# Follow-up Search for Ultra-High-Energy Photons from Gravitational Wave Sources with the Pierre Auger Observatory

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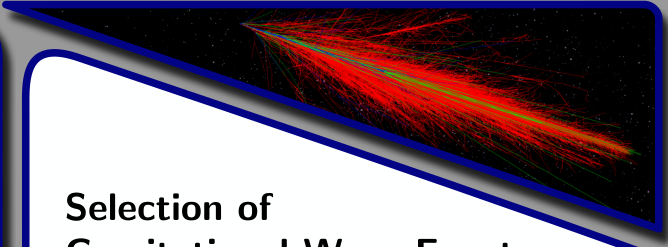
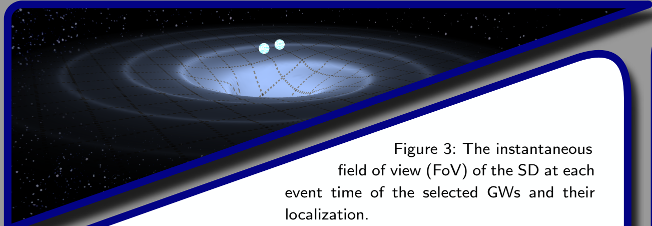




## Take-Home Message

- **Multimessenger astronomy** of transient events relies on **neutral messengers**.
- The **surface detector (SD)** of the Pierre Auger Observatory [1] has a unique exposure to **ultra-high-energy (UHE) photons** beyond $10^{19}$ eV.
- A **high sensitivity** to any UHE photon signal from a GW source can be achieved with the SD, allowing for a detection **beyond the $5\sigma$ level**.
- **First constraints on UHE photons from GW sources** are presented here by the Pierre Auger Collaboration.

## Search for UHE Photons

- The bulk of data received at the Pierre Auger Observatory originates in **cosmic rays of hadronic origin** [2].
- **No photon has been identified** so far. ⇒ **upper limits** on the diffuse photon flux above $2\times10^{17}$ eV [3].
- The SD covers an area of about **$3000\ \mathrm{km}^2$** and comprises **1660 water Cherenkov detectors** on a triangular grid with a spacing of $1.5$ km.
- A high **separation power between primary photons and hadrons** can be achieved with the SD for primary photons between $10^{19.0}$ eV and $10^{20.5}$ eV and zenith angles $30^\circ \le \theta < 60^\circ$.
- Almost **100% duty cycle**
  ⇒ efficient study of transient events like GWs.
- **Photon discrimination method** [3]: two photon-discriminating observables
  - ▸ $gL_{\mathrm{LDF}}$
  - ▸ $g\Delta$.

  are sensitive to the **delayed shower development poor muon content** respectively of photon-induced air showers as compared to hadron-induced showers (see Fig. 1).
- Observables **combined in a principal component analysis** to maximize the separation power.

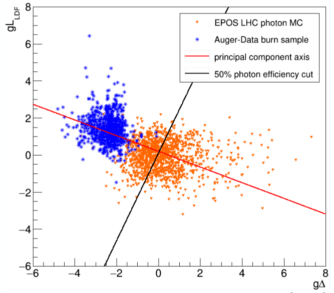



Figure 1: A set of SD training data (blue) and simulated photon events in the space of the photon discriminating air shower observables [3]. The red line indicates the principal component axis of the combined distribution and the black line represents the photon candidate cut in the observable space.

## Selection of Gravitational Wave Events

- Isotropic background from hadronic cosmic rays is non-zero.
  ⇒ **background reduction necessary** to maintain a high sensitivity to a possible photon signal.
  - ▸ Limit search region to the **50%-confidence GW localization**.
  - ▸ Limit observation period: **two mutual exclusive time windows** of $\pm500$ s around the GW event time and $1$ d after the GW observation
- In addition: favor **close and/or well localized sources**.
- **Three classes of accepted GW events** are defined in the space of source localization $\Omega_{50\%}$ and luminosity distance $D_{\mathrm{L}}$ (see Fig. 2).

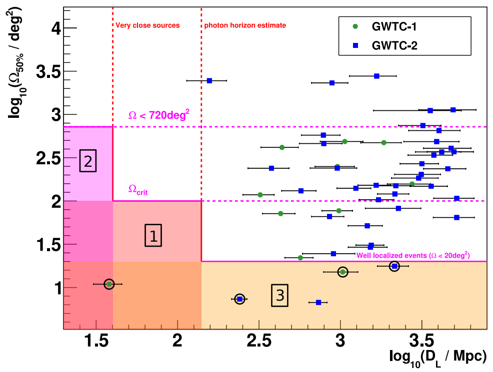
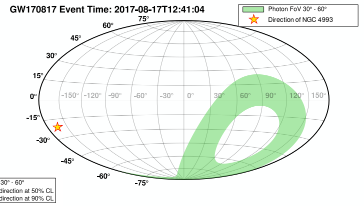


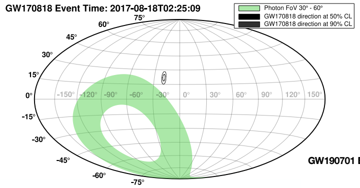

Figure 2: All GW events from GWTC-1 [4] (green dots) and GWTC-2 [5] (blue squares) in the space of source distance $D_{\mathrm{L}}$ and localization $\Omega_{50\%}$. The shaded regions define the set of accepted events and the circles mark those which could additionally be observed with the SD.

- The selected GW events contain
  - ▸ **2 binary black hole mergers** (GW170818 [4] and GW190701_203306 [5])
  - ▸ **1 binary neutron star merger** (GW170817 [4])
  - ▸ **1 black hole - neutron star merger** candidate (GW190814 [6]).
- **Host galaxy of GW170817 identifed** as NGC 4993 through electromagnetic follow-up observations
  ⇒ directional uncertainty of the source is negligible.

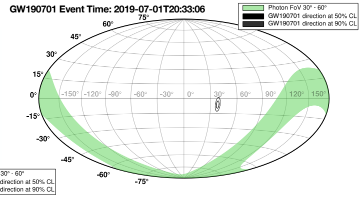
Figure 3: The instantaneous field of view (FoV) of the SD at each event time of the selected GWs and their localization.



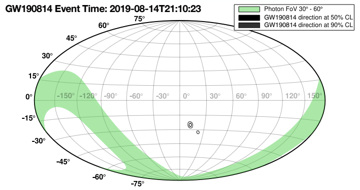

**GW170817**
(binary neutron star merger)
$D_{\mathrm{L}} = 41.0 \pm 3.1$ Mpc [7]




**GW170818**
(binary black hole merger)
$D_{\mathrm{L}} = 1060^{+420}_{-380}$ Mpc




**GW190701**
(binary black hole merger)
$D_{\mathrm{L}} = 2060^{+760}_{-730}$ Mpc




**GW190814**
(black hole - neutron star merger candidate)
$D_{\mathrm{L}} = 240^{+40}_{-50}$ Mpc

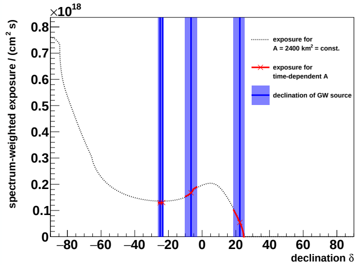
## Sensitivity

- Non-zero rate of **false-positive detections** ⇒ interpretation of a possible signal?
- Measure for the sensitivity: "**photon significance**" := the highest CL at which the lower bound of the Feldman-Cousins [9] confidence interval for an assumed photon candidate is not compatible with zero.
  ⇒ a photon significance **beyond the $5\sigma$-level is possible** for a photon candidate detection within a $1000$ s time window.
- For the four events that pass the GW selection, the individual photon significance in the $1$ d time window lies **between $4.8\sigma$ and $5.0\sigma$**.

## Results

- **Exposure to UHE photons** within one day: function of declination $\delta$ (see Fig. 4).
- Three GW events are **fully covered** by the field of view.
- Localization contour of GW170818 **is only partly covered**.

Figure 4: The spectrum-weighted exposure for an aperture $A = 2.4\times10^{13}\ \mathrm{cm}^2$. The bars indicated the declination band and the most likely direction of each of the four selected GW events. The red lines correct the exposure for the actual time-dependence of $A$.




- **No coincident photon candidate event** in the data.
  ⇒ **upper limits** at 90% CL on the UHE photon fluence (see Fig. 5).
- **Systematic uncertainties** from variations of the energy spectrum
  ⇒ variations of the upper limits **$\sim \pm20\%$**.
- Variations of the upper limits as caused by the finite source localization **strongly depend on the mean declination.**

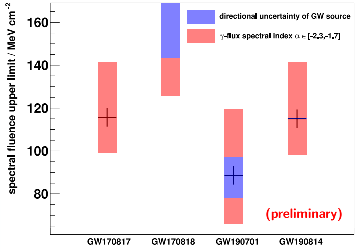



Figure 5: Upper limits on the spectral fluence for the 4 selected GW sources. Uncertainties imposed by the sky localization of the sources and a variation of the spectral index are indicated by the shaded bars.

## References

[1] Pierre Auger Coll., NIM A 798, 172 (2015).
[2] Pierre Auger Coll., JCAP 04, 038 (2017).
[3] Pierre Auger Coll., PoS(ICRC2019)398 (2019).
[4] LIGO, Virgo Colls., PRX 9, 031040 (2019).
[5] LIGO, Virgo Colls., PRX 11, 021053 (2021).
[6] LIGO, Virgo Colls., ApJL 896, L44 (2020).
[7] Hjorth, ApJL 848, L31 (2017).
[8] various Colls., ApJL 848, L13 (2017).
[9] Feldman, Cousins, PRD 57, 3873 (1998).