Multi-Messenger studies with the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

Virtual Conference

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Outline

Multi-messenger astrophysics

The Pierre Auger Observatory

- General
- Neutrinos
- Photons
- Neutrons

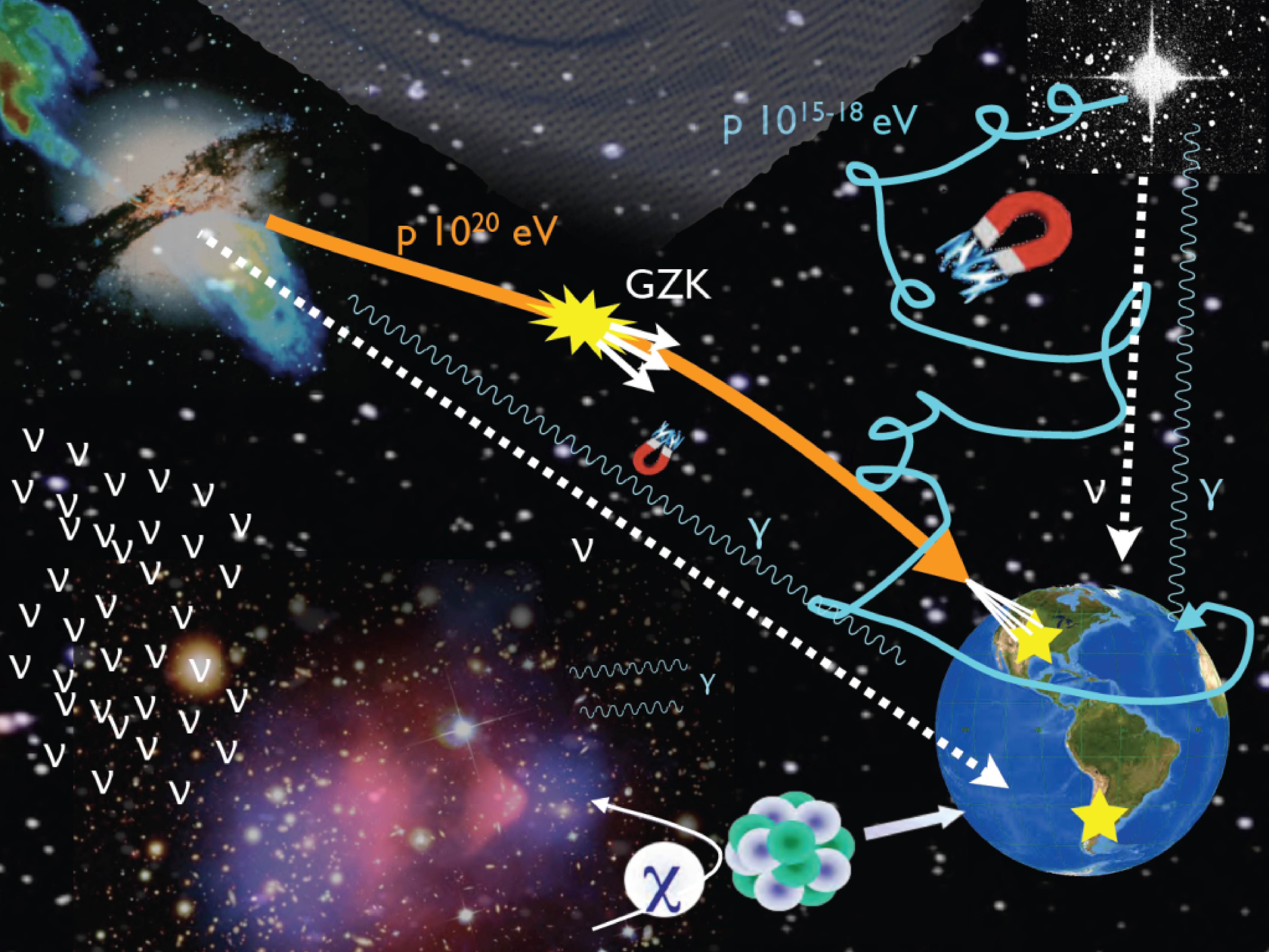
Global Networks

Conclusions

Multi-messenger astrophysics

Makes use of the messenger particles of all four of natures fundamental forces:

Strong – Cosmic Rays (**CR**s)	1912 Victor Hess, balloon, charged particles
Electromagnetic (EM) – photons (**γ**)	1990 Crab, Whipple Telescope, **VHE** γ
Weak – neutrinos (**ν**)	1987 detection of SN1987A
Gravity – Gravitational Waves (**GW**s)	2015 LIGO/Virgo discovery of GW2015


p 10^15-18 eV
p 10^20 eV
GZK
ν
γ
χ

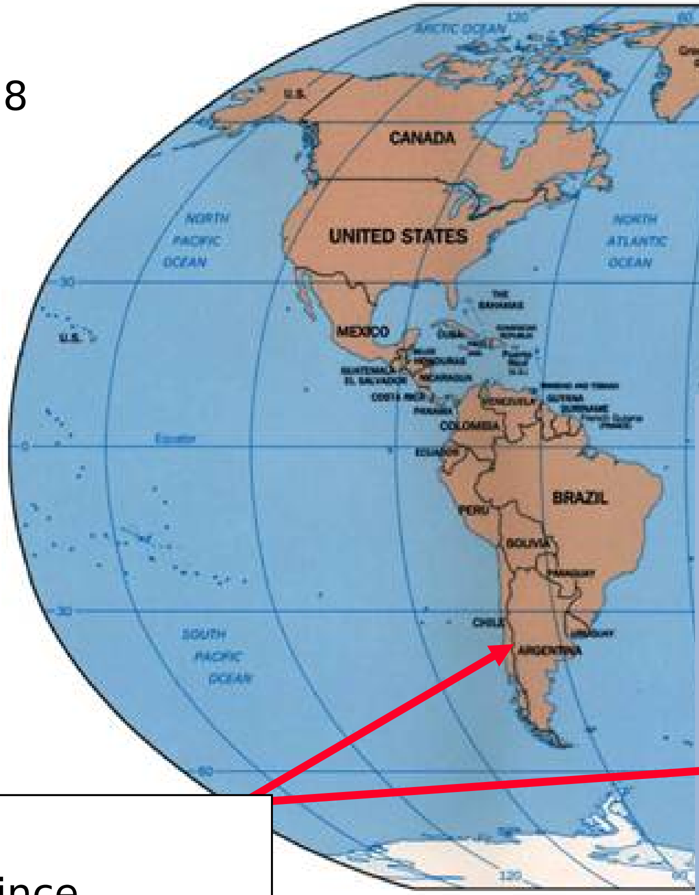
Multi-messenger astrophysics

Auger Datasets of interest for MM studies:

- ~ UHE Hadrons
  - deflected by cosmic magnetic fields ⇒ delayed arrival
- ✓ UHE Galactic neutrons
- ✓ UHE Neutrinos
- ✓ UHE Photons

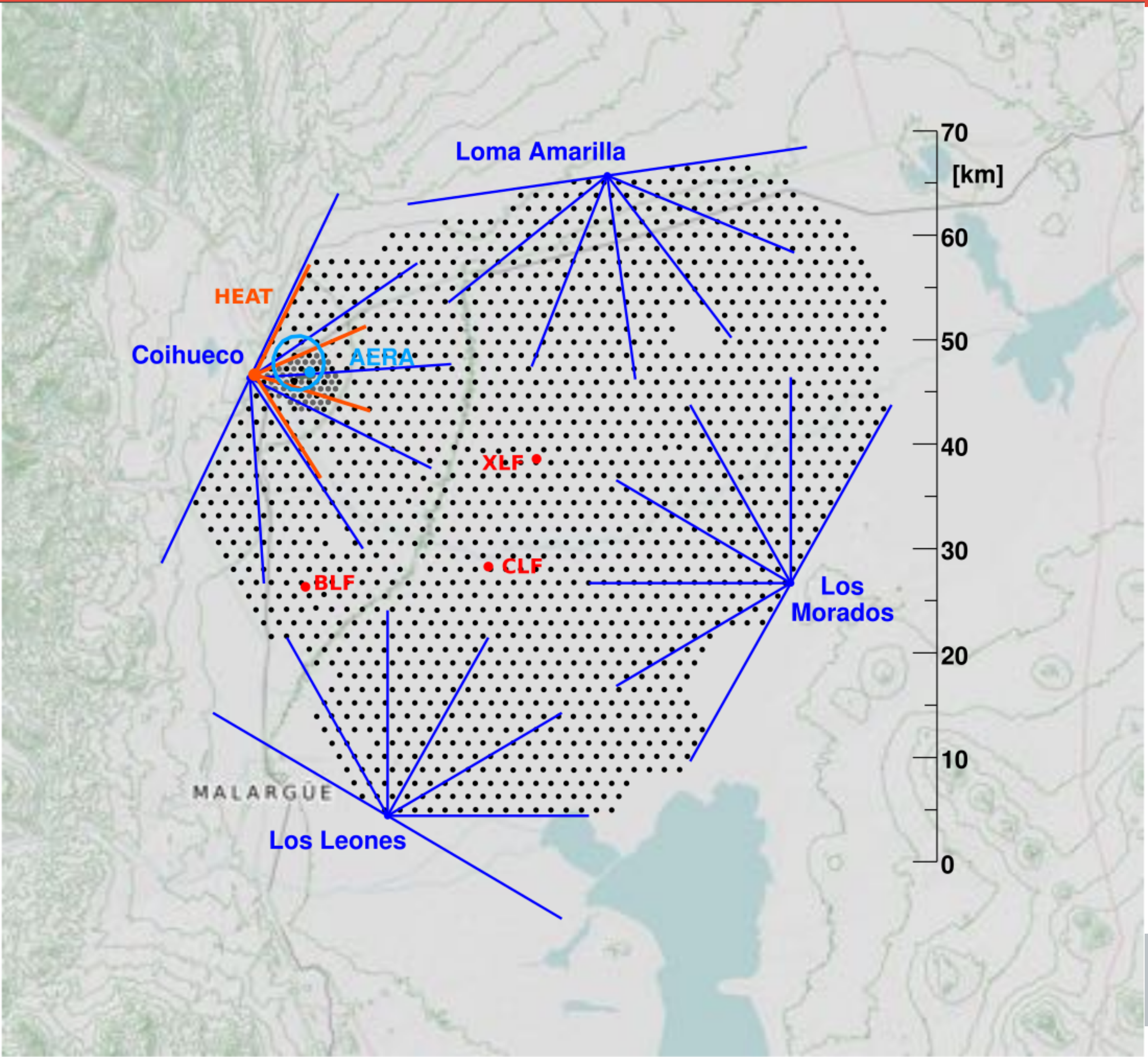
The Pierre Auger Observatory

Observatory completed 2008



Malargüe,
Mendoza Province,
Argentina,
~1400 m above sea level.

The Pierre Auger Observatory



World's largest UHECR detector

Surface Detector (SD):
water Cherenkov detectors

- 1600 stations, 1.5 km, 3000 km^2,
- 61 stations, 0.75 km, 25 km^2

~100% duty cycle

Fluorescence Detector (FD):

- 24 Tel. @ 4 sites, 1°-30° FoV
- 3 Tel. (HEAT), 30°-60° FoV

nighttime observations → 10-15% duty cycle

Atmospheric monitoring

Muon Detector (MD)

Upgrade: Radio Detector (RD)

Scintillators

The Pierre Auger Observatory

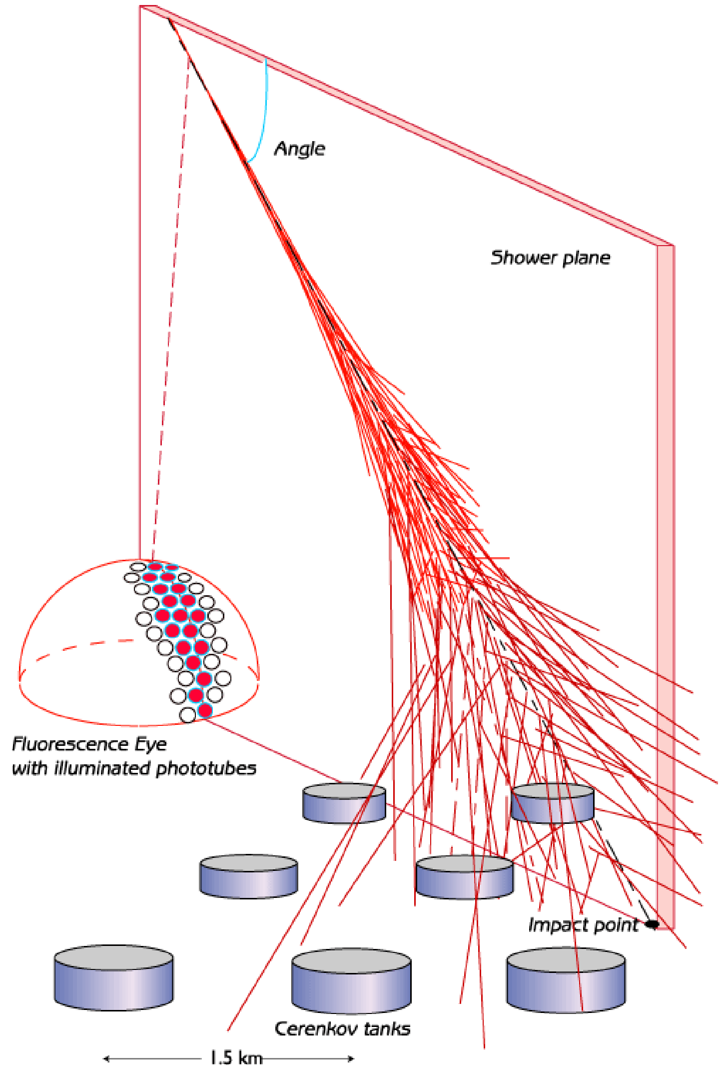
Hybrid detection of Ultra High Energy CRs (UHECRs)

Advantage:

- (More) accurate energy and directional information
- Low(er) energy threshold (SD)
- Small dependence on interaction models (FD)

Disadvantage:

- Only 10-15% duty cycle
  (due to FD)



Neutrinos

Why to look for UHE neutrinos?

Production models of UHE cosmic rays predict neutrinos (astrophysical and cosmogenic).

Information about:

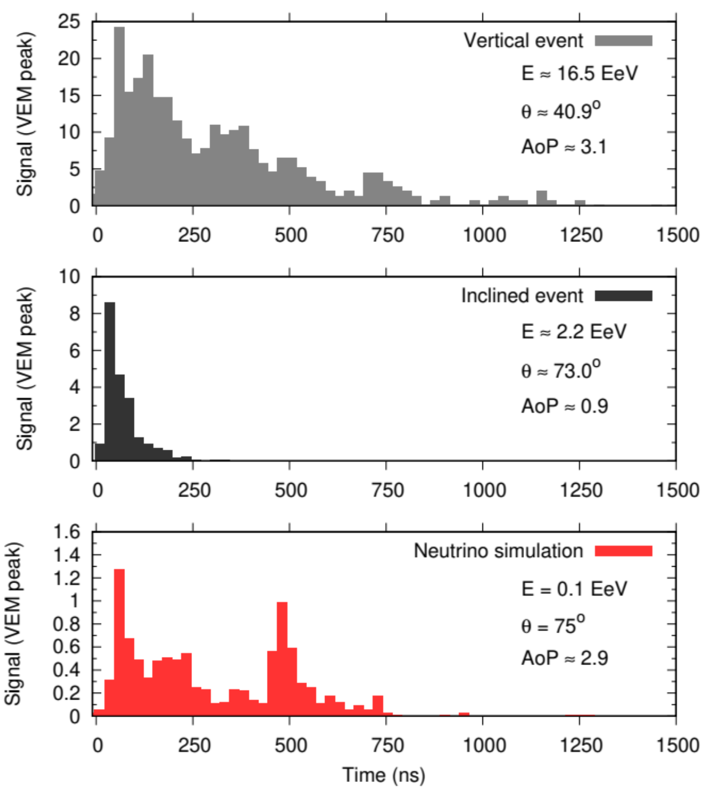
Localisation, acceleration processes, the local environment at the sources, and their evolution with redshift

The Pierre Auger Observatory is sensitive to EeV neutrinos (E > 10^17 eV)

Comparison - Air shower properties

→ Hadrons initiate inclined showers high in the atmosphere.
Shower front at ground: • EM component absorbed in atmosphere • mainly muons remaining

→ Neutrinos can initiate deep showers close to ground.
Shower front at ground: EM + muonic components



Searching for neutrinos

⇒ searching for inclined showers with EM component

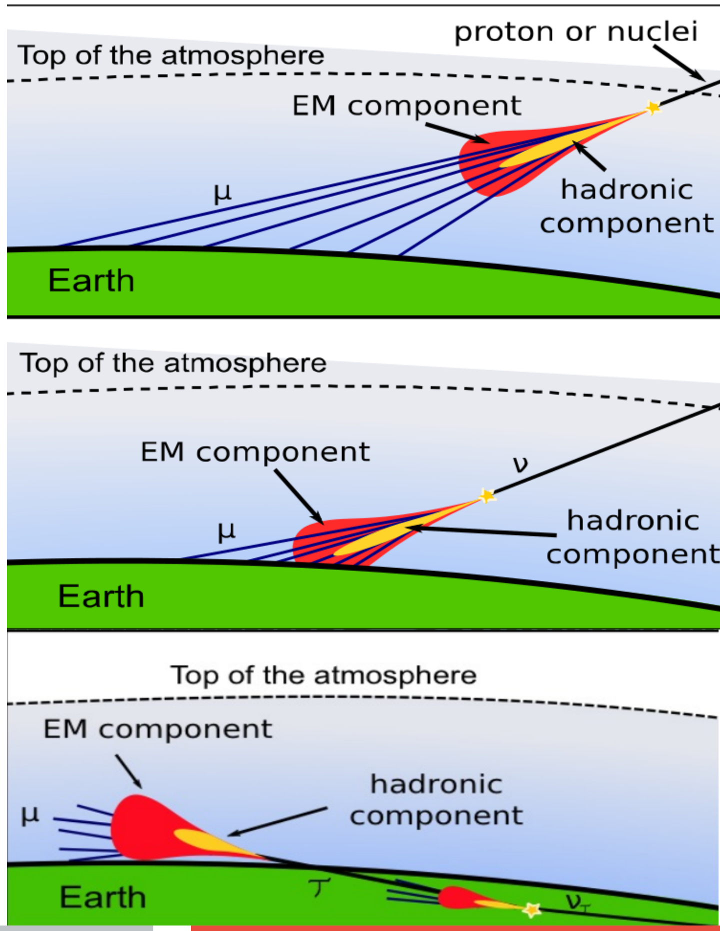
Down going: all flavours

Down-going low angle
DGL 60°-75°

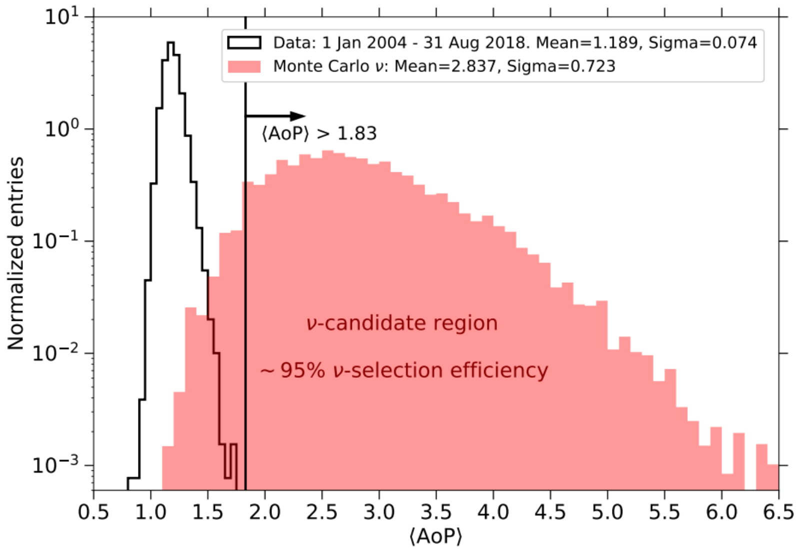
Down-going high angle
DGH 75°-90°

Up-going: ν_τ

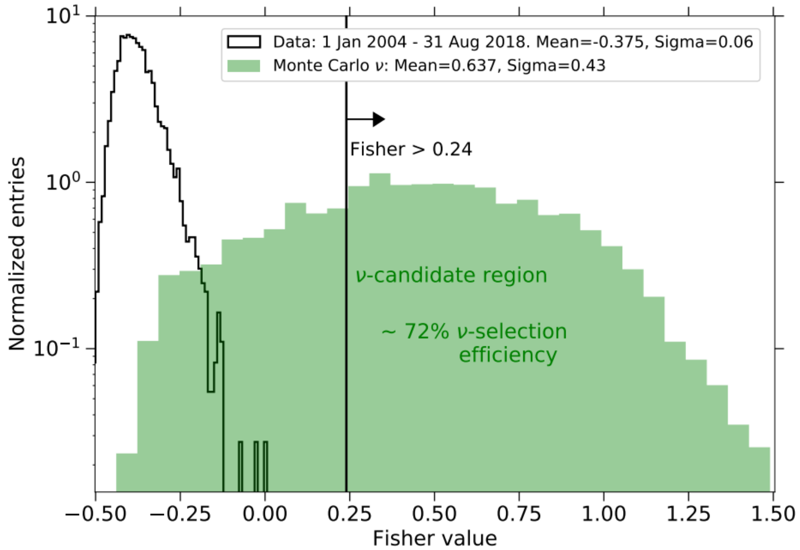
Earth-skimming ES 90°-95°



Identification of neutrino showers

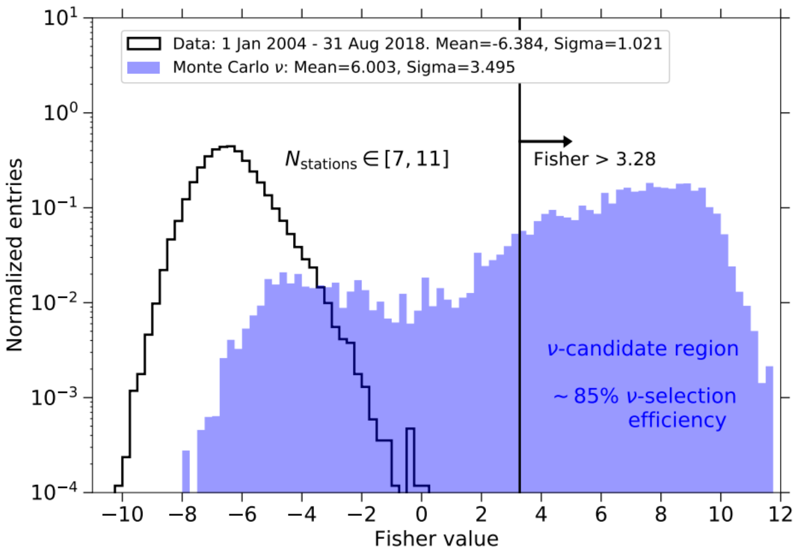


Up-going ES
single variable



DGL
MVA

DGH
MVA



Neutrinos – Limit on diffuse fluxes

Searches for cosmogenic neutrinos

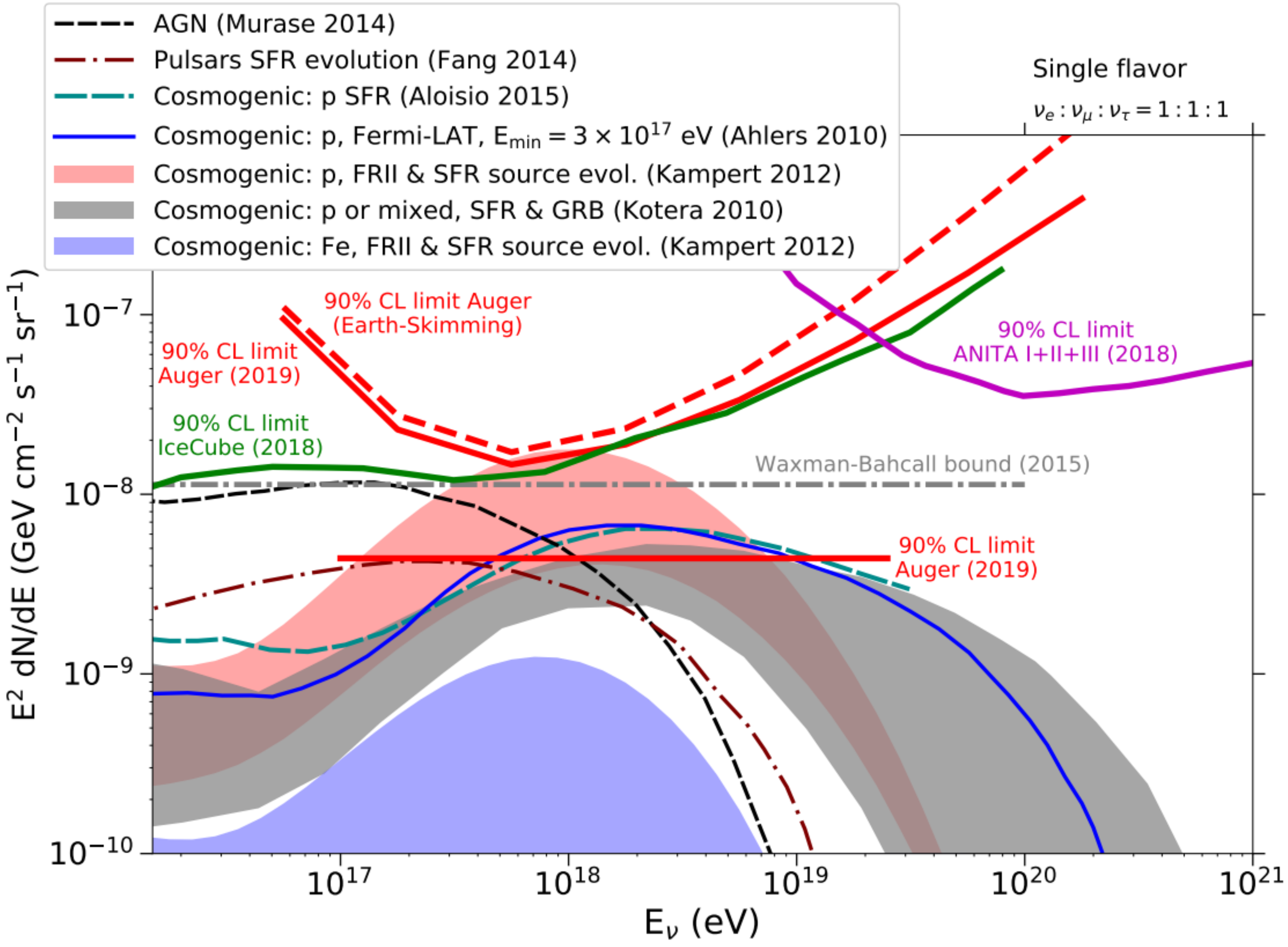
Assumption of differential neutrino flux:

$dN(E_\nu)/dE_\nu = k \cdot E_\nu^{-2}$

$k \sim 4.4 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}

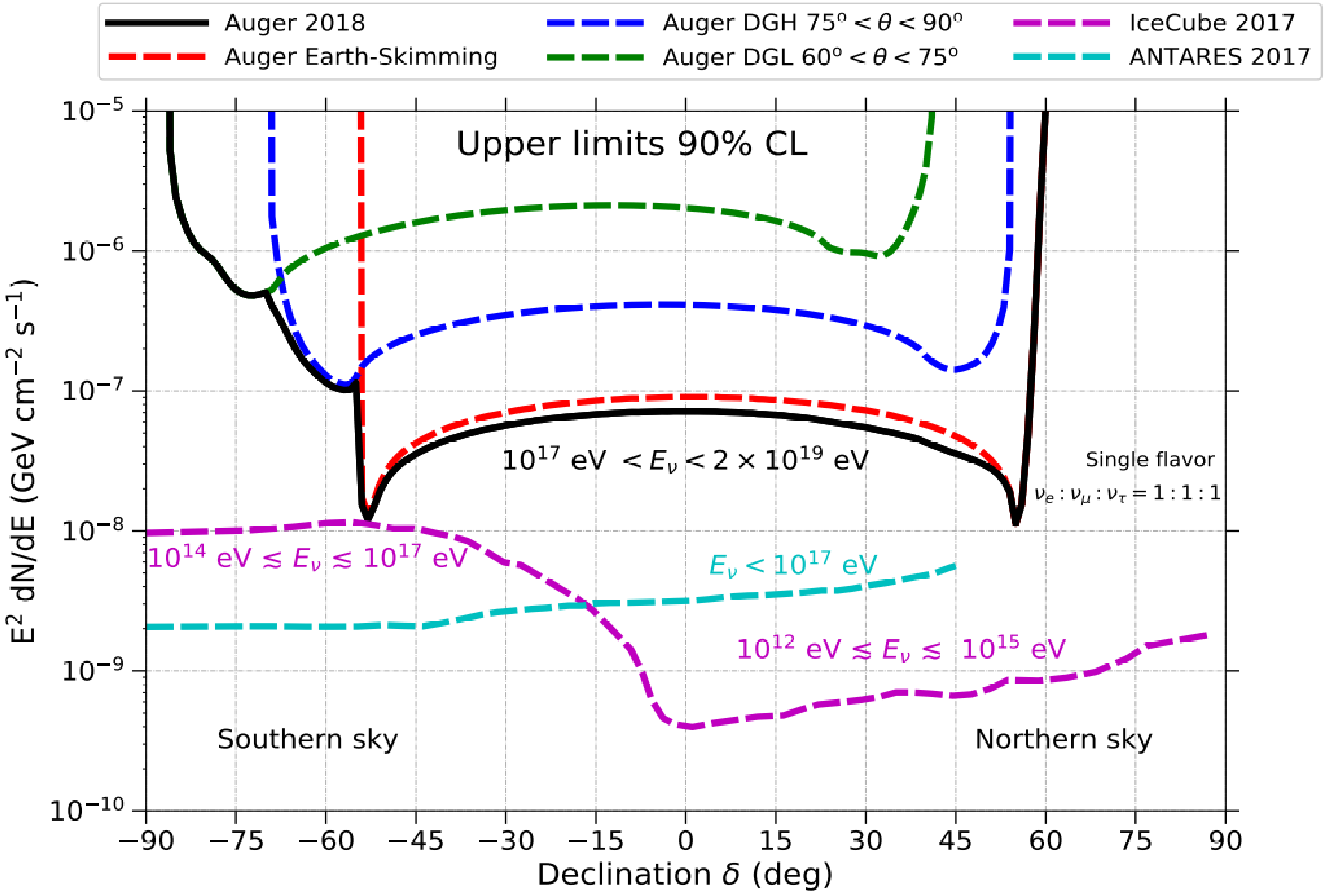
→ Comparable to IceCube at peak sensitivity (~1 EeV)

→ Exposure dominated by the "Earth-Skimming" channel



Neutrinos – Limit on point like sources

Energy range complementary to Icecube and ANTARES



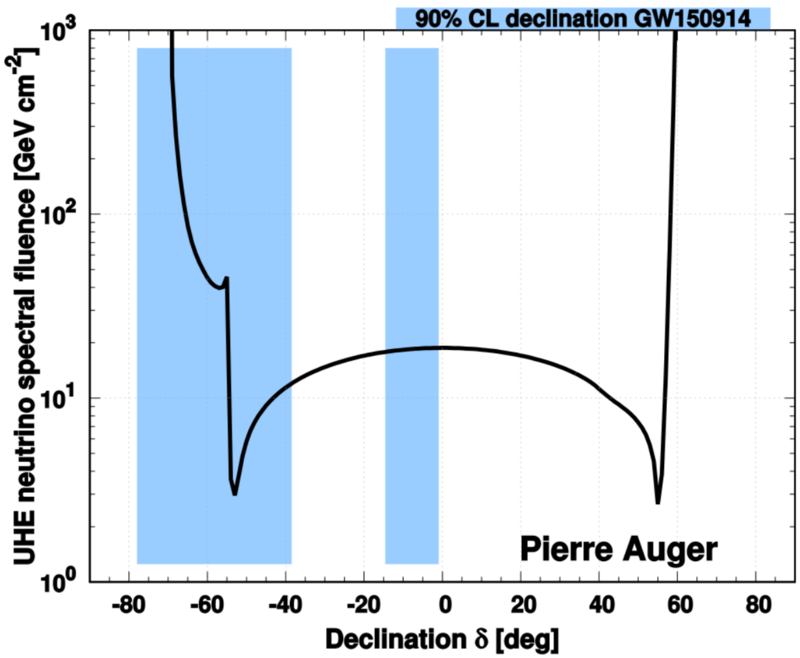
UHE Neutrino follow-up of GW events

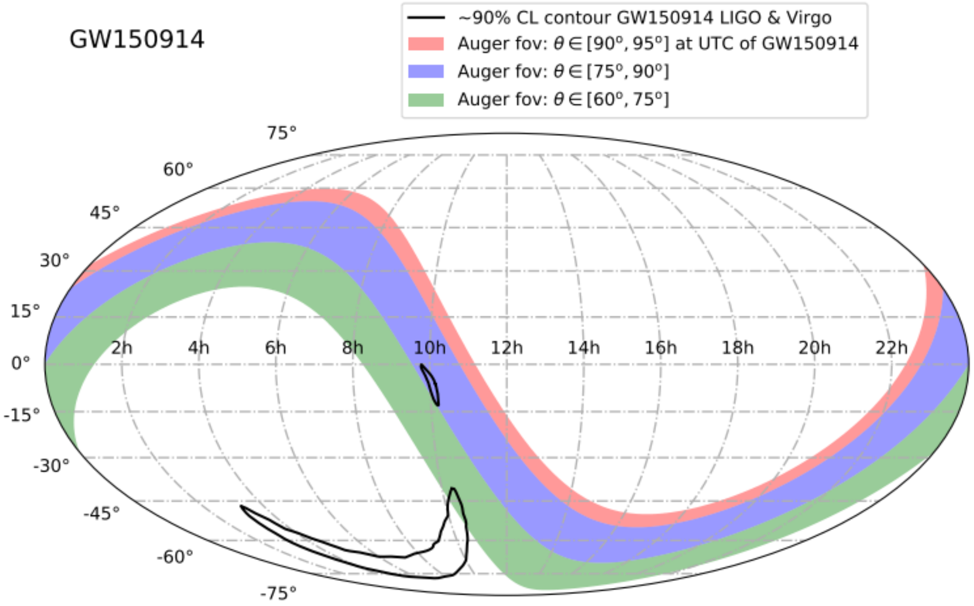
Several detection of GW events in the last few years from LIGO... BBH, BHNS, BNS

Target search for inclined deep showers in Auger data collected +/-500 s around the event and in the period of 1 day afterwards

→ No candidates found

→ Limits on Neutrinos fluence from GW events



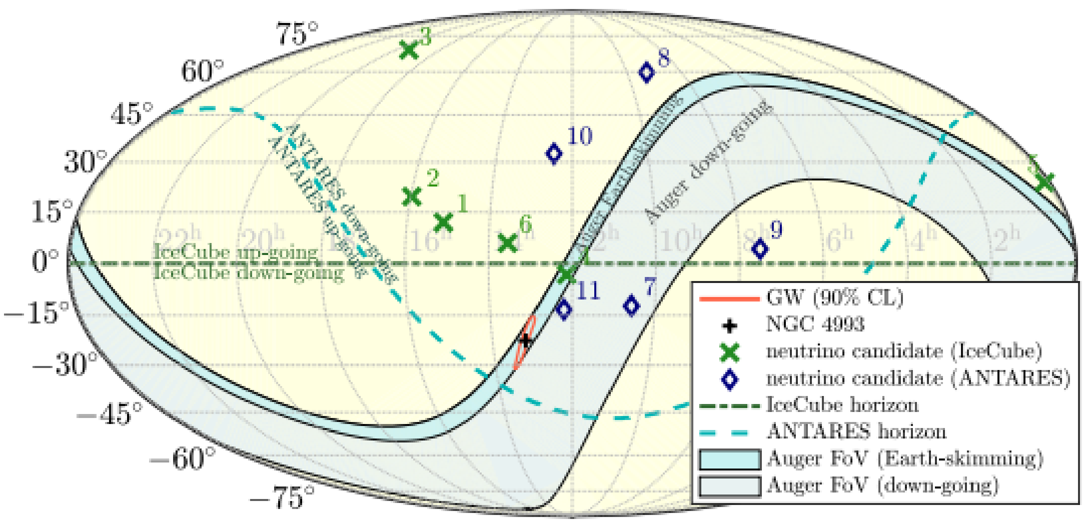


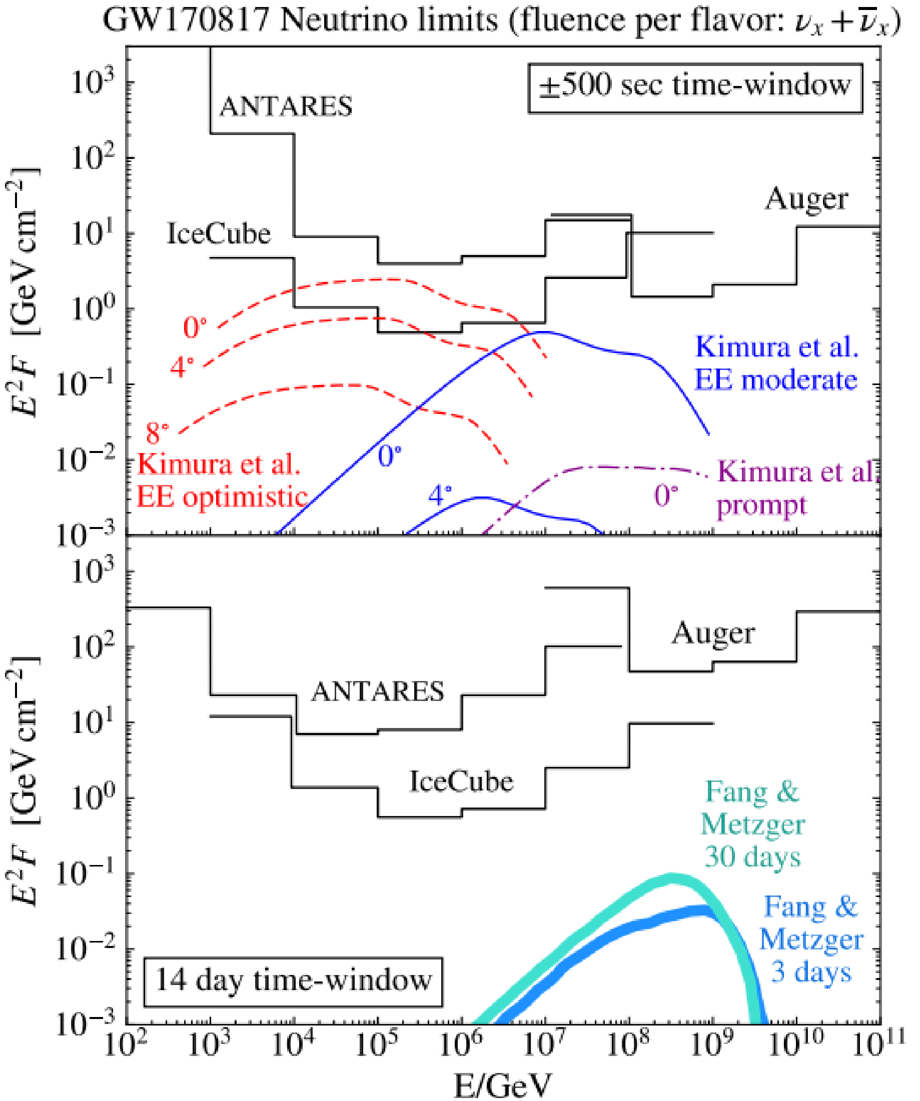
GW170817

Aftermath of this merger

Seen by **70** observatories on 7 continents and in space across the EM spectrum,

Significant breakthrough for multi-messenger astronomy





UHE Photons

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

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

With respect to p and nuclei, photons have:

→ deeper shower development

→ smaller muon content

As a consequence, they differ also in other observable characteristics:

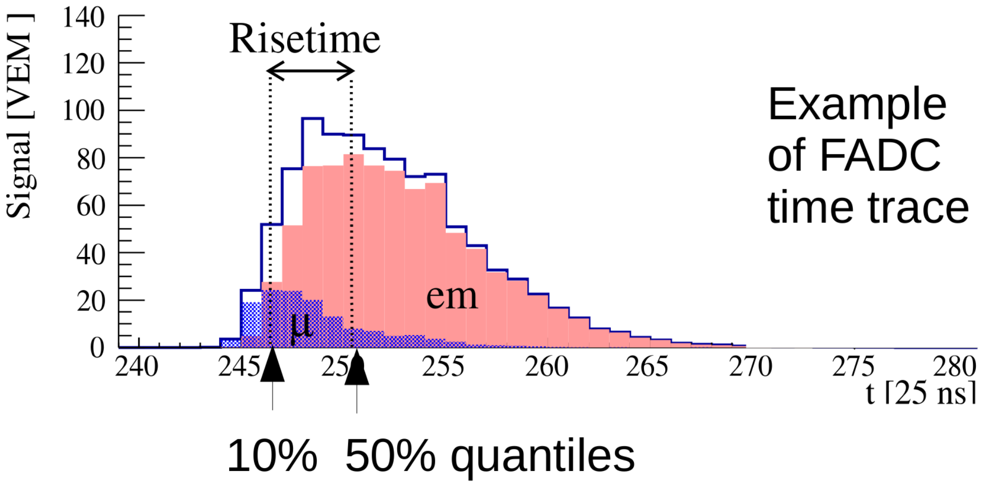
- steeper LDF
- smaller footprint (less triggered stations)
- broader time front

UHE Photons

SD ONLY DATA

Variables with separation power:

- The Risetime of the signal in a SD station,
- Curvature of the shower front,
- AoP,
- ...



Example of FADC time trace

Variables are added and combined in

a multivariate analysis.

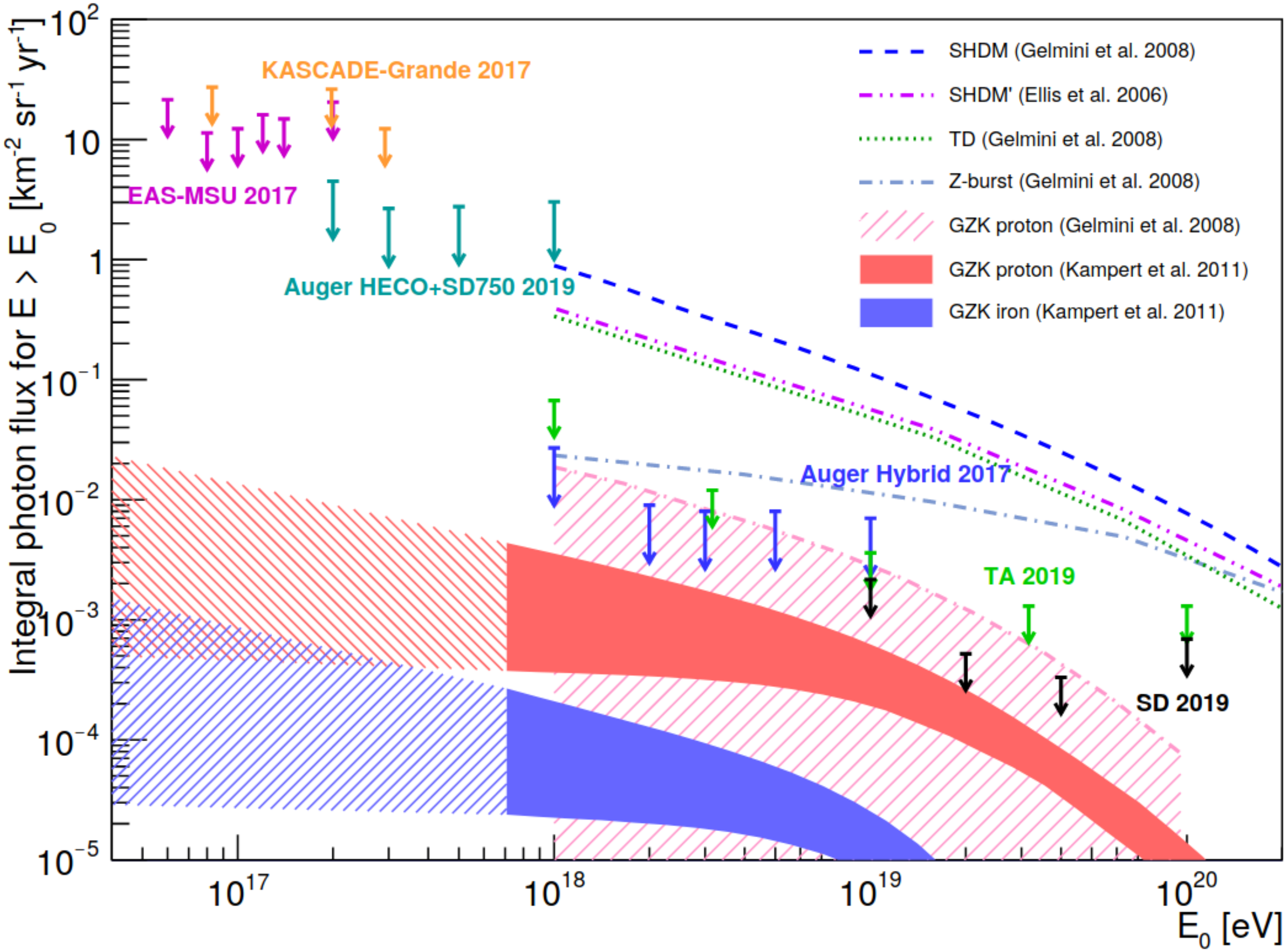
Limits at 95% C.L. for diffuse UHE Photon flux

ICRC 2019

Auger is most sensitive detector to photons @ E>0.2 EeV

exposure of 40,000 km² sr yr

Top-Down models excluded, also some models for cosmogenic γ in reach



Neutrons

Decay length is ~ 9.1 kpc E/EeV

→ neutrons with E ~ EeV can reach Earth from entire Galaxy

11 classes of sources in the Galaxy used as combined target sets for neutron searches

Searches in the first 9.75 years of data yielded no significant excess

→ 95% C.L. upper limits on the energy flux in neutrons have been deduced.

these limits already exclude energy fluxes on the level of the TeV photon energy flux from the target sets

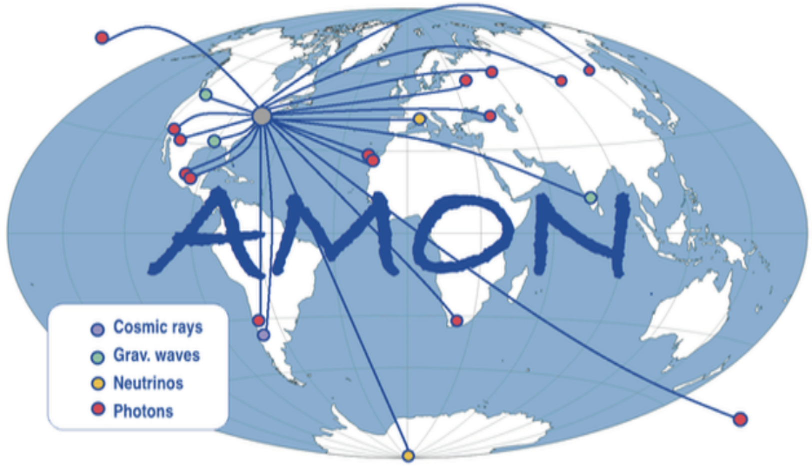
Strong limit

- Leads to the exclusion of an E^{-2} Fermi-acceleration of protons up to EeV energies,
- Placing a strong constraint on ultra-high energy proton production in our Galaxy

Global Networks

Deeper, Wider, Faster (DWF)

The Astrophysical Multi-messenger Observatory Network



Possibilities:

- Follow-up
- Sending trigger
- Both → Auger

Conclusions

The Pierre Auger Observatory is sensitive to Neutrinos, Photons and Neutrons in EeV

→ **is a MM detector**

Auger showed to have an Energy range for these messengers complementary to other observatories

Stringent upper bounds were placed to a flux of diffuse cosmogenic **neutrinos**

UHE neutrino follow-up searches performed for LIGO/Virgo mergers

Most sensitive **UHECR photon** search over about three orders of magnitude starting at 0.2 EeV set most stringent limits on the photon flux

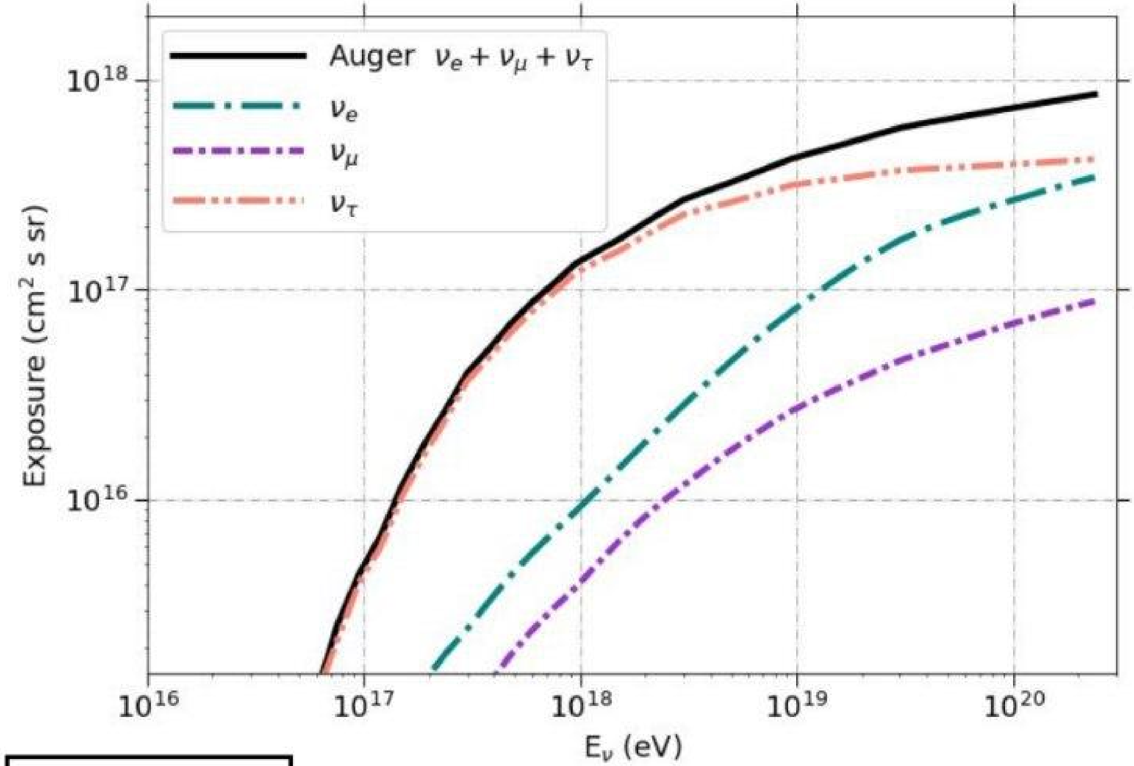
Neutron limits placing a strong constraint on UHE proton production in our Galaxy

Thank you!

Backup

Flavour contributions to Exposure

arXiv:1906.07422



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

SD Data:
Jan. 2004 –
August 2018

Auger sensitivity dominated by tau-neutrinos

UHECR – neutrino correlation searches

Exploring the correlation:

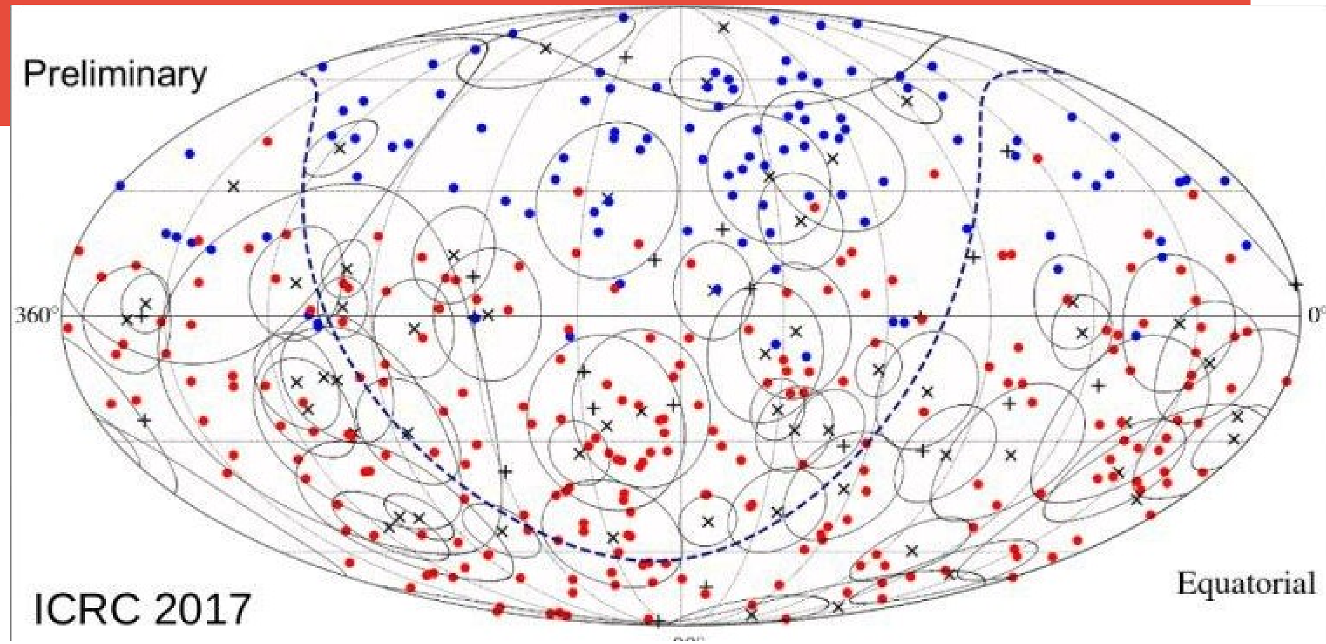
UHECR with E > ~ 50 EeV (Auger + TA)

vs.

Neutrinos (IceCube)

Two different methods:

- **Excess** of frequency of angular separation above isotropy assumption
- **Stacking likelihood** of angular correlations given MF models, assuming sources are at measured neutrino directions



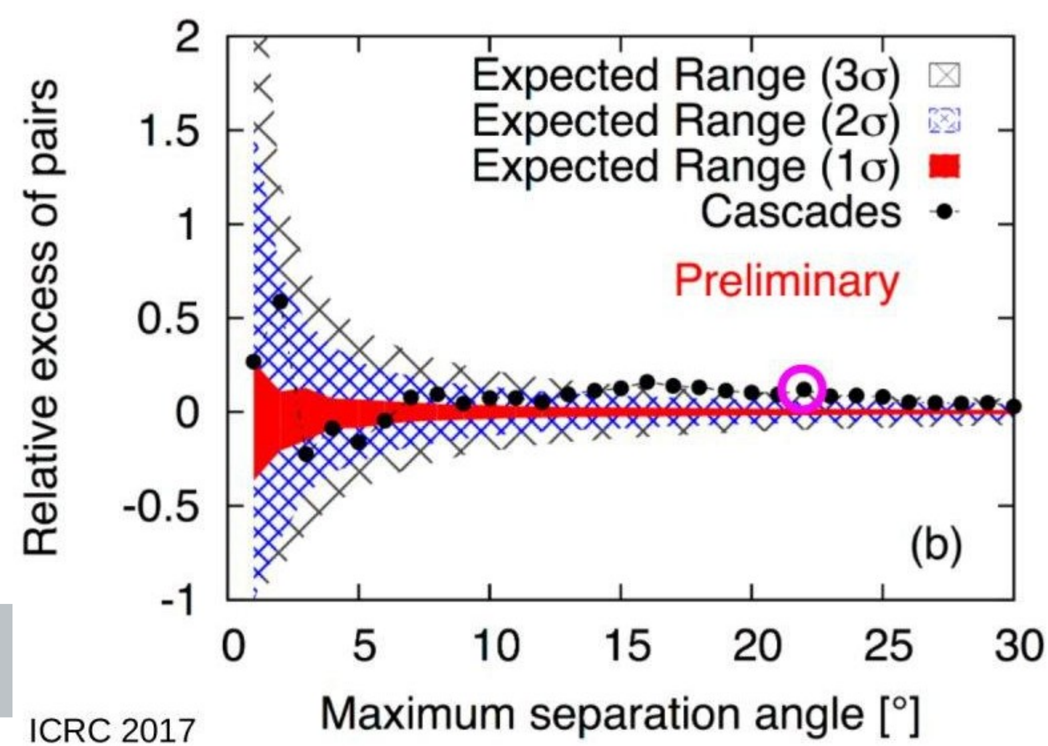
Most significant excess with IceCube **cascades** at $\Delta\Psi \sim 22°$

➔ Combination of **cascade angular Resolution (~15°)** and **UHECR deflection (~6°/E_{100})**

$p = 5 \times 10^{-3}$ (post trial)

$E_{100} = E / 100$ EeV

ICRC 2017



ICRC 2017