Multi-Messenger Physics with the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

XXVIII Cracow
Epiphany Conference

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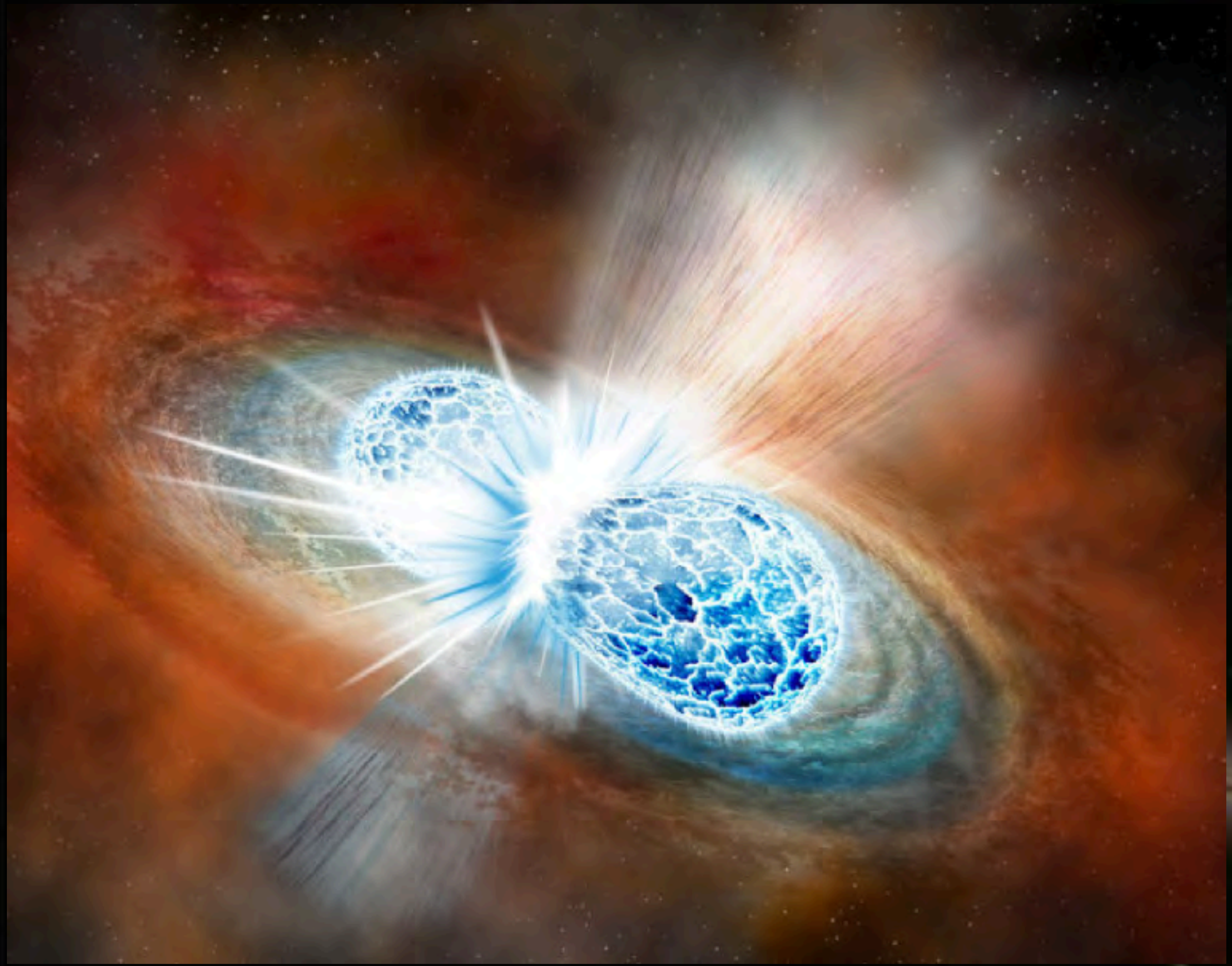
DFG Deutsche Forschungsgemeinschaft
Bundesministerium für Bildung und Forschung

2017: Birth of Multimessenger Astrophysics



Scientific Breakthrough of 2017

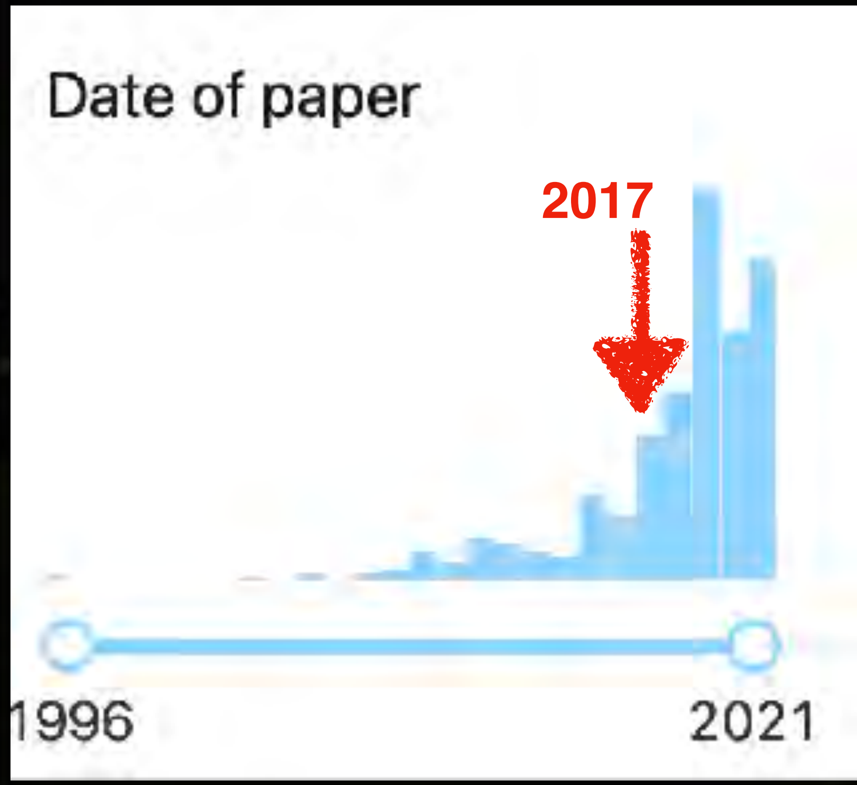
Neutron Star Merger GW 170817

observed also in broad range of
electromagnetic radiation
with strong bounds on
HE neutrino emission

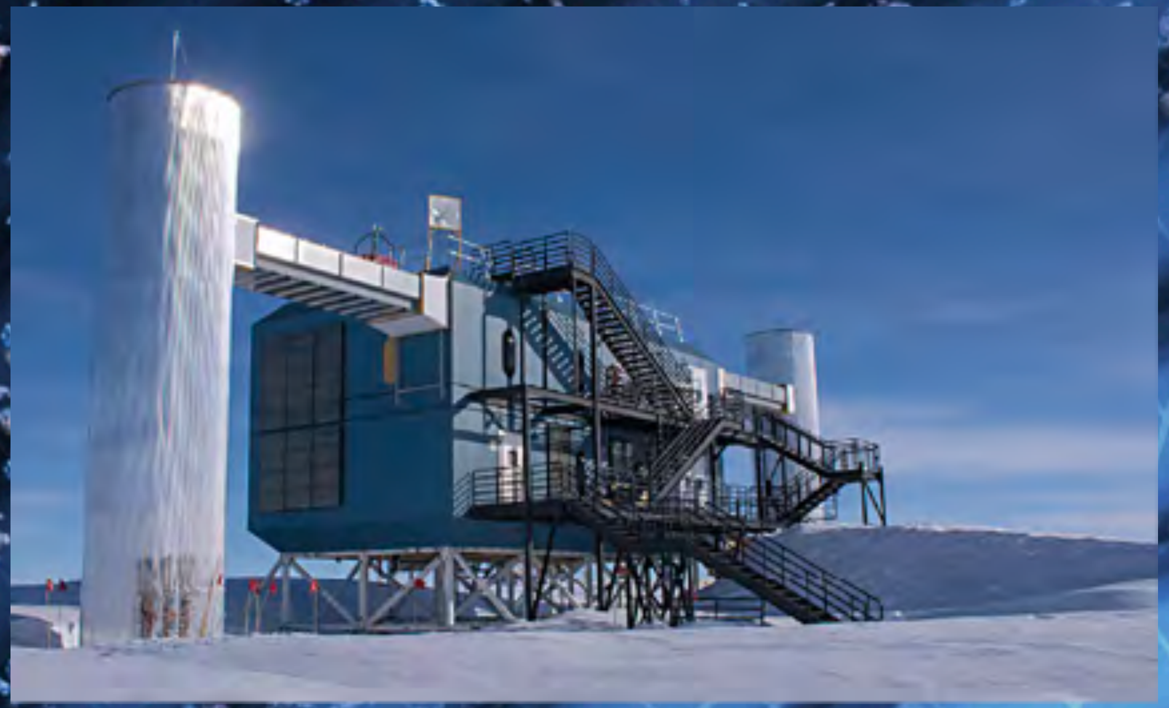
Joint publication by > 3000 authors (LHC scale)

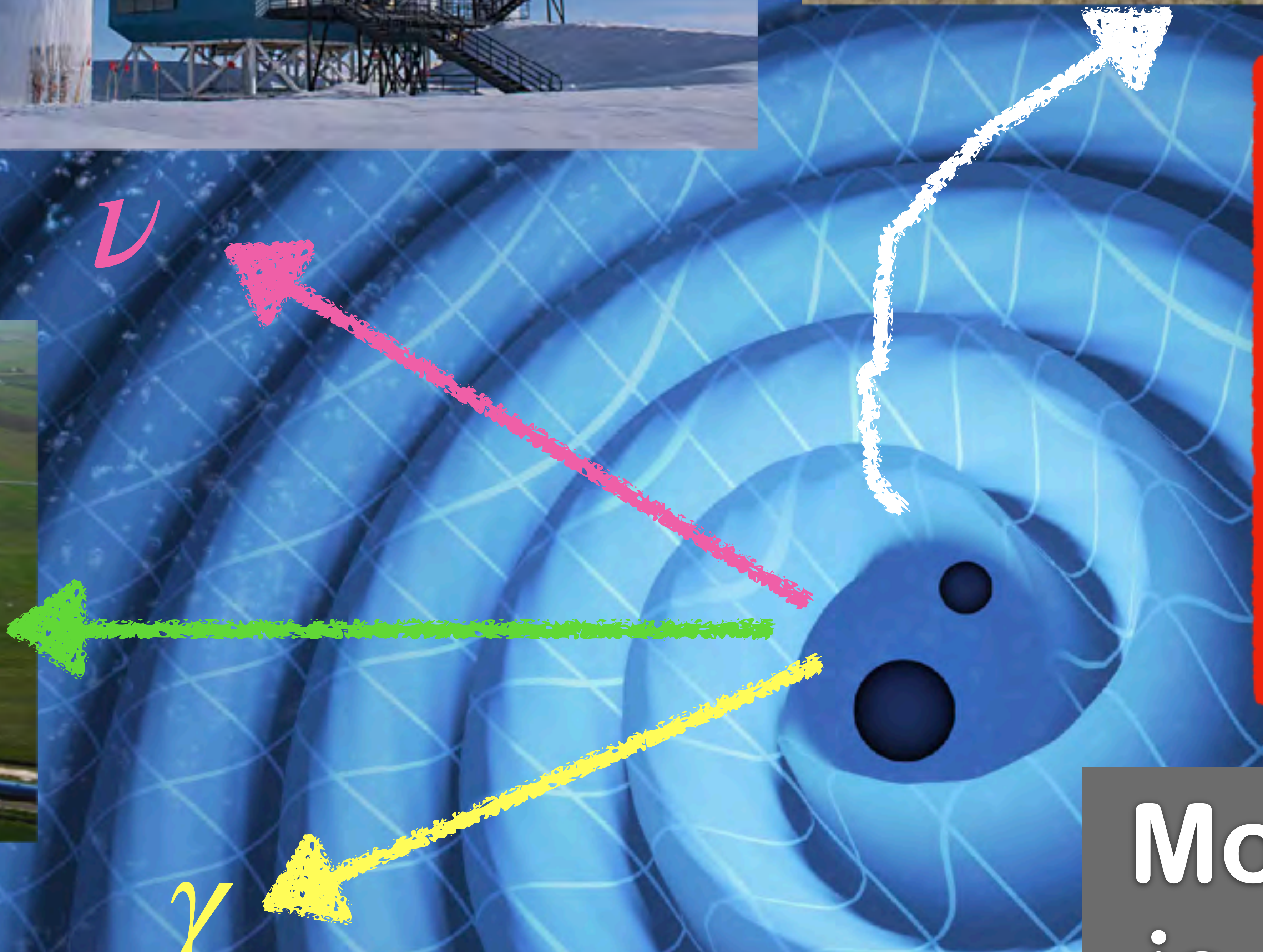
THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger



By now 510 Publications with „Multi-Messenger“ in their title
with a total of ~10000 citations
Most cited: ApJL 2017 joint observation paper (2215 citations by now)



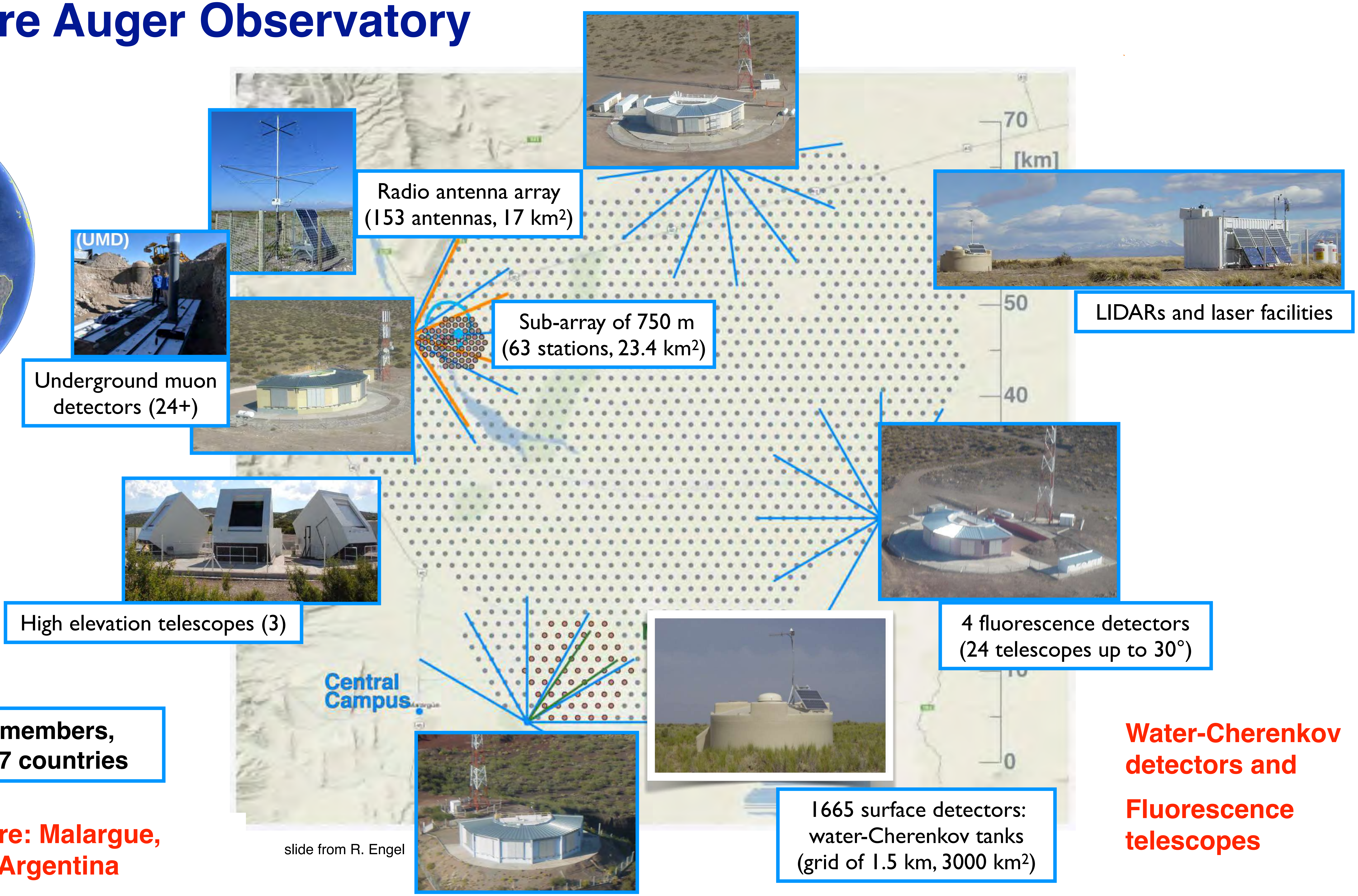


Note, by construction, a CR observatory is in general also a gamma, neutrino, and neutron-observatory

Moreover, MM physics is more than studying transient events (ToOs)

The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



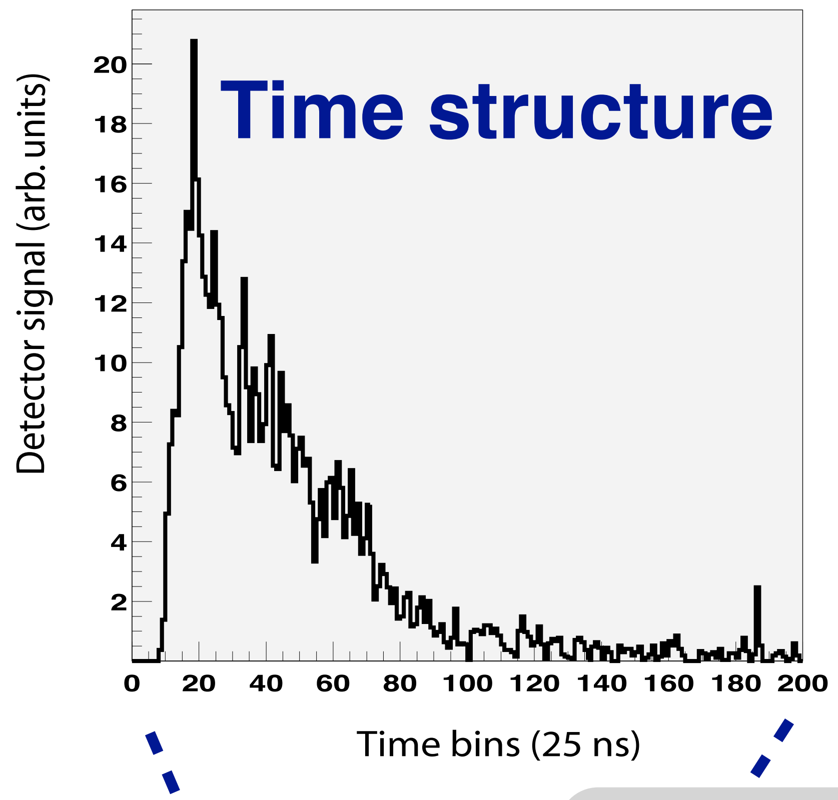
More than 400 members, 98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

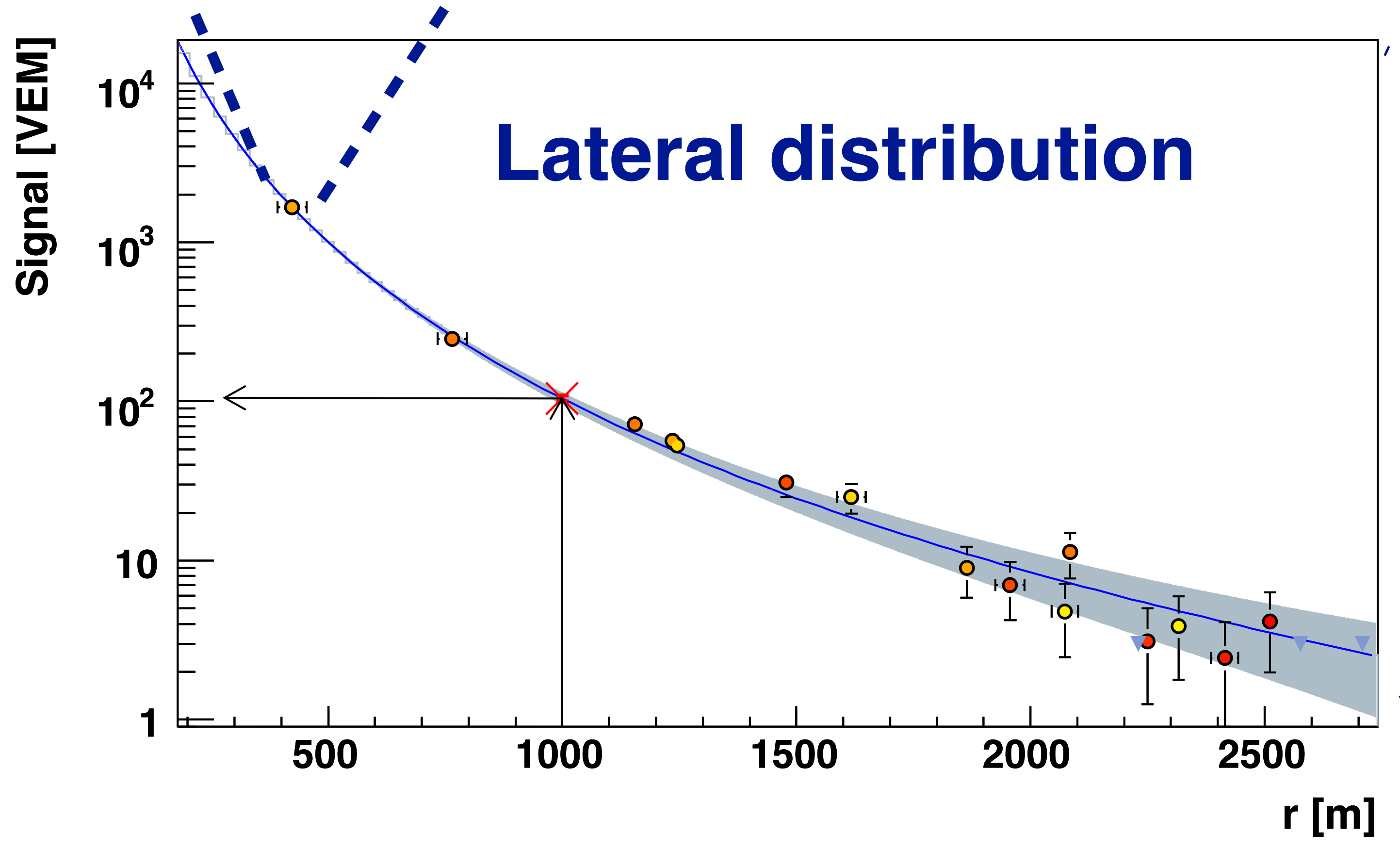
Water-Cherenkov detectors and

Fluorescence telescopes

Auger is a Hybrid Observatory

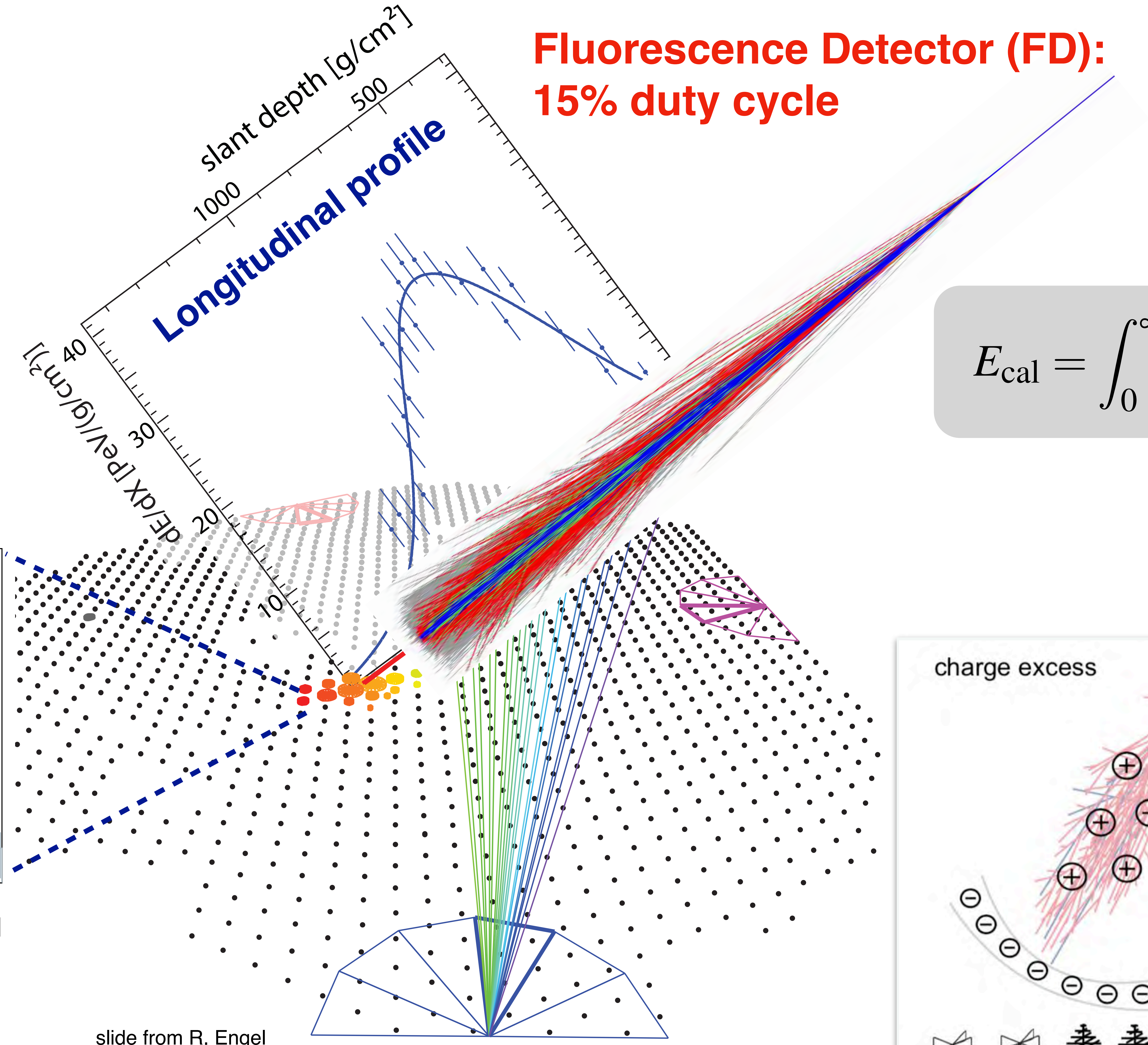


$$E_{\text{rec}} = f(S_{1000}, \theta)$$



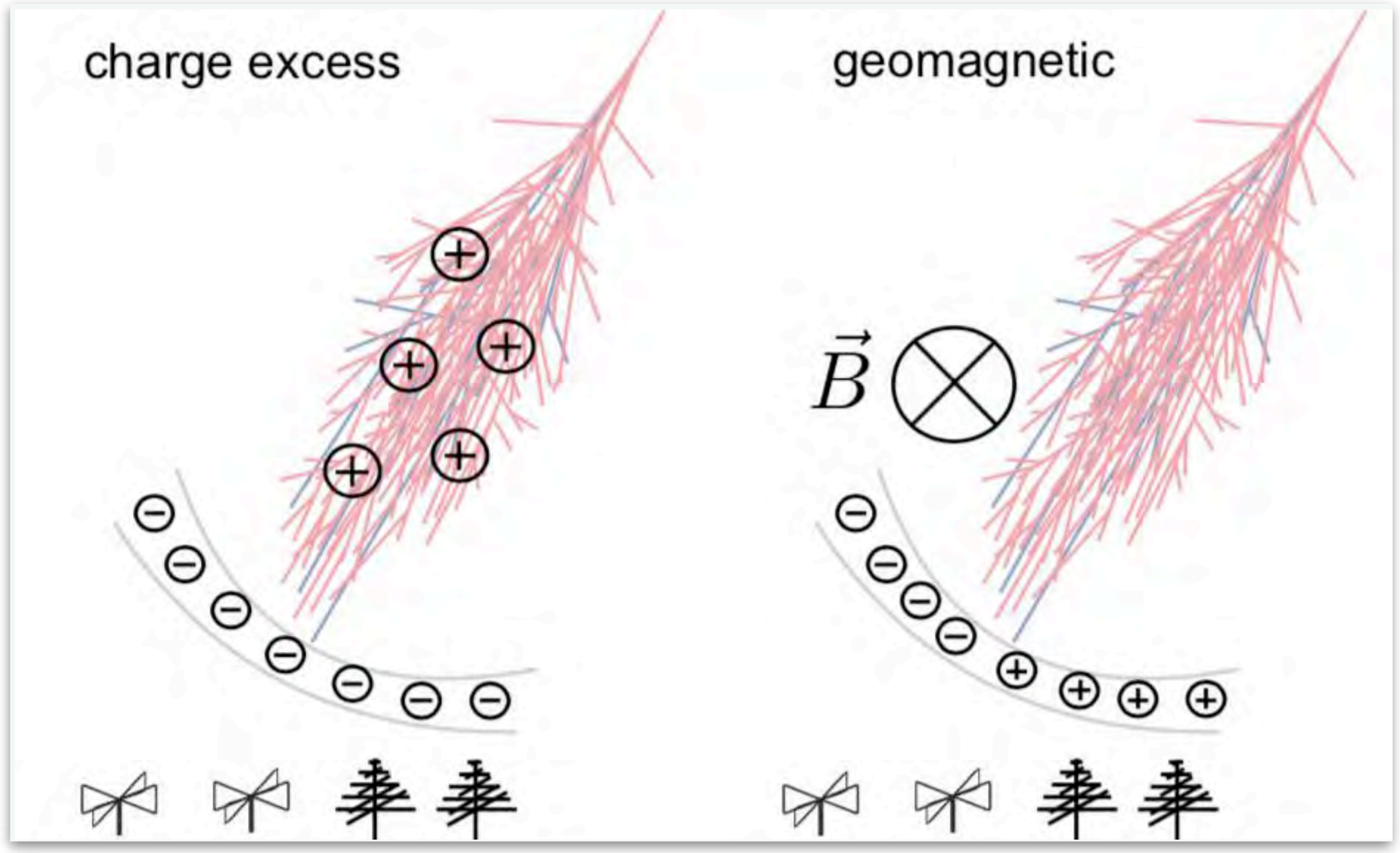
Surface Detector (SD)
100% duty cycle

Fluorescence Detector (FD):
15% duty cycle



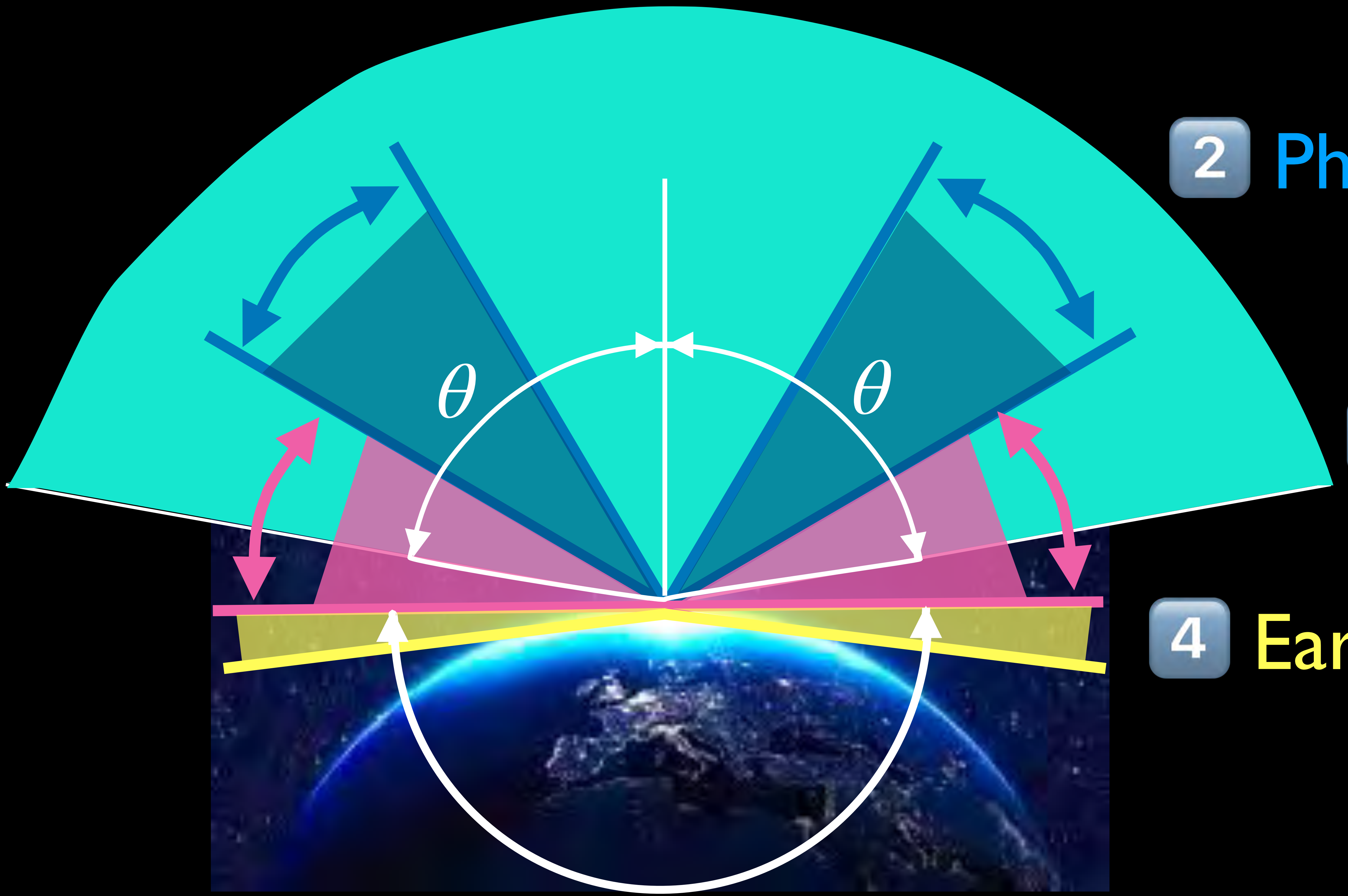
$$E_{\text{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\text{obs}} \mathrm{d}X$$

Radio Detector (RD):
100% duty cycle



Auger: 4π Sky Coverage for MM

1 Neutrons and charged CRs: Θ ≤ 80°



2 Photons: 30° ≤ Θ ≤ 60°

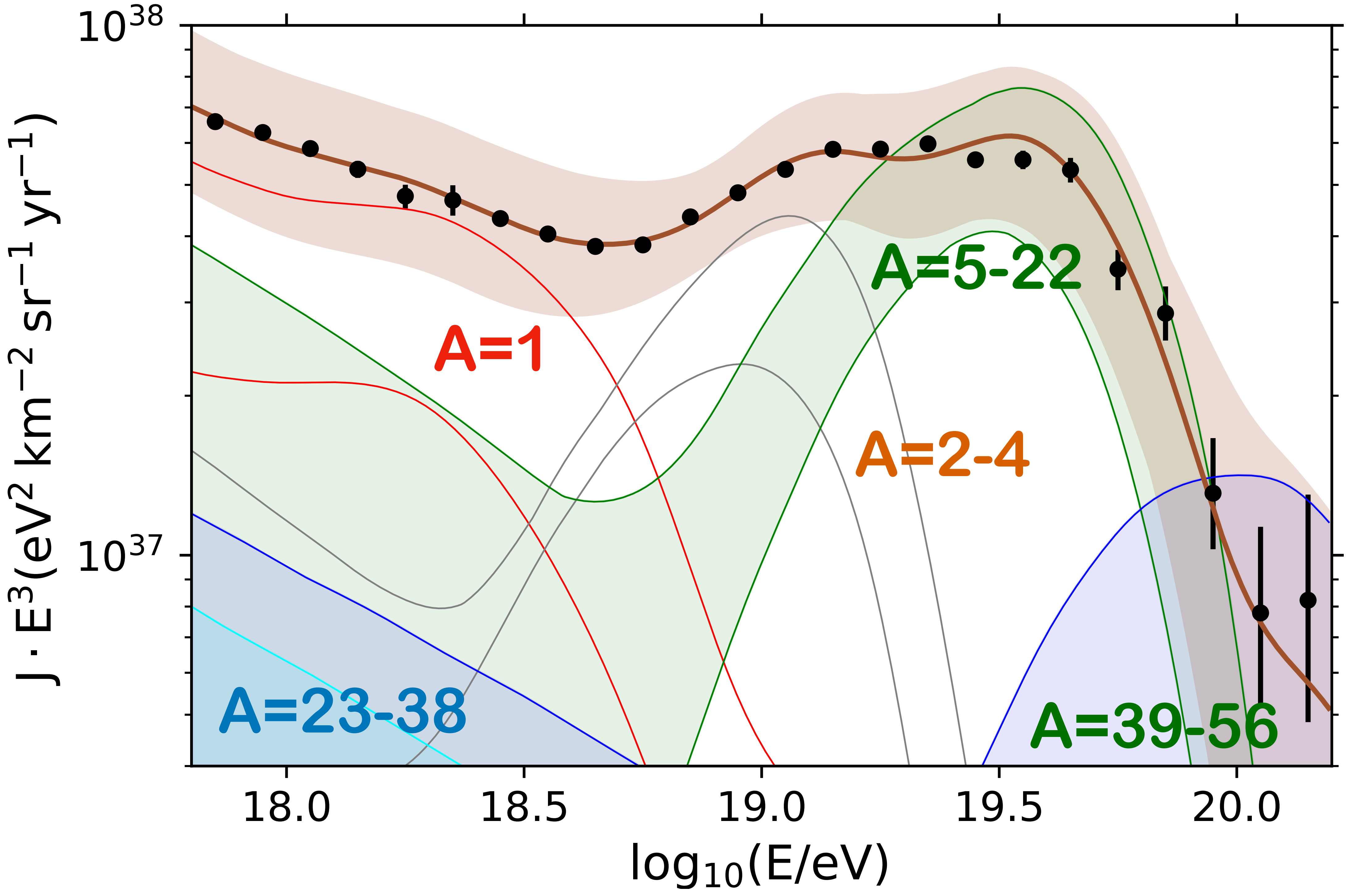
3 Down-Going Neutrinos: 60° ≤ Θ ≤ 90°

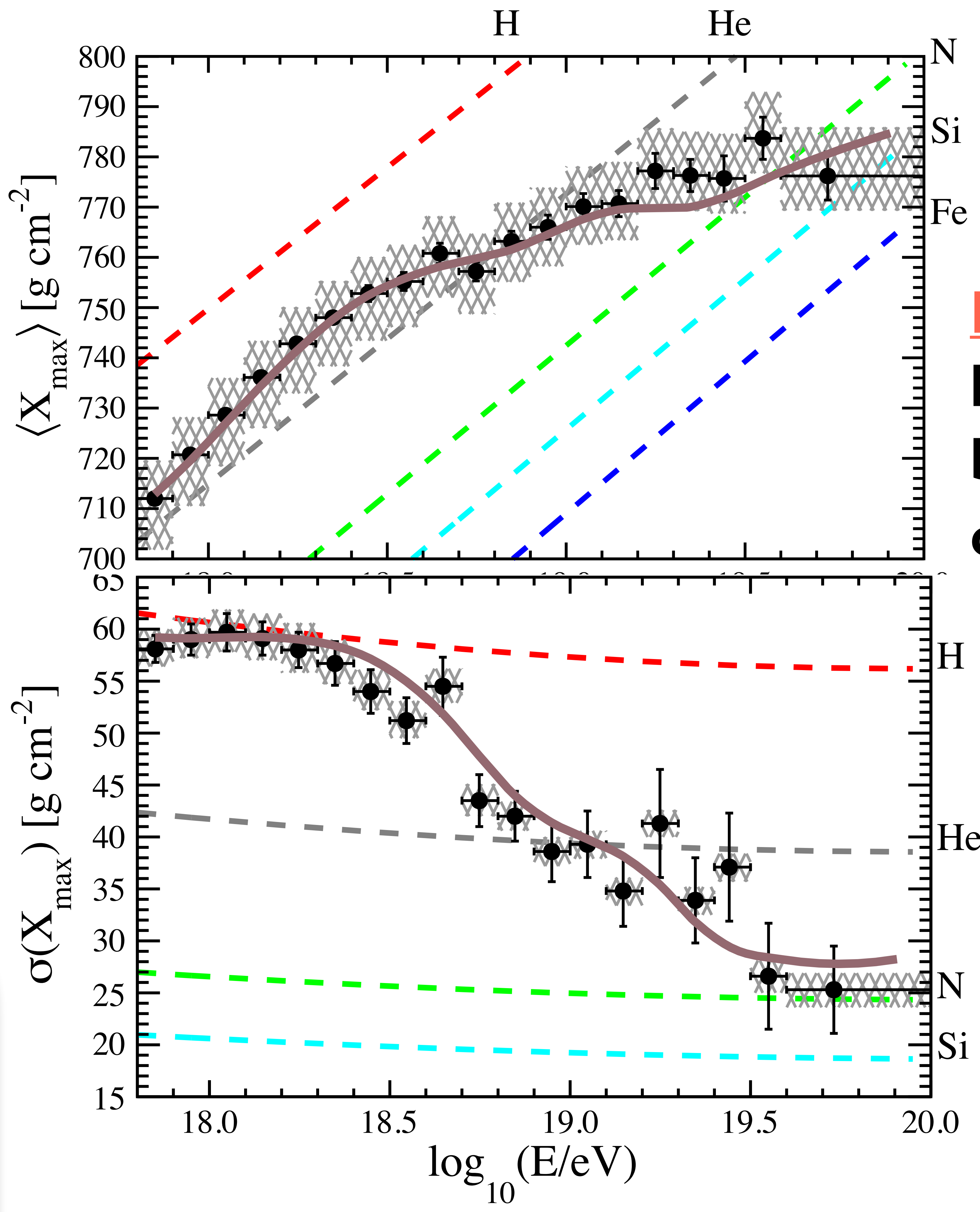
4 Earth Skimming Neutrinos: 90° ≤ Θ ≤ 95°

5 BSM Particles: Θ > 90°

(1) CRs as Multi Messenger Probe

E. Guido; Auger Collaboration, PoS (ICRC21) 311





Note:
heavy composition by itself reduces cosm. ν and γ fluxes!

Combined fit of all-particle energy spectrum and CR mass composition:
- assuming uniformly distributed identical sources
- and a rigidity dependent cut-off
- and accounting for propagation effects

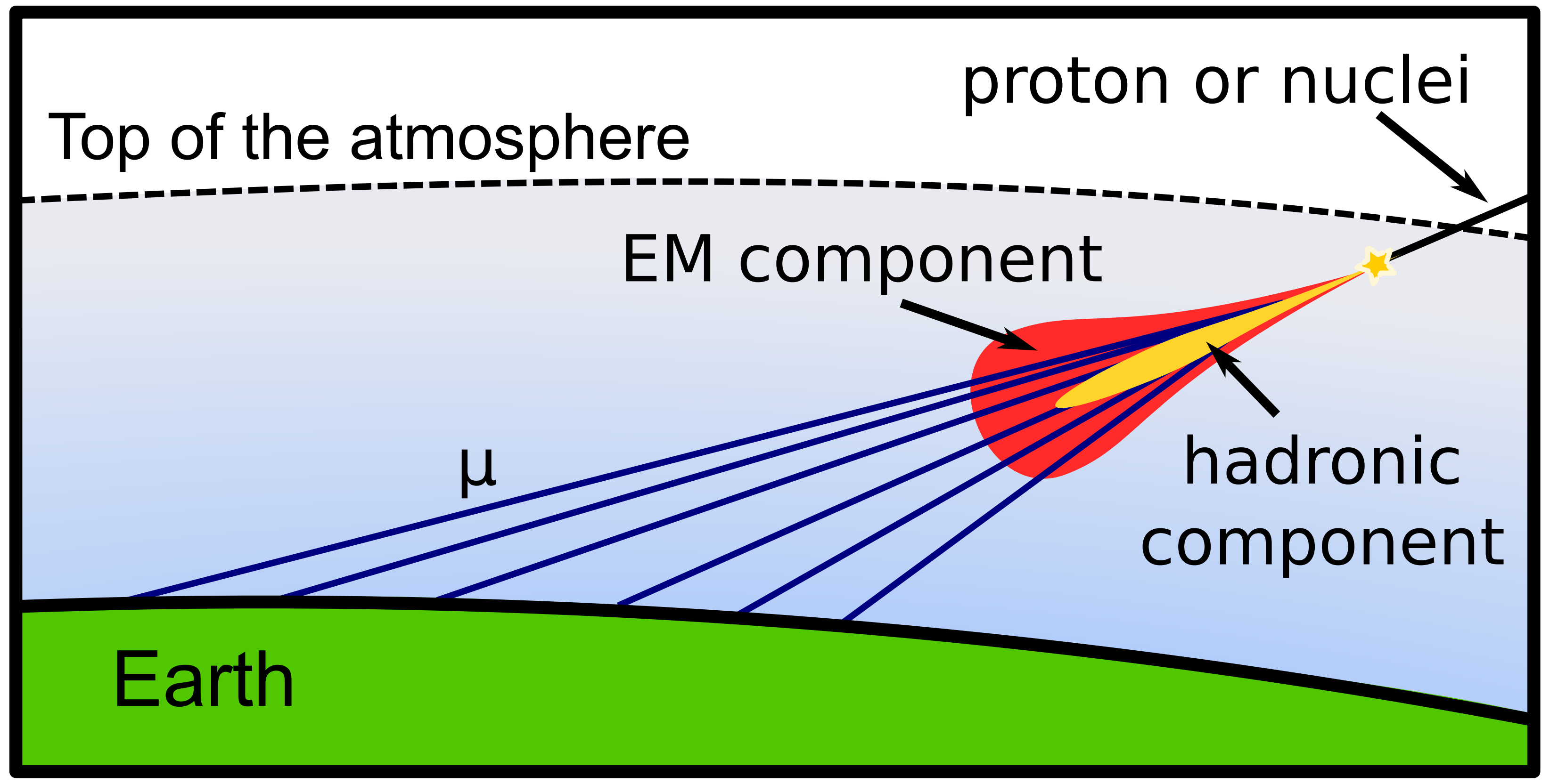
⇒ **Cut-Off appears mostly an effect of sources**

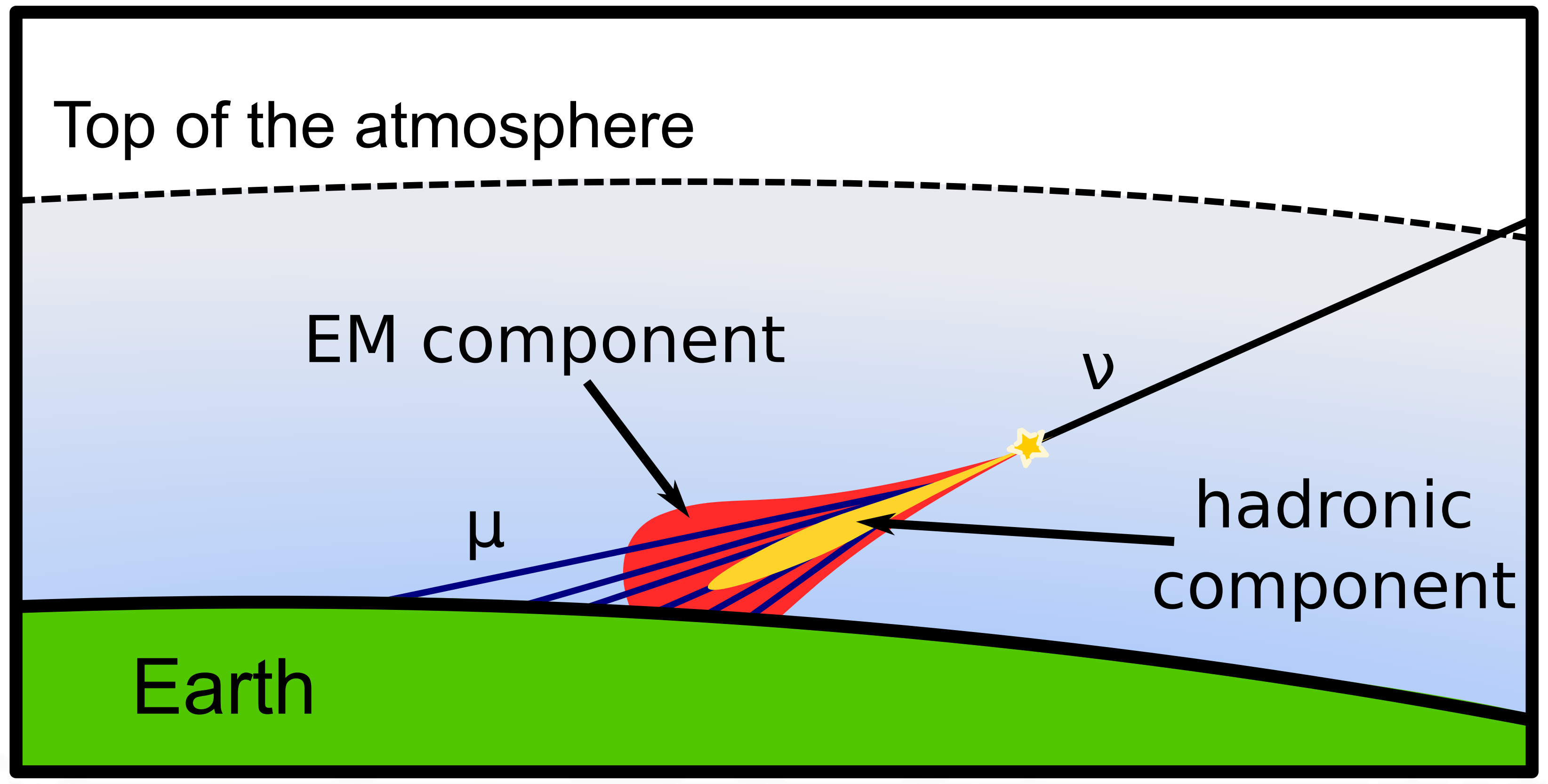
⇒ **Dramatic reduction of cosmogenic photons and neutrinos**

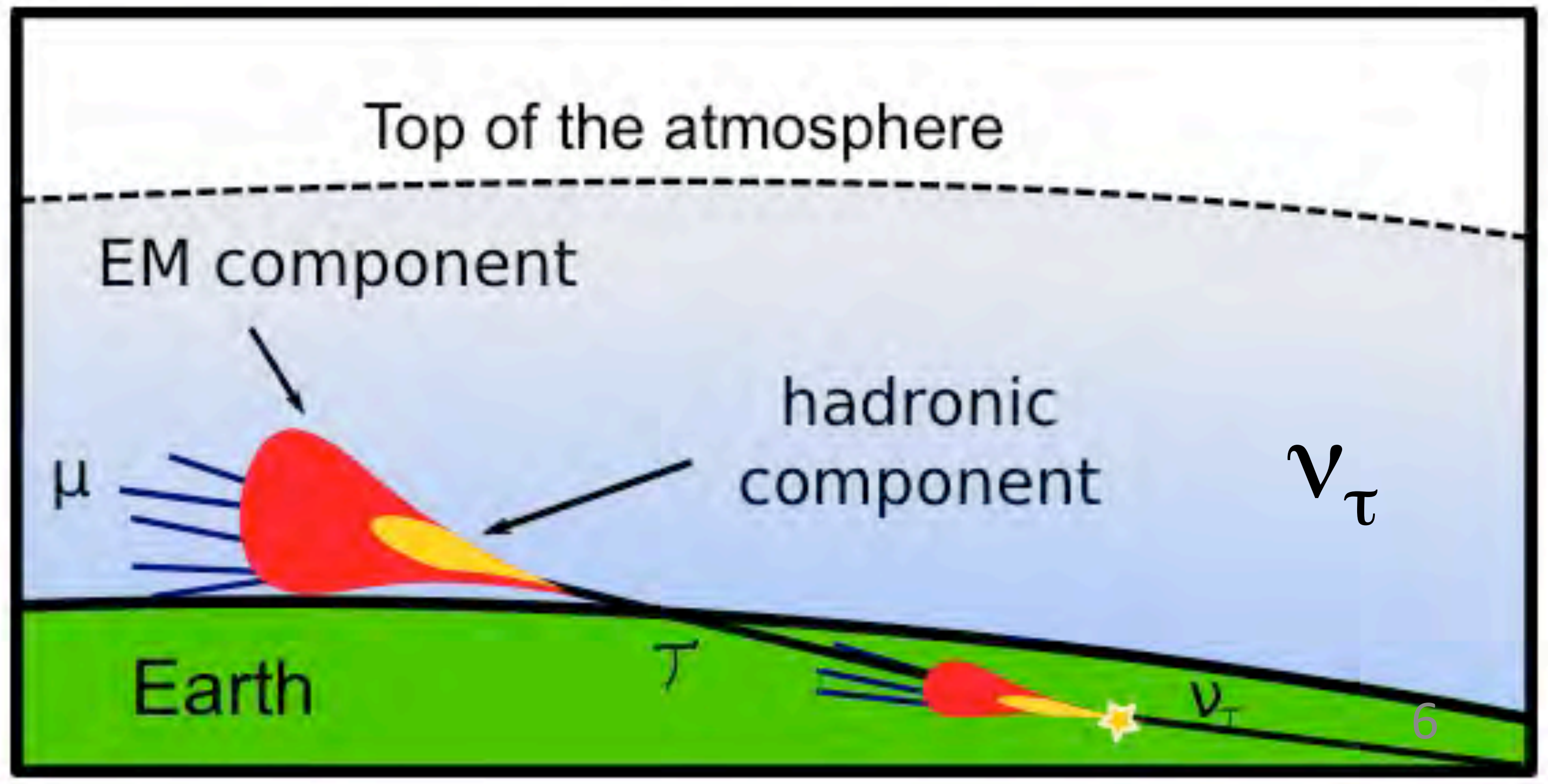
Inclined showers & UHE neutrinos

- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components

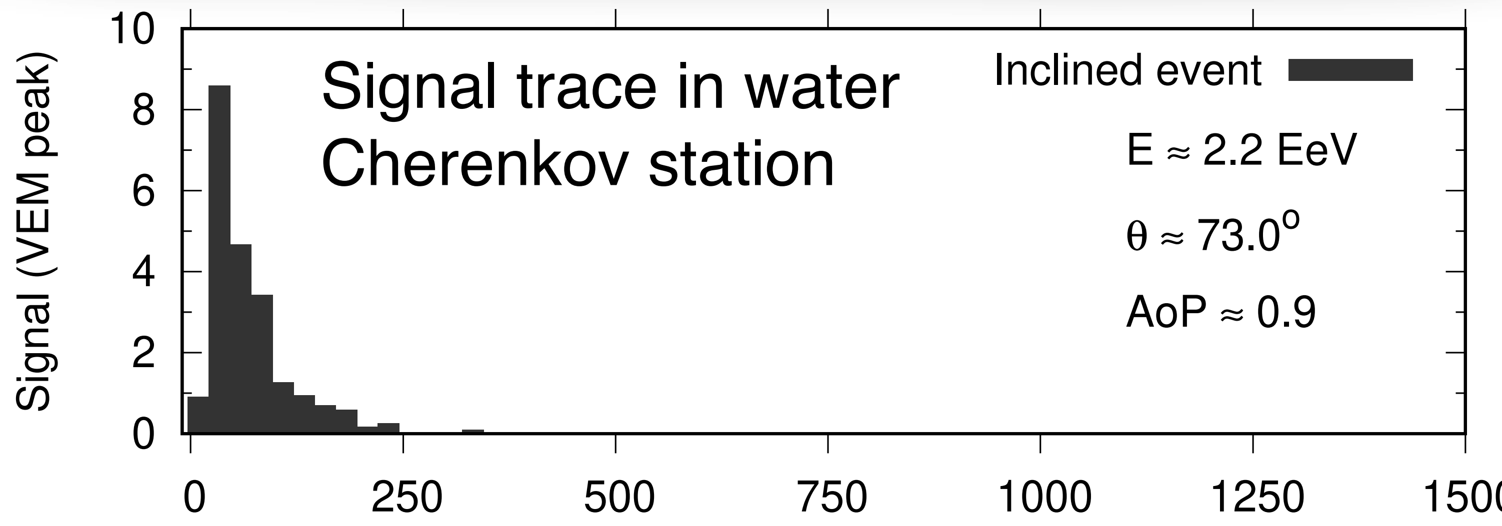
Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component



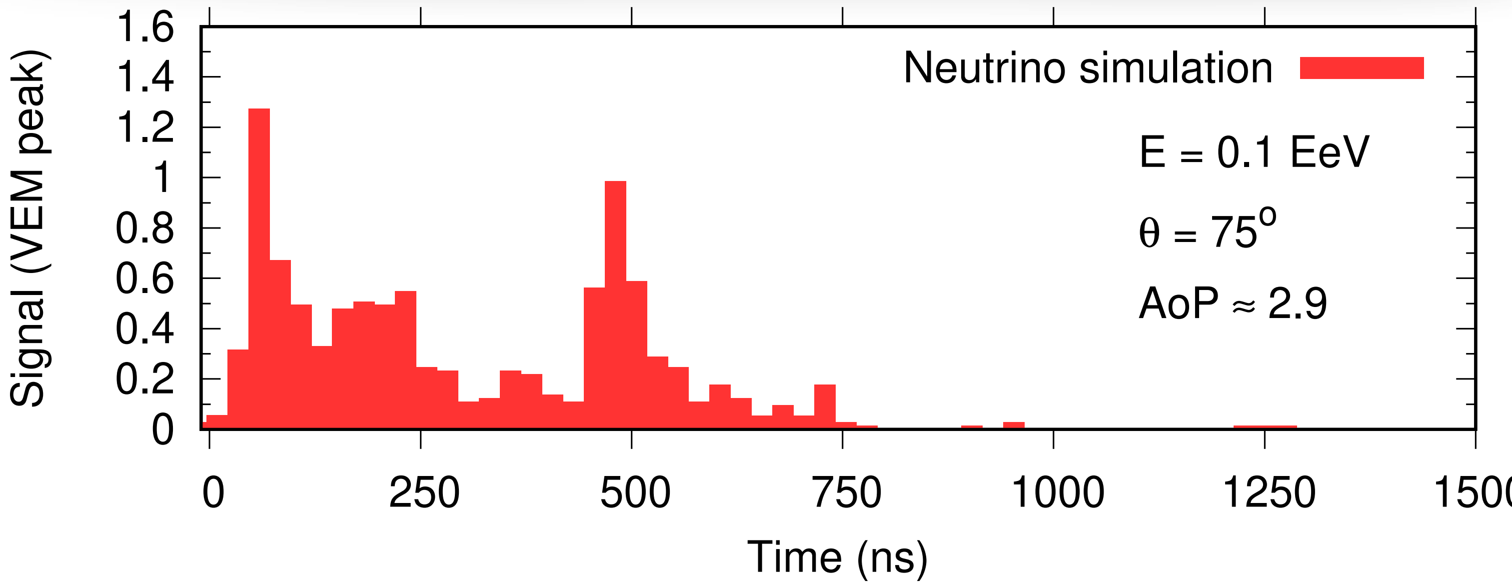


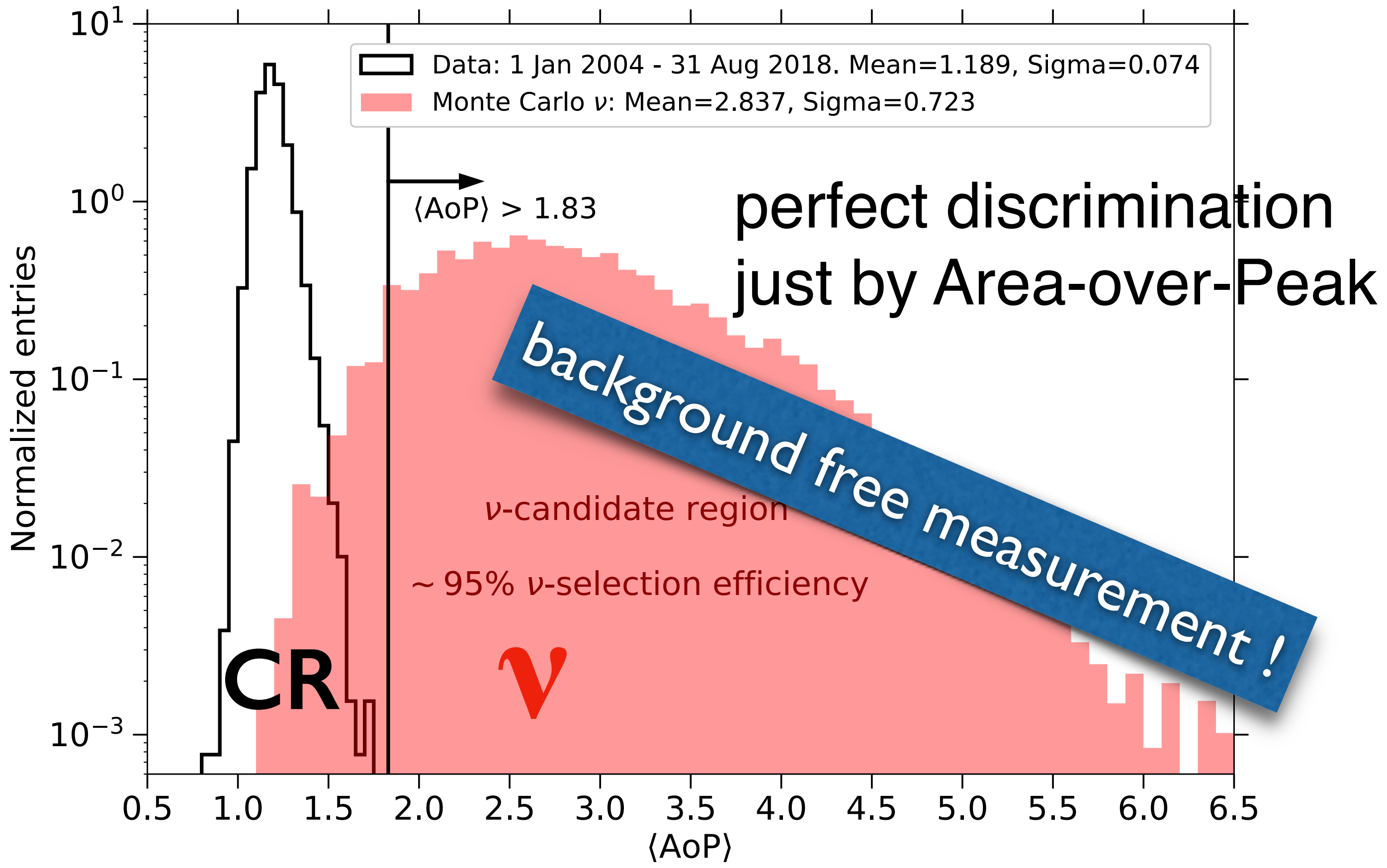


CR → old shower at ground



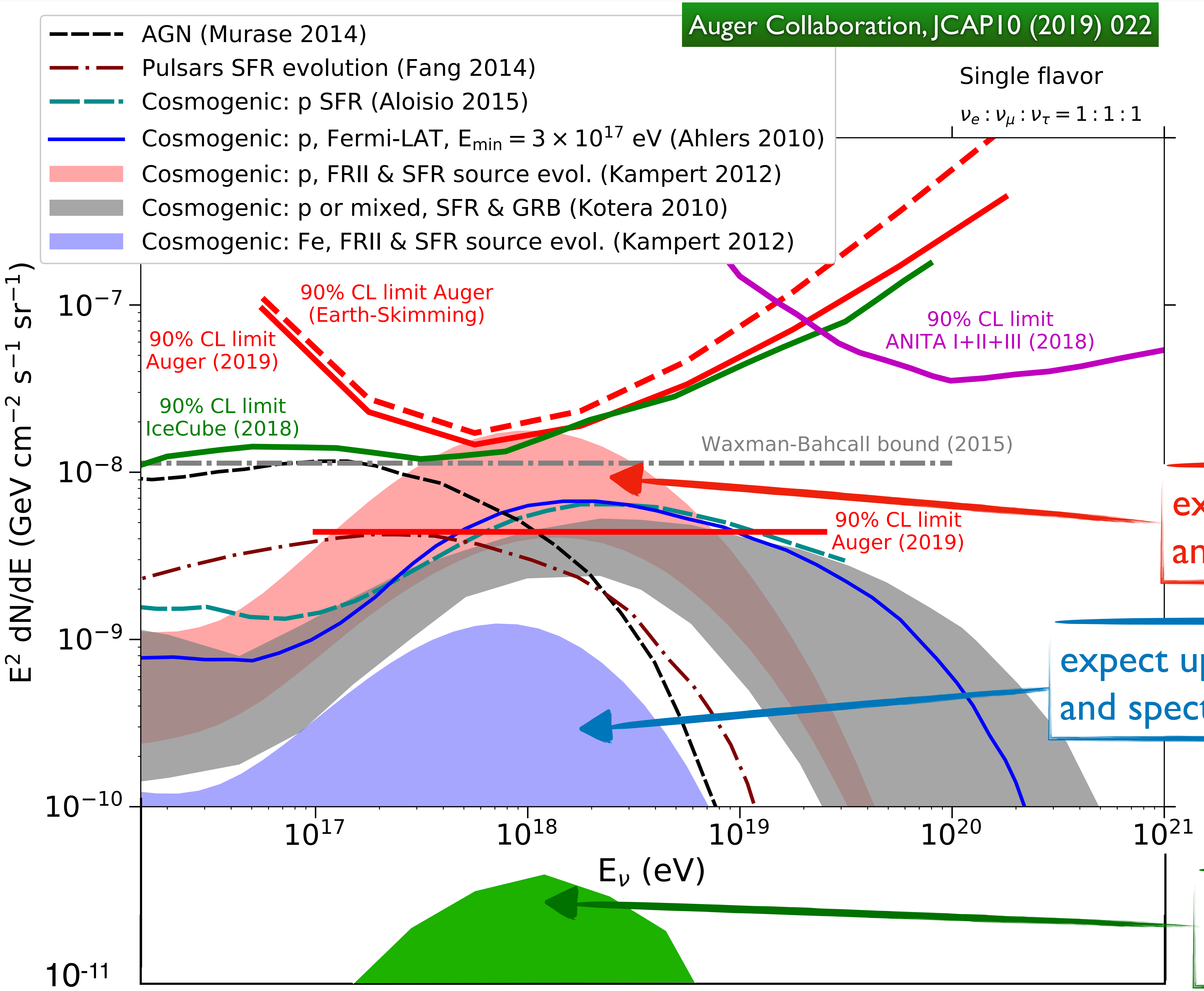
ν → young shower at ground

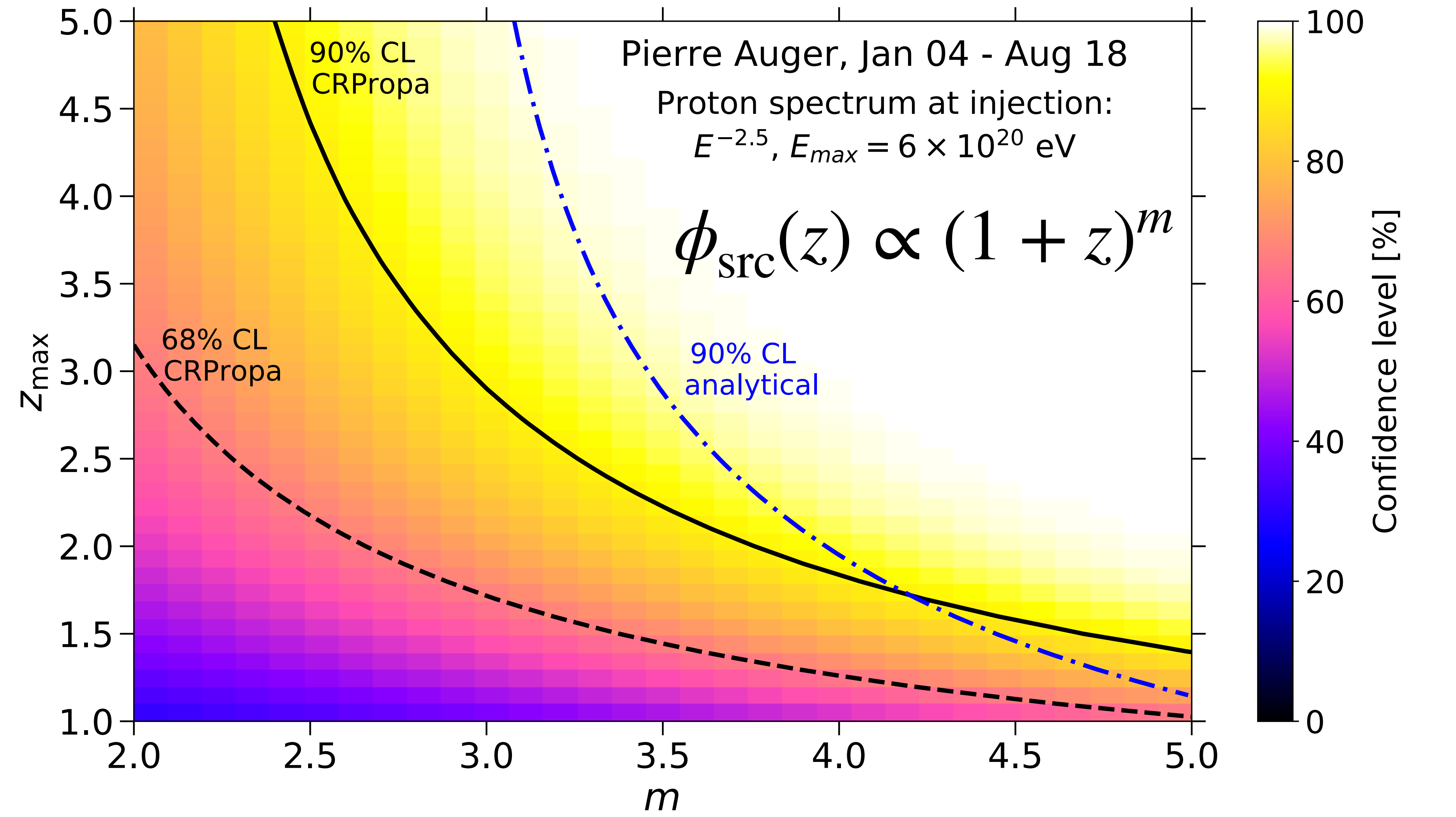




Bounds on cosmogenic neutrino fluxes

Auger Collaboration, JCAP10 (2019) 022





expect up to 6 νs for pure p-composition and spectral be caused by GZK-effect

expect up to 0.4 νs for pure Fe-composition and spectral be caused by GZK-effect

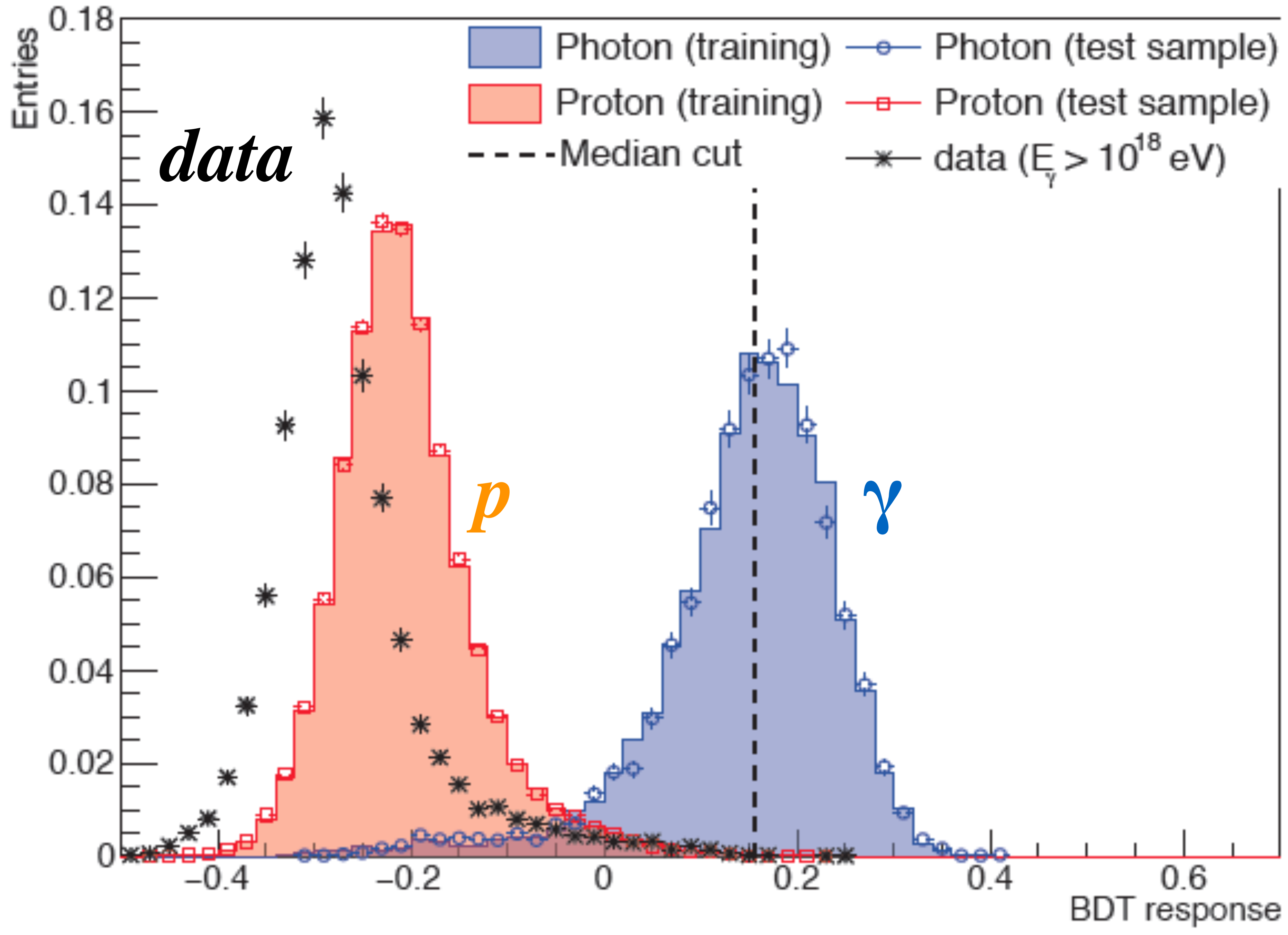
expect up to ~0.001 νs in Auger (& IceCube) for maximum source energy scenario

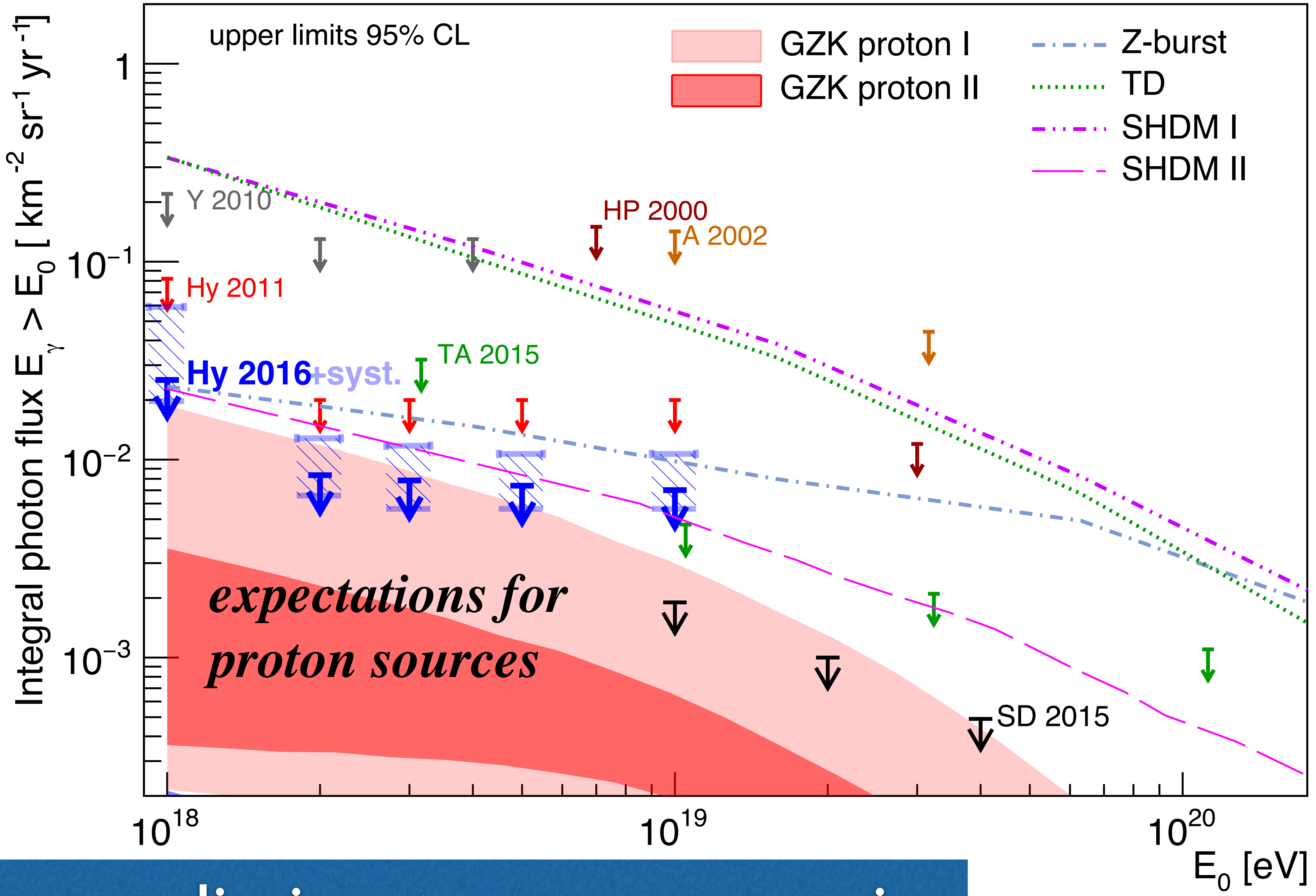
EeV Photon Limits challenge protons suffering GZK-losses

Auger Collaboration, JCAP04 (2017) 009

M. Niechciol (Uni Siegen), Diss. N. Krohm / P. Papenbreer (BUW)

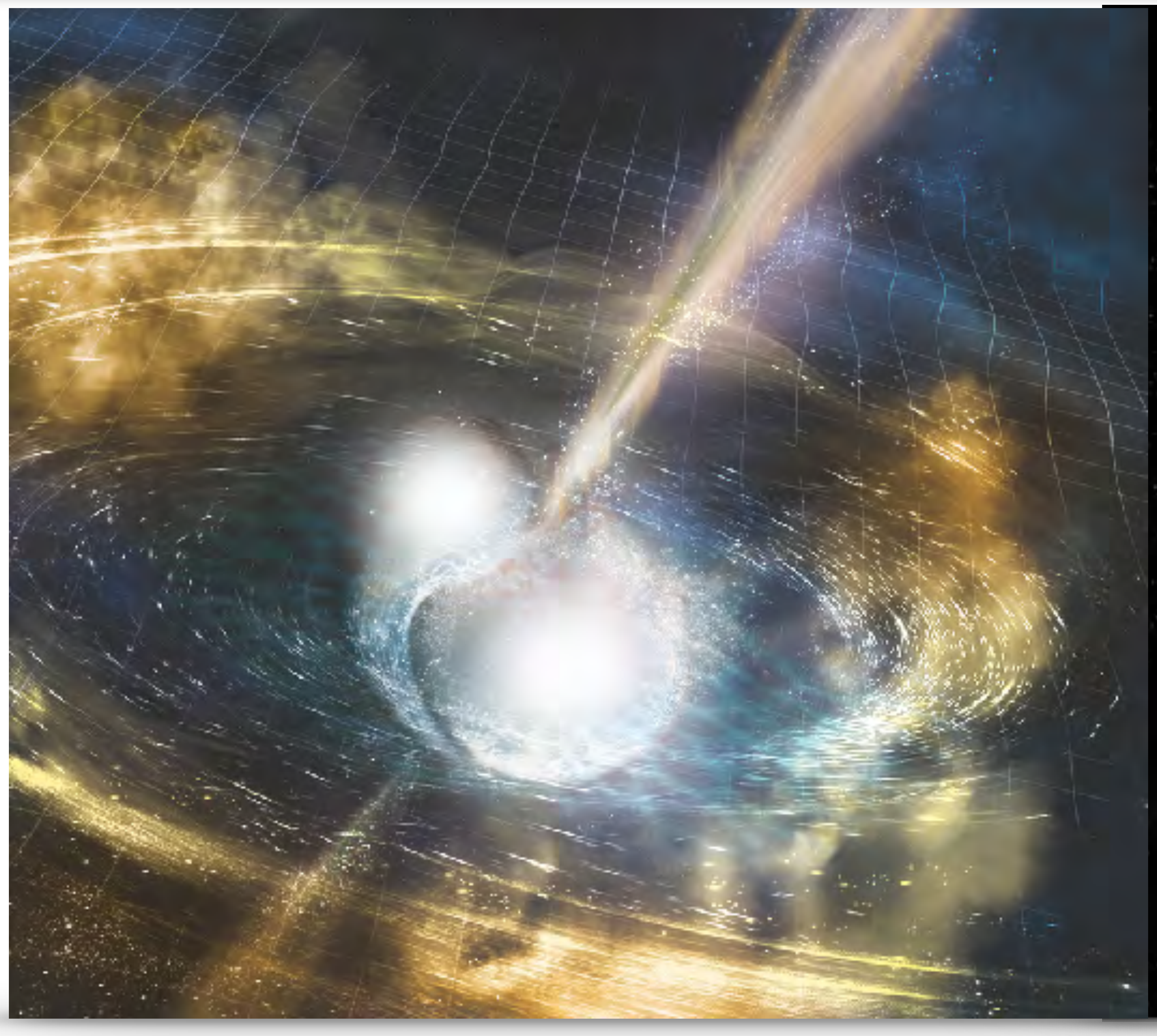
Photons can be identified by deep X_{max} and low muon number

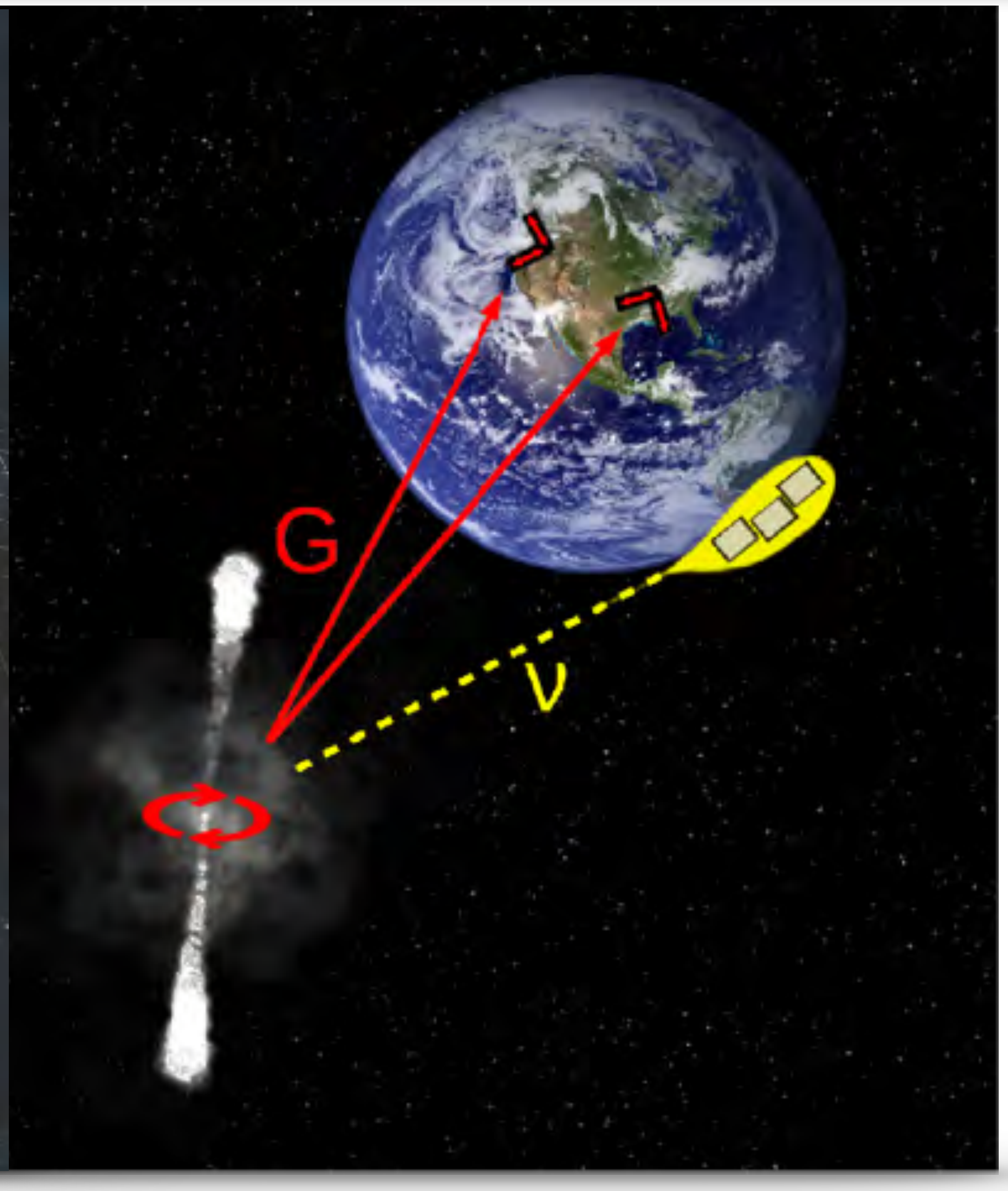


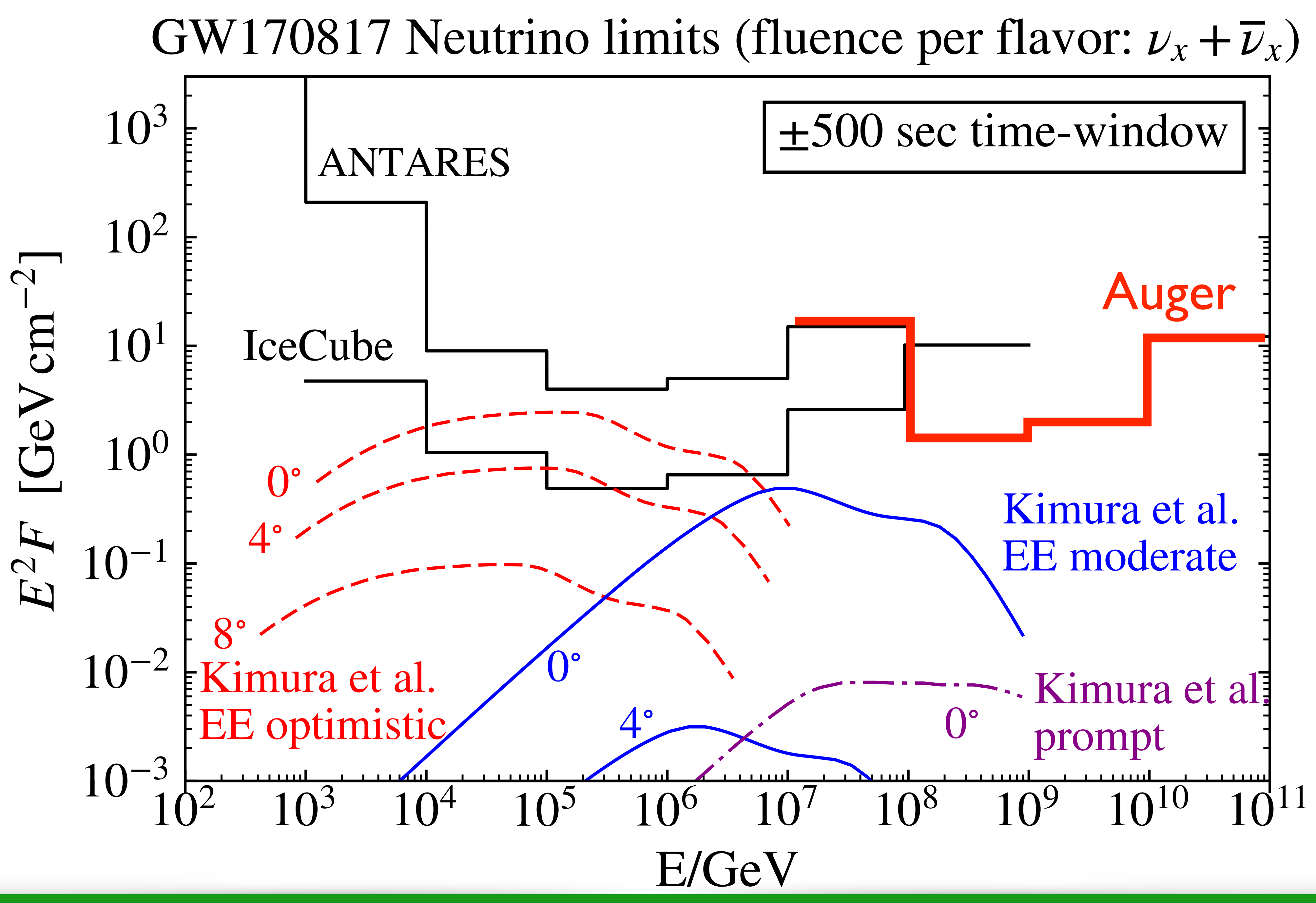


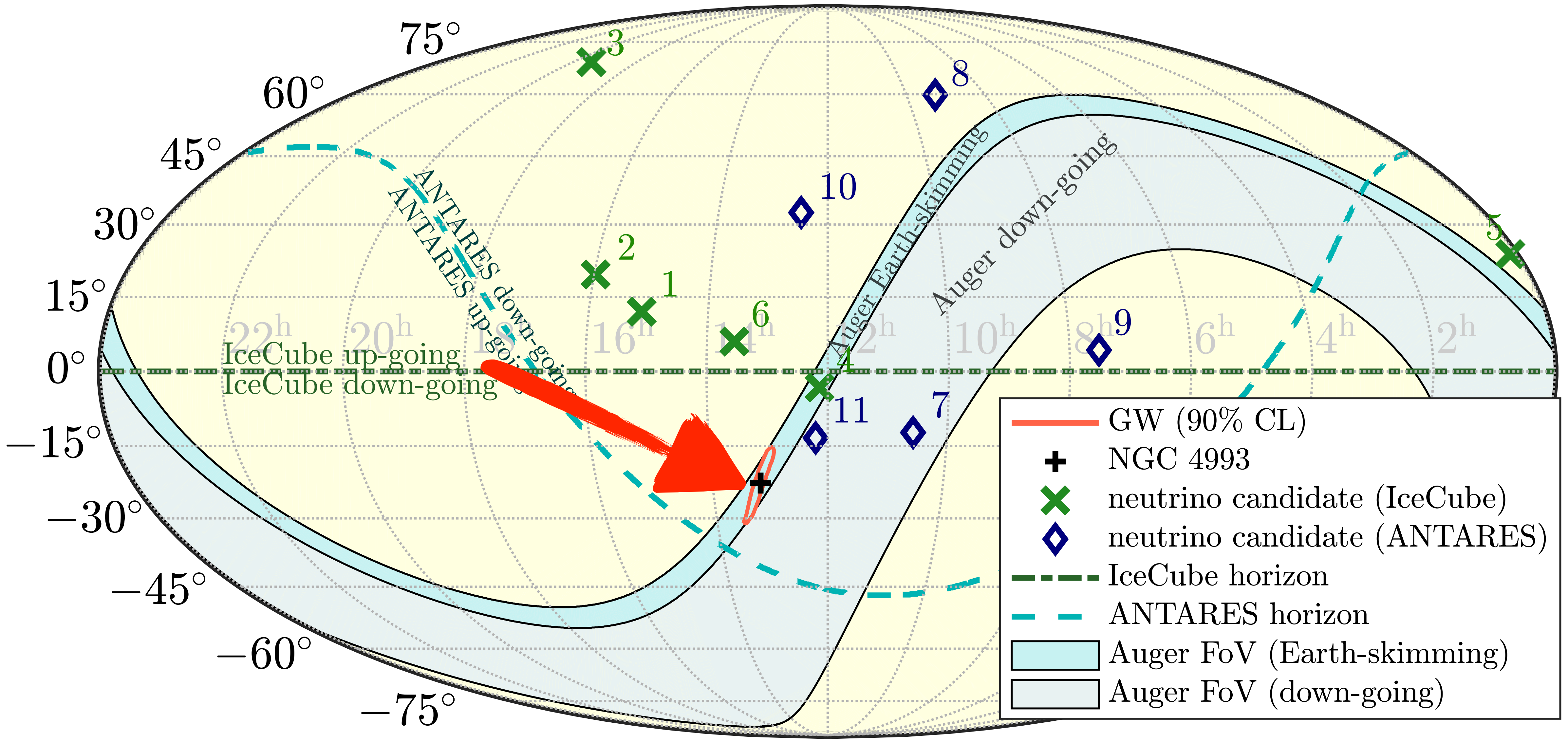
Similarly, photon upper limits start to constrain cosmogenic photon fluxes of p-sources

(2) Neutrino Upper Limits for GW170817









Absence of Neutrino consistent with SGRB viewed at >20° angle

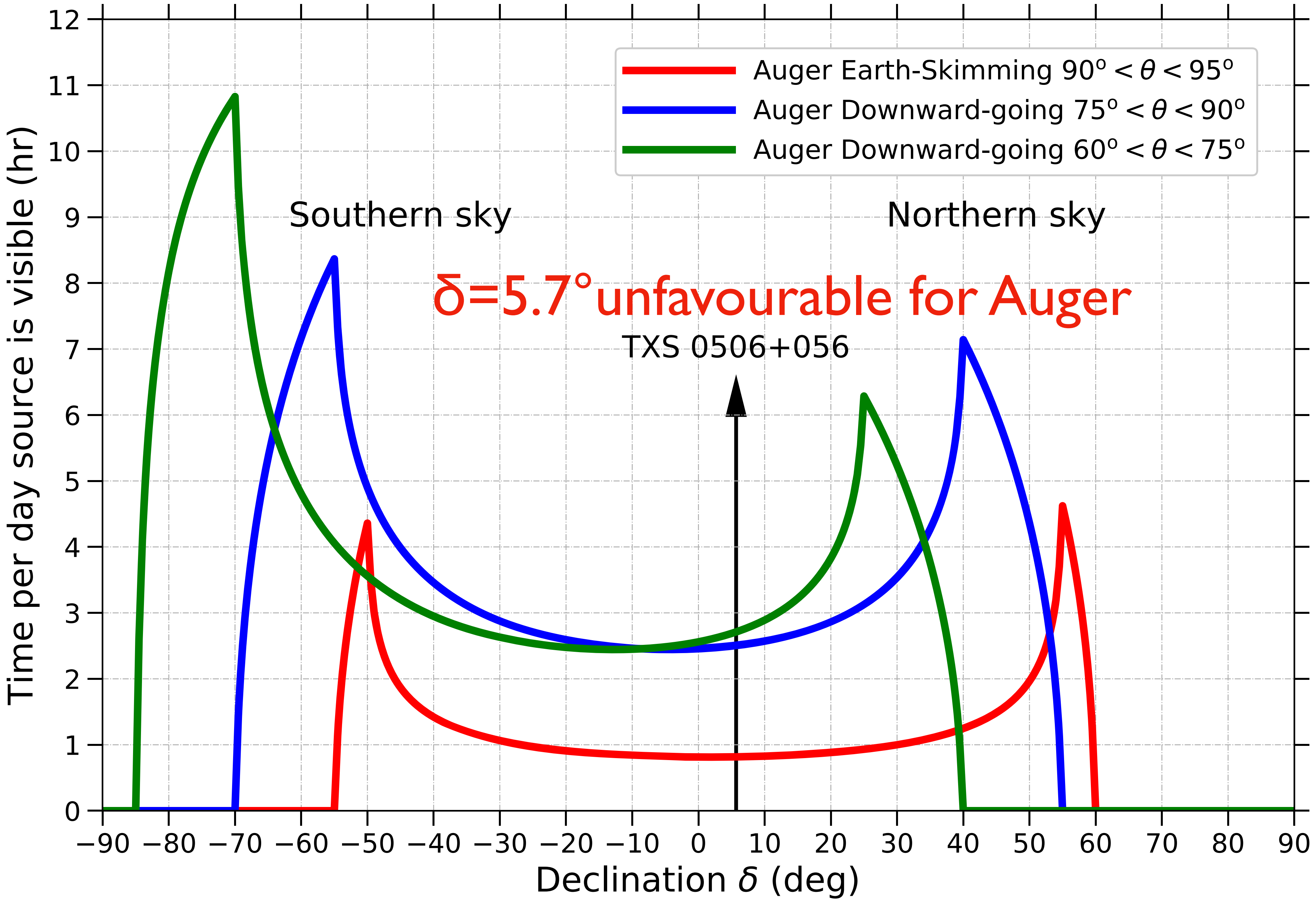
May have seen neutrinos if jet were pointing towards us

LIGO, ANTARES, IceCube, Auger,
The Astrophys. J. Lett. 850 (2017) L35

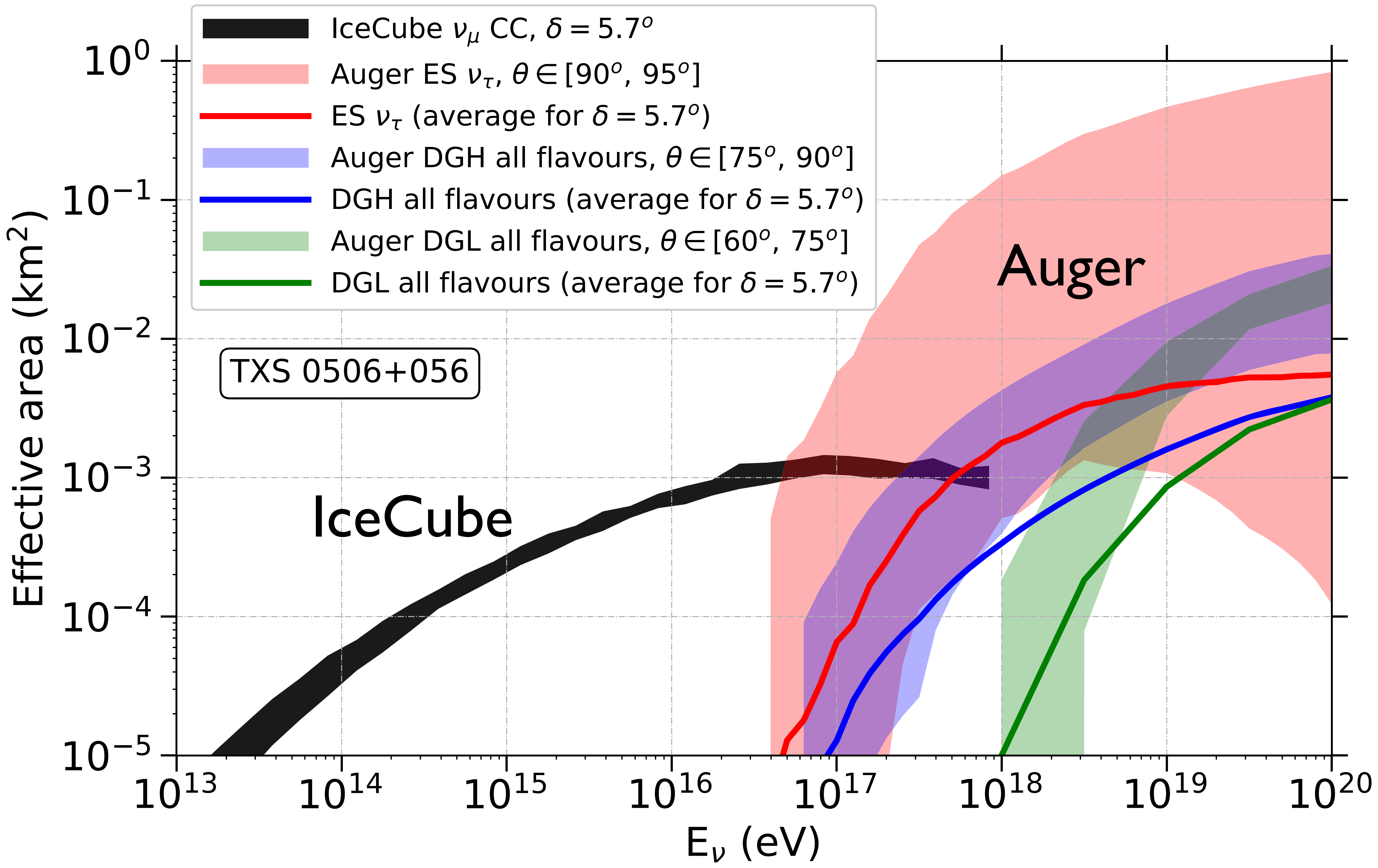
(3) Search for nu's from TXS 0506+56

In Sept. 2017, IceCube observed a 290 TeV nu from the direction of TXS 0506+59 during a flaring state; Science 361, 146 (2018)

daily visibility in ES channel of Auger: < 1 hrs



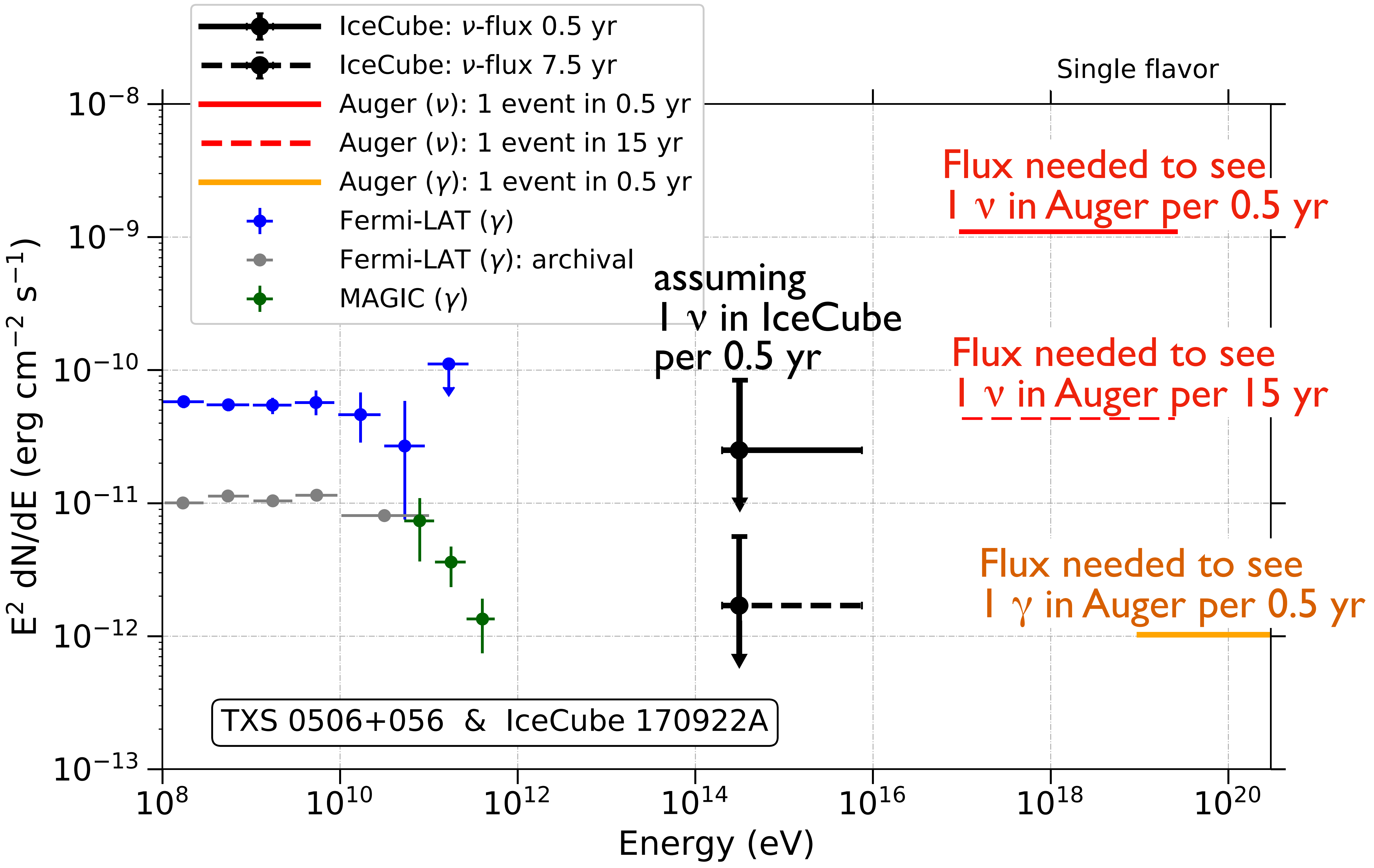
effective area in comparison to IceCube



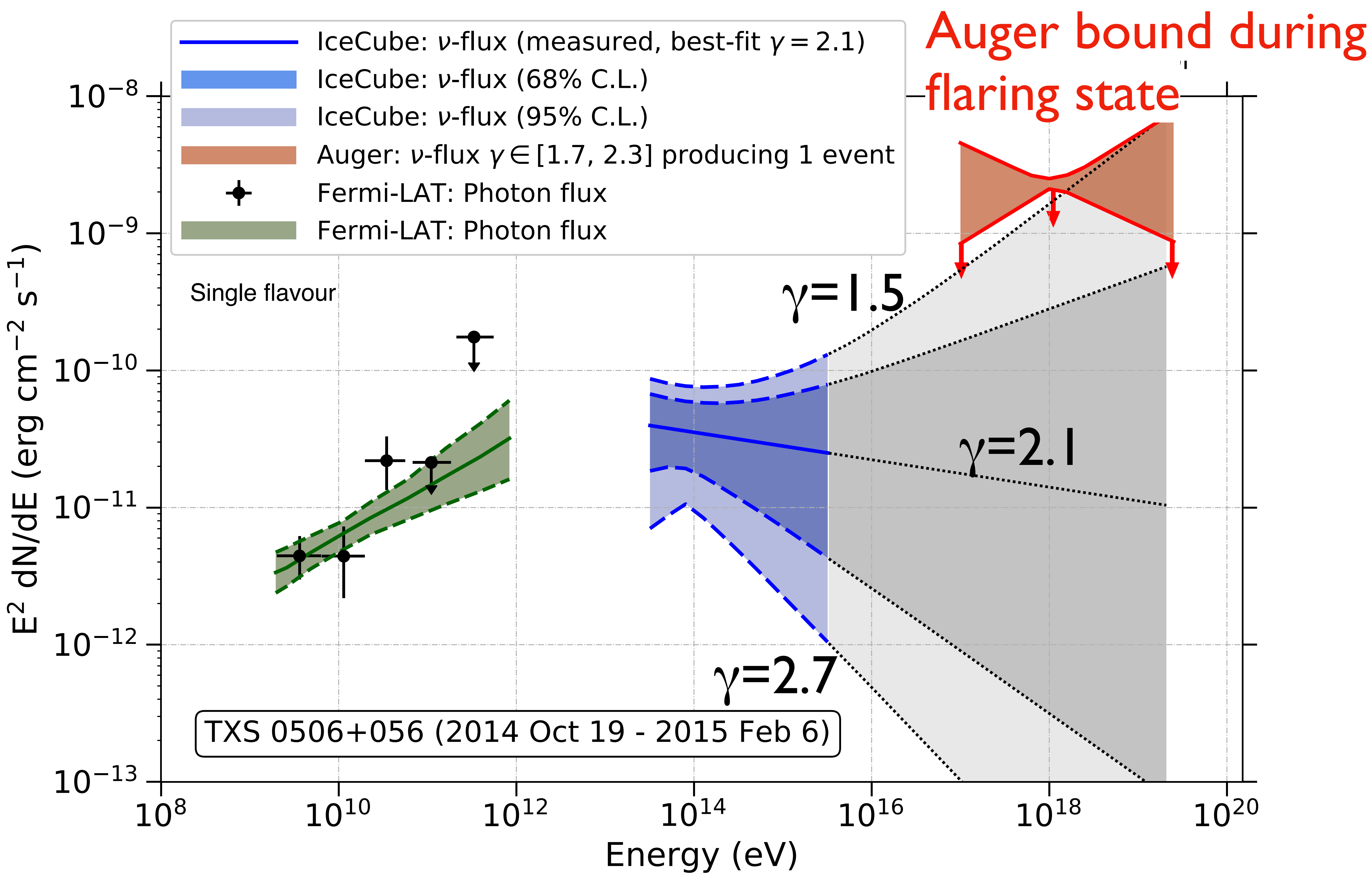
Auger Collaboration, ApJ 902 (2020) 105

(3) Search for nu's from TXS 0506+56

Flux comparison from single event assuming E^{-2} spectrum



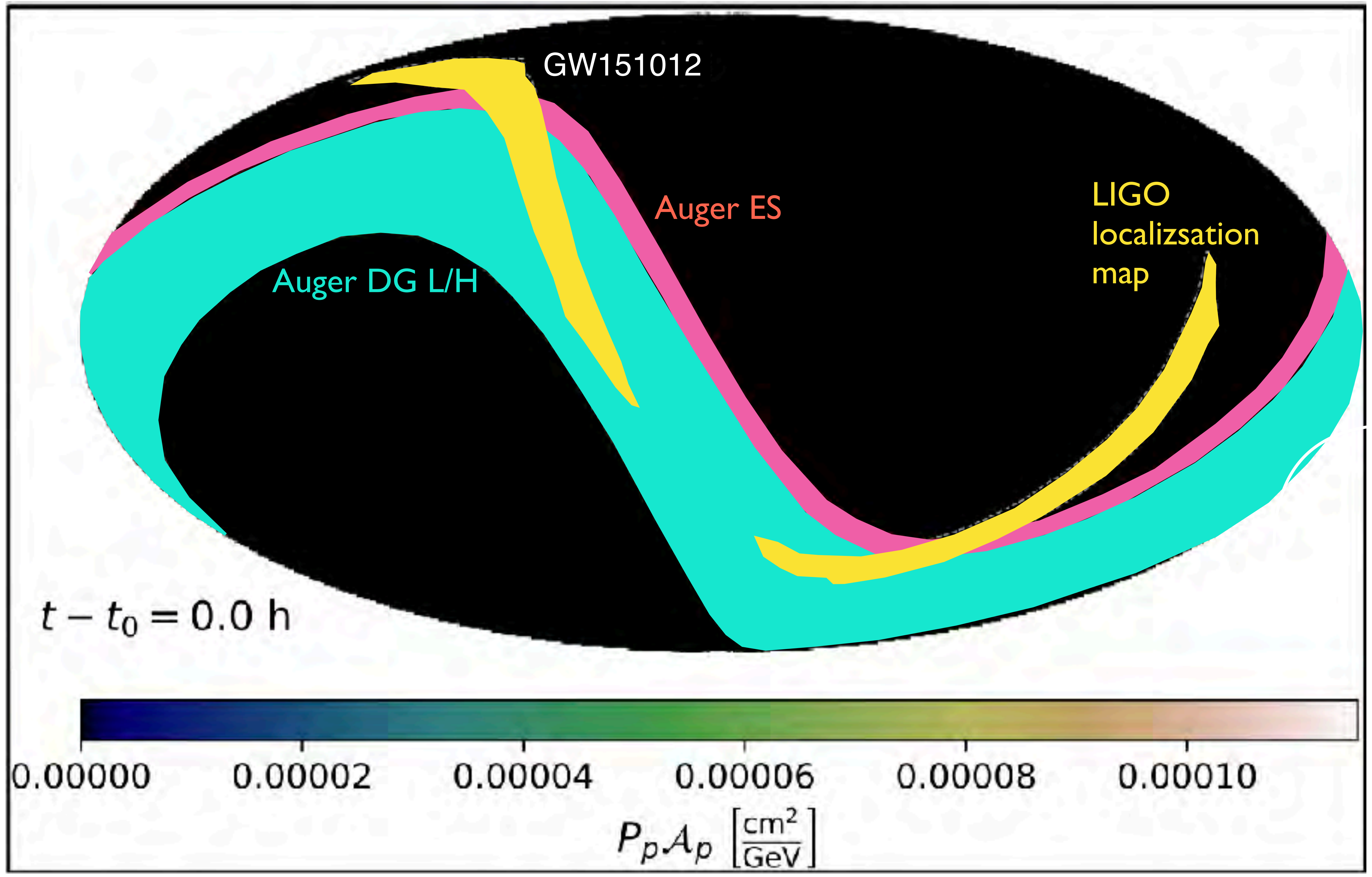
Sensitivity of Auger to 110 days „ν flaring state"

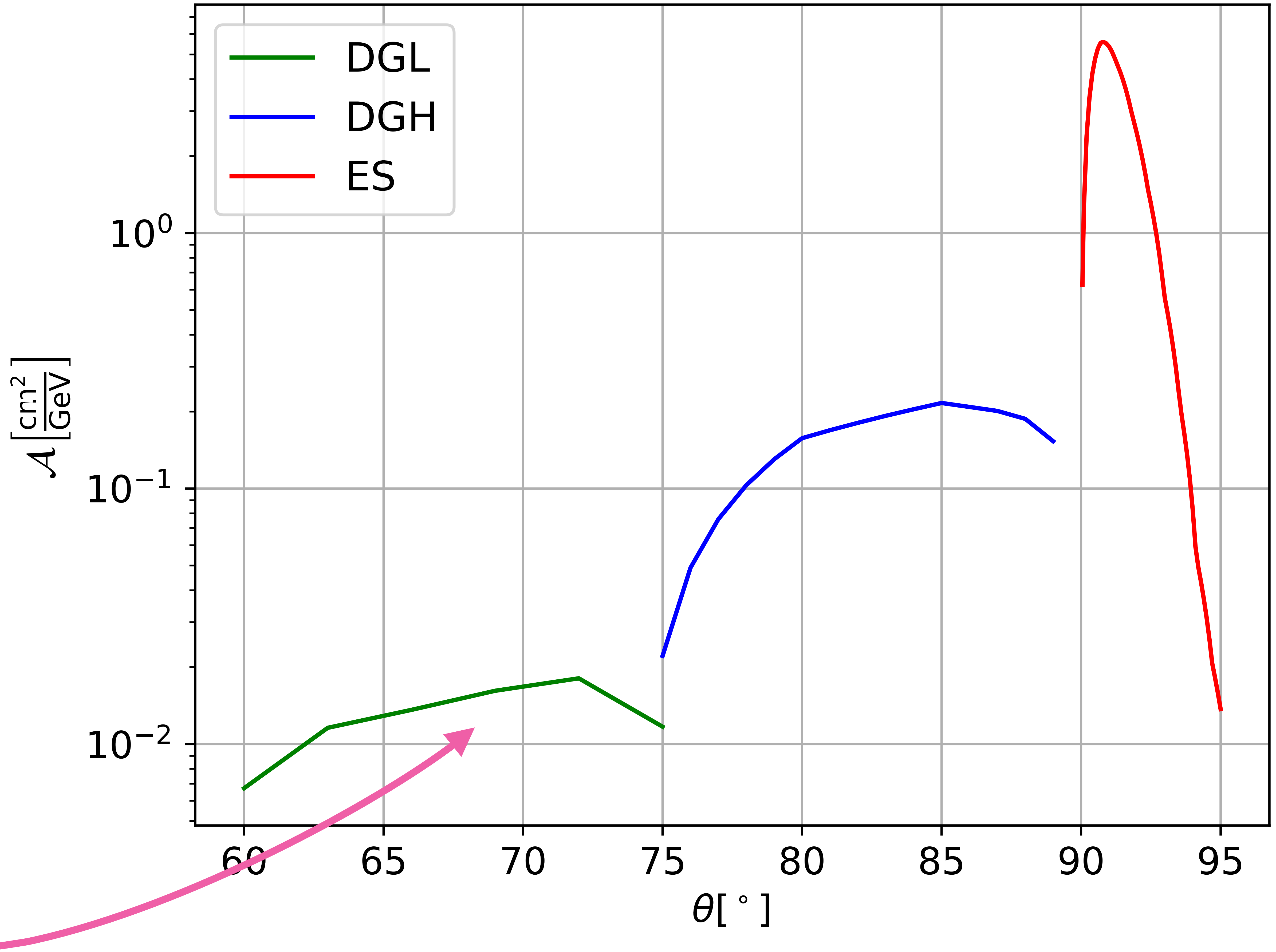


Auger Collaboration, ApJ 902 (2020) 105

Expected to detect a neutrino in Auger only in case of hard neutrino spectra (+2σ allowance of IceCube)

(4) Combining BBH Mergers





solid angle integration

$$N_{\nu,i} = L_i \, \Delta t \sum_s \frac{\sum_p P_{p,s} \mathscr{A}_{p,s,i}}{d_s^2}$$

effective area

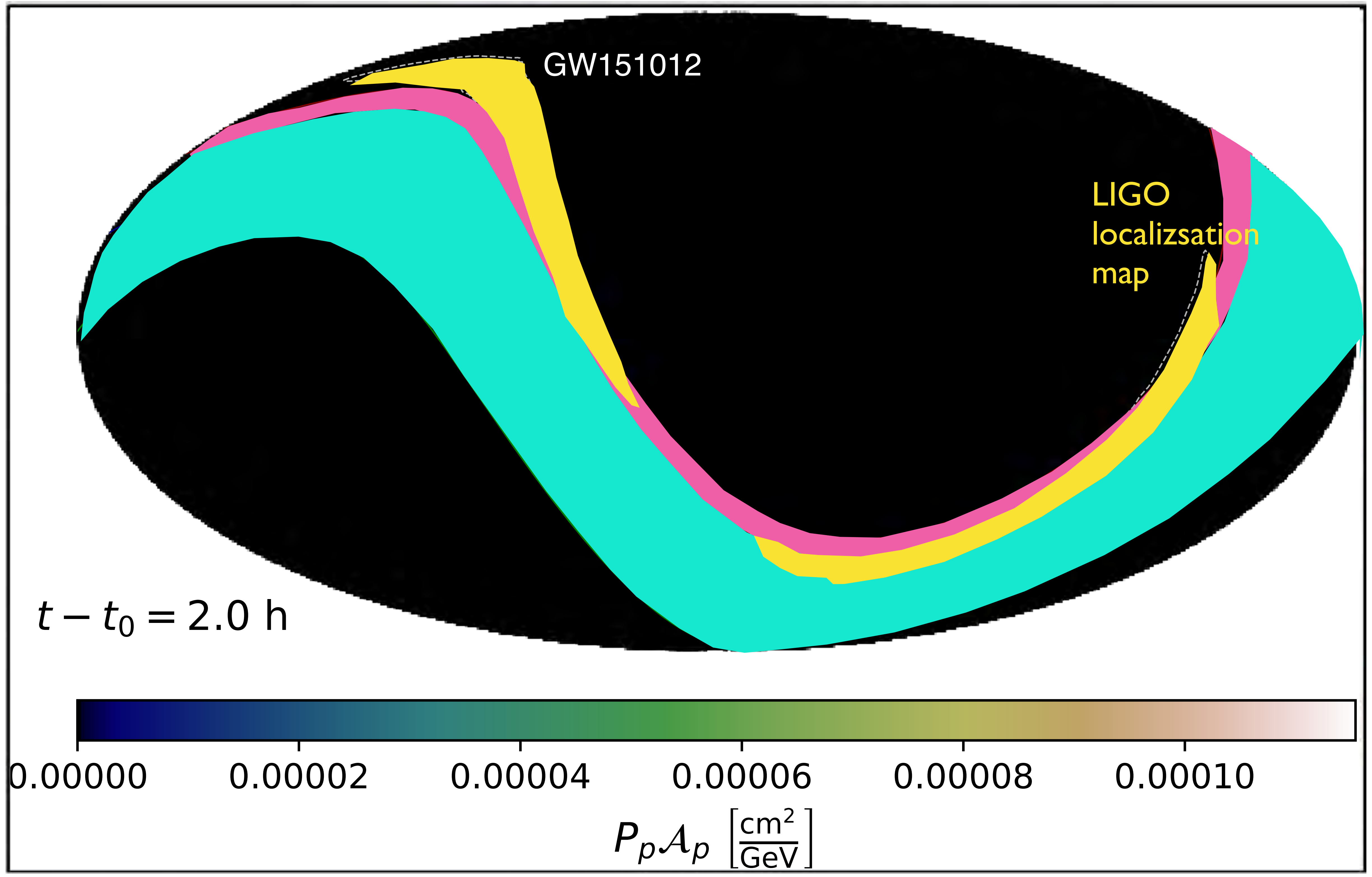
sum over all sources

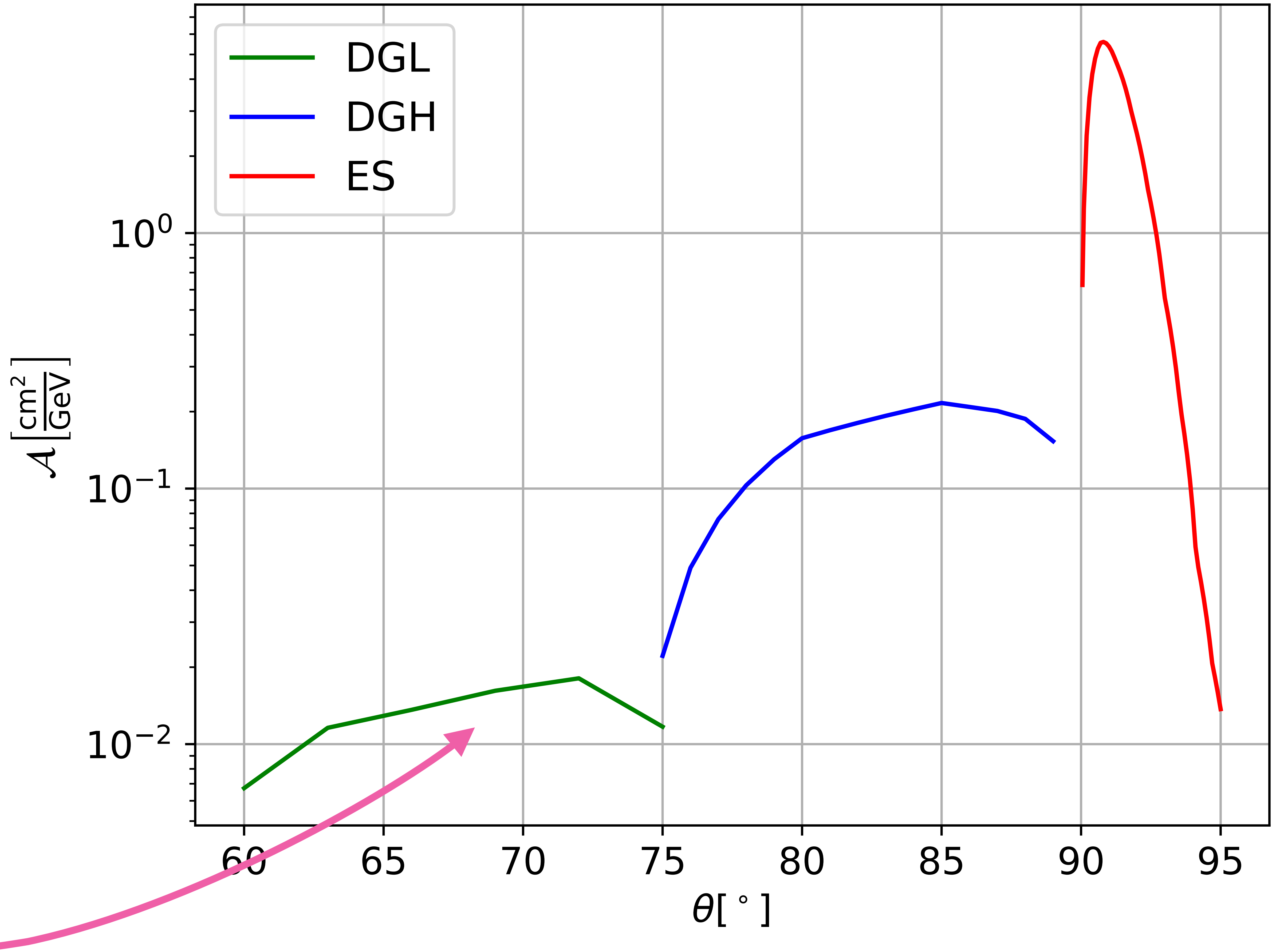
luminosity distance of source

Number of expected neutrinos per source proportional to weighted overlap area integrated over time time

*L*i: Neutrino luminosity (to be constrained)

(4) Combining BBH Mergers





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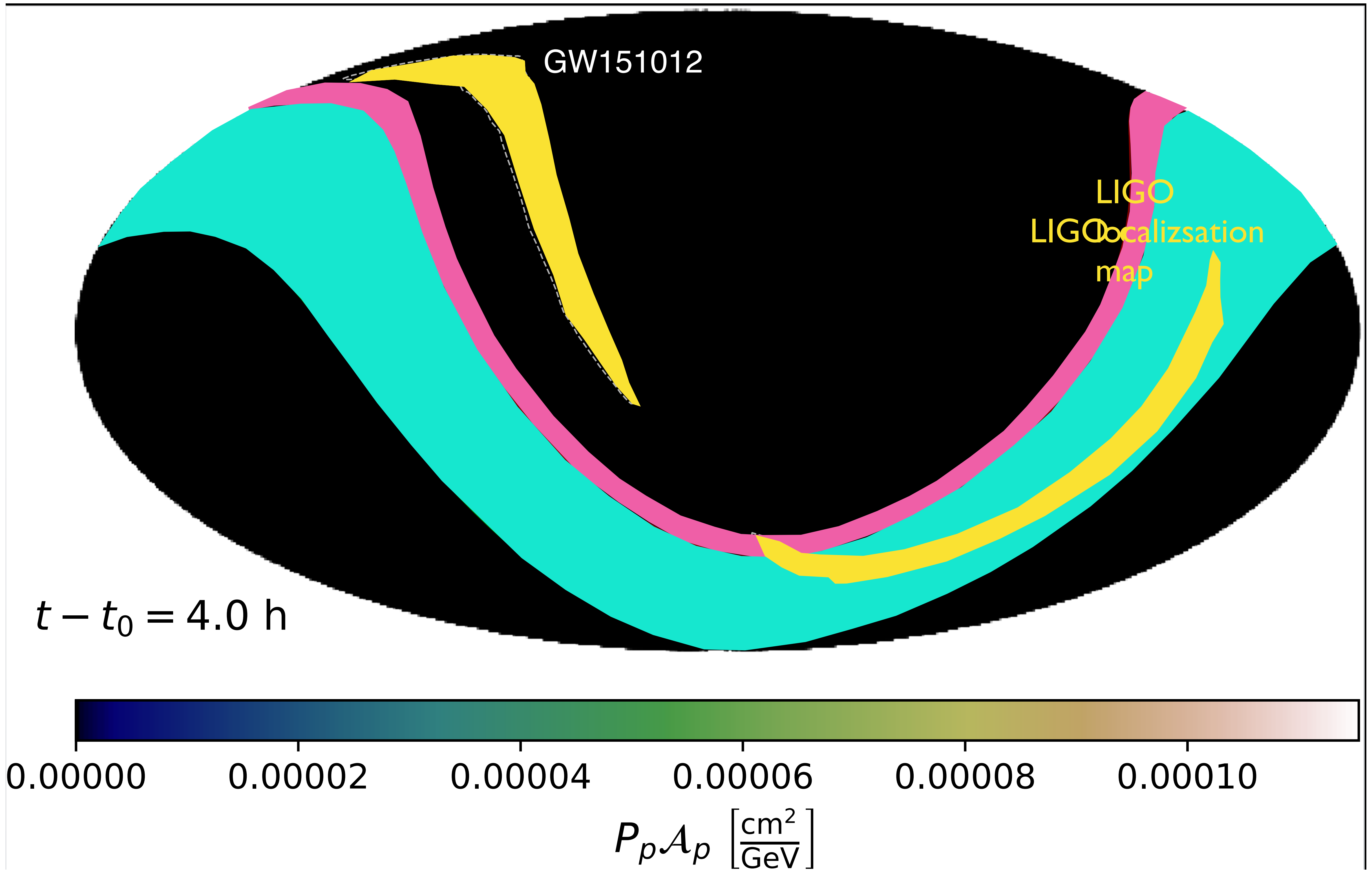

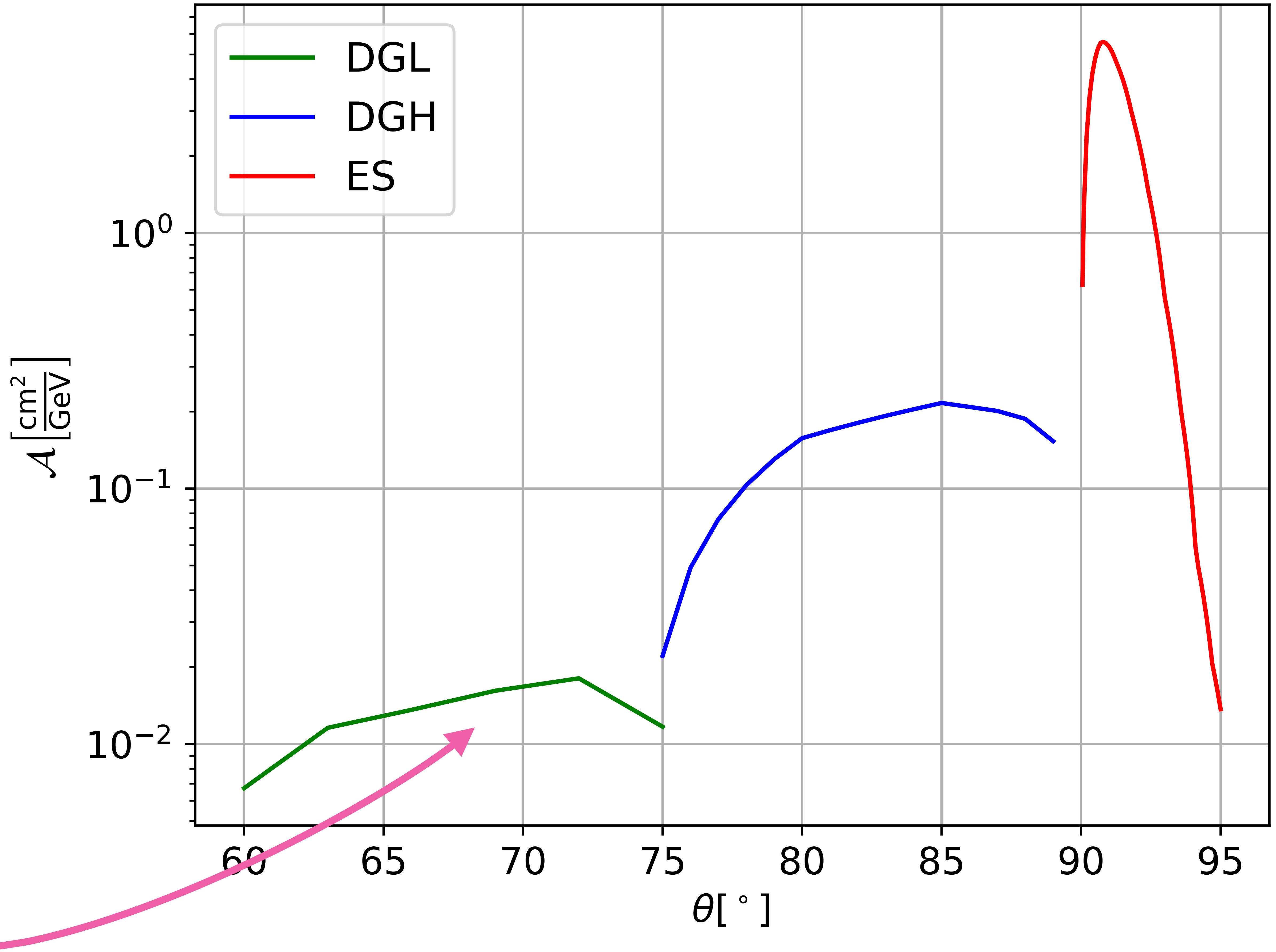

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sum over all sources

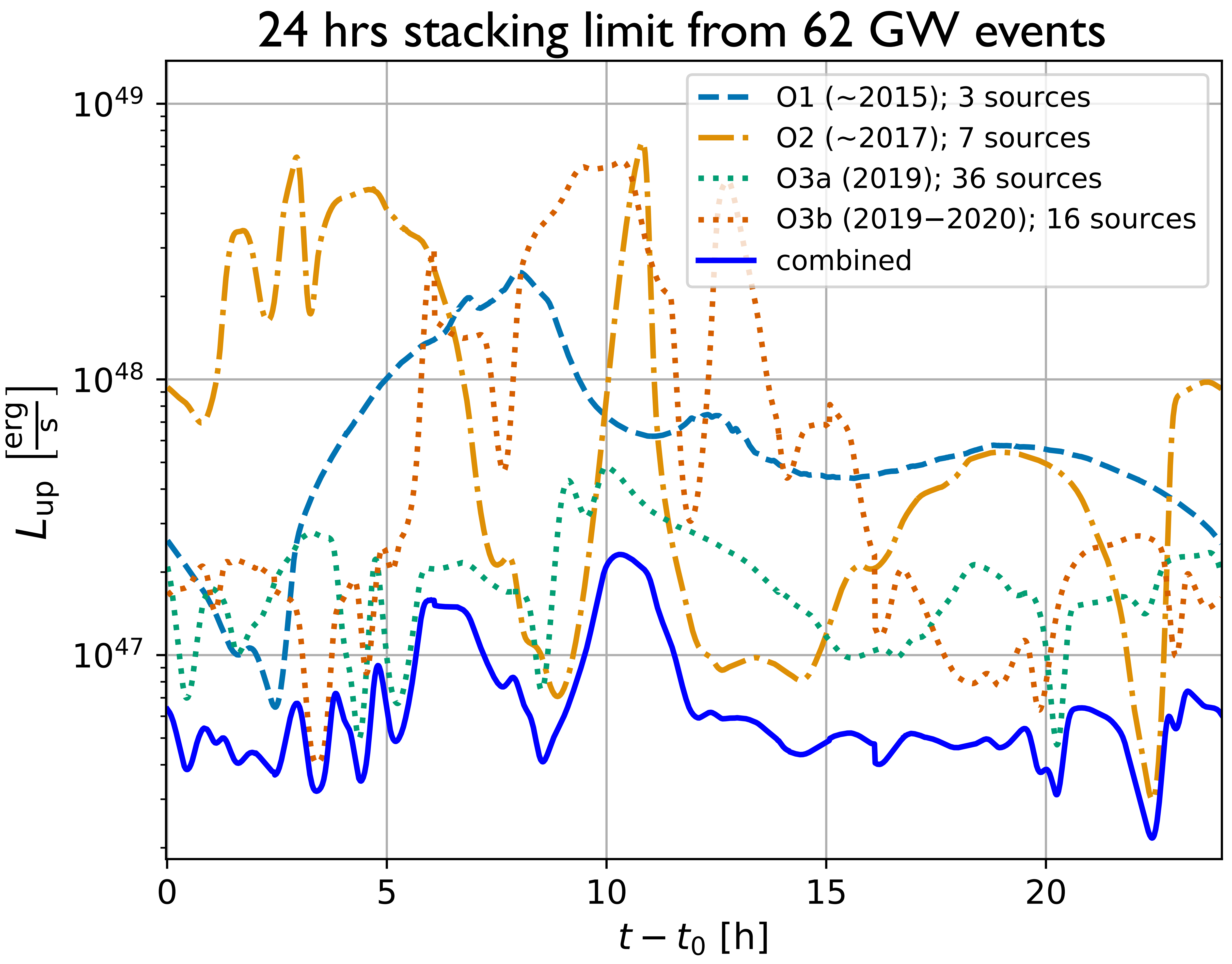
luminosity distance of source

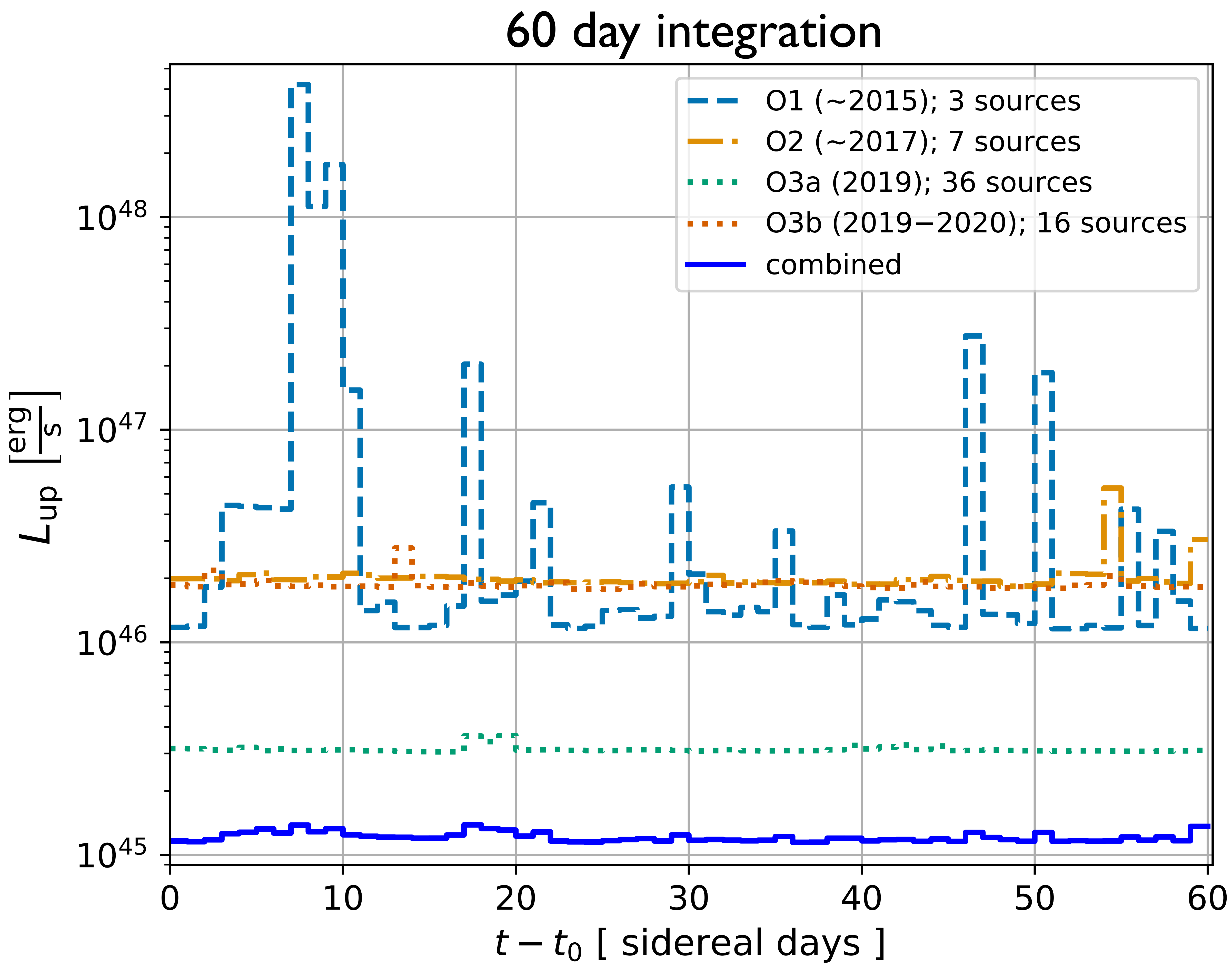
Number of expected neutrinos per source proportional to weighted overlap area integrated over time time

L_i: Neutrino luminosity (to be constrained)

Isotropic Neutrino Luminosity Bound

M. Schimp; Auger Collaboration, PoS (ICRC2021) 968





Neutrino emission energy limit $\sim M_{\odot}c^2/300$ as compared to $\sim M_{\odot}c^2$ radiated GW energy assuming isotropic emission and E_{ν}^{-2} flux

Photon Searches from GW Events

Two key differences for stacked sources:

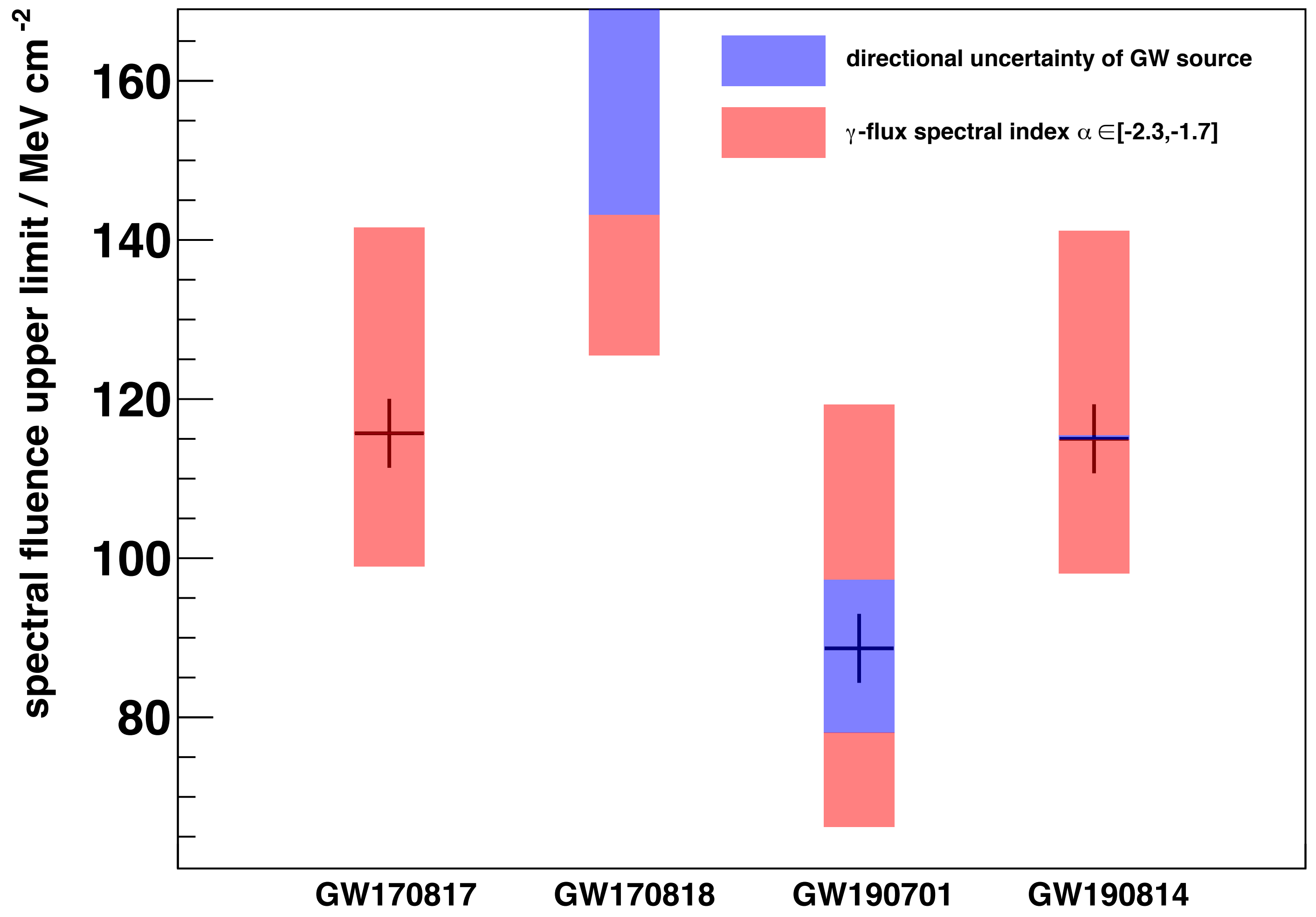
1. Photon horizon some 10 Mpc
2. Photon identification not free of background

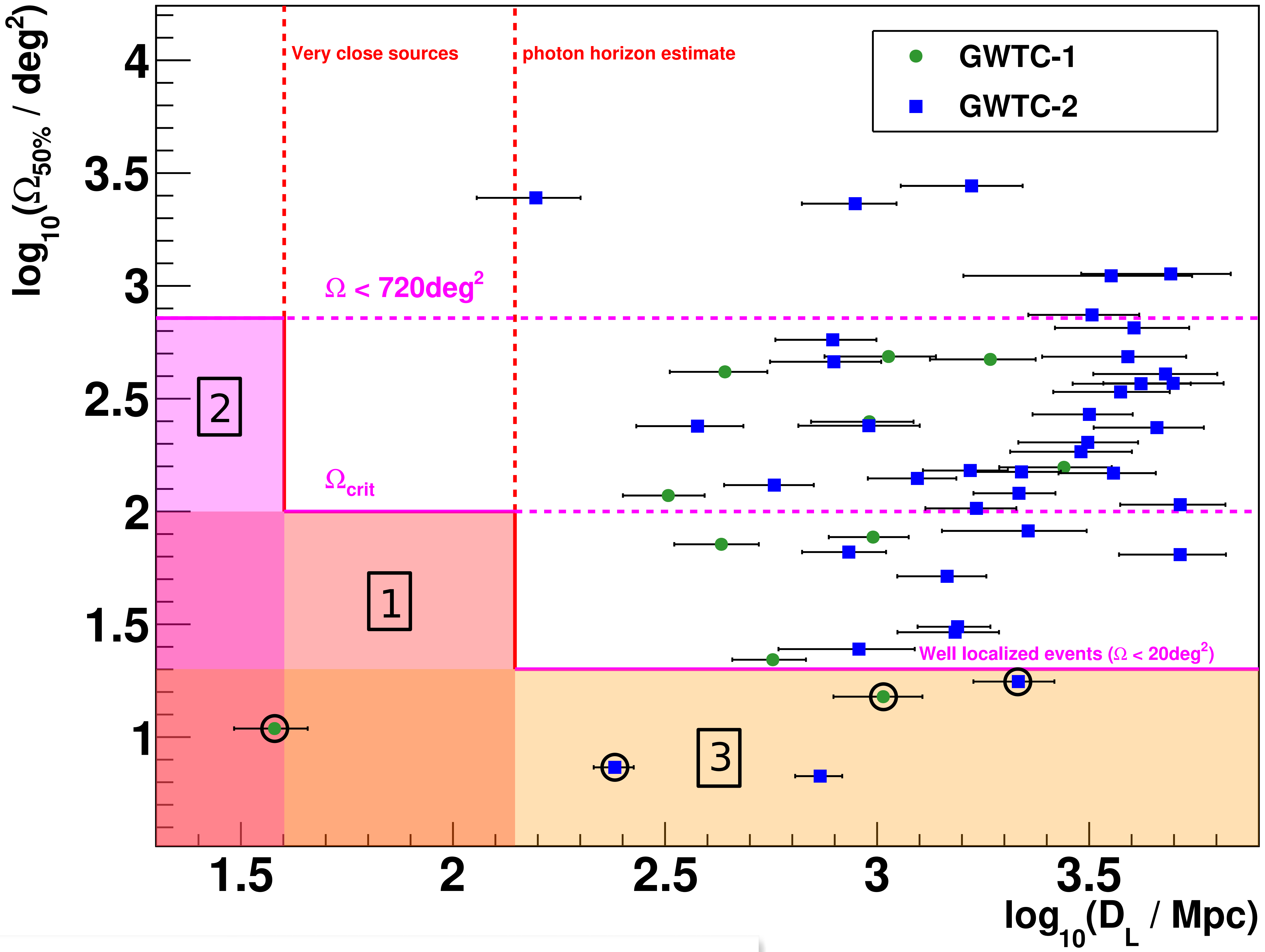
⇒ careful selection needed:

sources are required to be nearby (< 40 Mpc) and well localised

4 sources pass this event section:

1 BNS merger
2 HHB mergers
1 BH-NS merger candidate

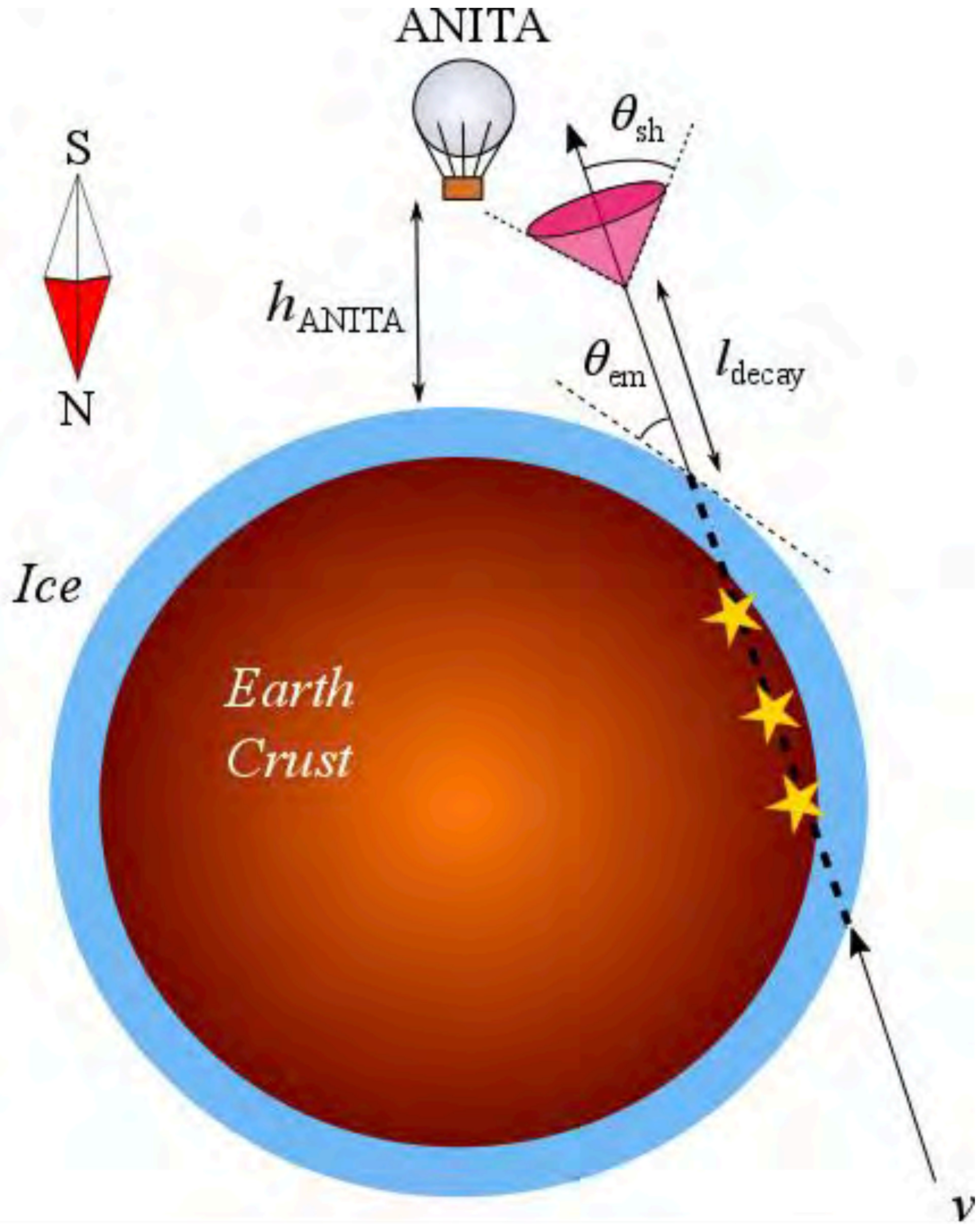




No coincident photon candidate identified
⇒ Upper limits on spectral fluence during 1 day

P. Ruehl; Auger Collaboration, PoS (ICRC2021) 973

(5) Search for Up-Going Air Showers

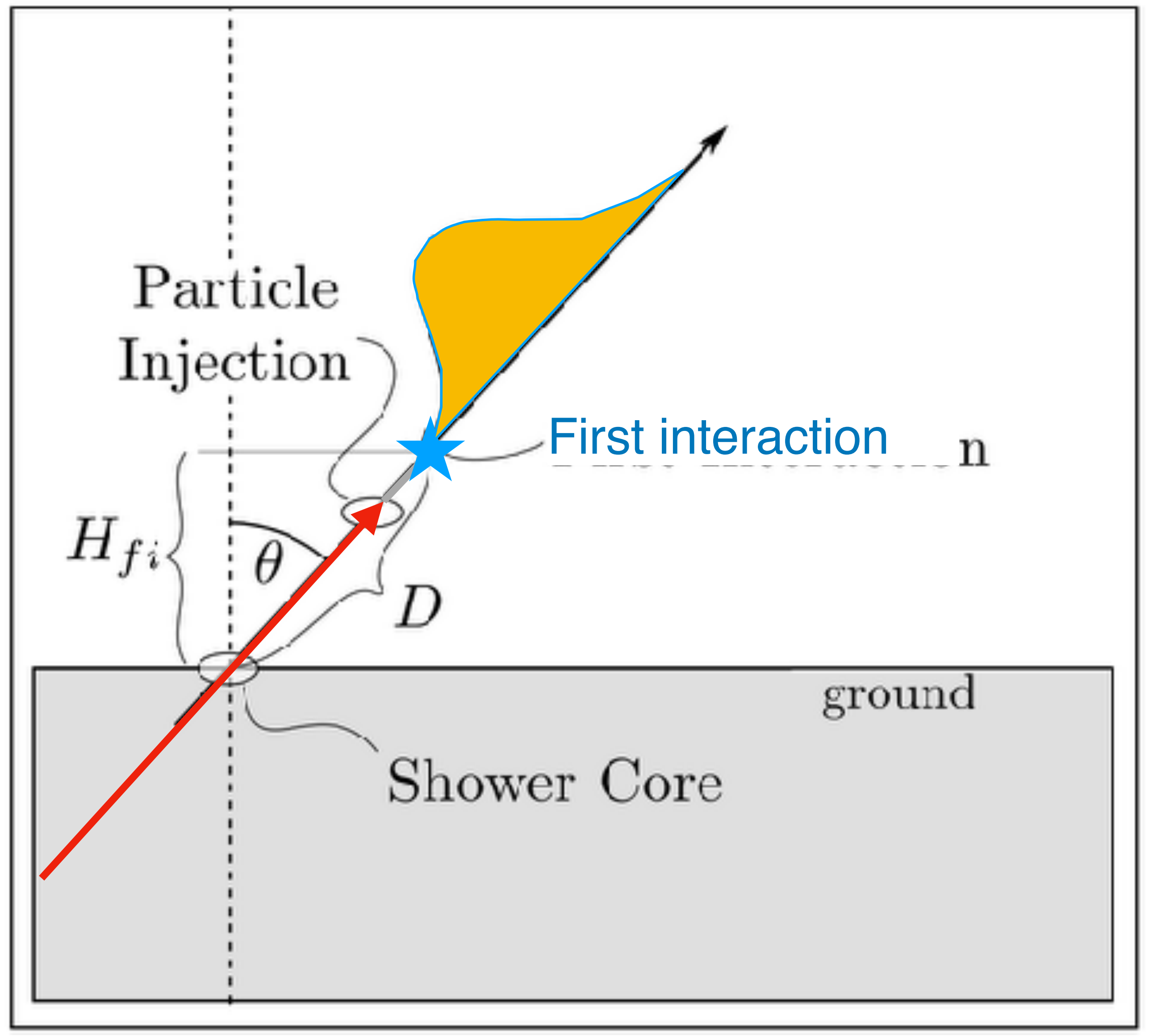


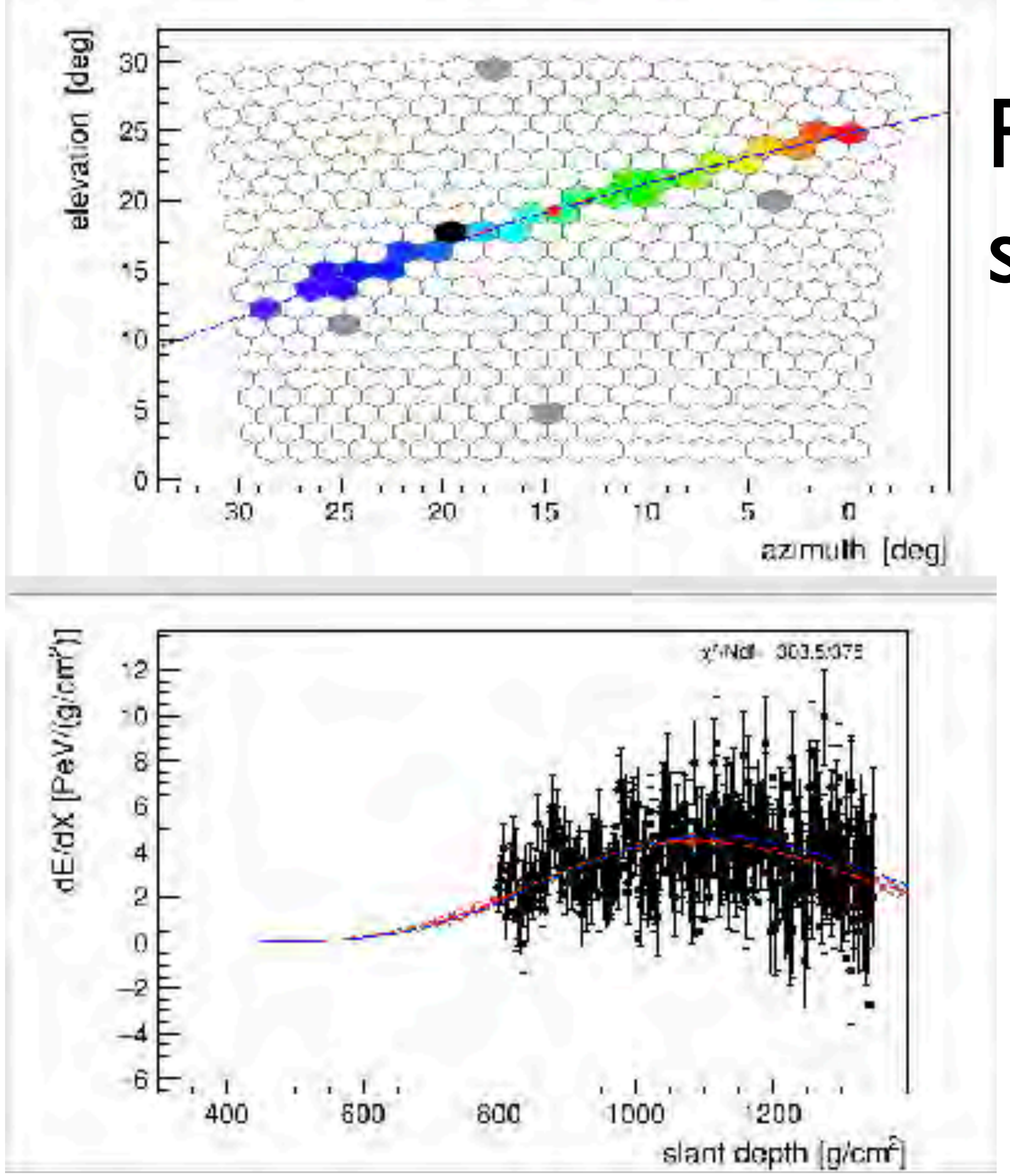
ANITA has detected two anomalous events with non-inverted polarity, consistent with upward-going showers:
$E_{1,2} \approx 0.2$ EeV ; exit angle $\approx 30°$

Fervent debate about interpretation:

- observational artefact ?
- BSM physics ? (ν's cannot penetrate Earth at these energies)

Auger has performed a dedicated search using 14 yrs of FD data

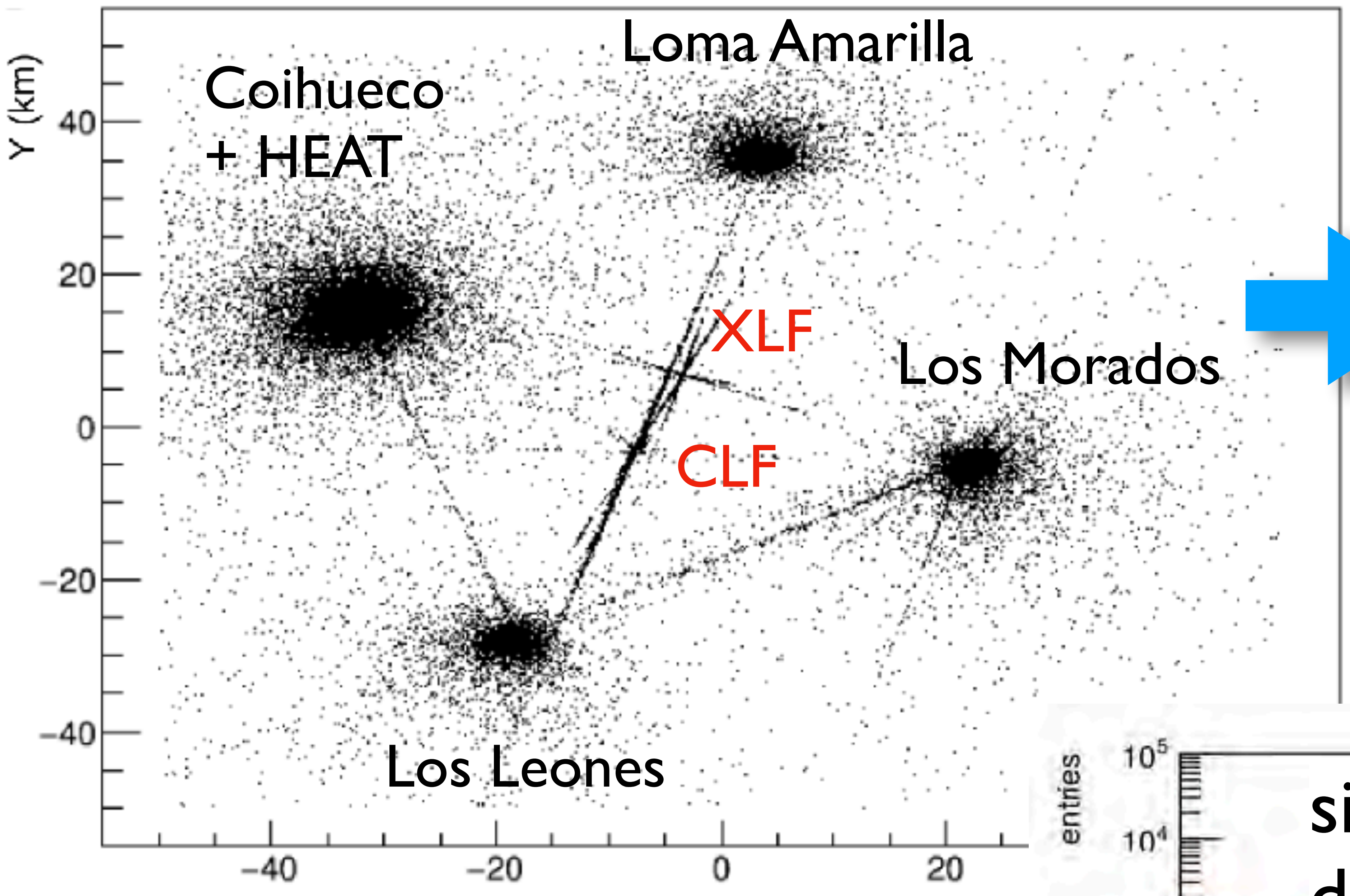




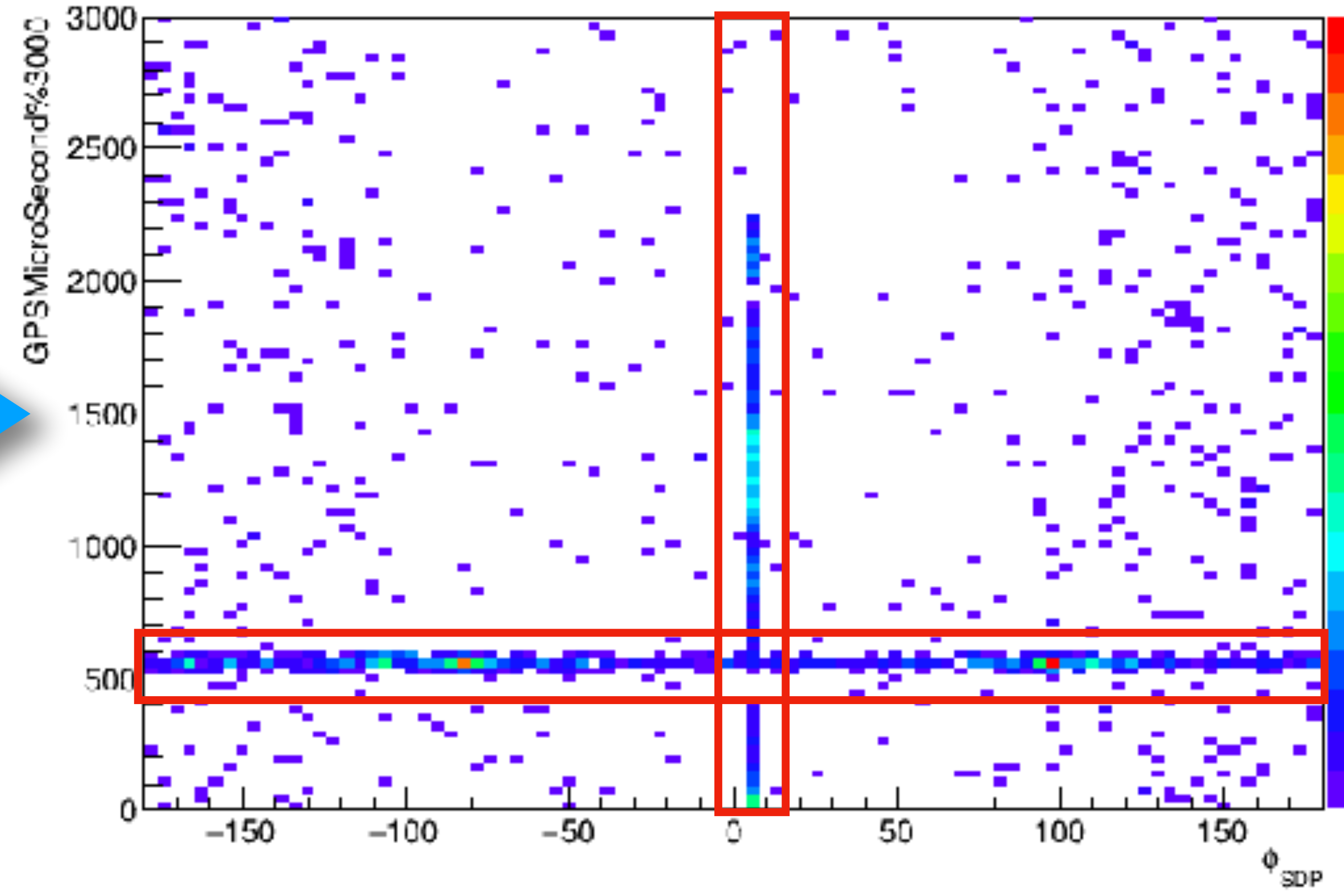
FD Signal simulation

Data Cleaning and Background Expectation

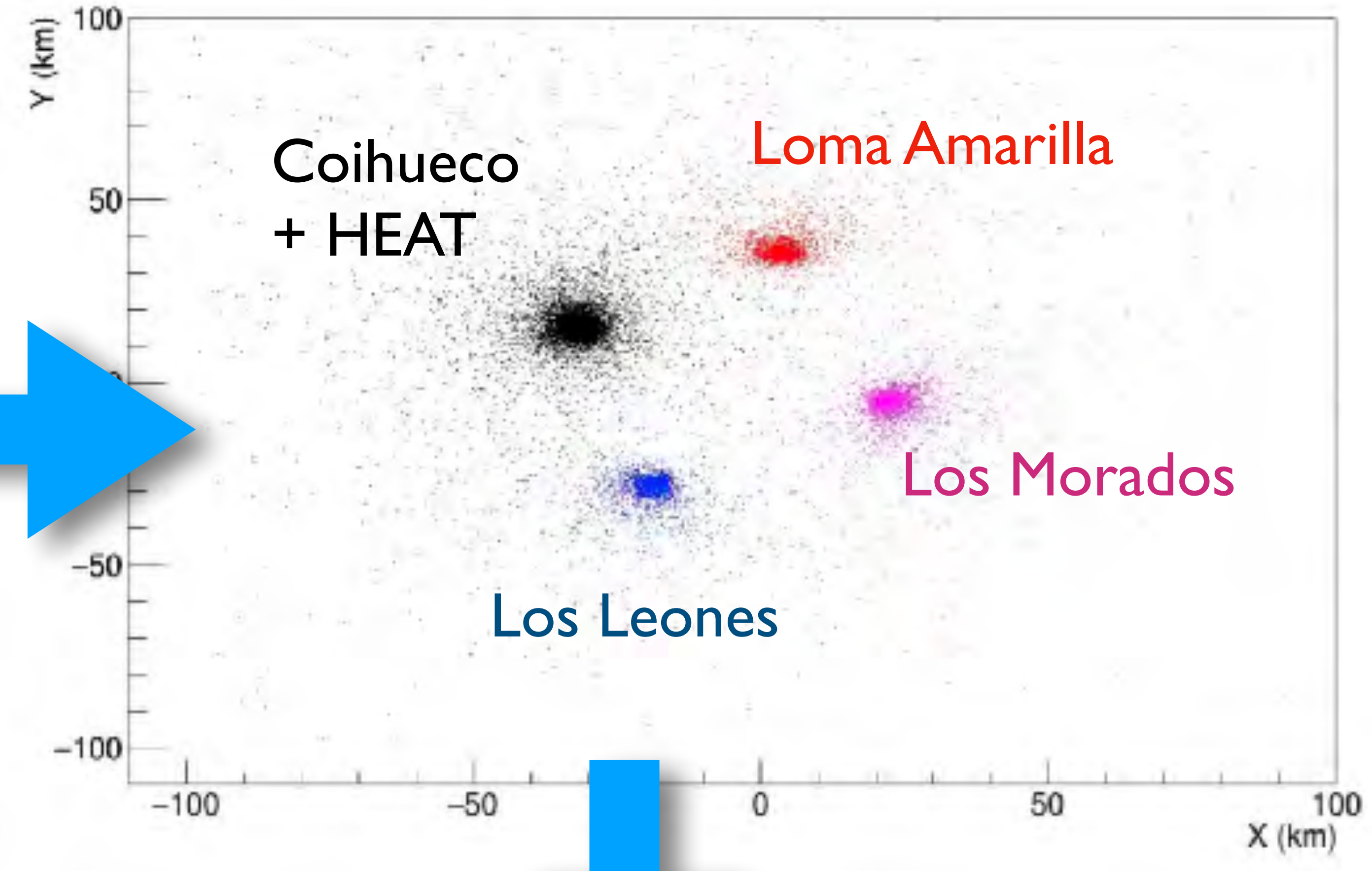
Careful rejection of laser events



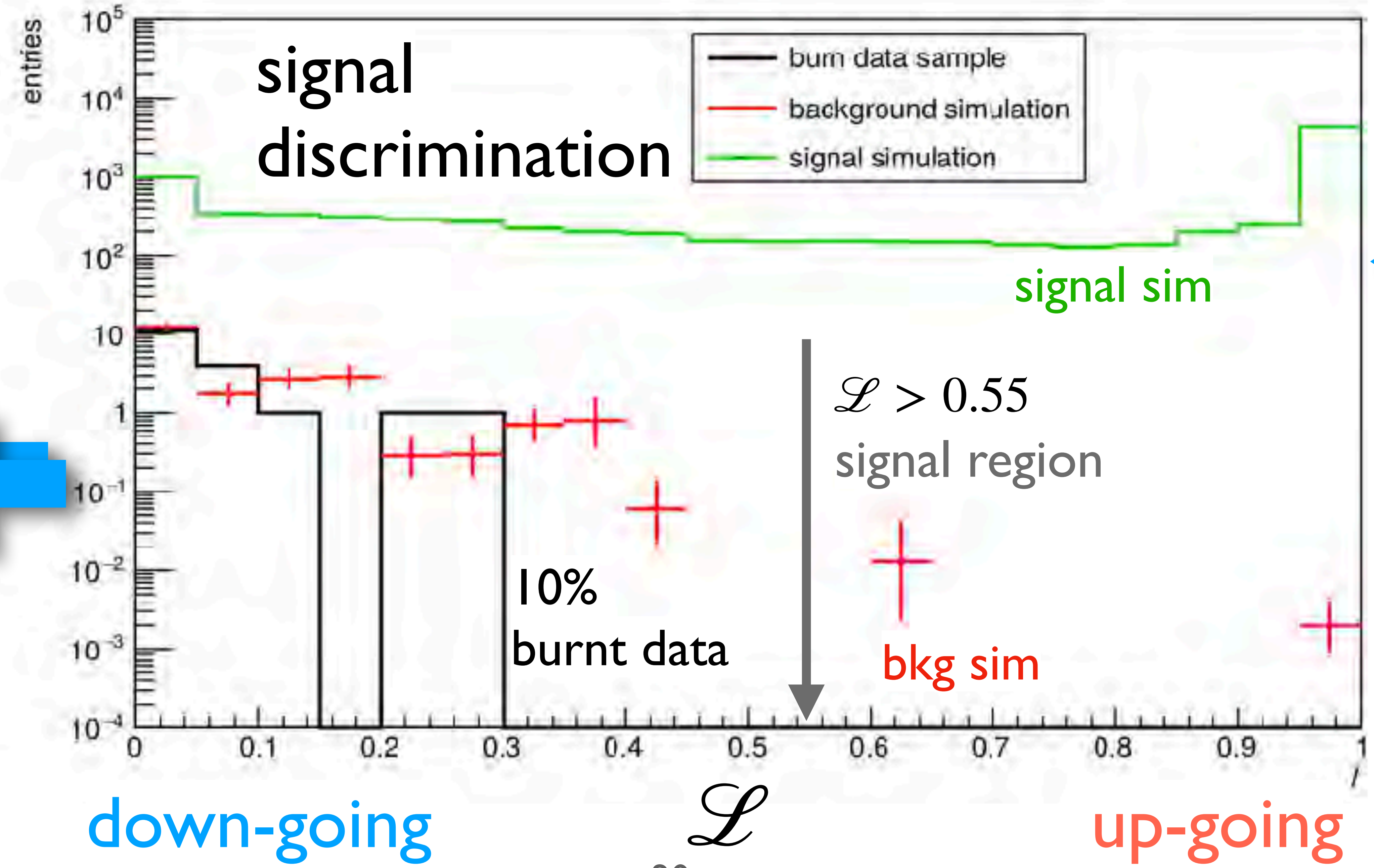
example of geometric cuts



„exit points“ after cleaning



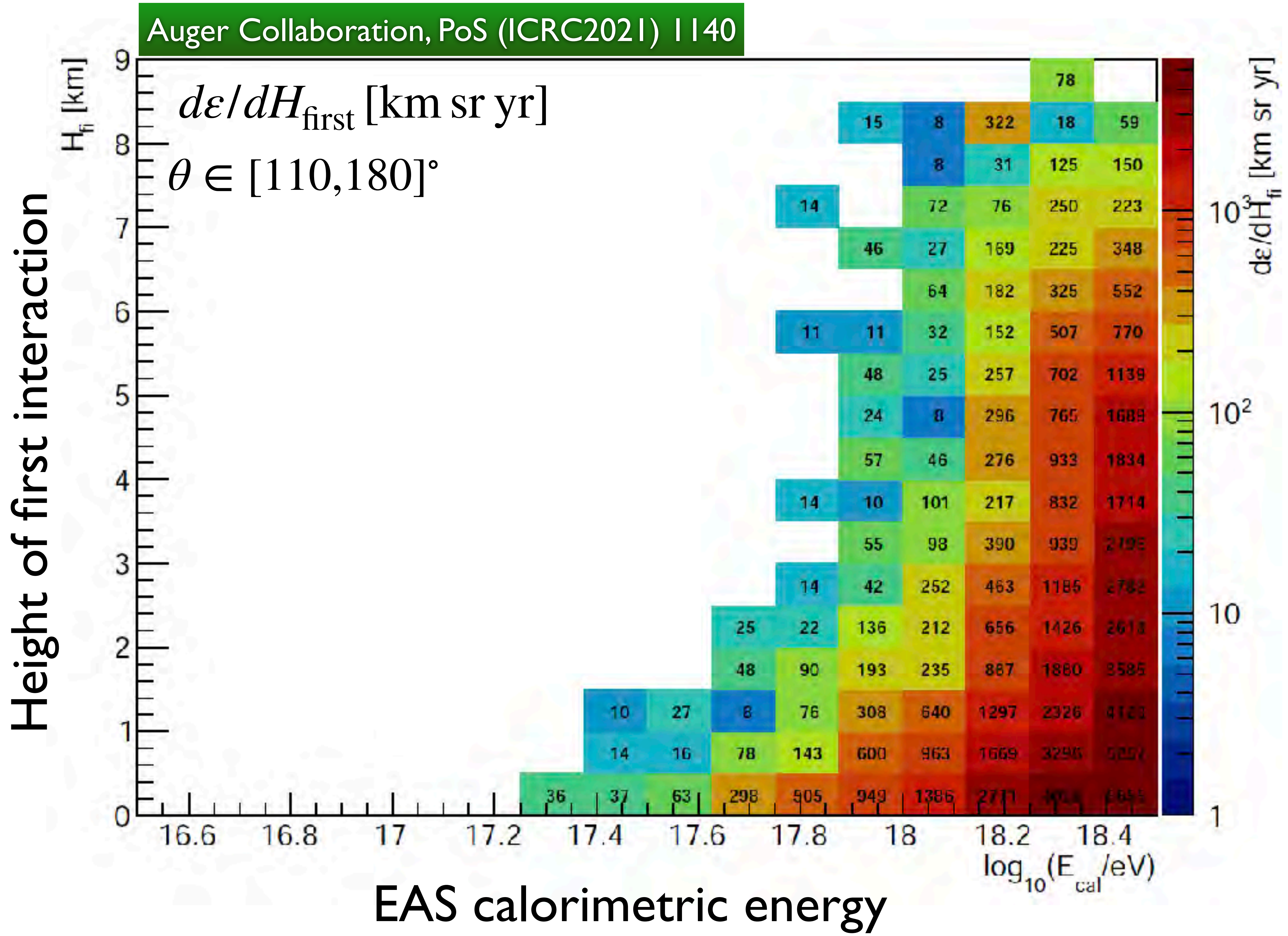
showers landing behind telescopes appear like up-going showers



expected Bkg-events in full data sample:
$n_{\rm bkg} = 0.45 \pm 0.18$

M. Mastrodicasa;
Auger Collaboration, PoS (ICRC2021) 1140

Differential Exposure and Signal Expectation



After unblinding, one 1 event was found fully in line with expectation
⇒ integral upper limit for log(E/eV)>17.5

$$F^{95\%}_{\gamma=1} = 3.6 \cdot 10^{-20} \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

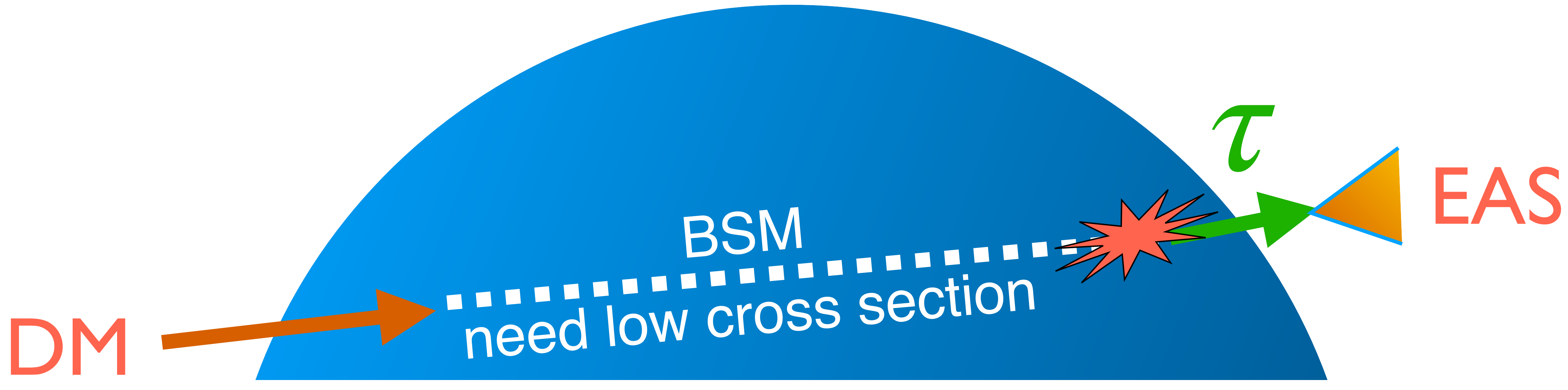
$$F^{95\%}_{\gamma=2} = 8.5 \cdot 10^{-20} \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

ANITA only published events, but did not provide their exposure
→ collaborating to provide an estimate

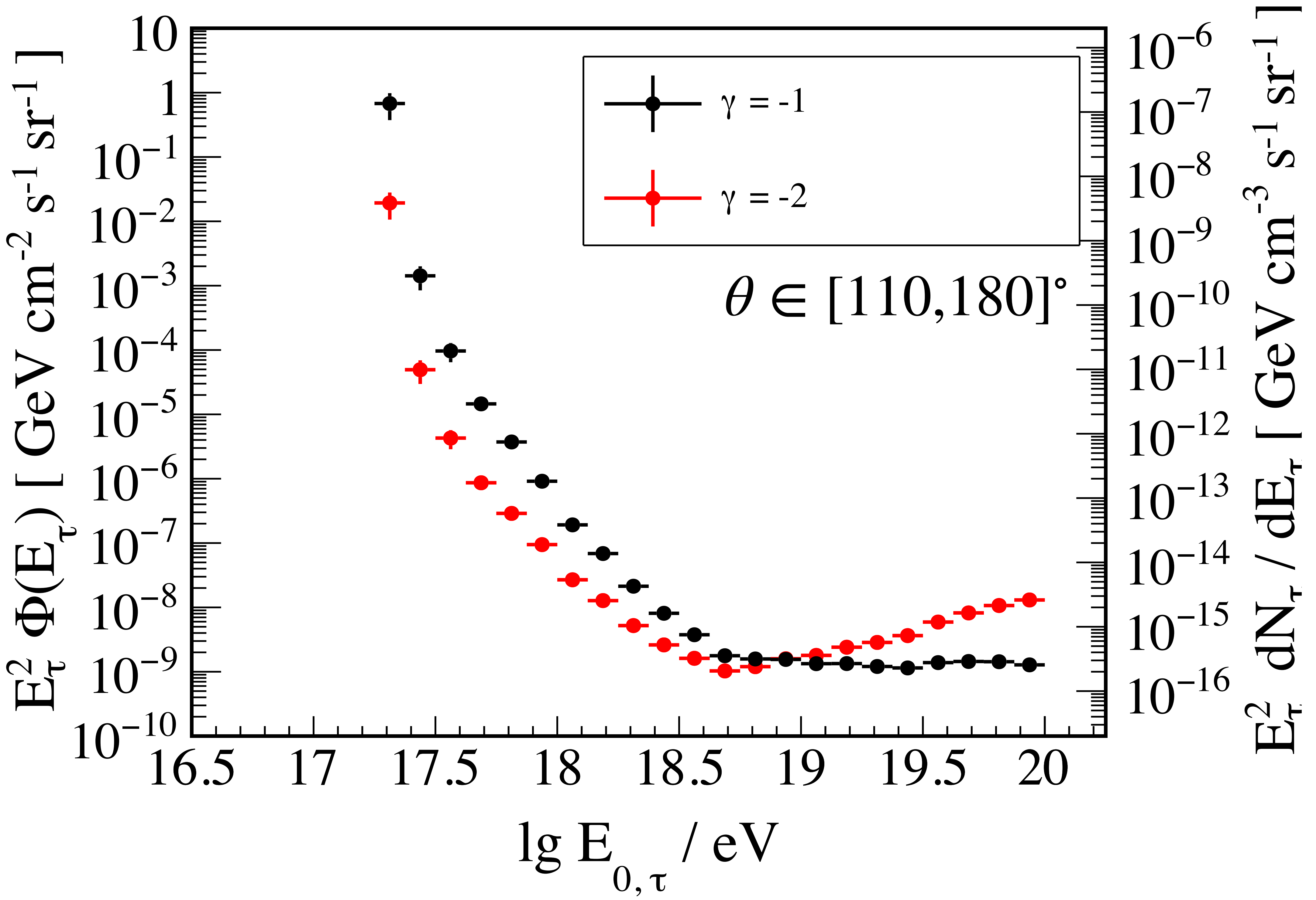
publication in progress…

(6) BSM Tests

ANITA observation triggered enormous number of interpretation papers (more than 30 by now)
Many of them involve τ-particles in the last stage, e.g.



Flux upper limit for τ-induced EAS



I. Caracas; Auger Collaboration, PoS (ICRC2021) 1145

Summary and Conclusions

- Auger is a multi-purpose multi-messenger observatory
- UHECR composition and energy spectrum decisive for next generation EeV neutrino observatories
- Unrivalled background free sensitivity to EeV neutrinos and photons
- No detection yet → strong(est) EeV flux bounds were provided
- Bounds will improve in direct relation to exposure and # of transient event
- Relevant parameter space of BSM physics can be tested
- AugerPrime is about to start and will provide significantly improved sensitivities