Propagation of Ultra-high-energy Cosmic Rays in Galactic Magnetic Field

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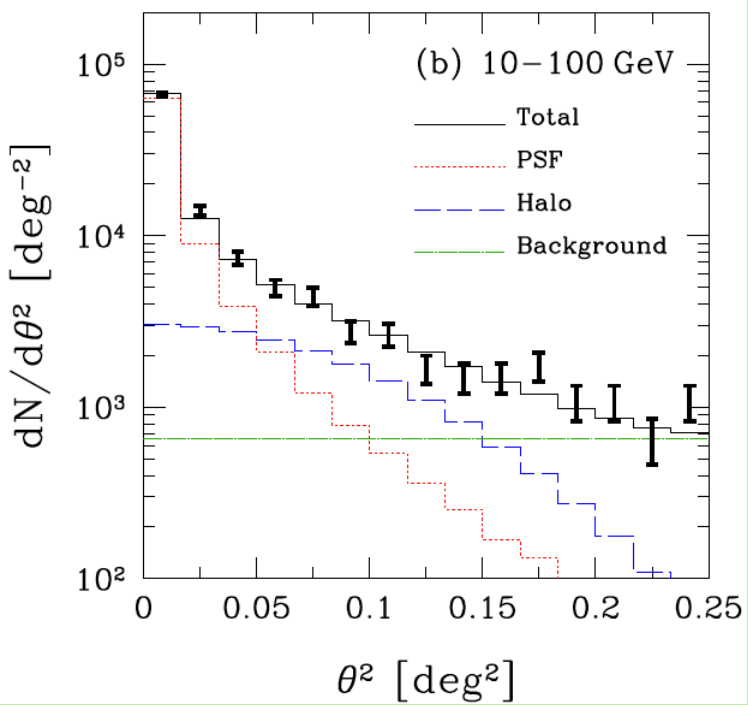
Why is Galactic Magnetic Field important?

1. GMF inevitably affects the trajectories of UHECRs

2. IGMF strength



Ando &Kusenko (2010)

- Faraday rotation measurements
  $B\, l_c^{1/2} < (1\ \mathrm{nG})\ (1\ \mathrm{Mpc})^{1/2}$

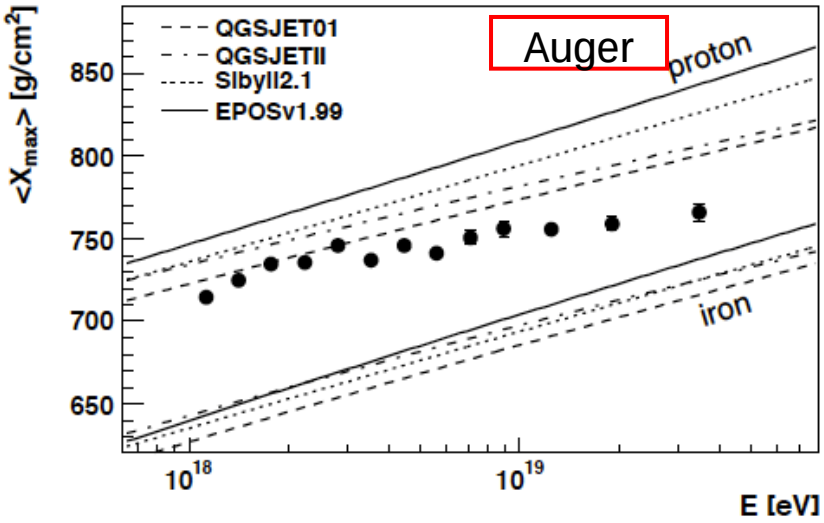
  Kronberg (1994)

- Constraints from γ-ray halos
  - $>10^{-15}$ G **Neronov&Vovk (2010), Tavecchio et al. (2010)**
  - $\sim 10^{-15}$G **Ando &Kusenko (2010)**
  - $>10^{-19}$ G **Dermer et al. (2010)**

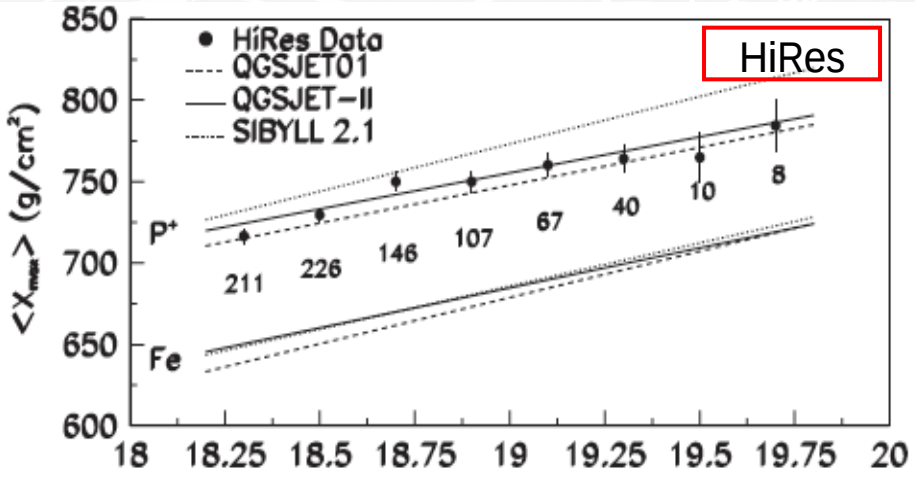
$$\theta(E,d) \simeq 0.8^\circ Z \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{d}{10\mathrm{Mpc}}\right)^{1/2} \left(\frac{l_c}{1\mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{1\mathrm{nG}}\right)$$

Small deflections by IGMF

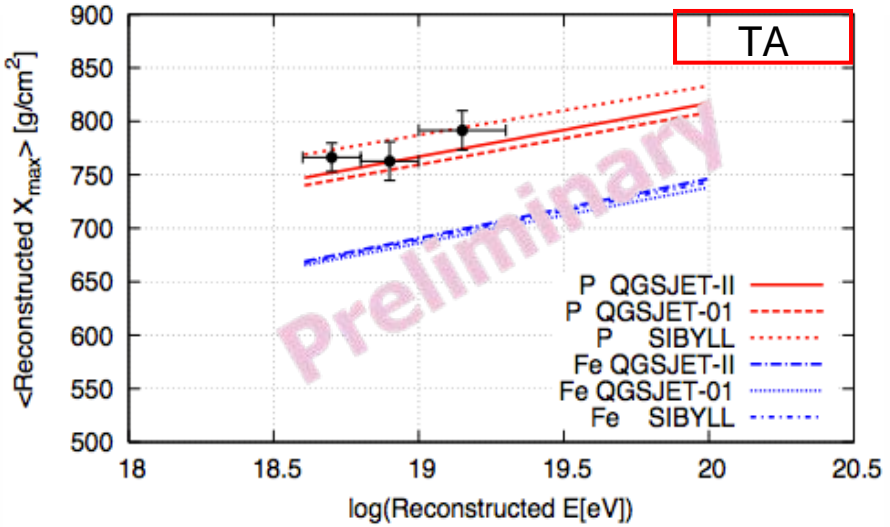
Composition Measurements



Abraham et al. (2010)



Abbasi et al. (2010)



Composition of UHECRs is a highly controversial issue.

UHECR propagation in GMF

Osbrone et al (1973), Stanev (1997), Medina-Tanco et al. (1998), Zirakashvili et al. (1998), Sigl&Lemoine (1998), Harari et al. (1999), O'Neille (2001), Kalashev et al. (2001), Alvarez-Muniz (2002), Tinyakov&Tkachev (2002), Harari et al. (2002), Prouza&Smida (2003), Yoshiguchi et al. (2003), Harari et al. (2003), Biermann et al. (2004), Yoshiguchi et al. (2004), Tinyakov&Tkachev (2005), HT et al. (2006), Chardonnet&Mattei (2006), Troitsky (2006), Kacheliess et al. (2006), HT & Sato (2008), Cuoco et al. (2008), Golup et al. (2009), Erdmann &Schiffer (2010), Yun-Ying et al. (2010), Giacinti et al. (2010), HT & Sato (2010), Nagar et al. (2010), Giacinti&Semikoz (2010), Harari et al. (2010)

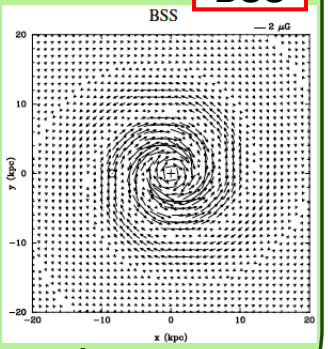
Many authors have been dedicated for studies on UHECR propagation in GMF.

GMF Models

B-field in the Galactic disk

- Parallel component
  - spiral
    - axi-symmetric (AS)
    - bi-symmetric (BS)
  - ring
    - field reversal

BSS

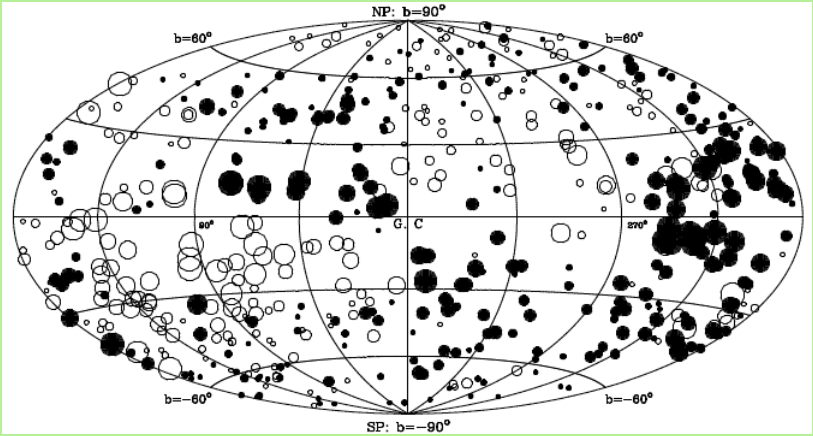


Sun et al. (2008)

- Vertical component
  - 0.2-0.3μG near the solar system

B-field in the Galactic Halo

- Parallel component to the disk



Han et al. (1997)

- Vertical component
  - mG filaments at around GC

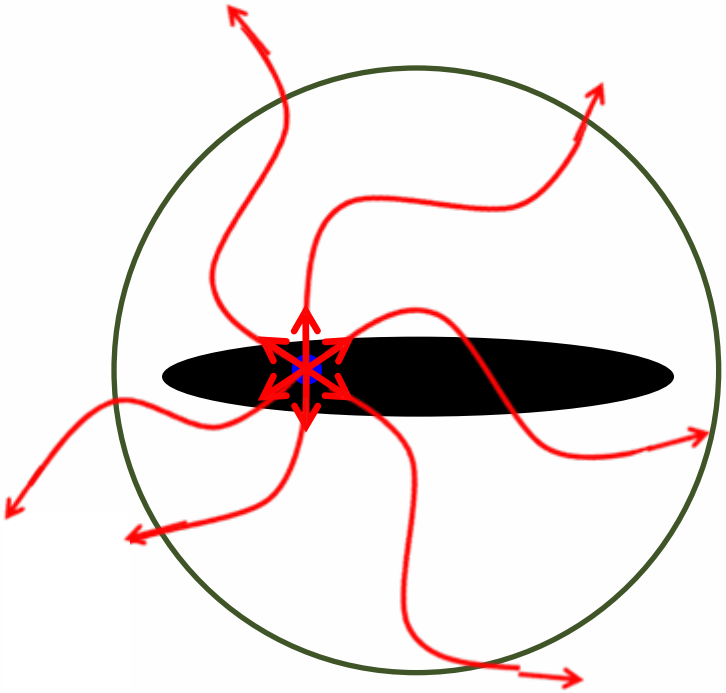
Random component

Random components are 0.5-2 times as large as coherent components.

Beck (2001)

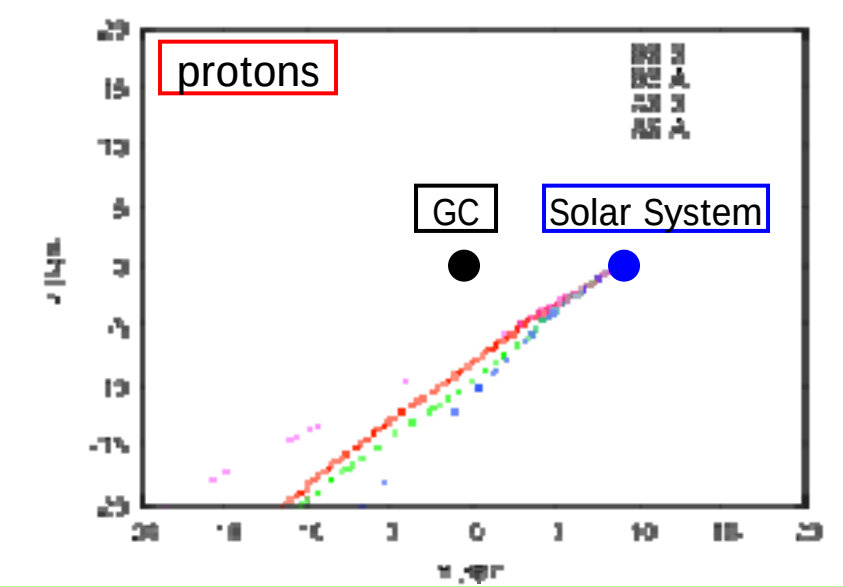
Backtracking Method

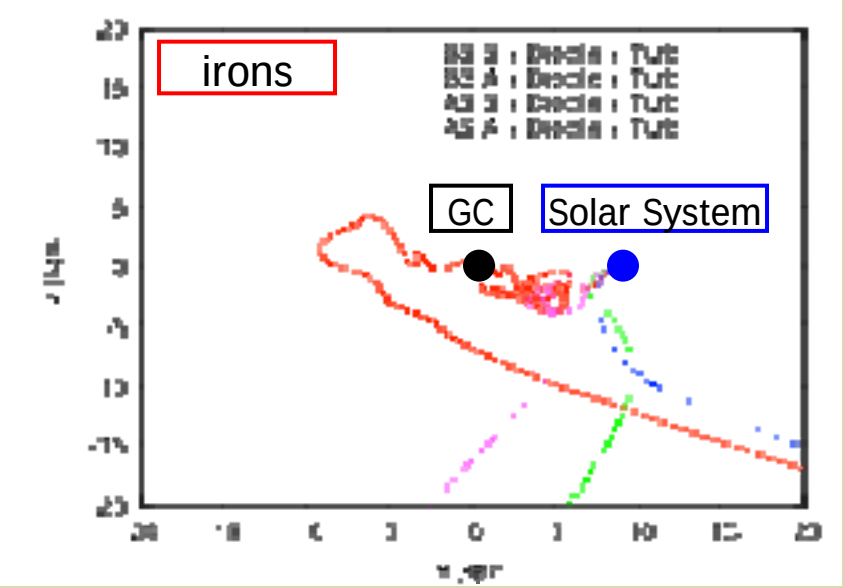
Considering the trajectories of oppositely-charged particles injected from Earth



- The trajectories can be regarded as the trajectories of particles from extragalactic space.
- We can focus only the trajectories of UHECRs arriving at the Earth.
- It allows us to save much CPU time
- This technique has been often adopted to investigate Earth magnetic field

Comparison of p and Fe propagation





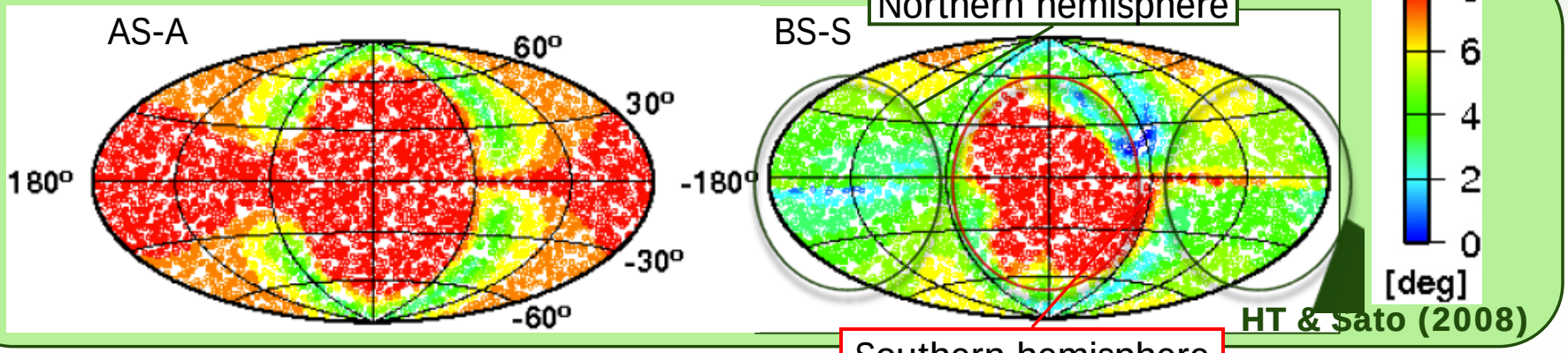
E~6x10^{19}eV

HT & Sato (2010)

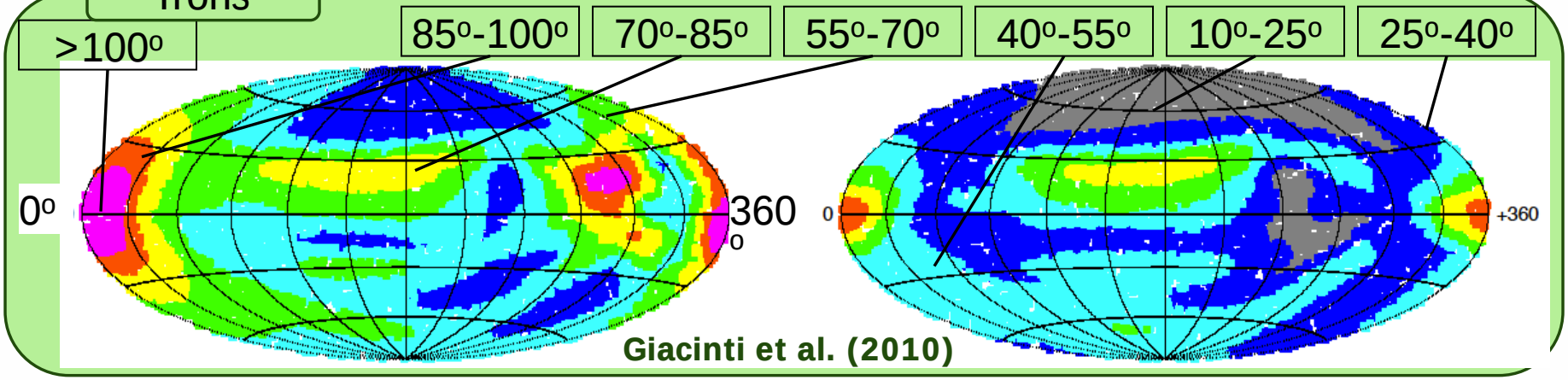
- The trajectories of protons and irons are completely different.
- GMF very close to the solar system contributes the total deflections.

Deflection Angles (E=6x10^{19}eV)

Protons



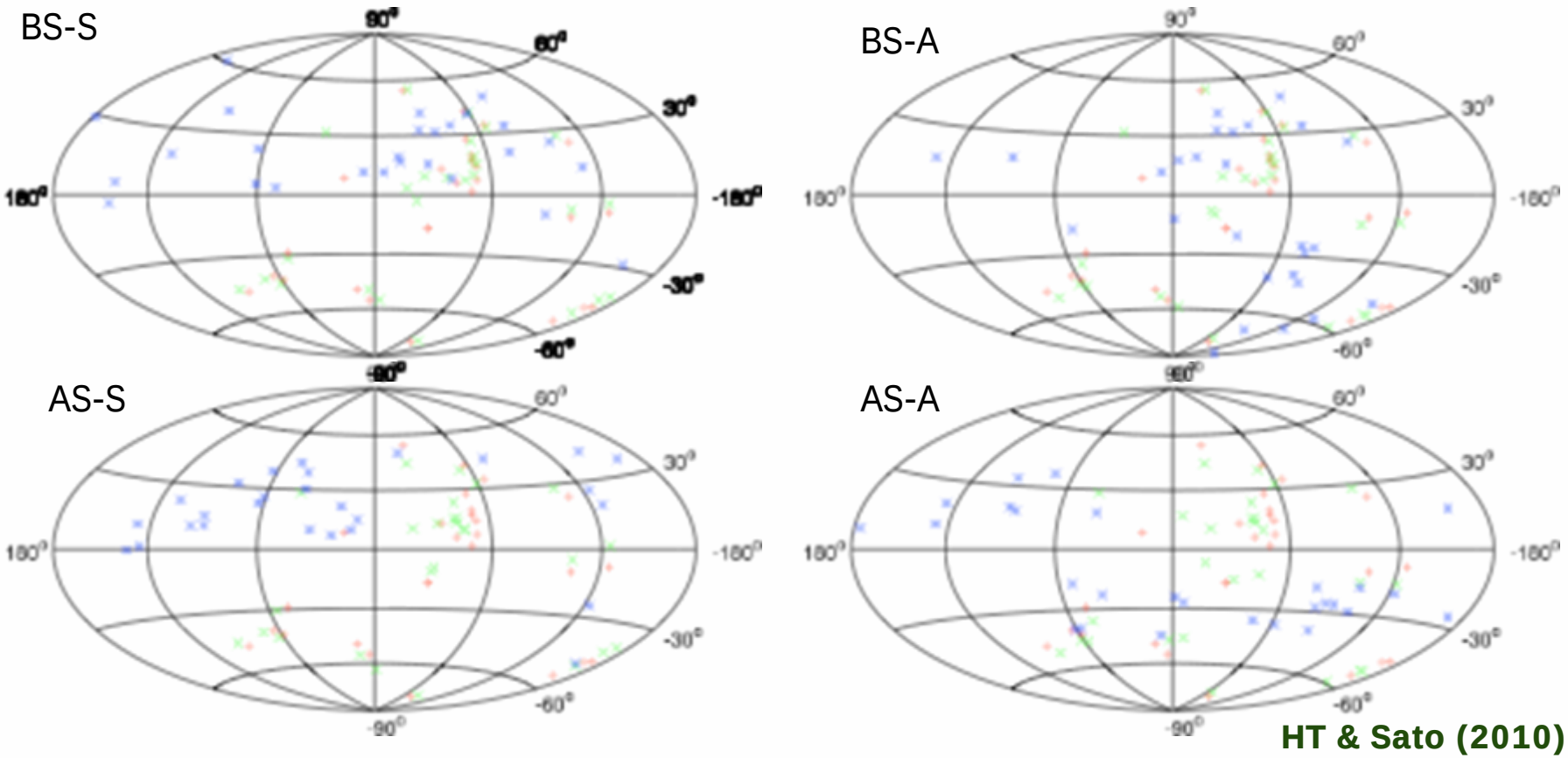
Irons



- Correlation between UHECRs and sources at small angular scale is not expected.
- Deflection patterns highly depend on models.
- Astronomically, the effects of GMF are different between North and South.

Arrival Directions of the Auger Events

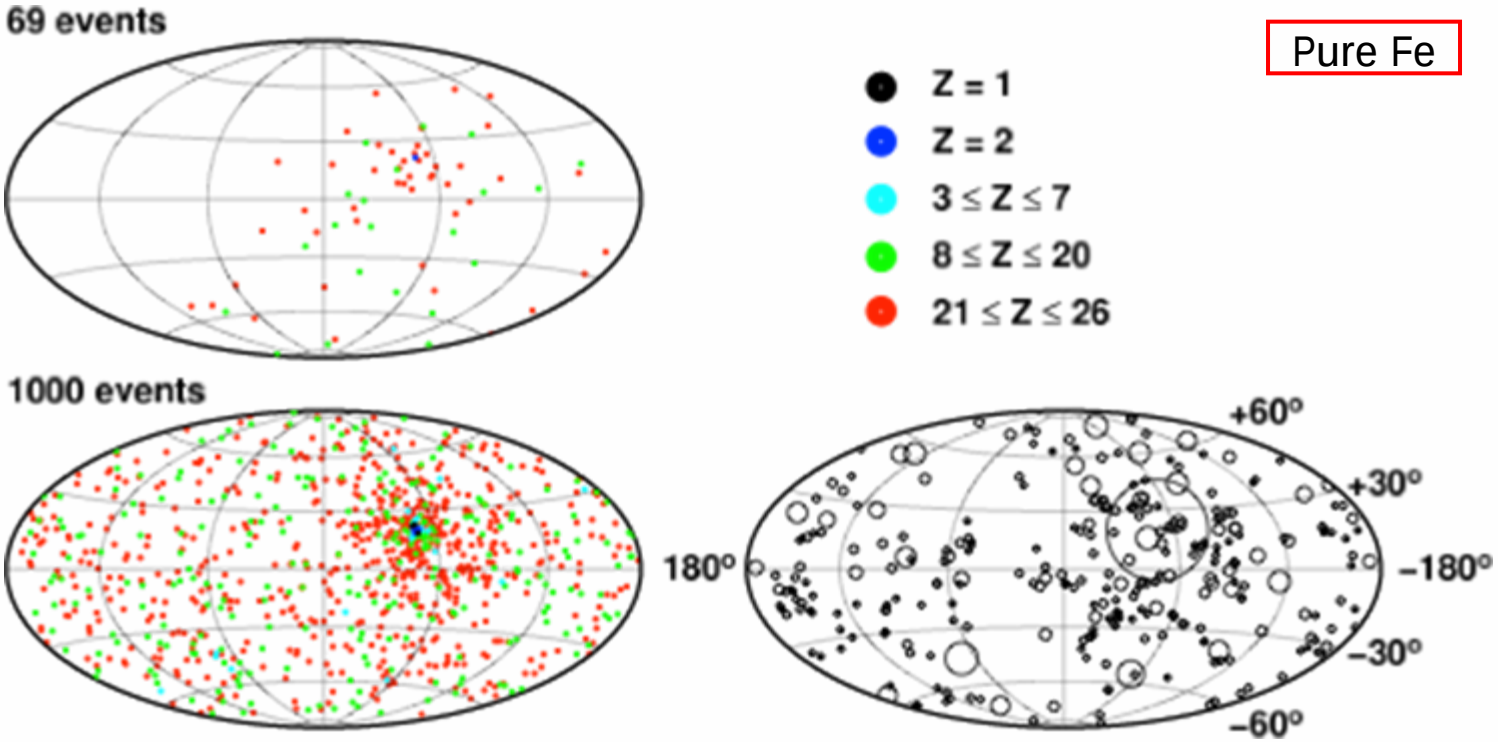
● : observed data, ● : protons, ● : irons, ● : galaxies



HT & Sato (2010)

The domination of heavy nuclei is not consistent with astrophysical sources?

Arrival Distribution of Nuclei



Pure Fe

HT, Inoue, Yamamoto (2010, in prep)

It is not possible that all the arrival UHECRs are irons due to propagation effects.

Correlation

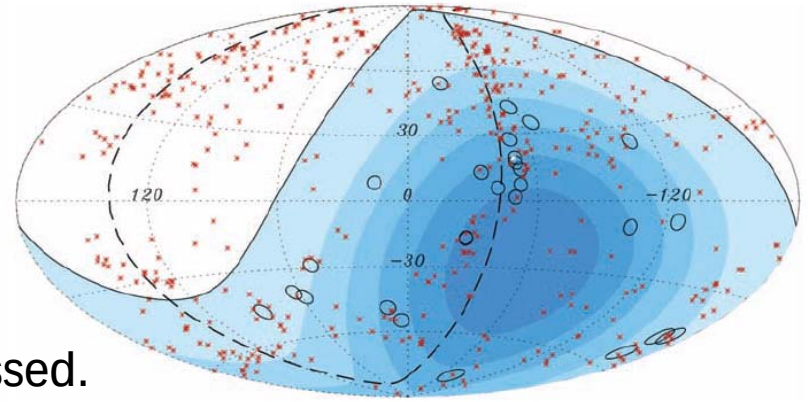
Many persons have tried analysis after the first Auger result.

The first Auger data

E>57EeV, z<0.018, θ=3.1^o, ~3σ

Recent Auger data

Significance is decreasing to ~2σ.
Large-scale anisotropy (~18^o) is discussed.

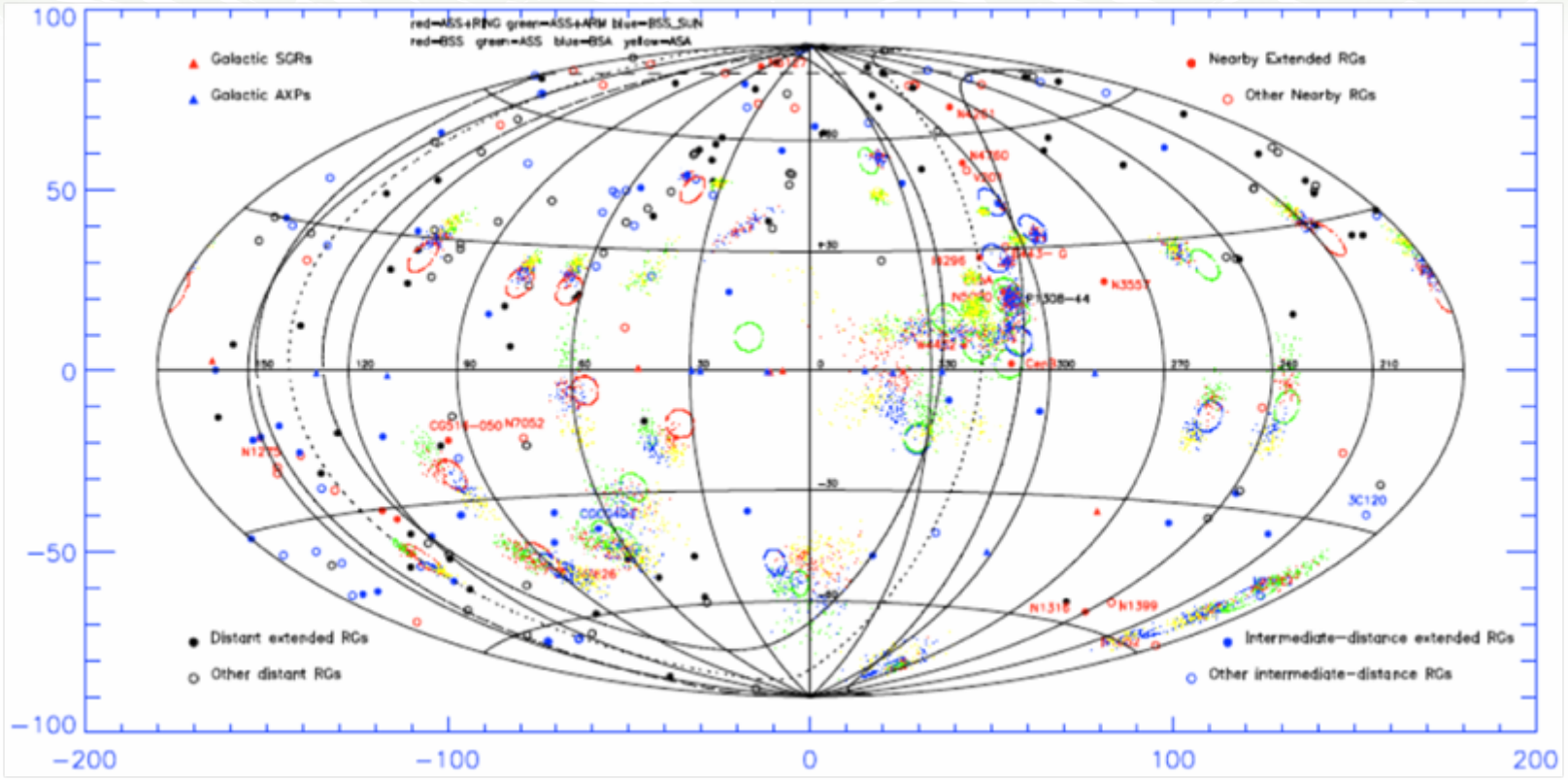


The Auger Collaboration (2007)

- IR galaxies (local structure) **Kashti& Waxman (2008), HT et al. (2009), PAO (2010)**
- X-ray selected AGNs **George et al. (2008)**
- HI selected galaxies (host of magnetars) **Ghisellini et al. (2008), PAO (2010)**
- Nearby Fermi sources (including starburst, radio-g, blazars) **Yun-ying et al. (2010)**
- (Extended) radio sources **Nagar et al. (2010)**

At least, astrophysical objects

Correlation studies incl. GMF modifications



Extened radio lobes?

Nagar et al. (2010)

Takahara (1990), Rachen&Biermann (1993), HT &Horiuchi (2010)

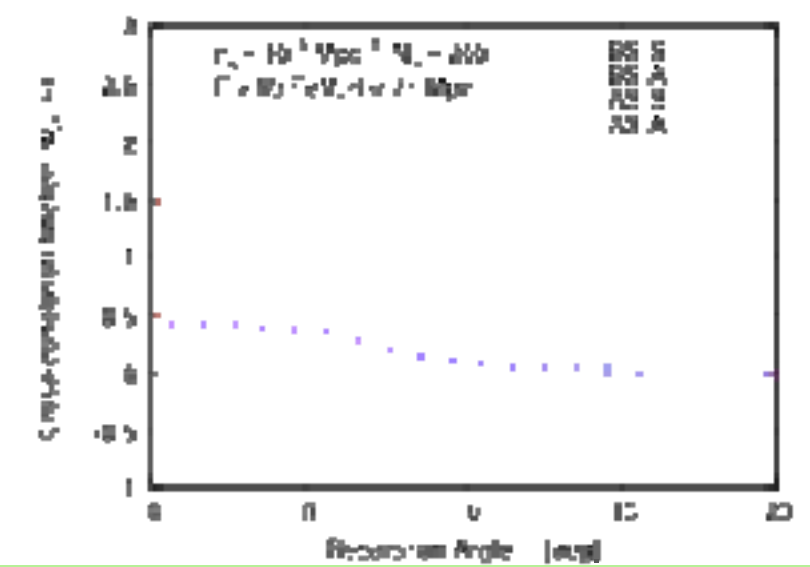
See also Tinyakov&Tkachev (2002) for blazars
Yun-Ying et al. (2010) for Fermi sources

Cross-correlation (protons)

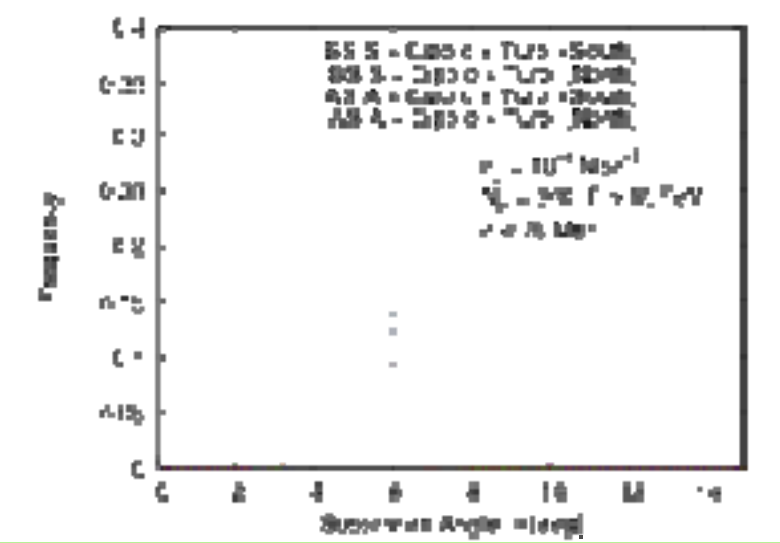
Cross-correlation

$n_s=10^{-4}Mpc^{-3}$, $N_p=200$, $E>6x10^{19}eV$, $d<75Mpc$

Cross-correlation functions



Angular scale with the strongest signal



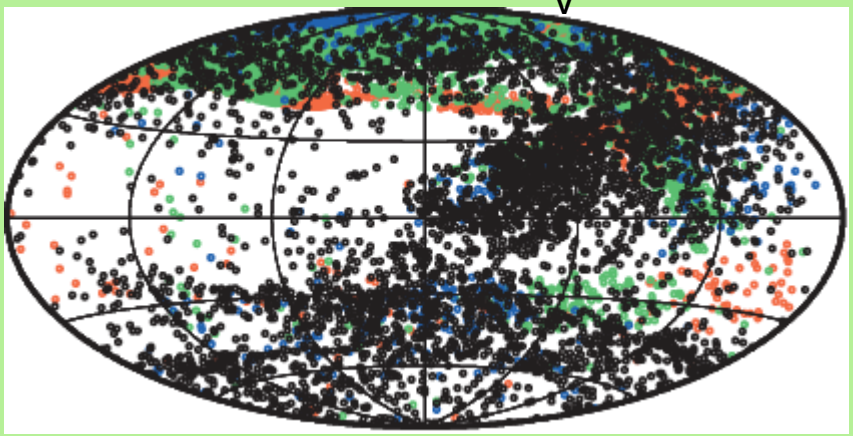
HT & Sato (2010)

Correlation between UHECRs and sources could be detected even considering GMFs.

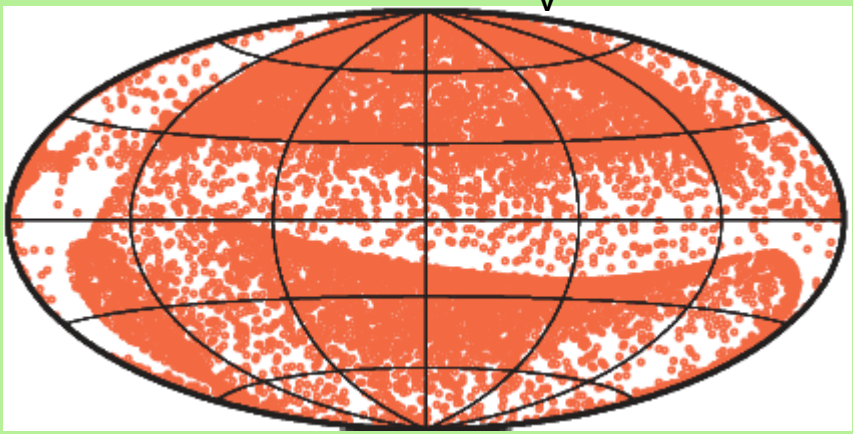
Magnetic Lensing/de-lensing

Back-tracked positions

$E_p = 10^{18}$eV → $E_{Fe} \sim 3 \times 10^{19}$eV



$E_p = 10^{19}$eV → $E_{Fe} \sim 3 \times 10^{20}$eV



Yoshiguchi et al. (2004)

The contribution of sources with specific directions could be enhanced or reduced.

See also Alvarez-Muniz (2002), Harari et al. (2002), Kacheliess et al. (2007), Giacinti et al. (2010)

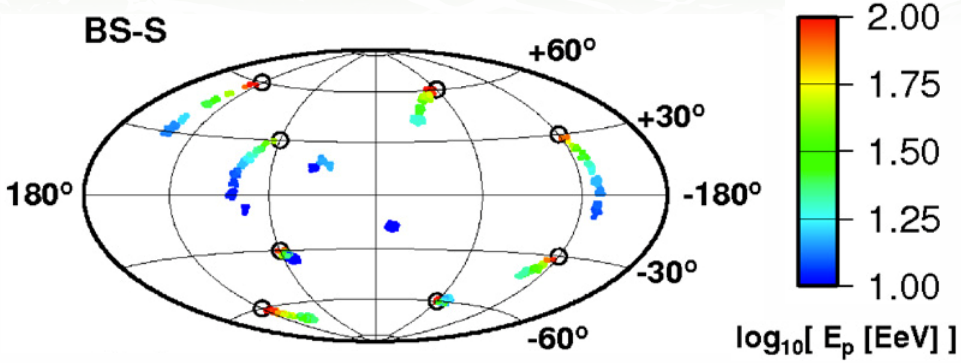
GMF reconstruction

source

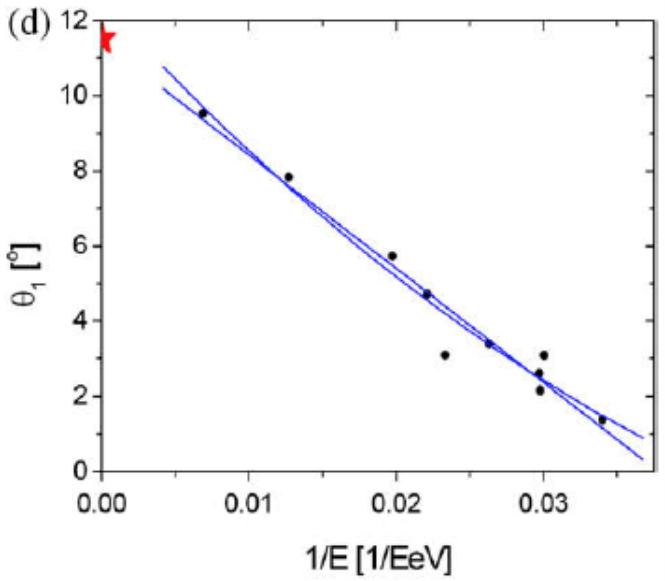
$$\vec{\beta} = \vec{\theta} + \frac{\vec{F}(\vec{\theta})}{E} \qquad \vec{F}(\vec{\theta}) = Ze \int_0^L d\vec{l} \times \vec{B}(\vec{l})$$

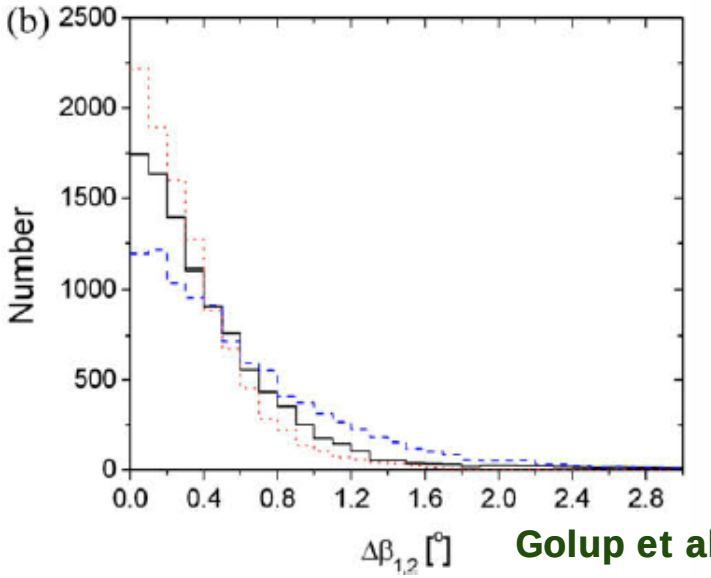
events

$$\theta_1 \simeq \beta_1 - \frac{F_{\theta_1}(\vec{\beta})}{E} + \frac{1}{E^2} F_{\theta_1}(\vec{\beta}) \frac{\partial F_{\theta_1}}{\partial \theta_1}\bigg|_{\vec{\beta}}$$



HT & Sato (2010)

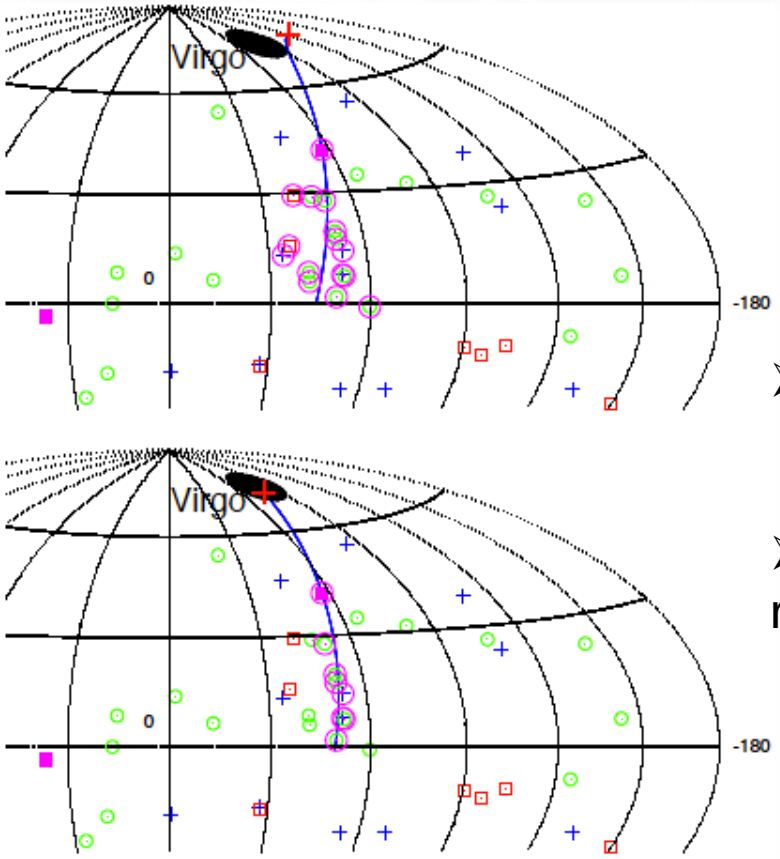




Golup et al. (2009)

See also Harari et al. (2002)

M87?



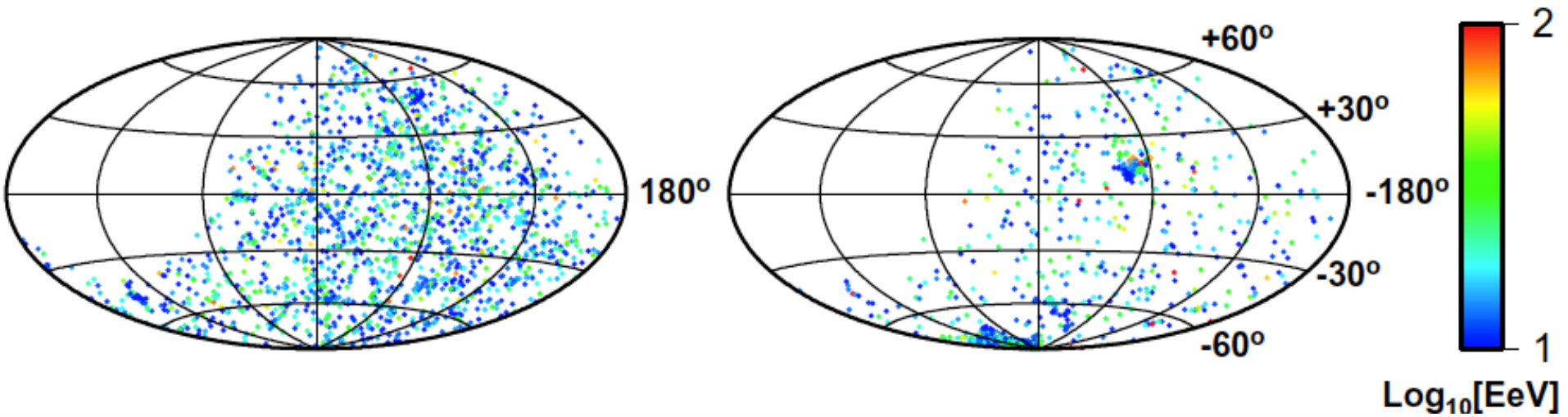
Giacinti&Semikoz (2010)

- Similar technique as in the former slide, applies to the real data
- Some of the Auger events in the Cen A region might come from Virgo region?

Summary

- Propagation of UHECRs in GMF highly depends on GMF modelings.
- Based on reliable GMF models, global correlation between UHECRs and their sources at small angular scale is difficult to be realized for heavy-dominated composition. It is possible for proton-dominated composition.
- Several authors have developed reconstruction methods of source positions and local GMF structure.

Arrival Distribution at ~10^{19}eV



HT & Sato (2009)