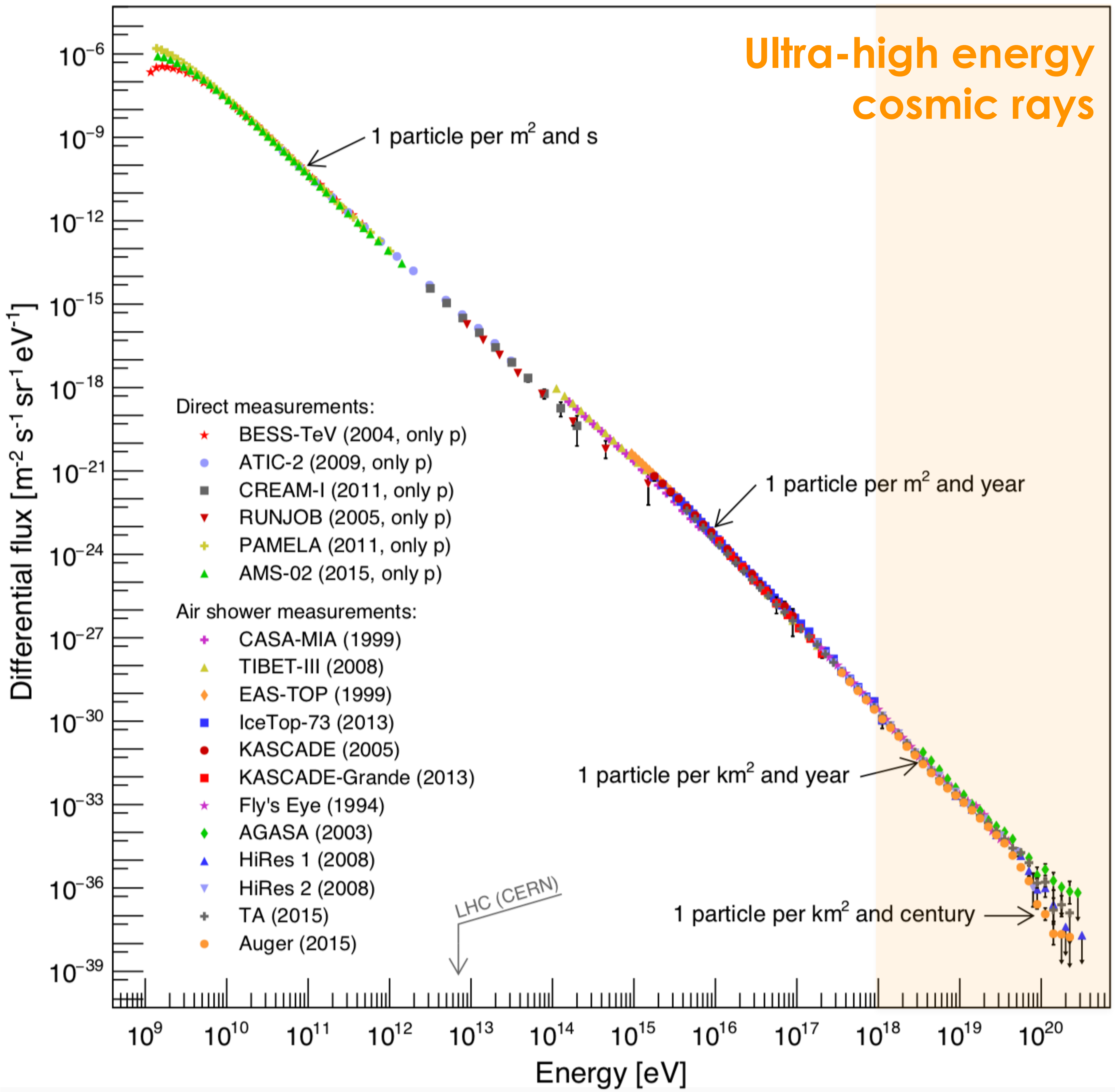
The Pierre Auger Observatory: studying the highest energy frontier

Inés Valiño
Gran Sasso Science Institute & INFN LNGS, Italy
on behalf of the Pierre Auger Collaboration

New Trends in HEP 2019
Одеса, 16/05/2019

Cosmic Rays



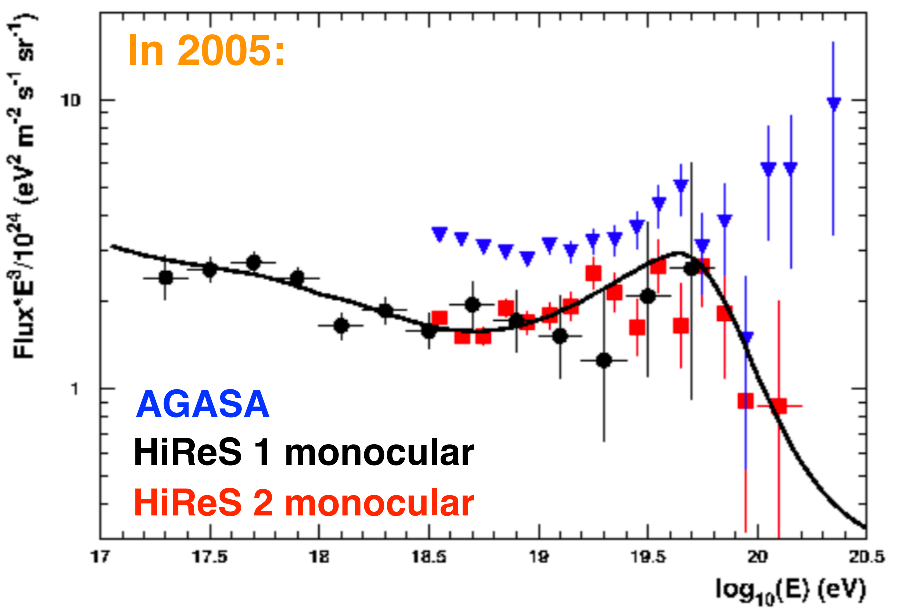
Big questions:

- What is the nature and origin of UHECRs?
- How are UHECRs accelerated to such extreme energies?
- Types of sources?

Previously on the UHECR field…

It was commonly believed that:

- **UHECR** were **protons**
- It could exist (or not!) a **cutoff** in the cosmic-ray flux at the highest energies due to **GZK** energy losses on the CMB.



- The ***ankle*** feature (flattening) in the spectrum at few EeV marked the **transition from** cosmic rays with a **Galactic** origin **to** an **extragalactic** proton-dominant component.
- **Speculation** if the UHECR above 10 EeV were **created in our Milky Way or in distant extragalactic objects**
- Many models to explain the origin of the UHECR (including ***top-down* scenarios** for where UHECRs originate from decay of supermassive particles).

Now

Discoveries made over the past decade thanks to the current UHECR observatories have dramatically advanced our understanding of UHECRs and their sources, but indicate a **complex astrophysical picture…**

Highlights from the Pierre Auger Observatory

Astrophysics

- **Energy spectrum: flux suppression**
- **Unexpected mass composition**
- **Challenging level of isotropy with a dipole**
- **Multi-messenger observations**: neutrinos and gamma rays
- Exotic scenarios ruled out

Particle physics well beyond LHC energies

- Constraints to hadronic interaction models:
  - **Muon deficit in simulated showers**
- Proton-air cross section at $\sqrt{s} = 57$ TeV

Other capabilities

- Laboratory for new detection techniques: radio
- Atmospheric science

https://www.auger.org/index.php/science/journal-articles

Pierre Auger Observatory

17 countries, ~90 institutions,
~400 authors (~100 PhD students)

Pierre Auger Observatory: state-of-the art cosmic ray detector

- The world's largest observatory to study CRs above 10^{17} eV
- Detection of extensive air showers induced by CR in the Earth's atmosphere

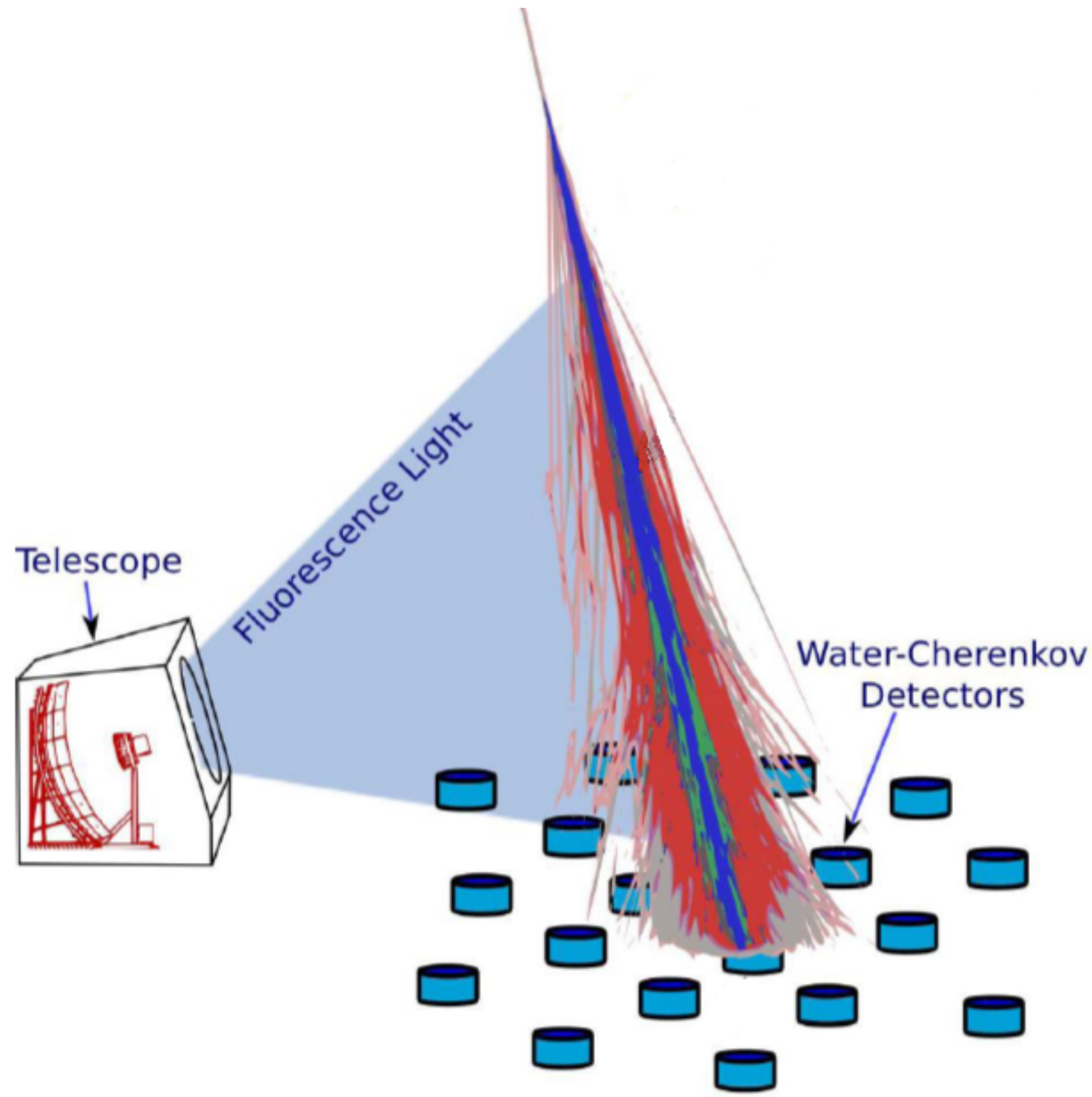
Hybrid concept

- **Fluorescence detector (FD)**

  fluorescence telescopes:
  - calorimetric energy measurement
  - ~13-15 % duty cycle

- **Surface detector (SD)**

  water-Cherenkov detectors:
  - sensitive to the μ and EM ($e^{\pm}$,γ) shower components
  - ~100% duty cycle



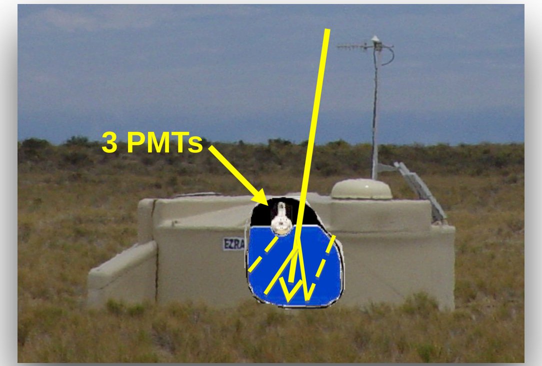
Pierre Auger Observatory: initial detectors

- **Fluorescence detector (FD)**

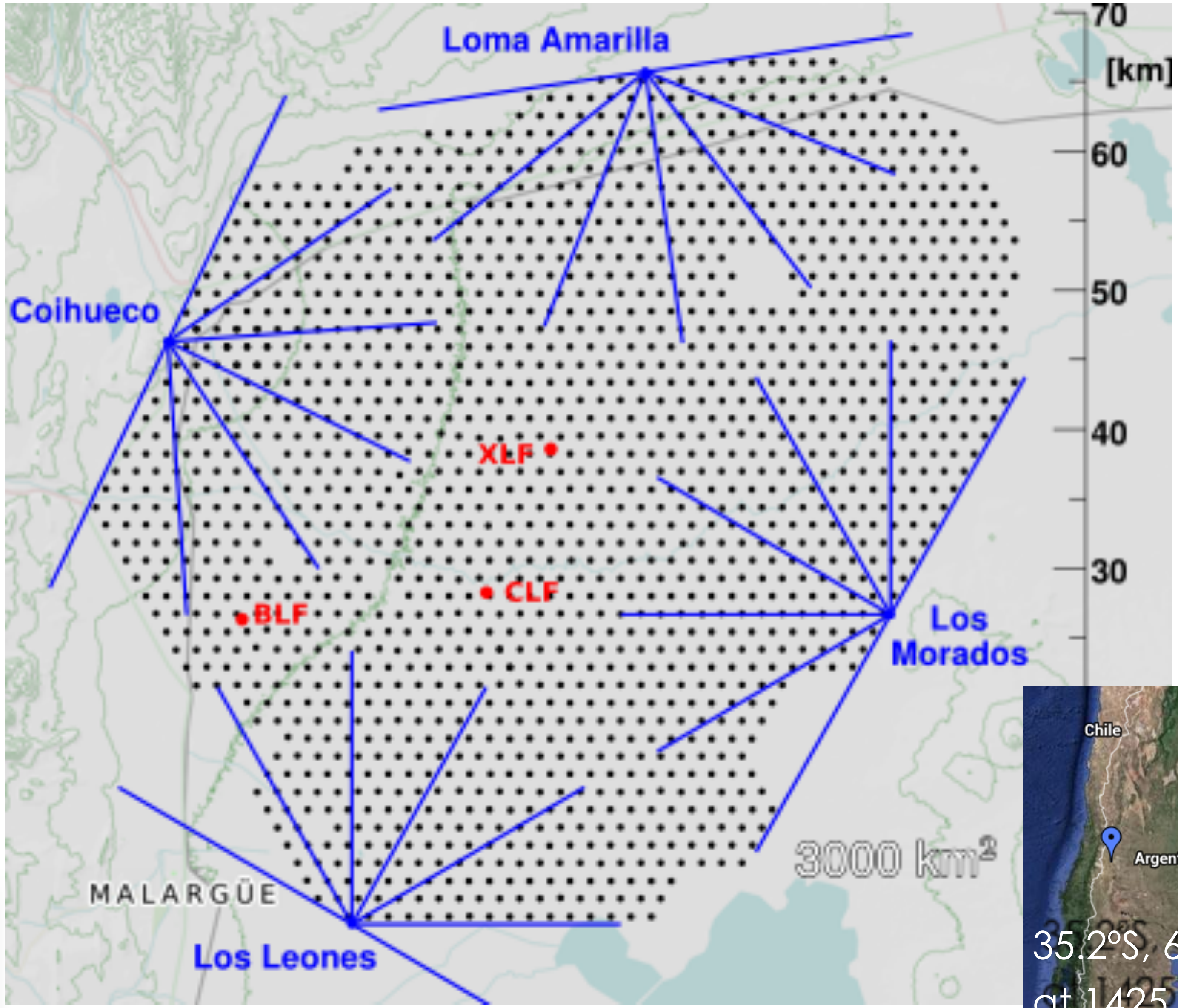
  24 telescopes in 4 sites
  - FoV: 0 - 30°
  - Full efficiency: E > 10^{18} eV

- **Surface detector (SD)**

  1660 stations in 1500 m grid
  - 3000 km^2
  - E > $10^{18.5}$ eV



Data taking since January 2004



[The Pierre Auger Collaboration, NIM A 798 (2015) 172-213]

Pierre Auger Observatory: multi-detector

- **Fluorescence detector (FD)**

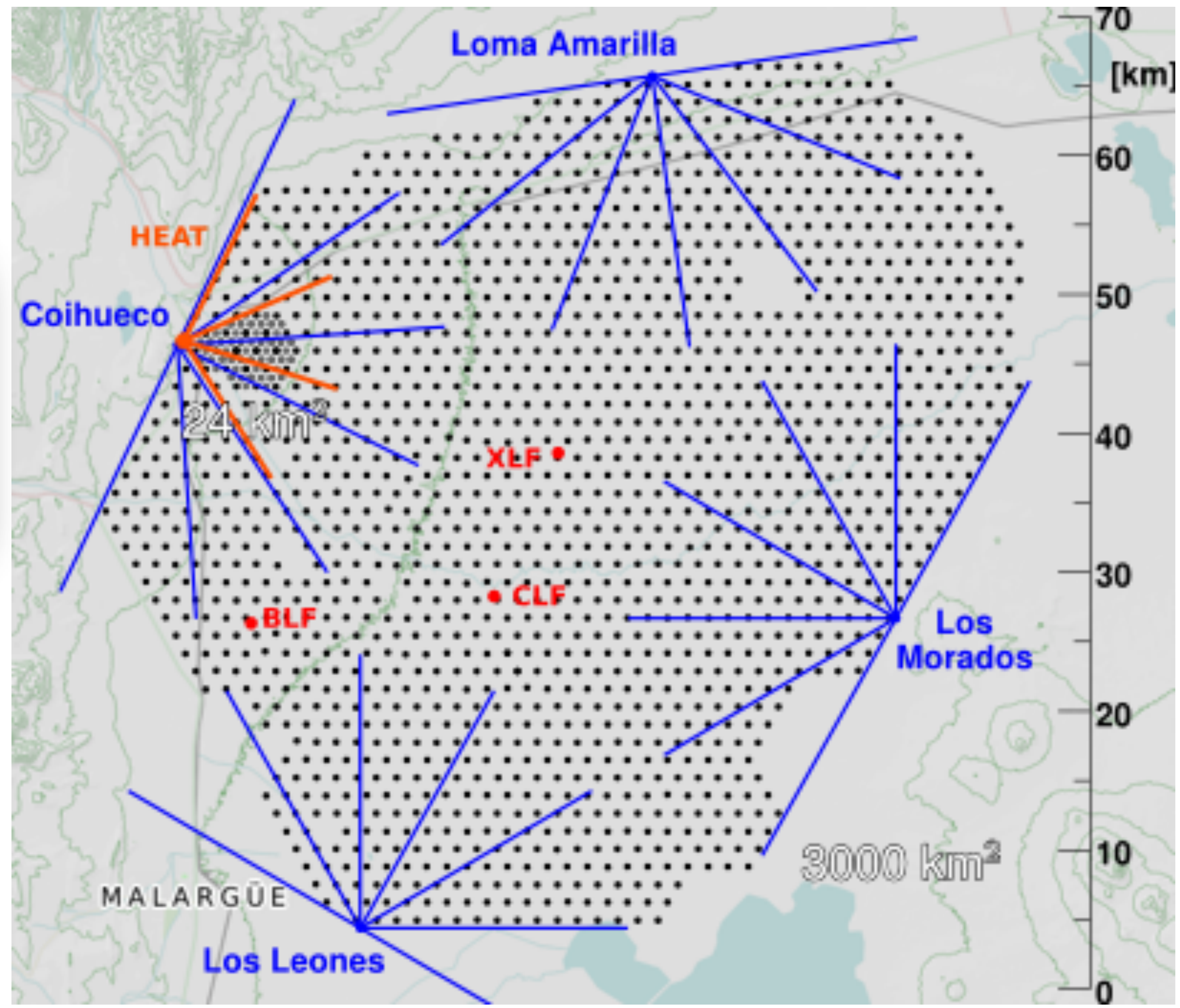
  24 telescopes in 4 sites
  - FoV: 0 - 30°
  - E > 10^{18} eV

  HEAT (3 telescopes)
  - **FoV: 30 - 60°**
  - **E > 10^{17} eV**

- **Surface detector (SD)**

  1660 stations in 1500 m grid
  - 3000 km^2
  - E > $10^{18.5}$ eV

  61 stations in 750 m grid
  - **23.5 km^2**
  - **E > $10^{17.5}$ eV**



[The Pierre Auger Collaboration, NIM A 798 (2015) 172-213]

Pierre Auger Observatory: multi-detector

• Fluorescence detector (FD)

24 telescopes in 4 sites

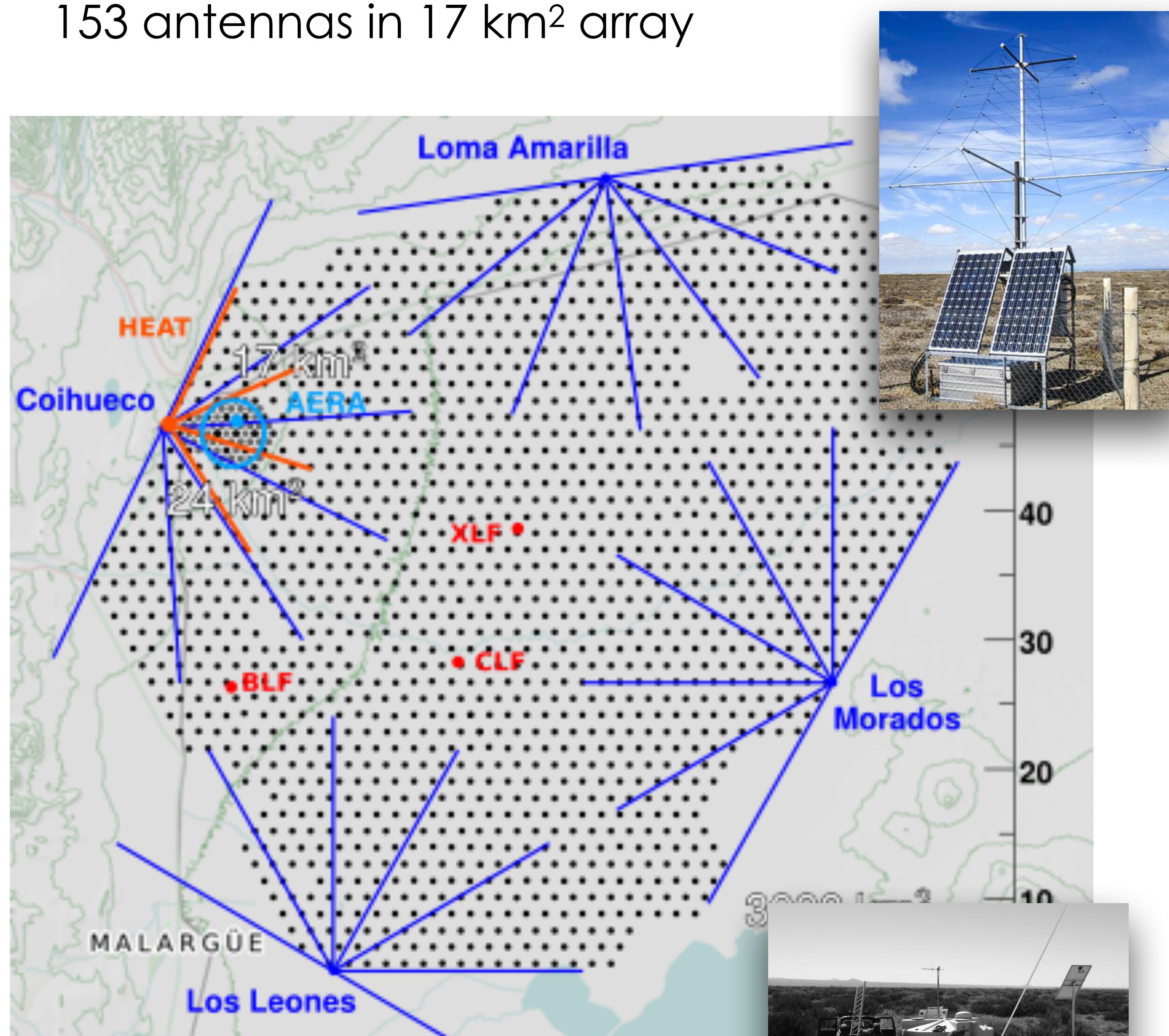
- FoV: 0 - 30°
- $E > 10^{18}$ eV

HEAT (3 telescopes)

- FoV: 30 - 60°
- $E > 10^{17}$ eV

• Auger Engineering Radio Array (AERA)

153 antennas in 17 km² array



• Surface detector (SD)

1660 stations in 1500 m grid

- 3000 km²
- $E > 10^{18.5}$ eV

61 stations in 750 m grid

- 23.5 km²
- $E > 10^{17.5}$ eV

• Underground muon detector

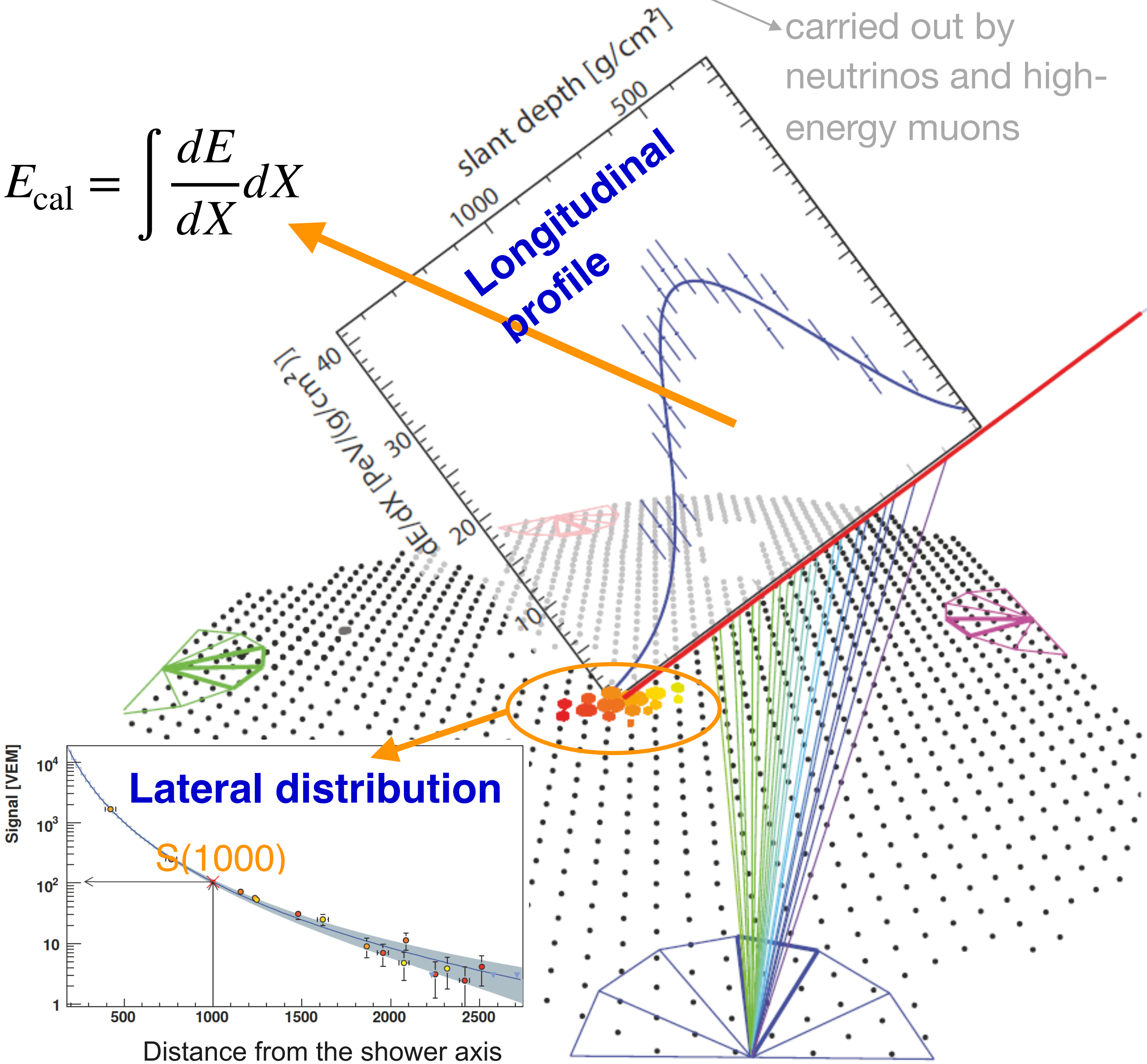
17 buried scintillators

Hybrid detection of air showers

Total energy: $E_{\mathrm{FD}} = E_{\mathrm{cal}} + E_{\mathrm{invisible}}$

carried out by neutrinos and high-energy muons

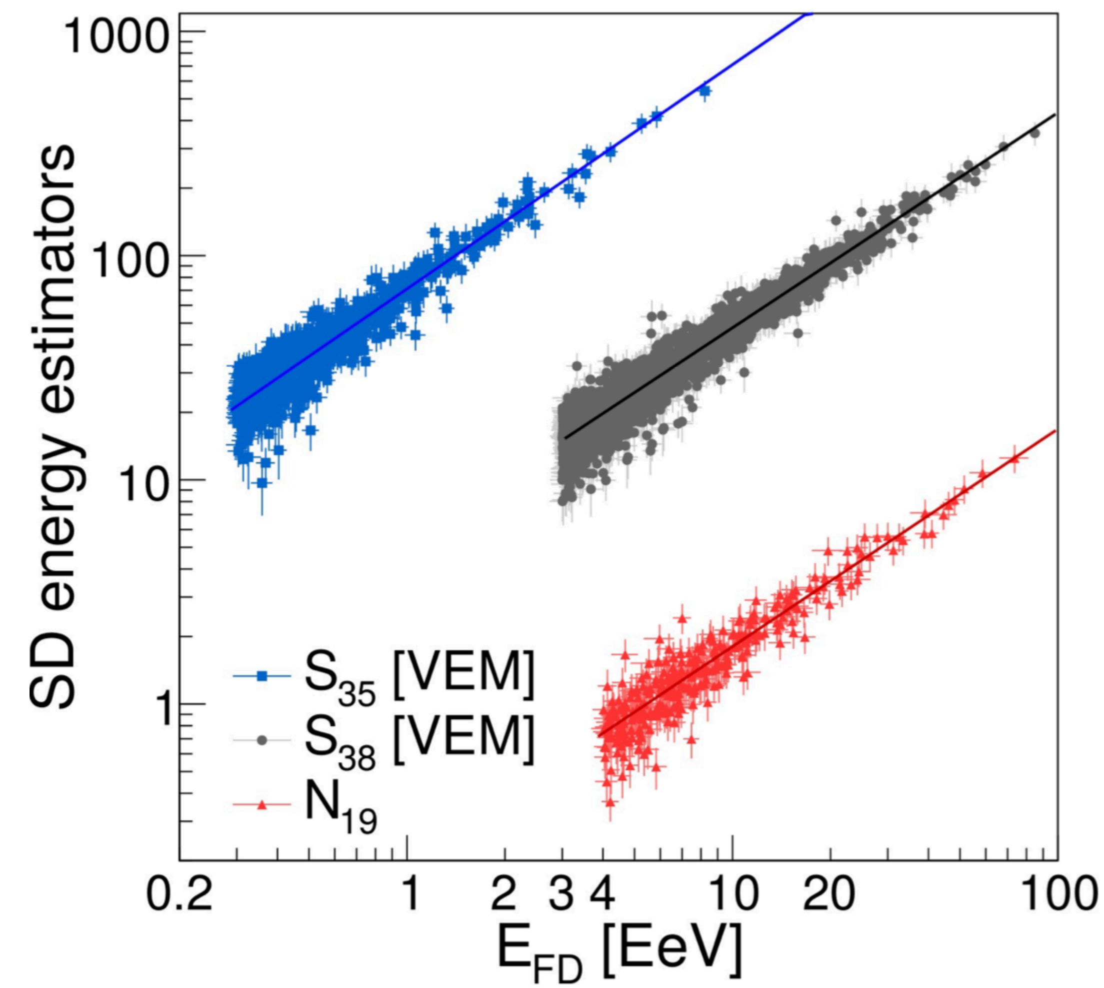
$$E_{\mathrm{cal}} = \int \frac{dE}{dX} dX$$



shower size at ground = energy estimator

SD absolute calibration based on experimental data

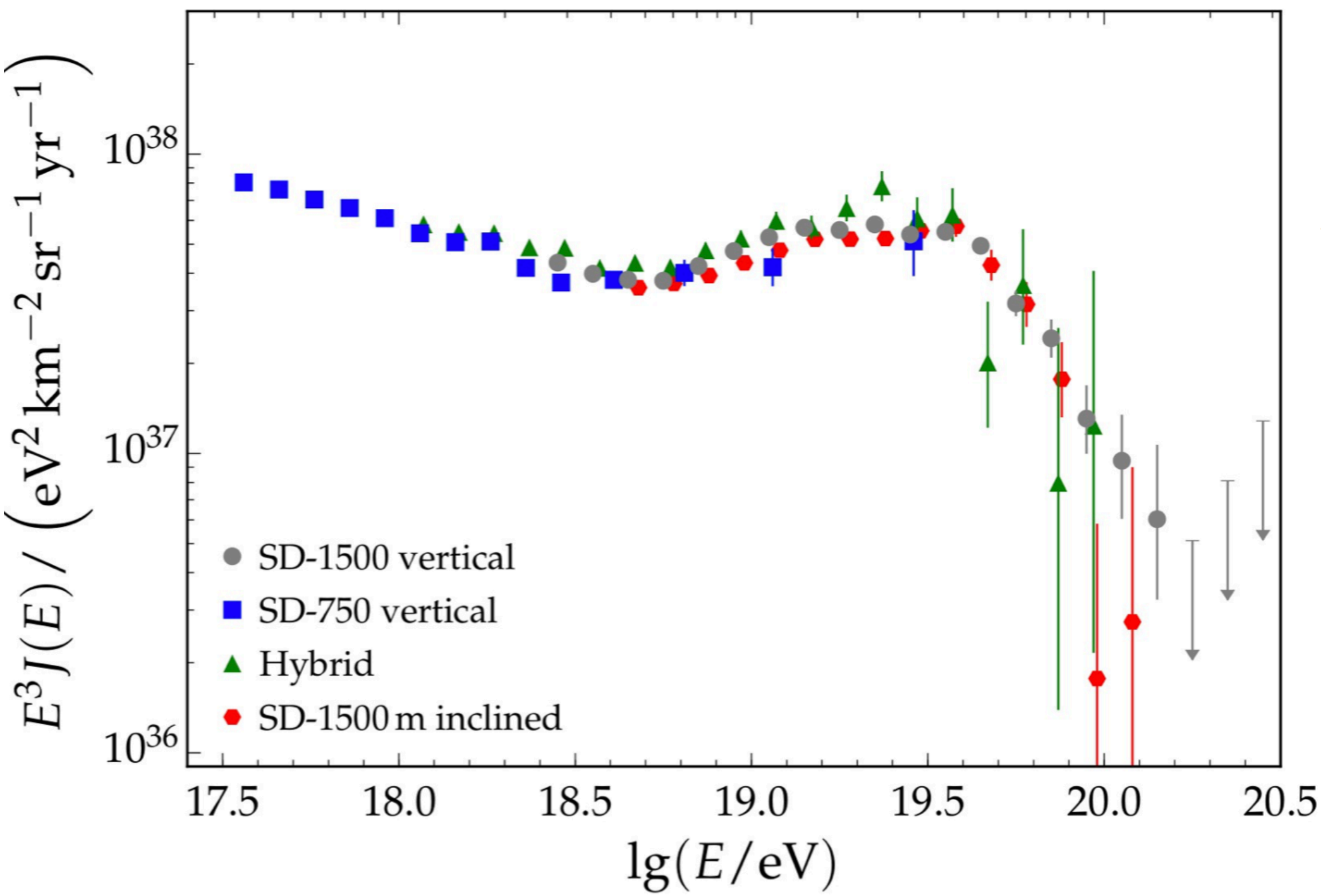
Systematic uncertainty on energy scale: 14%

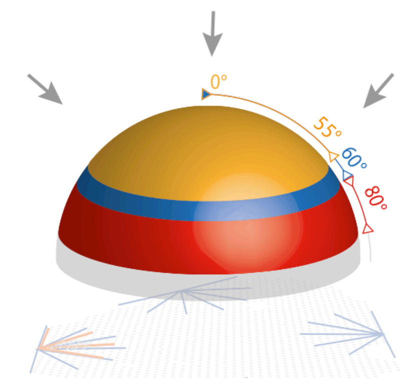


Auger energy spectra

Precise measurement over 3 decades in energy (full data-driven approach):

- 4 data sets using either SD and FD
- Auger ICRC2017: ~ 300,000 events; 67,000 km² sr yr exposure





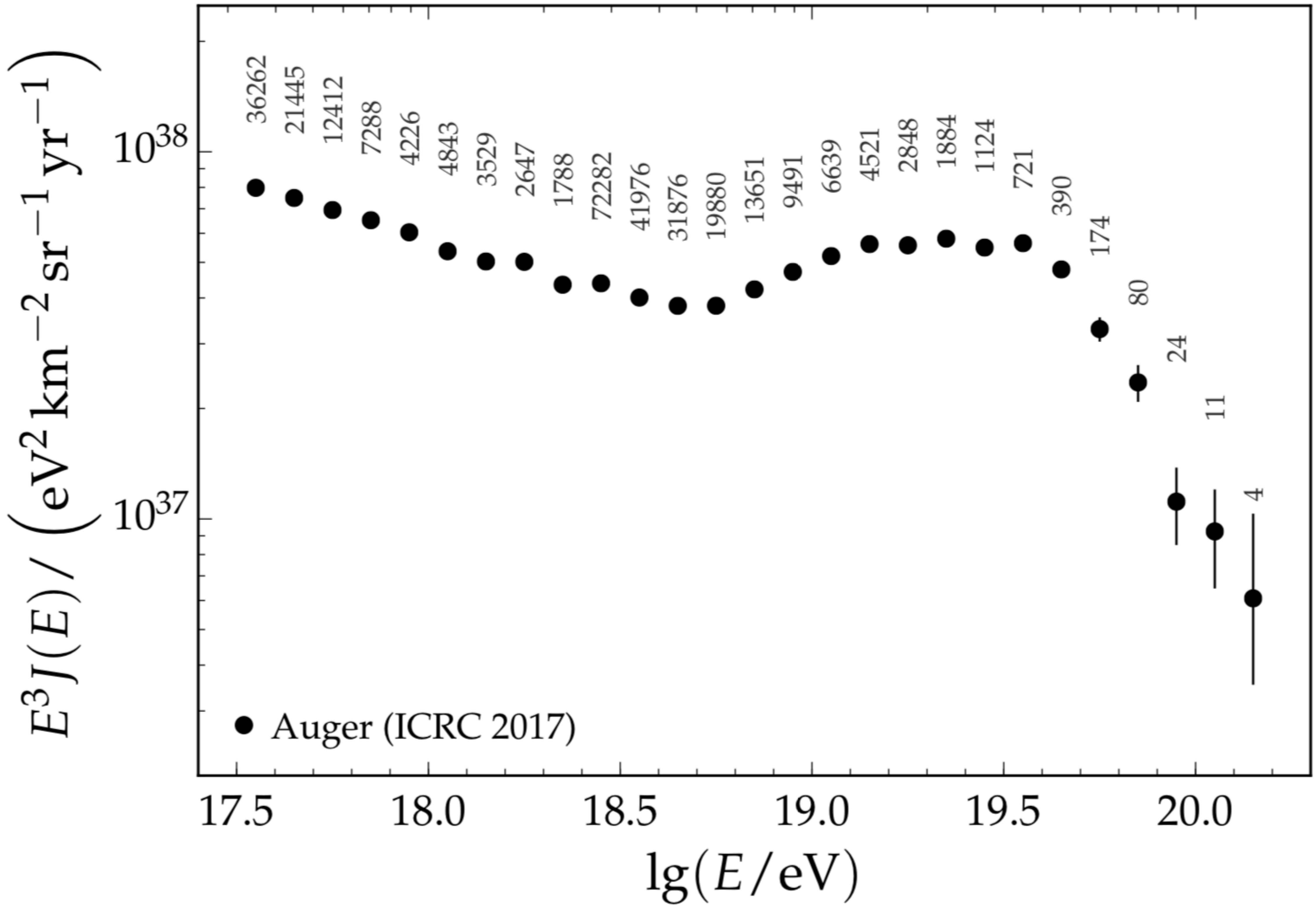
750m: 0°<θ<55° E> $3x10^{17}$ eV ´vertical´
1500m: 0°<θ<60° E> $3x10^{18}$ eV ´vertical´
1500m: 60°<θ<80° E> $4x10^{18}$ eV ´inclined´

Hybrid: events detected by FD with at least 1 SD detector

Good agreement of the individual spectra within the uncertainties ⇒ **combined spectrum**

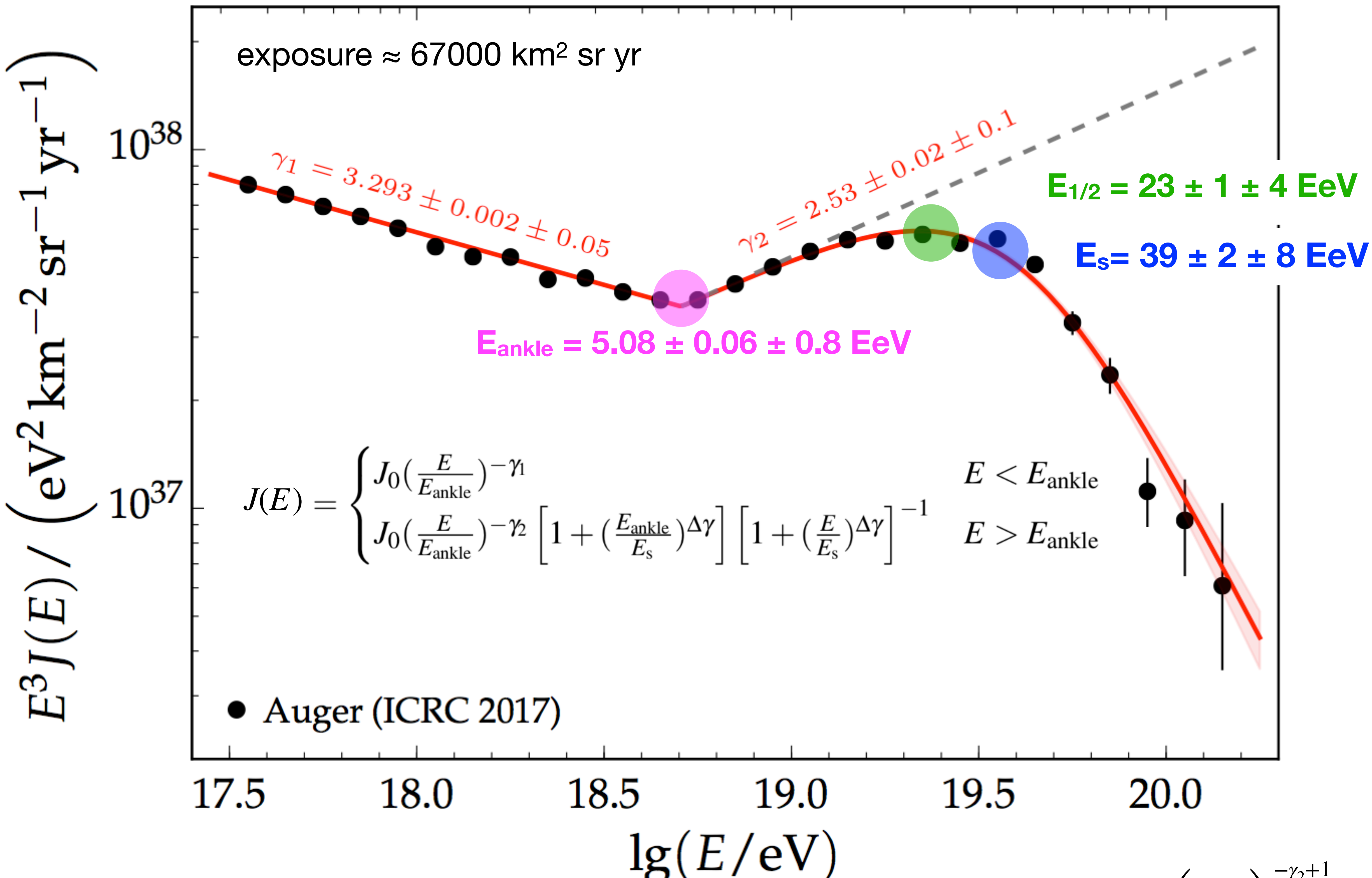
[F. Fenu for the Pierre Auger Collaboration, PoS(ICRC2017)486]

Combined energy spectrum



[F. Fenu for the Pierre Auger Collaboration, PoS(ICRC2017)486]

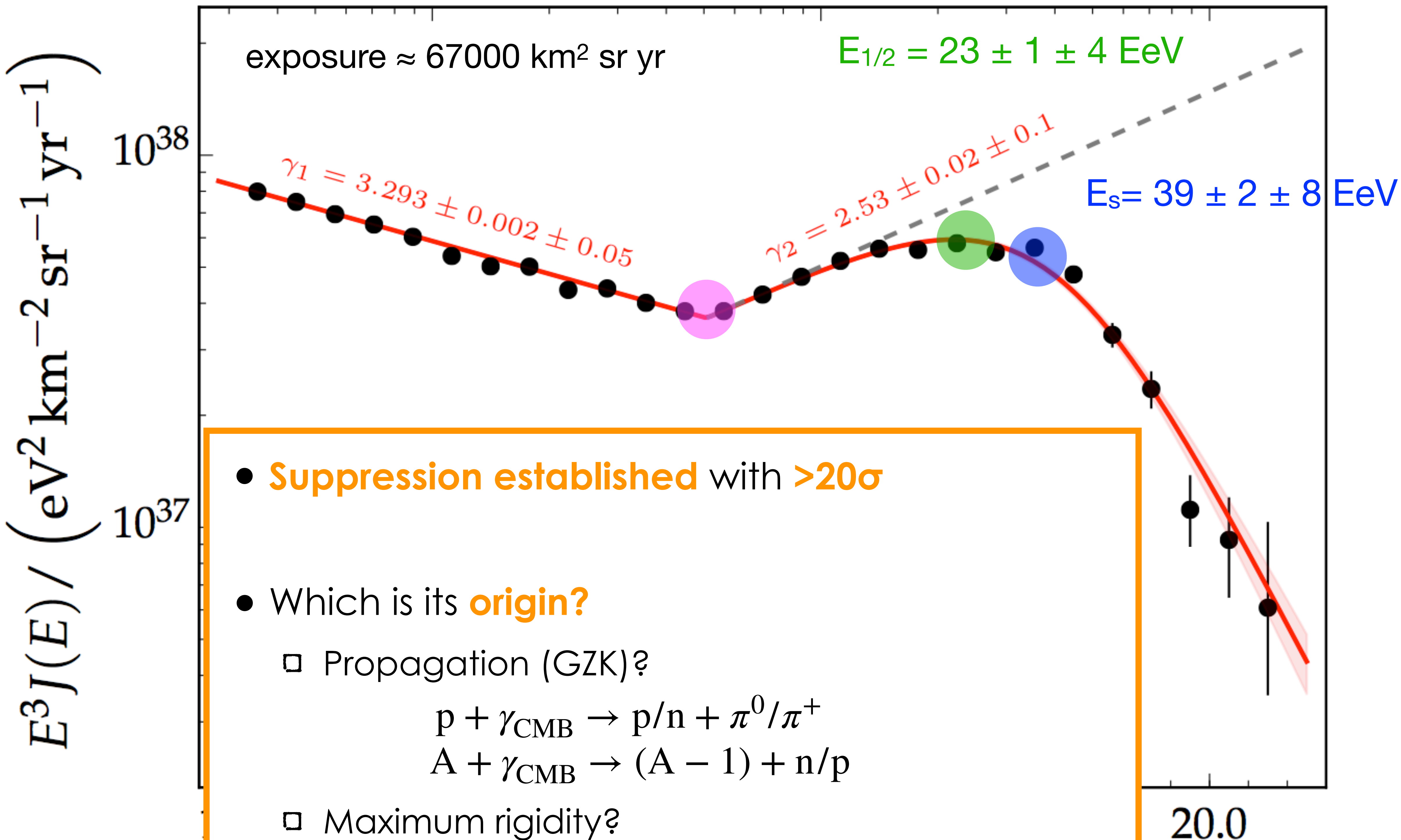
Combined energy spectrum: spectral features



$$I(E_{1/2}) = \frac{1}{2} I_0 \left(\frac{E_{1/2}}{E_s}\right)^{-\gamma_2+1}$$

[F. Fenu for the Pierre Auger Collaboration, PoS(ICRC2017)486]

Combined energy spectrum: spectral features



- **Suppression established** with **>20σ**

- Which is its **origin?**
  - Propagation (GZK)?

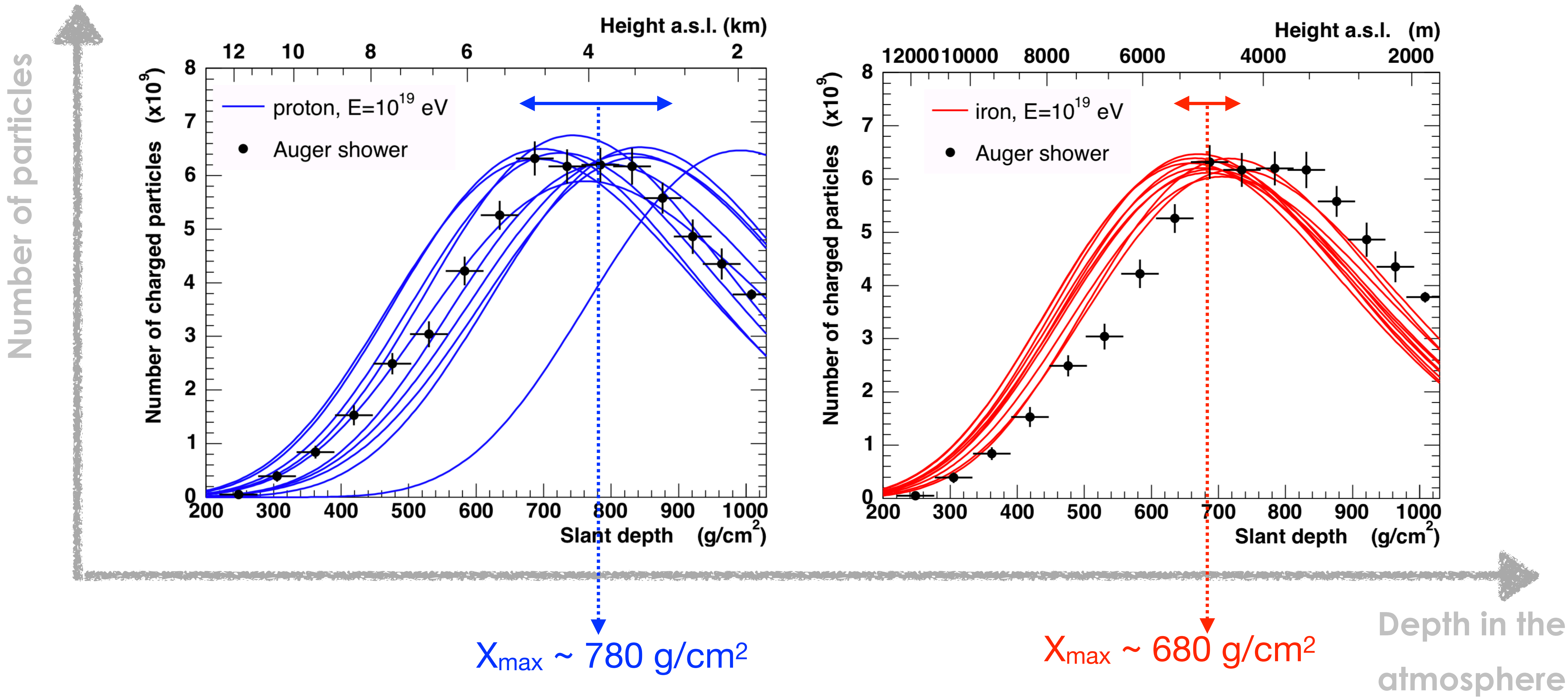
$$\mathrm{p} + \gamma_{\mathrm{CMB}} \rightarrow \mathrm{p/n} + \pi^0/\pi^+$$
$$\mathrm{A} + \gamma_{\mathrm{CMB}} \rightarrow (\mathrm{A} - 1) + \mathrm{n/p}$$

  - Maximum rigidity?

$$E_{\max} = ZE_p$$

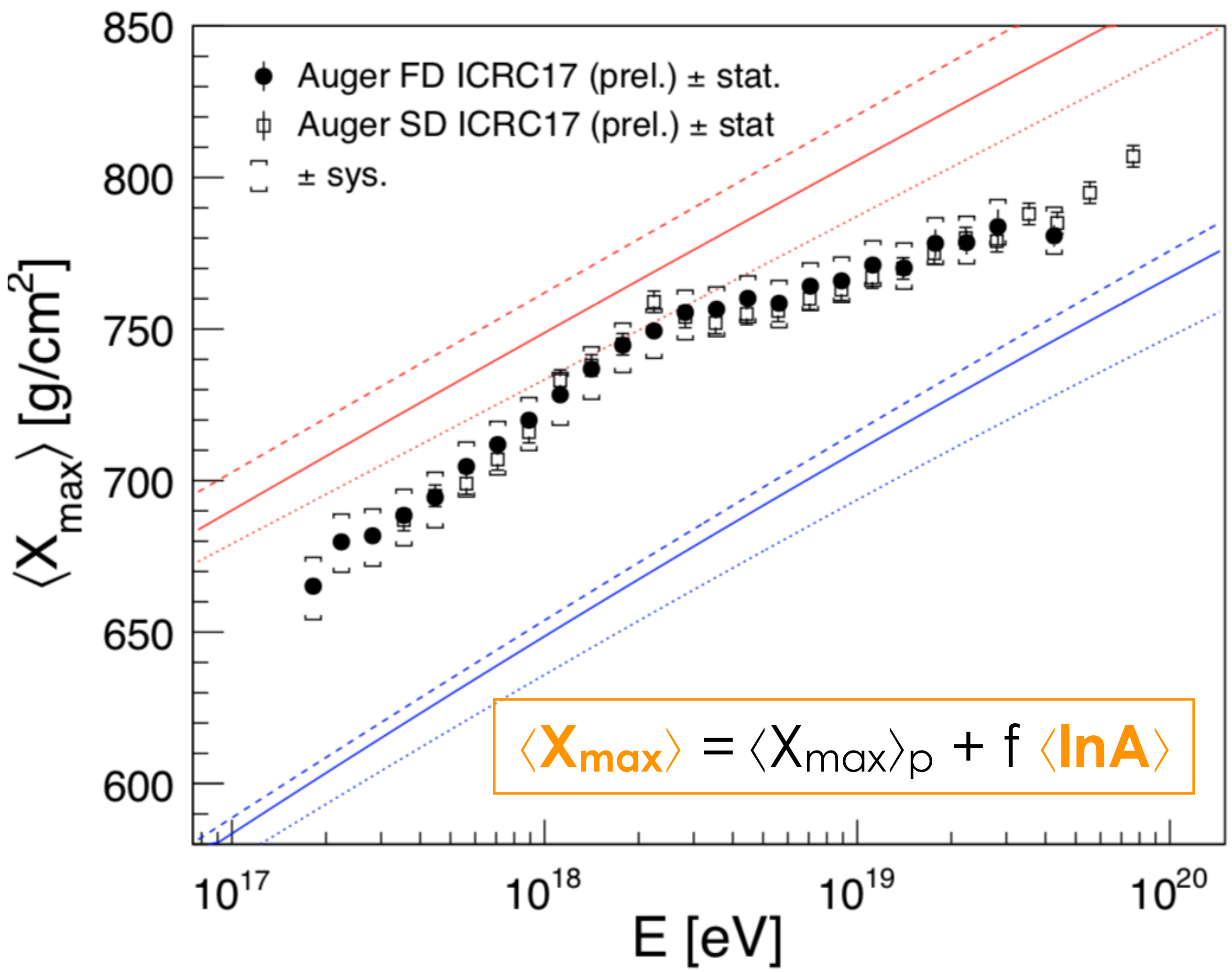
Mass composition: the X_{max} observable

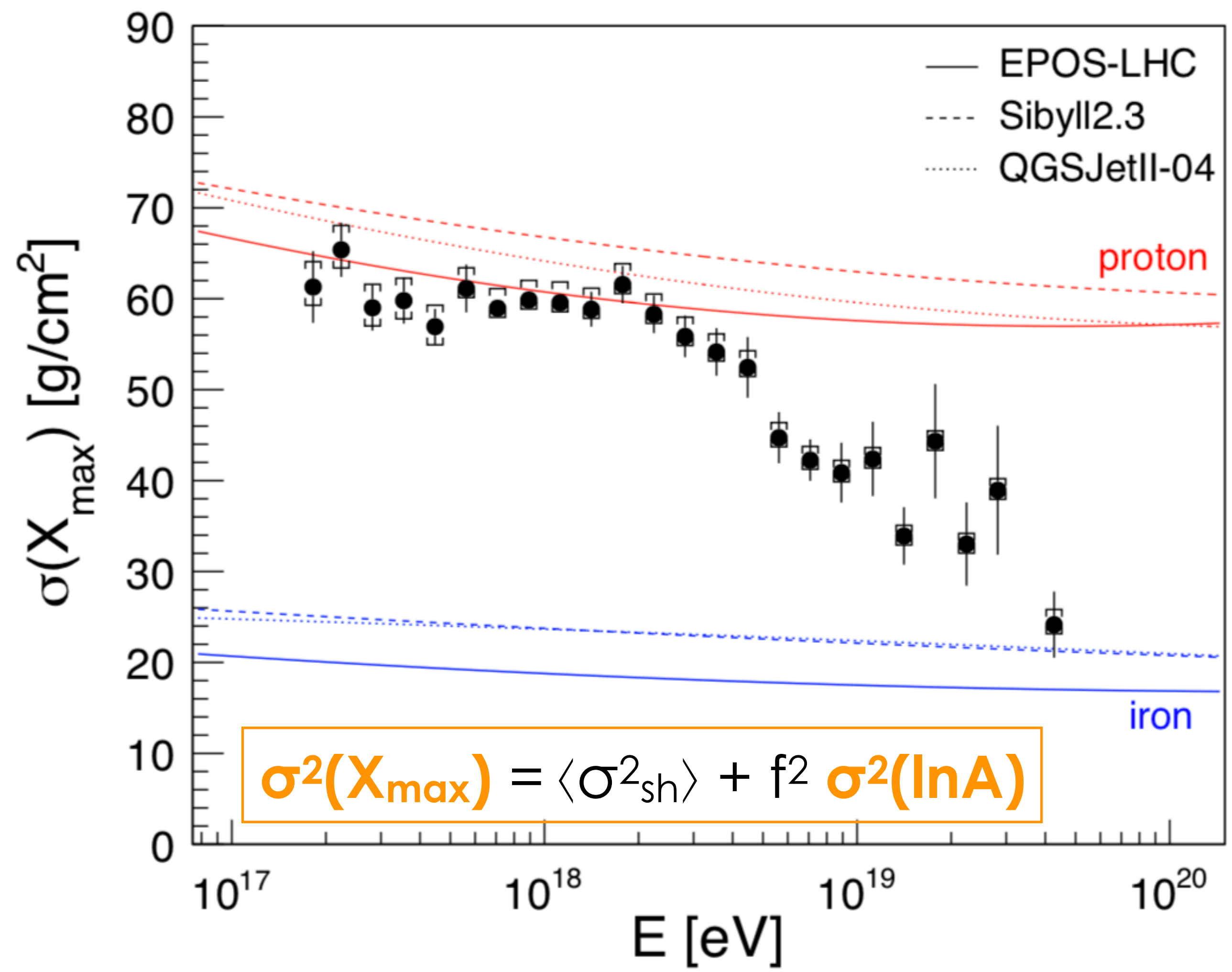
Hybrid measurements are sensitive to mass composition



Proton-induced showers develop deeper than Fe-induced ones, and have greater fluctuations ⇒ **X_{max} estimator of the mass composition**

Mass composition: X_{max} moments



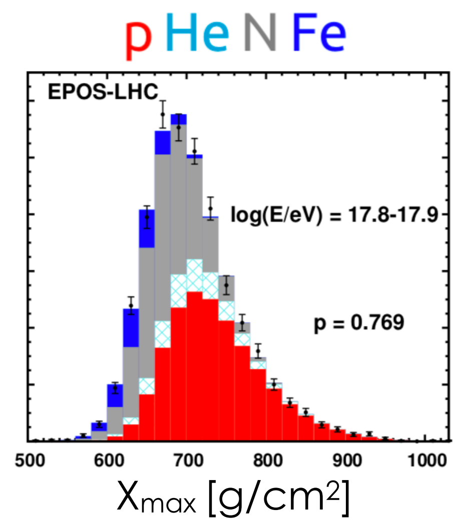


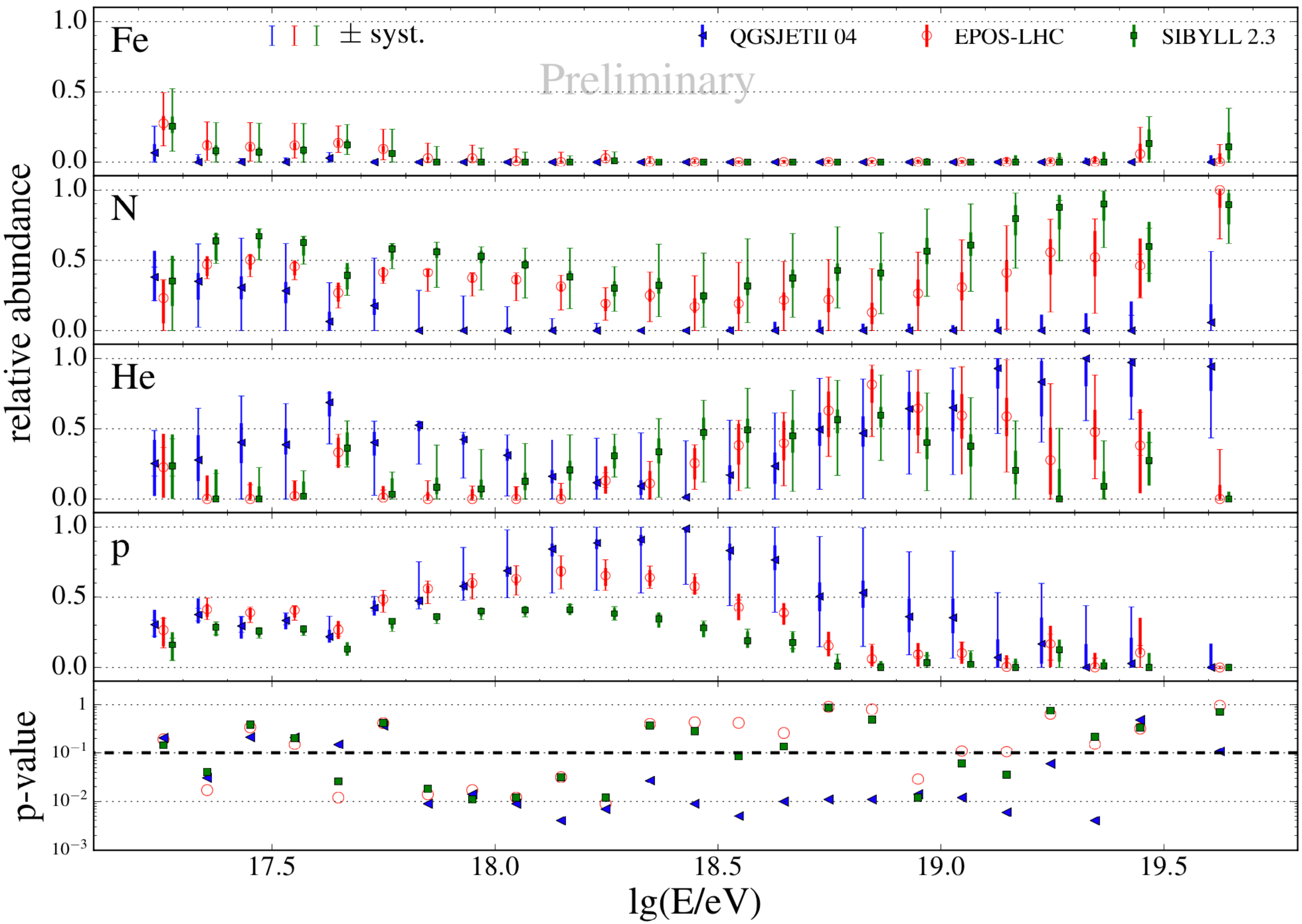
- Clear break at $10^{18.3}$ eV
- Predominant light composition at around the ankle
- Auger data suggests a gradual increases of mass with energy ($A \approx 14$ - 20 at $E \approx 10^{19.5}$ eV)

[The Pierre Auger Collaboration, Phys. Rev. D 96, 122003 (2017)]

[J. Bellido for the Pierre Auger Collaboration, PoS(ICRC2017)506]

Mass composition fractions





[J. Bellido for the Pierre Auger Collaboration, PoS(ICRC2017)506]

Search for the sources: Large-scale Anisotropy

Largest data set:

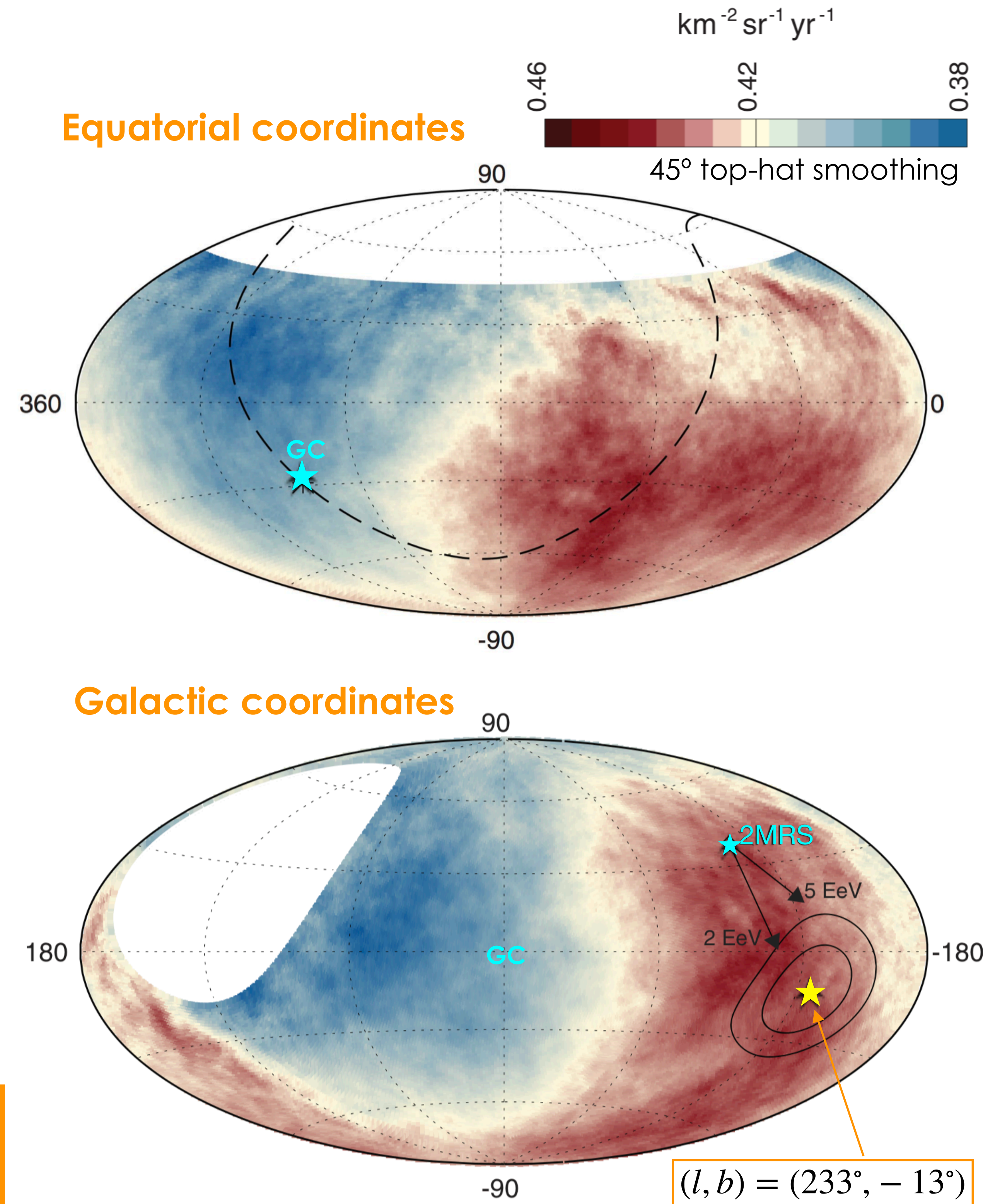
- ~114,000 SD events; 76,800 km^2 sr yr exposure
- 85% sky coverage

Rayleigh analyses of the first harmonic in high ascension α in 2 energy bins:

- 4-8 EeV: distribution compatible with isotropy
- **≥ 8 EeV**: 3D **dipole** of amplitude $6.5^{+1.3}_{-0.9}$ % (**5.2σ**) pointing to $(\alpha, \delta) = (100^{\circ}, -24^{\circ})$

Dipole structure expected if CRs diffuse to Galaxy from sources distributed as nearby galaxies (e.g. 2MRS catalog)

- Strong indication for an **extragalactic origin** of UHECRs above 8 EeV

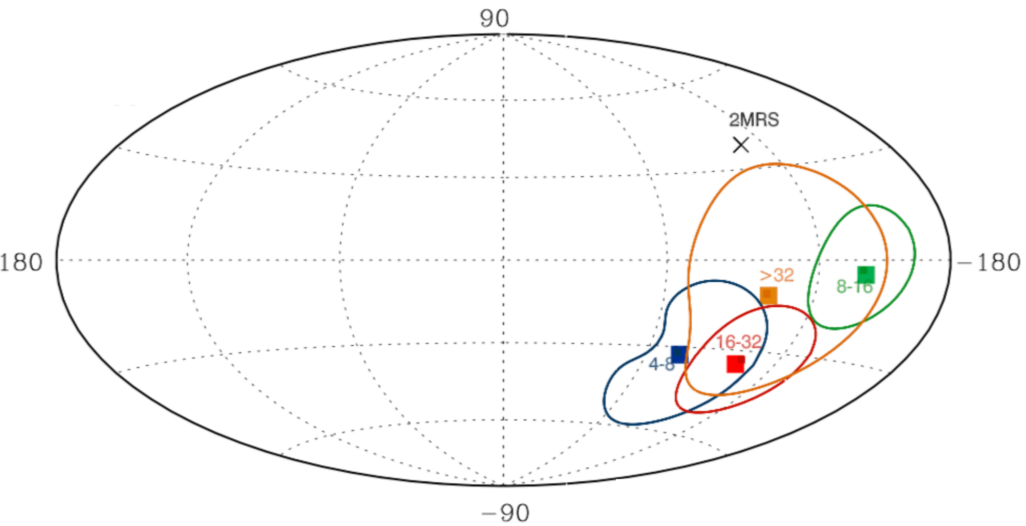


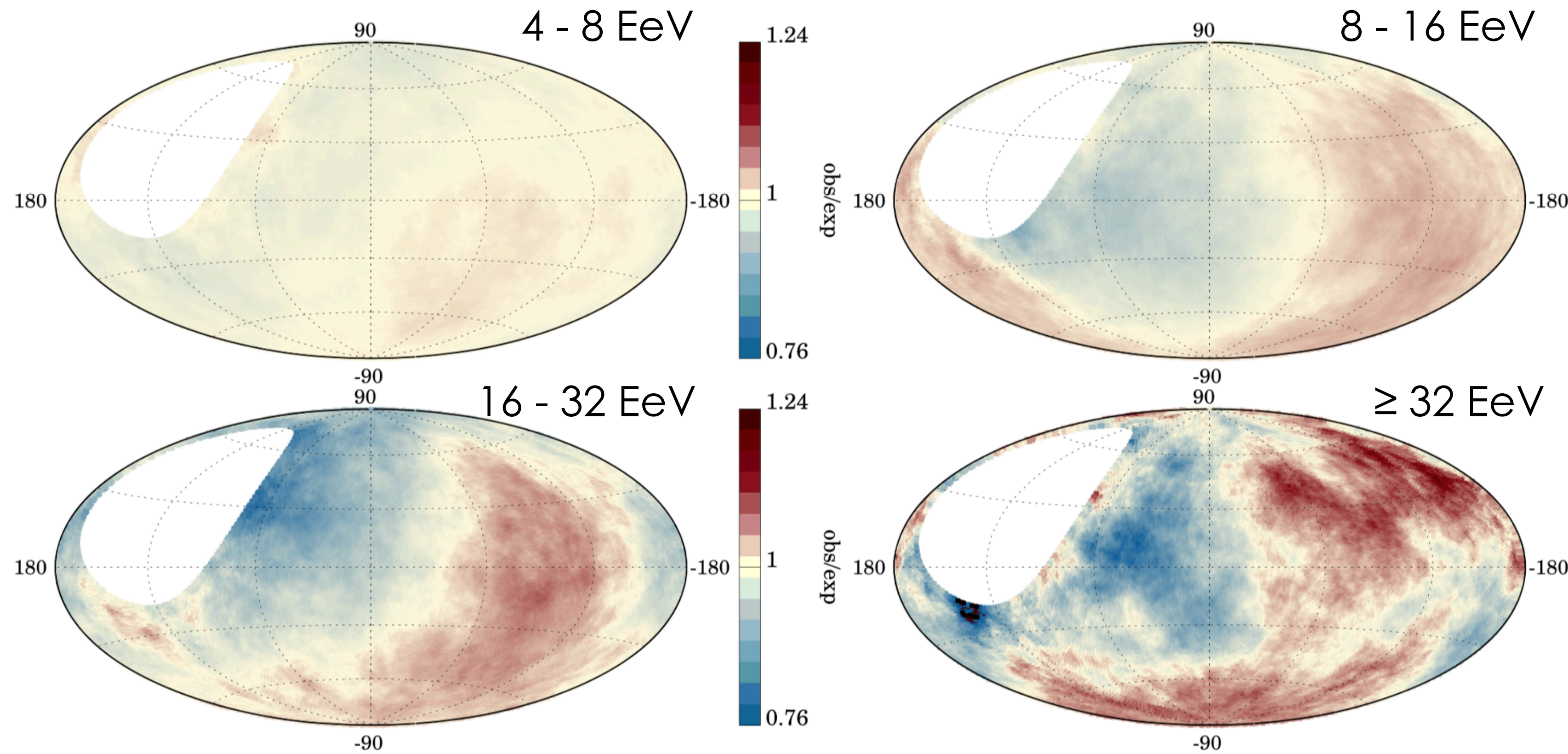
- ~125° away from GC
- ~55° away from 2MRS dipole

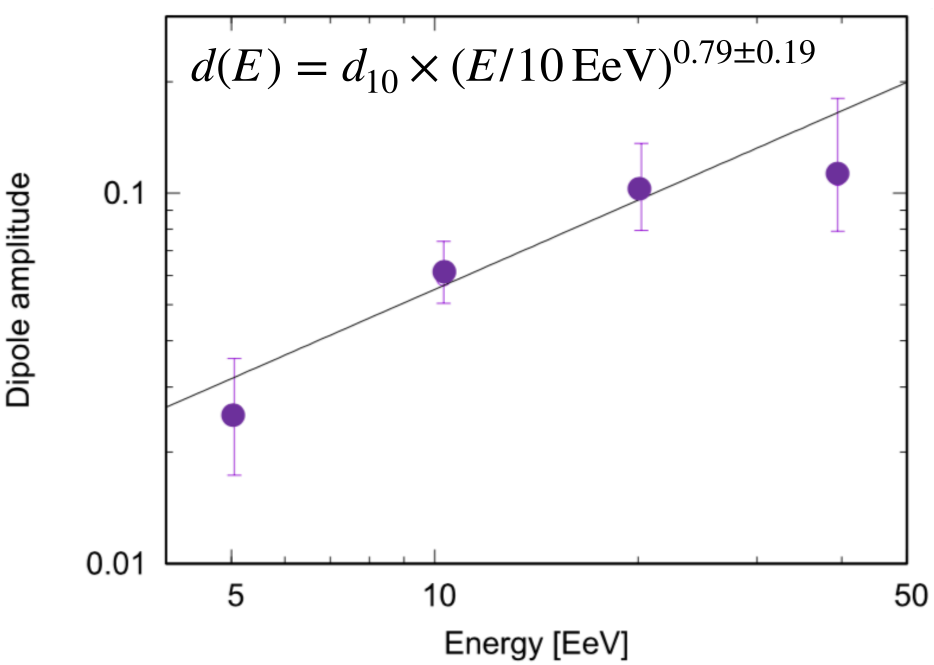
[The Pierre Auger Collaboration, Science 357 (2017) 1266]

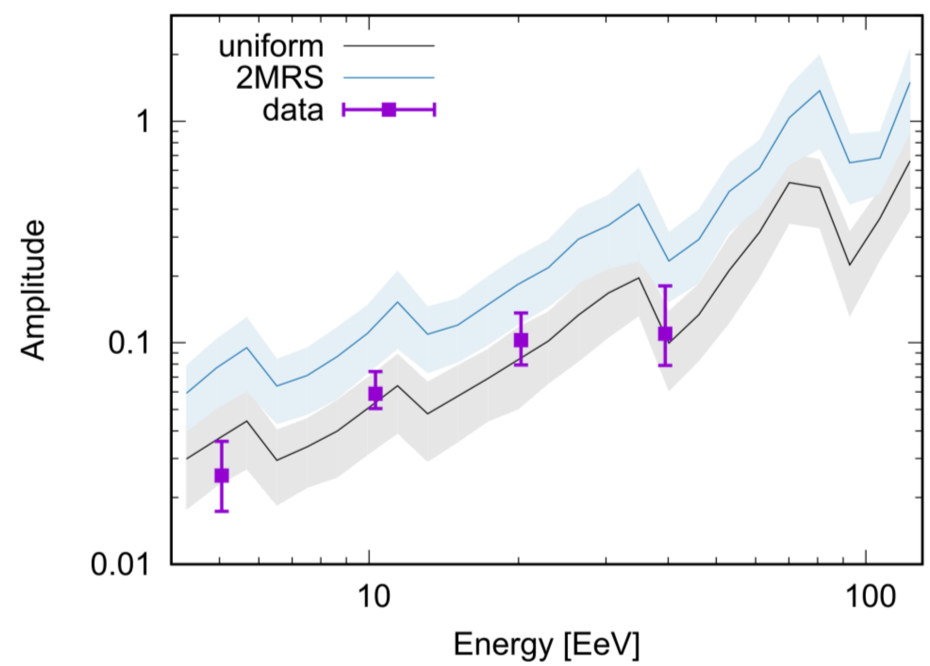
Energy dependence of the UHECR dipole

Dipole position in galactic coordinates









model predictions for scenario:

- mixed composition
- R_{max} = 6 EeV
- $\rho = 10^{-4}$ Mpc^{-3}
- GMF effects ignored

[The Pierre Auger Collaboration, Astrophys. J. 868 (2018) no.1, 4]

Search for the sources: Intermediate-scale Anisotropy

- At higher energies, Galactic and extragalactic deflections of UHECR nuclei are expected to smear point sources into warm/hot spots, for which evidence is accumulating.
- Compare the arrival direction of UHECRs with the expected flux pattern from catalogs

Fermi-LAT sources (GeV γ : full sky + no absorption for nearby sources):

- $D < 250$ Mpc
- Gamma-ray sources from 2FHL, > 50 GeV: 17 γAGN (blazars and radiogalaxies)
- 23 starburst galaxies with flux > 0.3 Jy

Auger data set:

- 5514 SD events with E > 20 EeV and θ > 80°
- 89,720 km^2 sr yr exposure

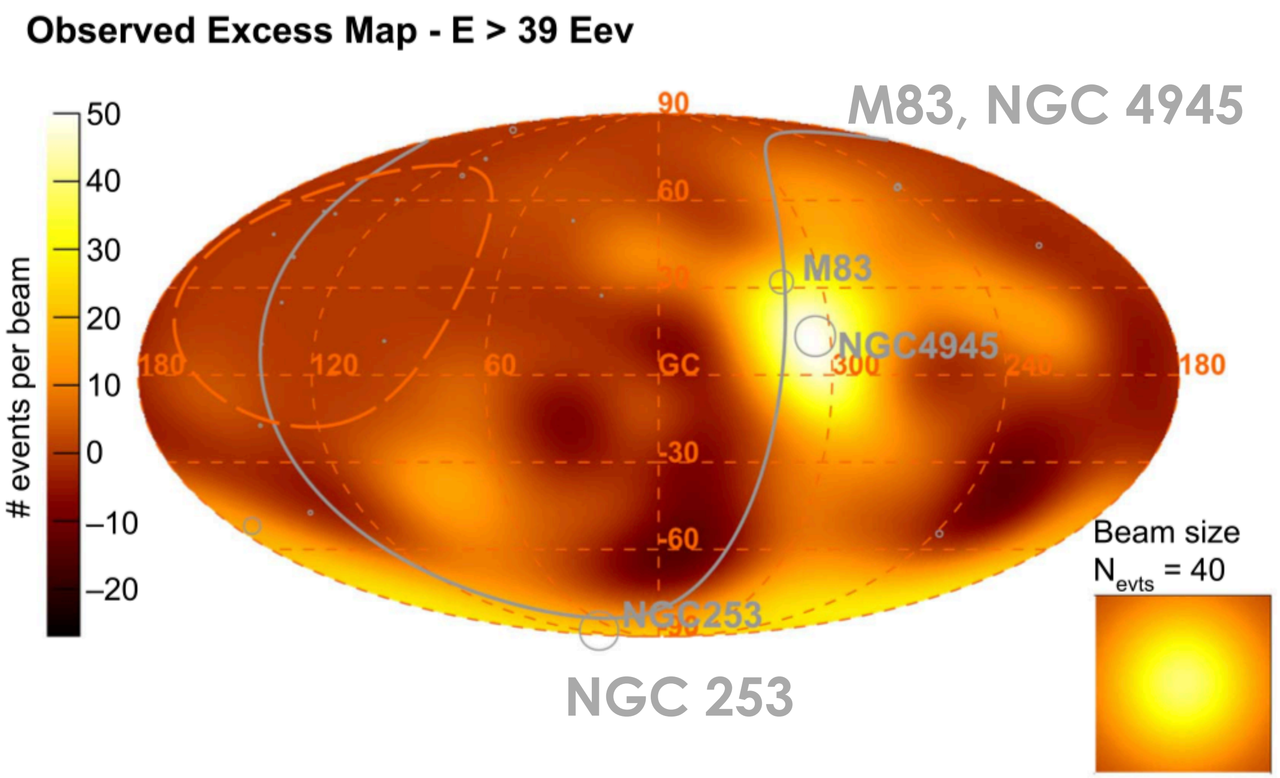
Analysis:

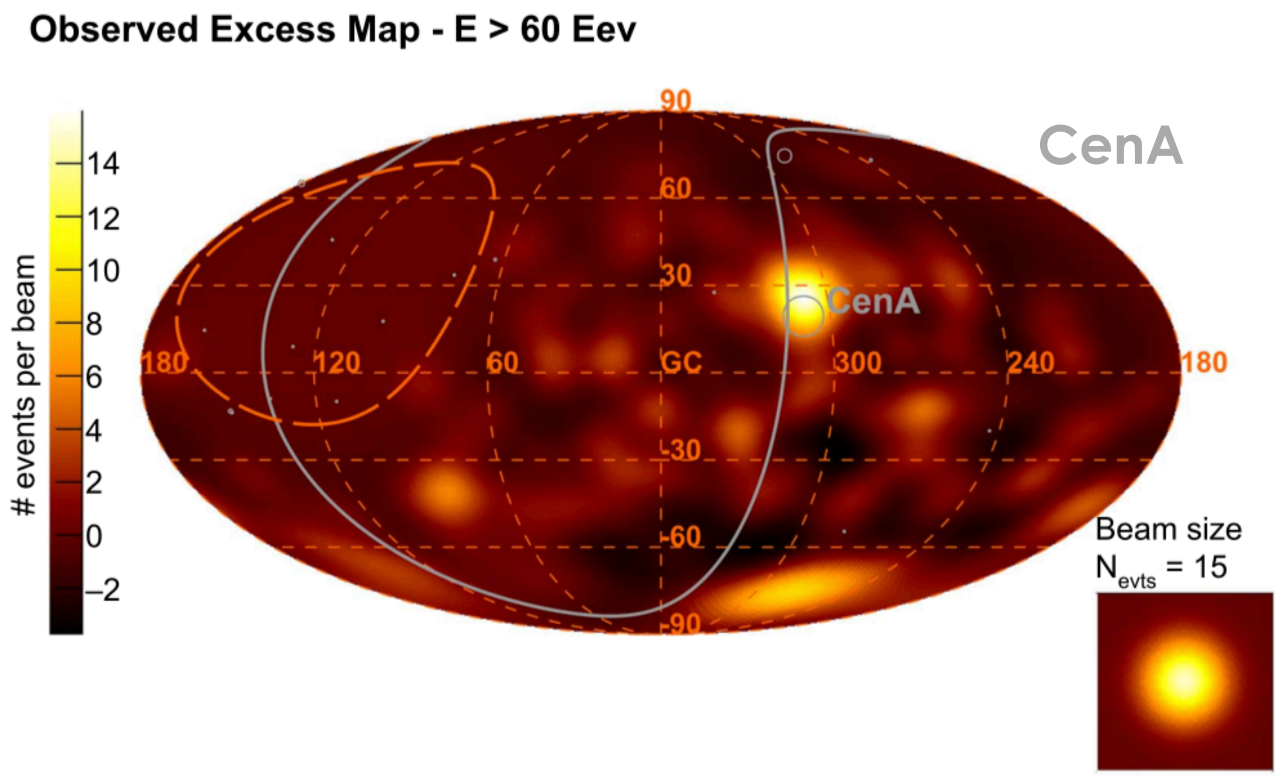
- Assumption: UHECR flux $\propto$ non-thermal photon flux
- Method: unbinned maximum likelihood analysis vs isotropy
  - Sky model: [**α** x sources + (1-**α**)x isotropic] with **α** fraction of UHECRs correlating with position and flux of sources

[The Pierre Auger Collaboration, ApJ. Lett. 853 (2018) L29]

Observed excess maps and results

Starburst galaxies | **γAGNs**





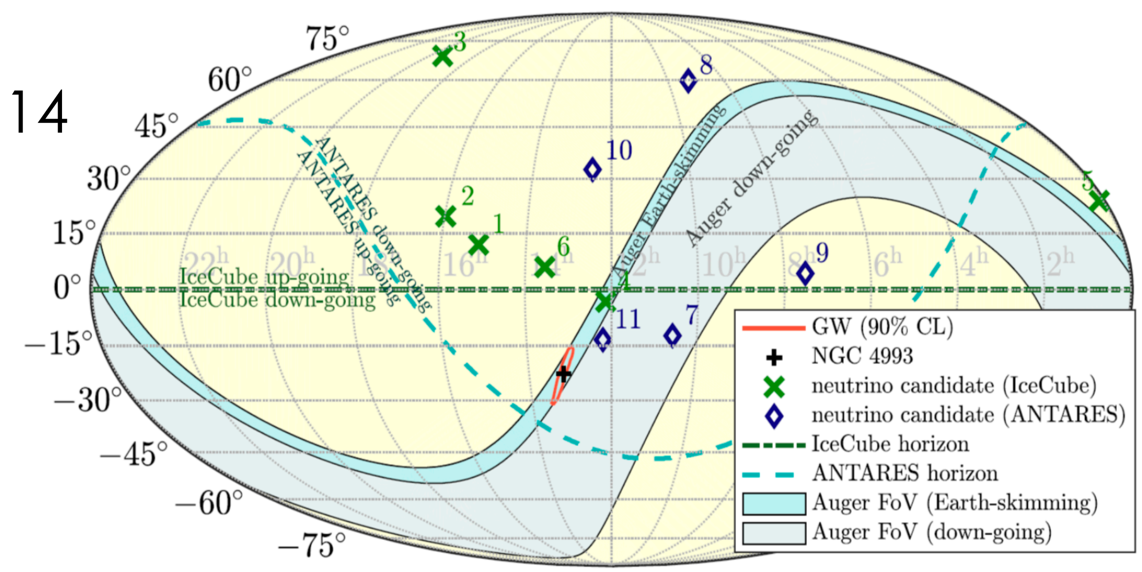
- **Starburst galaxies: Isotropy disfavored with 4σ** (E > 39 EeV - 7° window - 10% aniso. fraction)
- AGN: Isotropy disfavored with 2.7σ (E > 60 EeV - 13° window - 7% aniso. fraction)
- **Auger UHECR hotspot** in the direction of **CenA/M83/NGC 4945 group**

> Results indicate an excess of events from nearby **starburst galaxies**, but only preferred to other galaxies by ~3σ

[The Pierre Auger Collaboration, ApJ. Lett. 853 (2018) L29]

Auger in the multi-messenger era

- **The Auger Observatory** has good sensitivity to **UHE neutrinos** (> 100 PeV) and unrivalled sensitivity to transient sources if located in the right position in the sky.
  - **Searches for UHE neutrinos** in association with **gravitational wave events** detected by LIGO and Virgo
    - Search for neutrinos associated with GW150914 or GW151226 ⇒ **no candidates**
      [The Pierre Auger Collaboration, PRD 4, 1220087 (2016)]
    - ANTARES, IceCube and Auger search for neutrinos from the GW170817 binary neutron star merger ⇒ **no candidates**
      [The Pierre Auger Collaboration, ApJ. Lett. 850 (2017) L35]



  - Search in association with Blazar TXS 0506+056, candidate source for a IceCube neutrino
    [J. Alvarez-Muniz for the Auger Collab. UHECR 2018]

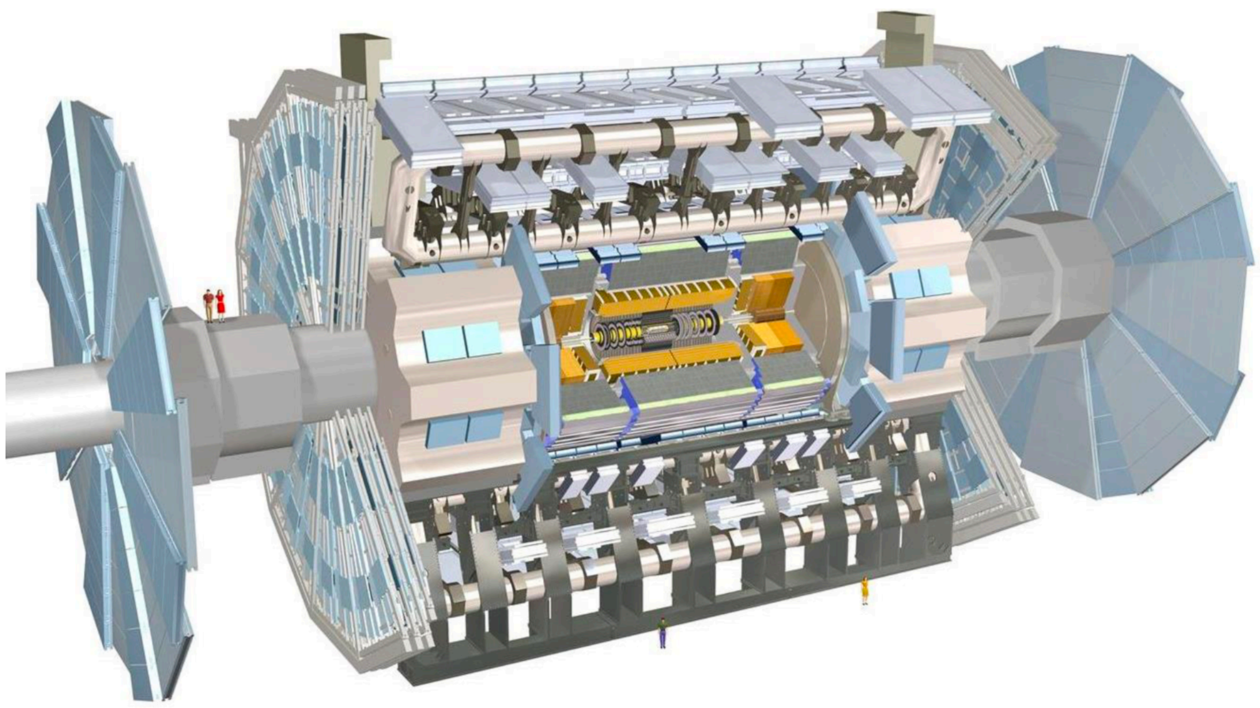
- Also unprecedented sensitivities to **UHE photons** (> 1 EeV)

- **Auger Observatory** is both triggering and a follow-up partner in the **Astrophysical Multi-messenger Observatory Network (AMON)**, which establish and distributes alerts for immediate follow-up by subscribed observatories of all messengers.

[The Pierre Auger Collaboration, Front. Astron. Space Sci. 6:34 (2019(]

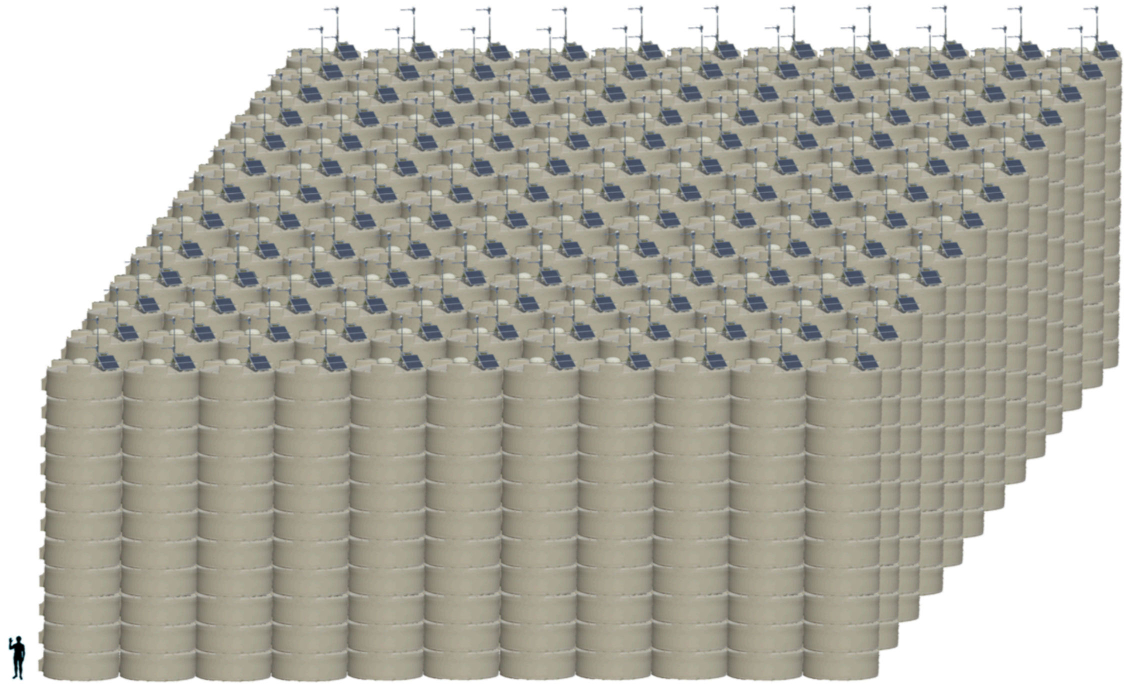
Particle physics at UHE

ATLAS@LHC



- E_{beam} = 6.5 TeV
- $\sqrt{s}$ = 13 TeV
- 7 kt detector

Pierre Auger Observatory*



- $E_{beam} > 1\times10^8$ TeV
- $\sqrt{s} > 400$ TeV**
- 20 kt water Cherenkov detector
- 25Gt air calorimeter

*to scale but stacked, actual area: 3000 km^2

** for p+air (> 60 TeV for Fe+air)

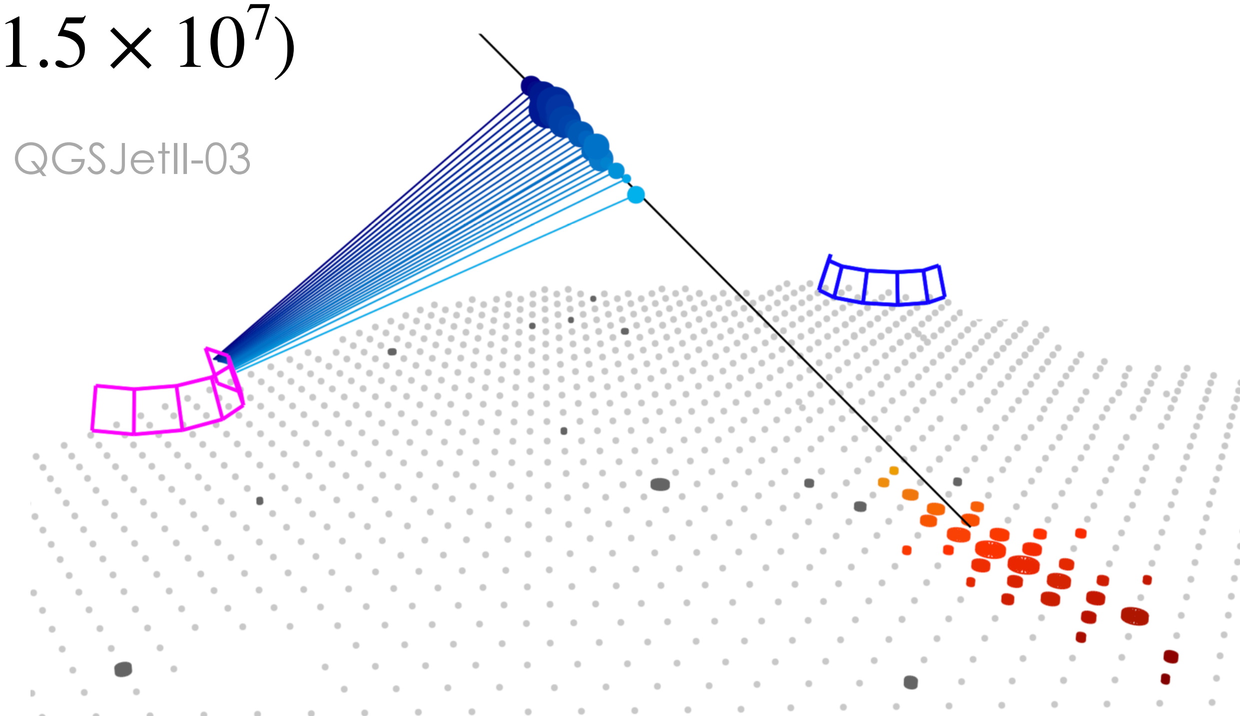
Slide from M. Unger (Auger collab.) ISAPP 2019

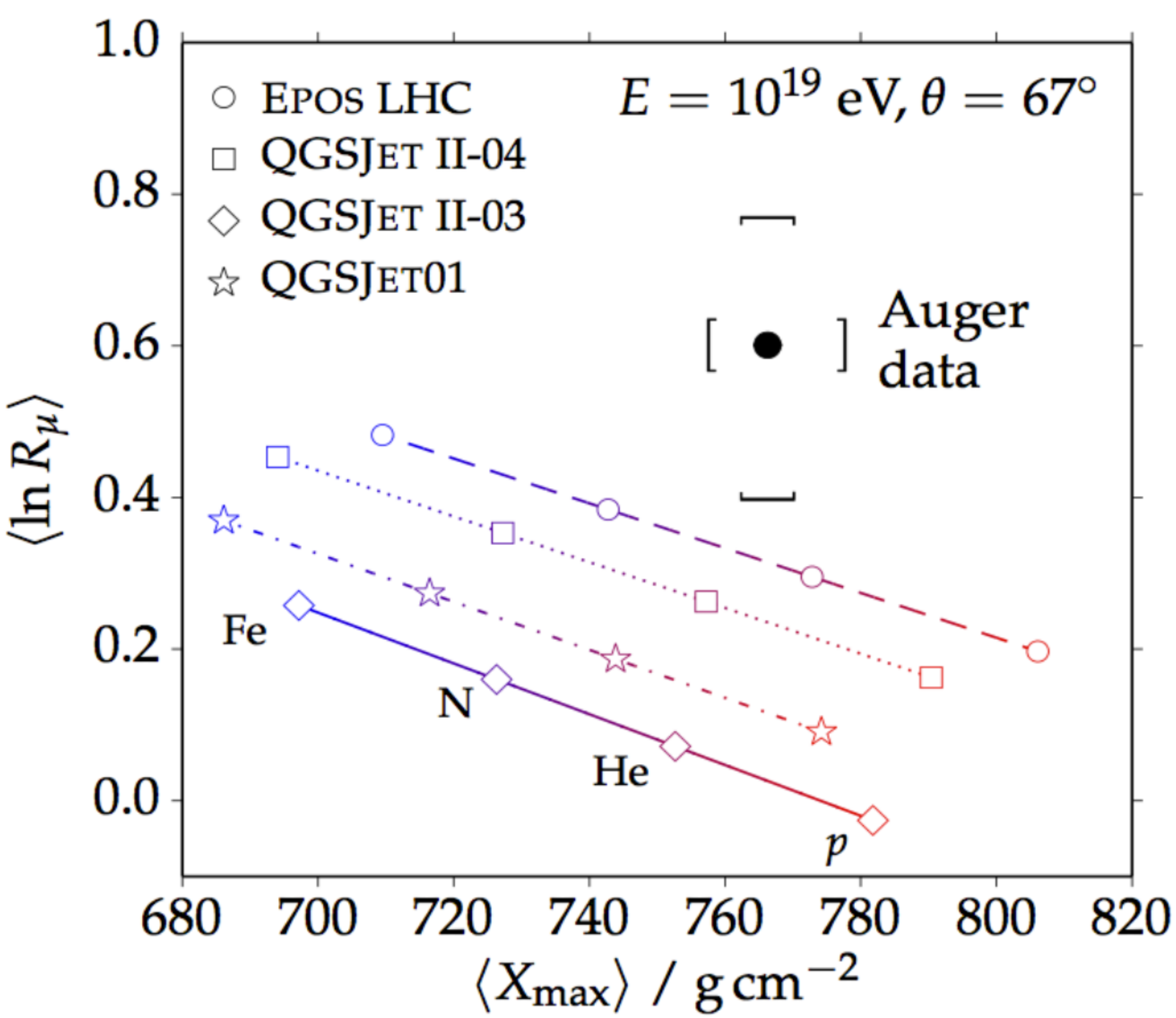
Muons in air showers:
testing hadronic interaction models

Estimation of muon content in air showers at ground level using **highly inclined events** (θ>62°) recorded by SD and FD:

$$R_\mu = N_\mu / N_{\mu,\mathrm{ref}} \sim N_\mu / (1.5 \times 10^7)$$

ref: p, E=10 EeV, QGSJetII-03



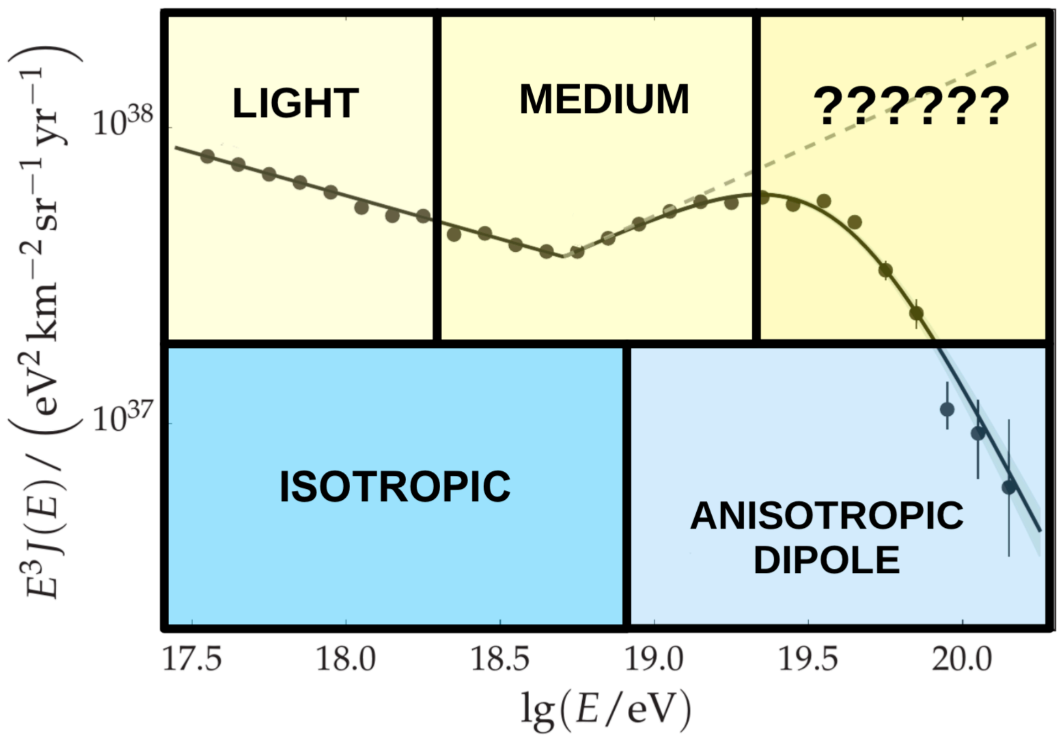


- At 10 EeV **models underestimate muon content** by 30-80% for <lnA> from X_{max}
- Muon deficit increases with energy

[The Pierre Auger Collaboration, PRD D91 (2015) 3, 032003]

AugerPrime: stepping up to the new challenges

- **Complex and unexpected picture of UHECR** emerging from the data



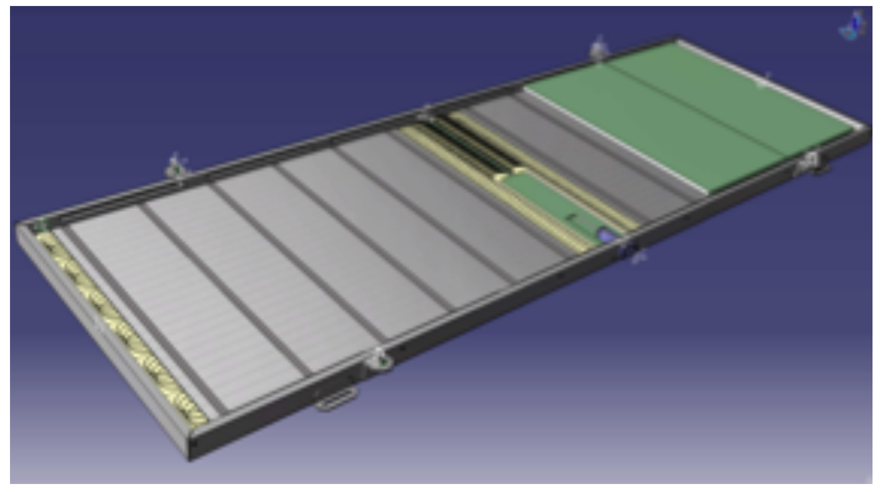
- Which is the **origin** of the **flux suppression**?
- $\langle X_{max} \rangle$ data suggest a gradual heavier **composition** towards highest energies, but detailed **interpretation limited** by uncertainties in **hadronic interaction models**.
- Fractions of **protons, neutrinos** and **photons** at highest energies?
- Large-scale anisotropies seen, but no point sources yet ⇒ **Composition-enhanced anisotropy studies**
- **Particle physics** at energies well beyond the LHC

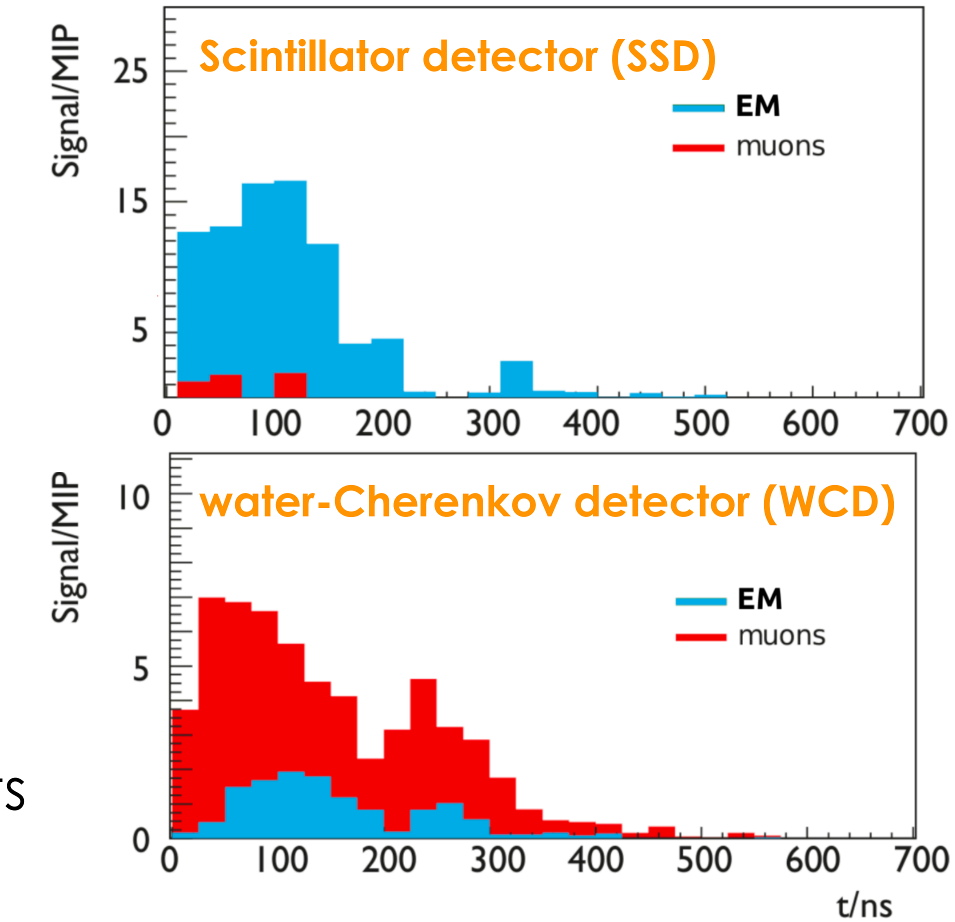
- **Open questions** cannot be answered with only more statistics
  - An upgraded detector that improves characterization of the muonic and EM shower components to increase the composition sensitivity, with a duty cycle of ~100%

  ⇒ **AugerPrime**

AugerPrime: upgrades

- An **3.8m² scintillator counter** on top of each water-Cherenkov detector



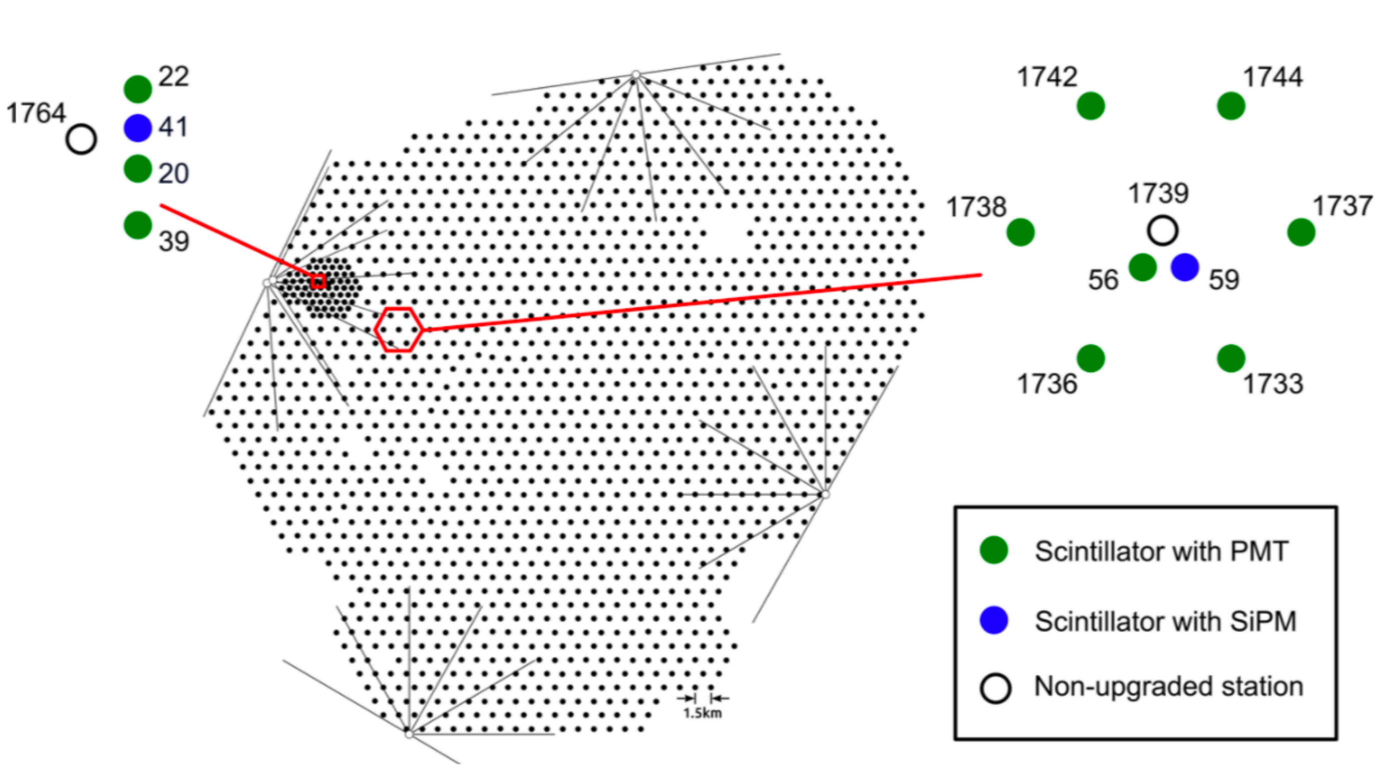


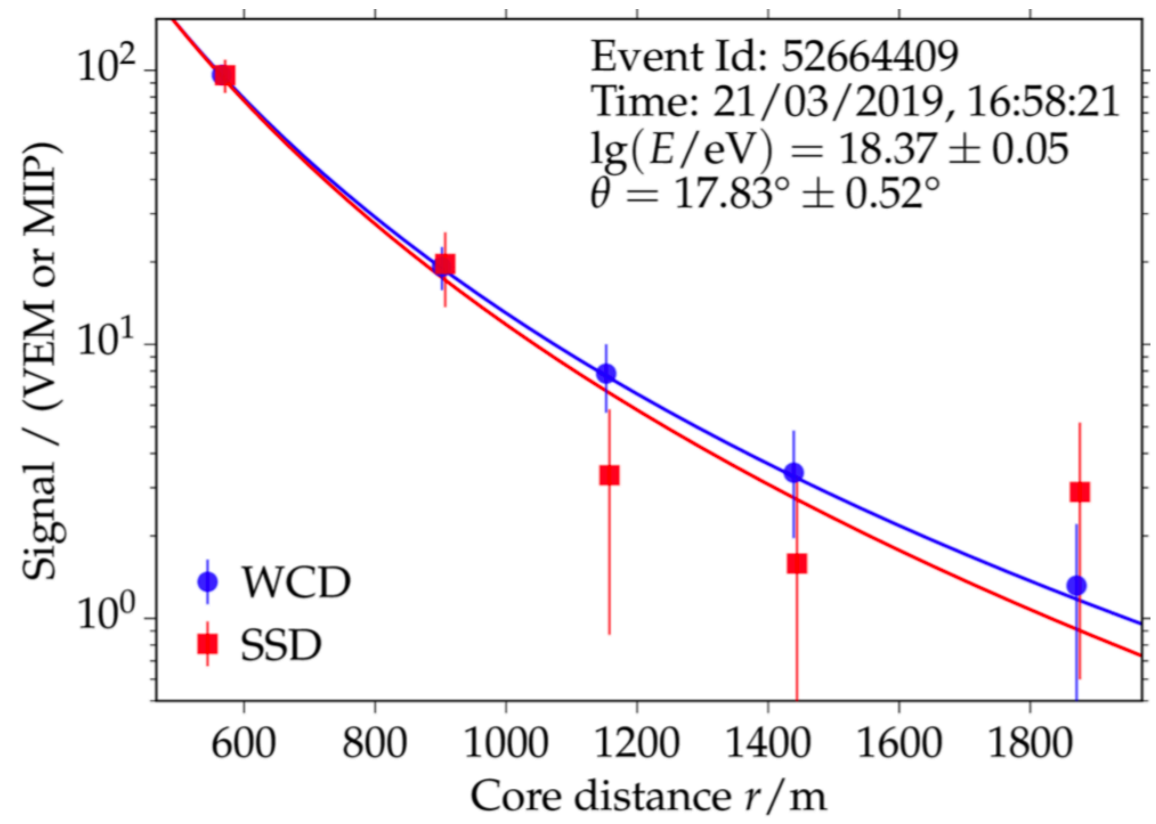
  - Exploit the difference response of the two detectors to the electromagnetic and muonic showers components

- **Additional (small) PMT to increase dynamic range**
- **Improved (faster) electronics** (from 40 to 120 MHz ADC, better GPS timing)
- Extension of the **FD duty cycle** by 50%
- **Buried muon counters** in the SD-750 m array for cross-checks (AMIGA)
- **Radio** upgrade: a radio antenna on top of each water-Cherenkov

[The Pierre Auger Observatory Upgrade: AugerPrime. Preliminary Design Report, arXiv:1604.03637

AugerPrime: pre-production array





- September 2016: deployment of an **SSD Engineering Array** (12 stations)
  - Since then data taking and first data analysis
- 2018: **design finalized and tested**, large-scale production of SSDs started
  - Deployment of the SSDs (5-10 per day) in the full SD array in 2018-2019
- **Data taking at least until 2025**
  - exposure ~ 40,000 km^2 sr yr

Summary

- The **Pierre Auger Observatory** has been successfully taking data since **more than 15 years**.

- **Key results:**
  - ☑ Precise measurement of the energy spectrum above $3x10^{17}$eV: **flux suppression above 40 EeV firmly established**
  - ☑ Measurements of X_{max} over 3 orders of magnitude in energy: **evidence for a mixed composition around the ankle**
  - ☑ Observation of a **dipole structure** above 8 EeV that strongly indicates an **extragalactic origin of the UHECRs.**
  - ☑ Intriguing **correlations with starburst galaxies above 39 EeV**
  - ☑ Highest-energy physics: **inconsistency in muon data**

- **Exciting years ahead:**
  - **AugerPrime has been started** to unveil the new questions about UHECRs
  - **New era of multi messenger astrophysics**

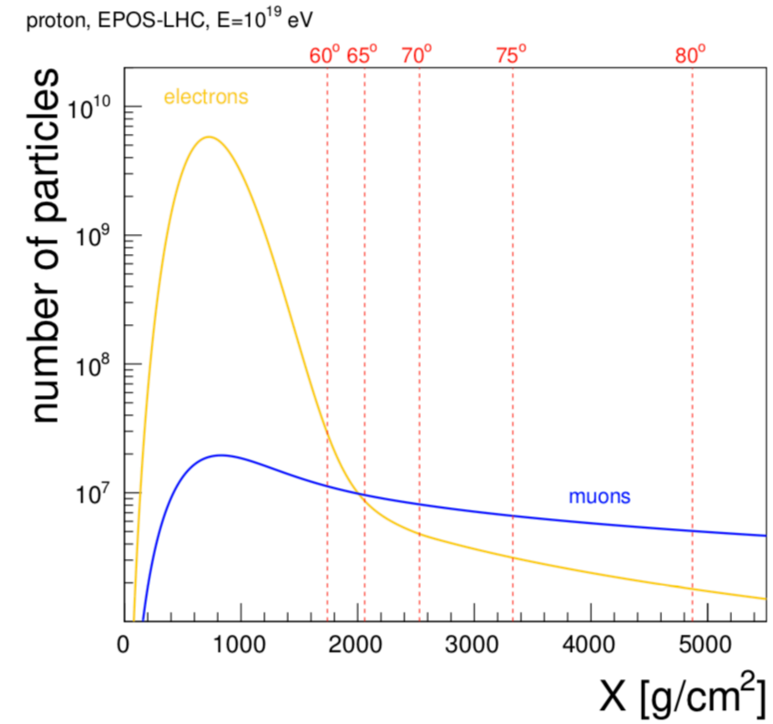
Thank you for your attention!

Image: S. Saffi

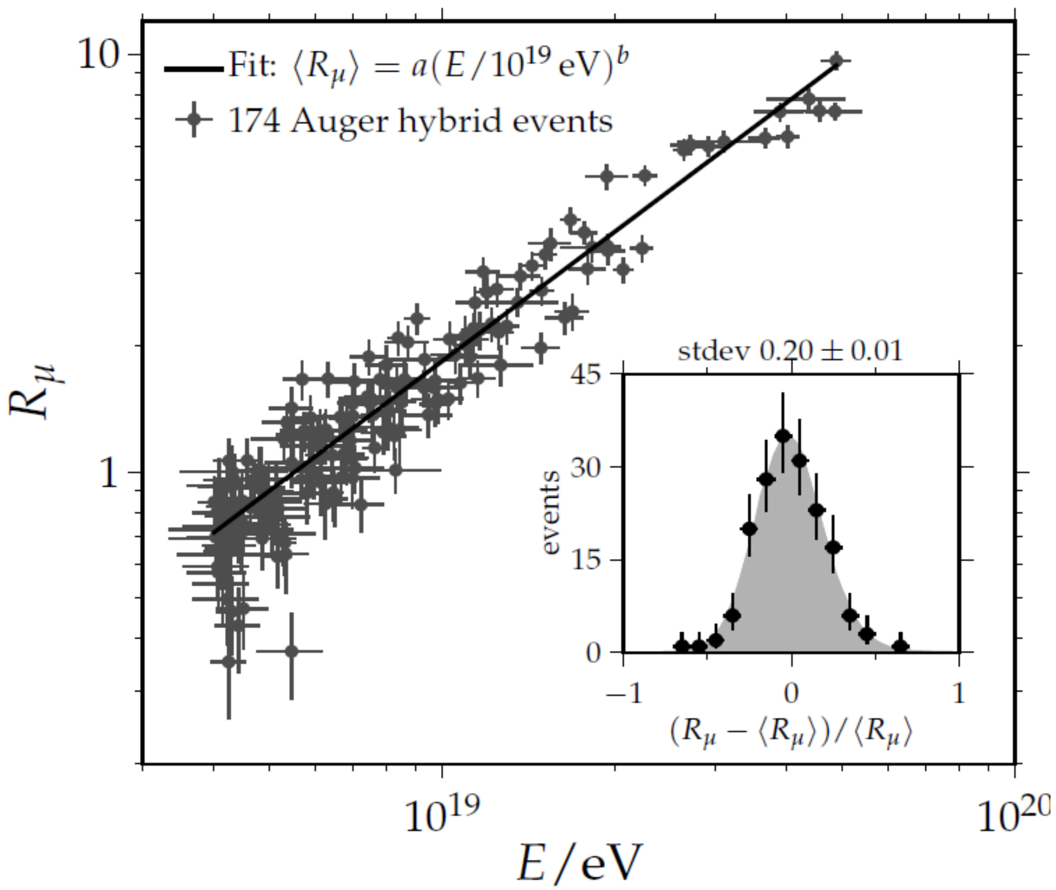
Backup

Hadronic interactions at UHE: Muons in air showers

Number of muons in an air shower: $N_\mu = A\left(\frac{E/A}{\xi_c}\right)^{\beta\approx 0.9 \text{ (from models)}}$ **sensitive to hadronic interaction properties**



Estimation of muon content in air showers at ground level using **highly inclined events** (θ > 62°) recorded by SD and FD



- The muon number derived by scaling a simulated reference profile of the lateral muon density distribution that fits the data:

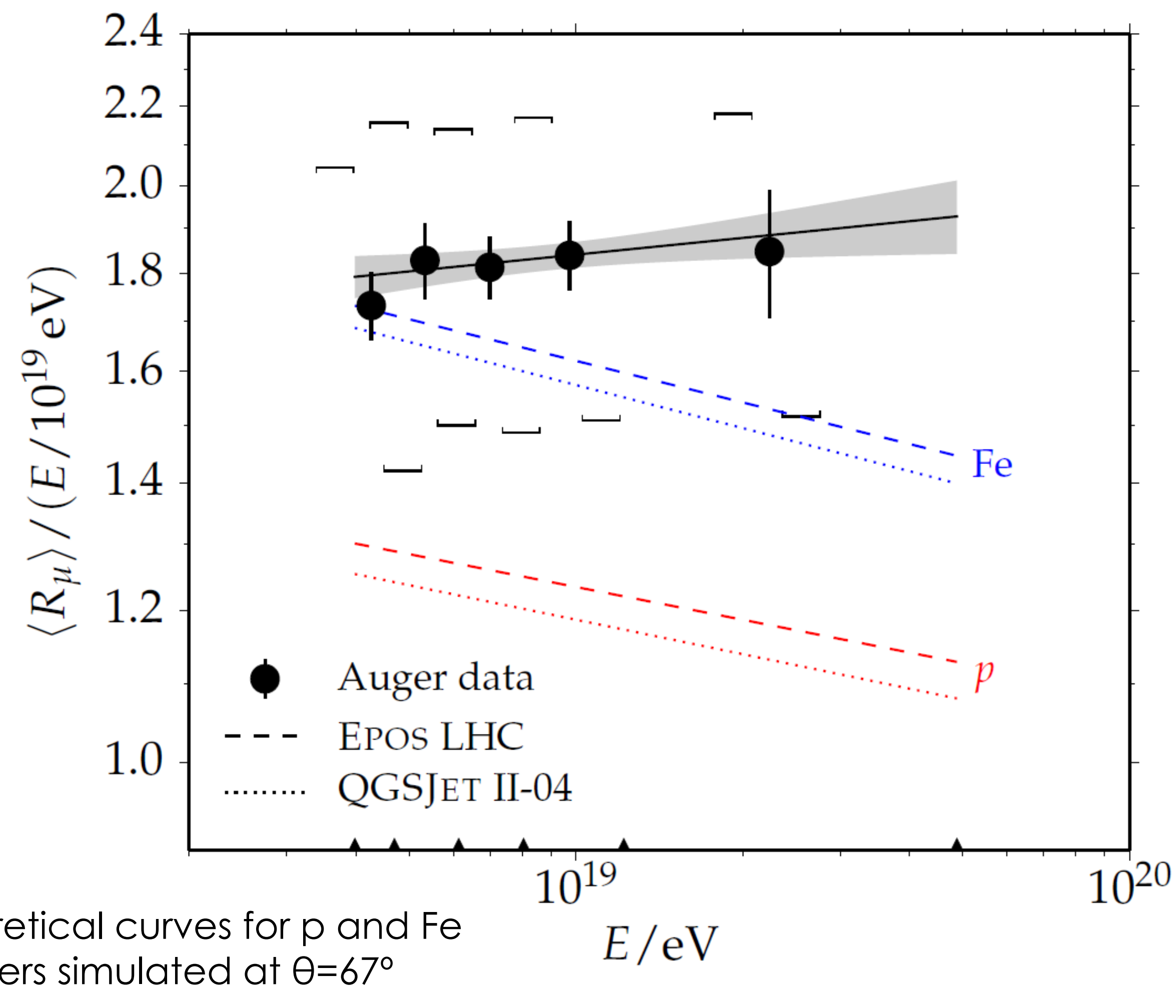
$\rho_{\mu,\text{data}} = N_{19} \times \rho_{\mu,\text{ref}} \Rightarrow$ $R_\mu = N_\mu / N_{\mu,\text{ref}}$

ref: p, E=10 EeV, QGSJetII-03;

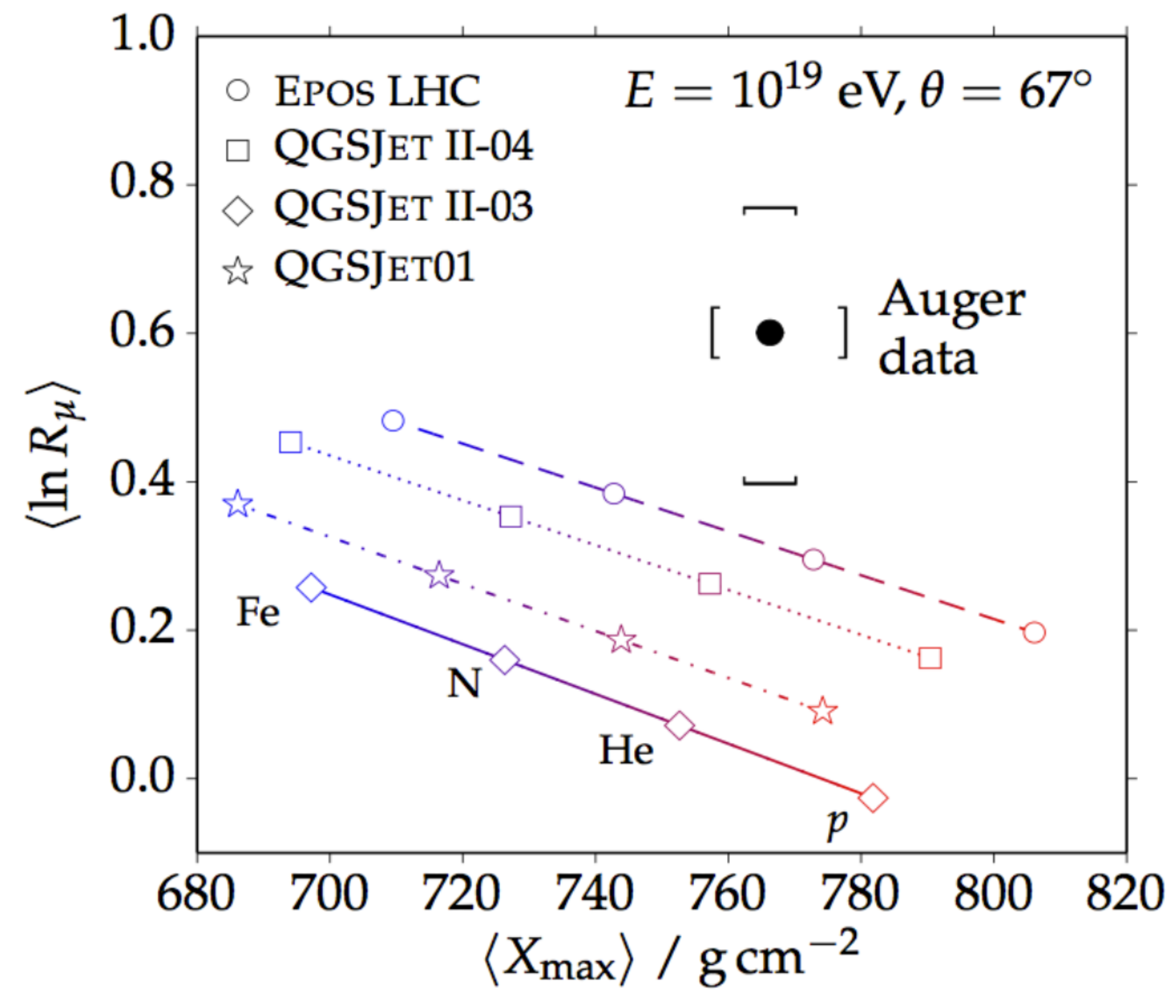
At θ=67°:

$N_{\mu,\text{ref}} = 1.5 \times 10^7$ muons with $E_\mu > 0.3$ GeV

Muon content in data vs model predictions



Theoretical curves for p and Fe showers simulated at θ=67°

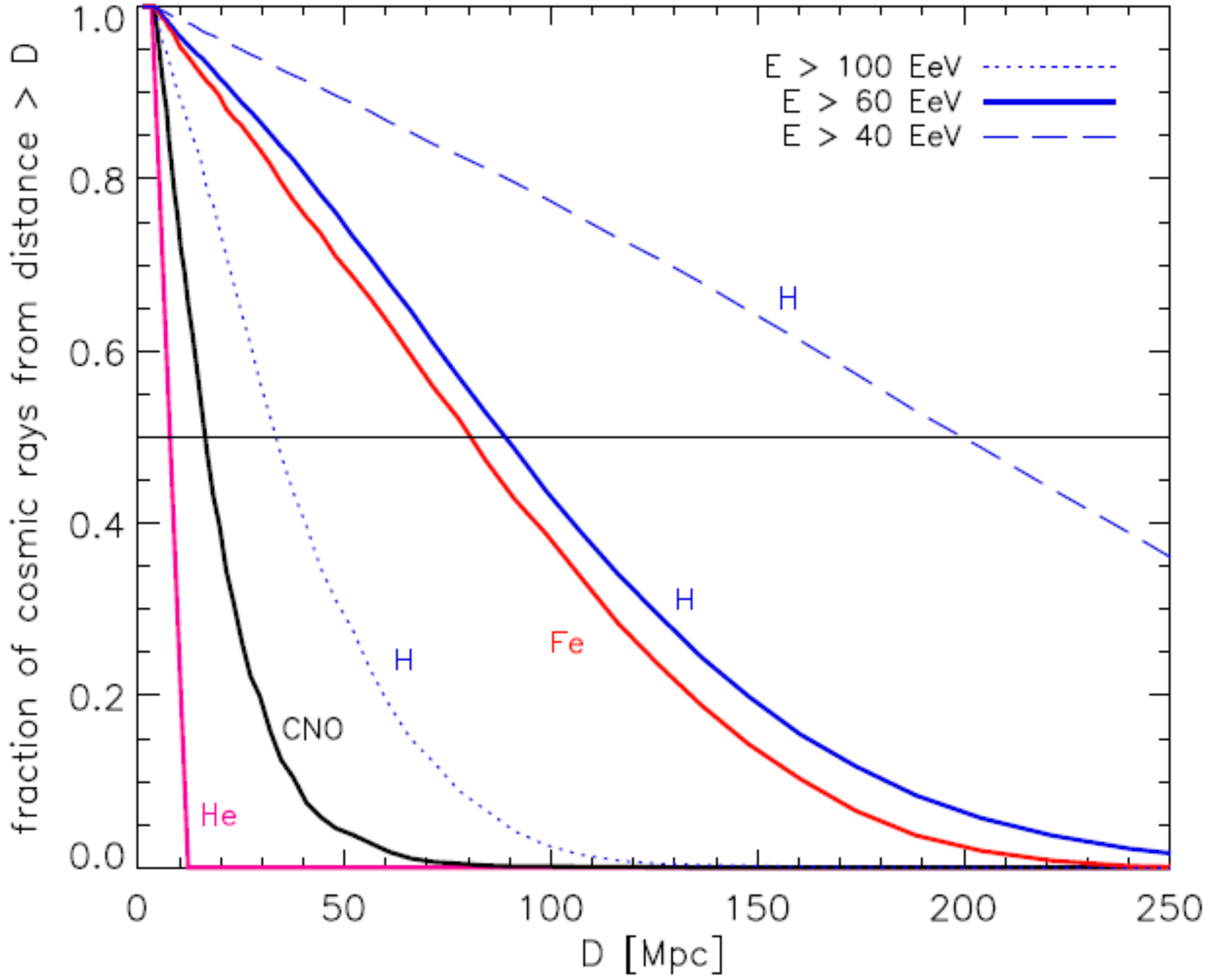


- At 10 EeV **models underestimate muon content** by 30-80% for <lnA> from X_{max}
- Increasing deficit with increasing energy

* √s ≈ 135 TeV in p+p collisions

[The Pierre Auger Collaboration, PRD D91 (2015) 3, 032003]

GZK horizons (uniform source distribution)



[Kotera, K., & Olinto, A. 2011, Ann .Rev. Astron. Astrophys., 49, 119]

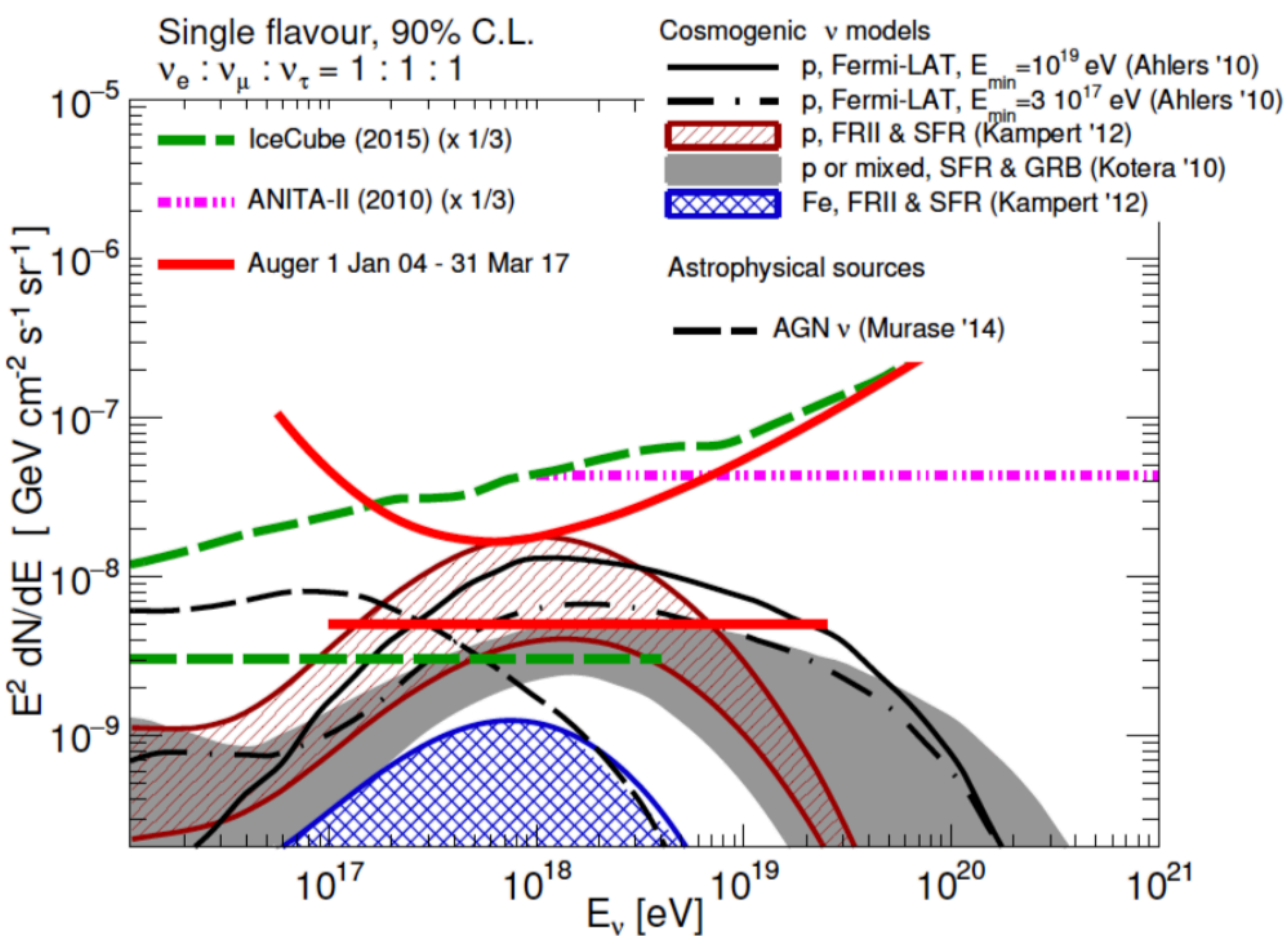
Populations investigated for Intermediate-scale Anisotropies

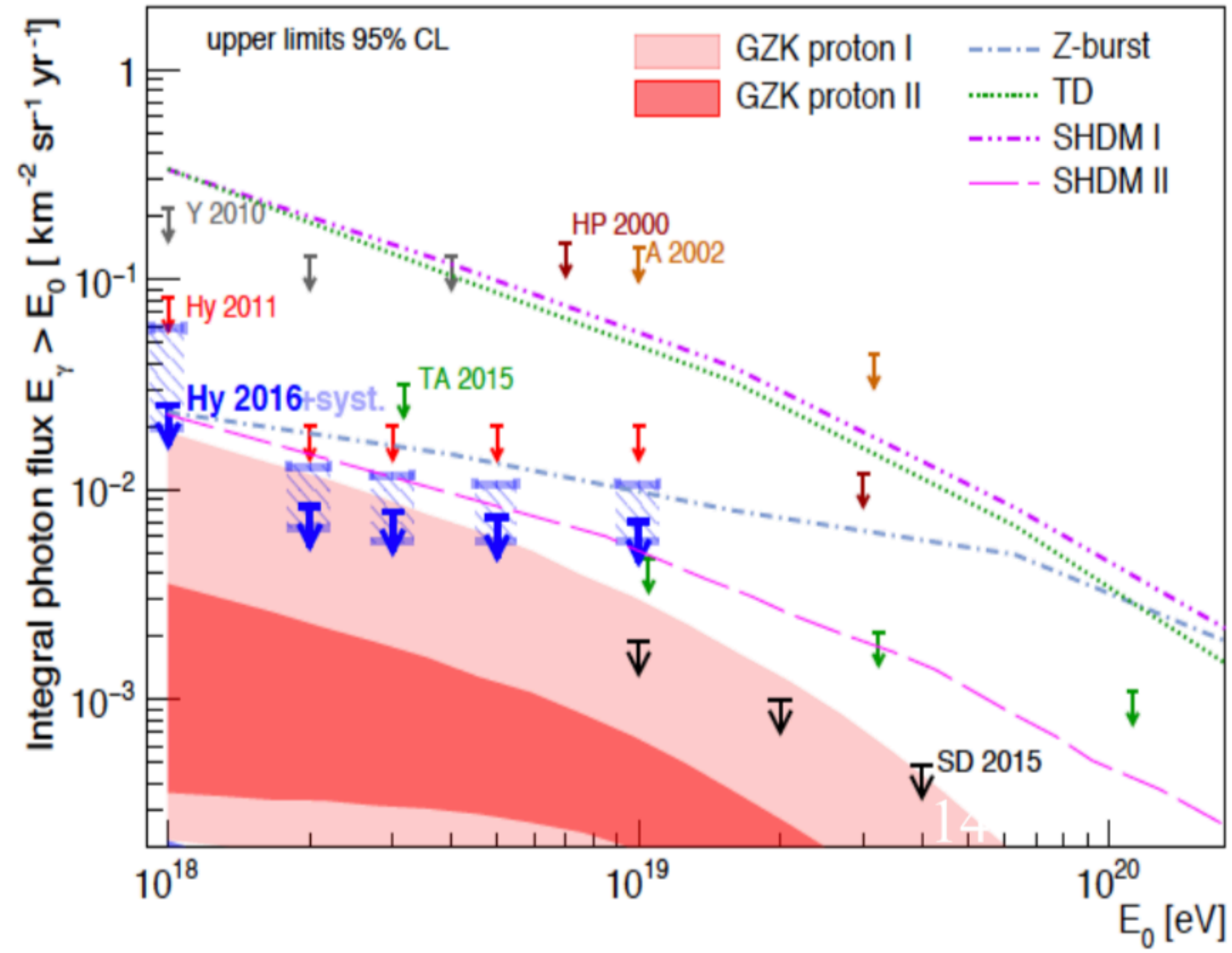
Table 1
Populations Investigated

SBGs	l (°)	b (°)	Distance[a] (Mpc)	Flux Weight (%)	Attenuated Weight: A/B/C (%)	% Contribution[b]: A/B/C (%)
NGC 253	97.4	−88	2.7	13.6	20.7/18.0/16.6	35.9/32.2/30.2
M82	141.4	40.6	3.6	18.6	24.0/22.3/21.4	0.2/0.1/0.1
NGC 4945	305.3	13.3	4	16	19.2/18.3/17.9	39.0/38.4/38.3
M83	314.6	32	4	6.3	7.6/7.2/7.1	13.1/12.9/12.9
IC 342	138.2	10.6	4	5.5	6.6/6.3/6.1	0.1/0.0/0.0
NGC 6946	95.7	11.7	5.9	3.4	3.2/3.3/3.5	0.1/0.1/0.1
NGC 2903	208.7	44.5	6.6	1.1	0.9/1.0/1.1	0.6/0.7/0.7
NGC 5055	106	74.3	7.8	0.9	0.7/0.8/0.9	0.2/0.2/0.2
NGC 3628	240.9	64.8	8.1	1.3	1.0/1.1/1.2	0.8/0.9/1.1
NGC 3627	242	64.4	8.1	1.1	0.8/0.9/1.1	0.7/0.8/0.9
NGC 4631	142.8	84.2	8.7	2.9	2.1/2.4/2.7	0.8/0.9/1.1
M51	104.9	68.6	10.3	3.6	2.3/2.8/3.3	0.3/0.4/0.5
NGC 891	140.4	−17.4	11	1.7	1.1/1.3/1.5	0.2/0.3/0.3
NGC 3556	148.3	56.3	11.4	0.7	0.4/0.6/0.6	0.0/0.0/0.0
NGC 660	141.6	−47.4	15	0.9	0.5/0.6/0.8	0.4/0.5/0.6
NGC 2146	135.7	24.9	16.3	2.6	1.3/1.7/2.0	0.0/0.0/0.0
NGC 3079	157.8	48.4	17.4	2.1	1.0/1.4/1.5	0.1/0.1/0.1
NGC 1068	172.1	−51.9	17.9	12.1	5.6/7.9/9.0	6.4/9.4/10.9
NGC 1365	238	−54.6	22.3	1.3	0.5/0.8/0.8	0.9/1.5/1.6
Arp 299	141.9	55.4	46	1.6	0.4/0.7/0.6	0.0/0.0/0.0
Arp 220	36.6	53	80	0.8	0.1/0.3/0.2	0.0/0.2/0.1
NGC 6240	20.7	27.3	105	1	0.1/0.3/0.1	0.1/0.3/0.1
Mkn 231	121.6	60.2	183	0.8	0.0/0.1/0.0	0.0/0.0/0.0
γAGNs						
Cen A Core	309.6	19.4	3.7	0.8	60.5/14.6/40.4	86.8/56.3/71.5
M87	283.7	74.5	18.5	1	15.3/7.1/29.5	9.7/12.1/23.1
NGC 1275	150.6	−13.3	76	2.2	6.6/6.1/7.5	0.7/1.6/1.0
IC 310	150.2	−13.7	83	1	2.3/2.4/2.6	0.3/0.6/0.3
3C 264	235.8	73	95	0.5	0.8/1.0/0.8	0.4/1.3/0.5
TXS 0149 + 710	127.9	9	96	0.5	0.7/0.9/0.7	0.0/0.0/0.0
Mkn 421	179.8	65	136	54	11.4/48.3/14.7	1.8/19.1/2.8
PKS 0229-581	280.2	−54.6	140	0.5	0.1/0.5/0.1	0.2/2.0/0.3
Mkn 501	63.6	38.9	148	20.8	2.3/15.0/3.6	0.3/5.2/0.6
1ES 2344 + 514	112.9	−9.9	195	3.3	0.0/1.0/0.1	0.0/0.0/0.0
Mkn 180	131.9	45.6	199	1.9	0.0/0.5/0.0	0.0/0.0/0.0
1ES 1959 + 650	98	17.7	209	6.8	0.0/1.7/0.1	0.0/0.0/0.0
AP Librae	340.7	27.6	213	1.7	0.0/0.4/0.0	0.0/1.3/0.0
TXS 0210 + 515	135.8	−9	218	0.9	0.0/0.2/0.0	0.0/0.0/0.0
GB6 J0601 + 5315	160	14.6	232	0.4	0.0/0.1/0.0	0.0/0.0/0.0
PKS 0625-35	243.4	−20	245	1.3	0.0/0.1/0.0	0.0/0.5/0.0
I Zw 187	77.1	33.5	247	2.3	0.0/0.2/0.0	0.0/0.0/0.0

Notes.
[a] A standard, flat ΛCDM model ($h_0 = 0.7$, $\Omega_M = 0.3$) is assumed. The distances of the SBGs are based on Ackermann et al. (2012), accounting for a small difference in h_0. The distances of the γAGNs are based on their redshifts, except for the nearby Cen A (Tully et al. 2013).
[b] % contributions account for the directional exposure of the array.

Neutrinos and Photons at Auger





- Auger limit constrains cosmogenic neutrino models with proton primaries & strong evolution of sources with redshift
- Not yet constrain models with heavier primaries

[E. Zas for the Pierre Auger Collab., Proc. 35th ICRC (2017)]

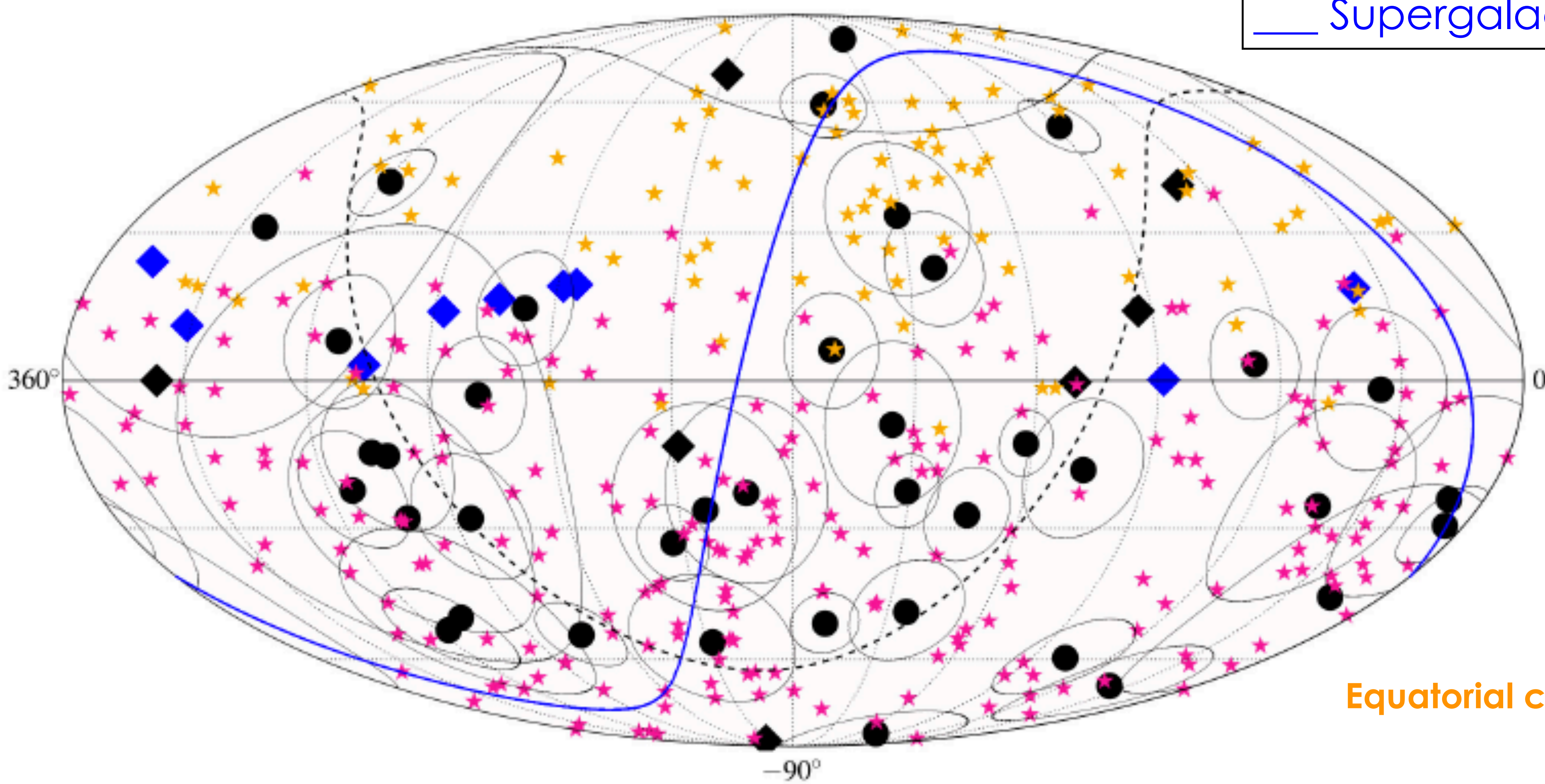
- Top-down models strongly disfavored

[M. Niechciol for the Pierre Auger Collab., Proc. 35th ICRC (2017)]

Correlation between Auger + Telescope Array UHECRs & IceCube ν

Three analyses to investigate correlations between 318 UHECRs in Auger + Telescope Array with samples of IceCube neutrino events.

★ Auger UHECRs
★ TA UHECRs
◆ IceCube HESE tracks
◆ IceCube tracks
• IceCube cascades
---- Galactic plane
___ Supergalactic Plane

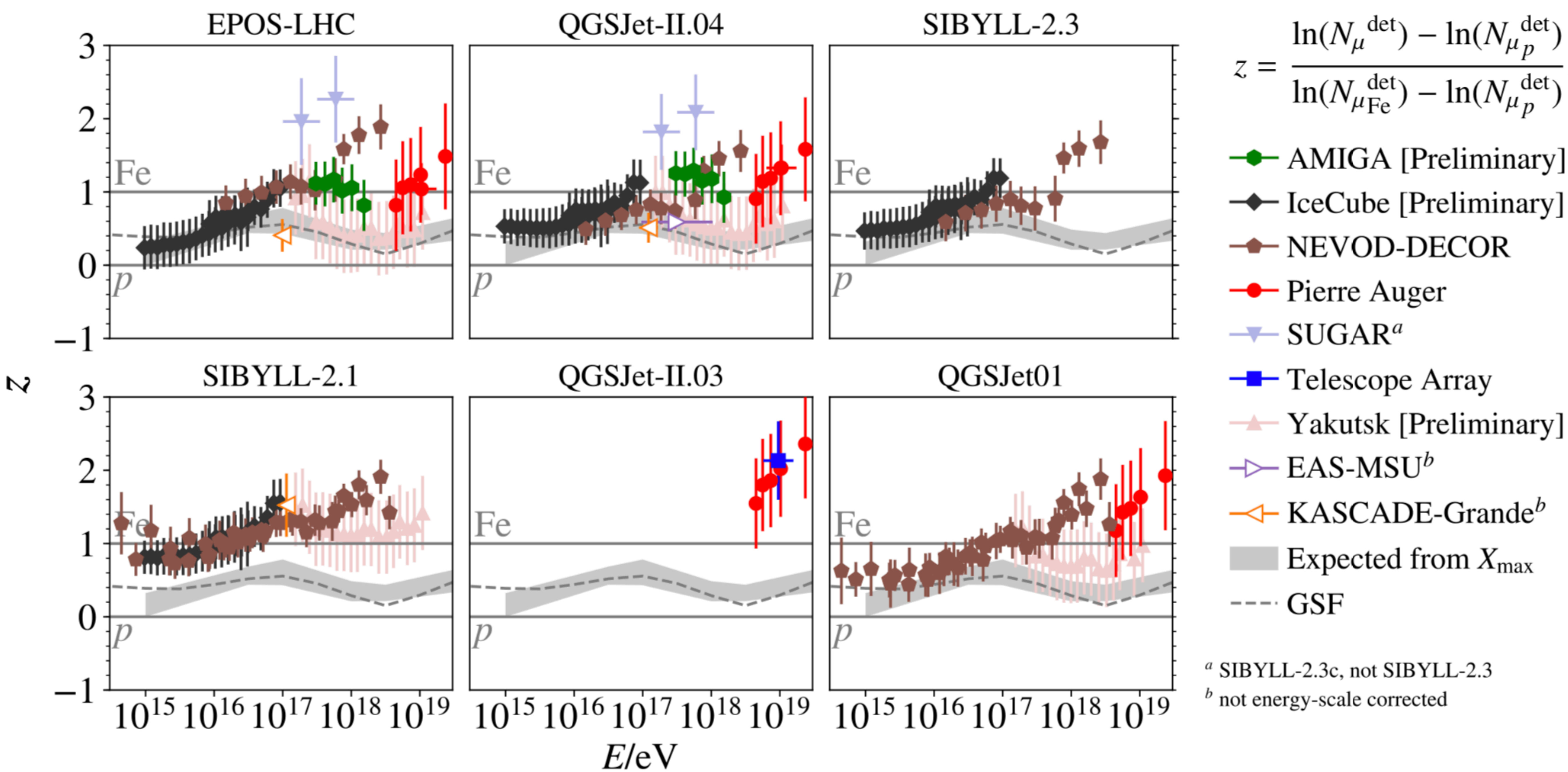


Equatorial coordinates

- **No indications of correlations above 3.3 σ**

[IceCube, Auger, Telescope Array JCAP **01** (2016) 37]

Combined experimental muon measurements

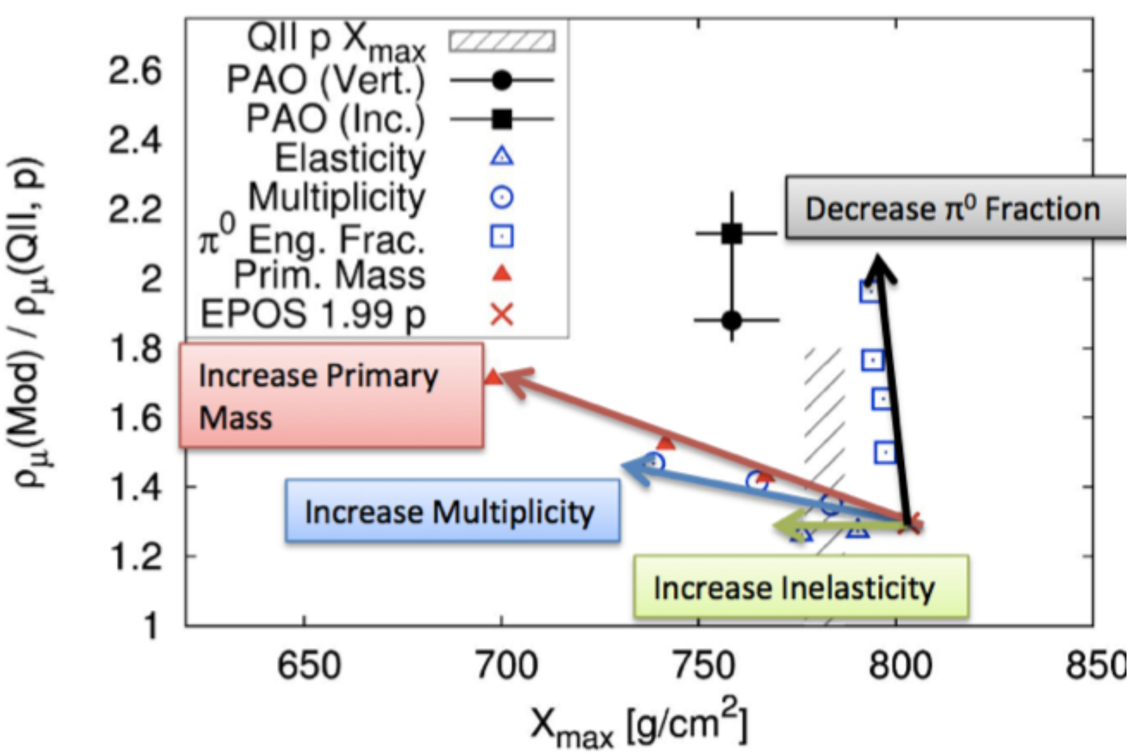


- **Most experiments show a muon excess in the data to the MC at E > 10^{16} eV**
- **Discrepancy increases with E,** and slope shows **8σ** for latest-generation models

[H. Dembinski et al for EAS-MSU, IceCube. KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array and Yakust EAS Array collaborations, Proc. UHECR 2018 arXiv: 1902.08124]

Correlations between X_{max} and muon density

J. Allen & G. Farrar., Proc. 33rd ICRC (2013) arXiv: 1307.7131]]



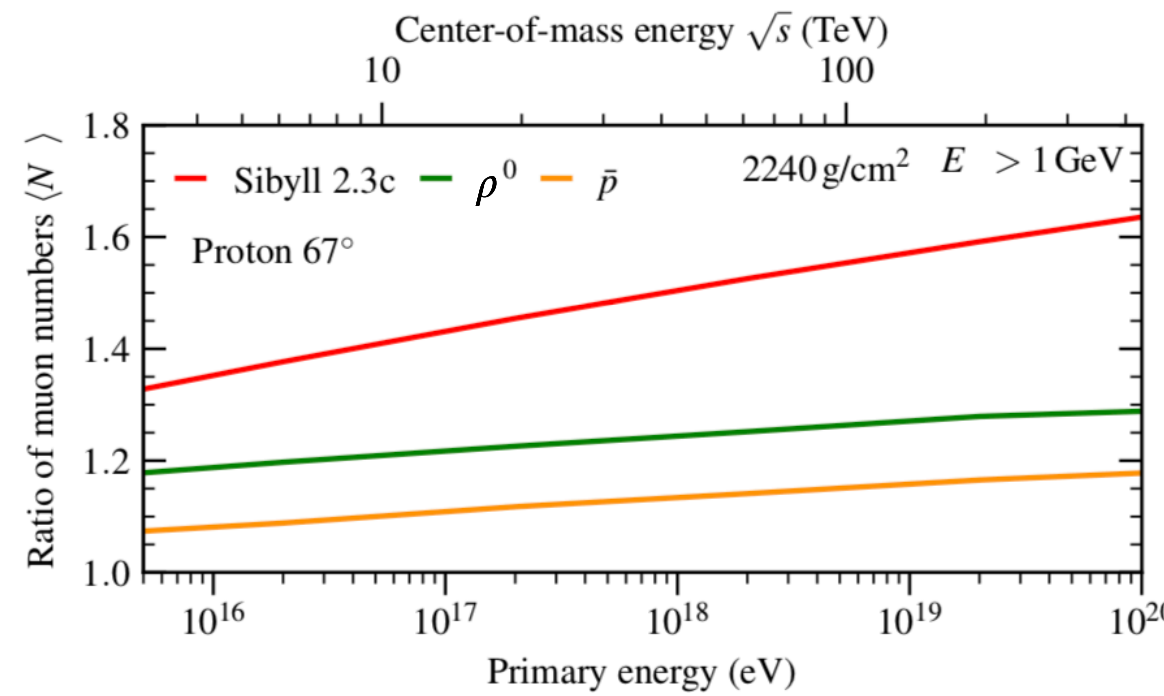
Modifications to models need to match the data on muons and maximum production depths for EM and μ components.

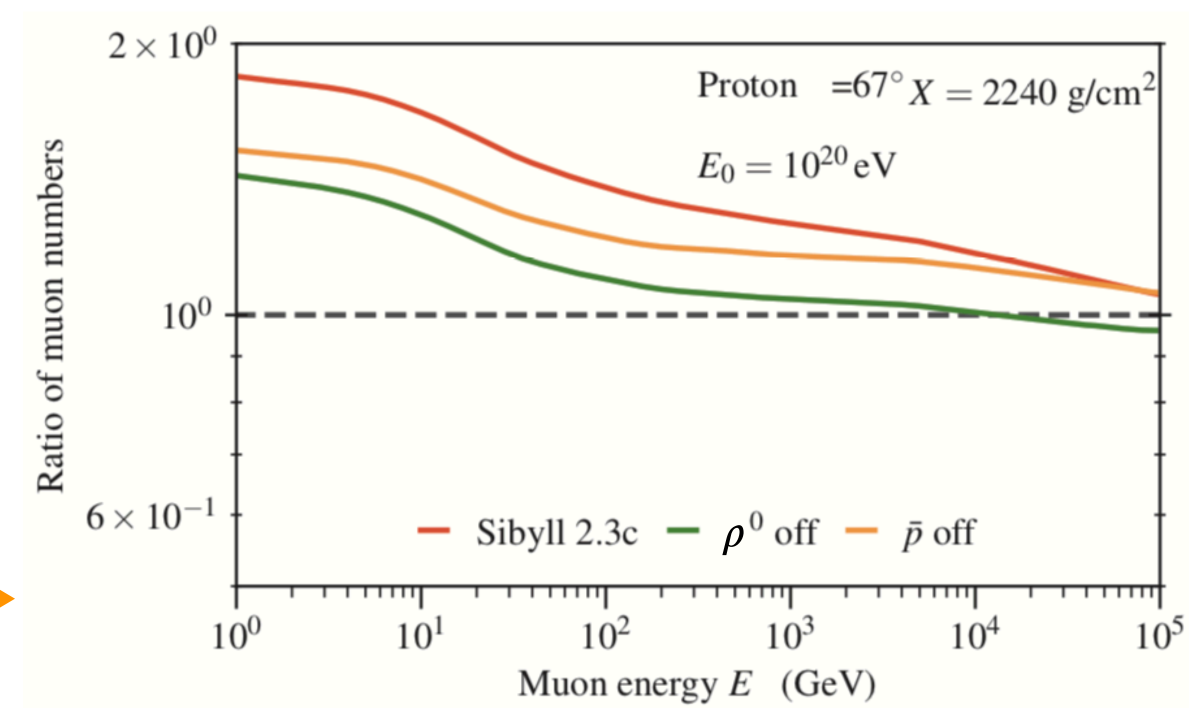
Mechanisms of muon production that do not modify X_{max}:

- Leading ρ^0 production
- Baryon-antibaryon pair production

Discussion of the mechanisms of muon production in EAS with Sybill 2.3c

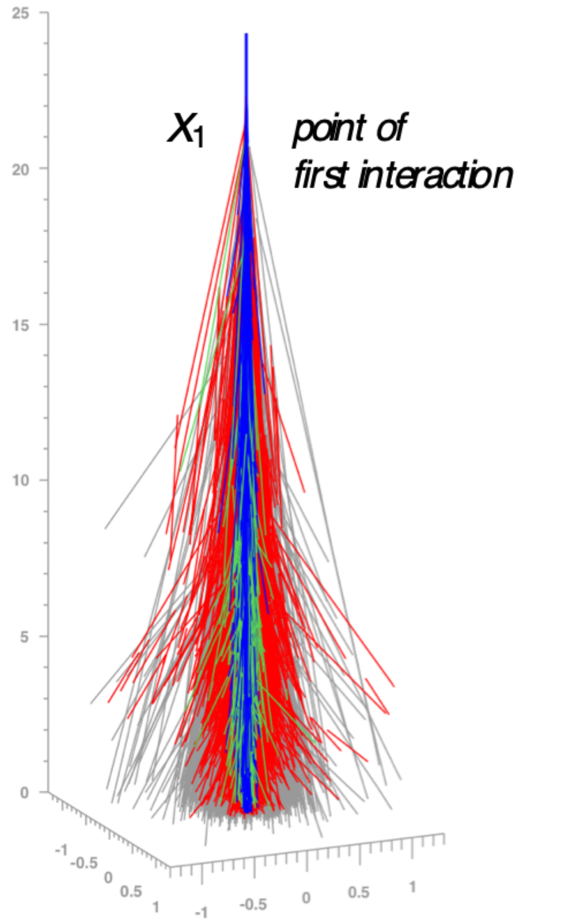
Relative to Sibyll 2.1, and switching off the mechanisms:

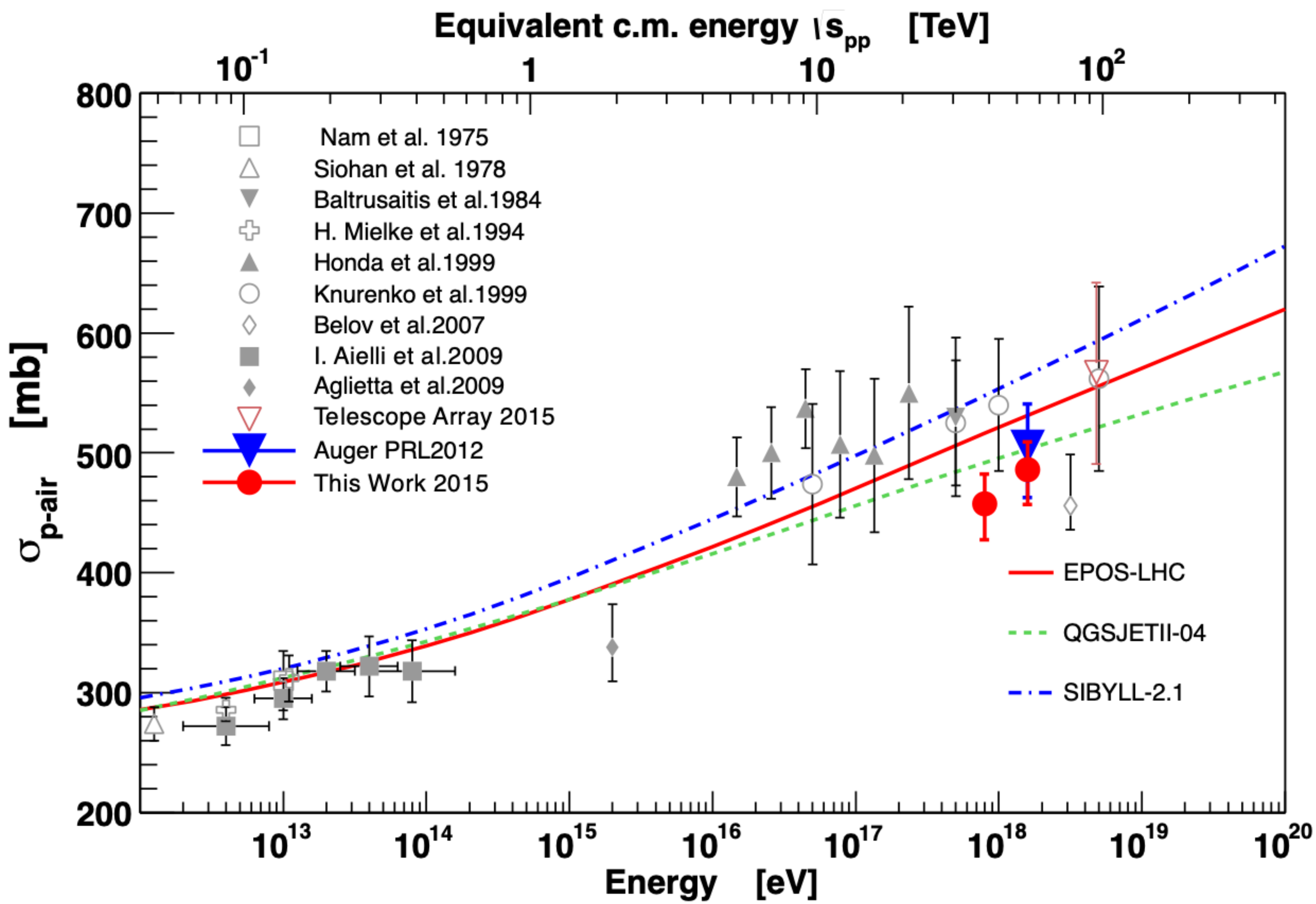




F. Riehn et at, Proc. ISVHECRI 2018, EPJ Web of Conferences 208, 11002 (2019)]

p-air cross section from Auger data





$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

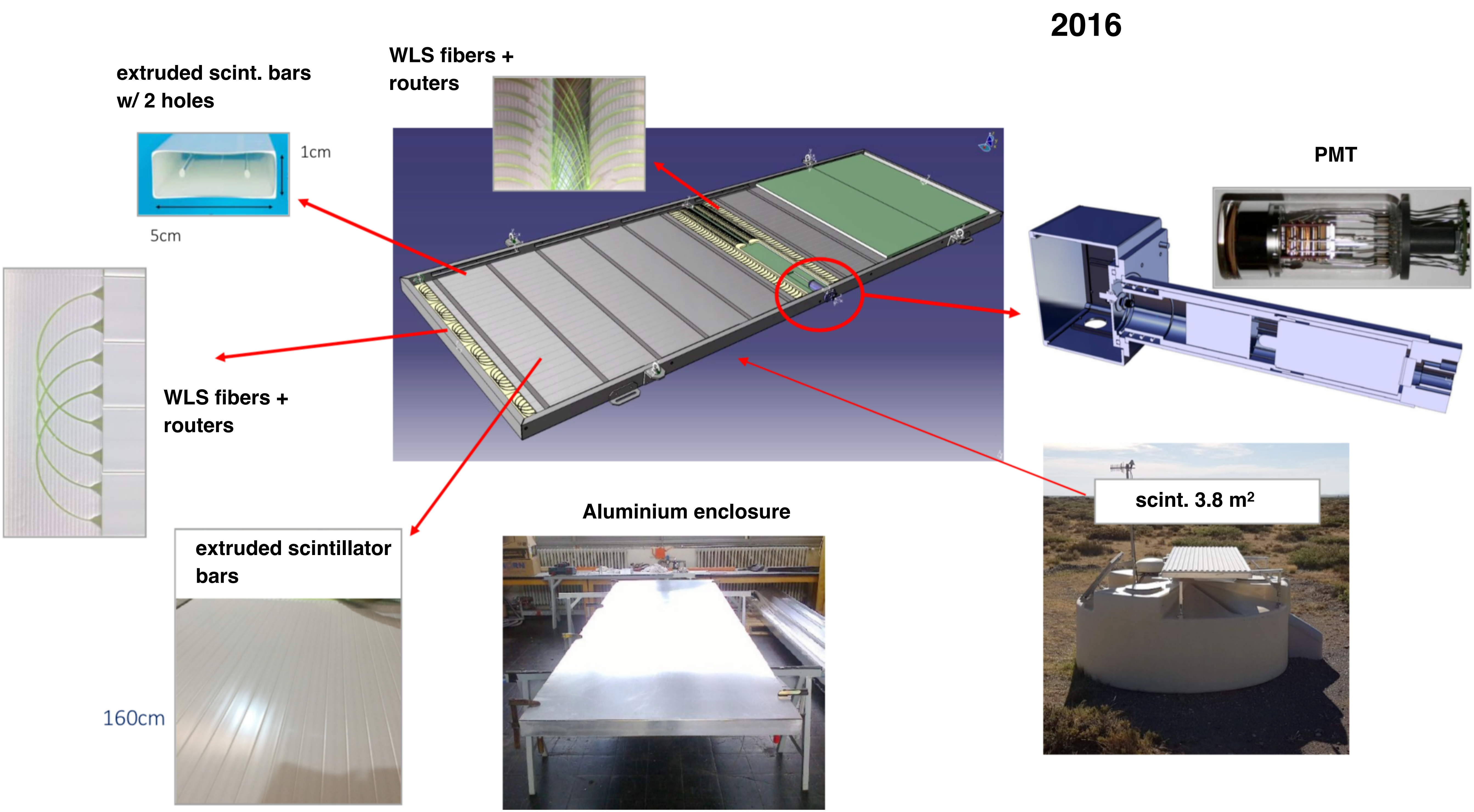
$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{int}}$$

$$\mathrm{RMS}(X_1) = \lambda_{int}$$

$$\sigma^{prod}_{p\text{-air}} = [505 \pm 22(\mathrm{stat})^{+28}_{-36}(\mathrm{syst})]\ \mathrm{mb}$$ PRL2012

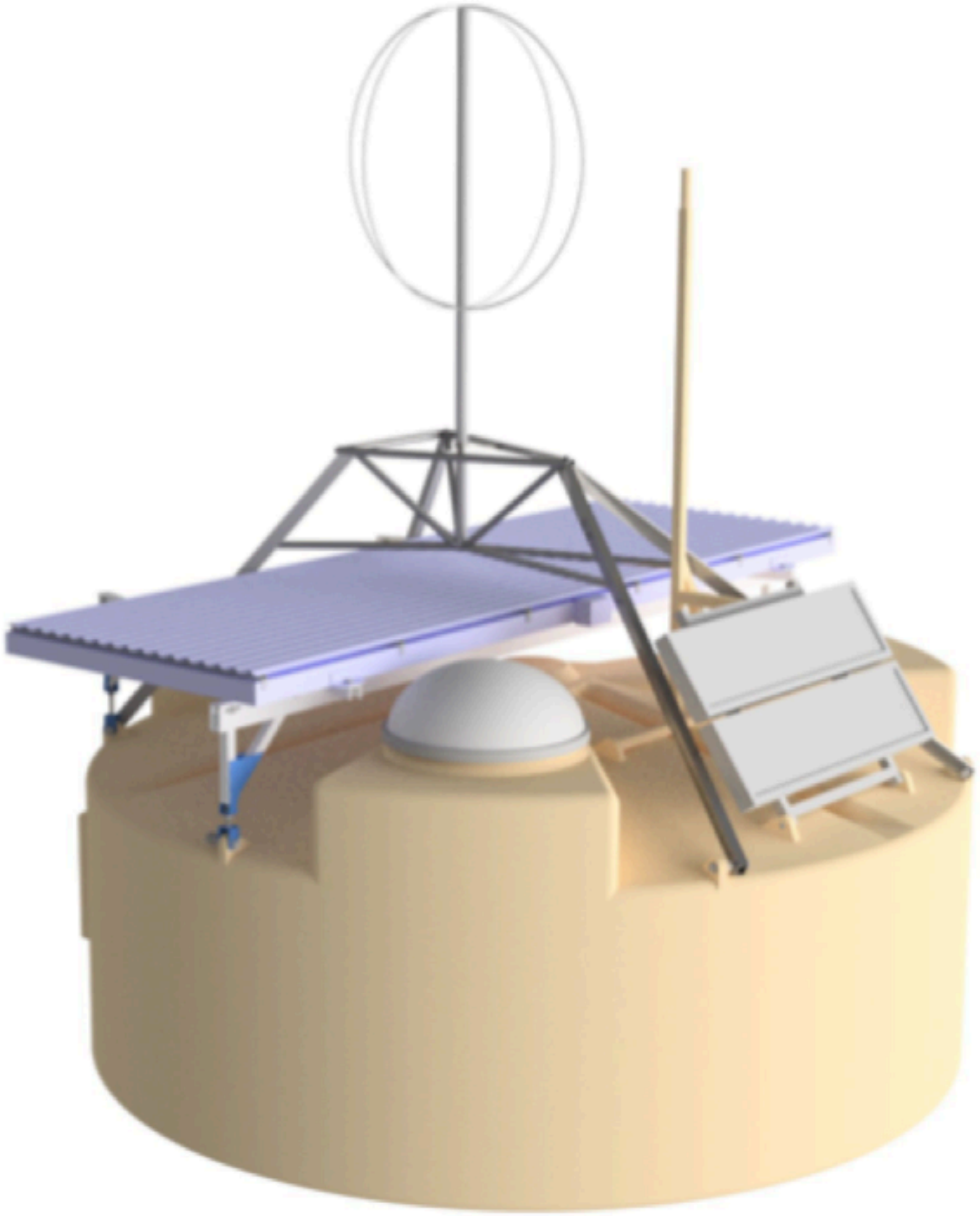
[R. Ulrich for the Pierre Auger Collab., Proc. 34th ICRC (2015), arXiv: 1509.03732]

Scintillator design



Slide from D. Veberic (Auger collab.) DPG 2019

Radio upgrade design



- To measure the CR properties above $10^{17.5}$ eV up to beyond 10^{20} eV
  - Measurement of highly inclined showers (60°<θ<84°) ⇒ extend EM-muon separation to high θ
  - Type of particle up to highest energies
  - Absolute energy calibration from 1st principles
  - Independent mass scale
- 100% duty cycle

- 1st prototype under evaluation
- Radio upgrade fully funded, and implementation currently ongoing

[J. R. Hörandel for the Pierre Auger Collab., Proc. UHECR 2018]