Ultra-high energy cosmic rays and large-scale structure of the Universe

P. Tinyakov

1Université Libre de Bruxelles, Bruxelles, Belgium

2Institute for Nuclear Research, Moscow, Russia

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Outline

Introduction

Case of small deflections

How small the deflections are?

Conclusions
INTRODUCTION & MOTIVATION

- Last generation of UHECR experiments (Auger in the South and TA in the North) are rapidly collecting events at highest energies $E > 10^{19}$ eV.
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- One of the questions is settled: there is a cut-off in the spectrum
  - HiRes: $5\sigma$
  - Auger: $20\sigma$
  - TA: $3.5\sigma$

However, there is not much progress (so far) in the other two key questions — (i) chemical composition and (ii) anisotropies and sources
- Auger data indicate heavy composition at high energies and anisotropy (excess around Cen A, correlation with nearby AGN). These are (potentially) contradictory statements.
- The HiRes and TA indicate light composition and isotropy. But this is also uncomfortable.

[Graphs showing energy distribution and cut-off analysis]
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The question addressed in this talk:
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Proceed as follows:
- First, assume the deflections are small and calculate expected anisotropy.
- Next, check if this assumption is reasonable and how the conclusions change if it is not satisfied.
SMALL DEFLECTIONS
FLUX CALCULATION

- At highest energies CR have propagation distance $\lesssim 100$ Mpc
- Matter distribution on these scales is inhomogeneous $\Rightarrow$ one expects flux variations over the sky
- Matter distribution can be accurately mapped out to $\sim 250$ Mpc from the 2MASS Galaxy Redshift Catalog (XSCz) (unpublished; provided by T. Jarrett)
- Assume the UHECR luminosity proportional to the matter density
- Calculate all propagation effects (interaction with photon backgrounds, redshift)
- Apply Gaussian smearing with the angular scale $\theta$ treated as a free parameter
- Obtain the prediction for the flux sky map
C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); PI: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); Ursa Major North group (20 Mpc) South group (20 Mpc); V: Virgo cluster (20 Mpc).
STATISTICAL TEST: FLUX SAMPLING

Events following the model would produce uniform distribution over the bands. No binning is actually needed (on the picture it is for illustration only): two distributions may be compared by the Kolmogorov-Smirnov test.
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WHAT IS SEEN IN TA

\[ E > 4 \times 10^{19} \text{ eV} \]
WHAT IS SEEN IN TA

E\textgreater{}40 EeV

95\% CL

smearing angle, degrees

probability

NULL = structure

NULL = iso

0.001
0.01
0.1
1

0 2 4 6 8 10 12 14

NULL = iso

95\% CL

probability

smearing angle, degrees

0 0.001 0.01 0.1 1
WHAT IS SEEN IN TA

\[ E > 5.7 \times 10^{19} \text{ eV} \]
WHAT IS SEEN IN TA

95% CL
E>57 EeV
NULL = structure
NULL = iso
smearing angle, degrees
probability
 0.001
 0.01
 0.1
 1

0  2  4  6  8  10  12  14
Statistical power is defined as the complement of the type-II error (type-II error is the probability of falsely accept null-hypothesis when the alternative hypothesis is true).

Statistical power is meaningful when it is close to 1 (say, larger than 0.5). Then two distributions separate.
STATISTICAL POWERS IN CASE OF TA

\[ E > 1 \times 10^{19} \text{ eV} \]

\[
\begin{array}{c|c|c|c|c|c}
N & 2000 & 1400 & 1000 & 700 & 500 \\
\hline
\text{statistical power} & & & & & \\
\end{array}
\]

\[ \theta, \text{ degrees} \]

\[ \text{NULL-structure ALT=iso E>10EeV} \]
$E > 4 \times 10^{19} \text{ eV}$

![Graph showing statistical powers in case of TA](image)
$E > 5.7 \times 10^{19} \text{ eV}$
CONCLUSIONS OF THE TEST:

- Present TA data are compatible with both structure and isotropy
- Need to double or triple the statistics to see the difference
ARE DEFLECTIONS SMALL OR LARGE?
Origin of “deflections”:

- Finite angular resolution
  - 1.5° for TA, ~ 1° for Auger
  - subdominant

- Deflections in the extragalactic magnetic fields
  \[ \theta = 1.8° \left( \frac{E}{10^{20} \text{eV}} \right)^{-1} \left( \frac{R}{50 \text{Mpc}} \right)^{1/2} \left( \frac{B}{10^{-9} \text{G}} \right) \]
  - a likely upper bound
  - may be larger in galaxy clusters (irrelevant for us)
  - may be larger in filaments (irrelevant for us?)
  - likely subdominant

- Deflections in the Galactic magnetic field
  - in the random component: likely subdominant
  - in the regular component: likely a dominant contribution
  \[ \theta = 0.52° \left( \frac{E}{10^{20} \text{eV}} \right)^{-1} \left( \frac{R}{1 \text{kpc}} \right) \left( \frac{B}{10^{-6} \text{G}} \right) \]
Origin of “deflections”:

- Finite angular resolution
  - $1.5^\circ$ for TA, $\sim 1^\circ$ for Auger
  - subdominant

- Deflections in the extragalactic magnetic fields
  \[ \theta = 1.8^\circ \left( \frac{E}{10^{20}\text{eV}} \right)^{-1} \left( \frac{l_c R}{50\text{Mpc}^2} \right)^{1/2} \left( \frac{B}{10^{-9}\text{G}} \right) \]
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GALACTIC MAGNETIC FIELD

- Coherent field in other galaxies:

M51

NGC891
Is there a coherent field in the Milky Way?

Smeared Faraday rotation measures

\[ \text{RM} \propto \int dl \ n_e \cdot B_{||} \]

by Kronberg & Newton-McGee (2011):
Is there a coherent field in the Milky Way?

NRAO VLA Sky Survey (NVSS) rotation measures catalogue:
GMF general structure

- Two components are necessary: symmetric disk + antisymmetric halo [Pshirkov, P.T., Kronberg, Newton-McGee arXiv:1103.0814]

[Previous studies: Simard-Normandin & Kronberg (1980); Han & Qiao (1994); Stanev 1997; Tinyakov & Tkachev (2002); Prouza & Smida (2003); Sun et al. (2008);]
Fit to data:

DATA

MODEL

Bin size $10^\circ \times 10^\circ$
SIZE OF DEFLECTIONS (protons, $E = 4 \times 10^{19}$ eV)

ASS model
SIZE OF DEFLECTIONS (protons, $E = 4 \times 10^{19}$ eV)

BSS model
CONCLUSIONS FROM GMF STUDY

- In case of protons of energy $E = 4 \times 10^{19}$ eV a typical deflection is $5^\circ - 10^\circ$ depending on direction (larger along the Galactic plane).
- This implies deflections of order $20^\circ - 40^\circ$ at $E = 10^{19}$ eV.
- Potential caveat: degeneracy in the GMF parameters which may affect deflections. In particular, a combination of the halo strength and height over the Galactic plane is poorly constrained from RM measurements. This gives the uncertainty of about factor 2 in deflections.
CONCLUSIONS

- The deflections in the Galactic magnetic field can be calculated with the uncertainty of about factor 2.
- If CR are protons, we should see anisotropy at least at highest energies with $O(100)$ events above $E = 5.7 \times 10^{19}$ eV.
- If CR are iron, the deflections are $90^\circ - 180^\circ$ at $E = 5.7 \times 10^{19}$ eV and we should see no anisotropy except may be at largest scales (like dipole or quadrupole).