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Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

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

Peter TINYAKOV
*Universite' Libre de Bruxelles
Belgium*

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

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

P. Tinyakov

[1]Université Libre de Bruxelles, Bruxelles, Belgium

[2]Institute for Nuclear Research, Moscow, Russia

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Outline

Introduction

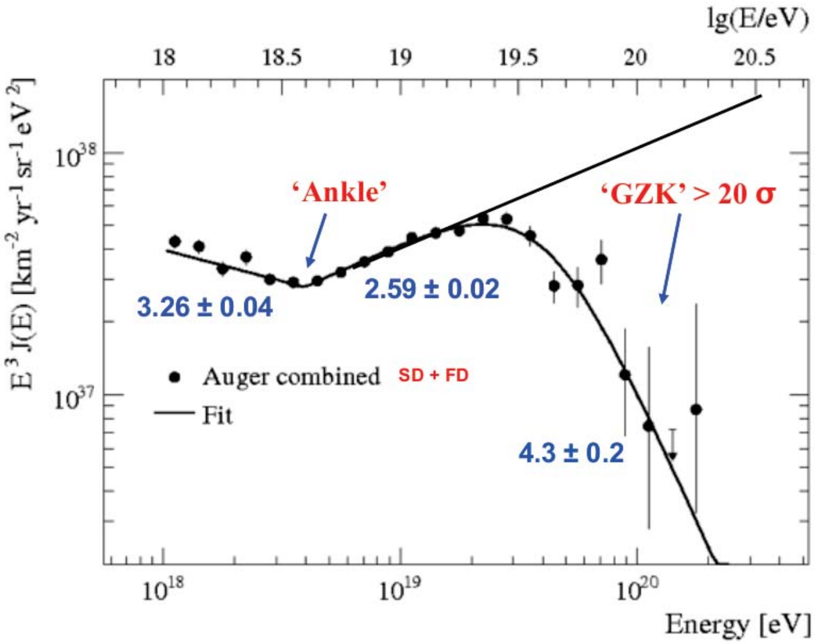
Case of small deflections

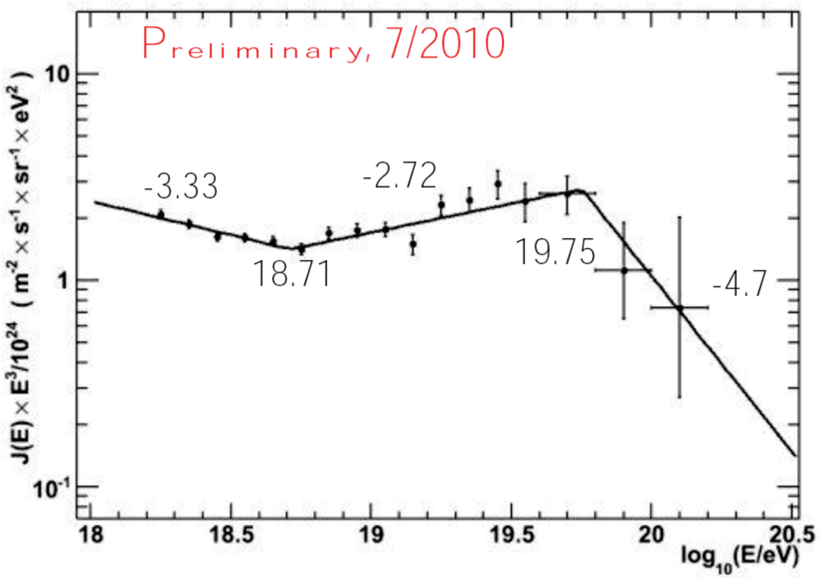
How small the deflections are?

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
- One of the questions is settled: there is a cut-off in the spectrum
  - HiRes: 5σ
  - Auger: 20σ
  - TA: 3.5σ





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
- One of the questions is settled: there is a cut-off in the spectrum
  - HiRes: 5σ
  - Auger: 20σ
  - TA: 3.5σ
- 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.

INTRODUCTION & MOTIVATION

The question addressed in this talk:
What anisotropy is expected at high energies?

More specifically:
If one assumes light composition (protons) as indicated by the TA data, what anisotropy must be present without any concrete assumptions about sources?

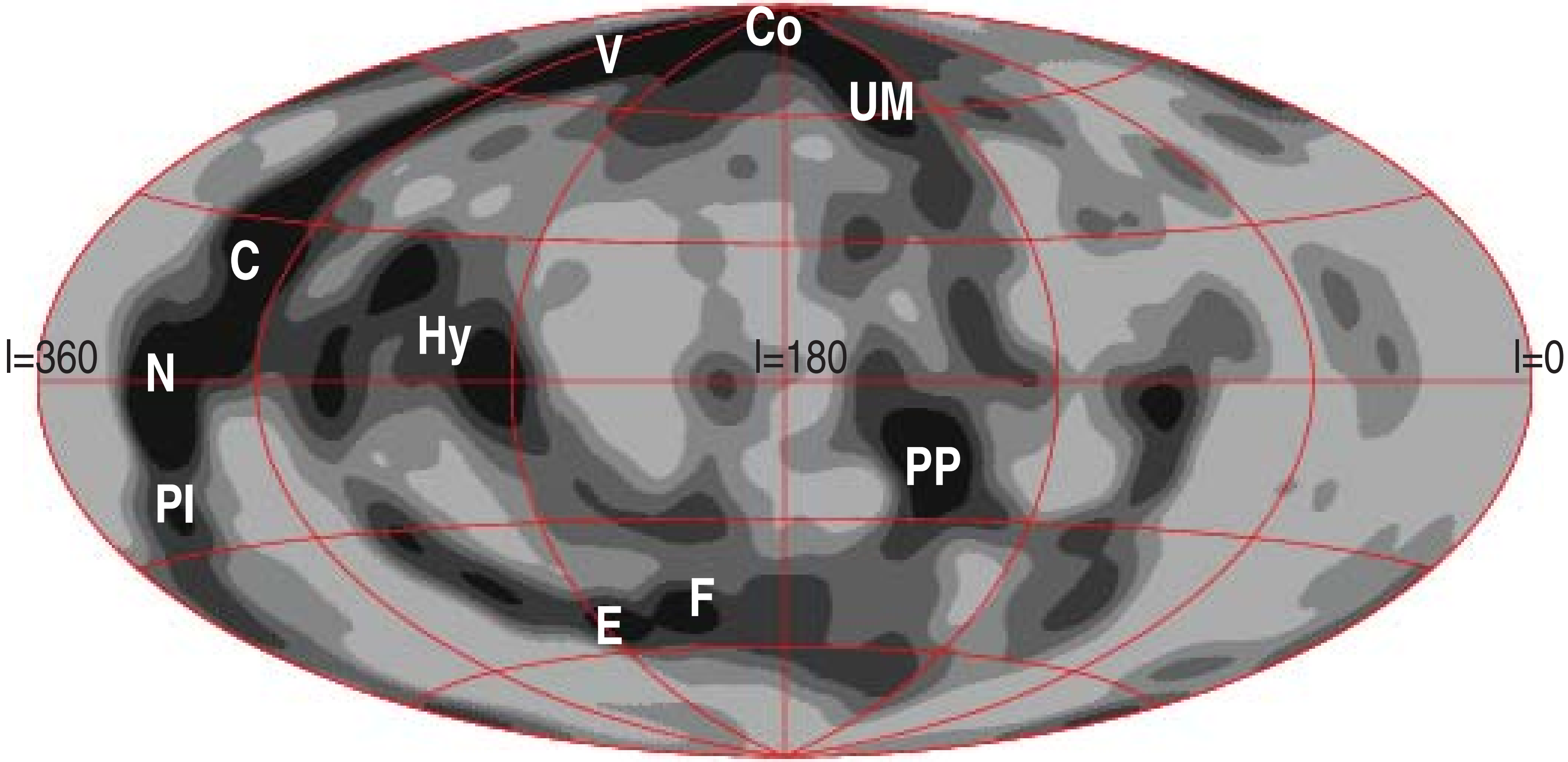
Proceed as follows:

- 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

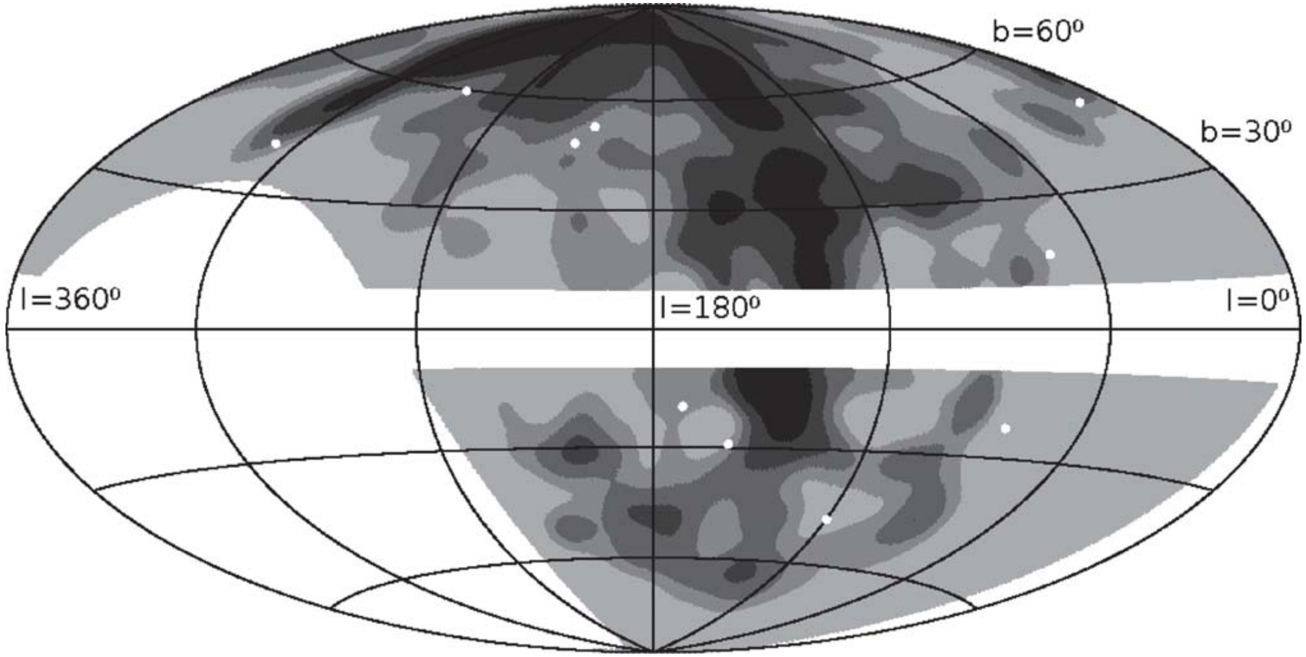
FLUX CALCULATION

- At highest energies CR have propagation distance $\lesssim 100$ Mpc
- Matter distribution on these scales is inhomogeneous $\Longrightarrow$ one expects flux variations over the sky
- Matter distribution can be accurately mapped out to ~ 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 θ treated as a free parameter
- $\Longrightarrow$ obtain the prediction for the flux sky map

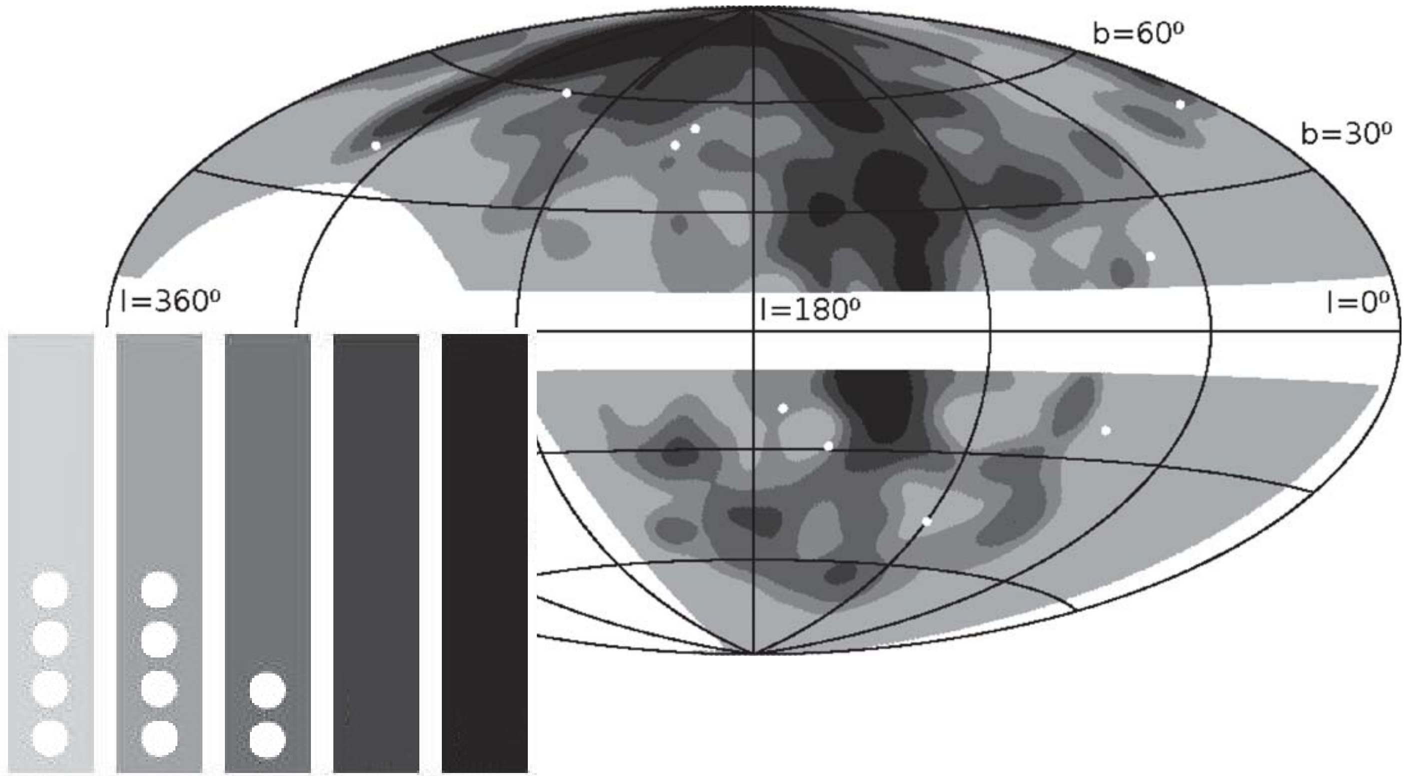


C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); PI: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); Ursa Major North group (20 Mpc) South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

STATISTICAL TEST: FLUX SAMPLING



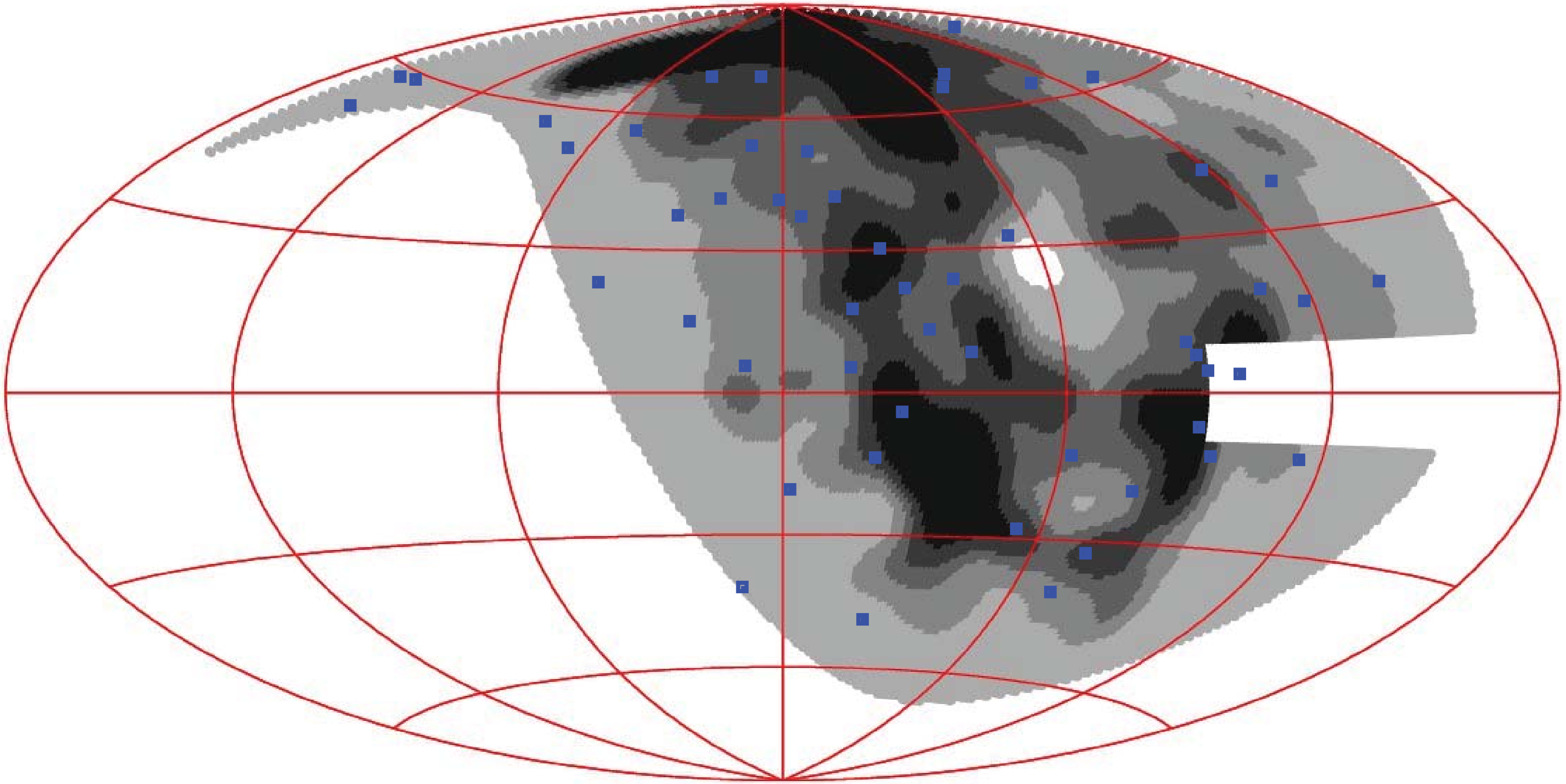
STATISTICAL TEST: FLUX SAMPLING



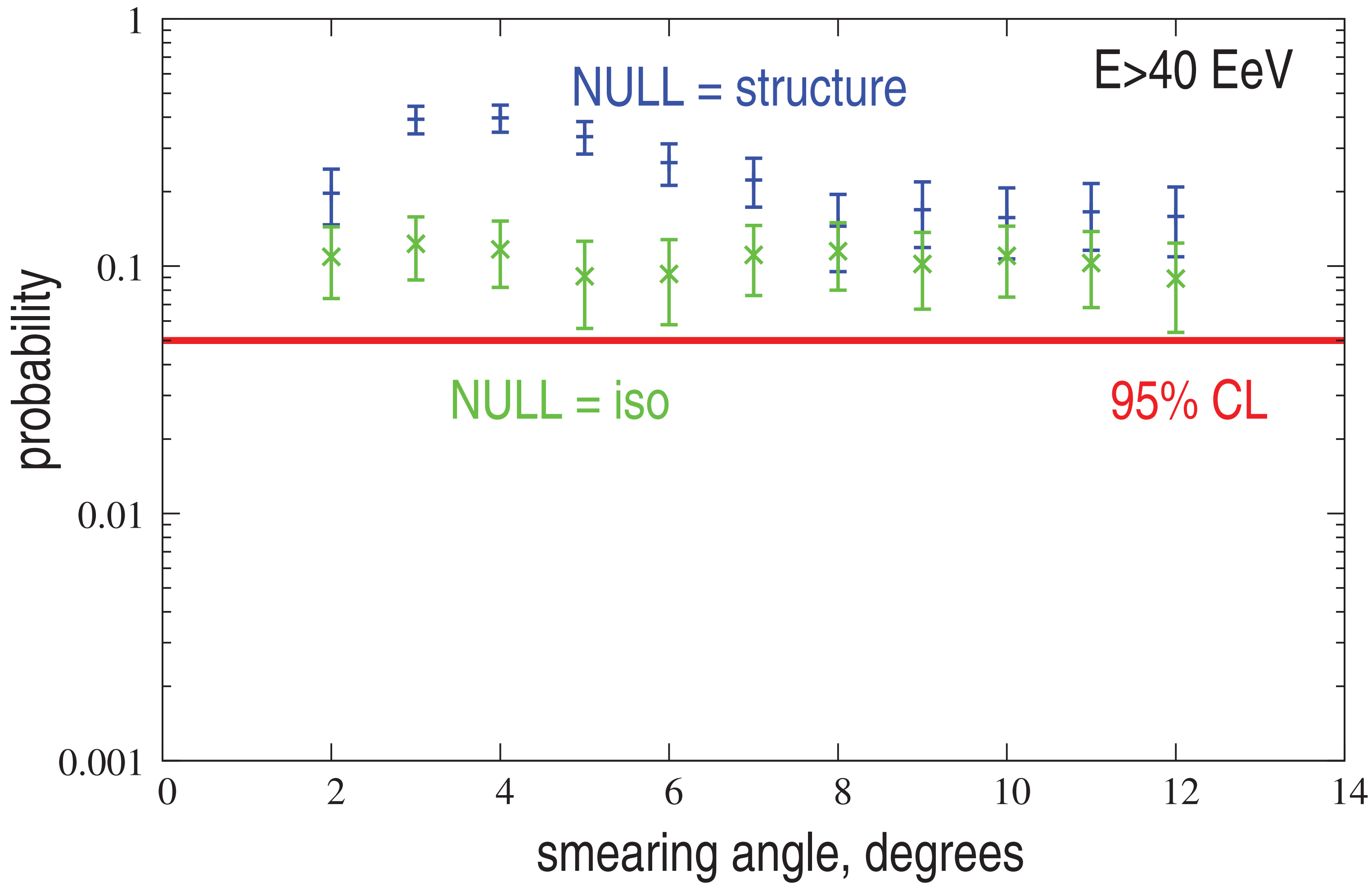
- Events following the model would produce uniform distribution over the bands
- No binning is actually needed (on the picture it is for illustration only): two distributions may be compared by the Kolmogorov-Smirnov test

WHAT IS SEEN IN TA

$E > 4 \times 10^{19}$ eV

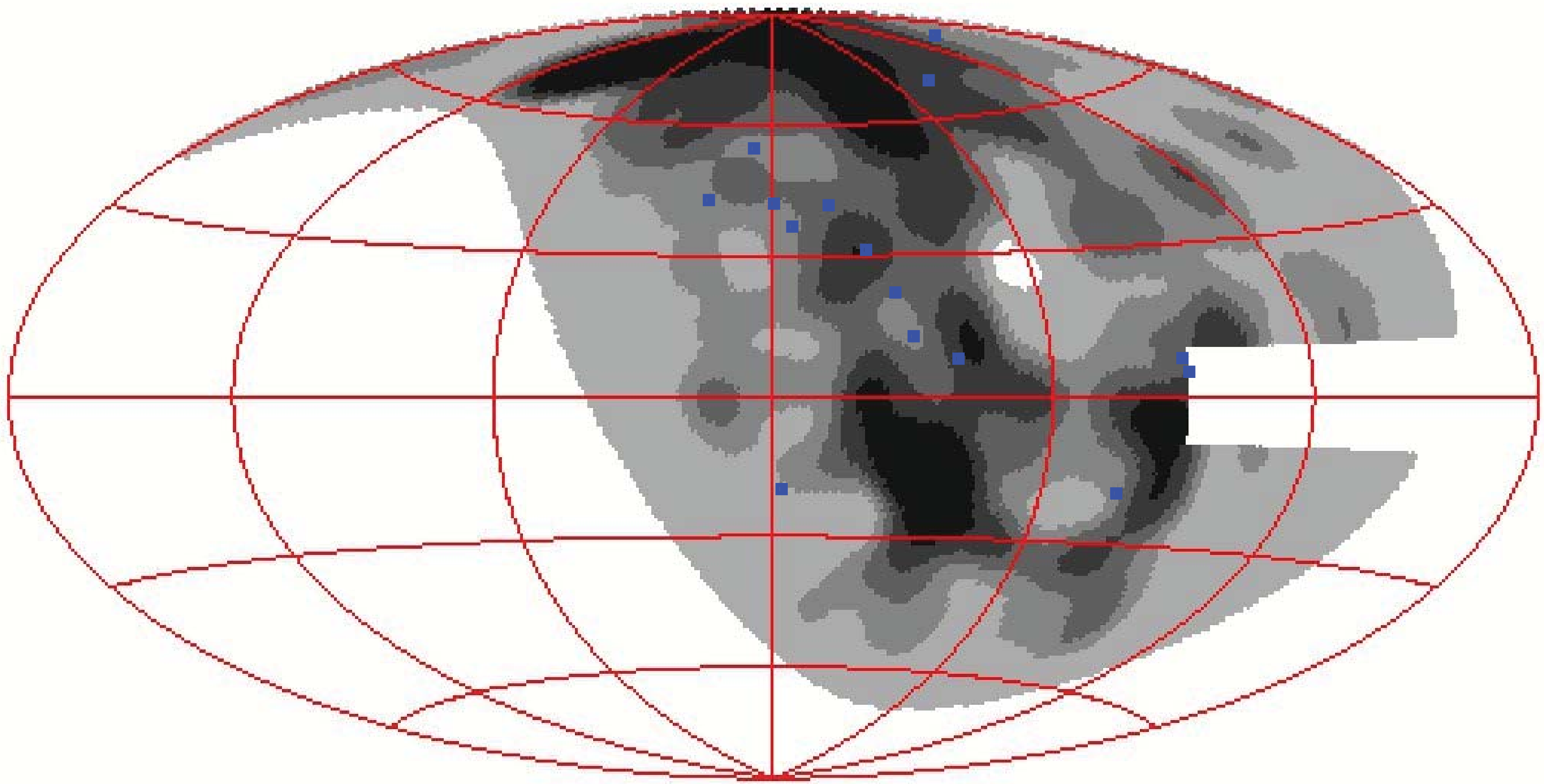


WHAT IS SEEN IN TA

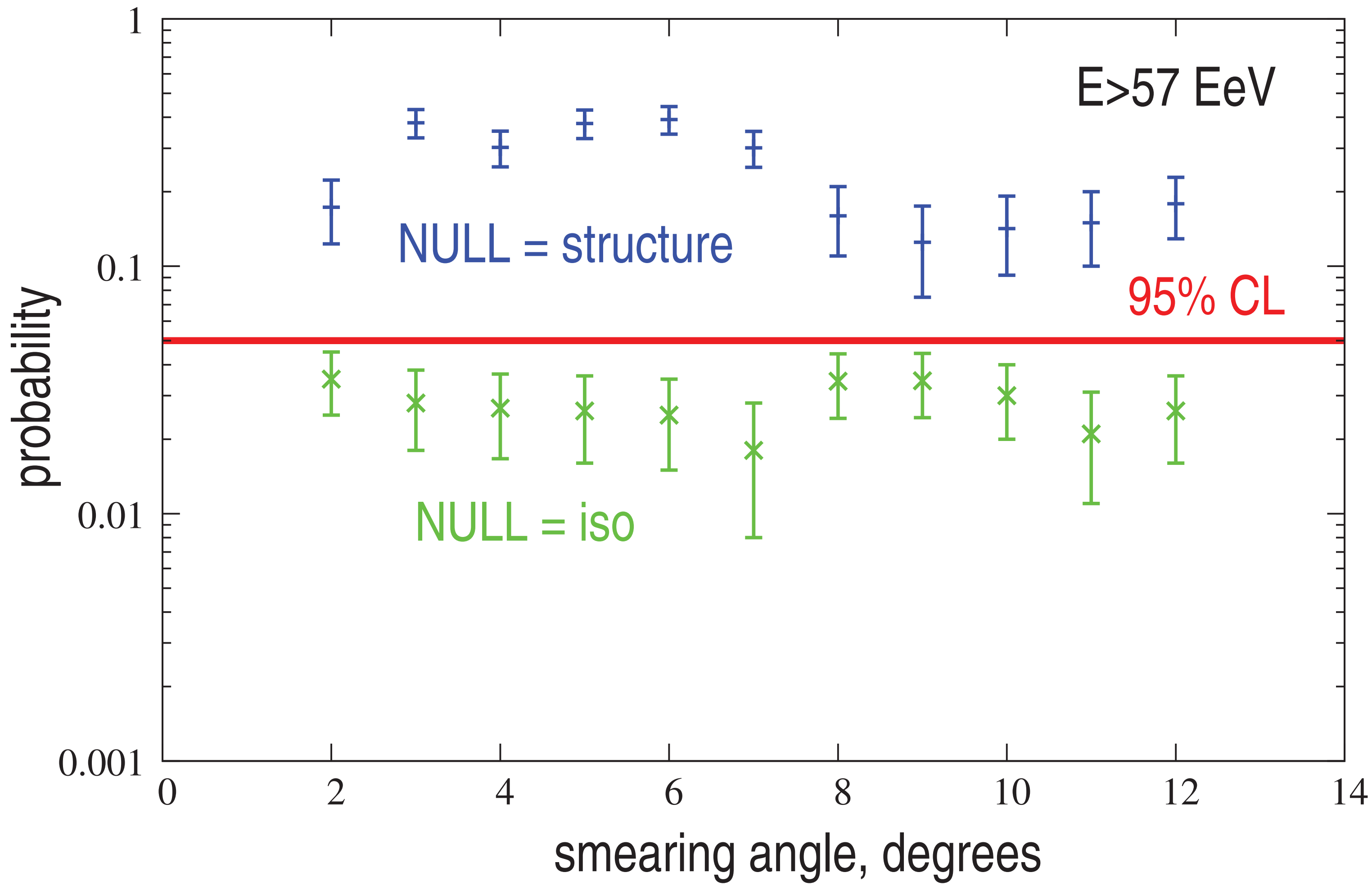


WHAT IS SEEN IN TA

$E > 5.7 \times 10^{19}$ eV

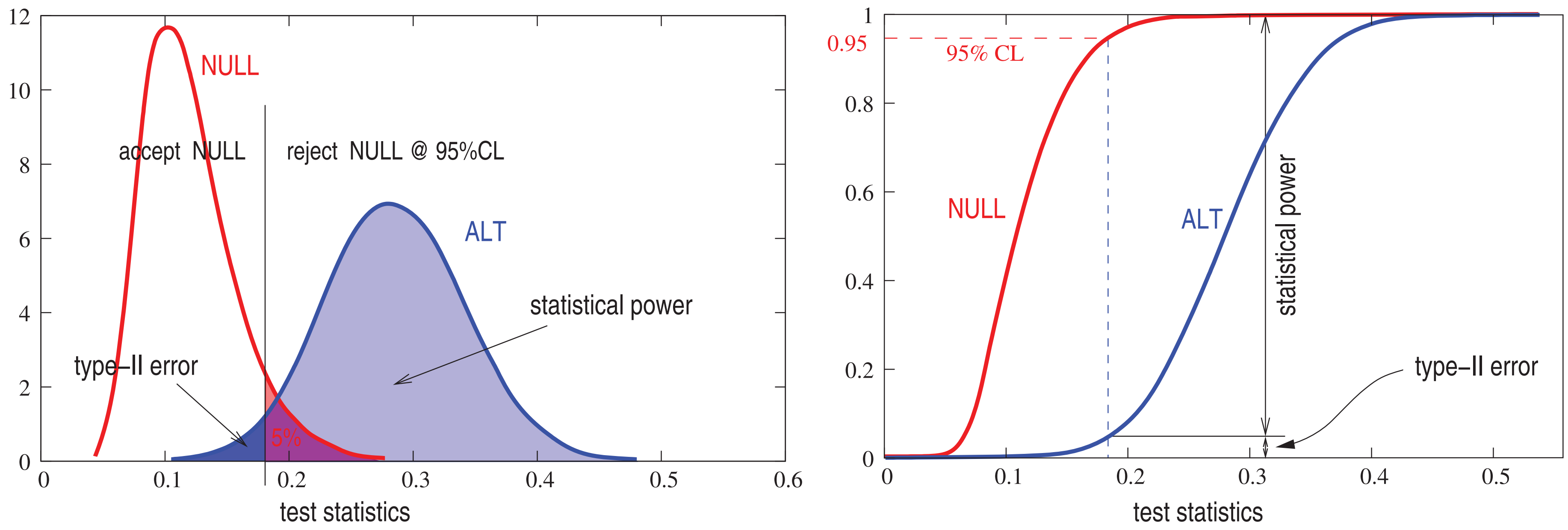


WHAT IS SEEN IN TA



STATISTICAL POWER OF THE TEST

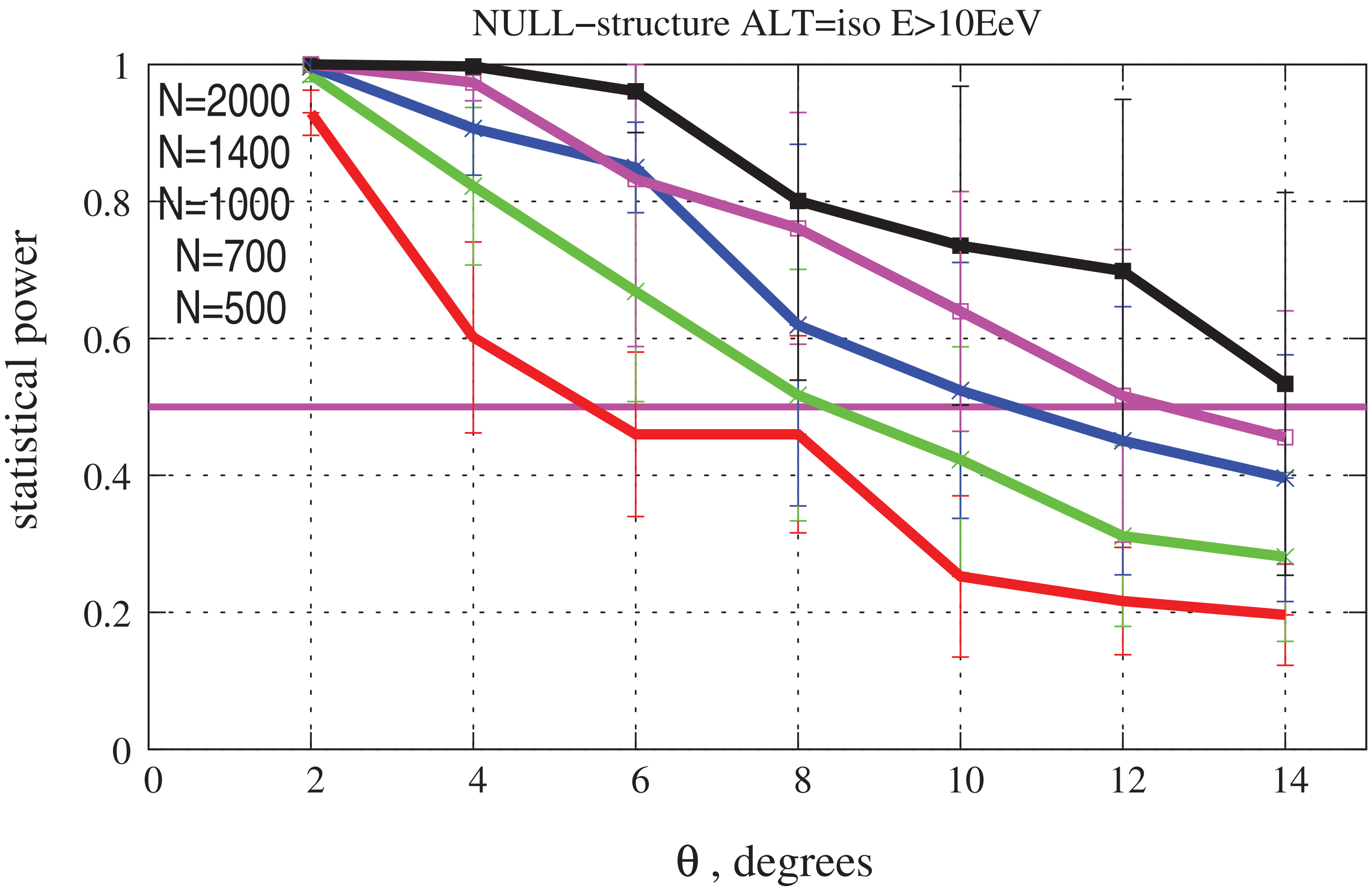
- Statistical power is defined as the complement of the type-II error (type-II error is the probability of falsely accept null-hypothesis when the alternative hypothesis is true)



- Statistical power is meaningful when it is close to 1 (say, larger than 0.5). Then two distributions separate.

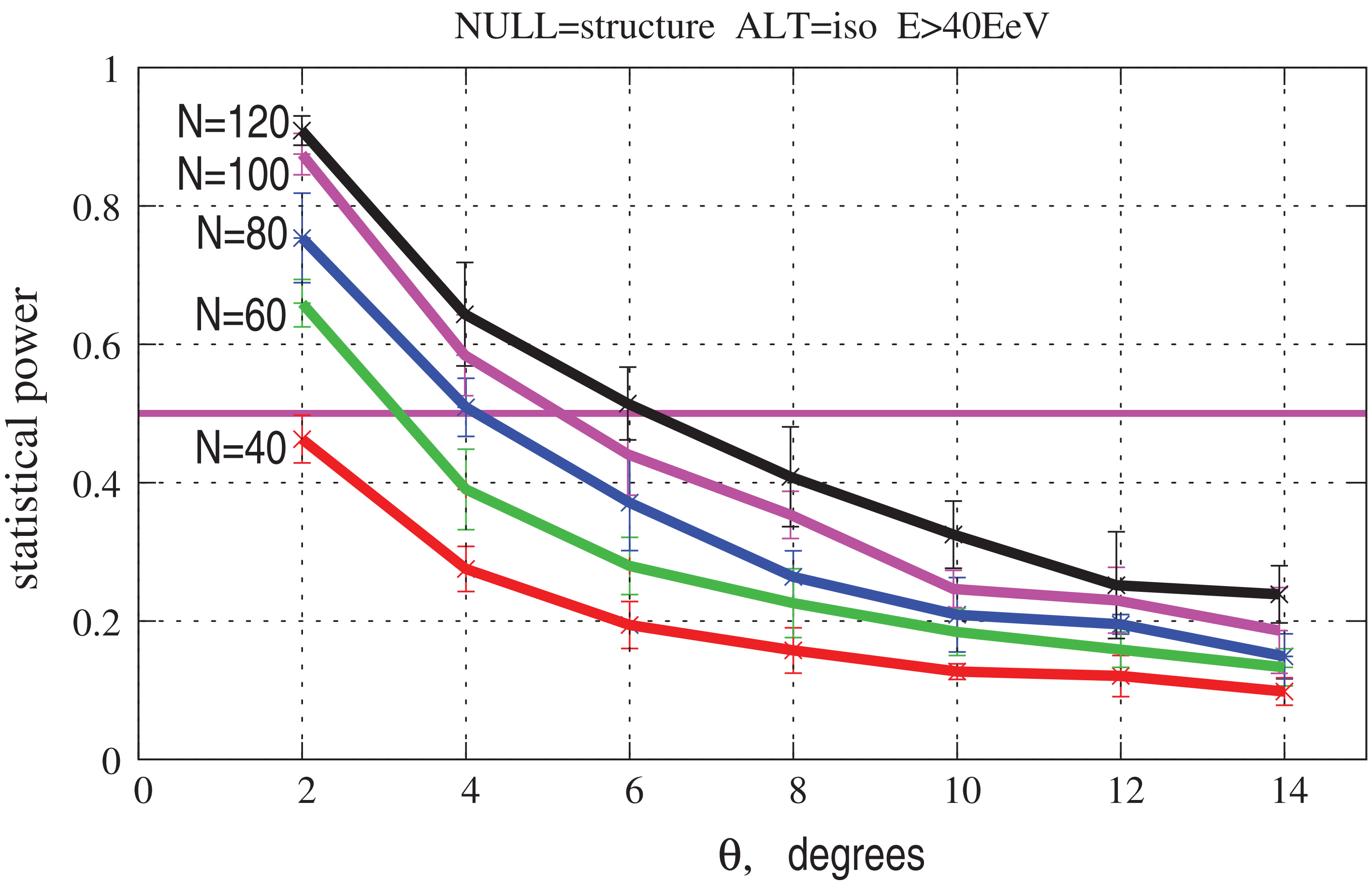
STATISTICAL POWERS IN CASE OF TA

$E > 1 \times 10^{19}$ eV



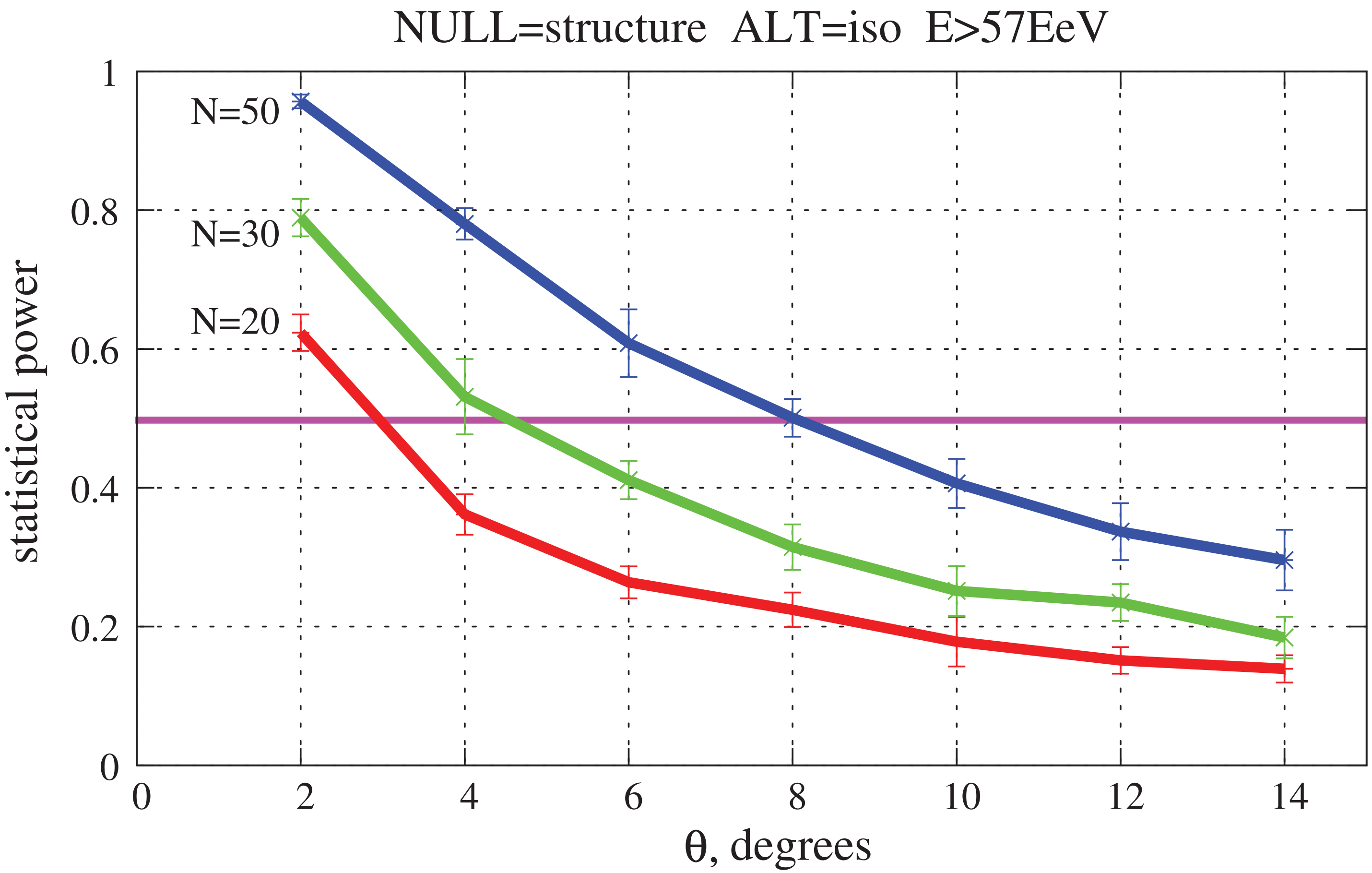
STATISTICAL POWERS IN CASE OF TA

$E > 4 \times 10^{19}$ eV



STATISTICAL POWERS IN CASE OF TA

$E > 5.7 \times 10^{19}$ 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?

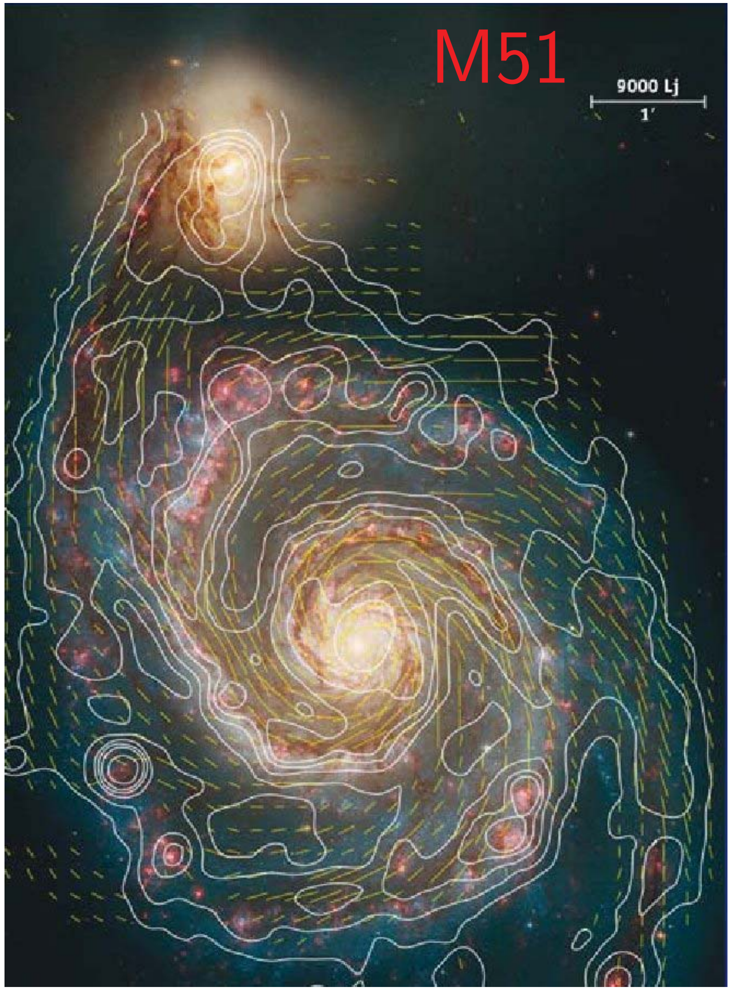
Origin of "deflections":

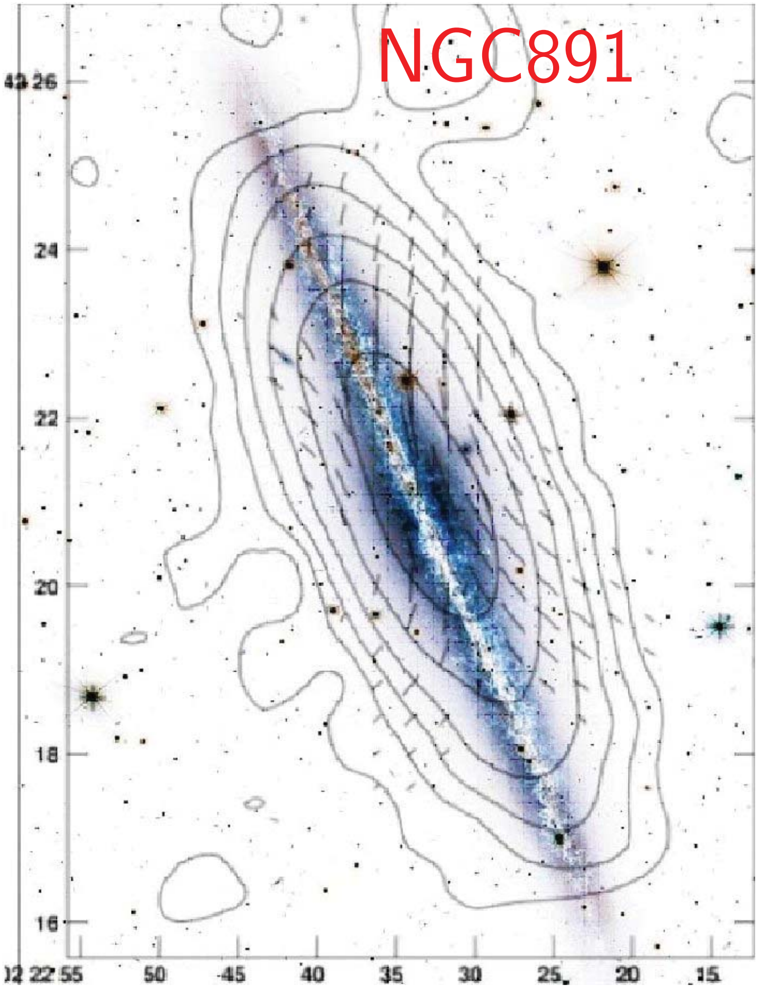
- Finite angular resolution
  - 1.5° for TA, $\sim 1°$ for Auger
  - subdominant
- Deflections in the extragalactic magnetic fields
  - $$\theta = 1.8° \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{l_c R}{50\mathrm{Mpc}^2}\right)^{1/2} \left(\frac{B}{10^{-9}\mathrm{G}}\right)$$
  - a likely 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

$$\theta = 0.52° \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{R}{1\mathrm{kpc}}\right) \left(\frac{B_\perp}{10^{-6}\mathrm{G}}\right)$$

GALACTIC MAGNETIC FIELD

- Coherent field in other galaxies:



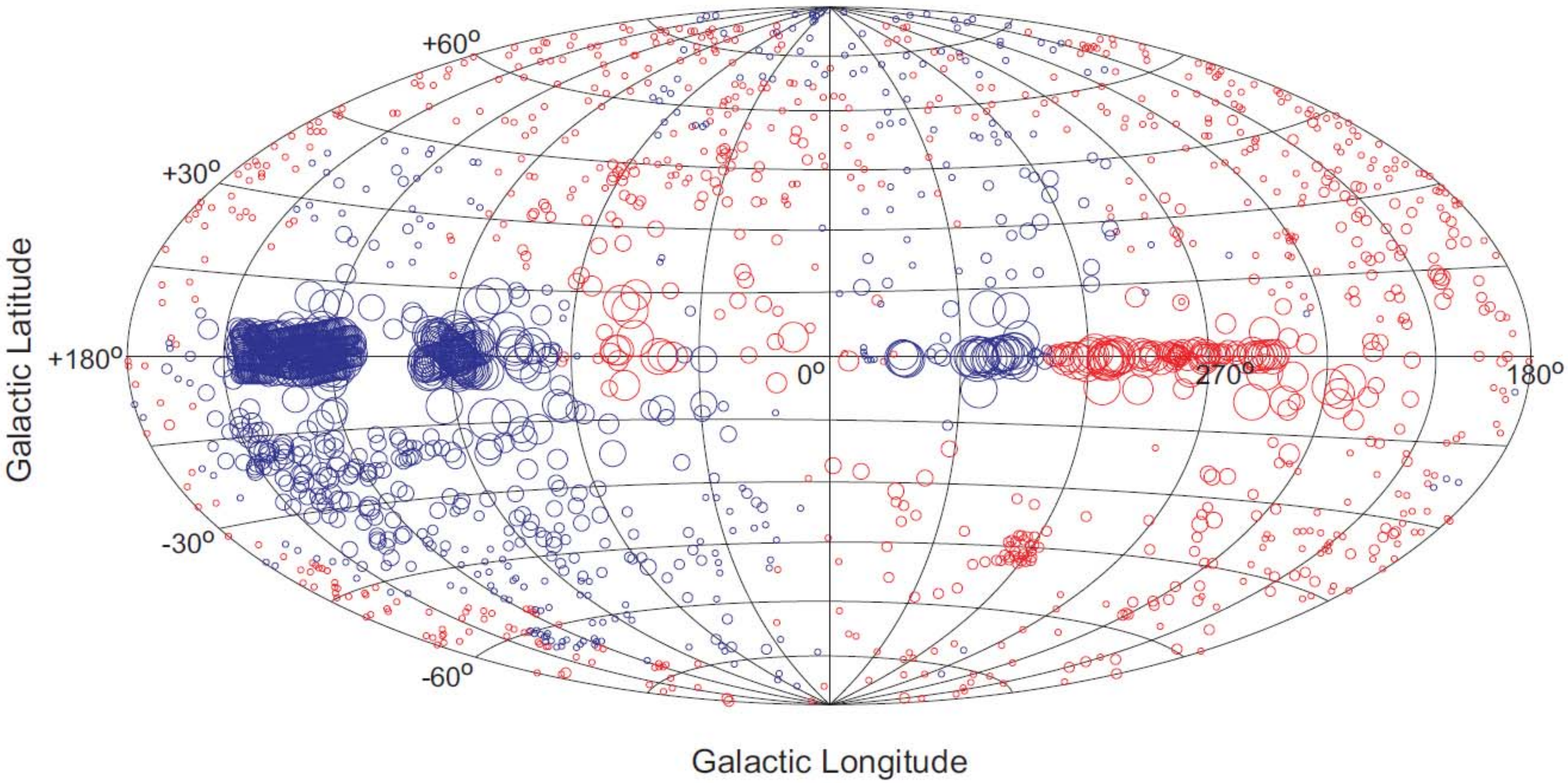


Is there a coherent field in the Milky Way?

Smeared Faraday rotation measures

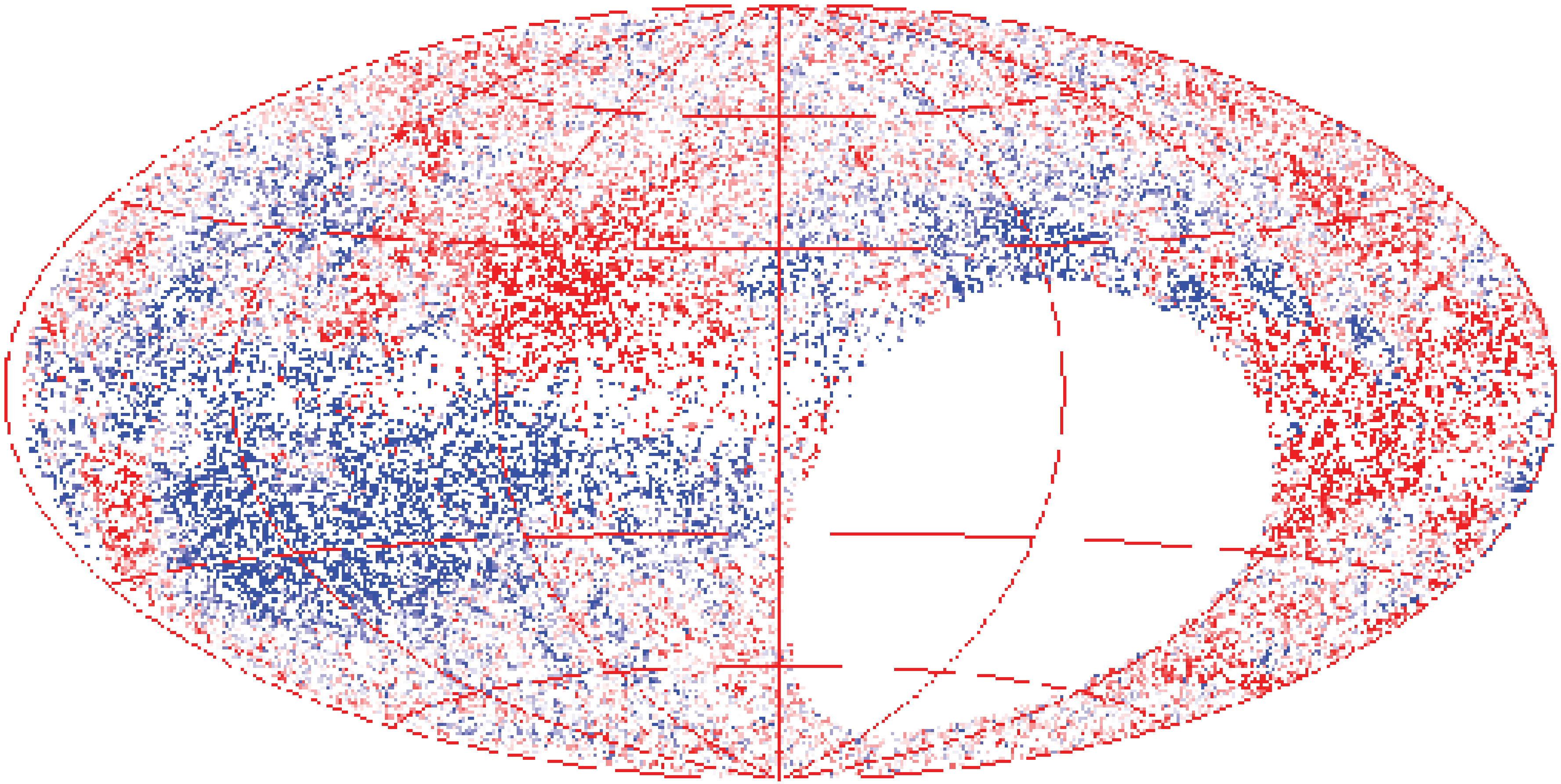
$$\mathrm{RM} \propto \int dl\, n_e \cdot B_{||}$$

by Kronberg & Newton-McGee (2011):



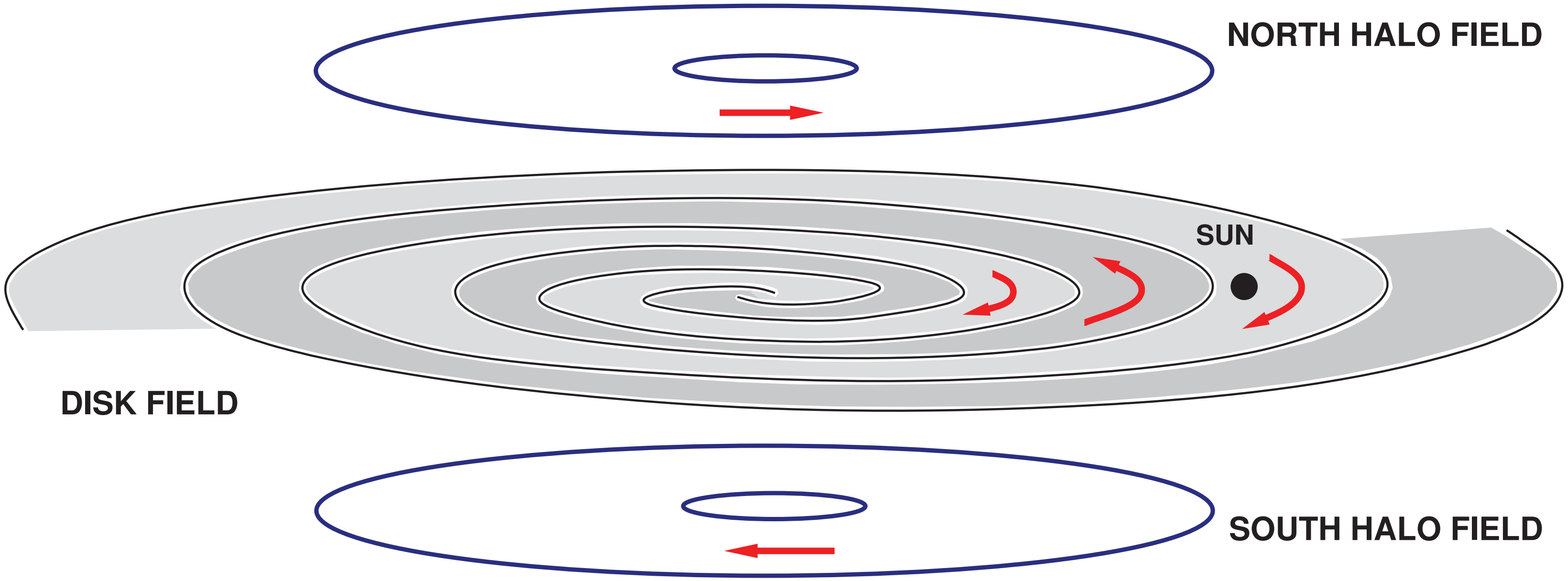
Is there a coherent field in the Milky Way?

NRAO VLA Sky Survey (NVSS) rotation measures catalogue:



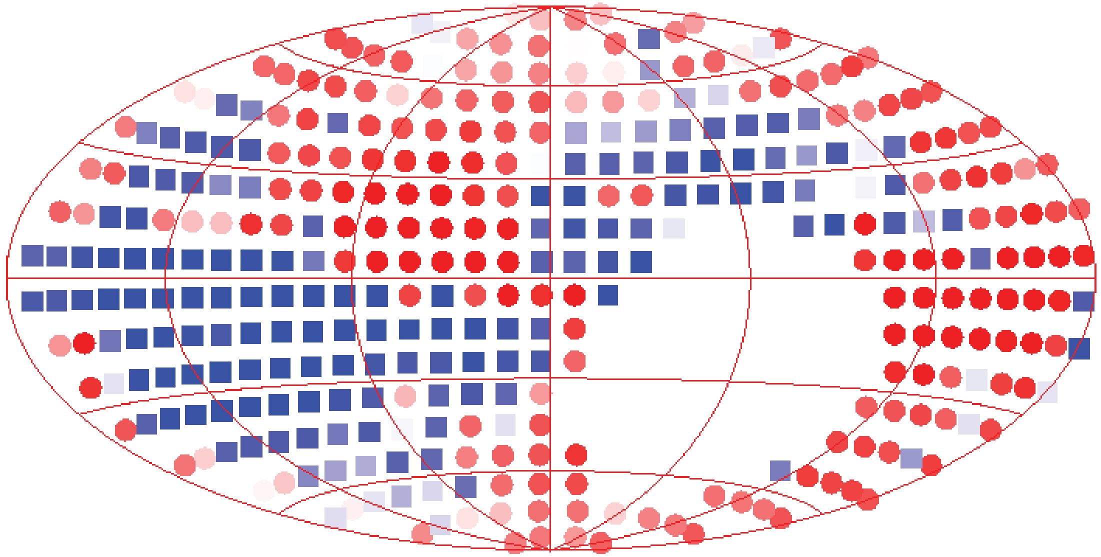
GMF general structure

- 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);]

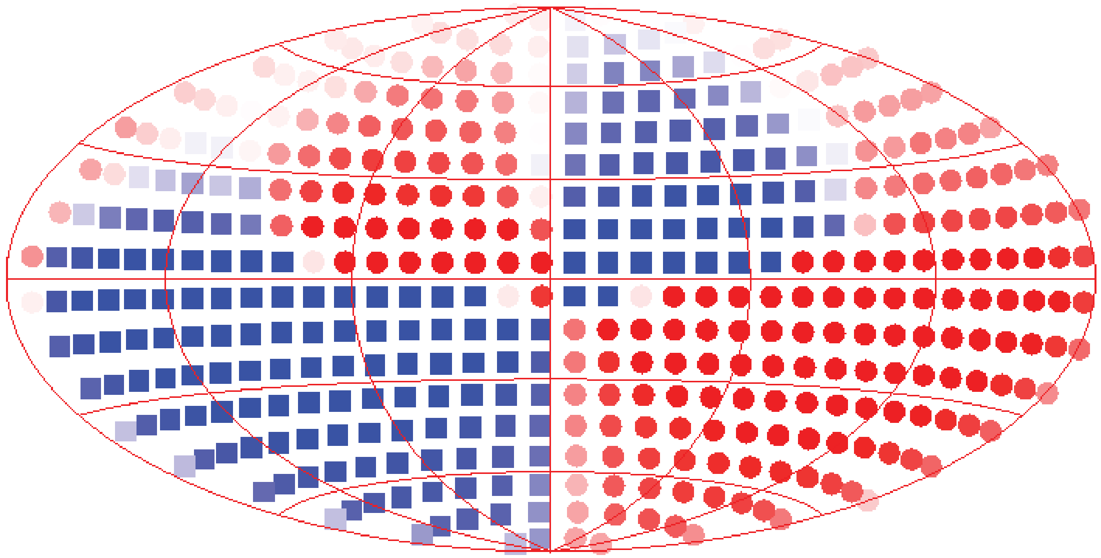


Fit to data:

DATA



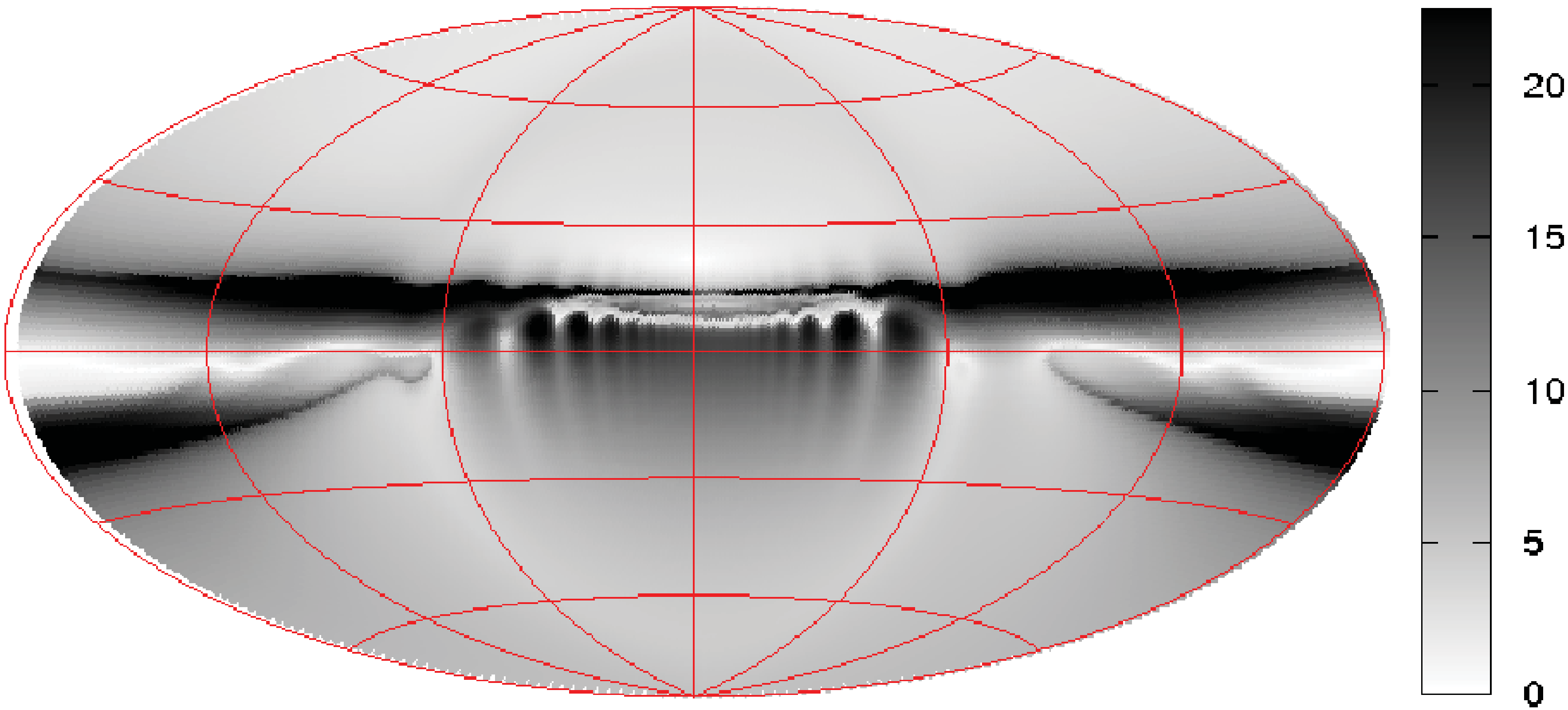
MODEL



Bin size $10^\circ \times 10^\circ$

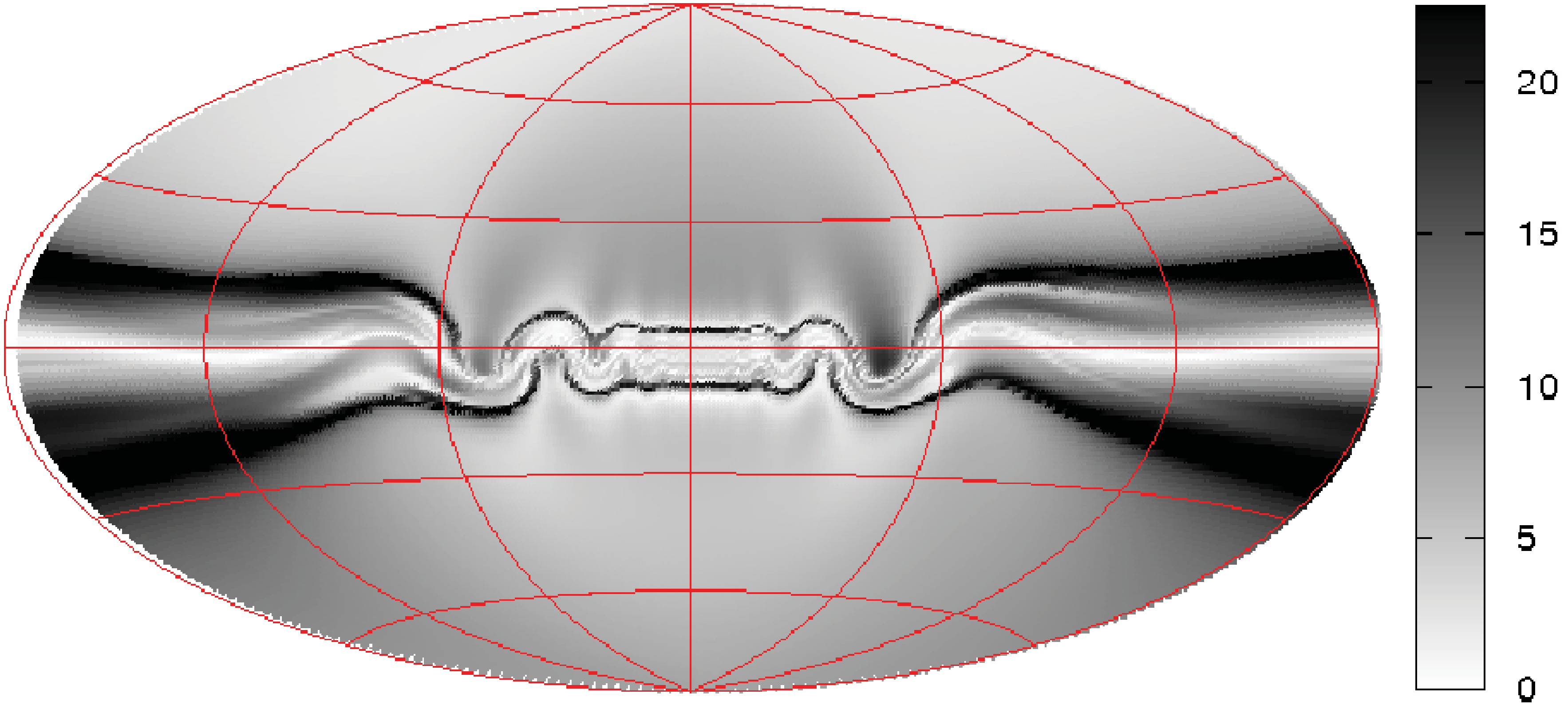
SIZE OF DEFLECTIONS (protons, $E = 4 \times 10^{19}$ eV)

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).