UHECRs at the Pierre Auger Observatory

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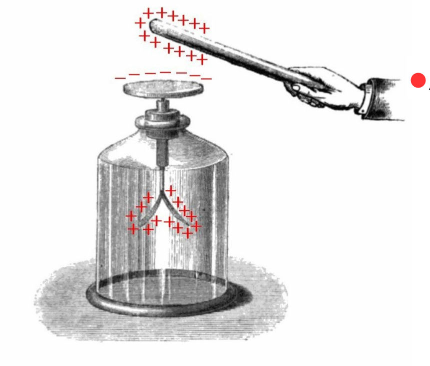
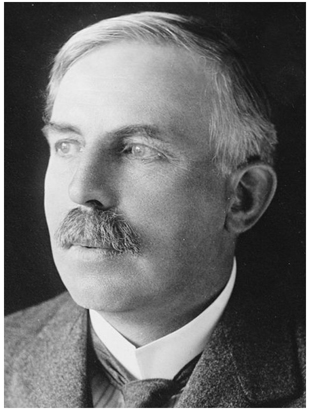
Cosmic Rays discovery in a nutshell

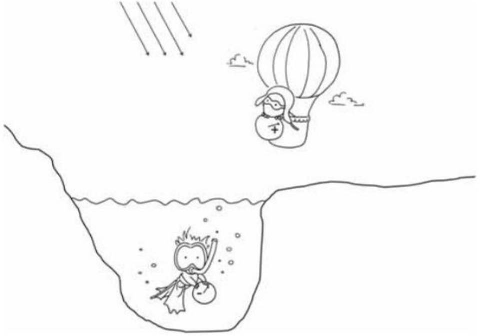


- Also before the twentieth century it was known that an isolated electroscope naturally discharges



- Ernest Rutherford proposed the natural radioactivity as responsible for the discharge
- radioactive nuclei emits alpha, beta, gamma

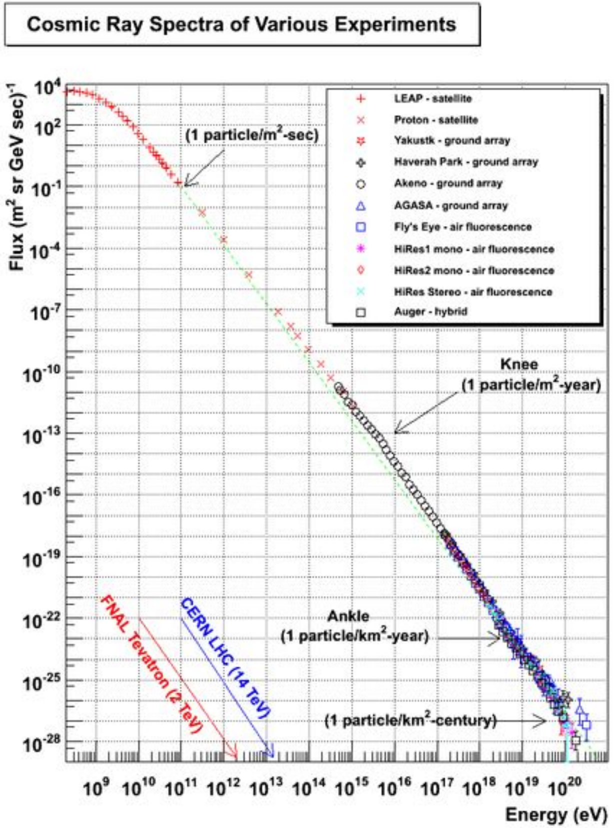
- Around 1910 independently Domenico Pacini and Victor Hess proved tha the radiation was coming from space



- 1930 Bruno Rossi suggests a n East-West effect if CRs are charged particles
- 1933-34: three independent experiments (Alvarez & Compton, Johnson, Rossi) find that the intensity of CRs is greater from the West than from the East

CR are positively charged particles!

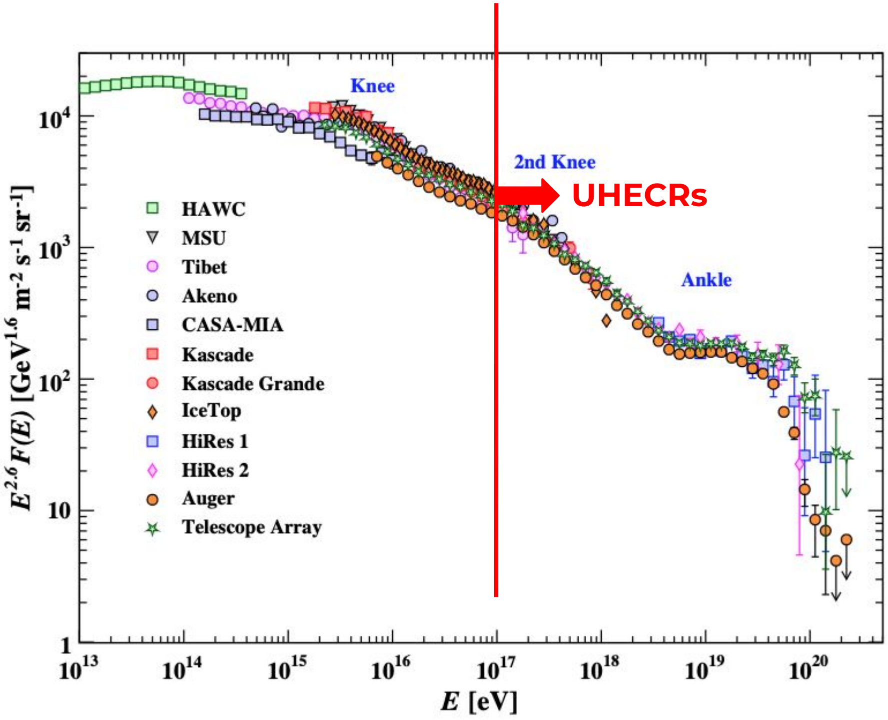
Cosmic Rays discovery in a nutshell



- CR spectrum spans over 10 order of magnitudes in energy and 30 in intensity
- The spectrum follow a power law with negative spectral index
- As the flux decrease direct measurements in space are not possible and huge arrays on Earth are necessary
- A sharp end of the spectrum is expected at extreme energies (propagation/source)

The Strange Science Case of the Ultra High Energy Cosmic Rays

Particles with E = 10^{17}-10^{20} eV , √s = 14-450 Tev



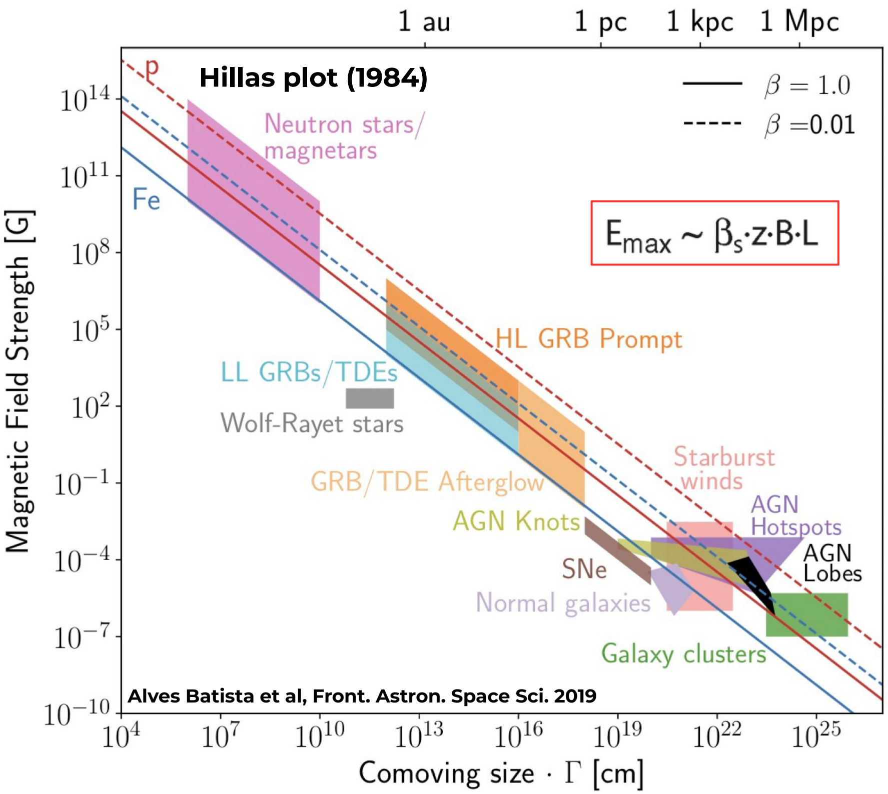
ASTROPHYSICS

- What is the nature and origin of UHECRs?
- What is causing the suppression of the flux at the highest energies?
- Which are the sources? can we perform UHECRs astronomy?
- How are UHECRs accelerated to such extreme energies?

FUNDAMENTAL PHYSICS

- Tests of fundamental interactions and their models in extreme energy regimes
- Constrain or find hints of new phenomena (e.g. Lorentz invariance violation)

How are UHECR produced?



With LHC technology need accelerator of size of Mercury's orbit to reach 10^{20}eV

<u>Realistic constraints more severe</u>

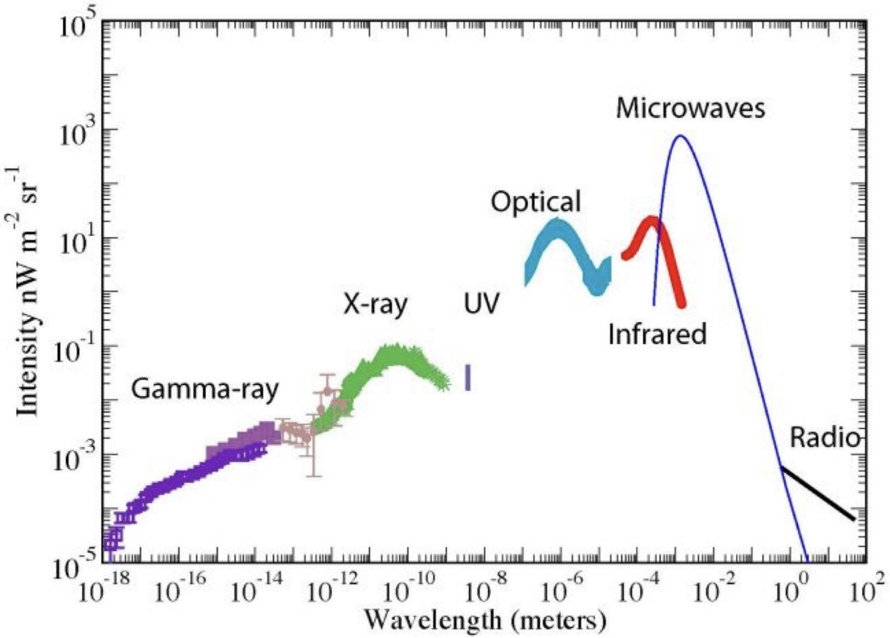
- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

How they reach Earth? (Astrophysics)

For the energies of the UHECRs, relevant photon fields are:

- Cosmic Microwave Background (CMB) : relic radiation from the Big Bang; black body at temperature 2.7 K
- UV-optical-IR (Extragalactic Background Light, EBL)
  - UV, optical and near IR is due to direct starlight
  - From mid IR to submm wavelengths, EBL consists of re-emitted light from dust particles
- Dependence on redshift to be considered
- Energy scale:

$$\varepsilon' = \varepsilon\Gamma(1 - \cos\theta)$$

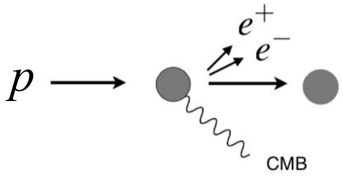


How they reach Earth? (Nuclear Physics)

Pair production on CMB

$$\varepsilon' > 1\,\mathrm{MeV}$$

$$p + \gamma \rightarrow p + e^+ + e^-$$



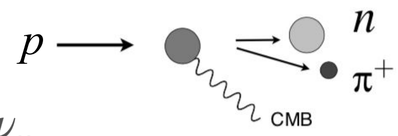
Pion production on CMB

$$\varepsilon' > 150\,\mathrm{MeV}$$

$$p + \gamma \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



$$p + \gamma \rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

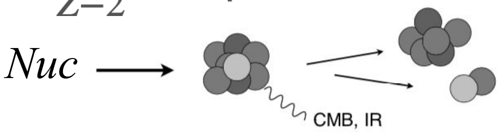
Disintegration

$$\varepsilon' > 8\,\mathrm{MeV}$$

$${}^A_Z X + \gamma \rightarrow {}^{A-1}_{Z-1} X' + p$$

$${}^A_Z X + \gamma \rightarrow {}^{A-1}_{Z} X' + n$$

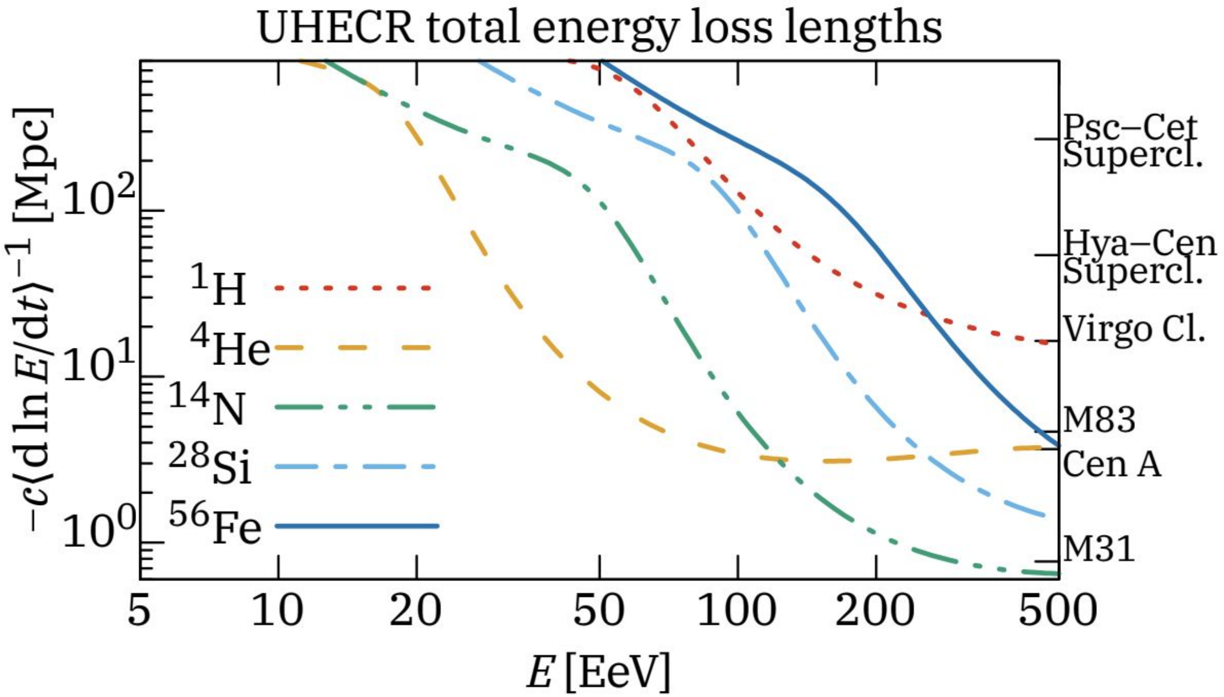
$${}^A_Z X + \gamma \rightarrow {}^{A-2}_{Z-2} X'' + \alpha$$



cosmogenic neutrinos

cosmogenic gammas

How they reach Earth?

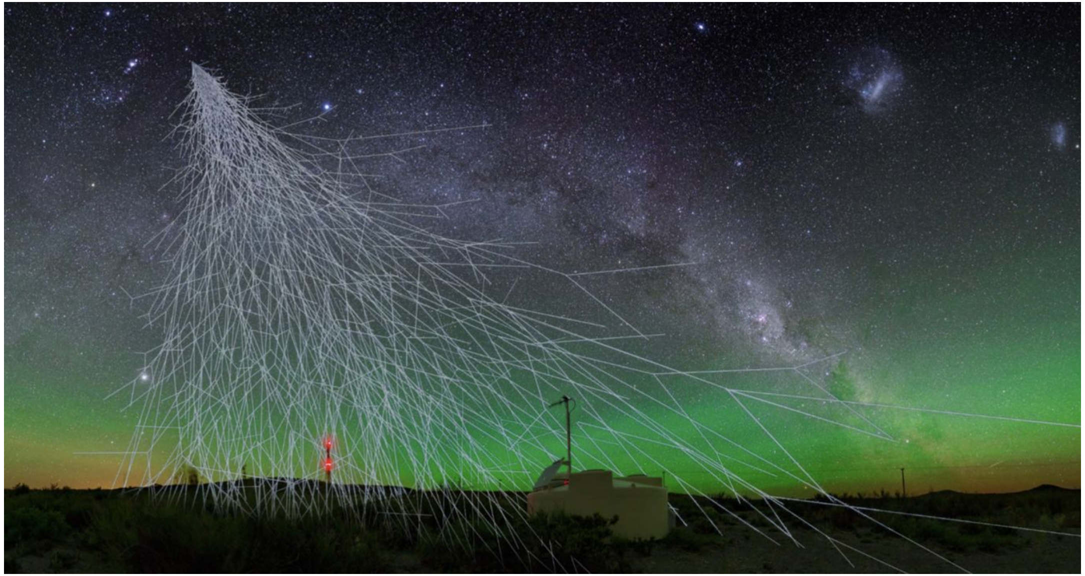


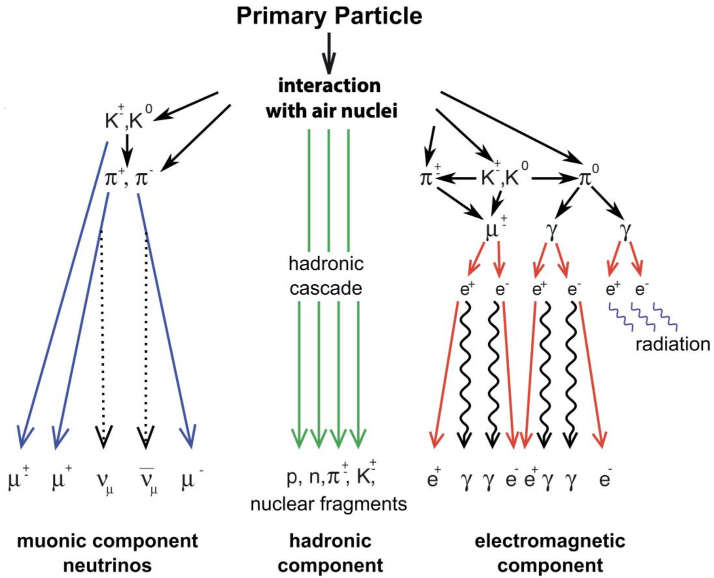
- NO He >50 EeV, CNO > 100 EeV expected
- Extreme-E CRs can only be: local, &/or protons, &/or heavy nuclei
- source or propagation scenario?

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

How to measure UHECRs?

- Due to the low flux of UHECRs (1 particle per km^2 yr^{-1} above 10^{19} eV) we need huge instrumented areas for detection
- UHE particles interacting with atmosphere (mainly N and O) initiate a cascade of ionised particles and electromagnetic radiation i.e extensive air shower (EAS)
- 3 components: muonic, hadronic, electromagnetic





How to measure primary mass?

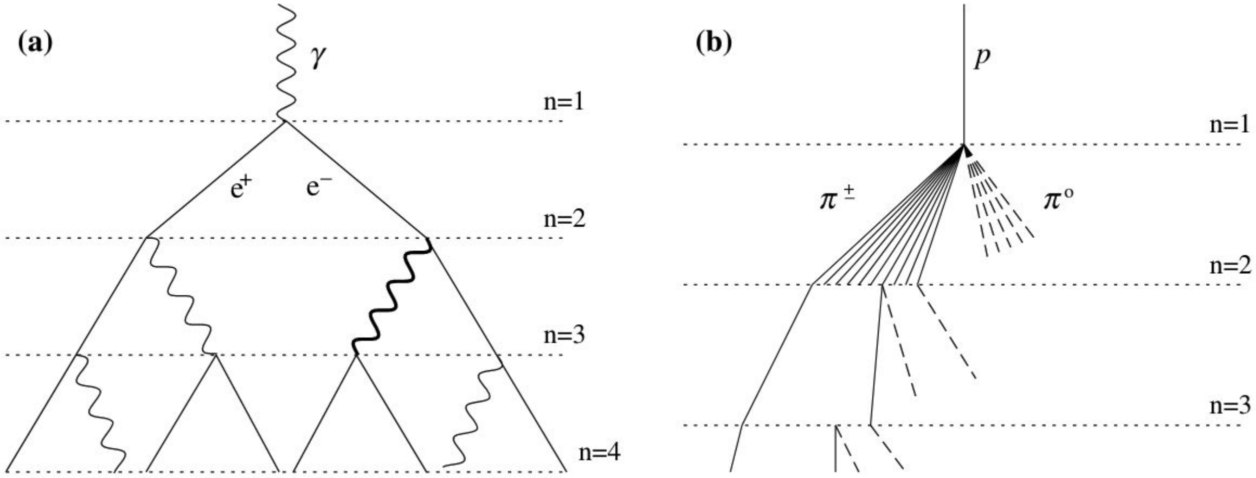
Heitler-Matthews model

$$N(X) = 2^{X/\lambda}$$

$$E(X) = \frac{E_0}{N(X)}$$

$$N(X_{max}) = \frac{E_0}{E_c}$$

$$X_{max} \propto \ln(E_0/E_c)$$

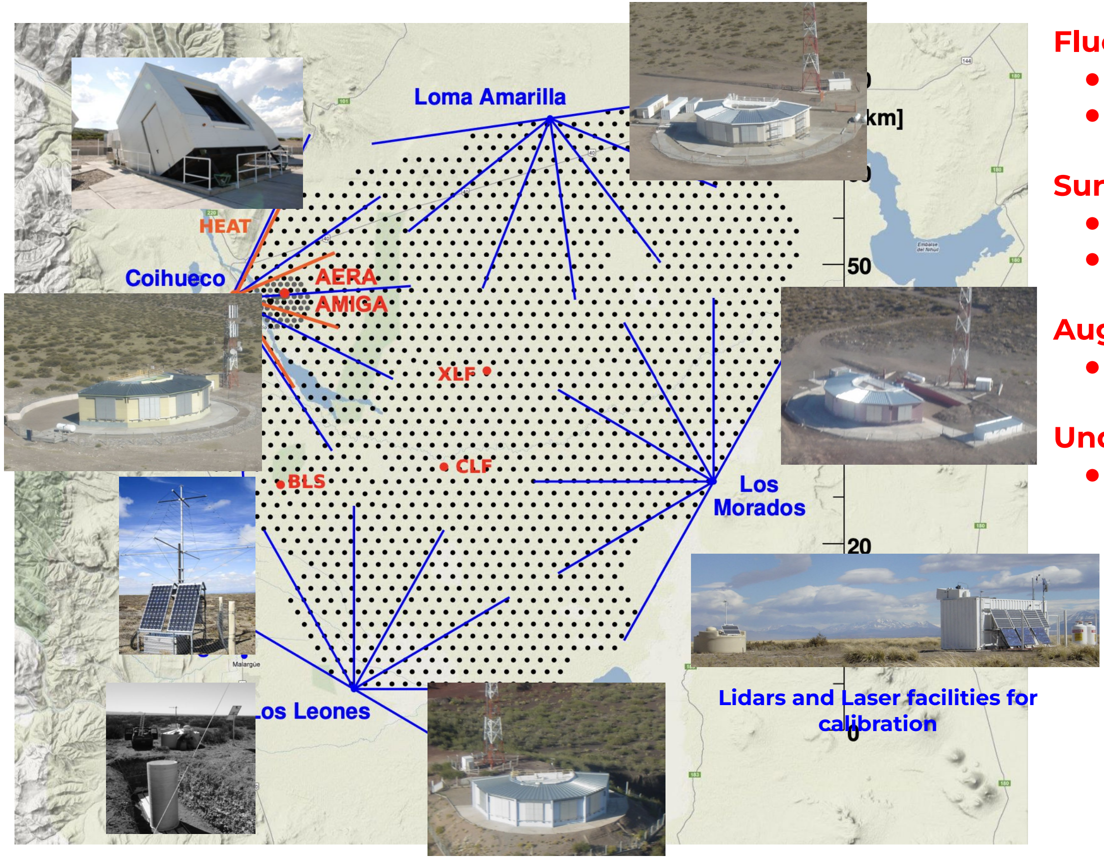


J. Matthews, Astroparticle Physics 22 (2005) 387–397

Using a pure superposition model: $^{A}X, E_0 \leftrightarrow A \times n, E_0/A$

$$X^A_{max} \propto X_{max}(E_0/A)$$

The Pierre Auger Observatory



Fluorescence detector (FD)

- 24 telescopes in 4 sites, FoV: 0-30º, E>10^{18} eV
- HEAT (3 telescopes), FoV: 30 - 60º, E>10^{17} eV

Surface detector (SD)

- 1660 stations in 1.5 km grid, 3000 km^2 E > $10^{18.5}$ eV
- 61 stations in 0.75 km grid, 23.5 km^2,E > $10^{17.5}$ eV

Auger Engineering Radio Array (AERA)

- 153 antennas in 17 km2 array

Underground muon detector

- 17 buried scintillators

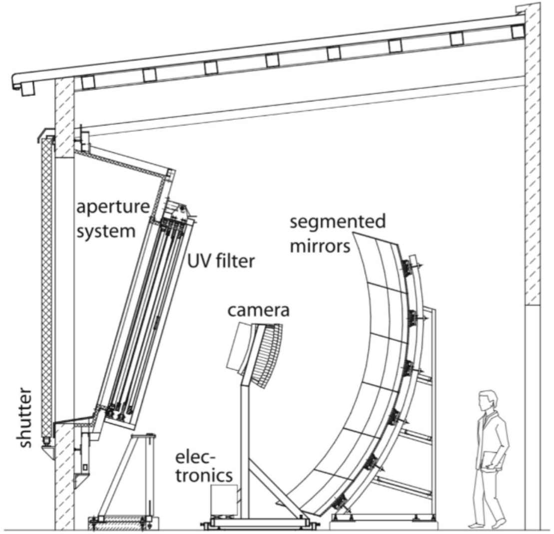
Auger Phase I data taking from 2004 on (from 2008 with the full array):

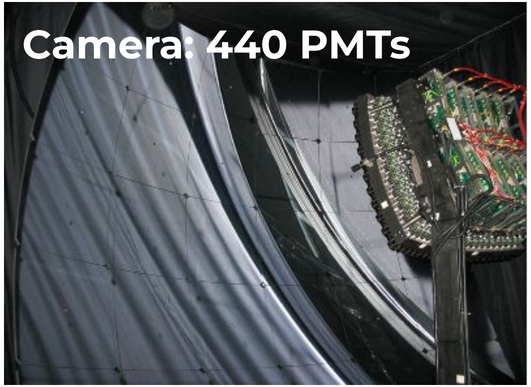
- > 120.000 km^2sr yr for anisotropy
- > 90.000 km^2sr yr for spectrum

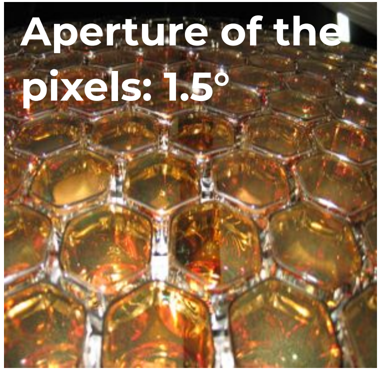
Auger Phase II data taking from 2023 to 2030...

- Multiple detectors
- UHECR detector test bench facility

Fluorescence Detectors

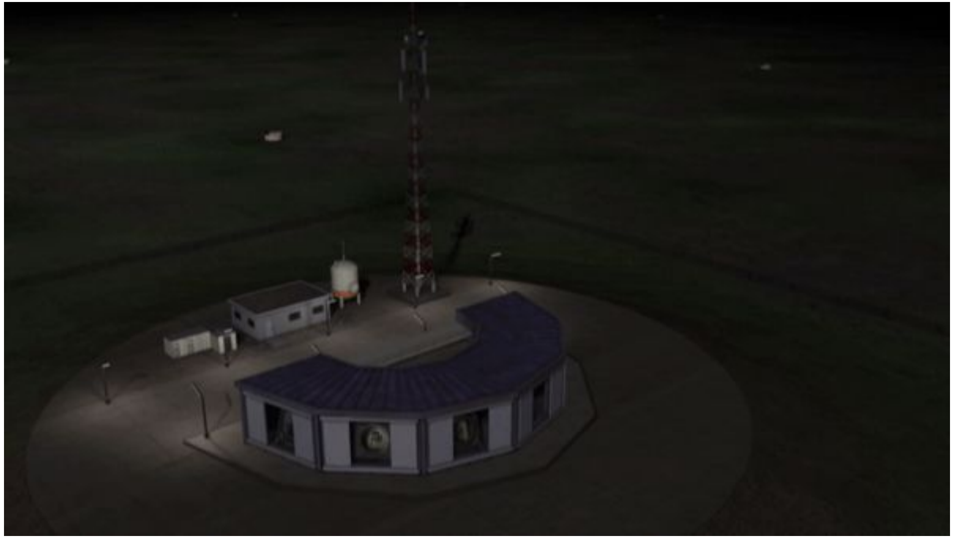


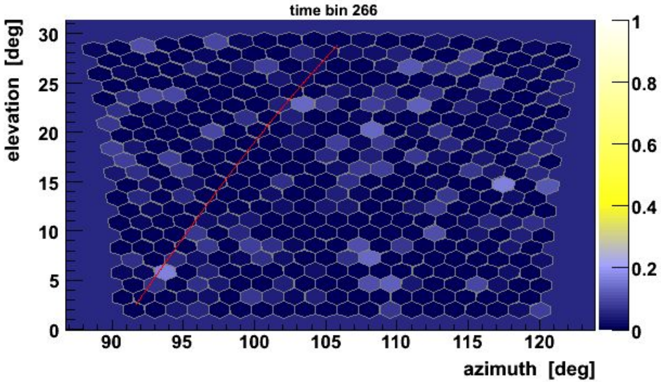




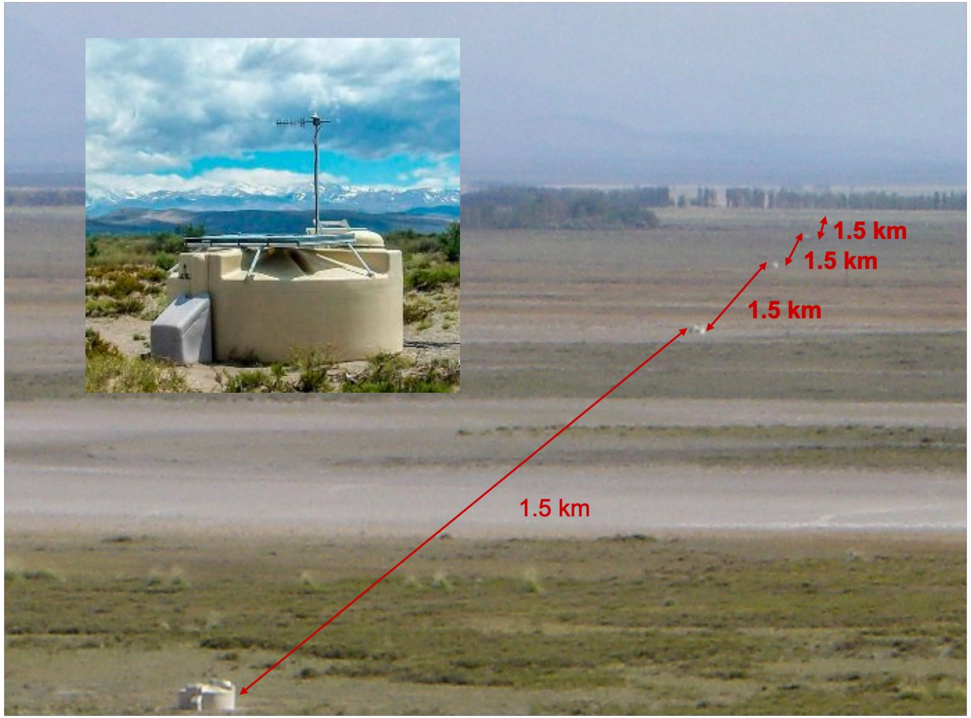
- FD measures the fluorescence light produced by the excitation of nitrogen in the atmosphere by the EAS particles
- 30° fov in elevation and azimuth for each telescope
- ~14% duty cycle (data taking during moonless clear nights)

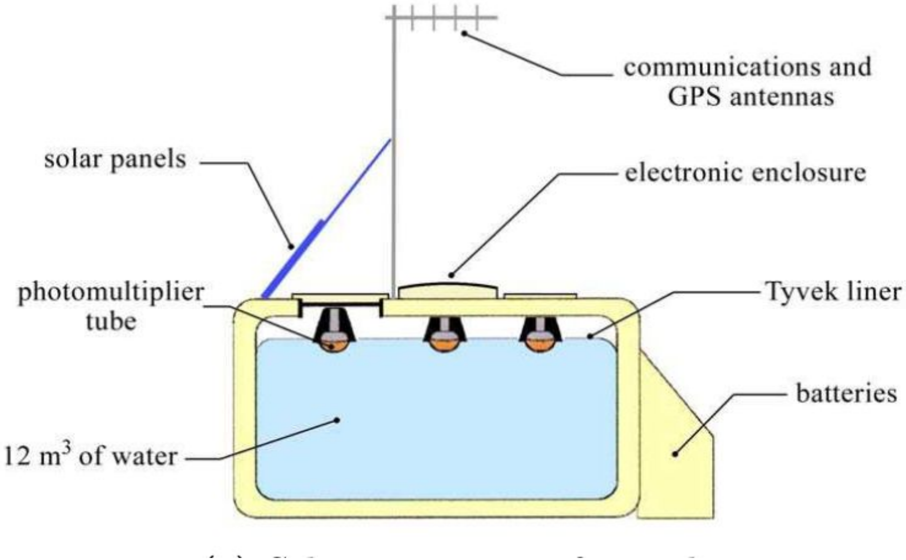
Fluorescence Detectors





Surface detectors

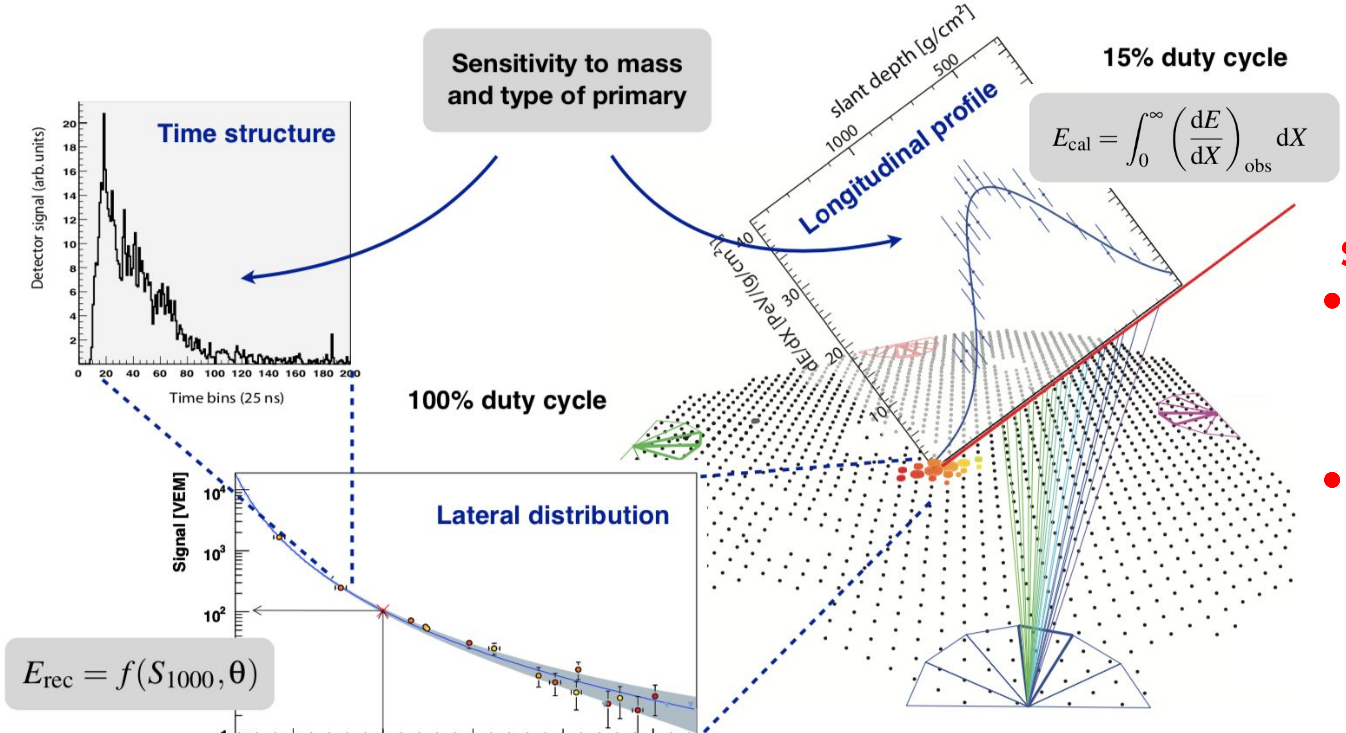




- SD measure the Cherenkov light produced in water by EAS particles at ground
- ~100% duty cycle

Surface detectors

The hybrid concept



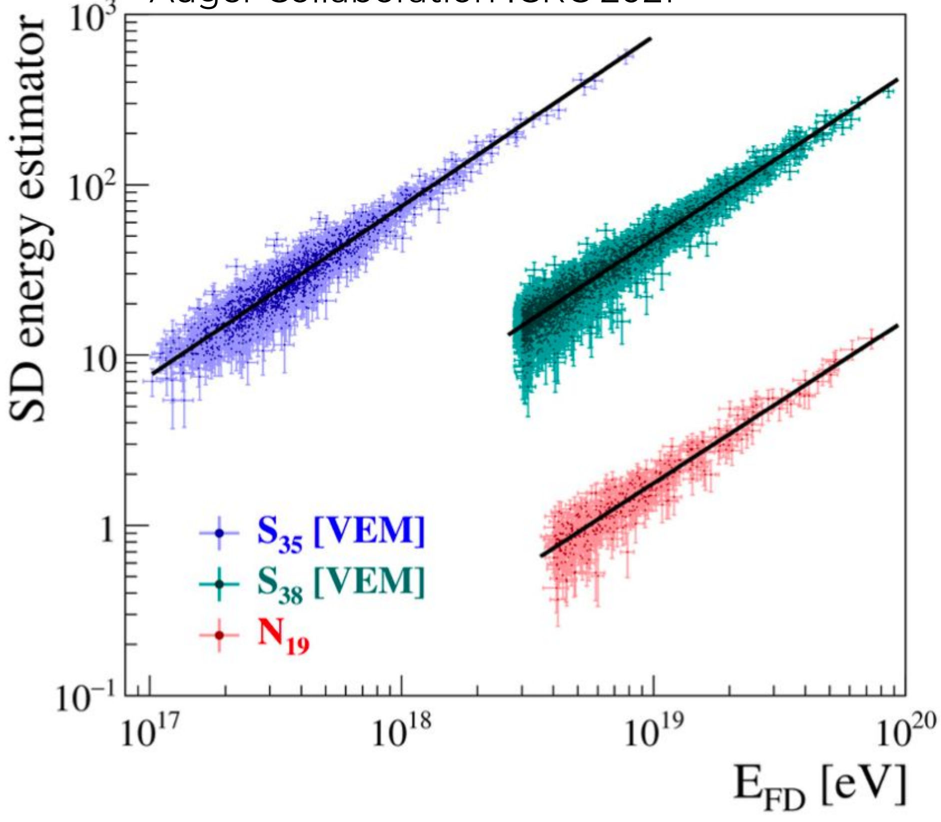
Example: event observed with Auger Observatory

STRATEGY

- Measure the same air showers with 2 independent detectors (golden hybrid events)
- use golden hybrids to calibrate the entire SD data sample

Calibration with FD energy scale

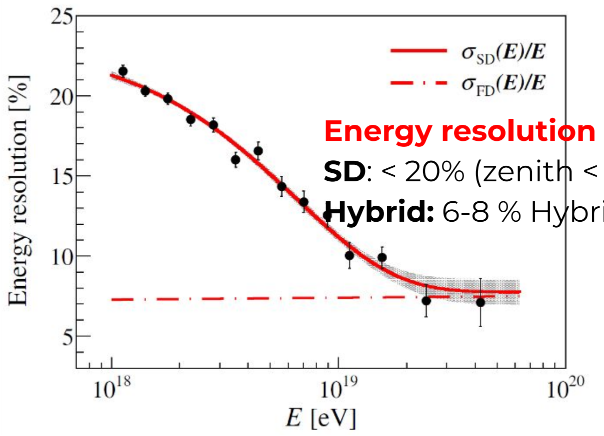
Auger Collaboration ICRC 2021



Energy scale uncertainty

ICRC 2013

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%

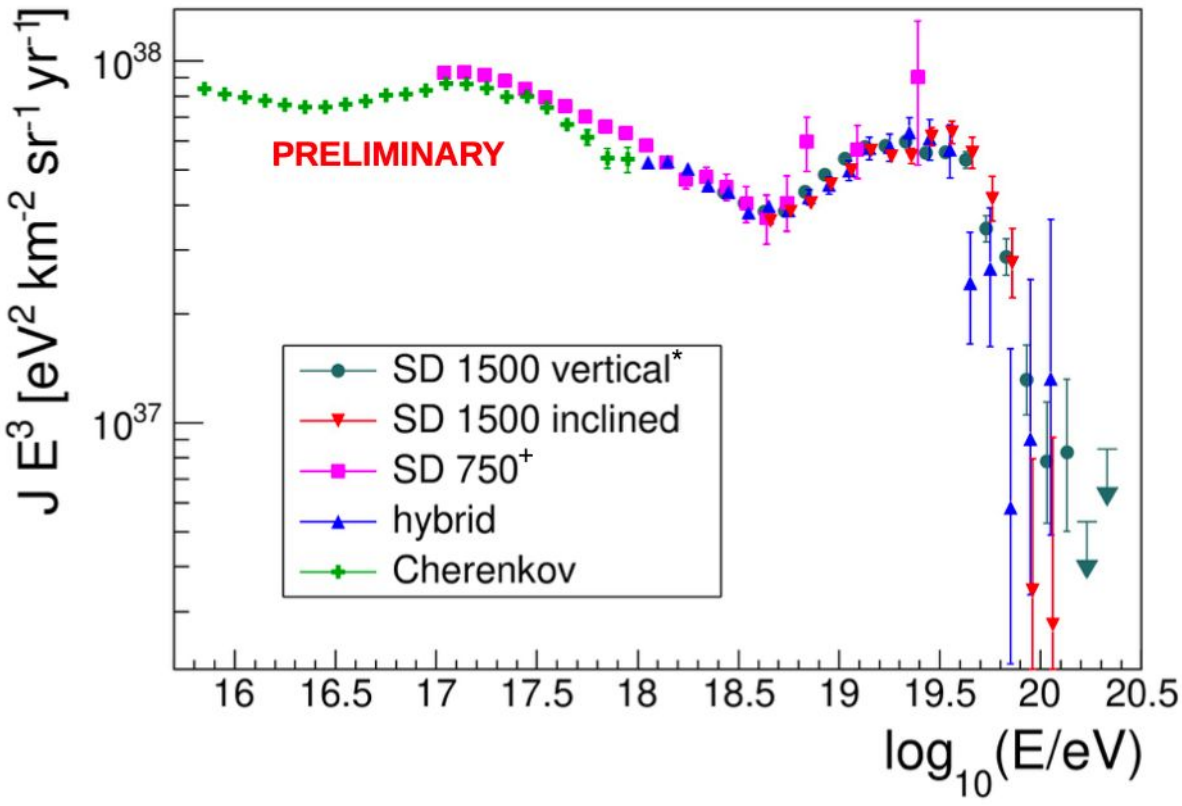


Energy resolution

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

Hybrid: 6-8 % Hybrid [ICRC 2019]

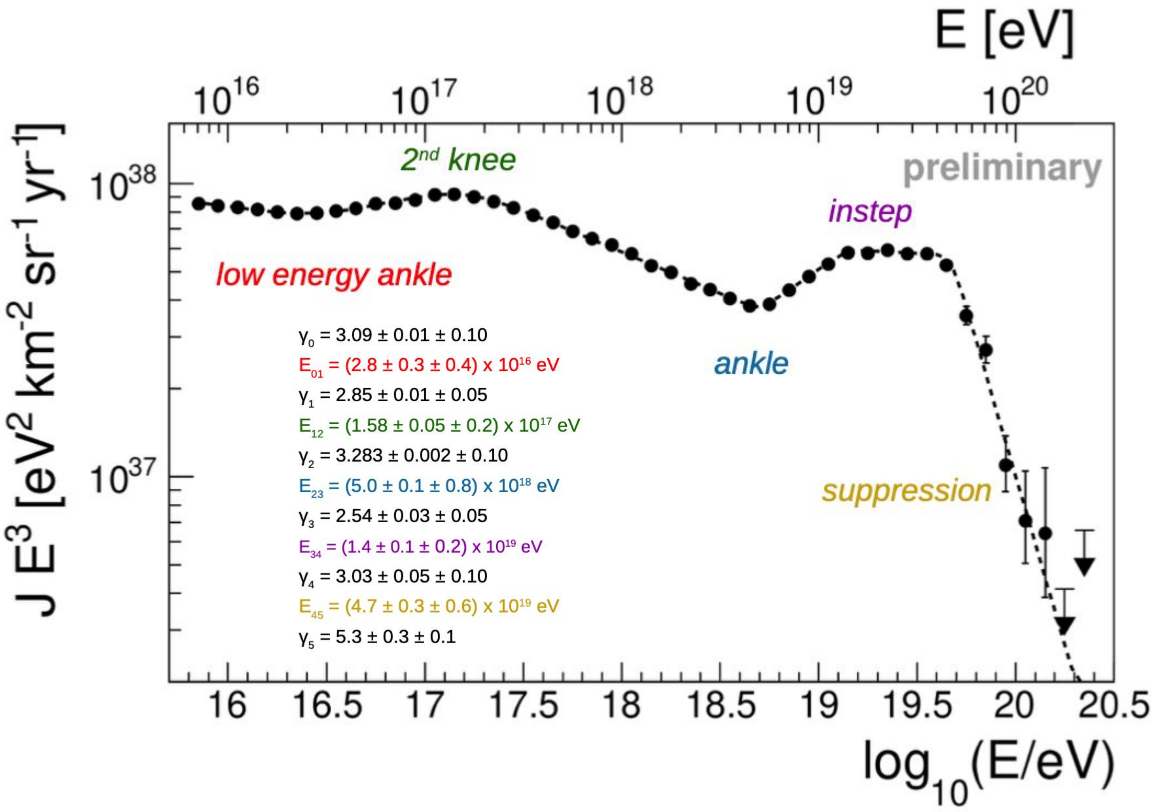
The Auger energy spectrum



SD Data sample:
215030 events 1/1/2004 – 31/8/2018
Exposure: 60400 km^2 sr

- Five measurements
- more than 3 order of magnitudes
- same energy scale
- Fluxes in agreement within systematic uncertainties (1%-7%)

The energy spectrum



2nd knee observed

- different models: more than one Galactic component? (H4a, GST)
- is the 2nd knee the iron one? (rigidity dependent cut-off)

ankle at ~ 5 10^{18} eV confirmed

- dip model
- mixed models: superposition of heavier nuclei

Suppression at ~ 5 10^{19} eV confirmed

light composition (p + <10% heavier)

- soft injection spectrum (slope ~ 2)
- production of cosmogenic ν

mixed composition

- hard injection spectrum (slope ~ 1)
- cosmogenic ν and γ suppressed

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

hint for low energy ankle at ~ 10^{17} eV

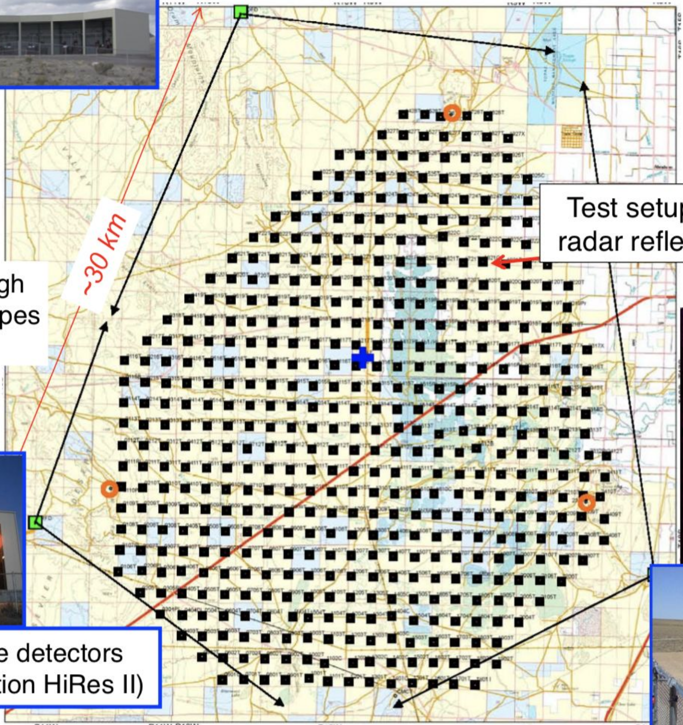
Telescope Array (TA)

Middle Drum: based on HiRes II

TALE (TA low energy extension)

LIDAR
Laser facility

Infill array and high
elevation telescopes



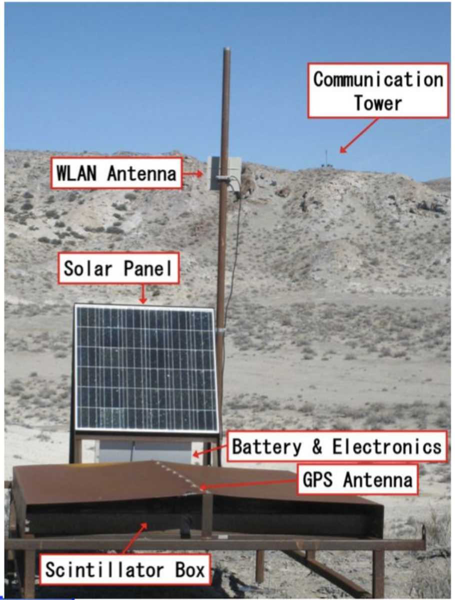
Test setup for
radar reflection

3 fluorescence detectors
(2 new, one station HiRes II)

Northern hemisphere: Utah, USA

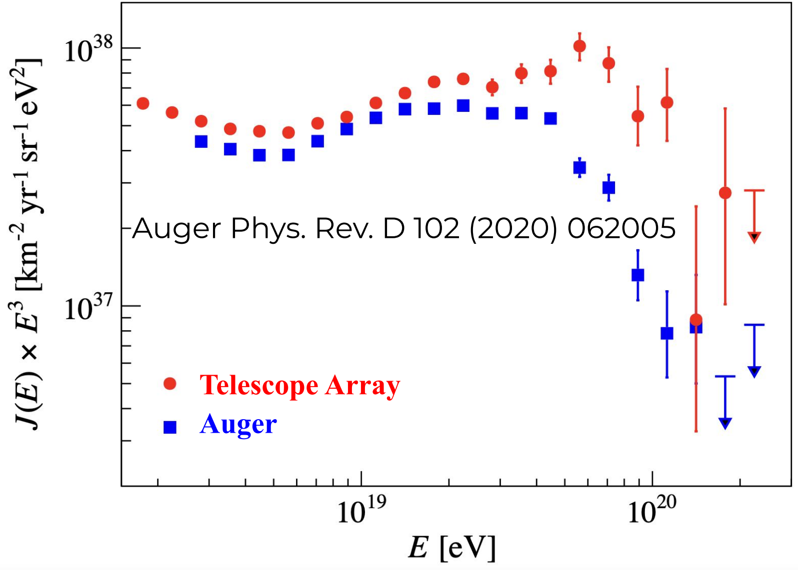
Detector Upgrade in progress , see next slides

Electron light
source (ELS):
~40 MeV

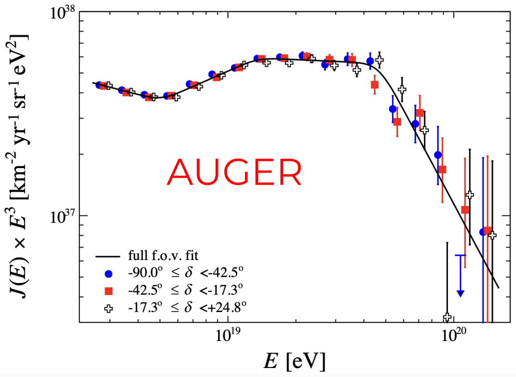


507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

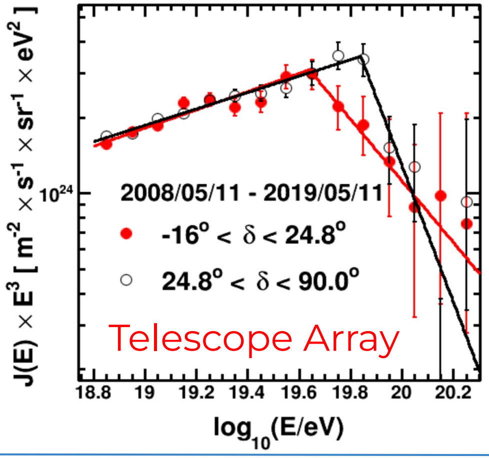
The energy spectrum in Auger and TA



DECLINATION DEPENDENCE



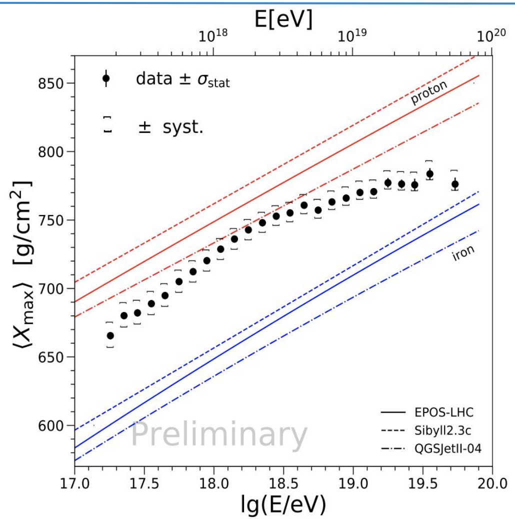
Auger: Only a trend for a slightly larger intensity in the South: consistent with dipole at E > 8 EeV

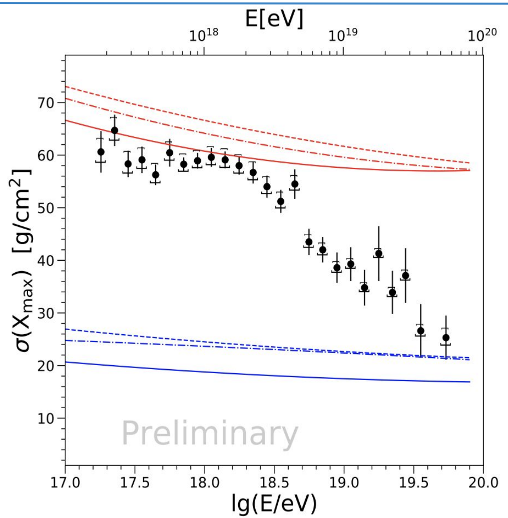


TA: Differences in the suppression energy, with an excess of intensity in the Northernmost sky

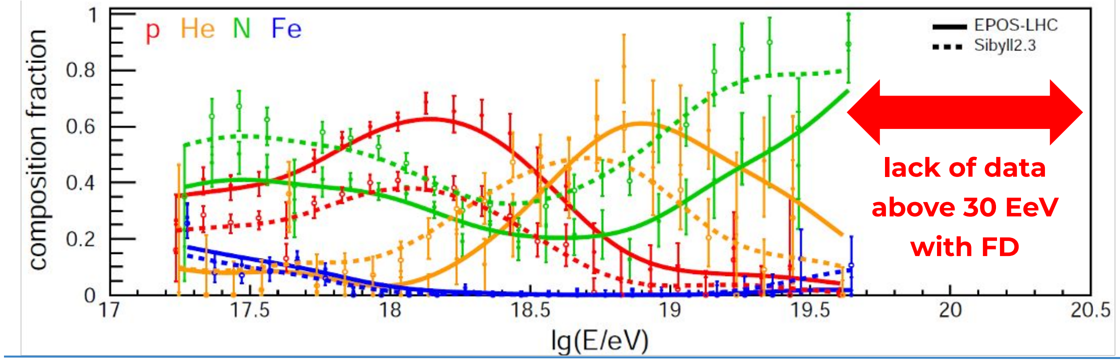
- Energy scale: different fluorescence yield and invisible energy models
- σ_{syst} on the two energy scales : **14% for Auger** and **21% for TA**
- **γ**0: is in agreement!
- 2nd knee position: within 1.8σ
- **γ**1: within 2.1σ
- general agreement rescaling the energies by **+5.2% for Auger** and **−5.2% for TA**

Mass composition





- change of slope of X_{max} and decrease of $\sigma(X_{max})$ across the ankle
- X_{max} and $\sigma(X_{max})$ indicate lighter composition up to ~2 EeV, heavier above this energy
- At higher energies, consistent with less mixed composition
- the uncertainties in the models are currently the main source of systematics

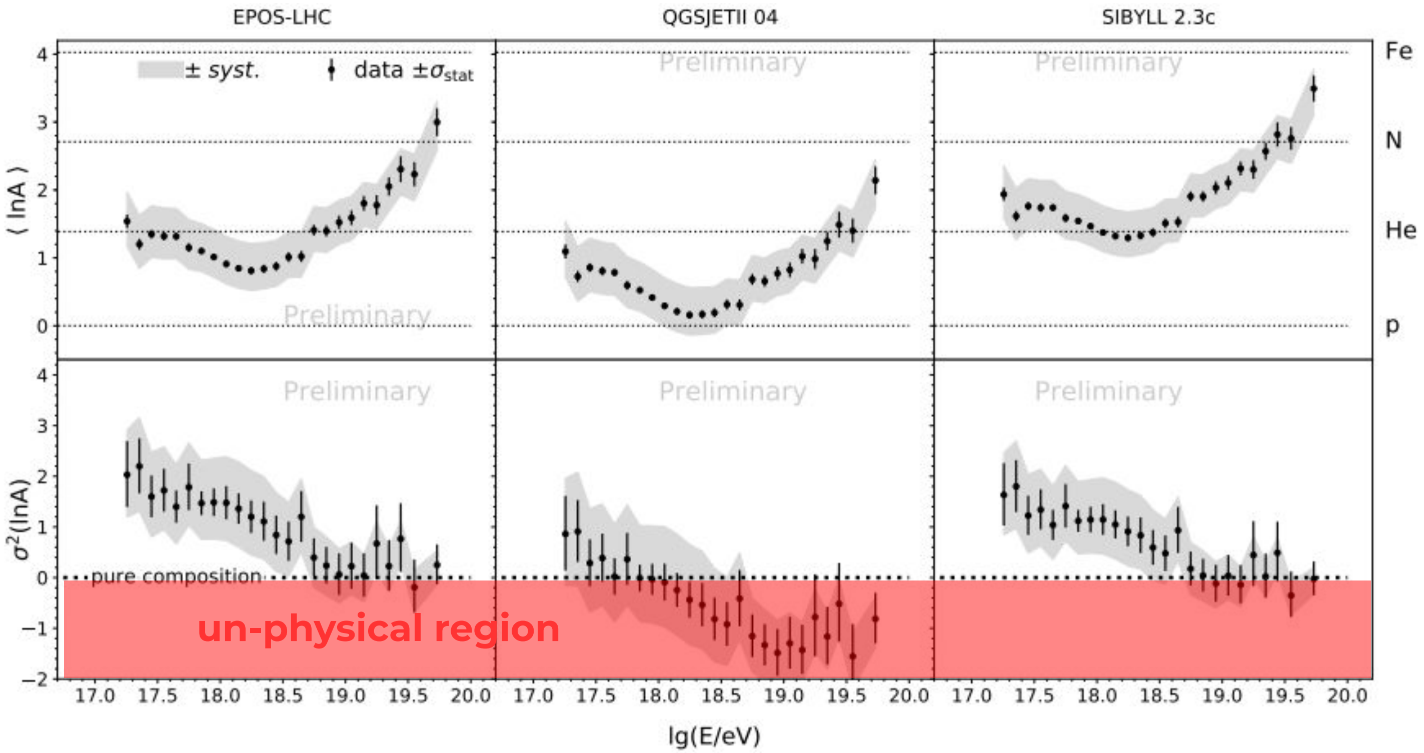


Mass fractions at Earth from fitting 4 mass groups to the measured X_{max} distributions

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

<lnA> and variance

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

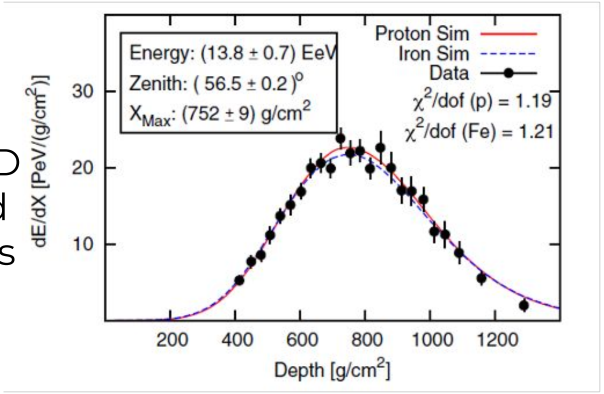


Auger Prime and NN approach will provide additional info on mass composition

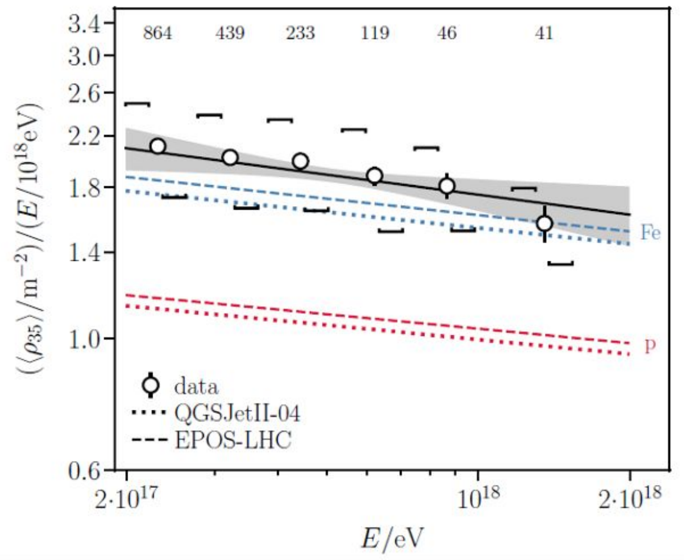
Hadronic interactions models

How well hadronic models reproduce Auger data?

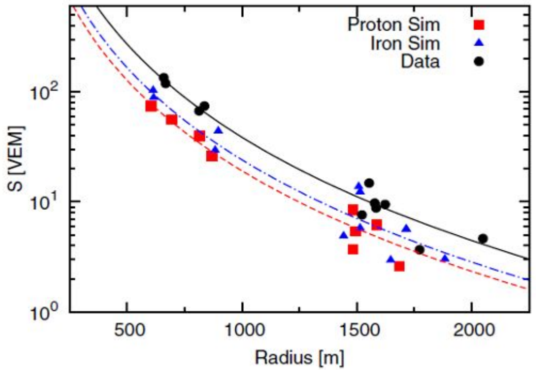
Observed longitudinal profile from FD is reproduced by simulations



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



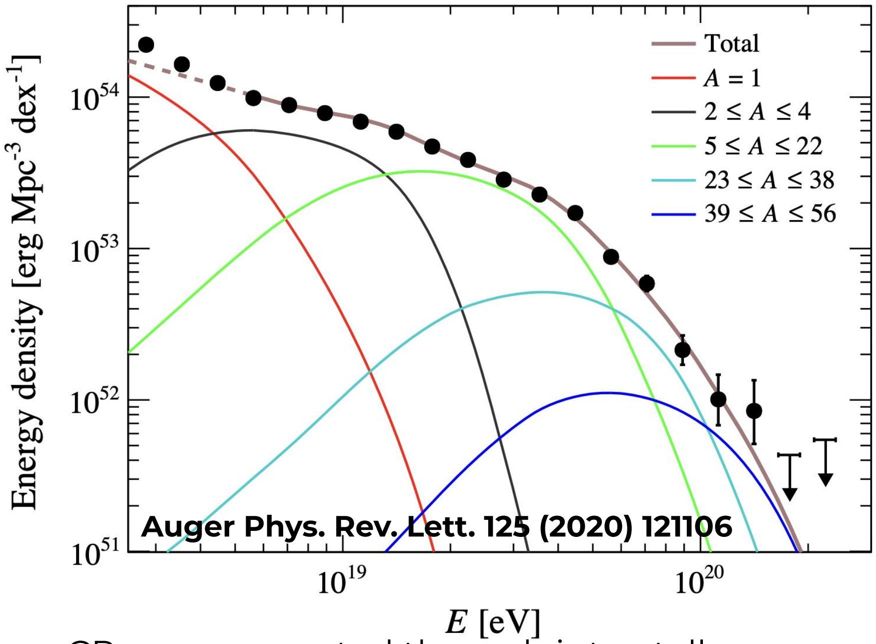
Measured signal at the ground differ for data and simulations

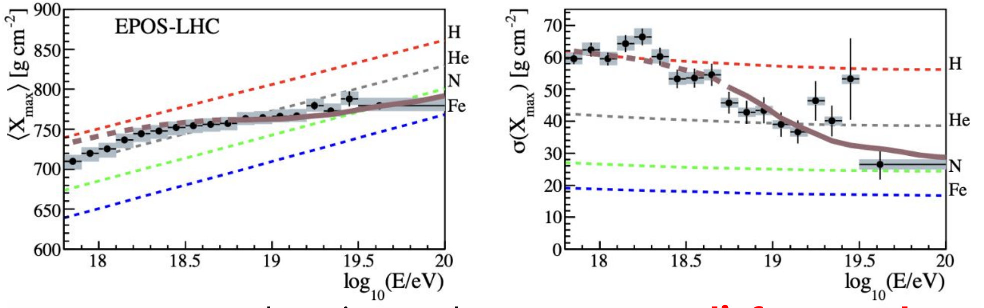


- Evidence of muon excess $1.3 < R_{had} < 1.6$
- Insensitive to energy scale uncertainty $R_E \sim 1$
- Muon number from models in tension with data
- fluctuations of muons are in agreement Phys. Rev. Lett. 126 (2021) 152002

Astrophysical scenarios

Simultaneous fit of **flux** and **composition** to find source scenarios more compatible with data





- sources accelerating only protons are **disfavoured**
- uniformly distributed sources accelerating nuclei [rigidity dependent] are **favoured**
- indication that "instep" at 10^{19} eV may be due to the **interplay between 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 constraints the luminosity density for extragalactic objects like AGN and SB

- CR are propagated through interstellar medium
- no magnetic fields

Large Scale anisotropy

Auger - Science 315 (2017) 1266

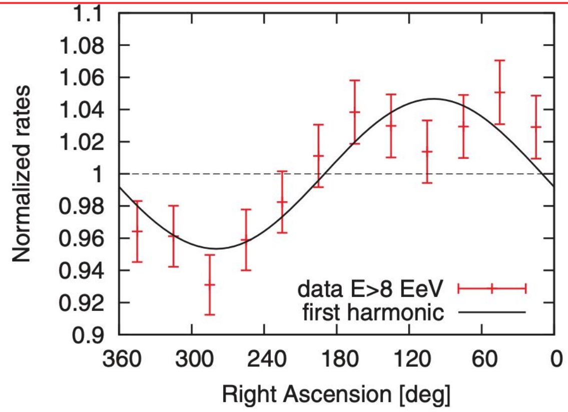
Rayleigh analysis of the first harmonic in right ascension

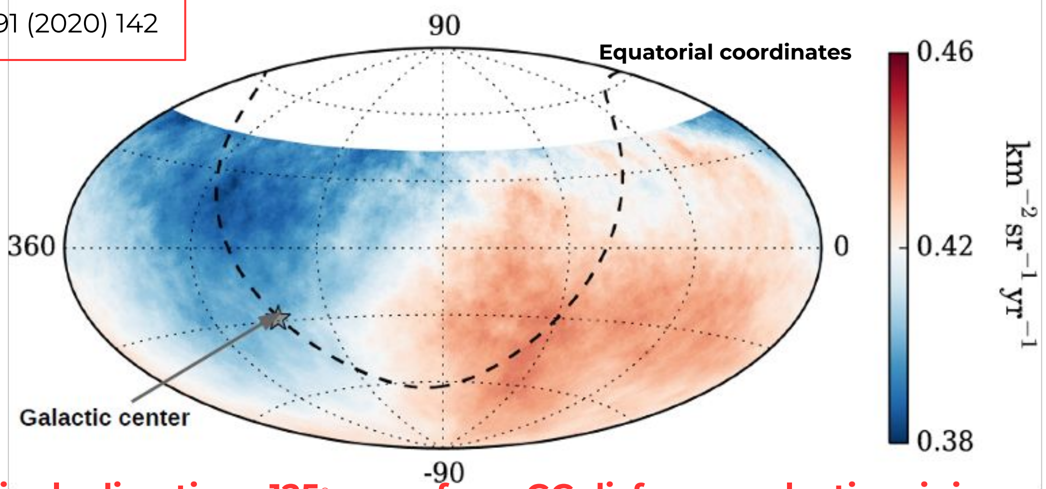
Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

E > 8 EeV

Exposure = 76800 km^{2}sr y

Modulation at **5.2σ** (**6σ** with 15% more data - Astrophys. J. 891 (2020) 142

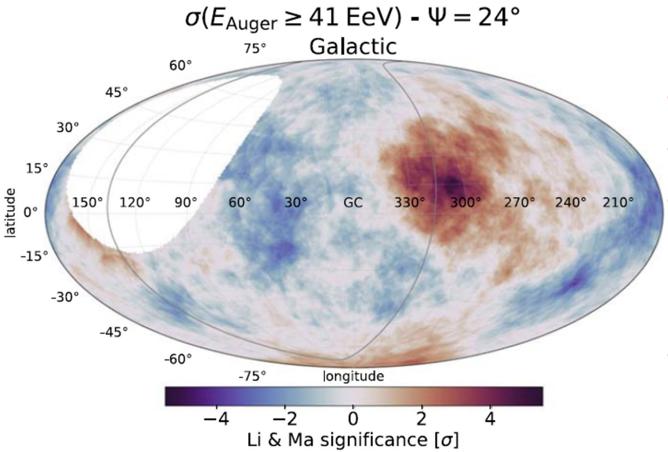


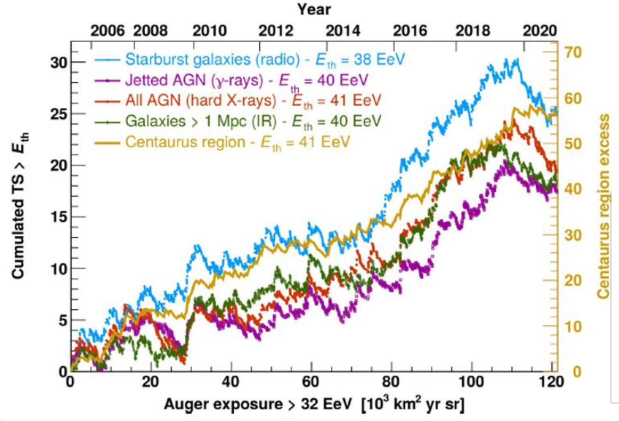


3D dipole amplitude $6.5^{+1.3}_{-0.9}$% at (α;δ) = (100°; -24°)

Dipole direction ~125° away from GC disfavors galactic origin

Intermediate Scale anisotropy





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 p.t., at ψ=24° E>41 EeV
  - direction fixed at Cen A 3.9 σ p.t., at ψ=27° E > 41 EeV
- autocorrelation with (GC, GP, SGP) not significant

Data available at **https://doi.org/10.5281/zenodo.6504276**

Likelihood test for anisotropy with astroph. catalogs

Most significant signal at E_{th} = 38-41 EeV,
ψ =23° - 27°, signal fraction 6-15%

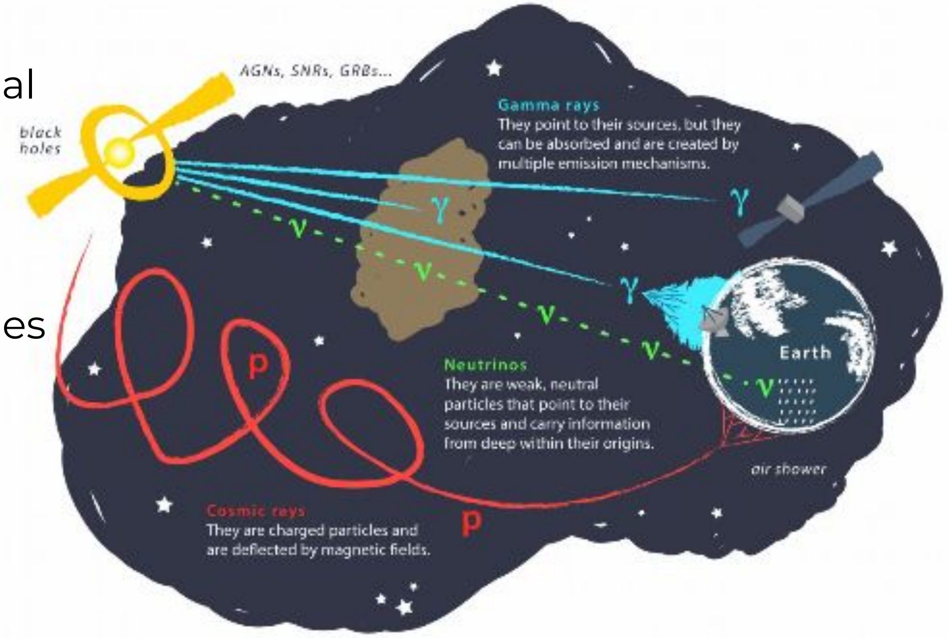
Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}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

4σ for SB
3.1 σ for Jetted AGN

Multi-messenger and Fundamental Physics

Different cosmic messengers provide complementary information about potential sources

- **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 i.e difficult to detect

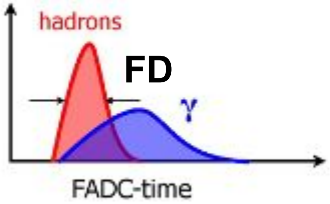


... and Fundamental Physics:
Dark Matter, LIV, BSM

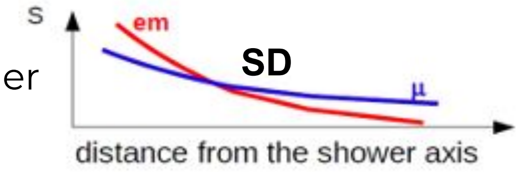
Photon searches

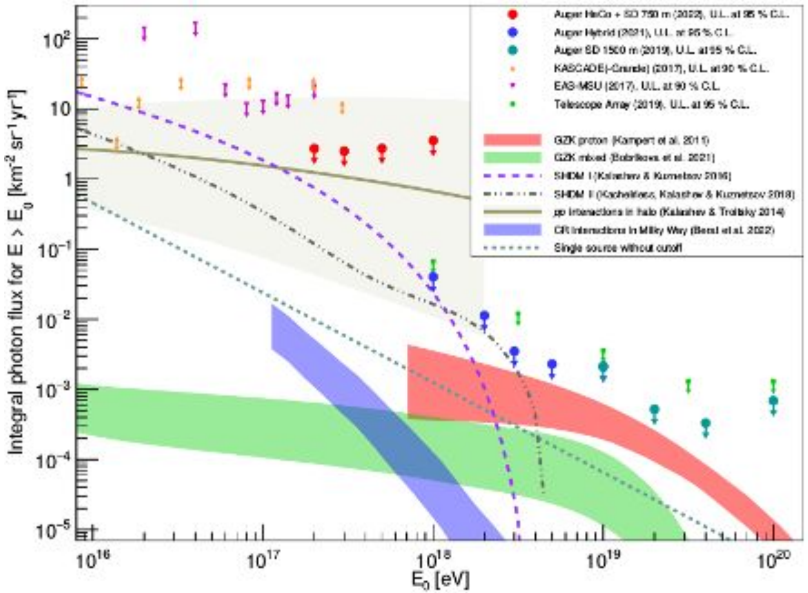
Photon signature:

- deeper Xmax, less muons



- steeper LDF and broader signal





Upper limits on diffuse photon flux

Recently published on Ap. J. 933 (2022)125:
11 candidates > 10 EeV (SD)
22 candidates > 1 EeV (Hybrid)

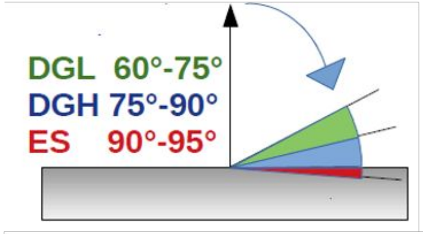
Targeted search **NO Candidates found**

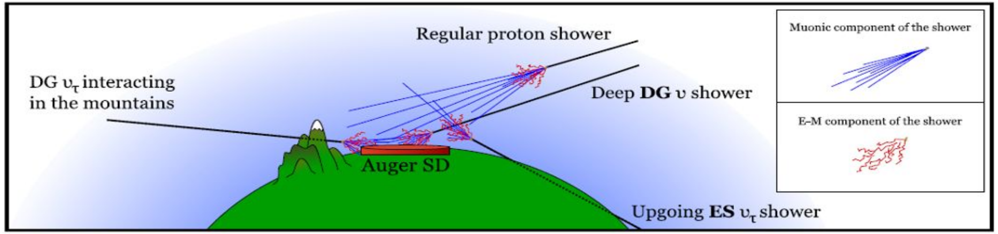
- In coincidence of known sources including **CenA** and the **Galactic Center** [UL extrapolating HESS flux]
- GW follow-up (4 events)

Top-down model disfavored

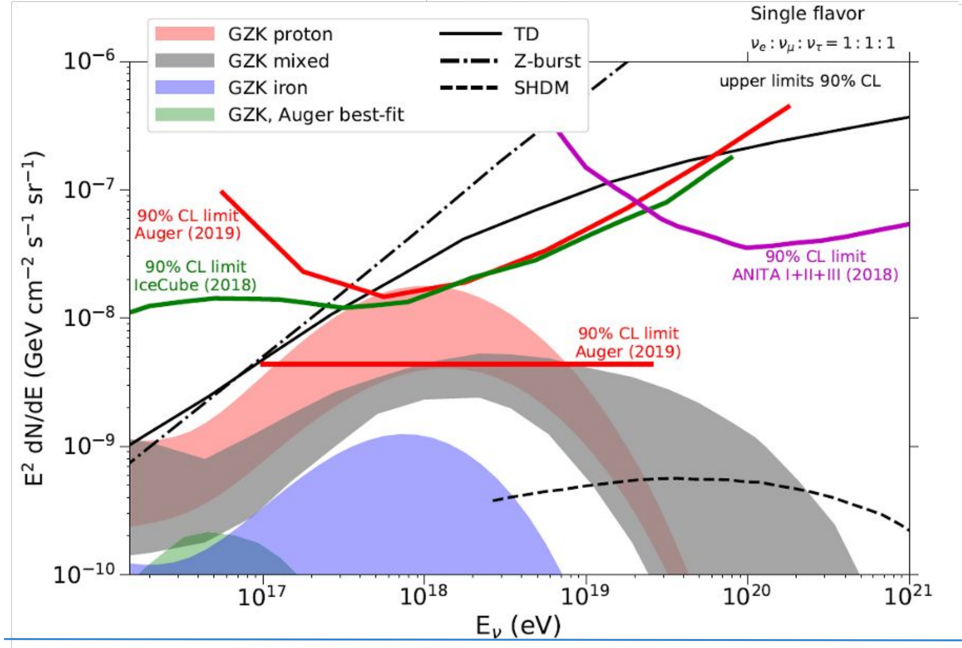
- CR proton dominated scenario disfavored
- constraining mass and lifetime of dark matter particles
- **Auger Phase II:** additional information for better photon/hadron separation or photon discovery

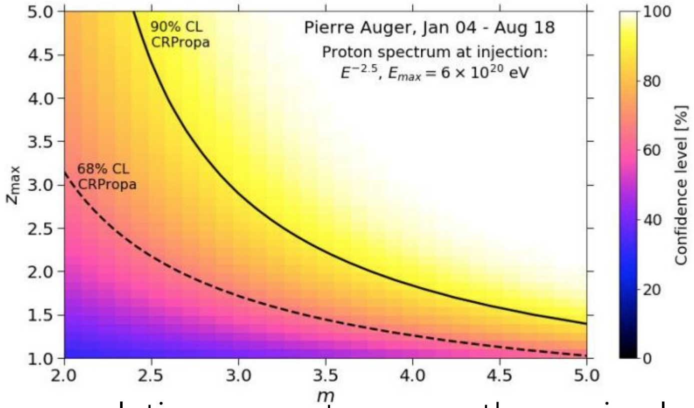
UHE Neutrino searches (SD)





SIGNATURE: inclined "young"showers





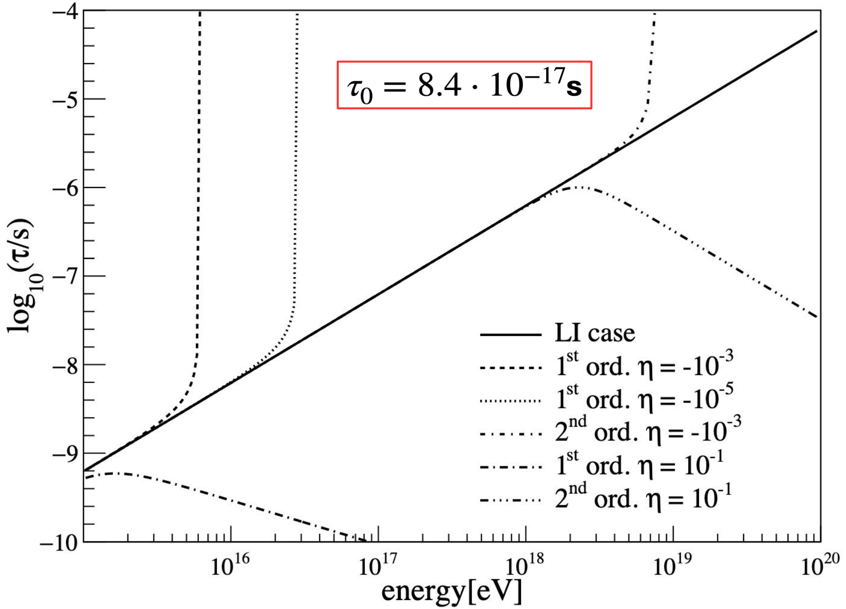
m: source evolution parameter z max : the maximal redshift at which UHECR are accelerated

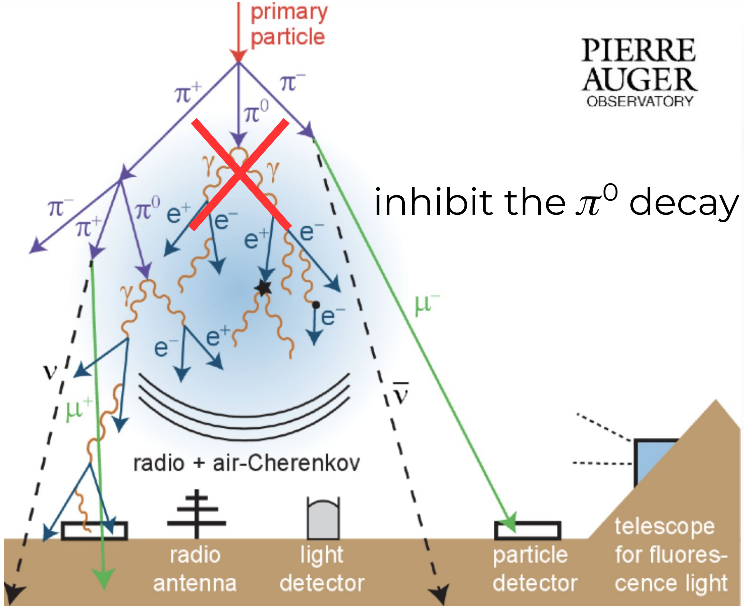
Exclusion of a significant region of parameter space (z_{max}, m) from non observation of ν assuming sources of CR accelerating only protons

Limits on the LIV with air showers

Lorentz Invariance Violation effects can be studied using a **modified dispersion relation** (Coleman, Glashow)

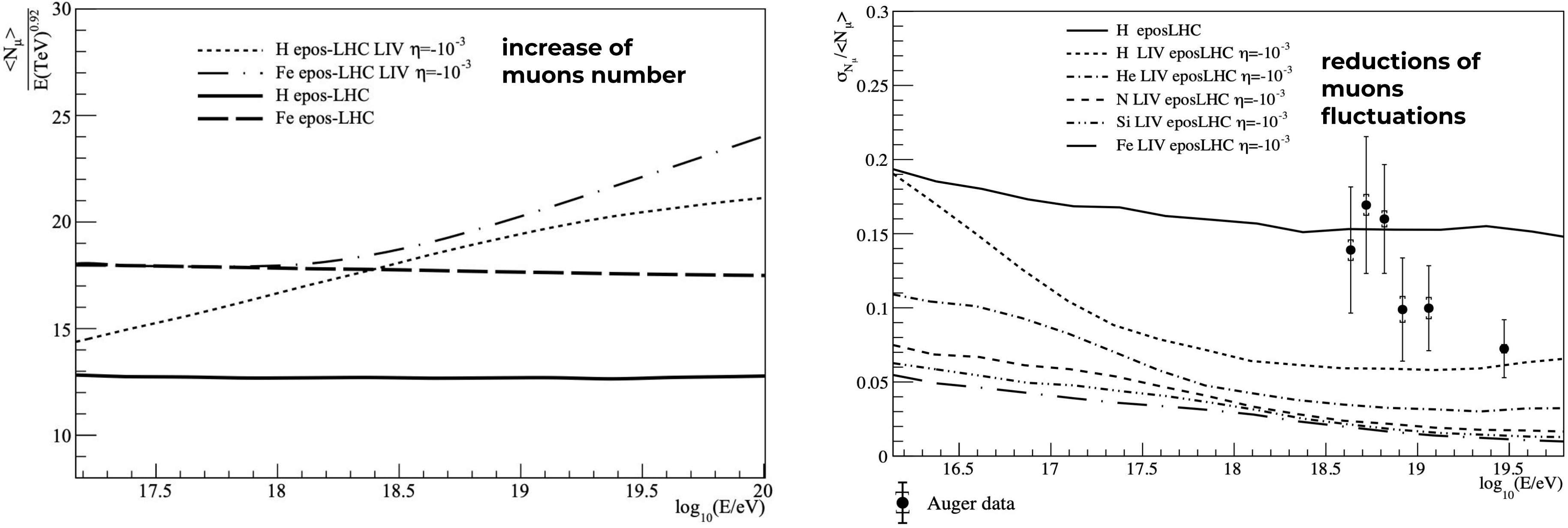
$$E^2 - p^2 = m^2 + \sum_{n=0}^{N} \eta^{(n)} \frac{p^{n+2}}{M_{Pl}^n} \quad \Rightarrow \quad m_{\rm LIV}^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n} \quad \Rightarrow \quad \gamma_{\rm LIV} = \frac{E}{m_{\rm LIV}} \quad \Rightarrow \quad \boxed{\tau = \gamma_{\rm LIV} \tau_0}$$





Limits on the LIV

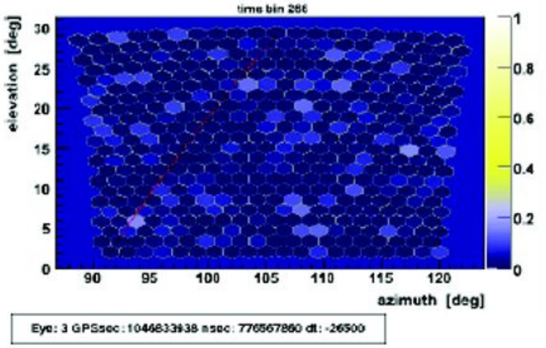
- From MC muons are very sensitive to LIV
- Using the muon fluctuations measurement at the Pierre Auger Observatory

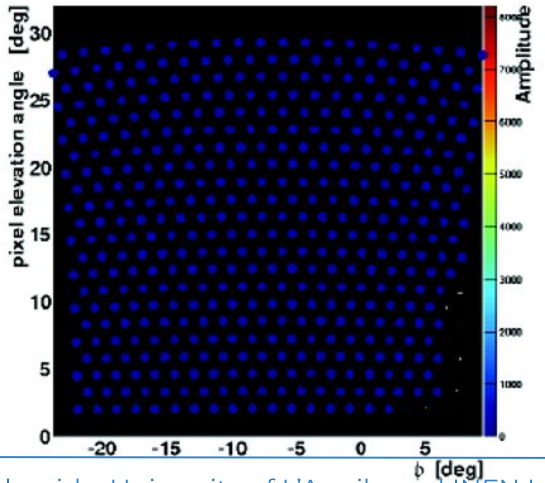


new bound for $\eta^{(1)}$ is $[-5.95 \cdot 10^{-6}, 10^{-1}]$ at 90.5% of CL

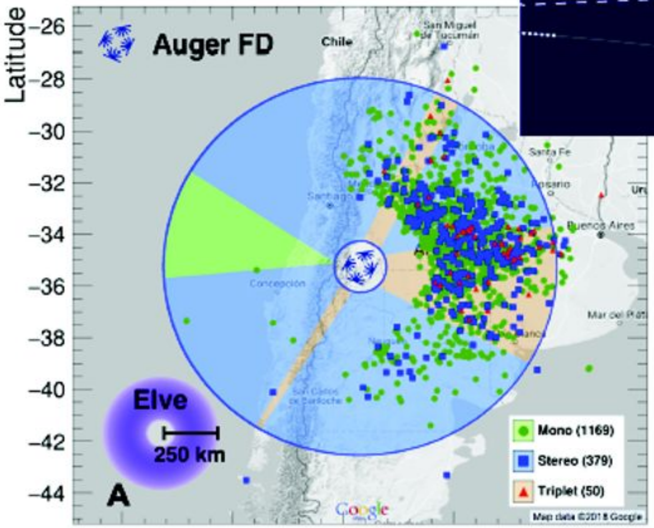
Auger as a laboratory for Earth phenomena

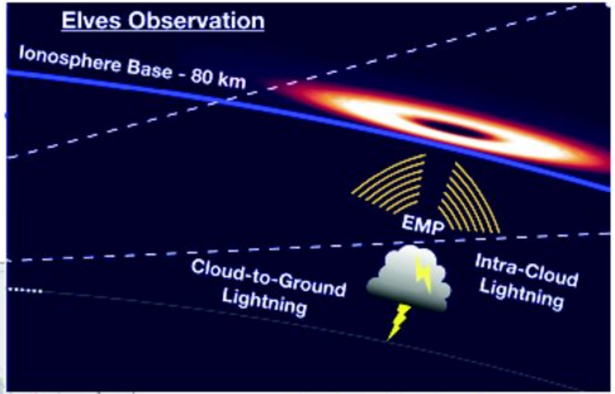
Observation of Elves with FD





Published on "Earth and Space Science" 7 (2020) e2019EA000582



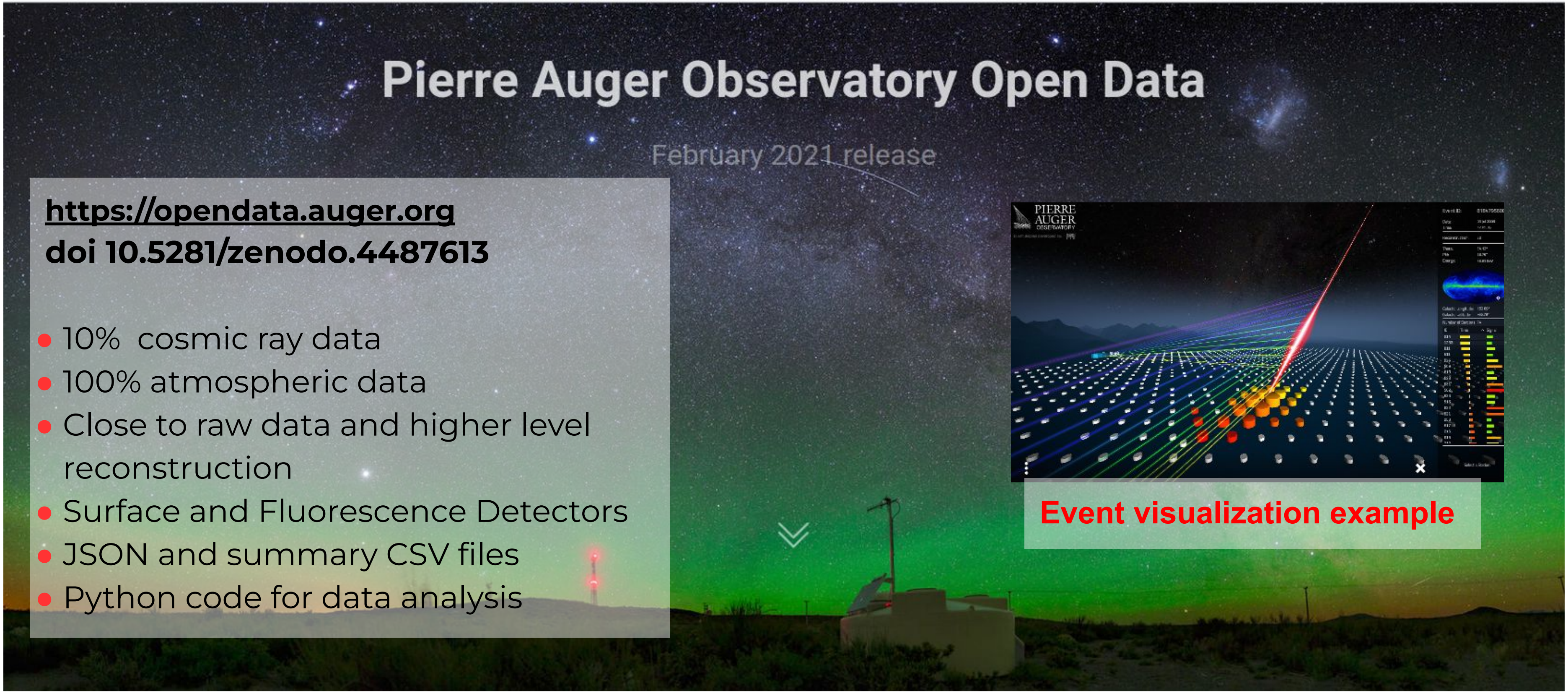


1600 elves observed

Short article to appear in EOS News

High-level publications of correlation with super bolts in preparation

Auger Open Data



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

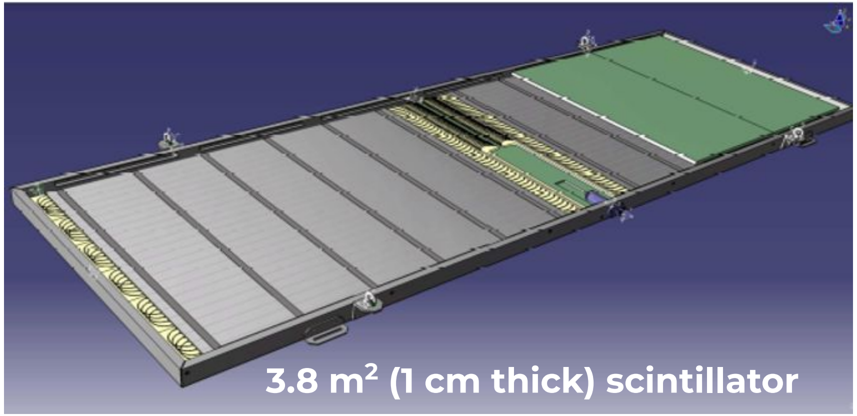
- 10% cosmic ray data
- 100% atmospheric data
- Close to raw data and higher level reconstruction
- Surface and Fluorescence Detectors
- JSON and summary CSV files
- Python code for data analysis

Event visualization example

The future of UHECR: Auger Prime upgrade

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



3.8 m^2 (1 cm thick) scintillator

UPGRADE PLAN

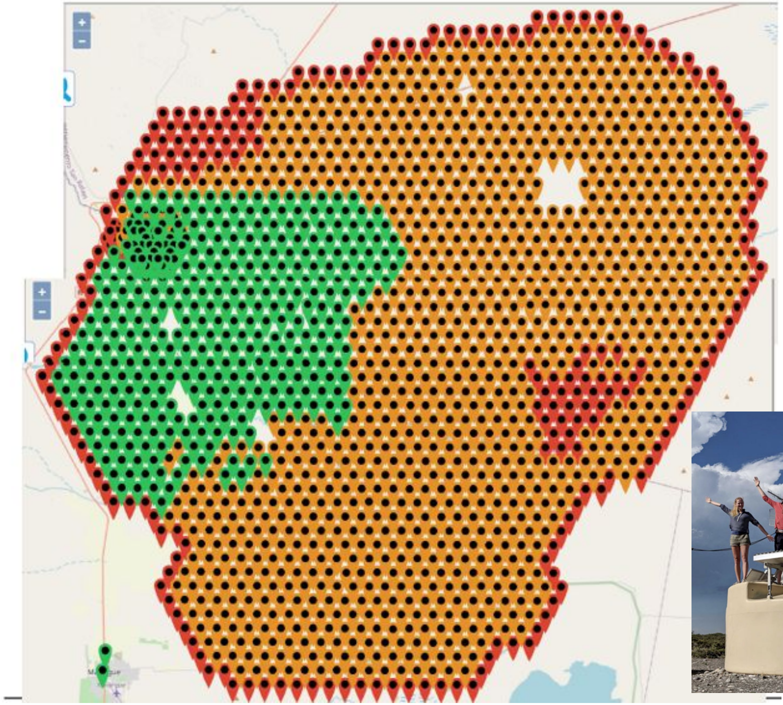
- Scintillators **SSD**
- Upgraded and faster electronics **UUB** (40 MHz - 120 MHz)
- Extension of dynamic range with small **sPMT**
- Underground buried **UMD** detectors
- Radio antennas **RD**

The future of UHECR: Auger Prime status

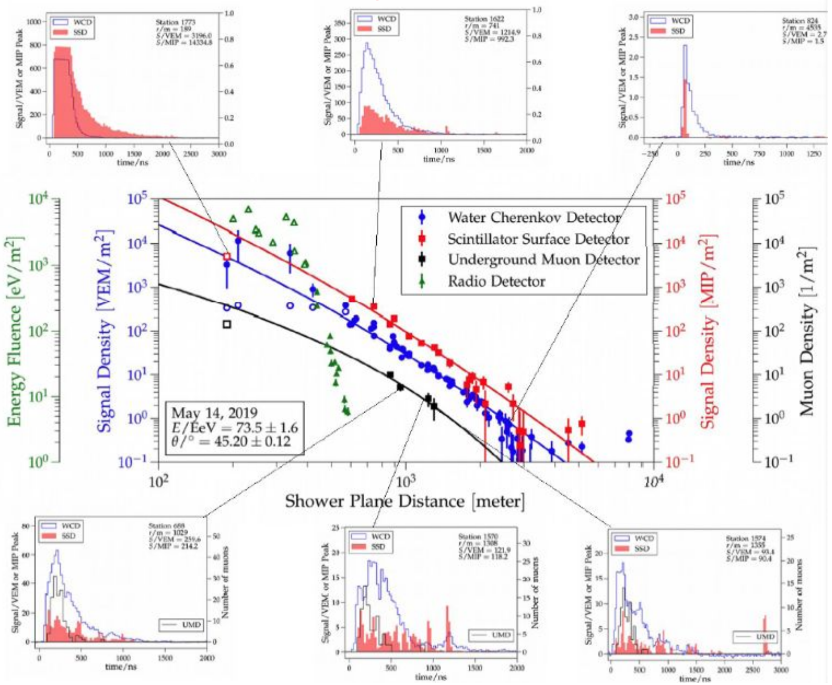
1436 SSD stations **deployed**

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

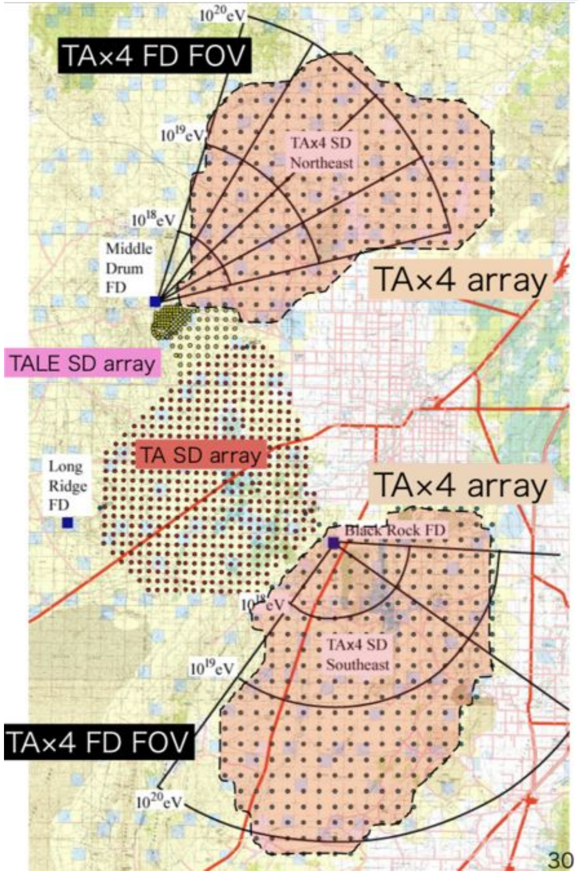
Installation completed with UUBs in early 2023



Super Hybrid event



The future of UHECR: TA x 4

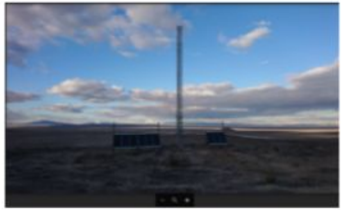


AIM: increase the coverage up to ~3000 km^2 to increment the statistics at UHE

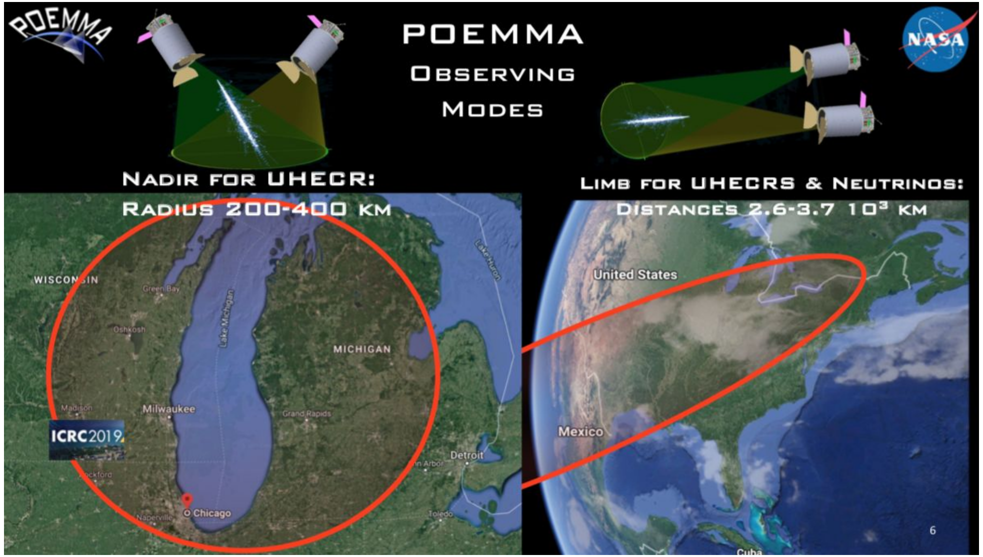
- **SD array:** increased by 500 stations with 2 km spacing
- **FD telescopes:** increased by 4 FD in the Northern site, 8 in the Southern site

Feb. 19 - Mar. 12, 2019:

- 257 SDs
- 6 communication towers



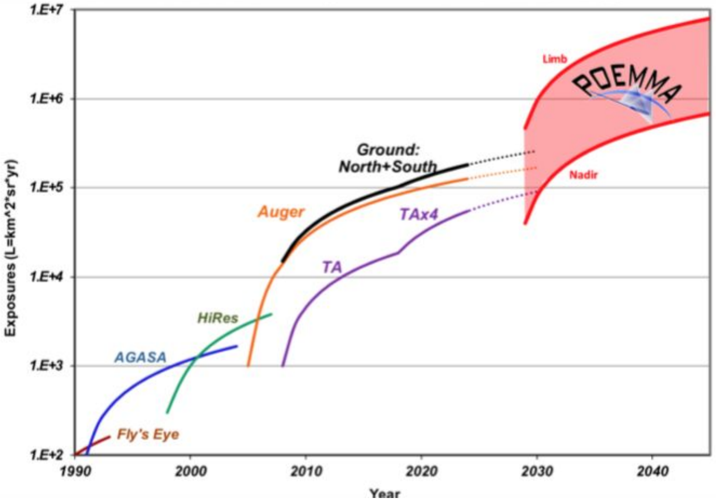
The future of UHECR: POEMMA



Probe **O**f **E**xtreme **M**ulti-**M**essenger **A**strophysics

- 2 satellites flying in loose formation
- 4 m wide FoV (45°) Schmidt mirrors
- fast (1μs) UV camera for fluorescence observation + ultrafast (10 ns) optical camera for Cherenkov obs.

GOAL: observation of UHE cosmic particles with E ≳ 10^{19} eV to study their origin



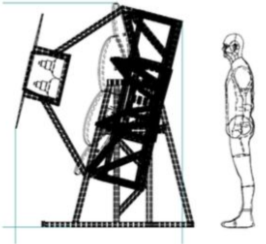
- huge gain in exposure (~10^5 km^2 sr yr) for both charged CRs and neutrinos
- full sky coverage of the celestial sphere
- sensitivity to neutrinos > 2 x 10^{19} eV from FD of ν-induced EAS
- follow-up of transients

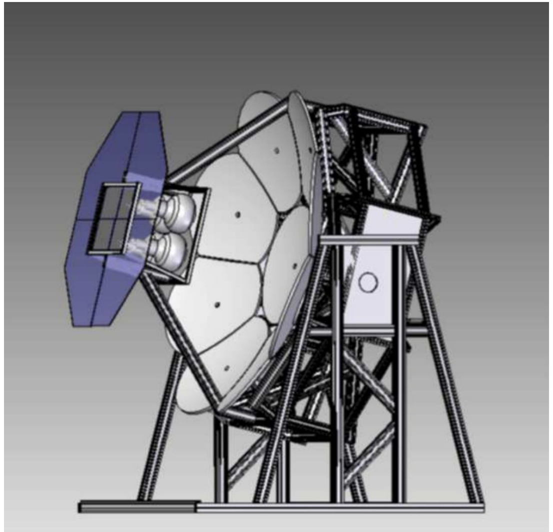
The future of UHECR: FAST

Fluorescence detector **A**rray of **S**ingle-pixel **T**elescopes

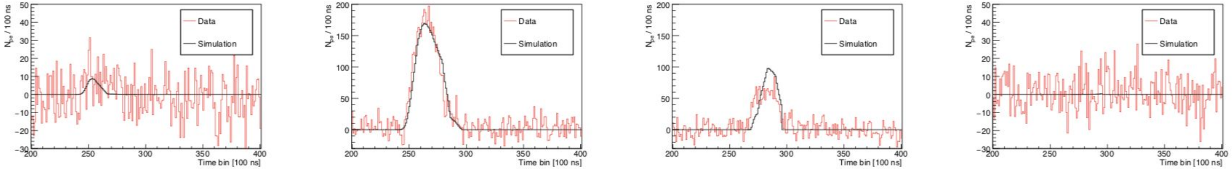
Reference: T. Fujii et al., Astropart.Phys. *74* (2016) 64-72

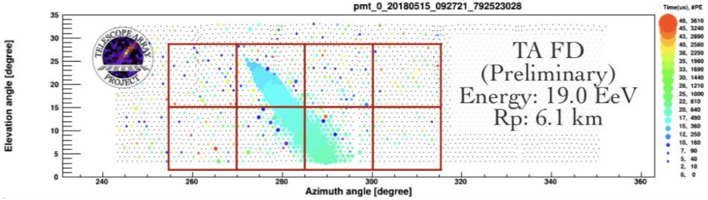
- UHECR and neutral particles **E > $10^{19.5}$ eV**
- mass discrimination on event by event basis
- huge target volume with lower cost w.r.t current FDs
- Deploy on a triangle grid with 20 km spacing, like "Surface Detector Array"





- Smaller optics and single or a few pixels 1 m^2 aperture, 15°×15° FoV
- Low-cost and simplified telescope
- installed for X-calibration and trigger at **Auger** and **TA**



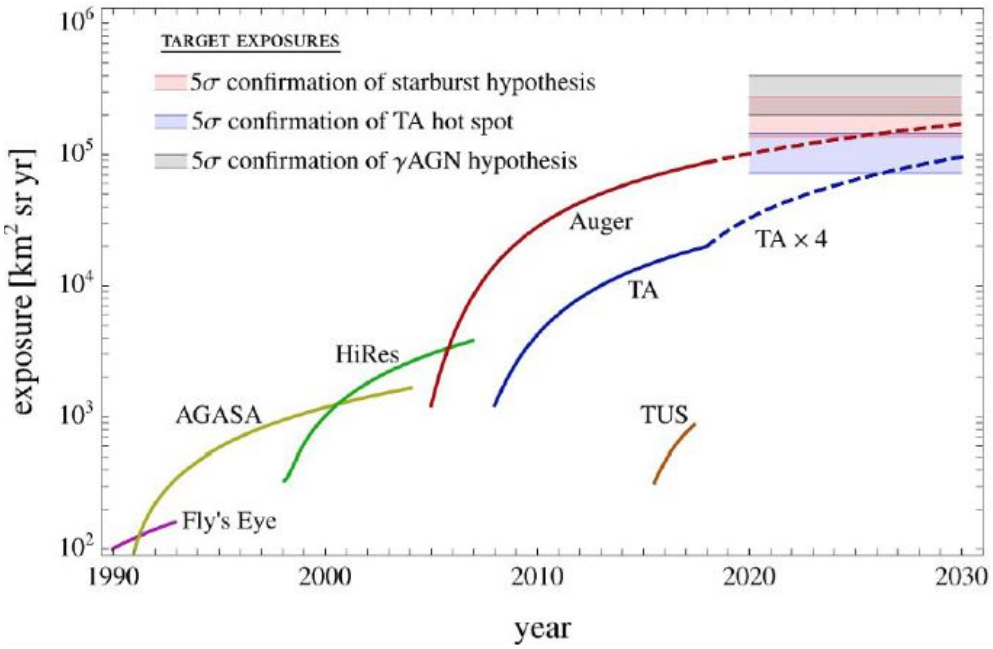


FAST top-down reconstruction (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
59.8 deg	-96.7 deg	7.9 km	-9.0 km	842 g/cm²	17.3 EeV

E = 1.73 x 10^{19}

Conclusion



OPEN QUESTIONS

1. **What is the origin of flux suppression?**
   - fundamental constraints on sources and their properties
2. **is there a fraction of protons above ~5 10^{19}eV?**
   - feasibility of charged particle astronomy
   - proof for future experiments
3. **can we disentangle composition and hadronic interaction systematics ?**
   - constraints on hadronic multiparticle production from EAS
   - constraints on new physics beyond the reach of LHC
   - new measurements at accelerators

FUTURE STEPS

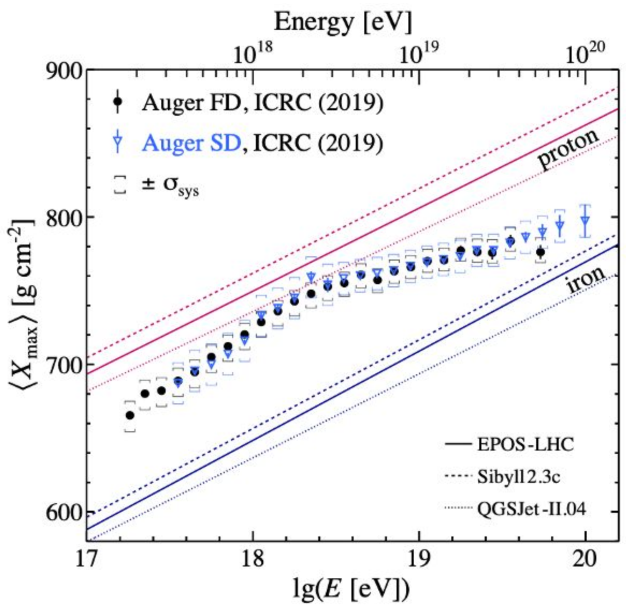
- Increase in statistics at UHE
- Composition sensitivity at and above the suppression region (E>4 10^{19} eV)
- More data on neutrinos (and photons)
- More information on hadronic interactions

Thanks for listening!

Fantastic Four 1961

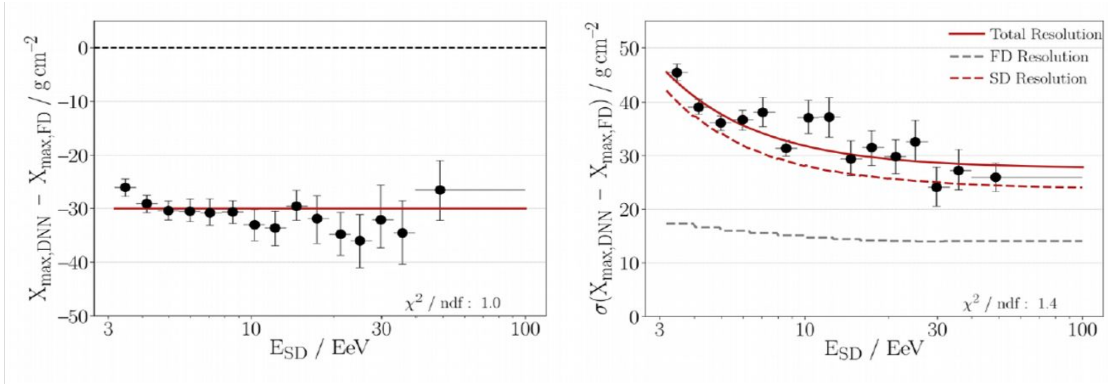
Backup slides

Mass composition (prospects)



Neural network approach tested with hybrid events

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



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

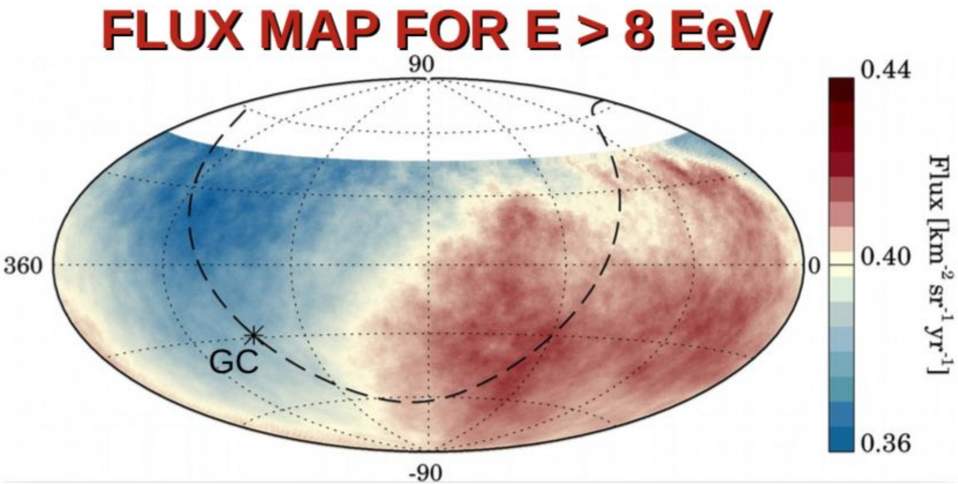
Large scale anisotropy

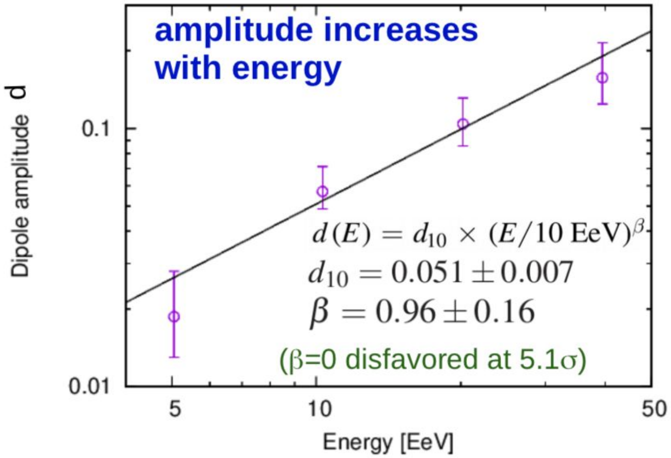
Weighted Fourier Analysis to obtain modulation in right ascension and azimuth

Auger data: Exposure >92000 km^2 sr yr

OBSERVATION (>5σ): 3D dipole above 8 EeV at (α,δ)=(98^0,-25^0): ($6.6^{+1.2}_{-0.8}$) %, 125^0 away from GC

the UHECRs are extra-galactic above 8 EeV, while predominantly Galactic below few EeV





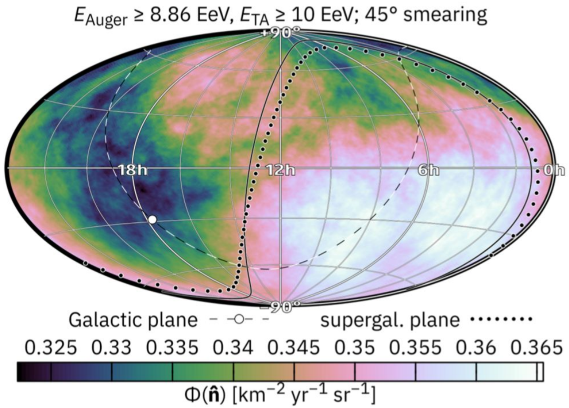
Full sky coverage with Auger + TA

Large Scale Anisotropy

Energy threshold
- 8.86 EeV for Auger
- 10 EeV for Telescope Array

Events
- ~31000 events

- Agreement with Auger alone, smaller uncertainty
- Hint for a quadrupole moment



Intermediate Scale Anisotropy (<30^0)

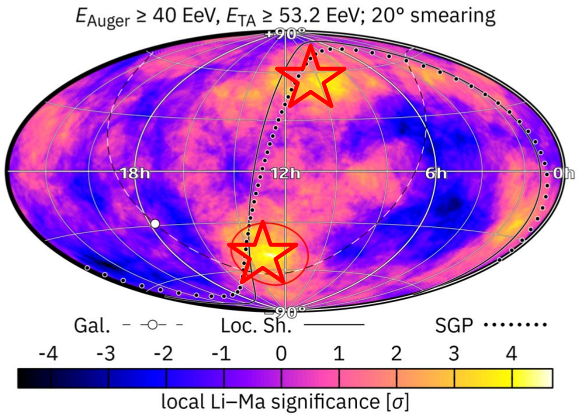
Energy threshold
- 40 EeV for Auger
- 53.2 EeV for Telescope Array

Events
- 969 events

Blind search

20^0 radius around ($\boldsymbol{\alpha}$=12^{h}50^m, $\boldsymbol{\delta}$= - 50^0), 2.6σ post-trial

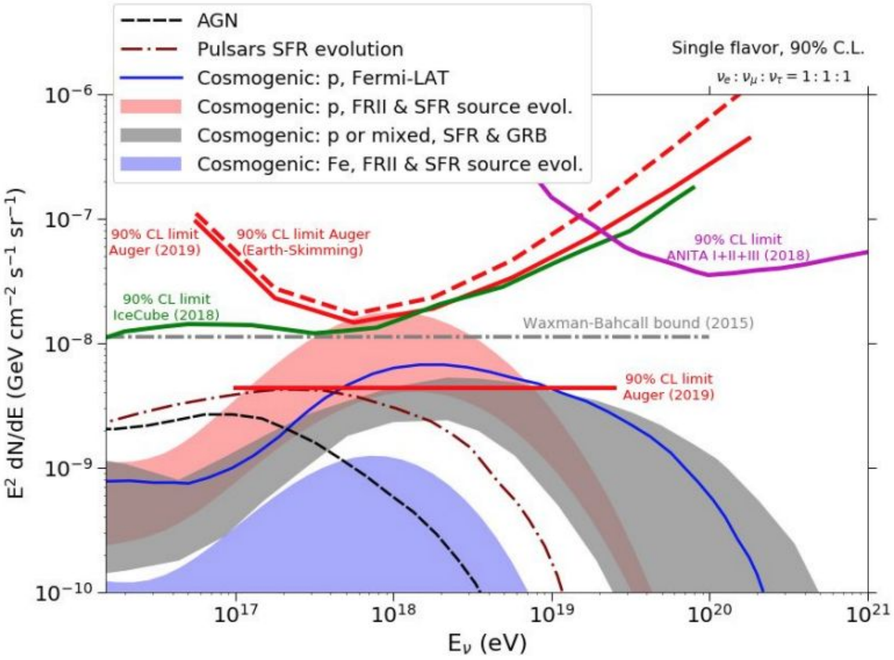
15^0 radius around ($\boldsymbol{\alpha}$= 9^{h}30^m, $\boldsymbol{\delta}$= +54^0), 1.5σ post-trial



Cosmogenic neutrinos

Expected events:
Red band: 1.4 - 5.9
Gray band: 0.8 - 2.0
Blue band (top): 0.4

$$p+\gamma \rightarrow n + \pi^+$$
$$\rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$



Maximum sensitivity around EeV k(90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

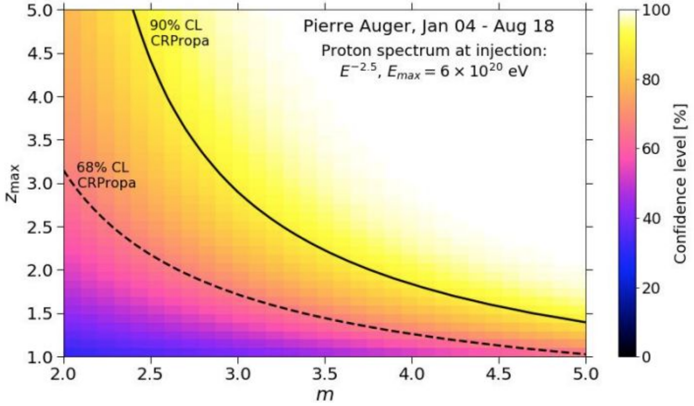
CONSTRAIN ON PROTON MODELS

UHECR source evolution models parameterized as :

$$\Psi(z) \propto (1+z)^m$$

m: source evolution parameter z max : the maximal redshift at which UHECR are accelerated

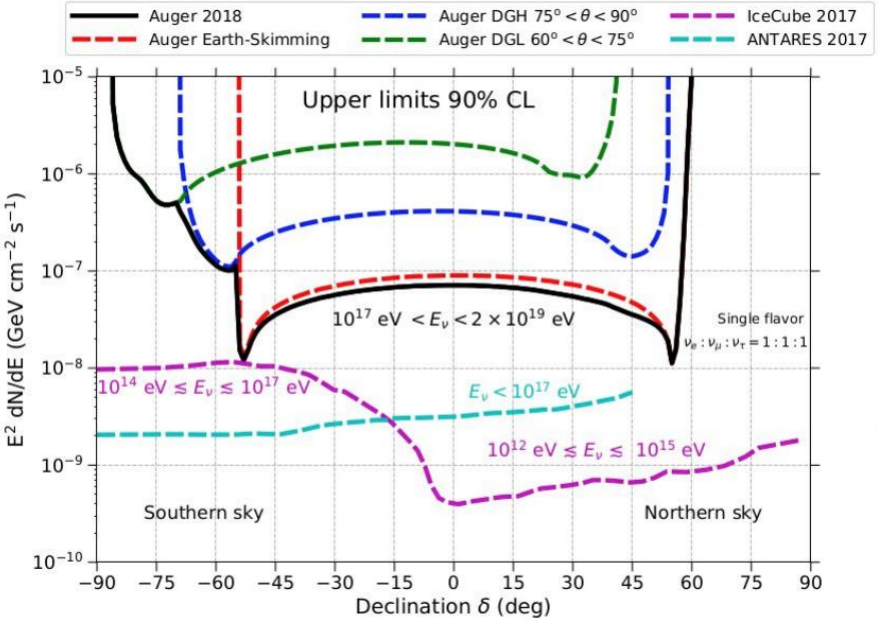
Exclusion of a significant region of parameter space (z_{max}, m) from non observation of ν



UHE neutrinos: point like sources

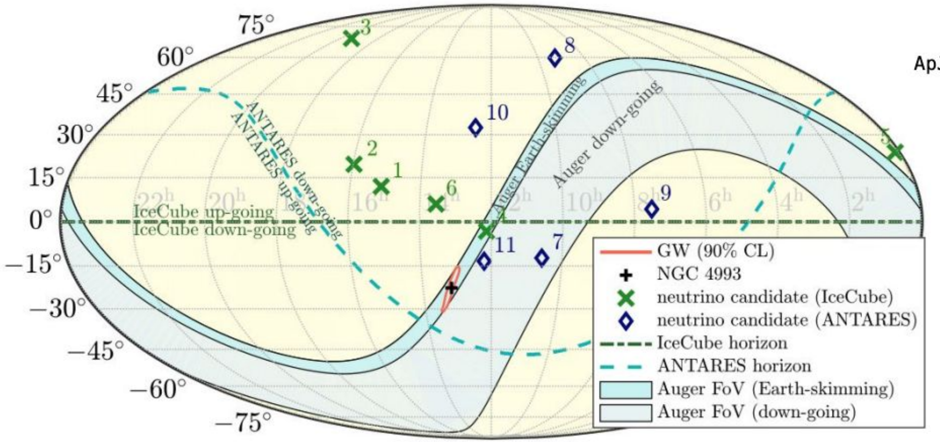
Steady sources

- Good sensitivity at EeV energies in a broad range in declination
- Energy range complementary to IceCube and Antares



Transient sources (e.g GW)

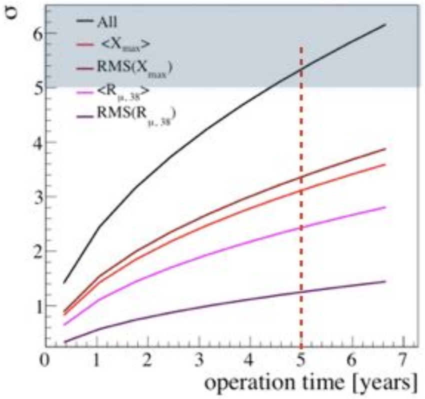
- ANTARES, Icecube & Auger searched for in coincidence with GW170817 from TeV to EeV
- Very good Auger sensitivity because source was in the FoV of Earth Skimming at the moment of merger
- Sensitive to neutrino luminosities below 5×10^{46}erg/s for certain periods during 1-day follow-up searches

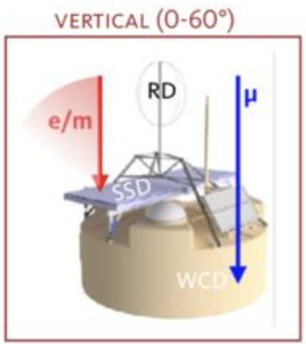


ApJ,

The future of UHECR: Auger Prime detectors

VERTICAL SHOWERS



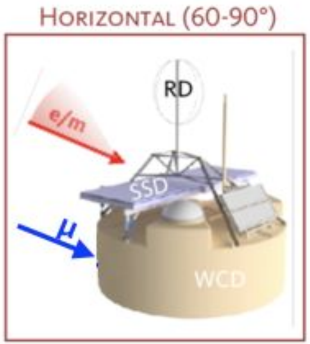


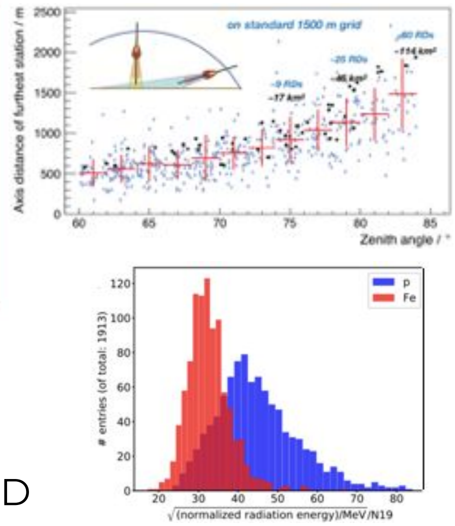
Significance of distinguishing two different realisations of "maximum rigidity model" :

- as it predicts, i.e. no protons at UHE
- adding 10% protons

>5σ in 5 years of operations

HORIZONTAL SHOWERS

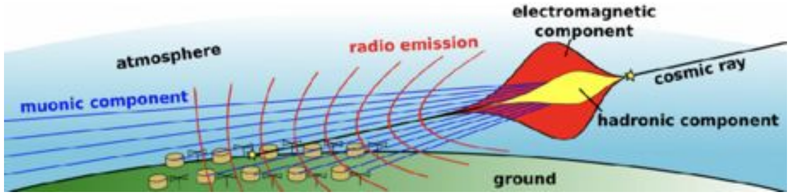




RADIO Hybrid:

E_{rad} from radio

muons from WCD

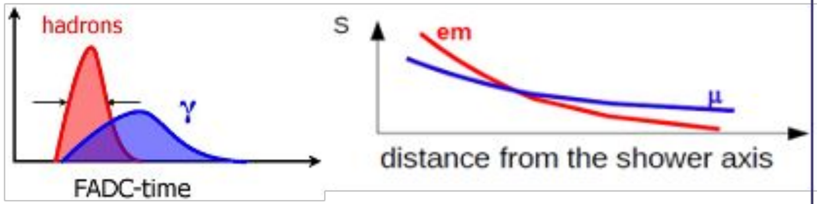


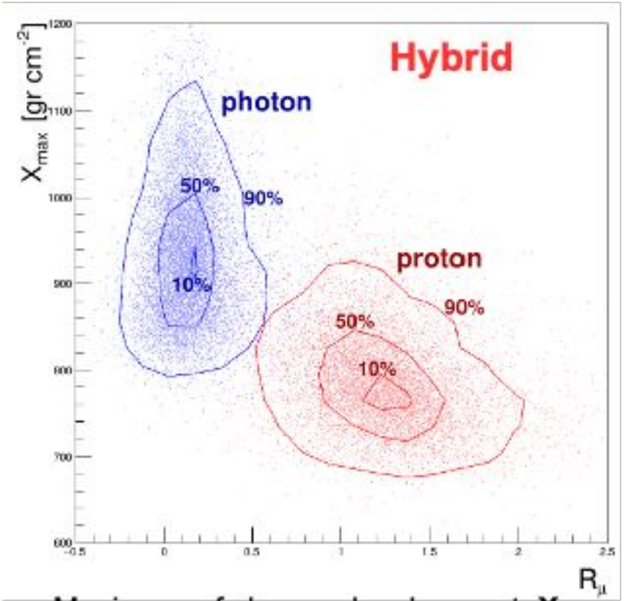
Hybrid and SD photon search

Photon signature

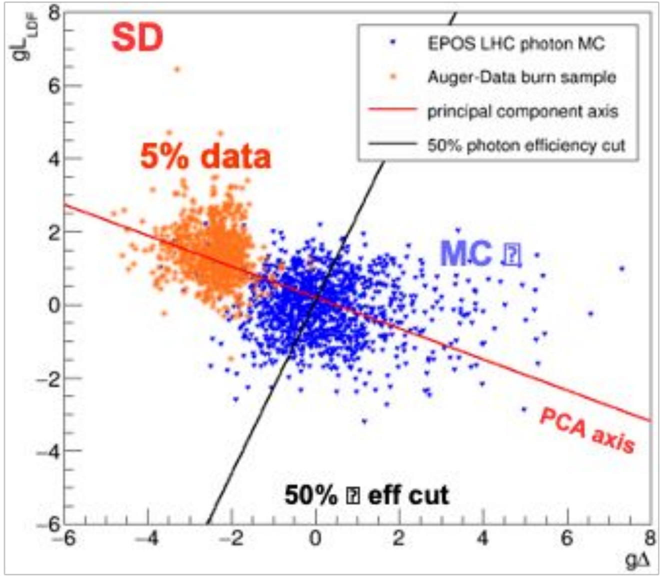
deeper Xmax, less muons

steeper LDF and broader signal





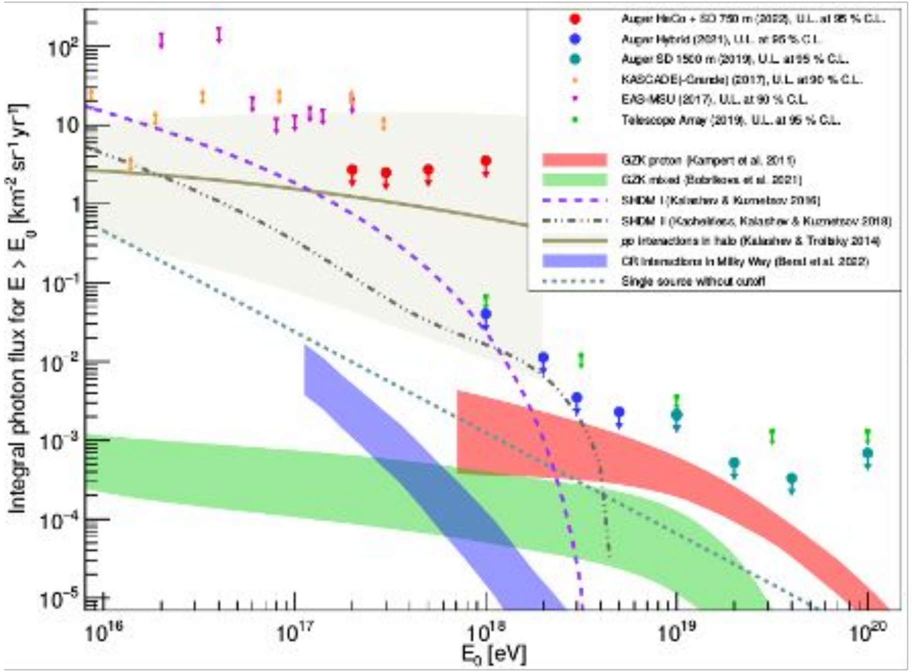
Maximum of shower development: $\mathbf{X_{max}}$
Muon content of the shower (universality): R_{μ}



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)

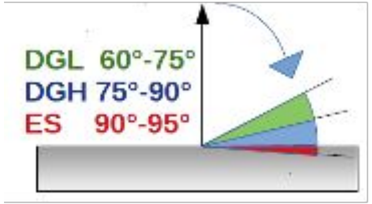
Targeted search
In coincidence of known sources including CenA and the Galactic Center [UL extrapolating HESS flux]

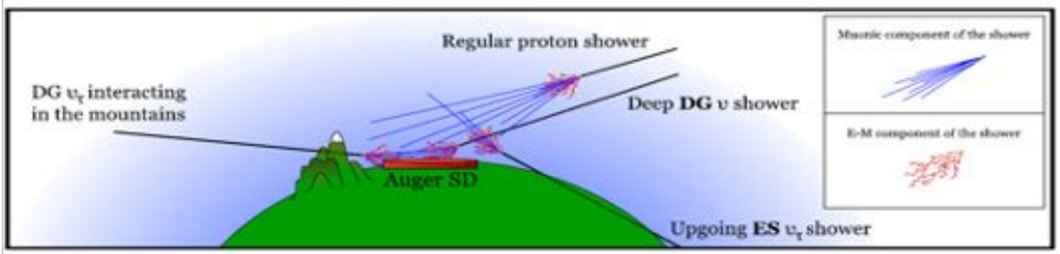
GW follow-up (4 events)

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

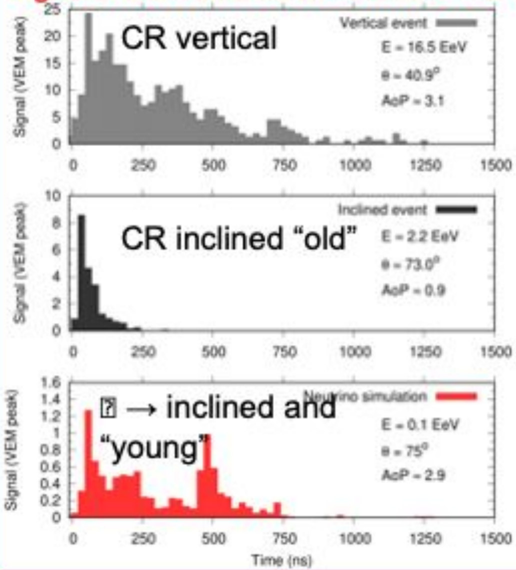
UHE neutrinos with the SD



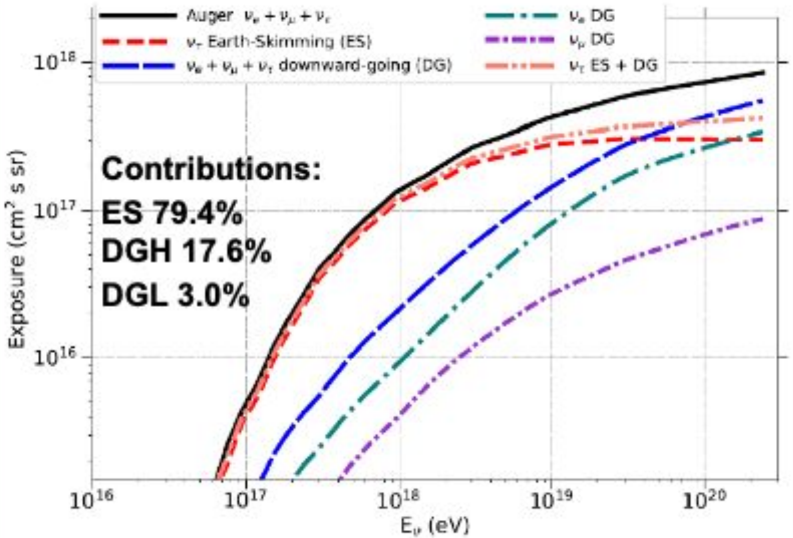


typical signal shapes

signature: distinctive Area-over-Peak



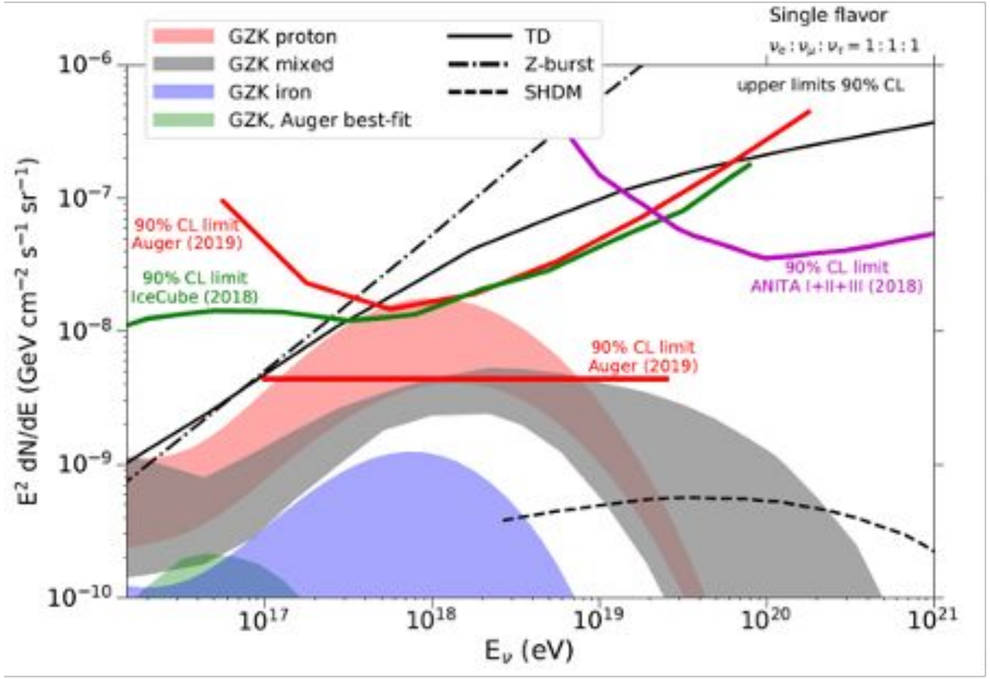
Sensitivity to different channels



ν_τ ES sensitivity dominant

Upper limits on the diffuse neutrino flux

Pierre Auger Coll., JCAP 10 (2019) 022



NO Candidates found

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

→ $k \sim 4.4 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} [0.1 – 25] EeV

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

Maximum sensitivity ~ **1 EeV**

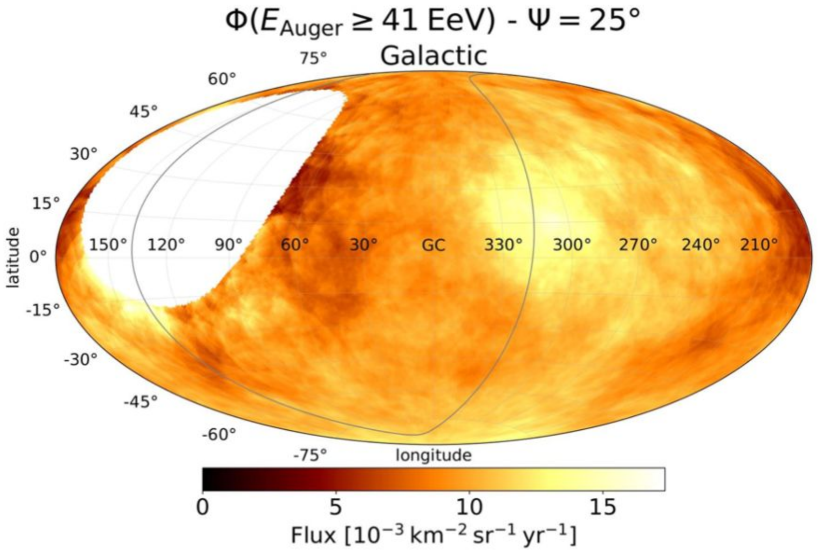
Blind search

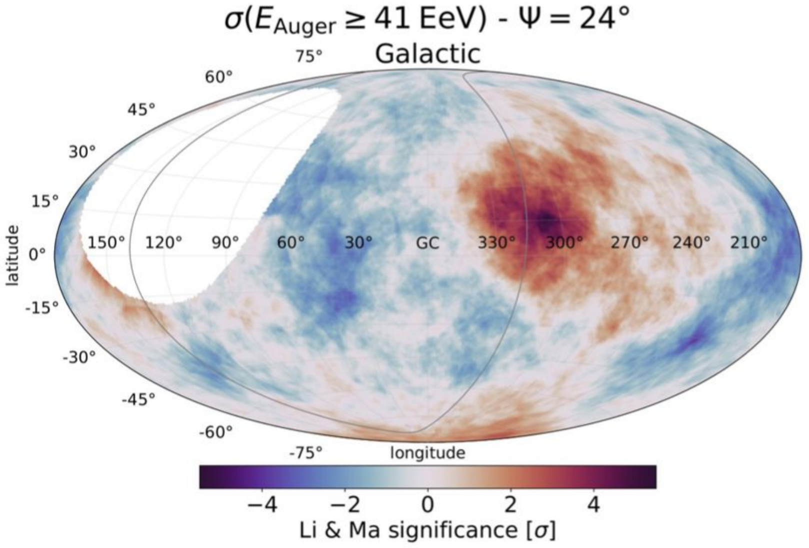
Search with little to **no *a priori***: most prominent overdensity in the whole observable sky

Parameter space is scanned in

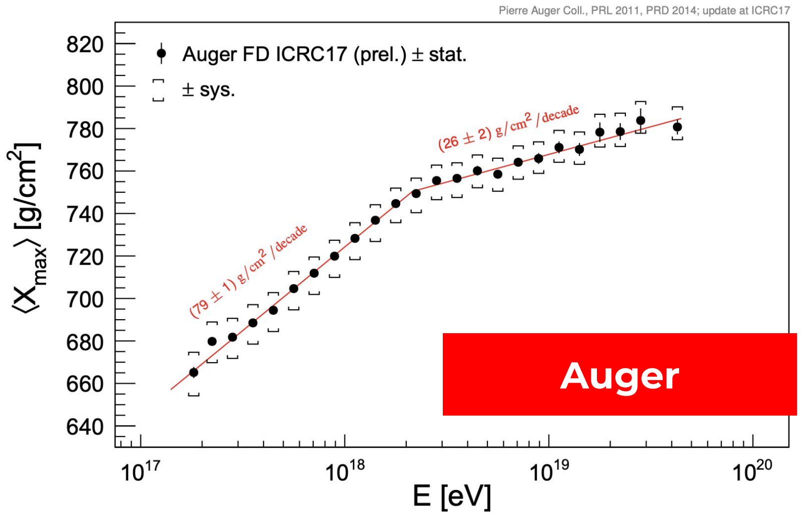
- Direction (R.A., Dec)
- Threshold energy 32 EeV ≤ Eth ≤ 80 EeV
- Top-Hat angular scale 1° ≤ ψ ≤ 30°

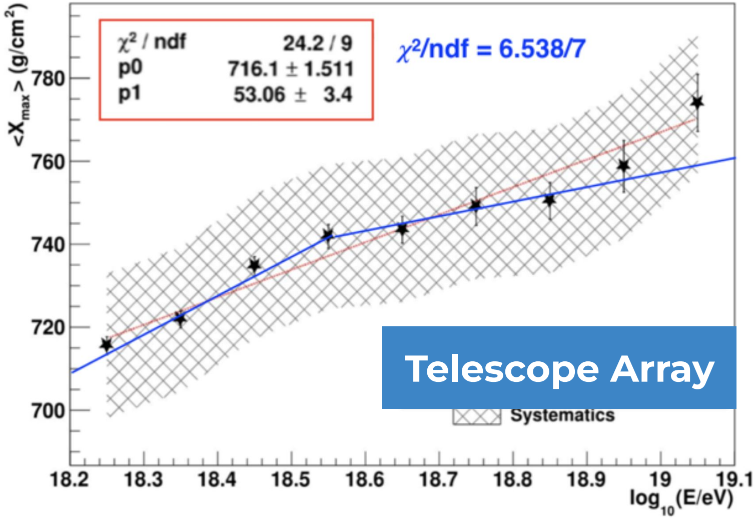
Largest significance post-trial **2.2σ**
found at (RA, dec)=(196.3°, -46.6°) or (l, b)=(305.4°, 16.2°)
Nobs = 156 vs Nexp=98 at Eth 41 EeV and Ψ=24°





Tension on composition between Auger and TA?





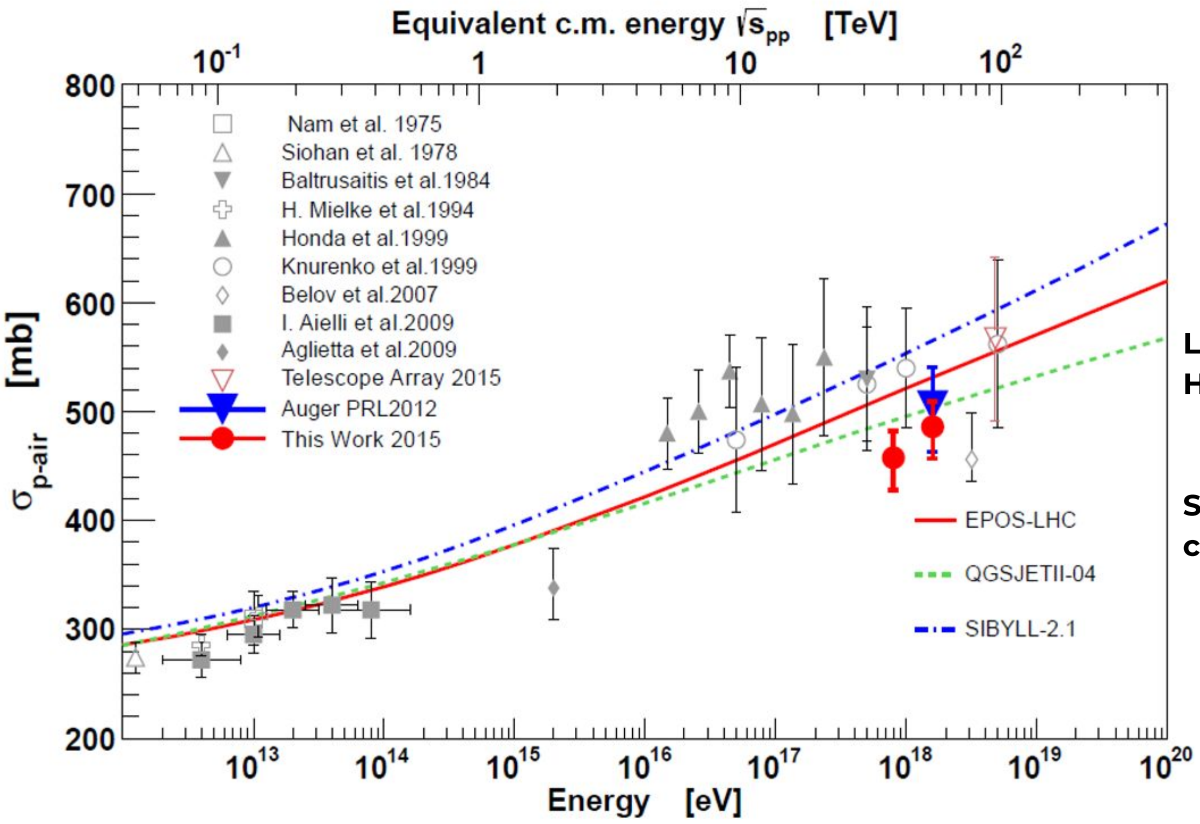
- X_{max} res. ~25 to ~15 g cm^{-2} (from $10^{17.8}$ eV to >$10^{19.7}$ eV)
- Systematic uncertainty on X_{max} ≤ 10 g cm^{-2}

- X_{max} res. 17.2 g cm^{-2} (from $10^{18.2}$ eV to 10^{19} eV)
- Systematic uncertainty on X_{max} ~ 17 g cm^{-2}

Auger data show trend towards heavier composition above $10^{18.4}$ eV

- TA data have less statistical separation power and larger systematics
- TA data compatible with mix of 4 elements with 75% (p+He) below $10^{19.1}$ eV
- direct comparison is difficult (AUGER unbiased measurement, TA biased by detector acceptance)
- CAVEAT: TA analysis with QGSJetII-04 only [excluded by Auger σ(Xmax) measurement]

p-air cross section



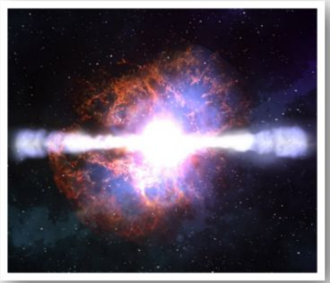
Lower energy [457±18(stat)+19/-25(syst)] mb
Higher energy [486±16(stat)+19/-25(syst)] mb

Sys uncertainty: method, models, helium contamination

Simulation and Procedure

CRs ejected by EG accelerators

Considered at the escape

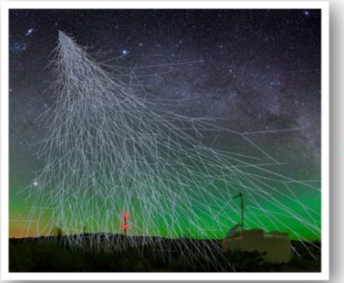


Propagation through the intergalactic medium

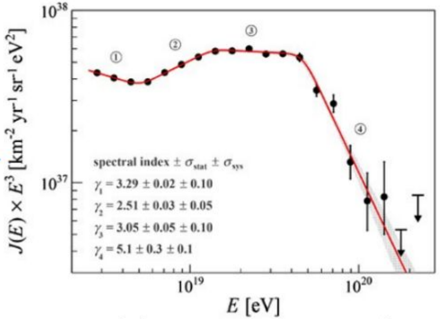
Choice of propagation models:
- EBL model
- Photo-disintegration cross section

Production of showers in the atmosphere

Choice of hadronic interaction model (EPOS-LHC)



Comparison with the data



Estimation of free parameters that characterize of the fluxes at the sources using combined fit

(GAP2021_040, PhD Thesis by A. Condorelli)

$$\frac{dN}{dE} \propto f_A \left(\frac{E}{10^{18} eV}\right)^{-\gamma} \times f_{cut}(E, Z_A R_{cut}) \times (1+z)^m$$