PIERRE AUGER OBSERVATORY

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Multi-messenger astrophysics with the Pierre Auger Observatory

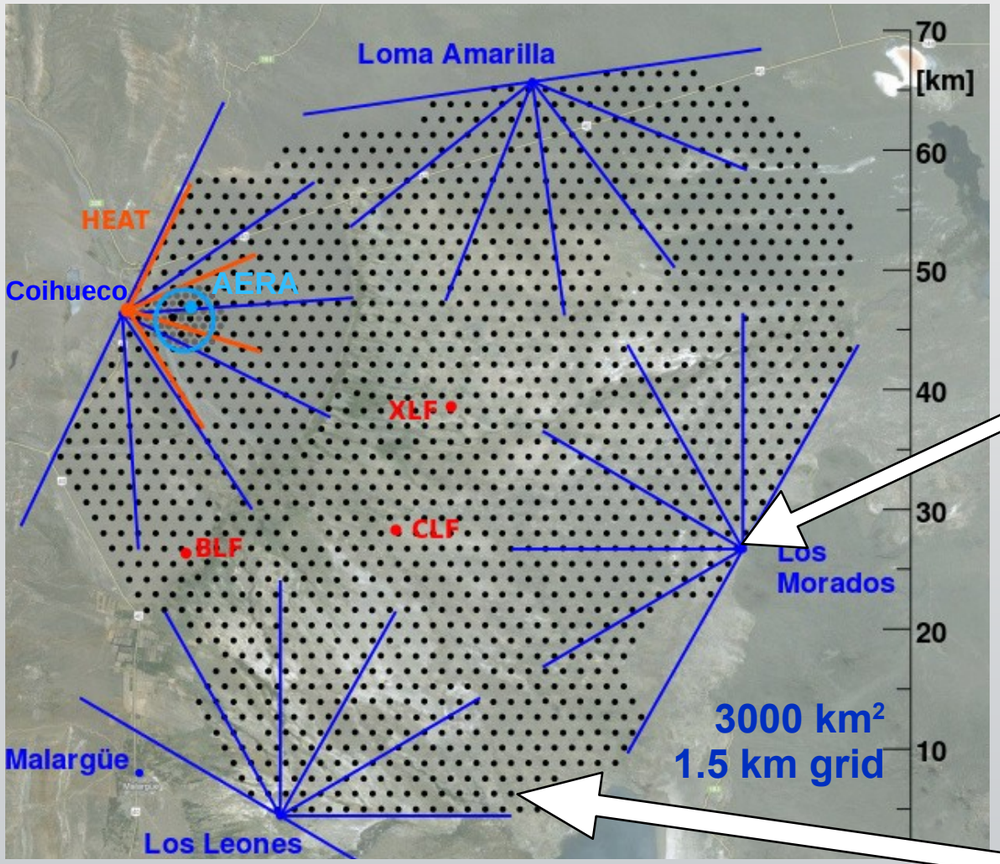
Michael Schimp
for the Pierre Auger Collaboration

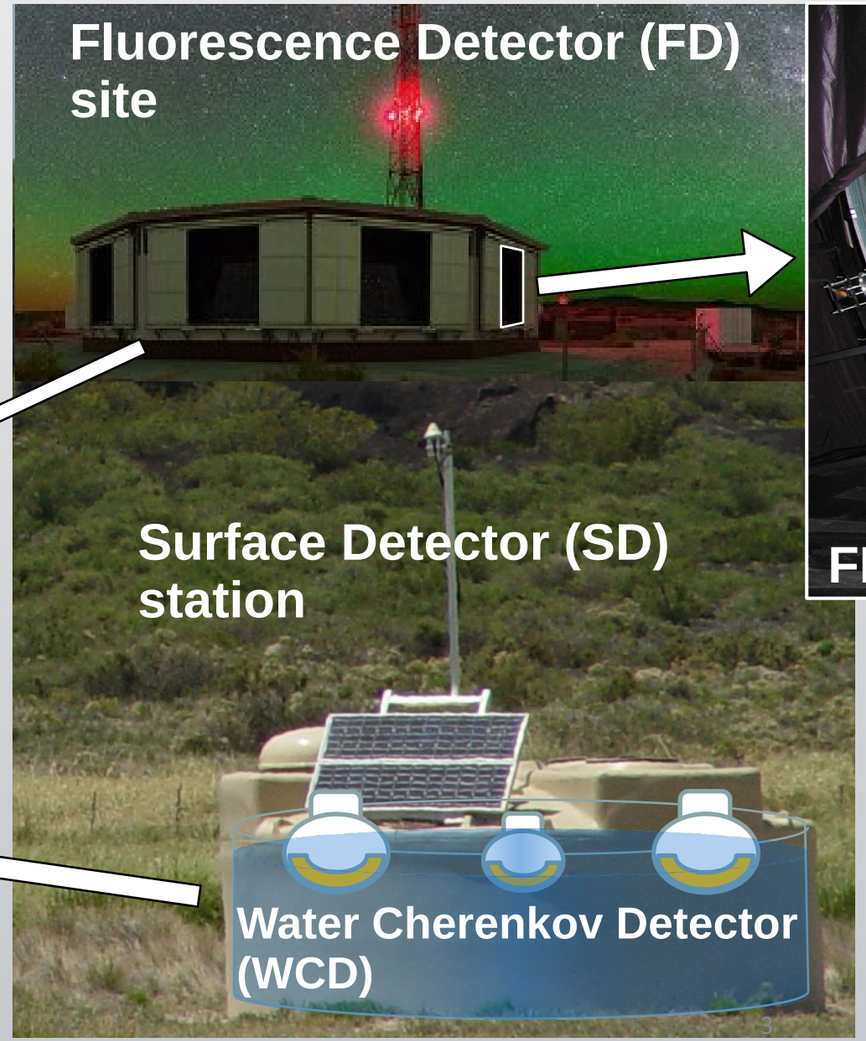
Low-latency alerts & Data analysis for Multi-messenger Astrophysics, Paris/Online

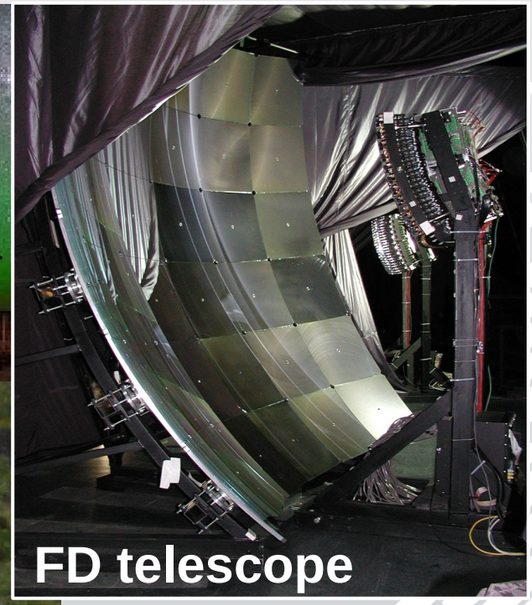
January 13, 2022

BERGISCHE UNIVERSITÄT WUPPERTAL

The Pierre Auger Observatory







1660 SD stations (~100% duty cycle)
27 FD telescopes (~15% duty cycle)

+

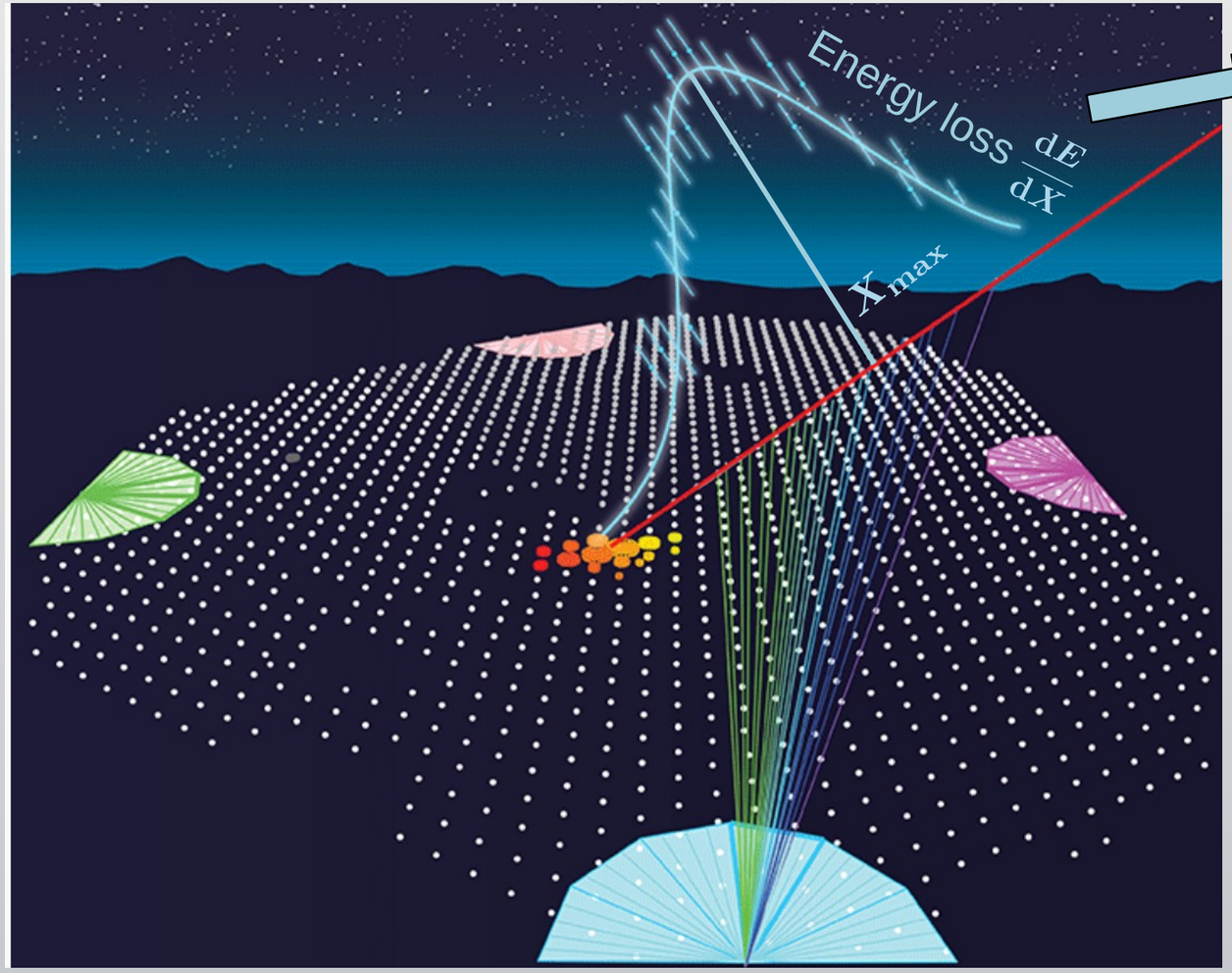
Engineering Radio Array (AERA)

Underground Muon Detectors

Atmospheric Monitoring

...

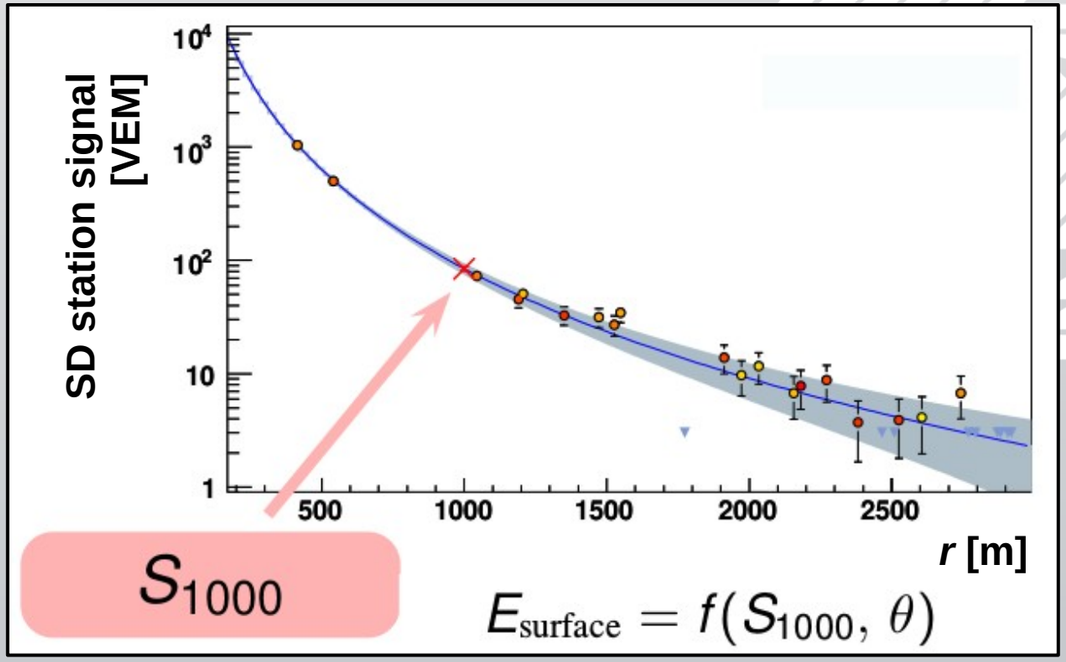
Cosmic ray detection



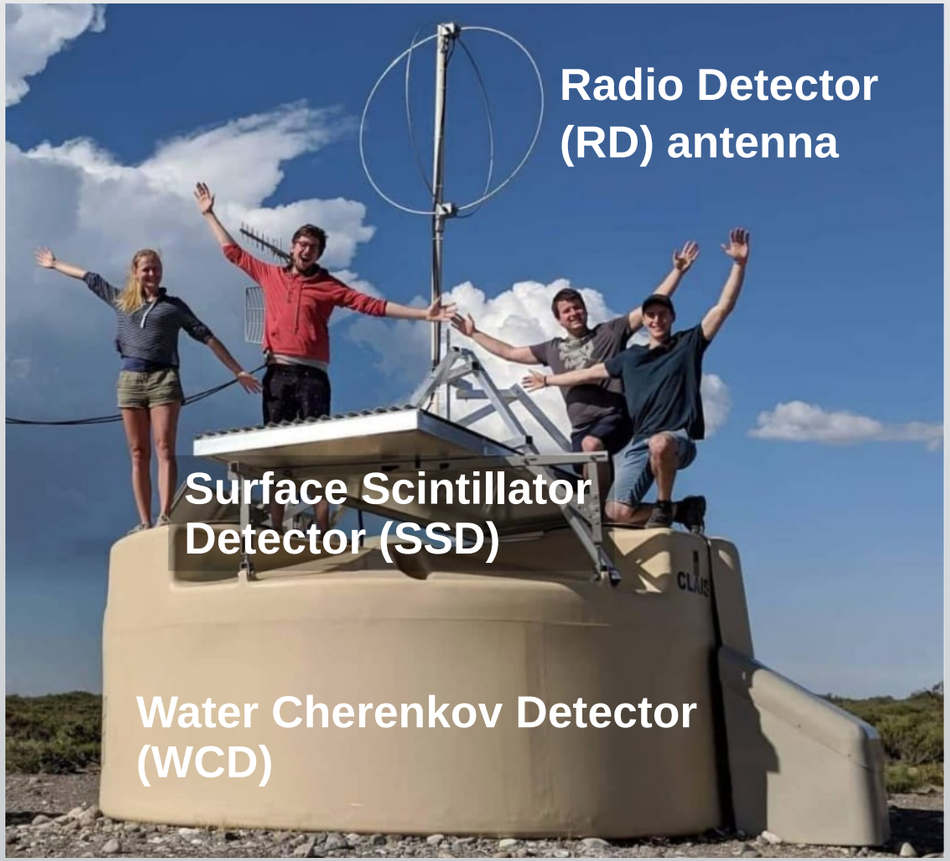
Calorimetric energy measurement with **FD**

$$E \propto \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$$

SD energy calibration via S_{1000}



Auger Prime



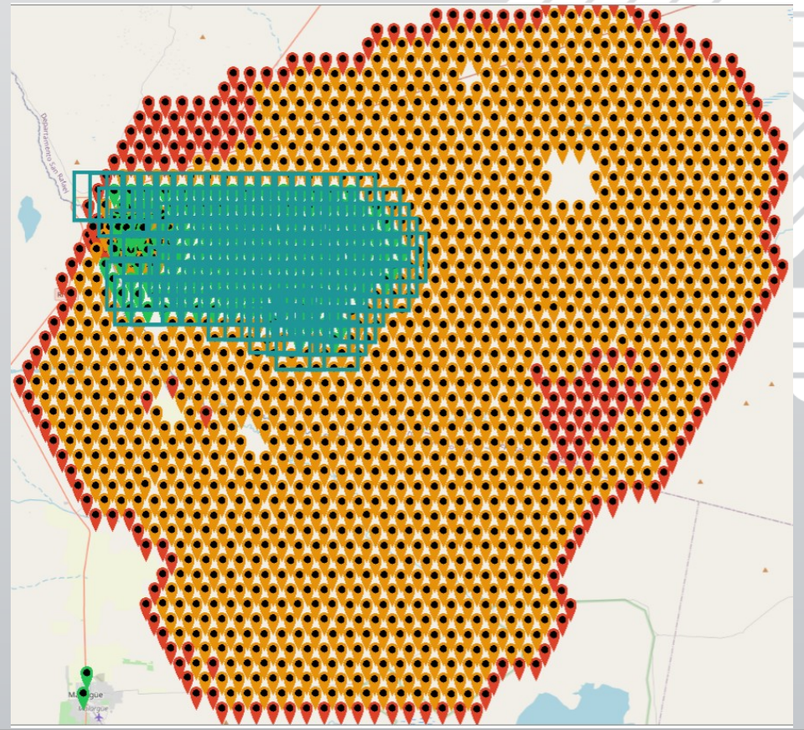
World's largest cosmic ray **radio** detector array

Electronics upgrade:
40 → 120 MHz sampling, more precise GPS, higher dynamic range, ...

Add **small PMT in WCD** to increase dynamic range

5 yrs runtime: Distinguish 0% ↔ 10% protons at highest energies with 5 σ

SSD installed w/ PMT	(163 stations)
SSD installed w/o PMT	(1268 stations)
no SSD installed	(236 stations)
Electronics upgraded	(134 stations)

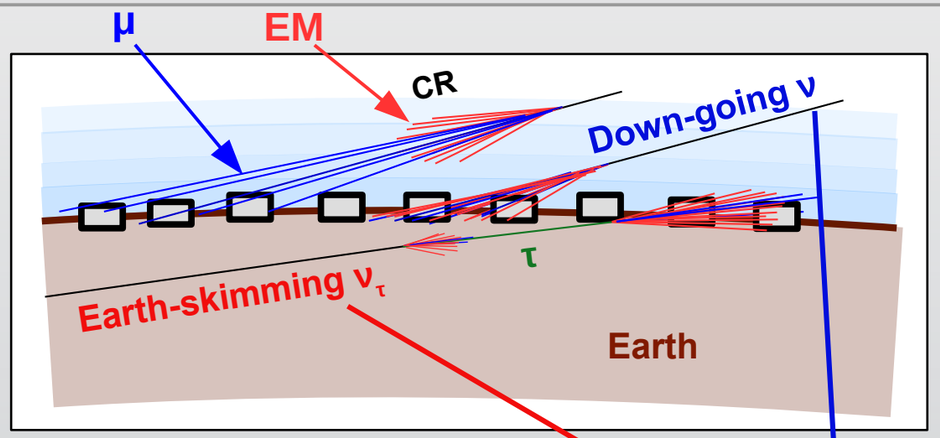


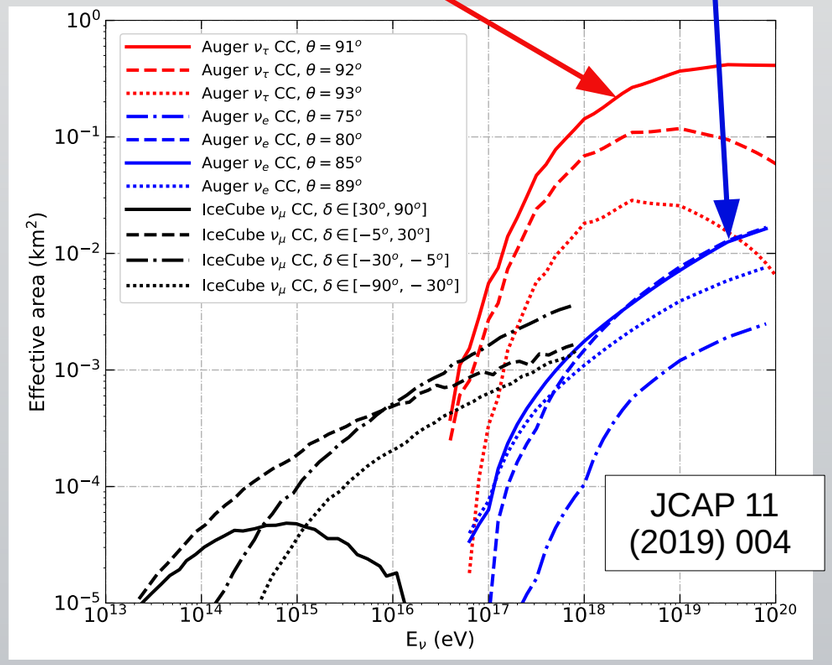
Electromagnetic (EM) ↔ muonic (μ) component
→ **Enhace mass composition measurement**

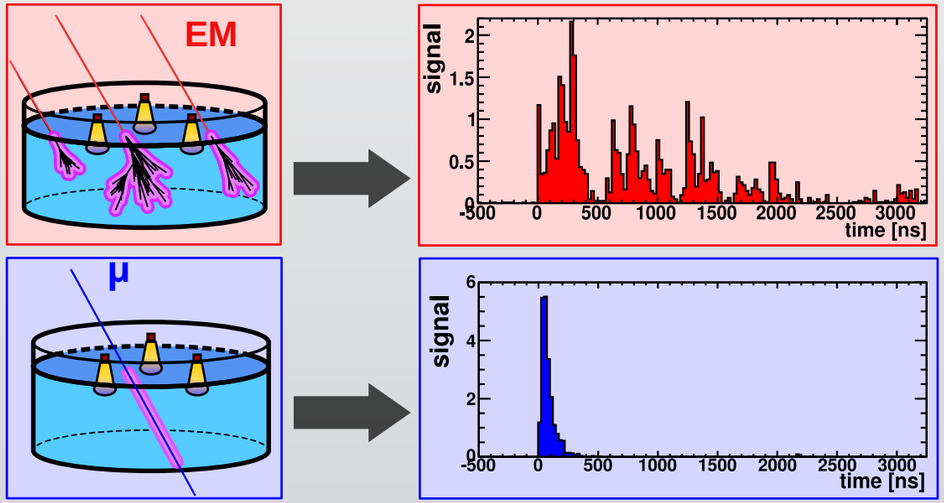
Multi-messenger activities

- GW follow-up searches with neutrinos and photons
- Photon real-time stream to AMON
- Deeper Wider Faster
- ANITA follow-up searches for upgoing air shower events
- UHECR-neutrino correlation searches (Auger, IceCube, TA)
- Neutrons from the Galaxy

Neutrino detection with the Auger SD







Many cascades
→ Broad signal(*t*)

Single particles
→ Narrow signal(*t*)

No neutrino candidates identified so far

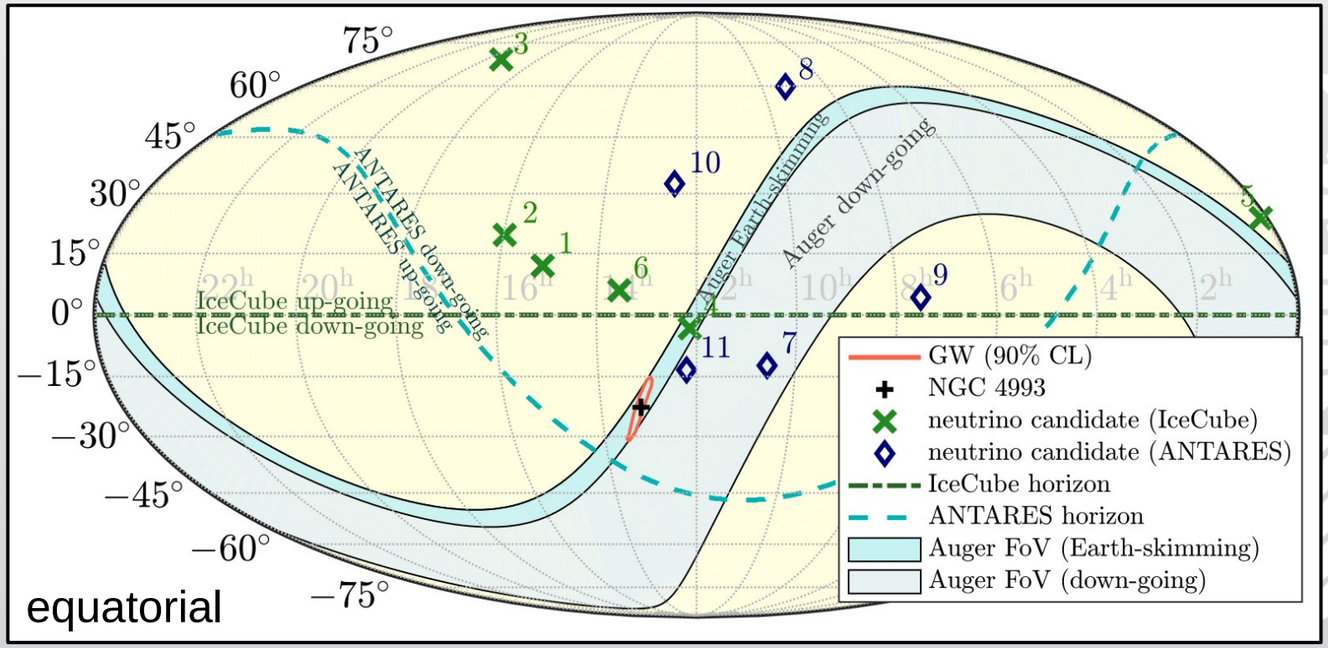
→ Limits on

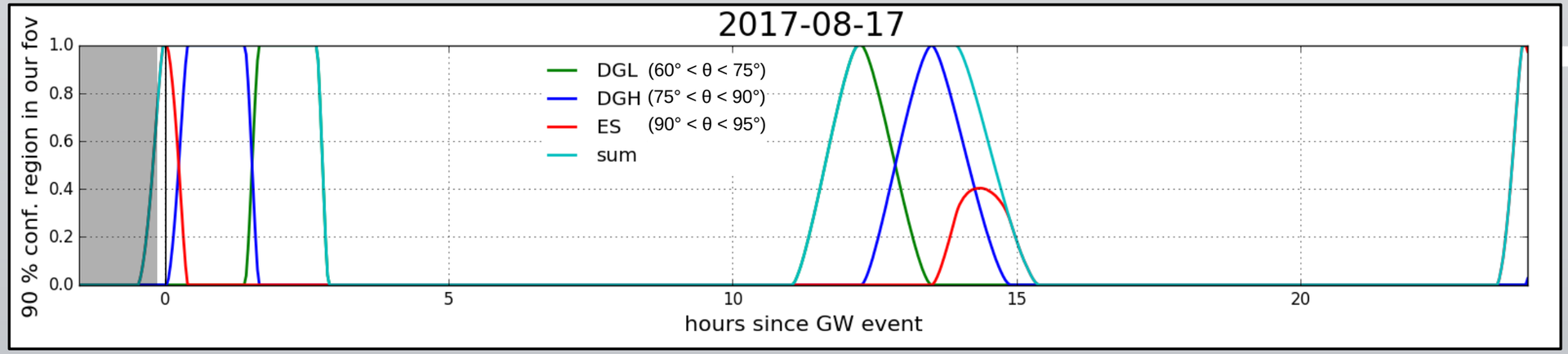
- Diffuse flux
- Point source flux
- Astrophysical and cosmological models
- Flux from followed-up sources

GW170817

ApJL 850, L35

- Excellent visibility of the merger
- Fast LIGO/Virgo + Fermi GCN circular
- Our follow-up routines were not automatized, manual “unblinding”
  - Now: **Immediate** search initiation



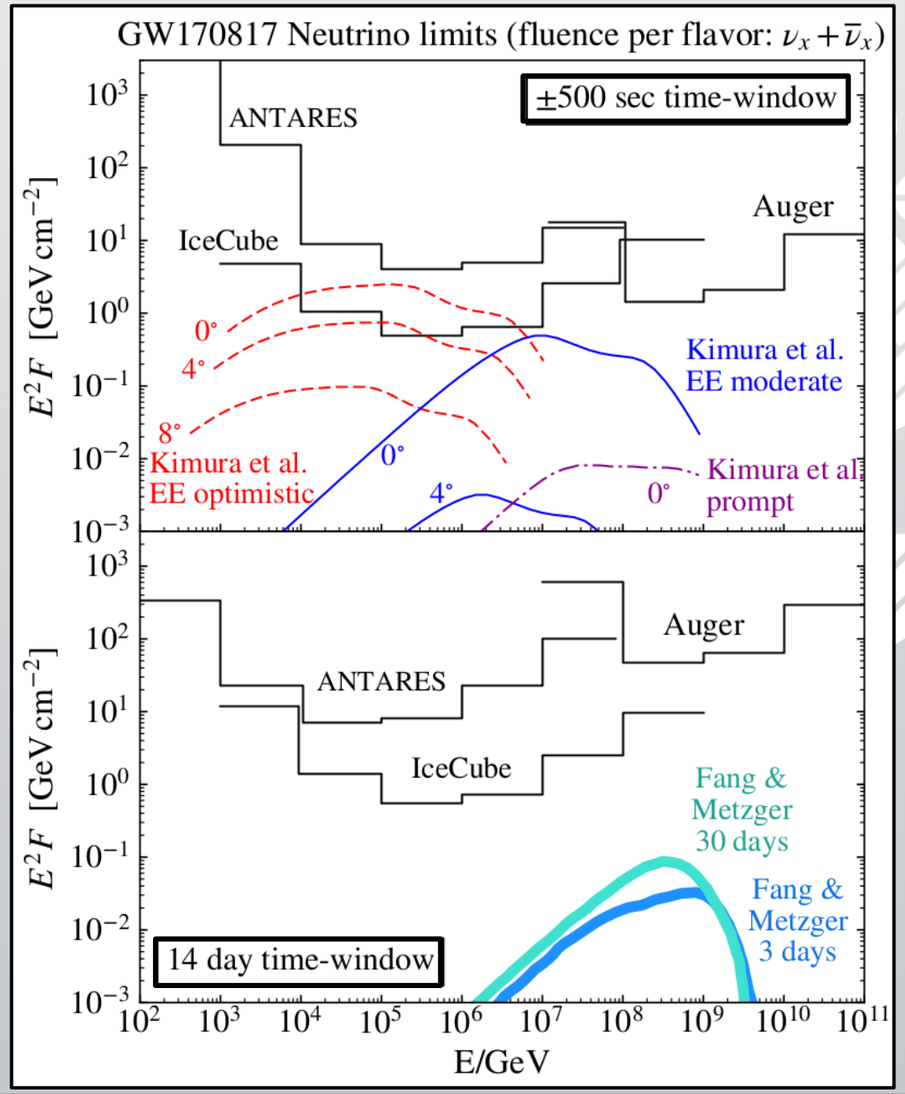


GW170817 neutrino limits

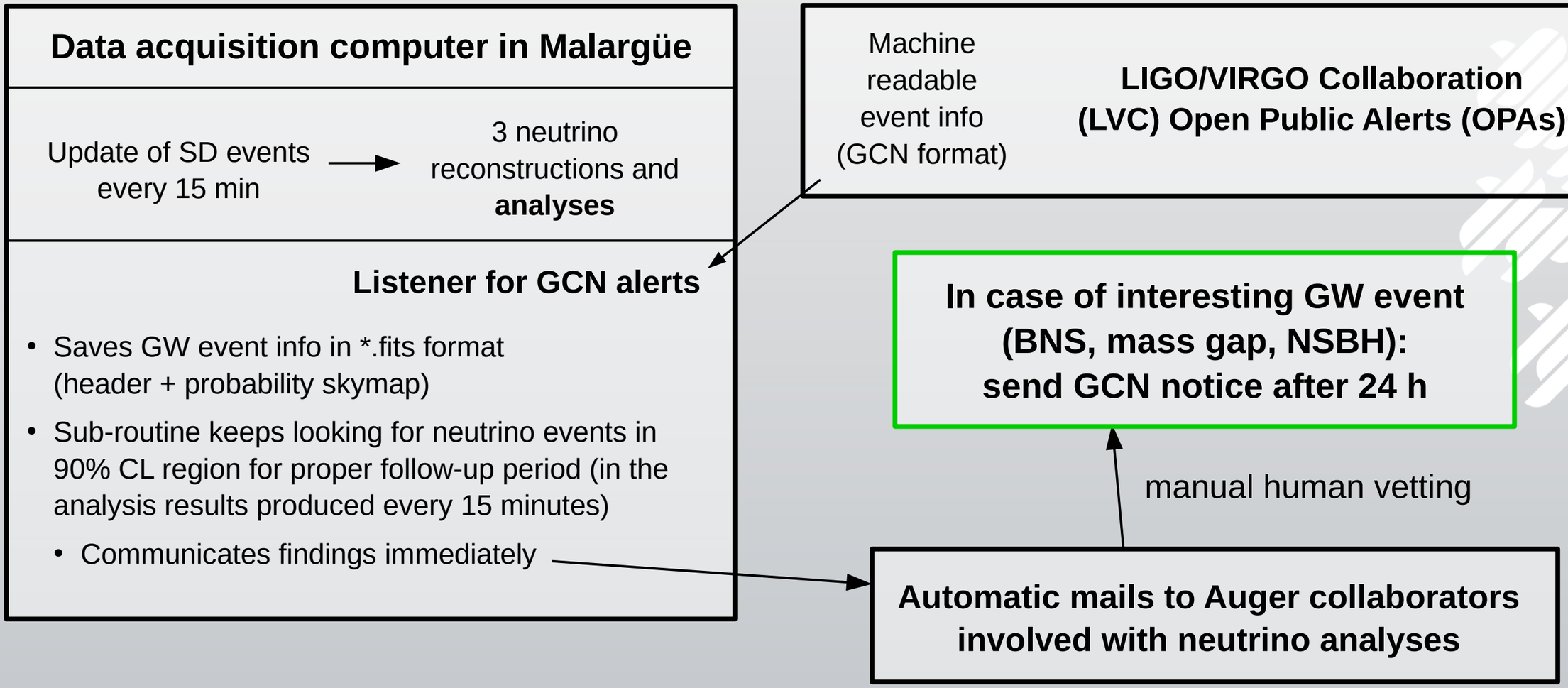
ApJL 850, L35

- **No related neutrinos** detected by ANTARES, IceCube, and Auger

- Auger sensitivity high for ±500 s but reduced for 14 days
  - Good vs. periodic visibility
  - Lesson: Lucky strikes happen, improved preparation (faster follow up) might pay off in the future



Automatic GW follow-up routine



Real-time stream of photon-like events to AMON

→ Hugo Alberto Ayala Solares, tomorrow 2:30 p.m.

- Side remark: Auger is already sending SD shower data with certain directional, energy, and quality cuts to AMON
- Work in progress
- Goal: Stream photon-like candidate events from Auger data to AMON via fast estimator(s)
  - MVA for fast and reliable photon discrimination utilizing:
    - Signal risetimes
    - Shower front curvature
    - Station multiplicity
    - Zenith angle

Deeper Wider Faster

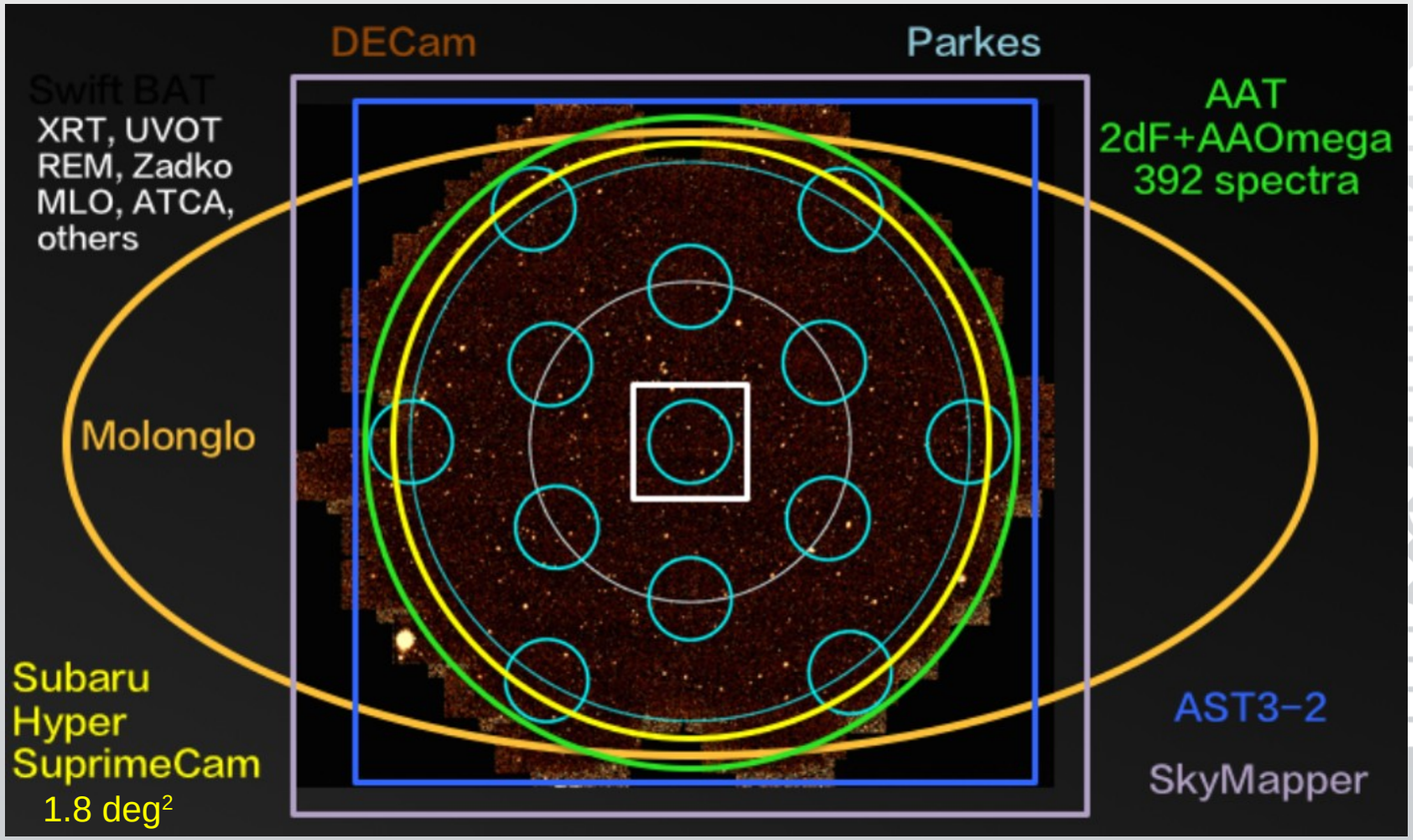
→ Jeff Cooke, tomorrow 3 p.m.

Multi-instrument (> 30) project

- Radio through **ultra-high energies incl. non-photons (Auger)**

~ 10 groups observe **simultaneously**

- Deep+wide-field fast (sampling and analysis) multi-wavelength + multi-messenger probing of **same field**



Auger:

- Full-SD events in DWF field of view shared, no significant coincidences found so far
- Future plan: include smaller sub-arrays of Auger for lower energy events

Pierre Auger Observatory Open Data

October 2021 release

The Pierre Auger 2021 Open Data is the public release of 10% of the Pierre Auger Observatory cosmic-ray data presented at the 36th International Cosmic Ray Conference held in 2019 in Madison, USA, following the Auger Collaboration Open Data Policy. The release also includes 100% of weather and space-weather data collected until 31 December 2020.
This website hosts the datasets for download. A brief overview of the Pierre Auger Observatory and of the Auger Open Data is set out below. An online event display to explore the released cosmic-ray events, and example analysis codes are provided. An outreach section dedicated to the general public is also available.

Check it out on opendata.auger.org

10% of data released to browse, visualize, and analyze w/ python code examples

Datasets

the released datasets and their complementary data

Visualize

an online look at the released pseudo raw cosmic-ray data

Analyze

example analysis codes in online python notebooks to run on the datasets

Outreach

a page dedicated to the general public

The End

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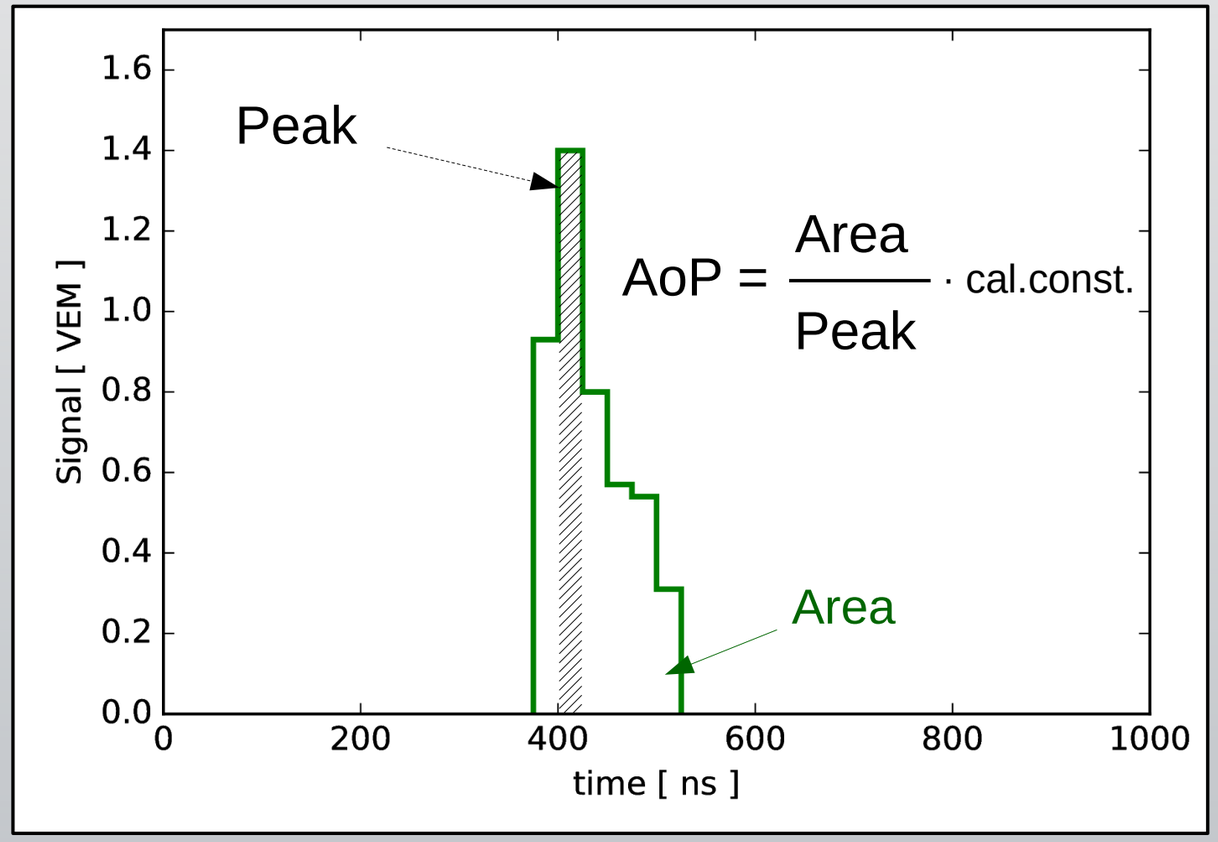
Follow-up of GW events O3

- LIGO/Virgo switched to **open public alerts (OPAs)**, communicated via GCN
- Previously: MoU to share data with LIGO/Virgo, now we **automatically** follow-up the OPAs

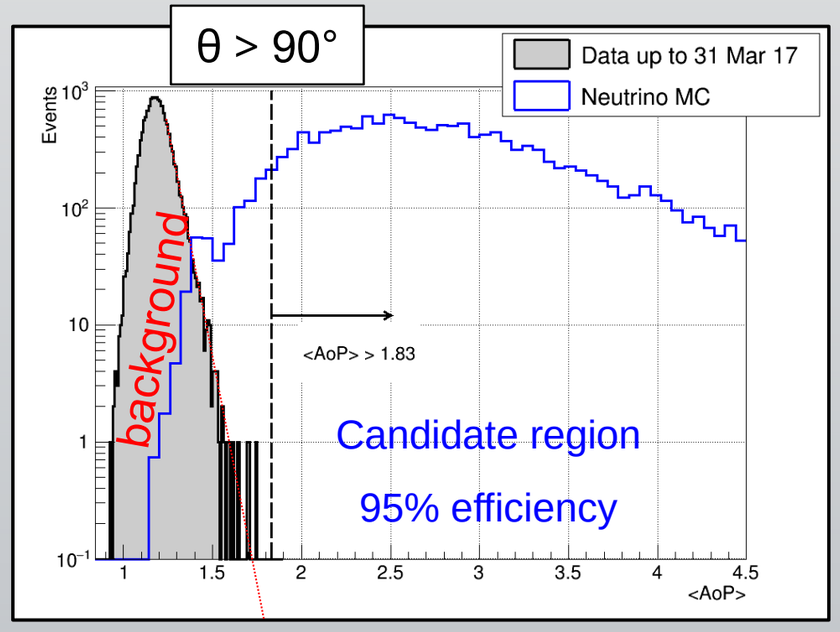
Neutrino search and identification

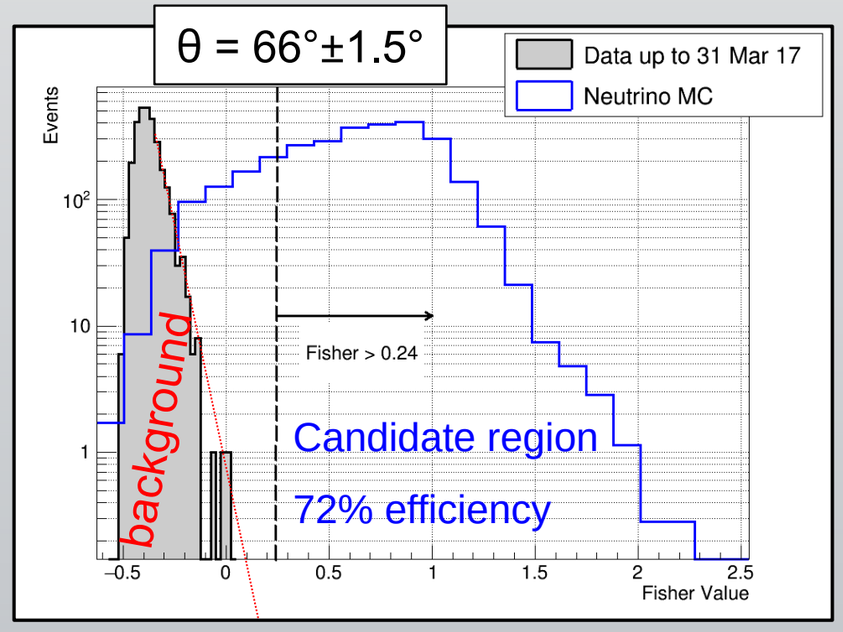
- Pre-select **inclined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
- Crucial variable: **Area over Peak (AoP)**



Neutrino search and identification

- Pre-select **inclined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
  - Earth-skimming: **<AoP>** of all stations in event
  - Down-going: Optimized linear discriminant
    - **Combination of AoPs** of certain stations (esp. early and late ones)
      - ➔ “Fisher value”

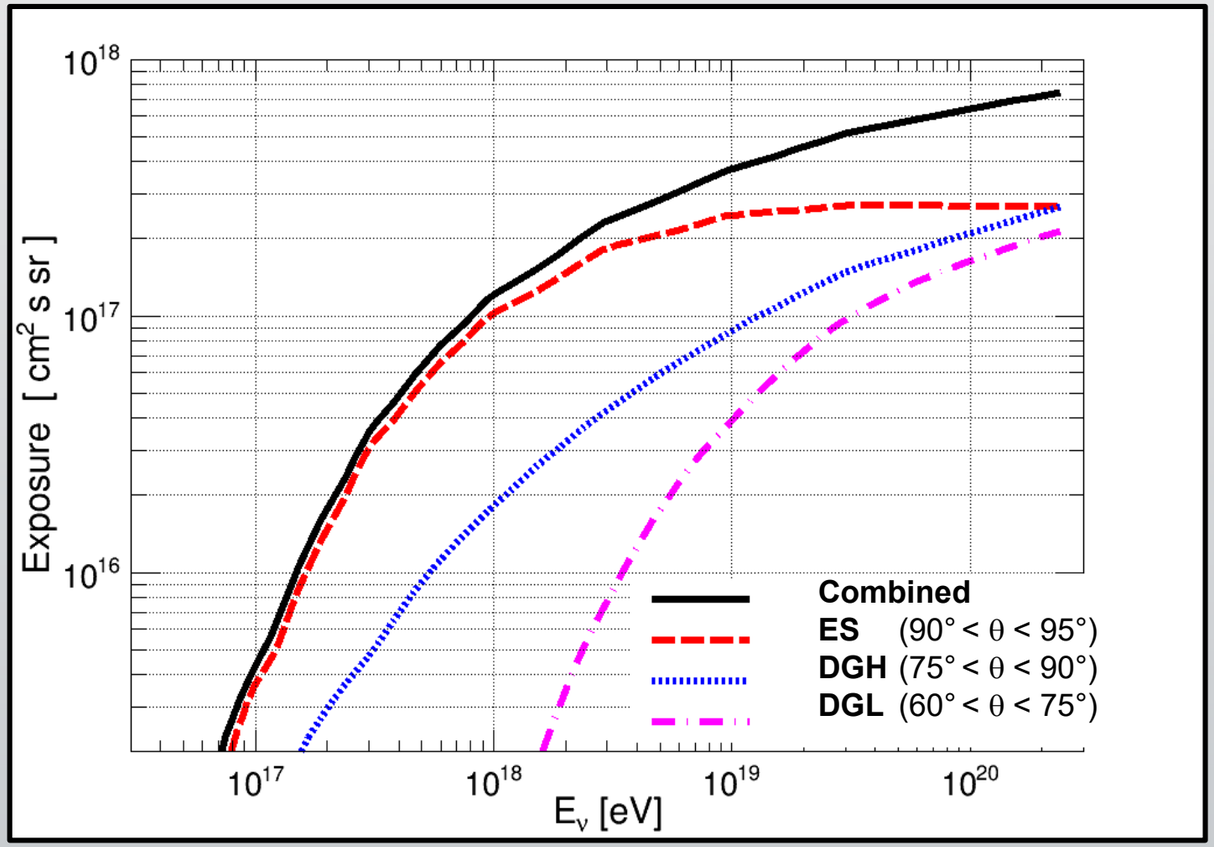




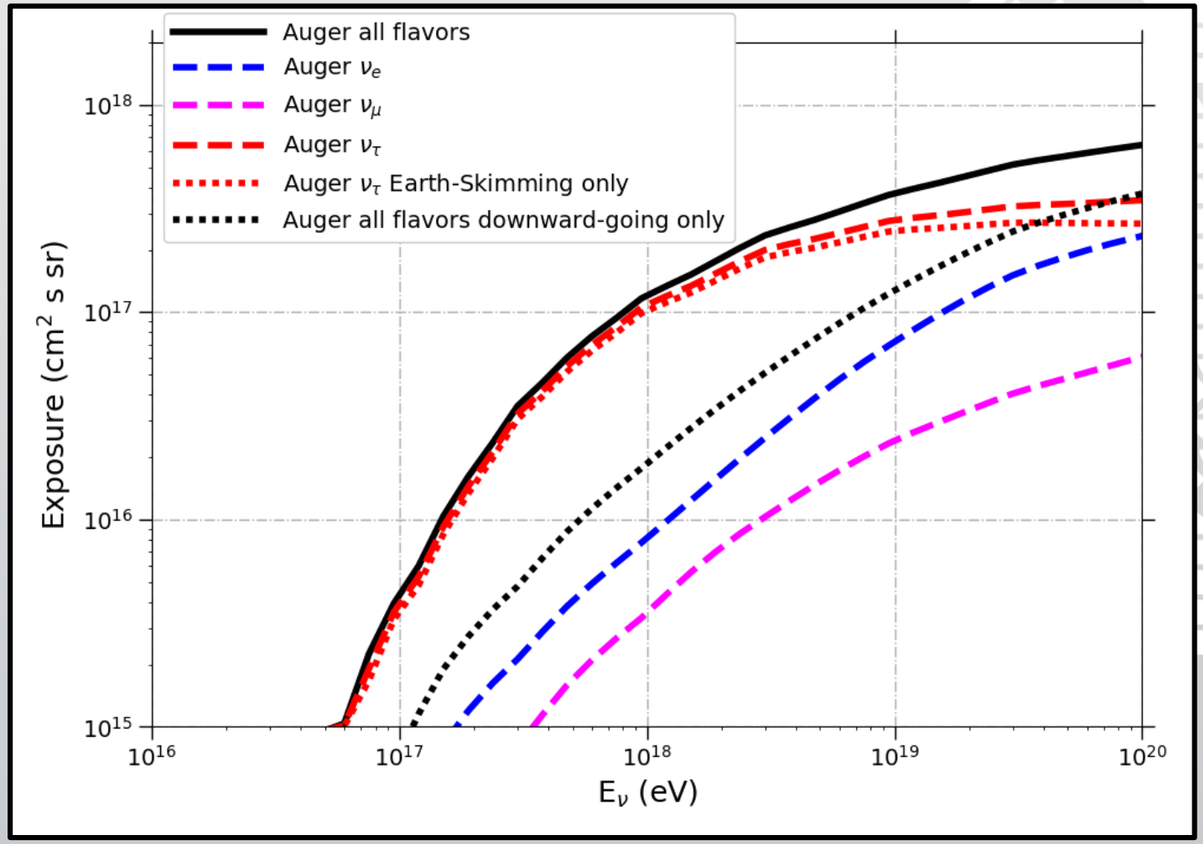
No candidates so far

Neutrino exposure

By direction

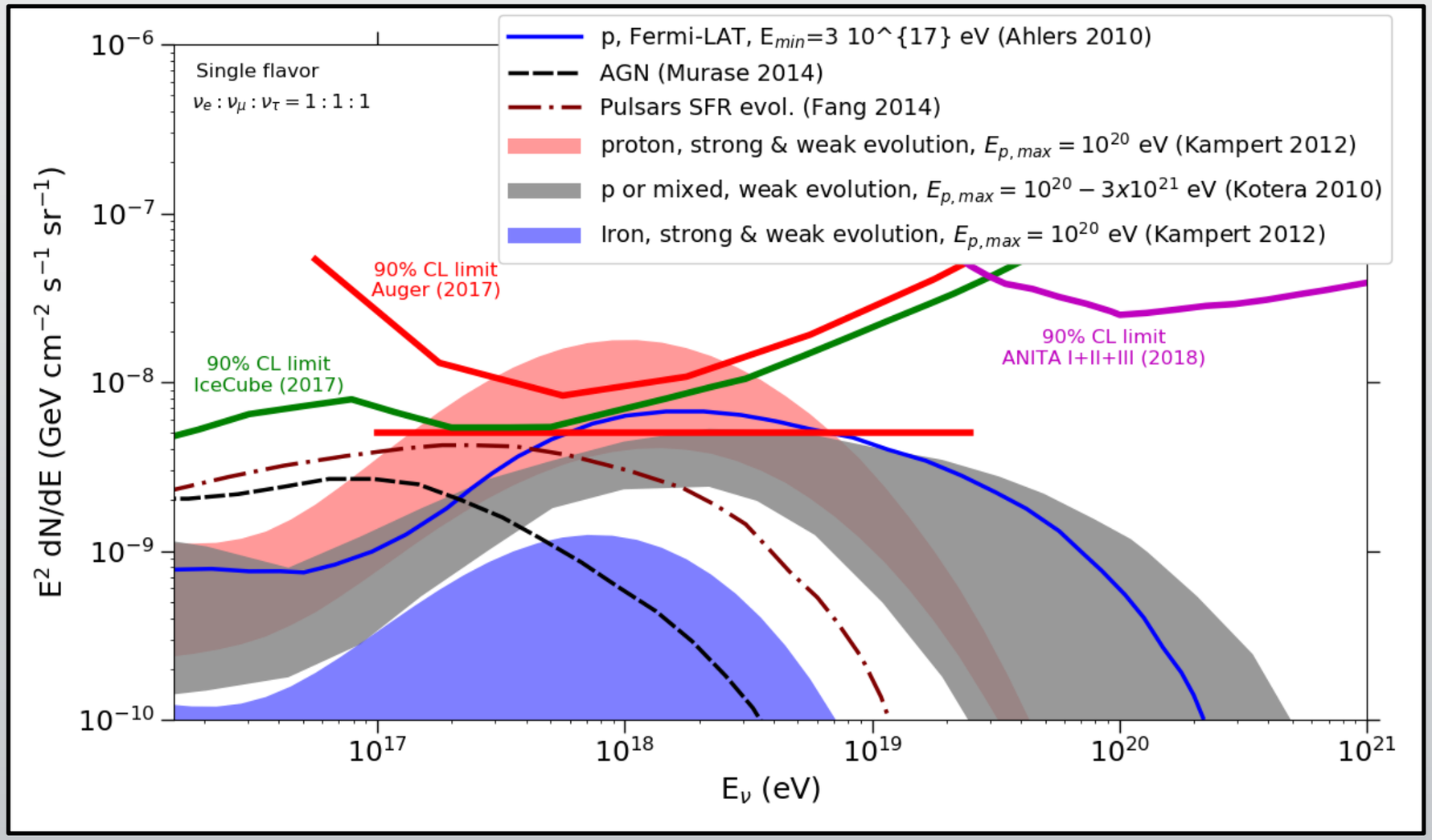


By flavor

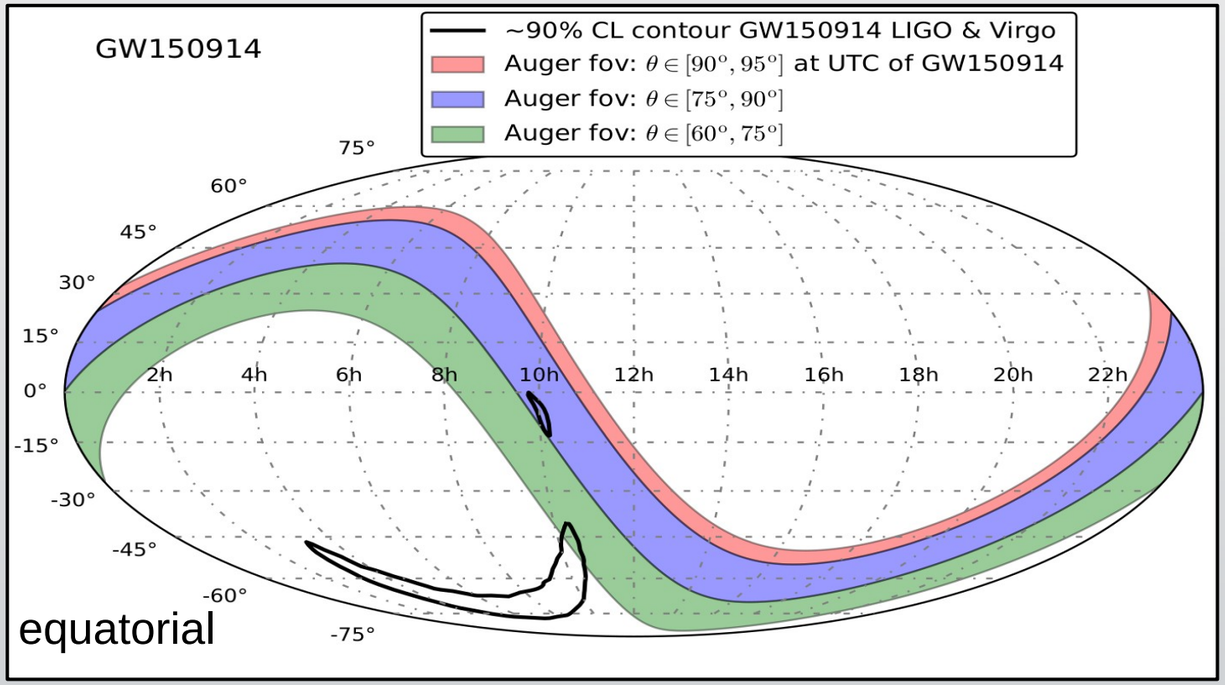


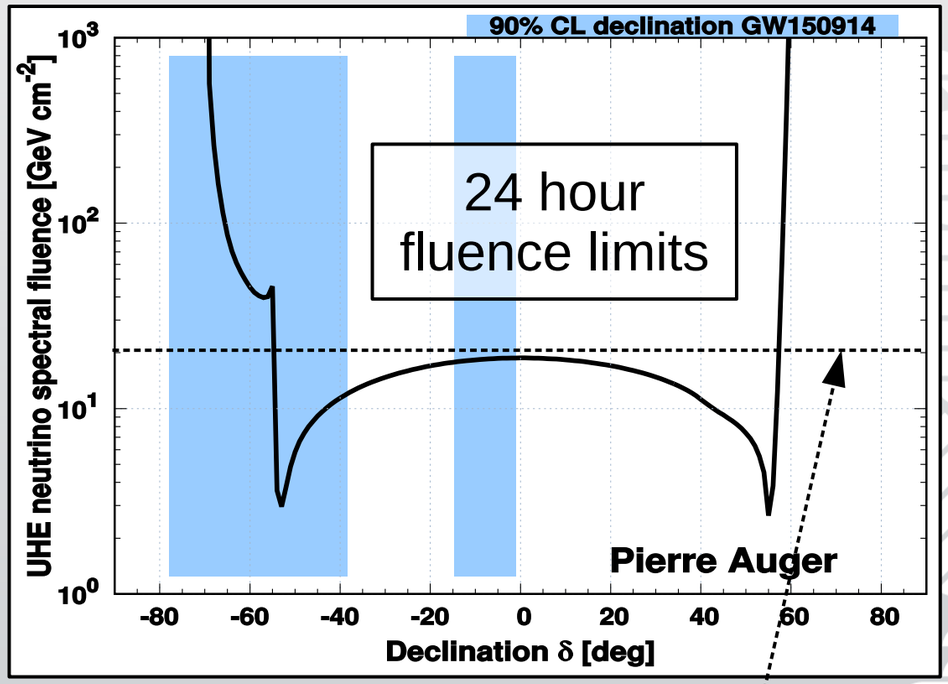
Enrique Zas, ICRC 2017

Limits on diffuse neutrino flux



Follow-Up of BBH merger GW150914





UHE neutrino sensitivity declination dependent

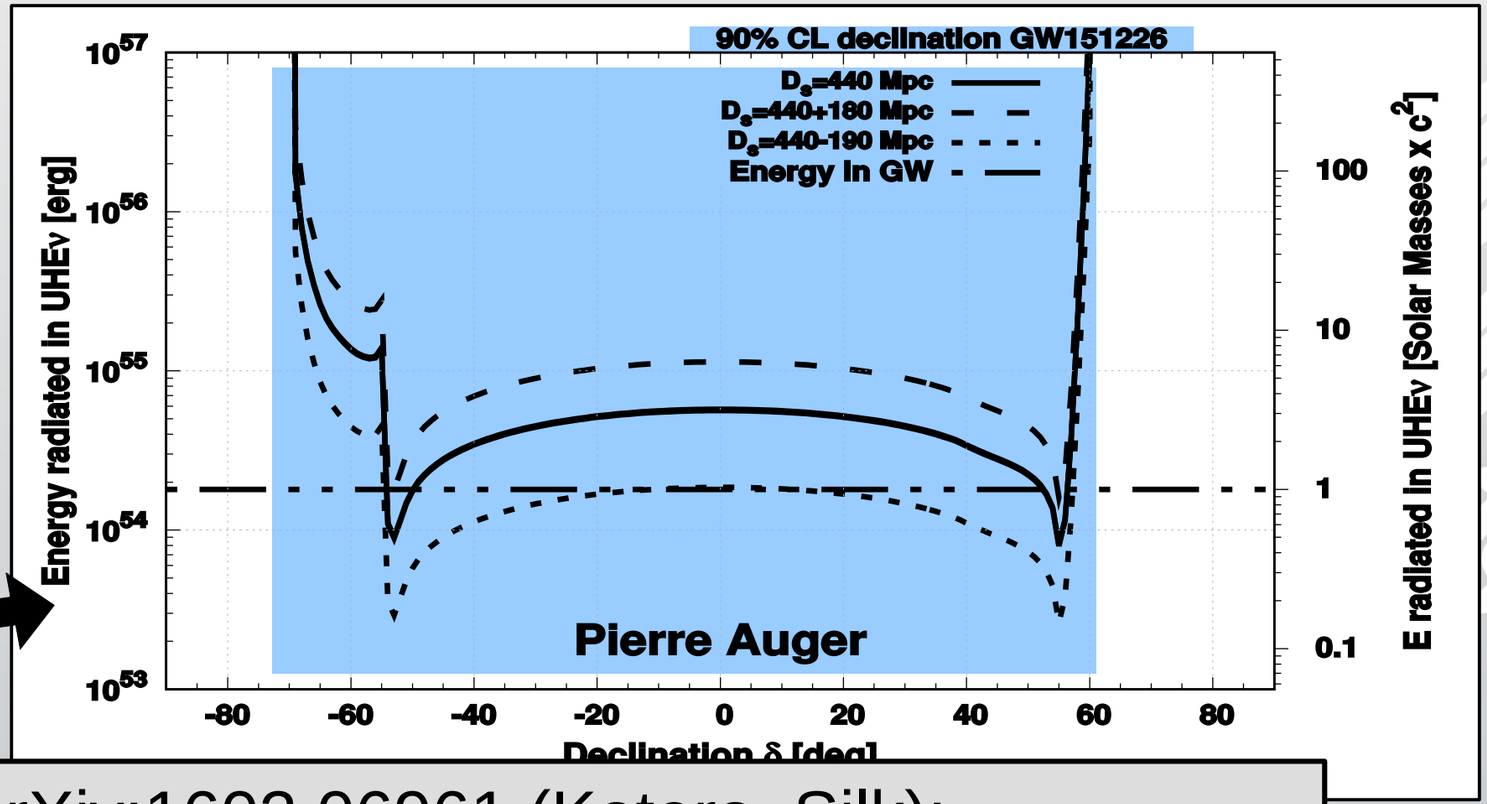
Newer events: More GW detectors

➔ improved localization by triangulation

total neutrino energy = emitted GW energy

GW151226 Follow-Up—Results

No candidates
→ Flux limit
→ Limit on total emitted UHE ν energy

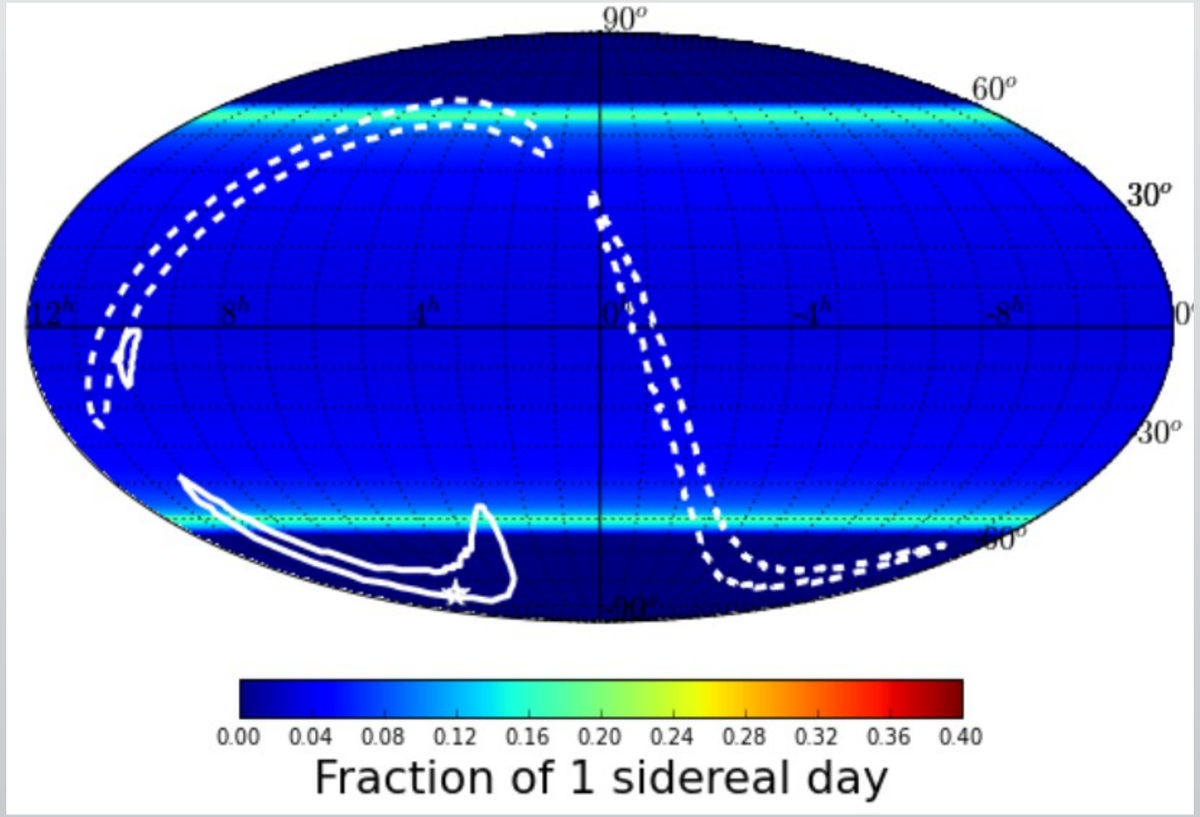


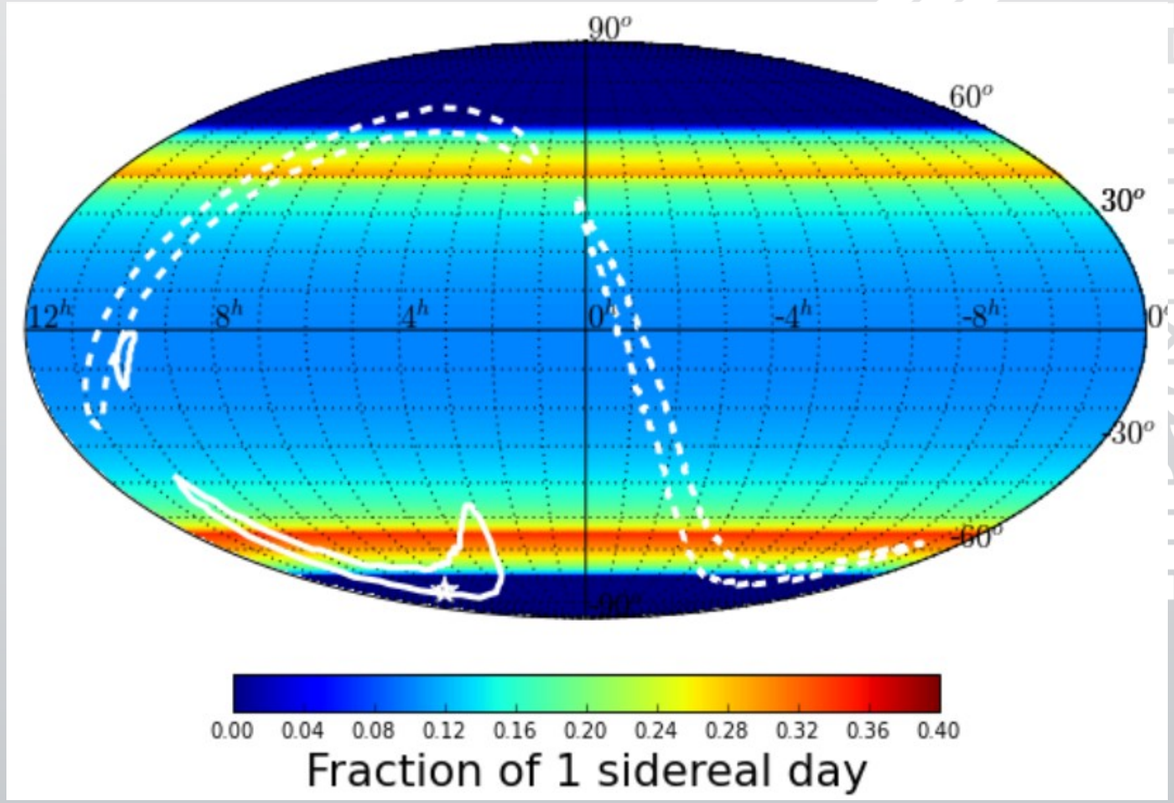
arXiv:1602.06961 (Kotera, Silk):
Binary BHs could produce the measured UHECR flux!
→ Needs ~ 3% “efficiency” (E_{UHECR}/E_{GW})

Systematic uncertainties (PRD 91 092008)

Source of systematic	Combined uncertainty band
Simulations	$\sim +4\%, -3\%$
ν cross section and τ E-loss	$\sim +34\%, -28\%$
Topography	$\sim +15\%, 0\%$
Total	$\sim +37\%, -28\%$

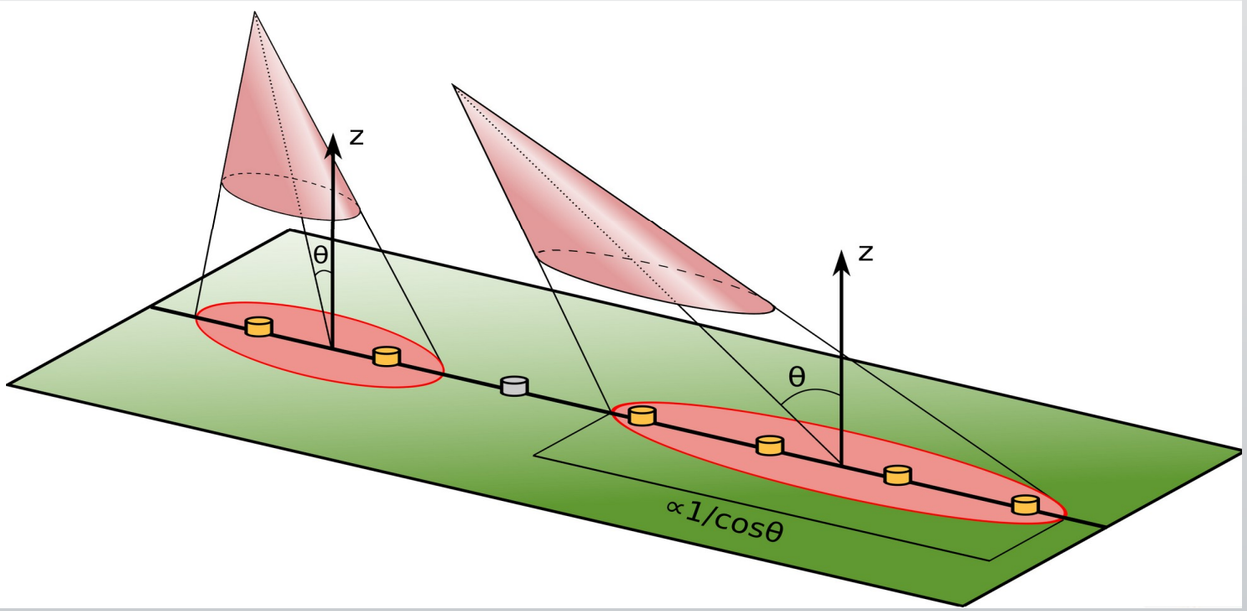
O1 GW Follow-Up



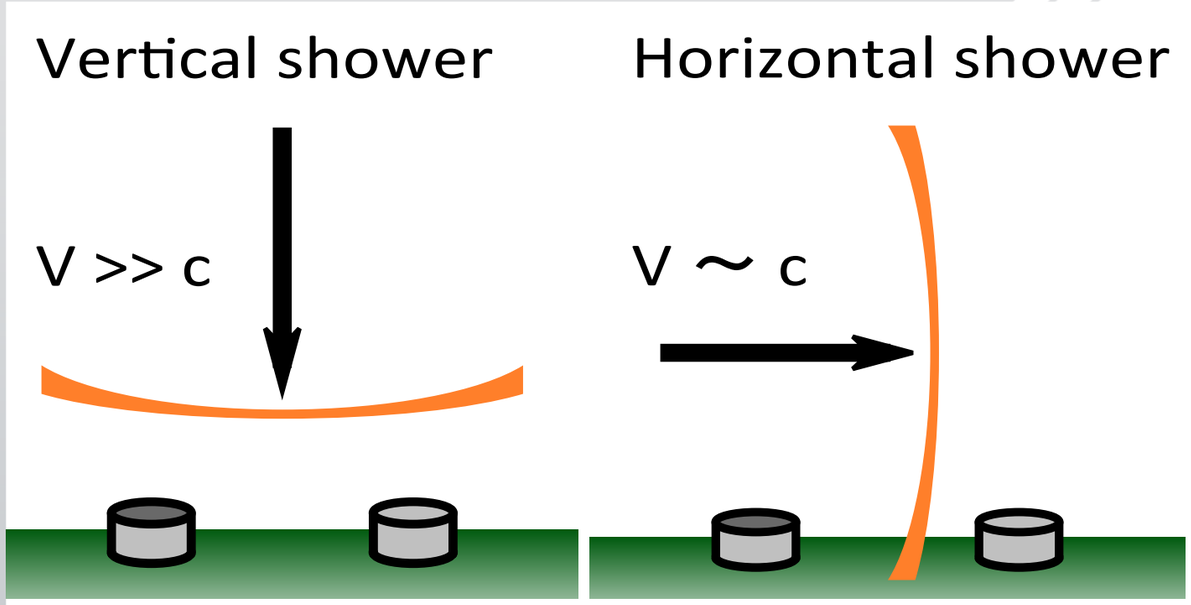


Earth-Skimming ν_τ Selection

Inclination: 90° < θ < 95°
→ elongated footprint



"Ground signal speed" ~ c



Reject "muonic" events → > 60 % stations ToT triggered