Searching for neutral particles at the highest energies at the Pierre Auger Observatory

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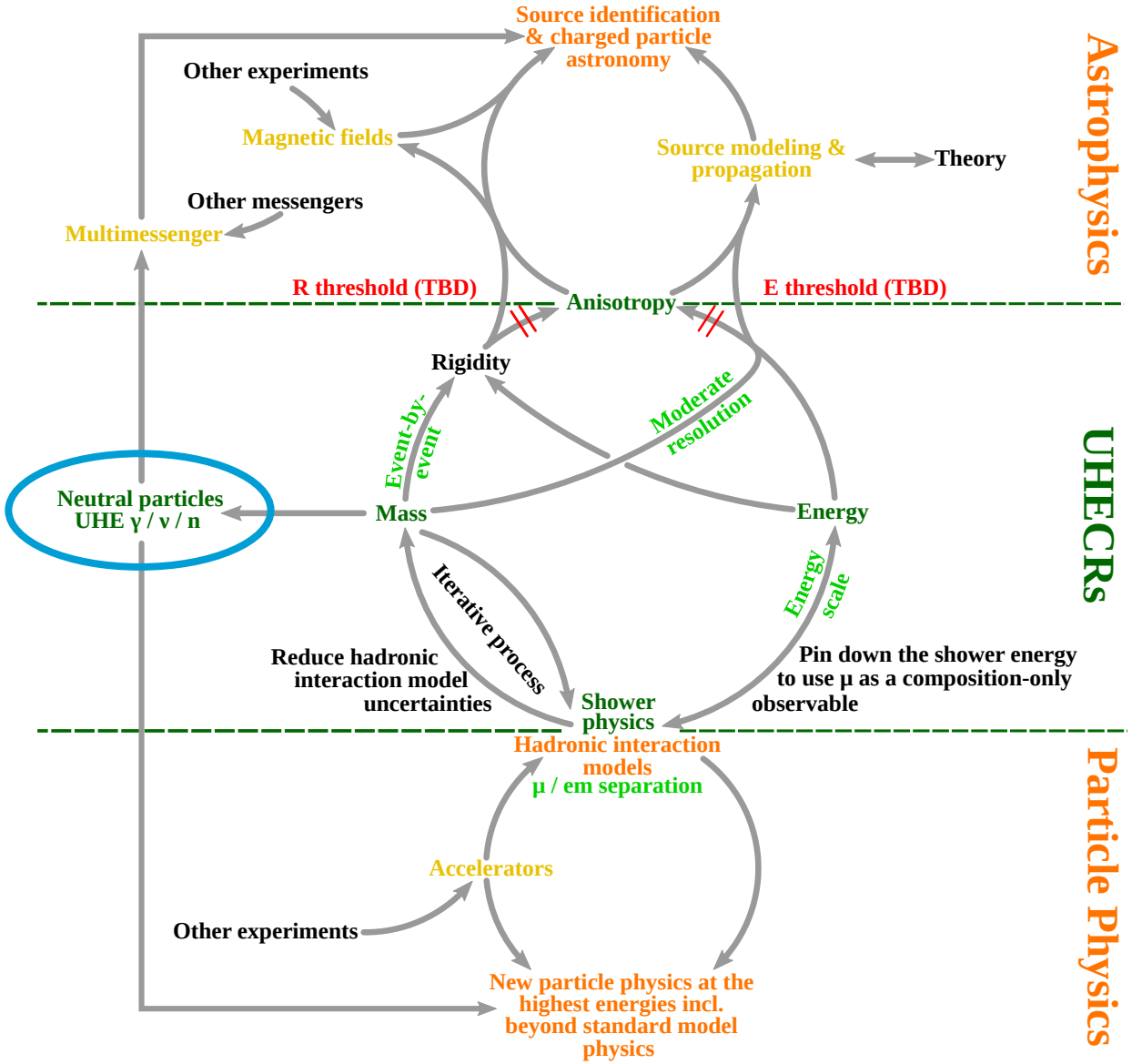
PIERRE AUGER OBSERVATORY

Universität Siegen

Why search for neutral particles at the highest energies?

- Neutral particles (here: photons and neutrinos) play a **crucial role** for the current efforts in **multimessenger astronomy**
  - One of the **main goals**: understanding where and how UHECRs are produced
  - **Intimate connection** between UHE photons and neutrinos and UHECRs
    - Can be produced either directly at the sources of UHECRs (**astrophysical γ/υ**) or during their propagation through the Universe (**cosmogenic γ/υ**)
  - **Complementary messengers**: photons trace the local Universe up to Mpc scales, while neutrinos can traverse the whole Universe
- Neutral particles can also serve as **cosmic probes of fundamental physics** and open a window to new physics
  - **Examples:** SHDM, Lorentz invariance, axions…

The Bigger Picture



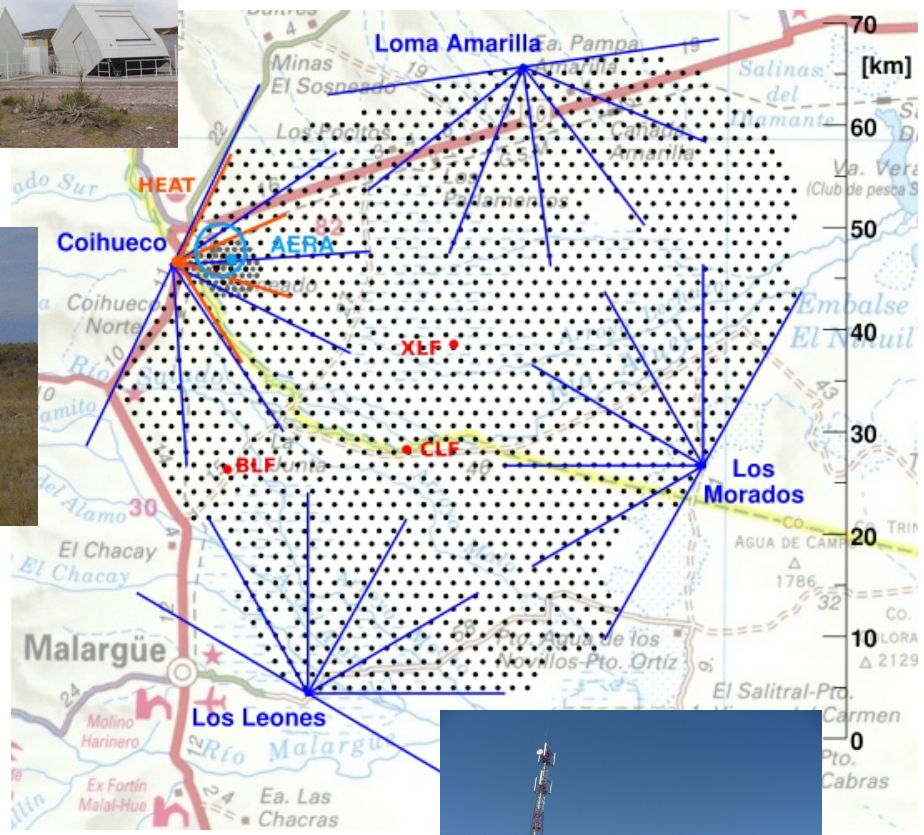
[Snowmass UHECR White Paper, arXiv:2205.05845]

How to search for neutral particles?

- The fluxes of UHE neutral particles are **far too small** for direct detection
- But: photons and neutrinos entering the Earth's atmosphere can **initiate extensive air showers**, just like charged cosmic rays – making indirect detection possible
  - In general, a cosmic-ray observatory measuring air showers can be, **by construction**, also a photon observatory and even a neutrino observatory
  - **Main challenge**: distinguishing photon- and neutrino-induced air showers from those initiated by protons and heavier nuclei

The Pierre Auger Observatory

- Located near **Malargüe, Argentina**
- **Surface detector array (SD)**
  - ~1600 water Cherenkov detectors (WCDs)
  - 1500 m distance, total area ~3000 km^2
  - Measuring **secondary particles on ground**
- **Fluorescence detector (FD)**
  - 4 stations with 6 telescopes each, overlooking the SD
  - Measuring the **longitudinal development** in the atmosphere
- Further detector systems:
  - **Infilled array**: denser sub-array of WCDs, 750 m distance
  - **High-elevation telescopes (HEAT)**: fluorescence measurements at lower energies
  - Plus radio antennas (AERA), underground muon detectors (UMD)…

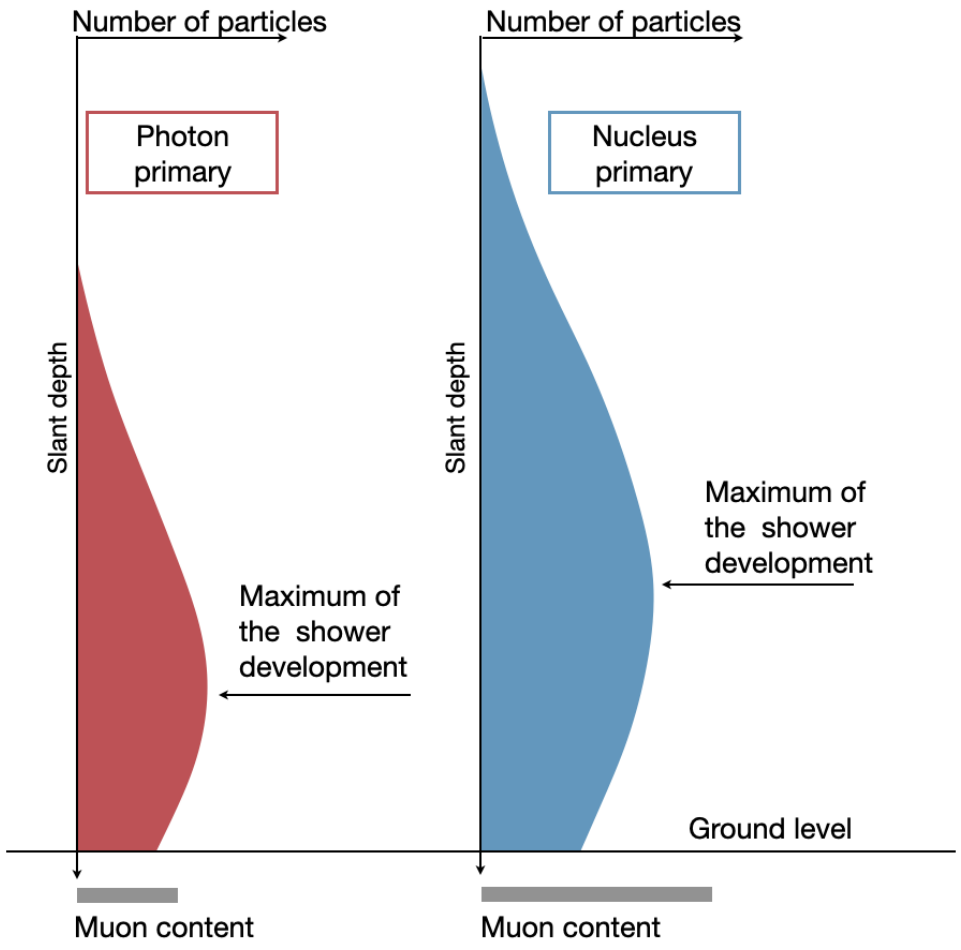


[Pierre Auger Coll., NIM A 798 (2015) 172]

Photons

How to identify a primary photon

- Photon-induced air showers are dominated by **electromagnetic interactions**
- Two **main differences** w.r.t. air showers initiated by protons or heavier nuclei:
  - **Deeper X_{max}** due to the lower multiplicity of electo-magnetic interactions w.r.t. hadronic interactions
  - **Smaller N_{μ}** due to only a small fraction of the total energy being transferred the hadronic (and subsequently muonic) channel through photo-nuclear interactions
- One consequence: **steeper lateral distribution** of secondary particles on ground and **smaller footprint**



Searches for photons at the Pierre Auger Observatory

- Searches for a **diffuse (i.e., direction-independent, unresolved)** flux of UHE photons
  - Three different energy ranges: between 2×10^{17} and 10^{18} eV (based on data from HEAT/Coihueco and the 750 m SD array), between 10^{18} and 10^{19} eV (FD + 1500 m SD array) and above 10^{19} eV (SD 1500 m)

- Searches for **point sources** of UHE photons
  - **Blind search** covering the full field of view [Pierre Auger Coll., ApJ 789 (2014) 160]
  - **Targeted search** involving different classes of potential sources [Pierre Auger Coll., ApJL 837 (2017) L25]

  } **not covered in this talk**

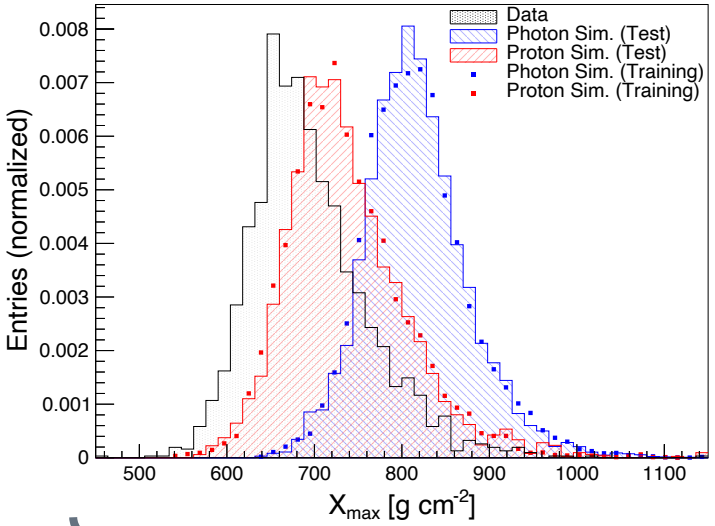
- Follow-up search for UHE photons in coincidence with **transient events**
  - **Gravitational wave events** [P. Ruehl (Pierre Auger Coll.), PoS (ICRC 2021) 973]
  - **TXS 0506+056** [Pierre Auger Coll., ApJ 902 (2020) 105]

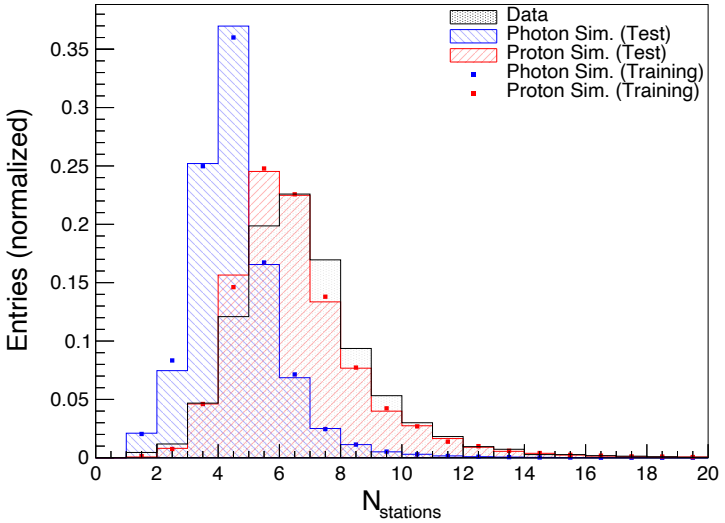
  } **see L. Perrone's talk later**

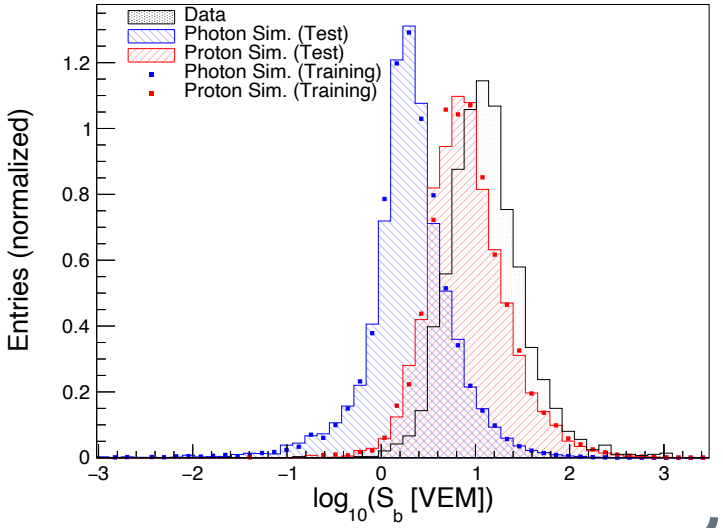
Search for photons between 2×10^{17} and 10^{18} eV

$$S_b = \sum_i S_i \times \left(\frac{R_i}{1000\ \mathrm{m}}\right)^b$$

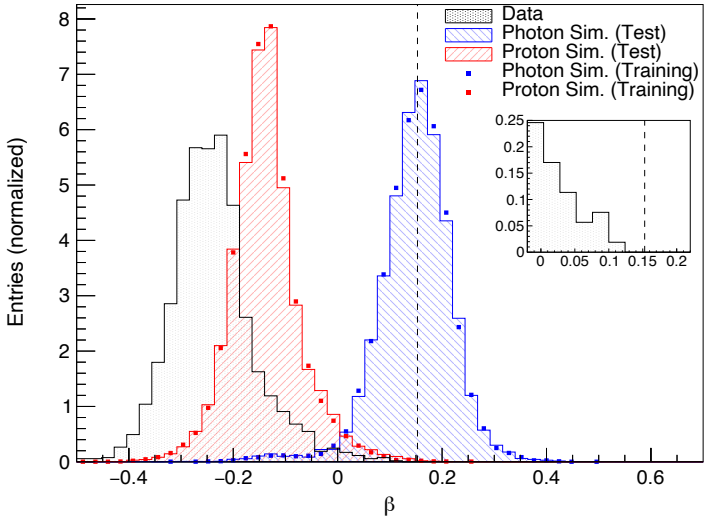
Observables







MVA (BDT)

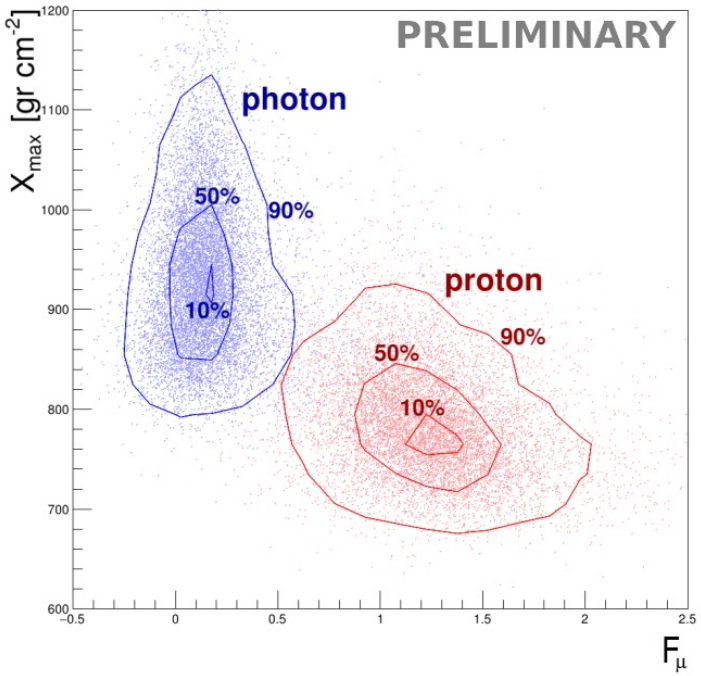


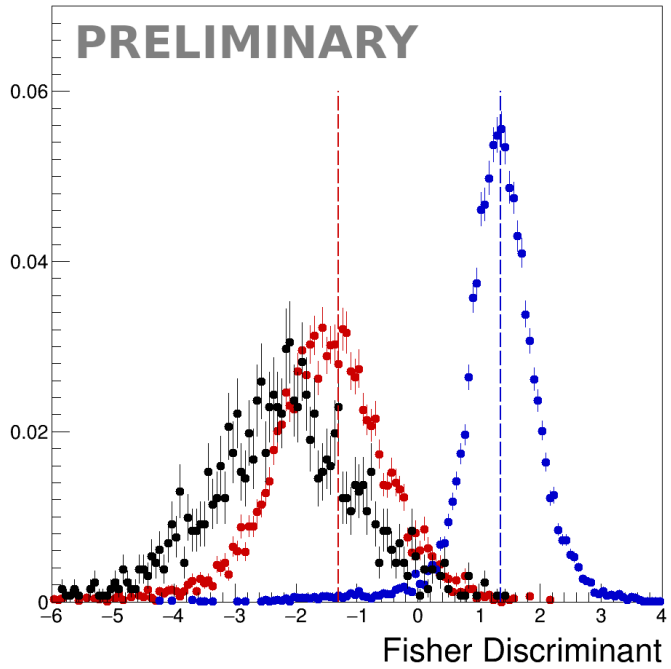
- **Photon candidate cut** chosen to ensure 50 % signal efficiency, leading to ~99.9 % background rejection
- **Data period:** 1 Jun 2010 – 31 Dec 2015
- **Exposure** to photons (from simulations): ~2.5 km^2 sr yr
- **No events** pass the candidate cut

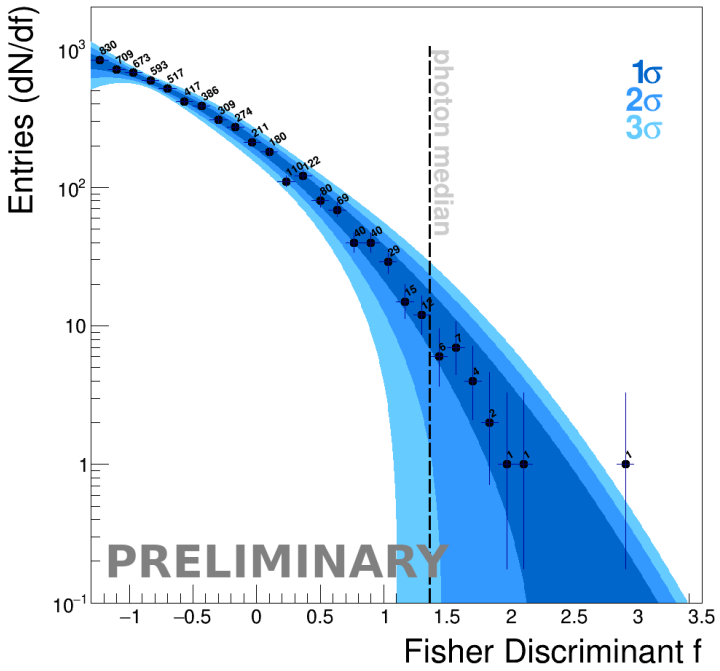
[Pierre Auger Coll., ApJ 933 (2022) 125]

Search for photons between 10^{18} and 10^{19} eV

- The **observable F_μ** is used as a proxy for the muon content calculated using a model based on **air-shower universality**
- Overall background rejection ~99.9 %
- **Data period:** 1 Jan 2005 – 31 Dec 2017; ~1000 km^2 sr yr





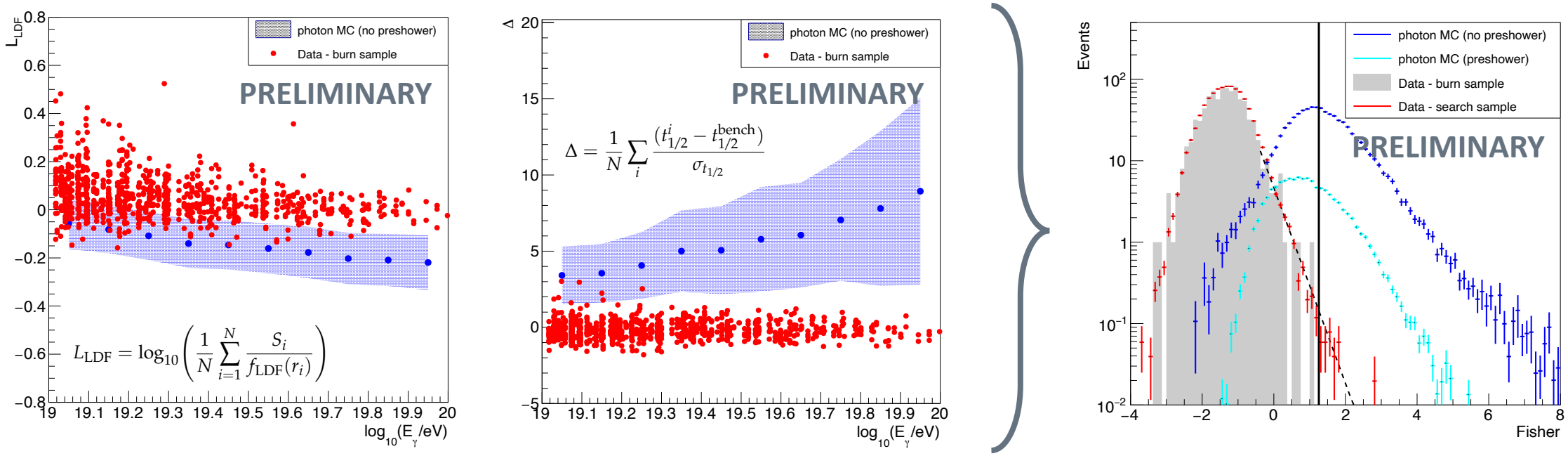


- **22 candidate events**, consistent with the expectation of 30±15, estimated using data

[P. Savina (Pierre Auger Coll.), PoS (ICRC 2021) 373]

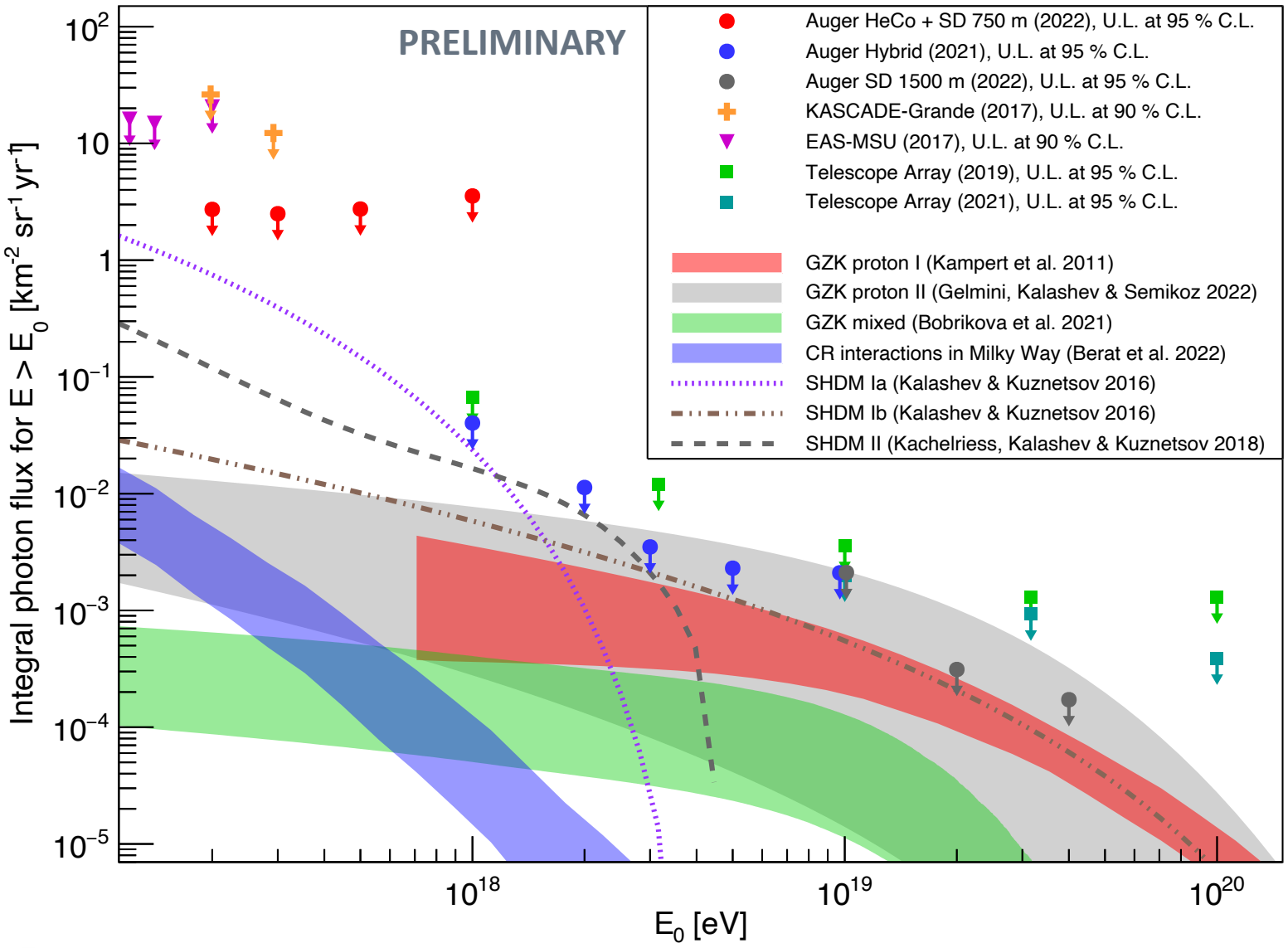
Search for photons above 10^{19} eV

- **Observables L_{LDF} and Δ** are based on benchmarks S_{LDF} and $t_{1/2}^{\mathrm{bench}}$, obtained from data
  - **No assumptions** needed on the cosmic-ray composition (i.e., the background)
- **Data period:** 1 Jan 2004 – 30 Jun 2020; ~17000 km^2 sr yr
- **16 candidate events**, consistent with the expectation



[Pierre Auger Coll., submitted to JCAP]

Upper limits on the integral flux of photons



- **Most stringent limits** to date on the diffuse flux of photons over a wide energy range
- **"Exotic" models** strongly constrained
- Predictions of some **cosmogenic models** (e.g., involving GZK interactions) are within reach
- Limits especially useful to constrain models involving **SHDM particles**

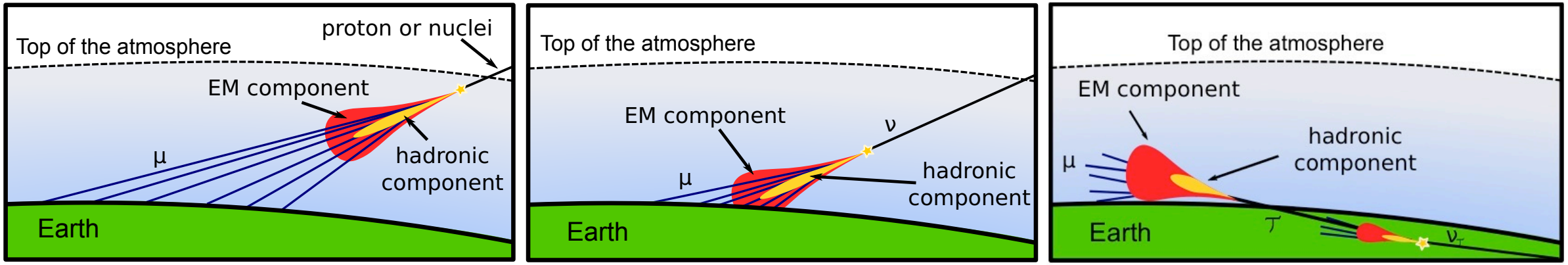
[Pierre Auger Coll., arXiv:2203.08854, arXiv:2208.02353]

[Pierre Auger Coll., submitted to Universe]

Neutrinos

How to identify a primary neutrino

- In a nutshell: Searching for UHE neutrinos means searching for **inclined showers with an electromagnetic component**
  - **Protons and nuclei** initiate air showers high in the atmosphere; at large zenith angles, the electromagnetic component is absorbed in the atmosphere and only muons arrive on ground
  - **Neutrinos** can initiate deep showers close to the ground, where the electromagnetic component can still be measured
- Additional search channel: **Earth-skimming υ_τ** leading to slightly upgoing showers



Search for neutrinos at the Pierre Auger Observatory

- All searches are based on **data from the 1500 m SD array**; three search channels:
  - **Earth-Skimming (ES)**, zenith angles between 90° and 95°
  - **Downward-going high-angle (DGH)**, zenith angles between 75° and 90°
  - **Downward-going low-angle (DGL)**, zenith angles between 60° and 75°
- Limits on the **diffuse flux** of UHE neutrinos [Pierre Auger Coll., JCAP 10 (2019) 022]
  - Here: **update** of the analysis with data until 31 December 2021
- Limits on **point-like sources** of UHE neutrinos [Pierre Auger Coll., JCAP 11 (2019) 004]

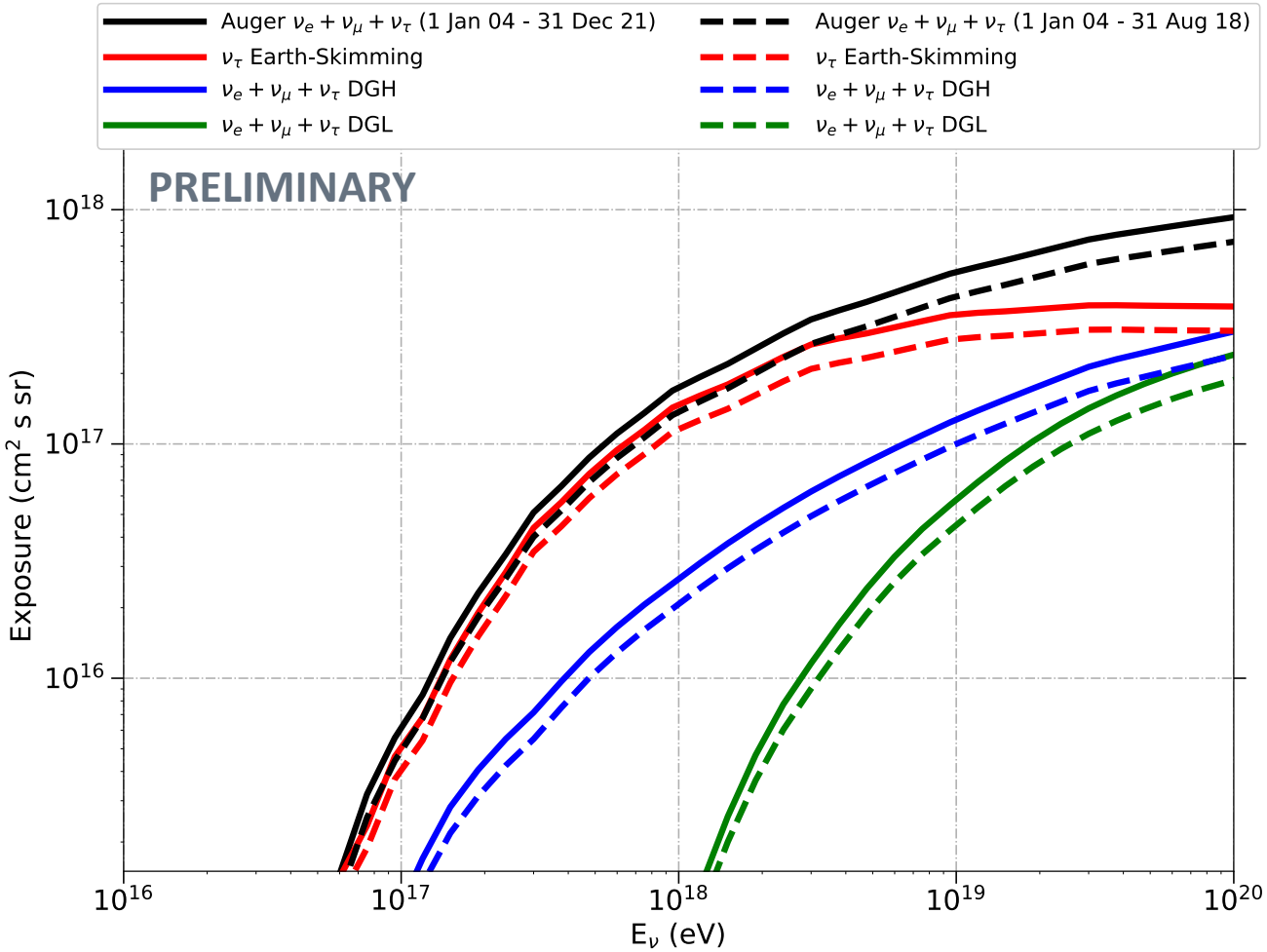
} **not covered in this talk**

- Follow-up search for UHE neutrinos in coincidence with **transient events**
  - **Gravitational wave events** [Antares, IceCube, Pierre Auger, Ligo Scientific and Virgo Colls., ApJL 850 (2017) L35]
  - **TXS 0506+056** [Pierre Auger Coll., ApJ 902 (2020) 105]

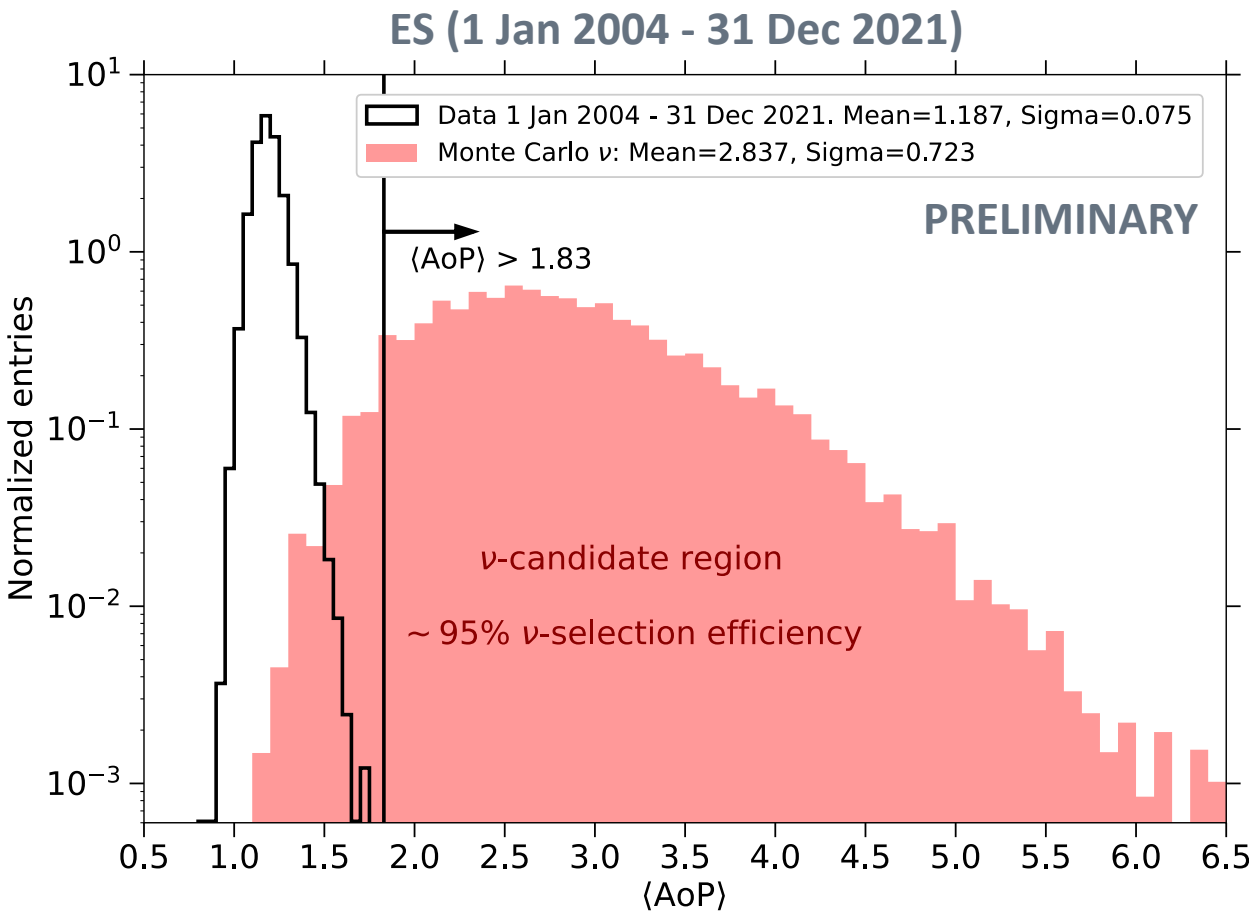
} **see L. Perrone's talk later**

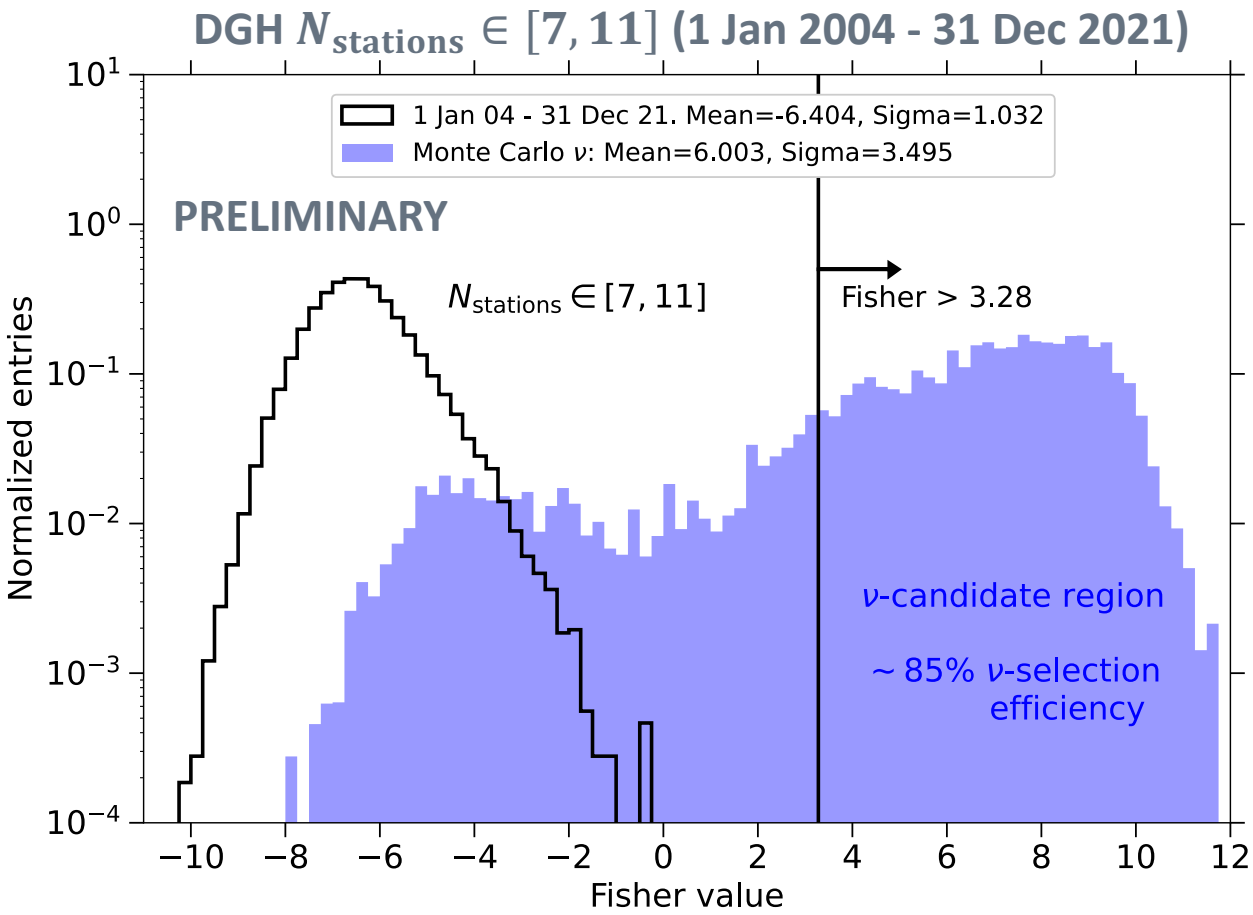
Exposure to neutrinos

- **Updated dataset**
  - JCAP 2019: [Pierre Auger Coll., JCAP 10 (2019) 022]
    - Data period 1 Jan 2004 – 31 Aug 2018
    - 9.8 “full Auger equivalent years”
  - UHECR 2022:
    - Data period 1 Jan 2004 – 31 Dec 2021
    - 12.5 “full Auger equivalent years”
- **Exposure** is dominated by the ES channel up to 4×10^{19} eV, then the DG channels takes over



Data unblinding (two examples)

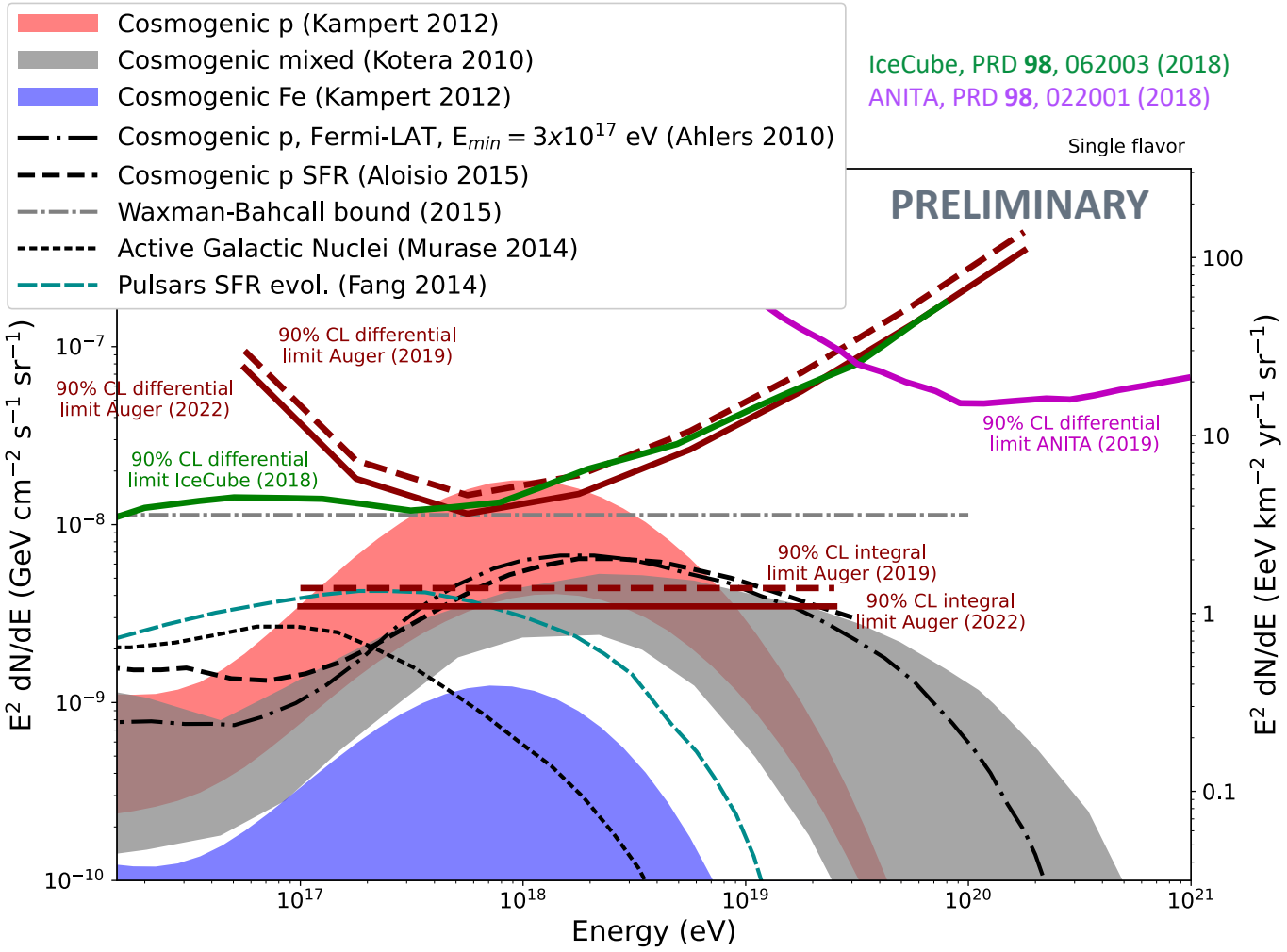




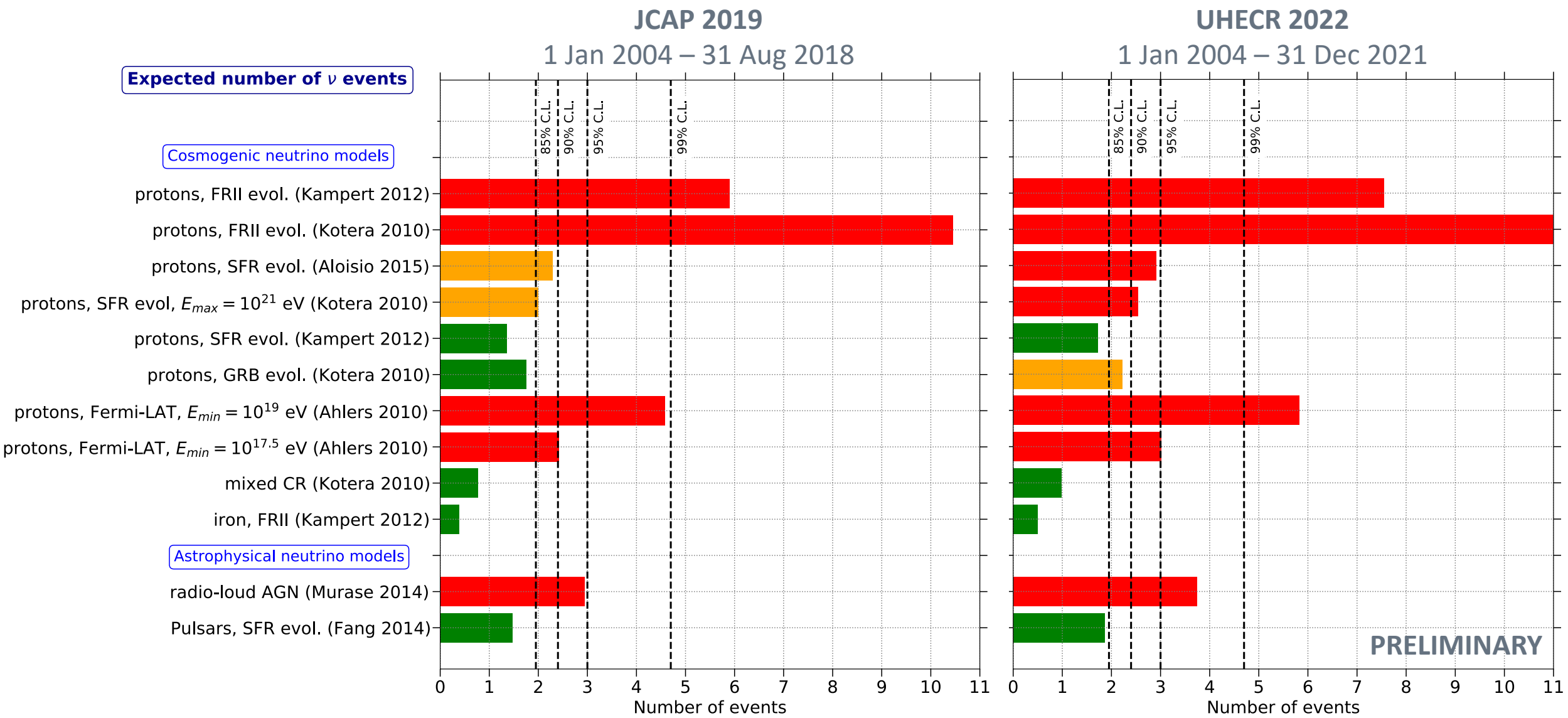
- **Neutrino candidate cut** chosen to get a false-positive rate of 1 event per 50 years
- **No candidate events** have been identified in any of the search channels

Upper limits on the diffuse flux of UHE neutrinos

- **Best sensitivity** to UHE neutrinos slightly below 10^{18} eV, comparable to that of IceCube
- **Integral limit** for neutrino energies between 10^{17} eV and 2.5×10^{19} eV: **3.5×10^{-9} GeV cm^{-2} s^{-1} sr^{-1}** or equivalently 1.1 EeV km^{-2} yr^{-1} sr^{-1}
- **Fractional contributions:**
  - **Channel:** ES 0.79; DGH 0.18; DGL 0.03
  - **Flavor:** υ_e 0.10; υ_μ 0.04; υ_τ 0.86



Expected event rates for selected models

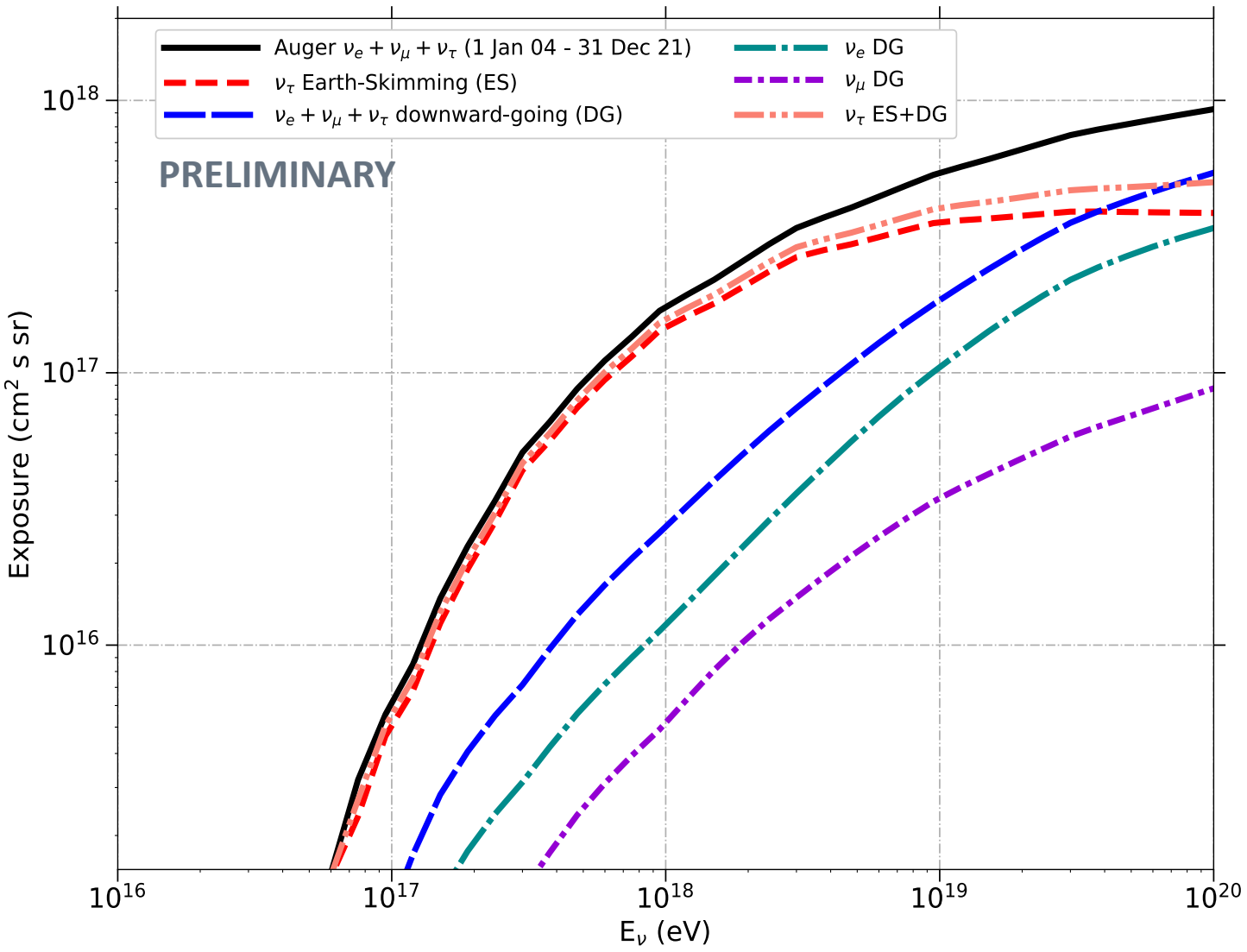


Summary

- The Pierre Auger Observatory offers an **unprecedented exposure** not only to UHECRs, but also to UHE photons and neutrinos
- **Stringent upper limits** on the diffuse flux of UHE photons and neutrinos
  - **Update of the neutrino limits** with more data until the end of 2021
- The Pierre Auger Observatory is a **key actor in multimessenger astronomy** at ultra-high energies – even more so with the upcoming **AugerPrime** upgrade

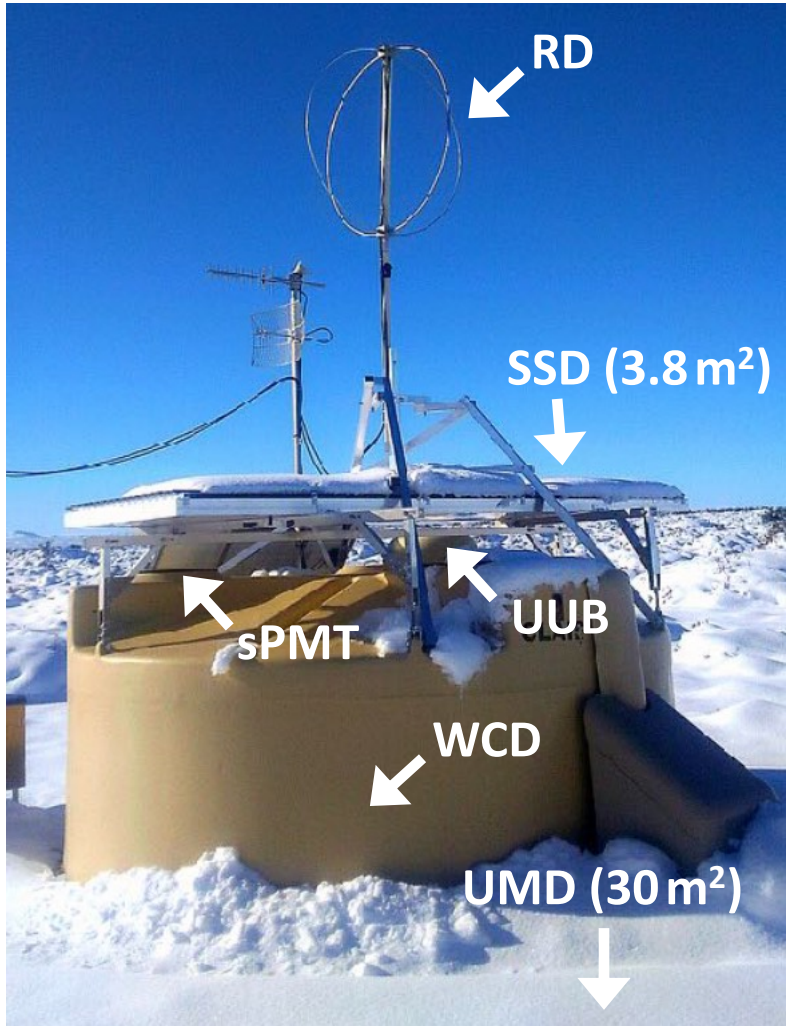
Backup

Exposure to neutrinos



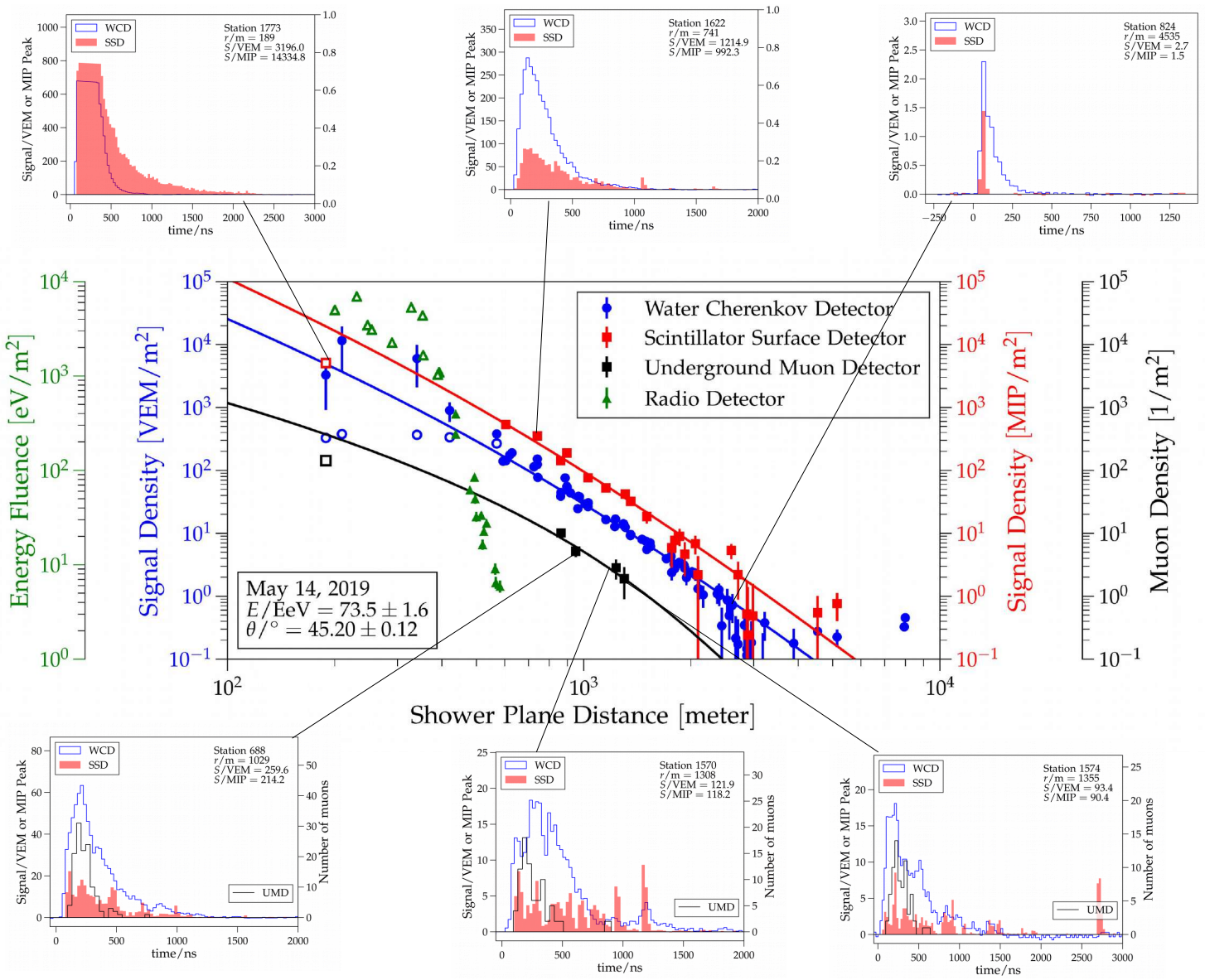
Components of AugerPrime

- **Surface Scintillator Detector (SSD)** on top of every WCD
  - Exploit the different detector responses to the electromagnetic and muonic shower components to disentangle the components
- **Upgraded Unified Board (UUB)**
  - Process the signals of all detectors; increased sampling rate
- **Small PMT (sPMT)**
  - Increase the dynamic range of the WCDs
- **Radio detector (RD)** on top of every WCD
  - Measure the radio emission of inclined air showers
- **Underground Muon Detector (UMD)**
  - Direct muon measurement in the region of the SD-750



[Pierre Auger Coll., arXiv:1604.03637]
[A. Castellina (Pierre Auger Coll.), EPJ Web Conf. 210 (2019) 06002]

Multi-Hybrid Measurements of Air Showers



"Phase II" of Auger

- Data taking 2022/2023 – 2030
- Collected exposure after 8 years for $\theta < 60°$: 40,000 km^2 yr sr ("Phase I": 80,000 km^2 yr sr)
- Re-analysis of the "old" data set using machine learning