Multi-messenger implications of the Pierre Auger Observatory measurements

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PIERRE AUGER OBSERVATORY

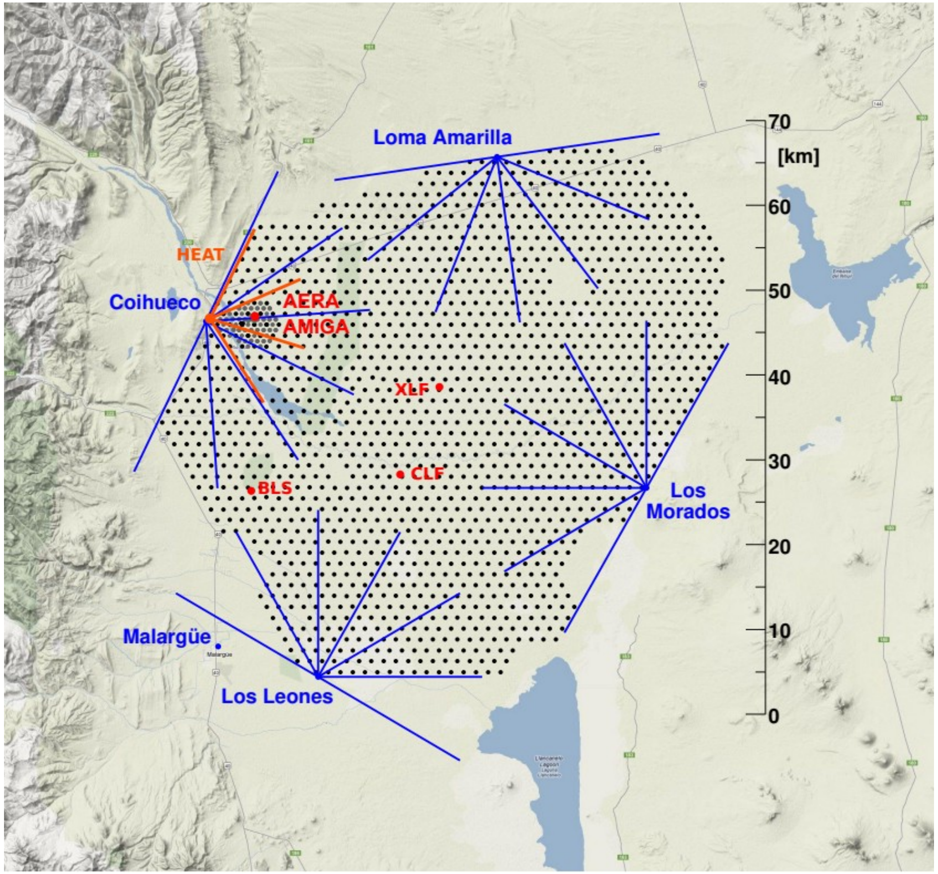
CRIS 2022

12th Cosmic Ray International Seminar

"The endless multiple voices fugue of the Universe"

15 September 2022

The Pierre Auger Observatory



Surface detector (SD)

- 1600 water-Cherenkov stations
- spacing 1500 m
- area ~3000 km^2
- duty cycle ~100 %

Fluorescence detector (FD)

- 4 sites with 24 telescopes
- looking horizontally – 0° - 30° in elevation
- duty cycle ~14%

Low-energy extension

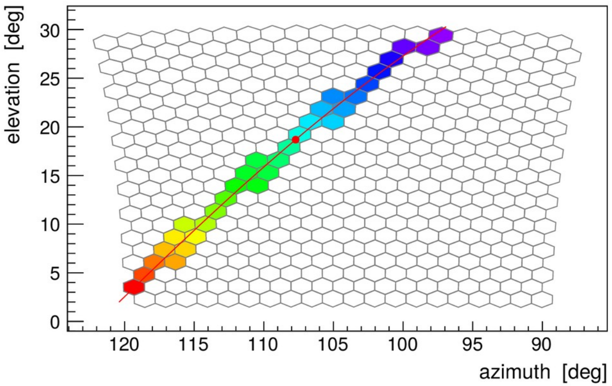
- 3 High-Elevation Auger Telescopes (HEAT)
- 50 additional SD stations to form 750 m array

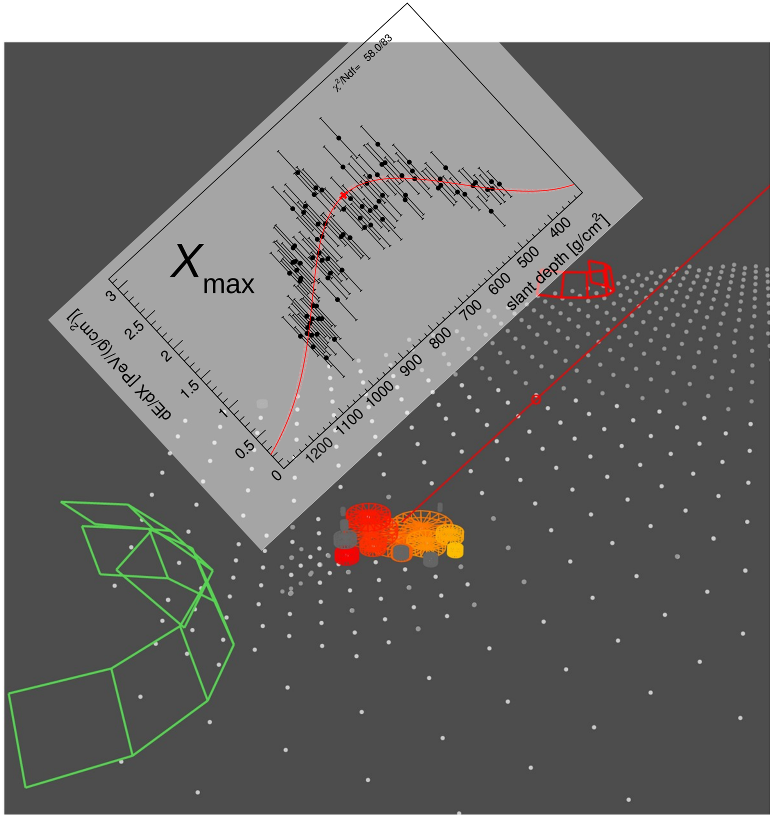
… a lot of other instruments and techniques ...

[Nucl. Instrum. Meth. A 798 (2015) 172–213]

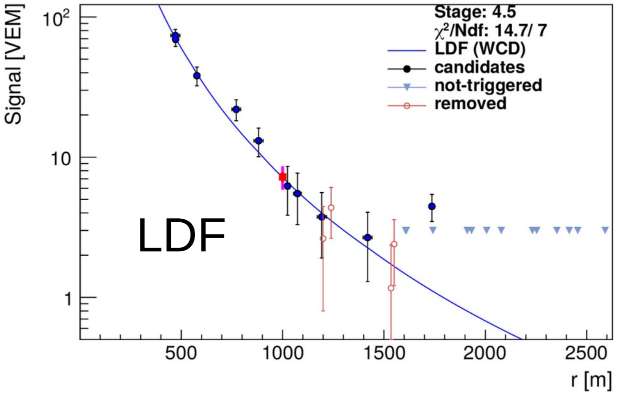
Hybrid detection of extensive air showers

FD





SD

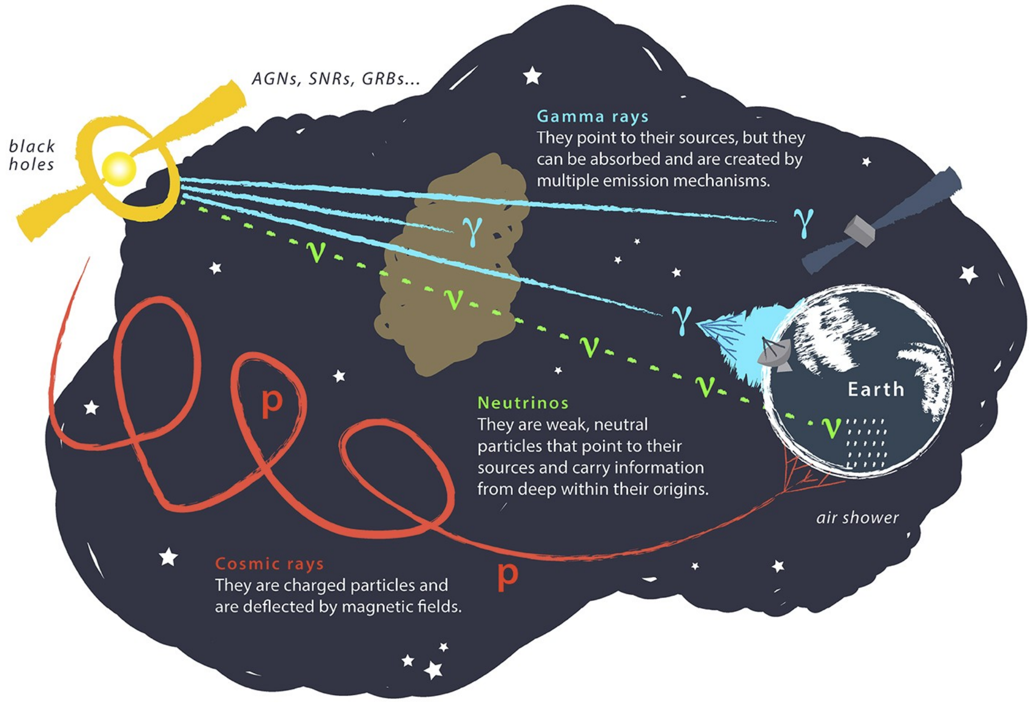


Outline of searches

UHE photons and neutrinos
- diffuse flux
- point-like sources
  - steady
  - transient

Correlations between UHECRs and neutrinos
- neutrinos from IceCube + ANTARES
- UHECRs from Auger Observatory + TA

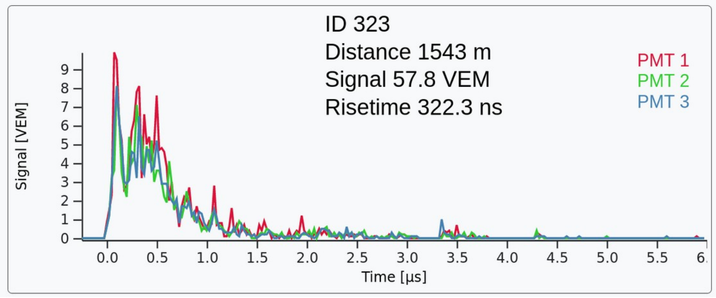
Upward-going showers – ANITA follow up
- would not fit into the Standard Model
- FD exposure for general usage
  - application to τ lepton model

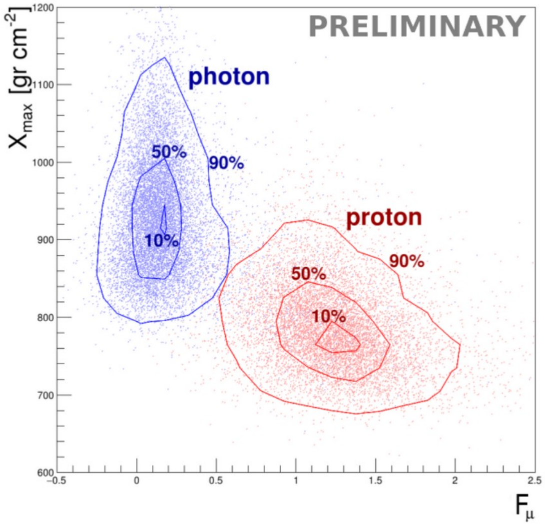


Diffuse UHE photons

Photon showers vs. UHECRs:
- smaller footprint
- less muons
- deeper X_{max}

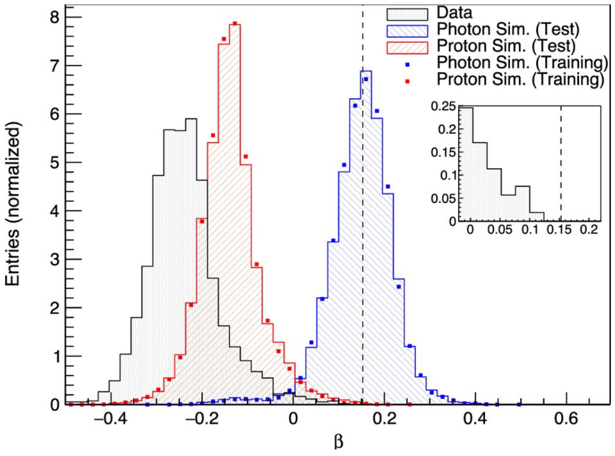
SD station - time trace





Three different analyses
- SD
  - steeper LDF, longer risetime
- hybrid
  - deep X_{max}, muon content from shower universality
- hybrid from low-energy extension
  - deep X_{max}, S_b, number of triggered stations

$$S_b = \sum_i S_i \times \left(\frac{R_i}{1000\ \text{m}}\right)^b$$



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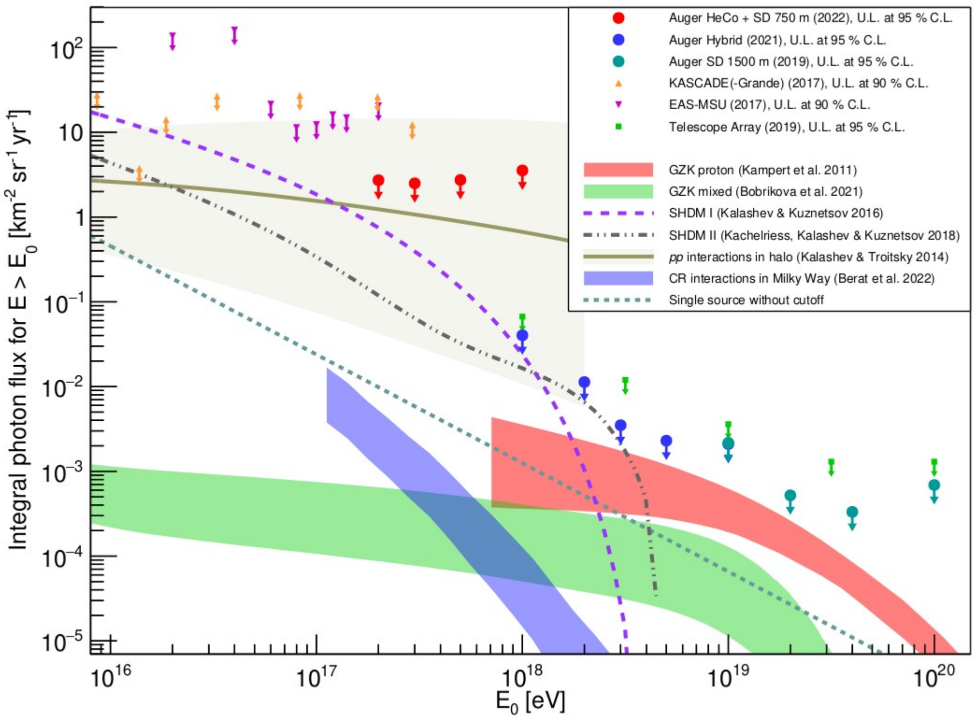


[ApJ 933 (2022) 125]

candidates compatible with background expectation

Upper limits on the integral above E_0 of the flux kE^{-2} (such flux expected in all searches)

Diffuse UHE neutrinos

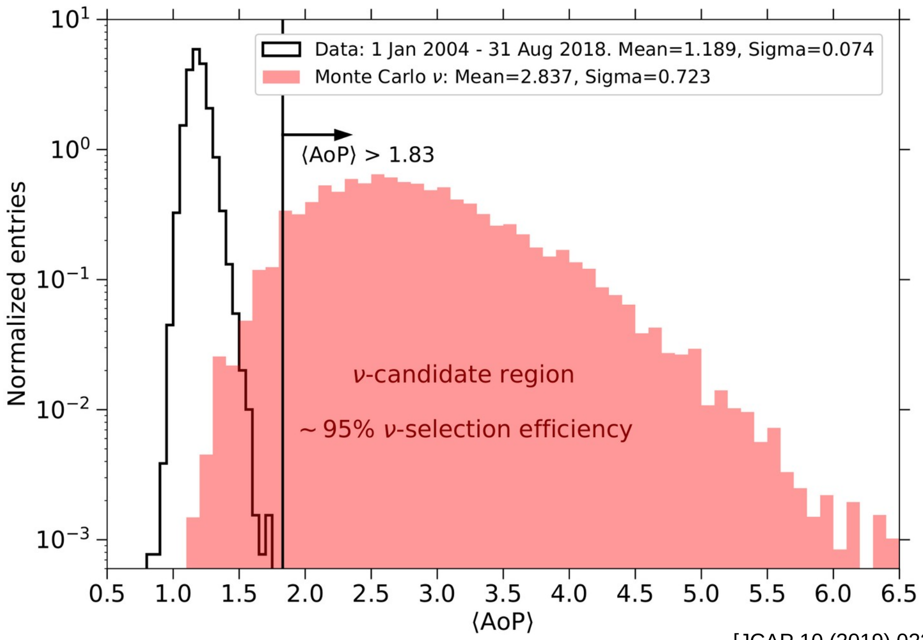
Neutrino showers vs. UHECRs:

- interaction deep in the atmosphere or in Earth
- sizable EM component for **inclined geometries**

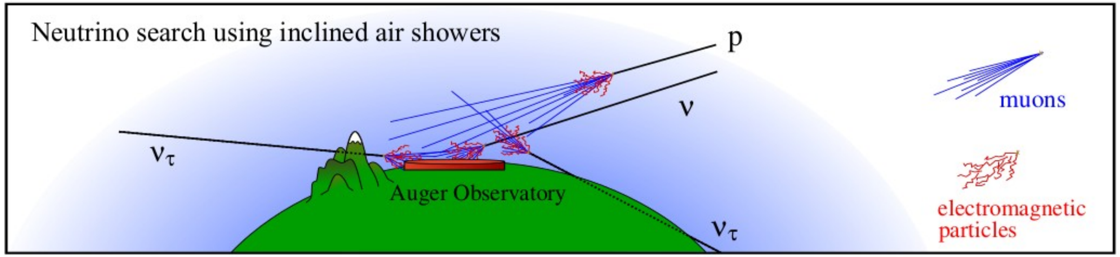
Three SD data sets (channels)

- downward-going – ν_e, ν_μ, ν_τ CC/NC
  - low zenith (**DGL**) - 60° < θ < 75°
  - high zenith (**DGH**) - 75° < θ < 90°
- Earth-skimming (**ES**) – ν_τ CC only - 90° < θ < 95°
- due to optimization of selection
  - AoP, L/W and apparent velocity

ES channel



[JCAP 10 (2019) 022]



even more efficient selection than for photons

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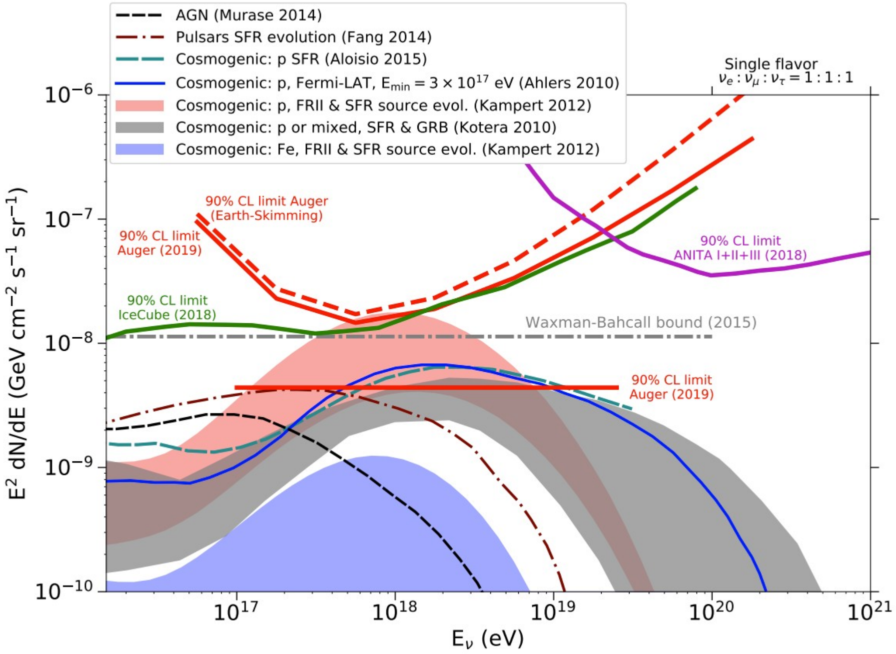
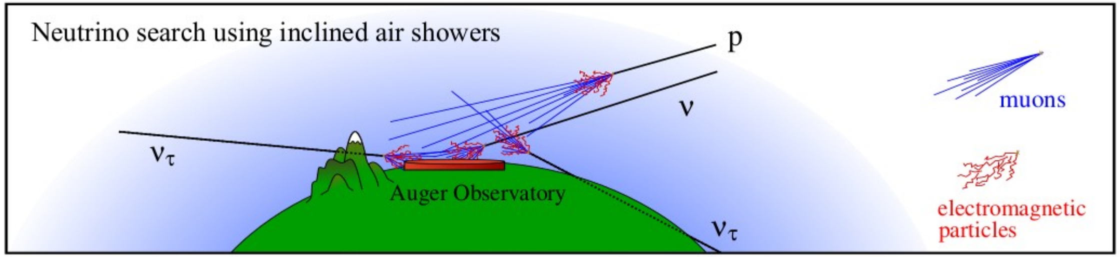


[JCAP 10 (2019) 022]



no candidates

Upper limits on differential flux

Diffuse UHE neutrinos

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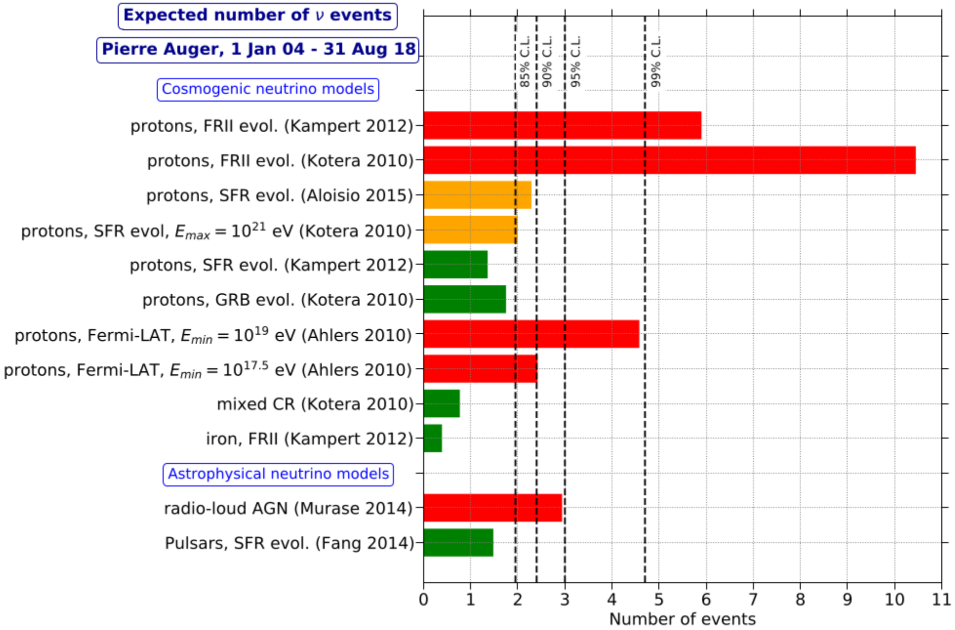
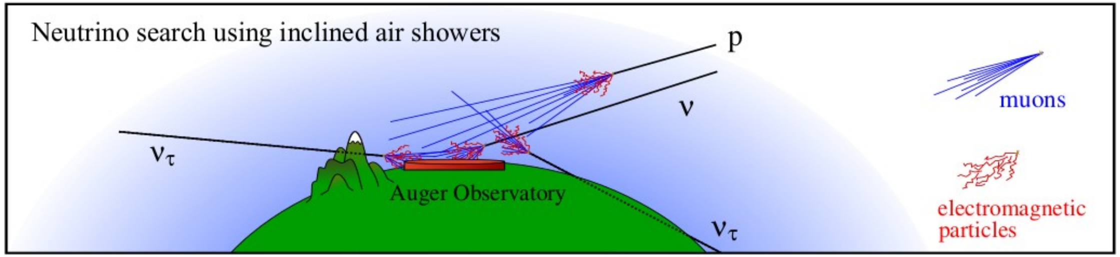


[JCAP 10 (2019) 022]



Some models of ν production ruled out

Neutrinos from point-like sources

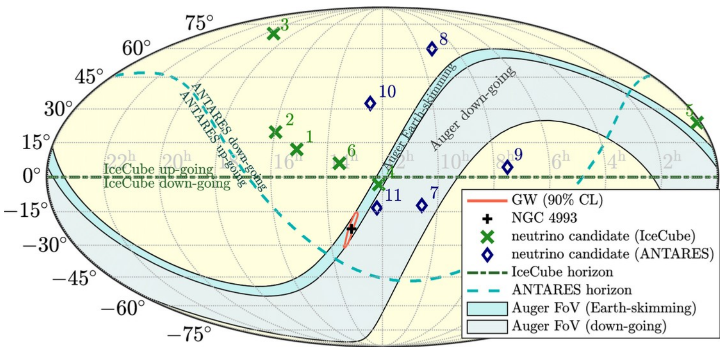
Steady sources

- exposure calculated for particular sky positions (δ, α)

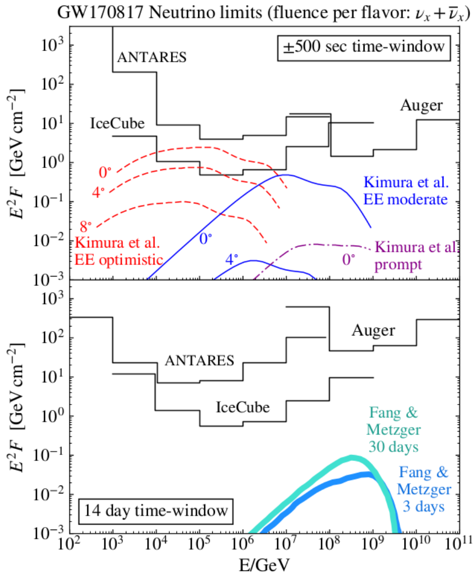
Transient events

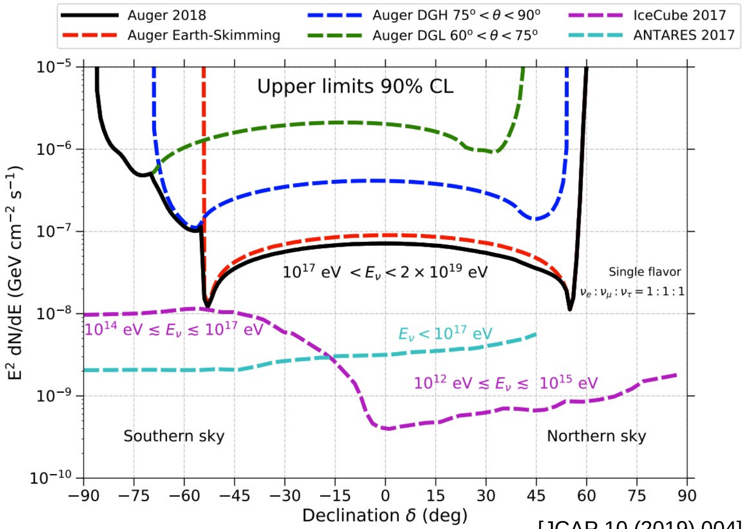
- GW170817 (NS-NS merger) – observed in ES channel
- TXS 0506+056 (blazar with IceCube ν) – less convenient position
- no candidates so far

GW170817

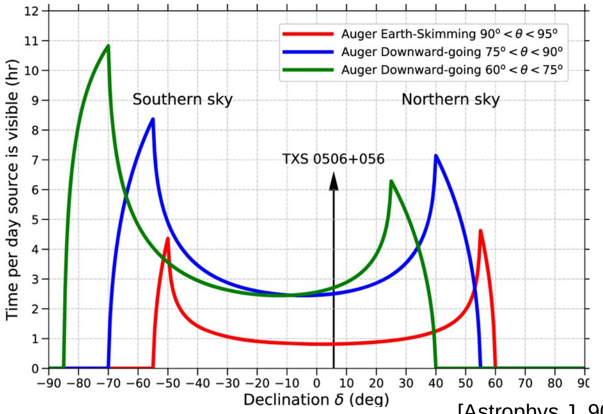


[Astrophys.J.Lett. 850 (2017) L35]





[JCAP 10 (2019) 004]



[Astrophys.J. 902 (2020) 105]

Correlations between UHECRs and neutrinos

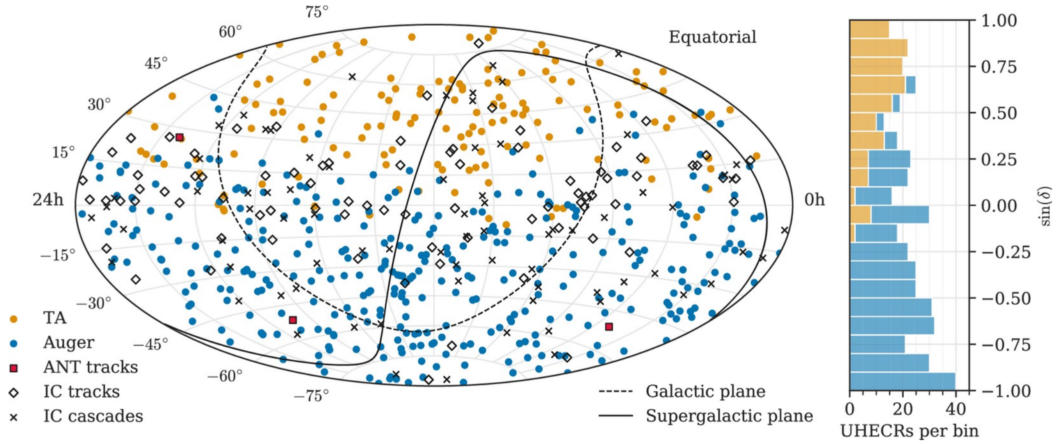
[Astrophys.J. 934 (2022) 164]

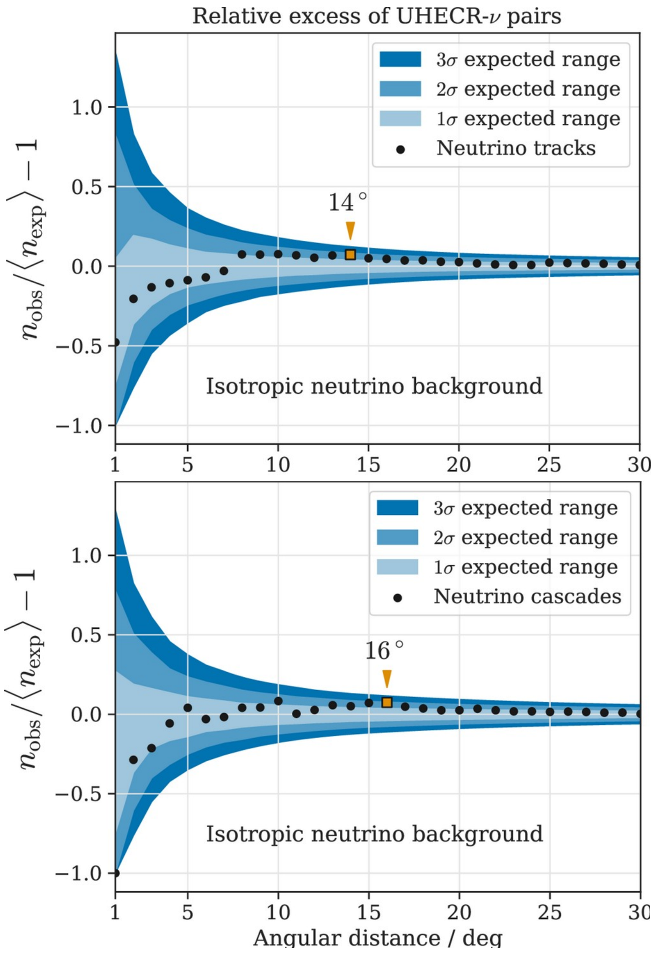
Catalogues of UHECRs and neutrinos – full sky covered

- UHECR – Pierre Auger Observatory, Telescope Array
- neutrinos – IceCube, ANTARES

Three searches (1+2 include deflections of UHECRs in GMF)

1) for point-like ν sources in UHECR directions
2) for excess of UHECRs in astrophys. ν directions
3) two-point correlation of UHECRs and high-energy νs





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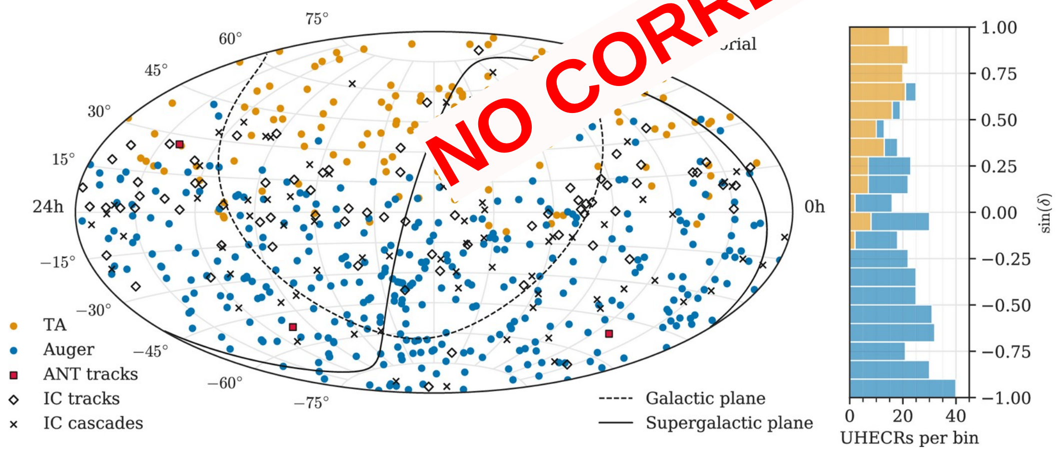
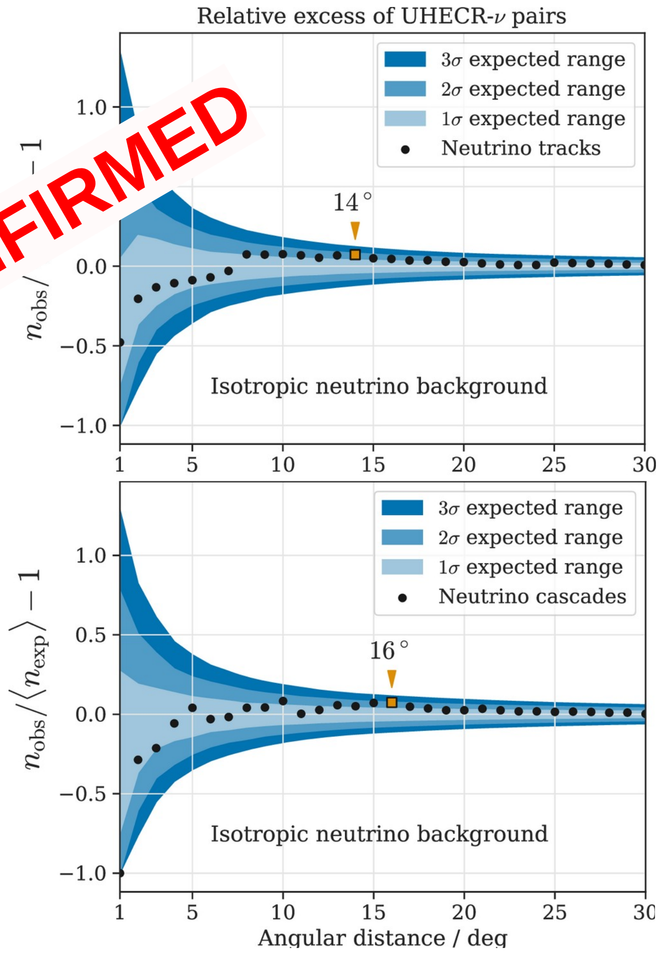
NO CORRELATION CONFIRMED

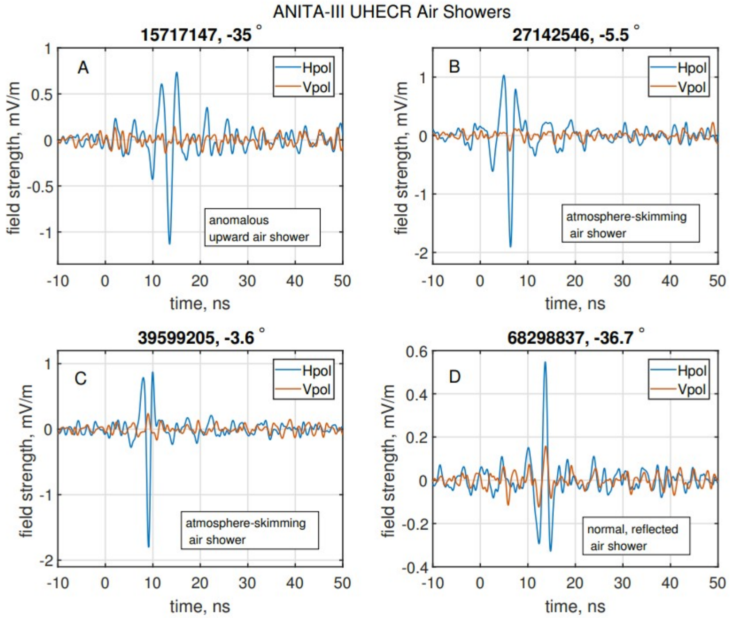


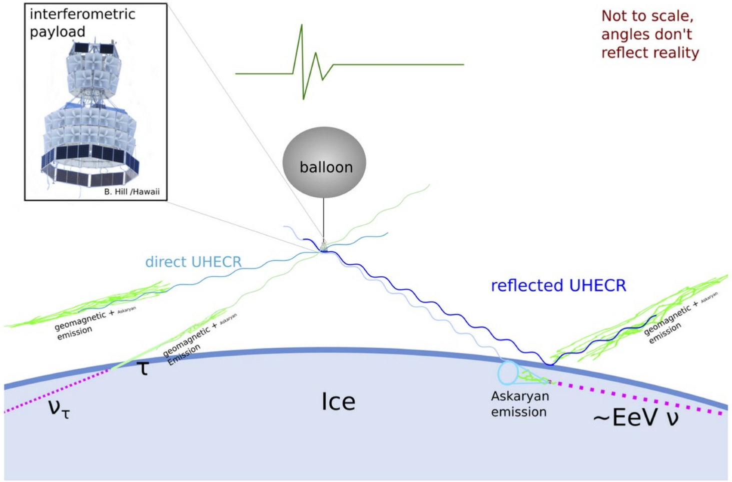


Unusual upward-going showers in ANITA

ANITA baloon experiment

- ~37 km above Antarctica
- detects radio pulses from EASs – looks for ν_τ
- reflected vs. direct observation from polarity
  - **two anomalous events** – too negative elevation
    - does not fit the Standard Model prediction for ν_τ





event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[(1)]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec[(2)]	282.14064, +20.33043	50.78203, +38.65498
$E_{shower}^{(3)}$	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

[1] Latitude, Longitude of the estimated ground position of the event.
[2] Sky coordinates projected from event arrival angles at ANITA.
[3] For upward shower initiation at or near ice surface.

[Phys. Rev. Lett. 121 (2018) 161102]

Upward-going showers at the Auger Observatory

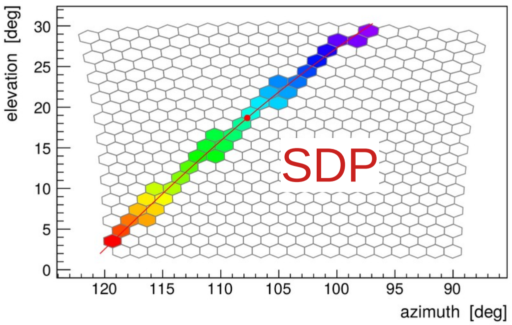
SD

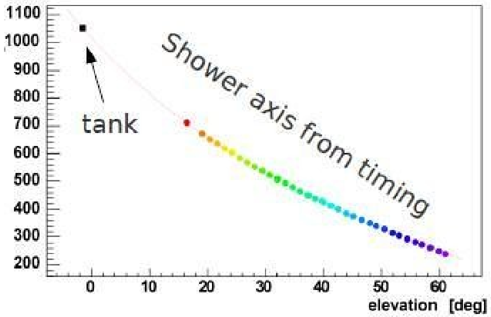
- could detect Earth-skimming EASs only for θ < 95°
    - geometrically limited by lateral spread of showers

FD

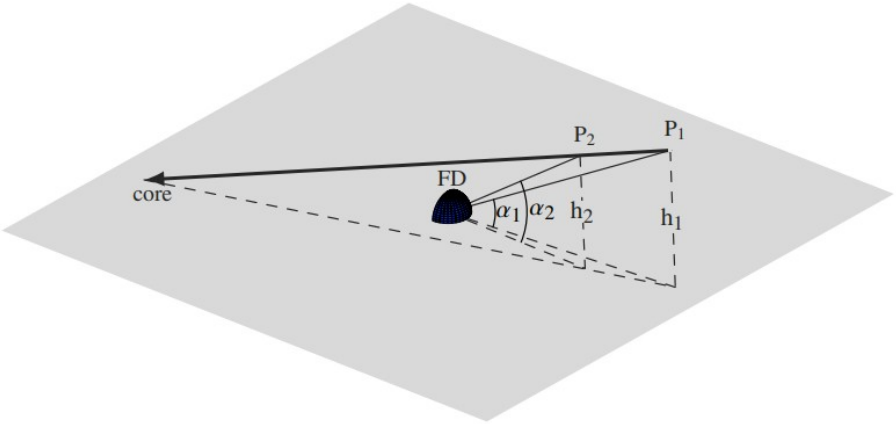
- sensitive at all zenith angles
    - exposure from Monte Carlo simulations
- monocular reconstruction instead of hybrid
- precise selection and **background estimation** needed
    - ordinary UHECRs can mimic upward geometry in mono.
        - extensive MC of downward-going showers

reconstruction of shower axis





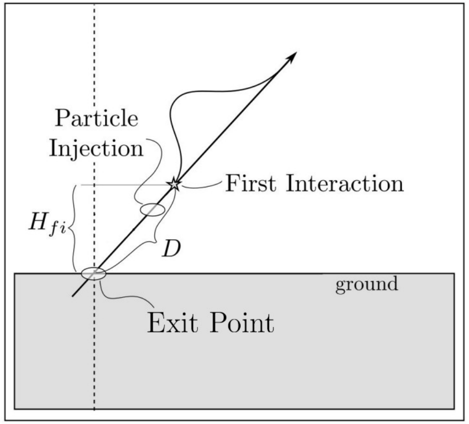
geometry of backgound events



Signal and background

Signal simulations

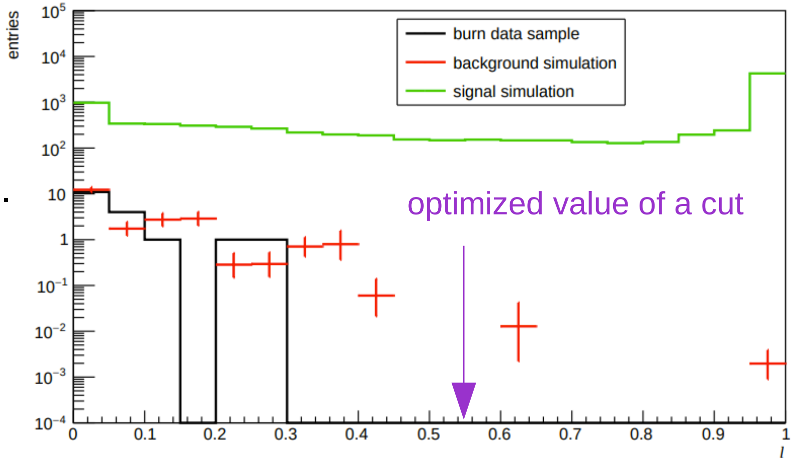
- zenith limited to 110°-180° - ES channel of ν_τ omitted
- FD sensitivity decreases with altitude of the first interaction
  - H_{fi} sampled between 0 km - 9 km



Background simulations and data cleening

- background sims. used to define cuts
  - large volume needed to cover all geometries
  - every event reconstructed as downward- and upward-going
    - profile-constrained geometry fit - maximum likelihood for each rec.
  - selection confirmed on a burnt sample (10 % of all data)

$$l = \frac{\arctan\left(-2\log\left(L_{\rm down}/\max(L_{\rm up}, L_{\rm down})\right)/50\right)}{\pi/2}$$



[PoS (ICRC 2021) 1140]

Results

1 candidate event observed

- compatible with background

$$n_{\text{bkg}} = 0.45 \pm 0.18$$

Exposure evaluated up to E = $10^{18.5}$ eV

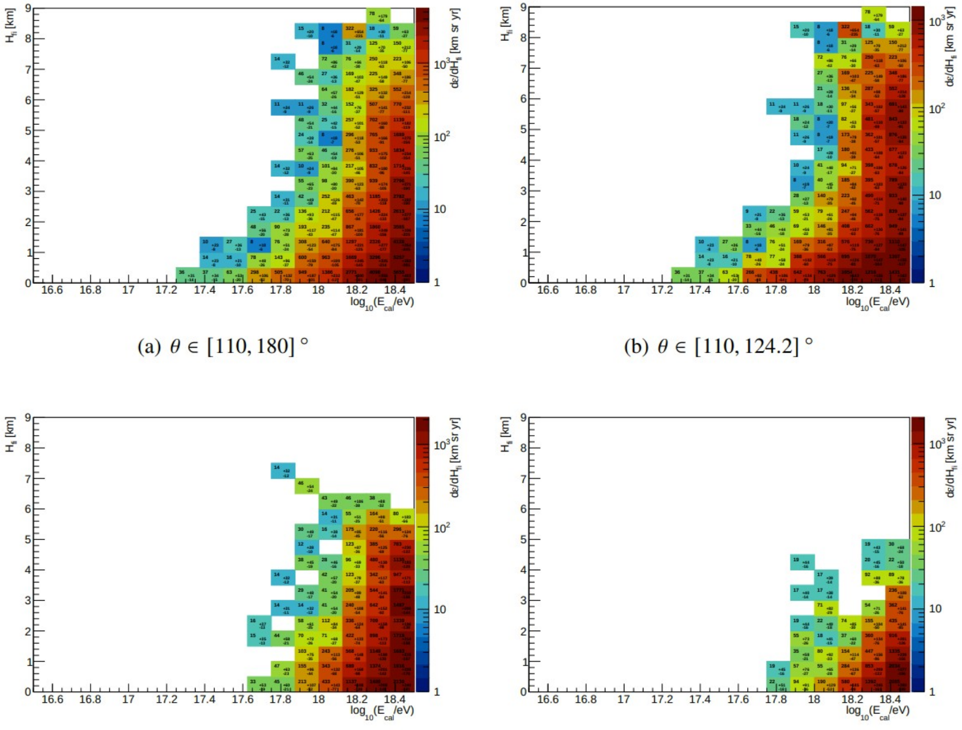
- for three zenith angles separately + combined
- significant height dependence

Integral limits

- valid for two spectral indeces γ = -1, -2

$$F^{95\%}_{\gamma=1}(E_{\text{cal}} > 10^{17.5}\,\text{eV}) = 3.6 \cdot 10^{-20}\,\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$$
$$F^{95\%}_{\gamma=2}(E_{\text{cal}} > 10^{17.5}\,\text{eV}) = 8.5 \cdot 10^{-20}\,\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$$

Preliminary



(a) $\theta \in [110, 180]^\circ$ (b) $\theta \in [110, 124.2]^\circ$

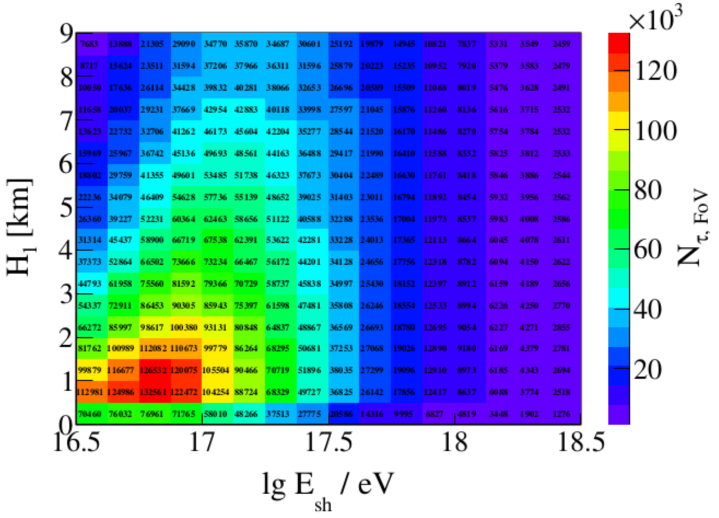
(c) $\theta \in [124.2, 141.3]^\circ$ (d) $\theta \in [141.3, 180]^\circ$

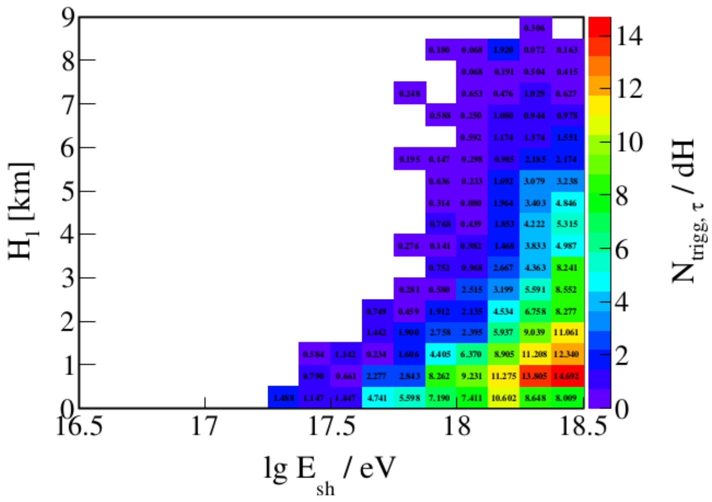
[PoS (ICRC 2021) 1140]

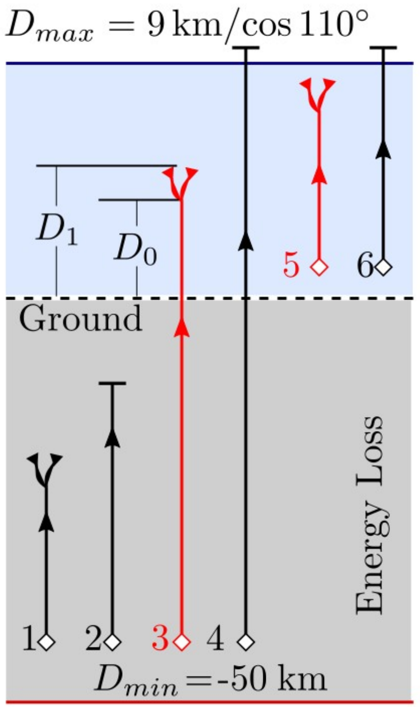
Limits on τ flux

Example application of double-differential exposure

- production of τ leptons by non-specified process (beyond SM)
- D_{inj} between -50 km and 26.3 km
- only cases 3 and 5 visible in FD
- decays of τ into π, K or e produce EAS with E_{sh}





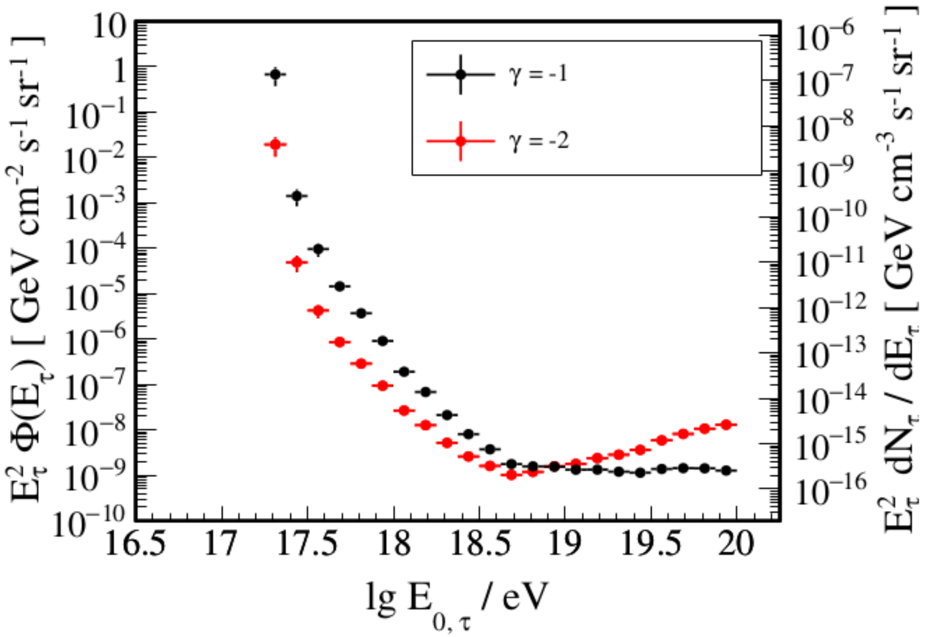


[PoS (ICRC 2021) 1145]

Limits on τ flux

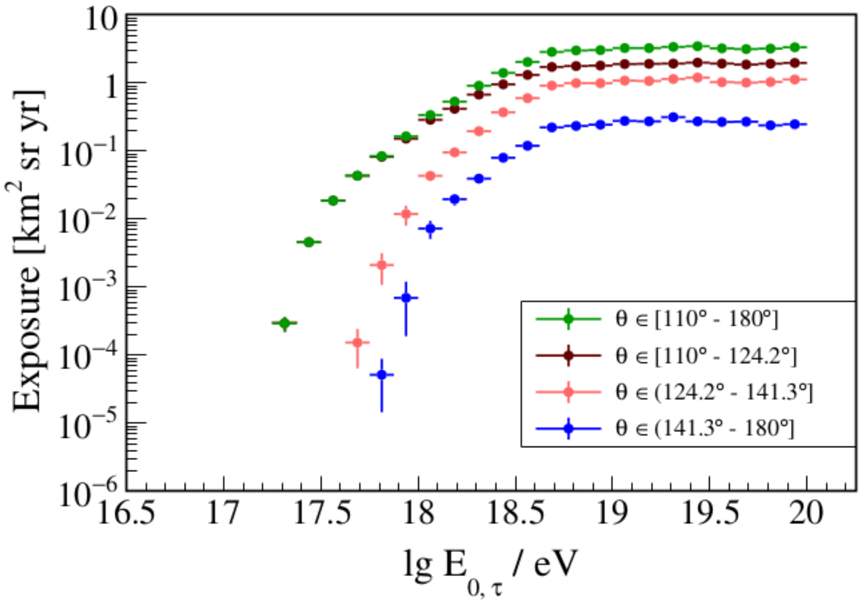
Upper limits on τ flux near ground

- E_{sh} backtracked to primary energy of τ, $E_{0,\tau}$
- two spectral incices of the τ flux assumed
  - propagate to the $E_{0,\tau}$ dependence of E_{sh}



Exposure in zenith bins + total one

- dominated by inclined geometries
- limits available also for specific θ ranges



[PoS (ICRC 2021) 1145]

Conclusions

No UHE photon nor neutrino signals observed

- upper limits presented - diffuse and point-like sources
- diffuse photon limits close to some cosmogenic production models
- diffuse neutrino limits competitive with IceCube and ANITA
    - Earth-skimming channel the most important
    - some models of ν production already ruled out

No correlation between high-energy neutrinos and UHECRs confirmed

- deflections of UHECRs in Galactic magnetic field are included in searches

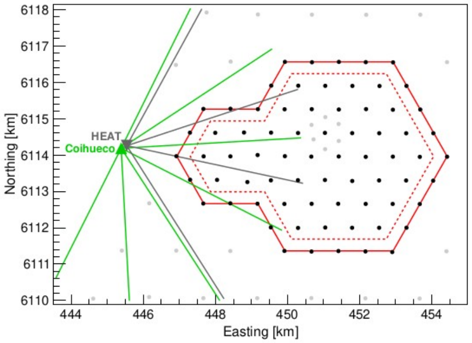
No upward-going showers observed for zenith > 110°

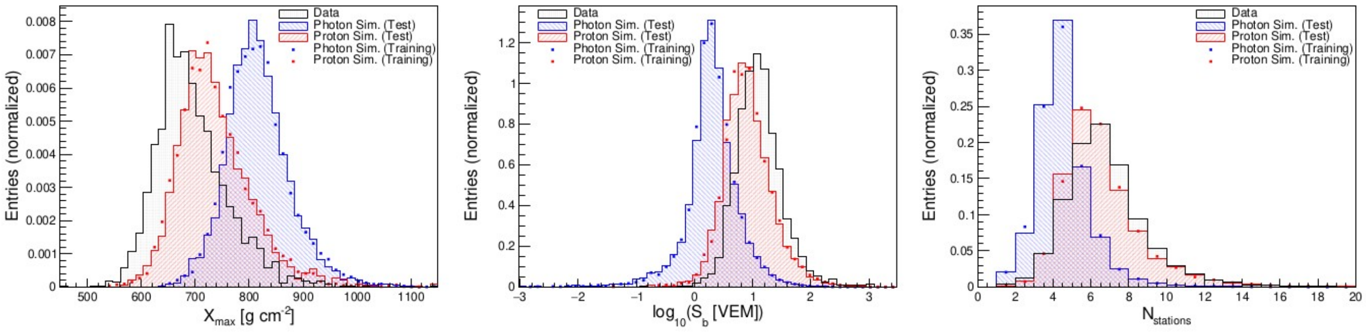
- 1 candidate event compatible with background expectation
- preliminary study, details to be finalized

Backup

Diffuse UHE photons

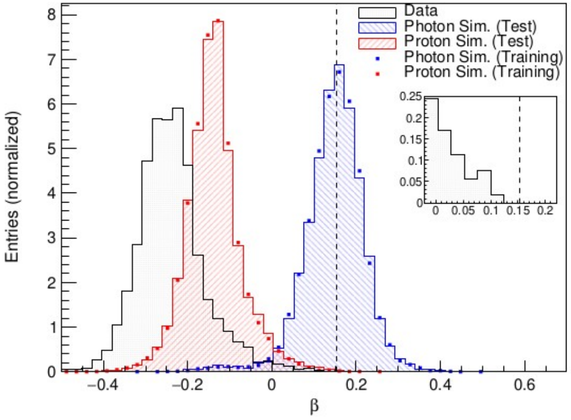
HeCo+SD 750 m selection





(a) (b) (c)

BDT



UHE photons from GW events

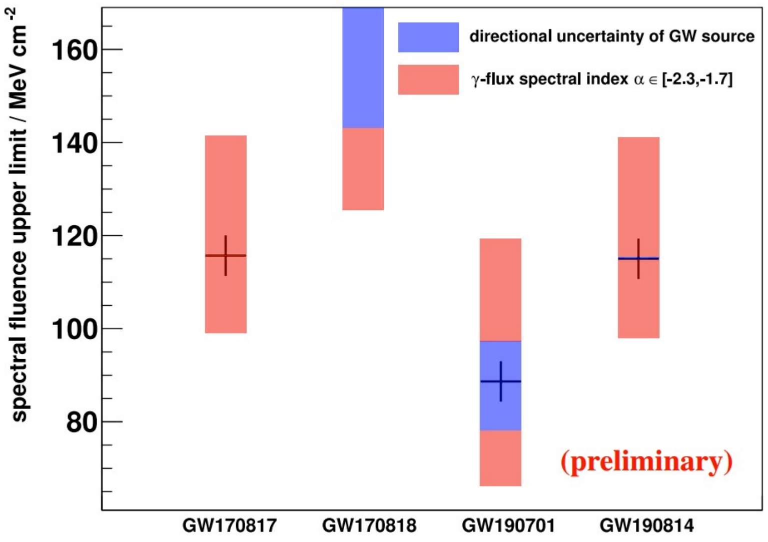
Similar analysis as for transient neutrino sources

- GW events selected to match either of the classes:

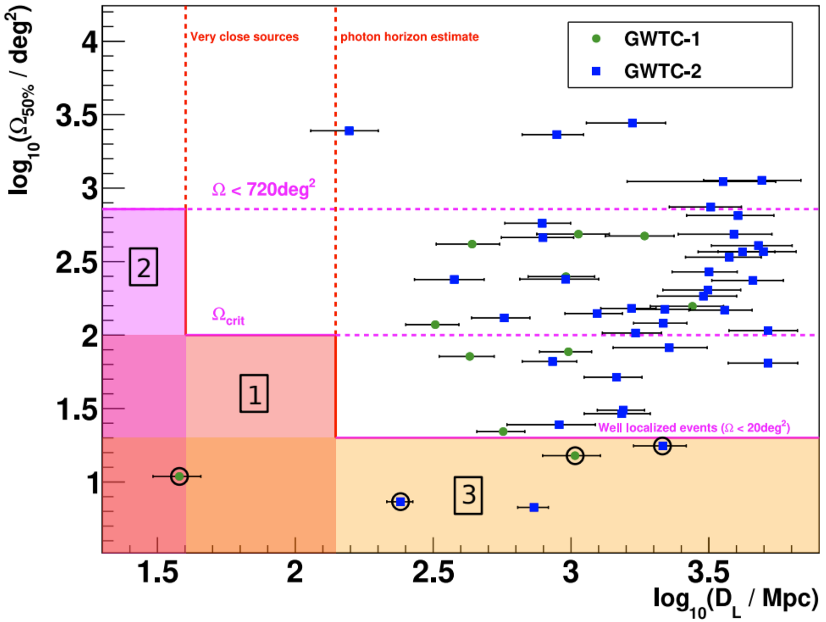
$$(D_L < 140\,\mathrm{Mpc} \quad \text{and} \quad \Omega_{50\%} < 100\,\mathrm{deg}^2) \quad \text{“class 1”}$$

$$(D_L < 40\,\mathrm{Mpc} \quad \text{and} \quad \Omega_{50\%} < 720\,\mathrm{deg}^2) \quad \text{“class 2”}$$

$$(D_L < \infty \quad \text{and} \quad \Omega_{50\%} < 20\,\mathrm{deg}^2) \quad \text{“class 3”.}$$

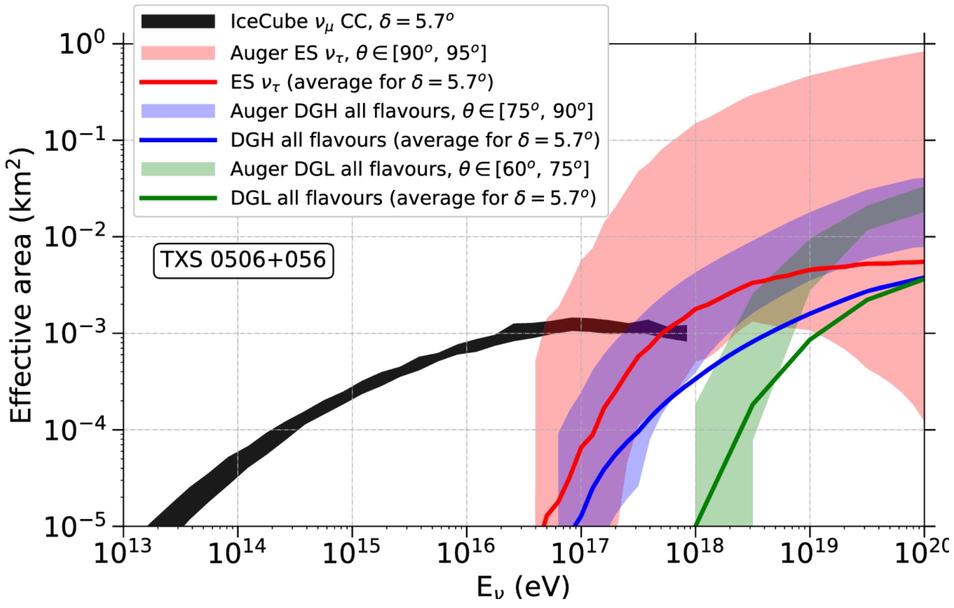


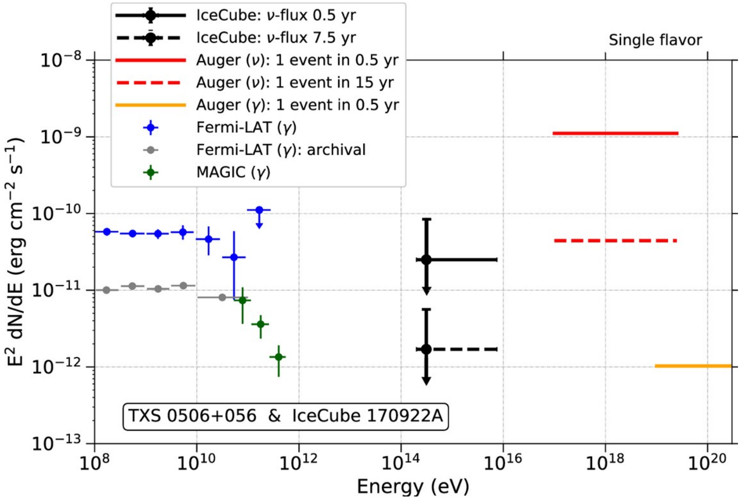
BNS BBH BH-NS

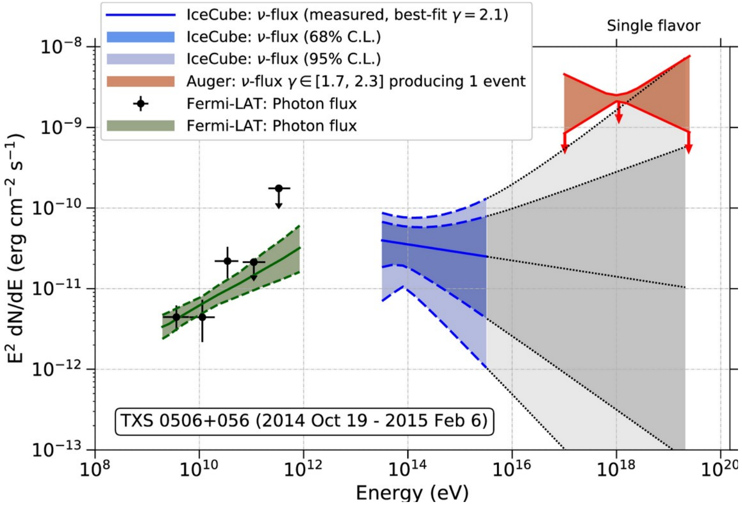


UHE neutrinos from TXS 0506+056

Instead of limits on flux, a reference flux that would produce 1 neutrino event is shown



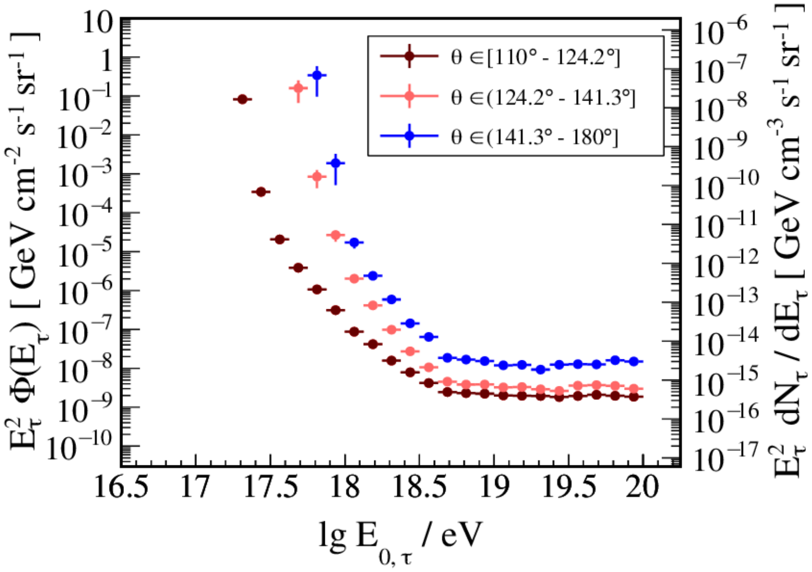




Limits on τ flux

Upper limits for the two spectral indices of the τ flux in three zenith angle ranges

$\Phi_\tau \sim E^{-1}$



$\Phi_\tau \sim E^{-2}$