Ultrahigh-Energy (EeV=10^{18} eV) multi-messengers at the Pierre Auger Observatory

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Ricap 18
Rome, Italy 4-7 September 2018

Multi-messengers: Properties

- Cosmic rays:
  - Charged particles: Do not maintain direction to the source (except maybe light nuclei at >> EeV)
  - Neutrons: Keep direction to the source, but sensitive only to sources in the Galaxy at EeV energies
- Photons: Travel undeflected, but their attenuation length is D ~ few Mpc at EeV (sensitive to sources in the local Universe)
- Neutrinos: Keep direction to the source, and can arrive from anywhere in the Universe

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- Gravitational waves

Auger in Multi-messenger

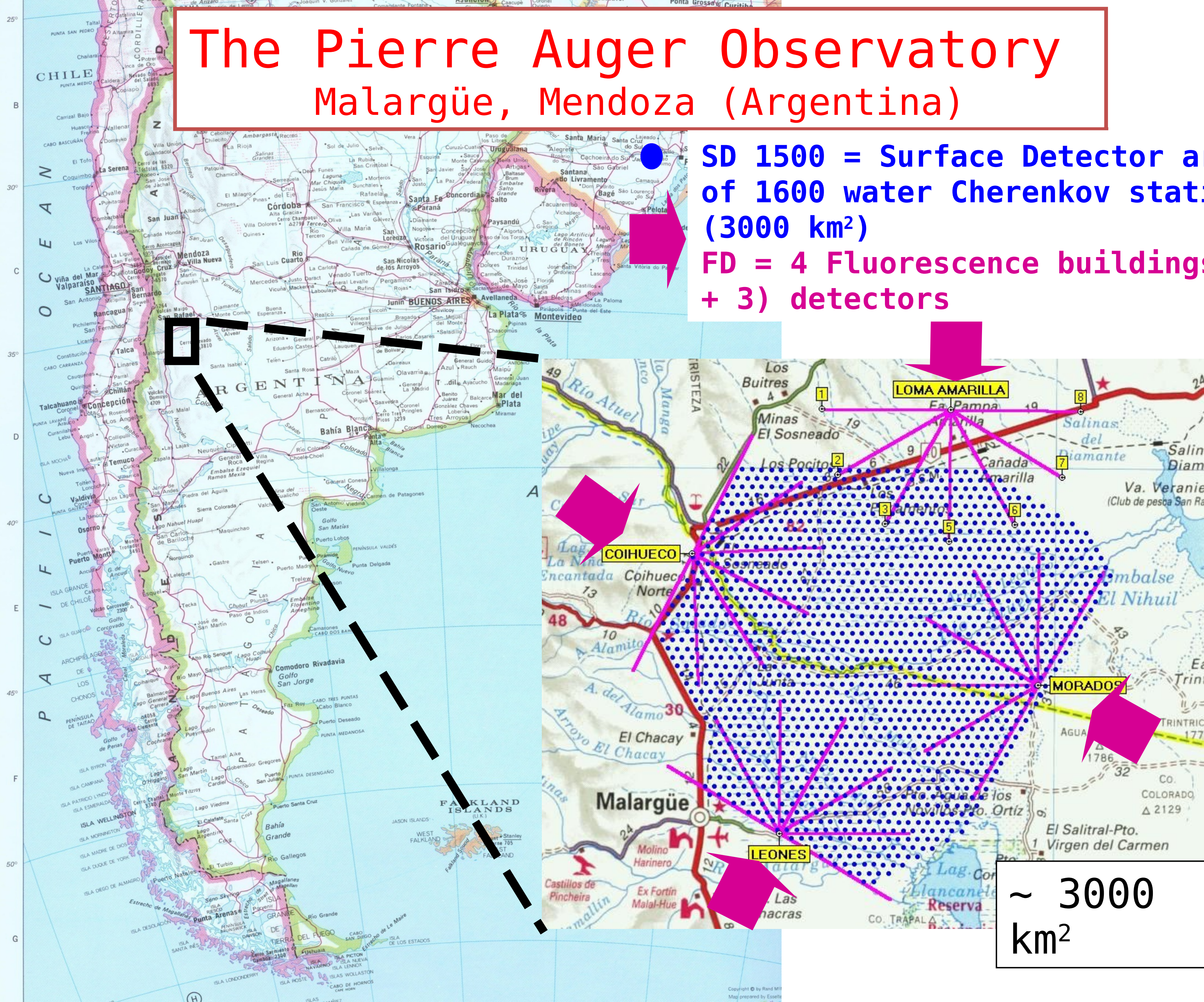
- With the Pierre Auger Observatory we can detect:
  - Cosmic rays ✓
  - Photons ✓
  - Neutrinos ✓

  at $\gtrsim$ EeV energies

  - Gravitational waves ✗

The Pierre Auger Observatory

Malargüe, Mendoza (Argentina)



SD 1500 = Surface Detector array of 1600 water Cherenkov stations (3000 km²)

FD = 4 Fluorescence buildings (24 + 3) detectors

~ 3000 km²

Detection technique

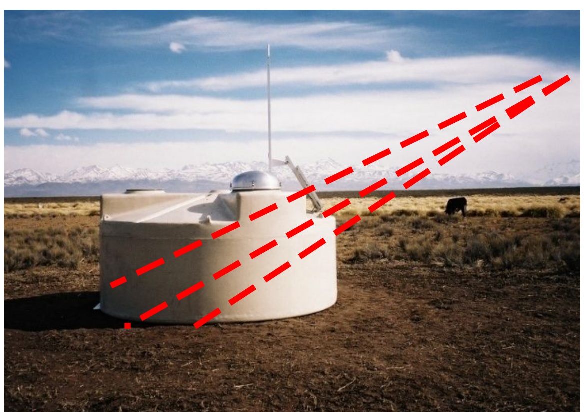
Auger combines 2 different techniques (hybrid mode):

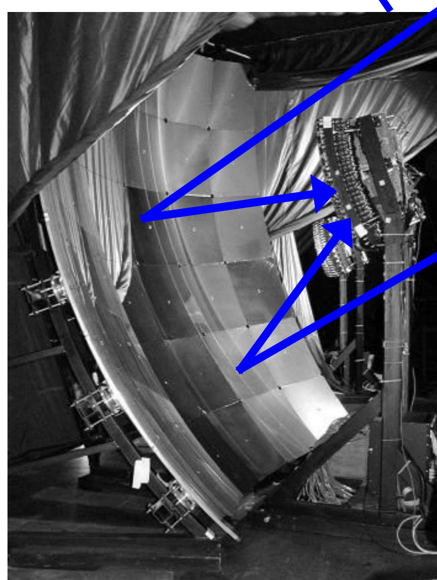
Fluorescence telescopes

Water-Cherenkov stations

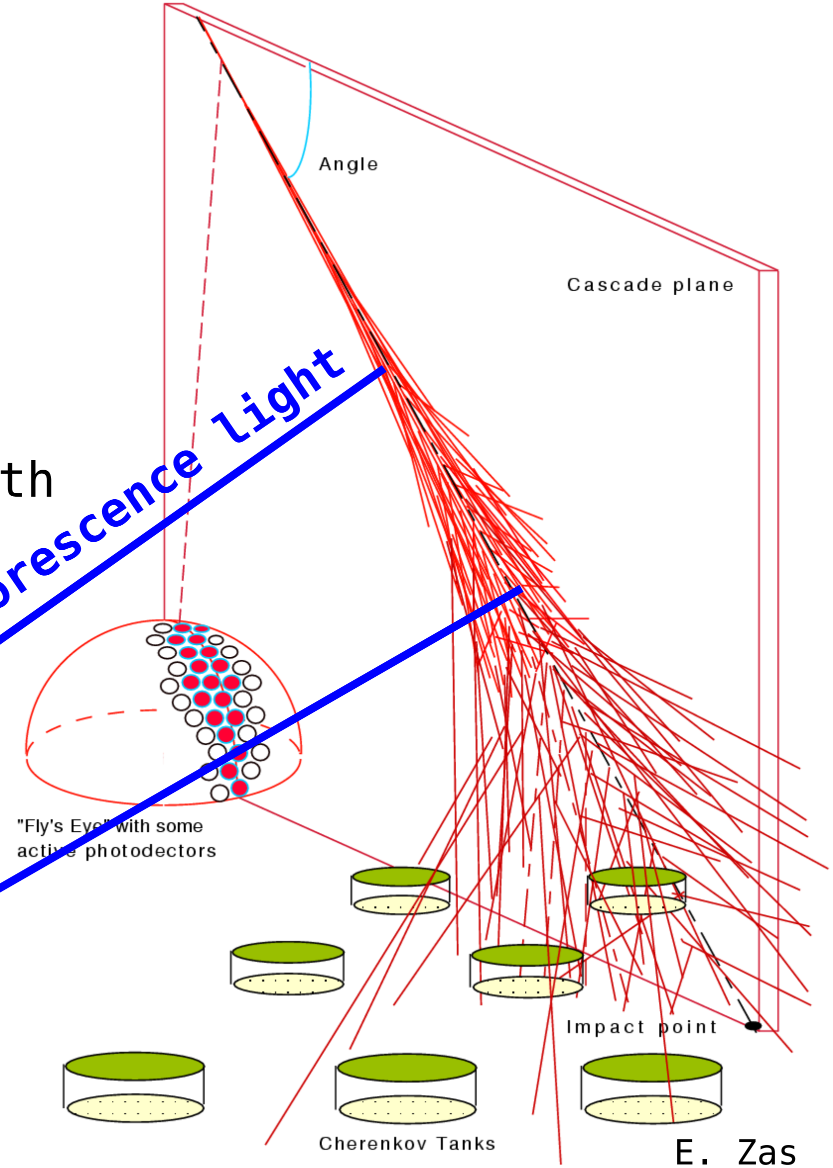
~ 10% of events are observed with both techniques: wealth of information about shower development.

Surface detectors





Fluorescence light



E. Zas

Search for neutrons and photons with Auger Observatory

- UHE Neutrons:
  - They induce showers that **cannot** be distinguished from proton/nuclei showers
  - We look for a excess of cosmic-ray events from particular directions (indicative of flux of neutral particles from a discrete source)
- UHE Photons:
  - They induce showers that **can** be distinguished from background proton/nuclei showers
  - We look for showers with deeper X_{max} and less muons than proton-induced showers
- More details in:
  - Neutrons: Pierre Auger Collab,ApJ 789 (2014) L34
  - Photons: Pierre Auger Collab, JCAP 04 (2017) 009

Search for neutrinos with Auger SD

- UHE Neutrinos induce showers that **can** be distinguished from proton/nuclei showers.

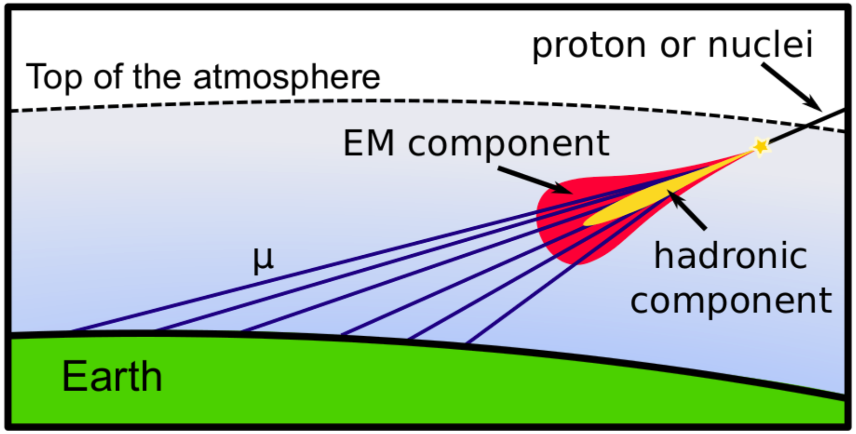
- They can penetrate large amounts of matter and generate a shower close to the surface detector with a significant electromagnetic component

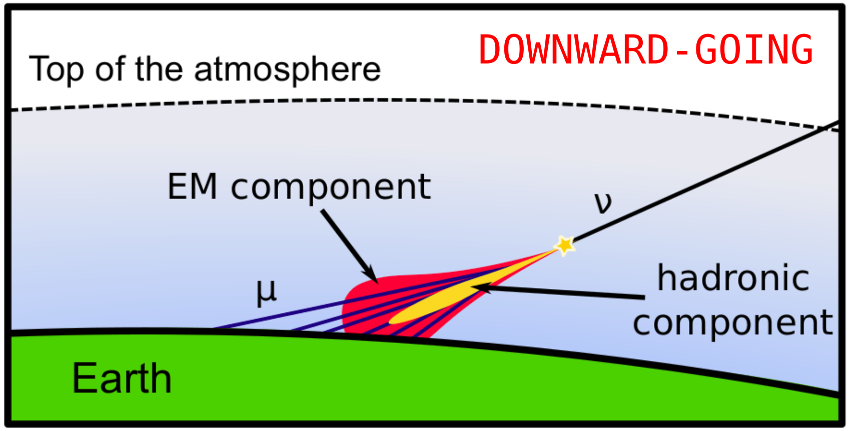
- We can find them searching for inclined (with zenith angle > 60º) and “young” showers (see next slide)

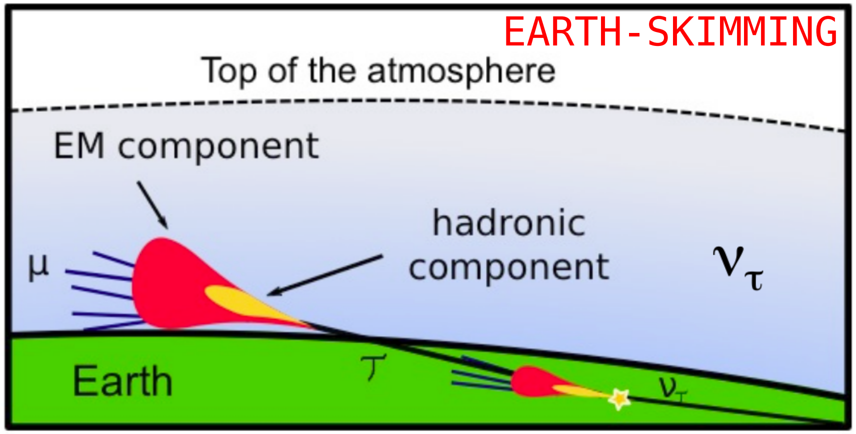
Inclined showers & UHE neutrinos

- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground don't have electromagnetic component (mainly muons).

- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components

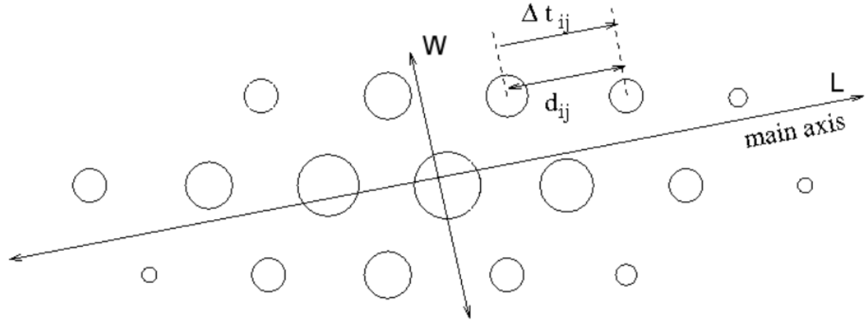




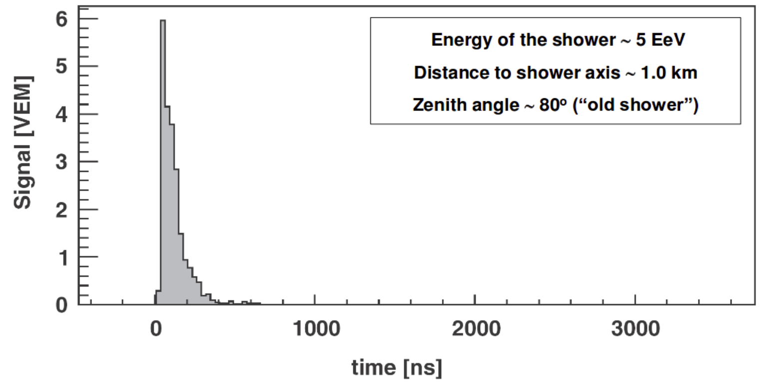


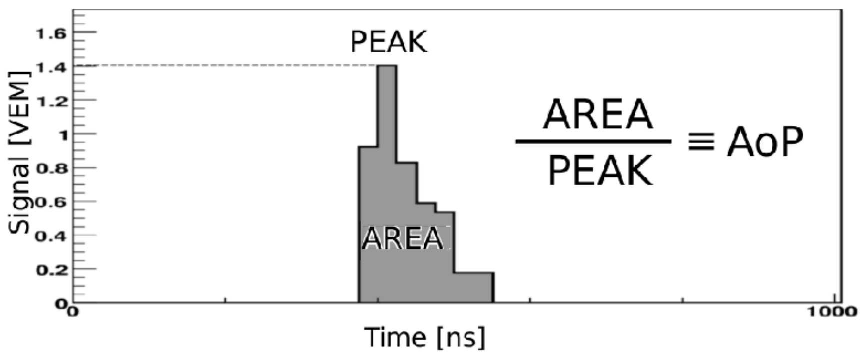
Ideas for the neutrino's search

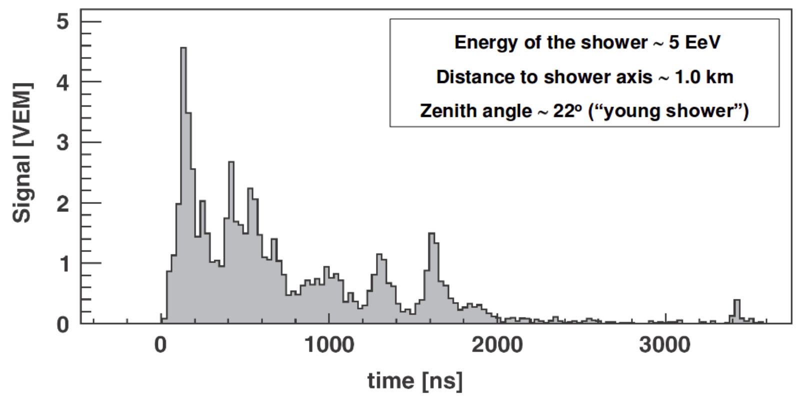
- Inclined showers:
  - L/W high
    - For ES: >5



- Young showers:
  - <AoP> high
    - For ES: >1.83







ν search results

No ν candidate events found in any of the analyses

Example: Earth-skimming analysis

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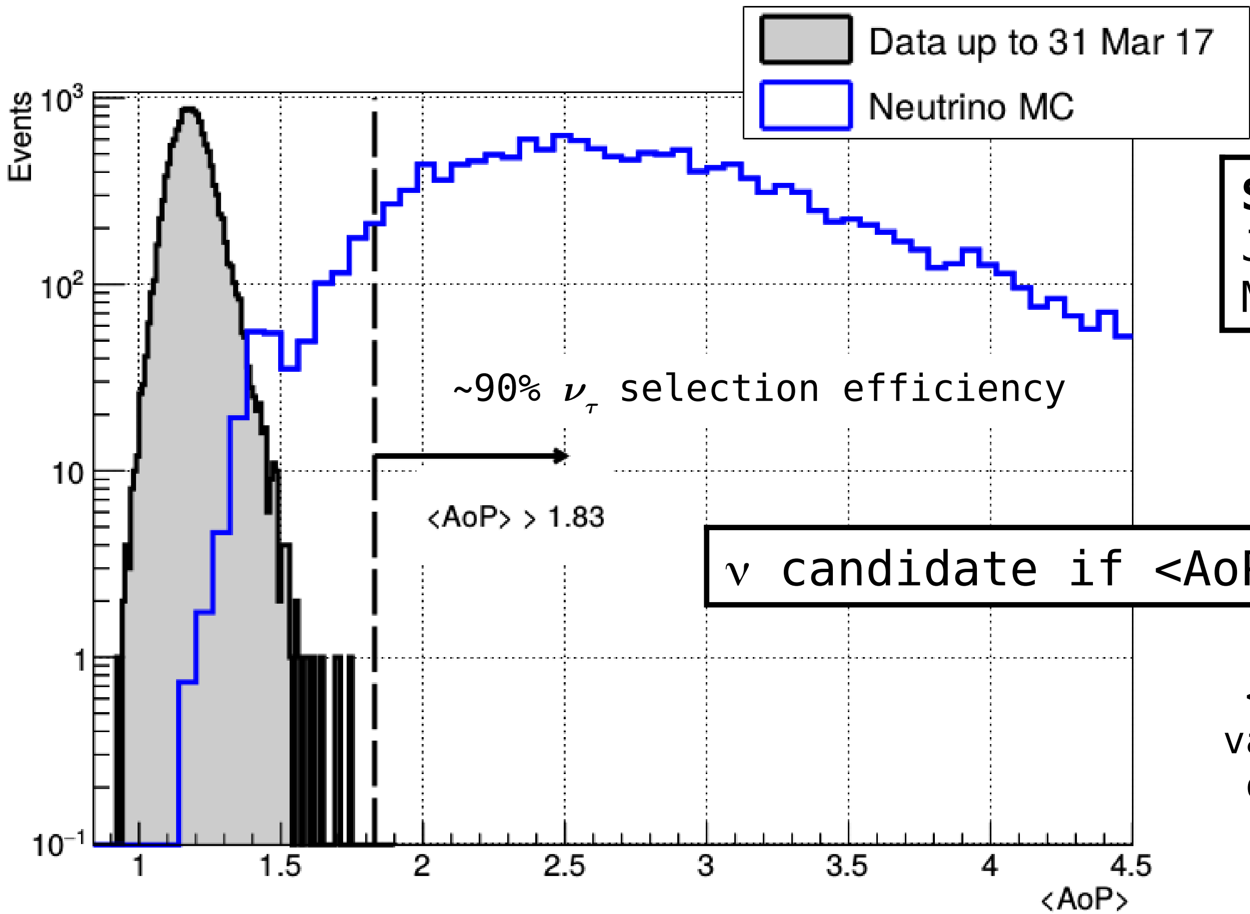
ICRC 2017



SD Data:
Jan. 2004 –
March 2017

ν candidate if <AoP> > 1.83

<AoP> = mean value of Area-over-Peak in event

Limit to the diffuse flux of UHEν

Single flavour, 90% C.L.

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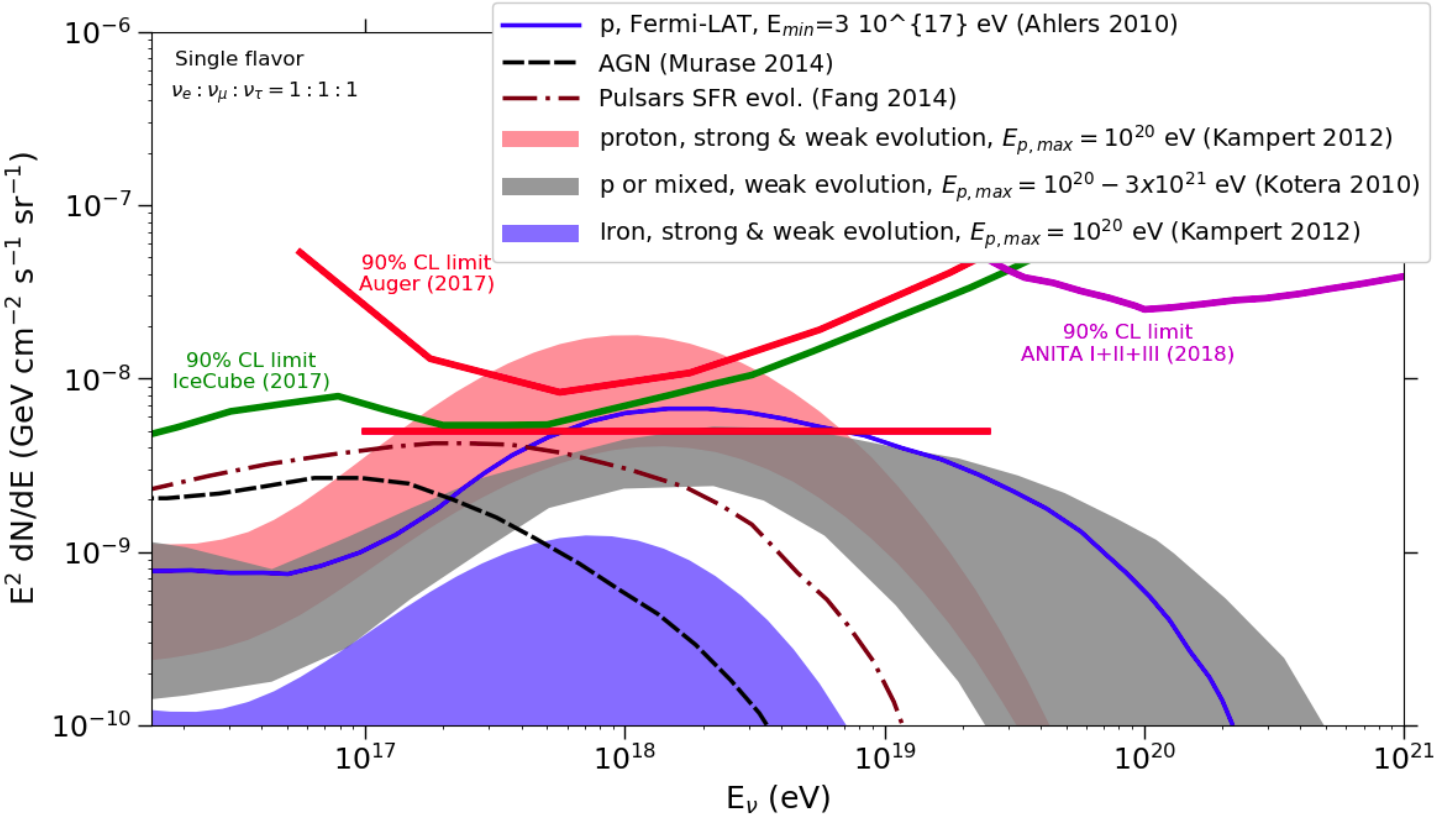

SD Data:
Jan. 2004 –
March 2017

$$k = \frac{N_{\rm up}}{\int_{E_\nu} E_\nu^{-2} \mathcal{E}_{\rm tot}(E_\nu) dE_\nu}$$

Auger Limit: dN/dE = kE^{-2}
k ~ 5.0×10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

Limit to point-like sources of UHEν

Single flavour, 90% C.L.

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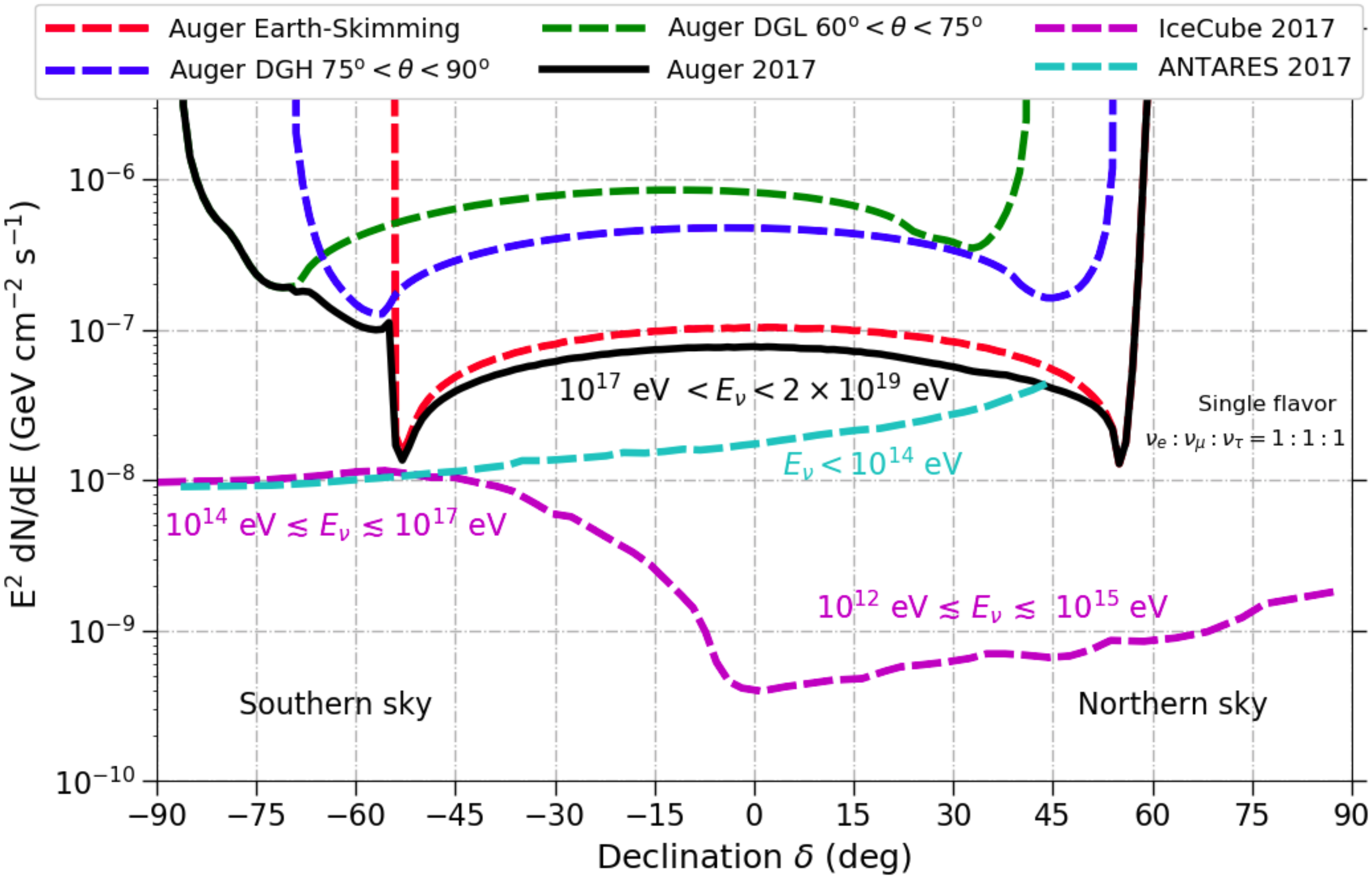


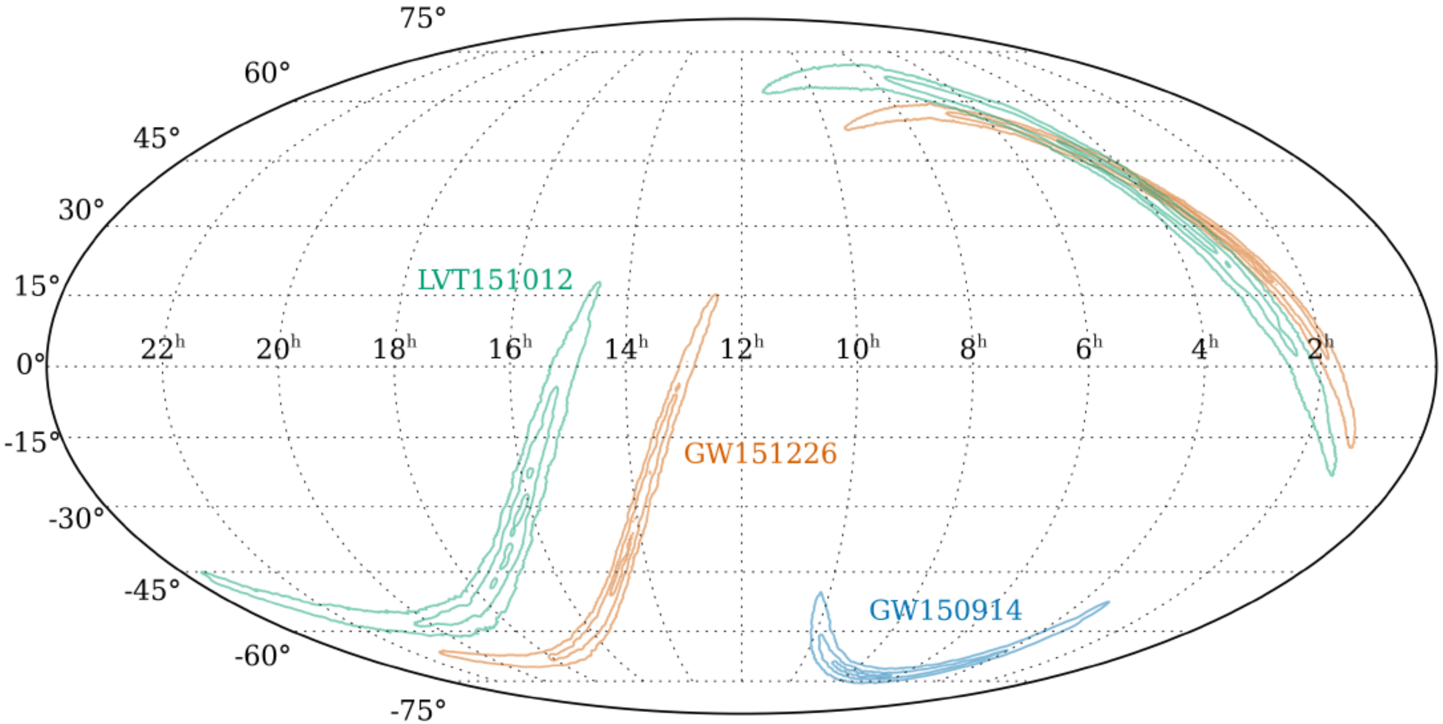
SD Data:
Jan. 2004 –
March 2017

Interesting limit in the region of the ES channel
(for zenith angles between -54.5° and 59.5°)

First Gravitational Wave events

Gravitational Wave events (GW150914 & GW151226) detected by Advanced-LIGO detectors (also LVT151012 candidate):

- Inferred source: **merger of binary black-hole** at D = 410 & 440 Mpc
- ~ 3 & 1 solar masses released in the form of GW
- Position in the sky uncertain: few 100 deg^2

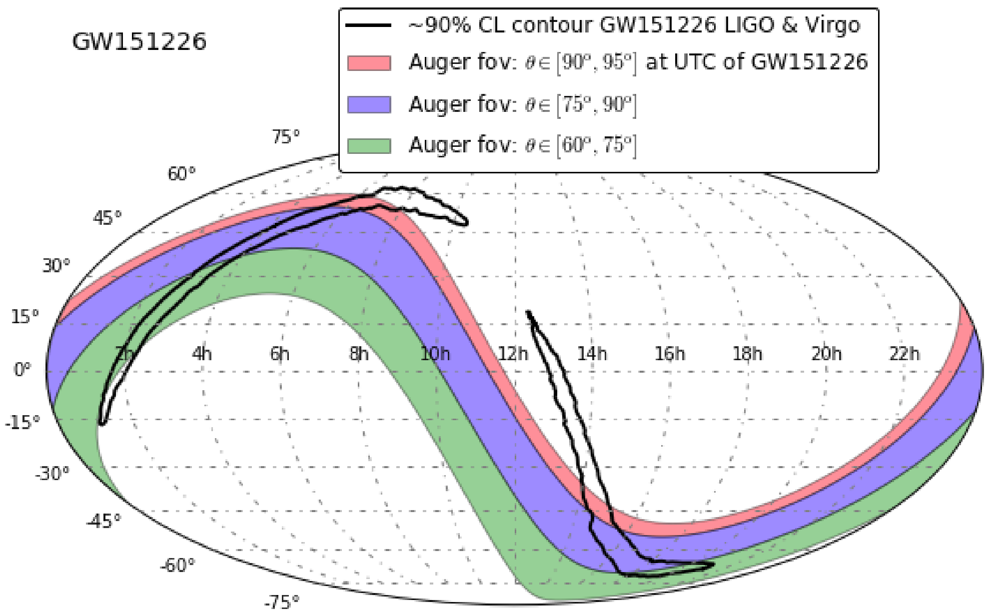


Searching for ν in coincidence with GW150914 & GW151226 (& LVT151012)

- We applied Auger Earth-Skimming and Downward-going neutrino selection to:
  - Data **+/- 500 s** around GW events.
  - Data **1 day after** GW events – GRB "afterglow" UHE neutrinos.

    (assuming they can be produced at any time 1 day after GW)

No neutrino candidates found in any of the data periods unblinded for any of the GW events



Constraints on energy radiated in the form of UHEν (E_ν > 10^{17} eV)

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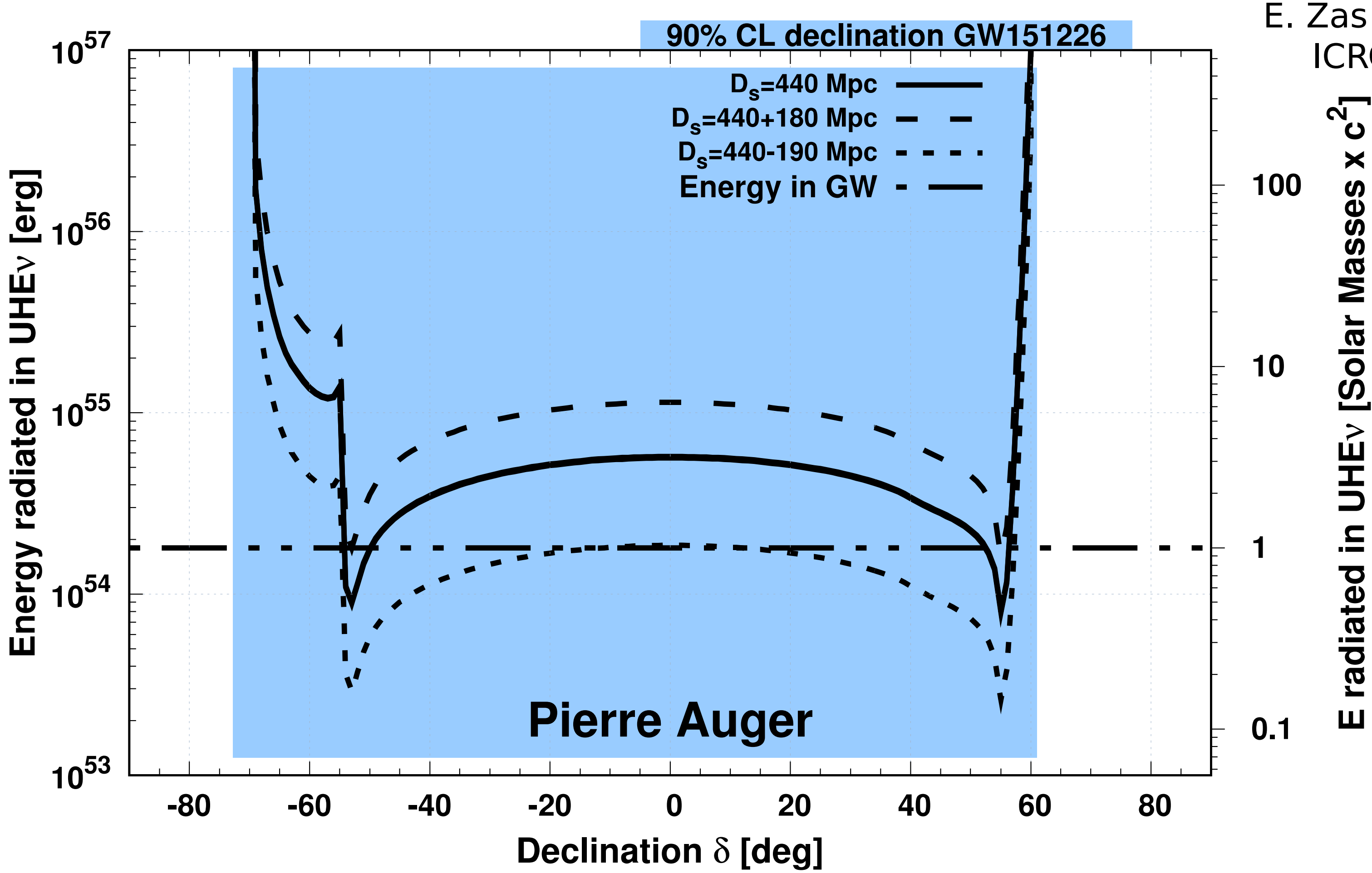


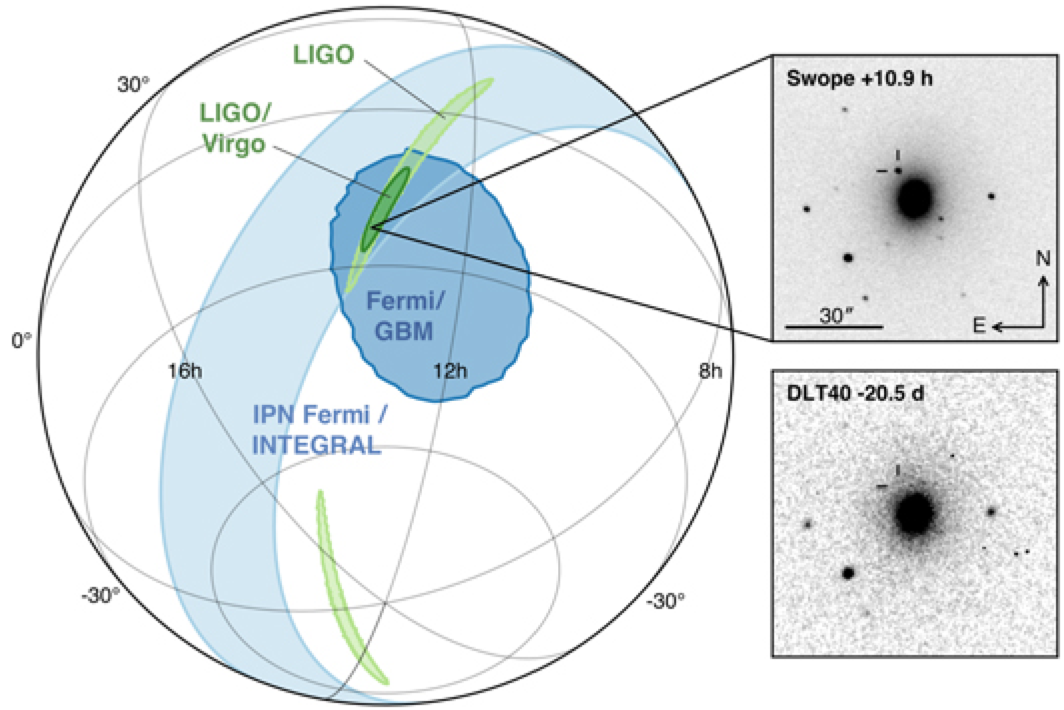
Constraints on energy radiated from **GW151226** in UHEν:
less than (0.5, 3) solar masses depending on source declination

Binary Neutron Star Merger

- GW170817 is the perfect example of multi-messenger astronomy.
- Observed in radio, optical, X-rays and GW:

  Abbott B. P., Abbott R., Abbott T. D. *et al.* 2017c, ApJ, 848, L12

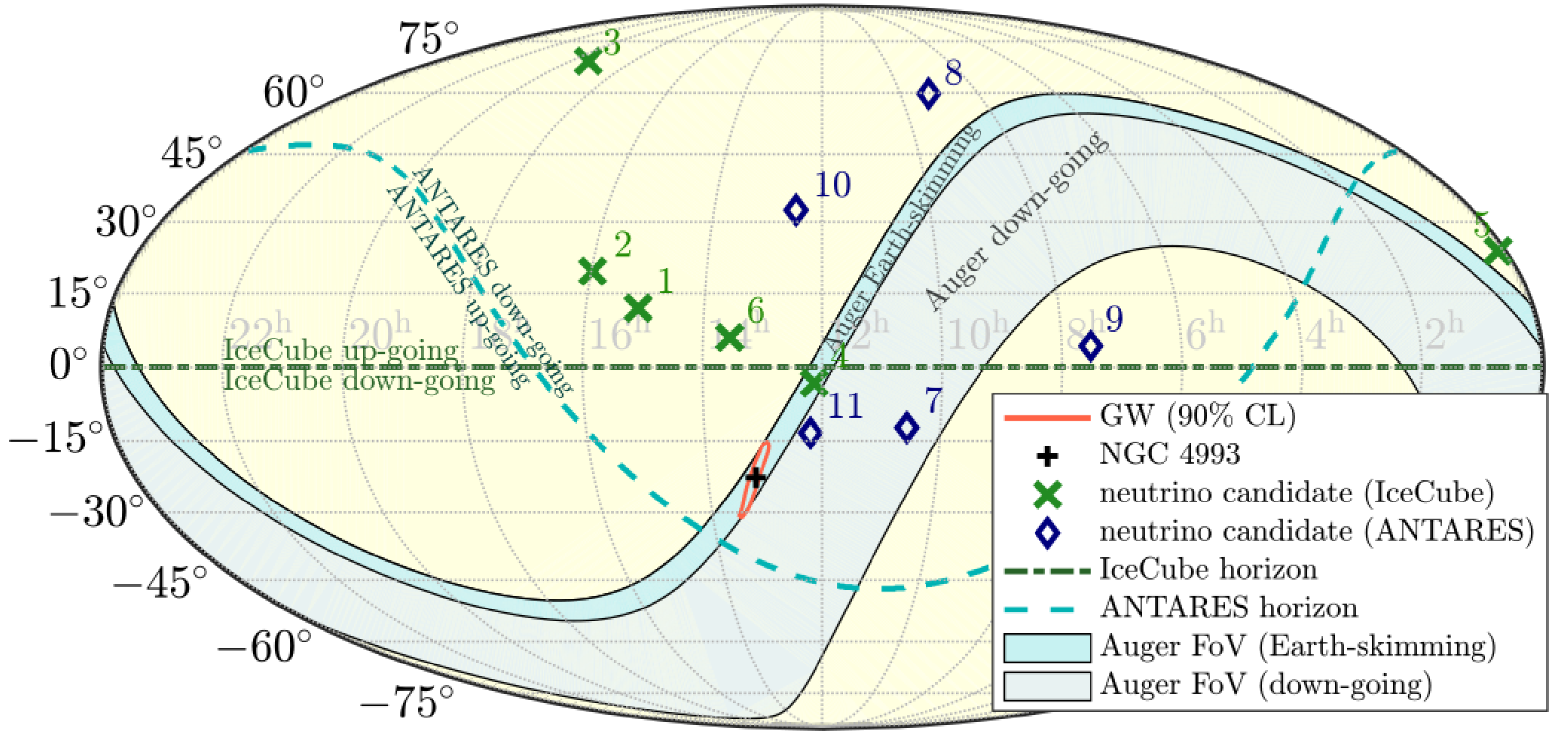
- Fermi detected a gamma-ray burst in coincidence with the GW170817 detected by LIGO and Virgo
- Source of GW at the galaxy NGC4993



Neutrinos in NS-NS merger

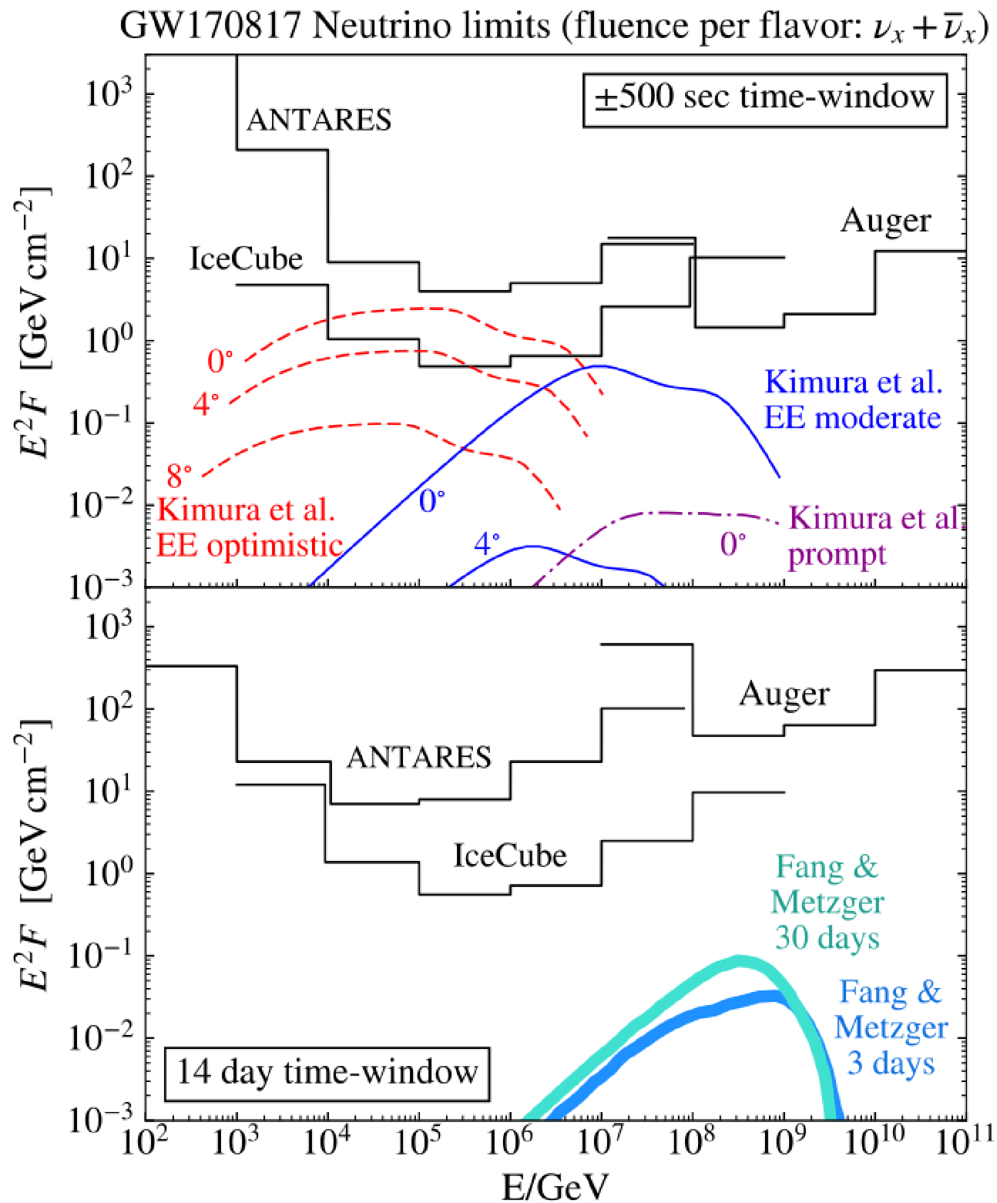
- ANTARES, Icecube & the Pierre Auger Observatories searched for νs in coincidence with GW170817 from TeV to EeV published a joint paper:

  A. Albert, M. André, M. Anghinolfi *et al.* 2017, ApJ, 850, L35
- The source of GW170817 was in an optimal position in the sky at the moment of emission for the search for ν with Auger



Neutrinos in NS-NS merger

- No candidates were found by any of the observatories
- We plot the neutrino fluence limits for ±500 sec and 14 days time-window for each collaboration
- Lack of detection consistent with expectations from a GRB viewed at a large ($\gtrsim$20°)off-axis angle



Conclusions

- Multi-messenger astronomy promises to give extraordinary insights into the working of the most extreme Universe. All collaborations detecting particles and radiation should work together
- The Pierre Auger Observatory is important in the multi-messenger astronomy at EeV energies due to the different kind of particles we can detect (photons, neutrons and especially neutrinos):
  - Very good sensitivity to UHE neutrinos with the SD
  - Large fraction of the sky can be probed
  - Good angular resolution (less than 2.5°)
  - Auger followed-up BH-BH and NS-NS merger events detected in GW and is getting ready for next LIGO and Virgo run O3 in 2019

Thank you for your attention!!