Multi-Messenger astrophysics with the Pierre Auger Observatory

Massimo Mastrodicasa on behalf of the Pierre Auger Collaboration

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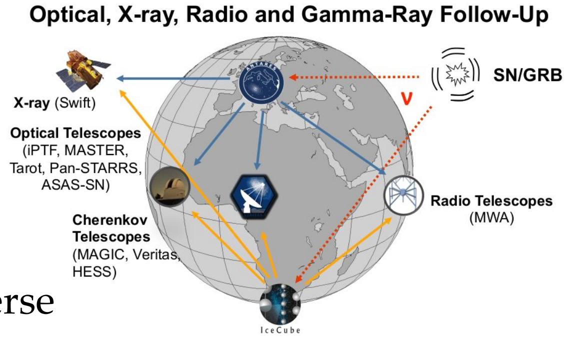
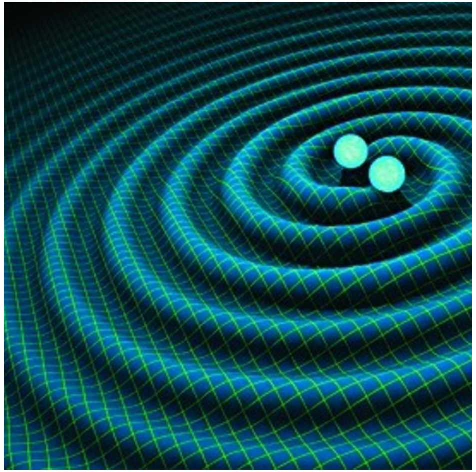
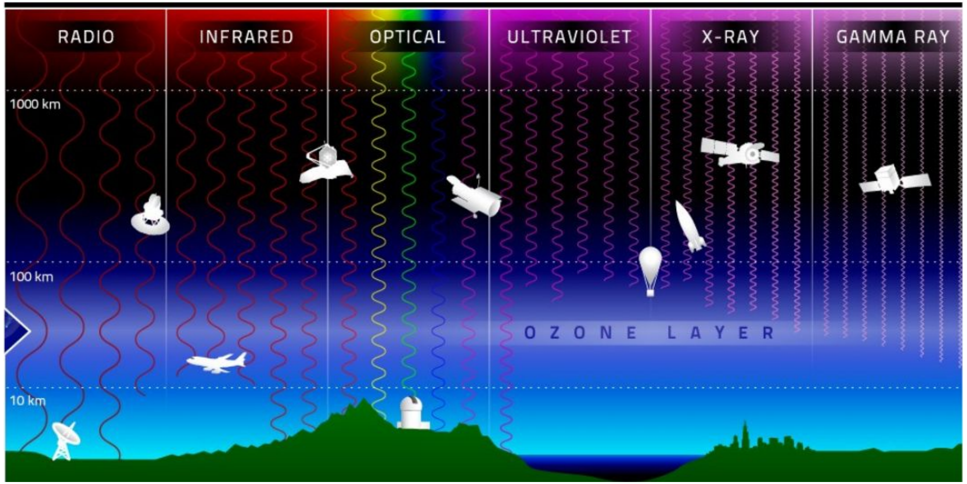
Multi-messenger astrophysics

- Complementary information from gravitational waves, electromagnetic radiation, neutrinos and cosmic rays
- Give a precise localization, identify host galaxy
- Study the physics of the progenitors and their environment
- More complete insight into the most energetic events in the universe

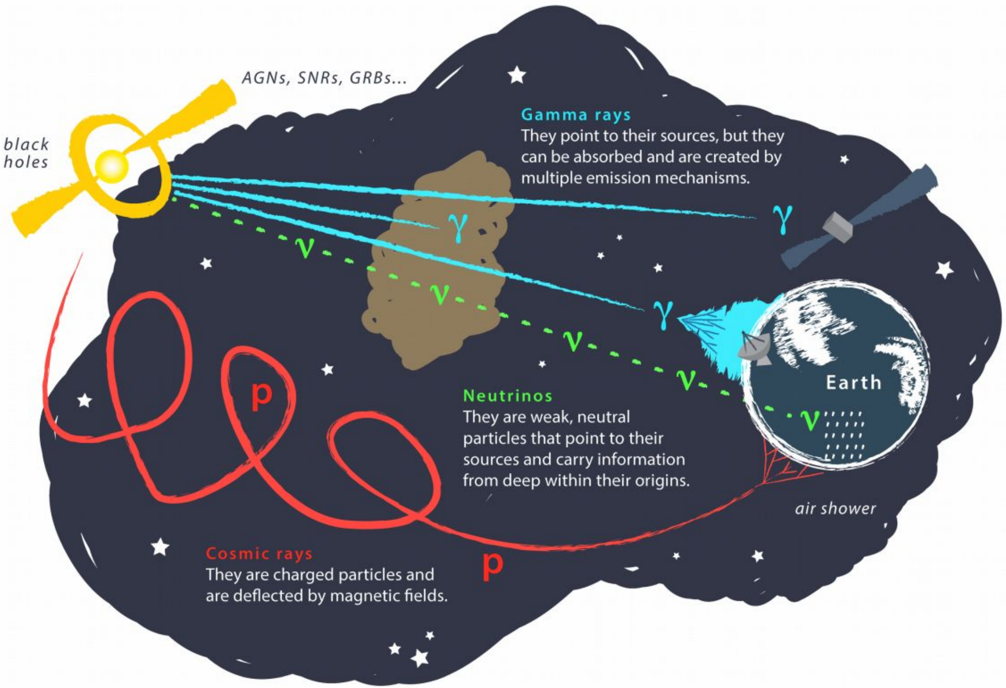






Cosmic messengers

- **Cosmic rays**
- **Photons and neutrinos**: produced in the interaction of Ultra high energy cosmic rays (UHECRs) with extragalactic photon fields or within the sources
- **Neutrons**: produced in charge exchange interactions of high energy protons with ambient photon fields, protons or nuclei
- **Gravitational waves**



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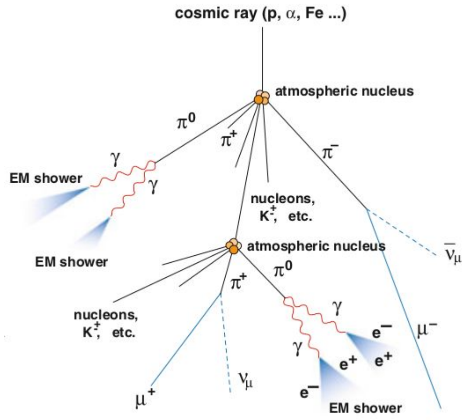
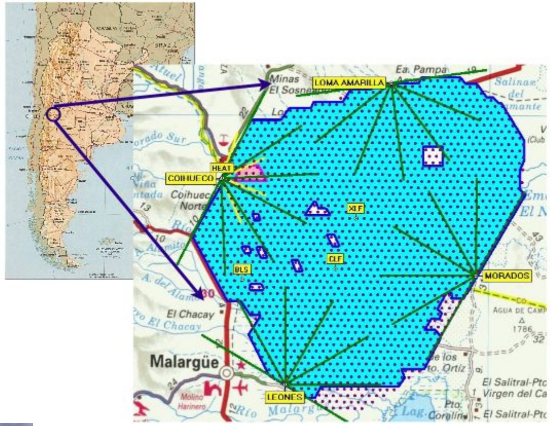
→ **They can be detected with the Pierre Auger Observatory**

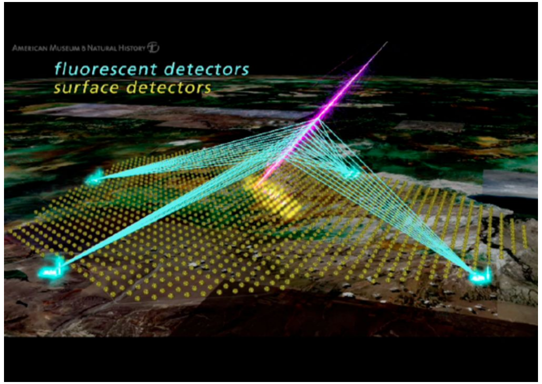
- **Gravitational waves**

The Pierre Auger Observatory

- The Pierre Auger Observatory is the largest Ultra High Energy Cosmic Ray experiment in the world
- The Observatory is located in Malargue, in the argentinian pampa
- Very low event rate at the highest energies → very large area
- It uses both surface detectors and fluorescence detectors
- Atmospheric monitoring system

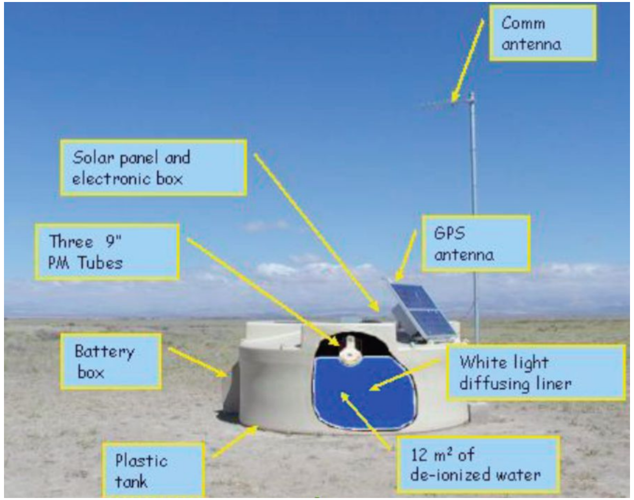


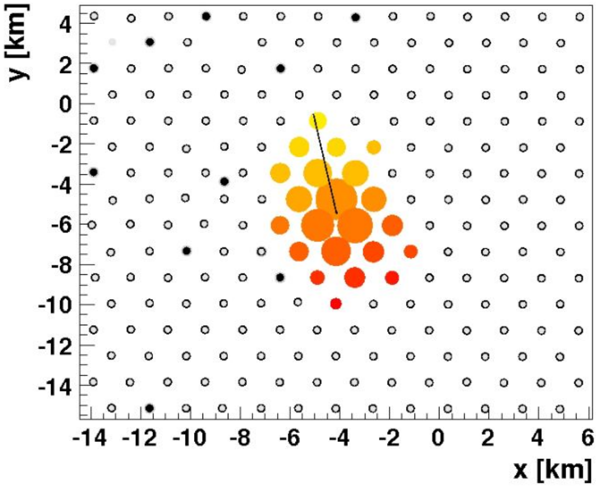


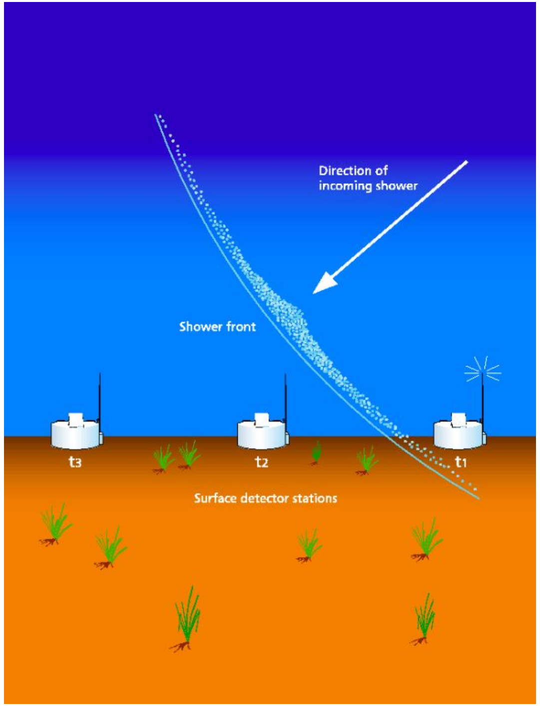


The Surface Detector (SD)

- 1660 water tanks on a surface of 3000 km^2 spaced at 1.5 km, plus 61 stations at a distance of 750 m called infill covering an area of 23.5 km^2 to detect showers with lower energies
- It detects the Cherenkov light produced by the particles that reach the ground
- It can be always operated regardless of atmospheric conditions

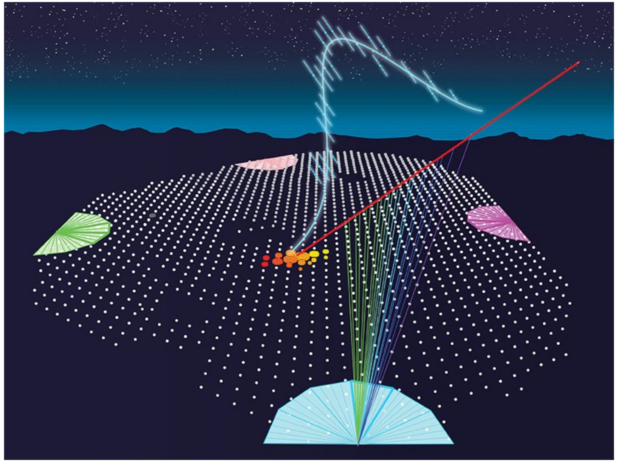


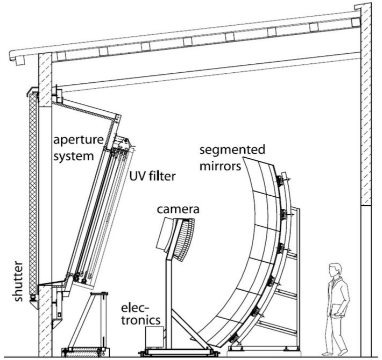




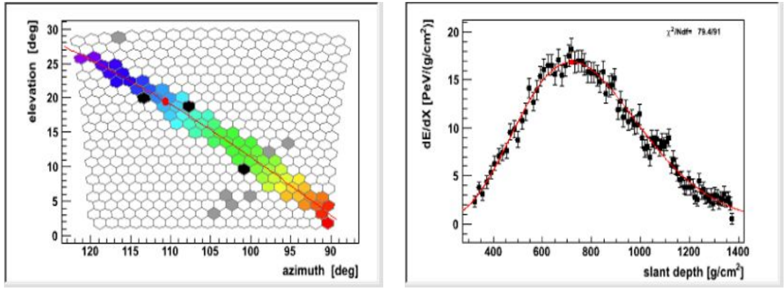
The Fluorescence Detector (FD)

- It detects the fluorescence light produced by the shower
- 24 telescopes with an elevation field of view of [1.5°,31.5°] plus 3 telescopes with an elevation field of view of [30°,58°] called HEAT
- It can be operated only during moonless and cloudless night (~14% of the cases)
- It allows to measure the complete development of the shower



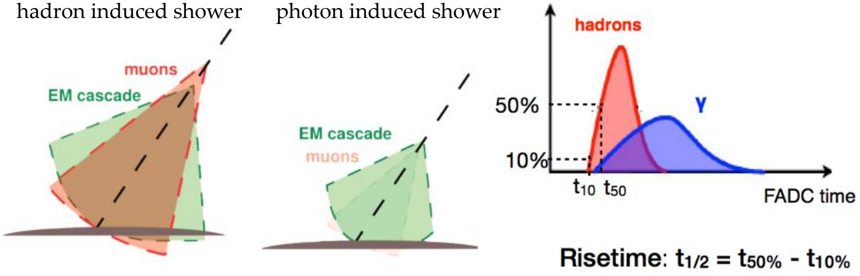


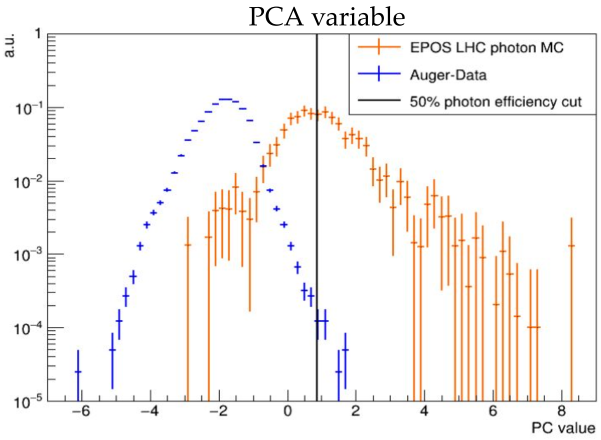
$E = 1.22 \cdot 10^{19}\, eV,\ X_{max} = 719\, g/cm^3$
$(\theta, \phi) = (55, 327)\, deg$



Search for diffuse photons at $E_\gamma > 10$ EeV

- Search performed **with the SD**
- Reduced muon content → Lateral Distribution Function (LDF) for photons steeper than that for hadrons
- The rise of the signal in the SD stations is slower
- Zenith angle range: $\theta_{zenith} \in [30, 60]°$, lower limit at 30° to ensure that most of the photon showers are fully developed
- Two discriminating observables, one based on the LDF and one based on the risetime of the SD signals, are used to perform a Principal Component Analysis (PCA)

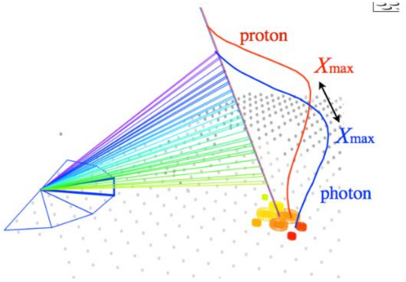


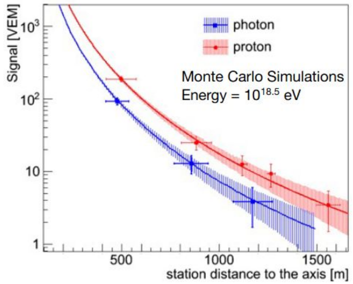


Cut set to have a 50% efficiency on the photon signal

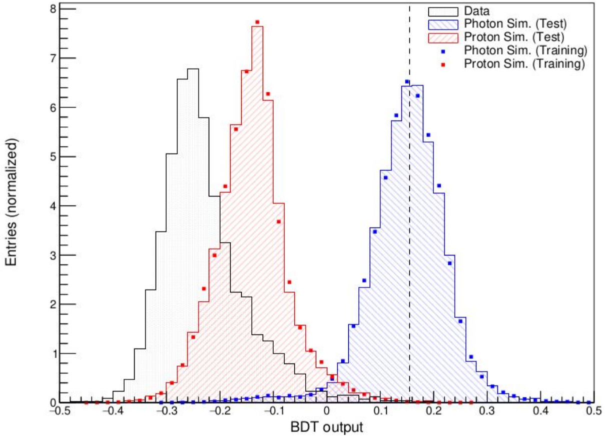
Search for diffuse photons at E_γ < 10 EeV

- Smaller number of SD stations N_{stat} with a signal → harder to discriminate between photon and hadron showers with SD only
- Deeper depth of the shower maximum X_{max} with respect to hadron induced showers → photon showers can be searched also with the FD → **hybrid measurements**
- Zenith angle range: $\theta_{zenith} \in [0, 60]°$
- Three discriminating observables, one based on X_{max}, one based on N_{stat} and one based on the difference in LDF, are used to train a Boost Decision Tree (BDT)
- Search extended below to E_γ < 1 EeV by using data from the infill array and HEAT





BDT variable



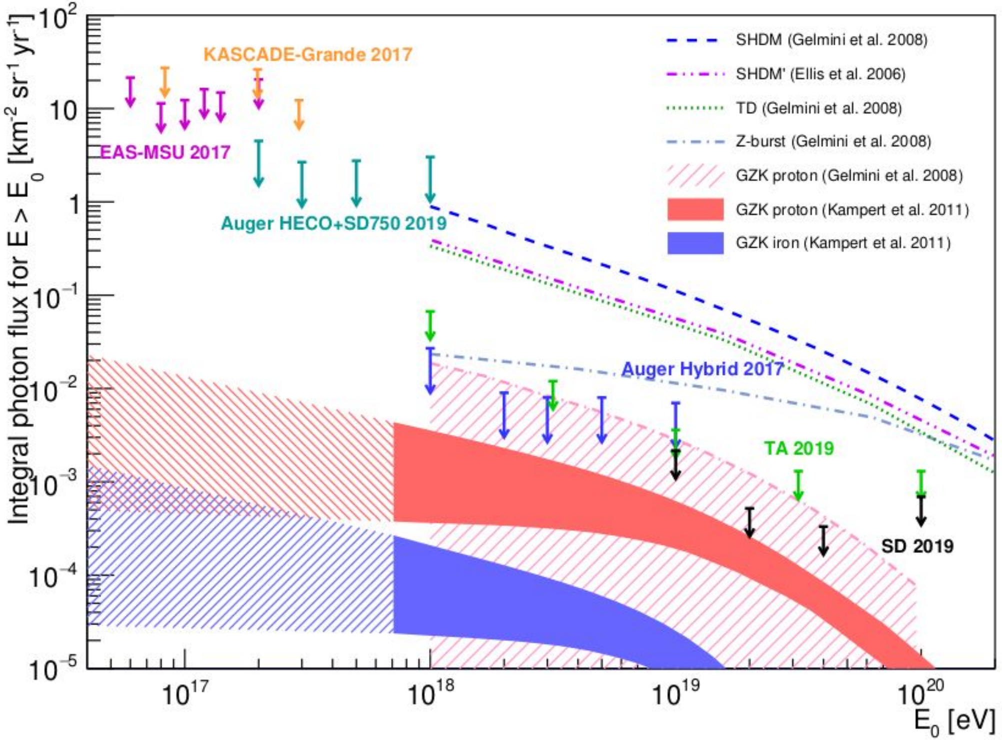
Cut set at 50% on the photon distribution

Upper limits on the diffuse photon flux

- No candidate events have been found → $\Phi_{UL}^{0.95}(E_\gamma > E_0) = \frac{N_\gamma^{0.95}(E_\gamma > E_0)}{\langle \varepsilon_\gamma \rangle}$

$N_\gamma^{0.95}(E_\gamma > E_0)$ → Feldman-Cousins upper limit

$\langle \varepsilon_\gamma \rangle$ → Weighted average exposure for $E_\gamma > E_0$ under the assumption of a E_γ^{-2} power law spectrum



- ★ Most stringent limits in the EeV energy range
- ★ Top-down models disfavoured
- ★ GZK region within reach

Search for photons from point-like sources

- TeV photon sources should produce EeV photons if their energy spectra are assumed to extend to EeV energies
- Sources grouped in twelve target sets → signal from more than one source more significant than that from a single source → only sources within the attenuation length of photons are considered
- $10^{17.3}$ eV < E_γ < $10^{18.5}$ eV, θ_{zenith} < 60°
- Discrimination provided by a BDT variable
- Each target is assigned with a p-value → p-values are combined to get a combined p-value P for each target set → no evidence of a statistical significance larger than 3σ was found

Class	No.	$\mathcal{P}_w$	$\mathcal{P}$
msec PSRs	67	0.57	0.14
γ-ray PSRs	75	0.97	0.98
LMXB	87	0.13	0.74
HMXB	48	0.33	0.84
H.E.S.S. PWN	17	0.92	0.90
H.E.S.S. other	16	0.12	0.52
H.E.S.S. UNID	20	0.79	0.45
Microquasars	13	0.29	0.48
Magnetars	16	0.30	0.89
Gal. Center	1	0.59	0.59
LMC	3	0.52	0.62
Cen A	1	0.31	0.31

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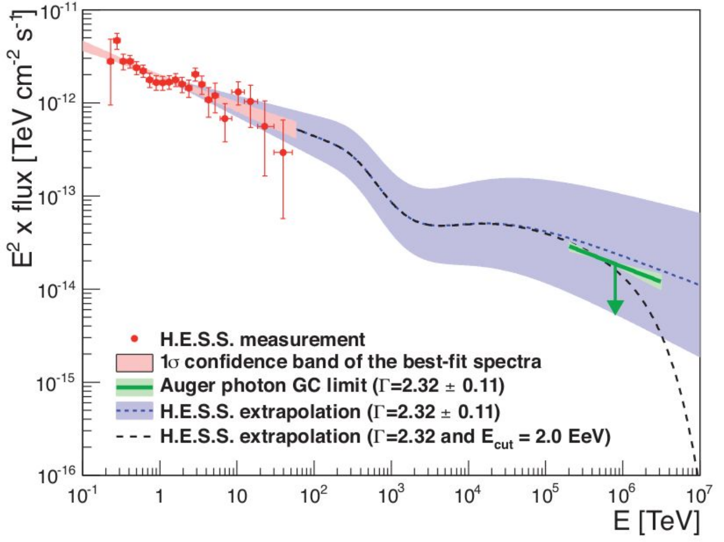
Upper limit on the photon flux of the Galactic center



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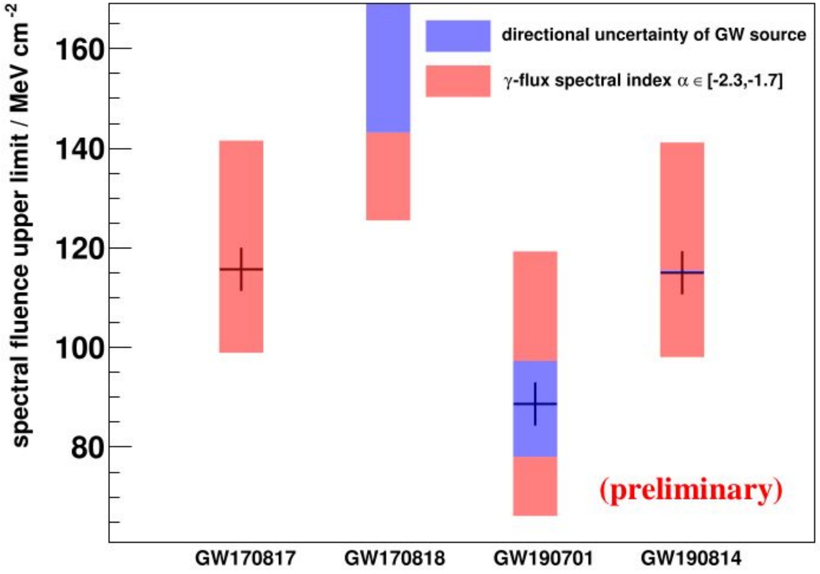
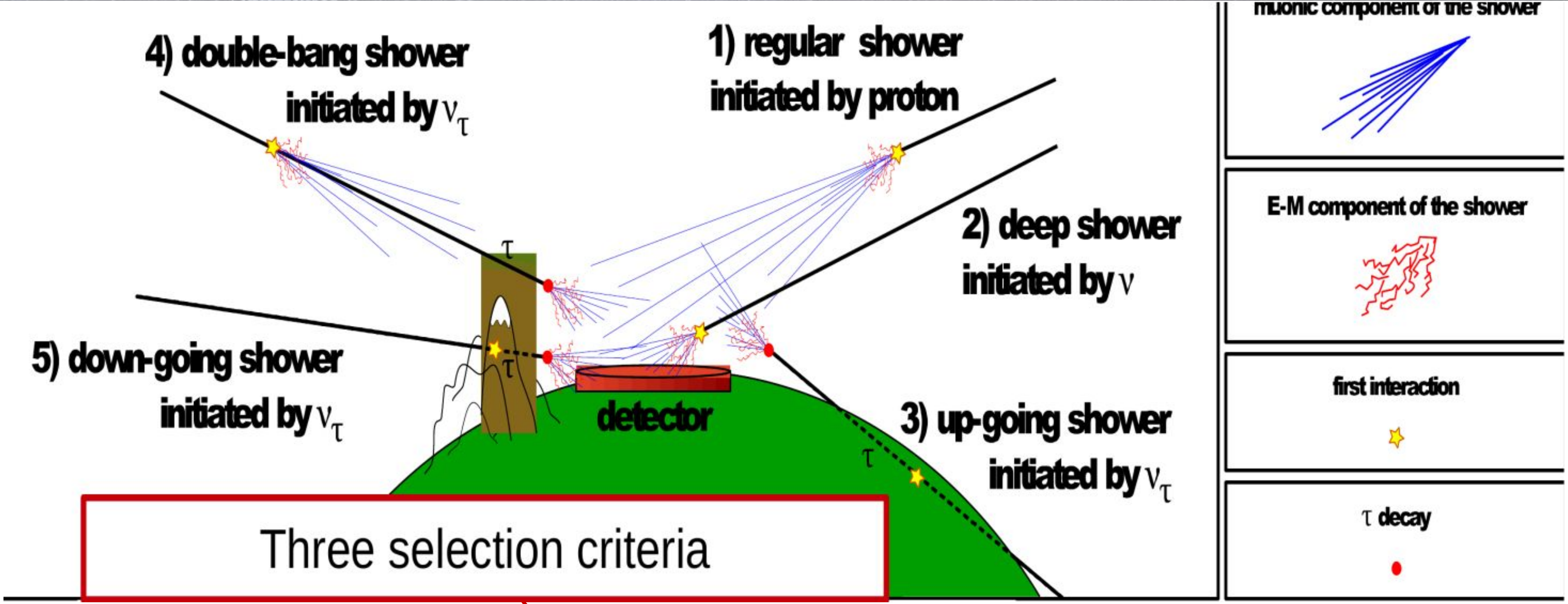
Photon follow-up of gravitational wave events

- Follow-up performed **with the SD**
- Diffuse photon search with the SD applied in both the time window between 500 s before and after the merger and the 24-hour period after the merger
- Close and well localized gravitational wave sources → reduce background and account for the attenuation length of photons
- Only four LIGO/Virgo sources found to have some overlap with the SD field of view during the 1 day period
- No candidate photon showers found → upper limit on the photon spectral fluence at 90% confidence level



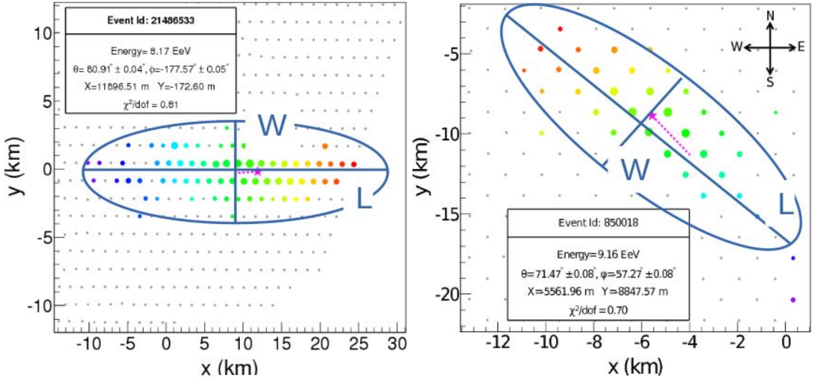
Search for neutrinos with the SD

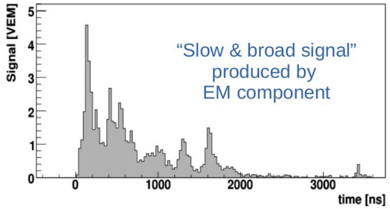


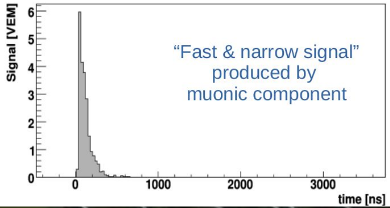
Three selection criteria depending on the zenith angle range: [60 , 75]°, [75 , 90]°, [90 , 95]°

Search for diffuse neutrinos

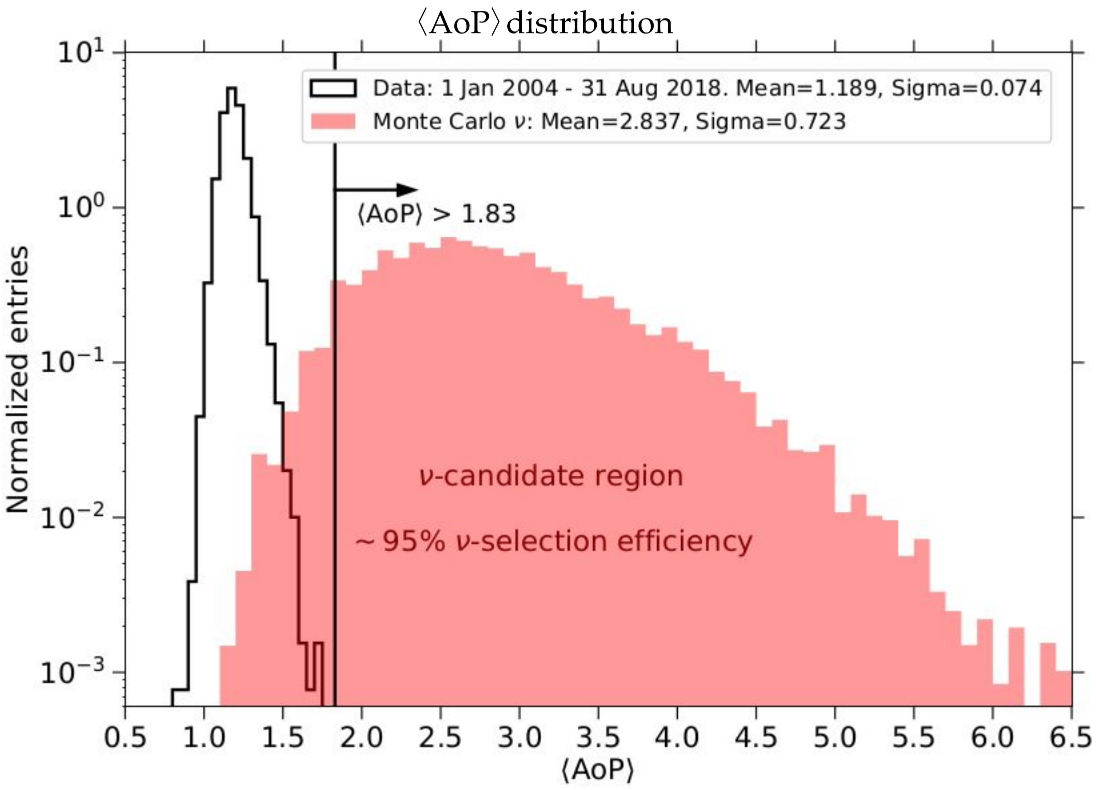
- Search performed **with the SD**
- At $\theta_{zenith} > 60°$ the electromagnetic component of hadron showers is almost completely absorbed → ground reached mainly by muons
- Neutrinos interact deep in the atmosphere → showers with a large concentration of electrons and photons at ground
- Inclined events → the footprint of the shower on SD stations have a high ratio L/W between the length L along the shower axis and the width W perpendicular to it
- The SD signal has a high Area-over-Peak (AoP) ratio → selection of showers that produce broad signals in the SD stations







Selection of nearly horizontal upward-going showers



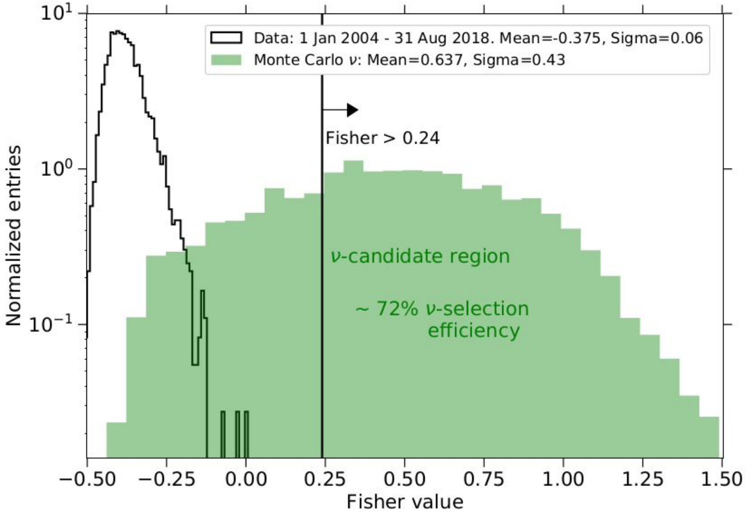
Discrimination variable for nearly horizontal upward-going showers ($\theta_{zenith} \in [90, 95]°$) → **no candidate events found**

Selection of inclined downward-going showers

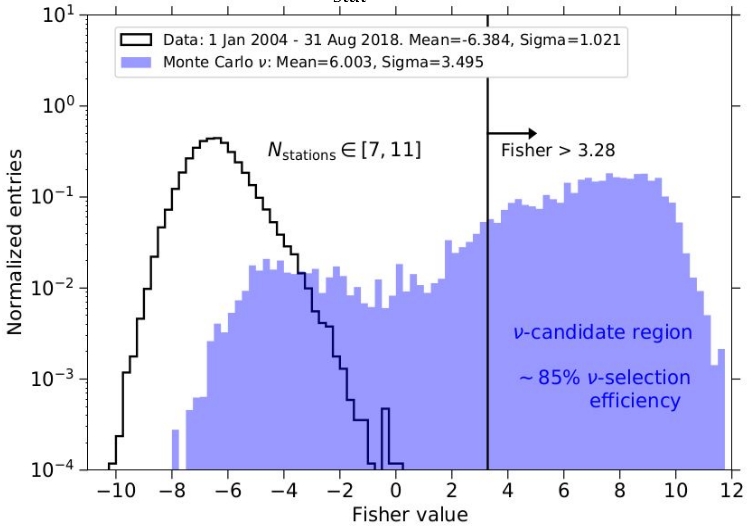
- ➔ $\theta_{zenith} \in [60, 75]°$ → events divided in five sub-samples depending on reconstructed zenith angle
- ➔ $\theta_{zenith} \in [75, 90]°$ → events divided in three sub-samples depending on N_{stat}

Different Fischer variable in each sub-sample → **no candidate events found**

$\theta_{rec} \in [58.5, 76.5]°$



$N_{stat} \in [7, 11]$

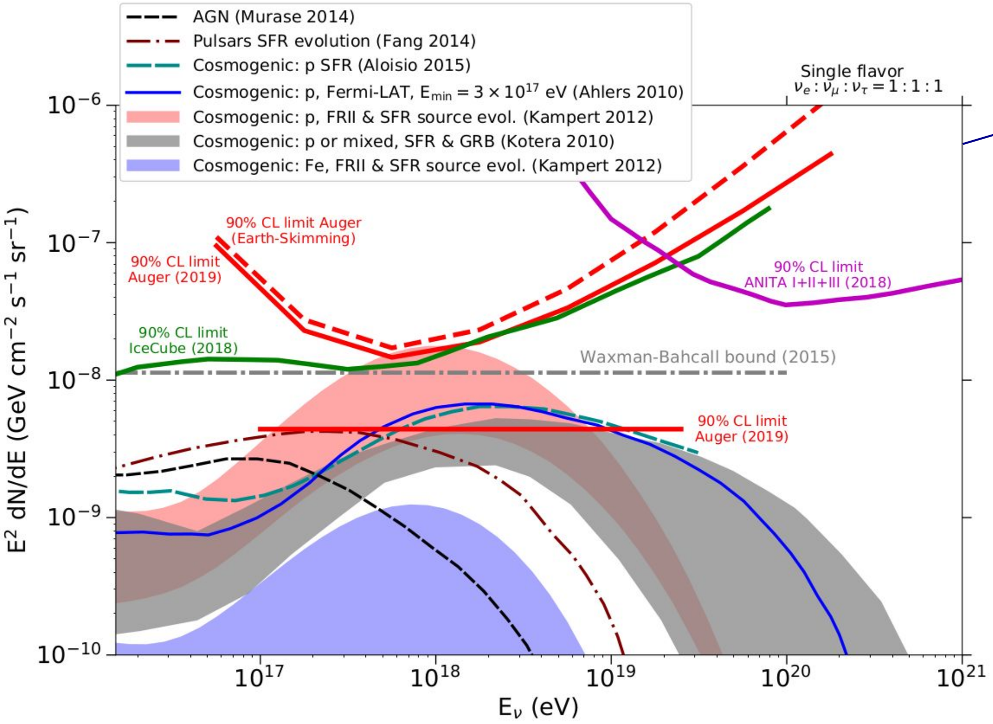


Upper limits on the diffuse neutrino flux

- Assuming $\Phi = k \cdot E_\nu^{-2} \rightarrow k^{0.90} = \dfrac{N_\nu^{0.90}}{\int_{E_\nu} E_\nu^{-2} \varepsilon_{\text{tot}}(E_\nu)\, dE_\nu}$

Feldman-Cousins upper limit

Total exposure (or Earth-skimming exposure for the Earth-skimming case)

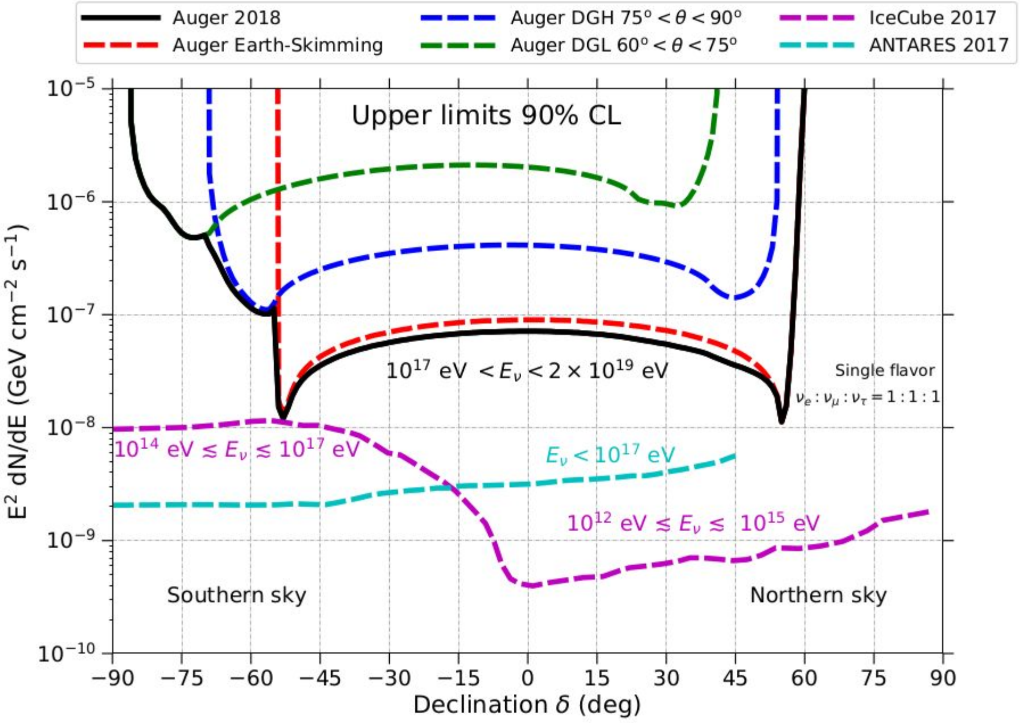


All limits are converted to single flavour

- ★ Maximum sensitivity at energies around 1 EeV, where most cosmogenic models also peak
- ★ Some cosmogenic models disfavoured

Search for neutrinos from point-like sources

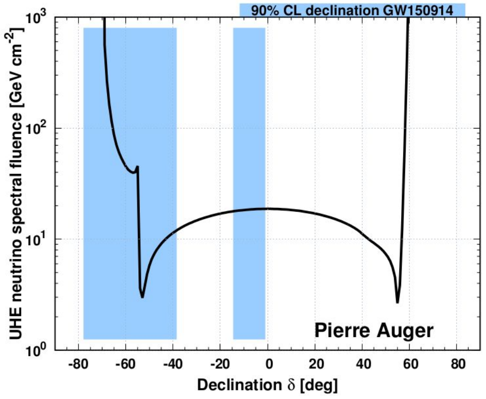
- Search performed **with the SD**
- Neutrinos from point-like sources can be searched for at a certain instant only from the region of the sky defined by the zenith angle ranges of the analysis for diffuse neutrinos
- Same exposure calculation as the analysis for diffuse neutrinos except for the solid angle integration over the sky
- No candidate events found→ upper limit on $k_{PS}(\delta)$



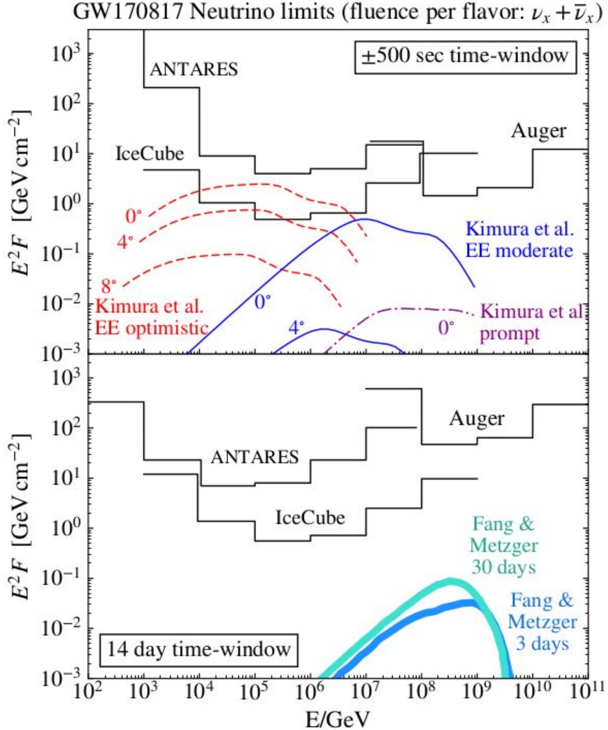
Neutrino follow-up of gravitational wave events

- Follow-up performed **with the SD**
- Diffuse neutrino search applied in the same time window of the photon follow-up
- Limited to periods when source localization in the sky is in the SD neutrino field of view
- No candidate neutrino showers found → upper limit on the neutrino spectral fluence

Neutrino follow-up for the first gravitational wave event ever detected GW150914



Neutrino follow-up for GW170817 performed by ANTARES, Auger, IceCube



Search for neutrons

- Neutrons necessarily produced in association with photons
- Mean decay path length 9.2 kpc · (E/EeV) → EeV neutrons should allow to identify sources within most of our galaxy
- Neutron induced showers can not be distinguished from proton induced ones → search for an excess of air showers from a given direction
- Eleven target sets → nine classes of possible photon sources + the Galactic center + the Galactic plane
- Each target assigned with a p-value → same procedure as photons from point-like sources
- No evidence of excess of a neutron flux found → upper limit on the neutron flux
- Upper limits derived are below the energy fluxes detected from TeV gamma ray sources in our galaxy → E^{-2} Fermi-acceleration of protons up to EeV energies from these sources excluded (more efficient production of neutrons with respect to photons of the same energy)

Summary

- UHE photons, neutrinos and neutrons can be searched for with the Pierre Auger Observatory
- UHE photon induced air showers can be discriminated from hadron induced ones by relying on their reduced muon content and deeper X_{max} → they are searched with both the SD and the FD
- No candidate events for diffuse photons, photons from point-like sources and photon follow up of gravitational wave events → stringent upper limits have been set
- UHE neutrino induced air showers produce showers with a large concentration of electrons and photons at ground → they are searched with the SD at $\theta_{zenith} > 60°$, where the electromagnetic component of hadron showers is almost completely absorbed
- No candidate events for diffuse neutrinos, neutrinos from point-like sources and neutrino follow up of gravitational wave events → stringent upper limits have been derived
- UHE neutron induced air showers can not be distinguished from those produced by protons → they can be identified by searching for an excess of air showers from a given direction
- No candidate events for neutron induced showers → upper limit on the neutron flux → E^{-2} Fermi-acceleration of protons up to EeV energies from these sources excluded

Thank you for your attention!