Search for ultra-high energy photons with the Telescope Array surface detector

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INR RAS, Moscow
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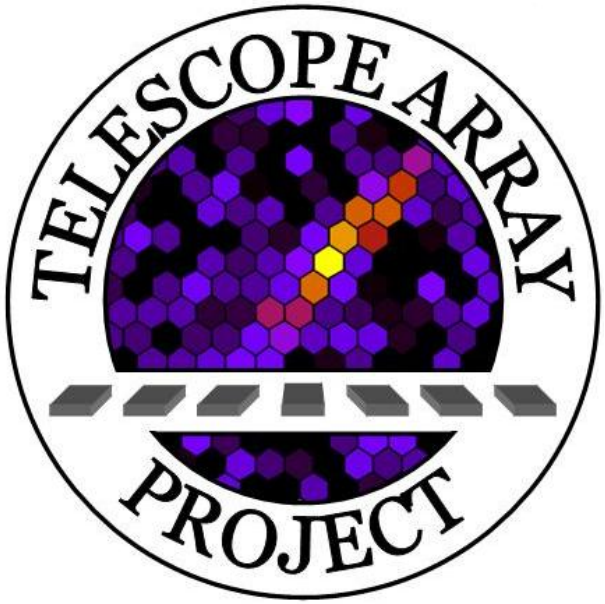
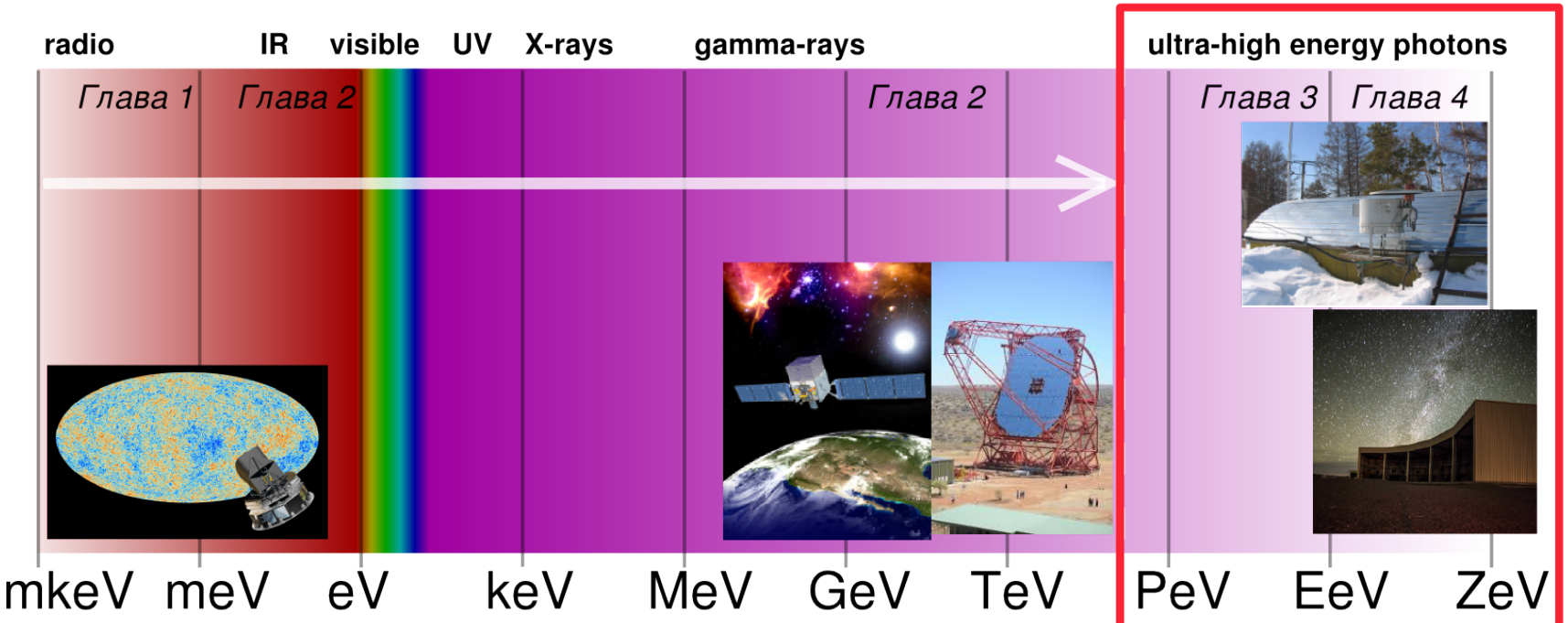
Quarks-2018,
Valday,
May 31, 2018



Techniques of photon detection



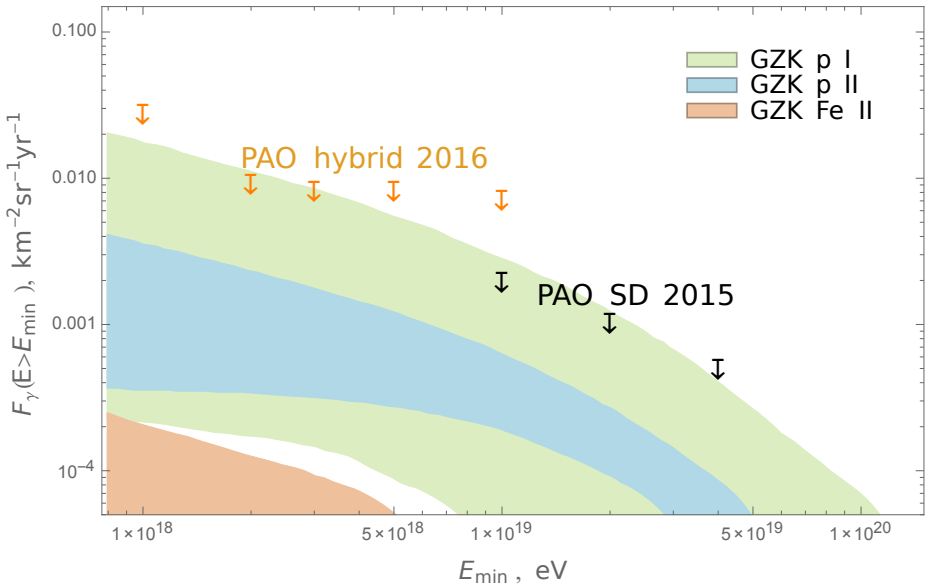
Only indirect detection by observation of extensive air showers (EAS) generated in the atmosphere

UHE photon search motivation: astrophysics

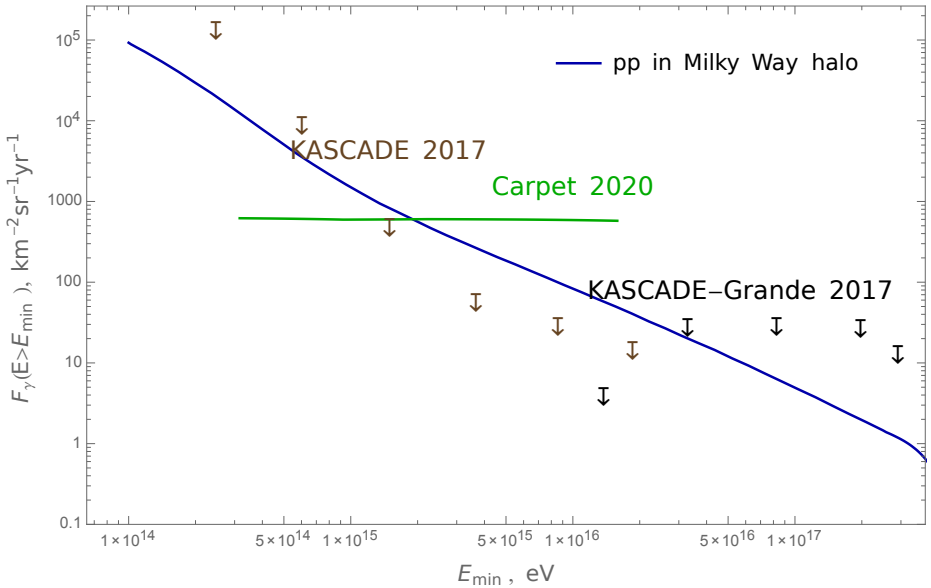
Ultra-high energy photons is a convenient tool to study astroparticle & cosmic ray physics: multimessenger approach

- Models of UHE cosmic-ray sources: accompanying γ signal
- Models of cosmic-ray propagation & mass composition: GZK γ production
- Models of high-energy neutrino production: accompanying γ signal

GZK-γ models vs. diffuse γ-limits



pp-γ models vs. diffuse γ-limits



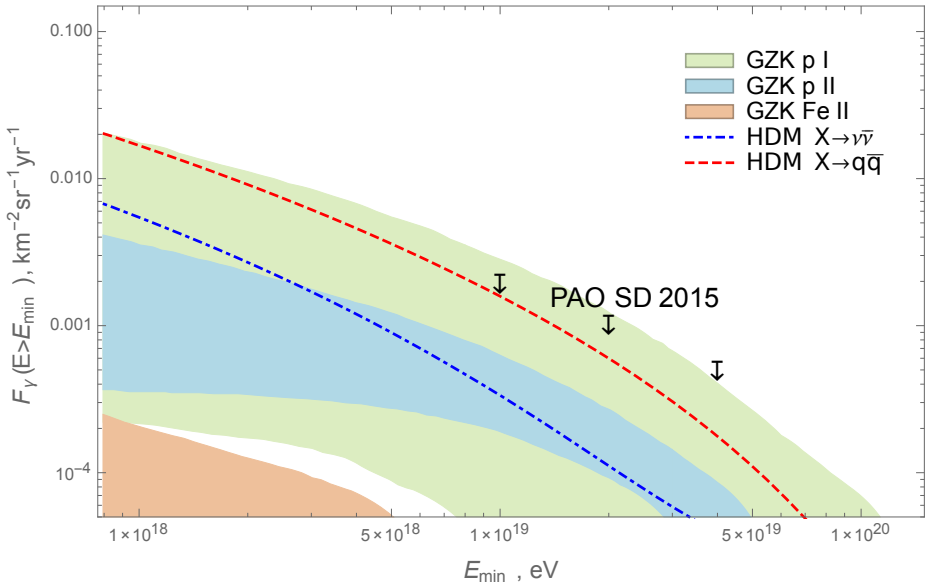
UHE photon search motivation: dark matter signal

Almost all heavy dark matter models produce γ-rays in decay/annihilation

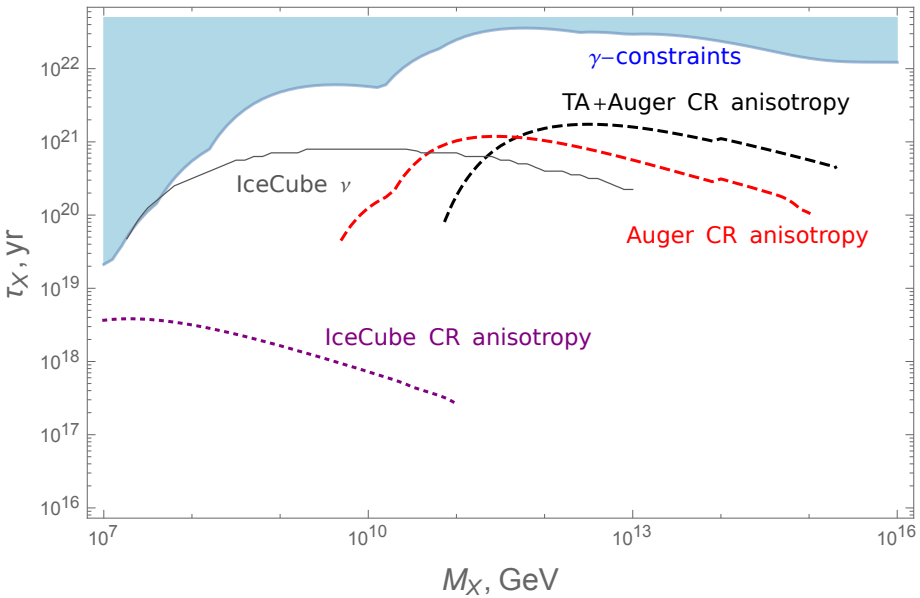
- Opportunity to search HDM γ-signal from Milky Way and its dwarf satellites
- Recent γ-ray flux limits constrain HDM stronger than any other messenger *O. Kalashev & MK JETP Lett. 106, 73 (2017)*
- It is possible to test HDM decay interpretation of IceCube events

M.Kachelriess, O. Kalashev & MK arxiv:1805.04500

GZK-γ vs. HDM models vs. γ-limits



Multimessenger constraints for HDM

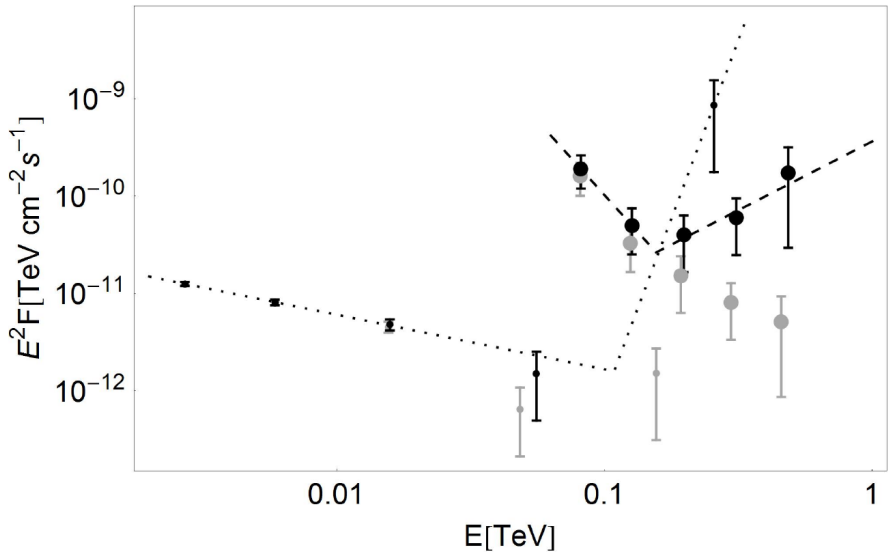


UHE photon search motivation: anomalous Universe transparency

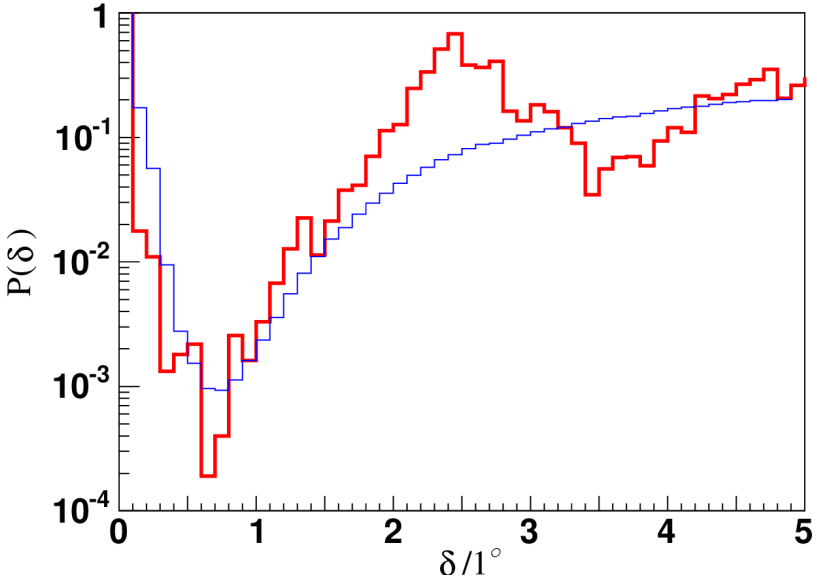
Indications for the anomalous high attenuation length of HE γ in the Universe

- Suspicious upward breaks in the de-absorbed γ-spectra of distant TeV-blazars (the break position depends on the distance to blazar): 12.4σ
  G. Rubtsov & S. Troitsky JETP Lett. 100, 355 (2014)
- HiRes experiment had observed correlation of 10^{19} eV cosmic–rays with distant BL Lacertae: 3.5σ *D. Gorbunov et. al JETP Lett. 80, 145 (2004)*
- Both results are inconsistent with the attenuation length of γ-rays in the cosmic medium: non-standard propagation is needed
  - $\gamma \to \text{axion} \to \gamma$ conversion in the source and in the Milky Way magn. field
  - Generation of additional γ-rays by GZK-effect of the same-source protons

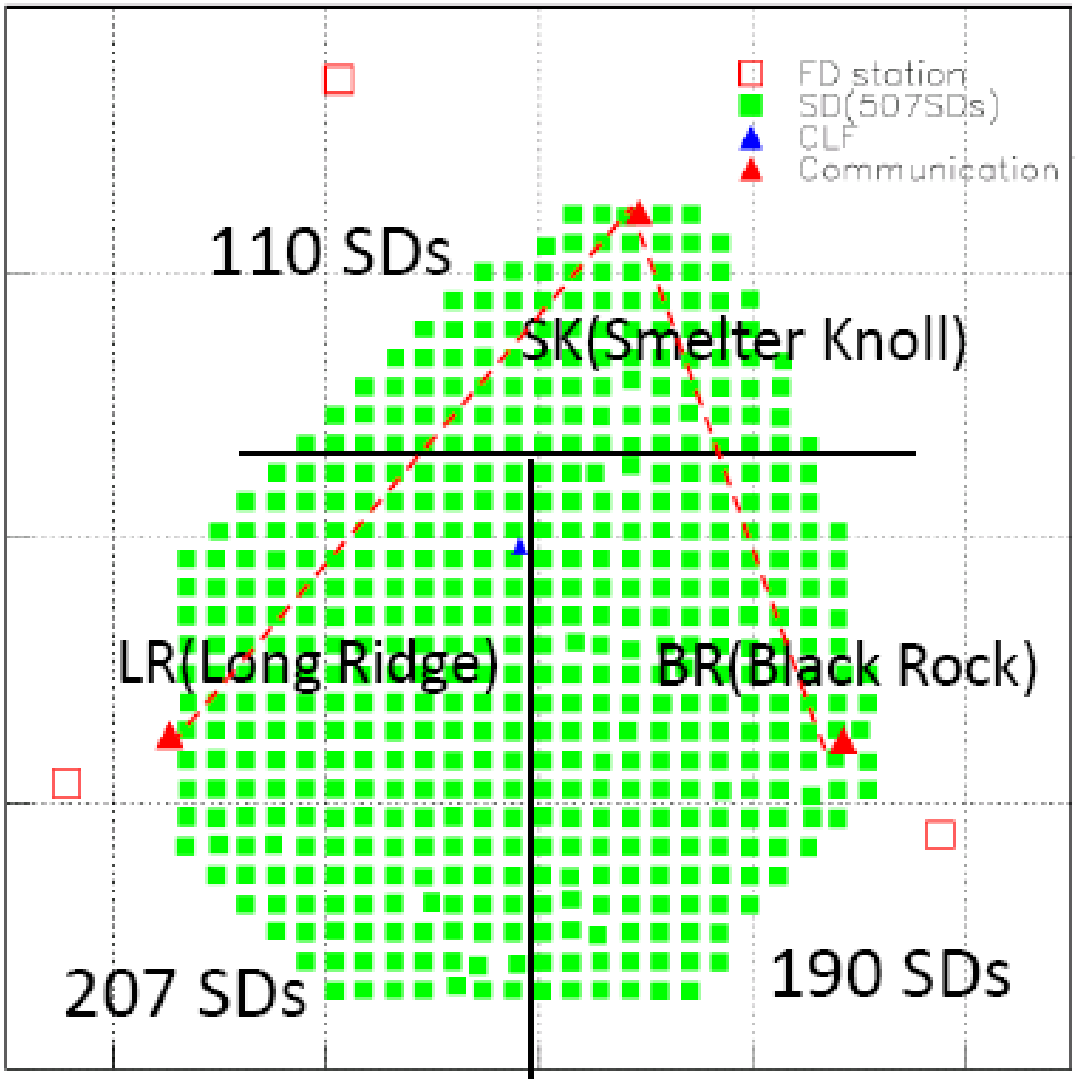
Breaks in the spectra of TeV-blazars



HiRes comis-rays — BL Lacs correlation



Telescope Array experiment: surface detector



- 507 SD's, 3 m^2 each
- 680 km^2 area
- 10 years of operation

Largest UHECR statistics in the Northern Hemisphere

Data and Monte-Carlo sets

- Data collected by TA surface detector for the 9 years:
  2008-05-11 — 2017-05-10
- p and γ Monte-Carlo sets with CORSIKA and dethinning

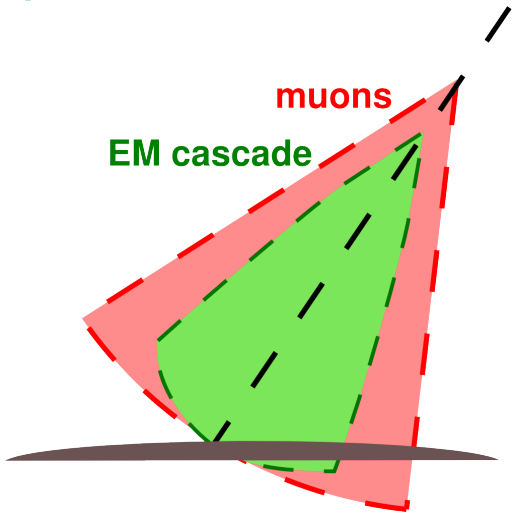
Stokes et al, Astropart.Phys.35:759,2012

Cuts for both data and MC:

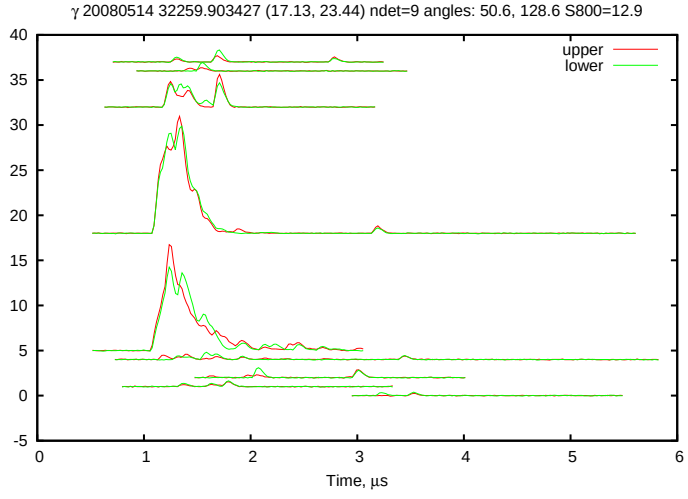
- 7 or more detectors triggered
- core distance to array boundary is larger than 1200m
- $\chi^2/\text{d.o.f.} < 5$
- $\theta < 60^\circ$
- $E_\gamma > 10^{18}$ eV (E_γ is estimated with photon Monte-Carlo)
- remove events coincident with lightnings (lightning events mimics γ-induced events)

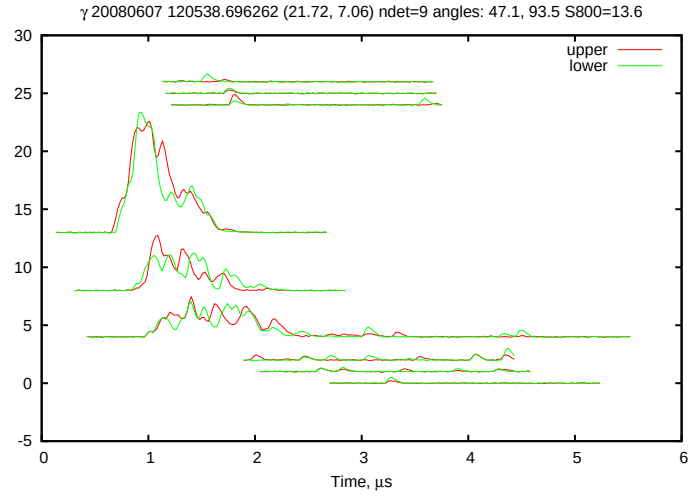
52362 events after cuts

p-induced EAS



γ-induced EAS





Photon-induced showers:

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

Photon search: list of relevant SD observables

1. Linsley front curvature parameter, a;
2. Area-over-peak (AoP) of the signal at 1200 m;

   Pierre Auger Collaboration, Phys.Rev.Lett. 100 (2008) 211101
3. AoP LDF slope parameter;
4. Number of detectors hit;
5. N. of detectors excluded from the fit of the shower front;
6. $\chi^2/d.o.f.$;
7. $S_b = \sum S_i \times r^b$ parameter for $b = 3$ and $b = 4.5$;

   Ros, Supanitsky, Medina-Tanco et al. Astropart.Phys. 47 (2013) 10
8. The sum of signals of all detectors of the event;
9. Asymmetry of signal at upper and lower layers of detectors;
10. Total n. of peaks within all FADC traces;
11. N. of peaks for the detector with the largest signal;
12. N. of peaks present in the upper layer and not in lower;
13. N. of peaks present in the lower layer and not in upper;

How to deal with this large amount of observables?

Multivariate analysis (MVA) & machine learning!

- 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.

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

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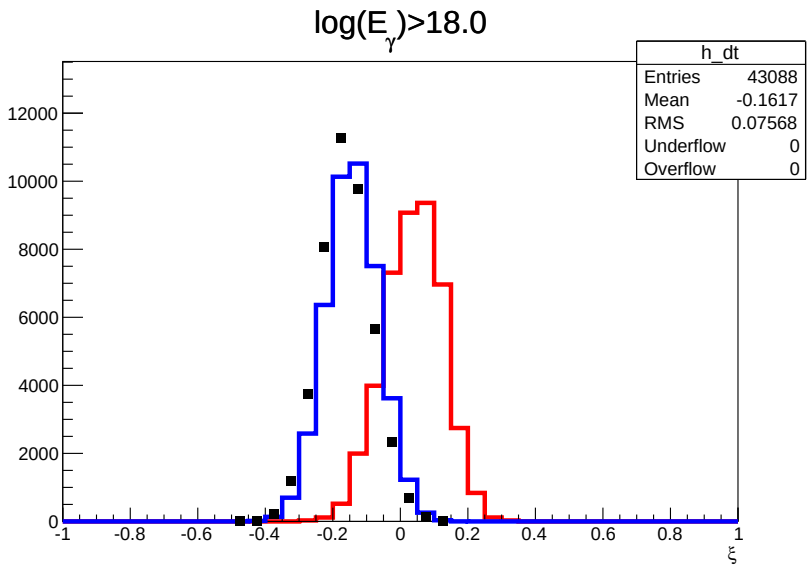
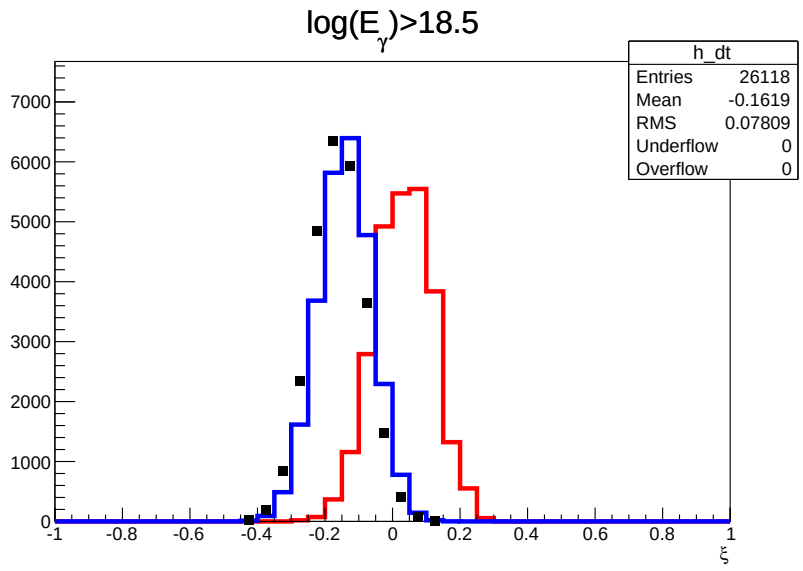
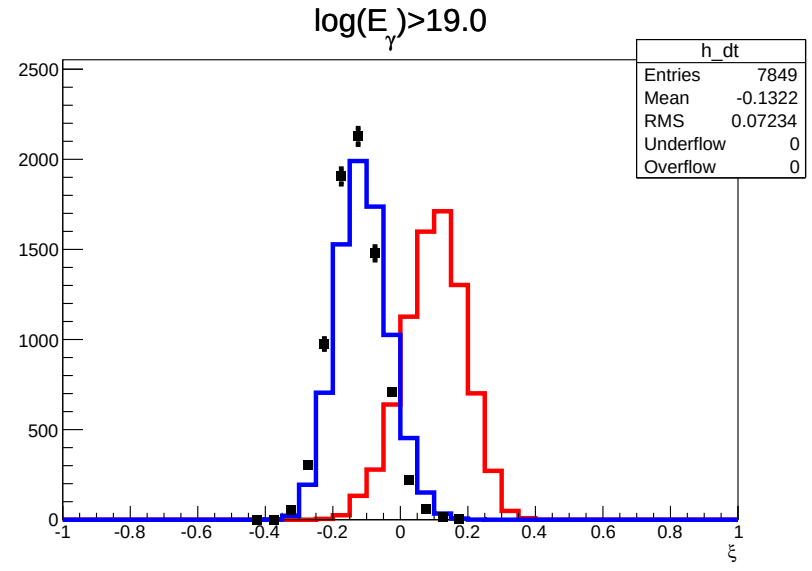
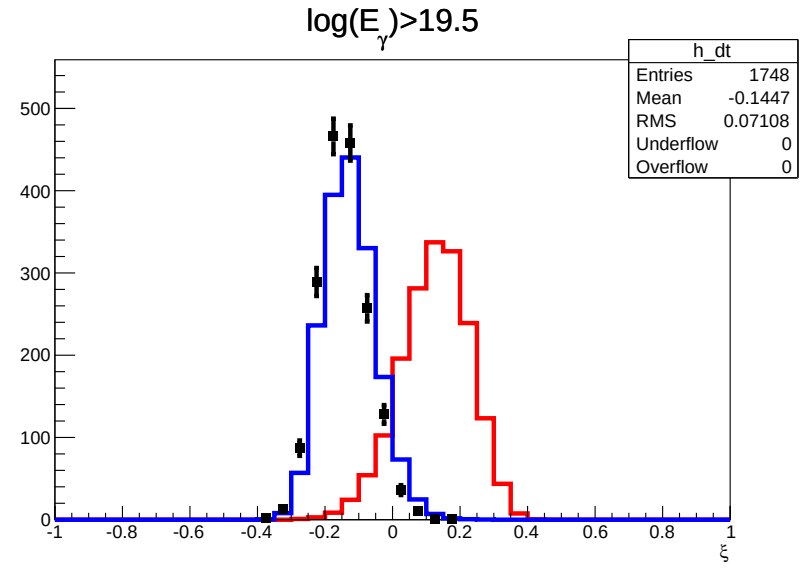
Distribution of MVA estimator ξ for data and MC









data photon MC proton MC

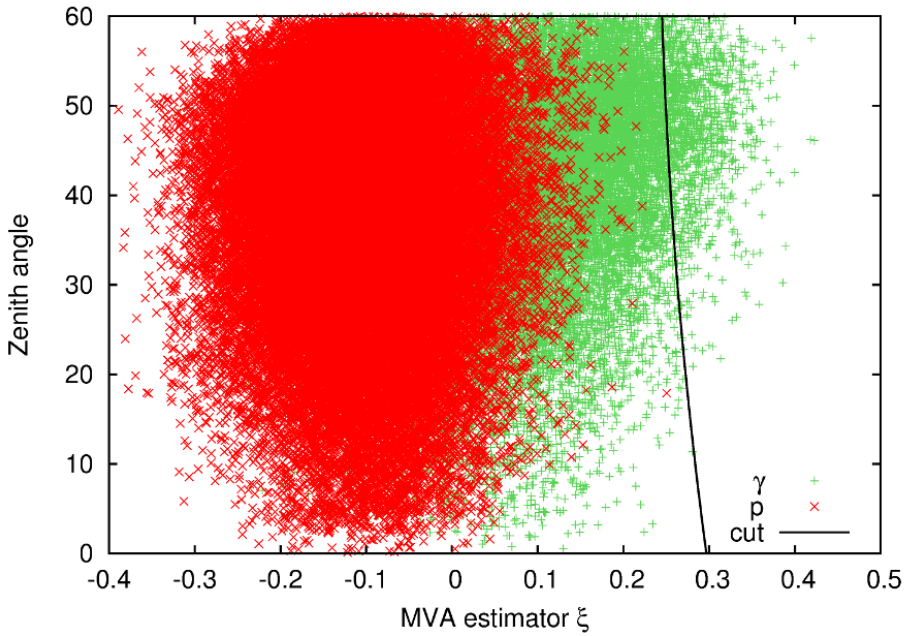
Diffuse photon search: cut optimization & effective exposure

- The γ candidates are selected using the MVA-cut: $\xi > \xi_{cut}(\theta)$
- The cut is approximated as a quadratic function of θ
- Cut is optimized using proton and photon Monte-Carlo in assumption of zero photon flux (null hypothesis)
- Geometric exposure for $\theta \in (0^\circ, 60^\circ)$: **12060 km^2 sr yr**
- Effective photon exposure $A_\gamma^{\rm eff}$ is estimated in each pixel separately assuming E^{-2} primary spectrum

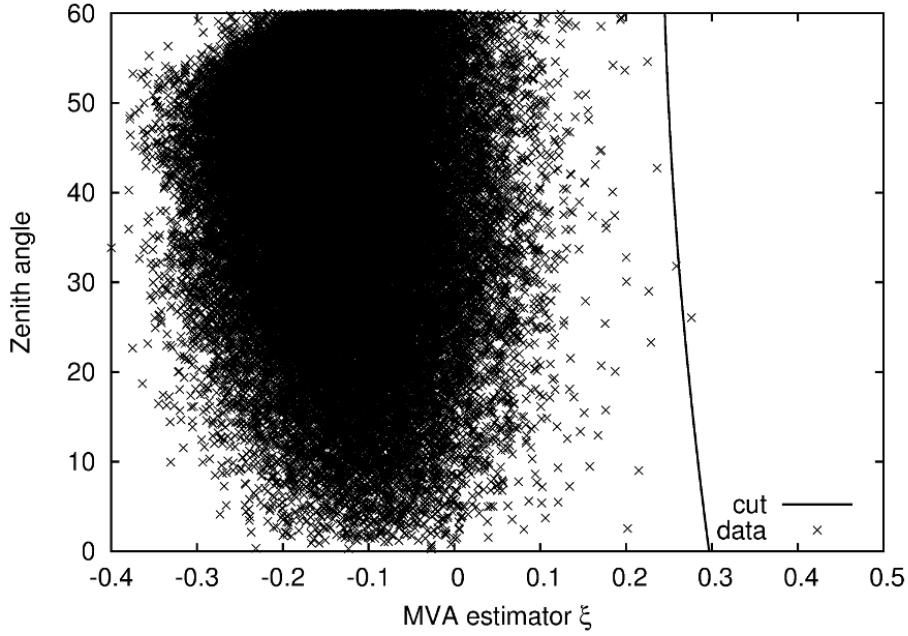
E_γ, eV	quality. cuts	ξ-cut	$A_\gamma^{\rm eff}$, km^2 sr yr
$10^{18.0}$	6.5%	9.8%	77
$10^{18.5}$	19.9%	10.6%	255
$10^{19.0}$	43.6%	16.2%	852
$10^{19.5}$	52.0%	37.2%	2351
$10^{20.0}$	64.2%	52.3%	4055

$E_\gamma > 10^{18}$ eV, zenith angle dependent cut on ξ

Monte-Carlo



Data

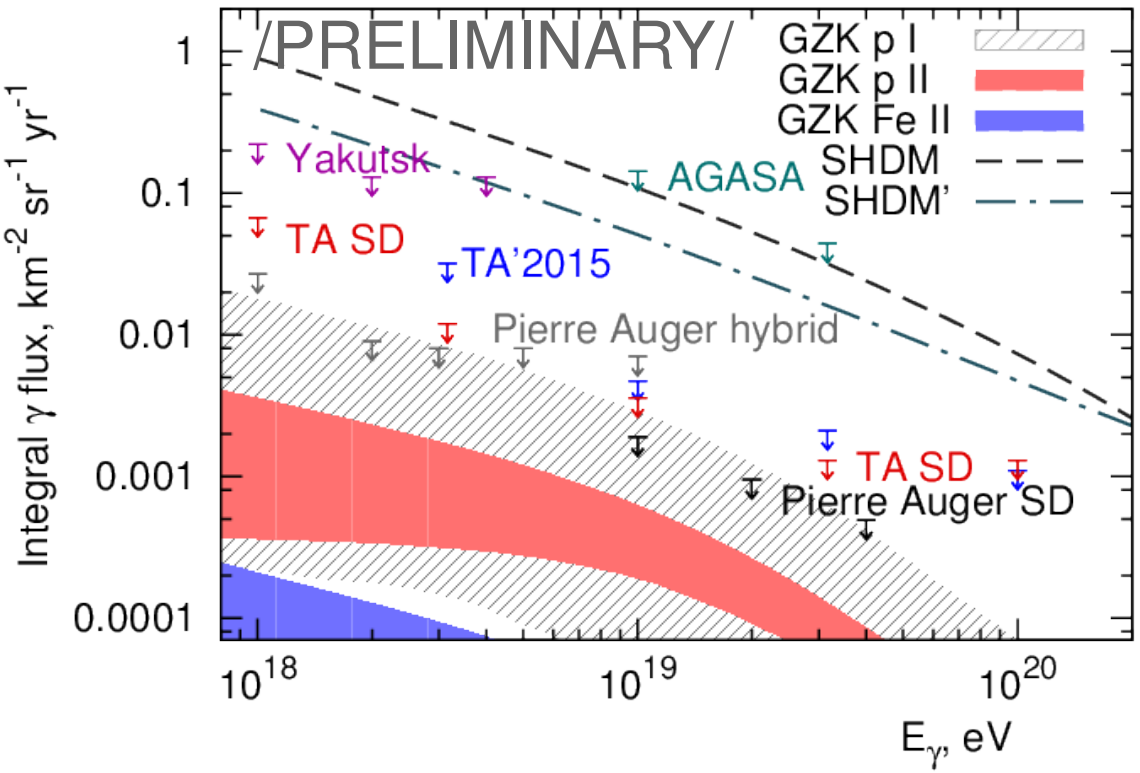


Optimisation of MVA-cut for γ flux upper-limit

- Assume the flux consists of protons only (null hypothesis): $F_{\text{total}} = F_{\text{p}}$
- Optimize the ξ-cut position using MC *p* and MC γ to obtain the minimum upper-limit: $F_\gamma^{UL} = \frac{\mu^{\text{UL}}_{\text{Poisson}}(N_p^\xi)}{A_\gamma^{\text{eff}}}$, where N_p^ξ = {number of MC *p* events passing the ξ-cut}

Results: diffuse photon flux upper-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}, km^{2}sr yr	77	255	852	2351	4055
F_γ, km^{-2}sr^{-1}yr^{-1} $<$	0.067	0.012	0.0036	0.0013	0.0013



95% C.L.

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

Search for point sources of photons: motivation

The way to improve the photon search sensitivity:

Hadron background is highly isotropic

$\Downarrow$

Assume that photons are emitted by point source

$\Downarrow$

In vicinity of the source on the skymap the **photon/hadron ratio** would be larger than in full TA field of view

$\Downarrow$

It is easier to separate photons from hadrons!

Bonus!

Specific photon source hypotheses could be tested by search in certain classes of directions

- BL Lacertae objects (photon-axion conversion hypothesis)
- Dwarf spheroidal galaxies (heavy DM decay hypothesis)
- Sources of GZK photons (astrophysical cosmic-ray generation models)

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Monte-Carlo: photon angular resolution

The geometry reconstruction of events is critical for point source search.

We correct all data and MC events for the mean value of the zenith angle θ reconstruction bias.

Angular reconstruction for photons (used in present search)

E_γ, eV	$\langle\theta_{\text{rec.}} - \theta_{\text{true}}\rangle$	ang. resolution
$10^{18.0}$	-2.25°	3.00°
$10^{18.5}$	-2.24°	2.92°
$10^{19.0}$	-2.16°	2.64°
$10^{19.5}$	-2.06°	2.21°
$10^{20.0}$	-1.72°	2.06°

Angular reconstruction for protons (for comparison)

E_p, eV	$\langle\theta_{\text{rec.}} - \theta_{\text{true}}\rangle$	ang. resolution
$10^{18.0}$	-0.94°	2.43°
$10^{18.5}$	-0.93°	2.18°
$10^{19.0}$	-0.84°	1.68°
$10^{19.5}$	-0.72°	1.26°
$10^{20.0}$	-0.62°	1.16°

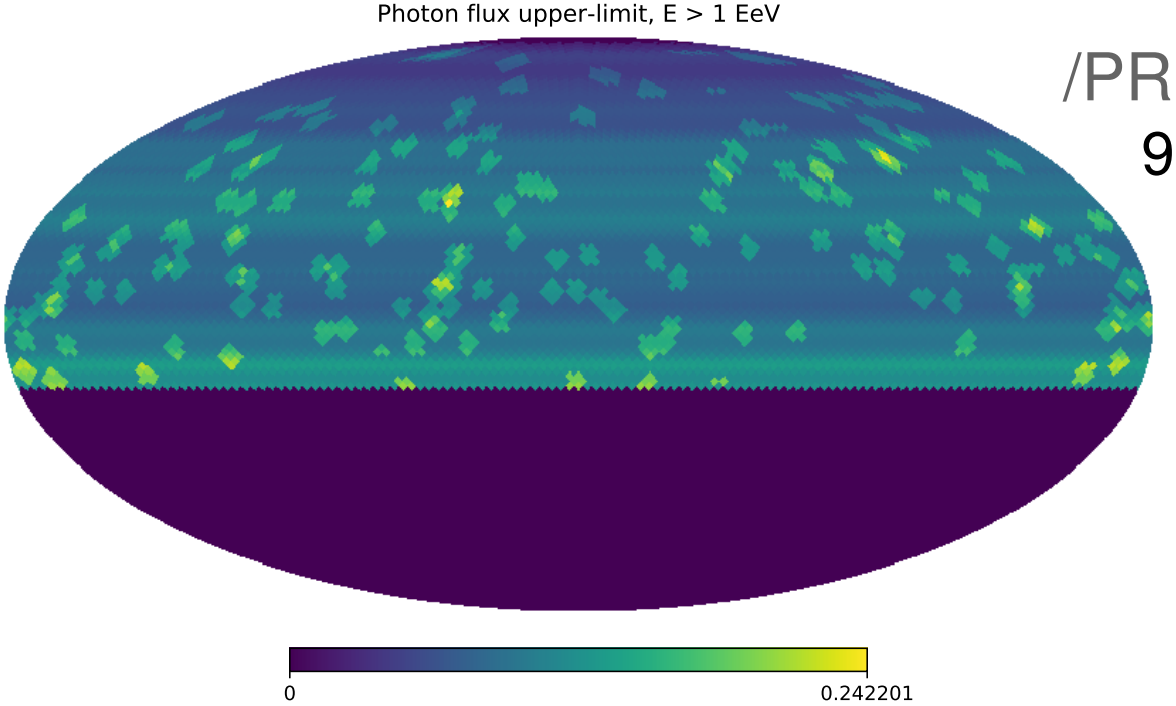
Features of γ point sources search: blind search

- Independent search for γ in each skymap pixel
- The size of the pixel is equal to the γ **angular resolution**
- The skymap is pixelized into 12288 directions with HEALpix

Optimisation of MVA-cut for γ flux upper-limit is the same as for diffuse γ limit:

- Assume the flux consists of protons only (null hypothesis): $F_{\text{total}} = F_{\text{p}}$
- Optimize the ξ-cut position using MC p and MC γ to obtain the minimum upper-limit: $F_{\gamma}^{UL} = \frac{\mu^{\text{UL}}_{\text{Poisson}}(N_p^{\xi})}{A_{\gamma}^{\text{eff}}}$, where N_p^{ξ} = {number of MC p events passing the ξ-cut}

Results: point-source photon flux upper-limits



/PRELIMINARY/

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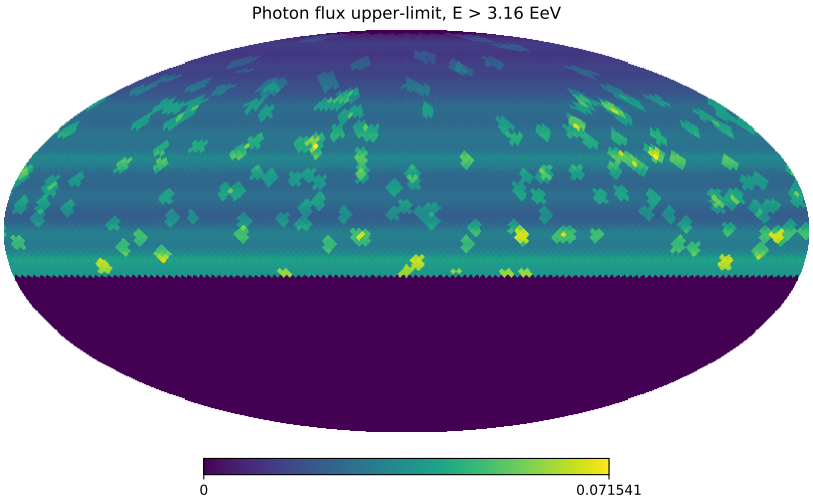
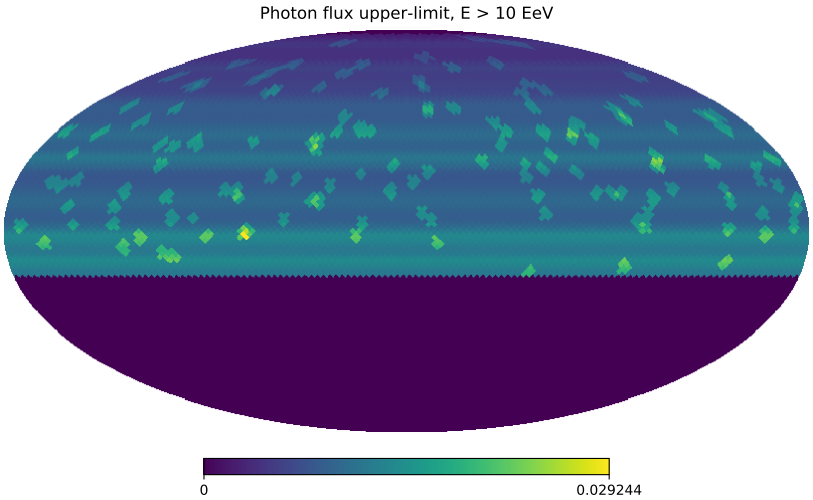
$E_\gamma \geq$, eV	$\langle F_\gamma \rangle \leq$, $\mathrm{km}^{-2}\mathrm{yr}^{-1}$	max. γ signif. (pre-trial)
$10^{18.0}$	0.094	2.72 σ
$10^{18.5}$	0.029	2.71 σ
$10^{19.0}$	0.010	2.89 σ
$10^{19.5}$	7.1×10^{-3}	2.76 σ
$10^{20.0}$	5.8×10^{-3}	3.43 σ

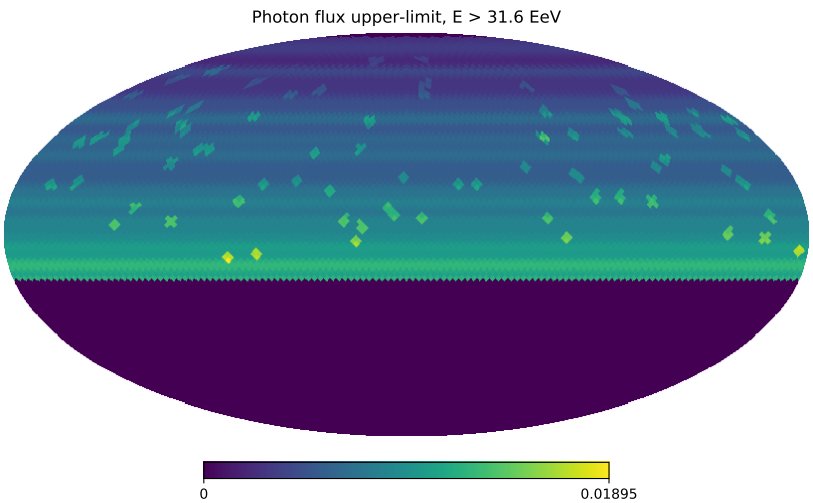
Pierre Auger: $\langle F_\gamma \rangle \leq 0.035\ \mathrm{km}^{-2}\mathrm{yr}^{-1}$ (1° ang.res., $10^{17.3} \leq E \leq 10^{18.5}$ eV)

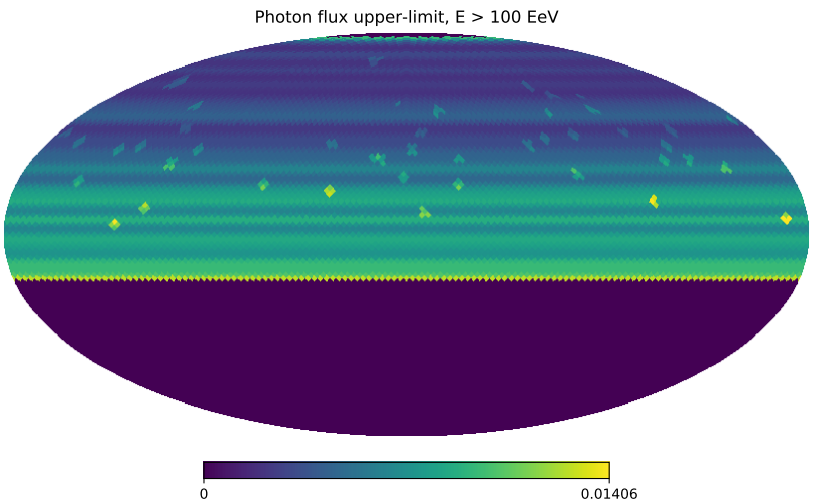
A. Aab et al. ApJ 789, 160 (2014)

Results: point-source photon flux upper-limits









/PRELIMINARY/

95% C.L.

Features of γ point sources search: target search

- Search for γ in stacked skymap pixels of certain sources class
- The size of each pixel is equal to the γ **angular resolution**

Optimisation of MVA-cut for γ search is different as for γ limit:

- Assume the flux consists of p and γ (first hypothesis): $F_{\text{total}} = F_{\text{p}} + F_{\gamma}$
- Optimize the ξ-cut position using MC p and MC γ to obtain the 3σ excess of $N_{\gamma} = F_{\gamma} A_{\gamma}^{\text{eff}}$ over N_{p} background with the minimum statistics

Target source class search I: dwarf galaxies

Probe for the possible decay of heavy dark matter (HDM)

- HDM decay produce significant amount of photons in any model*

  At high DM masses annihilation is practically unobservable since $\sigma_{\text{ann.}} < \frac{1}{M_{DM}^2}$

- DM is abundant in dwarf galaxies (Galactic center is outside the TA field of view)
- Target source set: 21 dwarf galaxies — satellites of Milky Way

  V. Bonnivard et al., MNRAS 453 (2015), 849

Results

- MVA-cut optimisation for γ detection: no evidence for photon signal ($N_{\gamma}^{\text{cand.}} = 0$ at all energies)
- MVA-cut optimisation for flux limit:

E_{γ}, eV	F_{UL}^{γ}, $\text{km}^{-2}\text{yr}^{-1}$
$10^{18.0}$	0.15
$10^{18.5}$	0.057
$10^{19.0}$	0.014
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Target source class search II: BL Lacertae

Test of the cosmic-rays — BL Lacs correlation observed by HiRes experiment *D. Gorbunov et al., JETP Lett. 80 (2004) 145*

- HiRes result implies that small fraction of CRs is emitted by BL Lacs and is not deflected by galactic magn.field.
- The most reasonable hypothesis is the emittance of UHE γ and $\gamma \to \text{axion} \to \gamma$ conversion in magn. field.
- Target source set: 156 BL Lac objects from Veron catalog

Results

- MVA-cut optimisation for γ detection: no evidence for photon signal ($N_{\gamma}^{\text{cand.}} = 0$ at all energies)
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Future prospects for photon search

Blind search

Improvement of the photon/hadron separation of MVA analysis

Target photon search

Zero result of photon search from BL Lacs does not falsify the HiRes result: the improve of the sensitivity is possibly needed

- Improvement of the photon/hadron separation of MVA analysis
- Reduction of the angular resolution for γ (isotropic hadron background grows as a square of ang.resolution)

Conclusions

- **Blind photon search**
  - The diffuse and directional upper-limits for photons with $E > 10^{18}$ eV are set
  - The directional upper-limits for $E > 10^{18.5}$ eV are set for the first time
  - No significant evidence for photon signal was found in blind search
- **Target photon search**
  - BL Lacertae and dwarf galaxies were searched for photons: no excess over background was found
  - The flux upper-limits were set for dwarf galaxies — it could be used to constrain heavy dark matter models

Thank you!

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