The Pierre Auger Observatory ultra-high energy neutrino follow-up of the LIGO GW events

Carla Bleve[1] for the Pierre Auger Collaboration[2]

[1] INFN and Department of Mathematics and Physics, University of Salento, Lecce, Italy
[2]Full author list http://www.auger.org/archive/authors_2016_08.html

The 2015 LIGO gravitational waves events

→ Breakthrough observation of GW events with the LIGO Advanced interferometer

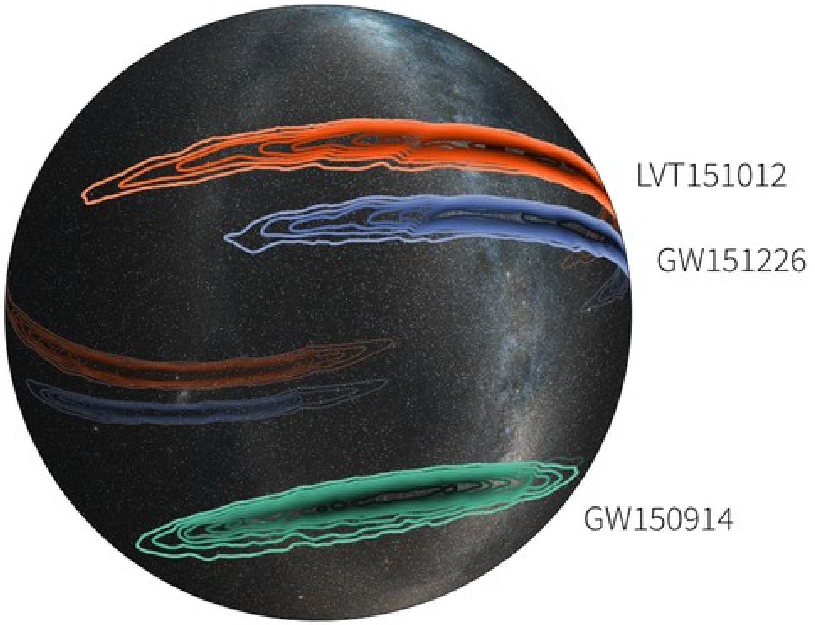
→ GW150914 and GW151226 (and LVT151012 candidate)

→ Inferred source: coalescence of a BH binary @ 410 and 440 Mpc

→ Position: few 100 deg^2 uncertainty

→ Energy released in form of GW: ~ 3 and 1 solar masses

Image: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

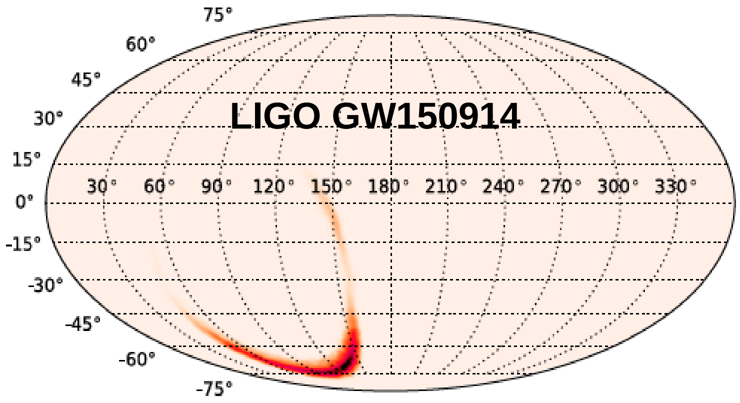


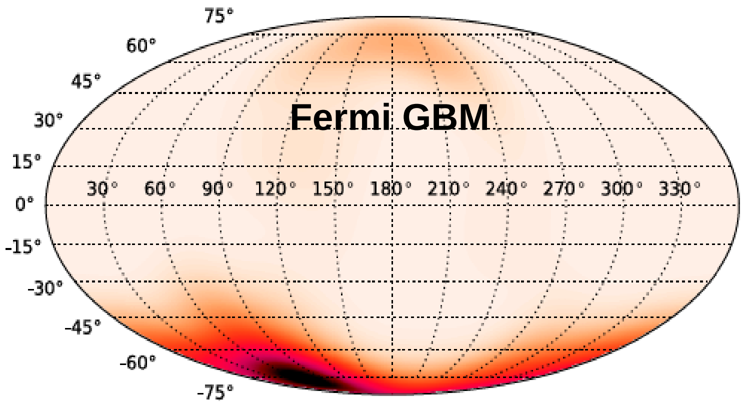
LIGO & Virgo Coll.
PRL 116, 061102, 241102 & 241103 (2016)

No electromagnetic counterpart generally expected from BH mergers

UHE νs from BH merger events?

→ Fermi GBM 3σ report of a 1s transient signal 0.4 s after GW150914 and consistent position





Connaughton et al, ApJL 826, L6 (2016)

→ Models predicting emission of UHE neutrinos:

- UHECR accelerated by Fermi mechanism if relic magnetic field and debris from BH formation => emission of UHE neutrinos and photons ***Kotera & Silk, ApJL 823, L29 (2016)***
- if accretion disk present, proton acceleration up to ~10 EeV energy by electric fields in disk dynamo, UHE neutrinos from interaction with bkg photons and gas around BH ***Ancordoqui, PRD 94, 023010 (2016)***

Search for UHE ν in coincidence with GW events with the Auger SD (E>100 PeV)

The surface detector (SD) of the Pierre Auger Observatory

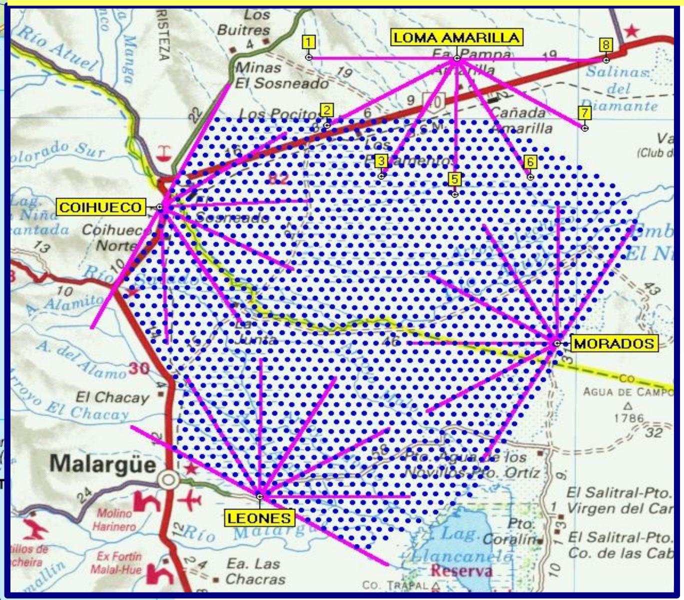
Detection of Extensive Air Showers through secondary particles at ground level

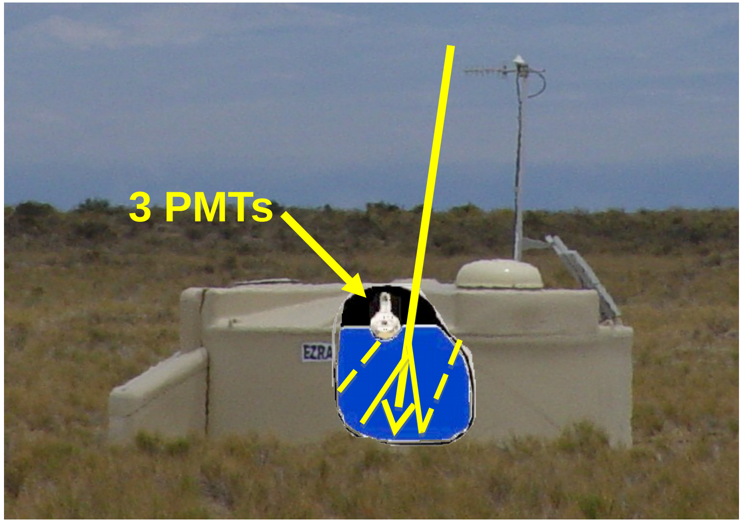
35.5º S, 69.3º W

1400 m a.s.l.
(880 g cm^{-2})

NIM A 798 (2015) 172-213

~1660 Water Cherenkov stations
triangular grid with 1500 m spacing
3,000 km^2 total area





→ sensitive to electromagnetic and muonic component
→ measure of the time structure of the signal induced by electrons and μs

Inclined showers and UHE neutrinos

→ Protons & nuclei initiate inclined showers high in the atmosphere.

Shower front at ground:

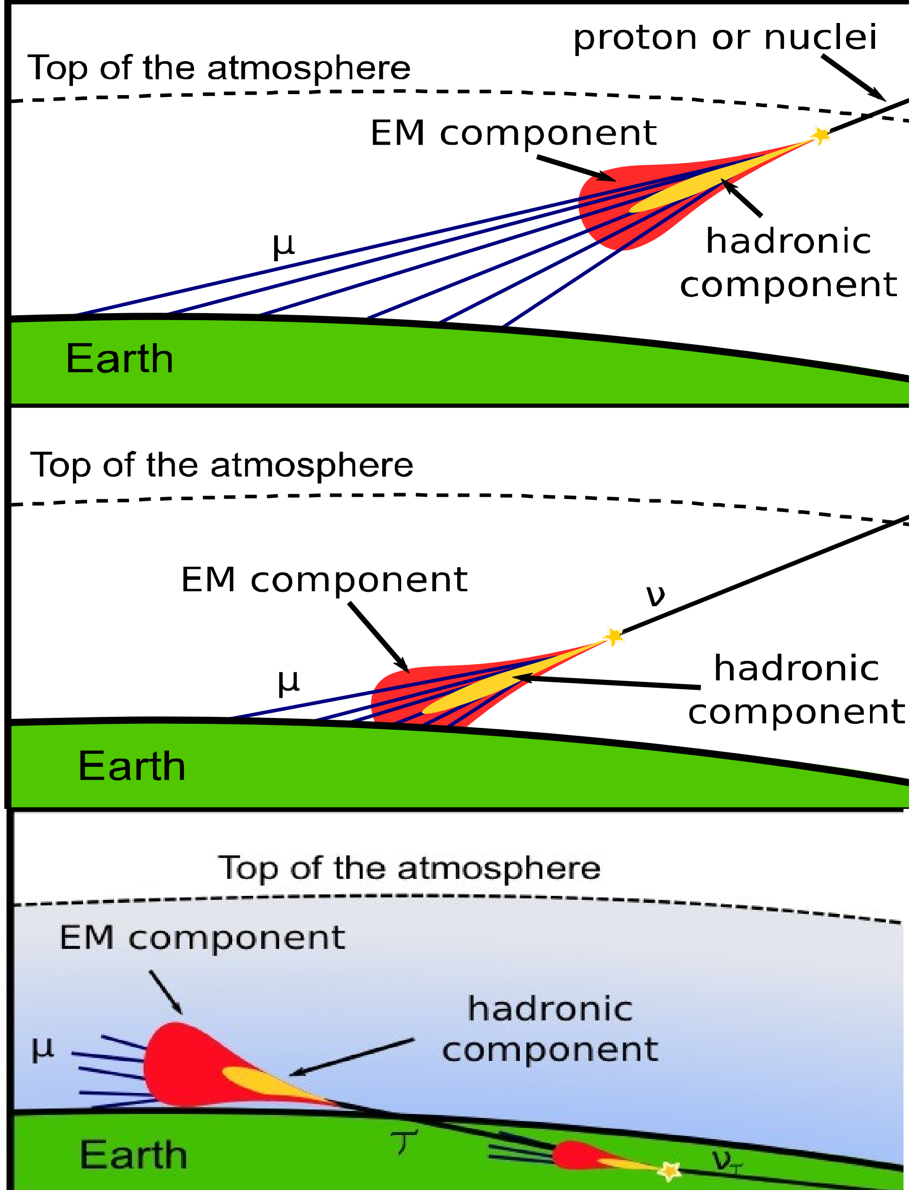
- electromagnetic component absorbed in atmosphere
- mainly muons remaining

→ Neutrinos can initiate deep showers close to ground.

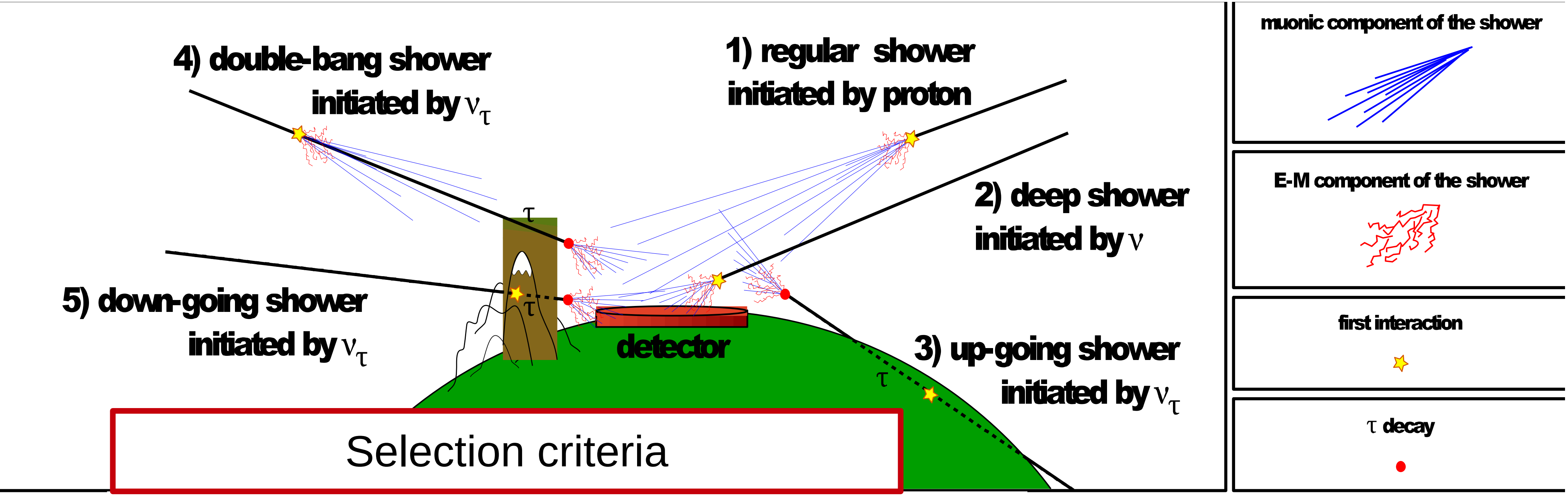
Shower front at ground:

electromagnetic + muonic components

Search for neutrinos
⇒ look for inclined showers with electromagnetic component



Sensitivity to all flavours and channels



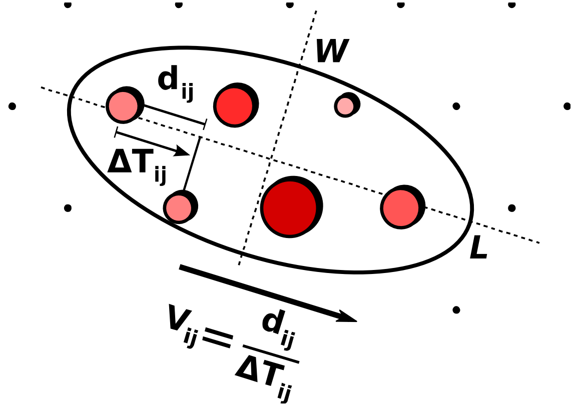
Selection criteria

Down-going high angle (2, 4 and 5) DGH 75º-90º } all flavours

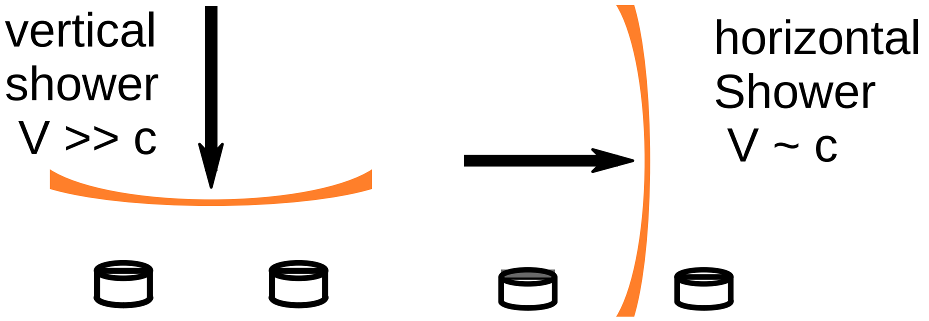
Earth-skimming (3) ES 90º-95º ν_τ

Selection of inclined events

(1) Elongated footprint



(2) Apparent velocity V of propagation of the shower front along major axis L

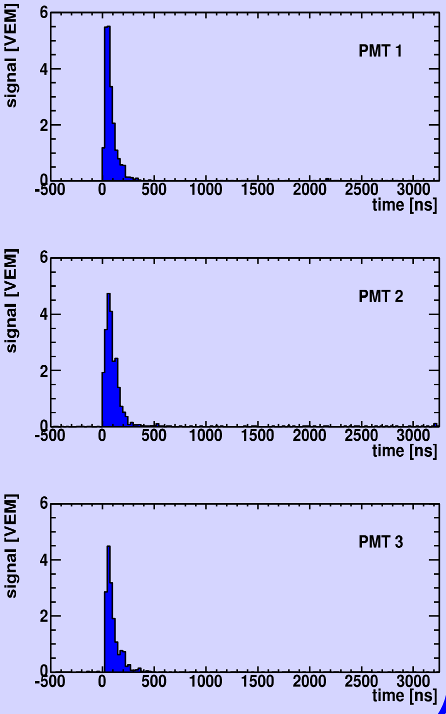


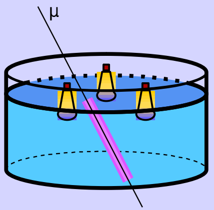
(3) Reconstructed zenith angle (DGH channel only)

	Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$
(1)	$L/W > 5$	$L/W > 3$
(2)	$\langle V \rangle \in (0.29,\ 0.31)$ m ns^{-1}	$\langle V \rangle < 0.313$ m ns^{-1}
	RMS$(V) <$ 0.08 m ns^{-1}	RMS$(V)/\langle V \rangle < 0.08$
(3)	–	$\theta_{rec} > 75°$

Identifying electromagnetic shower fronts

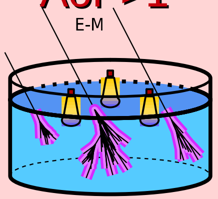
Muonic shower front: narrow signals

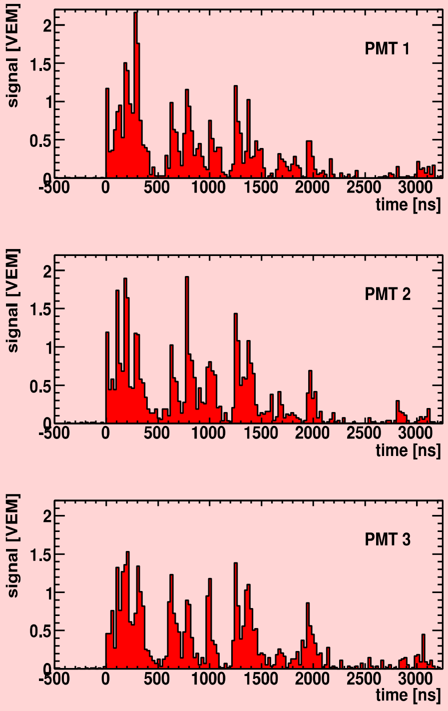




NO ToT
AoP~1

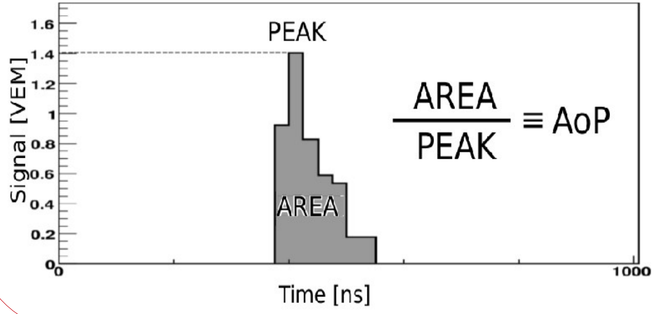
ToT
AoP>1





EM shower front: broad signals

Definition of
Area over Peak



$$\frac{\text{AREA}}{\text{PEAK}} \equiv \text{AoP}$$

Select stations with:

- ✓ Time-over-Threshold (ToT) trigger

AND/OR

- ✓ Large Area-over-Peak (AoP)

To find neutrinos => search for signals extended in time in inclined events.

Searching for UHE ν in coincidence with GW events

→ Neutrino search method already defined and applied to the data collected up to June 2013 (upper limits to the diffuse flux and steady point-like sources of UHE neutrinos)

Pierre Auger Coll., PRD 91, 092008 (2015) & ApJL 755, L4 (2012)

→ **Energy range: E > 100 PeV** - complementary to IceCube-Antares GW follow up

LIGO&VIRGO, IceCube, ANTARES Coll., PRD 93, 122010 (2016)

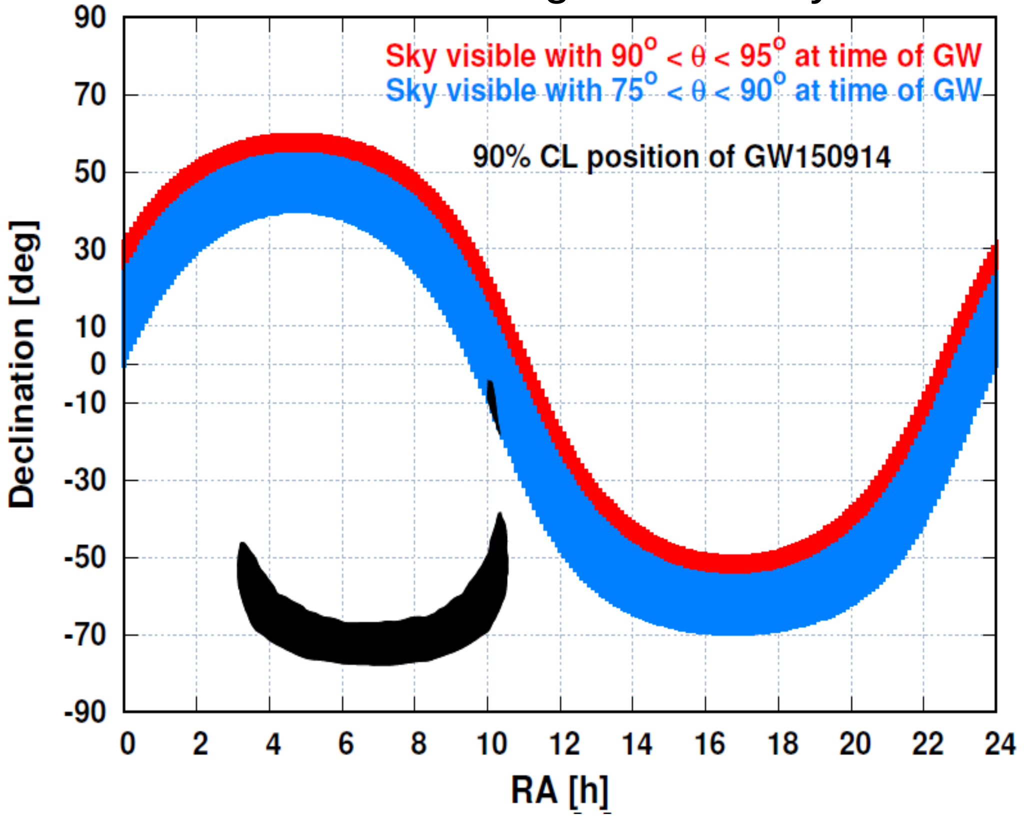
→ Earth-Skimming and Downward-Going neutrino selection applied to data in <u>spacial and temporal proximity to GW150914, GW151226 (and LVT151012).</u>

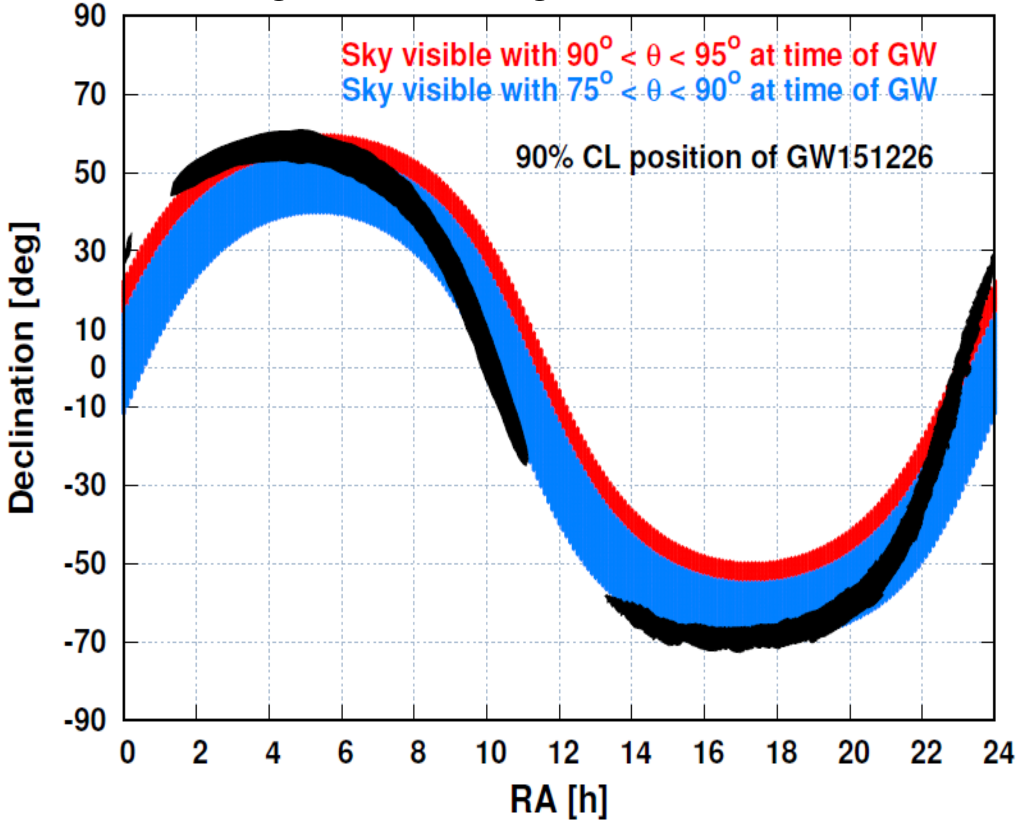
±500 s window around GW event time "coincidence" search

for each GW, data unblinded over an observations window T_{search} of 1d + 500s

Time coincidence with GW events: coverage

Auger sensitivity to UHEν limited to large zenith angles



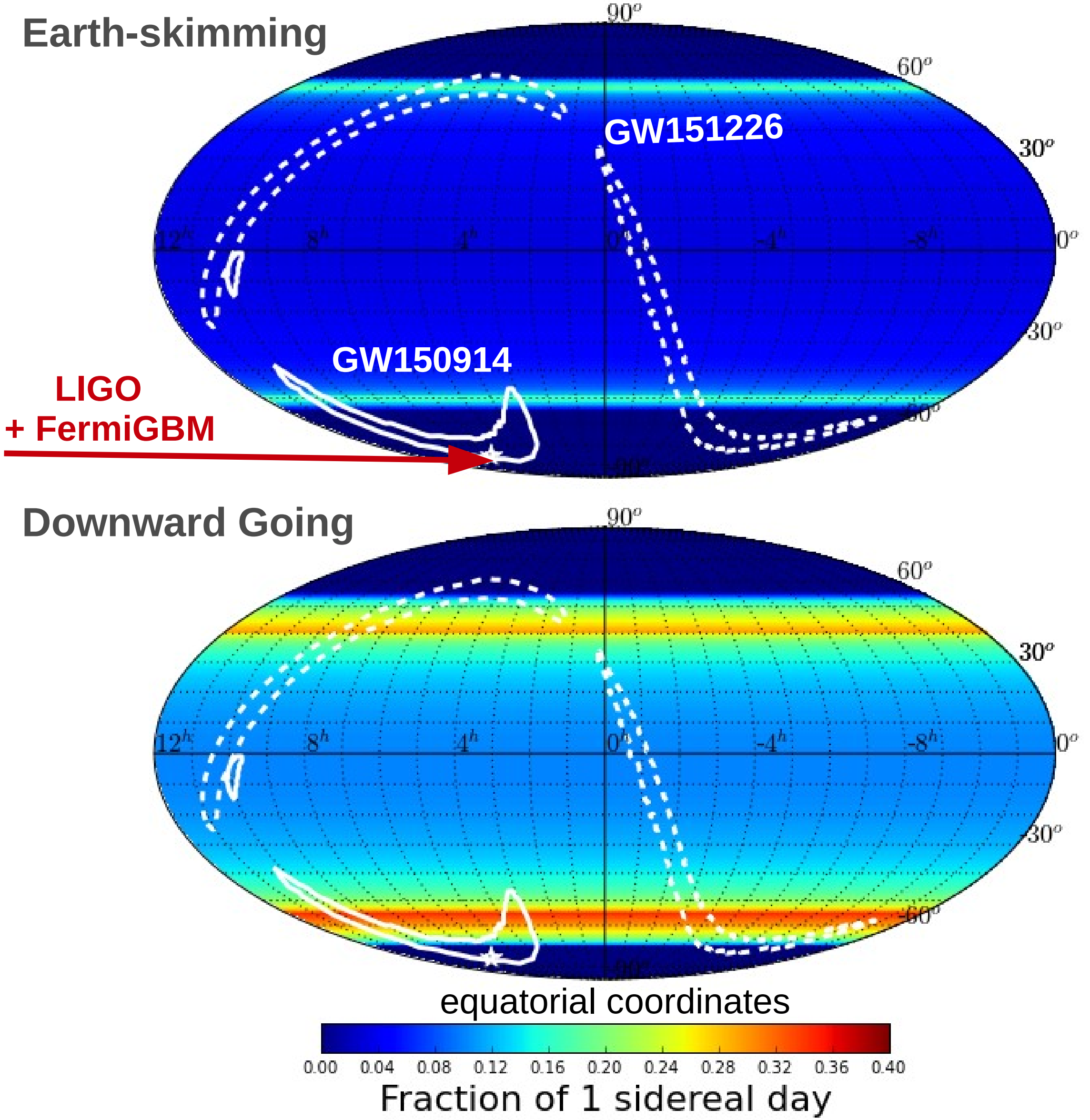


<u>No neutrino candidate</u> found in the time window ± 500 s around the GW events

Sky map of visibility time fraction in 1 sidereal day

<u>No neutrino candidate</u>
found in the 1 day window
after any GW events
in both search channels

Constraints to UHEν emission declination dependent

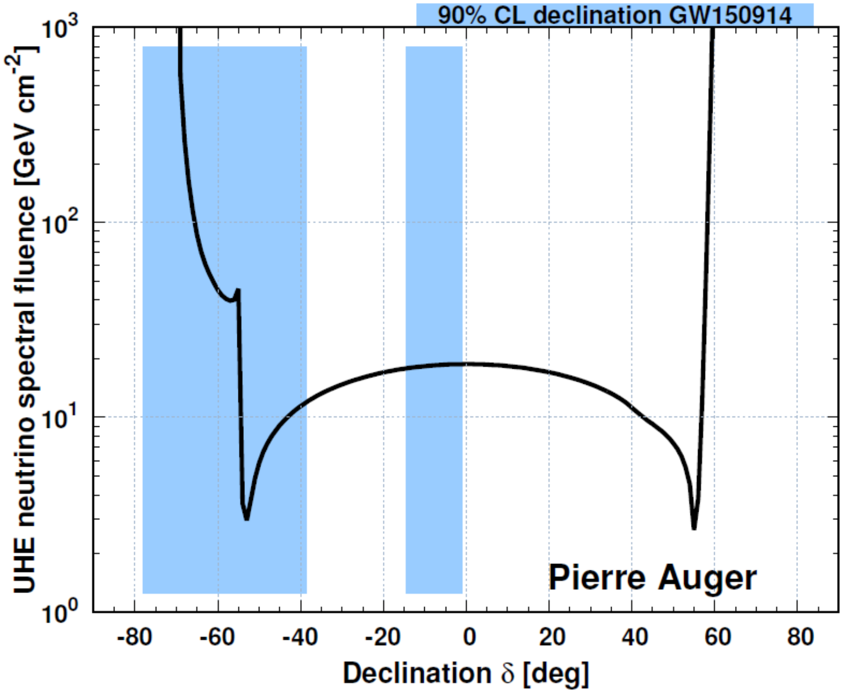


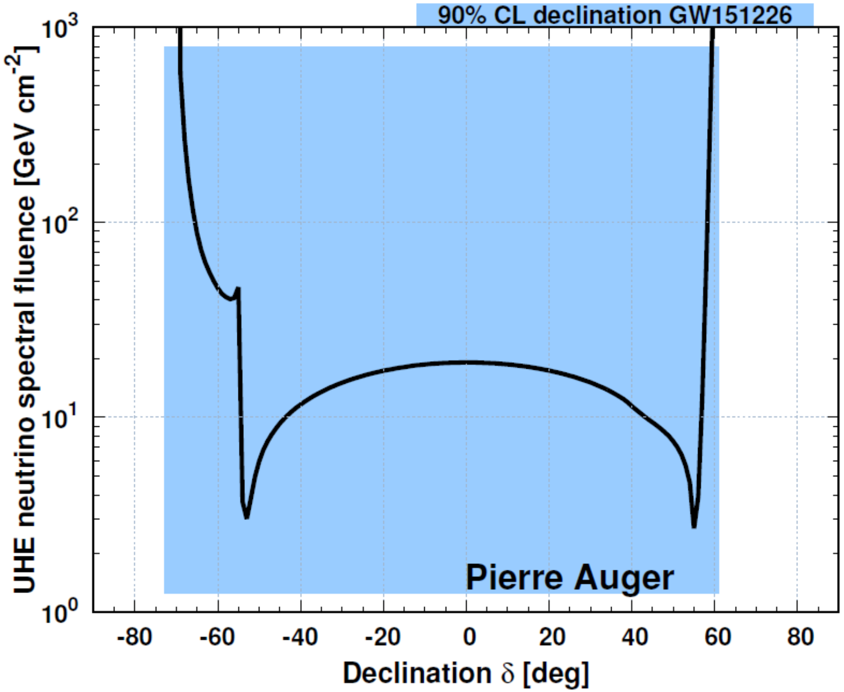
For a kE_{ν}^{-2} point source, U.L. to flux:

$$k^{GW}(\delta)=\frac{N^{GW}}{\int E_{\nu}^{-2}\,\varepsilon_{GW}(E_{\nu},\delta)\,dE_{\nu}}$$

Upper limits to the UHEν spectral fluence ($E_{\nu}>10^{17}$ eV)

Fluence U.L. derived combining the constraints from the two search channels and assuming constant flux and ocontinuous emission over T_{search}

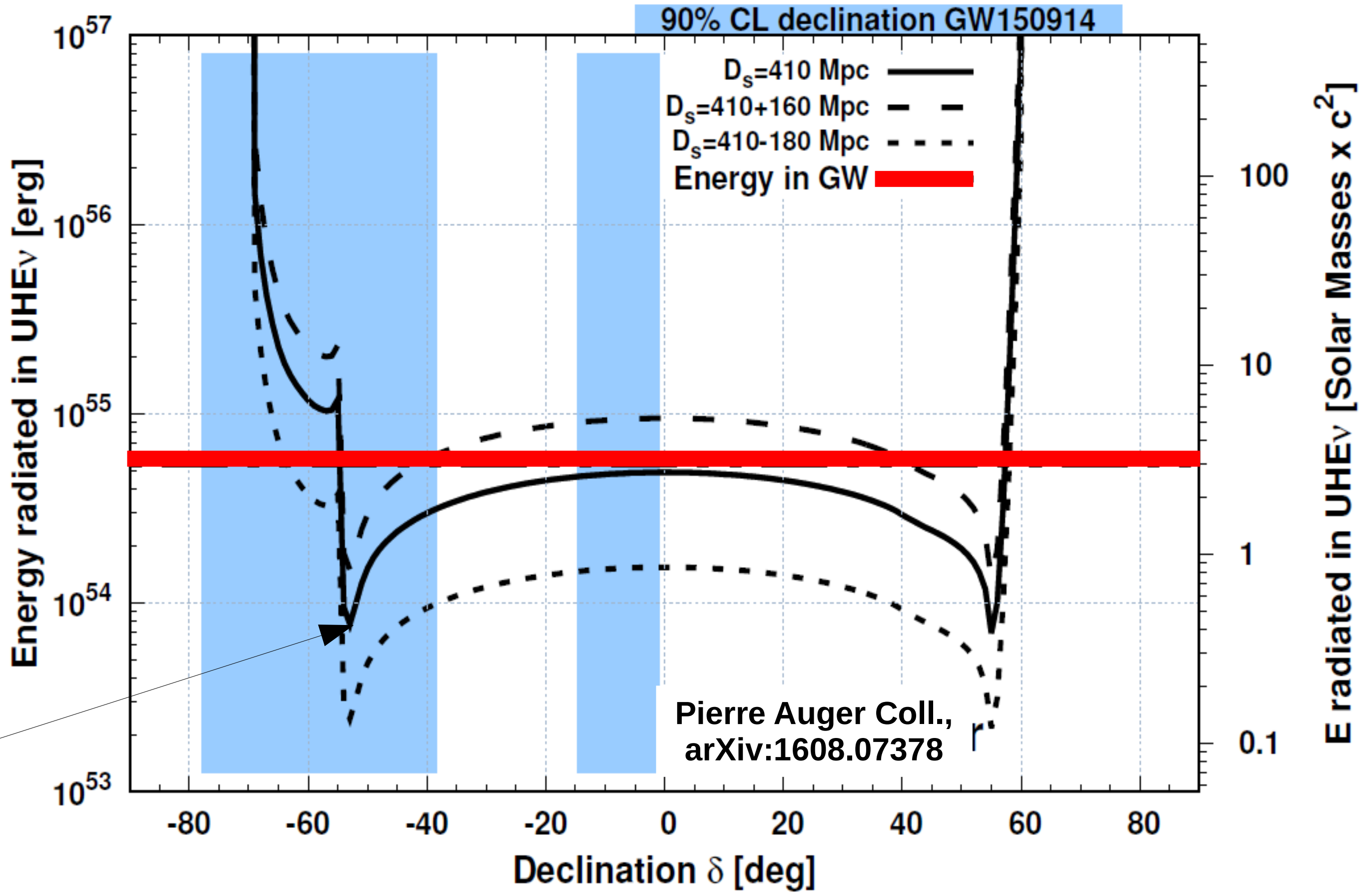




Constraints to the energy radiated in UHEν for GW150914 ($E_\nu > 10^{17}$ eV)

For isotropic emission, using luminosity distance.

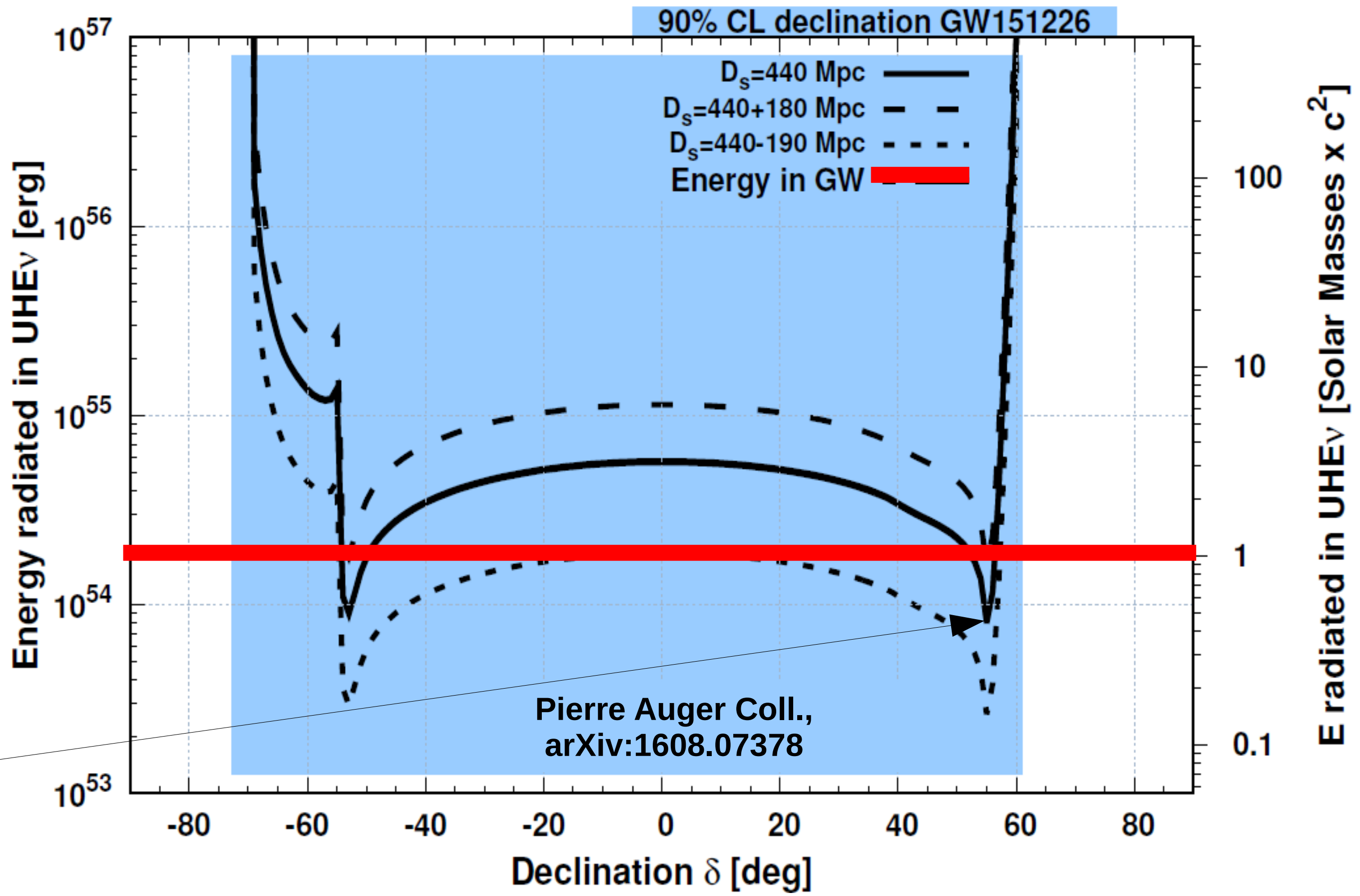
less than
(0.5,3) solar masses
depending on
the source declination



< 14% of E_{GW}

Constraints to the energy radiated in UHEν for GW151226 ($E_\nu > 10^{17}$ eV)

For isotropic emission,
using luminosity distance.



less than
(0.5,3) solar masses
depending on
the source declination

< 44.1% of E_{GW}

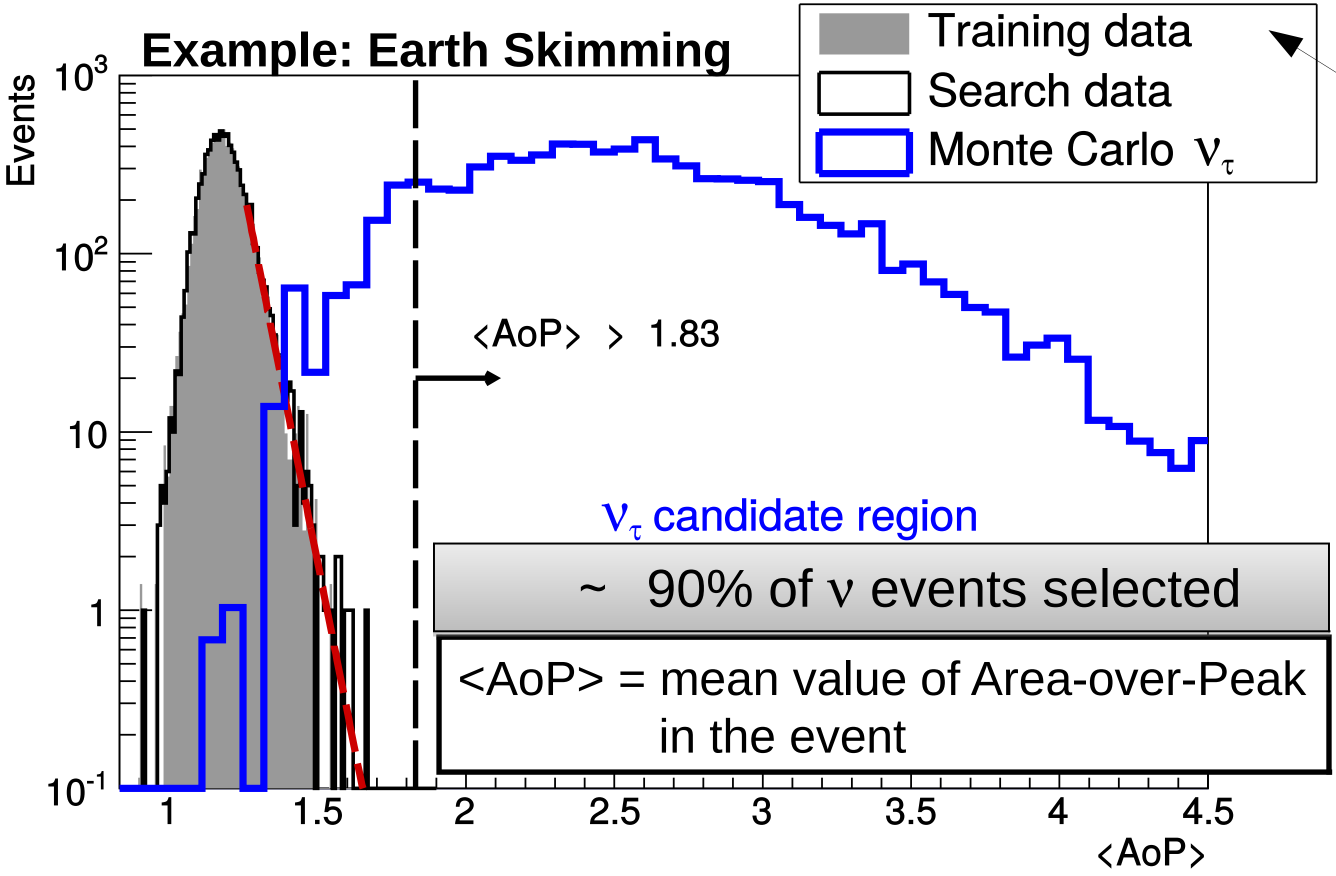
Conclusions

- Auger follow up of 2015 LIGO gravitational-wave events
  → search for UHE neutrinos in temporal and spatial proximity with LIGO GW events
  → no neutrino candidate found
  → first constraints at $E_\nu > 10^{17}$eV (complementary to IceCube)

- In future more GW events expected
  → closer, brighter or produced by other sources more likely to produce UHE neutrinos
  → UHE neutrino (and photons) counterparts if observed by Auger can help pinpointing the location of the source

Backup

Identification of UHE neutrinos in Auger data



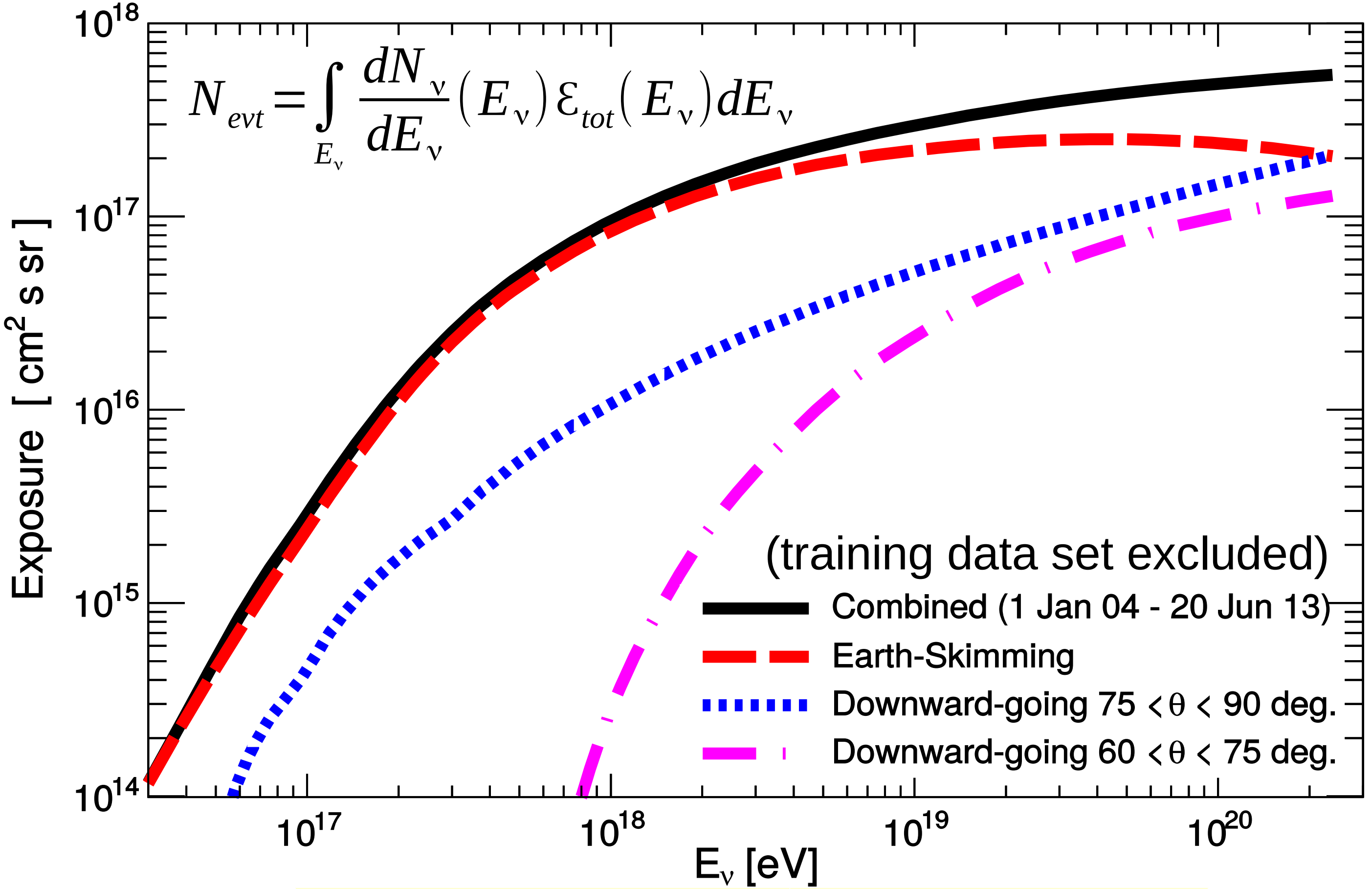
~20% of the data are used to estimate the expected background

Data taking:
01/01/04 – 20/06/13

Identification criteria applied “blindly” to the search data set
=> No candidates found in Earth Skimming or Downward-going

Neutrino exposure calculation

Upper limit to the number of neutrinos: Feldman-Cousins + Conrad (includes uncertainties in the exposure calculation)



Upper limits for a k E^{-2} spectrum:

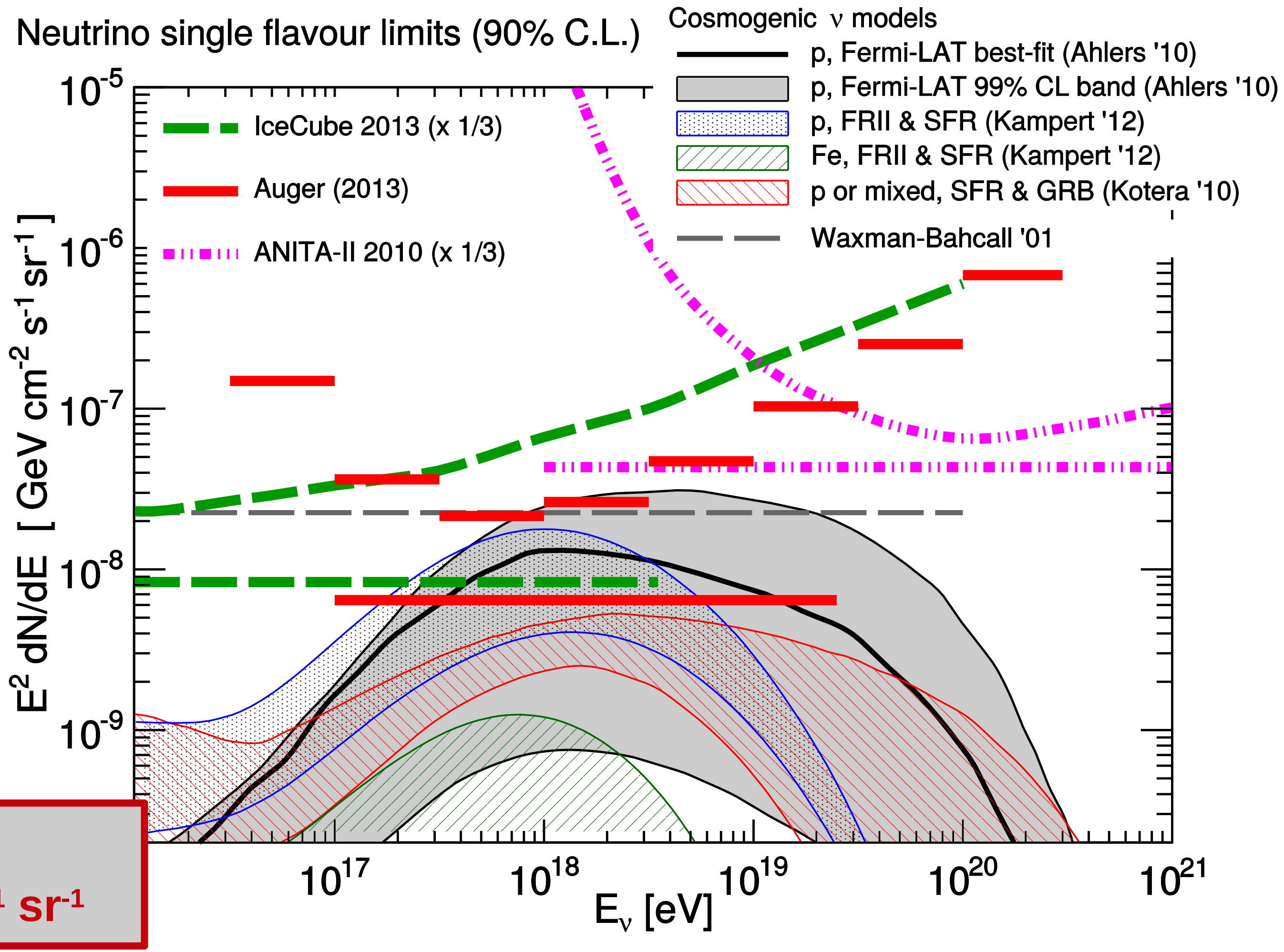
$$k^{90\%} = \frac{N^{90\%}}{\int E_\nu^{-2}\,\mathcal{E}_{tot}(E_\nu)\,dE_\nu}$$

Systematic Uncertainties

Simulations	~ +4%, -3%
ν cross-section & τ E-loss	~ +34%, -28%
Topography	~ +15%, 0%
Total	~ +37%, -28%

Upper limits to the diffuse flux of neutrinos

Phys. Rev. D 91 (2015) 092008



$dN/dE = k\ E^{-2}$

→ $k \sim 6.4 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}

90% C.L. in the energy range 0.1 – 25 EeV

Auger limit constrains models with proton primaries & strong evolution with redshift

Auger constraints on models

Pierre Auger, arXiv:1608.07378

- Kotera & Silk (ApJLett 823, L29, 2016): events such as GW1501914 can account for UHECR above 10^{19} eV
  - sufficient power to accelerate CR up to 10^{20} eV (if $B_{field} > 10^{11}$ G)
  - with < 3% of energy released in GW: UHECR energy budget achieved
- UHEν if BHs surrounded by debris where pγ interactions occur.

Upper limit to **diffuse** UHE neutrino flux from BH mergers:

$$E^2 dN/dE \sim 1.5 - 6.9 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ (theory)}$$

above Auger limit

$$E^2 dN/dE \sim 6.4 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ (Auger)}$$

- **Implications:**
  - optical depth to pγ SMALLER than 1
  - ONLY a fraction of energy in protons goes into charged pions -> neutrinos
  - ONLY a fraction of luminosity extracted from BH goes into UHECR acceleration