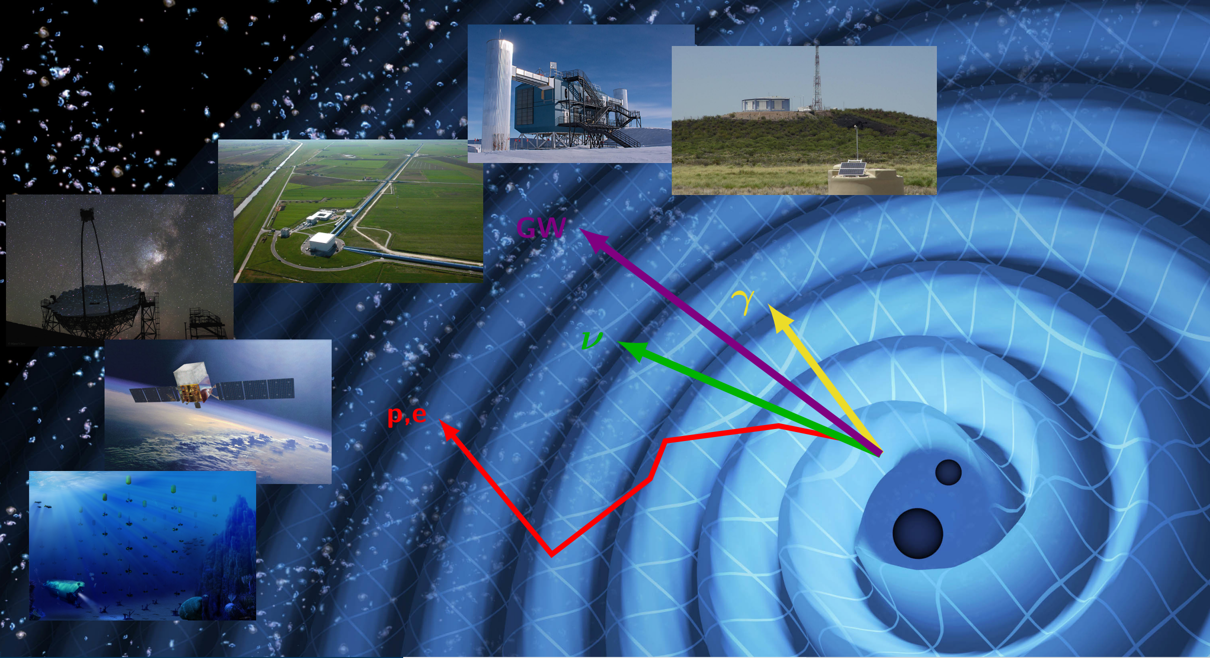
Multimessenger Astronomy of Transient Point Sources at the Pierre Auger Observatory

Philip Ruehl
on behalf of the Pierre Auger Collaboration

31st Texas Symposium on Relativistic Astrophysics

15.09.2022


GW
γ
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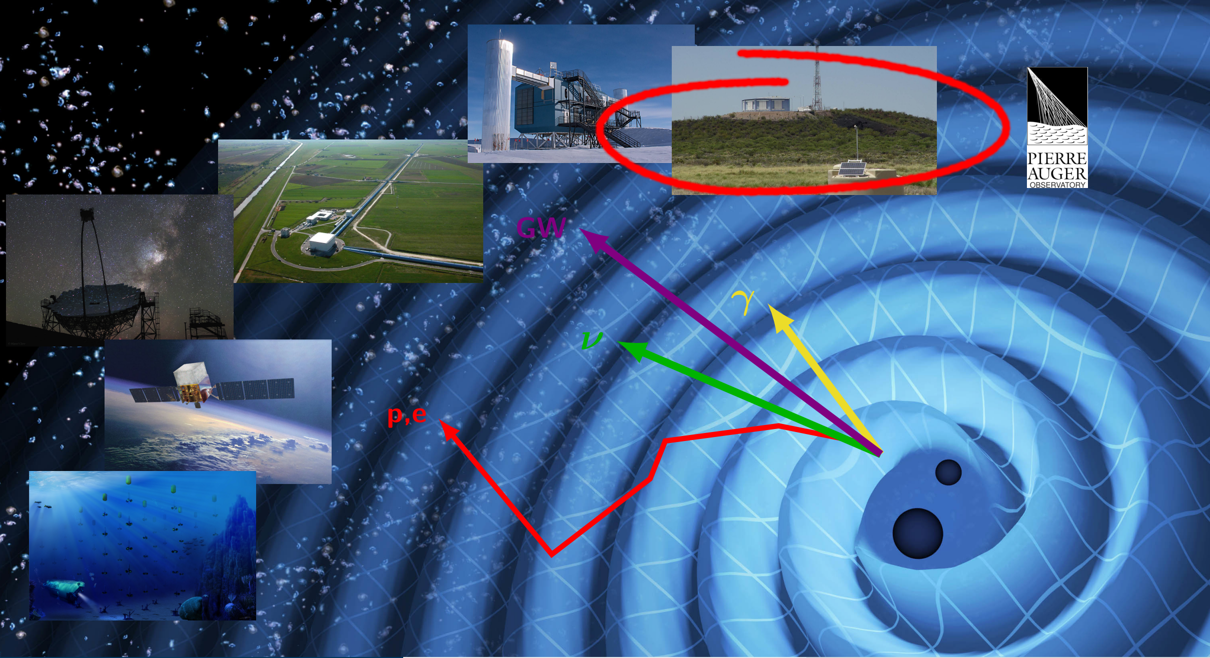
GW
γ
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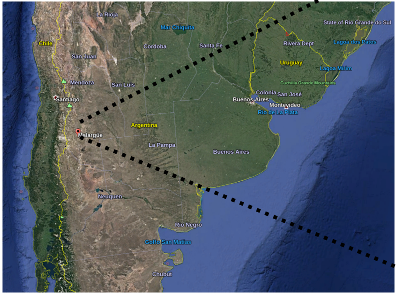
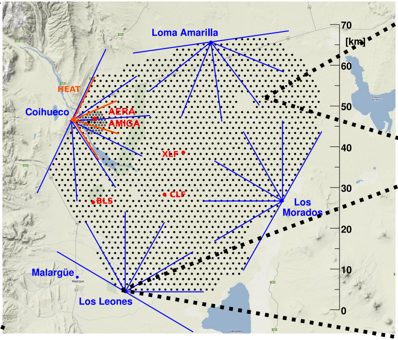
PIERRE
AUGER
OBSERVATORY

The Pierre Auger Observatory

The Pierre Auger Observatory

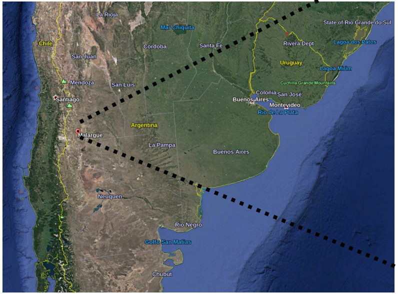
- World's largest cosmic-ray observatory ($\sim 3000\,\mathrm{km}^2$) for ultra-high-energy cosmic rays (UHECR).
- Located in the western part of Argentina, close to the city of Malargüe.
- Detector plane at $\sim 1400\,\mathrm{m}$ a.s.l., at the foot of the Andes mountains.

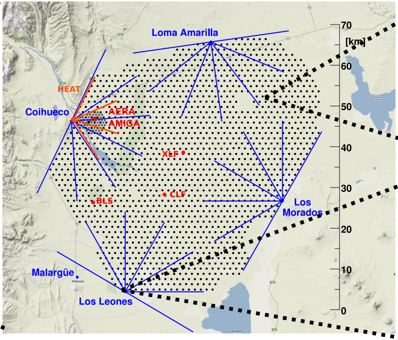




The Pierre Auger Observatory

- Surface Detector (SD):
  - 1660 water Cherenkov detectors with spacing of $1.5\,\mathrm{km}$ ($3000\,\mathrm{km}^2$).
  - Measure secondary particles of extensive air showers (EAS).
  - Duty cycle $\sim$ 100%.
- Fluorescence Detector (FD):
  - 27 fluorescence teleskopes at 4 sites.
  - Measure nitrogen fluorescence light, caused by EAS.
  - Duty cycle $\sim$ 15%.





Pierre Auger Observatorium

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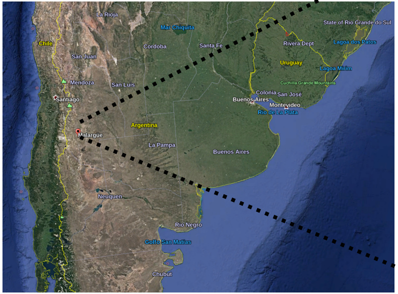
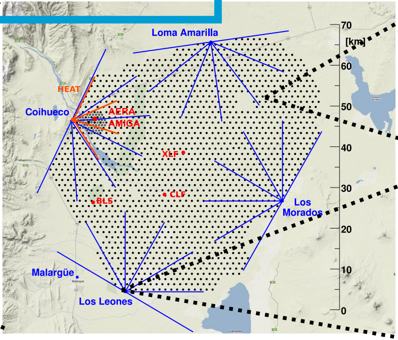
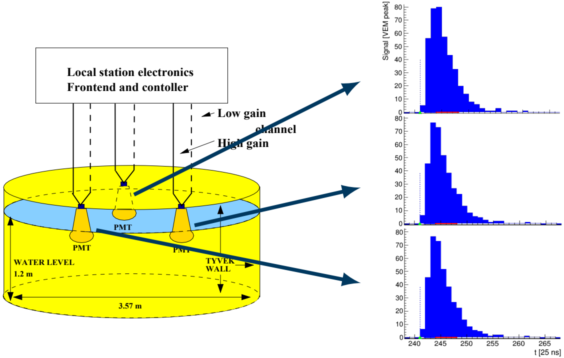




The Surface Detector (SD)

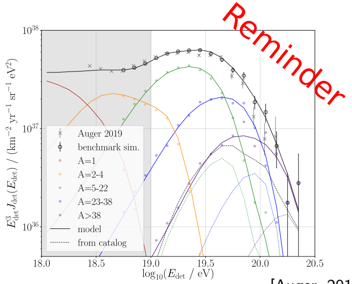


- Electromagnetic (EM) particles and muons penetrate the hull of an SD station.
- Cherenkov radiation in water is diffusely reflected by the inner layers.
- PMTs measure Cherenkov light as a function of time → signal traces.
- Energy correlates with total signal in the SD stations.
- Directional reconstruction through timing information.

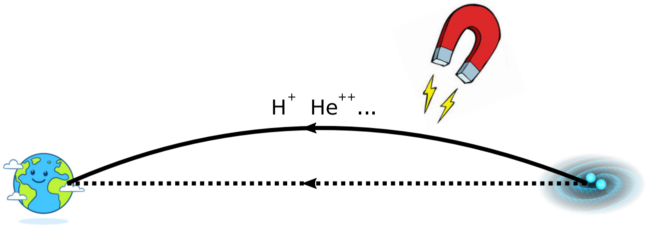
Multimessenger Astronomy with UHECR?

- Observatory was designed to measure cosmic rays.
- Cosmic rays at UHE consists primarily of charged nuclei.

↯ charged particles are not suited to analyze distant transients:



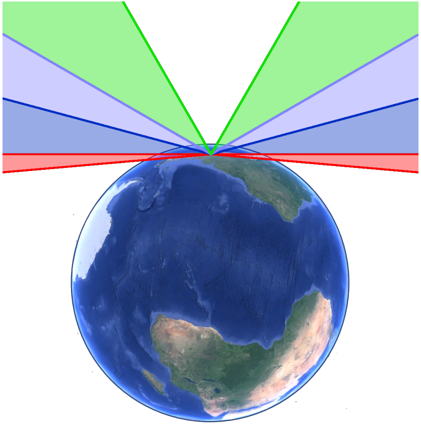
[Auger, 2019]



- Charged particles may be delayed by days, years or even centuries (for $D_L = 1\,\mathrm{Mpc}$).
- Typical gravitational wave (GW) sources at distances of some 100 Mpc

Search for UHE neutrinos and photons from transient sources

Field of View of the SD



Photons (30°... 60°):
EAS develop deeper in the atmosphere than for hadrons
$\rightarrow$ best sensitivity at $\theta = 30^\circ \ldots 60^\circ$.

ν - "Down going low" (DGL) (60°... 75°):
ν of all flavors interact via Charged Current (CC) or Neutral Current (NC) interactions.

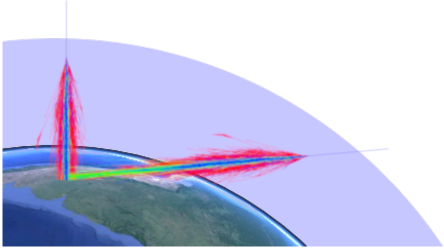
ν - "Down going high" (DGH) (75°... 90°):
like DGH, but with a better background suppression.

ν - "Earth skimming" (ES) (90°... 95°):
ν_τ interact via CC in the Earth's crust and produce an <u>upward going EAS</u>.

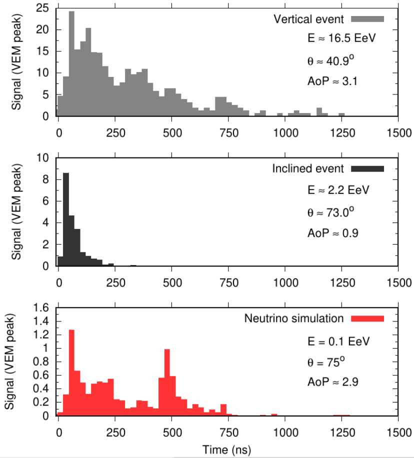
Search for UHE Neutrinos from Compact Binary Mergers (CBMs)

Discrimination between ν and hadronic particles:

- EM component dies out early in the atmosphere for inclined showers.



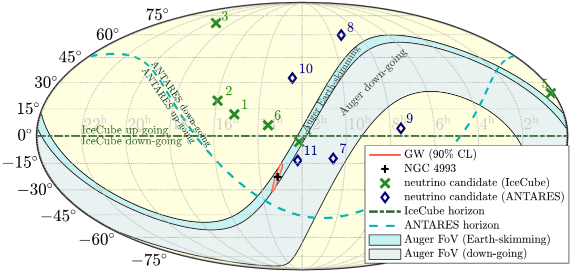
- Only muons reach the surface
  $\Rightarrow$ short peak in the singal traces.
- ν-shower may expose a fully developed EM component in the detector plane.

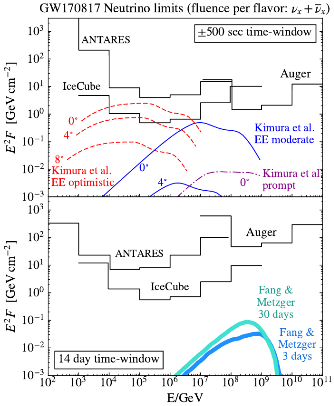


[Auger, 2019]

Neutrino follow-up after GW170817 (binary neutron star merger, BNS)

- Neutrino follow-up search with the Auger SD.
- Complements ANTARES and IceCube at $E > 10^{18}\,\mathrm{eV}$.
- No ν candidates $\Rightarrow$ upper limits on the ν fluence.
- ν candidates at Auger would have been highly significant: source exactly within the ES-channel!

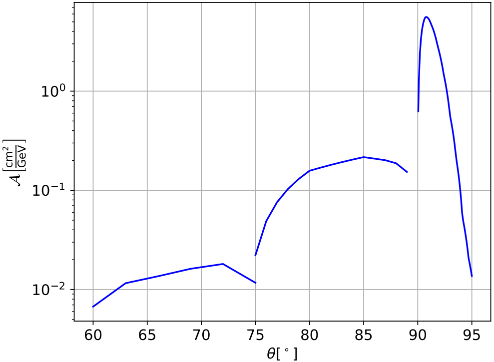


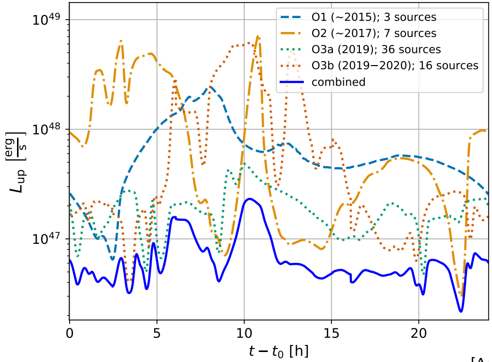


[Antares, IceCube, Auger, 2017]

Limits on UHE νs from BBH mergers

- Stacking analysis to constrain the source class of BBH mergers.
- Results mainly depend on the sensitivity of the ES channel (highest $\mathcal{A}$).
- Limits on ν-luminosity as a function of time.
- strongest constraints currently at $\sim 22\,\mathrm{h}$ after the GW.





[Auger, 2021]

Search for UHE Photons from CBMs

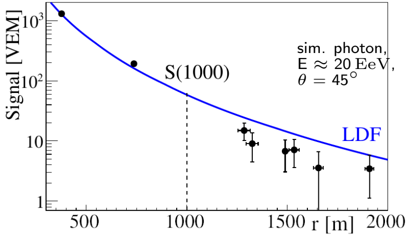
Identification of Primary Photons with the SD

Photon-induced showers: (typically) deeper and less muons.

SD observables for photon-identification:

lateral distribution function (L_{LDF}):

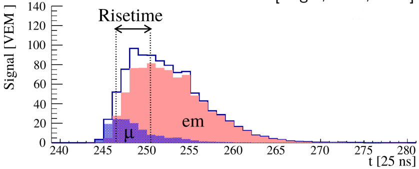
- EM particles closer to the shower axis than hadrons.
- Photon-induced showers have a steeper LDF.



Signal Risetime (Δ):

- Initial muon peak followed by a smeared-out EM trace.
- Large signal risetime for primary photons.

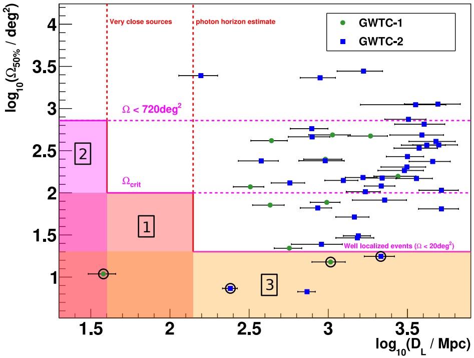
[Auger, 2015, 2019]



(Observables optimized for photon energies above 10 EeV and $30^\circ < \theta < 60^\circ$).

GW Event Selection for the Follow-up Photon Search

- Identification of primary photons more difficult than for neutrinos $\Rightarrow$ more background
- Introduce GW event selection strategy to reduce rate of false-positive detections.
- Focus on close and/or well-localized sources:
  - interactions with CMB $\Rightarrow$ "photon horizon" (class 1).
  - very close sources ($\lesssim$ 40 Mpc) may allow for strong constraints on the source luminosity (class 2).
  - channel for discovery of new physics (e.g. photon-axion mixing): well localized, but distant sources (class 3).
  - cuts on the maximum localization region help maintaining a high sensitivity towards a signal.



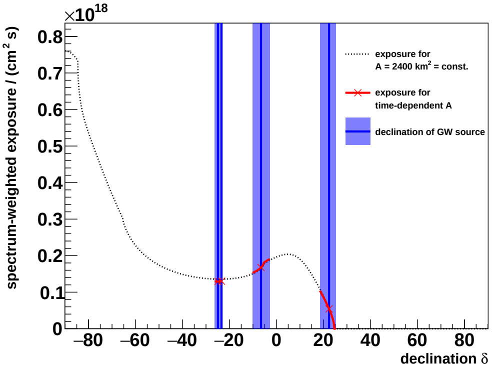
- 4 sources pass the event selection and are oberved by the SD:
  - 1 BNS merger
  - 2 BBH mergers
  - 1 BH-NS merger candidate

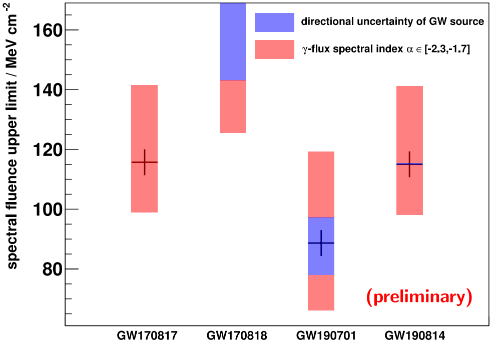
[Auger, 2021]

Upper Limits on Photons from CBMs (preliminary)

- No coincident photons could be identified.

  $\Rightarrow$ Upper limits on the photon spectral fluence during a 1 d time window.



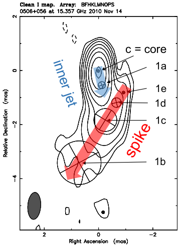


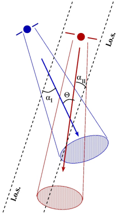
[Auger, 2021]

Follow-up Analysis of the IceCube neutrino observations from TXS 0506+056

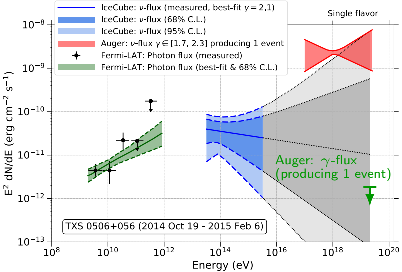
The blazar TXS 0506+056

- TXS 0506+056: anomalous blazar, formerly classified as BL LAC type.
- Redshift $z \approx 0.34$ ($\hat{=}\ 1.8\,\mathrm{Gpc}$).
- Radio measurements expose extremely curved jet pointing towards earth.
- BBH system with colliding jets?





[Britzen et al, 2019]



[Auger, 2020 (mod.)]

- IceCube: evidence for high energy ν-production in 2014/2015 (3.5σ) and 2017 (3σ).
- No neutrino or photon candidates found by the Pierre Auger Collaboration.
- Limits on photon flux about one order of magnitude lower than extrapolated ν-flux.

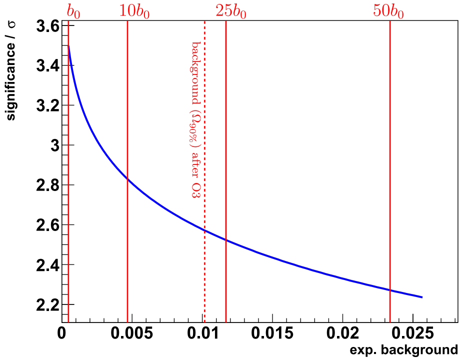
Summary

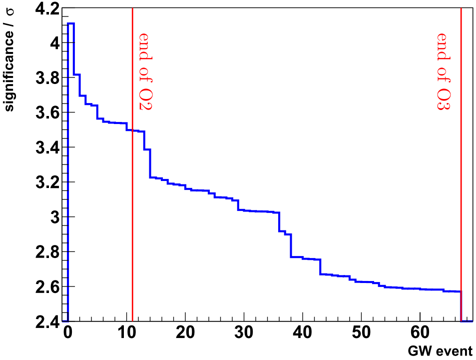
- The Pierre Auger Observatory extends the global multimessenger campaign into the UHE regime.
- Follow-up searches for UHE neutrinos and photons from astrophysical transients have been established.
- first analyses of GW sources and the blazar TXS 0506+056 did now show coincident neutrino- or photon-like signals.
- Stacking of BBH mergers will further improve the limits on the neutrino production of this source class.
- A dedicated GW event selection for the follow-up photon search provides a high sensitivity and opens a window for the discovery of new physics.

Backup

Impact of the Hadronic Background

- Photons cannot be discriminated unambiguously from the hadronic background.
- On average 1 background event per year passes the photon candidate cut.
- The significance of a discovery decreases with the expected amount of background:

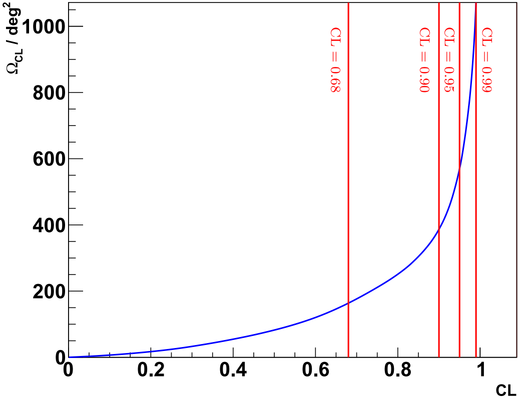




Reduction of the Background Rate

- Possibility to reduce the background: observing small regions on the sky.
- Best choice for a localization contour?

  $\rightarrow$ Look at the size of the contour Ω_{CL} as a function of its confidence level CL:



Example GW150914:

- Contour size at CL$=0.9$ about 4-6 times as large as at CL$=0.5$

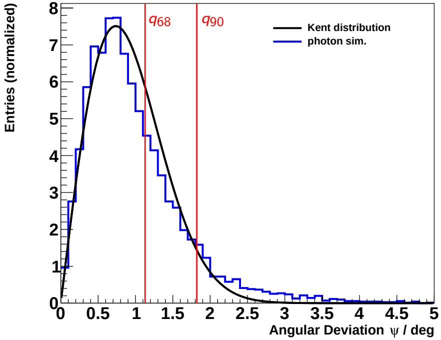
Averaged over all GW events:

- At CL$=0.5$, the relative variation of the contour size is $\approx 2\times$ the relative variation of the CL (compared with $6\times$ at CL$=0.9$).

$\Rightarrow$ 50% contour as a compromise between expected background and confidence in source coverage.

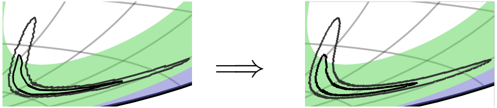
Convolution of Directional Uncertainties

- Auger SD has a limited directional resolution.
- Average resolution for photons above 10 EeV about 1°.
- Ansatz-distributino function of the directional uncertainty: Kent-distribution $K(\psi)$ ($\hat{=}$ 2-dim Gauß-distribution on the sphere).



- Search window: 50% contour of the convolved skyr

$$P(\alpha, \delta) = \iint_0^{4\pi} \mathrm{d}\Omega' P'(\alpha', \delta') K(\psi)$$

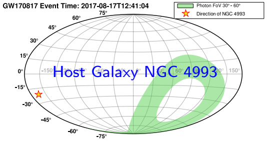


$\Rightarrow$ Convolution inflates contour typically about 20-30%.

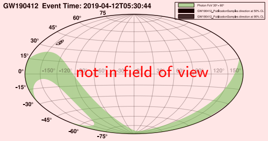
Selected GW sources

- 5 GW source pass the selection criteria
- 4 GW sources are within the field of view of the SD
- Selected GW sources:

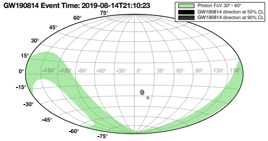
  - GW170817 (BNS)



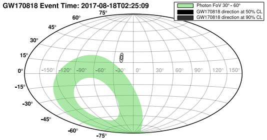
  - GW190412 (BBH)



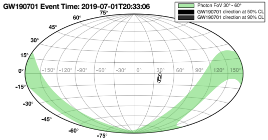
  - GW190814 (NSBH)



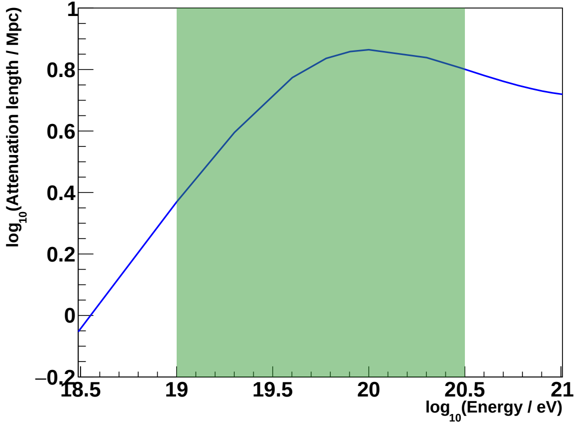
  - GW170818 (BBH)



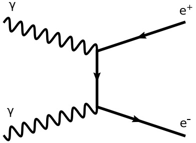
  - GW190701 (BBH)



UHE Photons in the Extragalactic Medium



- Interactinos between UHE photons and
  - photons of the CMB (2,7 K, 1.9 mm, dominant up to $\sim 110^{19.8}\,\mathrm{eV}$).
  - photons of universal radio background (dominant starting with $\sim 10^{20}\,\mathrm{eV}$).



$\Rightarrow$ Mean free path of UHE photons limited to a few Mpc.

Limits on UHE νs from the Source Class of BBH mergers

We have:

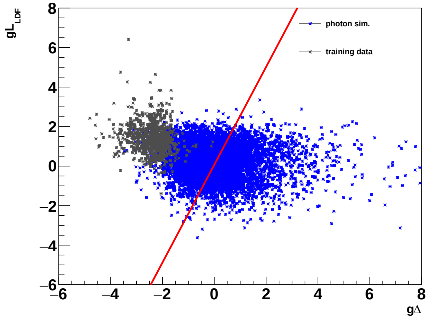
- Many individual limits on BBH mergers until the end of O3 (March 2020).
- A continuously growing set of GW detections.
- Presumably identical – oder at least similar – sources. (?)

$\Rightarrow$ Statistical combination to improve upper limits ("stacking").
Upper limits on ν-luminosity:

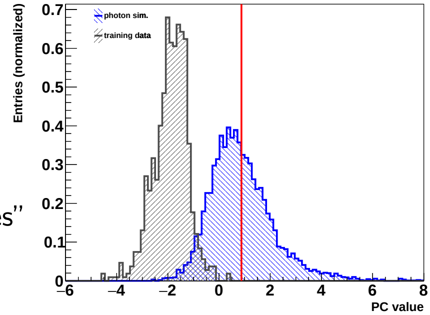
$$L_i^{UL} = \frac{2.44}{86400\,\mathrm{s}} \left(\sum_s \frac{\sum_p P_{p,s} \mathcal{A}_{p,s,i}}{d_s^2} \right)^{-1}$$

With the probability $P_{p,s}$ of a source s to be located within pixel p of the skymap and the specrum-weighted effective aperture $\mathcal{A} = \int_0^\infty E_\nu^{-2} A_{eff}(E_\nu, \theta, t) dE_\nu$ for a zenith angle θ and within the time bin i.

Identification of Primary Photonen with the SD



- Energy and zenith angle-normalized observables gL_{LDF} and $g\Delta$.
- Complementary information for the discrimination between primary photons and hadrons.



- Projection of the observable space onto the common principal component to reduce dimensionality.
- Events beyond the red line: "photon candidates"

$\Rightarrow$ Relative background rate: $\approx {}^{1}/_{4000} \ldots {}^{1}/_{3000}$