UHECR anisotropies and the Large-Scale matter distribution

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Outline

Introduction

Matter distribution in the Universe

Propagation of UHECR
- Attenuation
- Deflections

Flux predictions

Signatures

Conclusions

Introduction

- Identifying the sources of UHECR is one of the key problems in the field
- Without knowing the sources, can we still say something about the expected sky distribution of UHECR?
- In any reasonable model the sources of UHECR are made of baryonic matter $\Longrightarrow$ their distribution must follow that of the matter in the Universe
- Caveat:
  - Different types of objects cluster a bit differently; at this stage we do not need to worry about these details.
- A key parameter is the overall source density n
  - If it is smaller than $\sim (50\ \mathrm{Mpc})^{-3}$ the source distribution is essentially random (no structures at large scales)
- To proceed, we will assume here the opposite case:

$$n \gg (50\ \mathrm{Mpc})^{-3}$$

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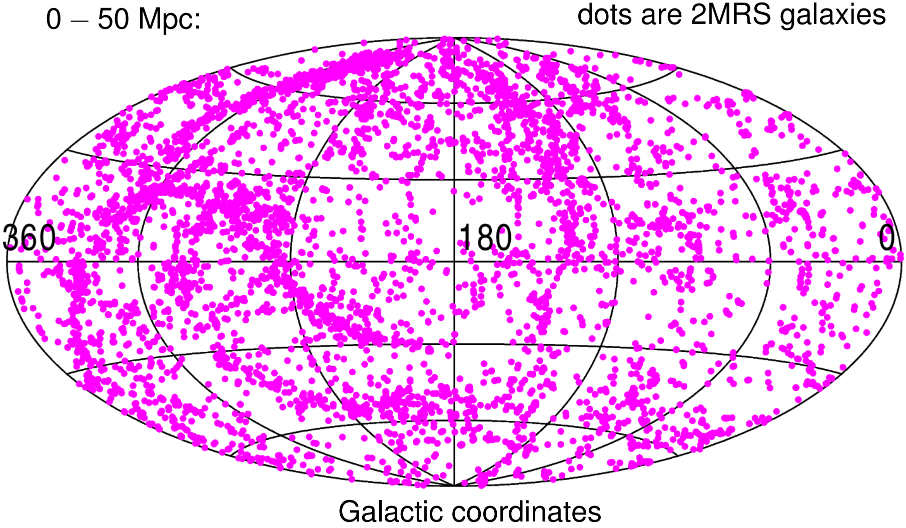
MATTER DISTRIBUTION IN THE UNIVERSE

Matter distribution in the Universe

- Can be deduced from the all-sky complete galaxy catalog – 2MASS Redshift Survey (2MRS) *Hucra et al, ApJ (2012) 199, 26*
  - contains redshifts (therefore, distances) of objects
  - $\sim 10^5$ objects within 250 Mpc
  - is complete except around the Galactic plane
  - is flux-limited, so represents better the nearby structures – good
  - has to be corrected for selection bias – bad

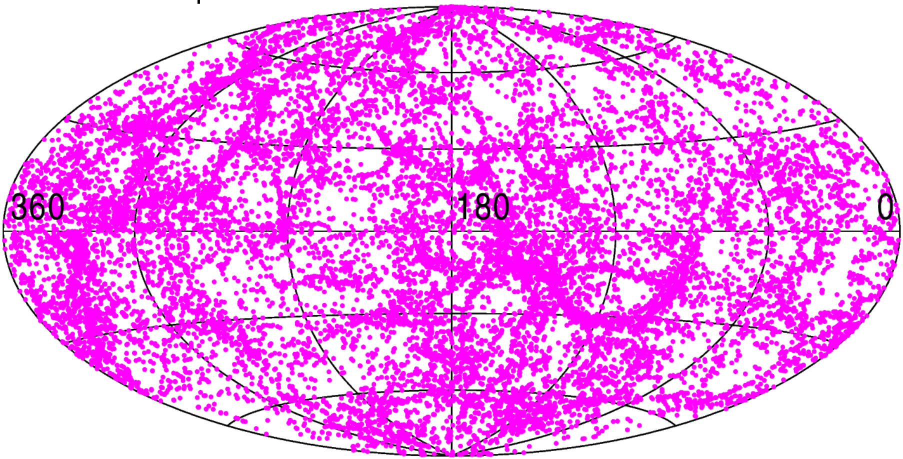
Matter distribution in the Universe



Matter distribution in the Universe

50 – 100 Mpc:

dots are 2MRS galaxies

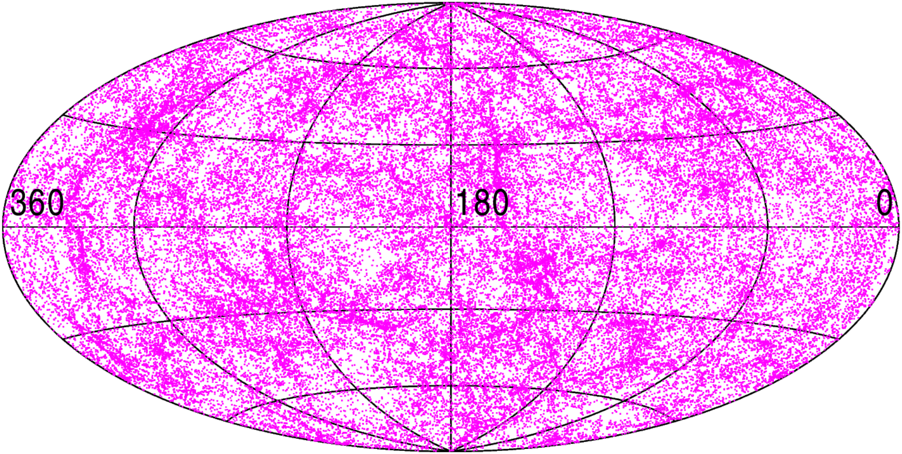


Galactic coordinates

Matter distribution in the Universe

100 – 250 Mpc:

dots are 2MRS galaxies

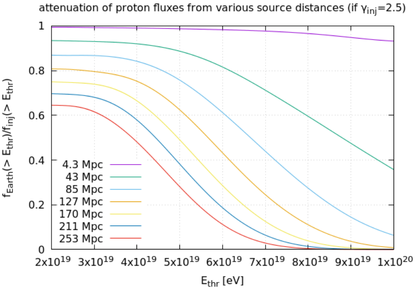


Galactic coordinates

PROPAGATION OF UHECR

Propagation of UHECR: attenuation

[plot by Di Matteo]



- CRs attenuate while propagating over large distances
- Attenuation grows with energy
- In case of primary protons — GZK effect
- In case of nuclei — spallation processes

- Qualitatively, the attenuation is similar for protons and heavy nuclei; light nuclei attenuate much faster
- Quantitatively: numerical codes CRPropa, SimProp, TransportCR, ...
- For concreteness we take proton attenuation as a model; this is not quantitatively accurate in case of heavy nuclei, but there are larger uncertainties anyway

Propagation of UHECR: magnetic deflections

- Barring exotic possibilities, CRs are electrically charged $\Longrightarrow$ they are deflected by cosmic magnetic fields

$$\text{regular}: \qquad \theta = 0.52^\circ Z \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{D}{1\mathrm{kpc}}\right) \left(\frac{B_\perp}{10^{-6}\mathrm{G}}\right)$$

$$\text{random}: \qquad \theta = 1.8^\circ Z \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{l_c D}{50\mathrm{Mpc}^2}\right)^{1/2} \left(\frac{B}{10^{-9}\mathrm{G}}\right)$$

- Extragalactic magnetic field is thought to be random with the corelation length $\lesssim$ 1 Mpc. The current bound on the magnitude is $B \lesssim 1$ nG *Pshirkov et al, PRL 116 (2016), 191302*
  - Caveat: B in filaments may be stronger — important if we are in a filament ourselves!
- Galactic field has both regular and random components. The regualr field is thought to dominate the deflections.
- Fortunately, we know the Galactic field better than EGMF.

Regular GMF models

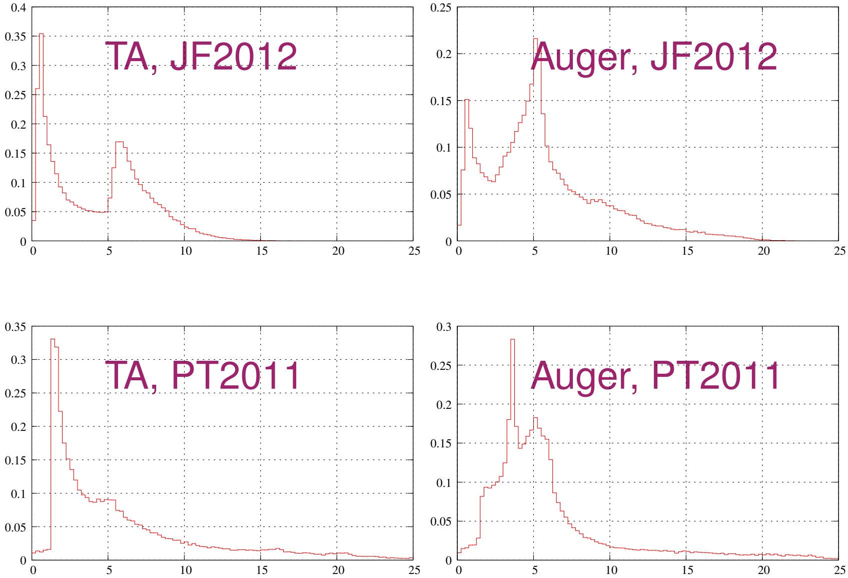
Old models based on pulsar data — some refs

- Y. Sofue and M. Fujimoto, Ap. J. 265 (1983) 722.
  T. Stanev, Ap. J. 479 (1997) 290, astro-ph/9607086.
  J. L. Han and G. J. Qiao, Astron. Astrophys. 288 (1994) 759.
  J. L. Han, R. N. Manchester, and G. J. Qiao, MNRAS 306 (1999) 371 [astro-ph/9903101]
  P.G. Tinyakov and I.I. Tkachev, Astropart.Phys. 18 (2002) 165-172

Recent models

- PT2011 model *Pshirkov et al, Astrophys.J. 738 (2011) 192*
  - Based on the NVSS Faraday rotation data
  - Fits Faraday rotation at Galactic $|b| > 10^\circ$
  - 10 (15) free parameters
- JF2012 model *Jansson and Farrar. Astrophys.J. 757 (2012) 14*
  - Based on NVSS Faraday rotations + synchrotron polarization data
  - 22 free parameters

DEFLECTIONS: regular GMF, protons of 57 EeV



In numbers:

Deflections of protons of $E = 57$ EeV in the regular GMF:

	mean	median	rms
PT2011 model, TA	6.0	4	5.2
PT2011 model, PA	6.1	5	4.5
JF2012 model, TA	4.4	4.5	3.2
JF2012 model, PA	5.7	5	3.8

RANDOM DEFLECTIONS

- Look in a few selected patches on the sky where the random field has been measured and calculate deflections. Outcome: random deflections are subdominant by a factor 0.3 – 0.1 *PT, Tkachev, Astropart.Phys. 24 (2005) 32-43*
- Bypass reconstruction of GMF, infer deflections directly from the RM distribution $\Longrightarrow$ consistent with the above

  Pshirkov, PT, Urban MNRAS 436 (2013) 2326

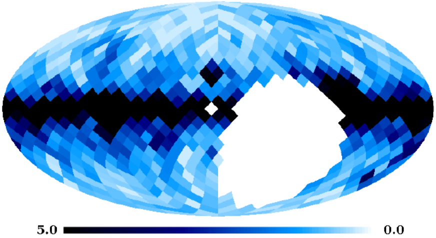


Figure 1. The map of displacements $\sqrt{\langle\theta^2\rangle}$ of protons with energy $E = 4\times10^{19}$ eV due to the random component of the GMF

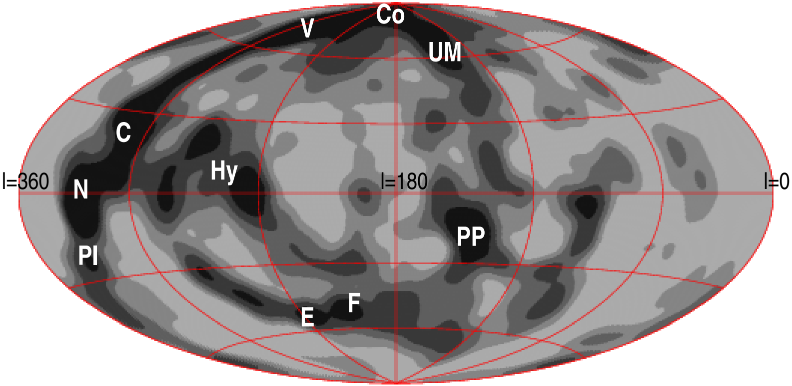
SUMMARY OF MAGNETIC DEFLECTIONS

- Typical deflections in existing models recalculated to $E = 100$EeV are $\sim 2^\circ - 3^\circ$ (median or mean)
- Distributions are not Gaussian; deflections are direction-dependent
- Caveat: large uncertainties in GMF modeling
- Random deflections are subdominant in all known scenarios

FLUX PREDICTIONS

PUTTING EVERYTHING TOGETHER

protons, $E = 57$ EeV, smearing $\theta = 6^\circ$; Galactic coordinates

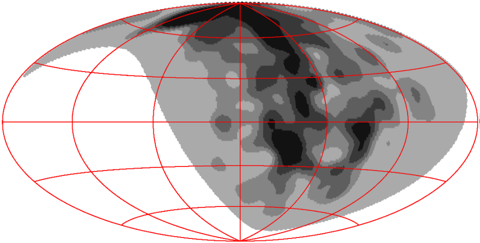


C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); Pl: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); Ursa Major North group (20 Mpc) South group (20 Mpc); V: Virgo cluster (20 Mpc).

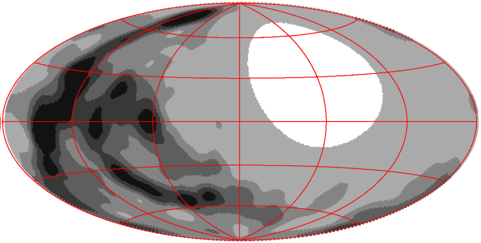
SUPERIMPOSED WITH EXPOSURE

Galactic coordinates; protons $E > 57$ EeV, smearing 6°

TA, $\theta < 55^\circ$



Auger, $\theta < 80^\circ$



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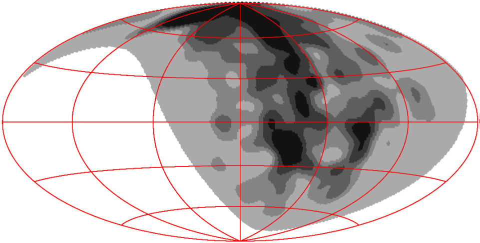

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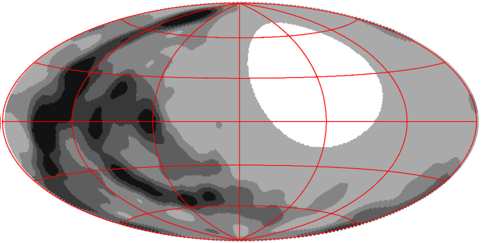
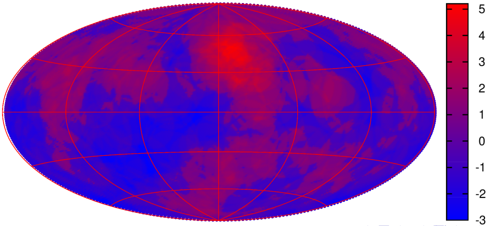
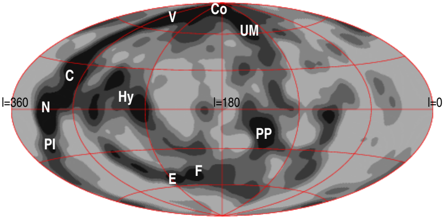
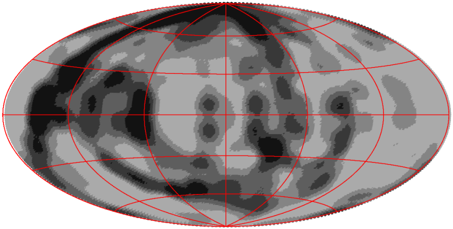




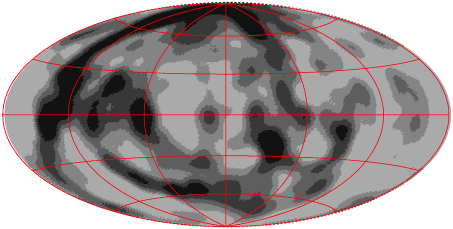
Including GMF deflections: $E = 57$ EeV, protons



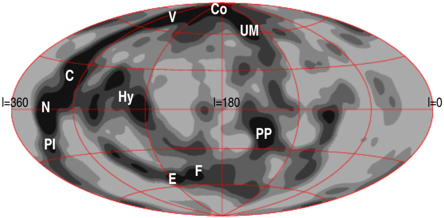
PT2011



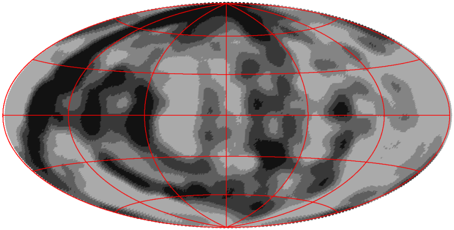
JF2012



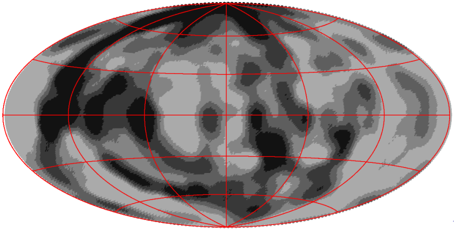
Including GMF deflections: $E = 40$ EeV, protons



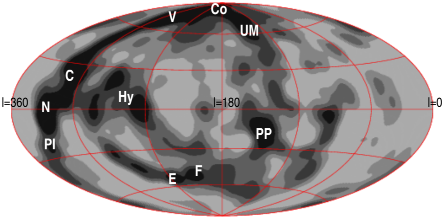
PT2011



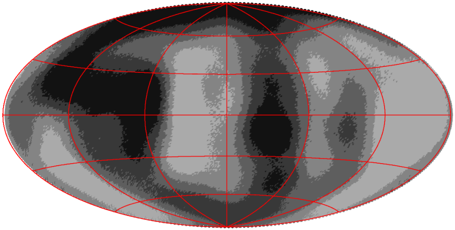
JF2012



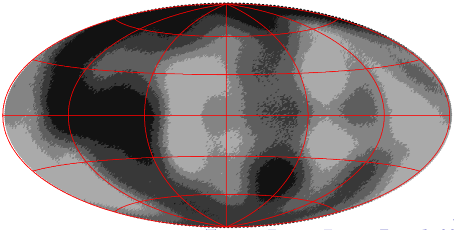
Including GMF deflections: $E = 10$ EeV, protons



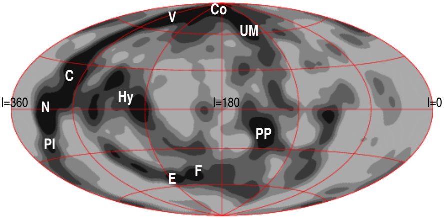
PT2011



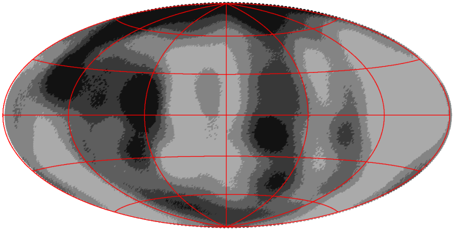
JF2012



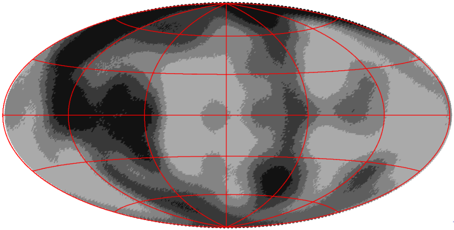
Including GMF deflections: $E = 57$ EeV, carbon $Z = 6$



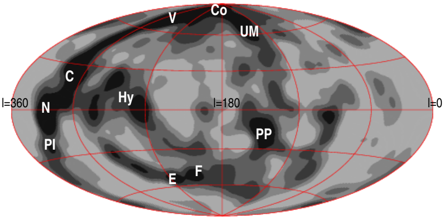
PT2011



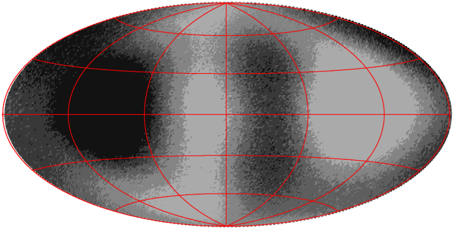
JF2012



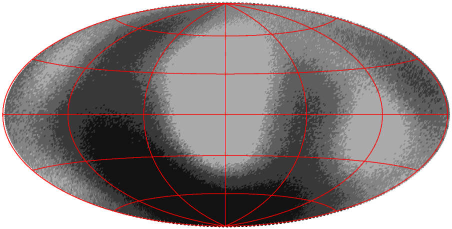
Including GMF deflections: $E = 57$ EeV, iron $Z = 26$



PT2011



JF2012



Magnetic field deflections: summary

- Corrections are reasonable for protons of highest energies but large in all other cases
- We cannot predict them reliably with our current knowledge of GMF — not in detail sufficient, e.g., for cross-correlations with catalogs

SIGNATURES

SIGNATURES

- Anisotropies are largest at high energies where the statistics is small and are small at low energies where the statistics is large $\Longrightarrow$ a difficult situation
- No reliable predictions can be made at small angles, except perhaps in case of protons at highest energies
- Several methods may be used to assess anisotropy generated by LSS:
  - auto-correlation — not specific to LSS
  - cross-correlations with LSS — predictions are model-dependent because of GMF; differences between models are not small
  - multipole decomposition — requires full-sky coverage (see talk by Di Matteo at this conference), and is also model-dependent. However, here there is a trick: power spectrum C_l is much less sensitive to GMF details than individual a_{lm}'s.

PT, Urban, JETP 120 (2015) 533

Multipole decomposition, example 1: protons at $E = 57$ EeV

- The GMF-corrected flux from LSS can be written as

$$\Phi(\vec{n}) = 1 + \vec{d} \cdot \vec{n} + \text{higher multipoles}$$

- PT2011 model:

$$\vec{d} = (0.23,\ 0.16,\ 0.06); \qquad |d| = 0.29$$

- JF2012 model:

$$\vec{d} = (0.21,\ 0.15,\ 0.09); \qquad |d| = 0.27$$

Multipole decomposition, example 2: protons at $E = 10$ EeV

- PT2011 model:

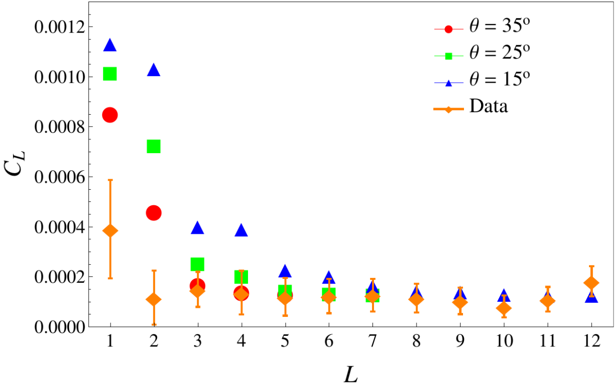
$$\vec{d} = (0.06,\ 0.06,\ 0.03); \qquad |d| = 0.09$$

- JF2012 model:

$$\vec{d} = (0.06,\ 0.04,\ 0.03); \qquad |d| = 0.08$$

Multipole decomposition, example 2: protons at $E = 10$ EeV

- Predictions for multipoles vs. the data (common Auger-TA set, Astrophys.J. 794 (2014) 172)



PT, Urban, JETP 120 (2015) 533

Multipole decomposition, example 3: iron at $E = 57$ EeV

- PT2011 model:

$$\vec{d} = (0.17,\ 0.02,\ -0.05); \qquad |d| = 0.18$$

- JF2012 model:

$$\vec{d} = (0.10,\ -0.18,\ -0.03); \qquad |d| = 0.20$$

- $\Longrightarrow$ even though the individual dipole components differ, the multipole C_1 (equivalently, $|d|$) is much less sensitive to model uncertainties

Conclusions

- Matter inhomogeneities in the nearby Universe create anisotropies in the CR flux that are potentially measurable
- Uncertainties in the composition of UHECR and in magnetic fields (notably, GMF) make the detailed predictions difficult at present
- There are observables (e.g., C_l's) that are not very sensitive to these uncertainties $\Longrightarrow$ LSS-related anisotropies should be discovered in the very near future
- Bottleneck — statistics in the Northern hemisphere

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