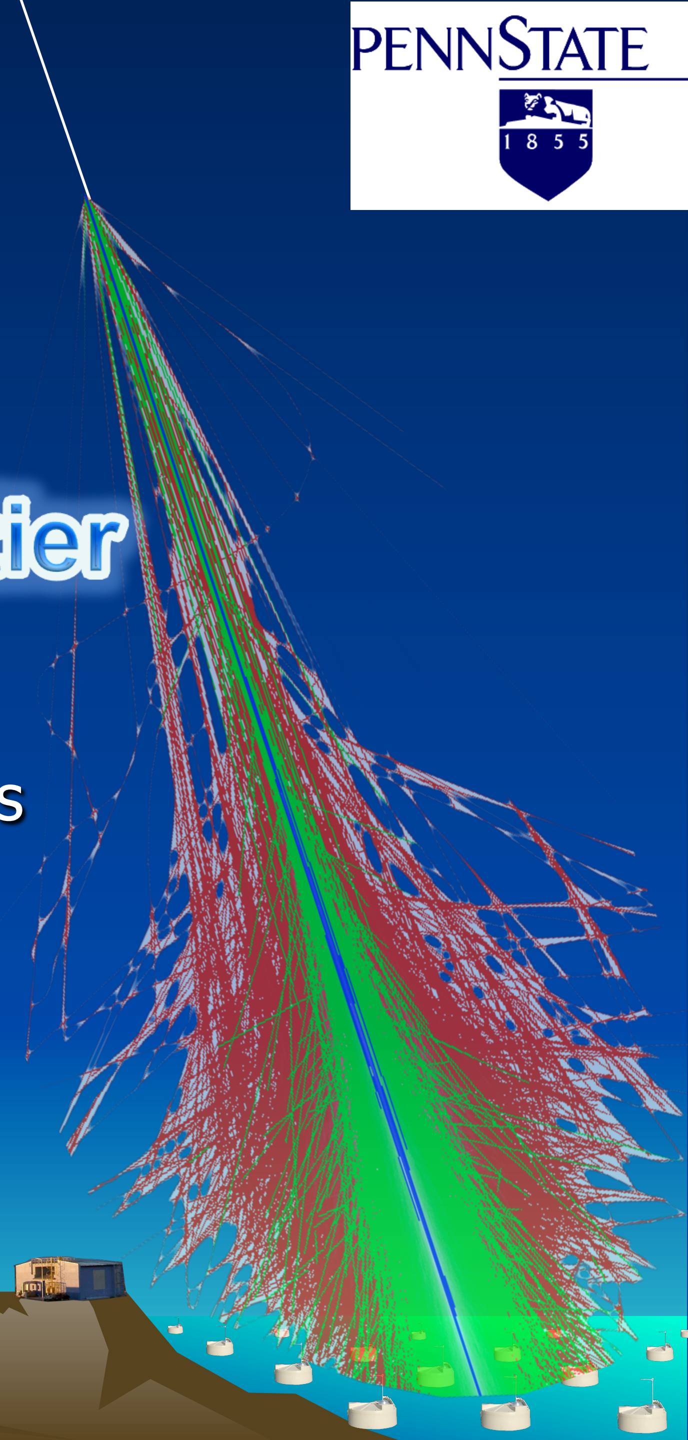
The Highest-Energy Frontier

Stéphane Coutu
Institute for Gravitation and the Cosmos
The Pennsylvania State University

DPF 2015
August 7, 2015
Ann Arbor



Outline

- UHE Cosmic Rays: messengers from the highest-energy Universe
  - Extreme experimental challenges, especially due to rates…
- Question:
  - What are the messengers?
  - What are the sources?
  - Acceleration? Maximum energy?
  - Highest-energy physics?

Observables:

Composition (Ze, ν, γ)

Arrival directions

Energy spectrum

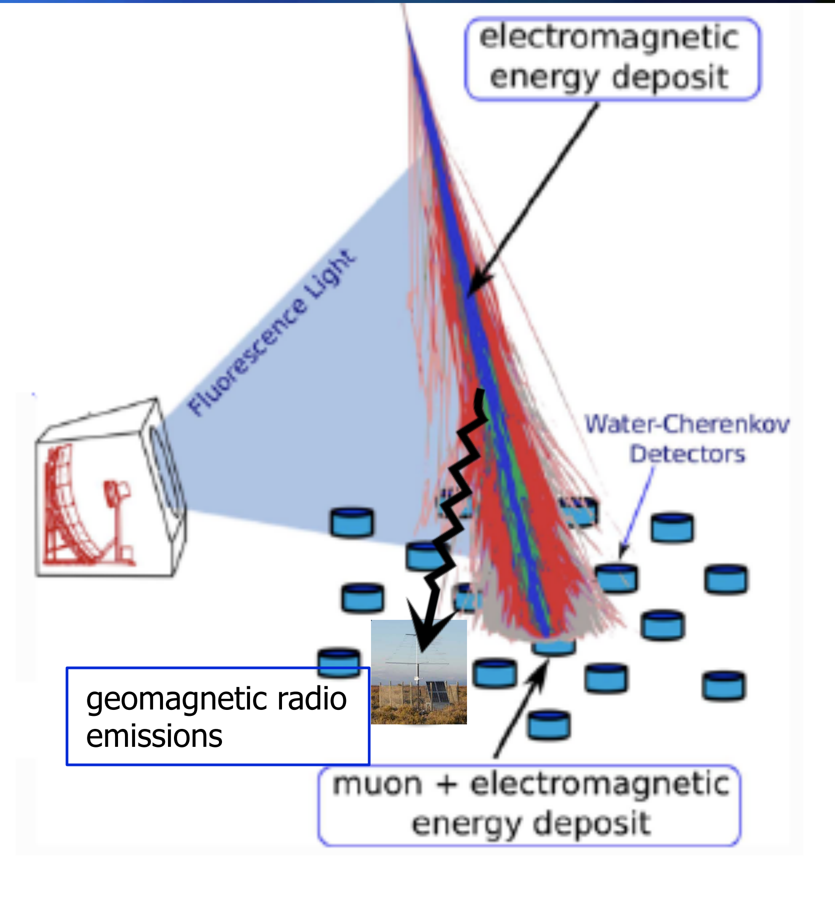
Air shower properties

- Current experiments
  - Telescope Array
  - Auger
- Many new results (2015 ICRC, The Hague, The Netherlands)
- and some puzzles.

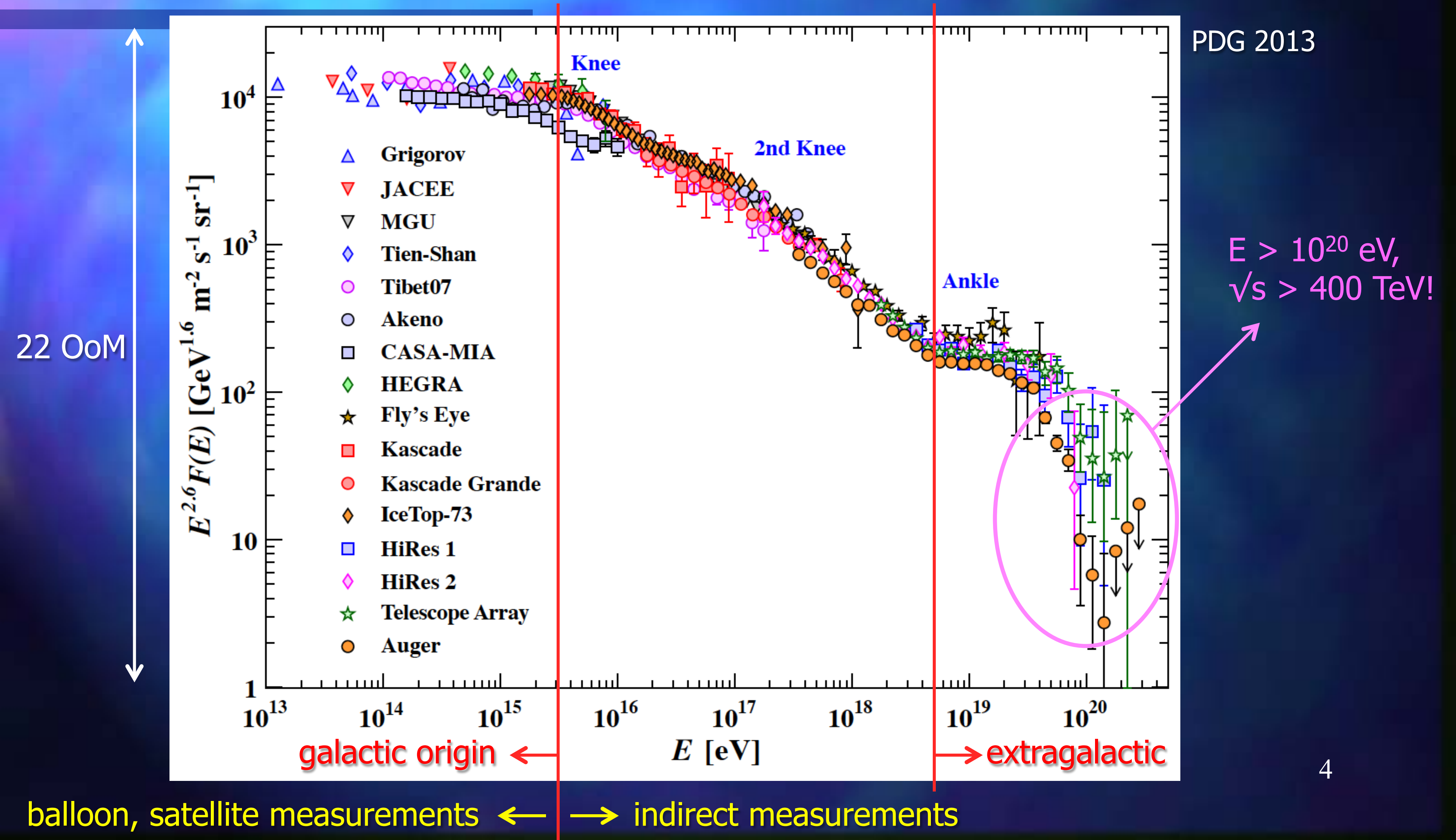
UHECR detection

- UltraHigh Energy Cosmic Rays (UHECRs) are rare and can only be detected through their atmospheric secondaries (air showers);
- 10^{20} eV yields 10^{11} particles at maximum.

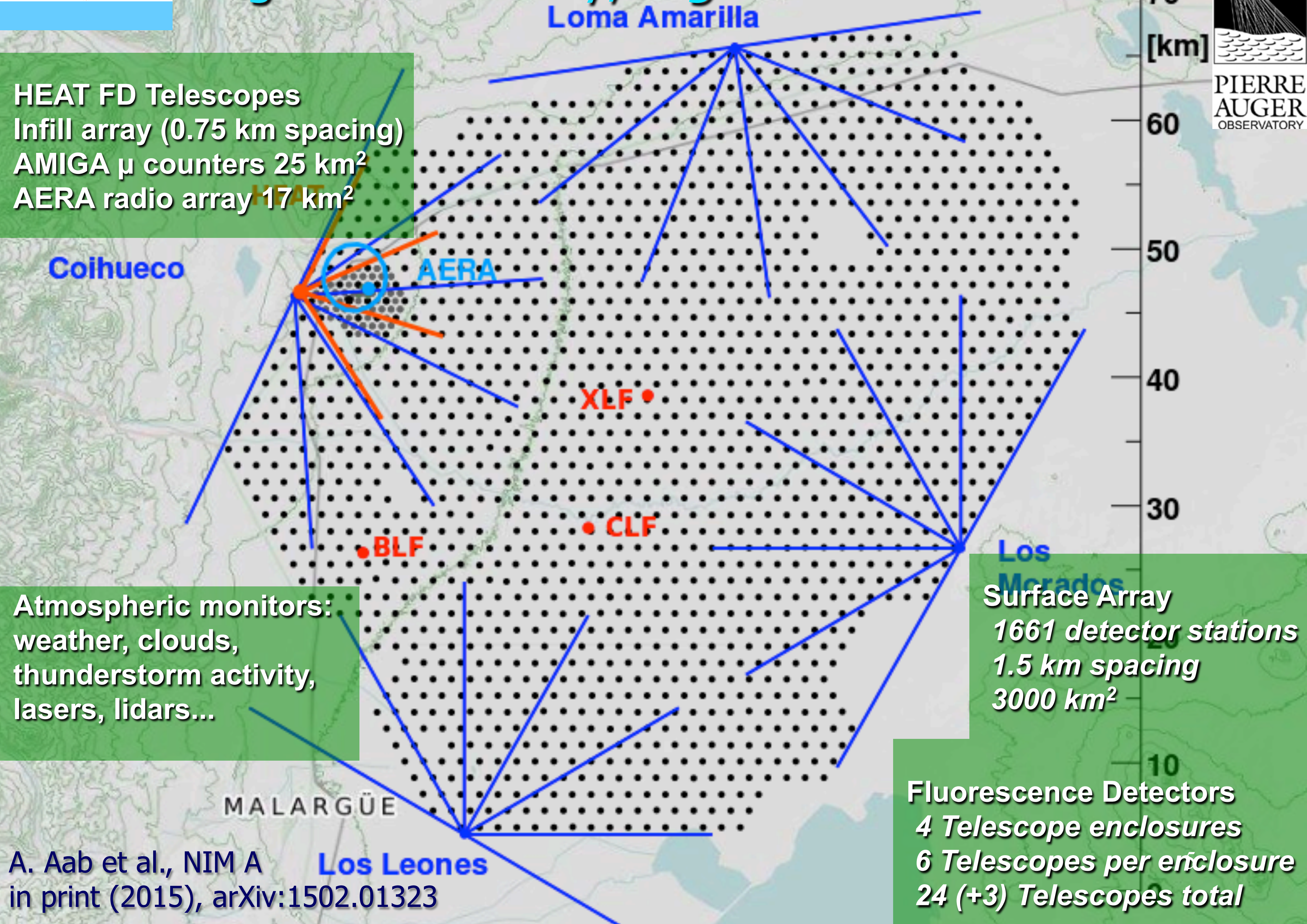
- Shower front particles can be directly detected on the ground (e.g., AGASA 1,600 km^2 sr yr);
- Showers excite nitrogen fluorescence, detectable on dark nights (10% duty) (e.g., HiRes 5,000 km^2 sr yr mono);
- Can detect both (e.g., Auger 50,000 km^2 sr yr so far TA 9,500 km^2 sr yr so far);
- Plus radio emissions...



Cosmic Ray Energy Spectrum: 45 years in the making



Auger Observatory, *Argentina*



HEAT FD Telescopes
Infill array (0.75 km spacing)
AMIGA μ counters 25 km²
AERA radio array 17 km²

Atmospheric monitors: weather, clouds, thunderstorm activity, lasers, lidars...

Surface Array
1661 detector stations
1.5 km spacing
3000 km²

Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 (+3) Telescopes total

A. Aab et al., NIM A in print (2015), arXiv:1502.01323

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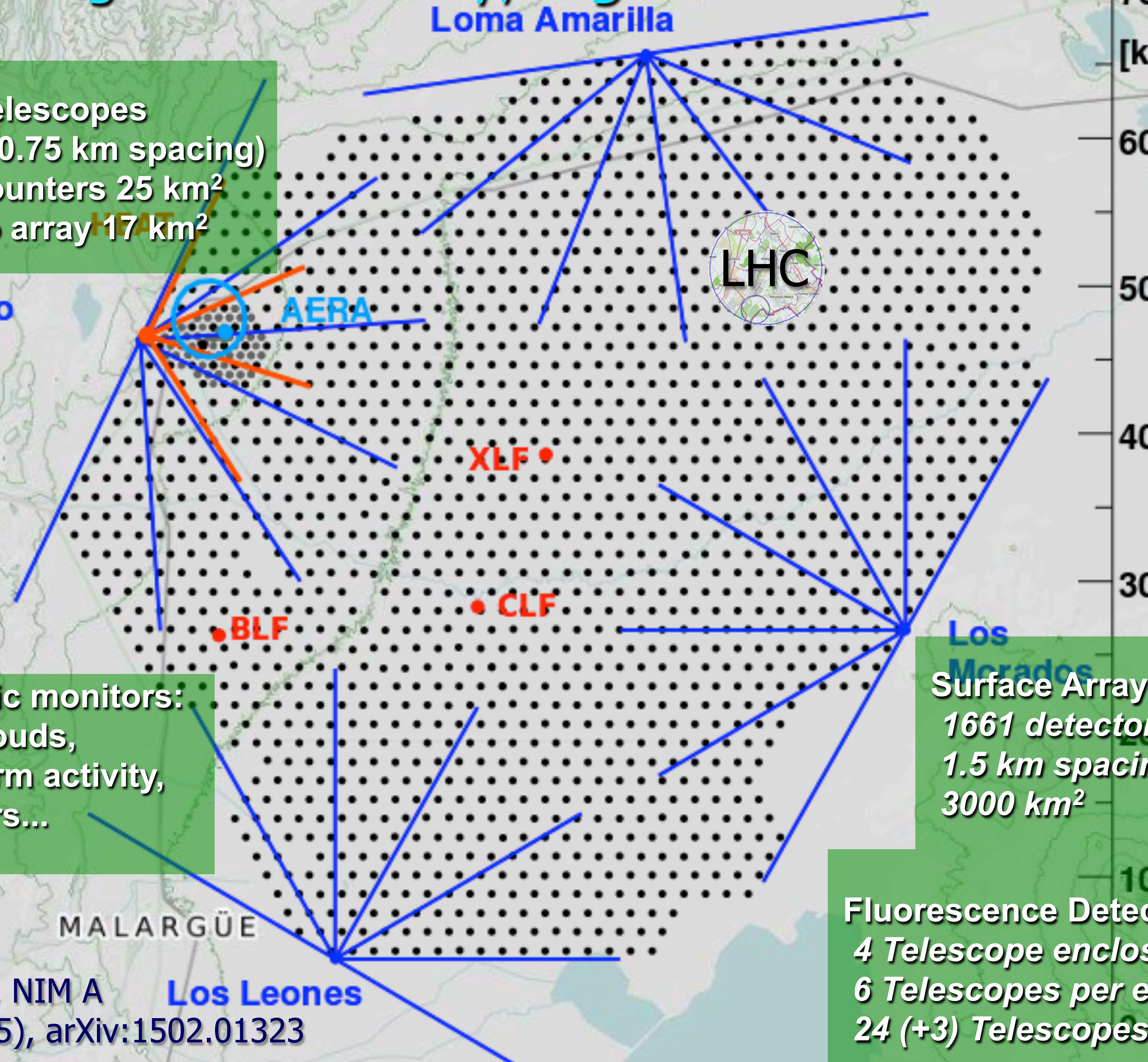

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PENNSTATE

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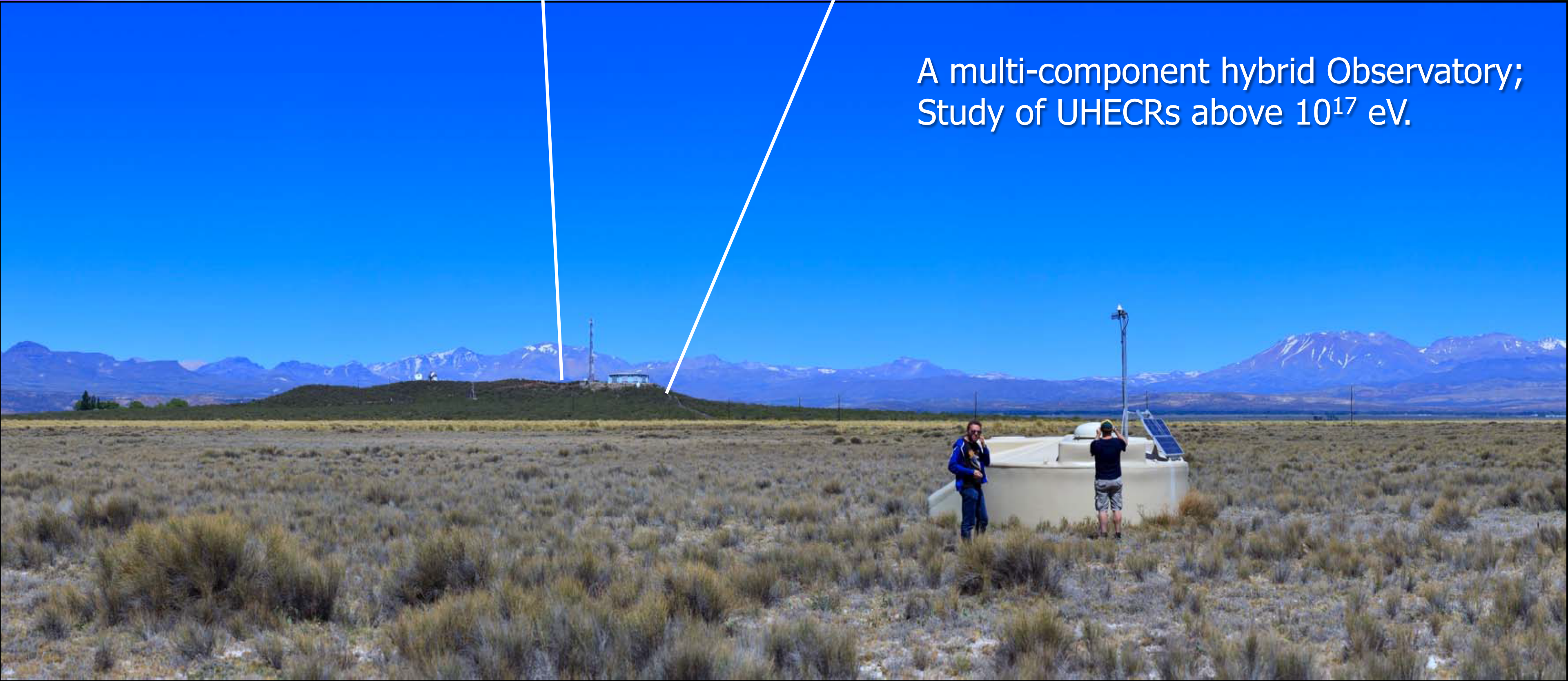
Hybrid design

~500 collaborators;
16 countries;
86 institutions.

A multi-component hybrid Observatory;
Study of UHECRs above 10^{17} eV.



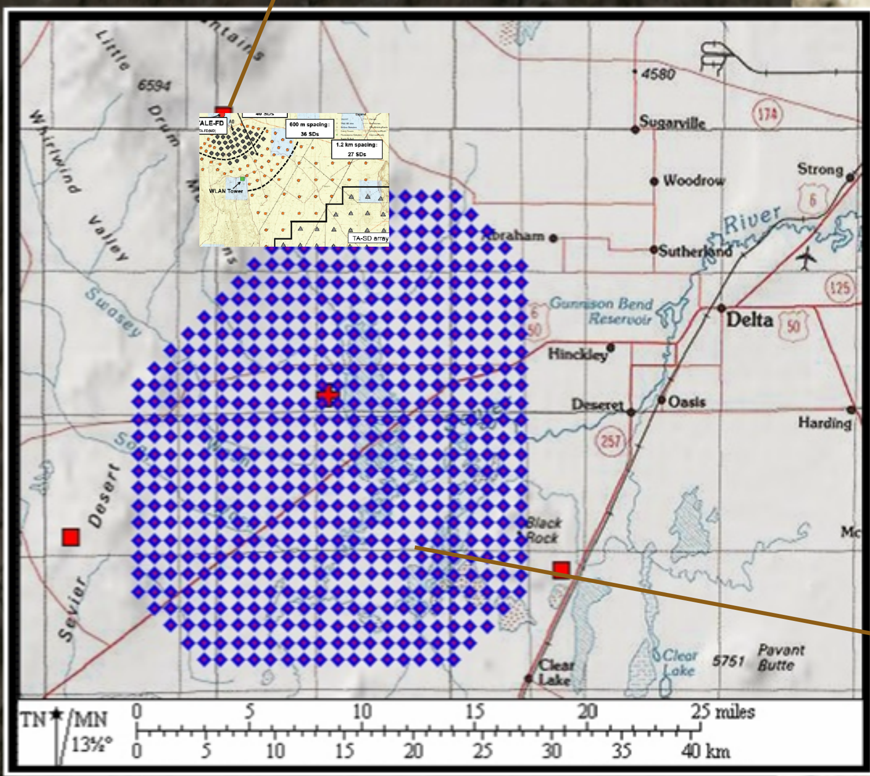
Telescope Array, *Utah, USA*

3 fluorescence detectors
12-14 telescopes each

Salt Lake City

TALE low-energy extension
+ graded scintillator array
atmospheric and laser facilities
TARA – radar CR detection

Delta

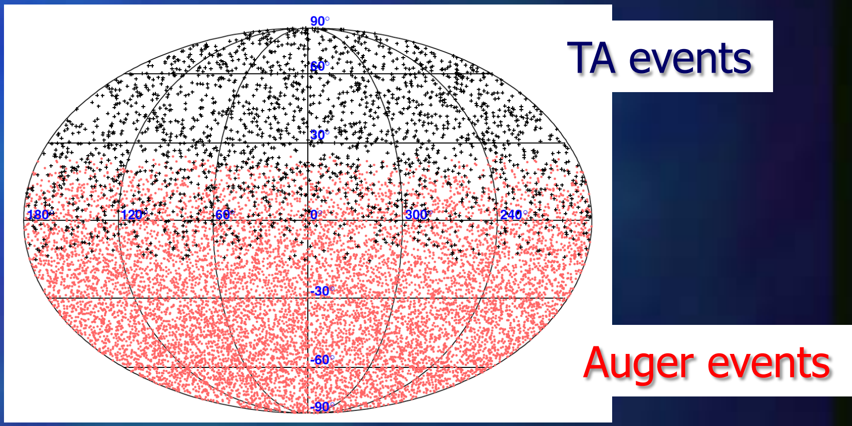


507 scintillator detectors
700 km², 1.2 km grid

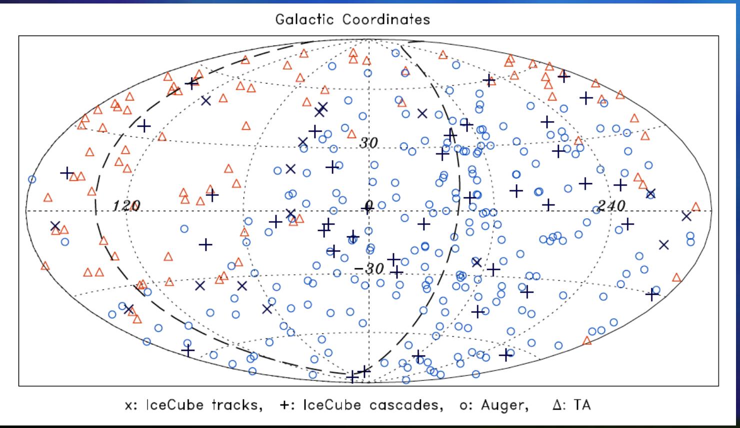
Joint Auger/TA work

Co-located hardware comparisons and cross-calibrations

Joint anisotropy searches (TA North, Auger South):



A. Aab et al., ApJ 794, 172 (2014)



IceCube / Auger / TA joint study

G. Golup et al., Proc. of 34th ICRC, The Hague (2015)

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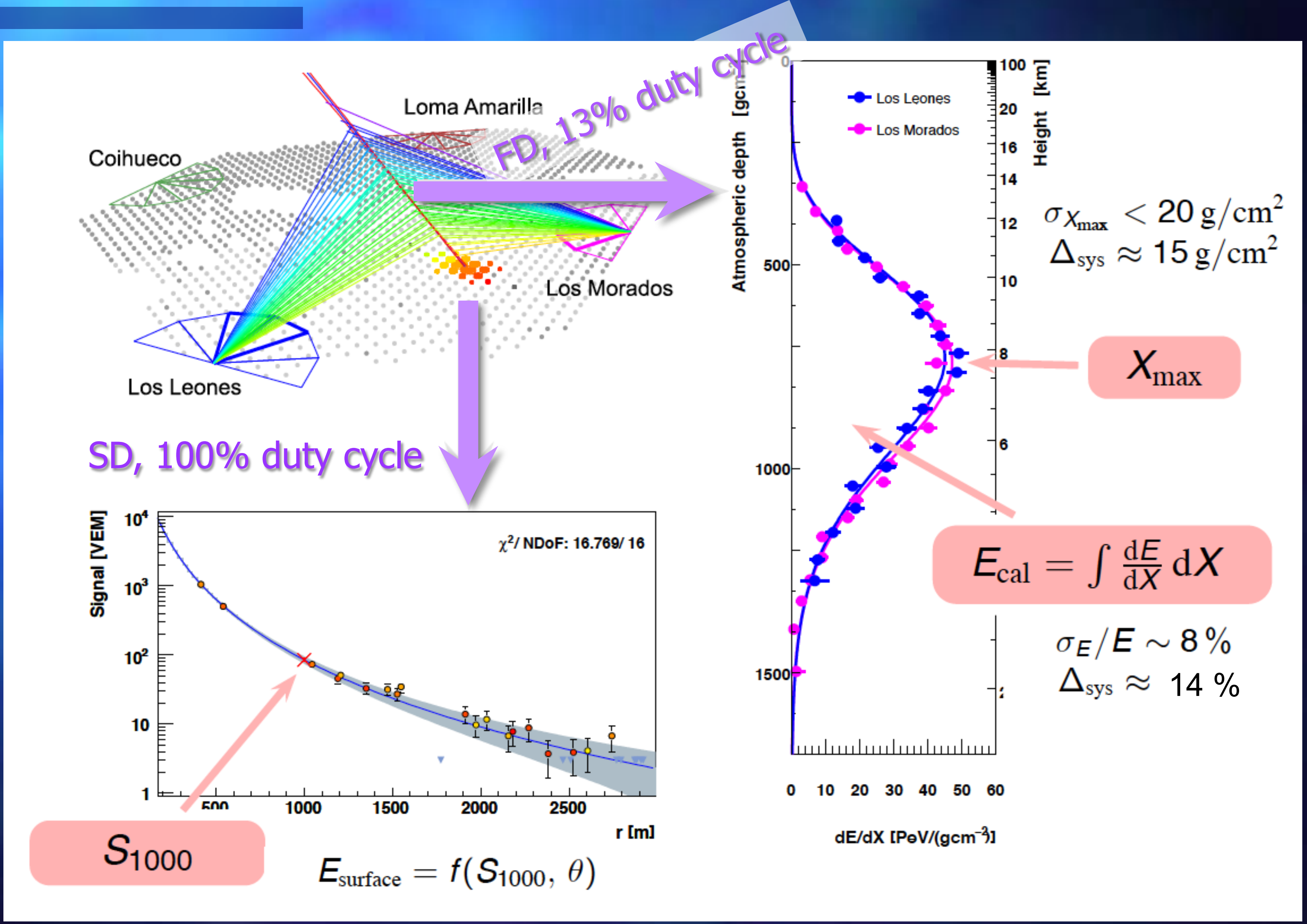
Event reconstruction

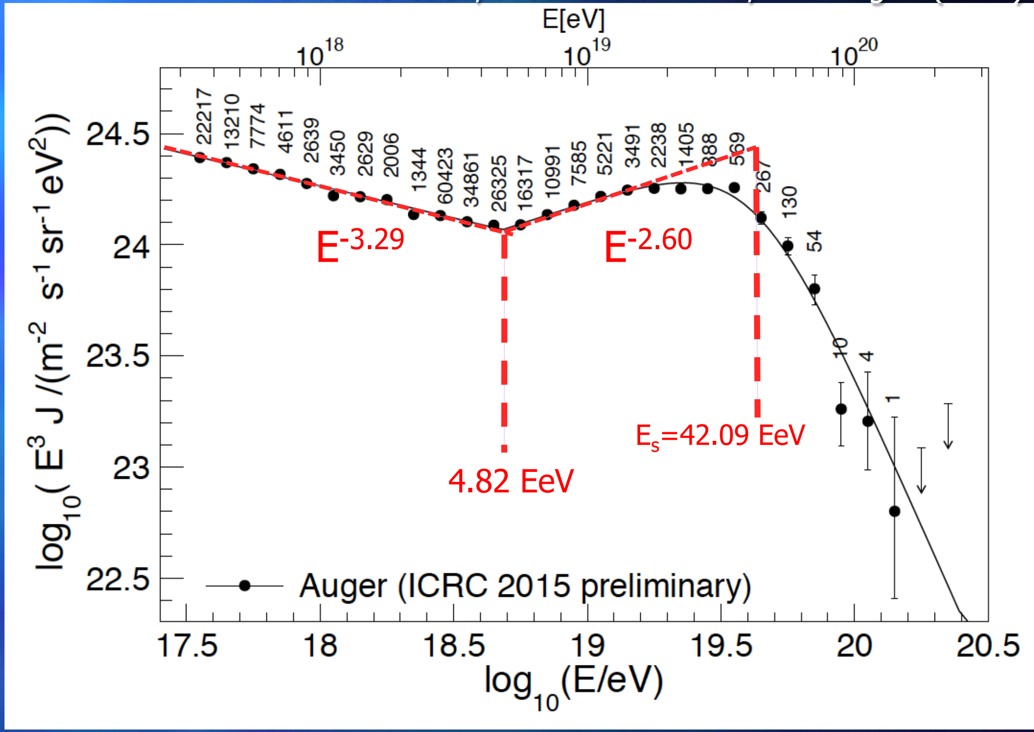


Energy spectrum

- Updated, combined Auger spectrum:
- 115,000 SD (>3 EeV) + 60,000 infill (>0.3 EeV) + 10,000 hybrid events (>1 EeV);
- Exposure = 50,000 km² sr yr .

GZK-like suppression definitely seen (>20σ)

I. Valino et al., Proc. of 34th ICRC, The Hague (2015)



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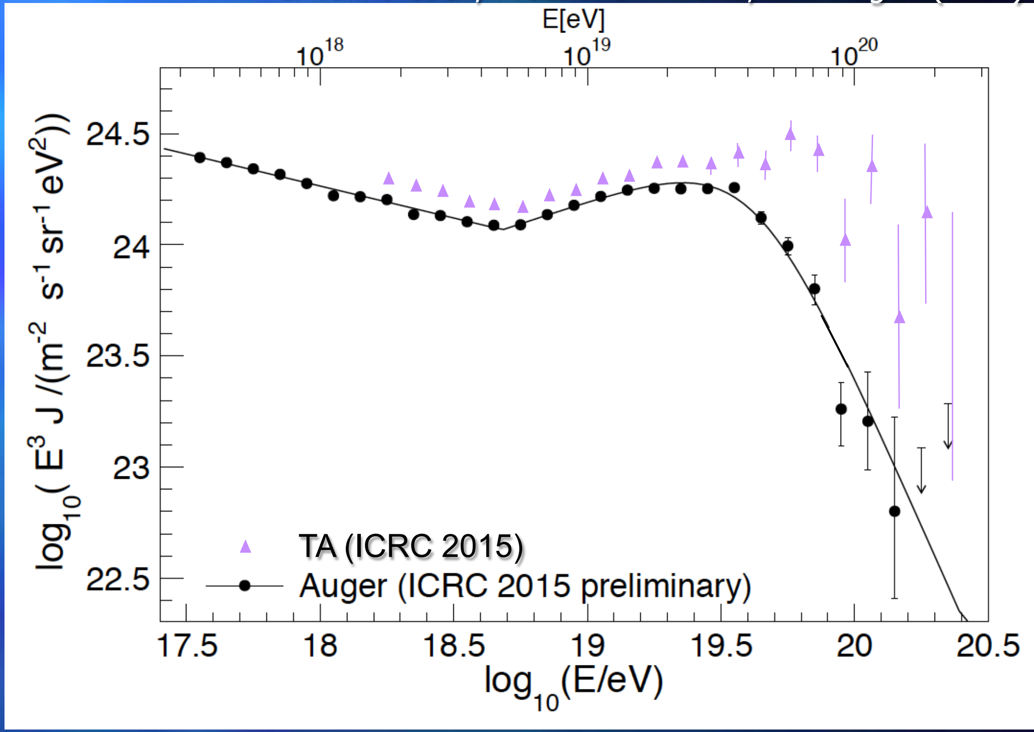
Differences between Auger and TA can be (mostly) accommodated within a systematic energy shift...

... but not easily at the highest energies.

I. Valino et al., Proc. of 34th ICRC, The Hague (2015)



D. Bergman et al., Proc. of 33rd ICRC, Rio de Janeiro (2013)
R.U. Abbasi et al., Astropart. Phys. 68, 27 (2015)

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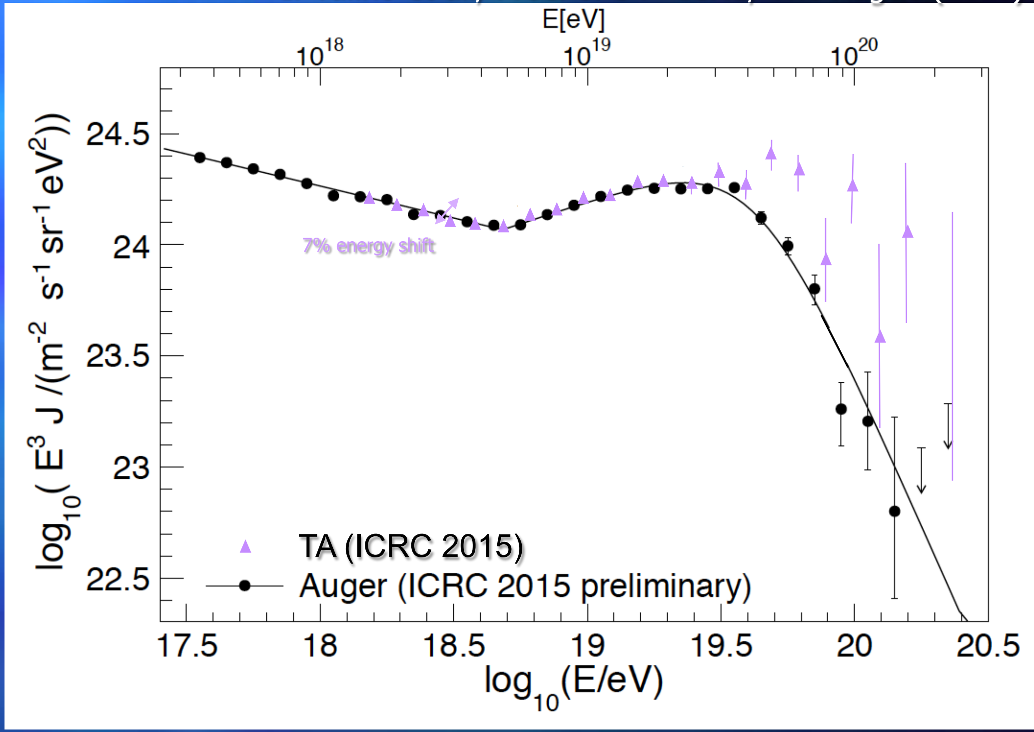


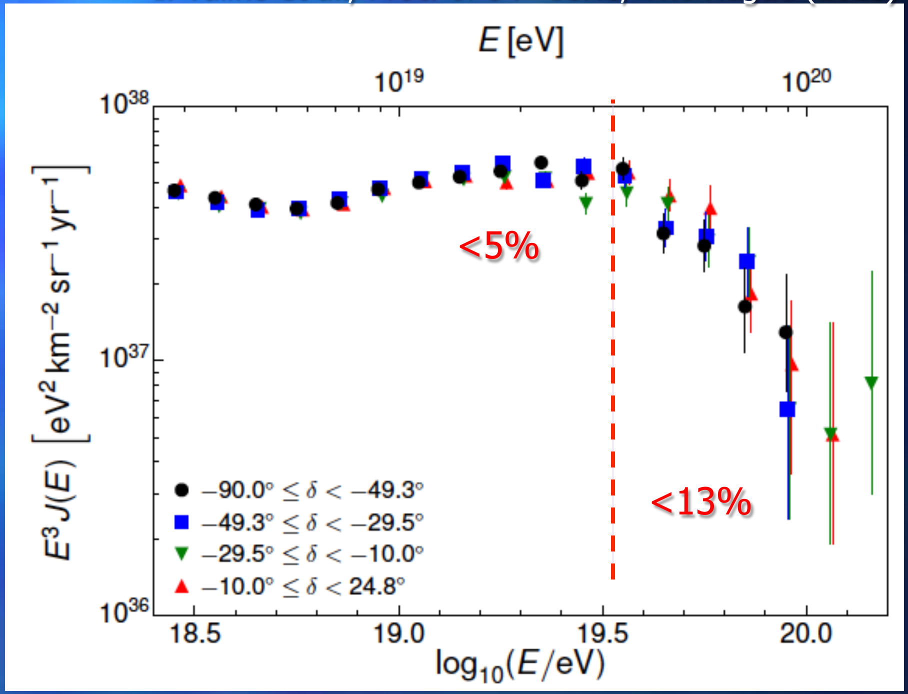
D. Bergman et al., Proc. of 33rd ICRC, Rio de Janeiro (2013)
R.U. Abbasi et al., Astropart. Phys. 68, 27 (2015)

A North/South difference?

Auger spectrum divided into 4 separate declination bands;

No evidence for spectral dependence on source location.

I. Valino et al., Proc. of 34th ICRC, The Hague (2015)



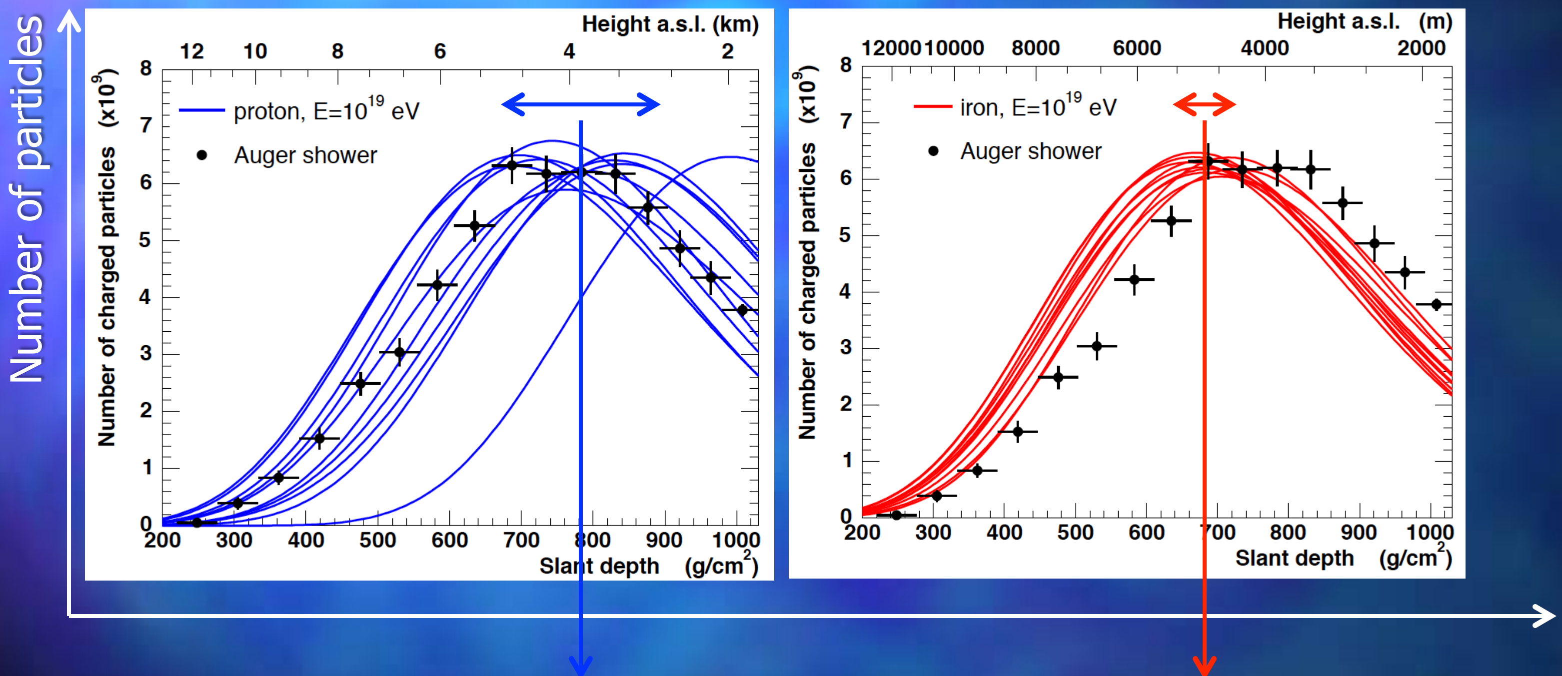
What is the nature of the spectral suppression?

- GZK propagation effects (attenuation due to CMB interactions)?
- Intrinsic difficulty of producing 10^{20} eV particles in astrophysical sources?

1) Study mass composition and air shower development (UHE physics);
2) Look for sources in arrival direction distribution.

Nature of UHECRs

Hybrid measurements are sensitive to mass composition



Depth in the atmosphere

X_{max} ~ 780 g/cm^2

X_{max} ~ 680 g/cm^2

p-induced showers develop deeper than Fe-induced ones

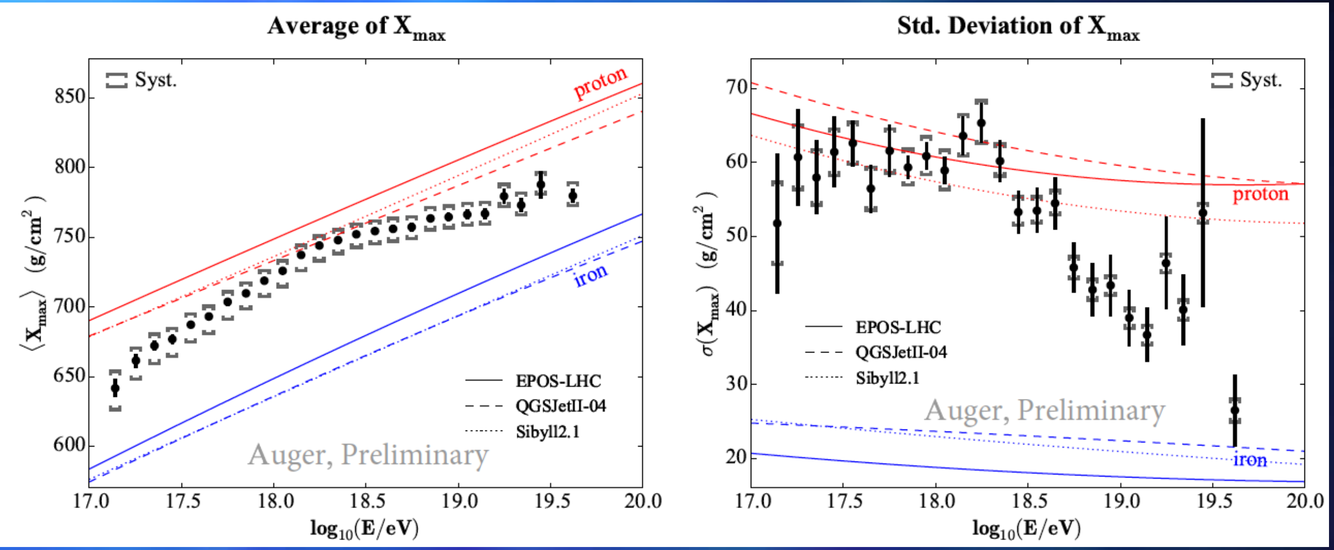
and have greater fluctuations

Mass composition

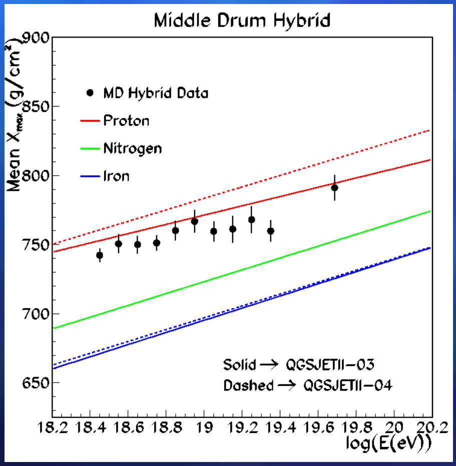
A. Porcelli et al., Proc. of 34th ICRC, The Hague (2015)

Clean hybrid events (strong anti-bias cuts); Detector-independent measurements.

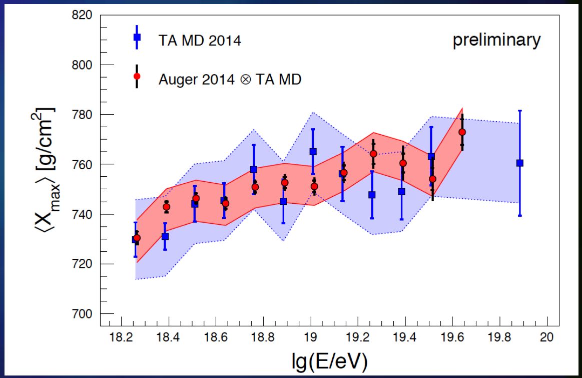
Hadronic interaction MCs tuned to 7 TeV LHC data.



TA distribution is *not* detector independent; instrumental biases folded into MC...



Fold Auger X_{max} distribution into TA MC algorithm... excellent agreement!



M. Unger et al., Proc. of 34th ICRC, The Hague (2015)

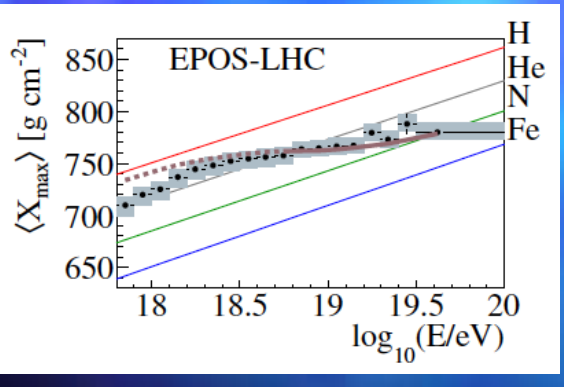
J.P. Lundquist et al., Proc. of 34th ICRC, The Hague (2015)

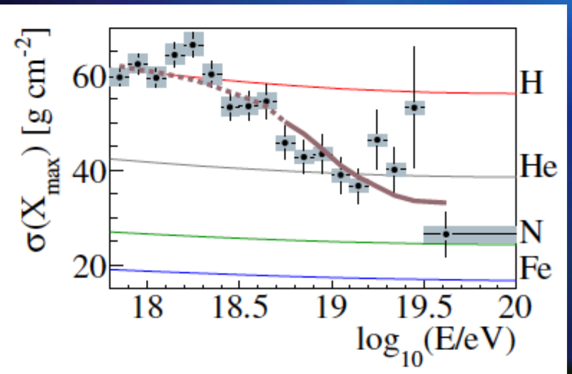
S. Coutu

Combining X_{max} and spectrum

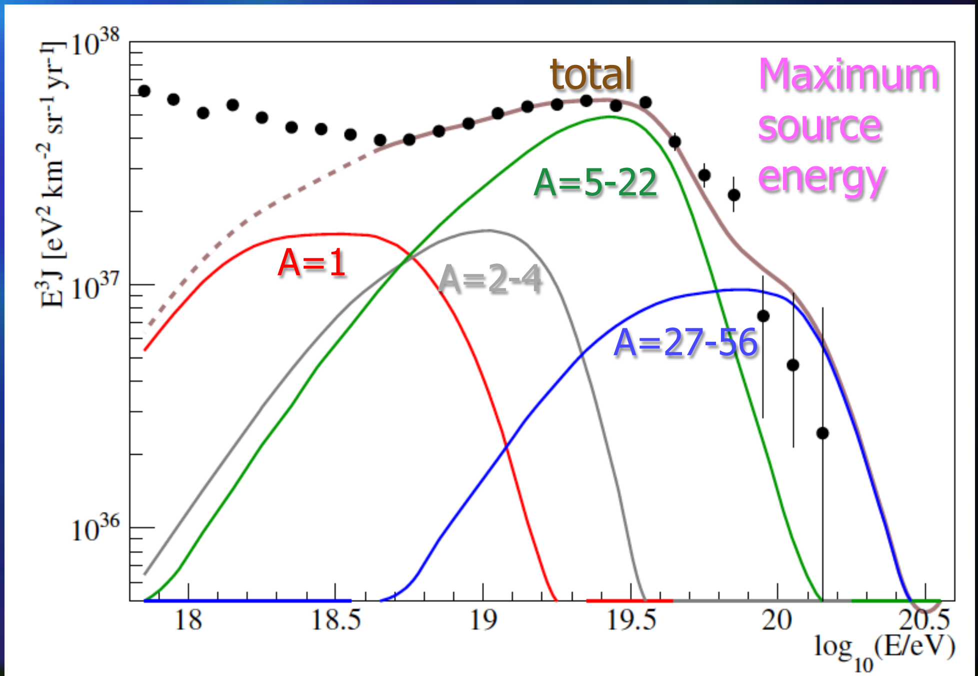
Homogeneous distribution of identical sources of p, He, N and Fe nuclei;
125 data points, 6 fit parameters: injection flux norm. and spec. index γ, cutoff rigidity R_{cut}, p/He/N/Fe fractions;
Best fit with very hard injection spectra (γ≤1).

Rich phenomenology !





A. di Matteo et al., Proc. of 34th ICRC, The Hague (2015)



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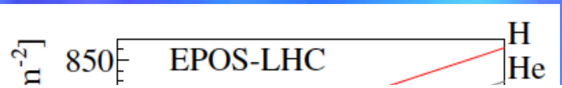

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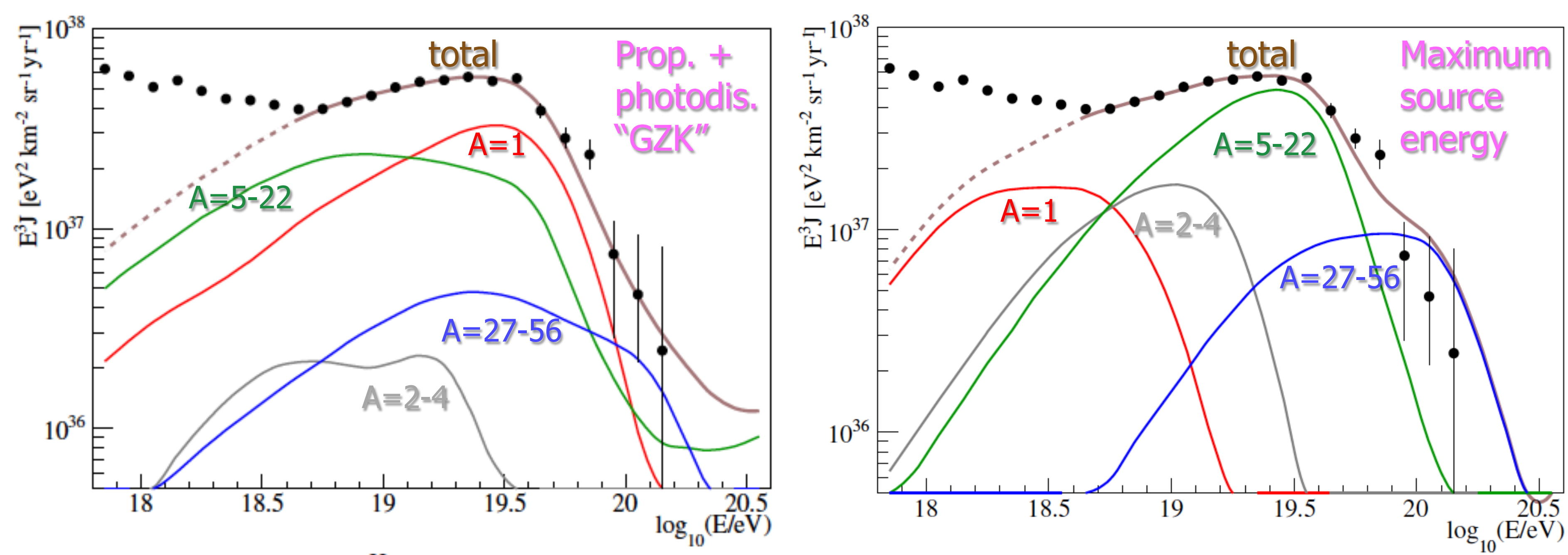
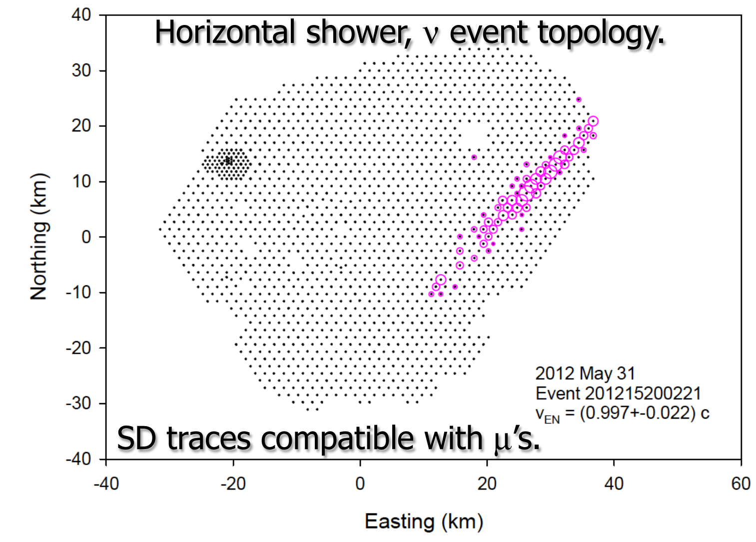


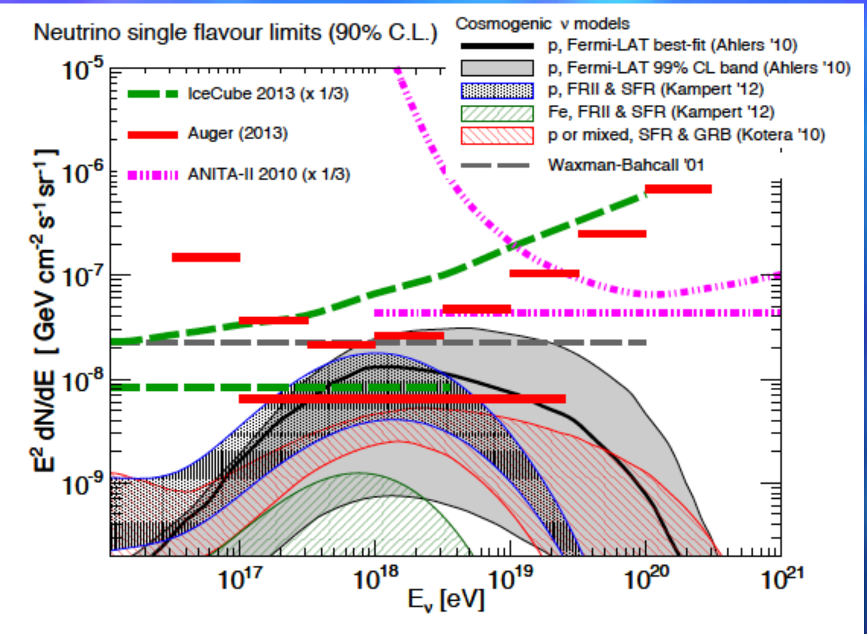
Neutral UHECRs?

None seen so far.

- Photons? Deep showers with low μ content;
  Shape of LDF, SD time structure.
- Neutrinos? Horizontal showers with EM activity;
  Shape of footprint, SD time structure.



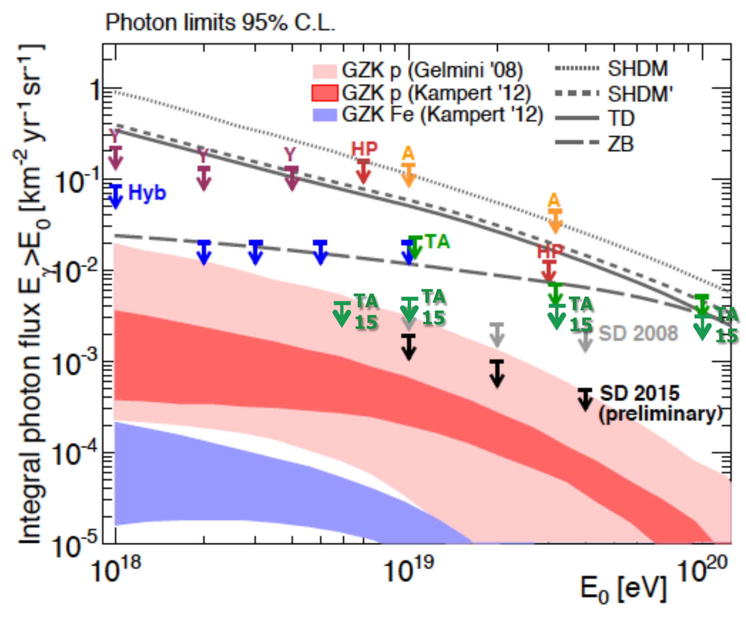
ν: A. Aab et al., PRD 91, 092008 (2015)
γ: A. Aab et al., ApJ 789, 160 (2014)



First ν limits from EAS array below WB

C. Bleve et al., Proc. of 34th ICRC, The Hague (2015)

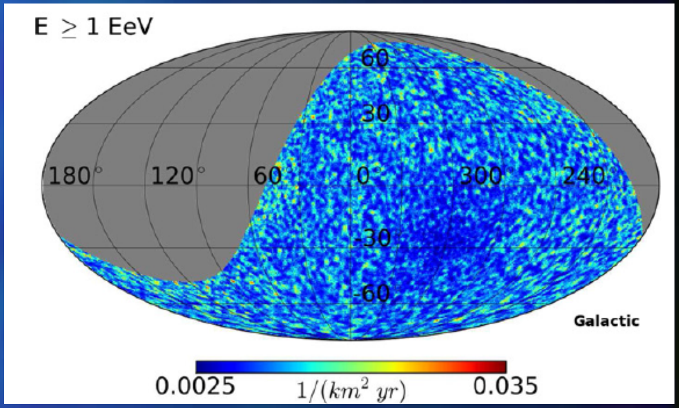
Top-down models strongly disfavored



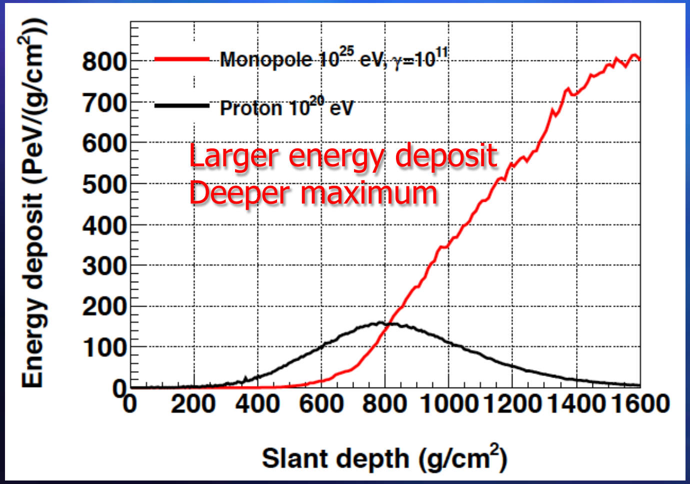
Other types of UHECRs?

- Neutrons? ~EeV air showers showing Galactic anisotropies;
  - Neutron decay length ~(9.2E) kpc, about galactic radius of solar system;
  - No significant excess in blind search or stacked search. n flux limits are below the detected TeV gamma ray fluxes.

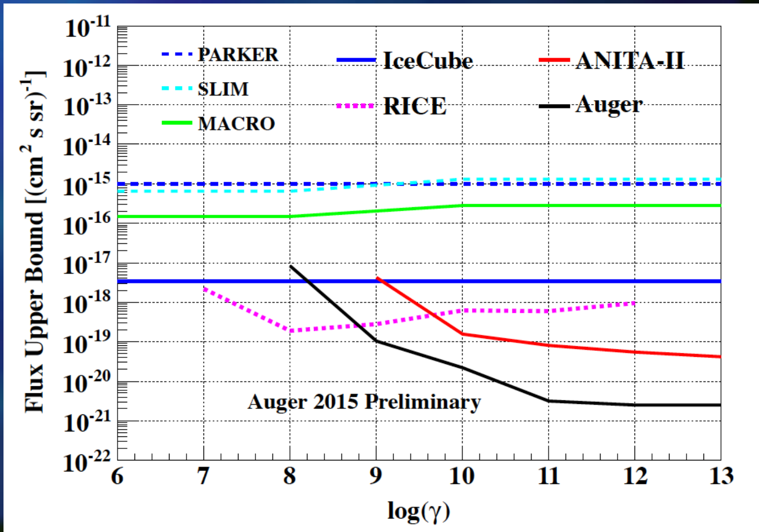
n: P. Abreu et al., ApJ 760, 148 (2012)
A. Aab et al., ApJ 789, L34 (2014)



- Magnetic monopoles? Ultra-relativistic monopoles (masses $10^{11} - 10^{20}$ eV/c^2 deposit a comparable dE/dx in air to UHECRs.



No candidate; first limit from EAS experiment; lowest limit for $\gamma > 10^9$.



T. Fujii et al., Proc. of 34th ICRC, The Hague (2015)

UHE physics

Hadronic interaction models developed by the cosmic-ray community fitted to LHC data:

D. d'Enterria et al., Astropart. Phys. 35, 98 (2011)

Cosmic-ray models

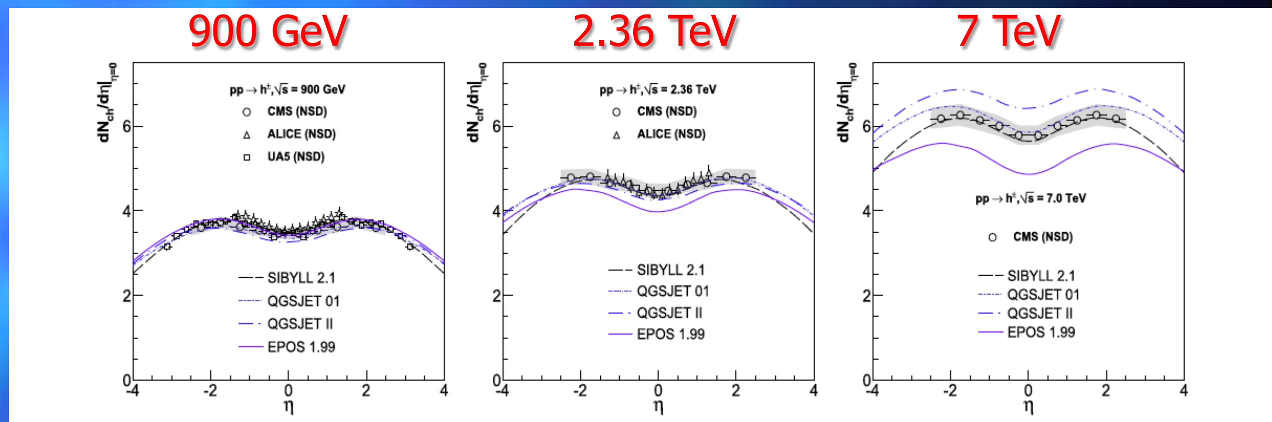
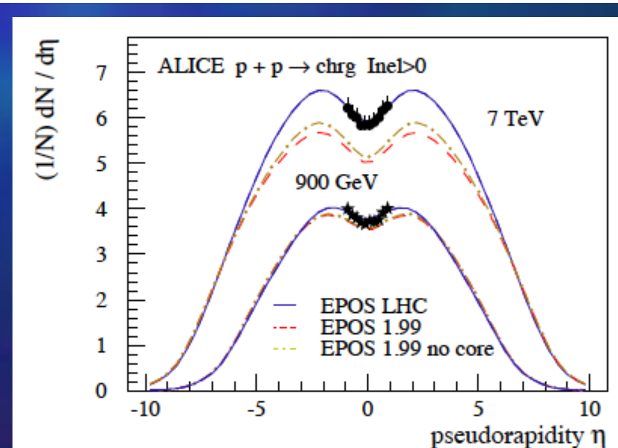


Fig. 3. Pseudorapidity distributions of charged hadrons, $h^{\pm} \equiv (h^{+} + h^{-})$, measured in NSD $p-p$ events at the LHC (0.9, 2.36 and 7 TeV) by ALICE [36,37] and CMS [38,39] (and by UA5 [42] in $p-\bar{p}$ at 900 GeV) compared to the predictions of QGSJET 01 and II, SIBYLL, and EPOS. The dashed band is the systematic uncertainty of the CMS experiment which is similar to those of the two other measurements.

After LHC tuning



T. Pierog et al., arXiv 1306.0121 (2013)

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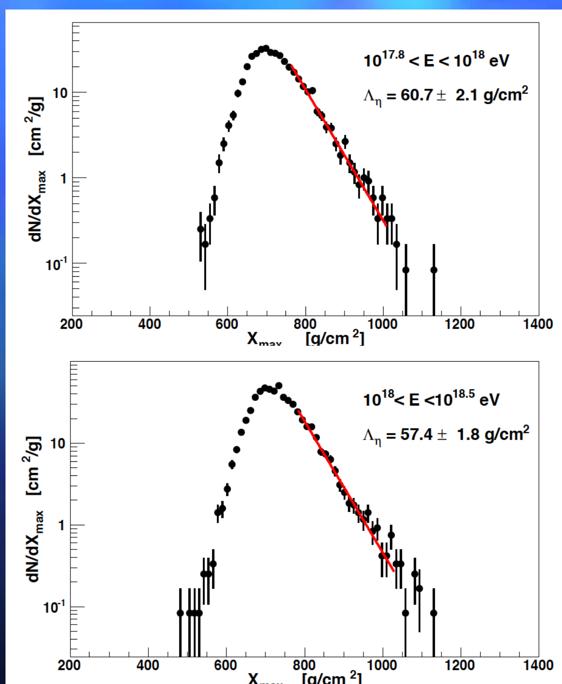
p-air cross section

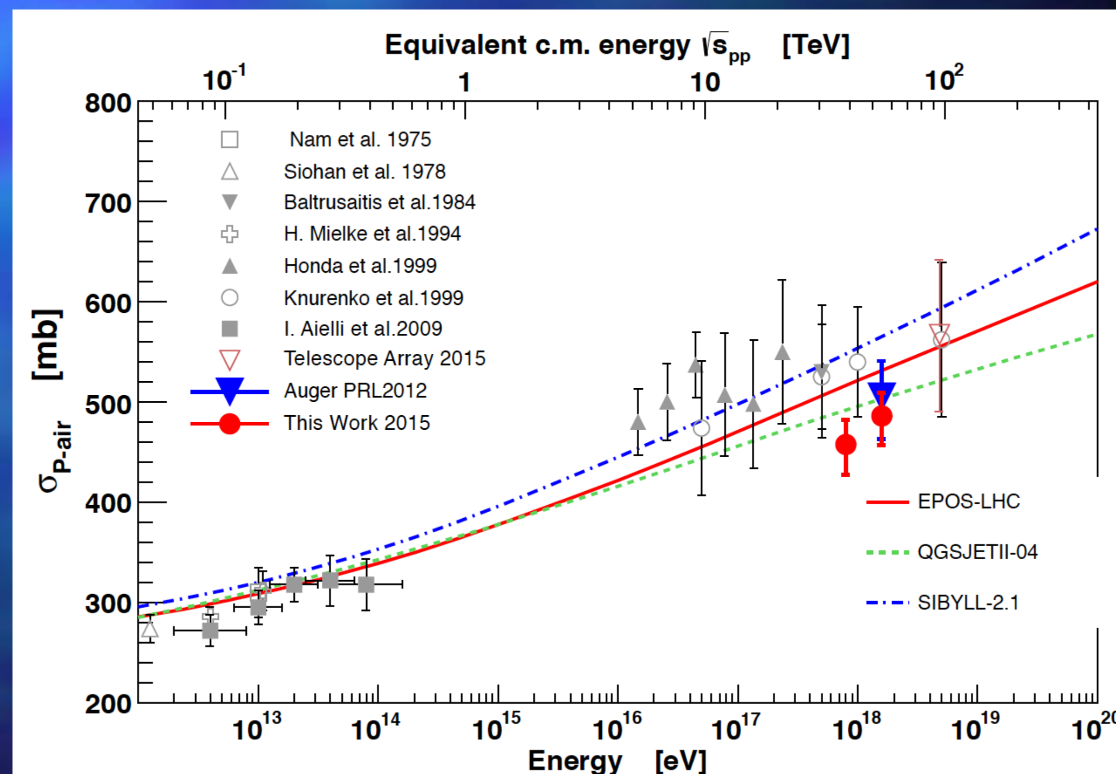
Tail of the X_{max} distribution sensitive to p-air cross-section (heavy nuclei have a shallower X_{max}).

Attenuation length converted to $\sigma_{p\text{-}air}$ using post LHC MC;

Rising cross-section with E, measured at $\sqrt{s}$ ~ 39, 56 TeV.

40,000 clean hybrid events in two energy bins





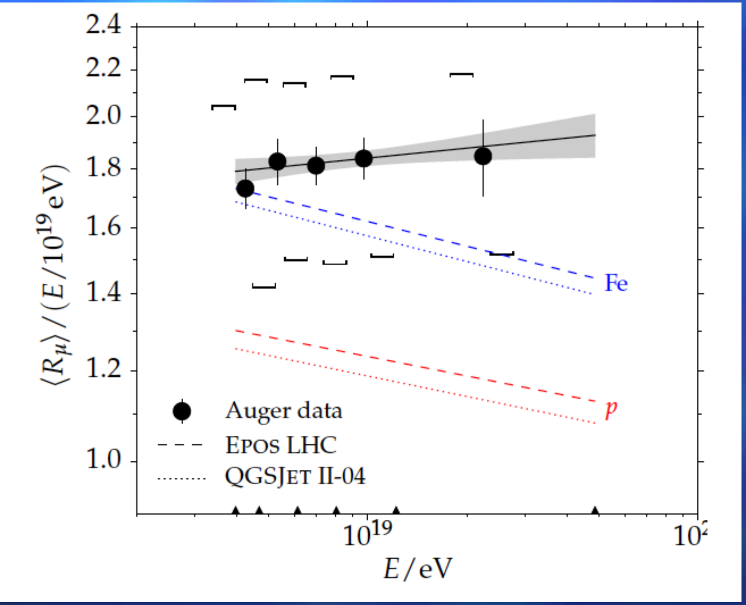
R. Ulrich et al., Proc. of 34th ICRC, The Hague (2015)

Muon production

For highly-inclined showers (θ>60°), SD signal is muon rich (EM component largely absorbed); use 174 high-quality hybrid showers with good FD energy measurement.

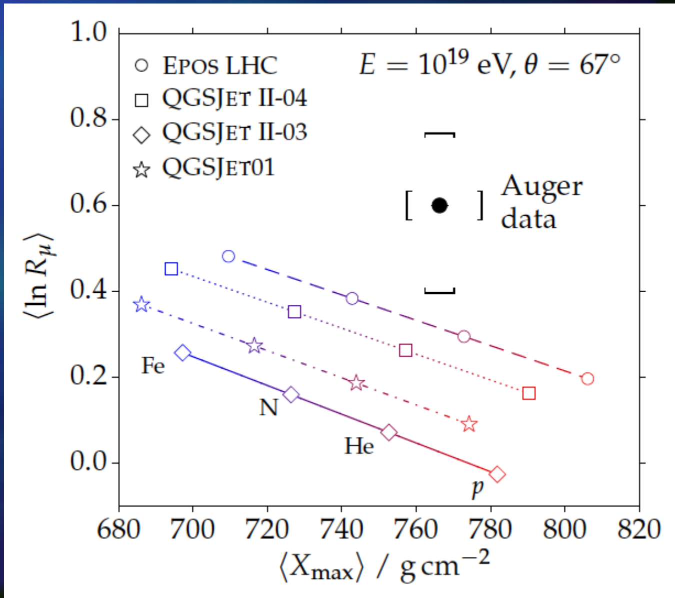
L. Collica et al., Proc. of 34th ICRC, The Hague (2015)

Average No. of muons



FD Energy

Same effect seen in muon no. vs $\langle X_{max} \rangle$

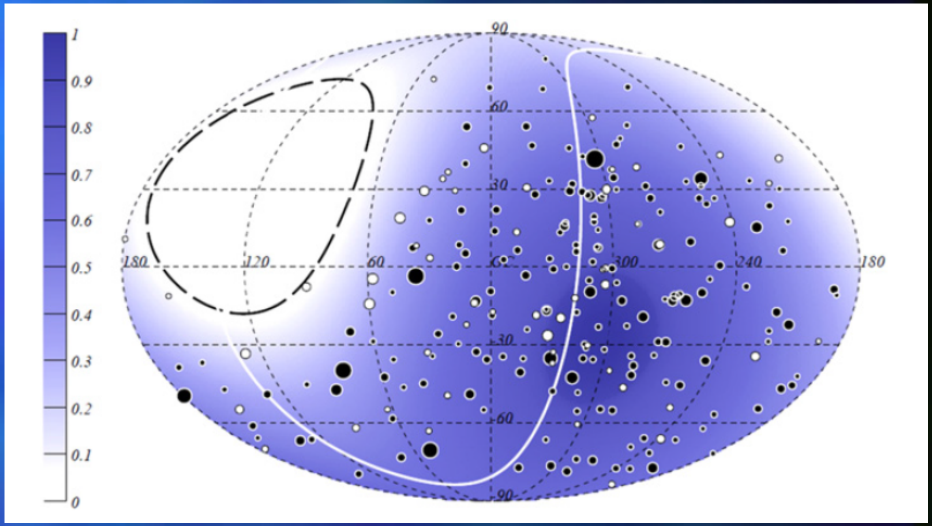


LHC-tuned hadronic interaction generators under produce the muons by 30% to 80%...

Anisotropy searches

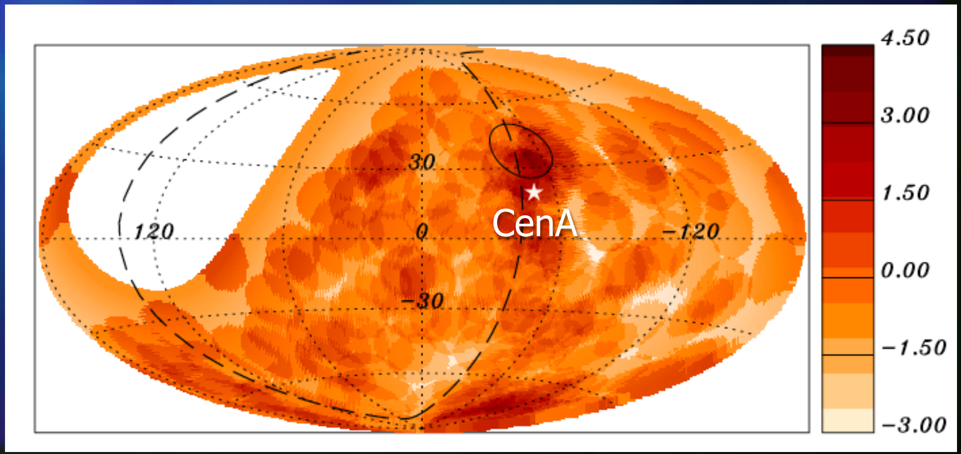
231 Auger events with E ≥ 52 EeV and θ<80°;
- look for flux excesses, autocorrelations (scan in circles 1-30°, with E_{thresh} from 40 to 80 EeV);
- compare with catalogs of AGNs and other objects.

A. Aab et al., ApJ 804, 15 (2015)



Li-Ma significance map in 12° circles;
largest excess 4.3σ, E_{thresh} = 54 EeV,
18° from CenA;
post-trial probability 69%, so compatible with isotropy.

J. Aublin et al., Proc. of 34th ICRC, The Hague (2015)



Note: 2007 69% AGN correlation has weakened to 28%, only 2σ above isotropy.

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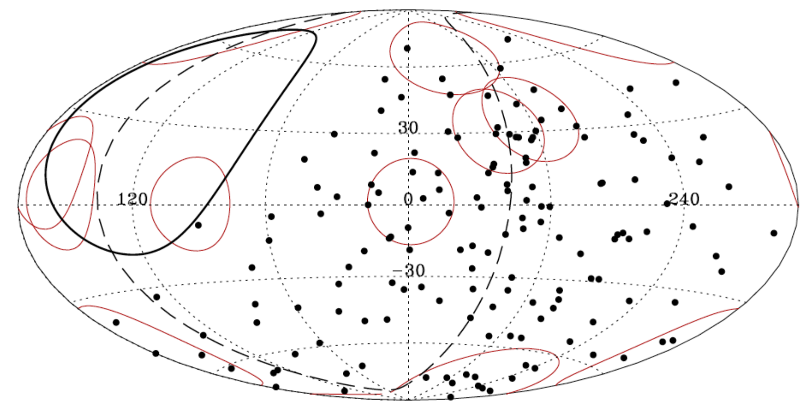
Anisotropy searches

Anisotropy tests with astrophysical structures:
Gal-Xgal planes, 2MRS galaxies, Swift-BAT AGNs, jetted radio galaxies, CenA;
scan over angles, E_{thresh}, luminosity for AGNs and radio galaxies.

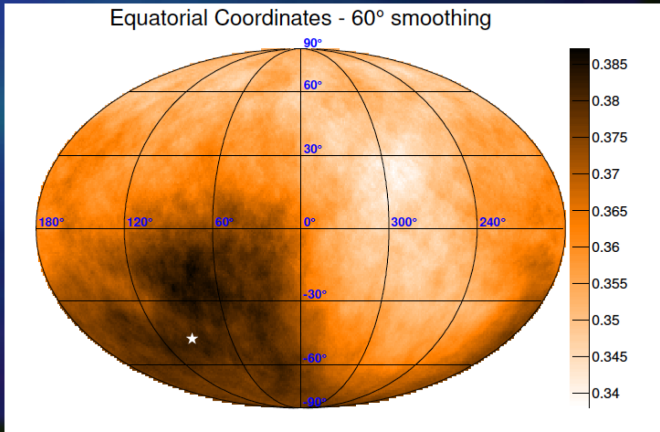
J. Aublin et al., Proc. of 34th ICRC, The Hague (2015)



Largest excess of pairs for Swift AGNs with E_{thresh} = 58 EeV, 18°circles, L > 10^{44} erg/s;
Post-trial probability 1.3%.

Challenges hope for anisotropies and source identification.

Auger/TA joint spherical harmonic analysis:
17,000 Auger and 2500 TA events > 10 EeV;
Dipole of amplitude 6.5±1.9% ($p=5\times10^{-3}$),
pointing to (a,d) = (93°±24°, -46°±18°).

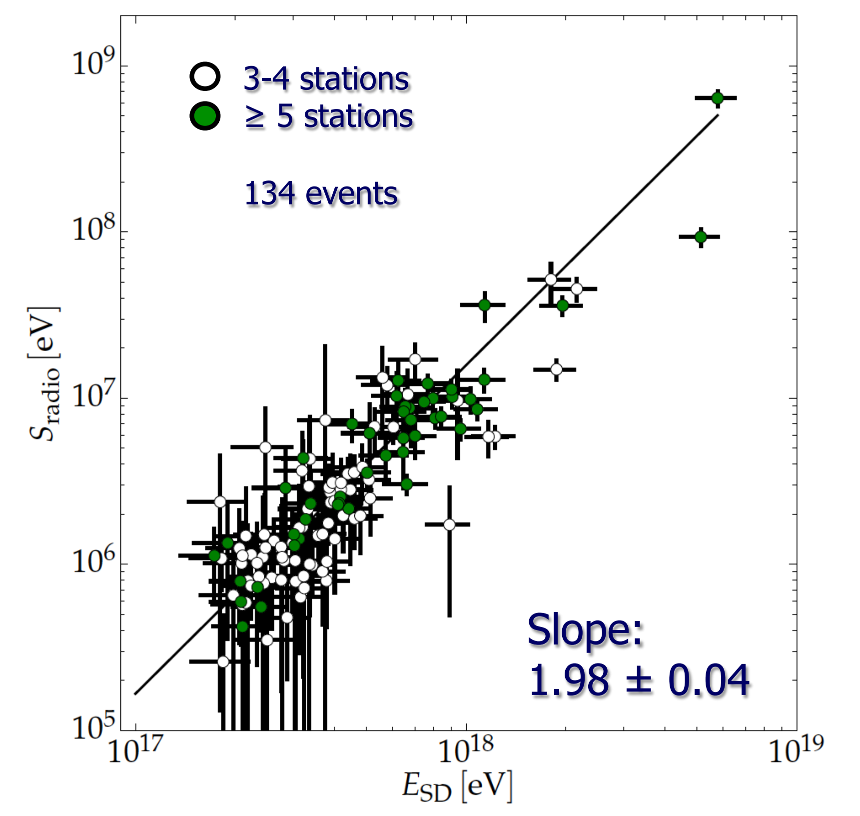


Challenges expectation of isotropy at these “low” energies.

O. Deligny et al., Proc. of 34th ICRC, The Hague (2015)

Radio energy reconstruction

Radio energy



Surface detector energy

Graded array of antennas (LPDA);
153 stations, 17 km^2
World's largest radio detector,
10^{17} eV threshold

In frequency range 30-80 MHz:

16 MeV in E_{radio} for 10^{18} eV CR

E_{radio} resolution: 17% (≥5 stations)

Good prospects with 100% duty cycle
(FD is ~13% for clear moonless nights)

C. Glaser et al., Proc. of 34th ICRC, The Hague (2015), about to be submitted to PRL

but now with *all* messengers!

- New initiative housed at Penn State (+ friends);
- coordinate subthreshold signals (e.g., from transient events) from multiple signatory observatories;
- similar to previous efforts to coordinate neutrino (SNEWS), gamma-ray burst (GCN), or gravitational wave detections;

- MOUs being negotiated (in various stages):
  - Triggering observatories [Swift, Fermi, LIGO, IceCube, Auger, HAWC, Antares];
  - Follow up observatories [HAT (Hungary), IUCAA (India), PTF (CA), VERITAS (AZ), ROTSE];
  - New members actively solicited!
- data sharing begun, first archival searches completing now.

In USA, thanks to

Conclusions

- Physics at the highest-energy frontier requires extraordinary measures!
- Some long-awaited answers are emerging:
  - Flux suppression above ~40 EeV; GZK effect? source exhaustion?
  - Sources do appear to be extragalactic;
  - Large-scale dipole in arrival distribution above 10 EeV;
  - Flux is disappointingly isotropic above 40 EeV, particle astronomy is *hard* !
  - Magnetic fields (Galactic, extragalactic) play a huge role;
  - X_{max} (and its RMS) evolution with energy suggest mass becomes heavier at the highest energies;
  - Important limits to fluxes of neutrinos, photons, neutrons, magnetic monopoles;
  - Highest-energy physics: reasonable cross-section, but inconsistency in muon data;
  - Hadronic interaction issues?
  - Improved knowledge of mass composition is needed:
    - radio techniques can give enhanced X_{max} data;
    - "AugerPrime" upgrade planned, with added scintillators above water-Cherenkov tanks.