Ultra High Energy Cosmic Rays In the Pierre Auger Observatory Era

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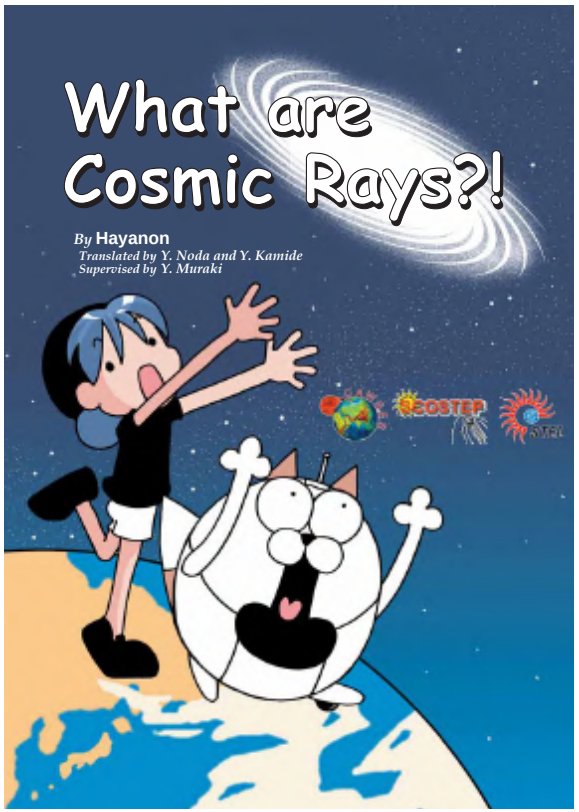
Cosmic Rays
Before the Pierre Auger Observatory Era

What are Cosmic Rays?

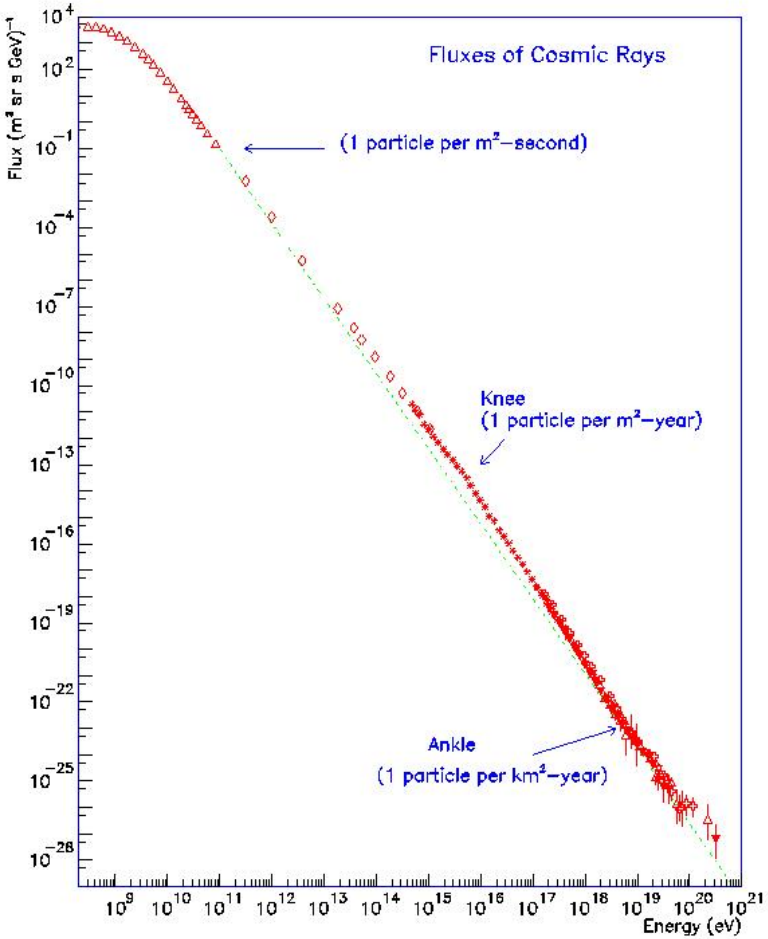
- Energetic radiation from space
- Discovered in 1912 by Victor Hess
- Named Cosmic Rays by Millikan

Reading for your (my) kids:



http://www.telescopearray.org/media/cosmicrays_e.pdf

Cosmic Rays Spectrum



- Power law with index 2.7
- 12 orders of magnitude in energy
- 32 orders of magnitude in flux
- only few features
  - Knee: 1 event/m^2/sr/year
  - Ankle: 1 event/km^2/sr/year

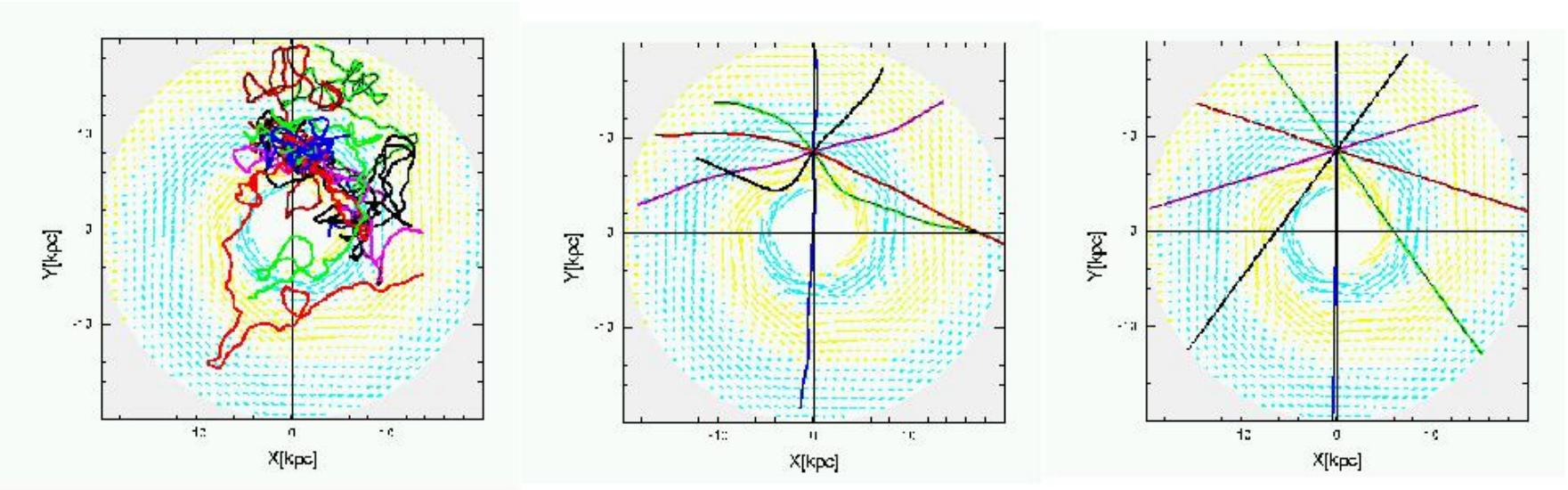
UHECR

- At 10^{20} eV: 1 event/km^2/sr/century
- First event: Volcano Ranch, 1962

UHECR Astronomy

Magnetic fields

At low energies, CR are deflected by galactic and extra-galactic magnetic fields.
UHECR (protons in particular) should point to the source

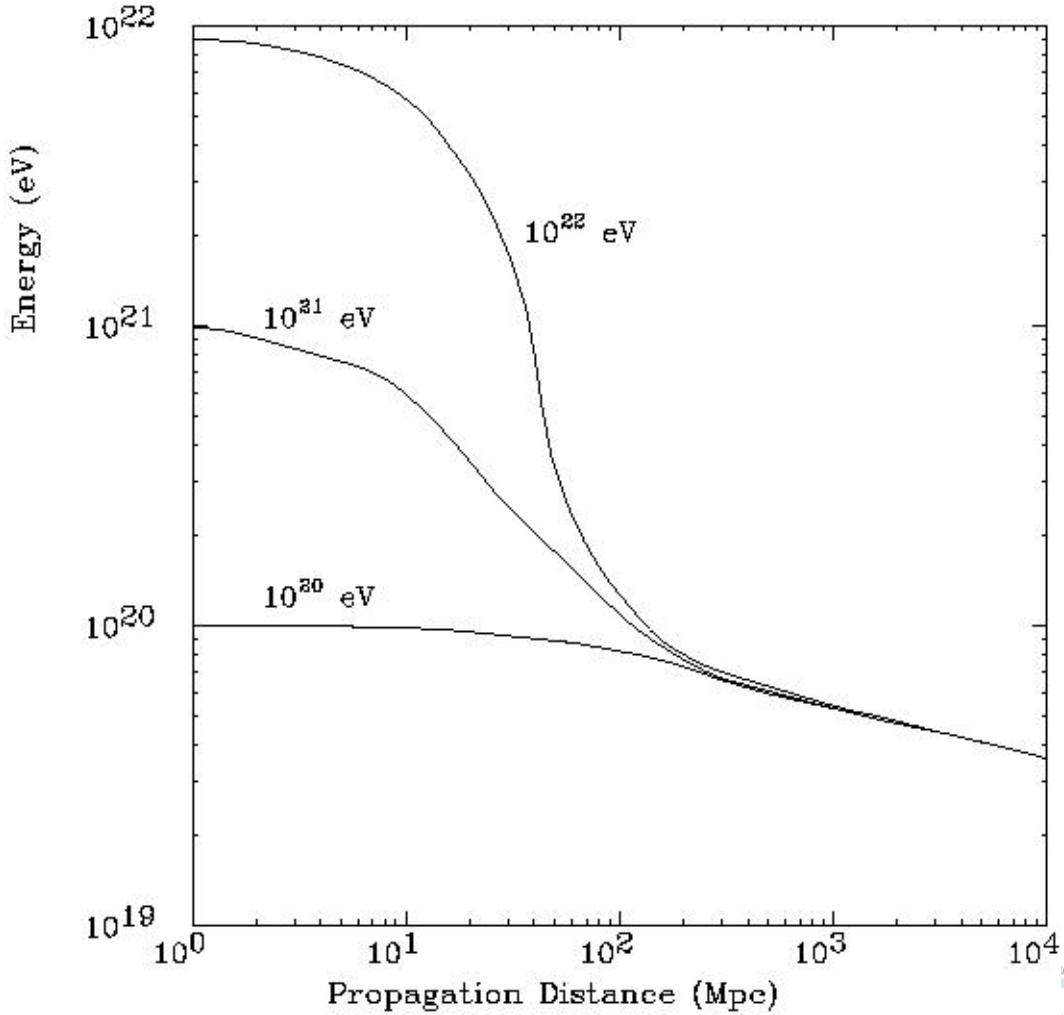


10^{18} eV 10^{19} eV 10^{20} eV

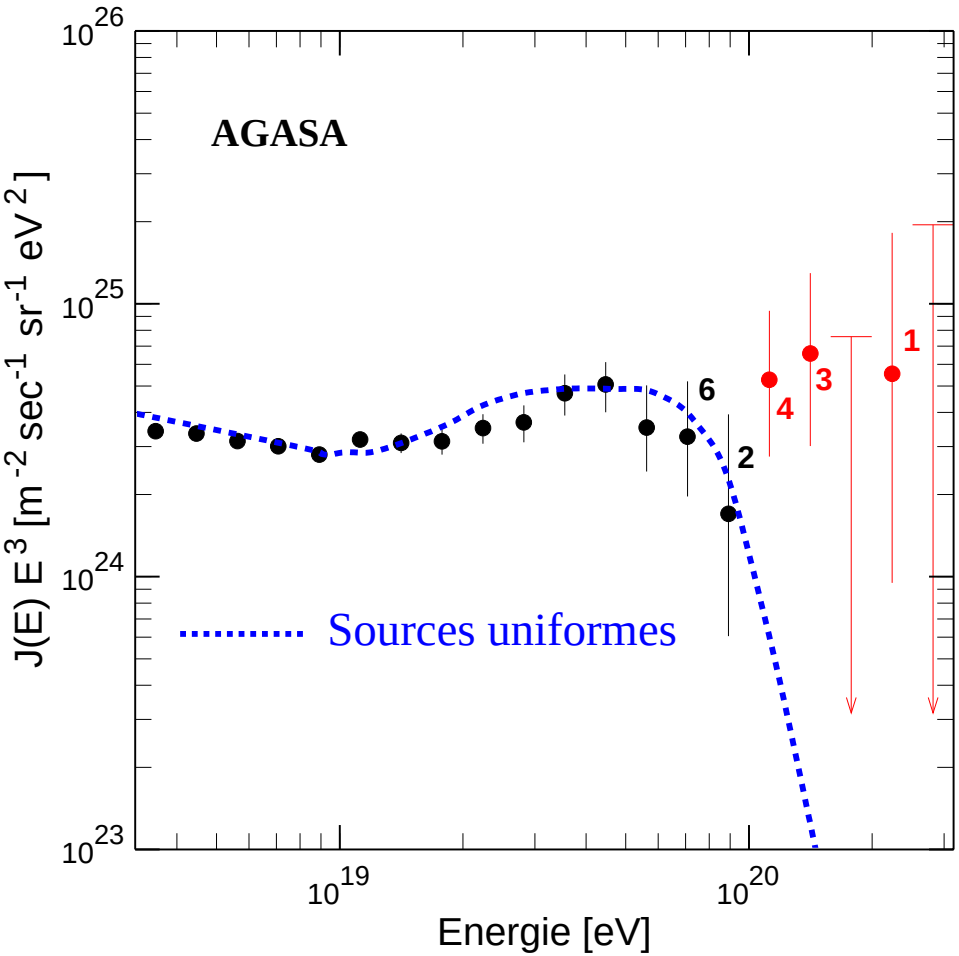
GZK cut-off

At UHE, protons interact with CMB photons by photo production, and nuclei with CMB and IR photons through photo dissociation

UHECR should lose energy quickly on short distances ($< 100\,\mathrm{Mpc}$)



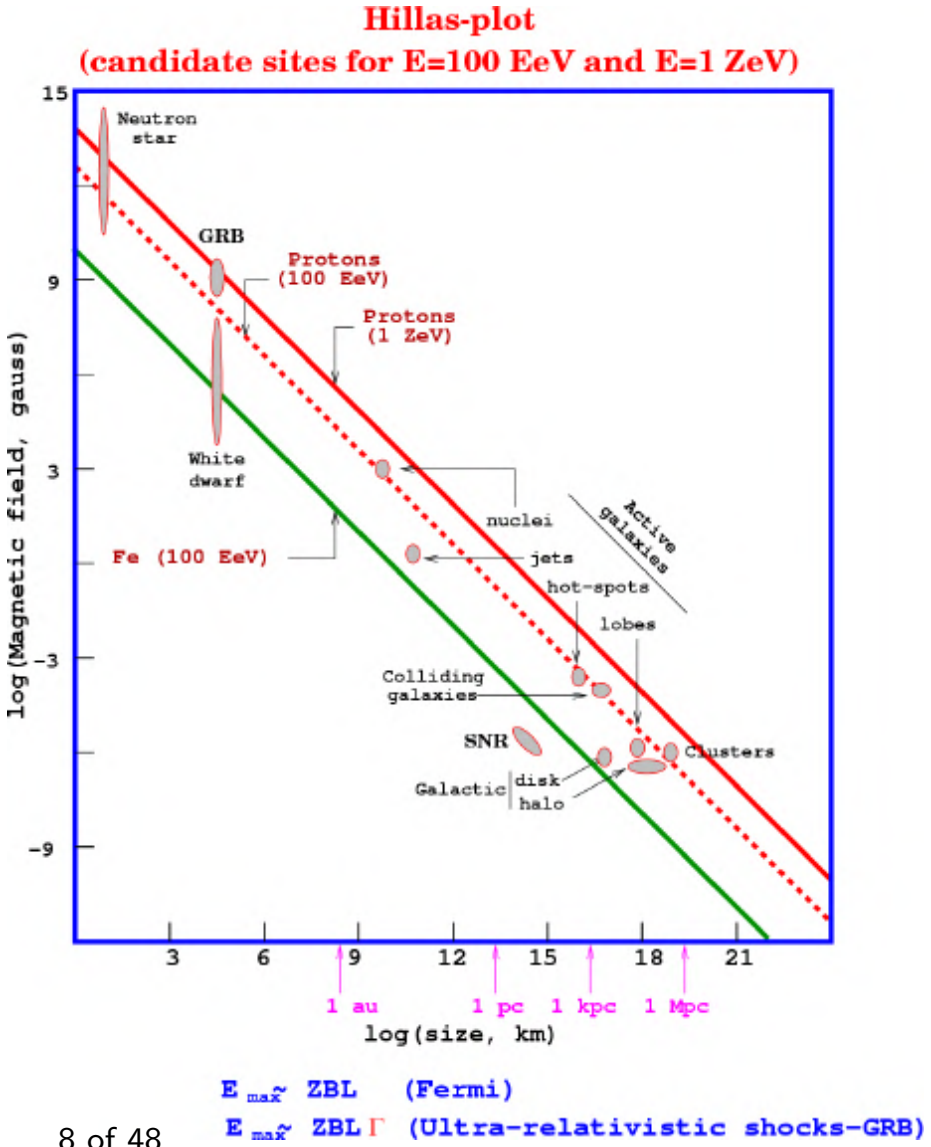
AGASA Spectrum (2002)



AGASA

- 111 scintillator detectors, over 100 km^2 for 11 years
- Exciting feature: softer slope at UHE
- Even better: post-GZK events

UHECR Sources?



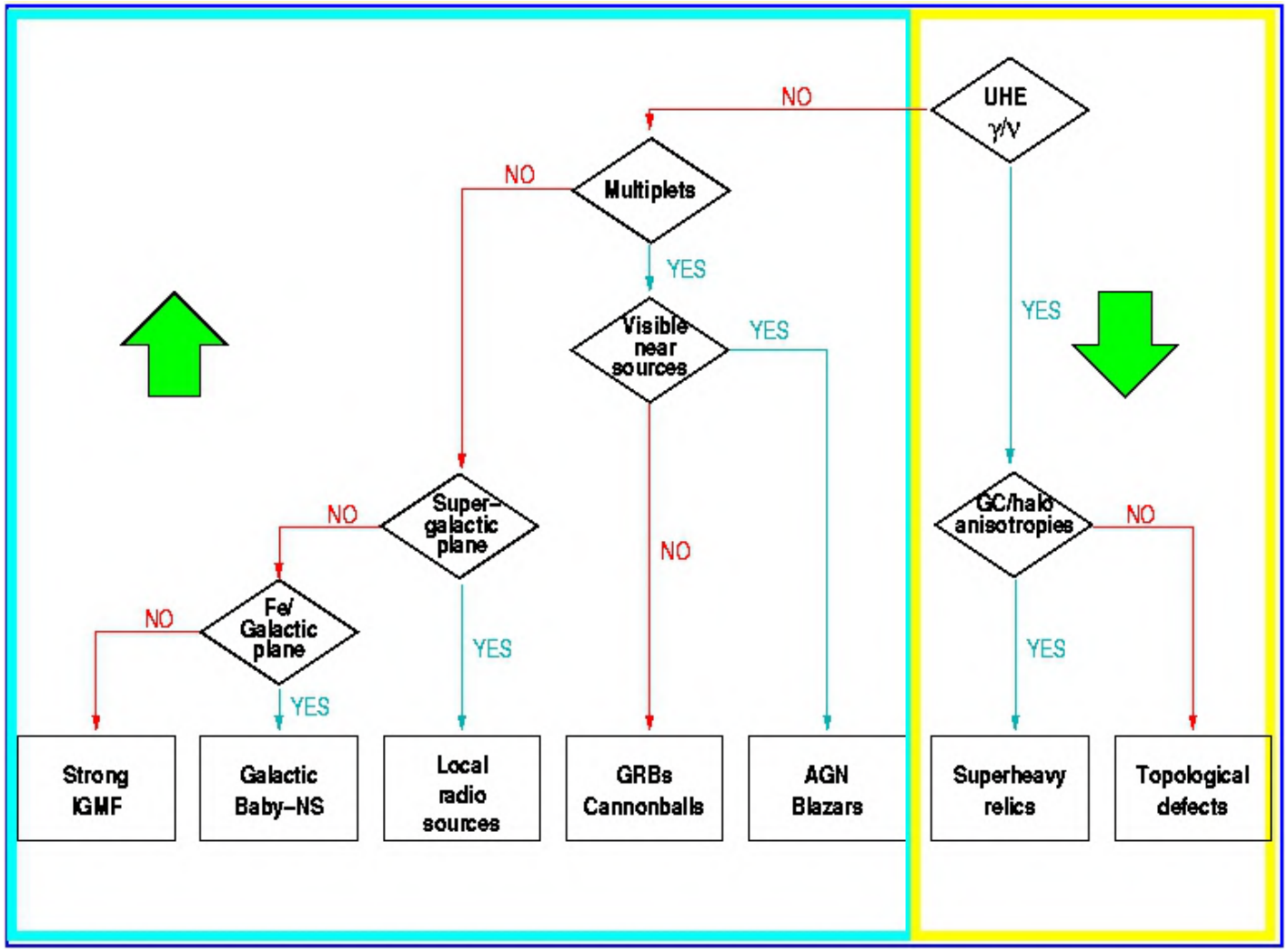
Bottom-Up

- $E_{max} \simeq Z\ B\ L$

Top-Down

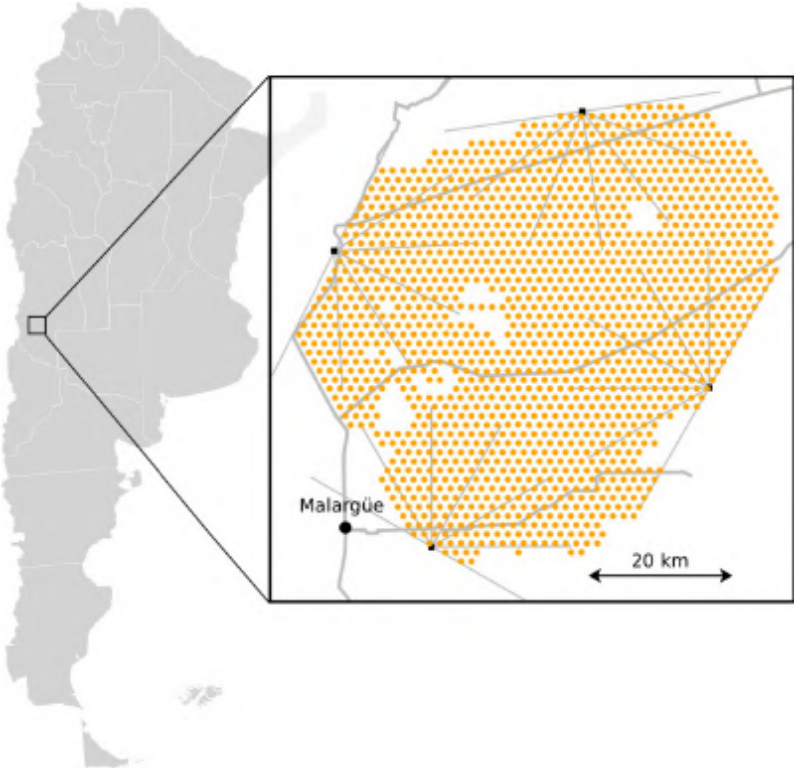
- Super massive particle
- Topological Defect

The Model Killer



the Pierre Auger Observatory

The Pierre Auger Observatory



In Malargüe (Argentina)

- 69.3° W, 35.3° S
- 1400 m a.s.l. (870 g cm^{-2})

Design

- UHECR study ($E \geq 10^{18}$ eV)
- Construction over in 2008

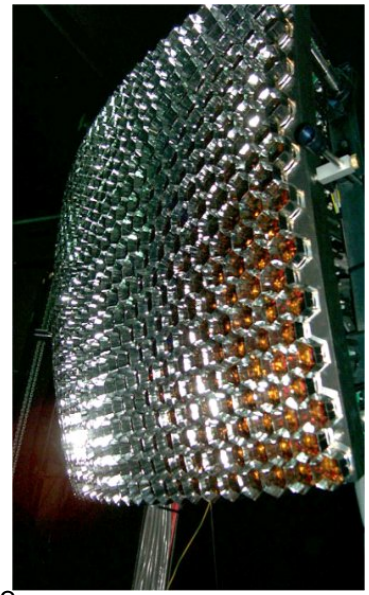
UHECR hybrid detection

- Ground detectors (SD): 1600 Water Cherenkov Detectors covering 3000 km^2 on a 1500 m triangular grid
- Fluorescence detectors (FD): 24 fluorescence telescopes in 4 sites observing over the SD area

Ground detectors: WCD

- $10\,m^2$ area rotationally molded polyethylene tanks
- $12\,m^3$ ultra pure water in a diffusive bag
- Cherenkov light collected by three 9" PMTs
- 40 MHz FADC digitization
- Radio wireless communication
- GPS based timing
- Battery and solar panel powered

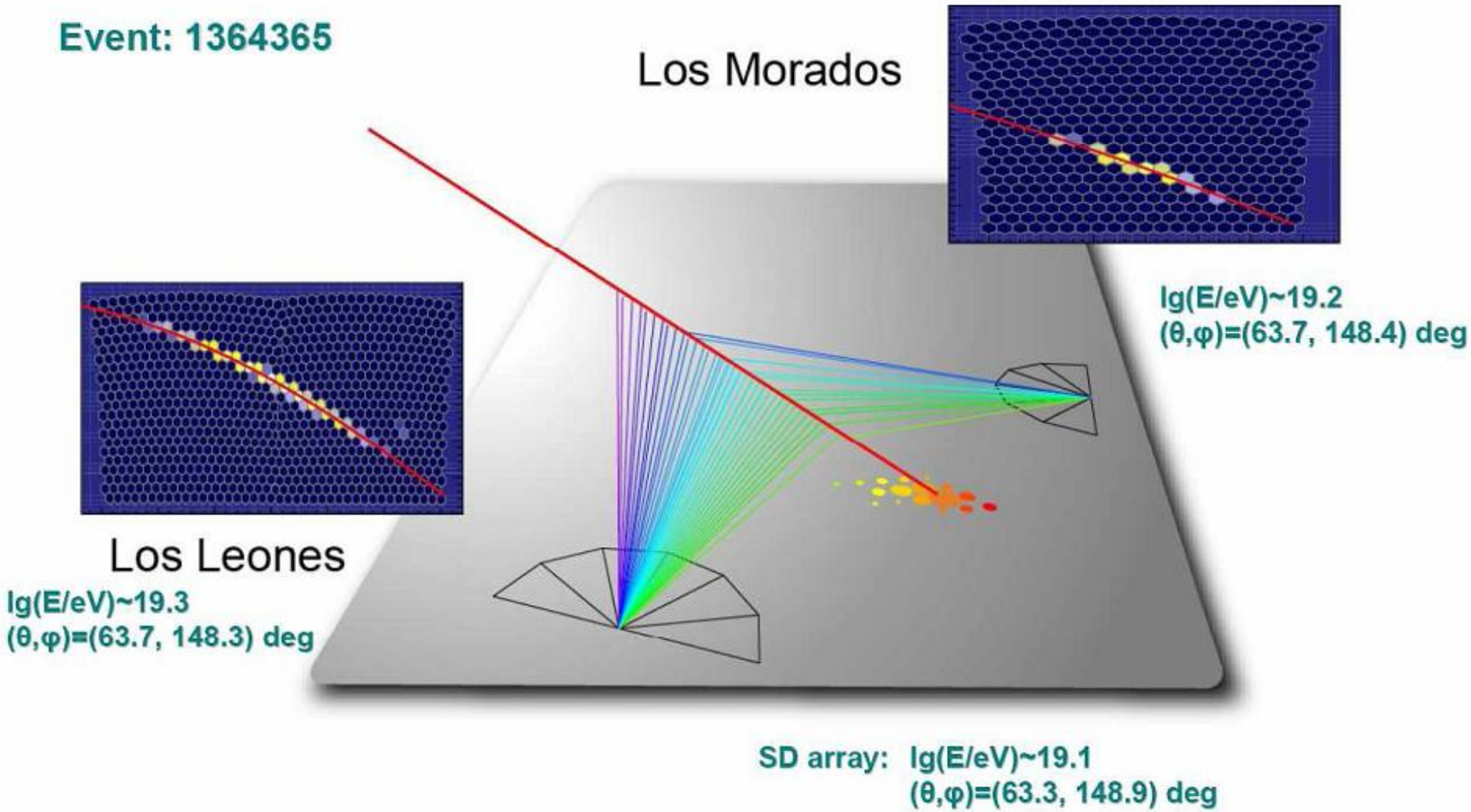
Fluorescence telescopes



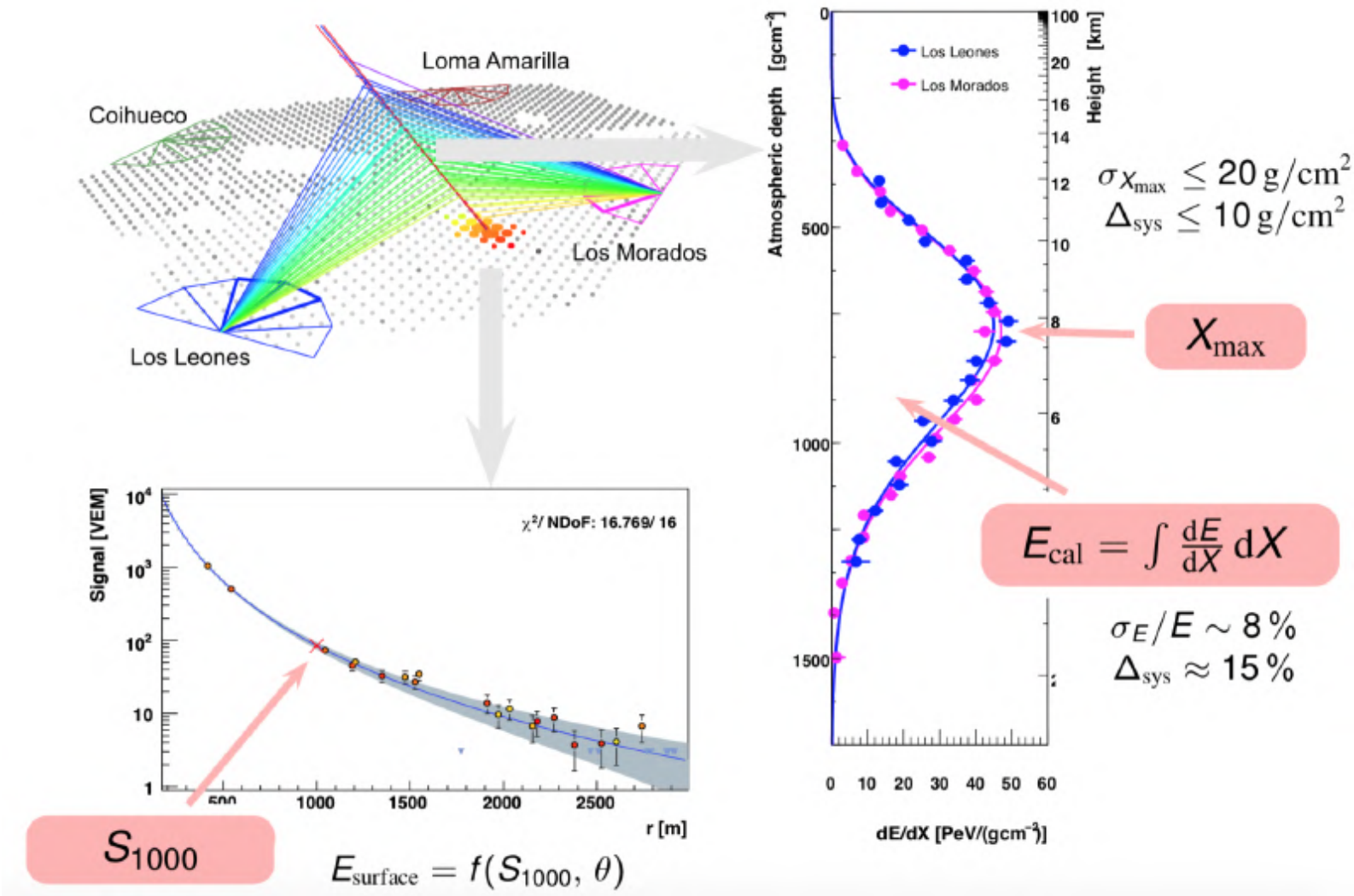
- 4 FD buildings
- 6 cameras per building
- UV filters
- 440 PMT per camera

- $180^\circ \times 30^\circ$ field of view
- 10% duty cycle
- Observes longitudinal development
- Calorimetric energy measurement
- Composition measurement (X_{max})

Hybrid events

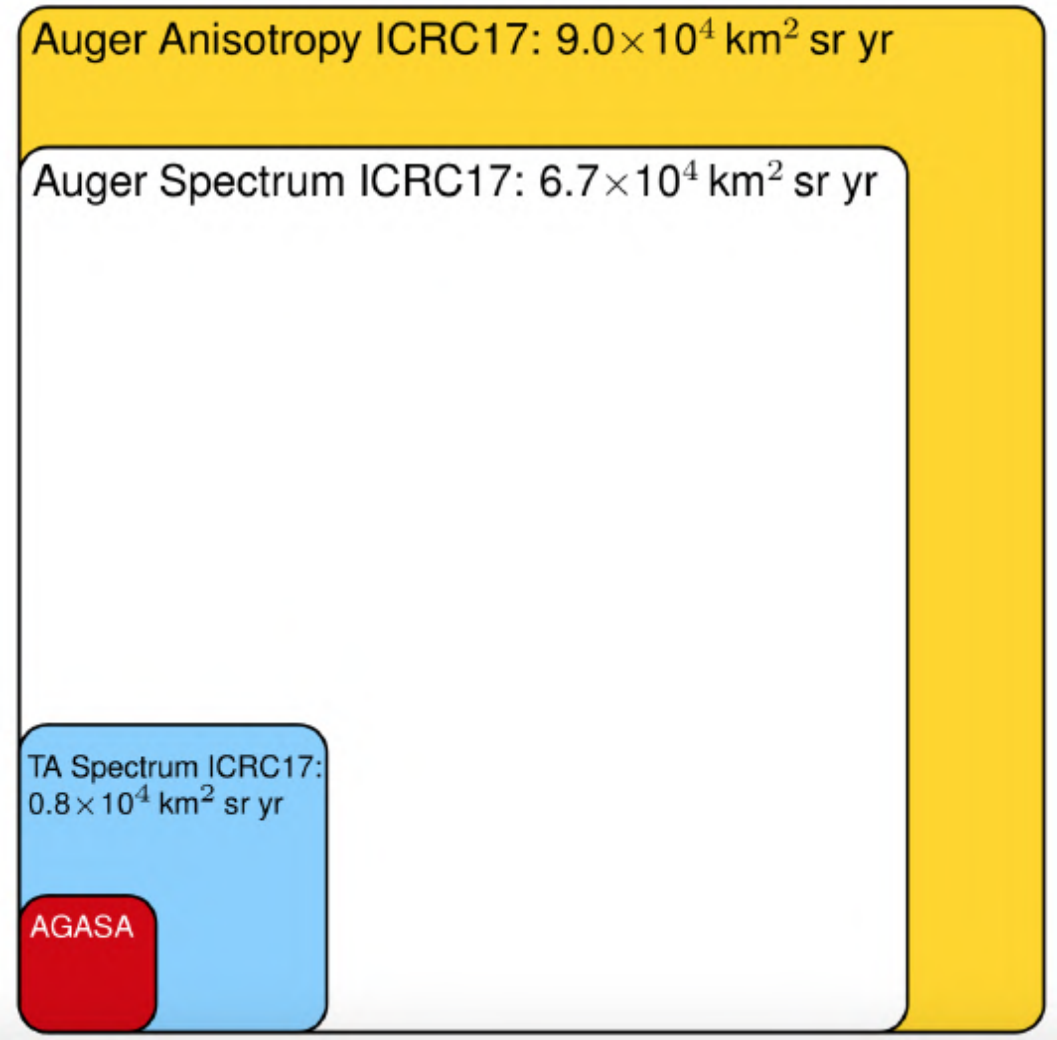


Hybrid reconstruction



The new Era for UHECR

UHE Exposure



The new Era for UHECR

Bottom Up vs Top Down

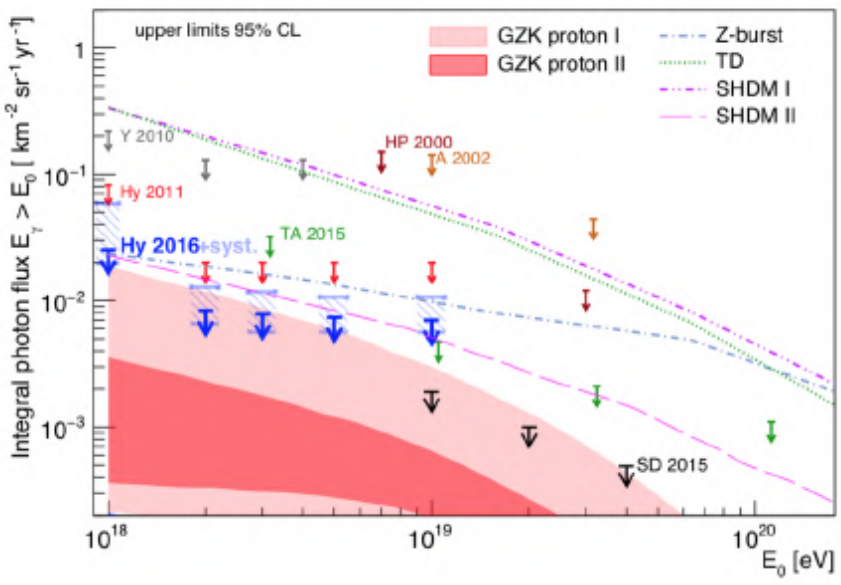
Spectrum

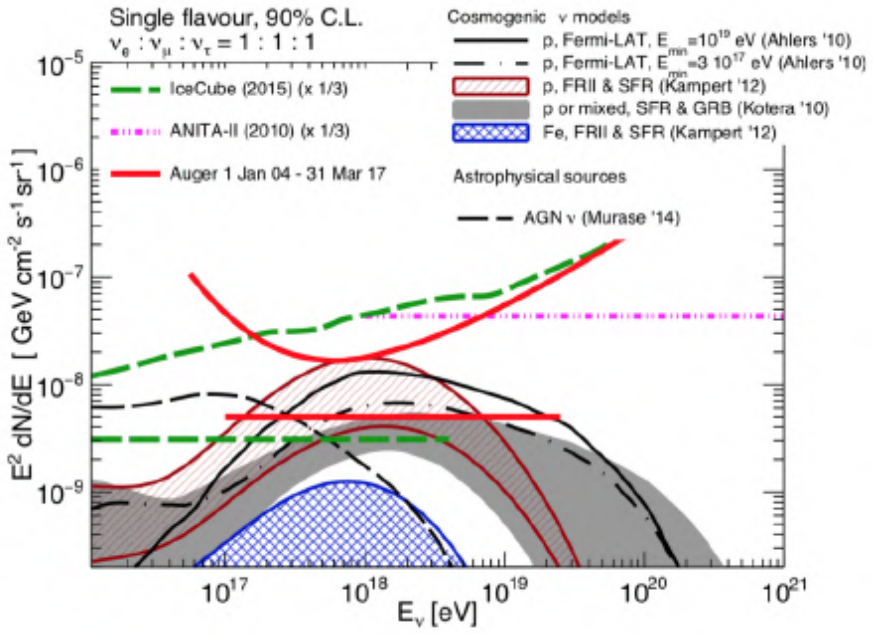
Composition

Looking for the sources

High Energy Physics

No photons, no neutrinos





- Top Down model interpretation of UHECR rejected
- Search for Cosmogenic Photons and Neutrinos started
- Search for multimessenger (Ex: Binary Neutron Star Merger)

The new Era for UHECR

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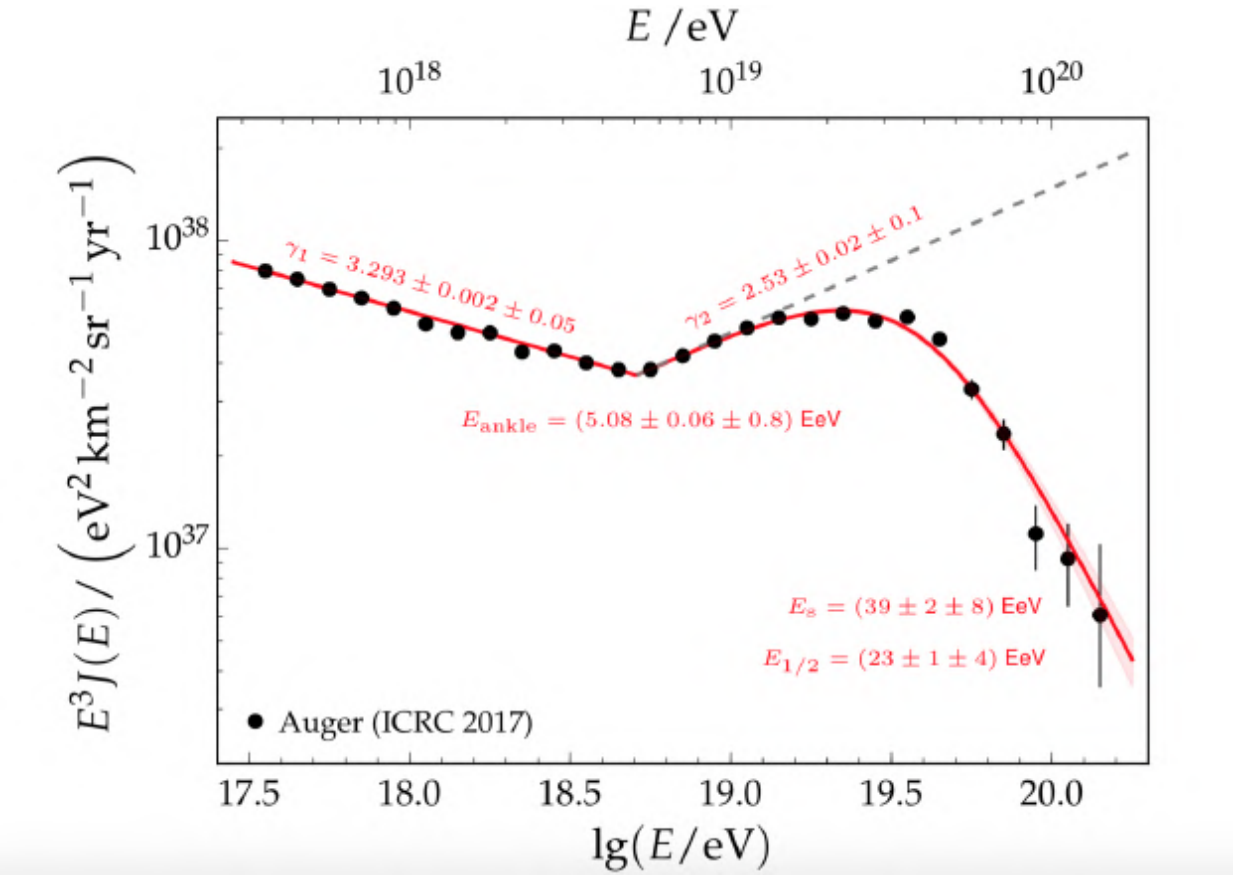
High Energy Physics

Energy Spectrum



- Strong suppression at 40 EeV (GZK? Source limit?)
- below 1 event per km.sr per milenium at 100 EeV

The new Era for UHECR

Bottom Up vs Top Down

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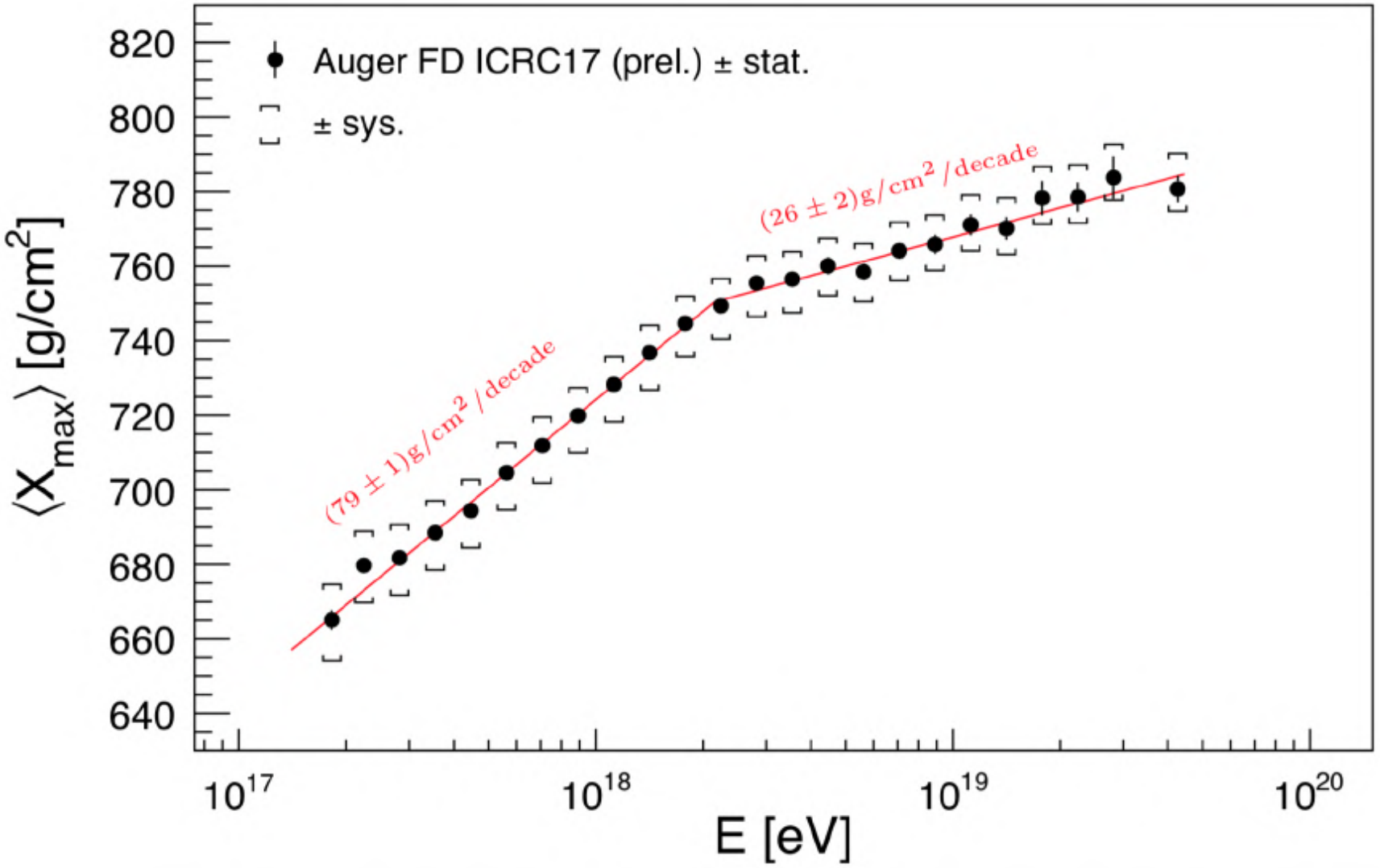
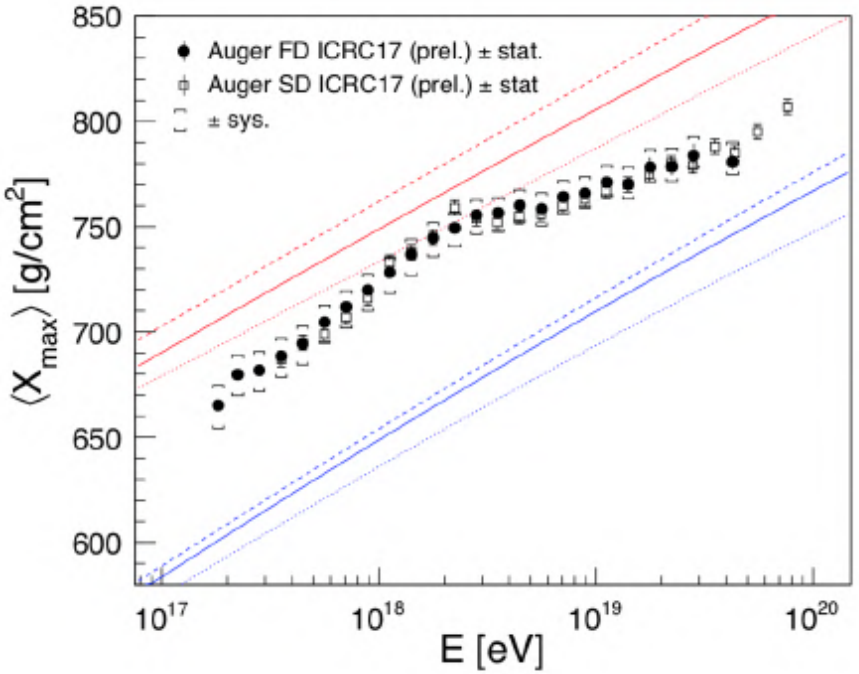
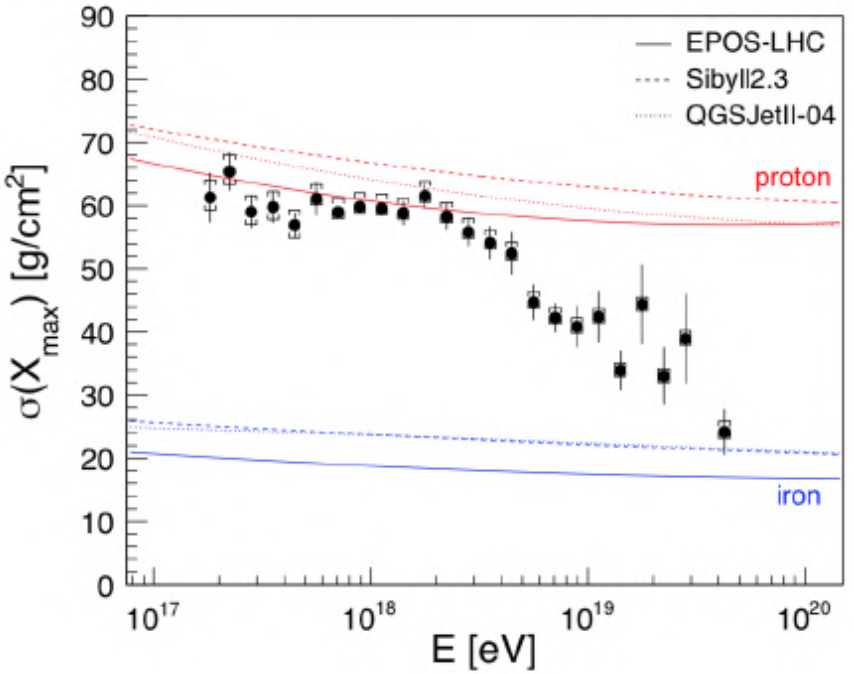
High Energy Physics

Average X_{max} measured by FD



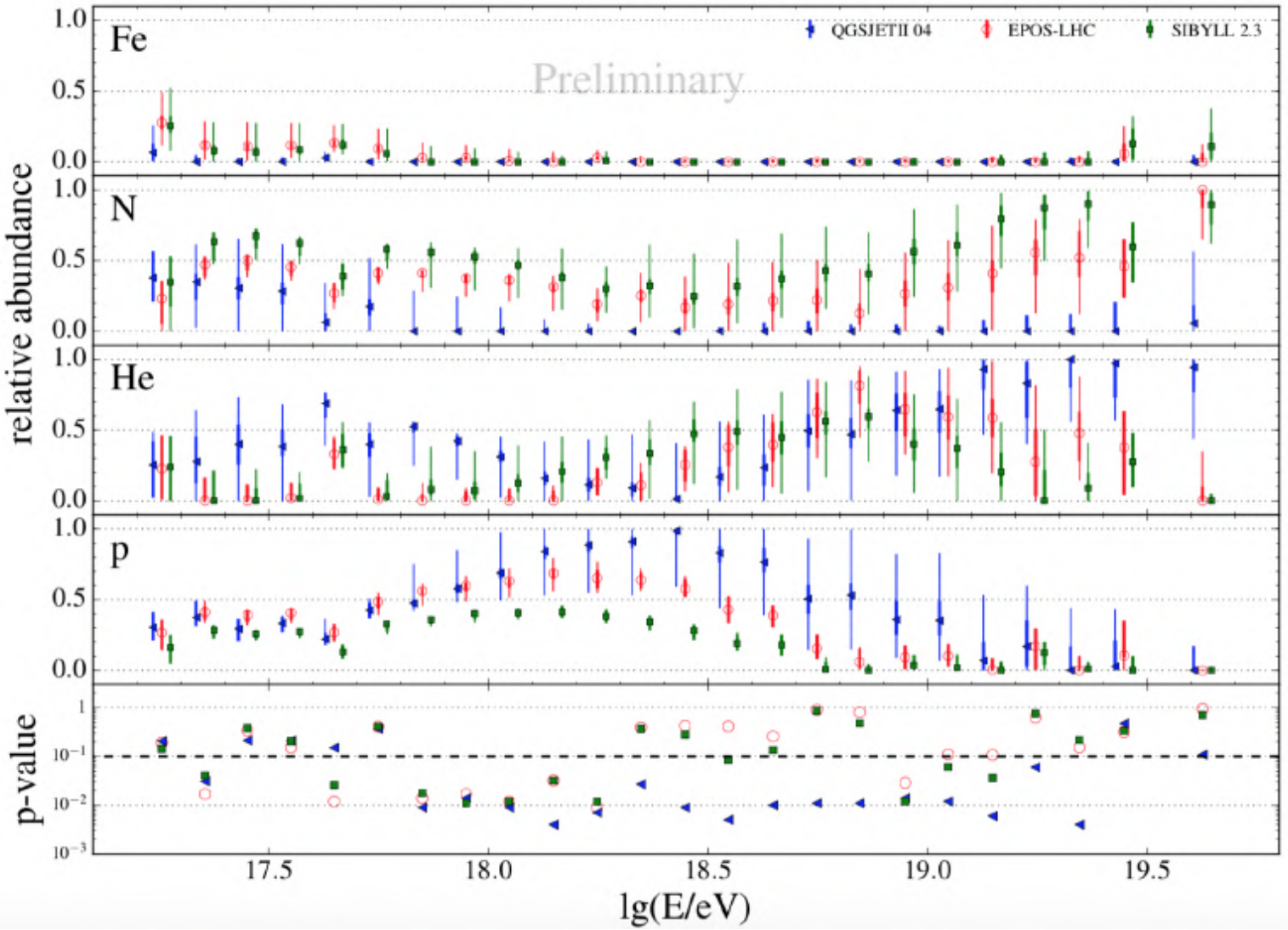
Composition measurements





- Lines from post-LHC models
- Composition trend changes around ankle
- UHECR heavy

4 components distribution fits



The new Era for UHECR

Bottom Up vs Top Down

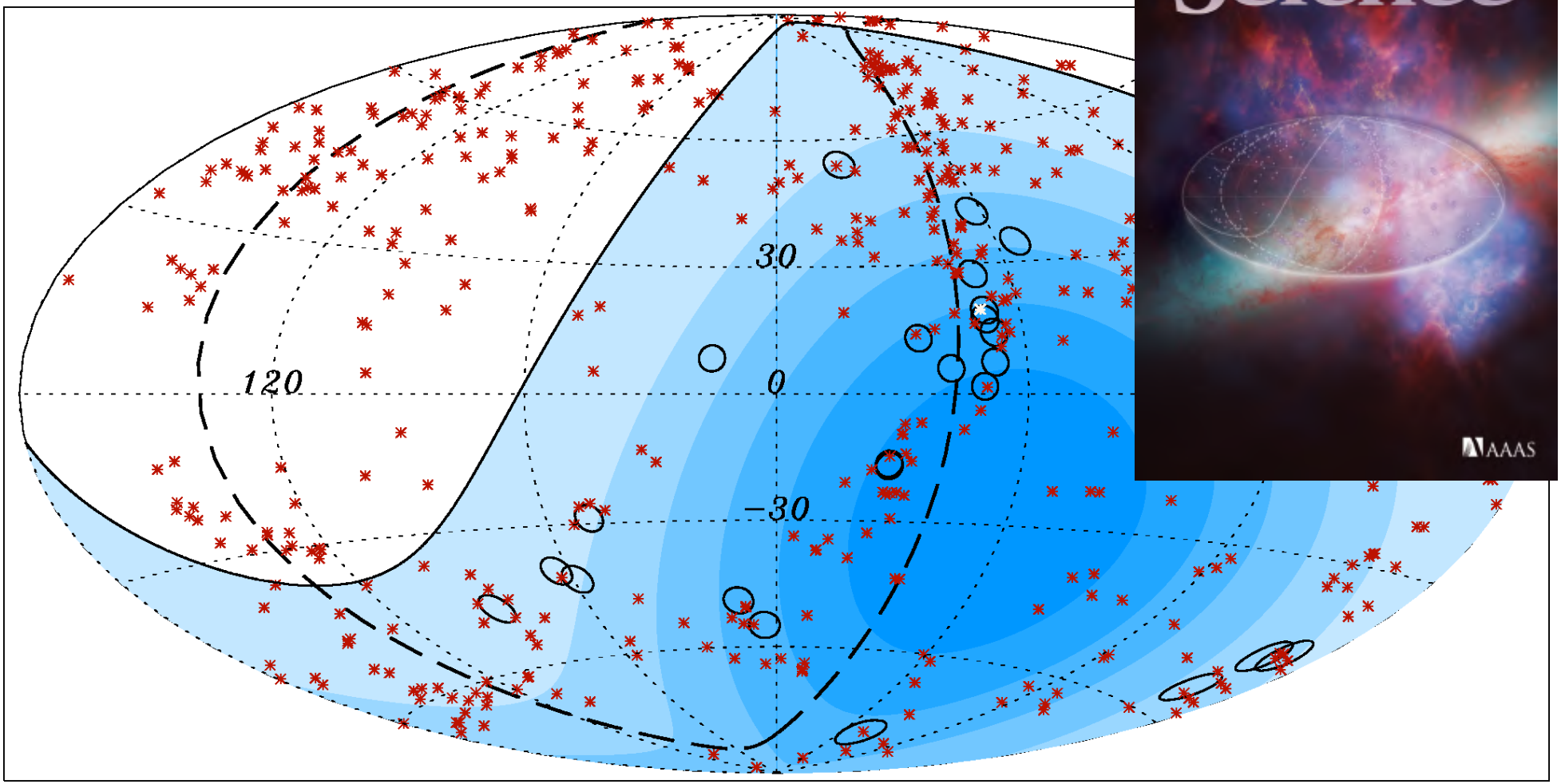
Spectrum

Composition

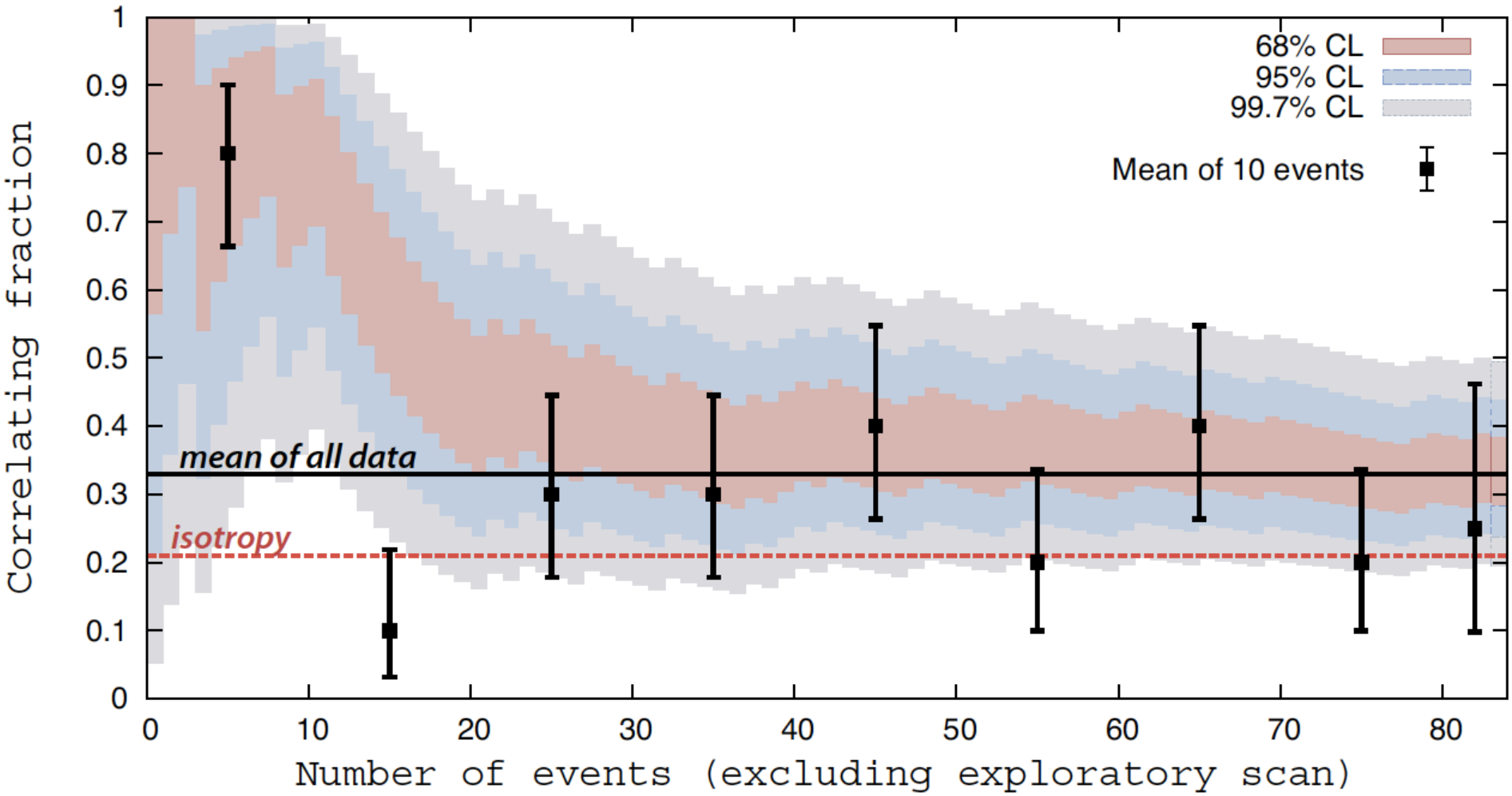
Looking for the sources

High Energy Physics

Correlation with close-by AGNs (2007)



Evolution of correlation with close-by AGNs

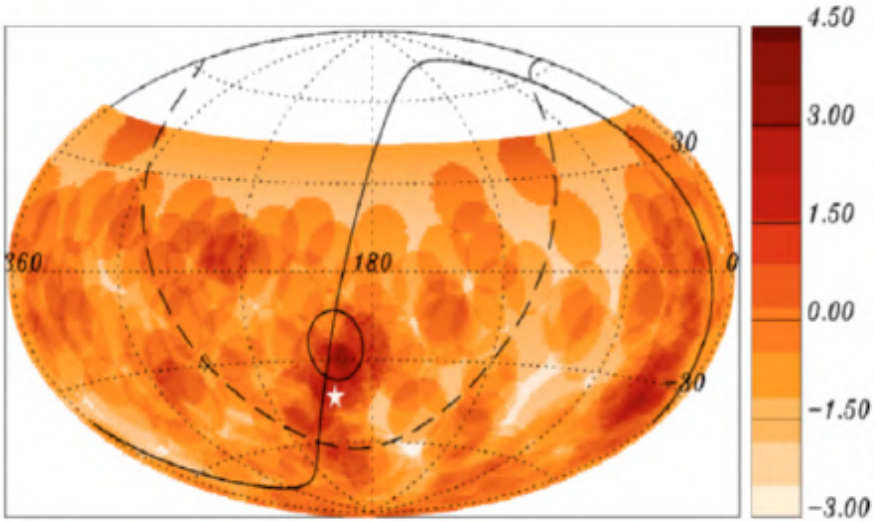


Small scale searches (Auger+TA)

Auger

- r = 1º – 30º, Δr = 1º
- E = 40 – 80 EeV, ΔE = 1 EeV

scan parameters

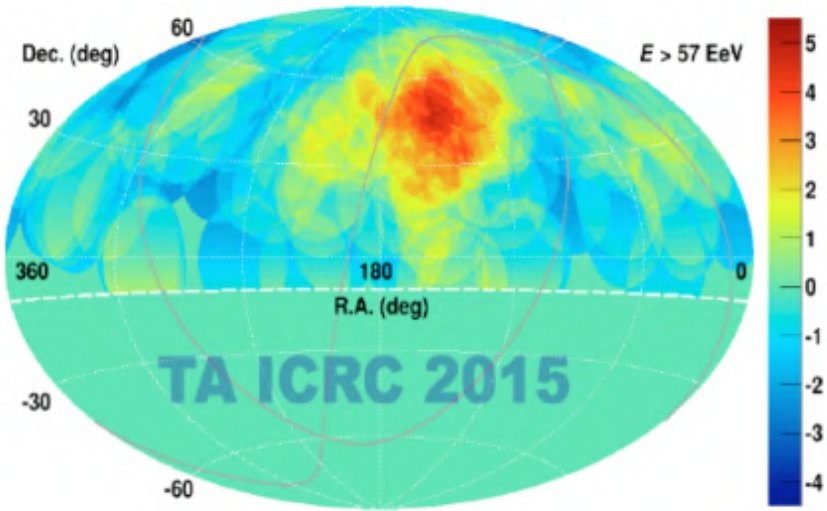


- r = 12º, E = 54 EeV
- n_{obs}/n_{exp} = 14/3.23
- pre-trial → 4.3 σ
- post-trial P = 69%

Auger, APJ 804 (2015),1

TA

- r = 15º – 35º, Δr = 5º
- E = 57 EeV

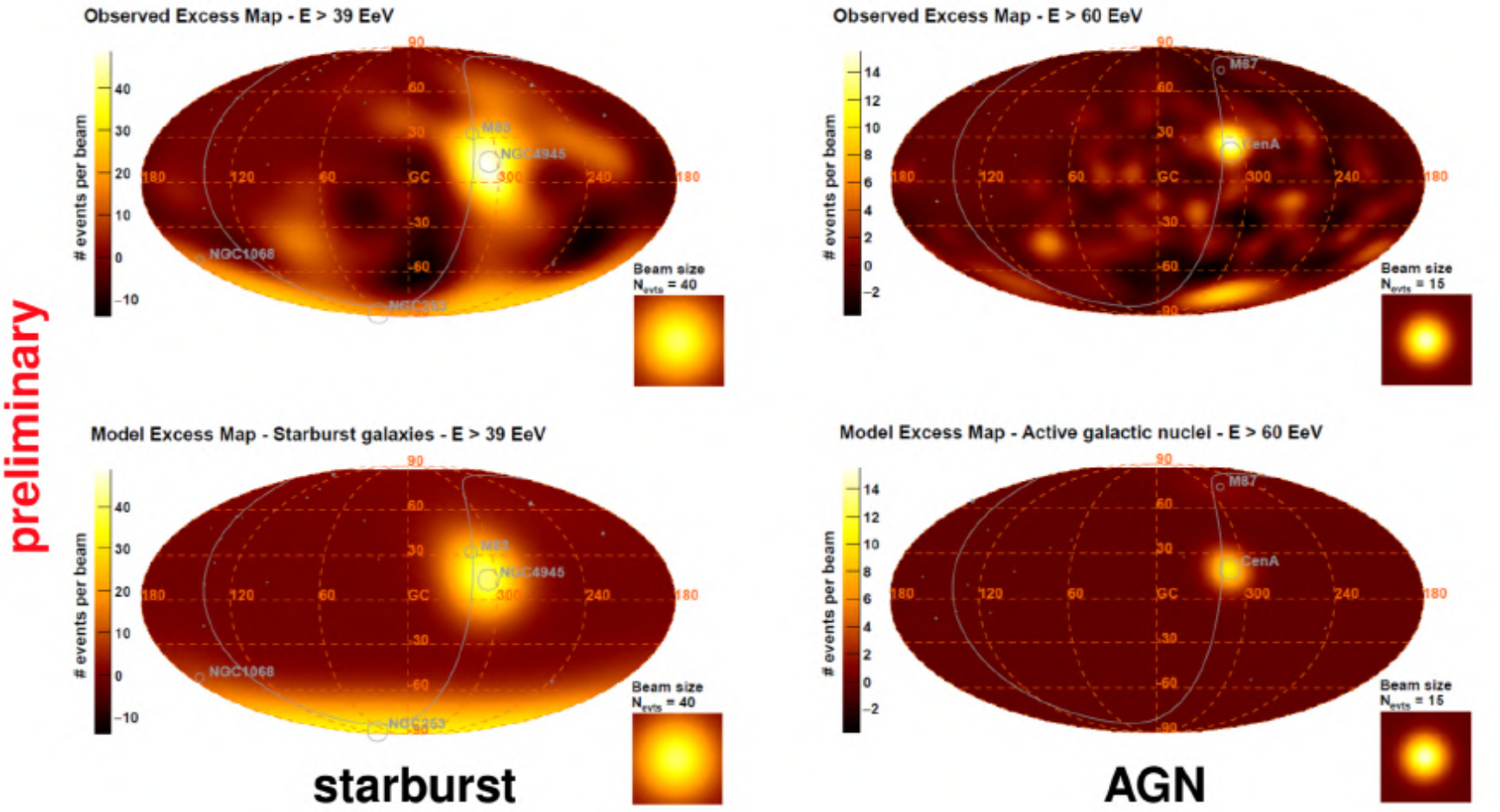


scan minima

- r = 20º, E = 57 EeV
- n_{obs}/n_{exp} = 24/6.88
- pre-trial → 5.1 σ
- post-trial → 3.4 σ

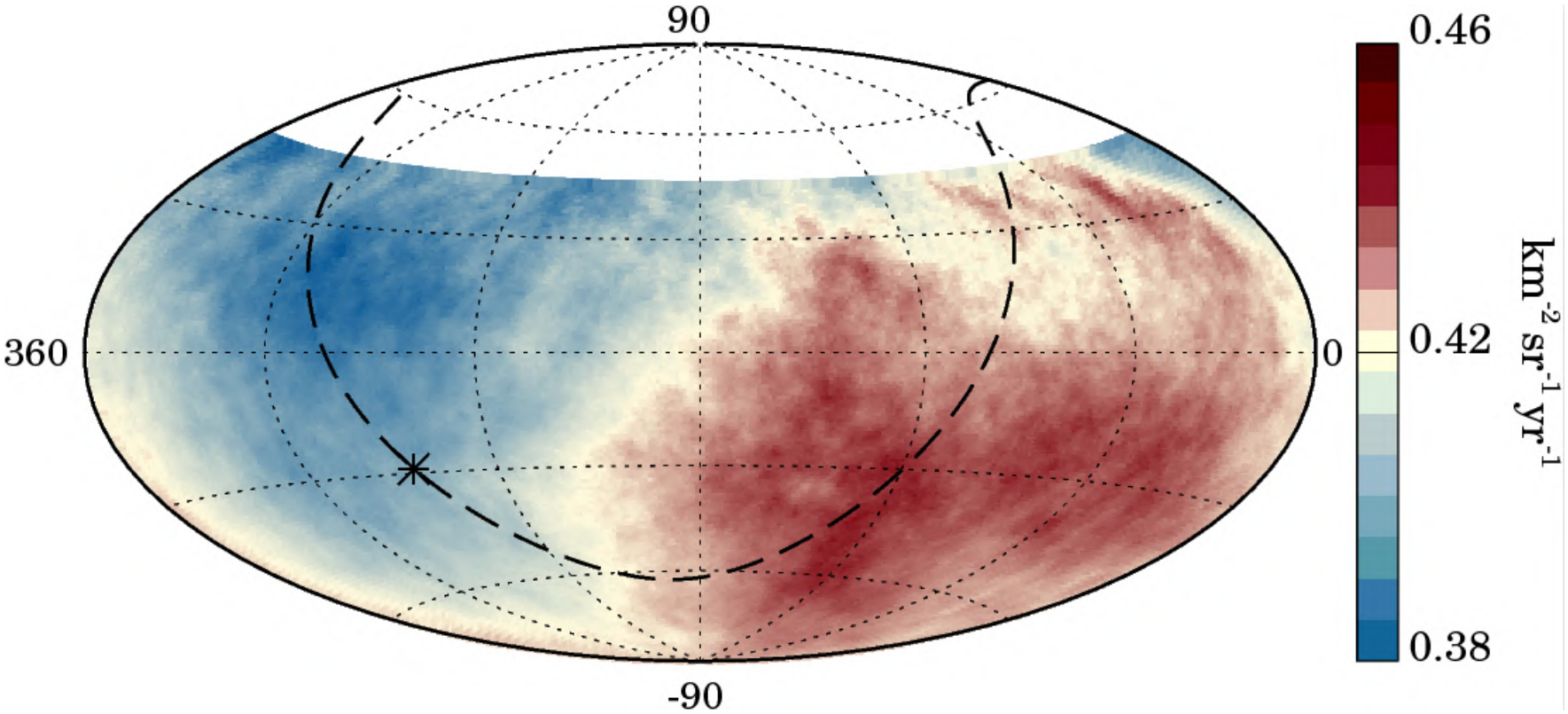
TA, ICRC 2015

Source catalogues comparison



Post-trial significance $3.9\,\sigma$ and $2.7\,\sigma$ respectively

Large scale anisotropies

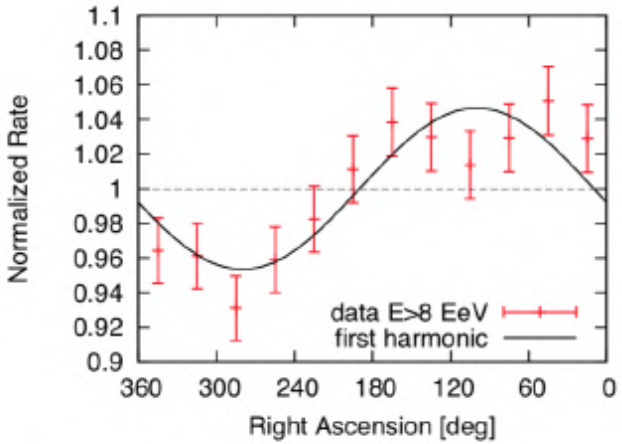


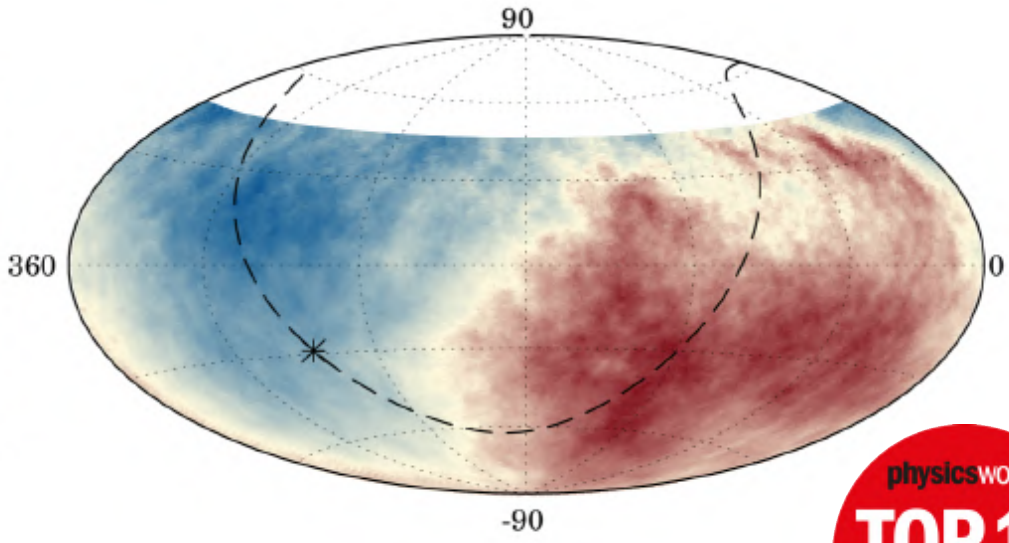
E $>$ 8 EeV, smoothing angle 45^o

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)



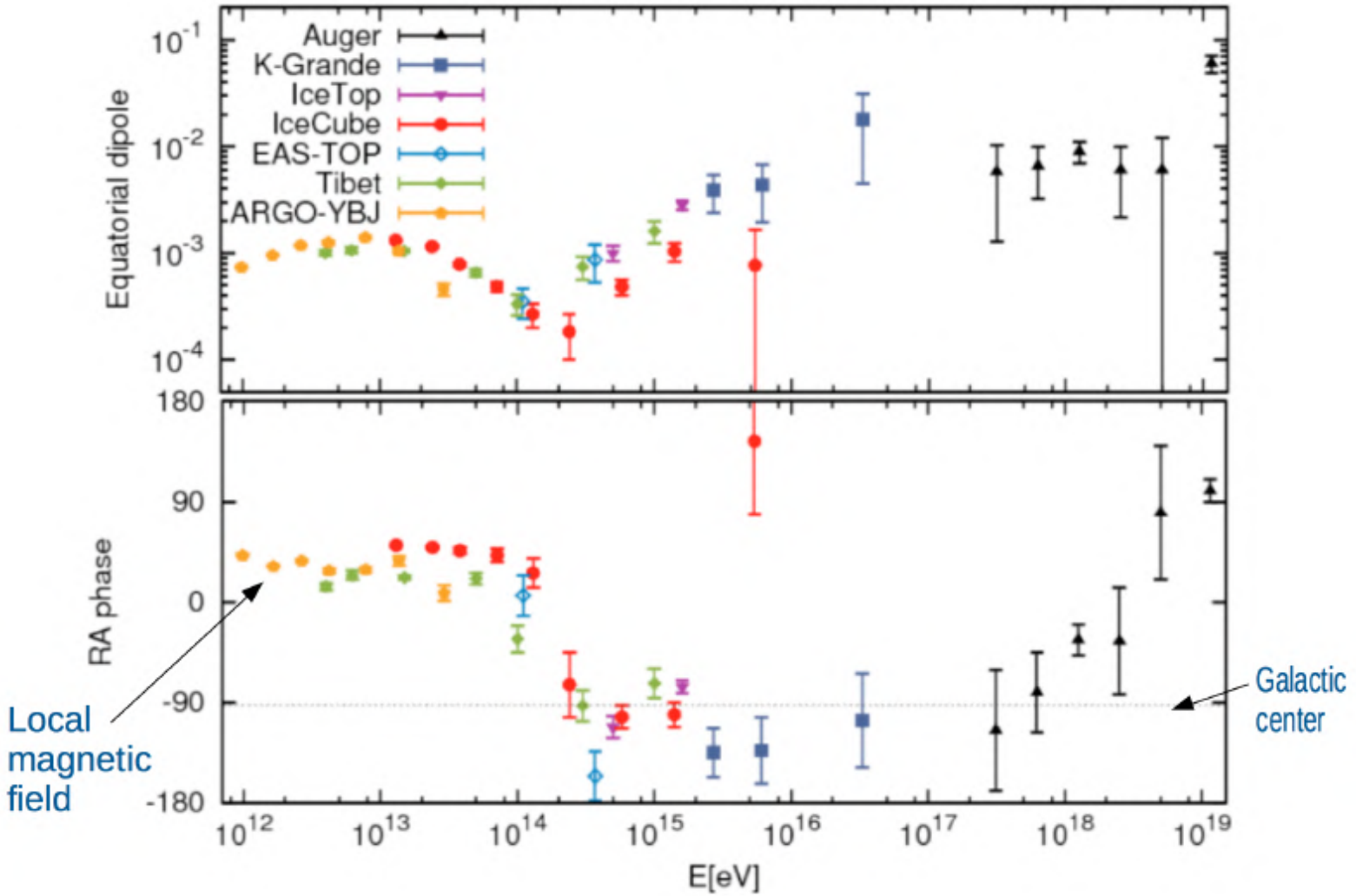


3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

physicsworld TOP 10 BREAKTHROUGH 2017

Large scale anisotropies



The new Era for UHECR

Bottom Up vs Top Down

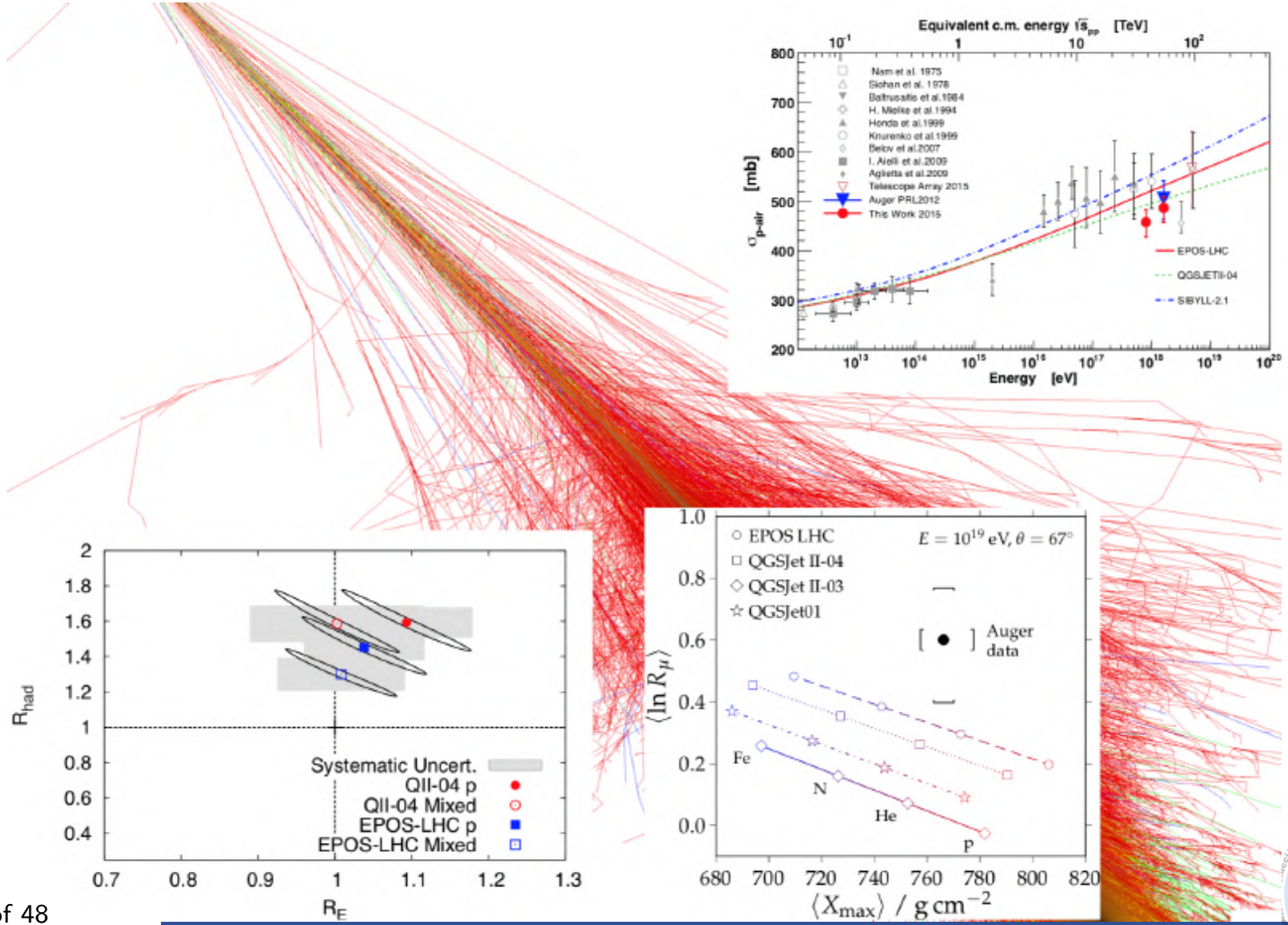
Spectrum

Composition

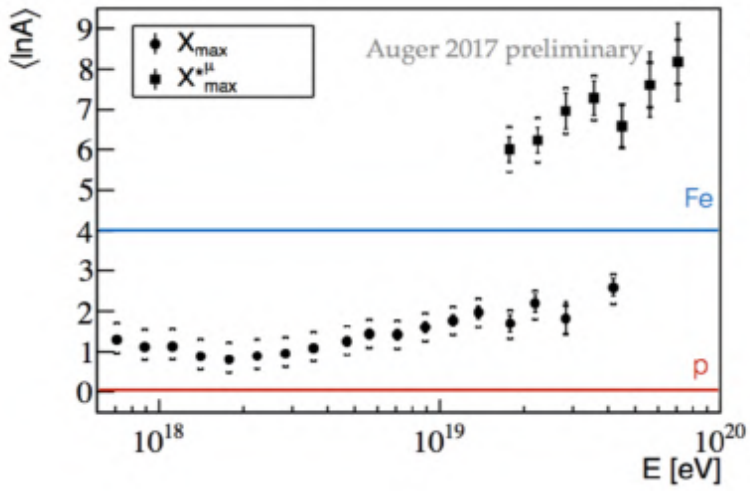
Looking for the sources

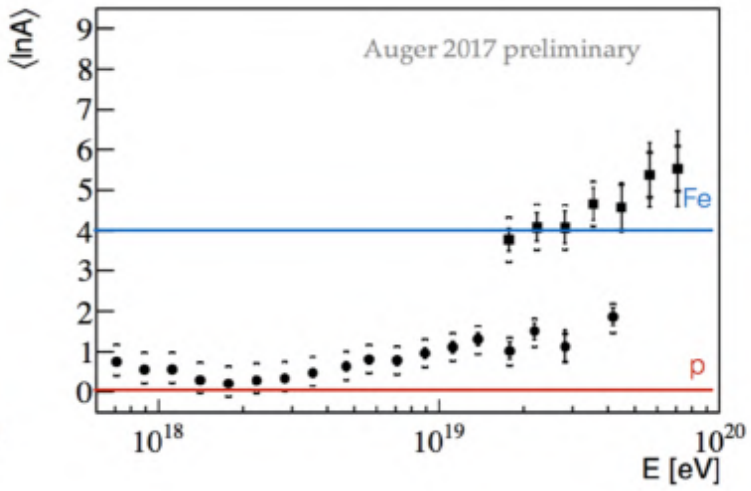
High Energy Physics

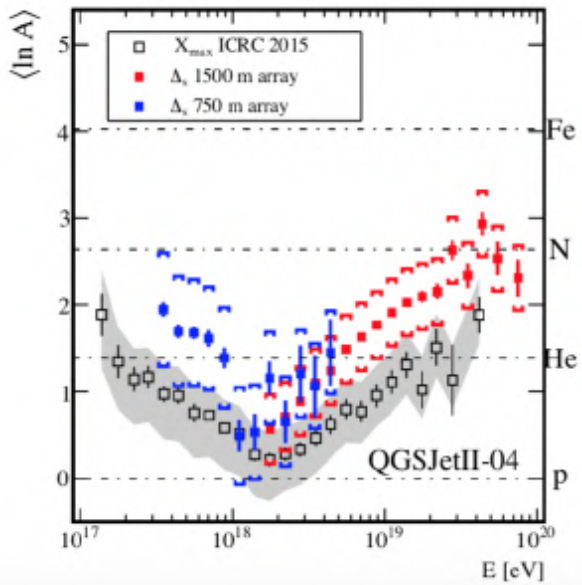
HEP with Auger

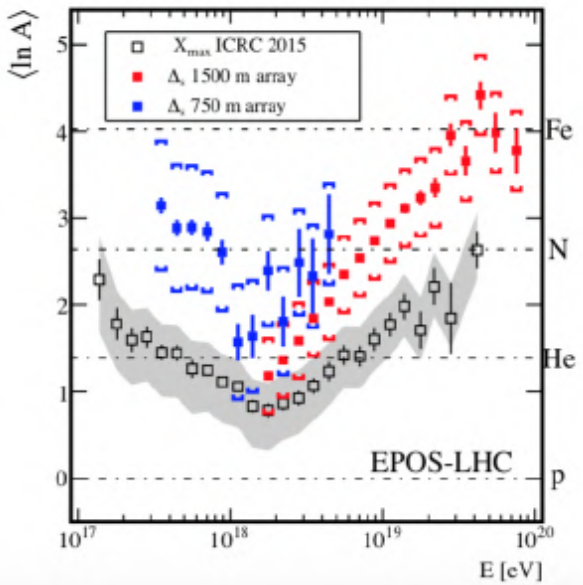


Still lacking coherent view









What we learned

- UHECR are accelerated in astrophysical sources
- Bottom-Up, no new physics
- Ankle likely transition from galactic to extragalactic sources?
- UHECR are extragalactic
- Strong suppression at UHE
- Muon deficit in models

we call that the disappointing model

What we learned

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- UHECR are extragalactic
- Strong suppression at UHE
- Muon deficit in models

we call that the disappointing model
we should call that the standard model

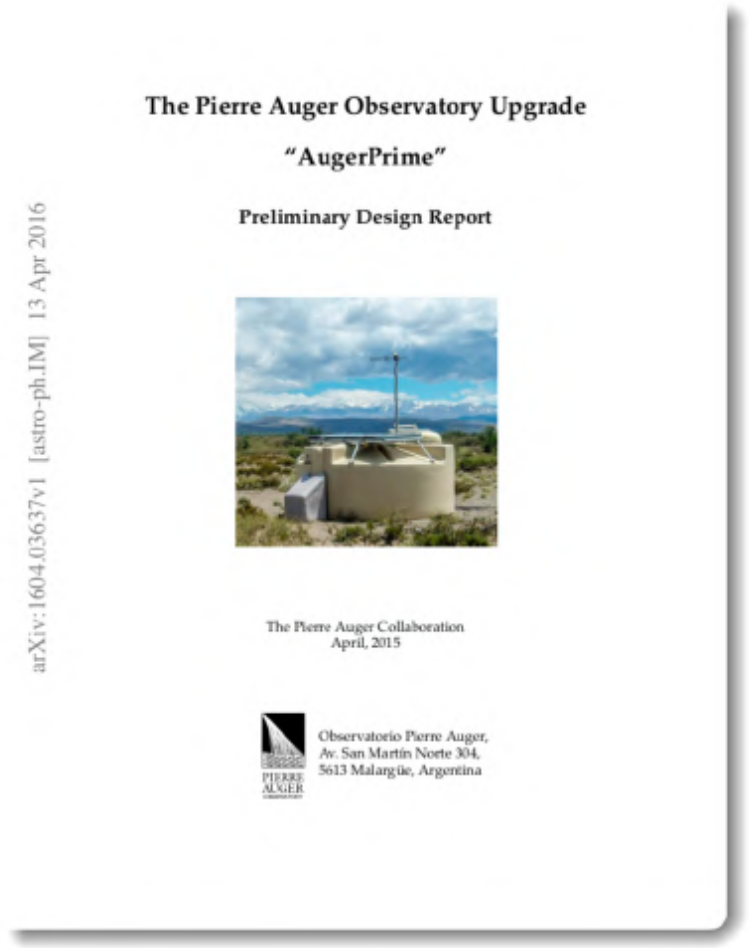
The next Era for UHECR

Auger Prime

What next?

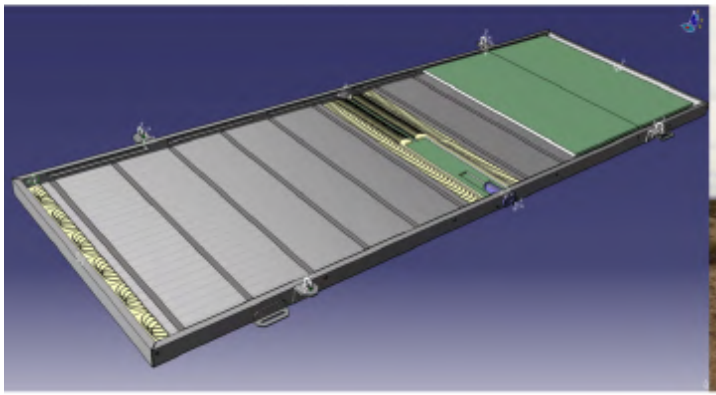
- Origin of the flux suppression?
- Proton fraction at UHE?
- Rigidity-dependence of anisotropies?
- Hadronic physics above $\sqrt{s} = 140$ TeV?

need large-exposure detector with composition sensitivity!

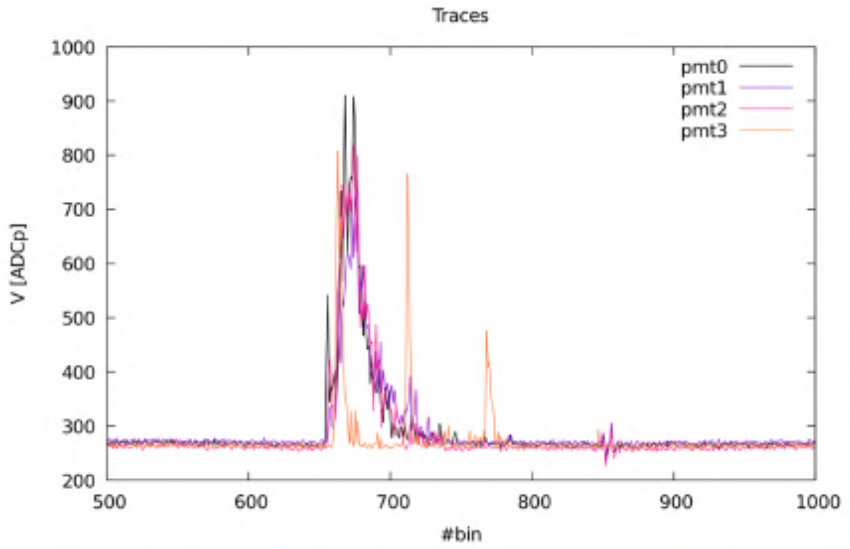


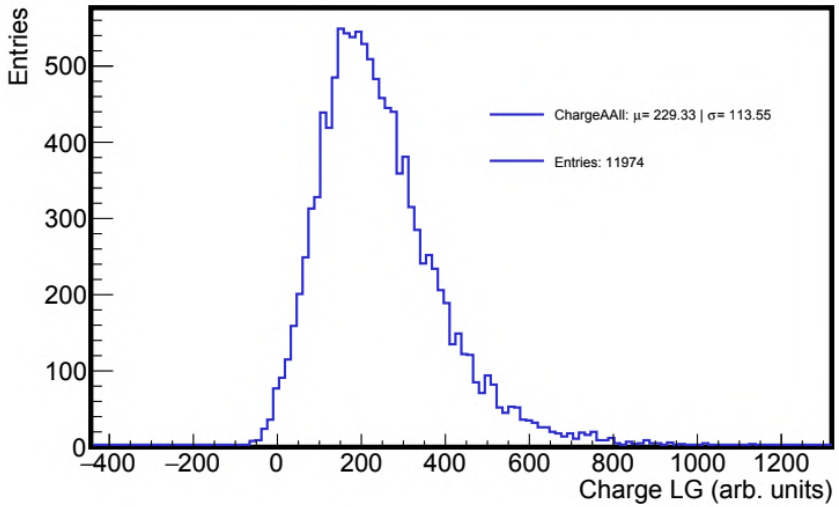
New detectors to get composition event by event

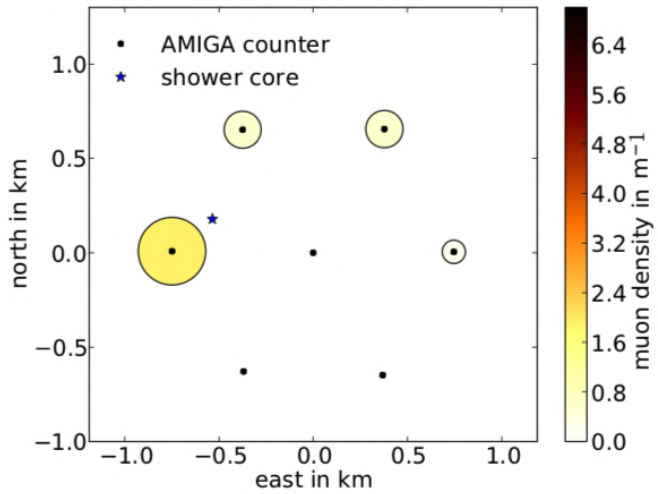
- 3.8 m^2 scintillators (SSD) on each 1500-m array station
- upgrade of station electronics
- additional small PMT to increase dynamic range
- buried muon counters in 750-m array (AMIGA)
- increased FD uptime

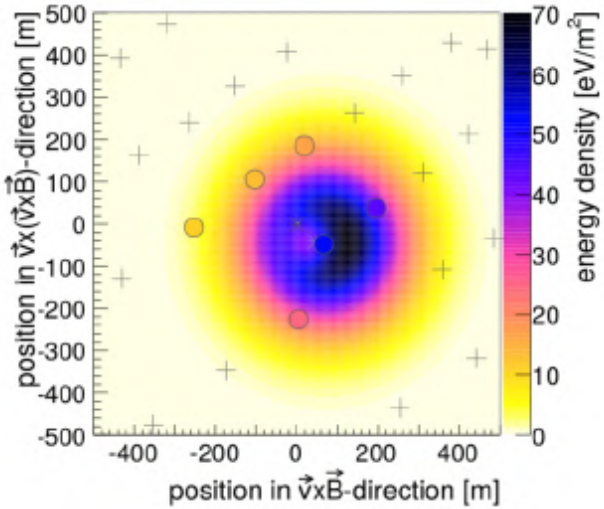


Upgrade data are already available









Other results from the Pierre Auger Observatory

- No excess from Galactic Center
- Point sources with neutral primary (neutrons, photons)
- Multi-messenger source search
- Radio detection of EAS (geosynchrotron - MHz, molecular bremsstrahlung - GHz?)
- Atmospheric studies
- Solar physics
- TLE/Elves/Lightning physics

- Very active "side physics" tasks

UHECR - Pierre Auger Observatory:

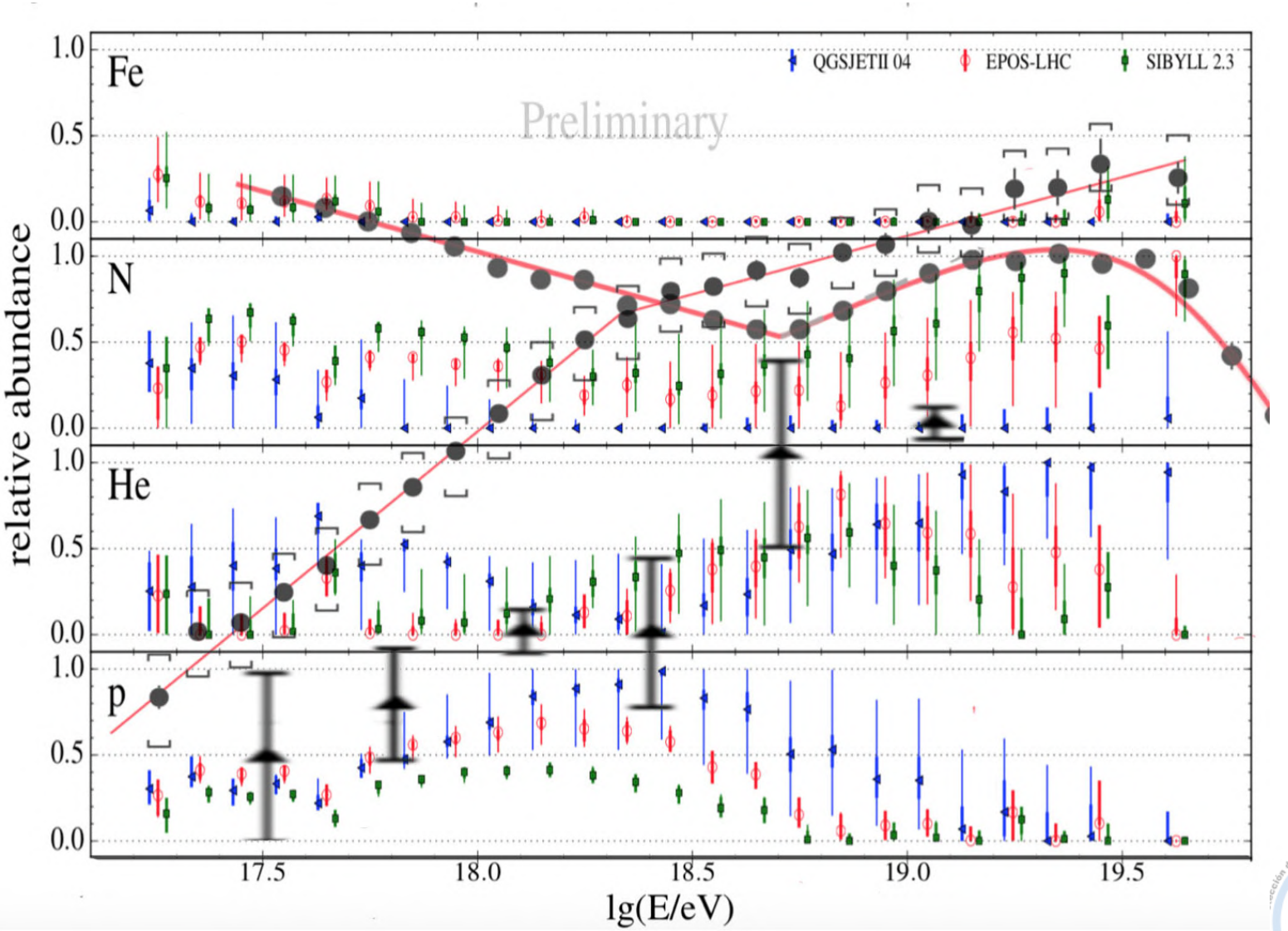
Take home message

Take Home Message

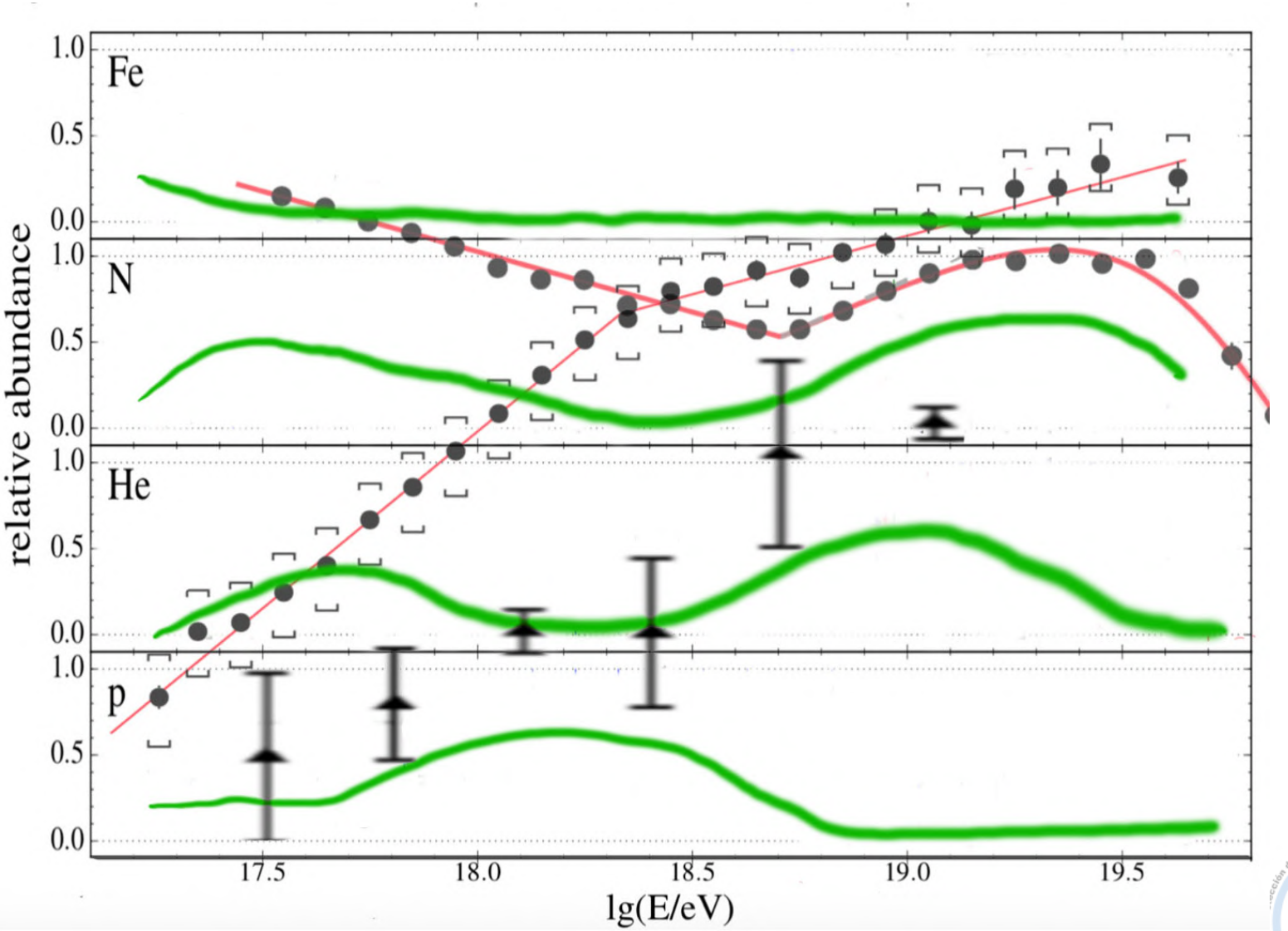
- 15 years of the Pierre Auger Observatory data changed greatly the community view of HECR
- Bottom Up CR acceleration
  - No new physics
  - Astrophysical sources
- Galactic - Extragalactic transition below Ankle?
- Flux suppression at highest energies
  - GZK effect?
  - Source acceleration limit?
- Muon deficit in models at highest energies
- Auger Upgrade designed to address these remaining questions

$\rightarrow$ Towards a standard model of UHECR

UHECR Standard Model?



UHECR Standard Model?



Thanks for the invitation