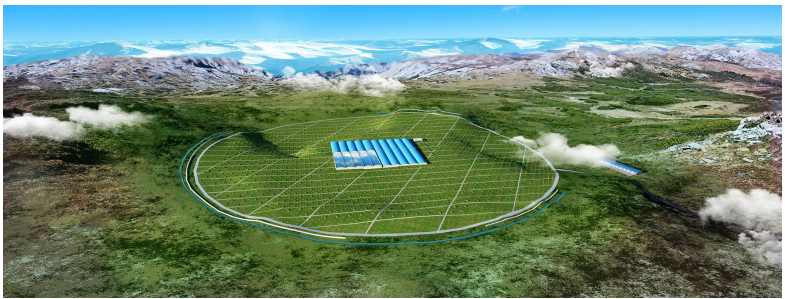
The Telescope Array Experiment: cosmic-ray anisotropy, search for photons and neutrinos

G.I. Rubtsov (INR RAS) for the Telescope Array Collaboration

LHAASO Multi-Messenger Astronomy Workshop 2019
Chengdu, April 26, 2019



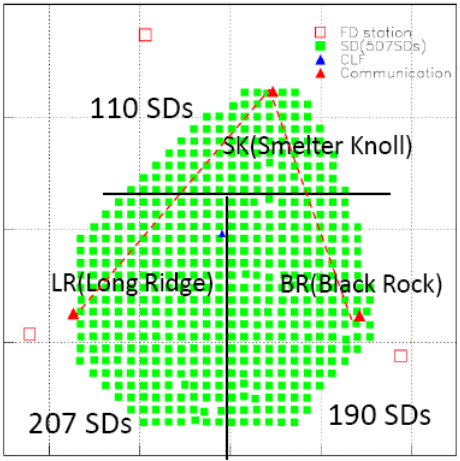
Telescope Array Collaboration

R.U. Abbasi[1] M. Abe[13] T. Abu-Zayyad[1] M. Allen[1] R. Azuma[3] E. Barcikowski[1] J.W. Belz[1] D.R. Bergman[1] S.A. Blake[1] R. Cady[1] M.J. Chae[20] B.G. Cheon[4] J. Chiba[5] M. Chikawa[6] E.J. Cho[4] W.R. Cho[7] T. Fujii[9] M. Fukushima[10;11] T. Goto[9] W. Hanlon[1] Y. Hayashi[9] N. Hayashida[10] K. Hibino[12] K. Honda[2] D. Ikeda[10] N. Inoue[13] T. Ishii[2] R. Ishimori[3] H. Ito[27] D. Ivanov[1] C.C.H. Jui[1] K. Kadota[15] F. Kakimoto[3] O. Kalashev[16] K. Kasahara[17] H. Kawai[18] S. Kawakami[9] S. Kawana[13] E. Kido[10] H.B. Kim[4] J.H. Kim[1] J.H. Kim[4] S. Kitamura[3] Y. Kitamura[3] V. Kuzmin[16] M. Kuznetsov[16] Y.J. Kwon[7] J. Lan[1] S.I. Lim[20] J.P. Lundquist[1] S. Machida[3] K. Martens[11] T. Matsuda[8] T. Matsuyama[9] J.N. Matthews[1] M. Minamino[9] Y. Mukai[2] I. Myers[1] K. Nagasawa[13] S. Nagataki[21] T. Nakamura[22] T. Nonaka[10] A. Nozato[6] S. Ogio[9] J. Ogura[3] M. Ohnishi[10] H. Ohoka[10] K. Oki[10] T. Okuda[23] M. Ono[30] A. Oshima[9] S. Ozawa[17] I.H. Park[20] M.S. Pshirkov[24] D.C. Rodriguez[1] G. Rubtsov[16] D. Ryu[19] H. Sagawa[10] N. Sakurai[9] L.M. Scott[14] P.D. Shah[1] F. Shibata[2] T. Shibata[10] H. Shimodaira[10] B.K. Shin[4] H.S. Shin[10] J.D. Smith[1] P. Sokolsky[1] R.W. Springer[1] B.T. Stokes[1] S.R. Stratton[1;14] T. Stroman[1] T. Suzawa[13] M. Takamura[5] M. Takeda[10] A. Taketa[25] M. Takita[10] Y. Tameda[10] H. Tanaka[9] K. Tanaka[26] M. Tanaka[9] S.B. Thomas[1] G.B. Thomson[1] P. Tinyakov[24;16] I. Tkachev[16] H. Tokuno[3] T. Tomida[27] S. Troitsky[16] Y. Tsunesada[3] K. Tsutsumi[3] Y. Uchihori[28] S. Udo[12] F. Urban[31] G. Vasilov[1] T. Wong[1] R. Yamane[9] H. Yamaoka[8] K. Yamazaki[9] J. Yang[20] K. Yashiro[5] Y. Yoneda[9] S. Yoshida[18] H. Yoshii[29] Ya. Zhezher[16] R. Zollinger[1] Z. Zundel[1]

[1]University of Utah [2]University of Yamanashi [3]Tokyo Institute of Technology [4]Hanyang University [5]Tokyo University of Science [6]Kinki University [7]Yonsei University [8]KEK [9]Osaka City University [10]University of Tokyo (ICRR) [11]University of Tokyo (Kavli Institute) [12]Kanagawa University [13]Saitama University [14]Rutgers University [15]Tokyo City University, [16]Russian Academy of Sciences (INR) [17]Waseda University [18]Chiba University [19]Chungnam National University [20]Ewha Womans University [21]Kyoto University [22]Kochi University [23]Ritsumeikan University [24]Universite Libre de Bruxelles [25]University of Tokyo (Earthquake Institute) [26]Hiroshima City University [27]RIKEN [28]Japanese National Institute of Radiological Science [29]Ehime University [30]Kyushu University [31] CEICO, Institute of Physics, Czech Academy of Sciences

Belgium, Czech Republic, Japan, Korea, Russia, USA

Telescope Array surface detector



- 507 SD's, 3 m^2 each
- 680 km^2 area
- 9 years of operation (this analysis)

Largest UHECR statistics in the Northern Hemisphere

Outline

- **I. Cosmic-ray anisotropy**
- II. Search for UHE photons
- III. Search for UHE neutrinos

Hunting for UHECR sources

- We know that the sources of most UHECRs are extragalactic.

  TA, Astropart. Phys. 86 (2017) 21

- How many sources there are?
  - The event clustering is not observed at $E > 50$ EeV
    $n > 10^{-4}$ Mpc^{-3} (for proton composition)

    Dubovsky,Tinyakov,Tkachev, PRL 85 (2000) 1154
  - Observation of dipole by Auger at $E > 8$ EeV
    $n \simeq 10^{-4}$ Mpc^{-3} (for mixed composition)

    Auger collaboration, ApJ 868 (2018) 4
- One of the sources is nearest. Model expectations for nearest source:
  - Distance: 4-20 Mpc
  - 2-10% of the total UHECR flux

Goal:

search for the nearest source with UHECR, photons and neutrino!

TA SD data

9-year data: 12.05.2008 – 11.05.2017

"anisotropy set"

- zenith angle <55°
- core inside array boundary
- angular resolution: <1.5°
- energy resolution: ~20%

- 3691 above 10 EeV
- 257 above 40 EeV
- 108 above 57 EeV

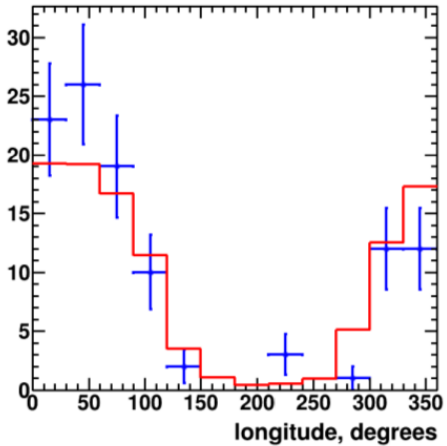
"hotspot set"

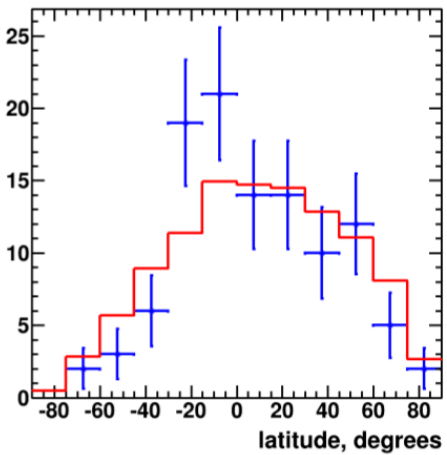
- loose cuts (4 stations)
- angular resolution: <1.7°

- 143 above 57 EeV
- 23 above 100 EeV

Global anisotropy

supergalactic coordinates

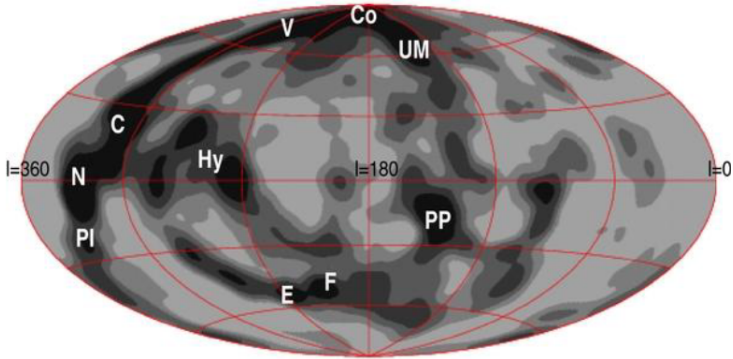




Kolmogorov-Smirnov p-value = 0.01 for SG latitude, E>57 EeV

other thresholds/coordinates = isotropic

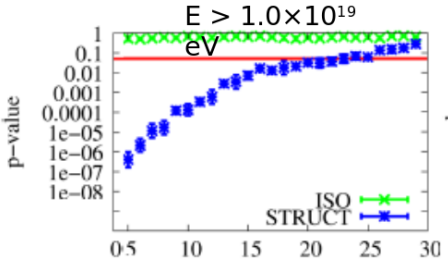
Large-Scale Structure

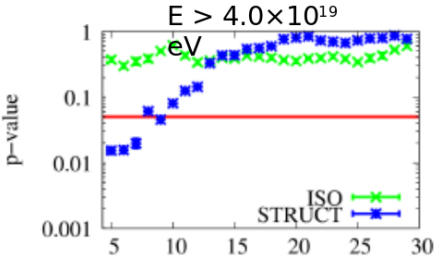


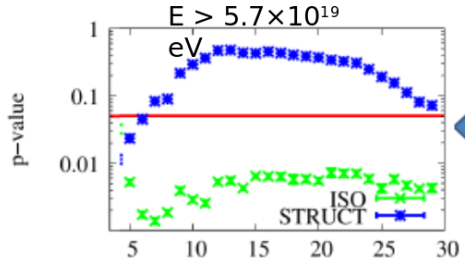
C: Centaurus SCl (60 Mpc); Co: Coma Cl (90 Mpc); E: Eridanus Cl (30 Mpc); F: Fornax Cl (20 Mpc); Hy: Hydra SCl (50 Mpc); N: Norma SCl (65 Mpc); PI: Pavo-Indus SCl (70 Mpc); PP: Perseus-Pisces SCl (70 Mpc); UM: Ursa Major Cl (20 Mpc); and V: Virgo Cl (20 Mpc).

- **Sky map of expected flux at *E* > 57 EeV (Galactic coordinates)**;
- smearing angle is 6°.

Large-Scale Structure





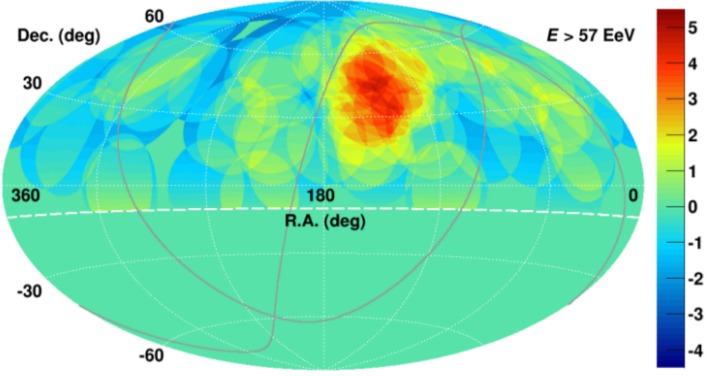


E>5.7×10¹⁹ eV
Consistent with LSS
Inconsistent with isotropy

Hot spot

E>57 EeV - Years 1-5 excess map

TA 2014



Total events: 72
Observed: 19
Expected : 4.5

Best circle center: RA=146.7^{o}, Dec=+43.2^{o}
Best circle radius: 20^{o}
Local significance : 5 σ
Global significance : 3 σ

Hot spot

Years 1-9 bin scan

TA preliminary

"Li-Ma":
approximation to Poisson statistics based on on-source/off-source exposure

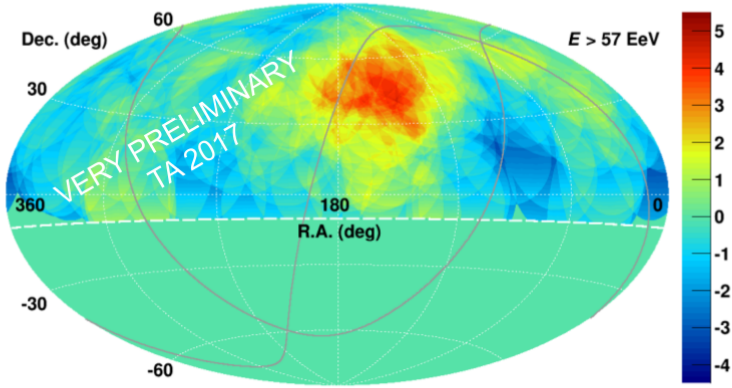
- "On": inside the circle, "off": the rest
- Scan for circle center (0.1 deg steps) and radius (15^o, 20^o, 25^o, 30^o, 35^o)

Bin size	15	20	25	30	35
σ	4.4	4.7	5.1	5.0	4.7

- Find the strongest excess ⇨ local significance
- Repeat the procedure for isotropic Monte-Carlo sets ⇨ global significance
  (look-elsewhere correction = penalty factor)

Hot spot

E>57 EeV - Years 1-9 excess map

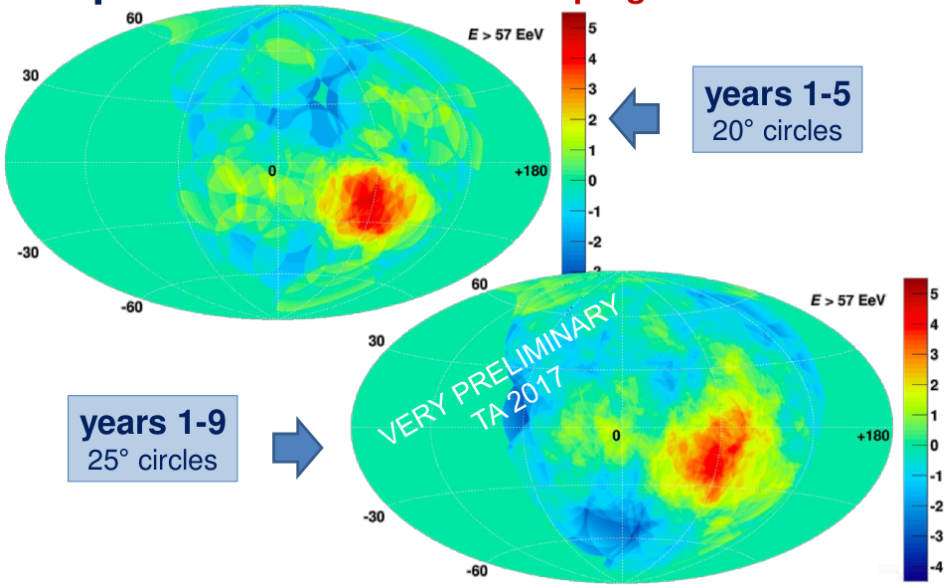


Total events: 143
Observed: 34
Expected : 13.5

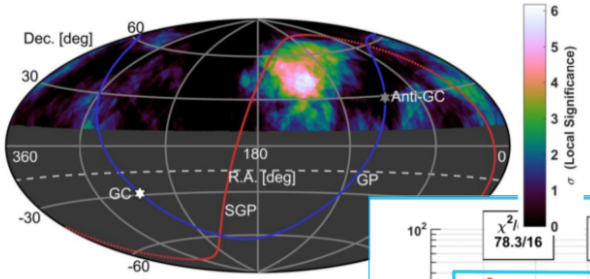
Best circle center: RA=144.3^{o}, Dec=+40.3^{o}
Best circle radius: 25^{o}
Local significance : 5 σ
Global significance : 3 σ

Hot spot

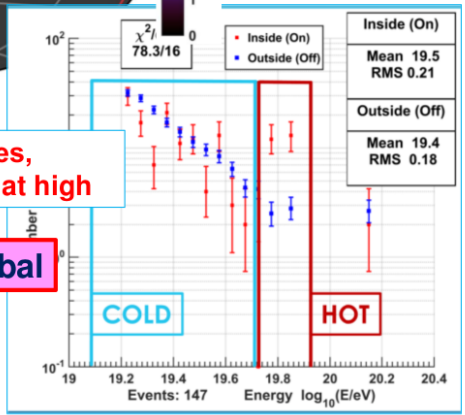
Supergalactic coordinates



Spectral anisotropy at the hot spot



$E \geq 10^{19.2}$ eV



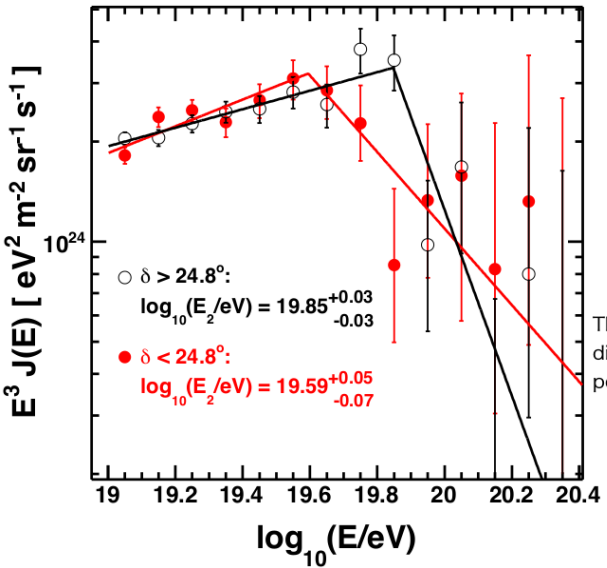
"cold spot" at lower energies, same place as the hot spot at high

3.7σ global

Astrophys.J. 862 (2018), 91

Declination dependence in TA

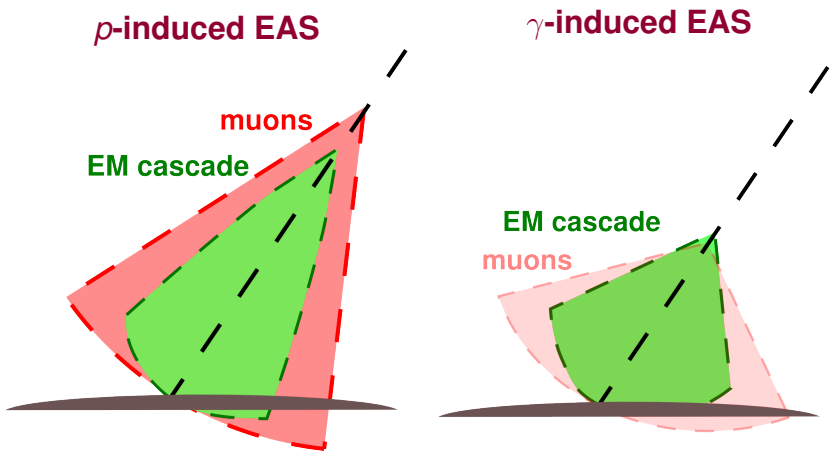
arXiv: 1801.07820



The overall significance of the difference between the two break points is 3.5 sigma

Outline

- I. Cosmic-ray anisotropy
- **II. Search for UHE photons**
- III. Search for UHE neutrinos



Photon-induced showers:

- arrive younger
- contain less muons
- $\Rightarrow$ multiple SD observables affected:
  - **front curvature, Area-over-peak, number of FADC peaks, $\chi^2/d.o.f.$, S_b**

Photon search: data and Monte-Carlo sets

- Data collected by TA surface detector for the nine years:
  2008-05-11 — 2017-05-11
- p and γ Monte-Carlo sets with CORSIKA and dethinning

Stokes et al, Astropart.Phys.35:759,2012

Cuts for both data and MC:

- 7 or more detectors triggered
- core distance to array boundary is larger than 1200m
- $\chi^2/\text{d.o.f.} < 5$
- $\theta < 60^\circ$
- $E_\gamma > 10^{18}$ eV (E_γ is estimated with photon Monte-Carlo)

52769 events after all cuts expect lightning cut

Note: MC set is split into 3 equal parts: (I) for training the classifier, (II) for cut optimization, (III) for exposure estimate.

Lightning-induced air showers

- It is shown that there are triggers of TA SD associated with the downward propagating ladders in lightning flushes.
  - Multiple SD triggers are observed within one millisecond

    Phys.Lett. A 381 (2017) 2565.
  - The results of Lightning Mapping Array (LMA) at TA site

    Journal of Geophysical Research: Atmospheres, 123, (2017) 6864-6879
- The lightnings induce electromagnetic showers, which may be identified as photons. At least five candidates of this sort passed the cuts, see *GR, ICRC'2017* for details.
- We use the National Lightning Detector Network (NLDN) data on lightnings at the location of TA SD.

  We appreciate Vaisala Inc's academic research policy
- Both data and Monte-Carlo events are removed within ± 10 min from NLDN events. An associated loss of exposure is only 0.66% of the total exposure time.

Photon search: list of relevant observables

1. Zenith angle, θ;
2. Signal density at 800 m from the shower core, S_{800};
3. Linsley front curvature parameter, a;
4. Area-over-peak (AoP) of the signal at 1200 m;

Pierre Auger Collaboration, Phys.Rev.Lett. 100 (2008) 211101

5. AoP LDF slope parameter;
6. Number of detectors hit;
7. N. of detectors excluded from the fit of the shower front;
8. $\chi^2/d.o.f.$;
9,10. $S_b = \sum S_i \times r_i^b$ parameter for $b = 3$ and $b = 4.5$;

Ros, Supanitsky, Medina-Tanco et al. Astropart.Phys. 47 (2013) 10

11. The sum of signals of all detectors of the event;
12. Asymmetry of signal at upper and lower layers of detectors;
13. Total n. of peaks within all FADC traces;
14. N. of peaks for the detector with the largest signal;
15,16. N. of peaks present in the upper layer and not in lower, lower and not upper;

Multivariate analysis

- The Boosted Decision Trees (BDT) technique is used to build p-γ classifier based on multiple observables.

Pierre Auger Collaboration, ApJ, 789, 160 (2014)

- root::TMVA is used as a stable implementation.

PoS ACAT 040 (2007), arXiv:physics/0703039

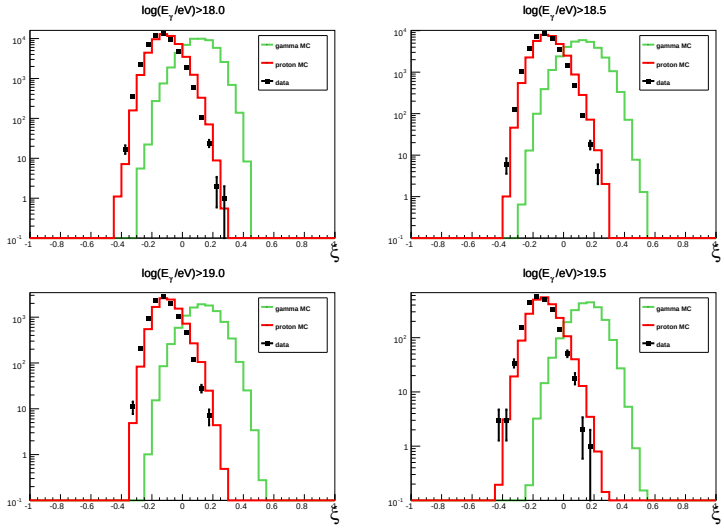
- BDT is trained with Monte-Carlo sets:

γ (Signal) and p (Background)

- BDT classifier is used to convert the set of observables for an event to a number $\xi \in [-1 : 1]$: 1 - pure signal (γ), -1 - pure background (p).

- ξ is available for one-dimensional analysis. The cut on ξ for the search is optimized using proton MC as a null-hypothesis.

Distribution of MVA estimator (ξ) for data and MC



data photon MC proton MC

Optimization of cut on ξ

- The photon candidates are selected using the cut on ξ:
  $\xi > \xi_{cut}(\theta)$
- The cut is approximated as a quadratic function of θ
- Cut is optimized in each energy range using proton and photon Monte-Carlo (cut optimization subsets)
- The merit factor is an average photon upper limit if the null-hypothesis is true (all protons)

Effective exposure

- Geometric exposure for $\theta \in (0°, 60°)$: **12060 km^2 sr yr**
- Effective exposure is estimated using photon MC assuming E^{-2} primary spectrum

E_0	quality cuts	ξ-cut	A_{eff} km^2 sr yr
$10^{18.0}$	6.5%	9.8%	**77**
$10^{18.5}$	19.9%	10.6%	**255**
$10^{19.0}$	43.6%	16.2%	**852**
$10^{19.5}$	52.0%	37.2%	**2351**
$10^{20.0}$	64.2%	52.3%	**4055**

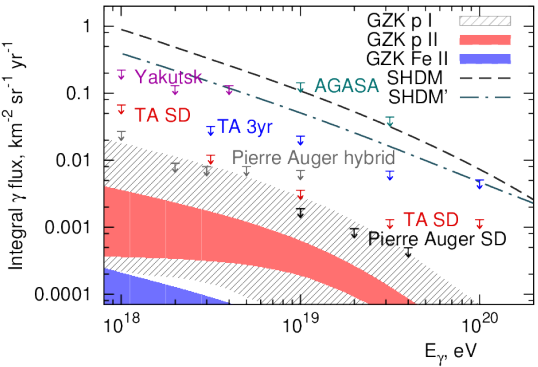
Photon candidate events

energy cut	event date and time
$E_0 > 10^{18.0}$ eV	2012-03-24 14:06:23
$E_0 > 10^{18.5}$ eV	none
$E_0 > 10^{19.0}$ eV	none
$E_0 > 10^{19.5}$ eV	none
$E_0 > 10^{20.0}$ eV	2012-03-24 14:06:23

- No thunderstorms in March 2012.
- Expected background from proton misclassification: $\sim$0.5 events in each energy range.
- The background estimate depends on composition and hadronic model. To stay conservative, zero background is assumed in the analysis.

Results: photon diffuse flux limits

E_0, eV	$10^{18.0}$	$10^{18.5}$	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	1	0	0	0	1
$\bar{n}$ <	5.14	3.09	3.09	3.09	5.14
A_{eff}	77	255	852	2351	4055
F_γ <	0.067	0.012	0.0036	0.0013	0.0013



Astropart.Phys. 110 (2019) 8-14

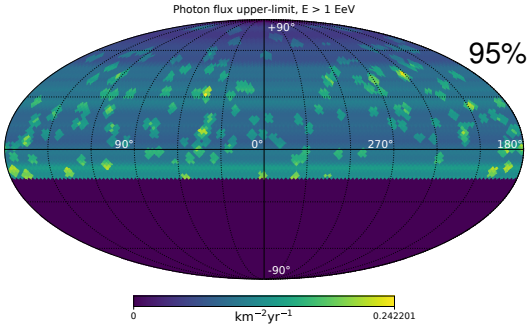
models from J. Alvarez-Muniz et al. EPJ Web Conf. **53**, *01009 (2013)*

Search for point sources of the ultra-high-energy photons

- The skymap is pixelized into 12288 directions with HEALpix
- An independent search with the cut optimization is performed in circles centered in each of the pixels;
  radius = angular resolution
- Angular reconstruction for photons:

E_γ, eV	ang. resolution 68%
$10^{18.0}$	3.00°
$10^{18.5}$	2.92°
$10^{19.0}$	2.64°
$10^{19.5}$	2.21°
$10^{20.0}$	2.06°

Point-source photon flux upper-limits



95% C.L.

$E_\gamma \geq$ eV	$\langle F_\gamma \rangle \leq$ km^{-2}yr^{-1}	max. γ signif. (pre-trial)
$10^{18.0}$	0.094	2.72 σ
$10^{18.5}$	0.029	2.71 σ
$10^{19.0}$	0.010	2.89 σ
$10^{19.5}$	7.1×10^{-3}	2.76 σ
$10^{20.0}$	5.8×10^{-3}	3.43 σ

arXiv:1904.00300

Pierre Auger: $\langle F_\gamma \rangle \leq 0.035\ \mathrm{km^{-2}yr^{-1}}$ (1° ang.res., $10^{17.3} \leq E \leq 10^{18.5}$ eV)

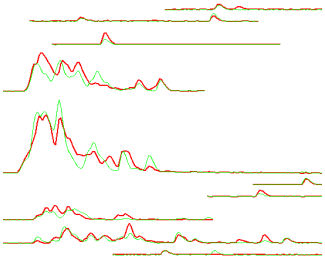
A. Aab et al. ApJ 789, 160 (2014)

Outline

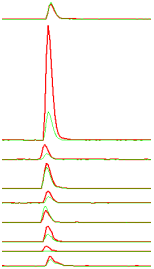
- I. Cosmic-ray anisotropy
- II. Search for UHE photons
- **III. Search for UHE neutrinos**

Neutrino search strategy

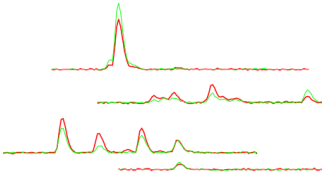
young shower, $\theta = 19.5°$



old shower, $78.3°$



neutrino shower, $\theta = 78.6°$



- Neutrino-induced showers are young while very inclined
- Waveform has many peaks

upper layer lower layer

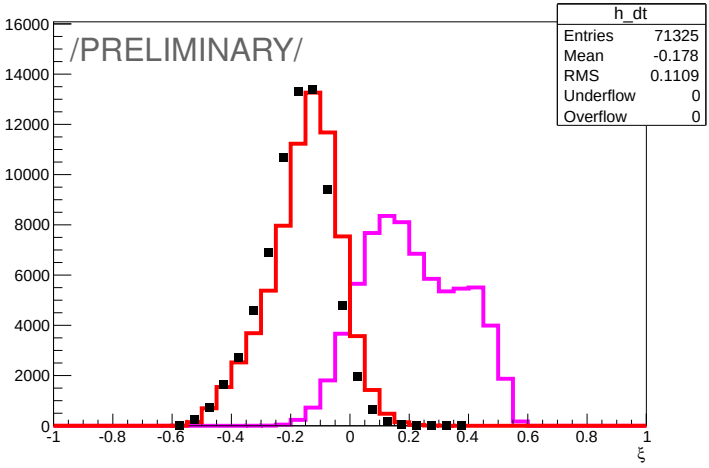
Method

- Cuts:
  - 5 or more detectors triggered
  - core distance to array boundary is larger than 1200m
  - χ^2/d.o.f. < 5
  - $45^\circ < \theta < 90^\circ$
  - no energy cut

197250 events after cuts

- Multivariate analysis is used
  - The set of observables is the same as for photon search (Energy is replaced with S_{800})
  - Method: Boosted decision tree trained with inclined proton (background) and all-flavor down-going neutrino (signal) Monte-Carlo
  - The cut on ξ is optimized in a similar to photon search way

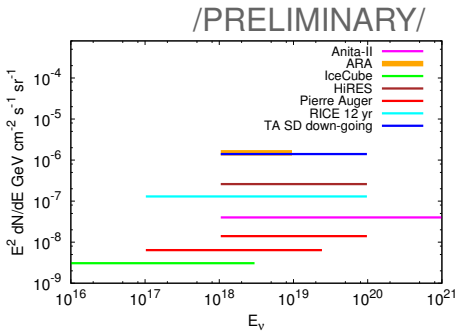
Distribution of MVA estimator (ξ) for data and MC



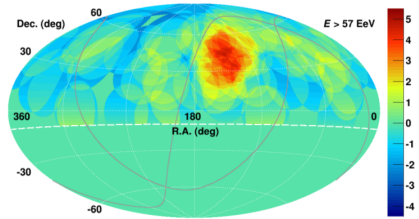
data neutrino MC proton MC

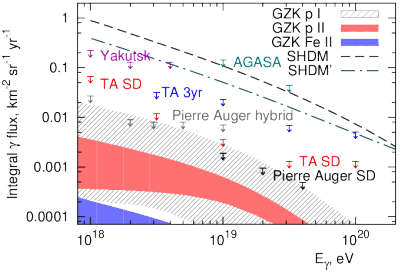
Neutrino search results

- 0 neutrino candidates after cuts, $\bar{n}_\nu < 2.44$ (90% C.L.)
- **Exposure:**
  - Geometric exposure for $\theta \in (45°, 90°)$: $8042\,\mathrm{km}^2\,\mathrm{sr\,yr}$
  - probability to interact in the atmosphere: 1.4×10^{-5}
  - trigger, reconstruction and quality cuts efficiency $\sim 7\%$
  - ξ cut efficiency: $\sim 24\%$
  - total exposure (all flavors): $A = 1.9 \times 10^{-3}\,\mathrm{km}^2\,\mathrm{sr\,yr}$
- Single flavor diffuse neutrino flux limit for $E > 10^{18}$ eV: $E^2 f_\nu < 1.4 \times 10^{-6}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$ (90% C.L.)



Conclusions





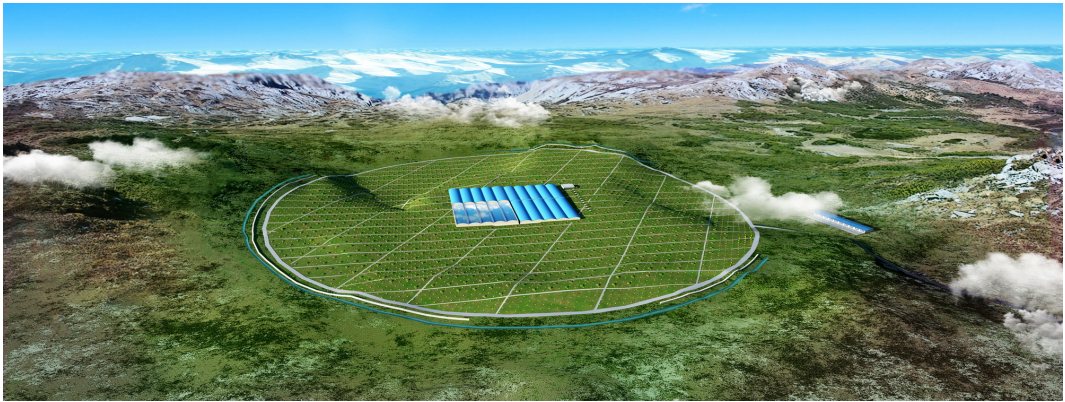
Results presented:

- Indications of intermediate-scale anisotropy is observed above 57 EeV.
- Diffuse and point-source photon flux upper limits above 1 EeV.
- Down-going neutrino diffuse flux limits above 1 EeV.

Prospects:

- The exposure and energy range will be extended with TAx4 and TALE SD experiments.
- Improved data analysis based on machine learning techniques (supported by Russian Science Foundation).

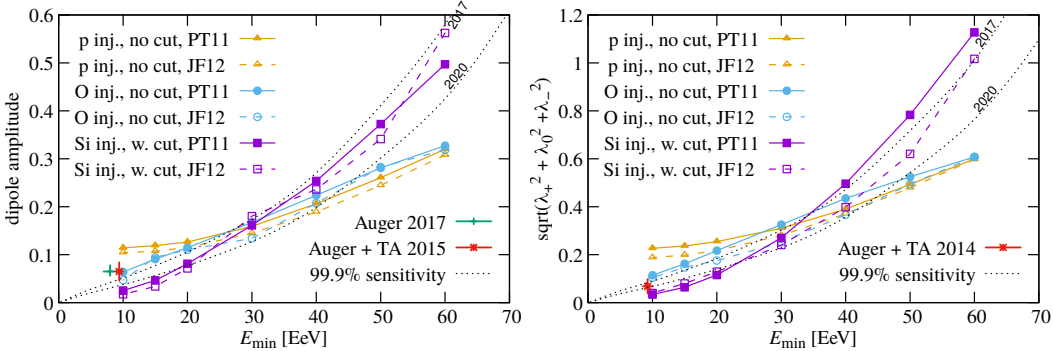
Congratulations to LHAASO!



Wish long-term success
and physics beyond expectations!

Backup slides

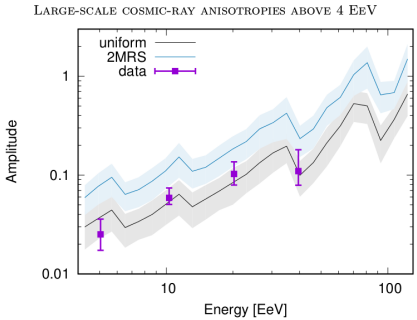
Search for dipole and quadrupole



di Matteo, Tinyakov, MNRAS 476 (2018) 715

- The growth with energy of dipole and quadrupole amplitude is predicted in the source model resembling LSS
- The Auger+TA dipole data agree with the prediction
- No quadrupole is observed by now

Search for dipole and quadrupole



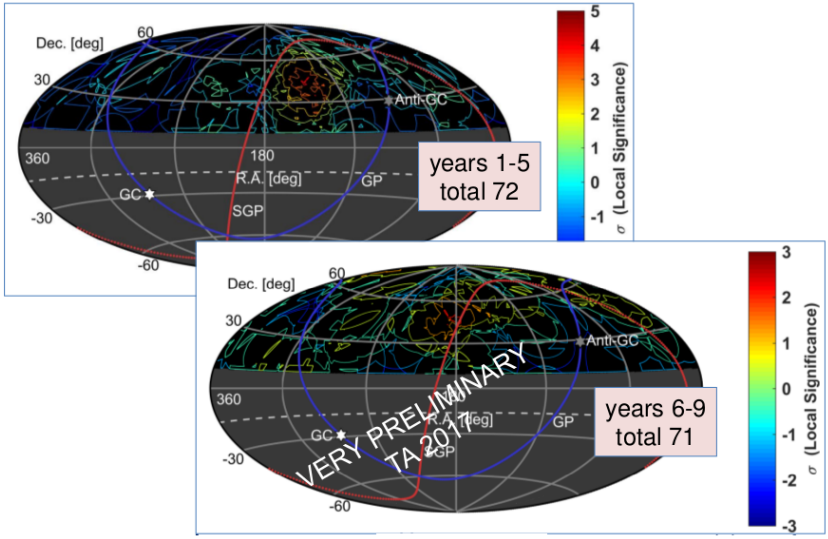
Auger collaboration, ApJ 868 (2018) 4

- discovery of dipole at 5σ for $E > 8$ EeV
- in agreement with the model of isotropic sources $\rho = 10^{-4}$ Mpc^{-3}

Hot spot

Years 6-9 vs. 1-5

no hypothesis – no tests



Hot spot

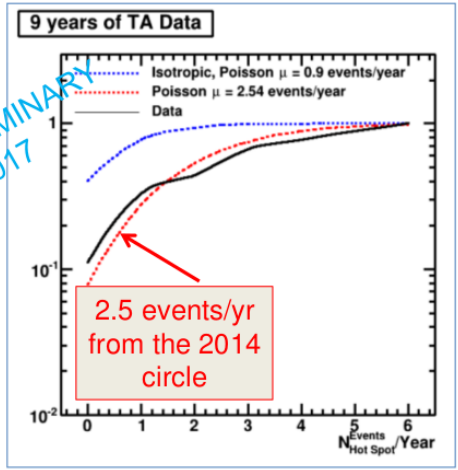
Years 6-9 vs. 1-5

"would-be hypothesis" – "would-be tests"

global ≠ local P-value ➡ positive fluctuation, need to correct our expectations

circle defined in *[TA, ApJ 2014]* = years 1-5:
center RA=146.7°, Dec=+43.2°, radius: 20°

	Years 1-5	Years 6-9
Expected (isotropic)	4.5	3.6
Expected (hot spot)	12.5	10.0
Observed	19	5



Hot spot

Years 6-9 vs. 1-5

“would-be hypothesis” – “would-be tests”

global ≠ local P-value ➡ positive fluctuation, need to correct our expectations

circle defined in *[TA, ApJ 2014]* = years 1-5:
center RA=146.7°, Dec=+43.2°, radius: 20°

	Years 1-5	Years 6-9
Expected (isotropic)	4.5	3.6
Expected (hot spot)	12.5	10.0
Observed	19	5

VERY PRELIMINARY
TA 2017