XVIII International
Workshop on
Neutrino Telescopes

Venice, March 19, 2019

Neutrino astronomy with the Pierre Auger Observatory

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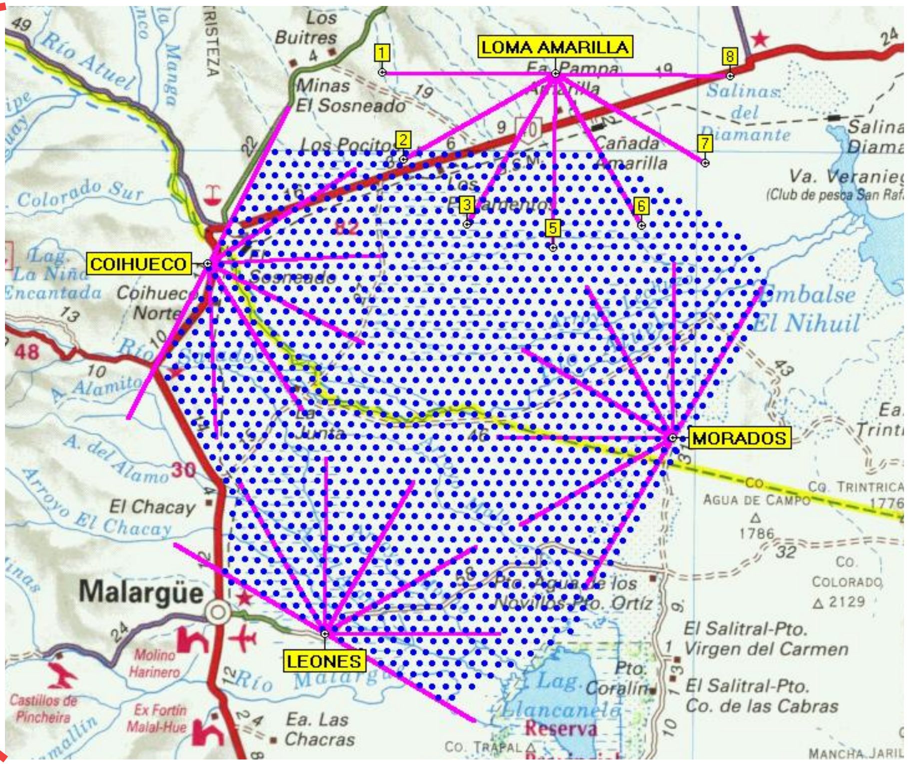
[2] www.auger.org/archive/authors_2019_03.html

The Pierre Auger Observatory

Total surface 3,000 km^2 (or 7.2 x Venice)

35.5º S, 69.3º W

1400 m a.s.l.
(880 g cm^{-2})



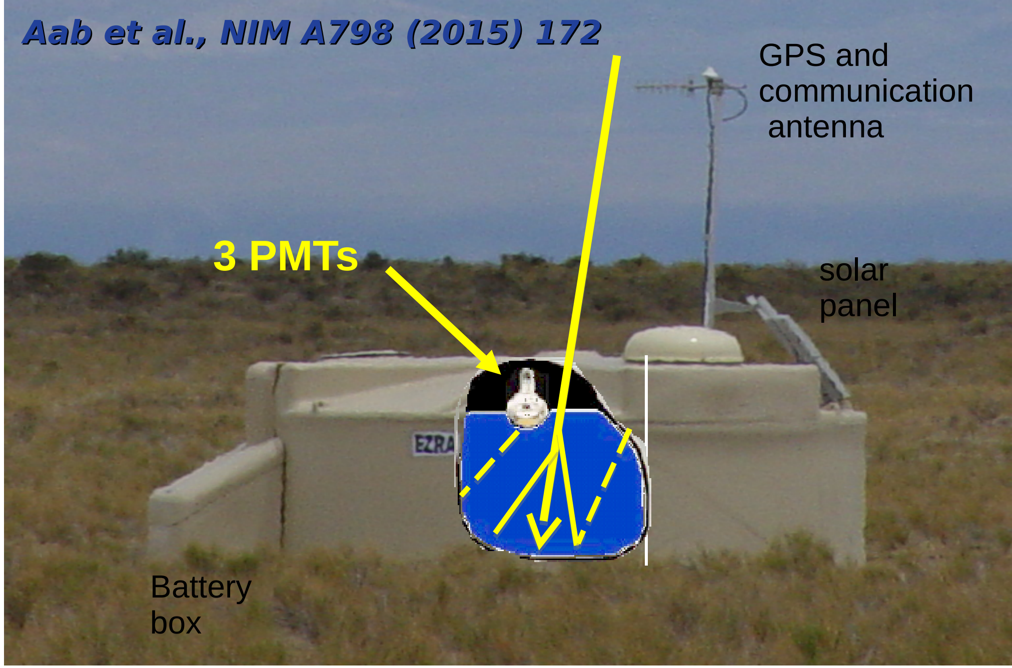
SD 1,600 Water Cherenkov Stations

on a triangular grid with 1.5 km spacing

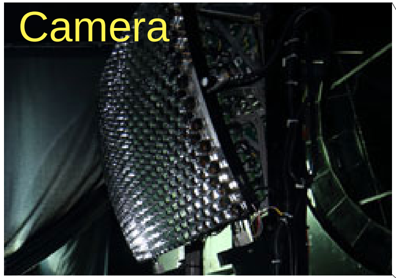
FD 24+3 fluorescence telescopes (4 sites)

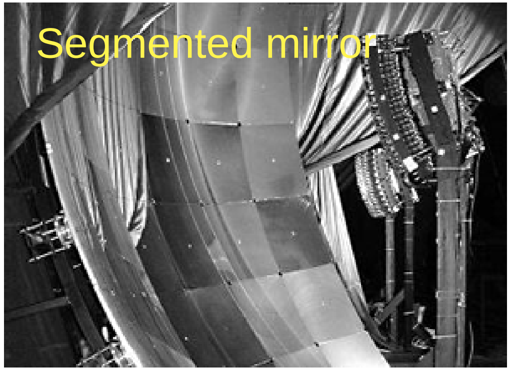
Combination of two detectors

Water Cherenkov Stations

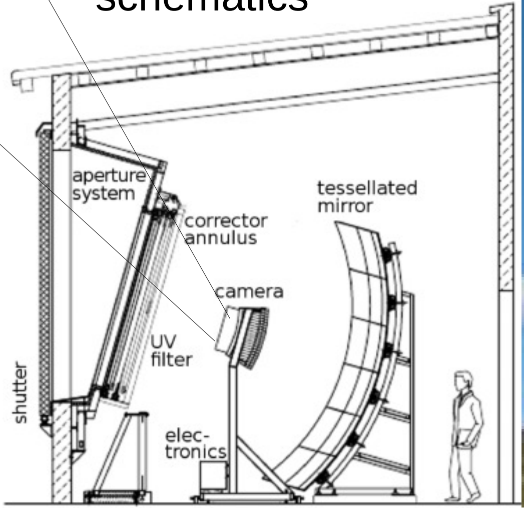


Fluorescence telescopes



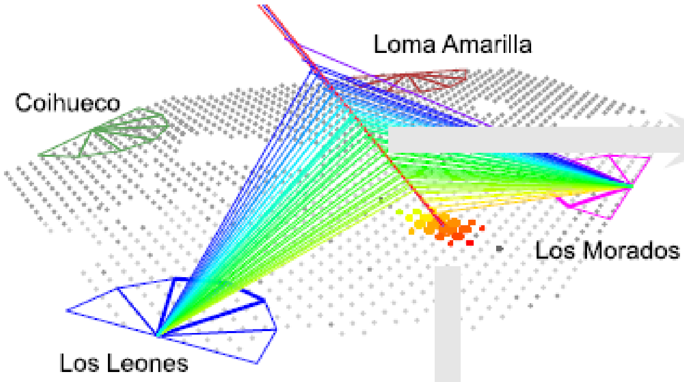


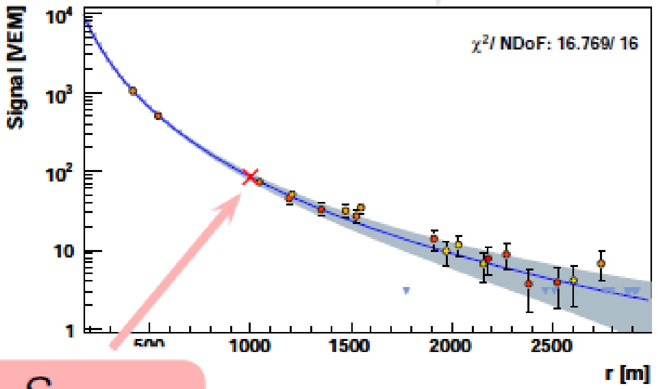
Telescope schematics



Hybrid detection of air showers

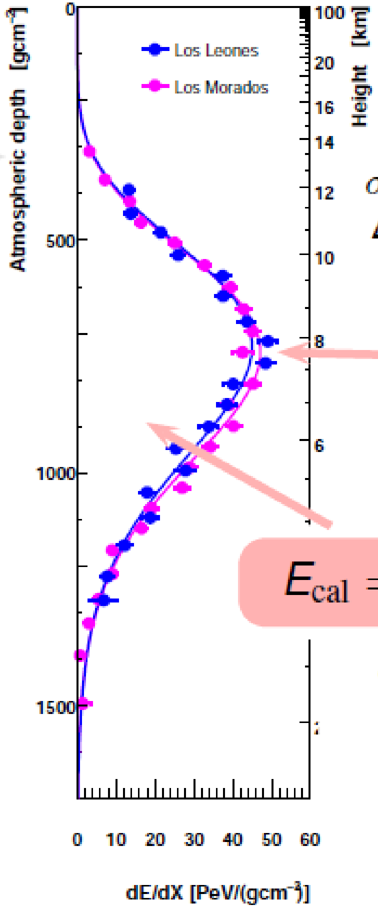
SD
~100% duty cycle
Energy scale from
FD (S1000 calibrated
with hybrid events)





S_{1000}

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



$\sigma X_{\mathrm{max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

X_{max}

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

FD
~14% duty cycle
operates in clear
moonless nights

M. Unger @ ICRC17

The Pierre Auger Observatory as a UHE neutrino telescope $E > 10^{17}$ eV

Searching for neutrinos with the Auger Surface Detector

→ Protons & nuclei initiate inclined showers high in the atmosphere.

Shower front at ground:

- electromagnetic component absorbed in atmosphere
- mainly muons remaining

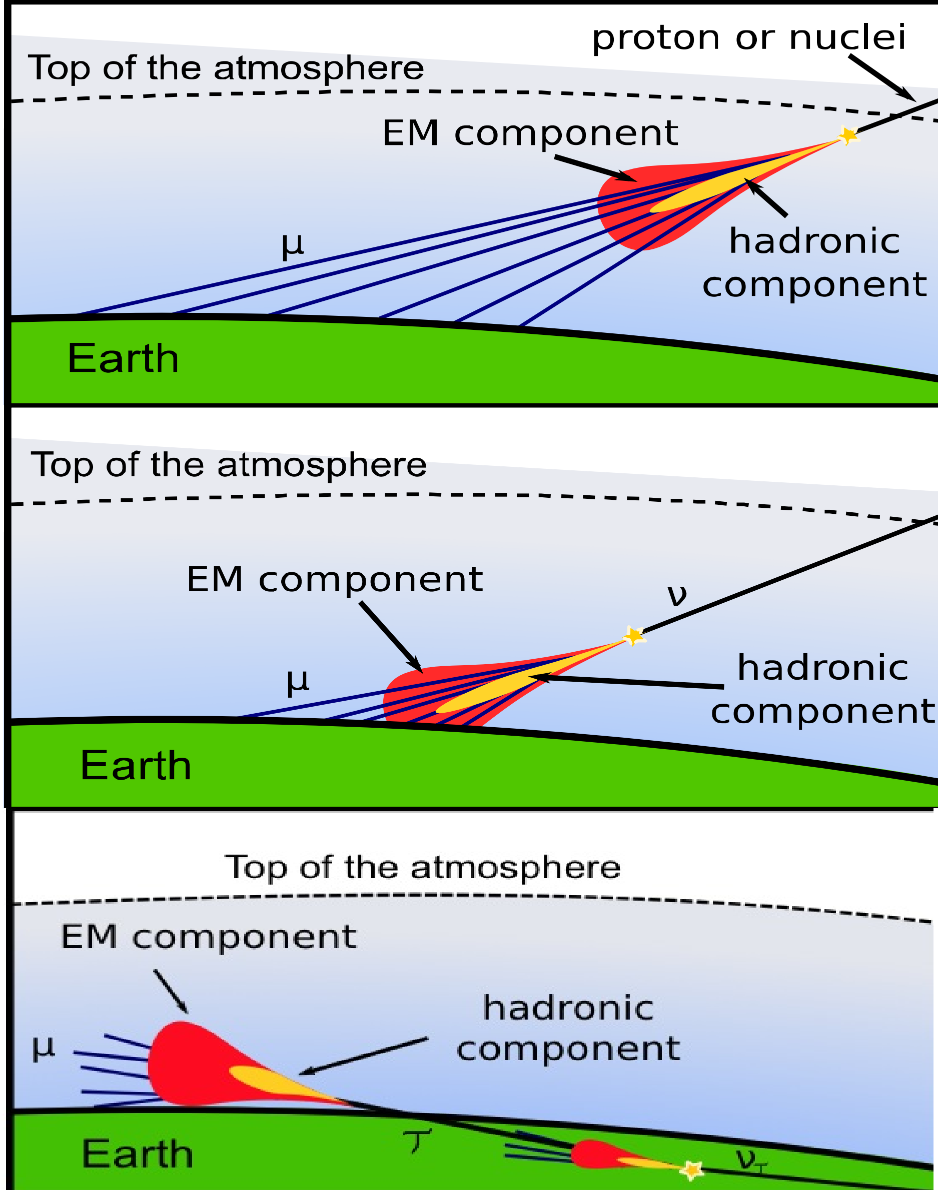
→ Neutrinos can initiate deep showers close to ground.

Shower front at ground:

electromagnetic + muonic components

Searching for neutrinos
⇒ searching for inclined showers with electromagnetic component

Zas, New J. Phys. (2005) 130



Searching for neutrinos with the Auger Surface Detector

Background

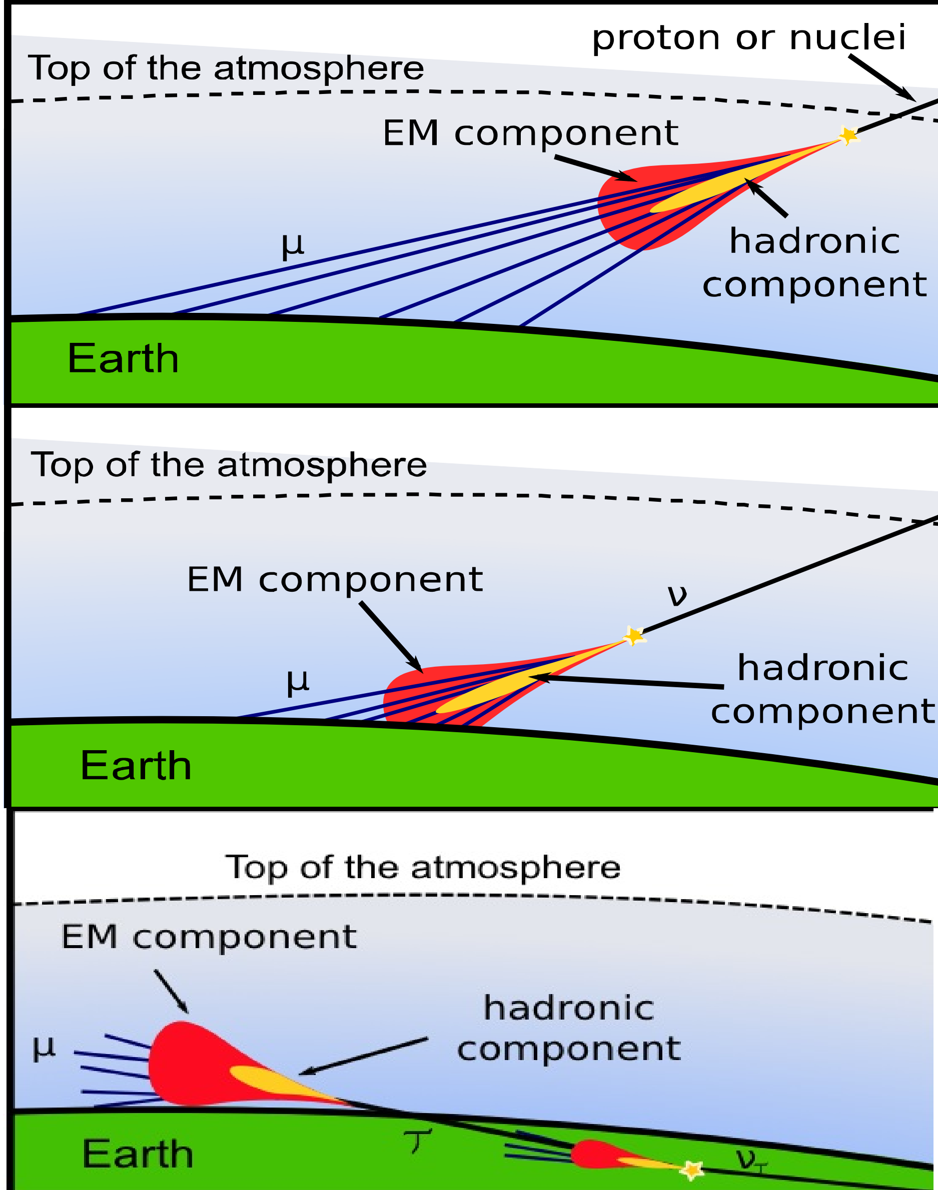
Down going: all flavours

Down-going low angle DGL 60º-75º
Down-going high angle DGH 75º-90º

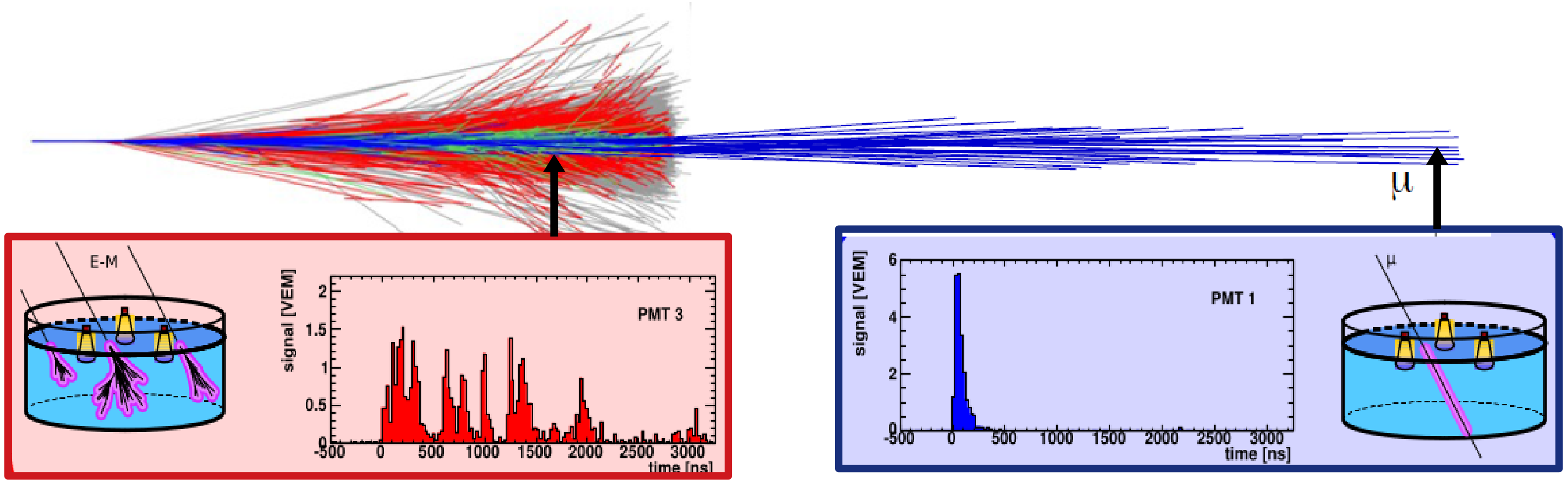
Up going: ν_τ

Earth-skimming ES 90º-95º

Aab et al., Phys. Rev. D91 (2015) 092008



Identifying electromagnetic shower fronts

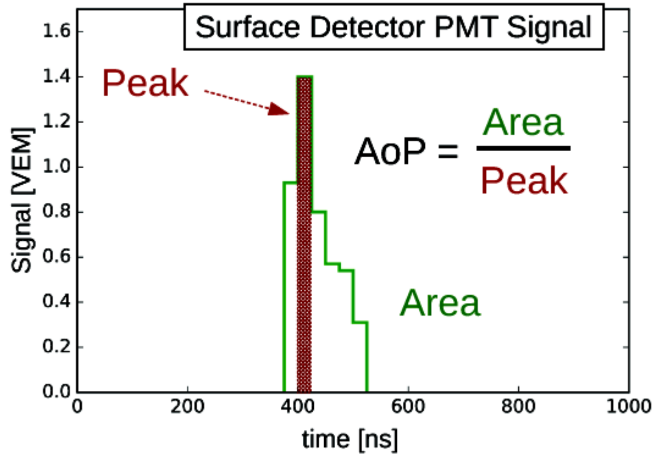


AoP>1

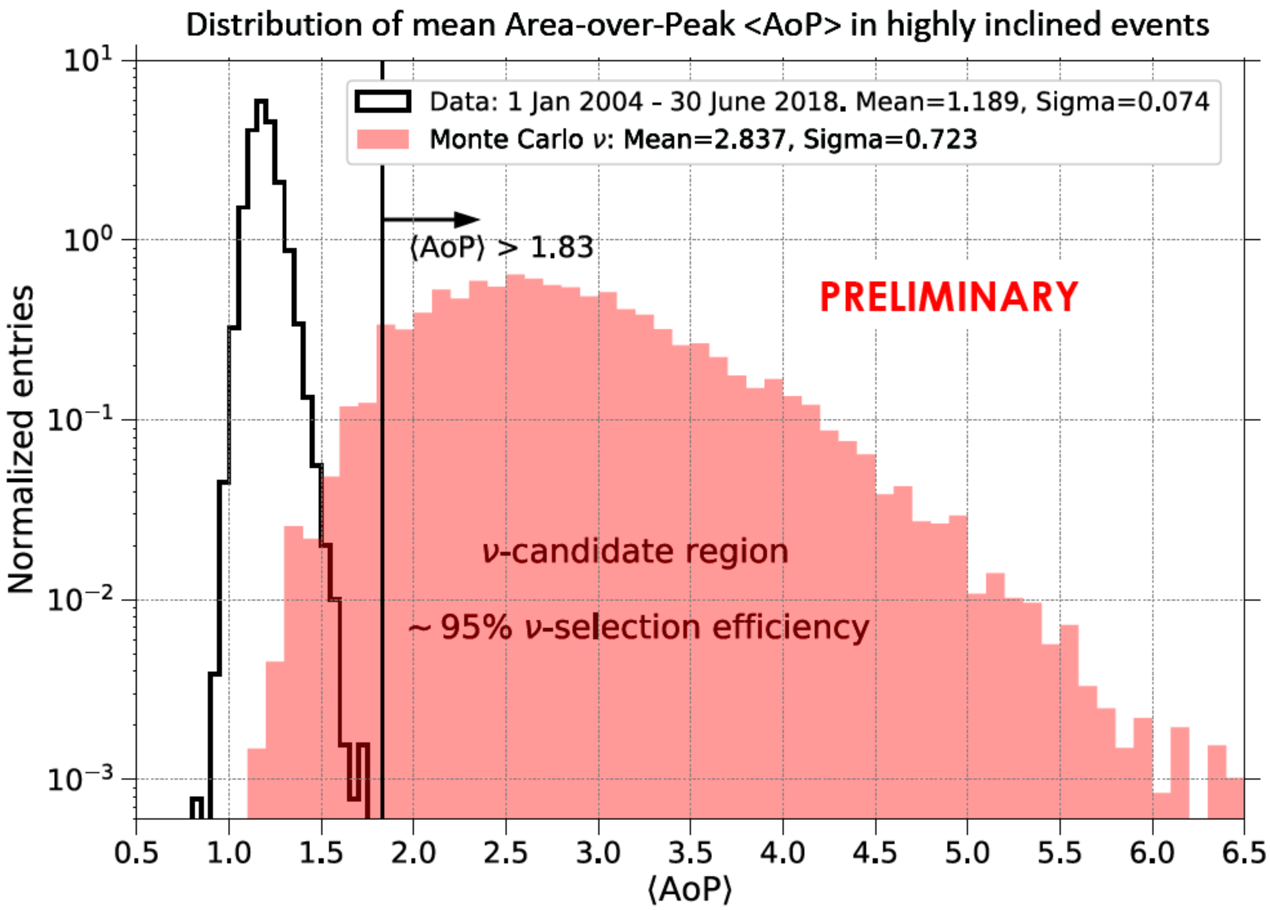
AoP~1

Searching for neutrinos
⇒ searching for inclined showers
with stations with large AoP

Definition of Area-over-Peak (AoP)



Identification of UHE neutrinos in Auger data



Data taking: **01/01/04 – 30/06/18** corresponding to 9.5 "full Auger" years

~10% of the data are used to estimate the expected background

ν-selection cut at a value for which <1 background event is expected in 50 y

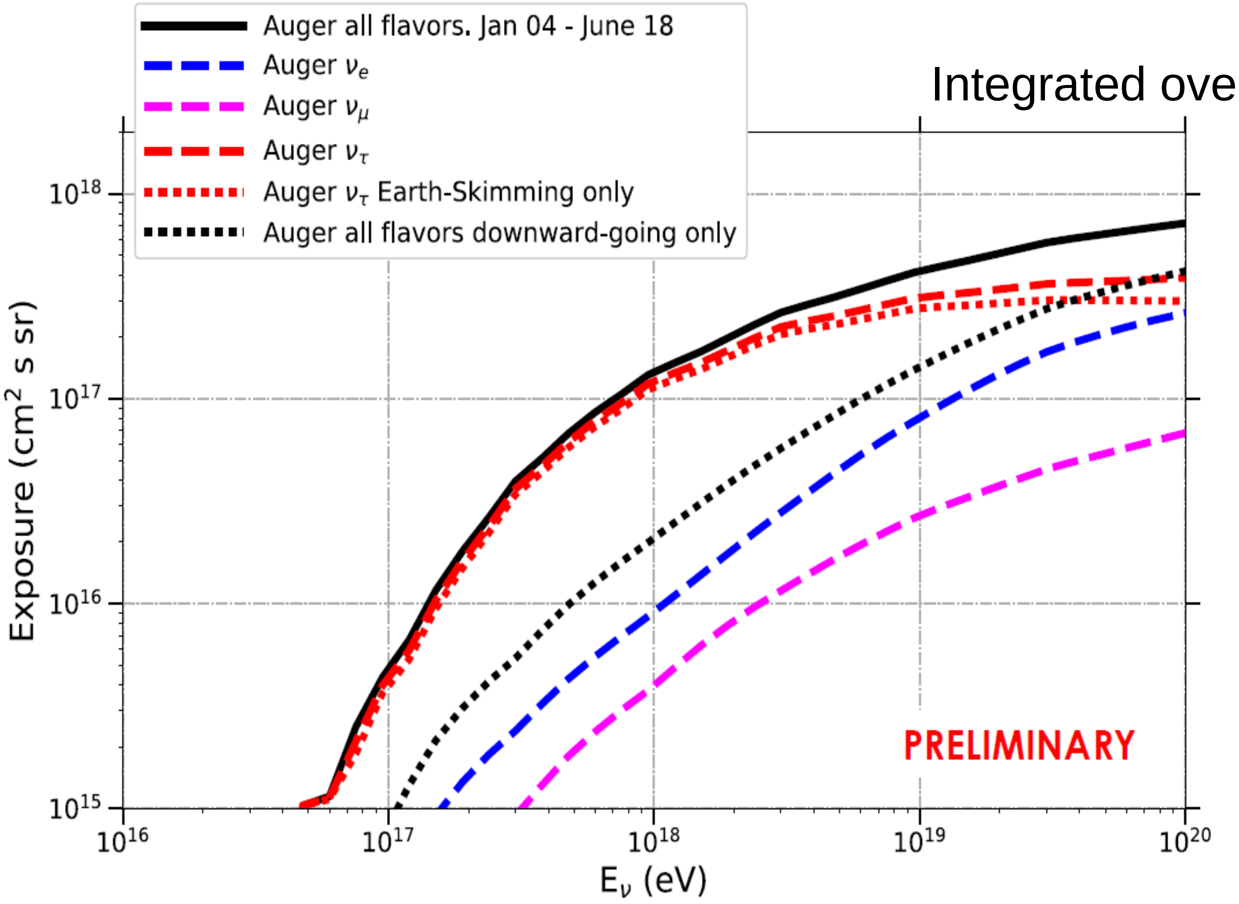
Downgoing channels have lower ν-selection efficiency (85% and 87%)

Identification criteria applied "blindly" to the search data set
=> No candidates found in Earth Skimming or Downward-going

Exposure

$$N_{evt} = \int_{E_\nu} \frac{dN_\nu}{dE_\nu}(E_\nu)\,\mathcal{E}_{tot}(E_\nu)\,dE_\nu$$

Integrated over the solid angle



For a E^{-2} spectrum the percentage contribution to the event rate is:

- By channel:
  - ES 79.4%
  - DGH 17.6%
  - DGL 3.0%
- By flavour:
  - τ 86.1%
  - e 10.1%
  - μ 3.8%

Implication of non observation of UHEν:

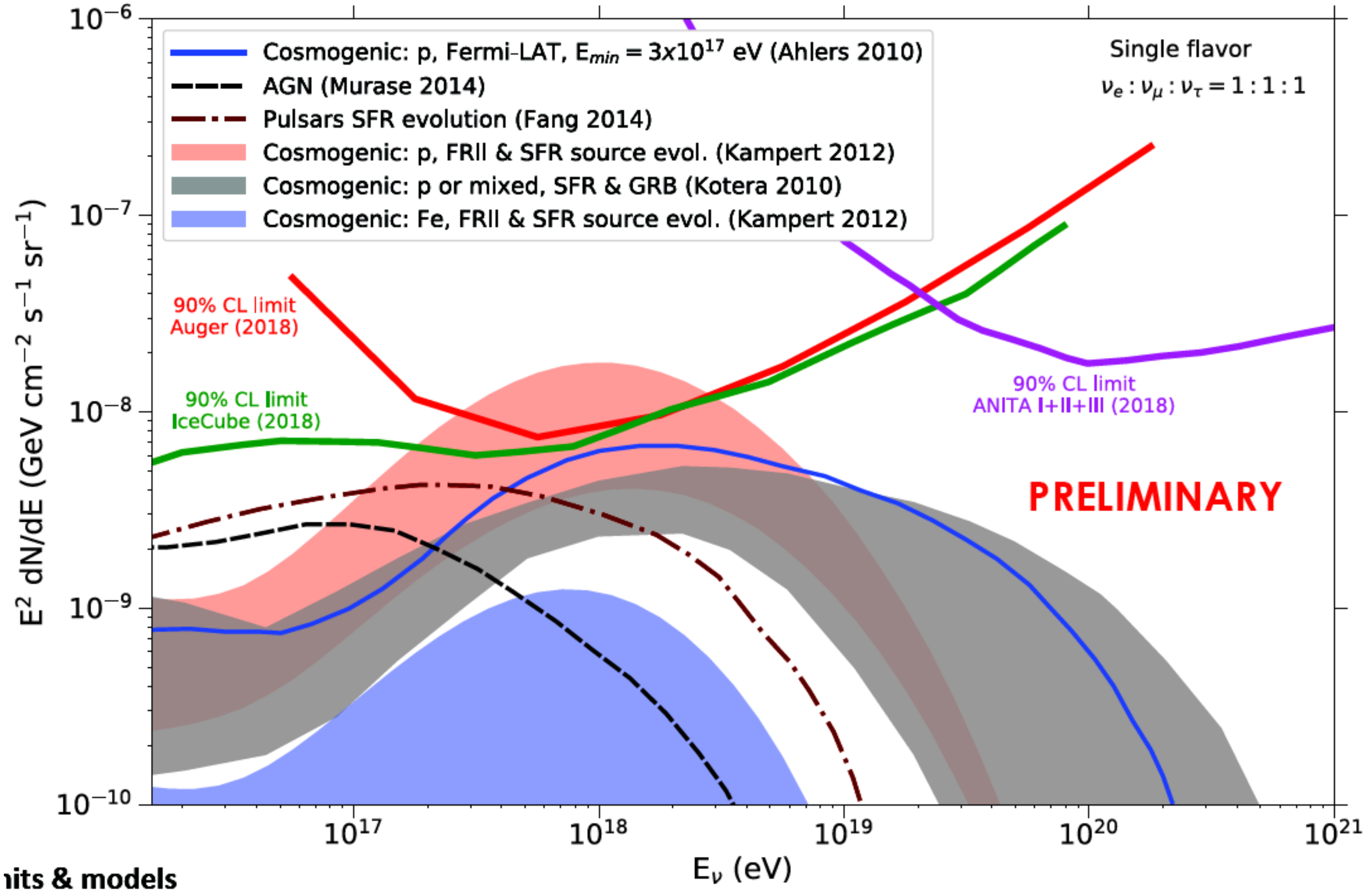
Diffuse fluxes

Point-like sources

J. Alvarez-Muniz, for the Pierre Auger Collaboration
“Multi-messenger Astrophysics at Ultra-High Energy with the Pierre Auger Observatory” to appear in Eur. Phys. J. Web of Conf. (2018).

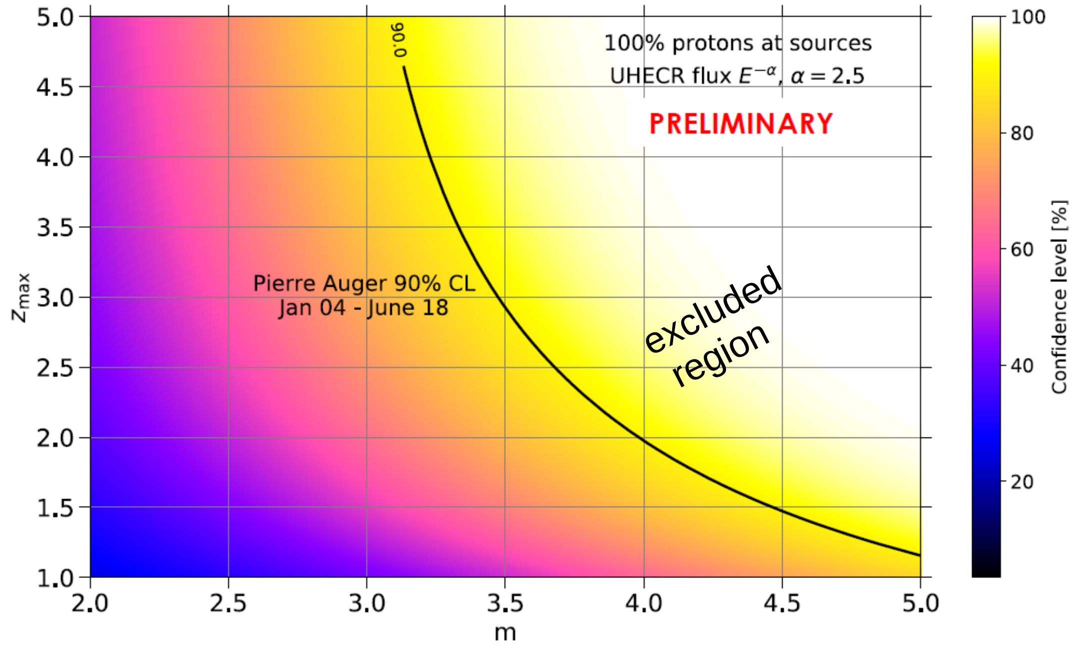
Upper limits to the diffuse flux of UHEν

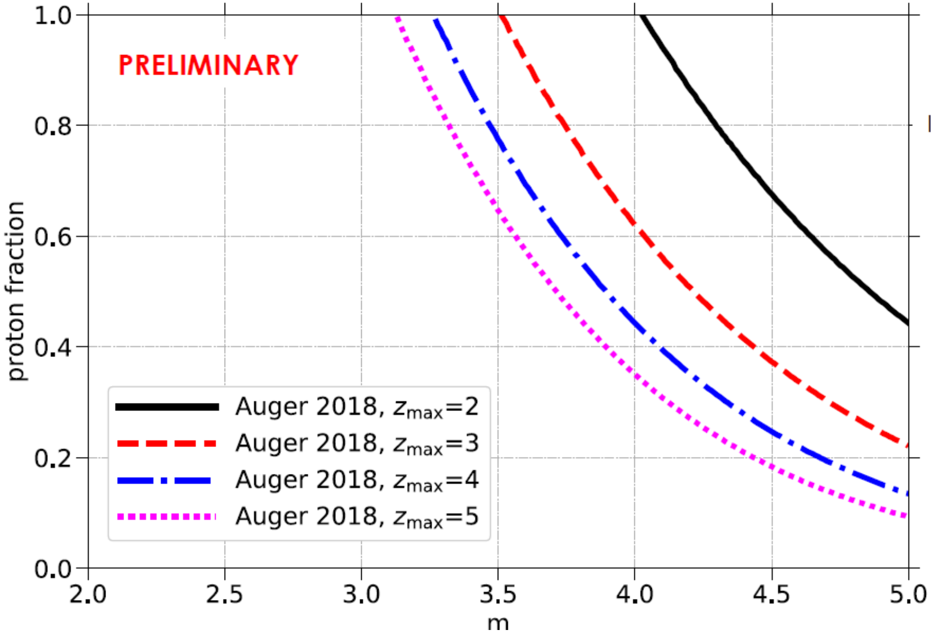
Comparable to IceCube at peak sensitivity (~1 EeV)



Integrated 90% C.L.the energy range 0.1 – 25 EeV: **4.4 x 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}**
start constraining models with weak source evolution

Implications on sources





Source evolution ~ $(1+z)^m$ up to z_{max}

Weaker constraints for smaller proton fractions

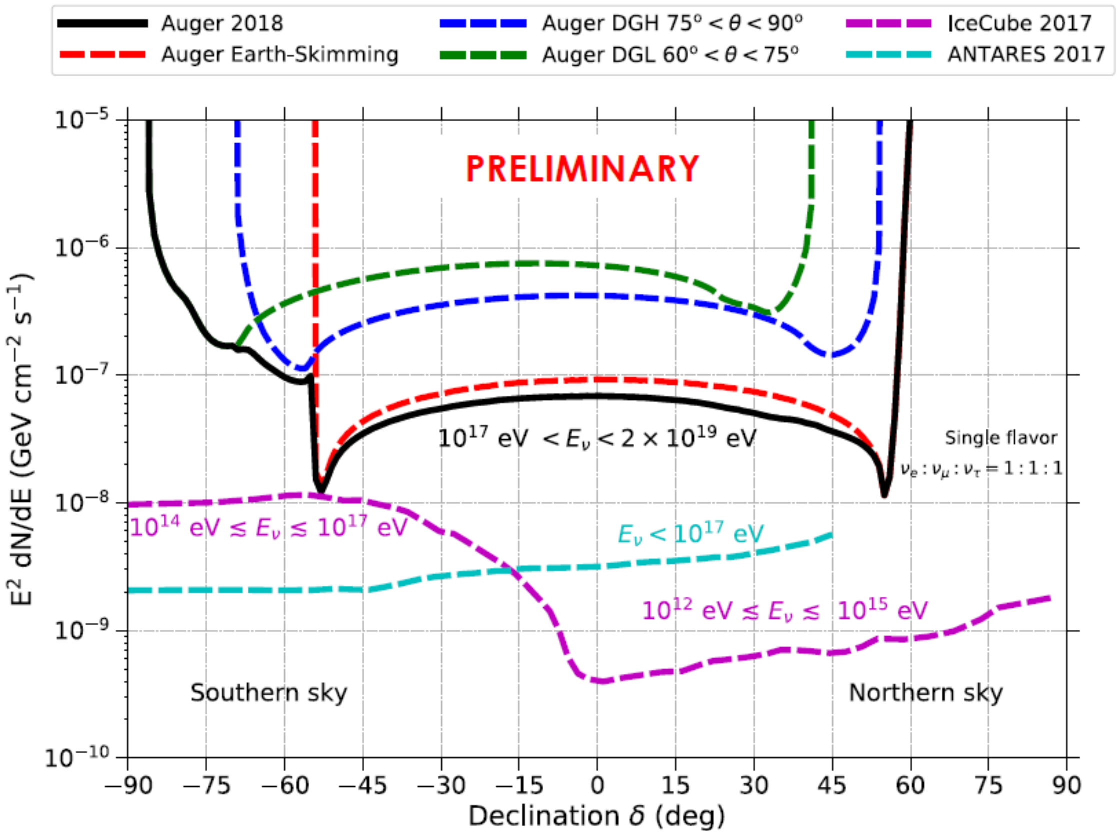
Implication of non observation of UHEν:

Diffuse fluxes

Point-like sources

J. Alvarez-Muniz, for the Pierre Auger Collaboration
“Multi-messenger Astrophysics at Ultra-High Energy with the Pierre Auger Observatory” to appear in Eur. Phys. J. Web of Conf. (2018).

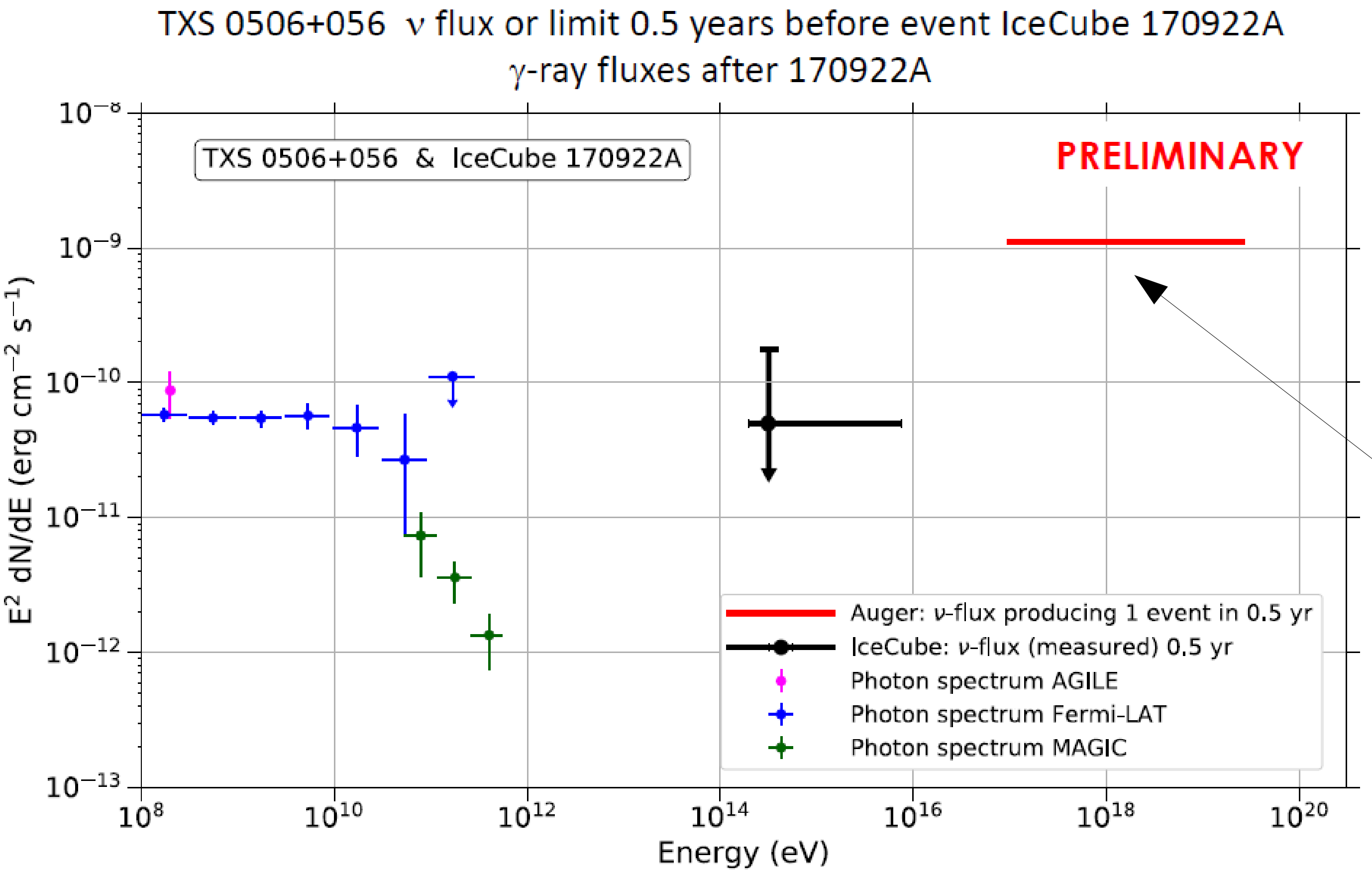
Limits to point-like steady sources



Angular resolution for inclined events depends on energy and zenith. Ranges between ~0.5° to a maximum of O(2°) in the worst configurations.

Different and complementary energy ranges for Auger, IceCube, Antares

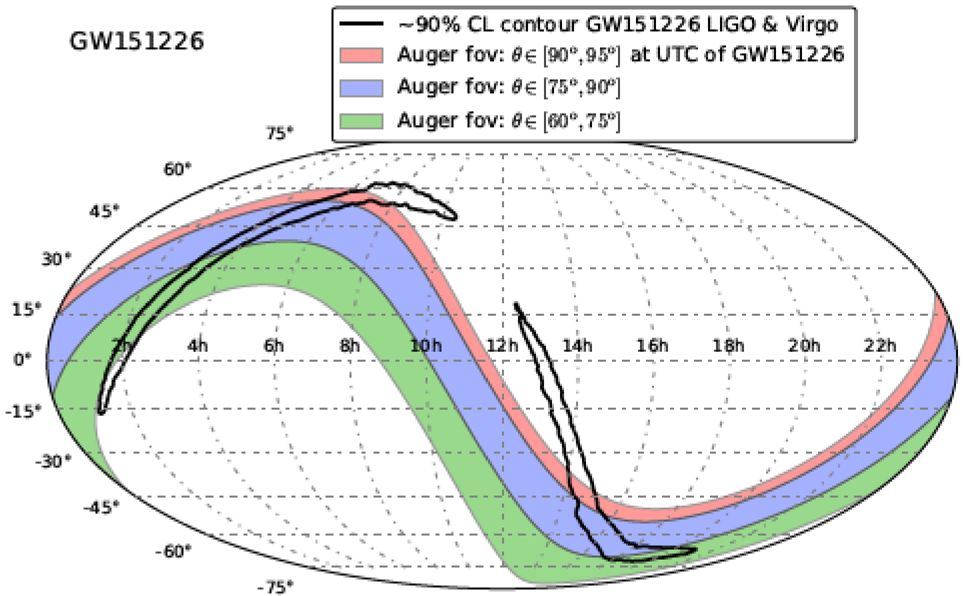
Limit on the UHEν flux of TSX 0506+056



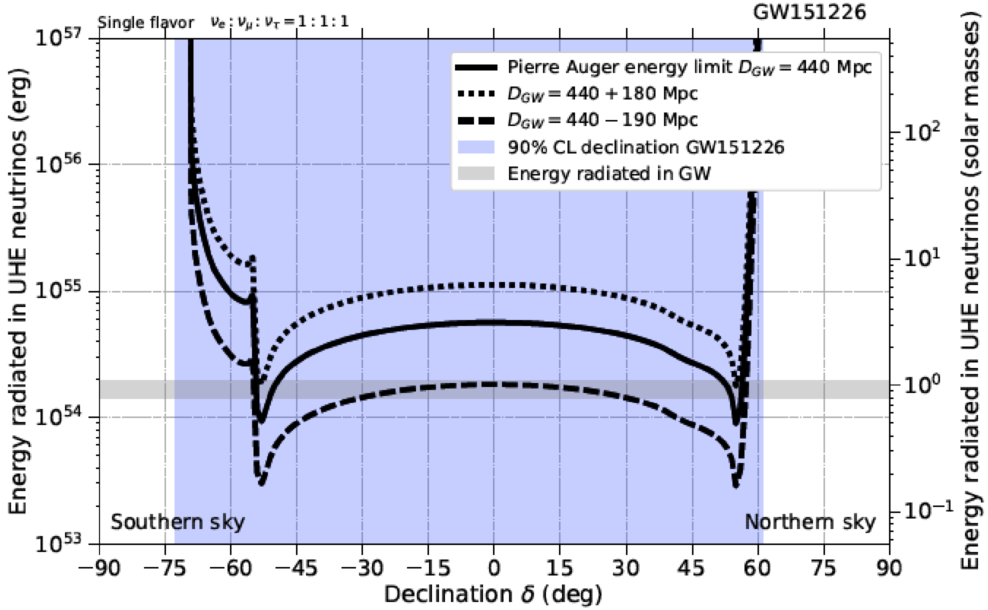
$\delta \sim 5.7^{o}$

First EeV limit on blazar TSX!

Follow-up of GW events (BBH mergers)



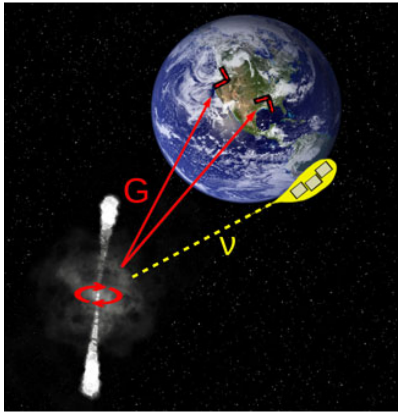
Assumptions: constant flux,
continuous isotropic emission over T_{search}



Searched the time window ±500 s and a longer 1 day one after the event.

Similar (weaker) results for other BBH GW events.
Compatible with no neutrino emission from “naked” BBH mergers.

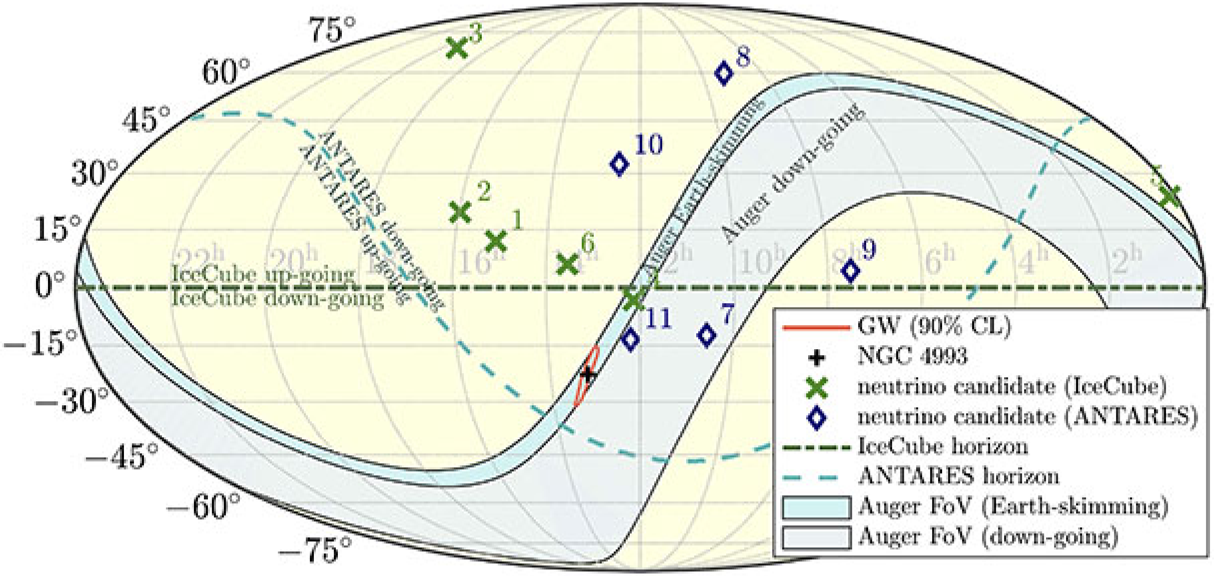
BNS merger GW170817 + short GRB

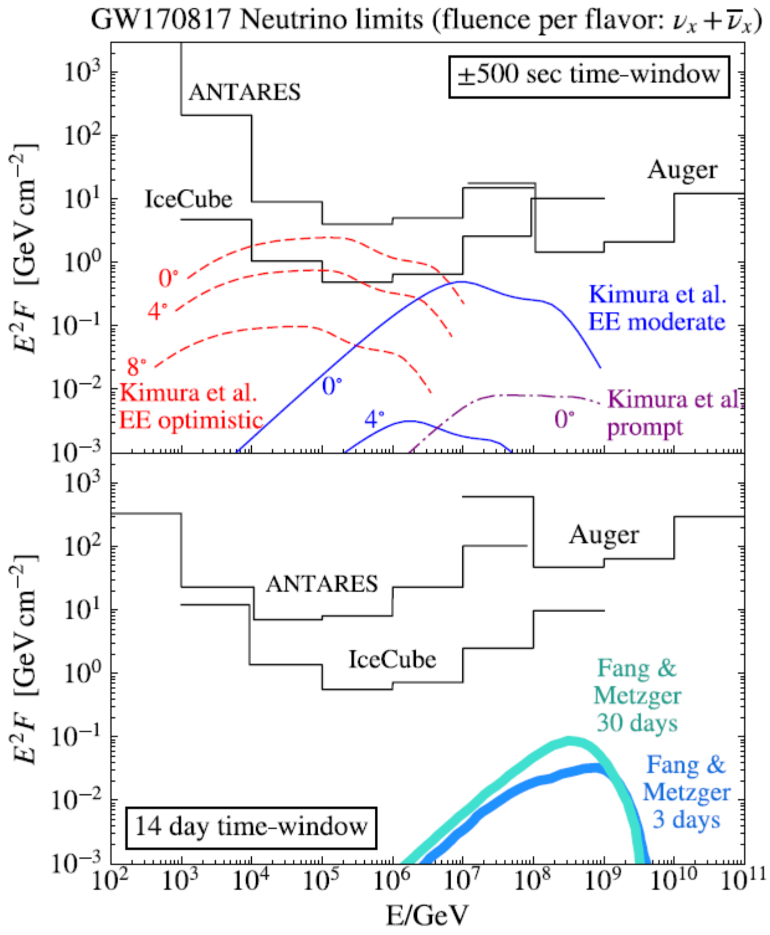


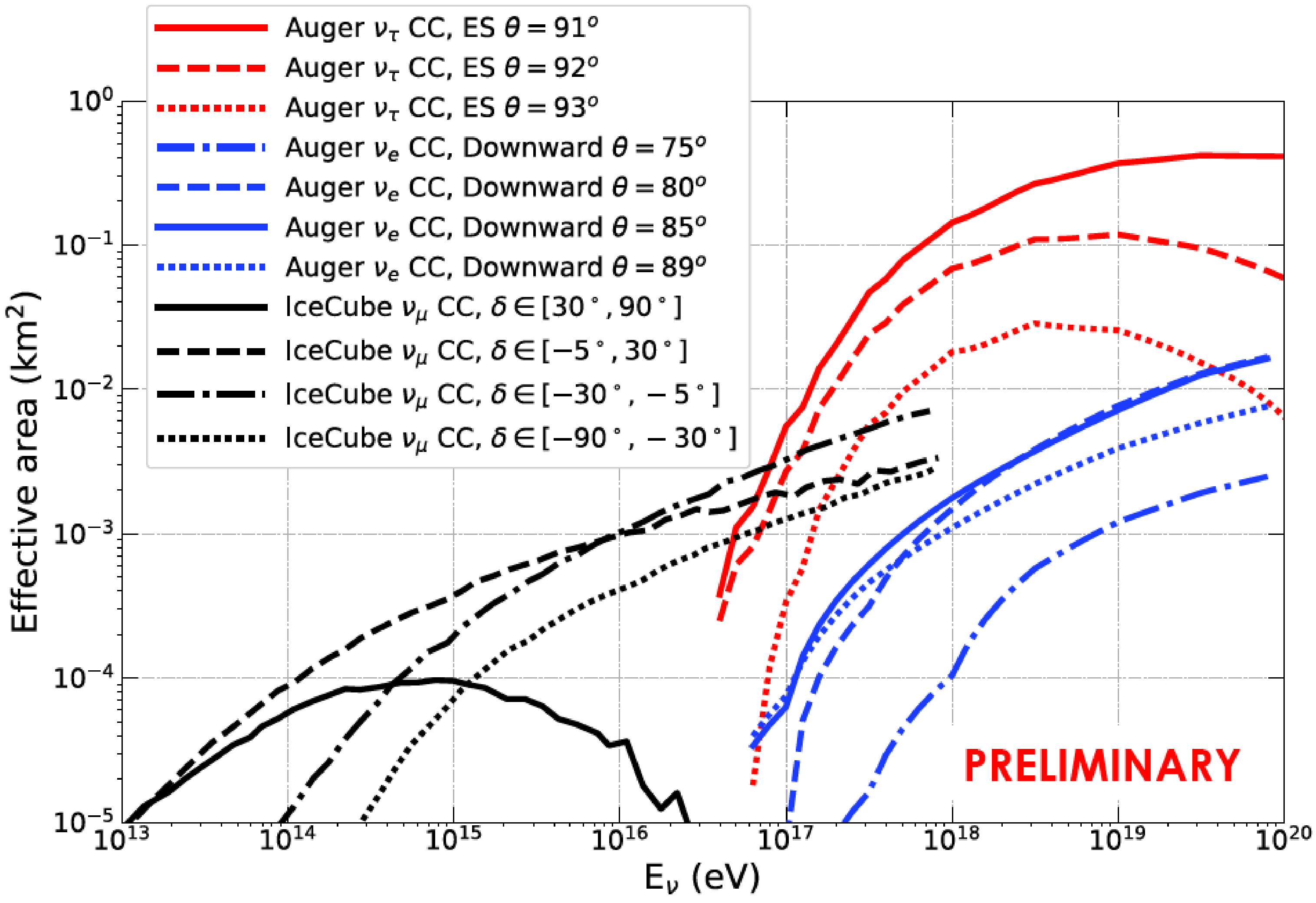
courtesy M.Schimp

Lack of ν consistent with short GRB viewed off axis.

In this case source located thanks to detection in a broad wavelength range. Sweet spot for Auger detection.







For short transients (up to ~1h) unrivalled sensitivity if the source is in the upgoing ES channel at the time of occurrence.

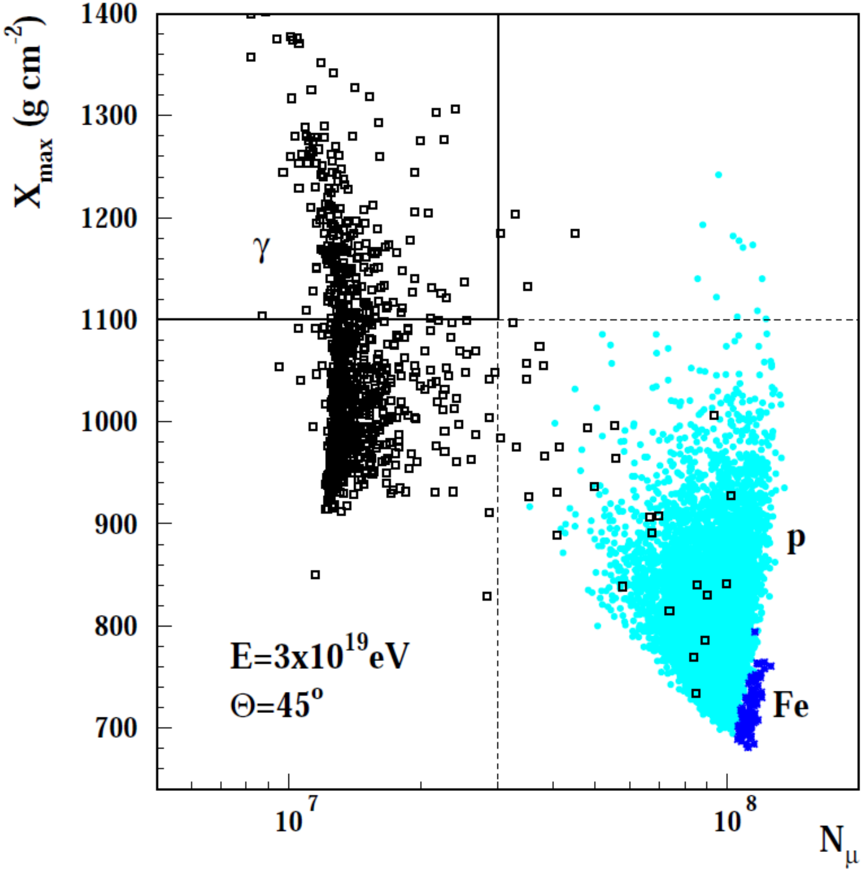
- LIGO/Virgo O3 starts in few weeks with increased sensitivity
- Increased rates/horizon/source volume could yield GW events closer, brighter or produced by other sources more likely to produce UHE neutrinos
- Auger can also contribute with UHE photon searches!

The Pierre Auger Observatory as a UHE photon telescope

(hybrid ad SD only data sets)

UHE photons, unlike neutrino, have a limited horizon, ranging between few 100 kpc and few Mpc in the range covered by Auger

How to recognize a photon shower



Risse & Homola. Mod. Phys. Lett A 22 (2007) 749

The γ/p difference in <Xmax> is O(100 gcm^{-2}) much smaller than in the case ν/p => separation more difficult

Photons produce mostly **EM** showers with minor photo-nuclear or muon pair production.

With respect to p and nuclei, photons have:

→ larger <Xmax>
→ smaller muon content

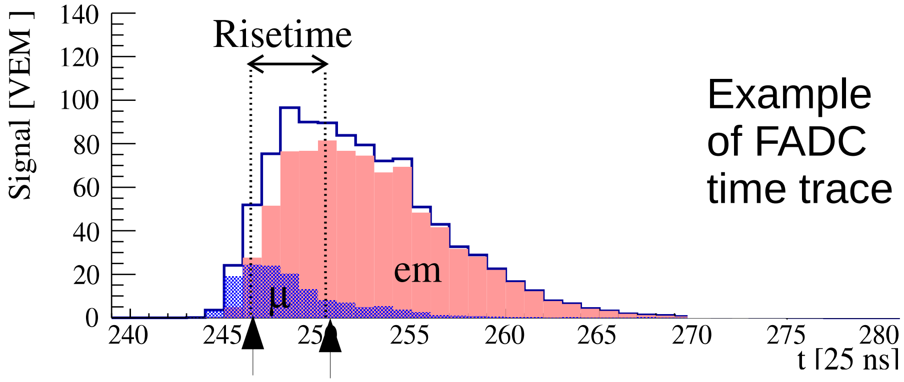
As a consequence, they differ also in other observable characteristics:
- steeper LDF
- smaller footprint (less triggered stations)
- broader time front

Experimental observables

HYBRID DATA (FD + SD)

Use Xmax

SD ONLY DATA
Cannot measure Xmax, use instead the **Risetime** of the signal in a SD station: an alternative to AoP to select signals rich in the em component



Example of FADC time trace

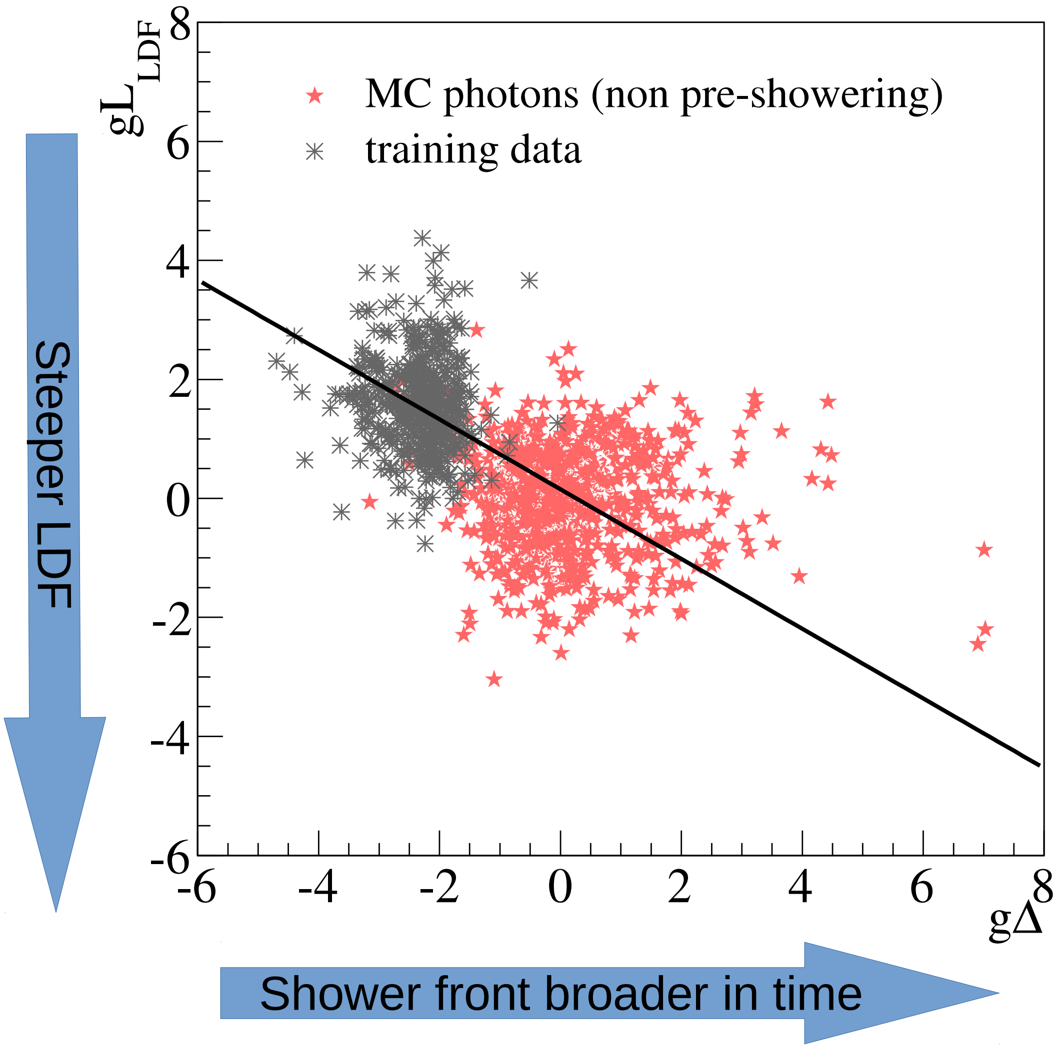
10% 50% quantiles

In both cases additional one ore more secondary variables are added and combined in a multivariate analysis. The ɣ-selection efficiency is set to 50% (a priori choice) in both cases.

Aab et al., JCAP 1704 (2017) 009

CB, for the Auger Coll., PoS ICRC2015 (2016) 1103

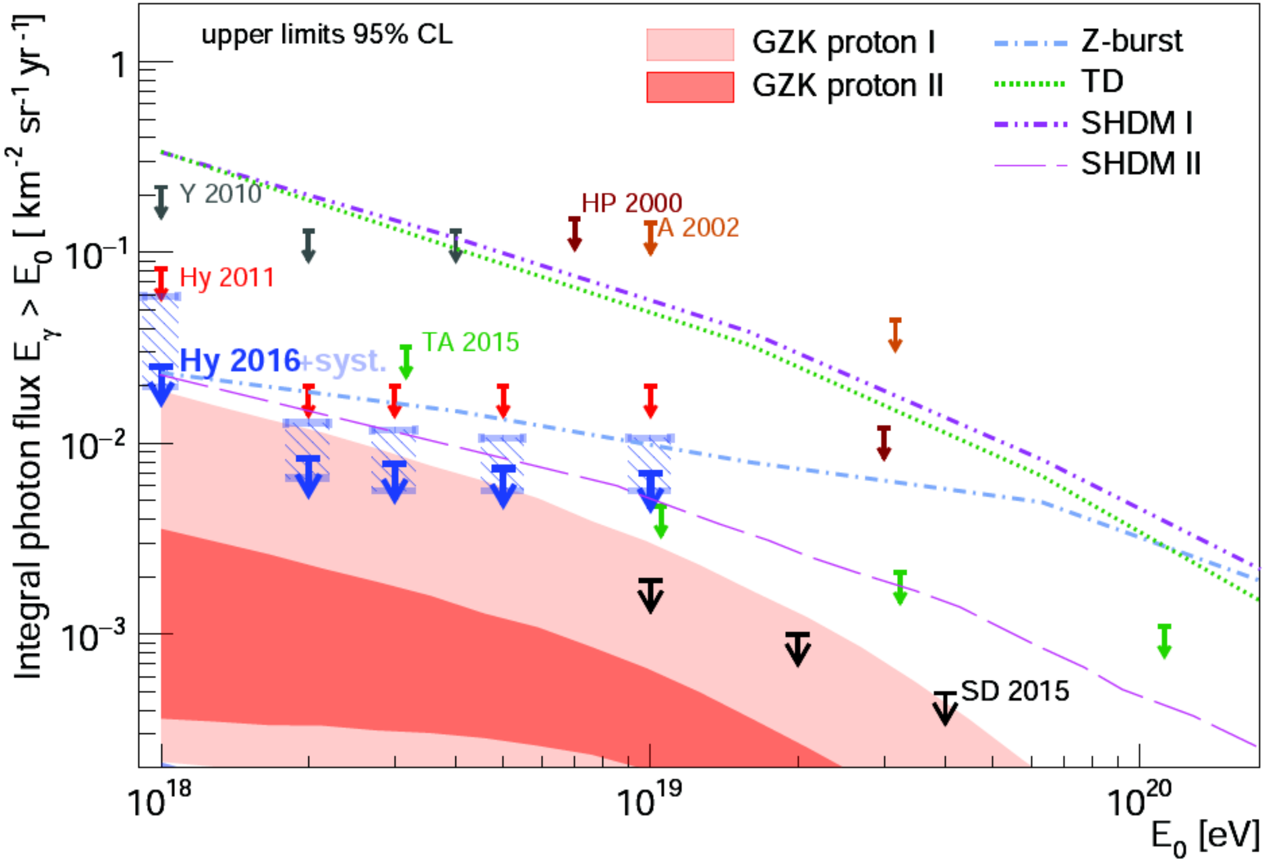
Example: SD only photon search (E>10 EeV)



The SD only analysis can be run in real-time and monitor continuously the overhead sky in the zenith band between 30° and 60°

Note: no instantaneous overlap with FoV of the neutrino search.

Upper limits to the integrated diffuse flux of UHEγ



Hybrid data
Jan 2005 – Dec 2013
3 candidates found, compatible with bkg expectation

SD data
Jan 2004 – May 2013
4 candidates found, more difficult to estimate bkg with SD only, conservatively considered as “signal” in the U.L. calculation

Most top-down models disfavoured. Start constraining most optimistic fluxes obtained in the assumption of 100% protons injected at the sources

Search for point-like (steady) sources of photons

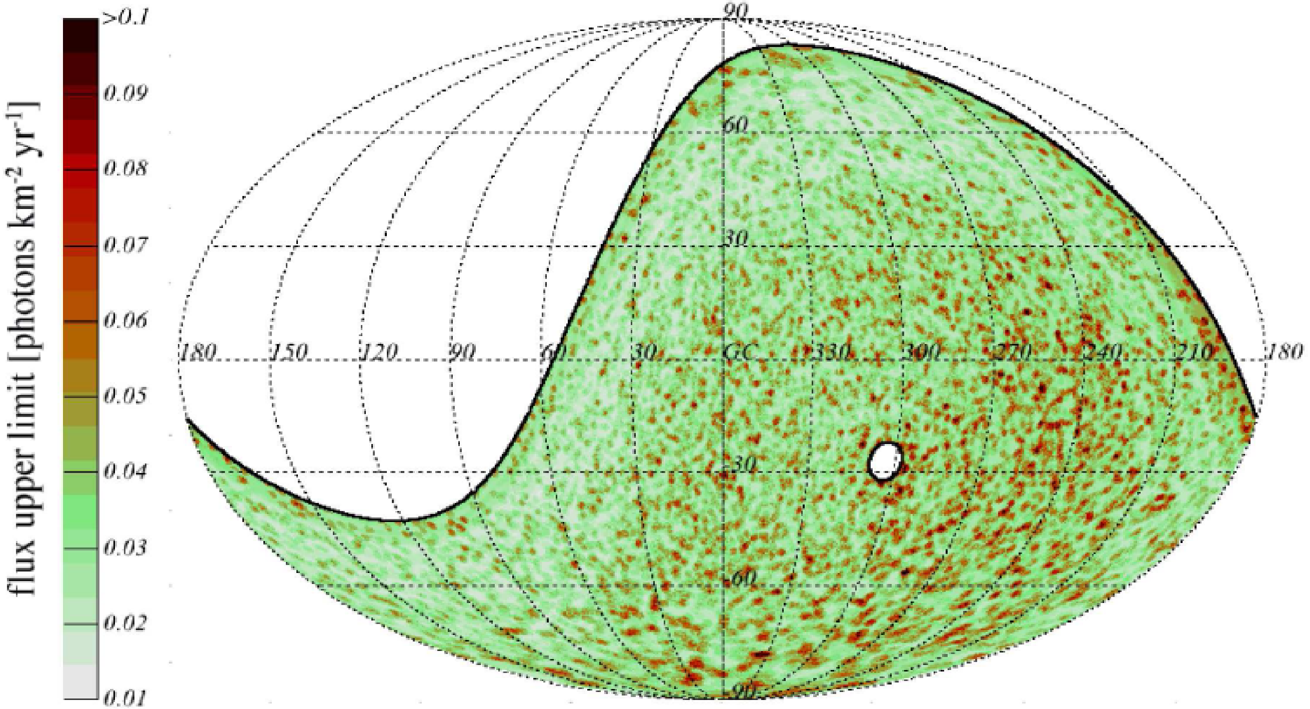
Idea: Use hybrid data Jan 2005-Dec 2011 and a multivariate analysis to reduce the level of background (instead of identifying photons) in the **0.2-3 EeV** range.

Angular resolution < 1º

A blind directional search in the resulting sample yelded no significant excess above the expected bkg fluctuation.

Directional upper limits

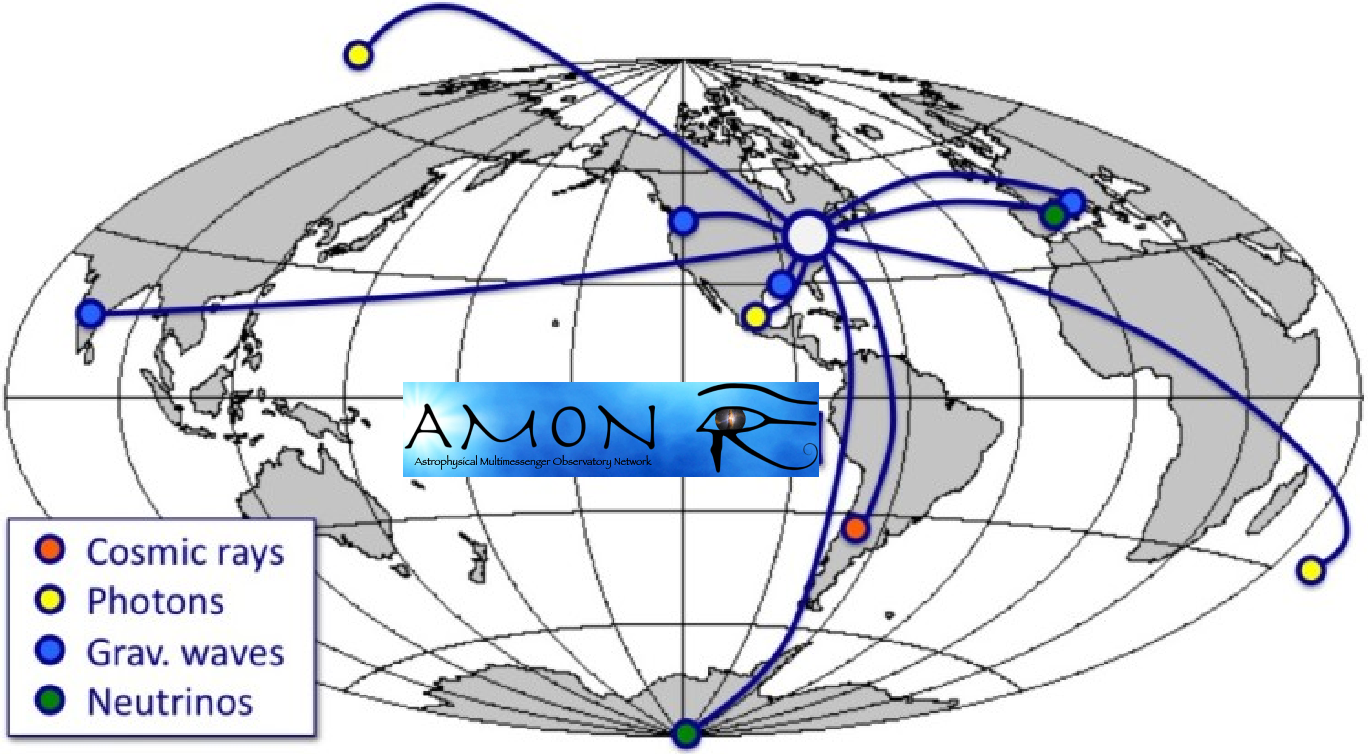
Aab et al., ApJ 798 (2014) 160



No evidence of galactic or nearby sources

- all Auger events with zenith < 60° and energy ≥ 3 EeV are sent to AMON with the goal of real-time coincidence analysis with IceCube, HAWC, and other participating observatories.

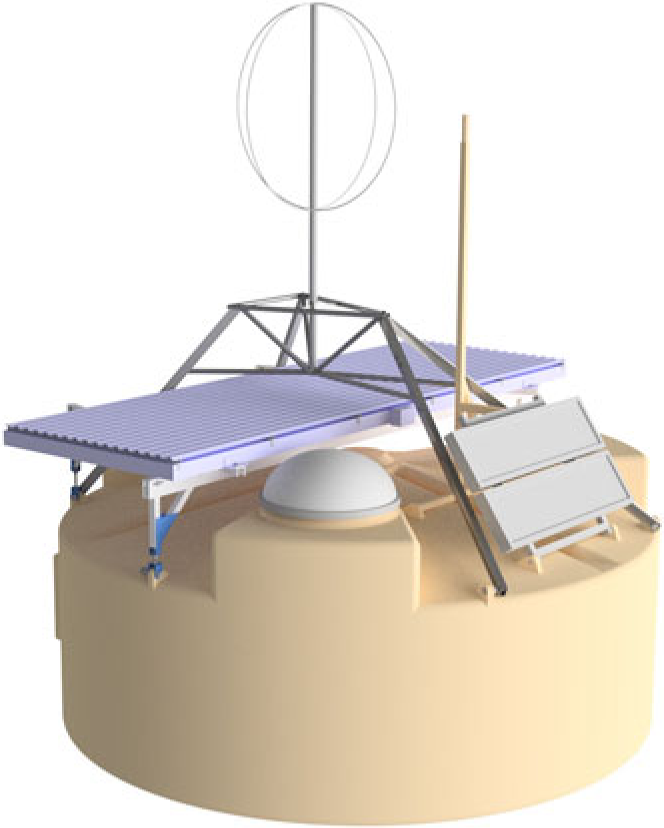
- 2 or more events observed within 100 s and < 3 deg. generate an AMON alert for other AMON-partner observatories to follow-up on.



Astrophysical
Multimessenger
Observatory
Network

www.psu.amon.edu

Ongoing upgrade: AugerPrime



~4 m^2 scintillators (SSD) on top of each Water Cherenkov detector will improve separation of em/muon components in traces

Electronics upgrade:
- 3x faster sampling of traces
- better timing

Small PMT in each SD station extends the dynamic range x32

New triggers to lower energy threshold and more oriented to traces dominated by em components

Aab et al., arXiv:1604.03637
Martello, for the Auger Coll., EPJ Web Conf. 145 (2017) 05001

Direct improvements in the neutrino and photon searches
in terms of lowering thresholds and improving the separation

Conclusions

Auger is already being used as a UHE neutrino and photon telescope contributing to multi-messenger astrophysics.

Competitive limits to the diffuses fluxes of UHE neutrinos and photons.

The good angular resolution allows for directional searches both blind and targeted after classes of sources or alarm triggers from other observatories.

First upper limit on TXS 0506+056 at EeV energies.

Unrivalled sensitivity for short transients if source is visible in the ES channel.

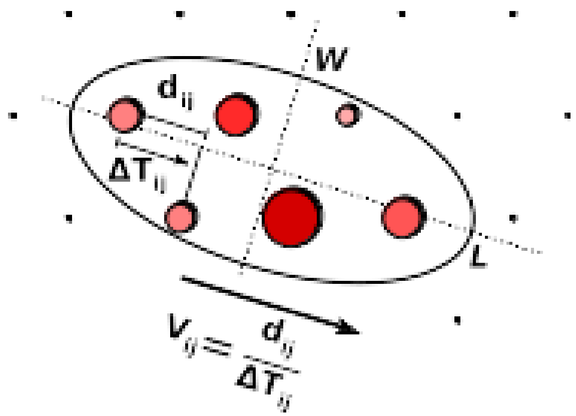
Follow-up of GW events in O1/O2 of LIGO/Virgo with neutrino searches only.
In O3 phase the neutrino selection will enter with a (almost) real-time analysis.
Photon analysis (using only the surface detector) will soon join.

The ongoing upgrade AugerPrime will improve signal/bkg separation and lower detection thresholds for photon/neutrino searches

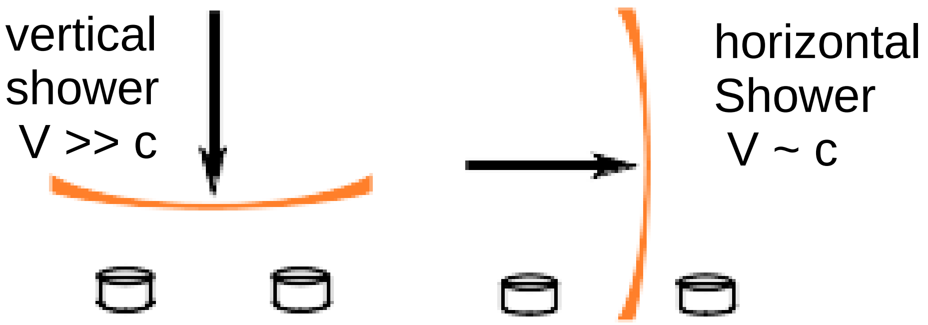
Thank you for your attention!

Selection of inclined events

(1) Elongated footprint



(2) Apparent velocity V of propagation of the shower front along major axis L



(3) Reconstructed zenith angle

	Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
(1)	$L/W > 5$	$L/W > 3$	–
(2)	$\langle V \rangle \in (0.29,\ 0.31)$ m ns^{-1}	$\langle V \rangle < 0.313$ m ns^{-1}	–
	RMS$(V) < 0.08$ m ns^{-1}	RMS$(V)/\langle V \rangle < 0.08$	–
(3)	–	$\theta_{\rm rec} > 75°$	$\theta_{\rm rec} \in (58.5°,\ 76.5°)$

Systematics – searches for ν diffuse fluxes

Upper limit to the number of neutrinos: Feldman-Cousins + Conrad (includes uncertainties in the exposure calculation)

Upper limits for a k E^{-2} spectrum:

$$k^{90\%} = \frac{N^{90\%}}{\int E_\nu^{-2} \varepsilon_{tot}(E_\nu) dE_\nu}$$

Neutrino Exposure: Systematic Uncertainties →

Simulations	~ +4%, -3%
ν cross-section & τ E-loss	~ +34%, -28% ⇦
Topography	~ +15%, 0%
Total	~ +37%, -28%