Results from the Pierre Auger Observatory

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The physics case at the highest energies

Ankle

Transition galactic to extra-galactic cosmic rays?

End of the spectrum

GZK?

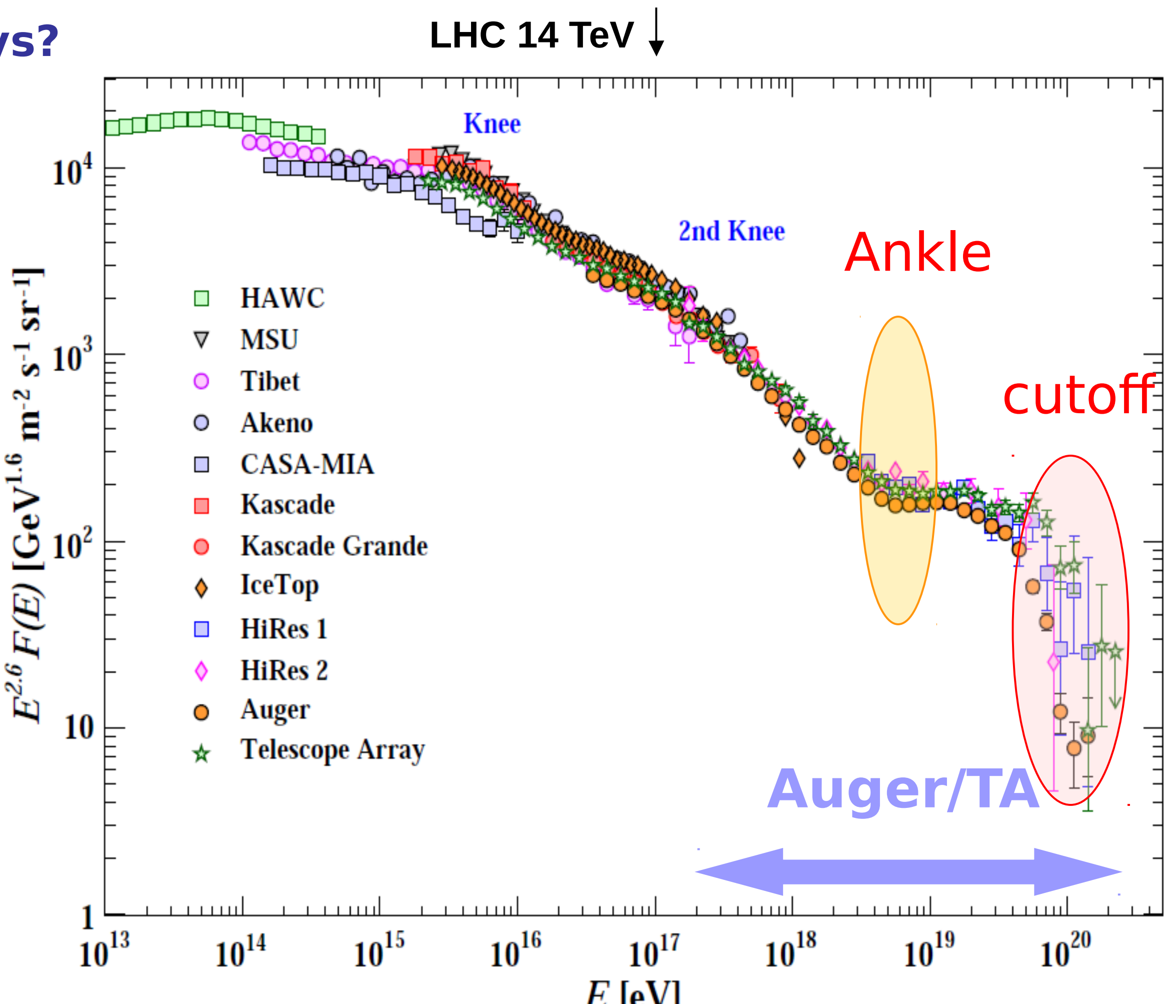
Energy spectrum

Arrival directions

Composition

Search for photon and neutrinos as primary cosmic rays

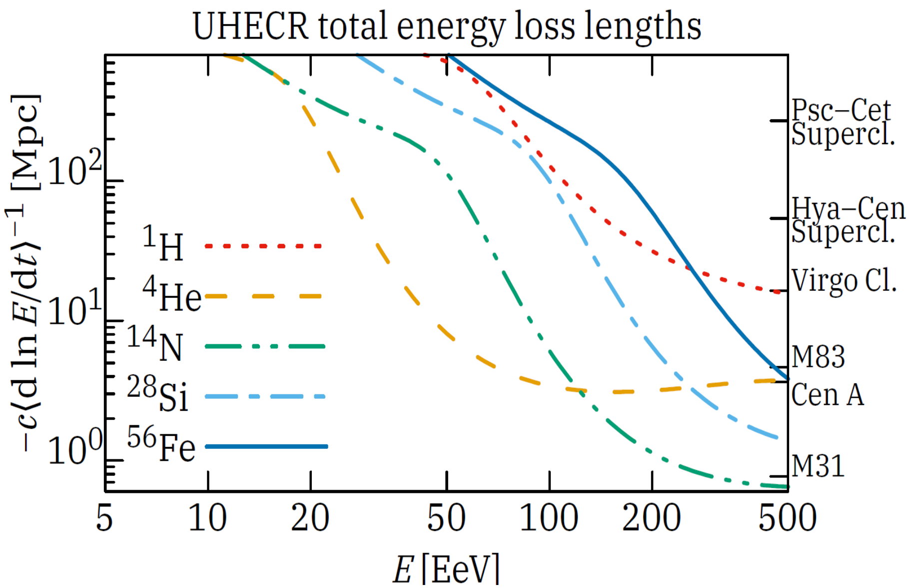
Hadronic physics



Particle Data Group

End to the cosmic ray spectrum

Greisen Zatsepin Kuz'min effect (1966):
Interaction with the cosmic microwave background (CMB)



propagation scenario

protons:

$$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$$
$$\left.\begin{array}{l} p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0 \\ p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+ \end{array}\right] \mathbf{E \geq 7\ 10^{19}\ eV}$$

nuclei: photo-disintegration and pair production on CMB (RB IR)

"horizon" (p and fe) ~ 100 Mpc (~10^{20} eV)

source scenario

We may be observing the end of cosmic ray accelerators "fuel". **$E_{max} \propto Z\ B\ R$**

Composition at the highest energies and the detection of cosmogenic neutrino and/or photons is of key importance

The Pierre Auger Observatory

~ 400 members, 17 countries

3000 km^2

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

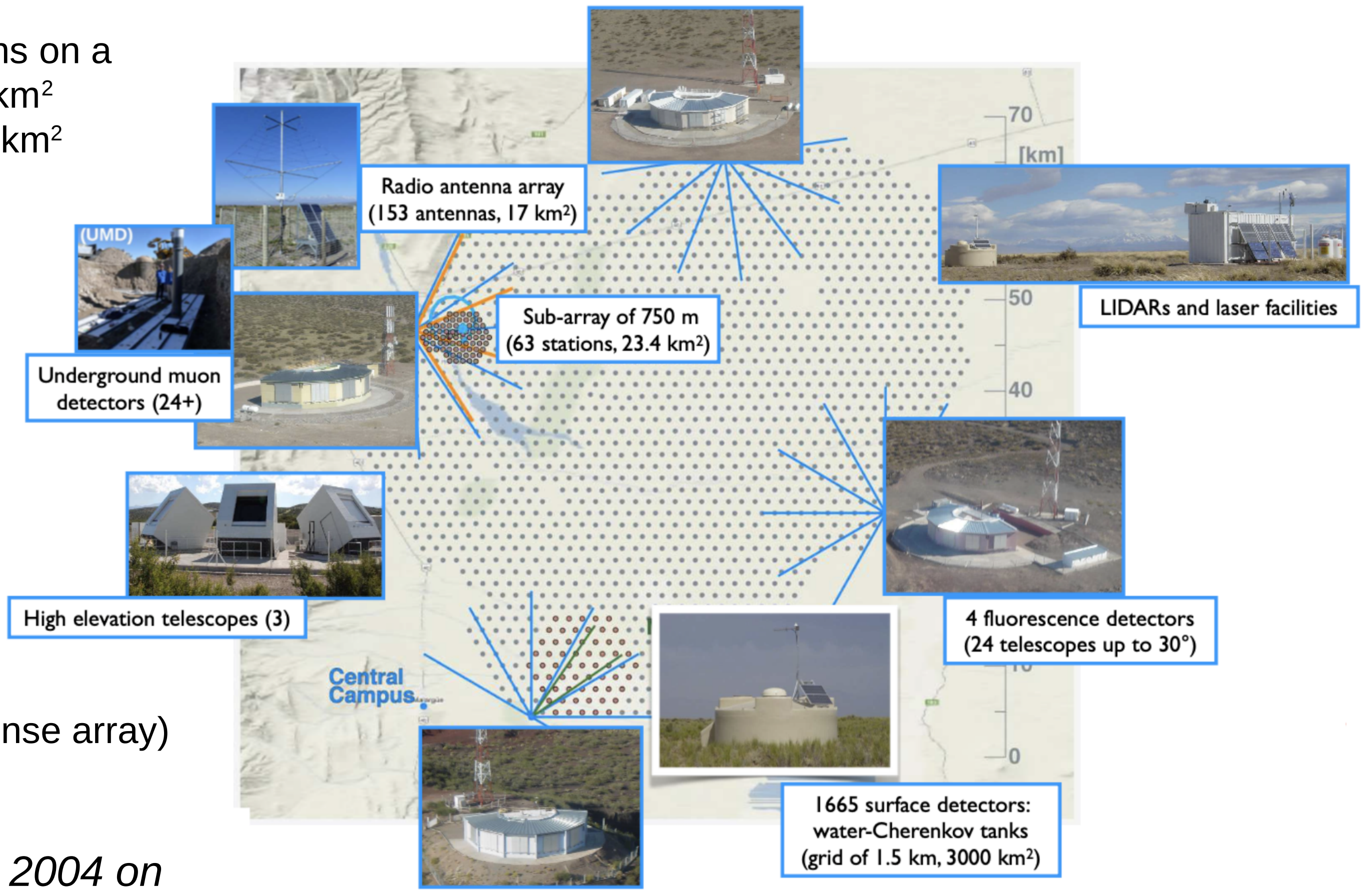
4+1 buildings overlooking the array (24 + 3 HEAT telescopes)

Radio detector

153 Radio Antenna → AERA

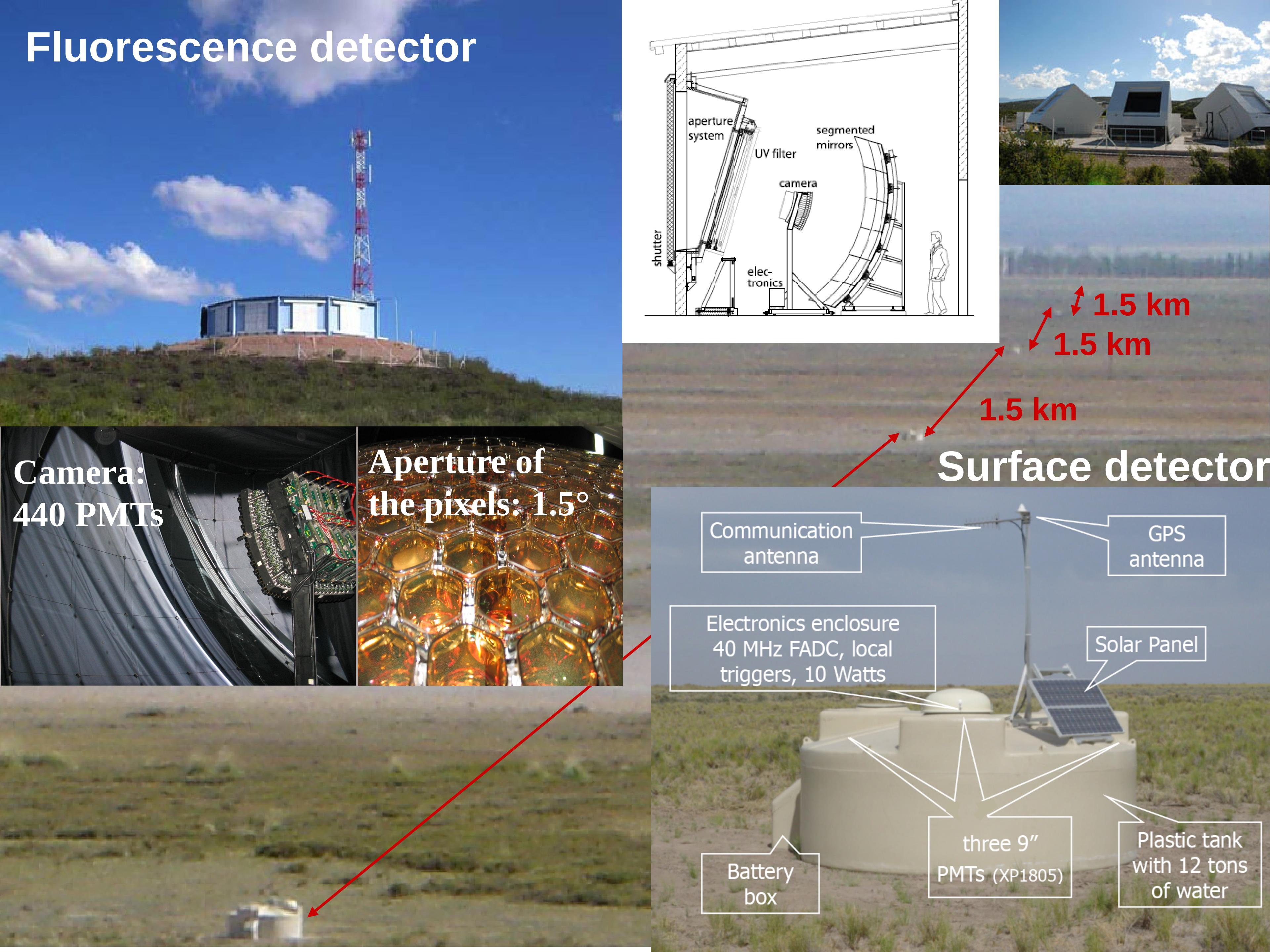
Muon Detectors

Buried scintillators (region of dense array)



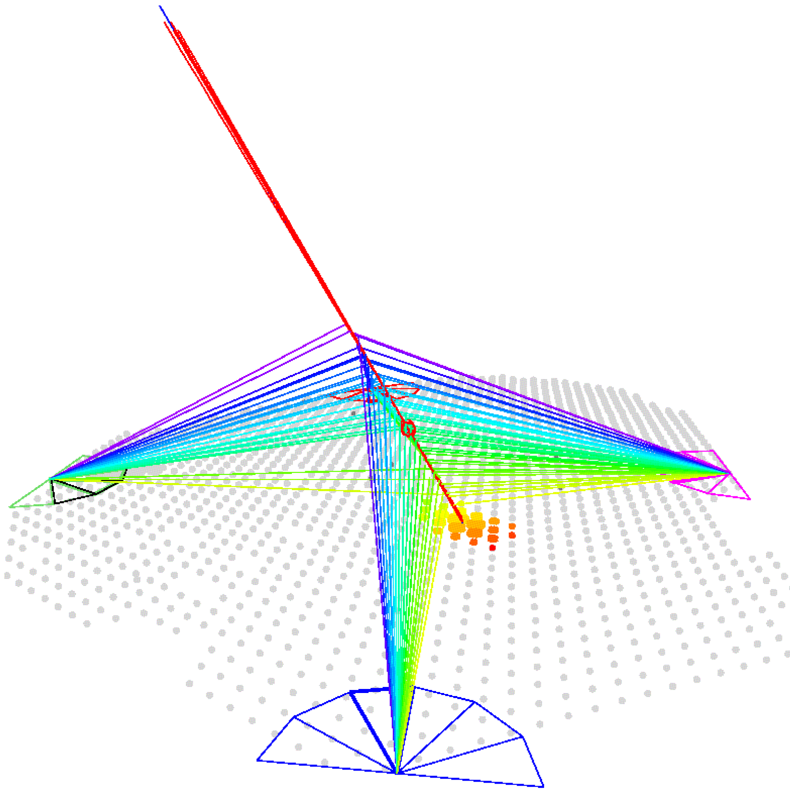
***Phase 1** : data taking from 2004 on (from 2008 with the full array in operation):*
- Over 120.000 km^2 sr yr for anisotropy studies
- Over 90.000 km^2 sr yr for spectrum studies

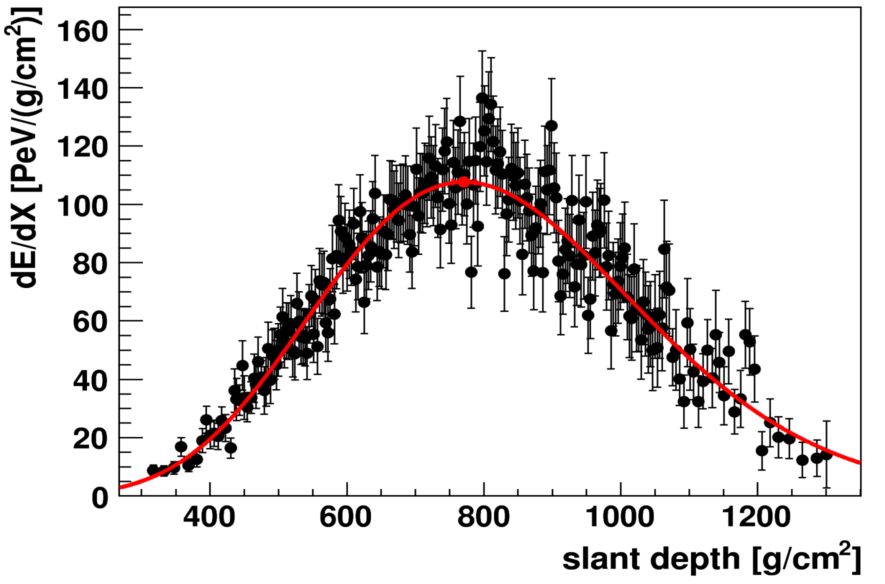
Phase 2 - the AugerPrime upgrade
Data taking from 2023 to 2030…
Multiple detectors

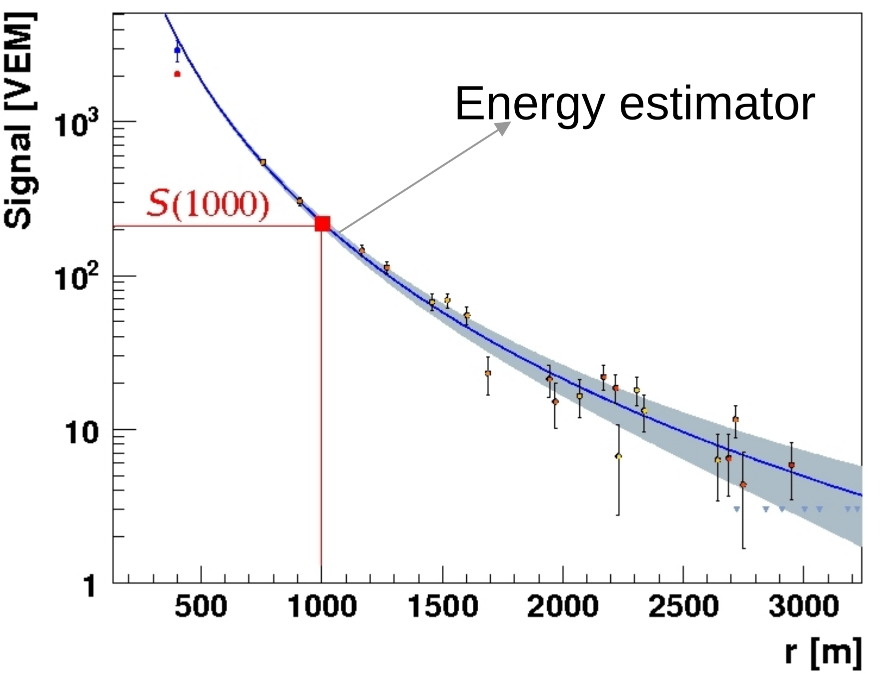


Fluorescence detector
aperture system
UV filter
segmented mirrors
camera
shutter
elec-tronics
1.5 km
1.5 km
1.5 km
Camera:
440 PMTs
Aperture of the pixels: 1.5°
Surface detector
Communication antenna
GPS antenna
Electronics enclosure
40 MHz FADC, local triggers, 10 Watts
Solar Panel
Battery box
three 9” PMTs (XP1805)
Plastic tank with 12 tons of water

The Hybrid paradigm







Longitudinal profile

FD - calorimetric measurement

- duty cycle 15%

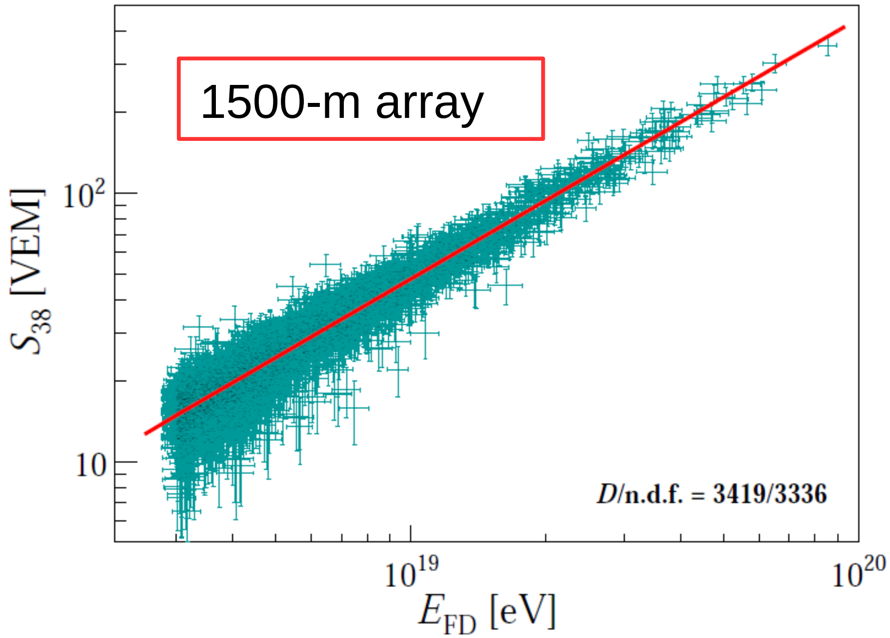
Density of particles at the ground

SD - duty cycle ~ 100%

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

Calibration with the FD energy scale: above 2.5 EeV

Auger Collaboration Phys. Rev. D 102 (2020) 062005



Energy scale uncertainty

ICRC 2013

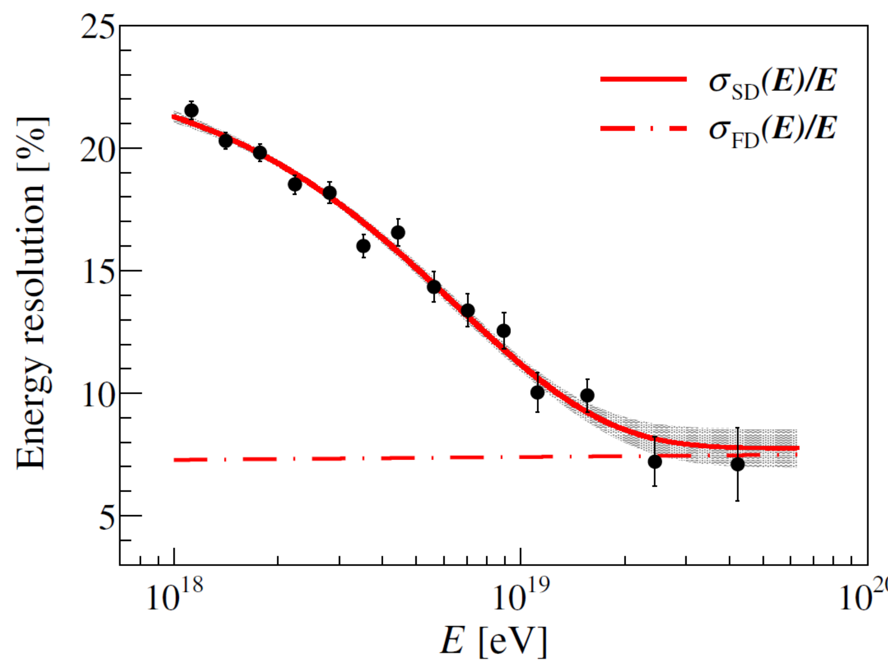
Systematic uncertainty in the energy scale	
Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Stability of energy scale	5%
TOTAL	14%

Energy resolution

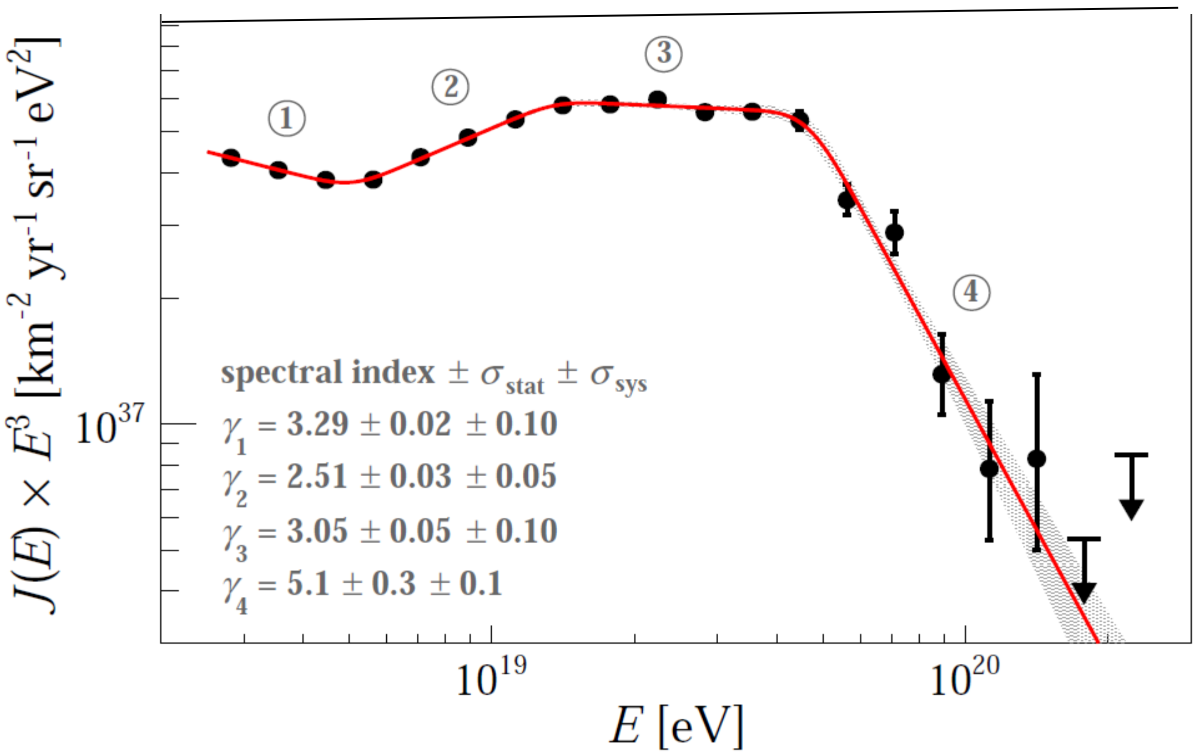
SD: < 20% (zenith < 60° and E > 2.5 EeV)

Hybrid: 6-8 % Hybrid [ICRC 2019]

Important to account for resolution effects in the SD-based spectra



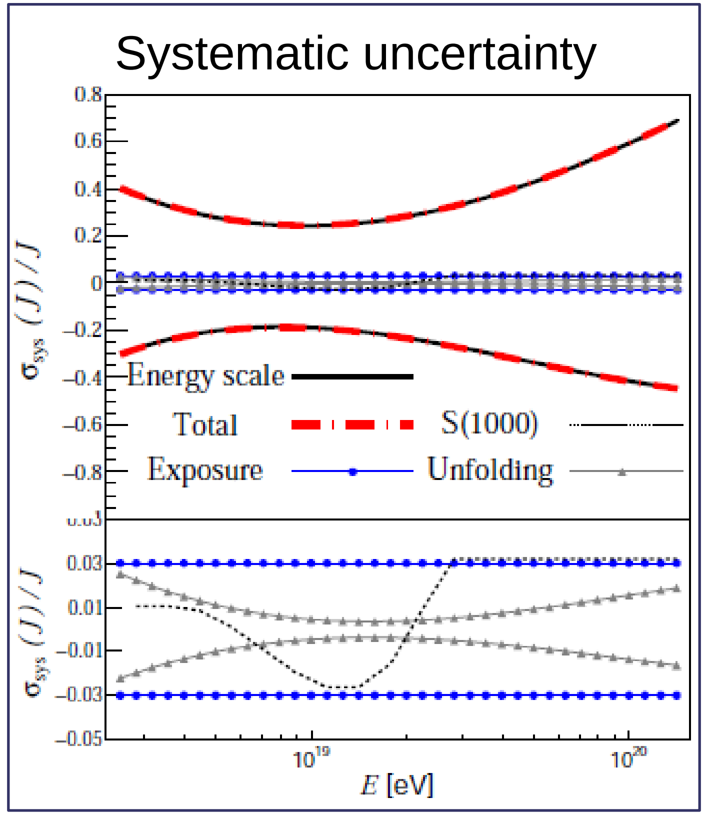
Auger Collaboration Phys. Rev. D 102 (2020) 062005



SD1500, zenith < 60°

Data sample:
215030 events
1/1/2004 – 31/8/2018

Exposure:
60400 km^2 sr y



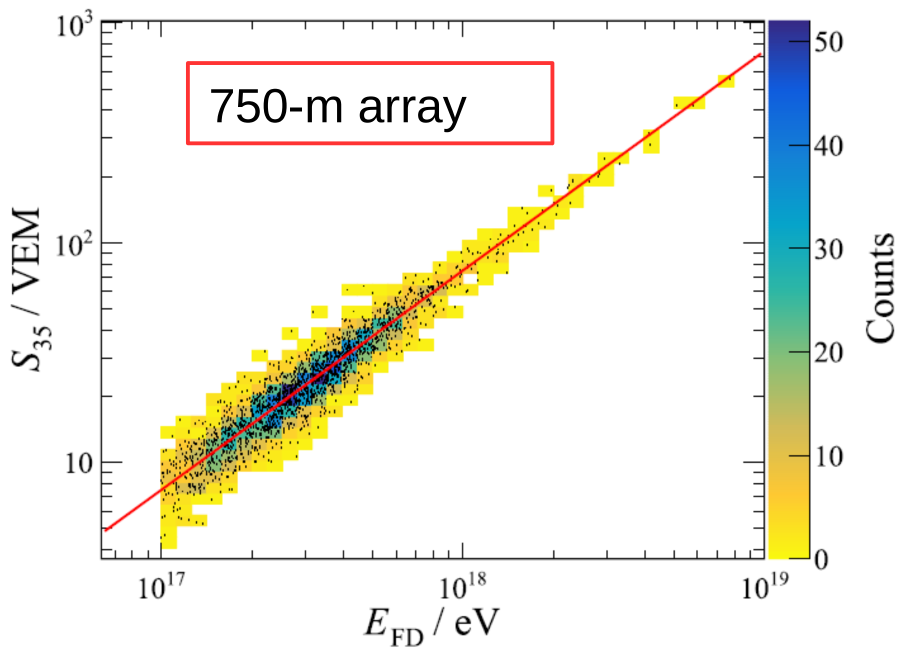
Cutoff at ~ 5 10^{19} eV confirmed

Ankle at ~ 5 10^{18} eV confirmed

new feature instep at ~ 10^{19} eV identified

Extending the SD spectrum down to 0.1 EeV

Auger Collaboration Eur. Phys J C. (2021) 81:966



Energy resolution

SD: < 20% (zenith < 40° and E > 0.1 EeV)

Hybrid: 6-8 % Hybrid [ICRC 2019]

2nd knee observed

Energy scale uncertainty

ICRC 2013

Systematic uncertainty in the energy scale	
Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
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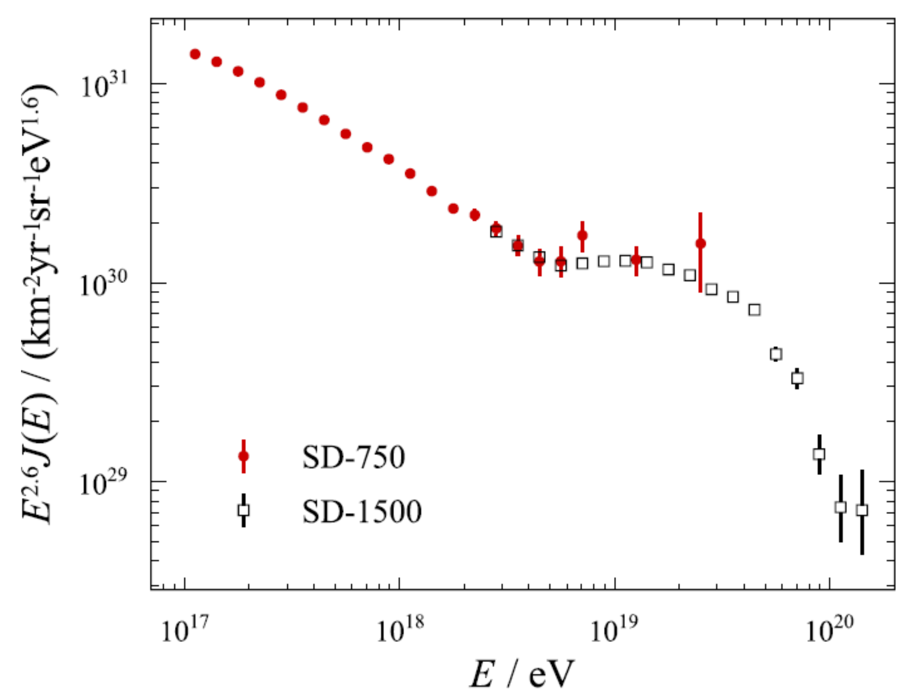
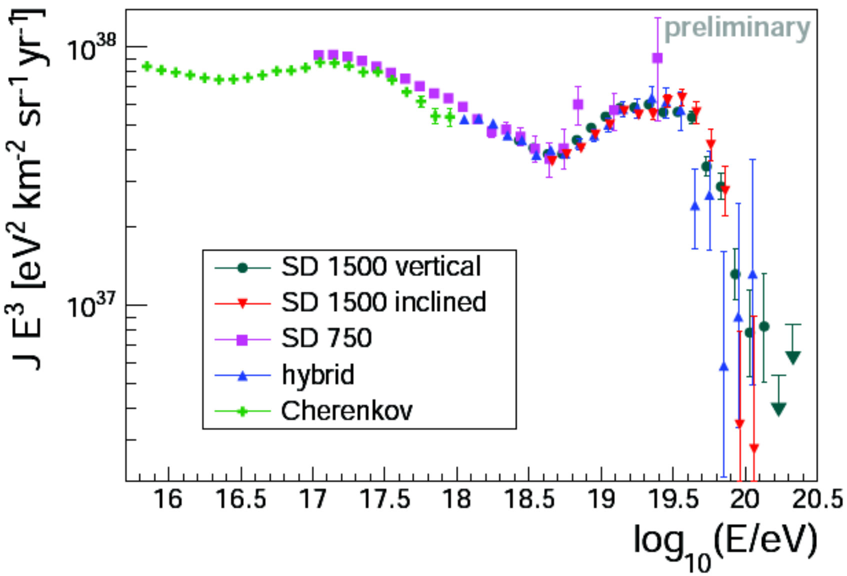


The Auger combined spectrum



Five measurements
- more than 3 order of magnitudes
- same energy scale

Fluxes in agreement
within systematic uncertainties

Combined energy spectrum

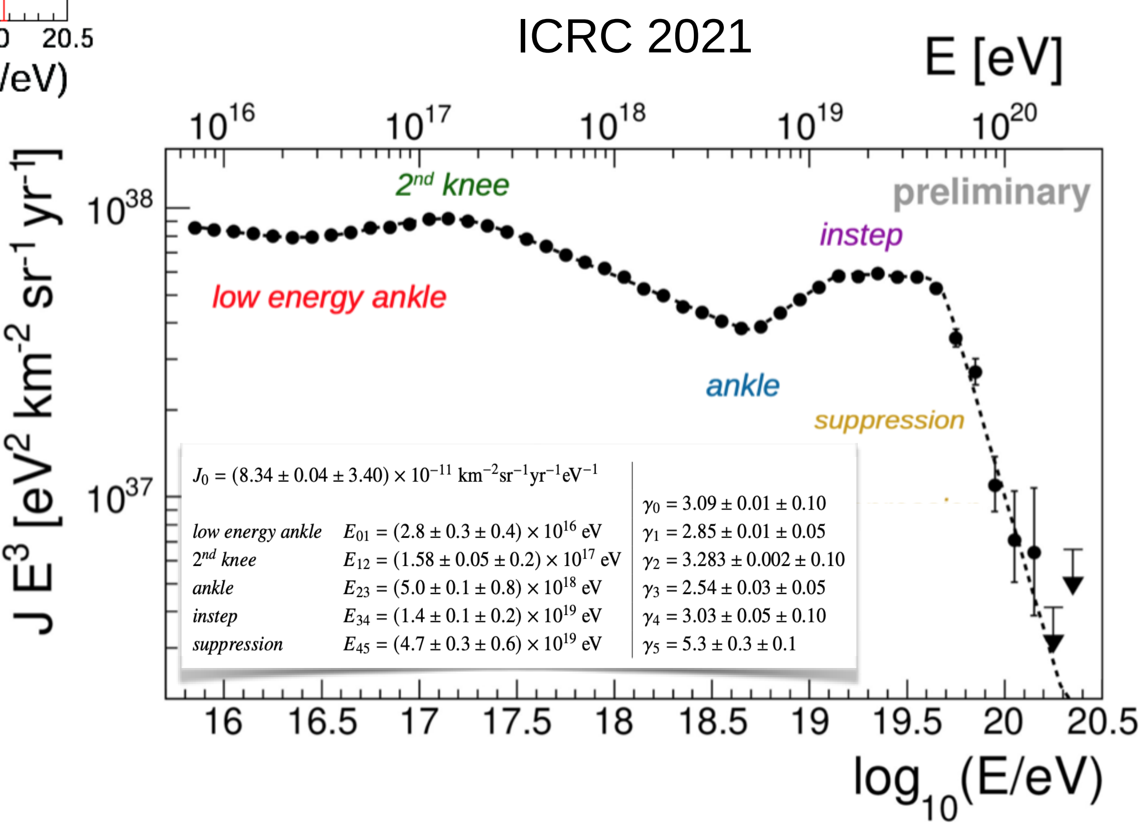
Cutoff at ~ 5 10^{19} eV confirmed

ankle at ~ 5 10^{18} eV confirmed

new feature instep at ~ 10^{19} eV identified

2^{nd} knee observed

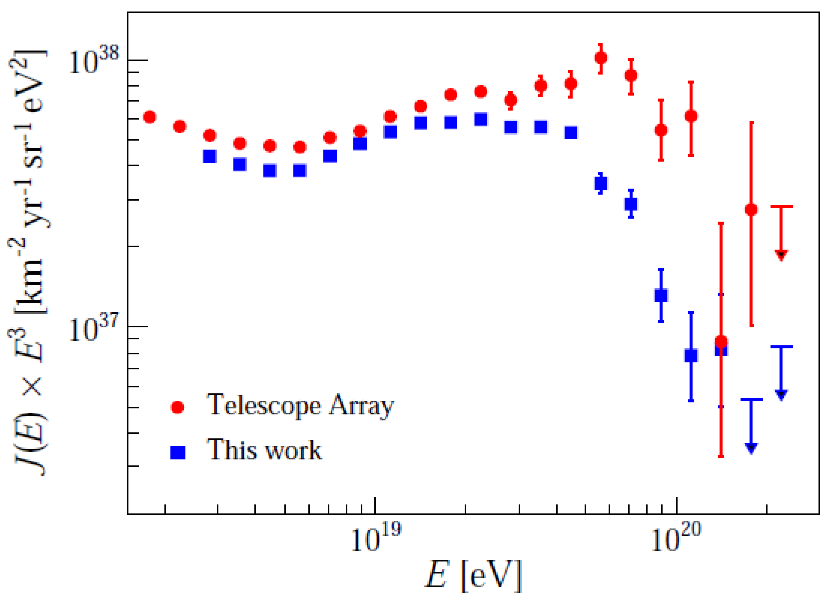
Hint for a low energy ankle



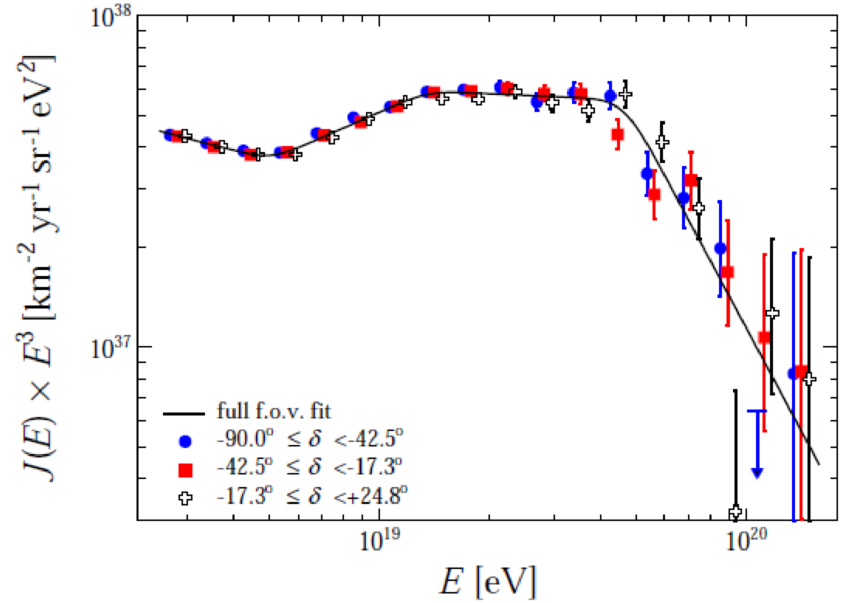
see A. di Matteo at this Conf.

AUGER vs Telescope Array

Auger Collaboration Phys. Rev. D 102 (2020) 062005



In agreement at the ankle within energy scale systematic uncertainties (Auger 14%, TA 21%)
Tension at the highest energies

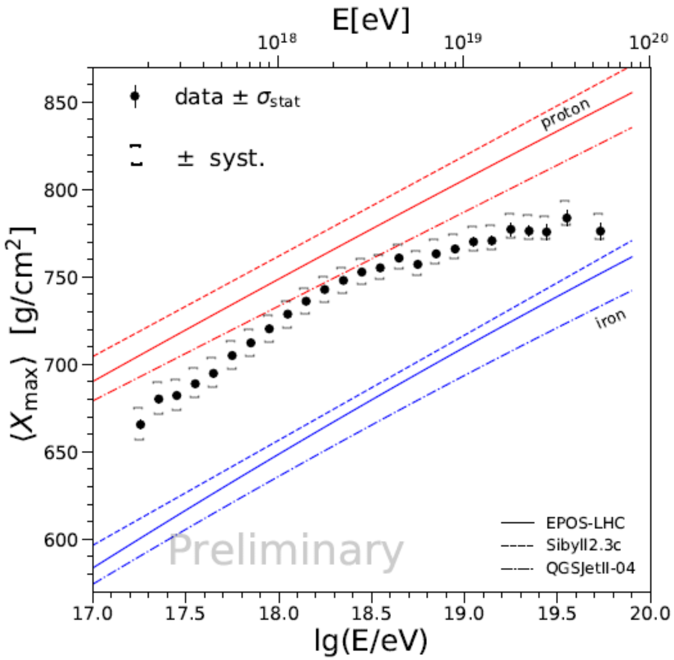


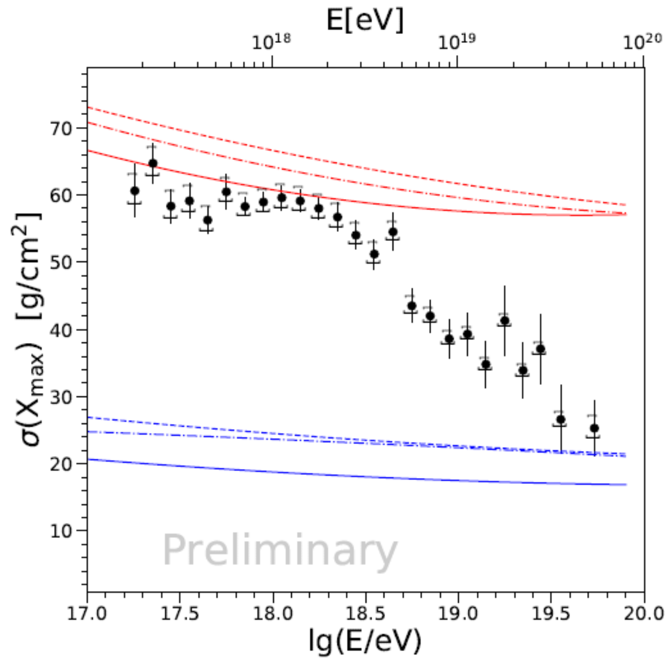
Auger spectrum is not changing with declination, flux compatible with the dipole anisotropy at E > 8 EeV

Cross check in the common declination band ($-15^0 < \delta < 24.8^0$): differences substantially smaller than in full-sky comparison but still noticeable, would need further energy-dependent shifts of ± 10%/decade to match highest energies

Joint Auger-TA working group working on tracking possible detector systematics

Chemical composition using the FD





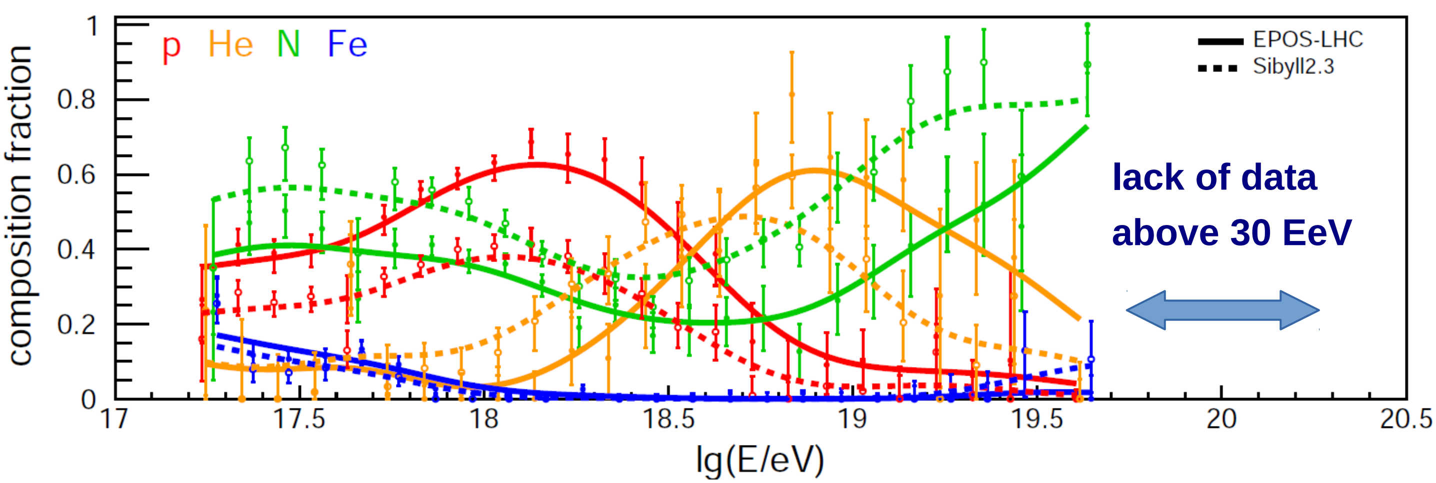
ICRC 2019

Xmax syst. uncertainty
~ 10 g cm^{-2} (20 g cm^{-2} at the lowest energies)

Xmax resolution
15 (25, 40) g cm^{-2}
E > 10^{19} eV (E~ $10^{17.8}$ eV, E~ $10^{17.2}$ eV)

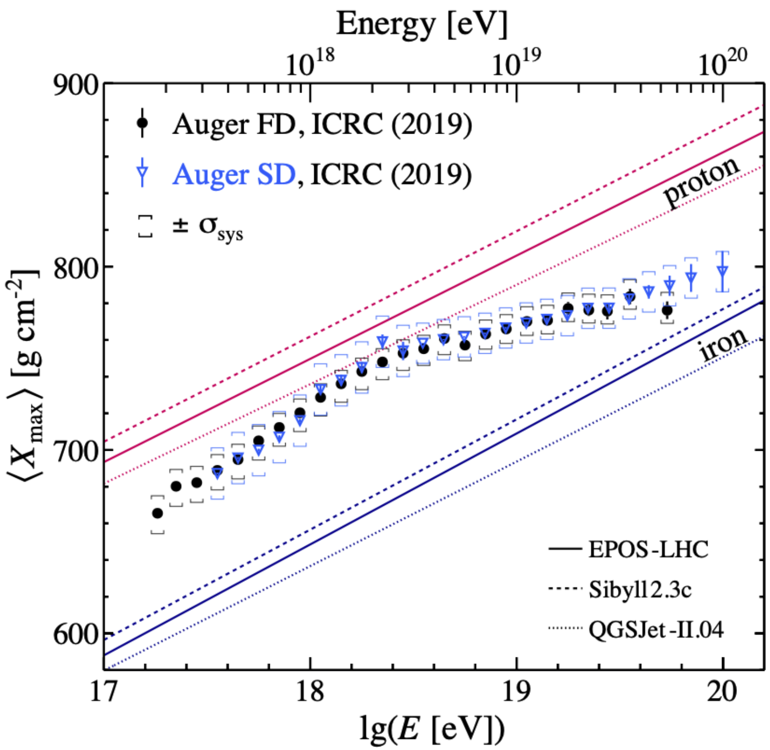
→ non constant composition, increase of the mean mass above and below ~ 2 EeV

→ interpretation depends on hadronic interaction models



Mass fractions at Earth from fitting templates of 4 mass groups to the measured X_{max} distributions

Front. Astron. Space Sci. 6 (2019) 23

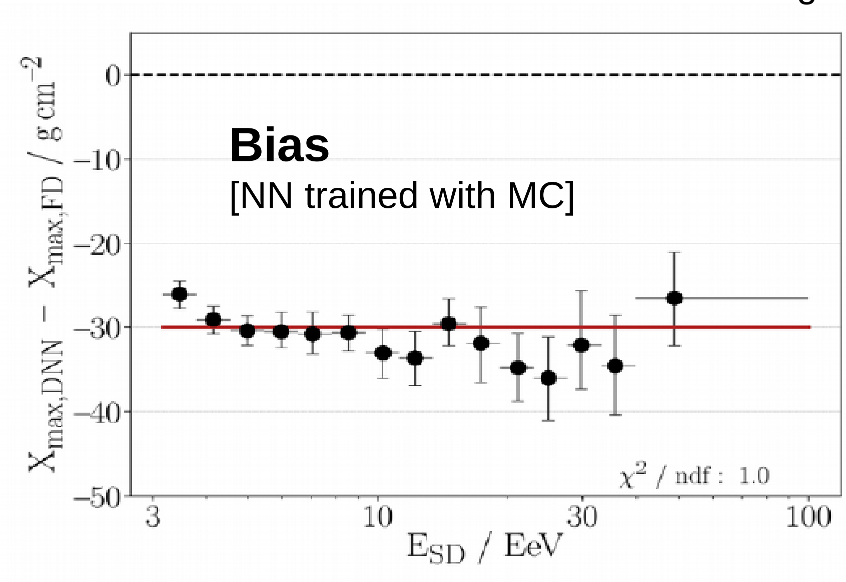


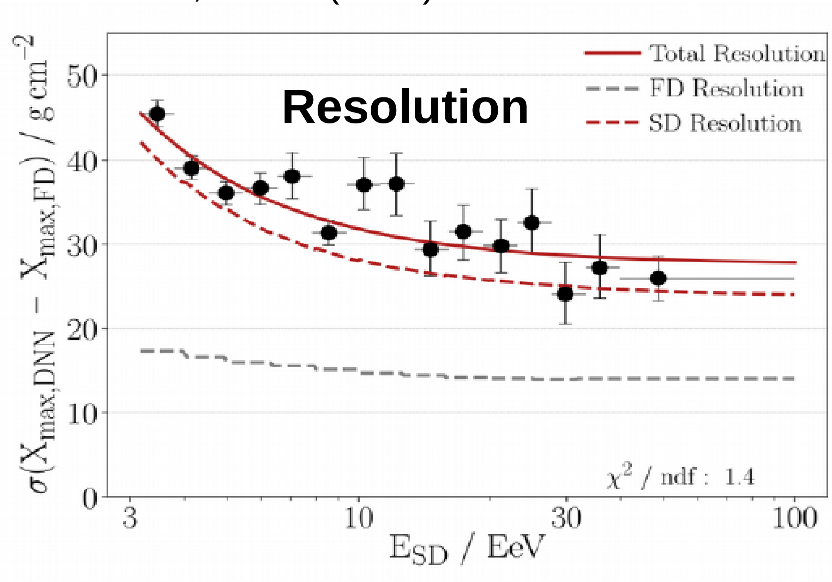
SD can extend the measurement of <Xmax> (worse resolution)

Neural network approach tested with hybrid events

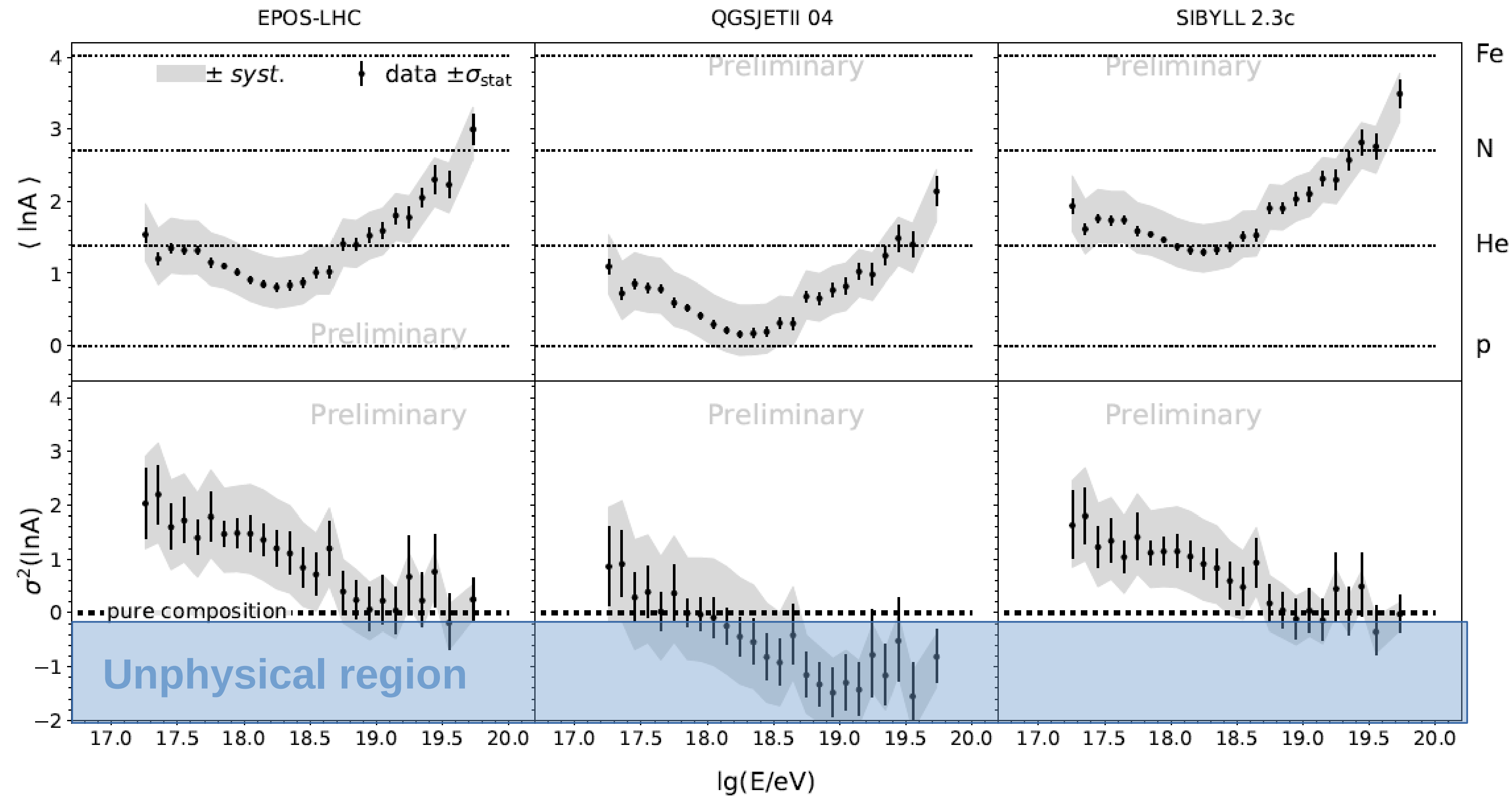
Promising in view of the additional info provided by the upgraded SD detector

The Pierre Auger Collaboration, JINST (2021) 16 P07019





<lnA> and variance for testing the interaction models



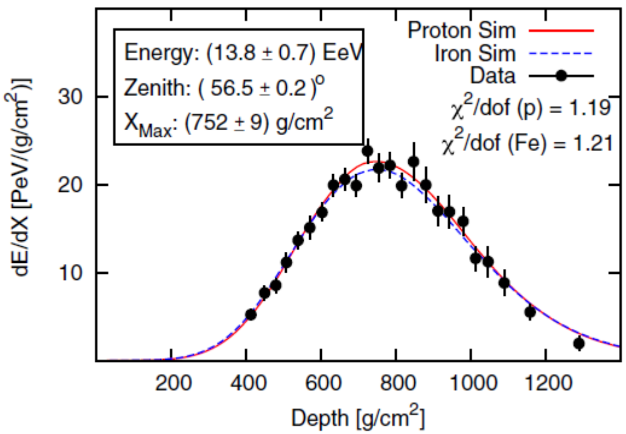
ICRC 2019

- Model-independent trend in <lnA>
- Pure composition excluded below and around the ankle
- QGSJETII04 is in tension with data

How well hadronic models match data?

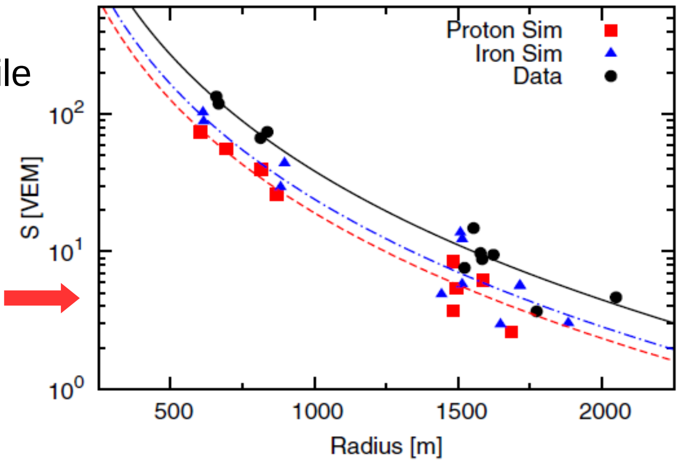
Hybrid events ~ 10^{19} eV, 0°< zenith 60°

PRL 117, 192001 (2016)



Observed longitudinal profile from FD is reproduced by simulations

Measured signal at the ground differ for data and simulations



R_{had} and R_E

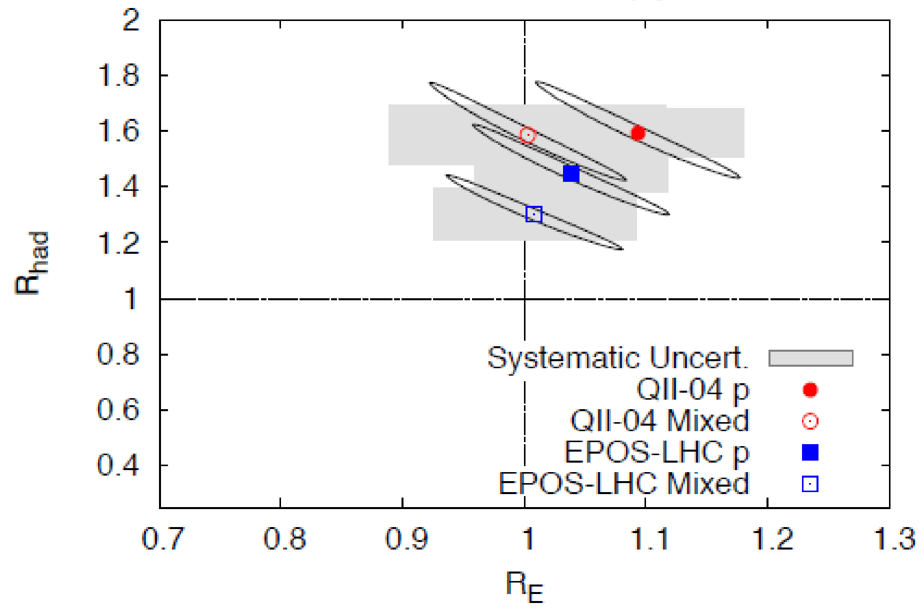
Scaling factors to match data

Evidence of muon excess

1.3< R_{had}<1.6

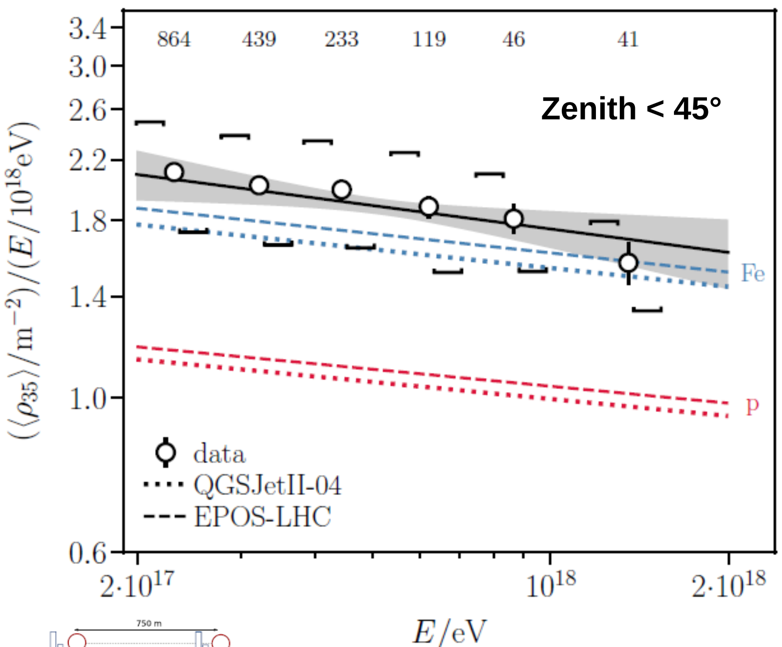
Insensitive to energy scale uncertainty

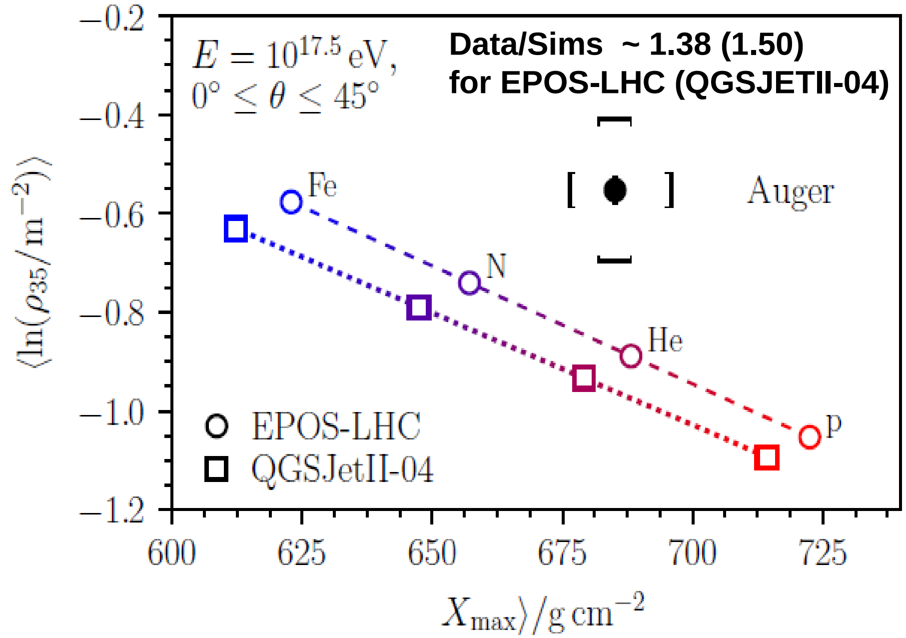
R_E~1

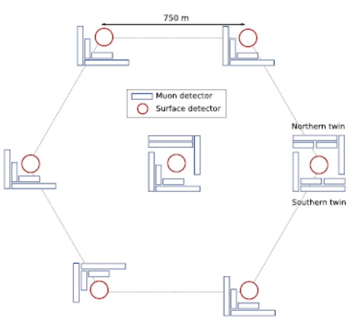


Measurement of muon density and impact on models

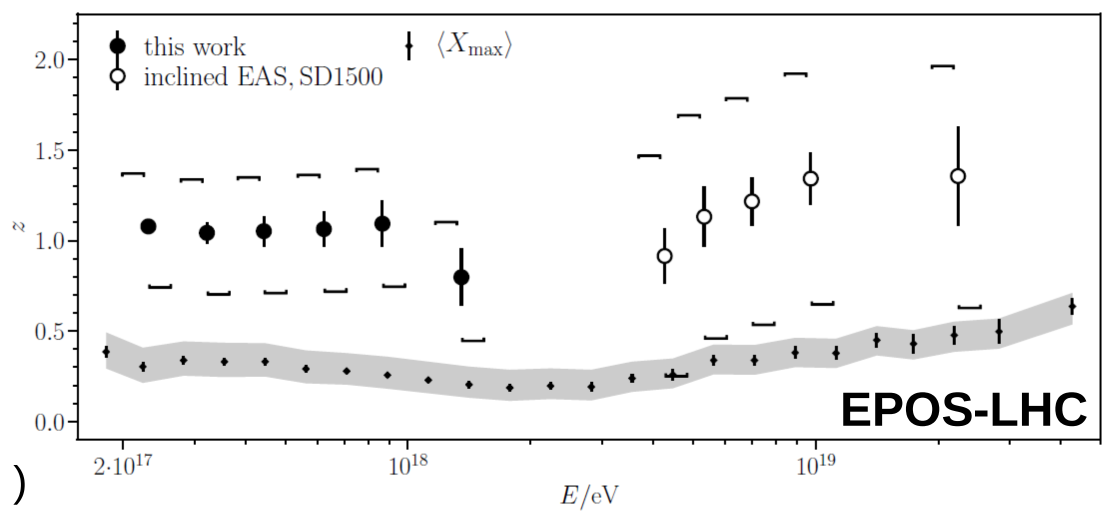
Eur. Phys J. C (2020) 80:751: first direct measurement of muon number with UMD at Auger







$$z = \frac{\langle \ln x \rangle - \langle \ln x \rangle_p}{\langle \ln x \rangle_{Fe} - \langle \ln x \rangle_p}$$

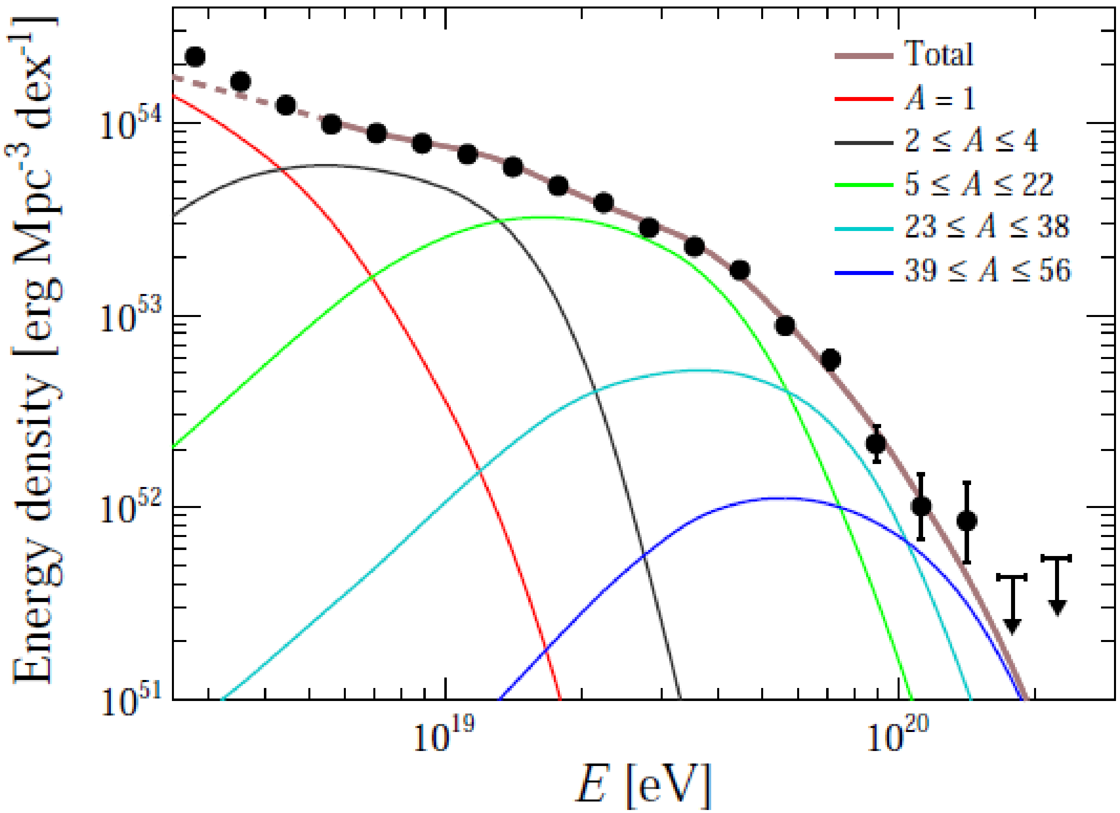


Muon number from models in tension with data

Fluctuation in agreement
(Phys. Rev. Lett. 126 (2021) 152002)

Combined fit of Auger data (spectrum and X_{max} simultaneously) vs astrophysical scenarios

Auger Collaboration Phys. Rev. Lett. 125 (2020) 121106



sources accelerating only protons → **disfavoured**

uniformly distributed sources accelerating nuclei [rigidity dependent] → **favoured**

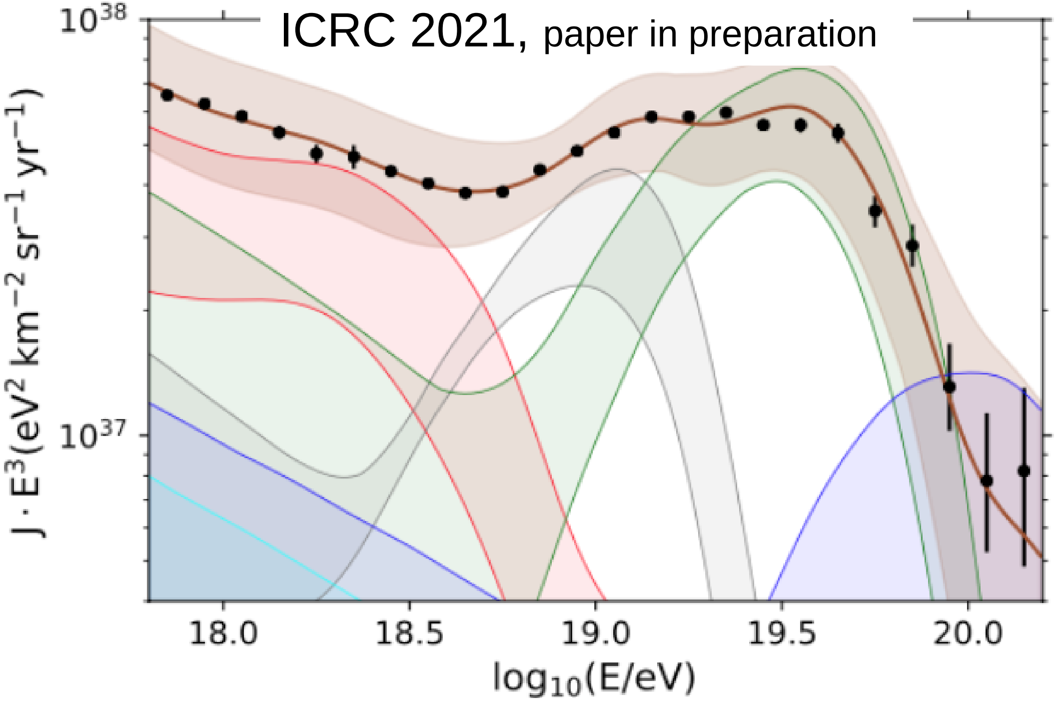
indication that the new feature at 10^{19} eV may be due to the interplay of He and CNO components (individual nearby source not favored, spectrum flat in declination)

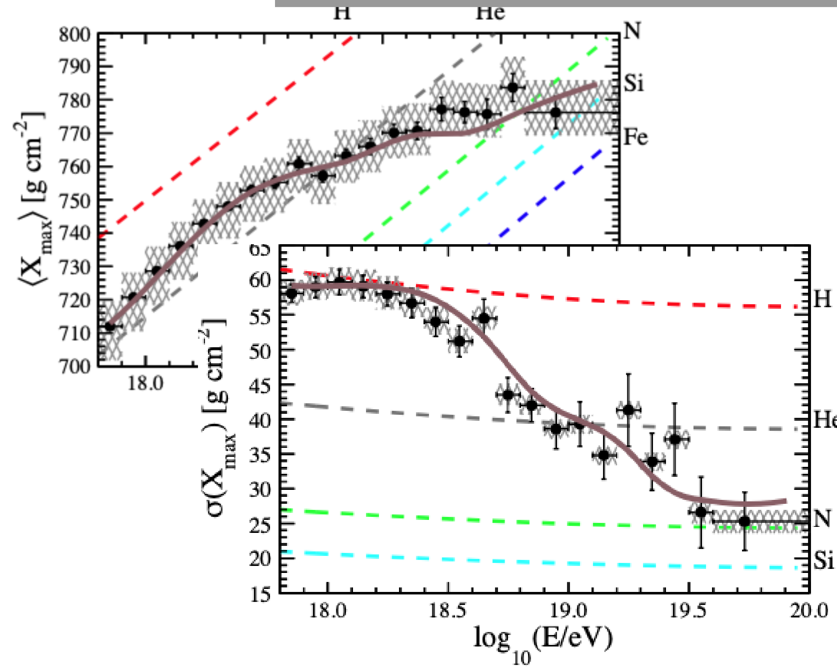
additional component required below 5 10^{18} eV (possibly a tail from galactic CR)

energy density in CR above the ankle (5.66 ± 0.03 ± 1.40) 10^{53} erg Mpc^{-3}
this constraints the luminosity density for classes of extragalactic

→ **sources such as AGN and SB match**

see A. Condorelli at this Conf.





<u>BEST FIT</u>

1) EG: hard HE component + soft LE component
2) possible Galactic component (N)

Scenarios compatible within systematics

Dominant experimental systematics

Only propagation, no magnetic fields

	1st scenario		2nd scenario	
Galactic contribution (at Earth)	N+Si		-	
J_0^{gal} [eV^{-1} km^{-2} sr^{-1} yr^{-1}]	$(1.07 \pm 0.06) \cdot 10^{-13}$		-	
$\log_{10}(R_{cut}^{gal}/V)$	17.48 ± 0.02		-	
f_N (%)	93.0		-	
EG components (at the sources)	Low energy	High energy	Low energy	High energy
$\mathcal{L}_0$ [erg Mpc^{-3} yr^{-1}]	$7.28 \cdot 10^{45}$	$4.4 \cdot 10^{44}$	$1.7 \cdot 10^{46}$	$4.5 \cdot 10^{44}$
γ	3.30 ± 0.05	-1.47 ± 0.12	3.49 ± 0.02	-1.98 ± 0.10
$\log_{10}(R_{cut}/V)$	24 (lim.)	18.19 ± 0.02	24 (lim.)	18.16 ± 0.01
I_H (%)	100 (fixed)	0.0	49.87	0.0
I_{He} (%)	-	27.17	10.92	28.60
I_N (%)	-	69.86	36.25	69.05
I_{Si} (%)	-	0.0	0.0	0.0
I_{Fe} (%)	-	2.97	2.96	2.35
D_J (N_J)	49.5 (24)		60.1 (24)	
$D_{X_{max}}$ ($N_{X_{max}}$)	593.8 (329)		554.8 (329)	
D (N)	643.3 (353)		614.9 (353)	

Large Scale anisotropy

Science 315 (2017) 1266

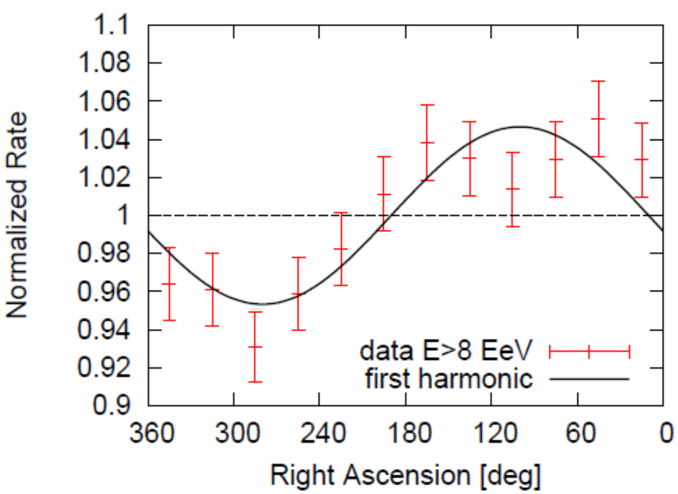
E > 8 EeV
Exposure=76800 km²sr y

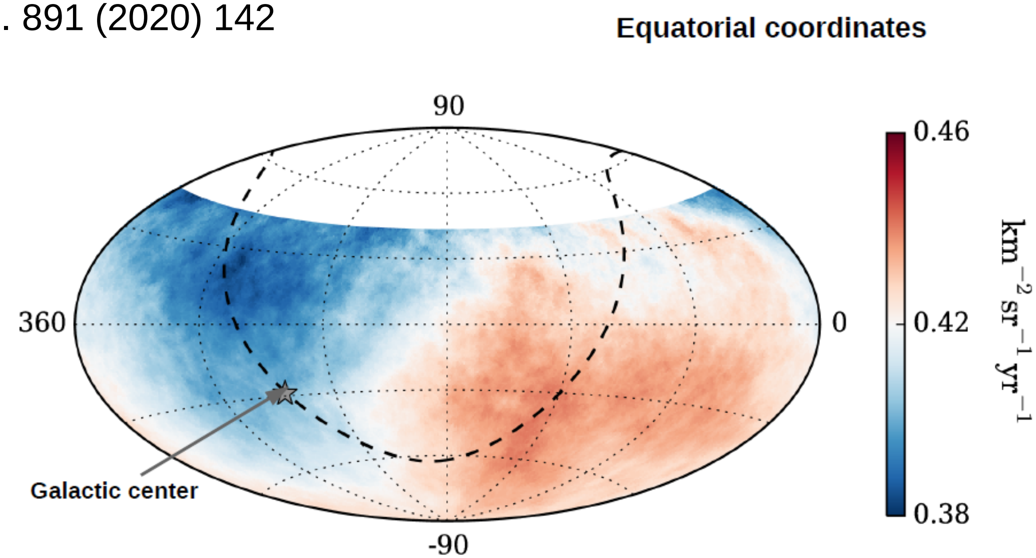
Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)

6 σ with 15% more data → Astrophys. J. 891 (2020) 142





3D dipole → $(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

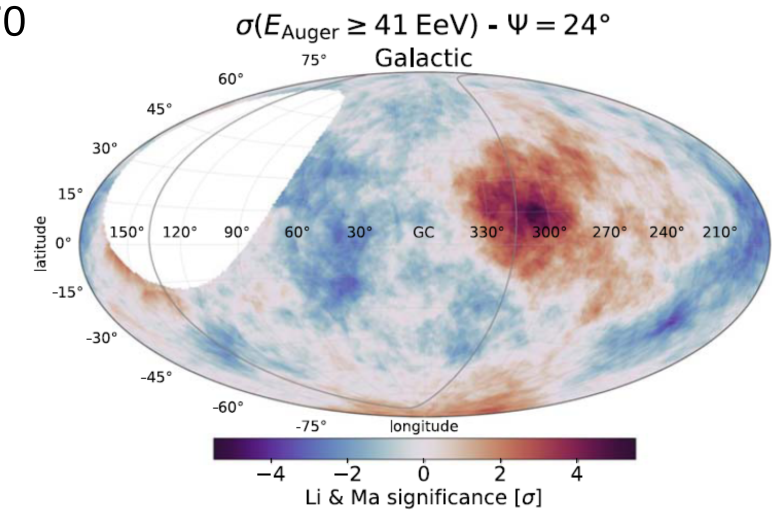
dipole direction ~ 125° from GC → **disfavors galactic origin**

Extragalactic origin favored

Anisotropy at intermediate scale

see L. Caccianiga at this Conf.

The Astrophysical Journal 935 (2022)170



Blind search for overdensities

Energy [32-80] EeV - zenith up to 80°

2635 events between 1/1/2004 and 31/12/2020

Centaurus A region:

most significant excess, 2.2 σ post trial, at ψ~24° E > 41 EeV

direction fixed at Cen A 3.9 σ post trial, at ψ~27° E > 41 EeV

Data available for public use!
https://doi.org/10.5281/zenodo.6504276

Autocorrelation with structures (GC, GP, SGP) not significant

Likelihood test for anisotropy with astrophysical catalogs

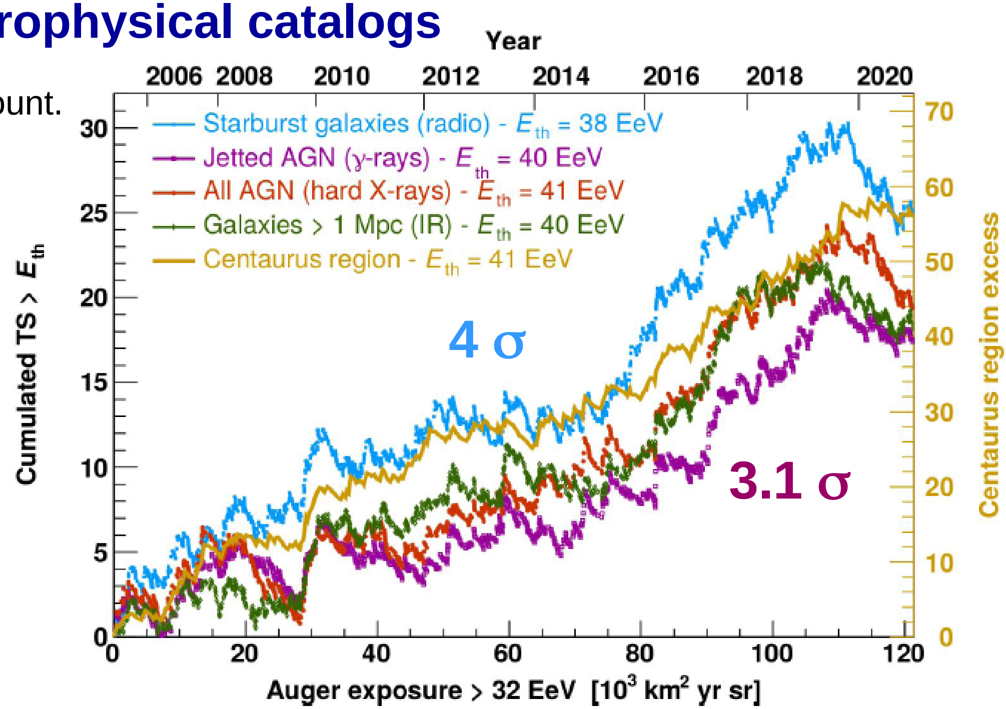
Attenuation and relative weight of sources taken into account.

Catalog	$E_{\rm th}$ [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}

Most significant signal at E_{th}= 38-41 EeV,

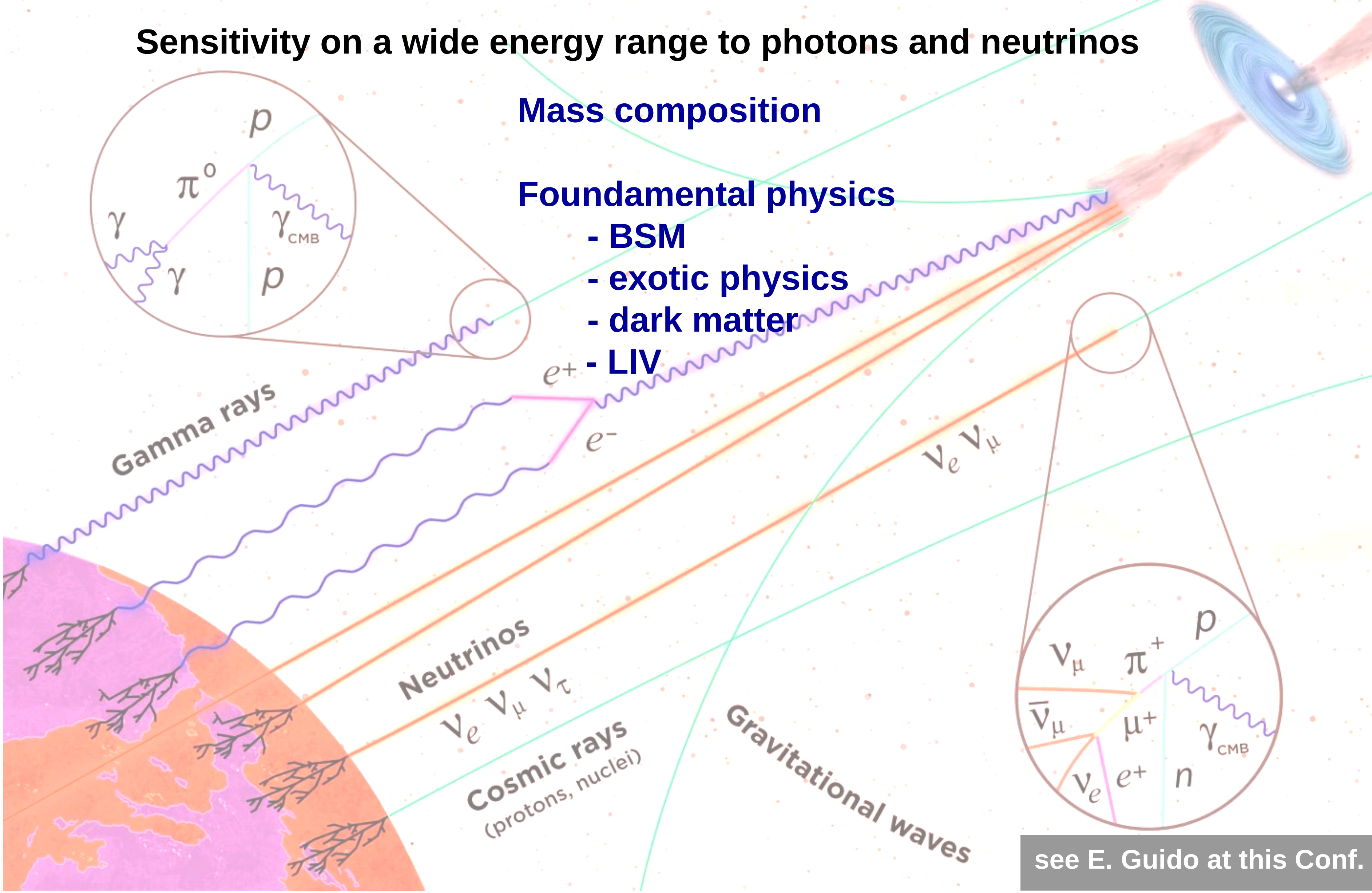
ψ =23° - 27°, signal fraction 6-15%

Significance 4 σ for SB
3.1 σ for jetted AGN



Multi-messenger physics (diffuse, targeted and follow up)

Sensitivity on a wide energy range to photons and neutrinos



Mass composition

Foundamental physics

- **BSM**
- **exotic physics**
- **dark matter**
- **LIV**

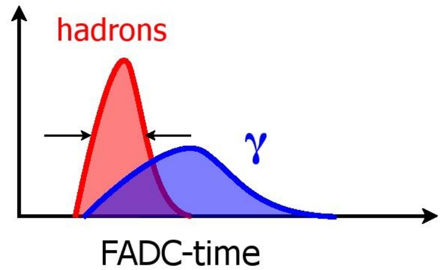
see E. Guido at this Conf.

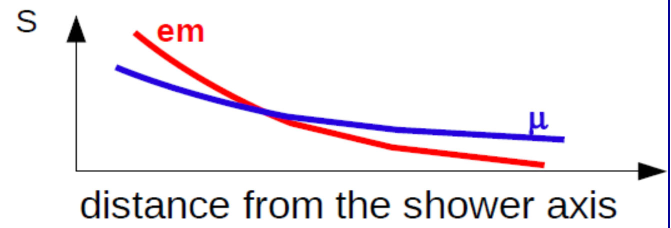
Hybrid and SD photon search

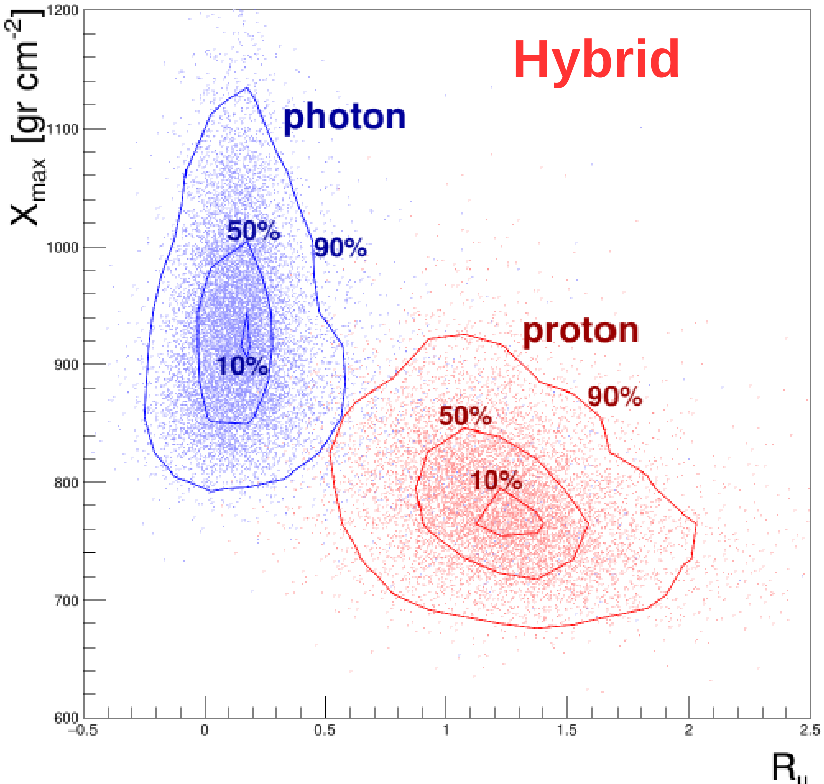
Photon signature

deeper Xmax, less muons

steeper LDF and broader signal

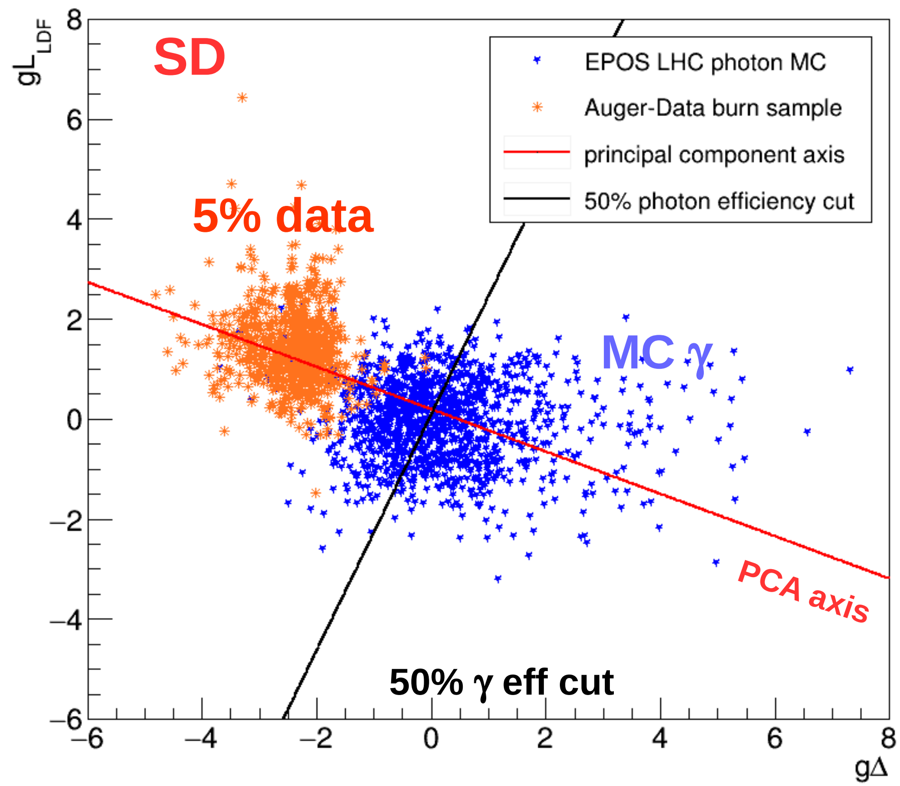






Maximum of shower development: $\mathbf{X_{max}}$

Muon content of the shower (universality): R_μ

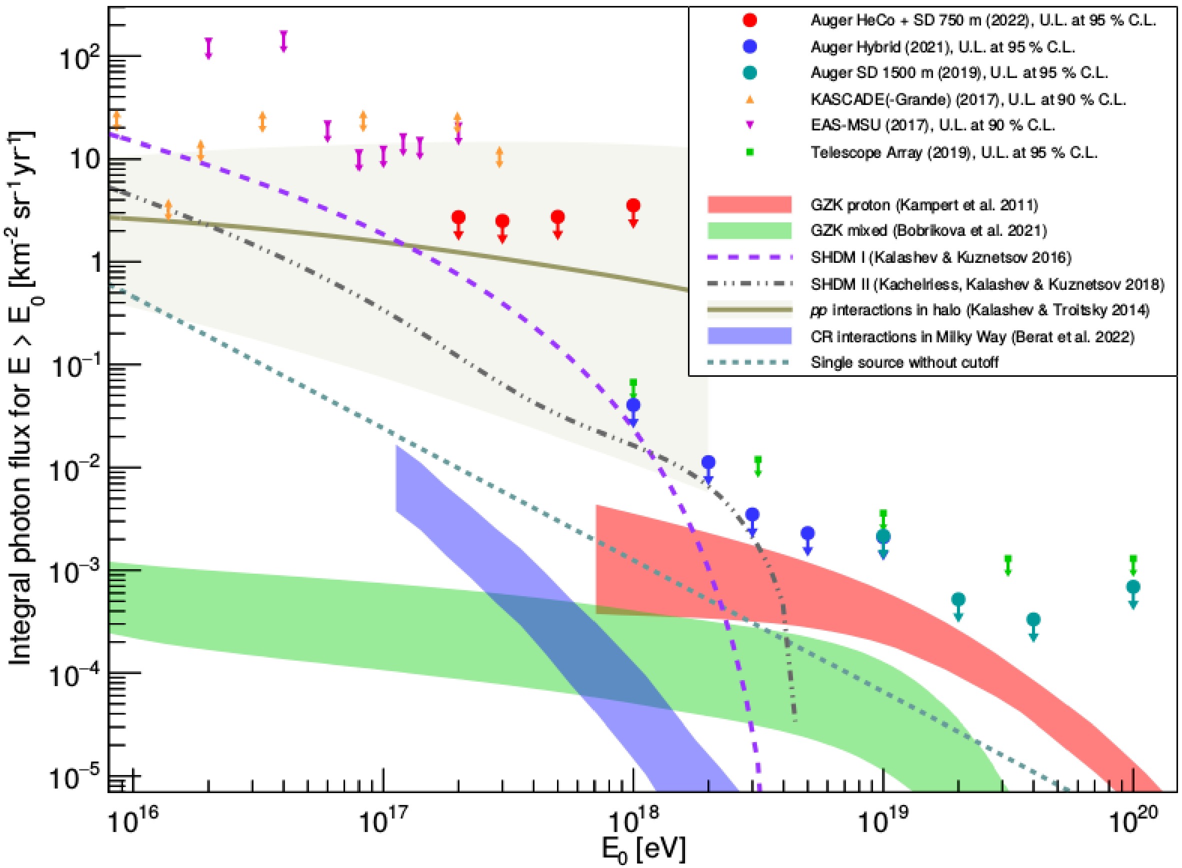


Deviation from data <LDF>: $\mathbf{gL_{LDF}}$

rise-time rel. event-wise quantity: $\mathbf{g_\Delta}$

Upper limits on diffuse photon flux

Ap. J. 933 (2022)125



Strictest limits at E> 0.2 EeV

11 candidates > 10 EeV (SD)

22 candidates > 1 EeV (Hybrid)

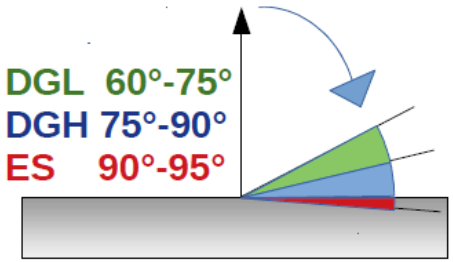
Targeted search
In coincidence of known sources including CenA and the Galactic Center [UL extrapolating HESS flux]

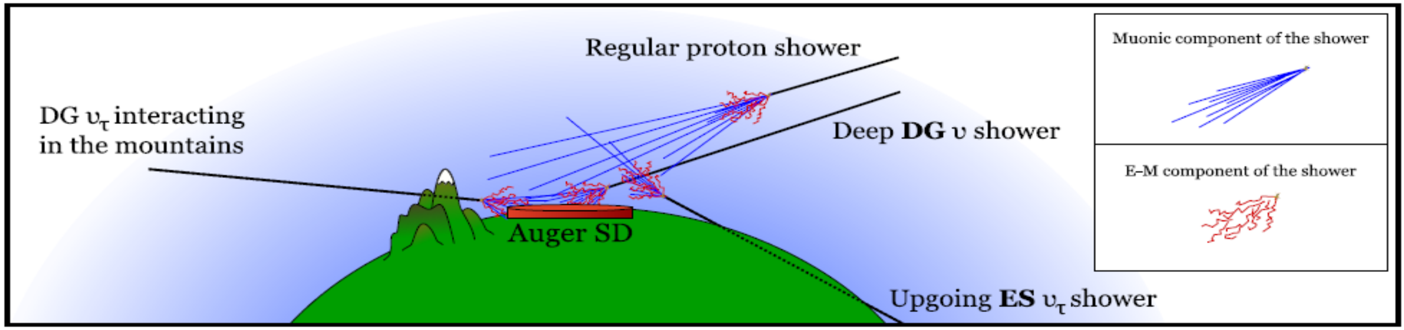
GW follow-up (4 events)

NO Candidates found

- Top-down model disfavored
- CR proton dominated scenario (also the most pessimistic cases) disfavoured
- constraining mass and lifetime of dark matter particles → **see R. Aloisio at this Conf.**
- Auger Phase II: additional information for better photon/hadron separation or photon discovery

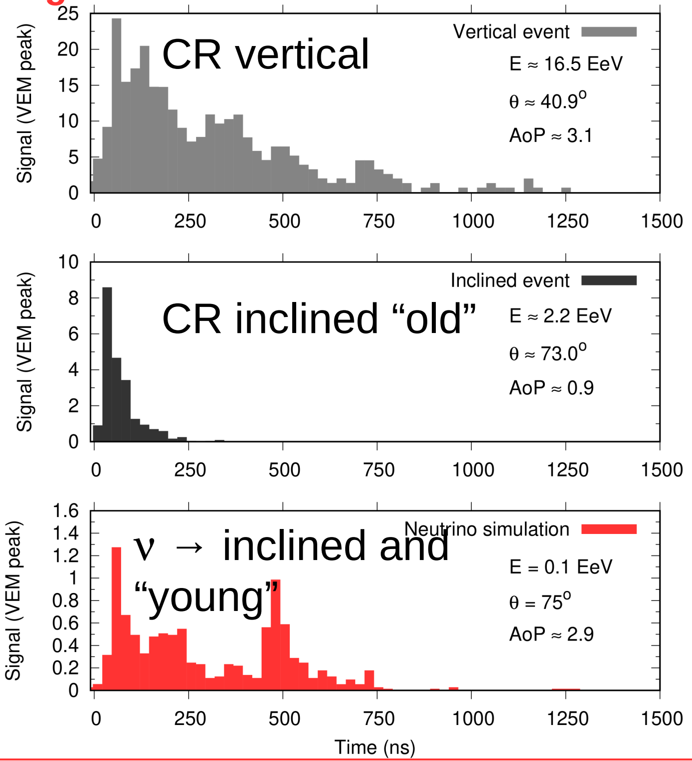
UHE neutrinos with the SD



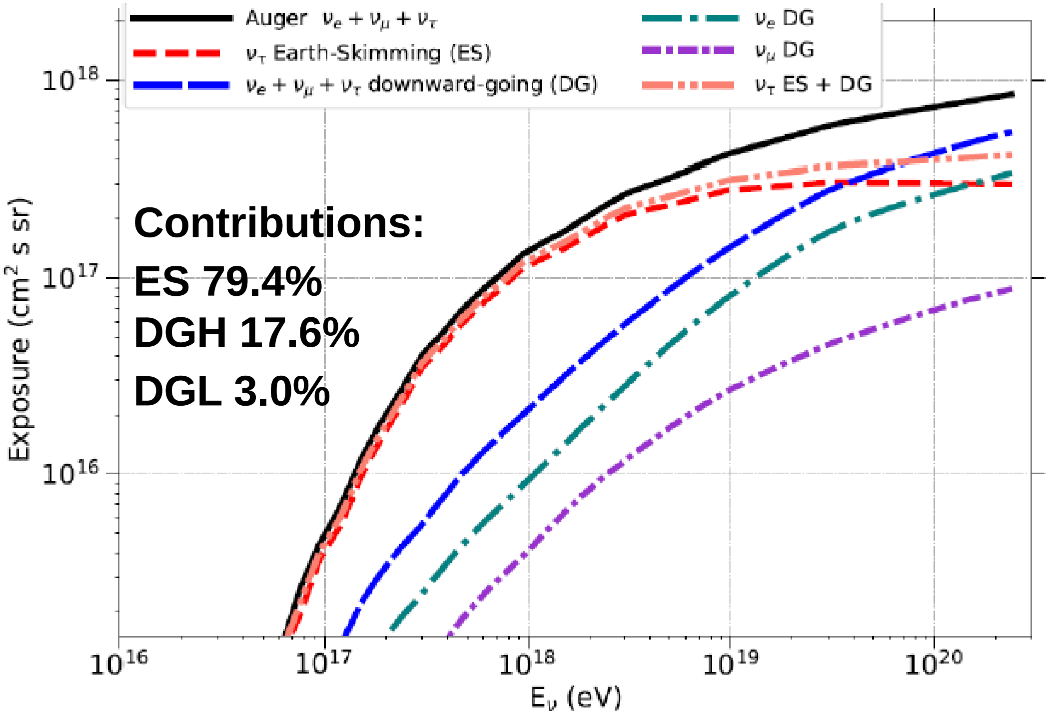


typical signal shapes

signature: distinctive Area-over-Peak



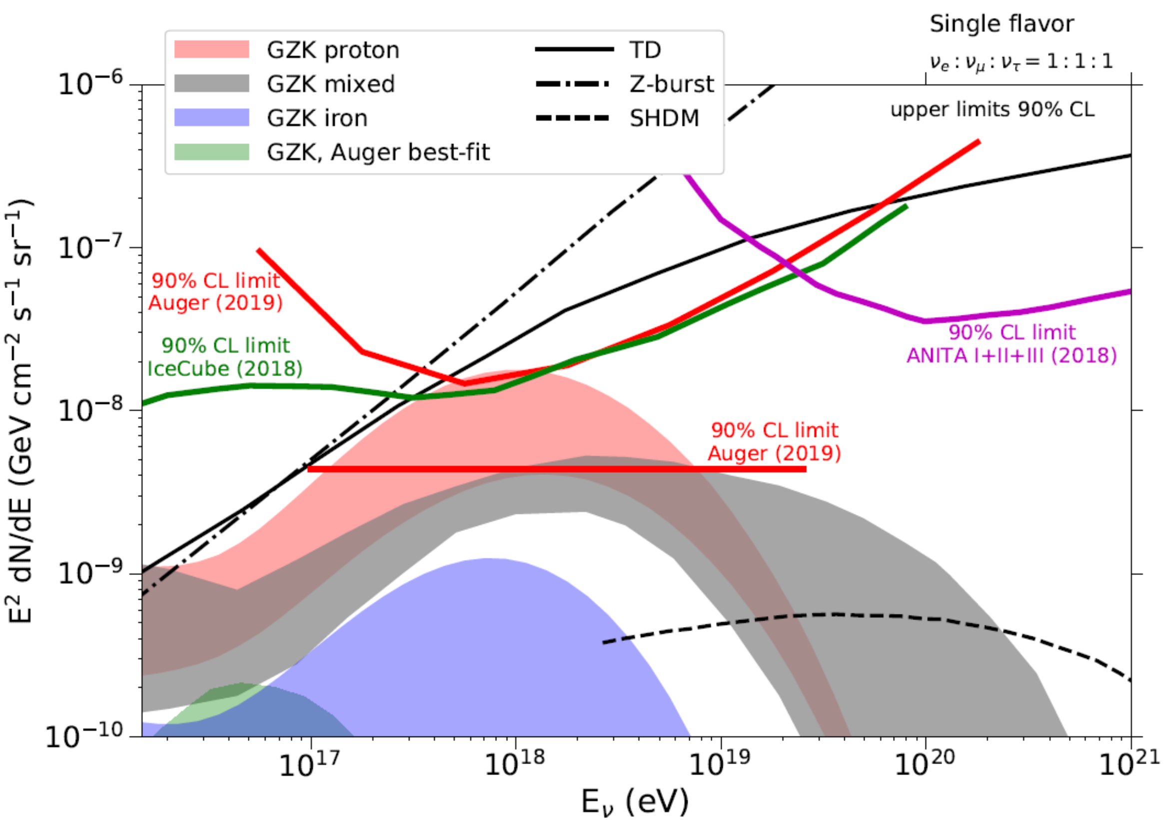
Sensitivity to different channels



ν_τ ES sensitivity dominant

Upper limits on the diffuse neutrino flux

Pierre Auger Coll., JCAP 10 (2019) 022



Identification criteria applied "blindly" to the search data set

Point-like sources
also in coincidence with observations by other experiments
For example TXS 0506+056

Coincidence with GW
For example GW170817
GW follow-up (62 events, stack analysis)

NO Candidates found

NO Candidates found

Maximum sensitivity ~ **1 EeV**

Upper limits set assuming dN/dE = k E^{-2}

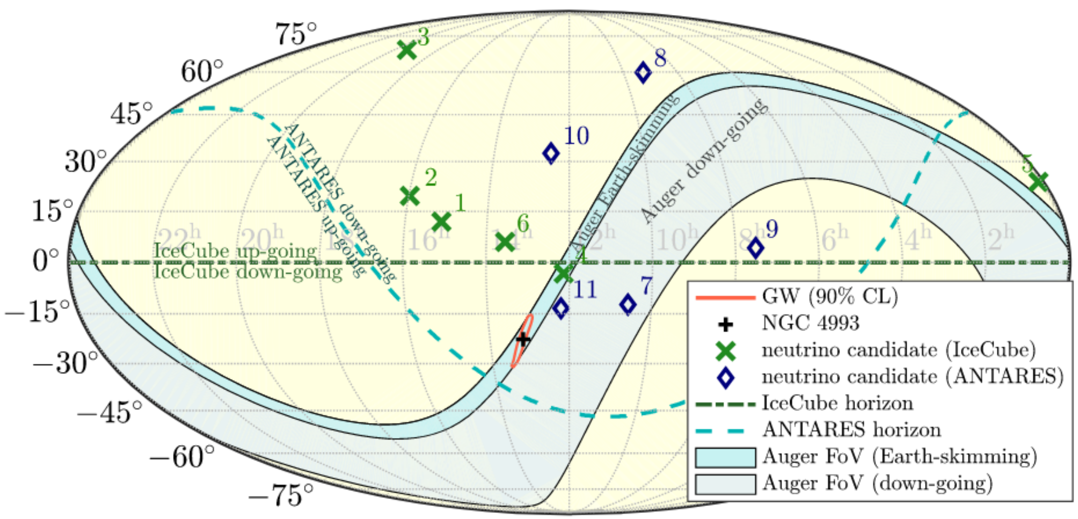
→ k ∼ 4.4 x 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} [0.1 – 25] EeV

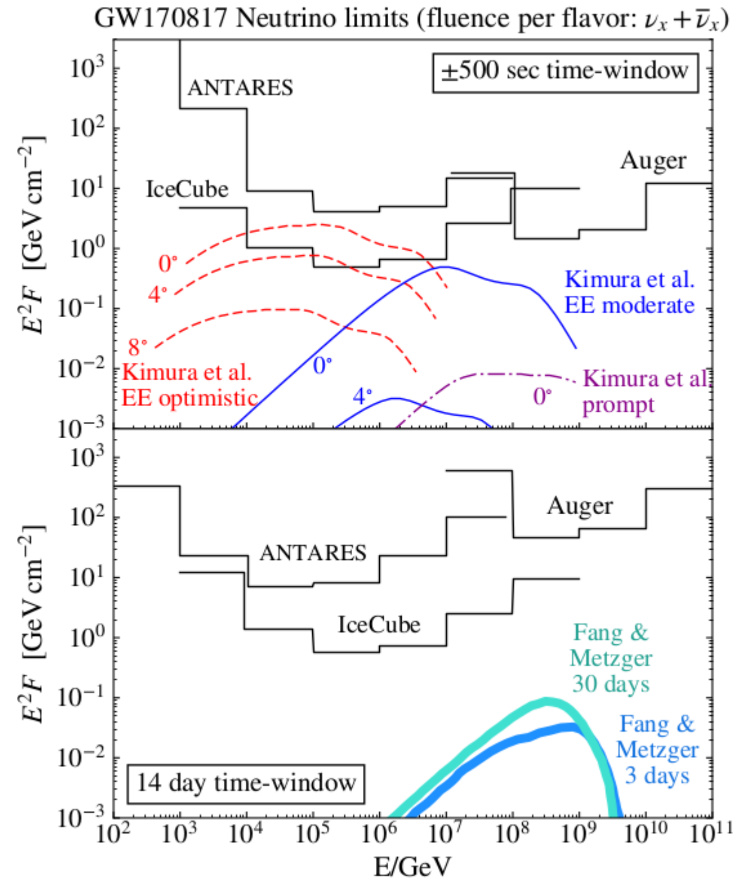
Heavy constraints on models assuming sources of CR accelerating only protons with strong evolution in z

Follow-up searches: GW170817

The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1

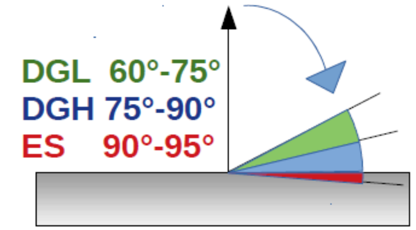
LIGO/Virgo BNS GW170817 & Fermi sGRB 170817A
→ EM counterpart Optical/IR KiloNova AT2017GFO

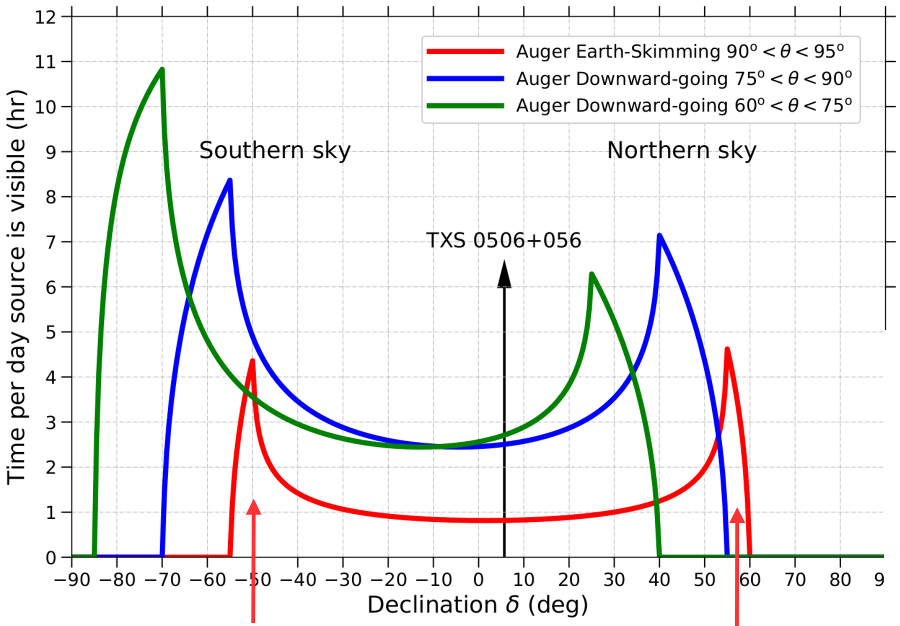




→ excellent visibility of the merger:
90% CL GW event location in FoV of ES channel
→ time dependent exposure leads to substantially lower 14-day neutrino fluence limits wrt to prompt

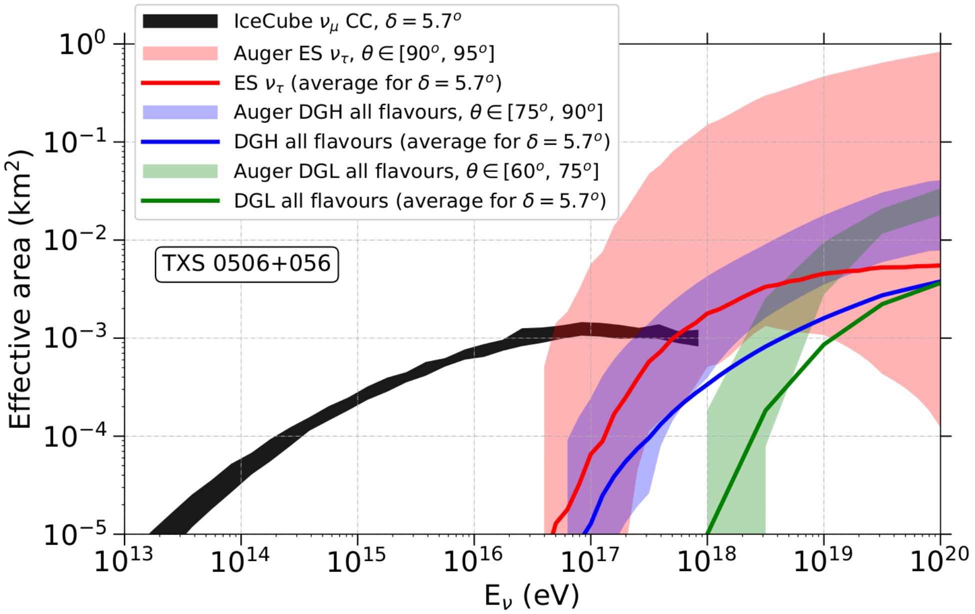
Auger UHE window: TXS0506





Optimal observation position: source δ in FOV of the Earth-skimming channel (right below the horizon)

TXS0506+056 declination = 5.7°
→ Non optimal sensitivity of the source in all channels

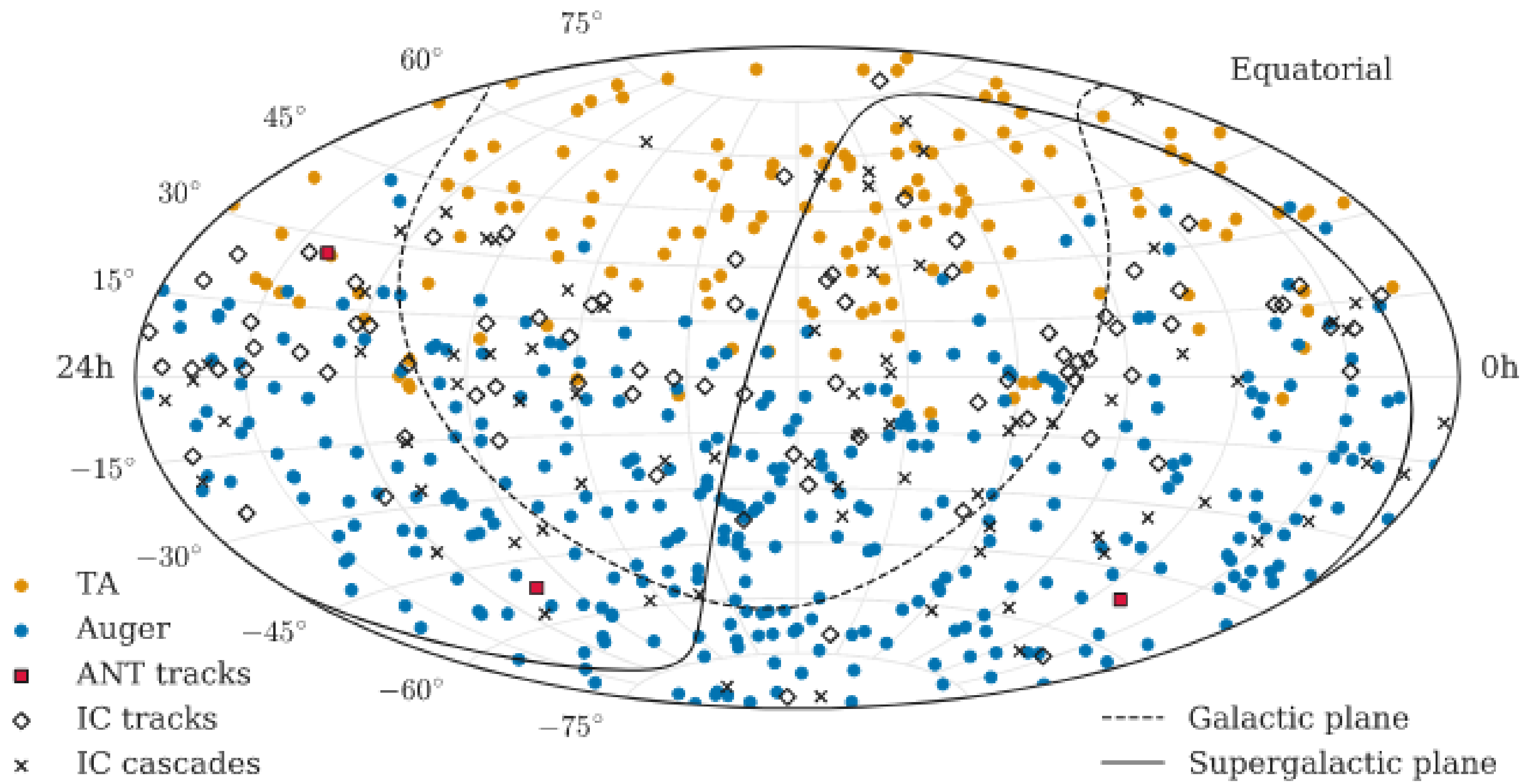


→ complementary to IceCube in the EeV range

Joint searches (UHECR and neutrinos)

Antares, **I**ce**C**ube, **A**uger, **T**elescope **A**rray

APJ 934 (2022)164



Three analyses strategies:

– UHECR-neutrino cross-correlation

– Neutrino-stacking correlation with UHECRs

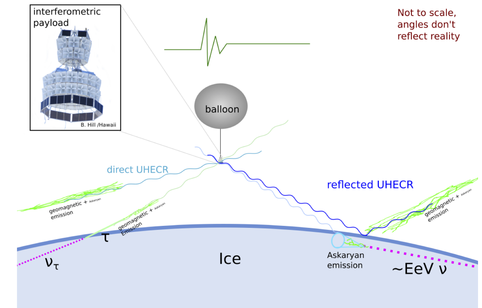
– UHECR-stacking correlation with neutrinos

All compatible with background

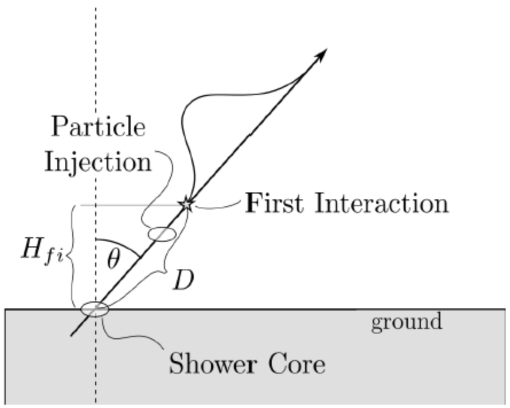
Search for upward-going showers with the FD

Debate triggered after the Observation of the anomalous events by the ANITA experiment

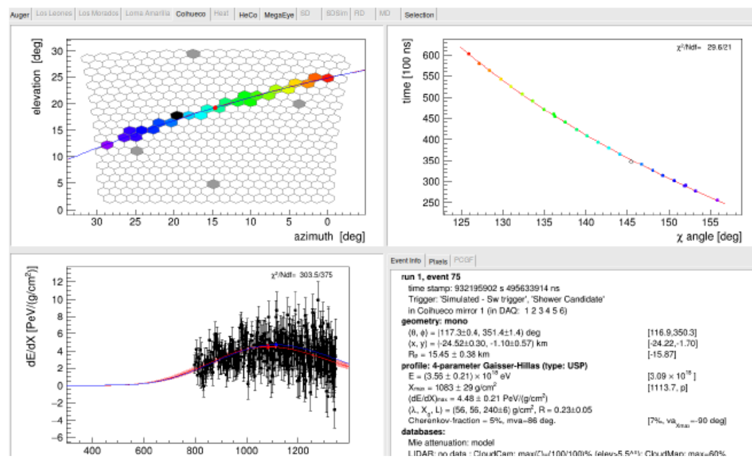
$E_{1,2} \gtrsim 0.2$ EeV, exit angle $\approx 27° \approx 35°$



SIGNAL SIMULATION



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



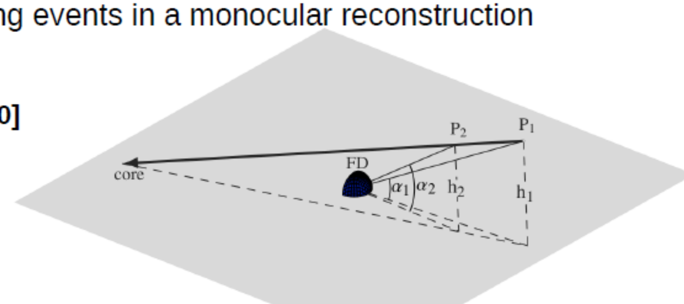
Quantify the sensitivity of the FD to upward-going showers

Use 14 years of FD data (2005-2018) for a dedicated search

BACKGROUND SIMULATION

Downward-going events with specific geometries can mimic upward-going events in a monocular reconstruction

Zenith [0°- 90°]
log10 (E/eV) [17-20]



$\alpha_1 < \alpha_2$
$h_1 > h_2$

Signal from P_1 reaches the FD before the signal from P_2 → downward-going event reconstructed as upward-going

Also events with a core far away from the array can produce background and need to be simulated

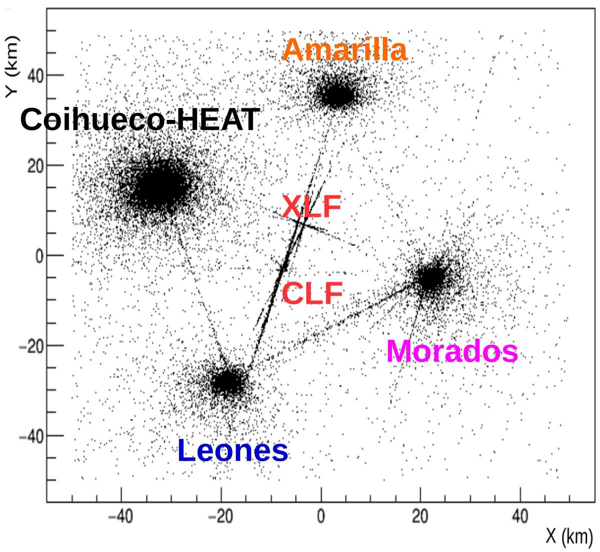
Data cleaning using a burnt data sample

Blind analysis performed using 10% of the FD data from 14 years of FD operation

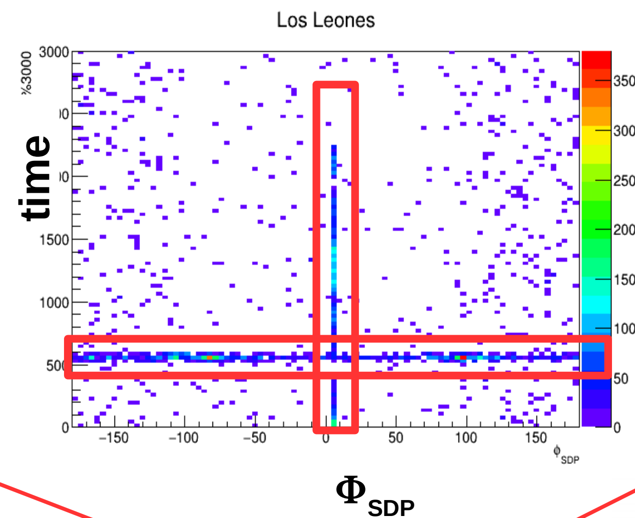
FIRST STEP: remove untagged laser events used to monitor the atmosphere

Lidar shots have a specific frequency of 333 Hz → they pile up in a GPSMicroSecond%3000 histogram

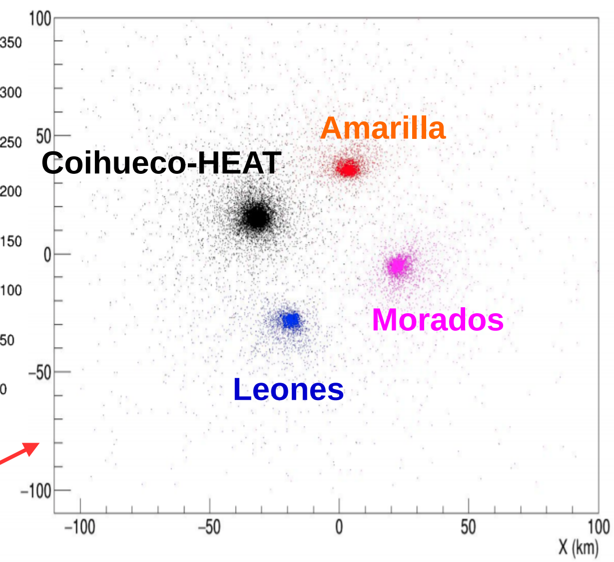
CLF and **XLF** have a known position → the angle Φ_{SDP} that define the intersection of the shower detector plane (SDP) with the ground can be used to identify the associated event



Exit points before cleaning



Data driven filtering algorithm

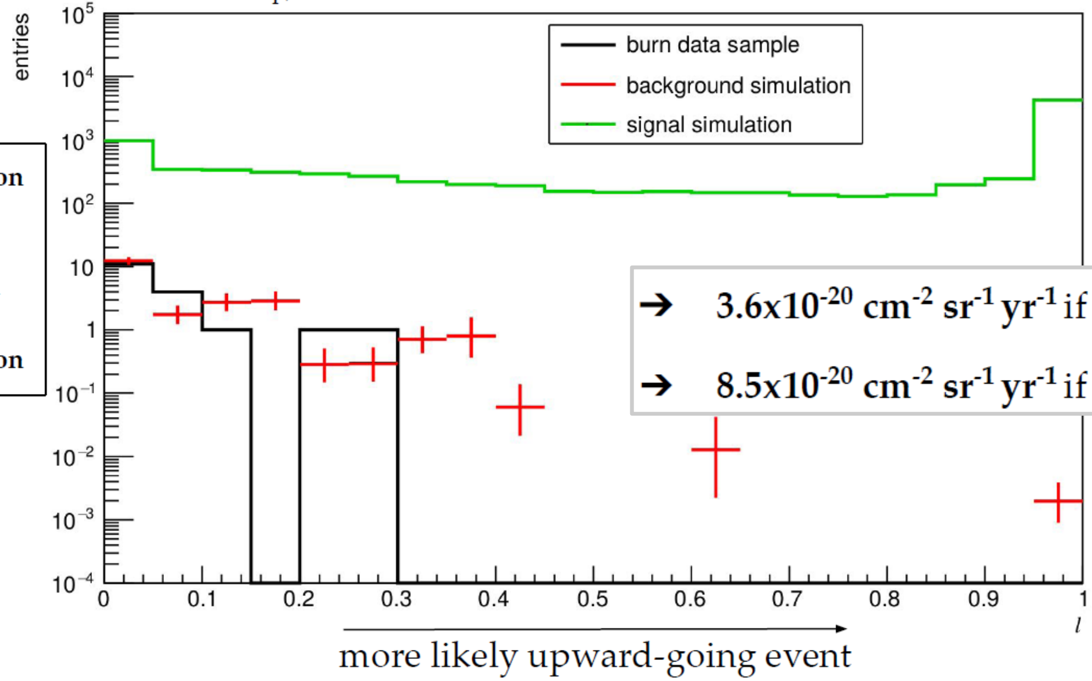


Exit points after cleaning

Upper limits: upward-going showers with the FD

ICRC 2021

- Variable $l = \text{atan}(-2\log(L_{down}/L_{up,down})/50)/(\pi/2)$ defined between 0 and 1



background simulation weighted to burn sample → good agreement between burn sample and background simulation

$n_{bkg} = 0.45 \pm 0.18$

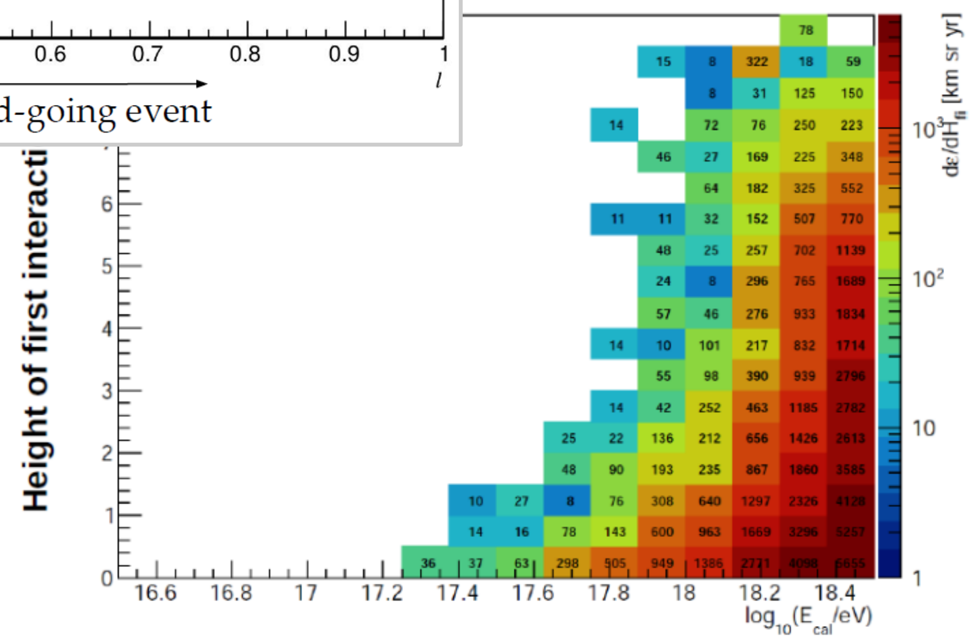
Upper limits

➔ $3.6\text{x}10^{-20}$ cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with E^{-1}

➔ $8.5\text{x}10^{-20}$ cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with E^{-2}

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

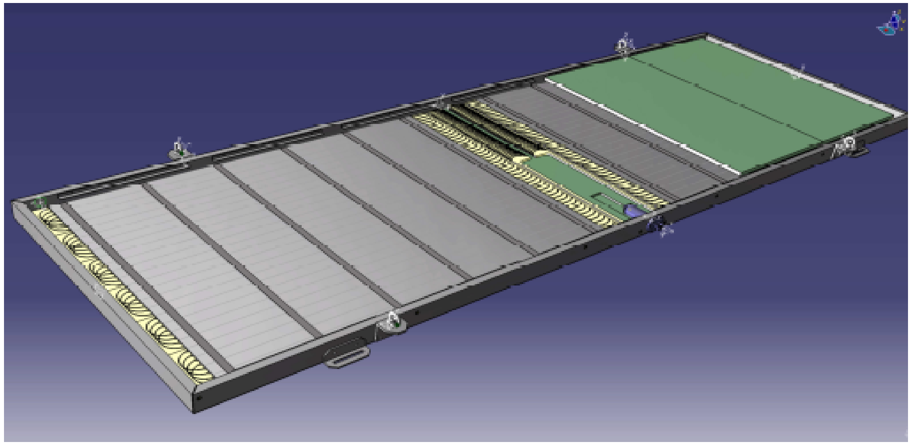
Useful to test various physics scenarios (taus, BSM)



EAS calorimetric energy

Auger upgrade program: Auger Prime

3.8 m^2 (1 cm thick) scintillators on each of the main array station



SSD: scintillators sensitive to the electromagnetic content of the shower

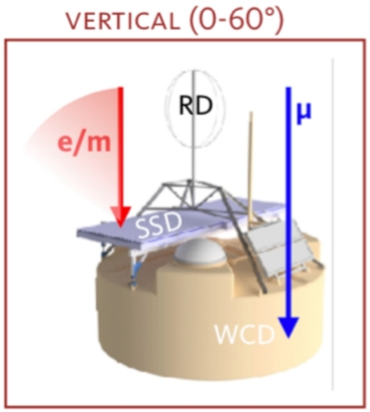
SCIENCE CASE

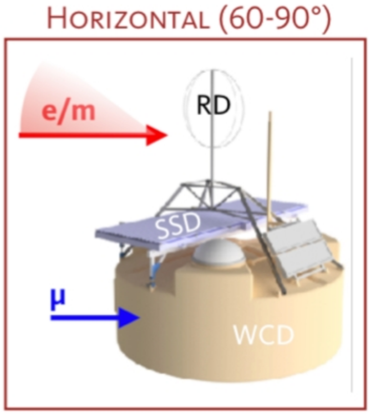
Origin of the flux suppression, GZK vs. maximum energy scenario

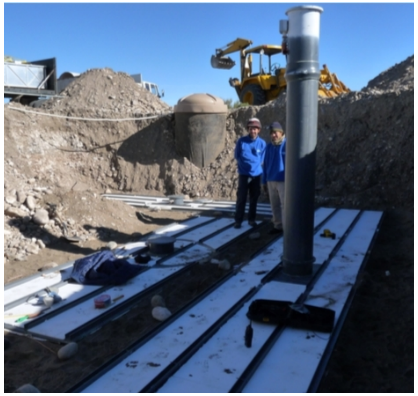
Search for a flux contribution of protons up to the highest energies at a level of ~ 10%

Study of extensive air showers and hadronic physics $\sqrt{s}$=70 TeV

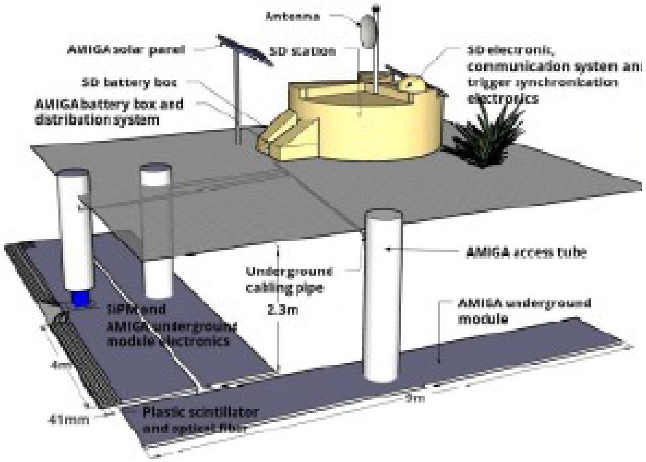
- Scintillators **SSD**
- Upgraded and fasterelectronics **UUB** (40 MHz - 120 MHz)
- Extension of the dynamic range with small **sPMT**
- Underground buried **UMD** detectors
- Radio antennas **RD**

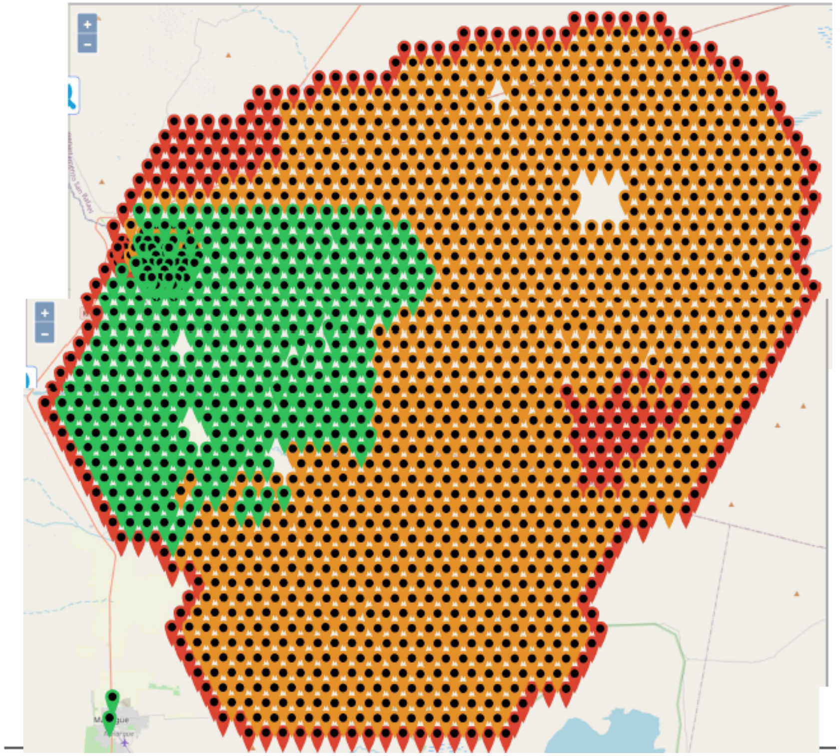






4 positions with 3 UMD each in the field



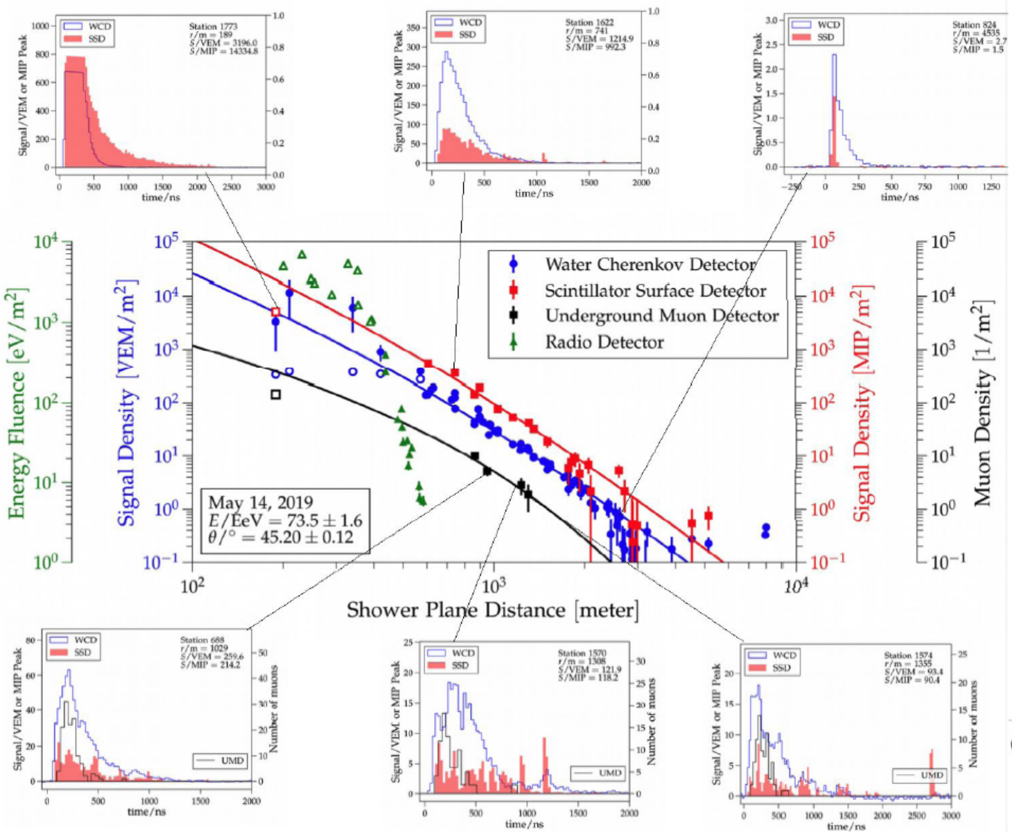


1436 SSD stations **deployed**

25% of the array equipped with UUB and SSD-PMT and sPMT

Installation completed with UUBs in early 2023

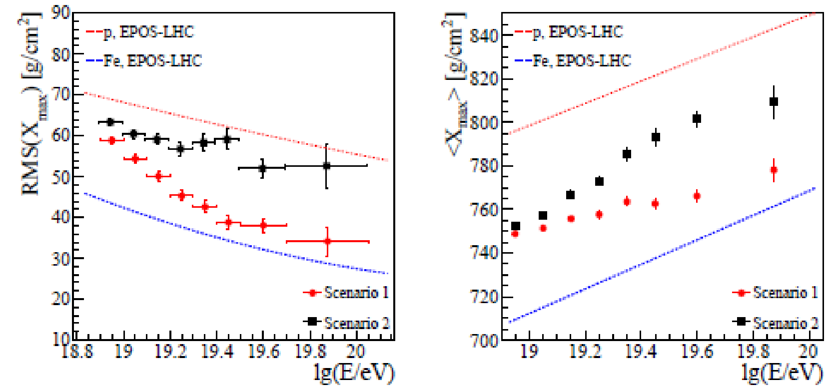
Exemplary “super” hybrid event



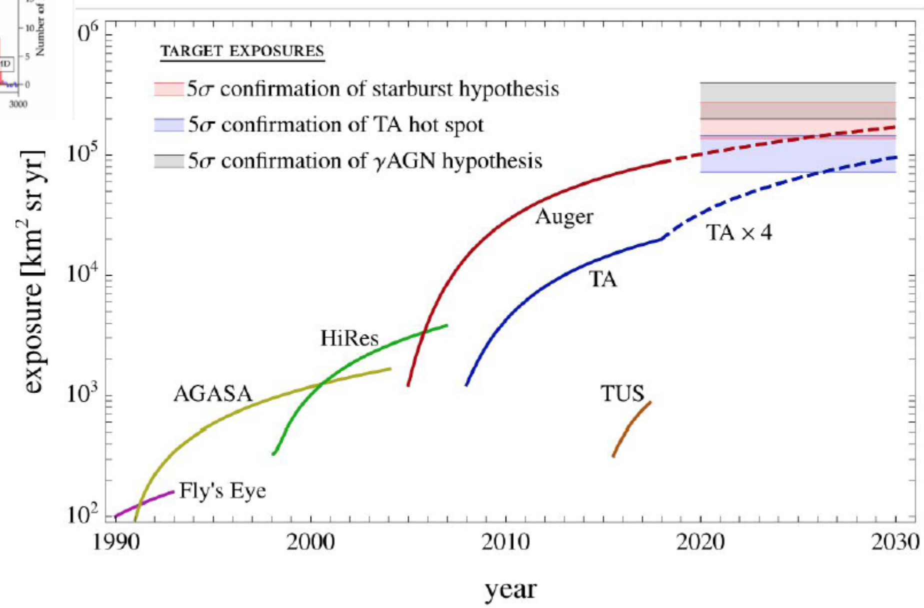
Complementary measurements up to highest energies

Scenario 1 : maximum rigidity

Scenario 2: photo-disintegration



Expected exposure increase and physics scenarios in reach



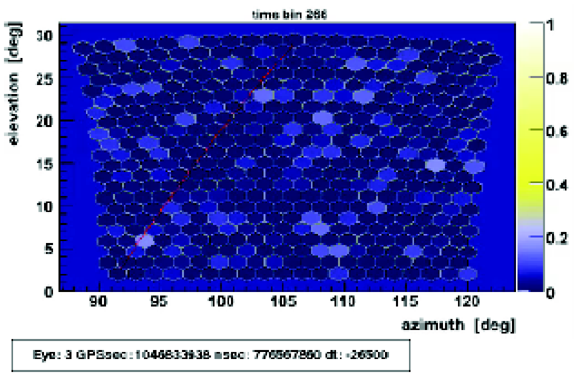
Auger as a interdisciplinary facility: Elves observation

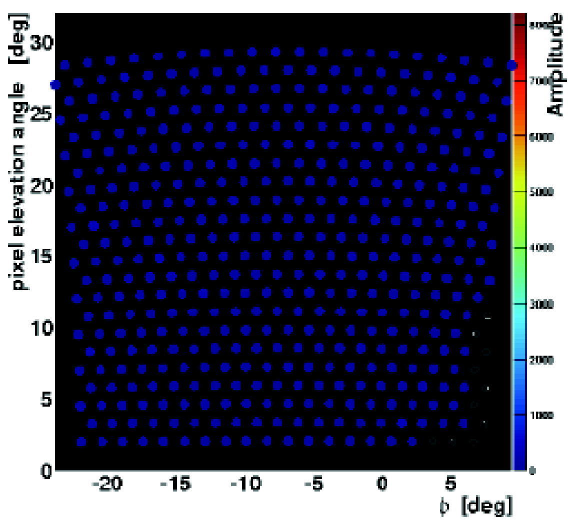
Earth and Space Science 7 (2020) e2019EA000582

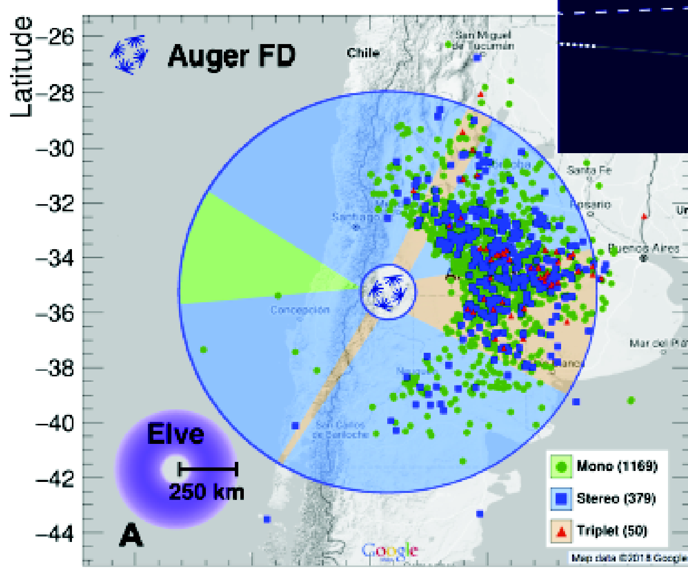
RESEARCH ARTICLE
10.1029/2019EA000582

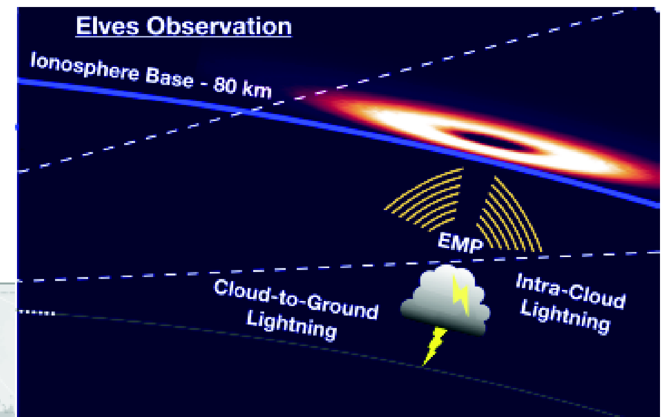
A 3-Year Sample of Almost 1,600 Elves Recorded Above South America by the Pierre Auger Cosmic-Ray Observatory

Key Points:
- Elves are observed in Argentina,









1600 elves observed

Short article to appear in EOS News

High-level publications of correlation with super bolts in preparation

Pierre Auger Observatory Open Data

February 2021 release

https://opendata.auger.org
doi 10.5281/zenodo.4487613

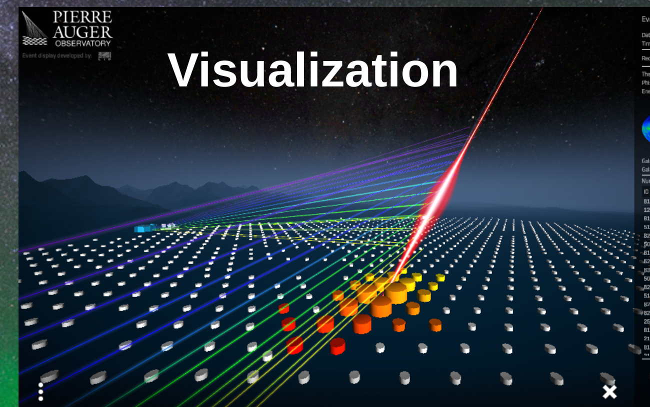
10% cosmic ray data
100% atmospheric data

Close to raw data and higher level reconstruction

Surface and Fluorescence Detectors

JSON and summary CSV files

Python code for data analysis



Datasets

the released datasets and their complementary data

Visualize

an online look at the released pseudo raw cosmic-ray data

Analyze

example analysis codes in online python notebooks to run on the datasets

Outreach

a page dedicated to the general public

Summary and perspectives

Spectrum	Combined measurements, ankle observed at about 5 10^{18} eV, new feature at ~ 10^{19} eV, suppression at E > 4 10^{19} eV), its nature still not fully understood
Composition	heavier with increasing energy (interpretation is model dependent).
Neutrals	flux photon limits above 0.1 EeV (top-down models disfavored, standard astrophysical sources expected). Absence of cosmogenic neutrinos disfavor pure proton composition
Models	Observed mismatch data models for muon content
Astronomy	Indication of a possible anisotropy at intermediate scale and evidence of dipole at large scale (and E > 8 EeV)

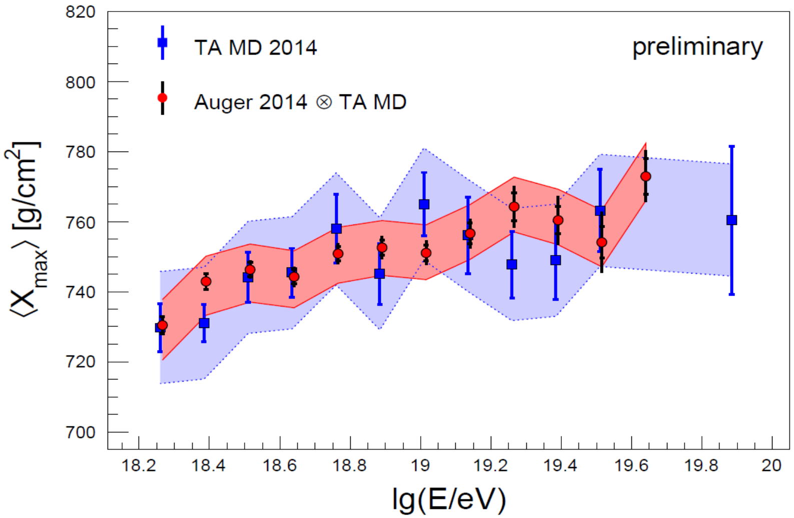
Uniformly distributed sources accelerating nuclei (rigidity based scenario) favoured

AugerPrime

- need composition data E> 40 EeV to better understand the suppression
- better understanding of hadronic interaction models
- separate a light component pointing back to astrophysical sources

BACKUP SLIDES

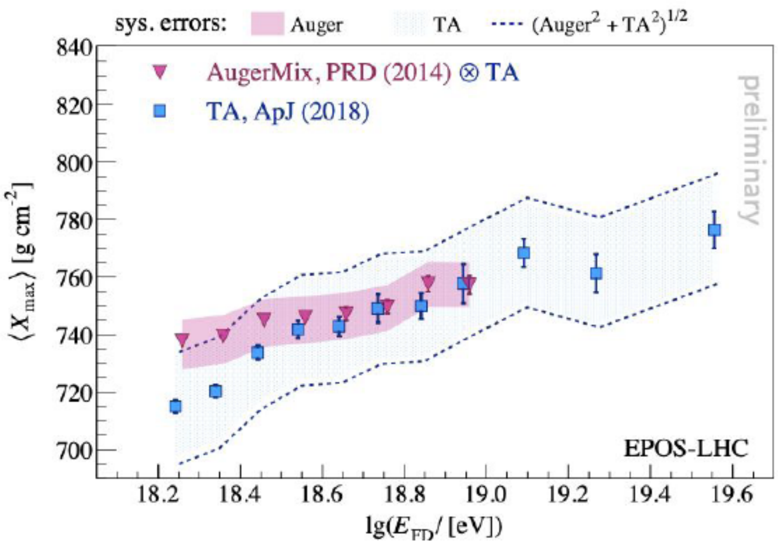
AUGER vs Telescope Array

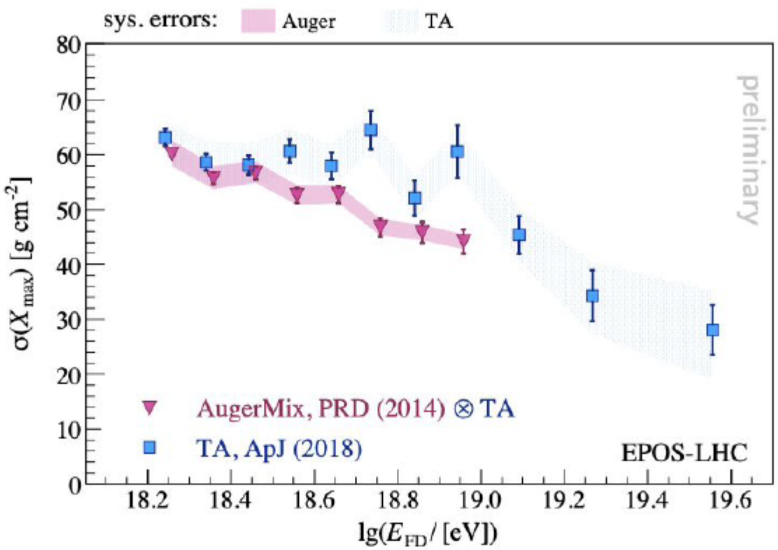


Auger data folded with TA acceptance are agreement with TA data

Joint Working Group (arXiv:1503.07540)

Auger&TA working group, JPS Conf.Proc. 9 (2016) 010016
Auger&TA working group, EPJ Web of Cons. 210 (2018) 010009





TA data consistent with Auger-mix composition at least up to 10 EeV at least up to 10 EeV but also with 100% protons, due to larger uncertainties

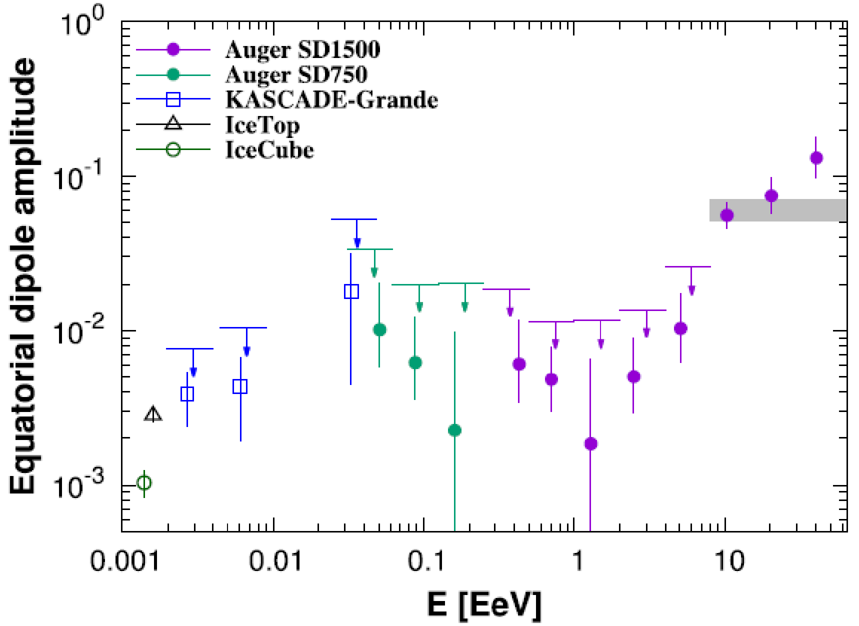
Astrophys. J. 891 (2020) 142

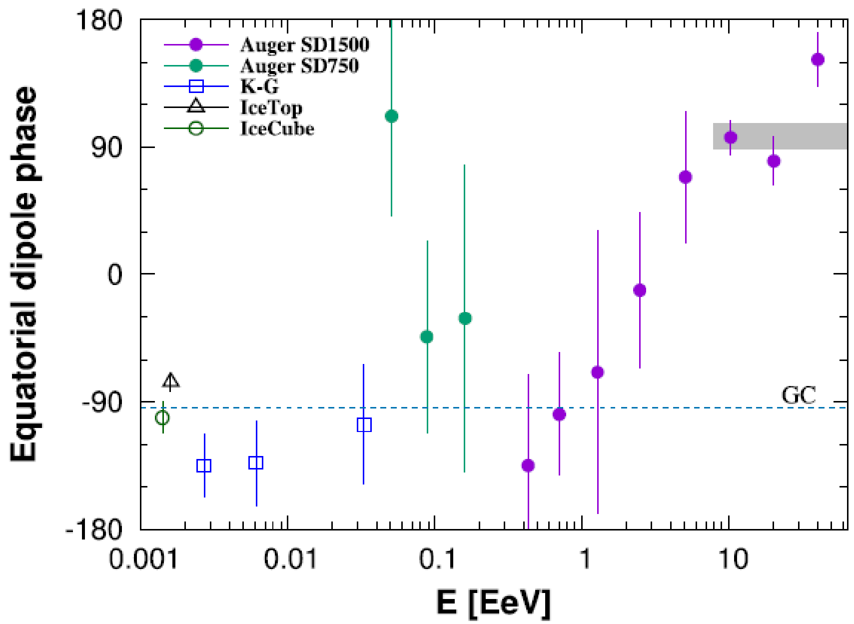
Large scale anisotropy confirmed **15% more data**

3D dipole 6.5%$^{+0.013}_{-0.09}$ → 6.6%$^{+0.012}_{-0.08}$

Modulation 2.6 10^{-8} → 1.9 10^{-9} (**6 σ**)

Study of the energy evolution of the dipole equatorial component and phase





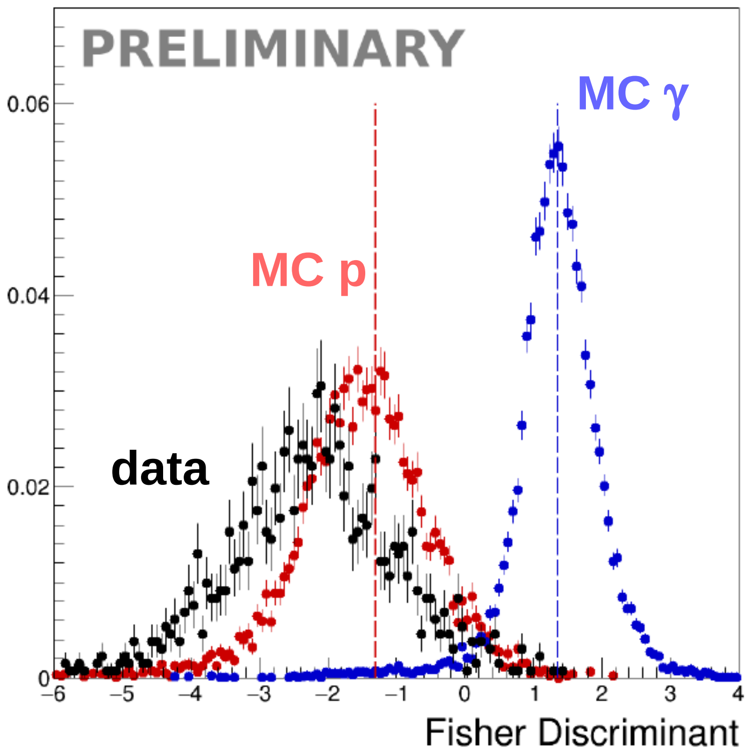
Amplitude increases from 1% to 10% above few EeV

Phase shifts from GC to the opposite at the highest energies

Transition to extragalactic above few EeV

Hybrid and SD photon search

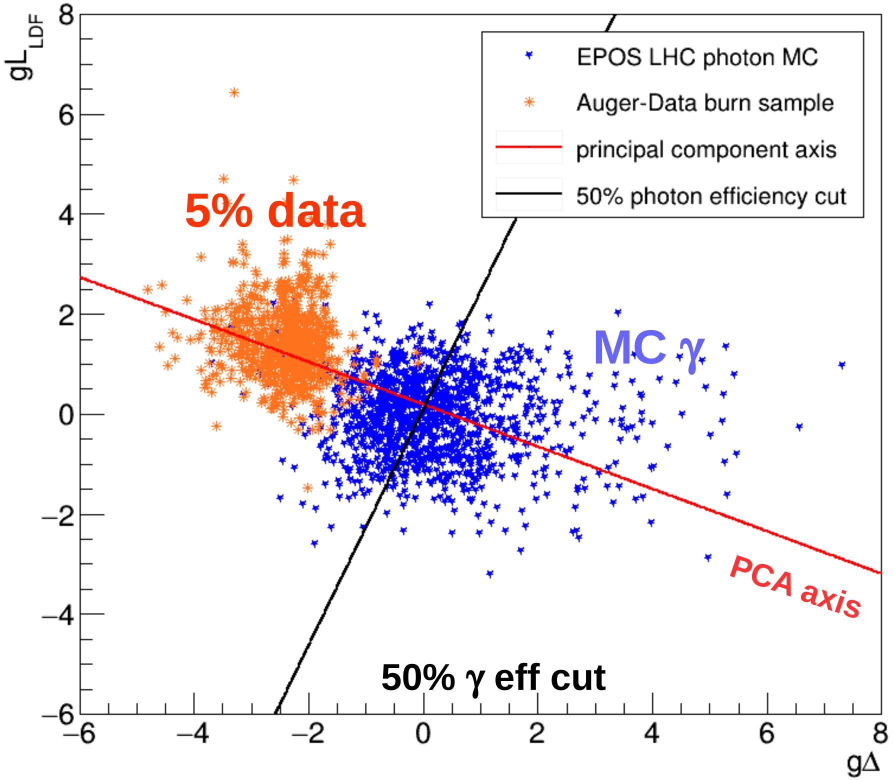
Hybrid selection: Fisher response



Maximum of shower development: $\mathbf{X_{max}}$

Muon content of the shower (universality): F_{μ}

SD selection: PCA transformed

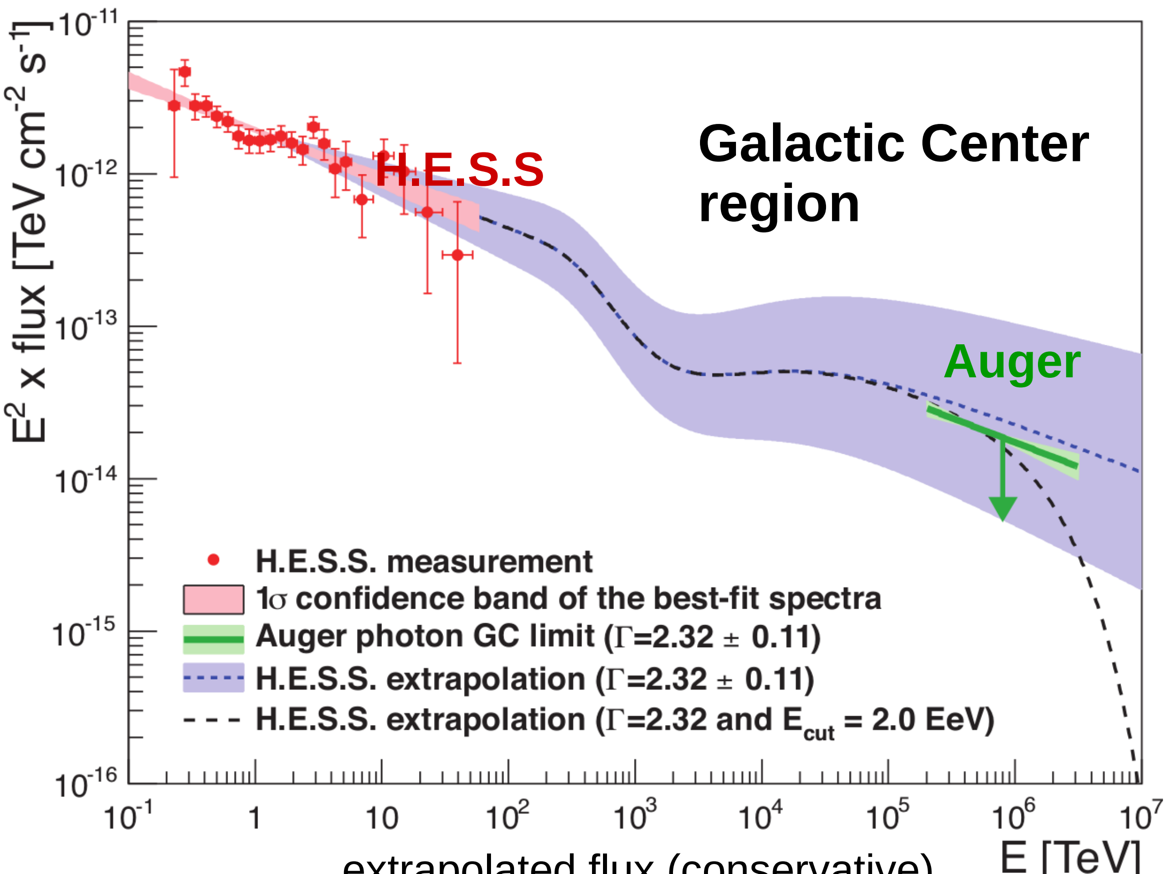


Deviation from data <LDF>: $\mathbf{gL_{LDF}}$

rise-time rel. event-wise quantity: $\mathbf{g_{\Delta}}$

Targeted searches

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



extrapolated flux (conservative)

- focus on **12 target sets** (364 candidates sources)
- stacked analysis

→ complement targeted neutron searches

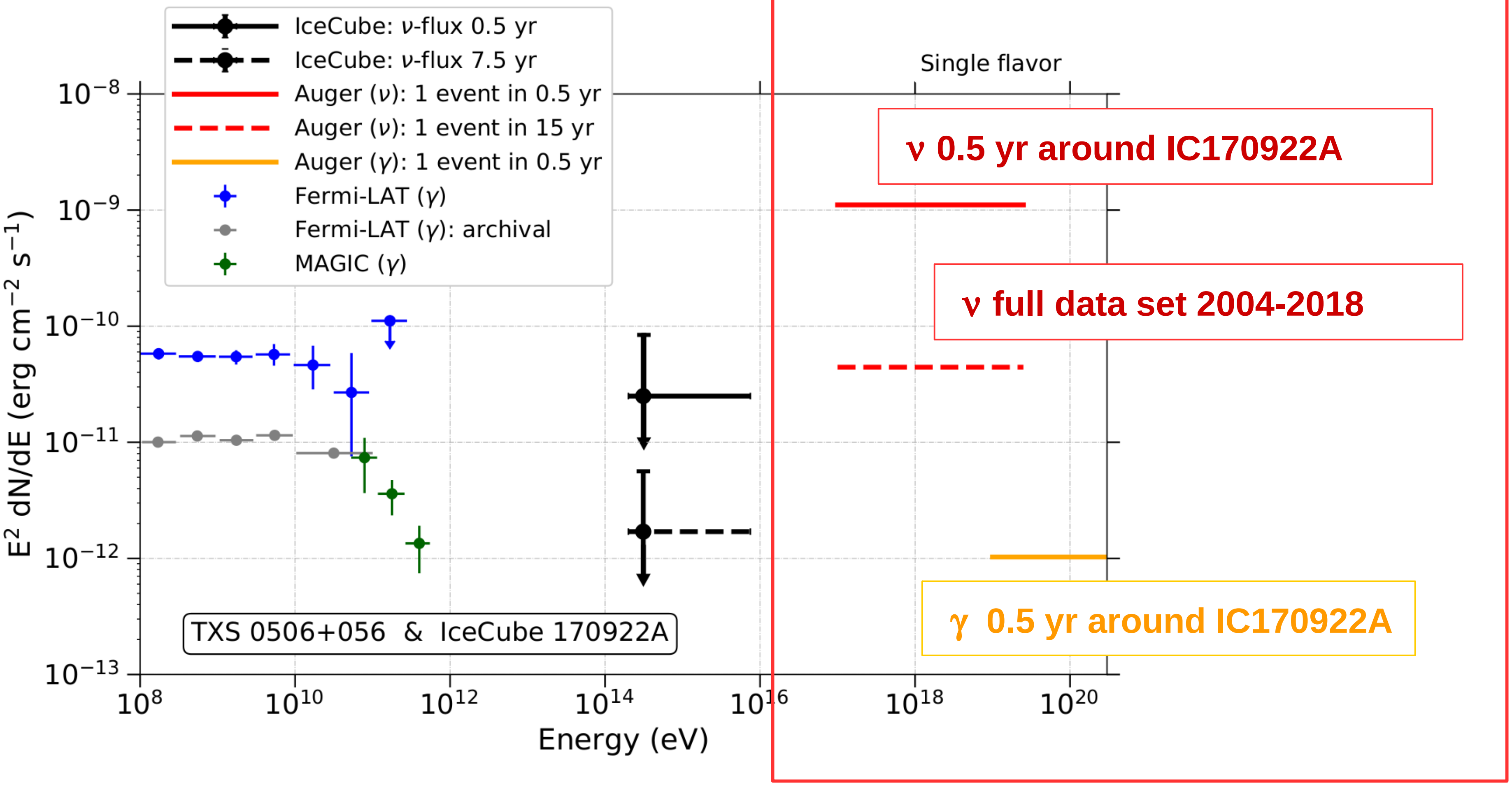
NO evidence for *nearby* photon-emitting *steady* sources in the EeV range

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

Auger TXS flux limits

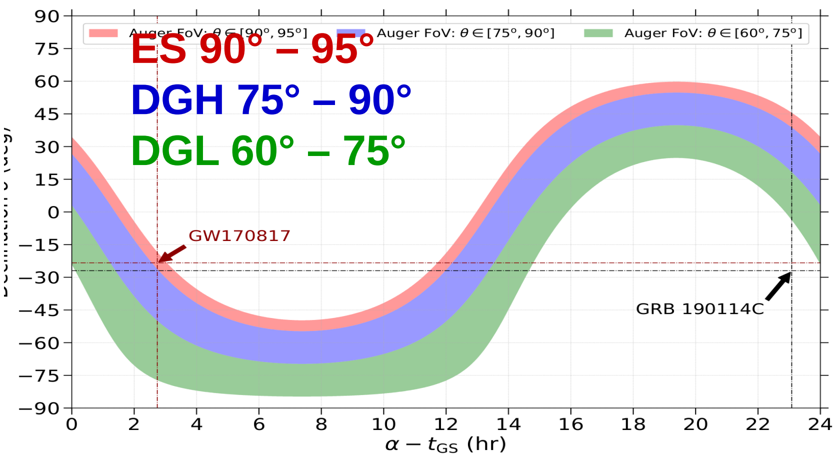
Reference flux for 1 event @ Auger

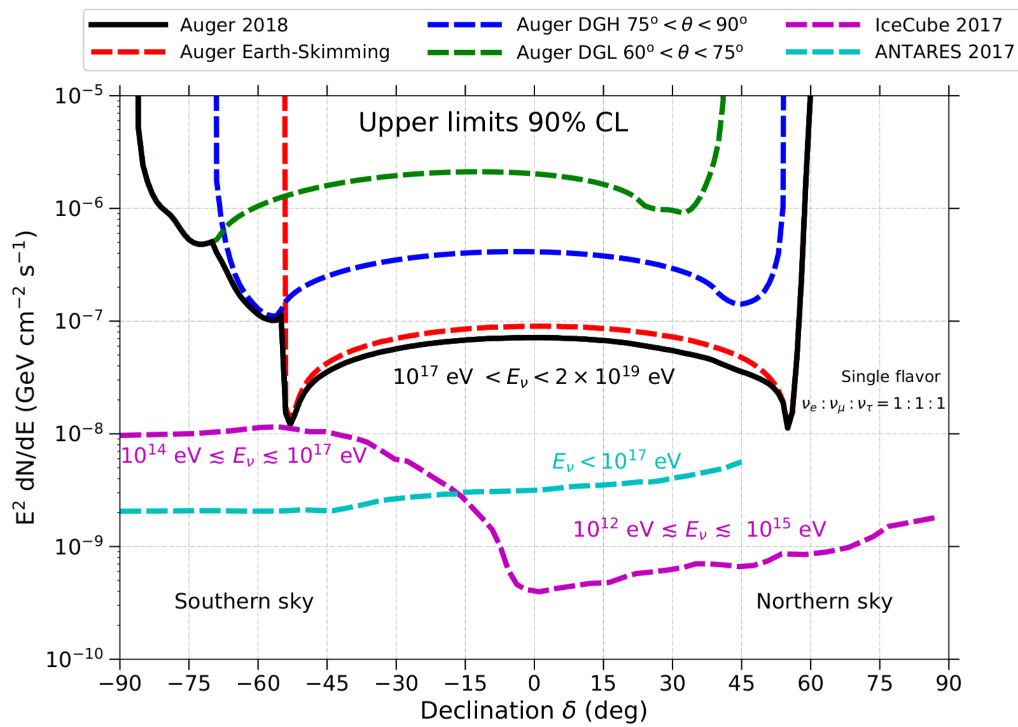
Pierre Auger Coll., Ap. J., 902:105 (2020)



UHE neutrinos: point sources sensitivity

Pierre Auger Coll., JCAP 11 (2019) 004





→ sensitivity strongly depends on source location and event timing

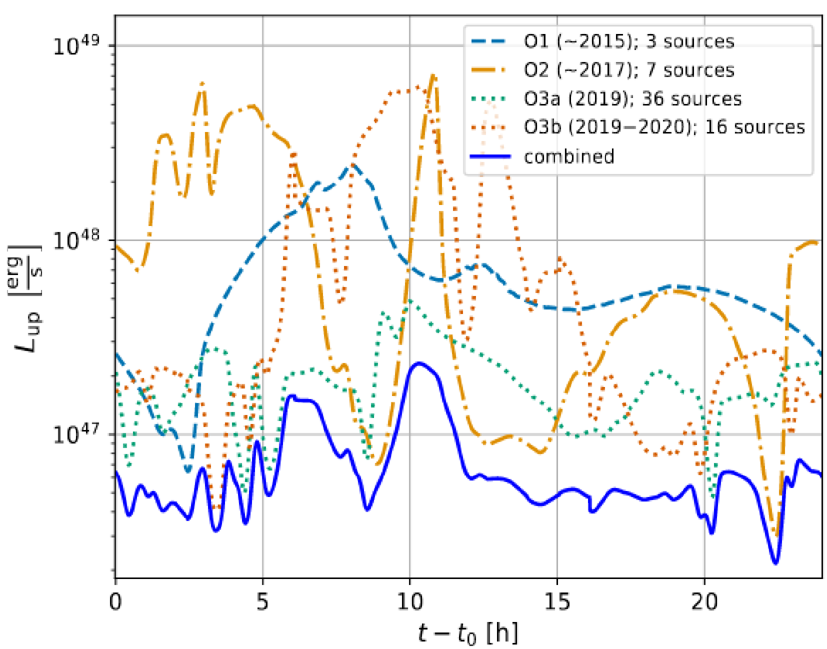
point sources transit through the field of view of each detection channel

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

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

GW follow-up (stacked): ν and γ searches

PoS(ICRC2021)968, paper in prep.



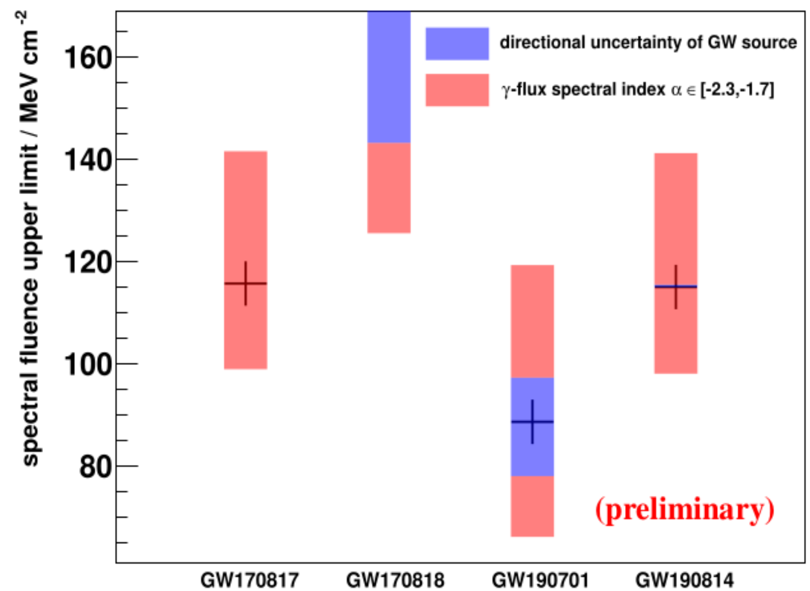
No UHE-neutrino events found for 62 GW events

upper limit on neutrino emission (1-day):

$E\nu < 6x10^{51}$ erg

→ well below the radiated GW energy

PoS(ICRC2021)973, paper in prep.



Photon Horizon ~ 10 Mpc

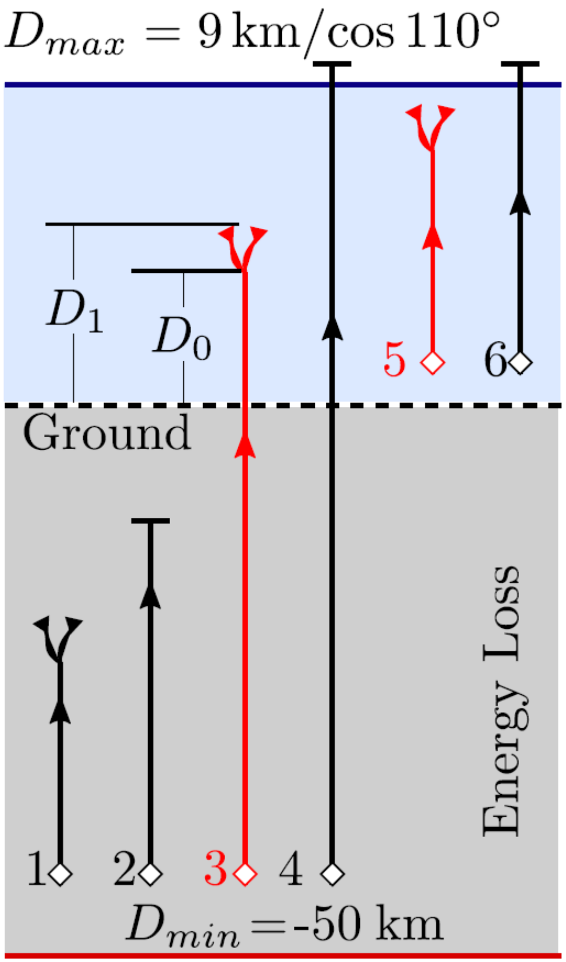
→ sources are required to be nearby and well localised

No coincident photon candidate identified

upper limits on spectral fluence (1 day)

A specific case: the tau scenario

PoS (ICRC2021) 1145



Tau propagation --> NuTauSim
J. Alvarez-Muñiz et al., Phys. Rev. D 97 (2018) 023021

Tau decay → Tauola
M. Chrzaszcz, et al. Comput. Phys. Commun. 232 (2018) 220

main decay branches considered
$e^{+/-}$, $\pi^{+/-}$, π^0, $K^{+/-}$, K^0, contributing to the formation of air showers.

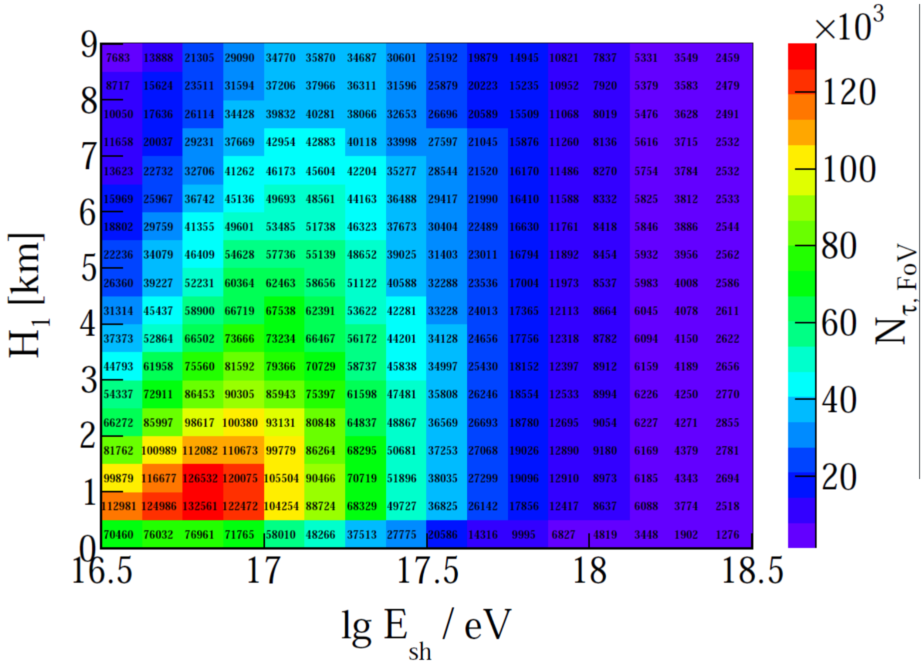
Dmin set by the tau range in standard rock

Dmax set by the FoV of the FD

Channel **3** and **5** are producing air showers within the field of view of FD

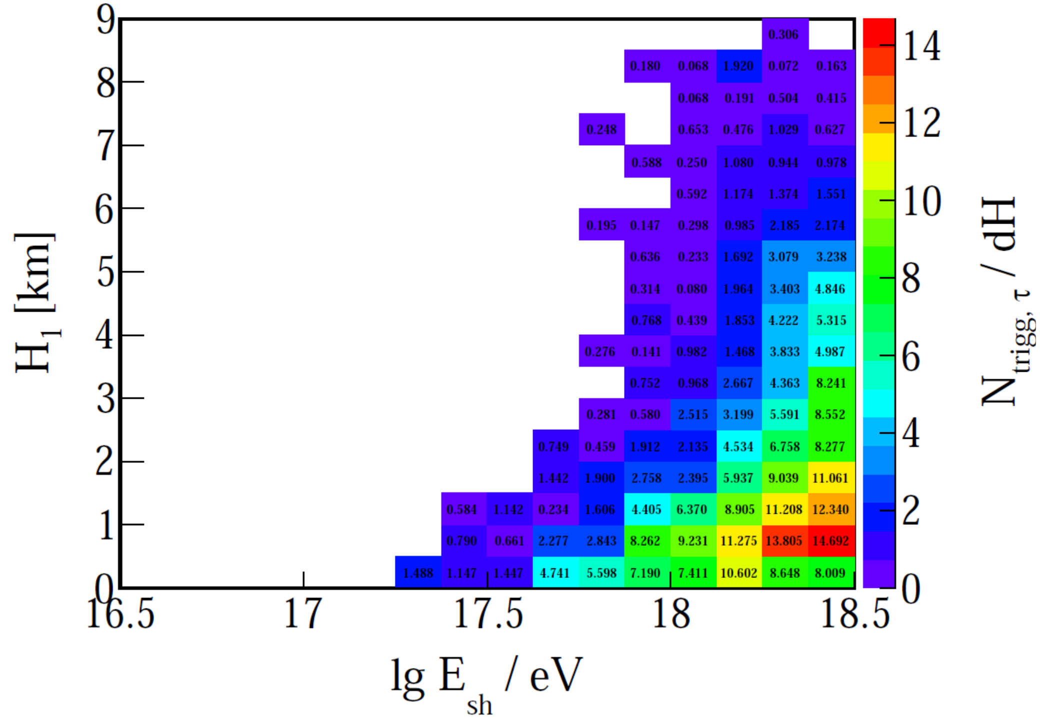
Height of first interaction H1 derived from average of the first interaction depth of each secondary, zenith and atmospheric profile

Folding the FD response with taus in FOV



⊗ FD detector acceptance for generic upwards-going EAS

Observable events

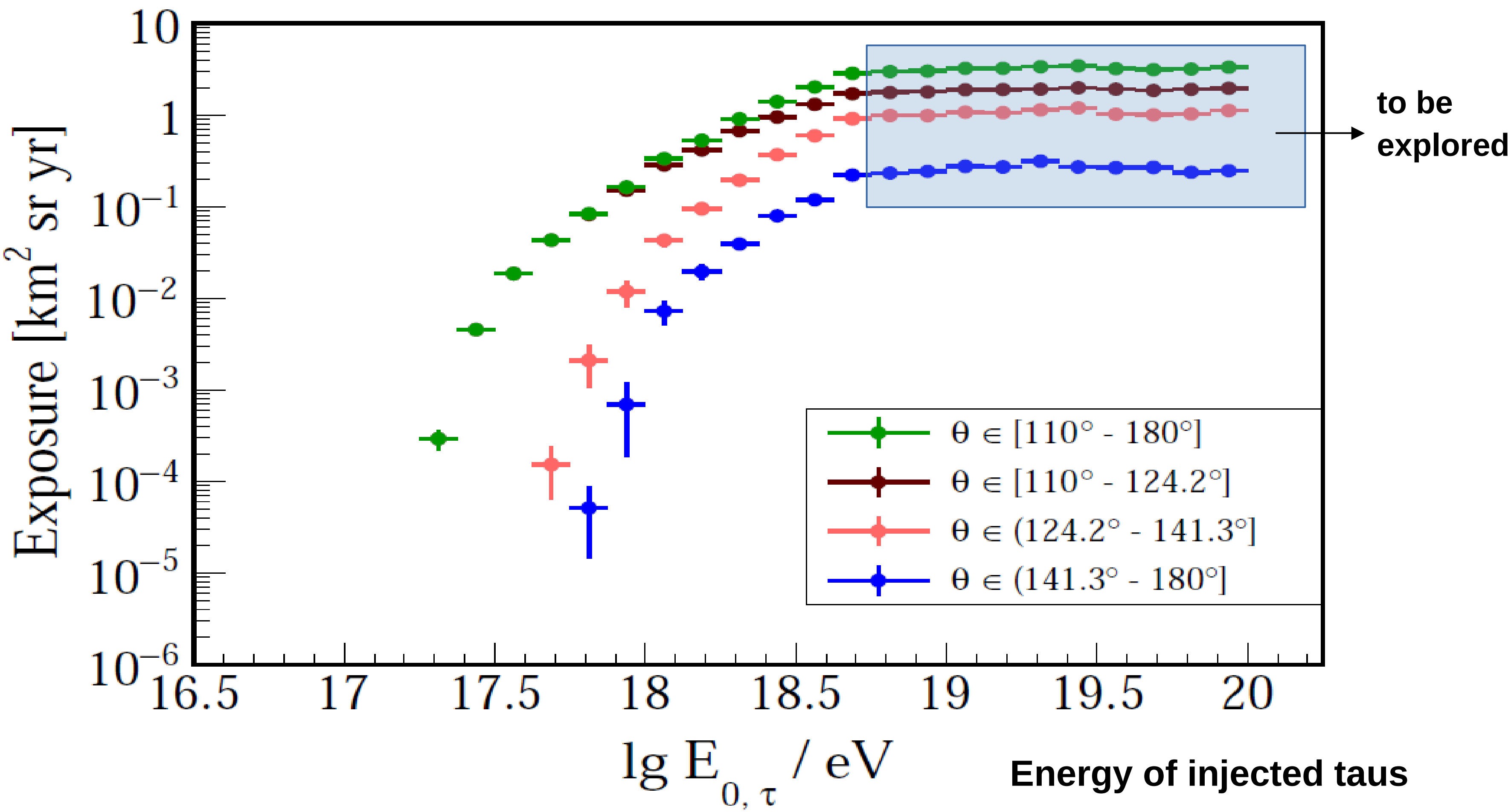


H_1 → height of first interaction

E_{sh} → energy of the induced shower

Selection criteria and energy range inherited from the generic search

Exposure for different zenith bands



lgE < 18.5 increasing detector efficiency with energy mitigated by the lengthening of tau decay length

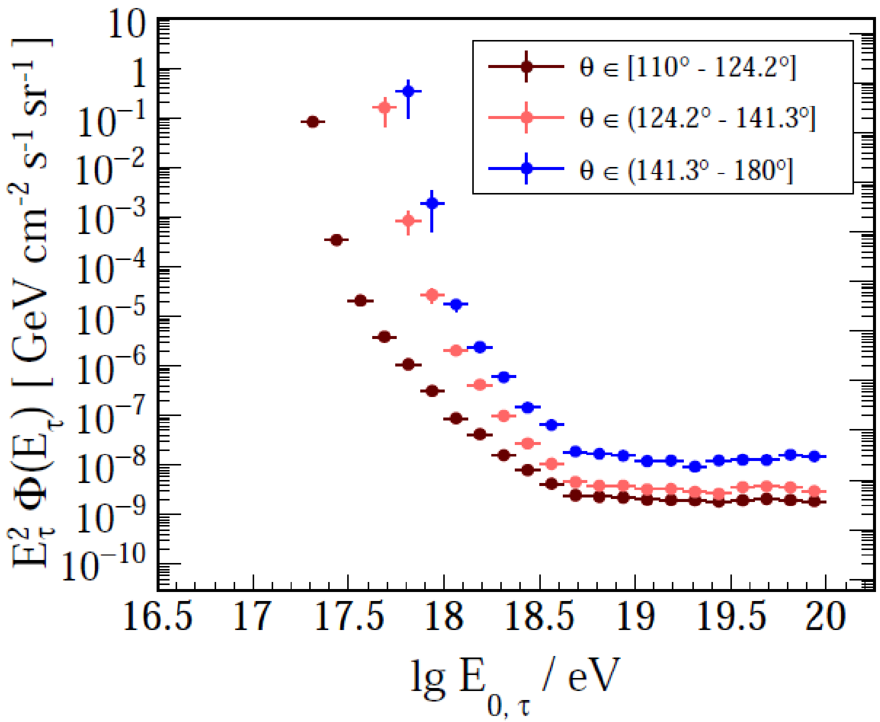
lgE > **18.5** FD response not explored yet (flattening is a reasonable assumption)

Differential upper limits

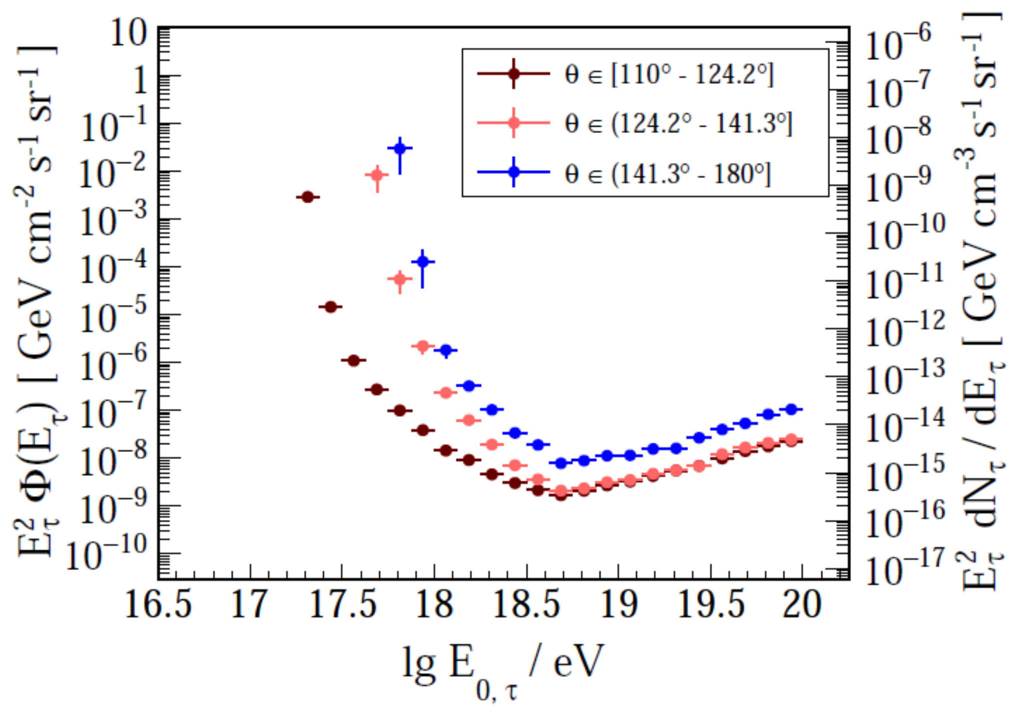
1 event observed, 0.5 expected

$$\Phi_{\tau}^{95\%}(E_0) = \frac{N_{FC}(E_0)}{\mathcal{E}_{\tau}(E_0)}$$

Two injection spectra



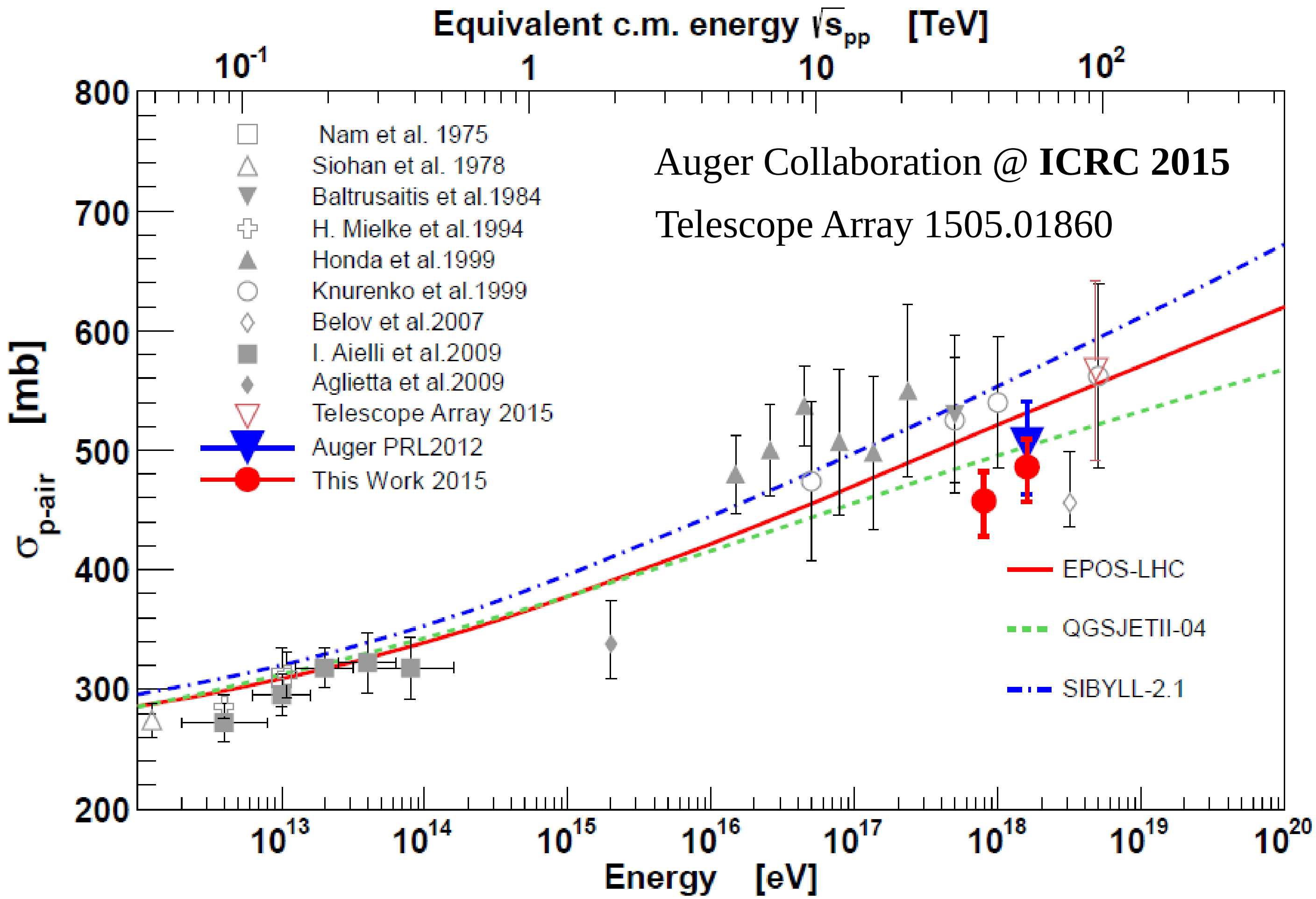
(a) $\Phi_\tau \propto E_0^{-1}$



(b) $\Phi_\tau \propto E_0^{-2}$

Better limits for inclined events

p-air cross-section

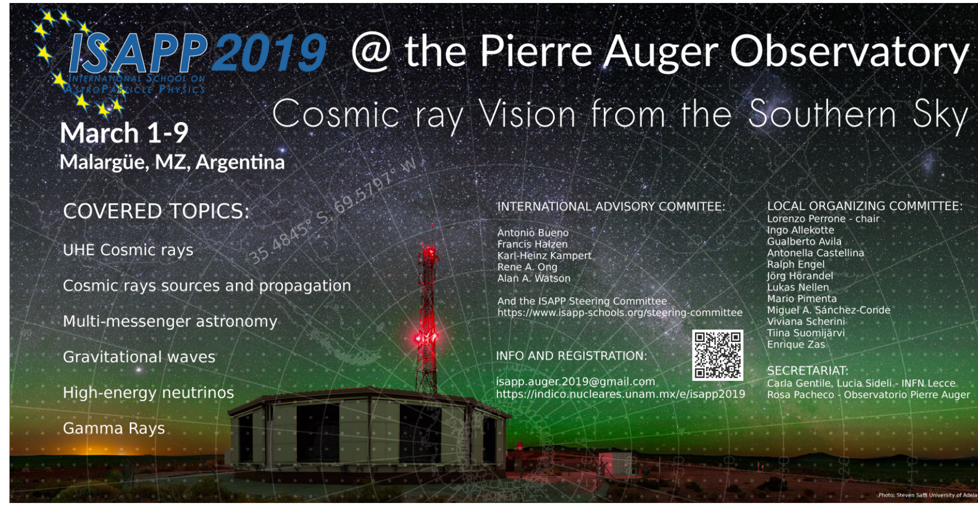


Lower energy [457±18(stat)+19/-25(syst)] mb

Higher energy [486±16(stat)+19/-25(syst)] mb

Sys uncertainty: method, models, helium contamination

Auger: education……



37 students, 16 from South America

and outreach