Pierre Auger Observatory
studying the universe's highest energy particles

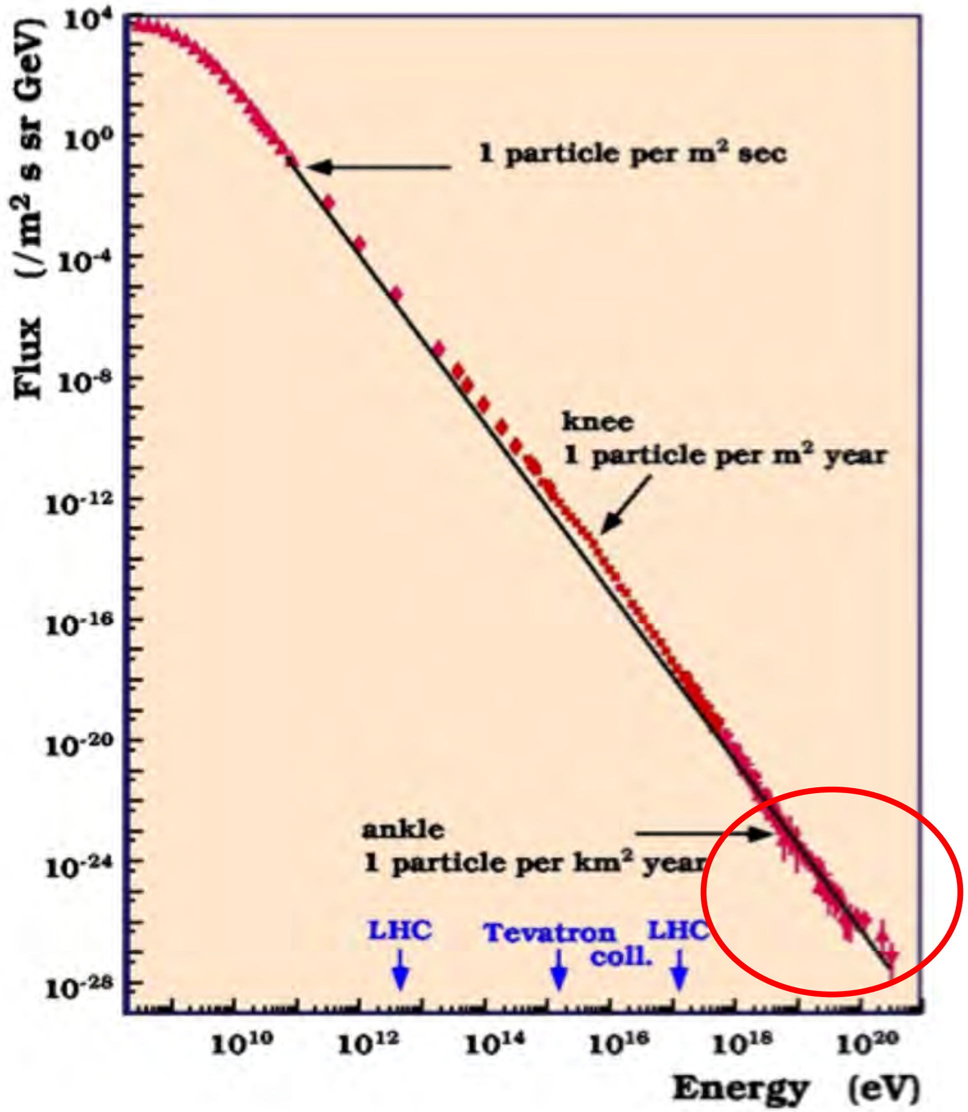
Physics and astrophysics with the Pierre Auger Observatory

Rogerio Menezes de Almeida, for the Pierre Auger Collaboration

Fluminense Federal University

STARS / SMFSN 2019 – La Habana

Cosmic rays and open questions



• (aproximately) power law spectrum: 10 orders of magnitude in E and 32 in flux!

Persistent questions

✓What are their sources?

✓ What are their chemical composition?

✓ How can they be accelerated at such high energies?

How can we try to answer these questions?

UHECR
- One event per century per km^2
- Many interesting questions

Pierre Auger Observatory

Main Detectors

Surface detector

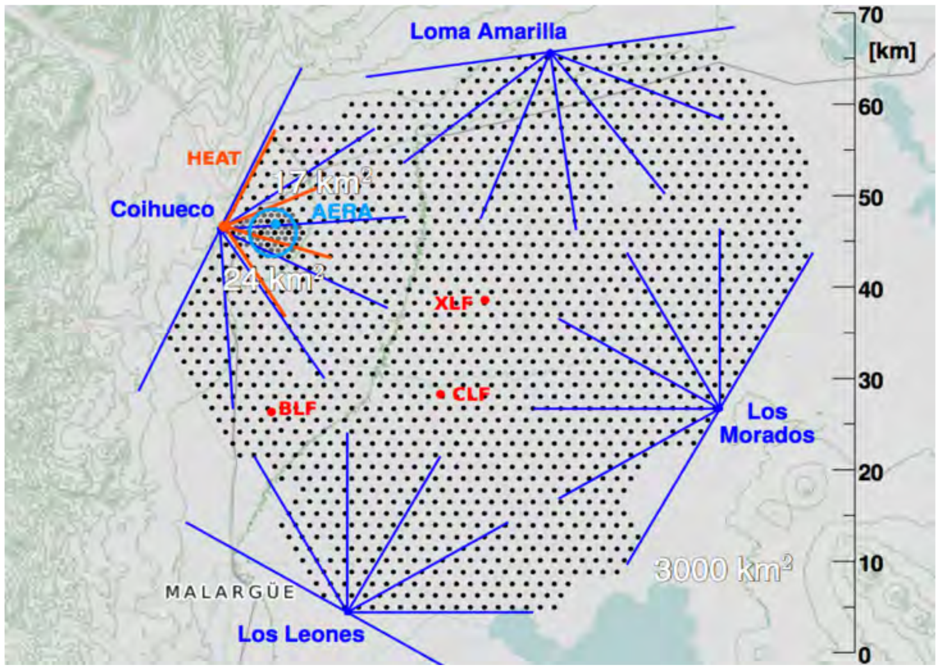
• array of 1660 Cherenkov stations on a 1.5 km hexagonal grid ~ 3000 km^2

• duty cycle ~ 100%

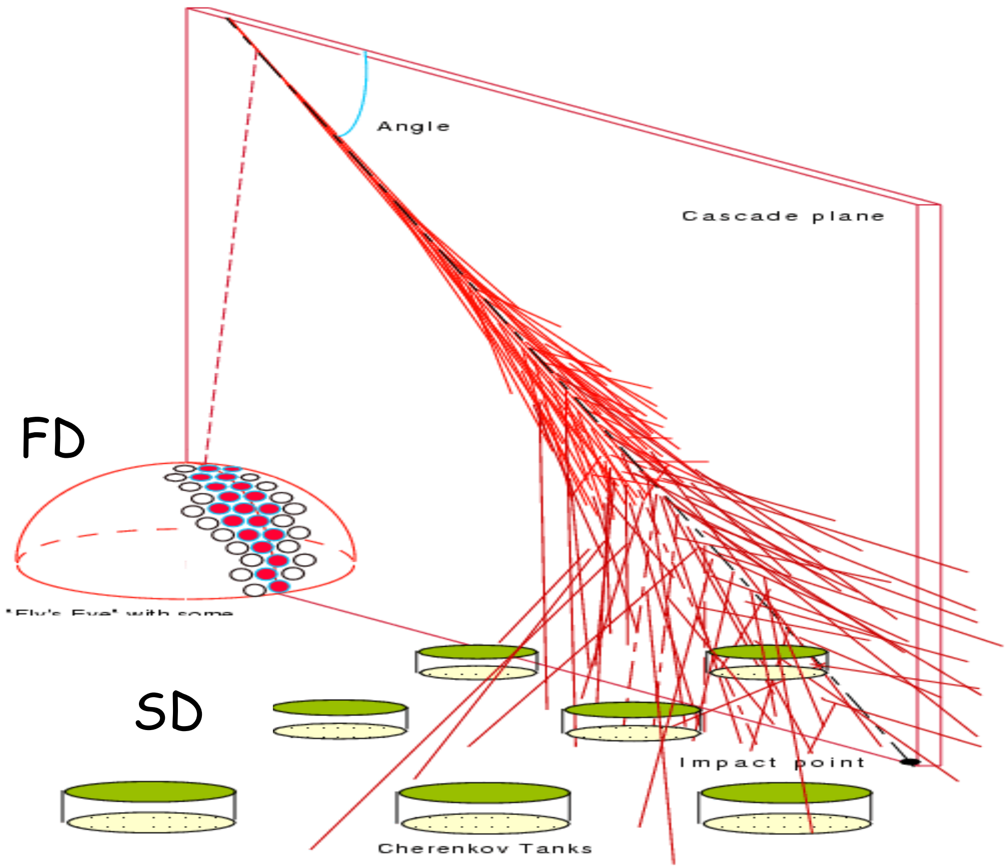
Fluorescence detector

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

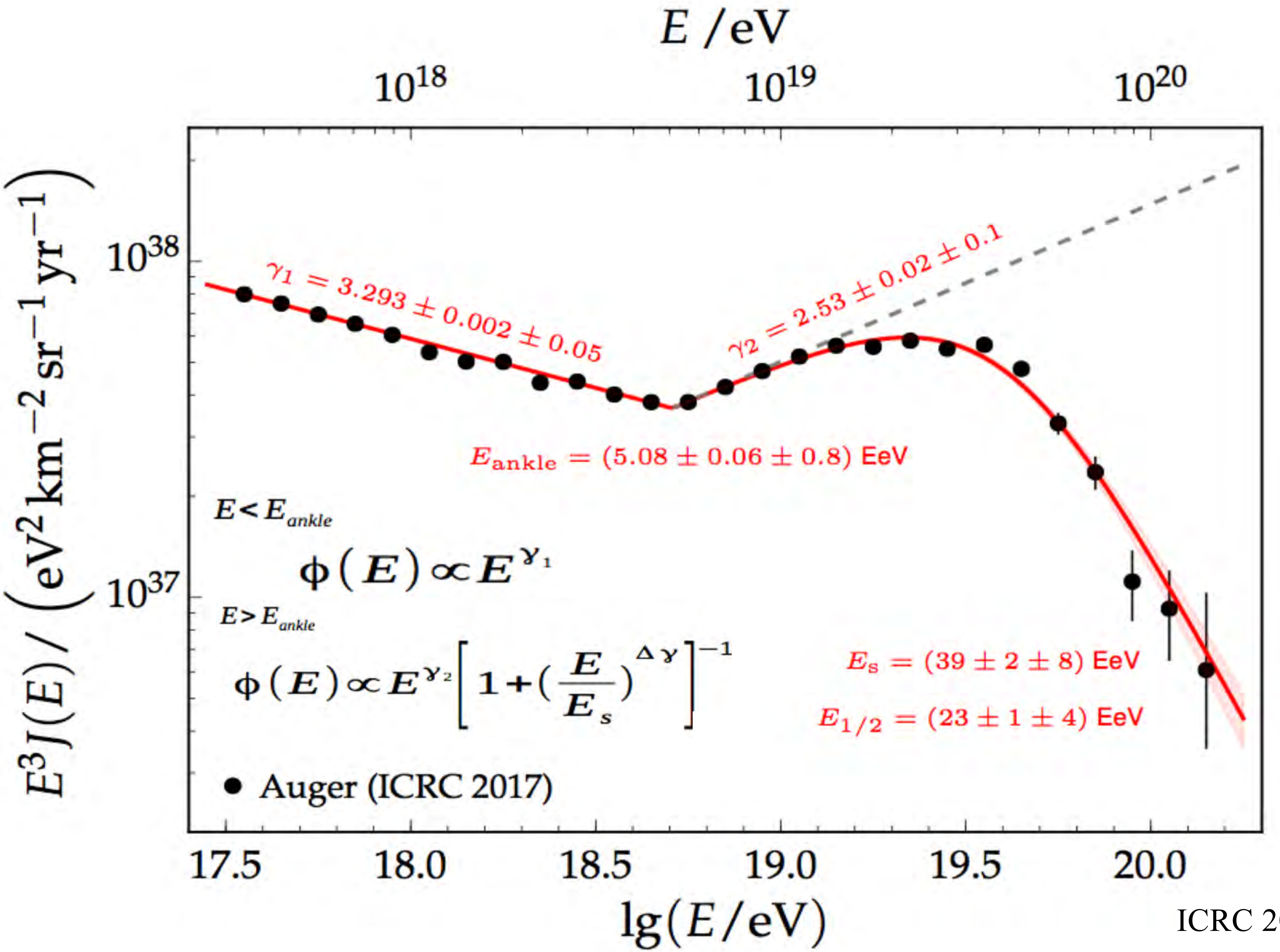
• duty cycle ~ 13%



3000 km², Malargue, Argentina



Energy Spectrum

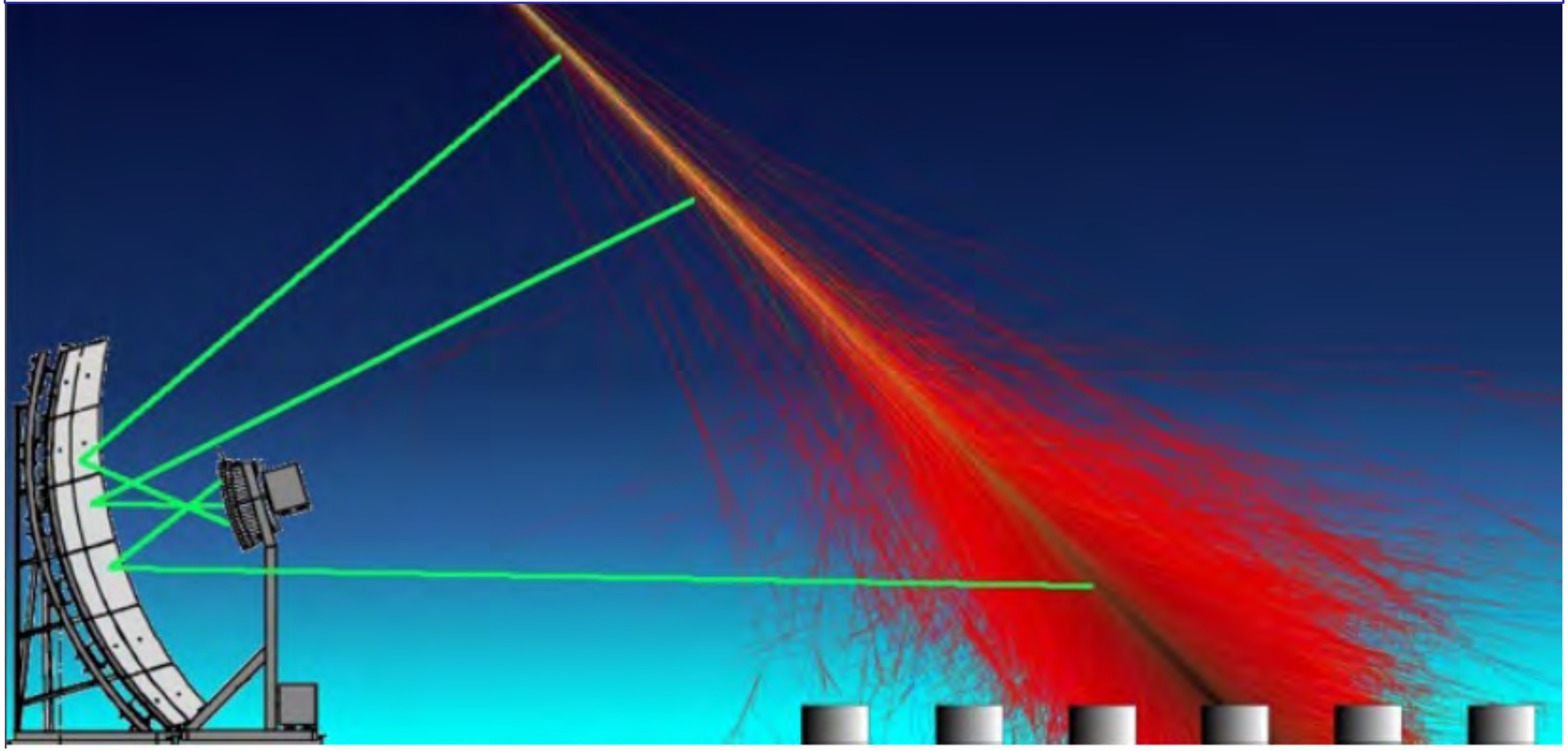


ICRC 2017

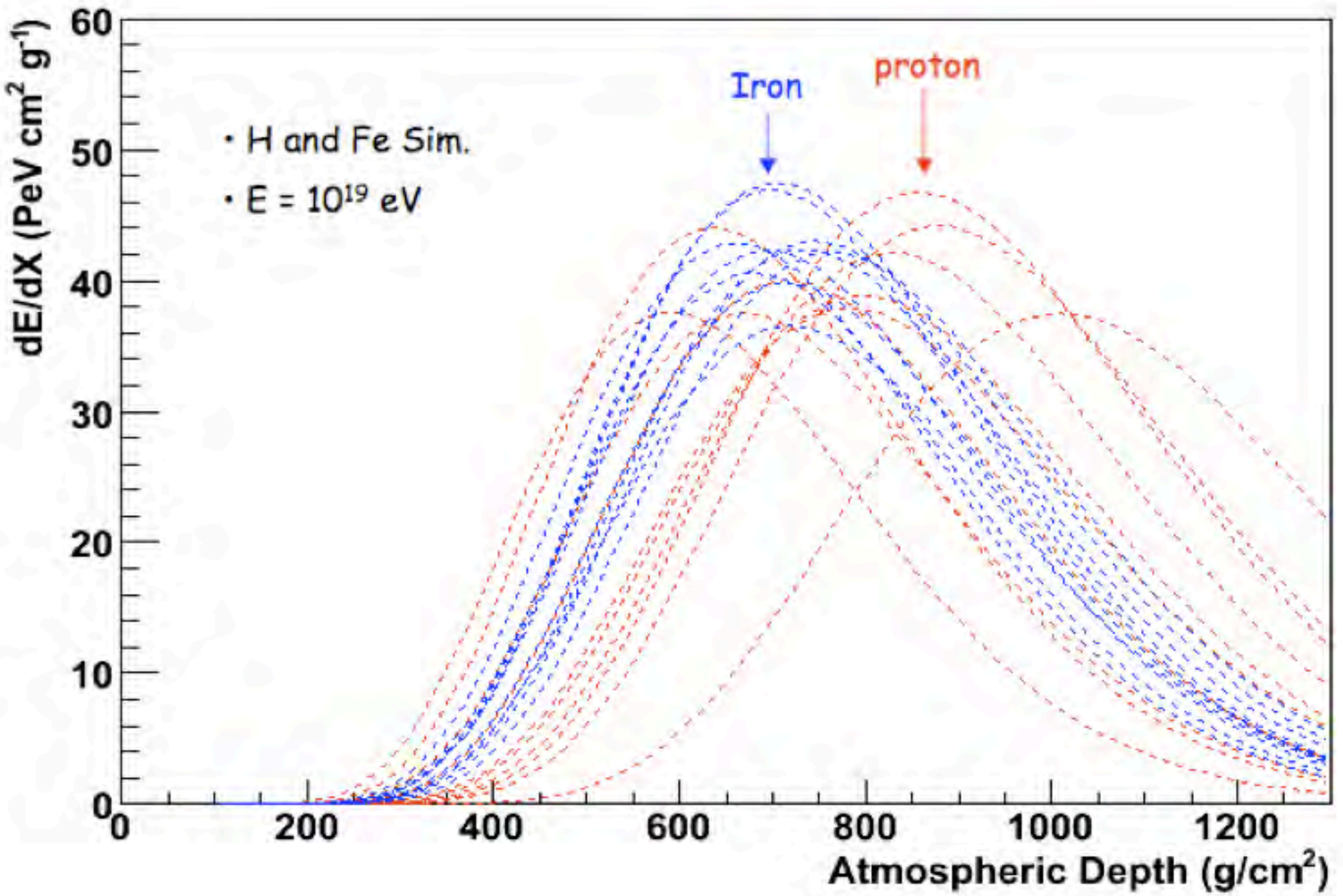
How can we infer the mass composition?

➔ looking for differences in the shower development

- Showers from **heavier nuclei develop earlier in the atmosphere** with **smaller fluctuations**
- They reach their maximum development higher in the atmosphere



X_{max} from simulations



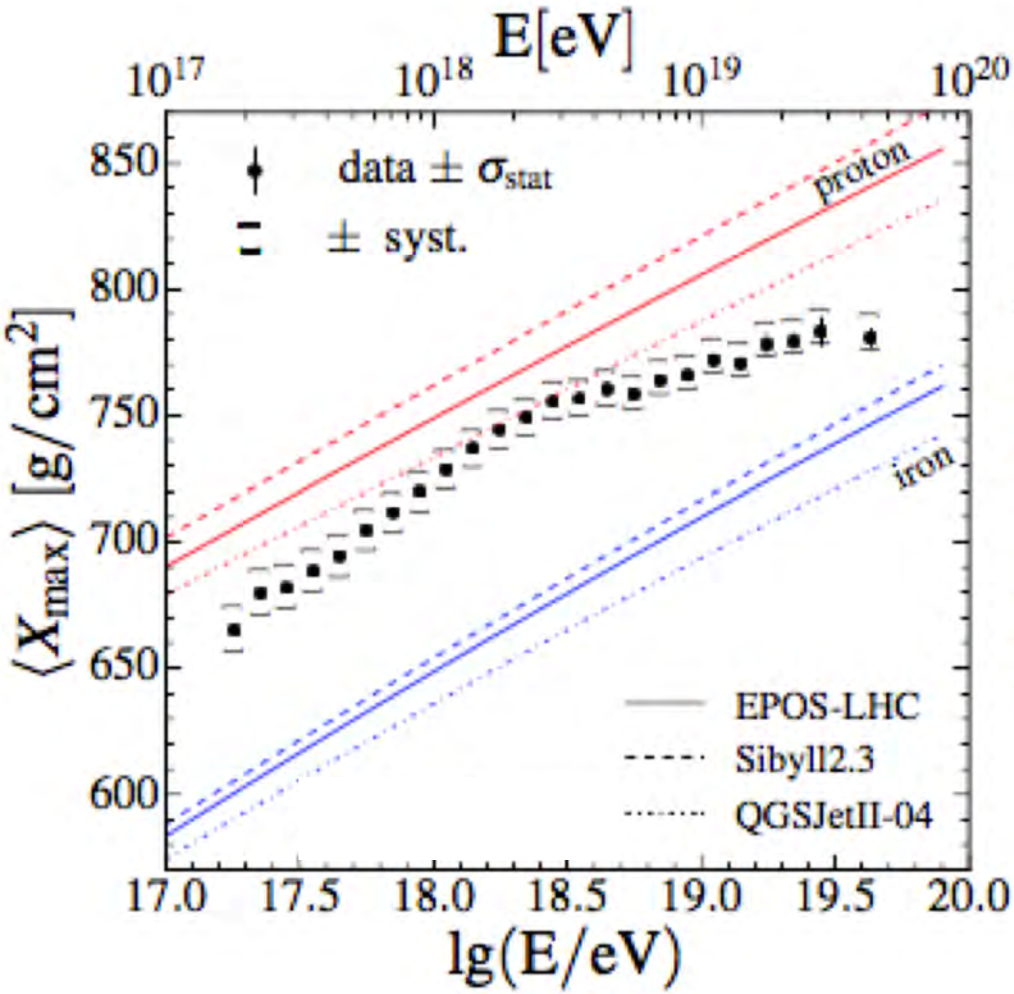
For a given hadronic interaction model, X_{max} is correlated with the mass of the incident cosmic ray particle

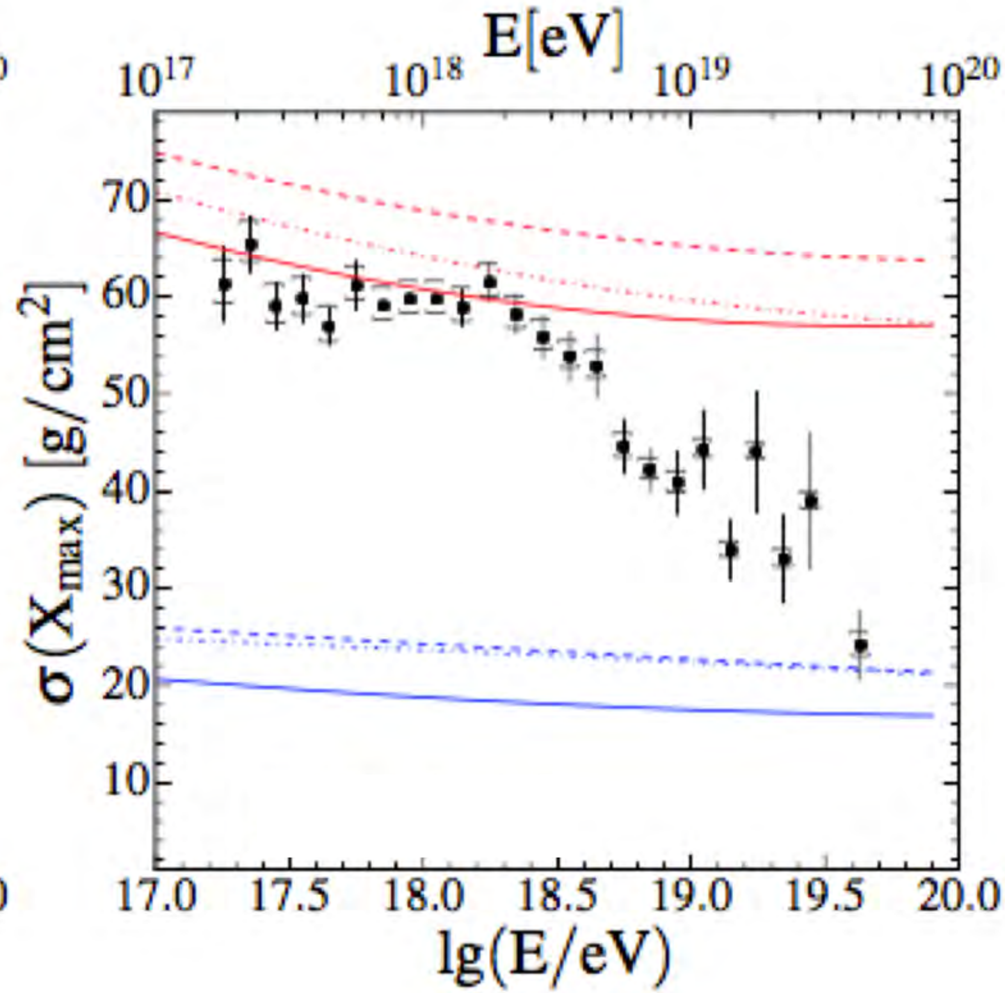
Shower to shower fluctuations, RMS(Xmax), is smaller for showers produced by iron

ΔXmax(p-Fe) ~ 50 g/cm^2

Average X_{max} and X_{max} fluctuations

ICRC 2017





Arrival Directions

- Indication for intermediate-scale anisotropy

  ApJ.Lett. 853:L29 (2018)853:L29

- Observation of Large-scale anisotropy

  Science 357 (2017) 1266
  APJ, 868, (2018) 1

Search for Intermediate-scale Anisotropies

Study motivated by Fermi-LAT observations of high-energy gamma rays

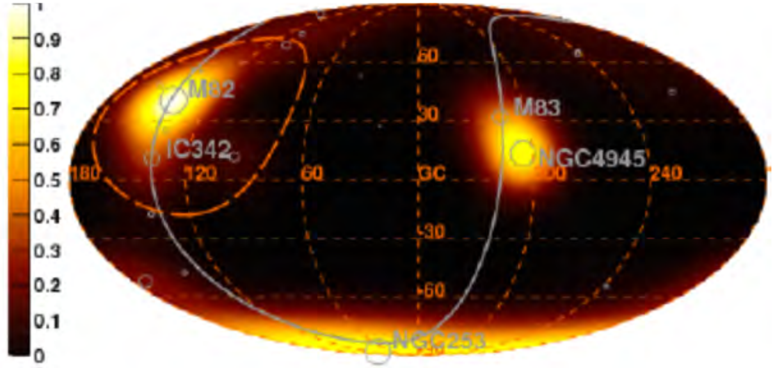
- SBG: 23 nearby starburst galaxies, $\Phi > 0.3$ Jy, w : radio at 1.4 GHz
- γAGN: 17 2FHL blazars and radio galaxies, $D < 250$ Mpc, w : γ-ray 50 GeV-2 TeV.

ω = UHECR flux proxy

Advantages of the present analysis

- Ansatzes for the relative UHECRS fluxes → potentially more sensitive than previous analysis based solely on the source direction
- Improved knowledge of energy-dependent compositions → attenuation fluxes
- Significant increase of the Pierre Auger Observatory exposure → data can reveal more subtle patterns

Search for Intermediate-scale Anisotropies



Analysis strategy

- Sky model probability maps:

Φ_i = flux model x attenuat. model x ang. smearing (σ) x exposure

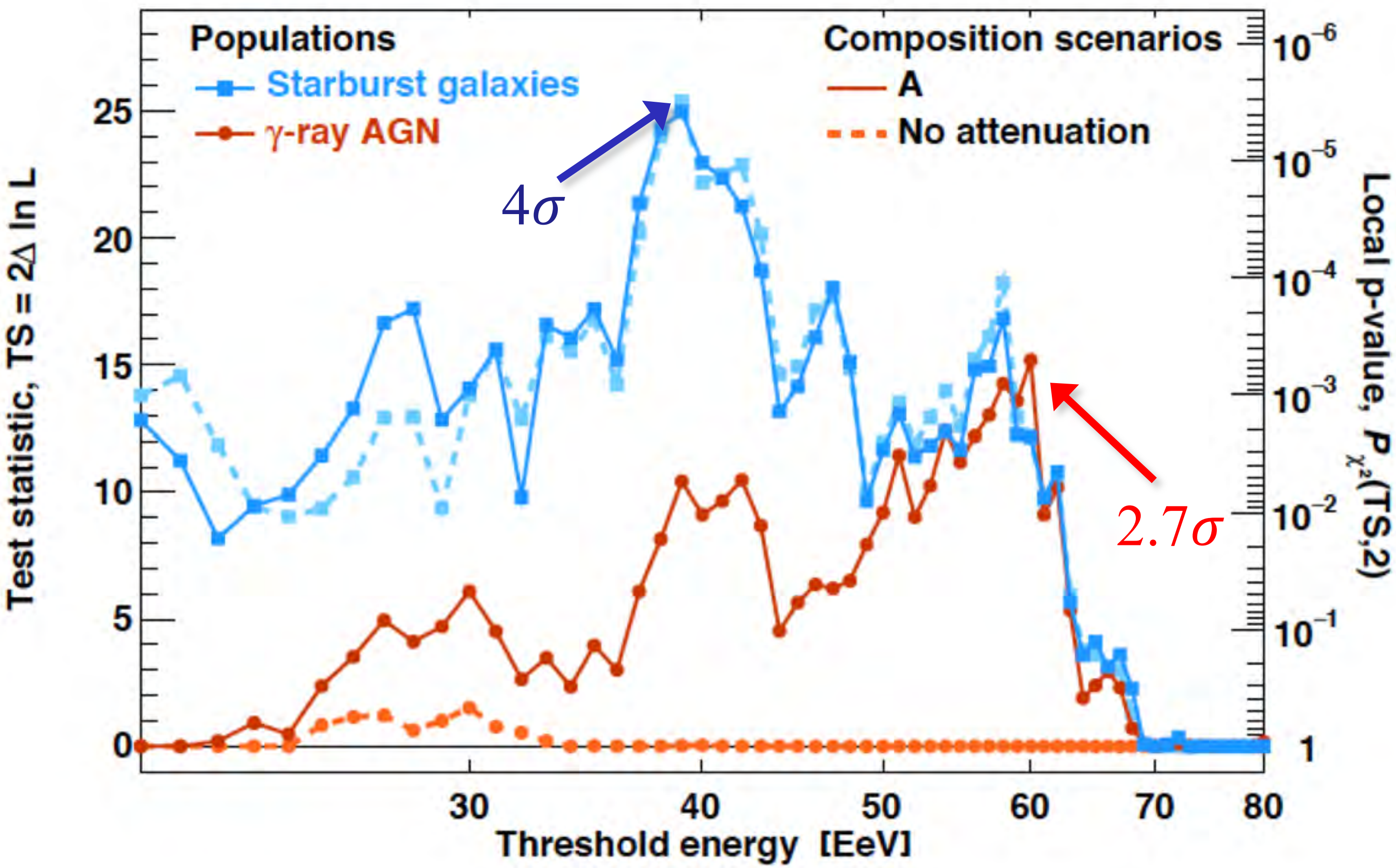
- Single population signal model H_1:

$\Phi = (1- f)\,\Phi_0 + f\,\Phi_{i.}$ **: (free parameters: σ and f)**

- Null hypothesis H_0: isotropy Φ_0
- Test statistics: $TS = 2\log(H_1/H_0)$
- p-value from Wilk's theorem: $p(TS) = p_{\chi 2}(TS,ndf)$

Test Statistic vs. Energy

SBG fits data better than isotropy at 4σ C.L. (penalized by the energy scan)

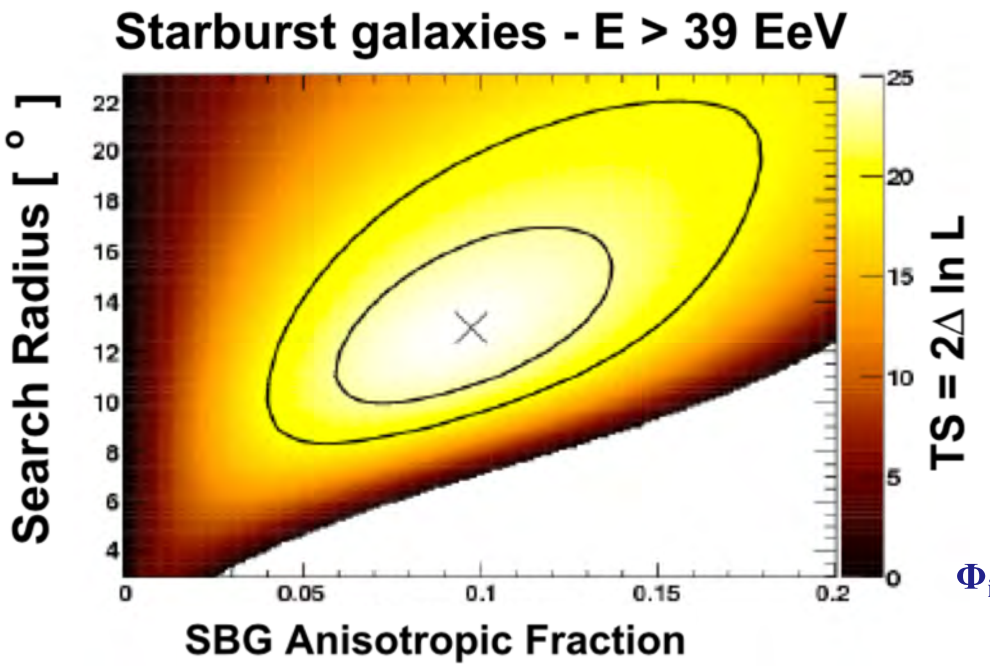


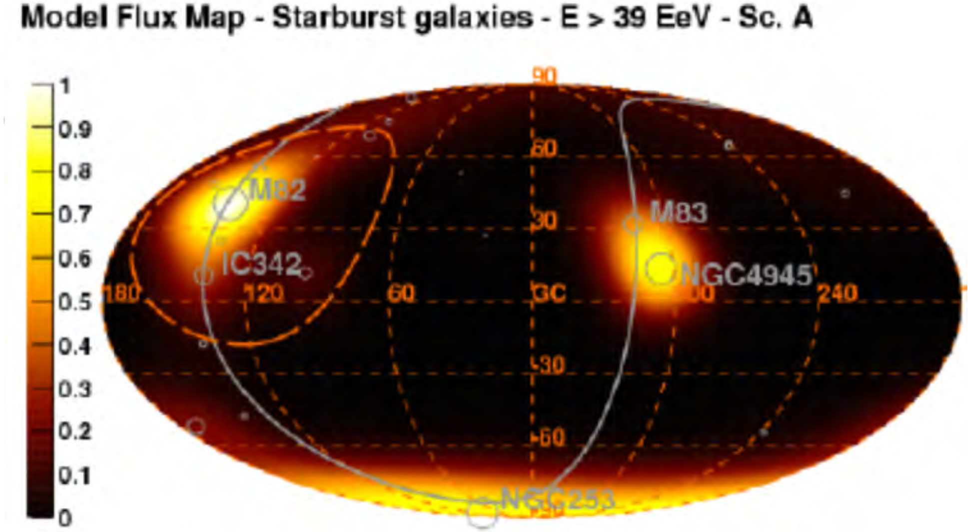
A: Auger best fit ==>

name	$\lg(R_{max}/V)$	f_p	f_{He}	f_N	f_{Si}	γ
EPO1st	18.68	0.000	0.673	0.281	0.046	0.96

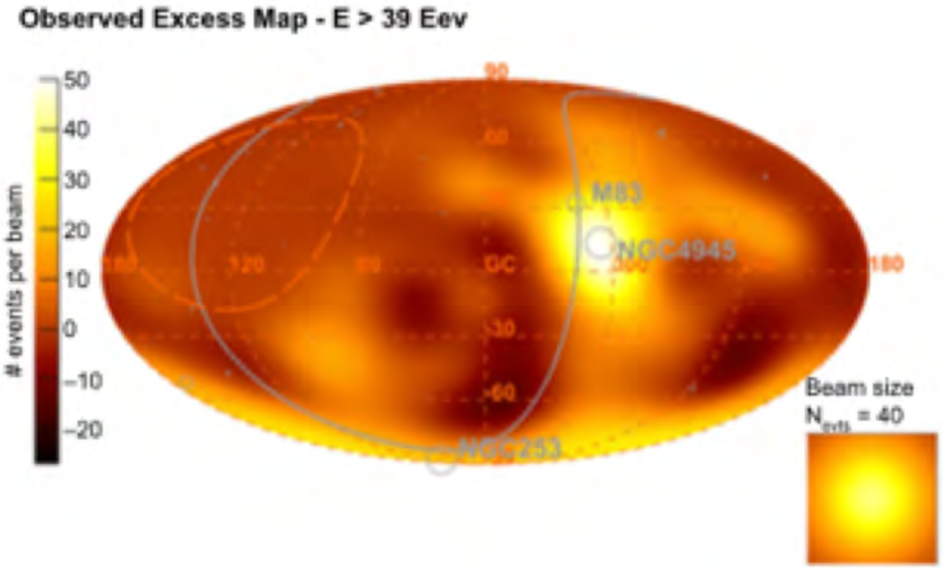
Pierre Auger Coll., JCAP **1704** (2017) 038

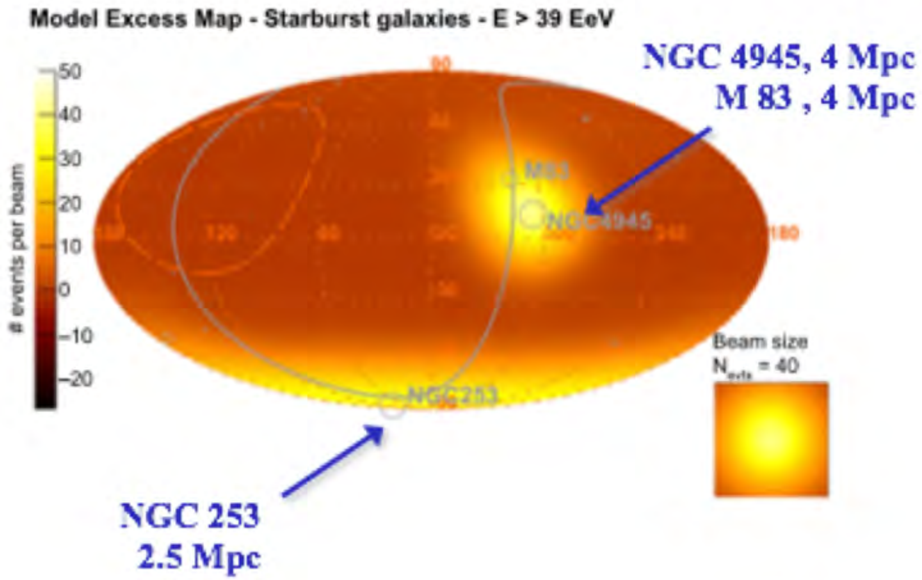
Best fit parameters





Φ_i = flux model x attenuat. model x ang. smearing (σ) x exposure





Arrival Directions

- Indication for intermediate-scale anisotropy

  ApJ.Lett. 853:L29 (2018)853:L29

- Observation of Large-scale anisotropy

  Science 357 (2017) 1266

  APJ, 868, (2018) 1

Observation of Dipolar anisotropy above 8 EeV

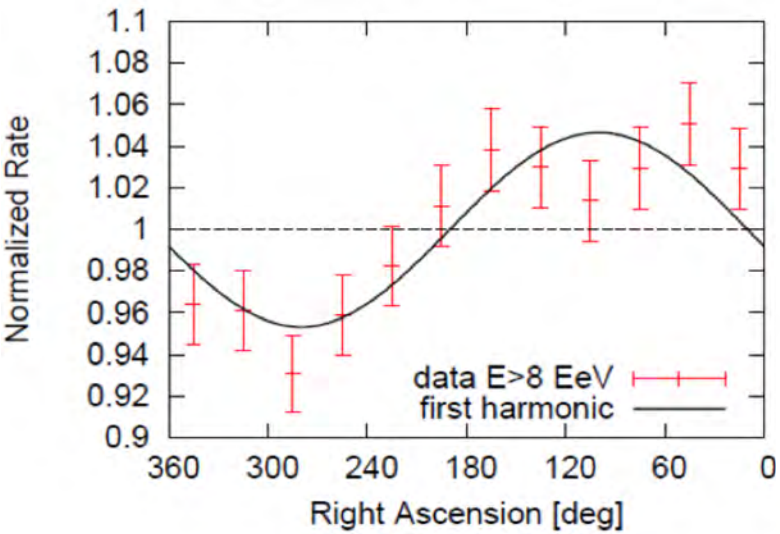
Science 357 (2017) 1266

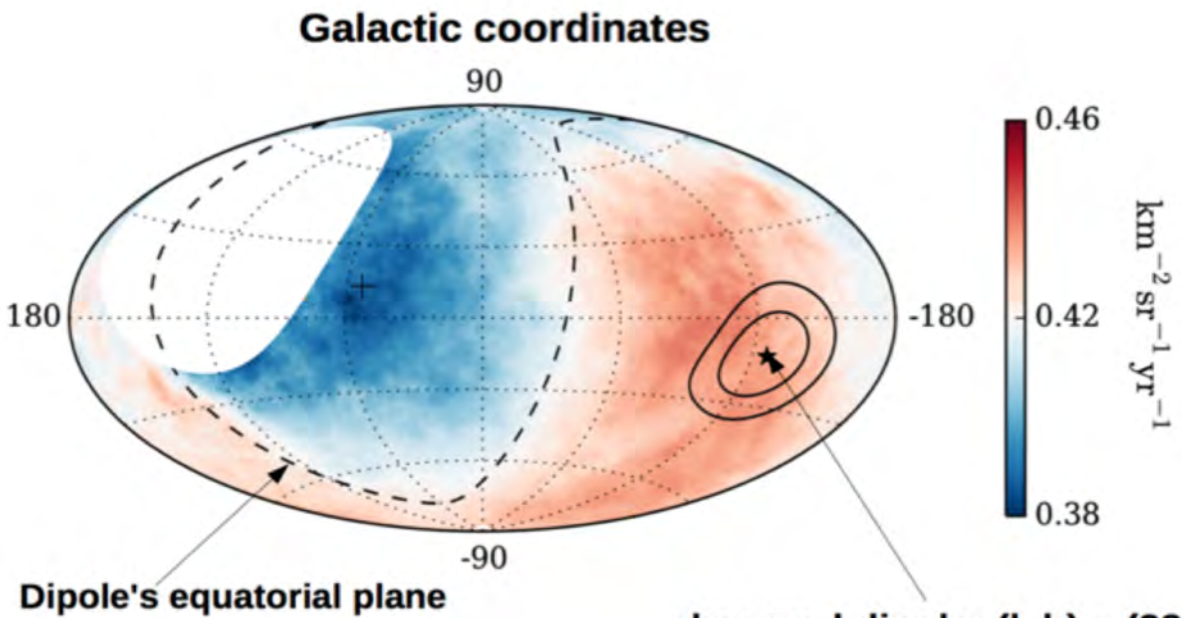
Harmonic analysis in right ascension α

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

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

ICRC 2017





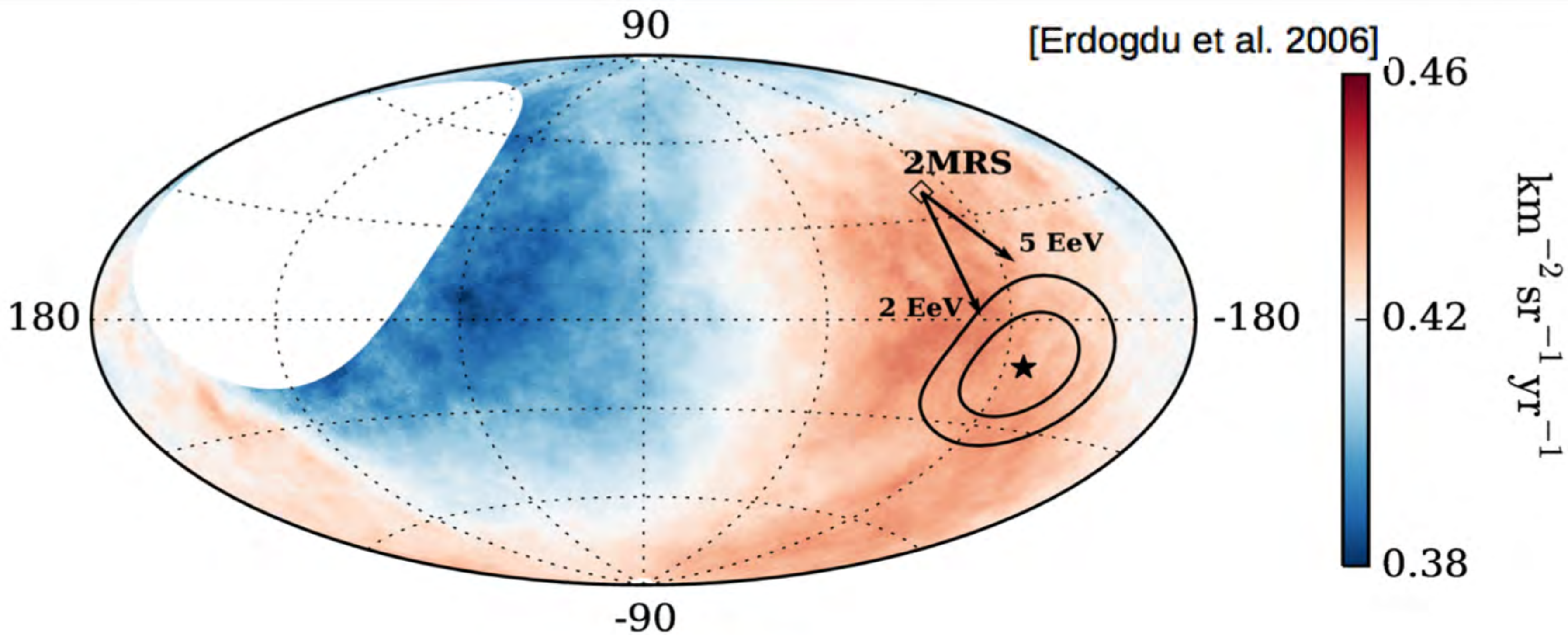
dipole direction ~ 125° from GC → disfavors galactic origin

Observation of Dipolar anisotropy above 8 EeV

Large scale anisotropy can arise from:

- Inhomogeneous large-scale distribution of sources
- Diffusion in X-gal magnetic fields from dominant nearby sources
- Typical dipole amplitudes ~ 5 – 20% at 10 EeV, depending on source distribution and CR composition

2MRSdipole (l,b) = (251°,38°) ~ 55° from observed dipole

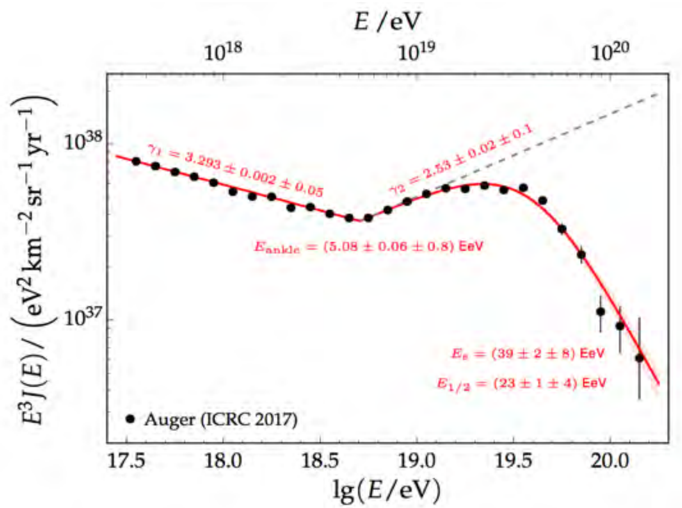


Accounting GMF deflections
[Jansson and Farrar ApJ 757 (2012) 14]

Z ~ 1.7 – 5 at 10 EeV → E/Z ~ 2 – 5 EeV ⇒ **Improves agreement observation ↔ 2MRS**

[Auger Coll. PRD 90 (2014) 122006]

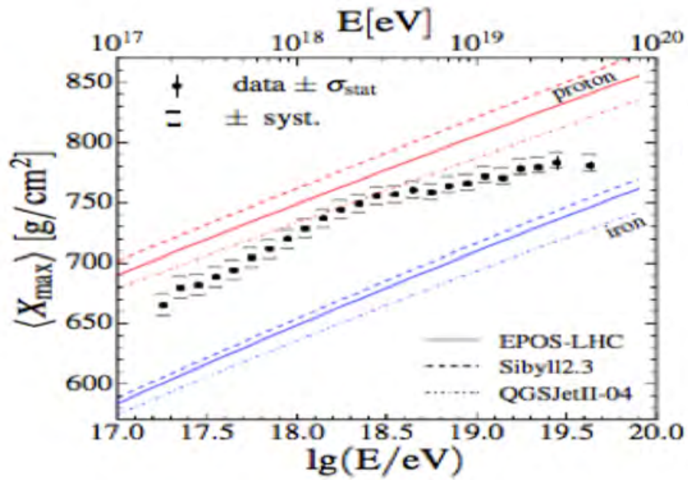
Summary and Results



Spectrum and composition

- high-exposure study of UHE flux

→ strong flux suppression



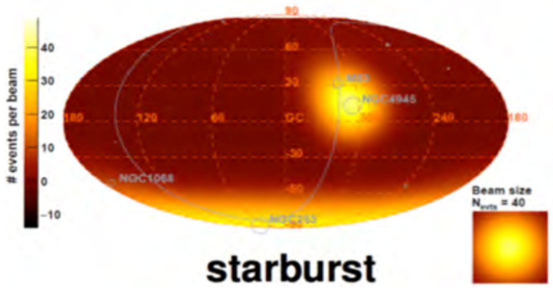
- FD/SD composition studies

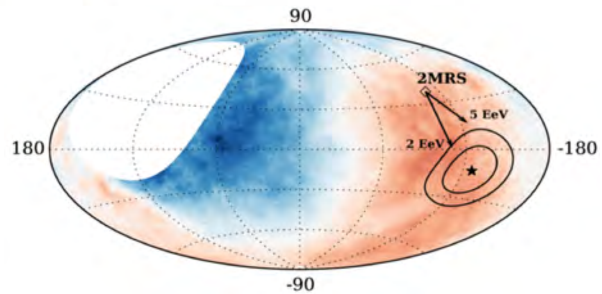
→ light composition at ankle

→ mixed composition at UHE

Arrival directions

- Indication for intermediate-scale anisotropy
- Observation of a dipolar anisotropy with 5.2 σ

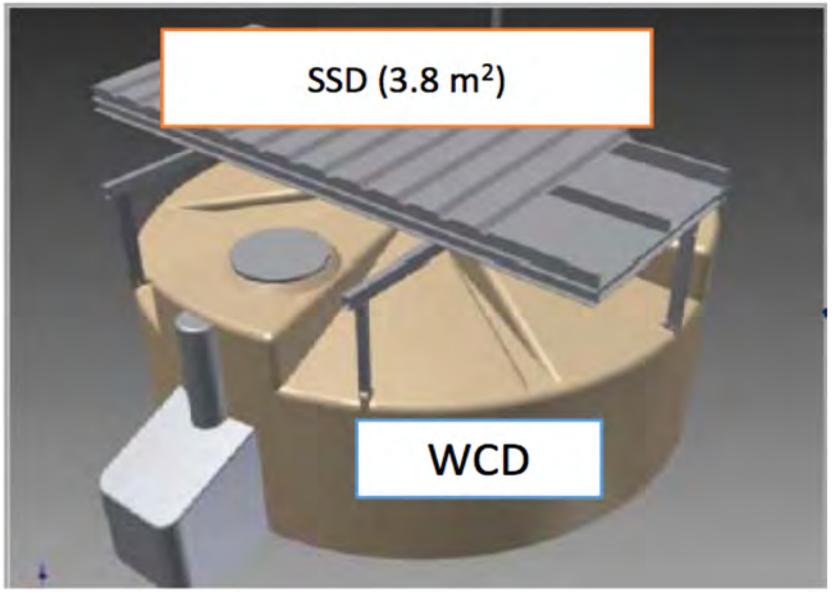




Summary and Results

Although the analysis of Auger data has led to major breakthroughs in the understanding of the origin and properties of the highest-energy cosmic rays, a coherent interpretation has not yet been achieved and new questions have emerged!

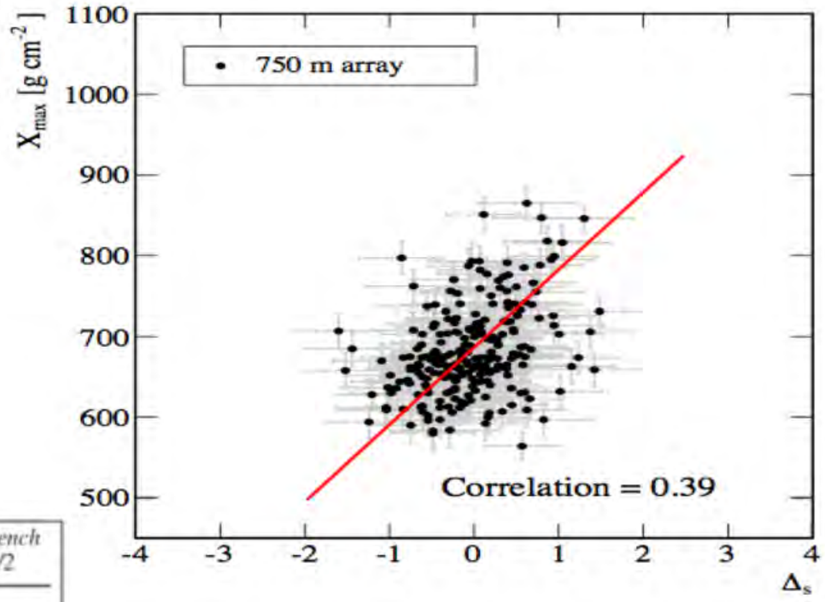
→ **AugerPrime**



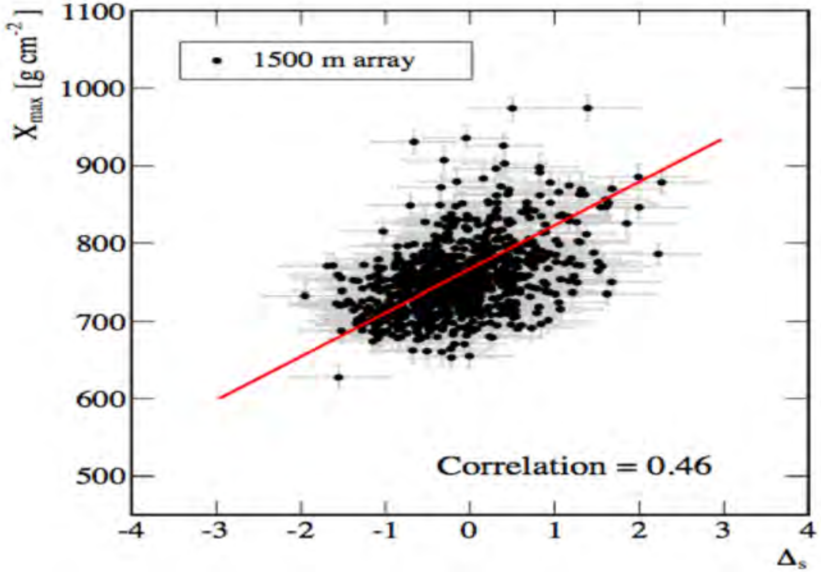
→ **Mass composition information for each new event detected in next years**

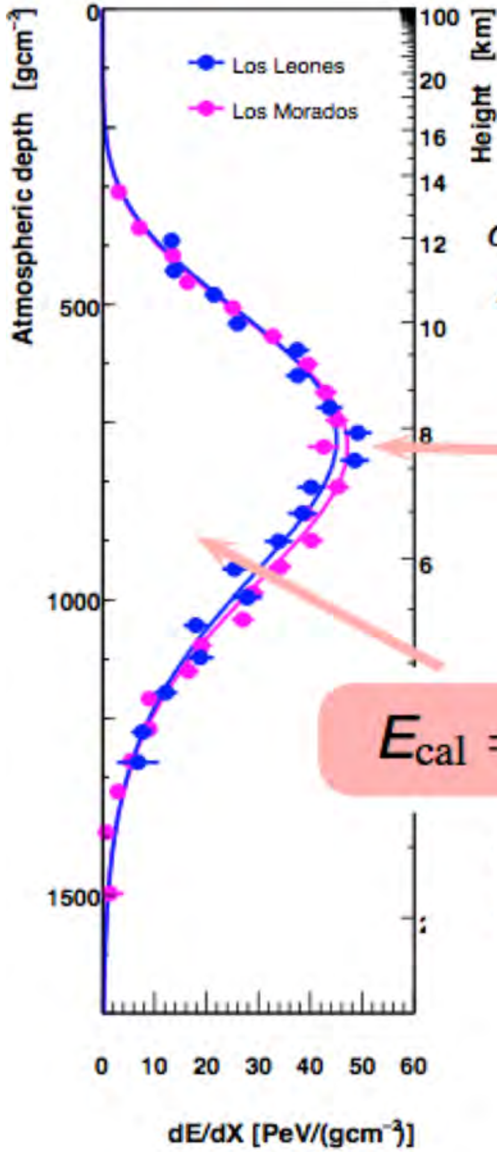
Backups

Mass Composition



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



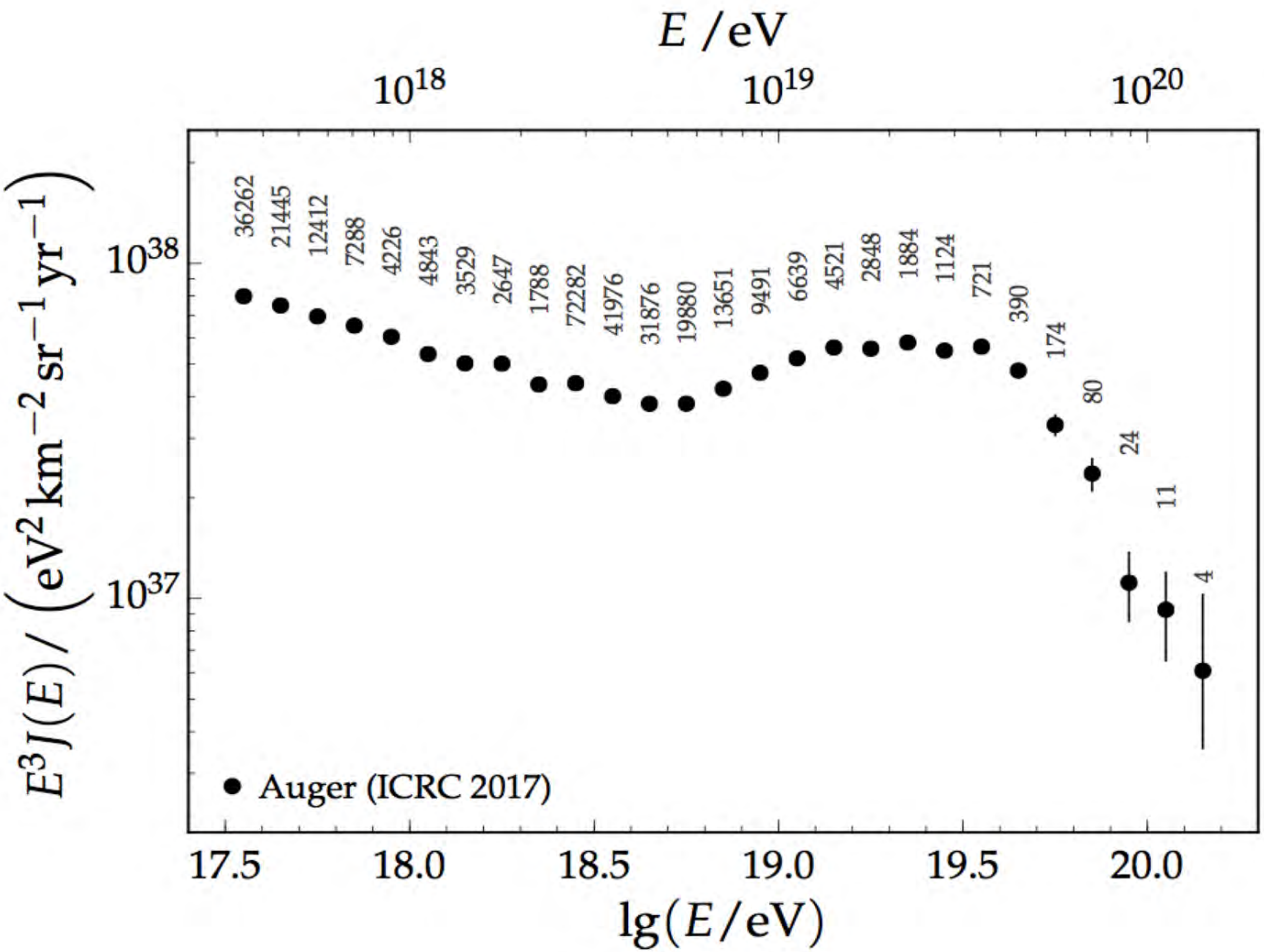


$\sigma X_{max} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{sys} \leq 10\,\mathrm{g/cm^2}$

X_{max}

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

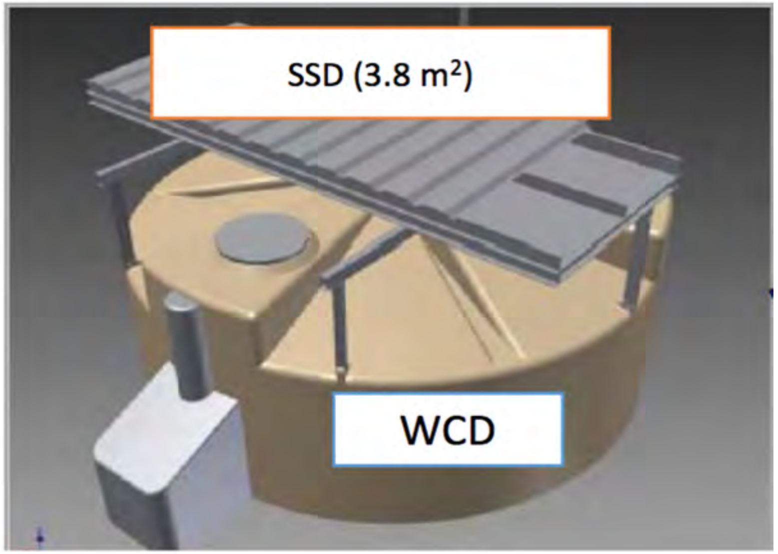
Combined Energy Spectrum



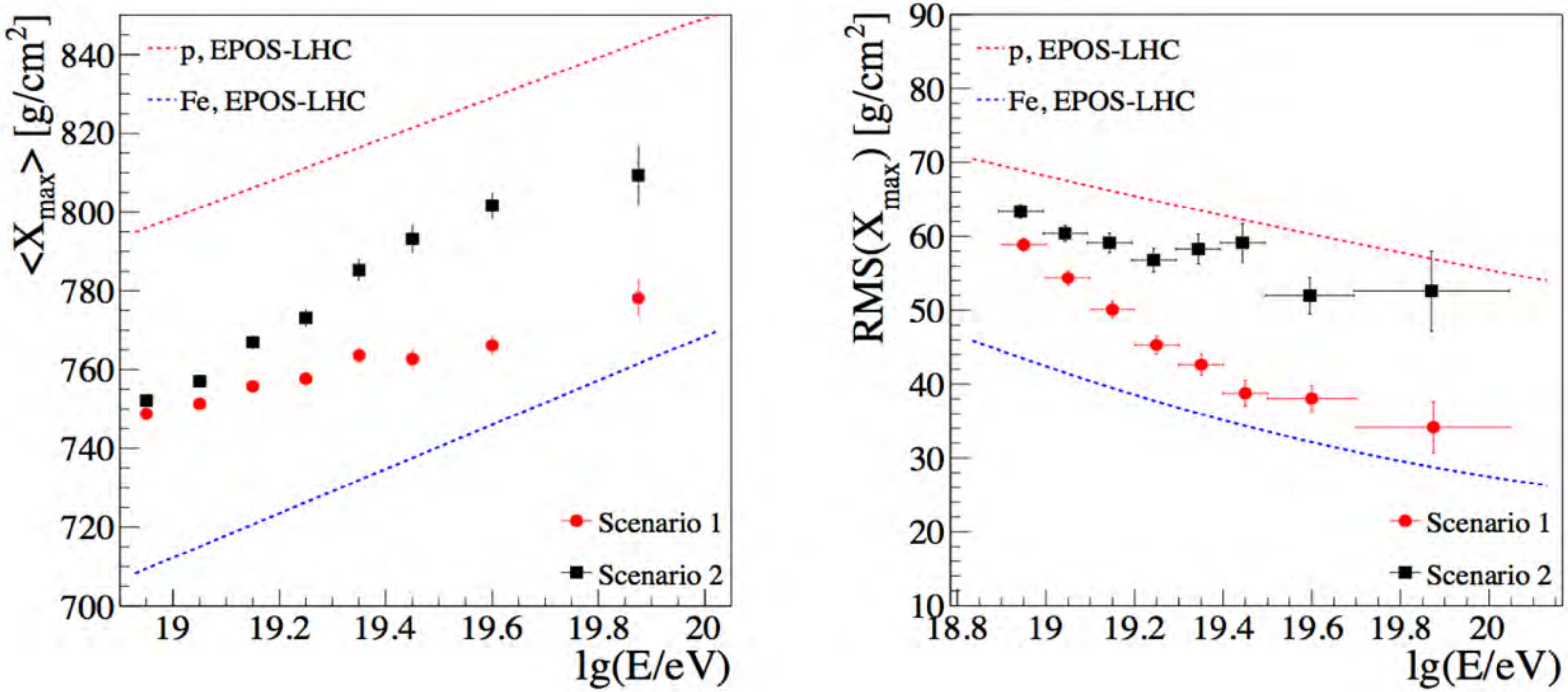
AugerPrime

- Origin of the flux suppression?
- proton fraction at UHE?
- Rigidity-dependence of anisotropies?
- Hadronic Physics above $\sqrt{s} = 140$ TeV?

Need large-exposure detector with composition sensitivity!



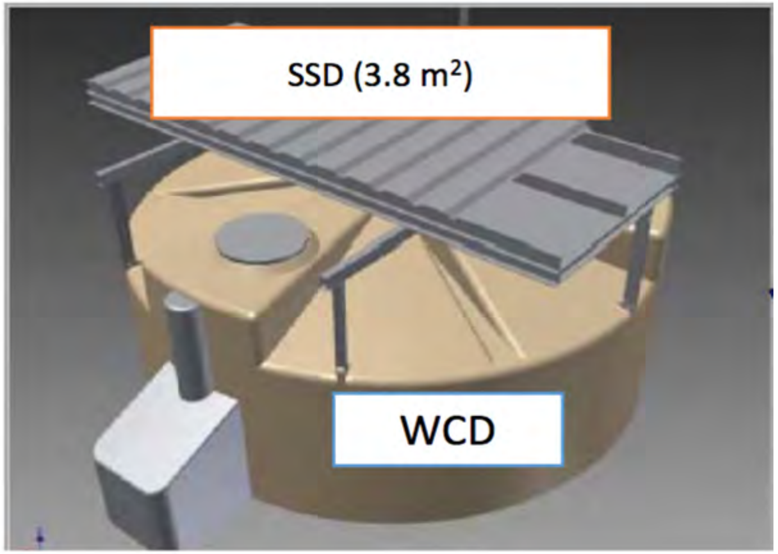
Expected performance: scenario 1: maximum-rigidity; scenario 2: photo-desintegration



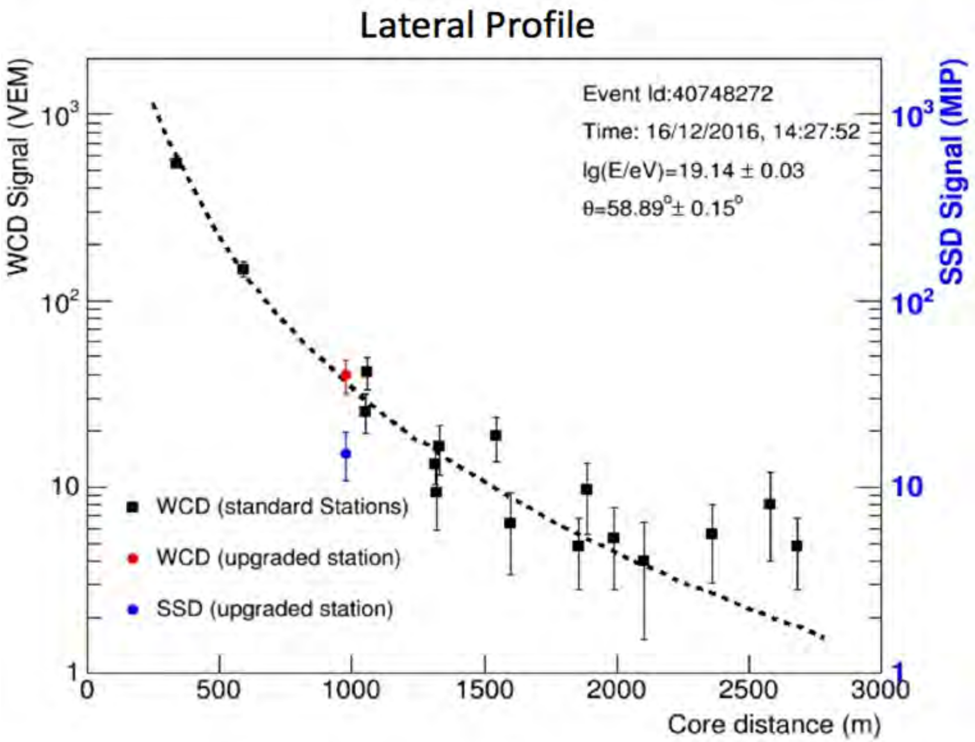
AugerPrime

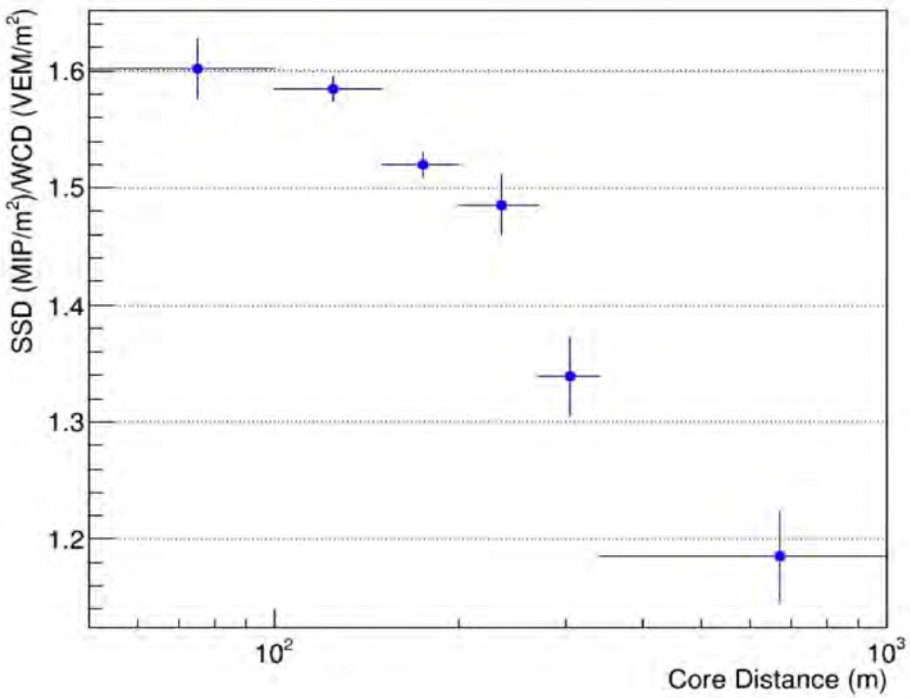
- Origin of the flux suppression?
- proton fraction at UHE?
- Rigidity-dependence of anisotropies?
- Hadronic Physics above $\sqrt{s} = 140$ TeV?

Need large-exposure detector with composition sensitivity!



The Engineering AugerPrime array





Combined Fit (Xmax and spectrum) of Auger data

Identical sources homogeneously distributed in a comoving volume

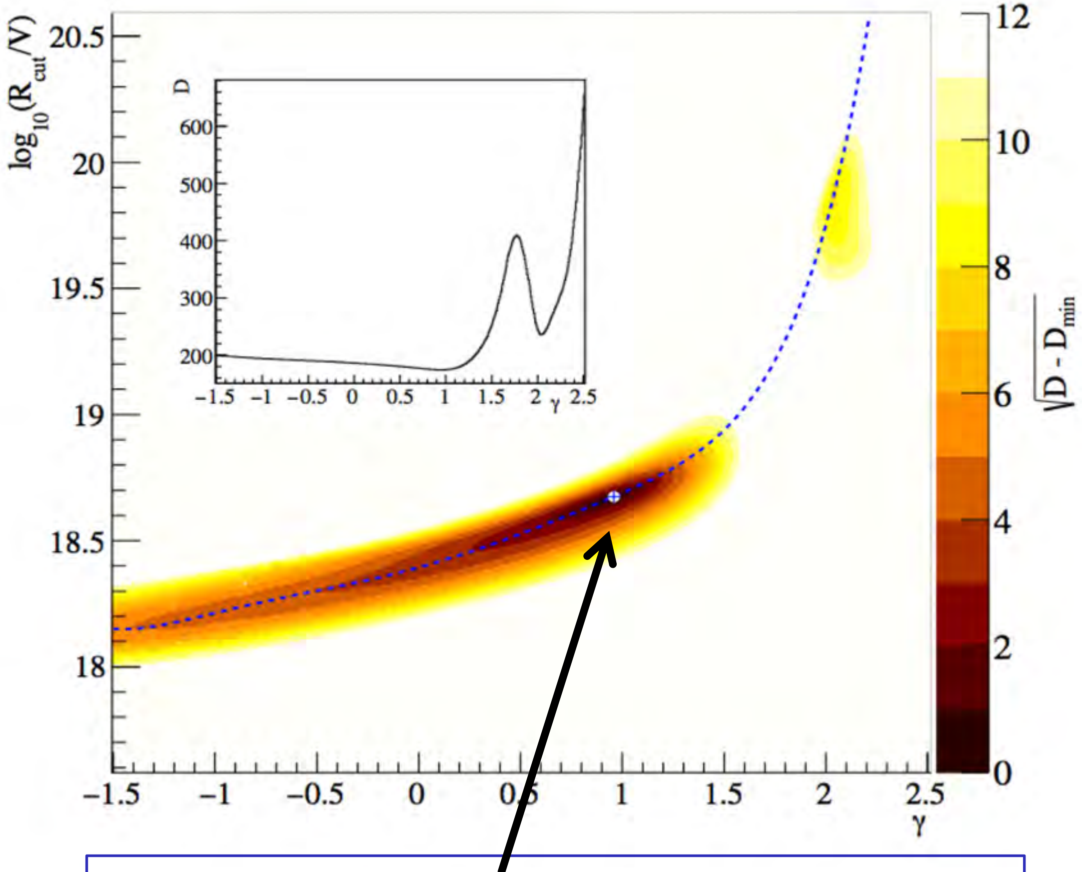
• Injection consisting only of H, He, Ni, Si and Fe (approximately equally space in ln A)

• Power low spectrum with rigidity-dependent exponentital cuttof

$$\frac{dN_{\text{inj},i}}{dE} = \begin{cases} J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{\text{cut}} \\ J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\text{cut}}}\right), & E/Z_i > R_{\text{cut}} \end{cases}$$

He,

p_{Ni} and p_{Si})

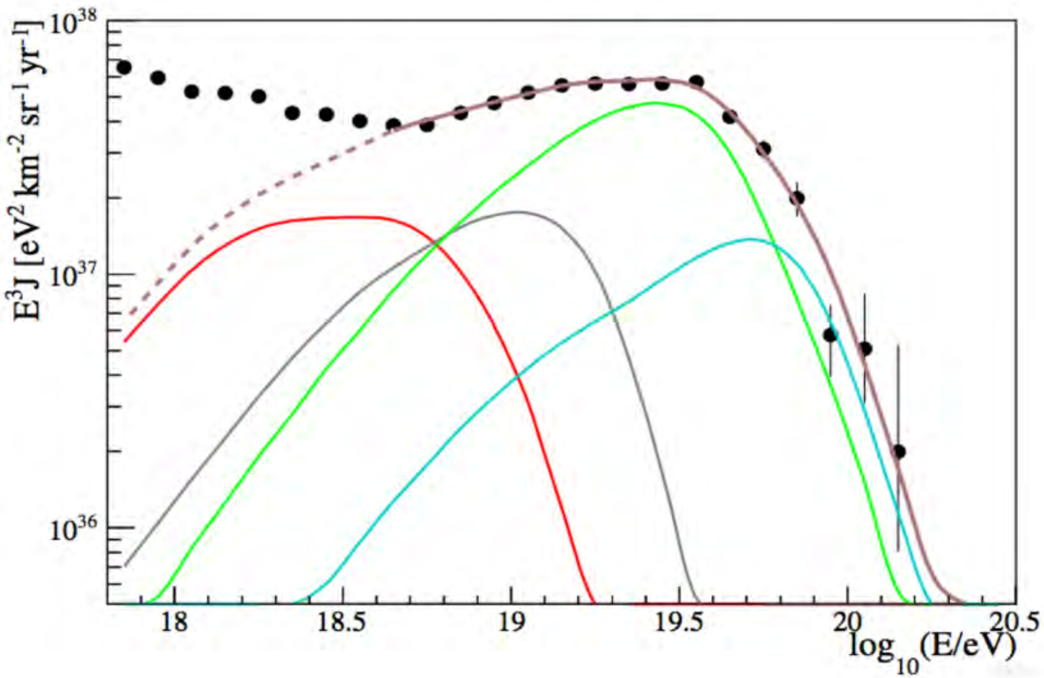


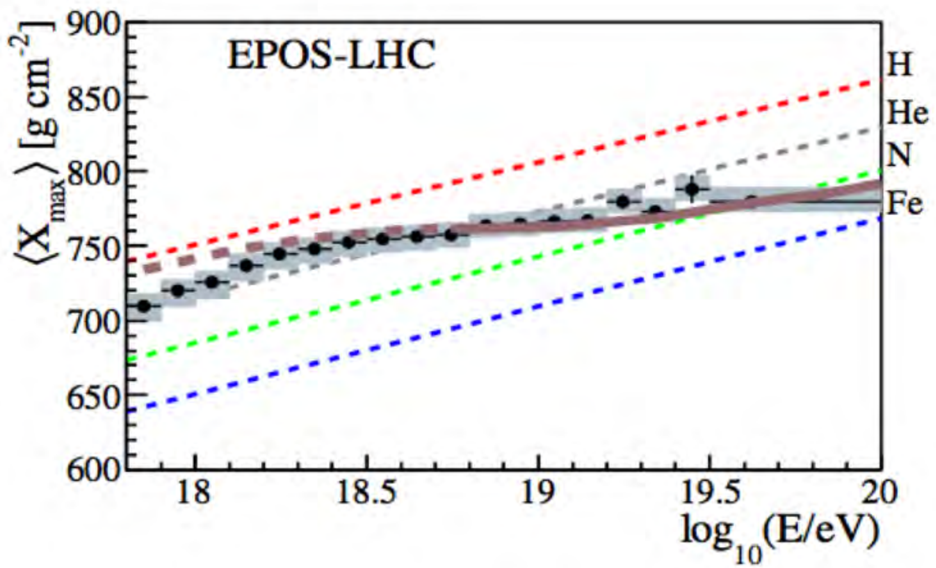
Best Fit

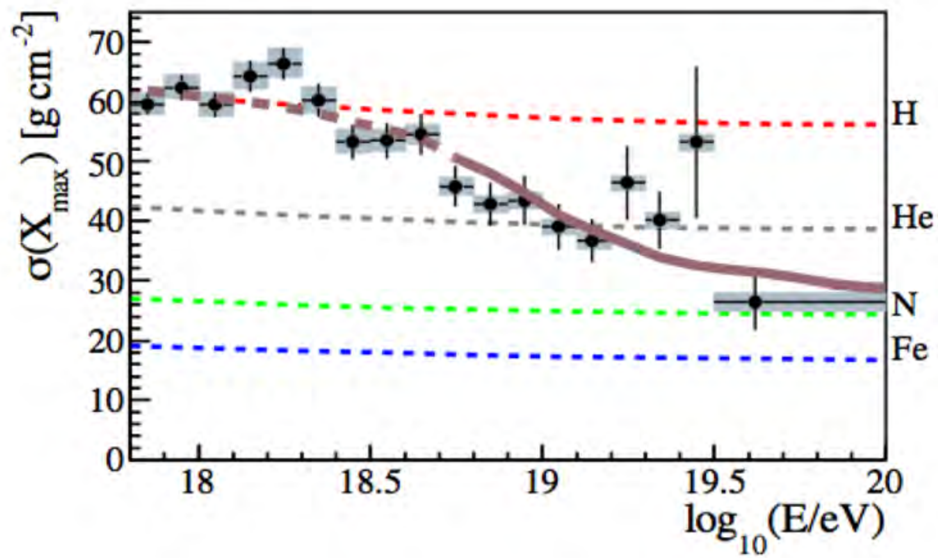
• Hard spectral index
• Low Cutoff energy
Exhaustion of source scenario favored

Caveat: dependence of the propagation models

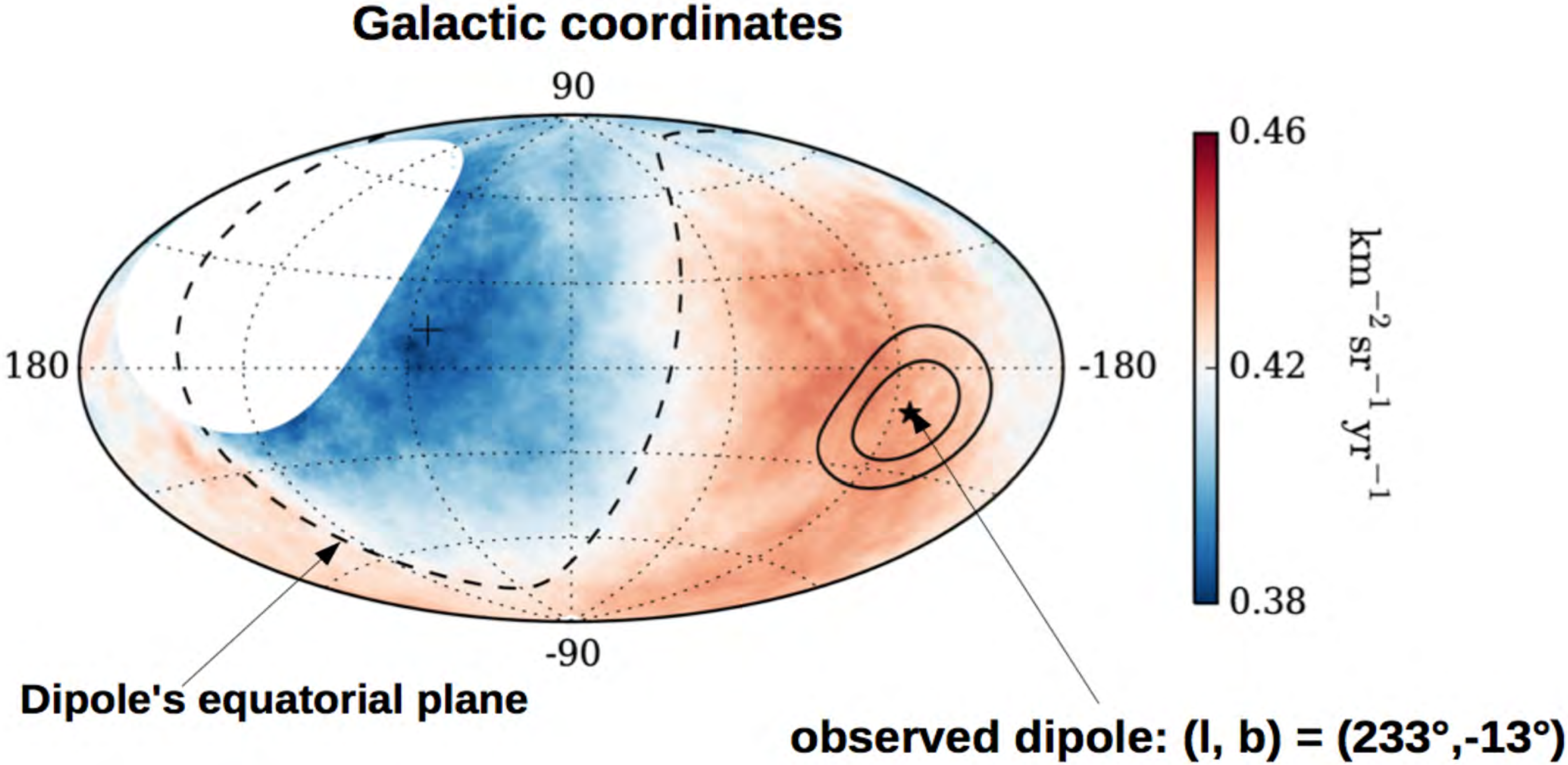
Combined Fit (Xmax and spectrum) of Auger data







Observation of Dipolar anisotropy above 8 EeV

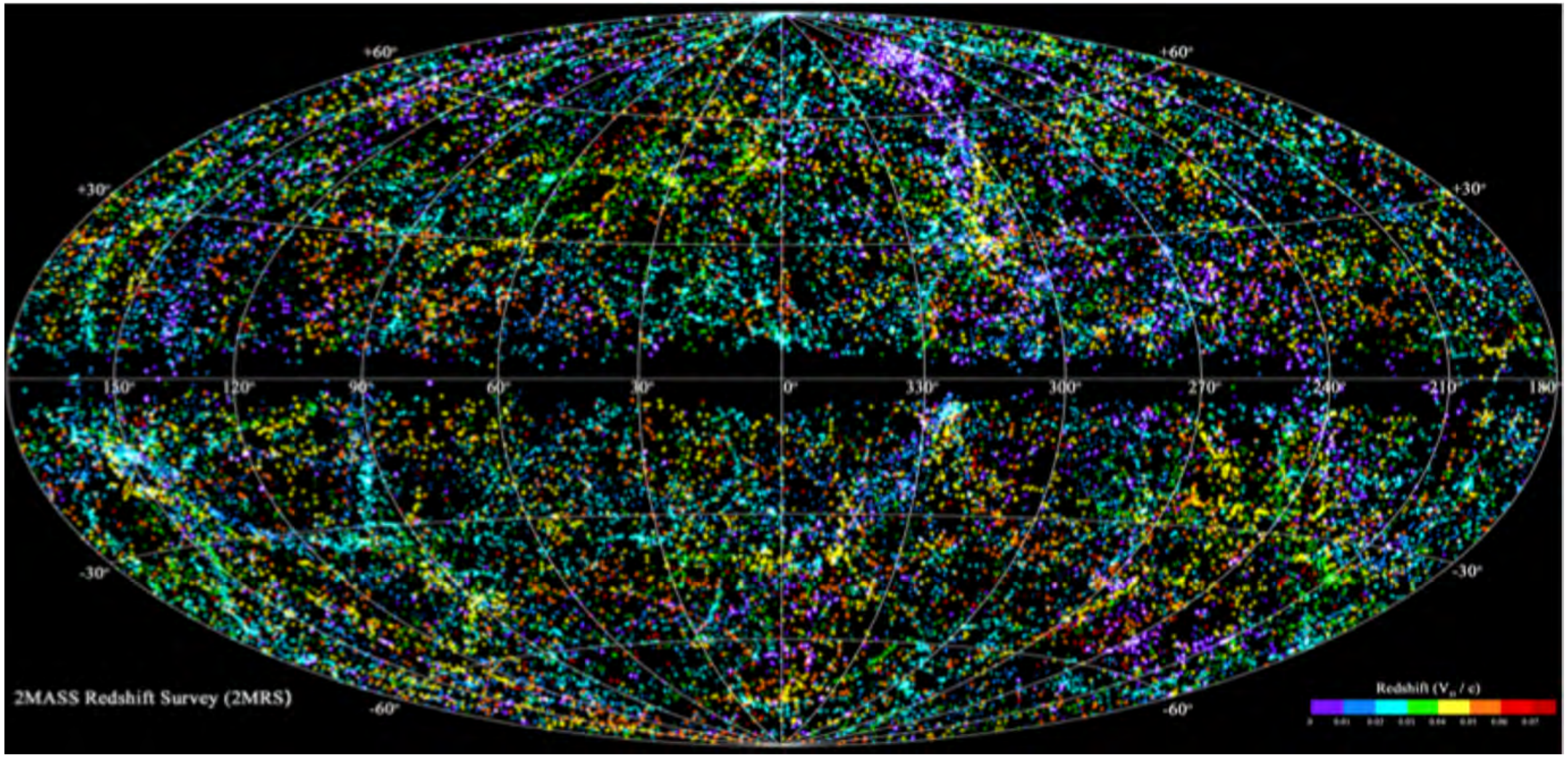


dipole direction ~ 125° from GC → disfavors galactic origin

Observation of Dipolar anisotropy above 8 EeV

Large scale anisotropy can arise from:
- Inhomogeneous large-scale distribution of sources
- Diffusion in extragalactic magnetic fields from dominant nearby sources

Typical dipole amplitudes ~ 5 – 20% at 10 EeV,
depending on source distribution and CR composition



The Pierre Auger Observatory

Surface detector
• array of 1660 Cherenkov stations on a 1.5 hexagonal grid ~ 3000 km^2
• duty cycle ~ 100%

Fluorescence detector
• 4 + 1 buildings overlooking the array (24 + 3) telescopes
• duty cycle ~ 13%

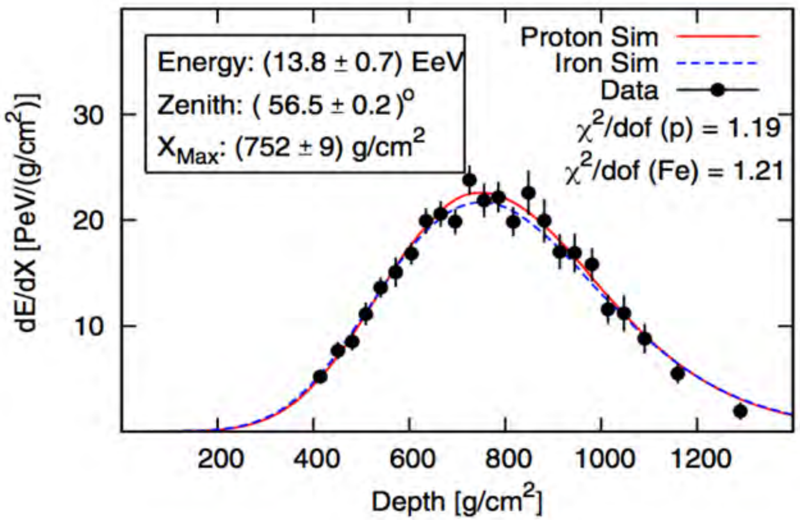
Radio Detector
• 153 Radio Antenna → AERA

Low energy extensions
• Dense array (24 km^2) + muon detectors → AMIGA
• 3 high elevation FD telescopes → HEAT

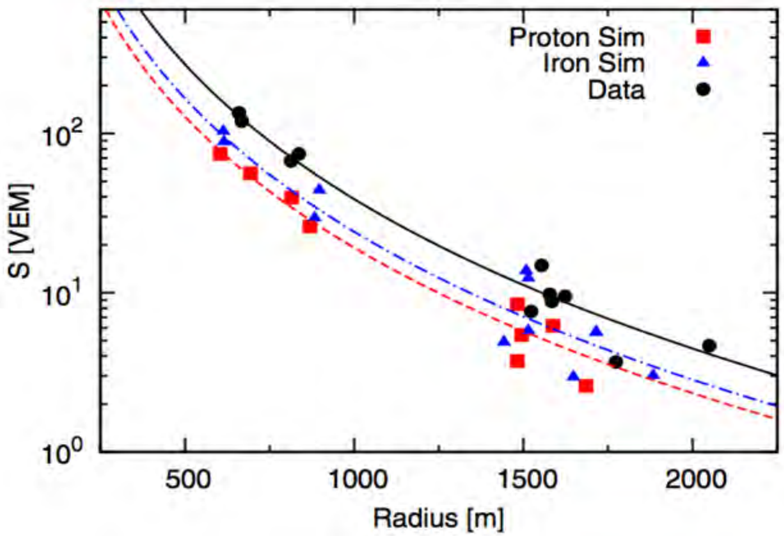
How well hadronic interactions match data?

Hybrid events with energy ~ 10^{19} eV

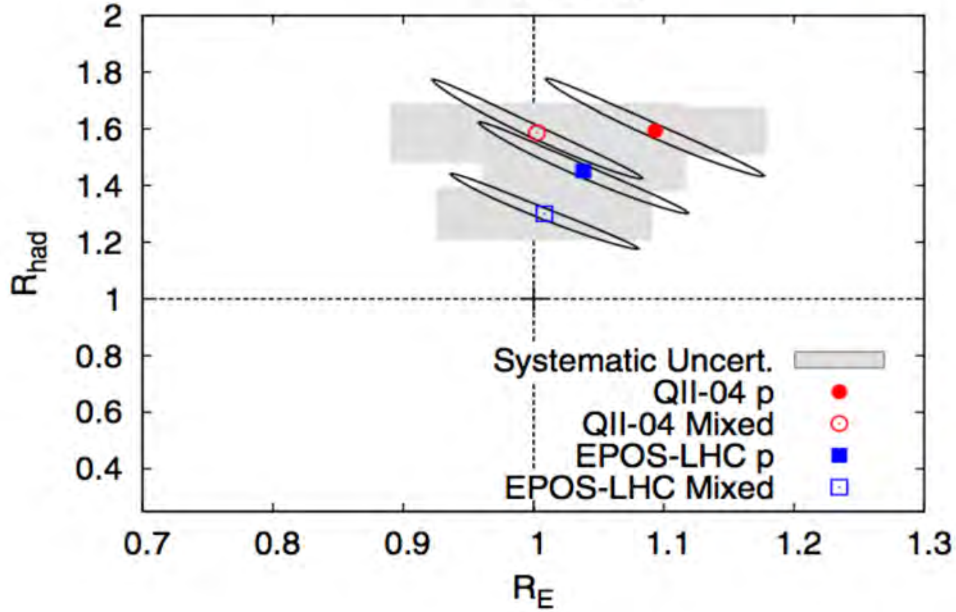
PRL 117, 192001 (2016)



Longitudinal profile from FD real event is reproduced by simulations



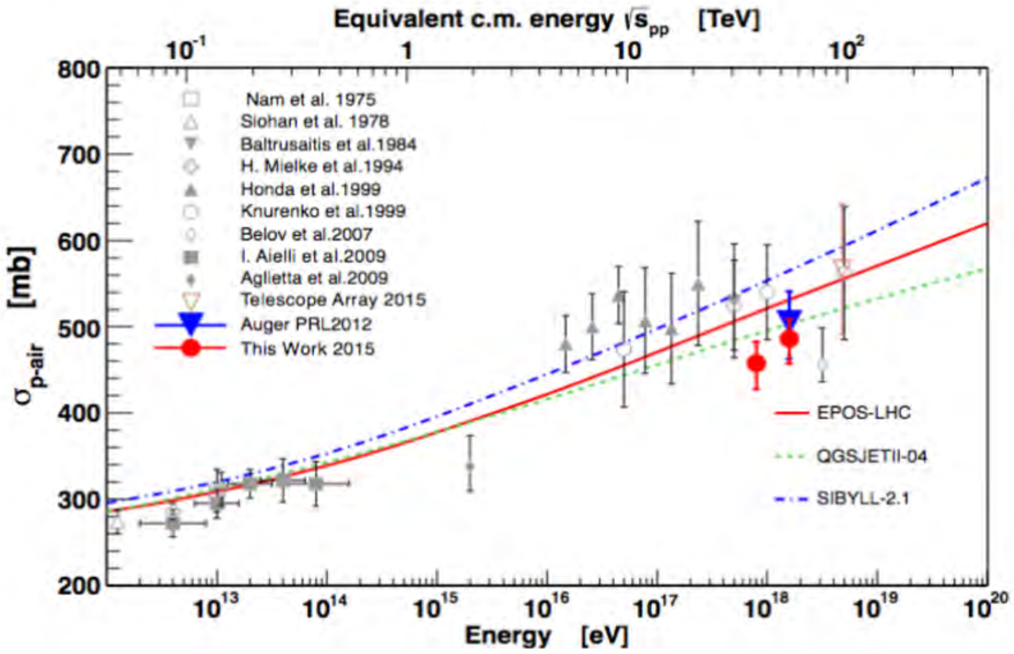
R_{had} and R_E: scaling factors to match data



- **Muon deficit in hadr. models: $1.3 < R_{had} < 1.6$**
- **Insensitive to energy scale uncertainty: R_E ~1**

p-air & p-p Cross-Section

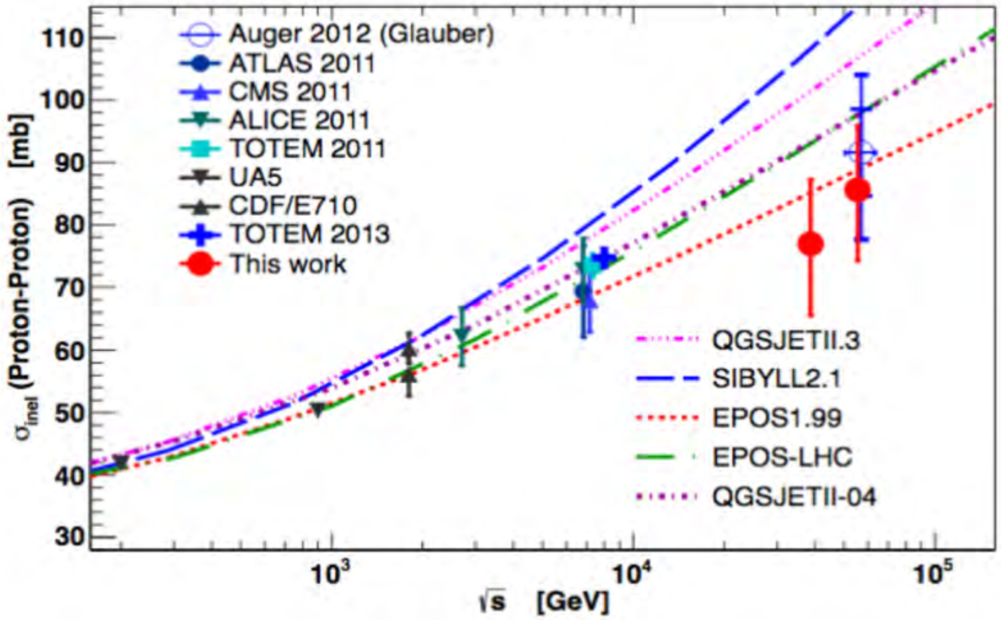
ICRC 2015



Results, $\sigma_{p\text{-}air}$ in mb

• lower energy point
457.5 ± 17.8 (stat) +19/-25 (syst)

• higher energy point
485.8 ± 15.8 (stat) +19/-25 (syst)

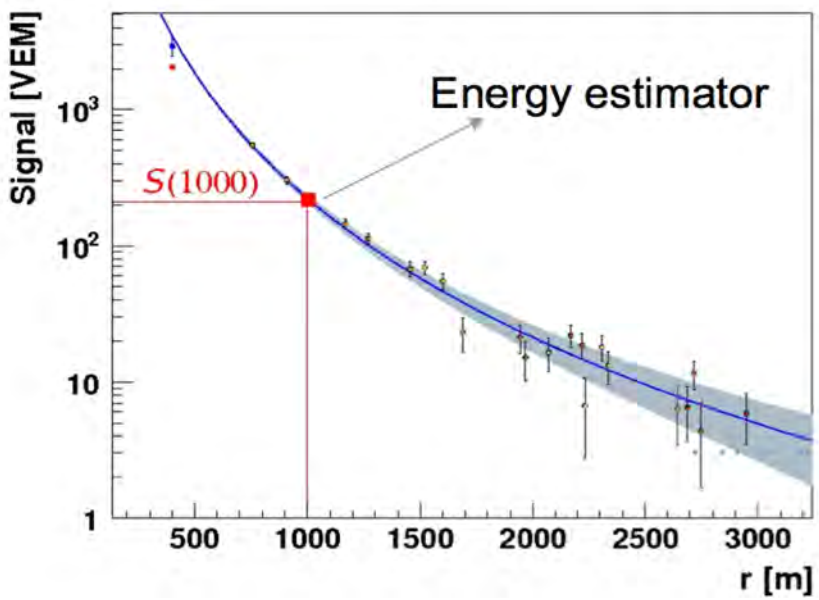


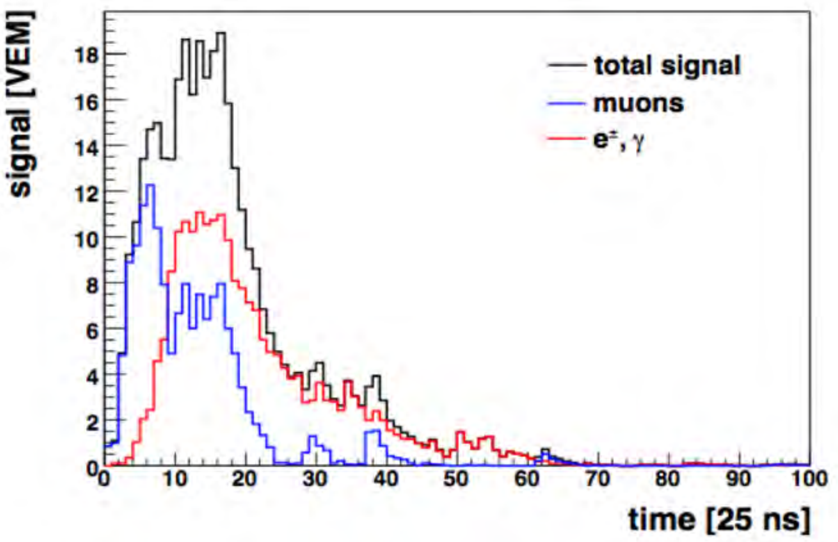
Results, inel $\sigma_{p\text{-}p}$ in mb

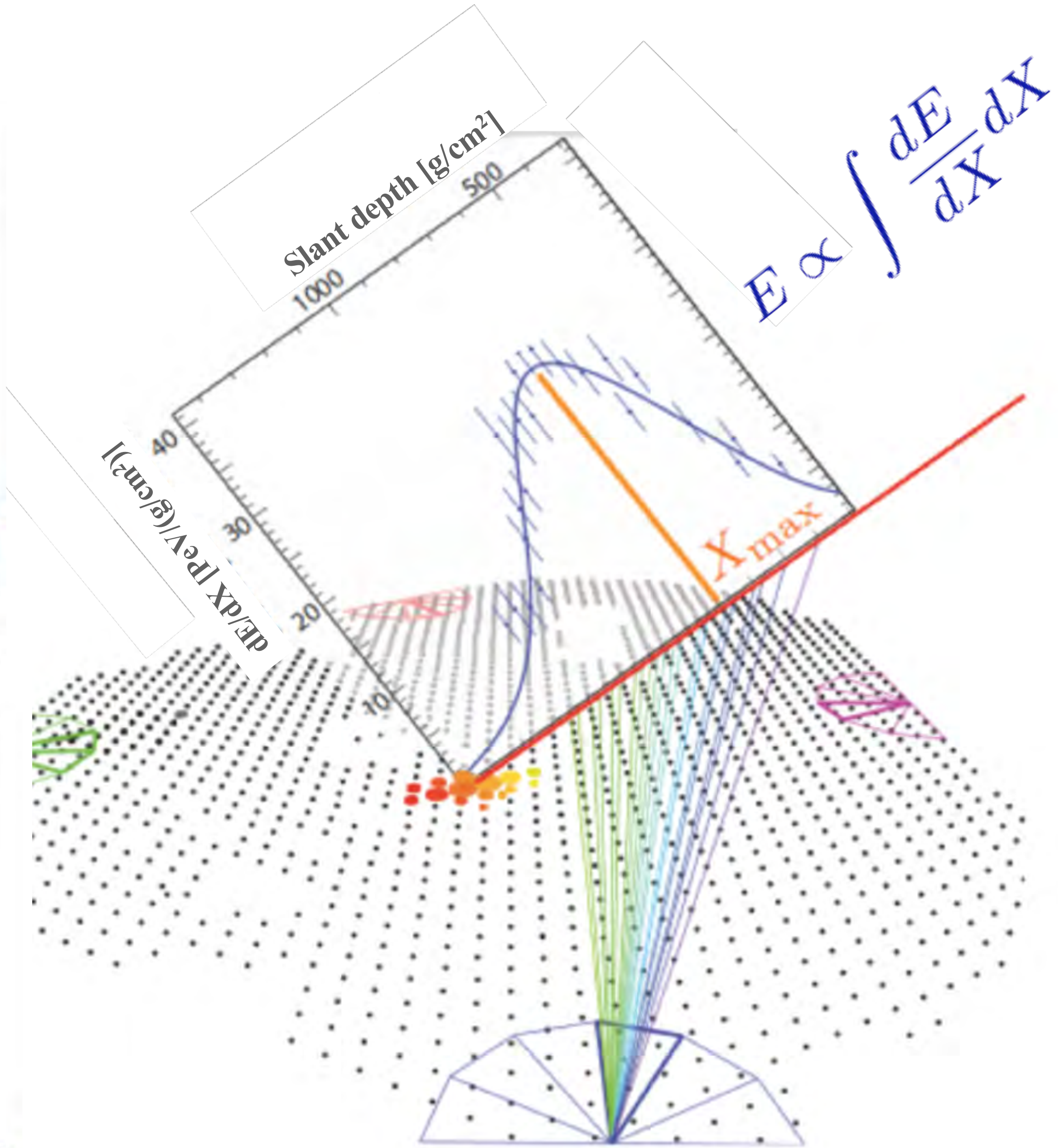
• lower energy point
76.95 ± 5.4(stat) +5.2/-7.2(syst) ±7 (glauber)
at $\sqrt{S_{pp}} = 38.7 \pm 2.5$ TeV

• higher energy point
85.62 ± 5(stat) +5.5/-7.4(syst) ±7.1 (glauber)
at $\sqrt{S_{pp}} = 55.5 \pm 3.6$ TeV

Hybrid Detection of Air Showers

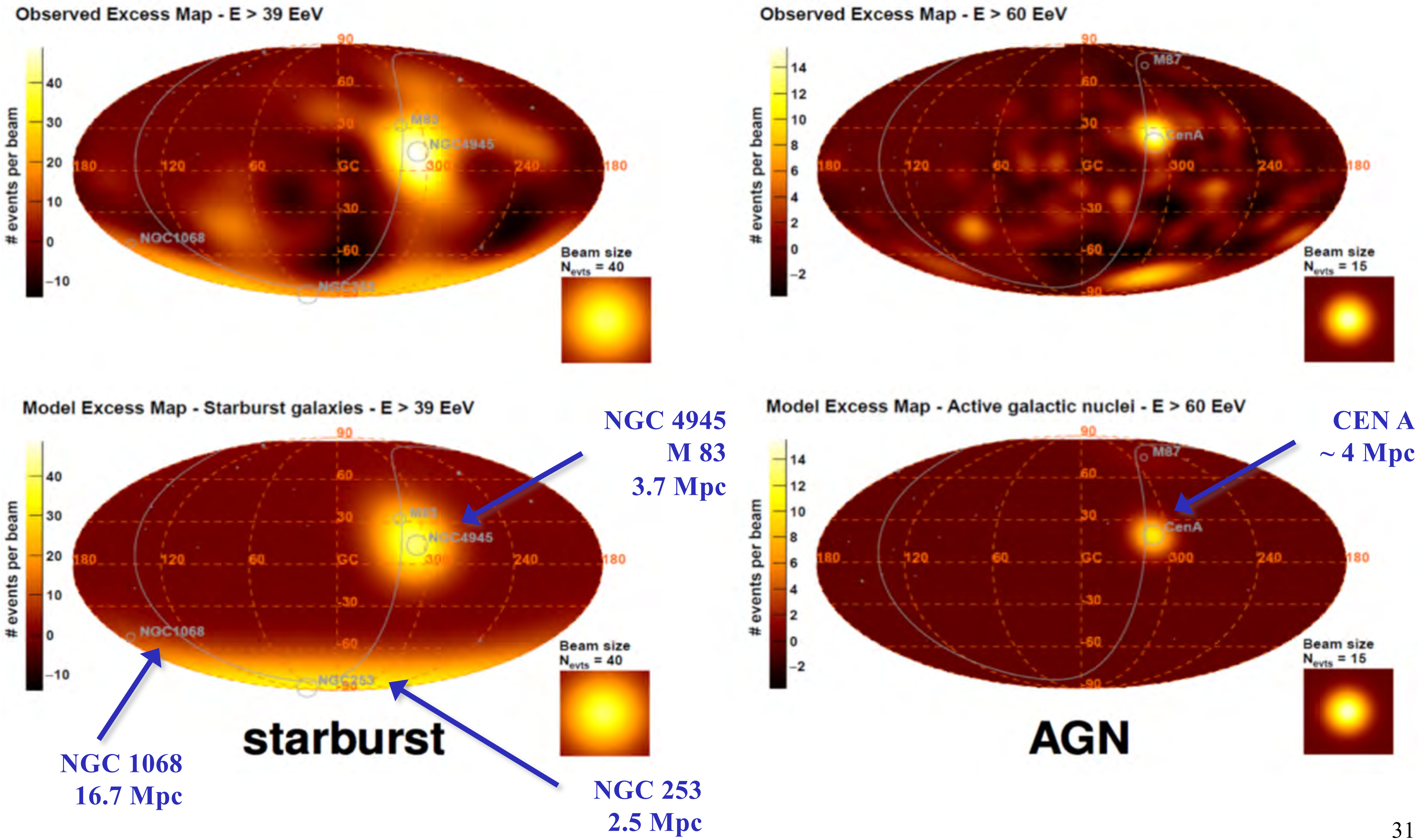




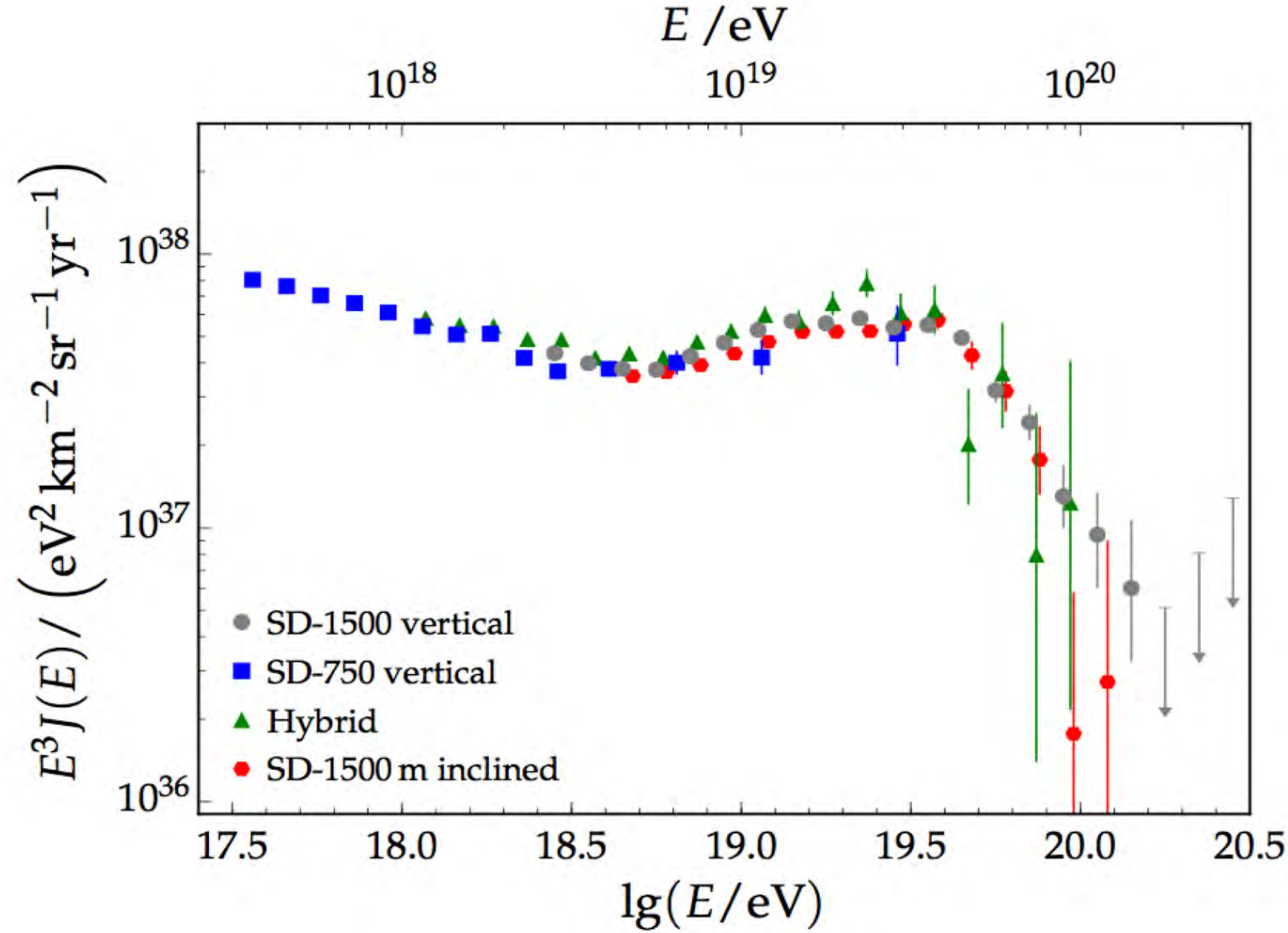


Indication of anisotropy at intermediate scale

ICRC 2017



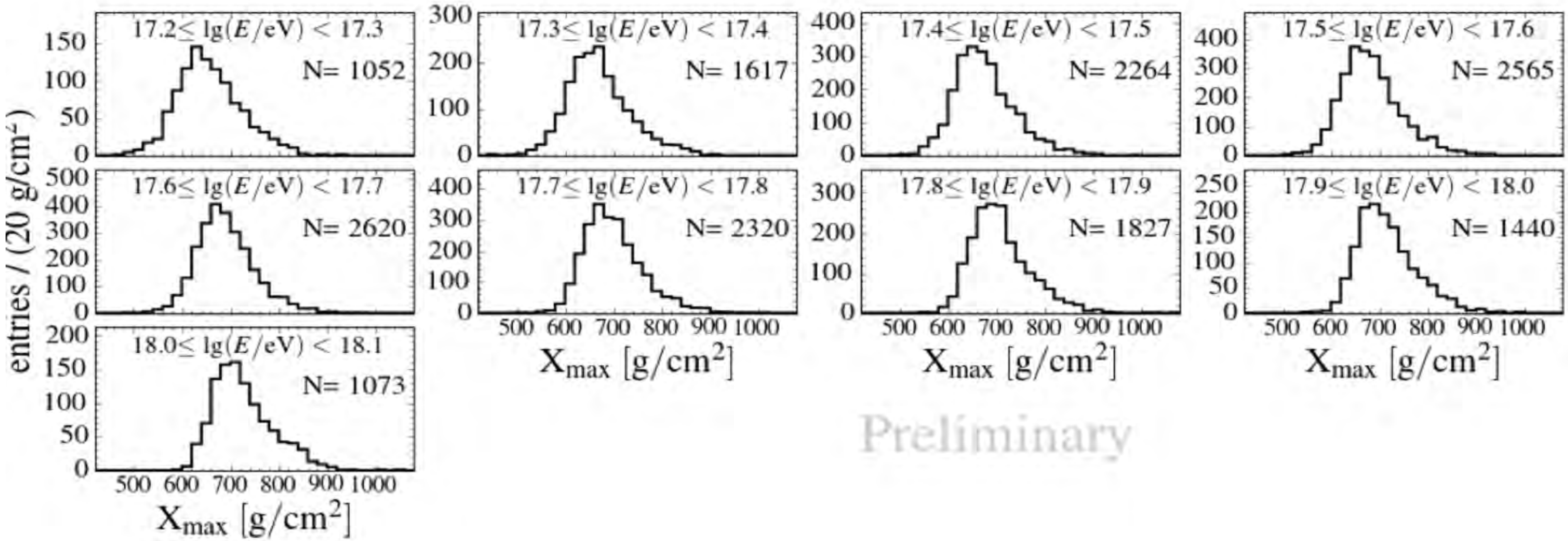
Energy Spectrum



ICRC 2017

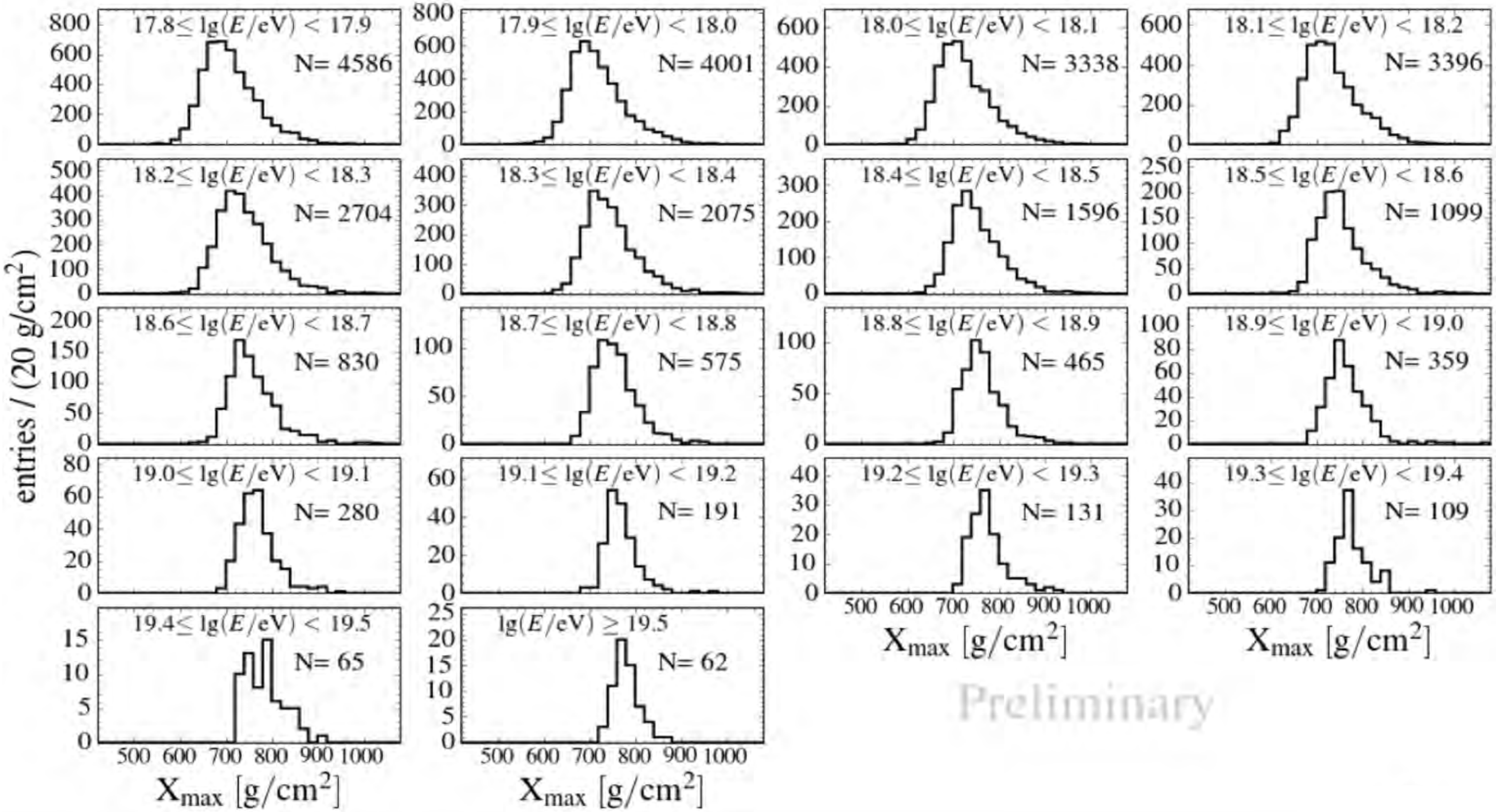
X_{max} distributions

ICRC 2017

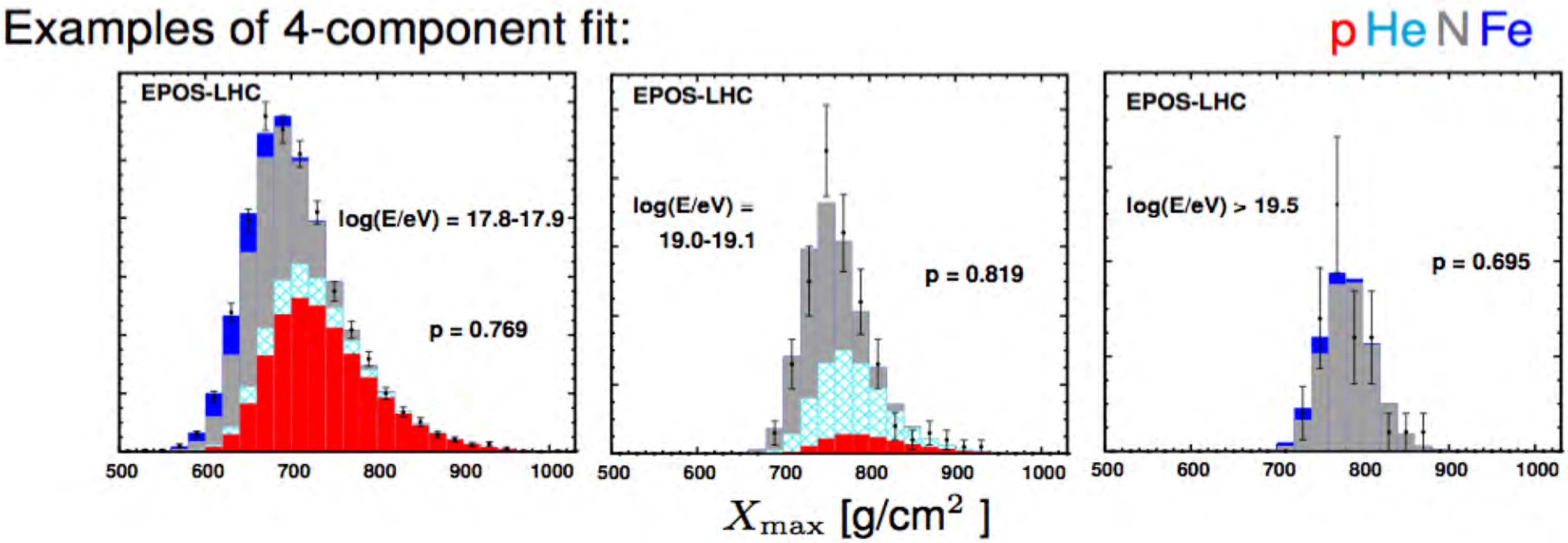


X_{max} distributions

ICRC 2017

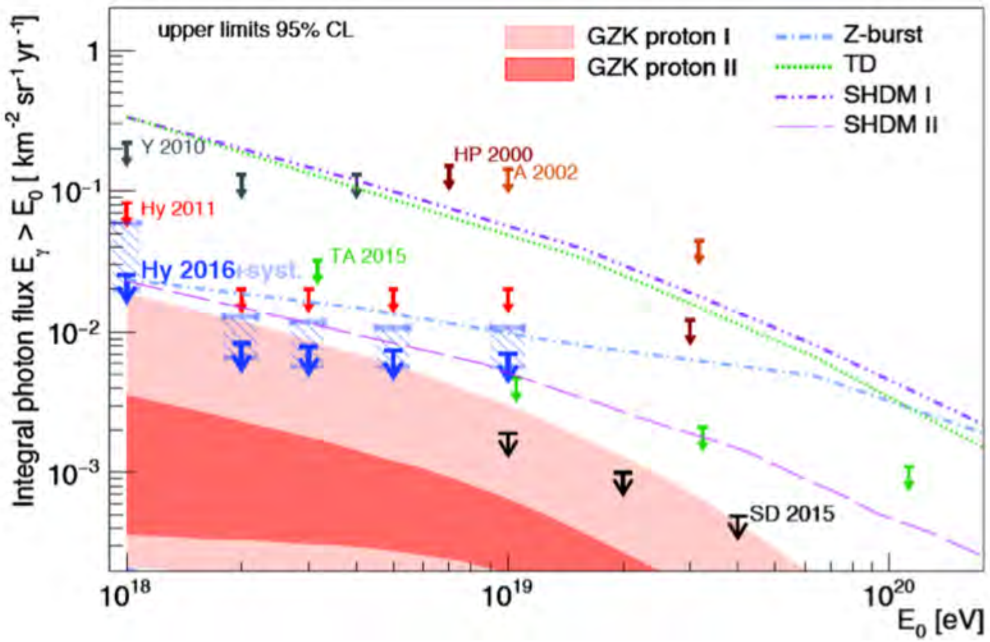


Composition fractions



Search for photons and neutrinos

JCAP04(2017)009



Photons

4 photons candidates above 10 EeV (SD)

3 photons candidates between 1-2 EeV (hybrid)

Strictest limits at E > 1 EeV

- Top-down model strongly disfavored
- CR proton dominated scenario start to be disfavored

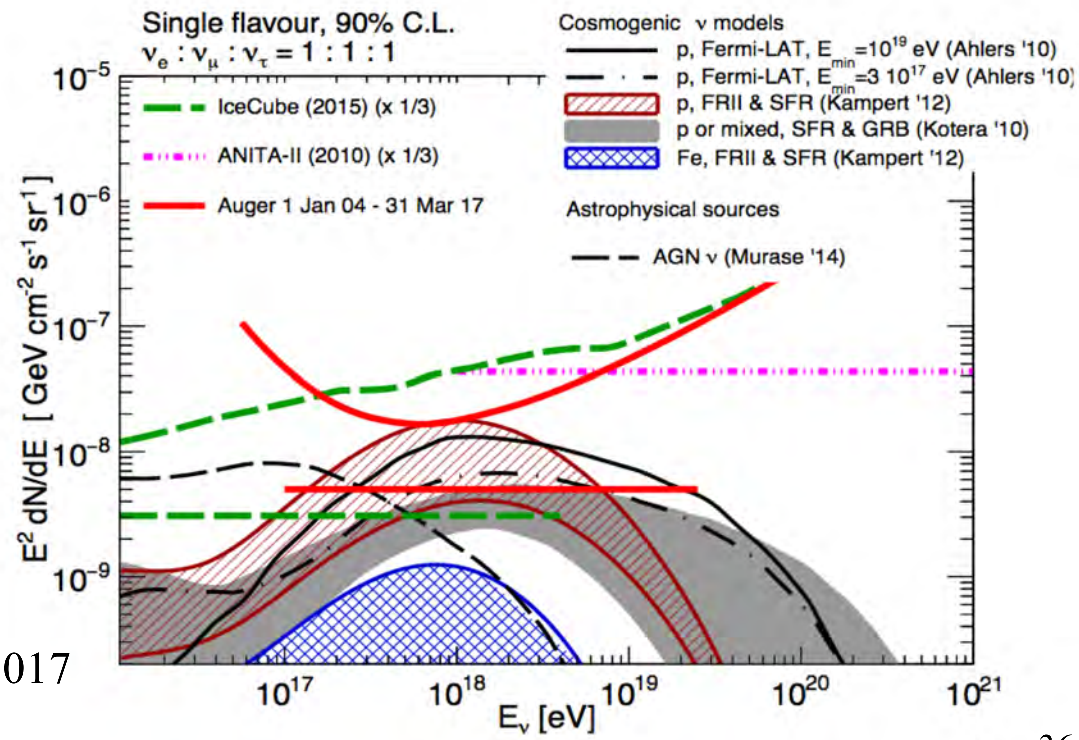
Neutrinos

No candidates

$dN/dE = k\ E^{-2}$

→ k ~ 5 x 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} [0.1-25] EeV

Auger limits constrain models with pure proton primaries



ICRC 2017

Hybrid detection

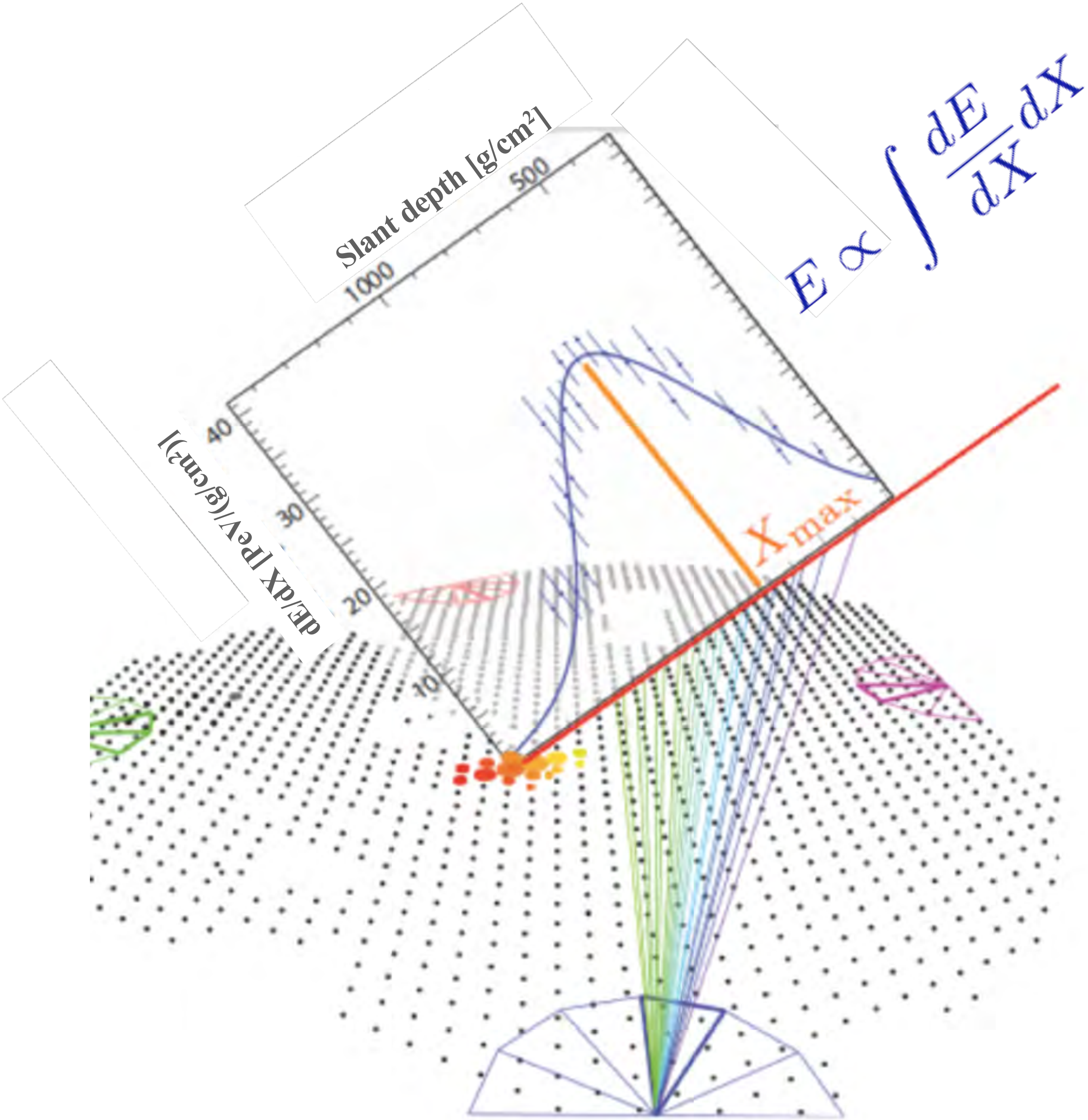
Hybrid Detection

Surface Detectors

- ✓ 1660 water cherenkov stations
- ✓ 1500 m grid
- ✓ duty cicle ~ 100%
- ✓ lateral density distribution

Fluorescence Detectors

- ✓ longitudinal profile
- ✓ 4 + 1 buildings, 27 telescopes
- ✓ duty cicle ~ 13 %



✓ Taking data since 2004
✓ Completed in 2008

Composition fractions

ICRC 2017