Ultra-high energy neutrino searches and GW follow-up 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

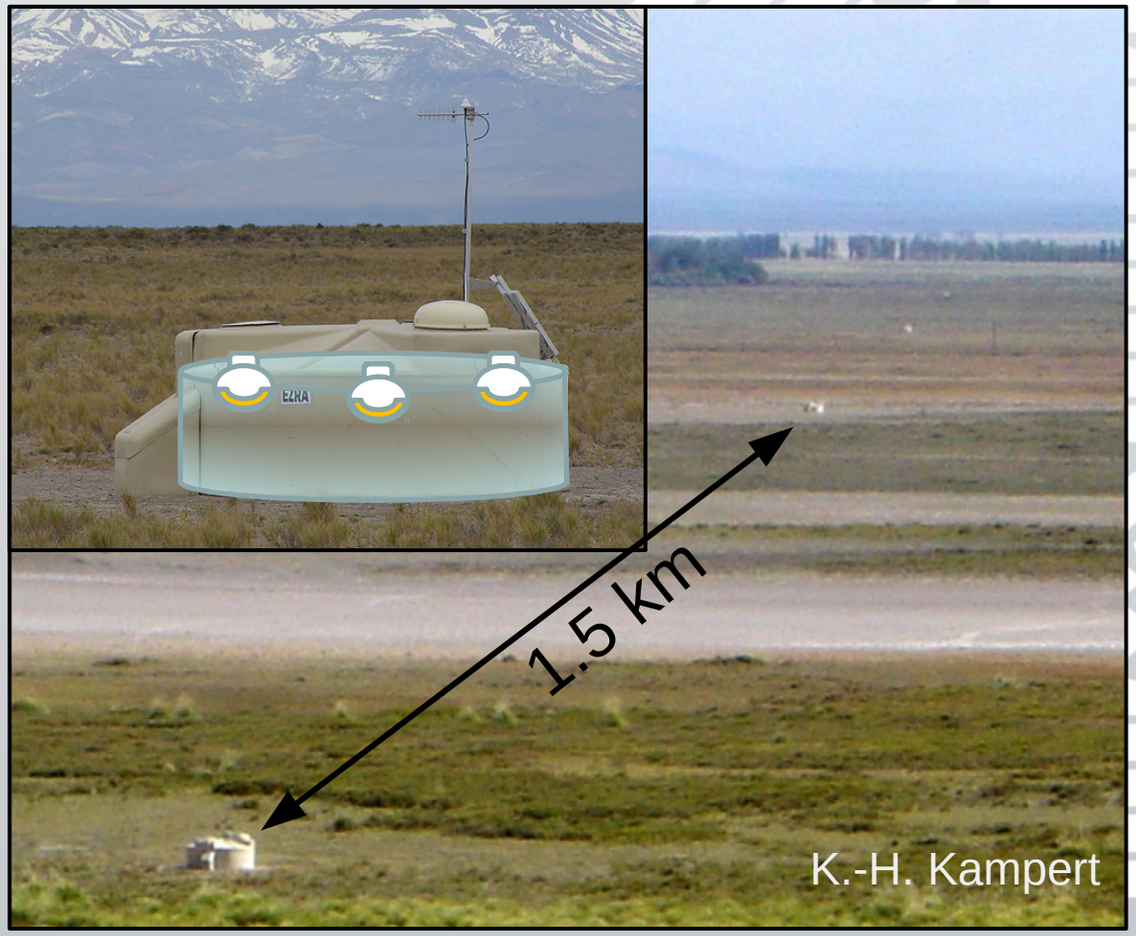
Pierre Auger Surface Detector (SD)

Large acceptance

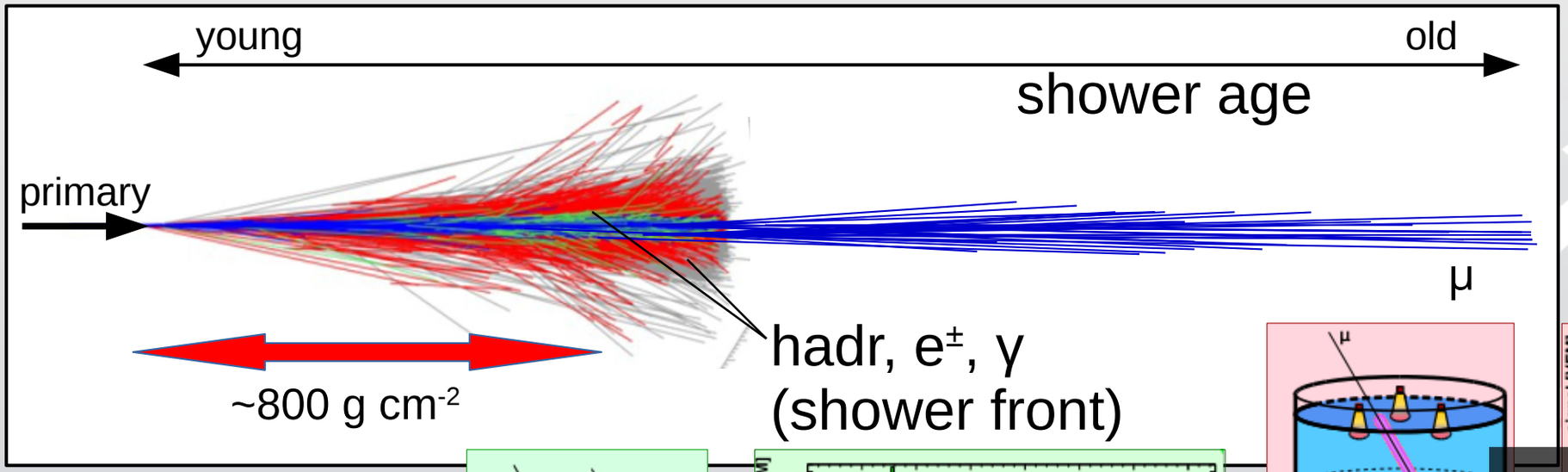
➔ Aiming for low fluxes

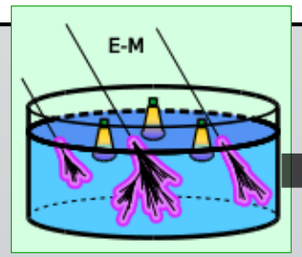
1.5 km spacing

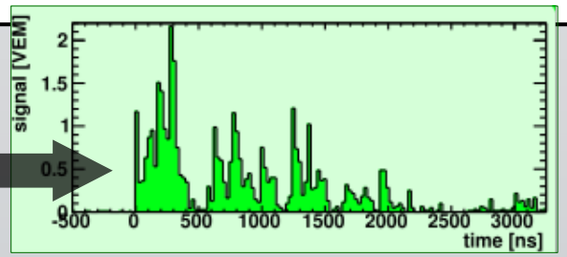
➔ Peak ν sensitivity ~1 EeV

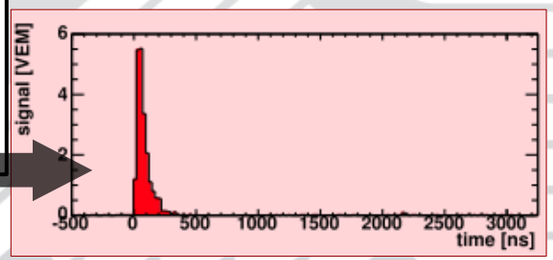


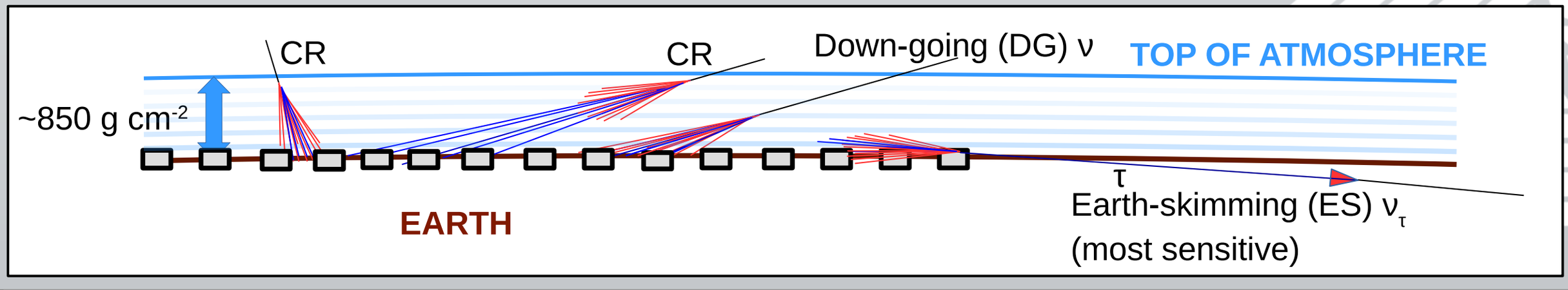
Neutrino detection with the Pierre Auger SD





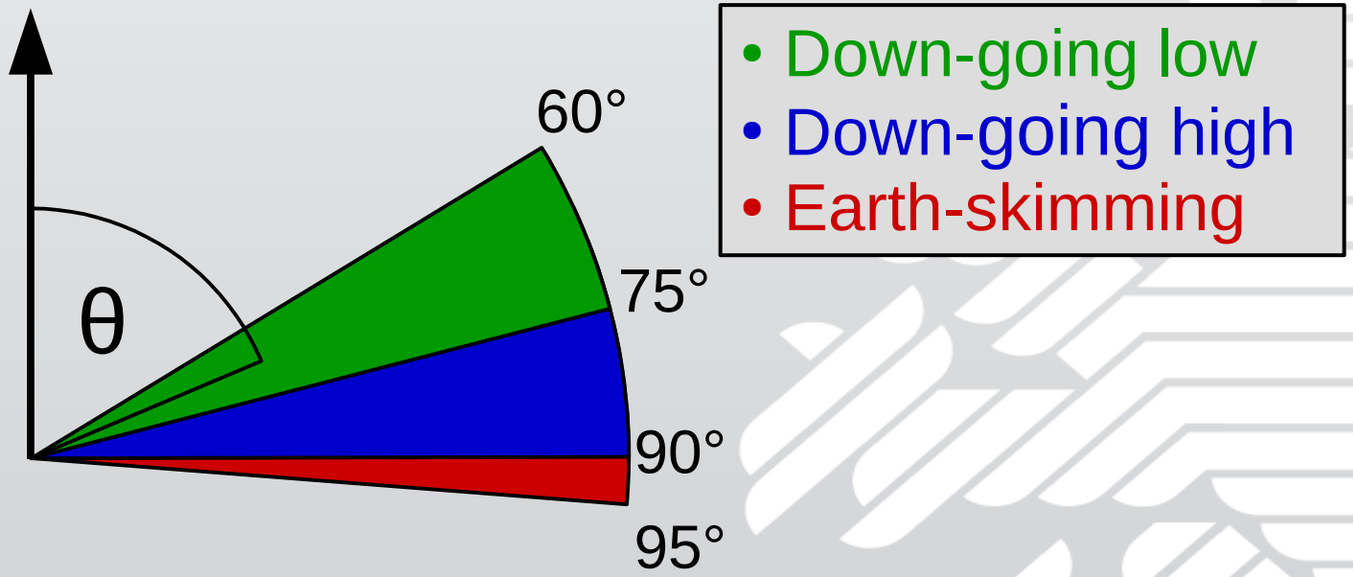


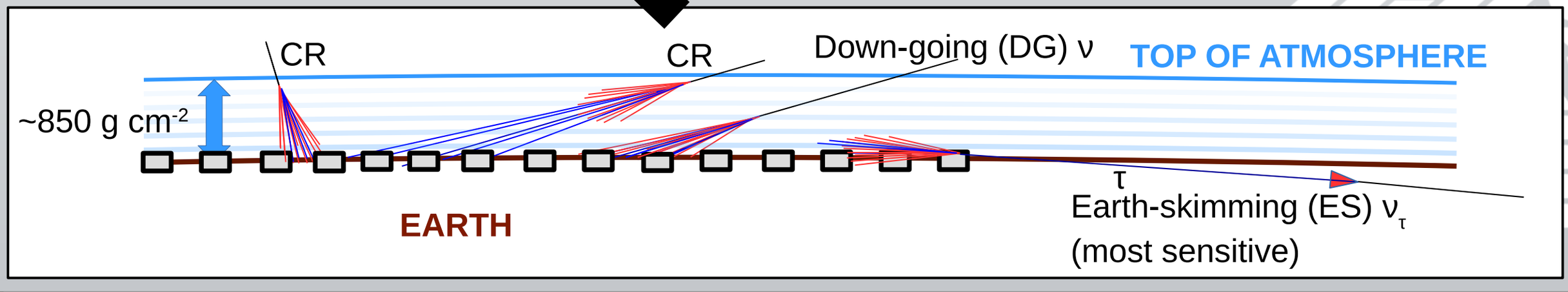




Neutrino detection with the Pierre Auger SD

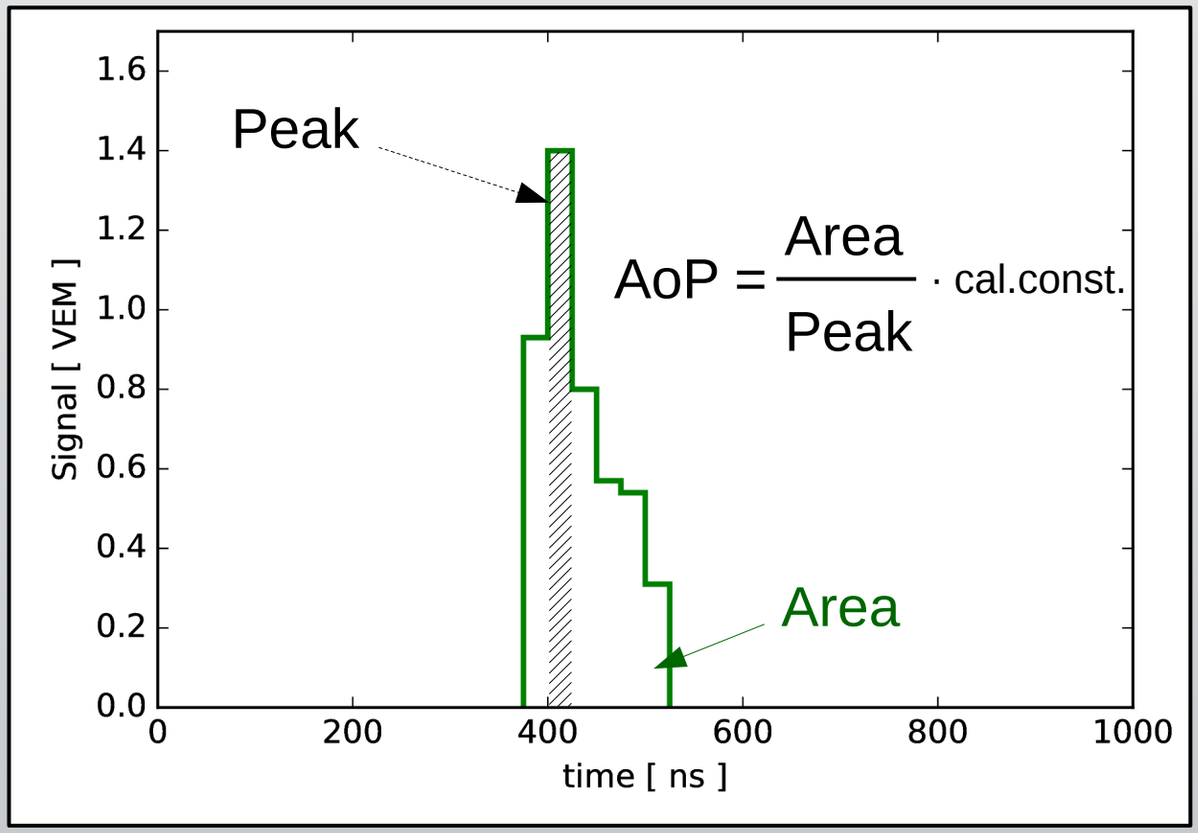
Reasonable separation:
θ > 60 deg





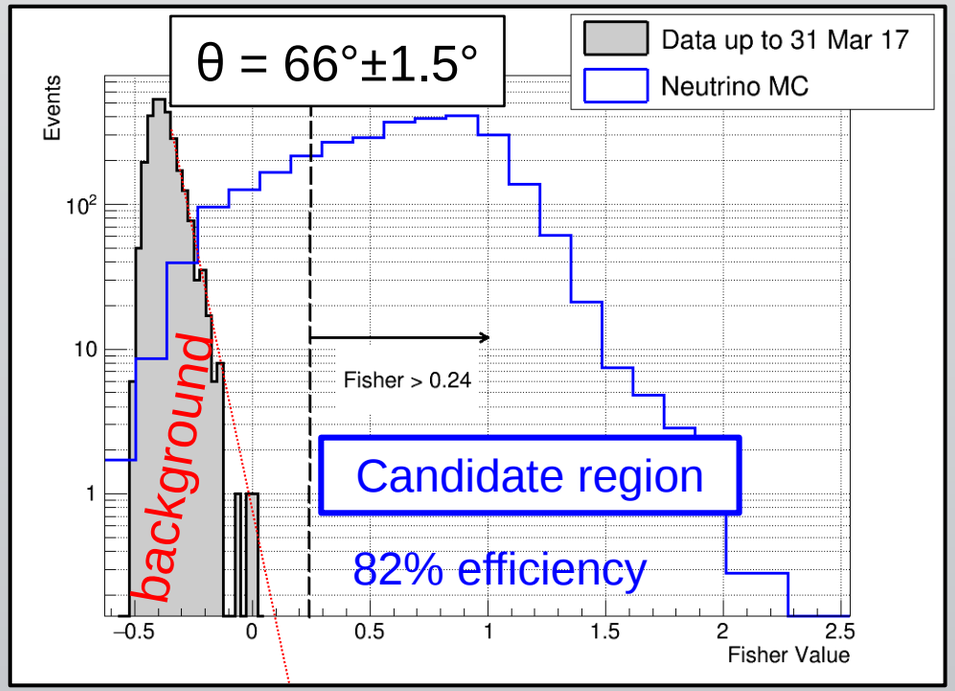
Neutrino search and identification

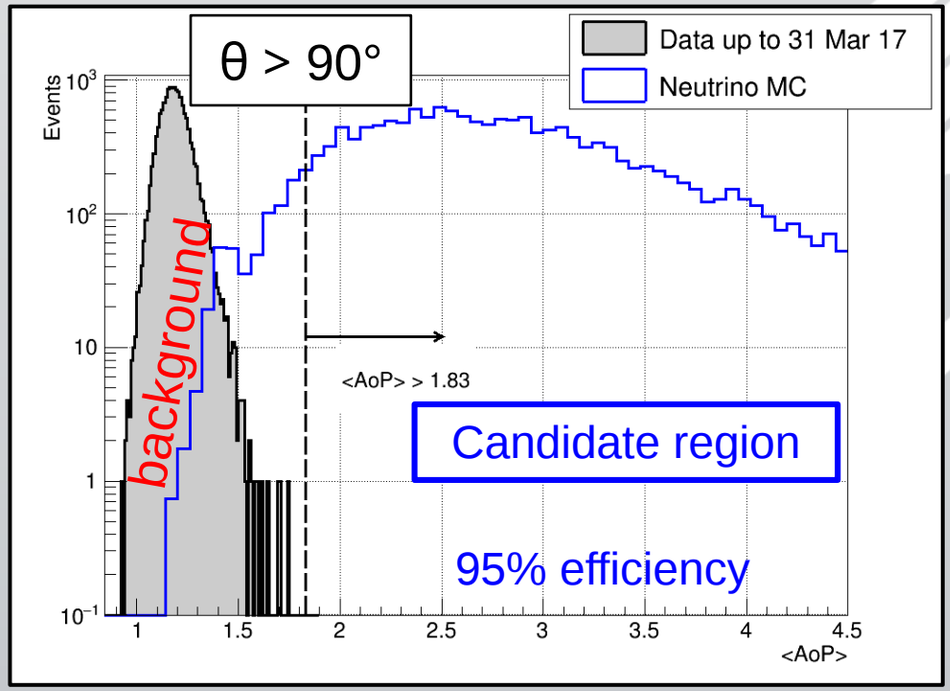
- Pre-select **inclined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
  - Earth-skimming: **<AoP>** of all stations in event



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
    - Linear **combination of AoPs** of certain stations (esp. early and late ones) and their products (to take into account non-linear behavior)
      → “Fisher value”

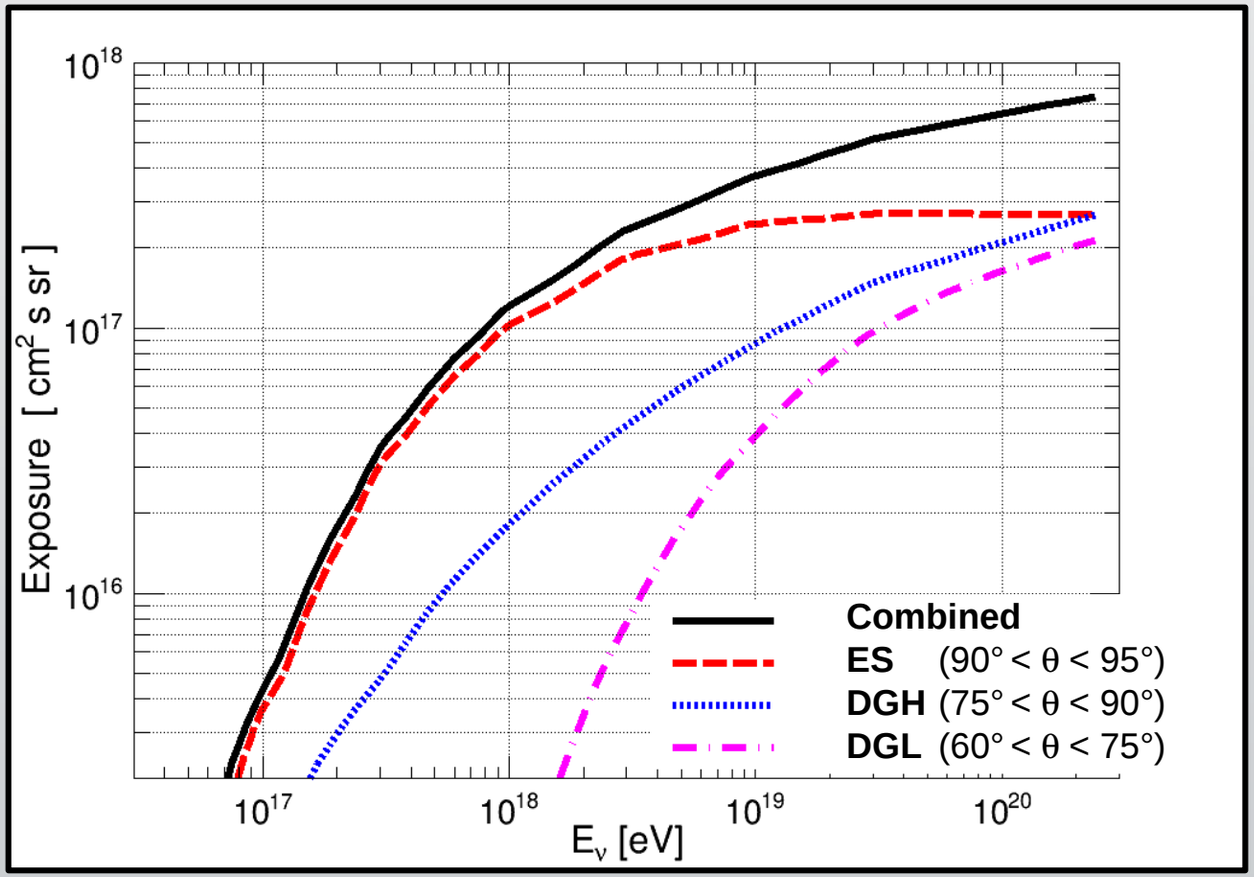




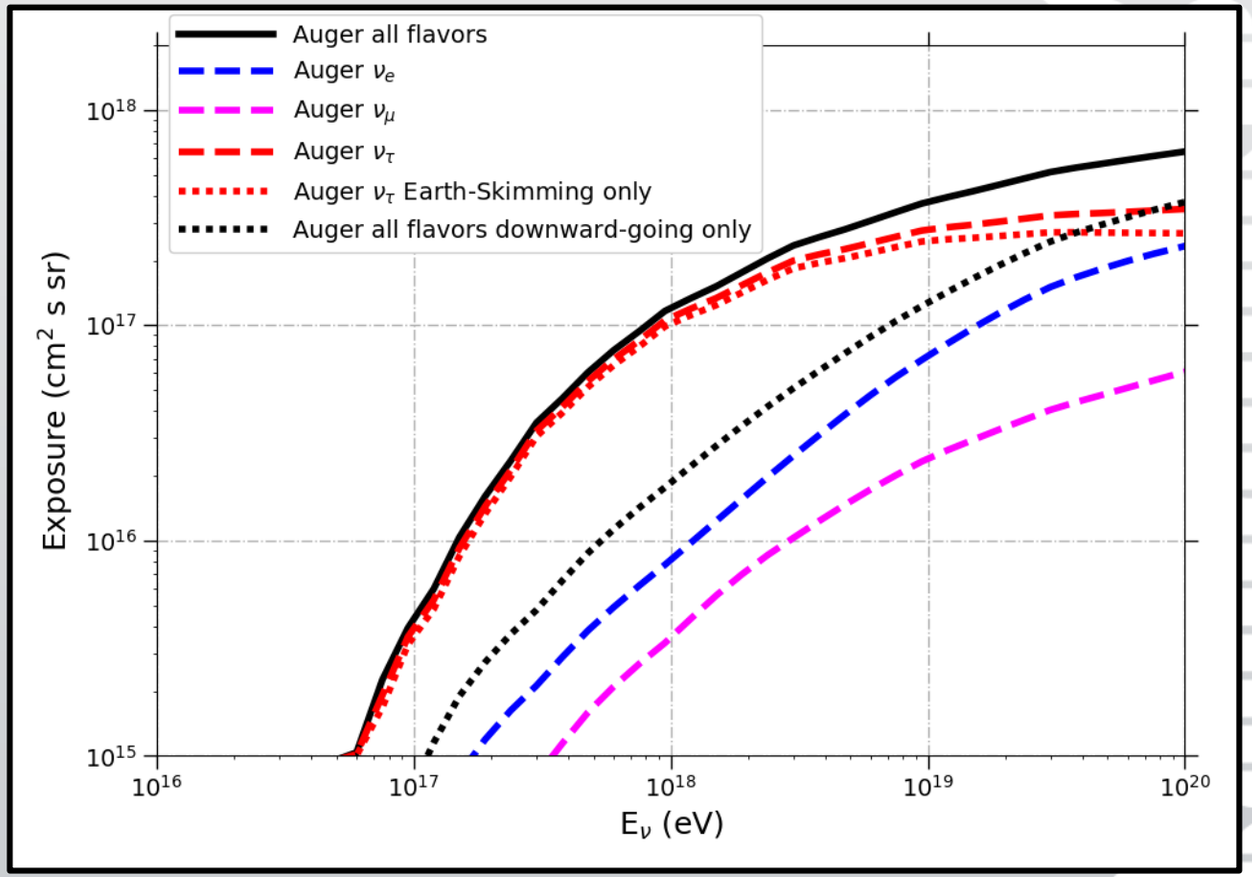
No candidates so far

Exposure

By direction

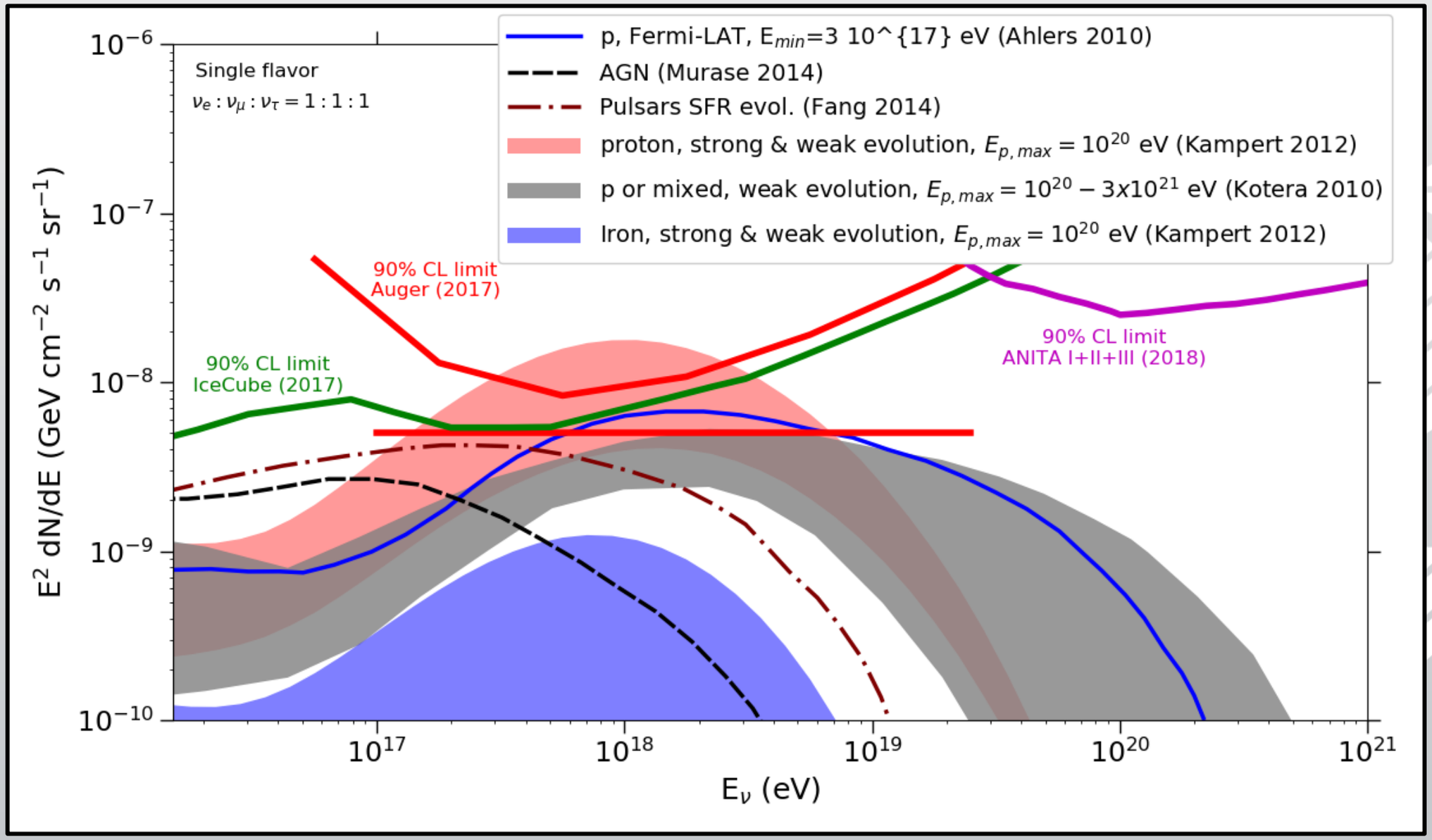


By flavor



Enrique Zas, ICRC 2017

Flux limits

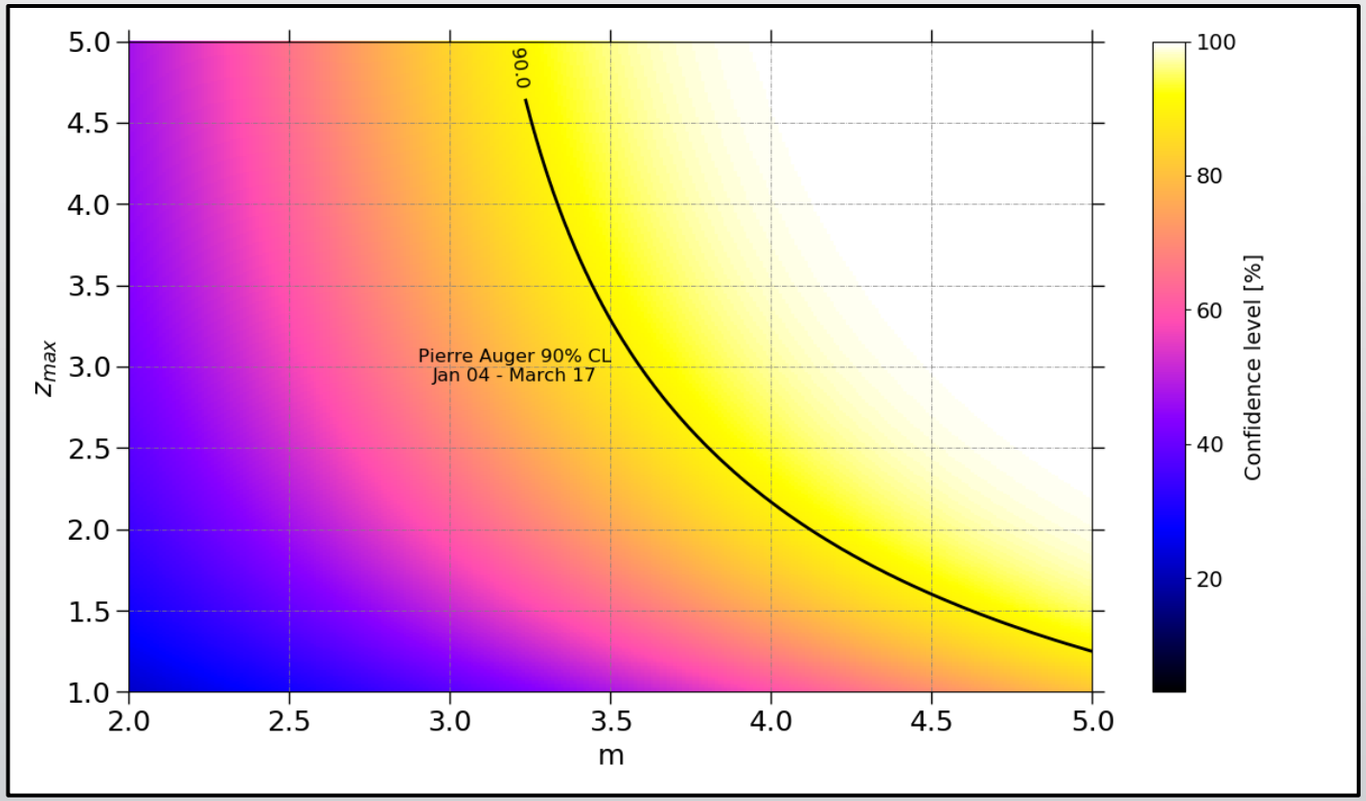

p, Fermi-LAT, E$_{min}$=3 10^{17} eV (Ahlers 2010)
AGN (Murase 2014)
Pulsars SFR evol. (Fang 2014)
proton, strong & weak evolution, $E_{p,max} = 10^{20}$ eV (Kampert 2012)
p or mixed, weak evolution, $E_{p,max} = 10^{20} - 3x10^{21}$ eV (Kotera 2010)
Iron, strong & weak evolution, $E_{p,max} = 10^{20}$ eV (Kampert 2012)
Single flavor
$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$
90% CL limit
Auger (2017)
90% CL limit
IceCube (2017)
90% CL limit
ANITA I+II+III (2018)
E^2 dN/dE (GeV cm^{-2} s^{-1} sr^{-1})
E_ν (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}

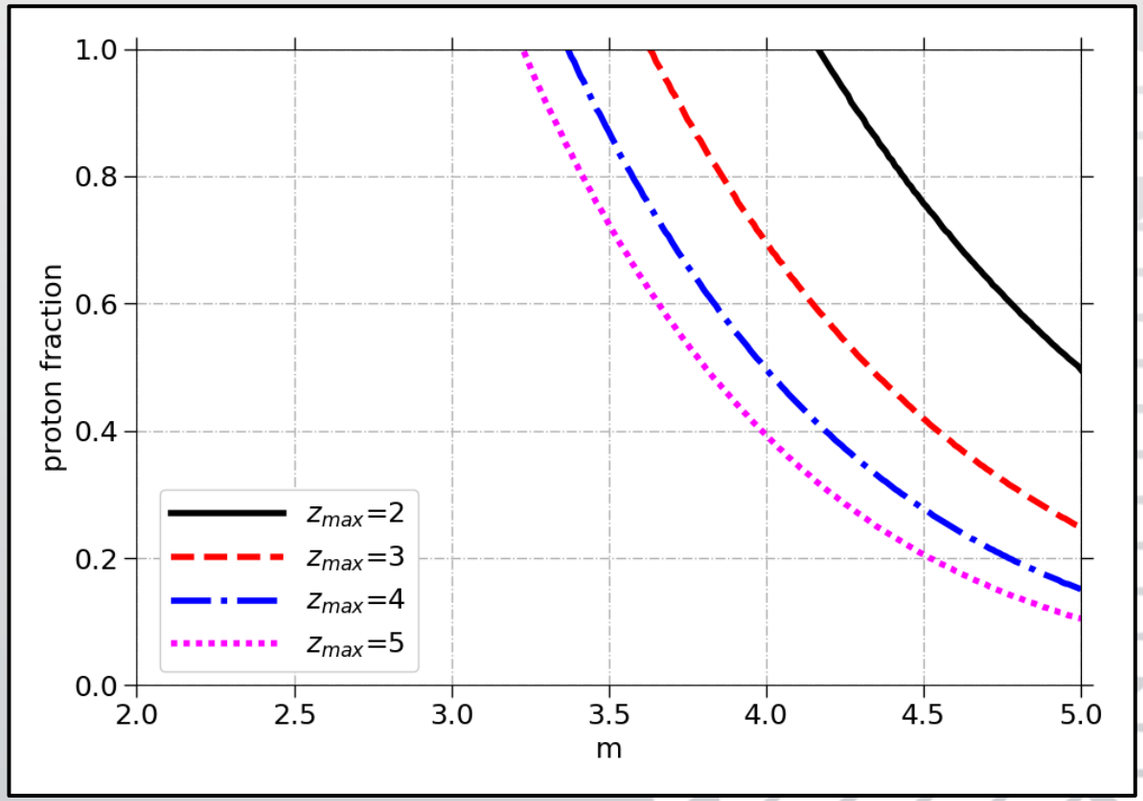
Implications on diffuse neutrino models

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, $E_{\rm max} = 10^{21}$ 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, $E_{\rm min} = 10^{19}$ eV (Ahlers 2010)	~ 4.0
Cosmogenic - proton, Fermi-LAT, $E_{\rm min} = 10^{17.5}$ 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

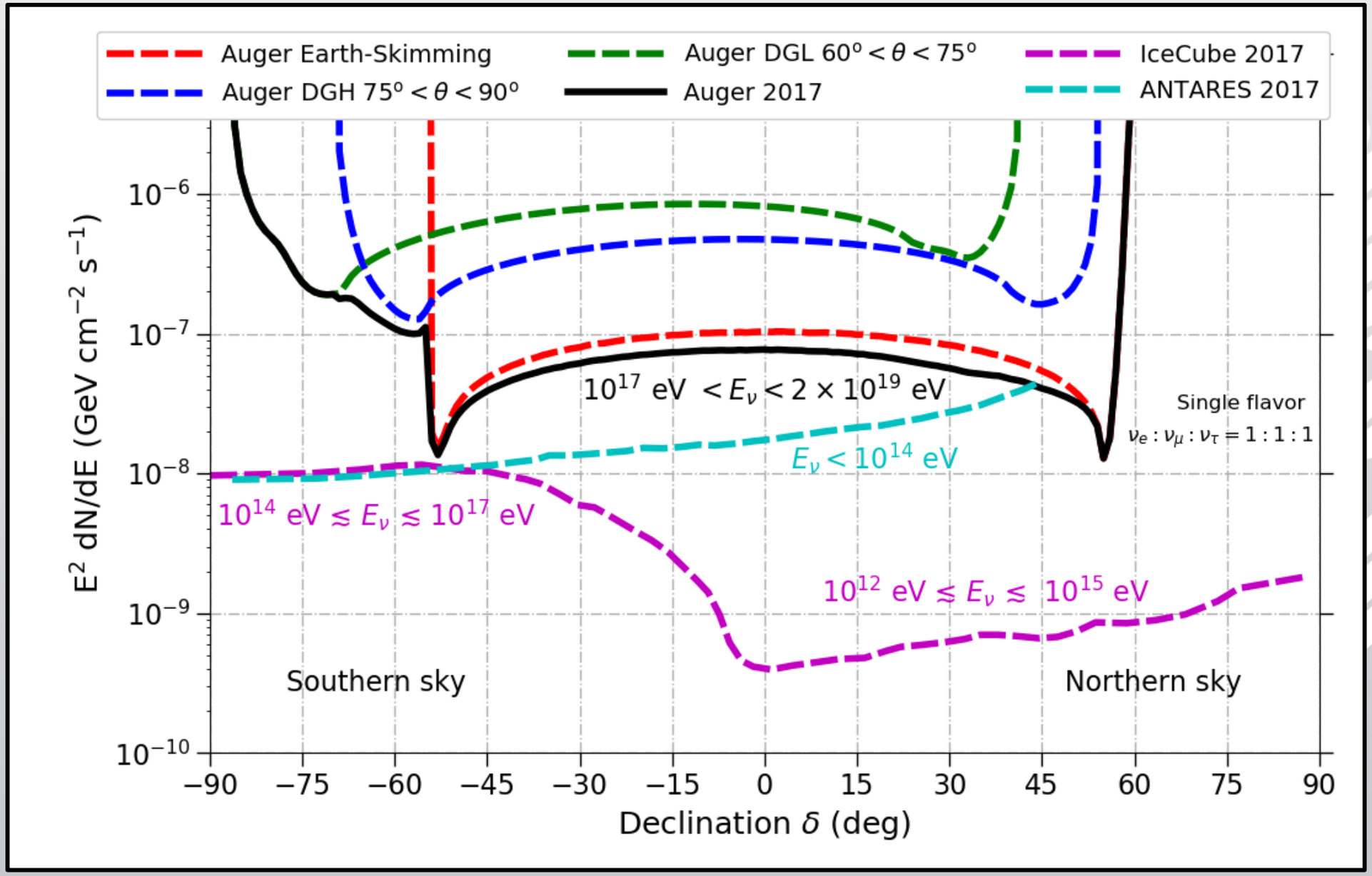




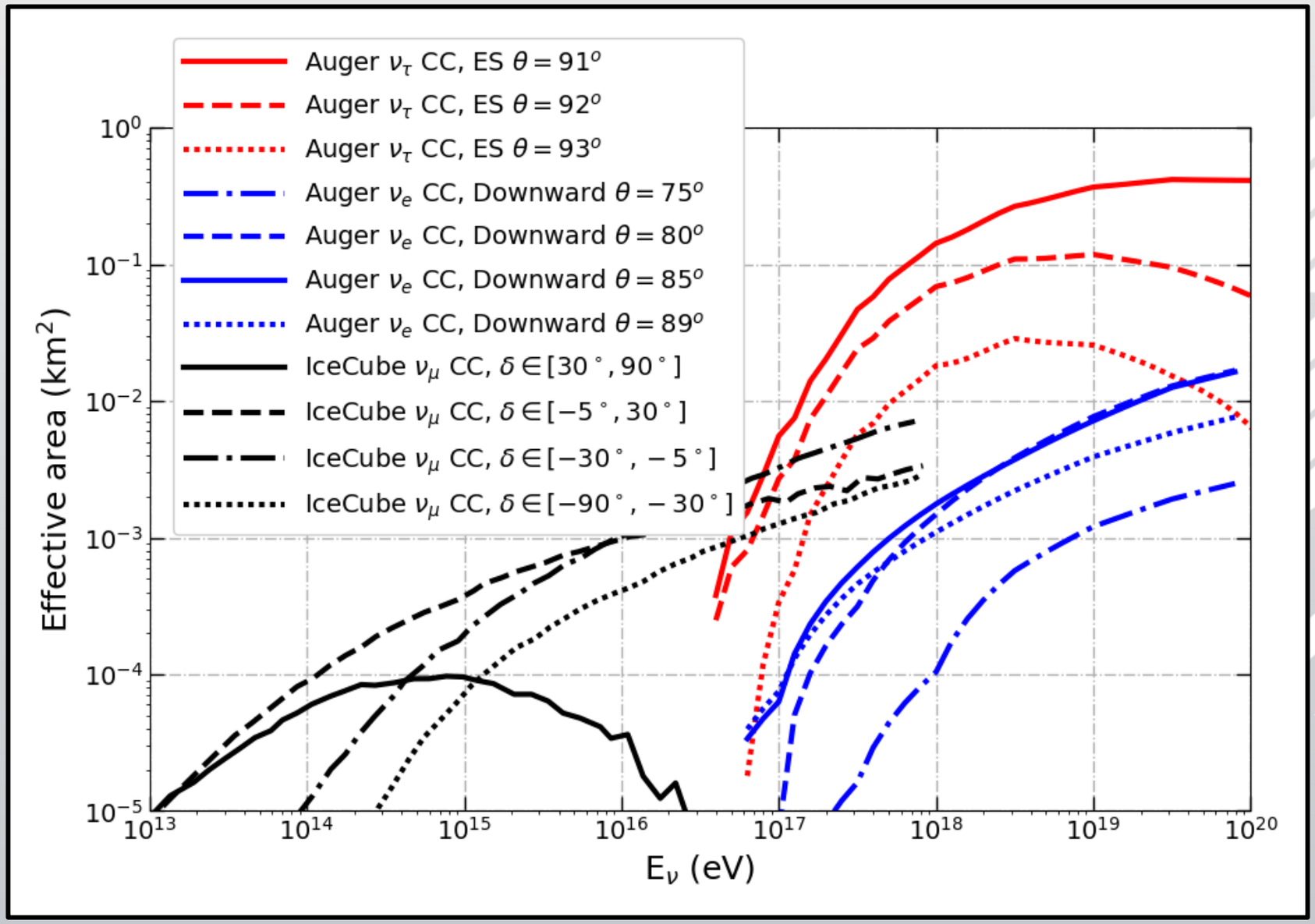
- Pure proton
- Source evolution ~ $(1+z)^m$ up to z_{max}
- $E^{-2.5}$ flux

- Smaller proton fractions
  → less sensitivity

Limits on steady point-sources



Effective area



Follow-up of GW events

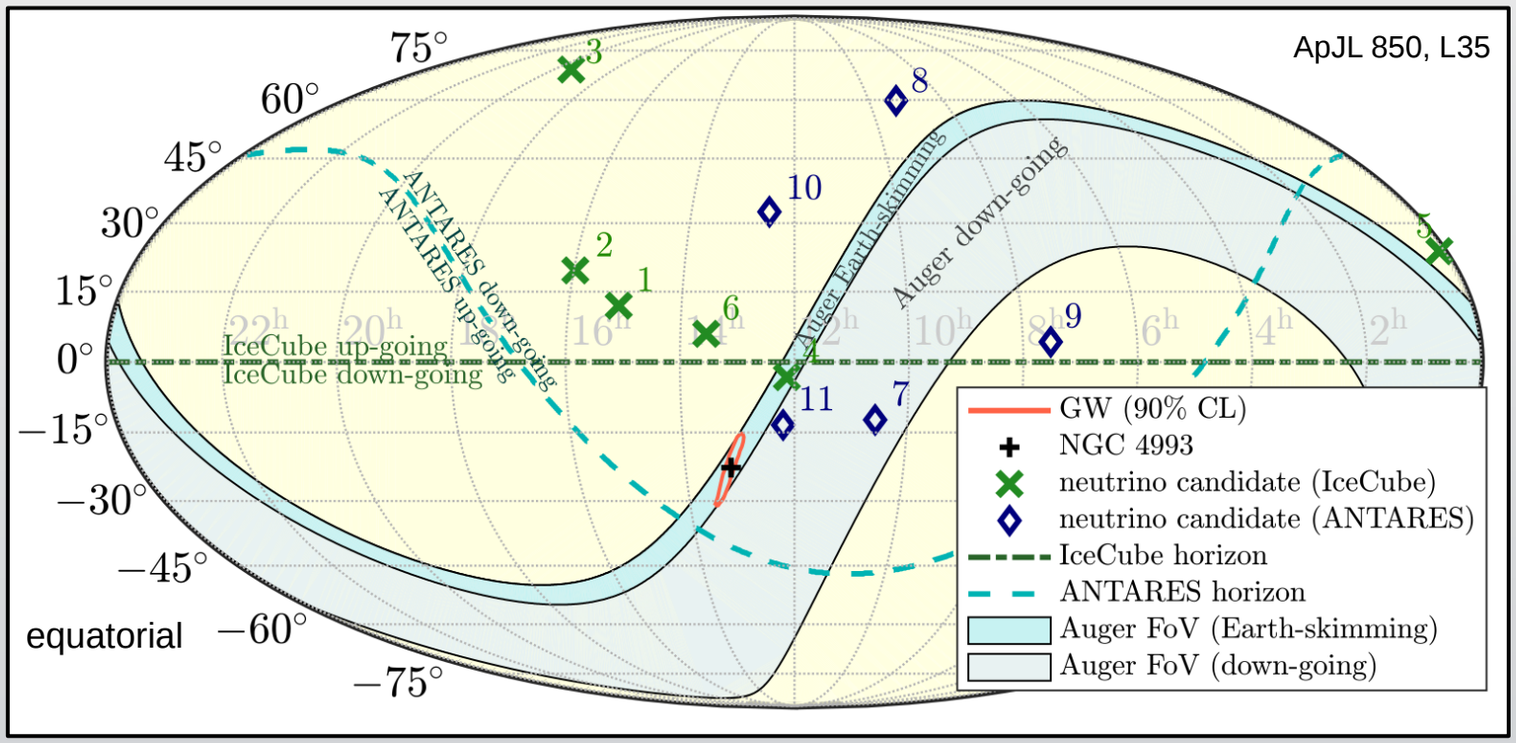
MoU between Auger and LIGO/Virgo fixed search properties:

Default neutrino search, considering only

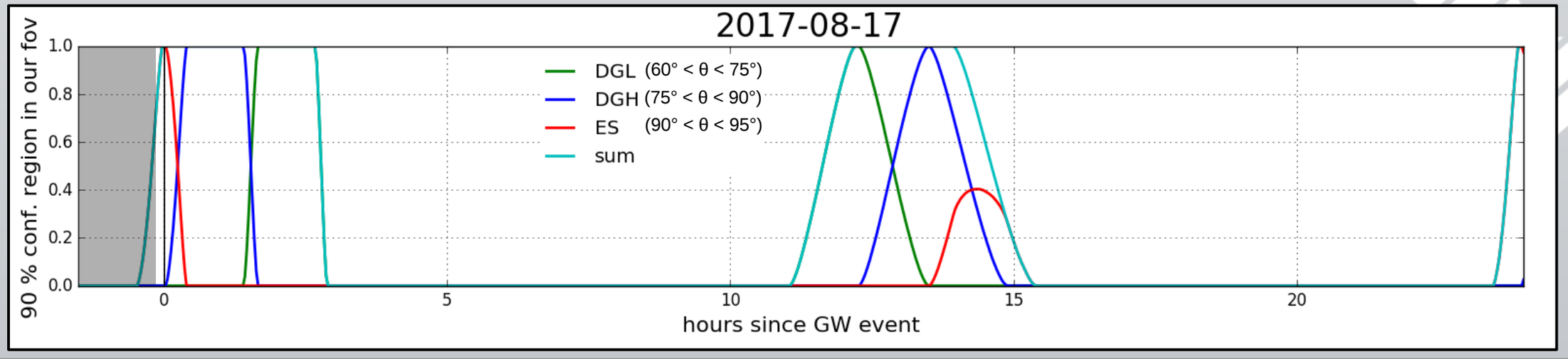
- ±500 s around & +1 day after GW event
- Times at which location of the GW event is visible

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

Visibility of GW170817



Good visibility at time of GW event

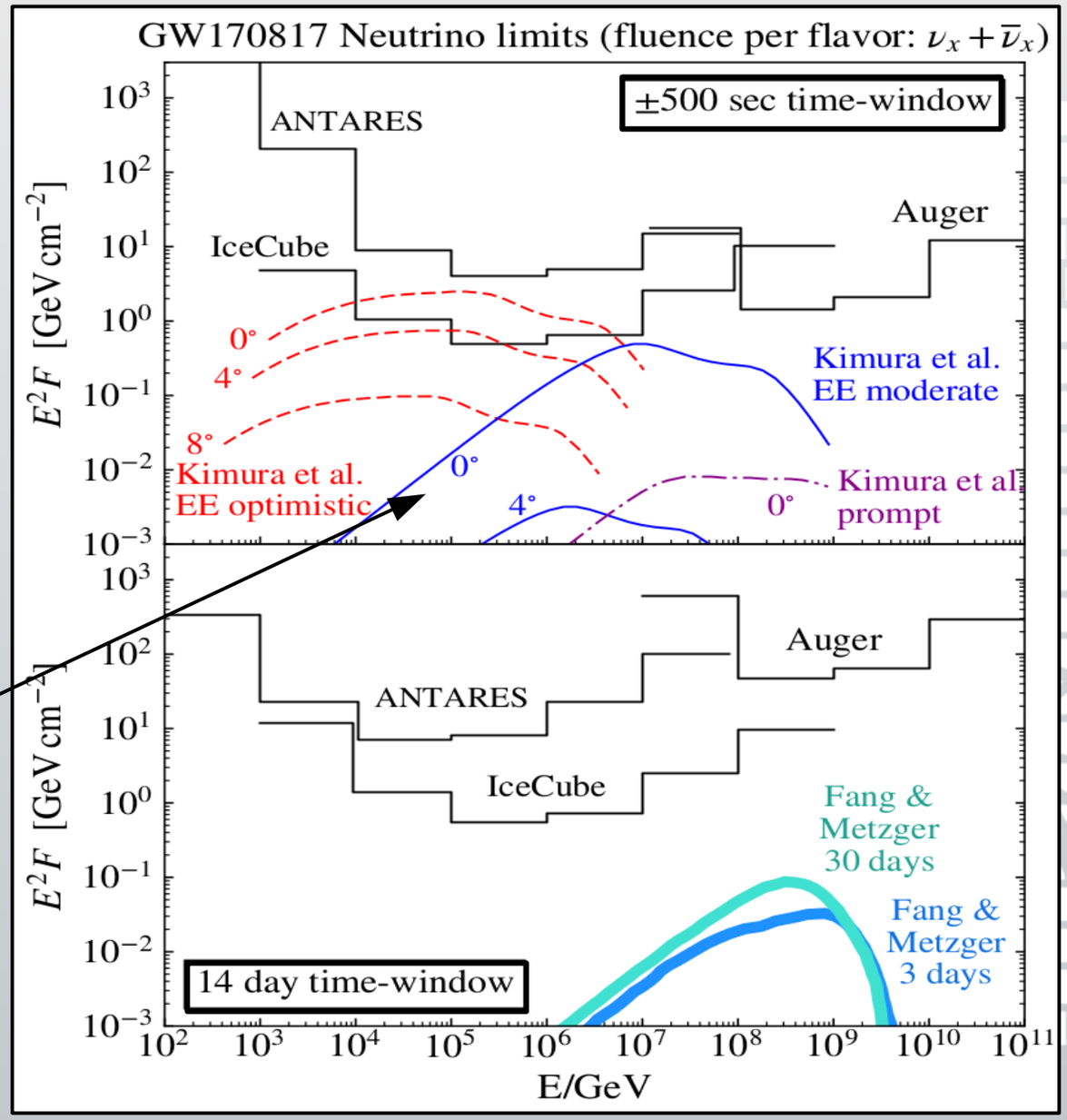


Neutrino limits for GW170817

- **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 that time)



Summary

- We’re sensitive to neutrinos in the EeV range and can **exclude** certain production models
  - ➔ Cosmogenic: **strong proton source evolution** & Fermi GeV normalization
  - ➔ Astrophys. UHE neutrinos from radio-loud AGN

- 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** (if we see them)
  - Northern Hemisphere at EeV energies

- Follow-up searches of published LIGO/Virgo GW events performed
  - ➔ GW170817 shown, fluence limits in the range of theoretical predictions

- More GW events to come, future promises increased event rates and precision

The End

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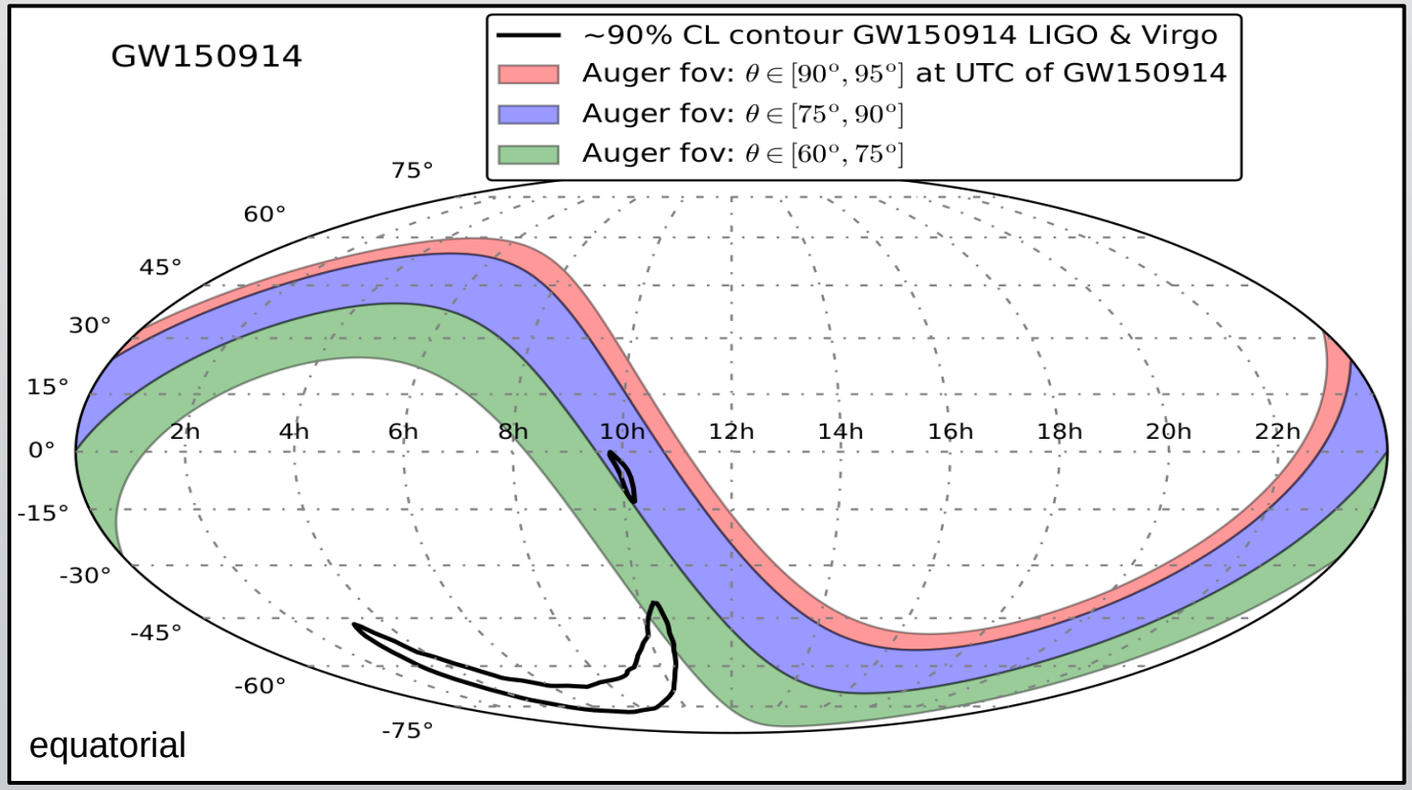
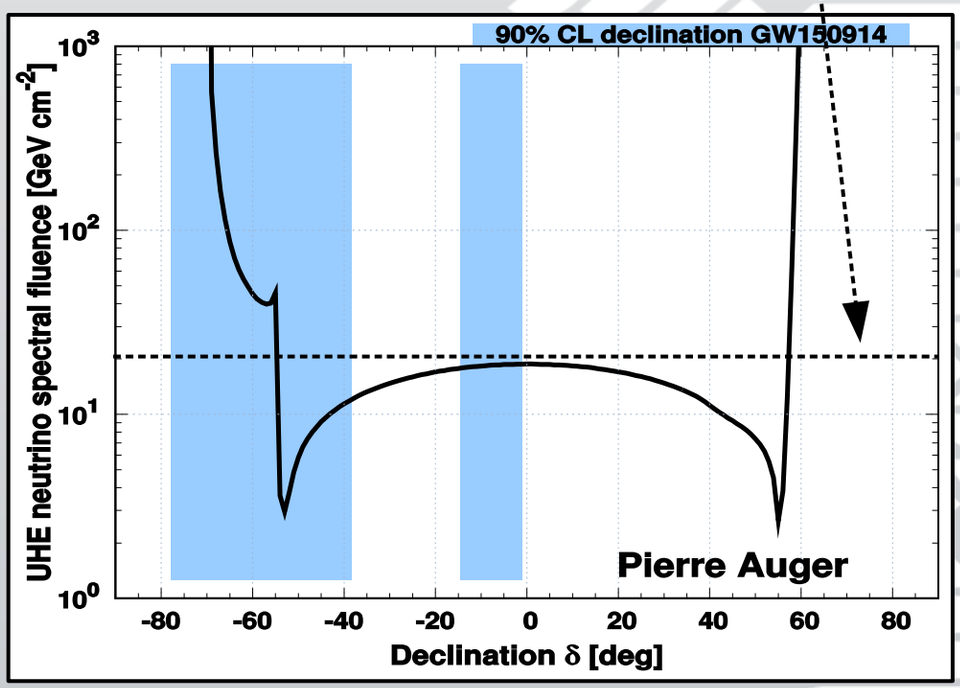
Follow-Up of BH-BH merger GW150914

Sensitivity very declination dependent

For newer events: More GW detectors
→triangulation→problem solved



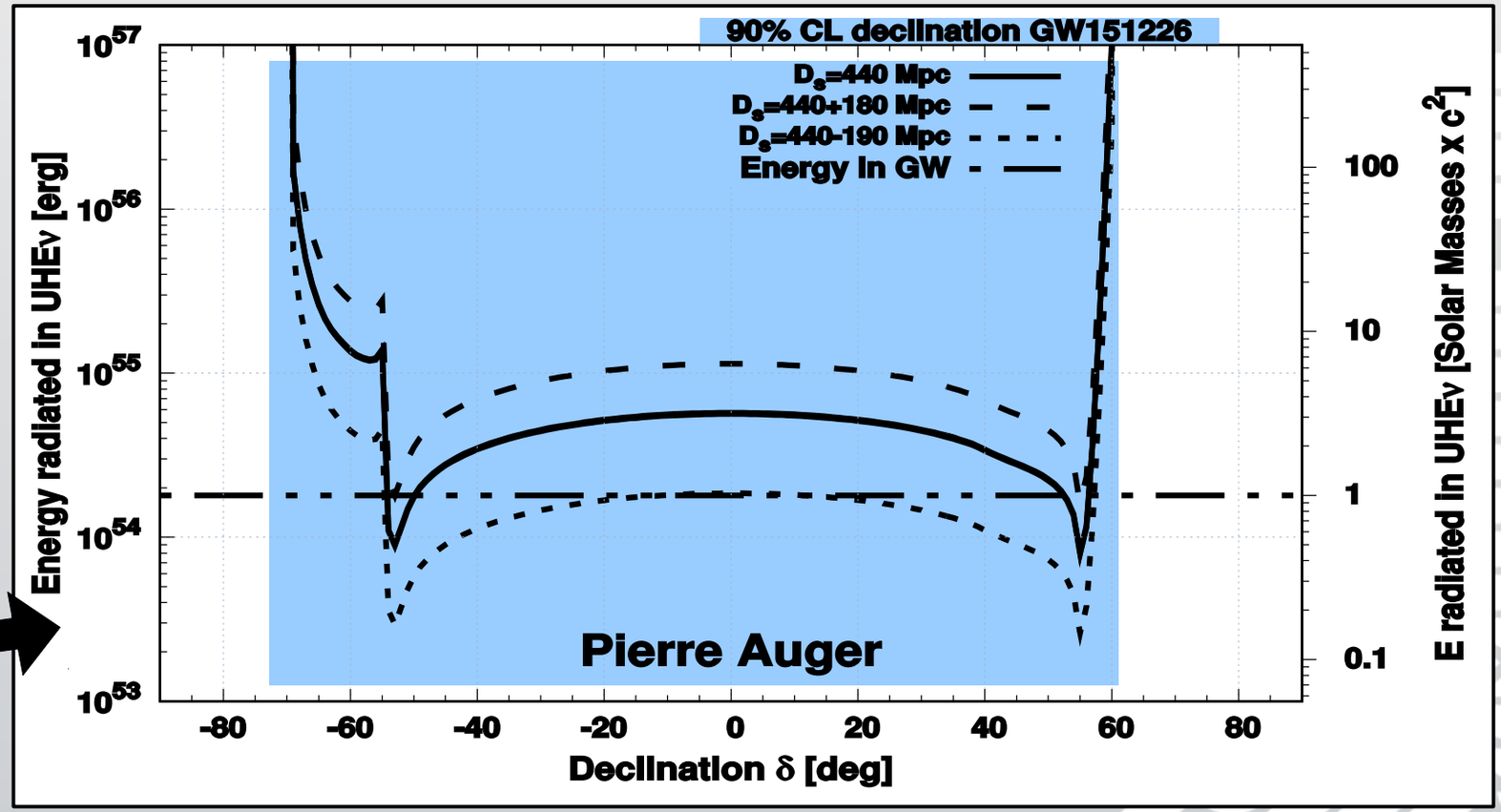
Total neutrino energy =
GW radiation energy



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

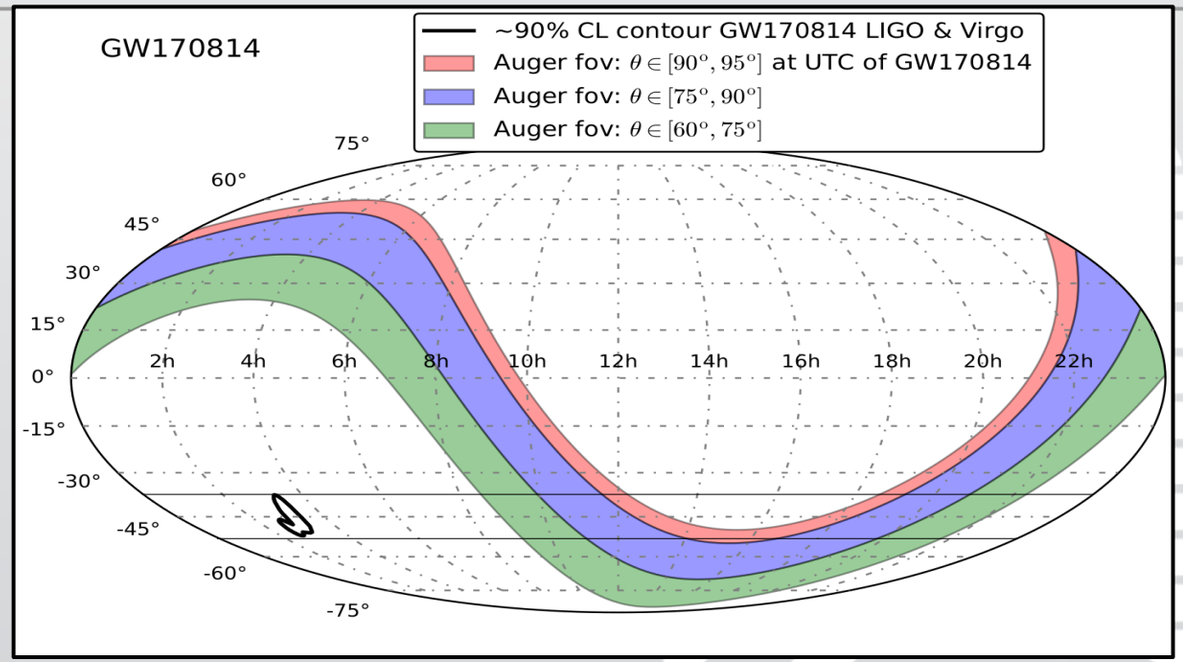
No candidates
→Flux limit
→Limit on total emitted UHE ν energy

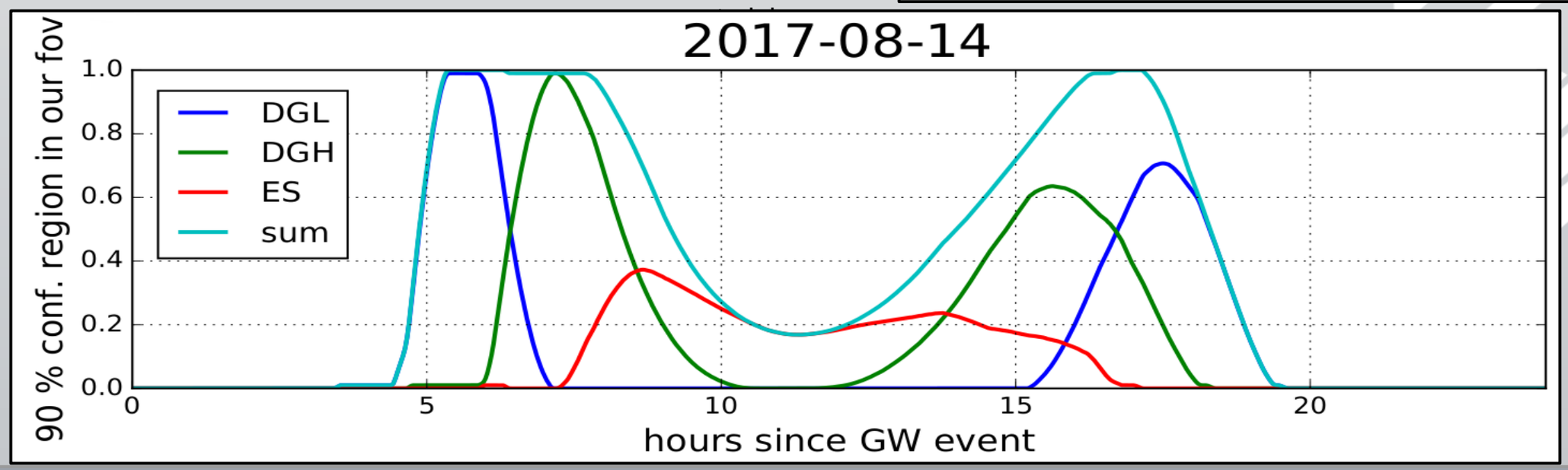


arXiv:1602.06961 (Kotera, Silk):
Binary BHs could produce the measured UHECR flux!
→Needs ~ 3% “efficiency” (E_{UHECR}/E_{GW})

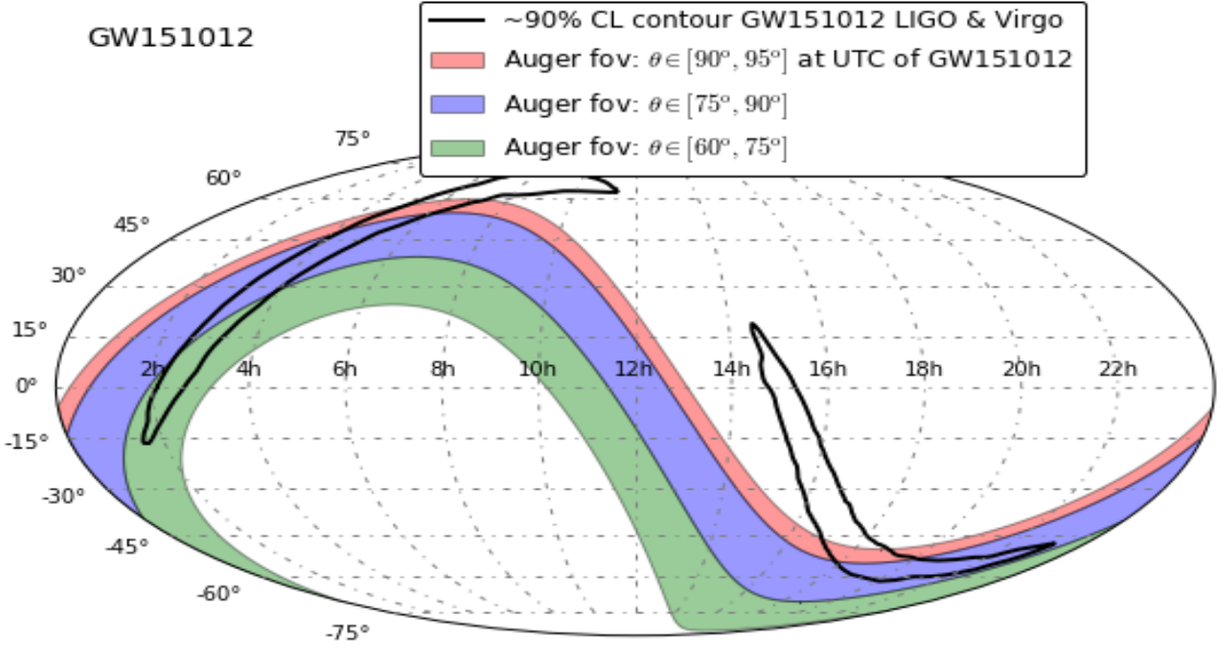
Preview on GW170814

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

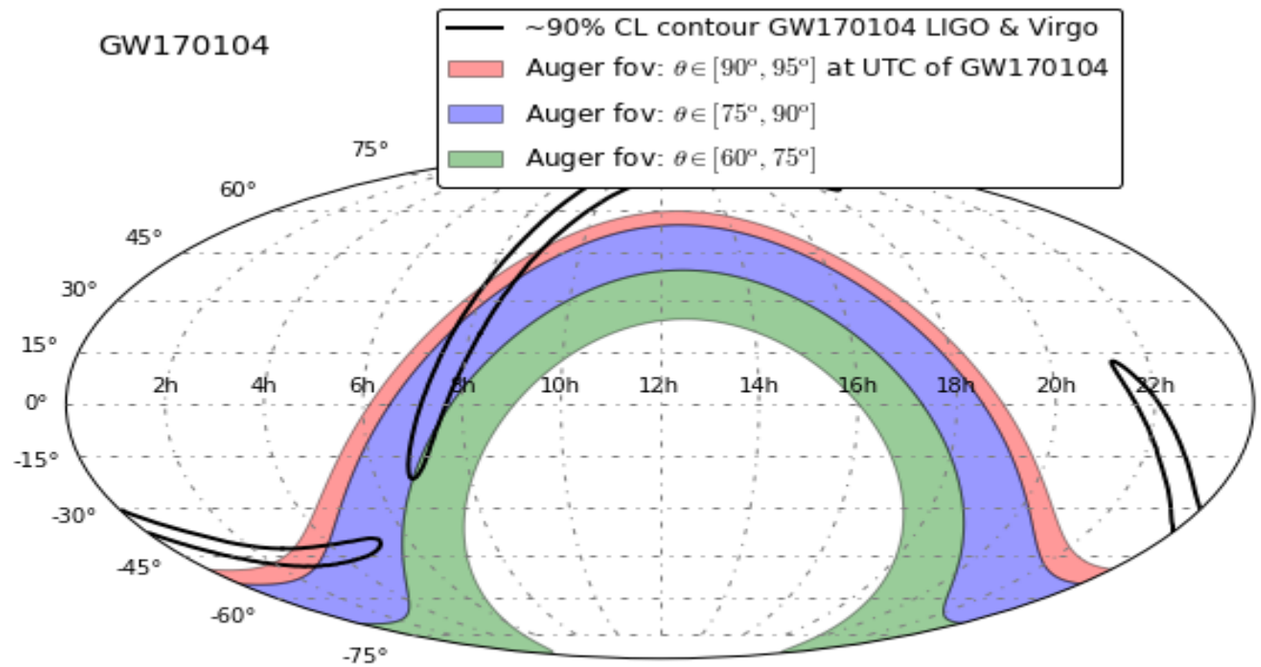




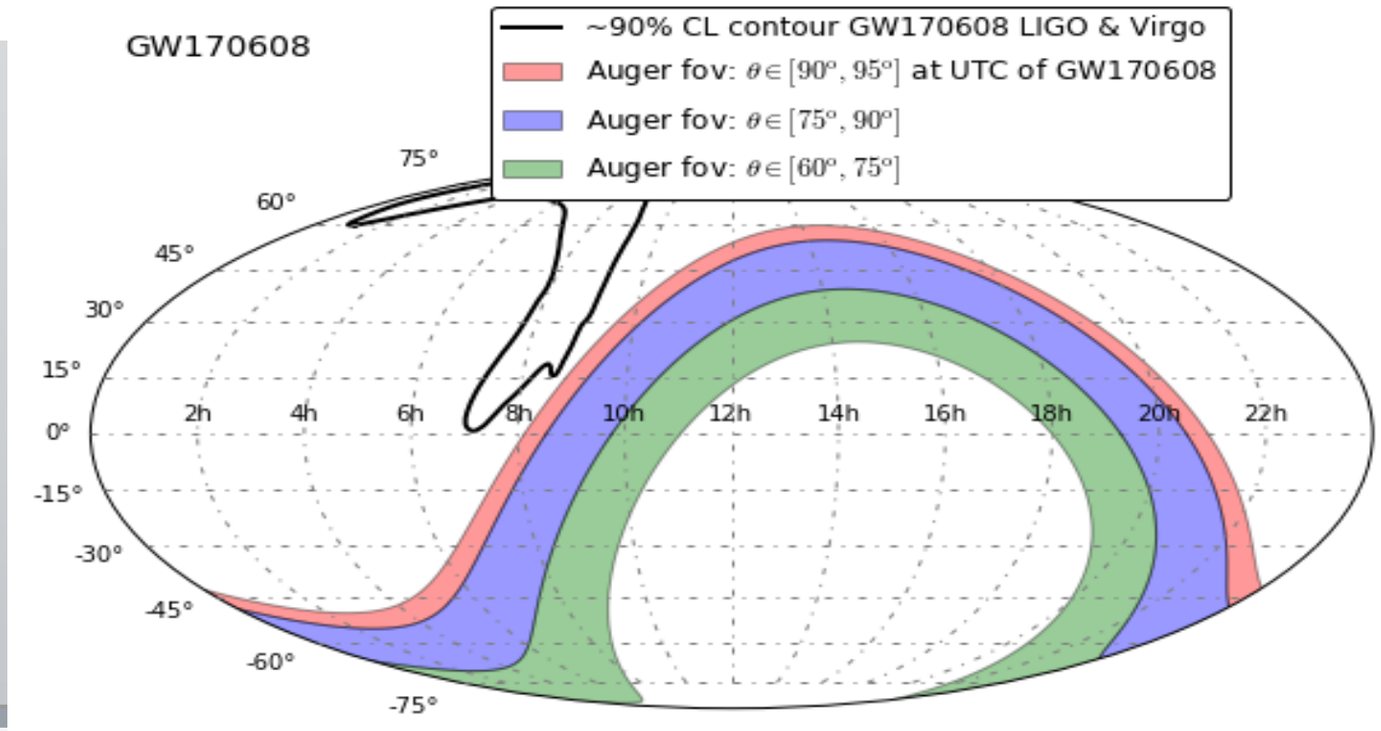
GW151012



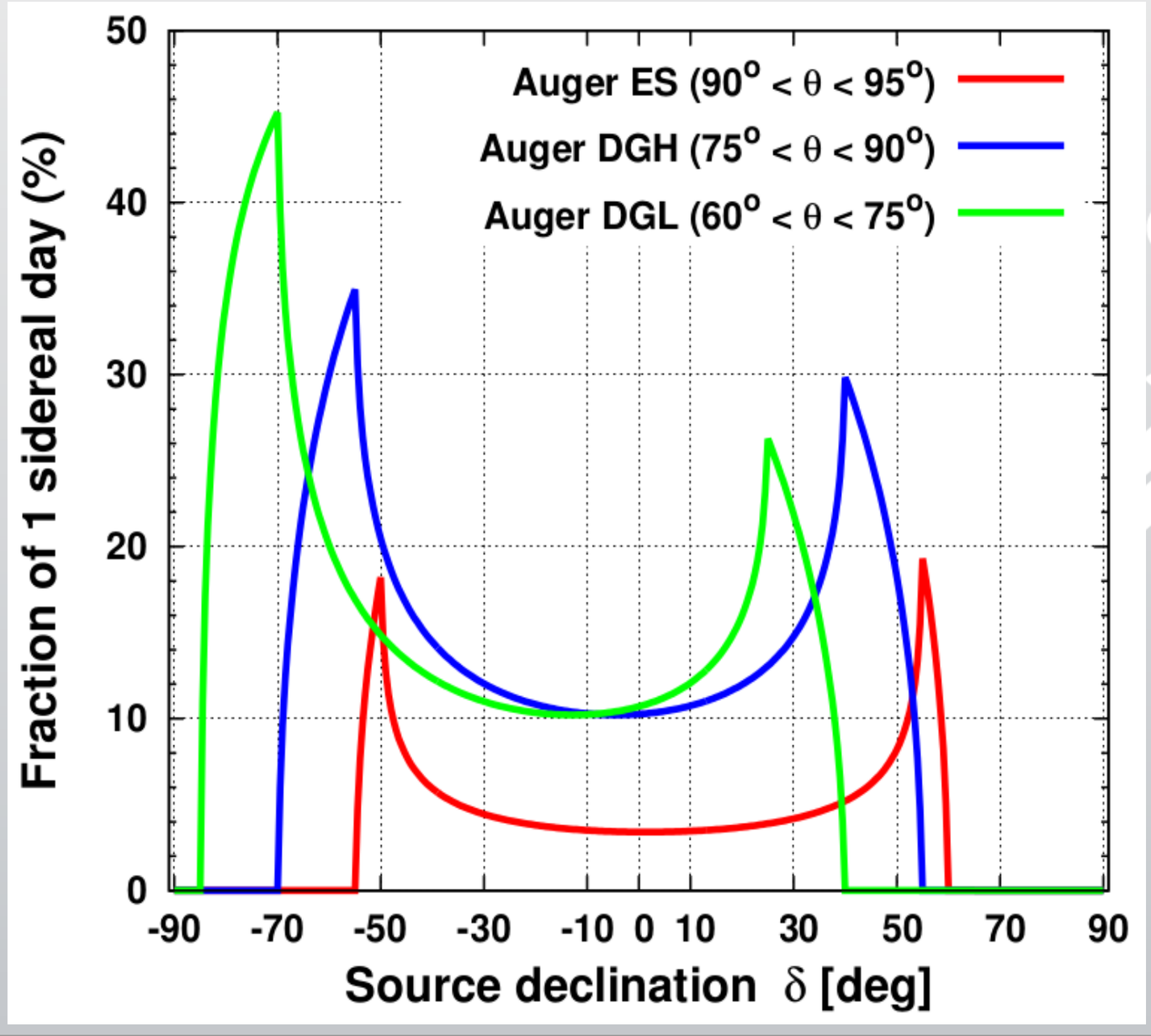
GW170104



GW170608



Visible Solid Angle



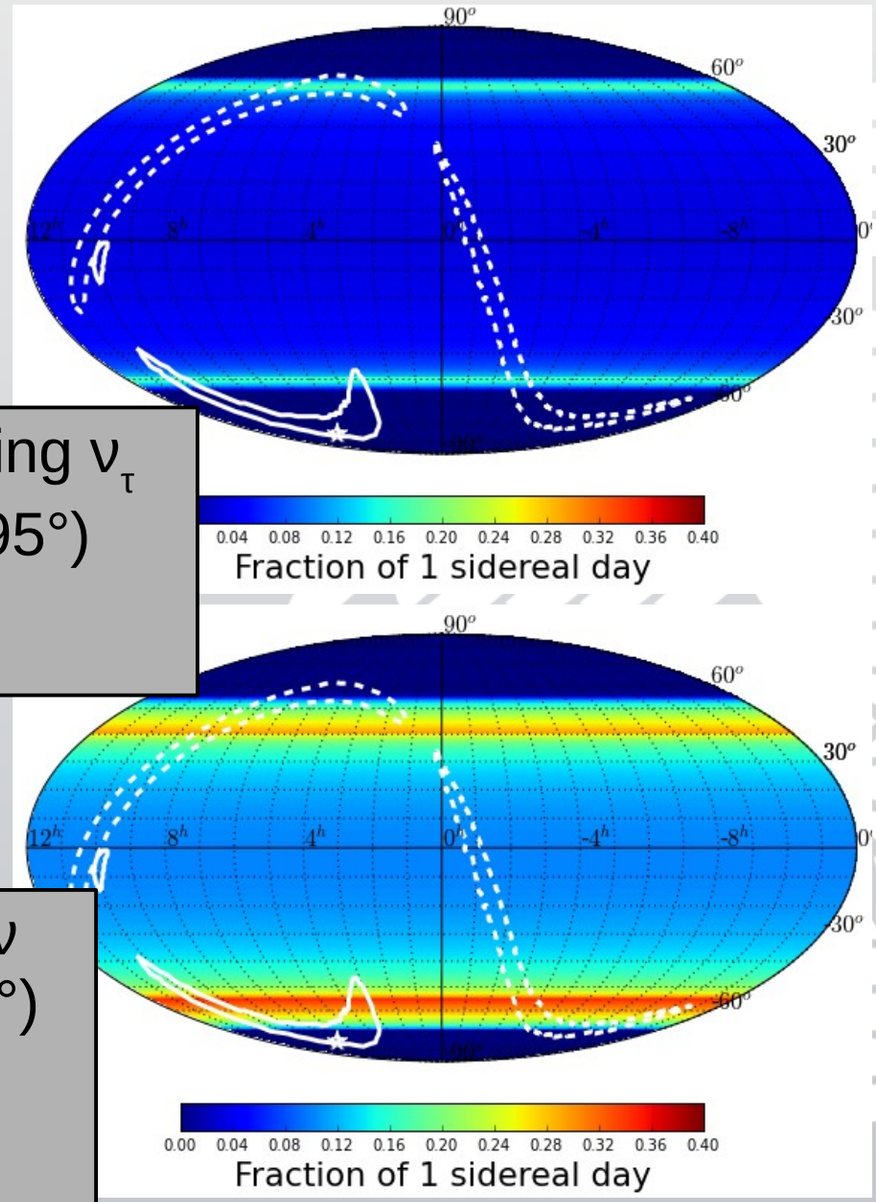
No candidate in [–500 s, 1 day] around GW events

→ Calculate **exposure** taking into account

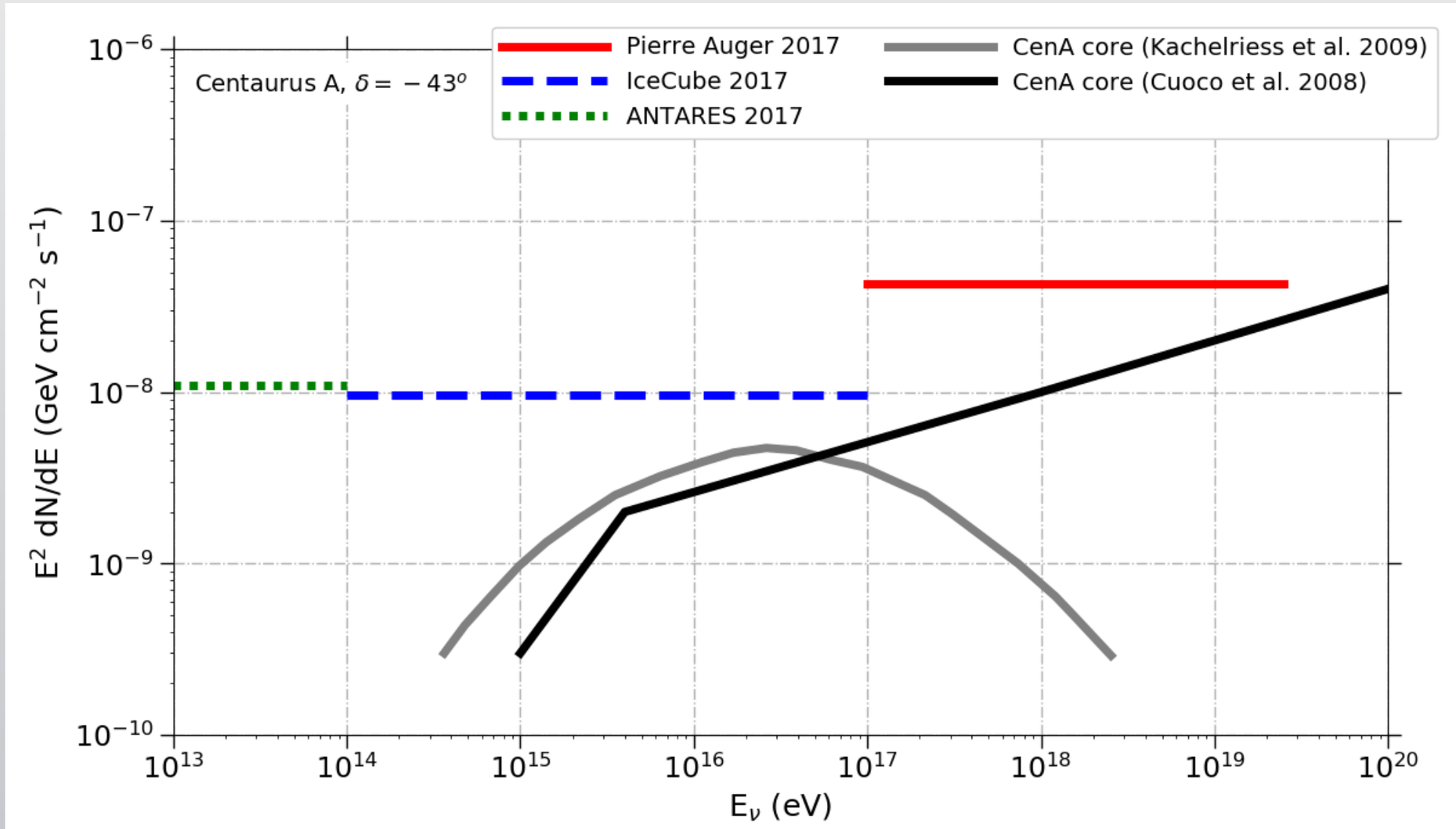
- Time-dependent aperture (area x solid angle)
- ν-nucleon cross section + efficienc
(E,δ)

Earth-skimming ν_τ
(90° < θ < 95°)

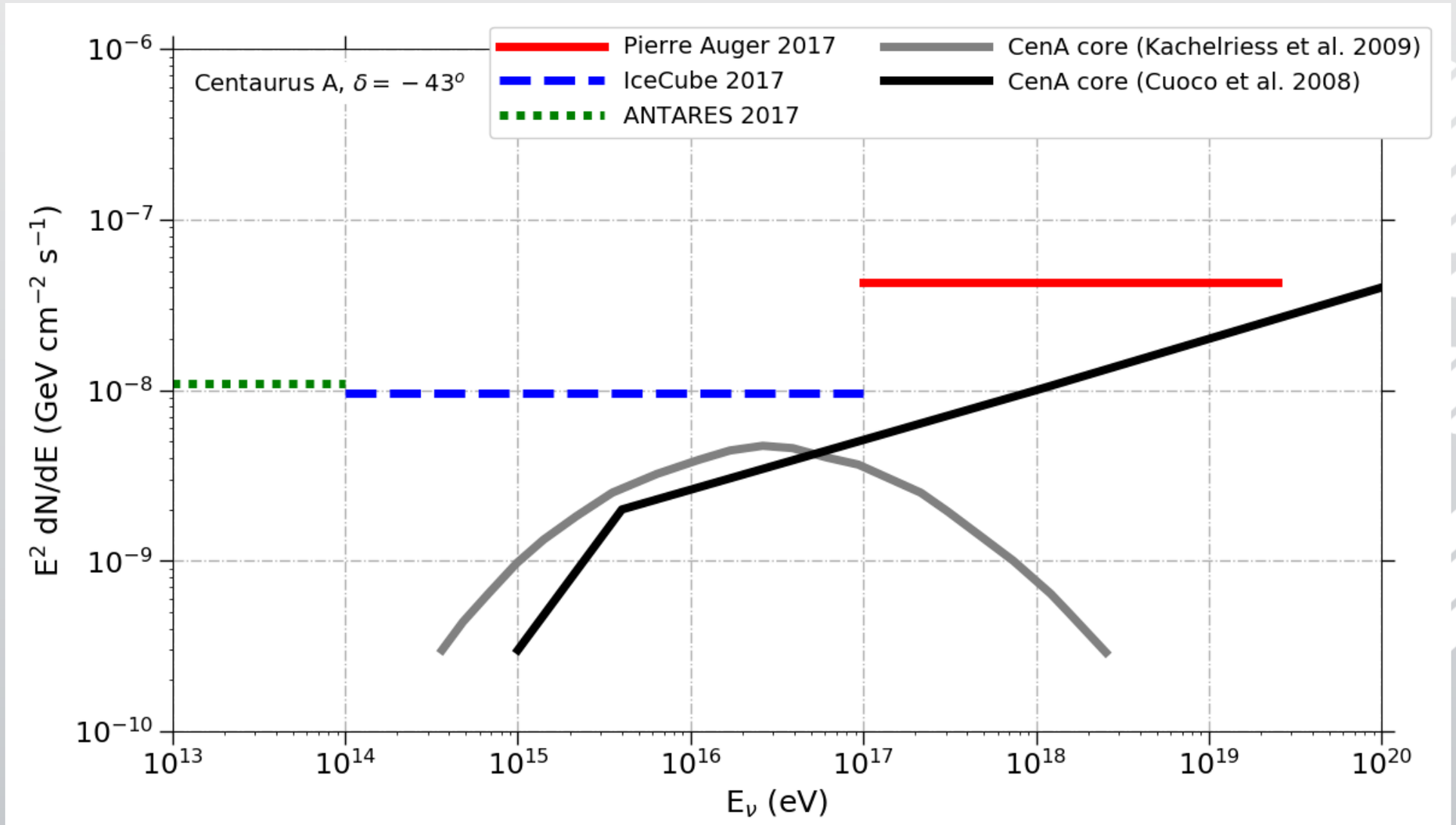
Down-going ν
(75° < θ < 90°)



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)
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}

Cen A limits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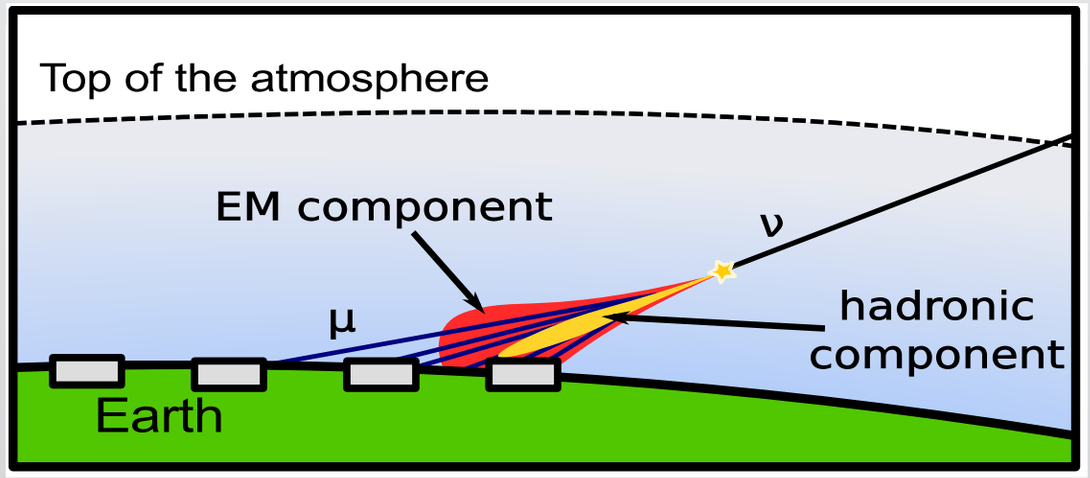
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

ν Event Channels in the Auger SD

Neutrino events

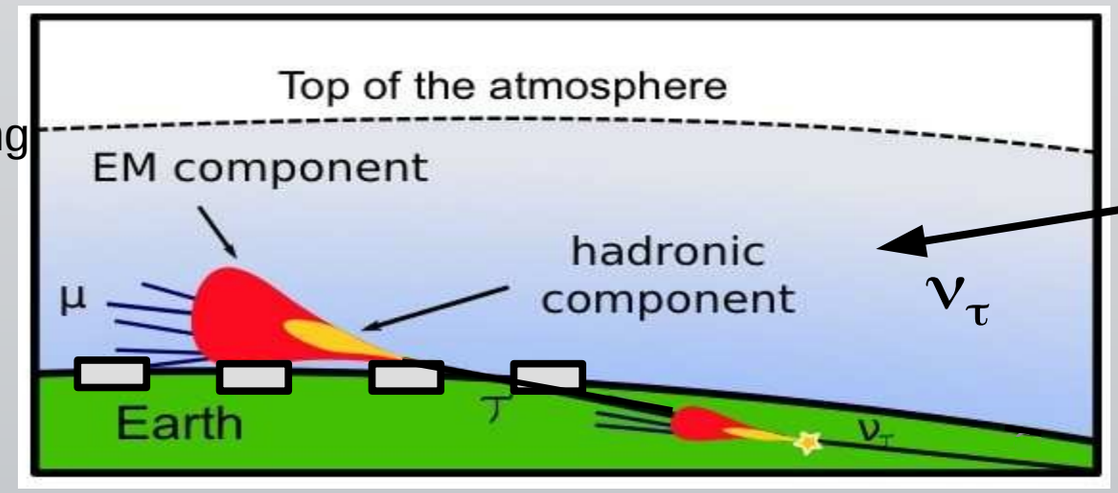
Down-going

All flavors, mostly ν_e



Earth skimming

ν_τ only



Overall most sensitive event class

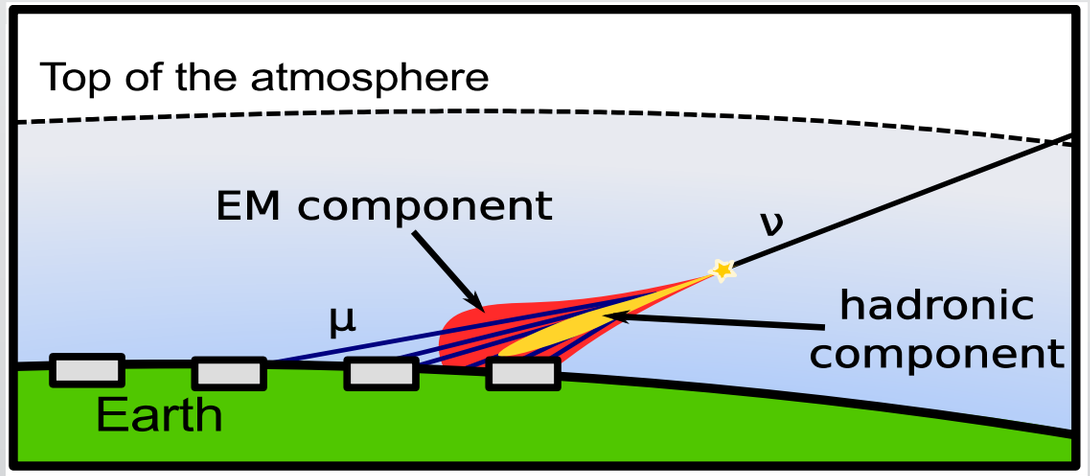
Figures: J. Alvarez-Muñiz

ν Event Channels in the Auger SD

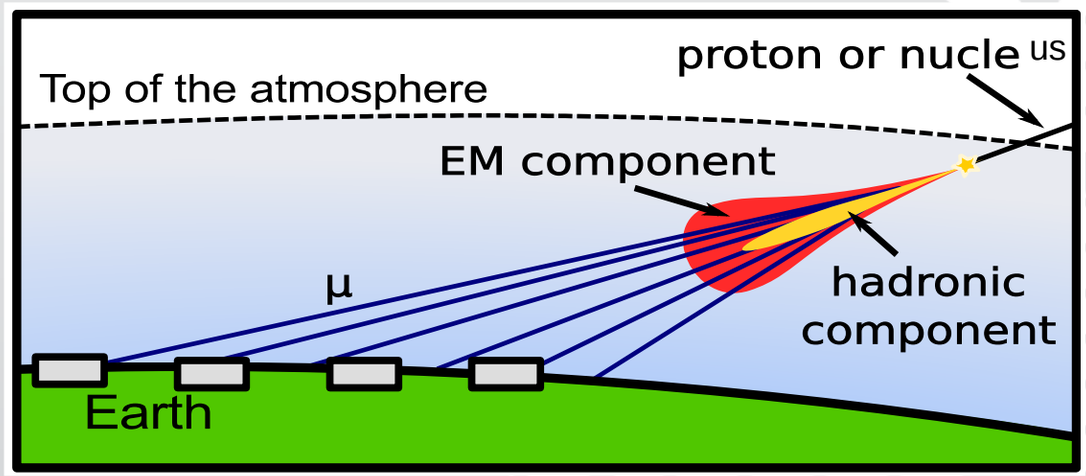
Down-going

All flavors, mostly ν_e

Neutrino events

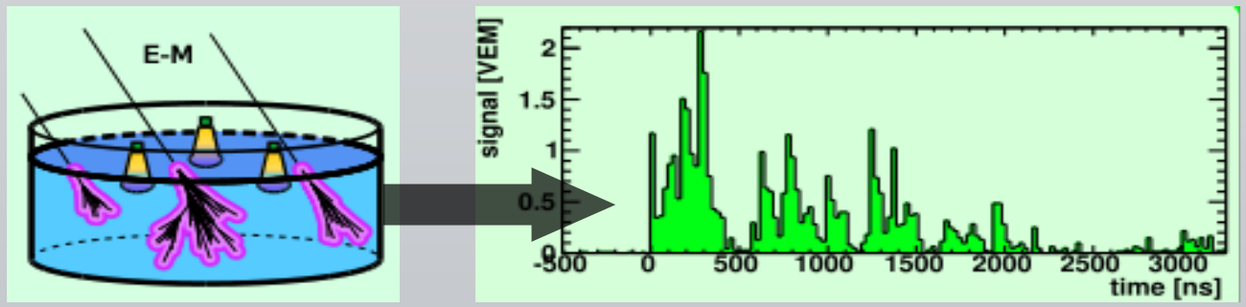


CR events

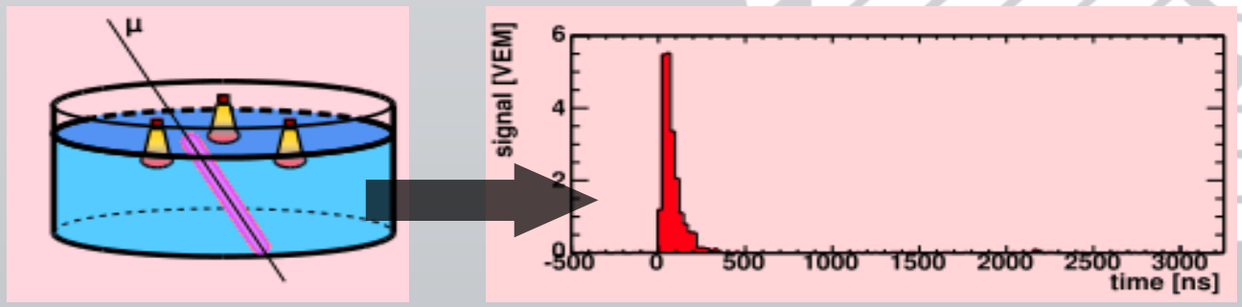


At ground:

EM shower front



Single muons



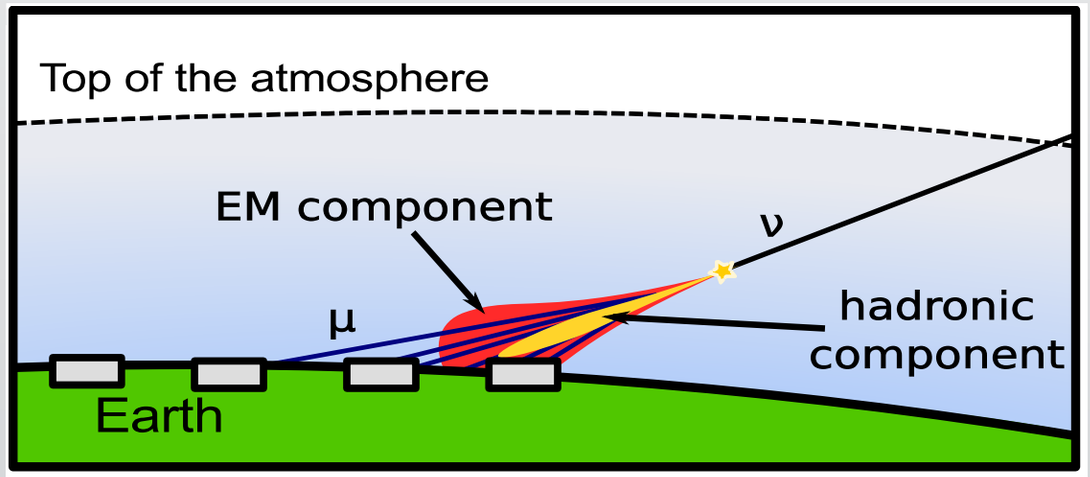
Figures: J. Alvarez-Muñiz

ν Event Channels in the Auger SD

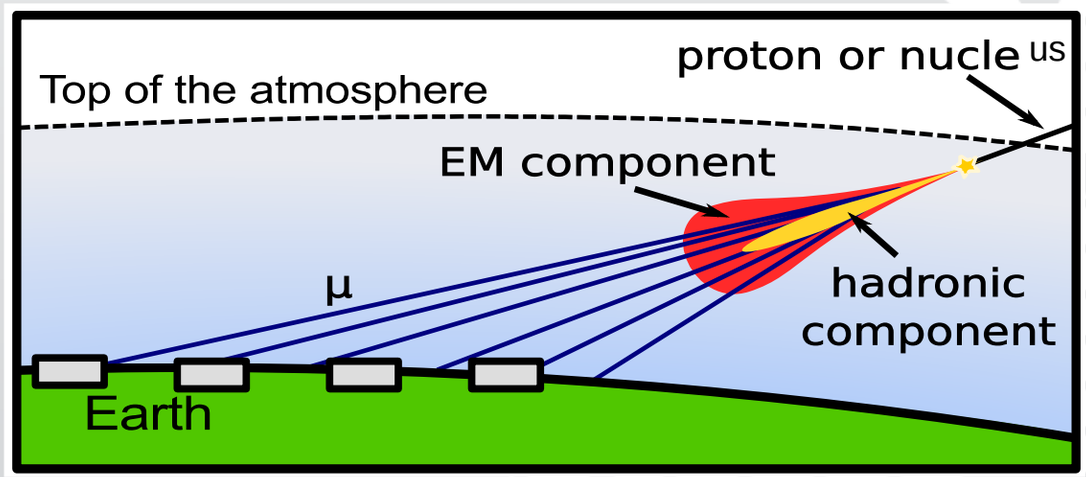
Down-going

All flavors, mostly ν_e

Neutrino events



CR events

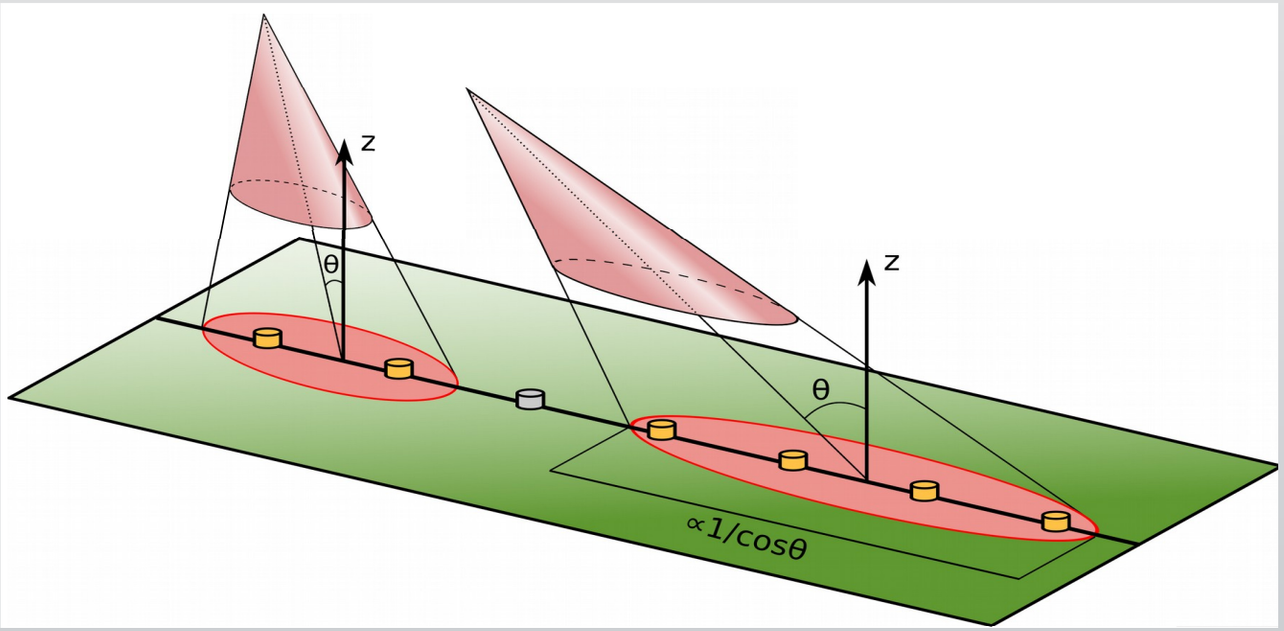


Vertical events: CR induced EM component reaches surface
→ Select zenith angles > 60°

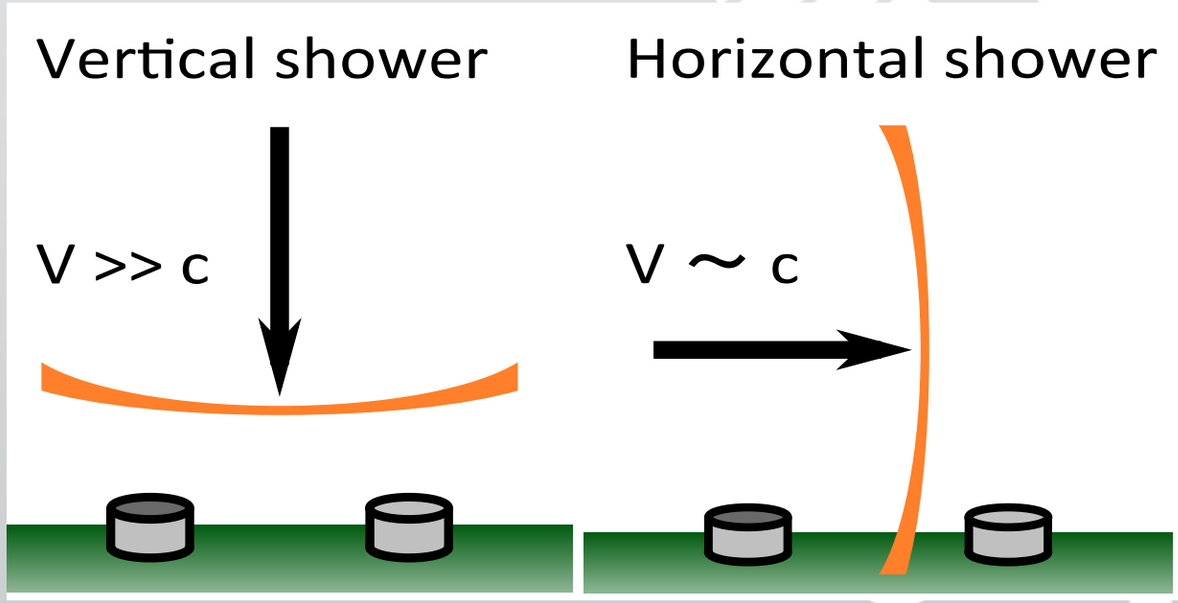
Figures: J. Alvarez-Muñiz

Inclination: 90° < θ < 95°

- Elongated footprint

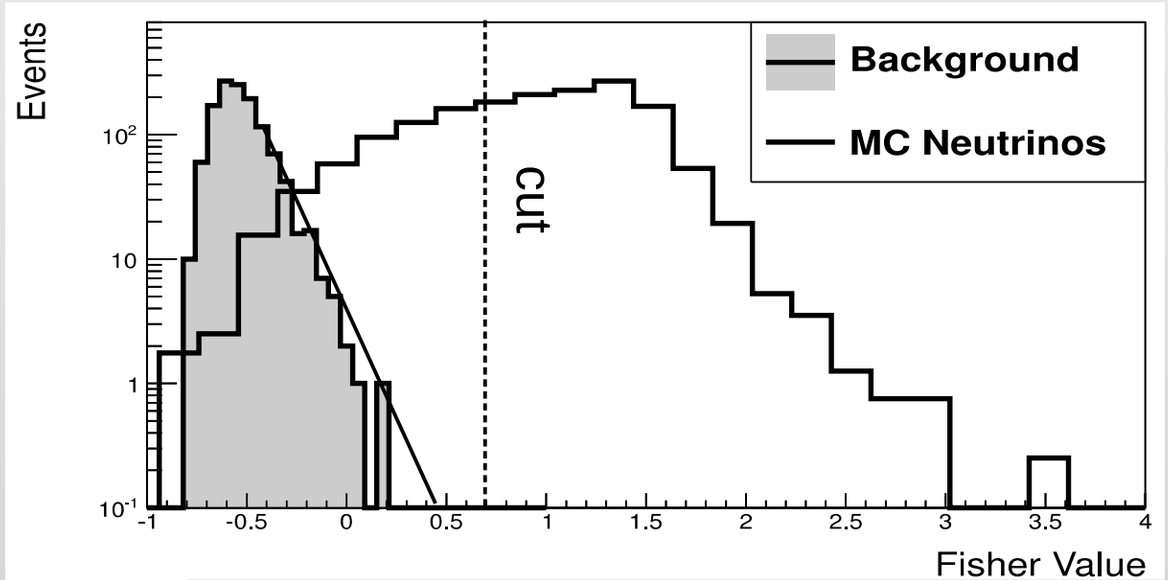


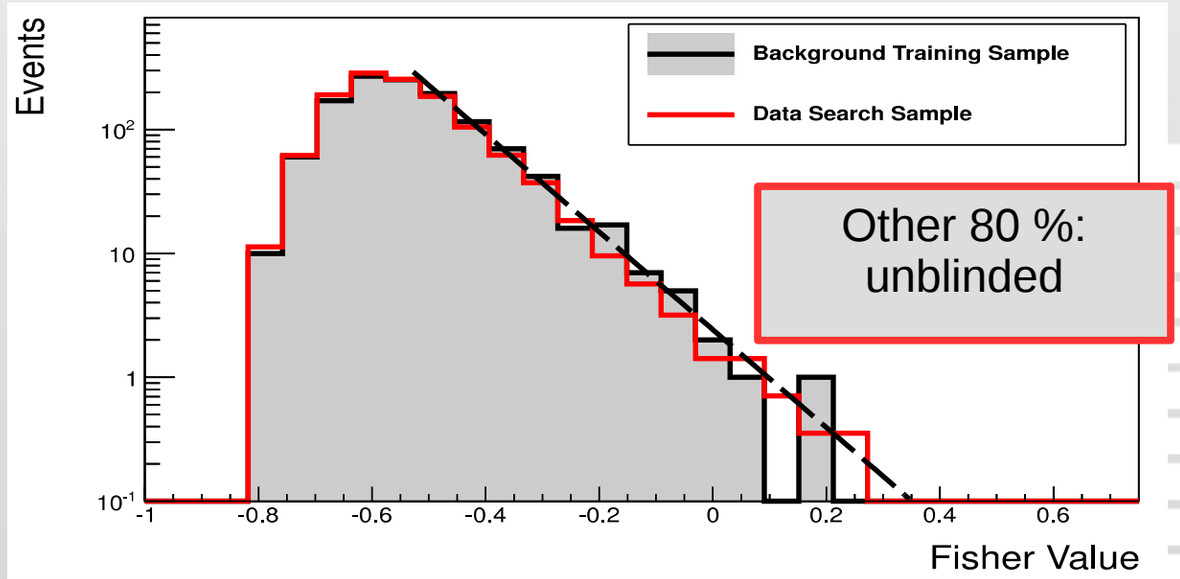
- “Ground signal speed” ~ c



Reject “muonic” events → > 60 % stations ToT triggered

Down-Going Low-Zenith UHEν Analysis



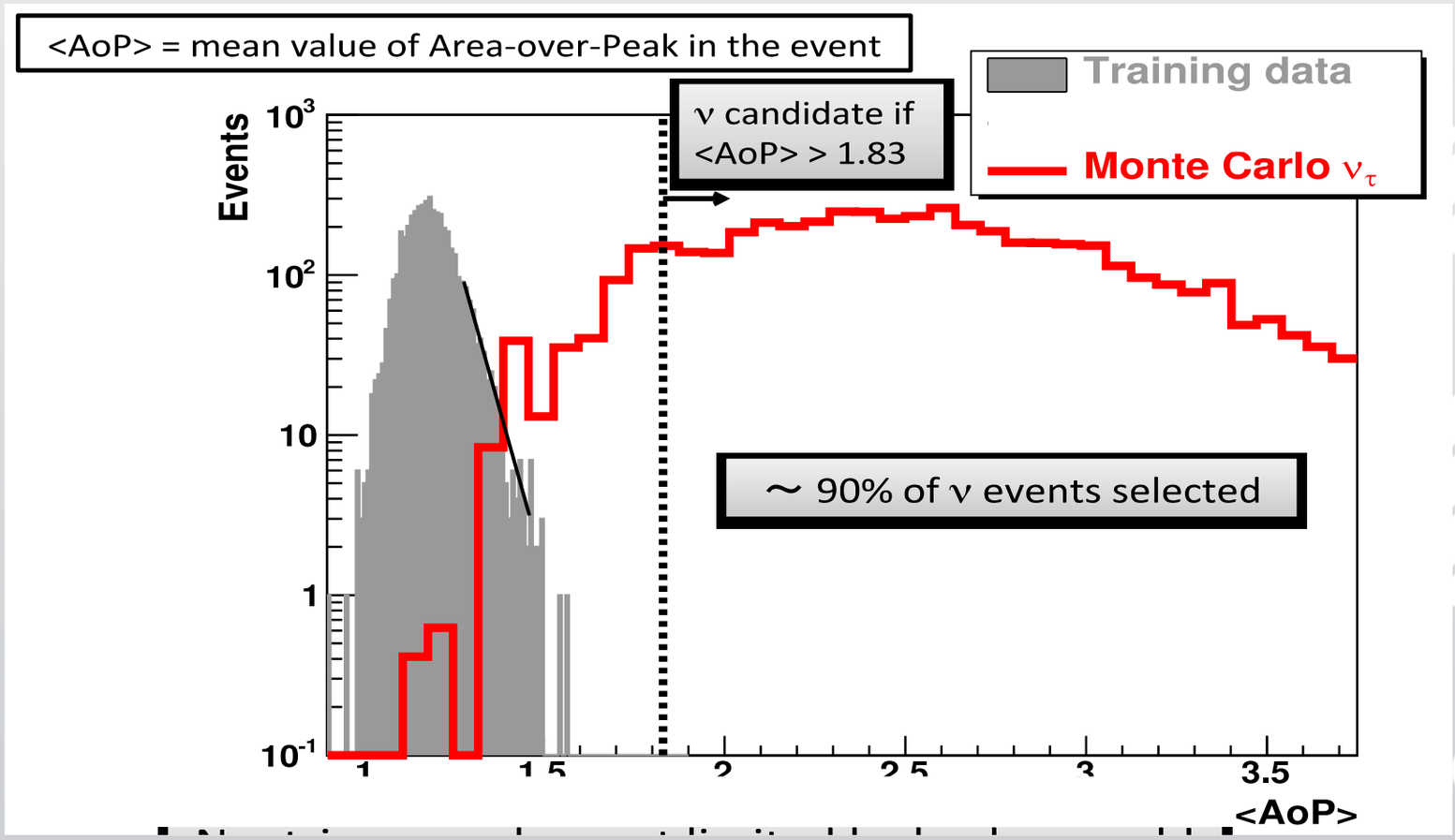


60°+-1.5° (most vertical = most signal-like)

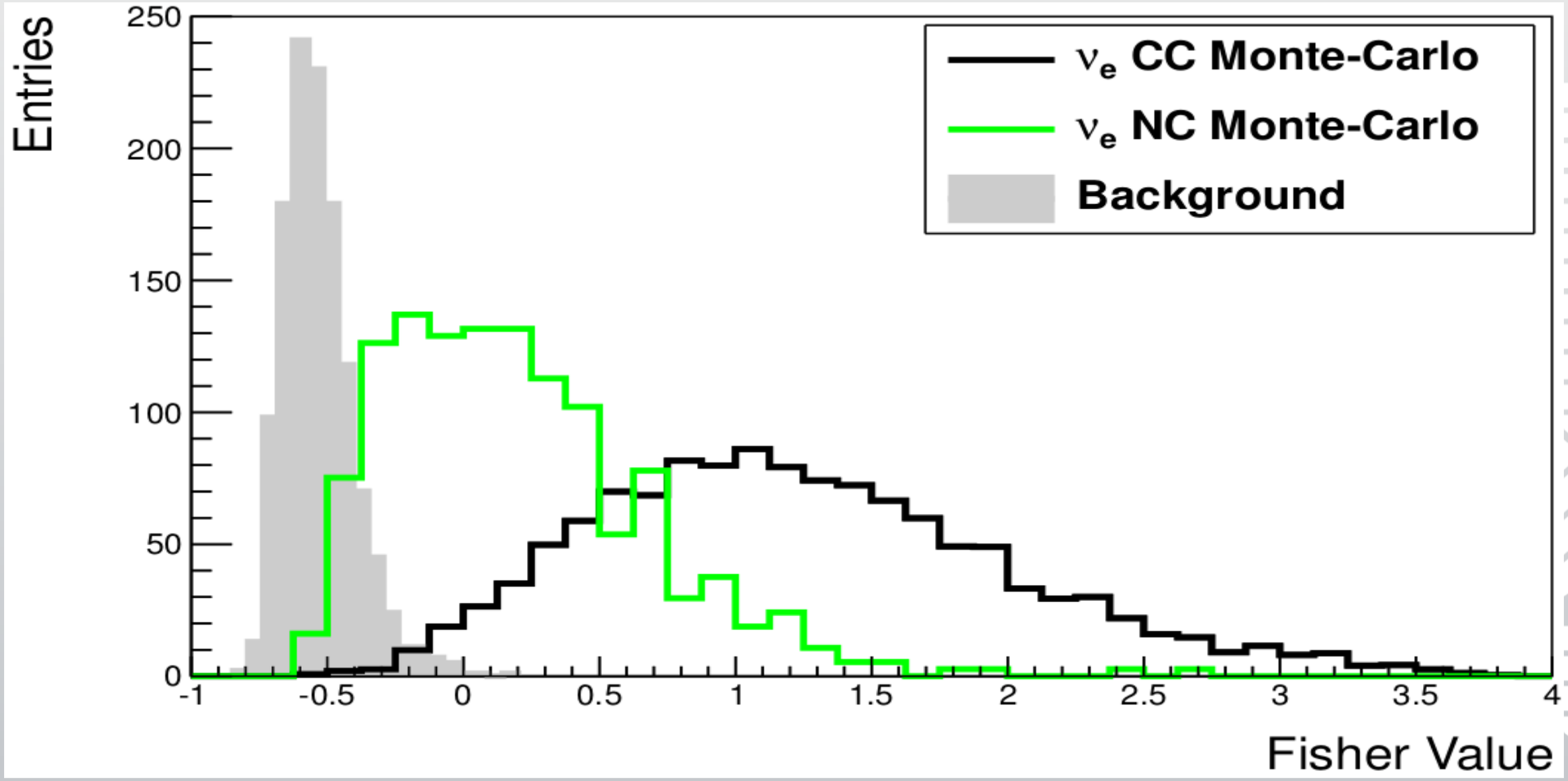
Found nothing → calculate limit

- Feldman-Cousins, 0 signal, 0 bg expected
- Stat. + syst.: Rolke & Conrad approaches
- Calculate exposure ξ
  → Diffuse flux limit ~ $N_{90\%CL,upper}$ / ξ

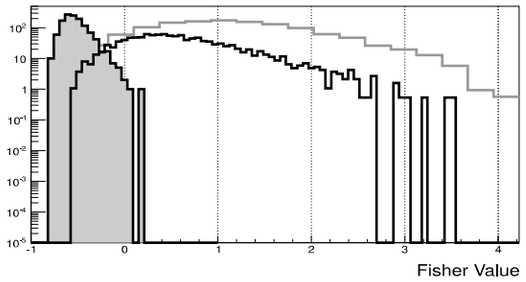
$N_{90\%CL,upper}$=2.37



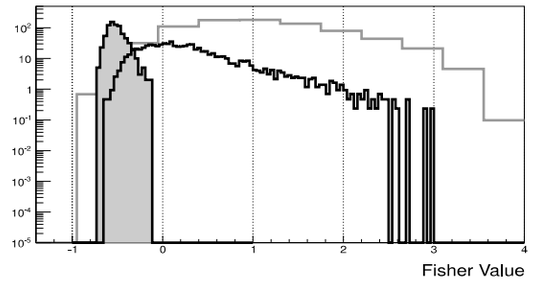
No event after <AoP> cut → calculate exposure
→ flux limit ~ event count limit / exposure


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

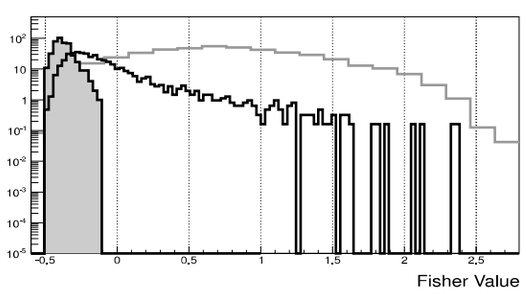
Neutrinos vs. Photons



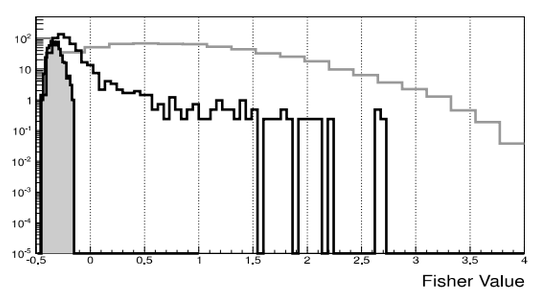
(a) $58.5^\circ < \theta_{\mathrm{Rec}} \leq 61.5^\circ$



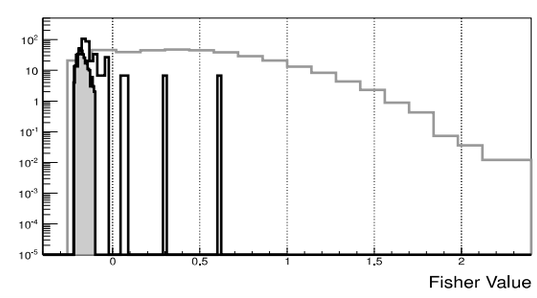
(b) $61.5^\circ < \theta_{\mathrm{Rec}} \leq 64.5^\circ$



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



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



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