Searches for Ultra-High-Energy Neutrinos with the Pierre Auger Observatory

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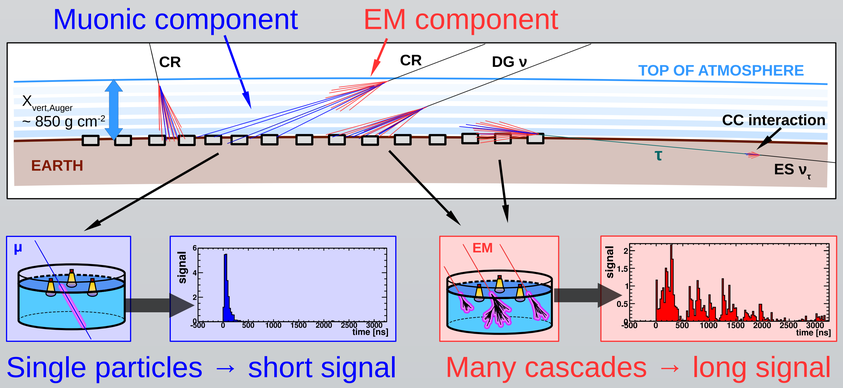
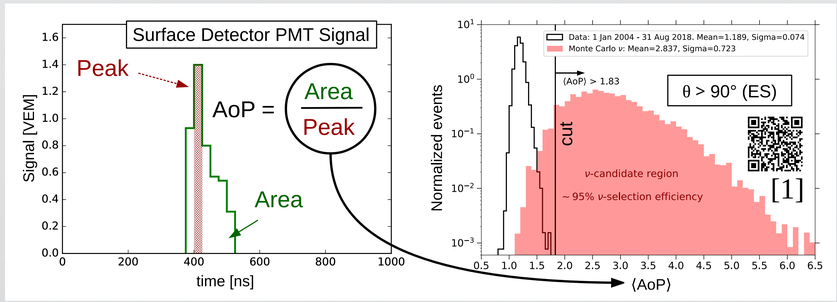
Neutrino air shower detection [1]

- Classes of ultra-high energy (UHE; > 0.1 EeV) **neutrinos**:
  - **Down-going (DG)**
    - Interact **deep in the atmosphere**
      - ➔ Induced air showers reach surface detectors with **large fractions of electromagnetic (EM) particles**
  - **Earth-skimming (ES)**
    - **Interact most likely inside the Earth**, producing τ leptons (CC interaction) that induce detectable air showers when decaying close to the surface
      - ➔ Also **large fractions of EM particles**
- **Highly inclined cosmic-ray (CR)** induced showers have **very small fractions of electromagnetic particles** at the surface

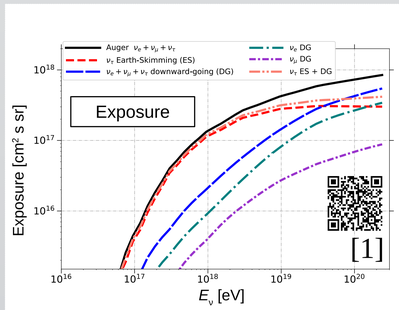
⇒ We search for **inclined showers** (zenith angle > 60°) with **significant electromagnetic components**.

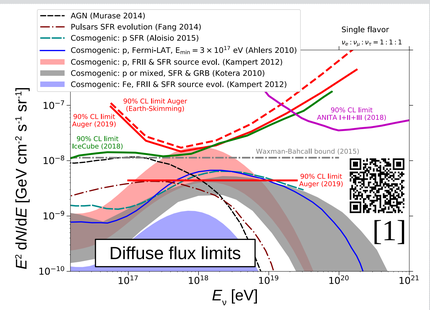


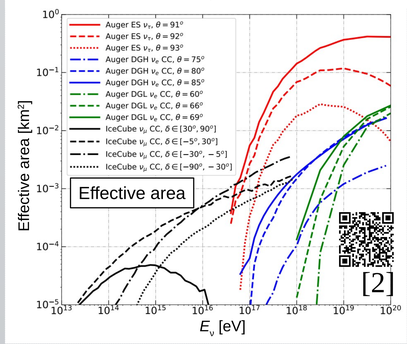
Neutrino search performance [1, 2]



No candidates in DG and ES searches







Top left: Area over Peak (AoP) illustration

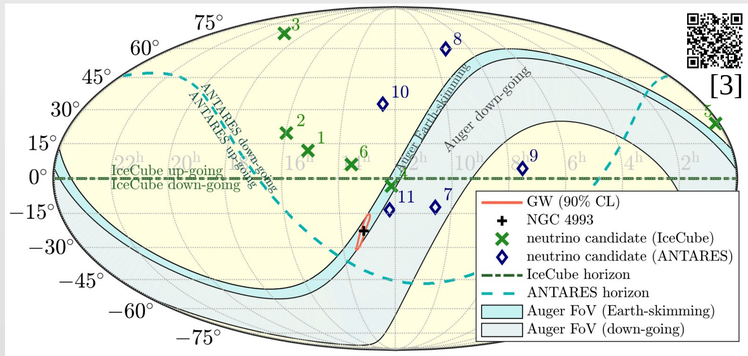
Top right: ⟨AoP⟩ distributions of ES neutrinos (MC) and measured data

Middle left: UHE neutrino exposure for different directions and flavors

Middle right: Upper limits on the diffuse flux of UHE neutrinos + model fluxes

Bottom left: Effective area for different zenith angles for Auger (colored) and different declinations for IceCube (black)

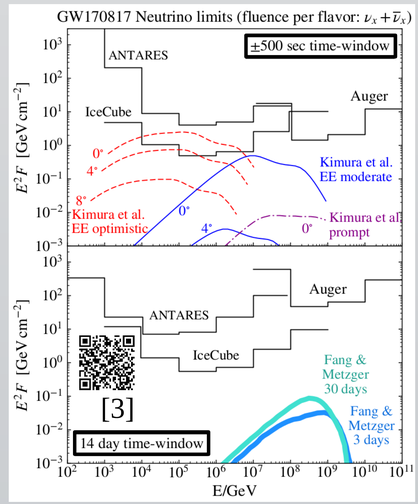
Follow-up searches of GW170817 [3] (first binary neutron star merger)



Location of the source of GW170817 and field of views / horizons of the Pierre Auger Observatory, IceCube, and ANTARES at t_0

- **No** coincident neutrino candidates found by ANTARES, IceCube, and the Pierre Auger Observatory
- **Excellent visibility of the merger:**

  Whole 90% CL region in the ES region (90° < θ < 95°), which is the **most sensitive** one



Fluence limits (90% C.L.) for two different periods:

- ± 500 s around the event
  - ➔ Best EeV limits due to **excellent visibility**
- 0–14 days after the event
  - ➔ Lower sensitivity due to **periodic visibility**

Angles (0°, 4°, 8°): Off-axis angles of respective models

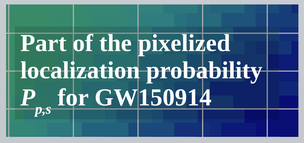
Future:
Increasing event rate → More effective probing of compact binary mergers involving neutron stars

Combined follow-up searches of gravitational wave events from binary black hole (BBH) mergers [4]

- Automatic follow-up search routine
  - Time: t_0 (time of merger) until t_0 + 1 d
  - Direction: 90% C.L. most probable localization region
- All published BBH merger events until 2019-06-02
- **No** neutrino candidates found

Combined limit on universal source luminosity $L(t\text{-}t_0)$

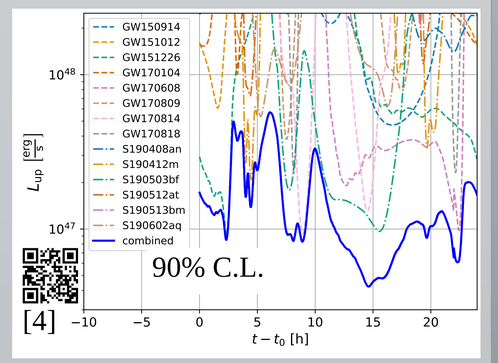
- Assuming E^{-2} spectrum
- Factors considered **for each source *s***:
  - Pixelized (pixels *p*) source localization probability $P_{p,s}$
  - Time-dependent (time bins *i* of length Δt = 1 s) effective area for each pixel *p*
  - Luminosity distance of each source d_s



$$L_{\mathrm{up},i} = \frac{N_{\mathrm{up},\nu,\mathrm{tot}}}{86400\ \Delta t} \left(\sum_s \frac{\sum_p P_{p,s} \mathcal{A}_{p,s,i}}{d_s^2} \right)^{-1}, \qquad \int_0^\infty E_\nu^{-2}\, A_{\mathrm{eff},p,s,i}(E_\nu)\, \mathrm{d}E_\nu$$

- **Alternating domination** by different sources according to time-dependent visibility
- Integral over 24 h → Upper limit on total emitted energy in UHE neutrinos:

  $E_{\mathrm{up,\ 24\ h}} = 1.35 \cdot 10^{52}$ erg



References: [1] JCAP **10**, 022 (2019) [2] JCAP **11**, 004 (2019) [3] Astrophys. J. Lett. **850**, L35 (2017) [4] Proc. 36th Int. Cosmic Ray Conf., PoS(ICRC2019)415