

Highlights of the Pierre Auger Observatory

**Antonella Castellina (INAF-OATo & INFN,Torino)
on behalf of the Pierre Auger Collaboration**



The Pierre Auger Collaboration

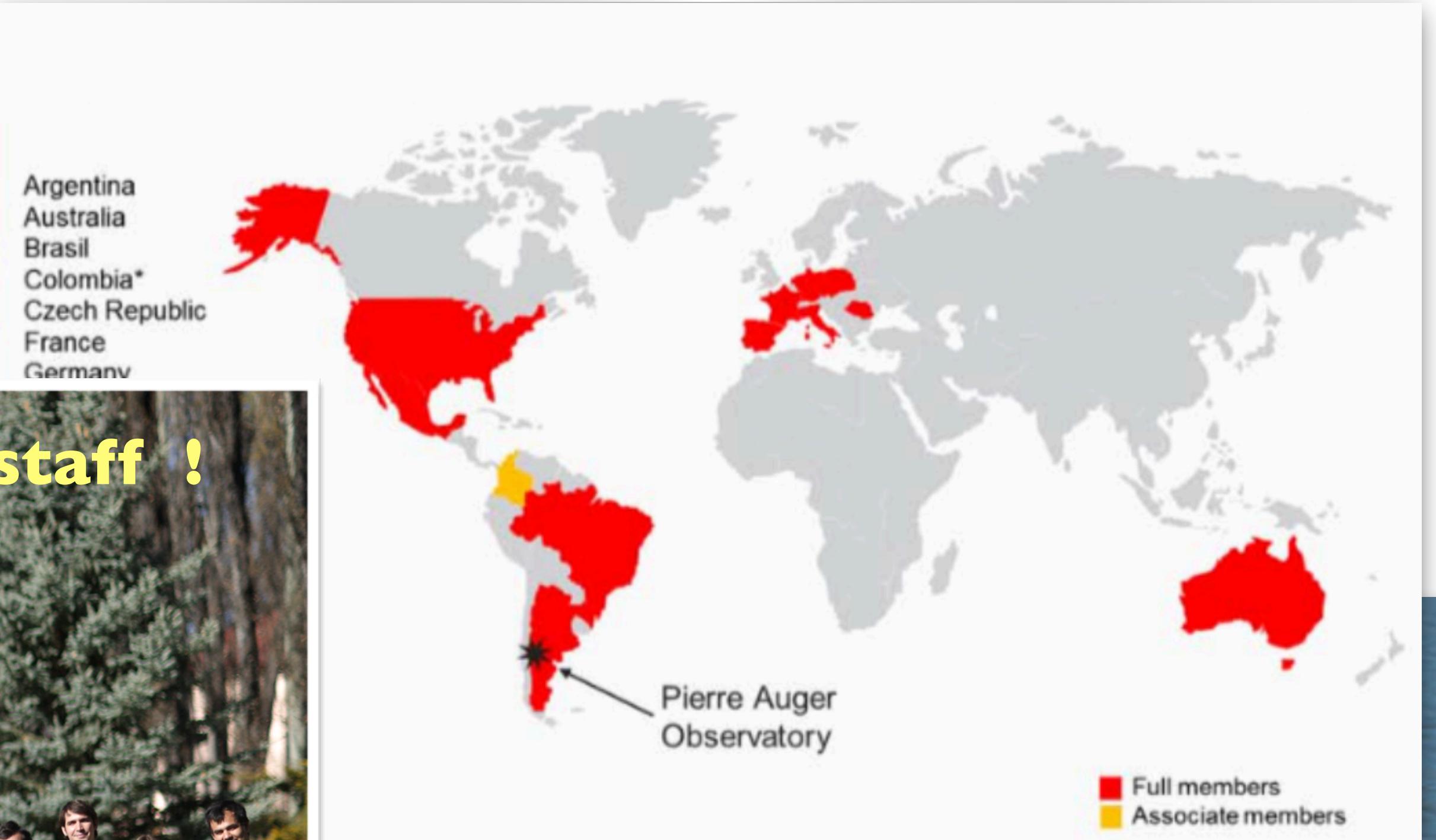
~500 members
from 89 institutions



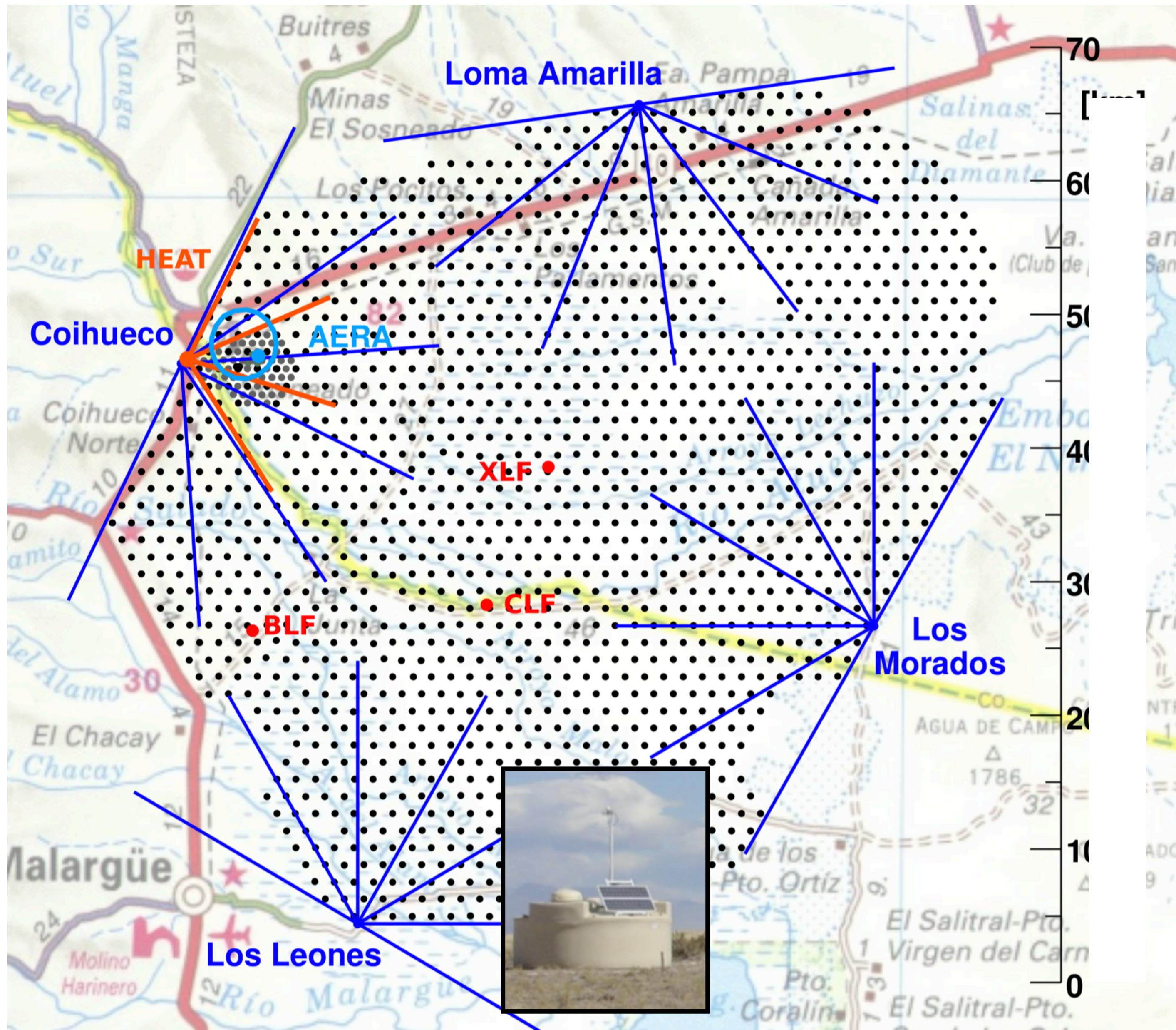
The Pierre Auger Collaboration

~500 members
from 89 institutions

...and our local staff !



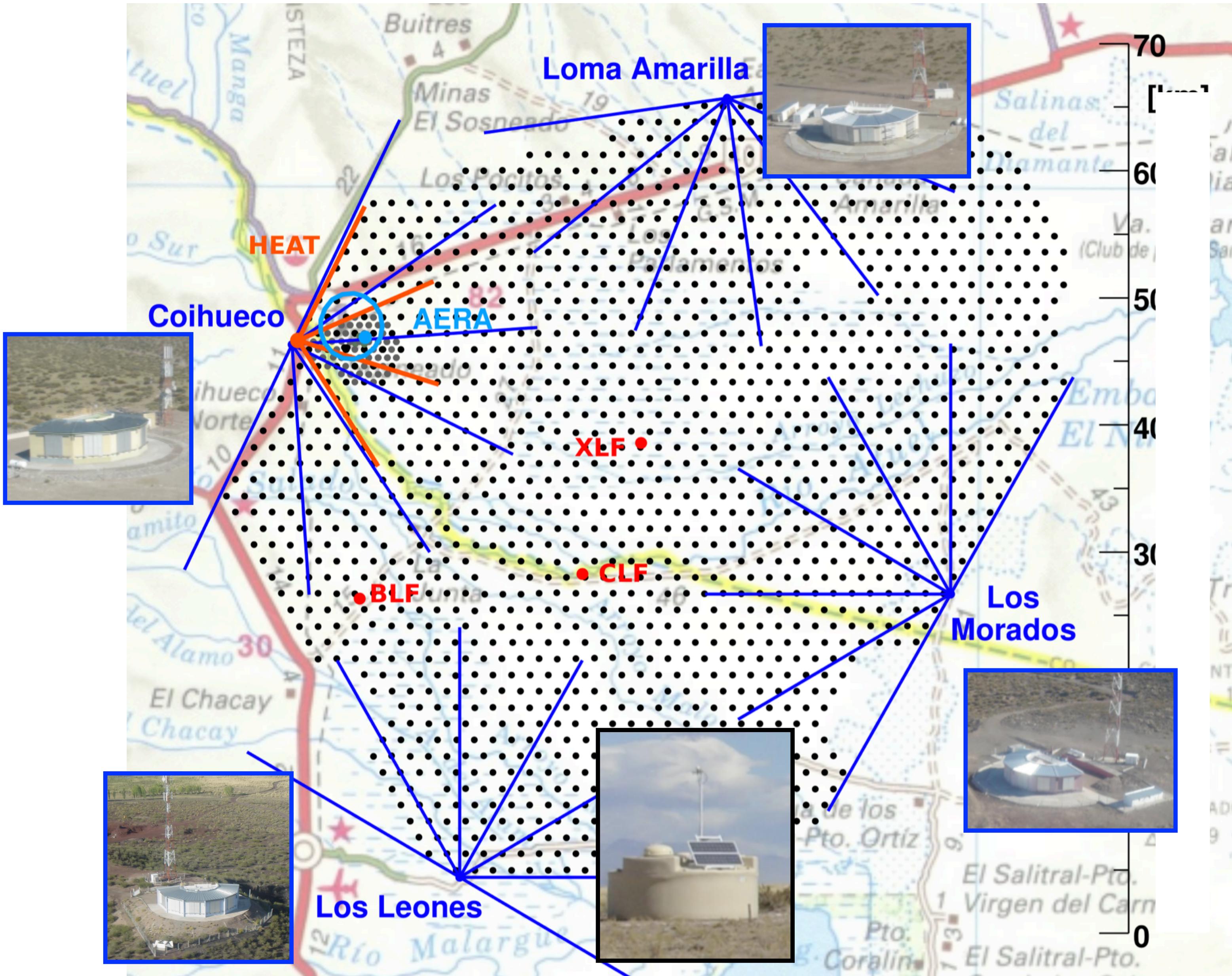
The Observatory



Water-Cherenkov stations

→ SD1500 : 1600, 1.5 km grid, 3000 km²

The Observatory



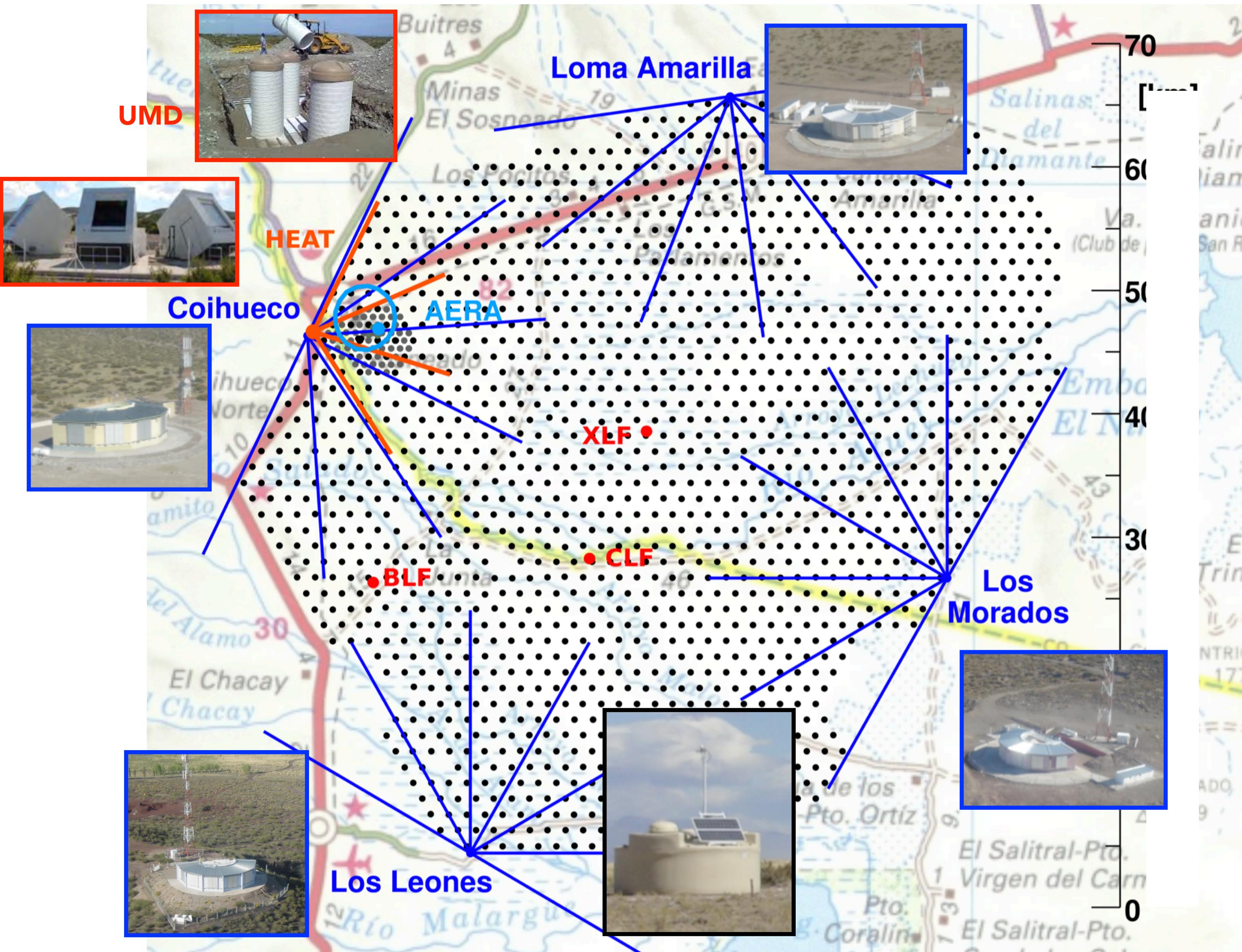
Water-Cherenkov stations

→ SD1500 : 1600, 1.5 km grid, 3000 km²

4 Fluorescence Sites

→ 24 telescopes, 1-30° FoV

The Observatory



Water-Cherenkov stations

- SD1500 : 1600, 1.5 km grid, 3000 km²
- SD750 : 61, 0.75 km grid, 25 km²

4 Fluorescence Sites

- 24 telescopes, 1-30° FoV

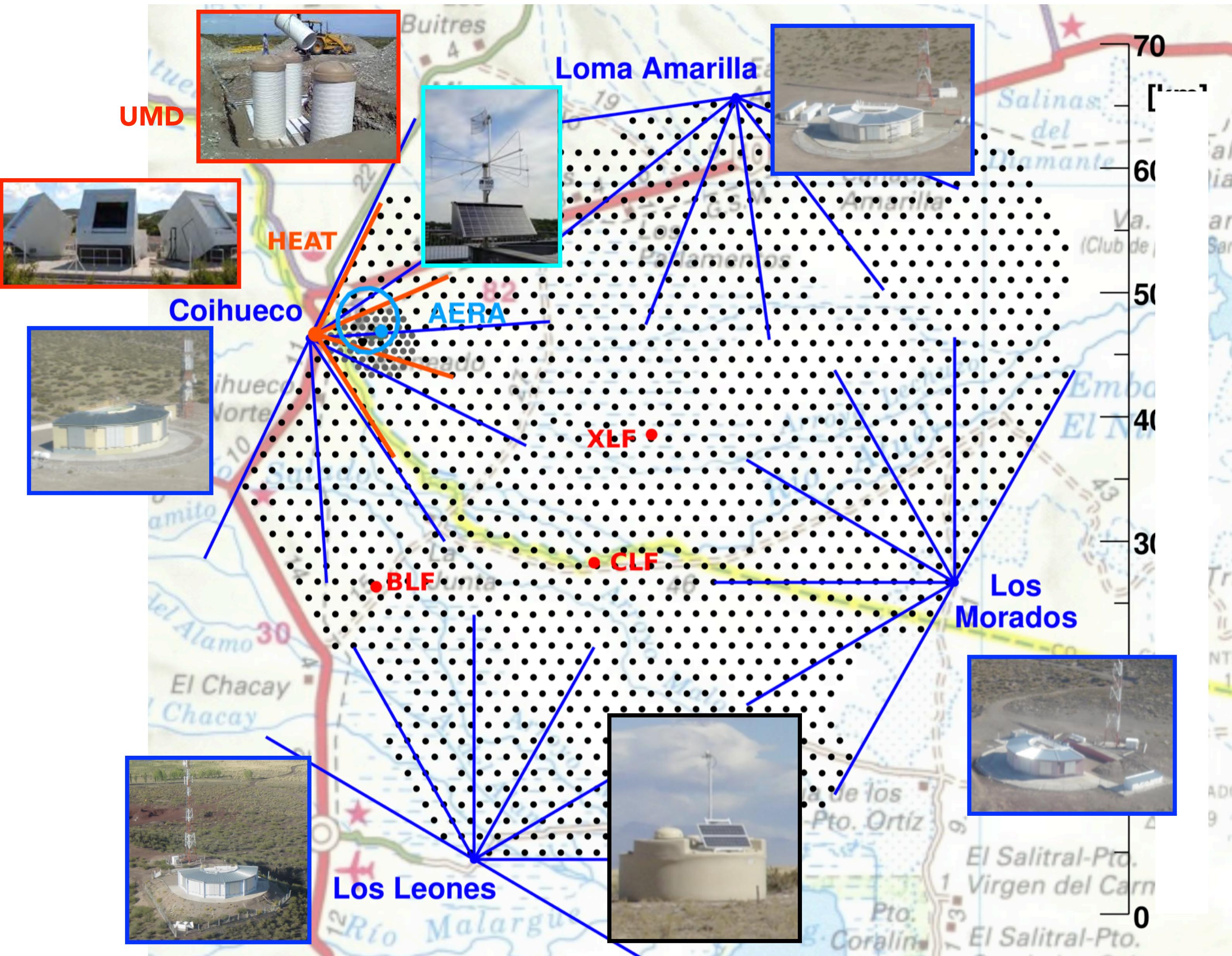
Underground Muon Detectors

- 7 in engineering array phase -
61 aside the Infill stations

HEAT

- 3 high elevation FD, 30-60° FoV

The Observatory



Water-Cherenkov stations

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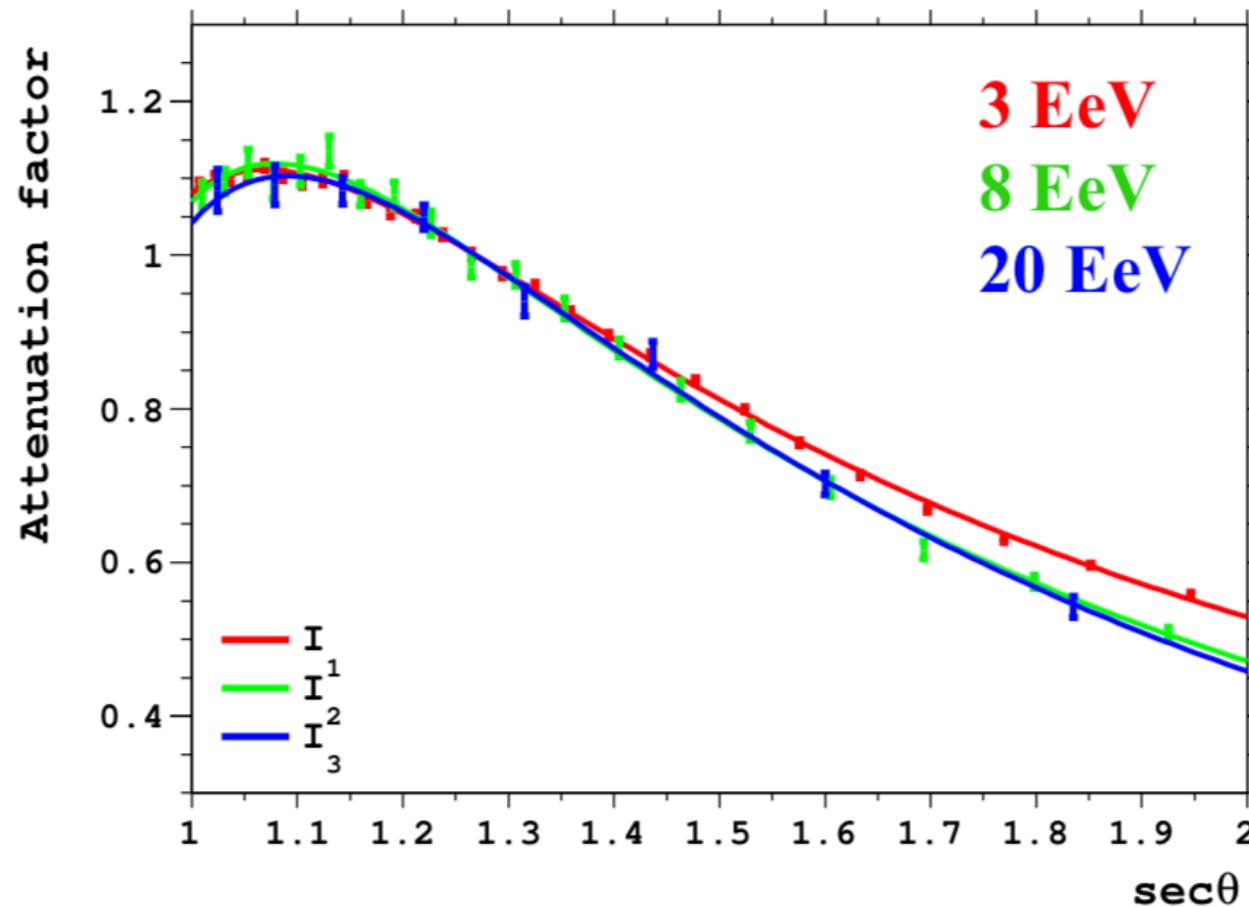
AERA radio antennas

- 153 graded 17 km²

+Atmospheric monitoring devices
CLF, XLF, Lidars, ...

Event reconstruction and energy scale

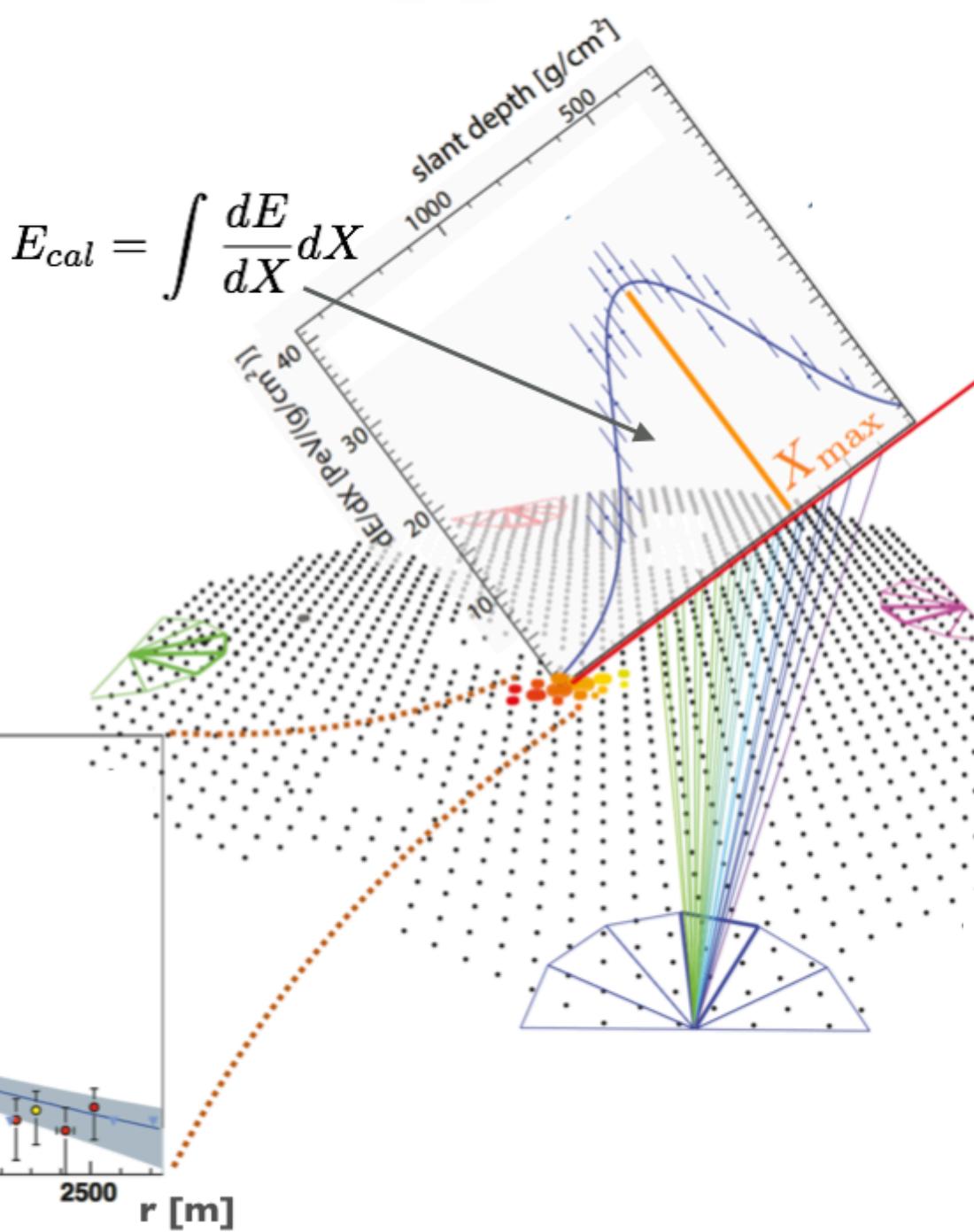
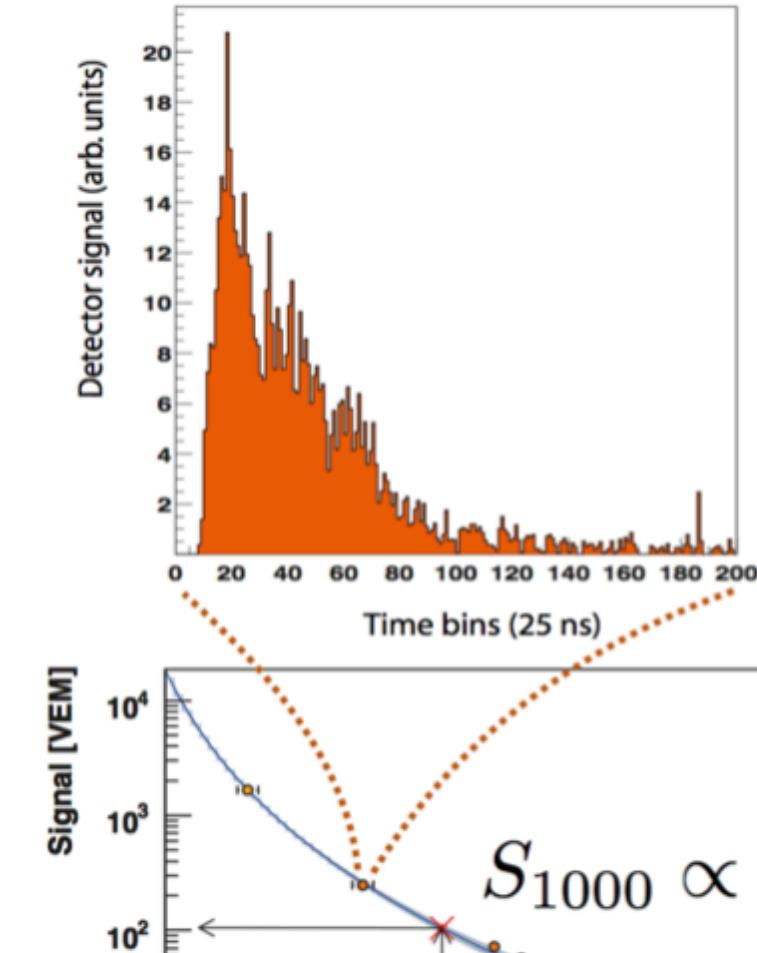
CIC evaluated at different energy thresholds



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

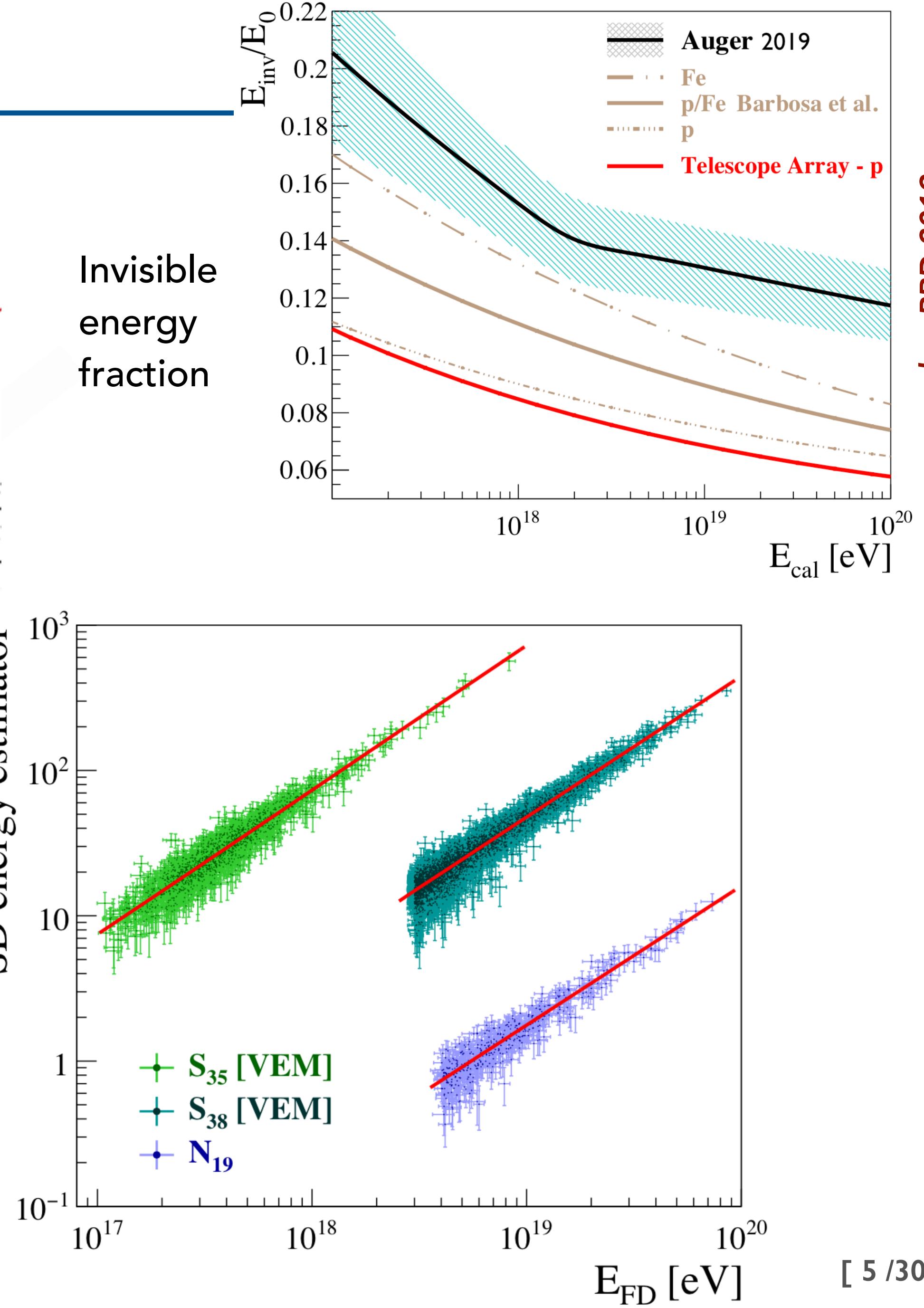
$$\sigma(E_{FD})/E_{FD} \sim 8\%$$

Systematic uncertainty 14%

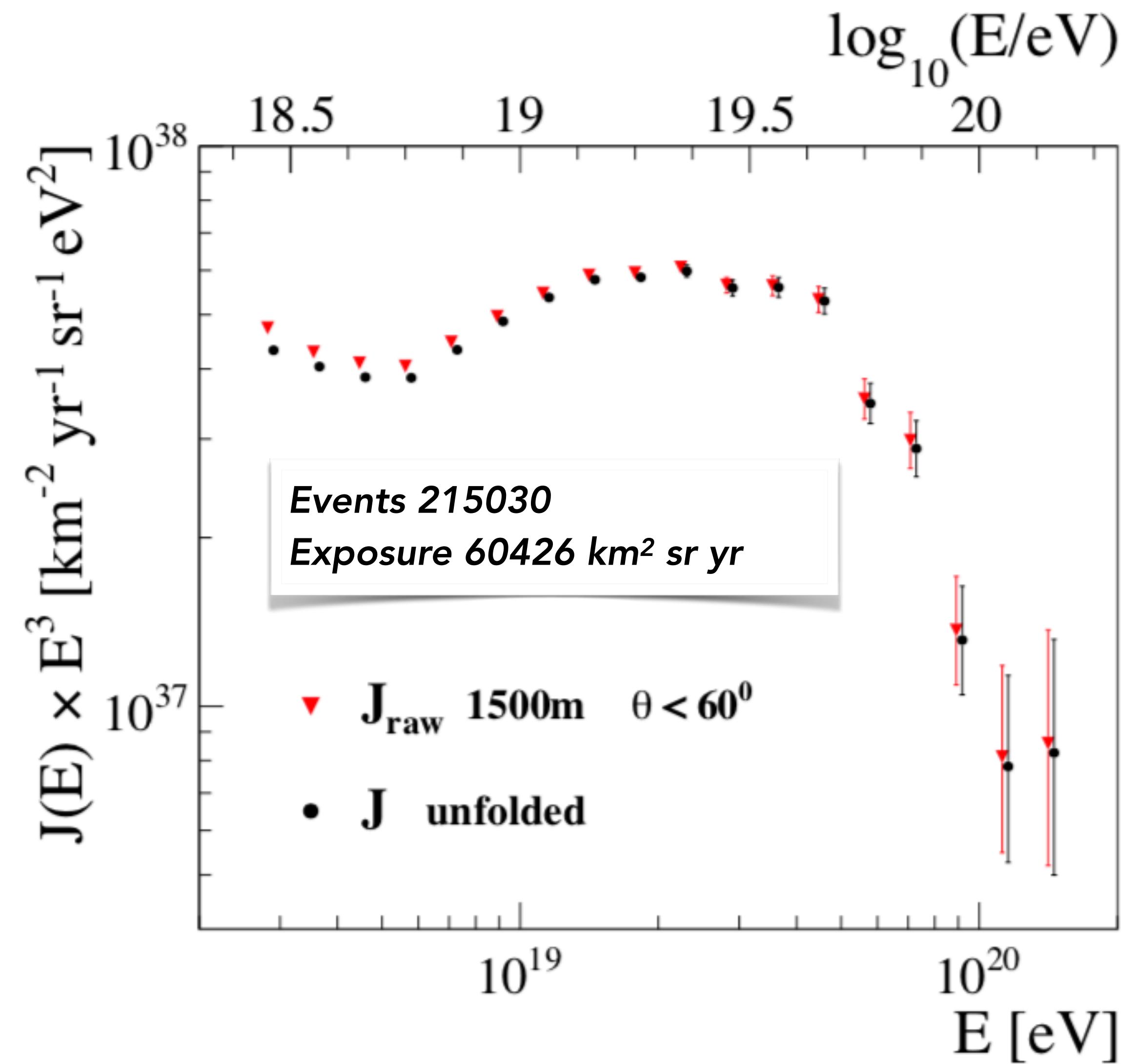
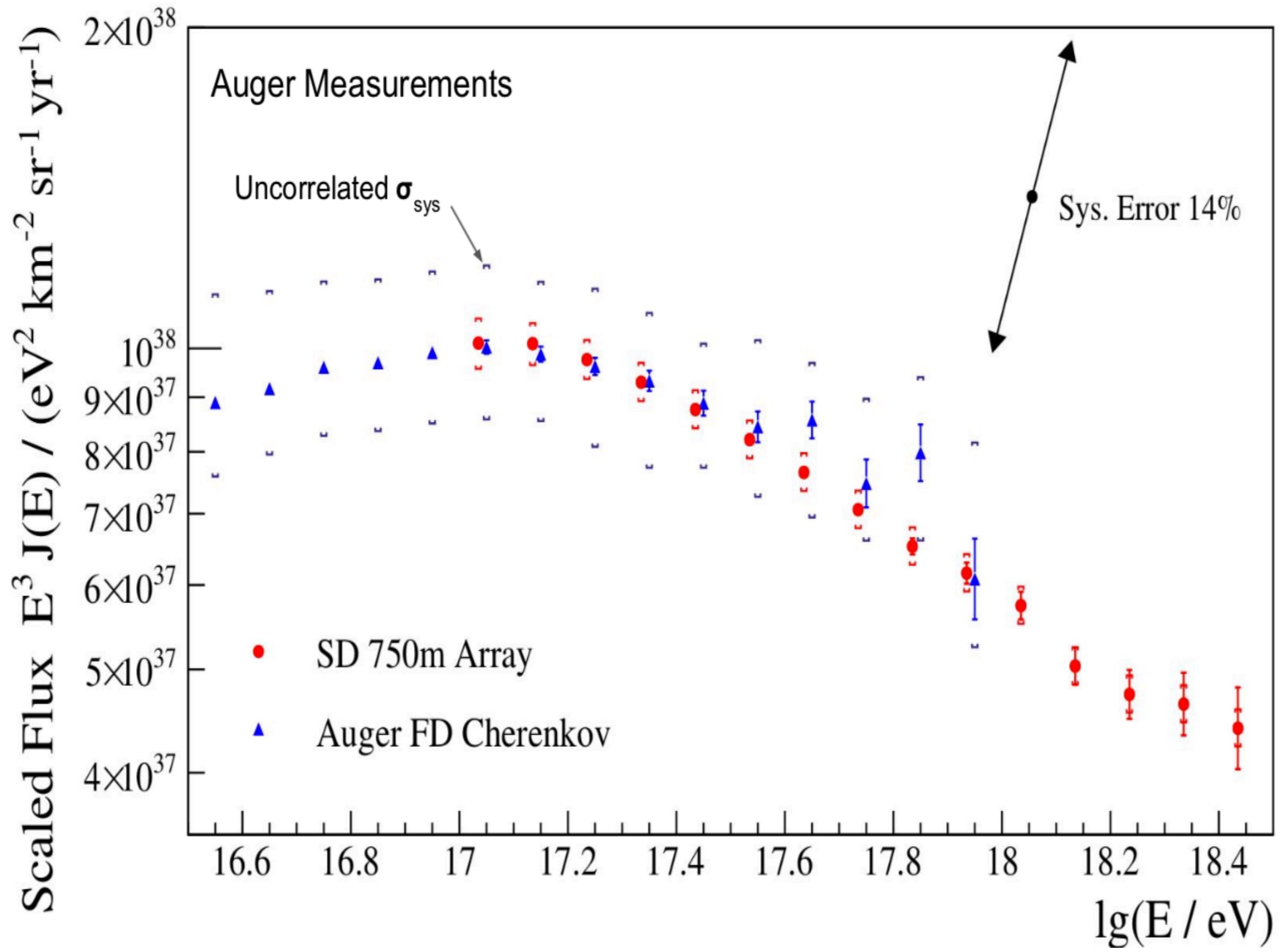


Invisible
energy
fraction

SD energy estimator



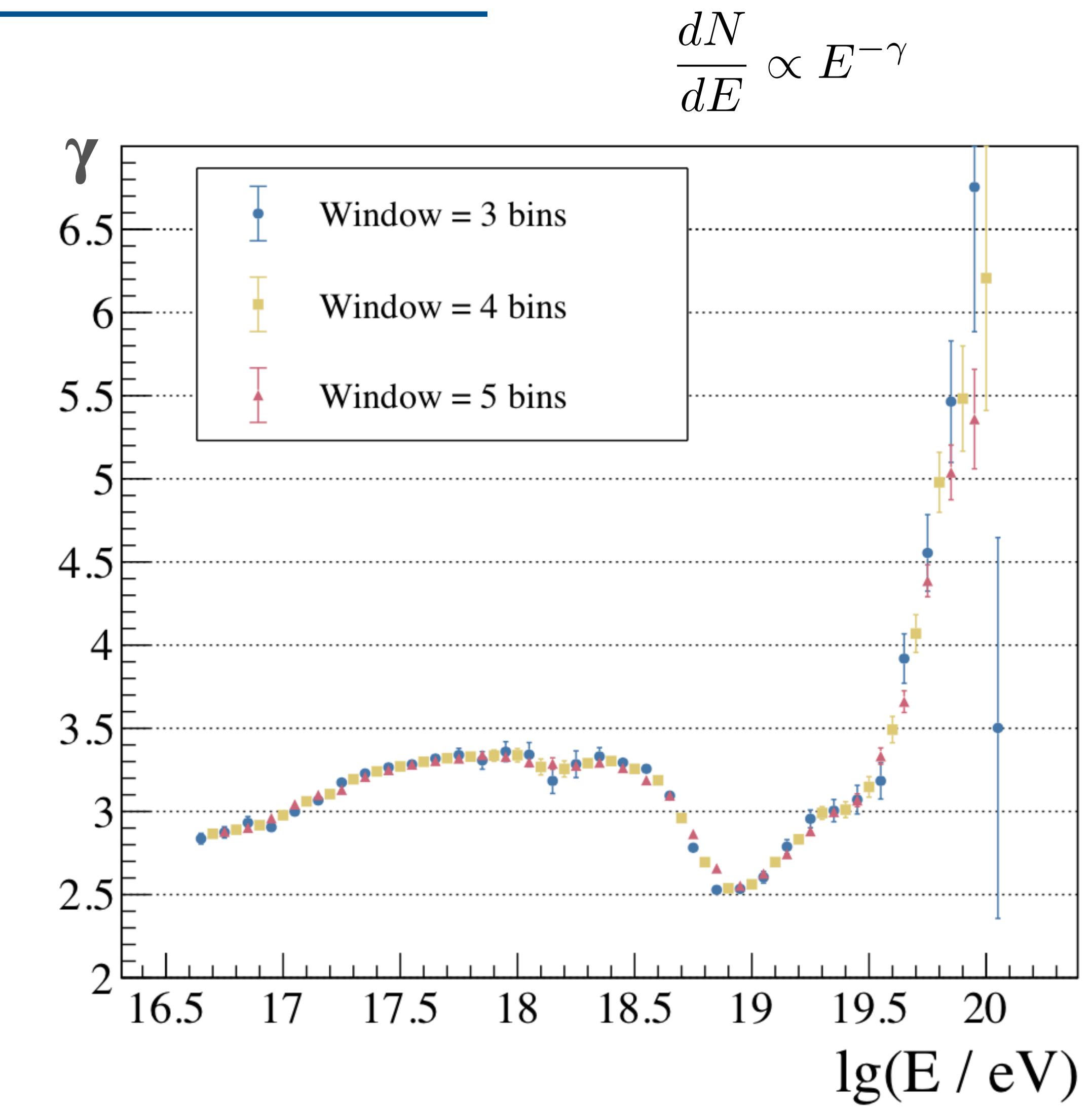
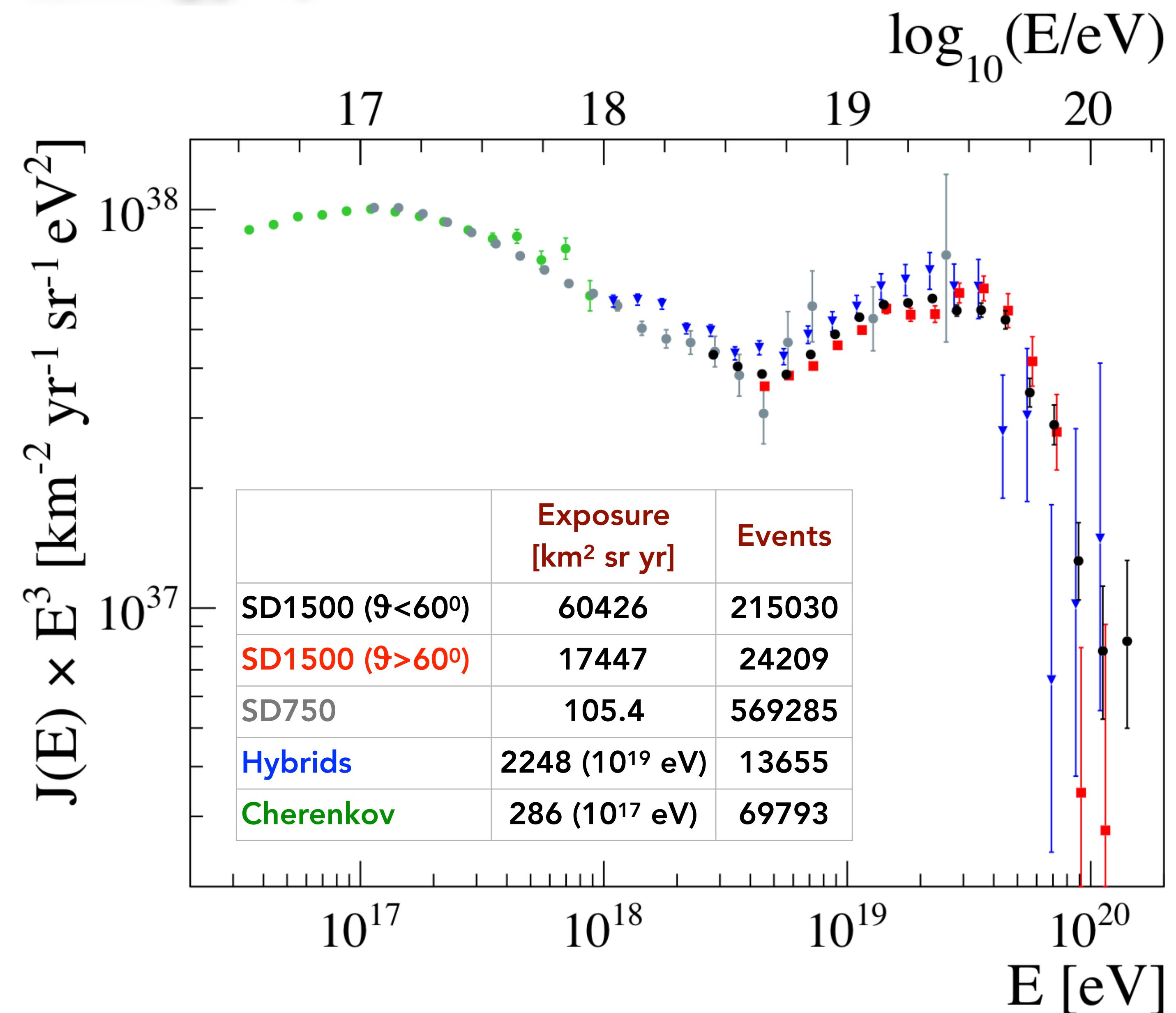
Energy spectrum



A. Coleman #225

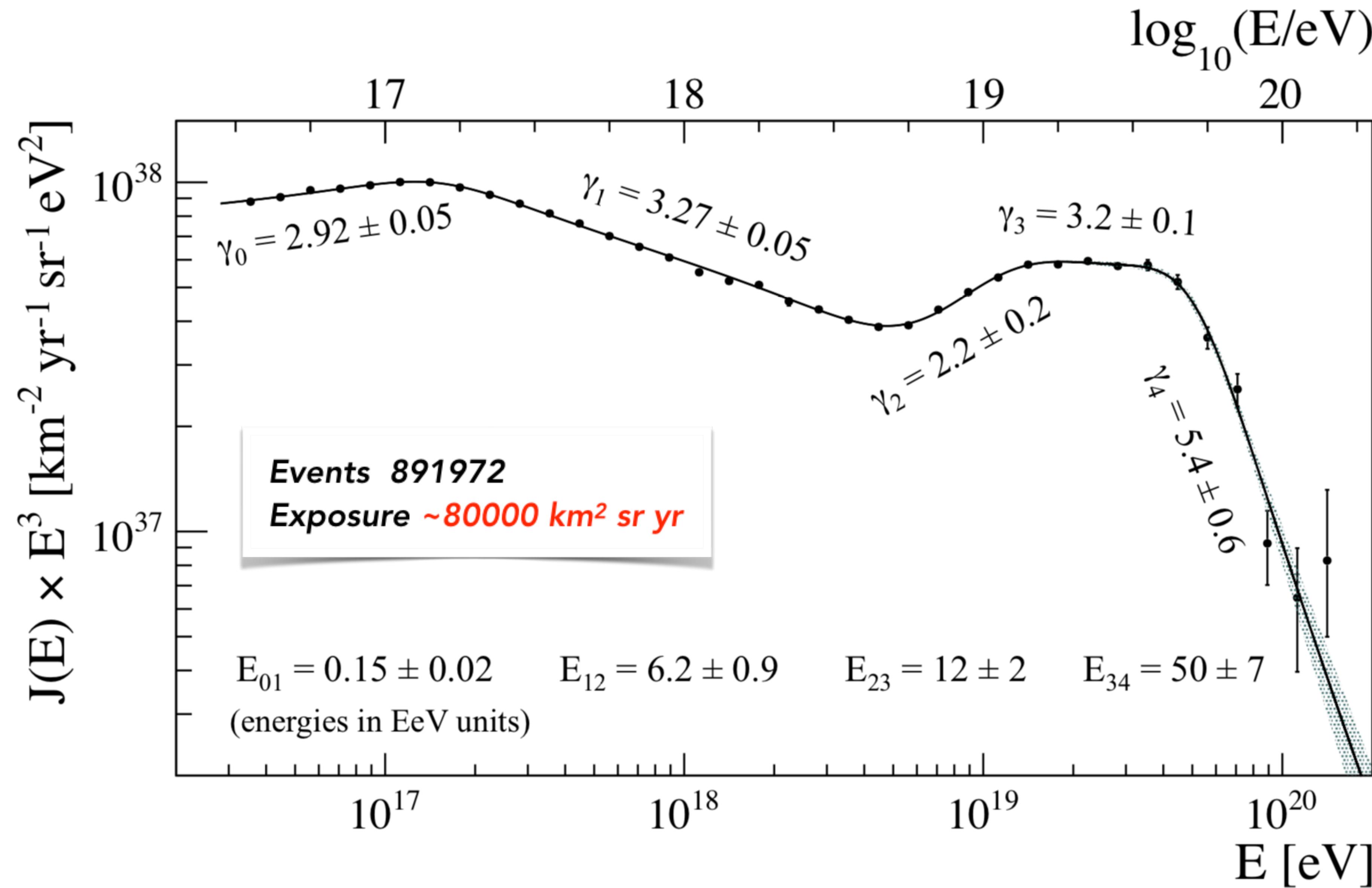
V. Novotny #374

Energy spectrum



Evolution of spectral slope with energy

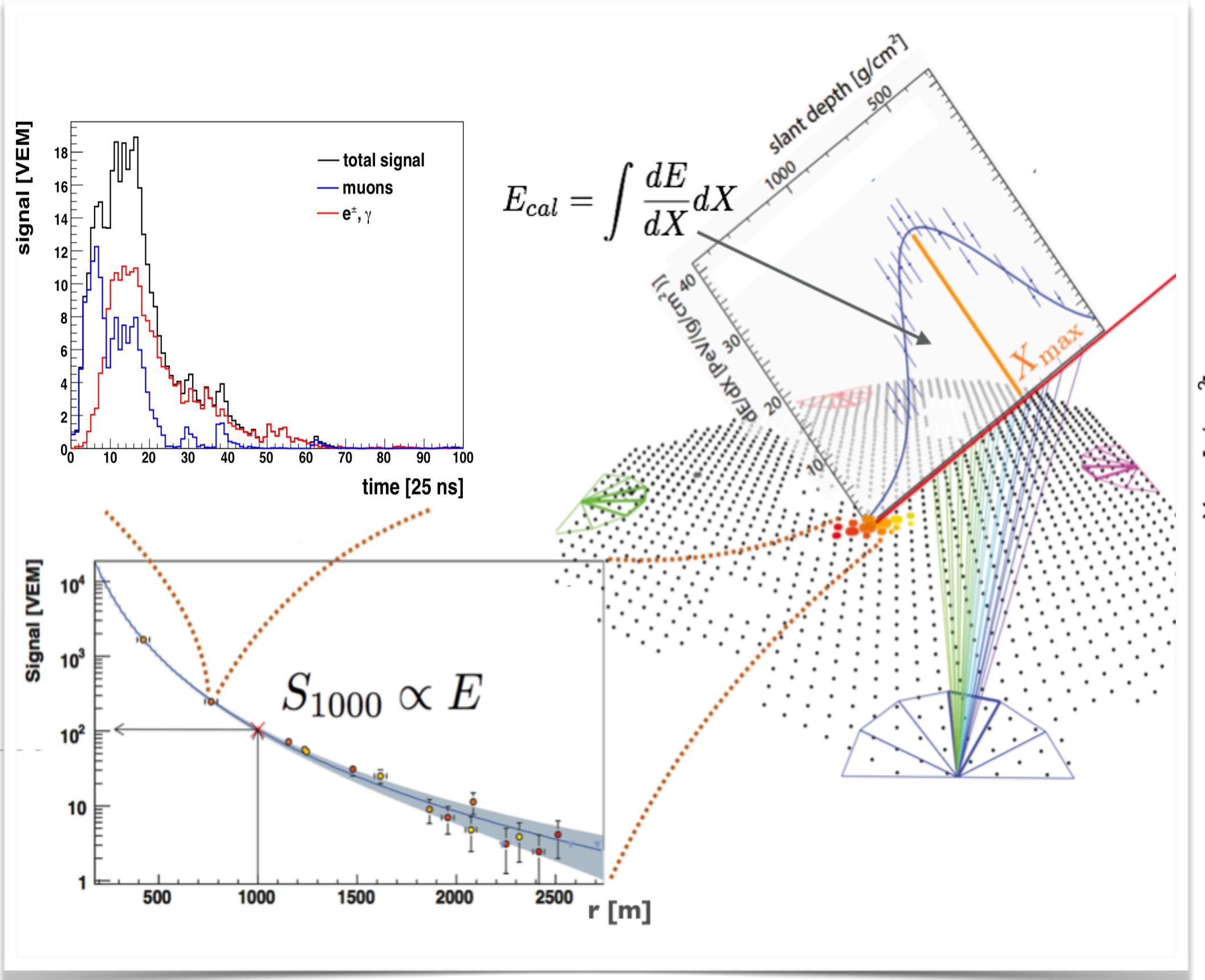
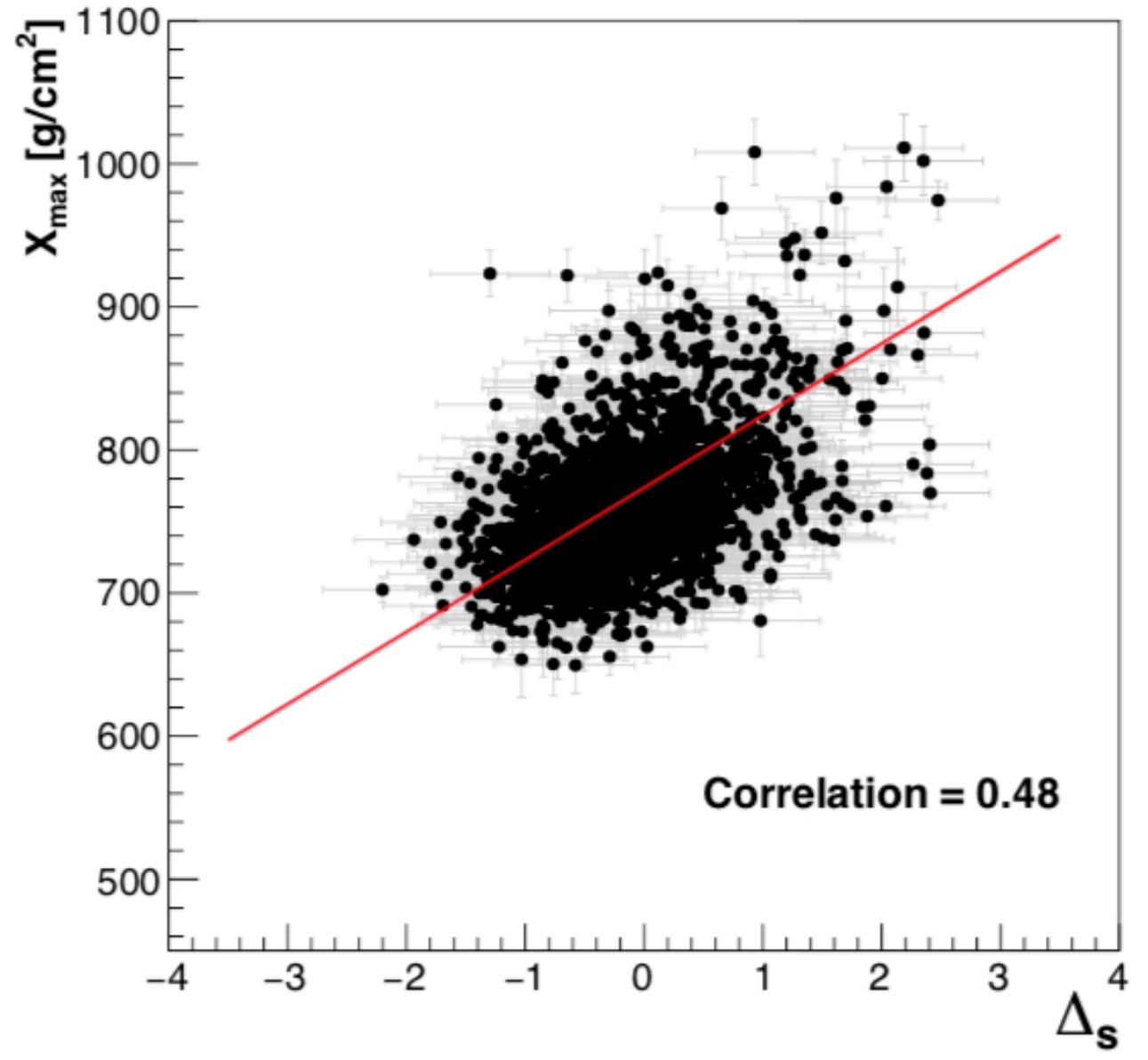
The energy spectrum



Mass composition

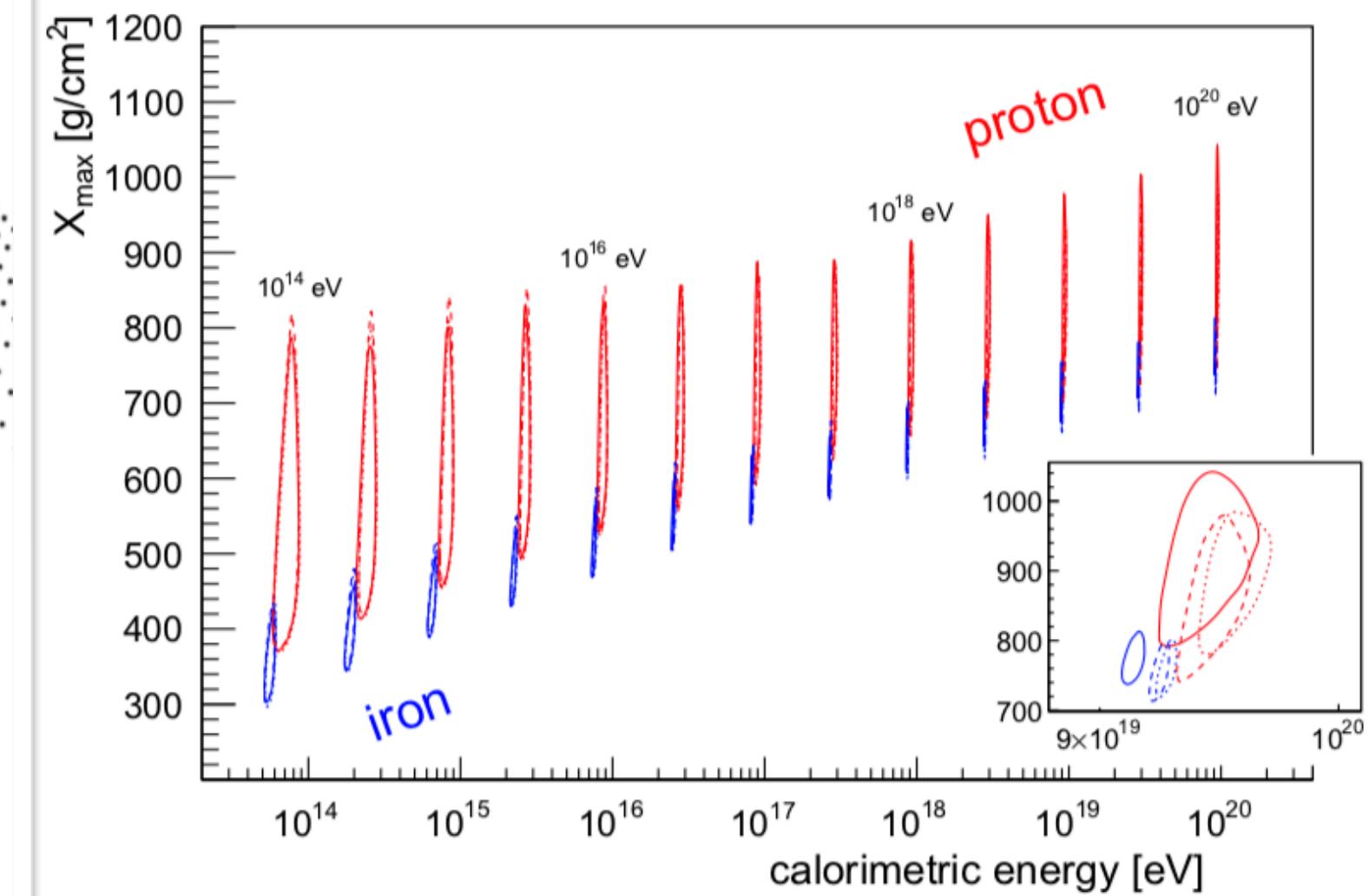
$$\Delta_i = \frac{t_{1/2} - t_{1/2}^{bench}}{\sigma_{1/2}}$$

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

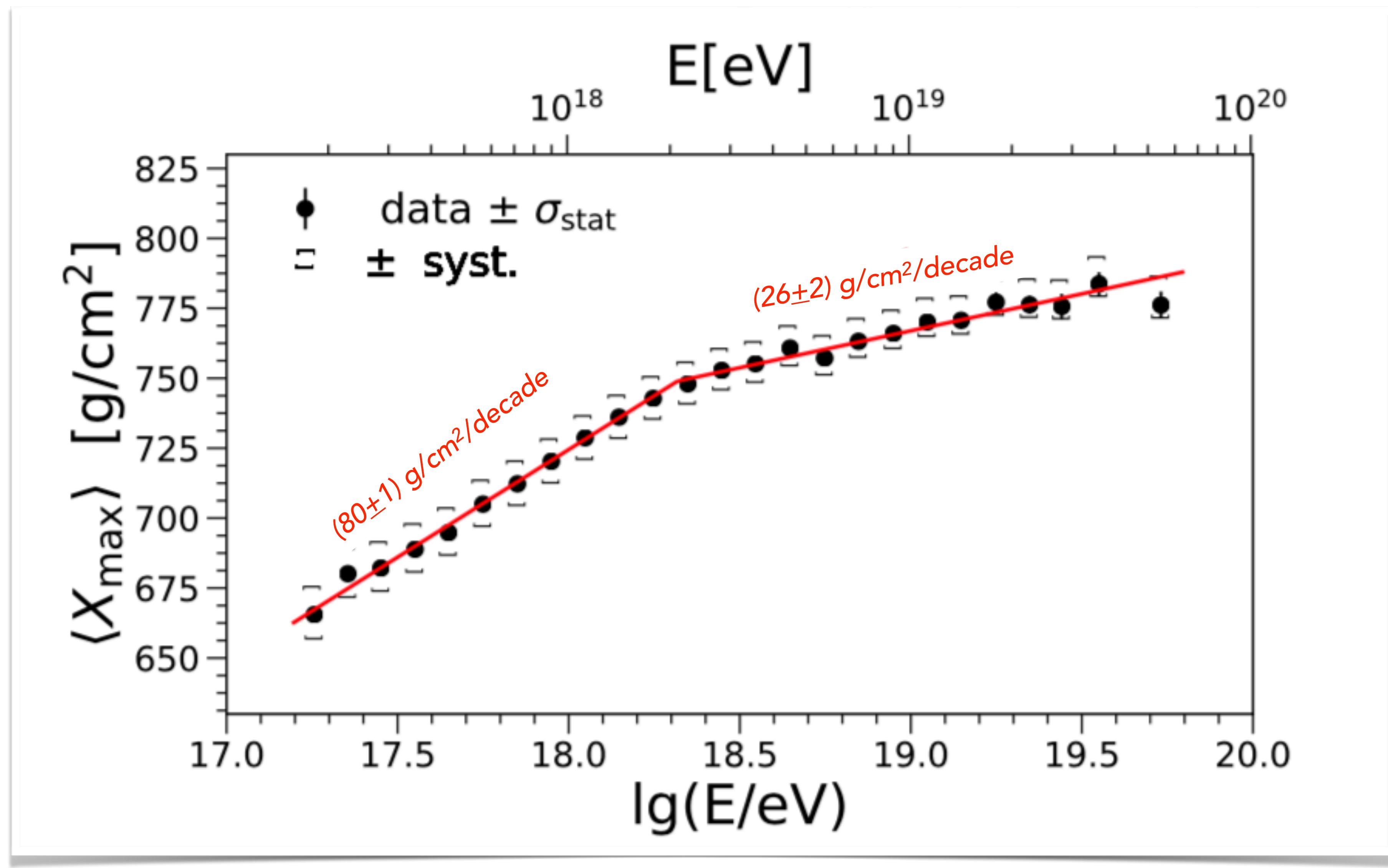


$$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f_E \langle \ln A \rangle$$

$$\sigma^2(X_{max}) = \langle \sigma_{sh}^2 \rangle + f_E \sigma^2(\ln A)$$



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



X_{\max} resolution

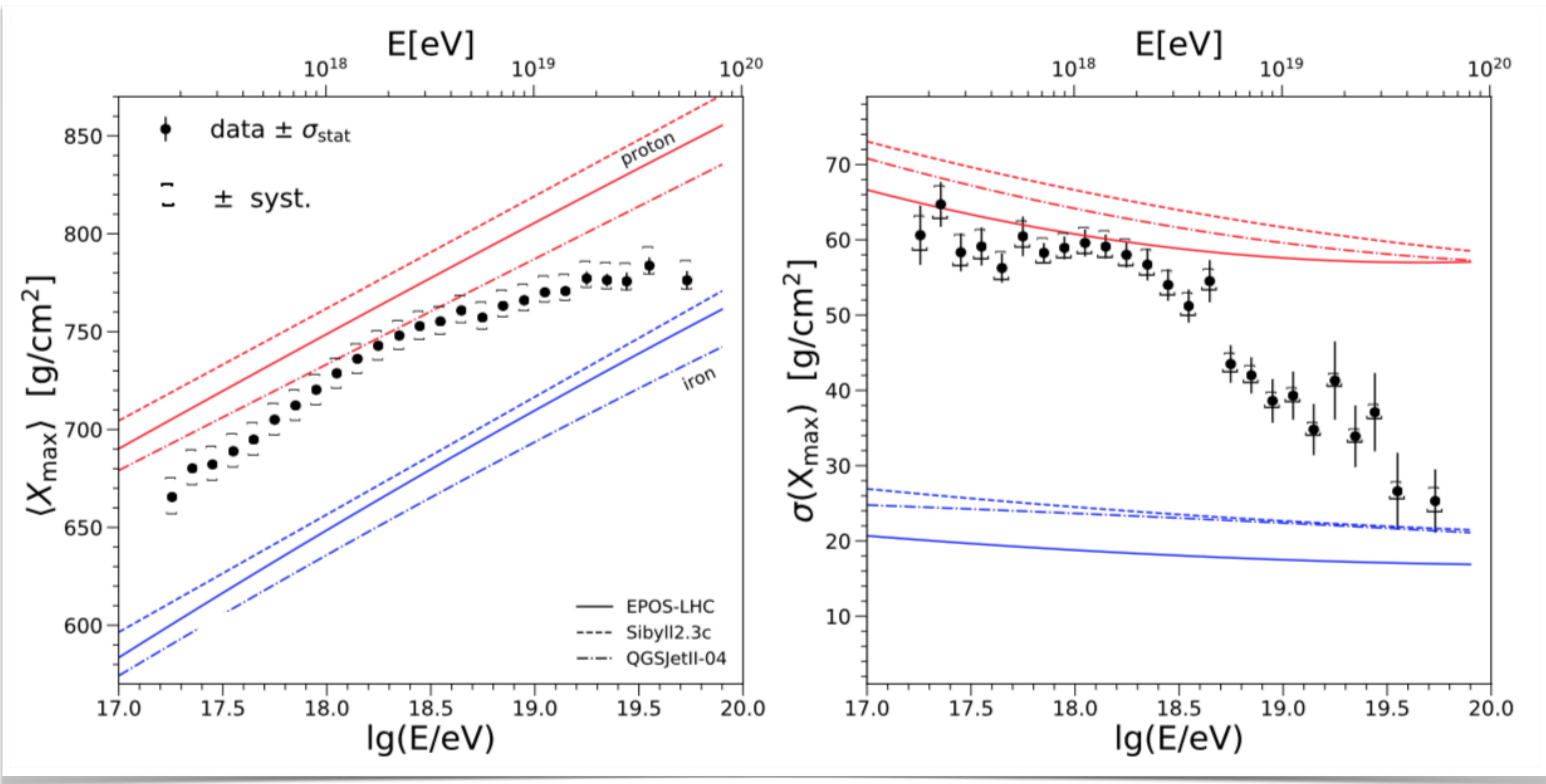
$\sim 25 \text{ g cm}^{-2}$ at $10^{17.8} \text{ eV}$

$\sim 15 \text{ g cm}^{-2}$ for $E > 10^{19} \text{ eV}$

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

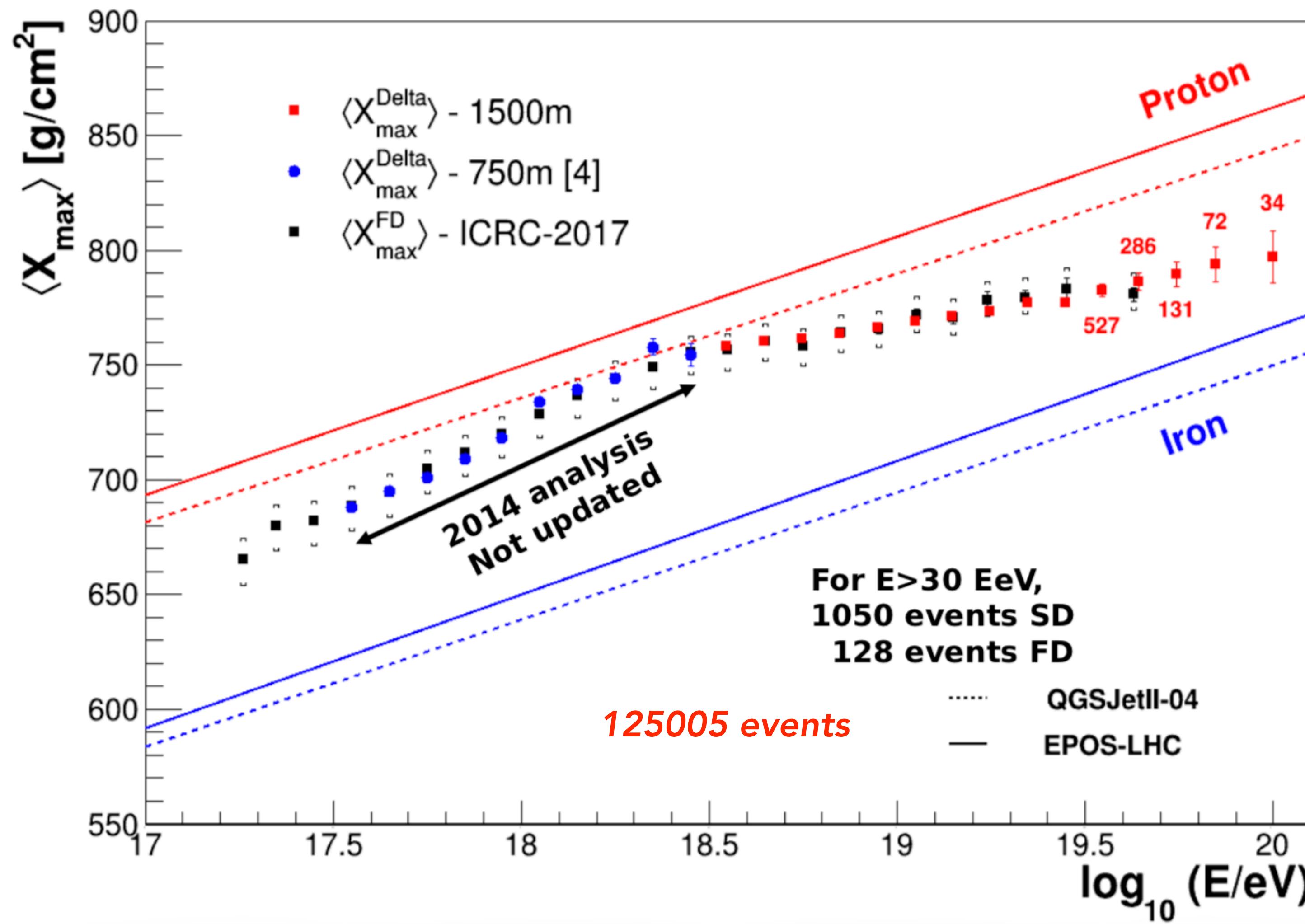
$\log_{10}(E/\text{eV})$	FD
18.5-18.6	1098
18.6-18.7	834
18.7-18.8	578
18.8-18.9	469
18.9-19.0	356
19.0-19.1	281
19.1-19.2	191
19.2-19.3	131
19.3-19.4	111
19.4-19.5	66
> 19.5	62
Total	4177

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



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

$\langle X_{\max} \rangle$ from SD



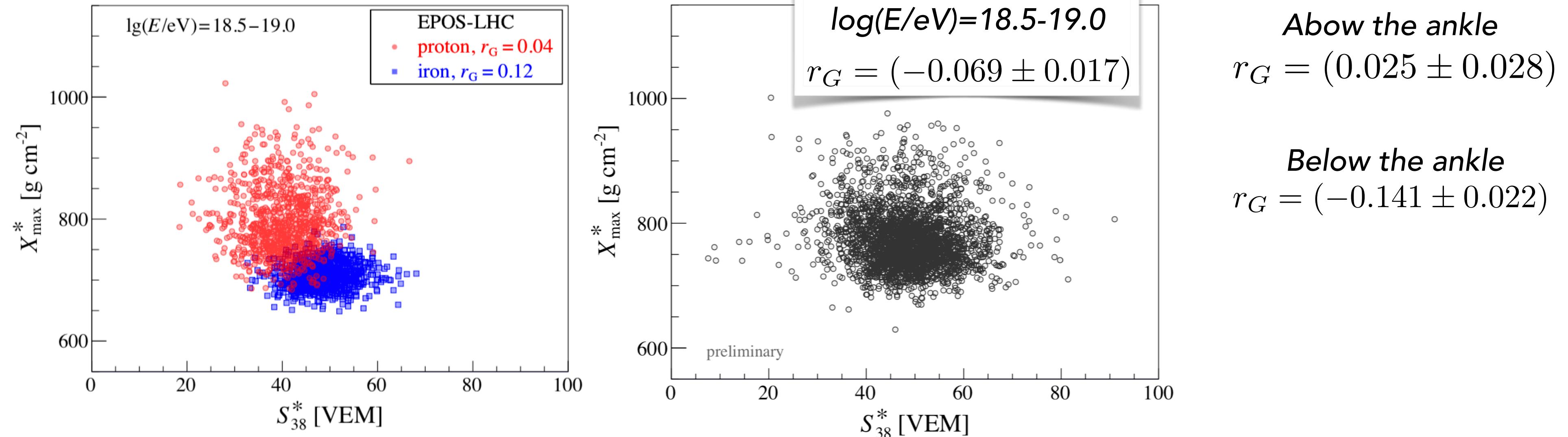
$\log_{10}(E/\text{eV})$	SD
18.5-18.6	45872
18.6-18.7	27783
18.7-18.8	17011
18.8-18.9	11631
18.9-19.0	7960
19.0-19.1	5489
19.1-19.2	3582
19.2-19.3	2290
19.3-19.4	1473
19.4-19.5	864
19.5-19.6	527
19.6-19.7	286
19.7-19.8	131
19.8-19.9	72
>19.9	34
Total	125005

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

Mass composition at the ankle

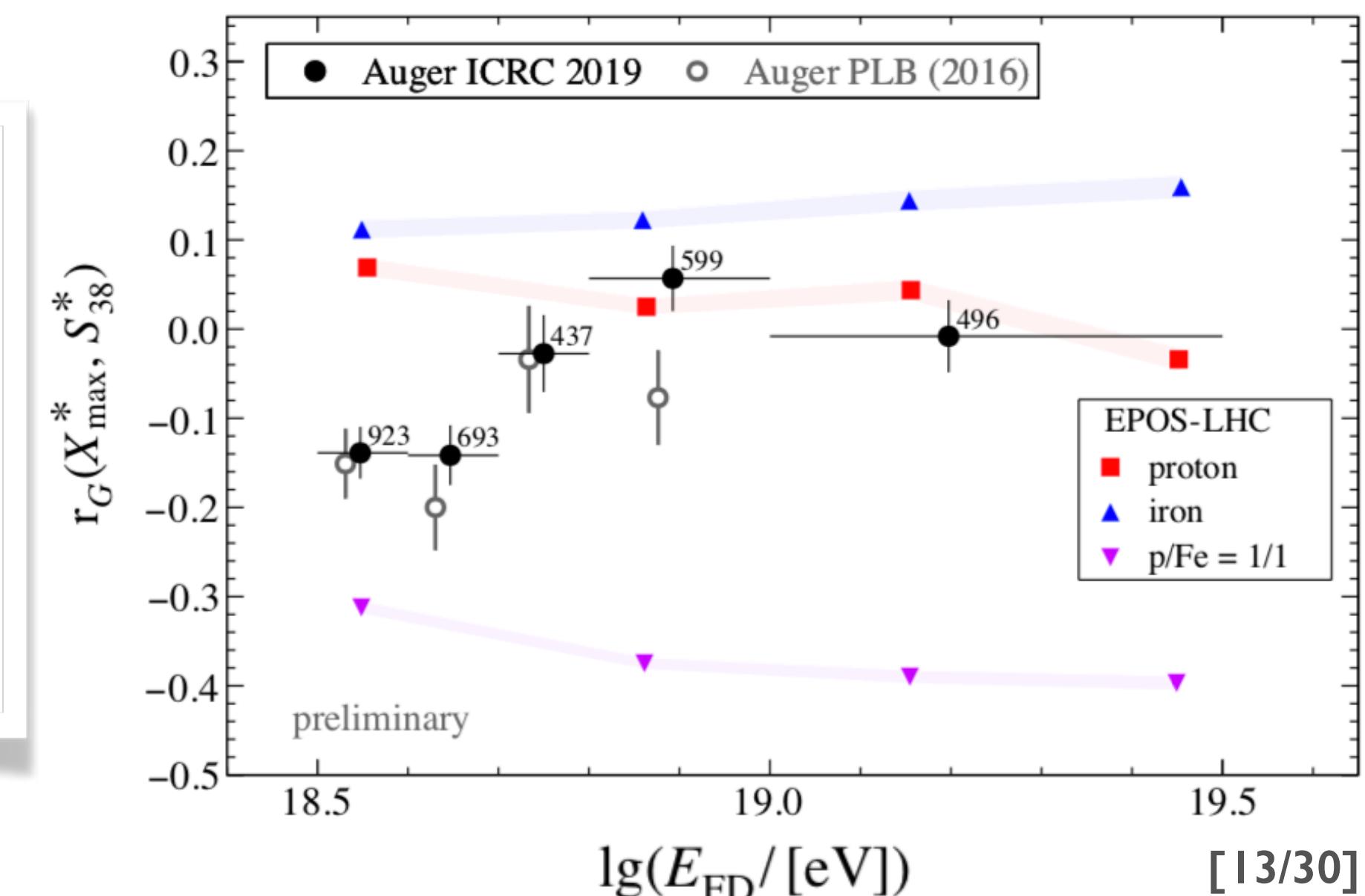
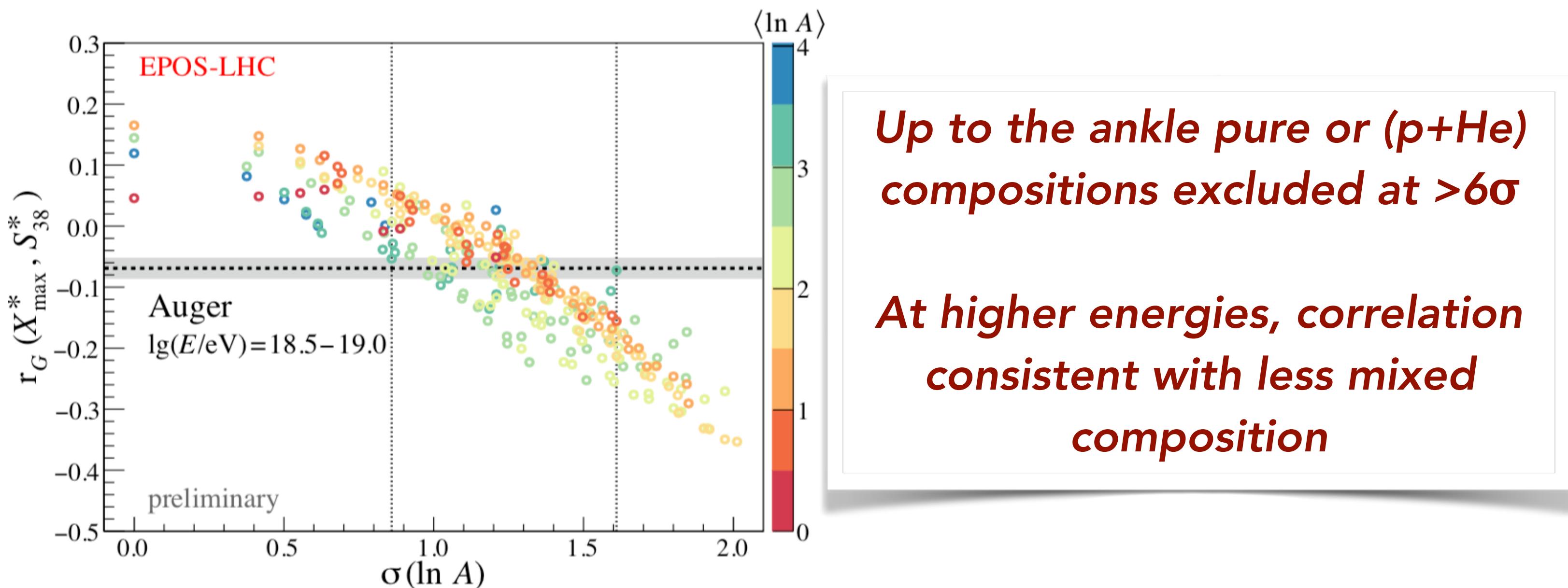
$S_{38^\circ}^*(1000)$
 X_{max}^*
 rescaled at 10 EeV

A. Yushkov #482

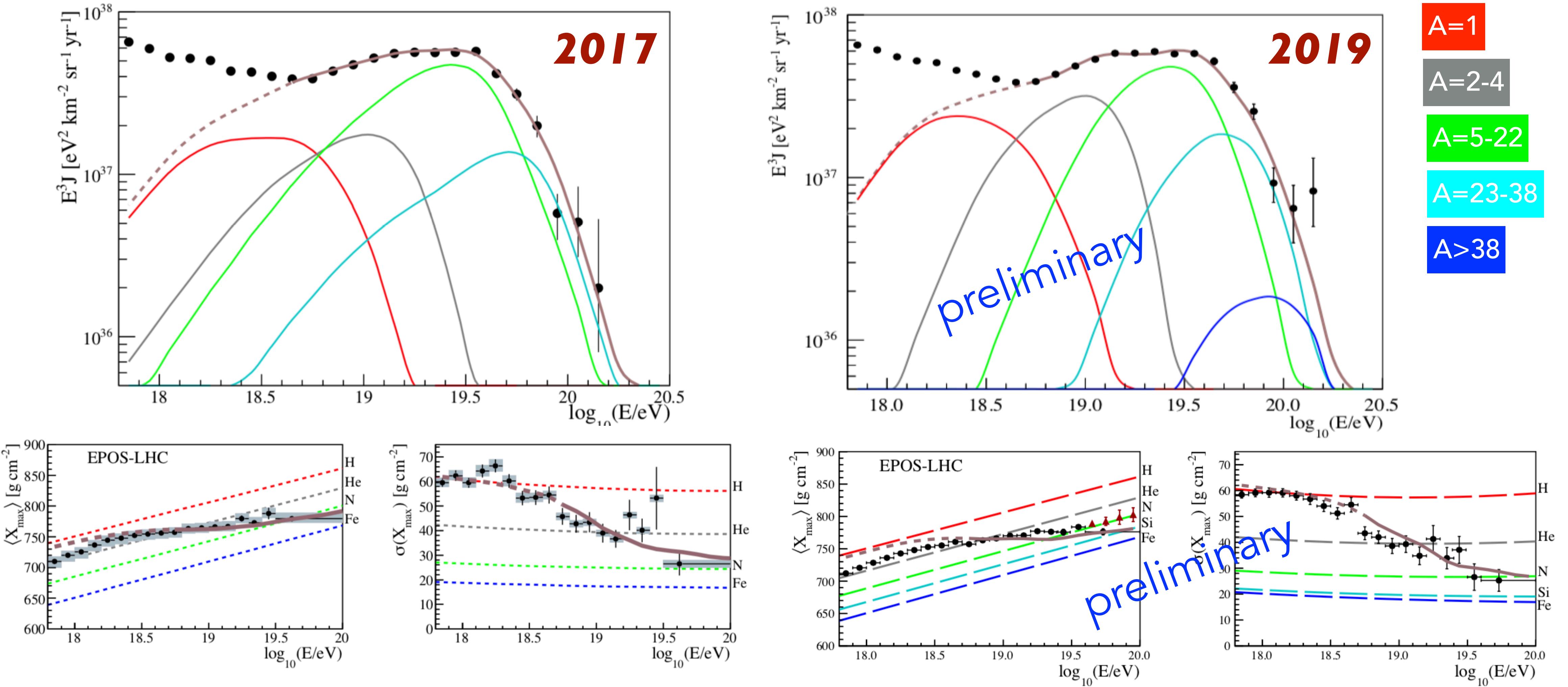


Abow the ankle
 $r_G = (0.025 \pm 0.028)$

Below the ankle
 $r_G = (-0.141 \pm 0.022)$



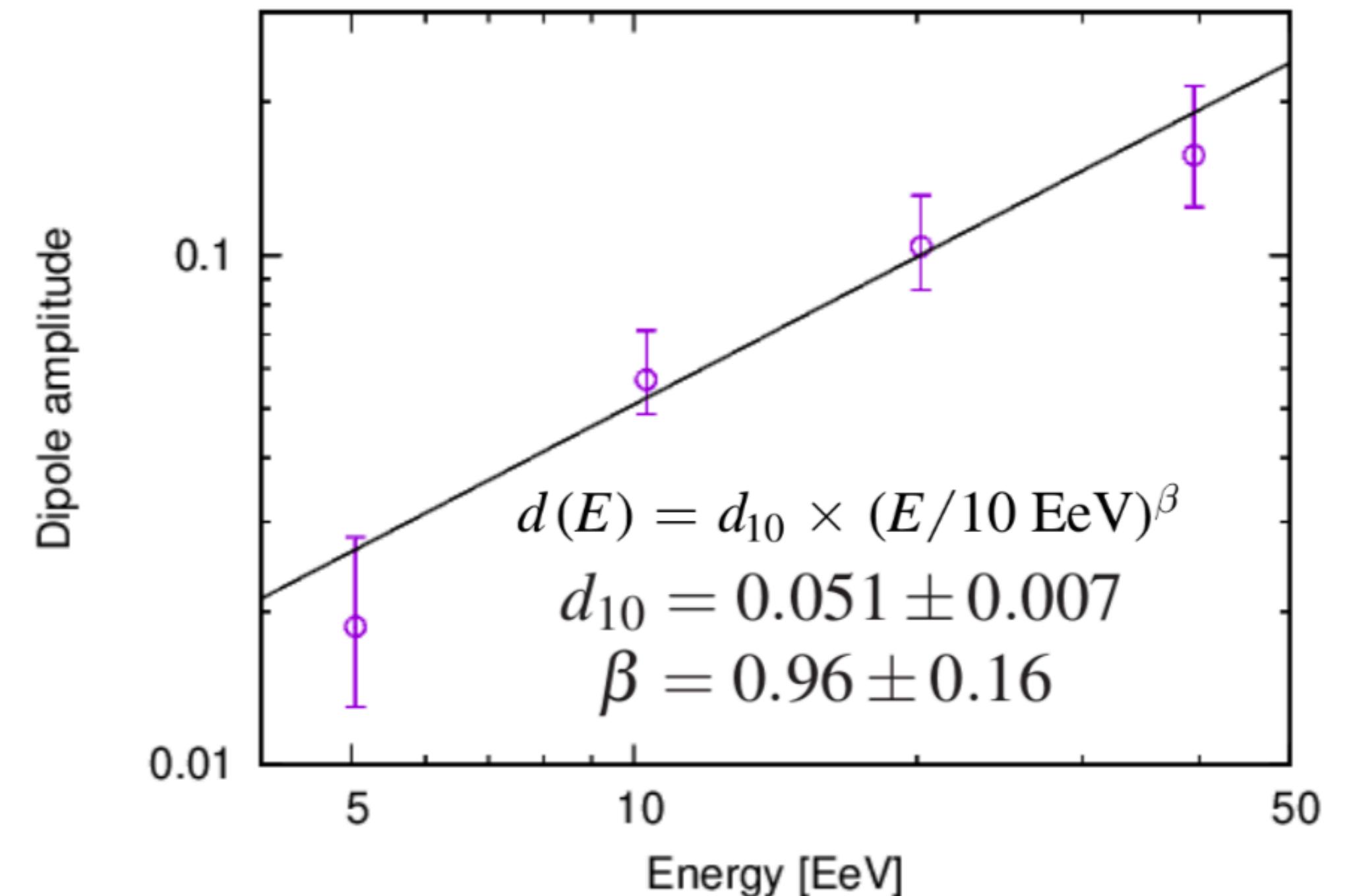
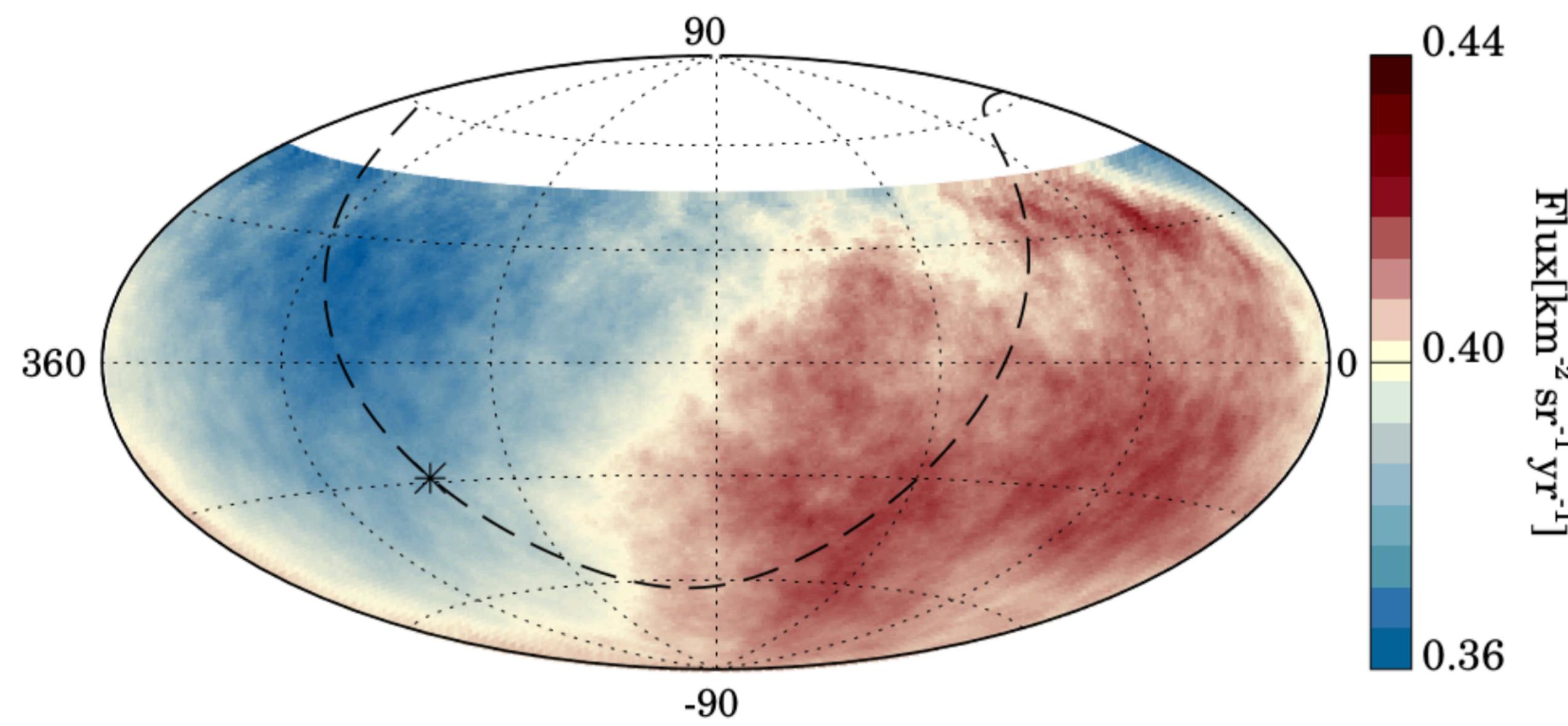
Combined fit of spectrum + X_{\max} distributions



Large Scale anisotropy

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

Exposure $>92000 \text{ km}^2\text{sr yr}$
for events with $\theta < 80^{\circ}$

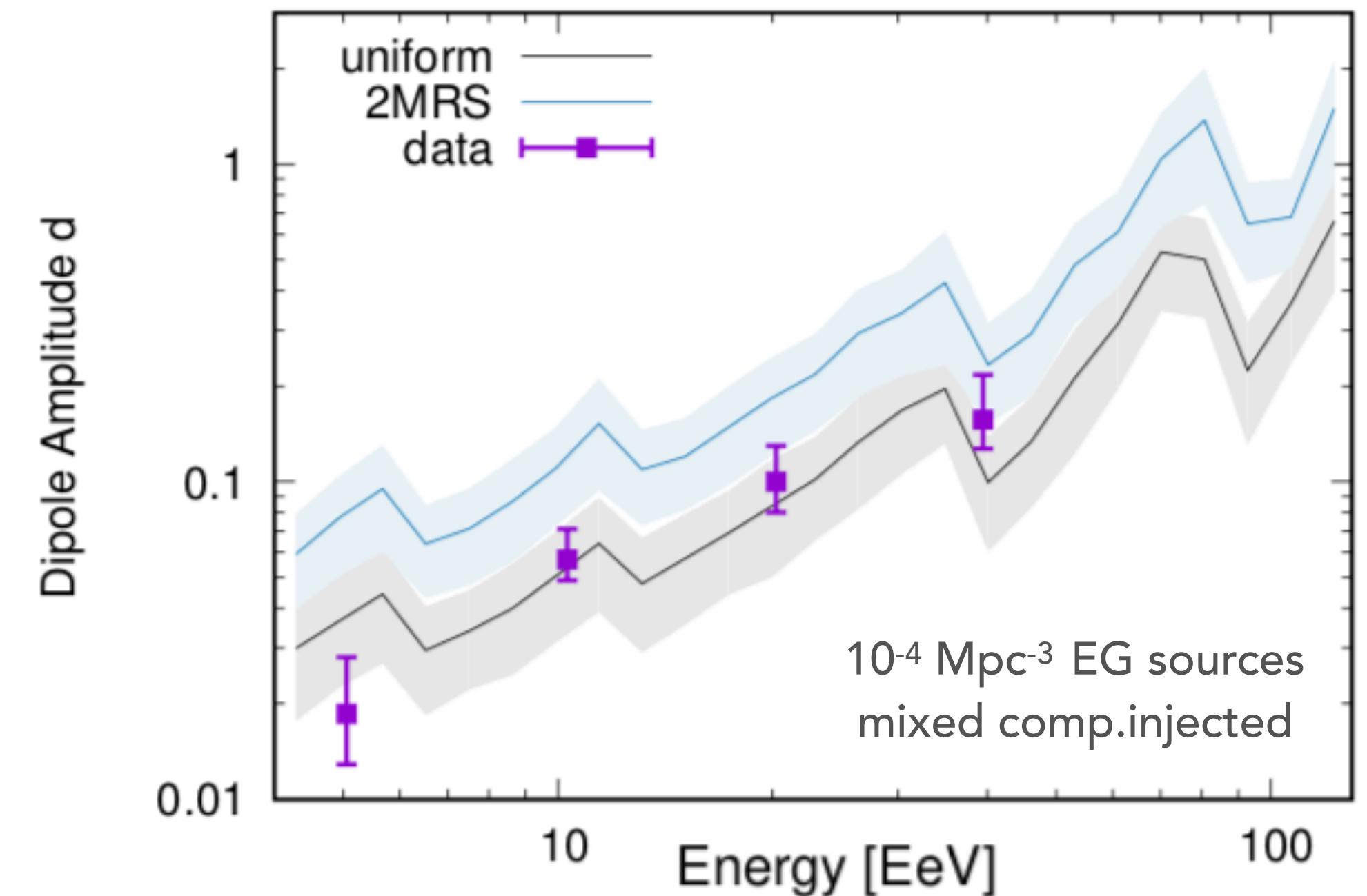
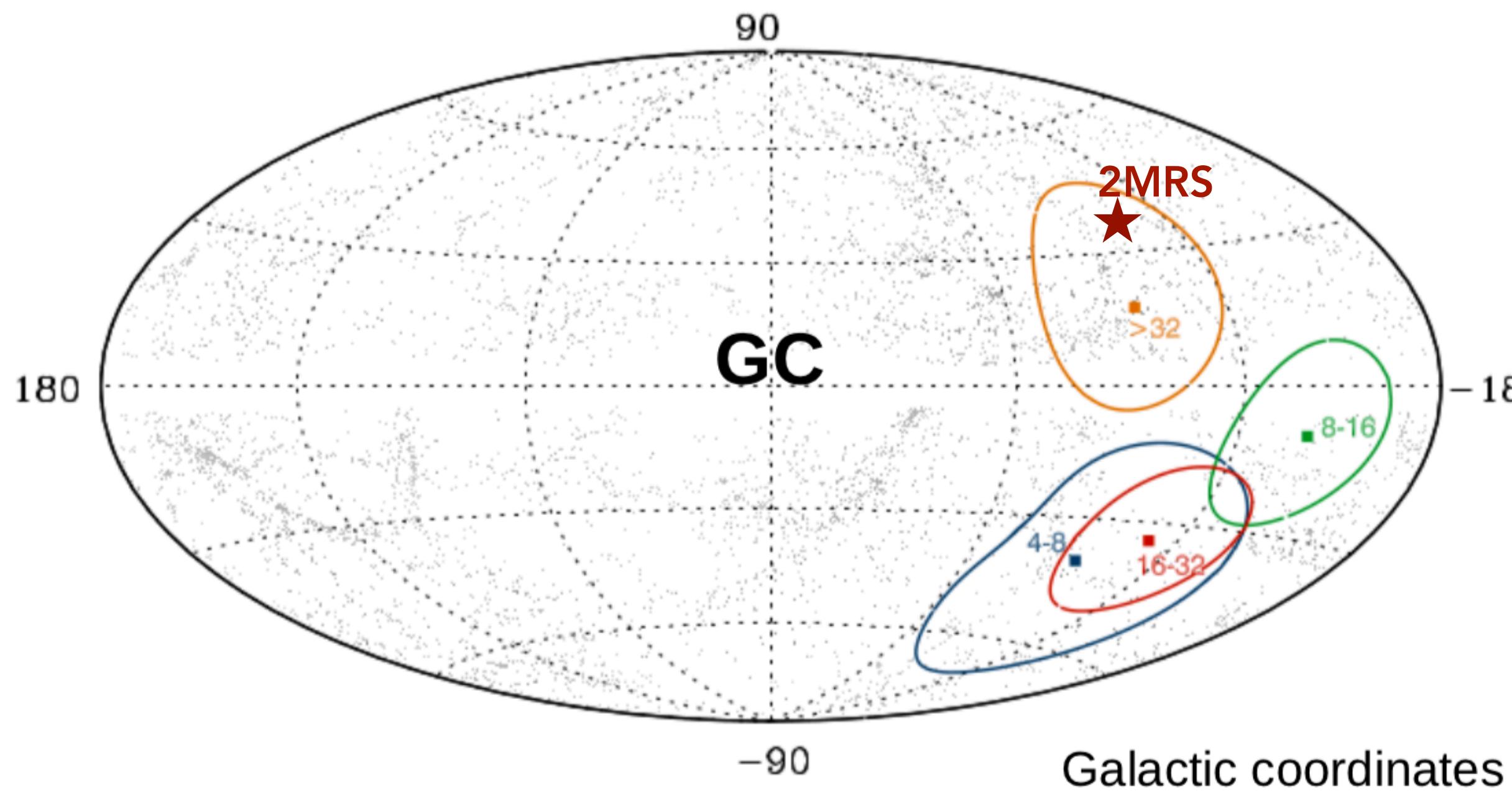


3-D Dipole above 8 EeV at $(\alpha, \delta) = (98^{\circ}, -25^{\circ})$: $(6.6^{+1.2}_{-0.8})\%$
Amplitude increasing with energy

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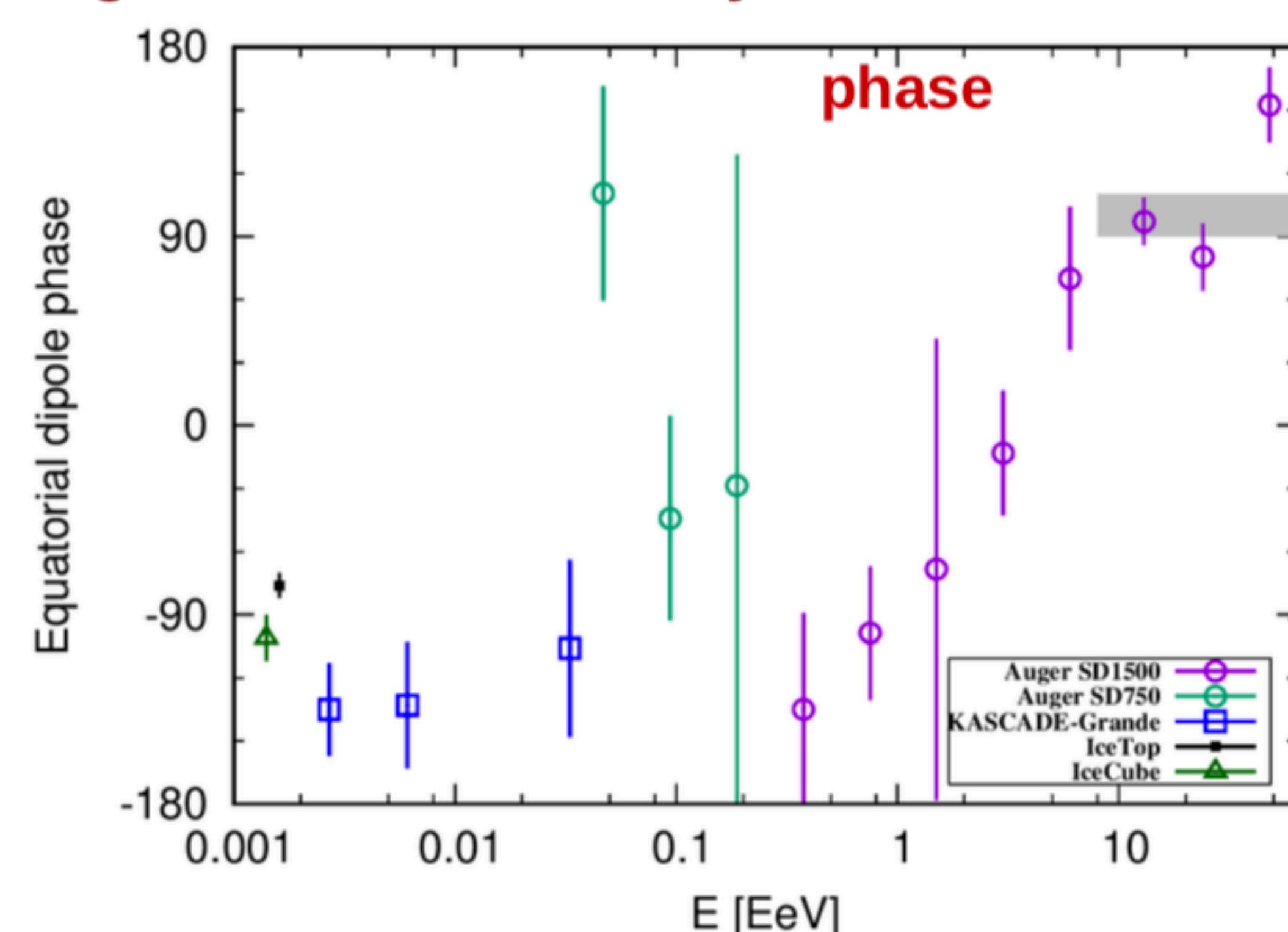
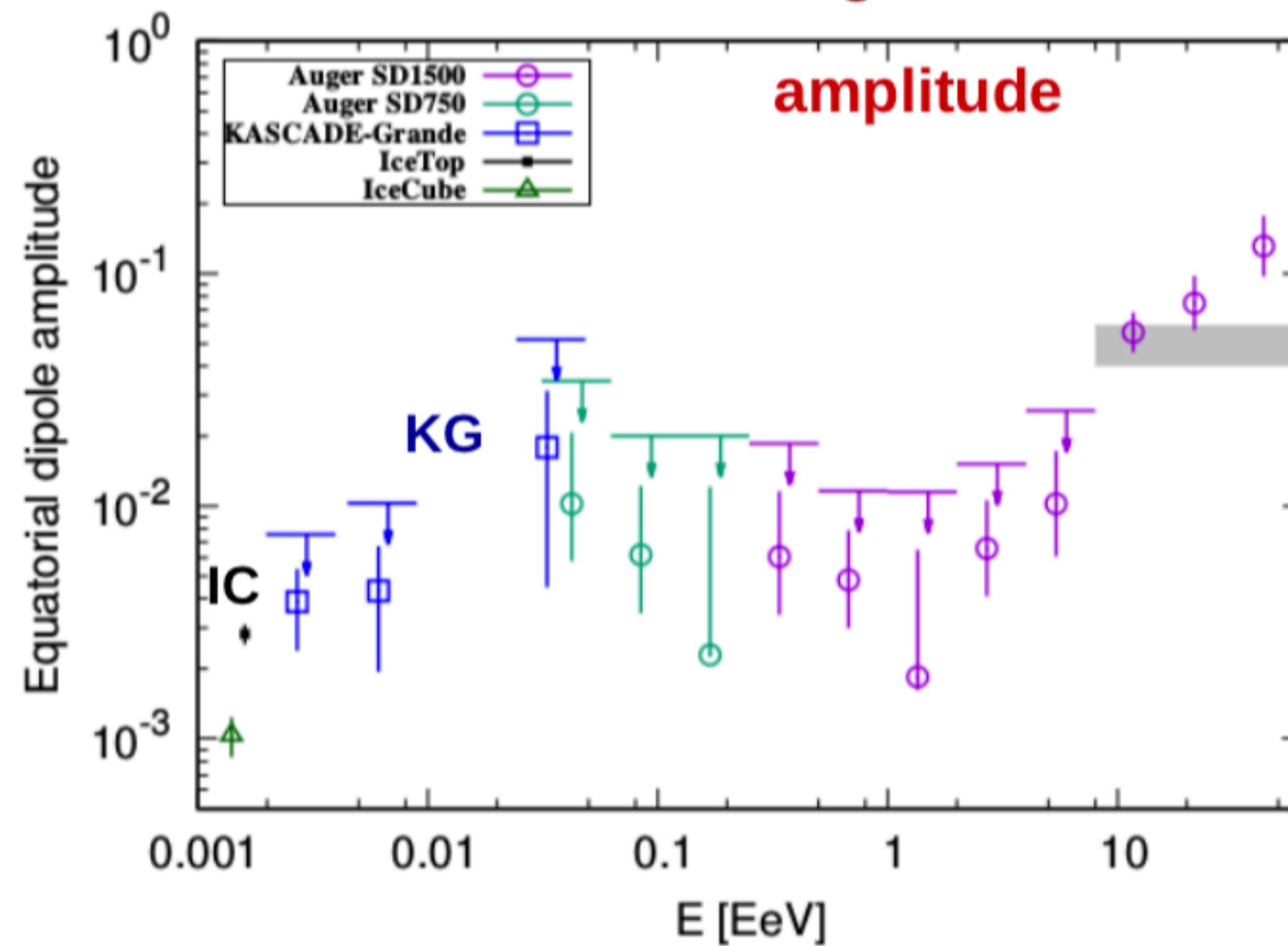


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Large Scale anisotropy

Search for large scale anisotropies down to 0.03 EeV

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

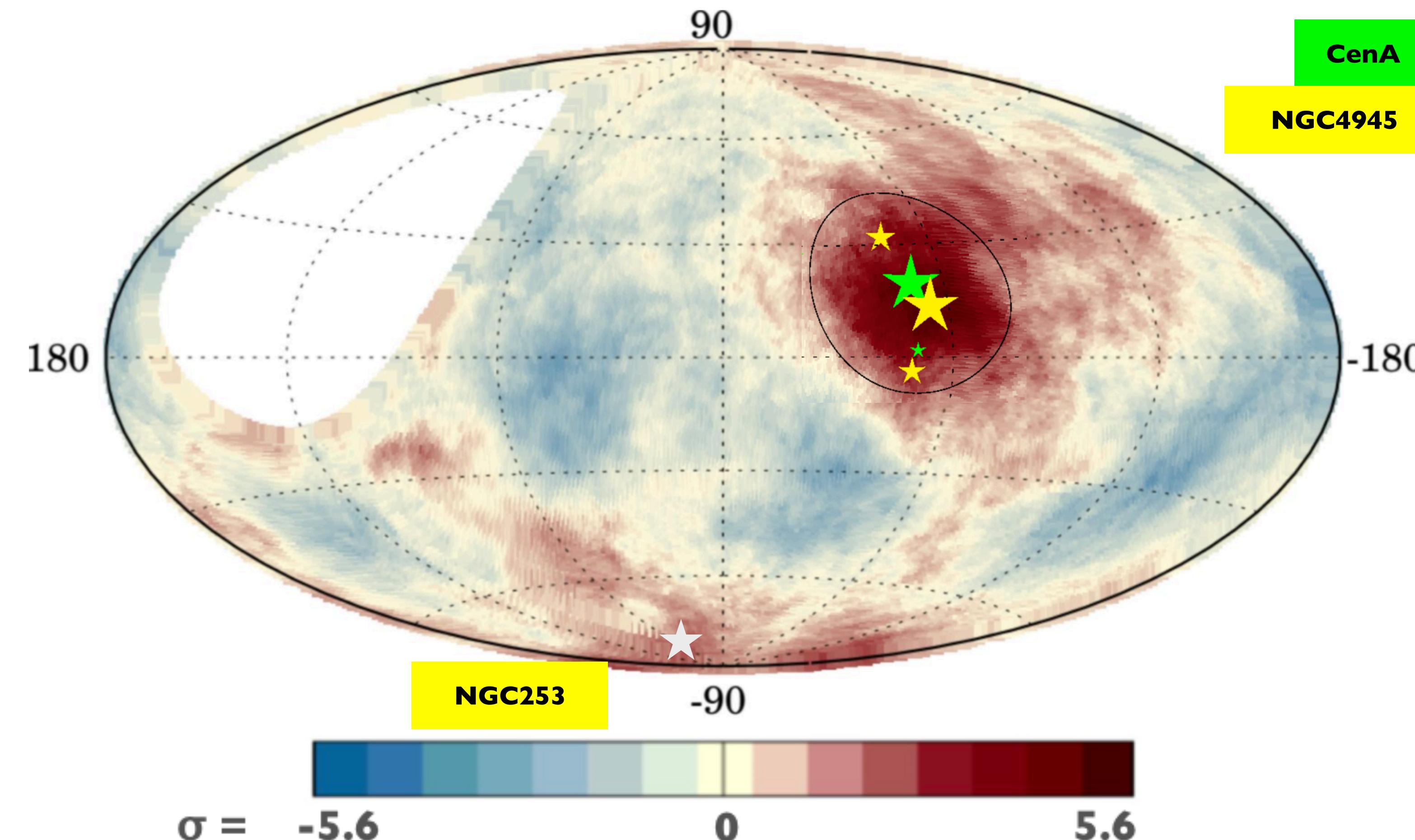


Predominantly Galactic origin below 1-2 EeV, extragalactic origin above

Intermediate anisotropy

Total SD events with $E > 32$ EeV : 2157

Total exposure $101,400 \text{ km}^2 \text{ sr yr}$



Blind search

Scan ranges:

$32 \text{ EeV} \leq E_{\text{th}} \leq 80 \text{ EeV}$ (1 EeV steps)

$1^\circ \leq \psi \leq 30^\circ$ (1° steps)

**Most significant excess for $E > 38$ EeV
($\alpha = 202^\circ, \delta = -45^\circ$) $\sim 2^\circ$ from CenA**

Centaurus A

**3.9σ effect (post-trial)
for $E > 37$ EeV, 28° window**

Intermediate anisotropy

γ AGNs

3FHL catalog < 250 Mpc

33 sources (CenA, Fornax A, M87...)

Flux proxy $\Phi(>10 \text{ GeV})$

Starburst Galaxies

32 sources (Circinus, M82, M83,...)

<250 Mpc

Flux proxy $\Phi(>1.4 \text{ GHz}), > 0.3 \text{ Jy}$

Swift-BAT

>300 radio loud and quiet sources

<250 Mpc

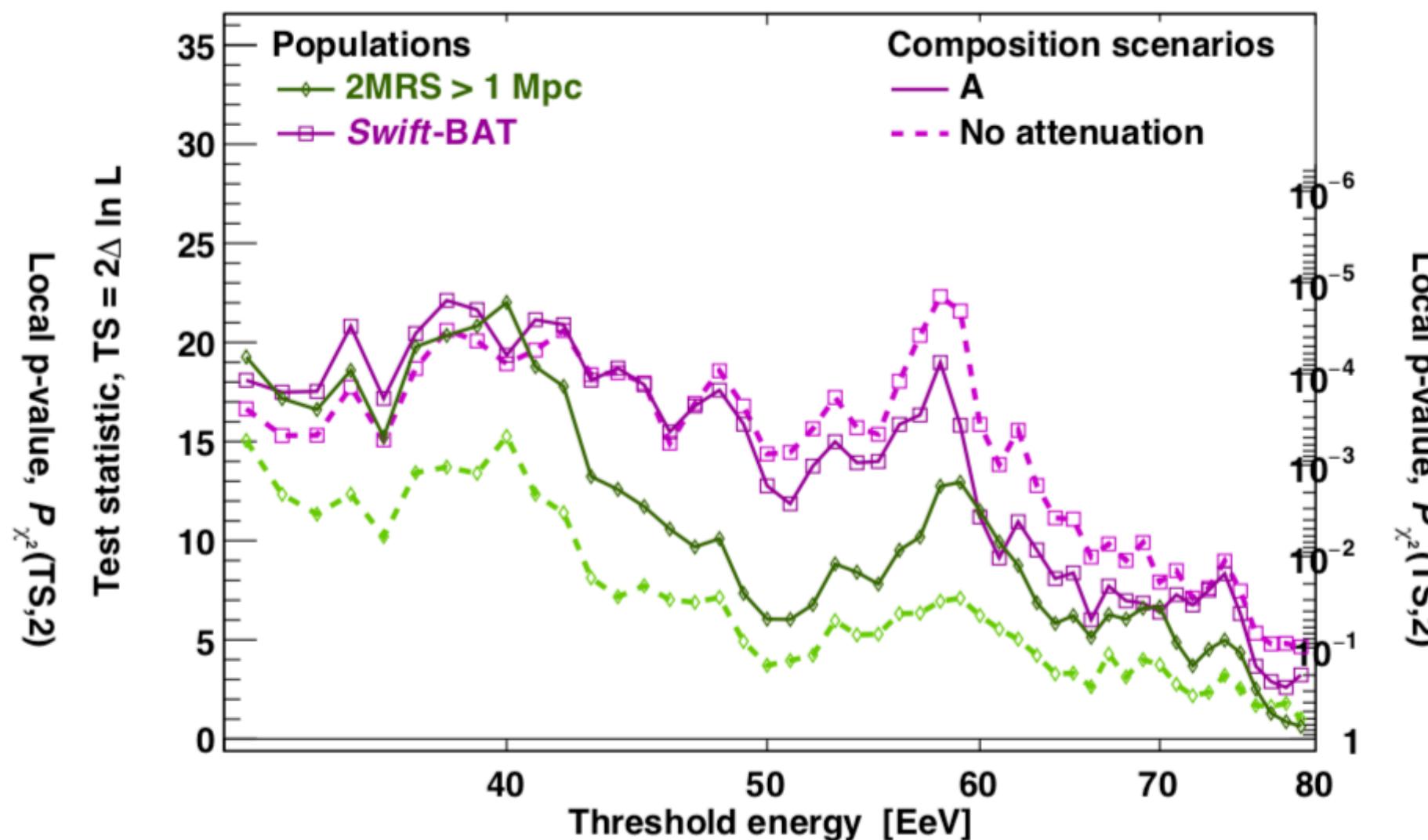
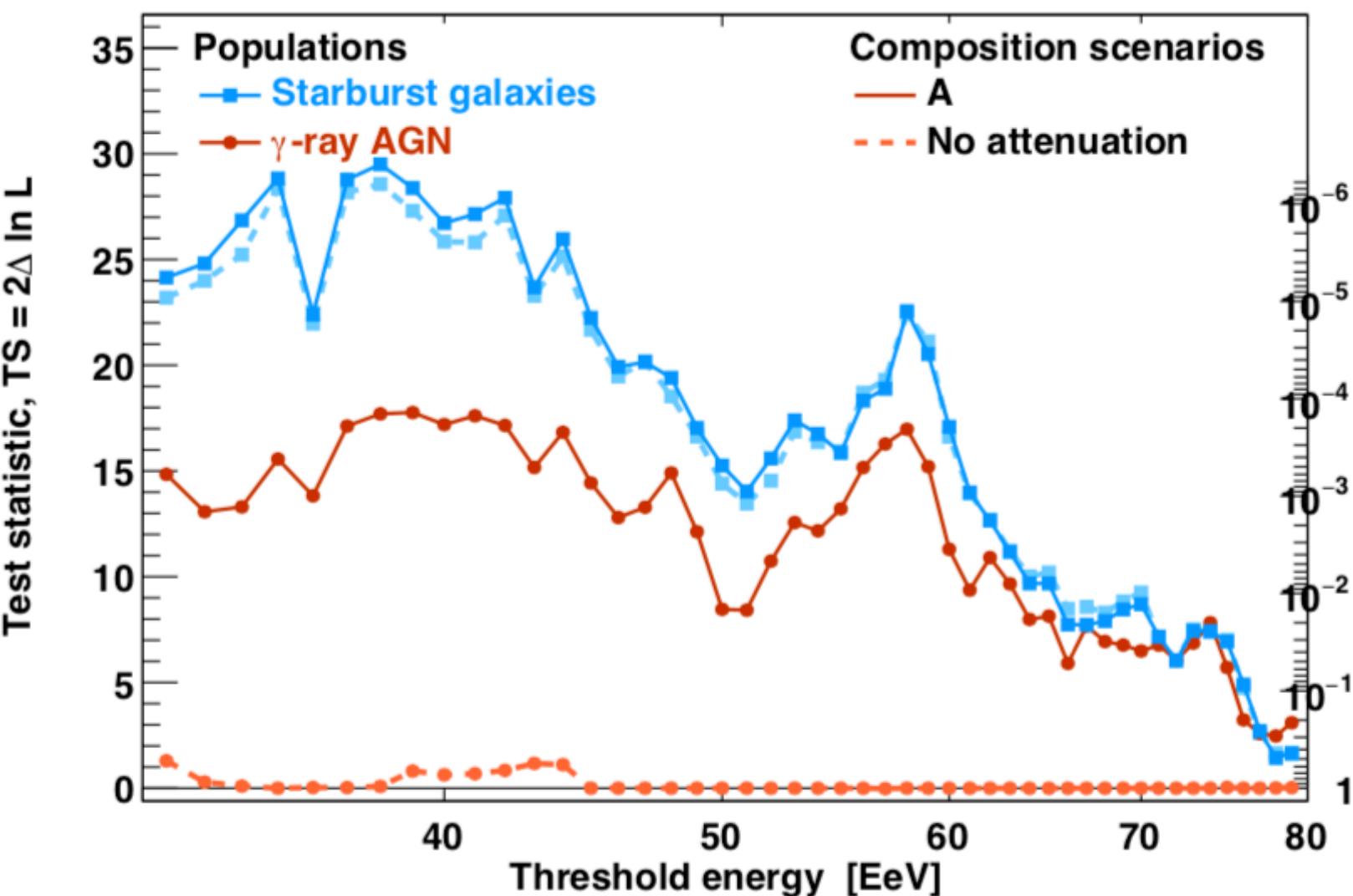
$\Phi > 13.4 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$

2MRS

~ 10^4 sources with D>1 Mpc

<250 Mpc

Flux proxy $\Phi(14\text{-}195 \text{ keV})$

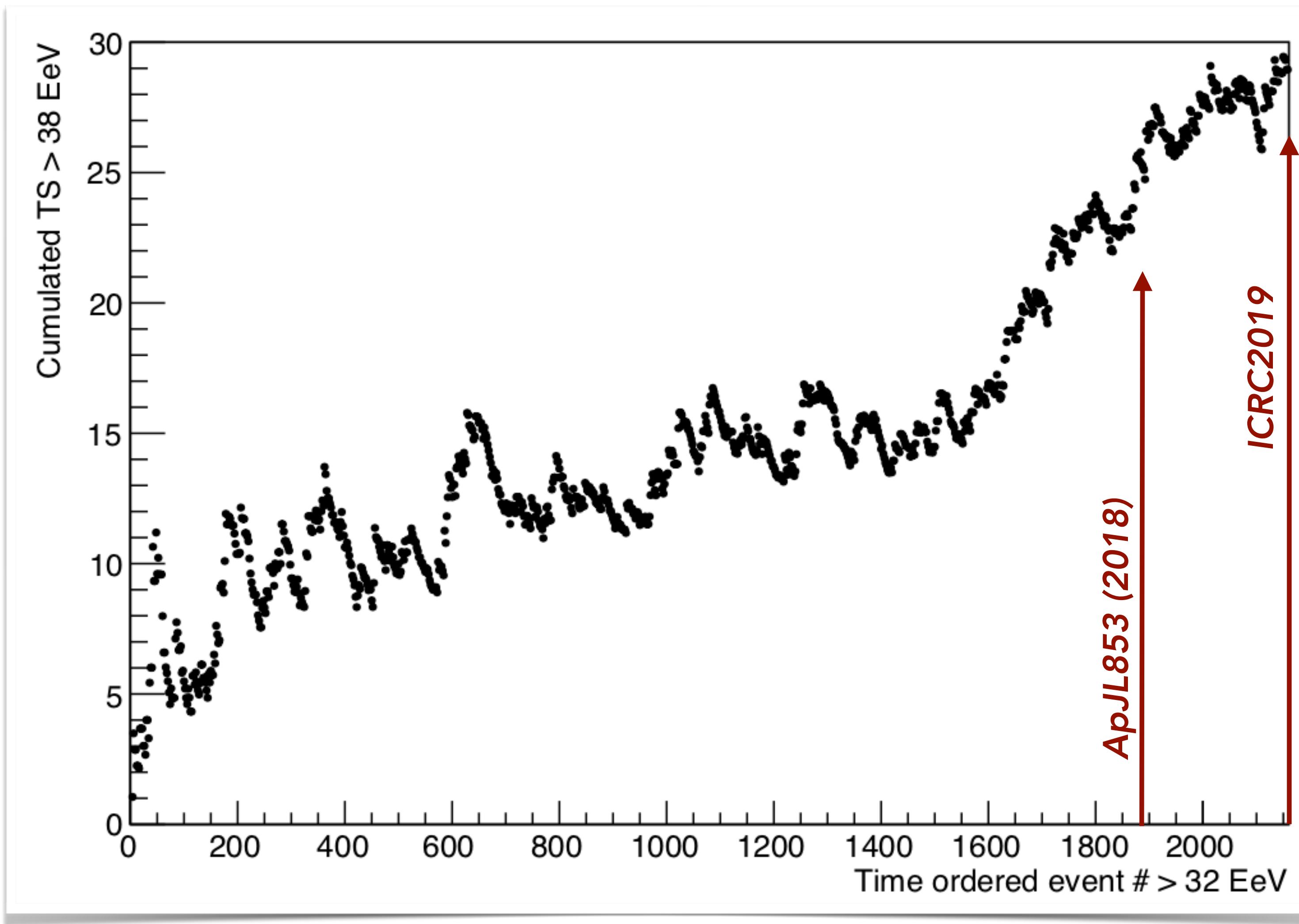


Likelihood analysis $TS = 2 \log [L(\psi, f_{aniso}) / L(f_{aniso} = 0)]$



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

Likelihood analysis with catalogs



Rejection of isotropy hypothesis

APJ

[Jan 2004-Apr 2017]

4.0σ for SBGs

2.7σ for γ -AGN

ICRC2019

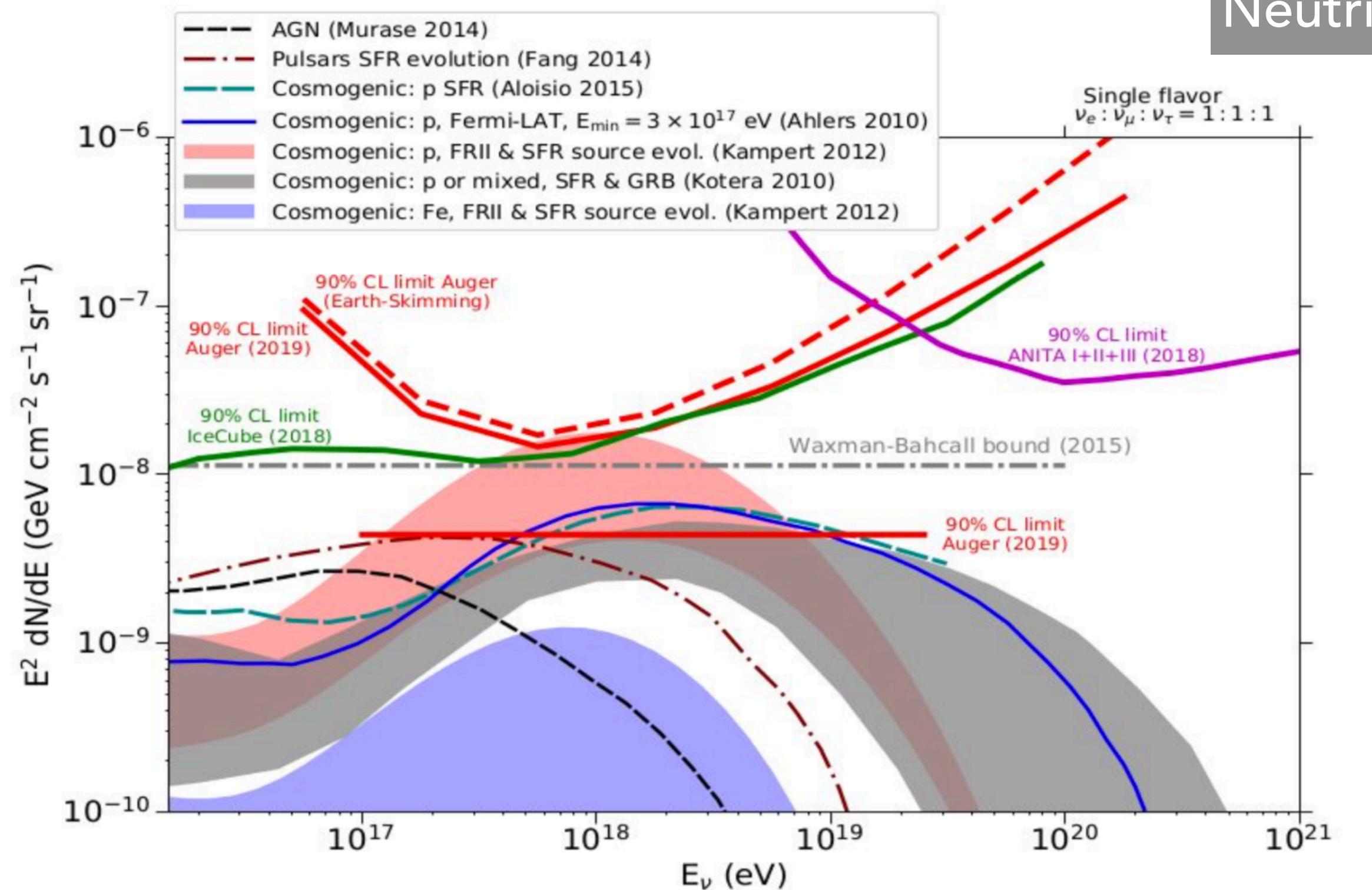
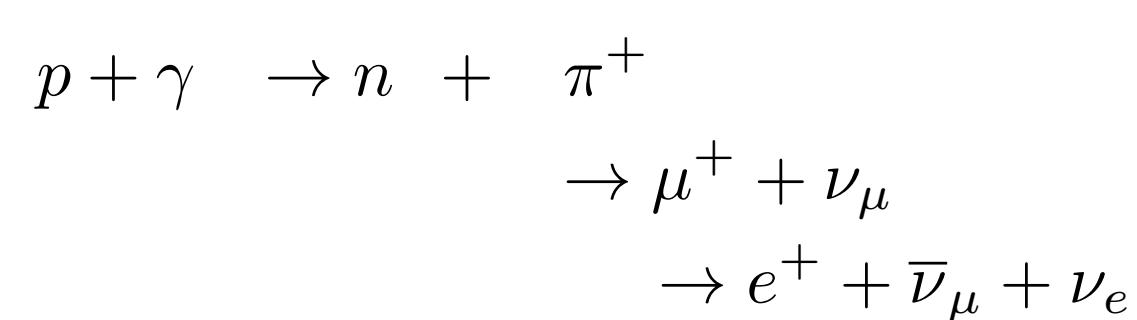
[Jan 2004-Aug 2018]

4.5σ for SBGs

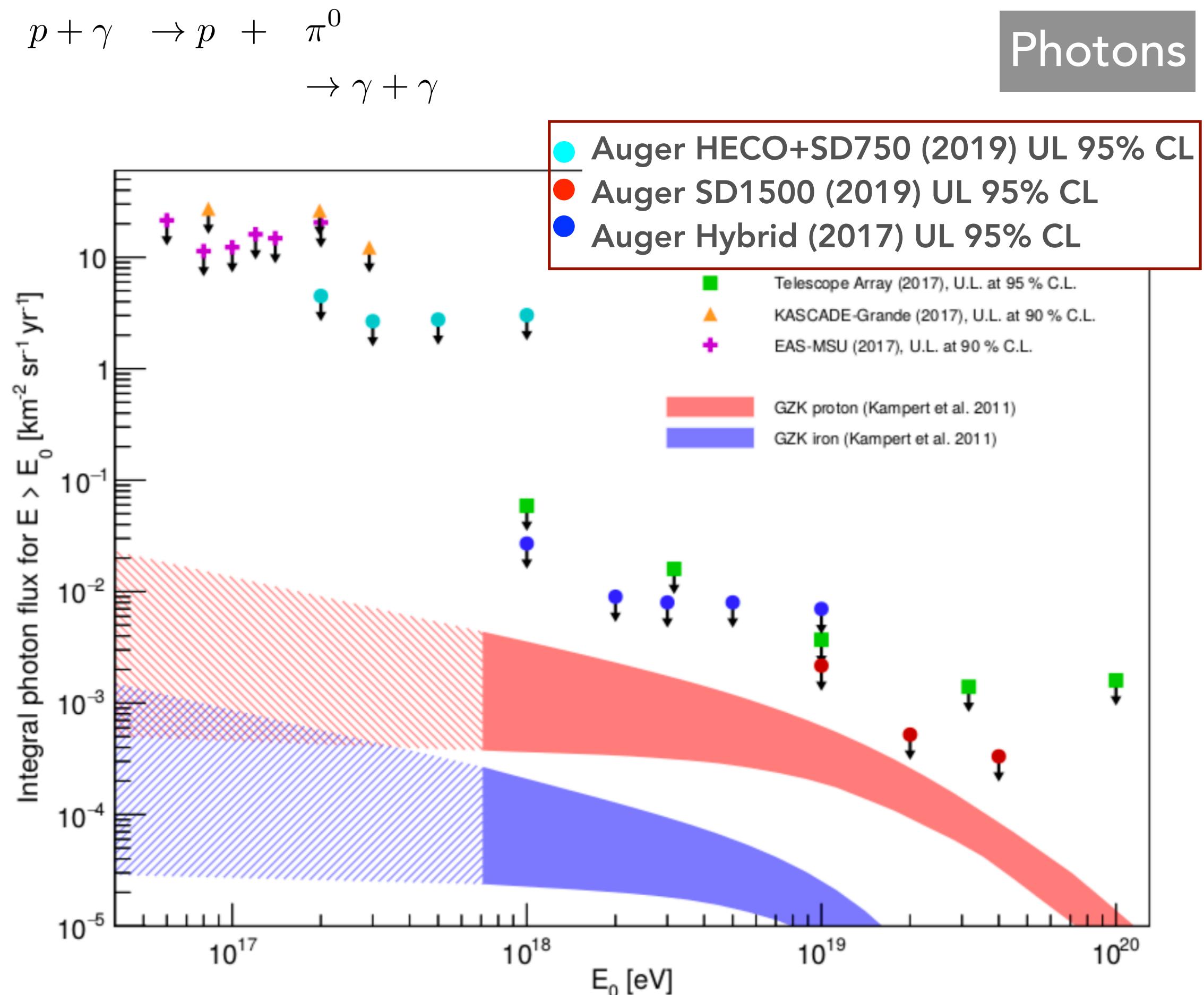
3.1σ for γ -AGN

Significance increasing with time !

Cosmogenic neutrino and photon fluxes

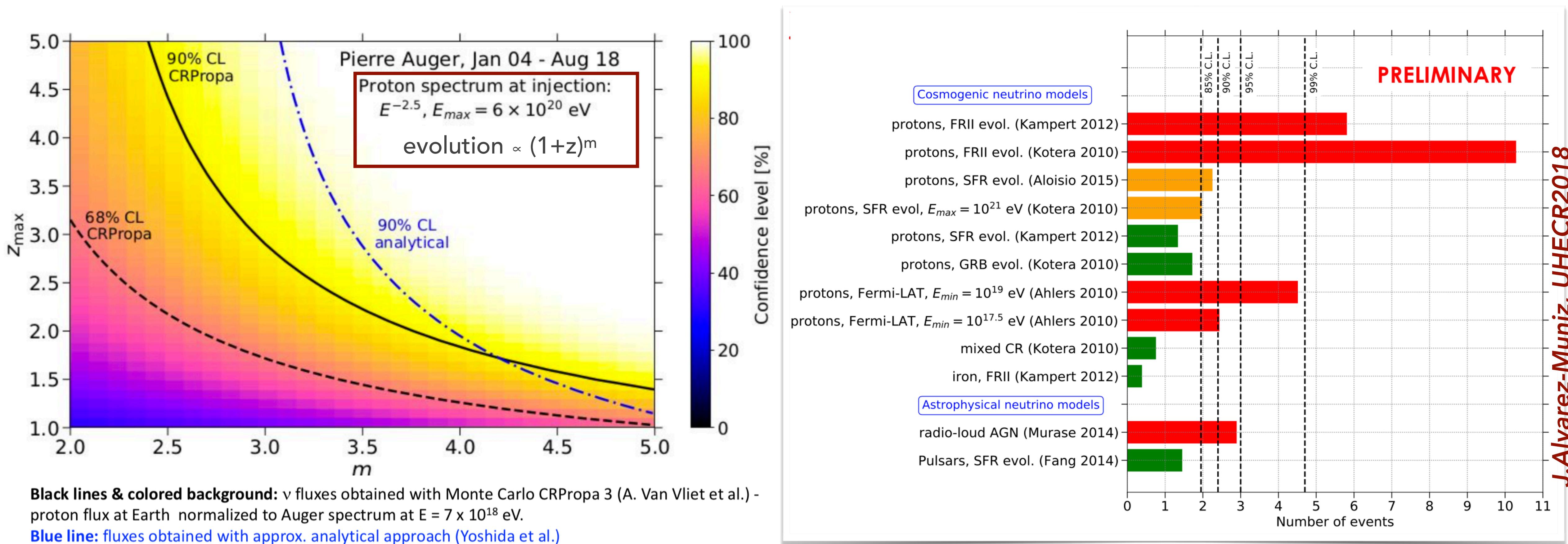


Maximum sensitivity around EeV
 k (90% CL) < $4.4 \cdot 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$



Most sensitive EAS detector for $E_\gamma > 0.2 \text{ EeV}$

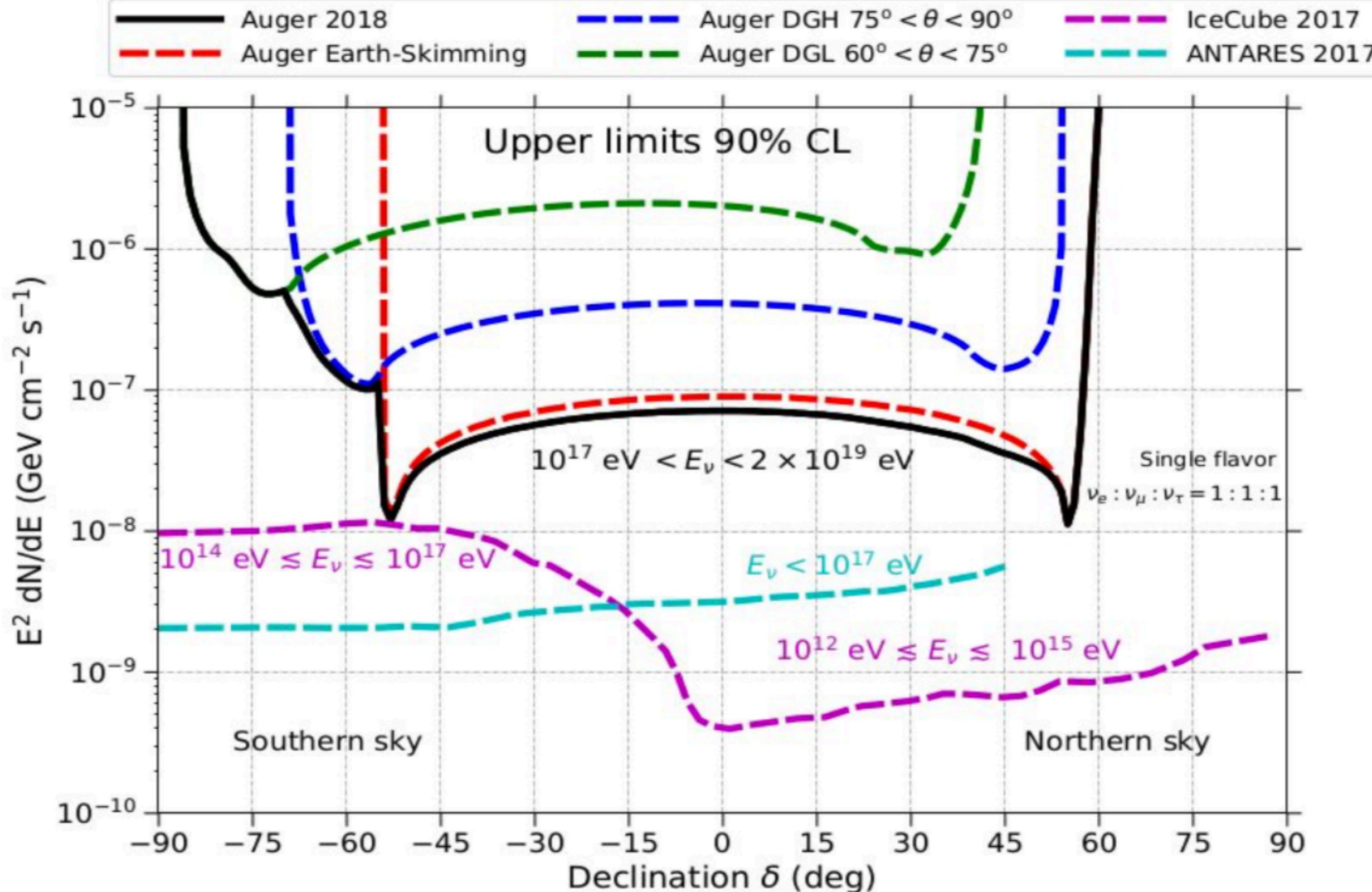
Constraints to neutrino models



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

Point-like sources of UHE ν

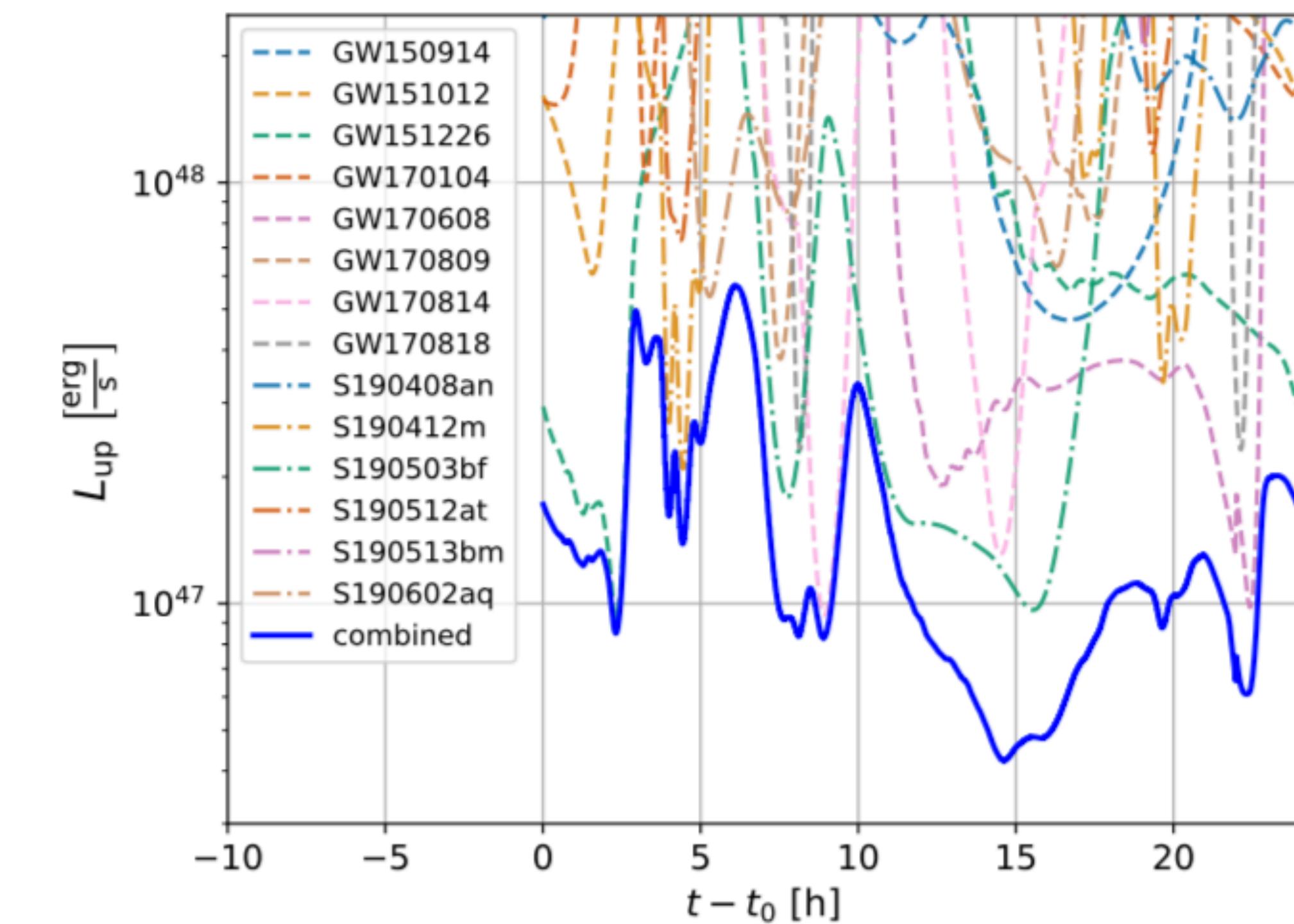
Steady sources



Energy range complementary
to Icecube and Antares

Binary Black Hole Mergers

21 sources (O1-O3), >250 Mpc



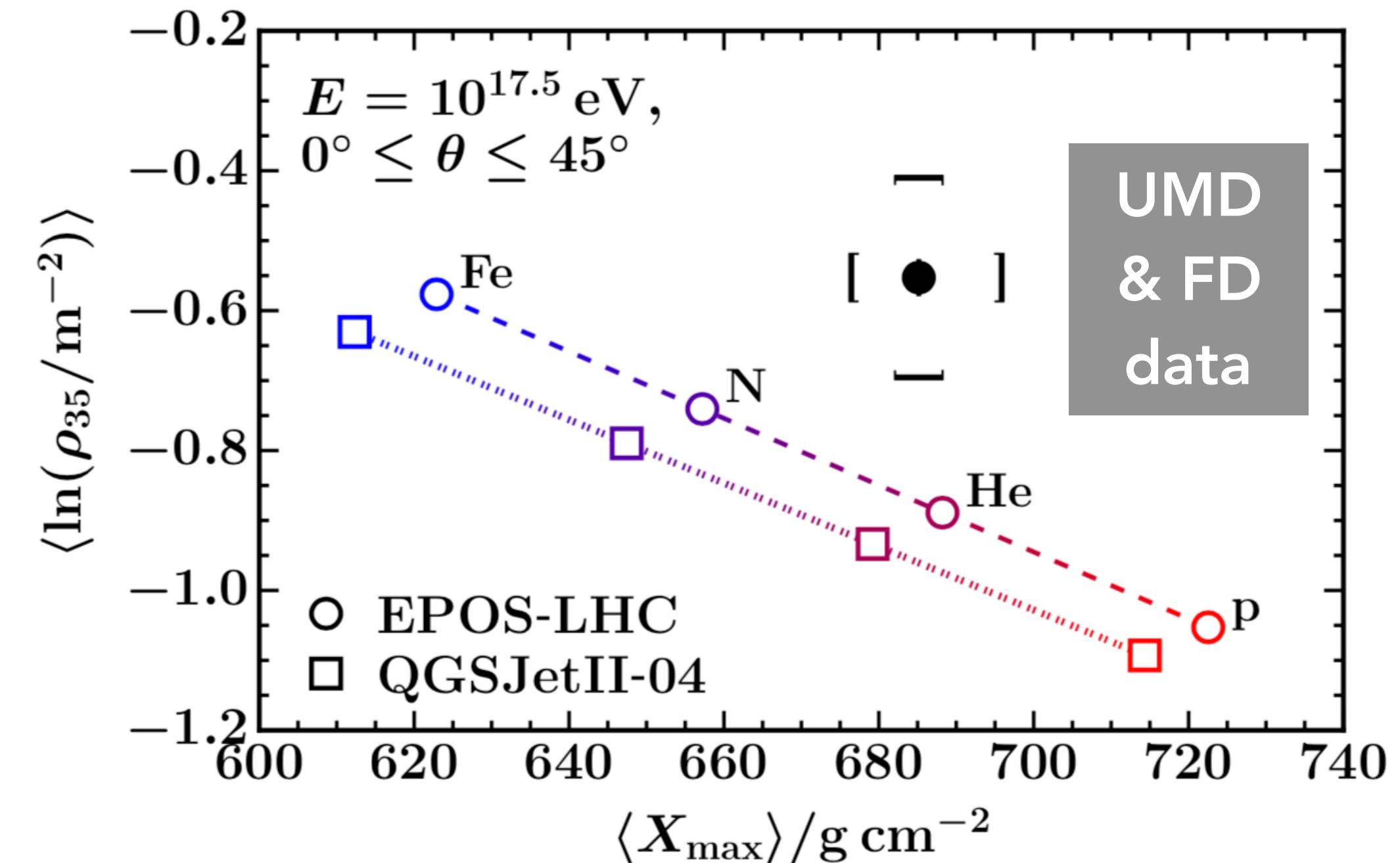
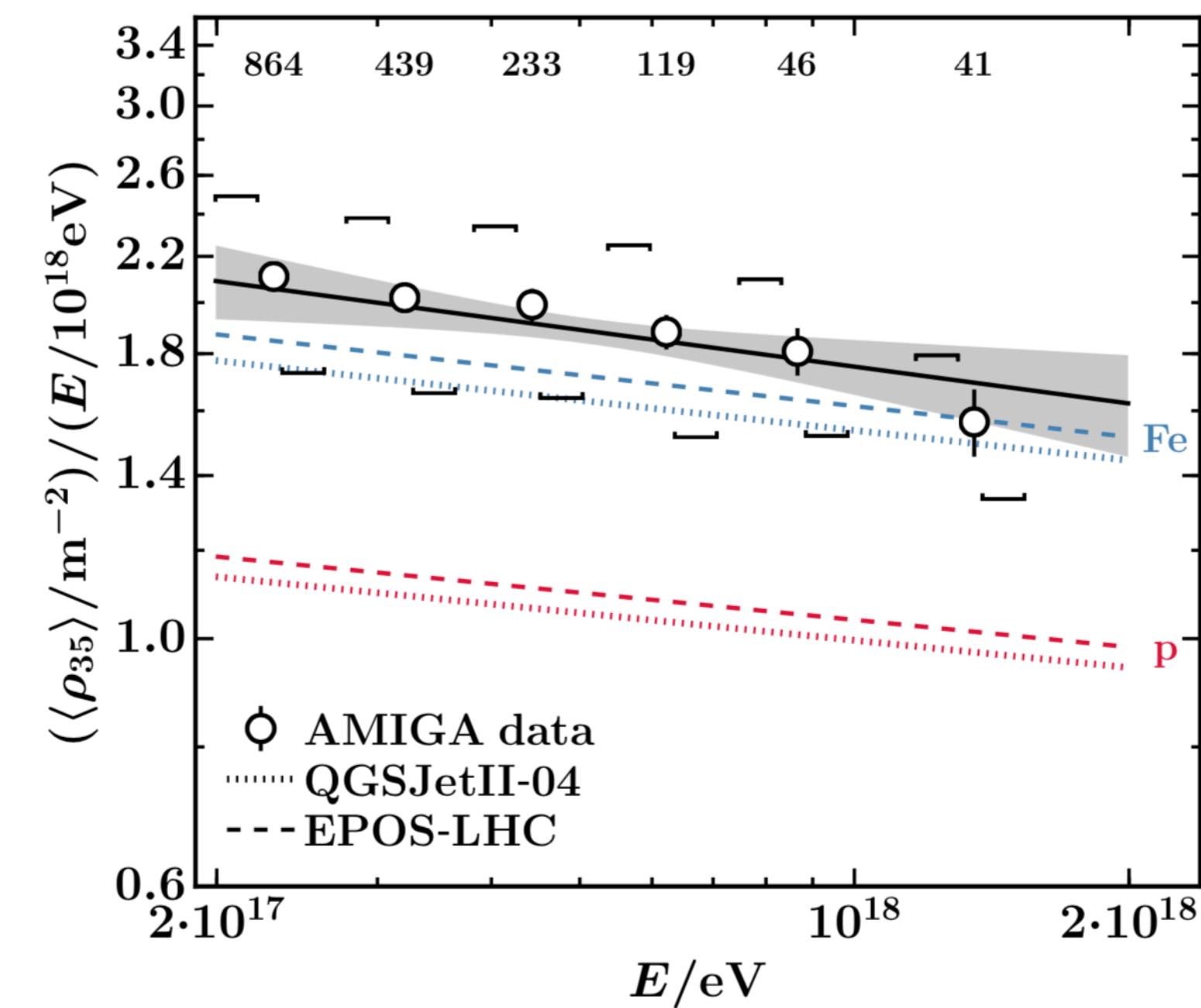
No neutrinos found

Sensitivity improved by
combining the sources

Muon content in air showers



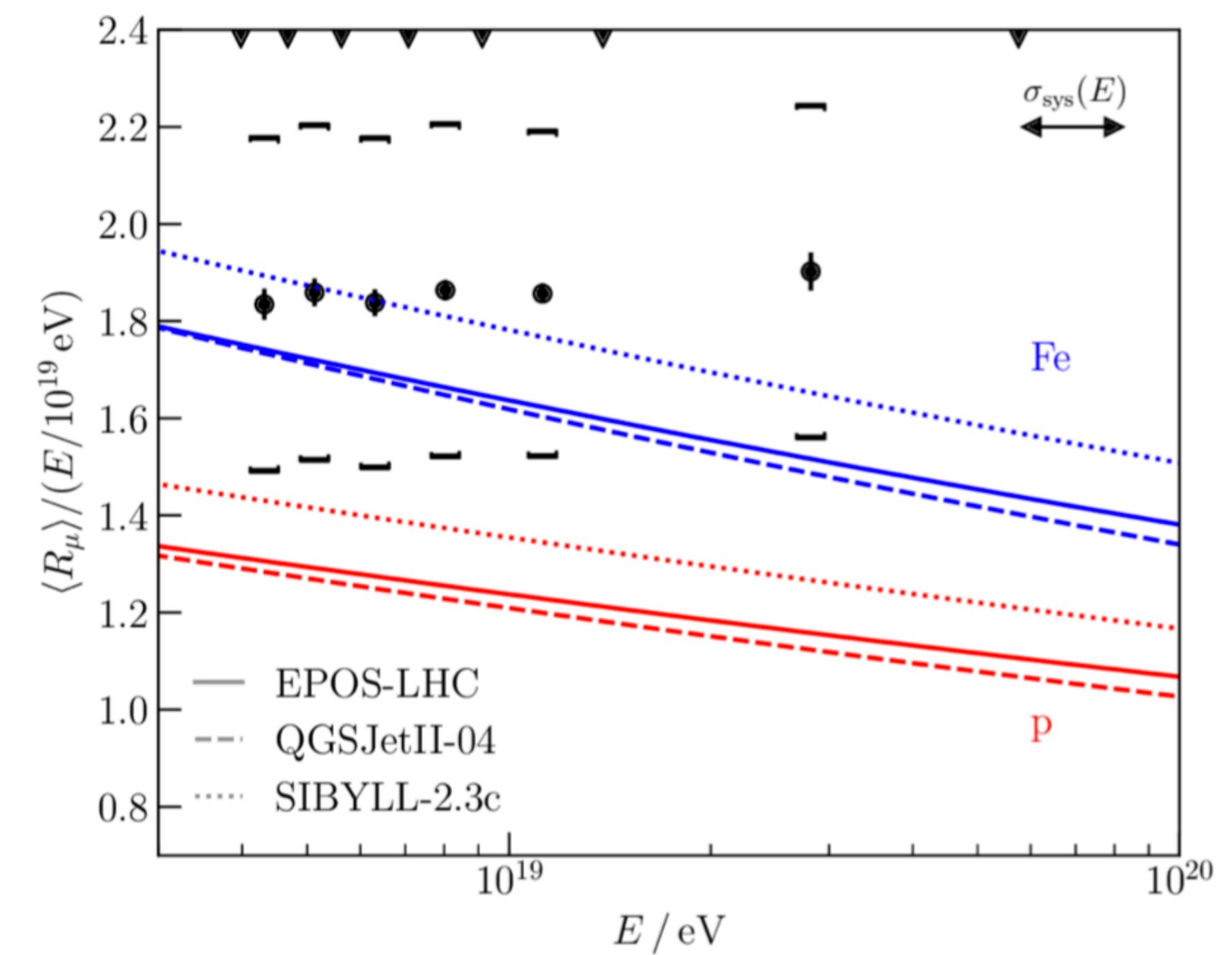
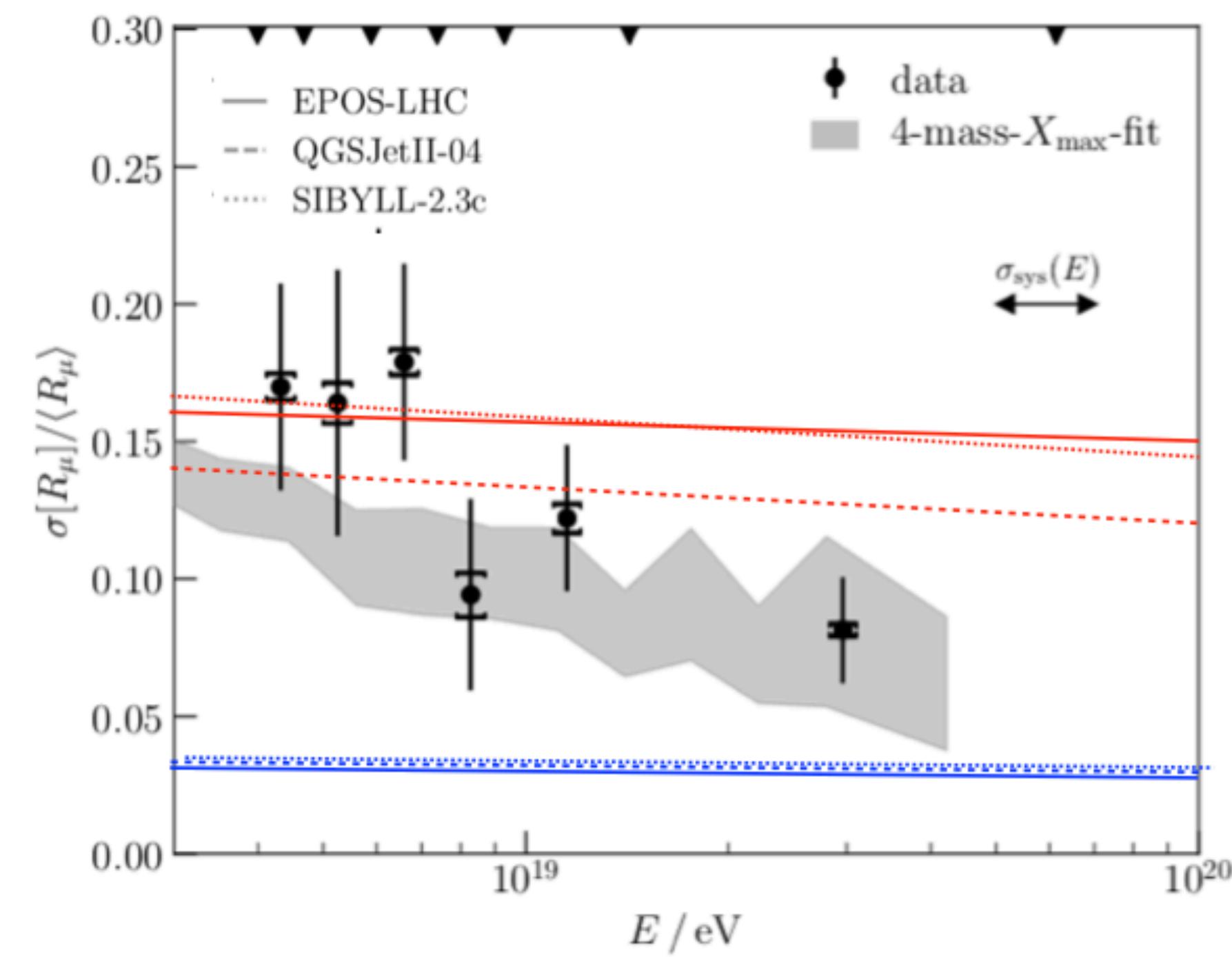
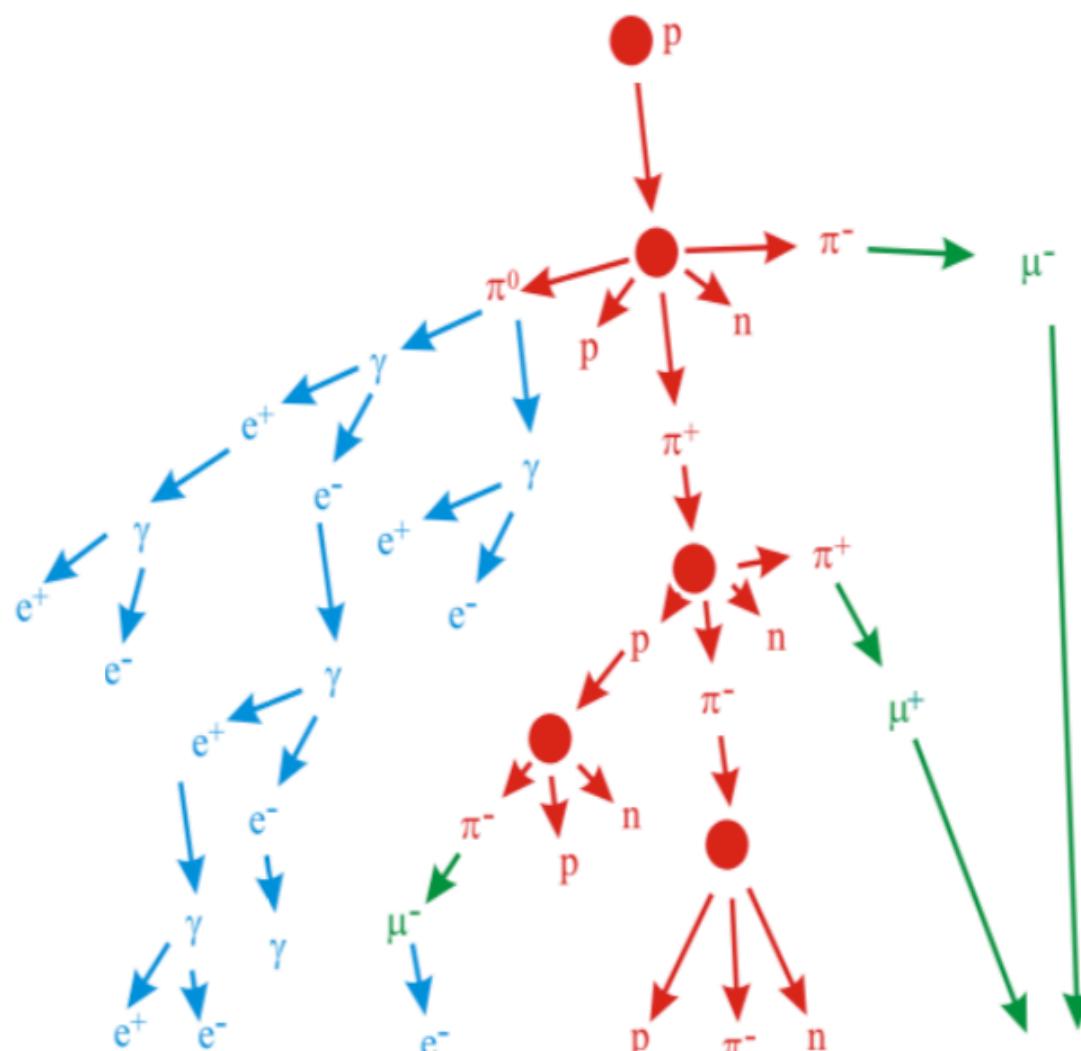
(UMD = Underground Muon Detector)



In the energy range 3×10^{17} eV to 2×10^{18} eV simulations fail to reproduce muon densities

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

Muons and their fluctuations



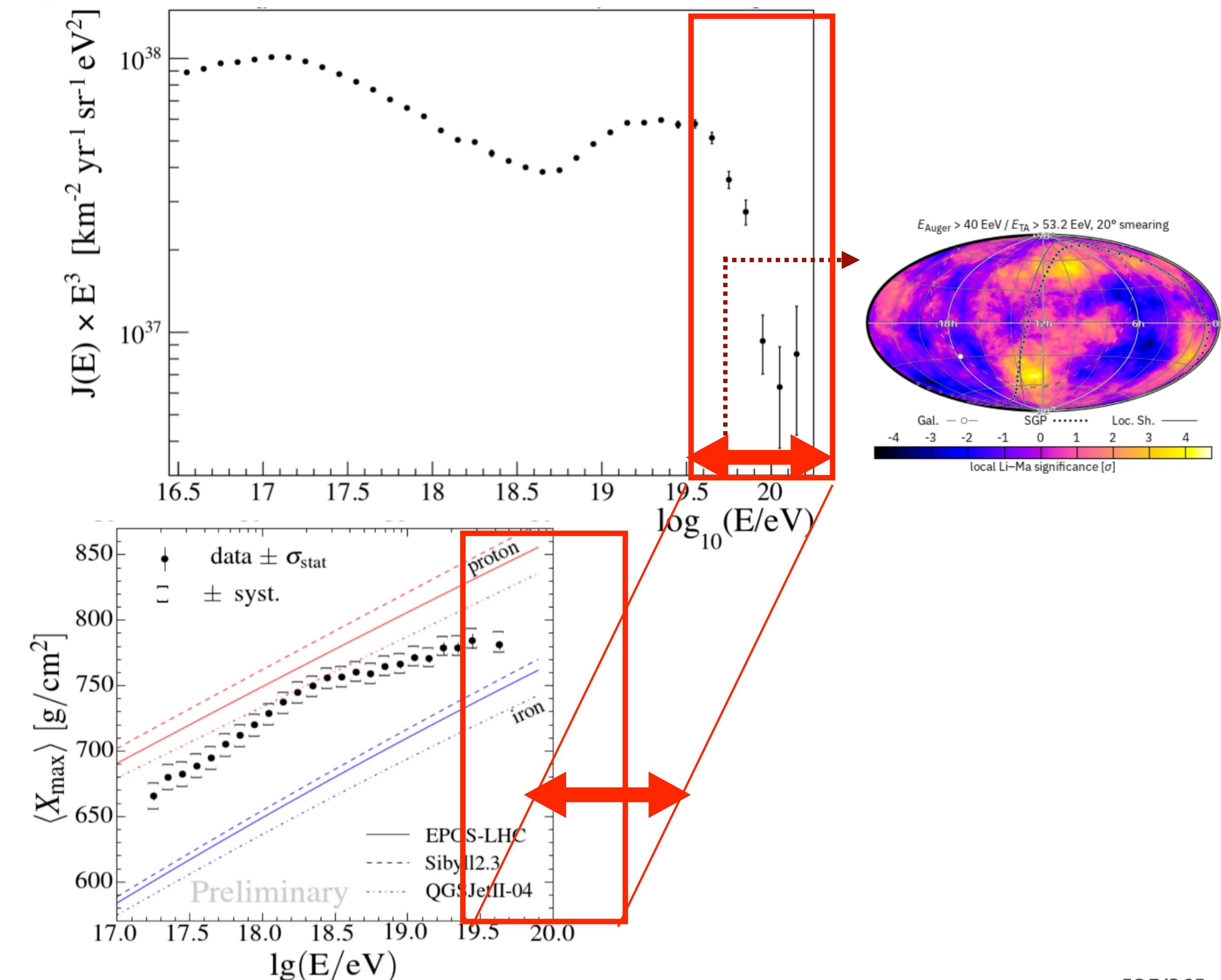
*Fluctuations in the muon number = probe of the first interaction at UHE
Post-LHC models give a good description of particle production in the first interaction*

The Science case for the Upgrade

- study the origin of the suppression
- select light primaries for charged particle astronomy
- provide better estimates of the neutrino and γ flux, as such establishing the potential of future CR experiments
- better measure the shower components to deepen the study of hadronic interactions at UHE and look for non standard physics

Extend operations to >2025,
increasing the statistics

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



AugerPrime : the Upgrade

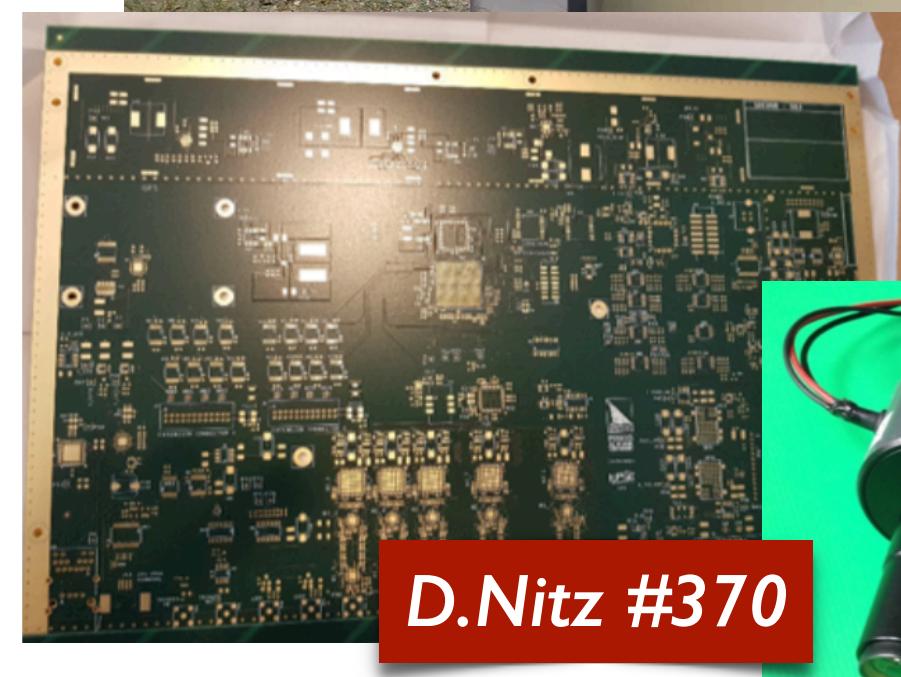
*a large exposure detector with
composition sensitivity above $\sim 4 \cdot 10^{19}$ eV*



B.Pont #395



B.Pont #395



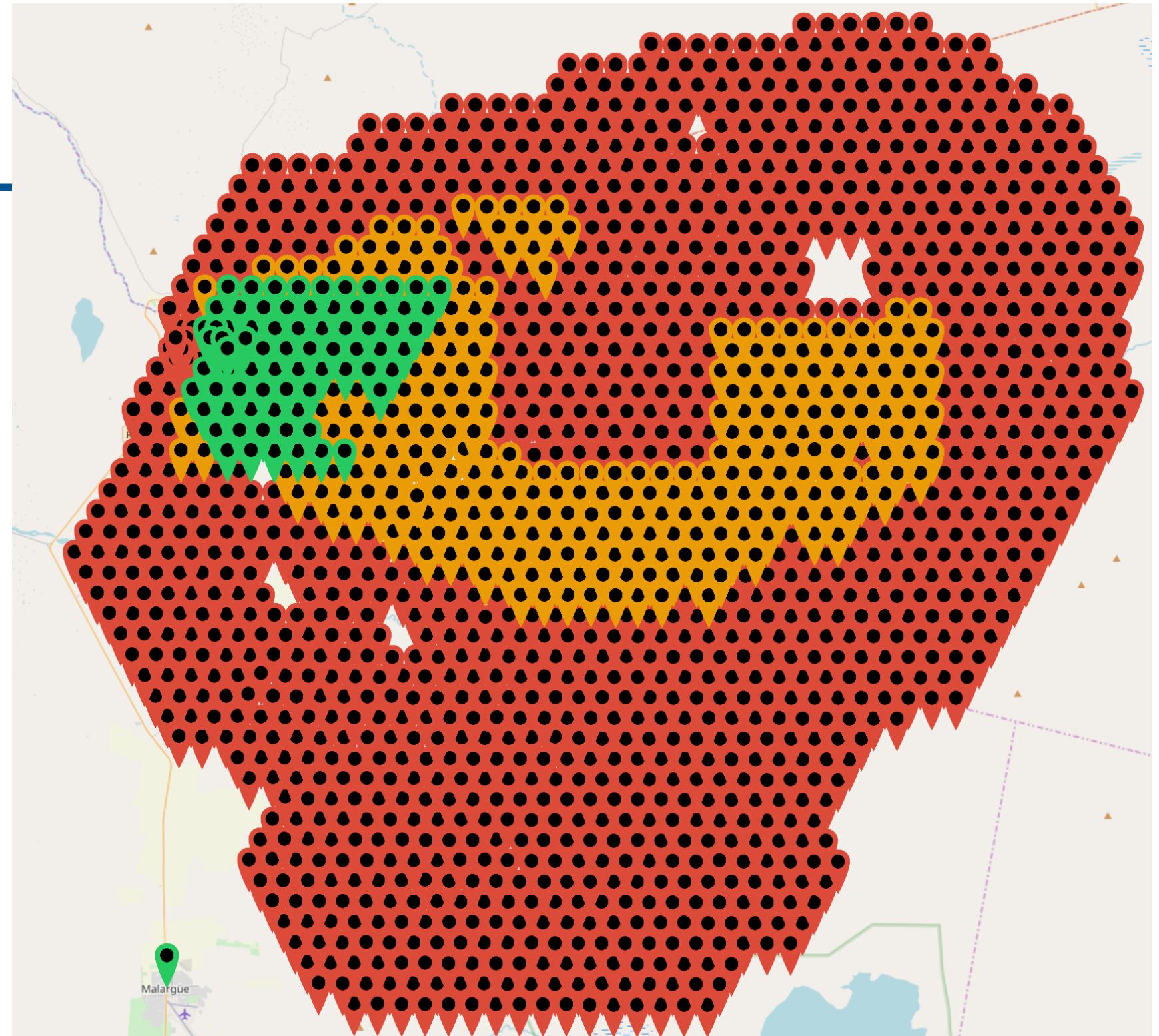
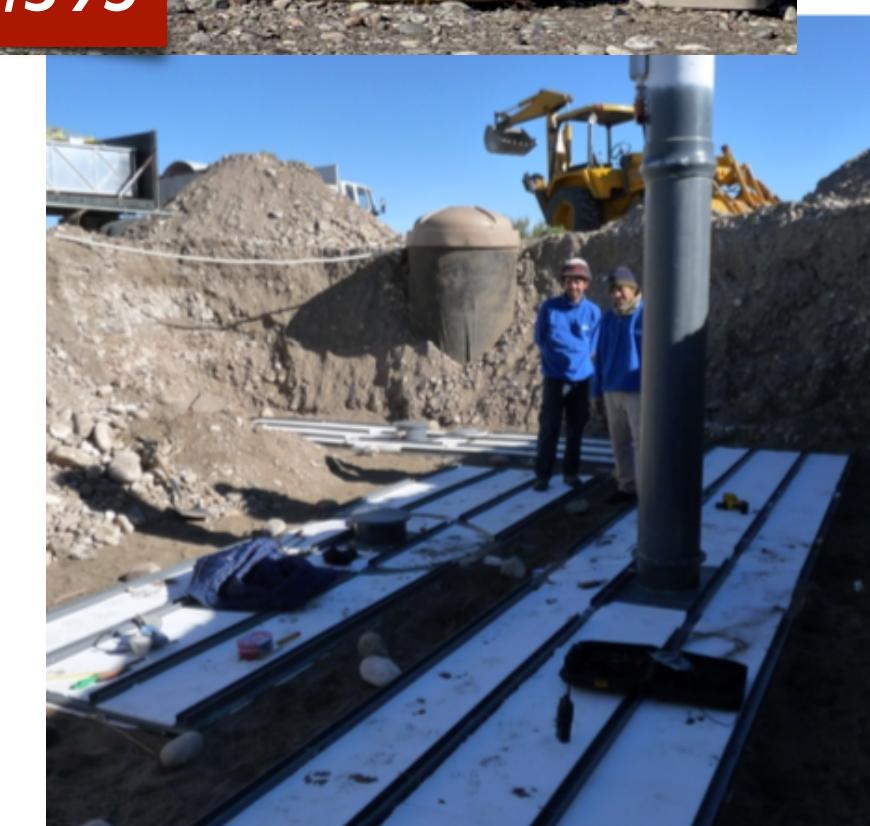
D.Nitz #370



M.Bohacova #199

J.Pekala #380

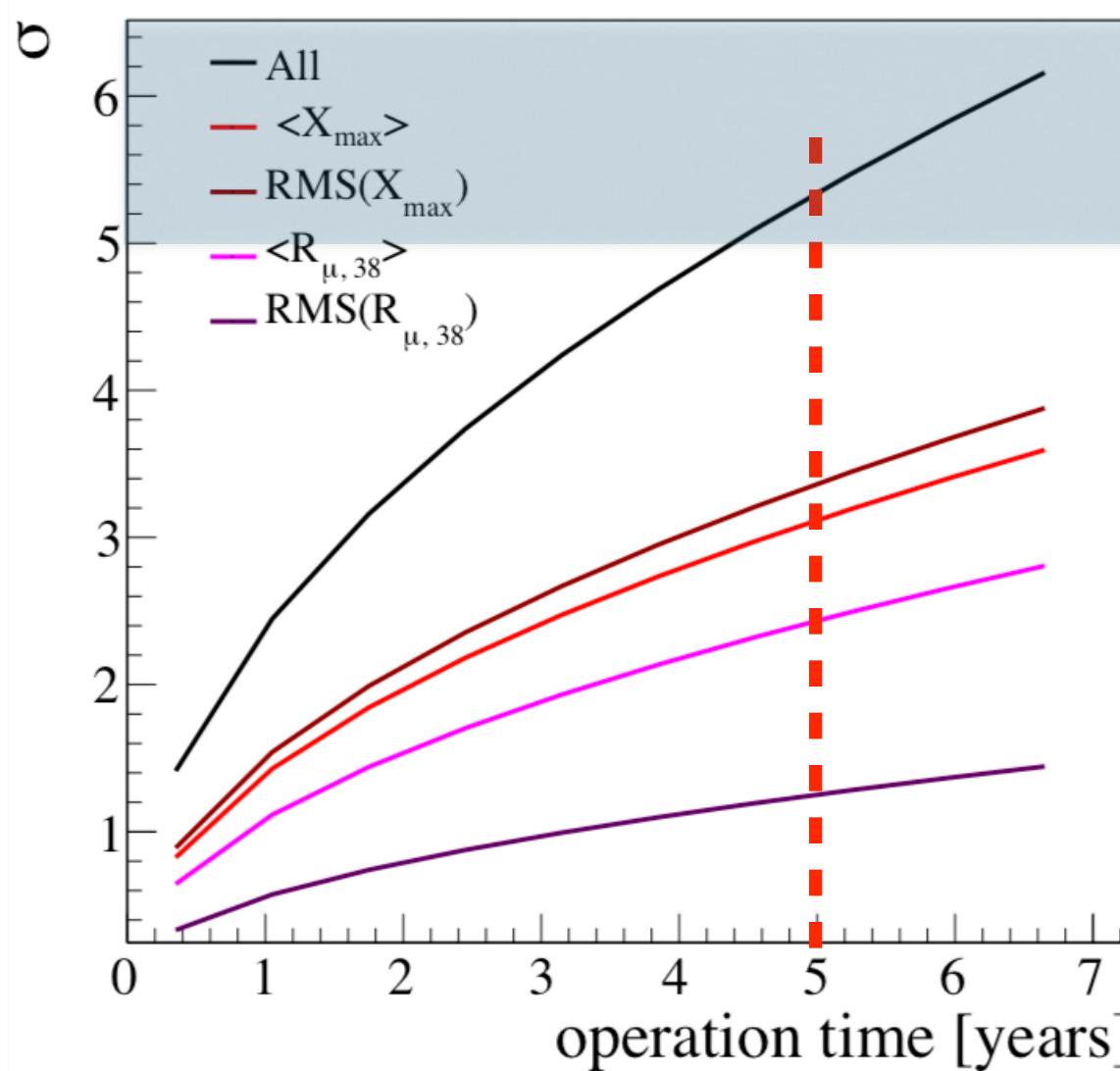
A.Taboada #434



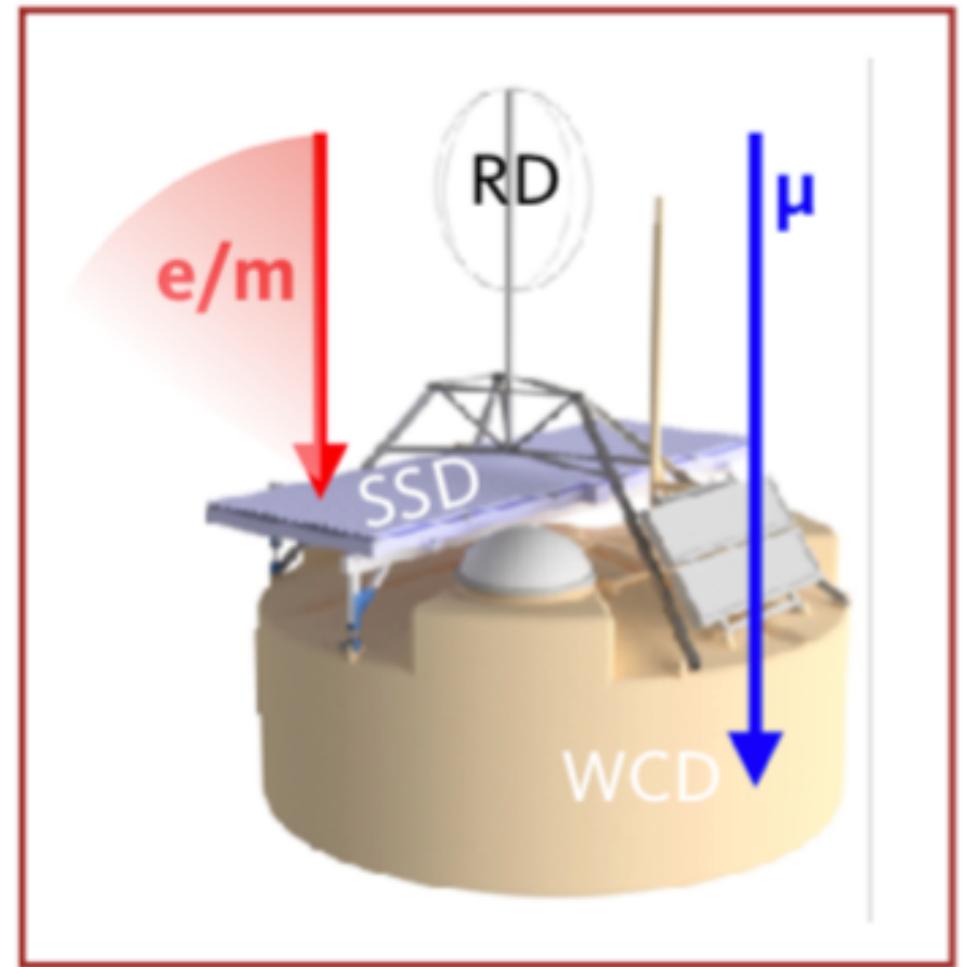
- 12 upgraded stations (Engineering Array) since 2016 with new electronics, higher sampling, large dynamic range
- the SSD preproduction array: 80 stations (since March 2019)
- 356 SSD stations already deployed
- Underground Muon detector
- the largest radio detector (3000 km²)

The new detectors of AugerPrime

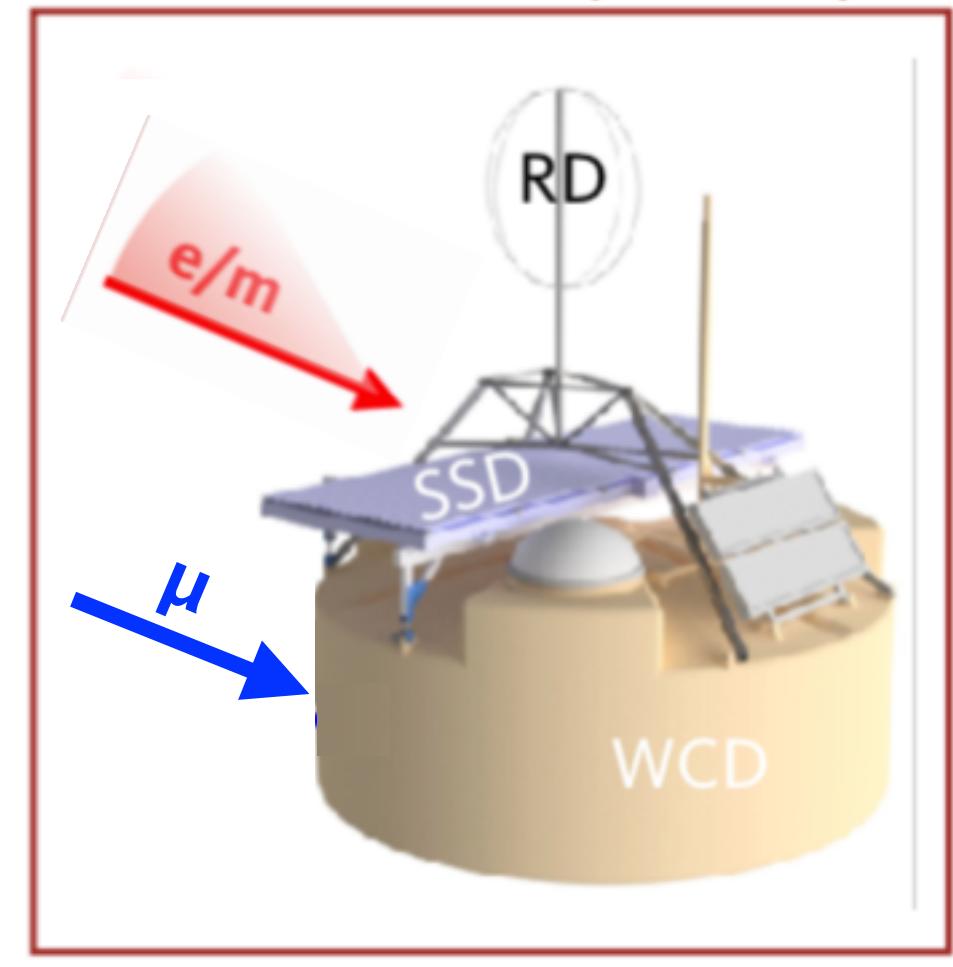
Vertical showers



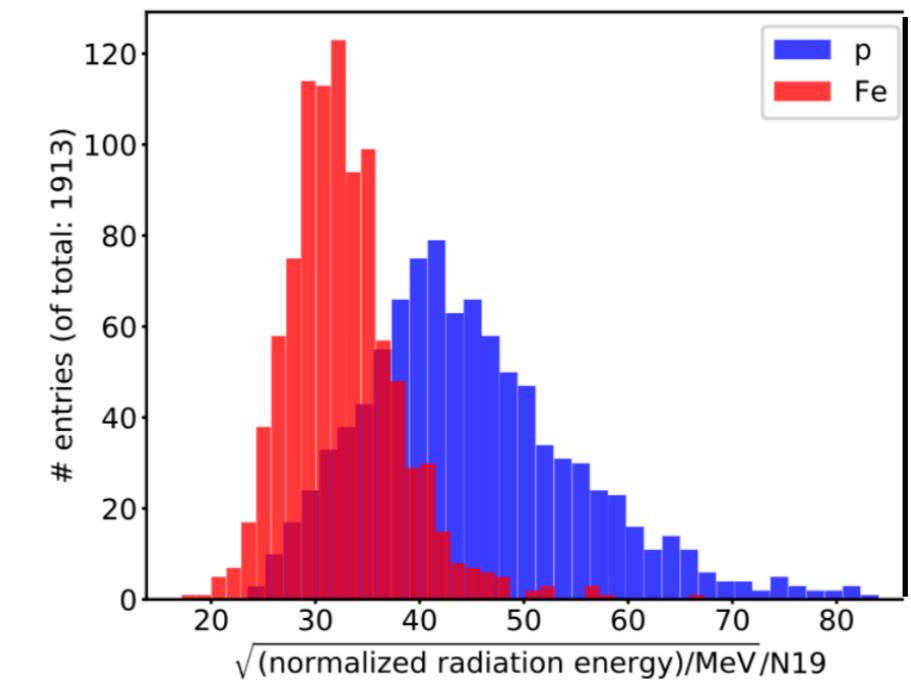
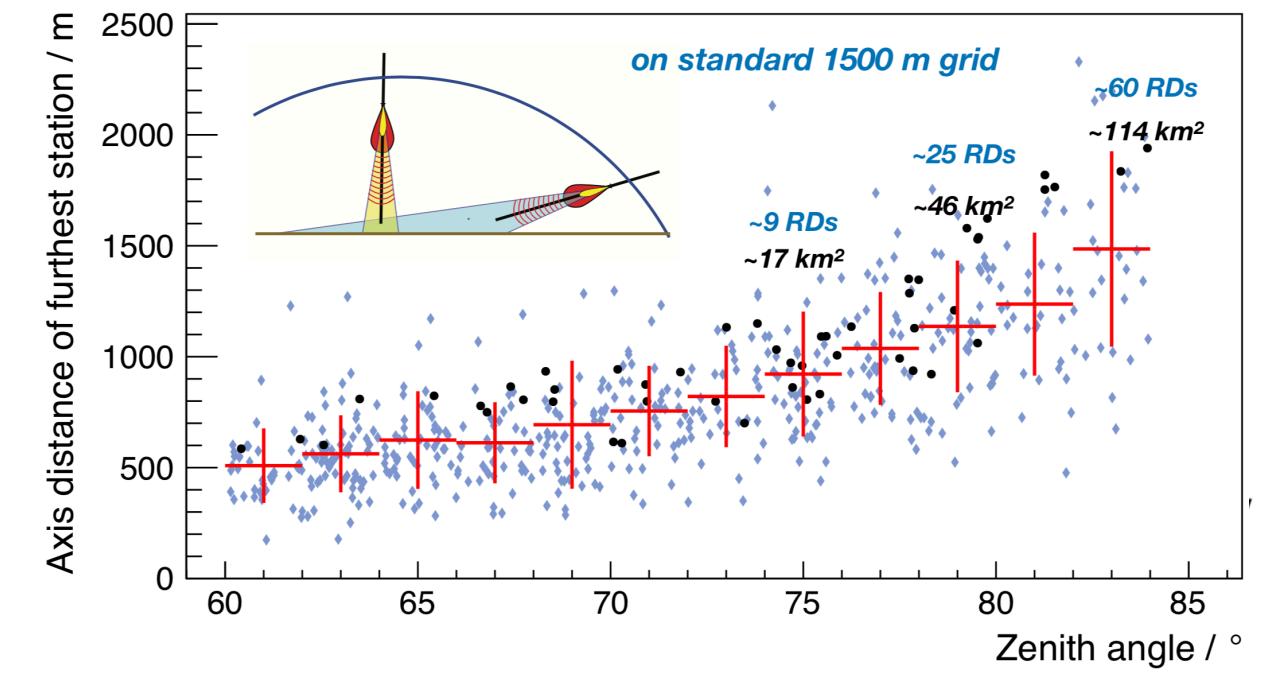
VERTICAL (0-60°)



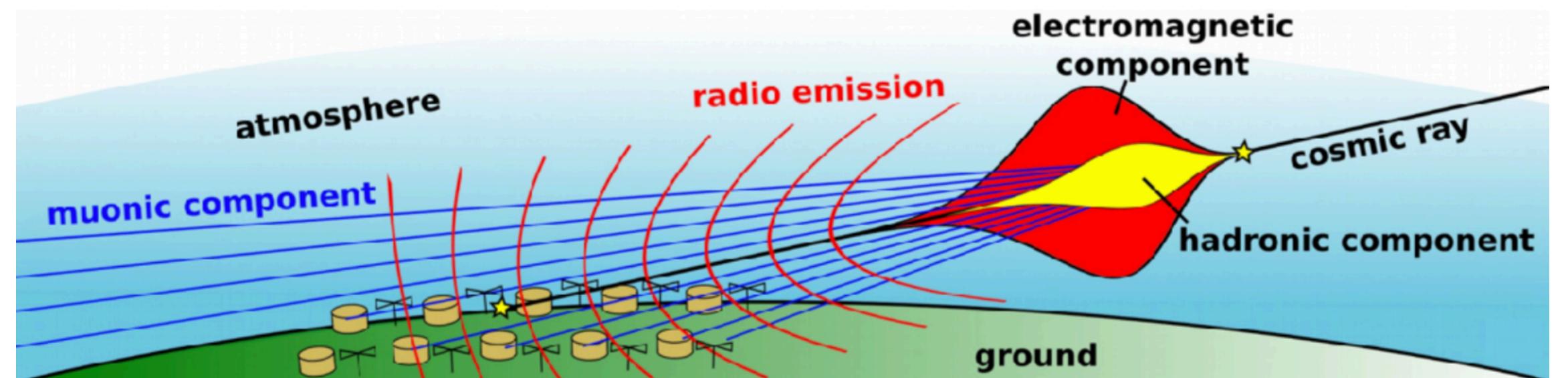
HORIZONTAL (60-90°)



Horizontal showers



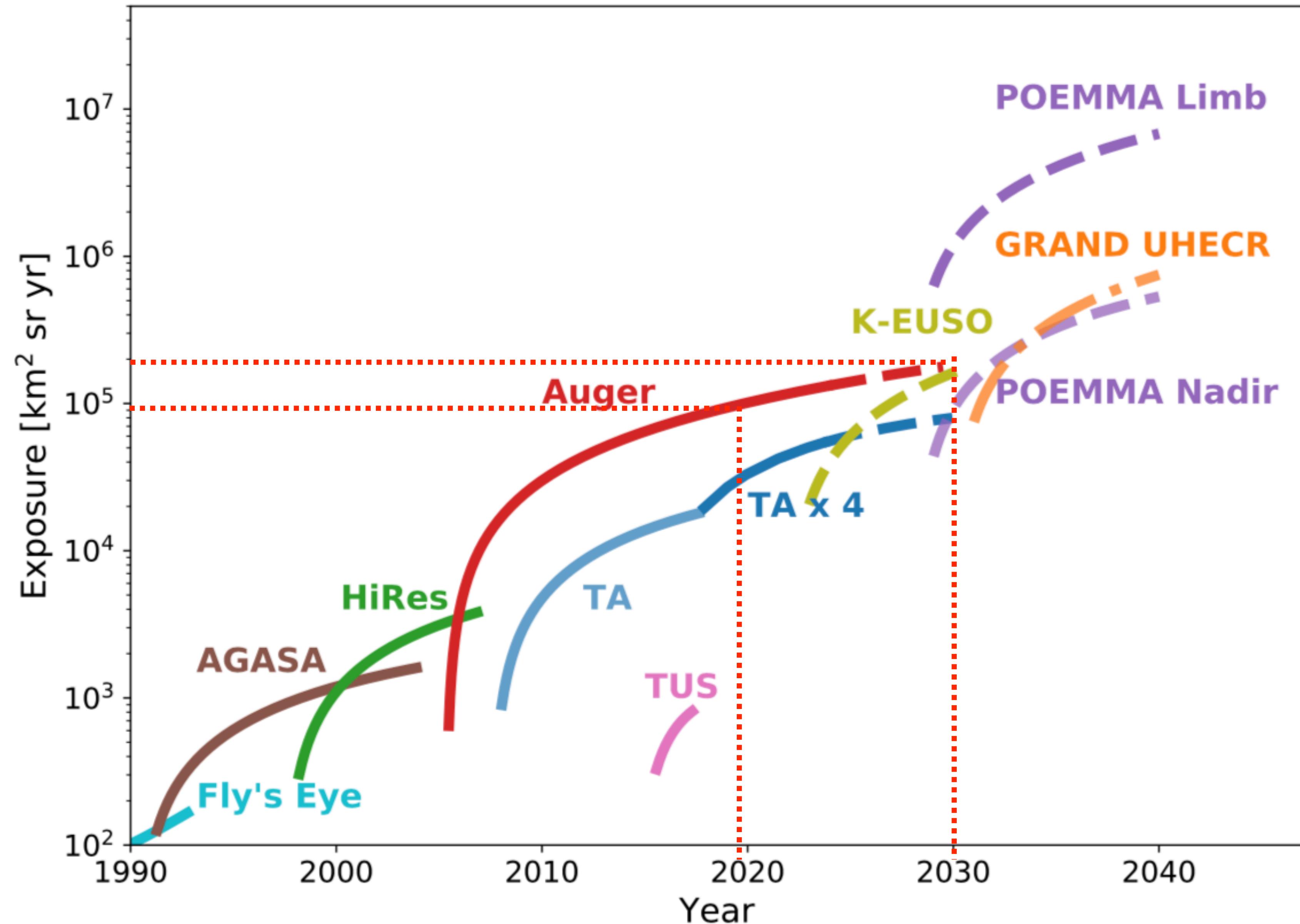
Hybrid:
 E_{rad} from radio
muons from WCD



- Significance of distinguishing two different realisations of Scenario 1 (maximum rigidity model) :
- as it predicts, i.e. no protons at UHE
 - adding 10% protons

>5 σ in 5 years of operations

Current status and perspectives



R.Batista et al., arXiv:1903.06714



20th Anniversary

of the Foundation of the
**Pierre Auger
Observatory**

November 2019

14-15 : Scientific Symposium
Guided tour to the Observatory
16 : Anniversary Celebration

<https://www.auger.org/>



We will celebrate in Malargüe
... Join us!

BACKUP slides

30 Contributions (+4 joint ones)

The Energy scale of the Pierre Auger Observatory
The energy spectrum above $10^{16.5}$ eV with Cherenkov
The energy spectrum of UHE cosmic rays
The cosmic ray flux near the second knee

Energy spectrum

Bruce Dawson
Vladimir Novotny
Valerio Verzi
Alan Coleman

Mass composition above $10^{17.2}$ eV with hybrid data
Estimating the X_{\max} with the Surface Detectors
The AMIGA underground muon detector

Mass composition

Alexey Yushkov
Carlos José Todero Pexoto
Federico Sanchez

Magnetically-induced signatures in the arrival directions
Large scale anisotropies above 0.03 EeV
Anisotropies of the UHECRs in 15 years of operation

Anisotropy

Markus Wirtz
Esteban Roulet
Lorenzo Caccianiga

Follow-up searches for UHEv and photons from transients
Bounds on diffuse and point source fluxes of UHEv
Limits on UHE photons

Multimessengers

Michael Schimp
Francisco Pedreira
Julian Rautenberg

Energy spectrum at Pierre Auger and Telescope Array
Combined analysis of muon density from 8 EAS arrays
Correlations of HE neutrinos and UHE cosmic rays
Full-sky searches for anisotropies at Auger and Telescope Array

Joint contributions

Olivier Deligny
Lorenzo Cazon
Anastasia Barbano
Armando di Matteo

The muon component of EAS above $10^{17.5}$ eV
Fluctuations in the number of muons in inclined EAS
Testing Lorentz Invariance violation

Hadr.interactions

Federico Sanchez
Felix Riehn
Rodrigo Guedes Lang

Elves reconstruction and characterisation
Data from the low energy modes of the Surface Detector

Cosmo-Geophysics

Roberto Mussa
Martin Schimassek

Real-time measurements with atmospheric instruments
Long term performances of the Pierre Auger Observatory
EAS reconstruction based on Deep Learning
Inclined air showers with the AERA Engineering Radio Array
AMIGA reconstruction
Reconstruction of vertical events by the SD
Social impact of the outreach of the Pierre Auger Observatory

Detector

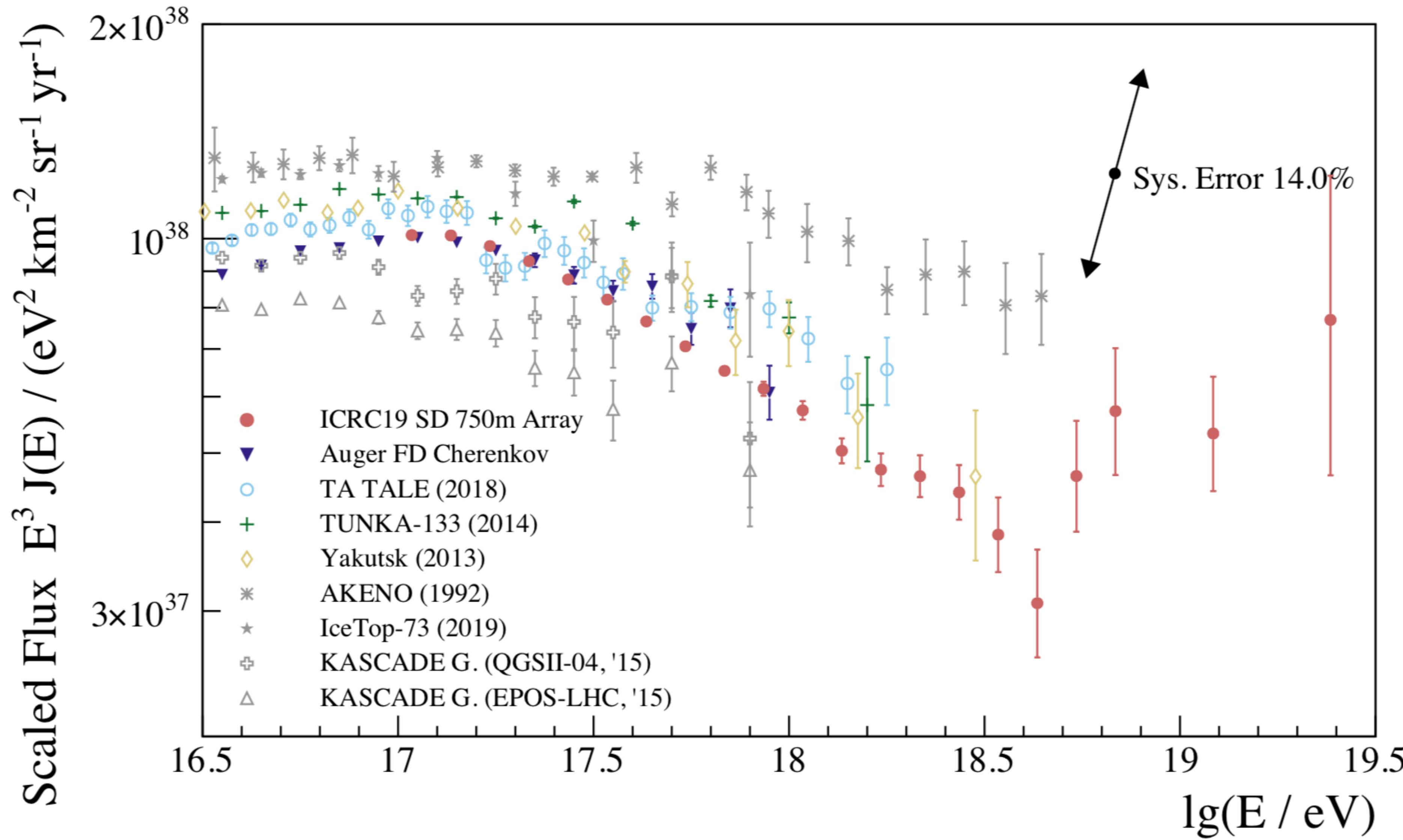
Violet Harvey
Koun Choi
Jonas Glombitza
Marvin Gottowik
Ana Martina Botti
Daniela Mockler
Beatriz Garcia

AugerPrime

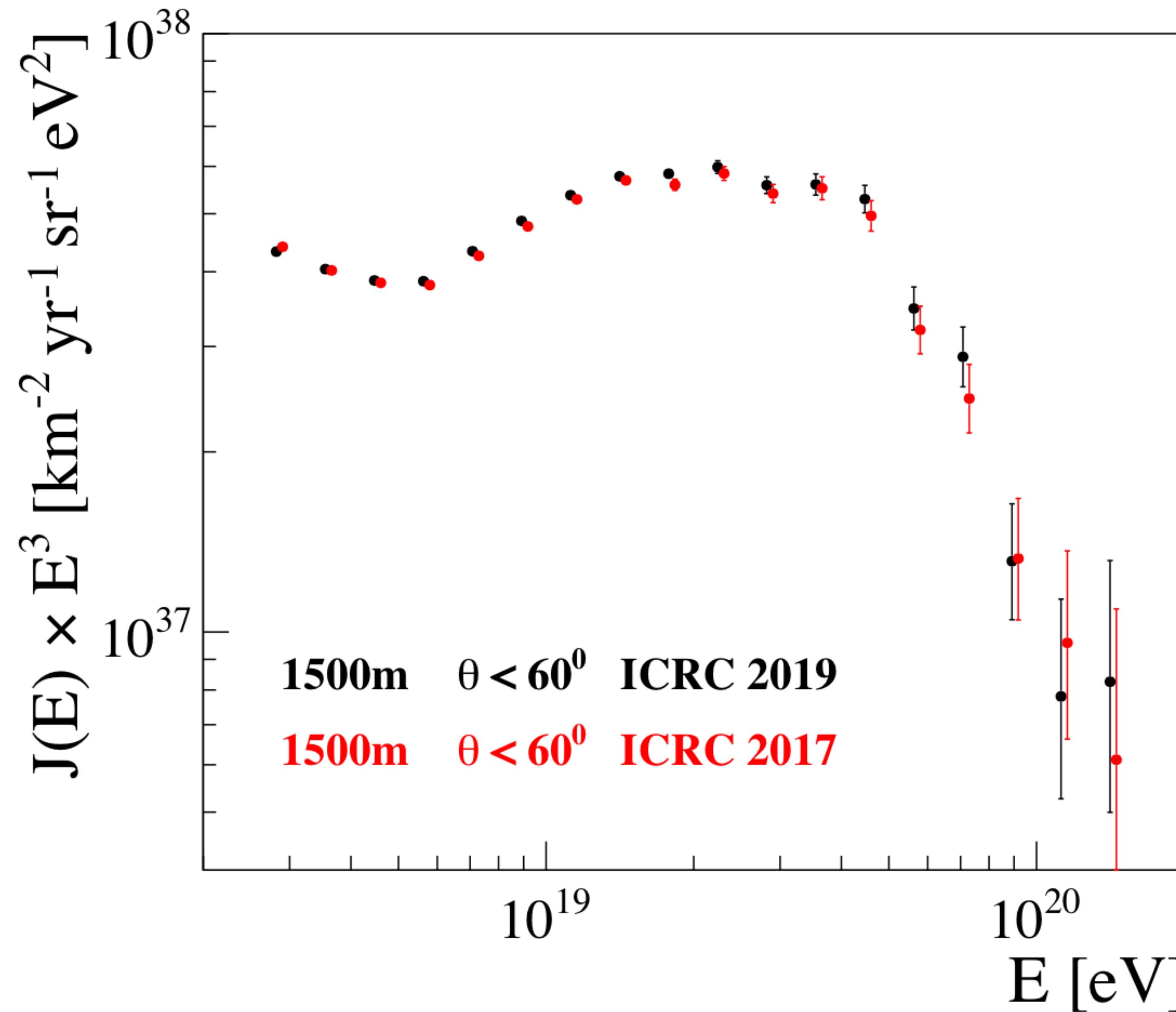
Bjani Pont
David Nitz
Martina Bohacova
Jan Pekala
Alvaro Taboada

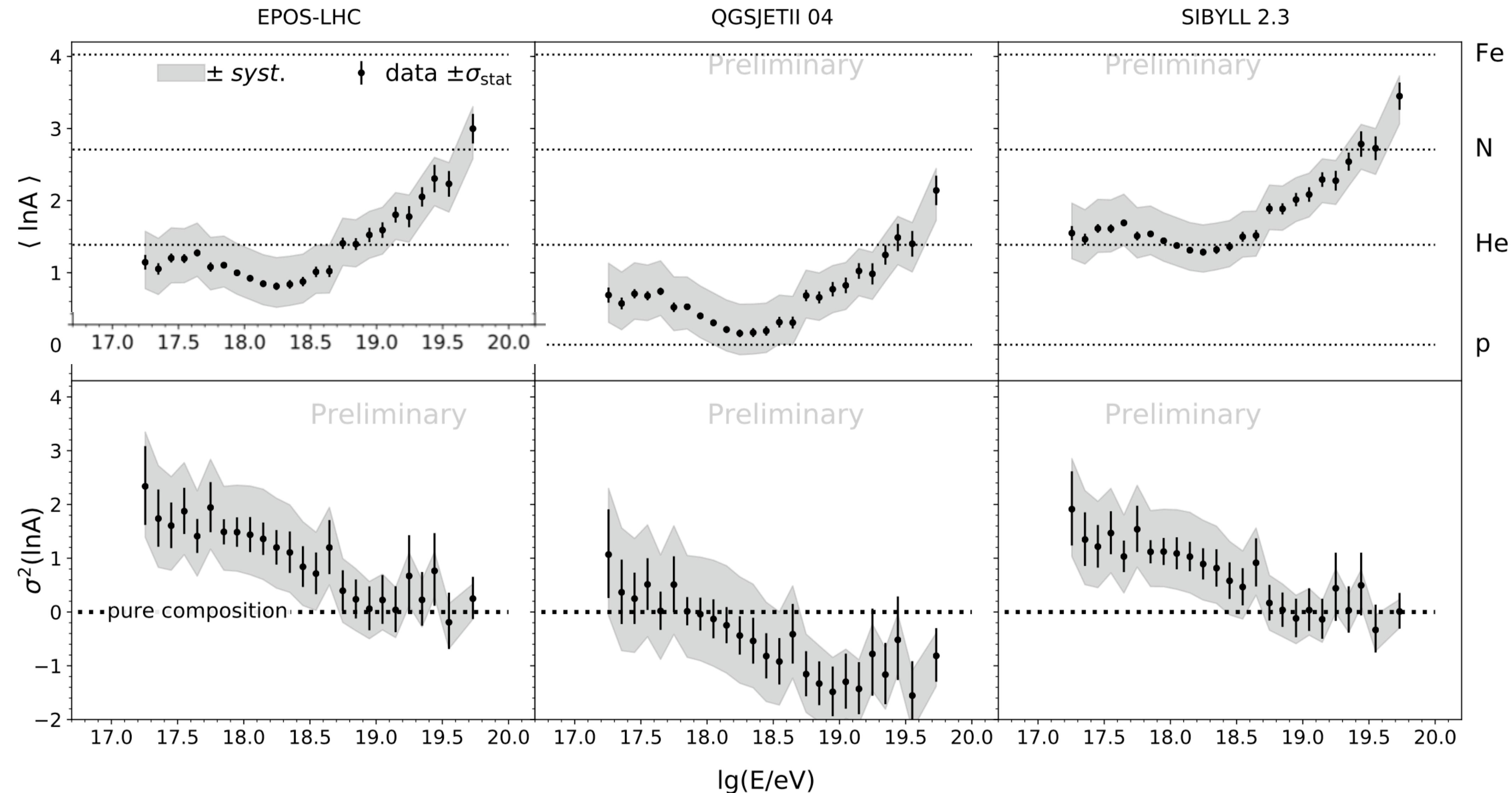
A large radio detector at the Pierre Auger Observatory
New electronics for the Surface Detectors
Test benches for the upgrade
Production and quality control of the scintillators of AugerPrime
Analysis of data from the SD of the AugerPrime Upgrade

Looking at the second knee



The vertical energy spectrum





Full sky search with Auger and Telescope Array

Large Scale Anisotropy

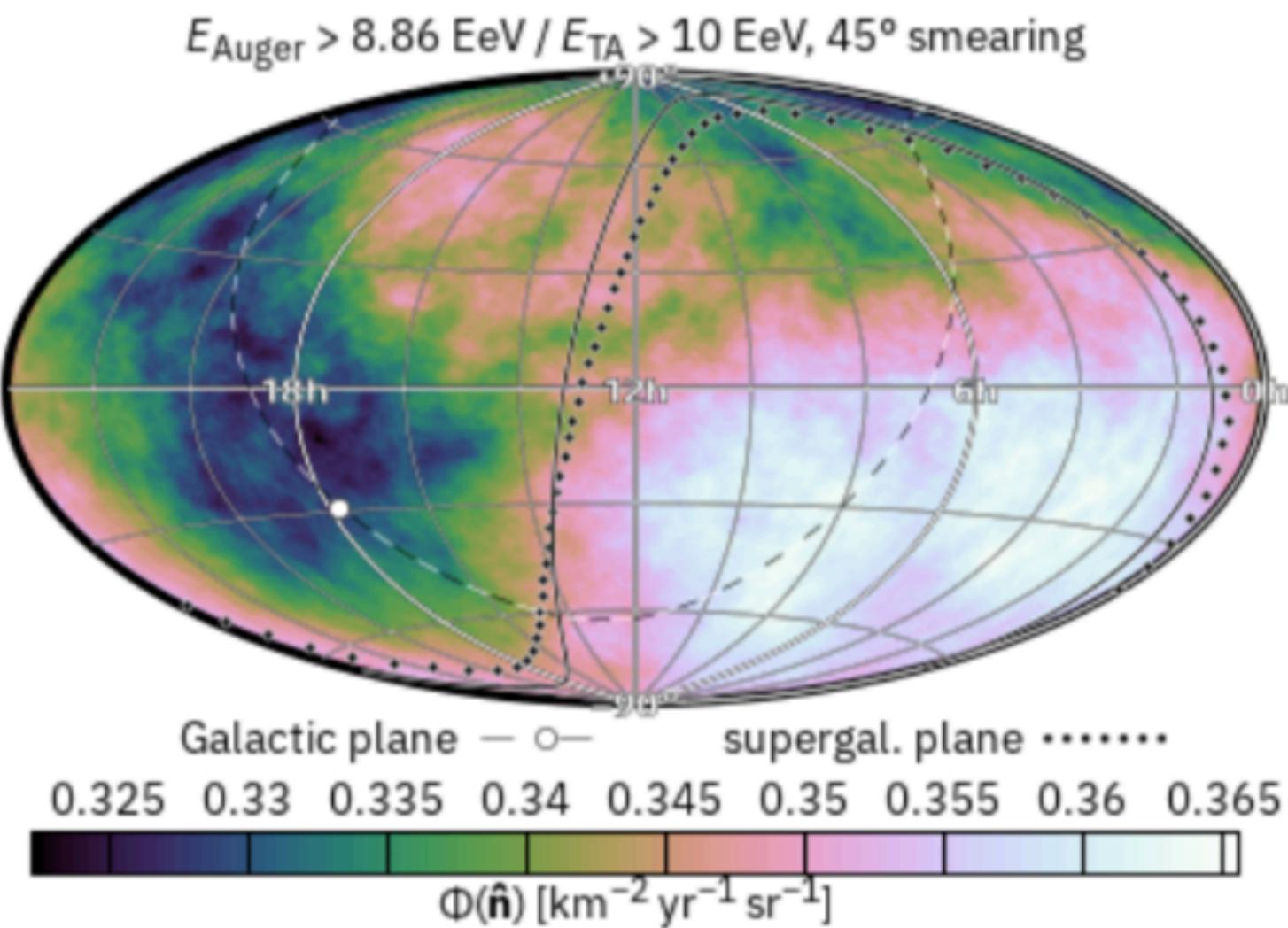
Energy threshold

8.86 EeV (Auger)

10 EeV (Telescope Array)

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

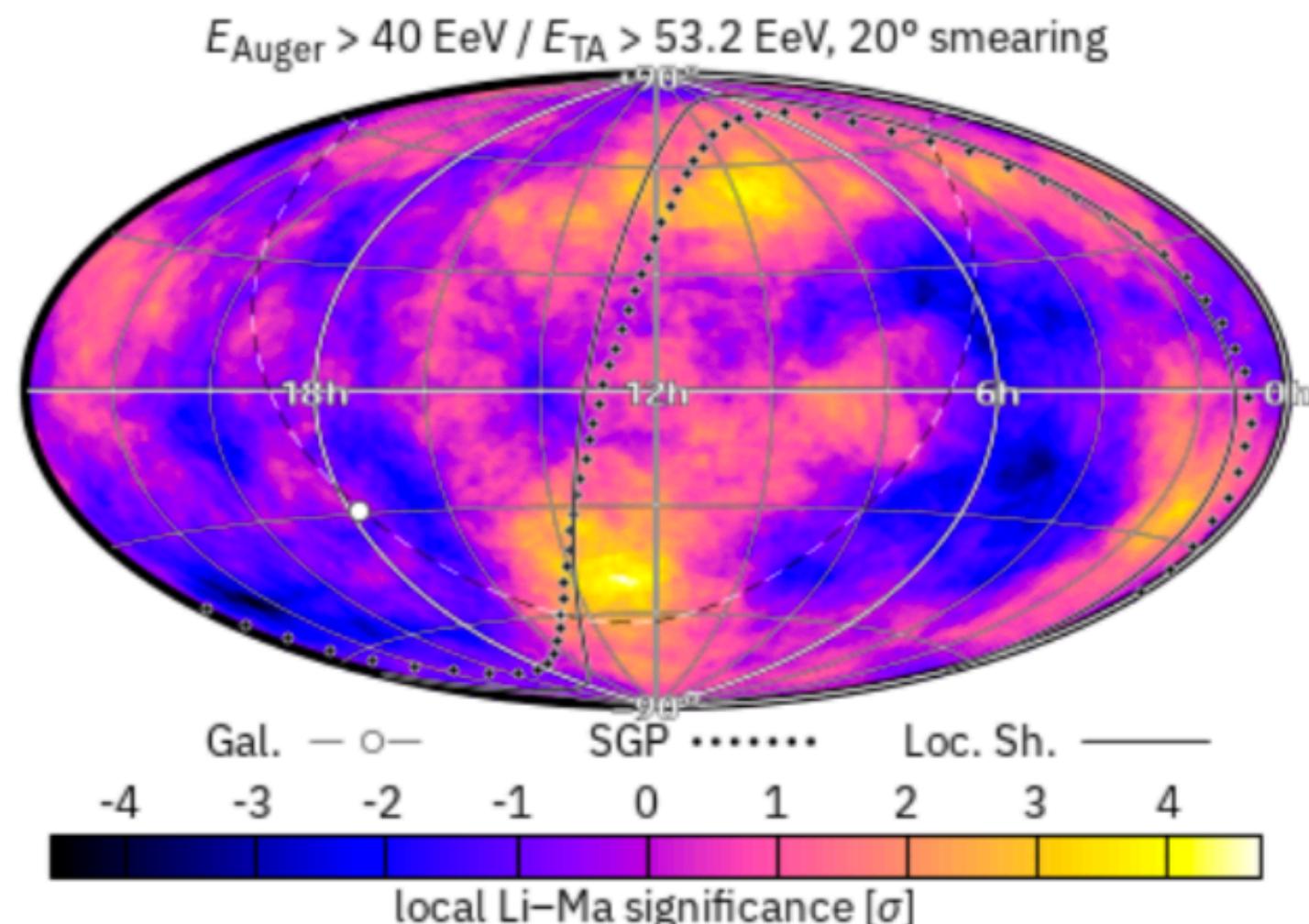
Energy threshold

40 EeV (Auger)

53.2 EeV (Telescope Array)

Events

969 events



Blind search

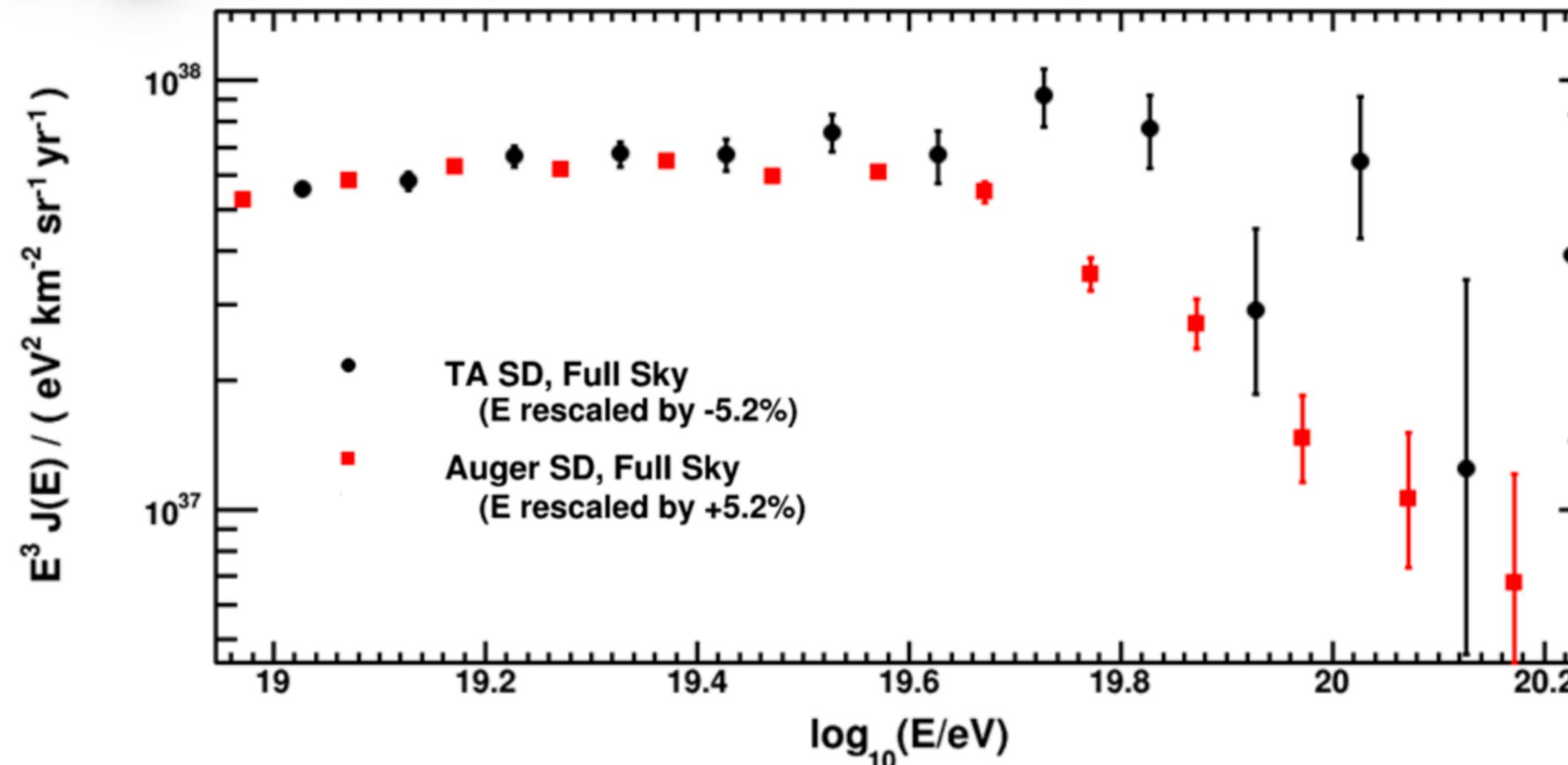
($\alpha = 12^{\text{h}}50^{\text{m}}$, $\delta = -50^{\circ}$), 4.7 local sign (2.6 post-trial)

($\alpha = 9^{\text{h}}30^{\text{m}}$, $\delta = +54^{\circ}$), 4.2 local sign (1.5 post-trial)

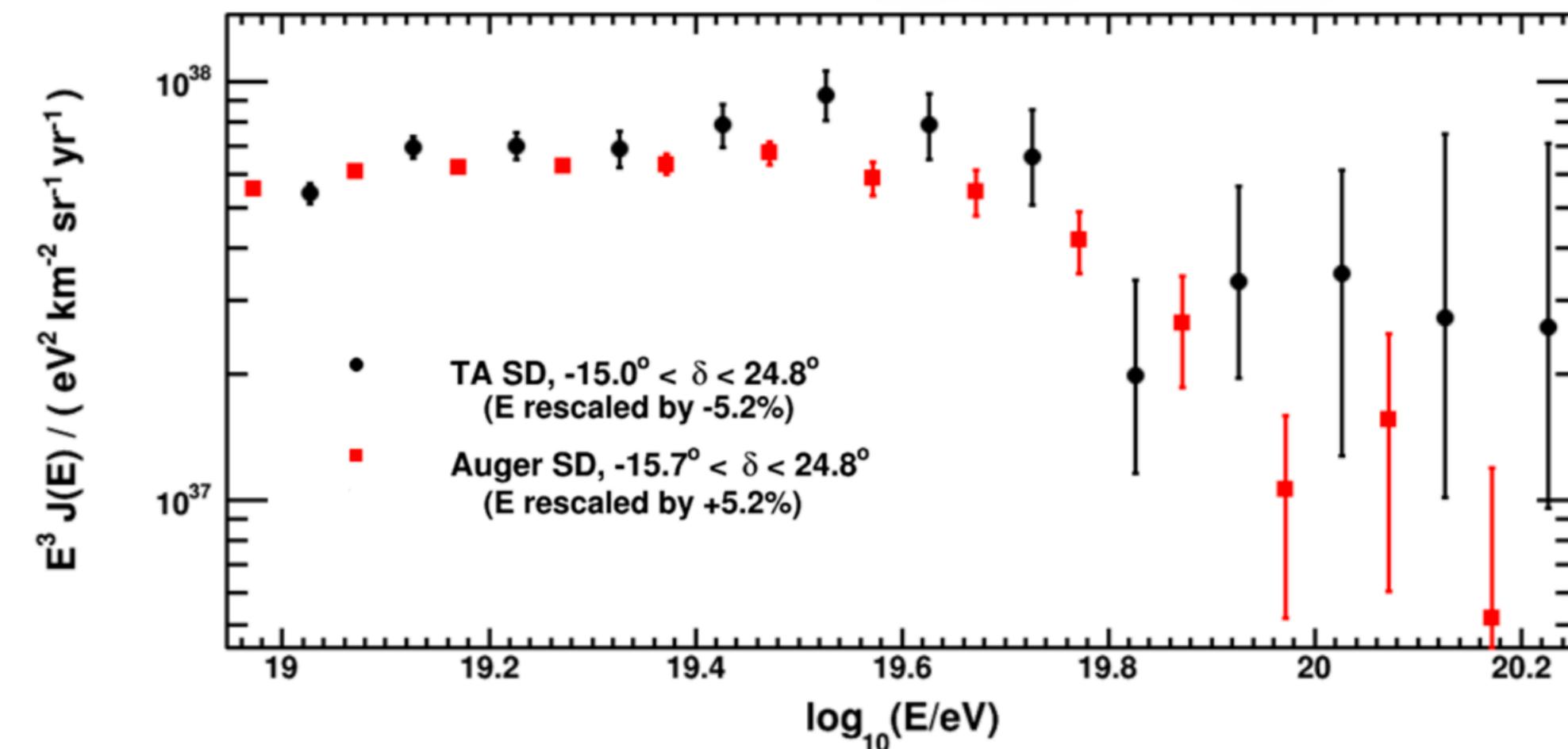
Local Sheet

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

Auger and Telescope Array spectrum working group



- Agree in the ankle region $10^{18.4} \text{ eV} < E < 10^{19.4} \text{ eV}$ after rescaling
- Difference above $10^{19.4} \text{ eV}$ persists after locking energy scales of experiments**



Better agreement between TA and Auger in the common declination band

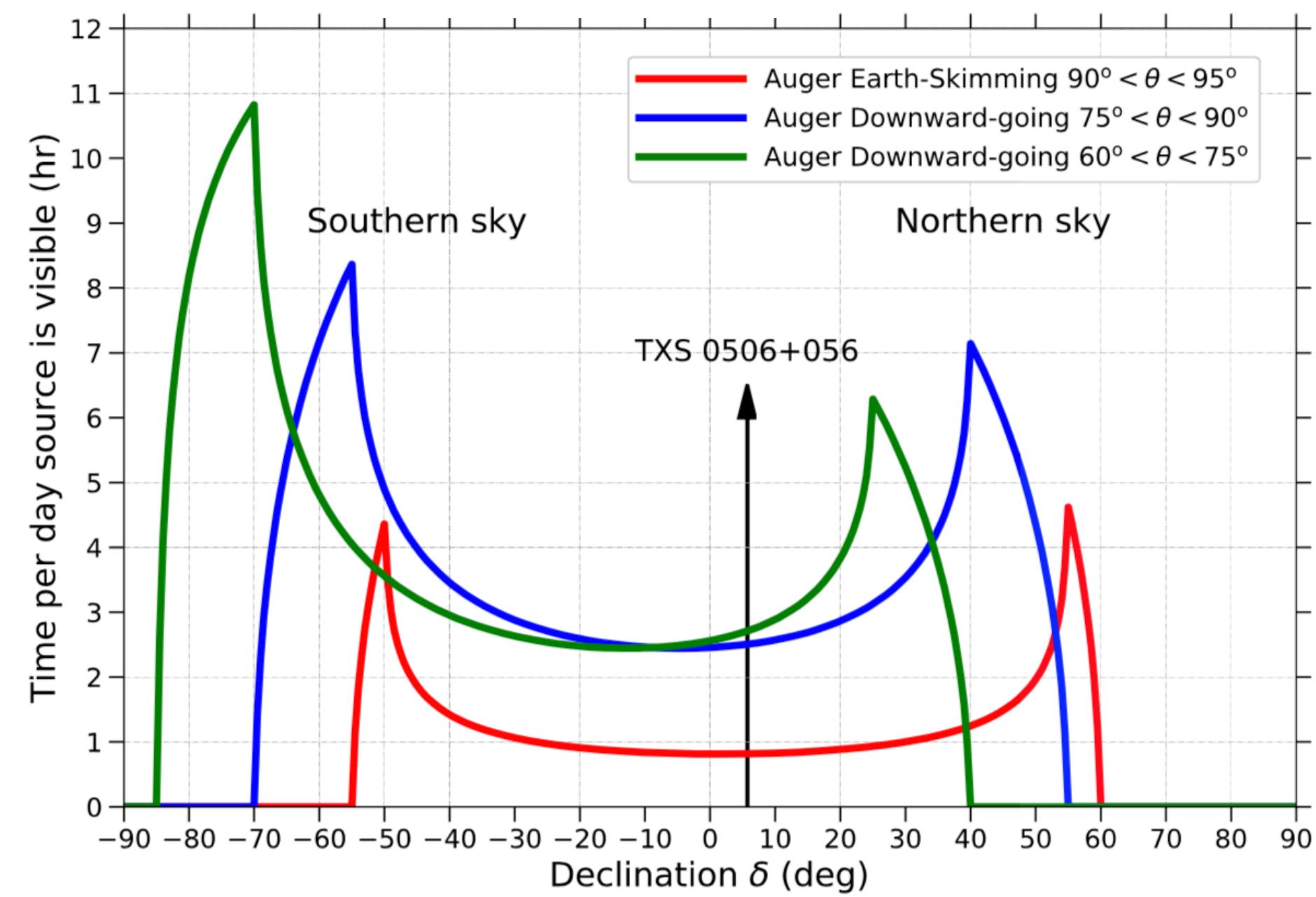
Source of Nonlinearity	Amount (percent per decade above 10^{19} eV)	
FD missing energy correction	1%	+/- 1%
FD Fluorescence Yield Model	-1%	+/- 1%
FD Atmospheric Conditions	1.7%	+/- 1%
SD and FD comparison:	-2%	+/- 9%
Net	-0.3%	+/- 9%

Sources of Energy-Dependent Energy Reconstruction Bias in Auger

Sources of nonlinearities	% per decade $> 10 \text{ EeV}$
Aerosols	$\pm 1\%$
stat. uncertainties calib. param.	$\pm 1\%$
check with hybrids SD/FD comparison	$\pm 2\%$
energy dependent CIC	$\pm 2\%$
Net	$\approx \pm 3\%$

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

