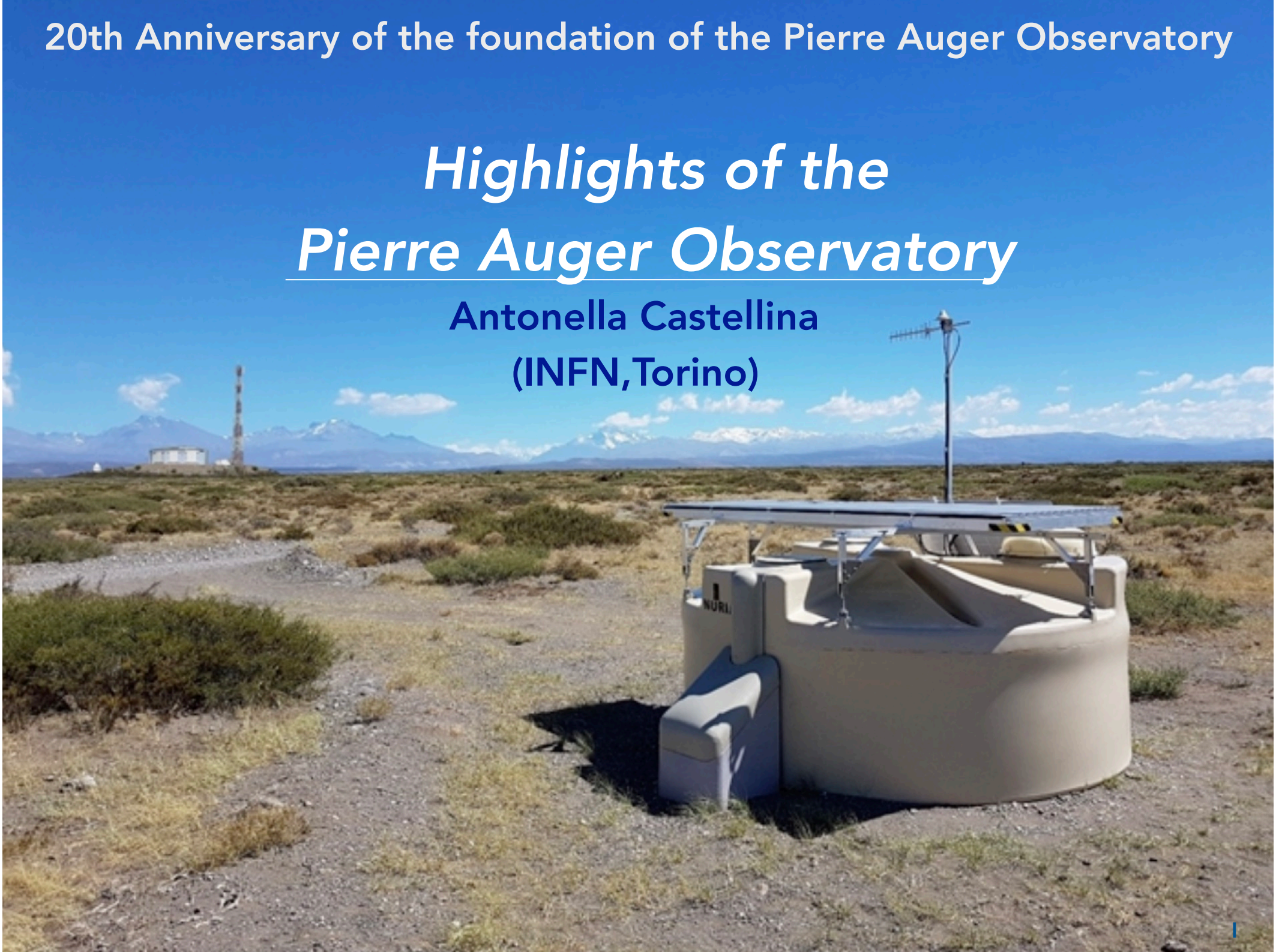
20th Anniversary of the foundation of the Pierre Auger Observatory

Highlights of the Pierre Auger Observatory

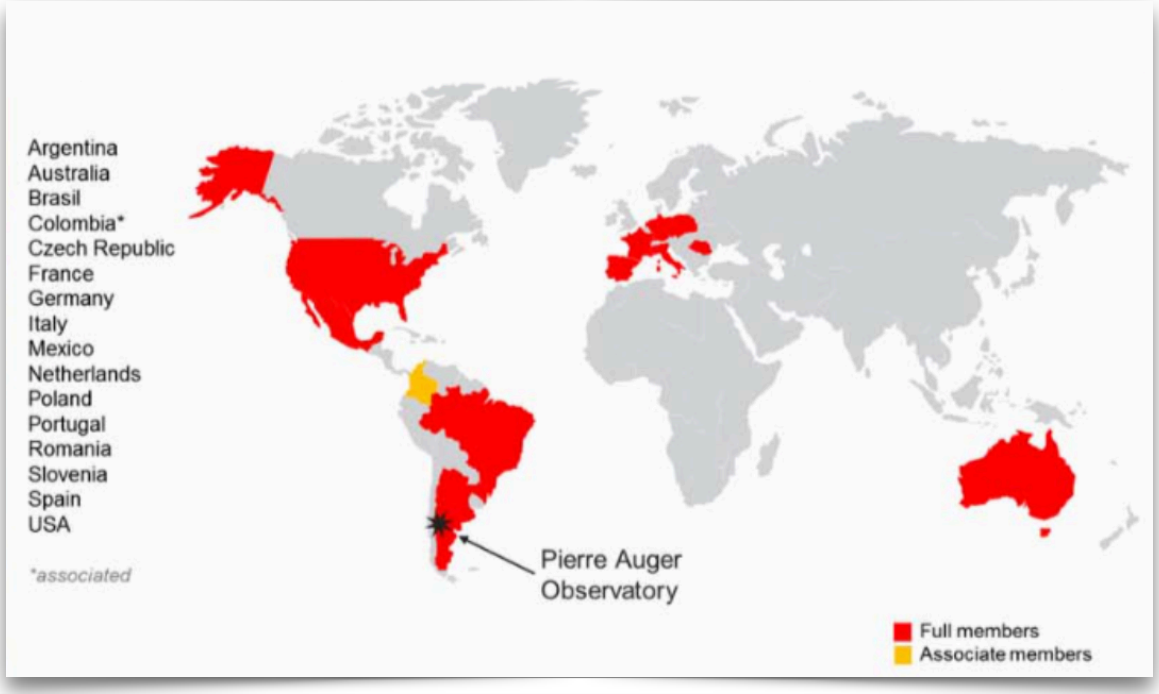
Antonella Castellina

(INFN,Torino)



The Pierre Auger Collaboration

~500 members
from 89 institutions,
17 countries



Doctoral researchers

- about 425 theses since beginning
- completed 324 PhD theses
- many new professorships

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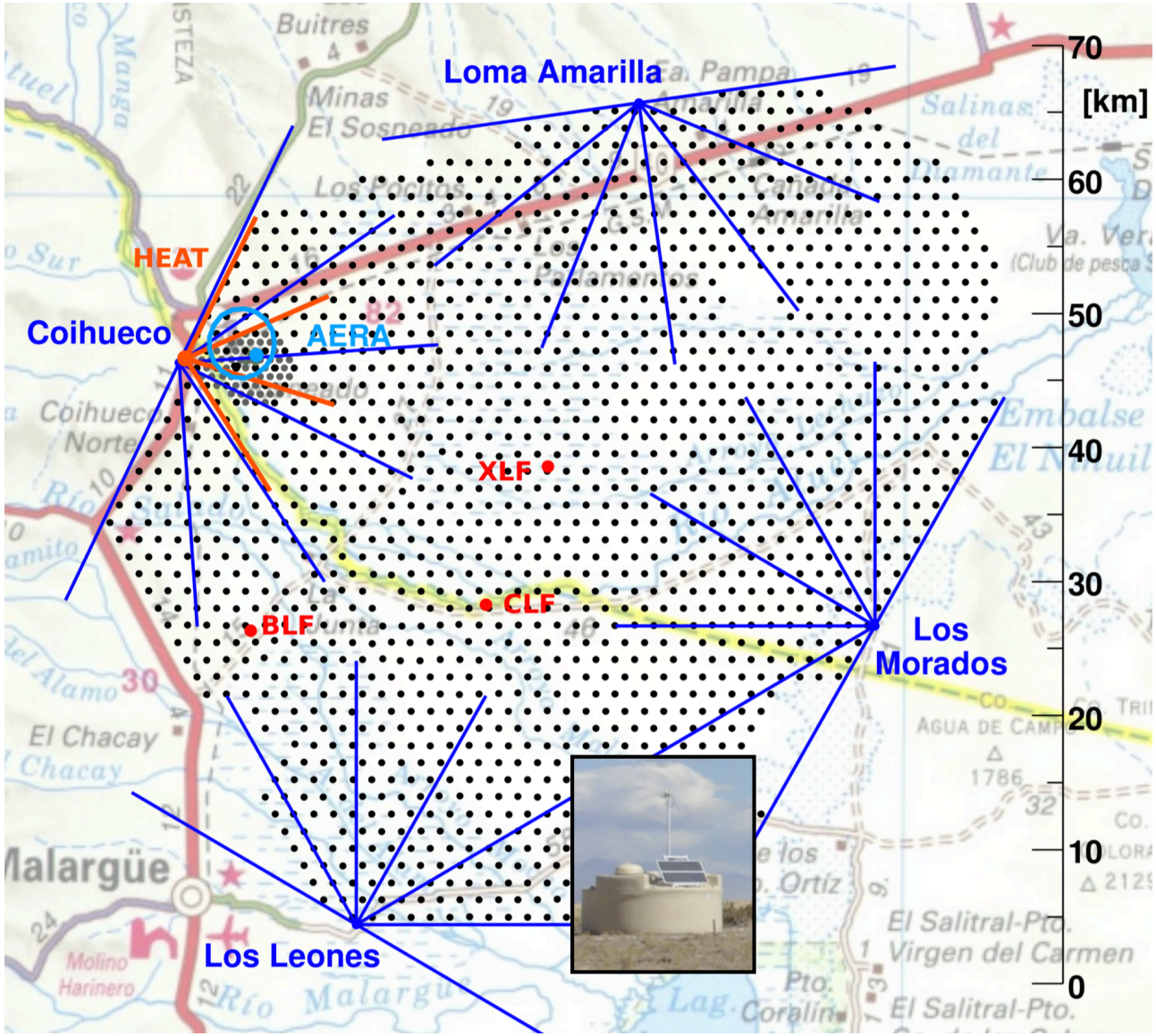
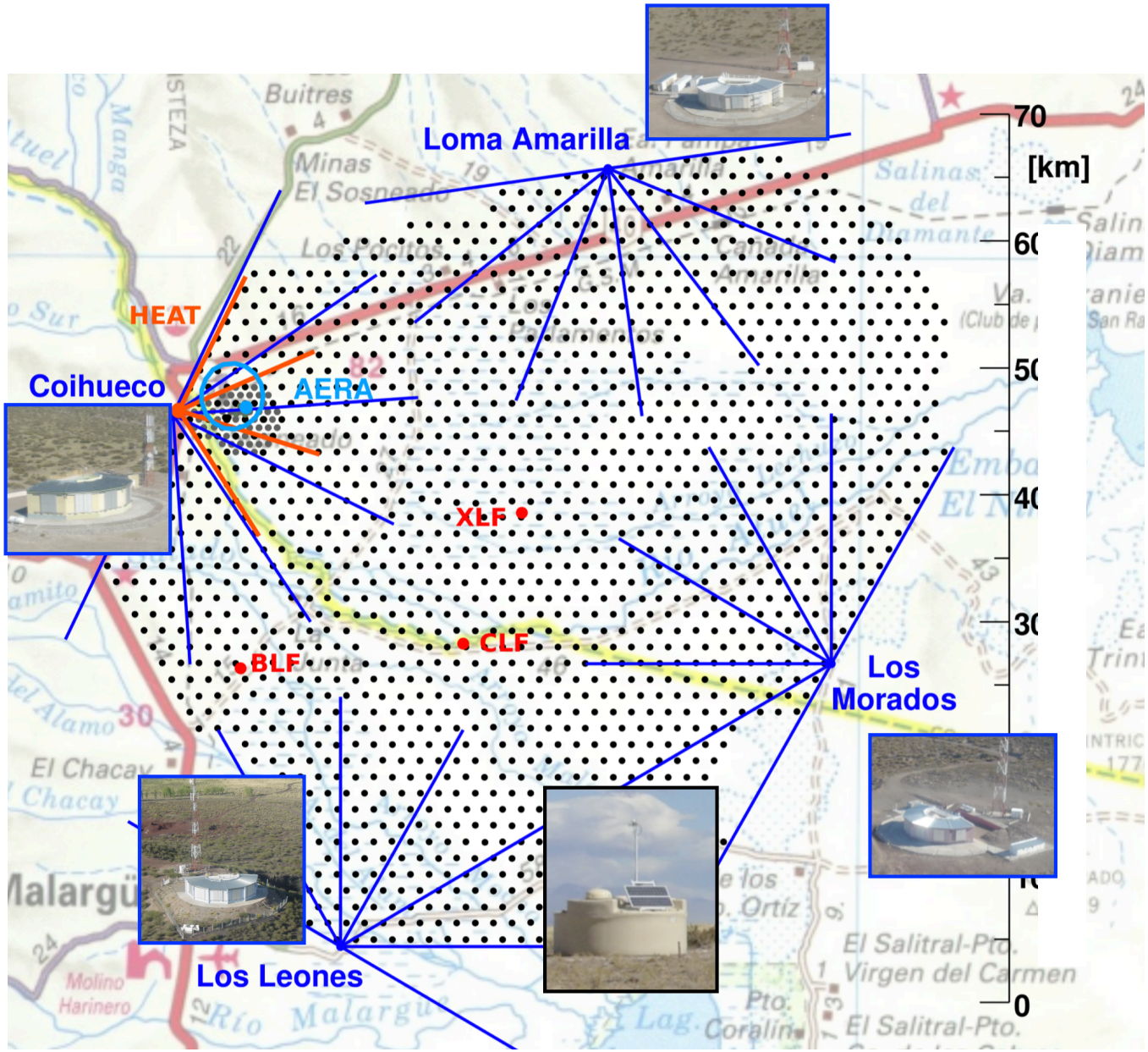
The Observatory



- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km^2

The Observatory



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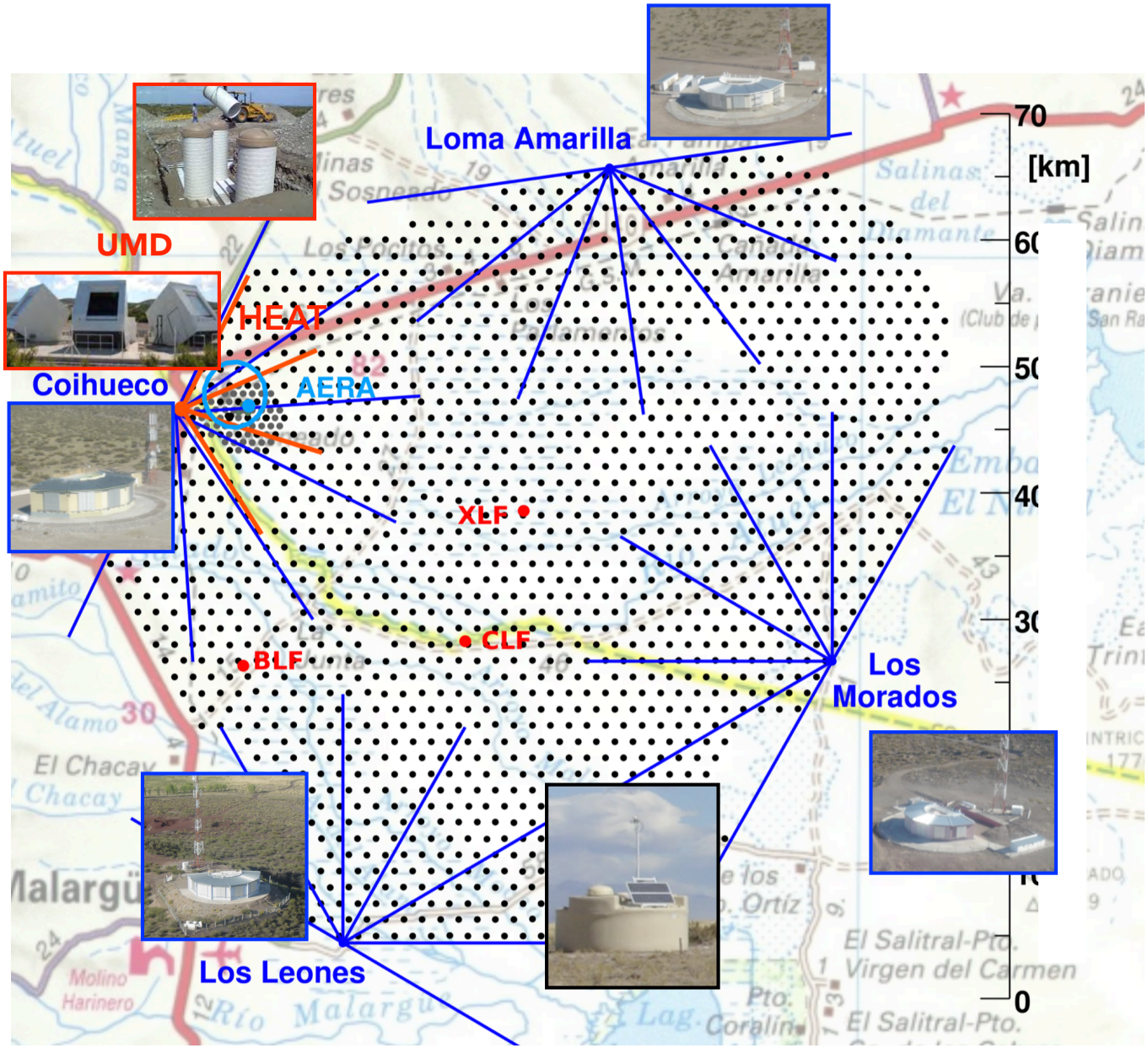
- 4 Fluorescence Sites
  - ➡24 telescopes, 1-30^0 FoV

The Observatory



- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km^2
  - ➡61, 0.75 km grid, ~25 km^2
- 4 Fluorescence Sites
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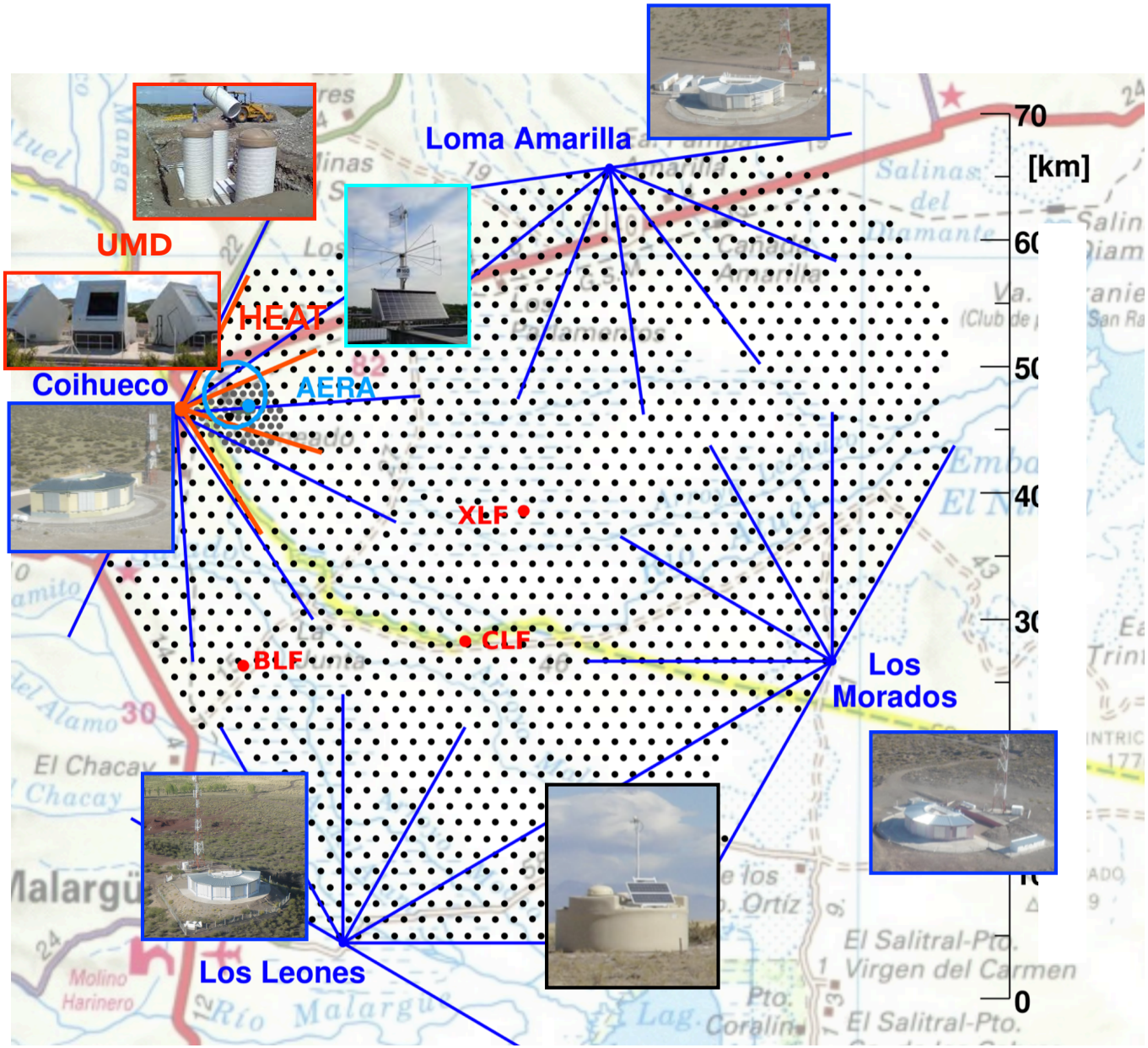
- HEAT
  - ➡3 high elevation FD, 30-60^0 FoV
- Underground Muon Detectors
  - ➡7 in engineering array phase - 61 aside the Infill stations

The Observatory



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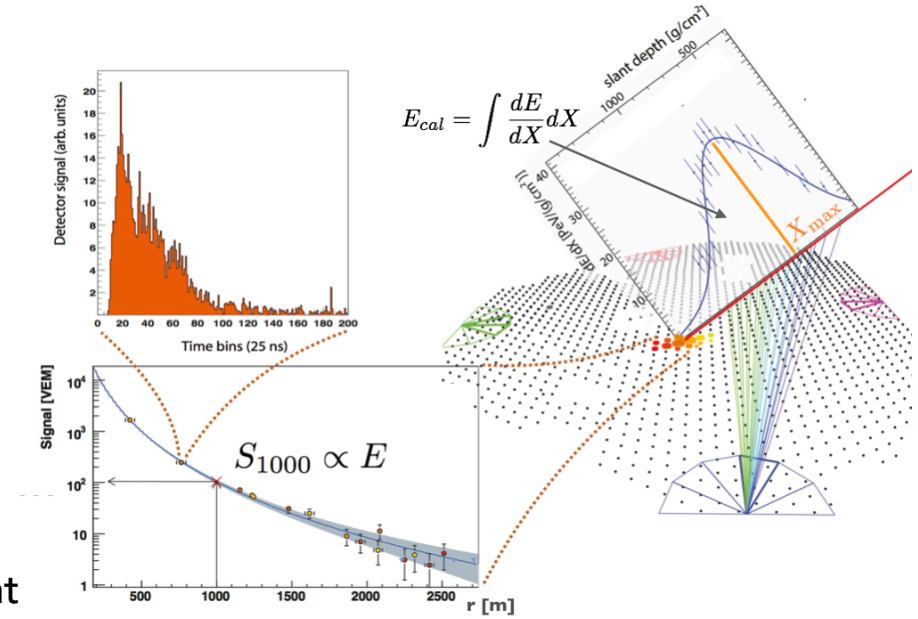
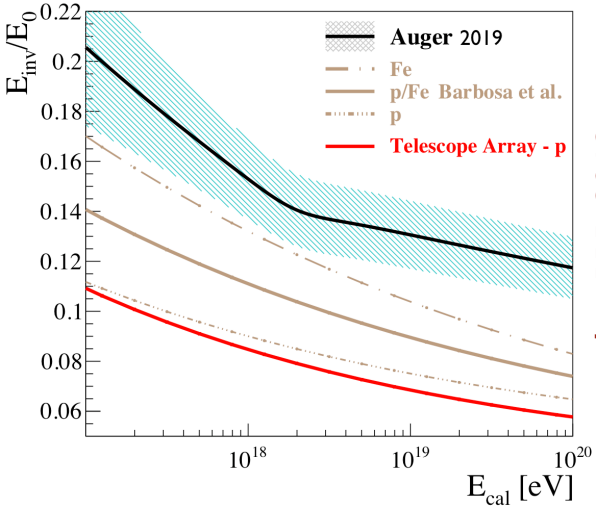
- AERA radio antennas
  - ➡153 graded 17 km^2

+Atmospheric monitoring devices
CLF, XLF, Lidars, …

Event reconstruction and energy scale

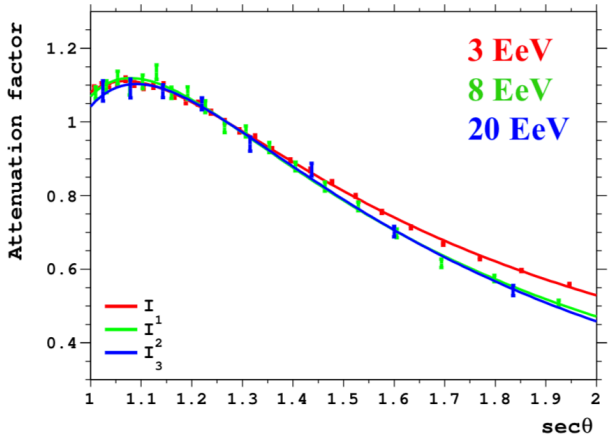


Invisible energy fraction



subm.PRD 2019

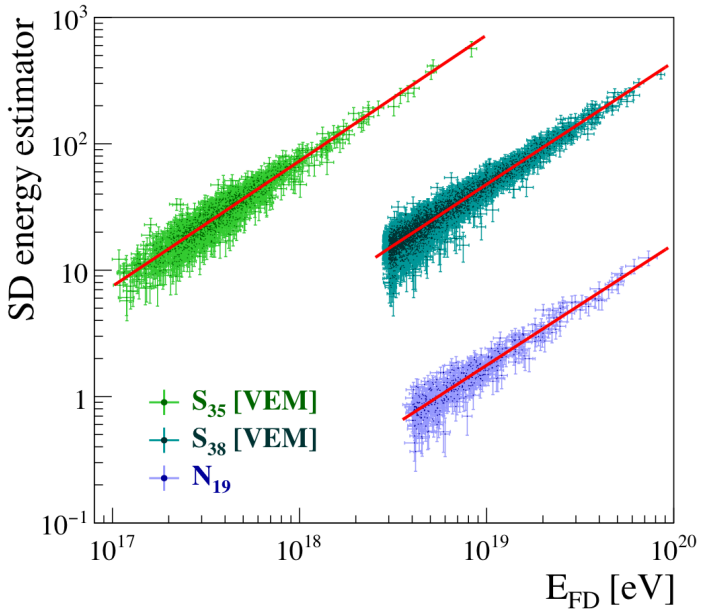
CIC evaluated at different energy thresholds



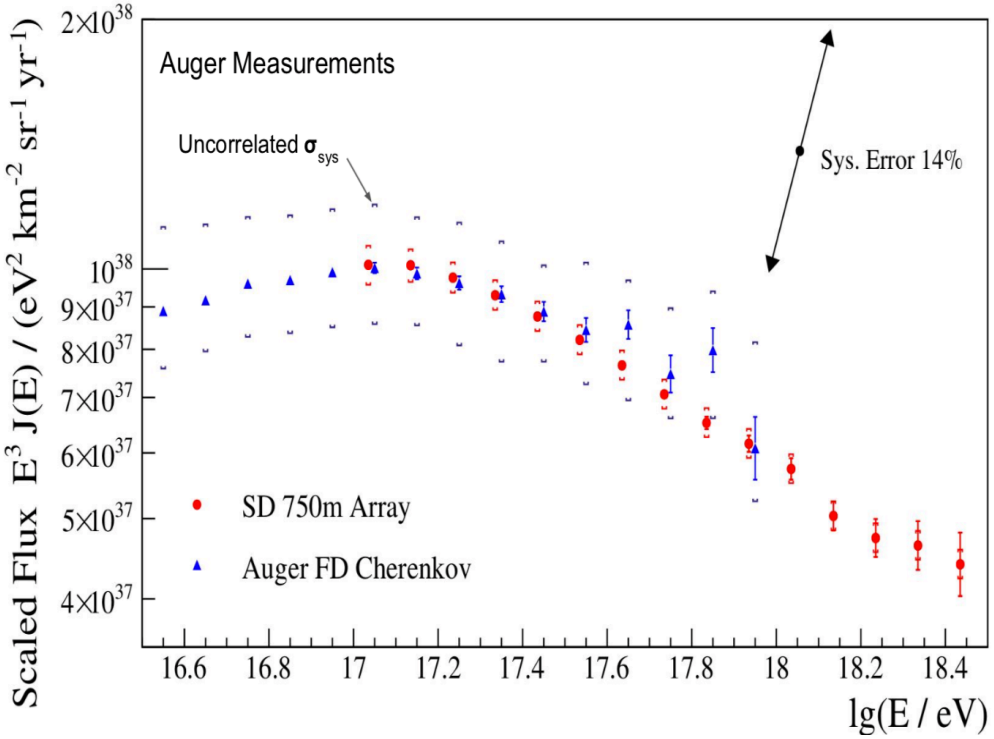
$$E_{FD} = E_{cal} + E_{inv}$$

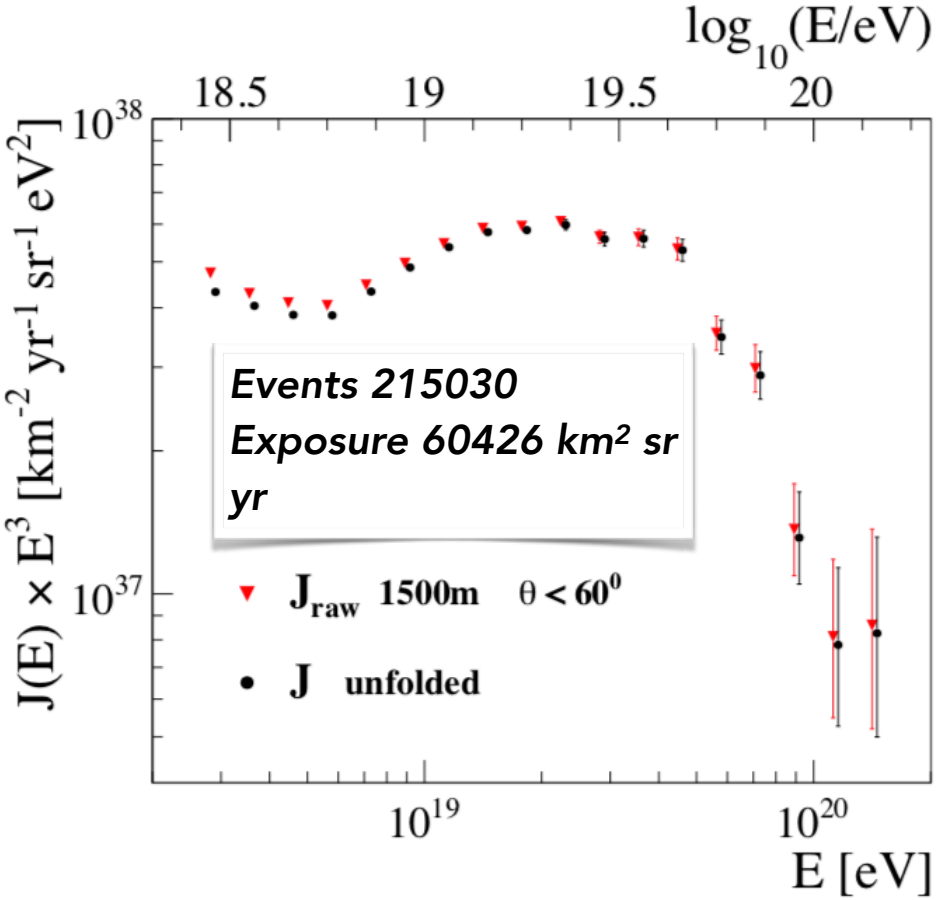
$\sigma(E_{FD})/E_{FD}$ ~ 8%

Systematic uncertainty 14%



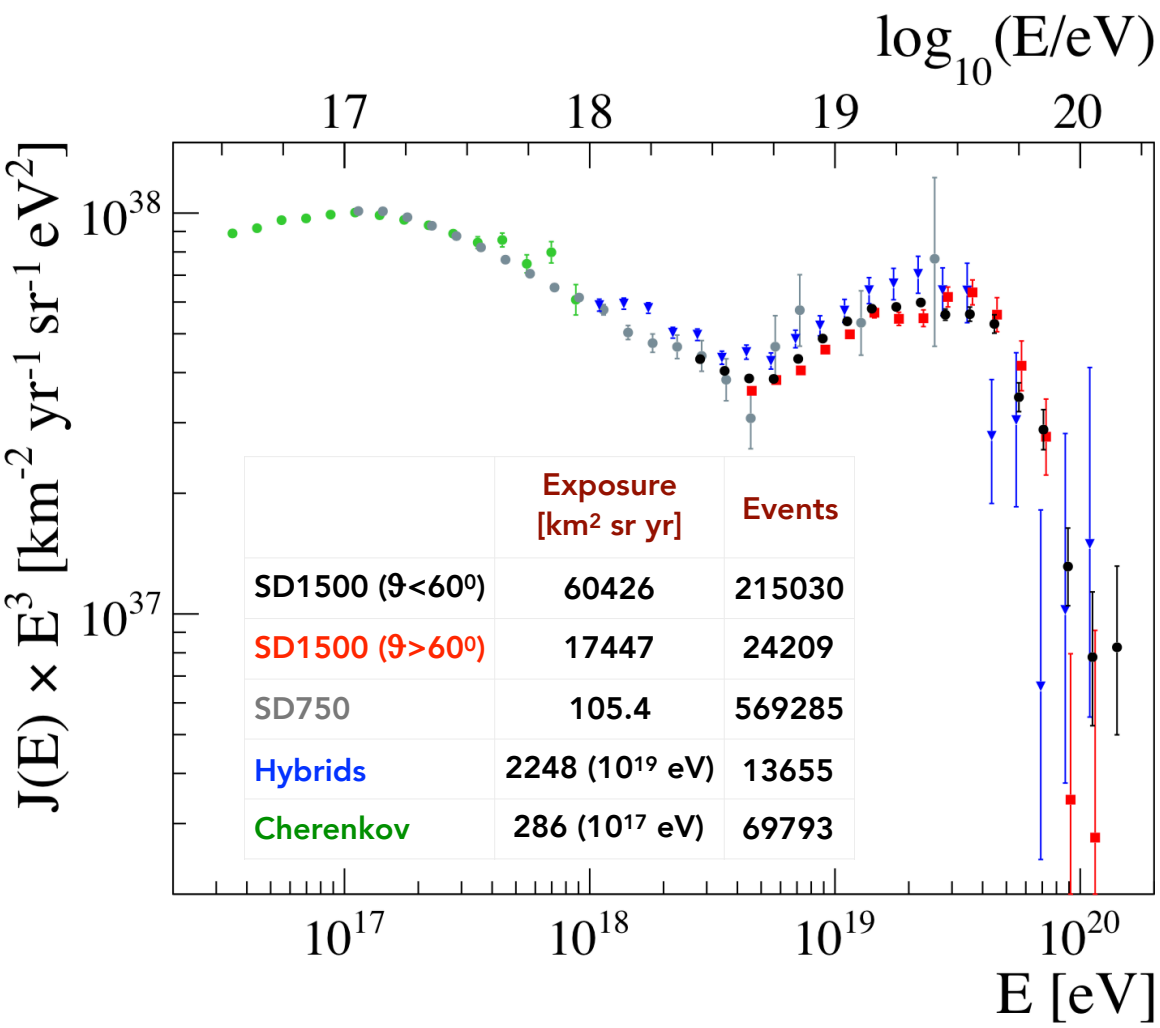
Energy spectrum



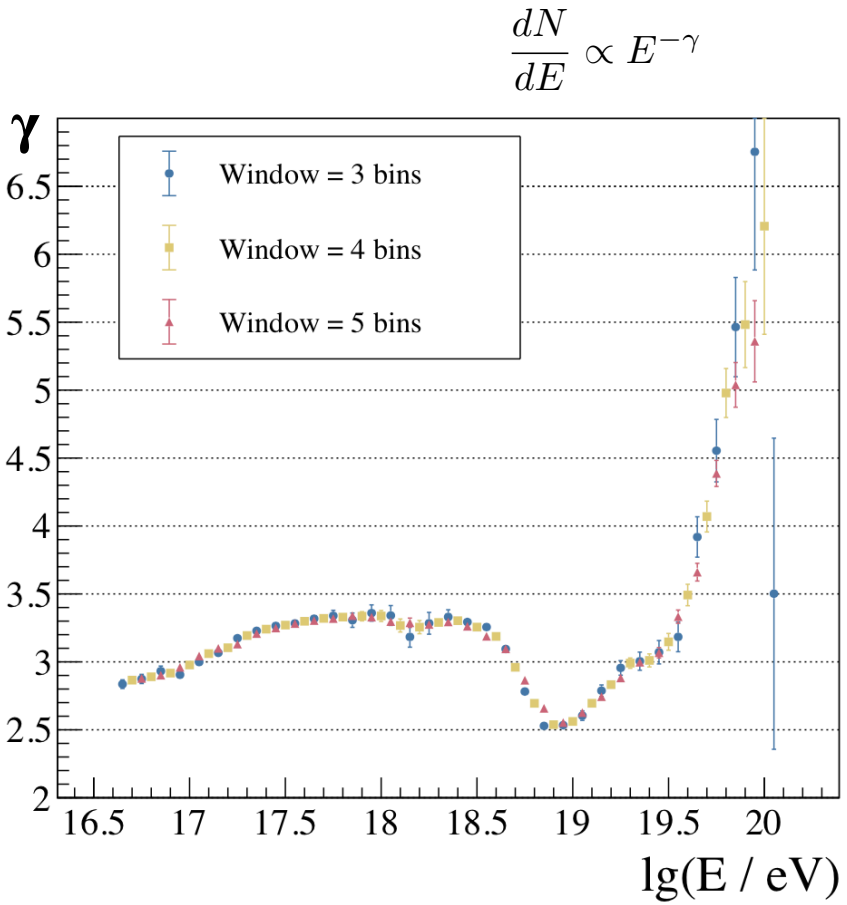


[Results mostly from ICRC2019]

Energy spectrum

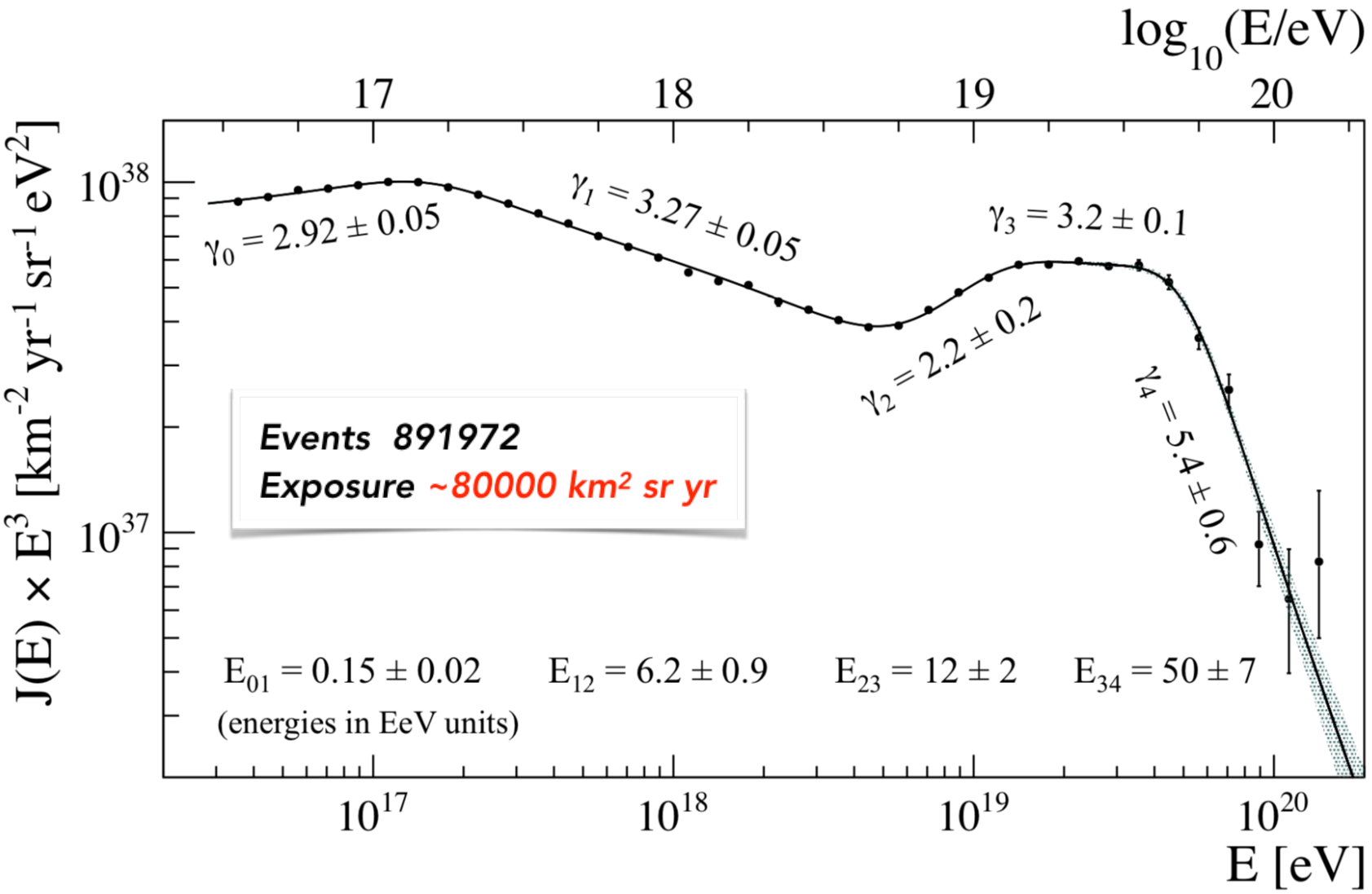


	Exposure [km² sr yr]	Events
SD1500 (ϑ<60⁰)	60426	215030
SD1500 (ϑ>60⁰)	17447	24209
SD750	105.4	569285
Hybrids	2248 (10^{19} eV)	13655
Cherenkov	286 (10^{17} eV)	69793



Evolution of spectral slope with energy

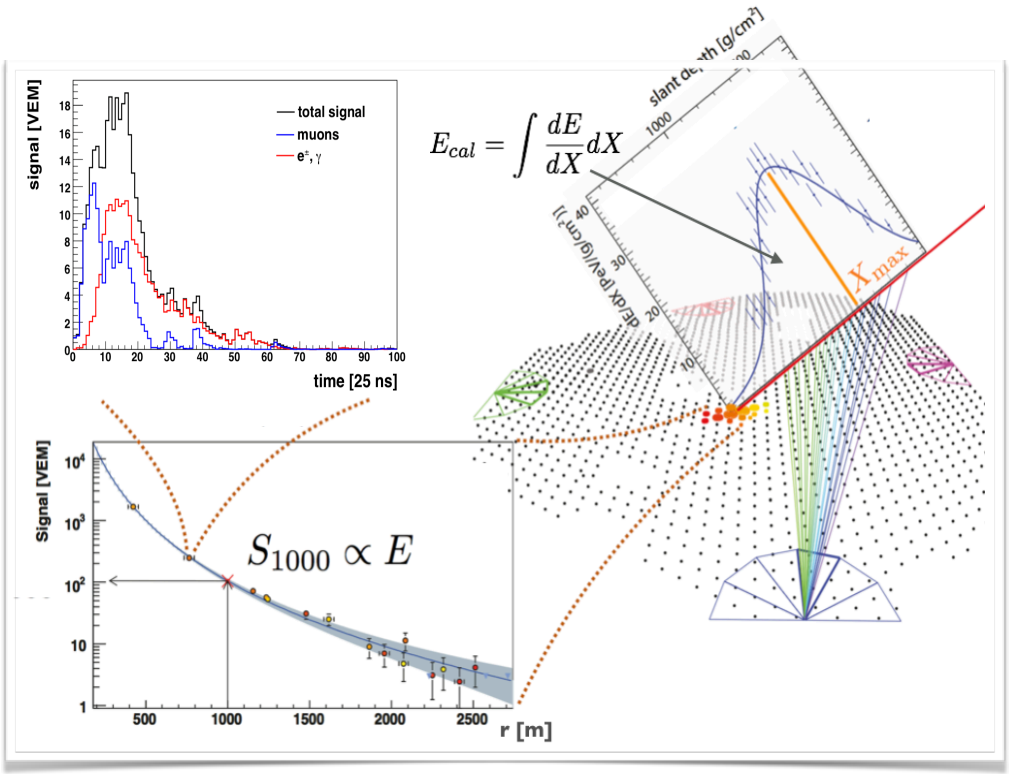
The combined energy spectrum

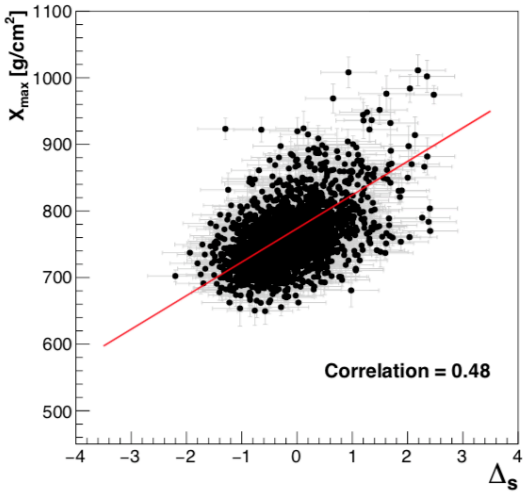


Mass composition

$$\Delta_i = \frac{t_{1/2} - t_{1/2}^{bench}}{\sigma_{1/2}}$$

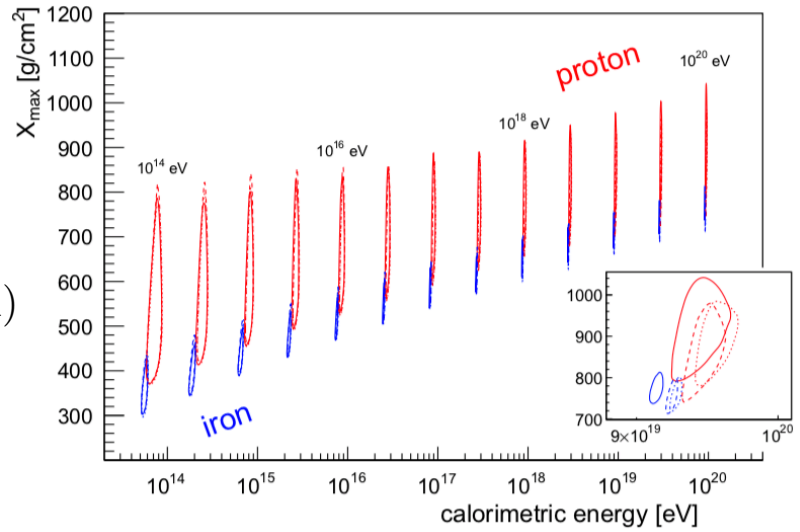
$$\Delta_s = \frac{1}{N}\sum_i \Delta_i$$





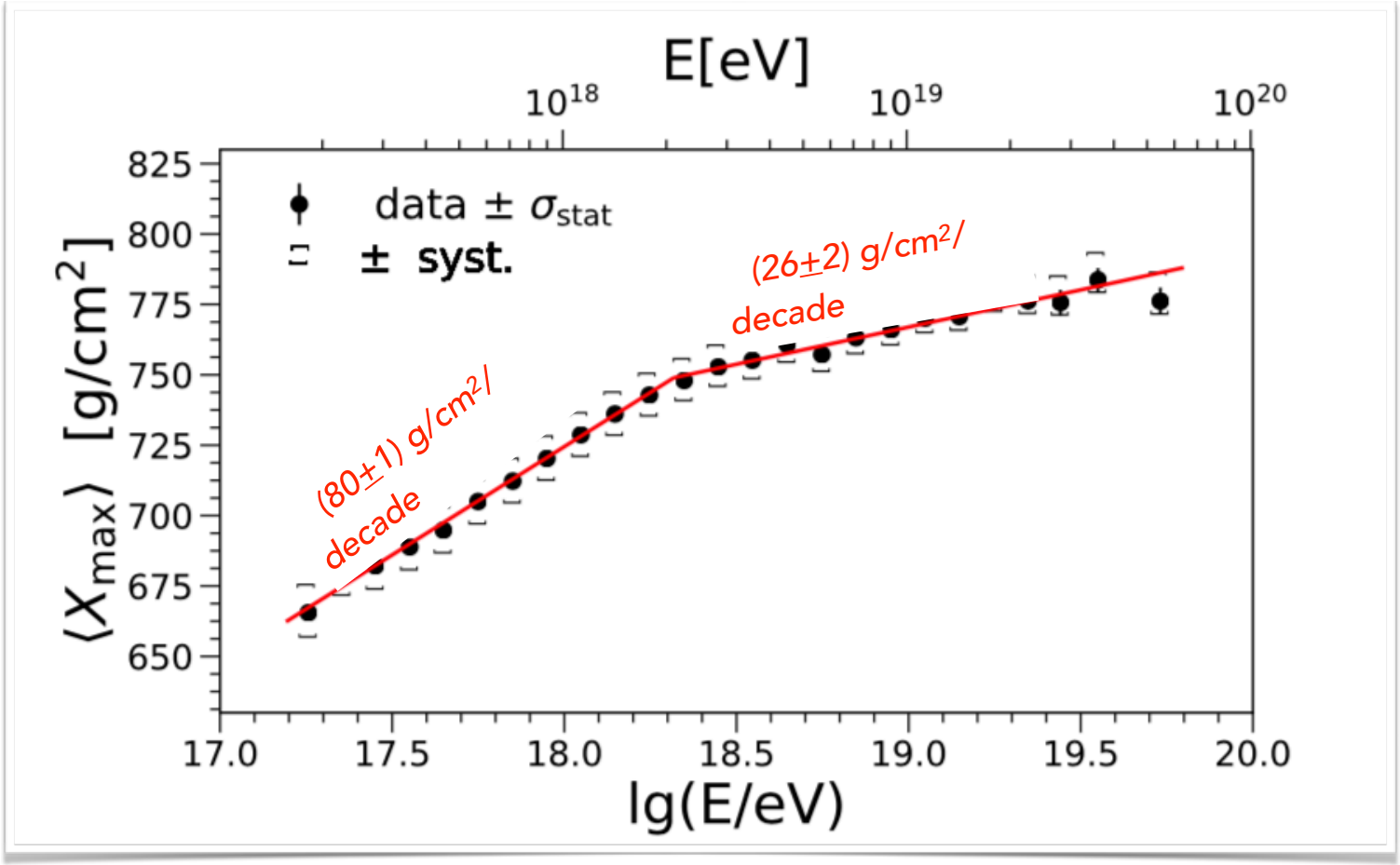
$$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f_E \langle lnA \rangle$$

$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E \sigma^2(lnA)$$



K.H.Kampert, M.Unger, AP35 (2012)

Evolution of $\langle X_{max} \rangle$ with energy



X_{max} resolution

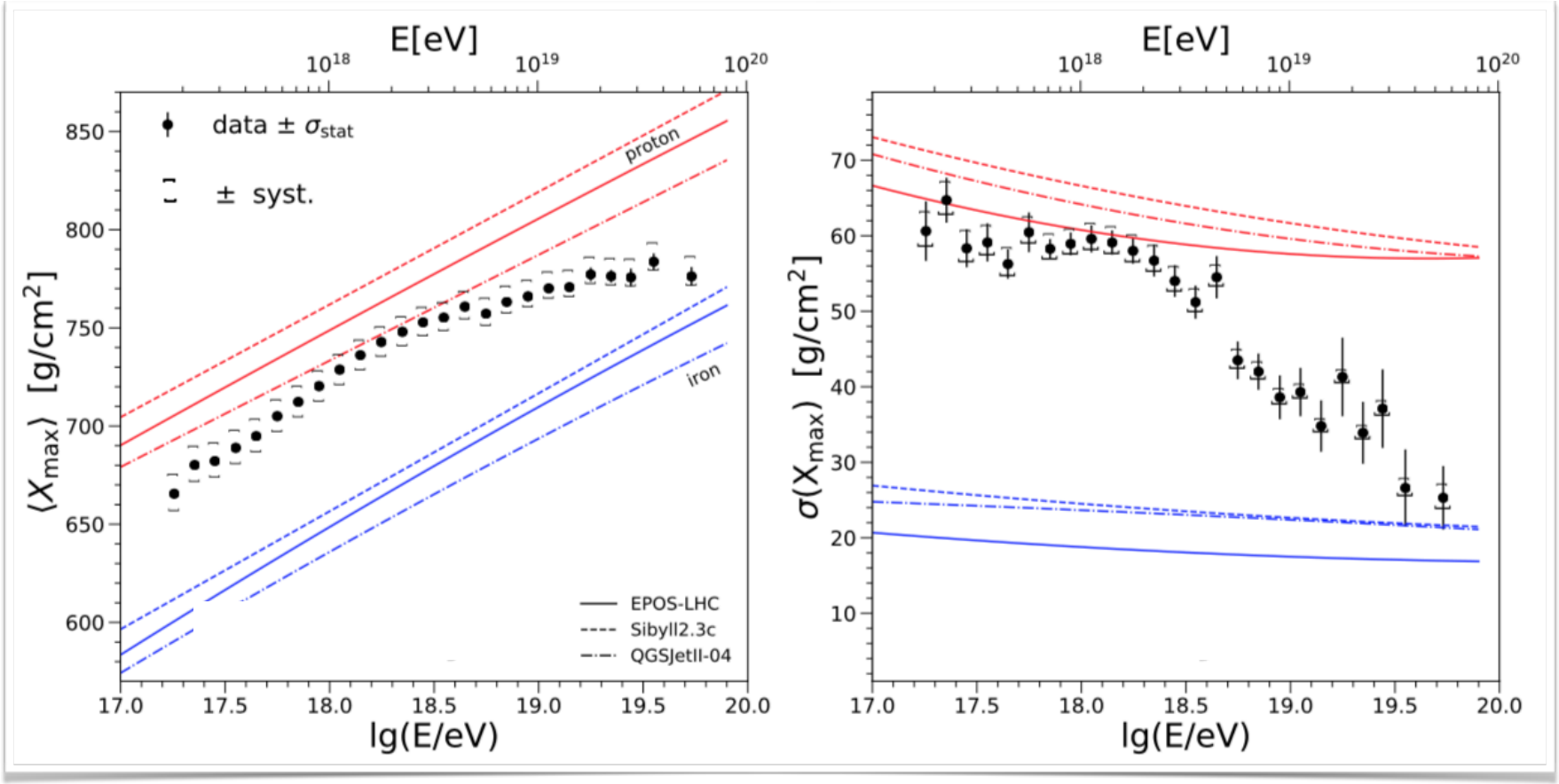
~25 g cm^{-2} at $10^{17.8}$ eV

~15 g cm^{-2} for E> 10^{19} eV

$\sigma_{sys} \leq 10$ g cm^{-2}

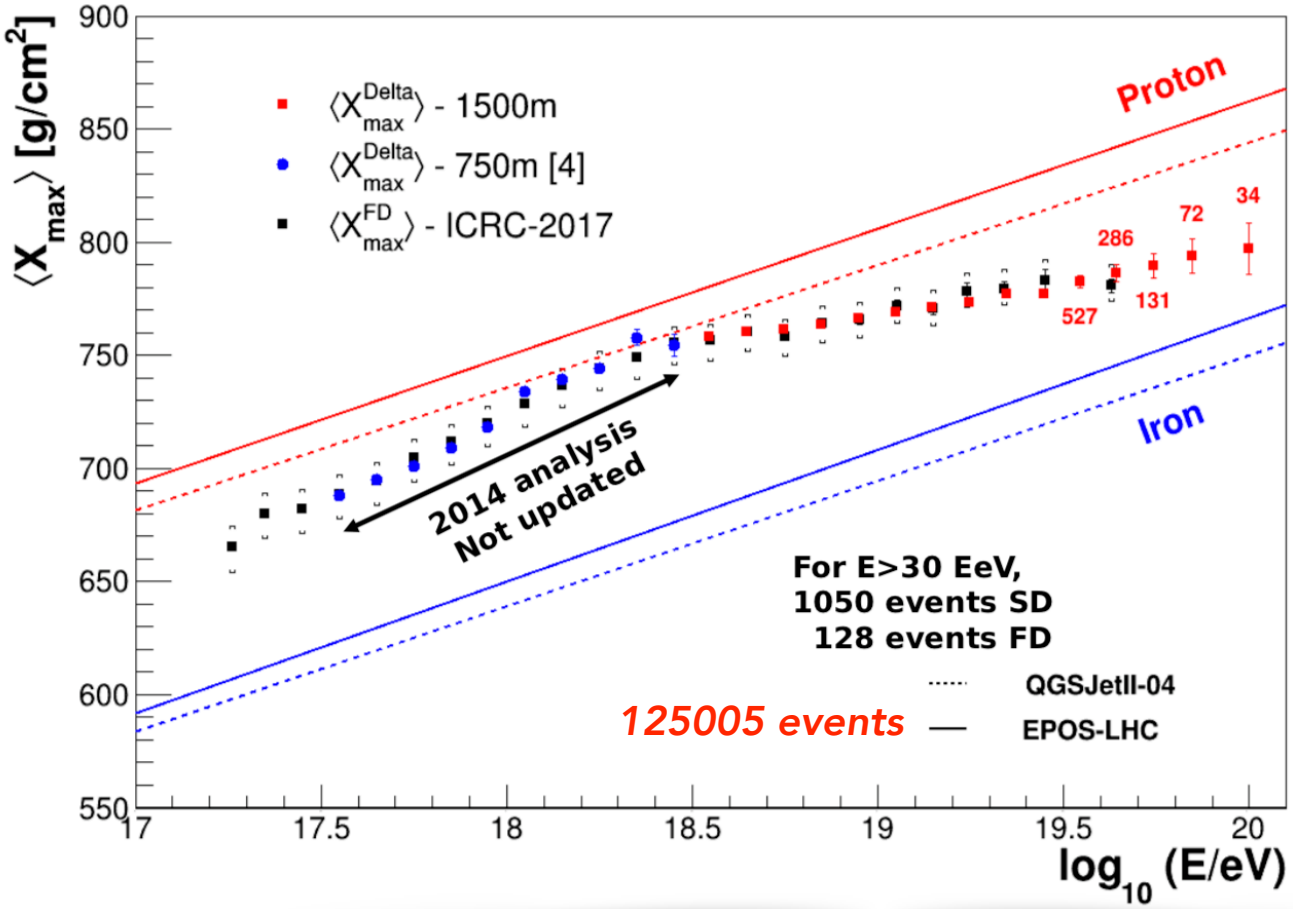
$\log_{10}$(E/eV)	FD
18.5-18.6	1098
18.6-18.7	834
18.7-18.8	578
18.8-18.9	469
18.9-19.0	356
19.0-19.1	281
19.1-19.2	191
19.2-19.3	131
19.3-19.4	111
19.4-19.5	66
> 19.5-	62
Total	4177

$\langle X_{max} \rangle$ and its fluctuations from FD



Lighter composition up to ~2 EeV, heavier above this energy

<X_{max}> from SD



$\log_{10}$(E/eV)	SD
18.5-18.6	45872
18.6-18.7	27783
18.7-18.8	17011
18.8-18.9	11631
18.9-19.0	7960
19.0-19.1	5489
19.1-19.2	3582
19.2-19.3	2290
19.3-19.4	1473
19.4-19.5	864
19.5-19.6	527
19.6-19.7	286
19.7-19.8	131
19.8-19.9	72
>19.9	34
Total	125005

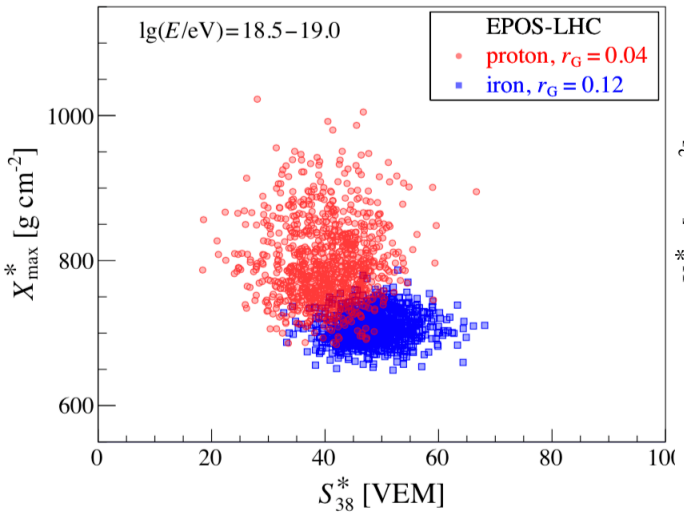
Rate of change of primary mass not constant with energy, in agreement with results from FD

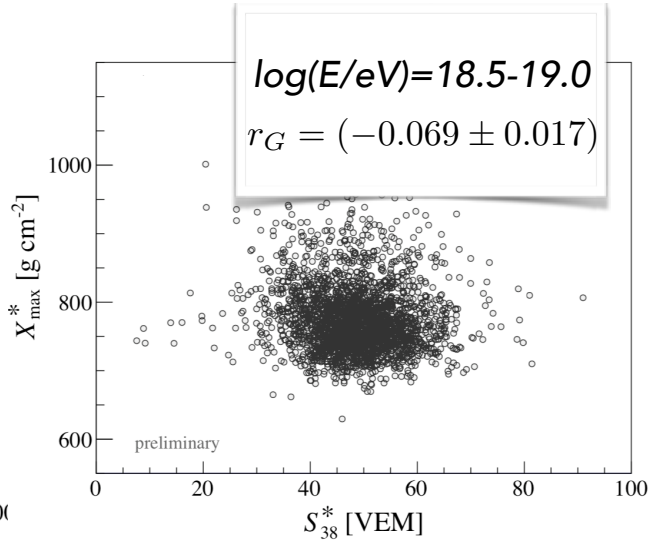
Mass composition at the ankle

$S^*_{38^\circ}(1000)$

X^*_{max}

rescaled at 10 EeV



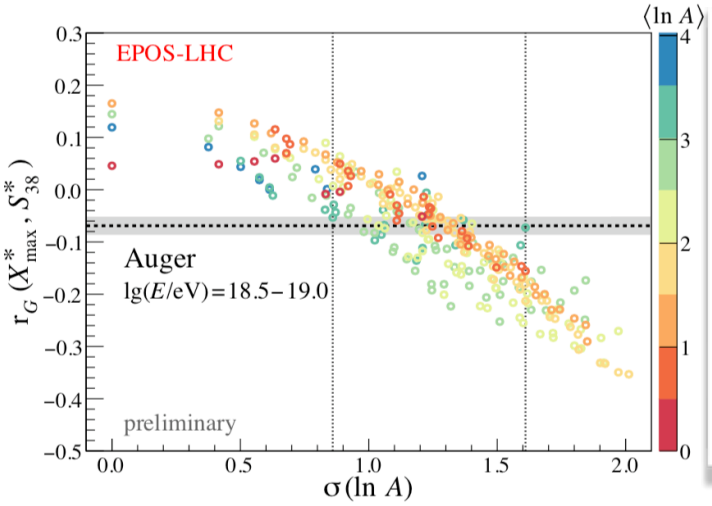


Abow the ankle

$r_G = (0.025 \pm 0.028)$

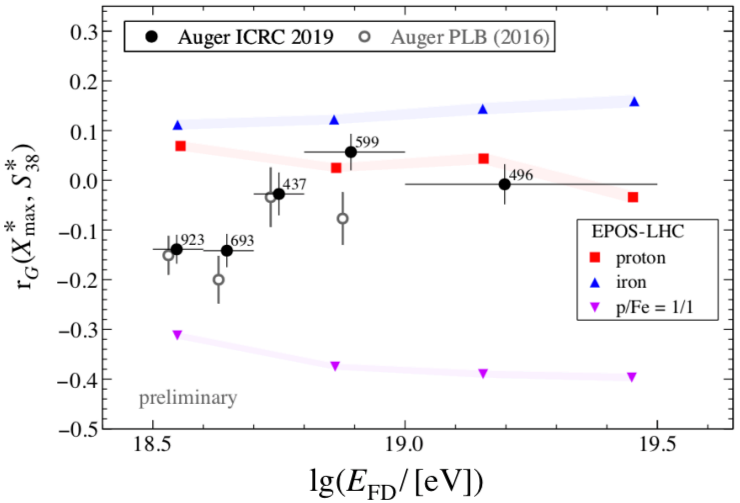
Below the ankle

$r_G = (-0.141 \pm 0.022)$



Up to the ankle pure or (p+He) compositions excluded at >6σ

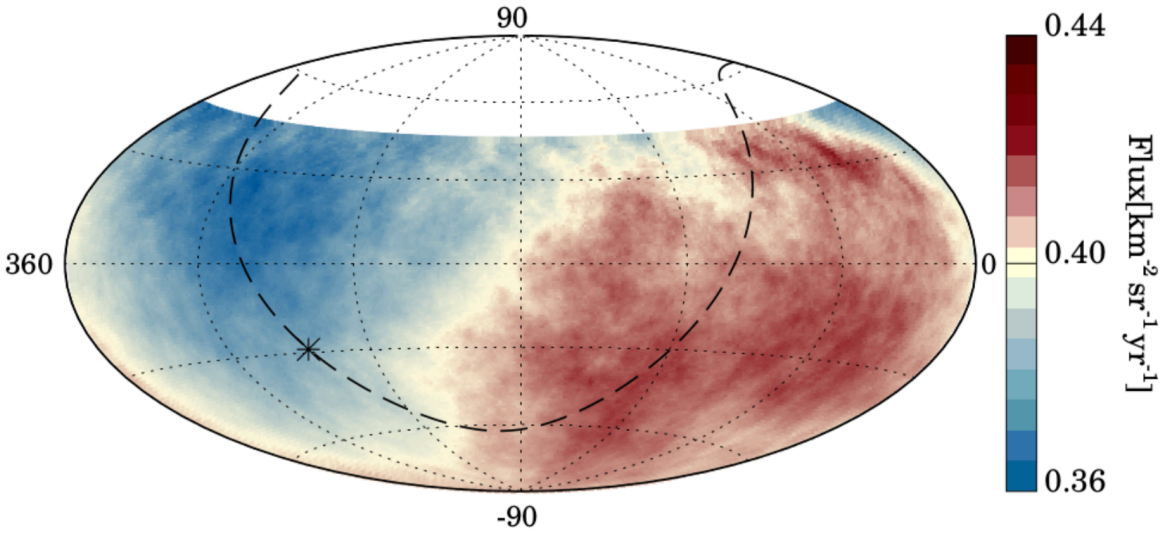
At higher energies, correlation consistent with less mixed composition

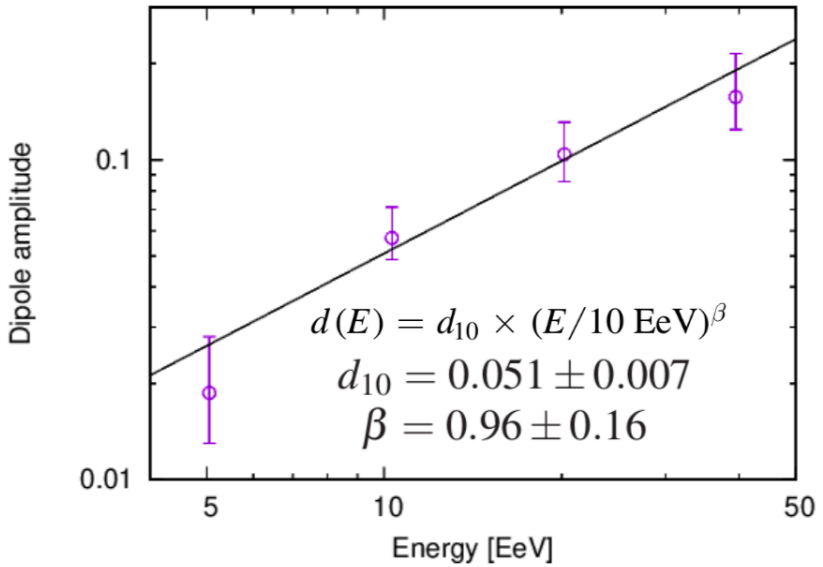


Large Scale anisotropy

Energy [EeV] interval	median	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]
4 - 8	5.0	88,317	$0.010^{+0.007}_{-0.004}$	-0.016 ± 0.009	$0.019^{+0.009}_{-0.006}$	70 ± 34	-57^{+24}_{-20}
≥ 8	11.5	36,924	$0.060^{+0.010}_{-0.009}$	-0.028 ± 0.014	$0.066^{+0.012}_{-0.008}$	98 ± 9	-25 ± 11

Exposure >92000 km²sr yr for events with ϑ<80⁰





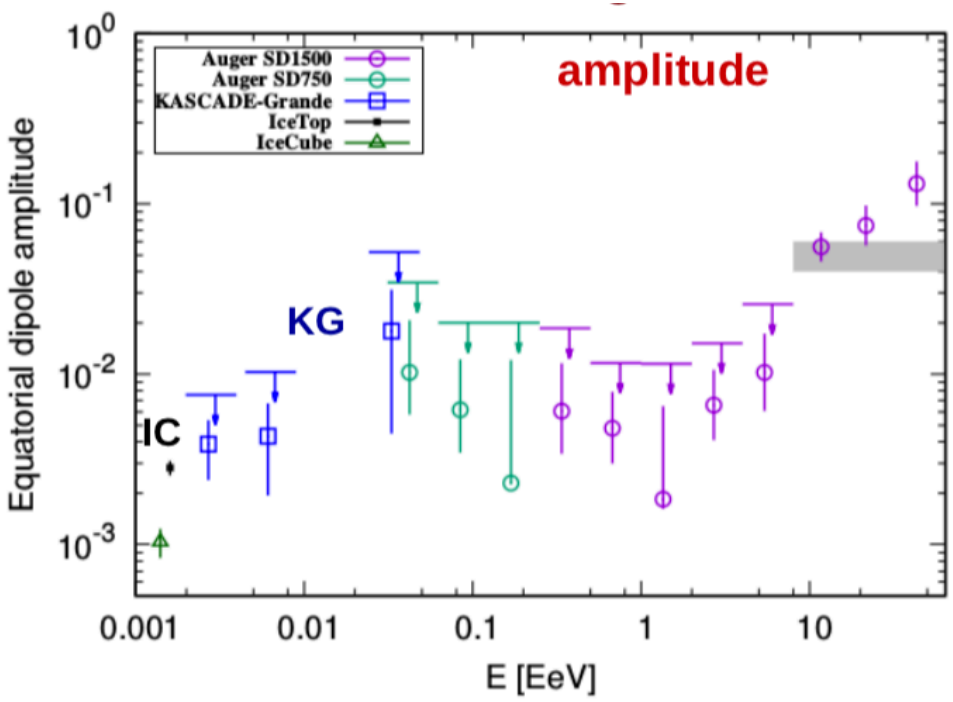
3-D Dipole above 8 EeV at (α,δ) = (98⁰,-25⁰) : $(6.6^{+1.2}_{-0.8})\%$

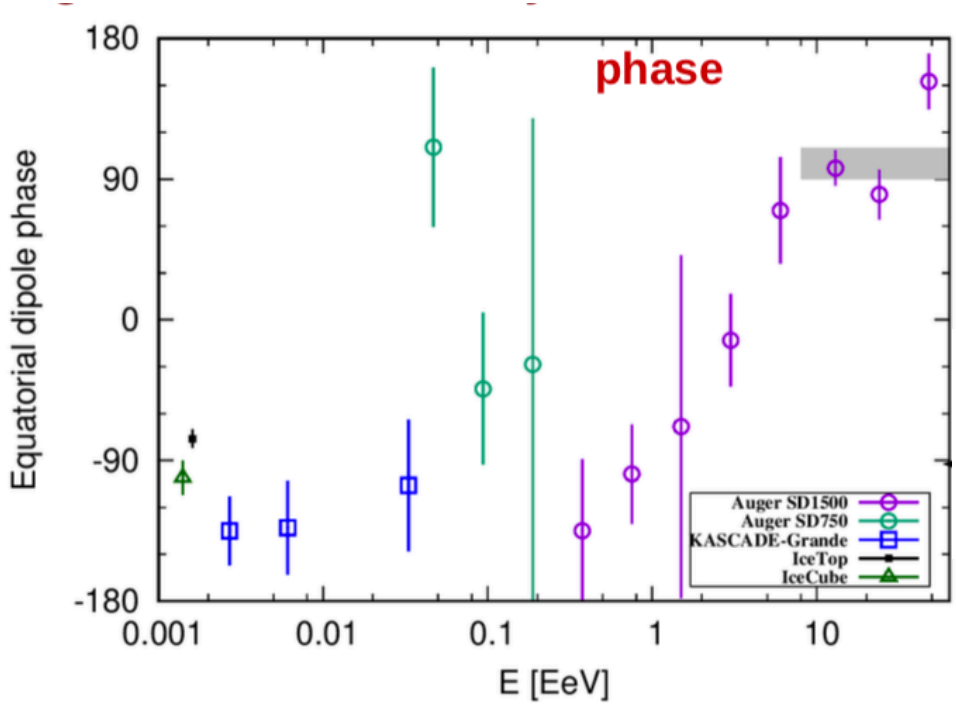
Amplitude increasing with energy

Large Scale anisotropy

Search for large scale anisotropies down to 0.03 EeV

- SD1500 + SD750 data,
- East-West method below 2 EeV



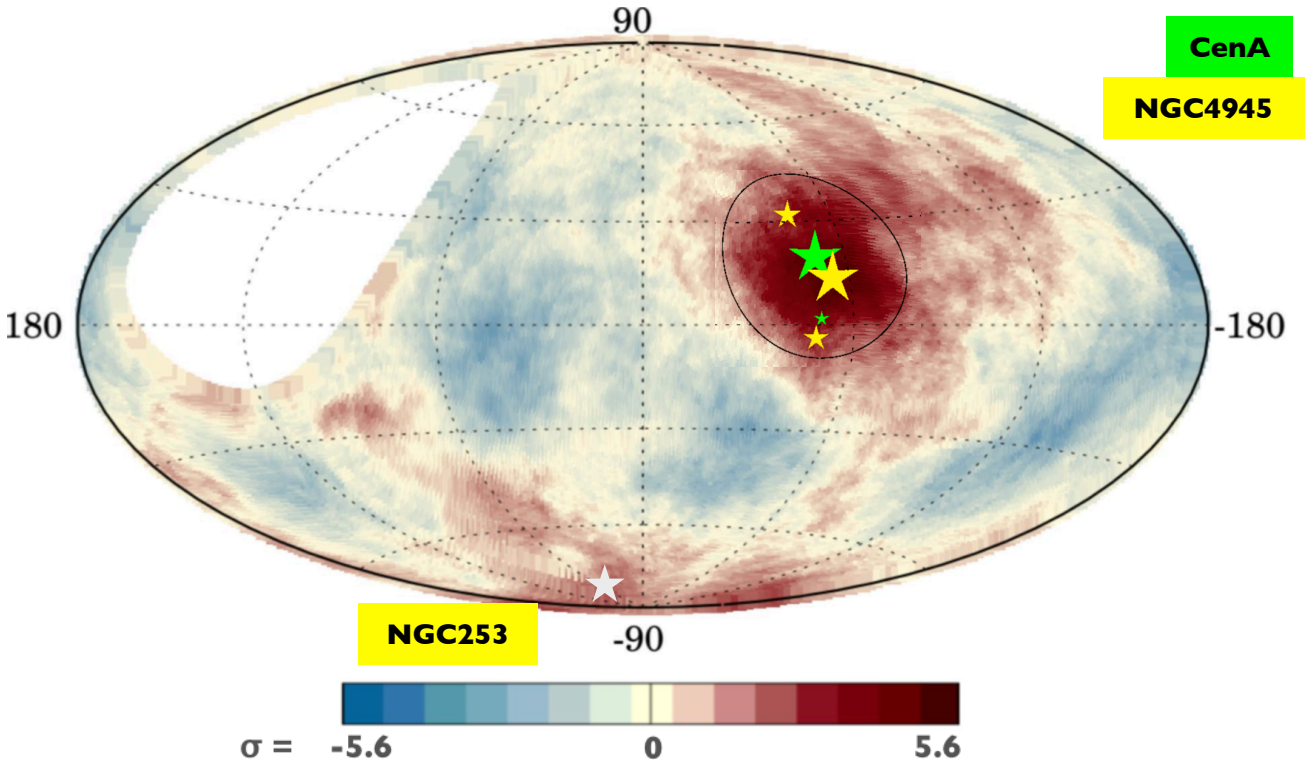


Predominantly Galactic origin below 1-2 EeV, extragalactic origin above

Intermediate anisotropy

Total SD events with E>32 EeV : 2157

Total exposure 101,400 km^2 sr yr



Blind search

Scan ranges:

32 EeV ≤ Eth ≤ 80 EeV (1 EeV steps)

1° ≤ ψ ≤ 30° (1° steps)

Most significant excess for E>38 EeV (α=202^0, δ= -45^0) ~2^0 from CenA

Centaurus A

3.9 σ effect (post-trial) for E>37 EeV, 28^0 window

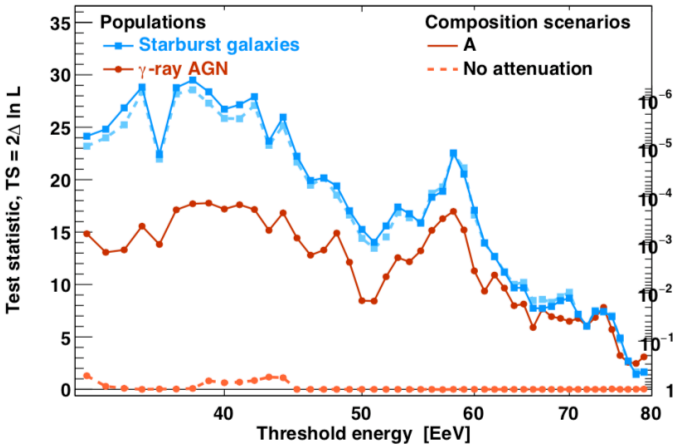
Intermediate anisotropy

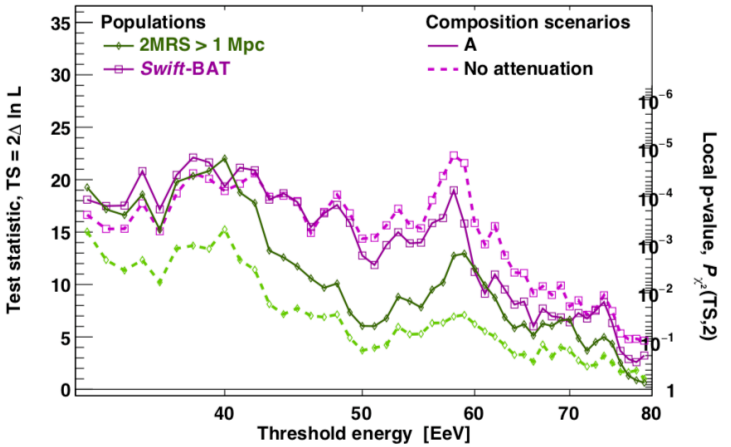
γ AGNs
- 3FHL catalog < 250 Mpc
- 33 sources (CenA, Fornax A, M87…)
- Flux proxy ϕ(>10 GeV)

Starburst Galaxies
- 32 sources (Circinus, M82, M83,…)
- <250 Mpc
- Flux proxy ϕ(>1.4 GHz), > 0.3 Jy

Swift-BAT
- >300 radio loud and quiet sources
- <250 Mpc
- ϕ>13.4 10^{-12} erg cm^{-2} s^{-1}

2MRS
- ~10^4 sources with D>1 Mpc
- <250 Mpc
- Flux proxy ϕ(14-195 keV)



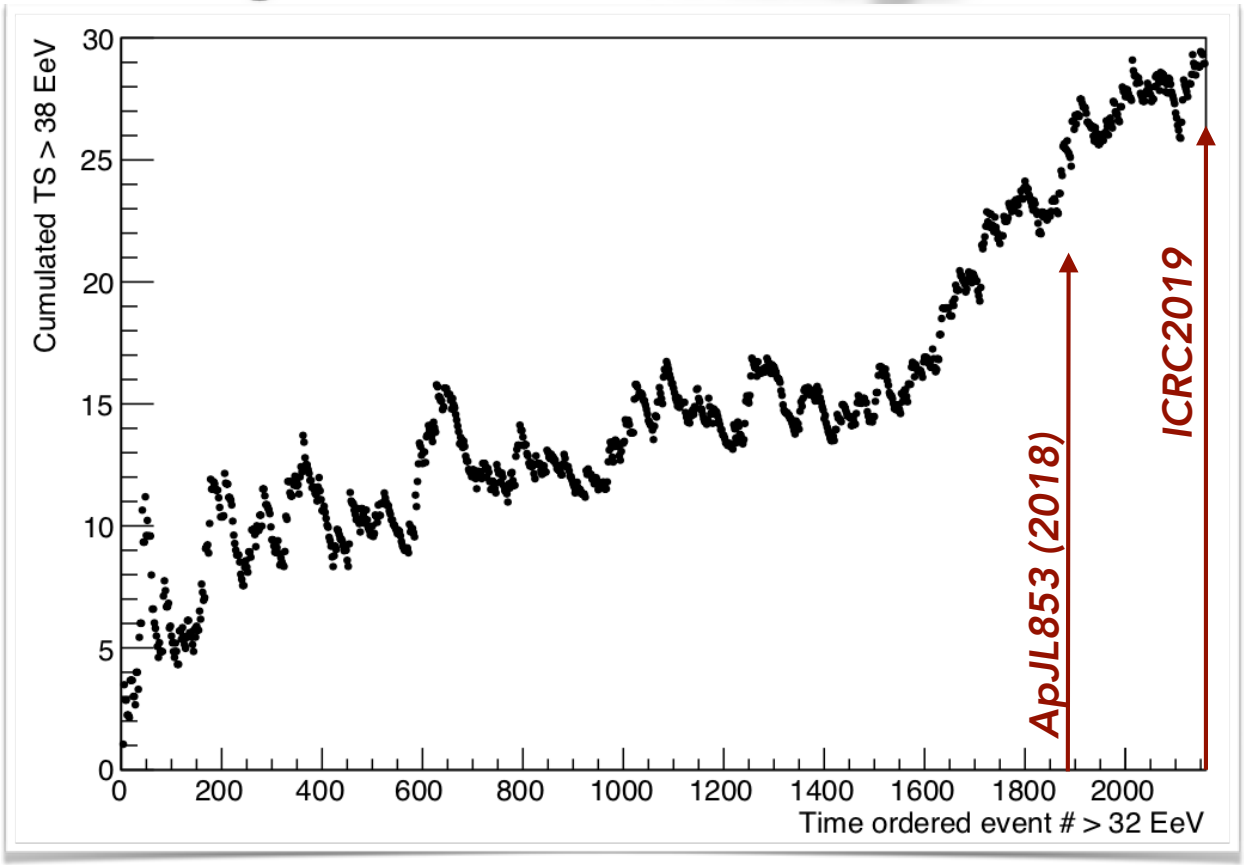


Likelihood analysis

$$TS = 2Log\left[L(\psi, f_{anis})/L(f_{anis} = 0)\right]$$

Catalog	E_{th}	TS	Local p-value	post-trial	f_{aniso}	θ
Starburst	38 EeV	29.5	4×10^{-7}	4.5 σ	11^{+5}_{-4}%	15^{+5}_{-4} °
γ−AGN	39 EeV	17.8	1×10^{-4}	3.1 σ	6^{+4}_{-3}%	14^{+6}_{-4} °
Swift-BAT	38 EeV	22.2	2×10^{-5}	3.6 σ	8^{+4}_{-3}%	15^{+6}_{-4} °
2MRS	40 EeV	22.0	2×10^{-5}	3.6 σ	19^{+10}_{-7}%	15^{+7}_{-4} °

Likelihood analysis with catalogs



Rejection of isotropy hypothesis

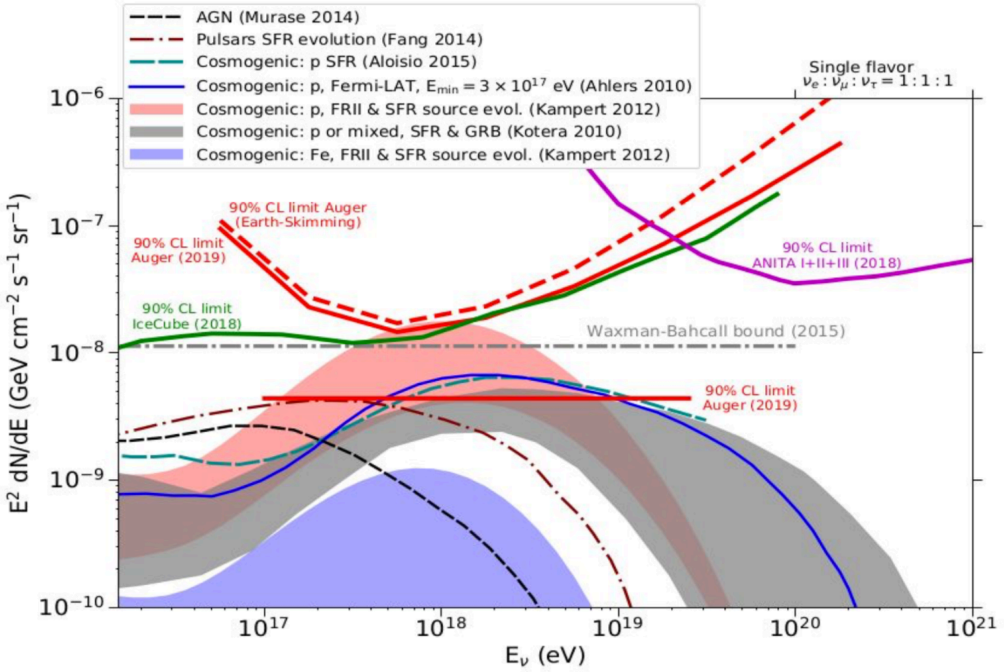
APJ	4.0 σ	for SBGs
[Jan 2004-Apr 2017]	2.7 σ	for γ-AGN
ICRC2019	***4.5 σ***	***for SBGs***
[Jan 2004-Aug 2018]	***3.1 σ***	***for γ-AGN***

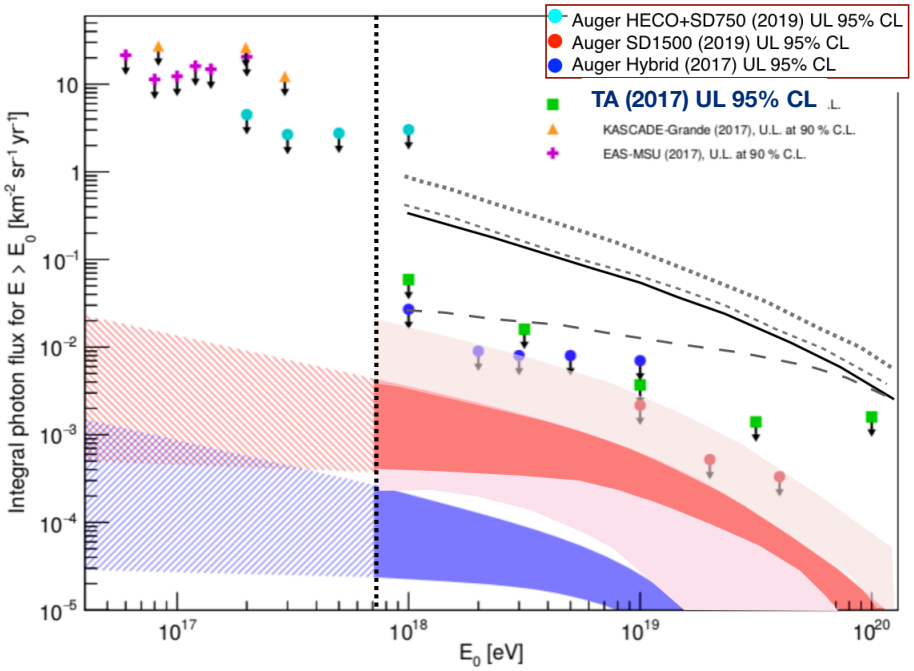
Significance increasing with time !

Cosmogenic neutrino and photon fluxes

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

- *Maximum sensitivity around EeV*
  k (90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}
- *Exclusion of a significant region of parameter space (z_{max}, m) from non observation of ν*





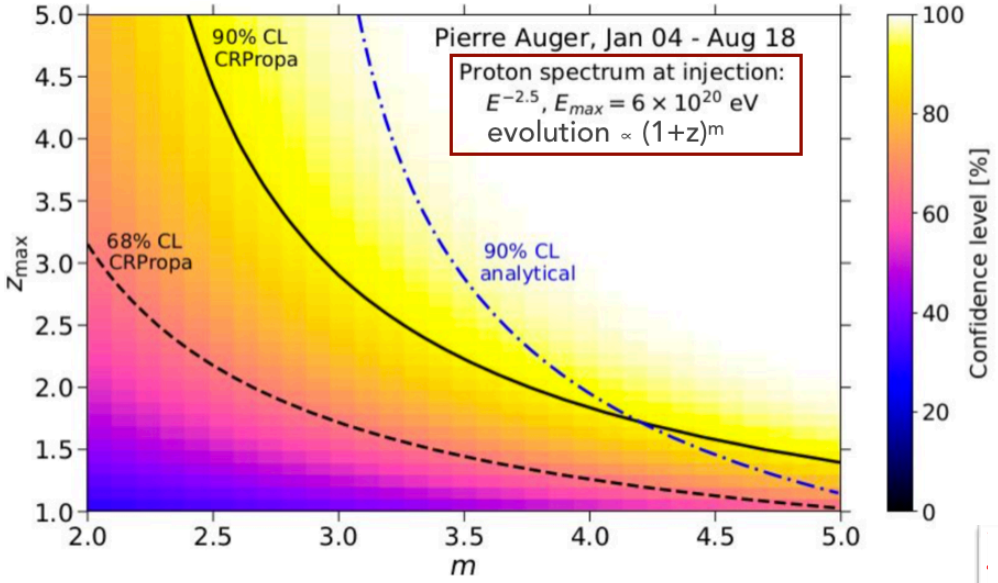
$$p + \gamma \rightarrow p + \pi^0$$
$$\rightarrow \gamma + \gamma$$

GZK p (Gelmini '08)
GZK p (Kampert+, 2011)
GZK Fe (Kampert+, 2011)

SHDM
SHDM'
TD
ZB

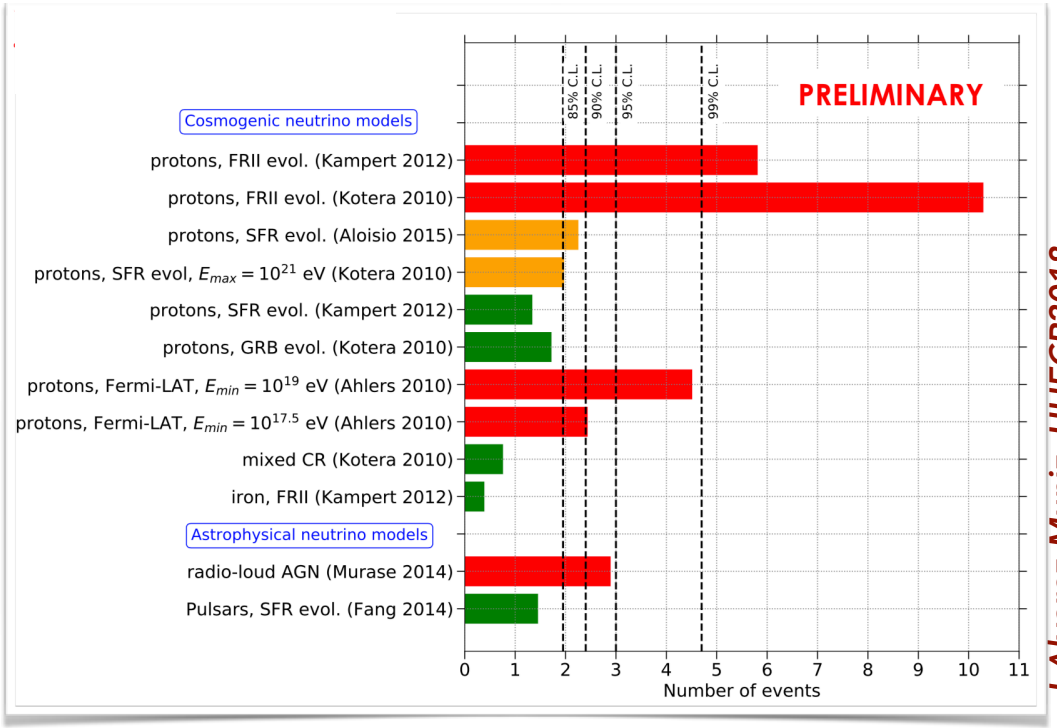
- *Most sensitive EAS detector for E_γ>0.8 EeV*
- *Most top-down models excluded by experimental result*
- *Most optimistic models with proton primaries already excluded*

Constraints to neutrino models



Black lines & colored background: ν fluxes obtained with Monte Carlo CRPropa 3 (A. Van Vliet et al.) - proton flux at Earth normalized to Auger spectrum at E = 7 x 10^{18} eV.
Blue line: fluxes obtained with approx. analytical approach (Yoshida et al.)

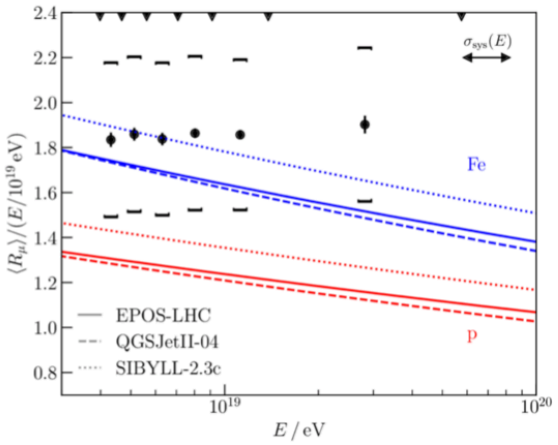
Exclusion of a significant region of parameter space (z_{max}, m) from non observation of ν

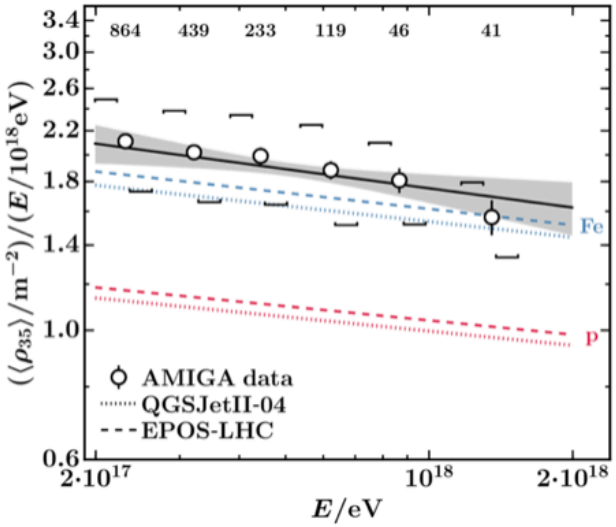


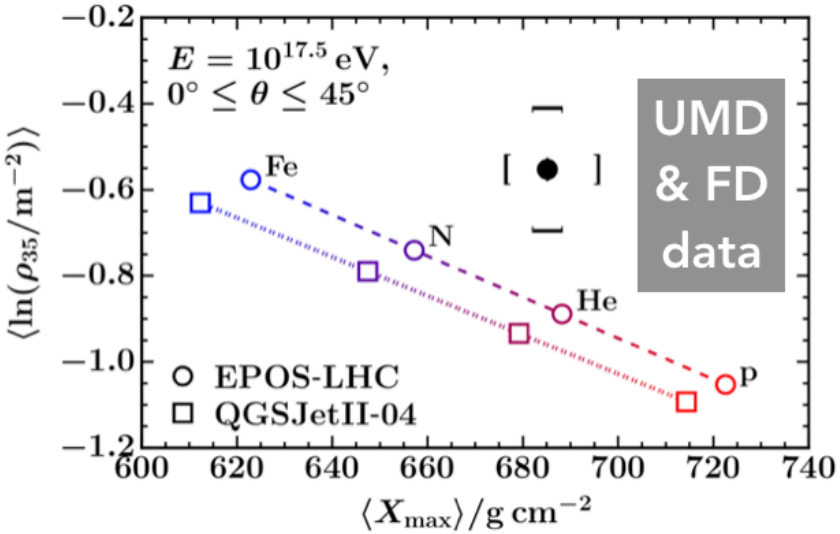
J.Alvarez-Muniz, UHECR2018

Muon content in air showers

(UMD = Underground Muon Detector)







In the energy range 3x10¹⁷ eV to 2x10¹⁸ eV simulations fail to reproduce muon densities

38% (53%) increase in $\langle N_\mu \rangle$ at 1 EeV needed for EPOS-LHC (QGSJetII-04)

More information from muons

$$N_\mu = A^{1-\beta}\left(\frac{E_0}{E_{dec}}\right)^{\beta}$$

Strong correlation between E_{had}/E_0 and N_μ, independent on the hadronic interaction model

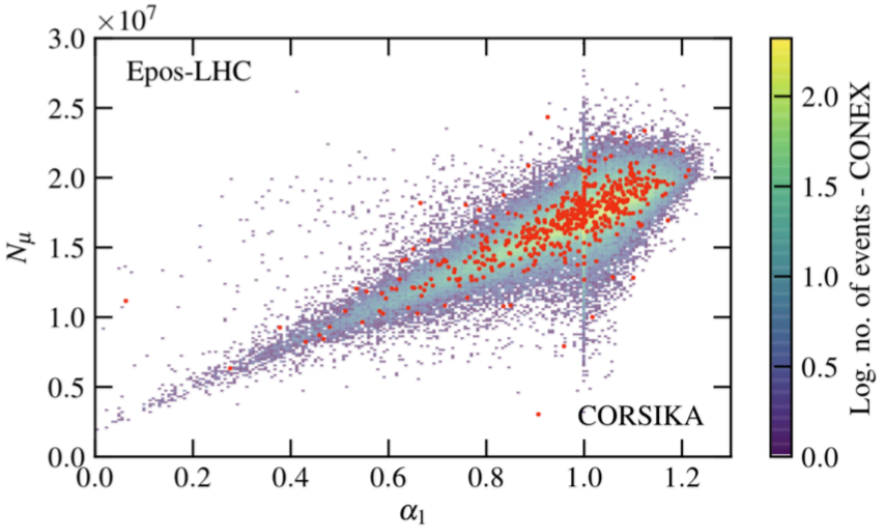
$$\alpha_1 = \sum_{i=1}^{m}\left(\frac{E_i^{had}}{E_0}\right)^{\beta} \qquad \beta = \frac{\log(m)}{\log(m_{tot})}$$

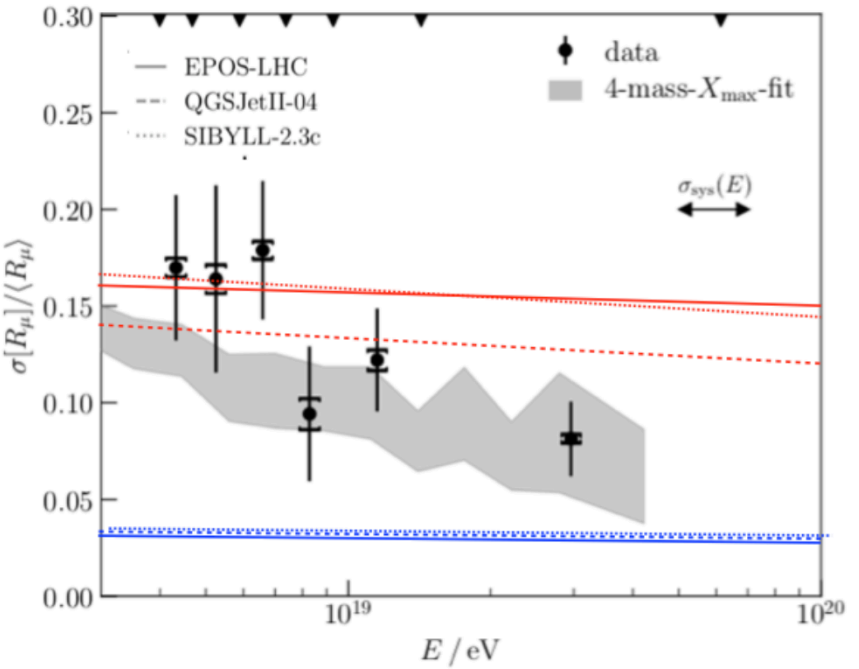
$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 \simeq \left(\frac{\sigma(\alpha_1)}{\alpha_1}\right)^2 + \left(\frac{\sigma(\alpha_2)}{\alpha_2}\right)^2 + \ldots + \left(\frac{\sigma(\alpha_c)}{\alpha_c}\right)^2$$

Fluctuations in the muon number = probe of the first interation at UHE

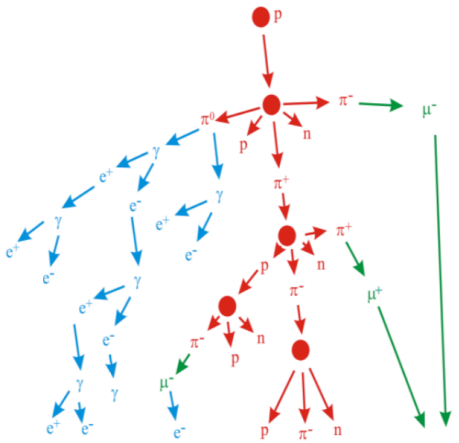
First measurement of intrinsic fluctuations of muons in EAS

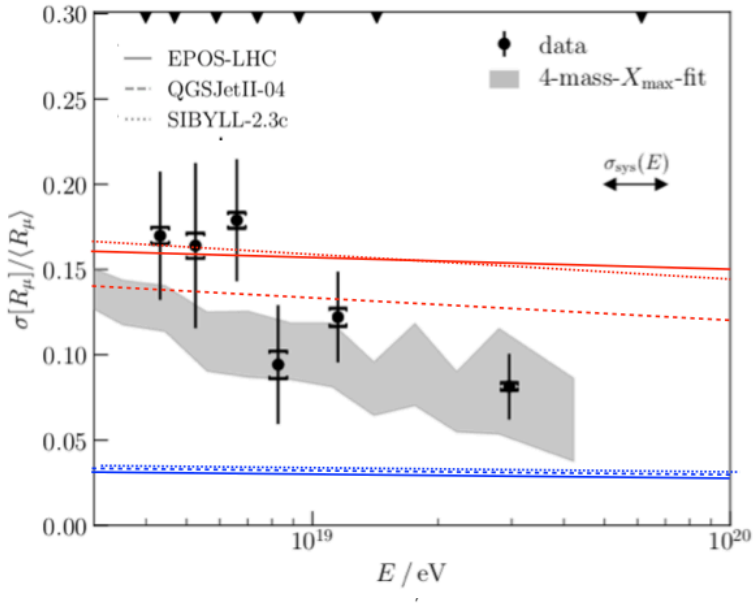
Post-LHC models describe well the fluctuations of energy partition in the first interaction up to UHE

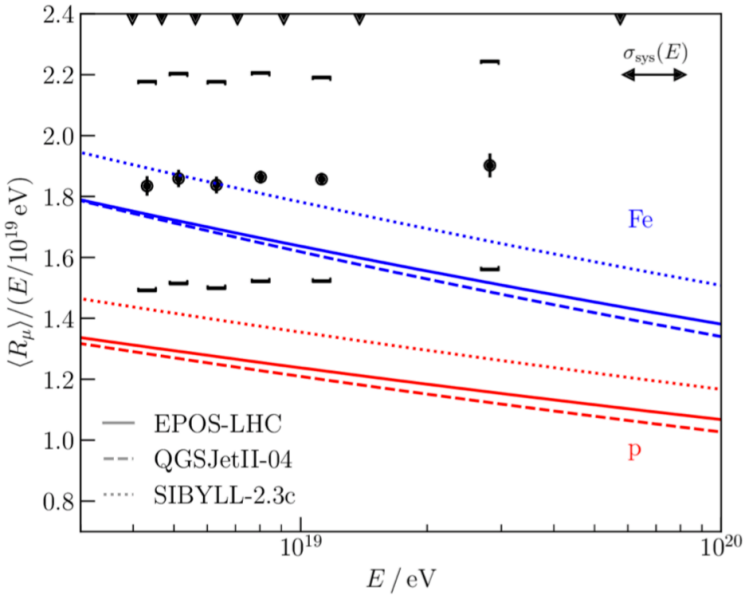




Muons and their fluctuations

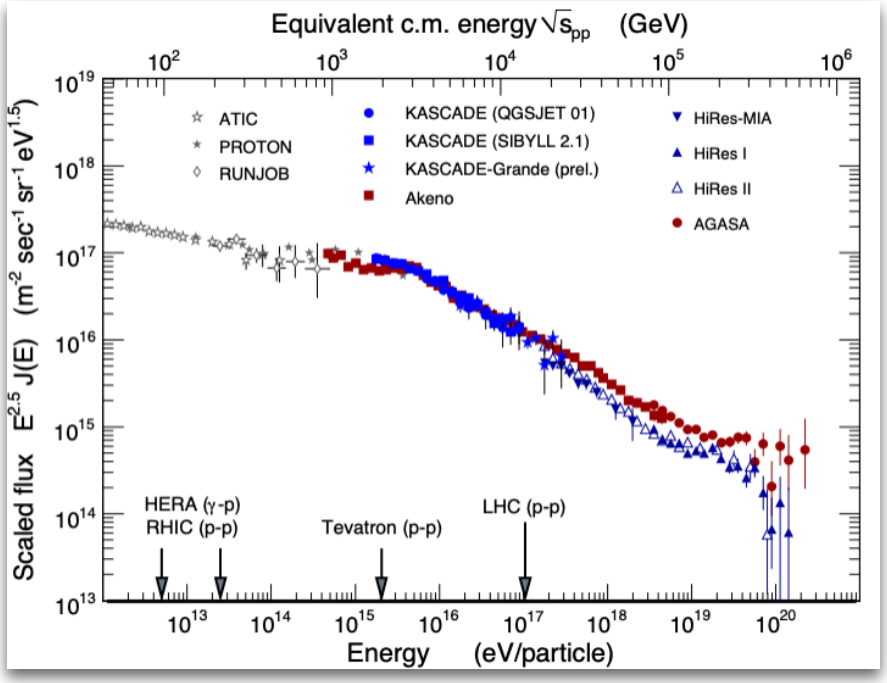


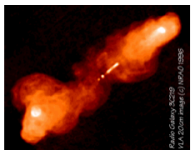




Fluctuations in the muon number = probe of the first interation at UHE
Post-LHC models give a good description of particle production in the first interaction

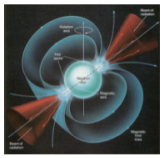
Before...





Active Galactic Nuclei (AGN):
Black Hole of ~10^9 solar masses

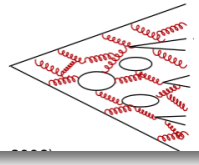
	Process	Distribution	Injection flux
AGNs, GRBs, ... (☆)	Diffuse shock acceleration	Cosmological	p ... Fe
Young pulsars (☆☆)	EM acceleration	Galaxy & halo	mainly Fe
X particles (☆☆☆)	Decay & particle cascade	(a) Halo (SHDM) (b) Cosmological	ν, γ-rays and p
Z-bursts (☆☆☆☆)	Z^0 decay & particle cascade	Cosmological & clusters	ν, γ-rays and p



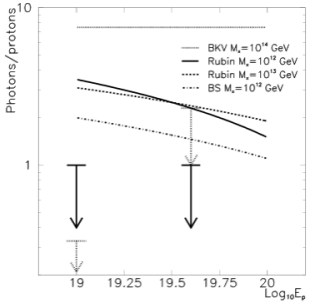
Magnetars:
magnetic field up to ~10^{15} G

X particles from:
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....

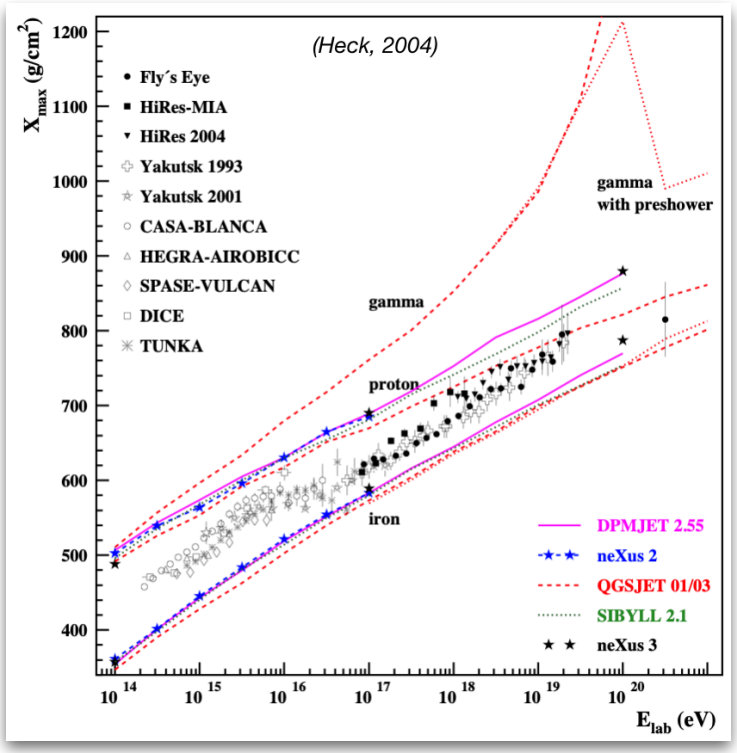
Big Bang:
super-heavy particles, topological defects:
M_X ~ 10^{23} - 10^{24} eV



large fluxes of photons and neutrinos



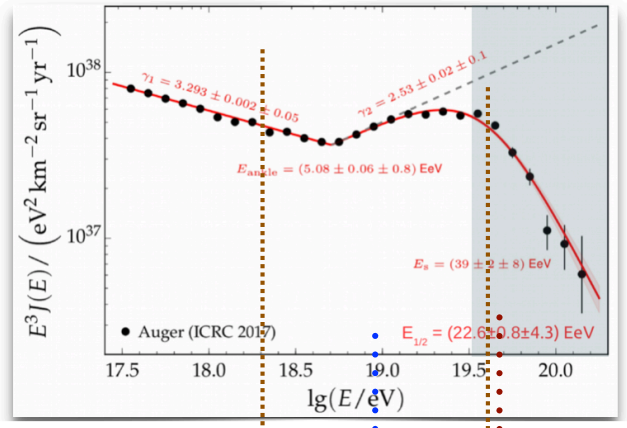
(Ave et al. PRD 2002)

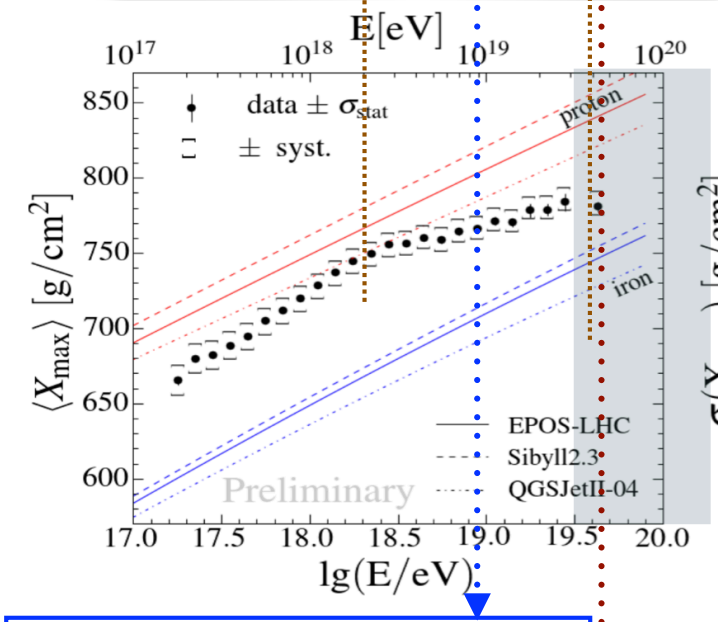


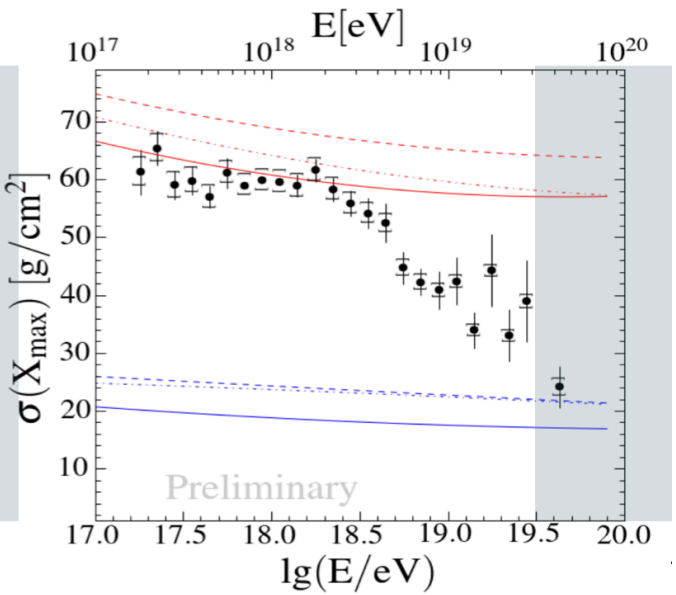
and now:

The Pierre Auger Observatory:

- >15 years of data
- the world largest exposure to UHECRS



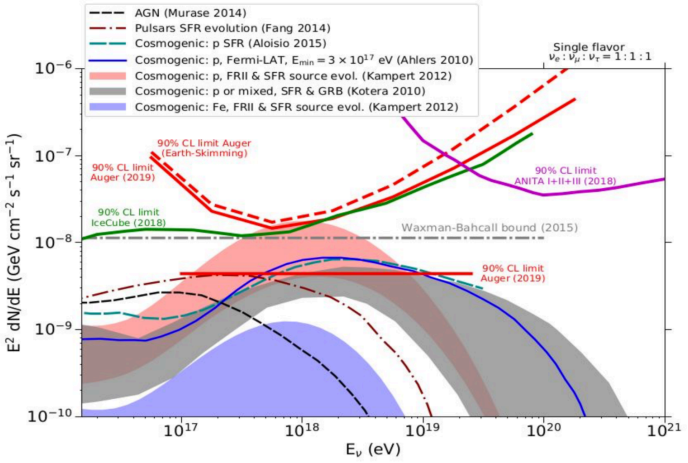




dipolar large scale anisotropy:
UHCRs > 8 EeV are extraGalactic

intermediate anisotropy hinted by correlations above 38 EeV (SBGs, 4**σ**; AGN, 3.5**σ**)

Dominance of heavier nuclei supported by non-observation of cosmogenic neutrinos



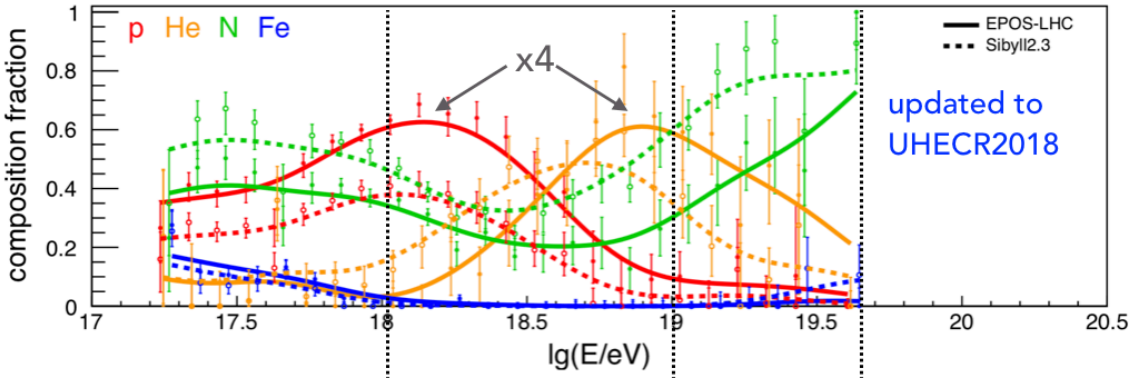
Astrophysical interpretation

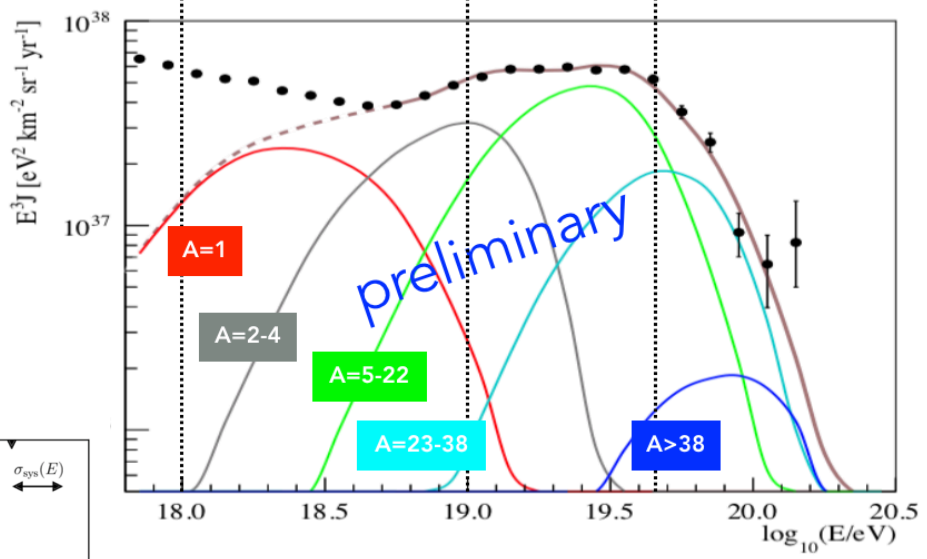
Mass fractions at Earth from fitting templates of 4 mass groups to the measured X_{max} distributions

Peter's cycle ∝ E/Z

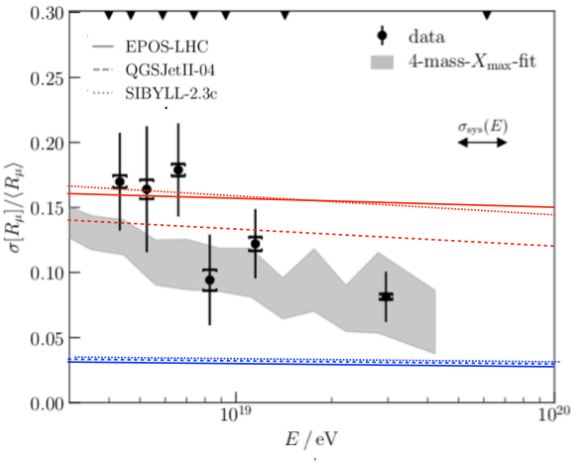
or

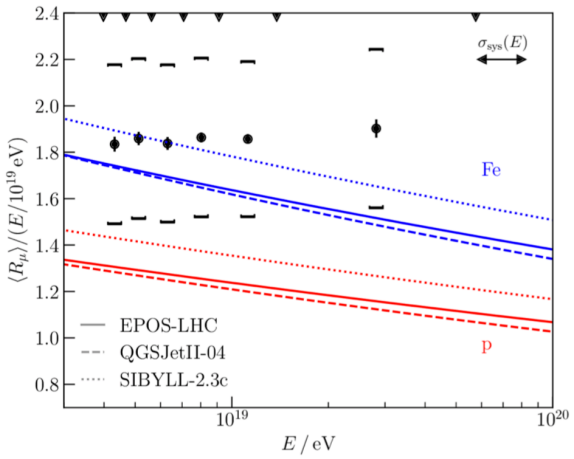
Spallation ∝ E/A ?





No data on mass composition in the UHE region





Large uncertainties from hadronic interaction models

The AugerPrime science case

- ***study the origin of the suppression***
  - ➡ fundamental constraints to the characteristics of the sources of UHECRs

- ***evaluate the existence of a fraction of protons at the highest energies***
  - ➡ feasibility of charged particle astronomy

- ***provide better estimates of the neutrino and γ flux***
  - ➡ potential of future CR experiments

- ***study the hadronic interactions at UHE and look for non standard physics***
  - ➡ exploration of different interaction phase space

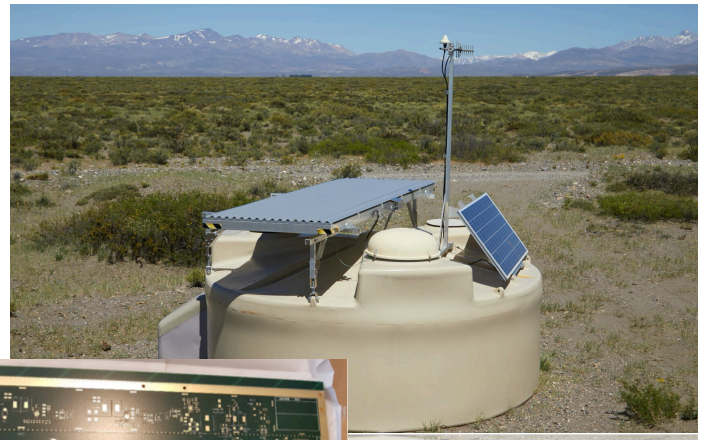
Extend operations to 2025, increasing the statistics

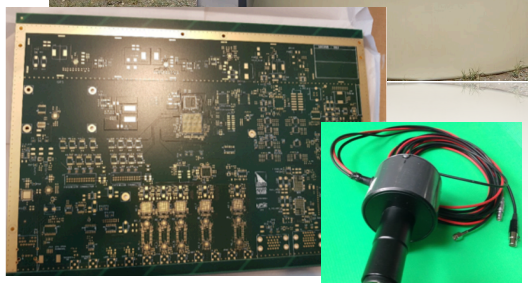
Improve the sensitivity to the composition at UHE : disentagle the electromagnetic and muonic components

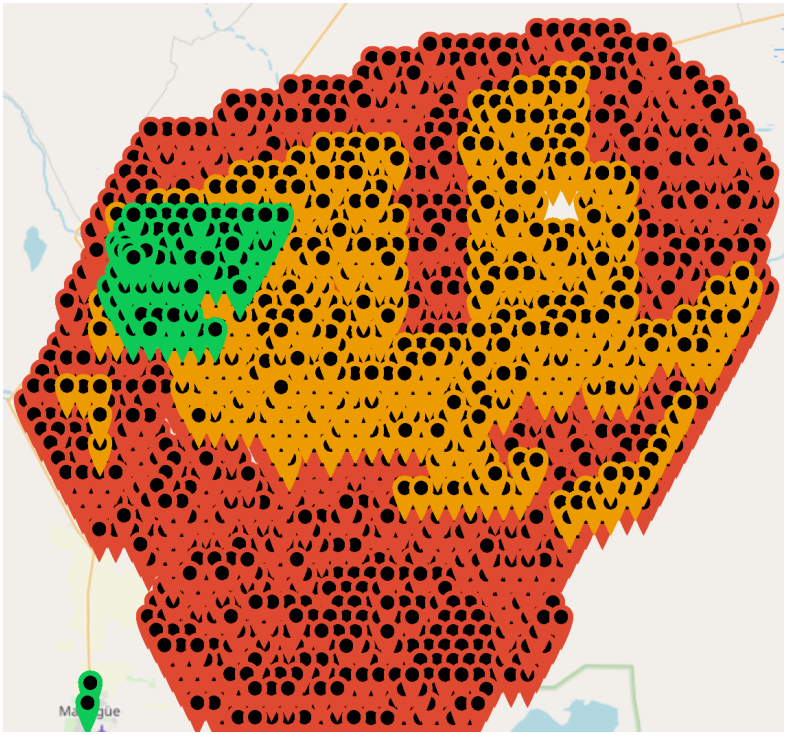
[AugerPrime Design Report, arXiv:1604.03637
EPJ Web of Conf.210 (2019) 06002]

AugerPrime : the Upgrade

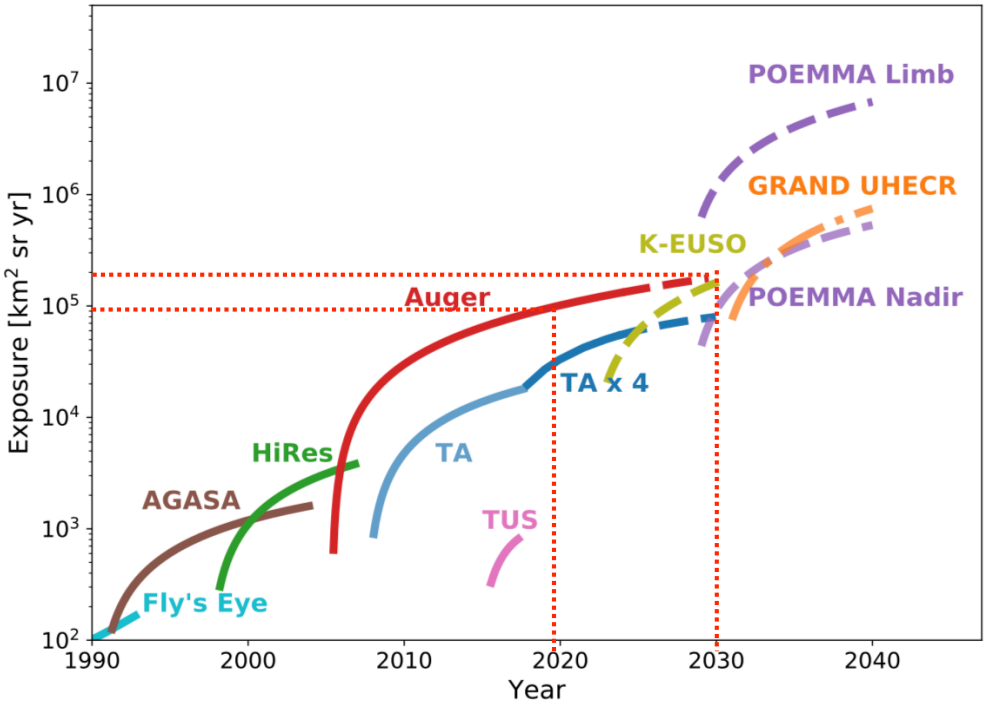
a large exposure detector with composition sensitivity above ~4 10^{19} eV







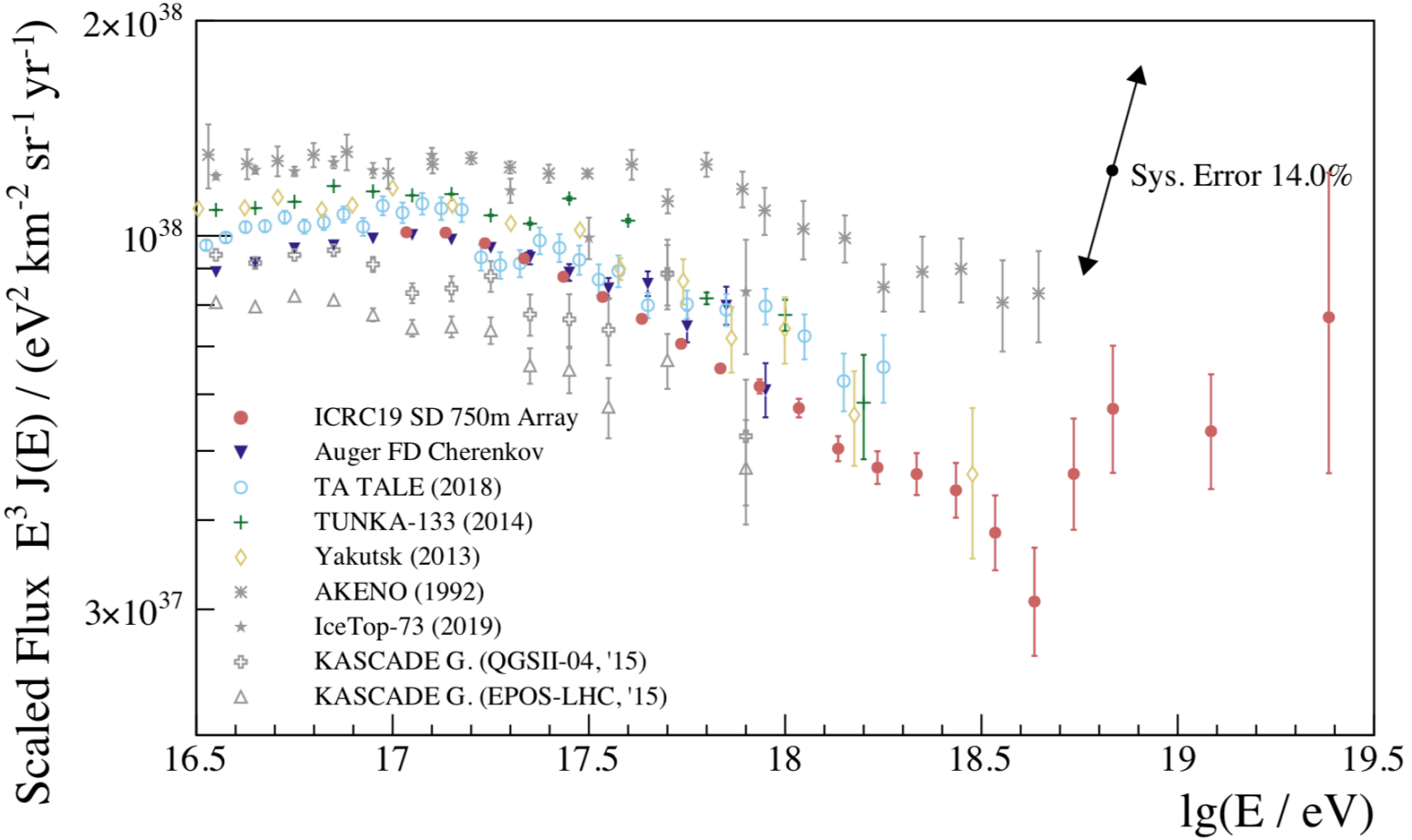
- **12 upgraded stations (Engineering Array)** since 2016 with new electronics, higher sampling, large dynamic range
- **the SSD preproduction array: 80 stations** (since March 2019): 120 km^2
- **587 SSD stations** already deployed
- Underground Muon detector
- the largest radio detector (3000 km^2)



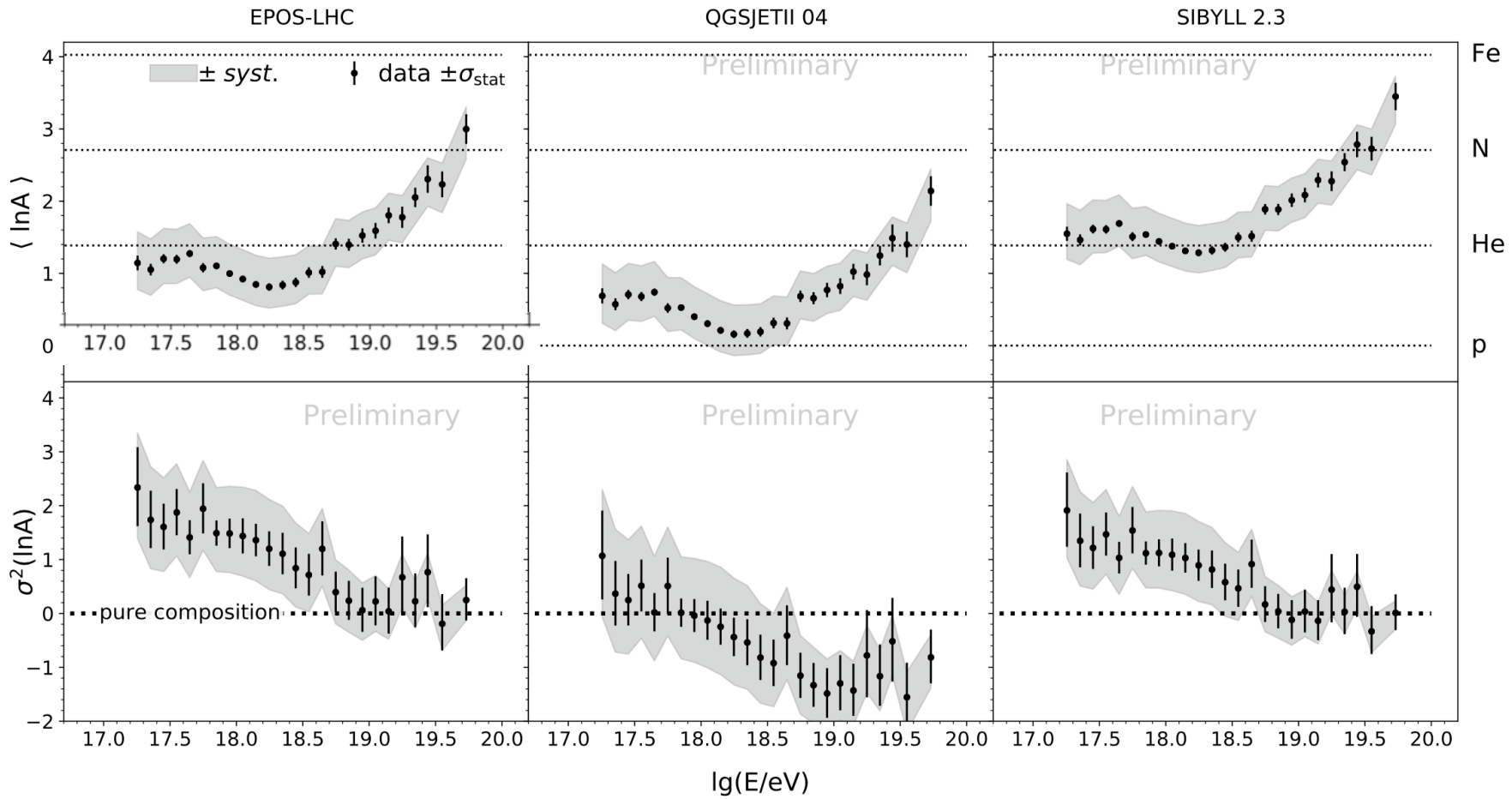
…looking forward to celebrating the 30th Anniversary in 2029 !

BACKUP slides

Looking at the second knee



lnA


EPOS-LHC
QGSJETII 04
SIBYLL 2.3
± syst.
data ±σstat
Preliminary
⟨ lnA ⟩
σ²(lnA)
pure composition
Fe
N
He
p
lg(E/eV)

Full sky search with Auger and Telescope Array

Large Scale Anisotropy

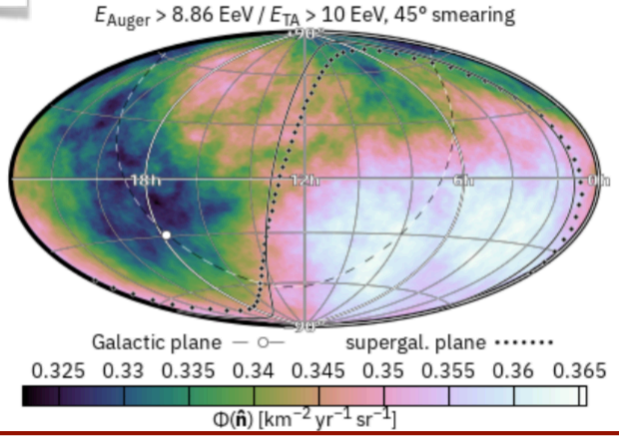
Energy threshold

8.86 EeV (Auger)

10 EeV (Telescope A

Events

~31000 events



$$d_x = (-0.7 \pm 1.1_{\text{stat}} \pm 0.01_{\text{calib}})\%$$
$$d_y = (+4.2 \pm 1.1_{\text{stat}} \pm 0.04_{\text{calib}})\%$$
$$d_z = (-2.6 \pm 1.3_{\text{stat}} \pm 1.4_{\text{calib}})\% \ (\pm 1.9\%_{\text{tot}})$$

Agreement with Auger alone, smaller uncertainty

Hint for a quadrupole moment

Intermediate Scale Anisotropy

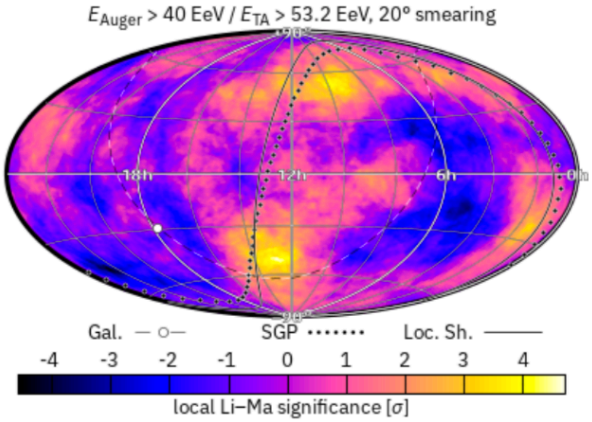
Energy threshold

40 EeV (Auger)

53.2 EeV (Telescope Array

Events

969 events



Blind search

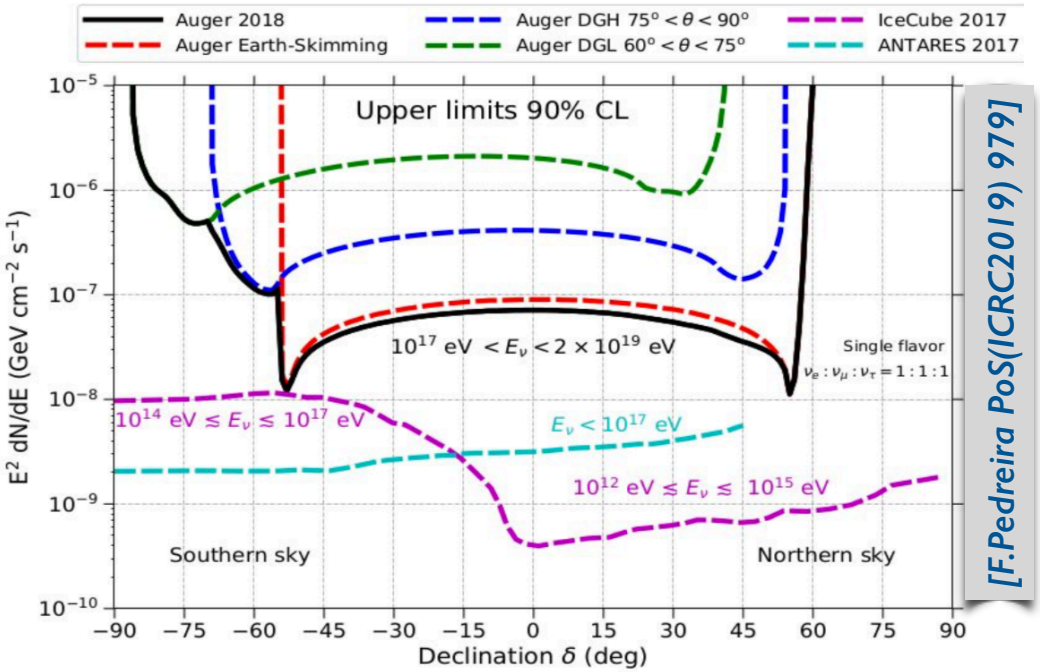
(α=12^{h}50^m, δ= - 50^0), 4.7 local sign (2.6 post-trial)

(α= 9^{h}30^m, δ= +54^0), 4.2 local sign (1.5 post-trial)

Local Sheet

26% higher flux in a band of $\pm 24^0$ around the Local Sheet (global significance 2.8σ)

Point-like sources of UHE ν



[F.Pedreira PoS(ICRC2019) 979]

Steady sources

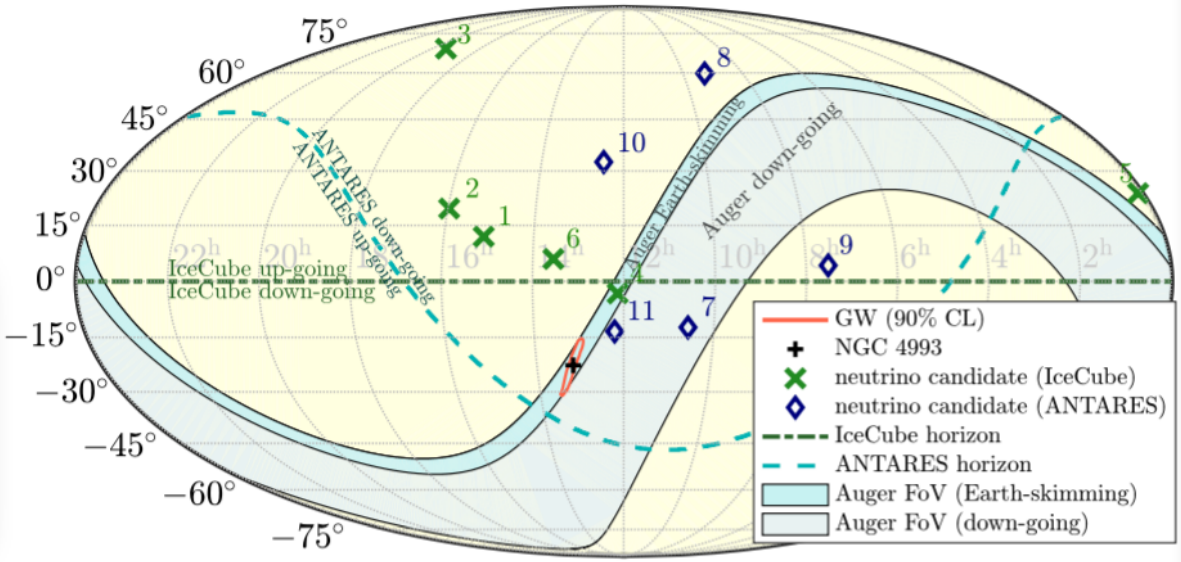
Energy range complementary to Icecube and Antares

Follow up of the GW170817 event

In the range 10^{17} - 2.5 10^{19} eV, the total energy emitted in ν_τ is

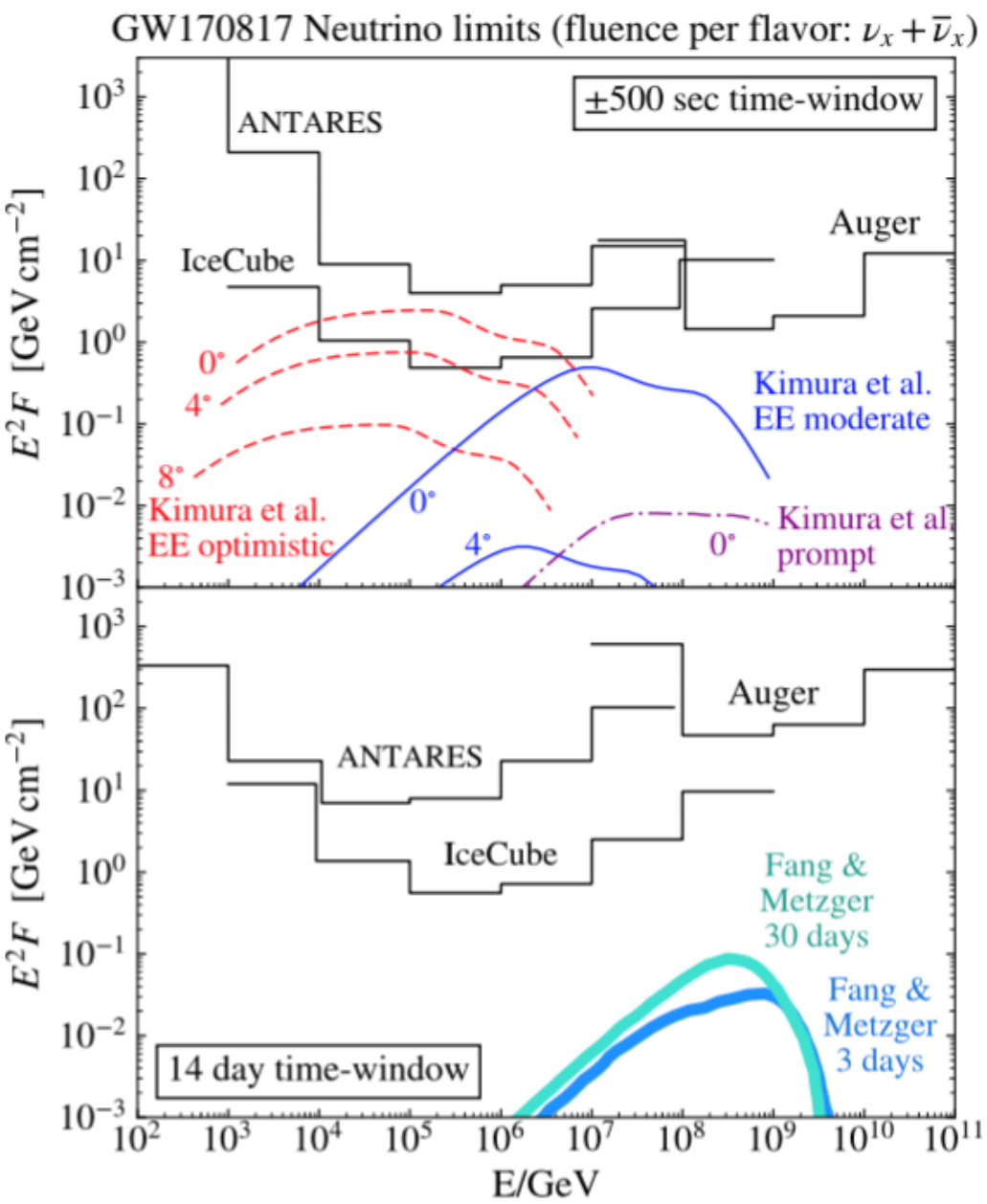
$\pm$500 s : $< 6.9\ 10^{-4}\ M_\odot$

+14 days : $< 2.3\ 10^{-2}\ M_\odot$



[LIGO,VIRGO.Auger.IceCube.Antares Coll., ApJL848 (2017) L12]

Constraints to models



sGRBs

- prompt emission (due to internal energy dissipation in the jet), extended emission (afterglow due to forward shocks around the burst)
- viewed on-axis or off-axis
- neutrinos can arise from close GRBs or EE

[S.Kimura+, ApJ848 (2017) L4]

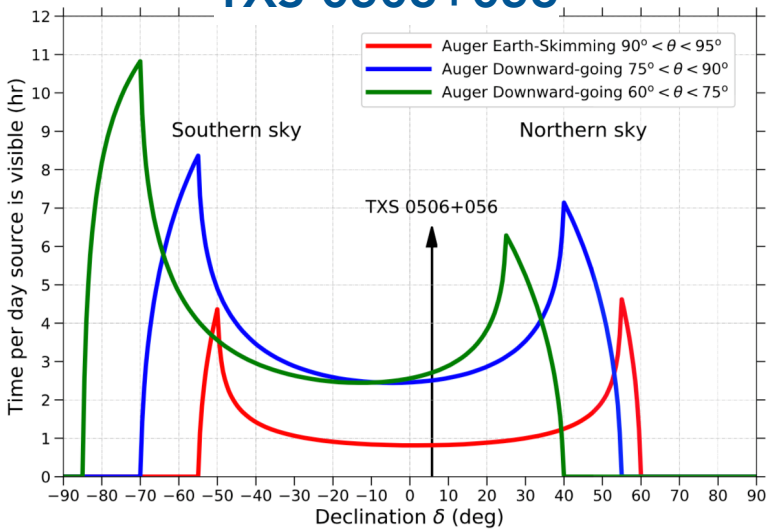
msec Magnetar remnant

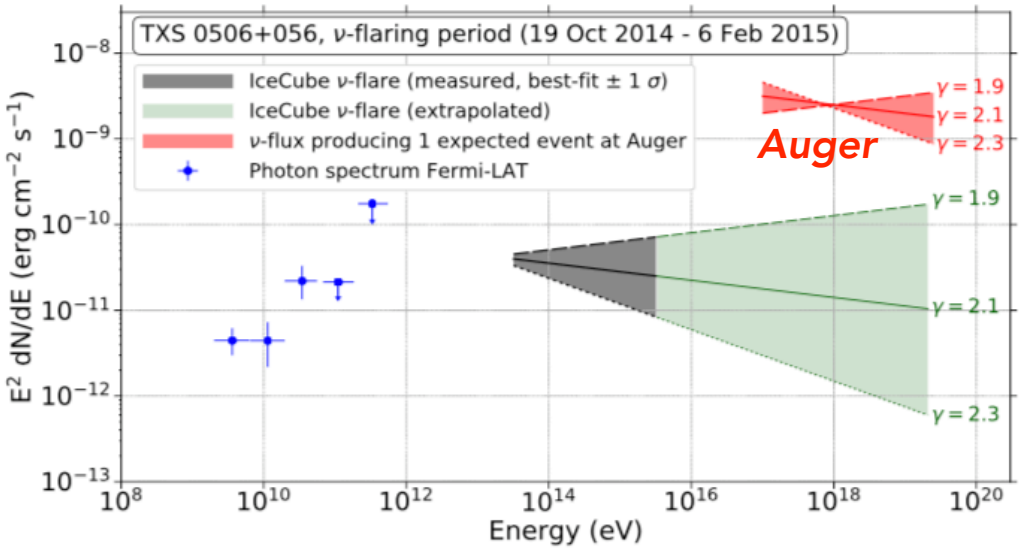
- promising site for accelerating particles to UHE
- neutrino late production from UHECRs interactions with ambient photons and baryons
- strong neutrino signal at 10^{18} eV if large contribution of magnetars to the bulk of UHECRs (light nuclei at $10^{17.5}$-10^{18} eV)

[K.Fang+, arXiv:1707.04263]

Transient sources of UHE ν

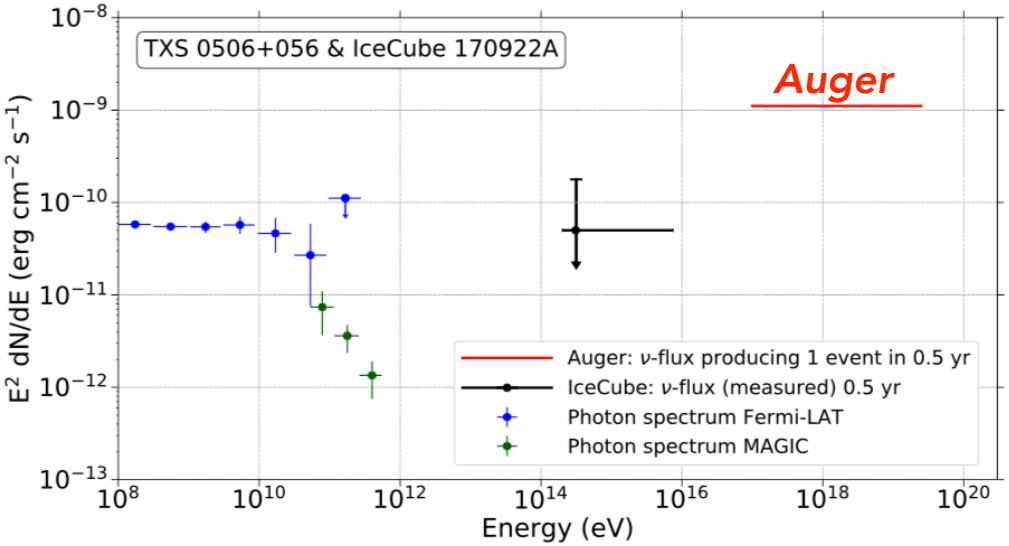
TXS 0506+056





No neutrinos found

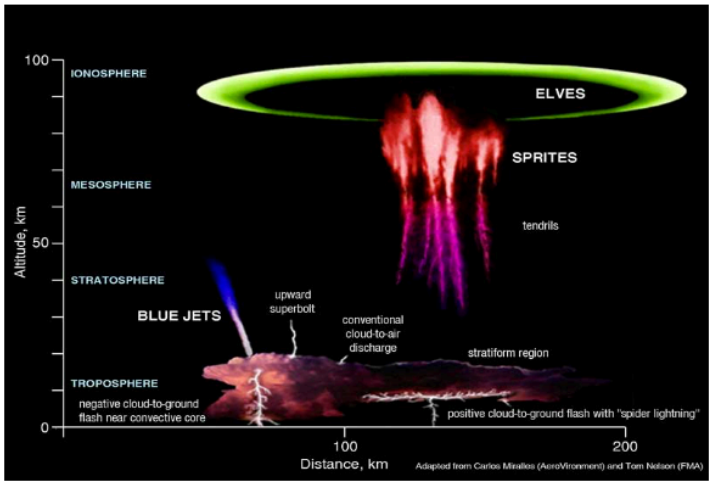
Flux needed for 1 ν in Auger
$\mathcal{O}(10^{-9})$ erg cm^{-2} s^{-1}
Complementary energy ranges



Cosmo-geophysics: ELVES in Auger

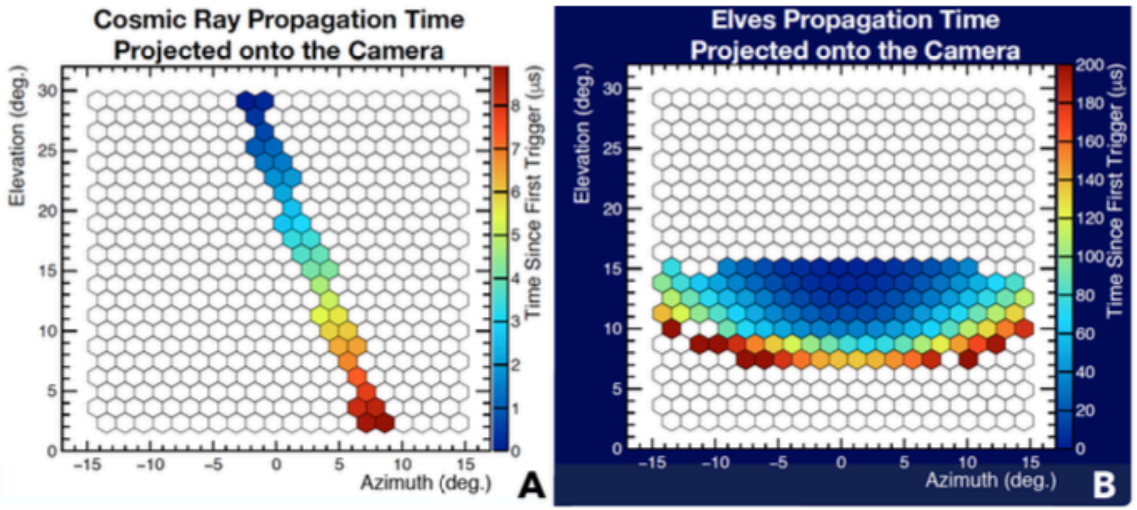
a class of TLE observed in ionosphere as rapidly expanding rings of light above certain storms

- 80-90 km height, hundreds km observable area
- a specific trigger is designed for the elves —> new one in 2017 (900 μs - 3x readout window)
- Observatory footprint for elves > 3 10^6 km^2
- more observed during Malargue summer
- >40% correlated to lightening of ~6 10^{21} - 3 10^{22} eV (WWLLN-World Wide Lightning Location Network)



ELVES : *Emissions of Light and Very low frequency perturbations due to Electromagnetic pulse Sources.*

ELVES vs Cosmic Rays in the Auger FD camera



Auger is the first and only ground-based facility that measures elves with year-round operation, full horizon coverage, controlled photon counting, and 100 ns resolution.

Searches for Lorentz invariance violation

$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_i^{(n)} E_i^{2+n} = m_i^2 + \eta_i^{(n)} \frac{E_i^{2+n}}{M_{Pl}^n}$$

Effects suppressed for low energy and short travel distances : UHECRs !!!

3 independent scenarios tested

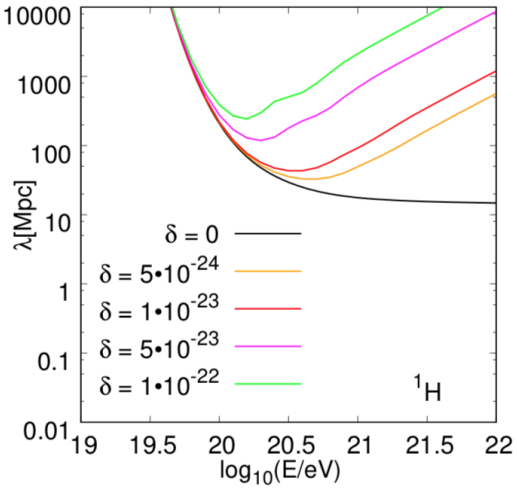
- Propagation of UHECRs
- Propagation of GZK photons
- Air shower physics

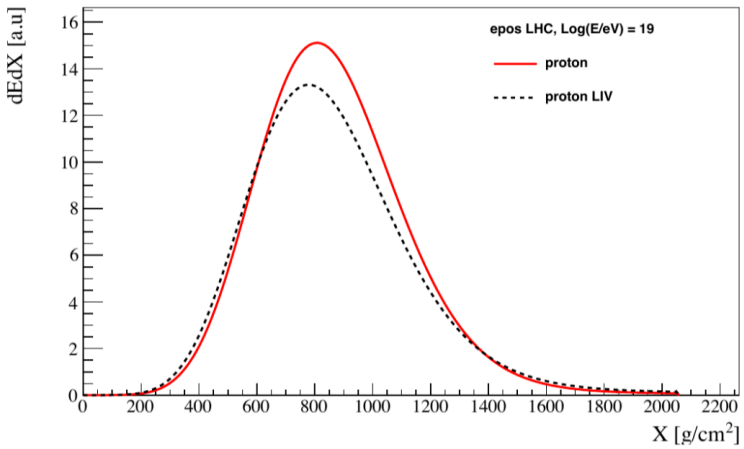
Auger data used

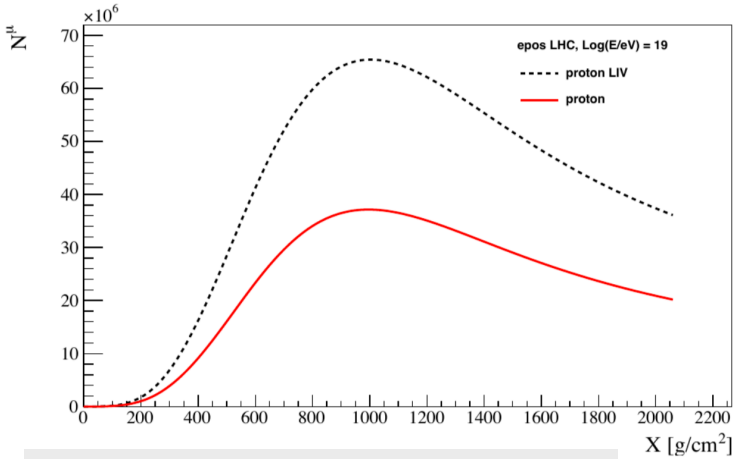
- Energy spectrum
- Xmax distributions

→ Combined fit starting from simple source model

- Upper limits on photon flux

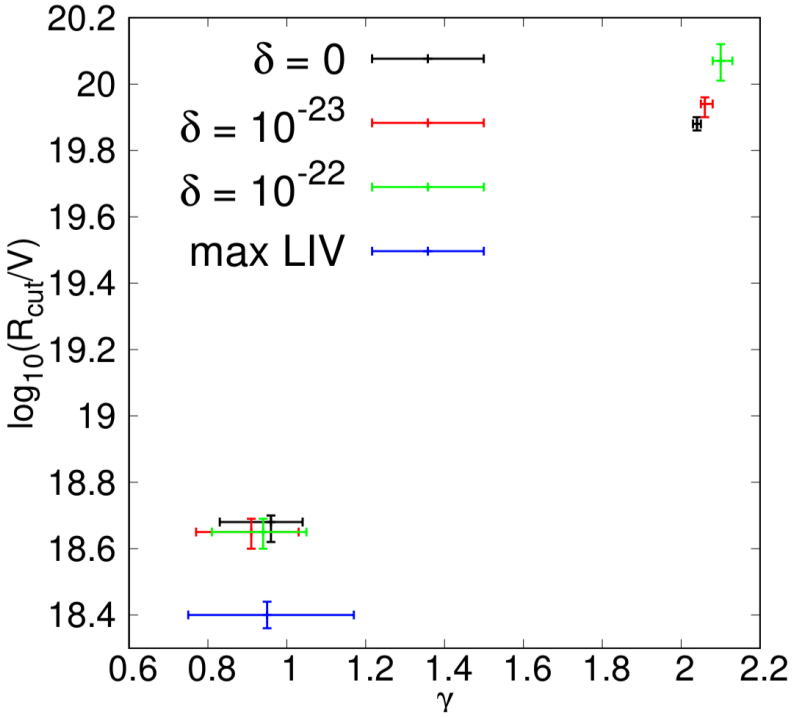






[@R.Guedes Lang, PoS(ICRC2019) 327]

LIV - hadron sector



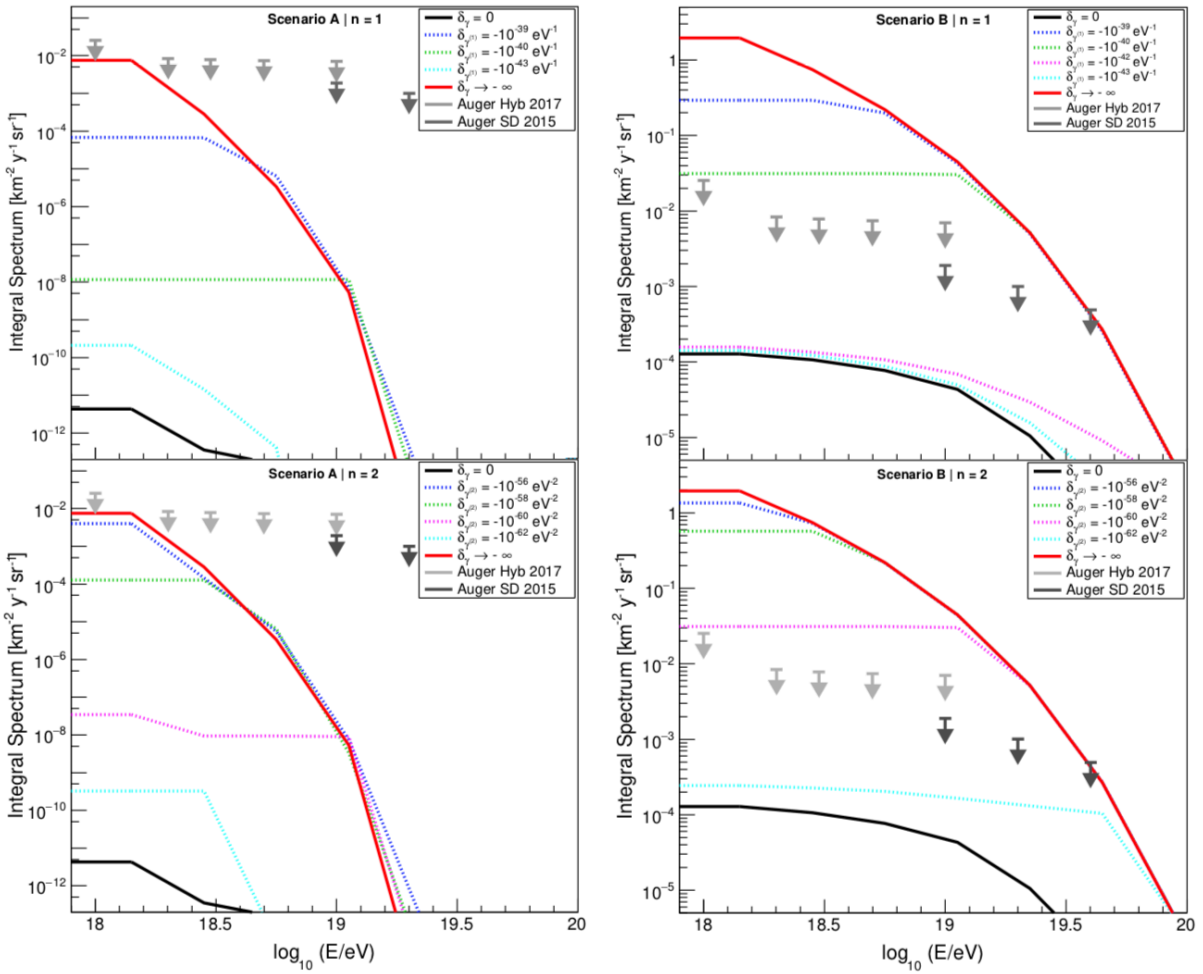
Combined fit

of spectrum+composition

Best fit: low maximum rigidity

LIV effects suppressed by energy

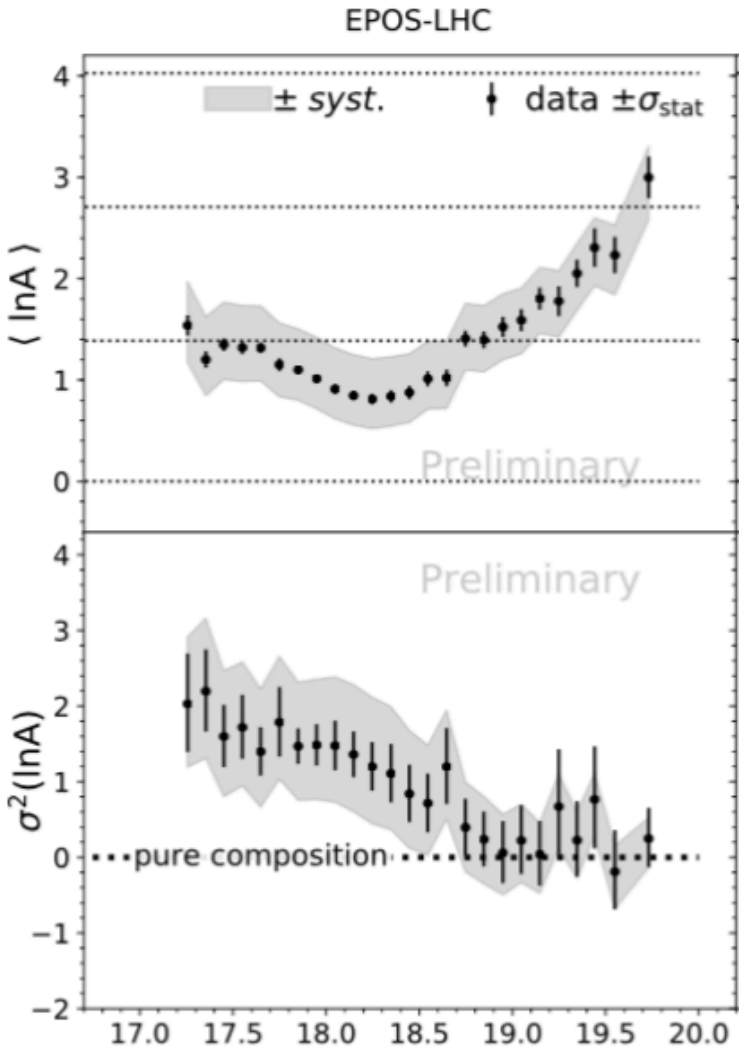
LIV - photon sector



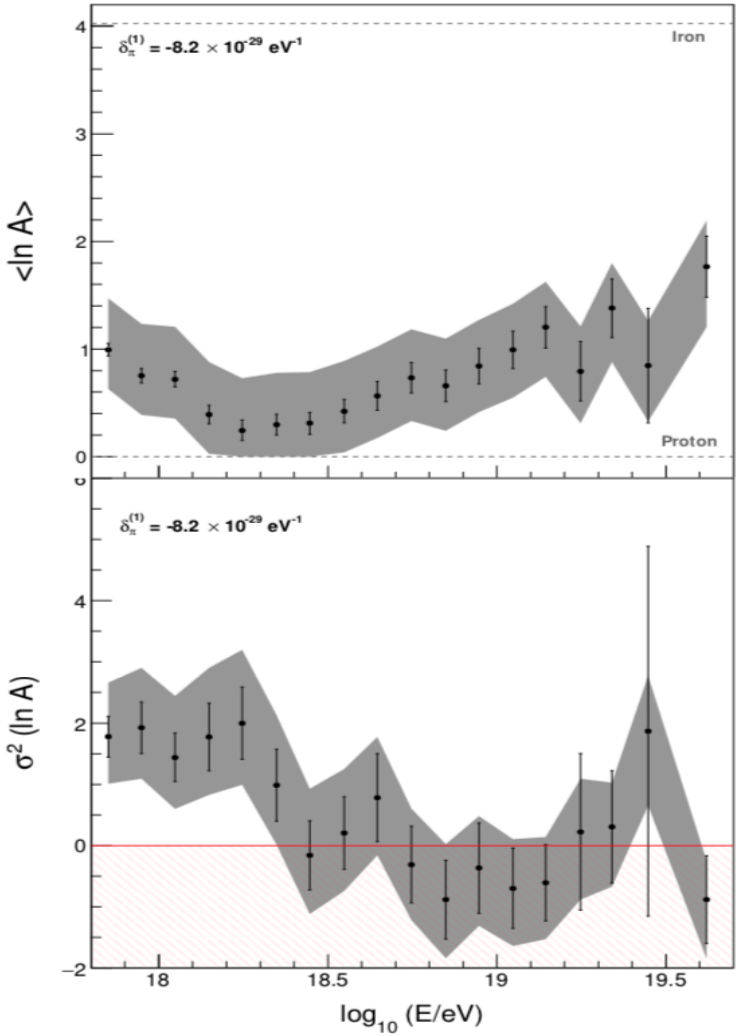
GZK photons propagated following the two scenarios (A=global and B=local minima)

- A: no limits on LIV can be imposed
- B: $\delta_\gamma^{(1)} \gtrsim -10^{-40}\,\mathrm{eV}^{-1}$ and $\delta_\gamma^{(2)} \gtrsim -10^{-60}\,\mathrm{eV}^{-2}$.
- ➡

LIV - air showers



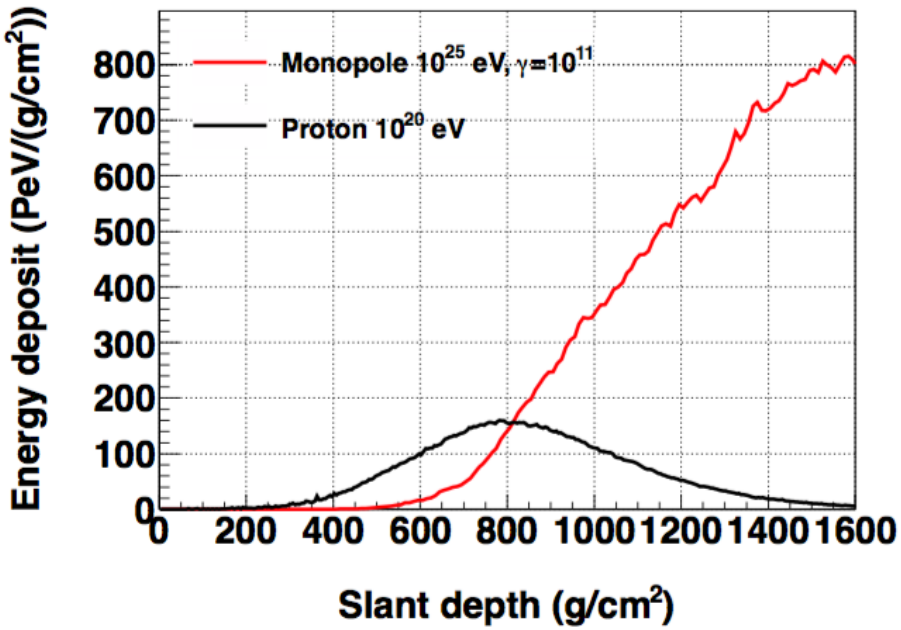
EPOS-LHC, LI

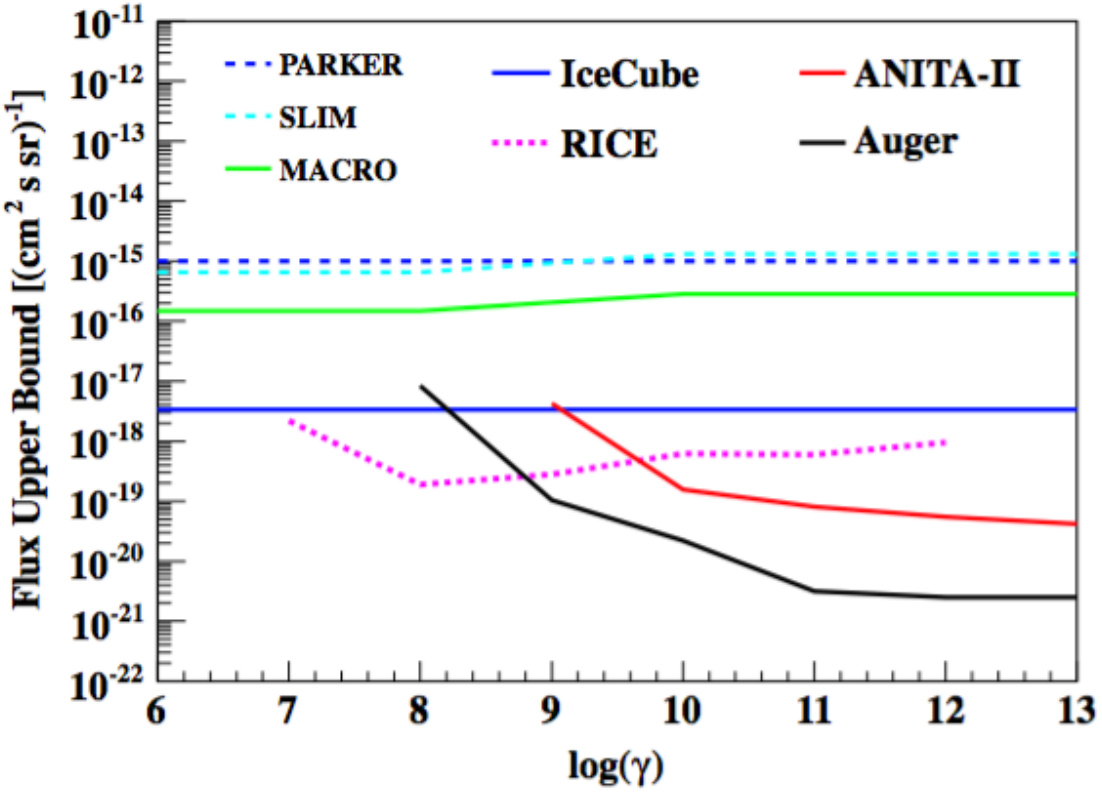


EPOS-LHC, LIV

Searches for magnetic monopoles

- intermediate mass ultra-relativistic monopoles with $M \sim 10^{11}$-10^{16} eV/c^2 (IMM), $E_{mon} \sim 10^{25}$ eV can be present today as relic of phase transitions in the early Universe
- search based on larger energy deposit and deeper development due to superposition of many showers produced by the IMM





$\log_{10}(\gamma)$	$\mathcal{E}(\gamma)$ (km^2 sr yr)	$\Phi_{90\%\,\mathrm{C.L.}}$ ((cm^2 sr s)$^{-1}$
8	1.16	8.43×10^{-18}
9	9.52×10^{1}	1.03×10^{-19}
10	4.50×10^{2}	2.18×10^{-20}
11	3.15×10^{3}	3.12×10^{-21}
≥ 12	3.91×10^{3}	2.51×10^{-21}

[@A.Aab et al (Auger Coll.) PRD94 (2016) 082002]