Multimessenger astrophysics with the Pierre Auger Observatory

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for the Pierre Auger Collaboration

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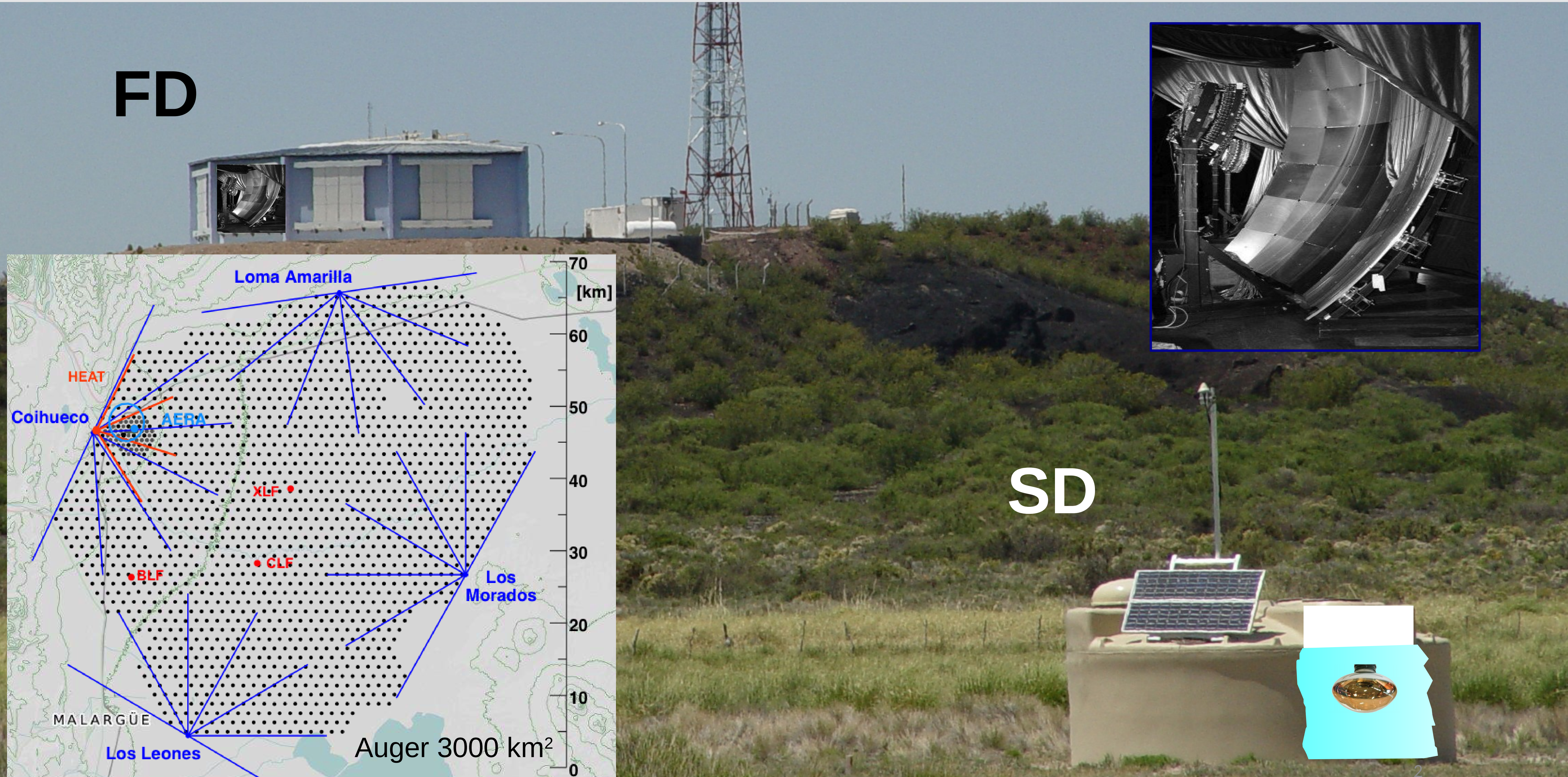
PIERRE AUGER OBSERVATORY

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

BERGISCHE UNIVERSITÄT WUPPERTAL

The Pierre Auger Observatory



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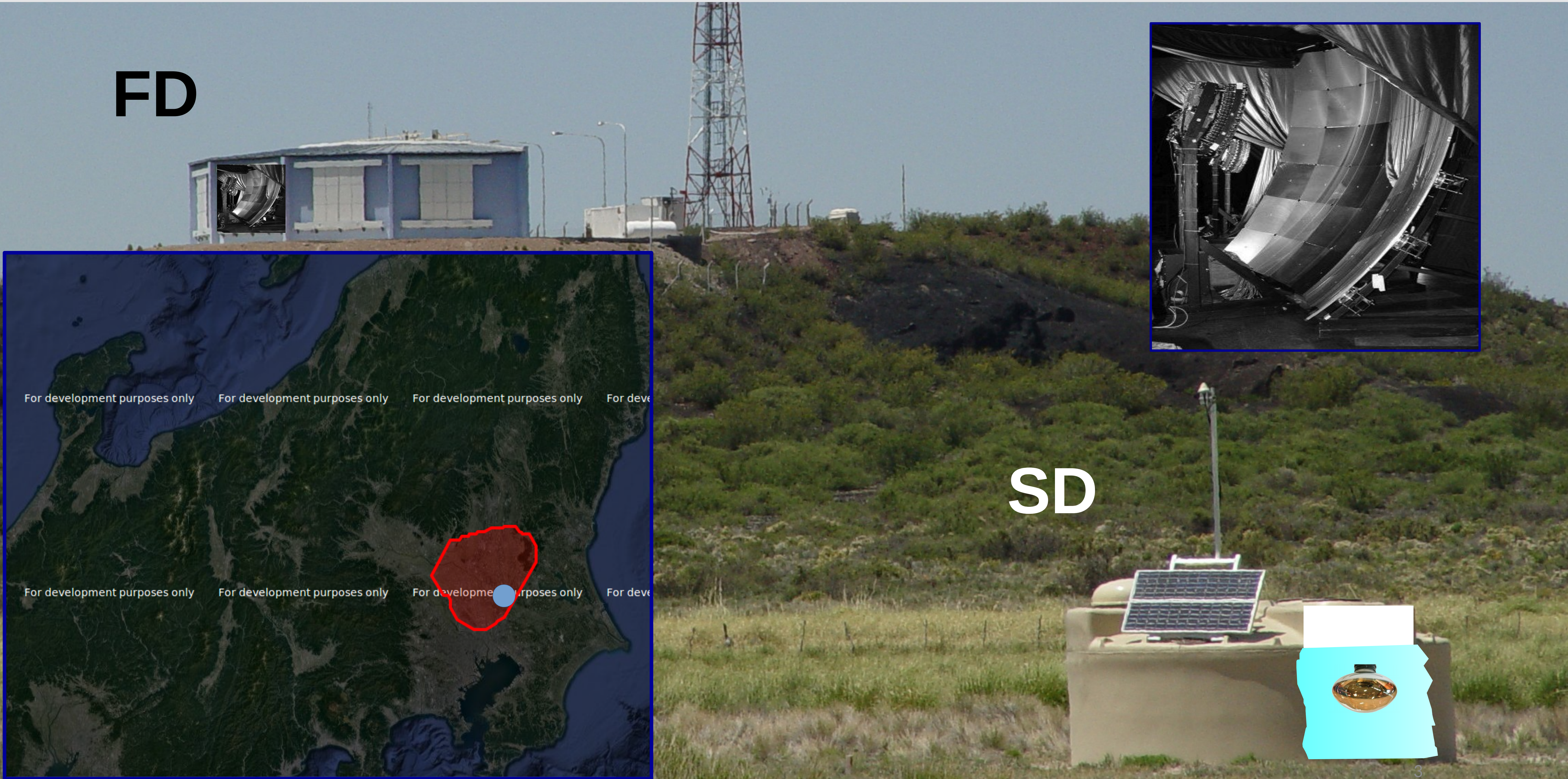
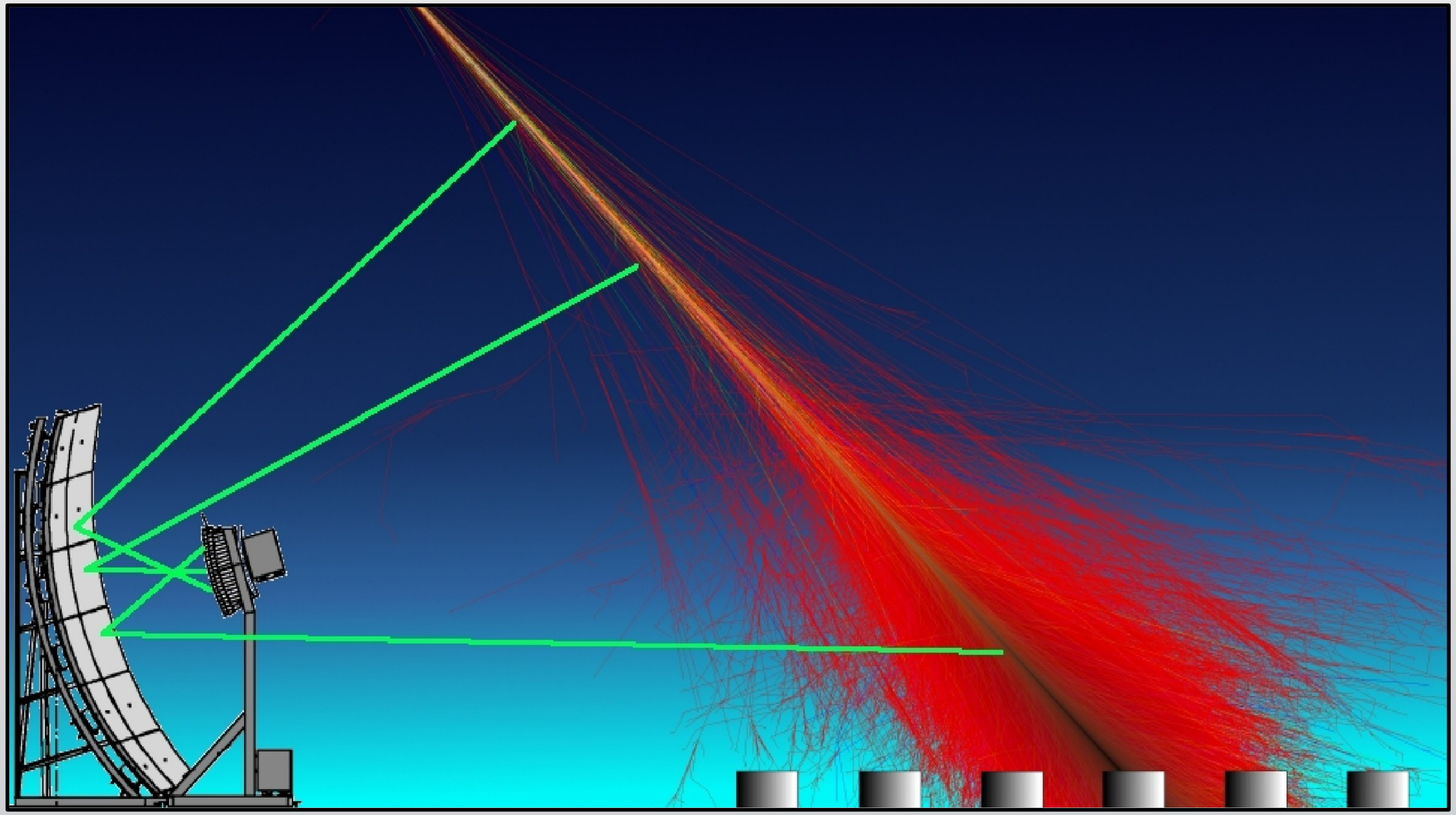
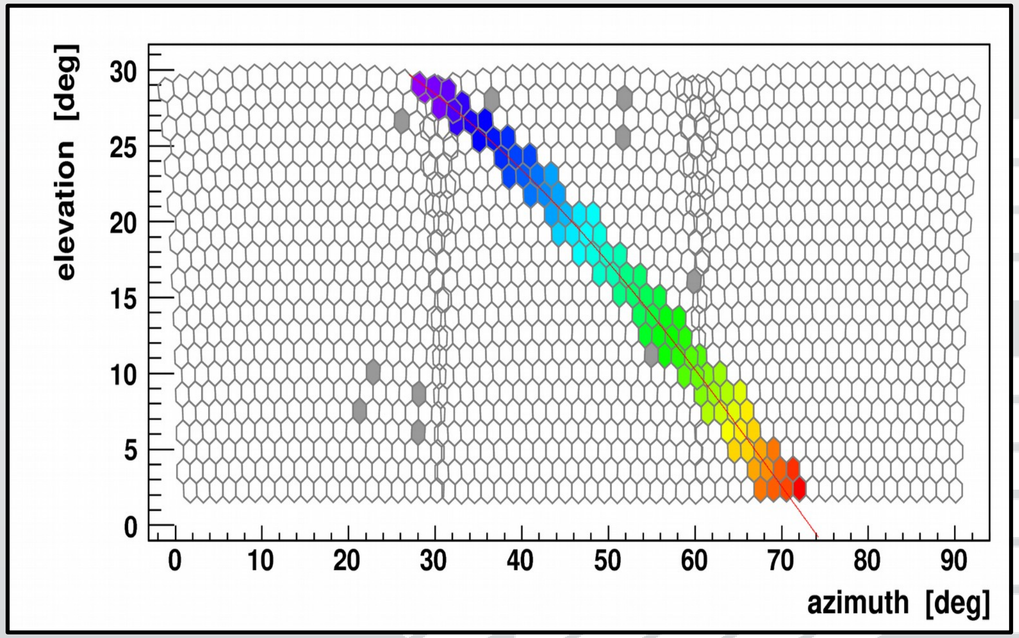
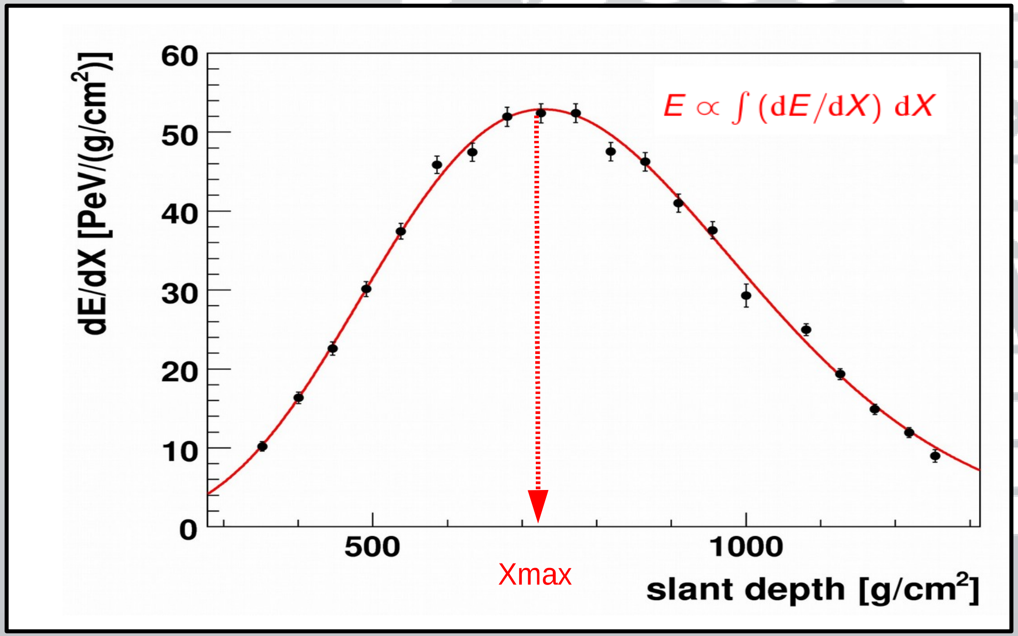


Energy estimation with the Pierre Auger Observatory

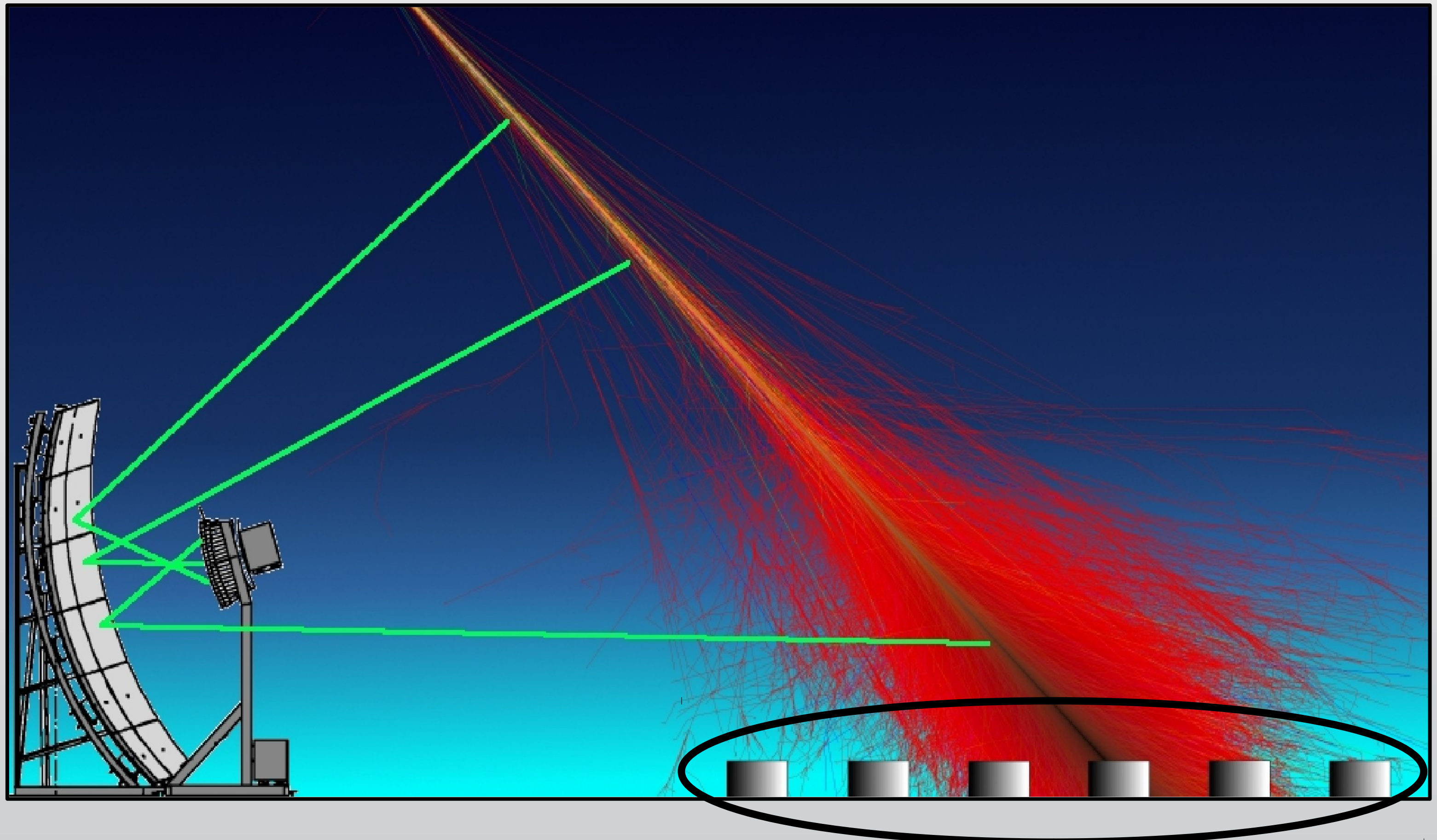




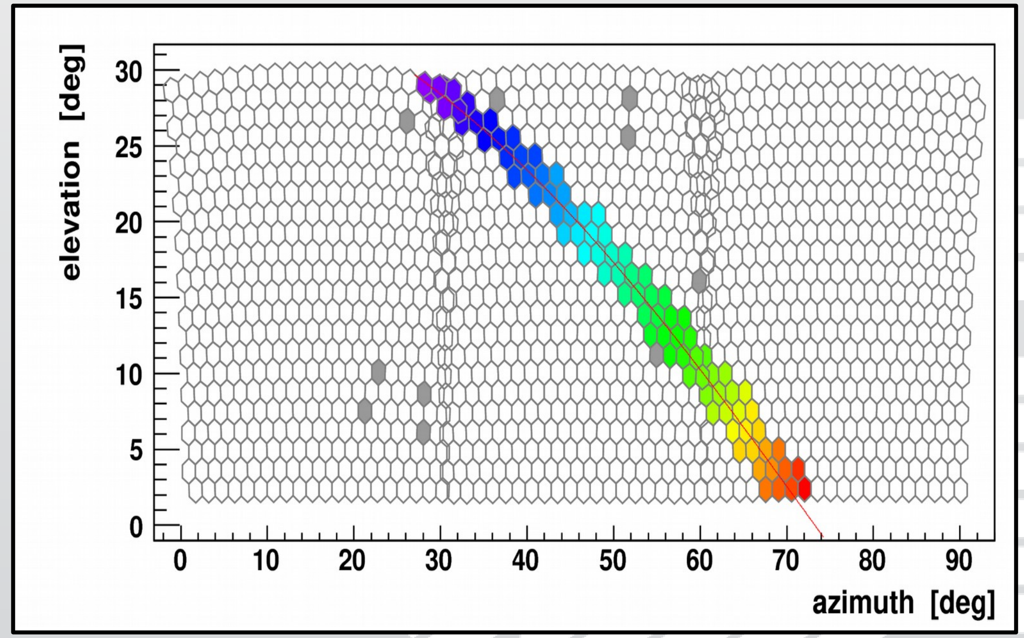


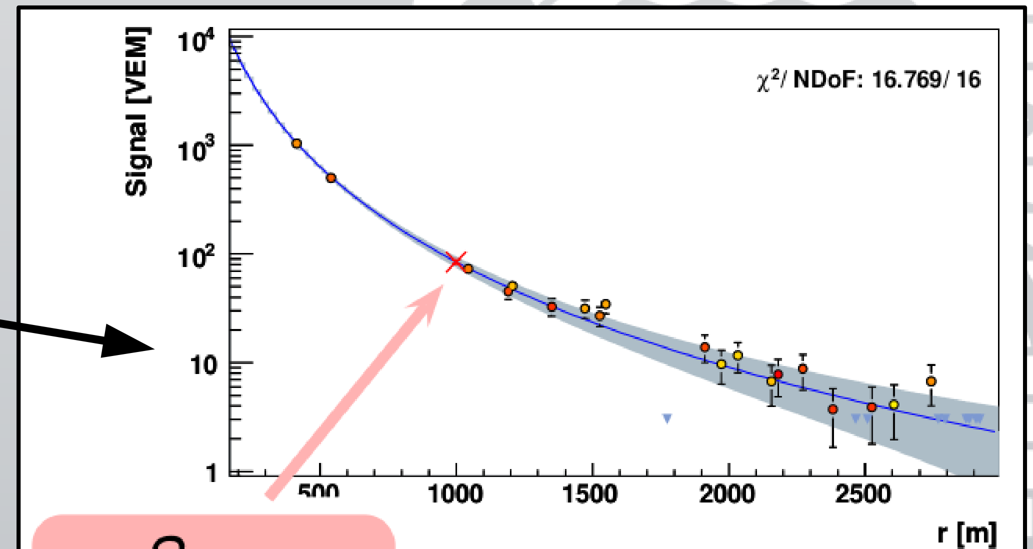
V. de Souza, Vulcano 2018

Energy estimation with the Pierre Auger Observatory



V. de Souza, Vulcano 2018





M. Unger, ICRC2017

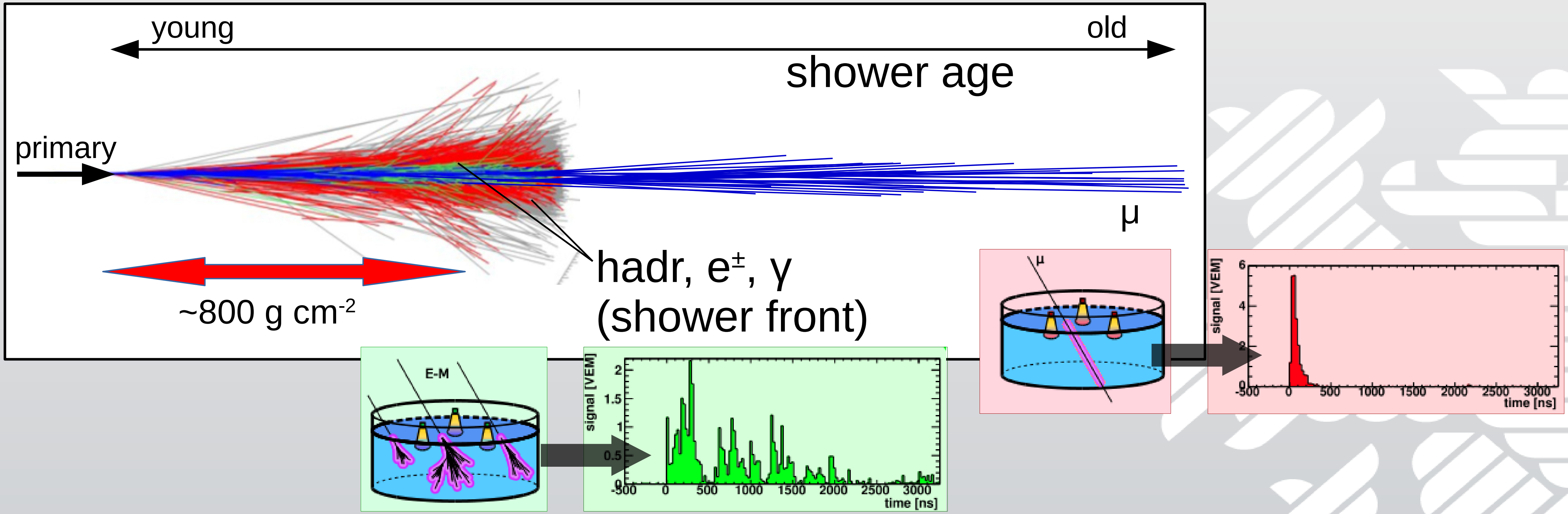
S_{1000}

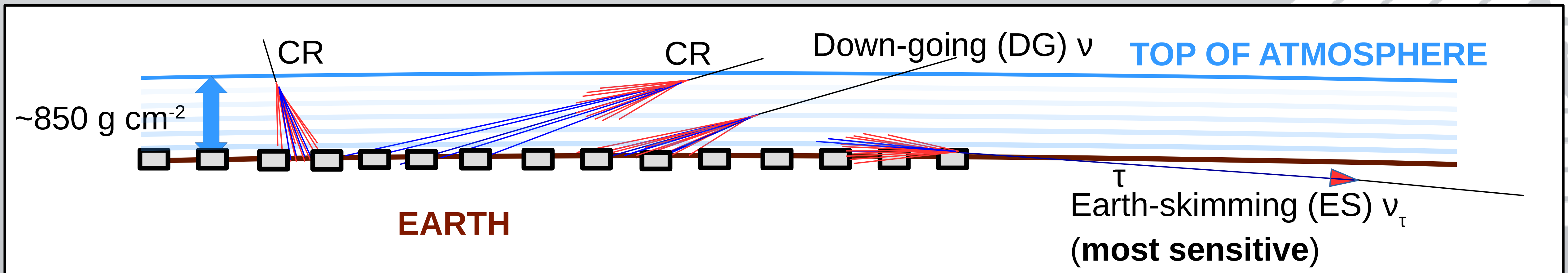
$$E_{\mathrm{surface}} = f(S_{1000},\, \theta)$$

Multimessenger activities

- GW follow-up searches with neutrinos (and photons)
  BBH mergers, BNS merger GW170817
- UHECR-neutrino correlation searches
  (Auger, IceCube, TA)
- Neutrons from the Galaxy
- Deeper Wider Faster

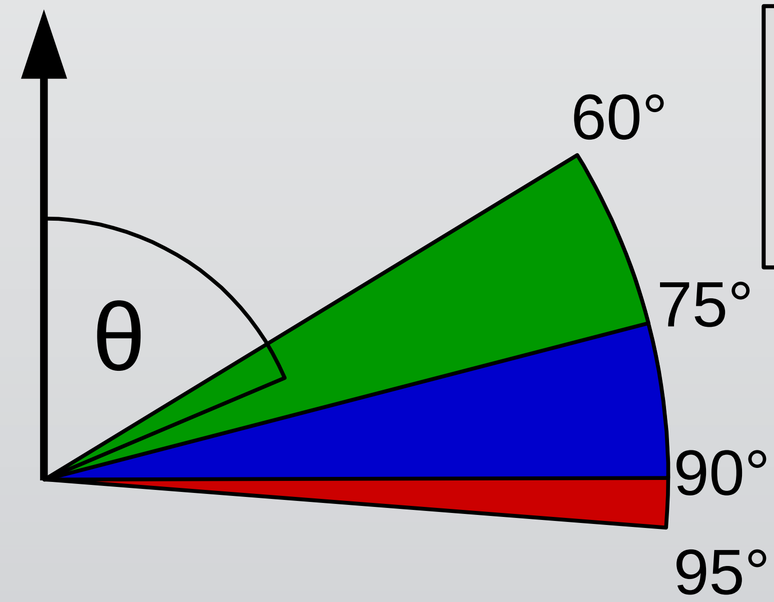
Neutrino detection with the Pierre Auger SD



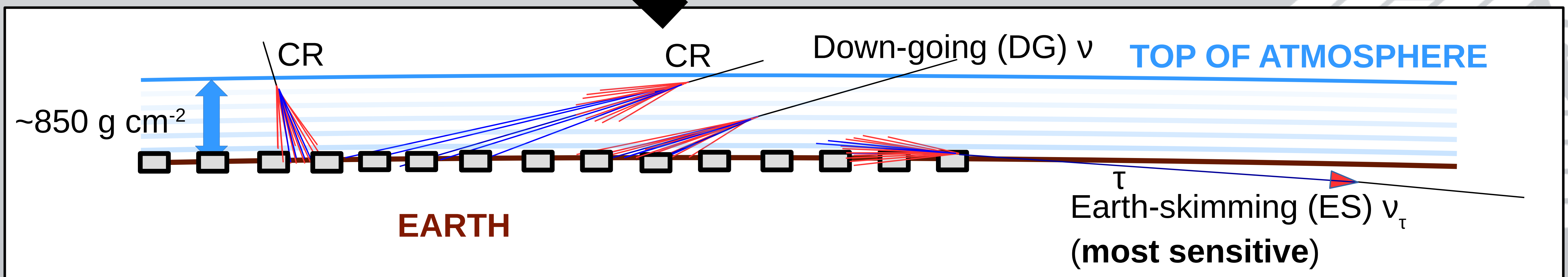


Neutrino detection with the Pierre Auger SD

Reasonable separation:
θ > 60°

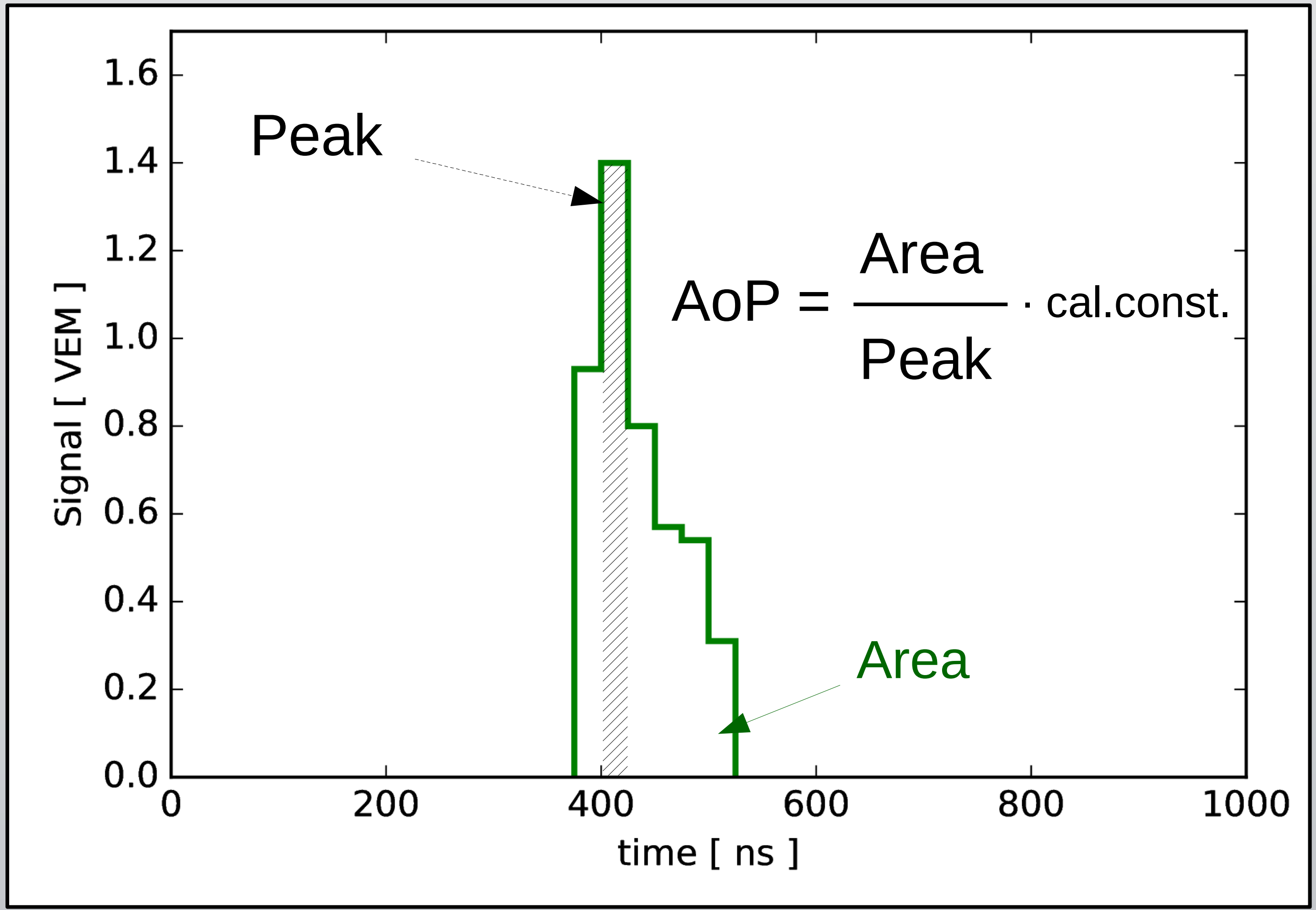


- Down-going low
- Down-going high
- Earth-skimming



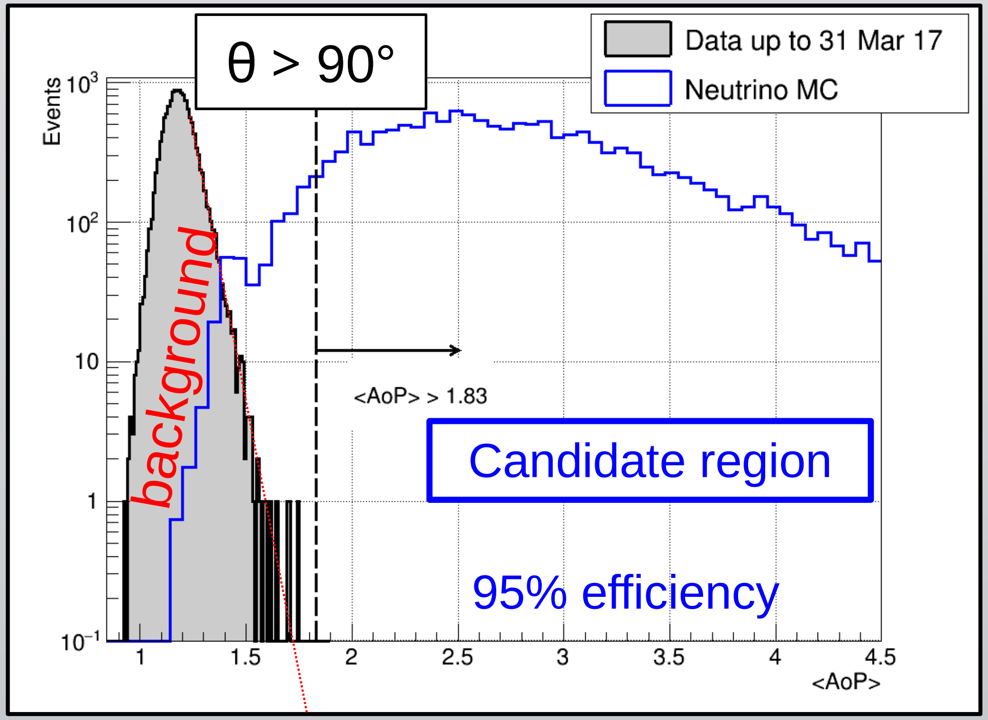
Neutrino search and identification

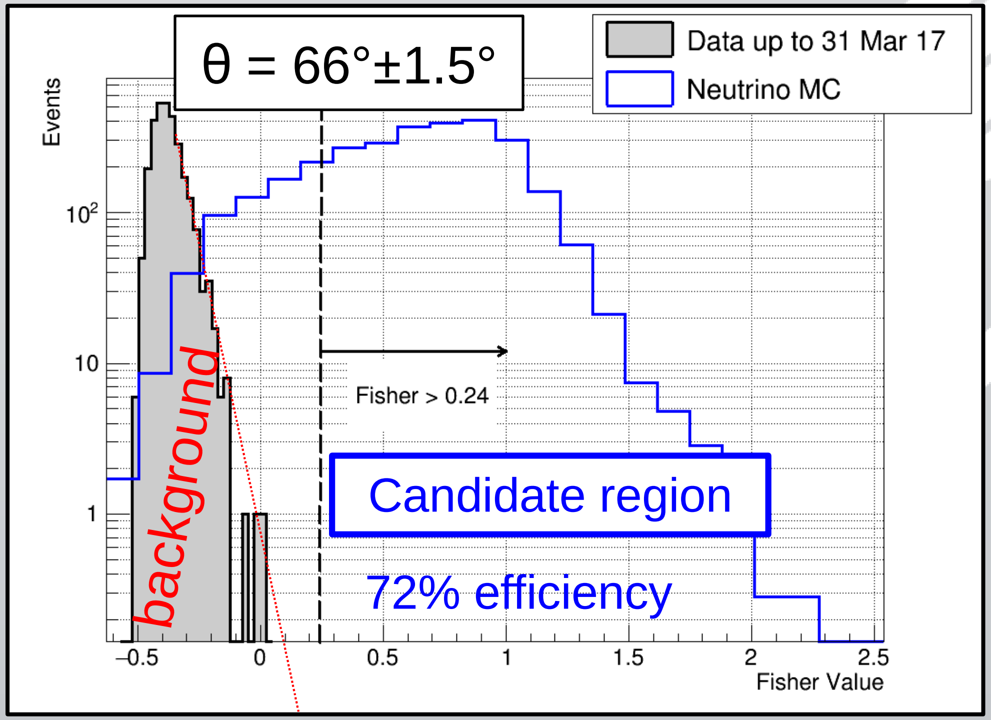
- Pre-select **inclined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
- Crucial variable: **Area over Peak (AoP)**



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"

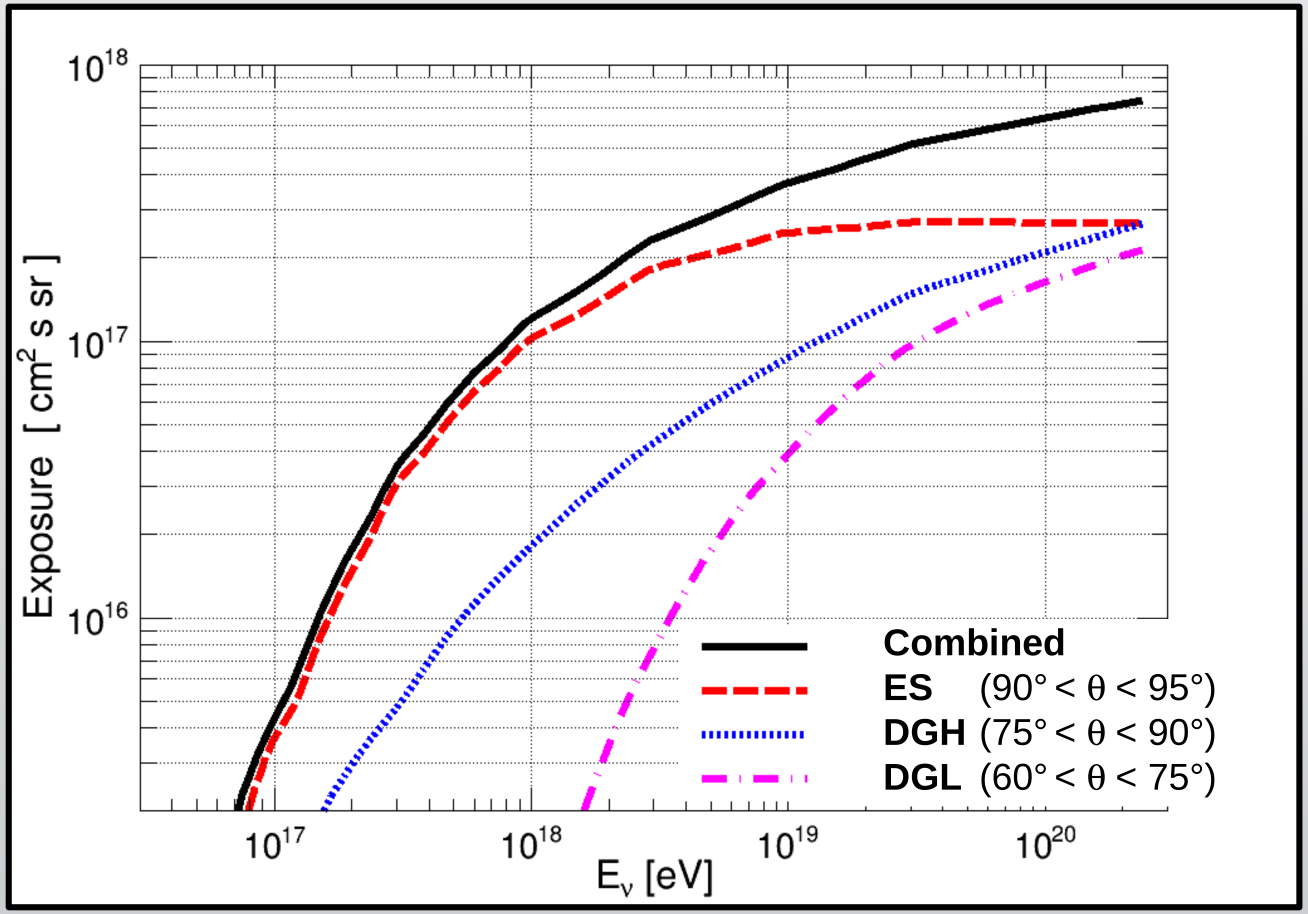




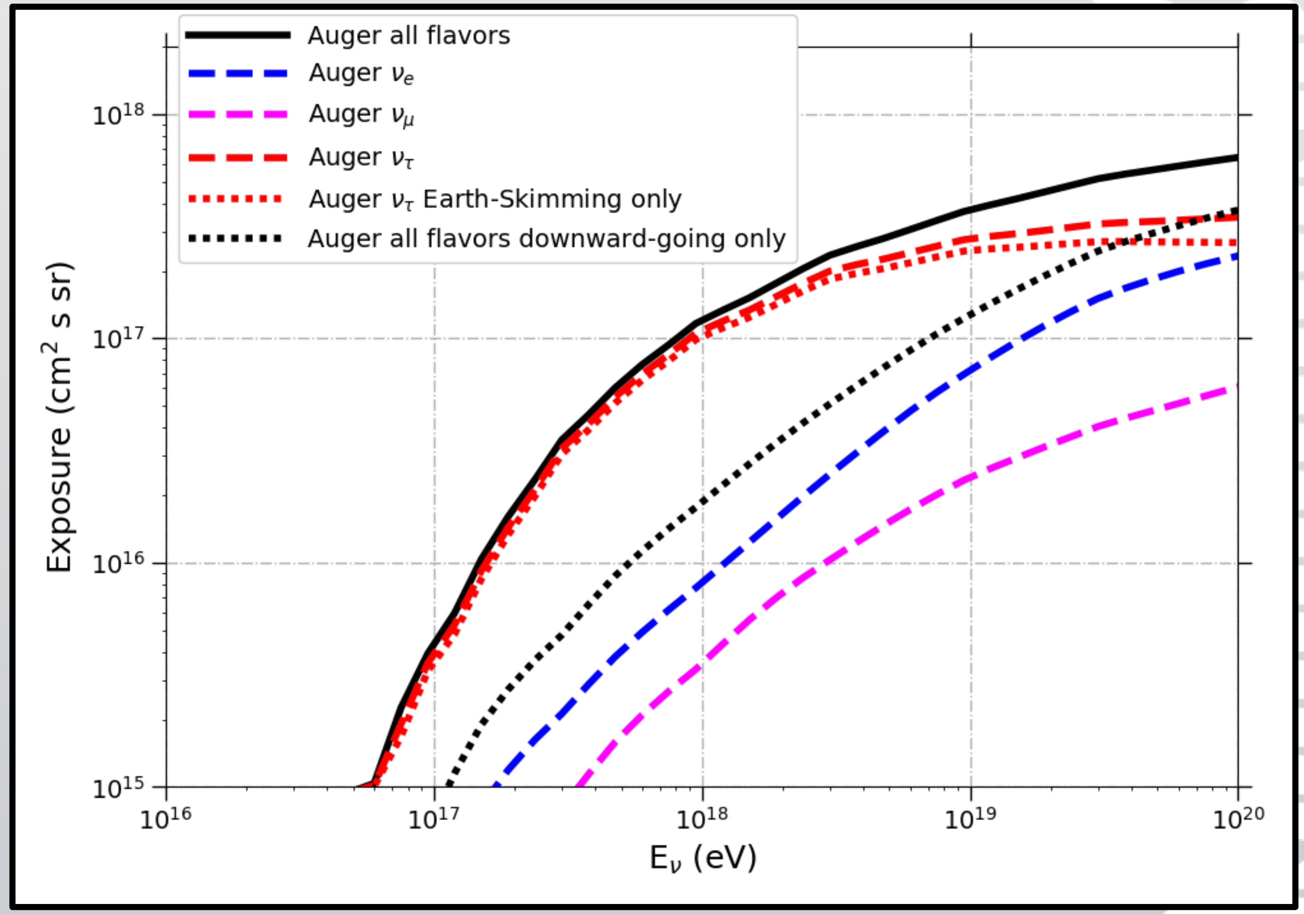
No candidates so far

Neutrino exposure

By direction

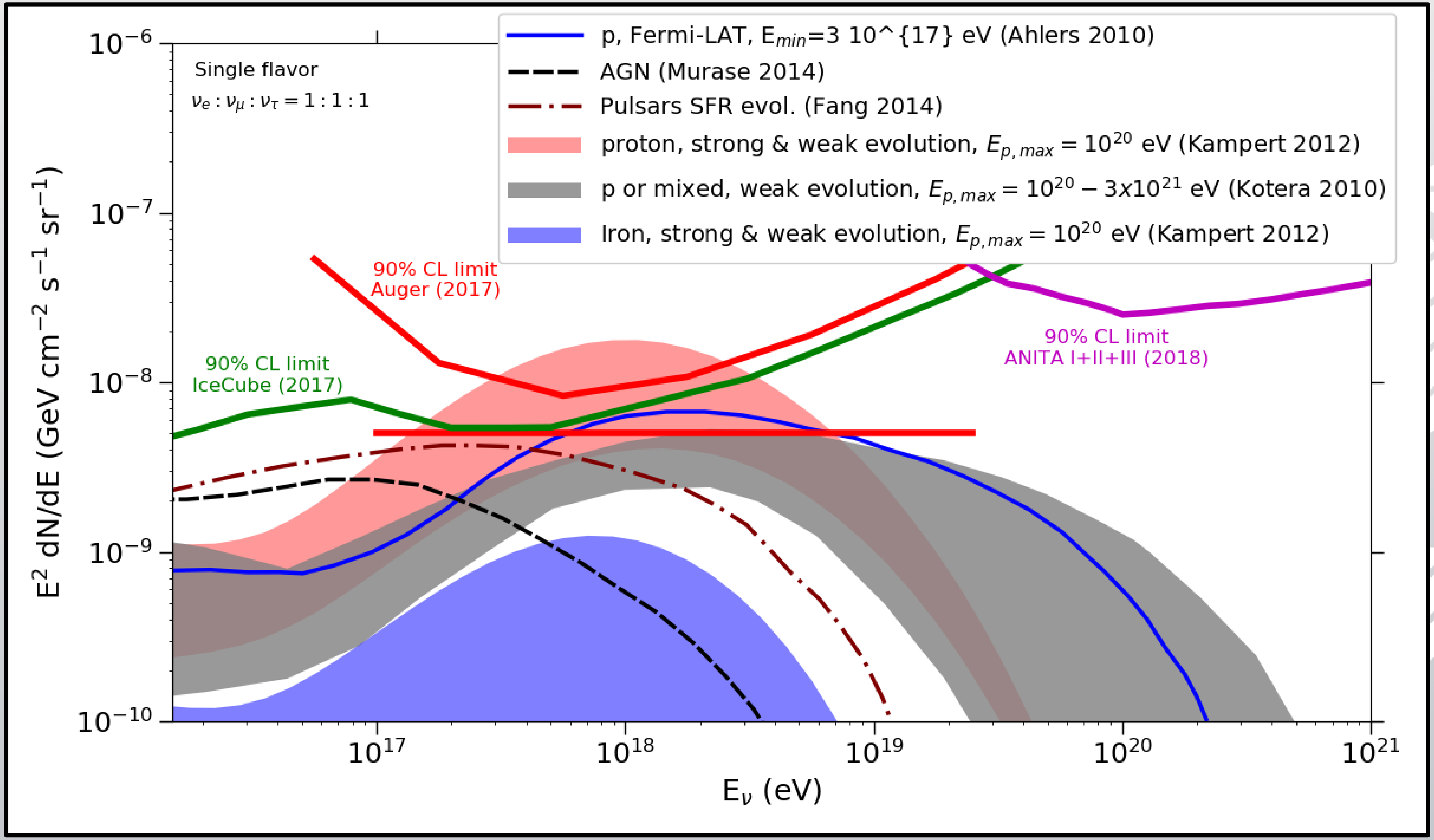


By flavor



Enrique Zas, ICRC 2017

Limits on diffuse neutrino flux

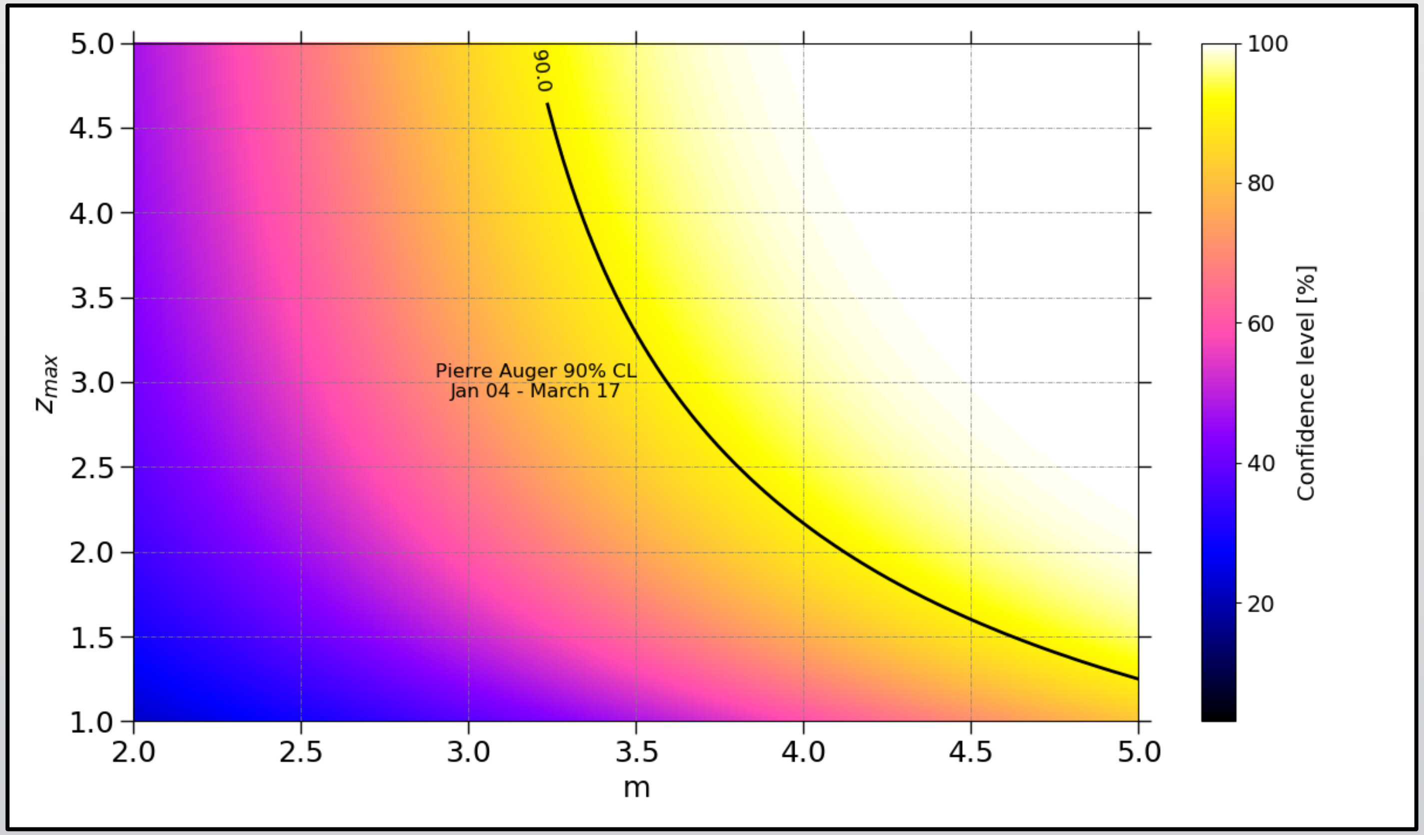


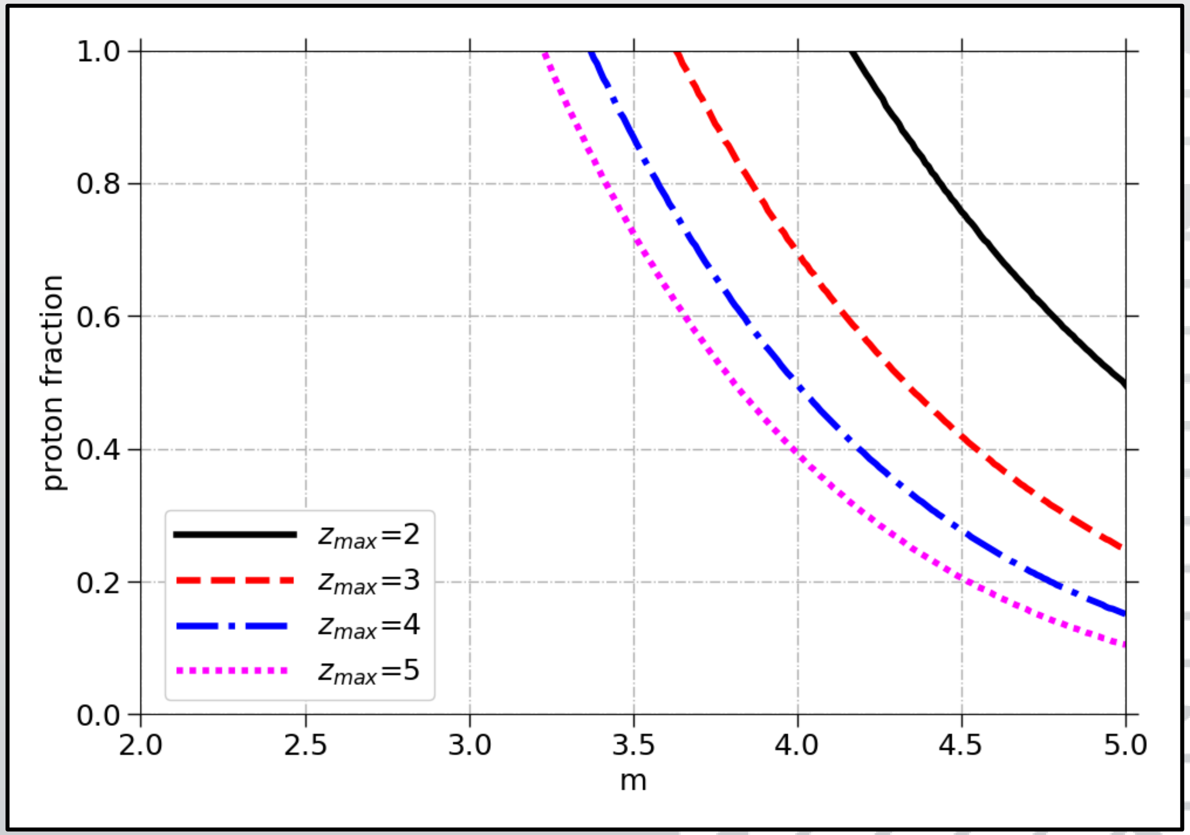
Implications on diffuse neutrino models

Diffuse flux neutrino model	Expected events (1 Jan 04 - 31 Mar 17)
Cosmogenic - proton - strong source evolution	
Cosmogenic - proton, FRII evol. (Kampert 2012)	~ 5.2
Cosmogenic - proton, FRII evol. (Kotera 2010)	~ 9.2
Cosmogenic - proton - moderate source evolution	
Cosmogenic - proton, SFR evol (Aloisio 2015)	~ 2.0
Cosmogenic - proton, SFR evol, $E_{max} = 10^{21}$ eV (Kotera 2010)	~ 1.8
Cosmogenic - proton, SFR evol. (Kampert 2012)	~ 1.2
Cosmogenic - proton, GRB evol. (Kotera 2010)	~ 1.5
Cosmogenic - proton - normalized to Fermi-LAT GeV γ-rays	
Cosmogenic - proton, Fermi-LAT, $E_{min} = 10^{19}$ eV (Ahlers 2010)	~ 4.0
Cosmogenic - proton, Fermi-LAT, $E_{min} = 10^{17.5}$ eV (Ahlers 2010)	~ 2.1
Cosmogenic - mixed and iron	
Cosmogenic - mixed (Galactic) UHECR composition (Kotera 2010)	~ 0.7
Cosmogenic - iron, FRII (Kampert 2012)	~ 0.35
Astrophysical sources	
Astrophysical - radio-loud AGN (Murase 2014)	~ 2.6
Astrophysical - Pulsars - SFR evol. (Fang 2014)	~ 1.3

Excluded at 90% CL:
> 2.4 events

Implications on sources

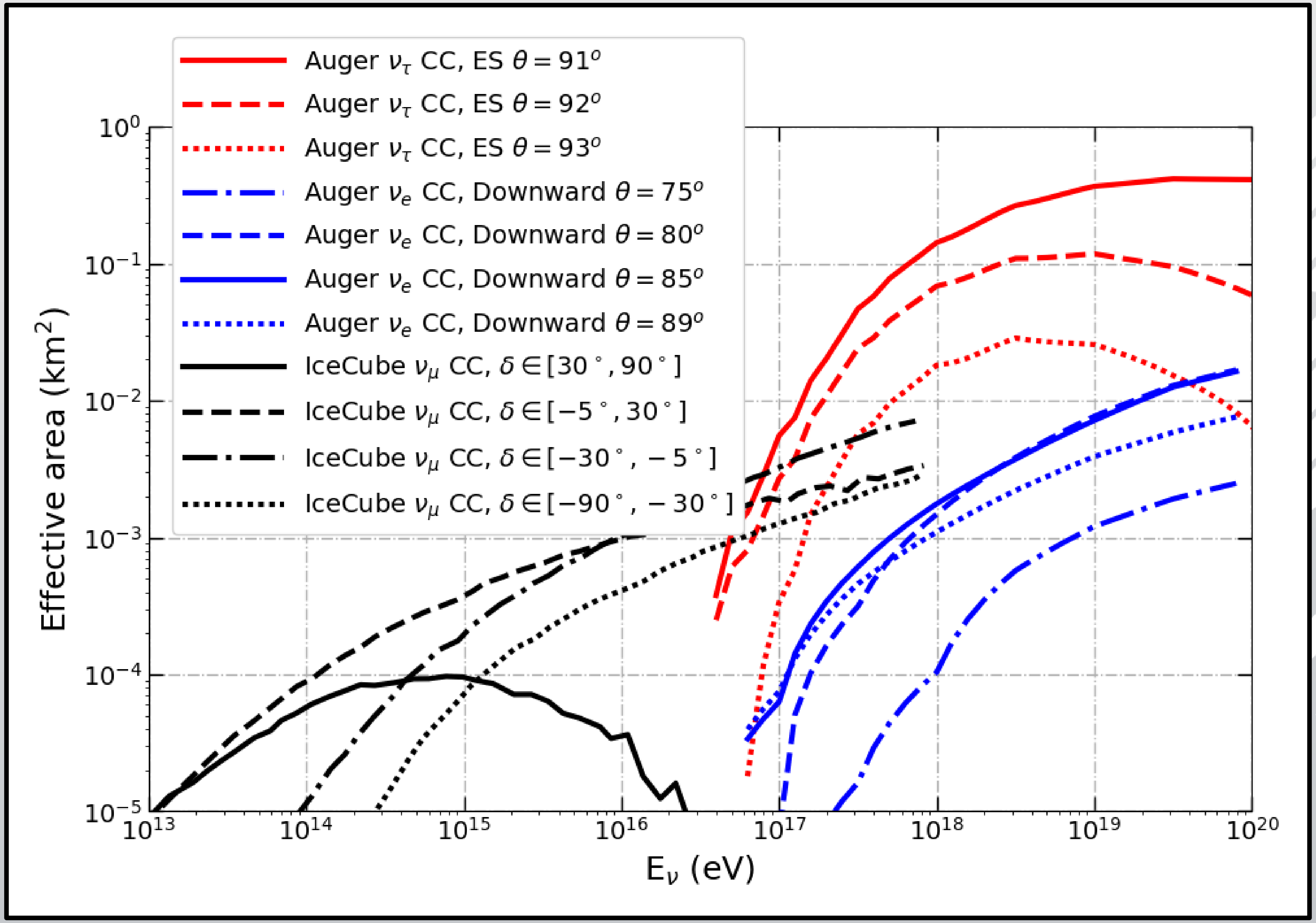




- Pure proton
- Source evolution ~ $(1+z)^m$ up to z_{max}
- $E^{-2.5}$ flux

- Smaller proton fractions → less sensitivity

Effective area



Follow-ups of GW events

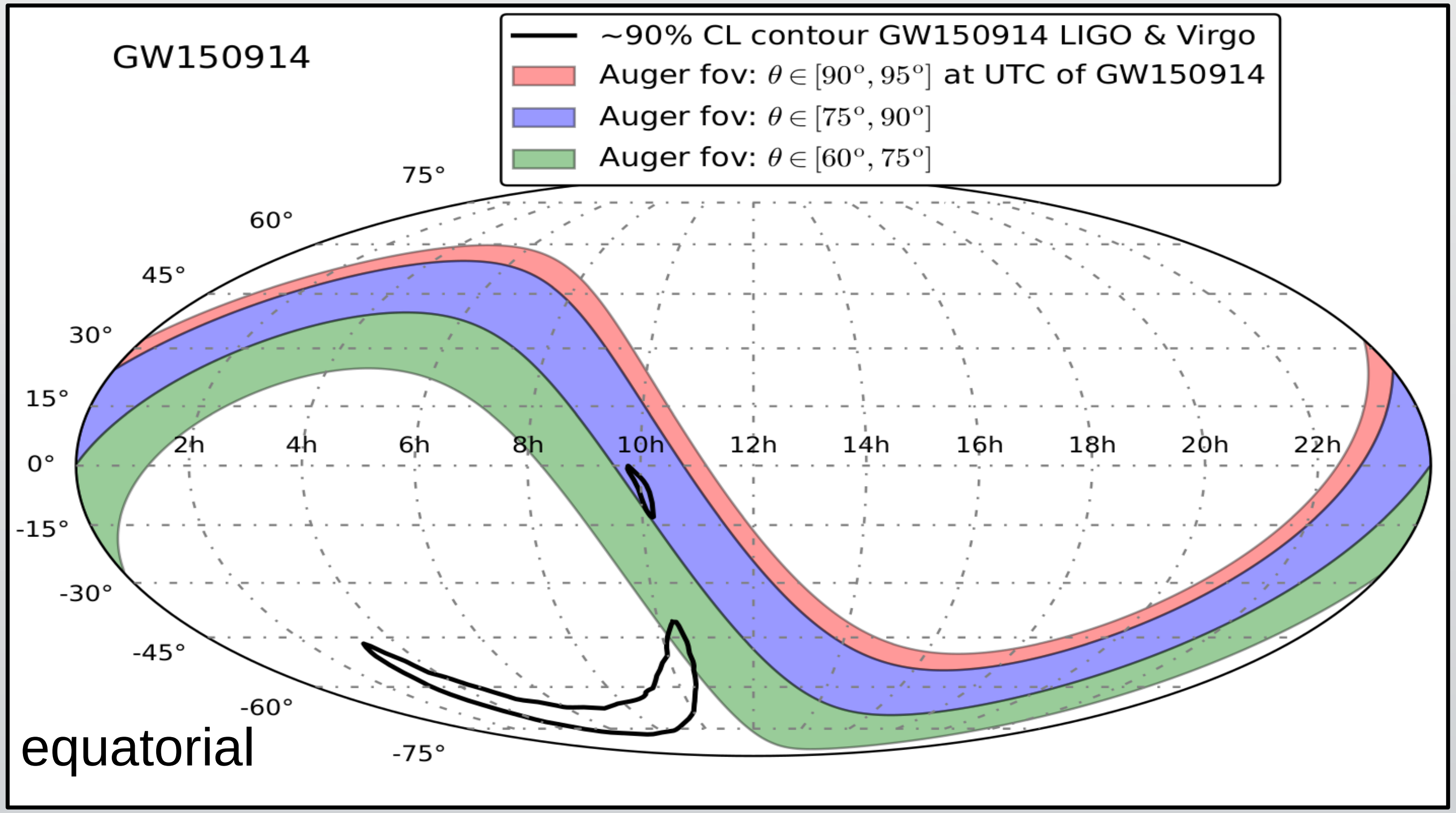
LIGO/Virgo O1+O2: MoU between Auger and LVC:

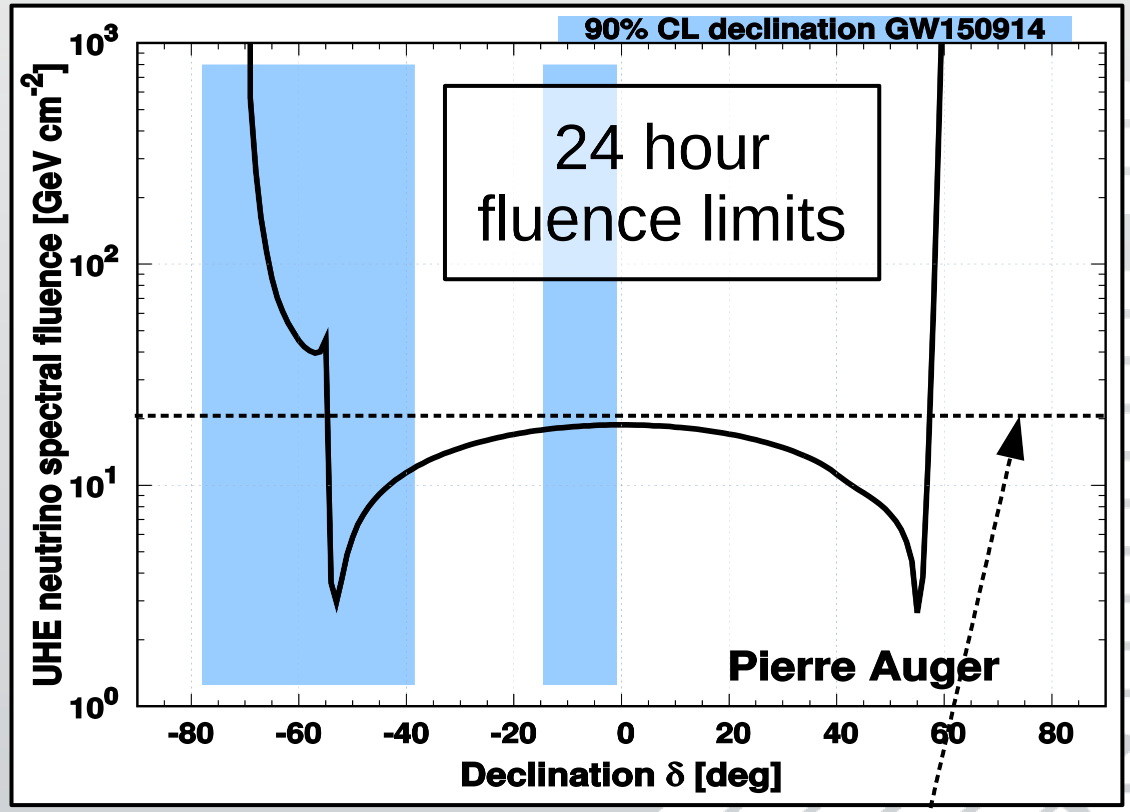
Default neutrino search, considering only

- ±500 s around & +1 day after GW event
- Times at which location of the GW event is visible

BNS merger GW170817: ±500 s & 14 day period after the event

Follow-Up of BBH merger GW150914



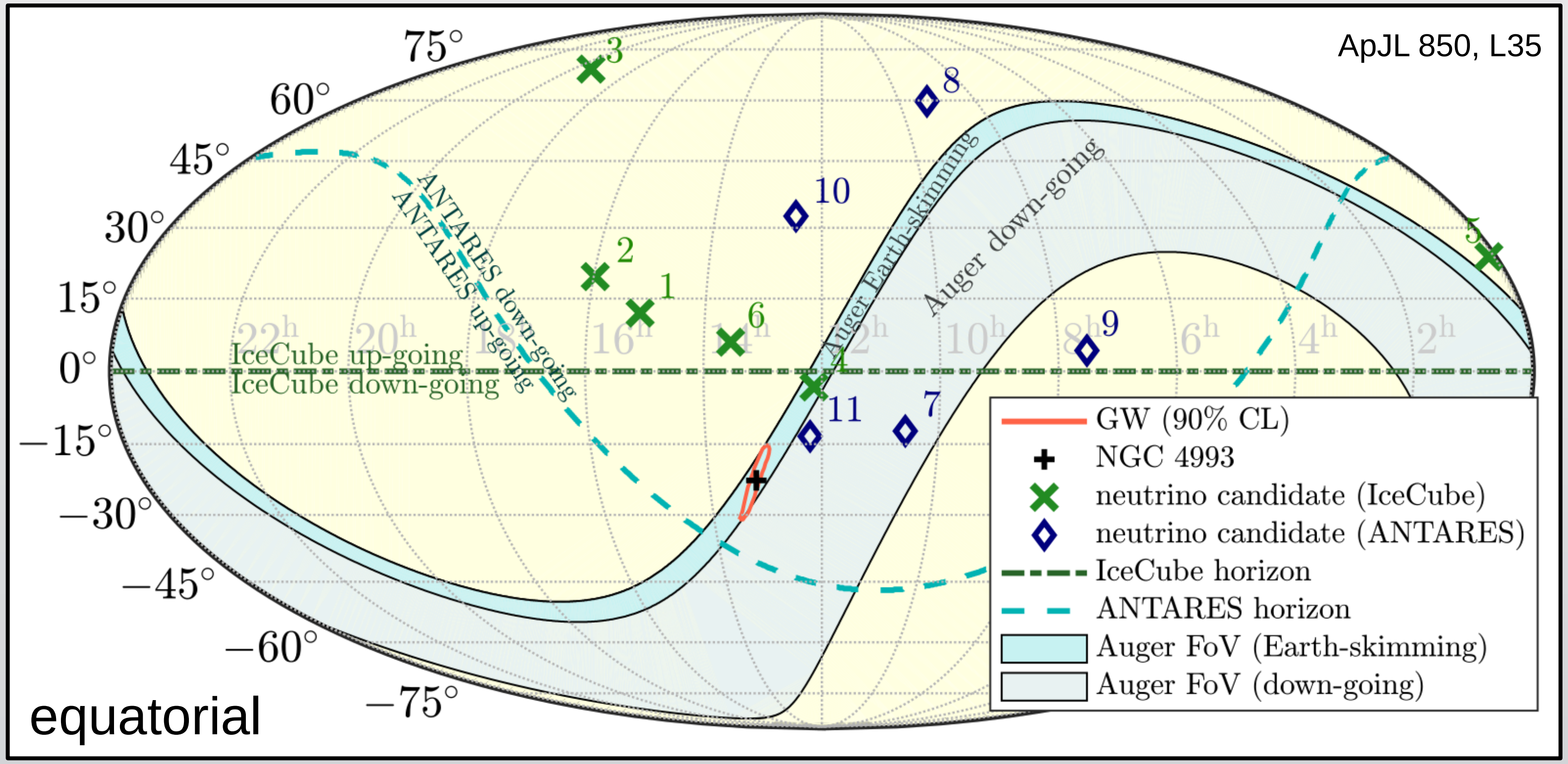


UHE neutrino sensitivity declination dependent

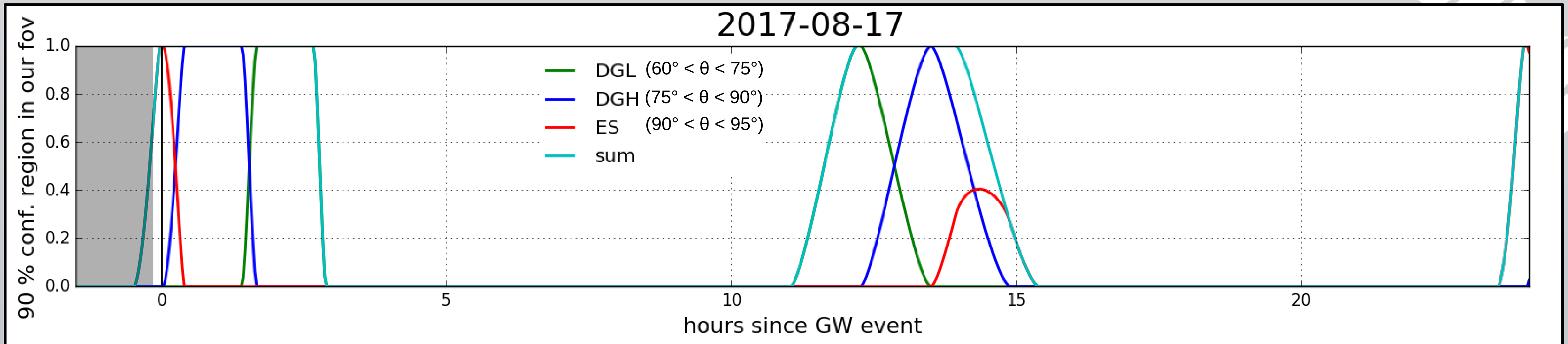
Newer events: More GW detectors
➔ improved localization by triangulation

total neutrino energy = emitted GW energy

Visibility of GW170817



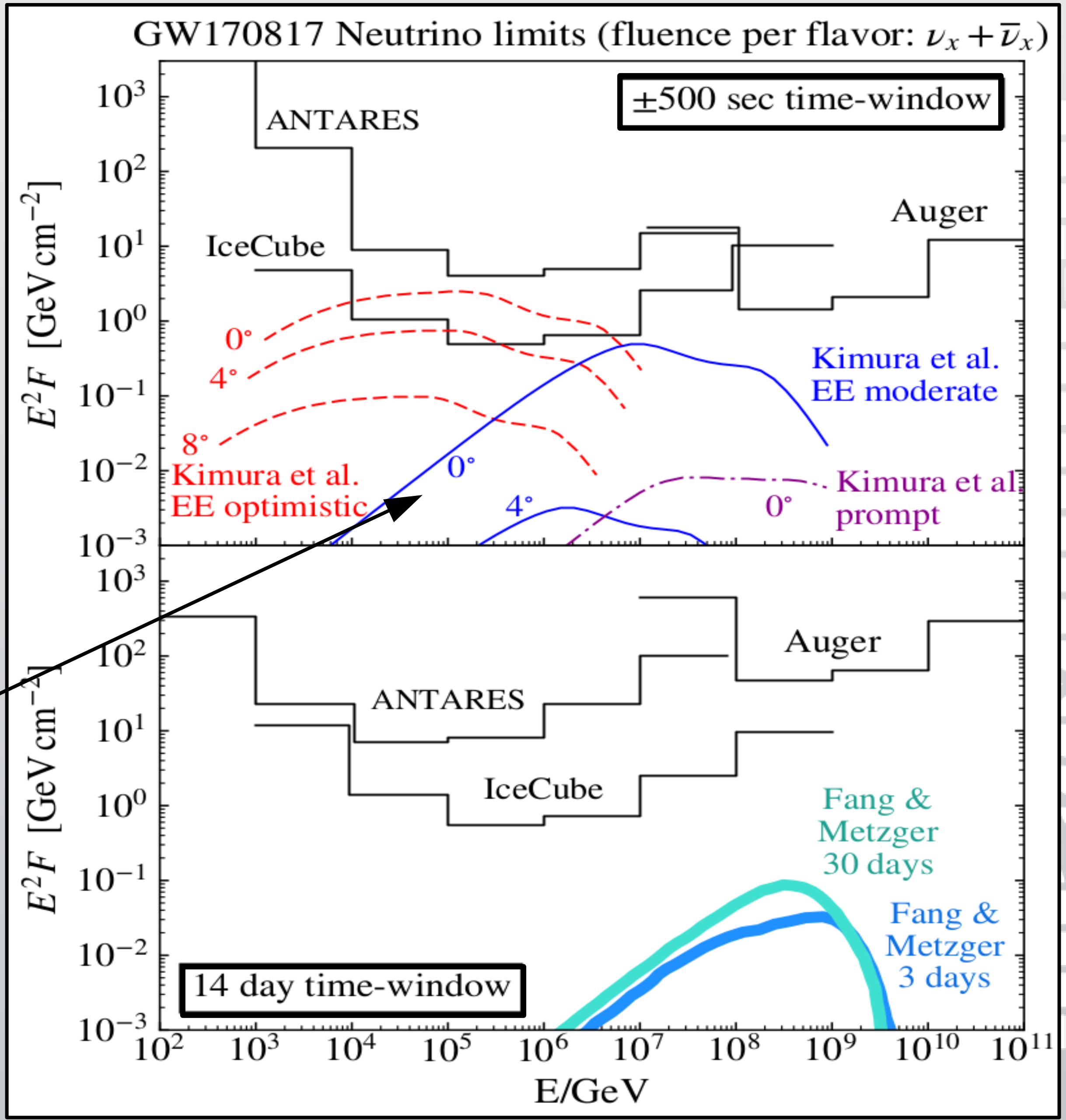
Good visibility at time of merger



Neutrino limits for GW170817

- **No related neutrinos** detected by ANTARES, IceCube and Auger
- Sensitivity high for ±500 s but reduced for 14 days
  - Good vs. periodic visibility

Viewing angle, constrained to < 36° (at time of publication)



Follow-up of GW events O3

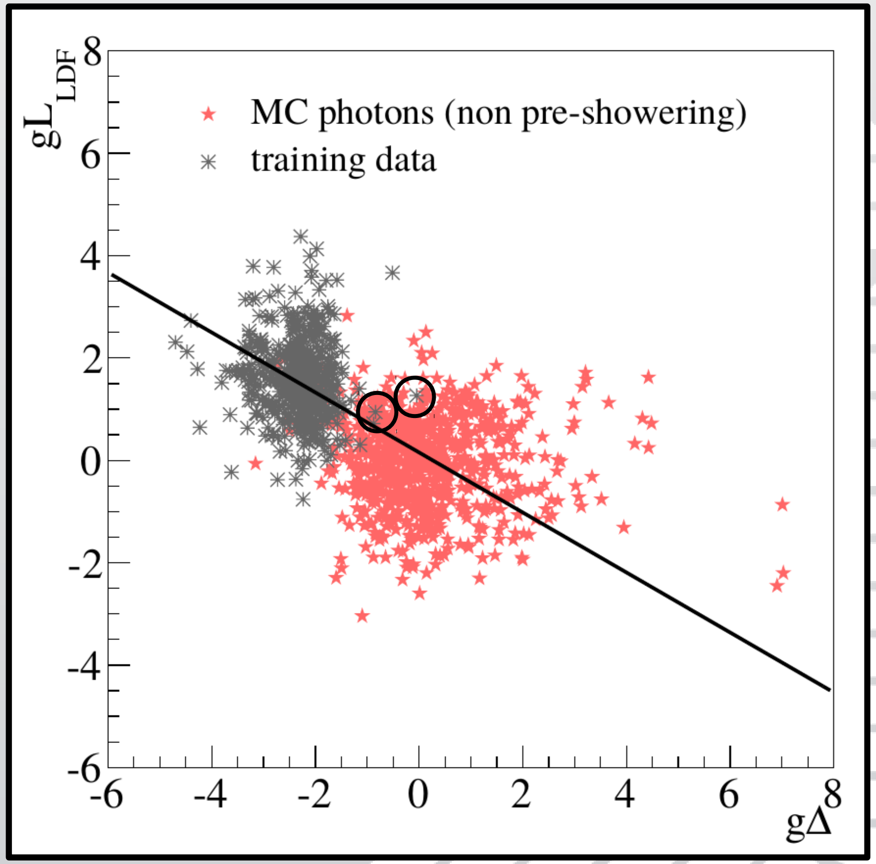
- LIGO/Virgo switched to **open public alerts (OPAs)**, communicated via GCN
- No MoU, we **automatically** follow-up the OPAs
- O3 starts in April 2019 with increased sensitivity
  - Increased rates / horizon / source volume

  + possibly NS-BH mergers
- Photon follow-up search will join in
- KAGRA?

UHE photon separability from protons (=worst case)

gL_{LDF}: accounts for **steeper** lateral particle density distribution (LDF) of photons

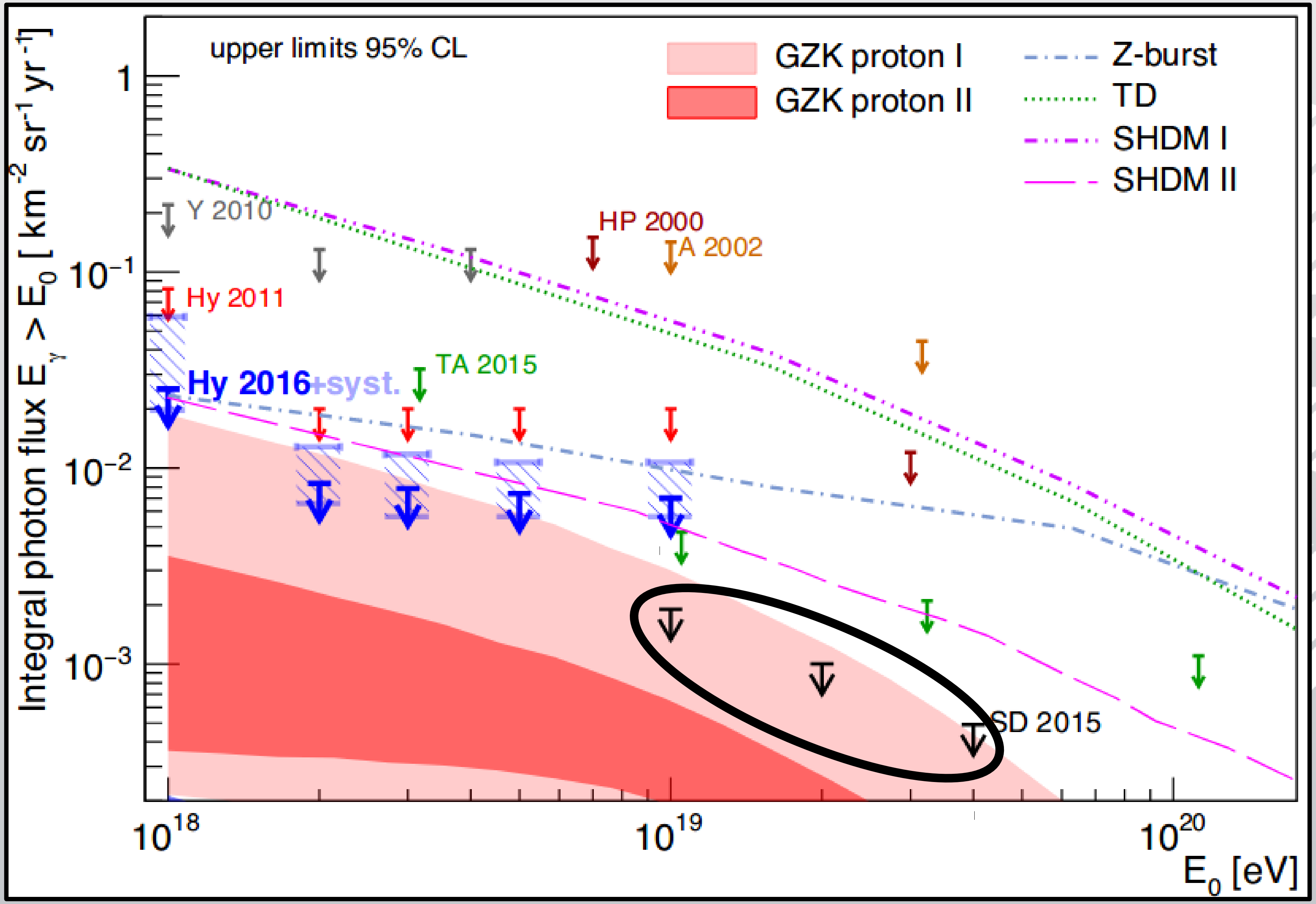
$g\Delta$: accounts for **slower rising signal** of photon induced air showers in the PMTs of the SD stations



Caveat: The GW events' sources so far are further away than the UHE photon horizon

➔ We prepared the follow-up routines (no publications), ready for LIGO/Virgo O3, hope for close-by sources

UHE photon search performance



Subsummary GW follow-up

- Auger is complementary to other neutrino telescopes
  - Flavor-dependency of sensitivity: Highest for ν_τ, smallest for ν_μ
  - **Largest effective area in the EeV range** (but moving field of view)
    - ➔ Great sensitivity to **transients** (when they are in fov)
  - Unique: Northern Hemisphere at EeV energies

Subsummary GW follow-up

- Neutrino follow-up searches of published LIGO/Virgo GW events performed
  - BBH mergers: Sensitivity to emitted neutrinos of the order of emitted gravitational waves (in terms of total energy)
  - BNS merger GW170817: good visibility, fluence limits in the range of theoretical predictions
  - Photons (more background-prone) are ready to join in

- Future: **increased event rates**, precision and maybe even other source classes

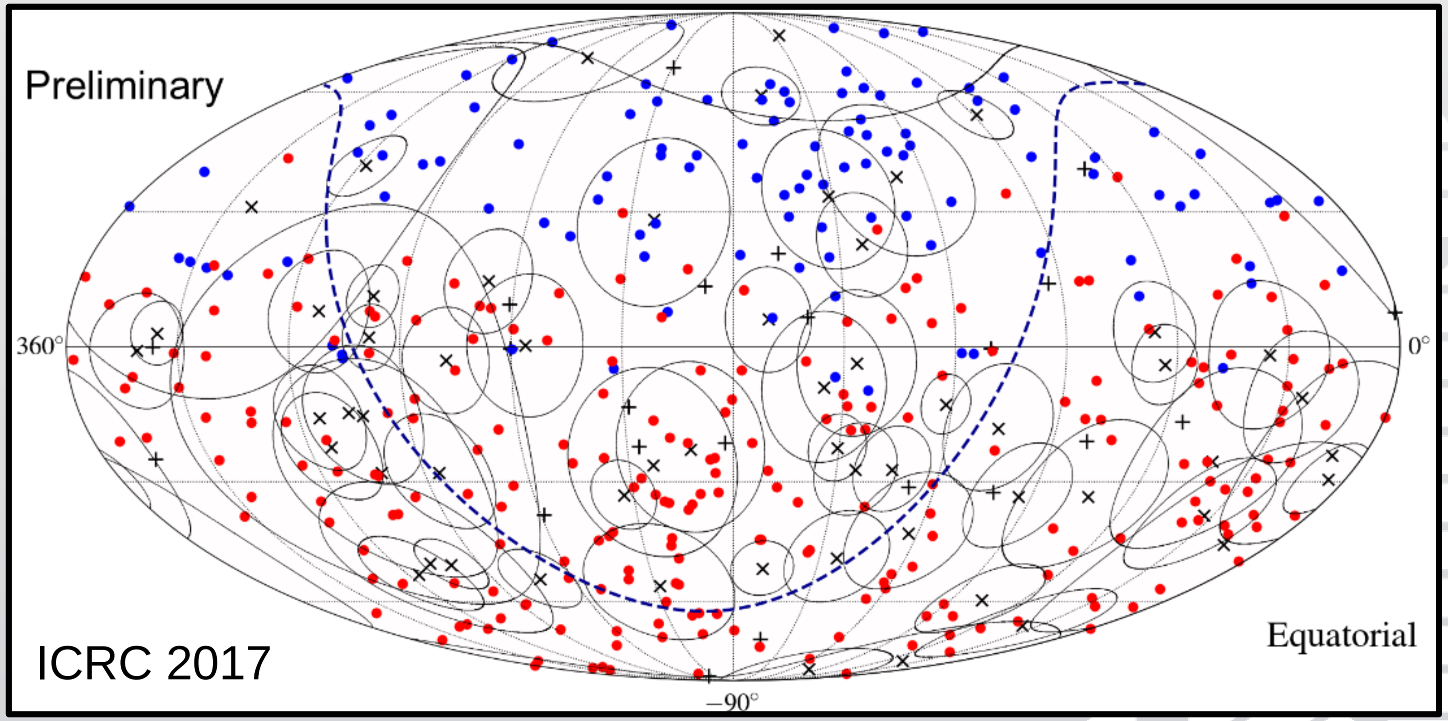
UHECR - neutrino correlation searches

Exploring the correlation:

UHECR with ***E* > ~ 50 EeV**
(Auger + TA)

↕

Neutrinos
(IceCube, soon ANTARES)



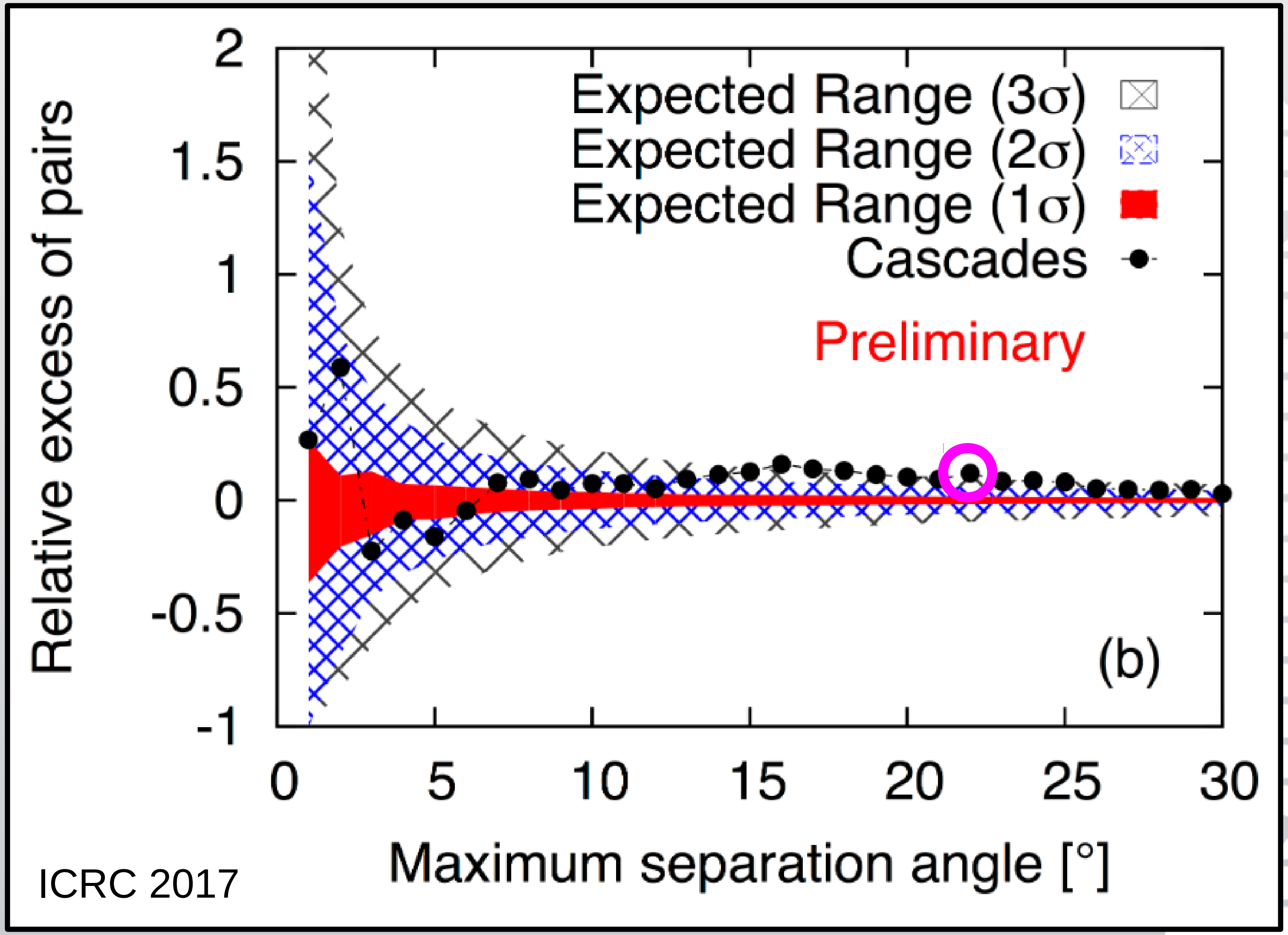
Two different methods:

- **Excess** of frequency of angular separation above isotropy assumption
- **Stacking likelihood** of angular correlations given MF models, assuming sources are at measured neutrino directions

UHECR - neutrino correlation searches

Most significant excess with IceCube **cascades** at $\Delta\Psi \sim$ **22°**

- Combination of **cascade angular resolution (~15°)** and **UHECR deflection (~6°/E_{100})**



p = 5 x 10^{-3} (post trial)

$E_{100} = E$ / 100 EeV

UHECR - neutrino correlation searches

Stacking likelihood analysis:
Most significant results with **cascades** and MF deflection of **~ 6°/E_{100}**, backing up the angular separation analysis

p = 2 x 10^{-2} (post trial)

Results used to be more significant (ICRC 2015)

- Vanishing of a fluctuation?
- Composition + MF deflection need to be better understood

Galactic neutrons

- **No** direct neutron identification possible in Auger
- Neutrons are not deflected in MFs and reach us from anywhere in the Galaxy at E > 2 EeV
- Assume hadronic photon and neutron production from
  - Galactic Center
  - Galactic Disc
  - Known gamma-ray sources (weighted combination)
- Look for increased particle flux from corresponding directions (i.e. missing diffusion by magnetic fields)

Galactic neutrons

- None of the searches provided evidence for a neutron flux from any "source class"

- Limit on neutron energy flux from Galactic gamma-ray sources w/ 6 years of data:
  0.10 – 0.15 eV cm^{-2} s^{-1} < measured TeV photon flux
  - Fermi E^{-2} acceleration (protons) would imply more than that!
    ➔ Excluded!

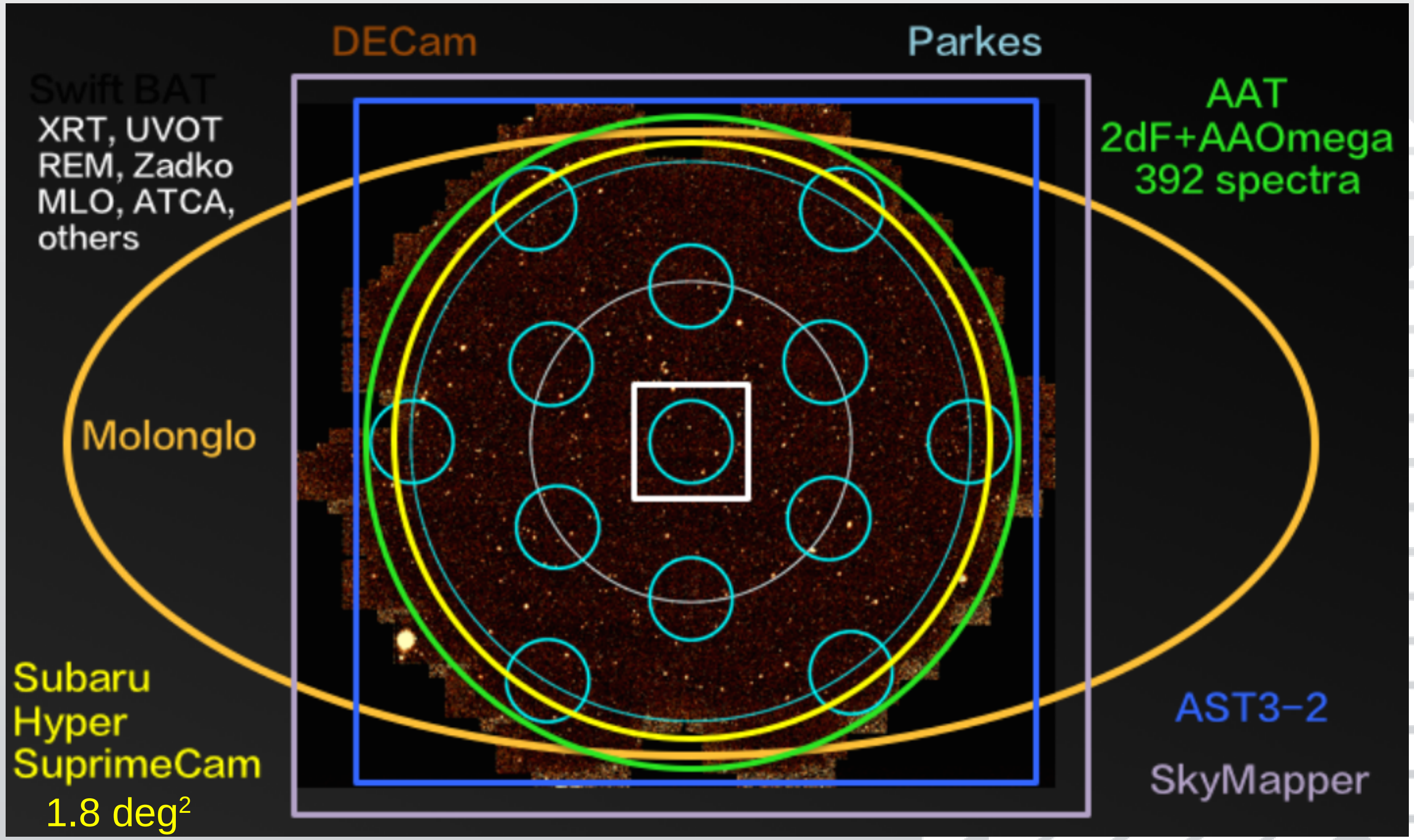
- Luminosity ratio $\boldsymbol{L_n / L_p}$ **< 0.006** (galactic plane, proton emission estimations)

Deeper Wider Faster

- Multi-instrument (> 30) project, participants from radio through **ultra-high energies and non-photons (Auger)**
  - University of Tokyo 1 m Telescope (for follow-up)
- ~ 10 groups observe **simultaneously** to get deep+wide-field fast-sampled multi-wavelength / multi-messenger measurements of the **same field**
  - Radio: **Fast radio bursts** (< 1 s)
  - Higher energies: second to hour transients, also GW
- Real-time (< ~ minutes) **candidate identification**
- Fast response (~ minutes) ToO **follow-up observations**
- Long-term follow-up with ~ 1 – 4 m-class telescopes

Deeper Wider Faster

- 4 to 6 consecutive nights per semester (next: June 2019)
- Auger: All SD events from DWF field of view selected, **no coincidences** so far



- Extensive software development (compression, transient identification, visualization, collaborative workspaces, machine learning)

Subsummary UHECR - neutrinos, neutrons, DWF

- Correlations between Auger + TA UHECRs and IceCube (soon + ANTARES) neutrinos are searched for
  - Most interesting correlation (p ~ 10^{-3} (post trial)) for IceCube **cascades**, corresponding to angular distances of ~ **20°**

- Galactic neutron searches
  - **No evidence** for substantial EeV neutron flux
  - Hadronic pion-production in gamma-ray sources with E^{-2} **up to highest energies** excluded

- Deeper Wider Faster
  - Extensive program of simultaneous multi-wavelength/messenger observations, targeting **FRBs** and other transients (**also GW**)
  - **No coincident** detection by Auger, project ongoing

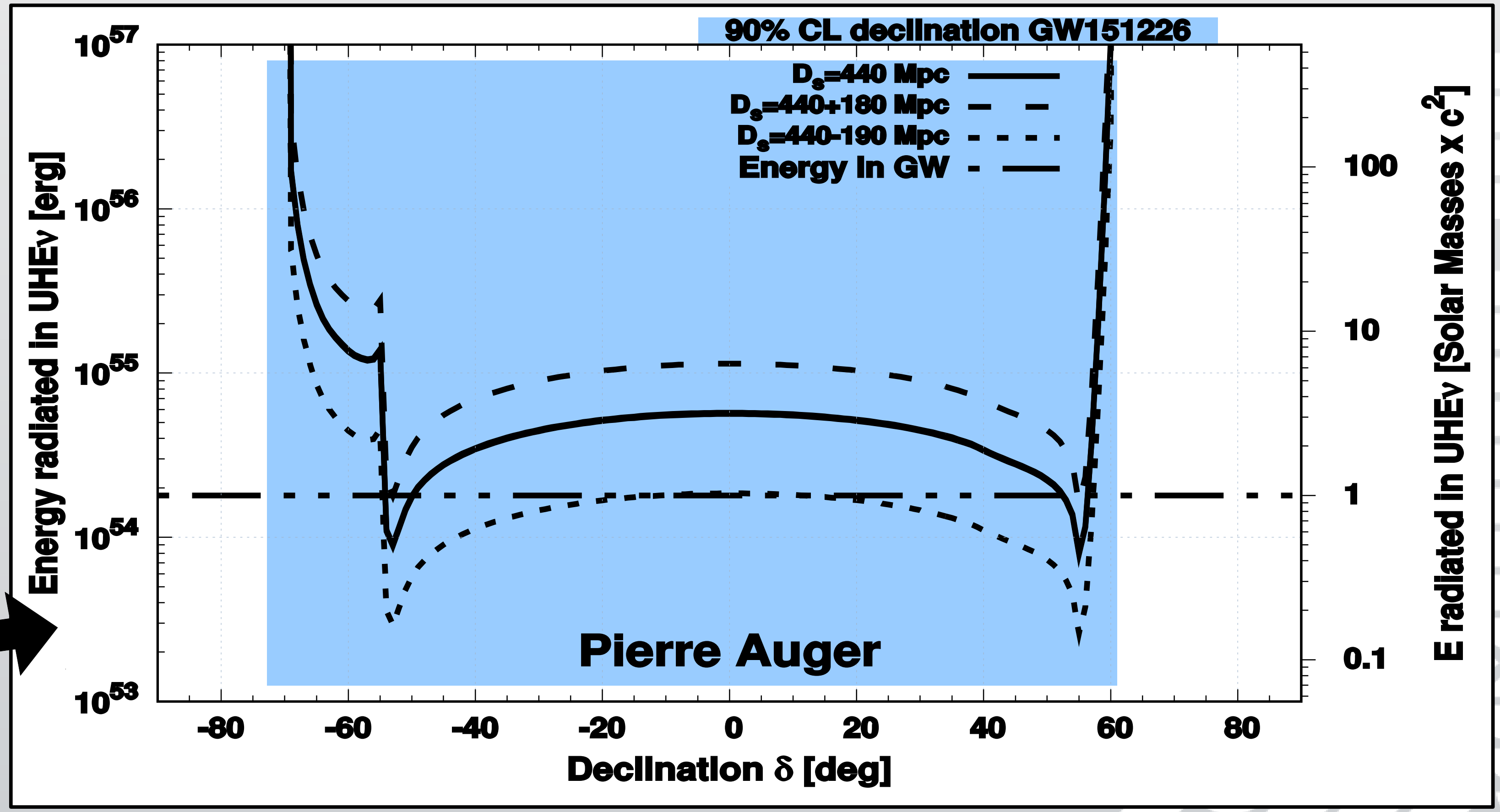
The End

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	$\sim +37\%, -28\%$

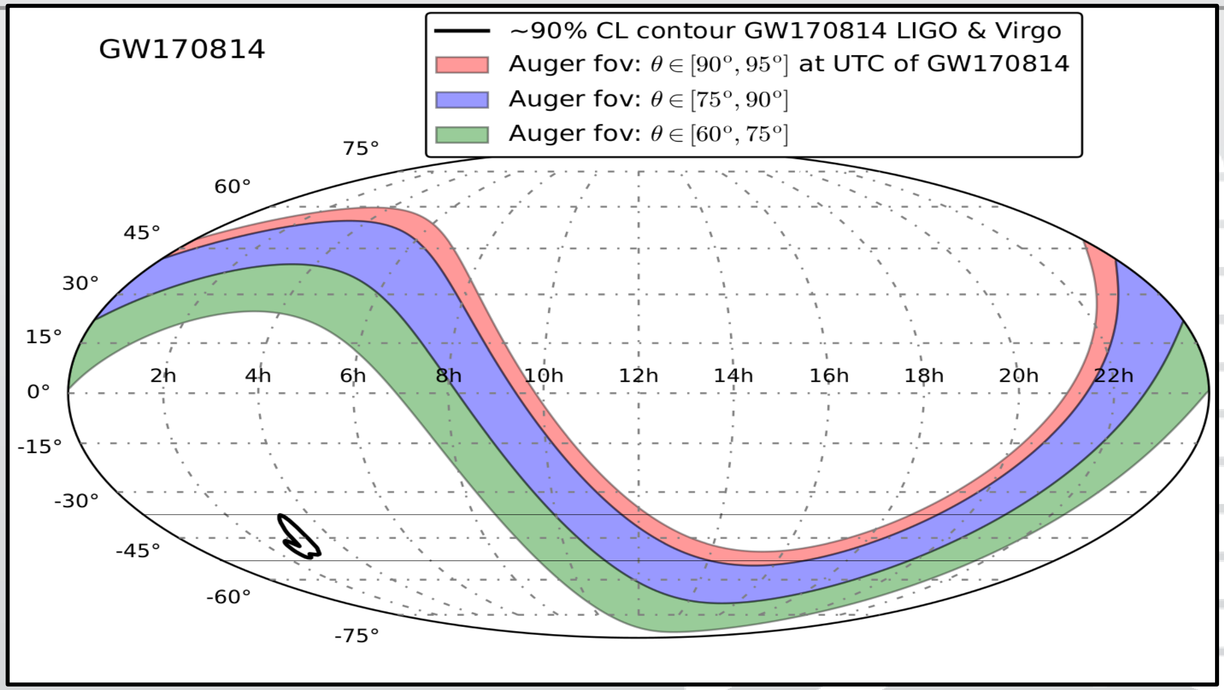
GW Follow-Up—Results (Münster slide)

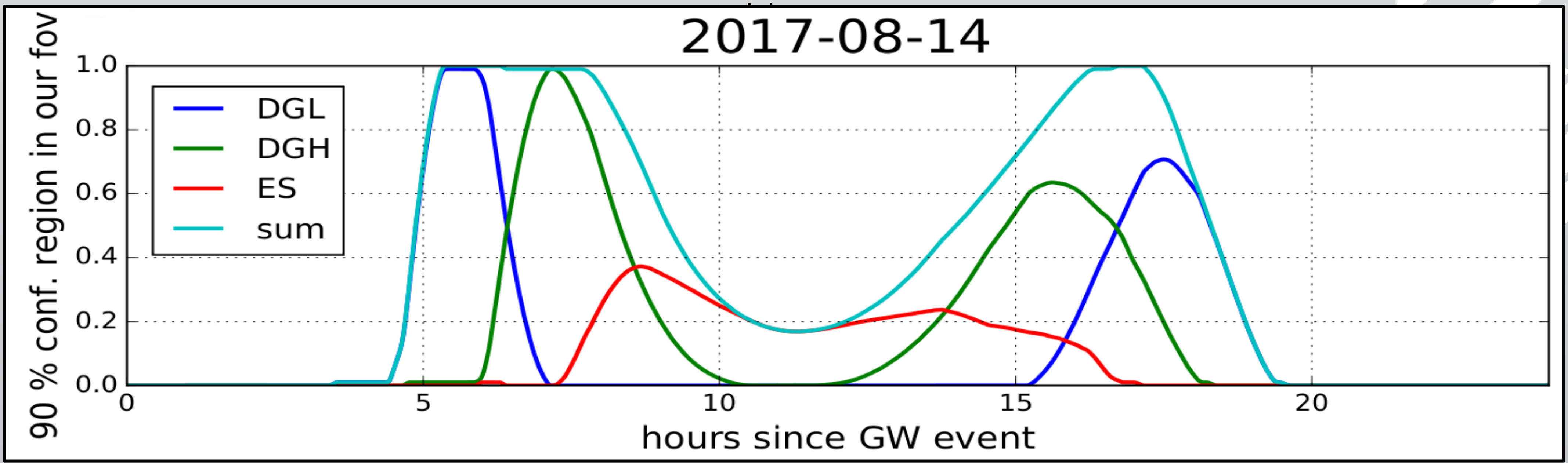
No candidates
→Flux limit
→Limit on total emitted UHE ν energy

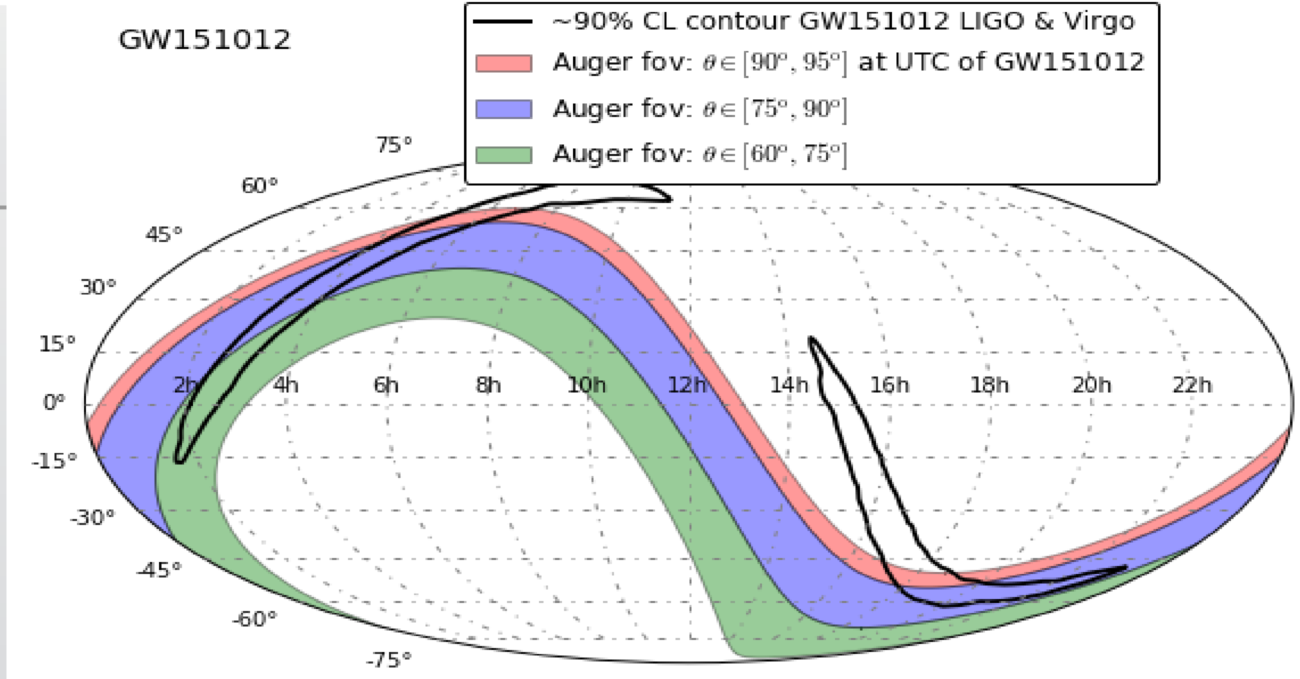


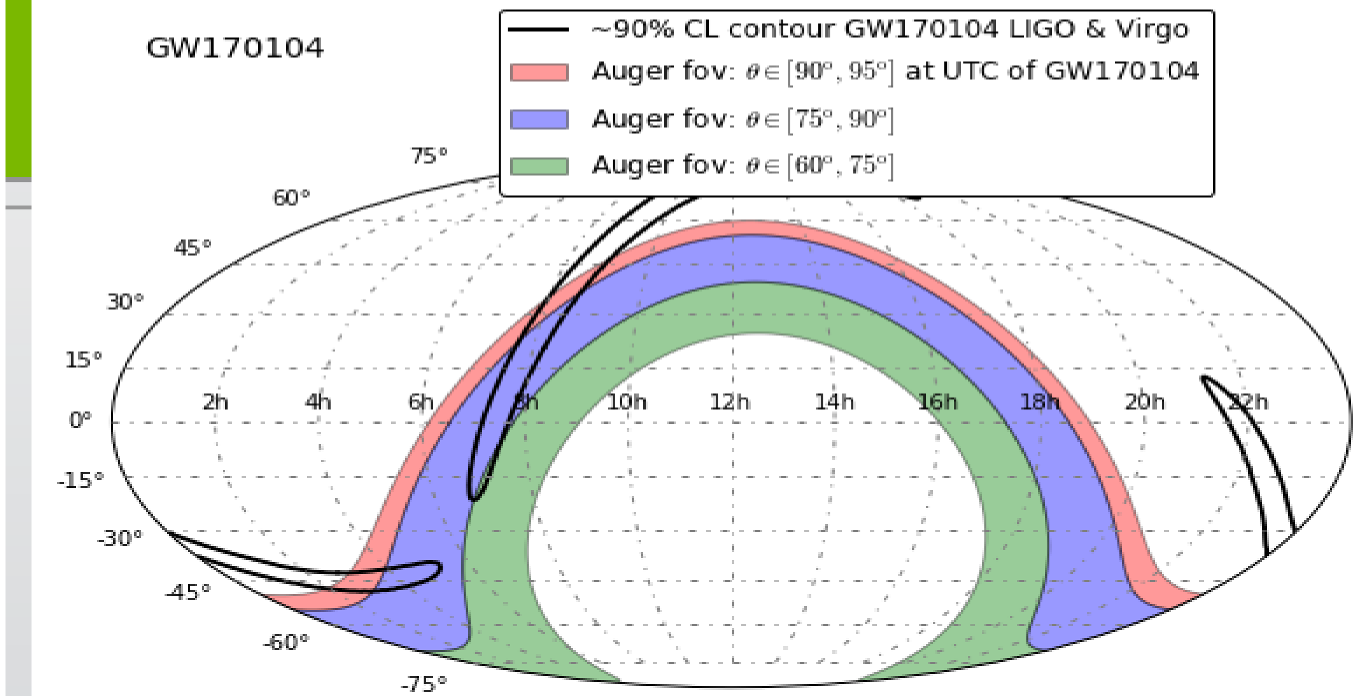
arXiv:1602.06961 (Kotera, Silk):
Binary BHs could produce the measured UHECR flux!
→Needs ~ 3% "efficiency" (E_{UHECR}/E_{GW})

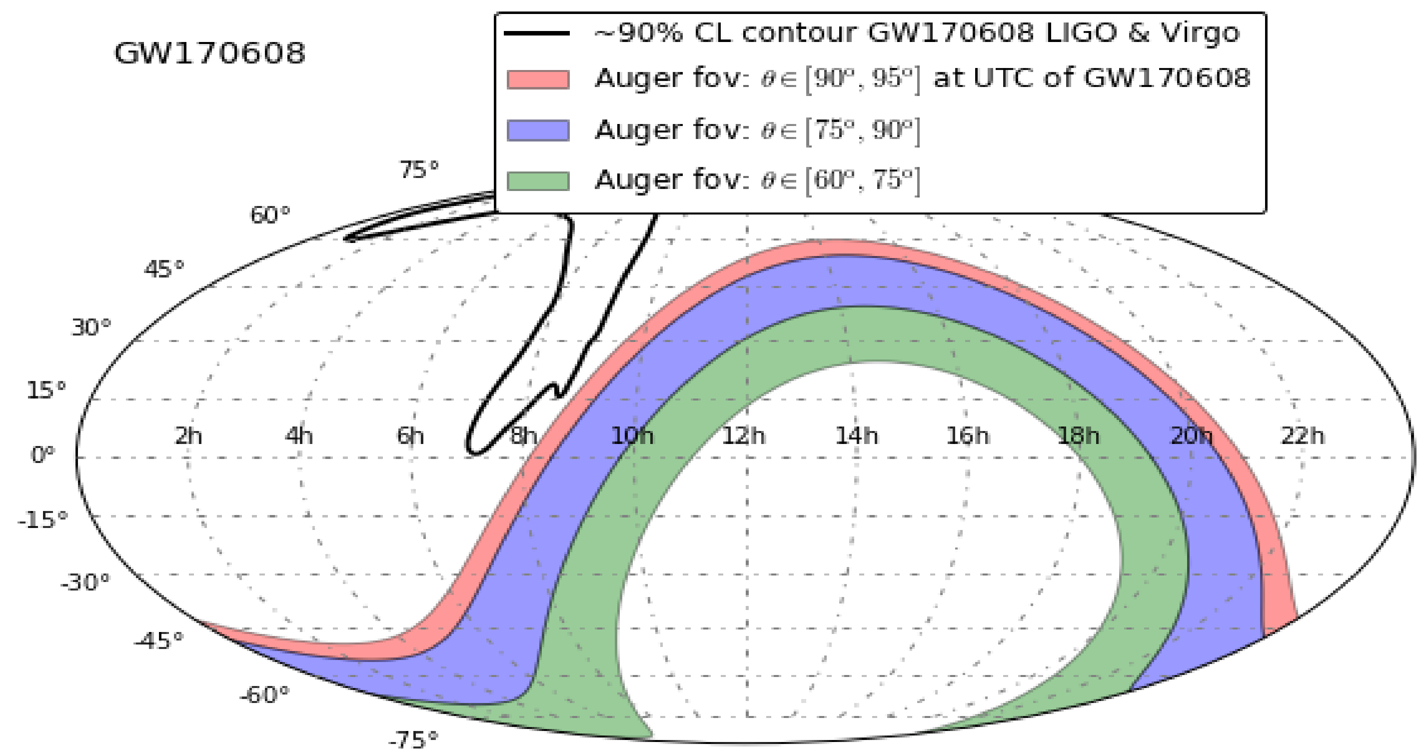
- Last published BH-BH merger so far
- Fluence limits to be calculated, expected to be good



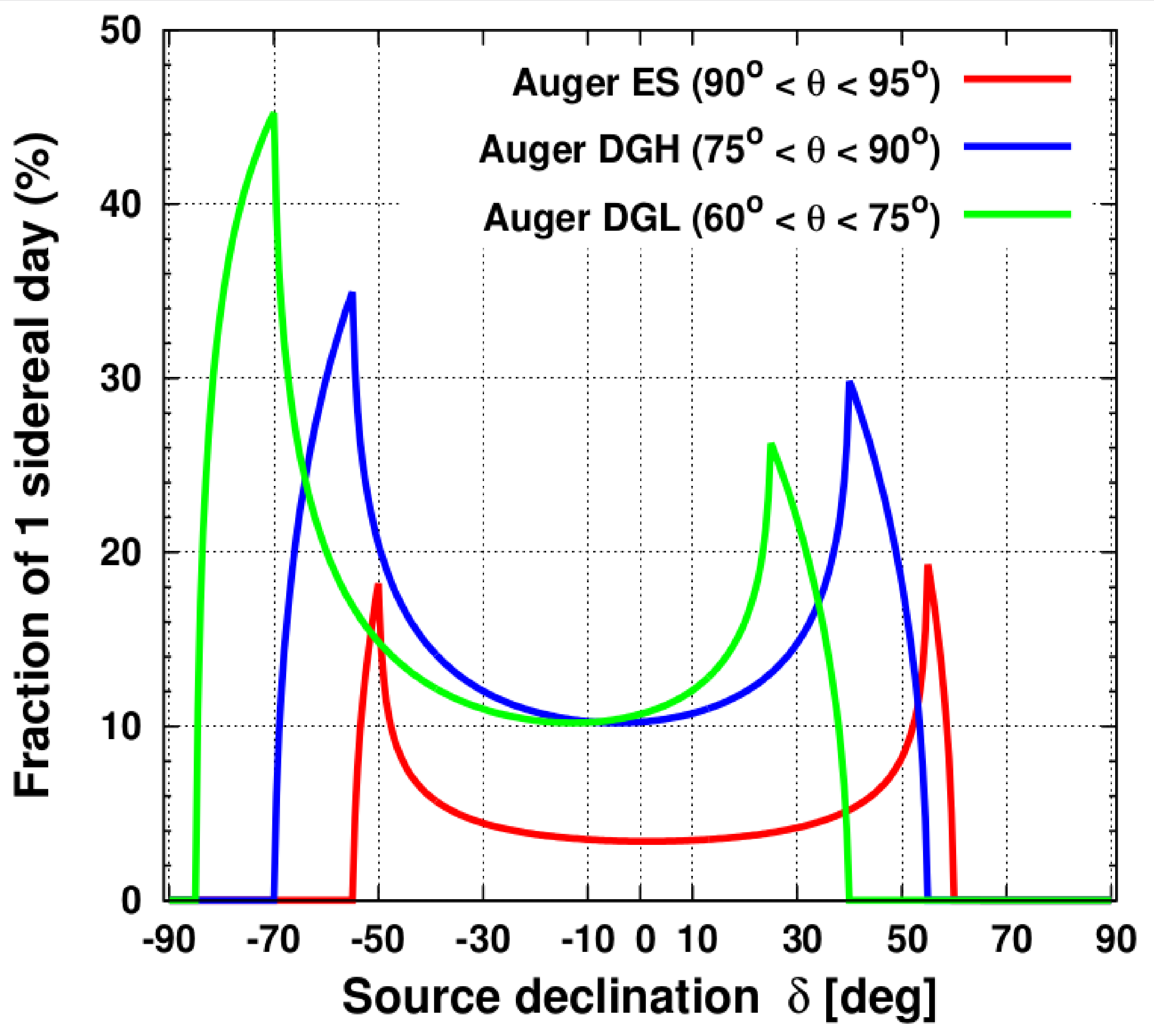



GW151012
~90% CL contour GW151012 LIGO & Virgo
Auger fov: $\theta \in [90^o, 95^o]$ at UTC of GW151012
Auger fov: $\theta \in [75^o, 90^o]$
Auger fov: $\theta \in [60^o, 75^o]$
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h


GW170104
~90% CL contour GW170104 LIGO & Virgo
Auger fov: $\theta \in [90^o, 95^o]$ at UTC of GW170104
Auger fov: $\theta \in [75^o, 90^o]$
Auger fov: $\theta \in [60^o, 75^o]$
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h


GW170608
~90% CL contour GW170608 LIGO & Virgo
Auger fov: $\theta \in [90^o, 95^o]$ at UTC of GW170608
Auger fov: $\theta \in [75^o, 90^o]$
Auger fov: $\theta \in [60^o, 75^o]$
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h

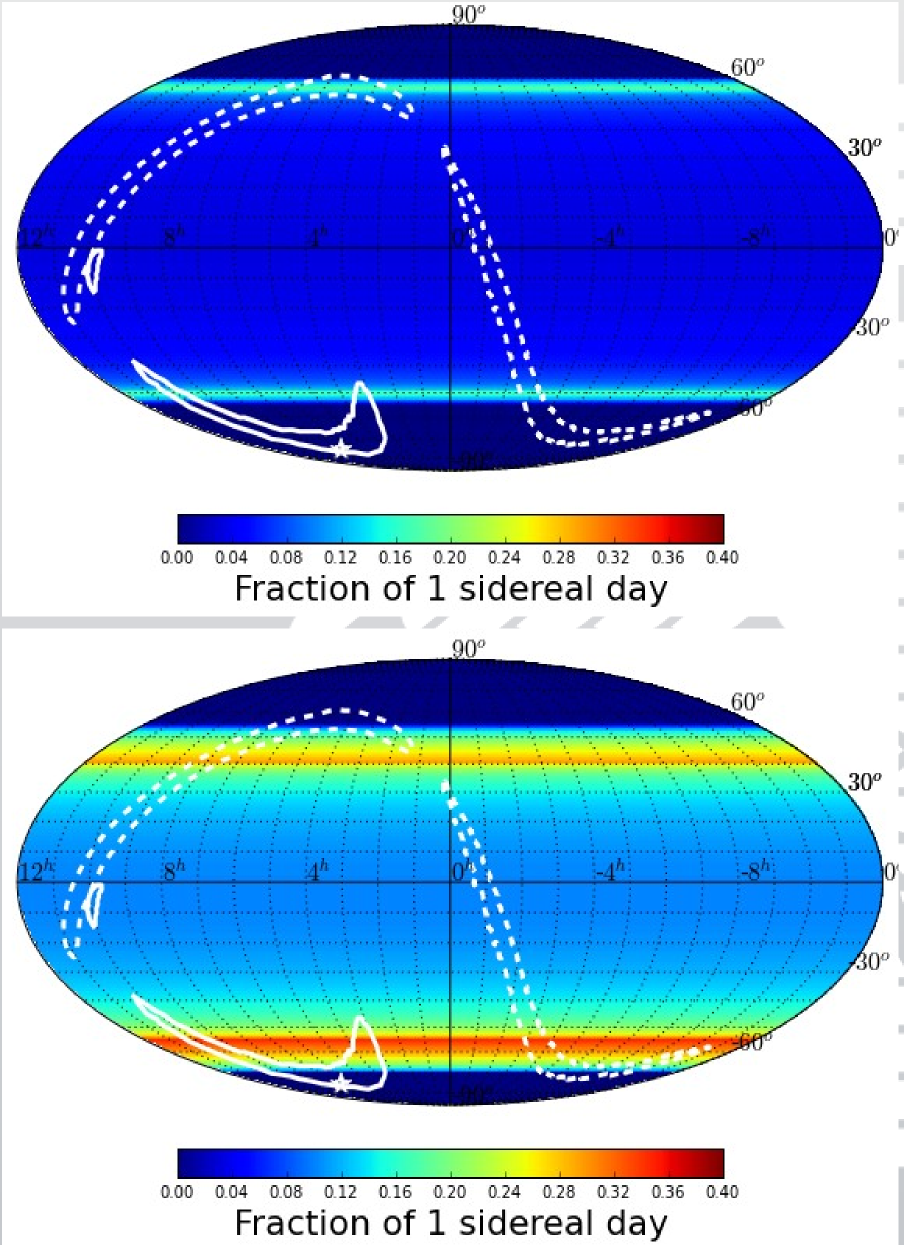
Visible Solid Angle



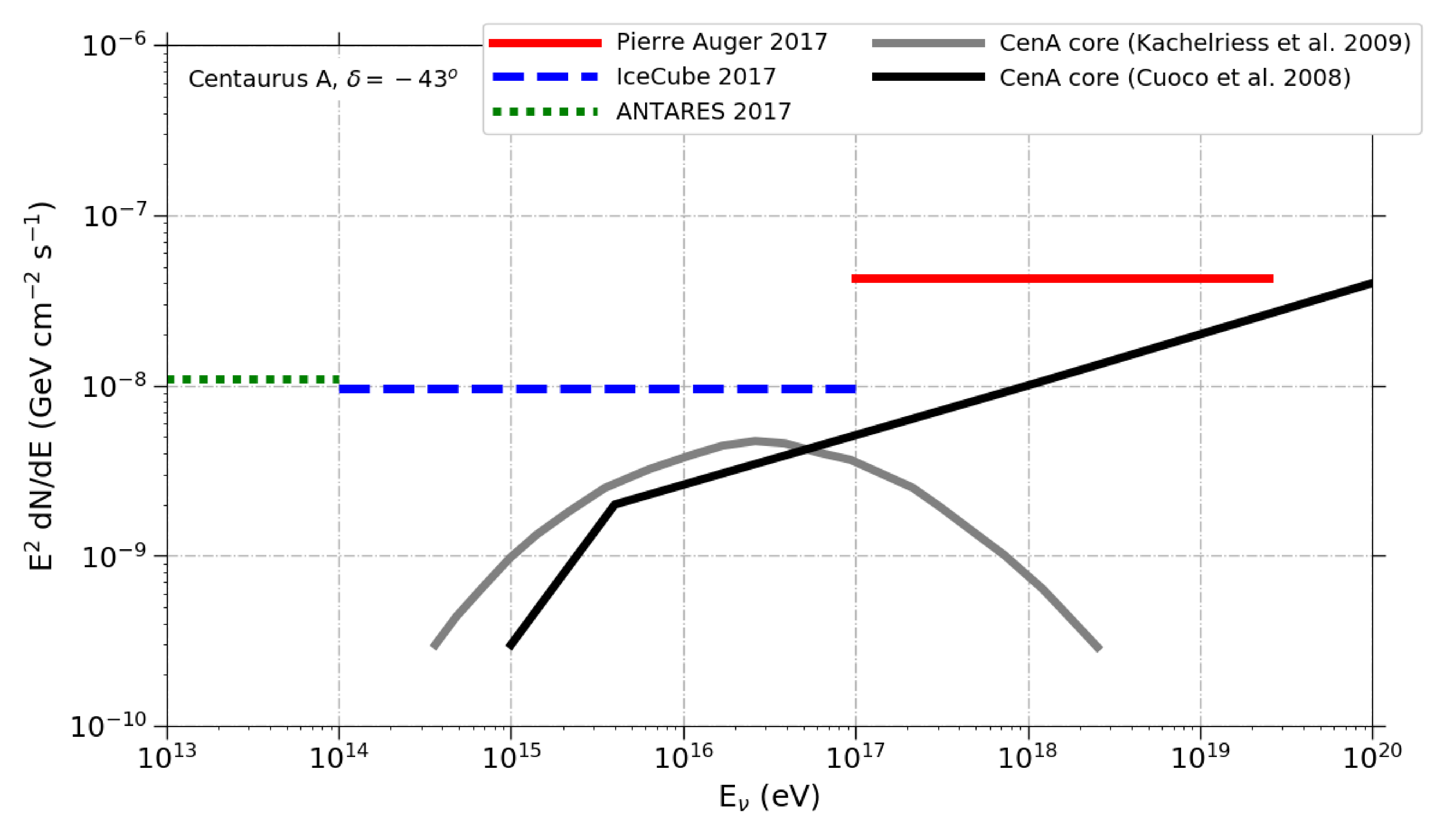
No candidate in [–500 s, 1 day] around GW events

→ Calculate **exposure** taking into account

- Time-dependent aperture (area x solid angle)
- ν-nucleon cross section + efficiencies (E,δ)

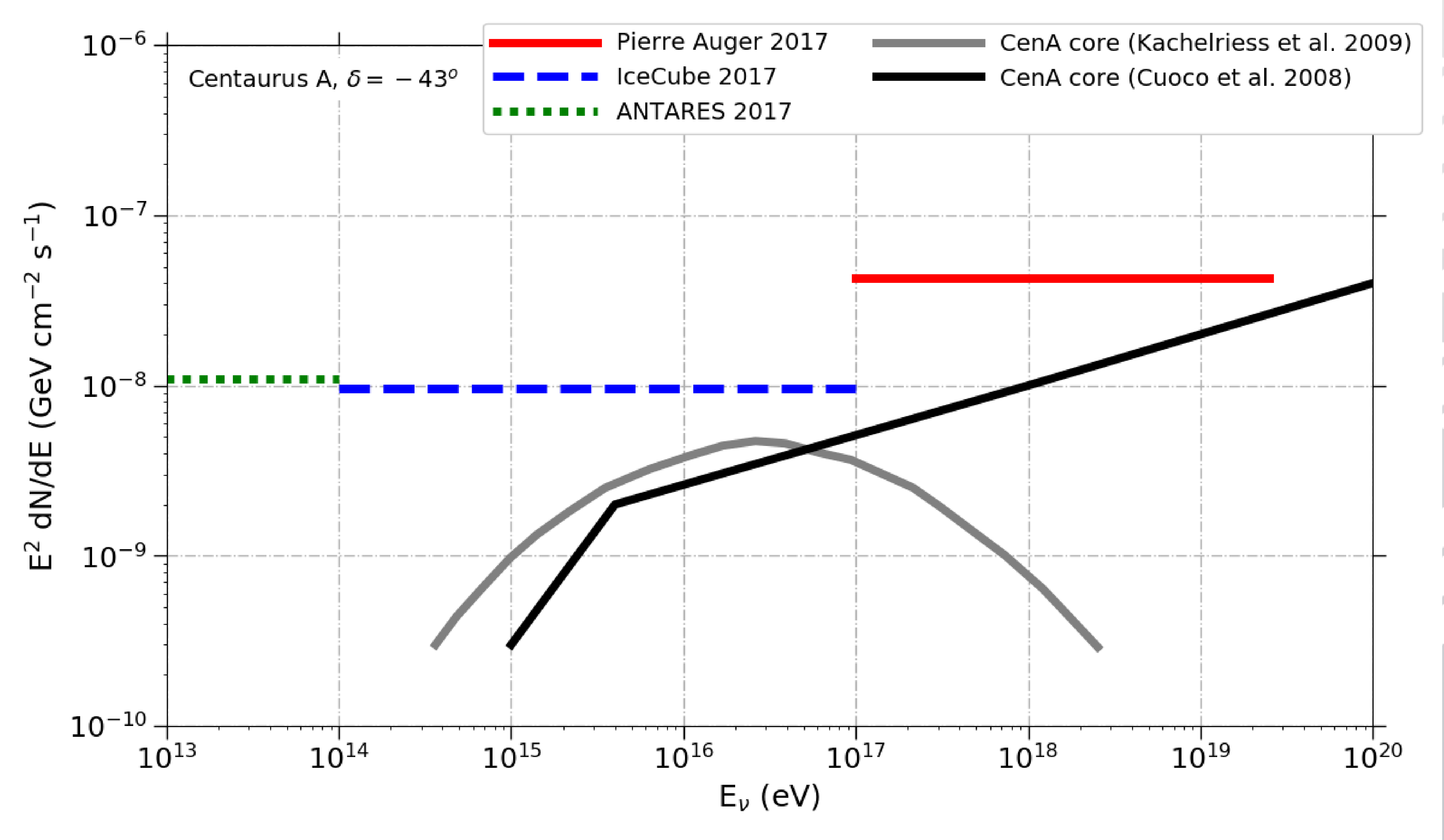


Cen A limits



Centaurus A, $\delta = -43^o$
Pierre Auger 2017
IceCube 2017
ANTARES 2017
CenA core (Kachelriess et al. 2009)
CenA core (Cuoco et al. 2008)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
E^2 dN/dE (GeV cm^{-2} s^{-1})
10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
E_ν (eV)

Cen A limits



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CenA core (Kachelriess et al. 2009)
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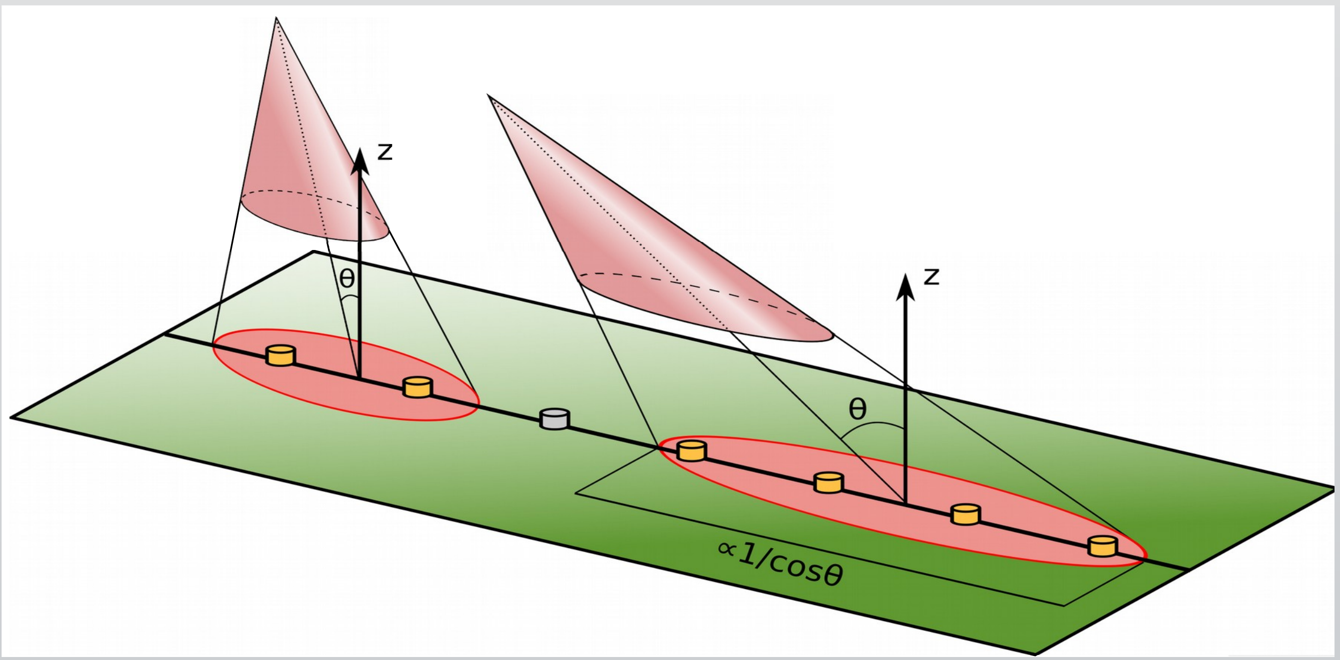
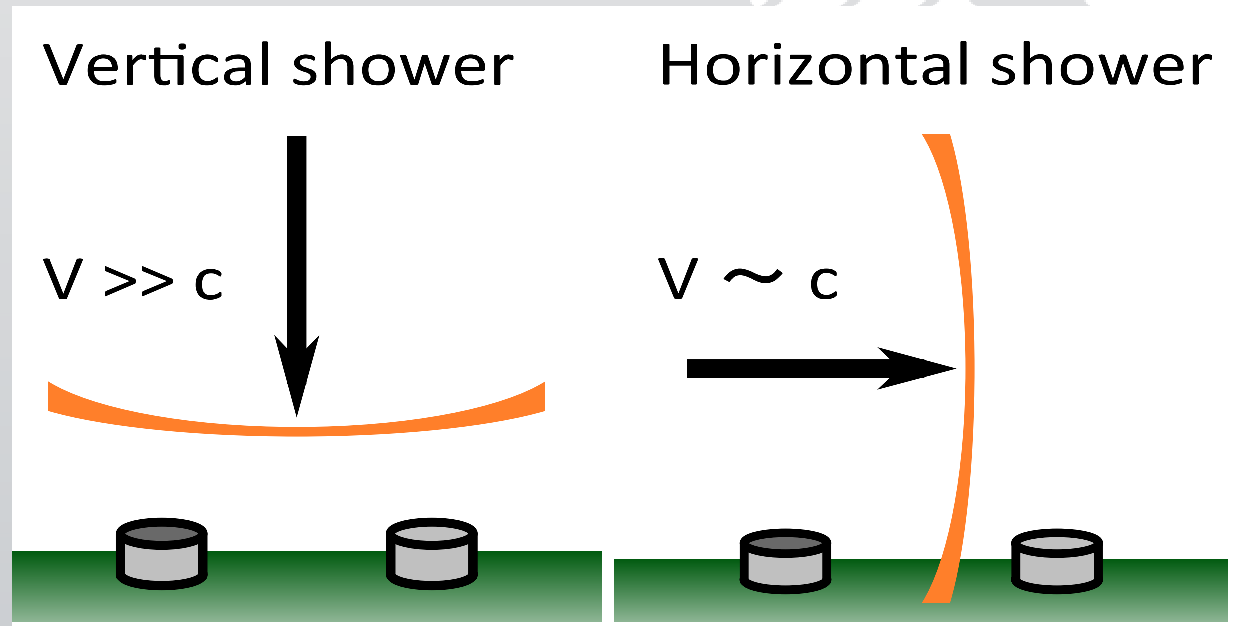
E^2 dN/dE (GeV cm^{-2} s^{-1})
E_ν (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

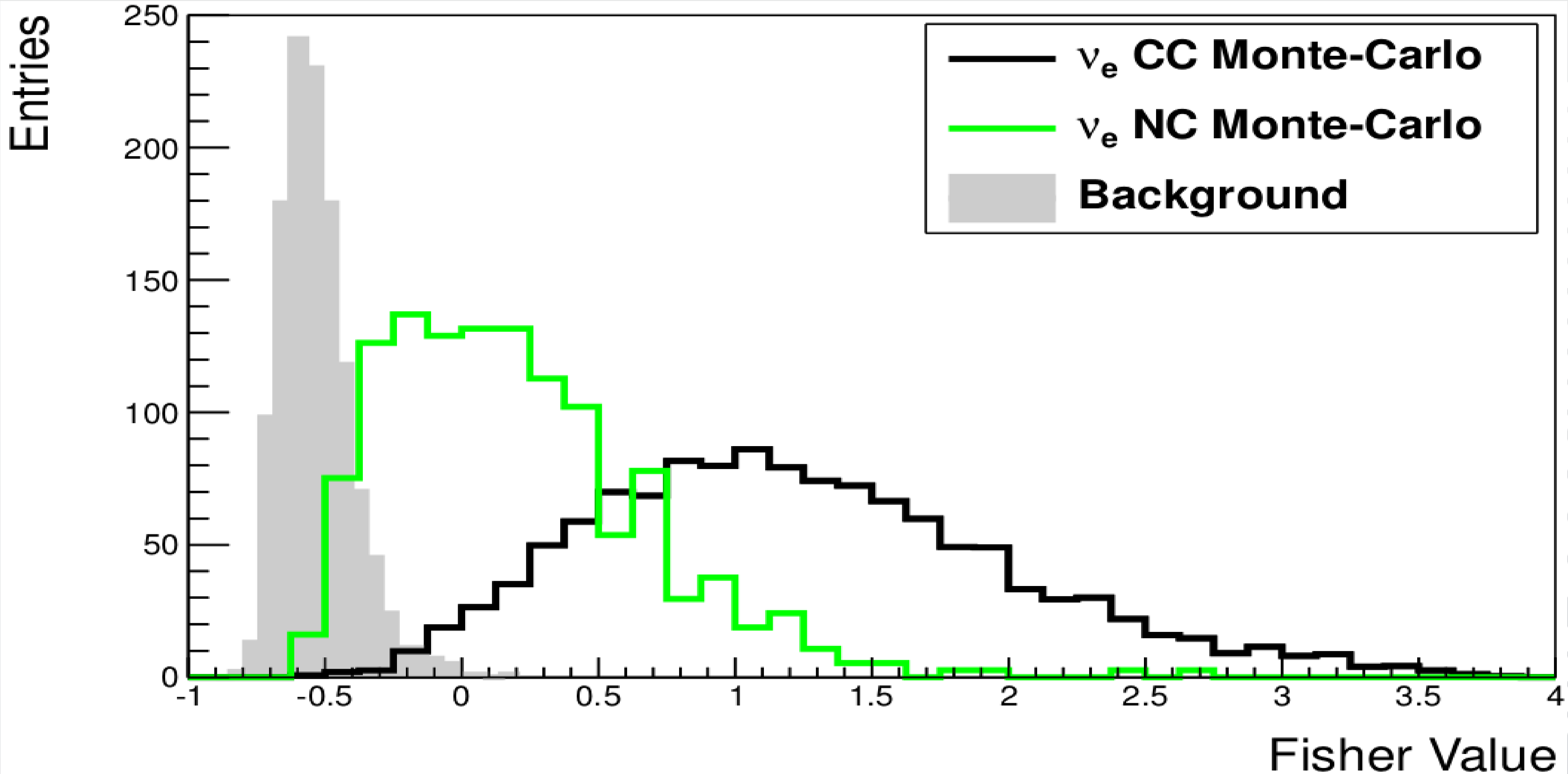
Inclination: 90° < θ < 95°

- Elongated footprint
- "Ground signal speed" ~ c



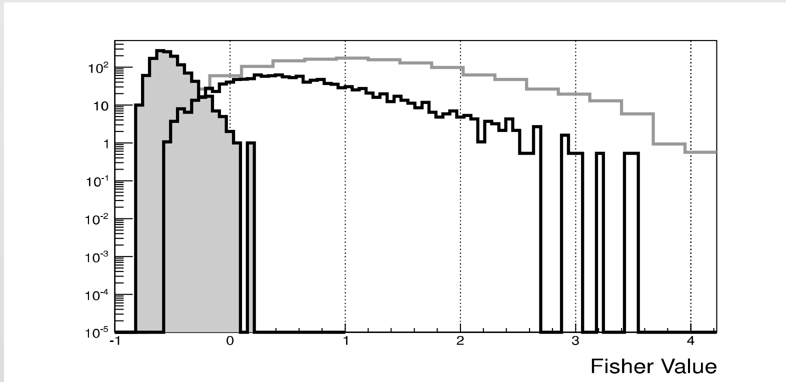


Reject "muonic" events → > 60 % stations ToT triggered

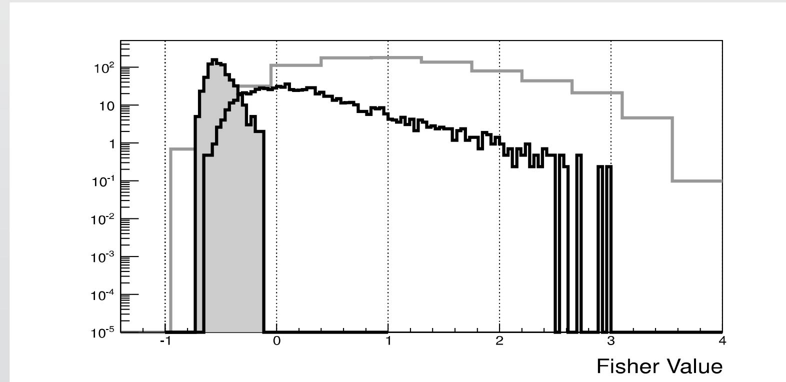


Entries
250
200
150
100
50
0
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
Fisher Value
ν_e CC Monte-Carlo
ν_e NC Monte-Carlo
Background

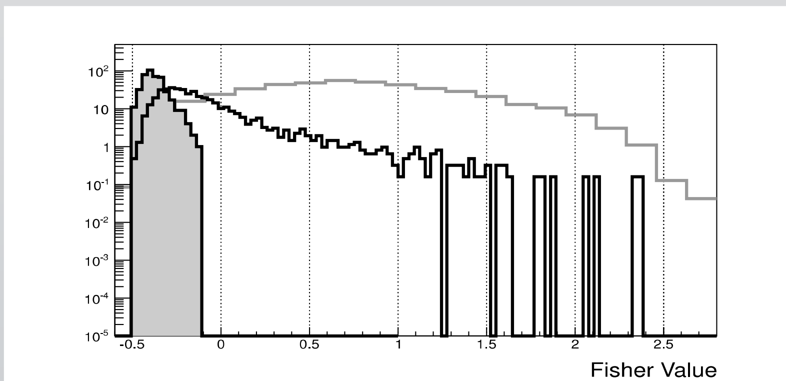
Neutrinos vs. Photons



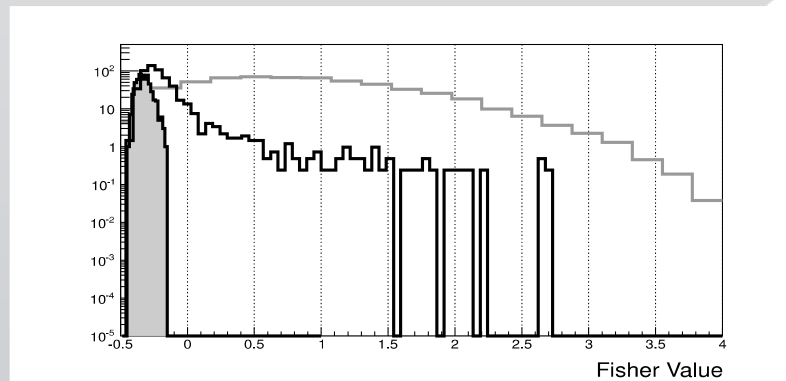
(a) $58.5° < \theta_{\mathrm{Rec}} \leq 61.5°$



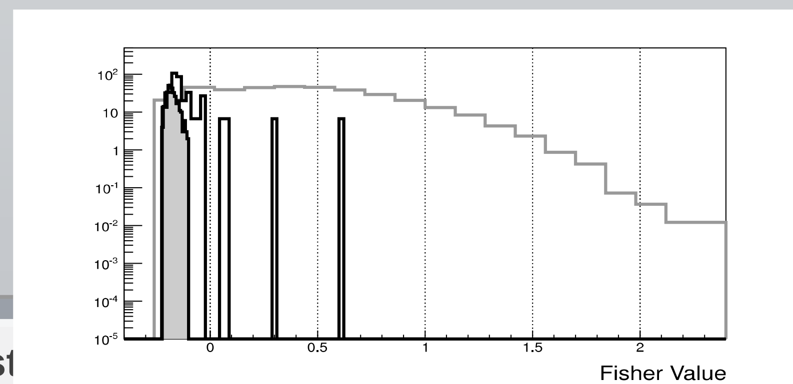
(b) $61.5° < \theta_{\mathrm{Rec}} \leq 64.5°$



(c) $64.5° < \theta_{\mathrm{Rec}} \leq 67.5°$



(d) $67.5° < \theta_{\mathrm{Rec}} \leq 70.5°$



(e) $70.5° < \theta_{\mathrm{Rec}} \leq 76.5°$