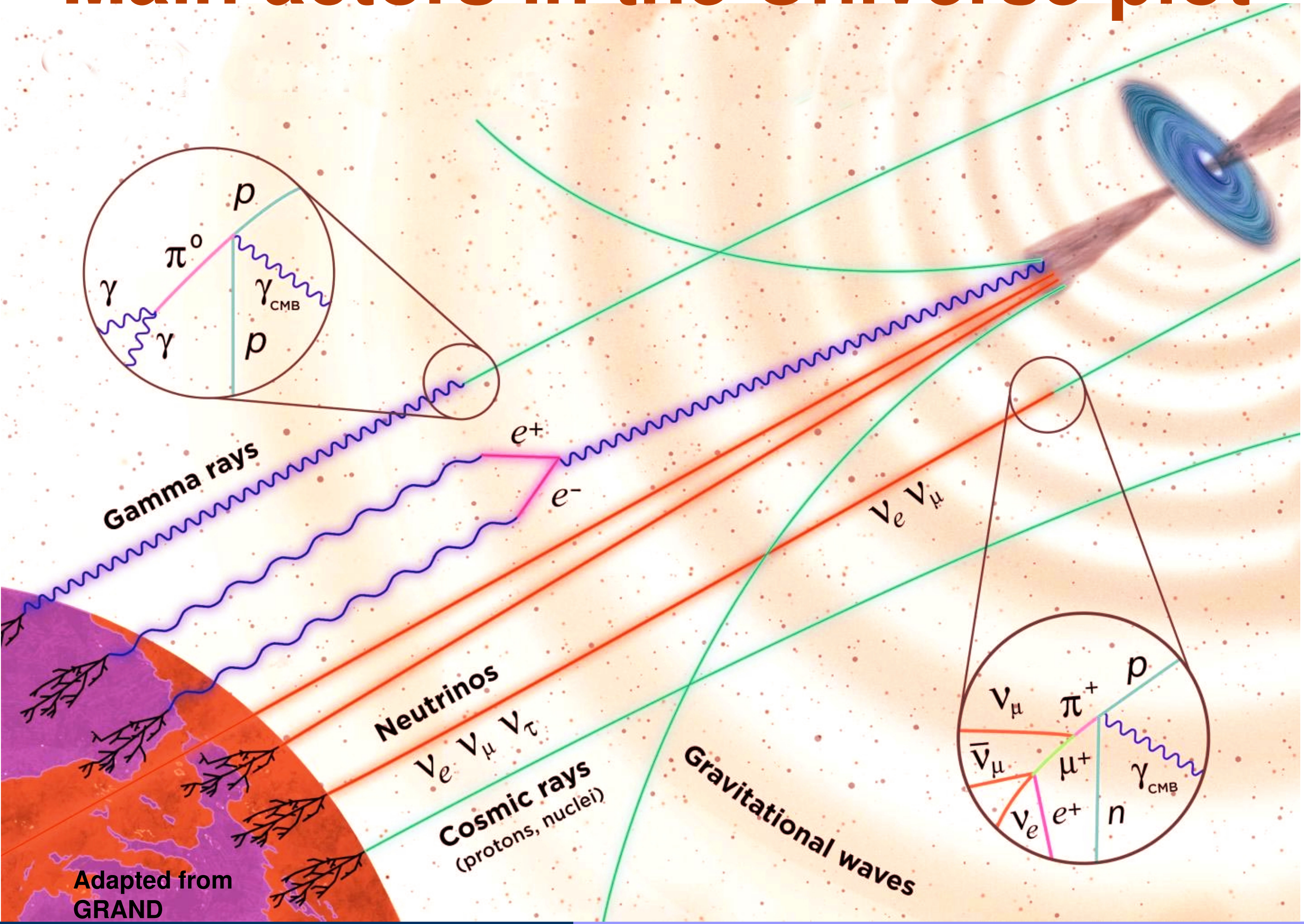
The Pierre Auger Observatory in the context of multi-messenger physics

Outline

- ▷ **Multi-messenger astronomy at the highest energies**
- ▷ **The Pierre Auger Observatory**
- ▷ **Searches for UHE neutral primaries:**
  - detection channels & sensitivity
  - diffuse & targeted searches
  - transients & GW follow-up studies

Main actors in the Universe plot



→ **Gravitational Waves:** Multi-wavelenght searches in combination with mergers

→ **Charged UHECR:** magnetic fields deflection

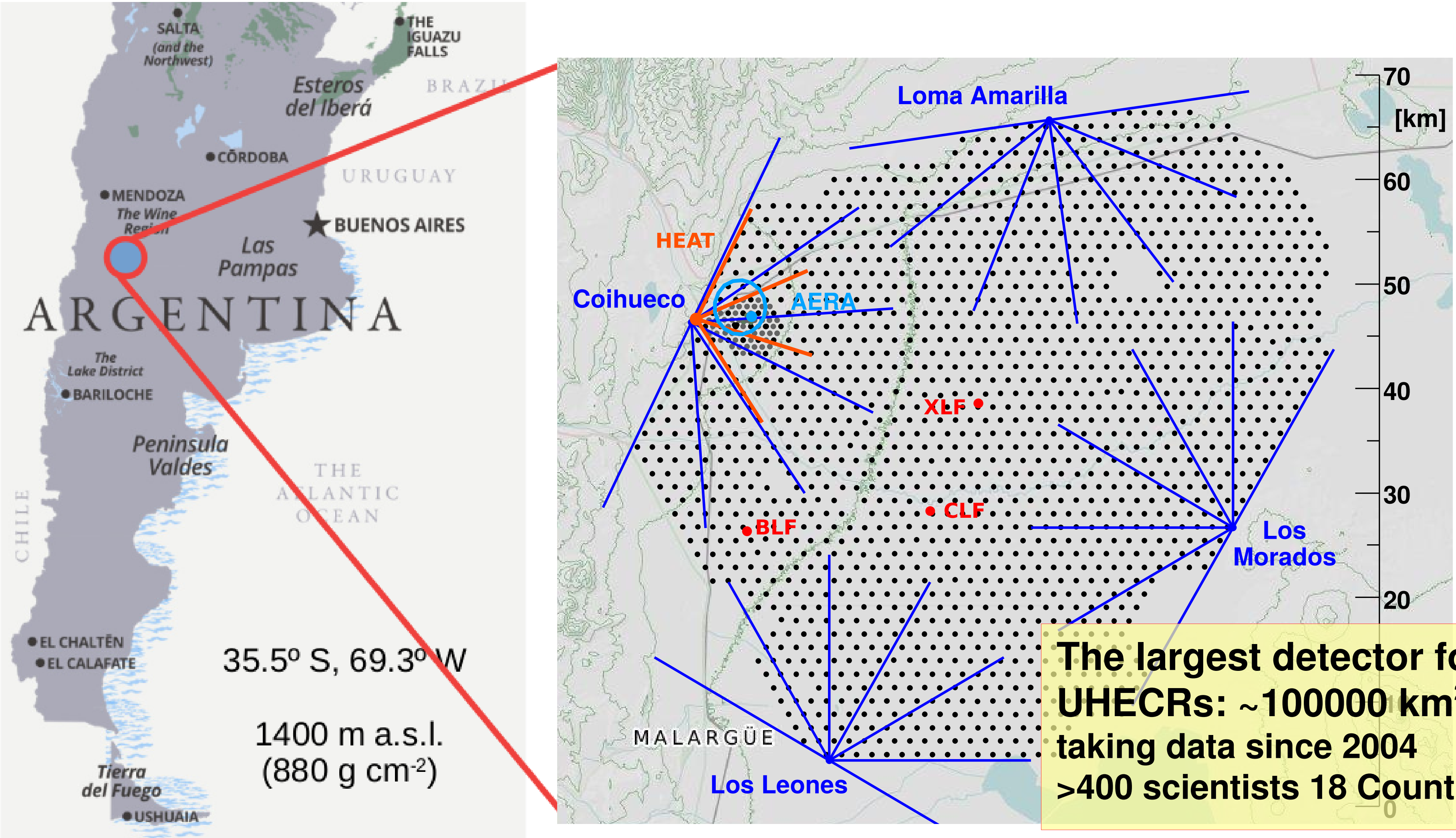
→ **UHE photons:** limited horizon local universe or hints for DM or new physics

→ **UHE neutrinos:** probing the most distant UHECR sources

→ **UHE neutrons:** excess of events from near sources

multi-messenger program: aimed at exploring the intimate connection between UHECR and neutrals
→ sources & propagation

The Pierre Auger Observatory



35.5º S, 69.3º W

1400 m a.s.l.
(880 g cm^{-2})

The largest detector for UHECRs: ~100000 km^2 sr yr
taking data since 2004
>400 scientists 18 Countries

The Pierre Auger Observatory

Surface detector

array of 1660 Cherenkov stations on a 1.5 km hexagonal grid of 3000 km^2
Dense sub-array (750 m) of 24 km^2

Fluorescence detector

4+1 buildings overlooking the array (24 + 3 HEAT telescopes)

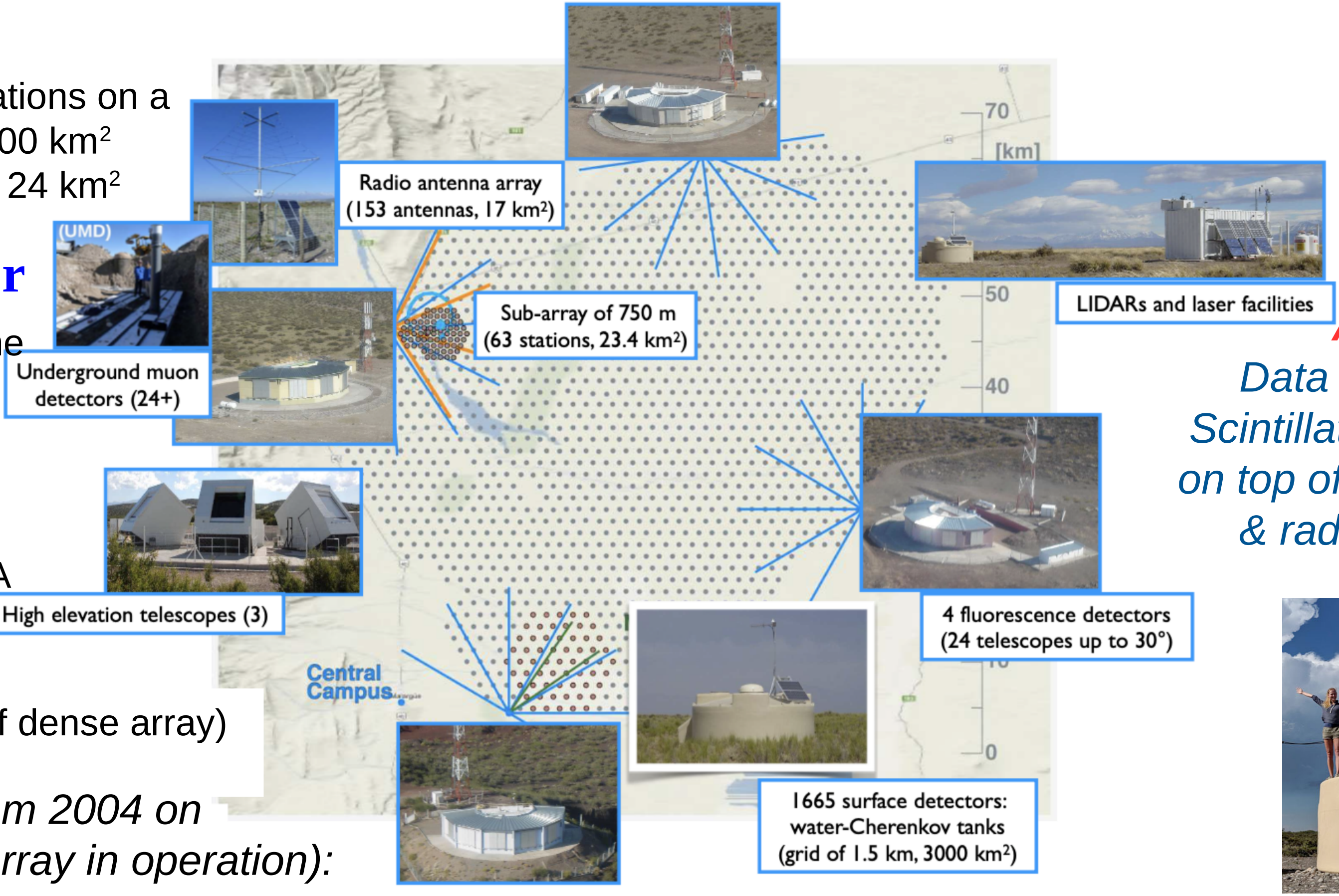
Radio detector

153 Radio Antenna → AERA

Muon Detectors

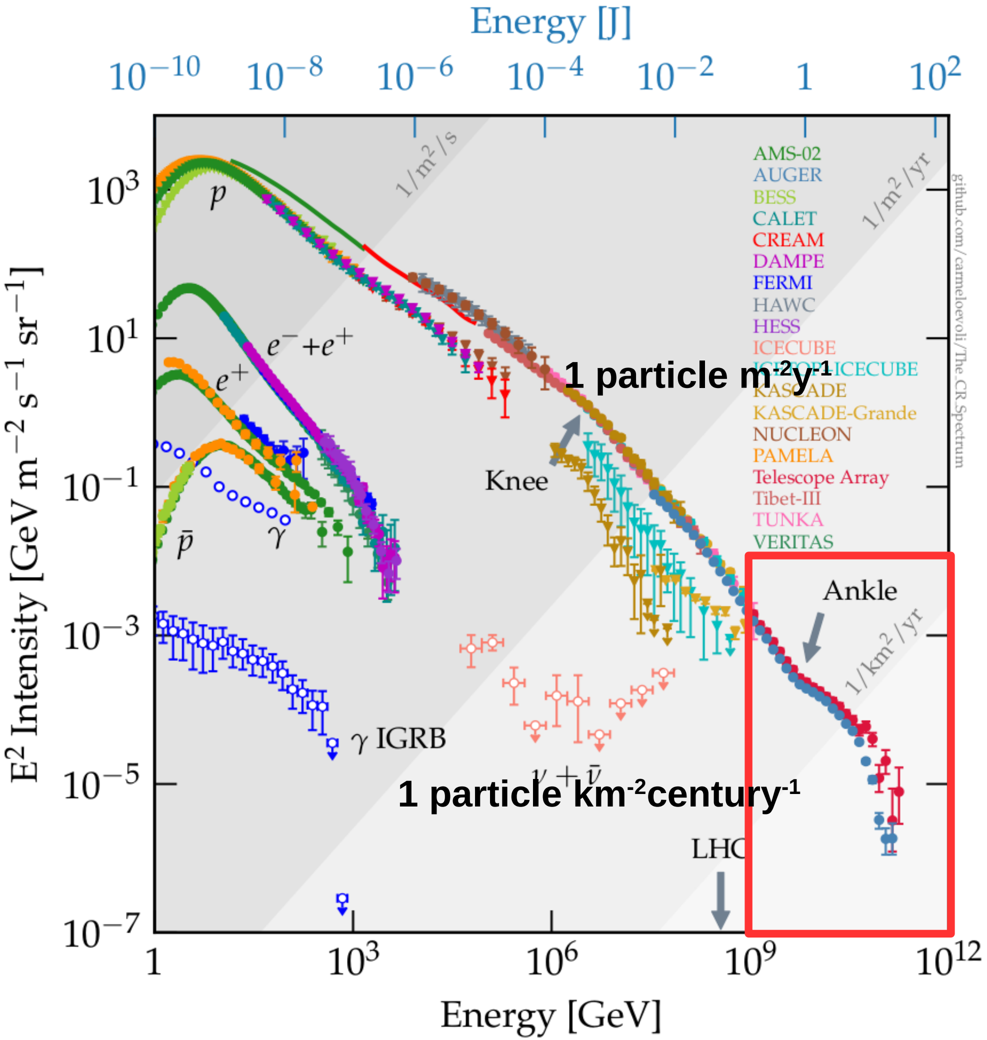
Buried scintillators (region of dense array)

Phase 1 *: data taking from 2004 on (from 2008 with the full array in operation):*



Phase 2
AugerPrime
Data taking 2023:
Scintillator detectors on top of SD stations & radio antennas

Physics case



Ankle

Transition galactic to extra-galactic cosmic rays

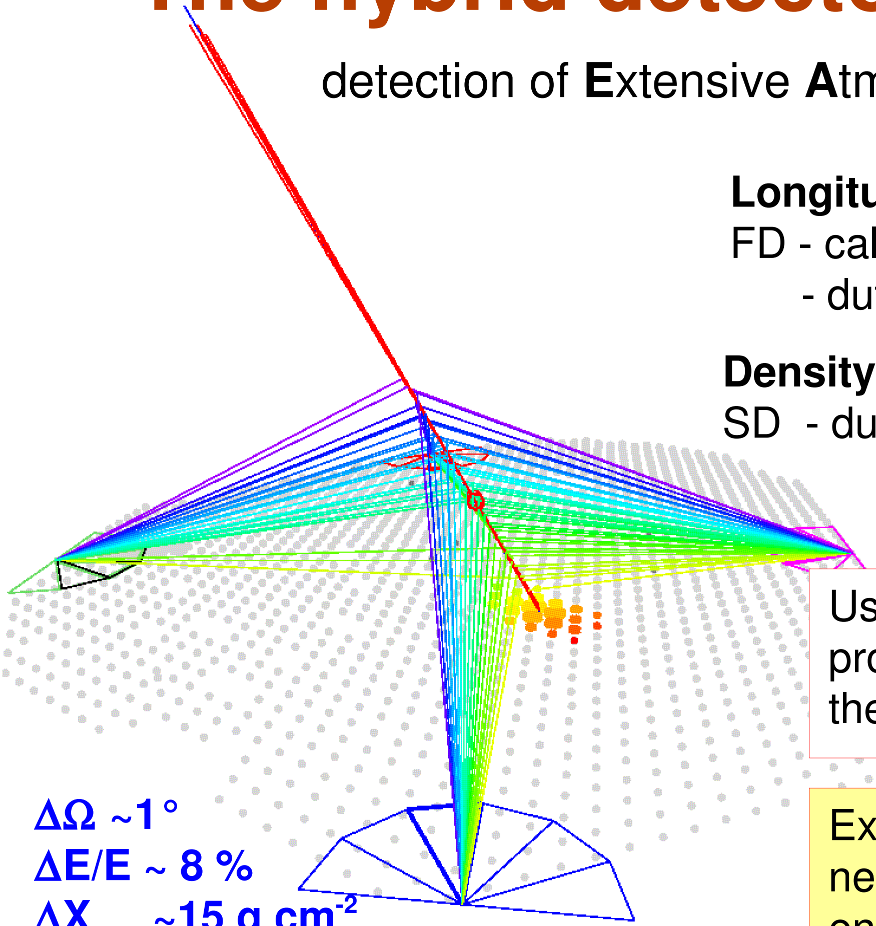
Suppression

End of the spectrum

- Energy spectrum
- Arrival directions
- Composition
- Search for photon and neutrinos as primary cosmic rays
- Hadronic physics

energy > 10^{18} eV thousands of times above man-made accelerators

The hybrid detector



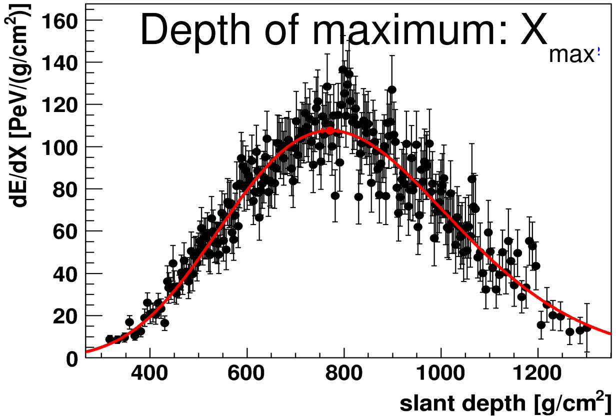
detection of **E**xtensive **A**tmospheric **S**howers

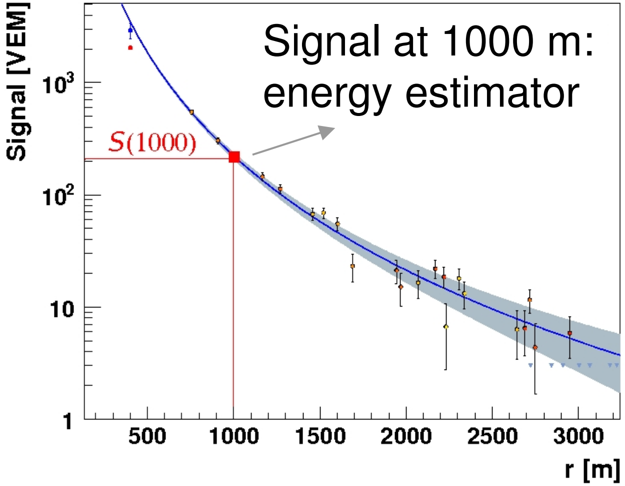
Longitudinal profile

FD - calorimetric measurement
- duty cycle 15%

Density of particles at the ground

SD - duty cycle ~ 100%



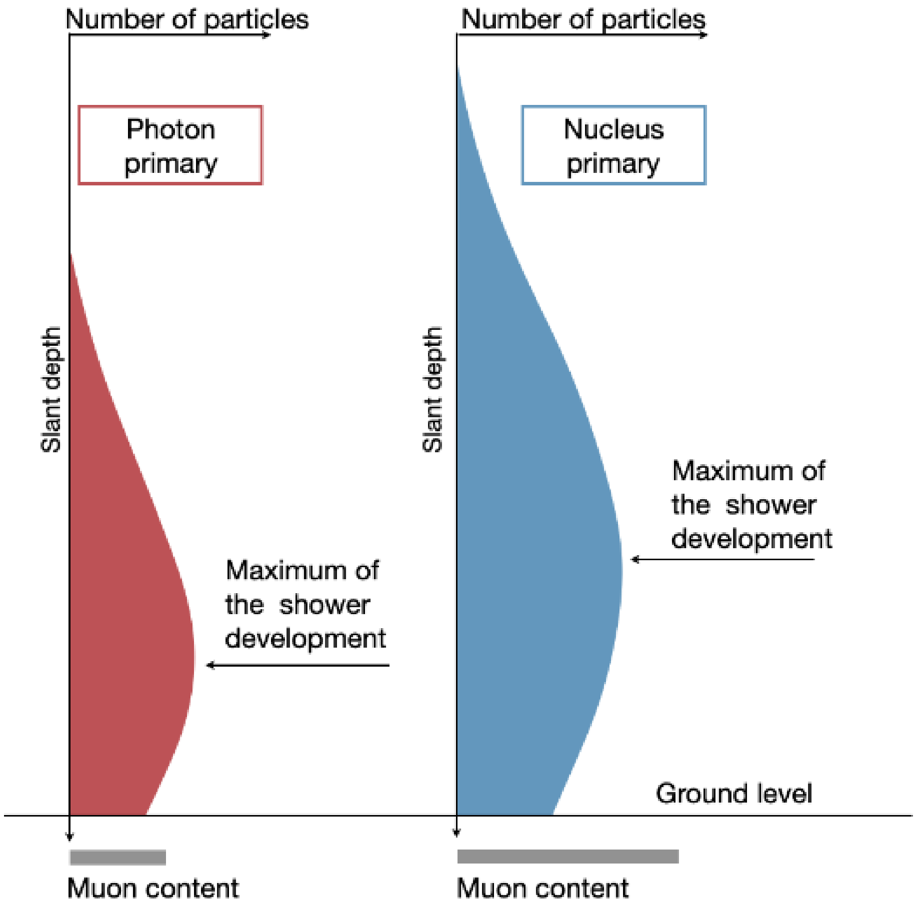


Use the energy scale provided by FD to calibrate the entire SD data sample

Excellent sensitivity also to neutral primaries in the EeV energy range

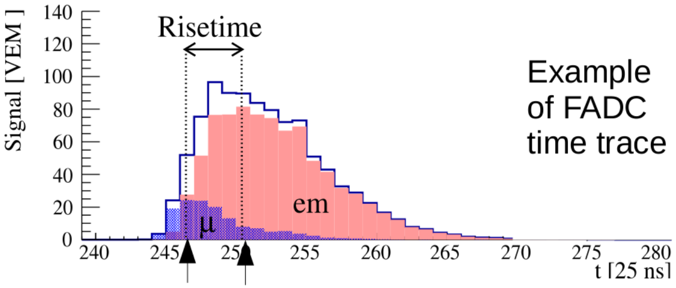
$\Delta\Omega$ ~1°
$\Delta E/E$ ~ 8 %
ΔX_{max} ~15 g cm^{-2}

UHE Photon induced cascades



Photon EAS distintive signature:
→ delayed shower developement
→ smaller muon content

observable characteristics:
- deeper <Xmax>
- steeper LDF
- smaller footprint
- broader signal traces

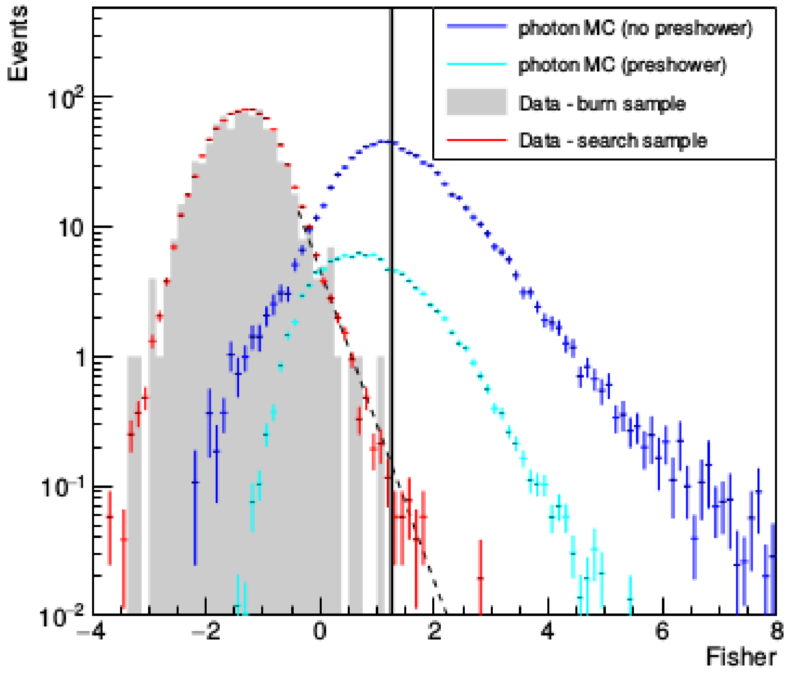


Example of FADC time trace

10% 50% quantiles

Photons: HYB and SD data selection

SD selection: Fisher response

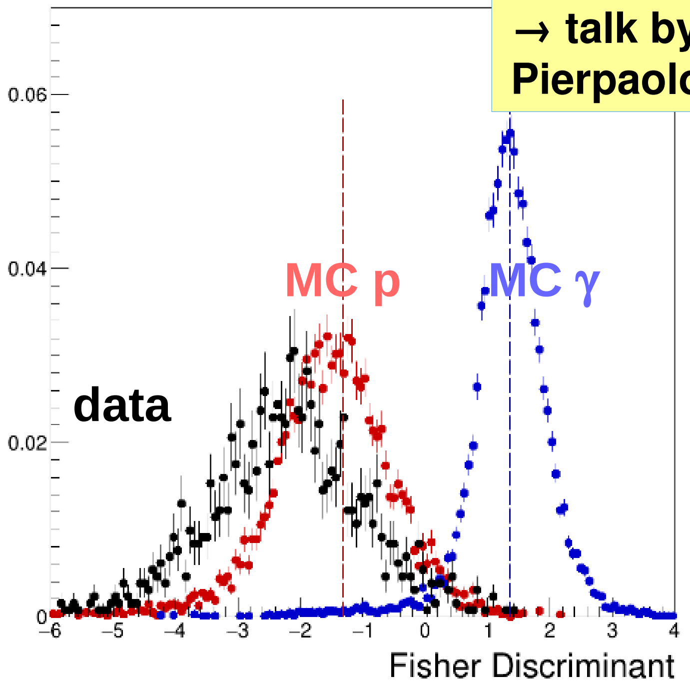


deviation from benchmark obtained from data:
→ based on LDF: $\mathbf{L}_{LDF}$
→ based on rise-time: $\boldsymbol{\Delta}$

JCAP 05 (2023) 021

Hybrid selection: Fisher response

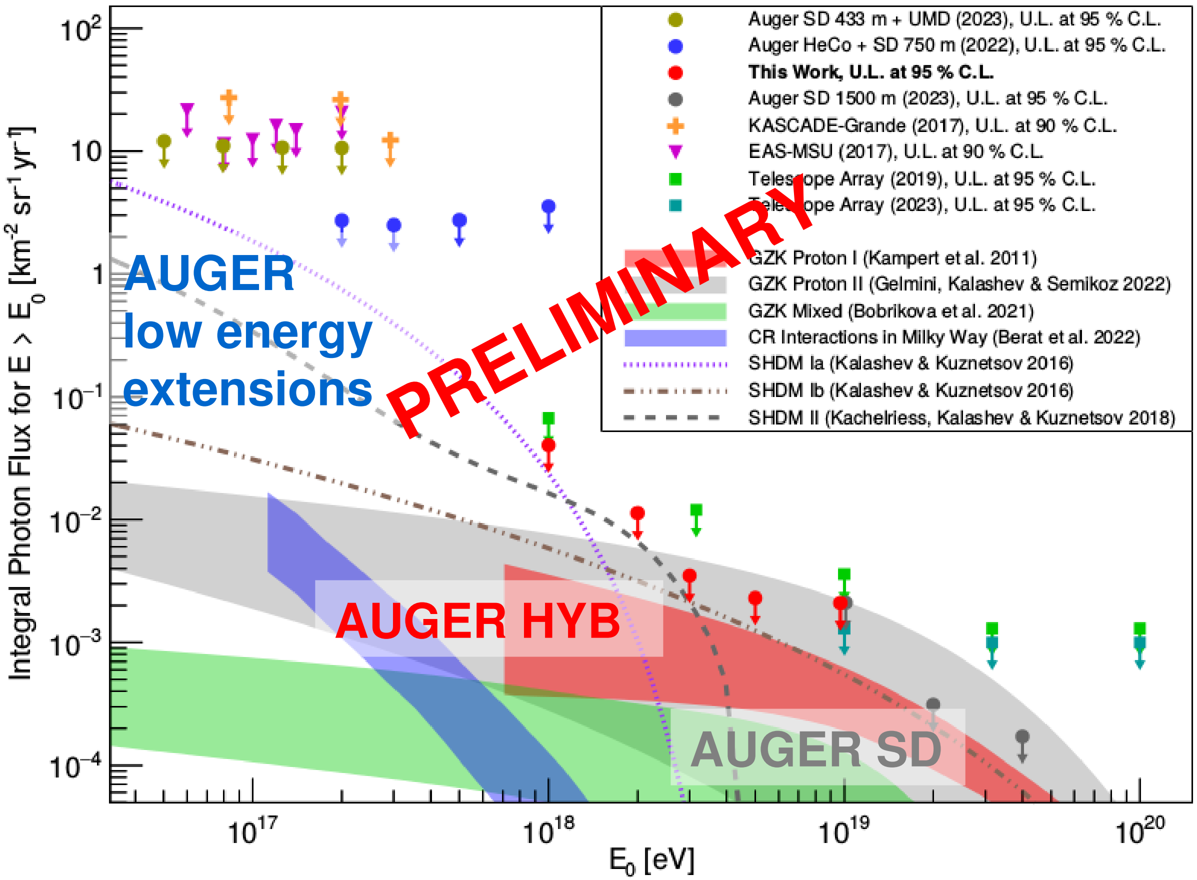
→ talk by Pierpaolo Savina



→ Maximum of shower development: $\mathbf{X}_{max}$
→ Muon content of the shower (universality): F_{μ}

PoS(ICRC2021)373, paper almost ready

Photon diffuse flux upper limits



Ap. J. 933 (2022)125
PoS (ICRC 2021) 373
JCAP 05 (2023) 021
PoS(ICRC2023)1488

→ measurements over ~4 decades

→ constraining cosmogenic predictions
→ disfavouring most top-down models
→ constraining mass and lifetime of dark matter particles

Phys. Rev. Lett., 130(6):061001, 2023
Phys. Rev. D, 107(4):042002, 2023

→ Auger Phase II: started 2023
additional information for better photon/hadron separation or... photon discovery!

Directional and targeted searches: photons

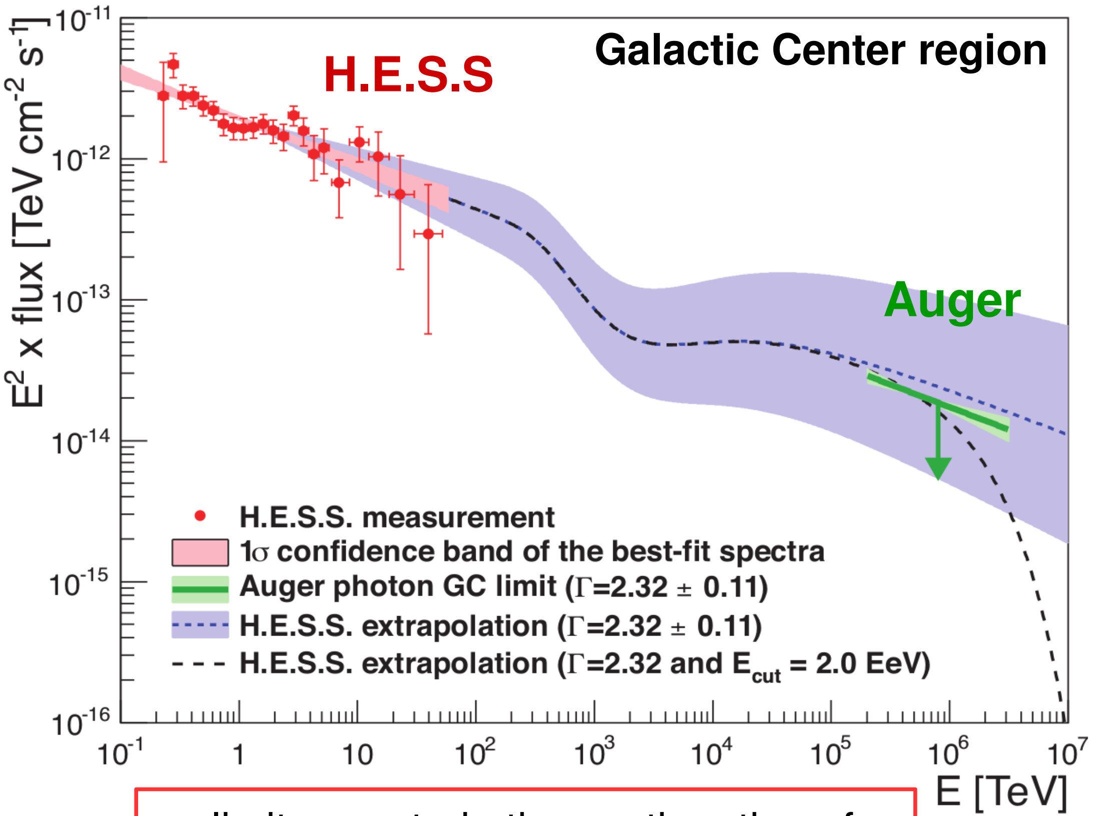
Pierre Auger Coll., ApJL 837: L25 (2017)

- **blind search** limits
- **12 target sets** Galactic sources (364 candidates sources)
- stacked analysis

→ complement neutron searches

→ talk by Danelise Franco

NO evidence for ***nearby*** photon-emitting ***steady*** sources in the EeV range
→ might be transients!



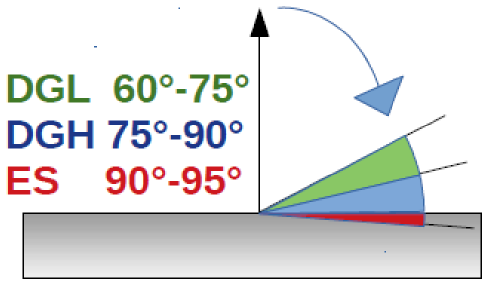
→ limits constrain the continuation of measured TeV fluxes to EeV energies

UHE neutrinos: detection channels

Earth-skimming (ES):
upward going τ neutrinos CC
zenith angle 90° ÷ 95°

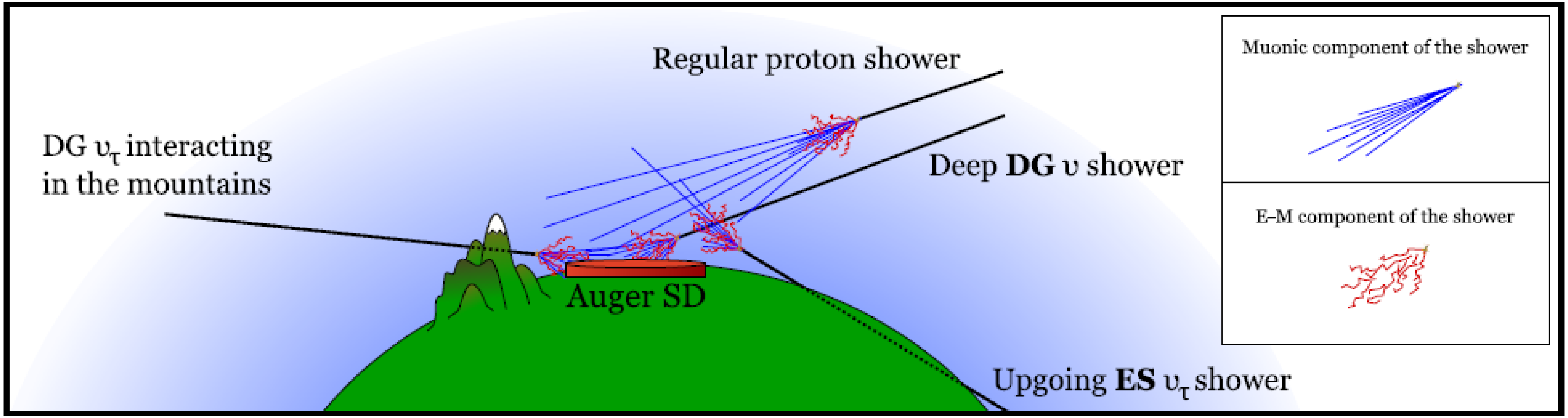
→ τ can emerge from the Earth crust and decay close to the detector

D. Fargion, Astrophys. J. 570, 909 (2002)
A. Letessier-Selvon, AIP Conf. Proc. 566, 157 (2001)

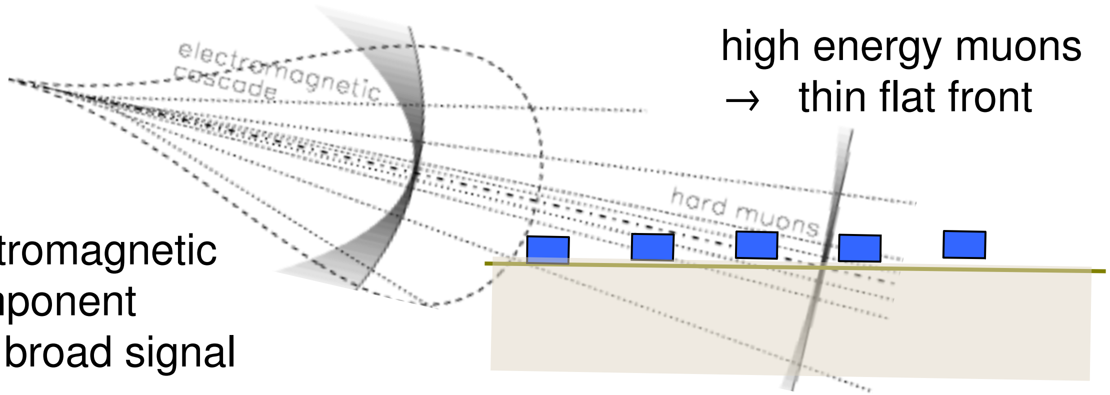


Downward Going (DG):
deeply interacting ν CC & NC
DGL 60°÷75° - DGH 75°÷90°

Sensitivity to ALL ν flavours and ALL interaction channels



UHE neutrinos: signature



high energy muons
→ thin flat front

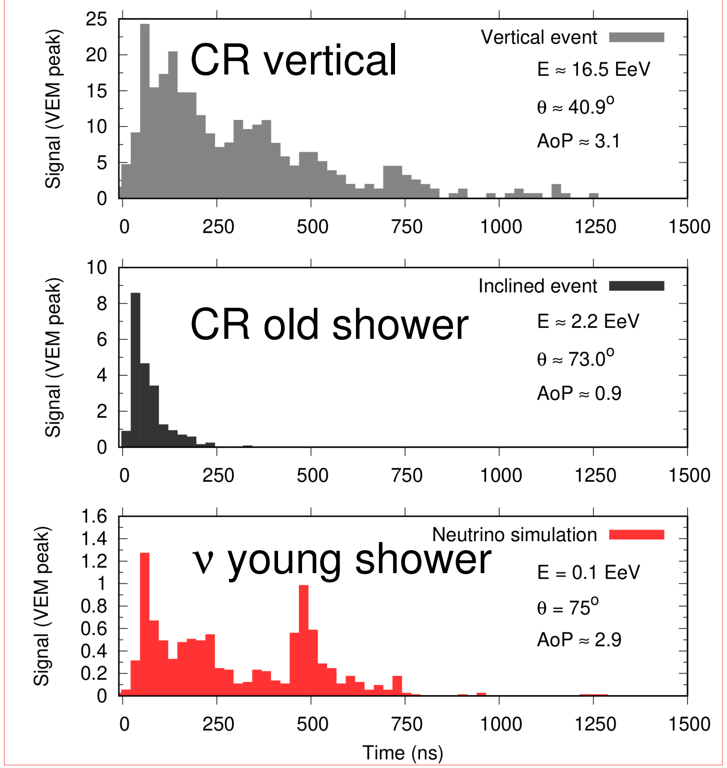
elettromagnetic component
→ broad signal

young shower i.e. with large electromagnetic component
→ inclined event with slow rising and broad signal

background composed by **muon-dominated hadronic showers** (EM component absorbed in the atmosphere)

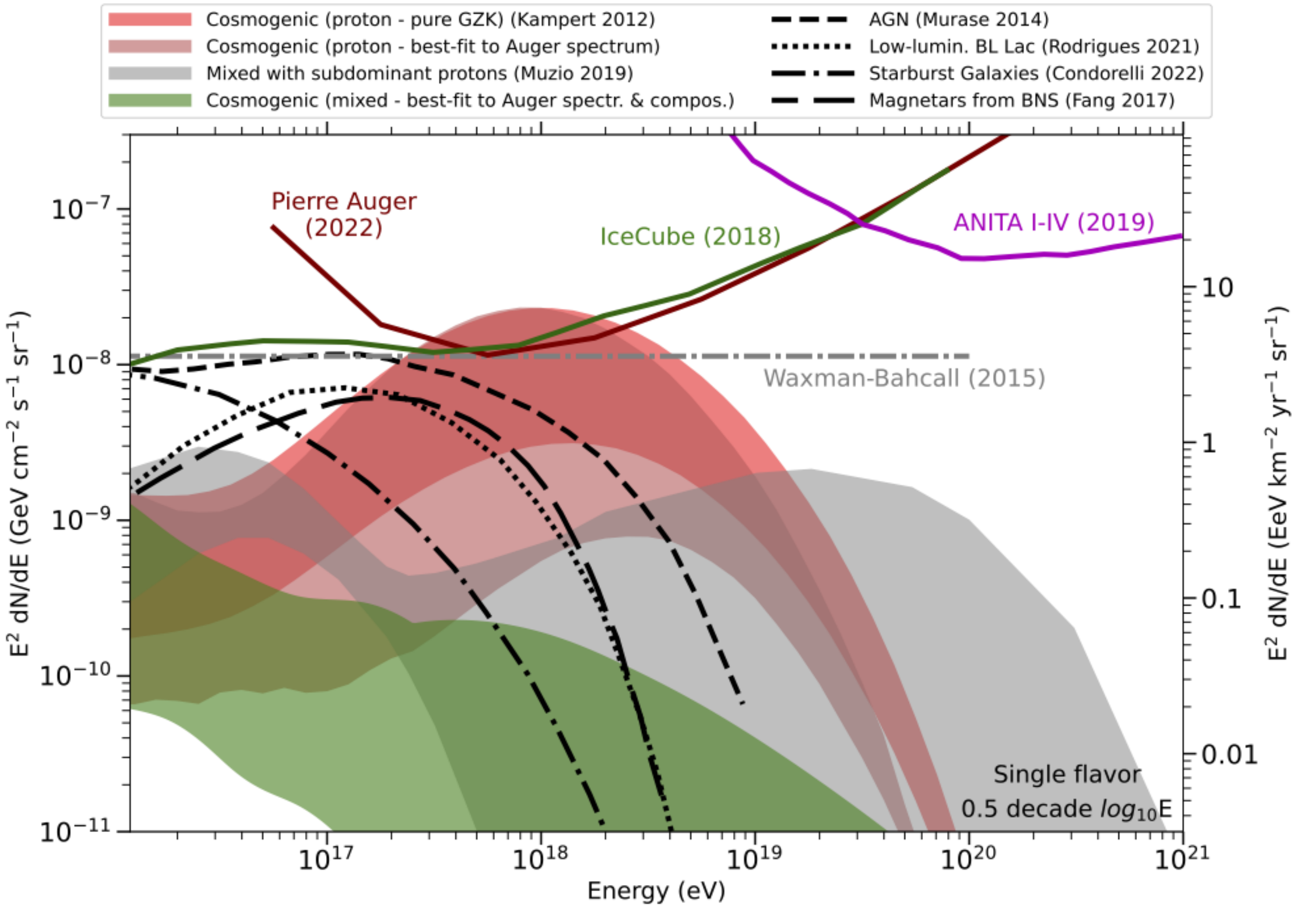
discrimination relies on the **different SD signal shapes** between hadronic and neutrino events
→ Area-over-Peak

typical signal shapes



UHE neutrinos: diffuse flux limits

SD data from 1 January 2004 until 31 December 2021



Pierre Auger Coll., JCAP 10 (2019) 022
EPJ Web Conf. 283 (2023) 04003

NO Candidates found

Max sensitivity ~ **1 EeV**

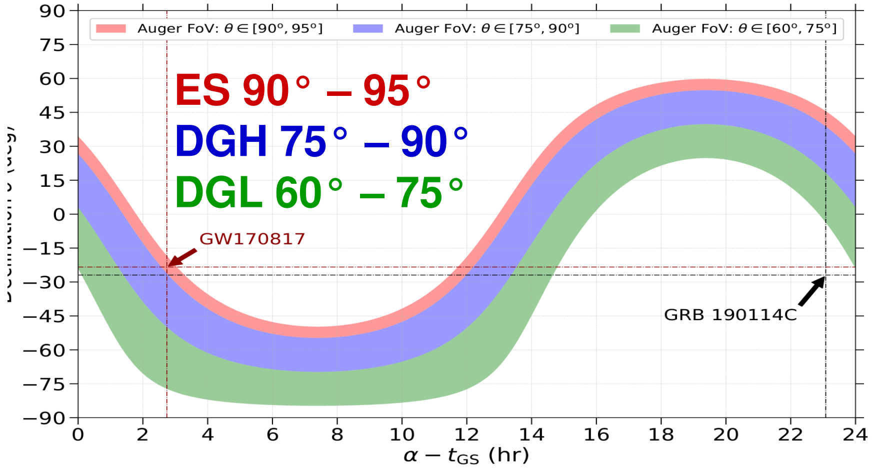
Integral UL normalization factor
k ~ 3.5 x 10^{-9} [GeV cm^{-2} s^{-1} sr^{-1}]

→ pure-proton disfavoured

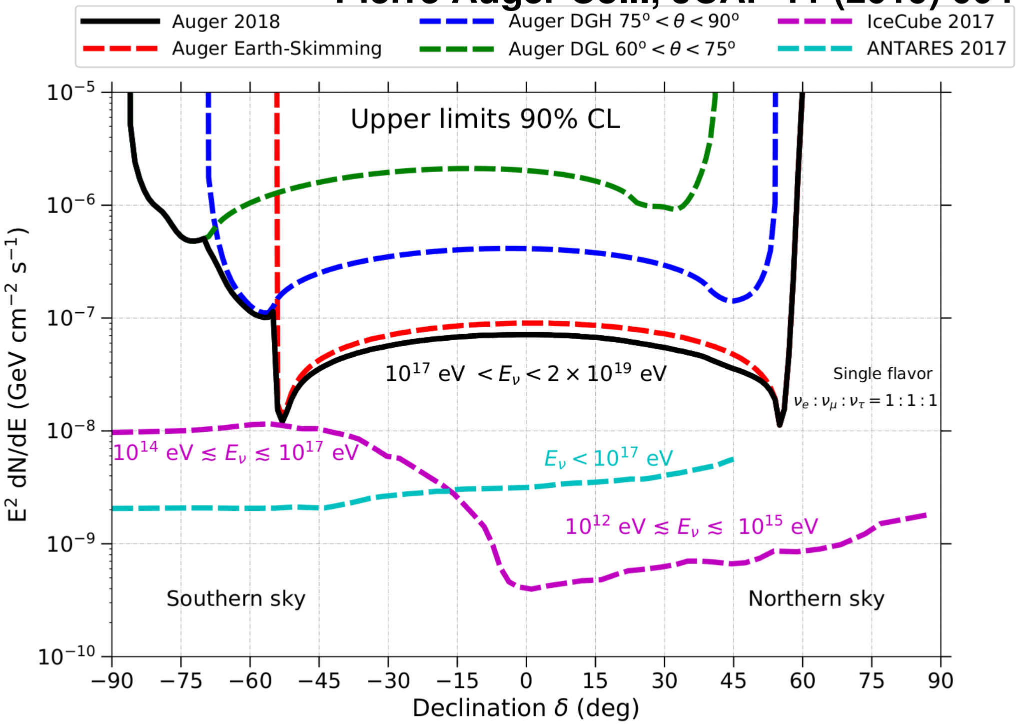
→ factor 3 exposure for probing mixed-composition scenarios

Corresponding limits on point-like sources complement IceCube and ANTARES

UHE neutrinos: point sources sensitivity



Pierre Auger Coll., JCAP 11 (2019) 004



point sources transit through the field of view of each detection channel

→ sensitivity strongly depends on source location and event timing

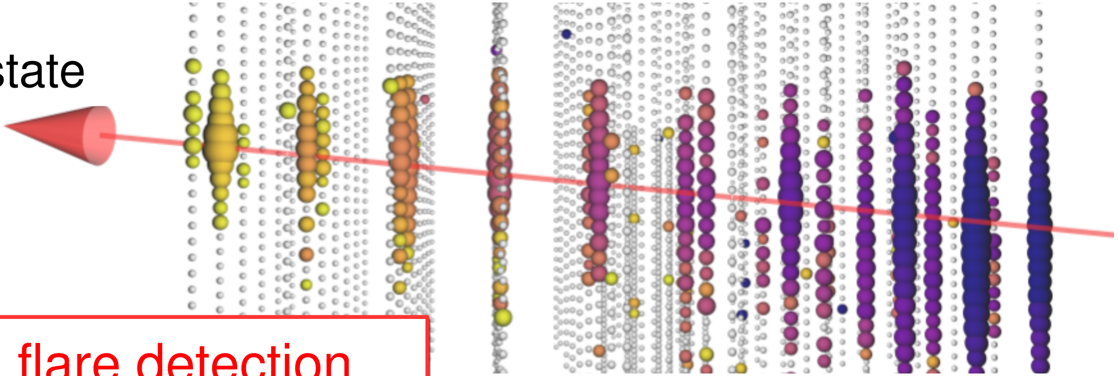
→ good sensitivity in the EeV range in a broad range of declinations

→ complementary energy range: $10^{17} \div 2 \cdot 10^{19}$ eV

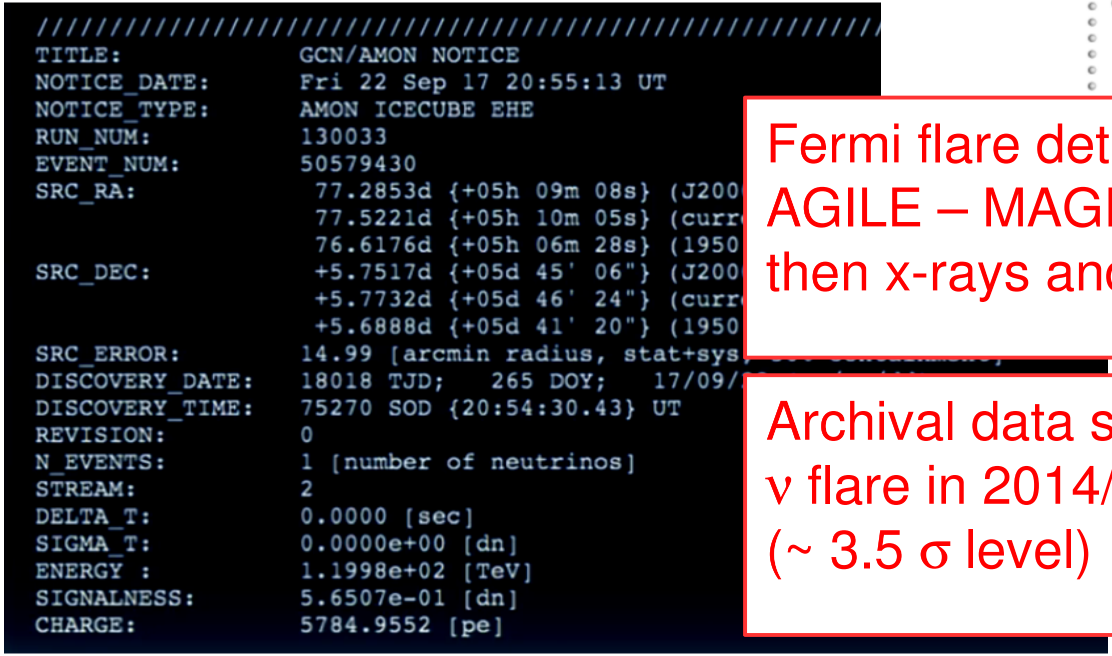
A source: TXS0506+056

Science 361, 146 (2018)

IceCube observed a 290 TeV ν in the direction of TXS0506+056 during flaring state



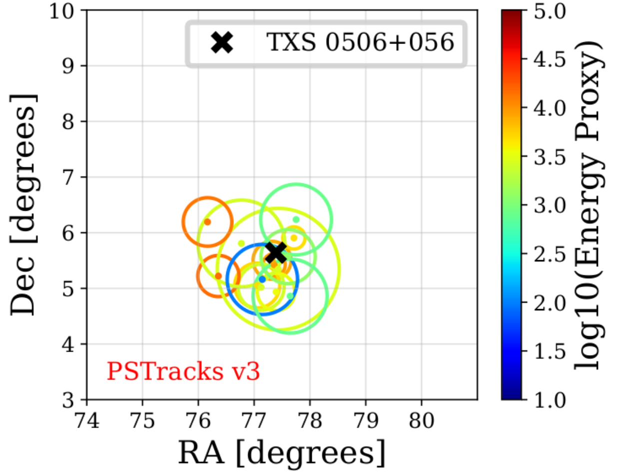
IceCube Alert IC170922A



```
//////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J200
                   77.5221d {+05h 10m 05s} (curr
                   76.6176d {+05h 06m 28s} (1950
SRC_DEC:           +5.7517d {+05d 45' 06"} (J200
                   +5.7732d {+05d 46' 24"} (curr
                   +5.6888d {+05d 41' 20"} (1950
SRC_ERROR:        14.99 [arcmin radius, stat+sys
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

Fermi flare detection
AGILE – MAGIC..
then x-rays and radio

Archival data shows
ν flare in 2014/2015
(~ 3.5 σ level)



Follow-up searches: TXS0506+056

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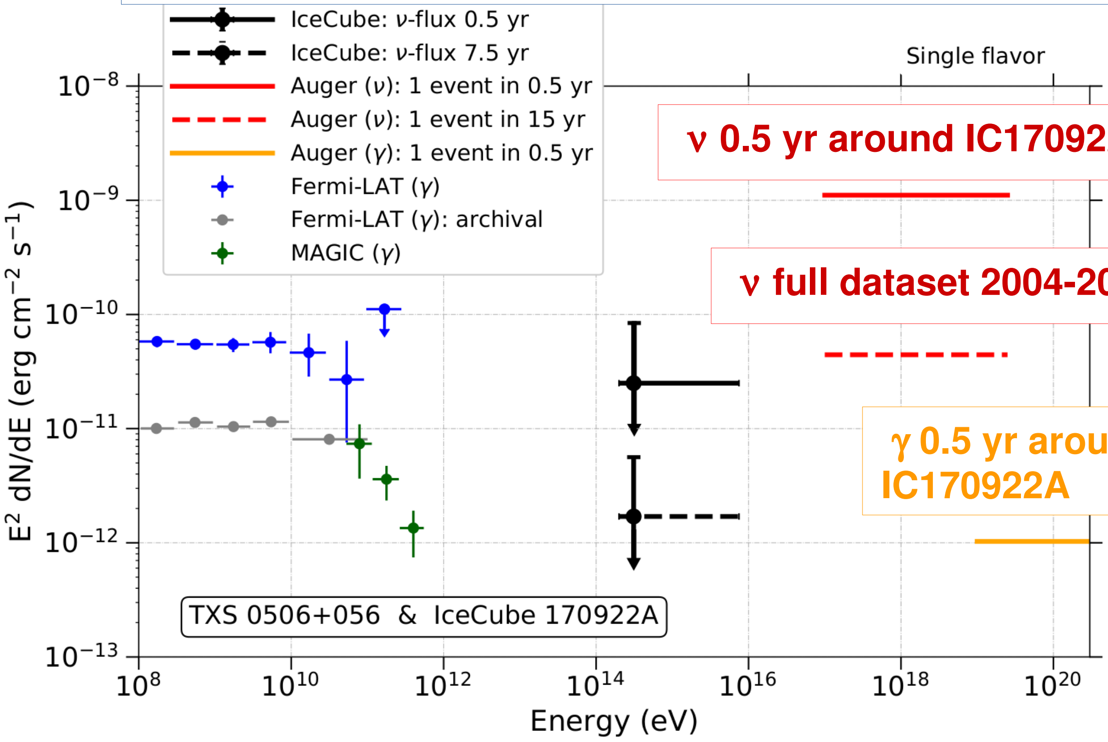
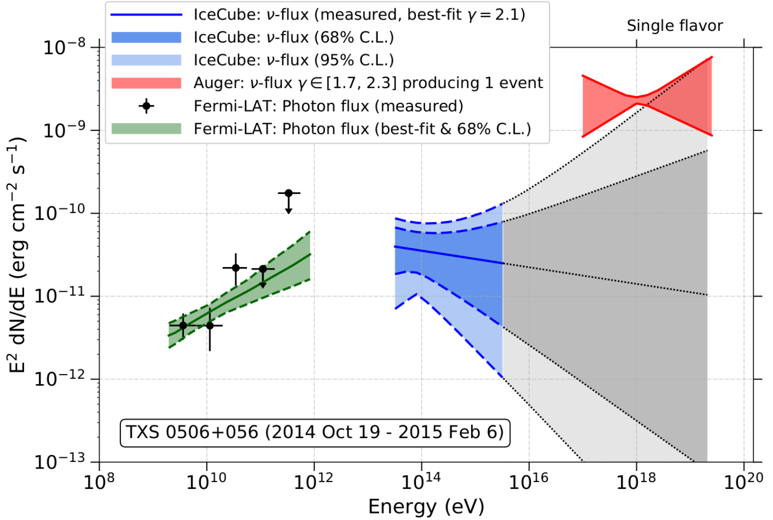


Reference flux for 1 event @ Auger

Pierre Auger Coll., Ap. J., 902:105 (2020)



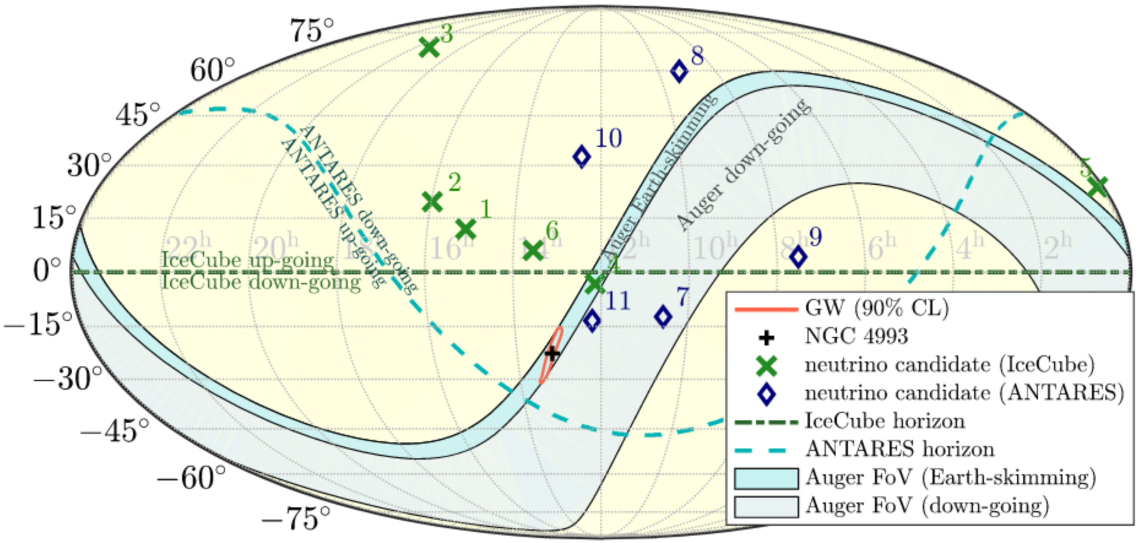
TXS0506 not in the most sensitive region

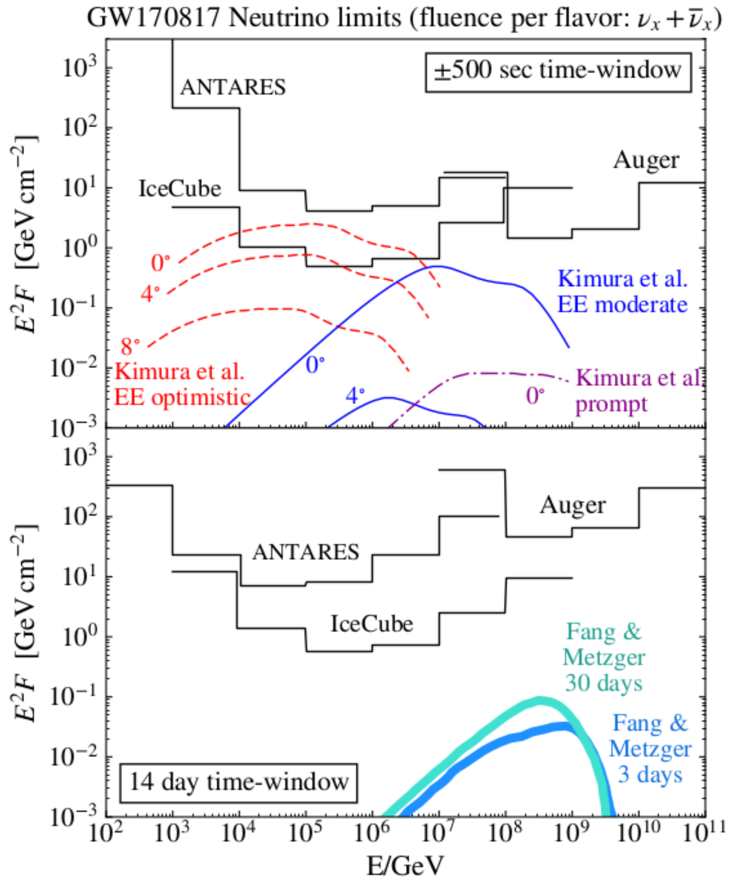
→ complementary to IceCube in the EeV range
→ observation only if hard (>1.5) spectral index up to EeV range

Follow-up searches: GW170817

ApJL 850 L35 2017

LIGO/Virgo BNS GW170817 & Fermi sGRB 170817A
→ EM counterpart Optical/IR KiloNova AT2017GFO

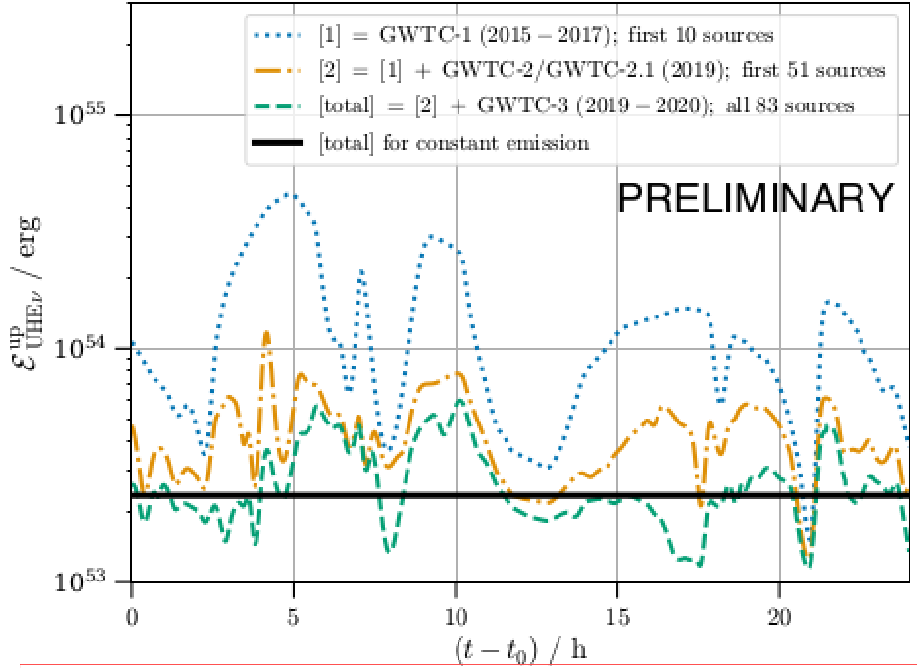




→ excellent visibility of the merger:
90% CL GW event location in FoV of ES channel
→ time dependent exposure leads to substantially lower 14-day neutrino fluence limits wrt to prompt

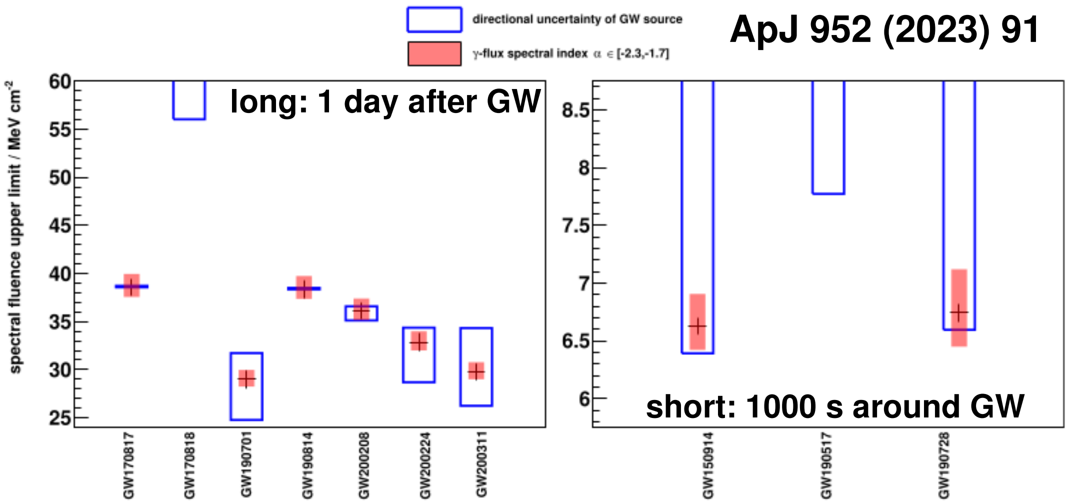
GW follow-up: ν and γ searches

PoS(ICRC2021)968, paper in prep. (2023)



No UHE-neutrino events found for 83 GW events
upper limit on neutrino emission: Eν ~ 2.3x10^{53} erg
→ well below the radiated GW energy

ApJ 952 (2023) 91

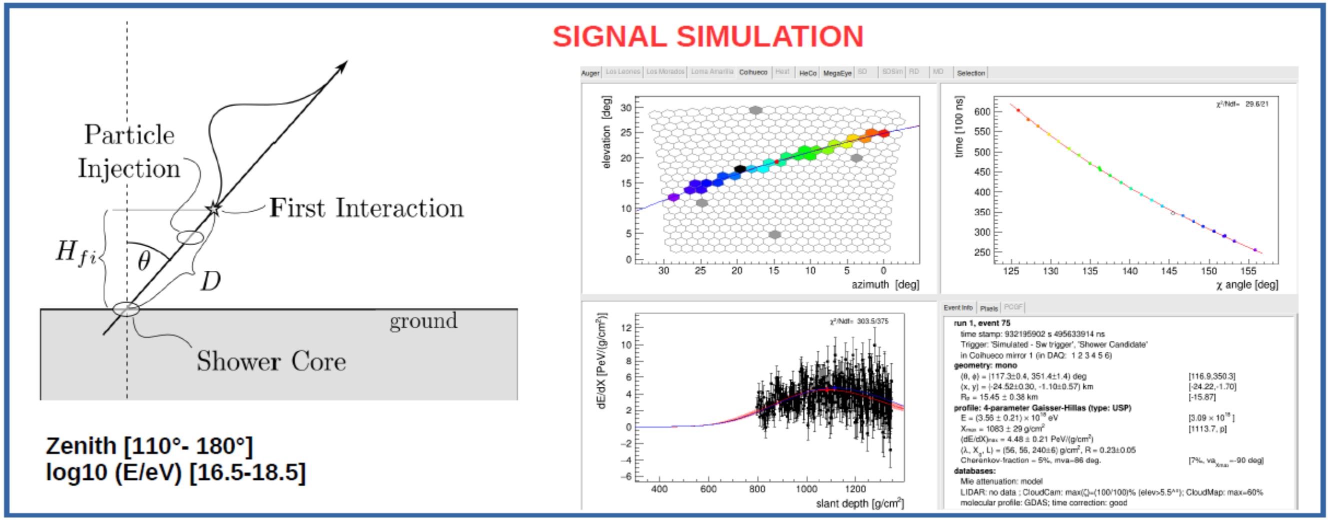


- focus on nearby and/or well localised sources
- window open to potential new physics

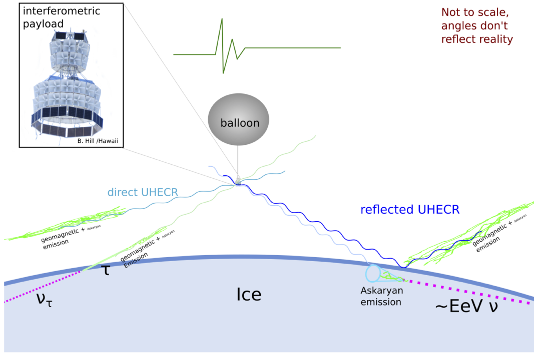
No coincident photon candidate identified
→ upper limits on spectral fluence
~ 7 MeV cm^{-2} and ~35 MeV cm^{-2}
→ constrain energy transferred into photons
to < 20% for GW170817

Search for upward-going events with the FD

paper in submission (PRL)



Zenith [110°- 180°]
log10 (E/eV) [16.5-18.5]



ANITA Observation:

$E_{1,2} \gtrsim 0.2$ EeV, exit angle $\approx 27°, 35°$

→ talk by Emanuele De Vito

Quantify the sensitivity of the FD to upward-going showers

→ derive the FD exposure as a function of shower energy and height of first int.

→ MC estimate of the expected background

Detector sensitivity over a wide range of energies and height of first interaction (zenith > 110°)

Useful to test various physics scenarios (taus, BSM)

Outlook

The Pierre Auger Observatory participates in the ongoing multi-messenger international effort to combine data from different experiments in complementary energy ranges

The Pierre Auger Observatory, the largest detector for UHECR:

→ **excellent sensitivity** to neutral primaries in the EeV range

→ stringent γ and ν diffuse limits in the EeV range

→ constraining exotic scenarios and testing cosmogenic flux predictions

indirect hint on primary CR mass composition

→ **coverage of a large fraction of the sky** with directional and targeted searches

→ **follow-up searches** of LIGO/Virgo mergers

← Fast LVC alert follow-up infrastructure in place
→ GCN notices, streaming to AMON & DWF

→ **upward-going searches** bounds to anomalous ANITA events & test BSM scenarios

→ The AugerPrime upgrade improving on sensitivity and background rejection
++ implementation of machine learning algorithms on multi-hybrid data

→ talk by Pierpaolo Savina

→ talk by Emanuele De Vito

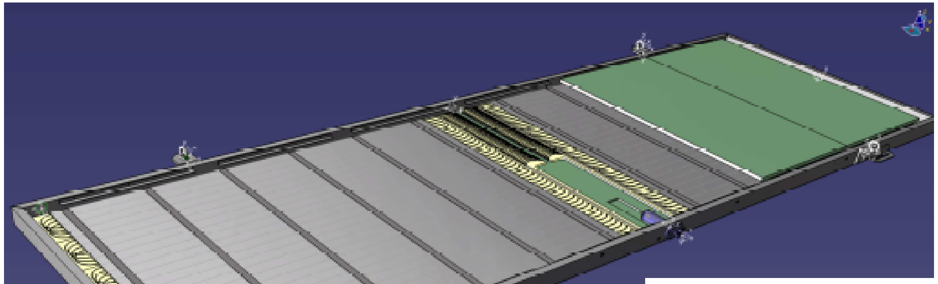
→ talk by Danelise Franco

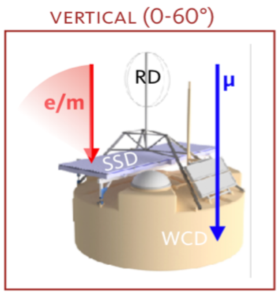
→ talk by Ugo Giaccari

→ talk by Matteo Conte

The Observatory upgrade: AugerPrime

Deployment of 1500 SSD completed!





3.8 m² (1 cm thick) scintillators

- upgraded and faster electronics (40 → 120 MHz)
- extension of the dynamic range – Small PMT
- underground muon detectors
- radio antennas

→ improve on signal/bkg separation
→ lower detection thresholds for photon/neutrino searches

Pierre Auger Observatory Open Data

February 2024 release

http://www.opendata.auger.org

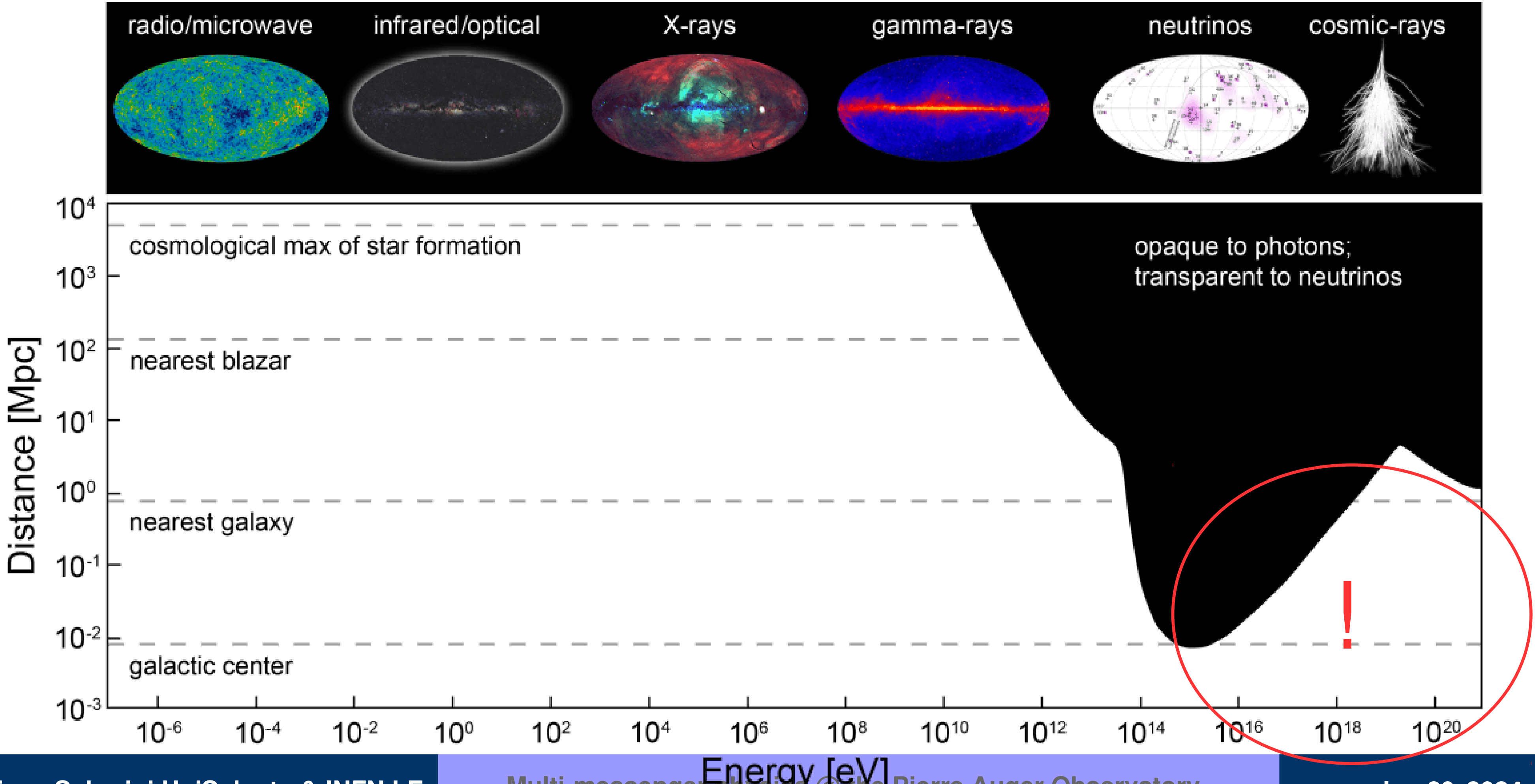
The Pierre Auger Open Data is the public release of 10% of the Pierre Auger Observatory cosmic-ray data published in recent scientific papers and at International conferences , following the Auger Collaboration Open Data Policy. The release also includes 100% of weather and space-weather data collected until 31 December 2020. This website hosts the datasets for download. Brief overviews of the Pierre Auger Observatory and of the Auger Open Data are set out below. An online event display to explore the released cosmic-ray events, and example analysis codes are provided. An outreach section dedicated to the general public is also available.

New data release upcoming!

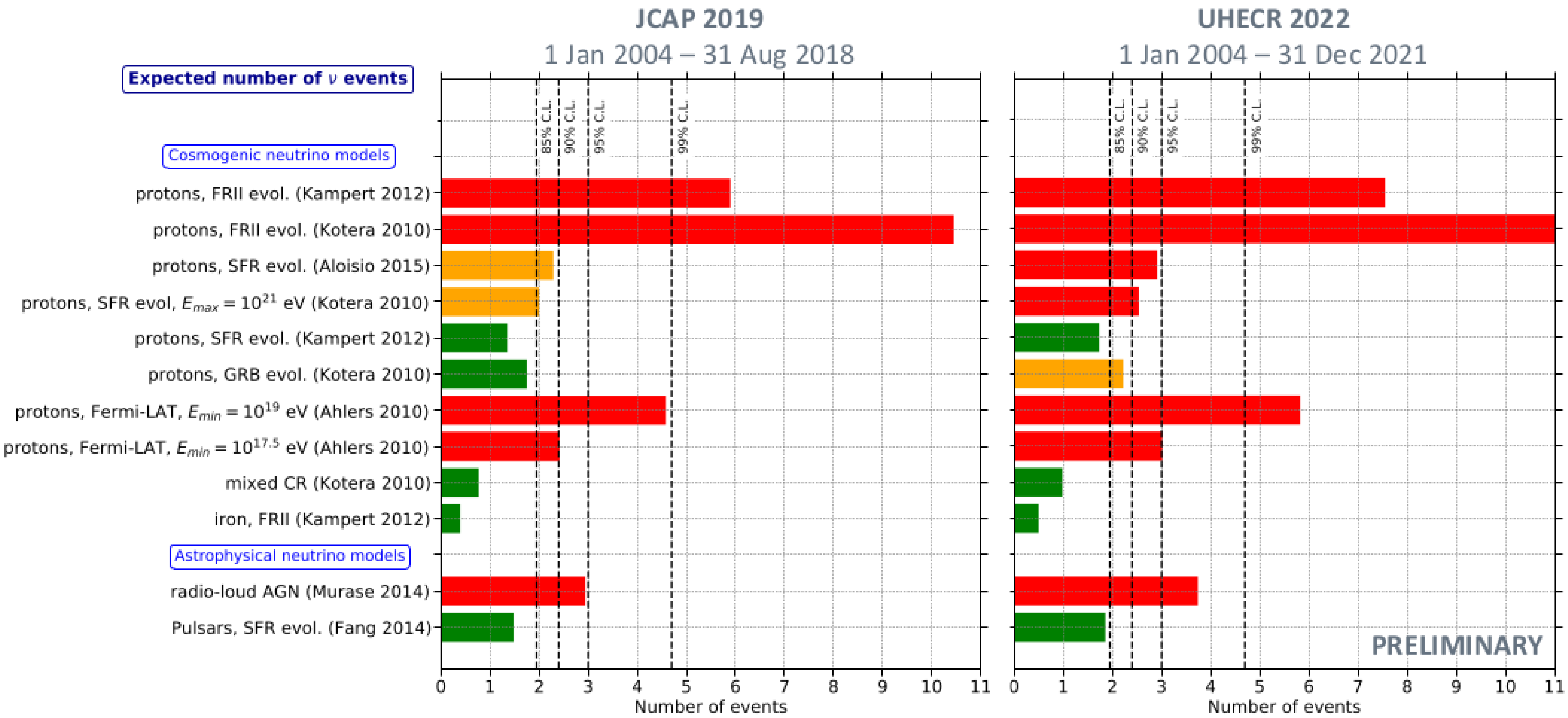
Datasets	Visualize	Analyze	Catalog	Outreach
the released	an online look at the	example analysis	of the highest-	a page dedicated

backup slides

Main actors in the Universe plot



Expected rates from model predictions



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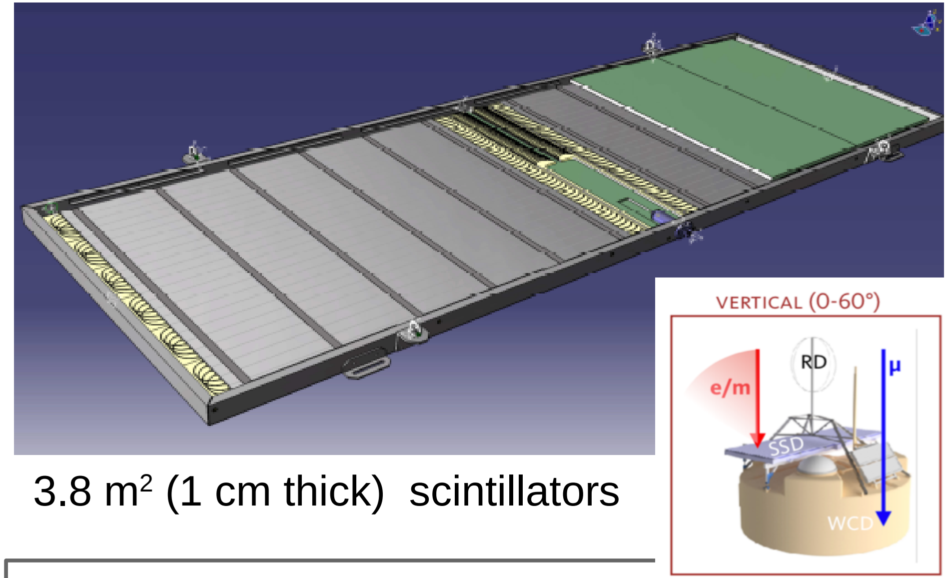

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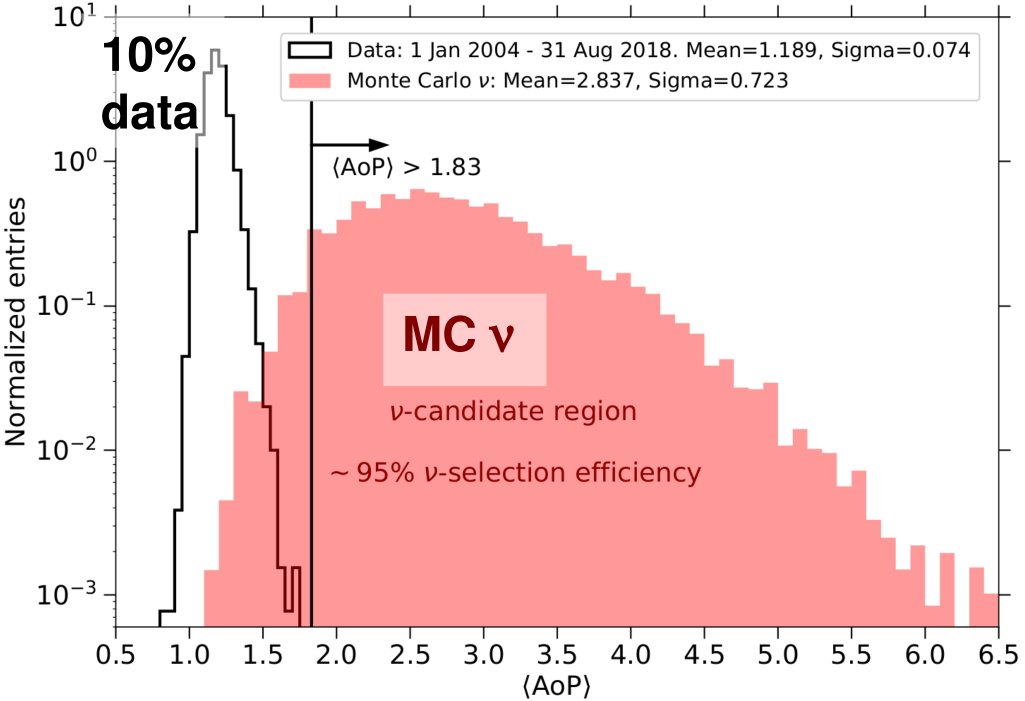
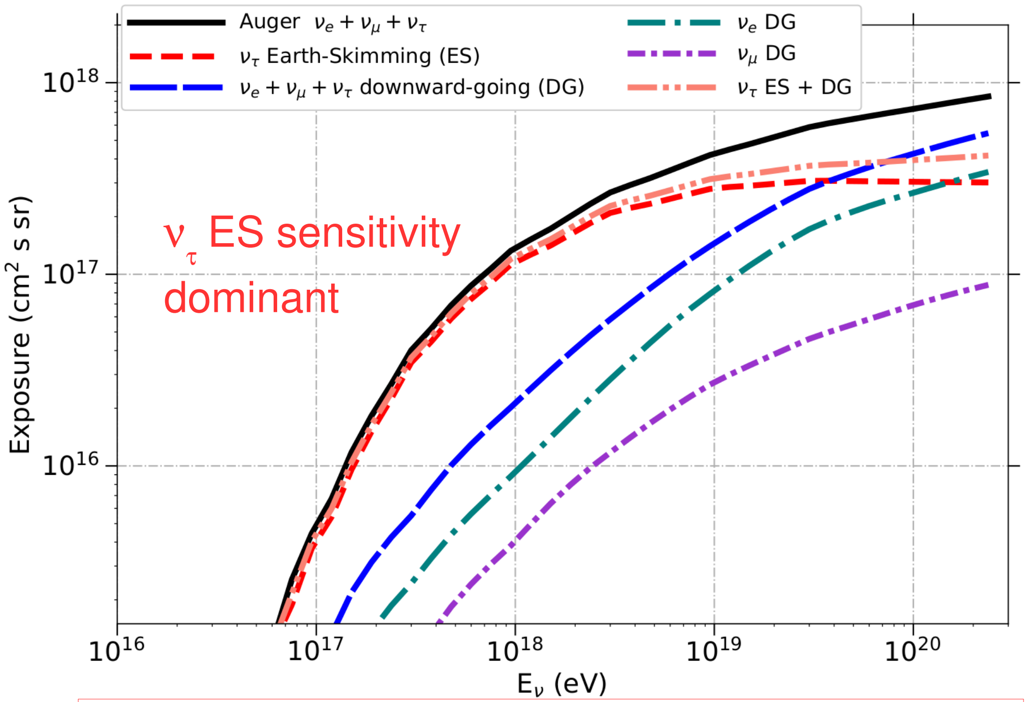
UHE neutrinos: data selection

Pierre Auger Coll., JCAP 10 (2019) 022



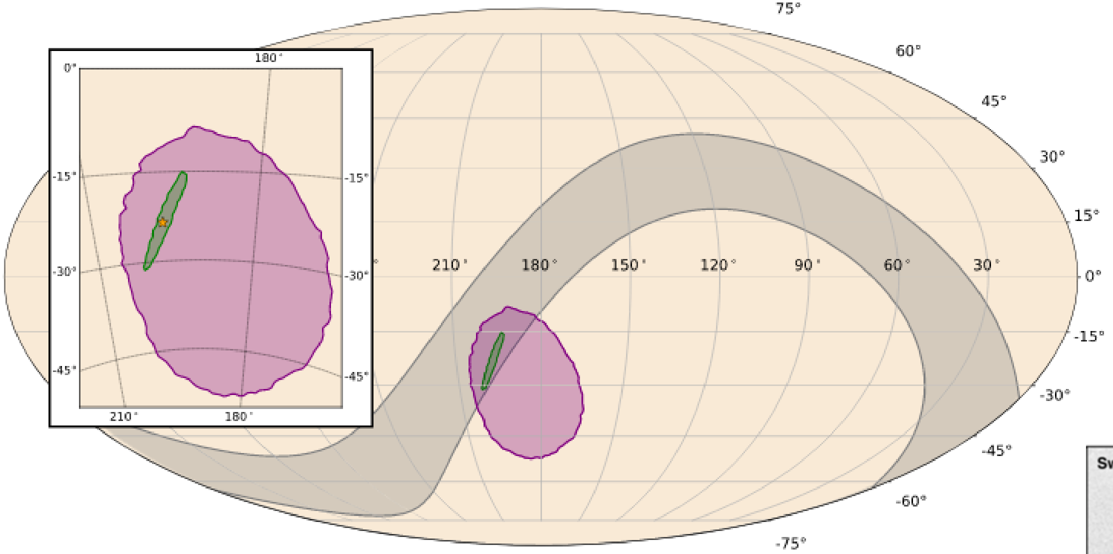


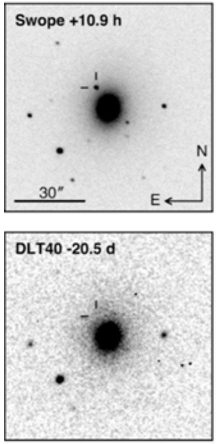
- Data 2004 – 2018: 14.7 yr of stable operation
  → **bkg expected: <1 event in 50 years**
- Selection tuned on the different det. channels

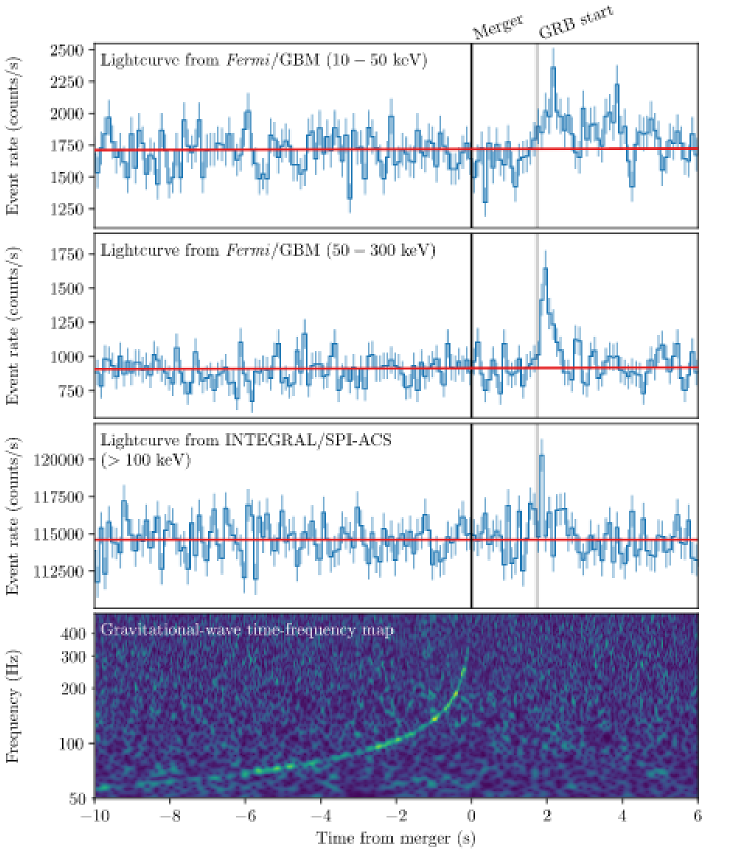
Contribution by channel:	Contribution by flavour:
ES 79.4%	τ 86.1%
DGH 17.6%	e 10.1%
DGL 3.0%	μ 3.8%

GW170817

LVC, Fermi; INTEGRAL, ApJ Lett., 848:L13 (2017)
Abbott B. P., et al., 2017, PRL, 119, 161101







→ GW170817 & sGRB 170817A

→ Optical/IR KiloNova AT2017GFO

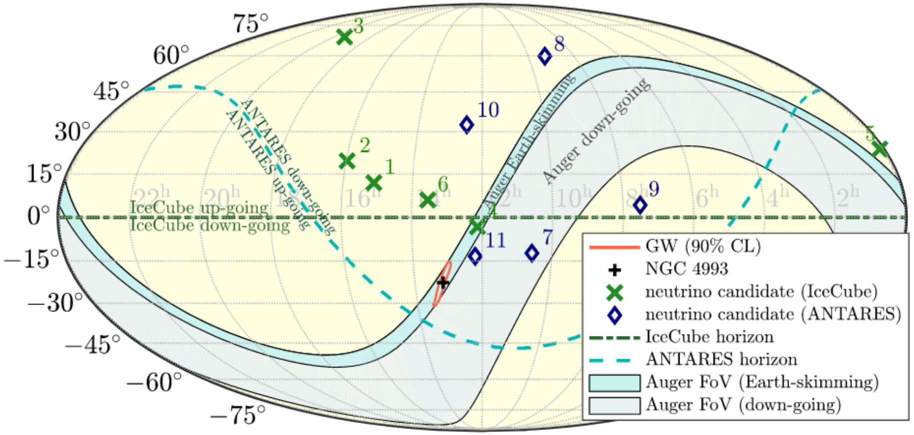
Andreoni I., et al., 2017, Astron. Soc. Australia, 34, e069

GW follow-up: ν searches

Routine in place to follow-up GW alerts

→ search for associated neutrinos with 15 mins latency in both channels (ES-DG)

→ sensitivity strongly depends on source location and event timing

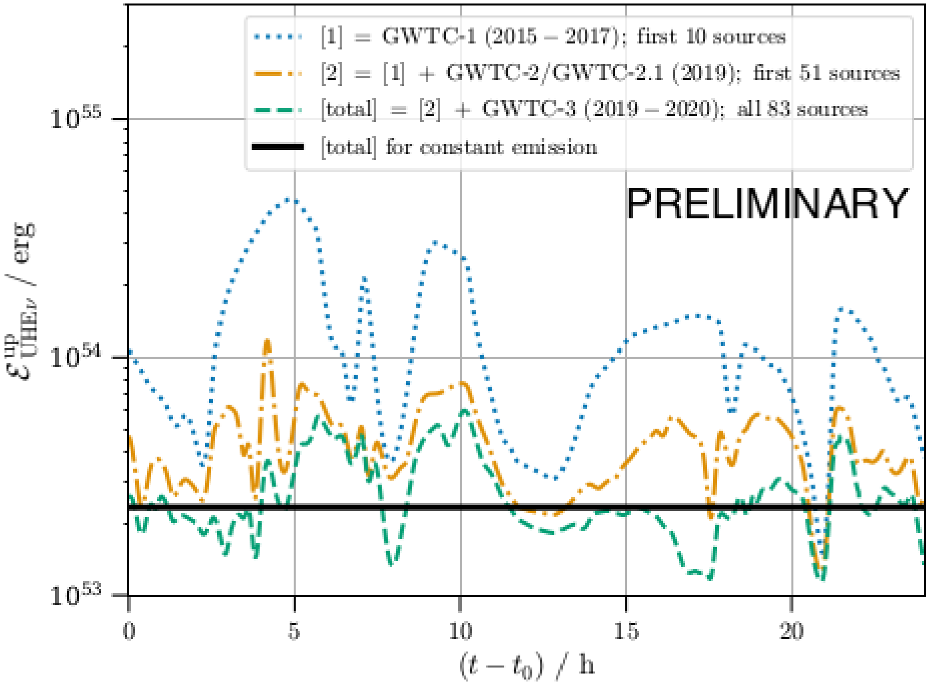


GW170817

Auger limits complement IceCube and ANTARES

ApJL850 (2017) L35

stacked analysis: PoS(ICRC2021)968, paper in prep. (2023)



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- window open to potential new physics

ApJ 952 (2023) 91

CLASS I (short)

D < ∞   Ω < 100 deg²

CLASS II (long)

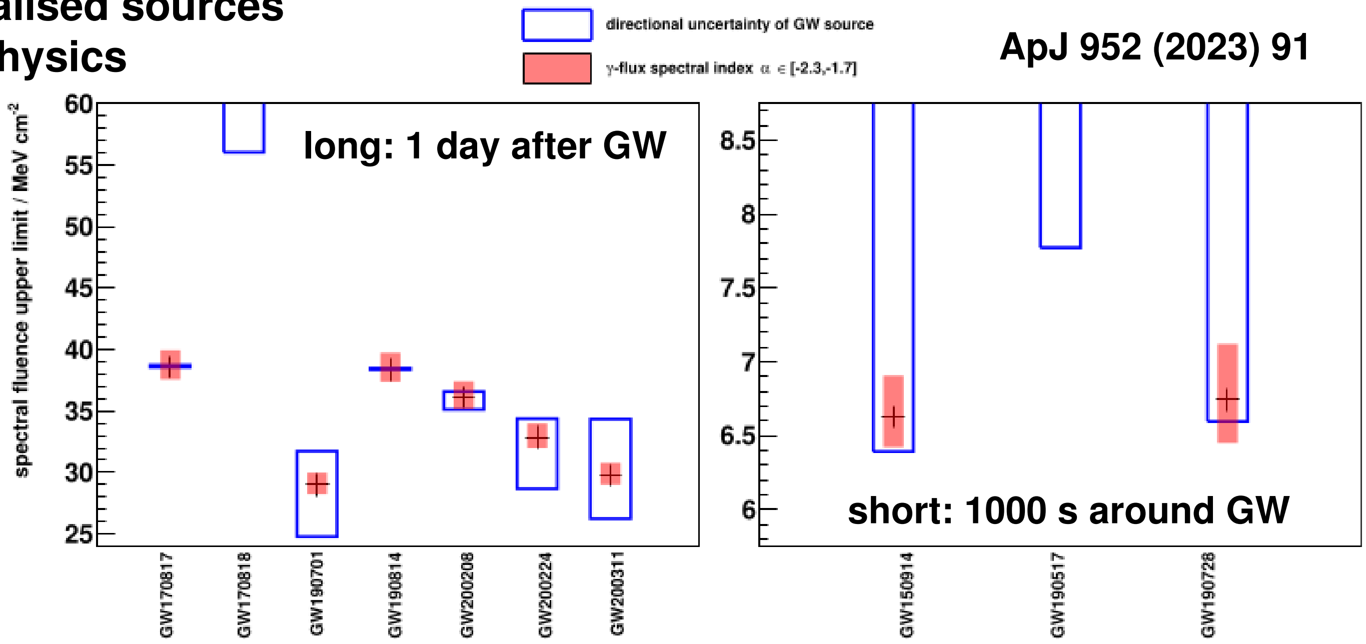
D < ∞   Ω < 20 deg²

CLASS III (long)

D < 180 Mpc   Ω < 100 deg²

CLASS IV (long-short)

D < 40Mpc   Ω < 720 deg²



No coincident photon candidate identified

→ upper limits on spectral fluence ~ 7 MeV cm^{-2} and ~35 MeV cm^{-2}

→ constrain energy transferred into photons to < 20% for GW170817

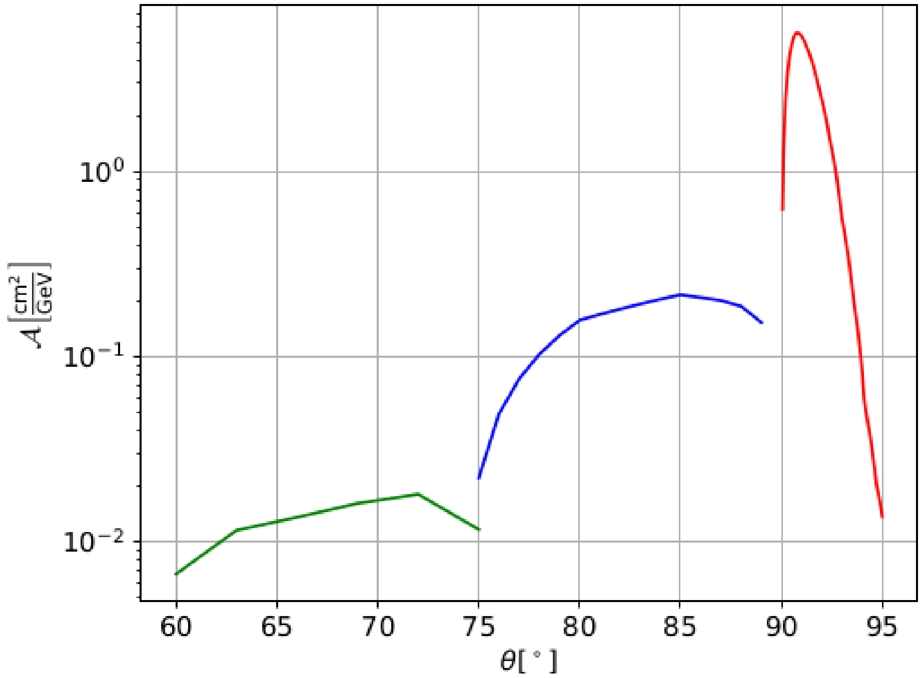
GW follow-up: combined ν search

PoS(ICRC2021)968, paper in prep.

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

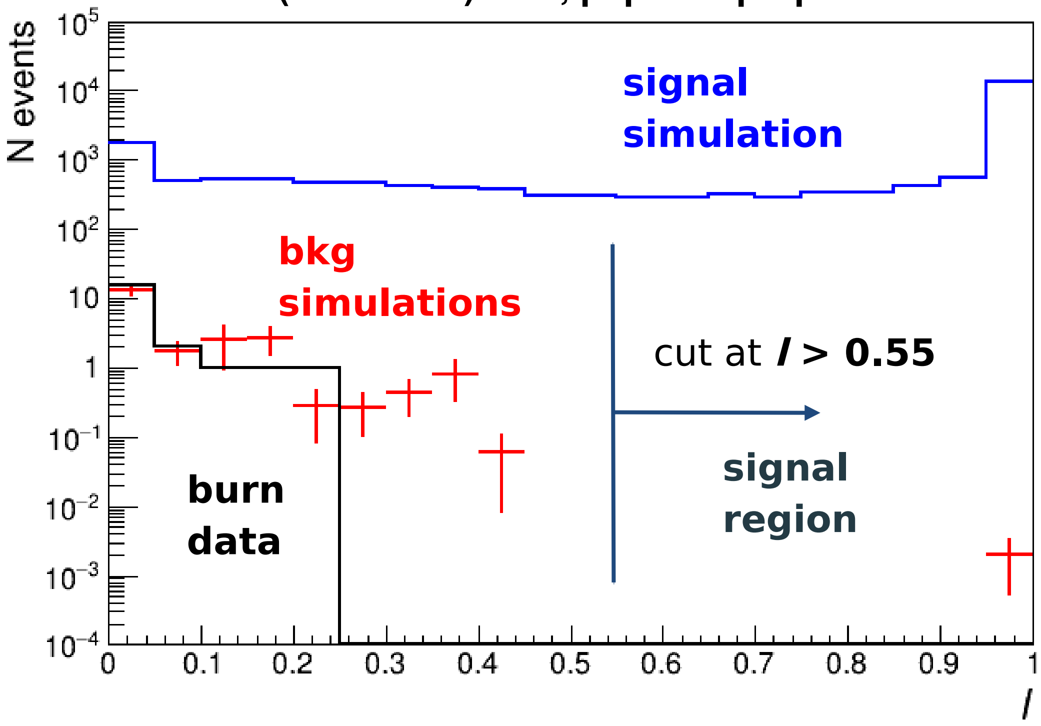
$$L_{up,i} = \frac{N_{up,i}}{T}\left(\sum_{s}\sum_{p\in\Omega_{90}(s)} P_{p,s}A_{p,s,i}\int_0^{\infty}\frac{\Pi_{p,s}(r)}{r^2}dr\right)$$

The limit reflects on the time-dependent visibility of the sources, which is a combination of the direction-dependent instantaneous neutrino acceptance of the Pierre Auger Observatory, and the 3D localization PDFs of the sources.



Search for upward-going events

PoS(ICRC2023)1099, paper in prep.



$$l = \frac{\arctan\left(-2\log\left(L_{down}/\max\left\{L_{down}, L_{up}\right\}\right)/50\right)}{\pi/2}$$

Signal simulations: protons, log(E/eV) [16.5, 19] zenith [110°, 180°] - h [0, 9] km - spectrum E^{-1}
→ 6.5 x 10^{7} showers

Background simulations: protons He, N, Fe, log(E/eV) [17, 19], zenith[0°, 90°] - CRspectrum
→ 2.5 x 10^{8} showers

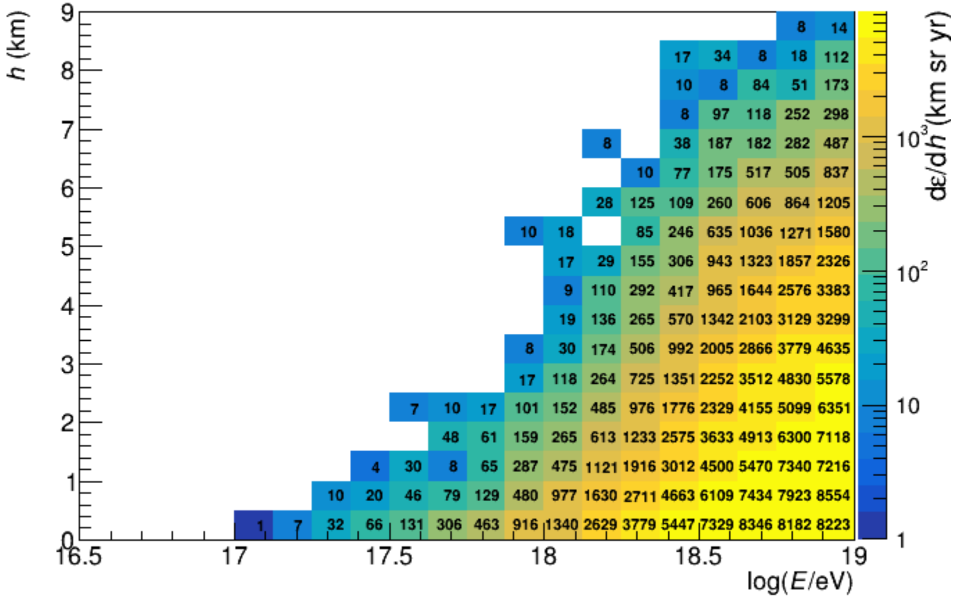
Data: 10% burn sample defining selection criteria

testing upward and downward reconstructions:
l = 0 downward favored, l → 1 upward favored

Full data sample 2004-2021:
1 candidate event found
→ consistent with background (~0.3 evts ± 0.12)

Search for upward-going events

PoS(ICRC2023)1099, paper in prep.



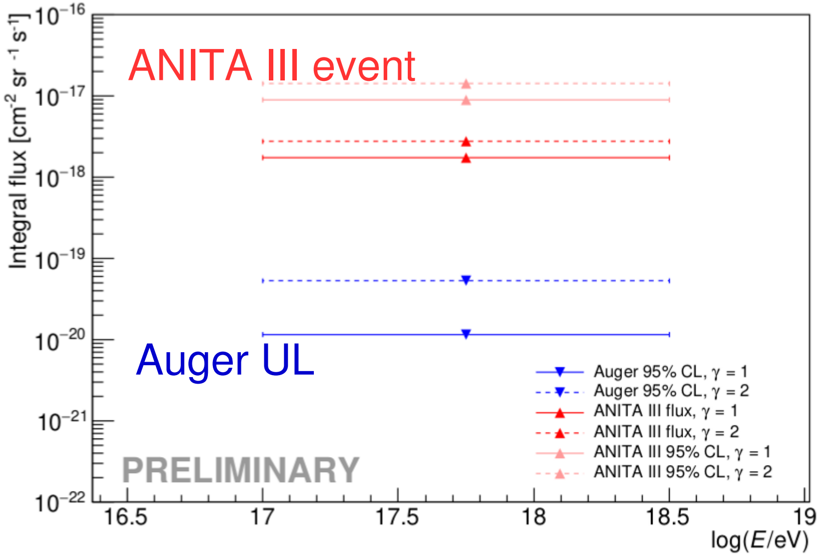
Integral upper limit above 10^{17} eV:

→ $(7.2 \pm 0.2) \times 10^{-21}$ cm^{-2} s^{-1} sr^{-1}, E^{-1} spectrum

→ $(3.6 \pm 0.2) \times 10^{-20}$ cm^{-2} s^{-1} sr^{-1}, E^{-2} spectrum

Upward-going shower detection efficiency can be used for testing BSM scenarios **PoS(ICRC2023)1095**

Joint work Auger-ANITA for calculating and comparing exposures



→ Auger limits are a factor ~100 (30) lower than ANITA fluxes, assuming E^{-1} (E^{-2}) spectrum