Multimessenger astrophysics at ultra-high energies: results from the Pierre Auger Observatory

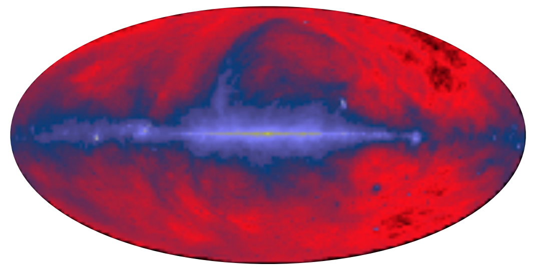
Antonella Castellina

INAF, Osservatorio Astrofisico di Torino

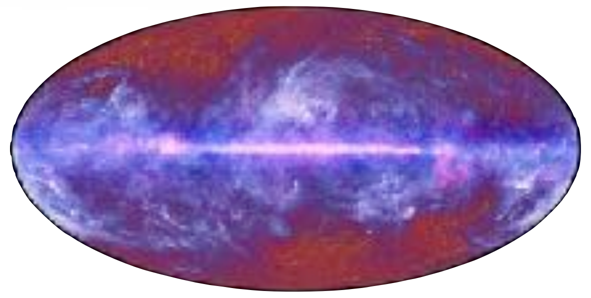
INFN, Sezione di Torino, Italy

TeVPA 2026, Tendo, Japan 30 Aug - 4 Sept

A multi-wavelength and multi-messengers sky

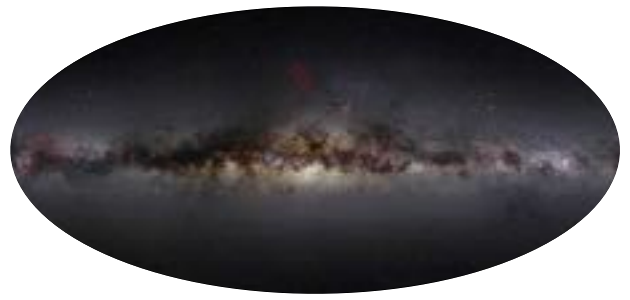


Radio band
(Parkes, MeerKAT, SKA…)

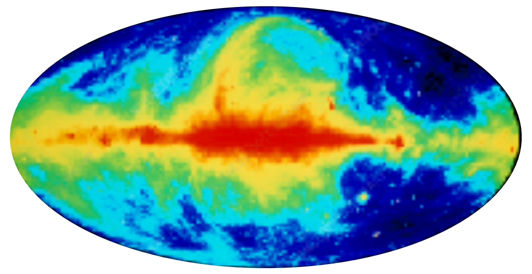


Microwave (Planck,SPT,LiteBIRD…)

Infrared
(JWST, Euclid…)

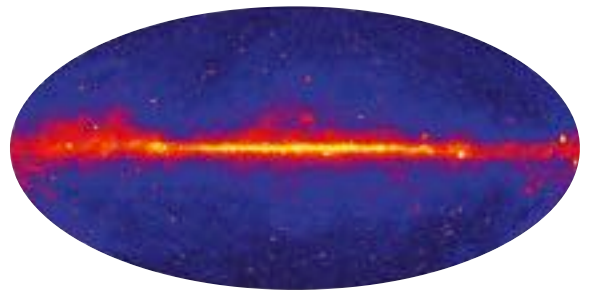


Optical (GTC, Vera Rubin Obs.,…)

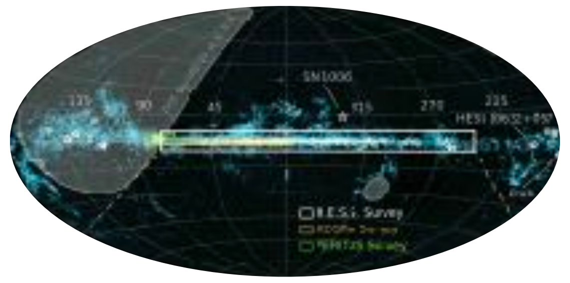


X-rays (Chandra, XMM-Newton, Einstein Probe,…)

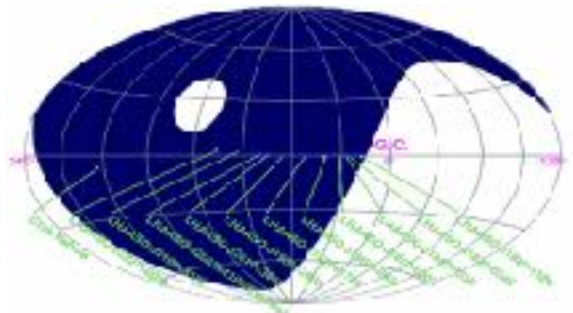
γ



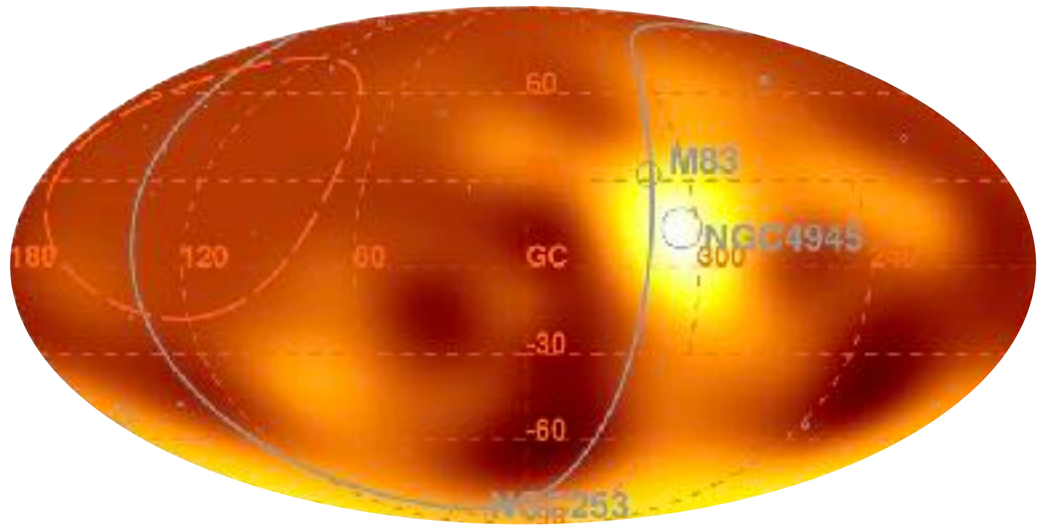
ɣ-rays (Fermi-LAT)



TeV ɣ-rays (IACTs: MAGIC; HESS, VERITAS)

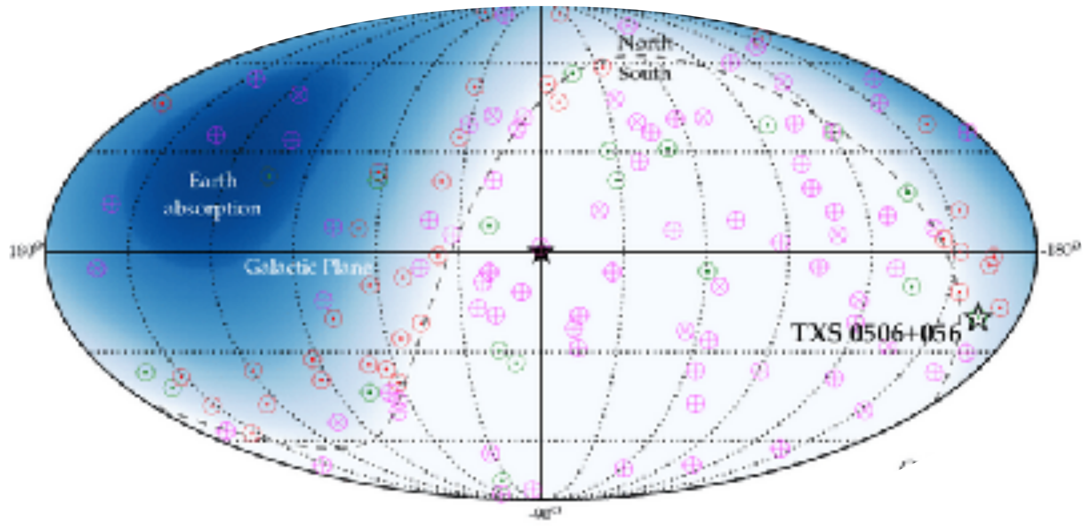


TeV-PeV ɣ-rays (EAS: HAWC, LHAASO)



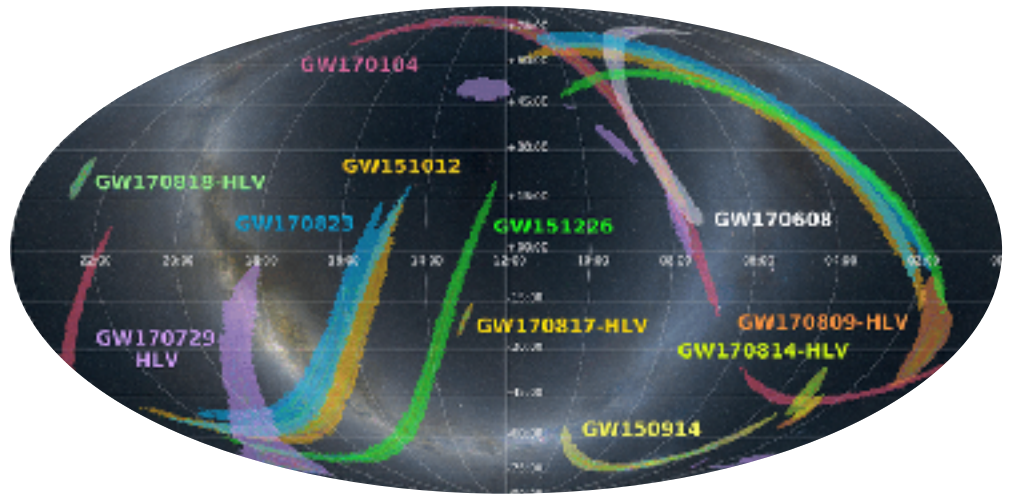
UHE cosmic rays

(Pierre Auger Observatory,
Telescope Array)
2004 →



Neutrinos

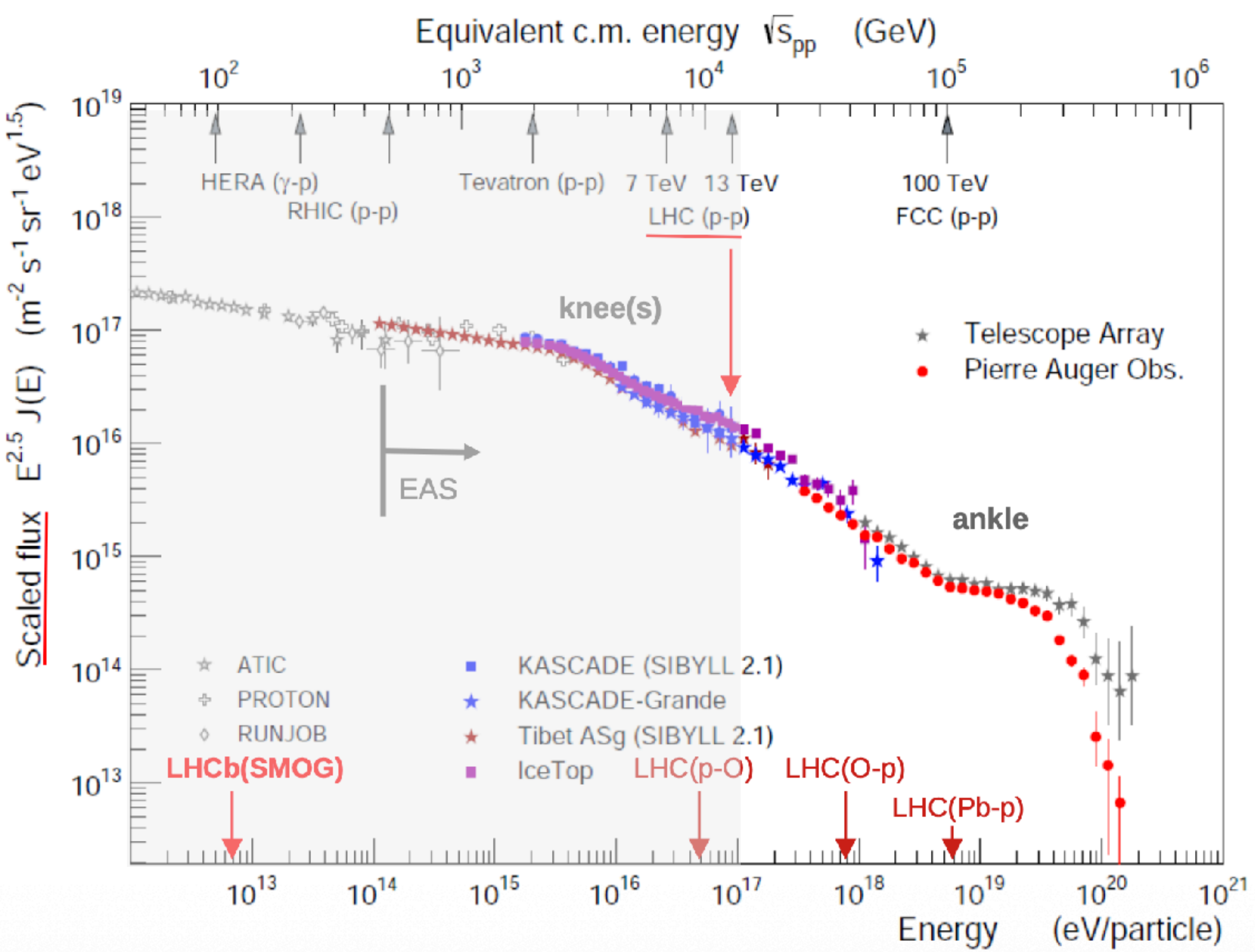
(IceCube, KM3net)
2010 →

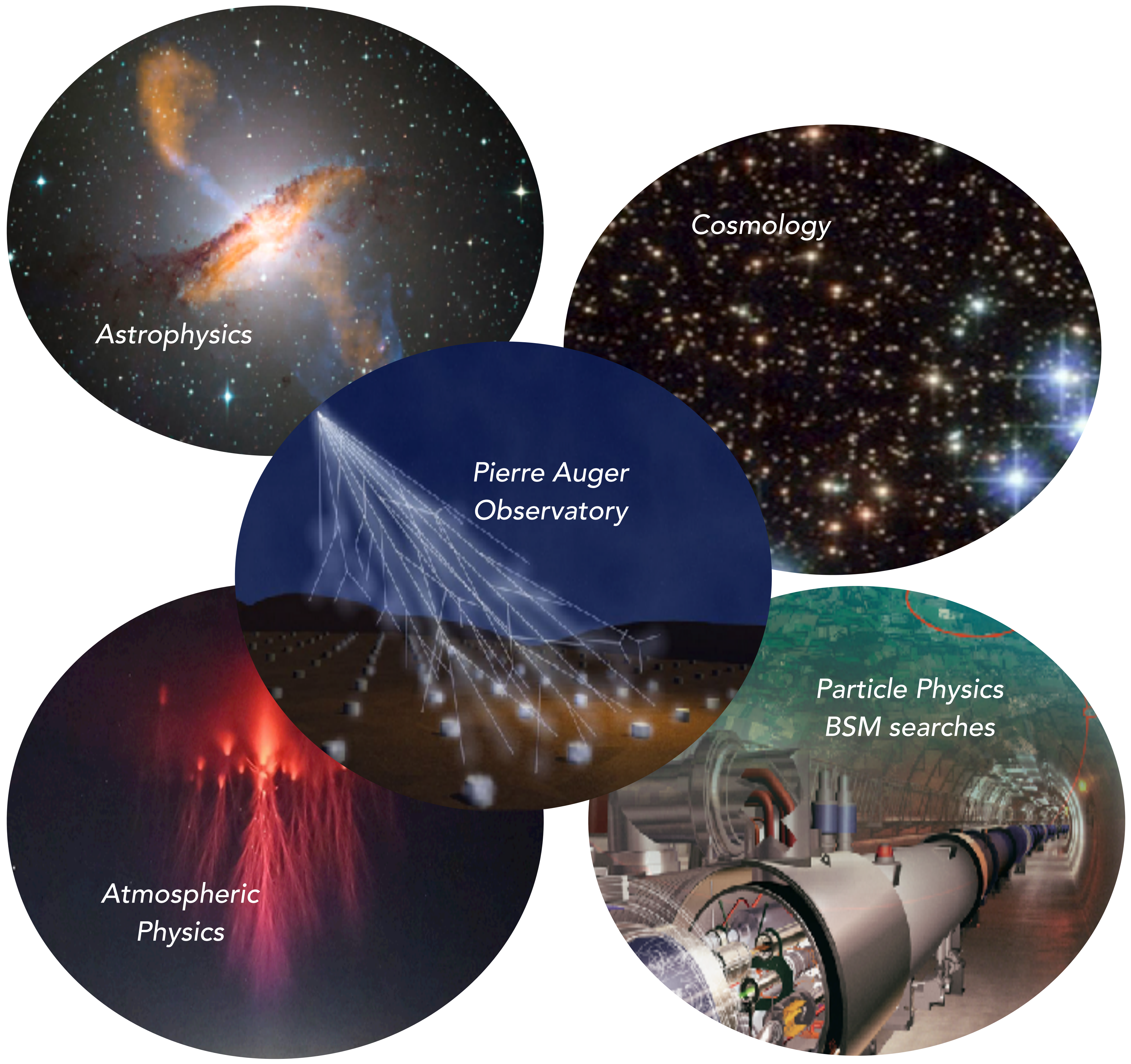


Gravitational waves

(LIGO, VIRGO, KAGRA)
2015 →

The Ultra-high energy cosmic rays (UHECRs)

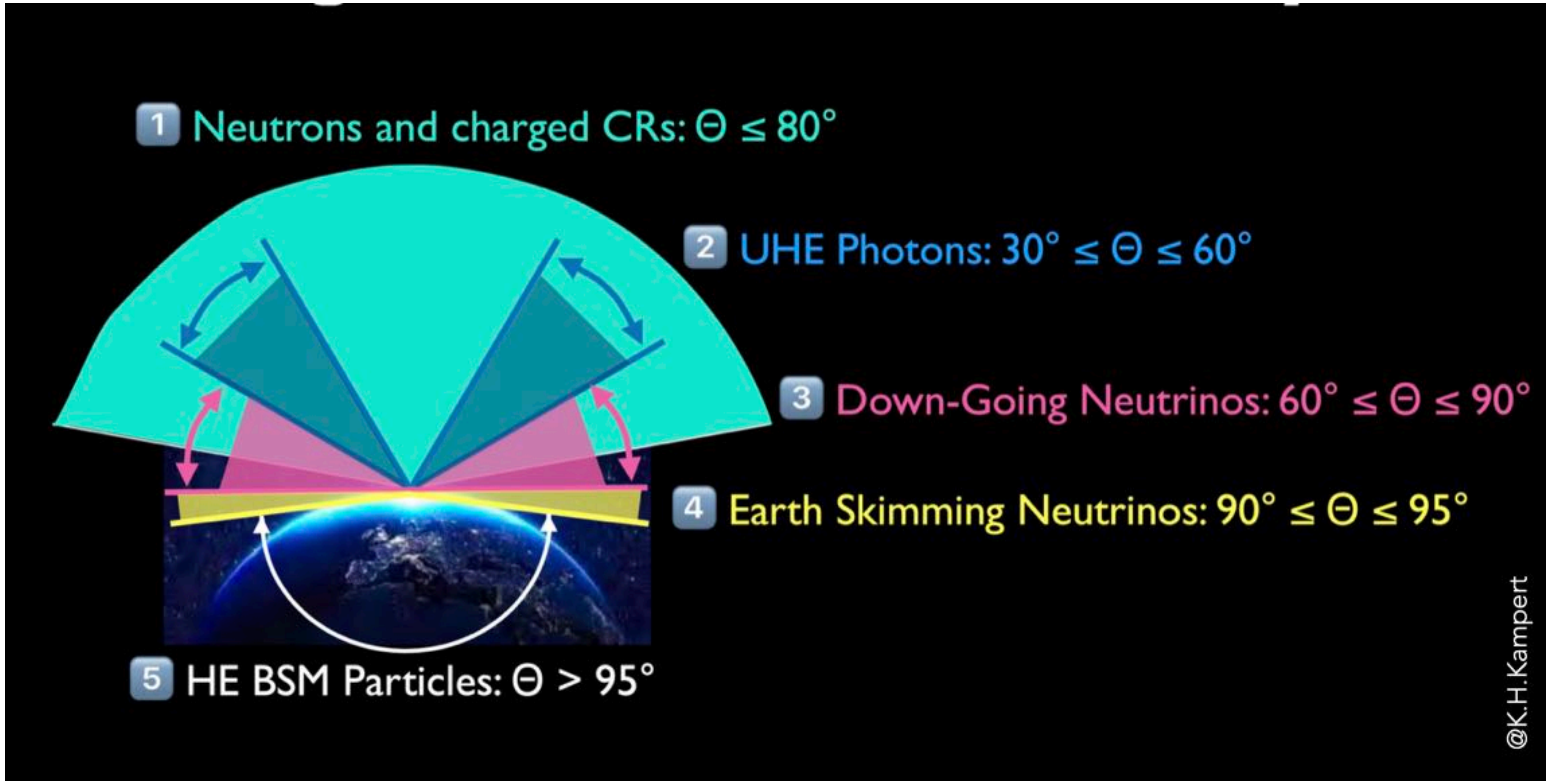




Auger is a 4π MM Observatory

It measures charged UHECRs

Energy spectrum
Mass composition
Anisotropies
Information on UHE hadronic interactions



It provides the largest exposure to UHE γ

Diffuse flux of UHE photons
Steady photon point sources
Follow-up searches in coincidence with transients

It allows studies on UHE neutrinos

Diffuse flux of UHE neutrinos
Steady neutrino point sources
Follow-up searches in coincidence with transients

…on Galactic neutron sources

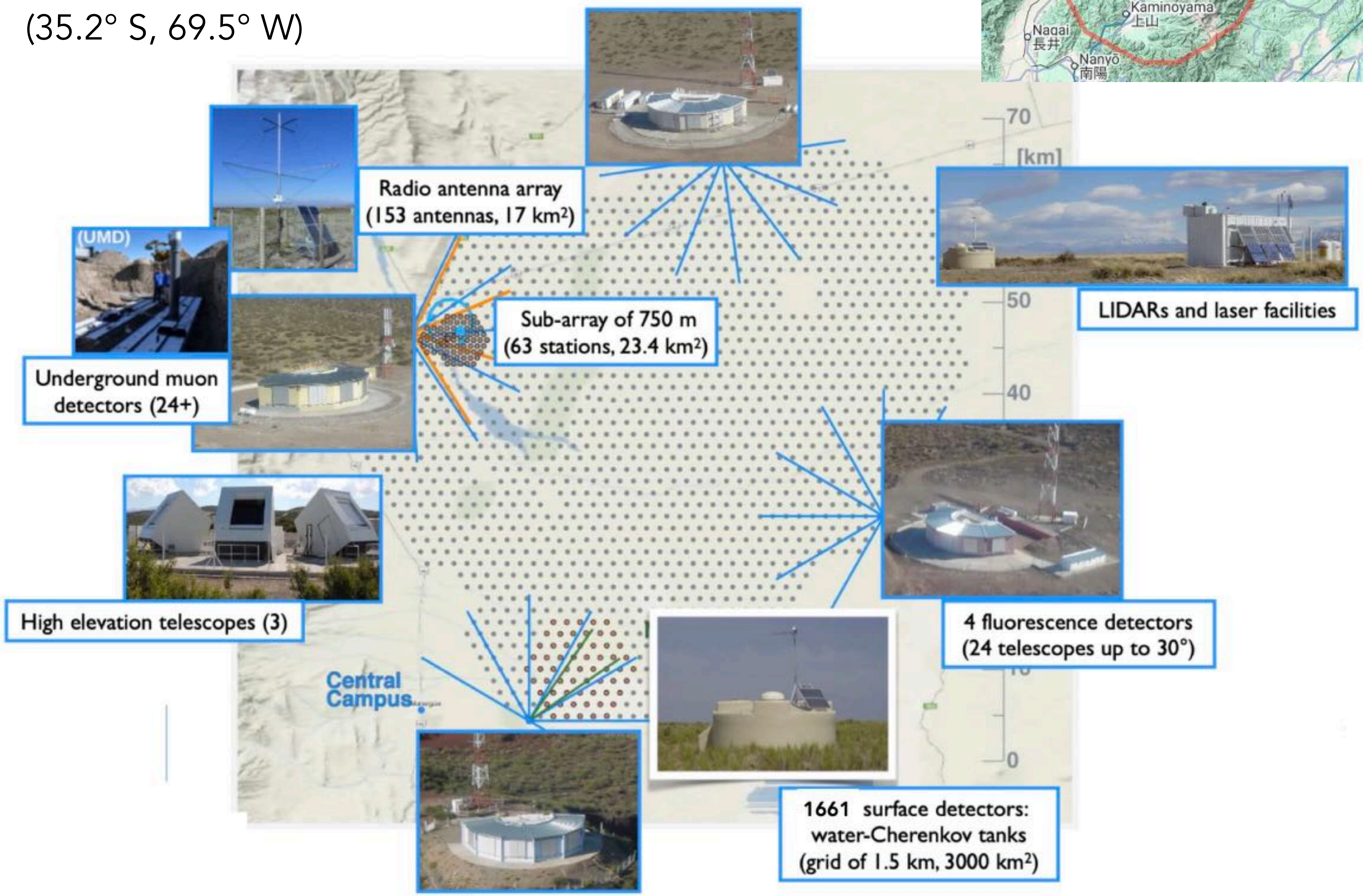
and searches on BSM effects

The Pierre Auger Observatory

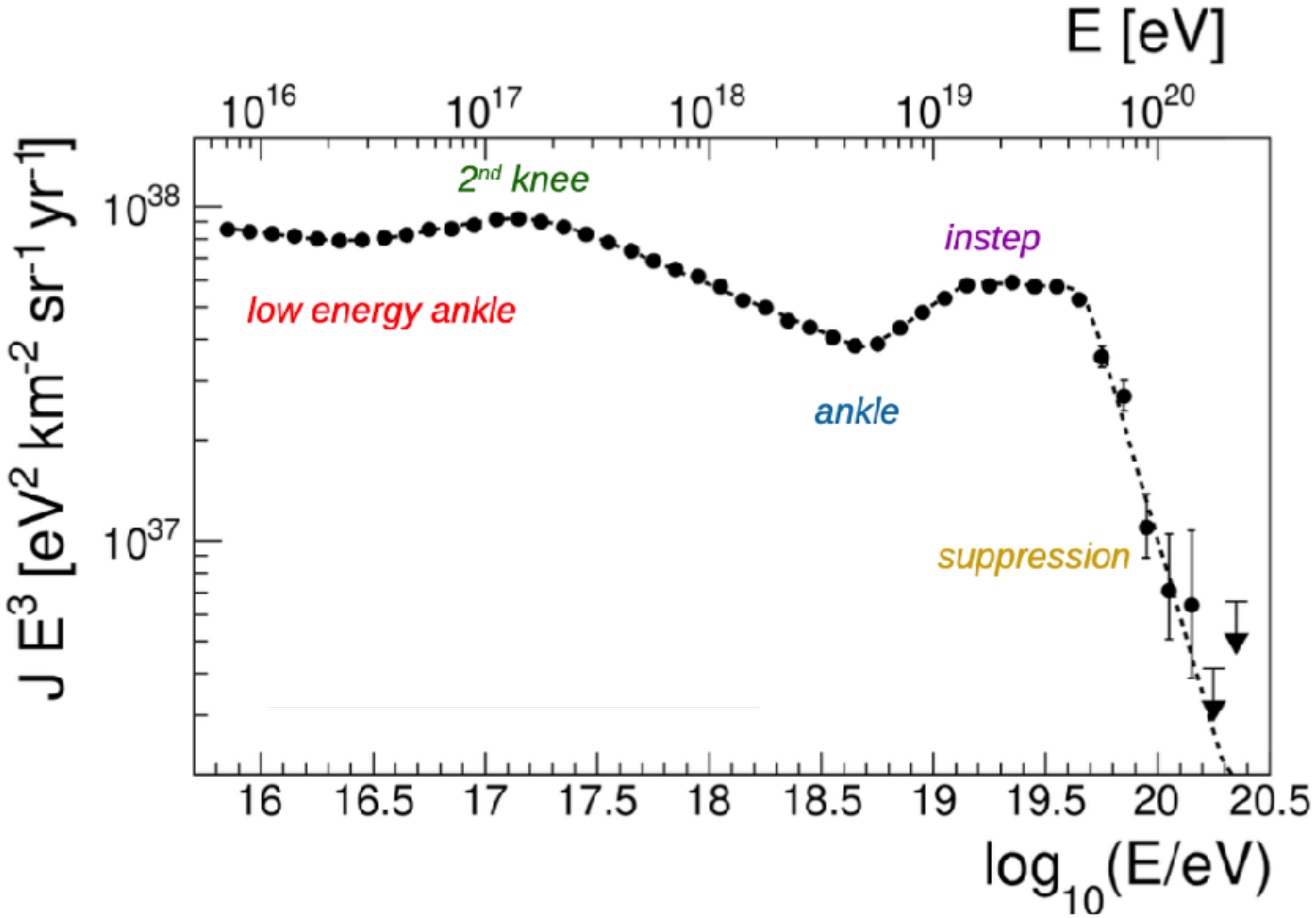
Total covered area
3000 km²

Pampa Amarilla
(Malargüe, Argentina
17 Countries
>400 members

(35.2° S, 69.5° W)



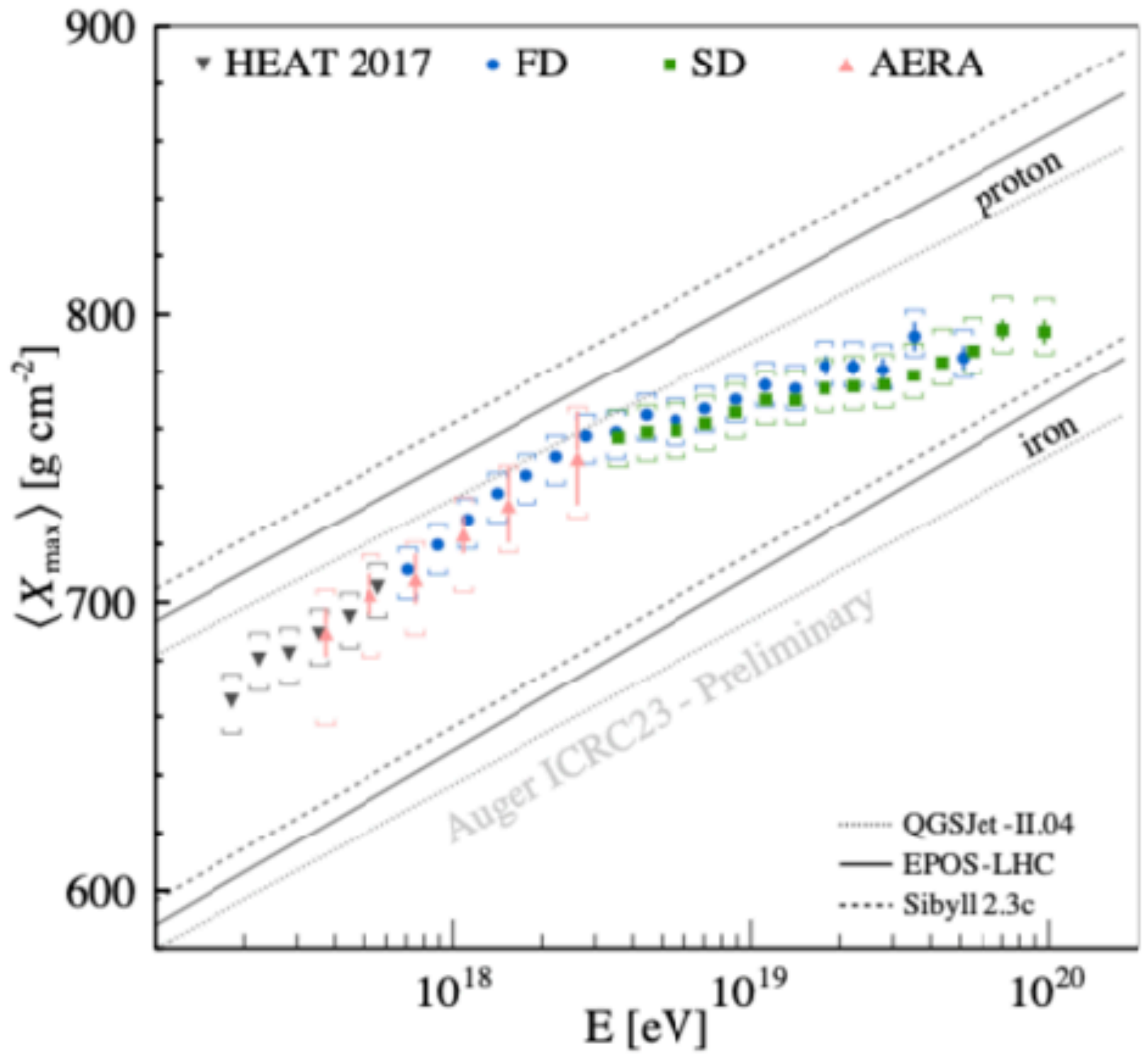
- **1661 Water-Cherenkov stations:**
  - SD1500 : 1600, 1.5 km grid;
  - SD750: 61, 750 m grid
  - SD433: 19, 433 m grid
- **4 Fluorescence sites:**
  - 24 telescopes, 1-30^0 FoV
  - 3 High Elevation Telescopes, 30-60^0 FoV
- **Engineering arrays in SD750 and SD433:**
  - AERA: 153 radio antennas
  - UMD: 24 underground muon detectors

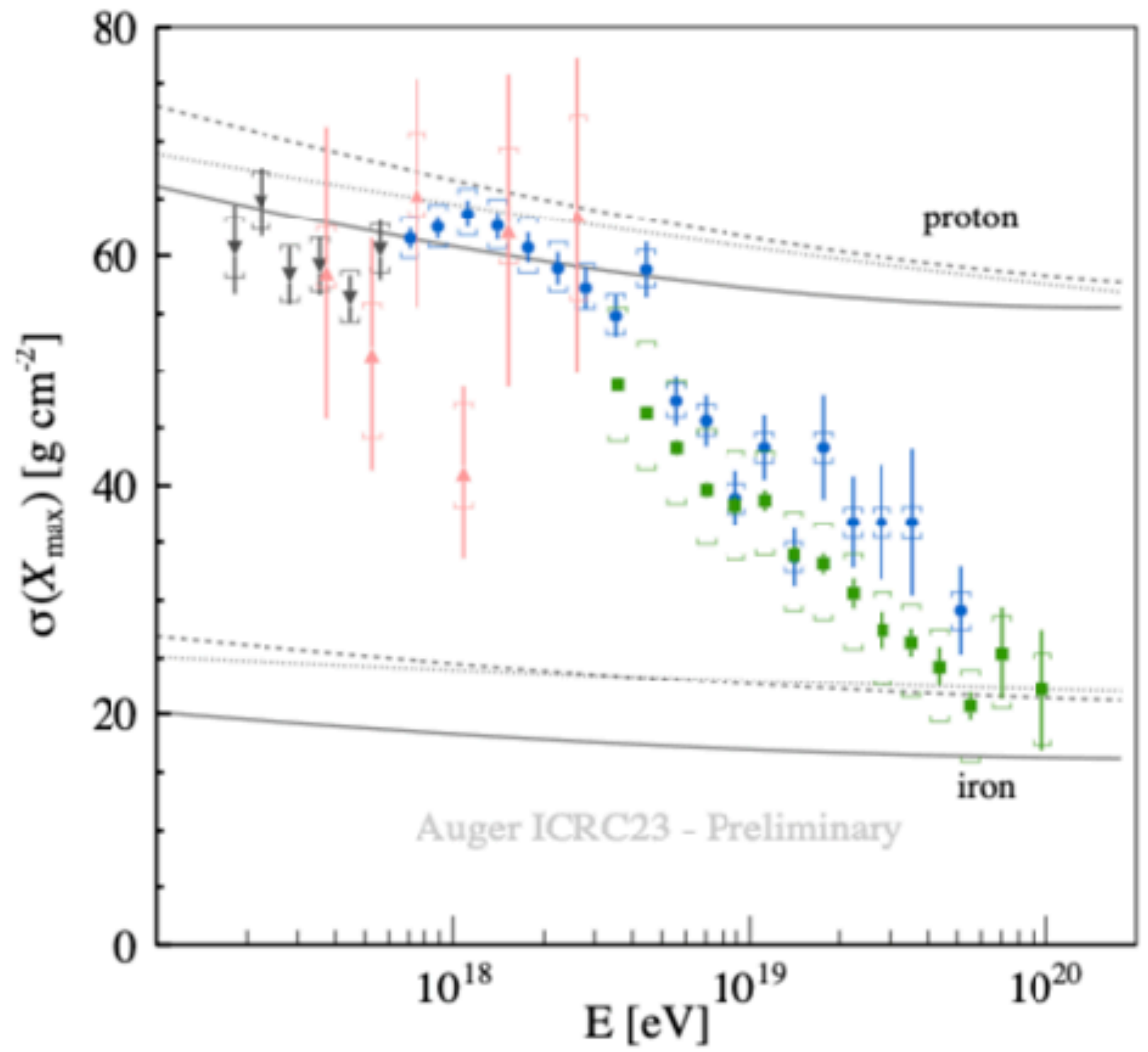


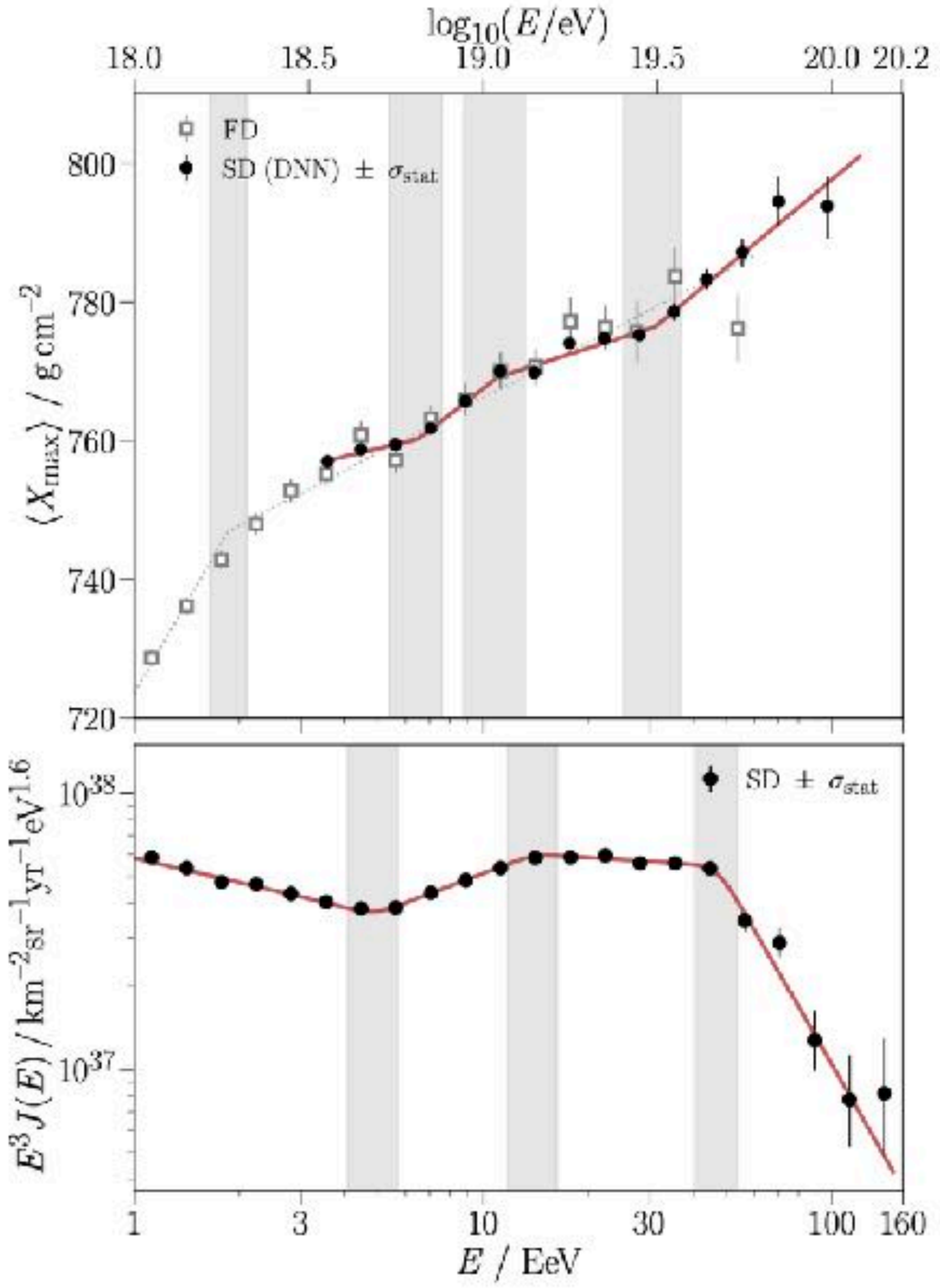
➡ First measurement of the energy spectrum over the entire declination range -90⁰ to +45⁰ (104,575 km² sr yr)

➡ A measure completely independent of any assumptions on the primary mass

Auger Coll., PRL135 (2025) 241002
PRD102 (2020) 062005
Eur. Phys. J. C 81 (2021) 966





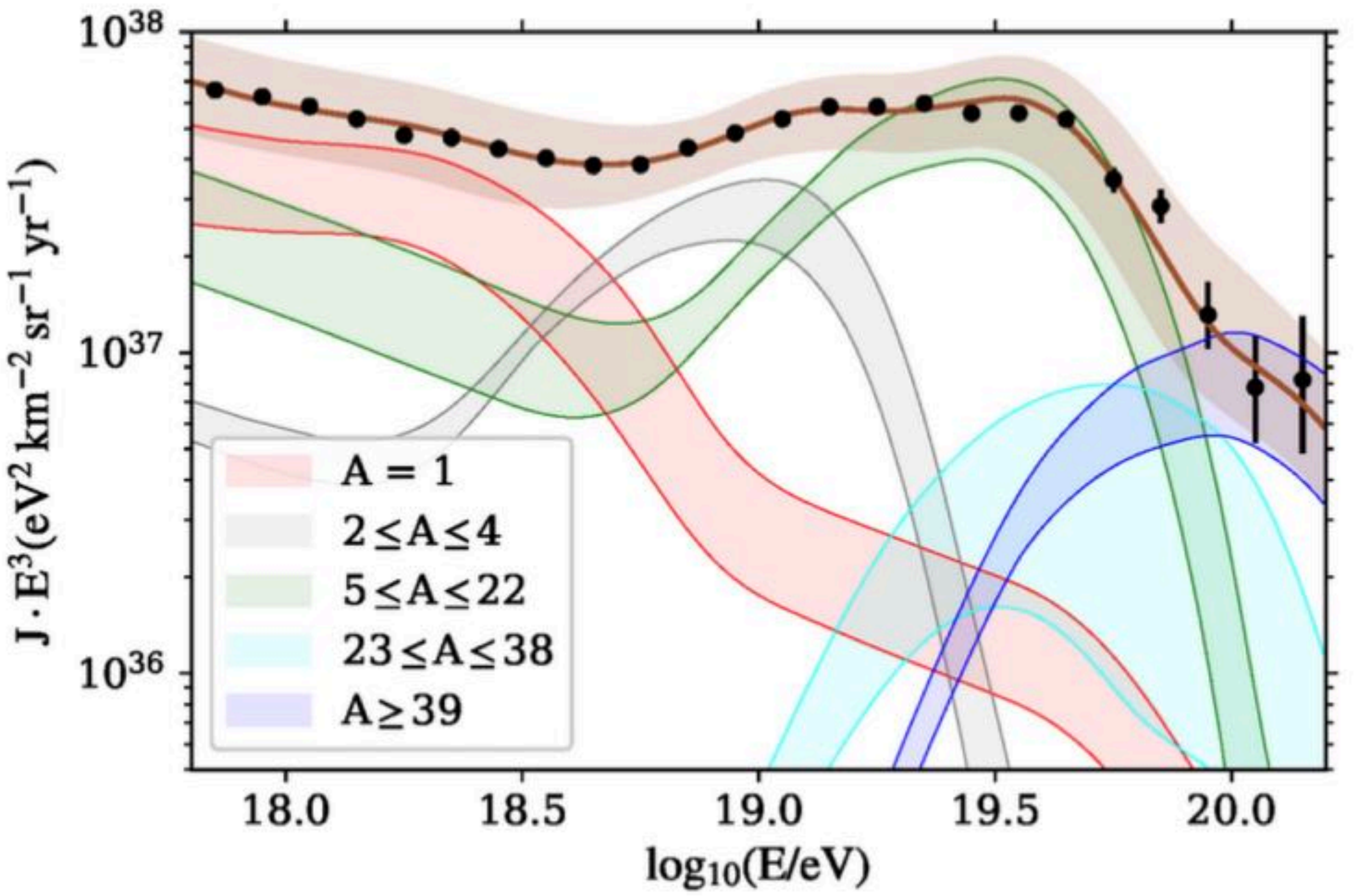


- Elongation rate in agreement with that found with FD
- Clear evidence of a structure in ER, **constant ER rejected at 4.4σ**

  incompatible with pure composition

Auger Coll., PRD 111 (2025) 022003
PRL 134 (2025) 021001

The contribution of charged UHECRs



Auger Coll., JCAP 05 (2023) 024
E.Roulet for Auger, PoS(ICRC2025) 373
D.Boncioli, CRIS-MAC 2026

A wealth of information on

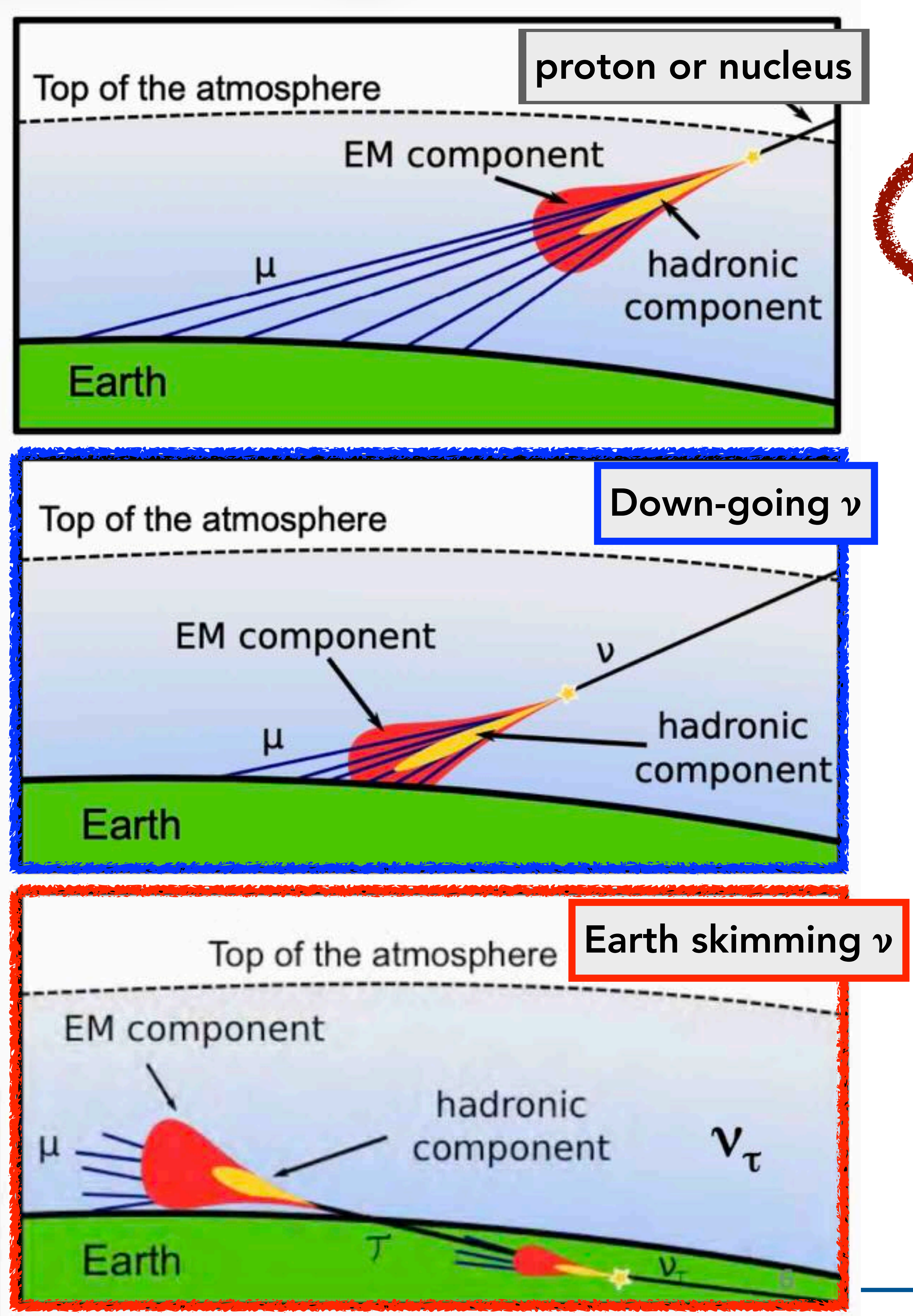
➡ origin of the spectral shape
➡ evolution of the composition
➡ source characteristics:
- ✓ evolution not too strong: $\propto (1+z)^m$, $m \gtrsim 5$ excluded
- ✓ hard escape spectra and low suppression at EHE due to exhaustion of sources besides GZK effect
- ✓ EG component below few hundreds PeV suppressed by magnetic horizon
- ✓ Rigidities: almost identical $\propto R^{-\beta}$ with $\beta > 4$
- ✓ Luminosity density ~ 6 x 10^{44} erg Mpc^{-3} yr^{-1} by continuously emitting sources to supply UHECR above the ankle - a rate matched e.g. by AGN and SBG

➡ Constraints on the expected flux of cosmogenic particles

...and of neutral particles

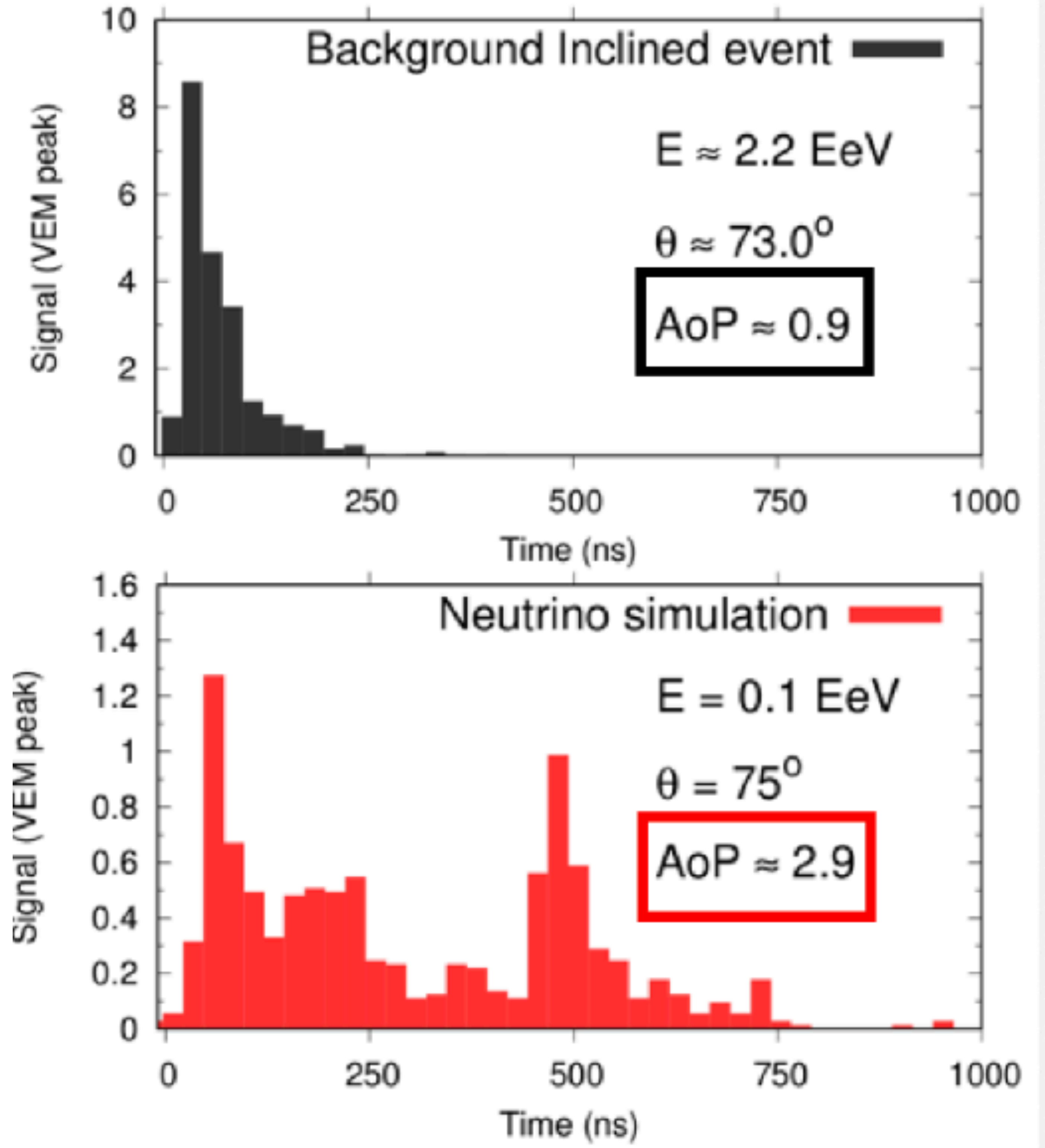
➡ Constraints on the proton fraction
➡ Upper limits on cosmogenic fluxes of ν and γ
➡ Exploration of distant Universe possible only with neutrinos
➡ Search for coincidences with GW, VHE neutrinos
➡ Search for hints of beyond standard model effects

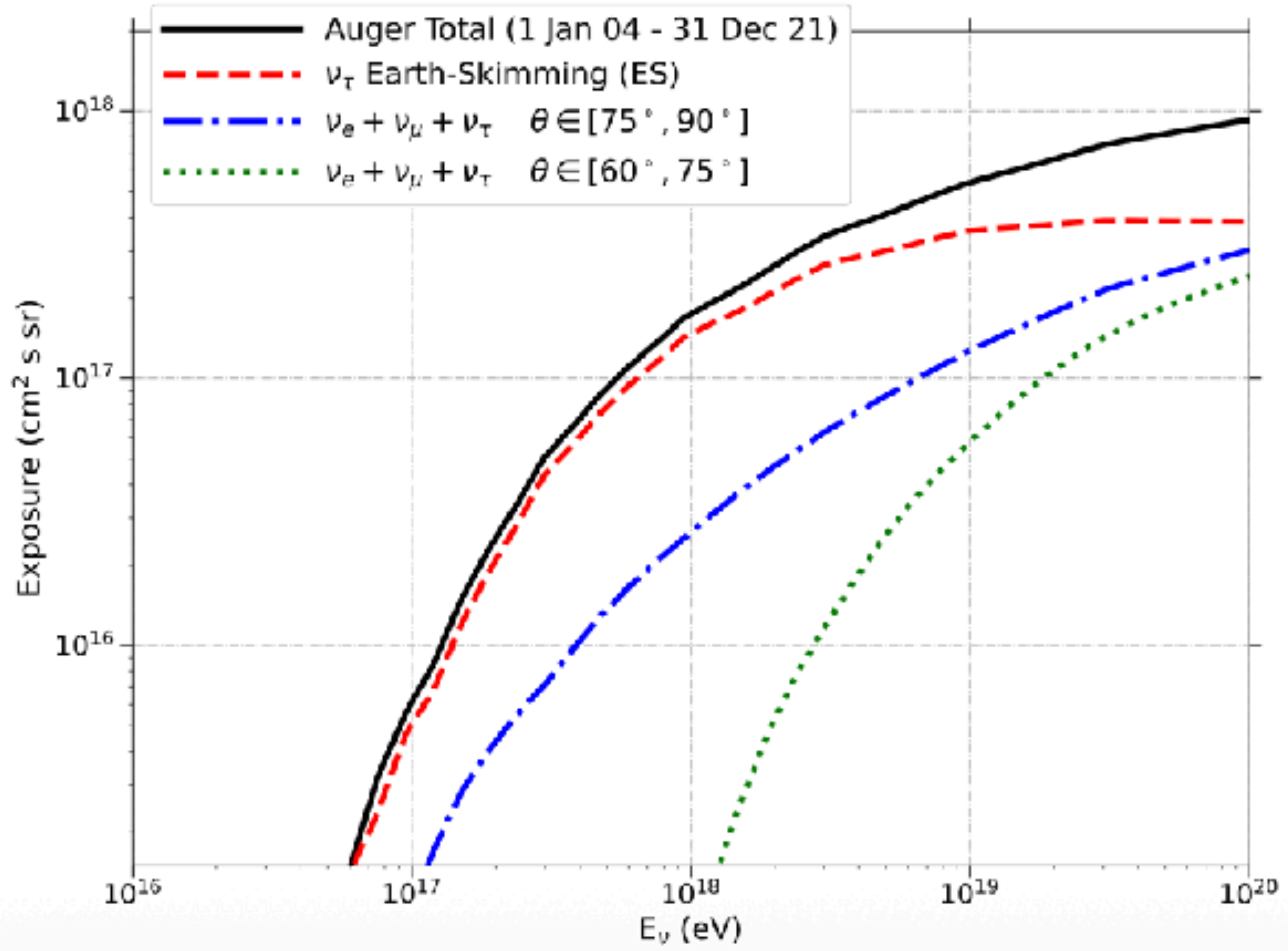
Detecting neutrinos in Auger



Neutrino-induced air showers:
- deep showers
- em+μ component at ground

Discrimination Methods
- selecting inclined showers
- with large electromagnetic component
- Large Area over Peak (~1 for muonic showers)





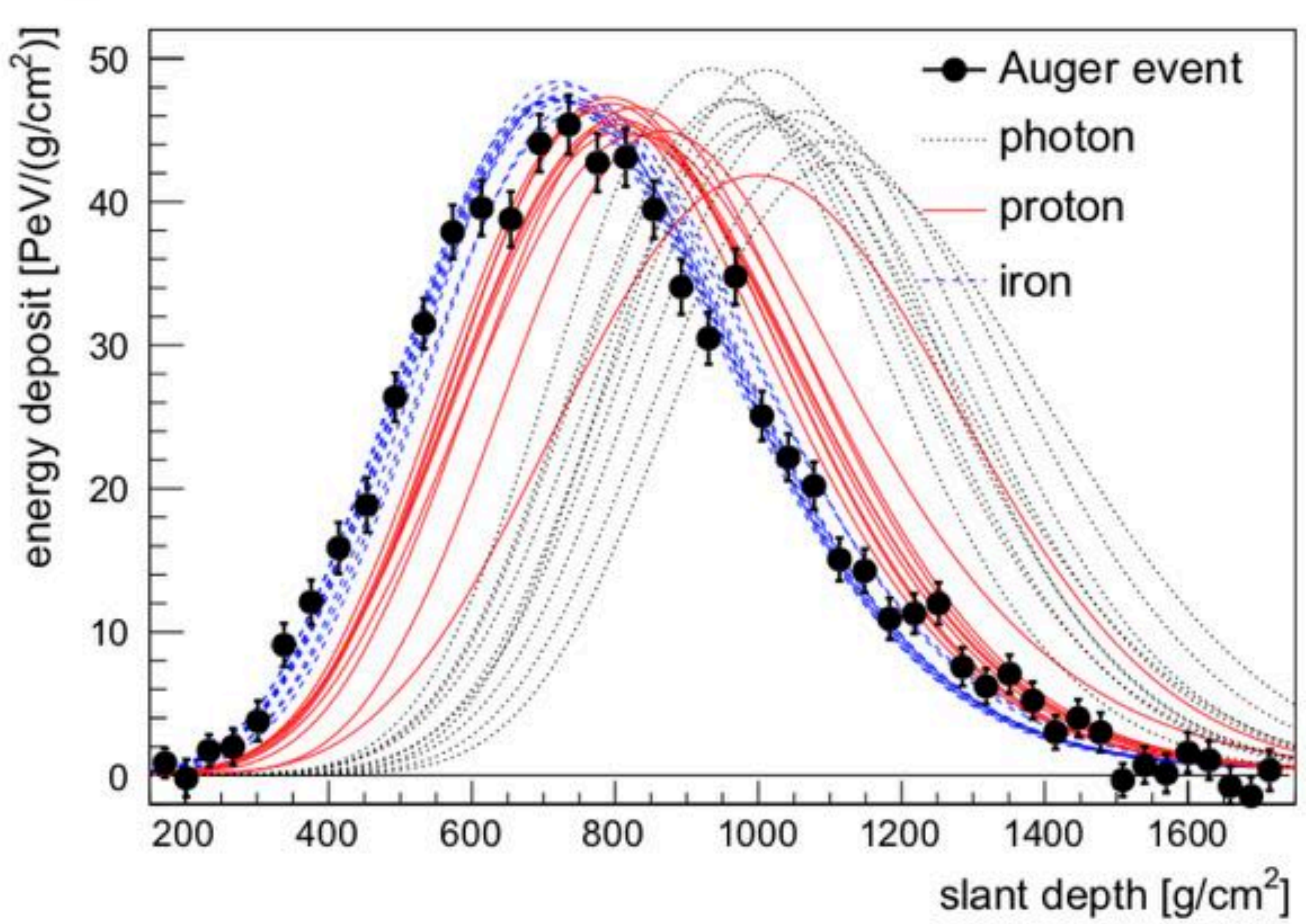
Among inclined showers we select
- Earth-skimming (ES) : 90⁰-95⁰
- Downgoing at high angle (DGH): 75⁰-90⁰
- Downgoing at low angle (DGL): 60⁰-75⁰

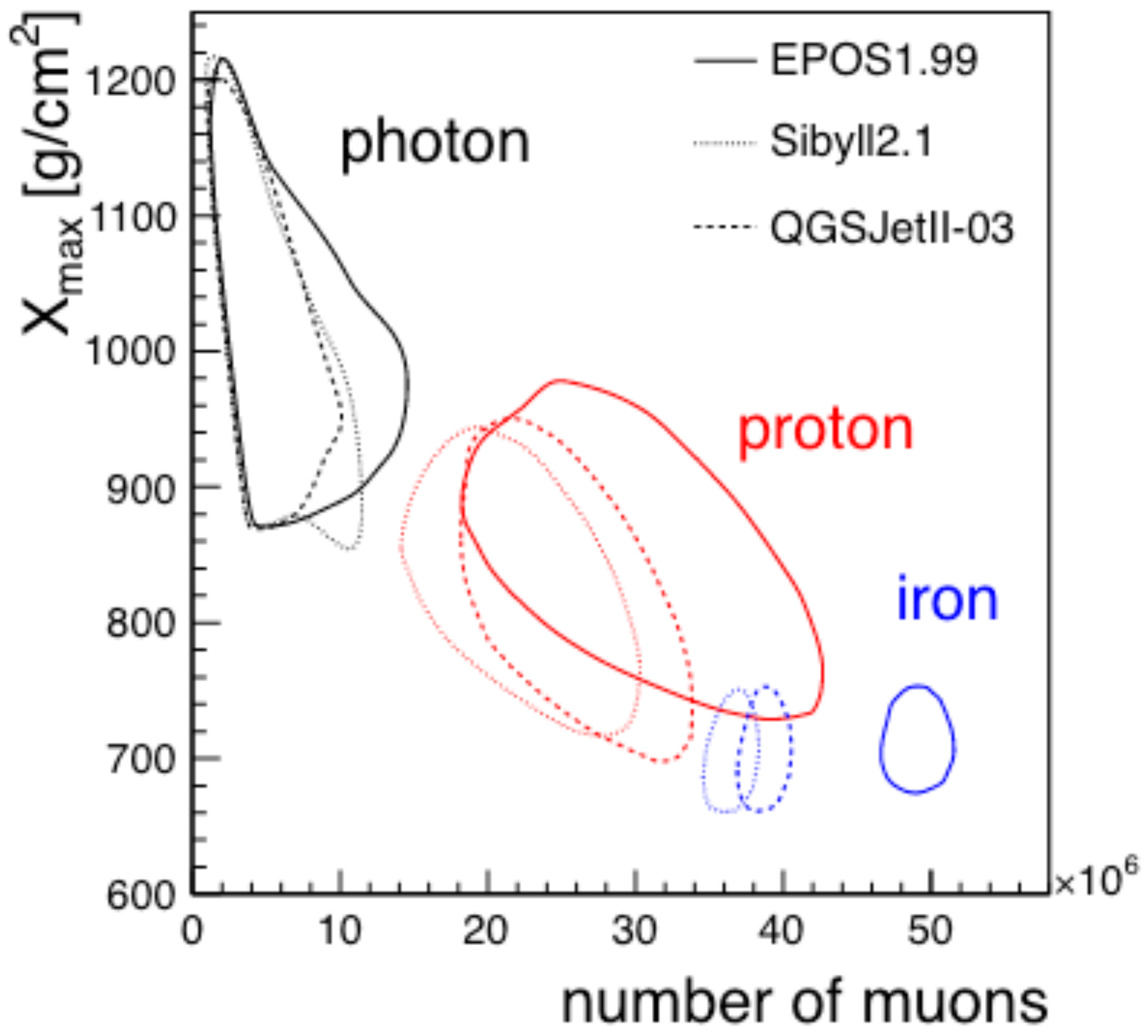
Auger Coll., JCAP 10 (2019) 022
M.Niechciol, PoS(ICRC2023)1488

Detecting photons in Auger

Photon-induced air showers are almost purely electromagnetic:

- deeper X_{max}
- μ-poor
- steeper lateral distribution
- spreaded in arrival time



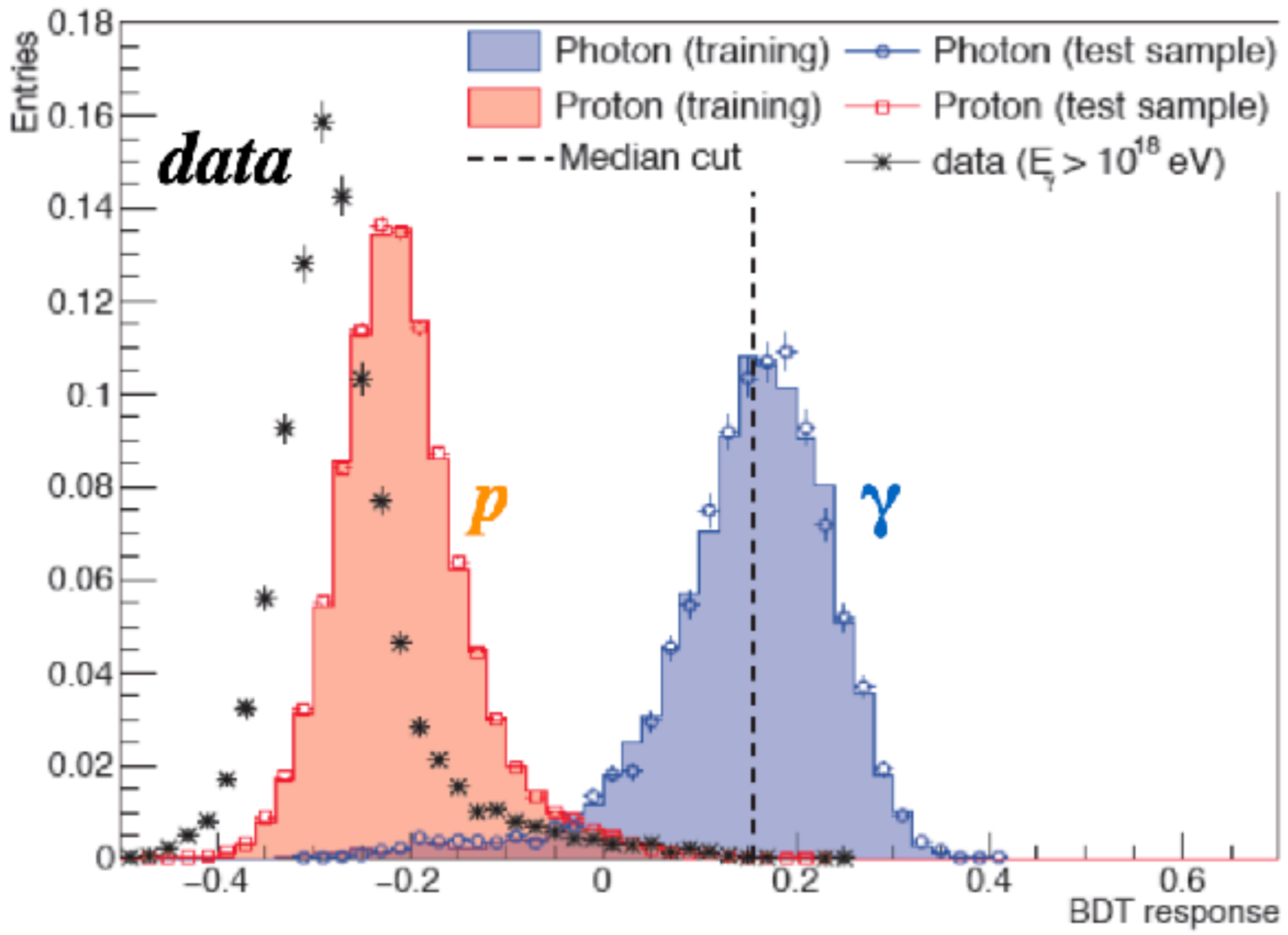


Discrimination Methods

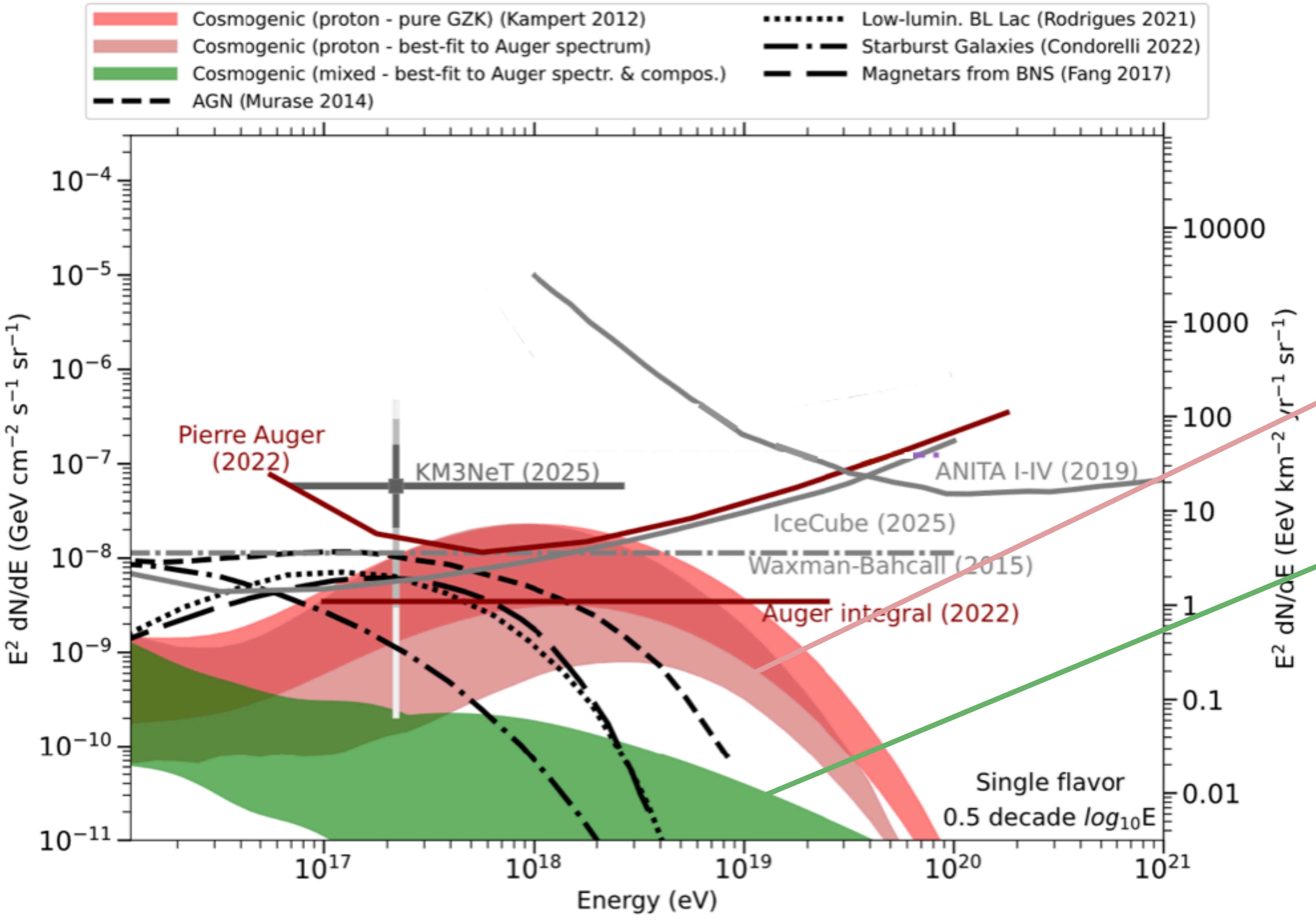
Different observables combined into a single discriminator

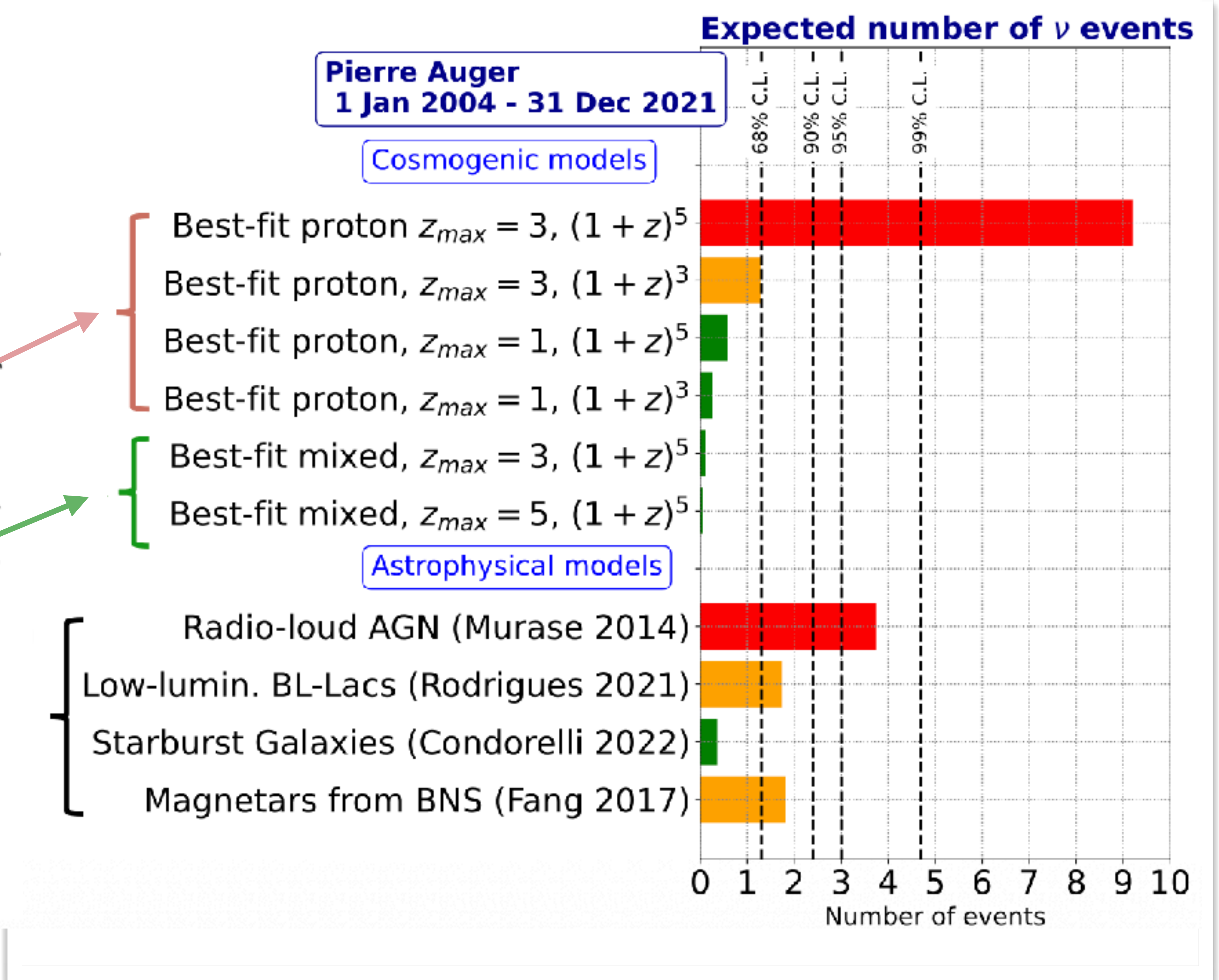
Candidate cut: median of the discriminant distribution (50% efficiency)

Measured and simulated events passing the cut are compared



Bounds on cosmogenic neutrinos

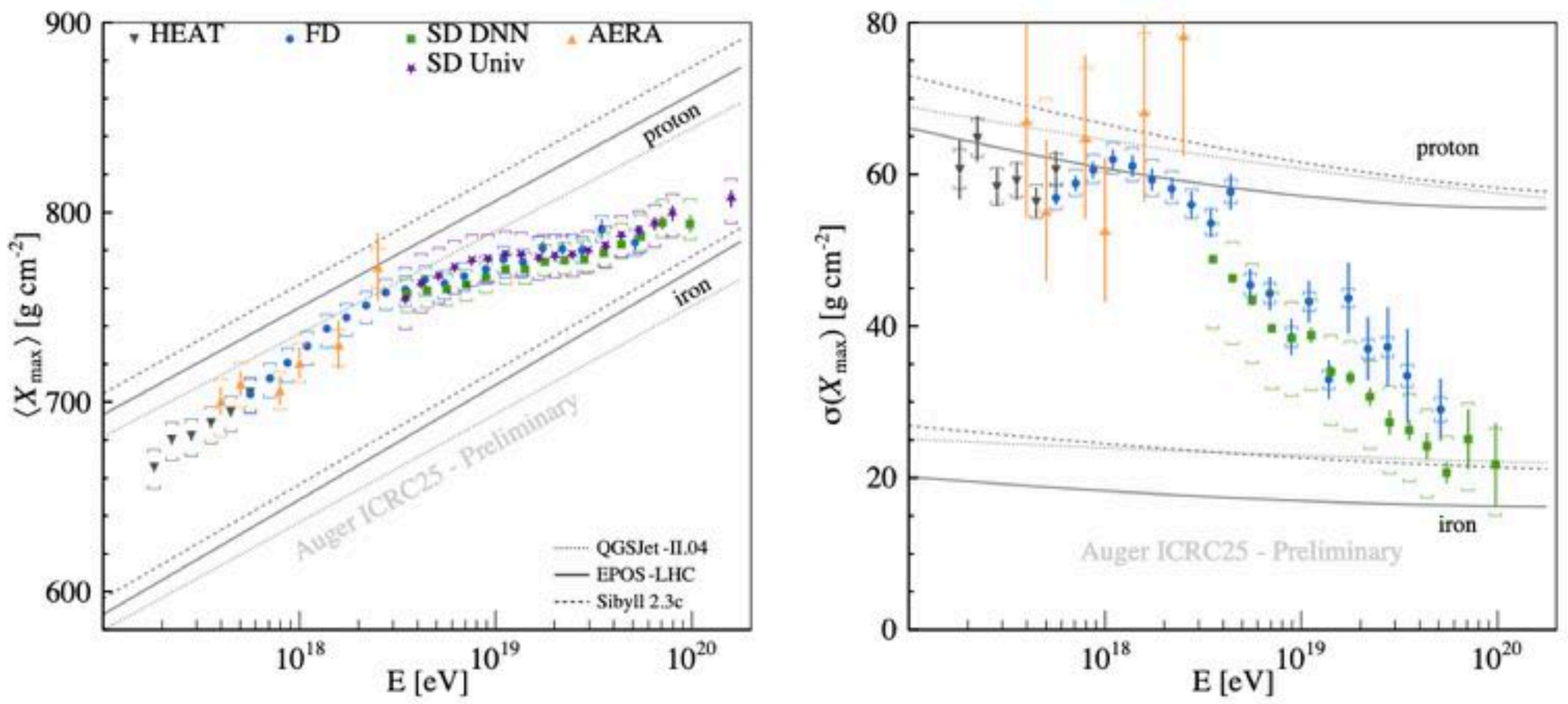




- ➡ No candidates found; best sensitivity slightly below 10^{18} eV
- ➡ Background very low, sensitivity limited by exposure
- ➡ Independent exclusion of proton-only scenarios for strong evolution

M.Roth, PoS(ICRC2025) 1402
J.Alvarez-Muniz, UHECR2024

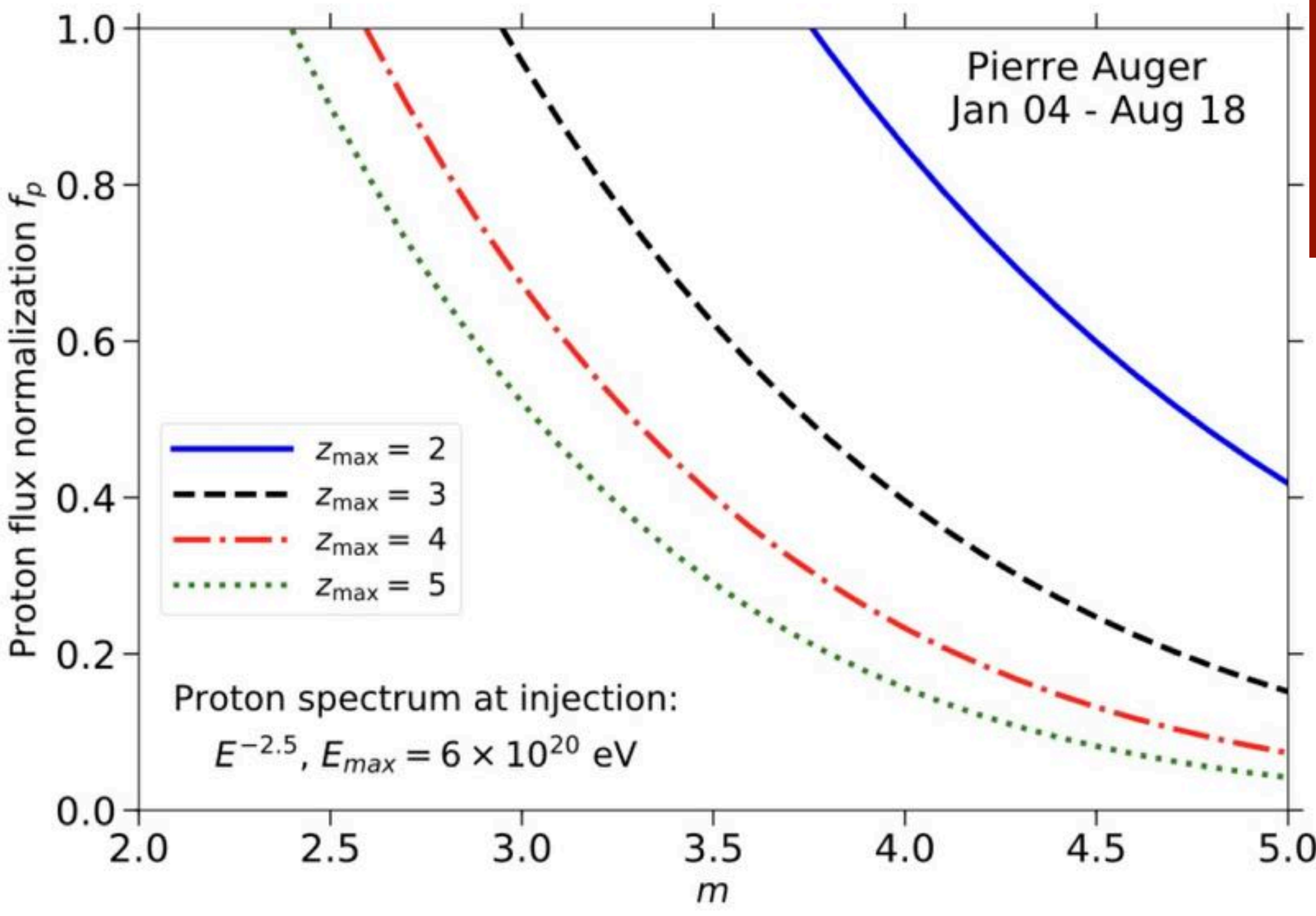
Constraints on the proton fraction



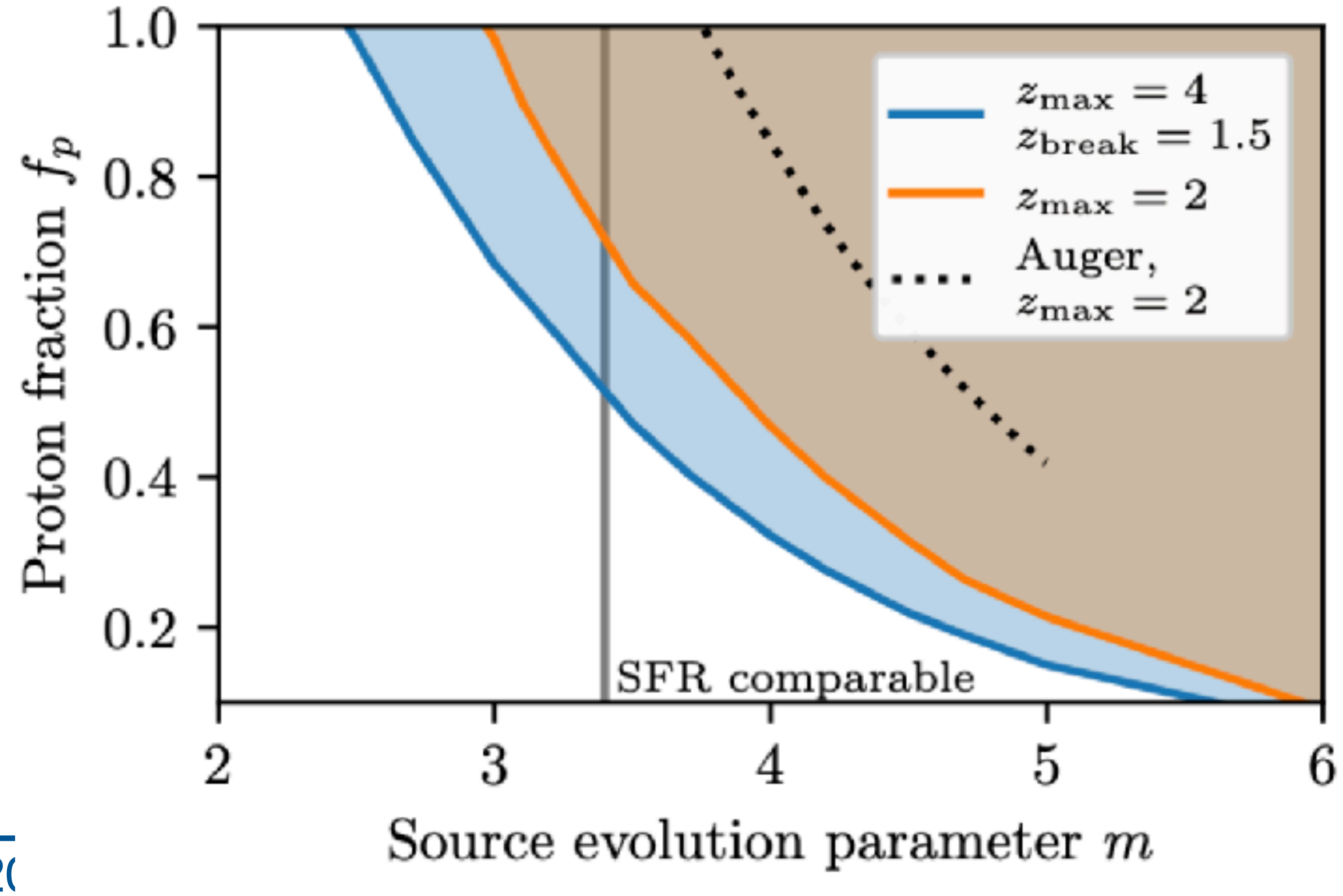
Composition measurements allow for a small fraction of protons at UHE, but they are prone to hadronic interactions uncertainties and FD low statistics.

Above 50 EeV, a sub-dominant proton component would strongly affect the expected neutrino flux

➡ Regions above the lines are excluded at 90% CL from the non observation of neutrinos
➡ fp larger than 40% are excluded for strong evolution of the sources (m=5)
➡ SFR-like case m~3.4: fp ≲70% for z_{max}=2 (IceCube)

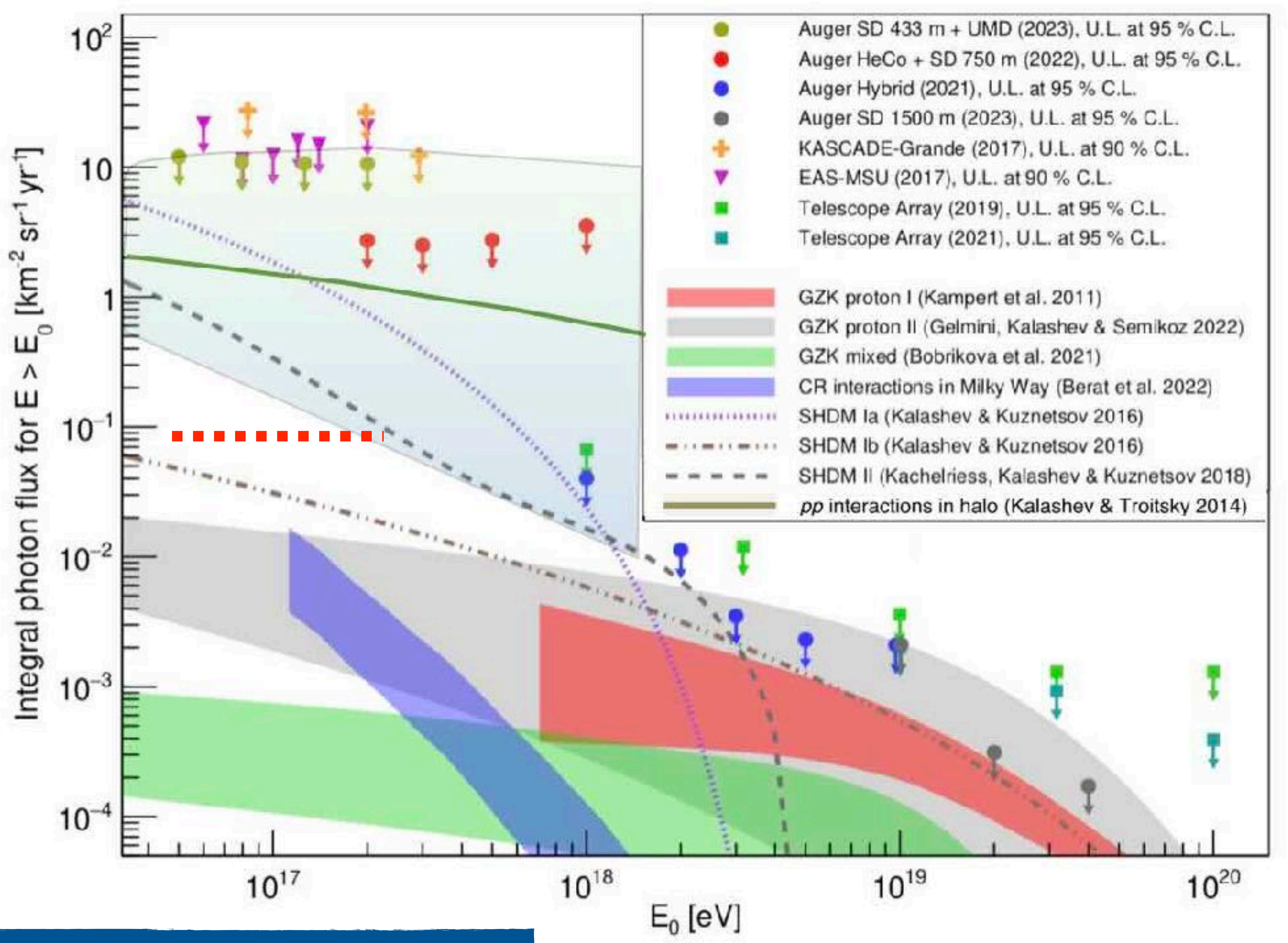


Auger coll., JCAP 10 (2019) 022



IceCube coll. PRL135 (2025) 03100

Bounds on cosmogenic photons



Auger Coll.,
SD433+UMD : JCAP 05 (2025) 061
SD750+FD : APJ 933 (2022) 125
SD1500+FD : PRD 110 (2024) 062005
SD1500 : JCAP 05 (2023) 021

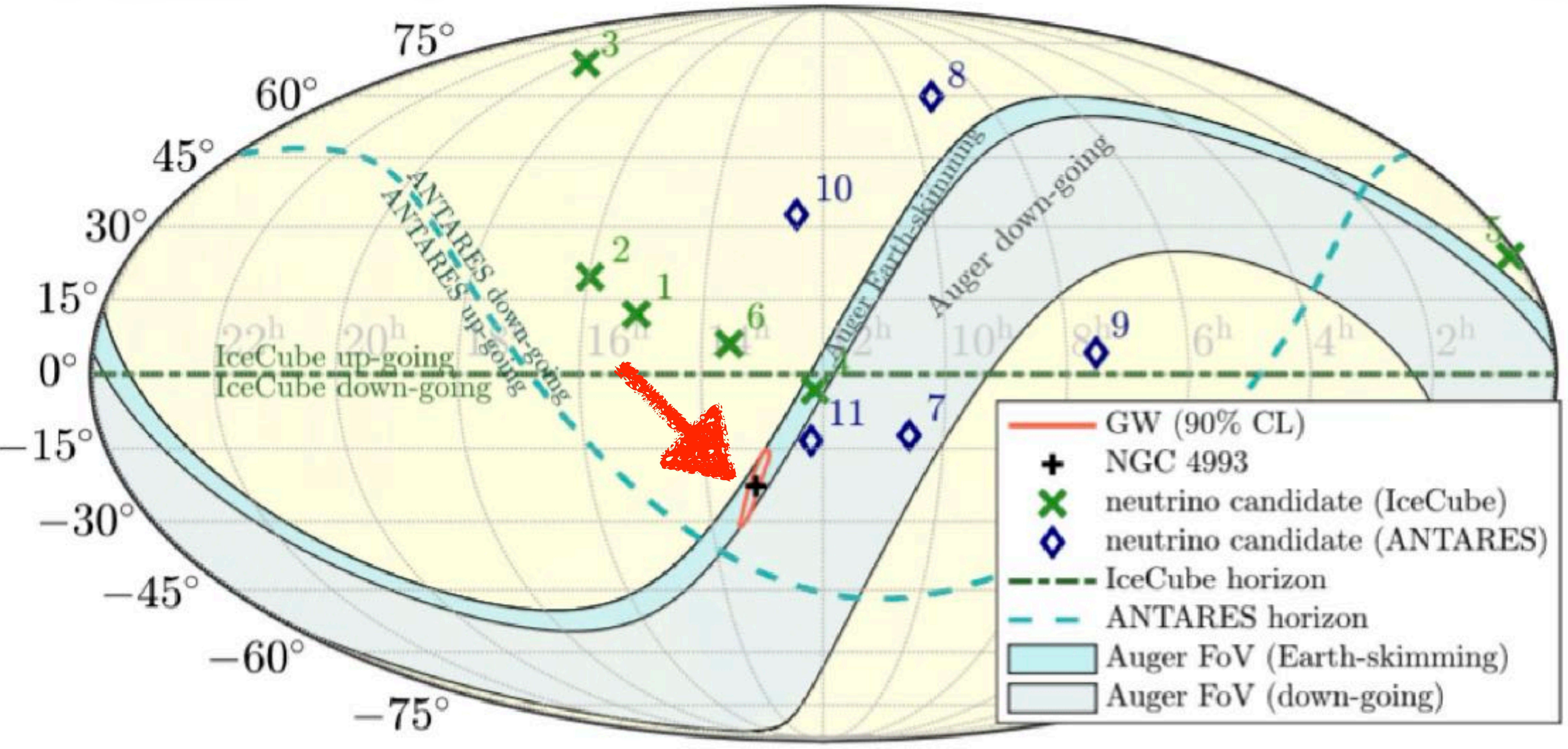
- ➡ Limits provided across 4 decades in energy
- ➡ Start closing the gap to the smaller air-shower experiments
- ➡ Below 10^{18} eV: most stringent limits available
- ➡ At the highest energies, most optimistic models of cosmogenic photon flux can be probed and excluded

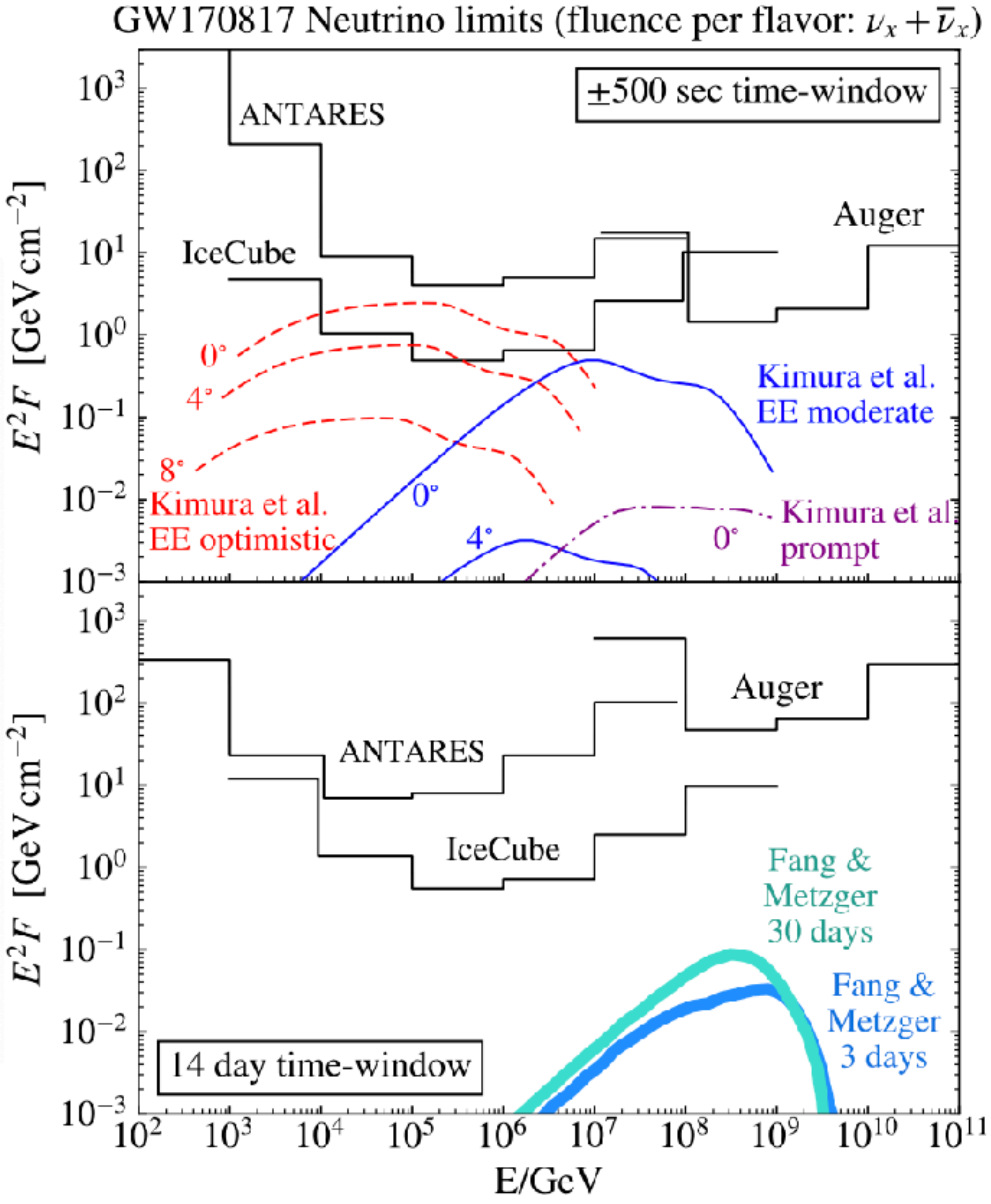
Improvements are expected from AugerPrime:
- larger data set
- better discrimination of photon-induced showers

Using AugerPrime exposure up to 2035

~ 1 odg better limits above 2 10^{17} eV
above 10^{18} eV we will constrain
above 10^{19} eV we will approach

Follow-up of GW170817 in neutrinos

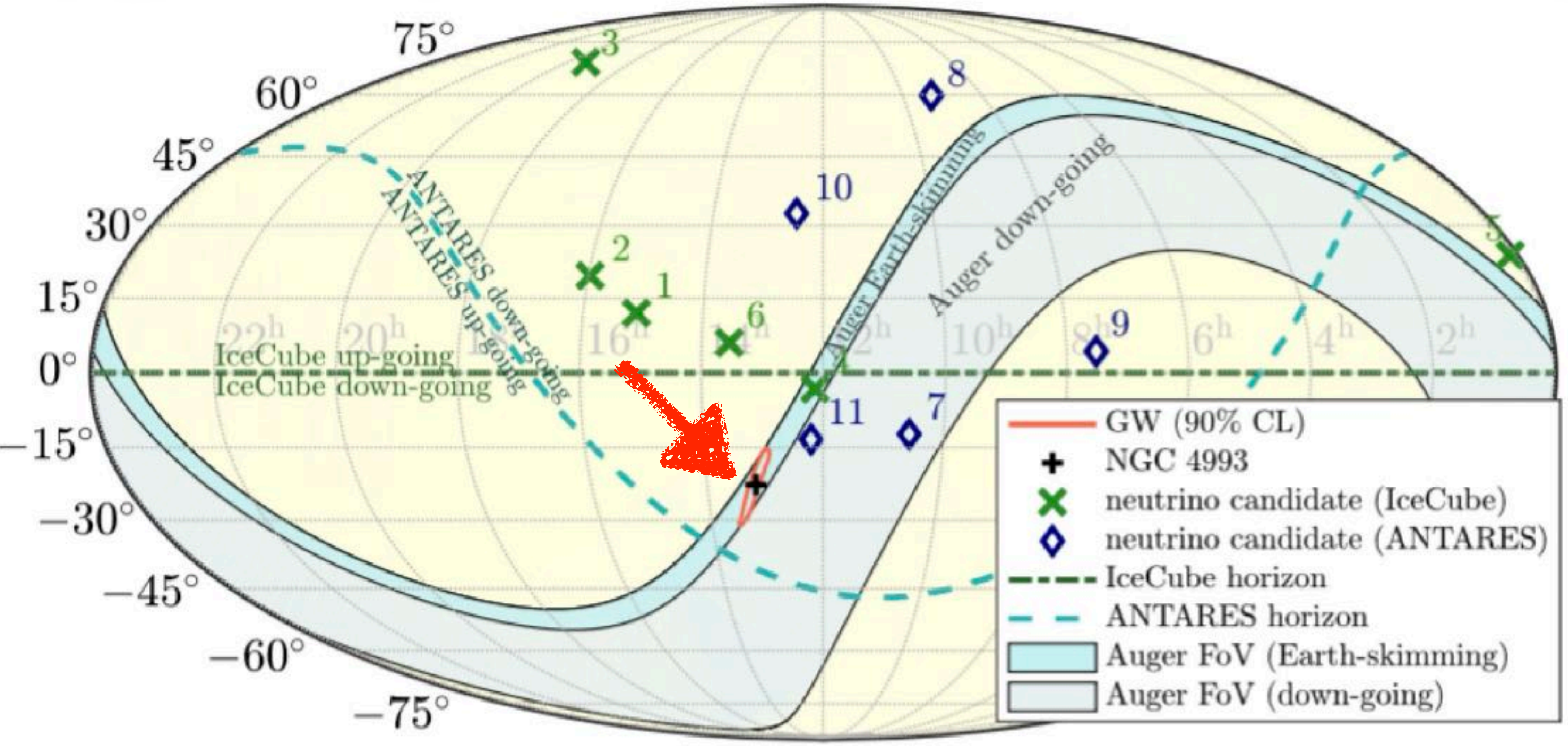


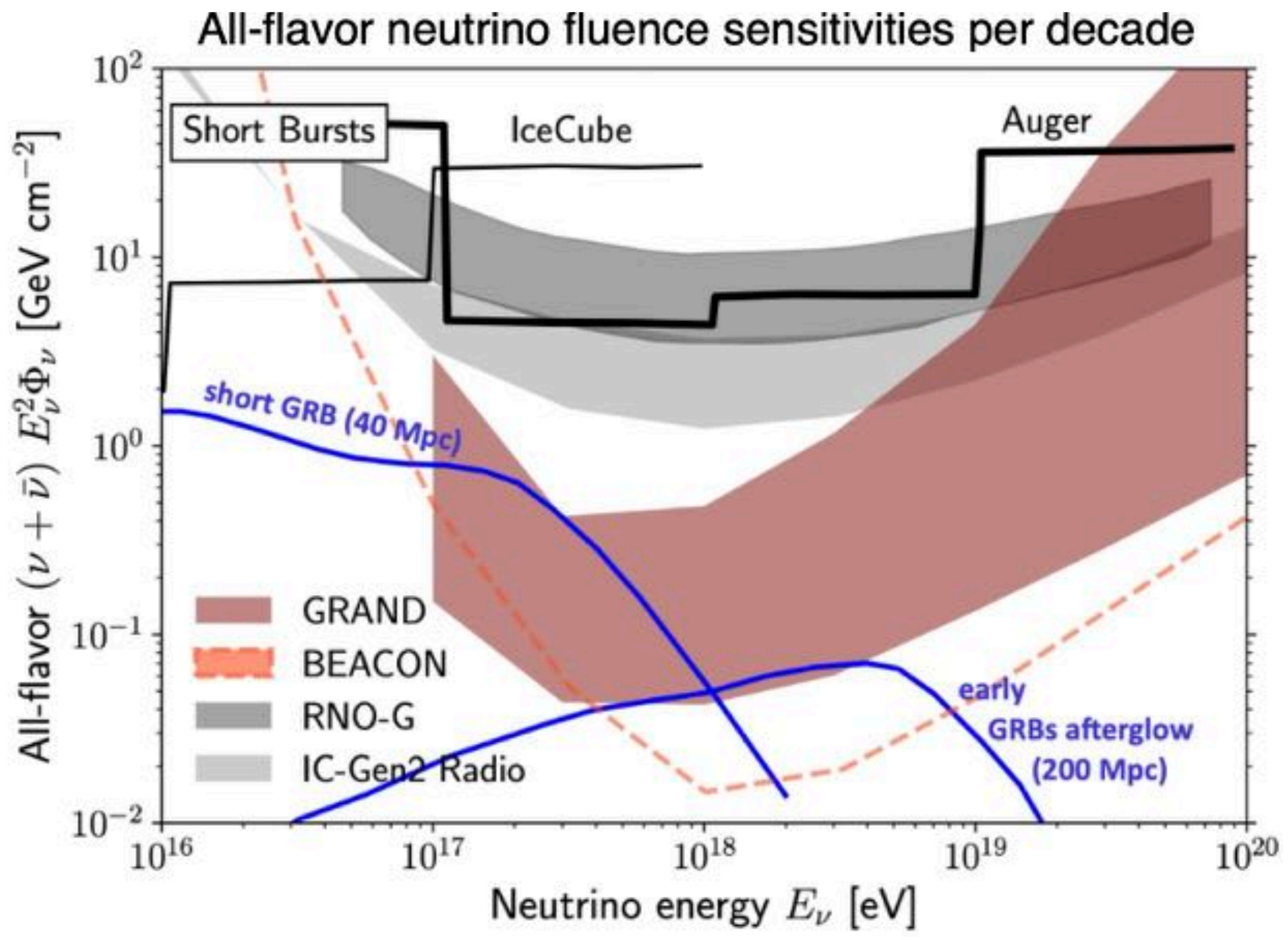


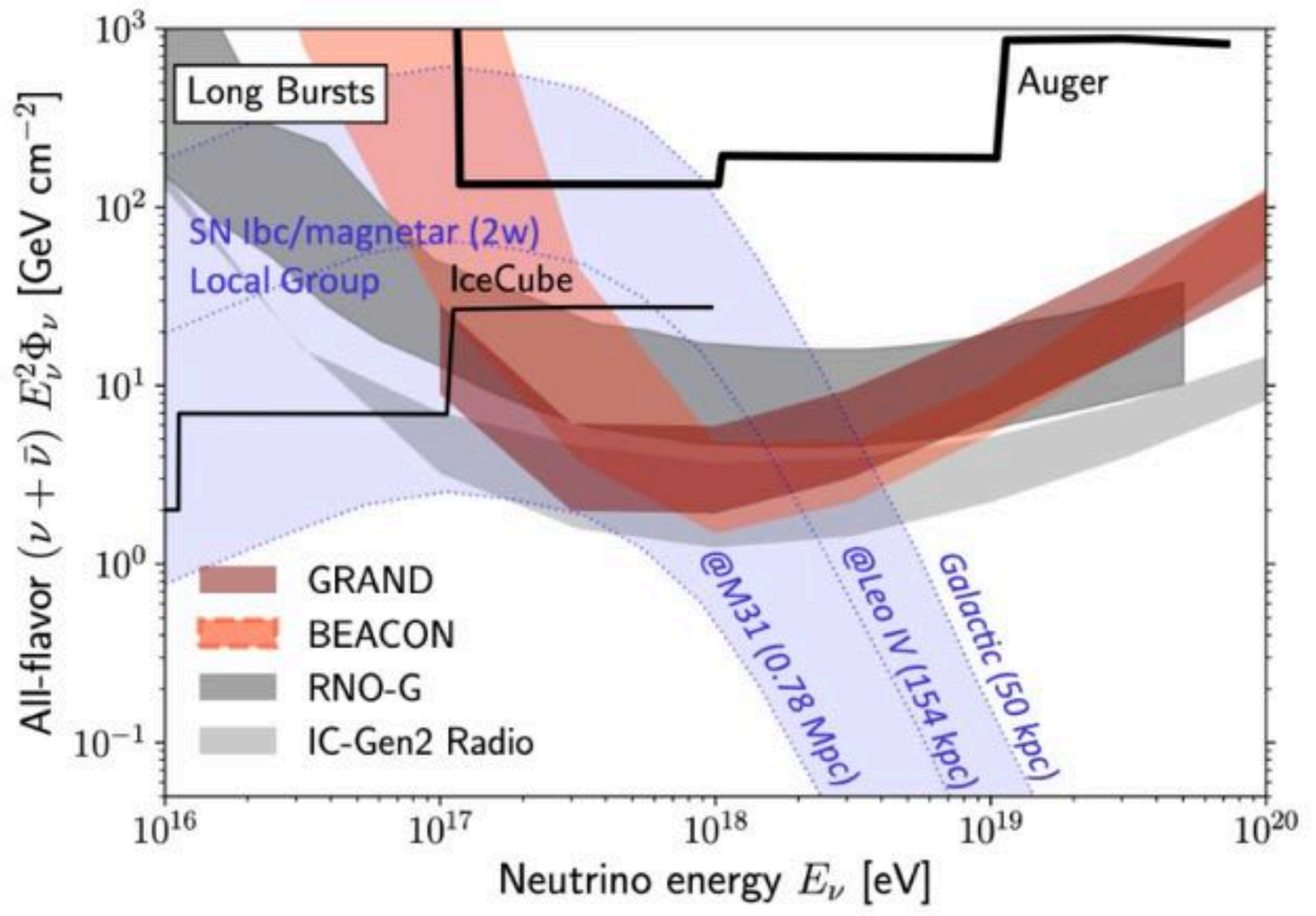
- ➡ Source in the field of view of ES neutrino search
- ➡ No UHE neutrino candidates found in either coincidence windows (±500 se around the GW or in the 14 days period after it)
- ➡ Limits on the total emitted energy in the range 10^{17}-2.5 10^{19} eV
  ±500 s : < 6.9 10^{-4} $M_\odot$ +14 days : < 2.3 10^{-2} $M_\odot$
- ➡ Lack of detection consistent with expectation from a short GRB viewed at off-axis angle >20^0

LVC, ANTARES, IceCube, Auger, ApJL 850 (2023) L35

Follow-up of GW170817 in neutrinos







- ➡ Source in the field of view of ES neutrino search
- ➡ No UHE neutrino candidates found in either coincidence windows ($\pm$500 se around the GW or in the 14 days period after it)
- ➡ Limits on the total emitted energy in the range 10^{17}-2.5 10^{19} eV
  $\pm$500 s : $< 6.9\ 10^{-4}\ M_\odot$ +14 days : $< 2.3\ 10^{-2}\ M_\odot$
- ➡ Lack of detection consistent with expectation from a short GRB viewed at off-axis angle $>20^0$

LVC, ANTARES, IceCube, Auger, ApJL 850 (2023) L35
K.Kotera et al., JCAP01(2026)027

γ searches from GW sources

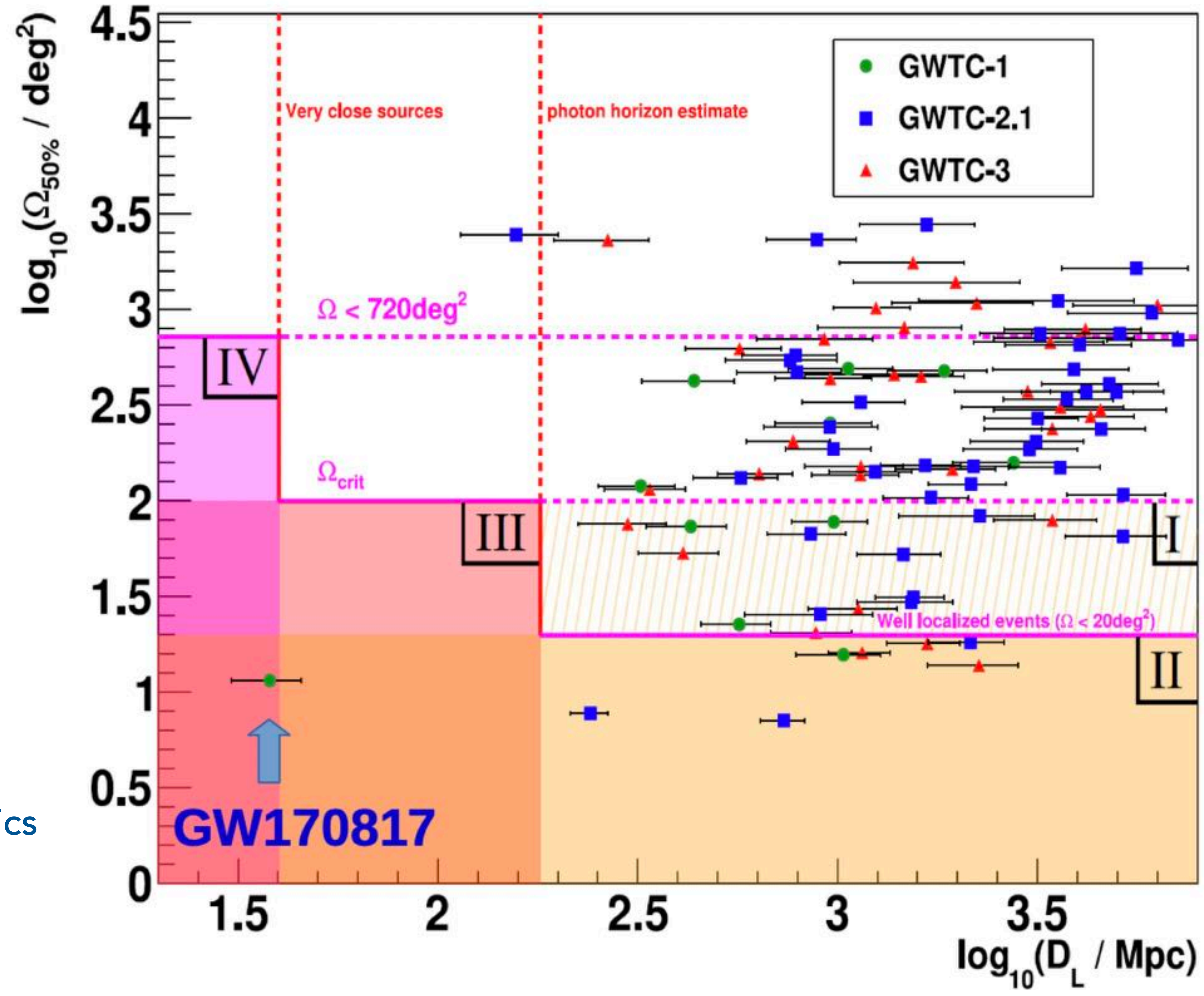
Search for γ from transients challenged by
- attenuation of UHE photons (λmax~few Mpc)
- Separation of γ from overwhelming hadronic background

Look for time and directional coincidence with 91 GW events from LIGO/Virgo runs O1-O3

Search region
- $\Omega_{50\%}$ solid angle contour in localization of the GW source
- Two mutually exclusive time windows: 1000 s centered at t_{GW} and 1 day after it

4 regions in distance and localization (not mutually exclusive)
- best region for observation if sources are closeby (IV)
- a candidate at large distance (I,II) could point to new physics

$$(D_L < \infty \text{ and } \Omega_{50\%} < 100\ \mathrm{deg}^2)_s \text{ “class I”}$$
$$(D_L < \infty \text{ and } \Omega_{50\%} < 20\ \mathrm{deg}^2)_l \text{ “class II”}$$
$$(D_L < 180\ \mathrm{Mpc} \text{ and } \Omega_{50\%} < 100\ \mathrm{deg}^2)_l \text{ “class III”}$$
$$(D_L < 50\ \mathrm{Mpc} \text{ and } \Omega_{50\%} < 720\ \mathrm{deg}^2)_{l,s} \text{ “class IV”}$$



Auger Coll., Astrop.J.952 (2023) 91

ɣ searches from GW sources

No air showers $>10^{19}$ eV in coincidence with GW time window
(in agreement with expected background 0.03 of random showers)

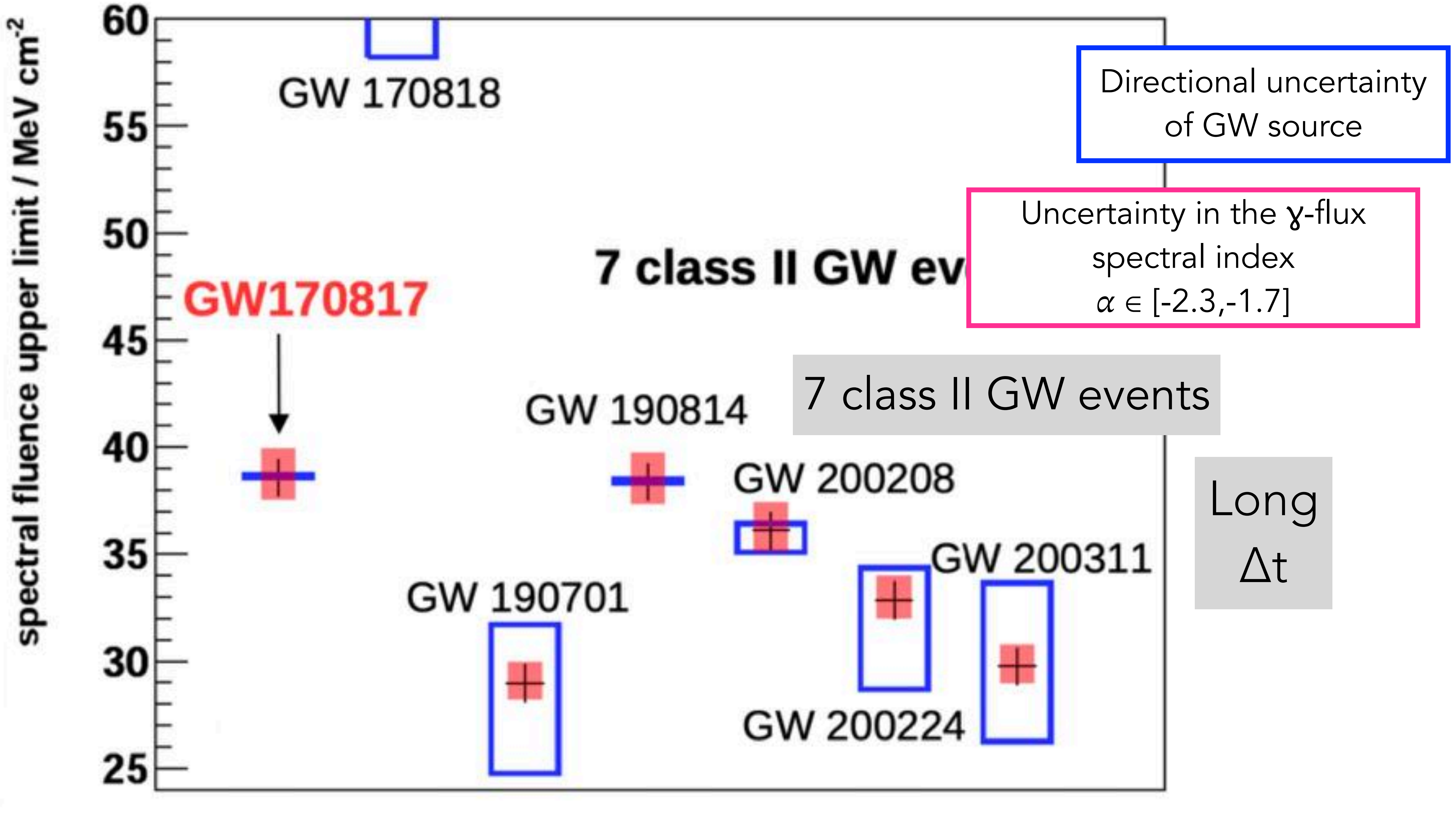
- ➡ 8 BBH (I,II)
- ➡ 1 NSBH : GW190814 (I and II)
- ➡ 1 BNS : GW170817 (all classes)

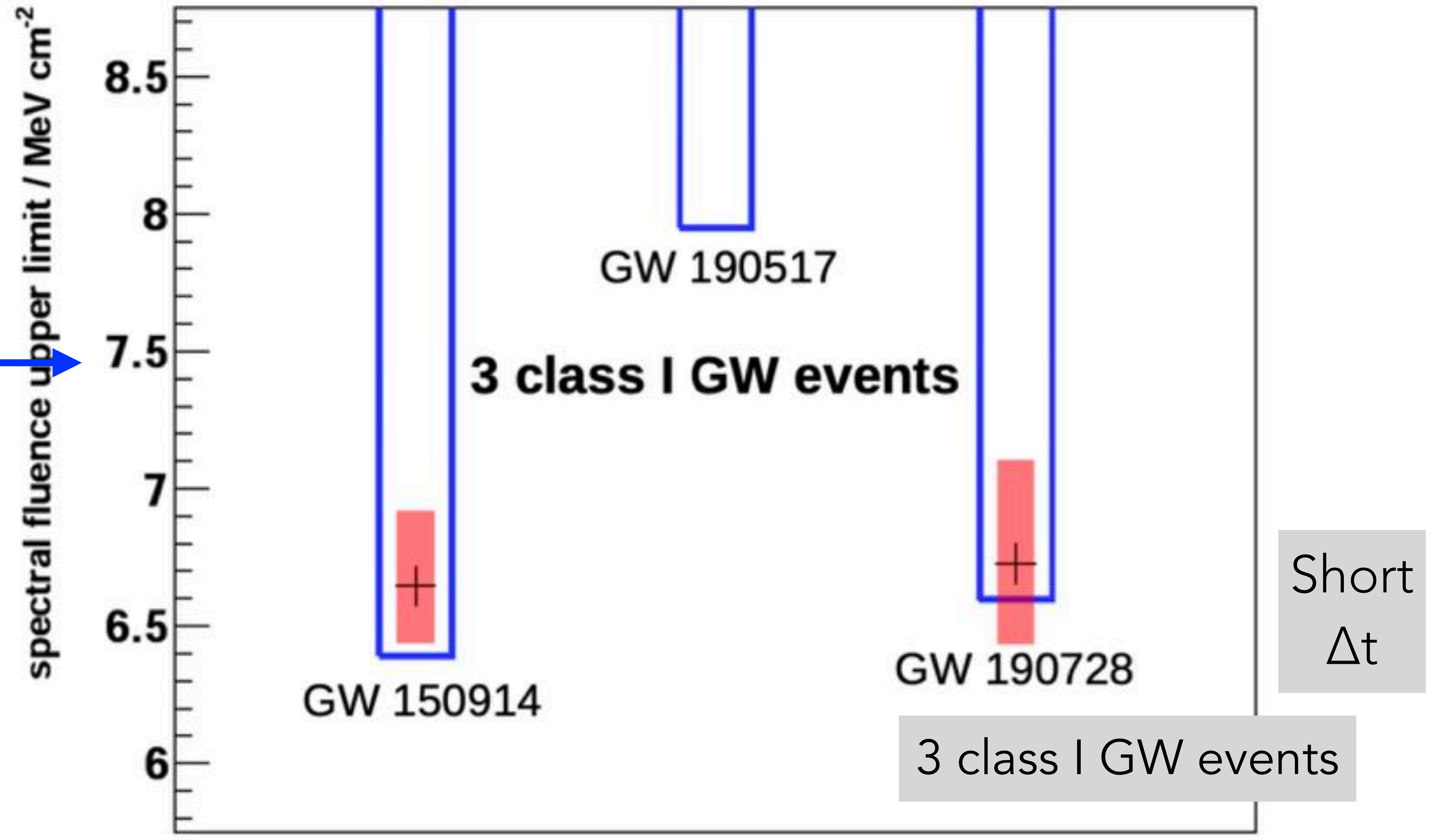
$$\frac{d\Phi_\gamma^{GW}}{dE_\gamma}(E_\gamma) = k_\gamma E_\gamma^\alpha$$

$$k_\gamma^{UL} = \frac{N_\gamma^{UL}}{\int_{E_0}^{E_1} dE_\gamma E_\gamma^\alpha \mathcal{E}(E_\gamma, \theta_{GW}, \Delta t)}$$

$$\mathcal{F}_\gamma^{UL} = \int_{t_0}^{t_1}\int_{E_0}^{E_1} dt\, dE_\gamma\, E_\gamma \frac{d\Phi_\gamma^{GW}}{dE_\gamma}$$

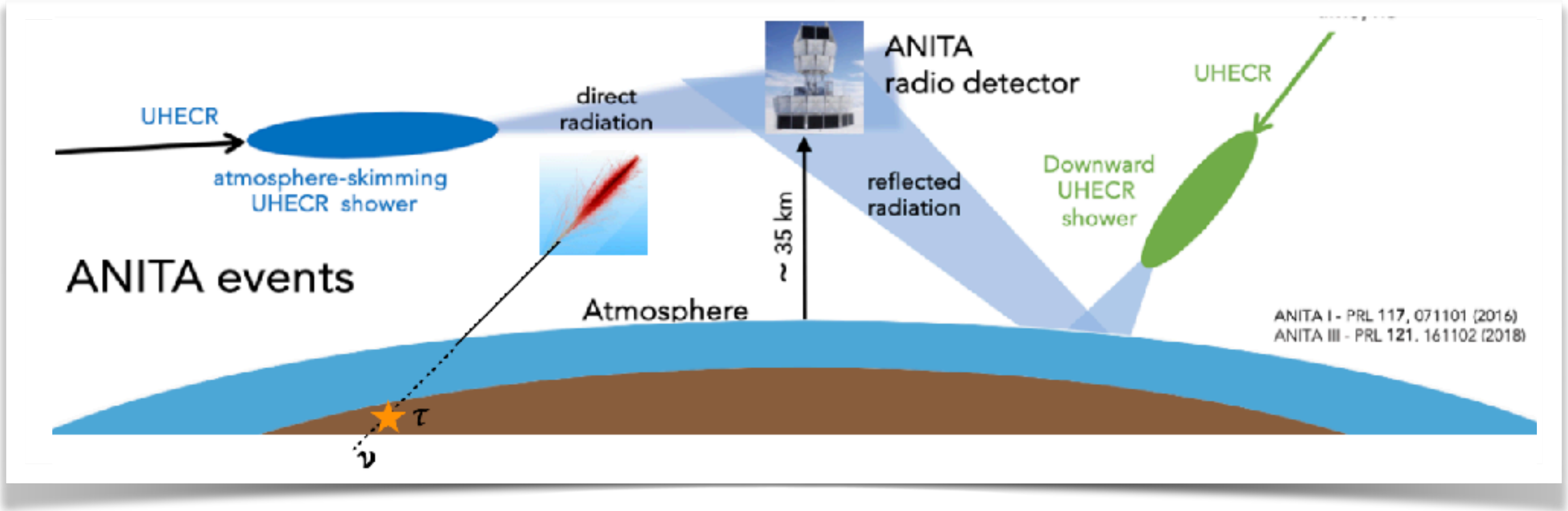
Spectral ɣ fluence

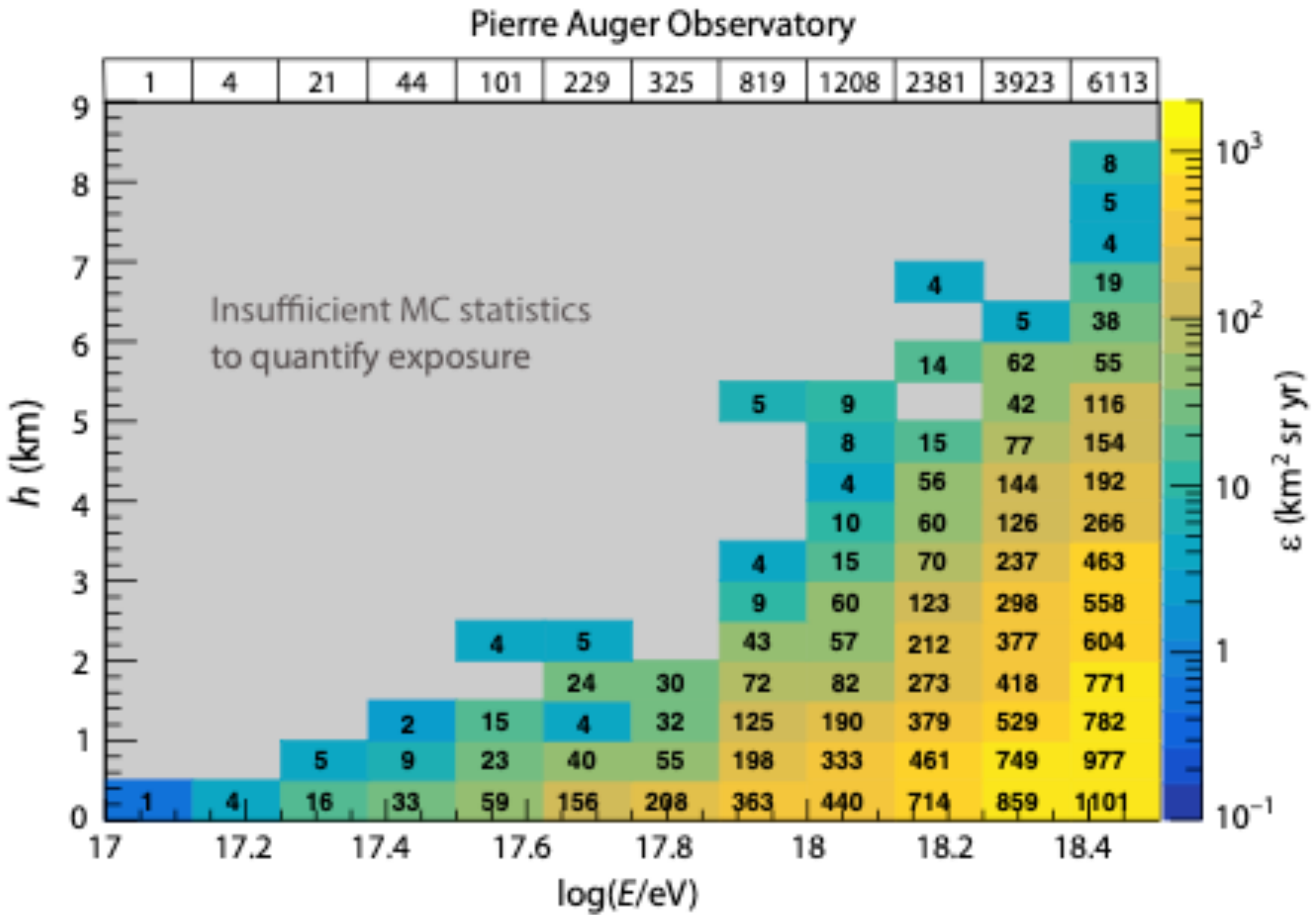




- ➡ First ever limits on ɣ from GW sources at UHE
- ➡ GW170817: best upper limit on the photons energy above 40 EeV, <20% of the GW energy goes to photons
- ➡ Expect great improvement from closer GW events

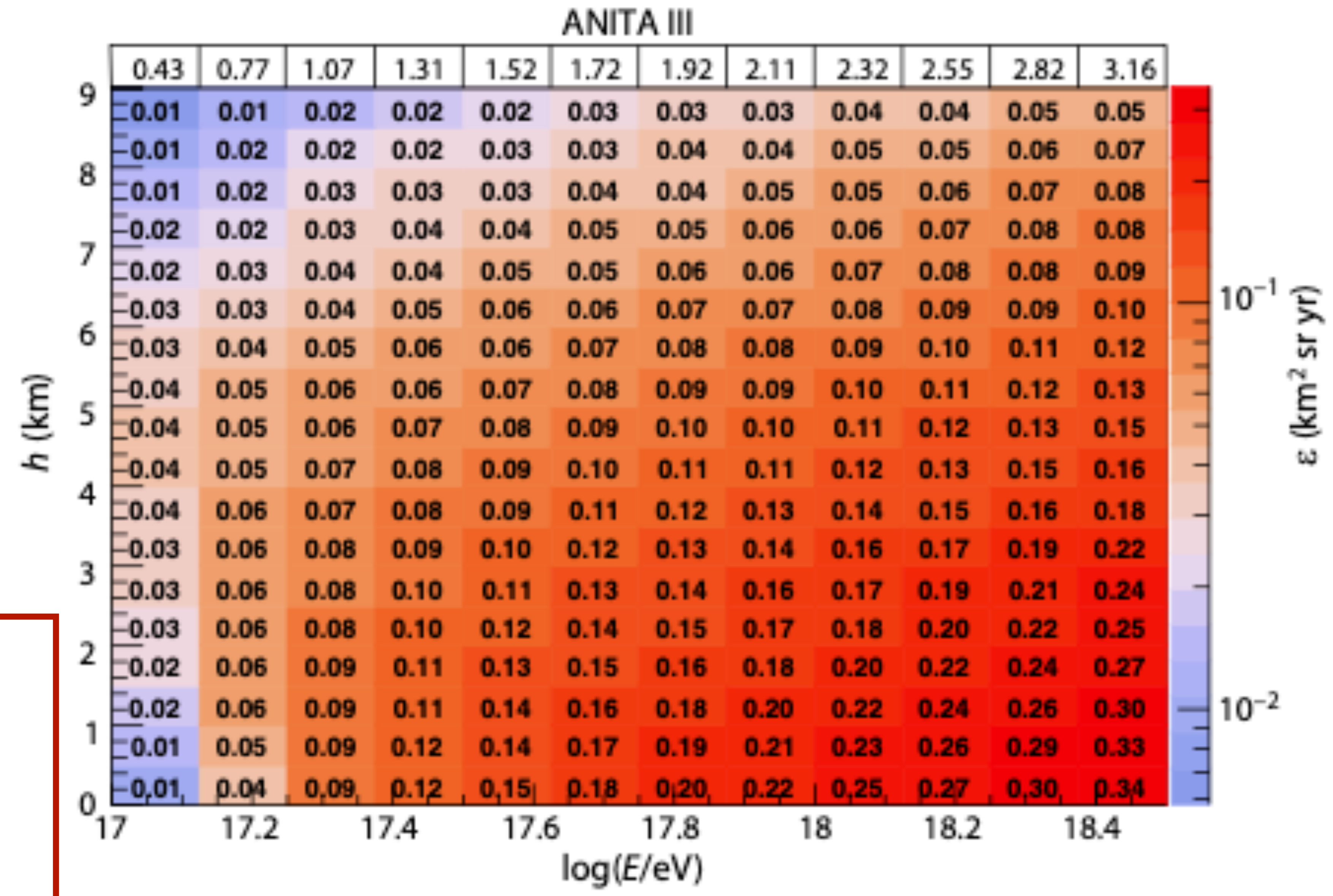
Constraints on ANITA events





ANITA detected 2 anomalous events at

$\vartheta=117^0$ and $\vartheta=125^0$, E ~ $\mathcal{O}$(1EeV) with no polarity inversion



- No standard acceptable explanations: ν at these energies are absorbed in the Earth (λ_{int} ~ 280 km vs Earth chord ~ 7000 km)
- Beyond SM new particles inducing upgoing showers: can be searched in Auger FD

Auger exposure for $\vartheta\in(110^0, 130^0)$: 2 to 3 orders of magnitude larger than that of ANITA

Auger should have seen from 8 to ~70 events

Auger result does NOT support the explanation of ANITA events as hint of BSM physics

Auger Coll., PRL 134 (2025) 121003

Search for neutrons from steady Galactic sources

$p + p \rightarrow n + p + \pi^+$ with E_n ~ 50% E_p

$p + \gamma \rightarrow n + \pi^+$ E_n ~ 80% E_p

$$\tau_n \sim 9.2 \text{ kpc} \times \text{E (EeV)}$$

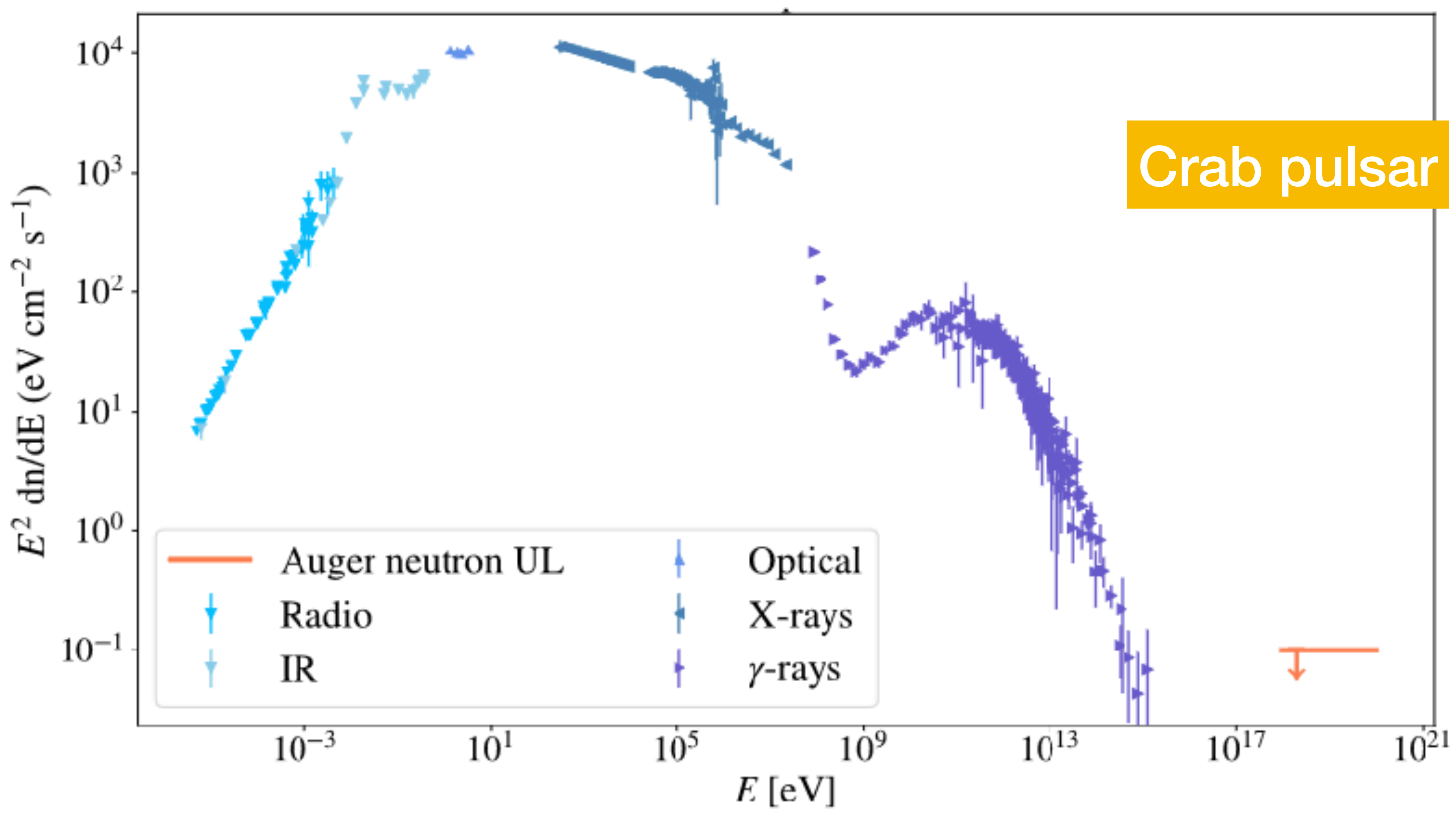
Neutron- and proton-induces EAS cannot be distinguished :
Define targets and look for excesses from point sources

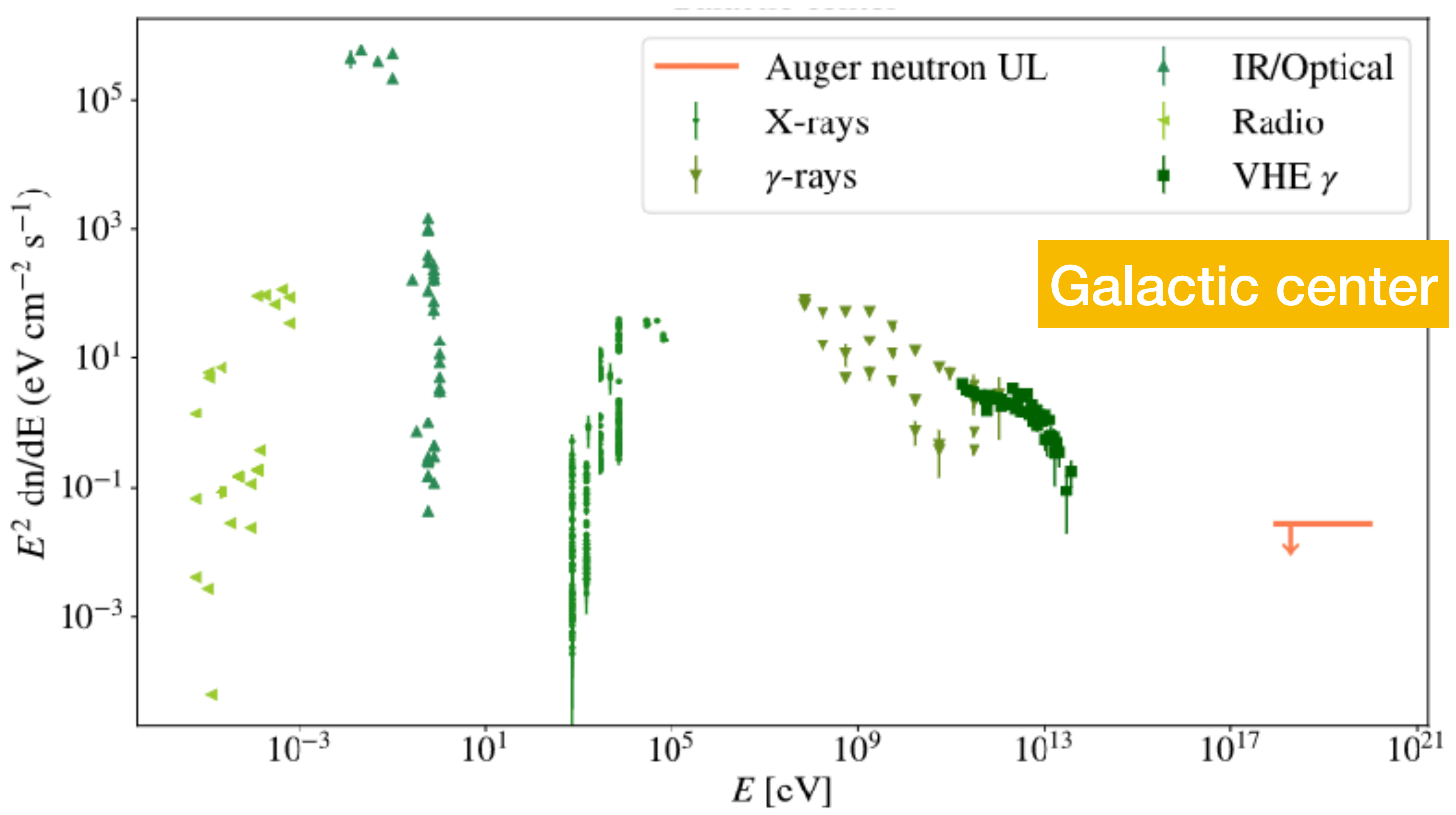
1092 targets
SD-1500 Phase I data (2004–2022)
SD-750 Phase I data (2008-2022)

➡ Since the neutron channel is the hadronic-only tracer, most stringent direct constraints on hadronic acceleration in Galactic sources above 100 PeV

➡ Expect to improve substantially from better background rejection in Phase II (AugerPrime)

Auger Coll., ApJ 99 (2026) 168





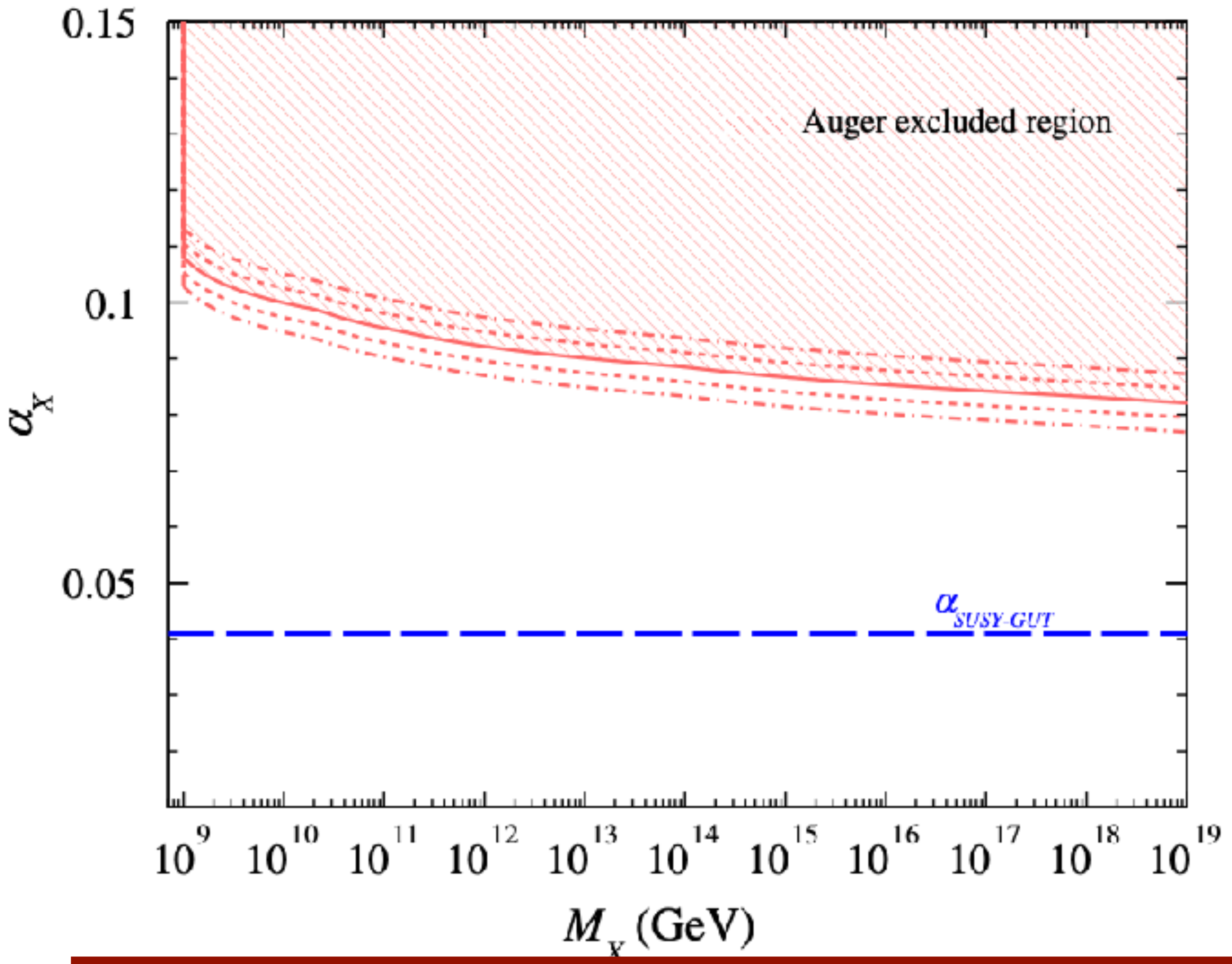
Hints for BSM effects from photons

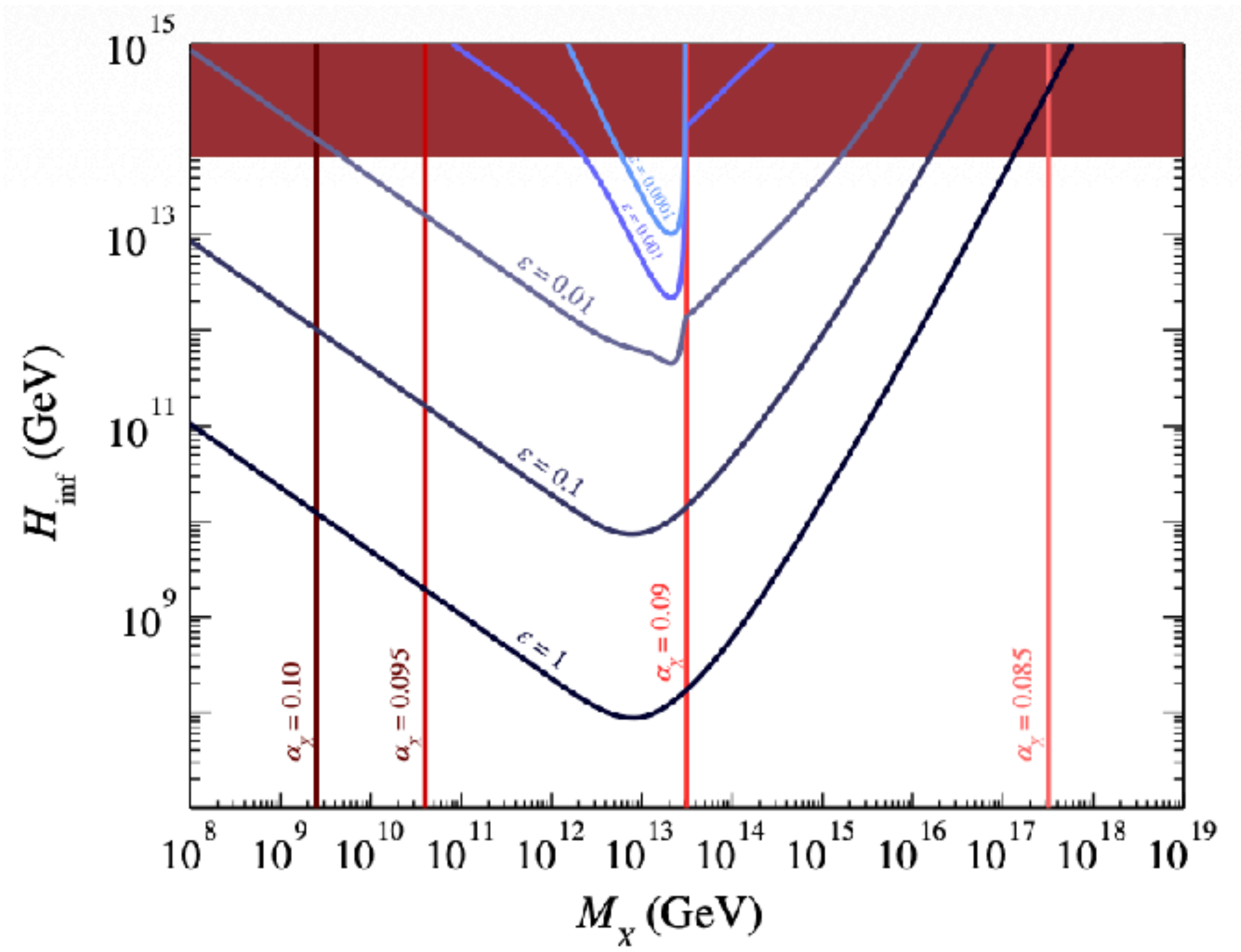
Auger Coll., Phys. Rev. Lett. 130 (2023) 061001
Phys. Rev. D 107 (2023) 042002

Instantons decay into standard particles (i=γ, ν, N…)

$$J_i^{Gal} = \frac{1}{4\pi M_X c^2 \tau_X} \int_0^\infty ds \rho_{DM}(\mathbf{x}_\odot + \mathbf{x}_i(s;n))$$

$$\tau_X = \hbar \, M_X^{-1} exp(4\pi/\alpha_X)$$





From the upper limits on the UHE γ flux: bound on the coupling constant α_X in the dark sector

$\alpha_X \lesssim 0.09$ (95% CL) for $10^9 \lesssim M_X$ /GeV$\lesssim 10^{19}$
α_X=0.09 excludes masses $M_X \gtrsim 3\times10^{13}$ GeV

If SHDM is produced from gravitational interactions alone during the reheating epoch:

Cosmological constraints on the regions of viable (H_{inf},M_X) values needed to set the right abundance of DM (Ω_{DM} h² ≈ 0.12)

Hints for BSM effects from photons and neutrinos

Specific model (Dudas set al., PRD 101, 2020):
Pseudo-scalar X coupled exclusively to the sterile neutrino sector

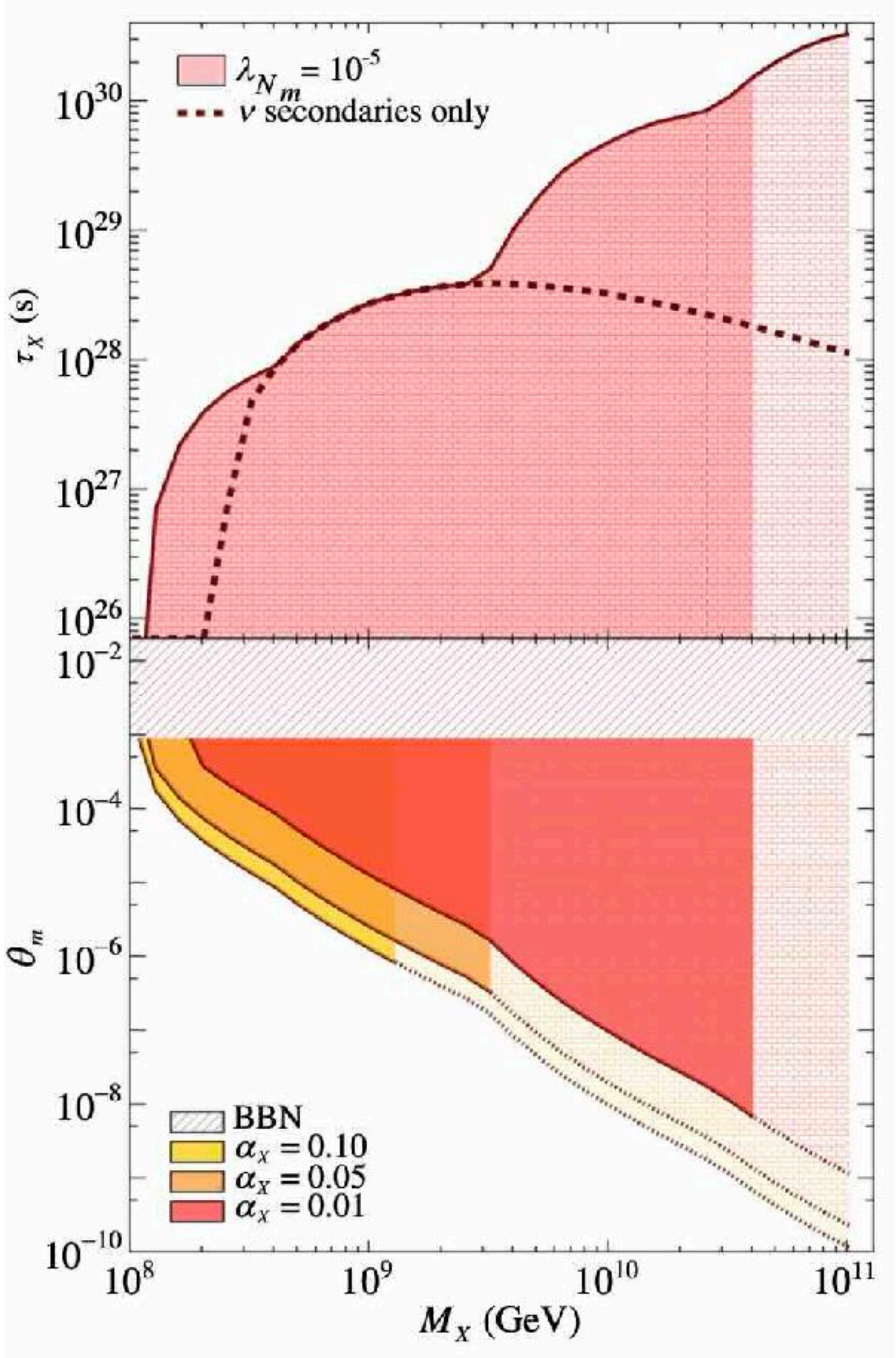
$$X \rightarrow H\, \nu_1\, \nu_2$$

Two sterile species are introduced:
N_M with $M_N \sim 10^{12}$–10^{14} GeV (the usual seesaw scale),
N_m with $m_N \sim$ sub-eV.

Stringent constraints on the ϑ_m angle of mixing between sub-eV sterile and active neutrinos can be obtained by exploiting the non observation of UHE neutrinos and photons in Auger:

For $\alpha_X = 0.1$ and for $10^8 \lesssim M_X\,/\mathrm{GeV} \lesssim 10^{11}$
$\vartheta_m \lesssim 1.5\ 10^{-6}\ (M_X/10^9\ \mathrm{GeV})^{-2}$

Auger Coll., Phys. Rev. D 109 (2024) L081101



AugerPrime (a.k.a. Auger Phase II)

More insight in the mass composition
+ increased statistics

will exploit the richness of extensive air showers performing hybrid measurements and applying new analysis techniques

Measure of the longitudinal development of the extensive air showers (EAS) while crossing the atmosphere

➡ *Fluorescence telescopes*

Discrimination between the EM and μ components of the EAS

➡ **Water Cherenkov Stations** and ***Scintillators***

➡ ***Larger dynamic range to measure high particle densities closer to the core***

Measure of the radio emission of EAS

➡ ***Radio antennas***

Direct measure of the μ component

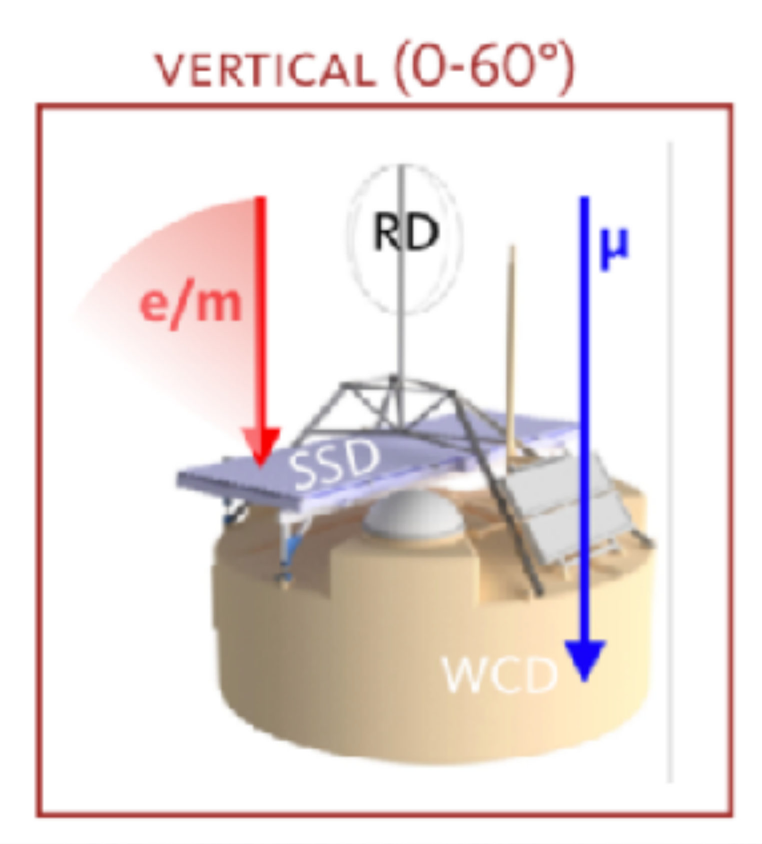
➡ ***Underground detectors***

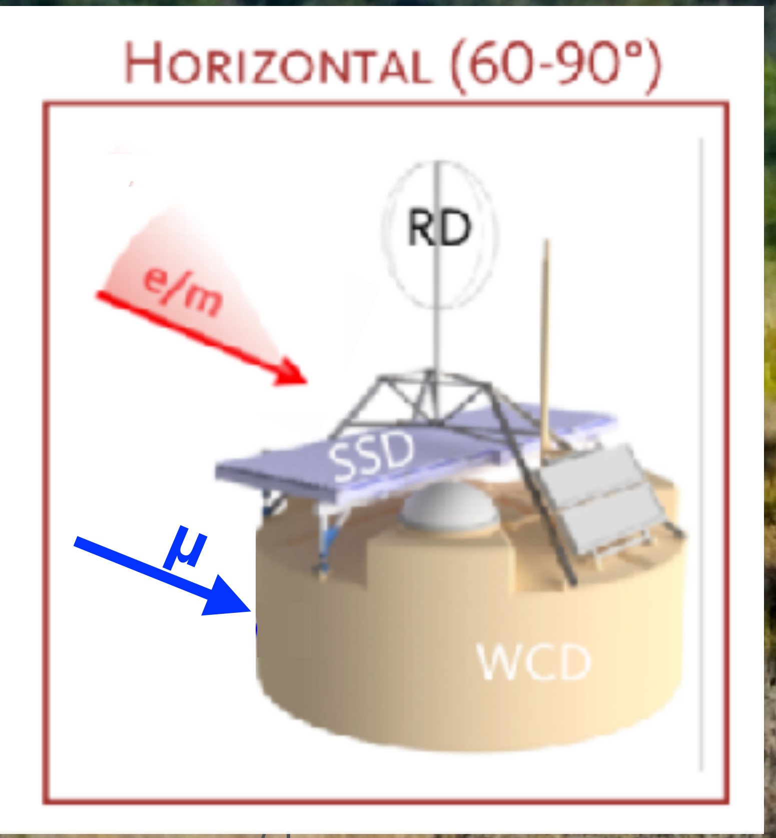
WCD/SSD/RD can collect multi-hybrid events with a 100% duty cycle

Separation of shower components can be obtained

- by WCD/SSD for events up to ~60^0
- by WCD/RD for inclined events >60^0
- by WCD/SSD/UMD extending the mass sensitivity to the lower energies and improving the photons/hadrons discrimination

New triggers will allow to lower the energy range of the measurements, improve signatures for ES and efficiencies for DG neutrinos

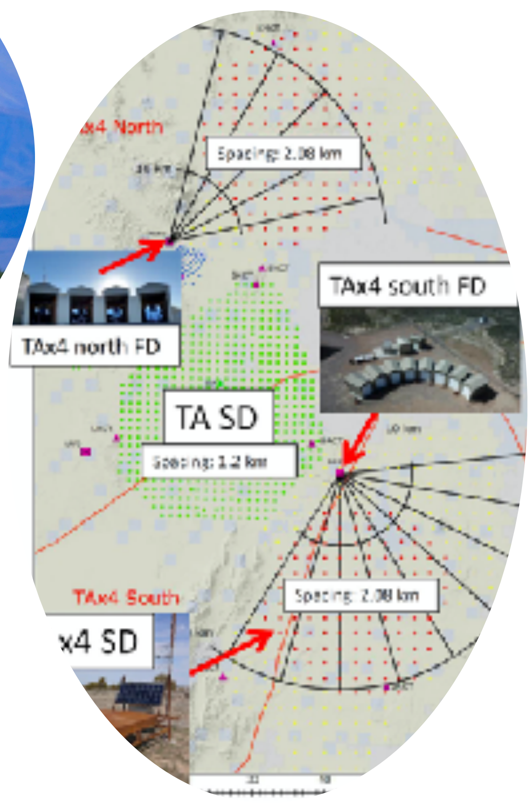




The Pierre Auger Observatory as part of the multimessenger network

Automatic Global Coordinate Network (GCN) alerts listener

- SD events update every 15′, 3 ν reconstruction analyses running
- Read GCN alerts and look for ν candidates in 90% CL region
- Automatic alert if any findings and possible GCN notice if confirmed



AMON and DWF triggering and follow-up partner

- Alerts from private or GammaCN notices
- High quality SD events shared every few minutes
- SD events in DWF field of view shared

ACME (Astrophysics Center for MM studies in Europe)

- Funded under EU Horizon Research and innovation Program till 2028
- Auger is one of the 12 offered research infrastructures
- Accepted proposals will be given expert support, improved access to data

A strong collaboration among the various communities (GW, γ, ν, CRs) is mandatory to bring new insights.

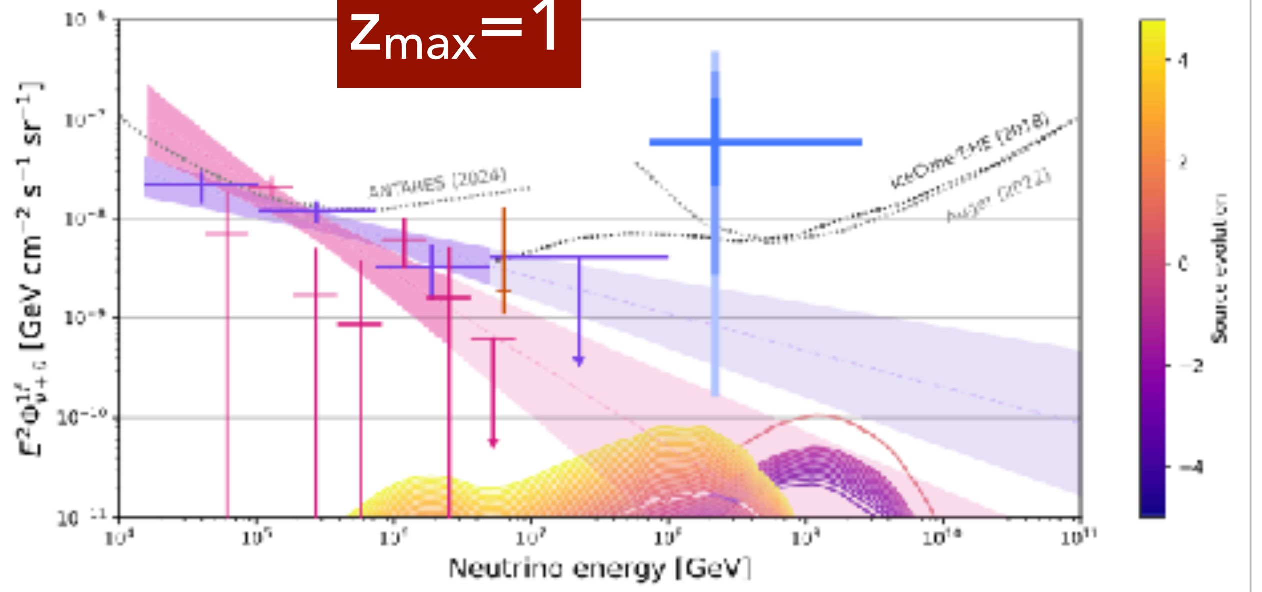
The different groups interconnections must be continued and improved

BACKUP

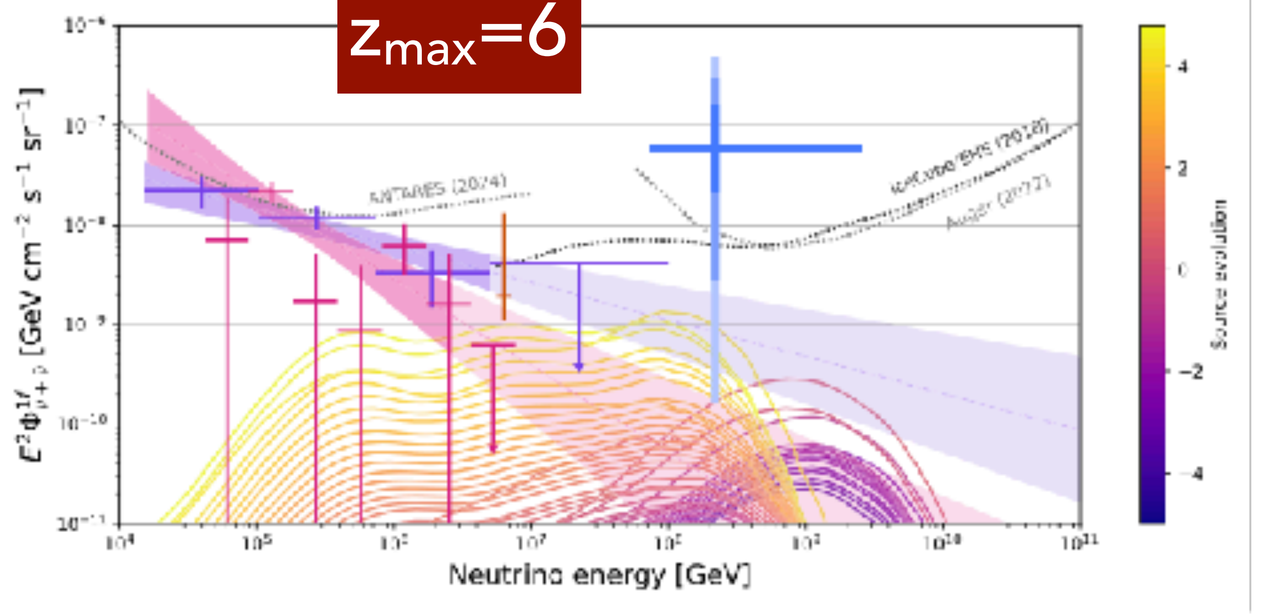
MM analyses to explain the Km3Net event

Auger spectrum+composition information above and below the ankle plus limits on $\phi\nu$

z_{max}=1

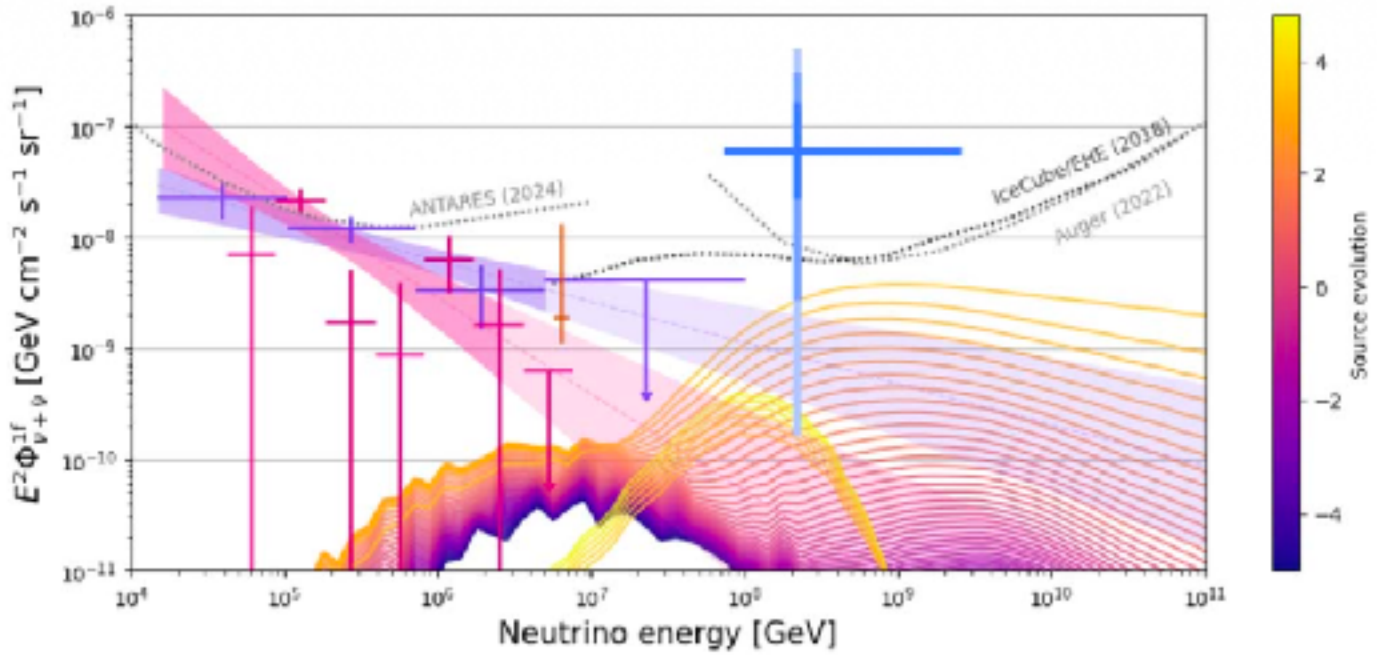


z_{max}=6



If the KM3NeT-230213A event is cosmogenic, higher probability to come from distant sources

With an even small proton fraction below the ankle, better agreement



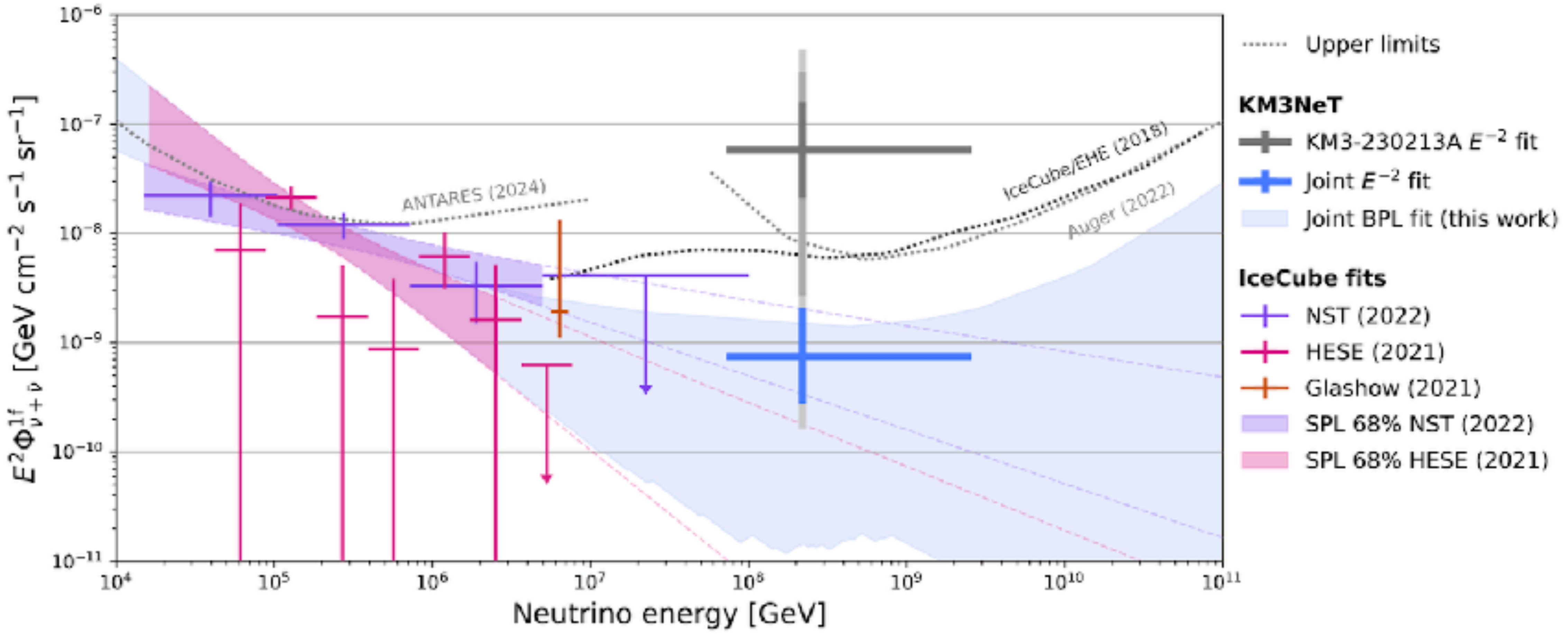
Adriani et al., ApJL 984:L41 (2025)

Is the KM3NeT-230213A event compatible with the non observation of EHE neutrinos by IceCube and Auger?

Km3Net-only flux $$E^2\Phi = 5.8 \times 10^{-8} \;\; GeV\;cm^{-2}sr^{-1}$$

Joint E-2 fit (Km3Net + IceCube EHE + UHE Auger)

$$E^2\Phi = 7.5 \times 10^{-10} \;\; GeV\;cm^{-2}sr^{-1}$$



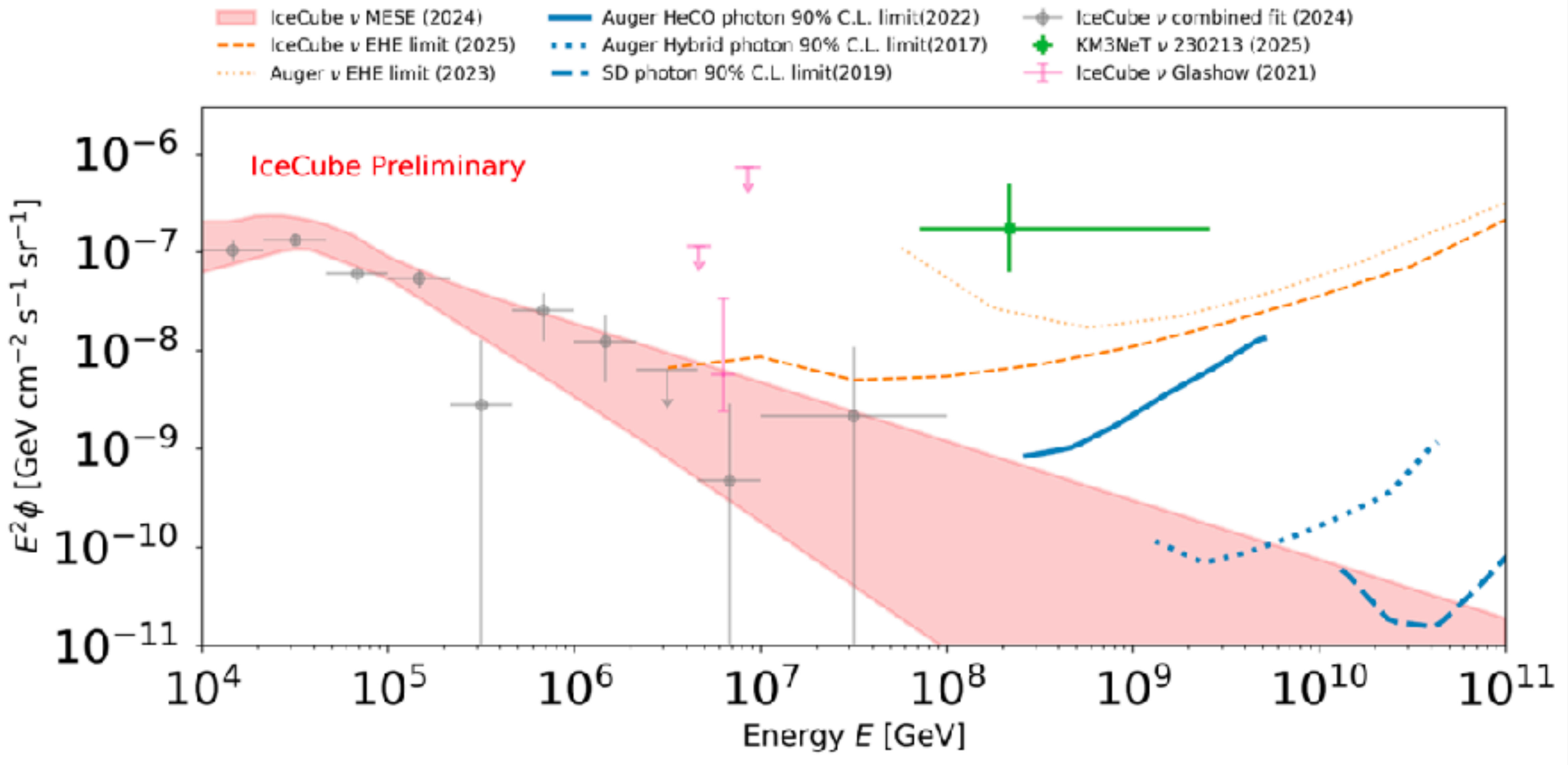
Mild to moderate tension 1.6-2.9 **σ**
most plausible explanation upward fluctuation of a UHE ν flux

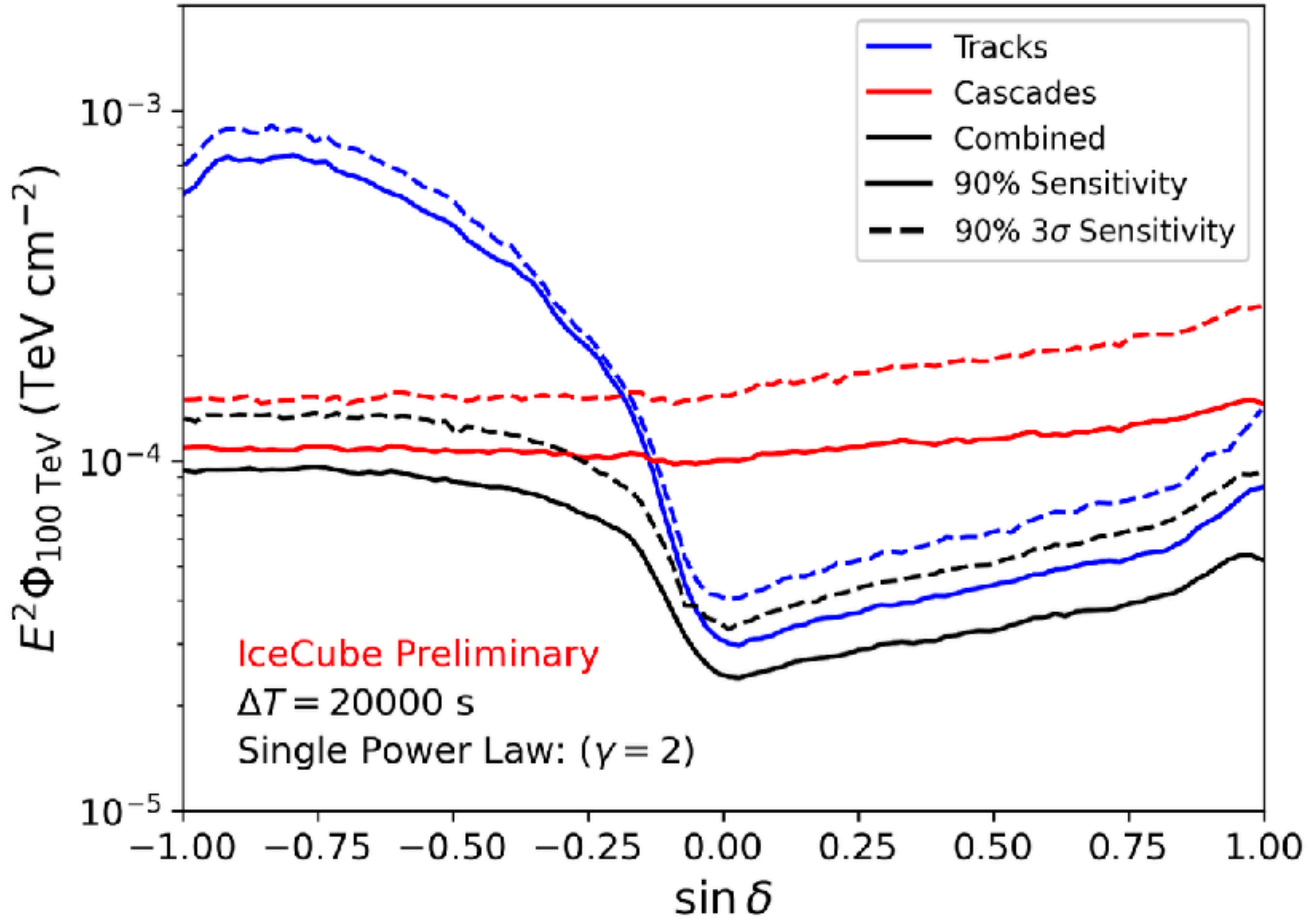
Adriani et al., PRX 15 (2025) 031016

Search for correlated ν and γ from UHE transient sources

Correlated emission of neutrinos and photons, arriving in close temporal and spatial coincidence could be expected from nearby transient sources of UHECRs

- 22 Auger hybrid EeV candidate photons, ~1⁰ directional uncertainty, used as spatial prior for source location
- IceCube multi-flavor neutrino sample (all-sky tracks + cascades matching Auger's FoV)





Transient sensitivity Method

- Tracks selection is most sensitive at the horizon
- Cascades selection is most sensitive in the Southern sky

The outcome

➡ **Detection :** Information on the transient sources, evidence for actual EeV photons

➡ **Non-detection :** Constrains on sources of UHE neutrinos and photons

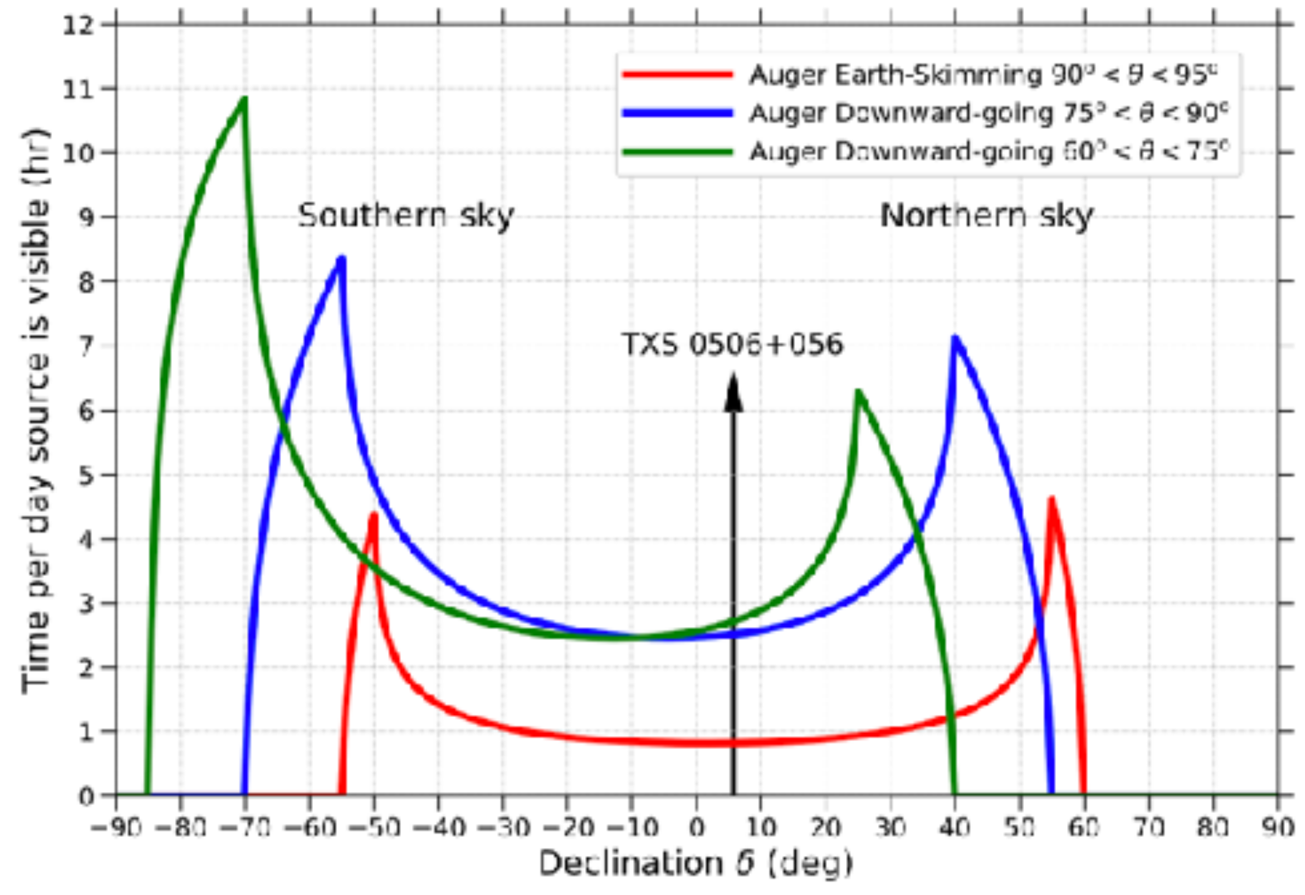
M.Nakos for Auger and IceCube, PoS(ICRC2025) 955

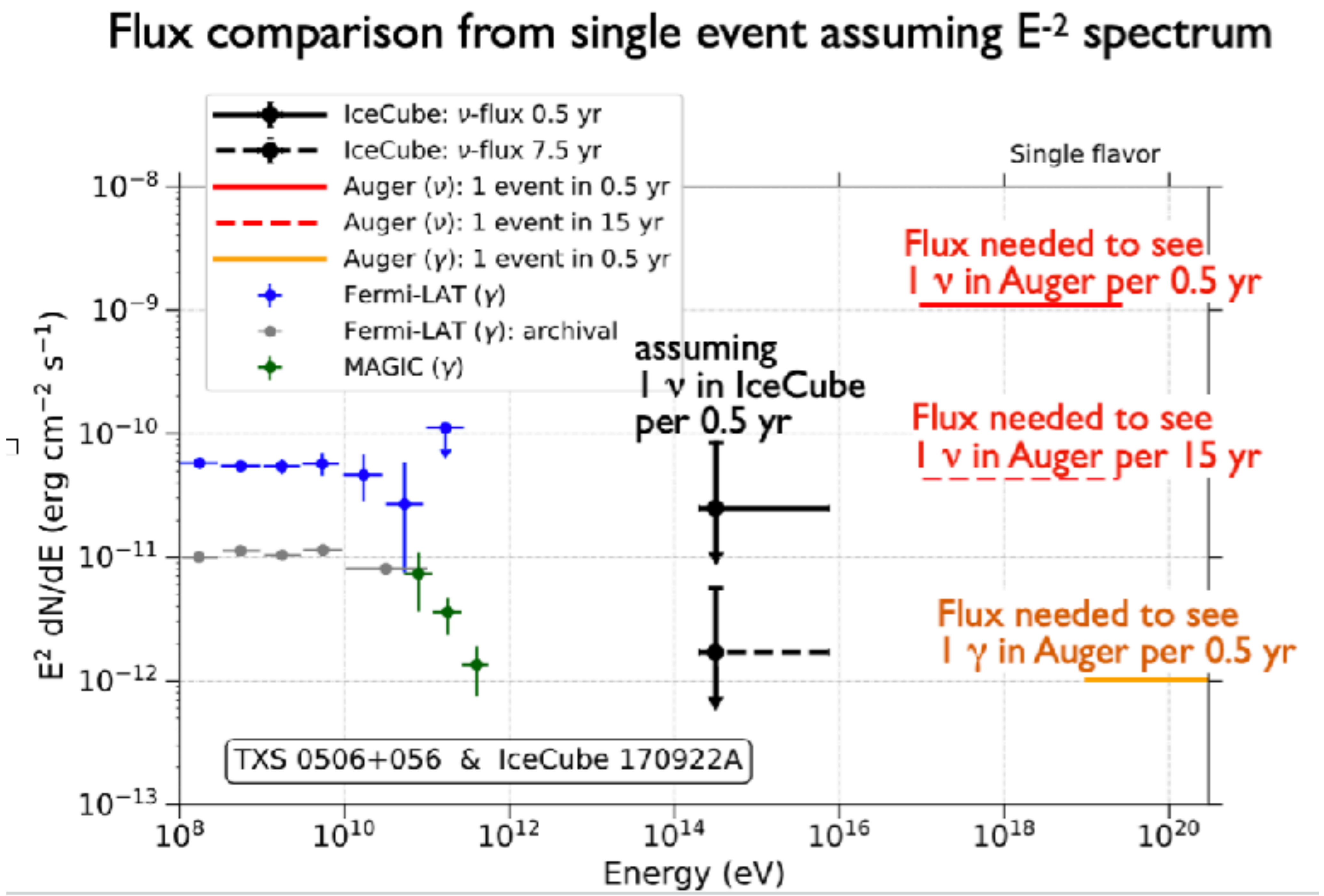
Neutrinos from TXS 0506+056

In Sept. 2017, IceCube observed a 290 TeV ν from the direction of TXS 0506+56

This source is ~21% T_{sid} in our FoV, but it was not at the time of neutrino detection

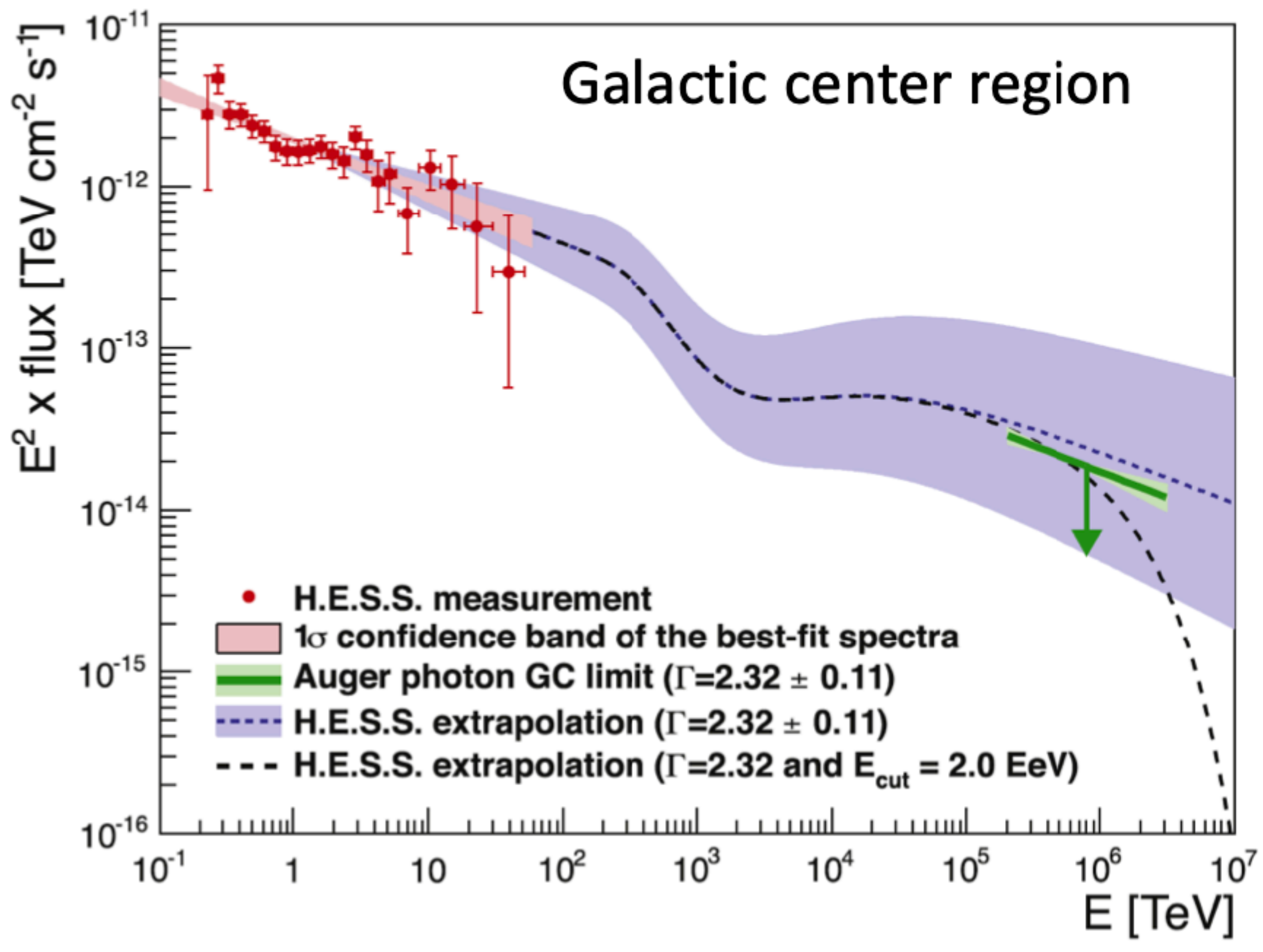
First ever limit to EeV neutrinos from an identified neutrino source



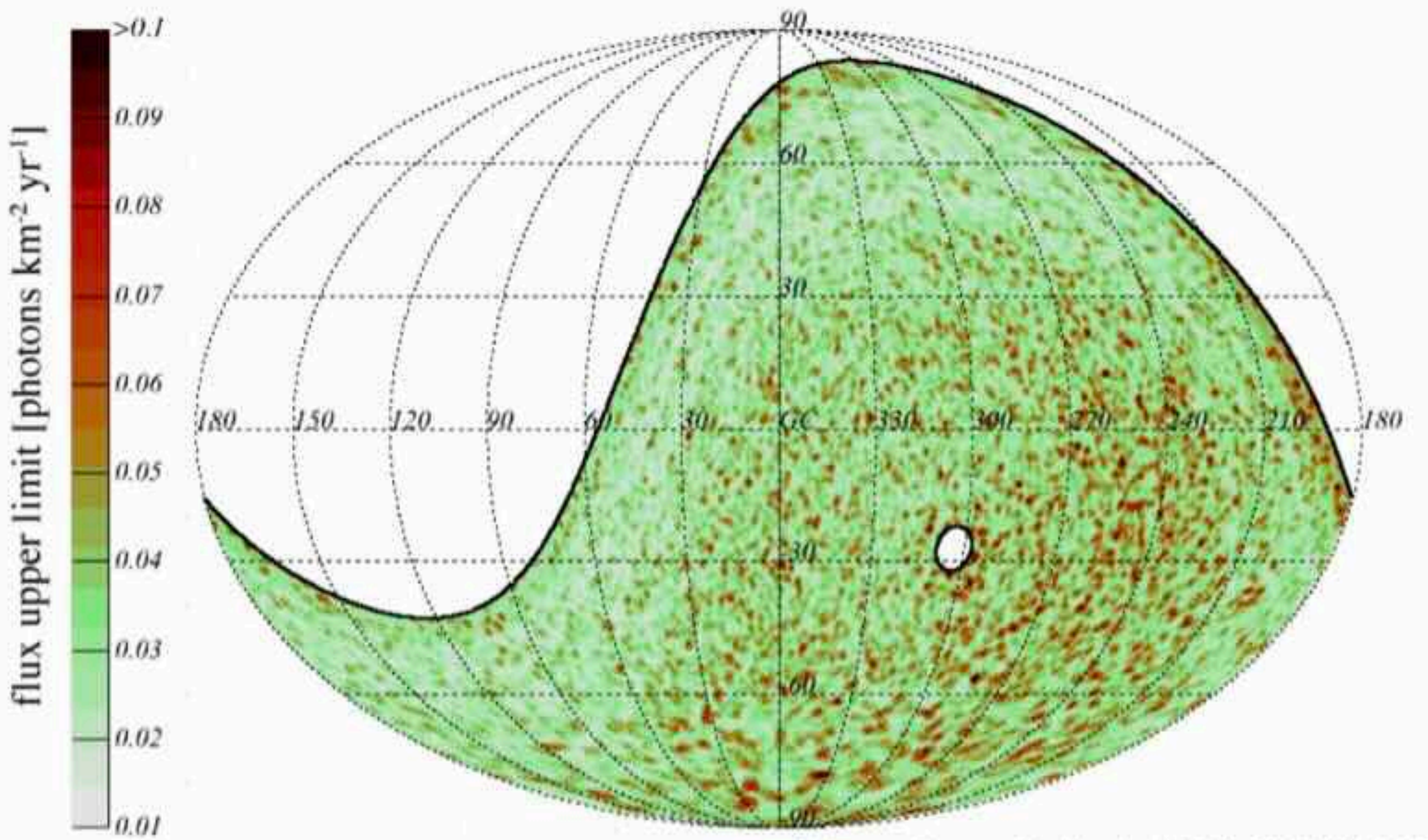


IceCube. Science 361, 146 (2018)
Auger Coll., ApJ 902 (2020) 105

Search for point-like sources of photons



Auger Coll., ApJ 837 (2017) L25



[Pierre Auger Coll., ApJ 789 (2014) 160]

Targeted search

- Stacked analysis focussing on 12 target sets (364 candidate sources in total)
- no compelling evidence for sources of EeV photons,
- constrains on the extrapolation of the HESS measurements of TeV fluxes from the Galactic center region to EeV energies
- upper limit on cut-off energy at ~ 2 EeV