ICRC 2023 SATELLITE WORKSHOP

August 7, 2023

Chiba University, Japan

Multi-messenger studies at the Pierre Auger Observatory

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Cosmic messengers at ultra-high energies (UHE)

✳ Messengers providing different information about the potential sources:

- Cosmic rays
- Gamma-rays
- Neutrinos
- Neutrons
- ✳ Gravitational waves

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Alerts crucial to study transient events

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They can be observed by the Pierre Auger Observatory

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✳ Gravitational waves

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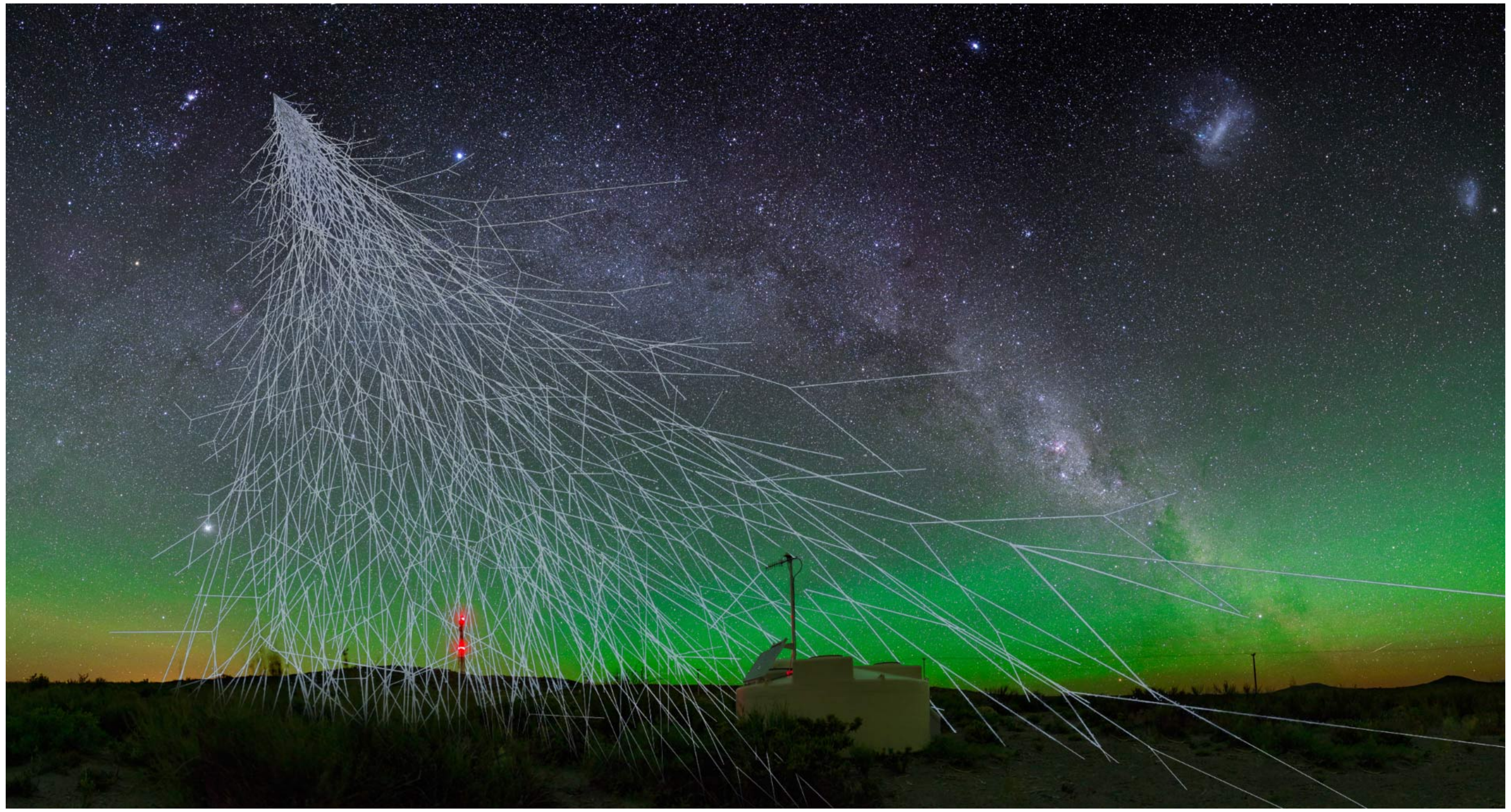
Neutral particles which point back to their origin

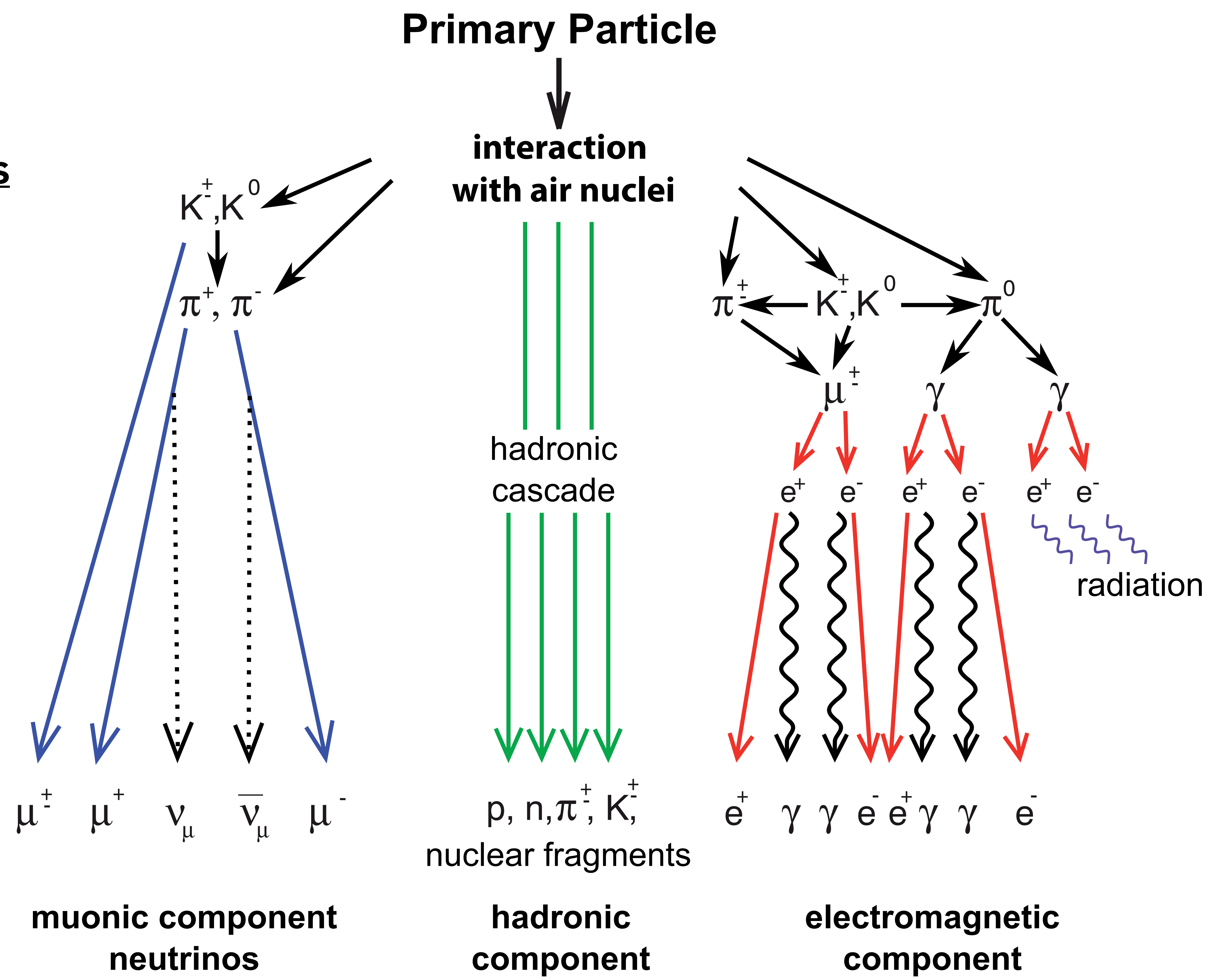
Alerts crucial to study transient events

Extensive air showers

Very low rate of particles at **ultra-high energies**→ detection through **extensive air showers** (EAS)

- UHE particles start interacting with atmospheric nuclei (N, O, Ar)
  → cascades of **ionised particles** + **electromagnetic radiation**
- Cascades observed by ground-based detectors, like the Pierre Auger Observatory
  → **the type of primary particle can be inferred from the air shower characteristics**



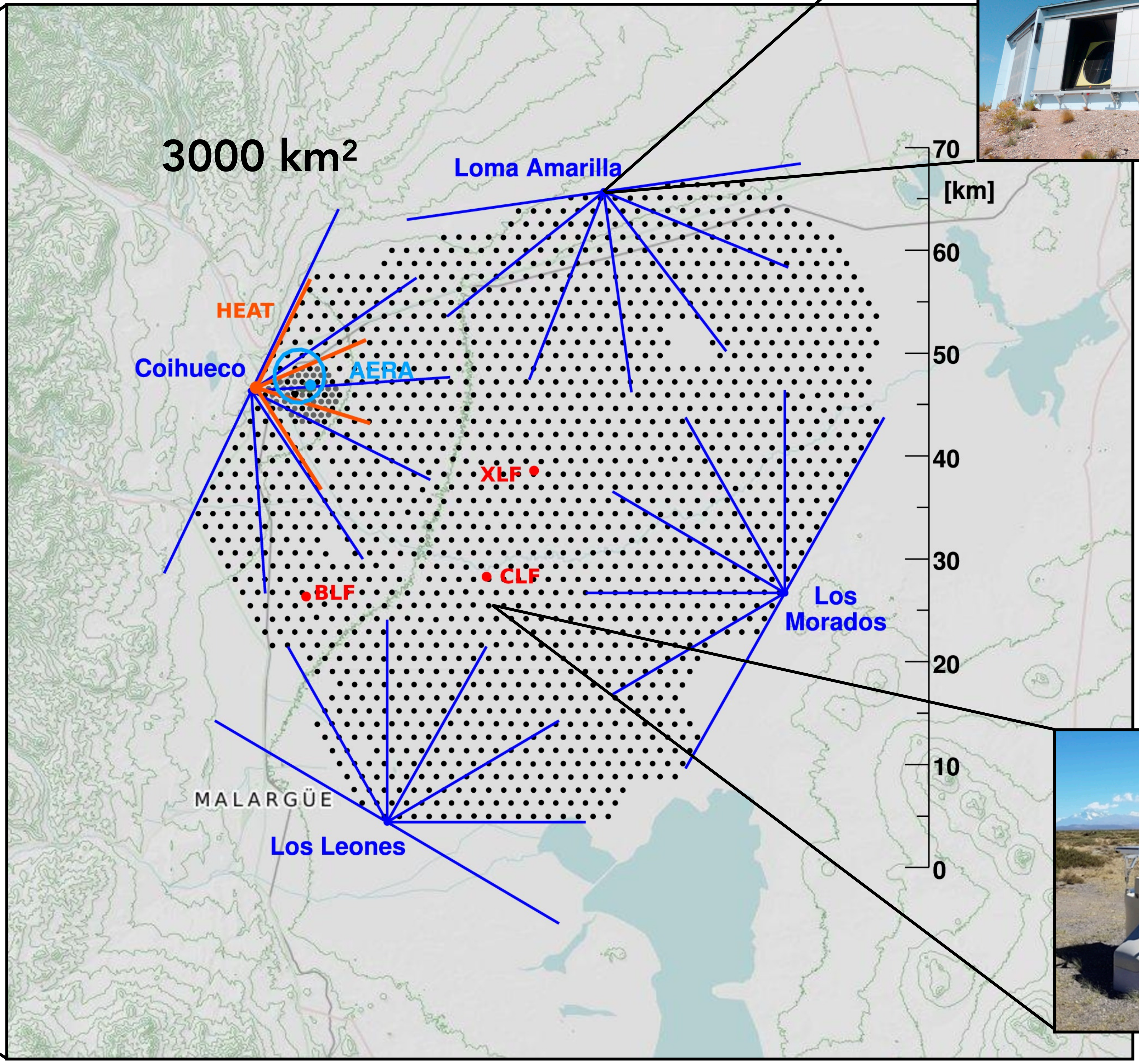


The Pierre Auger Observatory

Ground-based experiment, hybrid detection technique (Surface Detector (SD) + Fluorescence Detector (FD))
Located in Argentina, close to Malargüe (~1400 m a.s.l.)

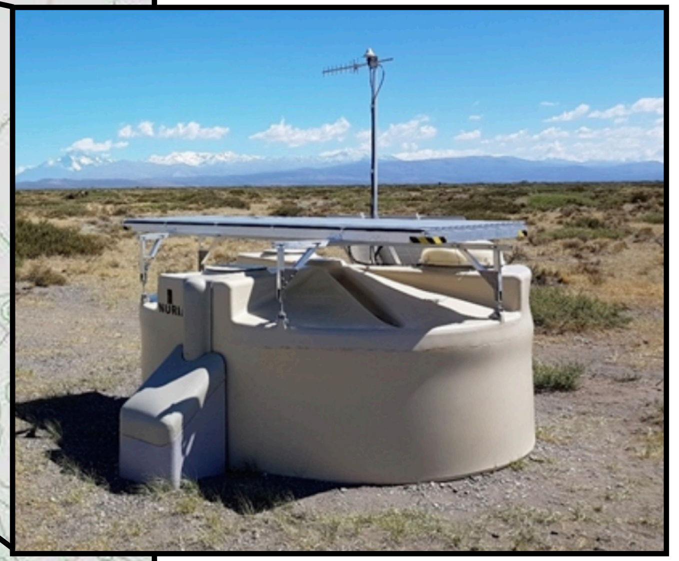
Largest observatory in the world for the detection of ultra-high-energy particles

~450 members from ~90 institutions in 17 countries



FD

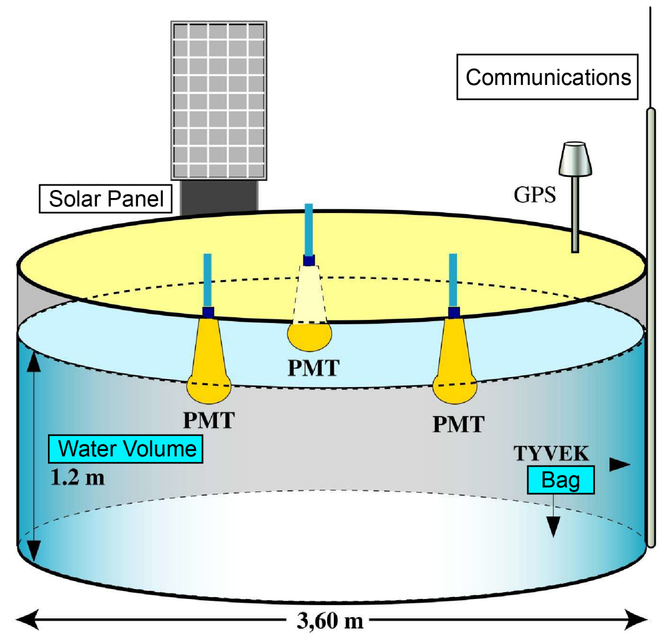
SD



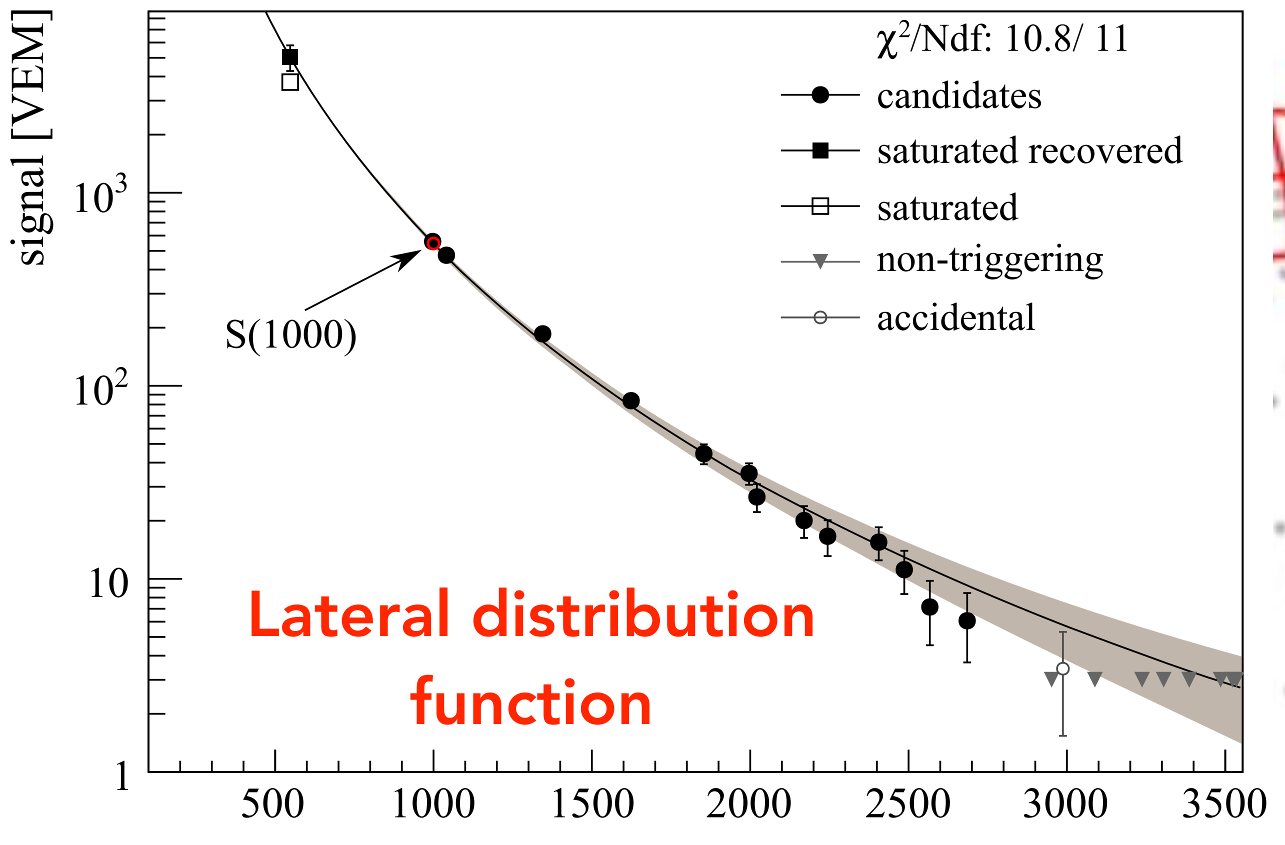
The Pierre Auger Observatory

Surface Detector (SD)

- 1660 water-Cherenkov tanks covering a ~3000 km^2 area, with a spacing of 1.5 km (and a denser smaller array for lower energies)
- 3 PMTs collecting the light produced within the tank



- Sampling the shower particles reaching the ground
- **Duty cycle: ~100%**
- Ongoing detector upgrade (AugerPrime)



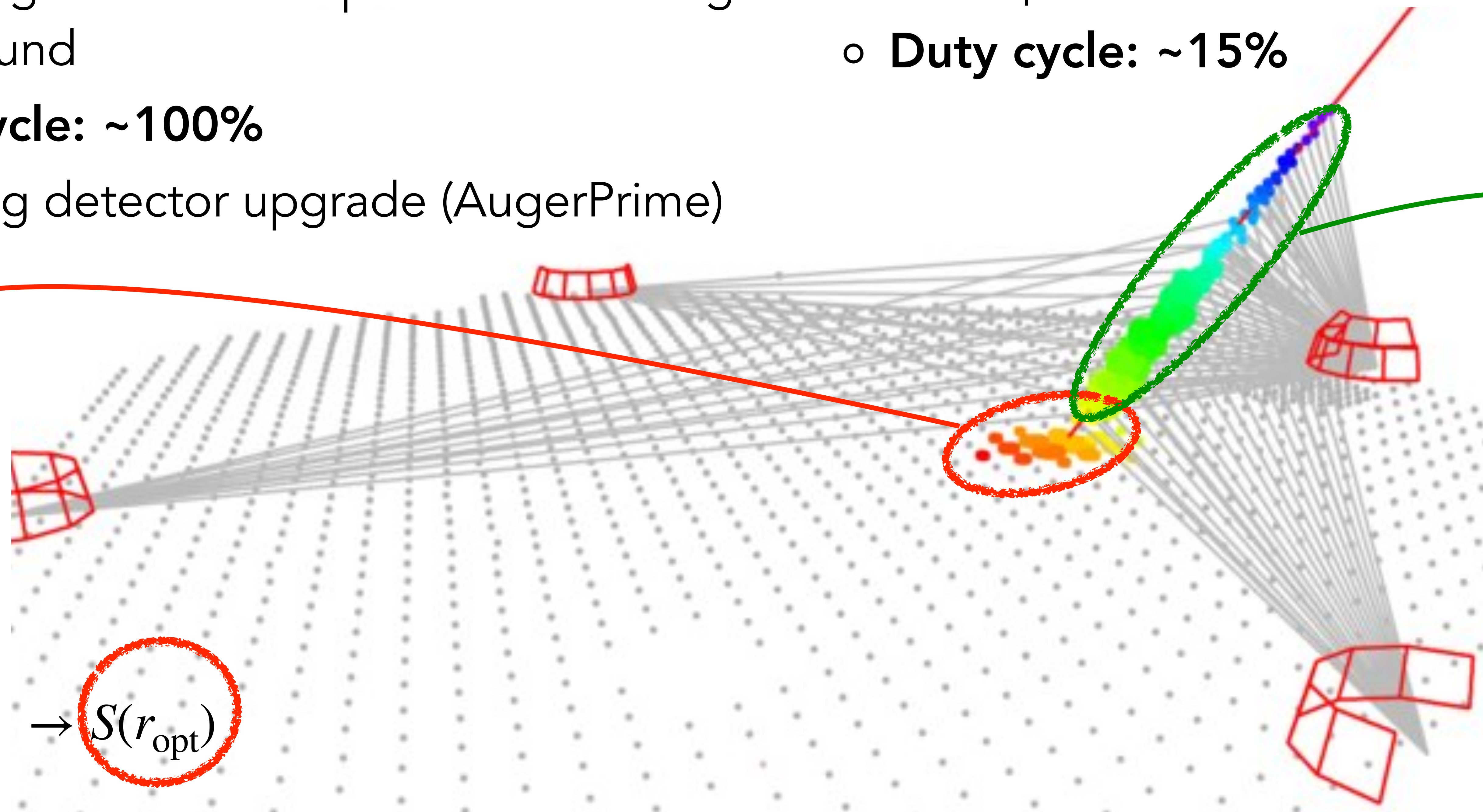
$S(r) \propto r^{\beta}(r + r_M)^{\beta+\gamma}$

$\rightarrow S(r_{opt})$

Signal at the optimal distance

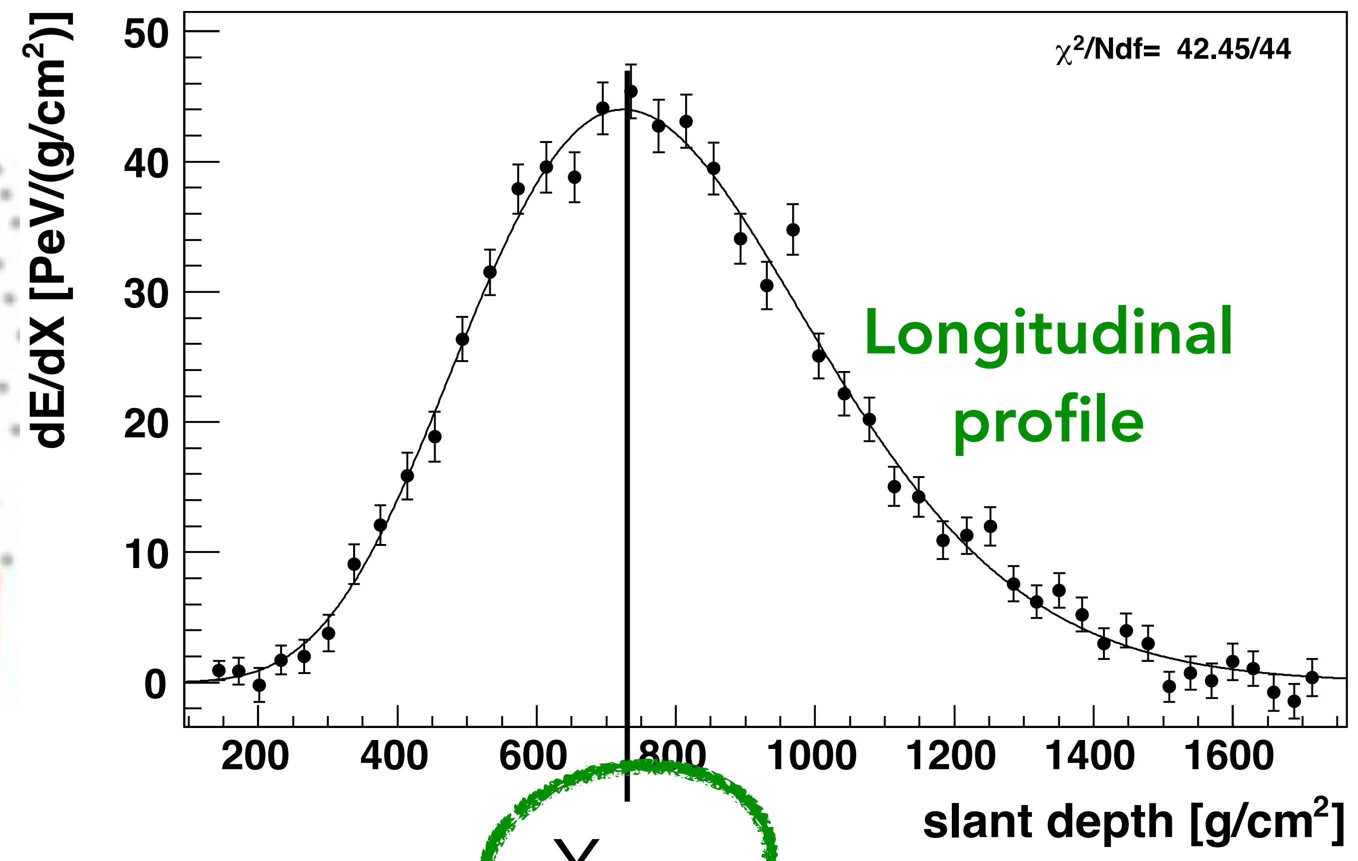
Fluorescence Detector (FD)

- 24 telescopes in 4 sites overlooking the SD (and 3 additional ones for lower energies)
- Collecting the nitrogen fluorescence light produced in the atmosphere
- **Duty cycle: ~15%**



$E_{cal} = \int \frac{dE}{dX} dX$

Calorimetric energy



X_{max}

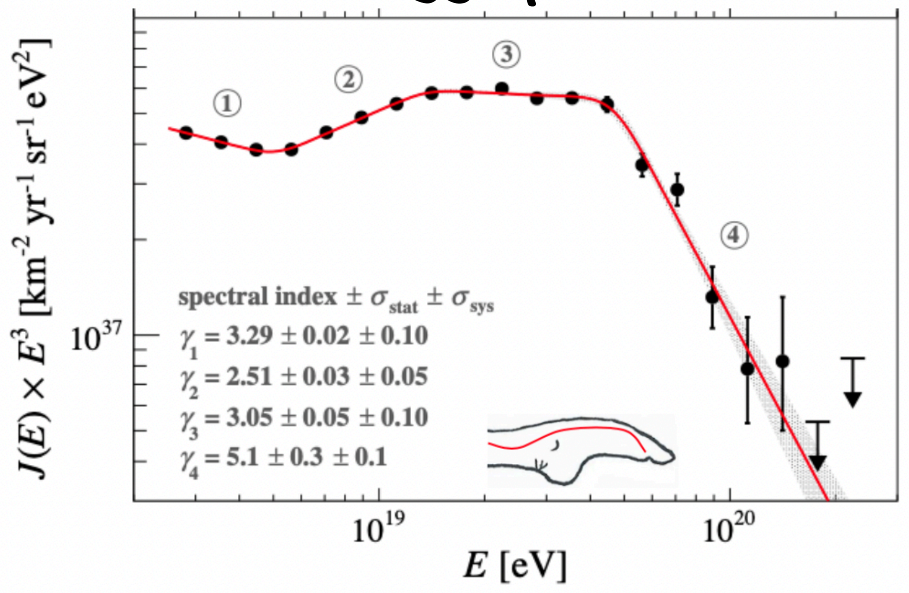
Depth of shower maximum

Hybrid events = observed by both detectors

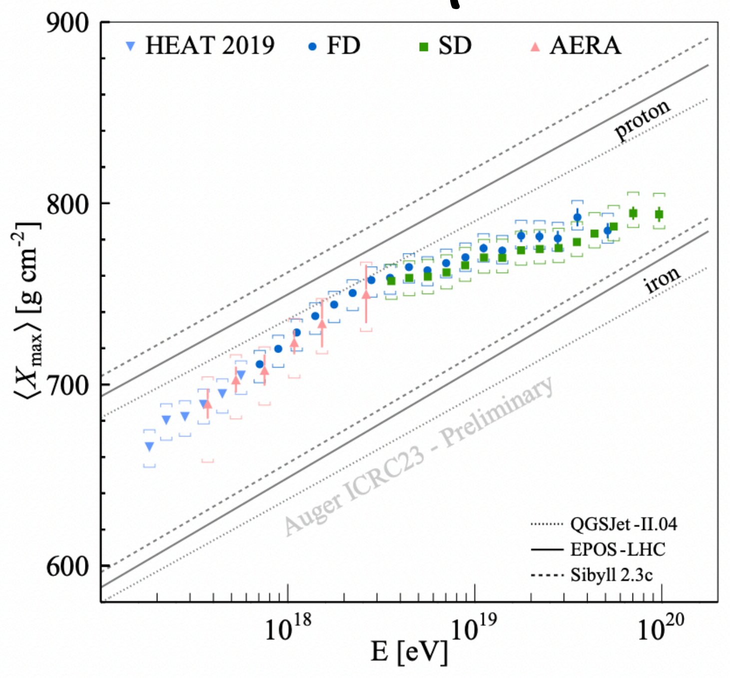
The Pierre Auger Observatory as a multi-messenger detector

COSMIC RAY MEASUREMENTS

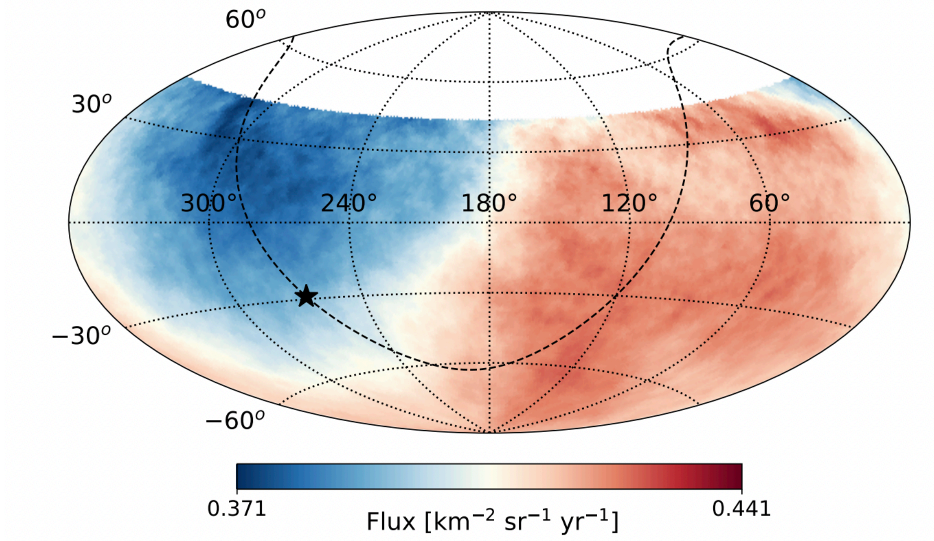
Energy spectrum

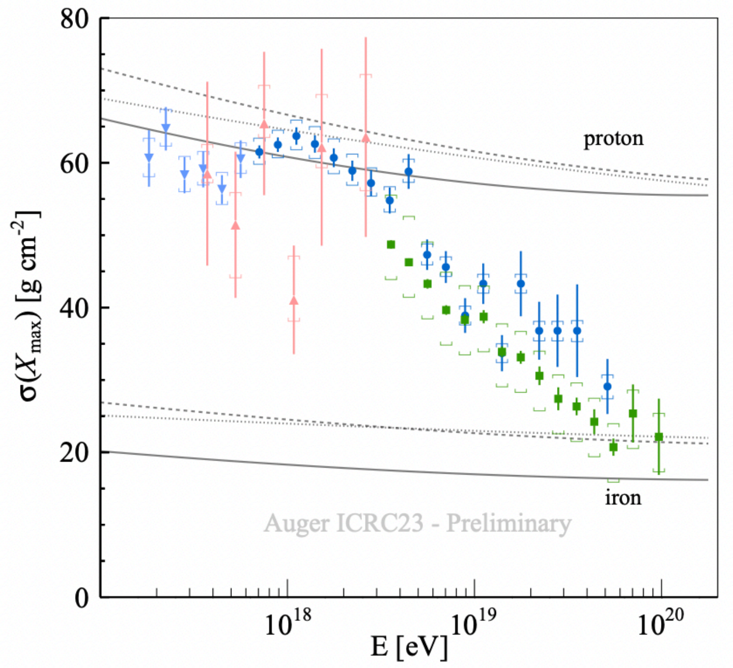


Mass composition



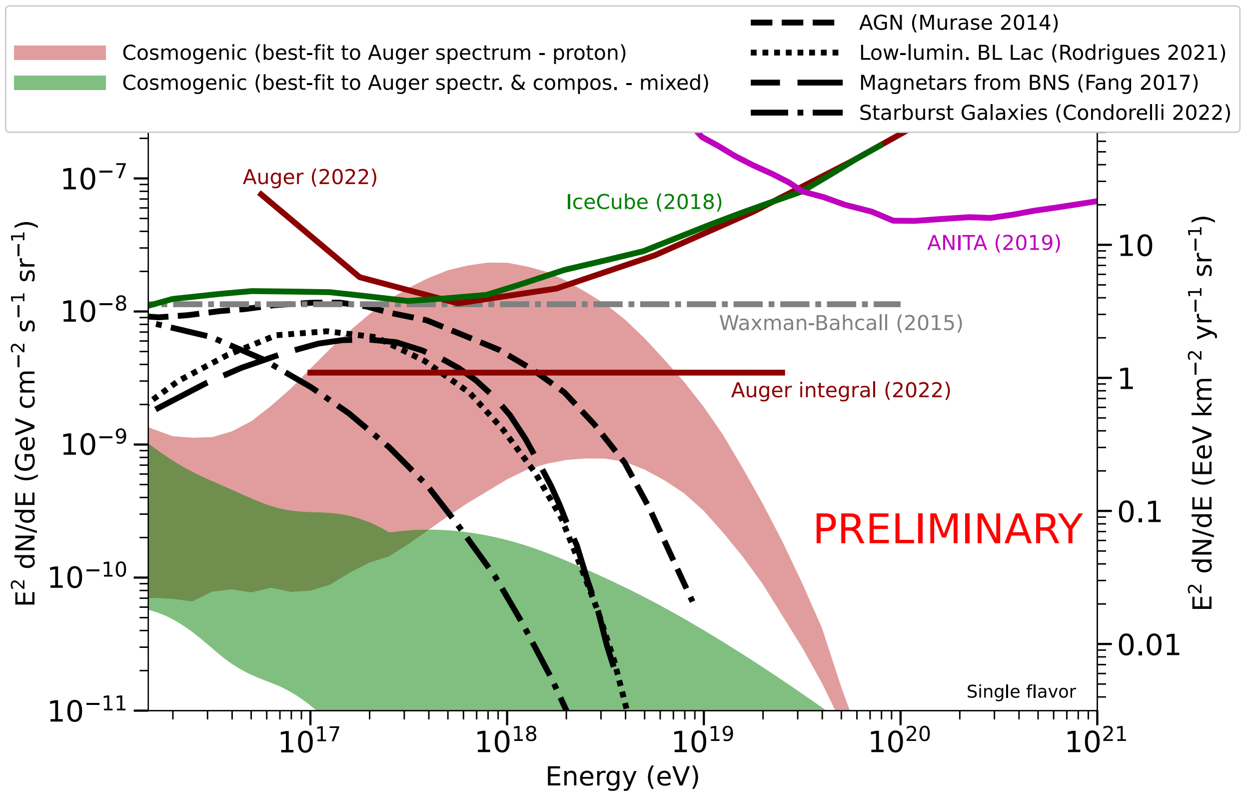
Arrival directions



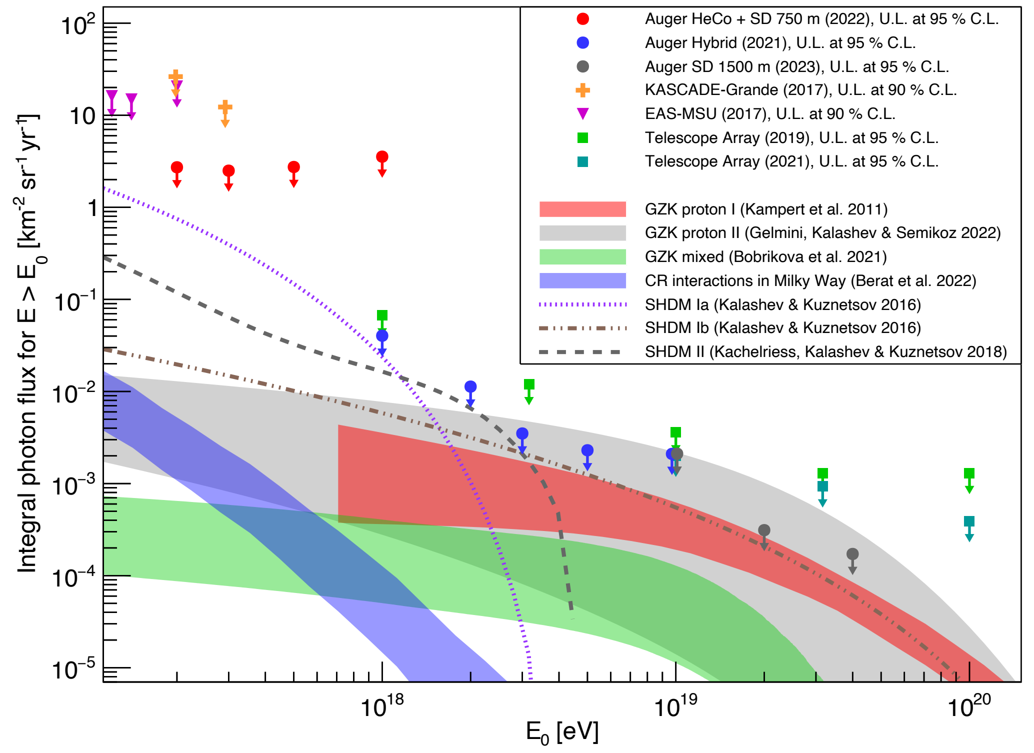


SEARCH FOR NEUTRINOS AND PHOTONS

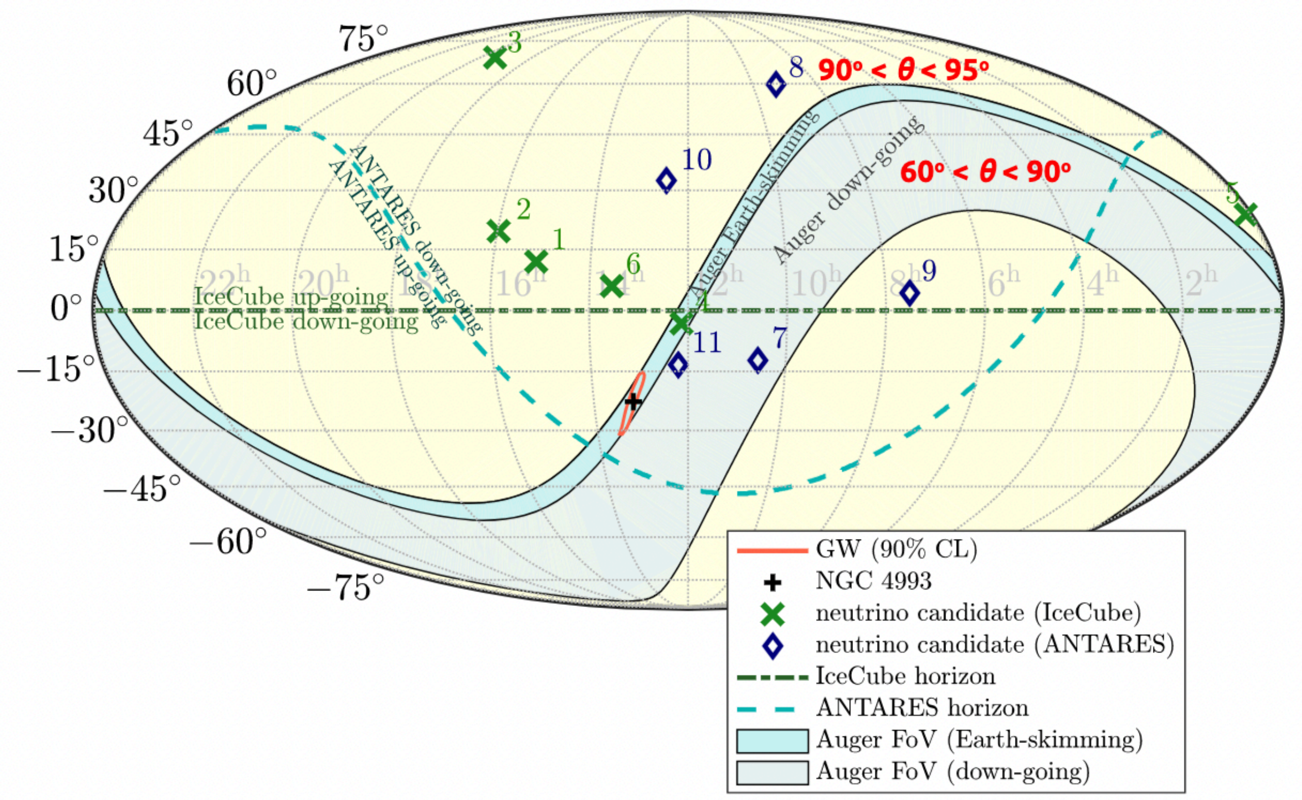
Diffuse neutrino flux



Diffuse photon flux



Follow-up of gravitational wave events



- Phys. Rev. Lett. 125, 121106
- PoS(ICRC2023)365
- PoS(ICRC2023)1488
- PoS(ICRC2023)252

COSMIC RAYS

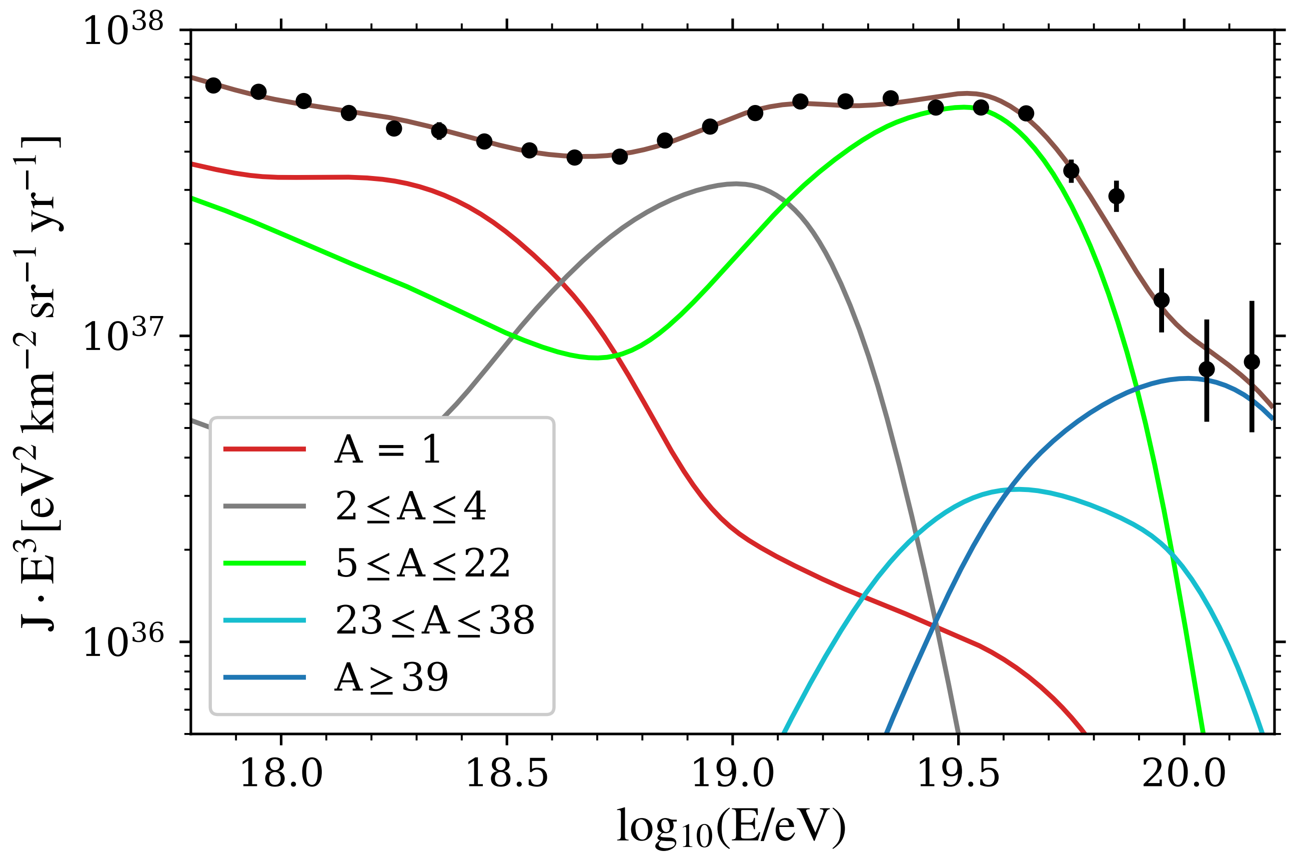
NEUTRINOS

PHOTONS

NEUTRONS

Cosmic rays as multi-messenger probes

- Ultra-high-energy cosmic rays are the main target of the Pierre Auger Observatory
- **Combined fit of the energy spectrum and mass composition** measurements above $10^{17.8}$ eV:
  - Identical and uniformly distributed extragalactic sources
  - Two populations are necessary to describe the ankle feature
  - Rigidity-dependent cutoffs
  - Propagation effects on the fluxes are considered

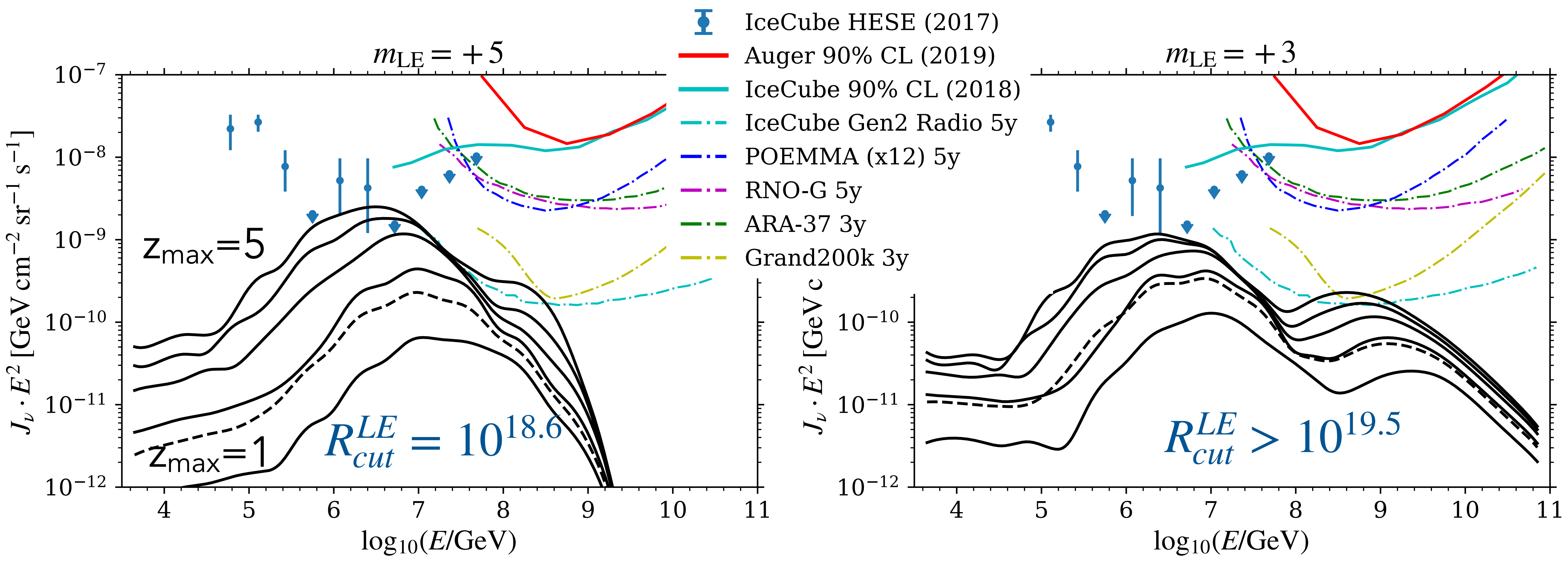


Predicted fluxes at Earth

Cosmogenic neutrinos (and gamma rays) are produced during the propagation of UHECRs

It is possible to compute the ν fluxes associated to the best fit results

- Mixed mass composition + low rigidity cutoff at high-energy → low ν fluxes
- **For strong source evolutions expected sensitivities of future detectors are reached**



• JCAP05(2023)024

COSMIC RAYS

NEUTRINOS

PHOTONS

NEUTRONS

Neutrino identification at the Pierre Auger Observatory

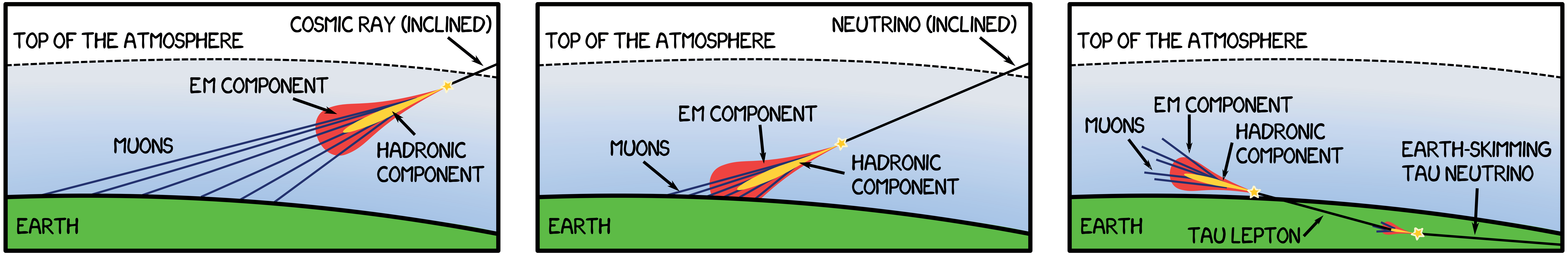
- ✳ The Pierre Auger Observatory is sensitive also to **UHE neutrinos**
- ✳ They are probes to specific astrophysical scenarios and can be used to study transient and steady sources
- ✳ **They rarely interact with matter → can travel very long distances**

How to distinguish neutrino-induced air showers? (from the background of hadron-induced ones)

1. **Neutrinos may interact <u>very deep in atmosphere</u>** → **even very inclined shower are still "young" at the ground level** (electromagnetic component still present)

2. **ν_τ may interact in the Earth crust producing a τ** → the lepton decays in the atmosphere and **an upward-going shower can be observed**

CR | **Downward-going neutrinos** | **Upward-going neutrinos**



[M. Niechciol]

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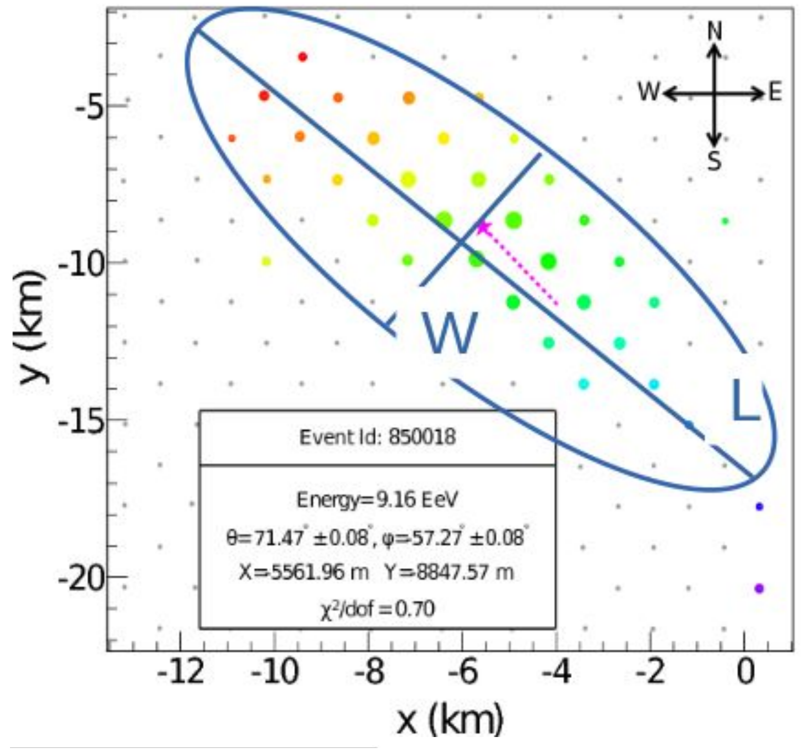
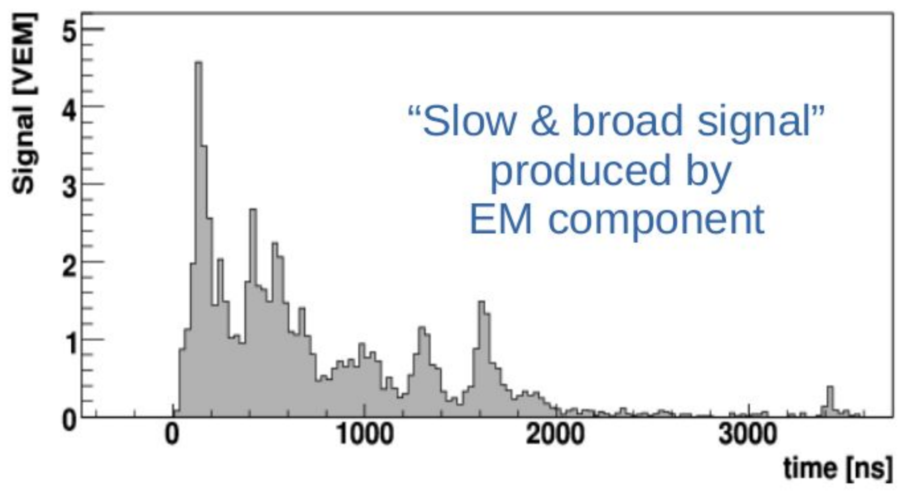
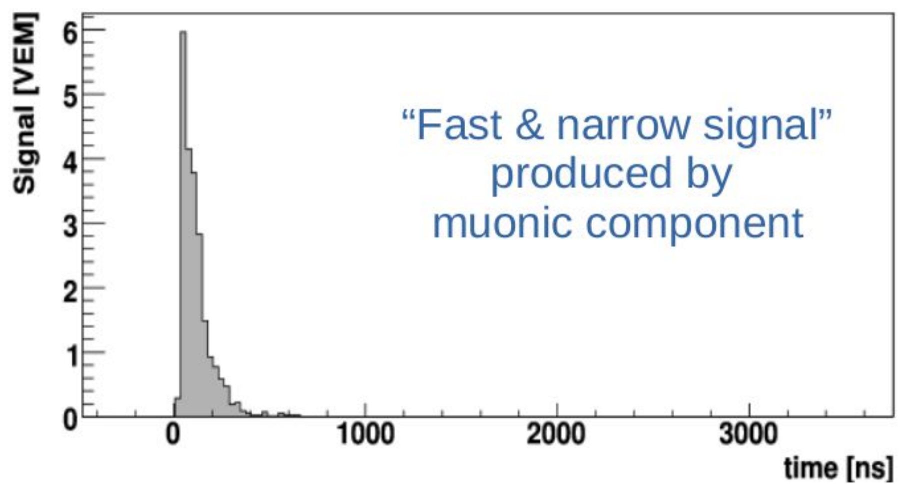
Search for **inclined showers** ($\theta > 60^o$) with a **large electromagnetic component** at the ground (SD data are used)

footprint on the SD stations (large L/W ratio)



Broader signal in each SD station (large Area-over-Peak ratio)





The neutrino diffuse flux

Downward-going showers

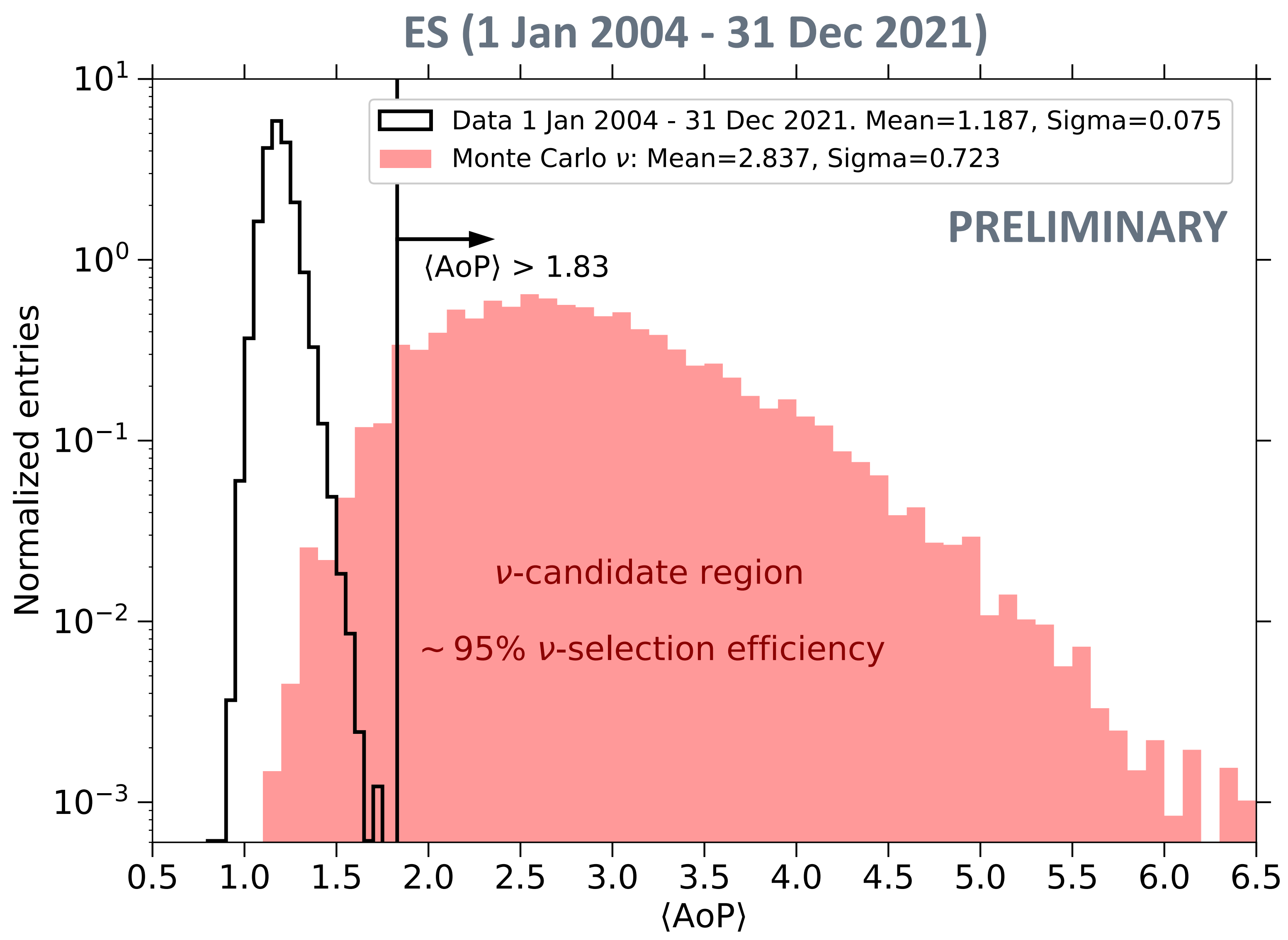
- ✳ $60^o < \theta < 75^o$ (high angle) → Events divided in 5 subsample basing on θ_{rec}
- ✳ $75^o < \theta < 90^o$ (low angle) → Events divided in 3 subsample basing on N_{stat}

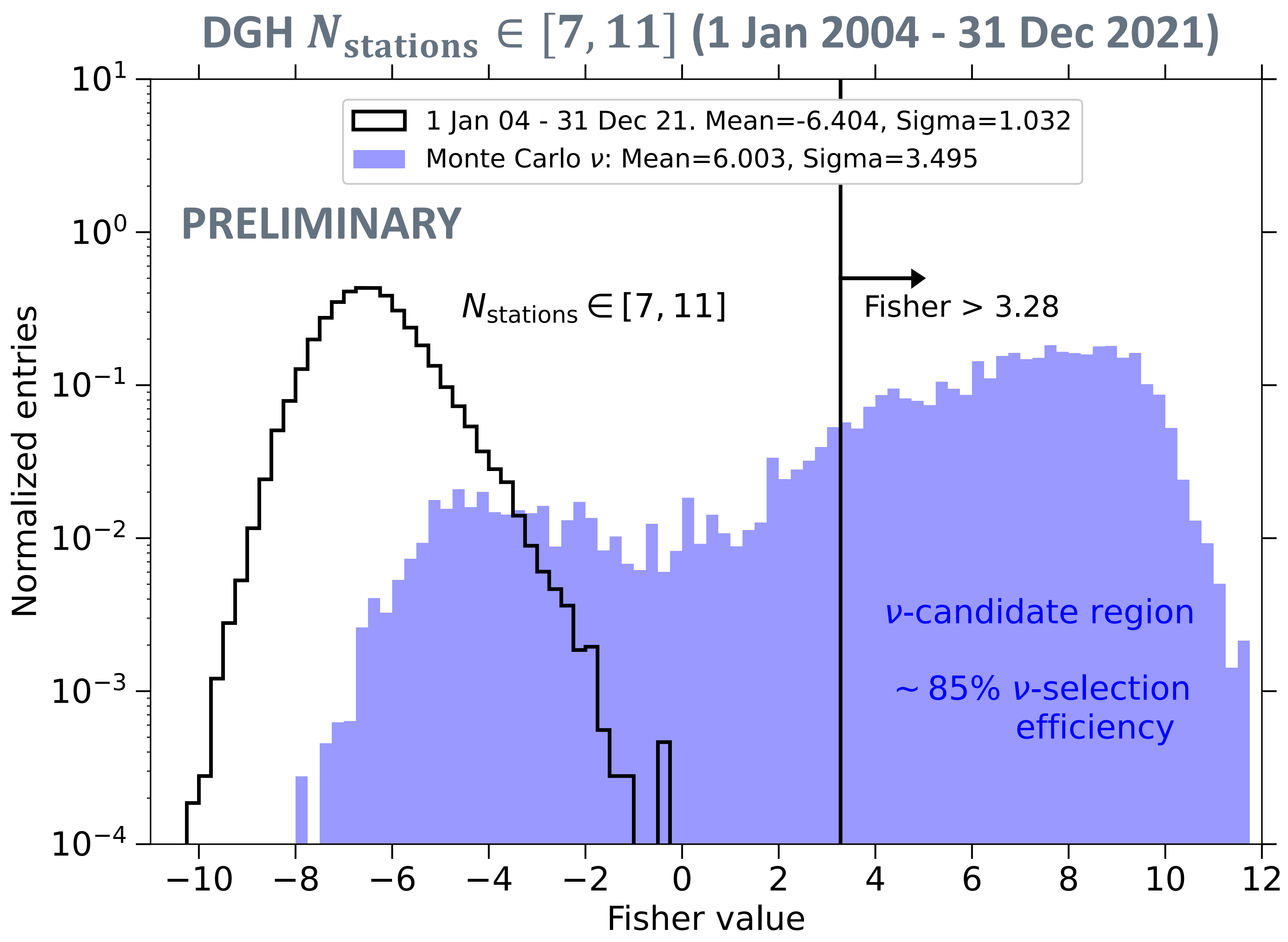
→ multivariate analysis: different observables in each subsample

→ Different **Fisher discrimination variables**

Earth-skimming showers

- ✳ $90^o < \theta < 95^o$ → Discriminating observable: <AoP> over all the triggered stations in the event



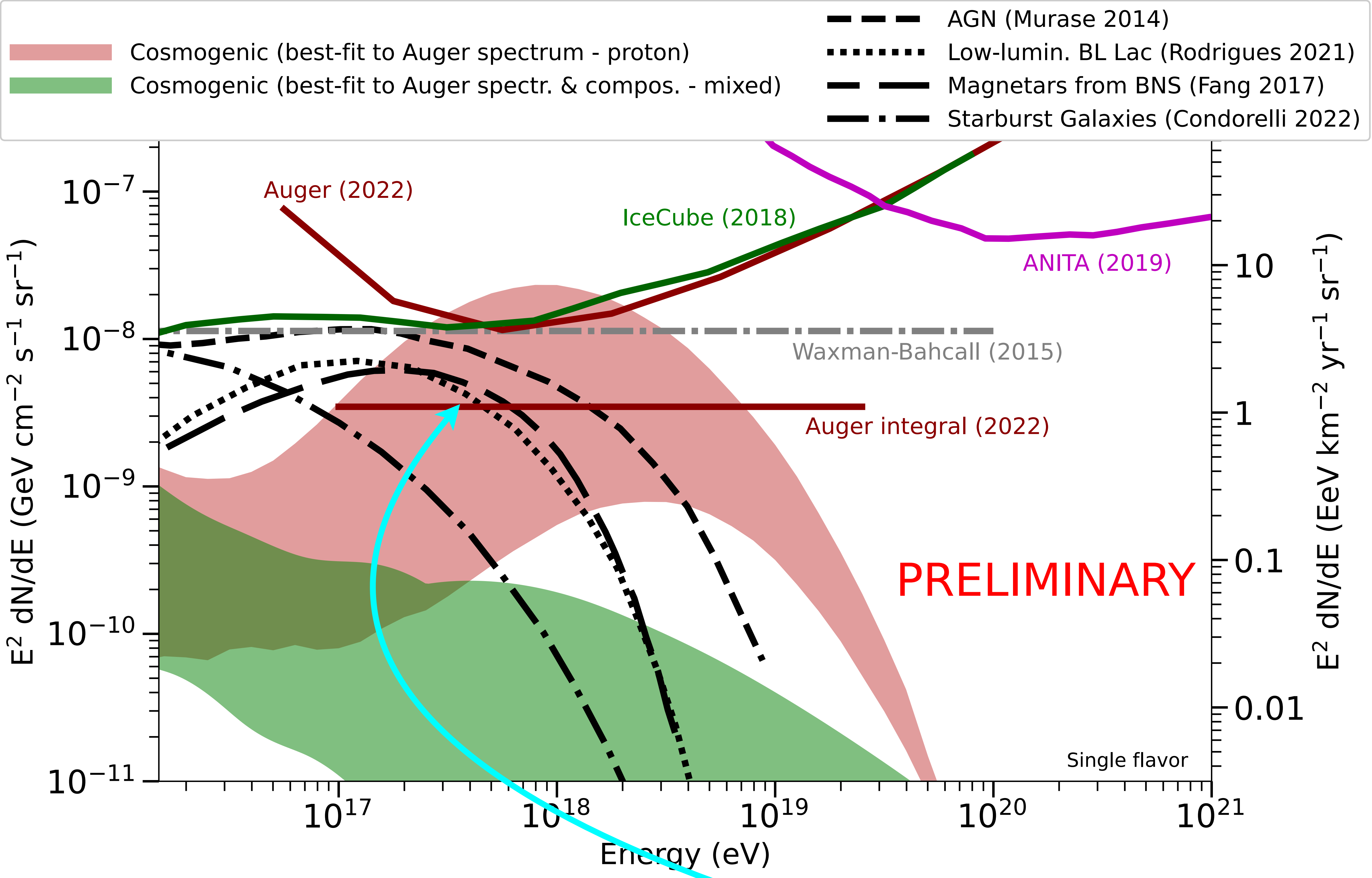


- Analysis recently updated with data until 31 December 2021
- Two search channels shown as an example
- **No candidate events have been identified in any of the search channels**

- JCAP 10 (2019) 022
- PoS(ICRC2023)1488

The neutrino diffuse flux

No neutrino candidate has been identified so far but **upper limits have been set above 10^{17} eV**



Assuming a differential flux $\phi = k \cdot E_\nu^{-2}$, the upper limit to k at 90% C.L. is given by:

$$k_{90} = \frac{2.39}{\int_{E_\nu} E_\nu^{-2}\, \mathcal{E}_{\text{tot}}(E_\nu)\, dE_\nu}$$

Feldman-Cousins factor in absence of background

Exposure

The integrated upper limit between 10^{17} eV and 2.5 x 10^{19} eV:

$$k_{90} < 3.5 \times 10^{-9}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

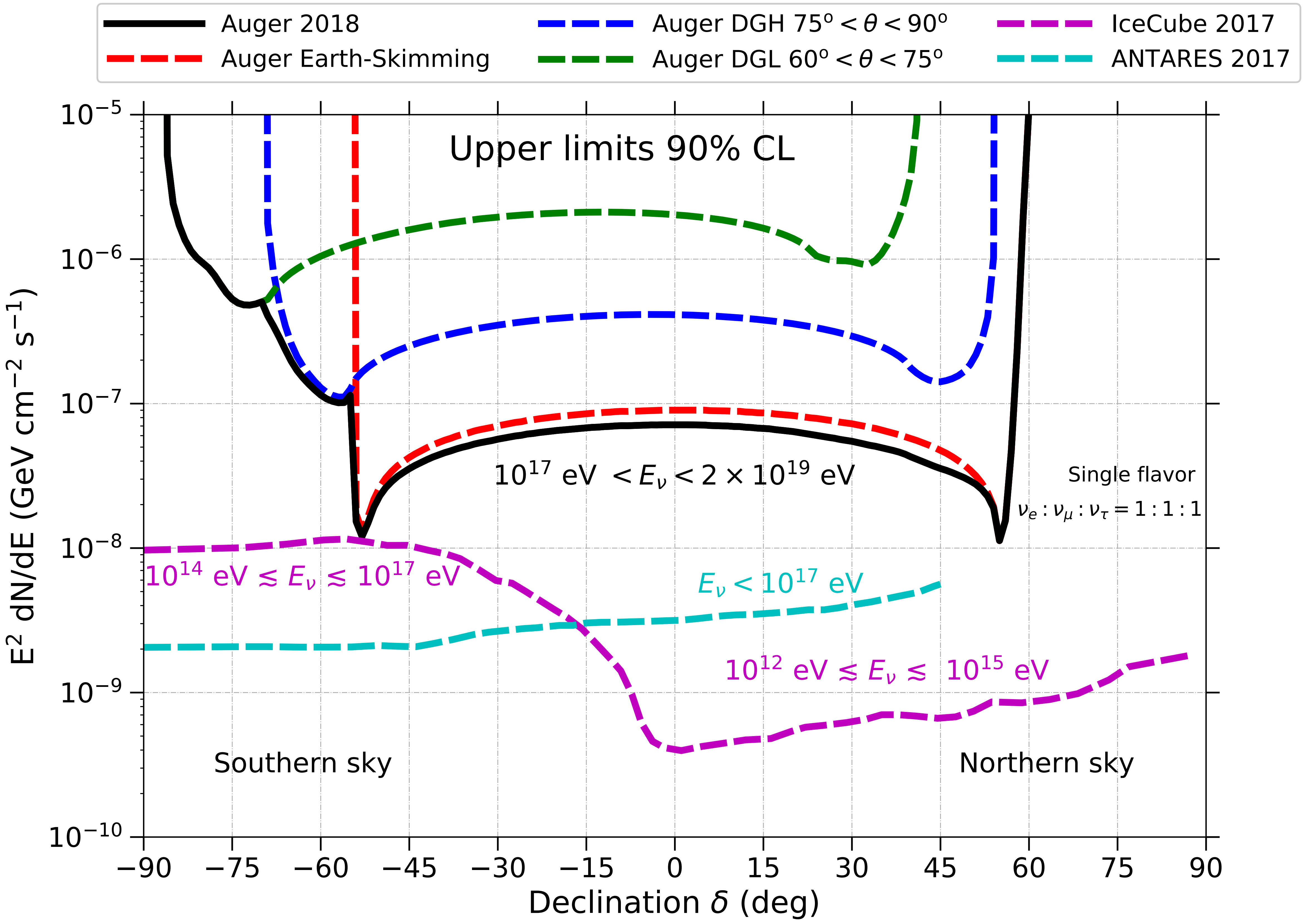
- Auger sets limits comparable with the IceCube ones
- Maximum sensitivity at ~EeV (peaks of most cosmogenic models)
- Several models for the production of cosmogenic and astrophysical neutrinos are already constrained

Cosmogenic models involving a pure-proton composition and a strong evolution of the sources with redshift are already excluded

Neutrinos from point-like sources

Neutrinos

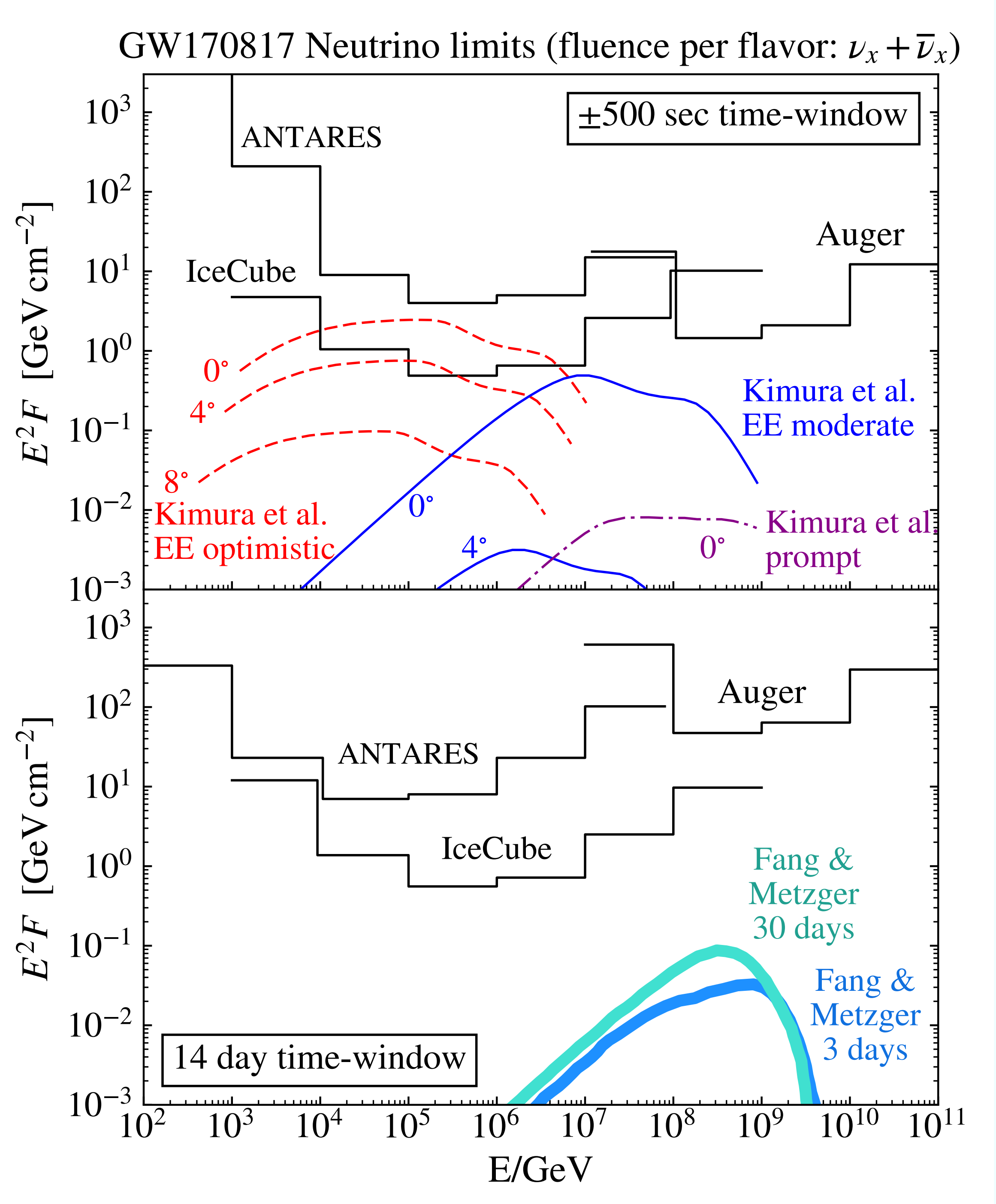
- ✳ The same sets of inclined events as in the diffuse flux search are considered
- ✳ At each instant, only neutrinos from a specific region of the sky corresponding to $60^o < \theta < 95^o$ can be detected.
- ✳ Same exposure calculation as in the analysis for diffuse neutrinos except for the solid angle integration over the sky
- ✳ **A blind search is performed and no neutrino candidate is observed**
- **Assuming a differential flux $\phi = k_{PS} \cdot E_\nu^{-2}$, the upper limit to $k_{PS}(\delta)$ at 90% C.L. according to Feldman-Cousins is computed**



Follow-up of gravitational waves

Neutrinos

✳ **Routine follow-up of gravitational-wave (GW) events**:
→ search for neutrinos in the ES and DG channels in a chosen time window around the event
→ no neutrinos found so far
→ limits complementary to those of IceCube and ANTARES



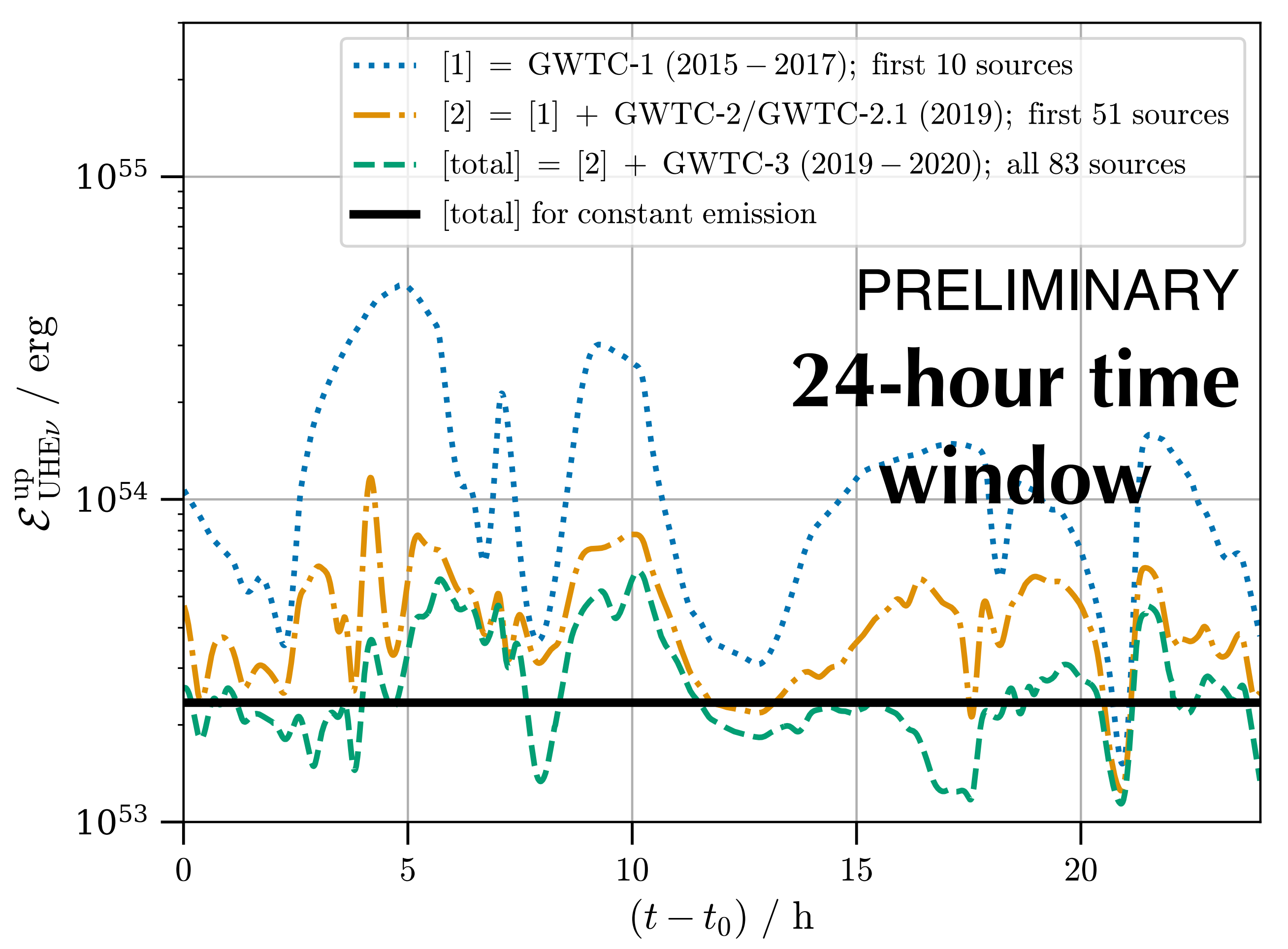
➡ GW170817 (binary neutron star merger) as an example
➡ In the FoV of the ES channel at the time of the event

✳ **Stacking analysis of 83 binary black holes (BBH) mergers** detected by LIGO and Virgo via gravitational waves

✳ Two hypothetical emission periods:
- Δ=24 h after the GW event
- Δ=60 d after the GW event

✳ $\propto E^{-2}$ spectrum and constant emission are assumed

✳ No neutrinos have been found → upper limits are set on the total energy emitted in UHE neutrino



➡ Limit per source at 90 % C.L.: ~2.3 × 10^{53} erg

- ApJL 850 (2017) L35
- PoS(ICRC2021)968
- PoS(ICRC2023)1488
- ApJ 952 (2023) 91

COSMIC RAYS

NEUTRINOS

PHOTONS

NEUTRONS

Photon identification at the Pierre Auger Observatory

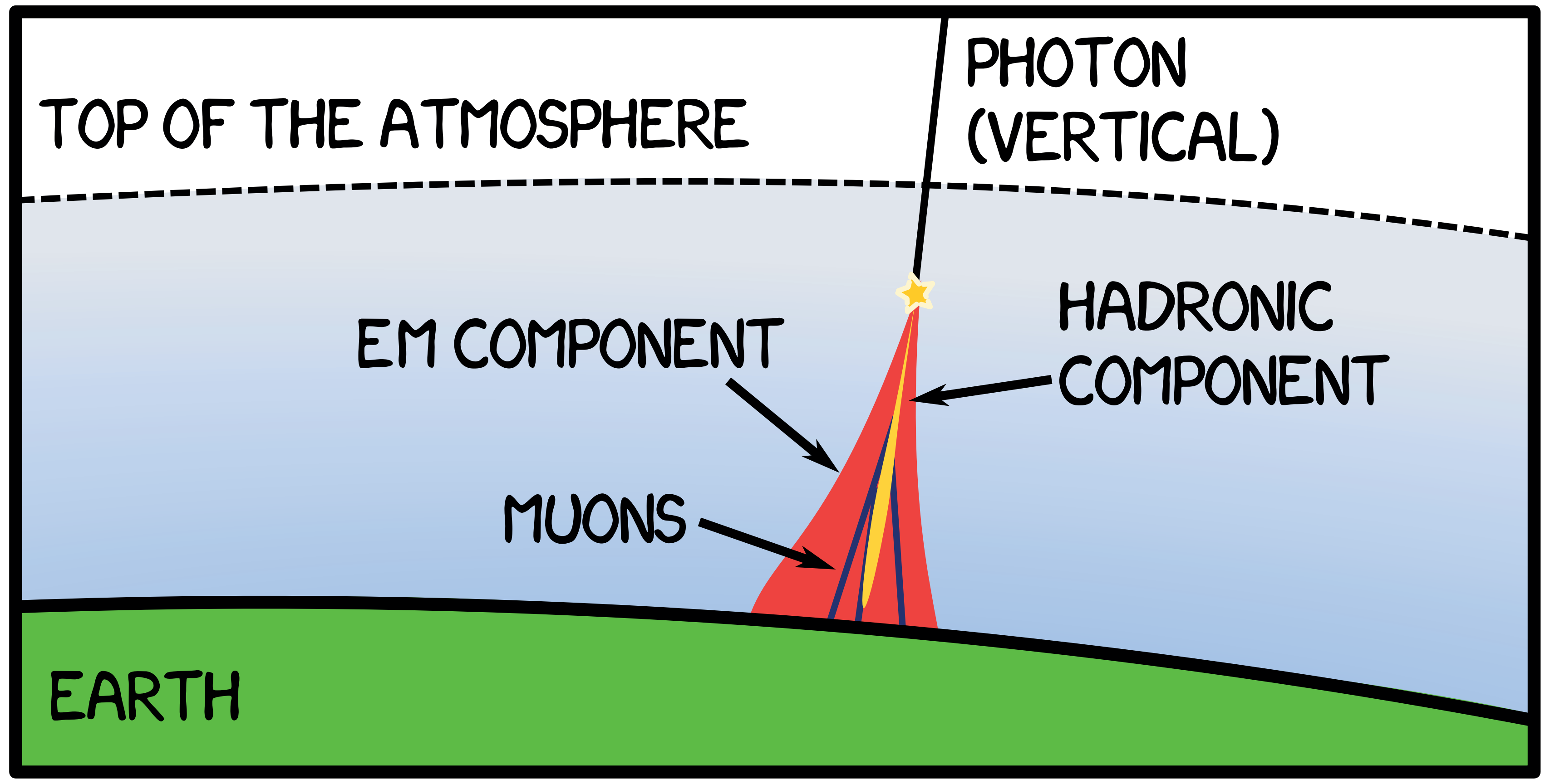
Photons

- ✳ The Pierre Auger Observatory is sensitive also to **UHE photons**
- ✳ They can be produced either at the sources or during the propagation of UHE cosmic rays
  → **constrain specific astrophysical scenarios** (e.g. GZK effect, top-down/bottom-up models for UHECRs production)
- ✳ Neutral particles → as UHE neutrinos, they are used to **study steady and transient sources**

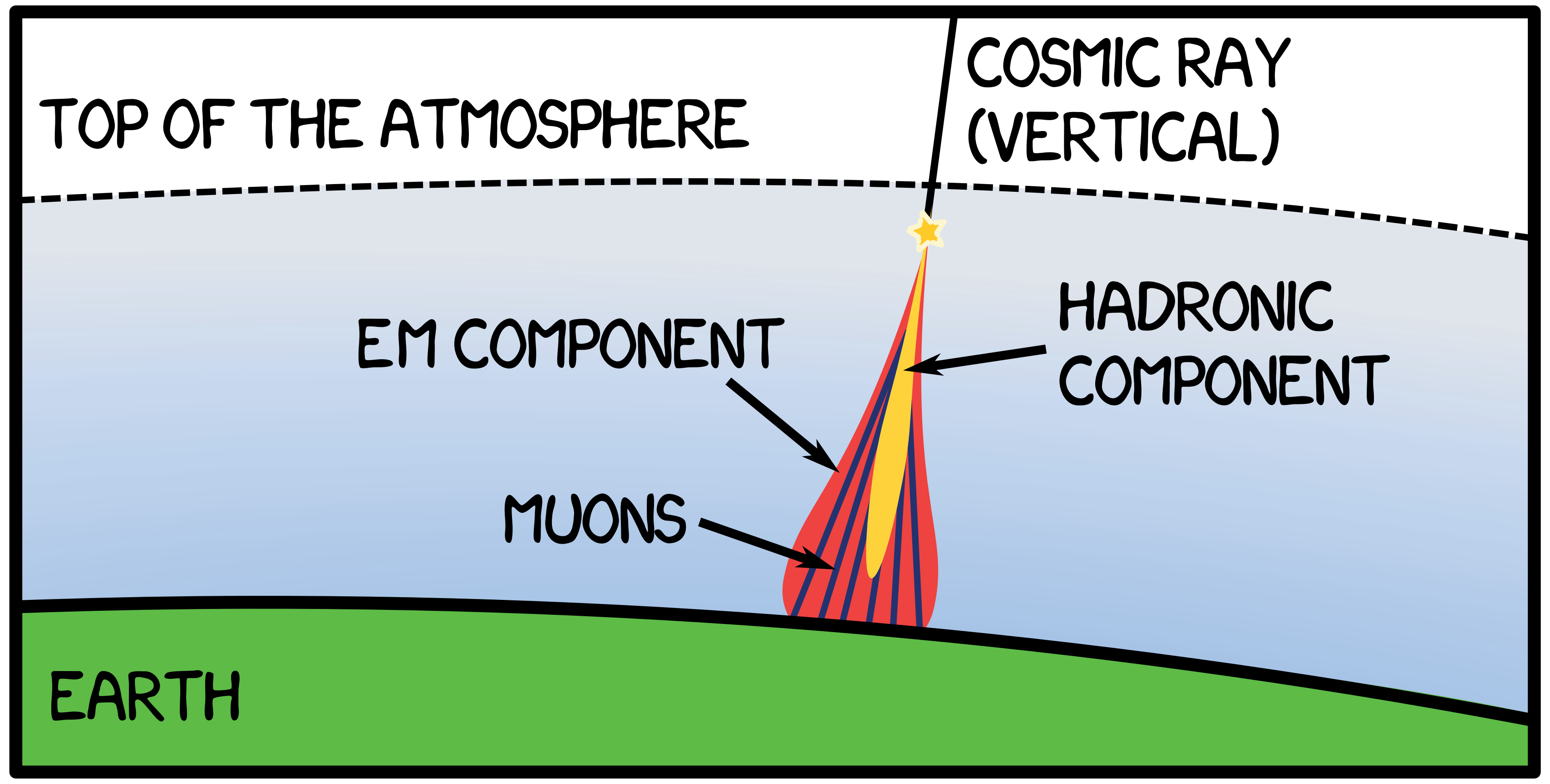
How to distinguish photon-induced air showers? (from the background of hadron-induced ones)

A photon-initiated shower is dominated by EM interaction
→ **deeper depth of shower maximum X_{max}**
→ **less muons at the ground level**

Photon



Proton



[M. Niechciol]

The diffuse photon flux

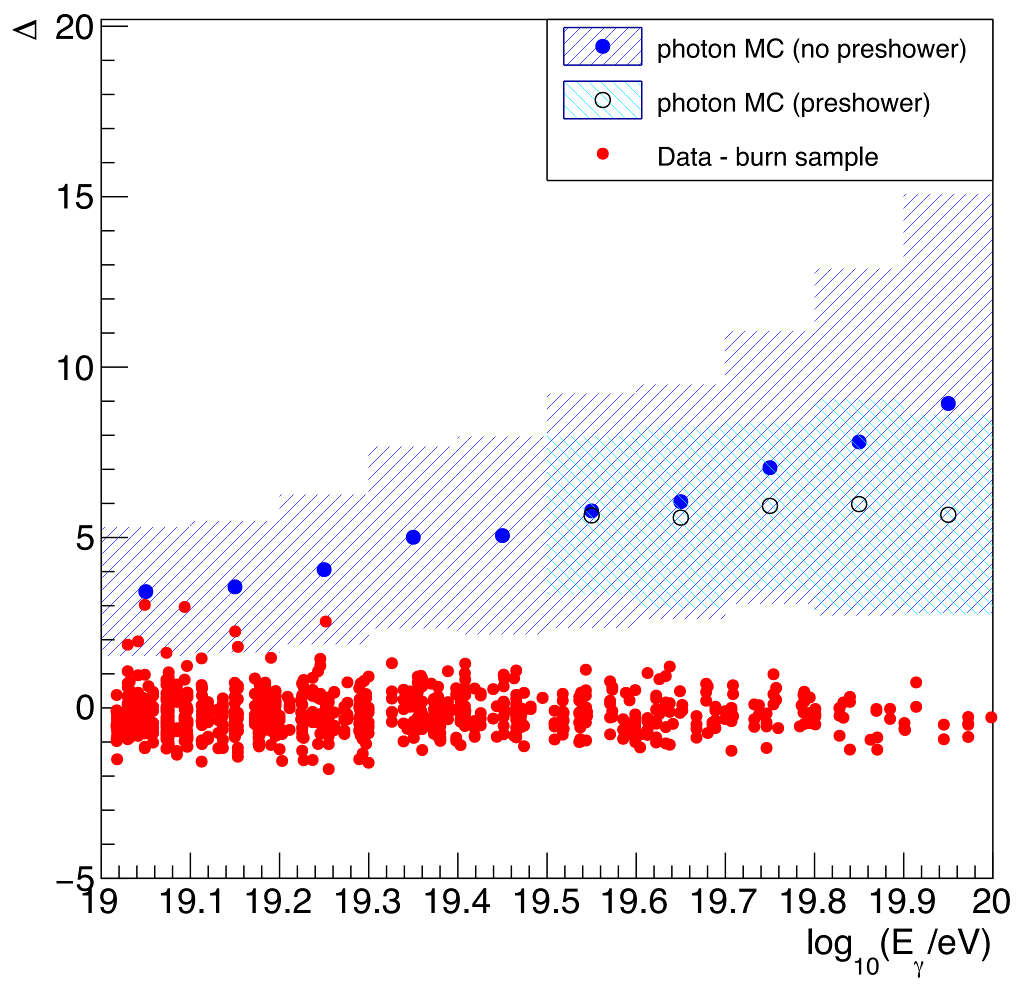
E > 10^{19} eV

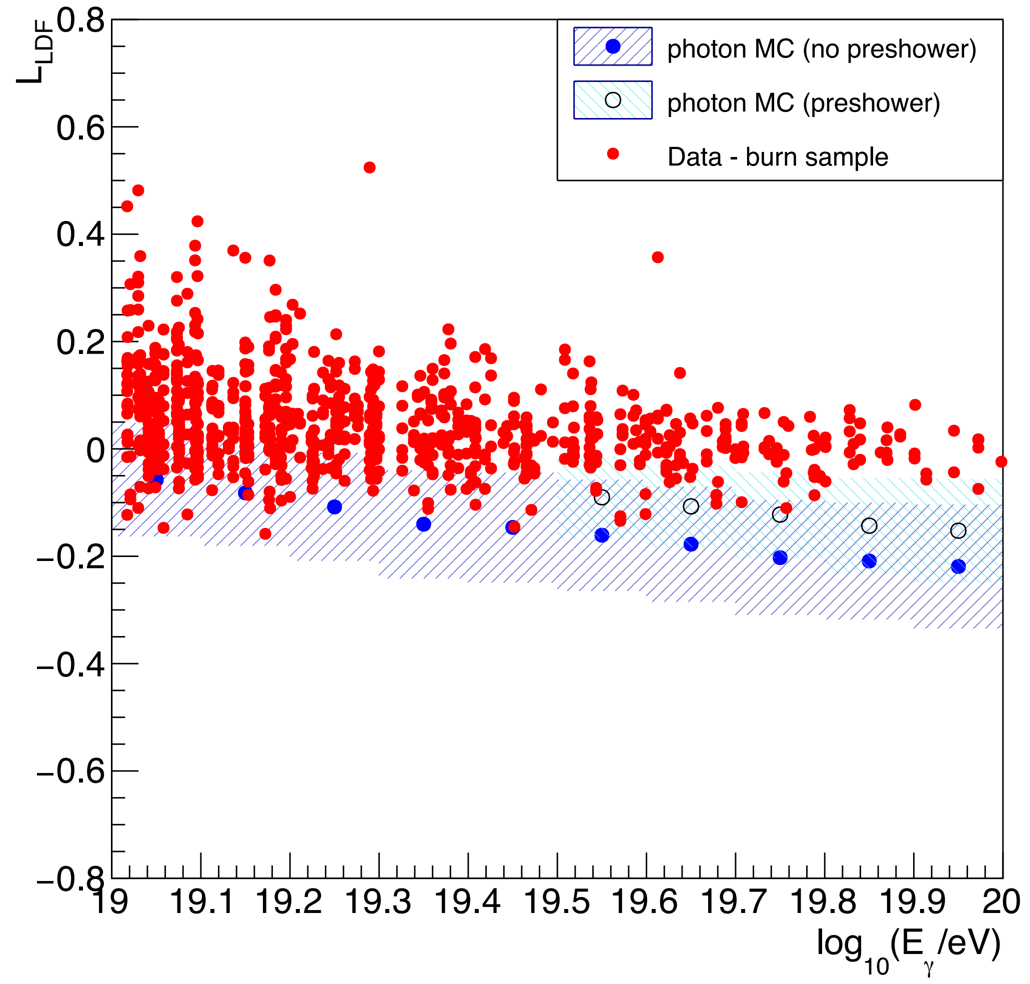
- Only the SD measurements are used
- Zenith angles between 30° and 60° (selection of fully developed showers)

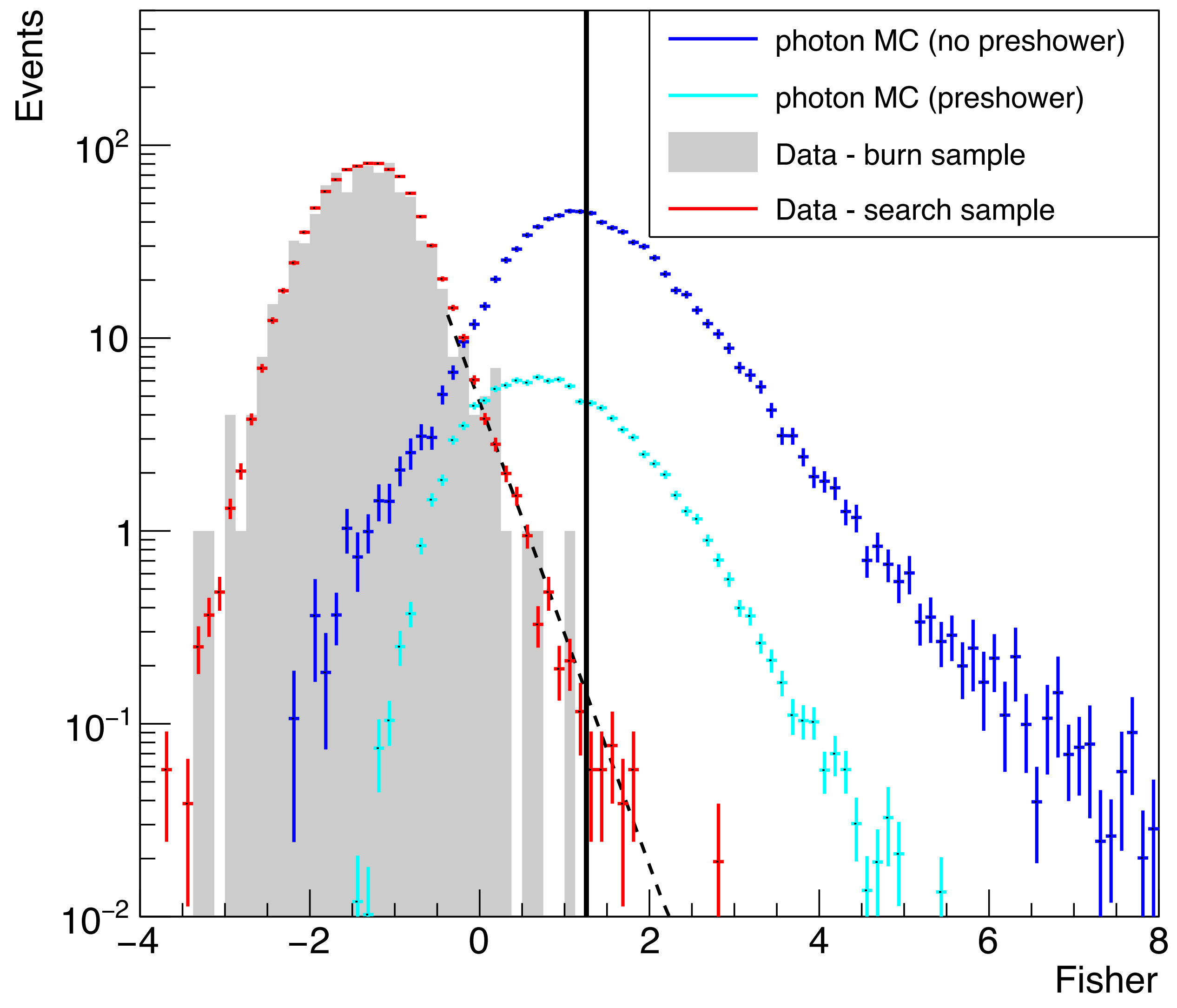
How to distinguish SD photon events:

- Steeper LDF (less muons) → observable $\mathbf{S_{LDF}}$
- Slower rising signal in the single SD triggered stations → observable related to the risetime Δ
- $\mathbf{S_{LDF}}$, **Δ** are are combined using a Fisher discriminant analysis

16 events from the data sample pass the photon candidate cut (consistent with the expectation from background)







<u>The photon candidate cut is the median of the photon test sample</u>

The diffuse photon flux

Photons

FD+SD are used (hybrid measurements) in the photons searches below 10^{19} eV

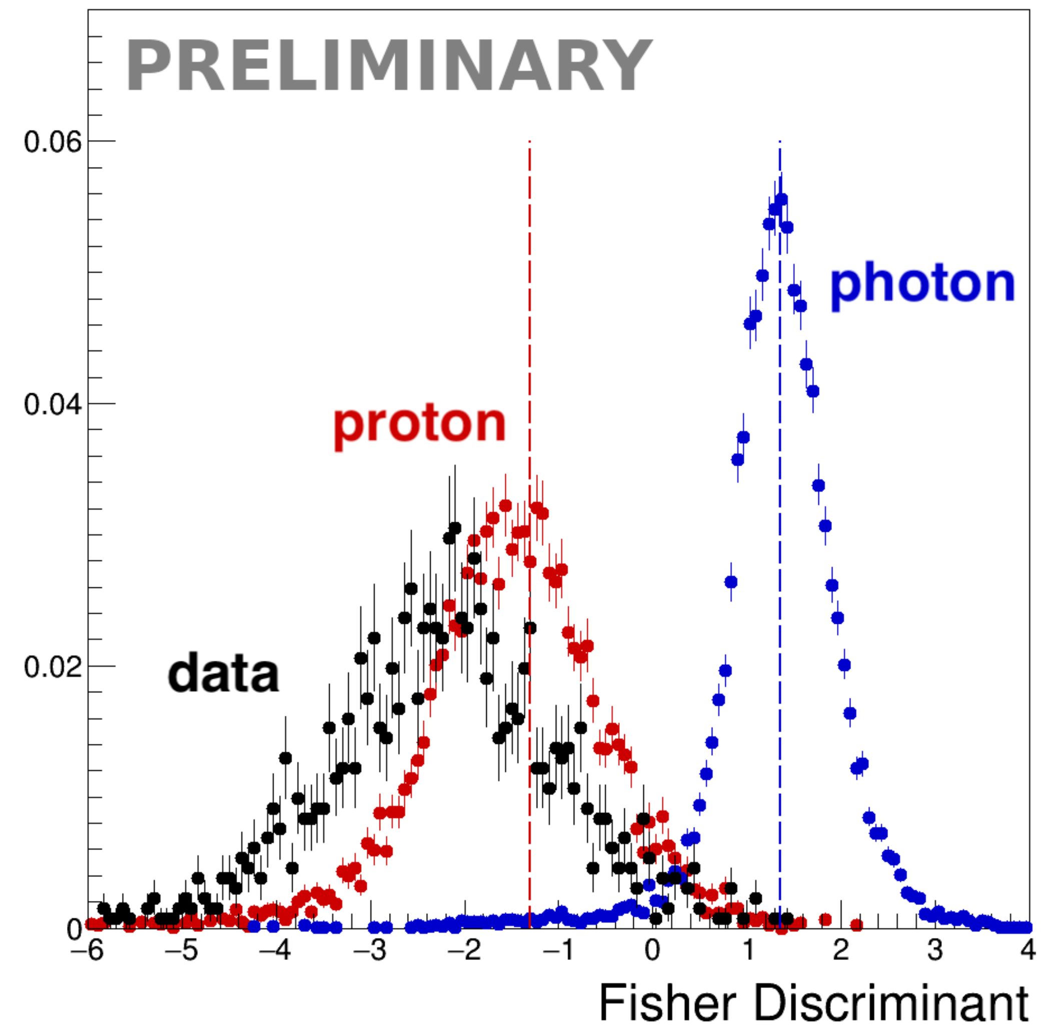
10^{18} eV < E < 10^{19} eV

- Zenith angles below 60°
- FD measurements:
  → Larger depth of shower maximum $\mathbf{X_{max}}$
- Muon content given by the parameter $\mathbf{F_{\mu}}$ (derived from the SD signals with air-shower universality concept)

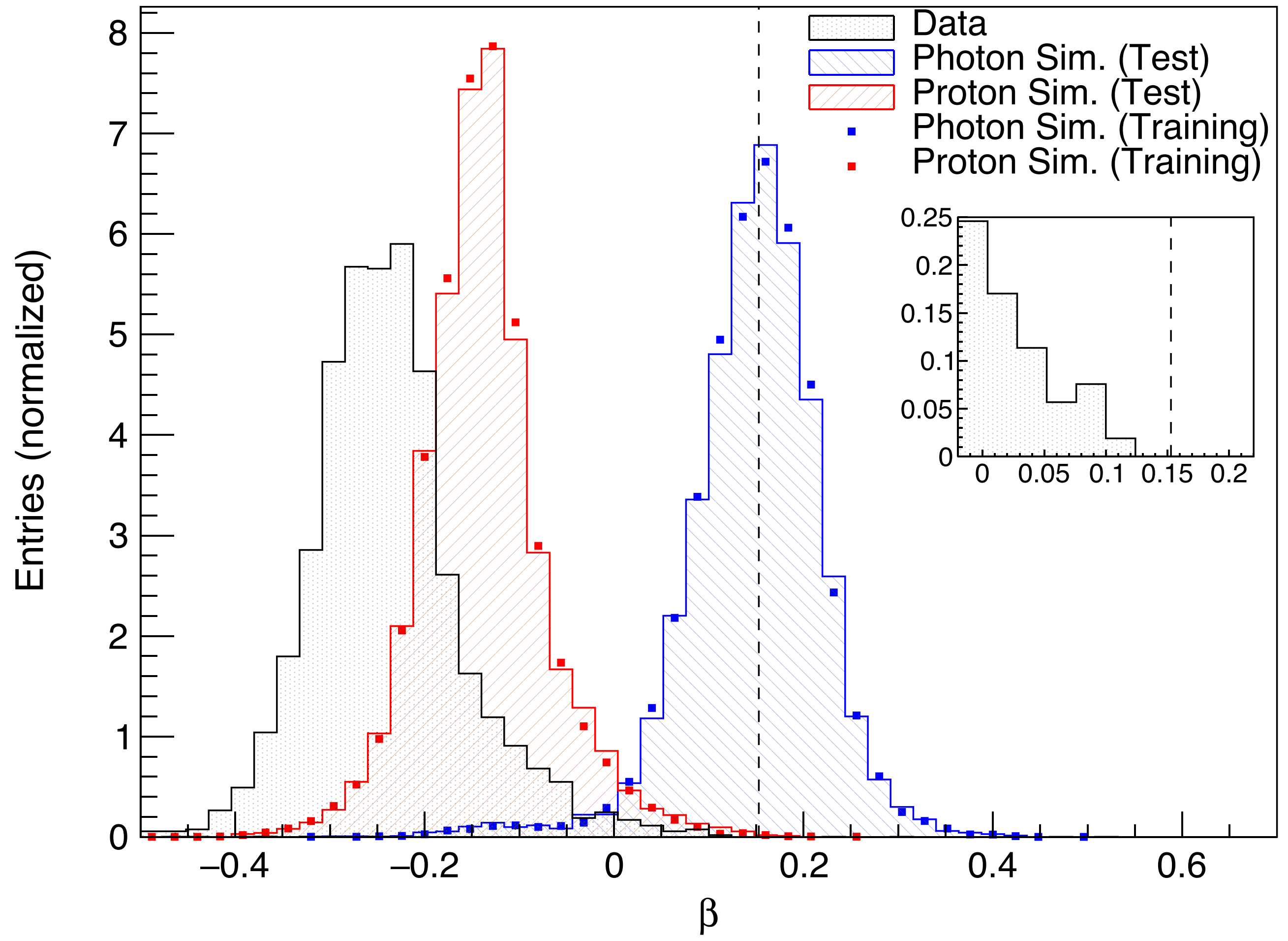
2 x 10^{17} eV < E < 10^{18} eV

- FD measurements:
  → Larger depth of shower maximum $\mathbf{X_{max}}$
- SD measurements:
  → Smaller number of triggered SD stations $\mathbf{N_{SD}}$
  → Steeper LDF (less muons) → observable $\mathbf{S_b}$

Standard data set (E > 10^{18} eV)



Low-energy data set (E > 2 x 10^{17} eV)



The observables are combined to obtain a discriminant

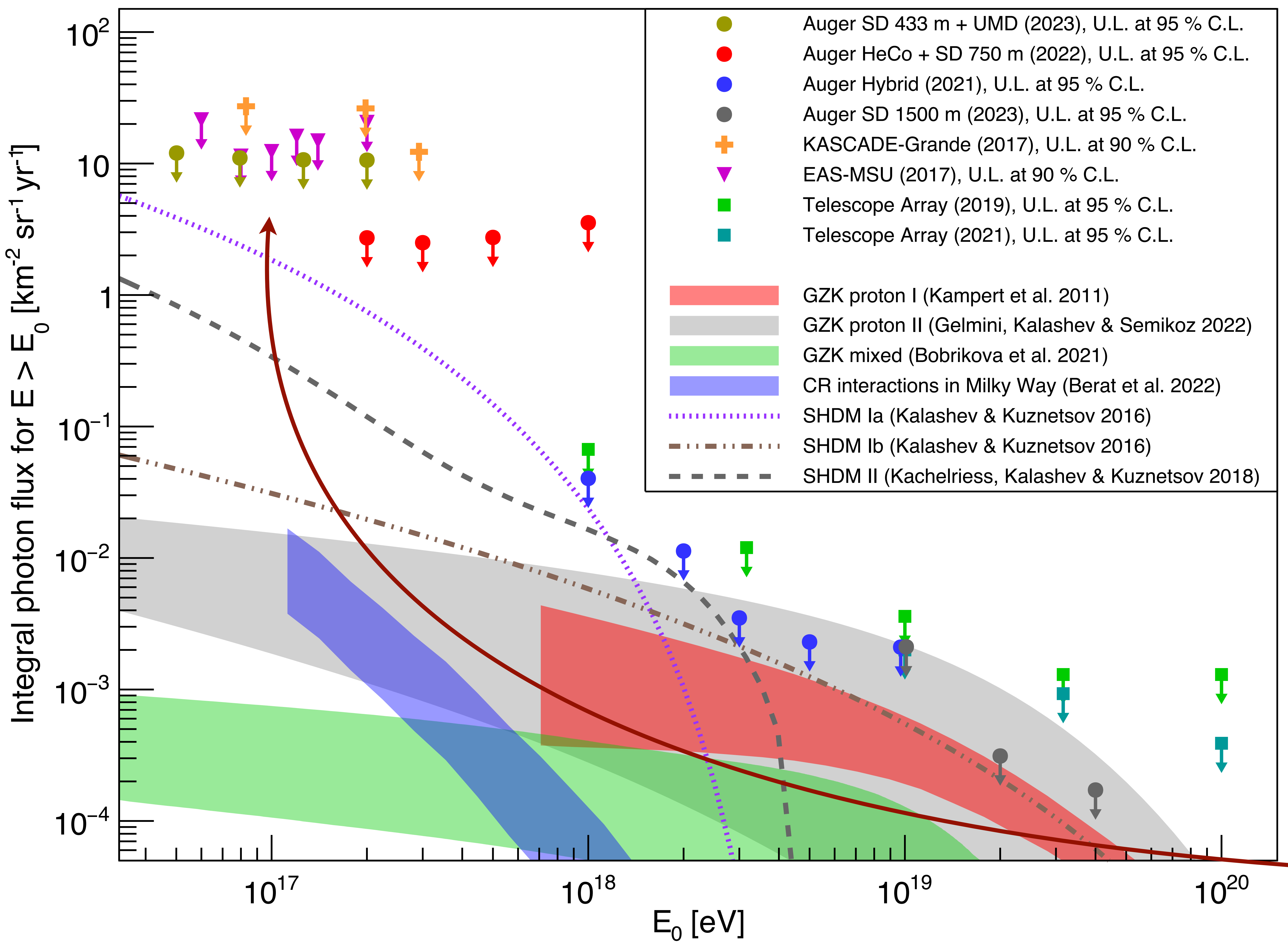
The photon candidate cut is the median of the photon test sample

- Universe 8 (2022) 579

The diffuse photon flux

Photons

No photon has been unambiguously detected so far but **upper limits have been set above 5 x 10^{16} eV**



Upper limit on the integral flux at 95% C.L.

$$\Phi_{UL}^{0.95}(E_\gamma > E_0) = \frac{N_\gamma^{0.95}(E_\gamma > E_0)}{\mathcal{E}_\gamma(E_\gamma > E_0 | E_\gamma^{-\Gamma})}$$

Feldman-Cousins upper limit for 0 background

Integrated exposure for $E^{-\Gamma} = E^{-2}$

- Auger set the most stringent limits above ~10^{17} eV
- Top-down models are already disfavoured
- GZK predictions still not constrained
  → slightly lowering the limits would put some constraints
- Improvement are expected in the next future (AugerPrime)

Ongoing analysis in the energy range 50 - 200 PeV
→ upper limits extended to lower energies

- Universe 8 (2022) 579
- PoS(ICRC2023)1488
- PoS(ICRC2023)191

Photons from point-like sources

Photons

✳ Goal: Identifying the first UHE photon point sources (or constraining their characteristics)

✳ Photons are attenuated by the interactions with background radiation

→ **sources within few Mpc (including Centaurus A)**

✳ Atmospheric Cherenkov telescopes (e.g. HESS) observed gamma-ray sources in the TeV region

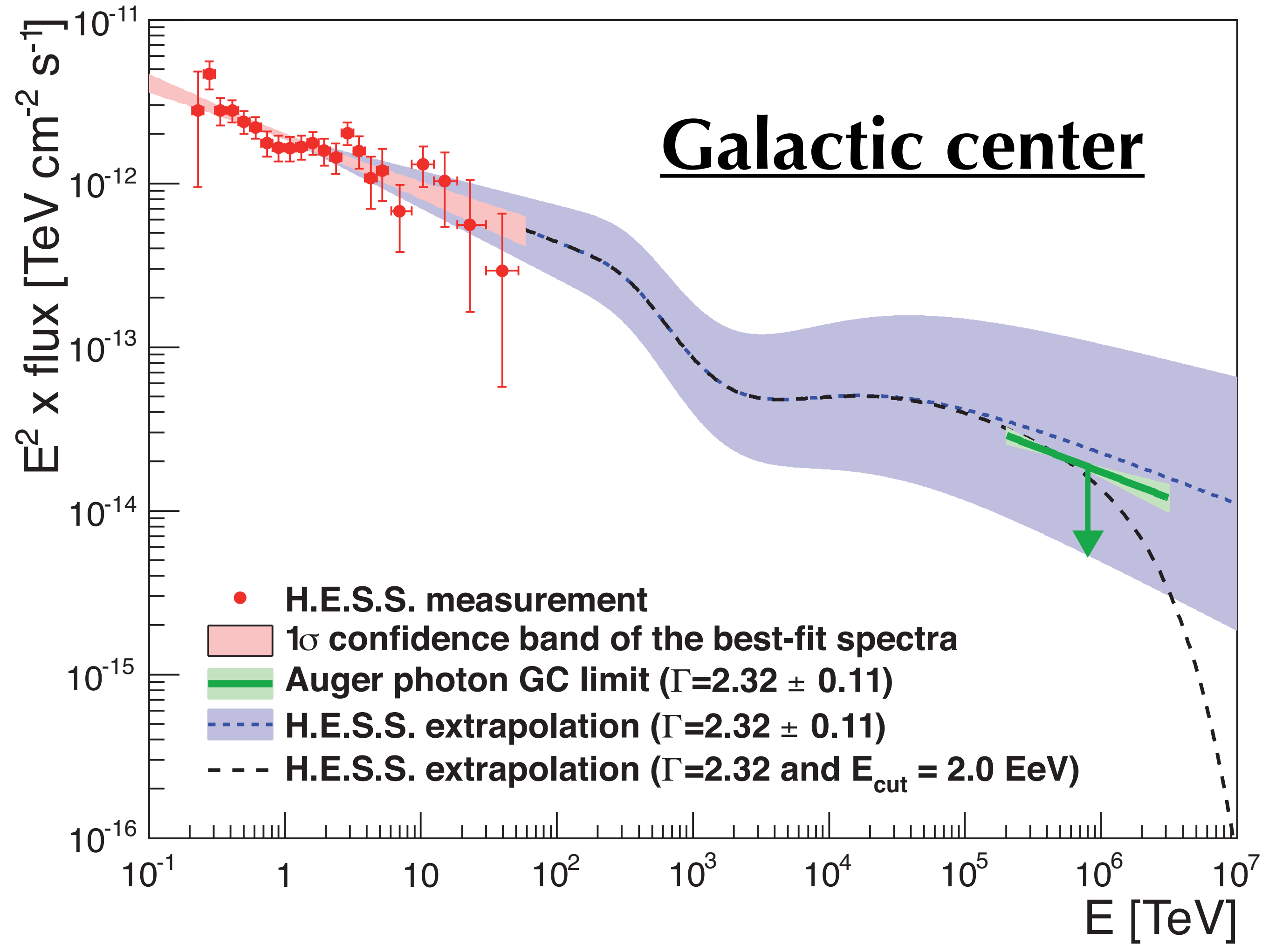
→ **the continuation of such spectra to EeV energy could be observed by Auger**

- Sources grouped in 12 target sets to have more significant signals (364 individual source candidates)
- Selected events: hybrid events, $\theta < 60^o$, $10^{17.3}$ eV $< E < 10^{18.5}$ eV
- 5 mass-sensitive observables used to train a BDT
- A combined p-value P is associated to each target

→ **no evidence of EeV photon** (statistical significance always lower than 3σ)

→ upper limits are set → constraints on the extrapolation of TeV spectra to EeV energies (e.g. E_{cut} < 2 EeV for the Galactic center)

Class	No.	$\mathcal{P}_w$	$\mathcal{P}$
msec PSRs	67	0.57	0.14
γ-ray PSRs	75	0.97	0.98
LMXB	87	0.13	0.74
HMXB	48	0.33	0.84
H.E.S.S. PWN	17	0.92	0.90
H.E.S.S. other	16	0.12	0.52
H.E.S.S. UNID	20	0.79	0.45
Microquasars	13	0.29	0.48
Magnetars	16	0.30	0.89
Gal. Center	1	0.59	0.59
LMC	3	0.52	0.62
Cen A	1	0.31	0.31



Follow-up of gravitational wave events

Photons

✳ Goal: search for UHE photons from the sources of gravitational waves (GW)

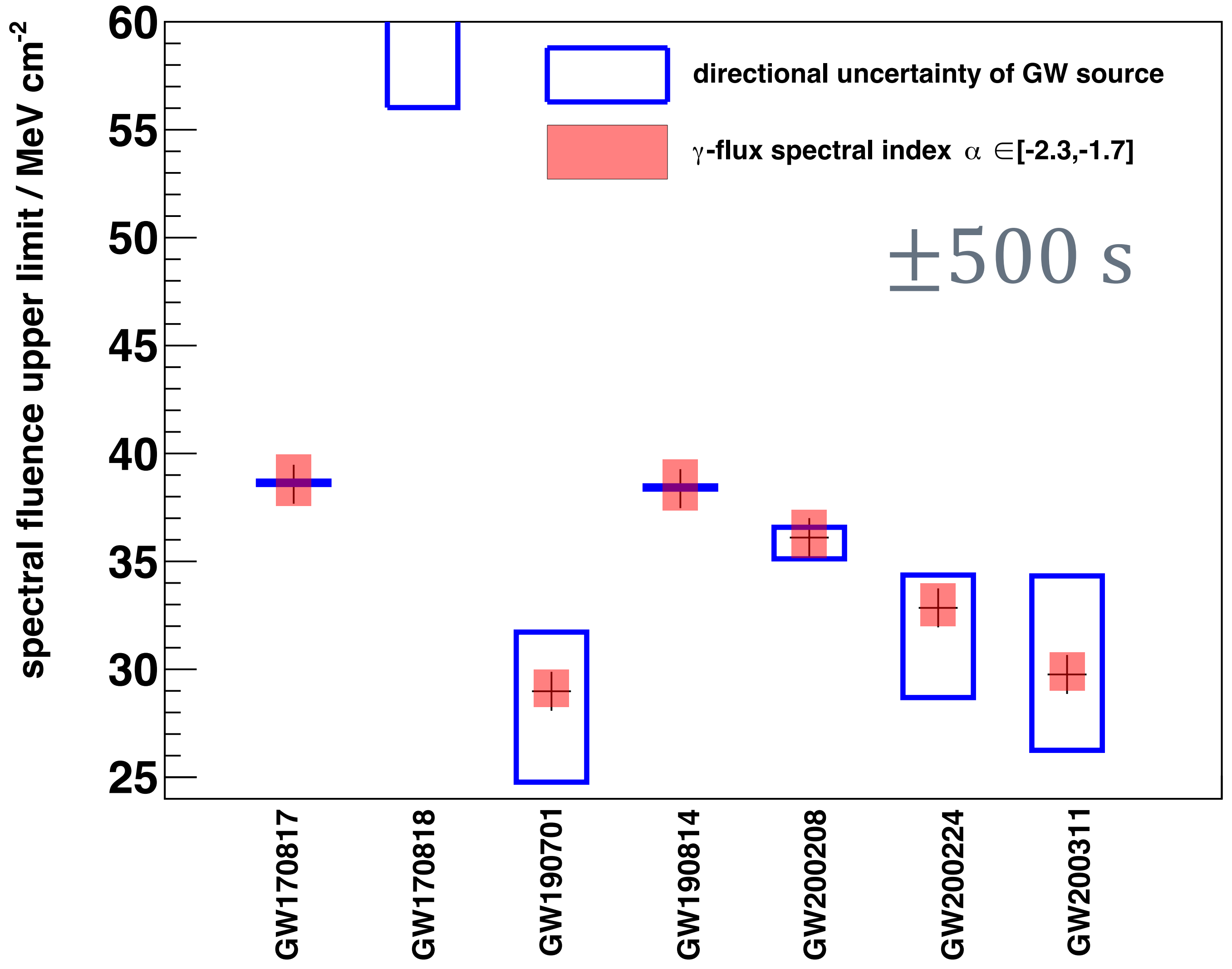
✳ The SD data above 10^{19} eV are used

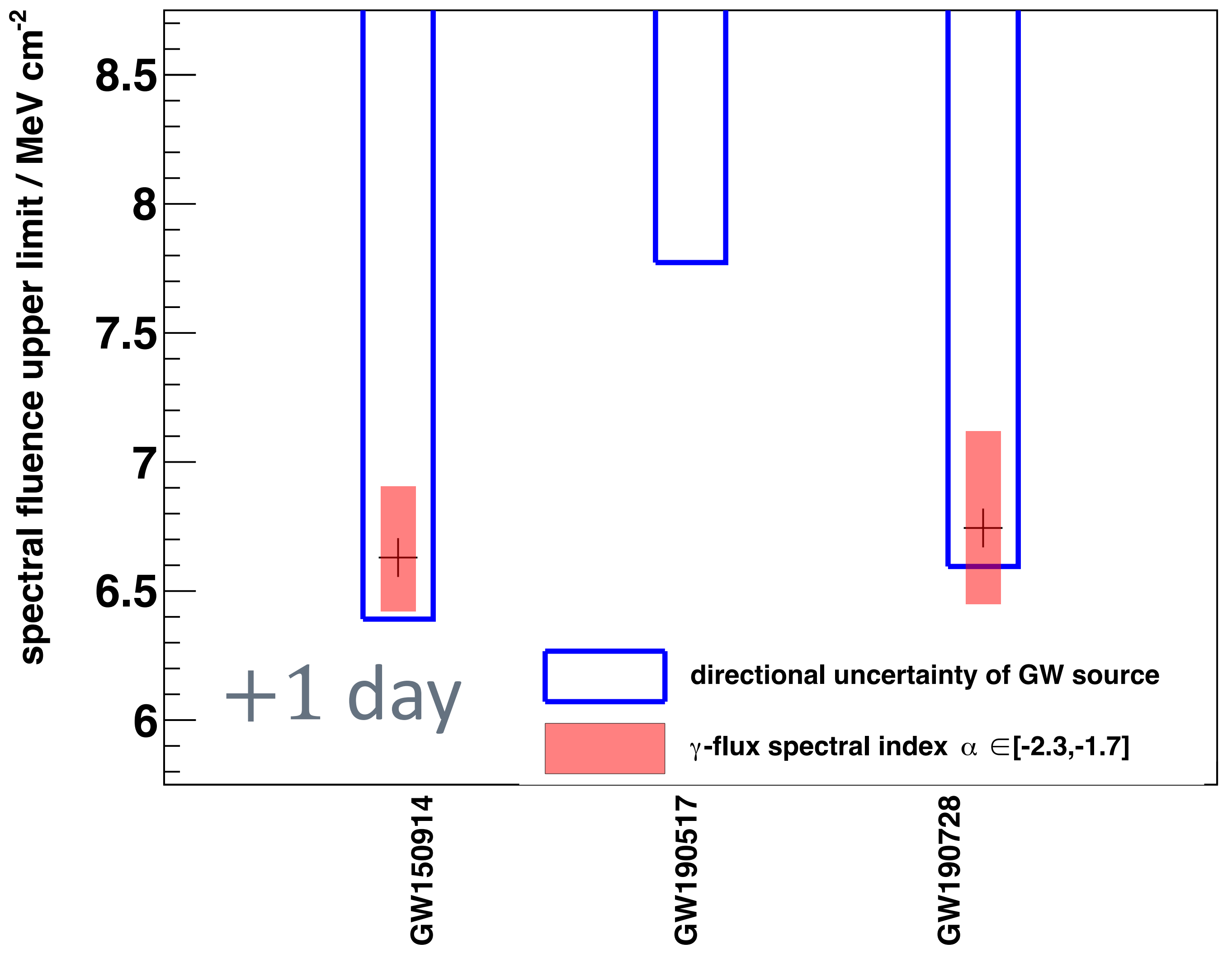
✳ Same method used for the search of the diffuse photon flux above 10^{19} eV

✳ **Two time windows: Δ=1000 s starting 500 s before the GW event**
Δ=24 h starting 500 s after the GW event

✳ Selection of GW events based on **localization quality and distance** (events within the photon horizon, farther events but very well localised, …)
→ **only 10 GW events overlap with the field of view of the SD during one of the two time windows**

- No photon candidate has been observed
- For each GW event upper limit on the photon spectral fluence at 90% C.L.





- PoS(ICRC2021)973
- ApJ 952 (2023) 91

COSMIC RAYS

PHOTONS

NEUTRINOS

NEUTRONS

Neutron search for source targets

Neutrons

✳ Also **UHE neutrons** are not deflected by magnetic fields and **may point back to their sources**

✳ Mean travel distance before decaying is 9.2 kpc E_n/EeV → neutrons above 1 EeV from sources in the Galactic disk can be detected

✳ Neutron-induced air showers cannot be distinguished from proton-initiated ones
→ **search for an excess in given directions (as in the targeted search of EeV photon sources)**

No evidence for a neutron flux from any target sets of sources
→ upper limits (95% C.L.)

- Energy flux upper limit, assuming an E^{-2} spectrum
- Analysis performed with the events of the SD array
- Plan to perform an updated blind search for a neutron flux from any direction

Class	R.A [deg]	Dec. [deg]	Flux U.L. [km^{-2} yr^{-1}]	E-Flux U.L. [eV cm^{-2} s^{-1}]	p-value	p^*
msec PSRs	286.2	2.1	0.026	0.19	0.0075	0.88
γ-ray PSRs	296.6	−54.1	0.023	0.17	5.0×10^{-5}	0.013
LMXB	237.0	−62.6	0.017	0.12	0.0069	0.51
HMXB	308.1	41.0	0.13	0.97	0.014	0.57
H.E.S.S. PWN	128.8	−45.6	0.016	0.12	0.0070	0.18
H.E.S.S. other	128.8	−45.2	0.014	0.11	0.022	0.63
H.E.S.S. UNID	305.0	40.8	0.15	1.1	0.0066	0.31
Microquasars	308.1	41.0	0.13	0.95	0.014	0.19
Magnetars	249.0	−47.6	0.011	0.079	0.15	0.99
LHAASO	292.3	17.8	0.038	0.28	0.024	0.20
Crab	83.6	22.0	0.020	0.15	0.71	0.71
Gal. Center	266.4	−29.0	0.0053	0.039	0.86	0.86

Summary

The Pierre Auger Observatory is sensitive not only to UHECRs, but also to UHE photons, neutrinos and neutrons

- **Photons** can be discriminated from hadrons because they initiate showers with reduced muon content and deeper X_{max}
  → they are searched with both the SD and the FD
- **Neutrinos** produce showers that develop deep in atmosphere → large electromagnetic component at the ground ("young" showers)
  → search for inclined events with the SD (electromagnetic component of hadron showers is almost completely absorbed)
- No candidate events → **stringent upper limits on the diffusive fluxes** (and on the fluxes from point-like steady sources)
- **Follow-up of gravitational wave events** has not led to the observation of candidates so far → **upper limits**

- **Cosmic rays** can be used as multi-messenger probes:
  → Predictions of cosmogenic neutrinos associated to astrophysical scenarios for UHECRs are compared to the ν upper limits
  → possible constraints on source properties (e.g. cosmological evolution, rigidity cutoff at the sources,…)
- **Neutrons** can be detected by looking for an excess of particles from a a given direction
  → analysis recently updated but no excess observed so far

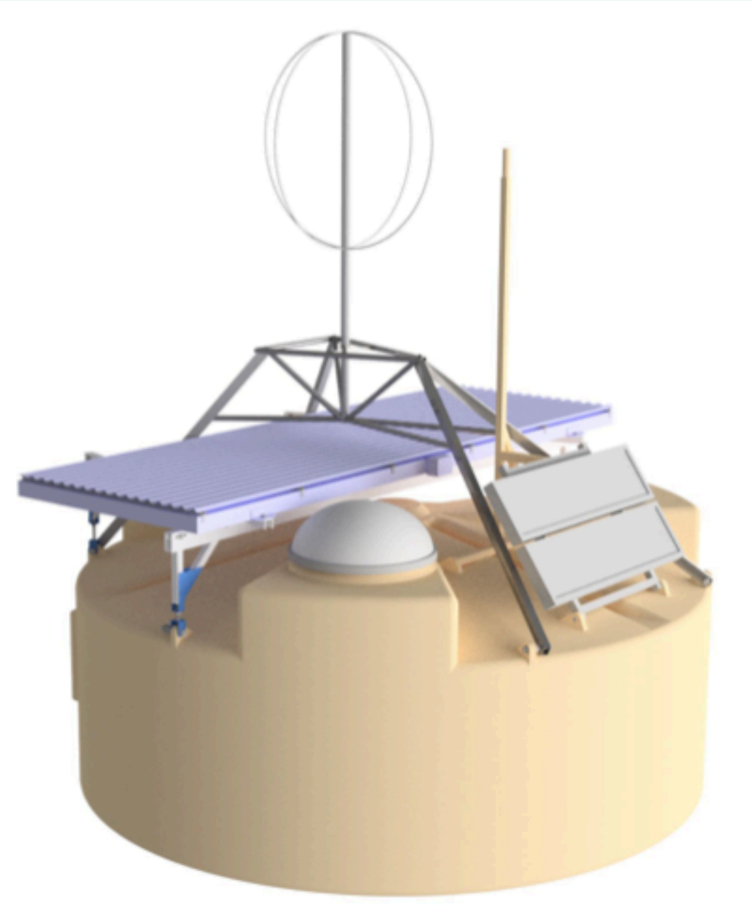
Outlook

✳ The current upper bounds will be lowered thanks to increasing exposure and number of transient event

✳ Expected improvements with **AugerPrime upgrade** → improved sensitivity of the SD to different primaries

- ✦ New electronics → improved resolution and larger dynamic range
- ✦ SD stations equipped with radio antennas → detection of radio signals in air showers
- ✦ Plastic scintillator on top of each SD station (Surface Scintillator Detectors)

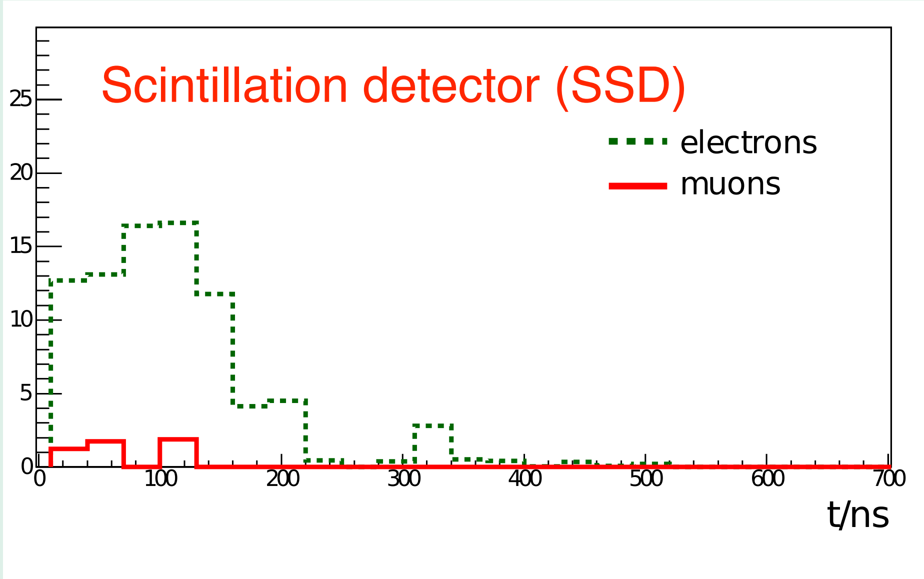
  → **different sensitivity to the muonic/electromagnetic components**

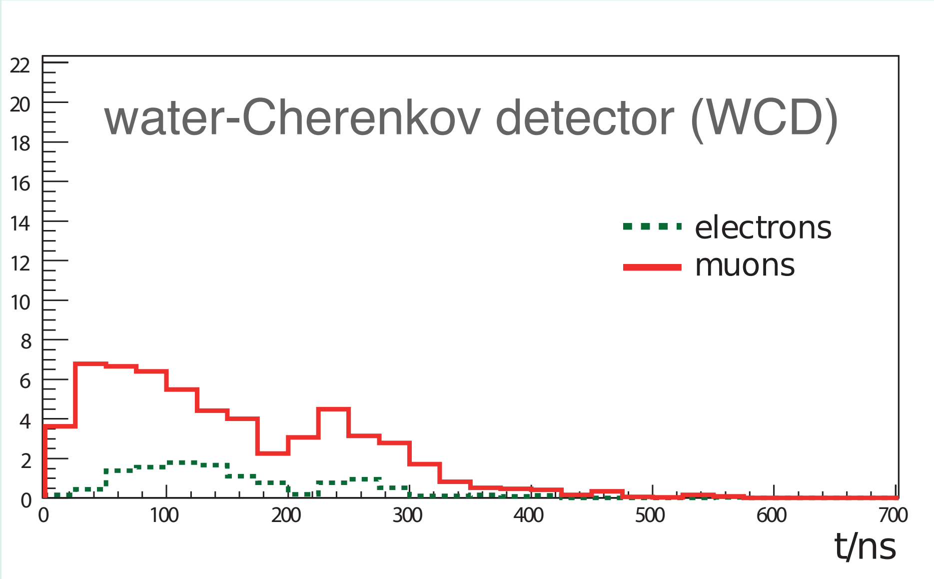


✳ SSD are more sensitive to electrons/positrons

✳ WCD are more sensitive to muons

→ **<u>Enhanced discrimination power of primary particles</u>**





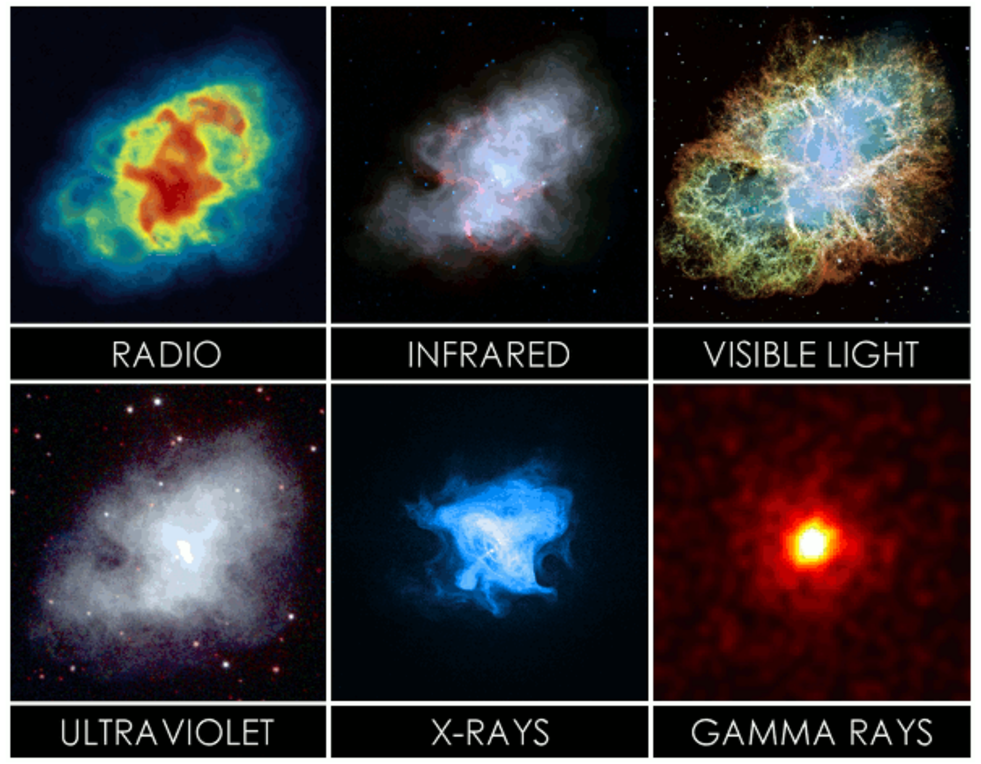
Auger with its unique sensitivity will continue to monitor the UHE sky and contribute to multi-messenger studies

Thank you for your attention

Multi-messenger astronomy

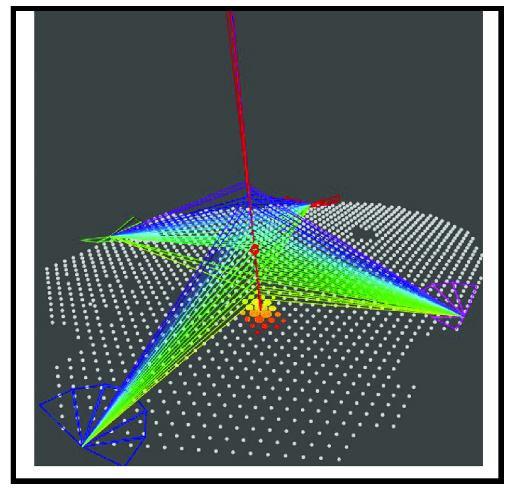
Combining the *information from any particle and radiation* coming from astrophysical objects
→ **complementary insight on the most energetic events in the Universe**

- Sources can be studied through different wavelengths of the electromagnetic spectrum
- SN1987A (neutrinos from SN): onset of multi-messenger astronomy
- Neutrino astronomy & observation of gravitational waves → **recent boost of multi-messenger studies:**
  - ✦ 2017: measurements of the **electromagnetic spectrum emission in coincidence with the first neutron star merger** observed by LIGO and Virgo
  - ✦ 2017: IceCube observed a **high-energy neutrino (~290 TeV) in coincidence with a flaring gamma-ray blazar.**
  - ✦ 2021: IceCube reported the association of a high-energy neutrino with a tidal disruption event
  - ✦ 2023: **first map of neutrinos emissions in our Galaxy**

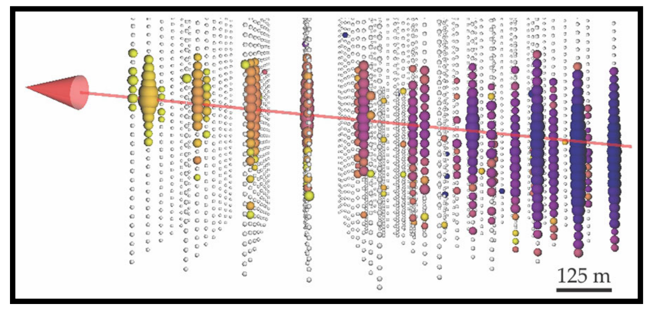


Electromagnetic wavelengths

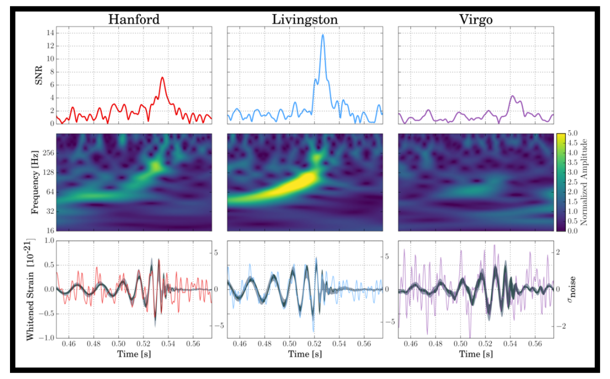
Cosmic rays



Neutrinos



Gravitational waves

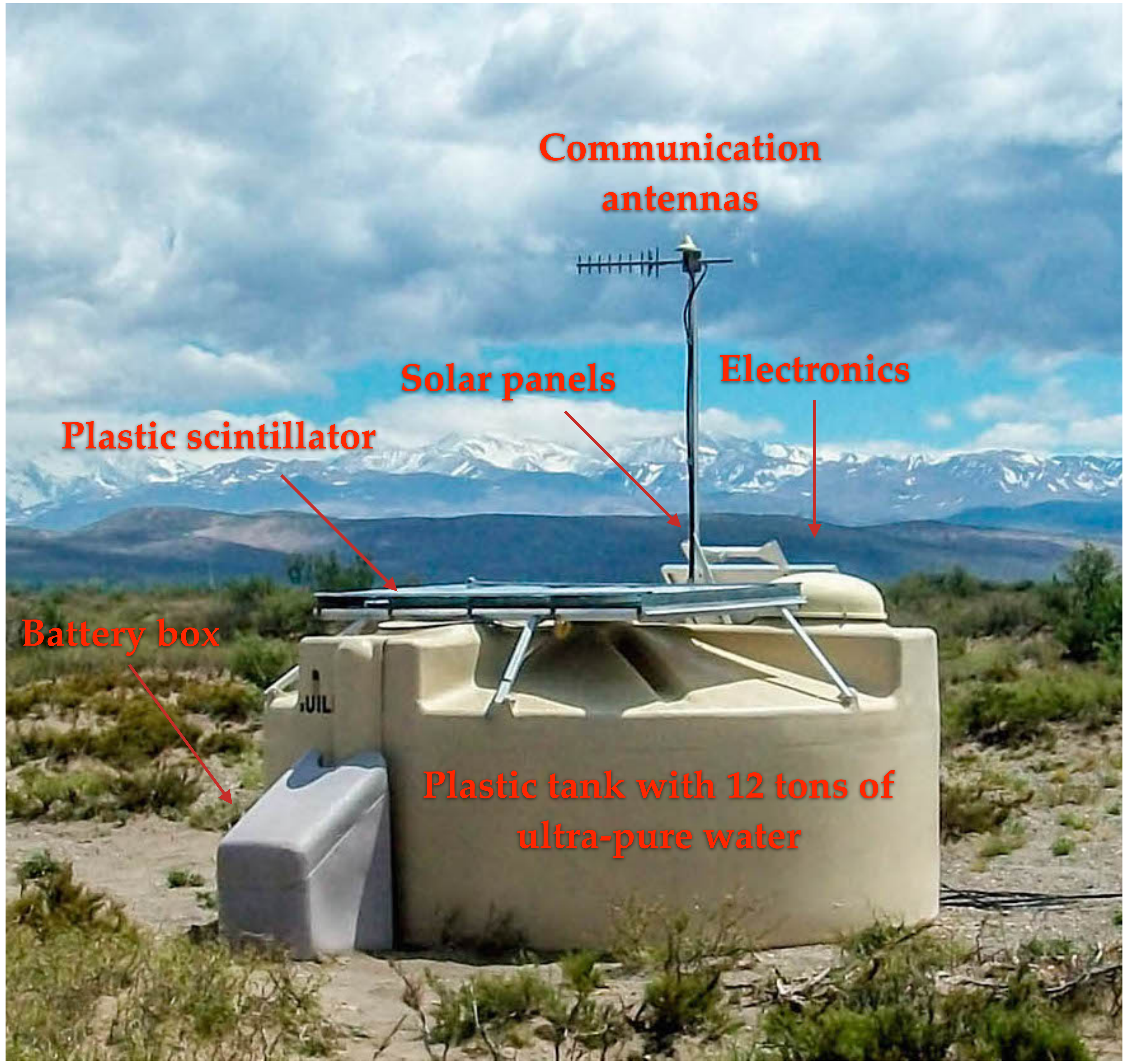


Additional messengers

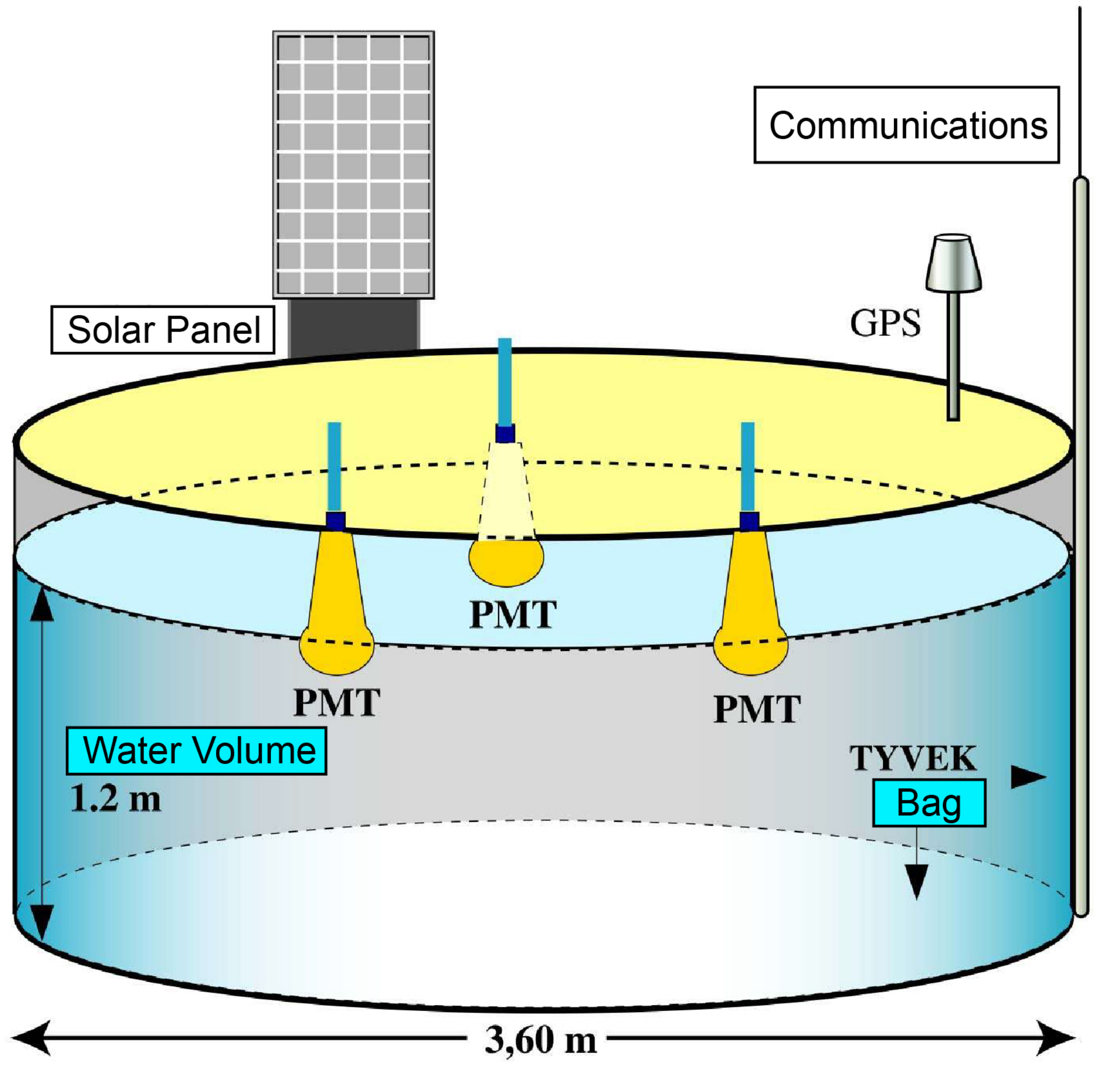
- Bionta et al., 1987
- Hirata et al., 1987
- IceCube Coll. 2023
- Abbott et al., 2017a
- Aartsen et al., 2018a
- R. Stein et al., 2021

The Pierre Auger Observatory

SD: water-cherenkov tanks (WCD) : 1661 covering 3000 km^2



- ~100% duty cycle
- 3 PMT looking into the water collect the Cherenkov light produced by the particles (mainly electrons and muons)



- **AugerPrime**: additional plastic scintillator on each tank →improved information on the primary particles

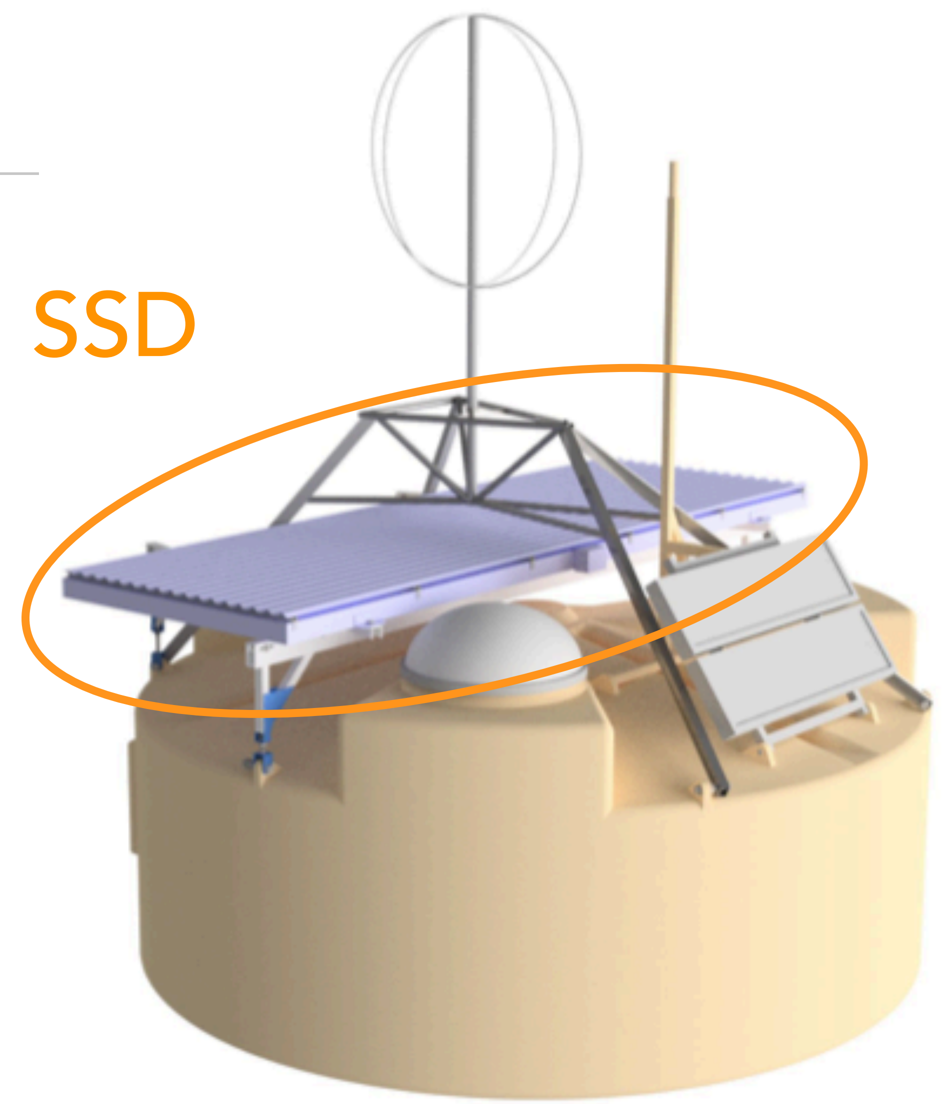
The AugerPrime data set

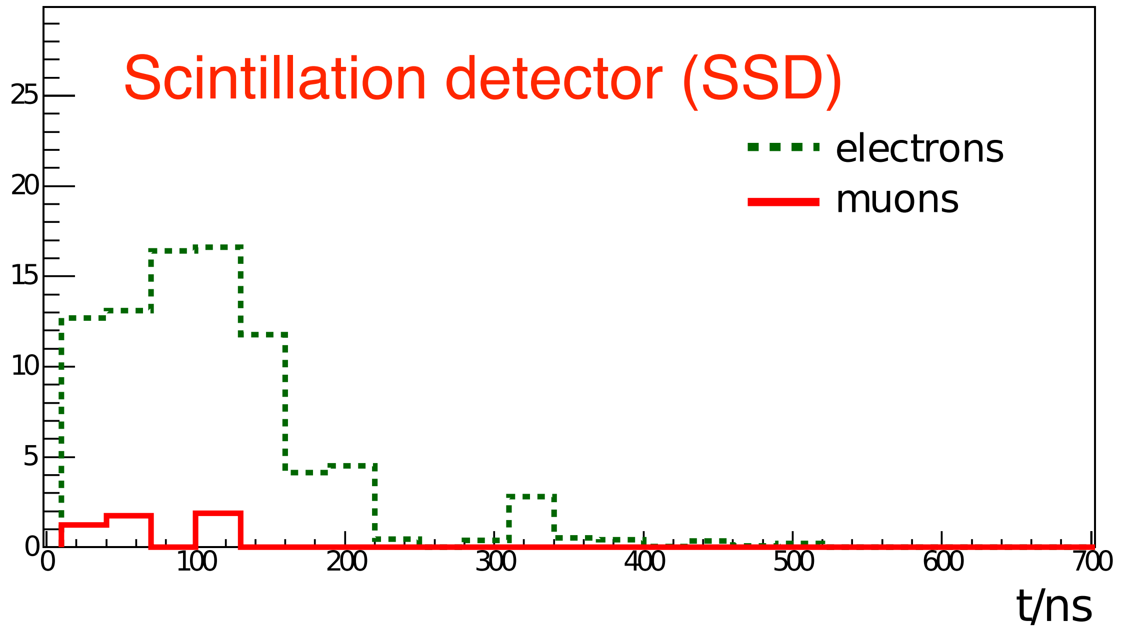
The Pierre Auger Observatory is undergoing an upgrade called “**AugerPrime**"

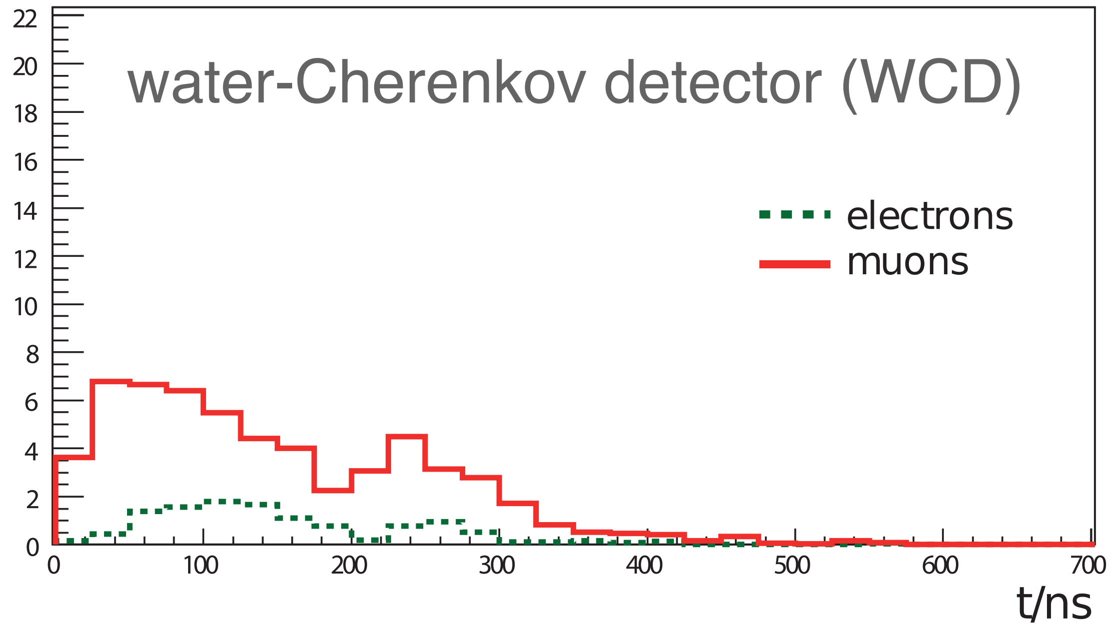
✴ Improved new electronics, addition small photomultiplier

✴ Plastic scintillator on top of each SD station (Surface Scintillator Detectors)

→ **different sensitivity to the muonic/electromagnetic components**





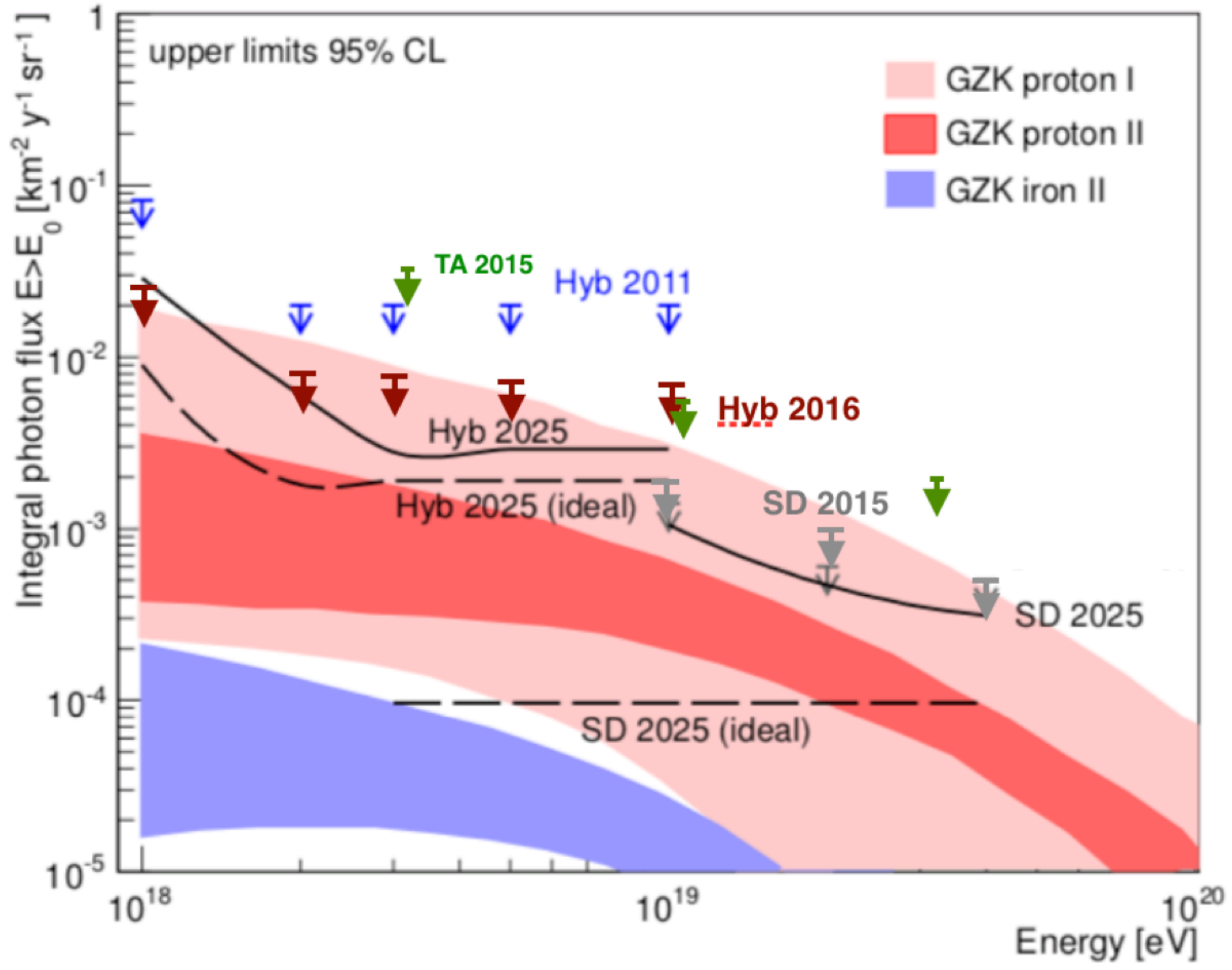


✴ SSD are more sensitive to electrons/positrons

✴ WCD are more sensitive to muons

→ <u>**Enhanced discrimination power of primary particles**</u>

✴ **Machine learning techniques** are also particularly suitable to combine different data sets

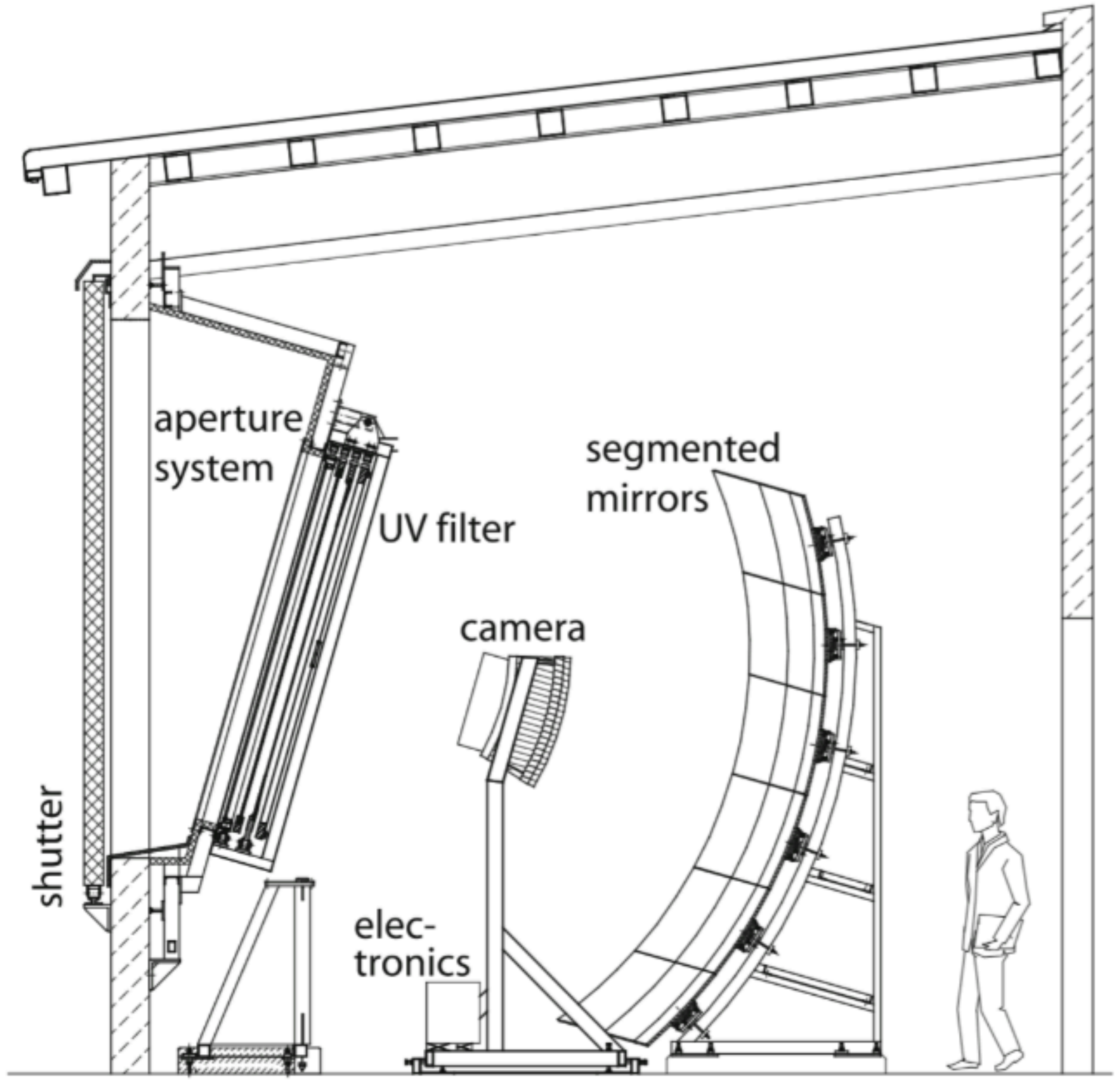


[The Pierre Auger Collaboration, AugerPrime: the Pierre Auger Observatory Upgrade, EPJ Web of Conferences, 2019]

The Pierre Auger Observatory

FD: fluorescence telescopes

- 24 in 4 sites overlooking the SD, covering an elevation up to 30°→ E>10^{18} eV
- 3 additional telescopes covering the elevation range between 30° and 58° (**HEAT**) → E>10^{17} eV



- Each FD site covers 180° x 30° in azimuth and elevation
- They collect the nitrogen fluorescence light produced in the atmosphere
- ~15% duty cycle (FD operate only on clear moonless nights)

The Pierre Auger Observatory

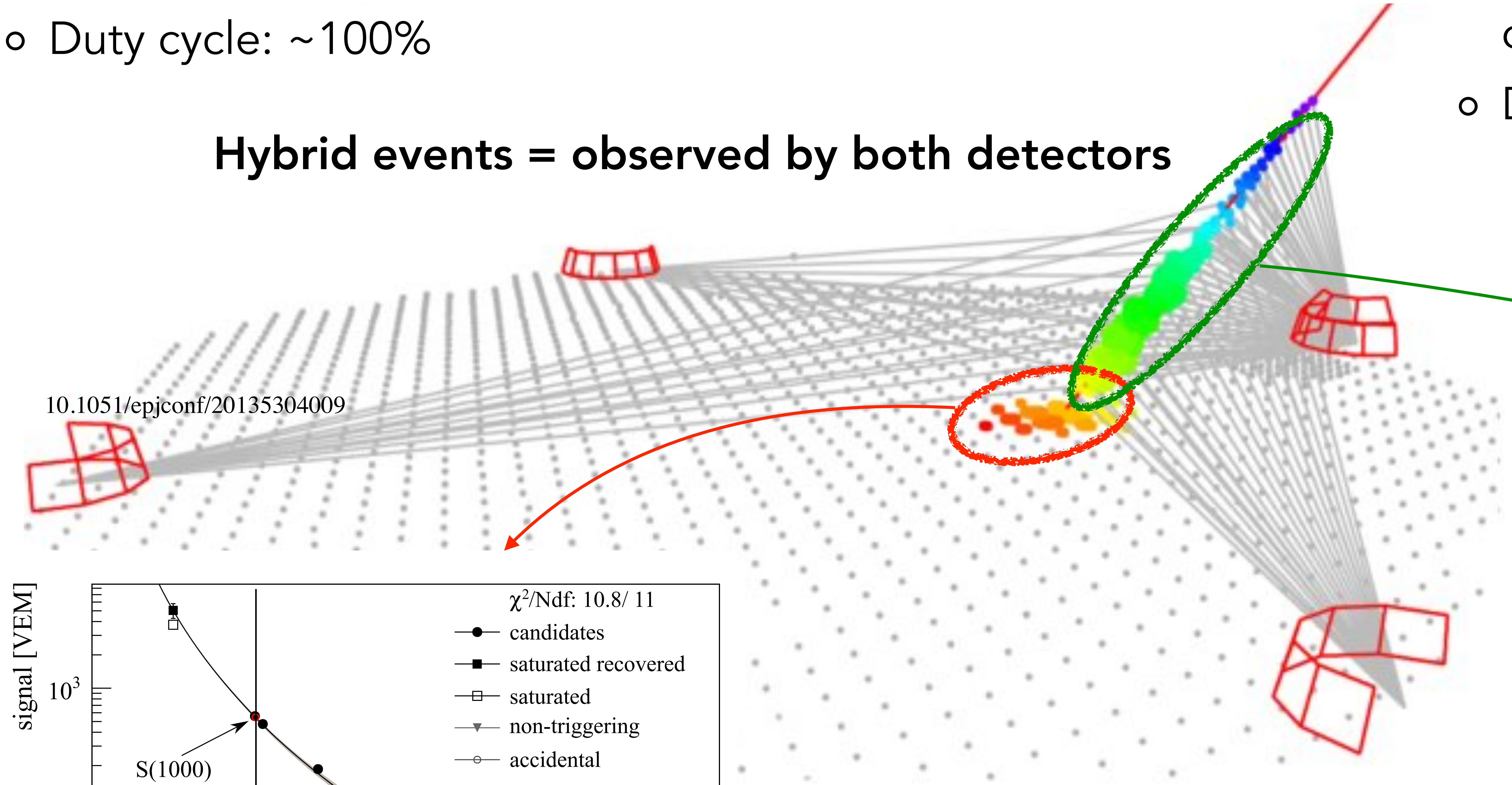
Surface Detector (SD)

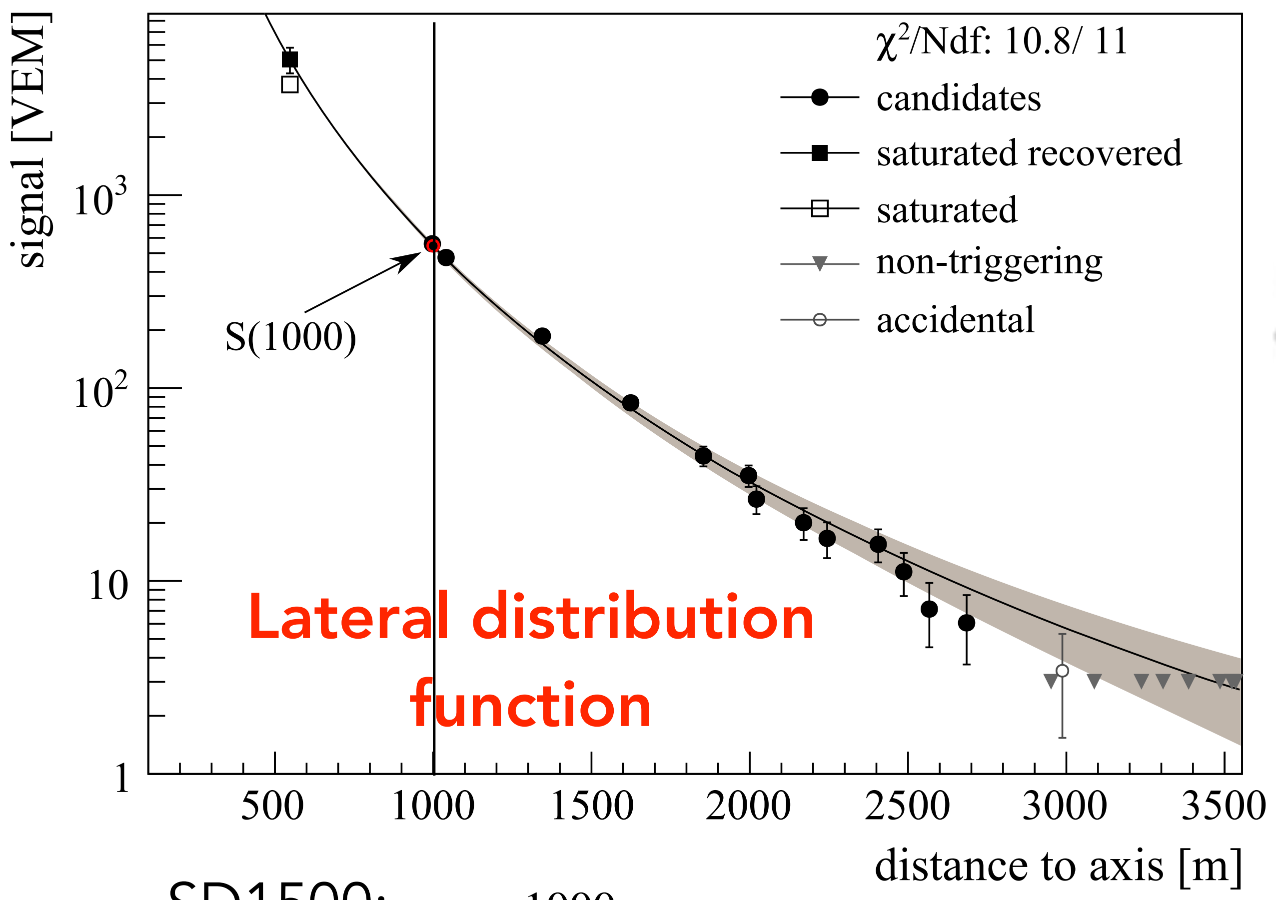
- Sampling the secondary particles reaching the ground
- Duty cycle: ~100%

Fluorescence Detector (FD)

- Measuring the fluorescence light produced by the de-excitation of atmospheric nuclei
- Duty cycle: ~15%

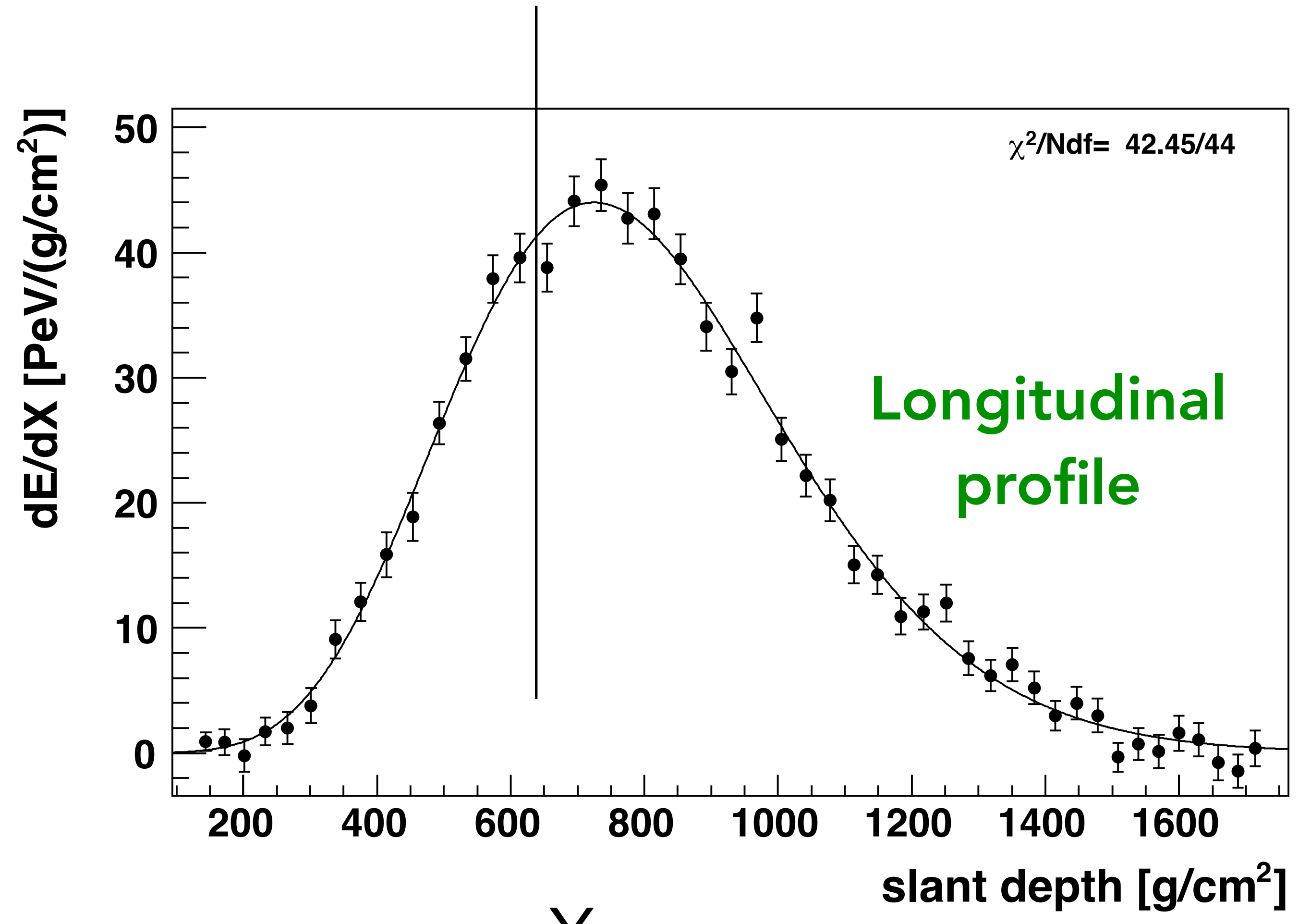
Hybrid events = observed by both detectors





SD1500: $r_{opt} = 1000$ m

SD750 (Infill): $r_{opt} = 450$ m



X_{max}

Estimator $S(r_{opt})$ = shower size at a distance r_{opt} from the core

$$S(r) \propto r^{\beta}(r + r_M)^{\beta+\gamma} \rightarrow S(r_{opt})$$

$$\frac{dE}{dX} = \left(\frac{dE}{dX}\right)_{max} \cdot \left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max} - X_0}{\lambda}} \cdot \exp\left(\frac{X_{max} - X_0}{\lambda}\right).$$

$$E_{cal} = \int \frac{dE}{dX} dX$$

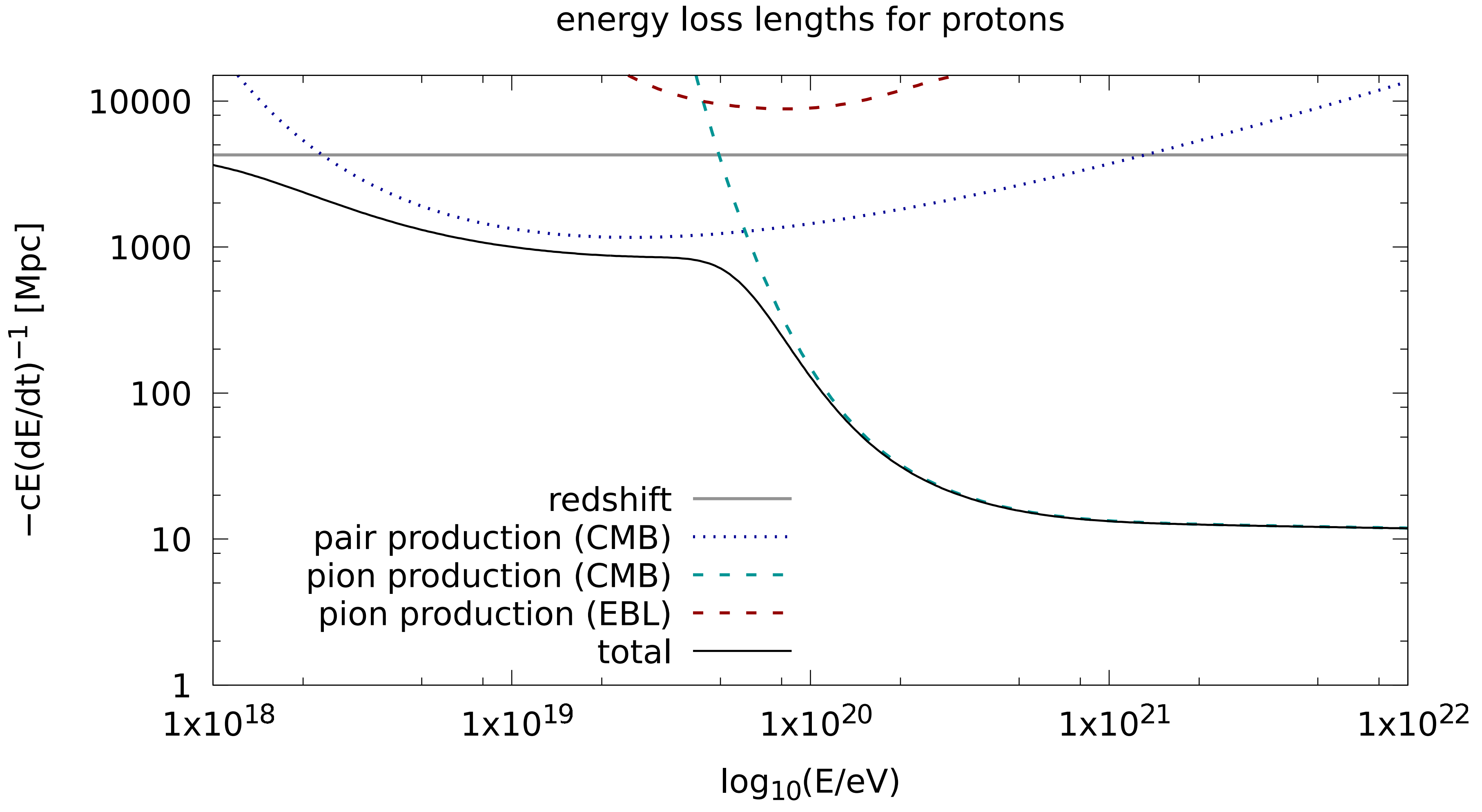
Calorimetric energy

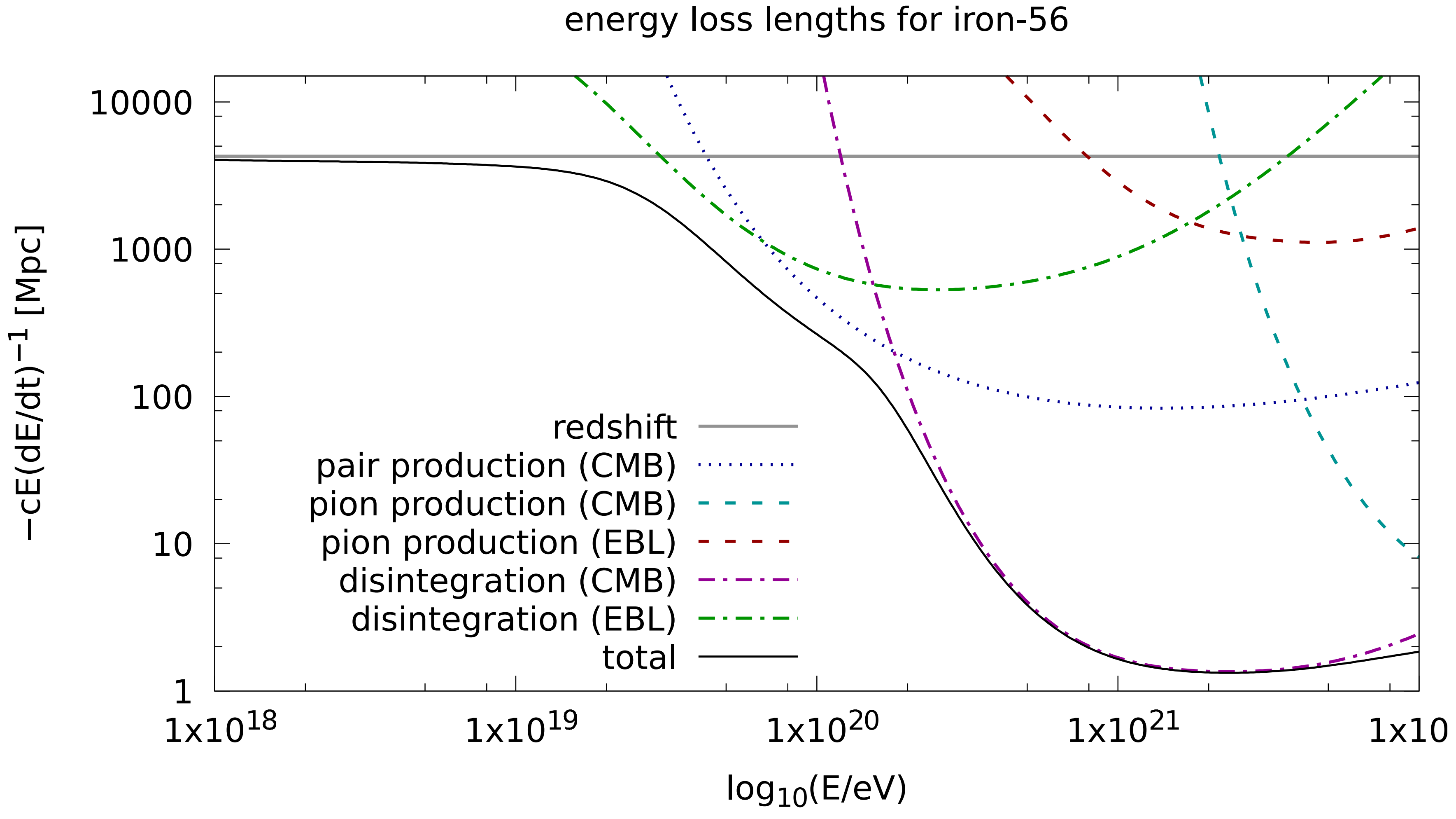
UHECRs propagation

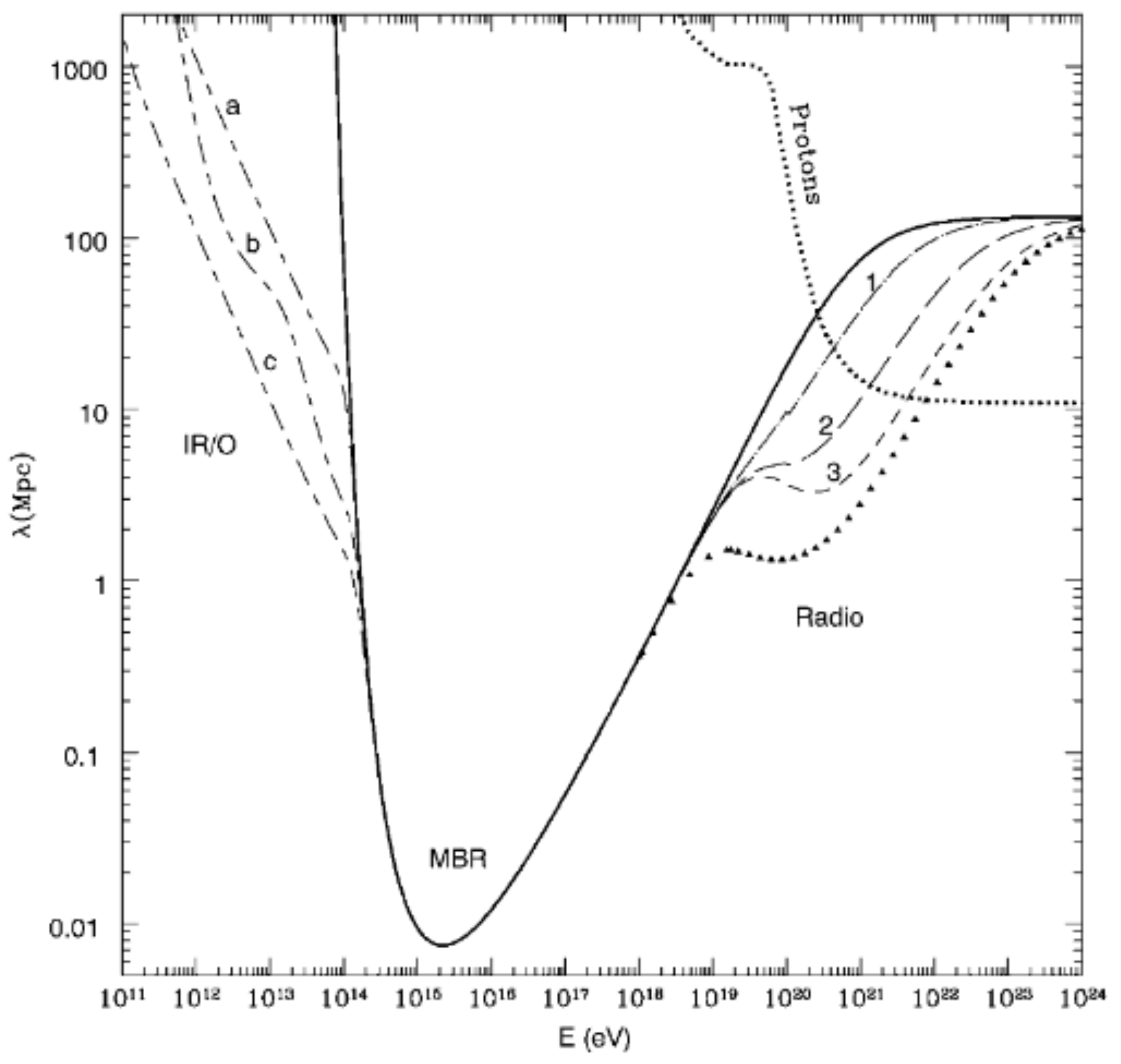
- **Consider the propagation effects → infer source properties from the measured fluxes**

Energy loss processes occurring for E > 10^{18} eV :

- **Adiabatic energy losses** (expansion of the Universe) $$-\left(\frac{1}{E}\frac{dE}{dt}\right)_{ad} = H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$$
- **Interactions** of nuclei **with background photons** (EBL, CMB)
  - Photo-pion production $N + \gamma \rightarrow N + \pi^0 \;/\; N + \pi^\pm$
  - Pair production $N + \gamma \rightarrow N + e^+ + e^-$
  - Photo-disintegration $(A, Z) + \gamma \rightarrow (A - n, Z - n') + nN$







Photons from point-like sources

- Goal: Identifying the first UHE photon point sources (or constraining their characteristics)
- Photons are attenuated by the interactions with background radiation
  → **sources within few Mpc (including Centaurus A)**
- Atmospheric Cherenkov telescopes (e.g. HESS) observed gamma-ray sources in the TeV region
  → **the continuation of such spectra to EeV energy could be observed by Auger**

Class	No.	$\mathcal{P}_w$	$\mathcal{P}$
msec PSRs	67	0.57	0.14
γ-ray PSRs	75	0.97	0.98
LMXB	87	0.13	0.74
HMXB	48	0.33	0.84
H.E.S.S. PWN	17	0.92	0.90
H.E.S.S. other	16	0.12	0.52
H.E.S.S. UNID	20	0.79	0.45
Microquasars	13	0.29	0.48
Magnetars	16	0.30	0.89
Gal. Center	1	0.59	0.59
LMC	3	0.52	0.62
Cen A	1	0.31	0.31

- Sources grouped in 12 target sets to have more significant signals (364 individual source candidates)
- Selected events: hybrid events, $\theta < 60^o$, $10^{17.3}$ eV $< E < 10^{18.5}$ eV
- 5 mass-sensitive observables used to train a BDT
- A combined p-value P is associated to each target
  → **no evidence of EeV photon** (statistical significance always lower than 3σ)
  → upper limits are set → constraints on the extrapolation of TeV spectra to EeV energies (e.g. E_{cut} < 2 EeV for the Galactic center)

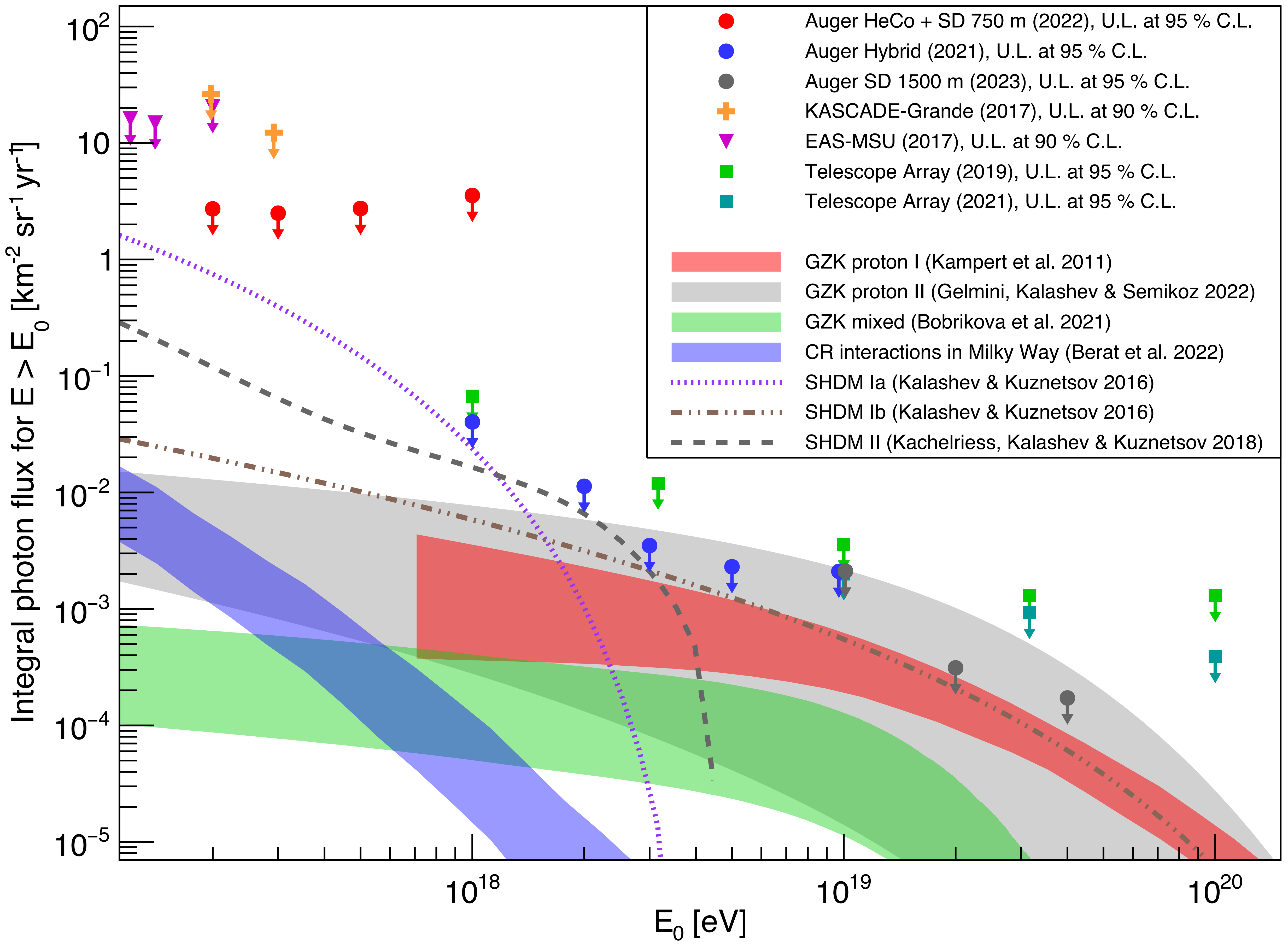
$$w_i = \frac{f_i \cdot \epsilon_i}{\sum_i f_i \cdot \epsilon_i}$$

$$p_i \equiv [\text{Poisson}(n_i, b_i) + \text{Poisson}(n_i + 1, b_i)]/2.$$

$$\mathcal{P}_w = \text{Prob}(\prod_i p_{i,\text{iso}}^{w_i} \leqslant \prod_i p_i^{w_i})$$

The diffuse photon flux

No photon has been unambiguously detected so far but **upper limits have been set above 2 x 10^{17} eV**



Upper limit on the integral flux at 95% C.L.

Feldman-Cousins upper limit for 0 background

$$\Phi_{UL}^{0.95}(E_\gamma > E_0) = \frac{N_\gamma^{0.95}(E_\gamma > E_0)}{\mathcal{E}_\gamma(E_\gamma > E_0 | E_\gamma^{-\Gamma})}$$

Integrated exposure for $E^{-\Gamma} = E^{-2}$

$$\mathcal{E}_\gamma = \frac{1}{c_E} \int_{E_\gamma} \int_T \int_S \int_\Omega E_\gamma^{-\Gamma} \epsilon(E_\gamma, t, \theta, \phi, x, y)\, dS\, dt\, dE d\Omega$$

$$c_E = \int E^{-\Gamma} dE$$

Follow-up of gravitational wave events

- Goal: search for UHE photons and neutrinos from the sources of gravitational waves (GW)
- **Two time windows: Δ=1000 s starting 500 s before the GW event**
  Δ=24 h starting 500 s after the GW event

- The ±500 s window: upper limit on the duration of the prompt phase of GRBs, when typically PeV neutrinos are thought to be produced in interactions of accelerated cosmic rays and the gamma rays within the GRB itself.
- The 1-day window after the GW event: conservative upper limit on the duration of GRB afterglows, where ultrahigh-energy neutrinos are thought to be produced in interactions of UHECRs with the lower-energy photons of the GRB afterglow.

The neutrino diffuse flux

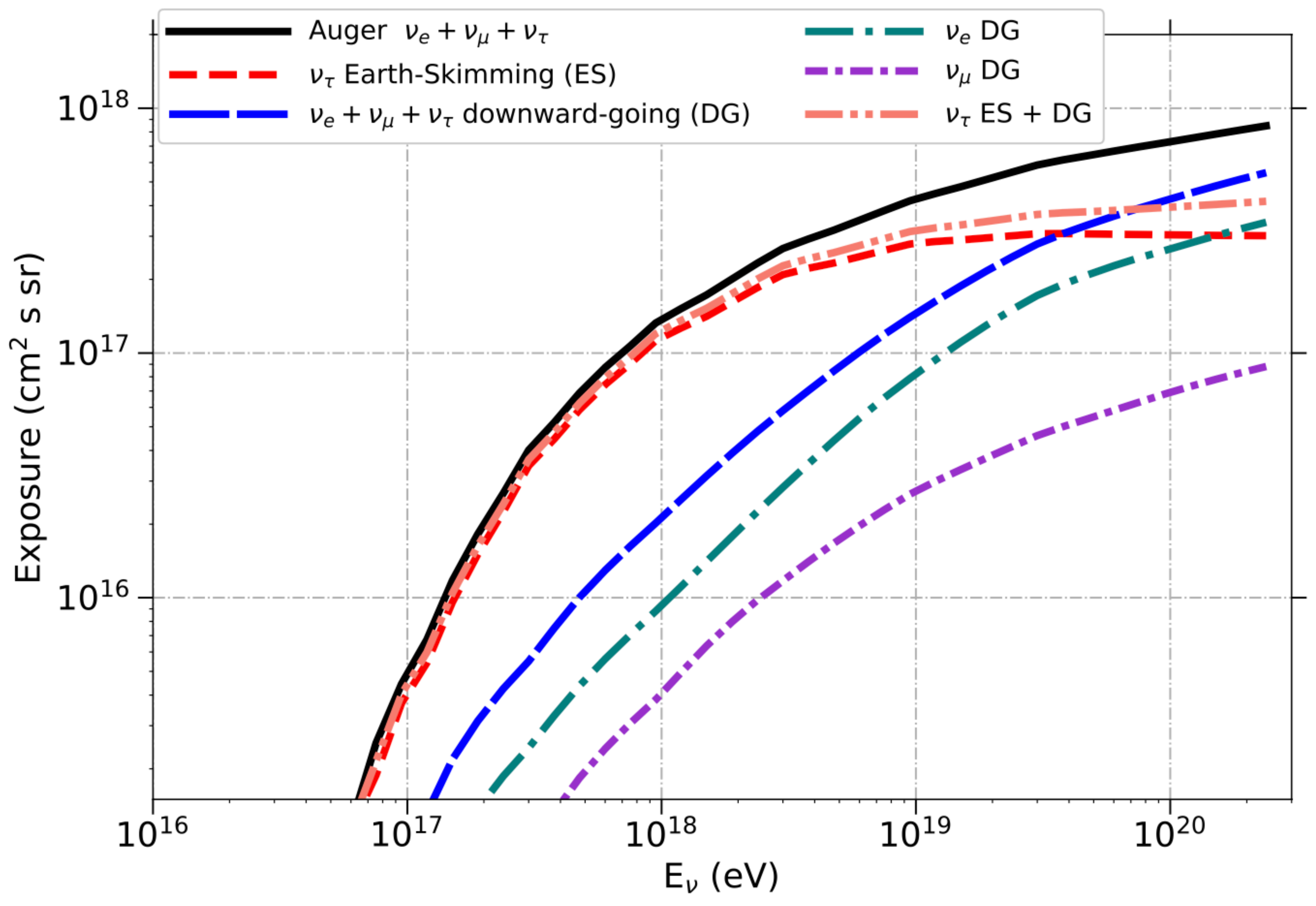


Figure 5. Exposure of the SD of the Pierre Auger Observatory (1 January 2004 - 31 August 2018) to UHE neutrinos as a function of neutrino energy for each neutrino flavor and for the sum of all flavors assuming a flavor mixture of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$. Also shown are the exposures to upward-going Earth-skimming ν_τ only and to the Downward-Going neutrinos of all flavors including CC and NC interactions.

The exposure of the SD of Auger needs to be calculated for the period of data taking:

- Monte Carlo simulations of neutrino-induced showers.
- The same selection and identification criteria applied to the data were also applied to the results of these simulations
- The identification efficiencies for each channel were obtained as the fraction of simulated events that trigger the Observatory and pass the selection procedure and identification cuts
- An integration over the whole parameter space, detection area, and time gives the exposure

[The Pierre Auger Collaboration, *JCAP10(2019)022]*

The neutrino diffuse flux

The total exposure folded with a single-flavor flux of UHE neutrinos per unit energy, area A, solid angle Ω and time, $\phi(E\nu)$ and integrated in energy gives the expected number of events for that flux

$$N_{\rm evt} = \int_{E_\nu} \mathcal{E}_{\rm tot}(E_\nu)\ \phi(E_\nu)\ {\rm d}E_\nu$$

Assuming a differential flux $\phi = k \cdot E_\nu^{-2}$, the upper limit to k at 90% C.L. is given by:

$$k_{90} = \frac{2.39}{\int_{E_\nu} E_\nu^{-2}\ \mathcal{E}_{\rm tot}(E_\nu)\ {\rm d}E_\nu}$$

Feldman-Cousins factor in absence of background

Exposure

Differential upper limits to the normalization of the diffuse flux: integrating the denominator in bins of width 0.5 in log (Eν) .

The integrated upper limit is:

$$k_{90} \ < \ 4.4 \ \times \ 10^{-9}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

value of the normalization of a differential flux needed to predict ~ 2.39 events

[The Pierre Auger Collaboration, *JCAP10(2019)022]*