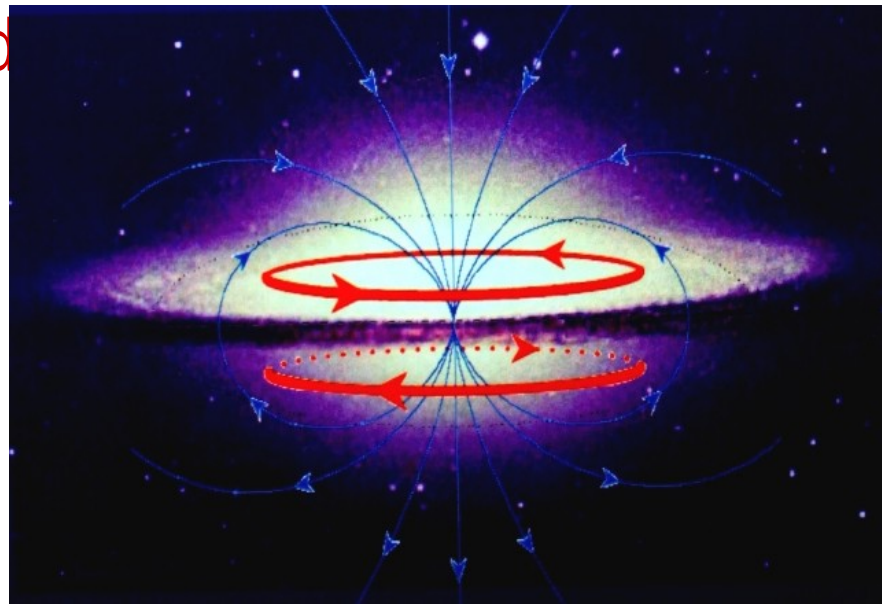


Galactic magnetic field model

- We construct a toy GMF model using the most updated measurements
- Three components:

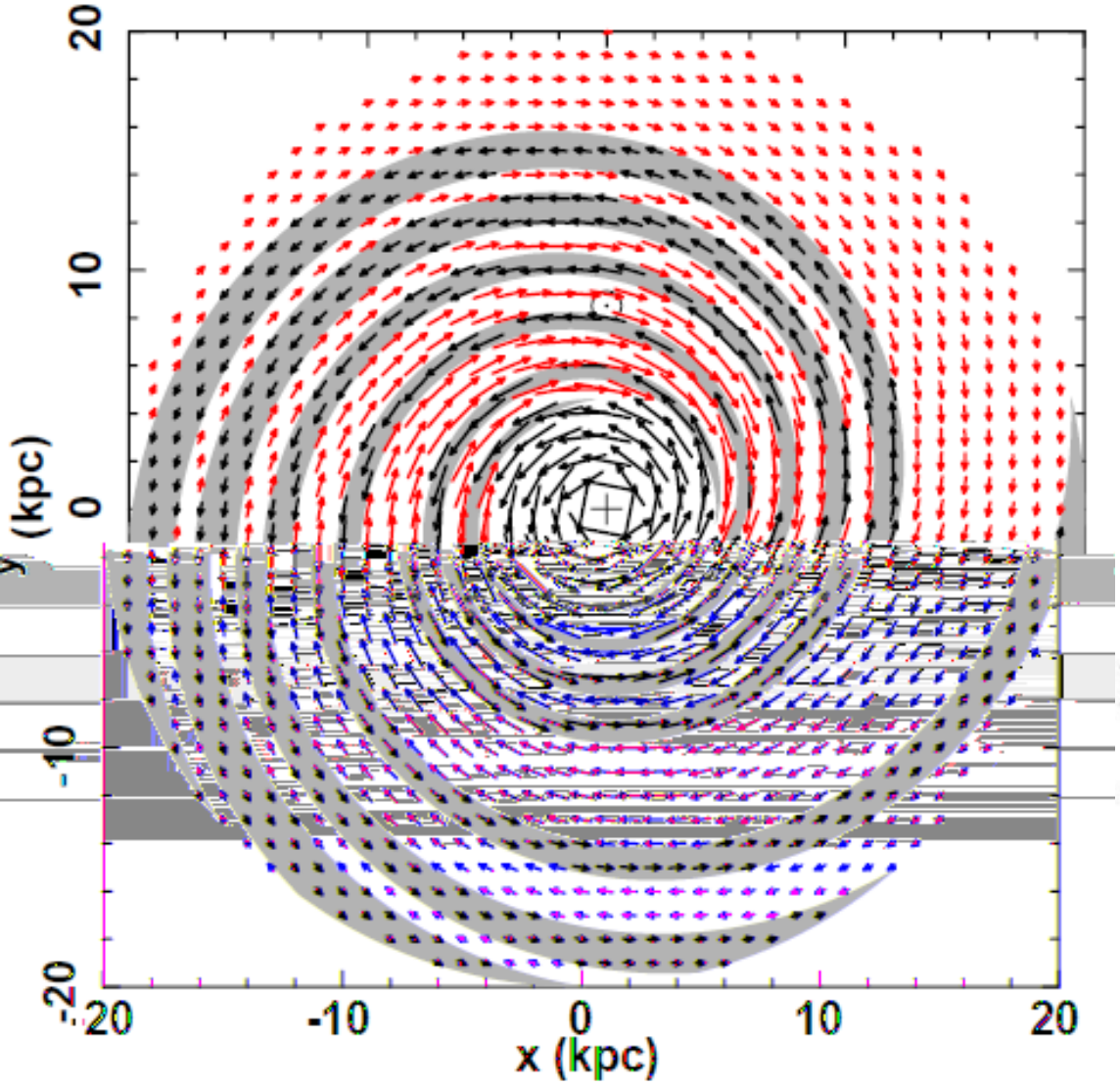
disk field: magnetic fields are reversed from arms to inter-arms (Han et al. 2006)

halo { dipole poloidal field
toroidal field



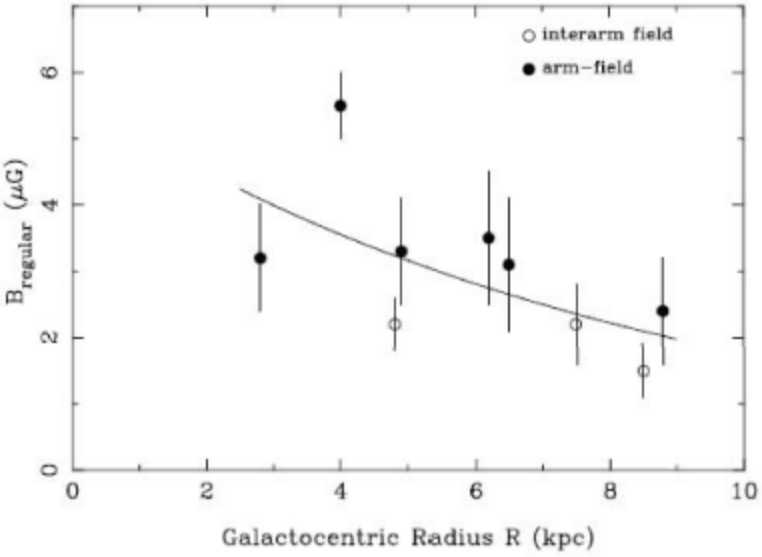
Han 2006

Disk field



four-arm model
(Hou et al. 2009)

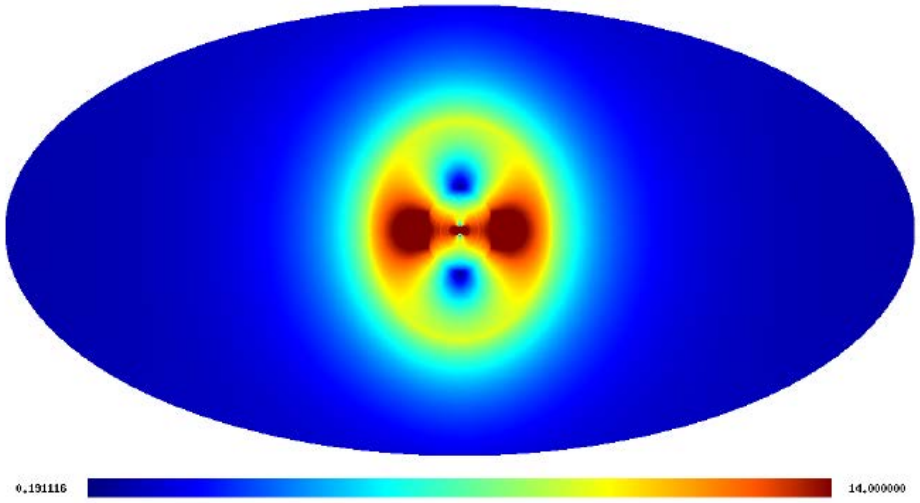
Near the Sun:
B～ 2.1μG



Han et al. 2006

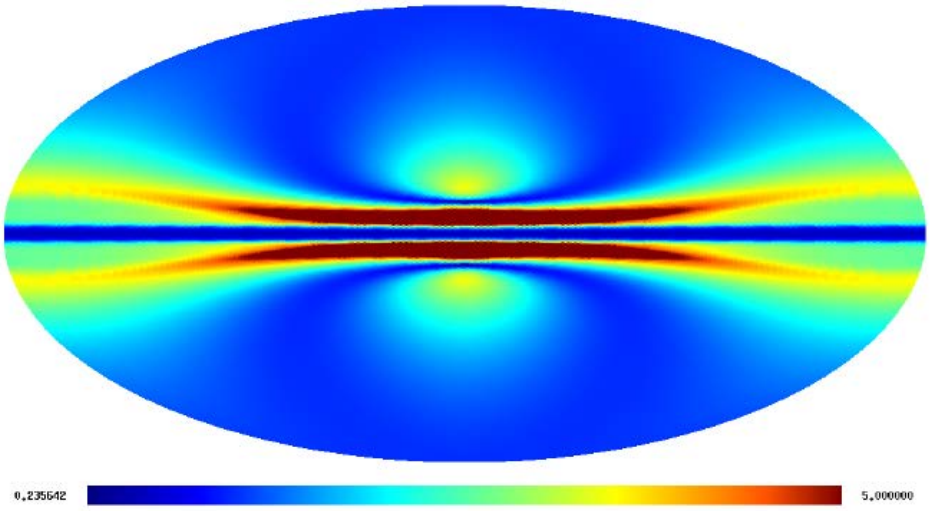
Halo field

Dipole poloidal field



Galactic center: 1 mG
Near the Sun: 0.2 μG

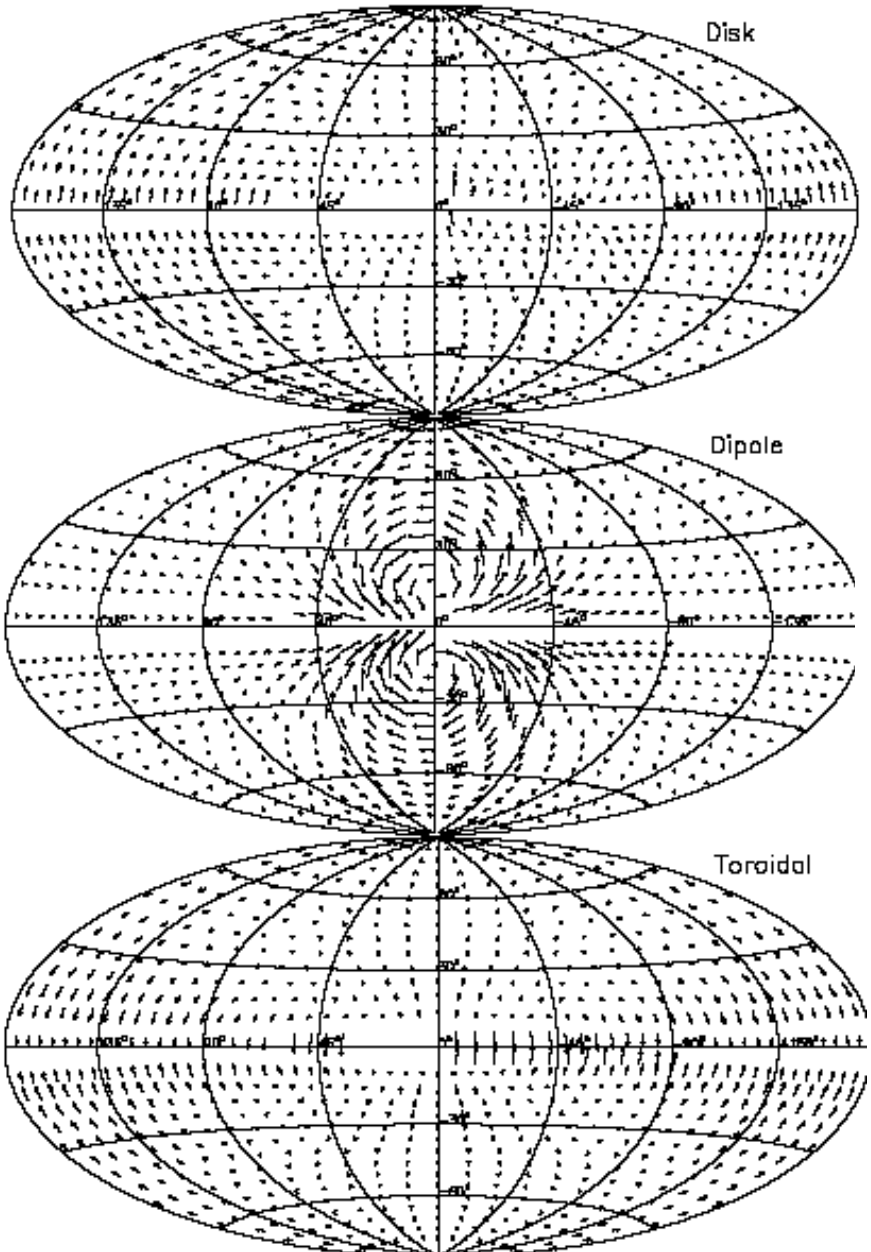
Toroidal filed

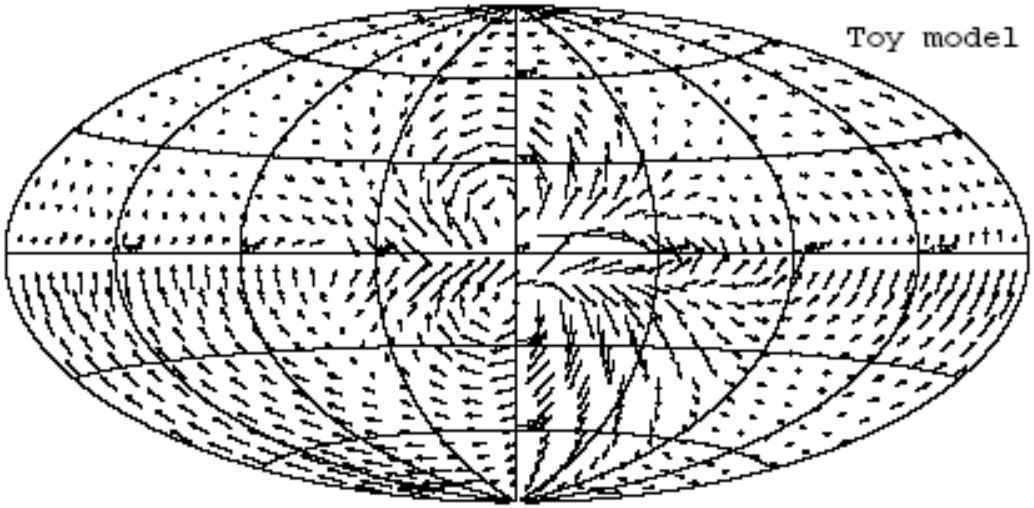


Bmax = 1 μG

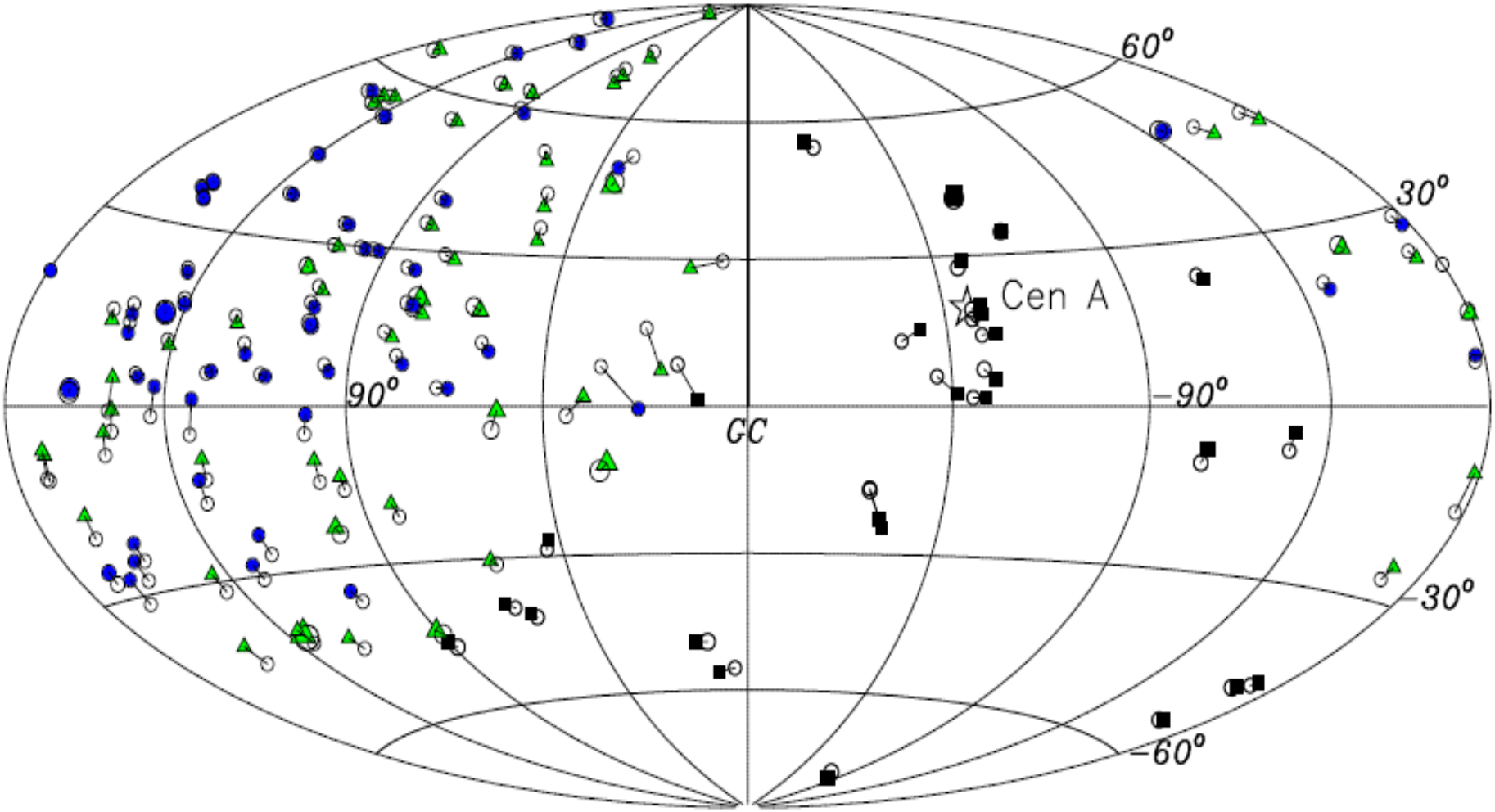
Deflection maps by GMFs

$$\Theta \approx \frac{Z\, q_e}{pc} \int d\vec{l} \times \vec{B}_t$$

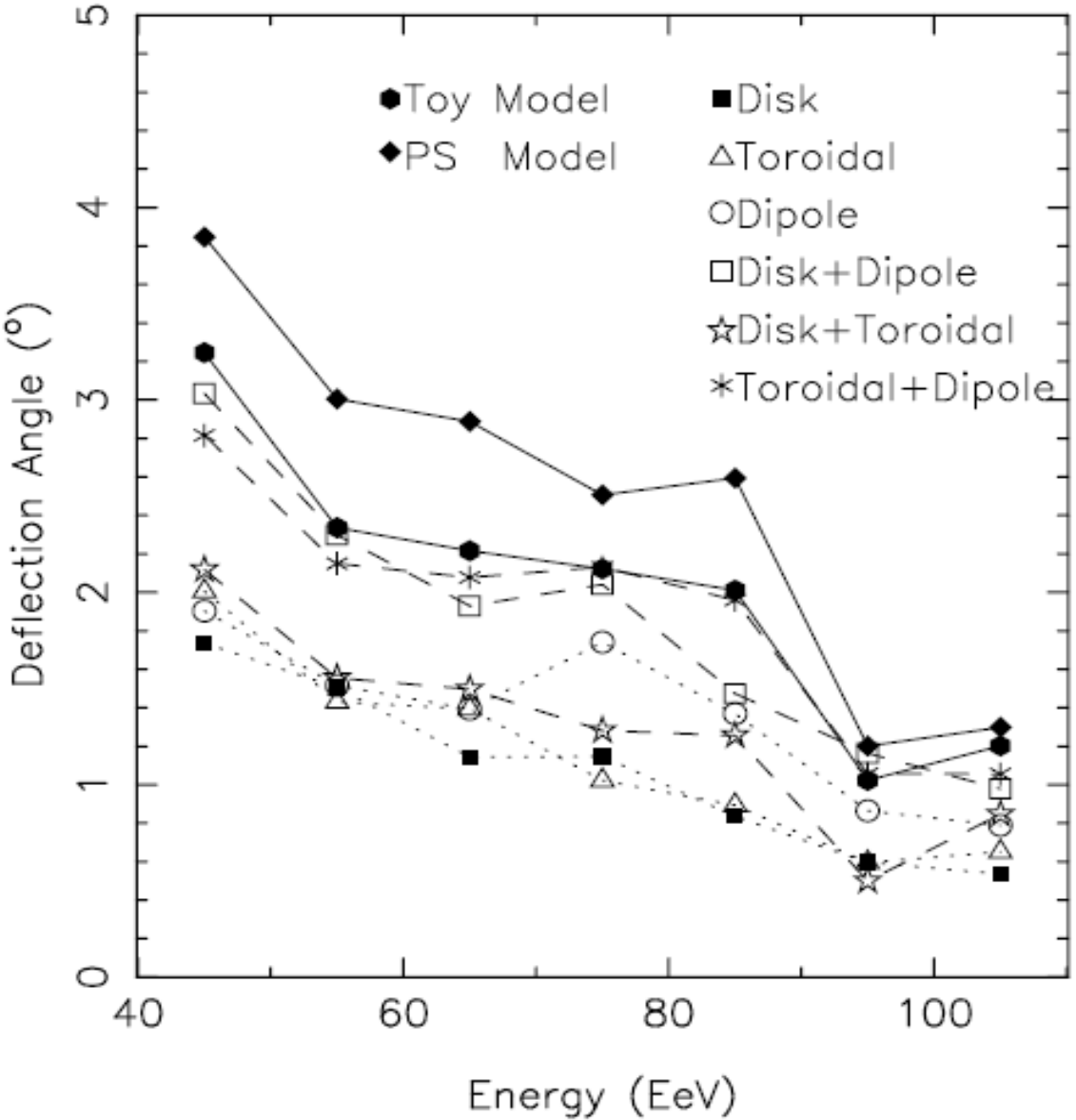




UHECR arriving direction correction by the GMF (assuming proton composition)



Deflection angle



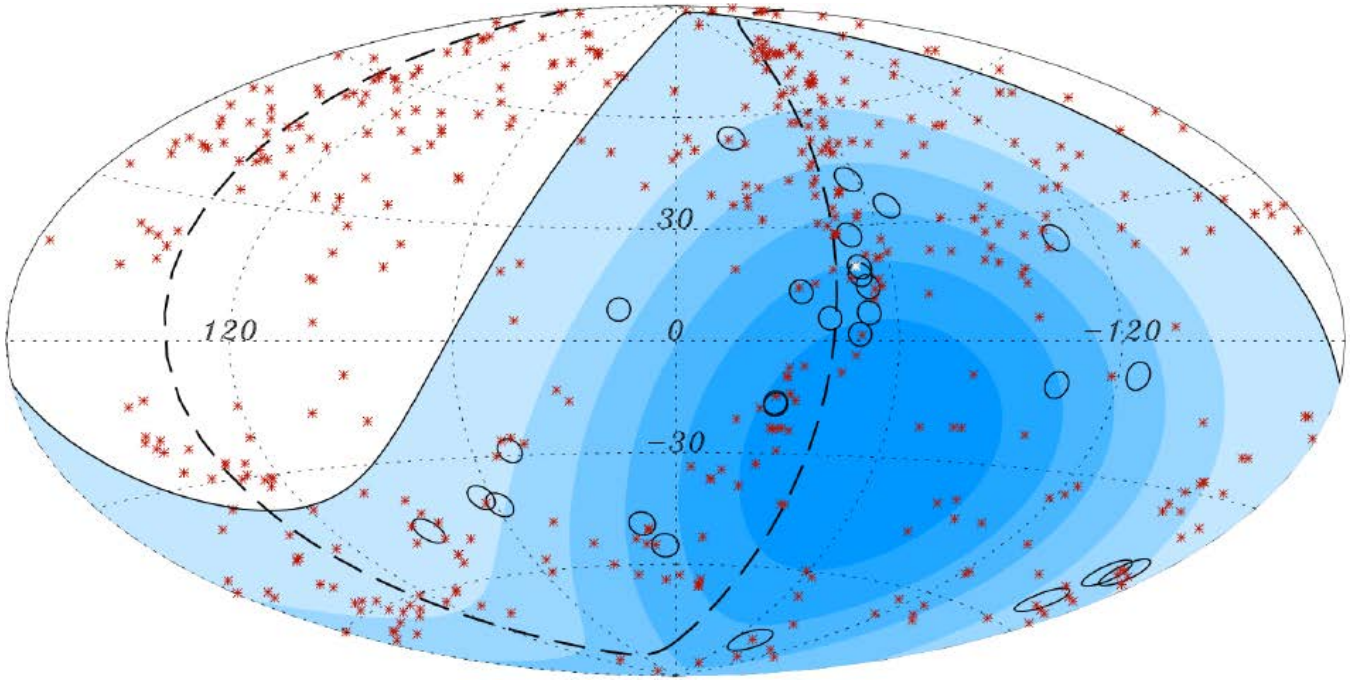
Proton composition

135 events

Average deflection angle < 4º

Correlation studies

- Angular correlation function
- Only consider the events and sources **|b|>10°**



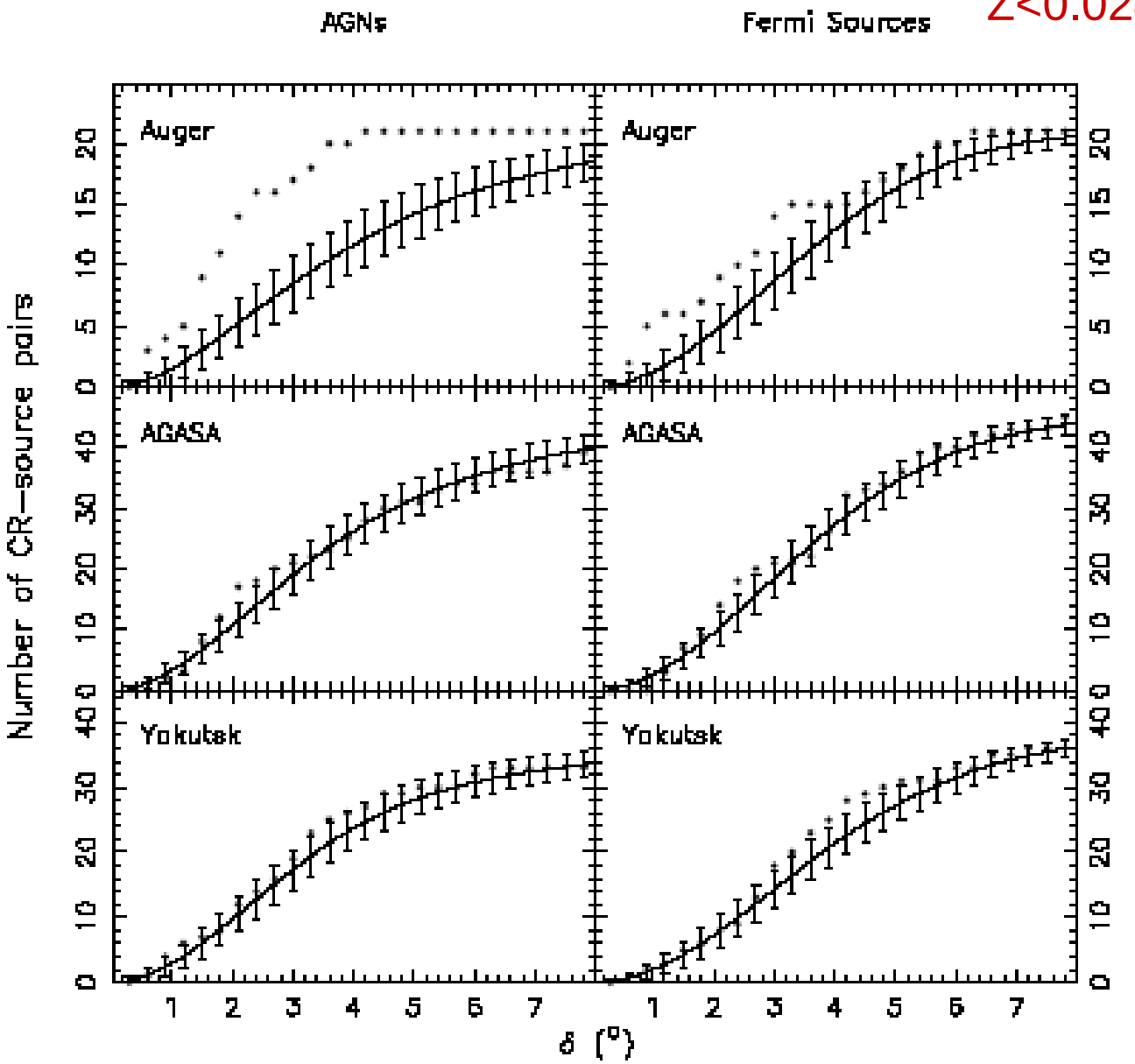
Counting the UHECR-source pair with function of bin-size of angle (from 0 – 10^{o})

Chance probability evaluations

- MC simulations
- Simulated UHECRs are isotropic
- Distributions of location constrained by exposure function of each experiments
- A large number of the UHECR samples ($N=10^6$), each sample has the same number of events as the real sample

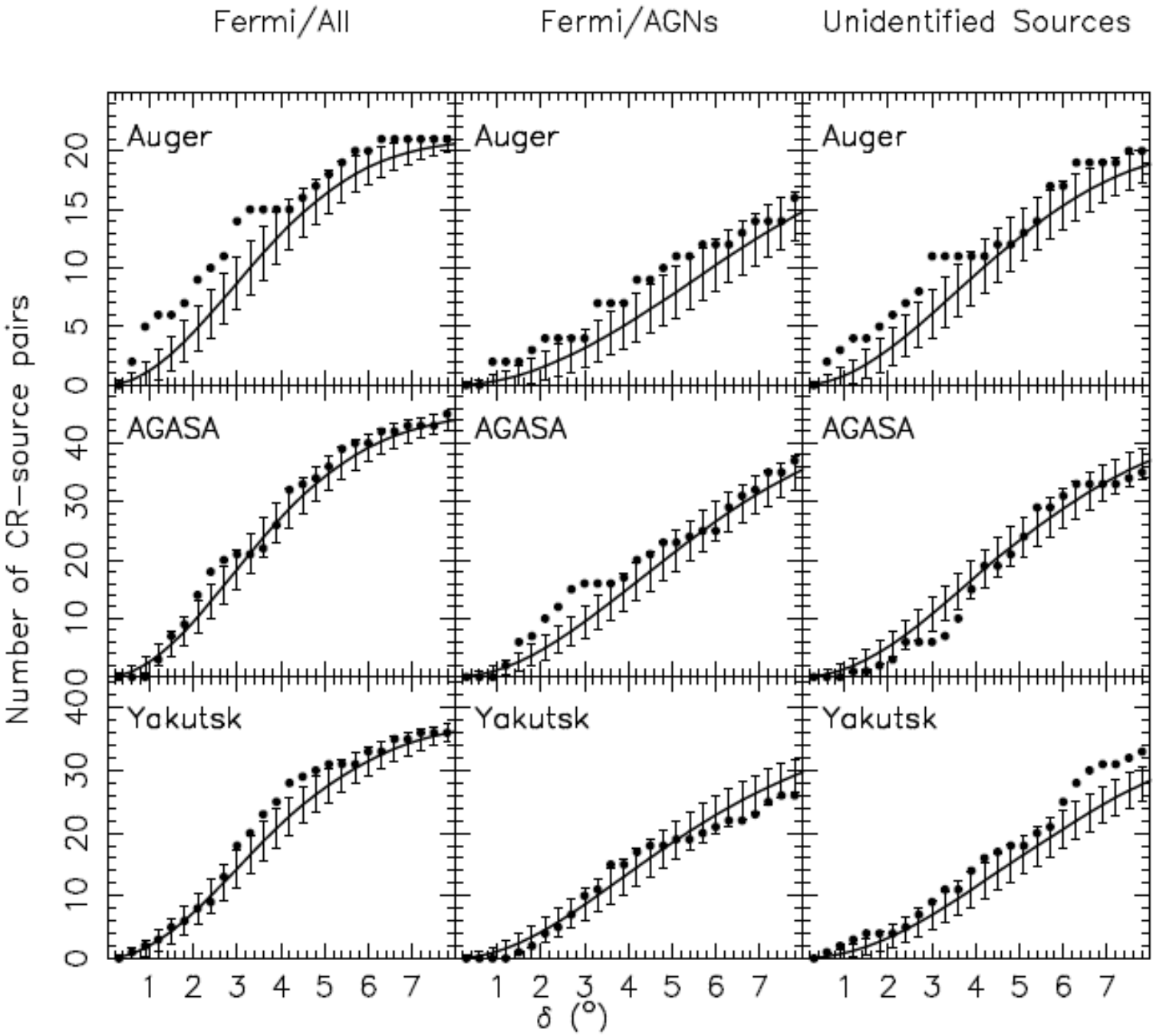
Nearby VCV AGNs (z<0.024)

For Gamma-ray AGN Z<0.024



Marginal correlation between Auger events and Fermi gamma-ray sources (4σ)

For known AGNs, z<0.024



UHECRs – nearby gamma-ray AGNs

- After deflection correlation by GMFs, 4 nearby gamma-ray AGNs (z<0.024) are located within 3^{o} of the direction of UHECRs.

		Fermi/活动星系核			UHECR			
(1) Name	(2) Association	(3) l (°)	(4) b (°)	(5) z	(6) l_{cr} (°)	(7) b_{cr} (°)	(8) E(10EeV)	(9) ϑ (°)
1FGL_J1325.6-4300	Cen A	309.52	19.42	0.002	-53.70	20.09	7.0	3.100
					-53.69	18.23	6.9	3.254
1FGL_J1307.0-4030	ESO 323-G77	306.02	22.37	0.015	-53.70	20.09	7.0	2.288
					-53.69	18.23	6.9	4.145
1FGL_J1305.4-4928	NGC 4945	305.27	13.34	0.002	-56.08	14.43	5.8	1.709
					-53.69	18.23	6.9	4.993
1FGL_J2038.1+6552	NGC 6951	100.90	14.85	0.005	101.21	14.81	9.8	0.303
					101.92	18.26	4.5	3.546

Potential UHECR candidates

- Cen A: nearest radio galaxy, radio lobes, X-ray jets
- NGC 4945: Seyfert 2 /starburst galaxy; non-thermal jet-like morphology
- ESO 323-G77: Seyfert 1 galaxy; mildly relativistic outflows in X-rays; strong Fe II emission; broadening Fe Kα line, implying a Kerr BH in the nuclei
- NGC 6951: LINER galaxy; a bipolar outflow associated with the nuclear jet

Summary

- The updated GMF model is applied to calculate the deflection effect of UHECRs;
- After considering the deflection correction, the correlation between nearby VCV AGNs and Auger events still exist;
- The Auger events show a marginal correlation with the Fermi gamma-ray sources;
- Four nearby gamma-ray loud AGNs (Cen A, NGC 4945, ESO 323-G77, NGC 6951) are potential candidates for production sites of UHECRs;
- We should note that unidentified gamma-ray sources could be interesting candidates.

Thank you !

Discussions on Galactic magnetic field models/observations, please refer to Han, J.L.

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