UHECR V2014
Latest Results from Telescope Array

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January 30th*, 2014

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* Wait, that's my birthday!

Fun Stuff

i Introduction to CR

ii Telescope Array

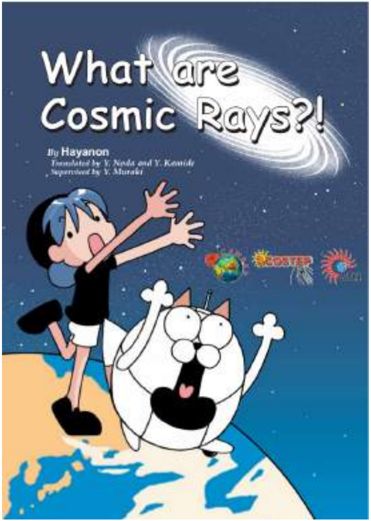
iii Anisotropies (and a Hotspot)

iv Joint TA-Auger Full Sky Analysis

v Bonus: The Galactic Magnetic Field and CR

Dear Cosmic Ray...

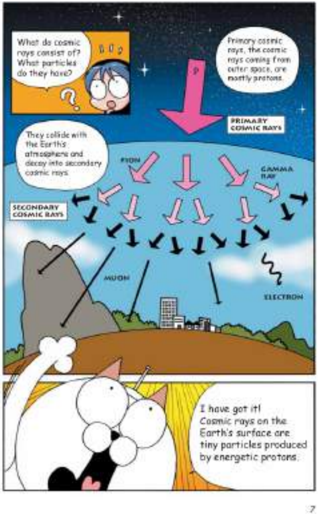
Cosmic Rays I



What are Cosmic Rays?!

By Hayanon
Translated by Y. Noda and Y. Kamide
Supervised by Y. Muraki

Cosmic Rays II

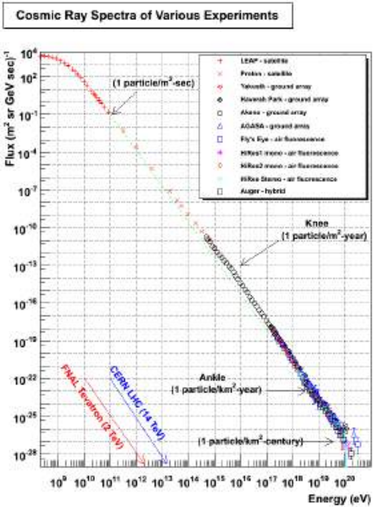


Cosmic Rays III

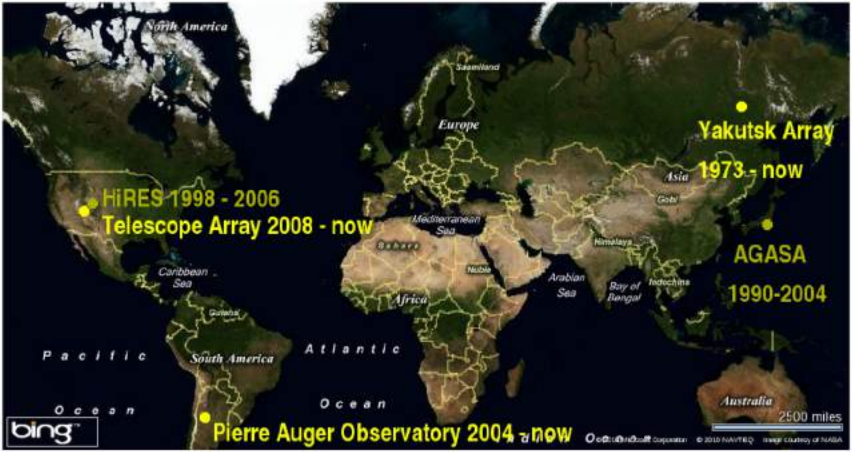
Cosmic Rays III

actually...

Spectrum


Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)$^{-1}$
10^4
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
(1 particle/m^2-sec)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
Knee
(1 particle/m^2-year)
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy (eV)

Observatories



Telescope Array

The Collaboration

The Telescope Array Collaboration

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P. Sokolsky[a], R.W. Springer[a], B.T. Stokes[a], S.R. Stratton[a,n], T. Stroman[a], S. Suzuki[h], Y. Takahashi[i], M. Takeda[j], A. Taketa[y], M. Takita[j], Y. Tameda[j], H. Tanaka[i],
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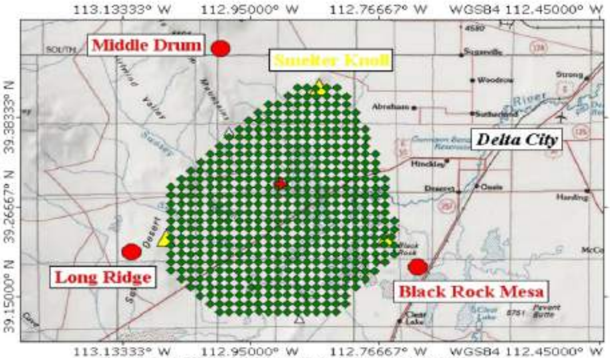
The Detector



Map created with TOPO!® ©2002 National Geographic (www.nationalgeographic.com/topo)

- 507 scintillator detectors covering circa 680 km^2
- 3 fluorescence sites, 38 telescopes
- Surface relative size: TA $\sim 9\times$ AGASA $\sim$ PAO / 4

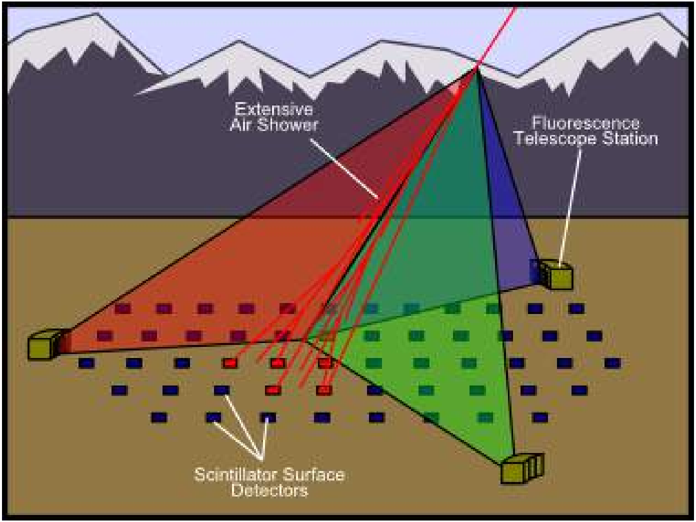
The Looks


Millard County Cosmic Ray Center
University of Utah
Black Rock Mesa
Surface Detector
Middle Drum

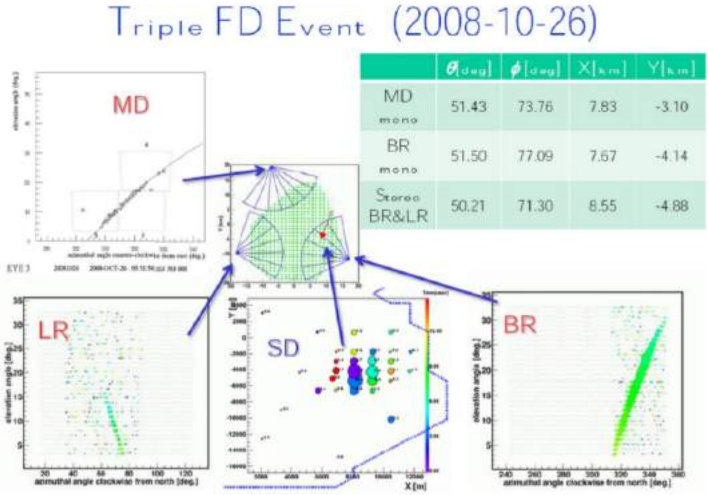
The Environment does not always Cooperate

Involuntary Friends

Hybrid Detector



Hybrid Example



Triple FD Event (2008-10-26)

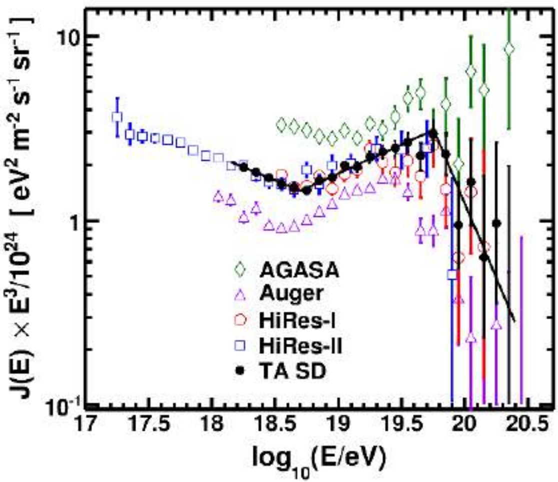
	θ[deg]	ϕ[deg]	X[km]	Y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88

May 2013 Data Release

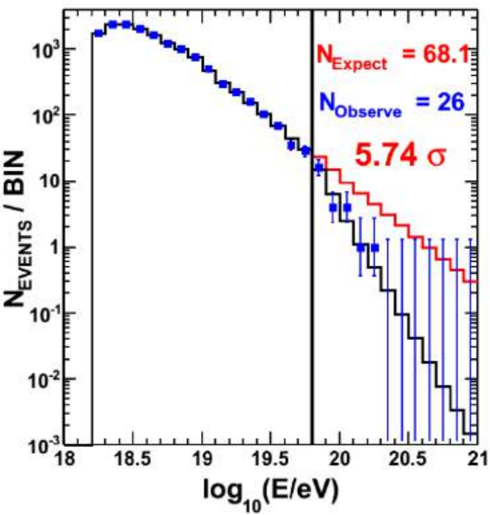
Anisotropy Data Set

- Events recorded 12/05/2008 $\Rightarrow$ 04/05/2013 (5yrs)
- Zenith angle up to 55°
- Energy above 10 EeV $\Rightarrow$ Geometrical Acceptance
- Total Exposure of 6200 km^2 yr sr
- Total of 2130 Events, of which 52 above 57 EeV (GZK)
- Angular Resolution $\lesssim 1.5^\circ$
- Energy Resolution $\sim 20\%$

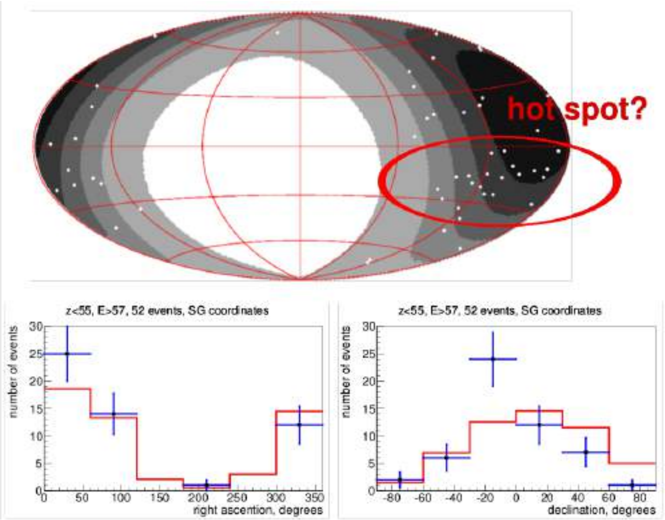
The 5yrs TA Spectrum



The GZK Suppression

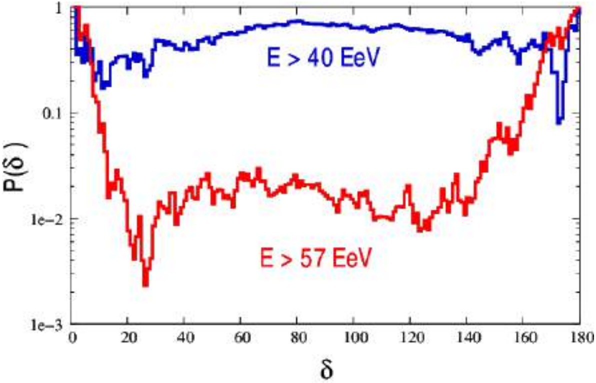


The Hotspot?


hot spot?
z<55, E>57, 52 events, SG coordinates
number of events
0
5
10
15
20
25
30
0
50
100
150
200
250
300
350
right ascention, degrees
z<55, E>57, 52 events, SG coordinates
number of events
0
5
10
15
20
25
30
-80
-60
-40
-20
0
20
40
60
80
declination, degrees

Autocorrelation Function

We can for example test it with the autocorrelation function



Large Scale Structure I

- The TA spectrum is consistent with proton primaries
- Above 10 EeV their trajectories are ballistic
- Their deflections in the GMF are small
  - — a few degress for GZK protons
- They propagate for up to 250 Mpc
- It's then plausible that the sources lie within the LSS

⇒ **Arrival directions should correlate with structures**

Large Scale Structure I

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⇒ **Arrival directions should correlate with structures**

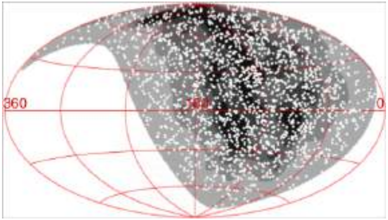
¿ Do they ?

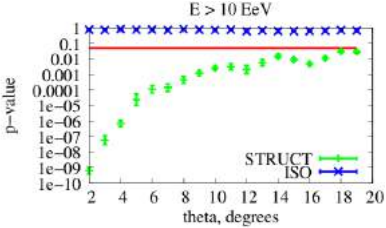
Large Scale Structure II

In practice:

- The expected CR flux is calculated from a galaxy catalogue
- All galaxies from 5 Mps to 250 Mpc are included
- Beyond 250 Mpc the flux is uniform
- Pick a given injection spectrum for protons (assumed)
- Propagation accounts for all losses + expansion
- Gaussian smearing is applied
  - — it mimics finite resolution and unknown deflections
- The predicted flux is compared with data
  - — this is done through a KS test

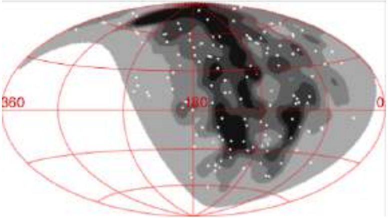
Structure at 10 EeV

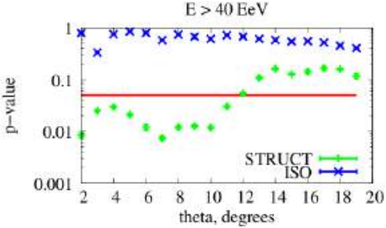




- As they should, small angle events do NOT correlate with LSS

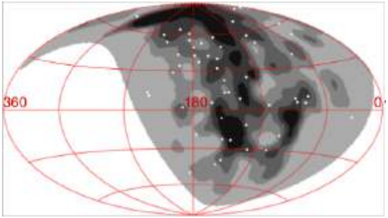
Structure at 40 EeV

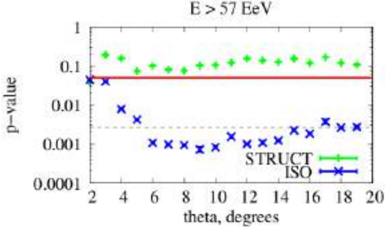




- Can't really say much from this picture...

Structure at 57 EeV





- At most angles isotropy is about 3σ away from the data
- If the trend is confirmed with new data releases, isotropy will be excluded

Joint TA-Auger Full Sky Multipole Analysis

The First Time

33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Pierre Auger Observatory and Telescope Array: Joint Contributions to the 33rd International Cosmic Ray Conference (ICRC 2013)

Spherical Harmonics

$$\Phi_{\hat{n}} = \sum_{l \geq 0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\hat{n})$$

- Any anisotropy fingerprint is encoded in the a_{lm} set
- Each multipole l corresponds to an angle of roughly l^{-1} radians
- A dipole moment could signal:
  - i propagation with a CR density gradient embedding the observer
  - ii the motion of the Earth / Milky-Way relative to a possibly stationary CR frame
- Excesses along a plane, for instance the SG one, would be detectable as a prominent quadrupole
- If sources follow the LSS, there will be a nonzero C_l power spectrum

Full VS Partial Sky

Partial Sky Coverage

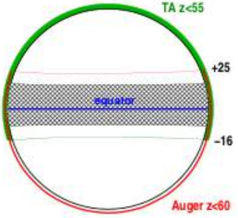
- Some multipoles can not be determined (i.e. north-south dipole)
- Reconstruction requires the inversion of an infinite convolution matrix, which needs to be cut
- Thus, the errors on these *will propagate* into other multipoles
- Hence, results are unstable against *assumptions* on the nature of the flux

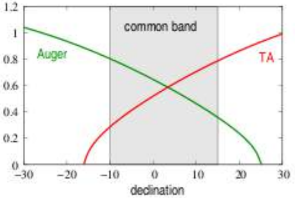
Full Sky Coverage

- No need to assume anything about the flux
- Reconstruction directly employs the everywhere non-zero exposure
- Even strongly inhomogenous coverage is much better!

Why Cross-Calibration?

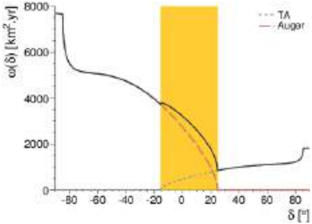
- To cover the whole sky we need to jostle the TA and Auger data sets
- The sets have different errors/cuts/acceptance/energy calibration...
- It's important to correctly cross-calibrate, or spurious multipoles would be introduced!
- The idea is to employ the band of common view around the equator





The Fudge Factor

- We choose energy cuts such that acceptance is purely geometrical
- With loose zenith cuts we cover the entire sky
- The combined geometrical exposure is highly inhomogeneous

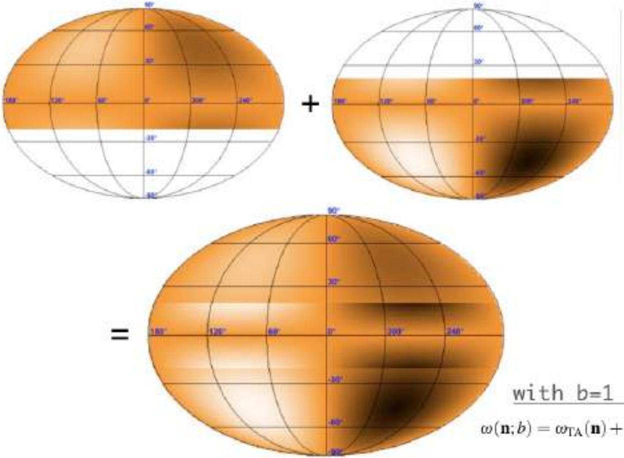


There remains an unavoidable relative exposure uncertainty

$$\omega(\hat{n}, b) = \omega_{\mathrm{TA}}(\hat{n}) + b\,\omega_{\mathrm{Auger}}(\hat{n})$$

where b is a fudge factor which absorbs all uncertainties (systematics)

Two Skies Become One



with b=1 in

$\omega(\mathbf{n};b) = \omega_{\mathrm{TA}}(\mathbf{n}) + b\omega_{\mathrm{Auger}}(\mathbf{n}).$

Cross-Calibration in Practice

- The events in the common band are given by

$$\Delta N = \Delta N_{\text{TA}} + \Delta N_{\text{Auger}} \propto \int_{\text{band}} \mathrm{d}\hat{n}\; \Phi_{\hat{n}}\; [\omega_{\text{TA}}(\hat{n}) + b\, \omega_{\text{Auger}}(\hat{n})]$$

- We can then extract the ratio

$$\frac{\Delta N_{\text{Auger}}}{\Delta N_{\text{TA}}} = b \cdot \frac{\int_{\text{band}} \mathrm{d}\hat{n}\; \Phi_{\hat{n}}\; \omega_{\text{TA}}(\hat{n})}{\int_{\text{band}} \mathrm{d}\hat{n}\; \Phi_{\hat{n}}\; \omega_{\text{Auger}}(\hat{n})}$$

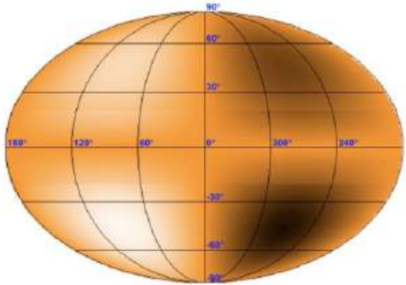
  which contains two unknowns: b and $\Phi_{\hat{n}}$

- Since Nature has given us one and only one flux, the two experiments should see the same in the band

Bootstrap I

Zeroth iteration: assume isotropic flux, $\Phi^{(0)}_{\hat{n}} = \Phi^{(0)}$ in the band

$$b^{(0)} = \frac{\Delta N_{\text{Auger}} \int_{\text{band}} \mathrm{d}\hat{n}\, \Phi^{(0)} \omega_{\text{TA}}(\hat{n})}{\Delta N_{\text{TA}} \int_{\text{band}} \mathrm{d}\hat{n}\, \Phi^{(0)} \omega_{\text{Auger}}(\hat{n})}$$

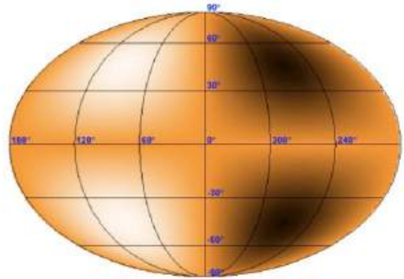


⇒ This provides a first guess on the (full sky) spherical harmonics $a^{(1)}_{lm}$

Bootstrap II

First iteration: use the $a_{lm}^{(1)}$ to generate the flux $\Phi_{\hat{n}}^{(1)}$ in the band

$$b^{(1)} = \frac{\Delta N_{\text{Auger}} \int_{\text{band}} \mathrm{d}\hat{n}\, \Phi_{\hat{n}}^{(1)} \omega_{\text{TA}}(\hat{n})}{\Delta N_{\text{TA}} \int_{\text{band}} \mathrm{d}\hat{n}\, \Phi_{\hat{n}}^{(1)} \omega_{\text{Auger}}(\hat{n})}$$

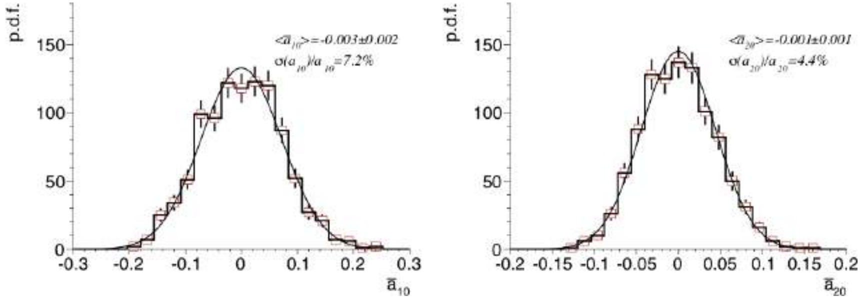


⇒ This provides a second guess on the (full sky) spherical harmonics $a_{lm}^{(2)}$

In practice this converges after a handful of steps

Isotropic Test

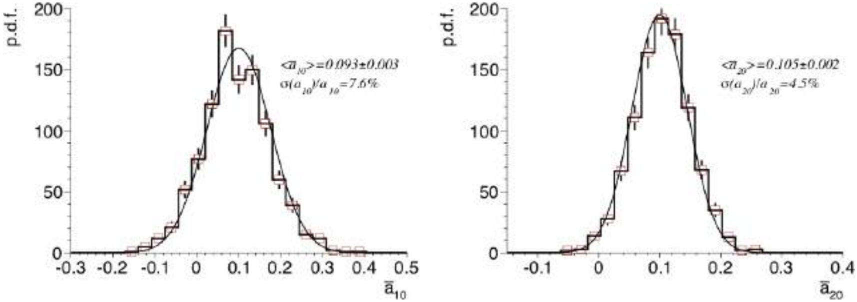
Isotropic $\Phi_{\hat{n}} \propto \Phi^{(0)}$ input



Isotropy is recovered perfectly – the error on a_{10} is or course the largest

Anisotropic Test

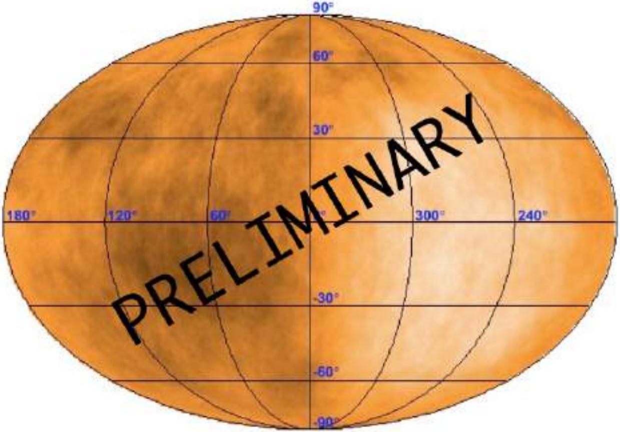
Anisotropic $\Phi_{\hat{n}} \propto 0.1 Y_{10} + 0.1 Y_{20}$ input



Also the input multipoles are extracted correctly without bias, the algorithm works

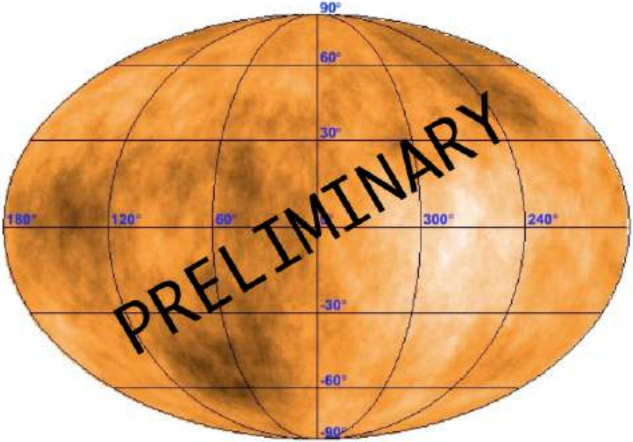
Dipole Map

Smoothen the map at about 60° to detect a dipole



Quadrupole Map

Smoothen the map at about 30° to detect a quadrupole



The Galactic Magnetic Field

UHECRs VS Magnetic Fields

CRs propagation is affected by Magnetic Fields
Which deviates their paths towards the Earth
Thence masking their actual original arrival direction
And impeding the identification of the sources

- UHECRs see both Galactic and Extragalactic Magnetic Fields
- Extragalactic fields are constrained to be $\lesssim 1$ nG

⇒ The Galactic Magnetic Field then provides the dominant effect

Regular and Random

1 The Regular Field (GMF)

Pshirkov, Tinyakov, Kronberg, Newton-McGee, Astrophys. J. **738** (2011) 192

Jansson, Farrar, Astrophys. J. **757** (2012) 14

2 The Random Field (rGMF)

Jansson, Farrar, Astrophys. J. **761** (2012) L11

Pshirkov, Tinyakov, Urban, Mon. Not. Roy. Astron. Soc. **436** (2013) 2326

Implementation

The Regular Field

Our code produces Skymaps of expected CR fluxes given

- I The map of the sources (e.g., a Galaxy Catalogue)
- II The injection spectrum
- III The GMF analytic model

These maps are then compared with the actual distributions of events to test their compatibility.

The Random Field

- The turbulent field produces unpredictable deflections of CRs which sum up to random displacements that smear the source image
- ...but this turbulent field is very little understood:
  - What is its morphology?
  - What is its spectral slope?
  - What is its amplitude?
- The rGMF also contributes to the scatter of Rotation Measures (RMs) of extragalactic radio sources

IDEA!

Use RM to estimate CR deflections, *bypassing* the rGMF

Data

Catalogue

- NVSS RM catalogue of 37,543 RM values of extra-galactic sources
- Cleaned the catalogue removing 1974 (2 rms off) outliers
- In total we then had 35,569 RMs

Binning

- Binned with HEALPix: 768 bins of area 53 sq. deg.
- On average there are 50 sources per bin
  - Good statistics
  - The regular field deflections are within the bin (more on this later)

RM and Deflections

Putting it to work.

Rotation Measures

$$RM(\hat{r}) = c_1 \int_0^D \mathrm{d}z\, n\, B_{\|}$$

Deflections

$$\vartheta_i(\hat{r}) = c_2 \int_0^D \mathrm{d}z\, \epsilon_{ij}\, B_j$$

Where

$$c_1 = 0.81\,\mathrm{rad\,cm^3/(m^2\,pc}\,\mu\mathrm{G)} \approx 2.7 \times 10^{-23}\,\mathrm{rad}/\mu\mathrm{G}$$

$$c_2 = Ze/(E\mu\mathrm{G})$$

Bypassing B

Let's look at the variances of these quantities

$$\langle RM^2 \rangle = c_1^2 \, \langle n \rangle^2 \langle \mathcal{I}^2(\delta B) \rangle + \alpha \, \langle \mathcal{I}^2(\delta B) \rangle + \beta$$

$$\langle \vartheta^2 \rangle = c_2^2 \, \langle \mathcal{I}^2(\delta B) \rangle$$

Assuming small α and β (see later...) we can write

Deflections from Rotation Measures

$$\langle \vartheta^2 \rangle = \frac{c_2^2}{c_1^2 \langle n \rangle^2} \, \langle RM^2 \rangle$$

No Magnetic Field $\langle \delta B^2 \rangle$

A Toy I

- The variance can be estimated within a simple cell model
- The random field is chopped into identical cells
- In each cell the magnetic field is uniform and has some random orientation
- RMs perform a random walk along the line of sight:

$$RM = k_1 RM_0 \sqrt{N}$$

- The deflections are described by a very similar formula:

$$\vartheta = k_2 \vartheta_0 \sqrt{N}$$

A Toy II

We follow the random walk numerically for $N = 100000$

- RM accumulation has only $B_\parallel$:

$$k_1 = \left| \sum c_{\phi_i} \right| / \sqrt{N} \;\Rightarrow\; k_1 = 0.56.$$

- Deflections instead have $B_\perp$:

$$k_2 = \sqrt{\left(\sum s_{\phi_i} c_{\psi_i}\right)^2 + \left(\sum s_{\phi_i} s_{\psi_i}\right)^2} / \sqrt{N} \;\Rightarrow\; k_2 = 0.63.$$

$$\boxed{\vartheta \approx 0.35/\mathrm{cm}\ RM/\langle n\rangle \quad \mathrm{VS} \quad c_2/c_1 \approx 0.28/\mathrm{cm}}$$

These numbers are for $E = 40$ EeV and $Z = 1$ (protons)

Parameters I – The average electron density

- NE2001 model with an increased vertical scale $d = 1.8\ \mathrm{kpc}$
- It decays as $\mathrm{sech}^2(h/d)$
- Density $n(h = 0) \approx 0.014\ \mathrm{cm}^{-3}$

Other models have the same general behaviour.

This is the only model input for our upper limit

Parameters II – The turbulent electron density

The spectrum of the electron density is little known
It shows up in α and β
These numbers are likely to change significantly in the future

- Kolmogorov electron density spectrum (slope $= 11/3$)
- Amplitude $C_n^2 = 10^{-3} m^{-20/3}$
- IR cutoff scale $l_0 = 100$ pc (at large b)

This does NOT impact our result
when interpreted as an upper limit

Parameters III – The regular magnetic field

- The average B field comes from Pshirkov et al. 2011
- The field is below 1 μG for most directions
- Alternatives are easily implemented

This is needed to test backtracing. It also enters in β

Galactic Morphology: cutoff at $D = d/\sin(b)$

Parameters IV – Results

Coefficients unveiled

$$\langle RM^2\rangle \simeq c_1^2\,\langle n\rangle^2\langle\mathcal{I}^2(\delta B)\rangle + c_1^2\left[3.1C_n^2 l_0^{2/3}\langle\mathcal{I}^2(\delta B)\rangle + 1.1C_n^2 D l_0^{5/3}\langle B\rangle^2\right]$$

- With our parameter choice the third term gives, at $b = 90^\circ$, 17 rad/m^2
- This is larger than the observed RM in most of the sky
- The second term is also dominant compared to the first

Interpretation

- The electron density variance parameters are not compatible with observed RM
- Our estimate turns into an UPPER LIMIT

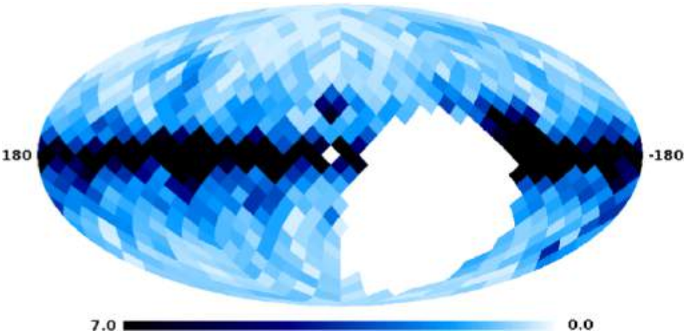
$$\boxed{\langle \vartheta^2 \rangle = \frac{c_2^2}{c_1^2 \langle n \rangle^2} \langle RM^2 \rangle}$$

Alternative set

- Flatter spectrum (slope = 3) from 1 pc to 100 pc
- Shorter vertical scale h = 1.3 kpc
- Our formula becomes an actual estimate: we can neglect α and β

The Map

Map of Displacements $\langle \Theta^2 \rangle = \langle \vartheta^2 \rangle / 3$



Galactic coordinates

A Lesson Learnt

1. No strong features in Galactic longitude
2. Regular dependence on Galactic latitude as $(\sin^2(b) + 0.15)^{-1}$
3. The displacements are bound to 1 to 2 degrees for the majority of directions
4. Close to the Galactic plane we observe $\sim 5^\circ$

Cross-Checks

Self-consistency:
The random displacements do not move events away from their bin

These constraints are conservative, but:

- Fermi Bubbles. Extended regions around the Galaxy with small n and large B are deceiving
- Resolution: the Dark Spot. It's a large-scale field with structure on scales smaller than the bin
- Intrinsic Variance. It goes like $1/\sin b$, amounts to about 10 rad$/m^2$

Thee Caveat

- The regular magnetic field deviates cosmic rays
- Imagine this is larger than the size of the bins
- Then we are comparing two different lines of sight
  1. The deflected cosmic ray
  2. A polarised radio wave

  which do not belong to the same bin
- With protons at 40 EeV this does not happen
- The algorithm still works for other species, but they need to be backtracked first

Conclusions

Summary

- UHECR carry information about the most energetic events ever registered in the Universe
- TA has been successfully running for 5yrs
- The new low-energy extension TALE is now taking data (since this summer)
- The highest data show a marginal incompatibility with isotropic distribution
- There is feeble evidence for a hotspot where events seem to cluster
- No significant correlation with AGN is seen
- TA and Auger are now actively collaborating and exchanging data
- For the first time we have seen Full Sky maps – paper underway
- Sidetrack: we developed a robust method to cope with the GMF (regular and random)