RICAP-22 ROMA INTERNATIONAL CONFERENCE
ON ASTRO-PARTICLE PHYSICS

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Searching for multi-messenger signals with the Pierre Auger Observatory

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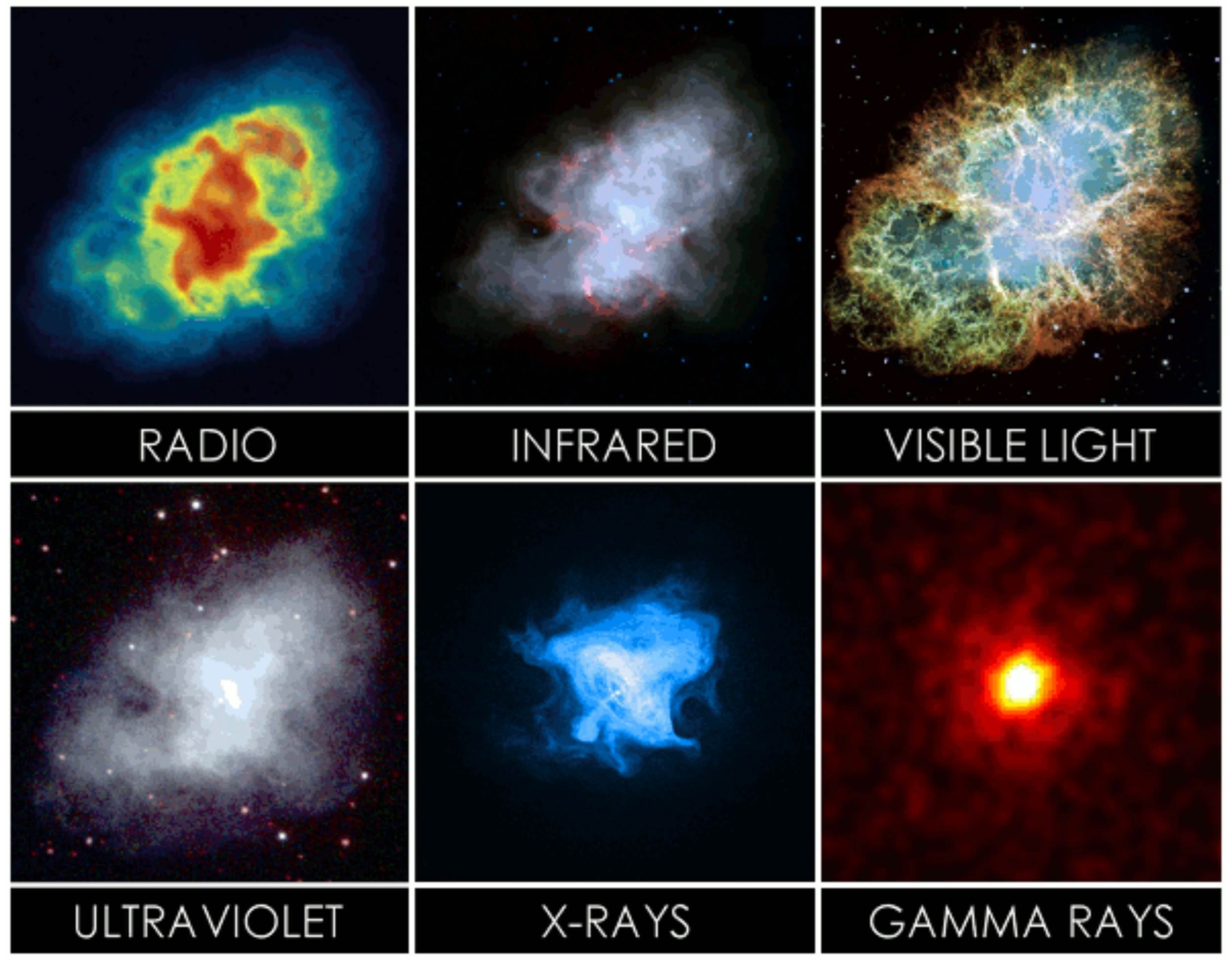
Multi-messenger astronomy

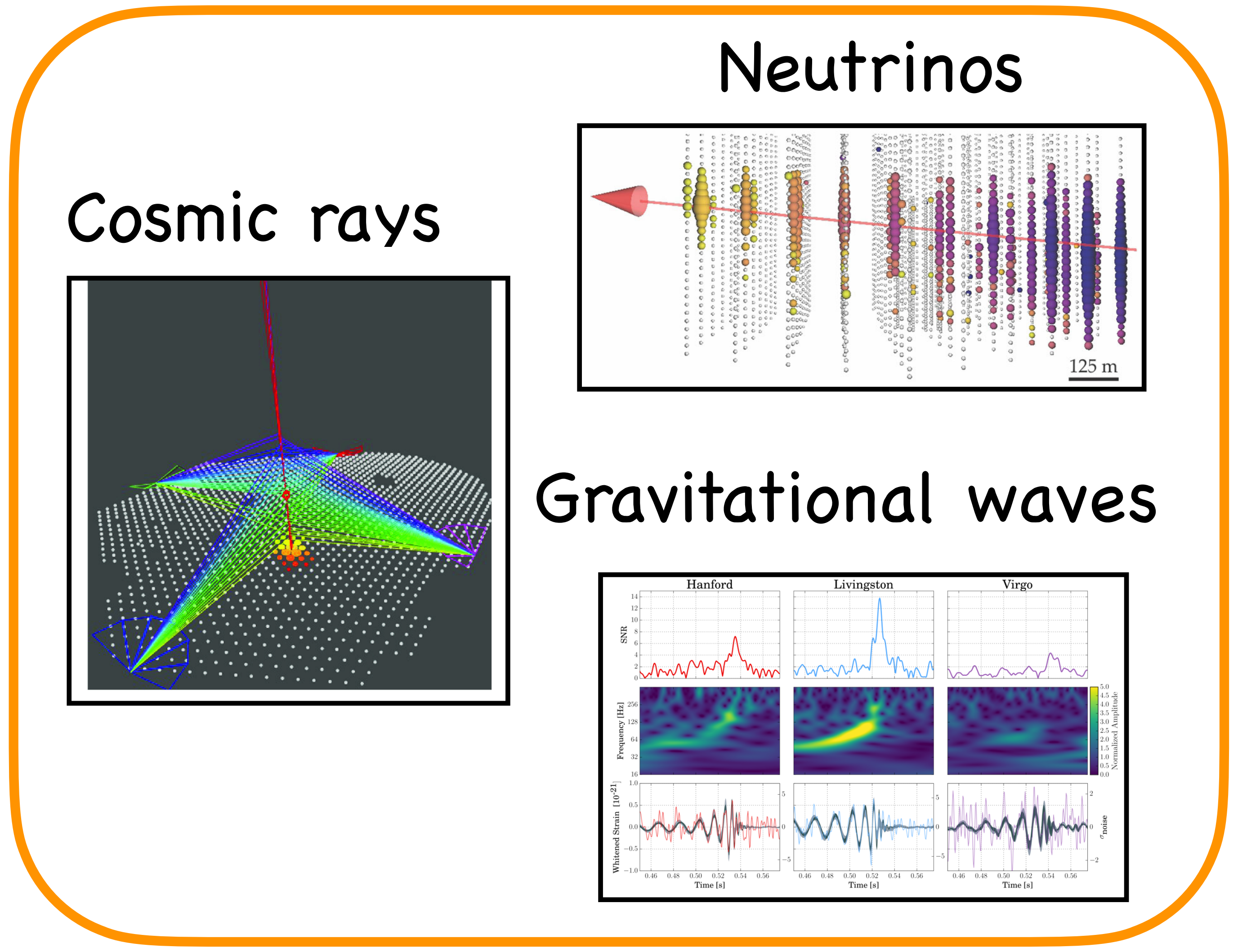
Combining the *<u>information from any particle and radiation</u>* coming from astrophysical objects

→ **complementary insight on the most energetic events in the Universe**

- Sources studied through different wavelengths of the electromagnetic spectrum + observation in 1987 of neutrinos coming from a SN



- Neutrino astronomy & observation of gravitational waves → **<u>recent boost of multi-messenger studies</u>**



Additional messengers

- 2017: measurements of the **electromagnetic spectrum emission in coincidence with the first neutron star merger** observed by LIGO and Virgo,
- 2018: IceCube observed a **high-energy neutrino (~290 TeV) in coincidence with a flaring gamma-ray blazar.**

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

They can be observed by the Pierre Auger Observatory

Neutral particles which point back to their origin

Alerts crucial to study transient events

Cosmic rays (nuclei):
- Accelerated by extreme astrophysical events
- **Deflected by magnetic fields**

Gamma-rays:
- Propagate in straight lines
- **Easily absorbed** at ultra-high energies

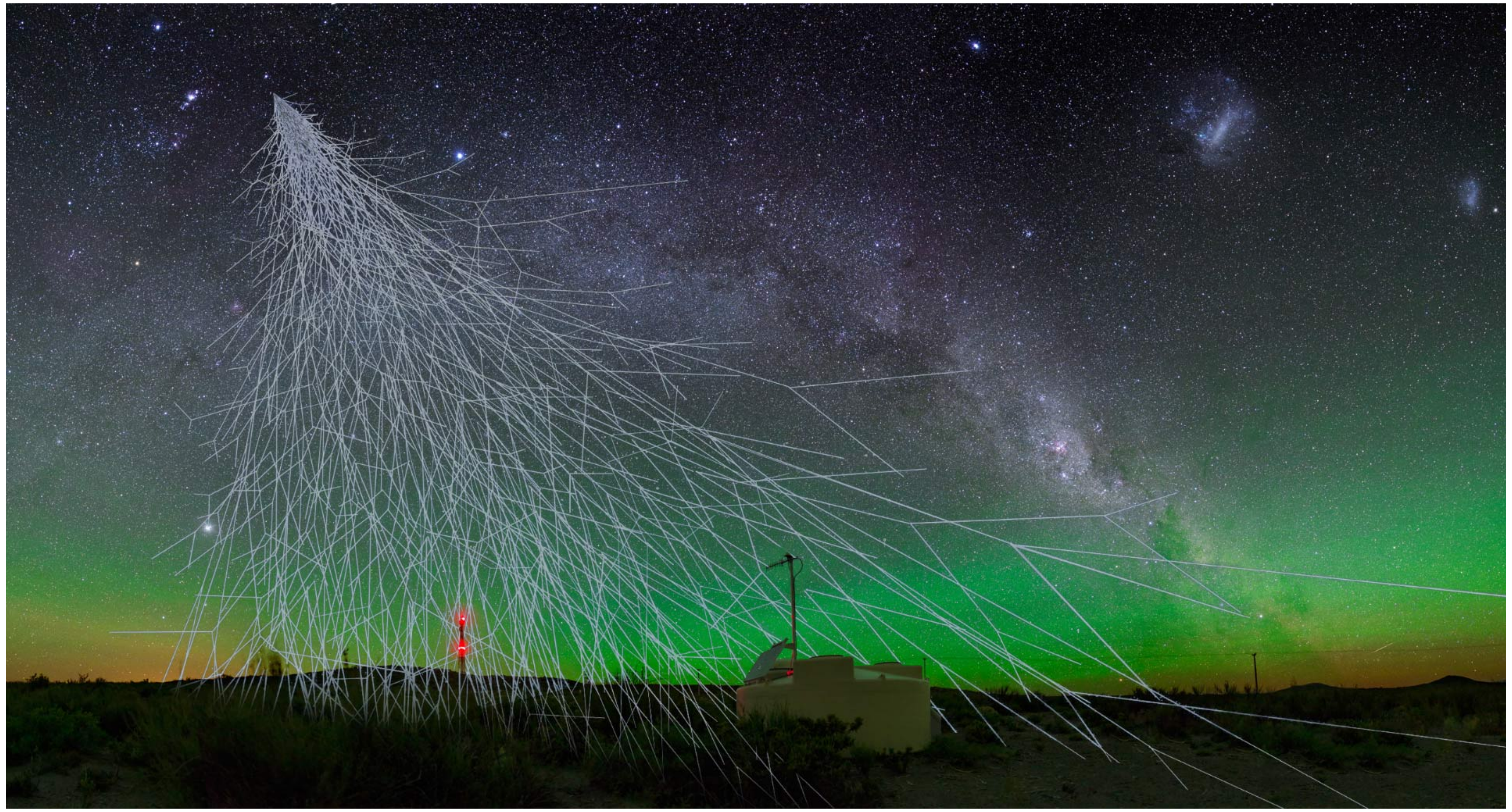
Neutrinos:
- Not deflected and not absorbed
- Low interaction rate → **difficult to detect**

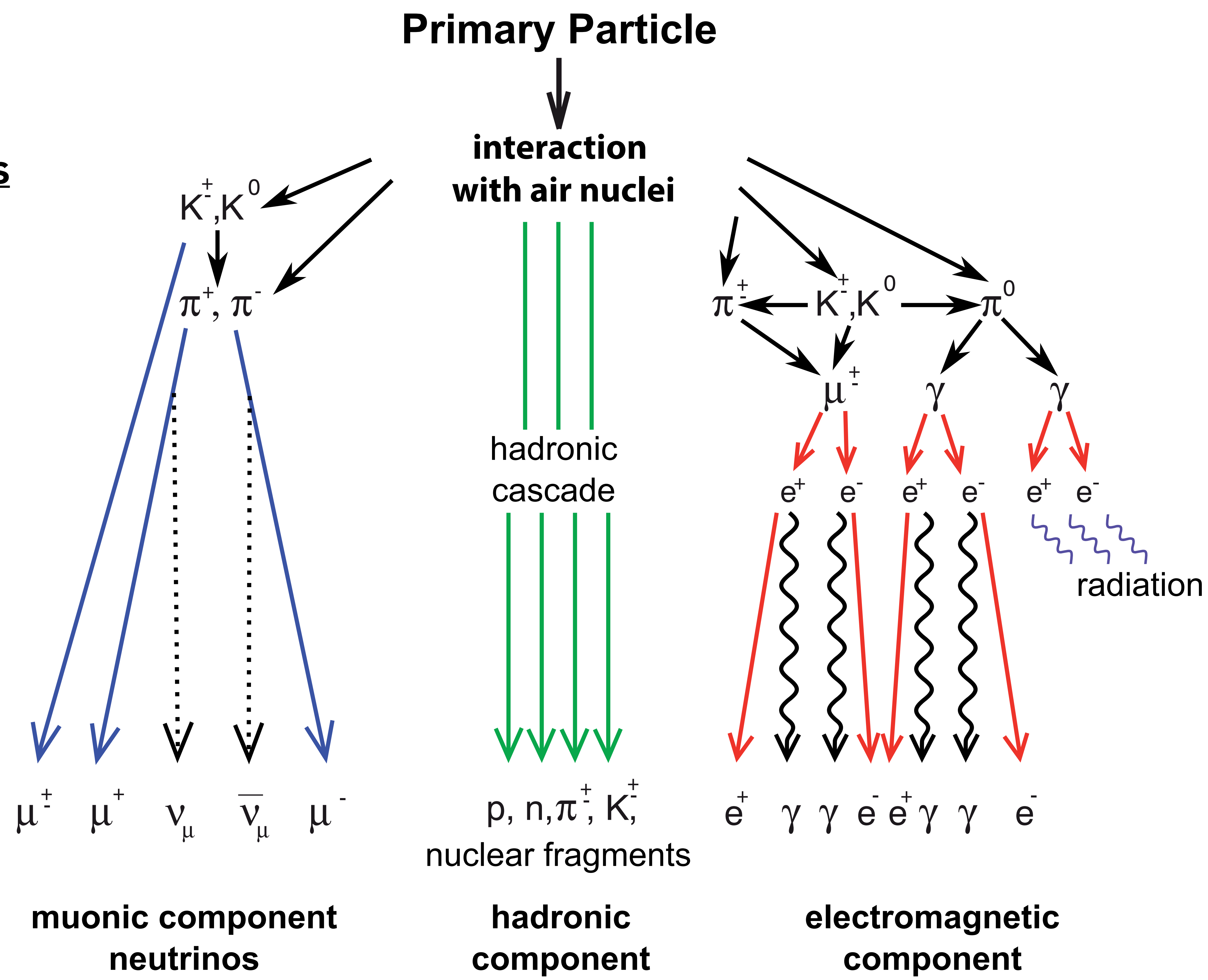
Neutrons:
- Propagate in straight lines
- **Not distinguishable from protons**

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**





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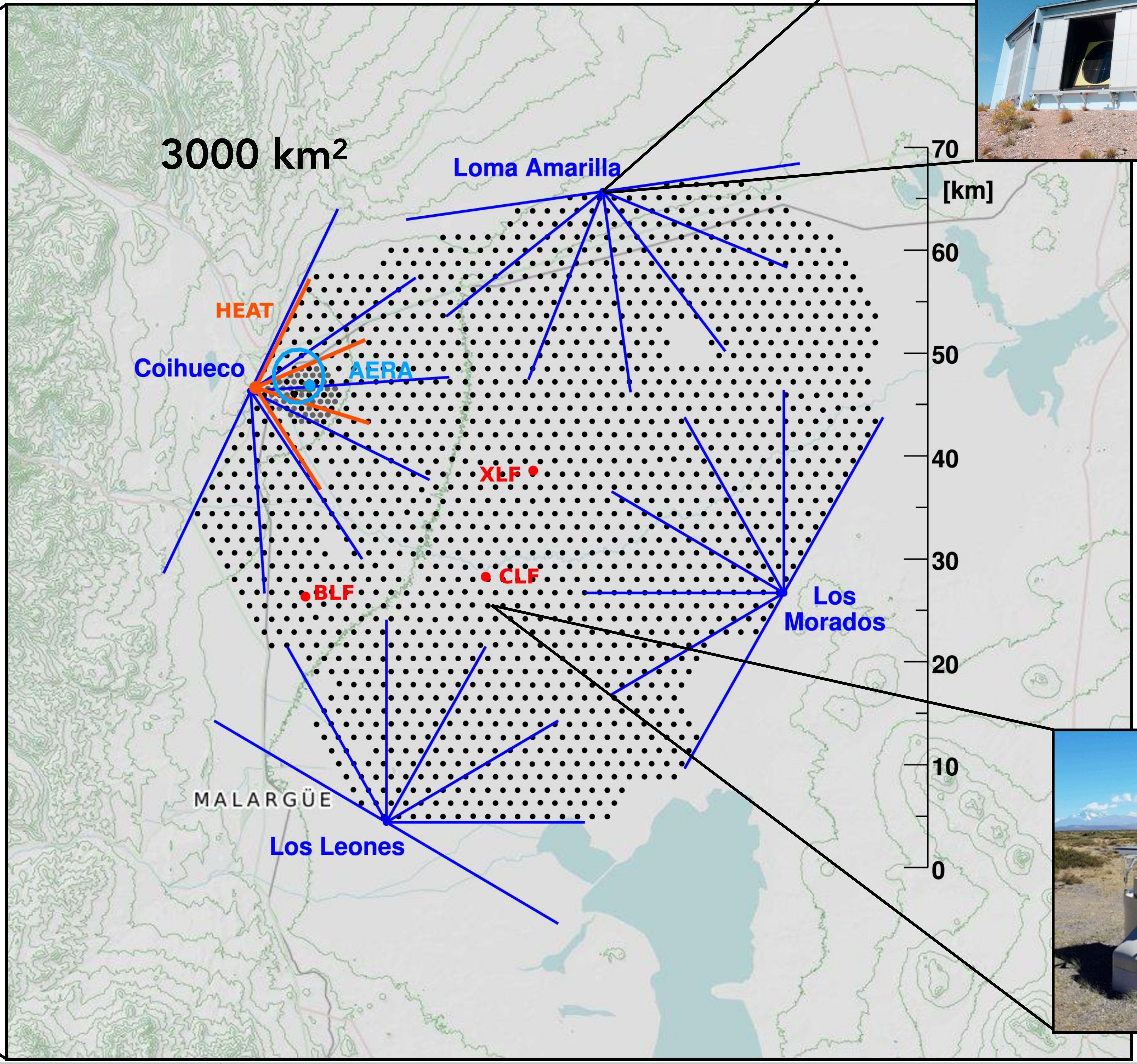
The Pierre Auger Observatory

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

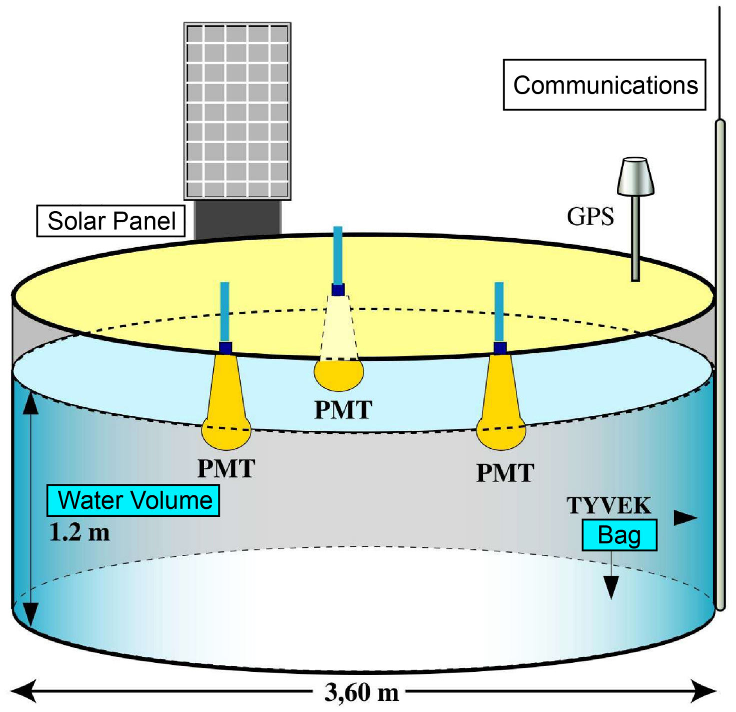
SD

4

The Pierre Auger Observatory

Surface Detector (SD)

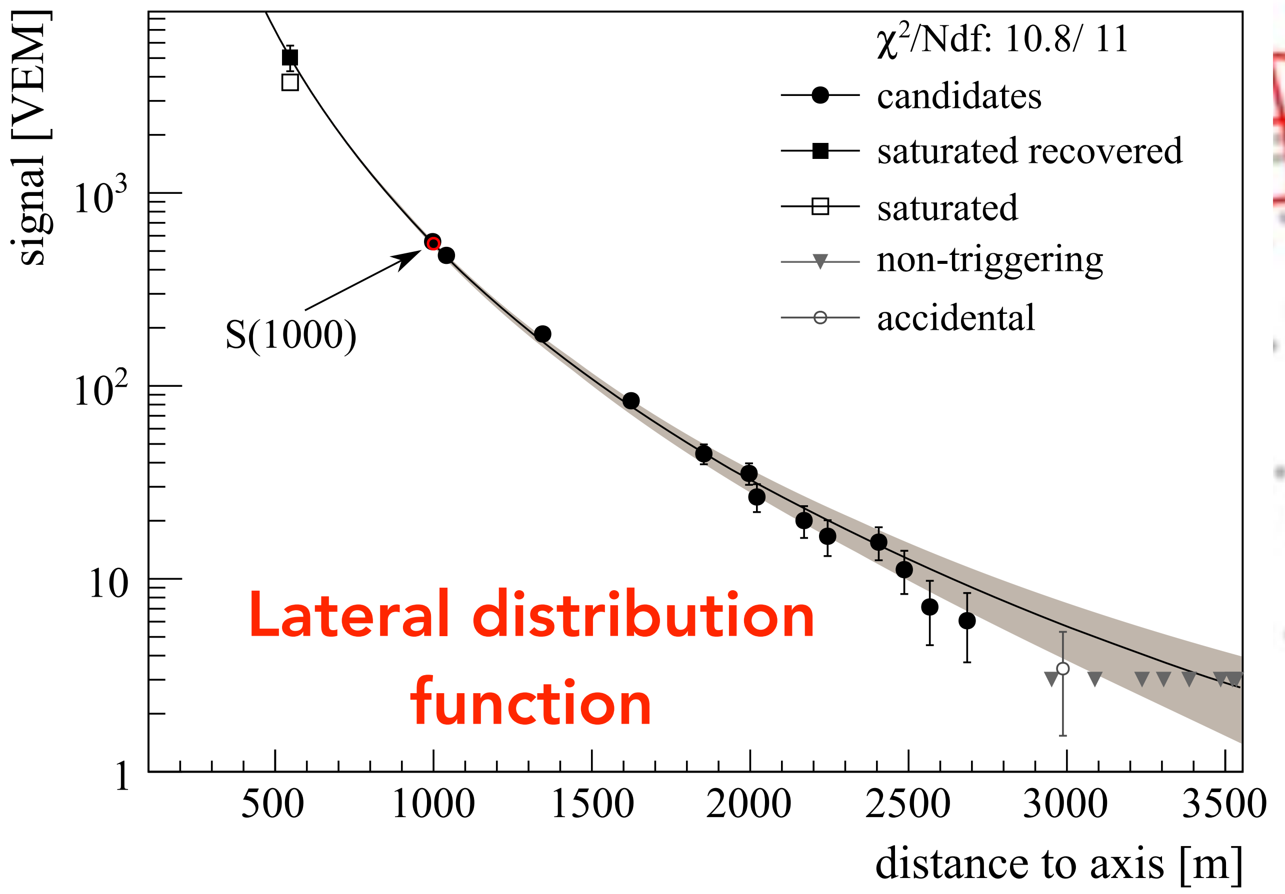
- 1660 water-Cherenkov tanks covering a ~3000 km^2 area, with a spacing of 1.5 km (and a denser smaller array for lower energies)
- 3 PMTs collecting the light produced within the tank

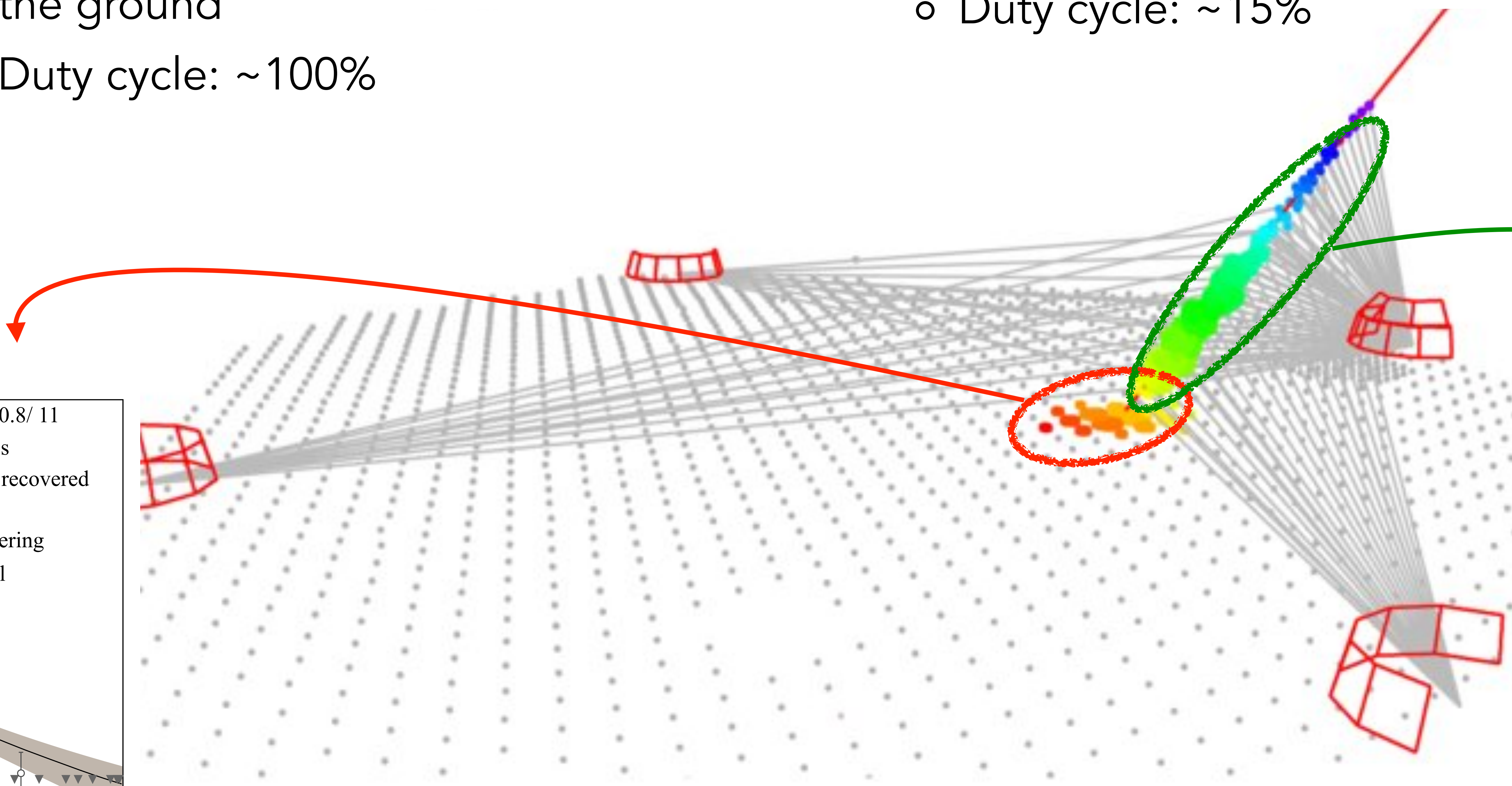


- Sampling the shower particles reaching the ground
- Duty cycle: ~100%

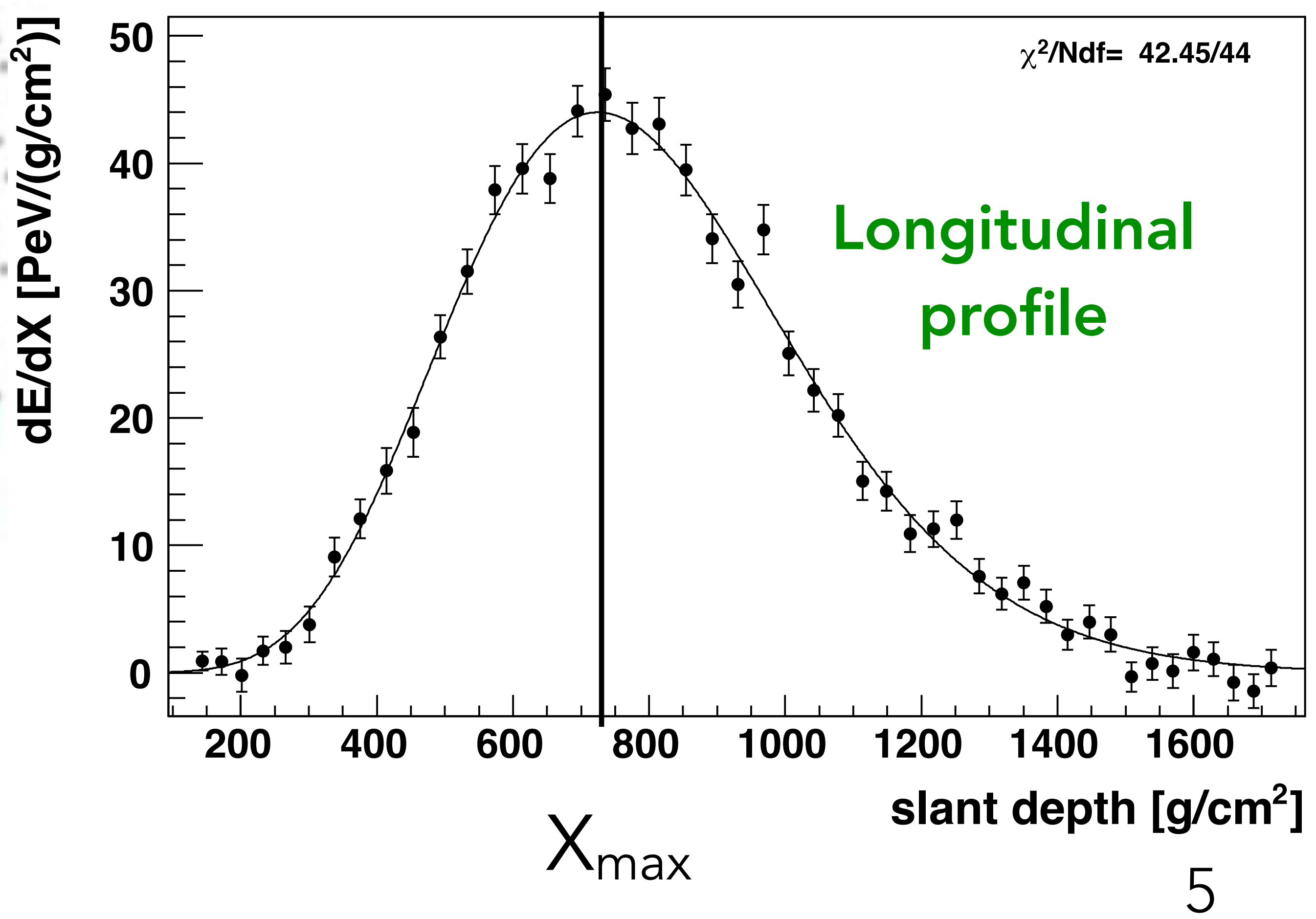
Fluorescence Detector (FD)

- 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%





Hybrid events = observed by both detectors



Photon identification at the Pierre Auger Observatory

Photon search

- ✳ The Pierre Auger Observatory is sensitive 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 → used to **study steady and transient sources**

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

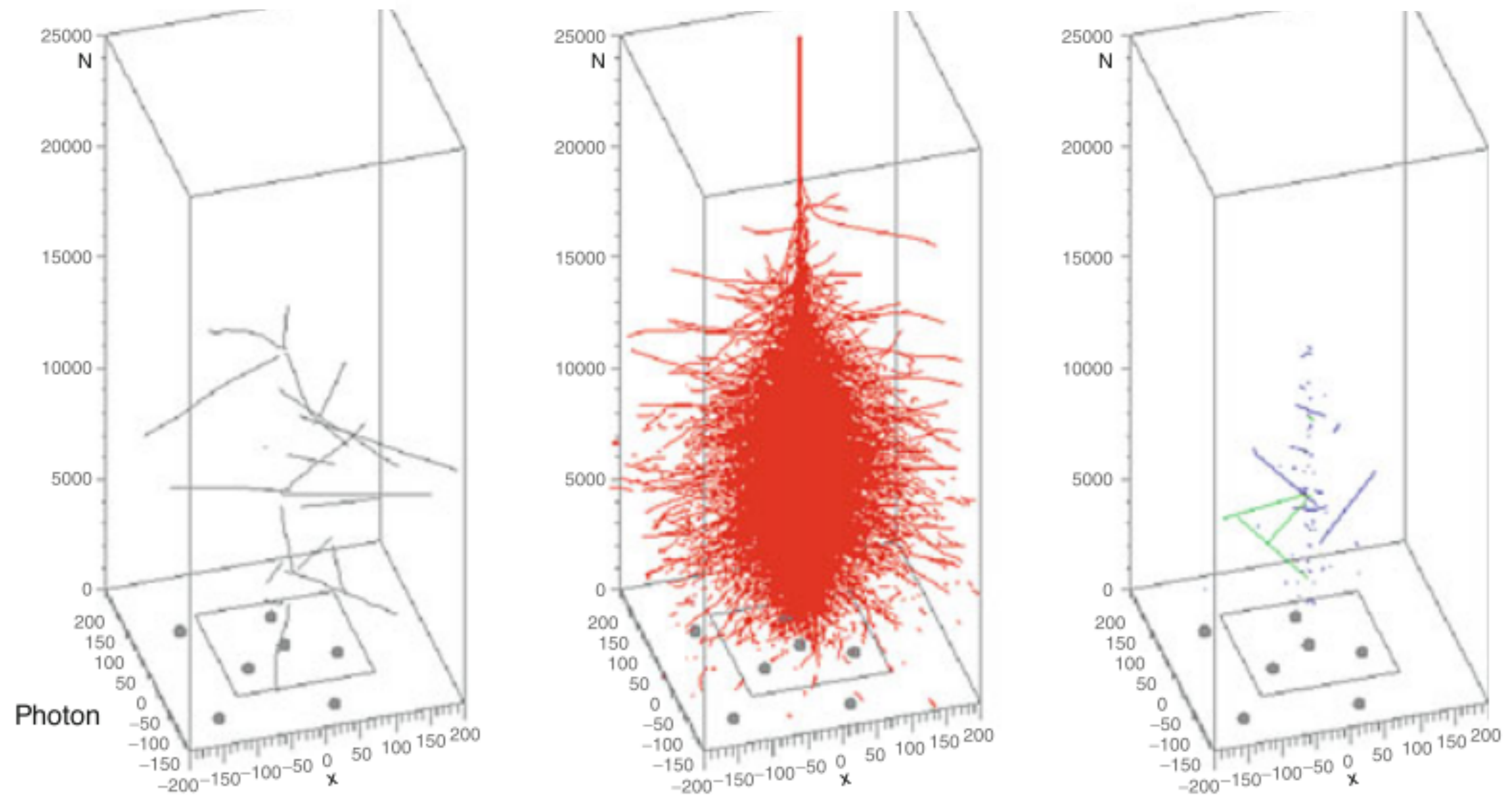
A photon-initiated shower is dominated by EM interaction

→ **deeper maximum of shower development**

→ **less muons at the ground**

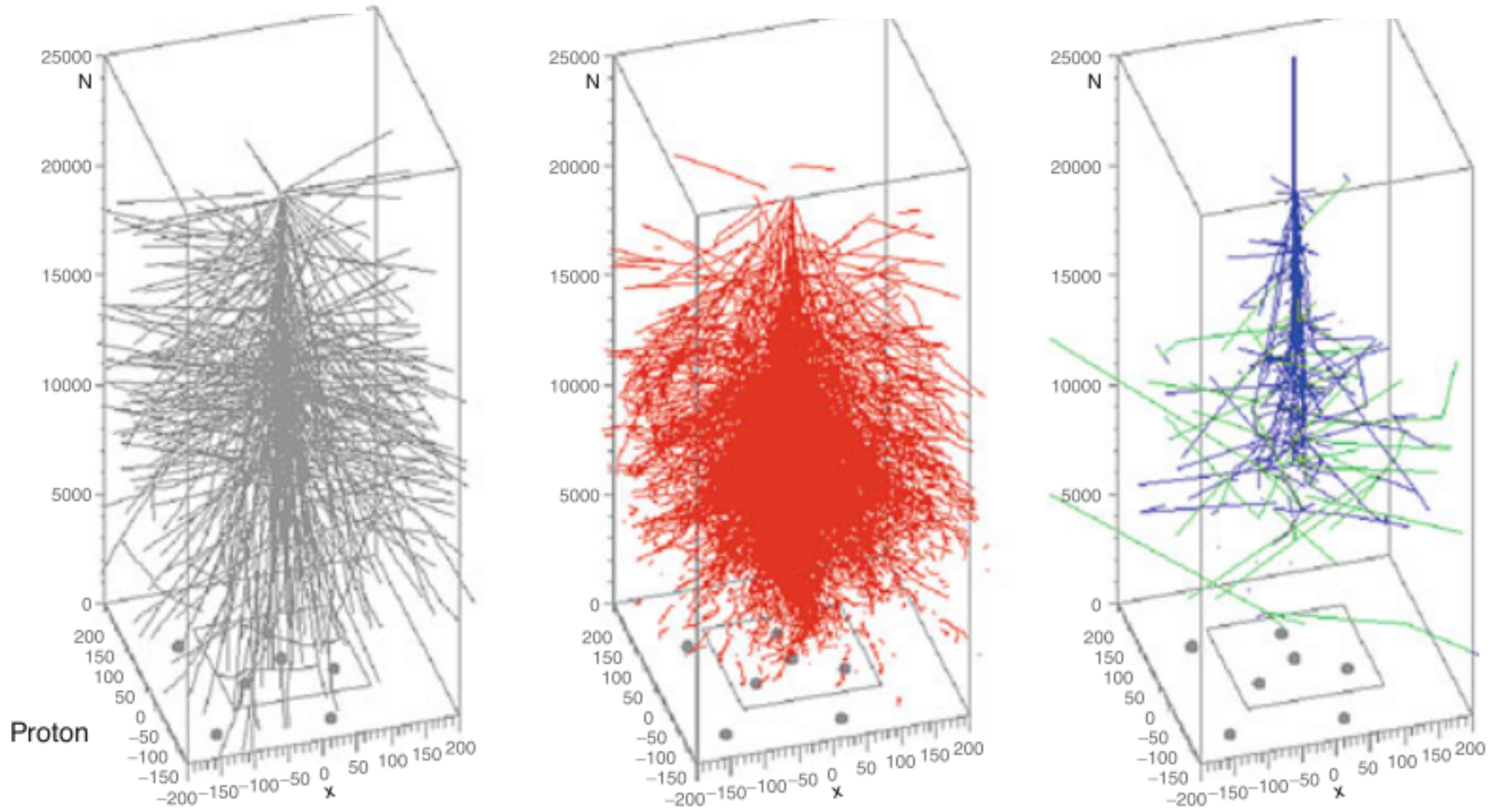
Muonic **Electromagnetic** **Hadronic**

Photon



Muonic **Electromagnetic** **Hadronic**

Proton



The diffuse photon flux

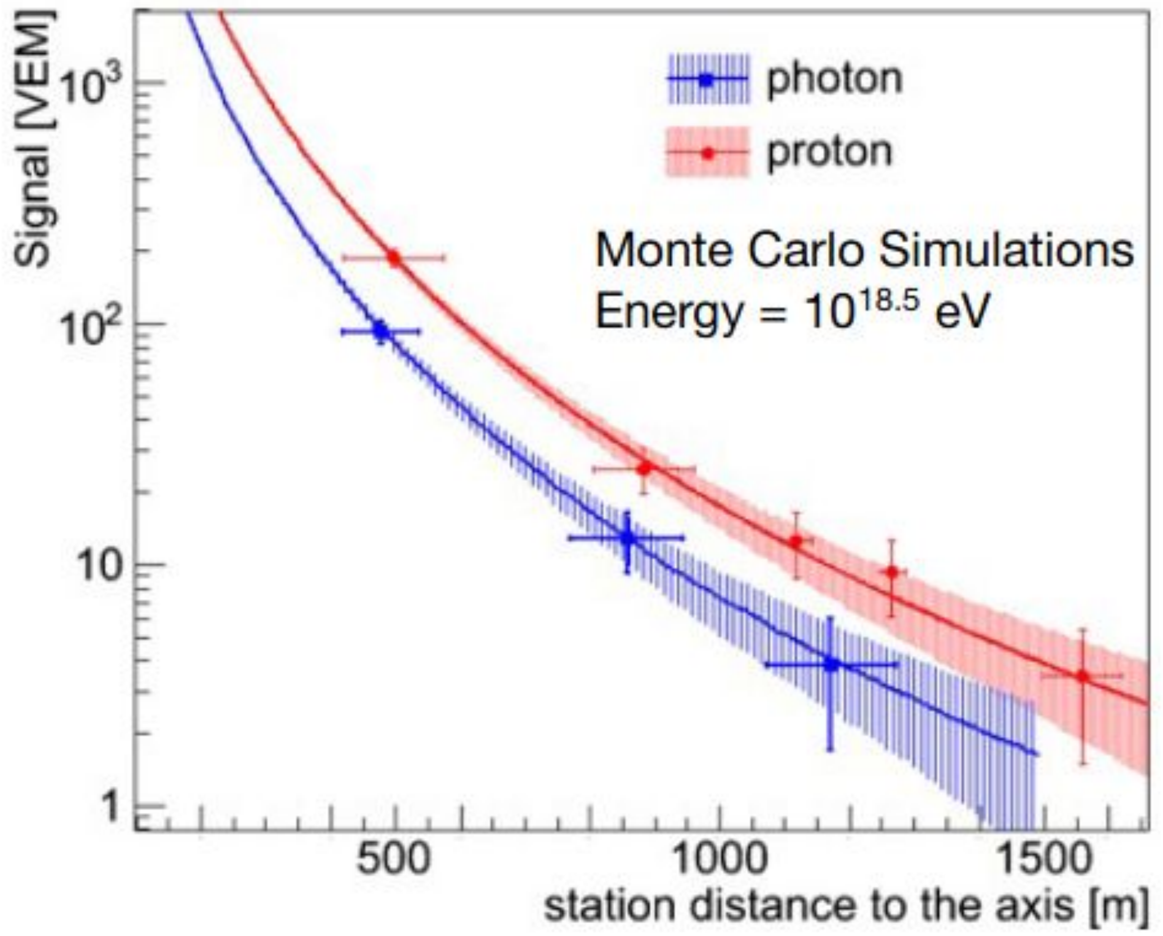
E > 10^{19} eV

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

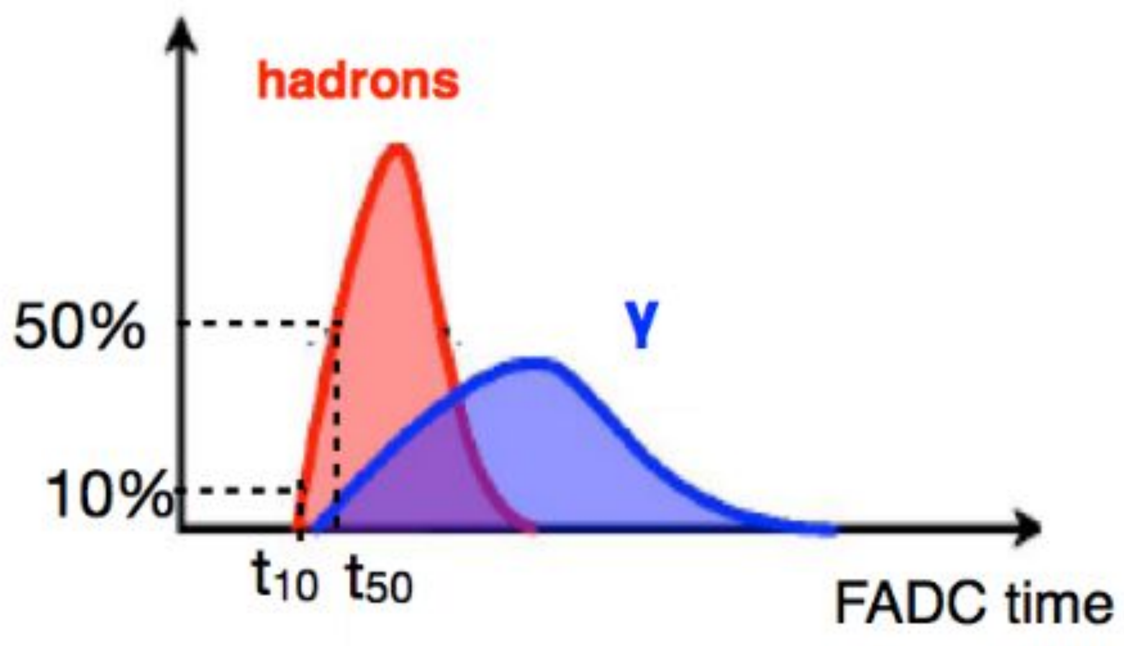
How to distinguish SD photon events:

- Steeper LDF (less muons) → observable $\mathbf{S_{LDF}}$
- Slower rising signal in the single SD triggered stations → risetime $\mathbf{t_{1/2}}$
- $\mathbf{S_{LDF}}$, $\mathbf{t_{1/2}}$ are transformed with a Principal Component Analysis (PCA).

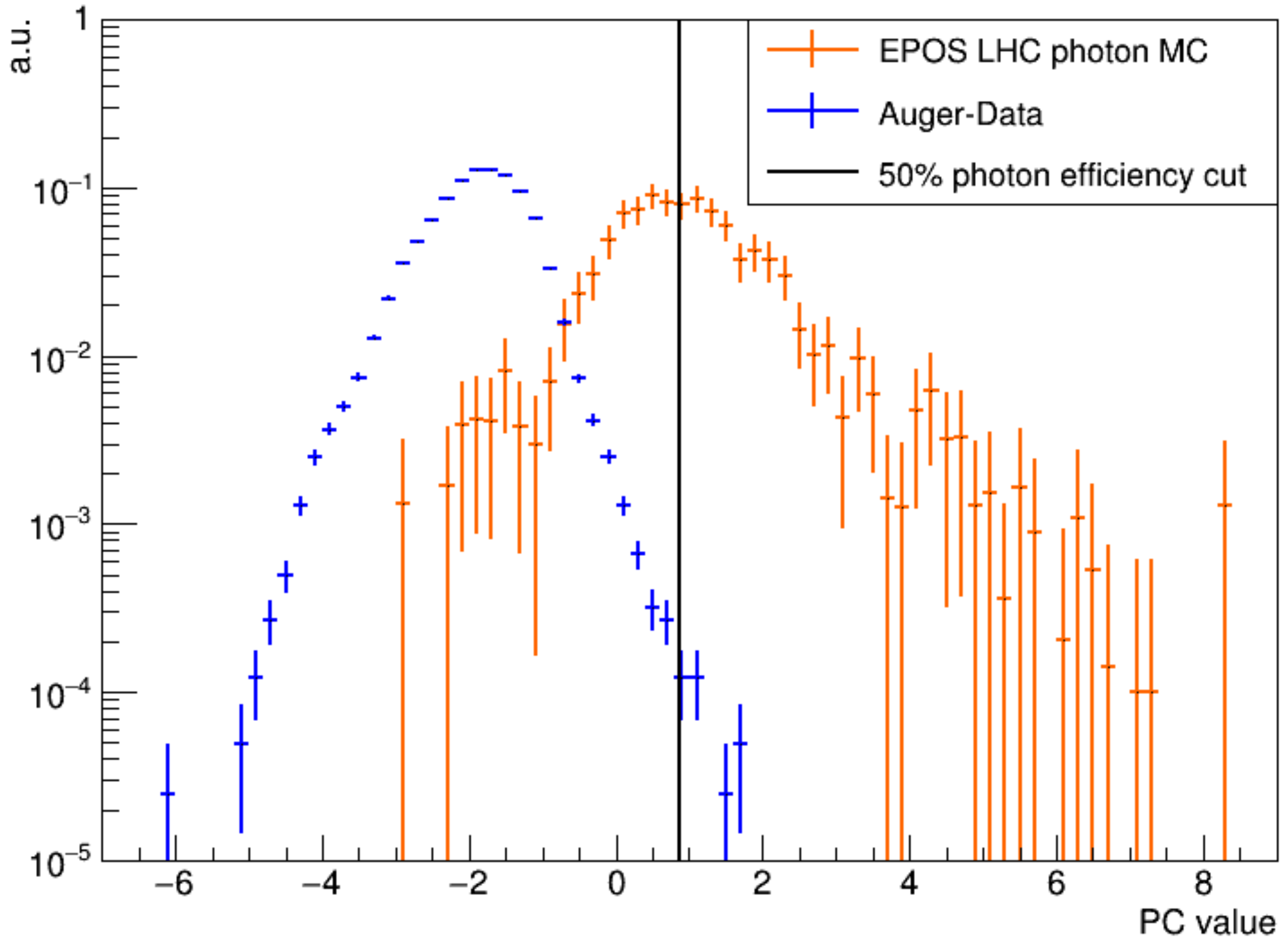
LDF



Signal risetime in a SD station



Risetime: $t_{1/2} = t_{50\%} - t_{10\%}$



Cut set at 50% of the photon distribution

The diffuse photon flux

Photon search

E < 10^{19} eV

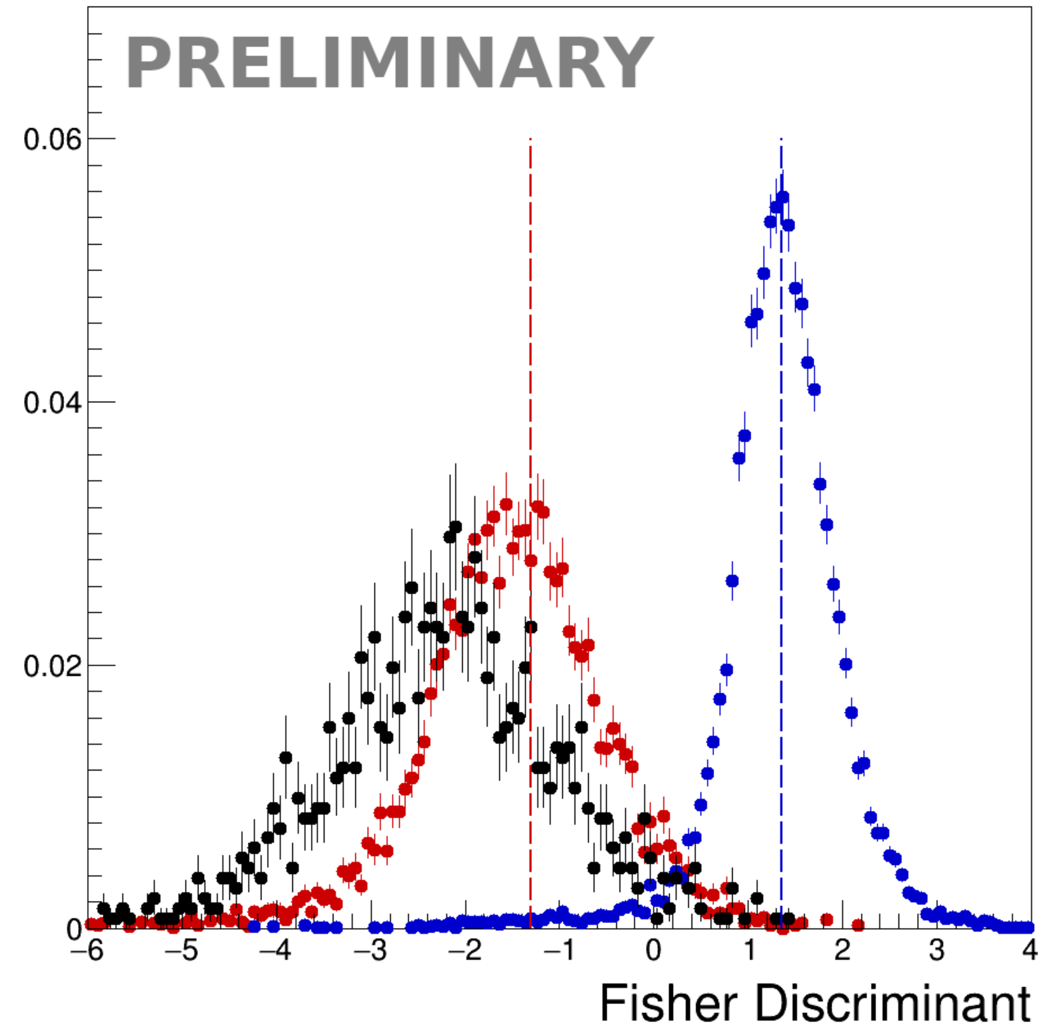
- FD+SD are used (hybrid measurements)
- Analysis applied also to the low-energy extensions of Auger → limits set above 2 x 10^{17} eV
- Zenith angles below 60°

How to distinguish hybrid photon events:

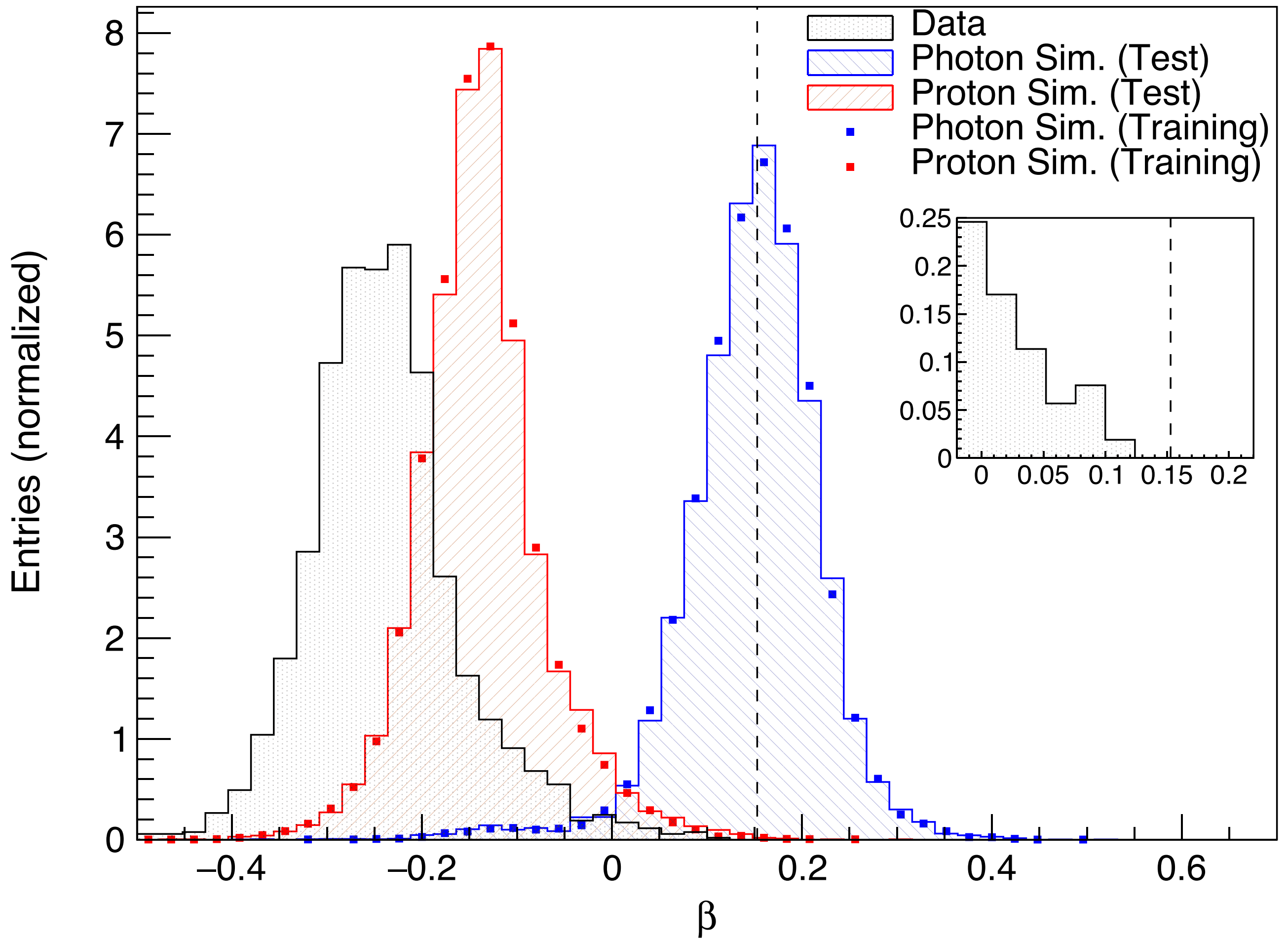
- FD measurements:
  → Larger depth of shower maximum $\mathbf{X_{max}}$
- SD measurements:
  → Smaller number of triggered SD stations $\mathbf{N_{SD}}$
  → Steeper LDF (less muons) → observable $\mathbf{S_b}$
- **The observables are combined to obtain a discriminant**

[The Pierre Auger Collaboration, *ApJ* **933** 125]

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



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

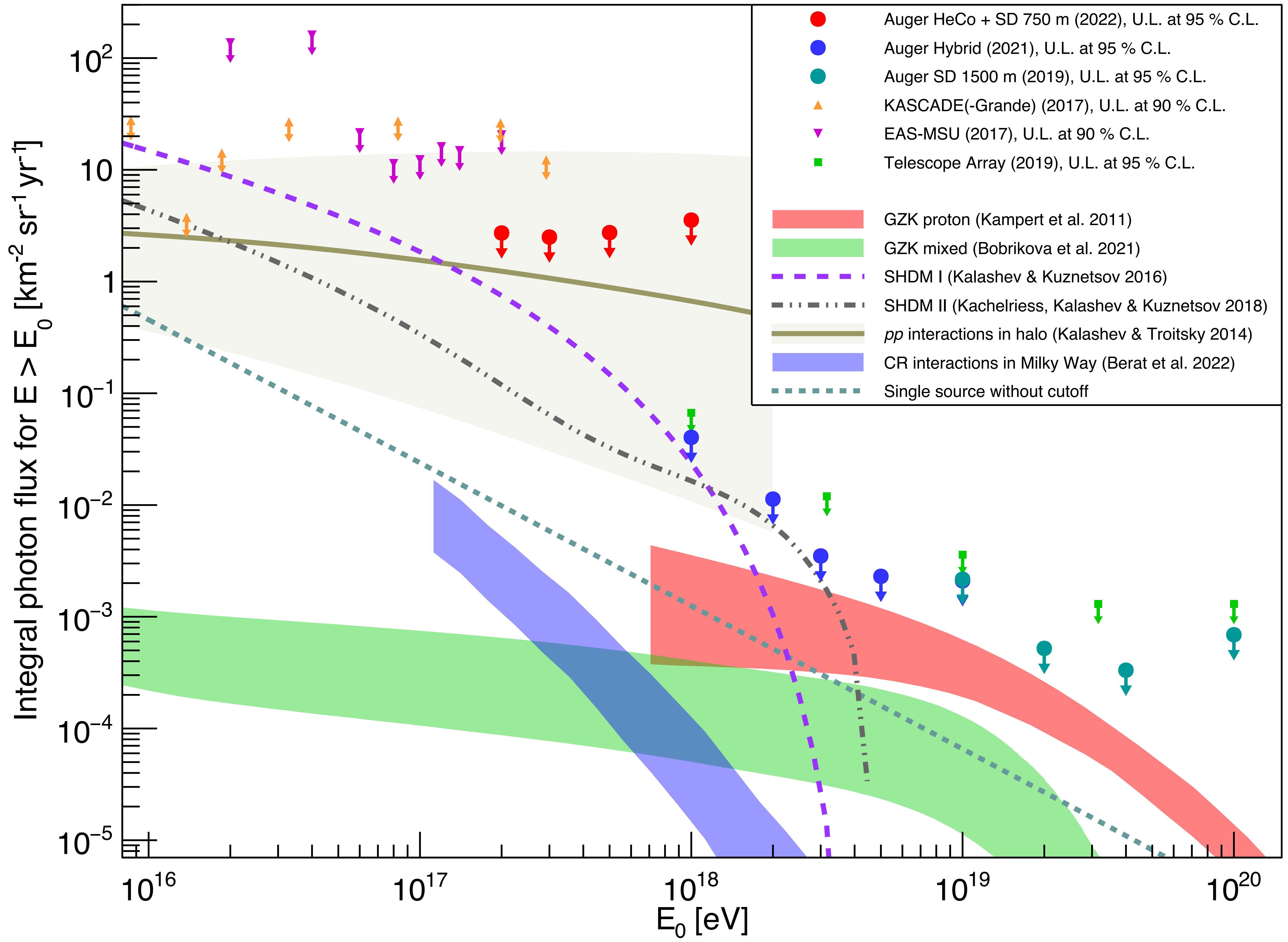


Cut set at 50% of the photon distribution

The diffuse photon flux

Photon search

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



<u>**Upper limit on the integral flux at 95% C.L.**</u>

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

Feldman-Cousins upper limit for 0 background

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

- Auger set the most stringent limits in that energy region
- 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)

[The Pierre Auger Collaboration, *ApJ* **933** 125]
[The Pierre Auger Collaboration, *JCAP04(2017)009*]
[The Pierre Auger Collaboration, *PoS(ICRC2019)398*]

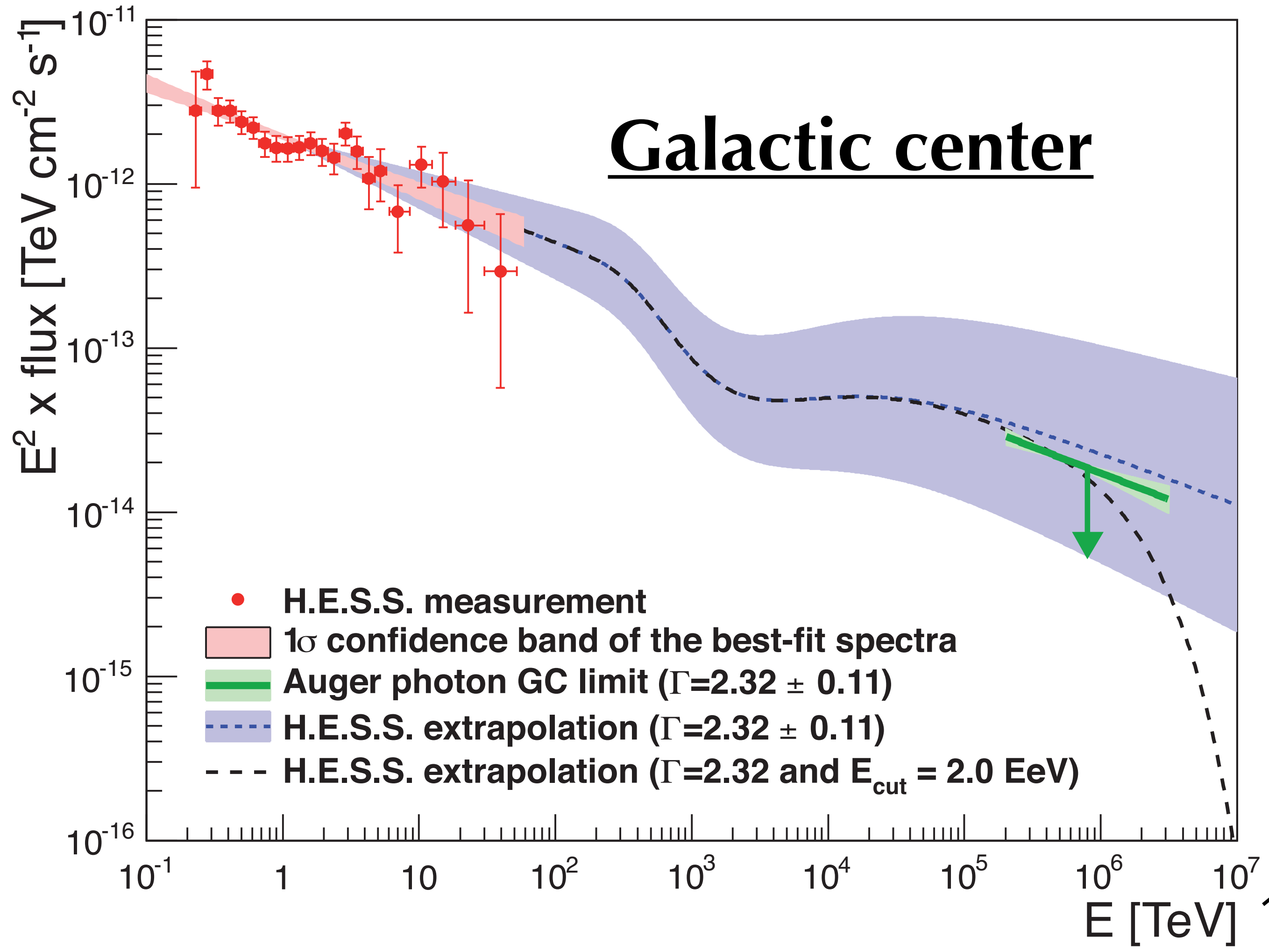
Photons from point-like sources

Photon search

- ✳ 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

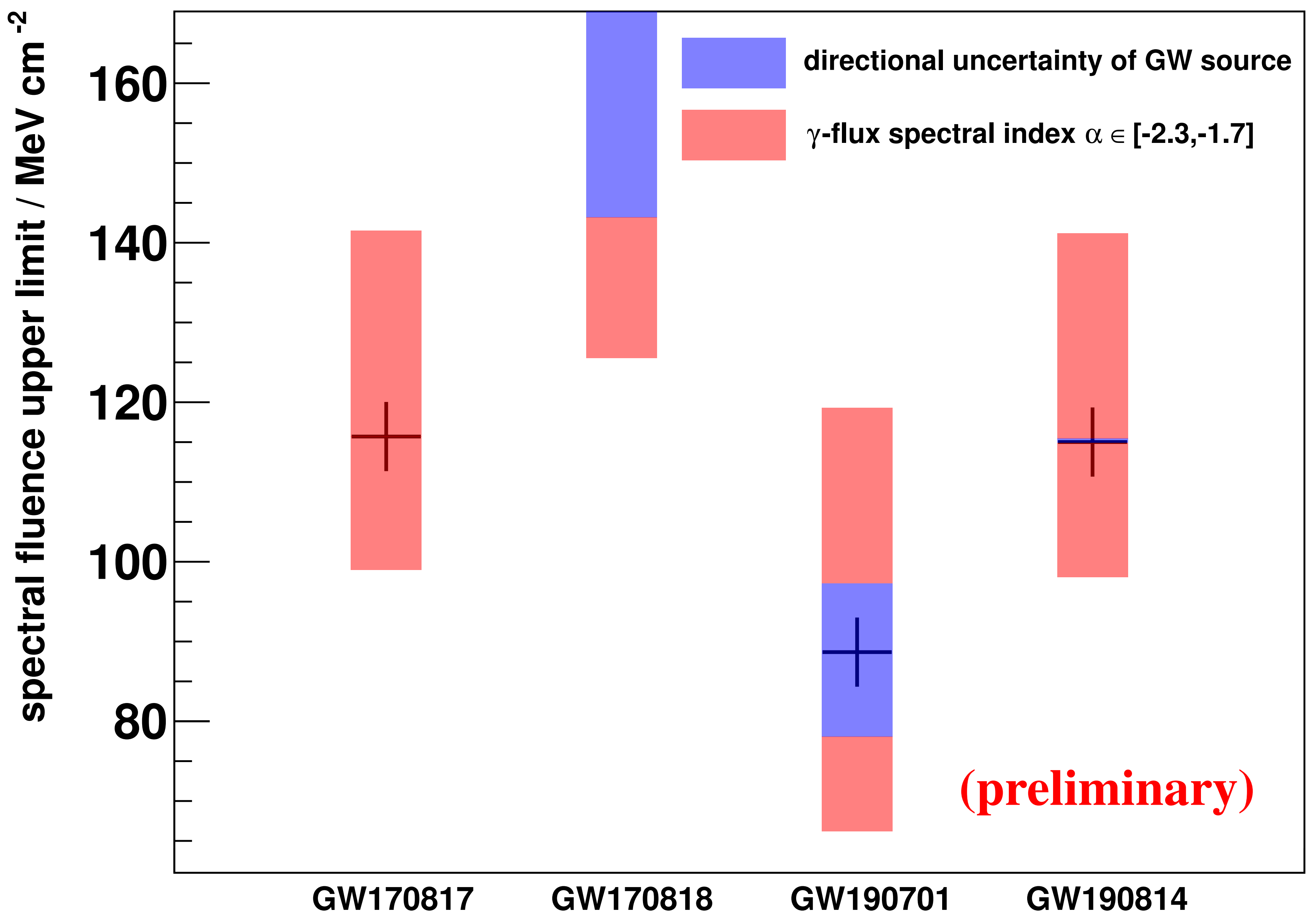
- Sources grouped in 12 target sets to have more significant signals (364 individual source candidates)
- Selected events: hybrid events, $\theta < 60^o$, $10^{17.3}$ eV $< E < 10^{18.5}$ eV
- 5 mass-sensitive observables used to train a BDT
- A combined p-value P is associated to each target
  → **no 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)



Follow-up of gravitational wave events

Photon search

- ✳ Goal: search for UHE photons from the sources of gravitational waves (GW)
- ✳ The SD data 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 4 GW events overlap with the field of view of the SD during the 1 day time window** (including a BNS merger event identified as hosted by the galaxy NGC 4993)



PoS(ICRC2021)973

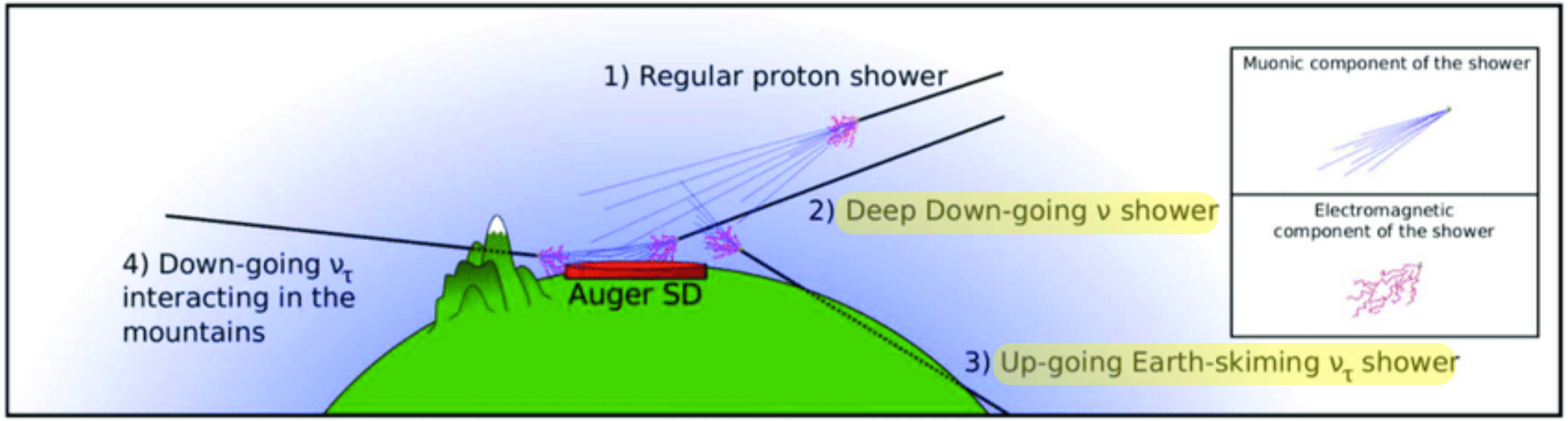
- No photon candidate has been observed
- For each GW event upper limit on the photon spectral fluence at 90% C.L.

Neutrino identification at the Pierre Auger Observatory

* The Pierre Auger Observatory is sensitive also to **UHE neutrinos**
* As UHE photons, 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**



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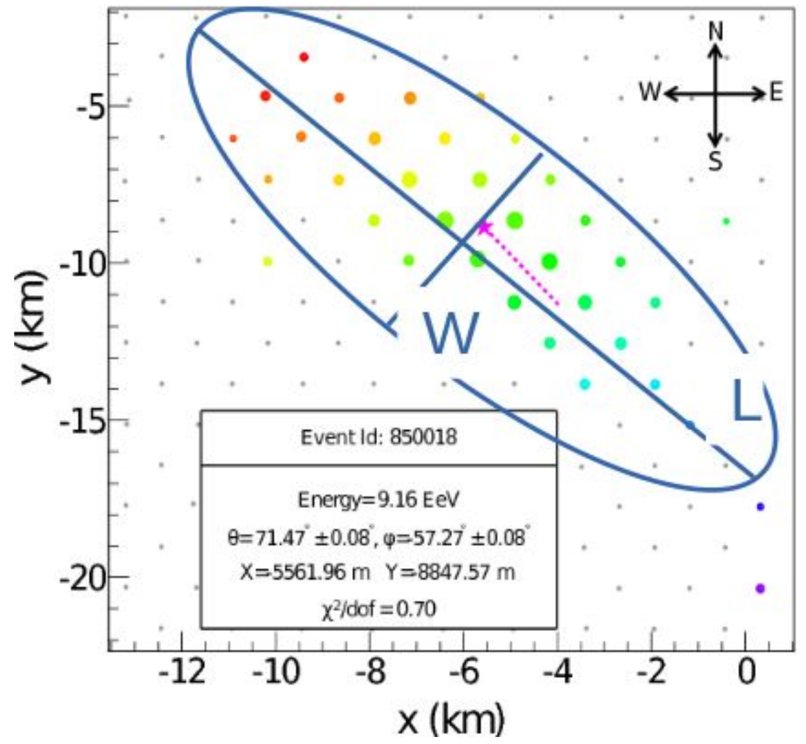
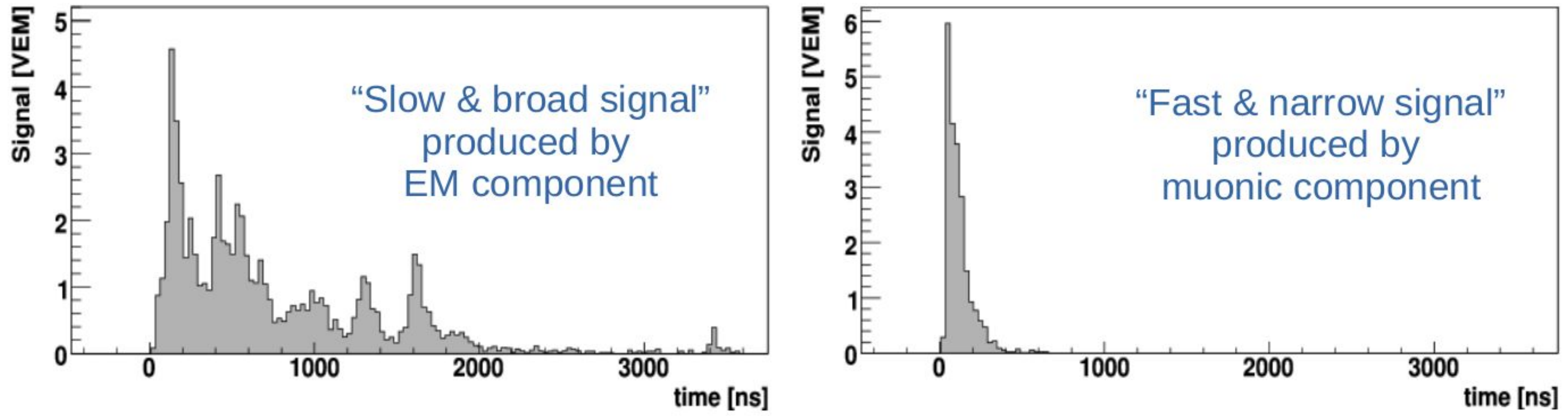
Search for **inclined showers** ($\theta > 60^o$) with a **large electromagnetic component** at the ground (SD data are used)

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

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

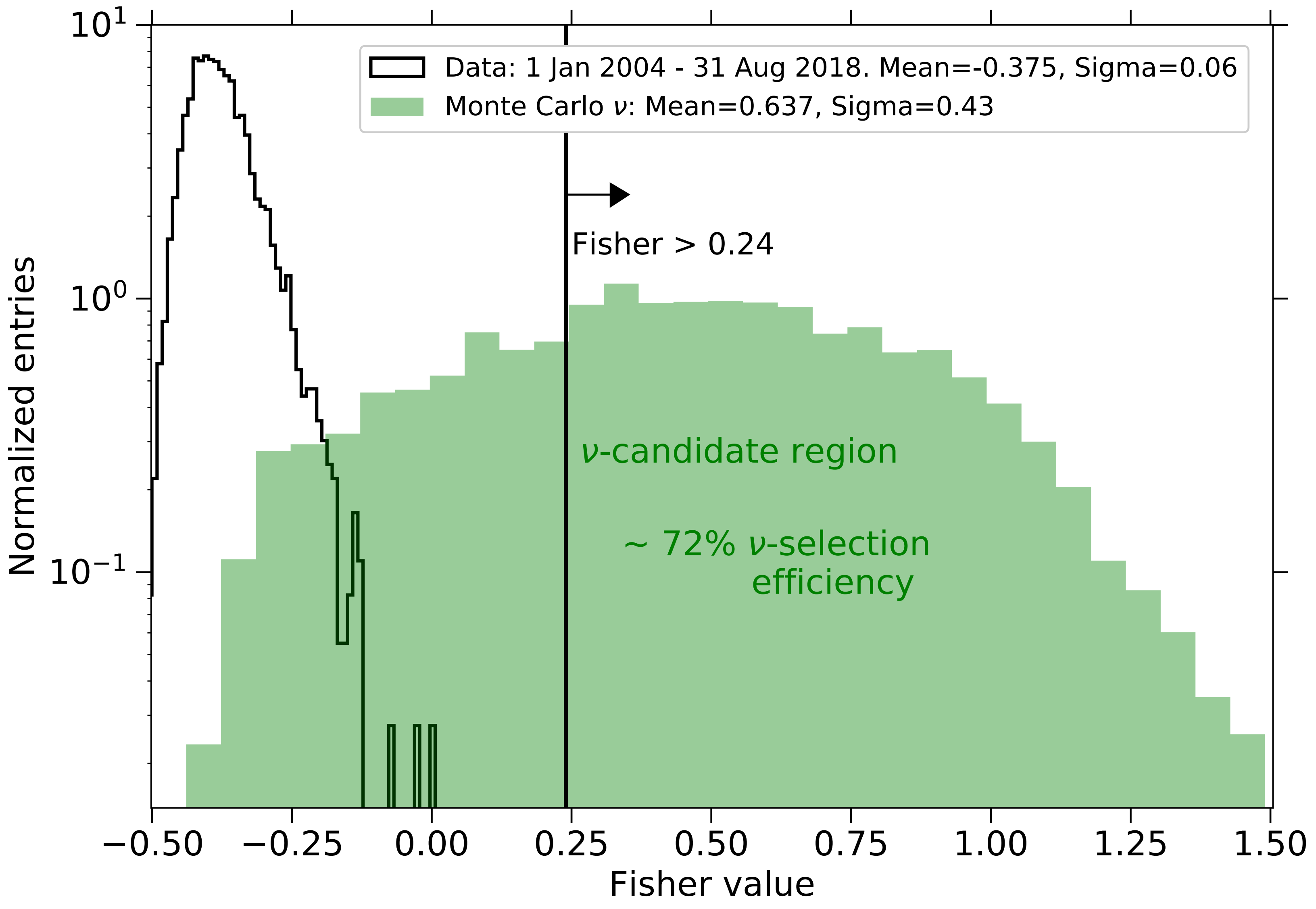
→ multivariate analysis: different observables in each subsample

→ Different **Fisher discrimination variables**

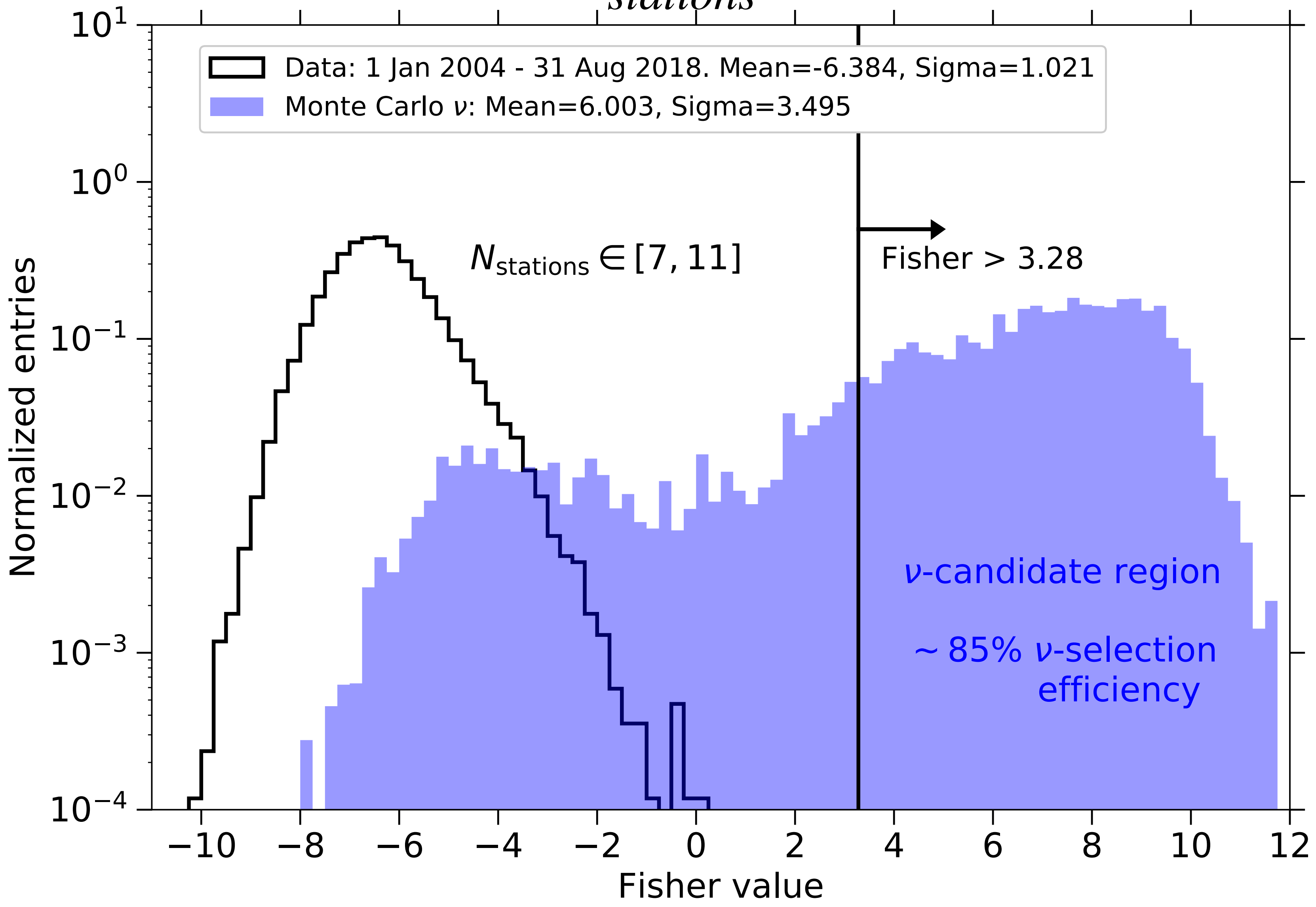
Earth-skimming showers

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

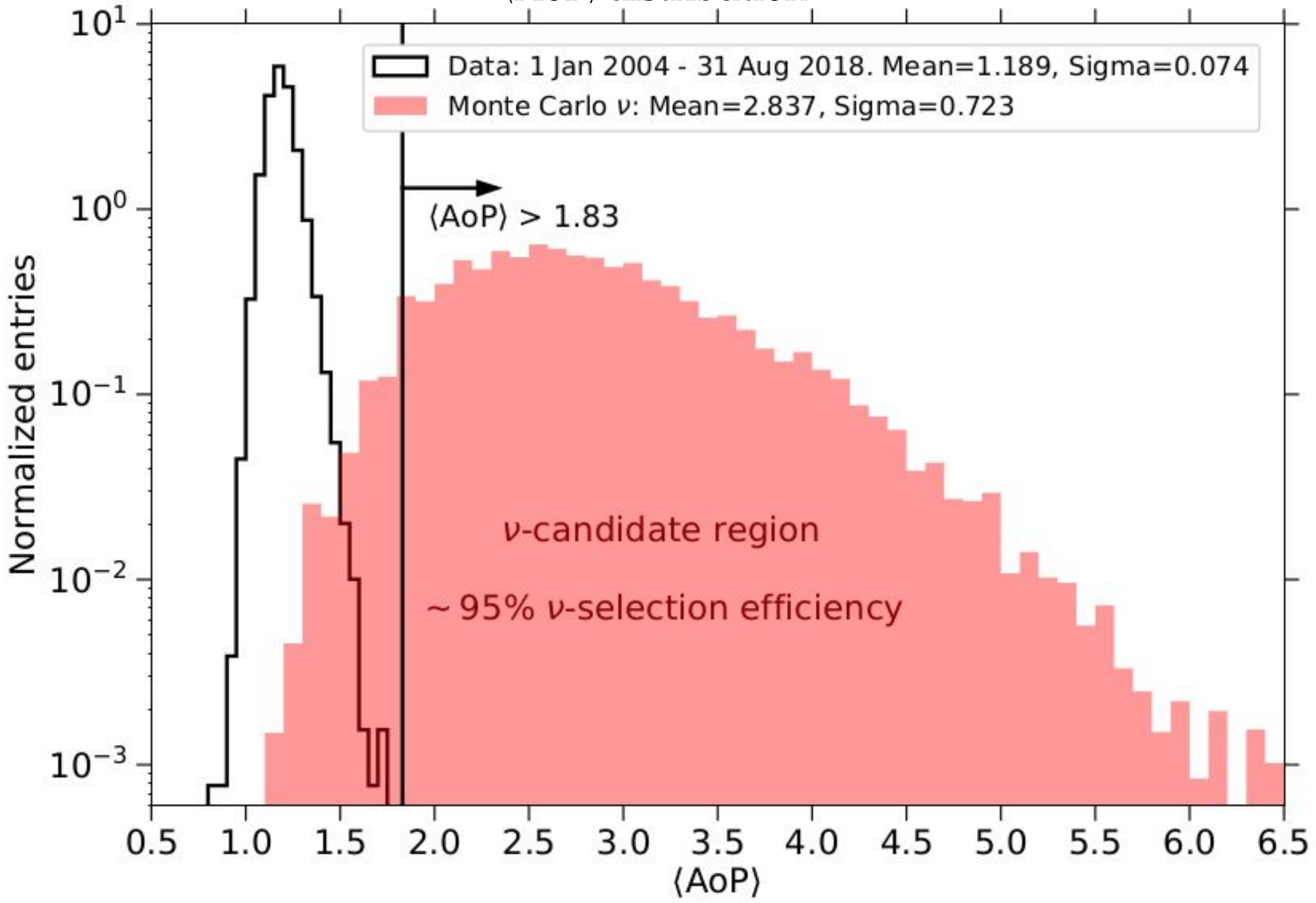
$64.5^o < \theta \leq 67.5^o$



$6 < N_{stations} < 12$



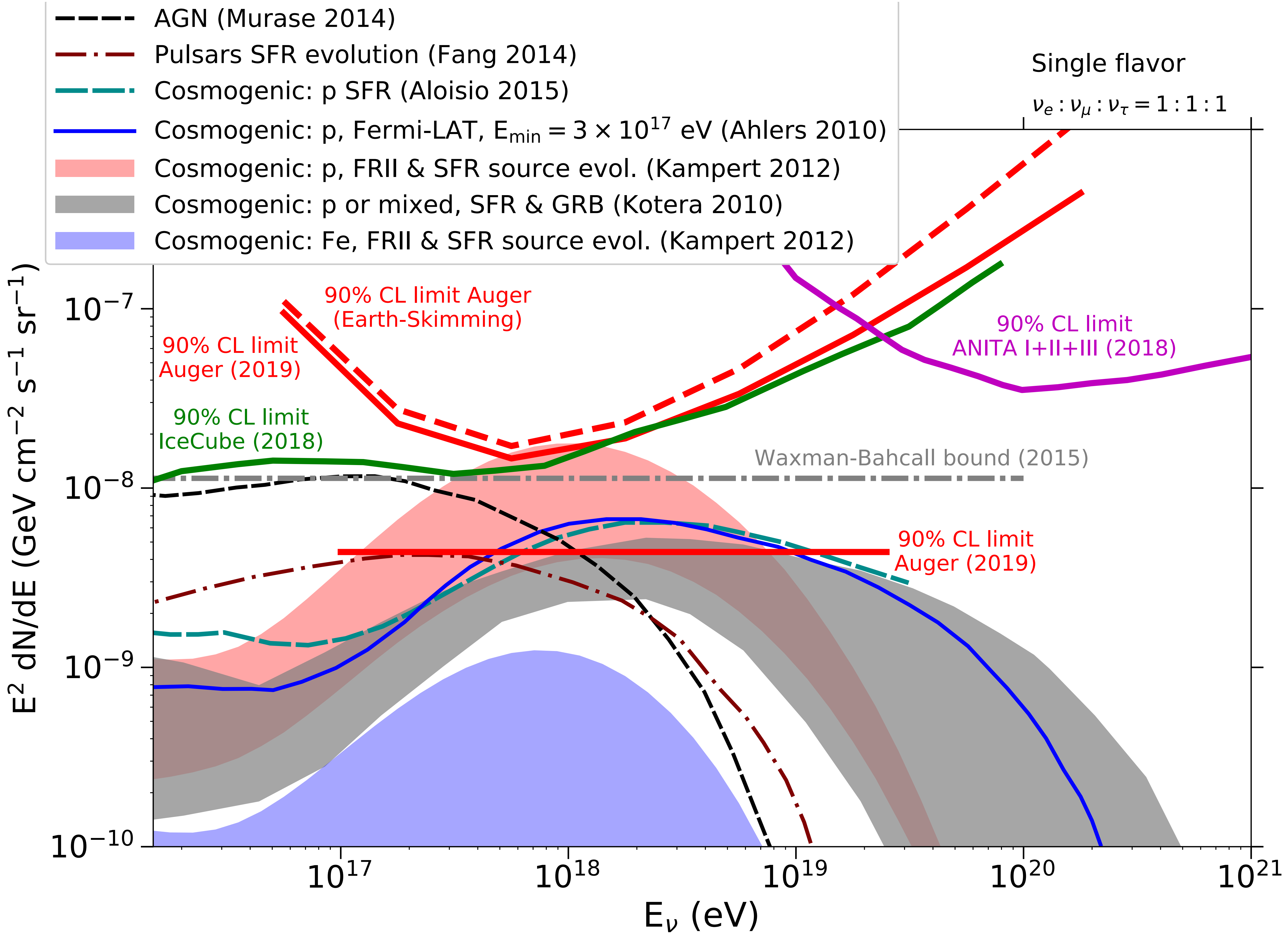
⟨AoP⟩ distribution



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

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:

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

Feldman-Cousins factor in absence of background

Exposure

The integrated upper limit is:

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

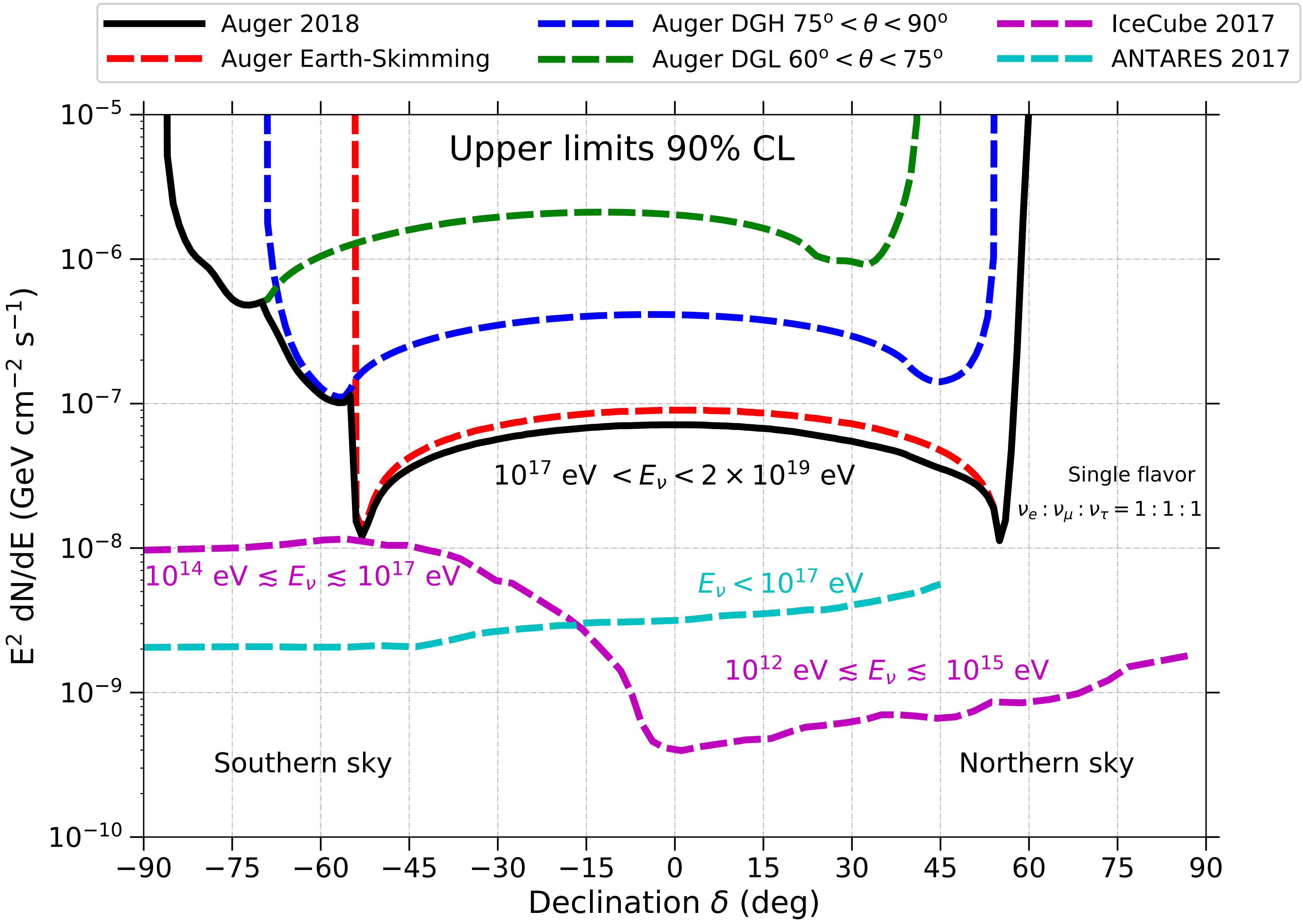
- Auger sets limits comparable with the IceCube ones
- Maximum sensitivity at ~EeV (peaks of most cosmogenic models)
- Some cosmogenic models are already disfavoured

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

Neutrinos from point-like sources

- ✳ 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**

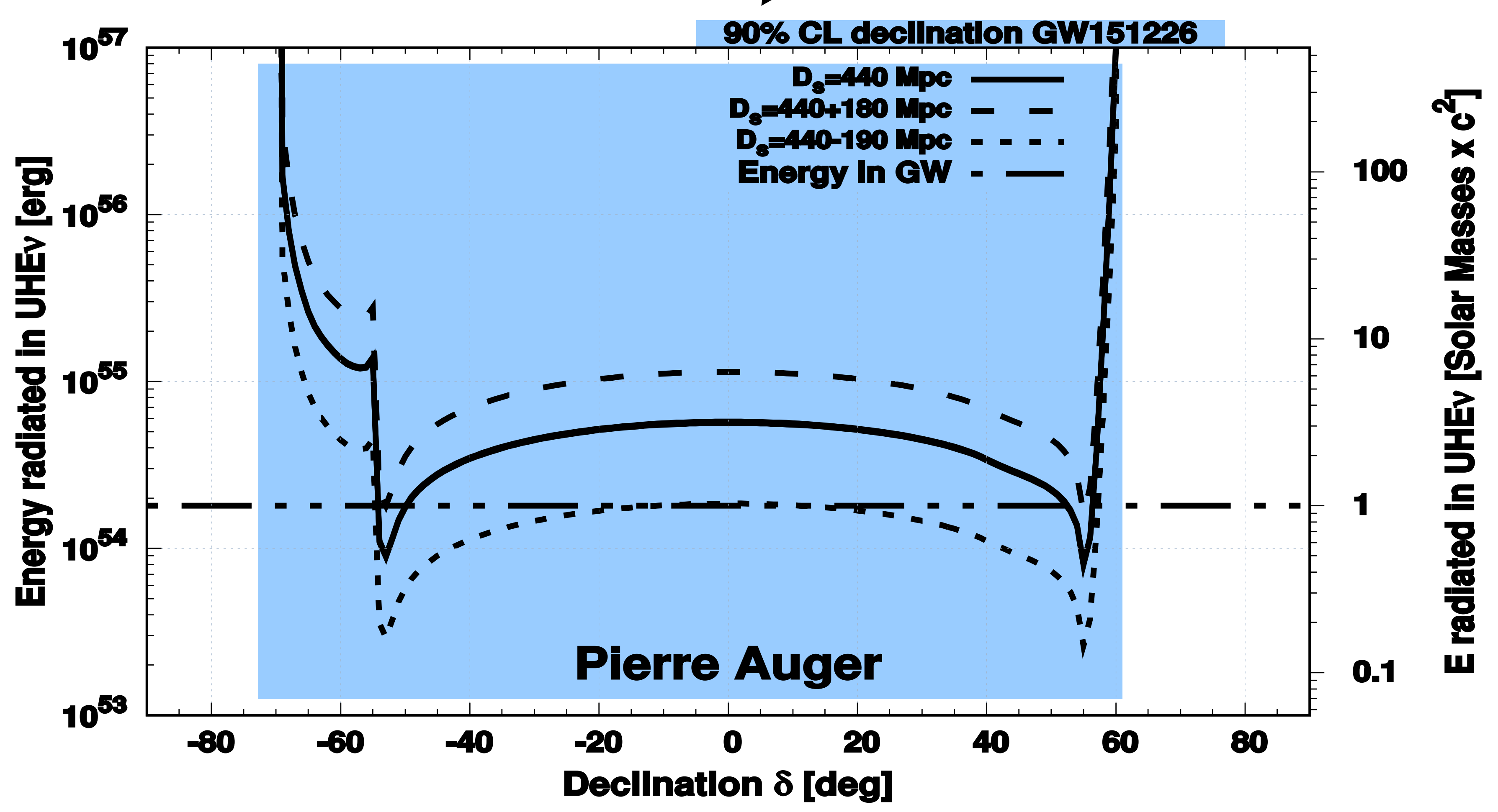
- **Assuming a differential flux $\phi = k_{PS} \cdot E_\nu^{-2}$, the upper limit to $k_{PS}(\delta)$ at 90% C.L. according to Feldman-Cousins is computed**



[The Pierre Auger Collaboration, JCAP 11 (2019) 004]

Follow-up of gravitational waves

- ✳ The regular neutrino search with the SD is used
- ✳ The same time windows used for the photon follow-up are chosen
- ✳ Only periods when the GW event localisation is in the field of view of the UHE neutrino search of the Pierre Auger Observatory
- ✳ No neutrinos have been found → limits calculated as for the flux from point-sources



Upper limits on the radiated energy in UHE ν per flavour from the source of GW151226 (BBH merger) as a function of the declination

- Energies above the lines are excluded at the 90% CL from the non-observation of UHE neutrinos in Auger.
- Limits for luminosity distance Ds = 410 Mpc (and for the 90% CL interval of possible distances to the source).
- Horizontal line is the inferred energy radiated in gravitational waves from GW150914

Summary

The Pierre Auger Observatory is sensitive to UHE photons, neutrinos and neutrons

Photons

- ✳ They 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
- ✳ No candidate events for diffuse photon flux, photons from point-like sources and photon follow-up of gravitational wave events → stringent upper limits

Neutrinos

- ✳ Their showers 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 for diffuse neutrino flux, neutrinos from point-like sources and neutrino follow-up of gravitational wave events → stringent upper limits

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

Thank you for your attentions

Neutron search for source targets

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

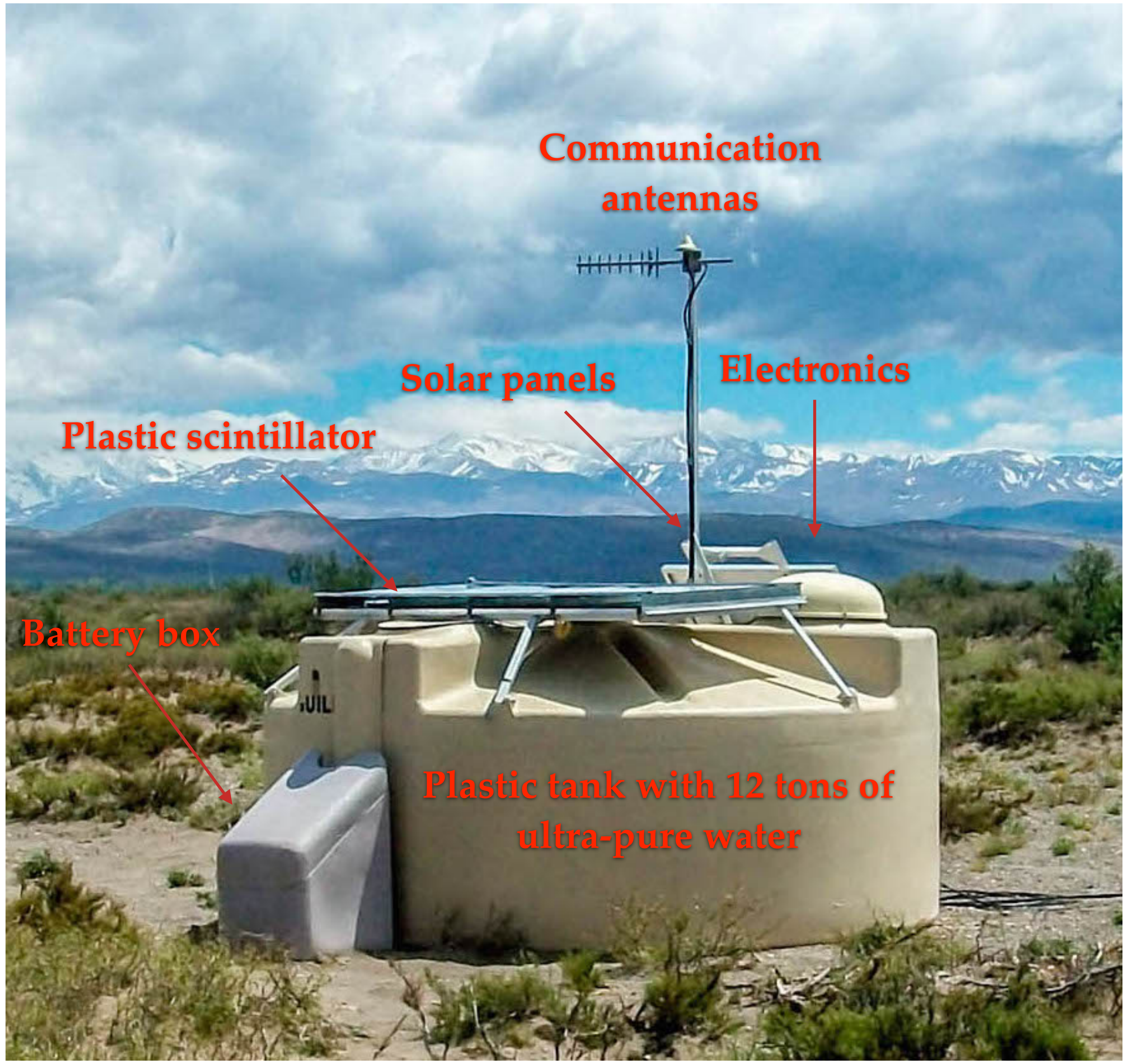
✳ Mean travel distance before decaying is 9.2 kpc E_n/EeV → neutrons above 1 EeV from sources in the Galactic disk can be detected

✳ 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)**

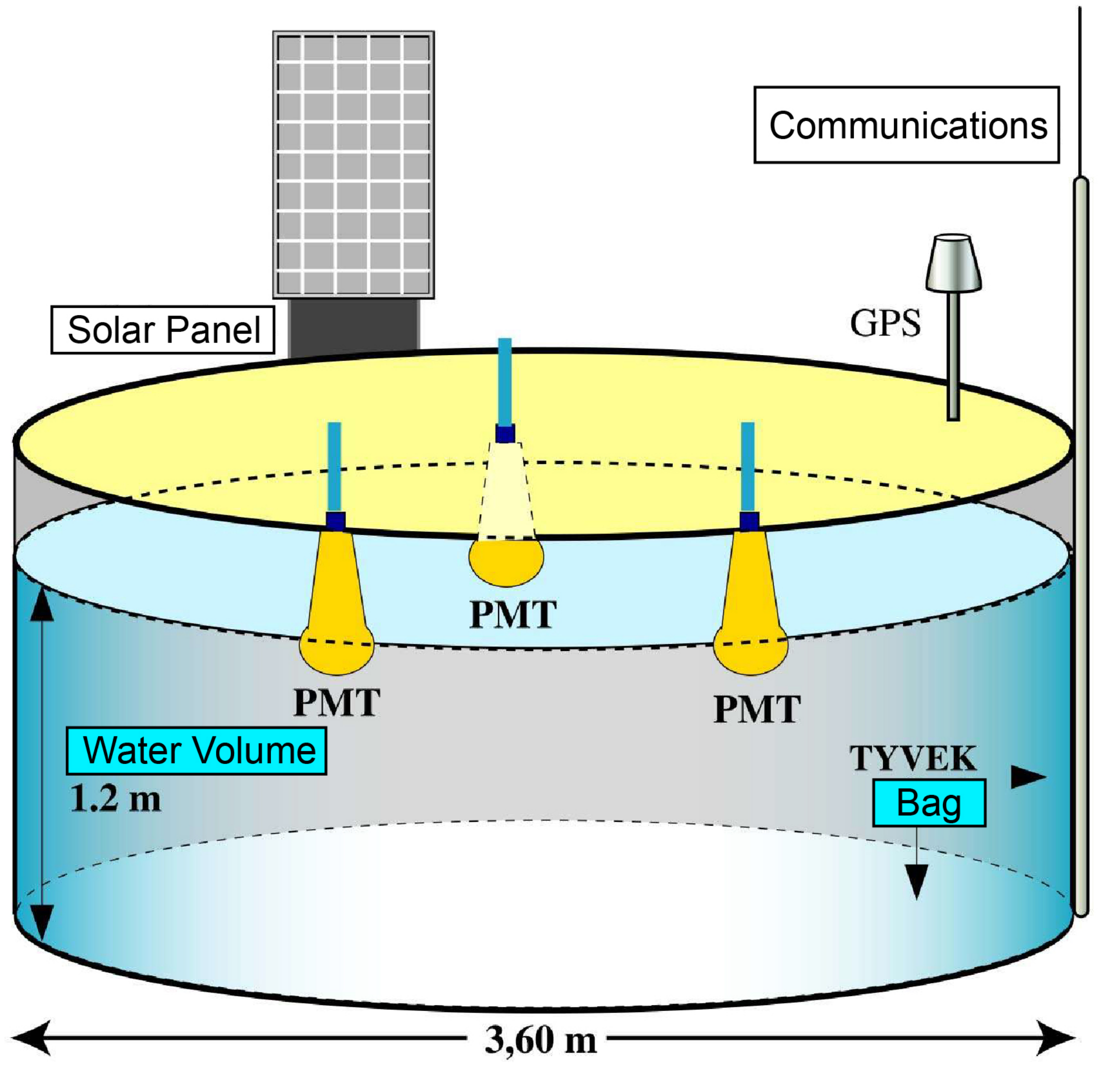
- No evidence for a neutron flux from any target sets of sources → upper limits
- Upper limits below the energy fluxes detected from TeV gamma ray sources in our galaxy → E^{-2} Fermi-acceleration of protons up to EeV energies from these sources is excluded (the flux in TeV gamma rays would be exceeded)
- Limits on the flux of neutrons from the Galactic plane → constraints on models for continuous production of EeV protons in the Galaxy

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

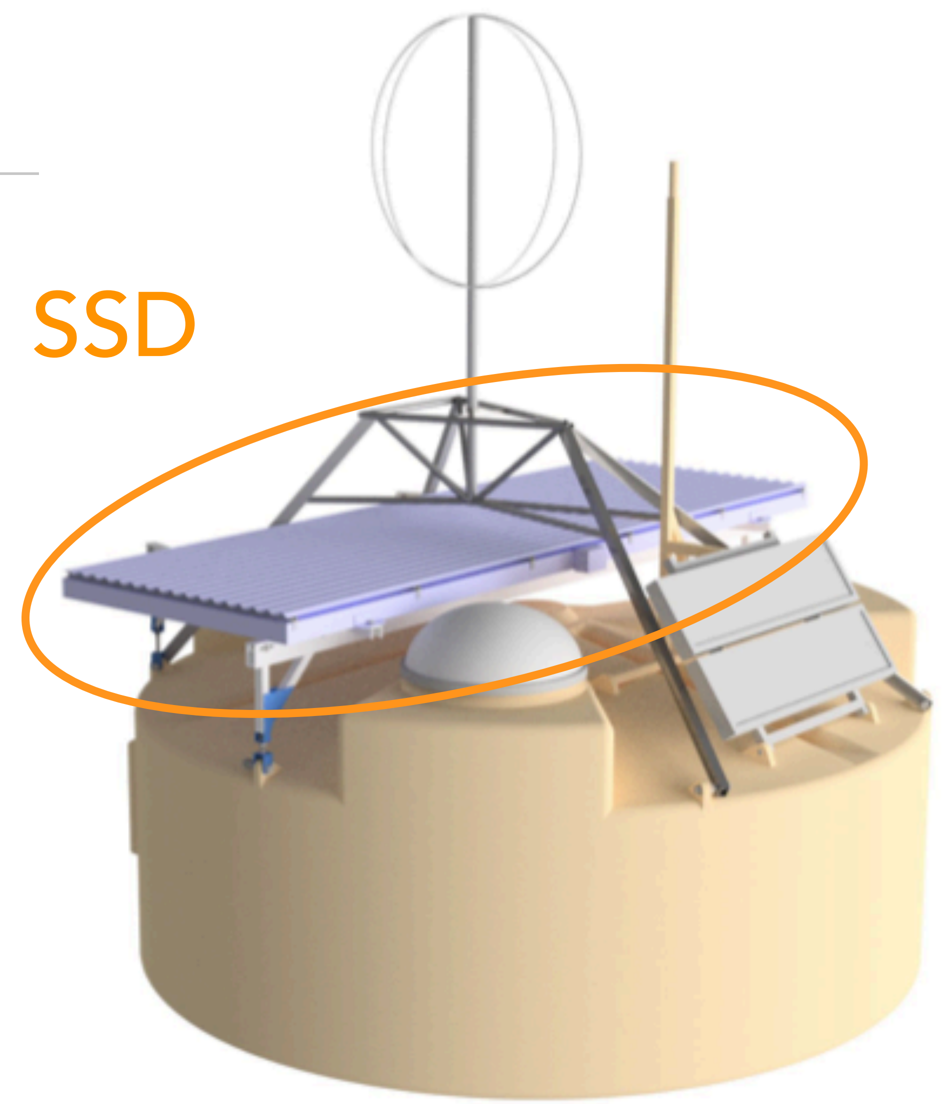
The AugerPrime data set

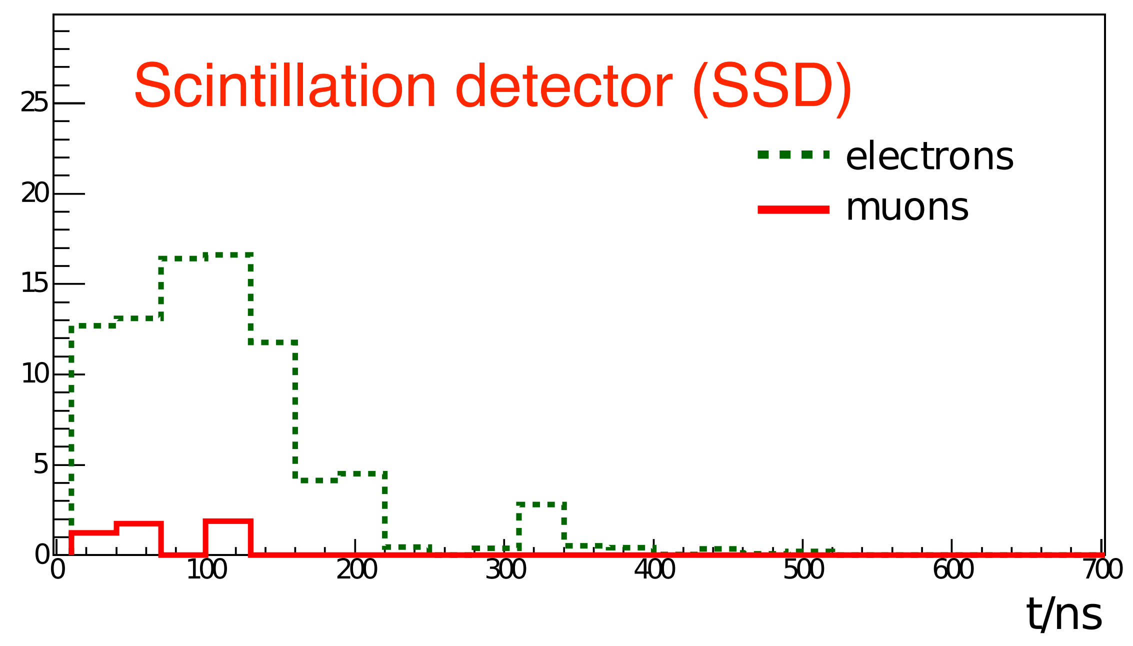
The Pierre Auger Observatory is undergoing an upgrade called "**AugerPrime**"

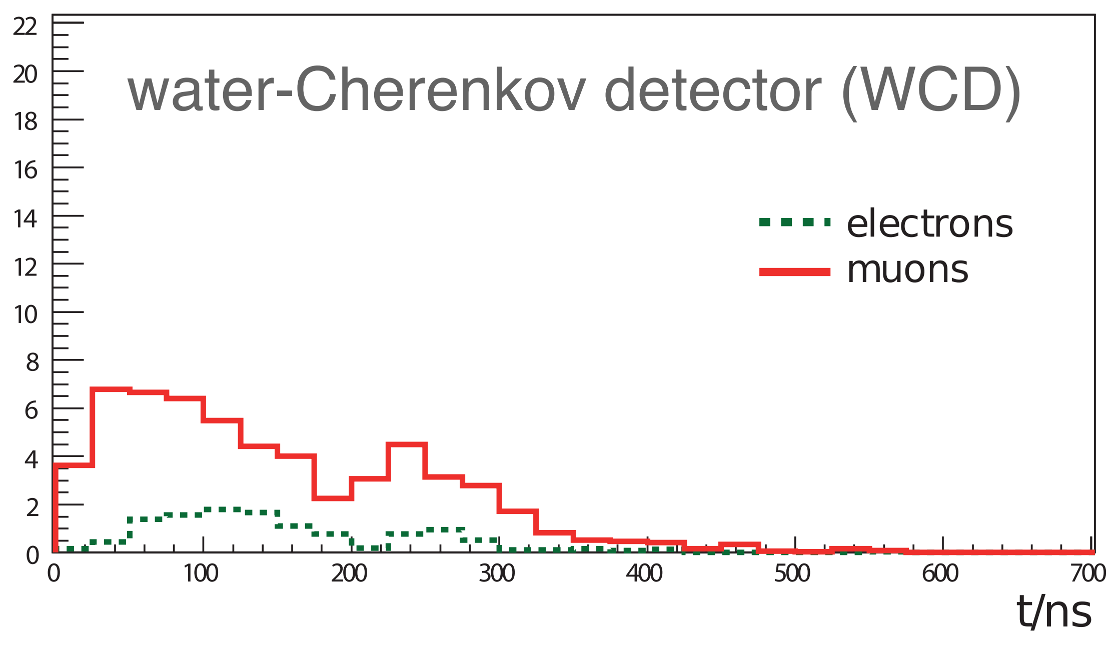
✳ Improved new electronics, addition small photomultiplier

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

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





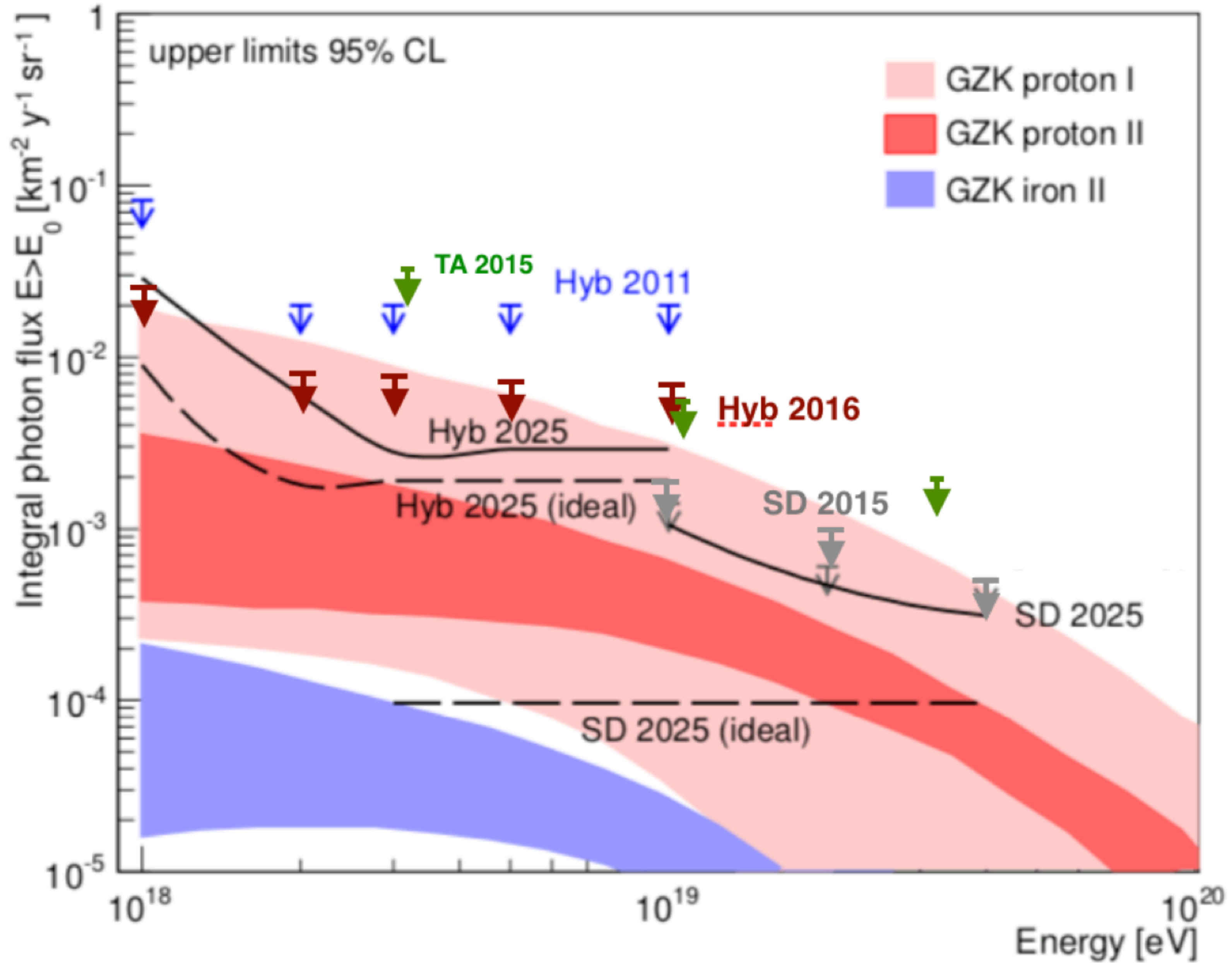


✳ SSD are more sensitive to electrons/positrons

✳ 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

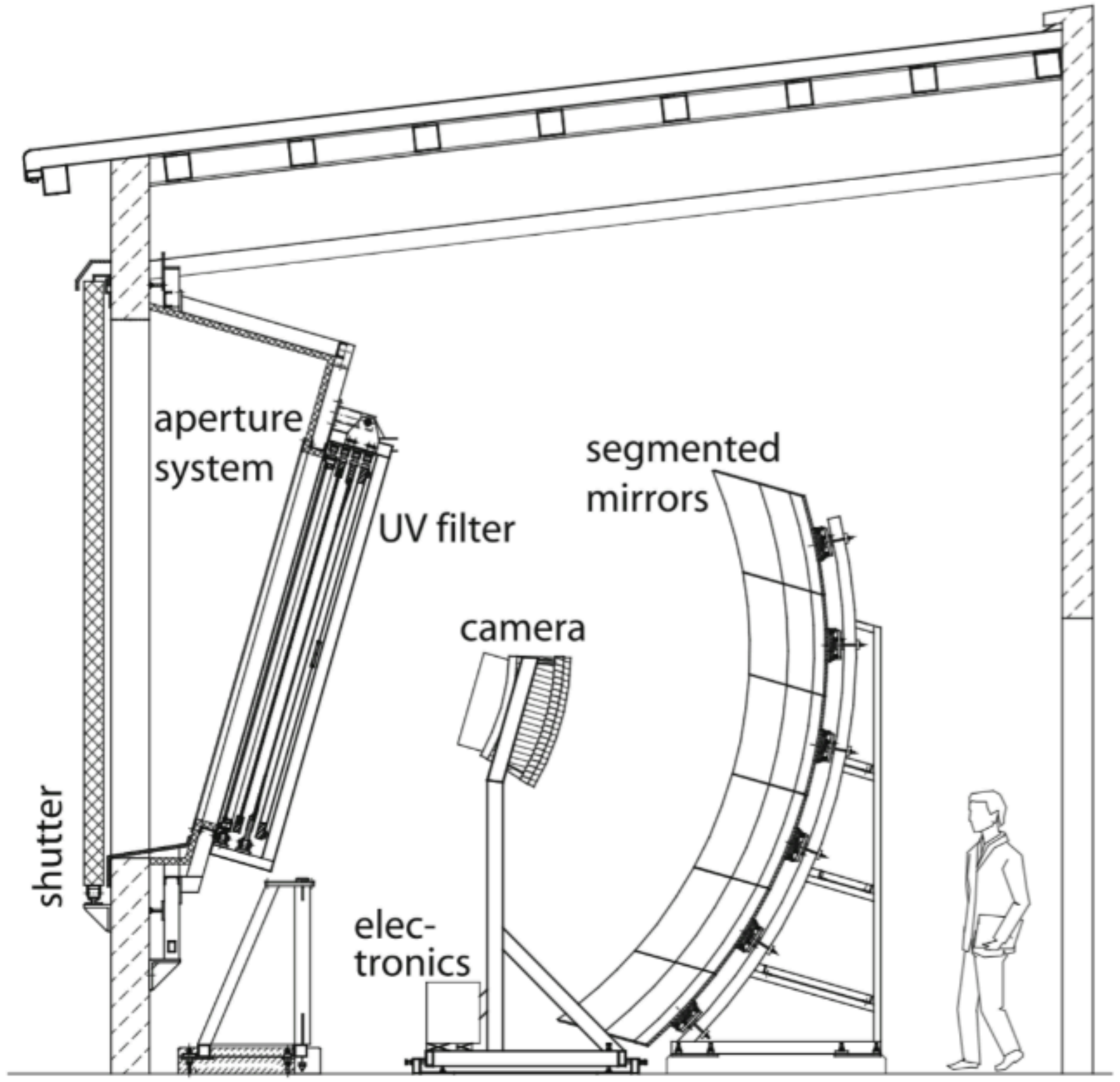


[The Pierre Auger Collaboration, AugerPrime: the Pierre Auger Observatory Upgrade, EPJ Web of Conferences, 2019]

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

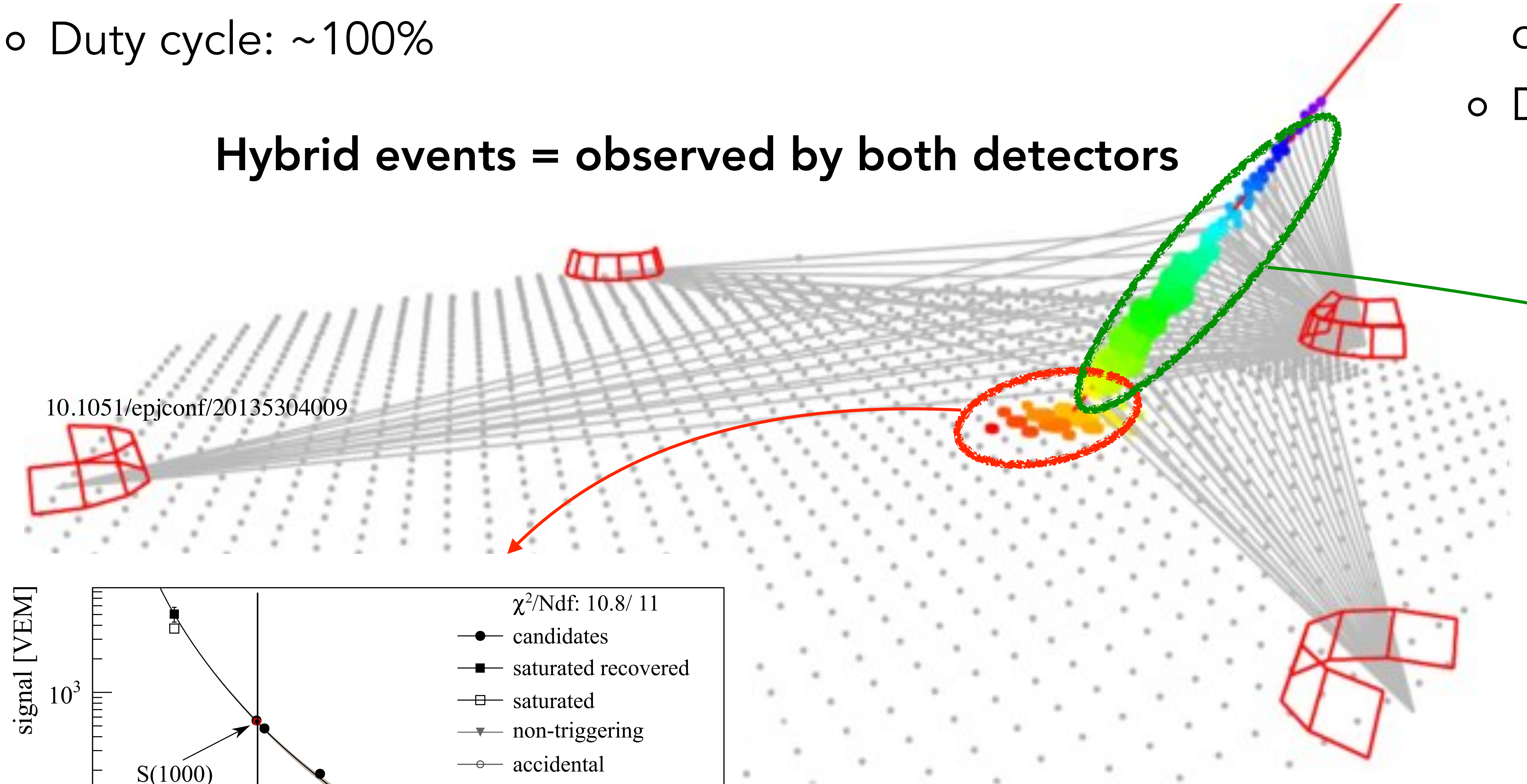
Surface Detector (SD)

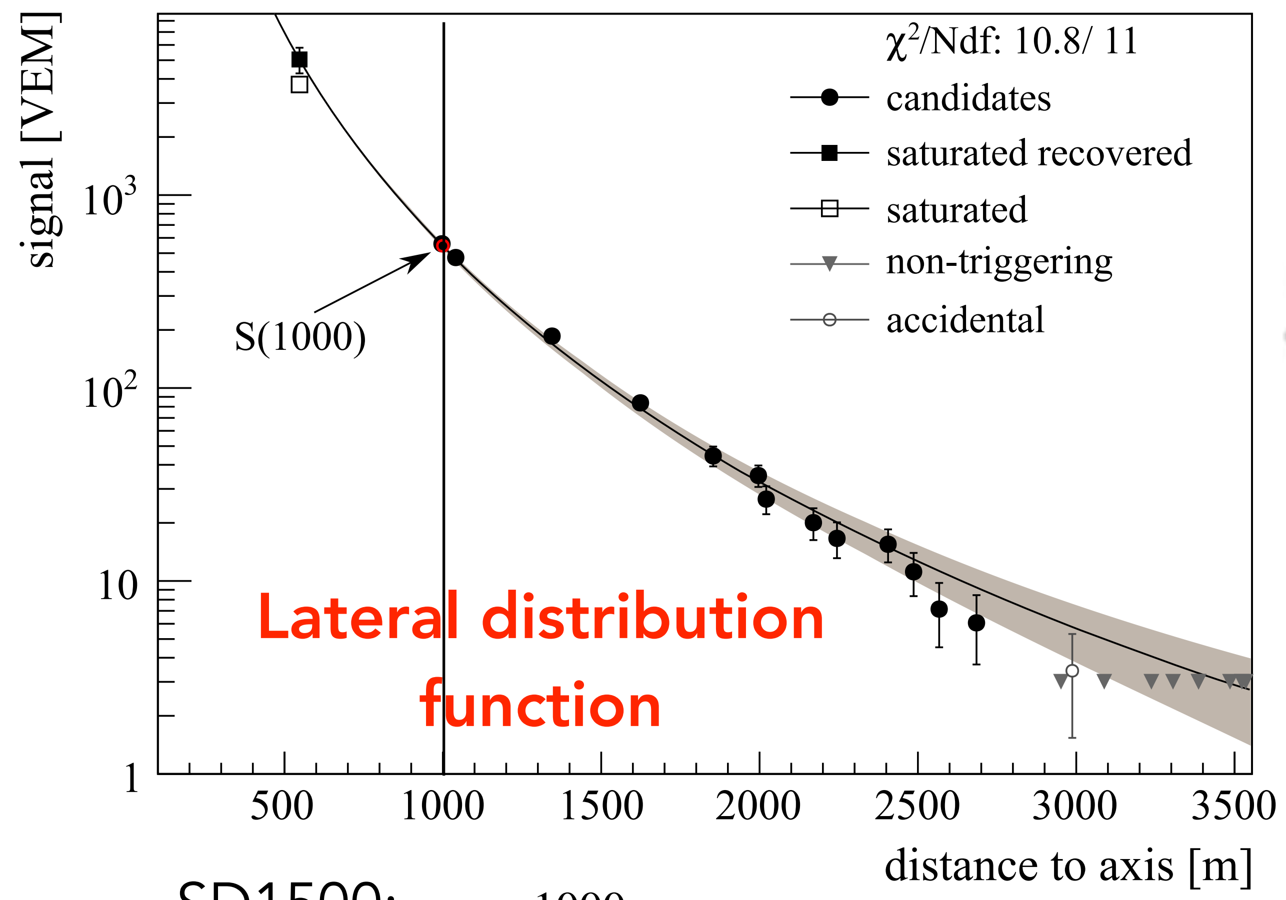
- Sampling the secondary particles reaching the ground
- Duty cycle: ~100%

Fluorescence Detector (FD)

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

Hybrid events = observed by both detectors



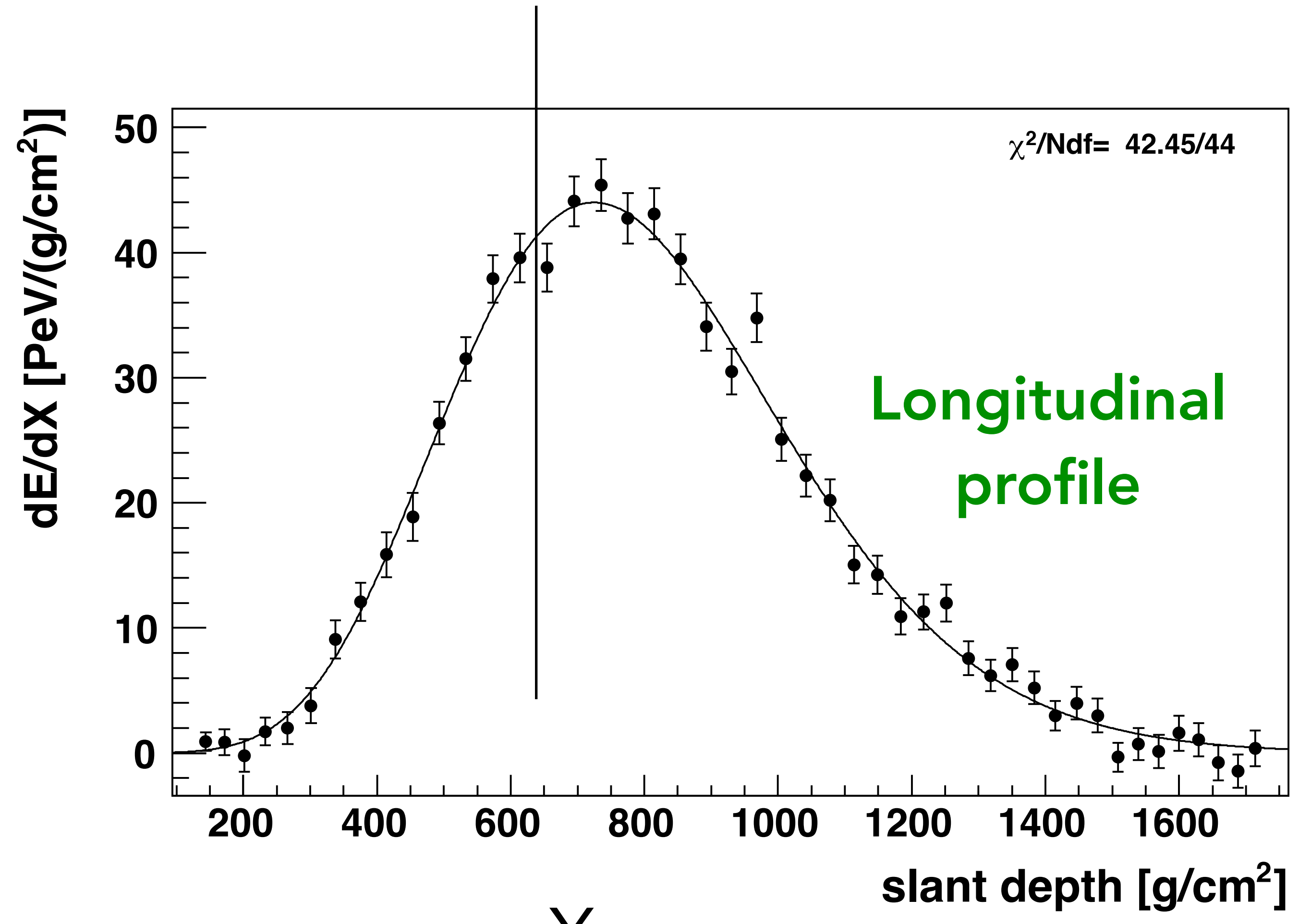


SD1500: $r_{opt} = 1000$ m

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

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

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



X_{max}

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

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

Calorimetric energy

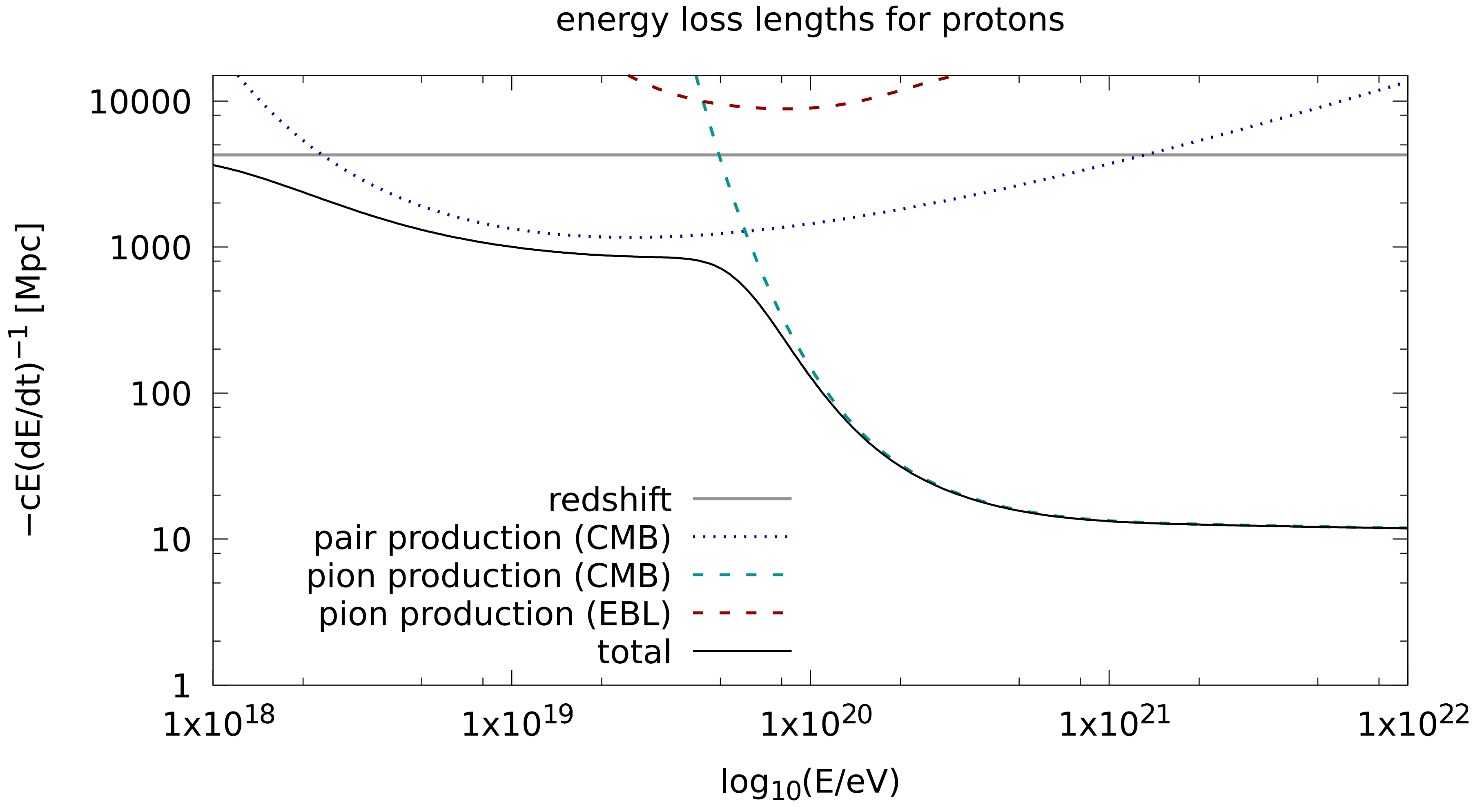
UHECRs propagation

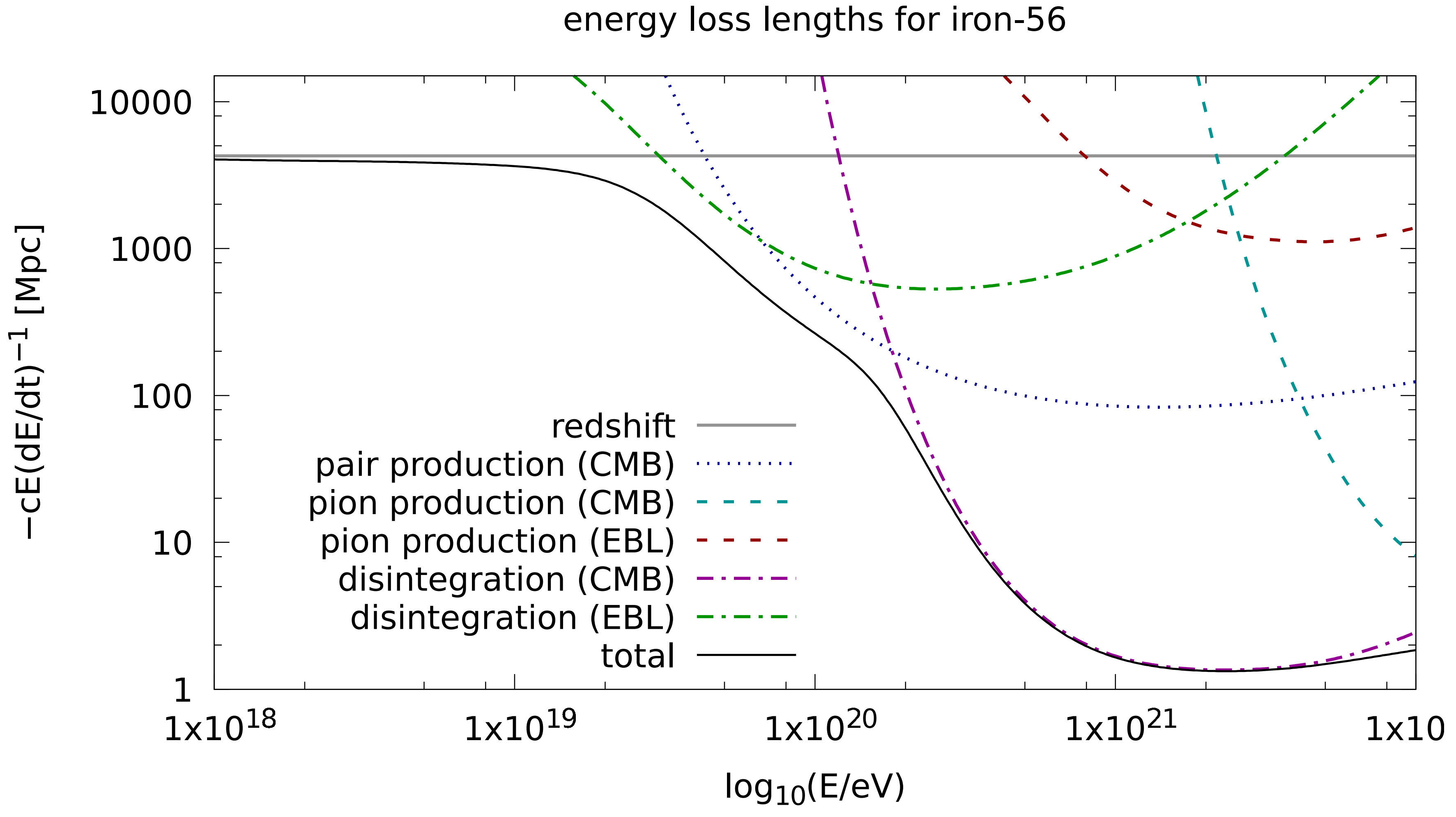
- **Consider the propagation effects → infer source properties from the measured fluxes**

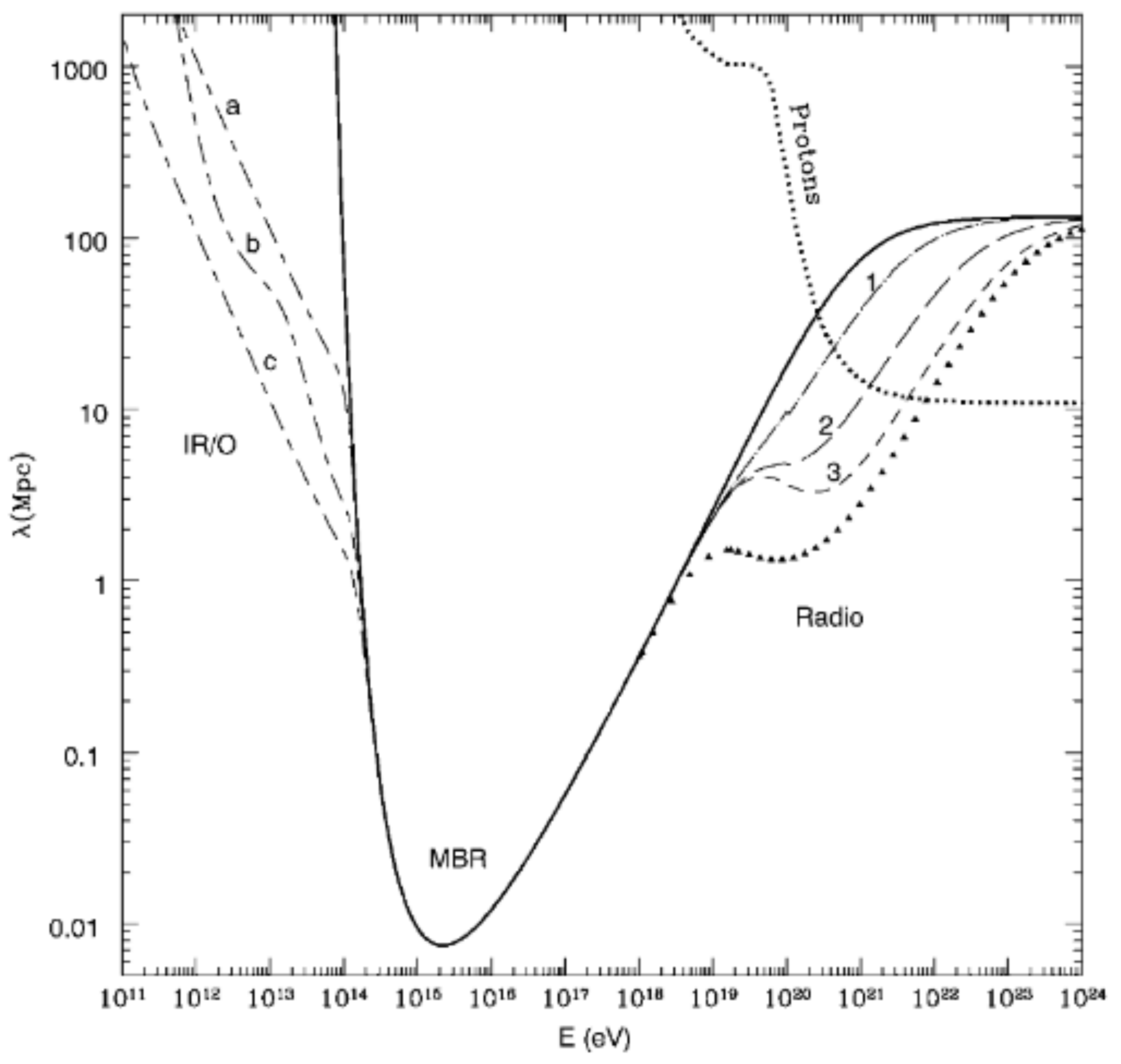
Energy loss processes occurring for E > 10^{18} eV :

- **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 $(A, Z) + \gamma \rightarrow (A - n, Z - n') + nN$







The diffuse photon flux

Photon search

E < 10^{19} eV

- FD+SD are used (hybrid measurements)
- Analysis applied also to the low-energy extensions of Auger → limits set above 2 x 10^{17} eV
- Zenith angles below 60°

How to distinguish hybrid photon events:

- 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 $\mathbf{S_b}$
- **The observables are combined to obtain a discriminant**

$$S_b = \sum_i^N S_i \left(\frac{R_i}{R_0}\right)^b$$

- $R_0 = 1000\,m$
- b=4

[The Pierre Auger Collaboration, *ApJ* **933** 125]

Photons from point-like sources

Photon search

✳ 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

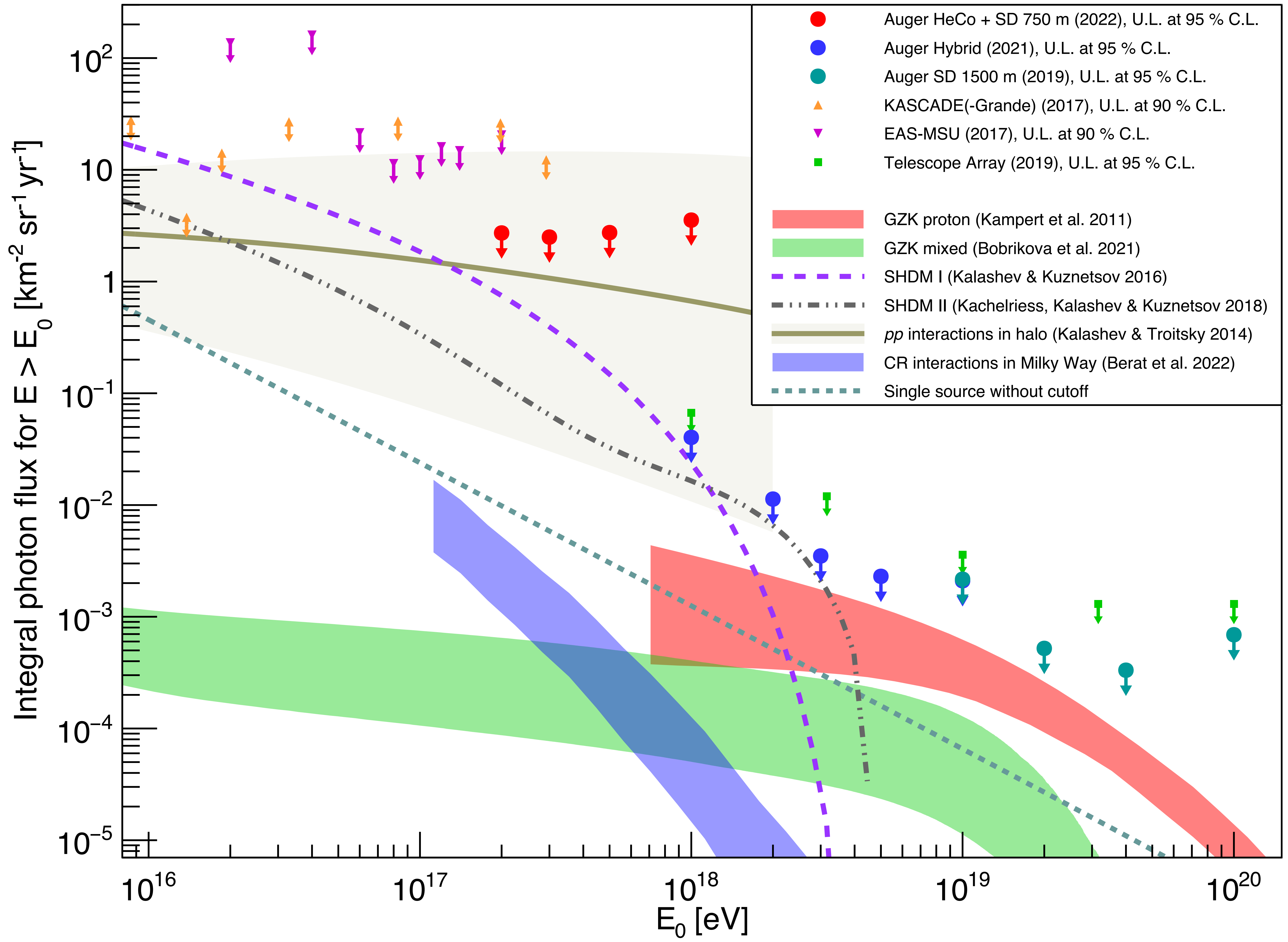
$$w_i = \frac{f_i \cdot \epsilon_i}{\sum_i f_i \cdot \epsilon_i}$$

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

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

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.

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

Feldman-Cousins upper limit for 0 background

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

Neutrino search

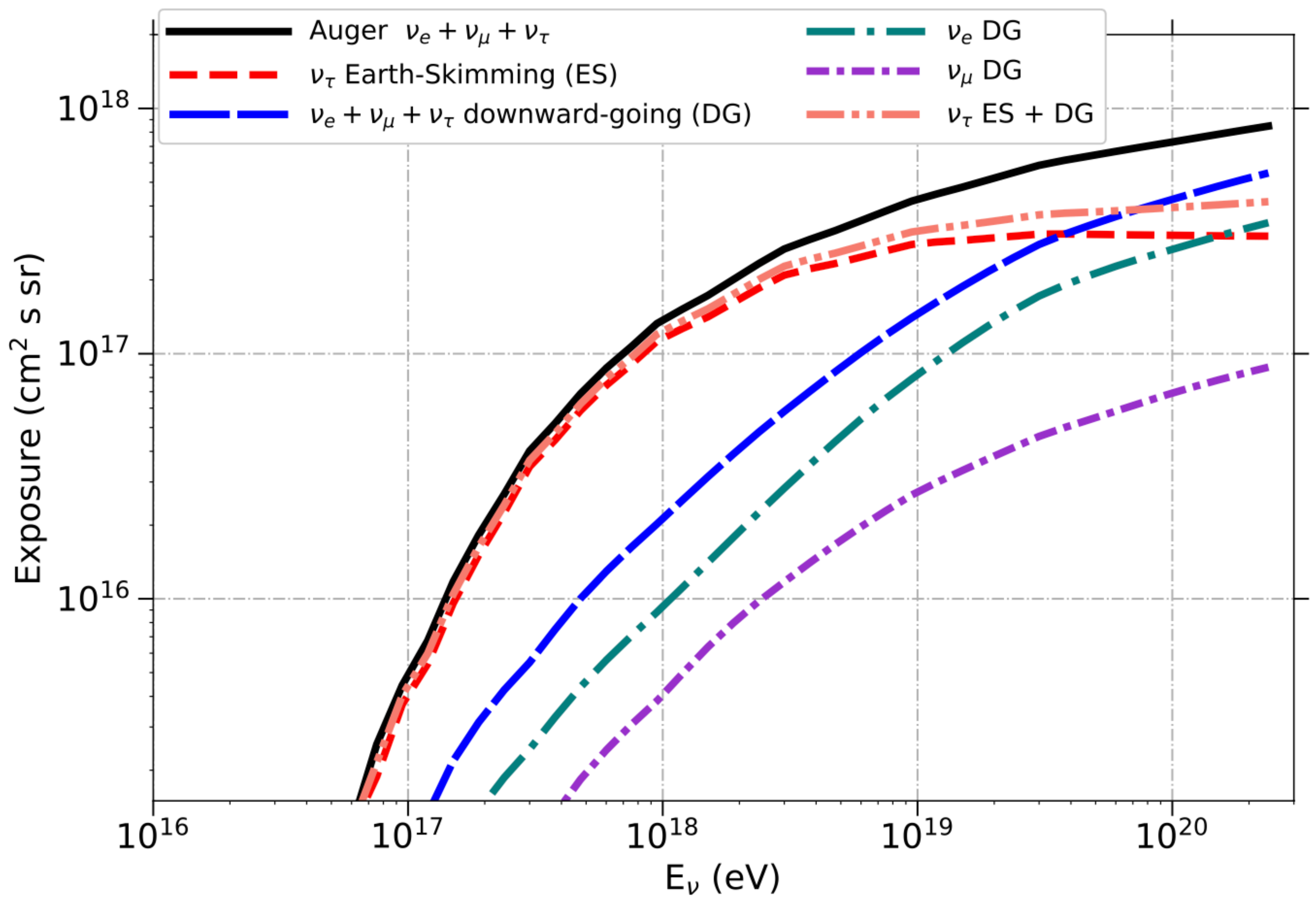


Figure 5. Exposure of the SD of the Pierre Auger Observatory (1 January 2004 - 31 August 2018) to UHE neutrinos as a function of neutrino energy for each neutrino flavor and for the sum of all flavors assuming a flavor mixture of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$. Also shown are the exposures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

Neutrino search

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

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

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

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

Feldman-Cousins factor in absence of background

Exposure

The integrated upper limit is:

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

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

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

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

Follow-up of gravitational waves

Neutrino search

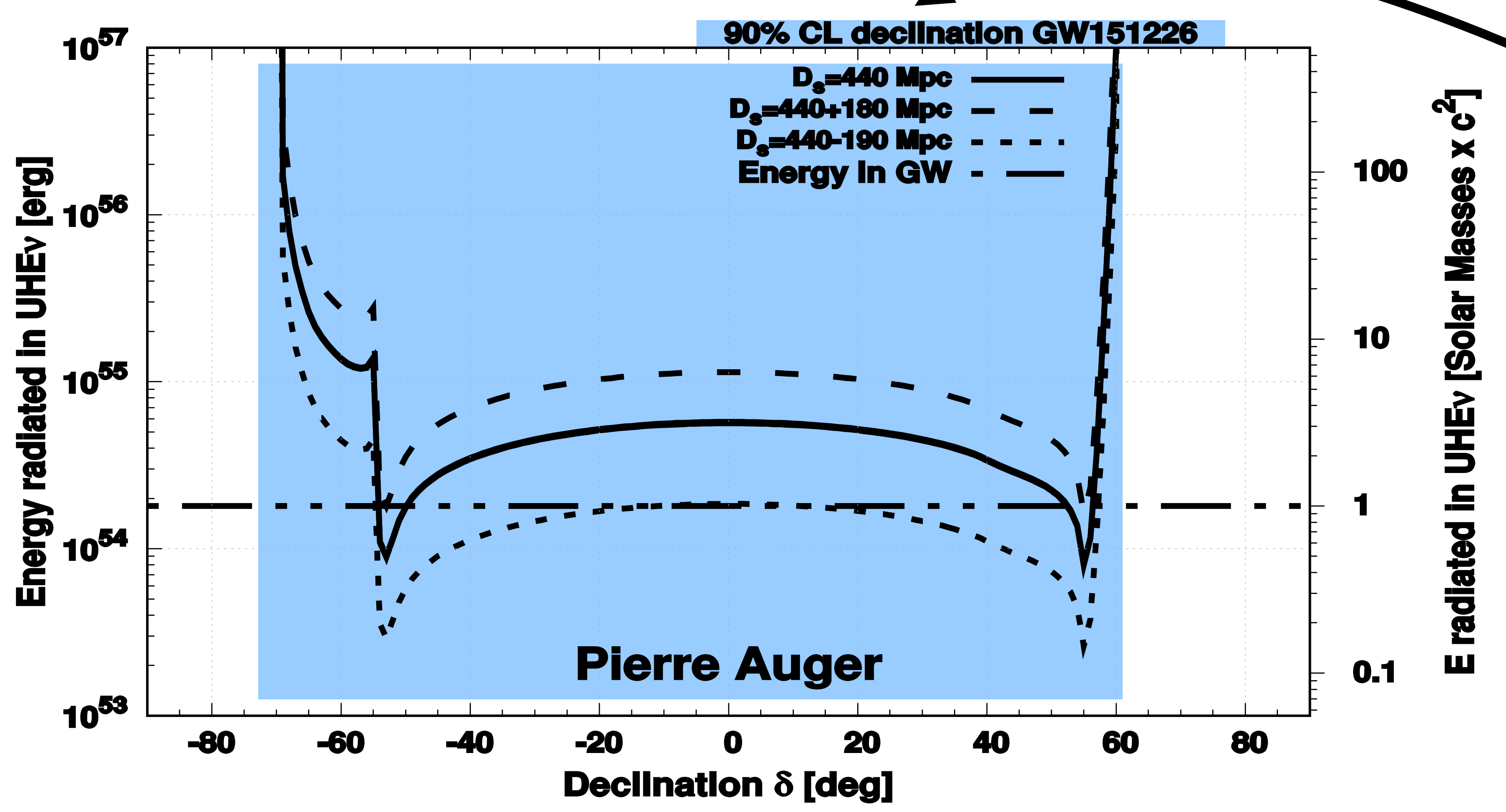
Assuming a standard E^{-2} energy dependence for a constant UHE neutrino flux per flavor from e.g. the source of GW151226 a 90% CL upper limit on k can be obtained

$$k^{\mathrm{GW}}(\delta) = \frac{2.39}{\int_{E_\nu} E_\nu^{-2}\, \mathcal{E}_{\mathrm{GW}}(E_\nu, \delta)\, dE_\nu}$$

From the limits to the flux normalization we obtained upper limits to the UHE neutrino spectral fluence radiated per flavor:

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \times T_{\mathrm{search}} = k^{\mathrm{GW}}(\delta)\, T_{\mathrm{search}}$$

Tsearch = 1 day + 500 s is the total search period interval

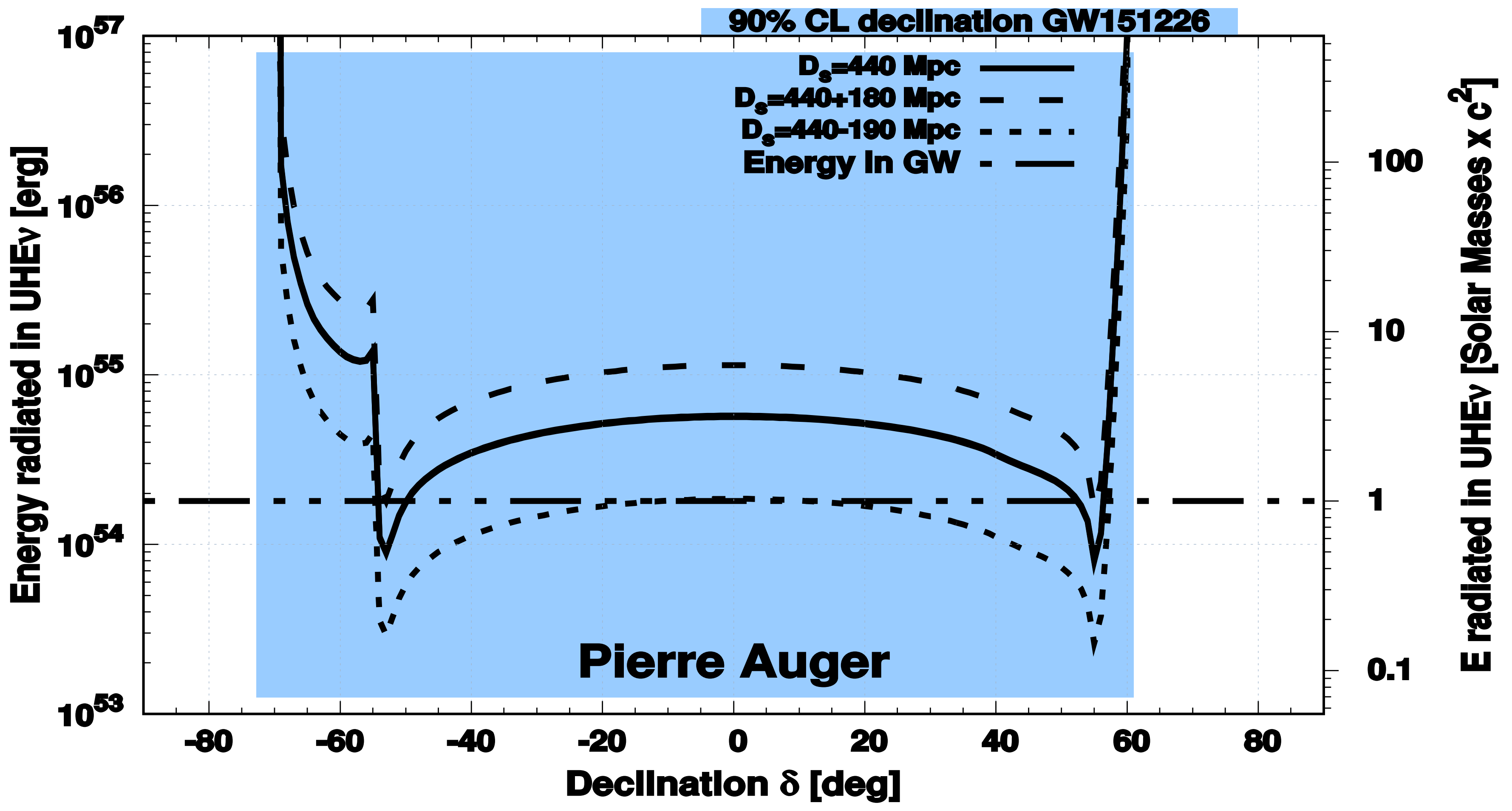


Upper limits on the radiated energy in UHE ν per flavour from the source of GW151226 (BBH merger) as a function of the declination

Follow-up of gravitational waves

Neutrino search

- The regular neutrino search with the SD is used
- The same time windows used for the photon follow-up are chosen
- Only periods when the GW event localisation is in the field of view of the UHE neutrino search of the Pierre Auger Observatory
- No neutrinos have been found → limits calculated as for the flux from point-sources



Upper limits on the radiated energy in UHE ν per flavour from the source of GW151226 (BBH merger) as a function of the declination

Fluence limits in the two time windows for event GW170817 (BNS merger)