Arrival directions at ultra-high energies

A review

Armando di Matteo[a] for the Auger/TA anisotropy working group

[a]Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium
E-mail: armando.di.matteo@ulb.ac.be

2016 International Conference on Ultra-High Energy Cosmic Rays,
11–14 October 2016, Kyoto, Japan

Outline

The datasets

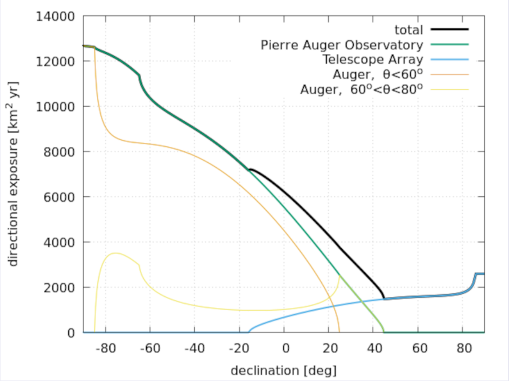
Telescope Array [May 2008–May 2015]

- zenith angles $\theta \leq 55°$
- 8 700 km^2 sr yr exposure
- 83 events $E > 57$ EeV

Pierre Auger Obs. [Jan 2004–Mar 2014]

- zenith angles $\theta \leq 80°$
- 66 452 km^2 sr yr exposure
- 602 events $E > 40$ EeV

Directional exposure



twice as much as in ApJ 794, 172 (2014)

Outline

1 The datasets
- Cross-calibration

2 Results
- The flux sky map
- Multipolar analysis
- Search for hotspots
- Correlation with large-scale structure

3 Conclusions

Cross-calibration

- Thanks to the addition of Auger inclined events ($60^\circ < \theta \leq 80^\circ$), there is now a wide declination band ($-16^\circ \lesssim \delta \lesssim +45^\circ$) where the datasets overlap.
- Regardless of the true arrival direction distribution, the quantity

$$\sum_{\text{events in band}} \frac{1}{\omega(\mathbf{n}_i)} \qquad \Big(\omega(\mathbf{n}) = \text{directional exposure } [\mathrm{km}^2\ \mathrm{yr}]\Big)$$

is an unbiased estimator of

$$\int_{\text{band}} \Phi(\mathbf{n})\, \mathrm{d}\Omega \qquad \Big(\Phi(\mathbf{n}) = \text{directional flux } [\mathrm{km}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{yr}^{-1}]\Big)$$

and should be the same for both experiments (modulo statistical fluctuations).

- We can use this to cross-calibrate the energy scales, by finding E_{Auger} and E_{TA} such that the Auger flux above E_{Auger} matches the TA flux above E_{TA}.
- (But we had better not get too close to the edges of the FoV where $1/\omega(\mathbf{n})$ is large, or else we would get large statistical fluctuations; here we use $-15^\circ \leq \delta \leq +40^\circ$.)

Statistical uncertainty on the cross-calibration

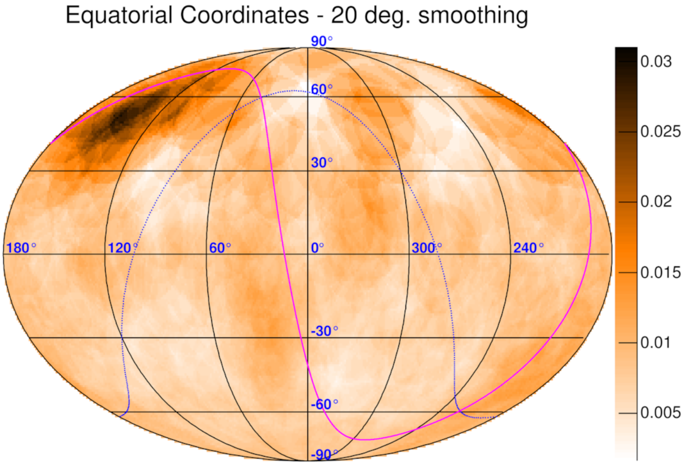
- Unfortunately, at high energy we have little statistics:
  - TA flux $E_{\text{TA}} > 57.0$ EeV: (0.0470 ± 0.0055) km^{-2} yr^{-1} over 5.66 sr (12% rel. stat. unc.)
  - PA flux $E_{\text{PA}} > 42.0$ EeV: (0.0470 ± 0.0033) km^{-2} yr^{-1} over 5.66 sr (7% rel. stat. unc.)
    $\rightarrow$ their ratio $= 1.00 \pm 0.14$
  - (also, $\approx 3\%$ systematic uncertainty on exposures)
- This means that $E_{\text{TA}} = 57$ EeV corresponds to $E_{\text{Auger}} = 42.0^{+2.5}_{-1.5}$ EeV.
- Solution: we use fixed energy thresholds for both experiments, but we scale the Auger exposure by a nuisance parameter b to compensate for any over- or under-estimate of the E_{Auger} matching $E_{\text{TA}} = 57.0$ EeV.

$$\omega_{\text{total}}(\mathbf{n}; b) = \omega_{\text{TA}}(\mathbf{n}) + b\,\omega_{\text{Auger}}(\mathbf{n})$$

- We have not taken into account the differences between TA and Auger energy resolutions, but we expect their effect to be small.

Outline

Estimated flux at $E_{\mathrm{TA}} > 57$ EeV ($E_{\mathrm{Auger}} > 42$ EeV)



Blue dashed: galactic plane

Magenta solid: supergalactic plane

Pre-trial significance of excesses/deficits $< 5\sigma$ everywhere, as shown in a later slide

Outline

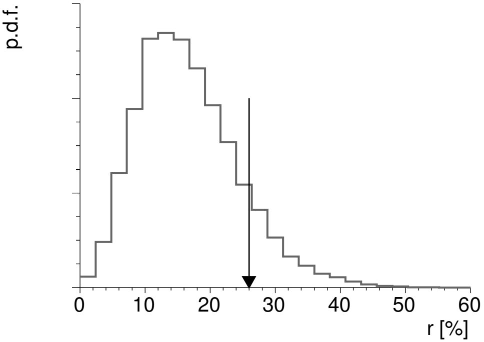
1 The datasets
- Cross-calibration

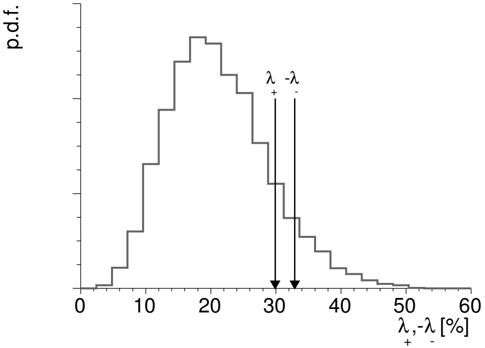
2 Results
- The flux sky map
- Multipolar analysis
- Search for hotspots
- Correlation with large-scale structure

3 Conclusions

Dipole and quadrupole moments

$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}\left(1 + r\mathbf{d}\cdot\mathbf{n} + \lambda_+(\mathbf{q}_+\cdot\mathbf{n})^2 + \lambda_0(\mathbf{q}_0\cdot\mathbf{n})^2 + \lambda_-(\mathbf{q}_-\cdot\mathbf{n})^2 + \ldots\right)$$





Compatible with expectation from isotropic flux

Angular power spectrum

Spherical harmonic expansion

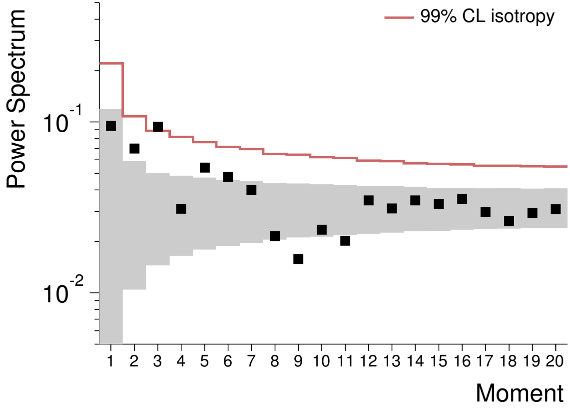
$$\Phi(\mathbf{n}) = \sum_{l=0}^{+\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\mathbf{n})$$

$Y_{lm}(\mathbf{n})$ normalized by
$\int_{4\pi} Y^*_{lm}(\mathbf{n}) Y_{l'm'}(\mathbf{n})\,\mathrm{d}\Omega = \delta_{ll'}\delta_{mm'}$

Angular power spectrum

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{+l} |a_{lm}|^2$$

measures anisotropies on angular scales $\sim 1/l$ rad.



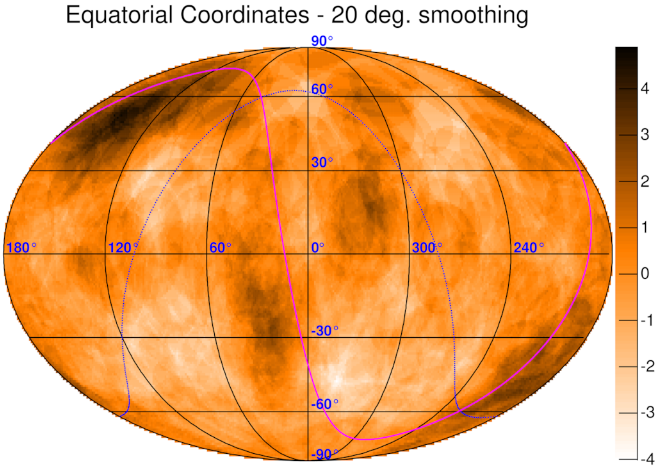
Outline

1 The datasets
- Cross-calibration

2 Results
- The flux sky map
- Multipolar analysis
- Search for hotspots
- Correlation with large-scale structure

3 Conclusions

Significance sky map (excesses above $E_{\text{TA}} = 57$ EeV, $E_{\text{Auger}} > 42$ EeV in 20° disks)



Excess/deficit over isotropic expectation in pre-trial standard deviations

Arbitrary (historical) choice of threshold energy and disk size

We should check what will happen if we change them, but we still haven't.

Outline

Likelihood ratio

- Unbinned likelihood L defined by

$$\log L = \sum_{\text{events}} \log \frac{\omega(\mathbf{n}_i)\Phi(\mathbf{n_i})}{\int_{4\pi} \omega(\mathbf{n})\Phi(\mathbf{n})\,\mathrm{d}\Omega}$$

- Given two flux models $\Phi_1(\mathbf{n})$, $\Phi_2(\mathbf{n})$, the likelihood ratio

$$\frac{L_1}{L_2} = \exp(\log L_1 - \log L_2)$$

tells us how many more times the first model is more likely than the second.

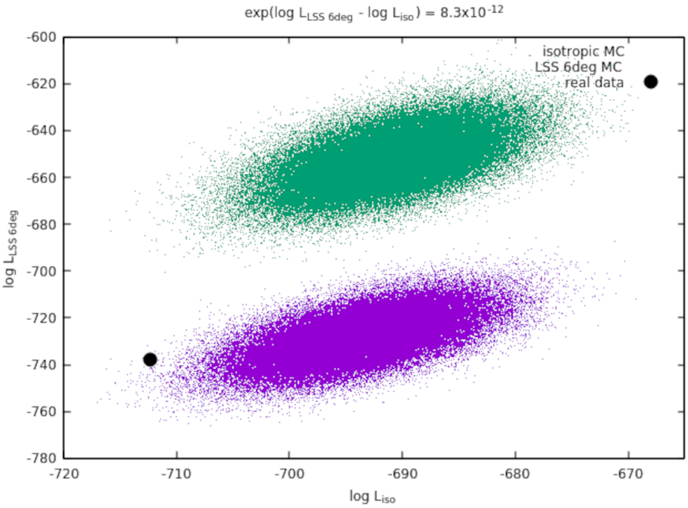
Correlation with large-scale structure

- We consider the flux model

$$\Phi_{\mathrm{LSS}}(\mathbf{n};\sigma) \propto \sum_{\text{source catalog}} w_i \exp\left(\frac{\mathbf{n}\cdot\mathbf{n}_i}{\sigma^2}\right)$$

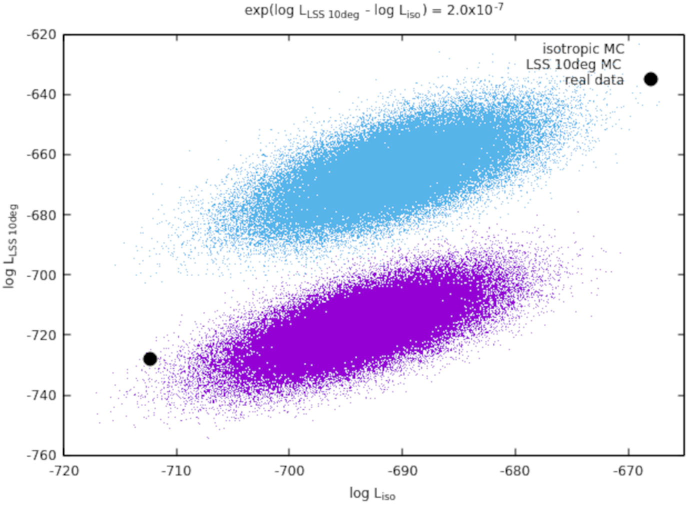
(Weighed sum of von Mises–Fisher distributions, approx. Gaussian for small σ; w_i = weight to take into account non-uniform catalog exposure and flux attenuation due to propagation)

Isotropy vs LSS with 6° smoothing



Strongly incompatible with smoothed LSS, marginally compatible with isotropy

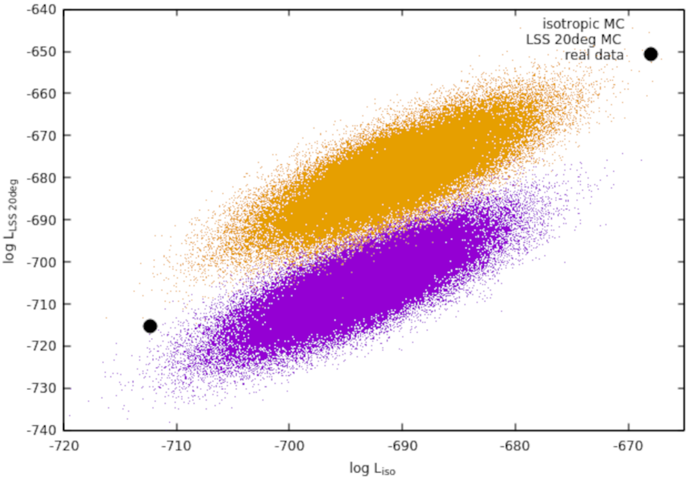
Isotropy vs LSS with 10° smoothing



Similar situation

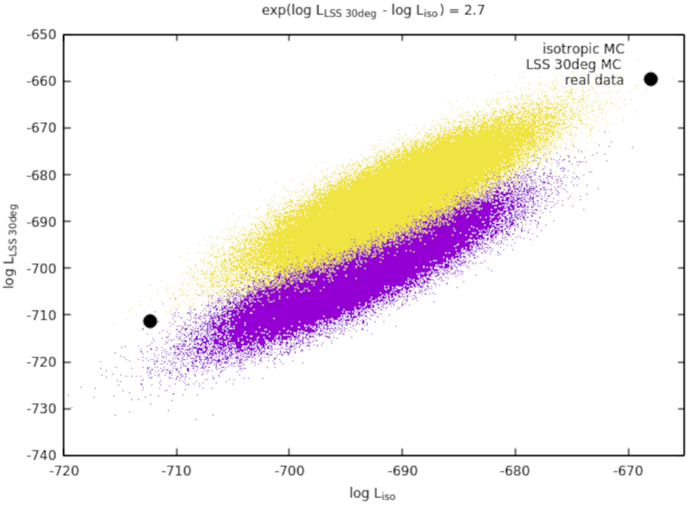
Isotropy vs LSS with 20° smoothing

$\exp(\log L_{LSS\ 20deg} - \log L_{iso}) = 5.4 \times 10^{-2}$



Almost compatible with smoothed LSS, but isotropy is still better

Isotropy vs LSS with 30° smoothing



Smoothed LSS slightly better than isotropy now

Conclusions

- First attempt to produce a UHE Auger/TA sky map above 57 EeV (TA scale) / 42 EeV (Auger scale)
- Cross-calibration of the flux in the common band:
  - Correcting for anisotropies of experimental origin
  - Effective energy threshold affected by large uncertainties
- No statistically significant large-scale anisotropy
- Hints of 20° hotspot(s) and correlation with LSS smoothed by 30°
  - But we should check what happens with different energy thresholds.
- More statistics are needed
  - Planned Telescope Array expansion: TA$\times$4
  - Auger will continue data taking through 2025.