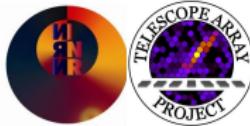


Can we detect anisotropy in the mass composition from the Telescope Array Surface Detector data?

Yana Zhezher for the Telescope Array Collaboration

Institute for Nuclear Research RAS

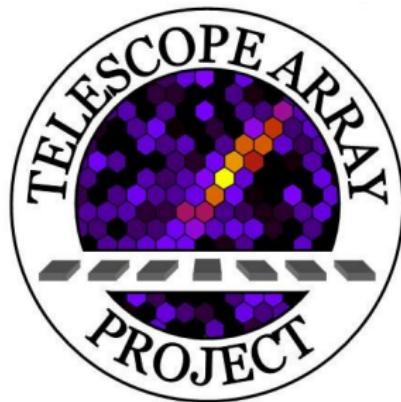
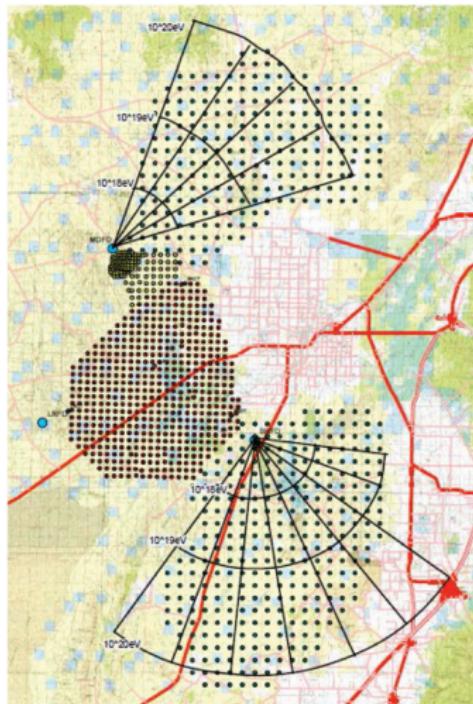
ICRC'19, 30 July 2019



Introduction: mass composition anisotropy state-of-art

- ▶ The anisotropy of cosmic ray mass composition is predicted in multiple astrophysical models (B. R. d'Orfeuil et al., Astron. Astrophys. 567, A81 (2014)).
- ▶ Due to large shower to shower statistical fluctuations, primary particle type can't be assigned for each event. Mass composition obtained by averaging over large number of events.
- ▶ We are in need of mass composition indicator, as discriminating as possible, to study it's spatial distribution.
- ▶ Is the TA SD BDT ξ parameter a plausible candidate?
- ▶ Test of ξ parameter sensitivity to mass composition anisotropies with the use of the Monte-Carlo.

Introduction: the Telescope Array experiment



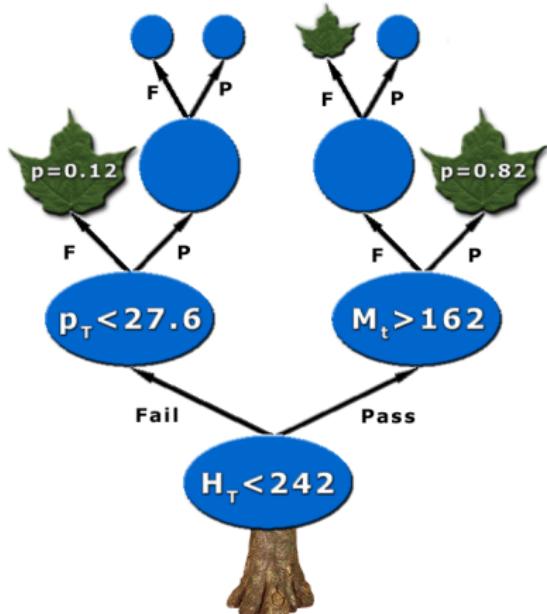
- ▶ Utah, USA
- ▶ 507 surface detectors,
 $S = 3 \text{ m}^2$, distance
1.2 km
- ▶ 3 fluorescense stations
- ▶ > 11 years of constant
data acquisition

The largest UHECR experiment
in the Northern Hemisphere

Mass composition study with the TA SD

Boosted Decision Trees:

ROOT::TMVA



SD detector array: > 90 % duty cycle, larger data statistics compared to FD

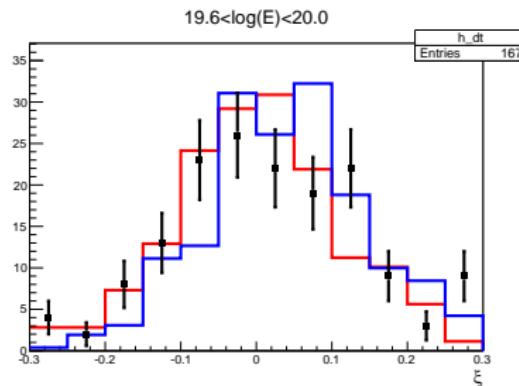
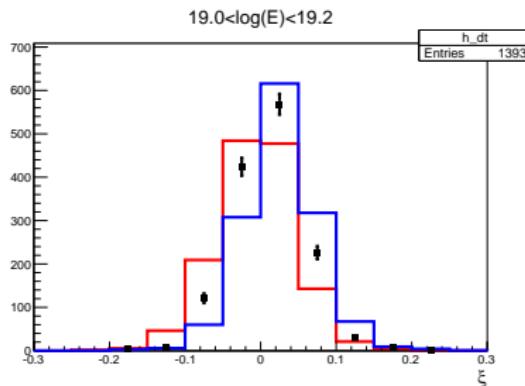
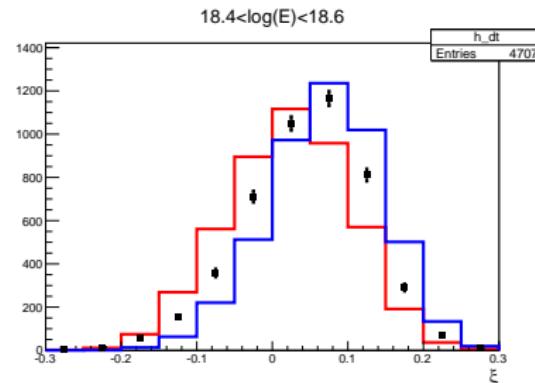
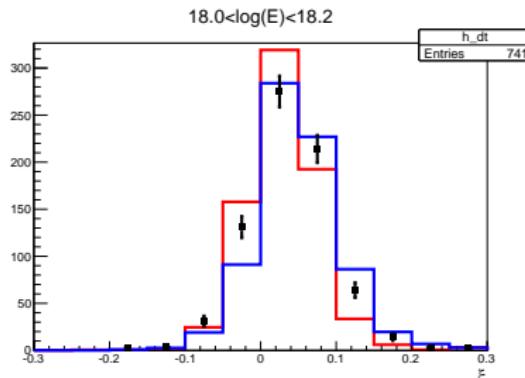
Comparison of ξ distributions for data with Monte-Carlo modelling

$$\langle \ln A \rangle (E)$$

$$(a, AoP, \dots) \rightarrow \xi$$

TA, Phys. Rev. D 99, 022002 (2019)

ξ parameter distribution



proton, iron, data

Monte-Carlo setup

Three MC sets are constructed for testing potential composition anisotropy:

1. Isotropic set with data composition ($p + Fe$ mixture).
 2. Set with data composition and light “hotspot” at energies $\log E > 19.2$.
 3. Set with data composition and heavy “hotspot” at energies $\log E > 19.2$.
-
- ▶ Two energy ranges: full energy range $\log E > 18.0$ and “hotspot” energy range $\log E > 19.2$.
 - ▶ Hotspot position: $R.A. = 146.7^\circ$, $Dec. = 43.2^\circ$ (TA, ApJ 790 L21 (2014)).

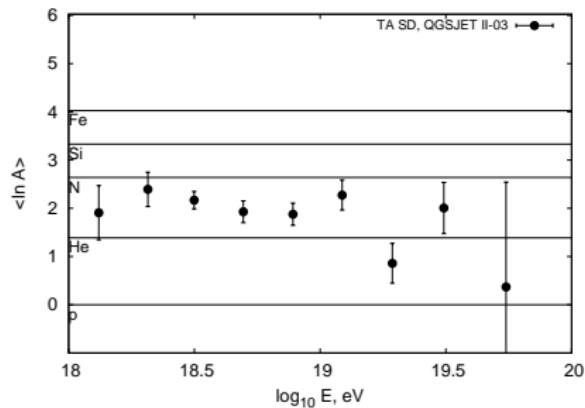
Monte-Carlo setup

p and Fe Monte-Carlo spectral sets with QGSJETII-03 – 9 years.
Statistics: 78487 proton events, 117010 iron events.

Quality cuts:

1. event includes 7 or more triggered stations;
2. zenith angle is below 45° ;
3. reconstructed core position inside the array with the distance of at least **1200** m from the edge of the array;
4. $\chi^2/d.o.f.$ doesn't exceed 4 for both the geometry and the LDF fits;
5. $\chi^2/d.o.f.$ doesn't exceed 5 for the joint geometry and LDF fit.
6. an arrival direction is reconstructed with accuracy less than 5° ;
7. fractional uncertainty of the S_{800} is less than 25 %.

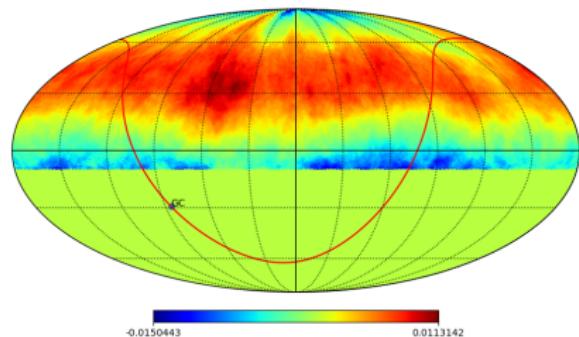
Data composition and statistics



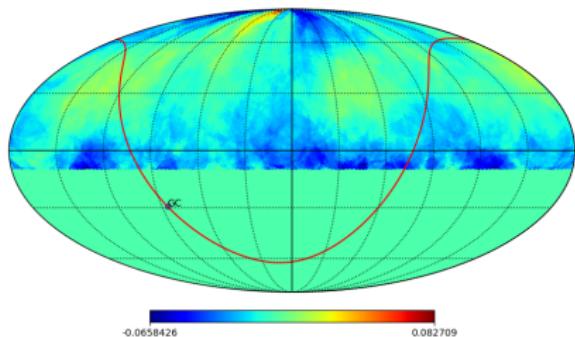
$\log E$	ϵ_p	N. of events
18.0-18.2	0.76	744
18.2-18.4	0.46	3482
18.4-18.6	0.52	4707
18.6-18.8	0.53	3834
18.8-19.0	0.58	2766
19.0-19.2	0.47	1397
19.2-19.4	0.83	691
19.4-19.6	0.54	280
19.6-20.0	0.72	167

TA, Phys. Rev. D 99, 022002 (2019)

Isotropic “composition” MC oversampling, 20° spherical caps



$$E > 10^{18.0} \text{ eV}$$



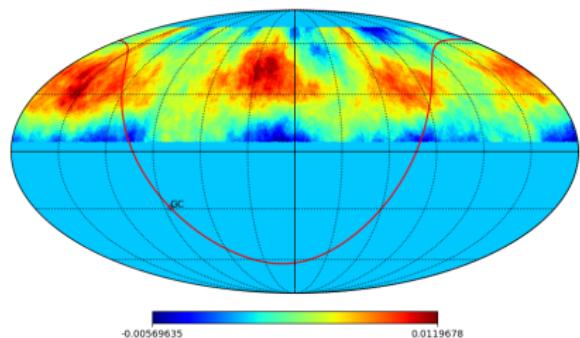
$$E > 10^{19.2} \text{ eV}$$

“Spots” may appear as statistical fluctuations,
task for a future analysis.

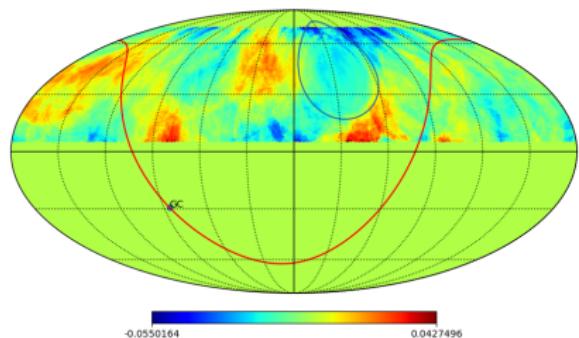
red line: Galactic Plane

N. Hayashida et al. 1999, Astropart. Phys., 10, 303

Light “hotspot” MC oversampling, 20° spherical caps



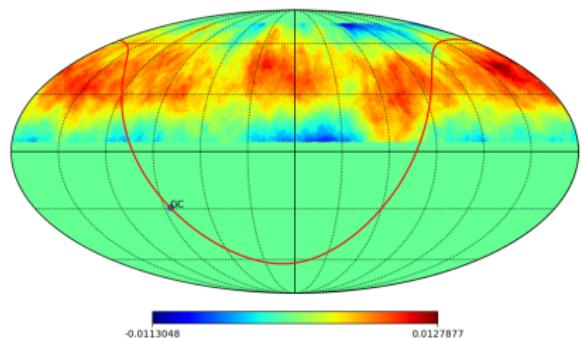
$$E > 10^{18.0} \text{ eV}$$



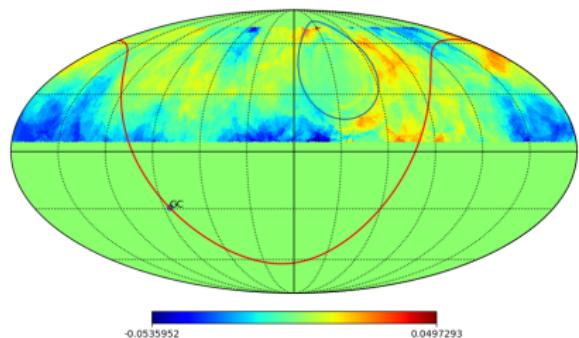
$$E > 10^{19.2} \text{ eV}$$

red line: Galactic Plane

Heavy “hotspot” MC oversampling, 20° spherical caps



$$E > 10^{18.0} \text{ eV}$$



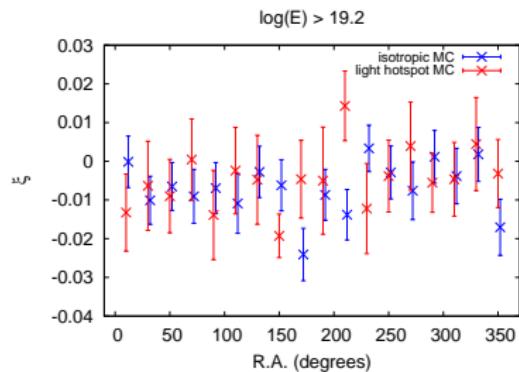
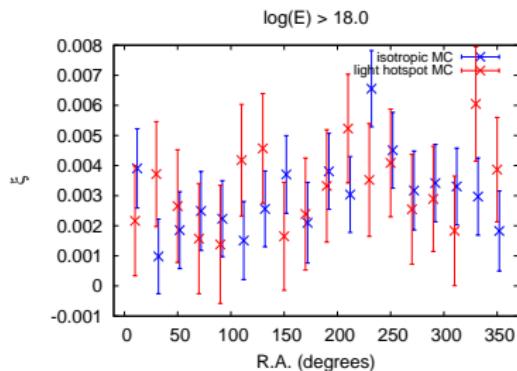
$$E > 10^{19.2} \text{ eV}$$

red line: Galactic Plane

1D test: ξ distribution over R.A.

- r.a. bins with 20° width.
- Average ξ in each bin.
- χ^2 -test for different MC sets.

Light “hotspot”: no significant sensitivity to anisotropies

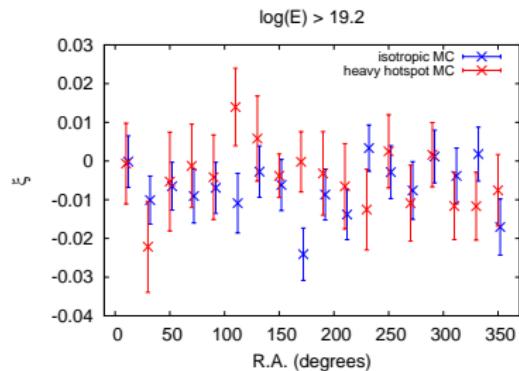
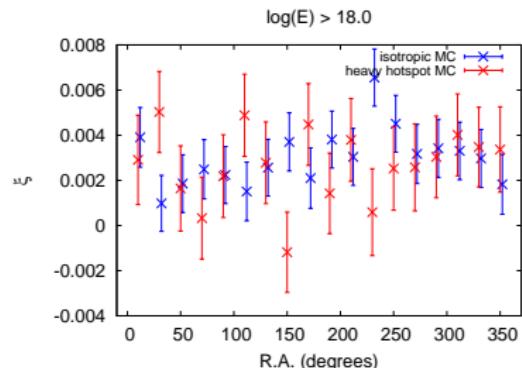


$$\chi^2/d.o.f. = 0.66, p = 0.85$$

$$\chi^2/d.o.f. = 0.99, p = 0.46$$

1D test: ξ distribution over R.A.

Heavy “hotspot”: no significant sensitivity to anisotropies



$$\chi^2/d.o.f. = 1.24, p = 0.22$$

$$\chi^2/d.o.f. = 0.89, p = 0.56$$

2D test: HEALPix maps comparison

- ▶ How to take into account large-scale gradients of ξ ? Spatial distribution of average ξ may be pixelized (i.e. HEALPix, K.M, Gorski et. al., *Astrophys.J*, 622:759-771, 2005).
- ▶ HEALPix maps are one-dimensional arrays, each pixel refers to a specific position on the sky.
- ▶ HEALPix maps are suitable for χ^2 -test.
- ▶ Resolution: `nside= 8` to make the statistics sufficient enough in each pixel.

2D test: HEALPix maps comparison

- ▶ Light “hotspot” vs isotropic MC:

$$\begin{array}{ll} \log E > 18.0 & \log E > 19.2 \\ \chi^2/d.o.f. = 1.04, p = 0.25 & \chi^2/d.o.f. = 1.47, p = 6.9 \times 10^{-5} \\ & \downarrow \\ & \textcolor{red}{3.8 \sigma} \end{array}$$

- ▶ Heavy “hotspot” vs isotropic MC:

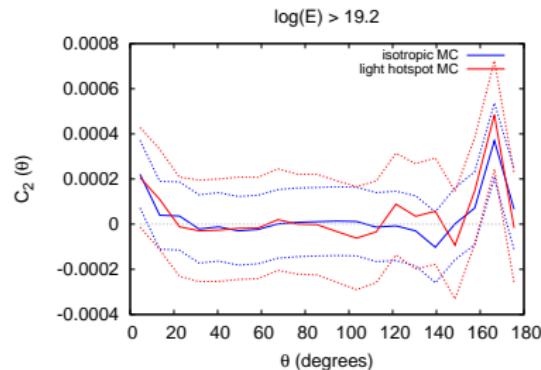
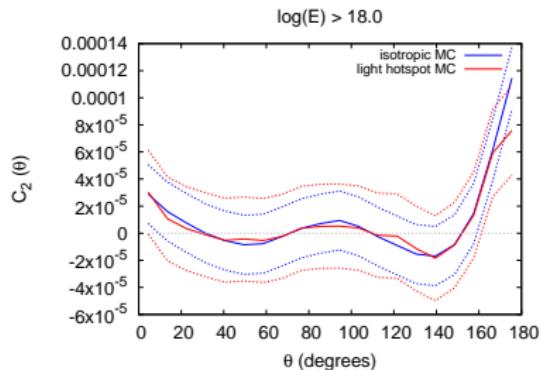
$$\begin{array}{ll} \log E > 18.0 & \log E > 19.2 \\ \chi^2/d.o.f. = 1.01, p = 0.43 & \chi^2/d.o.f. = 1.63, p = 6.3 \times 10^{-7} \\ & \downarrow \\ & \textcolor{red}{4.8 \sigma} \end{array}$$

Dicrimination between isotropic and anisotropic ξ distributions.

2D test: two-point correlation function

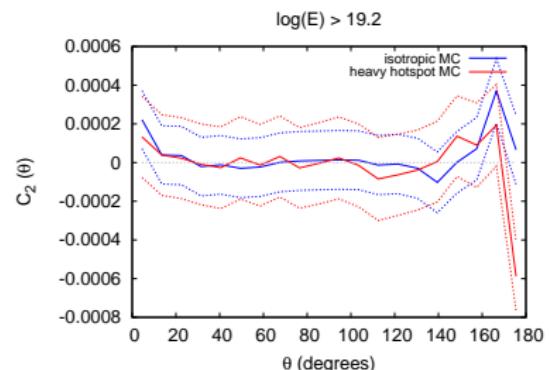
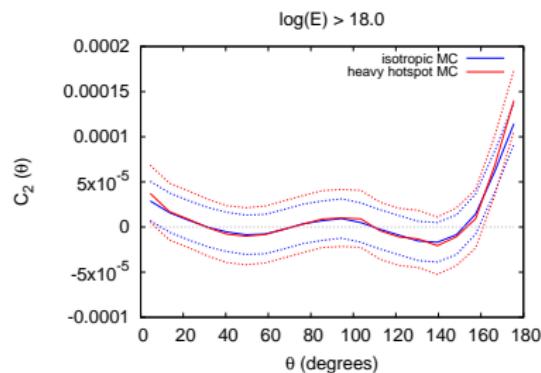
- Correlation functions in cosmology: distribution of galaxies and clusters of galaxies, non-Gaussianity in the CMB (Totsuji & Kihara (1969), Peebles (1973)).
- $C_2(\theta_1, \theta_2) = \langle (F(\theta_1) - \langle F \rangle)(F(\theta_2) - \langle F \rangle) \rangle$

Light “hotspot”: no significant sensitivity to anisotropies



2D test: two-point correlation function

Heavy “hotspot”: no significant sensitivity to anisotropies



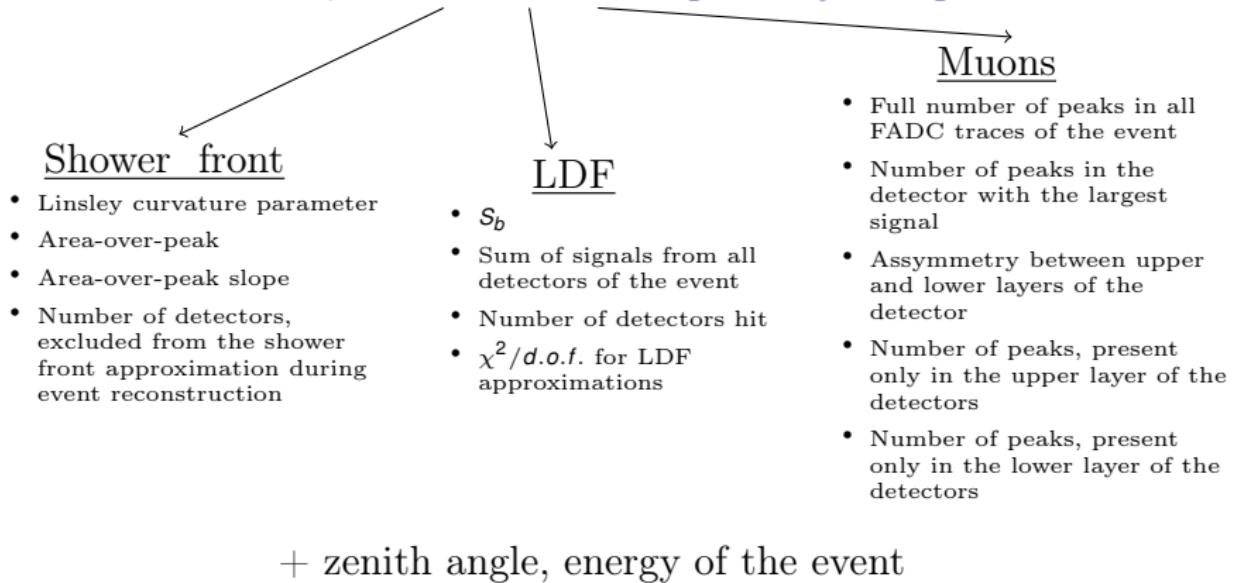
Summary

1. Potential capability to distinguish the mass composition anisotropy in the experimental data by using the BDT ξ parameter for both light and heavy “hotspot” scenario.
2. HEALPix pixelization is the strongest approach at the moment.
3. Better discrimination always needed: neural network-based composition studies (see poster by O. Kalashev & M. Kuznetsov CRI172, Tue & Wed).

Supported by Russian Science Foundation

Backup

Observables, sensitive to the primary composition



Linsley front curvature parameter

Shower front is fit with the following function:

$$t_0(r) = t_{plane} + a \times 0.67 (1 + r/R_L)^{1.5} LDF(r)^{-0.5}$$
$$LDF(r) = S(r)/S(800 \text{ m})$$
$$S(r) = \left(\frac{r}{R_m}\right)^{-1.2} \left(1 + \frac{r}{R_m}\right)^{-(\eta - 1.2)} \left(1 + \frac{r^2}{R_1^2}\right)^{-1}$$

$$R_m = 90.0 \text{ m}, R_1 = 1000 \text{ m}, R_L = 30 \text{ m}$$

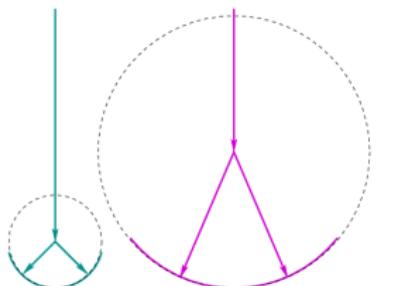
$$\eta = 3.97 - 1.79(\sec(\theta) - 1)$$

$$t_{plane}^i = \frac{1}{c} \vec{n} (\vec{R}_i - \vec{R}_{core})$$

t_{plane} – plane front arrival time

a – Linsley front curvature parameter

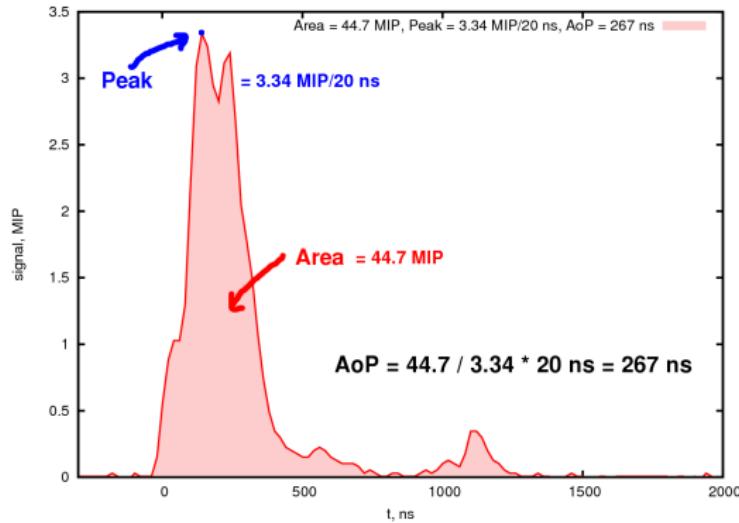
LDF – Lateral distribution function



Deeper shower maximum means more curved shower front.

Area-over-peak (AoP) and area-over-peak slope

- Time-resolved signal from a station



- $AoP(r)$ fit with the following function:
 - $AoP(r) = \alpha - \beta(r/r_0 - 1.0)$
 - $r_0 = 1200$ m, α - AoP at 1200 m, β - slope parameter

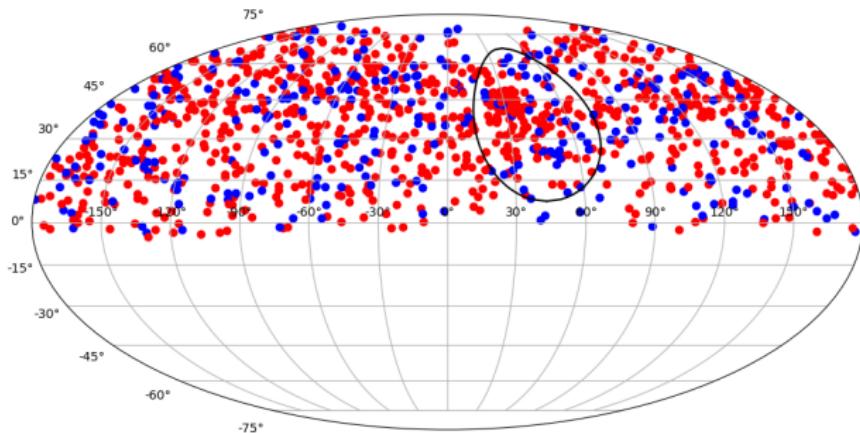
S_b parameter

$$S_b = \sum_{i=1}^N \left[S_i \times \left(\frac{r_i}{r_0} \right)^b \right],$$

where S_i – i-th detector signal, r_i – distance to the shower core in m , $r_0 = 1200$ м – characteristic distance. $b = 3$ и $b = 4.5$ are chosen as providing the best separation between primaries.

G. Ros, A. D. Supanitsky, G. A. Medina-Tanco et al., Astropart. Phys., 2001

“Hotspot” MC set



proton, iron