Cosmic rays arrival direction maps

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Goal

Evaluate the arrival direction of cosmic rays by atomic mass.

First milestone:
Produce arrival direction sky maps.

In particular, if there is an interest in a multipolar structure, it is advantageous to average out (**smooth**) smaller structures in the AD maps.

Benchmark

Science paper

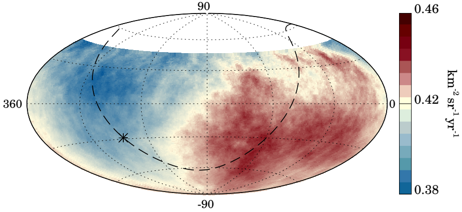


Table 2: **Three dimensional dipole reconstruction.** Directions of dipole components are shown in equatorial coordinates.

Energy [EeV]	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d [°]	Dipole right ascension α_d [°]
4 to 8	-0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
8	-0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

Reconstruct the flux sky-map

Two methods

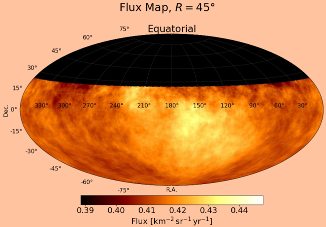
Method N/E

Smoothing function:

$$N_{\text{smoothed}}(\alpha,\delta) = \int_{\text{Sphere}} N(\alpha,\delta)\,\overbrace{S(\alpha,\delta,\theta,\phi)}^{\text{Smoothing function}}\,d\Omega$$

$$\omega_{\text{smoothed}}(\alpha,\delta) = \int_{\text{Sphere}} \omega(\alpha,\delta)\,S(\alpha,\delta,\theta,\phi)\,d\Omega$$

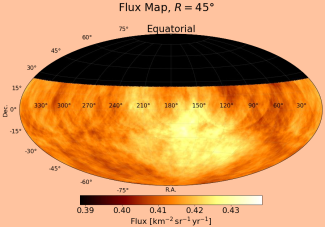
$$\Phi_{\text{smoothed}}(\alpha,\delta) = \frac{N_{\text{smoothed}}(\alpha,\delta)}{\omega_{\text{smoothed}}(\alpha,\delta)}$$



Method 1/ω

$$\Phi_{\text{raw}}(\alpha,\delta) = \frac{N(\alpha,\delta)}{\omega(\alpha,\delta)}$$

$$\Phi_{\text{smoothed}}(\alpha,\delta) = \int_{\text{Sphere}} \Phi_{\text{raw}}(\alpha,\delta)\,S(\alpha,\delta,\theta,\phi)\,d\Omega$$



Tasks

- Compare smoothing functions, defining a relationship between them;
- Using HEALPix[1], plot the arrival direction maps;
- Recover previously published results, as a consistency test;
- Incorporate the 2 methods for obtaining the flux map;
- Check effects and discuss.

[1] `http://healpix.sourceforge.net`

Distribution functions

To ensure the Gaussian distribution have a concentration such that, up to the a distance R', the number of events within this region is the same as in the top-hat distribution, e.g. 68%.

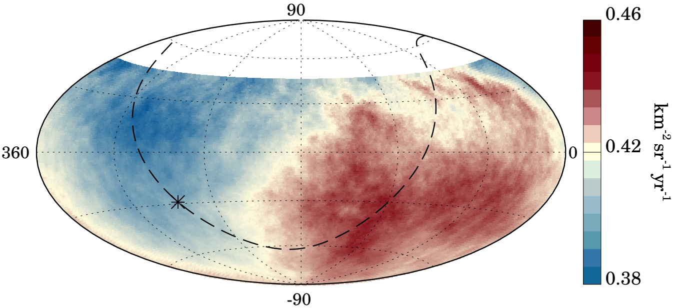
Equating both cumulative distribution functions:

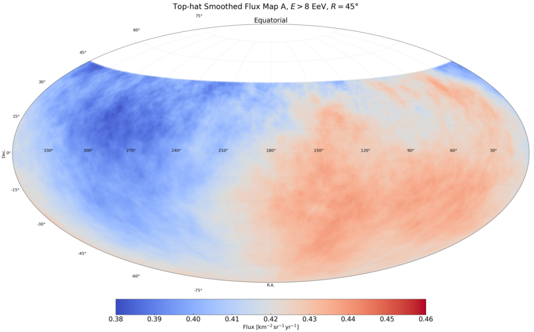
$$\int_0^{2\pi}\int_0^{R'} \frac{1}{\pi \mathrm{R}^2} r \; dr \; d\theta = \int_0^{2\pi}\int_0^{R'} \frac{1}{2\pi\sigma^2} \mathrm{e}^{\frac{-1}{2}\left(\frac{r}{\sigma}\right)^2} r \; dr \; d\theta \quad = 0.68 \tag{1}$$

This leads to the relationship: $\sigma = 0.545317$ R.

R is the scale of the smoothing (the beam window radius).

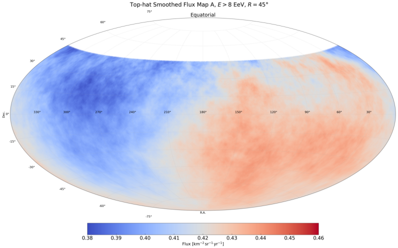
Science paper

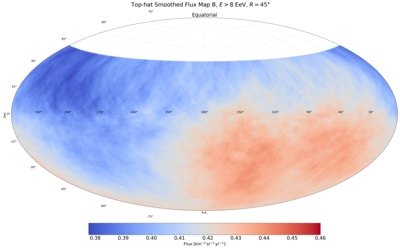




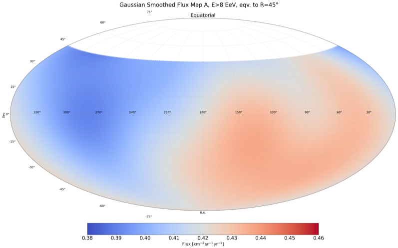
A	B

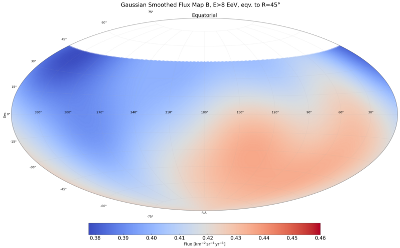
Top-hat





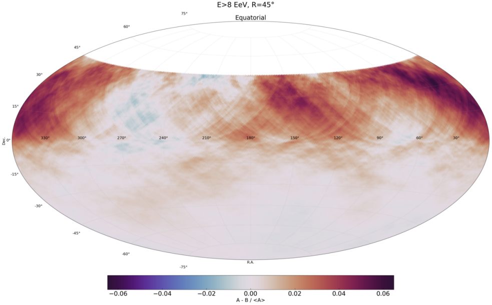
Gaussian



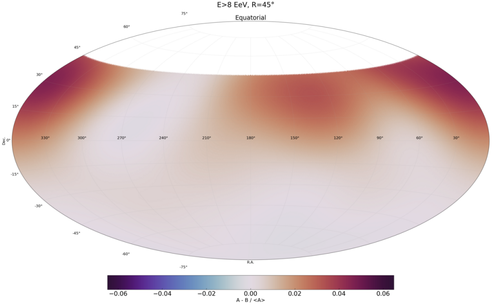


A - B / < A >

Top-hat

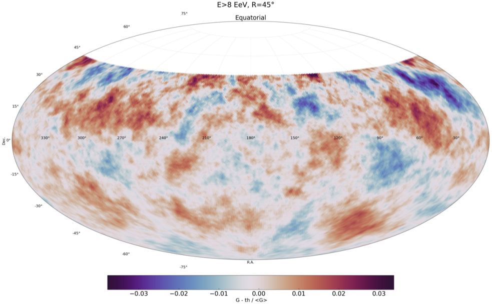


Gaussian

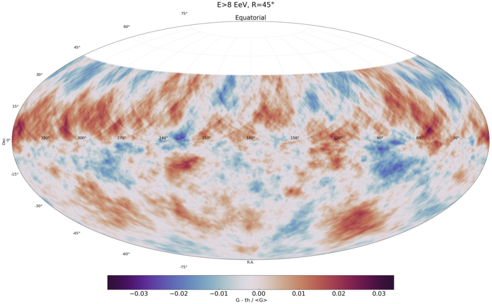


G - th / < G >

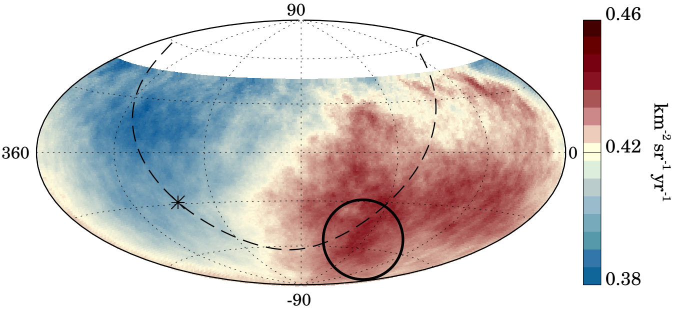
A

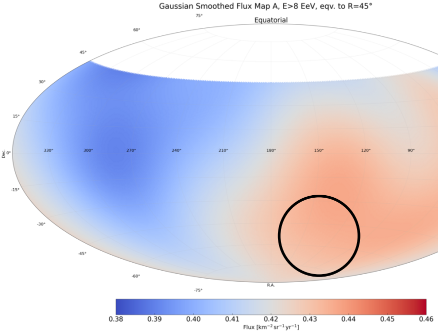

E>8 EeV, R=45°
Equatorial
Dec.
R.A.
−0.03 −0.02 −0.01 0.00 0.01 0.02 0.03
G - th / <G>

B


E>8 EeV, R=45°
Equatorial
Dec.
R.A.
−0.03 −0.02 −0.01 0.00 0.01 0.02 0.03
G - th / <G>

Science paper





Top hat	Gaussian	G - th / < G >

45°

60°

90°

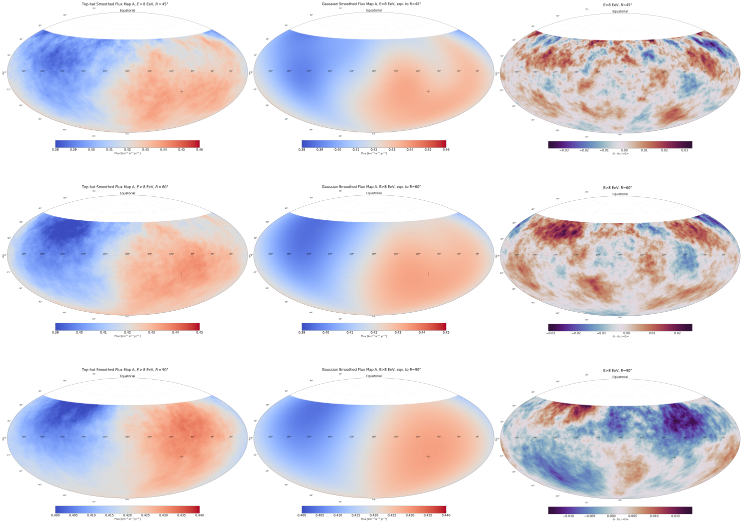


Figure 1: Flux maps for Science paper dataset. Marker **+** represents dipole coordinates (ra, dec) = (100°,-24°).

Top hat	Gaussian

45°

60°

90°

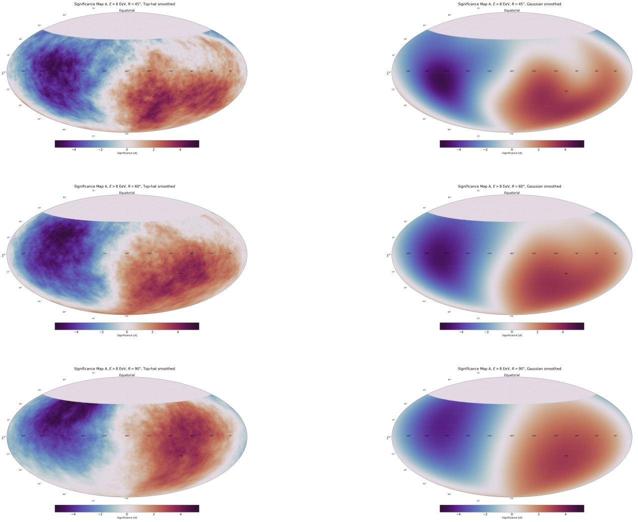


Figure 2: Significance maps for Science paper dataset. Marker **+** represents dipole coordinates (ra, dec) = (100°,-24°).

Summary

- In both flux-calculation methods, the Gaussian smoothed maps present no localized excess regions;
- Since the goal of applying smoothing is to overlook smaller structures, we proposed for the AD group to adopt the Gaussian function for this purpose in the upcoming publications;
- **The impact is restricted to the visualization of the data;**
- Ongoing discussion on optimal scale to perform such smoothing;
- A GAP note is under preparation.

Muito obrigada!

Backup & additional information

Dataset

The datafile *eventsutc_a8.dat* used for this analysis is available at the AD Auger Wiki.
It corresponds to the events recorded by SD 1500m from 01/01/2004 to 31/08/2016 with zenith < 80° and energies above 8 EeV. The 6T5 and 5T5-pos+ events are included and corrected for geomagnetic and weather effects, official Bad Periods excluded.
Events are weighted as described in the Science paper.

Healpy

- We use **healpy.sphtfunc.smoothing** to smooth the maps;
- The above takes the **healpy.sphtfunc.gauss_beam** as default, which "Computes the spherical transform of an axisymmetric gaussian beam "as smoothing beam window;
- To use the top-hat, we modify the beam window used in *healpy.sphtfunc.smoothing* as done in the DR notebook;
- Key aspect is: Healpy takes a 1D function as a profile of the 2D function, deems it as axisymmetric and translates it to the spherical space by performing spherical harmonics transforms.

Healpy parameters

- nside = 64 this corresponds to over 49 thousand equal-area pixels.

HEALPix Pixel Information				
Res	NSide	NPixels	Mean Spacing (deg)	Area (sterad)
0	1	12	58.6323	$1.0471976 \times 10^{+00}$
1	2	48	29.3162	$2.6179939 \times 10^{-01}$
2	4	192	14.6581	$6.5449847 \times 10^{-02}$
3	8	768	7.3290	$1.6362462 \times 10^{-02}$
4	16	3072	3.6645	$4.0906154 \times 10^{-03}$
5	32	12288	1.8323	$1.0226539 \times 10^{-03}$
6	64	49152	0.9161	$2.5566346 \times 10^{-04}$
7	128	196608	0.4581	$6.3915866 \times 10^{-05}$
8	256	786432	0.2290	$1.5978967 \times 10^{-05}$
9	512	3145728	0.1145	$3.9947416 \times 10^{-06}$
10	1024	12582912	0.0573	$9.9868541 \times 10^{-07}$