The Pierre Auger Observatory and the Multi-Messenger Physics

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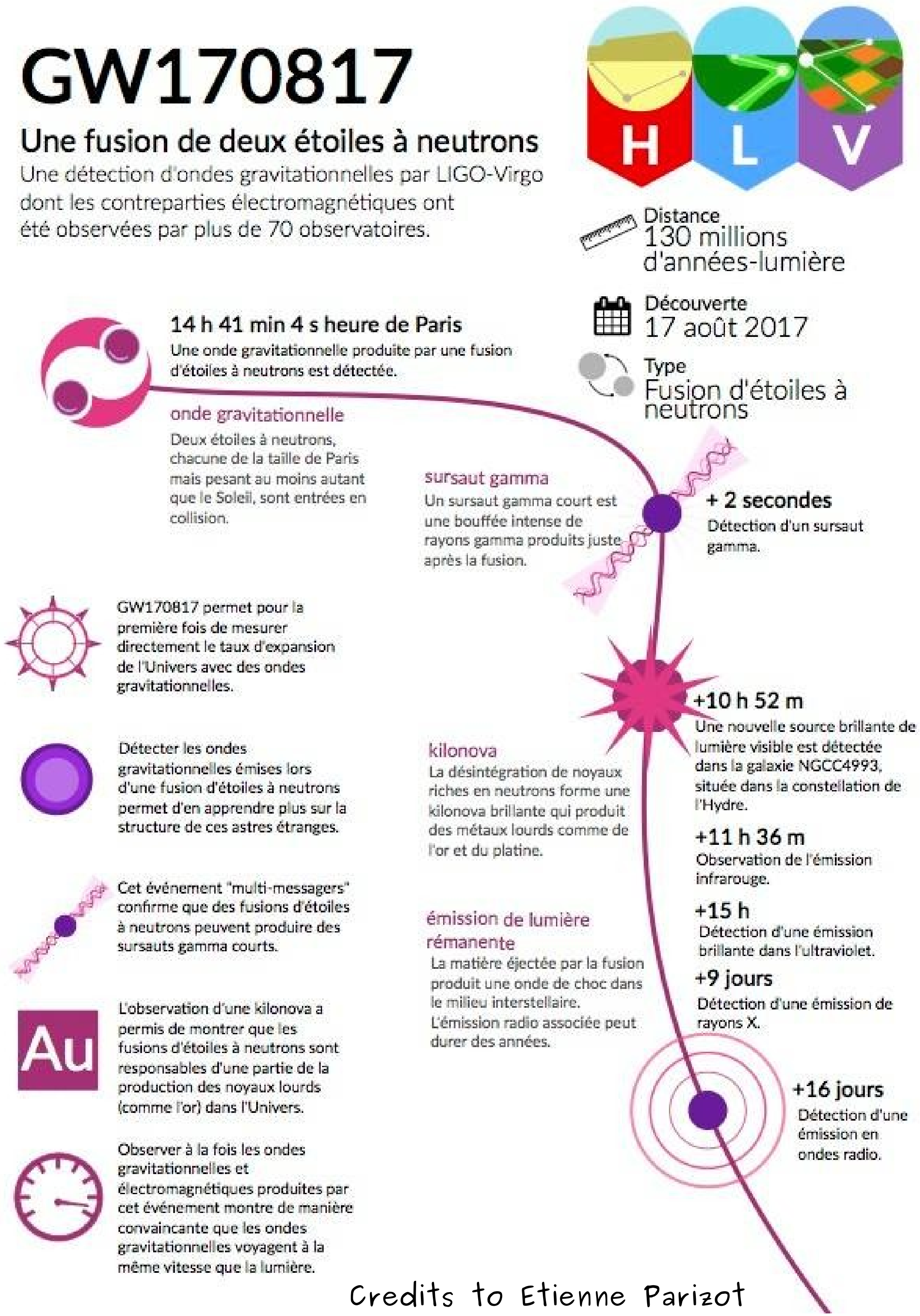
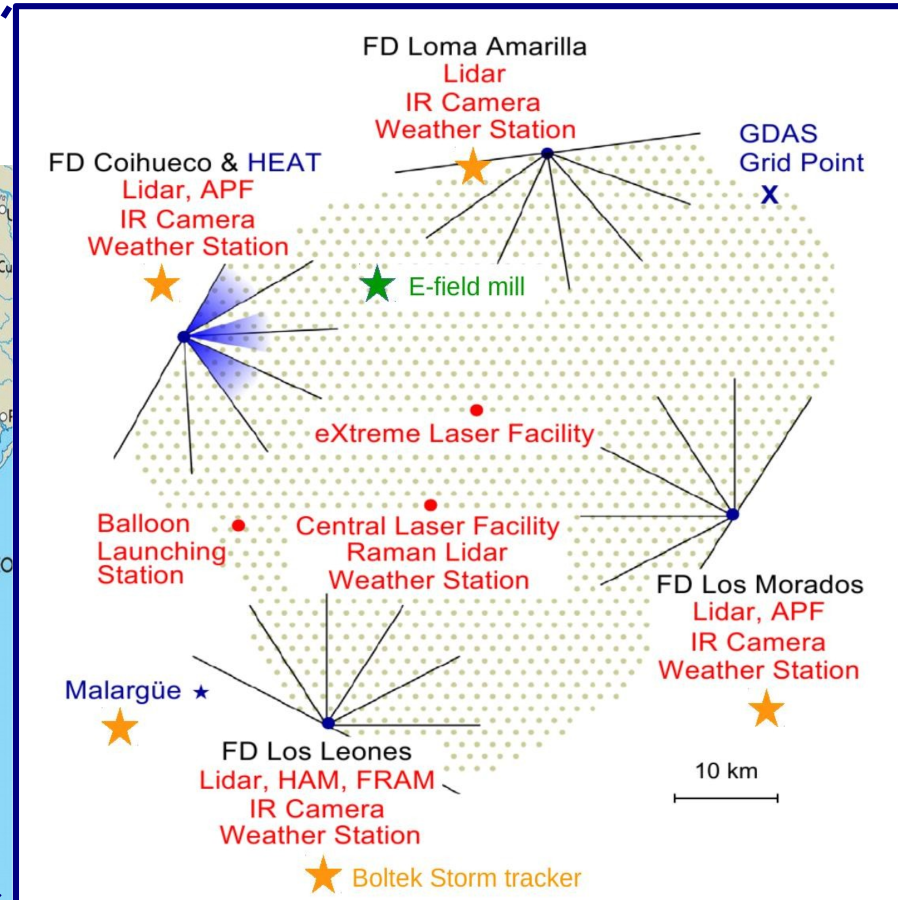


Credits to Etienne Parizot

The detection of GW170817 was rapidly followed up by the IceCube and ANTARES neutrino observatories and by the Pierre Auger Observatory to search for coincident, high-energy (GeV–EeV) neutrinos emitted in the relativistic outflow produced by the BNS merger.

The Pierre Auger Observatory

The biggest hybrid detector in the world designed to observe cosmic rays at the highest energies (UHECR).

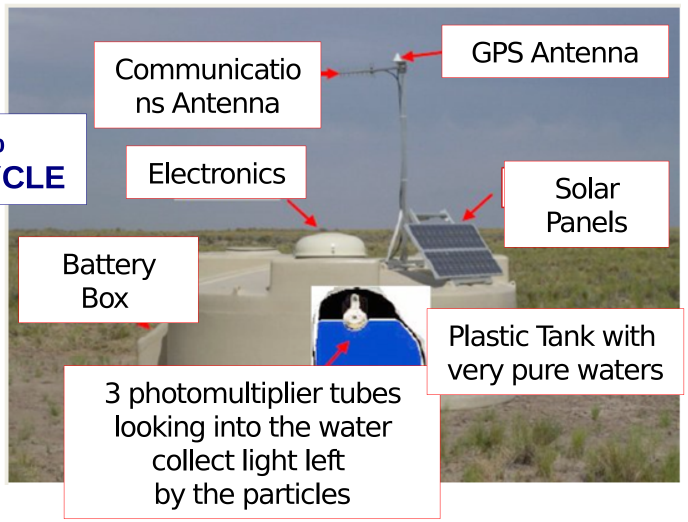


Goals of the Experiment:

- Energy Spectrum
- Mass Composition
- Arrival Directions - Anisotropy

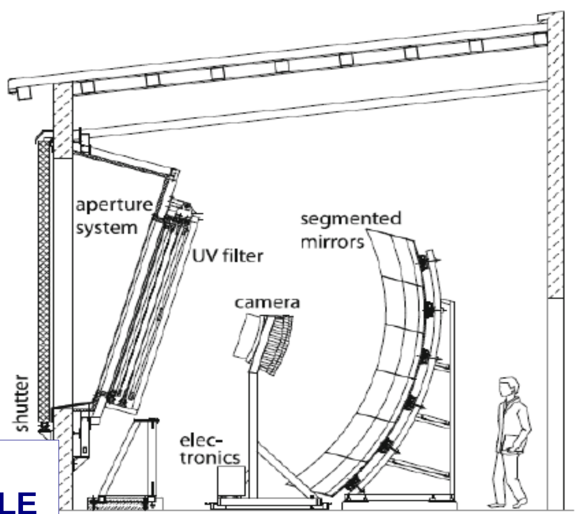
The Pierre Auger Observatory

100% DUTY CYCLE



SD detector: 1660 Water Cherenkov detectors, covering 3000 km^2 and arranged in a triangular grid with 1500 m spacing. The PMT signals are sampled by flash analog-to-digital converters (FADC) with a time resolution of 25 ns. This provides good discrimination of electrons and muons entering the detector station from the top.

~15% DUTY CYCLE

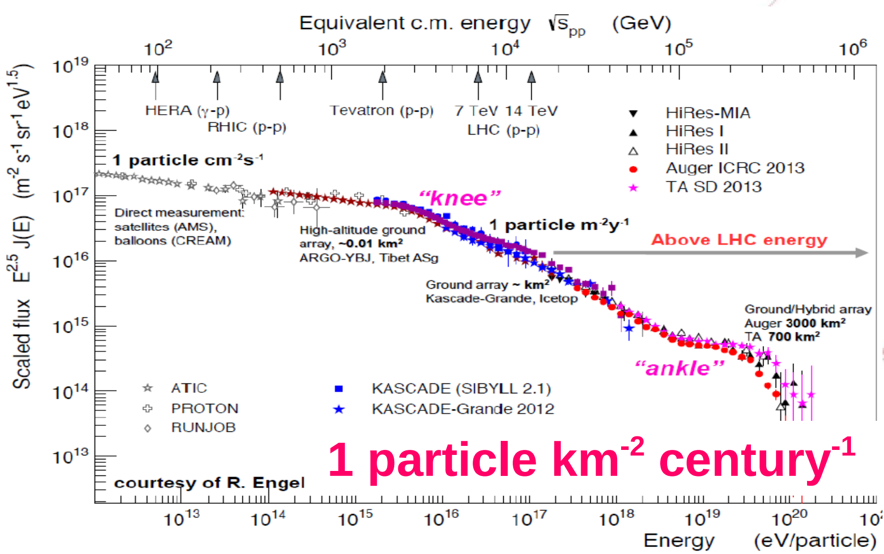


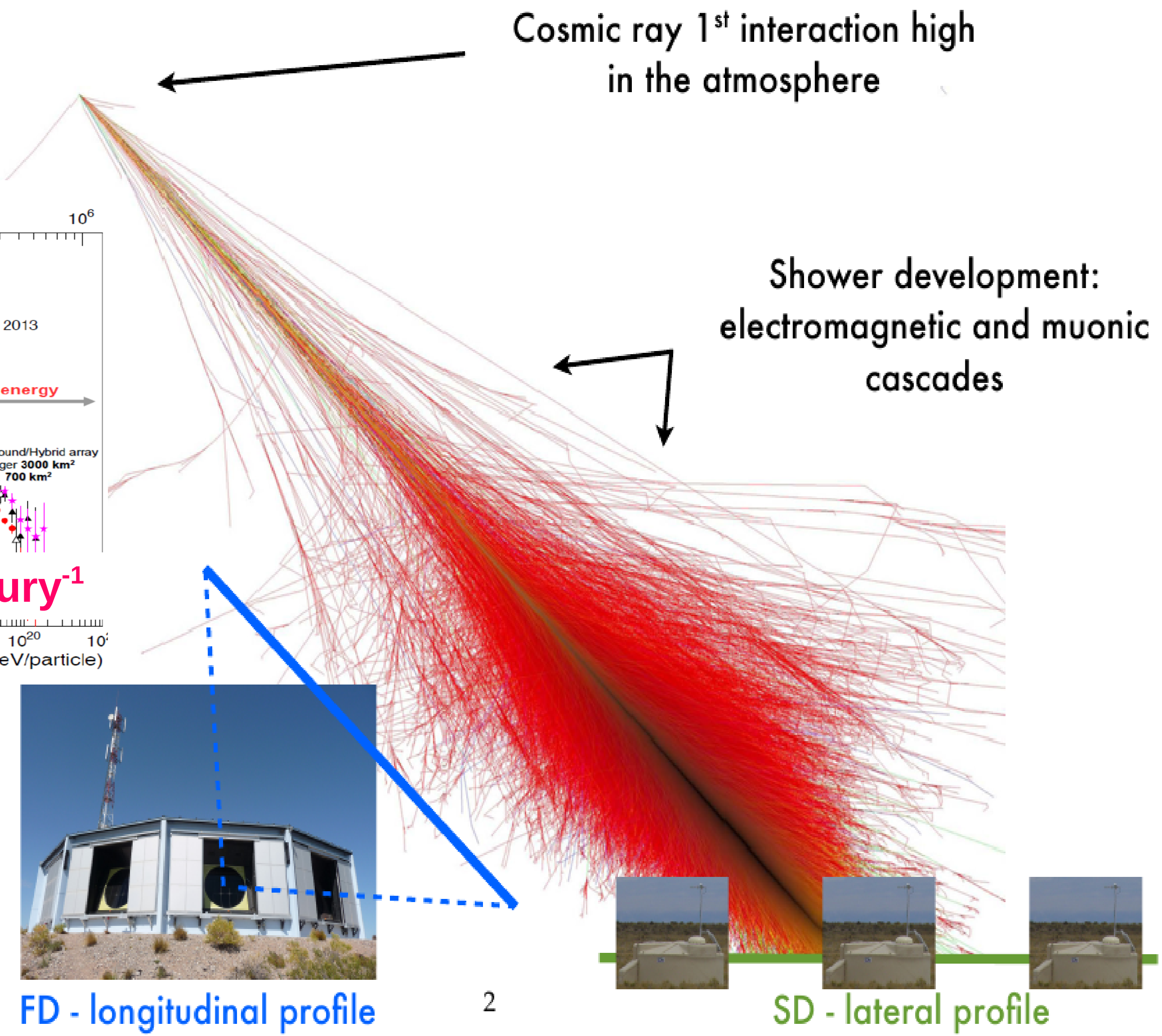
FD detector: 24 telescopes, 6 for each sites, arranged to overlook the area covered by the SD. The site is located in the Argentinian pampa, at ~ 1400 m above sea level (880 g/cm^2).

- **Large Aperture** (about 7000 km^2 sr)
- **Hybrid Detection Technique**

doi:10.1016/j.nima.2015.06.058

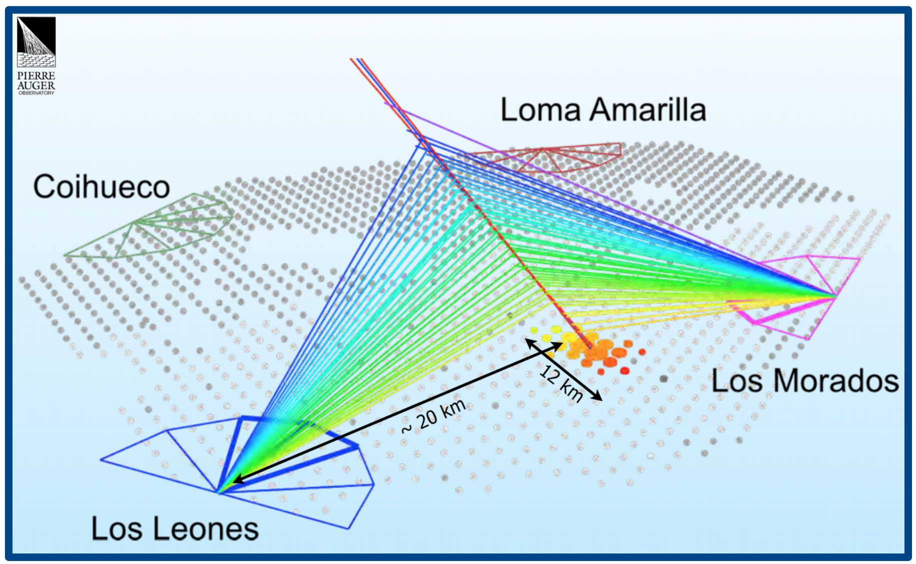
Indirect Measurements with Auger

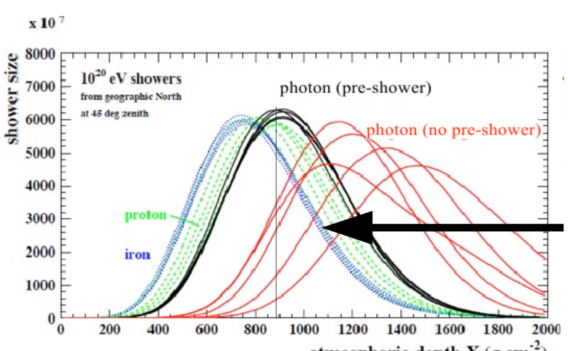




An Auger Event

- **SD:** lateral distribution of shower particles at ground;
  large statistics, fully efficient at 3 EeV.
- **FD:** longitudinal development of the shower; E >= 10^{18} eV,
  calorimetric measurement of the energy, duty cycle ~ 15%.
- **Energy resolution** → ~ 15%.
- **Angular resolution** → 1°-2°(SD) - < 1° (hybrid).

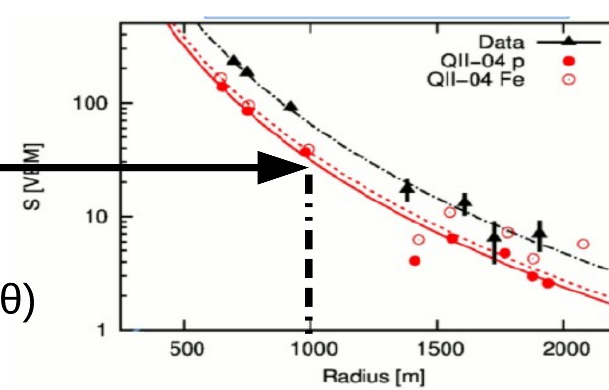




$E_{cal} = \int dE/dX\, dX$

X_{max}

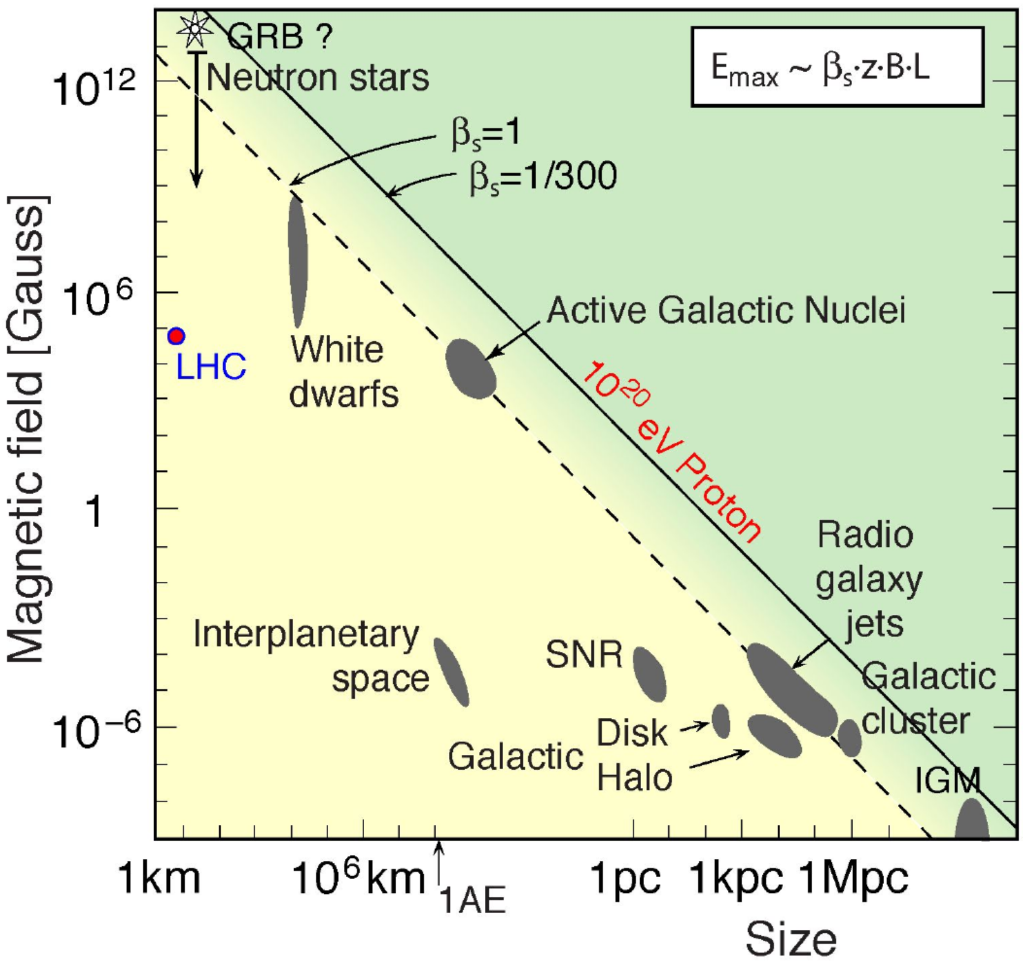
S_{1000}



$E_{surface} = f(S_{1000}, \theta)$

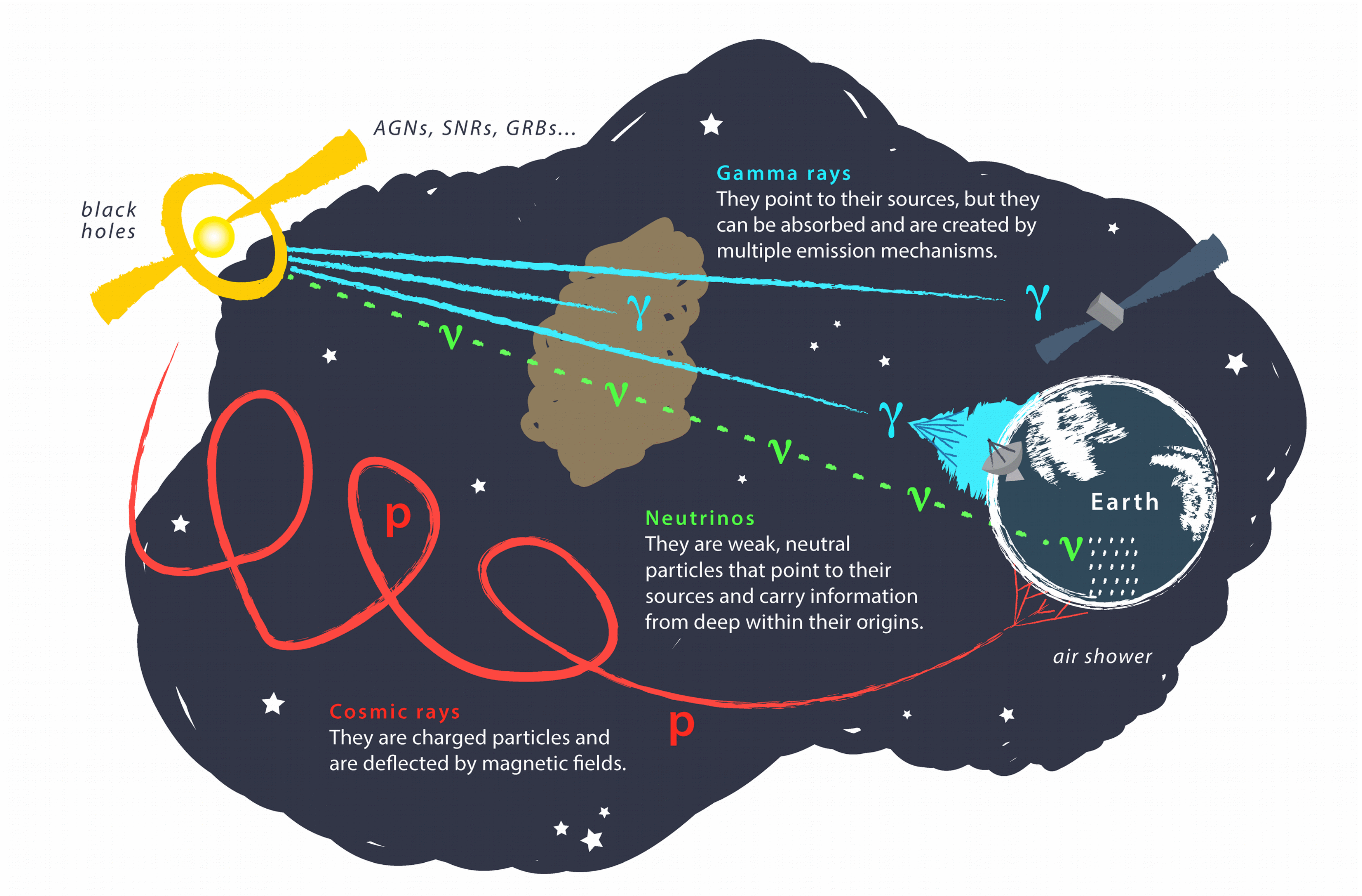
Search for Astrophysical Sources

"…What extraordinary processes are capable of accelerating particles to such enormous energies? In the hope of finding clues to the solution, physicists would like to know whether the most energetic particles come from all directions or only from certain regions of the sky…" Bruno Rossi, 1964



Cosmic Messengers

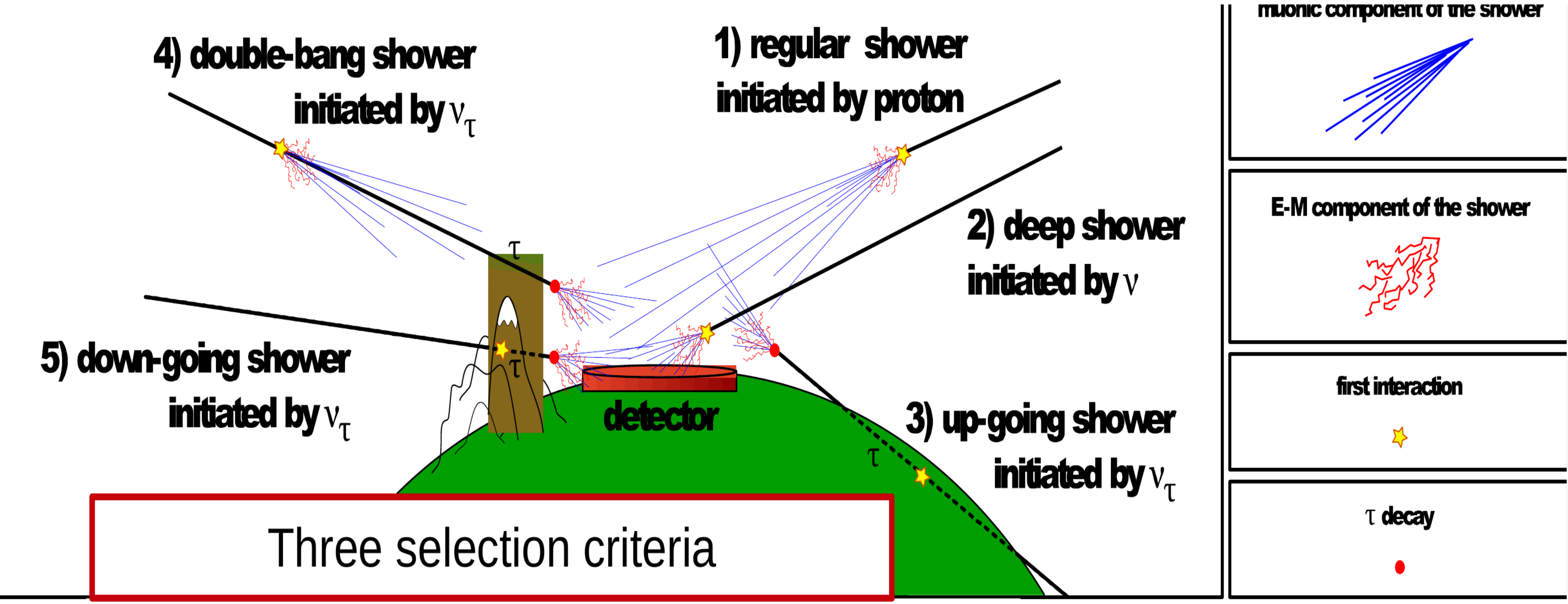
$$p + \gamma/p \rightarrow \pi^{+} + n \rightarrow \mu^{+} + \nu_{\mu} + n \rightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e} + \nu_{\mu} + n$$
$$\rightarrow \pi^{0} + p \rightarrow \gamma + \gamma + p$$



Auger Analyses with Multi-Messenger Implications

- Neutrino Search;
- Photon Search;
- Neutron Search;
- Association of UHECR with Source Populations;
- Search for UHECR-Neutrino Correlations: Auger/TA – Antares/IceCube

Neutrino Search



Down-going low angle: (2, 4) - DGL (60°-75°)

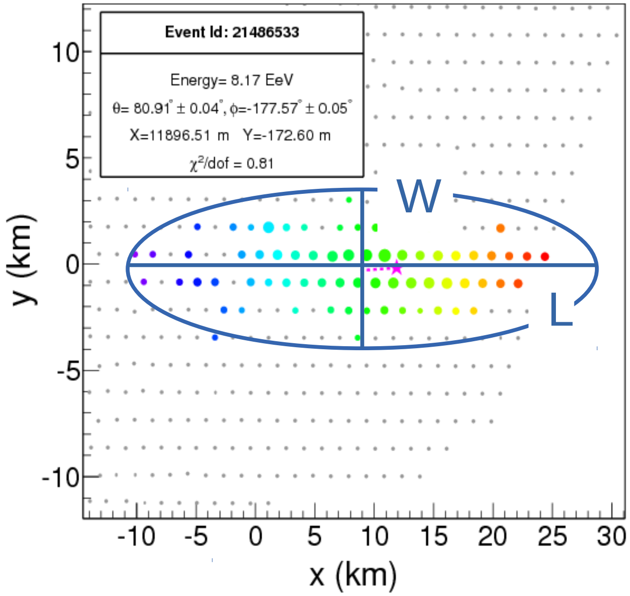
Down-going high angle: (2, 4, 5) - DGH (75°-90°)

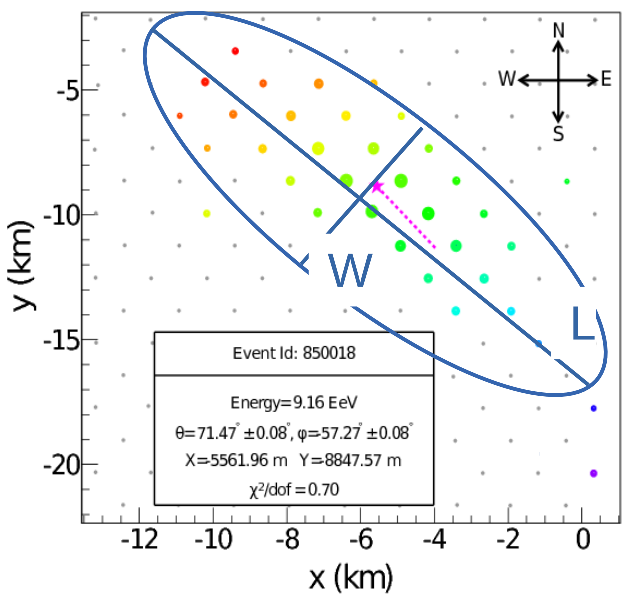
Earth-Skimming: (3) – ES (90°-95°)

doi:10.1103/PhysRevD.91.092008

Neutrino Search

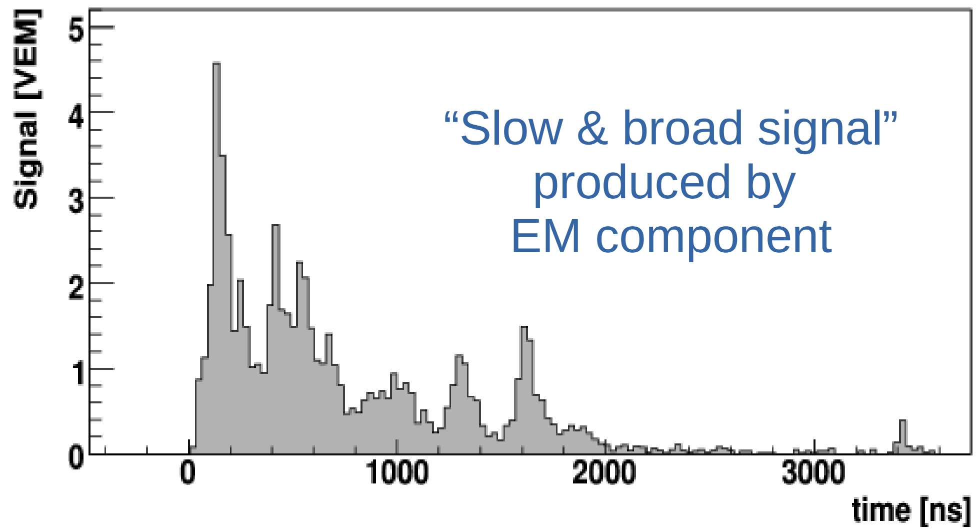
Inclined Showers

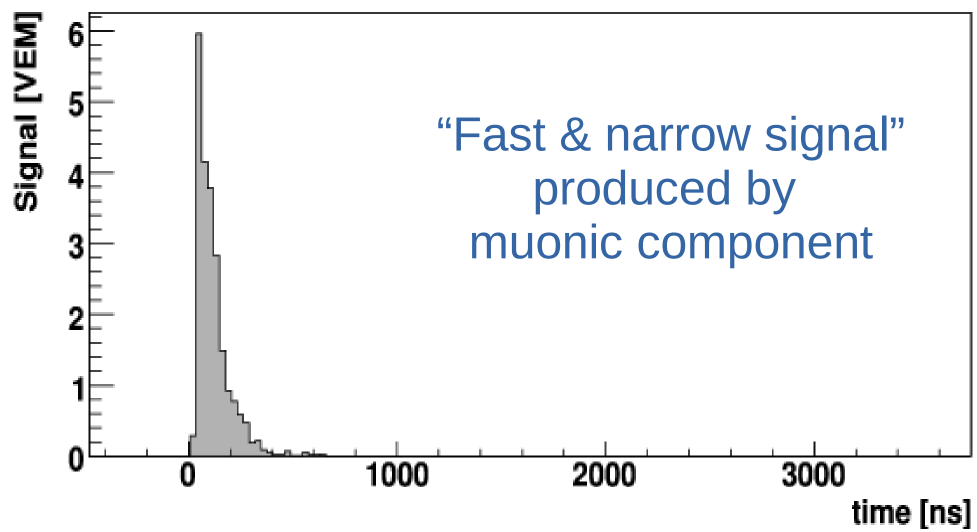




L/W large

Young Showers

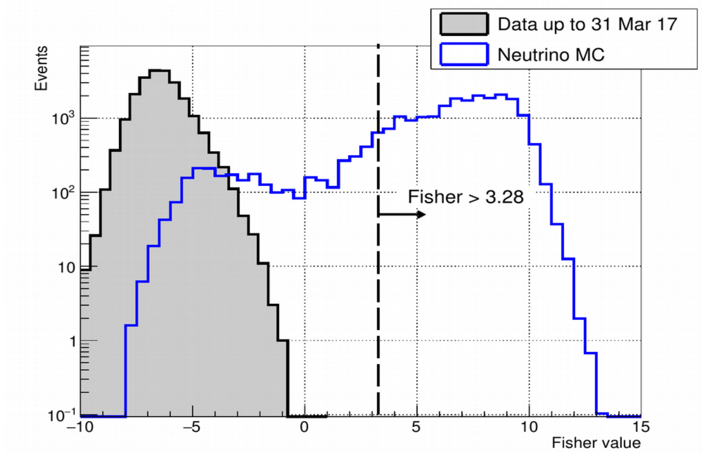




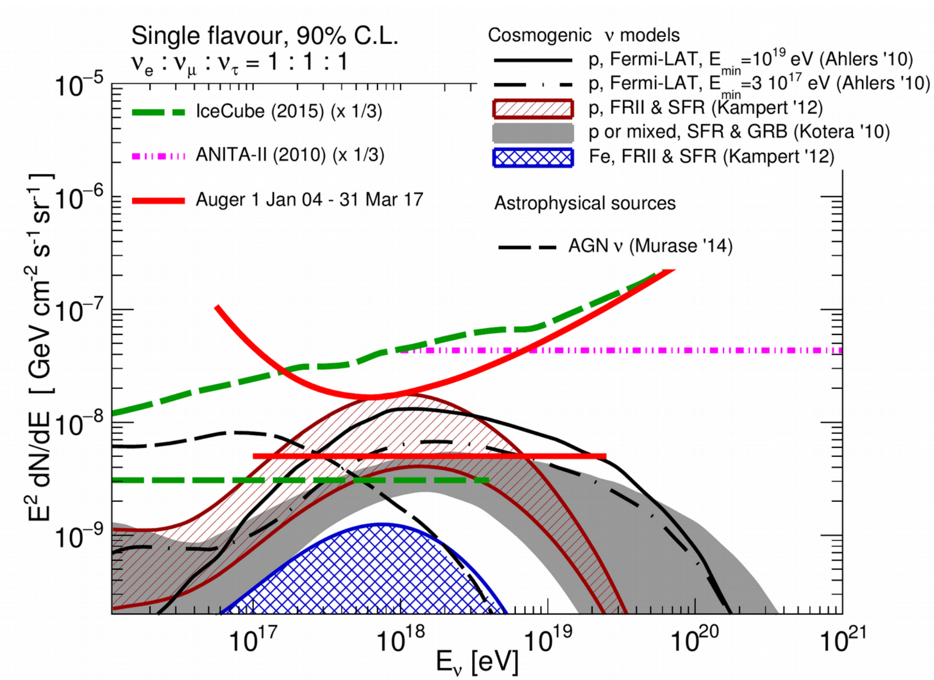
AoP large

Neutrino Search

Selection	Earth-skimming (ES)	Downward-going *high* angle (DGH)	Downward-going *low* angle (DGL)
Flavours and interactions	ν_τ CC	ν_e, ν_μ, ν_τ CC & NC	ν_e, ν_μ, ν_τ CC & NC
Angular range	$\theta > 90°$	$\theta \in (75°, 90°)$	$\theta \in (60°, 75°)$
N° of stations (N_{st})	$N_{st} \geq 3$	$N_{st} \geq 4$	$N_{st} \geq 4$
Inclined showers	$L/W > 5$ $\langle V \rangle \in (0.29, 0.31)$ m ns^{-1} rms$(V) < 0.08$ m ns^{-1}	$\theta_{rec} > 75°$ $L/W > 3$ $\langle V \rangle < 0.313$ m ns^{-1} rms$(V)/\langle V \rangle < 0.08$	$\theta_{rec} \in (58.5°, 76.5°)$
Young showers	$\geq 60\%$ of stations with ToT trigger and AoP > 1.4 $\langle$AoP$\rangle > 1.83$ AoP$_{min} > 1.4$ if $N_{st} = 3$	Fisher discriminant based on AoP of *early* stations	$\geq 75\%$ of stations close to shower core with ToT trigger and Fisher discriminant based on AoP of *early* stations close to shower core



Distribution of the Fisher variable for the DGH search



NO EVENTS OBSERVED

DIFFERENTIAL BOUND: calculated over consecutive energy bins of 0.5 in $\log_{10} E_\nu$

INTEGRAL BOUND: $dN/dE = k\,E^{-2}$
$\rightarrow k \sim 5 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}

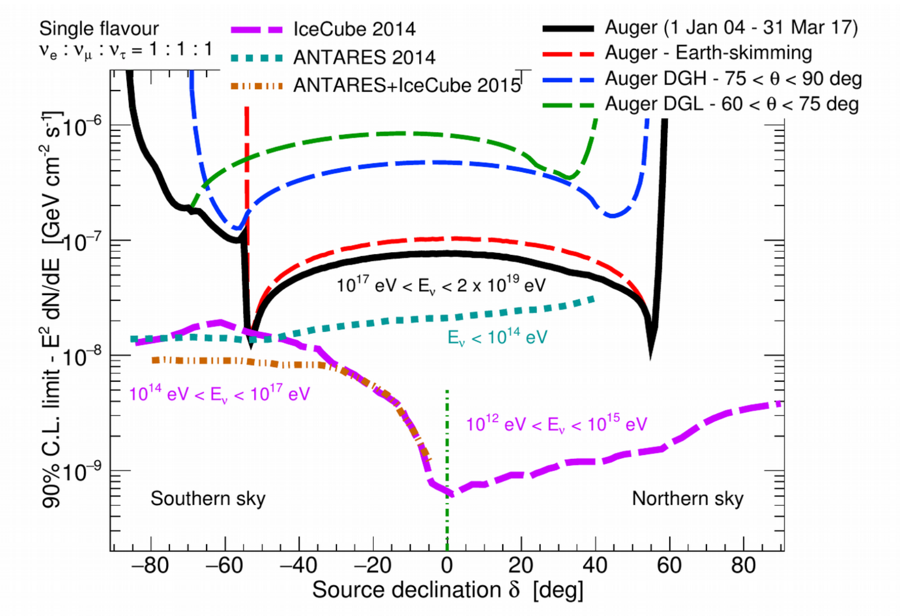
90% CL in the energy range 0.1-25 EeV

Auger limits constrain models that assume a pure primary proton composition injected at the sources and a strong evolution of the sources.

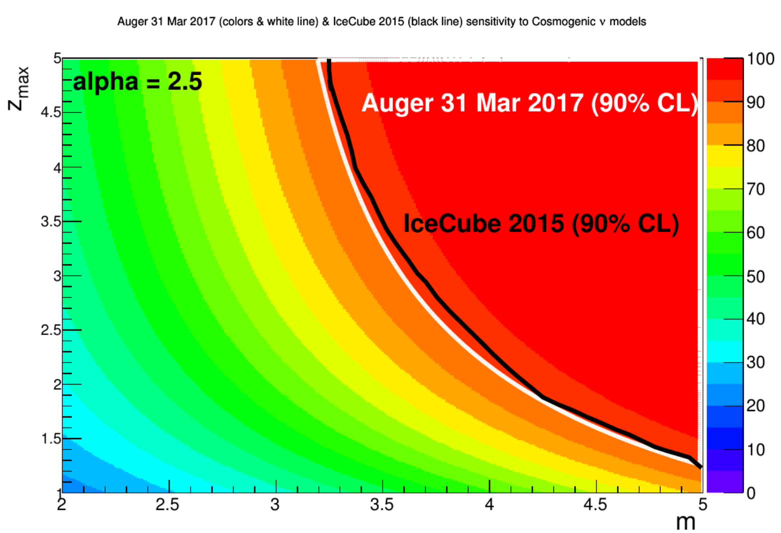
doi:10.22323/1.301.0972

Directional Neutrino Search

The non-observation of neutrino candidates is cast into a bound on point sources which is calculated as a function of declination, δ, also assuming a flavor ratio of 1:1:1.



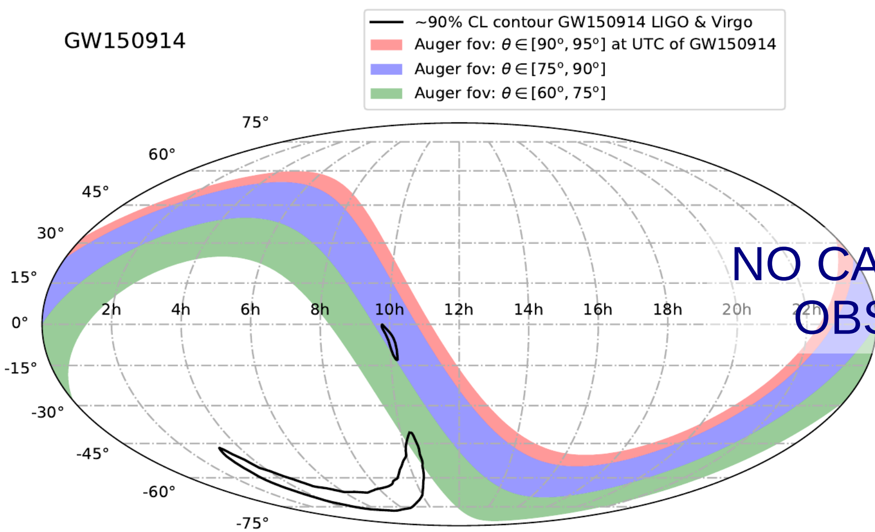
- The exposure of the SD as a function of the ν energy and of the source position in the sky, $\varepsilon(E_\nu,\delta)$, is evaluated by folding the SD aperture with the neutrino interaction probability and the selection efficiency for each ν channel.
- Typically, the search for neutrinos from point sources is performed on a pre-selected time interval chosen to match plausible emission times according to theoretical models describing the mechanisms acting within the sources.



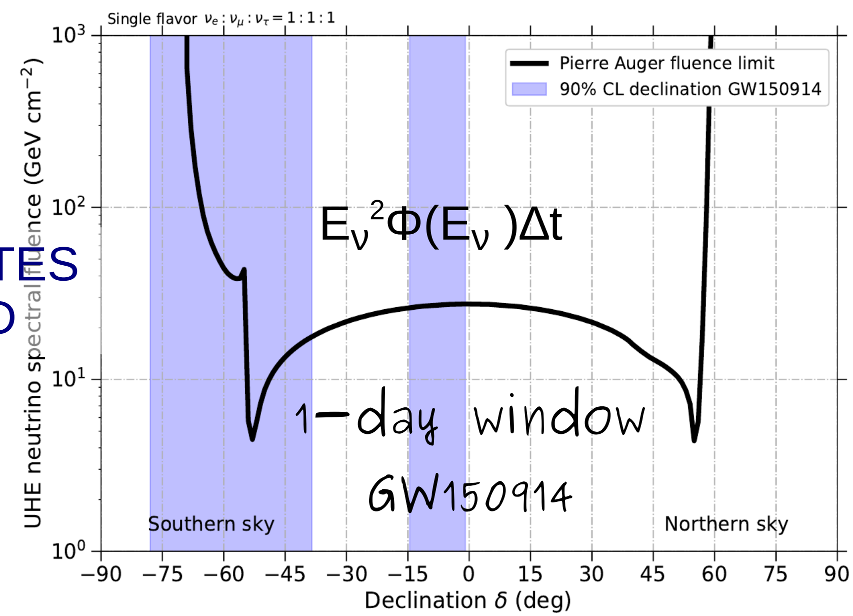
Constraints on parameter space for cosmological neutrinos in proton models (assuming a power-law dN/dE ∝ $E^{-2.5}$) as a function of the source evolution (m) and the maximum redshift of the sources (z_{max}). Colored areas represent different confidence levels of exclusion. The region above the black (white) line is excluded at 90% C.L. by IceCube (Auger) data.

GW150914/151226

BH mergers could accelerate cosmic rays to the highest energies and produce neutrinos provided there are magnetic fields and disk debris from the progenitor stars.
Search in two periods of time: ±500 s (GRB prompt phase) around the UTC times at which the mergers were observed and one day (GRB afterglows) following their occurrence.



NO CANDIDATES OBSERVED



Field of view of the Observatory exemplified at the instant of detection of the black hole coalescence event GW150914 by Advanced LIGO for the neutrino search into ES, DGH and DGL channels. The black contours give the 90% C.L. region of the reconstructed position of the BH merger as obtained by LIGO observations.

Upper limit at 90% C.L. to the neutrino spectral fluence in the 100 PeV to 25 EeV range as a function of declination to consider the poor localization of these events detected only by the two LIGO sites. The blue band is the 90% C.L. of the reconstructed source declination.

GW150914/151226

The spectral fluence is related to the total energy emitted in neutrinos, which can be compared to the energy radiated in gravitational waves.

The most restrictive limit assuming emission during a single day for GW150914 (GW151226) is obtained for $\delta = -53°$ ($\delta = 55°$) and would corresponds to a total energy radiated in UHE neutrinos smaller than 7.7×10^{53} (9.7×10^{53}) erg when integrated from 100 PeV to 25 EeV. This corresponds to 14.3% (44.1%) of the radiated energy in gravitational waves.

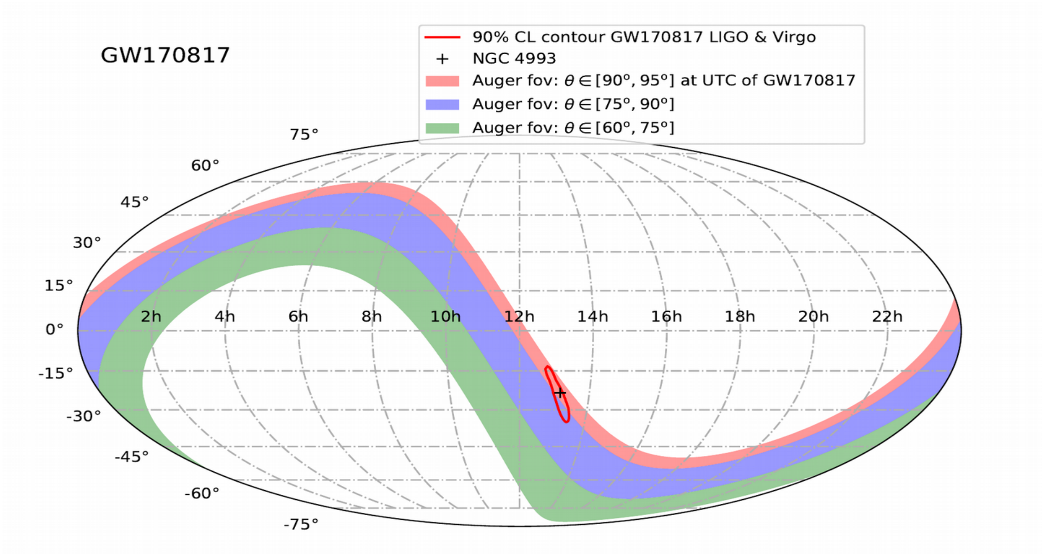
The limits found by IceCube and ANTARES apply to lower neutrino energies and give more restrictive limits on the total energy radiated in these neutrinos.

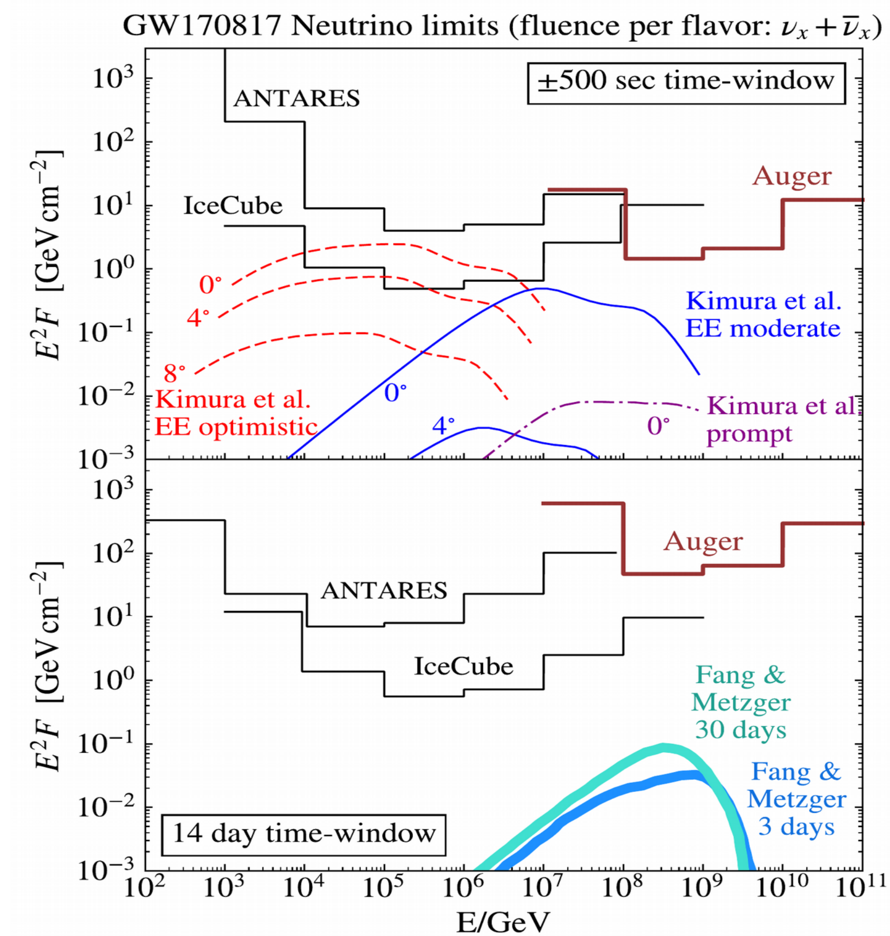
The upper limits were obtained averaging the instantaneous aperture over a day. If the emission time was shorter than one day, more stringent limits would be obtained provided the source was in the neutrino field of view during the neutrino emission, especially if it was in the ES field of view. Due to the poor localization of both events, it is not possible to know if the events were in the neutrino field of view at the detection time. Given the 90% C.L. contour of GW151226 (GW150917), the overlap with the field of view of the neutrino search is 68.9% (13%) for a time window of 1000 s. The overlap over a whole sidereal day is 100% in both cases.
The detection of black hole mergers closer to us and with more directional precision could provide more stringent constraints for models which assume that part of the associated GW energy goes into UHE neutrinos.

doi:10.1103/PhysRevD.94.122007

GW170817

doi:10.3847/2041-8213/aa9aed





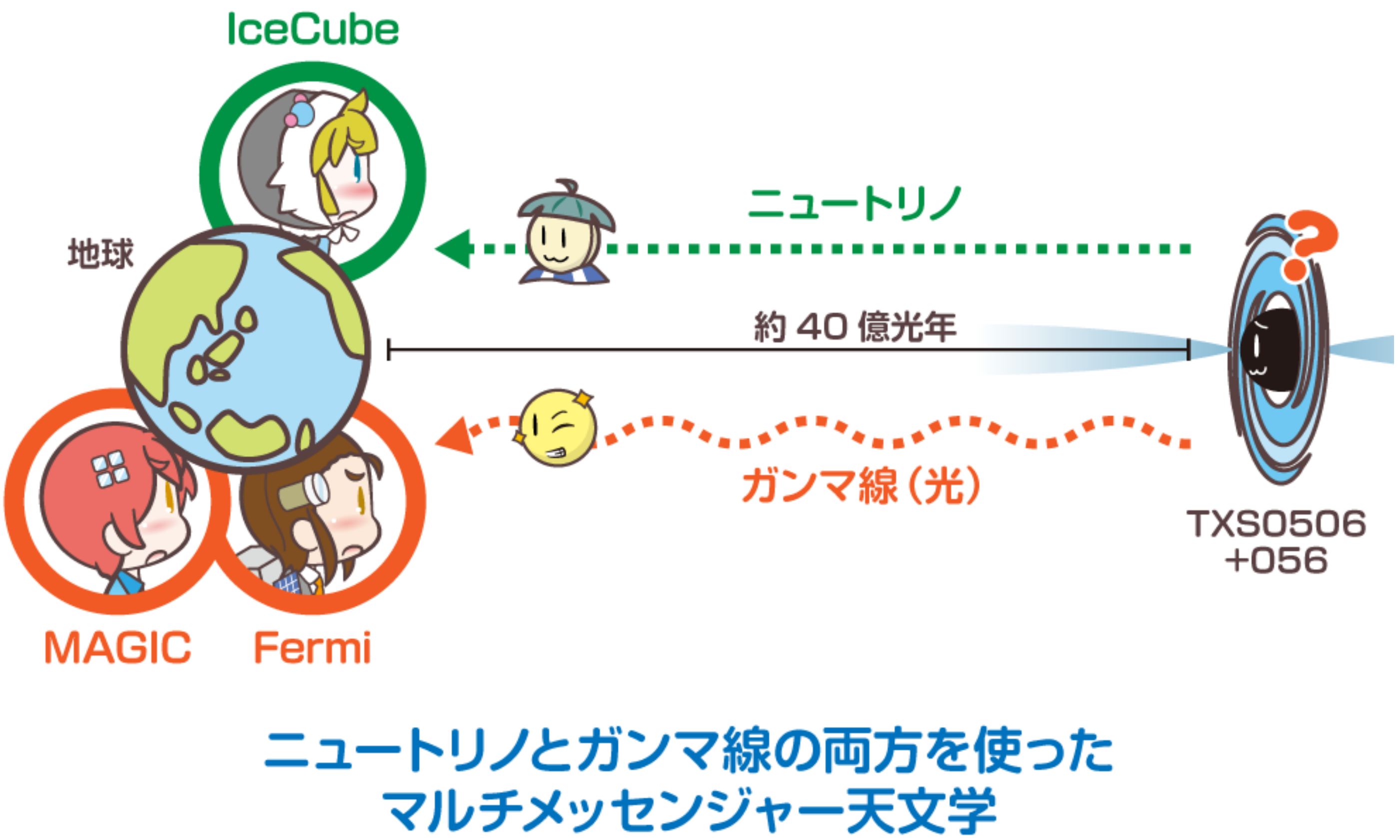
At the time of the GW detection, the source was located at a zenith angle of 91.9° at the Auger site, just below the horizon and extremely close to the sweet-spot for ES neutrinos.

When considered in a time interval of ±500 s about the detection (93.3° < θ < 90.4°), the EeV exposure is larger than that of dedicated neutrino telescopes and provides the most stringent upper limit to the neutrino fluence at 90% C.L. in the 100 PeV to 25 EeV interval, complementary to IceCube and ANTARES.

The analysis was also made for a longer time window of 14 days matching predictions from longer-lived emission processes.

IceCube bounds allowed constraints to be placed on the orientation angle relative to the jet axis for one of the most optimistic models.

γ and ν from TSX 0506+056



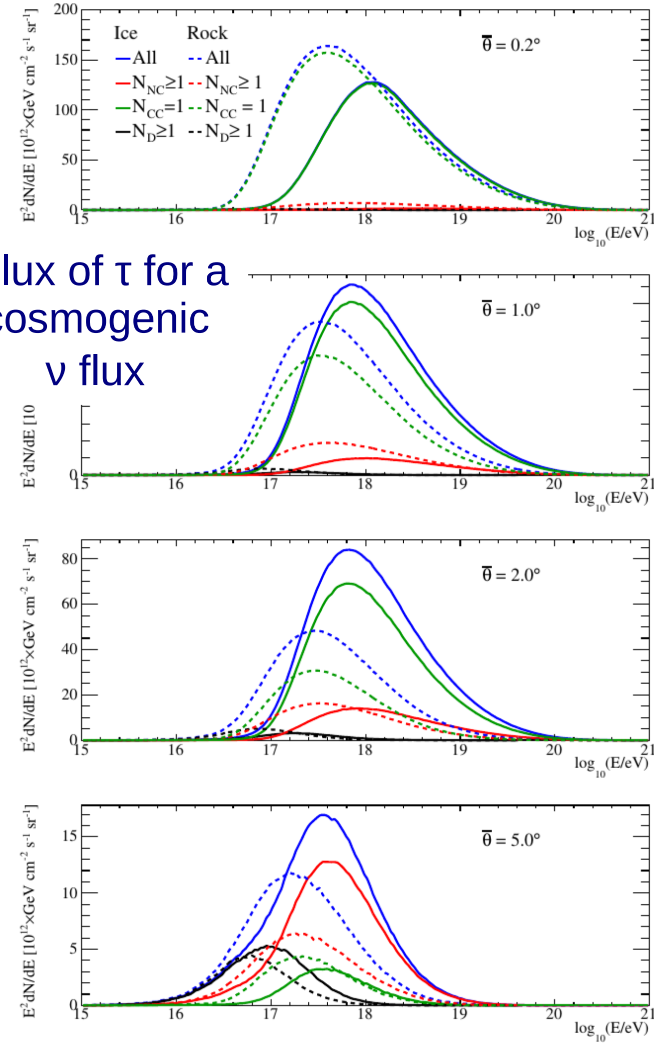
A search for possible coincident signals at the Auger Observatory was also performed. This source is 21% of the sidereal day in the field of view of the neutrino search but it was not in the field of view at the exact time of the neutrino detection.

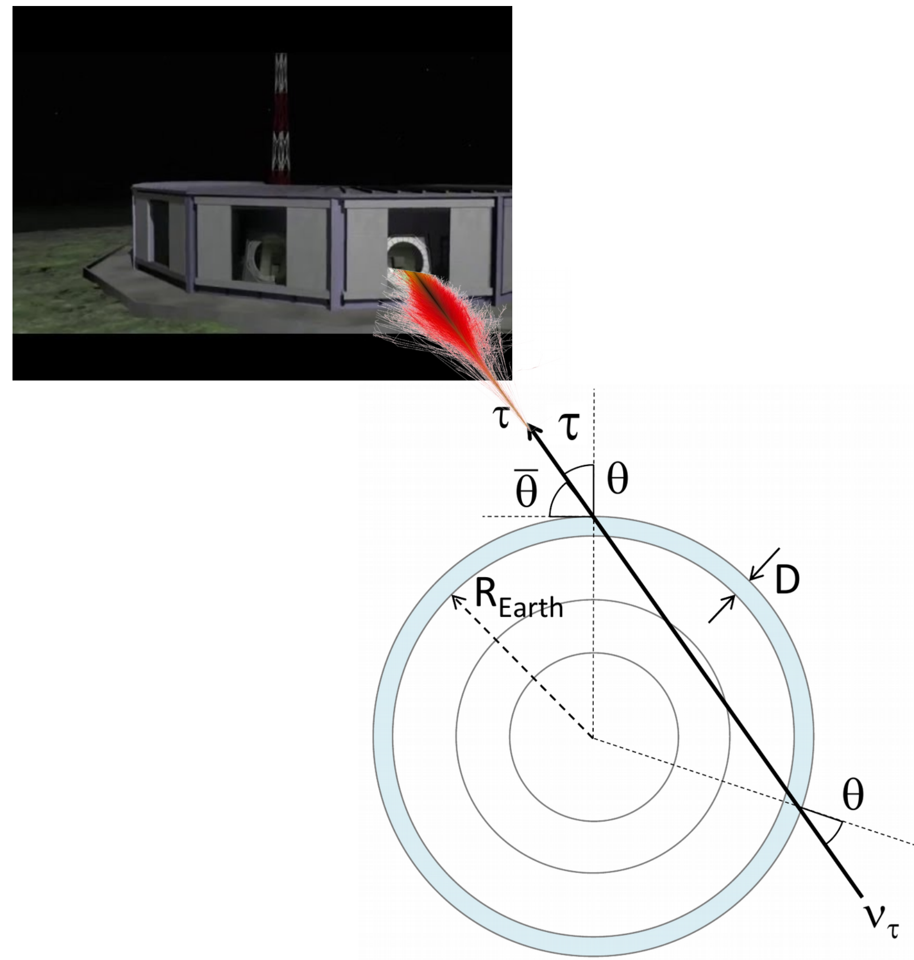
No neutrinos were found.

Neutrino Search with the FD

When a ν_τ enters the Earth it produces τ leptons as a result of nuclear charged current interactions. In some cases, this process results in a τ exiting the surface of the Earth, which can decay in the atmosphere and produce an upward-going air shower. It can be detected via fluorescence, optical Cherenkov, or geomagnetic radio emission.

Flux of τ for a cosmogenic ν flux

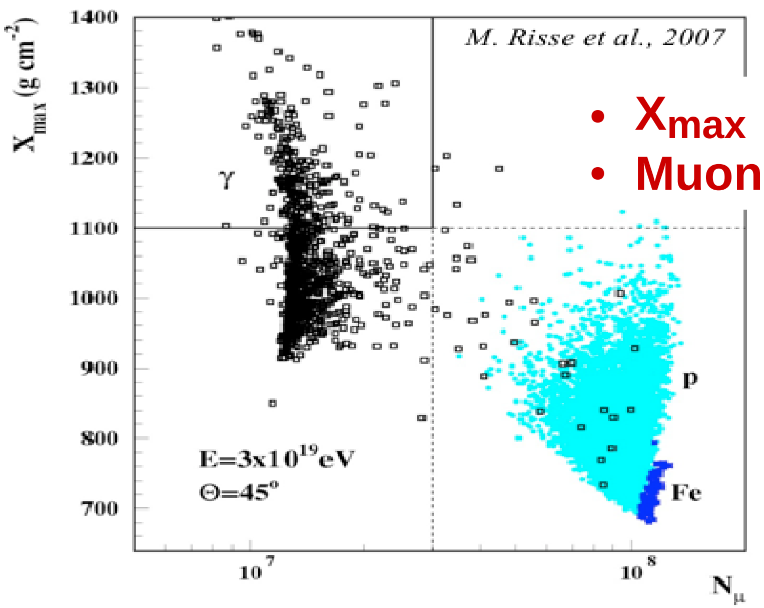




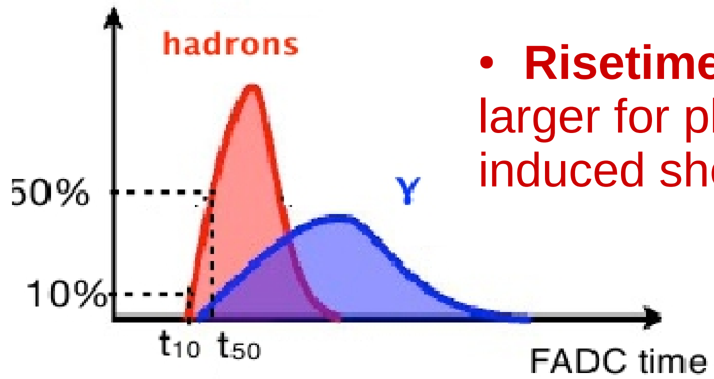
doi:10.1103/PhysRevD.97.023021

doi:10.1016/j.astropartphys.2004.11.008

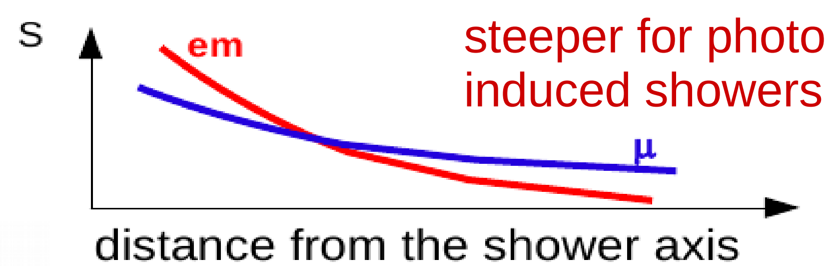
Photon Search



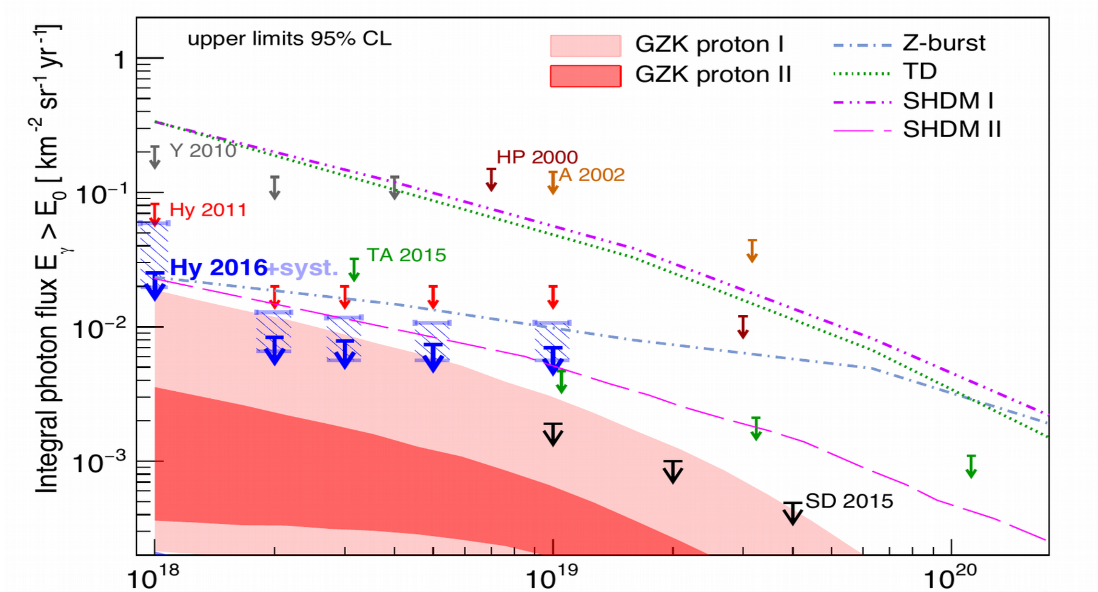
- X_{max}
- **Muon Content**



- **Risetime:** t50-t10, larger for photon-induced showers



- **LDF of total signal:** steeper for photon-induced showers



Hybrid data: Jan. 2005 – Dec. 2013

- No photon events observed;
- “Top down” models strongly disfavoured.

10-30 EeV:
$6.80 \cdot 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1} at 90 % C.L.

doi:10.1088/1475-7516/2017/04/009

Directional Photon Search

Photons undergo interactions with the extragalactic background light (EBL) inducing electromagnetic cascades. This process makes photons sensitive to the extragalactic environment, but it also limits the volume from which EeV photons may be detected. It is small compared to the GZK-sphere, but large enough to encompass the Milky Way, the Local Group of galaxies, and possibly Centaurus A, given an attenuation length of about 4.5 Mpc at EeV energies.

If the energy spectra of TeV γ sources measured by atmospheric Cherenkov telescopes extend to EeV energies, it is plausible that photons and neutrons from these sources are detectable also by the Auger Observatory. Sources that produce particle fluxes according to an E^{-2} energy spectrum inject equal energy into each decade. Thus, a measured energy flux of 1 eV cm^{-2} s^{-1} in the TeV decade, as is found for a number of Galactic sources, would result in the same energy flux in the EeV decade if the spectrum continues to such high energies and energy losses during propagation are negligible.

A source of specific interest is the galactic center for which the H.E.S.S.-collaboration measured a gamma-ray flux up to about 50 TeV without any observation of a cutoff or a spectral break → the Galactic center could host a peta-electron volt accelerator, called PeVatron.

It is still debated whether these photons are produced in hadronic processes. An interesting test for this is provided by a search for neutrons from this direction.

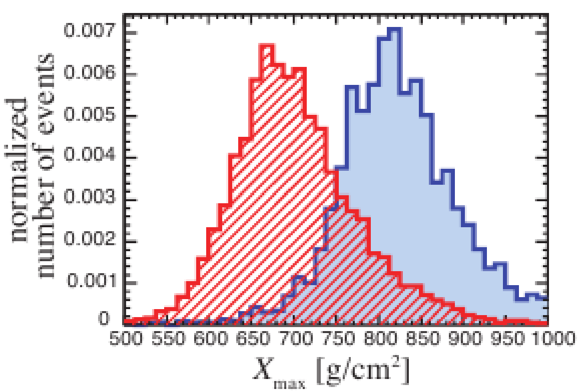
Directional Photon Search

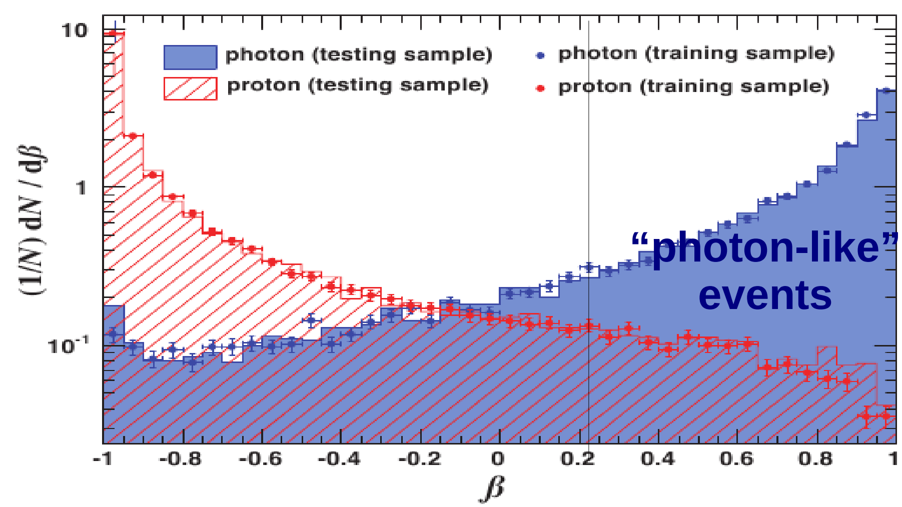
For each candidate source direction, an optimized cut in the multivariate output distribution is determined which depends on the expected number of isotropic background events in that direction.

This number is calculated takes into account detector efficiencies and aperture features.

For each target direction, a top-hat counting region of 1° is assumed.

Averaging over all considered target directions, the multivariate cut is expected to retain 81.4% of photons while rejecting 95.2 % of background hadrons.



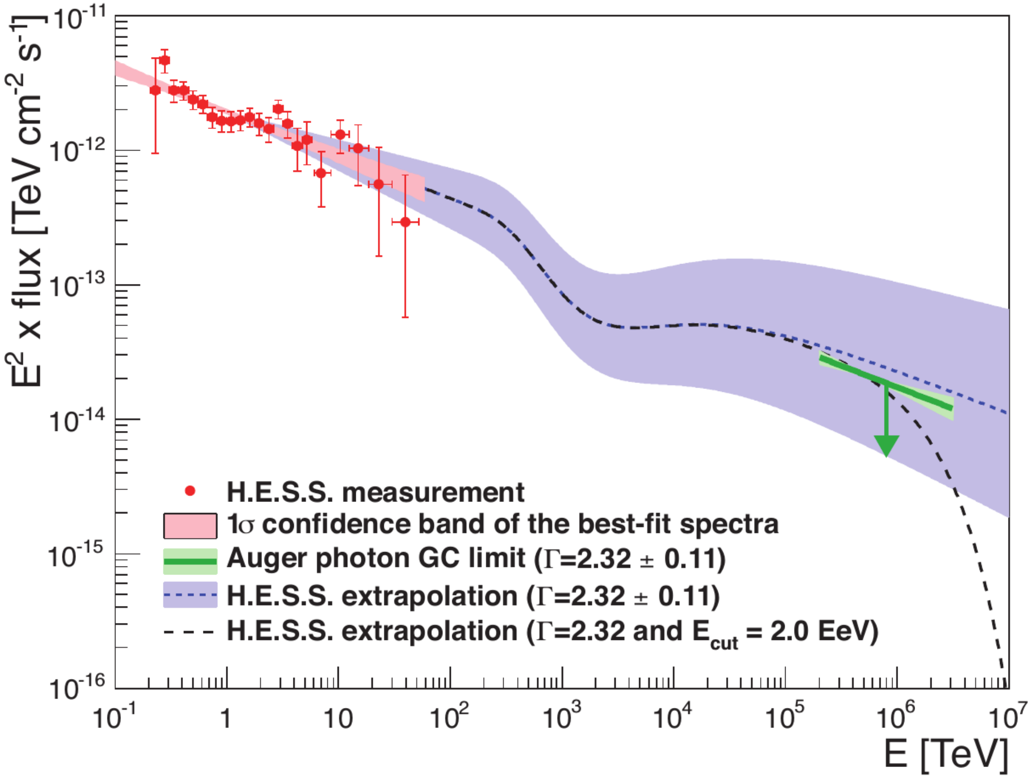


only X_{max} and S_b → separation=0.645
All variables: separation=0.668

doi:10.1088/0004-637X/789/2/160

Photon Search: the Galactic PeVatron by H.E.S.S.

In none of the sources and source classes could EeV photons be detected.
The result for the Galactic center is shown.



Conservatively, the extrapolation of the H.E.S.S. data to EeV energies does not take into account the increase of the pp cross-section by about 40% relative to TeV energies.
The current upper limit of 0.044 eV cm^{-2} s^{-1} (95% C.L.) at energies above 0.2 EeV can already constrain the allowed parameter space for a flux continuation to EeV energies.

doi:10.3847/2041-8213/aa61a5

Photon Search: the Galactic PeVatron by H.E.S.S.

- The observation of photon fluxes from individual sources or from stacked sets of targets would have proved that EeV protons are being accelerated at those considered sources within the galaxy or its neighborhood.

- The null results leave open the possibility that protons observed at EeV energies are of extragalactic origin.

- The absence of detectable photon fluxes, as reported here, does not exclude the production of EeV protons within the Galaxy because the derived flux limits are time-averaged values. EeV photons might be produced in transient sources, such as gamma-ray bursts or supernovae, or be aligned in jets not pointing to us.

- Extending the searches to bursting sources of EHE photons is a goal of ongoing multi-messenger analyses within Auger.

Neutron Search

- An air shower produced by a neutron is indistinguishable from an air shower produced by a proton;
- neutrons are not deflected by magnetic fields in the Galaxy, so their arrival directions point back to their sources;
- a flux of neutrons from a single direction can be detected as an excess of air showers arriving from that direction within the angular resolution of the Observatory;
- the mean travel distance for relativistic neutrons is 9.2 kpc$\times E_n$/EeV
  → sources in part of the Galactic disk, including the Galactic center, should be detectable via neutrons above 1 EeV. Above 2 EeV, the volume for detectable neutron emitters includes most of the Galaxy;
- neutrons are produced by charge exchange interactions of high energy cosmic-ray protons with ambient photons, protons, or nuclei leading to the creation of a π^+. Neutron emerges with most of the proton energy. **The production of neutrons via creation of π^+ is necessarily accompanied by photons**, originating from decay of similarly produced π^0. **Photons acquire only a small fraction of the proton energy**, so that the production of neutrons exceeds the hadronic production of photons of the same energy
  → **the search of high energy neutrons is a highly relevant and sensitive probe for Galactic hadronic cosmic ray accelerators.**

Neutron Search: Method and Results

Vertical SD events → from **2004 January 1** to **2013 October 31**
Four energy ranges: 1 EeV ≤ E < 2 EeV (621,375 events); 2 EeV ≤ E < 3 EeV (135,444 events);
E ≥ 3 EeV (97,451 events);
E ≥ 1 EeV (cumulative range).

Definition of a **solid angle** for each target: target circle of radius 1.05 times the angle within which 68% of neutron arrival directions from the candidate source should be included after the eventreconstruction.
Galactic plane: strip centered on Galactic latitude b = 0° with half thickness |b| < 0.93ψ, where ψ is the mean angular resolution along the Galactic plane (and within the exposure of the Observatory) for a given energy range.

Most Significant Target – 95% CL

Class	R.A. [°]	Decl. [°]	Obs	Exp	Flux U.L. (km^{-2} yr^{-1})	E-Flux U.L. (eV cm^{-2} s^{-1})	*p*-value	*p*-value (penalized)
msec PSRs	260.27	−24.95	237	214	0.019	0.14	0.058	0.98
γ-ray PSRs	8.59	−5.58	176	149	0.024	0.18	0.016	0.70
LMXB	264.57	−26.99	265	219	0.028	0.20	0.0012	0.10
HMXB	152.45	−58.29	283	248	0.019	0.14	0.014	0.49
H.E.S.S. PWN	128.75	−45.60	275	248	0.018	0.13	0.043	0.53
H.E.S.S. other	269.72	−24.05	235	211	0.019	0.14	0.054	0.59
H.E.S.S. UNID	266.26	−30.37	251	227	0.018	0.13	0.055	0.57
Microquasars	262.75	−26.00	247	216	0.022	0.16	0.020	0.23
Magnetars	81.50	−66.08	268	241	0.016	0.11	0.040	0.48
Gal. center	266.42	−29.01	234	223	0.014	0.10	0.24	...
Gal. plane	|Gal. lat.| < 1°17		16965	17197	0.077	0.56	0.96	...

No evidence for a neutron flux from any class of candidate sources

doi:10.1088/2041-8205/789/2/L34

Neutron Search: Method and Results

No evidence for a neutron flux from any class of candidate sources

- Are EeV protons produced in the Galaxy or do they fill the space also between galaxies?

- Might EeV protons be produced in transient events within the Galaxy, like supernova explosions or rare gamma ray bursts?

- Protons emitted in jets would produce neutron jets with possibly none of them pointing toward Earth.
  This hypothesis is better constrained by the absence of any strong anisotropy of the protons themselves.

Arrival Directions: UHECR and Source Population

Search for an excess arrivals from strong, nearby sources. The data consist of 5514 events above 20 EeV with zenith angles up to 80° recorded before 2017 April 30.

Sky models of cosmic-ray density have been created for two distinct populations of extragalactic gamma-ray emitters: active galactic nuclei from the second catalog of hard Fermi-LAT sources (2FHL) and starburst galaxies from a sample that was examined with Fermi-LAT.

Each model has two free parameters:

1. the fraction of events correlating with astrophysical objects;
2. an angular scale characterizing the clustering of cosmic rays around extragalactic sources.

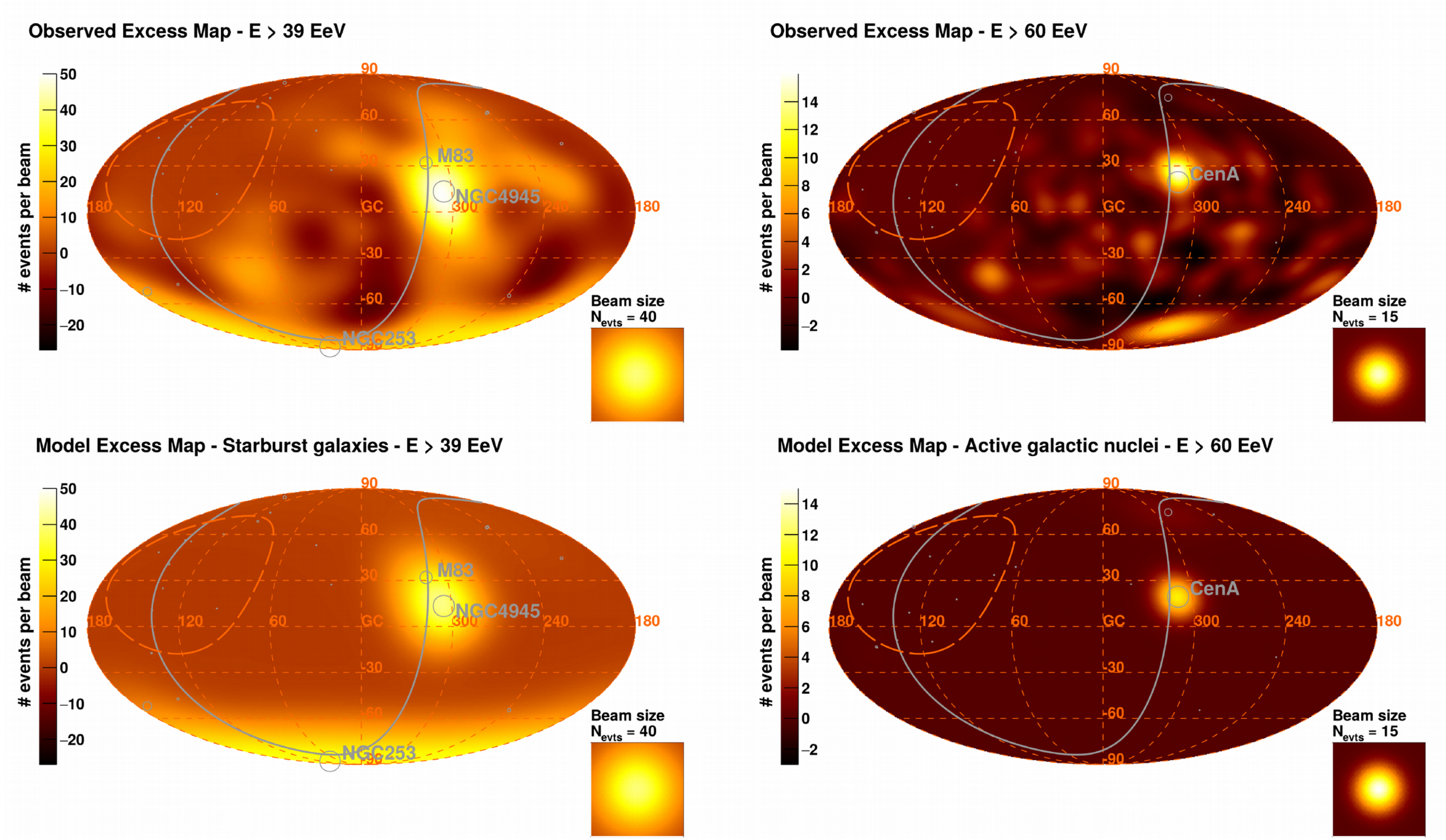
A maximum-likelihood ratio test is used to evaluate the best values of these parameters and to quantify the strength of each model by contrast with isotropy.

Flux-limited samples, which include all types of galaxies from the Swift-BAT and 2MASS surveys, have been investigated for comparison.

doi:10.3847/2041-8213/aaa66d

Arrival Directions: UHECR and Source Population

The maximum test statistic (TS) obtained for SBGs and γAGNs, within a scenario that assumes a homogeneous distribution of sources in the local Universe (EPOS-LHC and γ=1), correspond to 4.0σ (894 events above 39 EeV) and 2.7σ (177 events above 60 EeV) deviations from isotropy, respectively.



Arrival Directions: UHECR and Source Population

For Swift-BAT and 2MRS sources, the TS results correspond to 3.2σ above 39 EeV and to 2.7σ above 38 EeV.

The different degrees of anisotropy obtained from each catalog are due to the UHECR hotspot in the direction of the Centaurus A / M 83 / NGC 4945.
The γAGN model (> 60 EeV) and Swift-BAT model (> 39 EeV) are dominated by Centaurus A, which is 7° and 13° away from NGC 4945 and M 83, respectively.
The starburst model additionally captures the UHECR excess close to the Galactic South pole, interpreted as contributions from NGC 1068 and NGC 253, yielding an increase in the anisotropy signal from ∼3 to 4σ.

To conclude: The pattern of UHECR arrival directions is best matched by a model in which about 10% of those cosmic rays arrive from directions that are clustered around the directions of bright, nearby SBGs.We evaluated the possibility of additional contributions from nearby γAGNs, such as Centaurus A, and from more distant sources through a comparison with samples tracing the distribution of extragalactic matter.

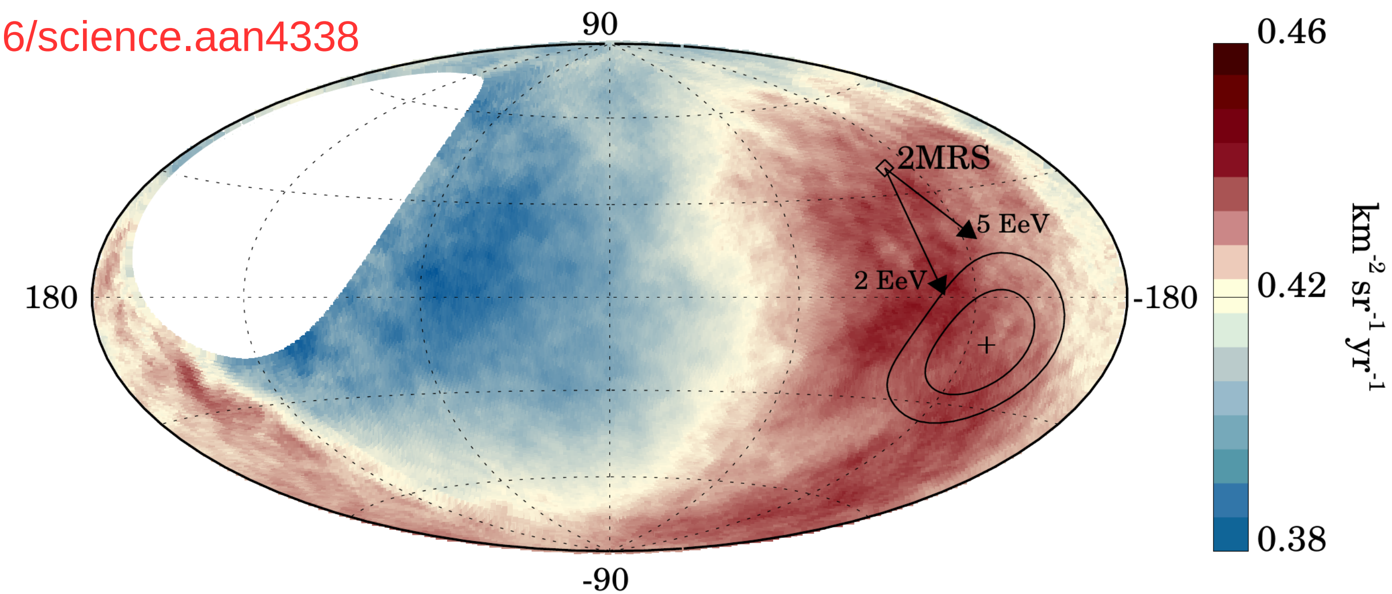
Caution is required in identifying SBGs as the preferred sources prior to understanding the impact of bulk magnetic deflections.

Large Scale Anisotropy

Data collected between 1 January 2004 and 31 August 2016. Events with θ < 80° enabling the declination range − 90° < δ < 45° to be explored, thus covering 85% of the sky.
Two energy ranges explored: 4 EeV < E < 8 EeV and E ≥ 8 EeV.
Harmonic analysis in right ascension, α.

For the energy bin 4 EeV < E < 8 EeV, the result is consistent with isotropy, with a bound on the harmonic amplitude of < 1.2% at the 95% confidence level.

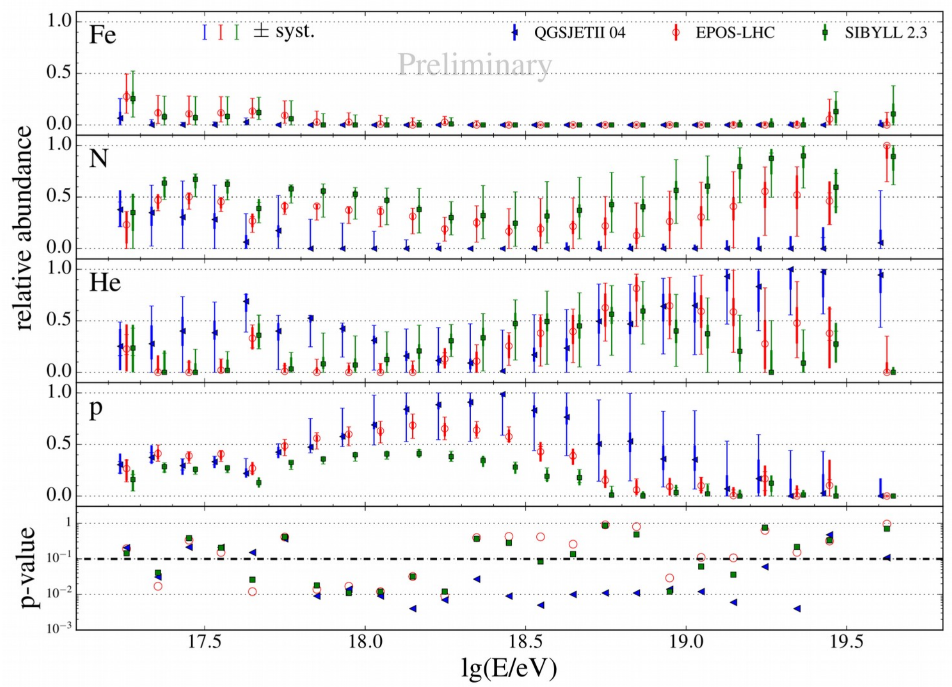
doi:10.1126/science.aan4338



E ≥ 8 EeV: sky map in equatorial coordinates of flux, in km^{-2} yr^{-1} sr^{-1} units, smoothed in angular windows of 45° radius.
An anisotropy, that can be described by a dipole, **was observed** with a significance level of **5.2σ**.
The dipole amplitude is d=6.5%, pointing toward (α, δ) = (100° ± 10° , −24° $^{+12}_{-13}$).

Large Scale Anisotropy

4 EeV < E < 8 EeV: the dipole amplitude is d = 2.5%, pointing close to the celestial south pole, at (α, δ) = (80°, -75°) , although the amplitude is not statistically significant. Models proposing a Galactic origin up to the highest observed energies are in increasing tension with observations. If the Galactic sources postulated to accelerate cosmic rays above EeV energies, such as short gamma-ray bursts or hypernovae, were distributed in the disk of the Galaxy, a dipolar component of anisotropy is predicted with an amplitude that exceeds existing bounds at EeV energies.



This tension could be alleviated if cosmic rays at a few EeV were dominated by heavy nuclei such as iron, but this would be in disagreement with the lighter composition inferred observationally at these energies.

E ≥ 8 EeV: if we assume a Galactic origin, we expect that the maximum of the flux might be expected to lie close to the Galactic center region. The direction of the dipole determined above 8 EeV lies ∼125° from the Galactic center. This suggests that the anisotropy observed above 8 EeV is better explained in terms of an extragalactic origin.

Search for UHECR-Neutrino Correlations

2014

2017

UHECRs accelerated in astrophysical sources are naturally expected to produce high-energy photons and neutrinos in interactions with the ambient matter and radiation

→high-energy neutrinos are powerful probes of the sites of production and acceleration of cosmic rays and ground-based cosmic ray detectors like the Pierre Auger Observatory and the Telescope Array have reached an unprecedented accuracy in the determination of the features of the cosmic rays at the highest energies

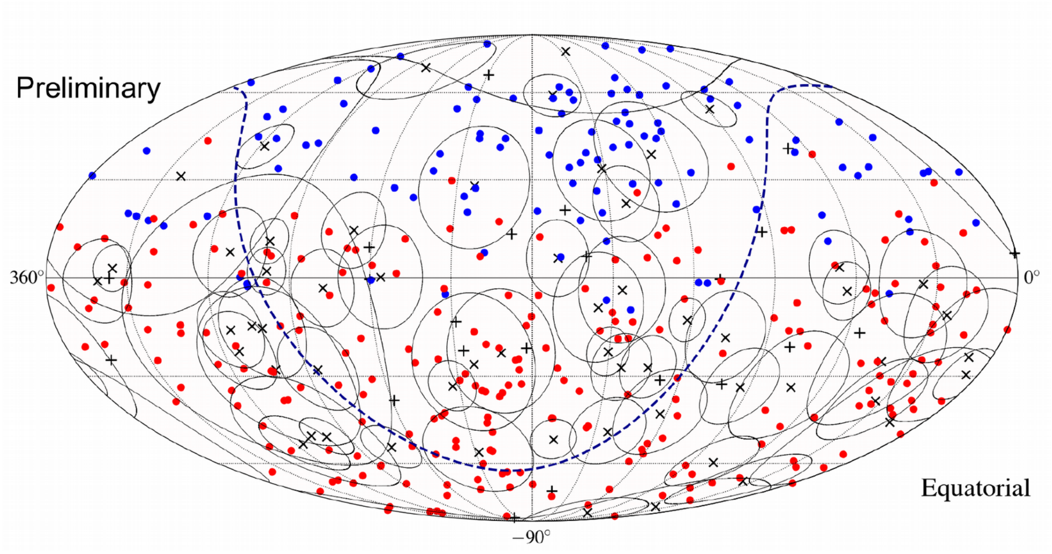
→ effort of four collaboration to identify directional correlations between the arrival directions of the highest-energy cosmic rays from both hemispheres and of the most probable cosmic neutrino events detected by IceCube and Antares.

Search for UHECR-Neutrino Correlations (ICRC 2017)

Auger dataset: 231 cosmic rays with energies $E_{CR} \geq 52$ EeV recorded with the SD array from January 2004 to March 2014. The cut on the zenith angle $\theta \leq 80°$ allows for a field-of-view ranging from −90° to +45° in declination.

TA dataset: energy $E_{CR} \geq 57$ EeV and zenith angles smaller than 55°. 87 events detected from May 2008 to May 2014 + 22 collected in an additional year of data.

IceCube dataset: HESE (High-Energy Starting Events) dataset → all flavors neutrinos with deposited energies ranging from 60 TeV up to 2 PeV: shower-like events (cascades) with an angular resolution of ∼ 15° above 100 TeV and track-like events induced by muons with an angular resolution of ≤ 1° → 58 cascades + 15 tracks constituting the six-year HESE dataset.



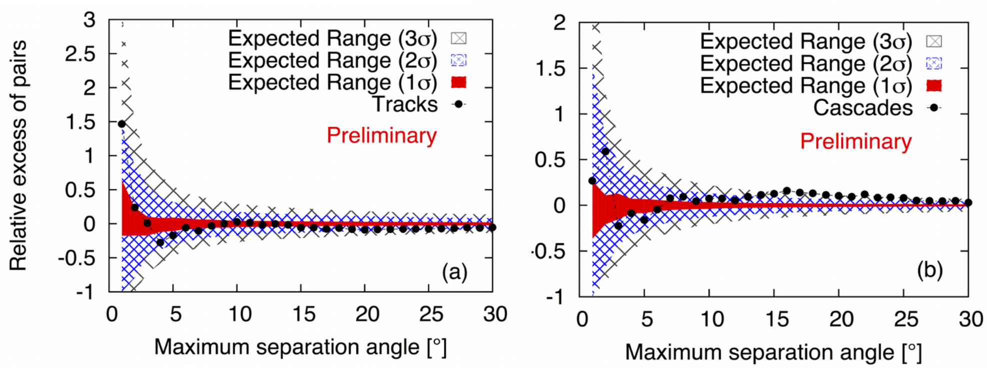
- UHECR by TA;
- UHECR by Auger;
- x Cascades by IceCube;
- \+ Tracks by IceCube

doi:10.22323/1.301.0961

Search for UHECR-Neutrino Correlations (ICRC 2017)

Cross-Correlation Method:

consists in computing the relative excess in the number of ν-UHECR pairs as a function of their angular separation over the expectation of isotropically distributed CR arrival directions, keeping the arrival directions of the neutrinos fixed and vice versa.

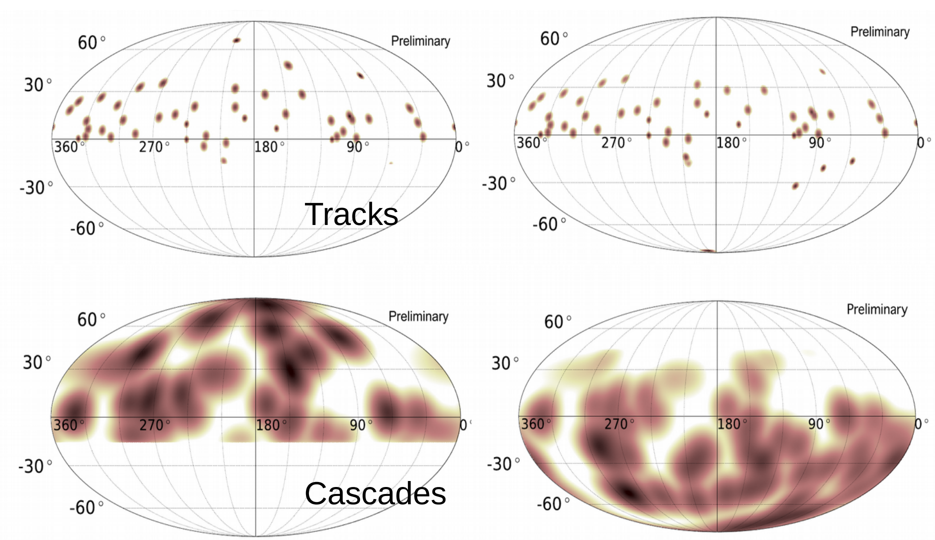


The maximum departure from the expectation for an isotropic CR flux, keeping the arrival directions of the neutrinos fixed, occurs at an angular distance of 1° for tracks and 22° for cascades. In the picture, The 1σ, 2σ and 3σ fluctuations expected from an isotropic distribution of CRs, with ν fixed, are shown in red, blue and grey, respectively.

Fixing the arrival directions of the CRs, we find that for cascades the maximum departure from isotropic expectations is at 16°.

Unbinned-Likelihood Method:

is a stacking likelihood test assuming that the stacked sources are the neutrino directions. This test requires a hypothesis on the CR deflections. We have made a scan on different values of the deflections also to account for the uncertainty on the composition of the CRs.



The signal PDFs before the Gaussian smearing and convolved with the exposure of each CR observatory in equatorial coordinates.

The most significant deviation from an isotropic flux of CRs occurs for the magnetic deflection parameter D = 6° with the high-energy cascades.

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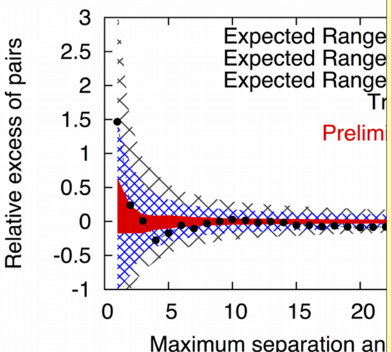

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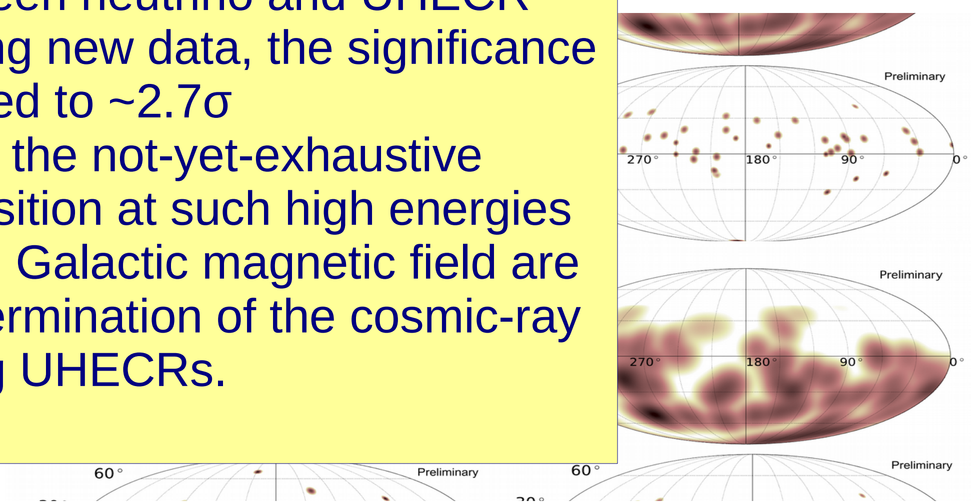

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Previous results of this work provided a potentially interesting connection between neutrino and UHECR directions at the 3σ level. Adding new data, the significance level decreased to ~2.7σ
The biggest problems are the not-yet-exhaustive knowledge of the CRs composition at such high energies and the poor knowledge of the Galactic magnetic field are the main limitations to the determination of the cosmic-ray sources using UHECRs.

AMON establishes and distributes alerts for immediate follow-up.

Auger receives alerts from AMON, but also sends alerts:

- AMON registers all vertical, high-quality, Auger SD events, with energy above 3 EeV with a cadence of at most a few minutes;

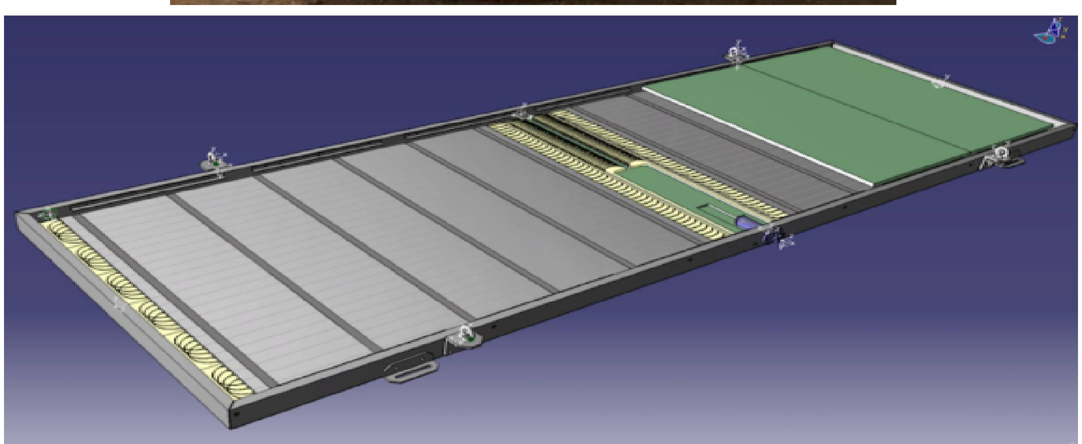
- AMON establishes clusters of two or more Auger events received correlated in time and arrival direction as alerts. These are excesses of events expected from neutral (photon or neutron) UHECRs;

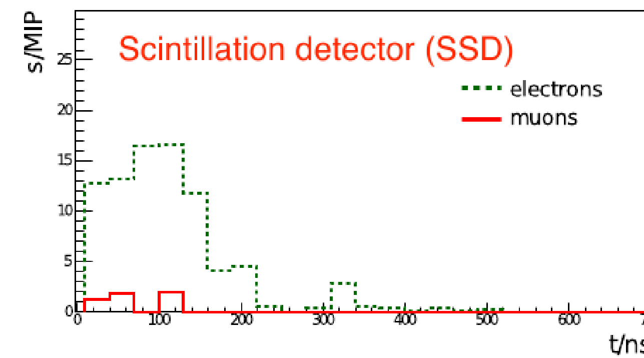
- AMON also receives and transmits the significance of each of the alerts, which depends on the energy and declination of each event. Thus high-significance alerts can be preferentially followed-up;

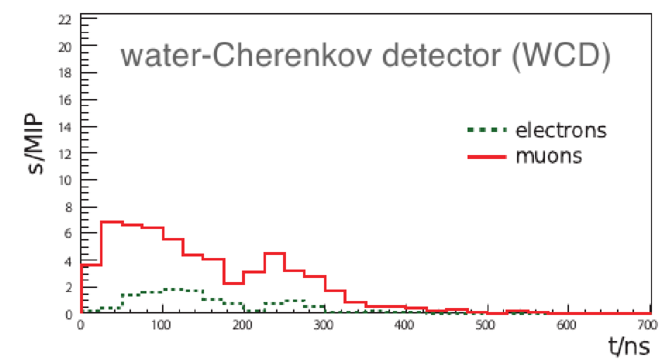
- To improve the overall significance of alerts and to enhance future photon and neutrino searches in general, additional improved hardware triggers have been implemented to the existing surface detector array of the Observatory. Besides enhancing the sensitivity to photons and neutrinos, they allow reducing their detection thresholds.

AugerPrime

- Faster and more powerful electronics, small PMT in the tank to increase the dynamic range;
- Scintillator (SSD) above the WCD to measure the mass composition with 100% duty cycle;
- Underground Muon Detector with AMIGA to have a direct muon measurement;
- Extended FD operation to periods with higher night sky background to have more statistics.







$$\boxed{S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}}$$

doi:10.1051/epjconf/201614505001

Conclusions and Prospects

- The Pierre Auger Observatory was designed as a multi-purpose observatory for the high-energy Universe with multi-messenger observations being foreseen from the beginning.

- Observations of photons in the so far dark Universe at $E_\gamma \geq 10^{17}$ eV or of a neutrino at these energies would be a major breakthrough by itself. However, the non-observation of point sources and diffuse fluxes of photons and neutrinos allowed the derivation of upper bounds that constrain models very effectively
→ top-down models are strongly disfavoured by Auger limits;
→ bounds started to constrain the GZK-effect as a dominant process for explaining the observed flux suppression of the most energetic UHECR;
→ the absence of γ-sources at the highest energies suggests that their maximum source energy does not reach out to the threshold energy of the Observatory and/or that their spectrum is significantly softer than $dJ/dE \propto E^{-2}$.

- The Auger Observatory reached a neutrino flux sensitivity above 100 PeV that was over an order of magnitude higher than of any other neutrino observatory presently operated. The absence of neutrinos at Auger, IceCube and ANTARES in correspondence of GW signals allowed constraining the jet properties of the neutron star merger.
For the run O3, mechanisms are set up to automatically react to GW or other astrophysical alerts and search for neutrinos and photons.

- AugerPrime will be operated into 2025 and will improve the statistics for composition information and composition enhanced astronomy by about a factor of 10.