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MARIE CURIE ACTIONS

Search for ultra-high energy photons and neutrinos with the Pierre Auger Observatory

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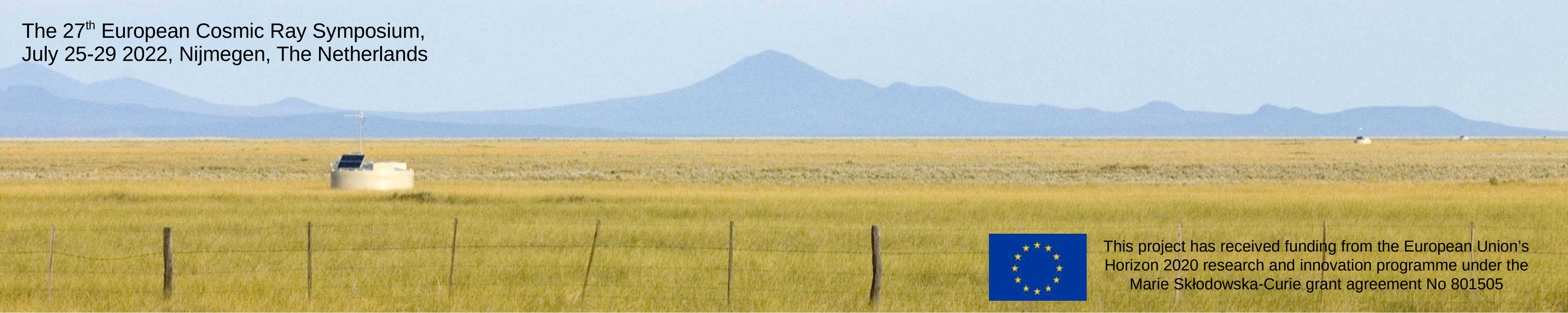
Inter-University Institute of High Energies



The 27th European Cosmic Ray Symposium,
July 25-29 2022, Nijmegen, The Netherlands

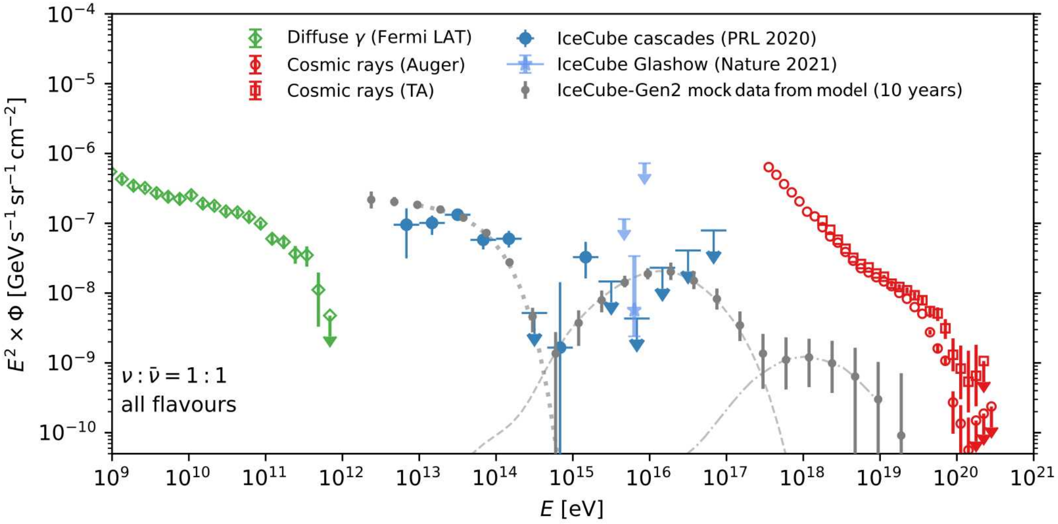
This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 801505

Neutral particles are probes of the Universe

► Produced in cosmic-ray acceleration sites (astrophysical fluxes), during cosmic-ray propagation (cosmogenic fluxes) or in the decay of putative dark matter particles

► Photons trace the local Universe while neutrinos travel through cosmological distances
→ complementary messengers of astrophysical phenomena

2205.05845, Snowmass 2021



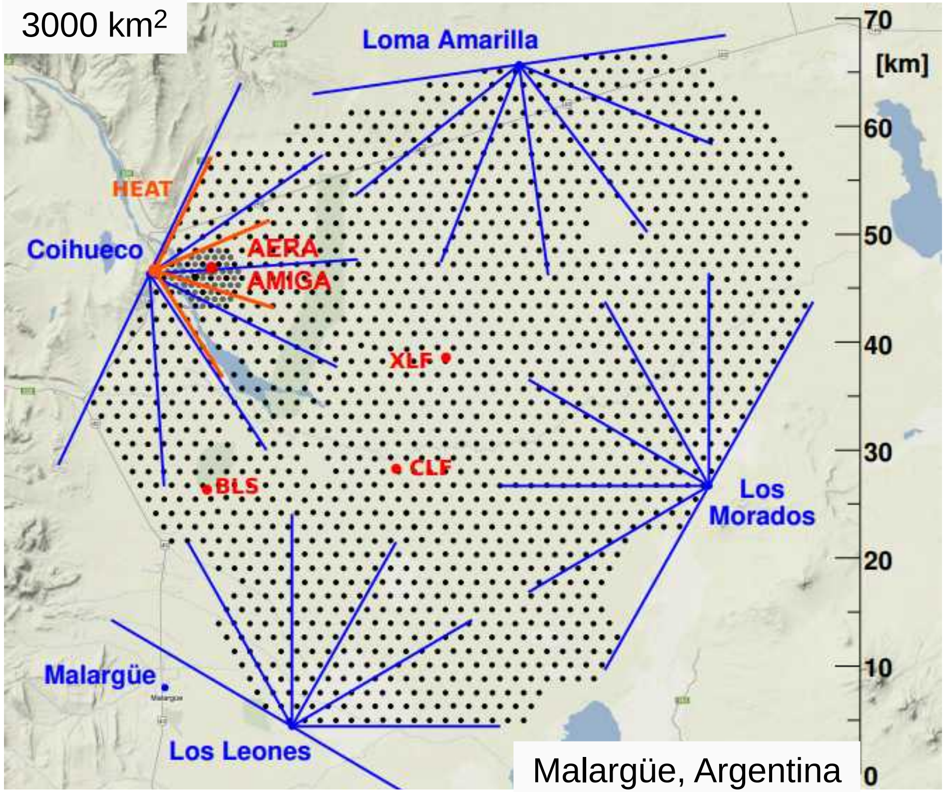
Elusive particles → need for ground arrays with large exposures

Nucl. Instrum. Meth. A 798 (2015) 172-213

The Pierre Auger Observatory

Surface detector (SD)
- 1500 m array
1600 stations
- 750 m array
61 stations

→ measurements of secondary particles on ground

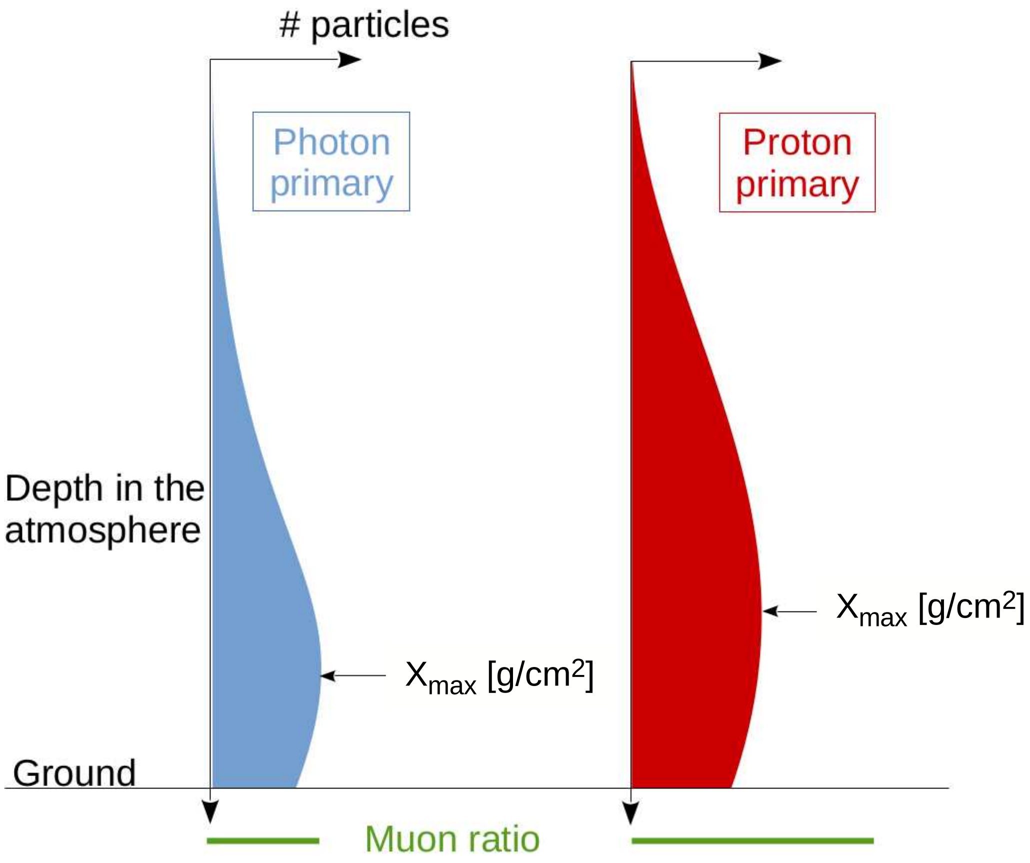


Fluorescence detector (FD)
- 24 telescopes across 4 sites
- 3 high-elevation telescopes (HEAT)

→ measurements of longitudinal shower development

Unprecedented exposure to photons and neutrinos above 0.1 EeV

How can we identify a photon primary?

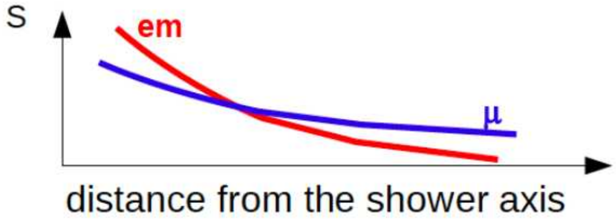


Credits to J. Bouchard

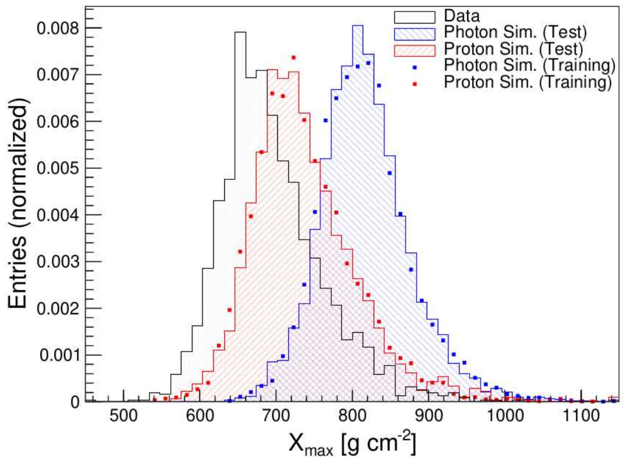
Air-showers initiated by photon primaries follow a nearly pure electromagnetic (EM) development

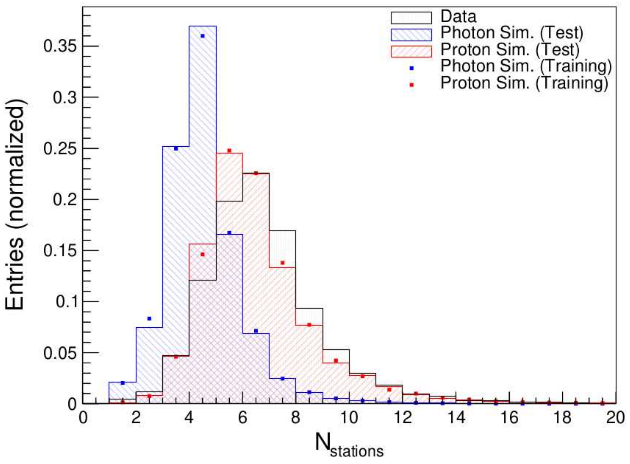
- ► Deeper X_{max} due to lower multiplicity of EM interactions
- ► Less muon production due to suppressed $\pi^{\pm}$ generation channels

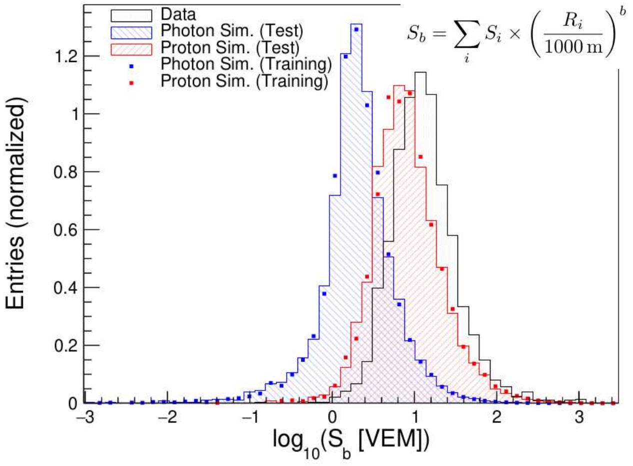
→ steeper lateral spread of signals and smaller footprint

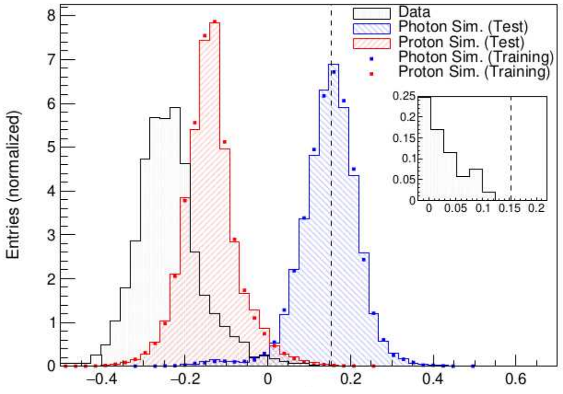


Photon search at 0.2 EeV – 1 EeV









Boosted decision trees observable

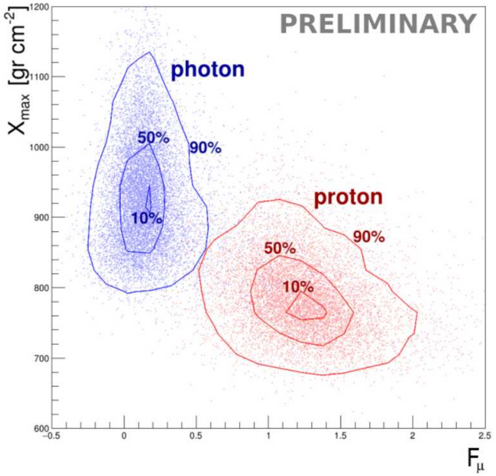
► Candidate events determined with a cut ensuring 50% signal efficiency

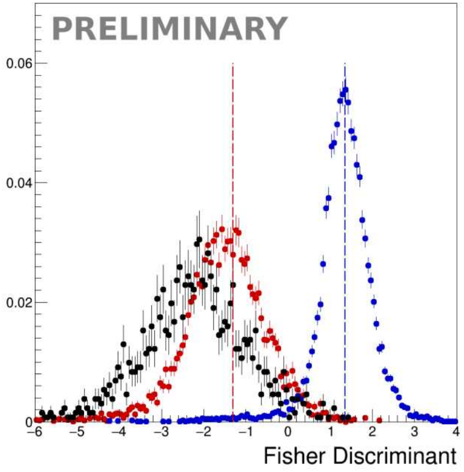
► Expected bkg rejection of ~99.9% bkg rejection, i.e. 2 estimated bkg events in data set

► Data set spanning 5.5 years → ~2.5 km² sr yr

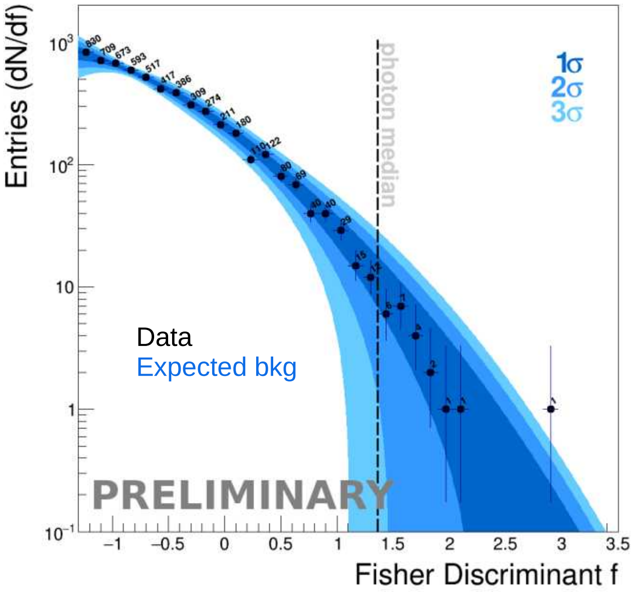
► No events pass the cut

Photon search at 1 EeV – 10 EeV





- ► Bkg contamination estimated with data
- ► Data set spans 12 years → ~1000 km² sr yr
- ► 22 candidate events but consistent with the expected bkg of 30 ± 15 events

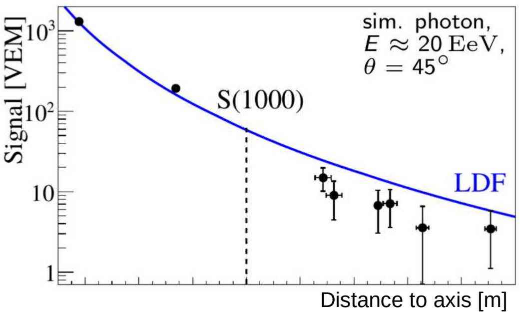


- ► F_μ is a proxy of the muon content
- ► Estimated by matching the measured signal in SD stations to S_{pred} which is a decomposition in EM and muonic components (S_{comp}) parametrized via Universality

$$S_{\text{pred}} = \sum_{i=1}^{4} \beta^i(F_\mu) \cdot S^i_{\text{comp}}$$

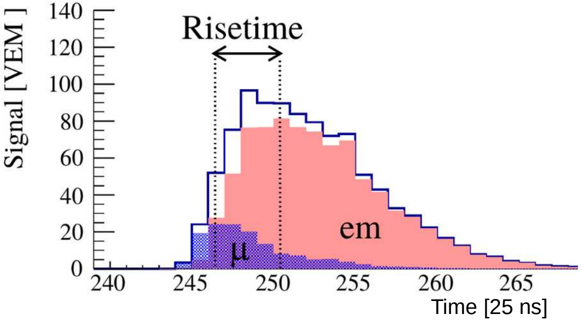
Photon search at > 10 EeV

Steeper lateral spread of particles (LDF)

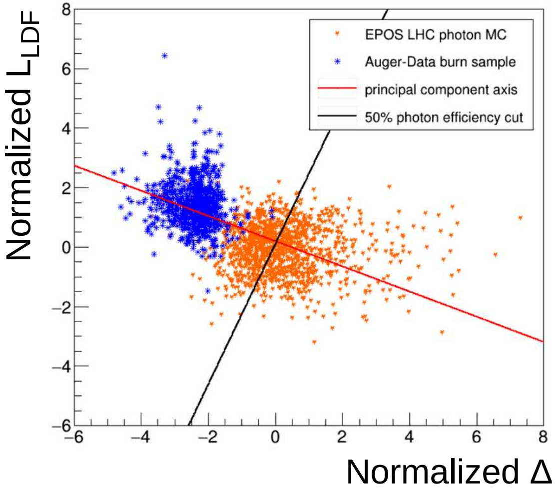


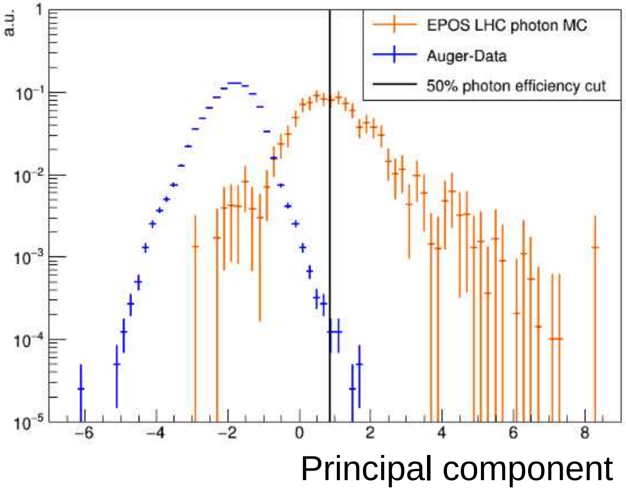
$$L_{\mathrm{LDF}} = \log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}\frac{S_i}{S_{\mathrm{LDF}}(r_i)}\right)$$

Longer signal risetime



$$\Delta = \frac{1}{N}\sum_{i=1}^{N}\frac{t_{1/2}^{i} - t_{1/2}^{\mathrm{bench}}}{\sigma_{t_{1/2}}^{i}}$$

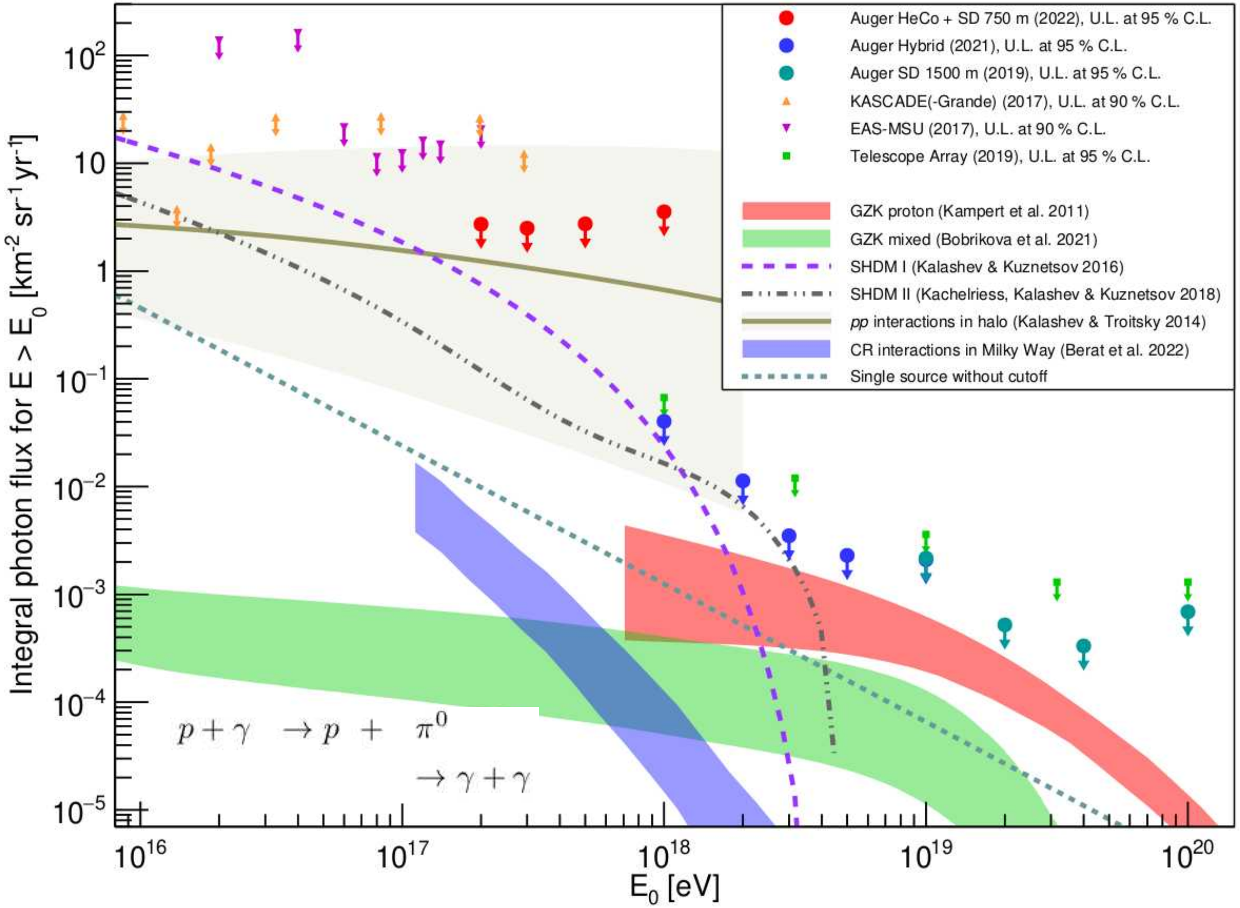




- ▶ Benchmarks $t_{1/2}^{\mathrm{bench}}$ and S_{LDF} obtained with data
  → method free of cosmic-ray composition assumptions
- ▶ Data set spans 14 years → 40000 km² sr yr
- ▶ 11 candidate events, compatible with bkg expectation
- ▶ Updated results to be published soon

2205.14864, accepted ApJ

Upper limits to ultra-high energy photons



► Most stringent limits above 0.1 EeV with 15 years of data

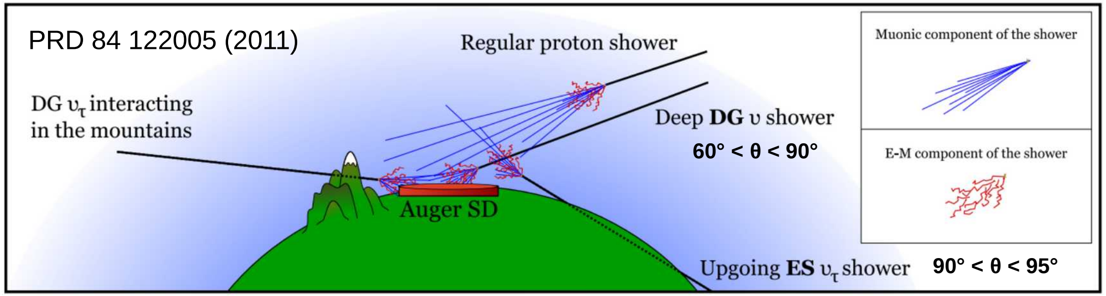
► Constrains mass and lifetime of dark matter particles

► Need more exposure to probe cosmogenic fluxes

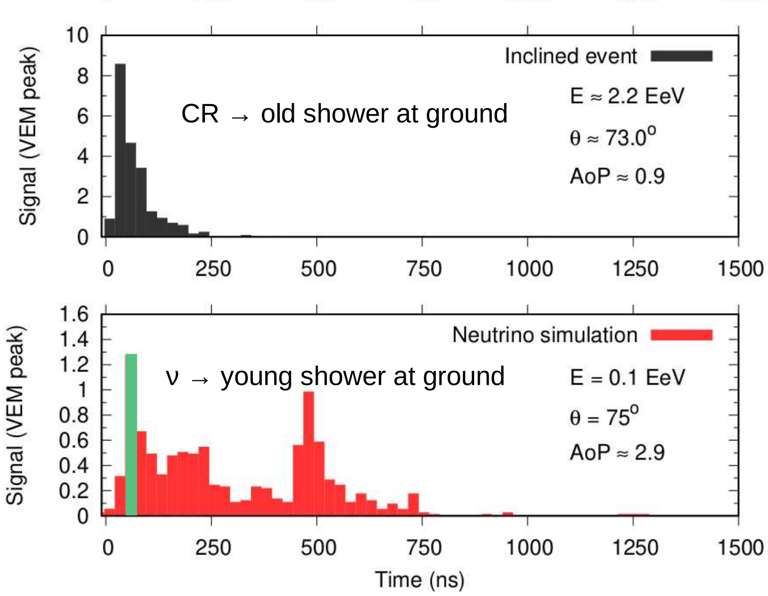
► Photons generated by cosmic rays irradiating the Galaxy may be predominant below 0.1 EeV

► Note that these limits are time-averaged. EeV photons may still be produced in transient events!

How can we identify a neutrino primary?



JCAP10 (2019) 022



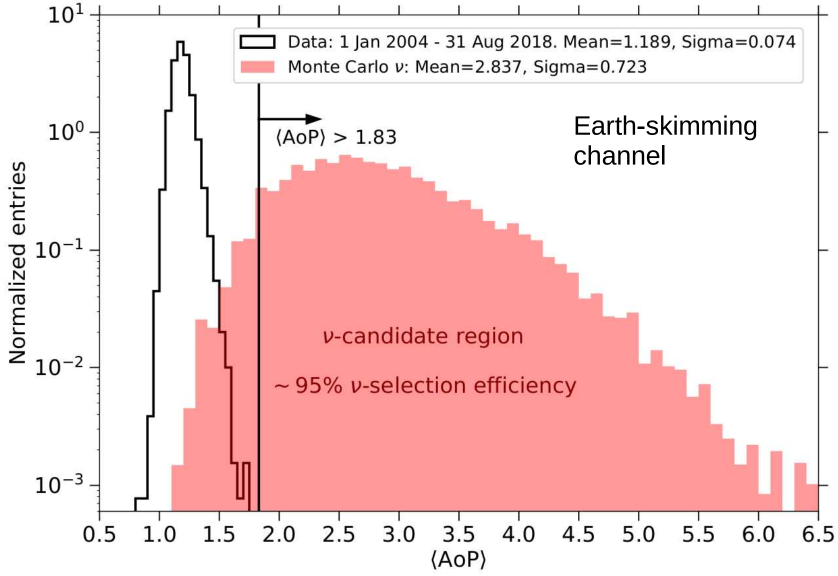
► Down-going (DG) channel: ν interacting deep in the atmosphere. Sensitive to all flavors

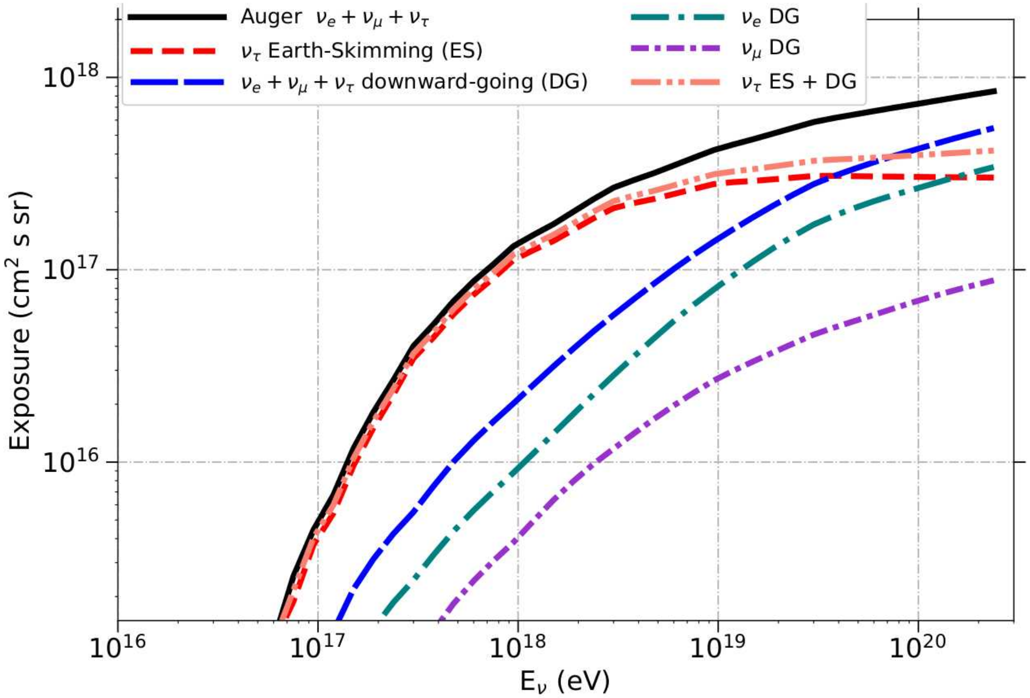
► Earth-skimming (ES) channel: ν_τ interacting in Earth's crust. τ lepton initiating an up-going shower close to the ground

► Background composed by muon-dominated hadronic showers (EM component absorbed in the atmosphere)

► Discrimination relies on the different SD signal shapes between hadronic and neutrino events → **Area**-over-**Peak**

Discrimination power of the neutrino search





► Neutrino air-showers have large AoP

► Neutrino cut such that 1 bkg event expected in 50 years

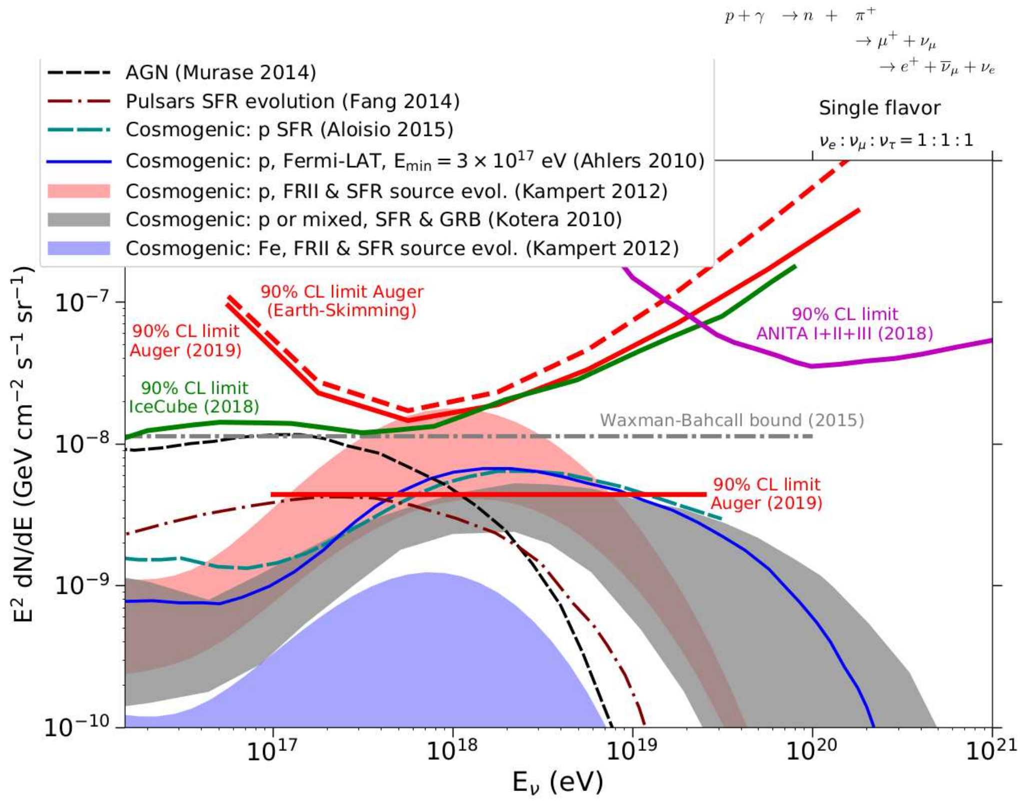
→ sensitivity limited only by operation time. Not affected by bkg contamination

► Sensitivity dominated by ES channel because of larger target matter wrt the atmosphere in DG channel

► ES saturates above ~40 EeV because τ is more likely to decay at much higher altitude above the SD

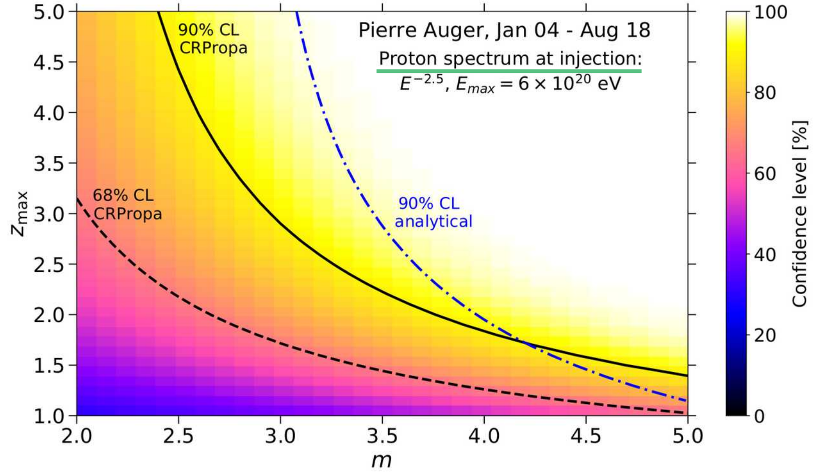
JCAP10 (2019) 022

Diffuse neutrino search



► Integral limit of ~ 4.4 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

► Non-observation disfavors a large parameter space in z_{max} and m [sources evolving as $(1+z)^m$]



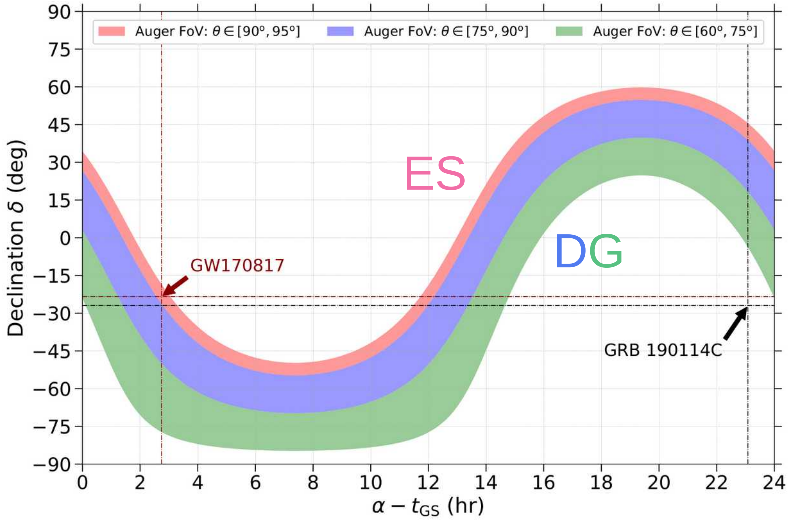
Best sensitivity at 1 EeV, comparable to that of IceCube

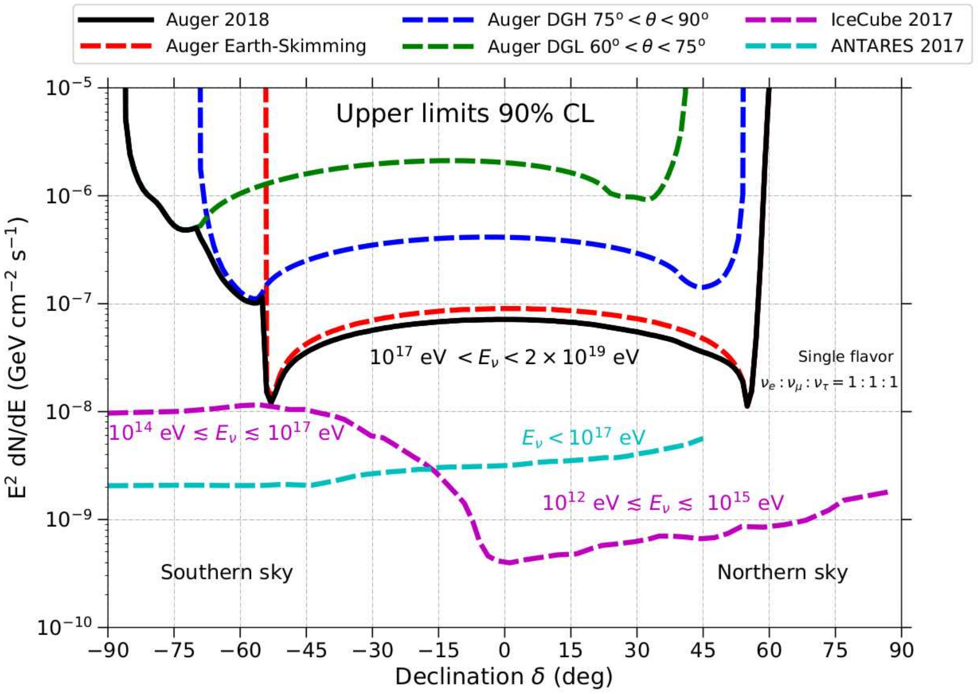
► Pure-proton models strongly disfavoured

► 3-fold increase in exposure needed to probe mixed-composition models

JCAP10 (2019) 004

Sensitivity to steady point sources





► Due to Earth's rotation, point sources transit through the field of view of each channel

► Longest daily transit 4-5 hours in ES channel or 7-12 hours in DG channel

► Total field of view covering δ (-85°,60°)

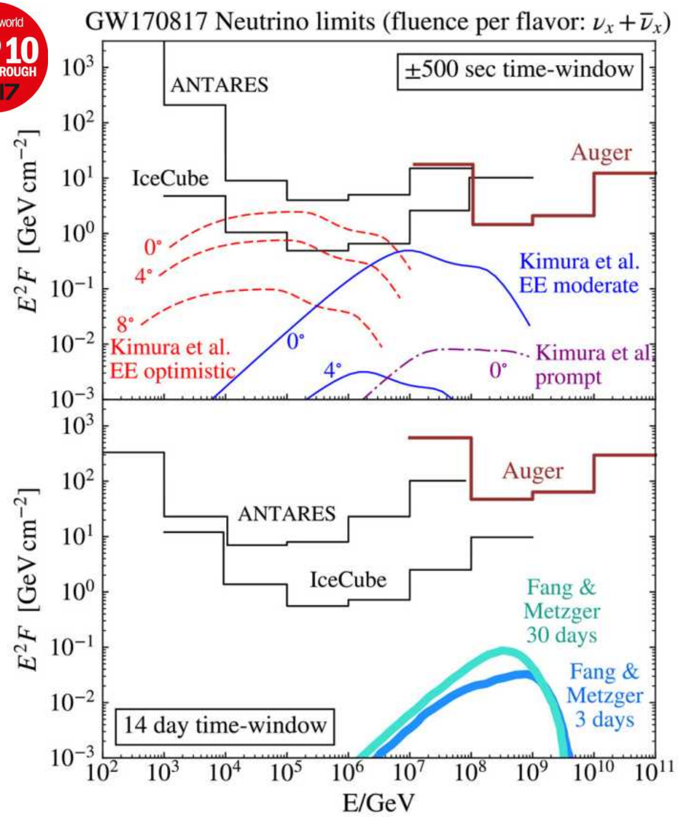
► Sweet spots for longest transit in the ES channel

Complementary energy ranges of experiments

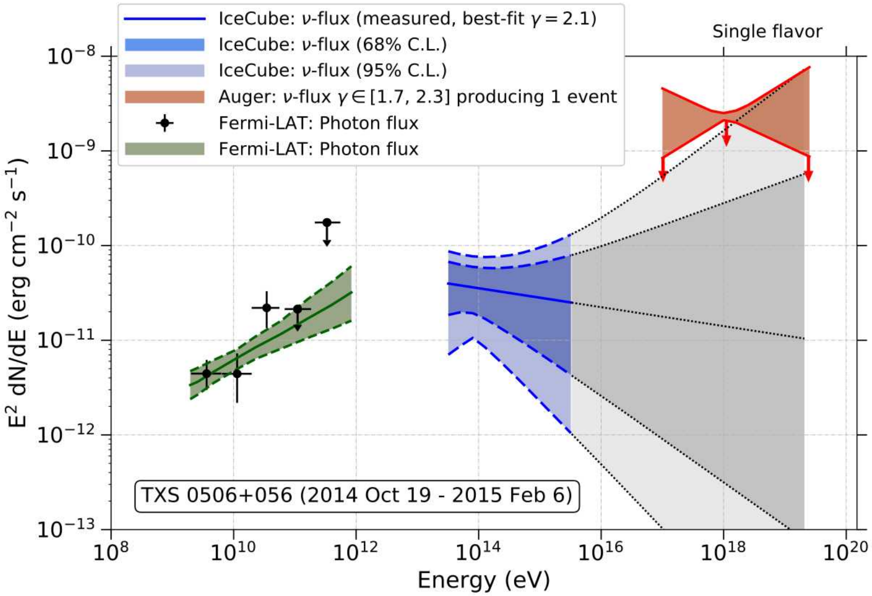
Auger participation in follow-up campaigns

ApJ Lett. 850:L35 2017
ApJ 902:105 2020
Fron. Astron. Space Sci. 6:24 2019

physicsworld TOP 10 BREAKTHROUGH 2017



► Upper limits consistent with an off-axis short gamma-ray burst

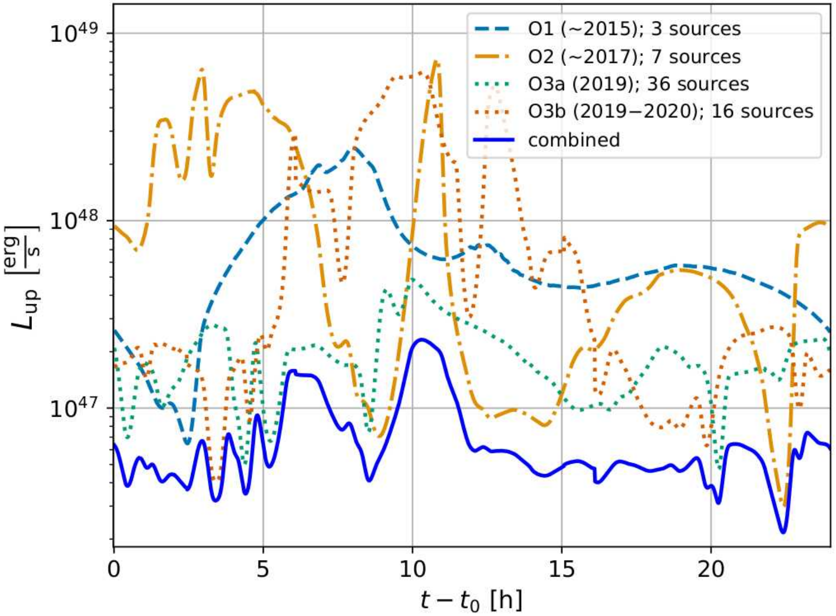


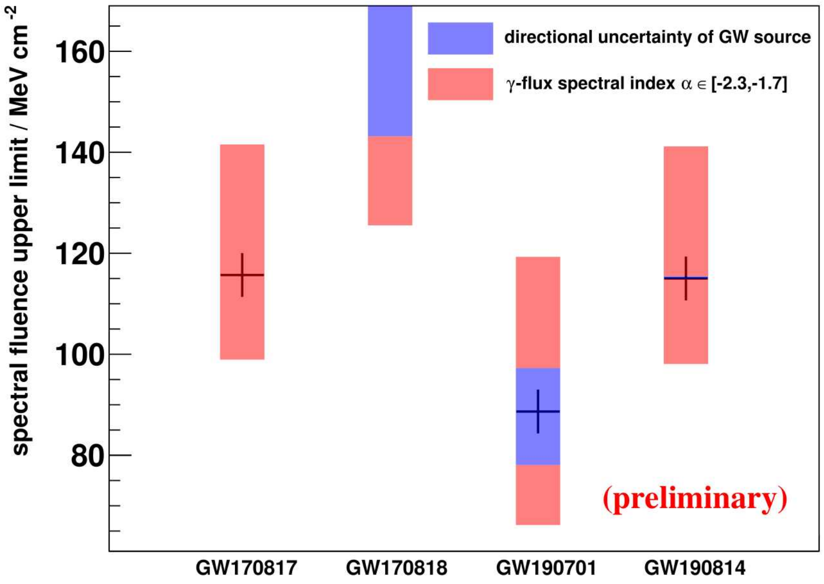
► Blazar detected by Fermi-LAT and IceCube in Sep 2017

► Neutrino excess in IceCube archived data

► Auger would have detected 1 event at ~EeV if extrapolated neutrino spectrum were sufficiently hard

Multi-messenger studies by stacking sources





► Upper limit to the neutrino emission in a 1-day window by stacking 62 gravitational wave (GW) events: $E_\nu < 6 \times 10^{51}$ erg

► Sensitivity improves by combining sources

► First follow-up photon searches in coincidence with nearby GW events above 10 EeV in 1-day window

► If a photon candidate event were detected, the bkg hypothesis would have been rejected at 4.65σ

Summary

► Unrivalled exposure to photons: most stringent flux limits across three decades in energy above 0.2 EeV

► Background-free sensitivity to diffuse EeV neutrinos

► Depending on declination, Auger has an excellent sensitivity to transient neutrino point-sources at EeV, specially if detected via ES channel

► Auger is a key actor in the multi-messenger astronomy at ultra-high energies thanks to its large sky coverage → bounds in models of transient events, dark matter physics, ...

Next stop: AugerPrime

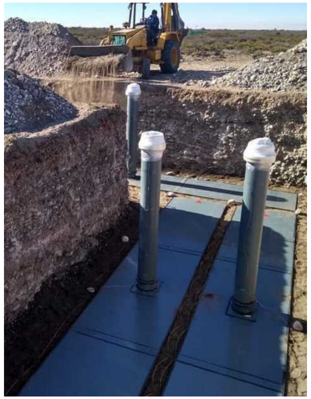
► Aiming at a better separation between shower components.

► Better constrains of ultra-high energy photon and neutrino models or even the first detection!

4 m^2 scintillators

+ faster electronics and extended dynamic range for the SD

30 m^2 buried scintillators



Radio antennas

EPJ Web Conf. 145 (2017) 05001

Backup – Directional γ limits

ApJ 789 160 (2014)
ApJ 837 L25 (2017)

95% CL

Jan 2005 – Sep 2011
0.2 EeV < E < 3 EeV

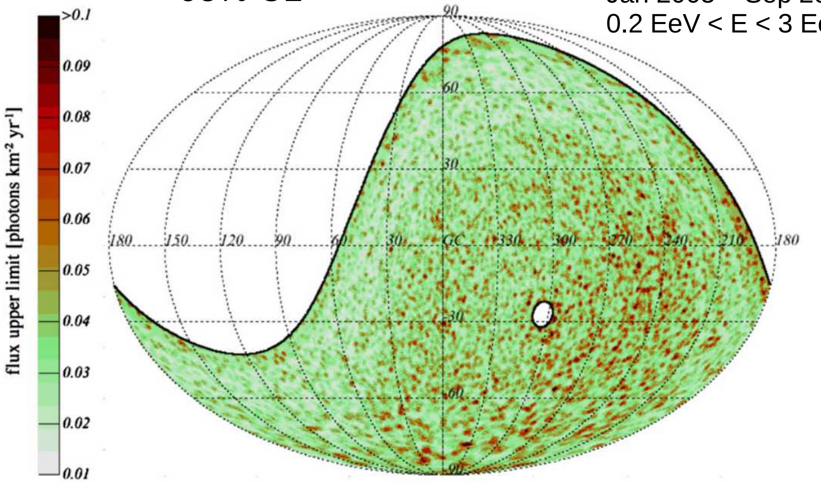
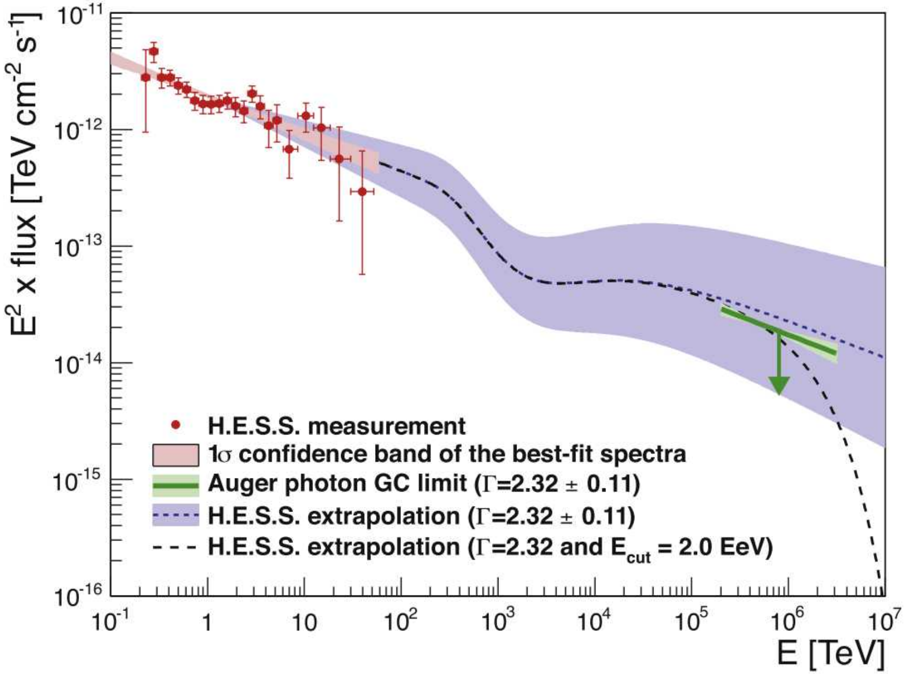


Figure 10. Celestial map of photon flux upper limits in photons km^{-2} yr^{-1} illustrated in Galactic coordinates.



► Multi-variate analysis using hybrid data to select enriched samples of photon-like events

► No significant excess of photon-like events from any direction in the sky

► Upper limits compatible with either:
- extragalactic sources farther than 5 Mpc
- galactic sources but transient
- galactic sources have a small optical depth

► Auger limits to photon flux from Galactic Center constrains allowed parameter space for a HESS extrapolated flux

Backup – Discrimination power of DG channel

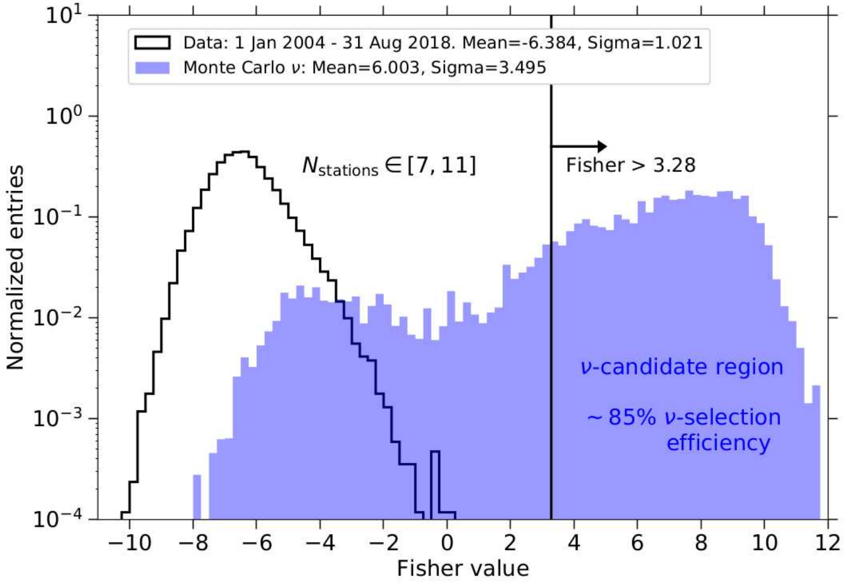


Figure 3. Distribution of the Fisher variable after the downward (DGH) inclined event selection for events with number of triggered stations between 7 and 11. Black histogram: full data set up to 31 August 2018 containing 33885 events. Blue-shaded histogram: Monte Carlo simulated ν DGH events.

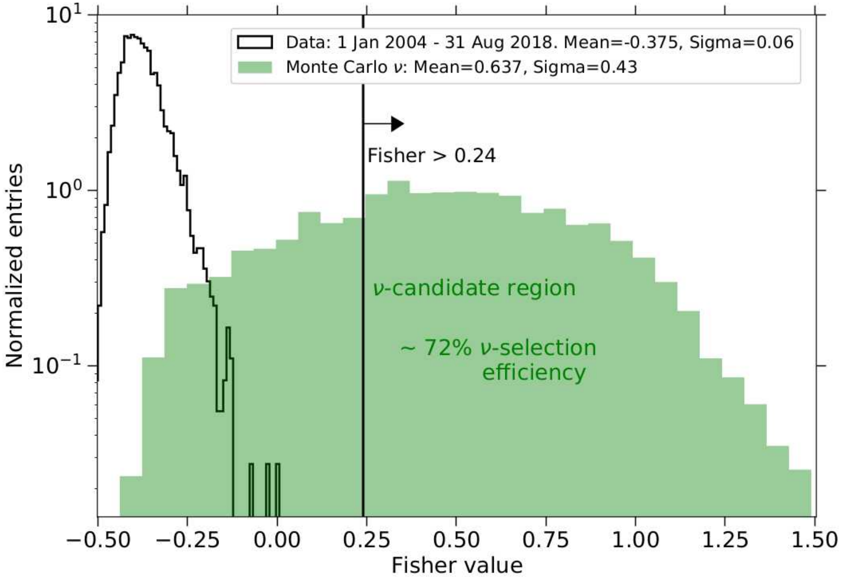
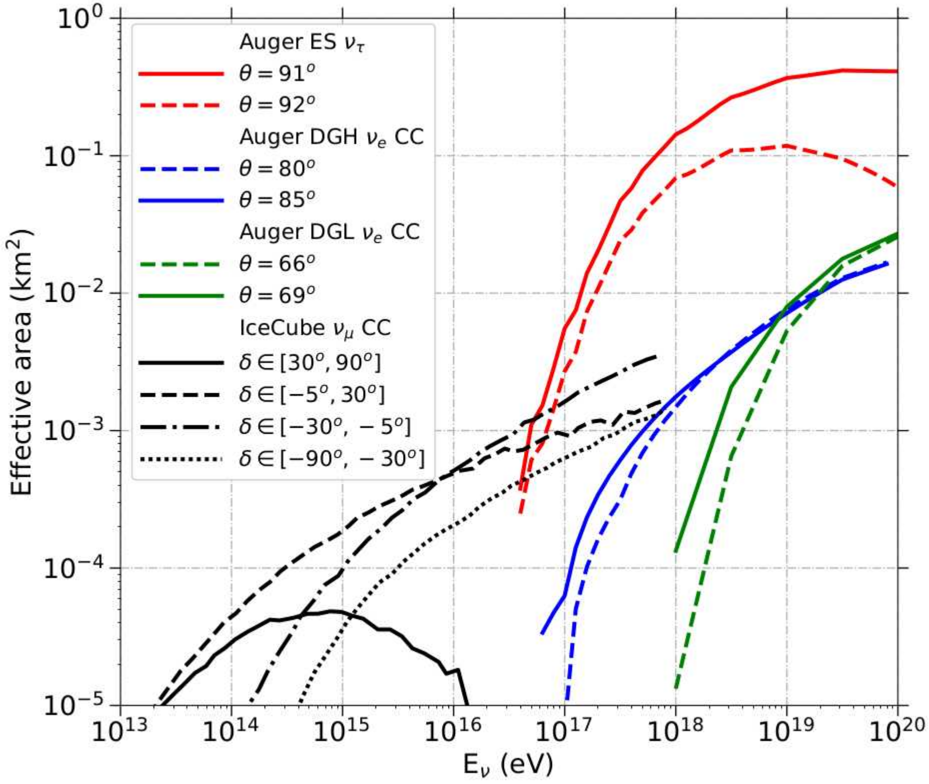


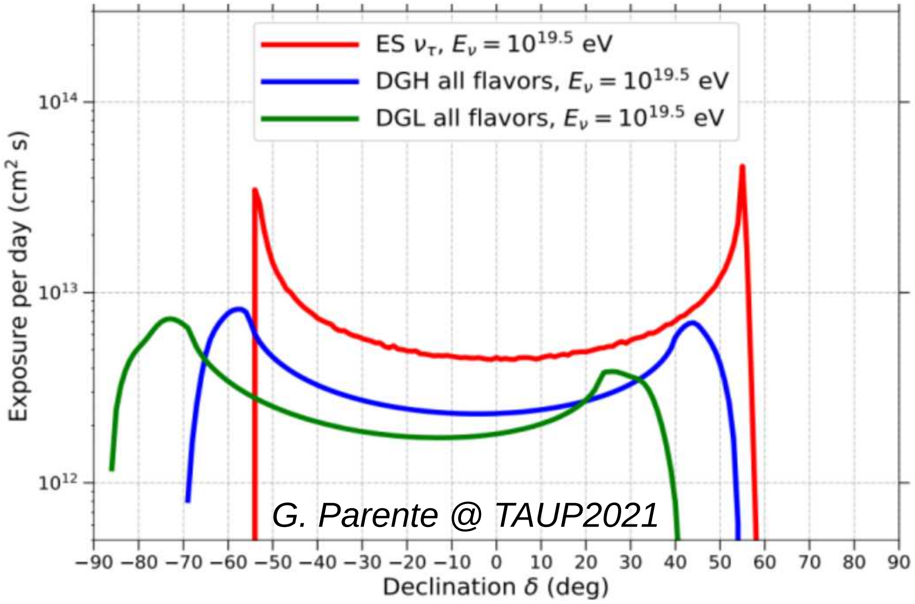
Figure 4. Distribution of the Fisher variable after the downward (DGL) inclined event selection for events with reconstructed zenith angle $64.5° < \theta \leq 67.5°$. Black histogram: full data set up to 31 August 2018 containing 3948 events. Green-shaded histogram: Monte Carlo simulated ν DGL events.

Flavor	Relative contribution
ν_e	0.10
ν_μ	0.04
ν_τ	0.86
Channel	Relative contribution
Earth-skimming ν_τ	0.79
Downward-going $\nu_e + \nu_\mu + \nu_\tau$	0.21

Table 1. Top of table: relative contribution of the three neutrino flavors to the event rate in Auger due to a neutrino flux $\phi_\nu \propto E_\nu^{-2}$. Bottom: relative contribution to the rate in the Earth-skimming (ES) and Downward-going (DG) channels.

Backup – Auger+IceCube complementary exposure





Average exposure per day for different detection channels for the period 1 May 2008 to 31 Aug 2018

Figure 3: Left panel: Instantaneous effective areas for all the channels as a function of neutrino energy for selected zenith angles as labeled, compared to those of IceCube [11].

ApJ Lett. 850:L35 2017

Backup – GW170817 in the Auger FoV

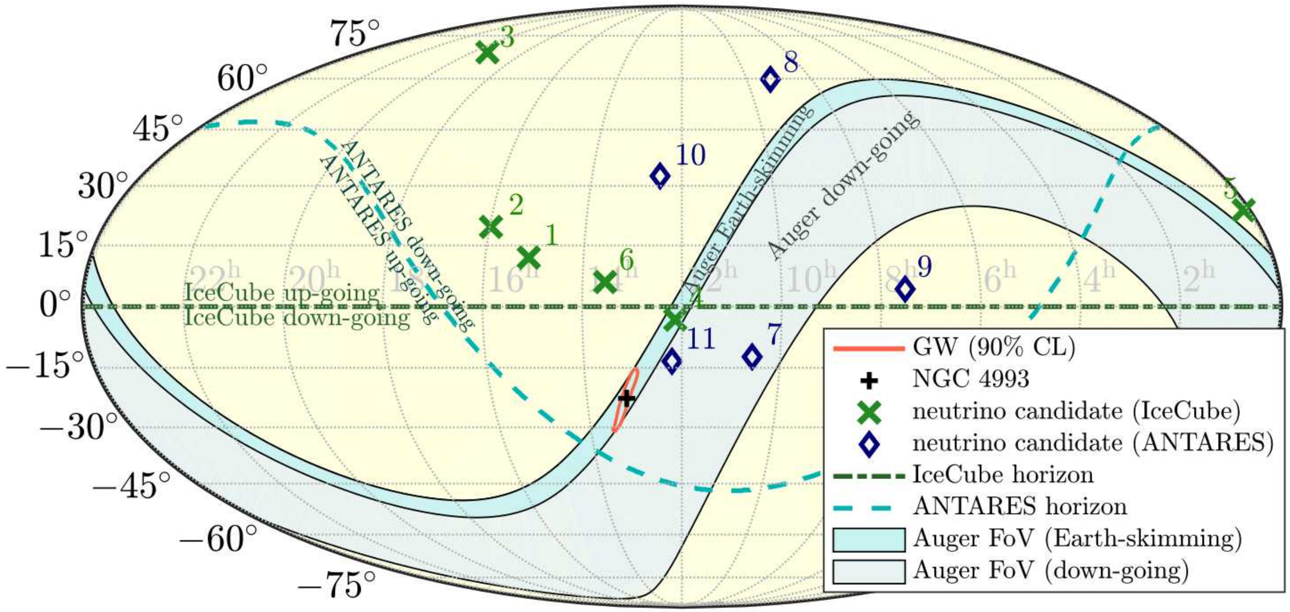


Figure 4. Left: Sensitive sky areas of ANTARES, IceCube and Auger at the time of the event GW170817 in Equatorial Coordinates. The red contour marks the 90% C.L. location of the event GW170817 [1, 18].

The BNS merger was in optimal position for the detection of UHE ν_τ from Auger at the instant of emission of GW170817