XV Mexican Workshop on Particles and Fields

2-6 November 2015 Playa Mazatlan Beach Hotel

Ultra-High Energy Cosmic Rays

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Mexico

Outline

Physics Motivation
Auger Observatory
Telescope Array
Recent Results

- ***Energy spectrum***
- ***Mass composition***
- ***Anisotropies***

Future Prospects

Physics Motivation

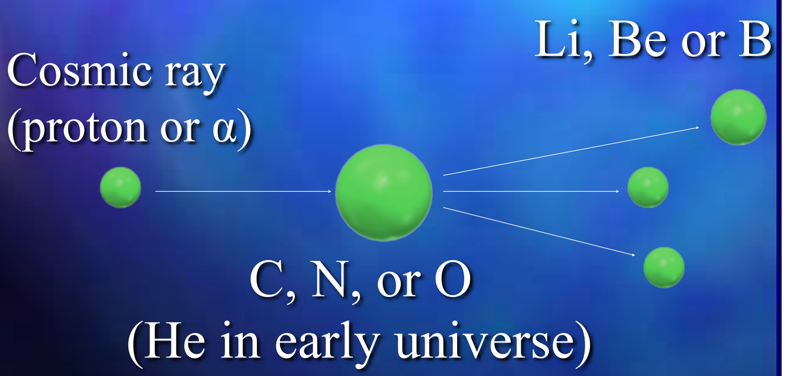
Still many open questions!

What are cosmic rays?
How do we detect them?
Where do they come from?
How do they get their huge energy?
What can we learn about their sources?
What can we learn about their propagation?

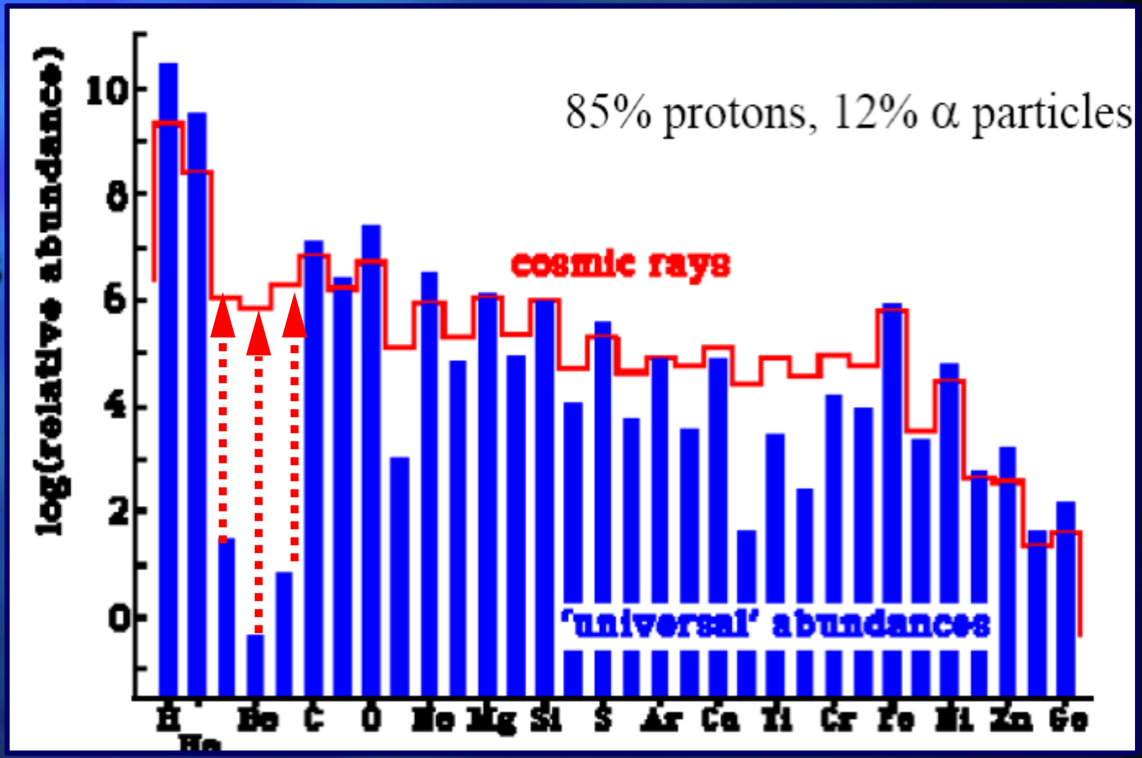
What can we learn about the galactic and extra galactic magnetic fields?

What are cosmic rays?

- There are more cosmic rays of certain elements than there should be
  - Due to collisions with other atoms somewhere in space!
  - These collisions are a major source of lithium, beryllium and boron in the universe

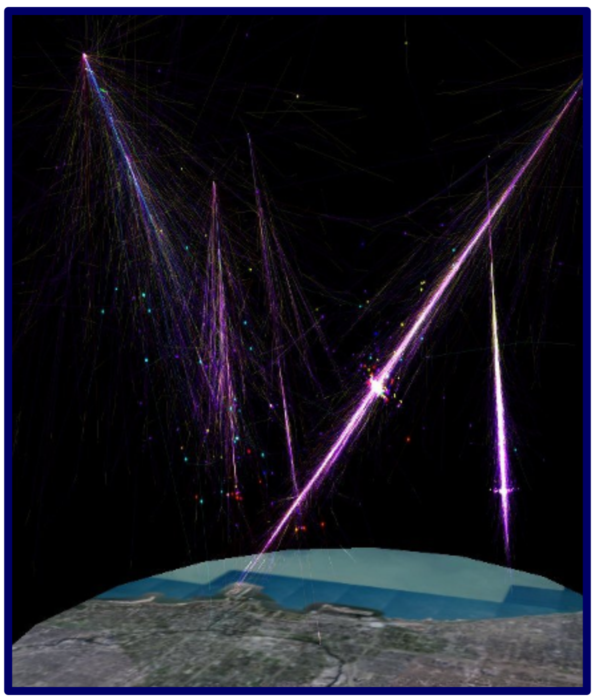


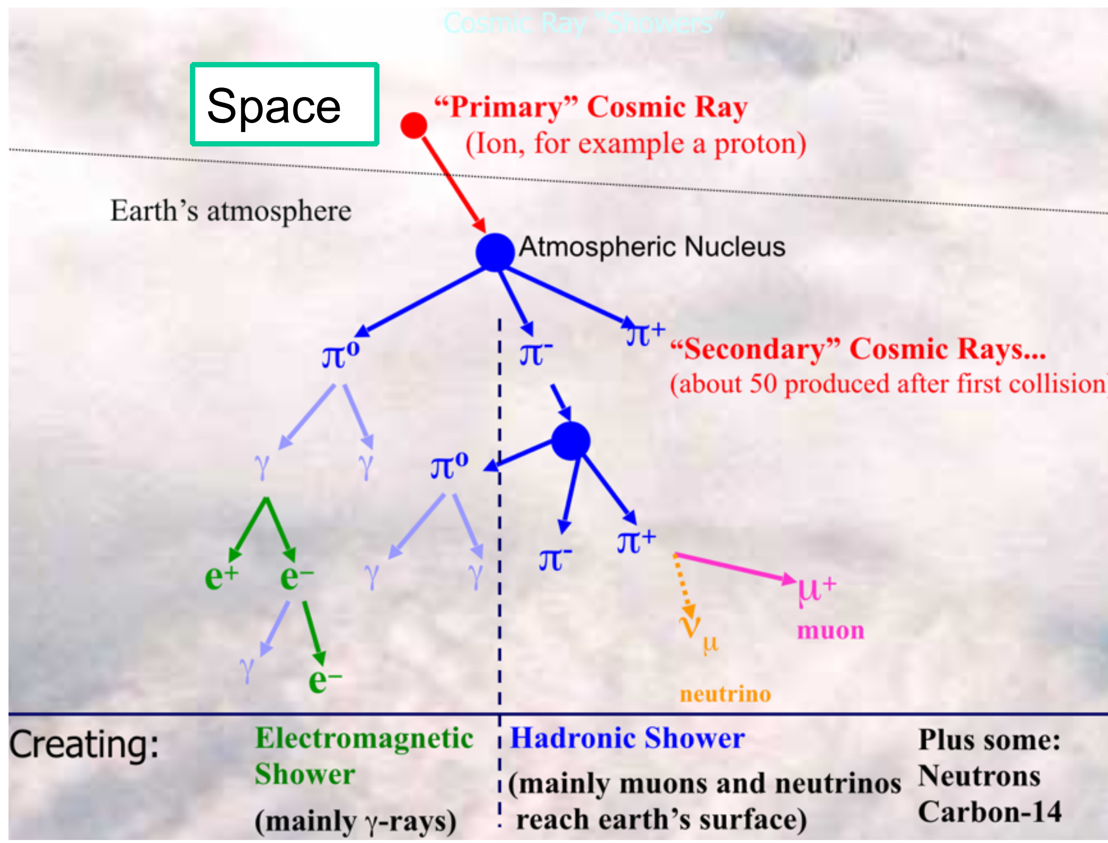
Cosmic ray spallation



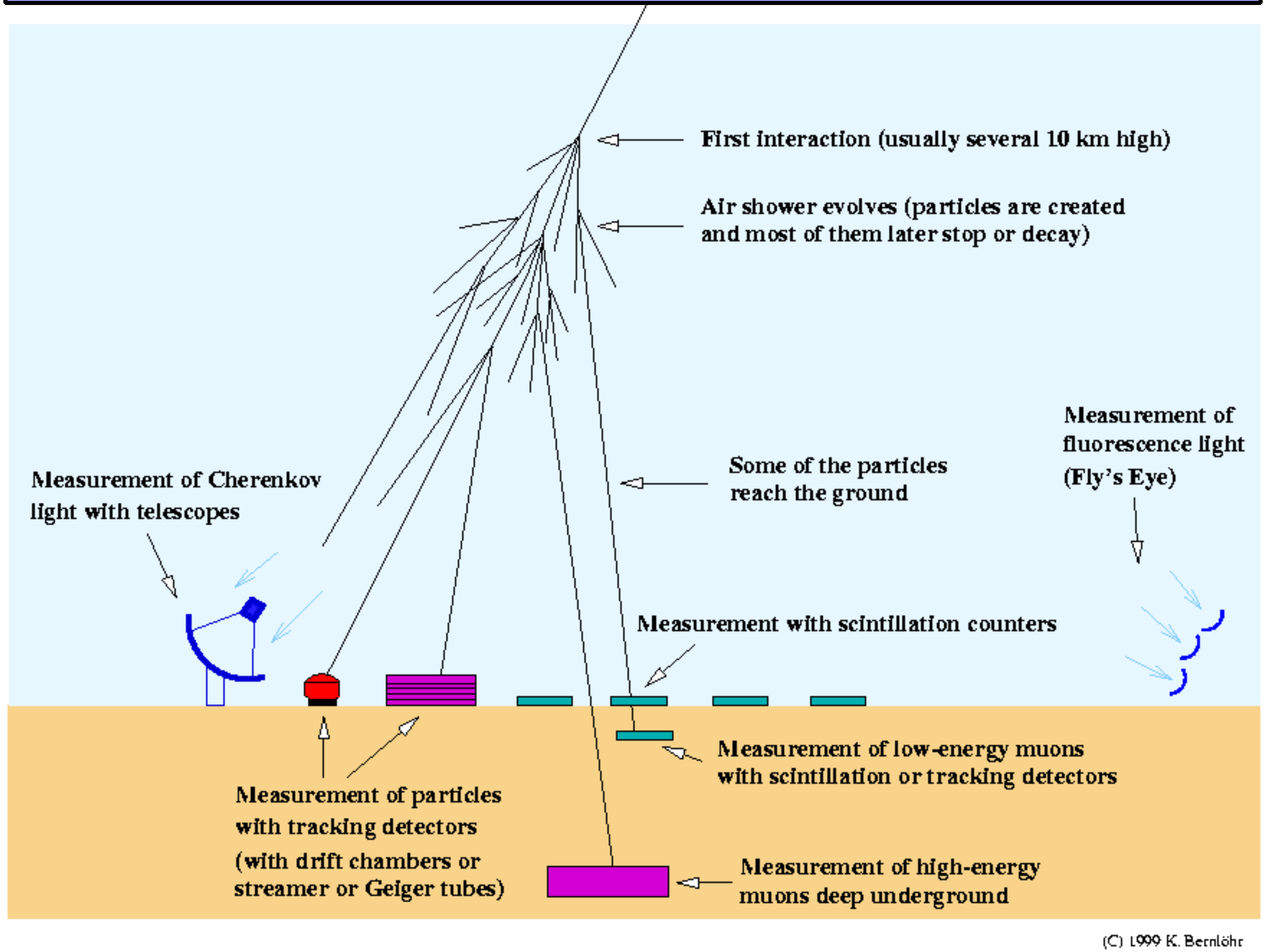
What are cosmic rays?

- 1932-1933 Millikan (photons) vs Compton (charged particles). Latitude effect
- They are charged particles arriving at the Earth from outer space composed of:
- 85% protons
- 12% helium nuclei (α particles)
- 2% electrons
- 1% heavier nuclei

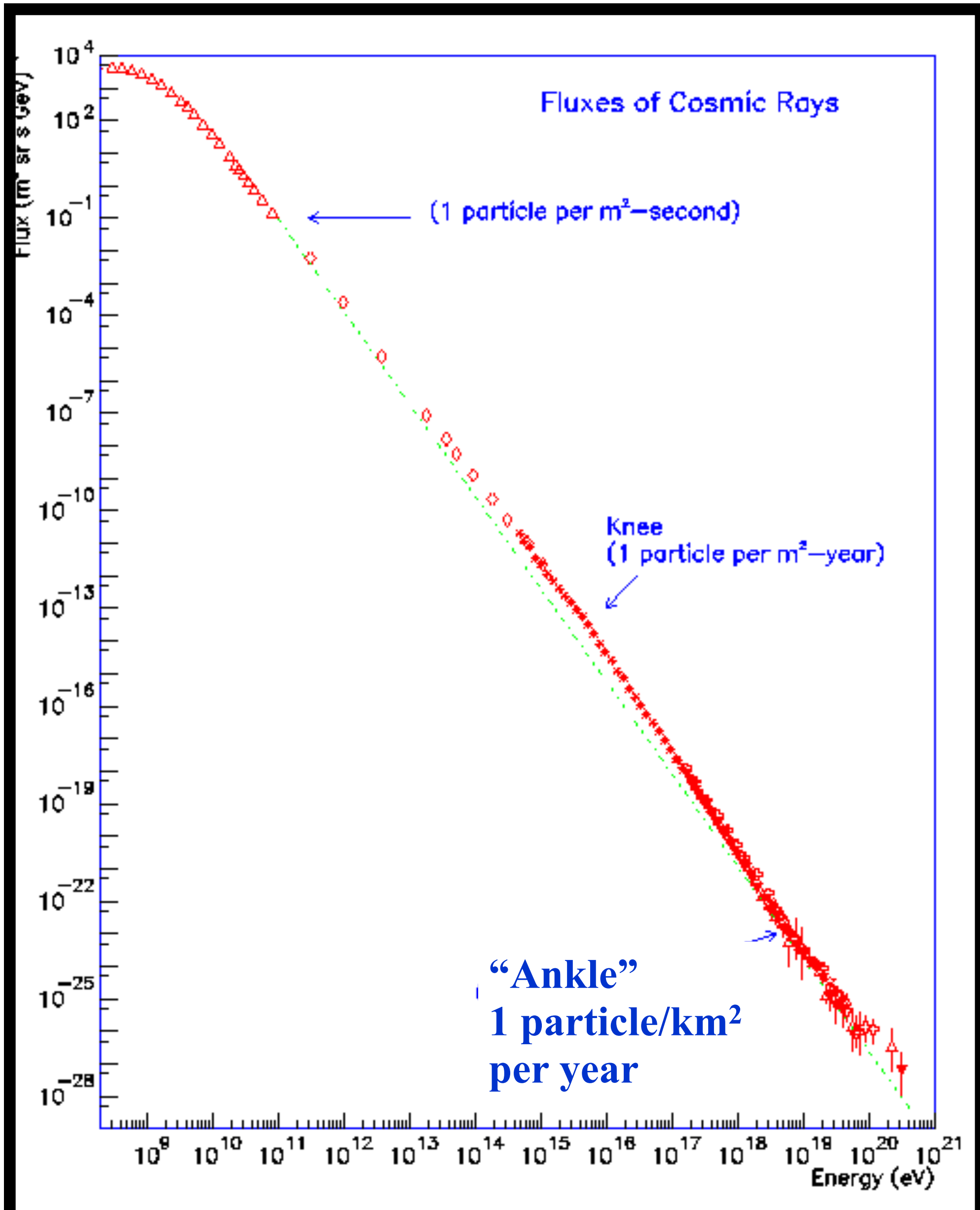




How do we detect Cosmic Rays?



Spectrum of Cosmic Rays



The cosmic ray spectrum stretches more than 12 orders of magnitude in energy and more than 30 in differential flux

$dN/dE \sim E^{-\gamma}$

γ steepens from 2.7 to .1 at $E \sim 3\times10^{15}$ eV

steepens to 3.3 at 8×10^{16} eV (2nd. knee)

hardens to 2.6 at 4.8×10^{18} eV (ankle)

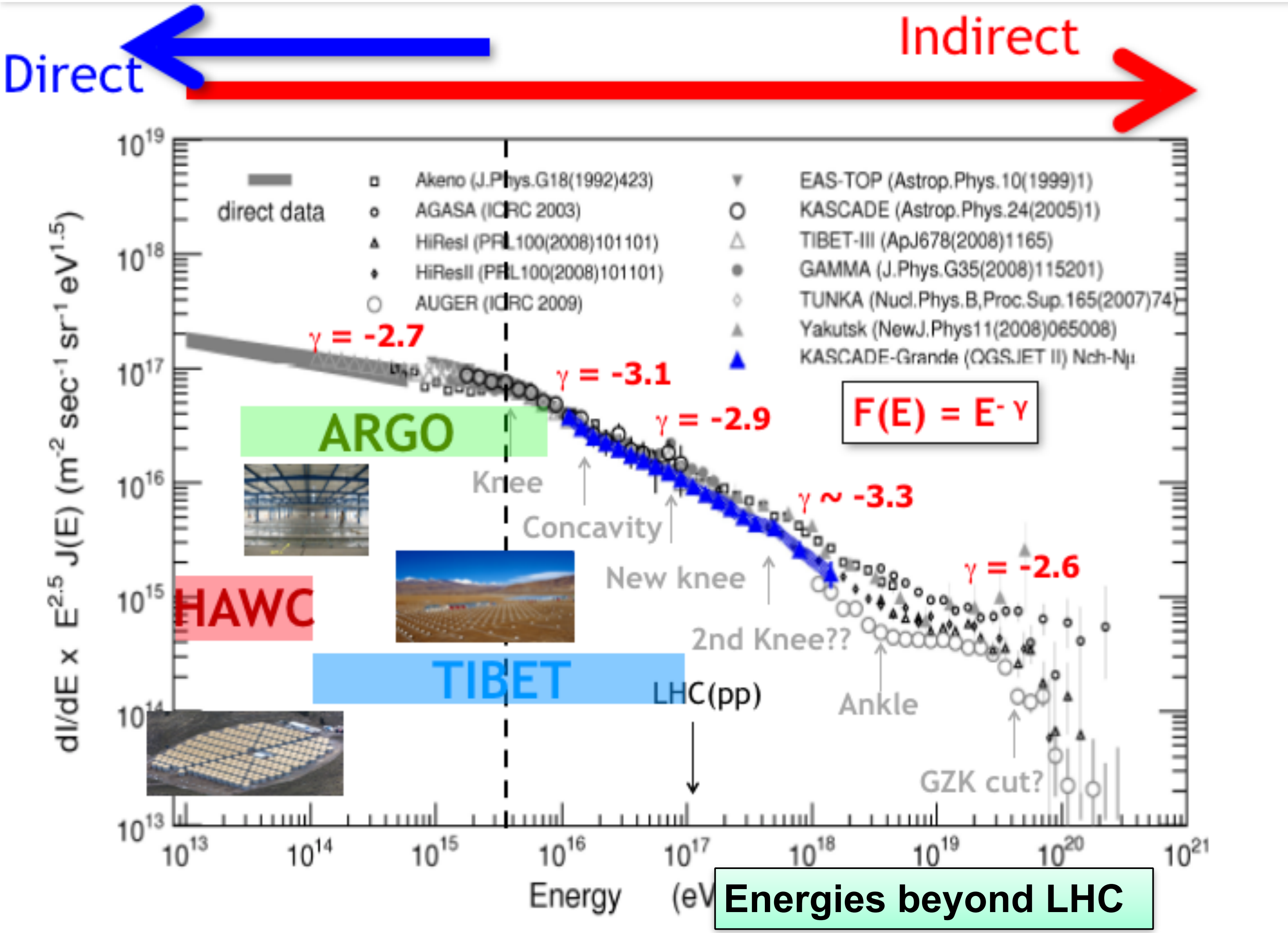
gets suppressed above 48×10^{18} eV (ankle)

For $E > 10^{20}$ eV the flux is lower than 1 per sq. km per century

Observations are improving at all energies, both in terms of higher statistics and reduced systematics

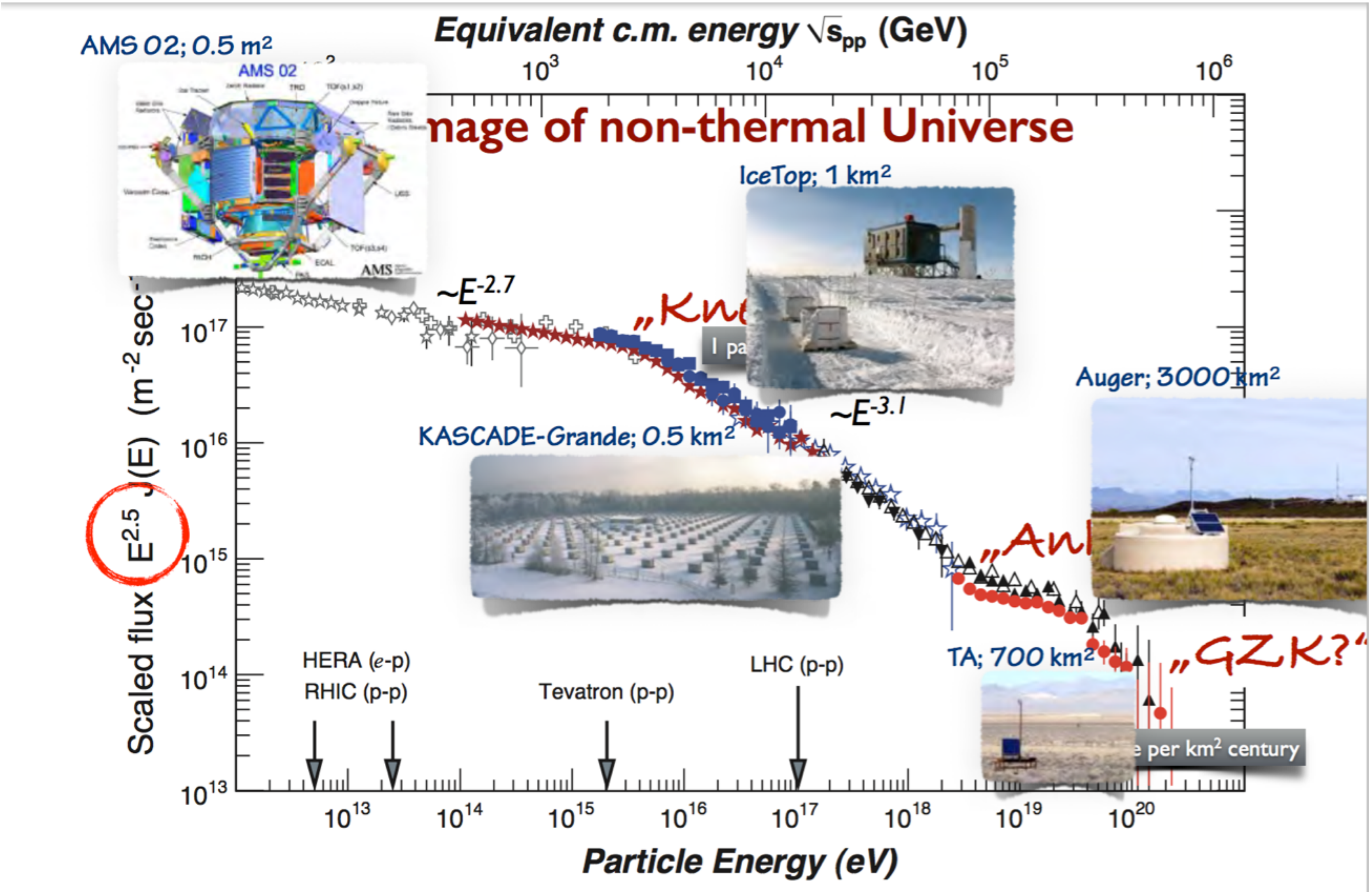
E ~ 50 Joules in a single particle

Spectrum of Cosmic Rays

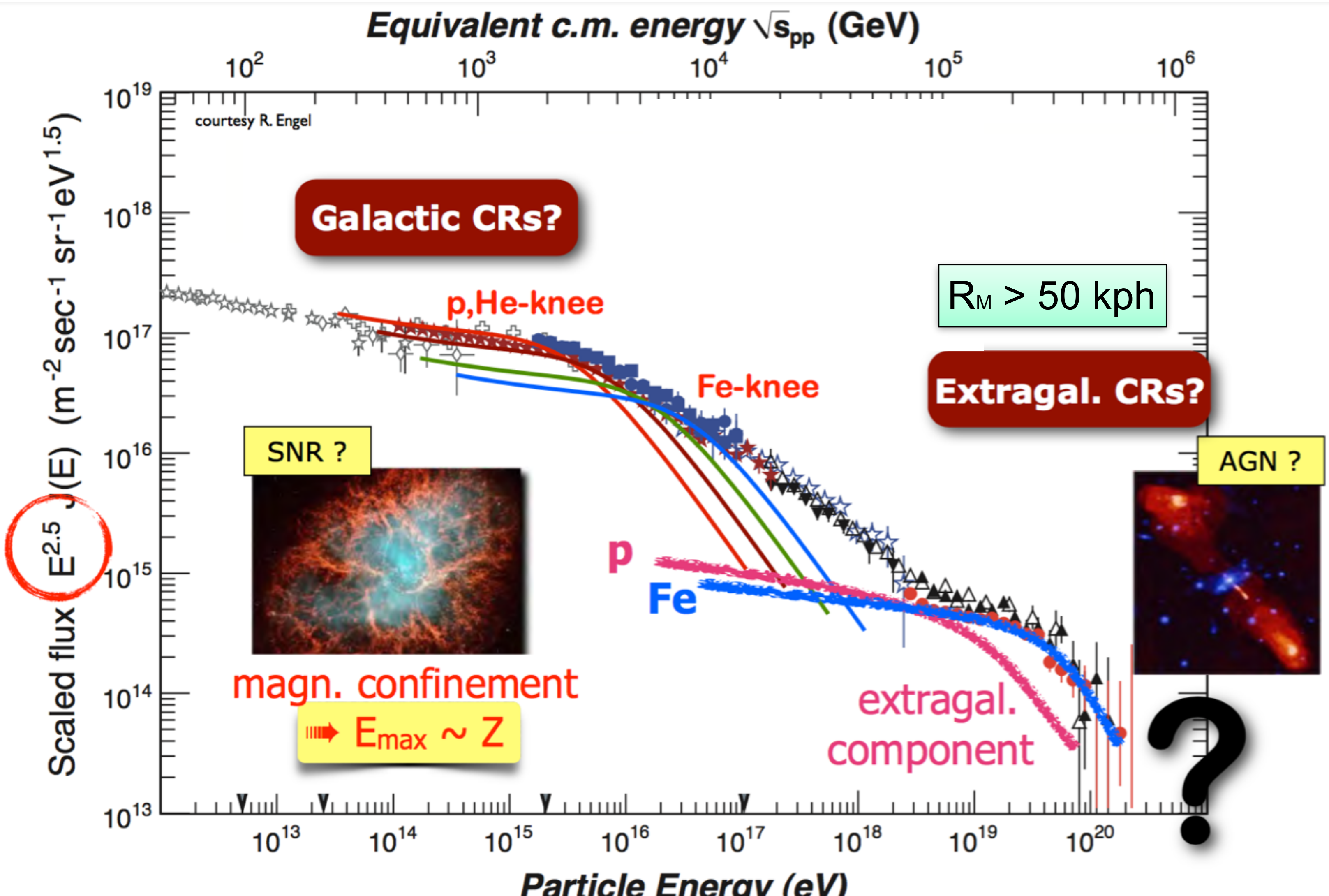


J.C. Arteaga, MWPF, 2015

The structure of the spectrum and scenarios of its origin

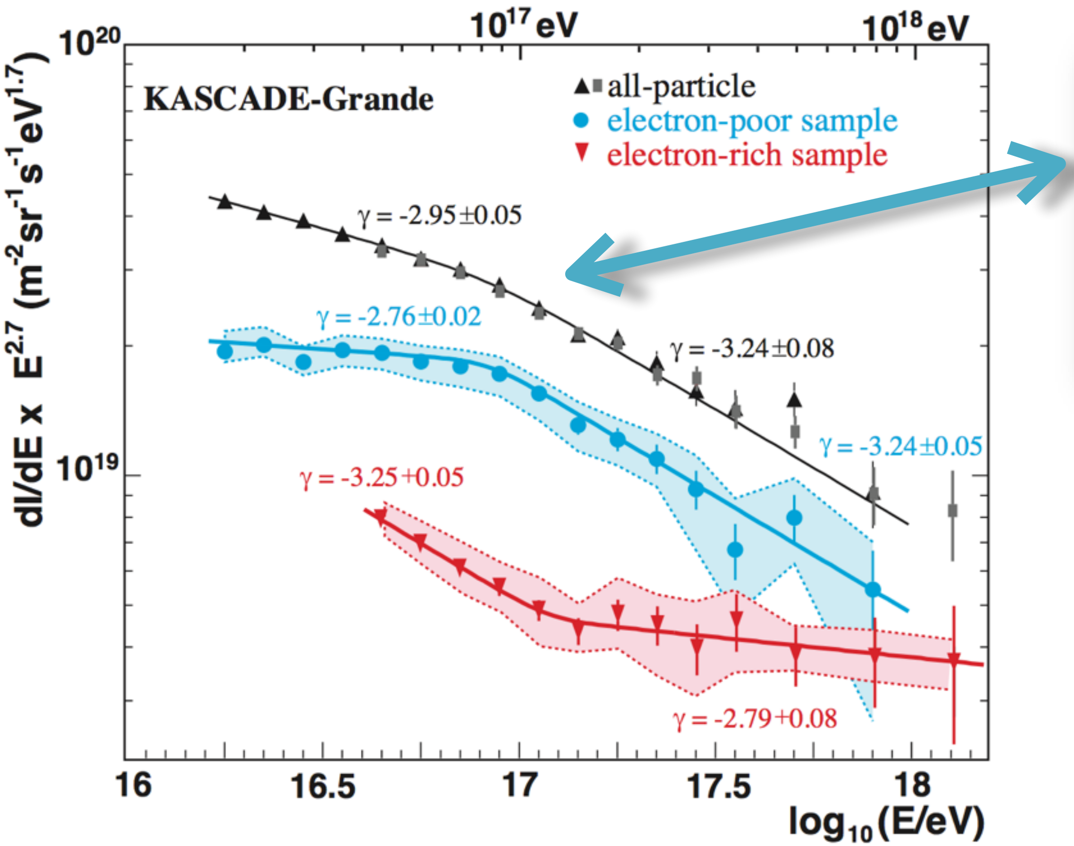


The structure of the spectrum and scenarios of its origin



K-H Kampert, Marcel Grossman Meeting 2015

Recent Results from Cascade Grande on the Fe-like Knee



$E_{knee}^{p} \sim 3\text{x}10^{15}$ eV

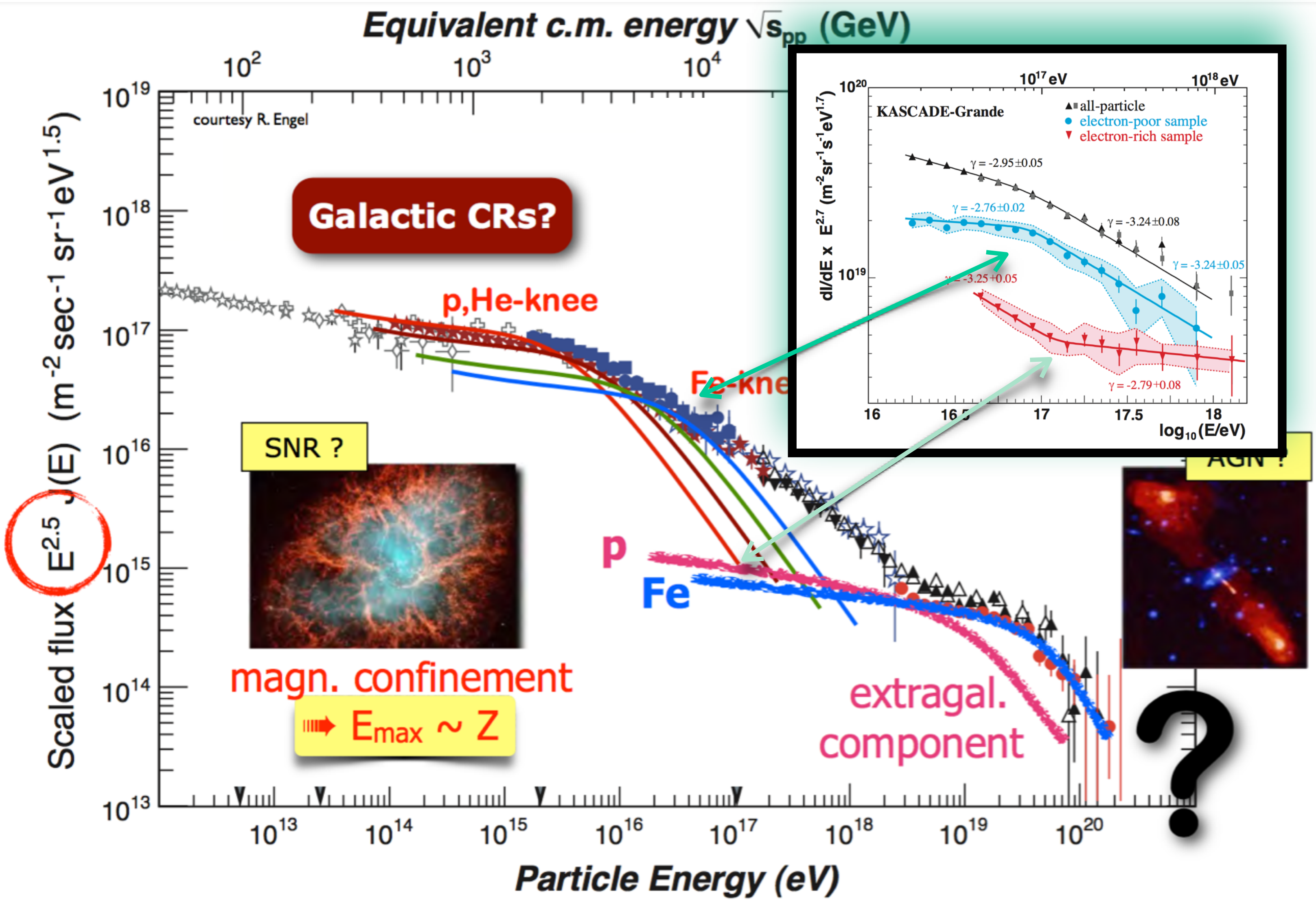
$E_{knee}^{Fe} \sim 8\text{x}10^{16}$ eV

$E_{knee}^{Fe} \sim 26 \times E_{knee}^{p}$

- Second knee at $10^{16.9}$ eV with a statistical significance of 3.5σ KASCADE-Grande-Collaboration, Phy Rev. Lett. 107, 171104 (2011)

- Ankle-like feature in the light component at $10^{17.1}$ eV with a significance of 5.8σ, KASCADE-Grande-Collaboration, Phys. Rev. D 87, 081101(R) (2013).

The structure of the spectrum and scenarios of its origin

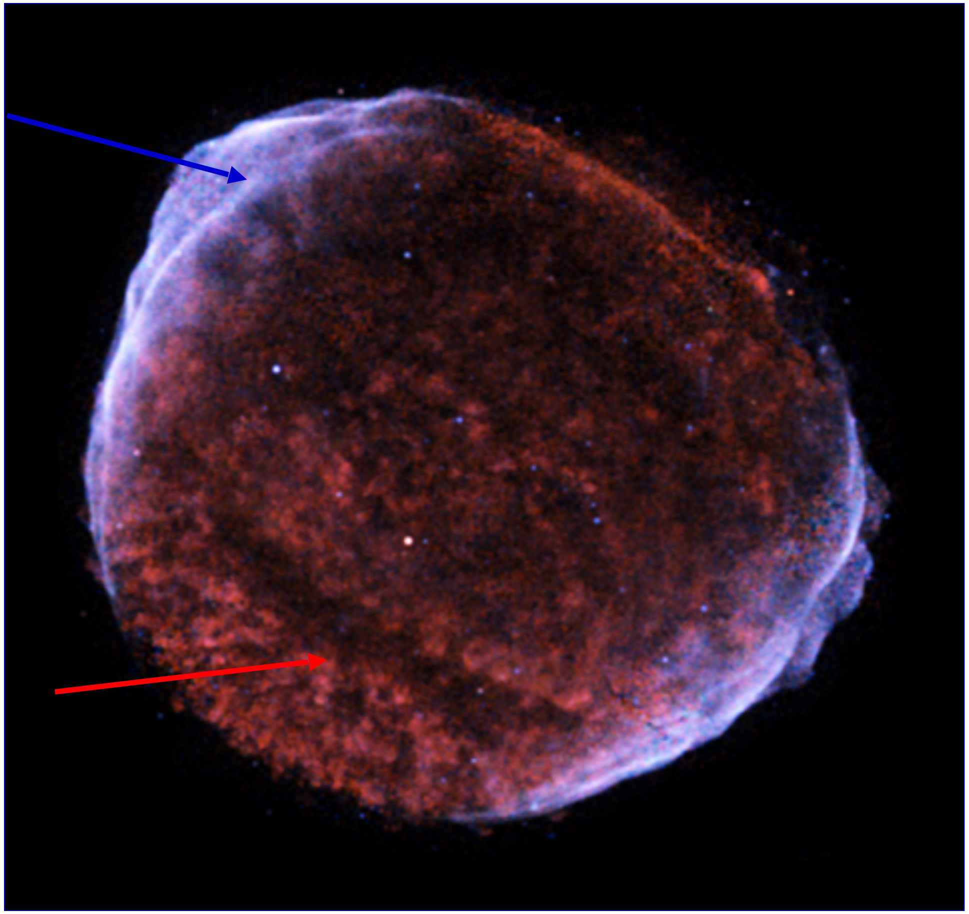


K-H Kampert, Marcel Grossman Meeting 2015

Supernovas: a source of Cosmic Rays?

X-ray image by Chandra of Supernova 1006

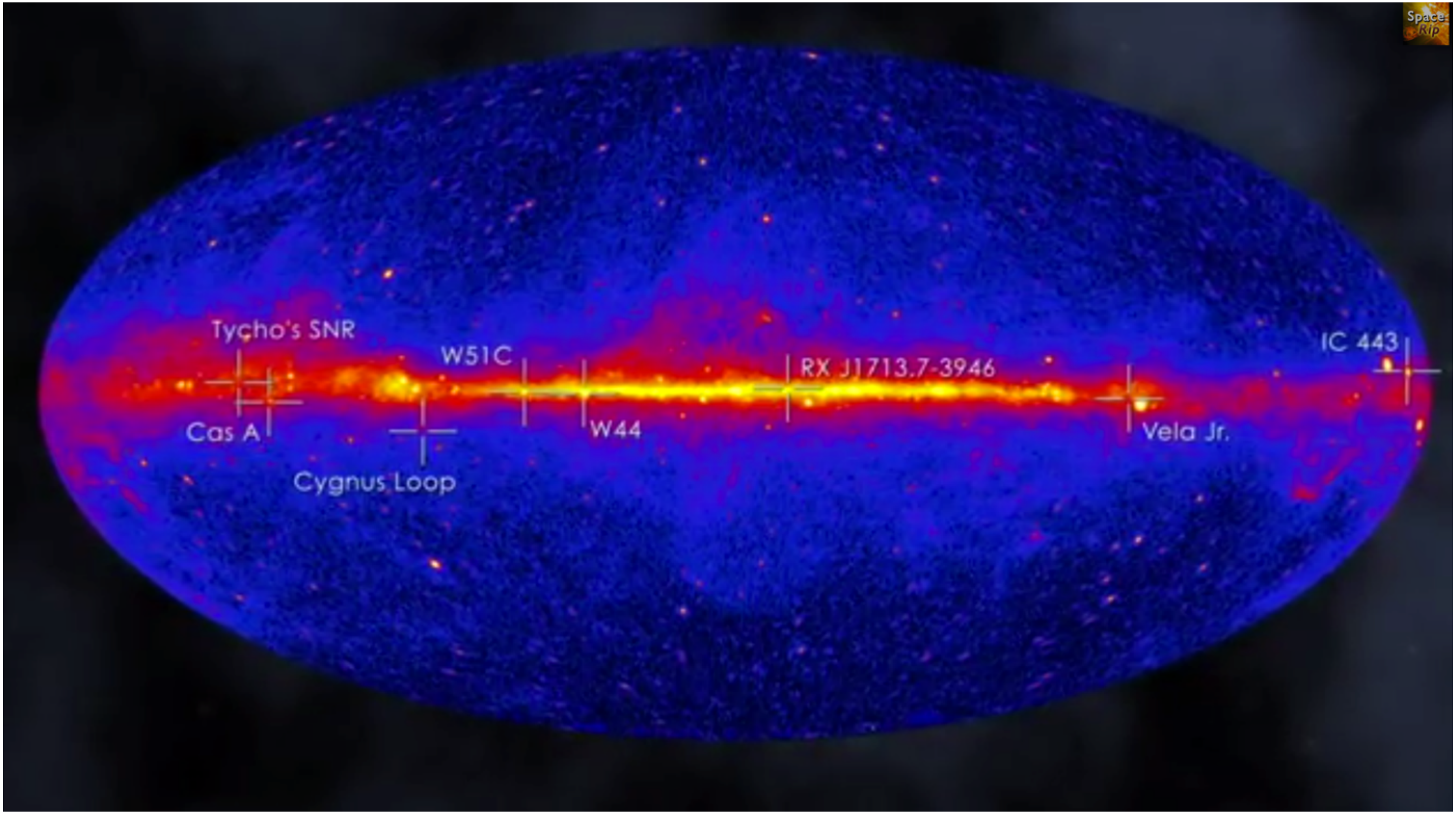
Blue: X-rays from high energy particles



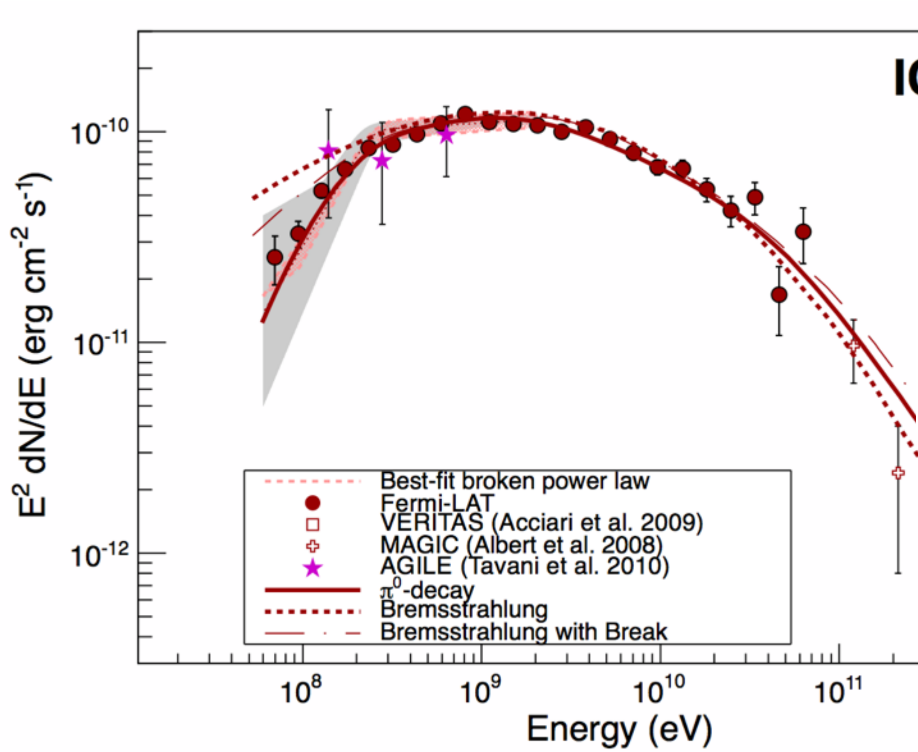
Red: X-rays from heated gas (reverse shock)

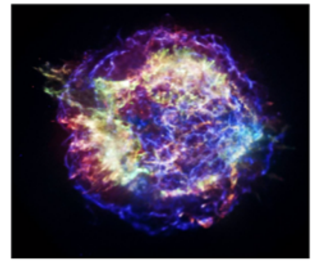
Shockwaves from the supernova hit gas surrounding the explosion, possibly accelerating CRs to 10^{15} eV. Not enough energy for UHECRs!

Detection of the Characteristic Pion-decay Signature in Supernova Remnants

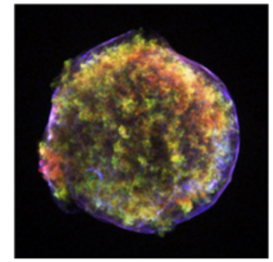


Detection of the Characteristic Pion-decay Signature in Supernova Remnants

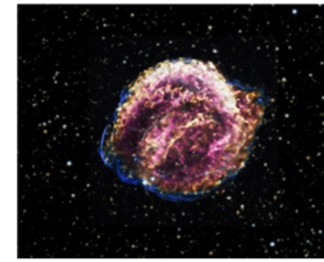




Cassiopea A

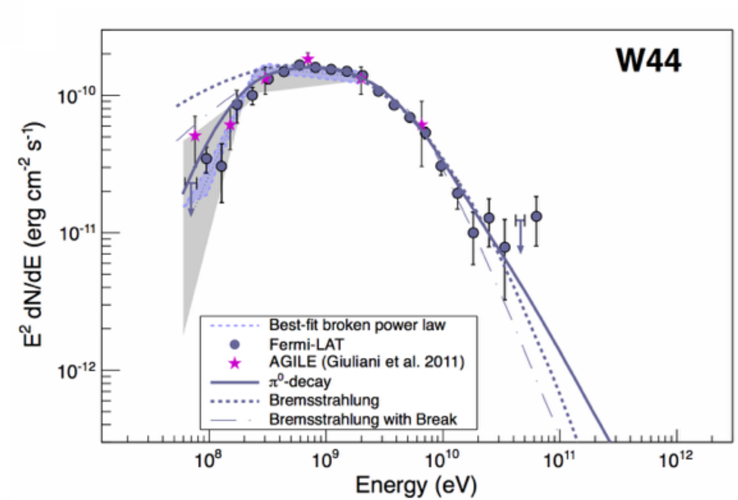


Tycho

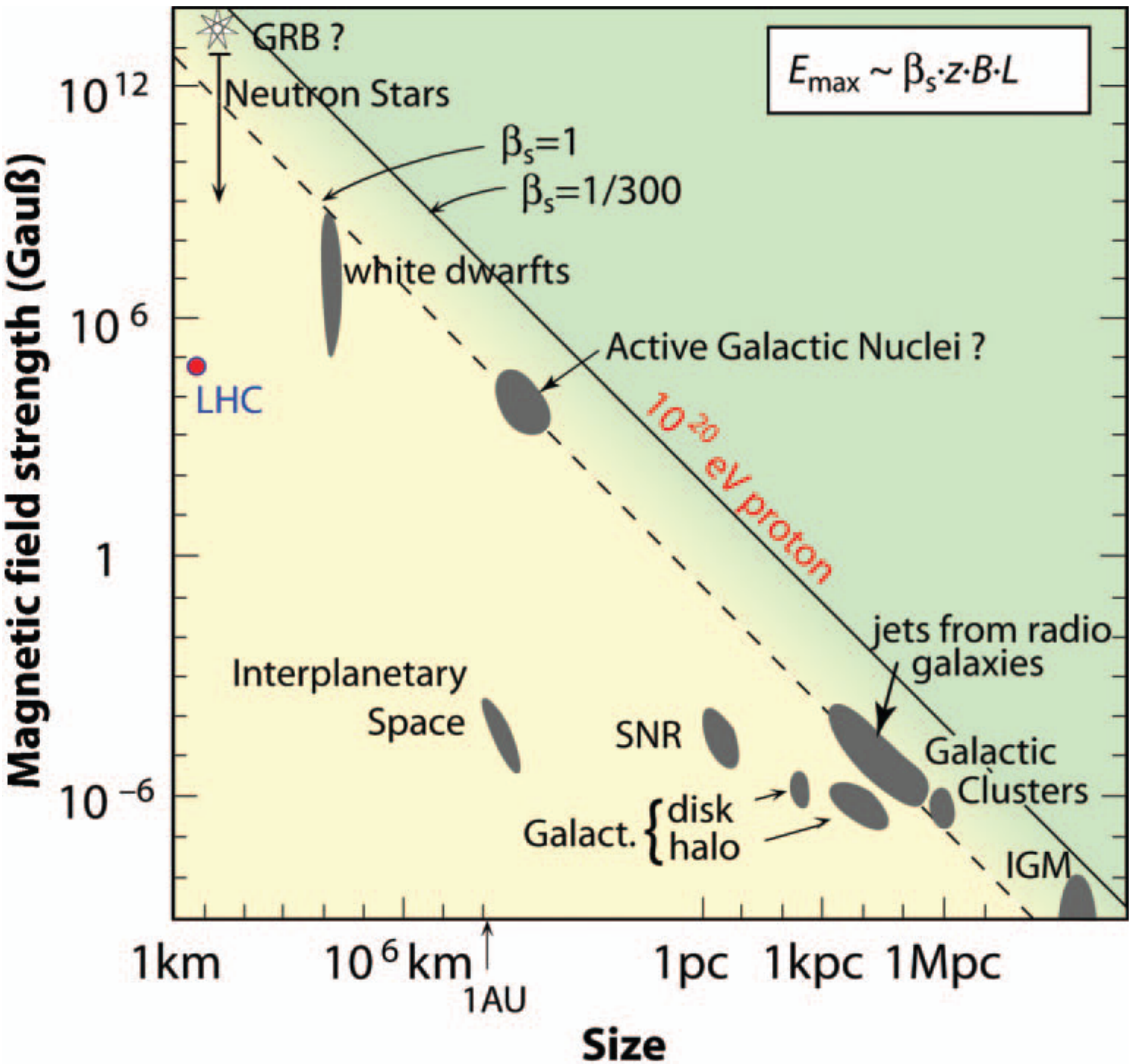


Kepler

Fermi-LAT
Science 15 February 2013:
Vol. 339 no. 6121 pp. 807-811
DOI: 10.1126/science.1231160

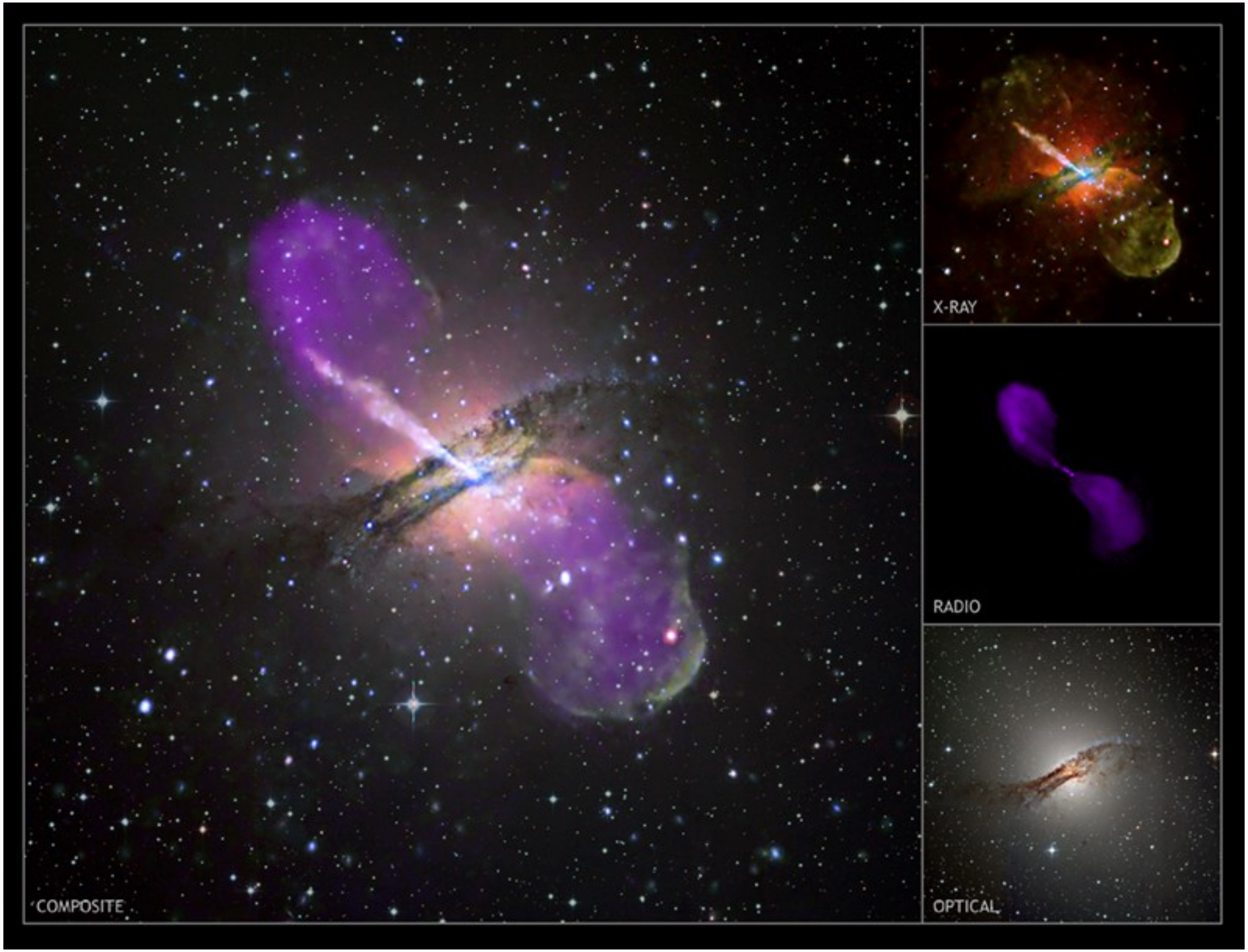


Possible Known Sources



The Hillas plot:
Ann Rev A&A 1984

Messengers from exploding stars and other more powerful objects



Centaurus A

Closest AGN black hole with a mass of 55 million suns

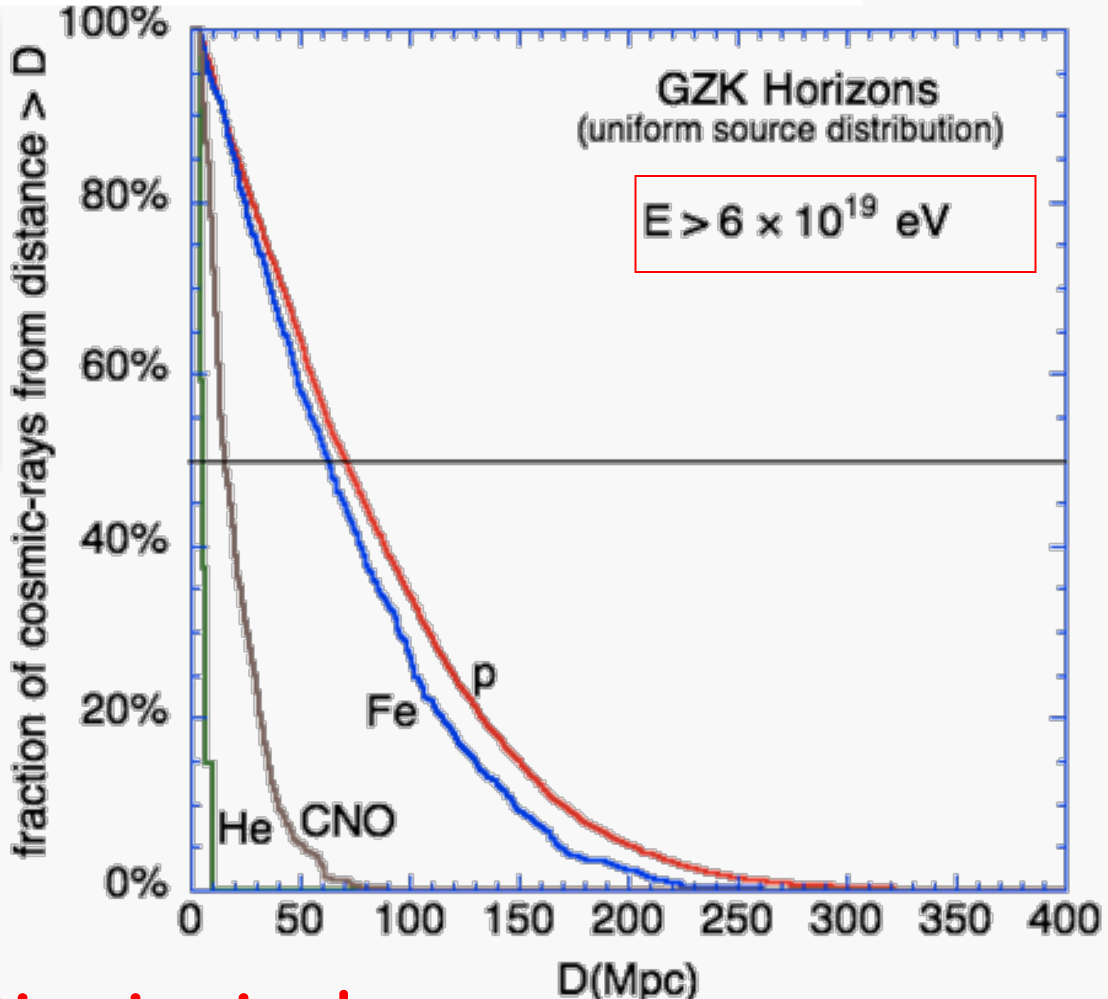
Distance : 3.8 ± 0.1 Mpc

Greisen-Zatsepin-Kuz'min Cutoff

$$\gamma_{2.725\,K} + p \rightarrow \Delta^{+} \rightarrow p + \pi^{o} \text{ or } n + \pi^{+}.$$

Cosmic Microwave Background

Light and intermediate nuclei photodisintegrate more rapidly.

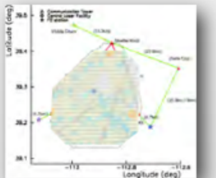


Trans-GZK composition is simpler

Auger and the Telescope Array Observatories

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

Taking data since 2007

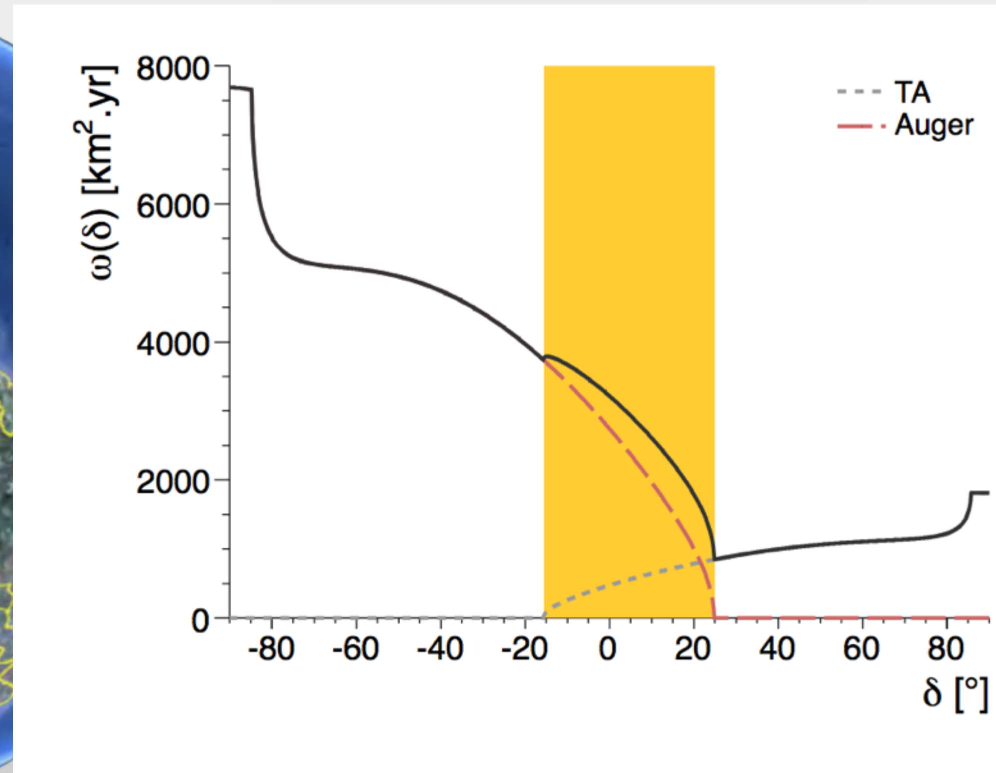


same scale

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

Taking data since 2004

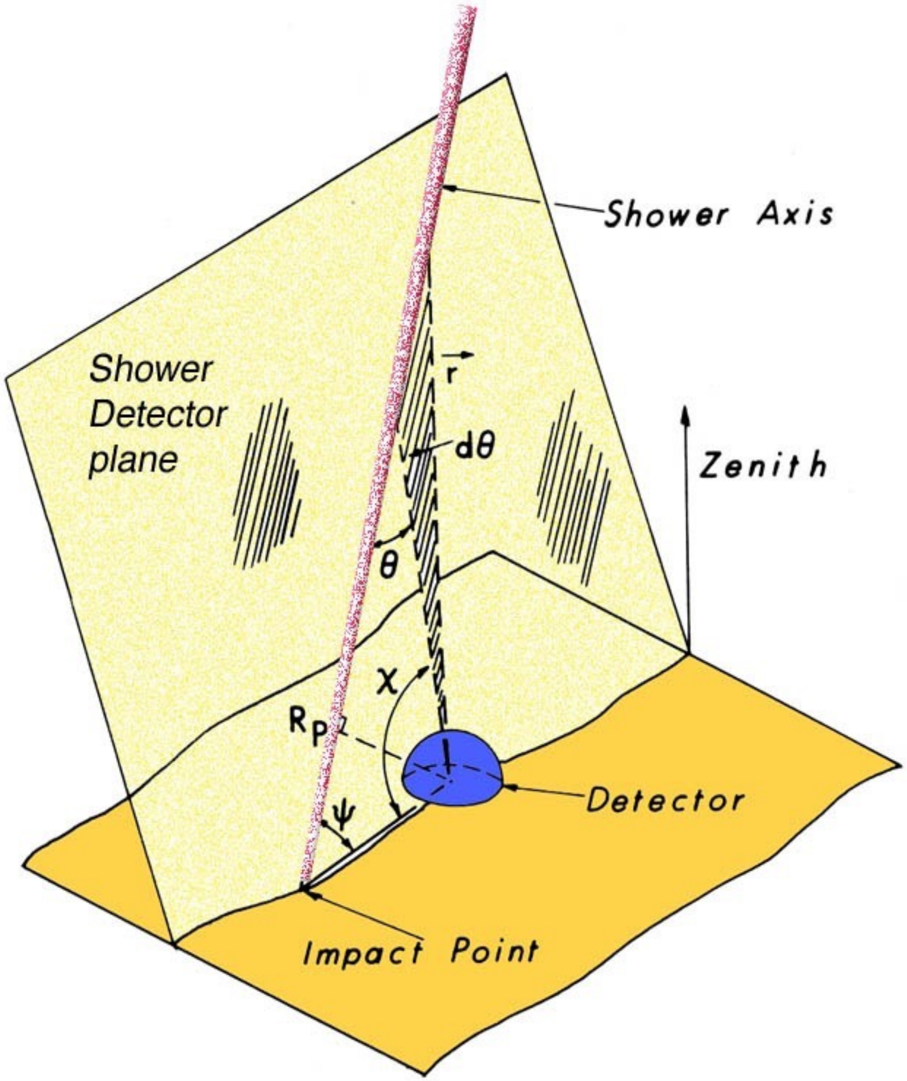
Auger and TA can see the same sky



Auger exposure ~8 times that of TA

K-H Kampert, Marcel Grossman Meeting 2015

Hybrid Detector: Two Different Detection Techniques



SD Array + FD Telescopes

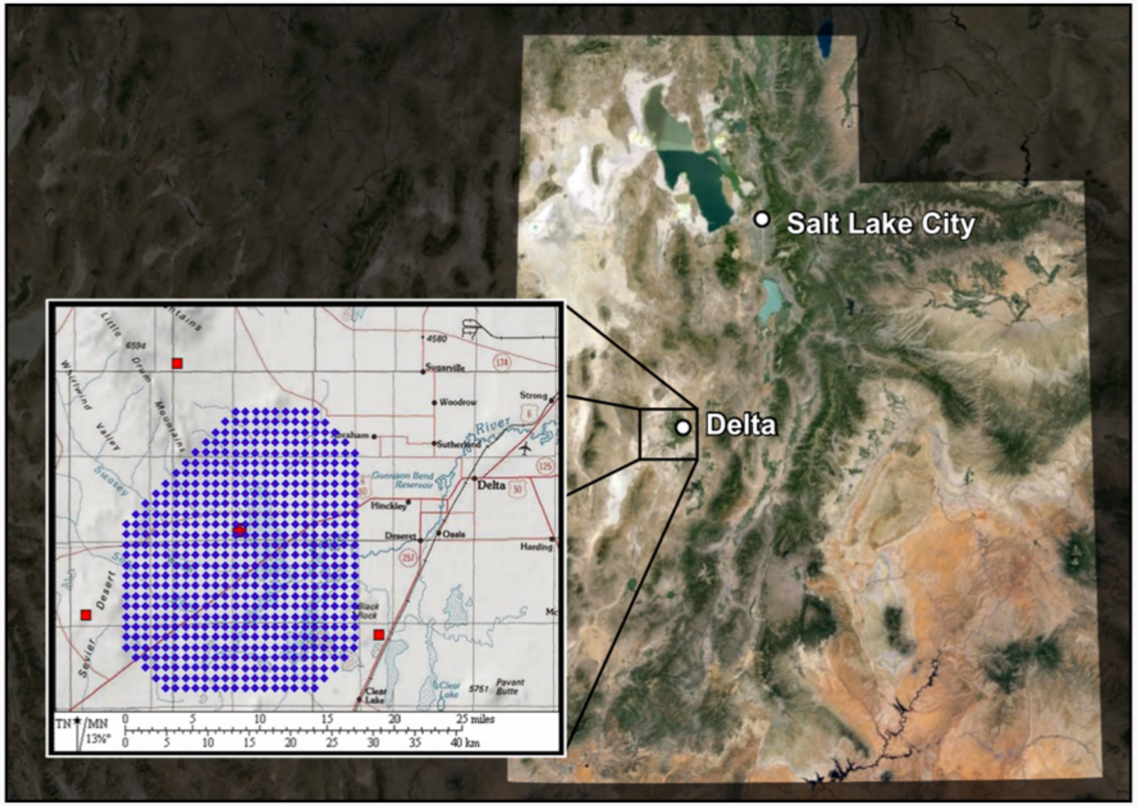
Much better accuracy in geometrical reconstruction of arrival direction and core position of air showers.

Improved reconstruction even with a single SD station.

These two techniques measure complementary parameters allowing understanding of systematic errors and study of primary composition

The calorimetric model-independent measurement of the air shower energy from the FD can be correlated with the LDF measured with the SD.

Telescope Array



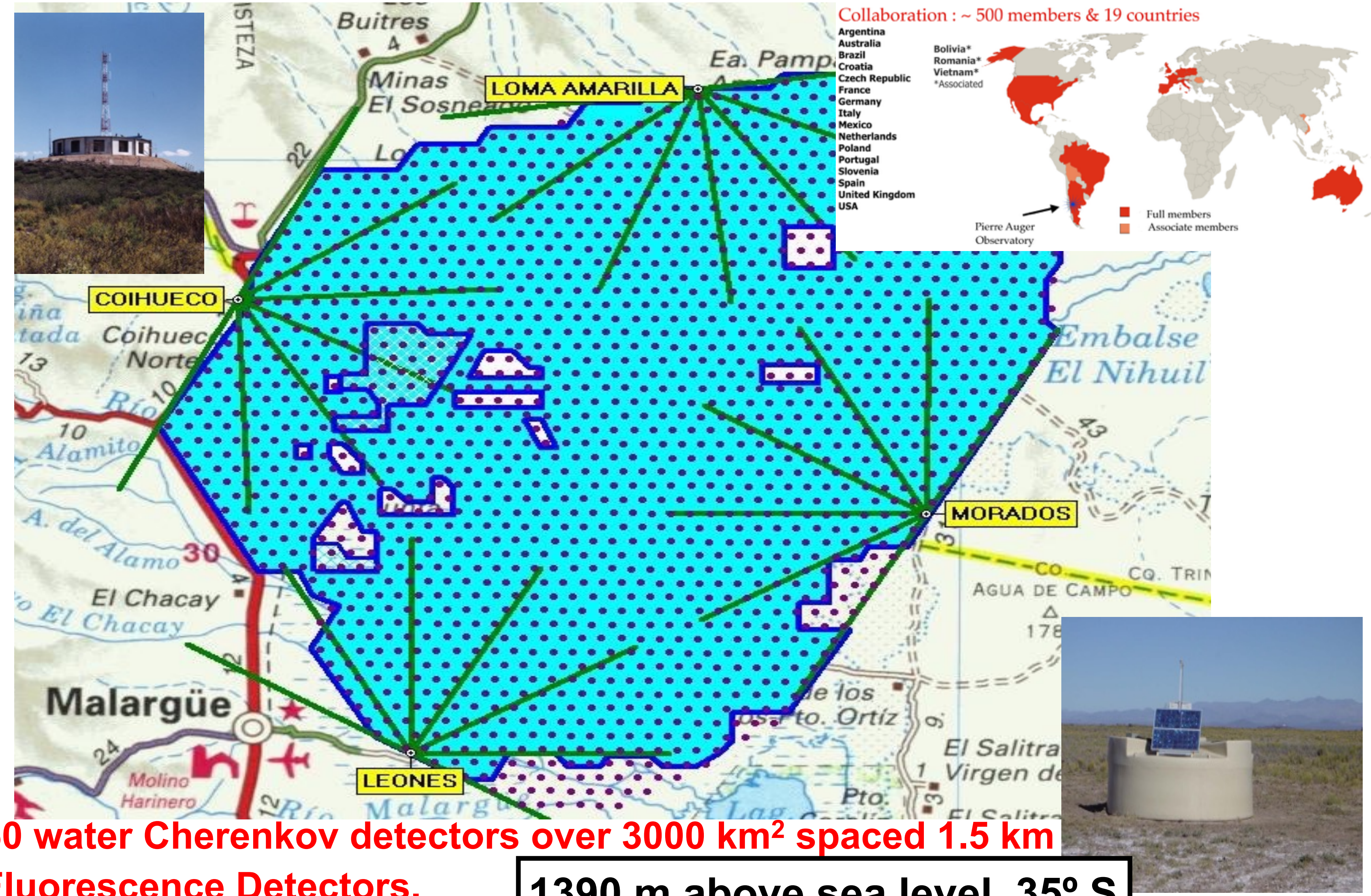
www.alamy.com - CFPAHR

39.3°N, 112.9°W ∼1400 m a.s.

3 FD buildings with 38 telescopes

507 plastic scintillator SDs 1.2 km spacing ∼700 km^2

Pierre Auger Observatory



1660 water Cherenkov detectors over 3000 km^2 spaced 1.5 km

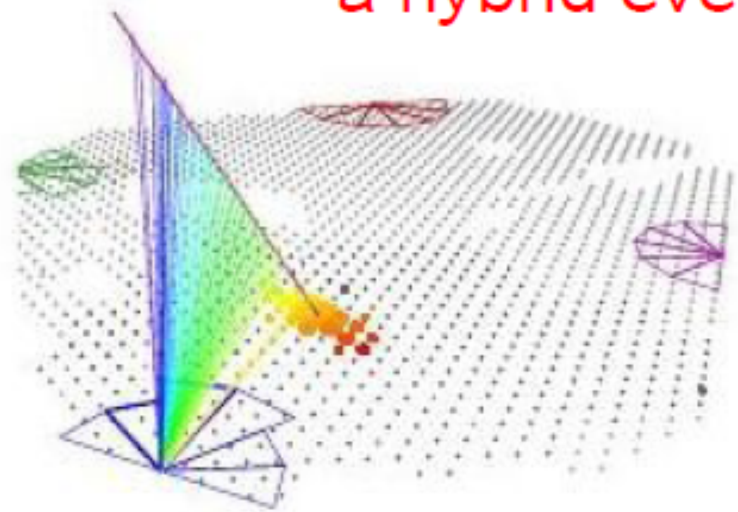
4 Fluorescence Detectors.

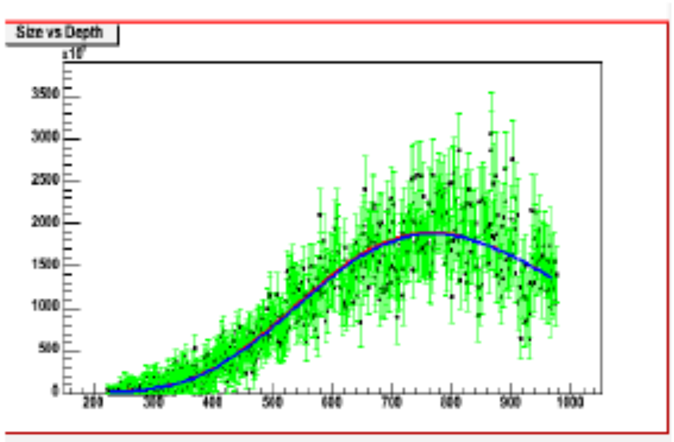
1390 m above sea level, 35º S

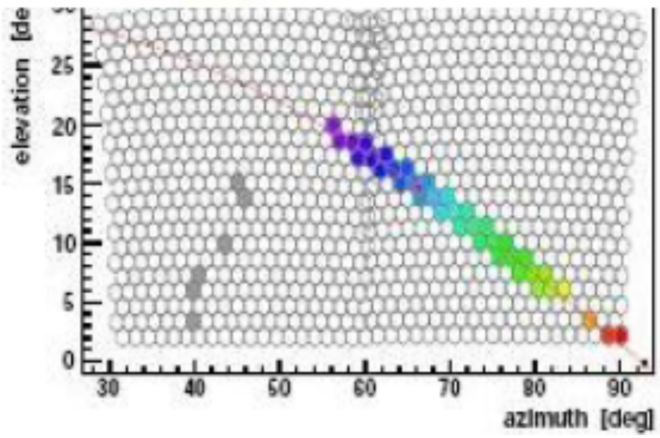
Data-taking started on 1 January 2004. Construction finished in 2008.

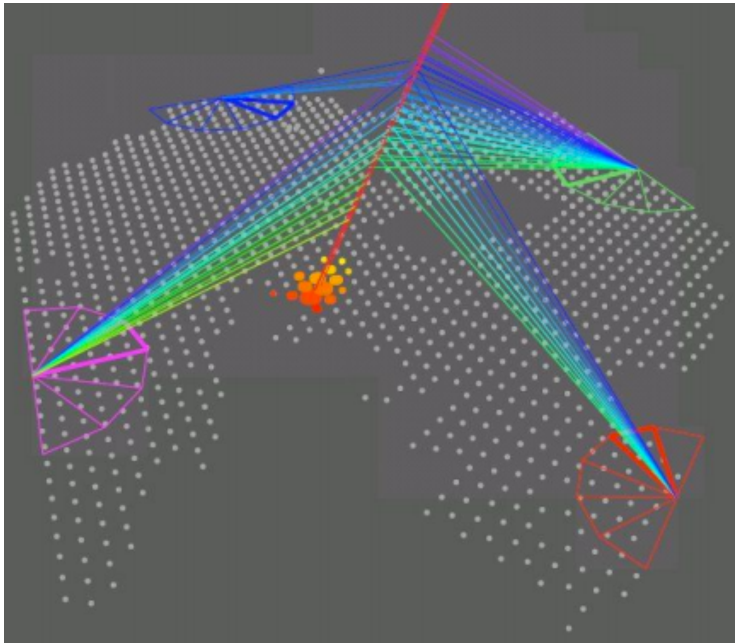
Hybrid Events in Auger

a hybrid event





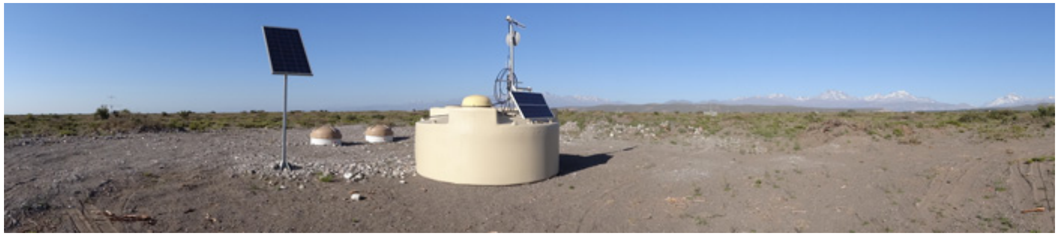




Quadruple Hybrid event

New Detectors in Auger

HEAT
High Elevation Auger
Telescope



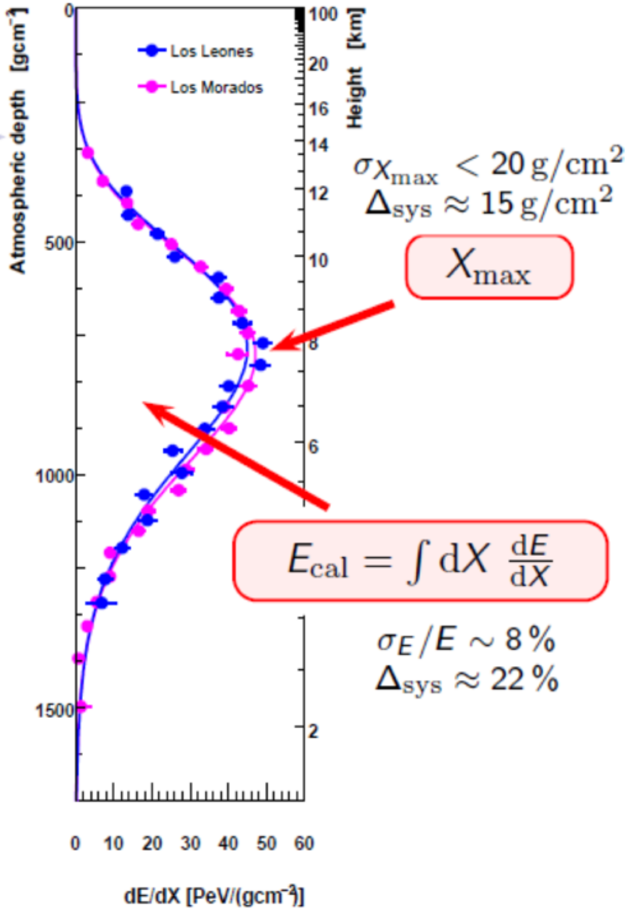
Auger Muons and Infill for the Ground Array

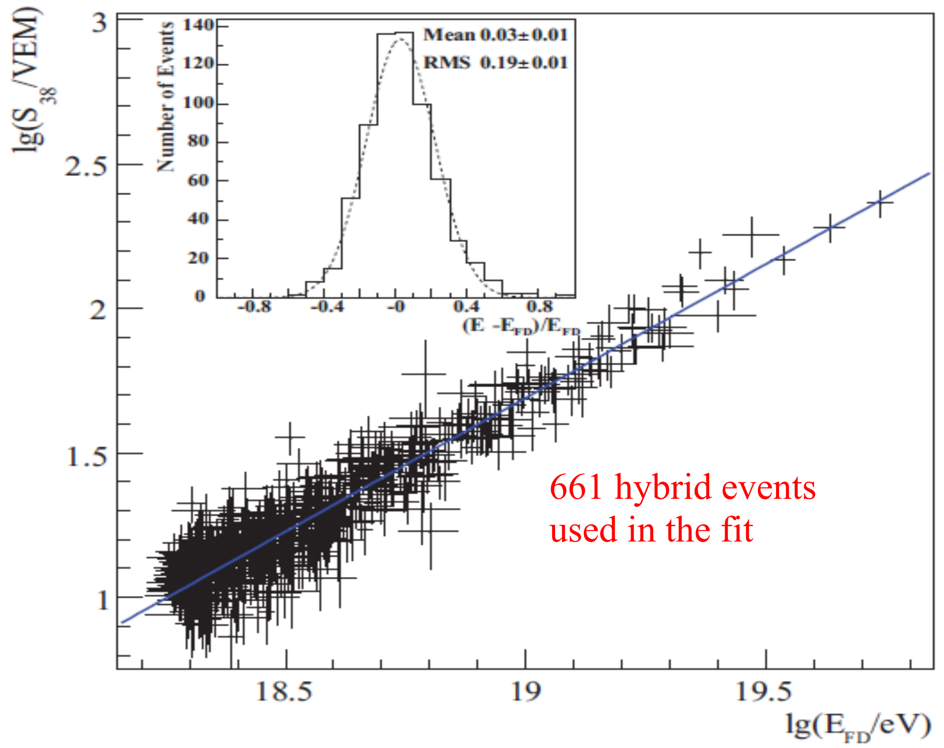
AERA

Auger Engineering Radio Array,

Energy Scale

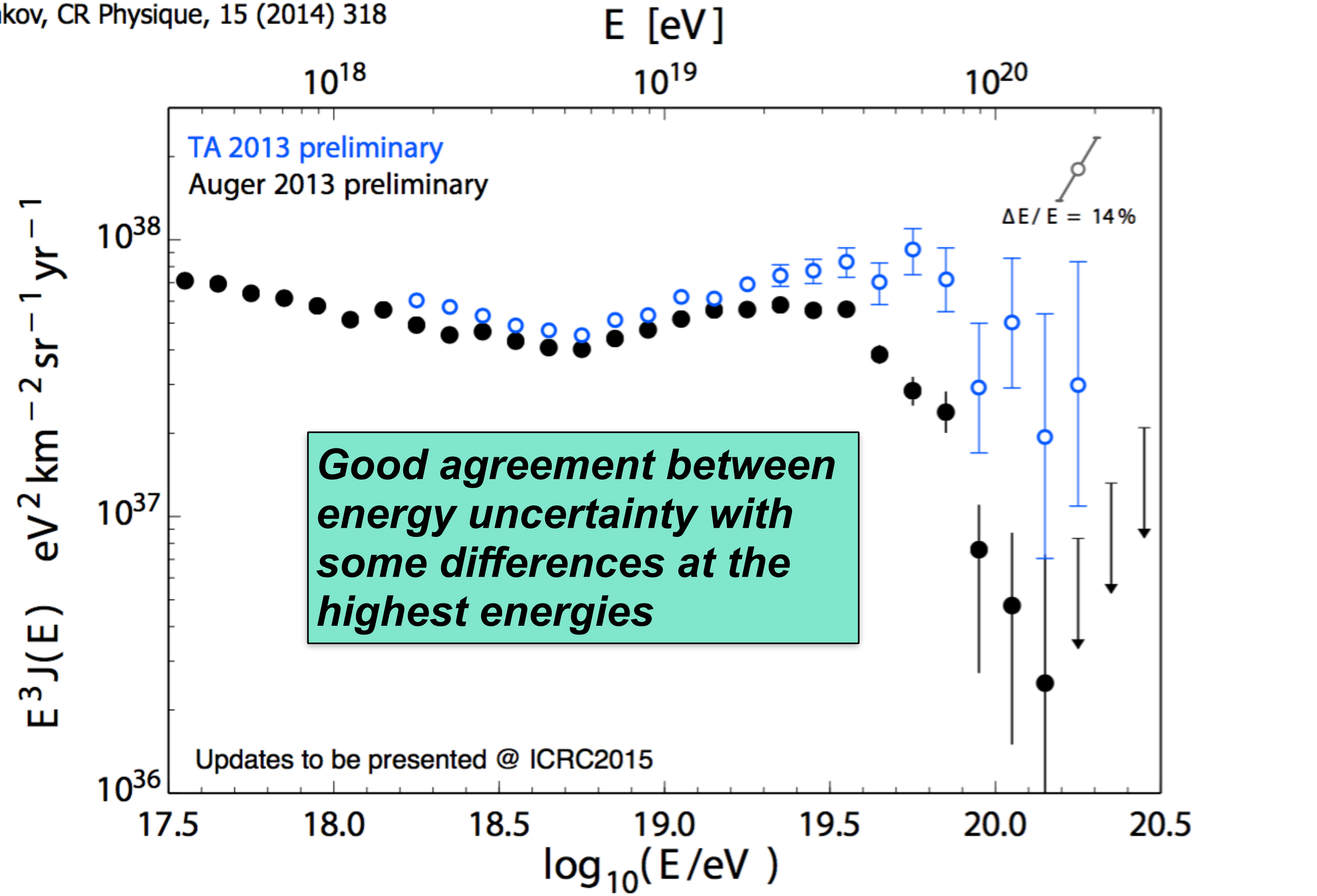
The energy scale is derived from fluorescence observations of extensive air showers, i.e., a calorimetric technique independent of MC simulations



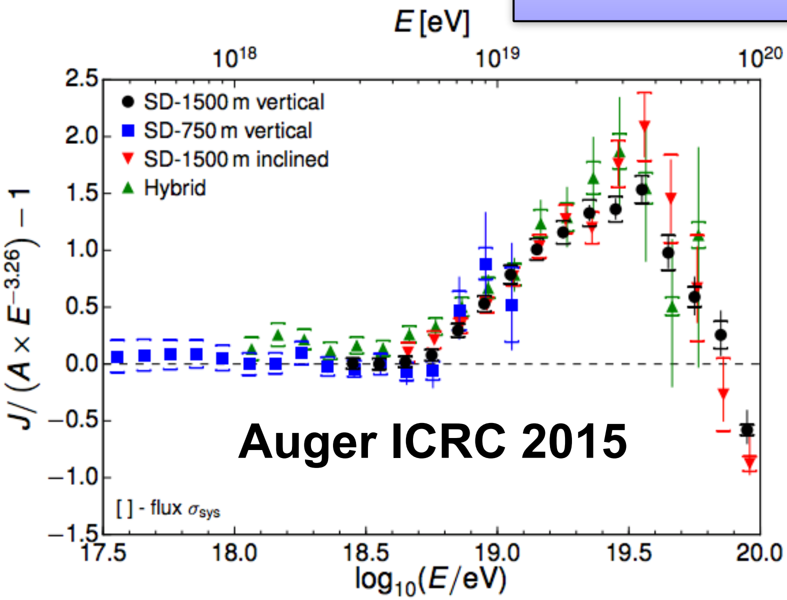


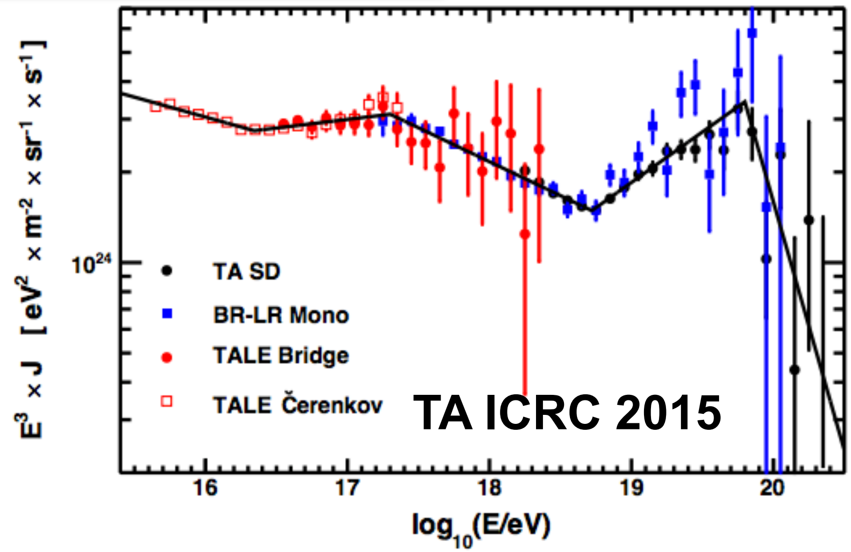
Energy Spectrum

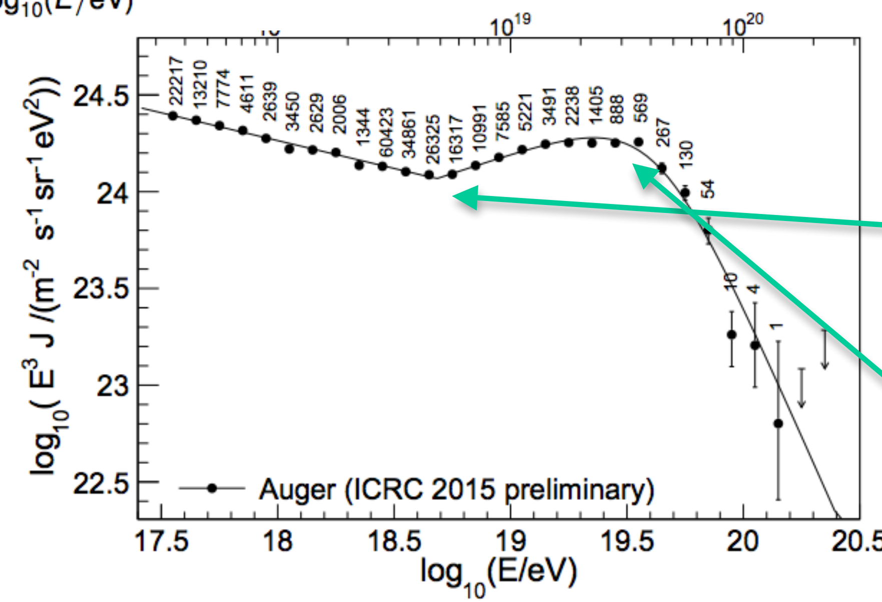
Kampert & Tiniakov, CR Physique, 15 (2014) 318



Energy Spectrum







"Ankle": Transition from galactic to extra galactic?

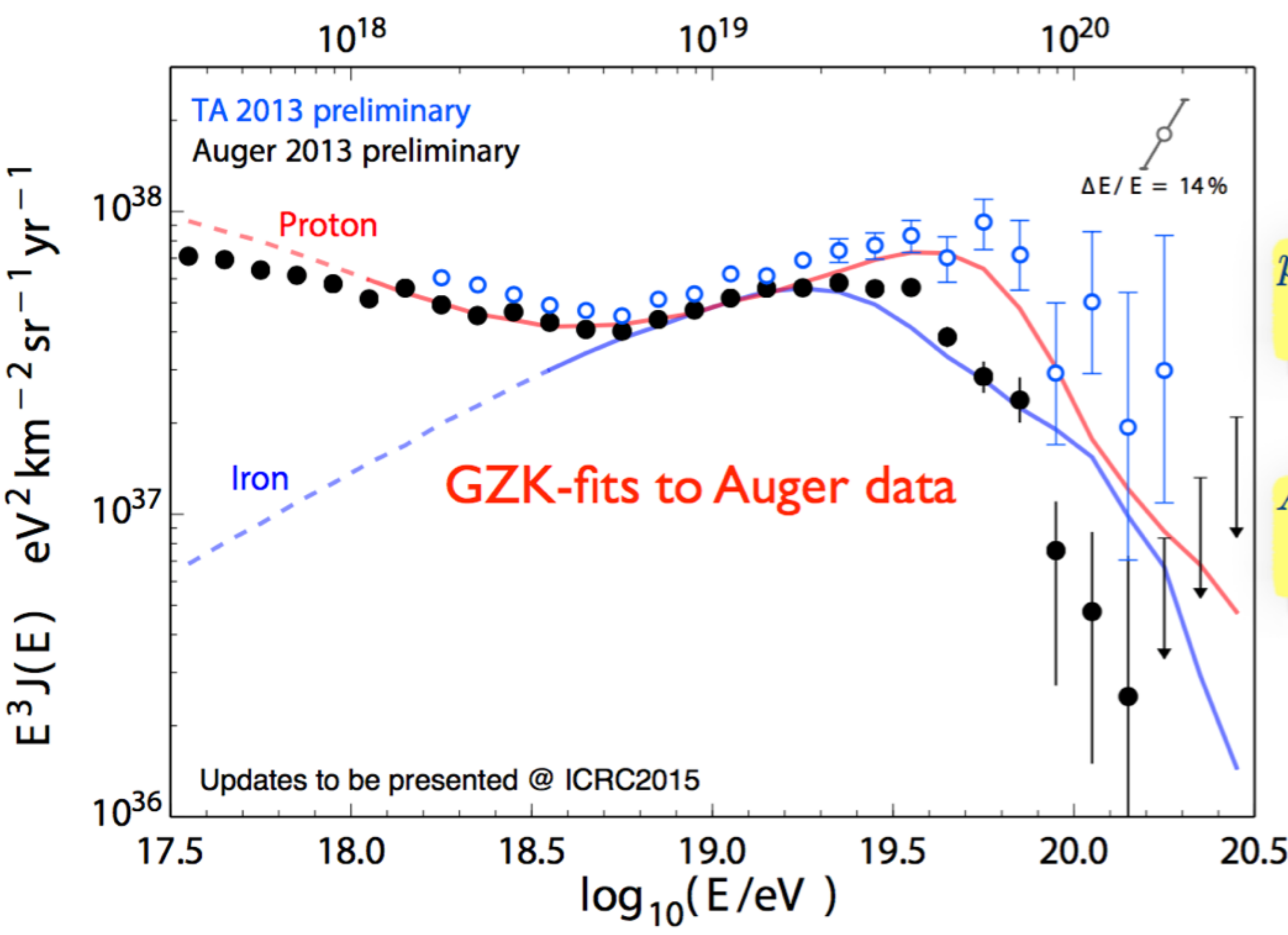
Suppression of flux significat at 20 σ
GZK or Injection cutoff at sources?

E_{Ankle}=4.82±0.07±0.8 EeV (ICRC 2015)

E_S=42.09±1.7±7.61 EeV (ICRC 2015)

Energy Spectrum: Possible Interpretations

Kampert & Tiniakov, CR Physique, 15 (2014) 318

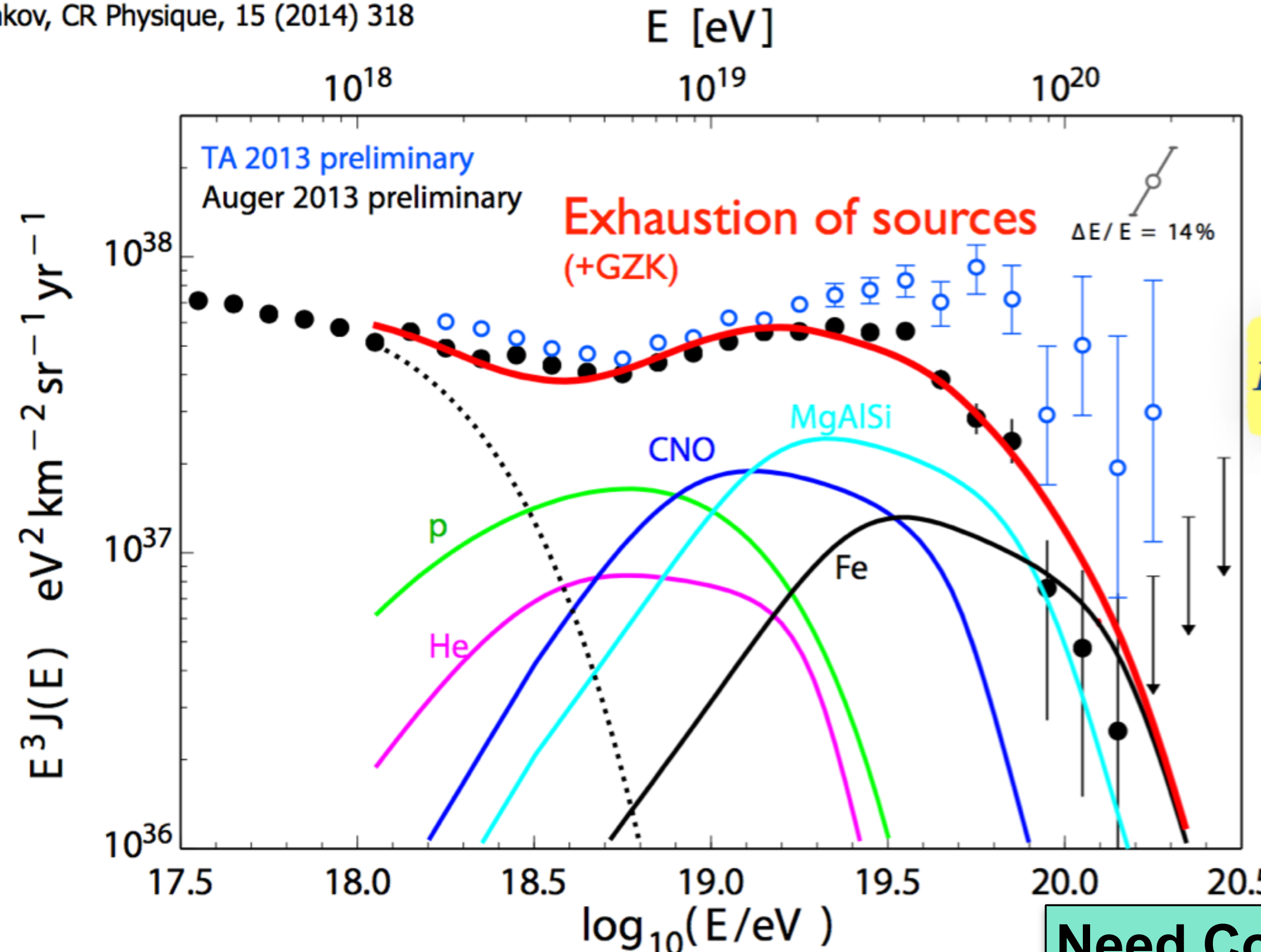


$$p + \gamma_{CMB} \to \Delta \to p + \pi$$

$$A + \gamma_{CMB} \to (A-1) + n\ldots$$

Energy Spectrum: Possible Interpretations

Kampert & Tiniakov, CR Physique, 15 (2014) 318

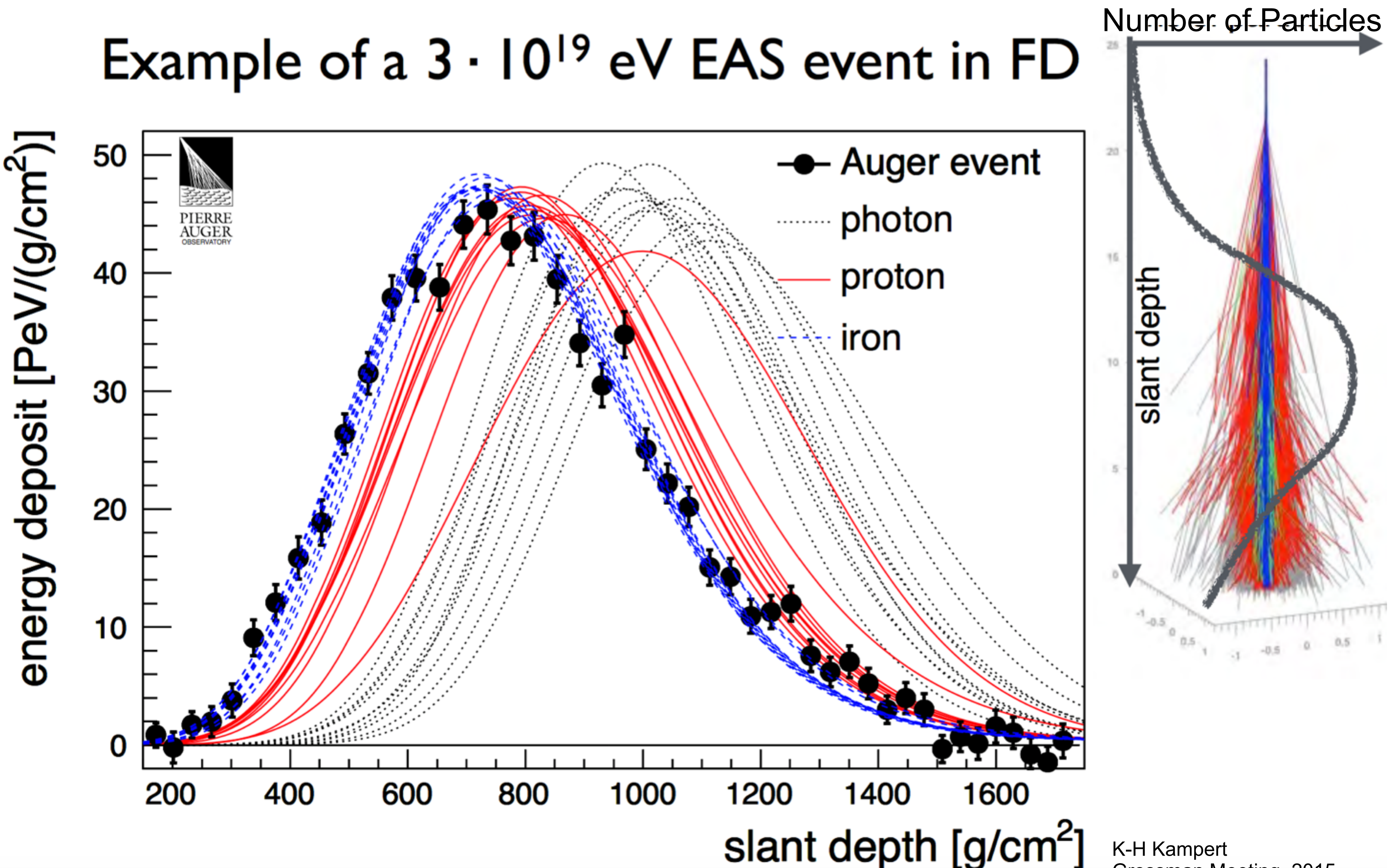


$$E^Z_{max} \propto E^p_{max} \times Z$$

Fit by Blasi et al.
JCAP 2014
arXiv:1312.7459v1

Need Composition!!

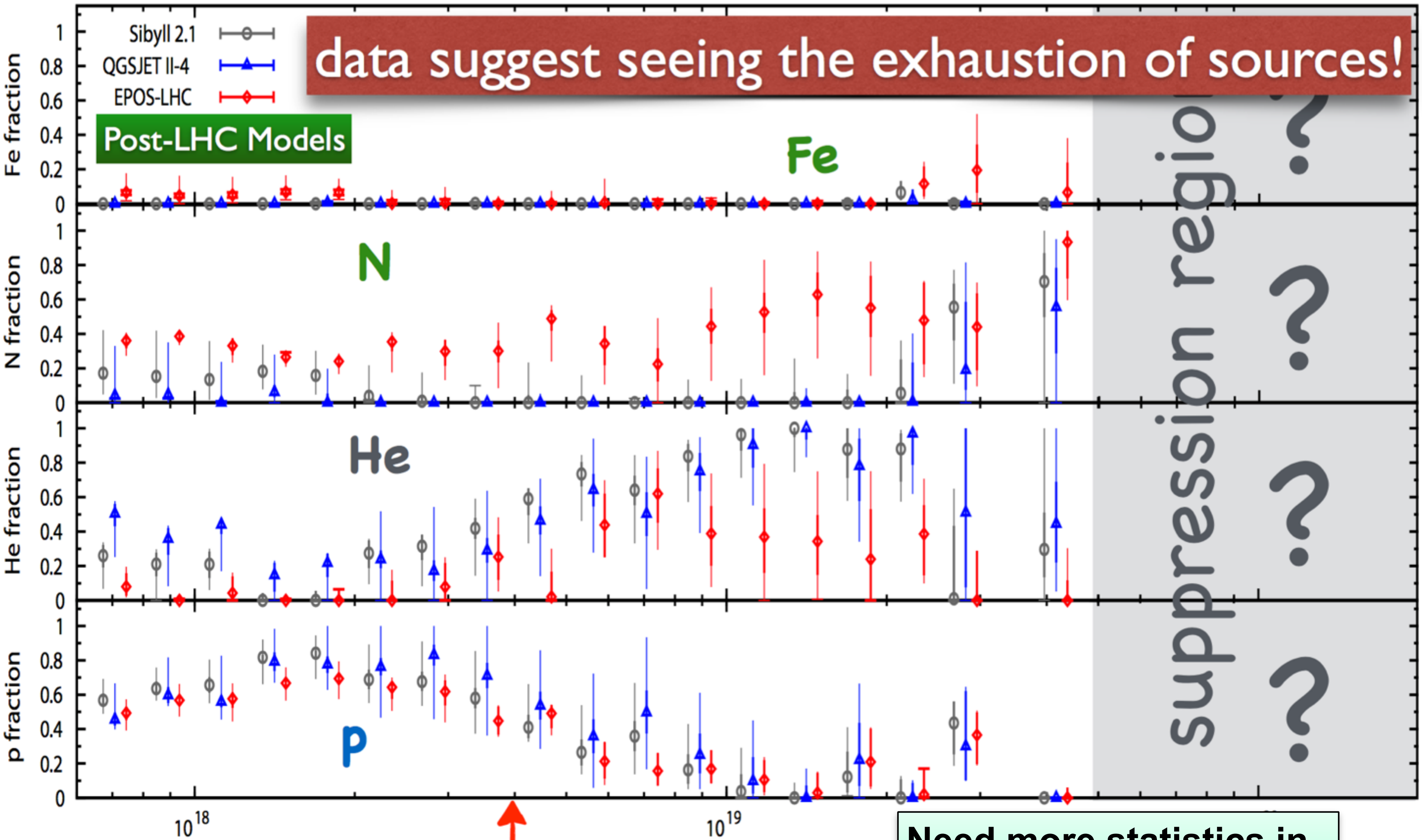
Mass Composition



K-H Kampert
Grossman Meeting, 2015

Mass Composition

Auger collaboration, Phys. Rev. D 90, 122006 (2014)

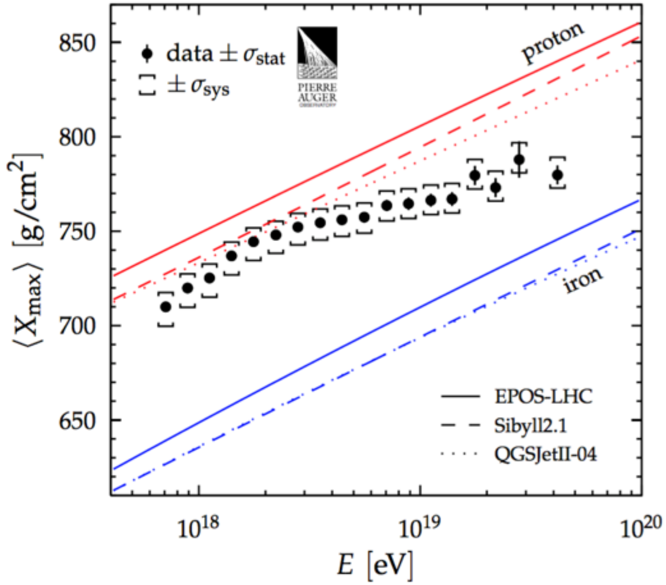


no pure beam at ankle!

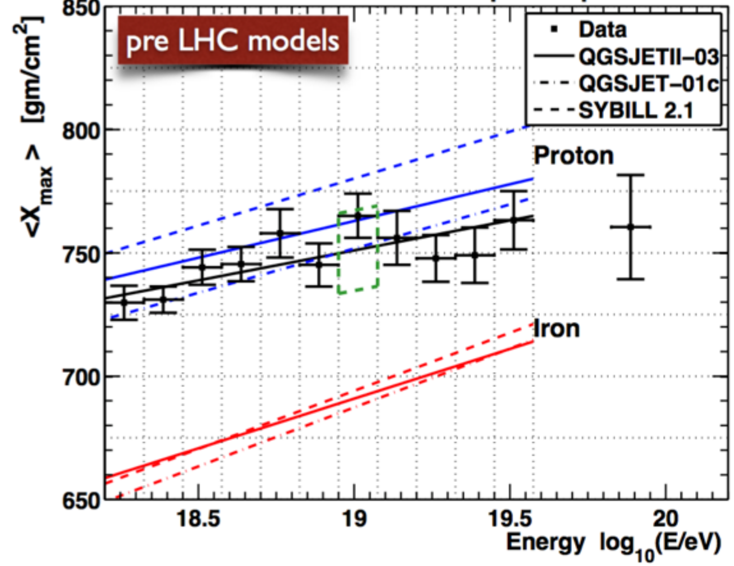
Need more statistics in the suppression region!

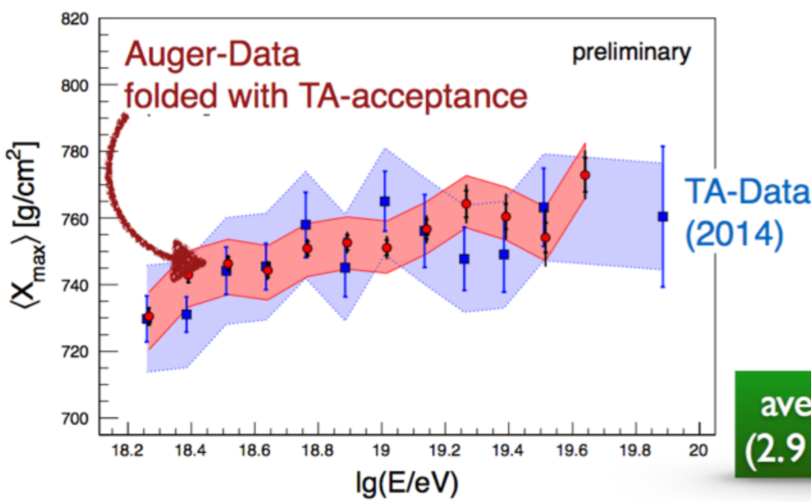
Mass Composition

Auger; Phys. Rev. D 90, 122005 (2014)
bias-free due to anti-bias cuts



Telescope Array Collaboration, APP 64 (2015) 49
models are folded with exp. acceptance



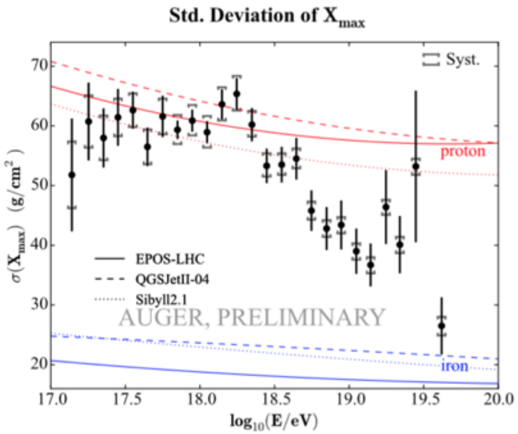


Joint Working Group (UHECR2014; arXiv:1503.07540)

„Two data sets are in excellent agreement, even without accounting for the respective systematic uncertainties on the X_{max} scale.“

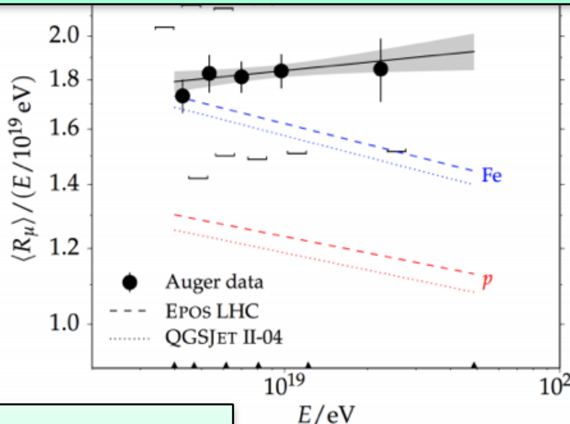
average diff. between data points:
(2.9 ± 2.7 (stat.) ± 18 (syst.)) g/cm^2

Mass Composition



- Apparent transition towards heavier composition
- Break in <X_{max}> behavior seems to occur around the Ankle energy
- Break in RMS(X_{max}) at roughly the same energy
- Appears to be confirmed by SD composition analysis as well

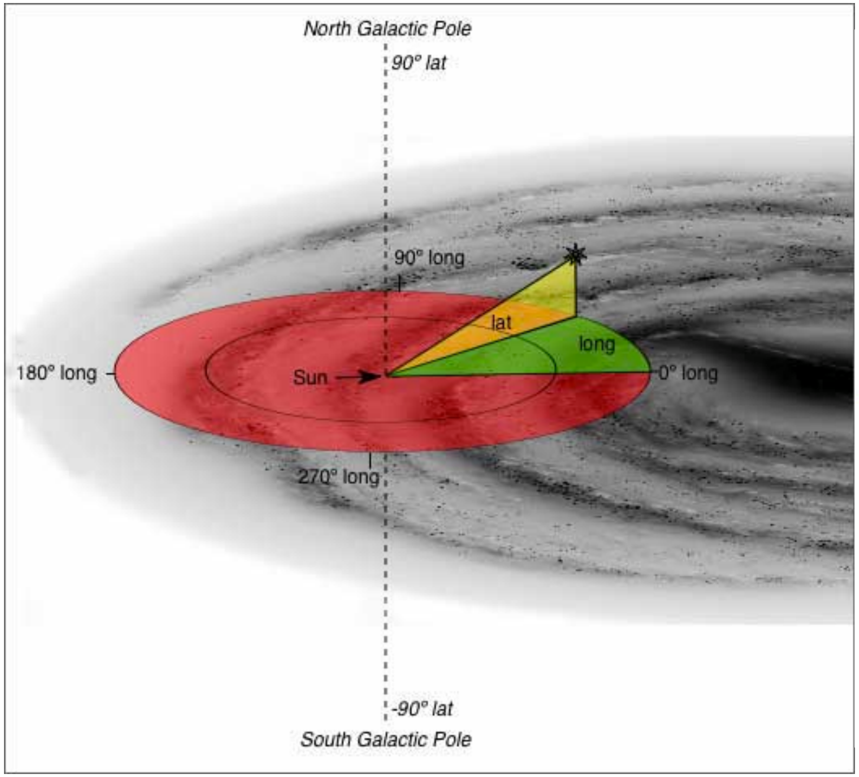
Composition change towards heavy nuclei?
Or protons interacting differently than expected above the LHC regime?

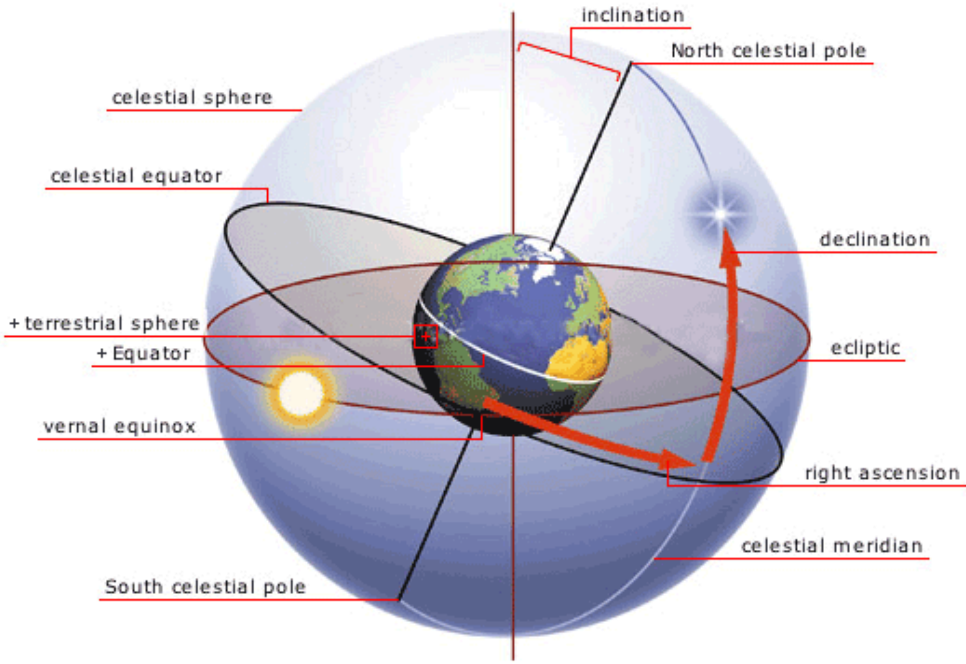


Auger
ICRC 2015

Hadronic interaction models have been updated with LHC data, still there is an excess of muons

Galactic and Equatorial Coordinates





<u>l: galactic longitude</u>
<u>b: galactic latitude</u>

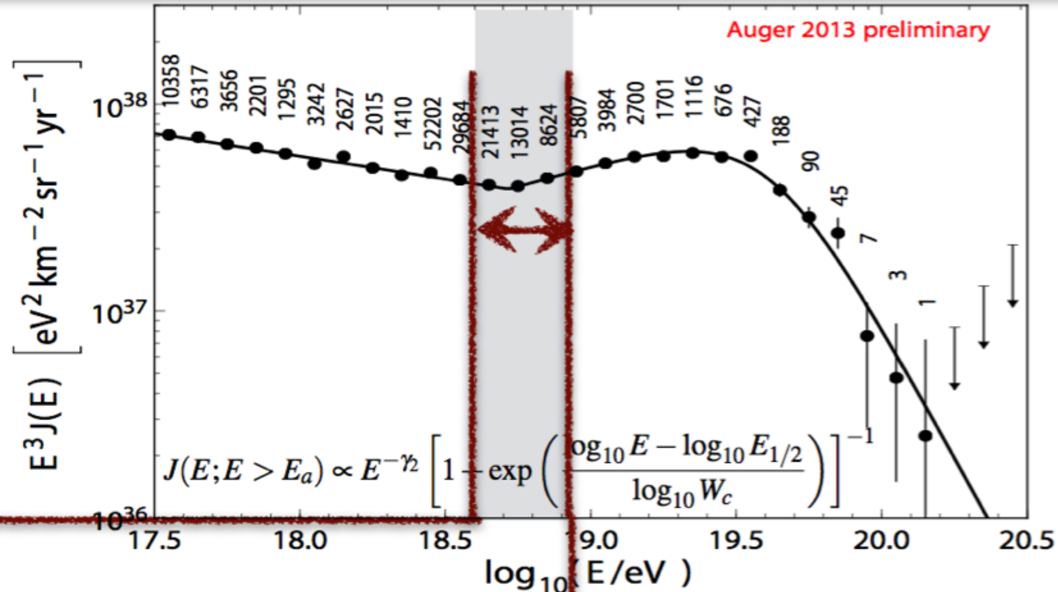
Galactic center: l=0, b=0

Direction of motion: l=90, b=0

<u>Declination</u> (delta): angular distance from the celestial equator (+=north, -=south)

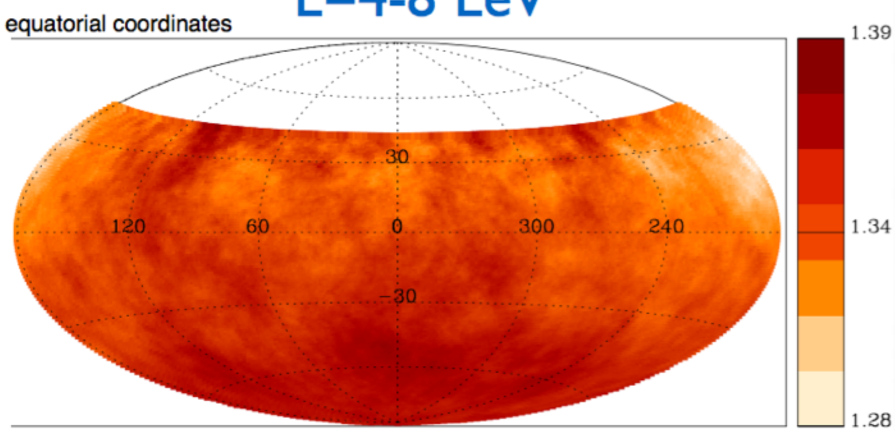
<u>Right Ascension</u> (alpha): angular distance along circles parallel to the equator. Define zero point to be the vernal equinox, the point where the Sun's position crosses the celestial equator as it moves north. Right ascension increases going eastward.

Anisotropy



isotropic distribution

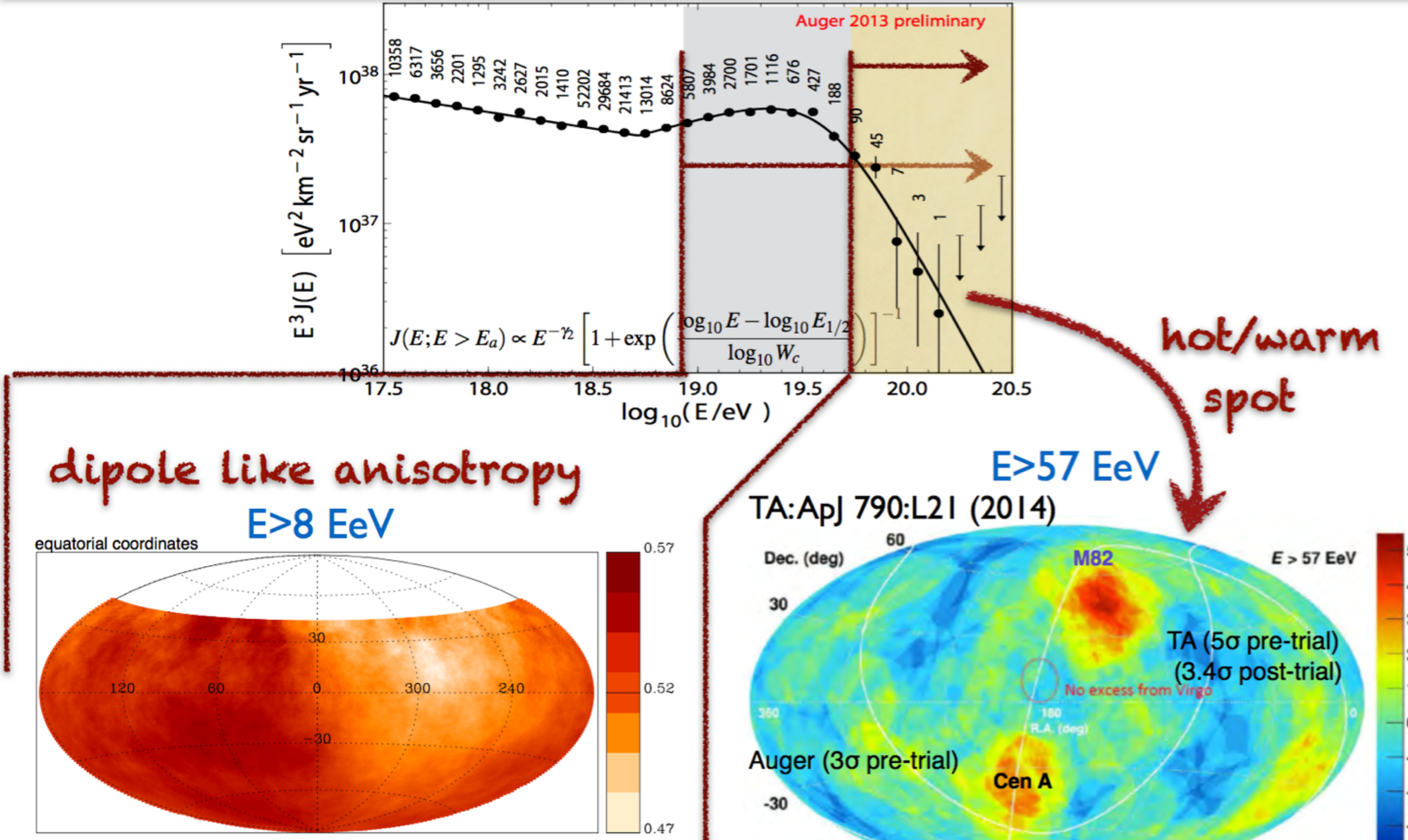
E=4-8 EeV



Auger Collaboration ApJ 802:111 (2015)

K-H Kampert, Marcel Grossman Meeting 2015

Anisotropy



Auger Collaboration ApJ 802:111 (2015)
Amplitude: (4.4±1.0)%; $p=6.4 \cdot 10^{-5}$

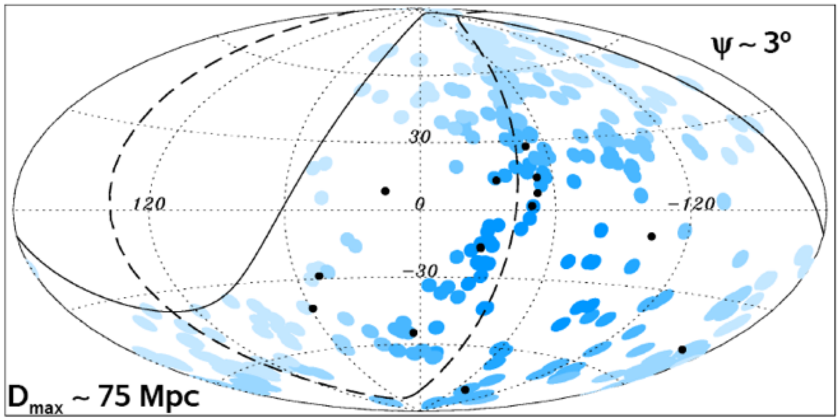
Auger: APP 34(2010) 314

see also:
D. Fargion; arXiv:1412.1573

Correlation of UHECRs with AGN

First scan gave $\psi < 3.1°$, $z < 0.018$ (75 Mpc) and $E > 56$ EeV

Exploratory scan: data until 27 May 2006

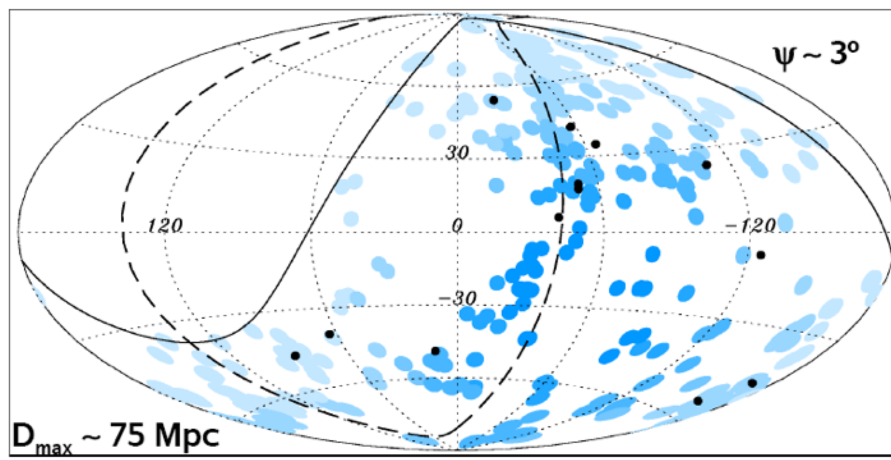


Largest significance for $E_{th} \sim 6\times10^{19}$ eV $\psi \sim 3°$ $D_{max} \sim 75$ Mpc

Exposure-weighted fraction of sky around AGN: 21%

Period	total	AGN hits	Chance hits	Probability
1 Jan 04 - 26 May 2006	14	11	3.2	Initial Scan
27 May 06 – 31 August 2007	13	8	2.7	0.0017

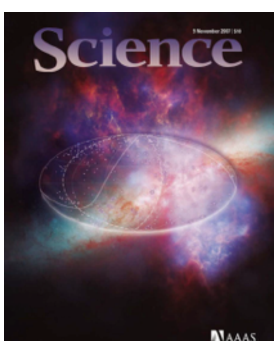
Test over independent data set



Data from 27 May 2006 until 31 August 2007

8/13 events

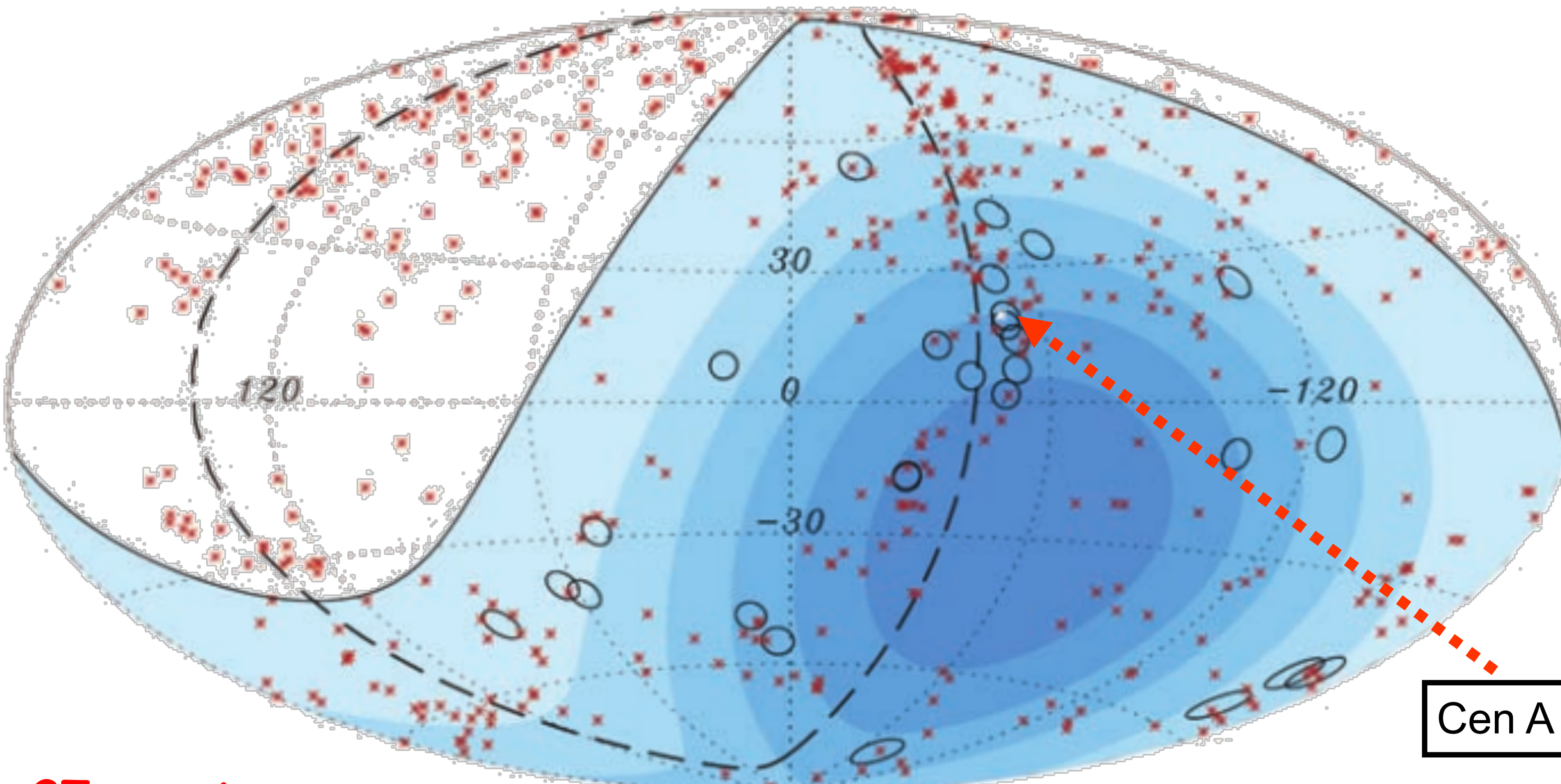
11/14 events close to AGNs in Veron-Cetty 12th ed. Catalog



2007

The Auger Sky in UHECRs

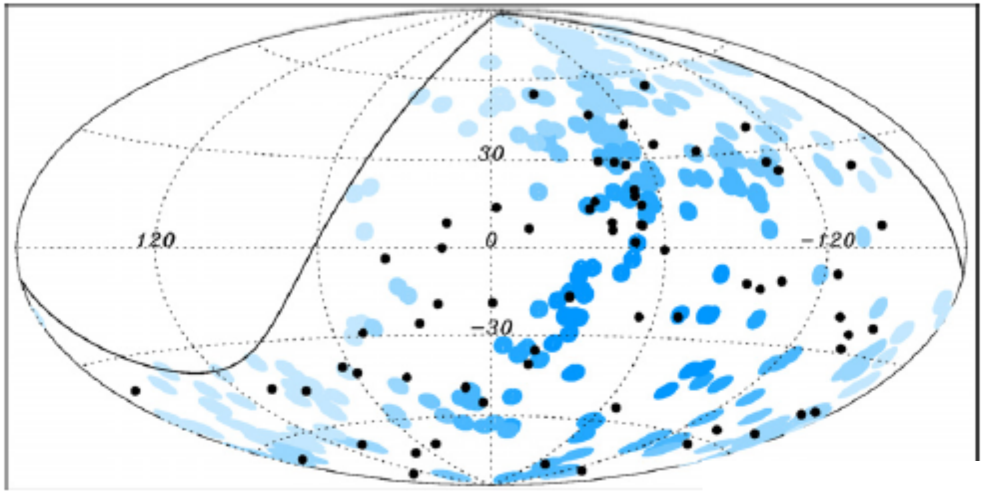
Situation as at November 2007: Science article



27 events

The correlating fraction is 69% compared with 21% expected for isotropic cosmic rays.

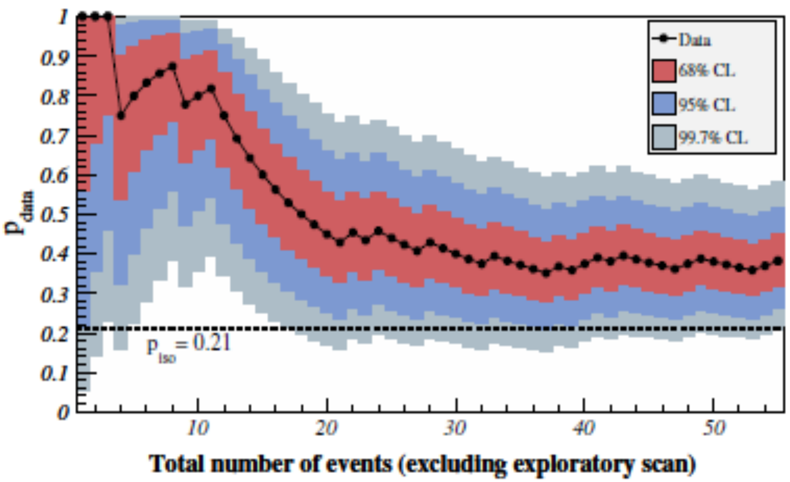
The Auger Sky in UHECRs

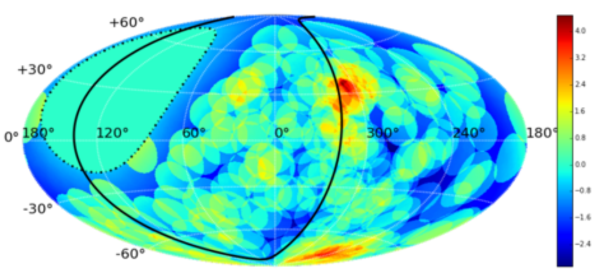


Astroparticle Physics 34 (2010) 314–326

69 events now (318 AGNs in the VCV)

The correlating fraction went down from 69% in 2007 to 38% in 2010

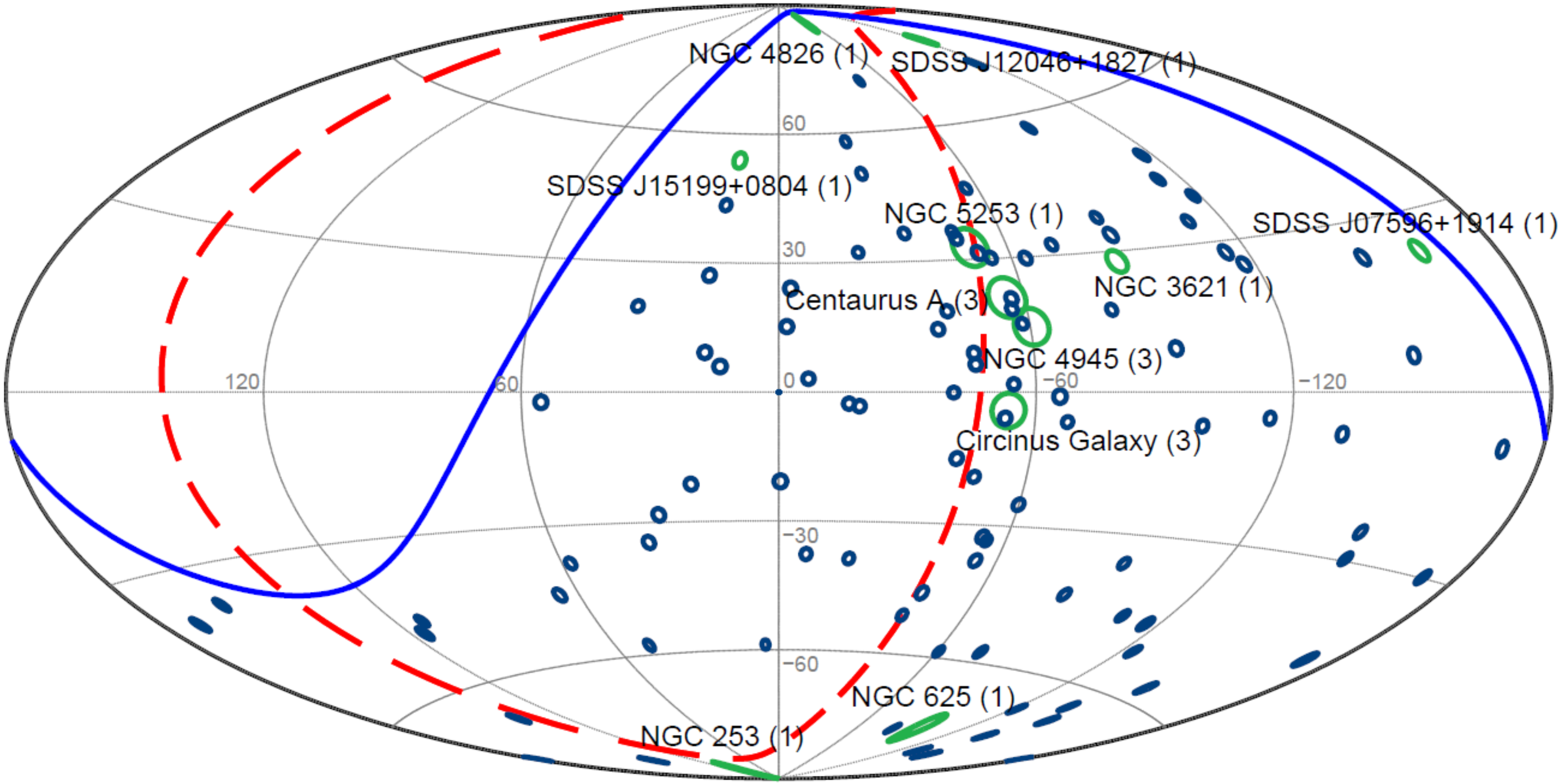




Astrophys.J. 804 (2015) 15

"fraction of events with energy above 53 EeV correlating with AGNs in the VCV catalog is $28.1^{+3.8}_{-3.6}$%,"
"for energies above 54 EeV more significant excesses are obtained in 69% of isotropic simulations under a similar scan"

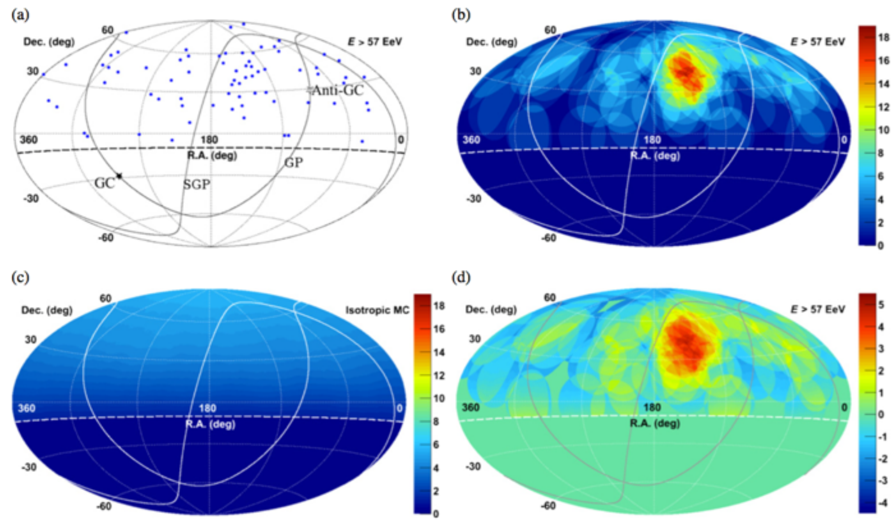
The Auger Sky: Possible Sources



More data are required to identify sources and to study the galactic and extragalactic magnetic fields

Where do cosmic rays come from?

THE ASTROPHYSICAL JOURNAL LETTERS, 790:L21 (5pp), 2014 August 1 ABBASI ET AL.



Telescope Array, 2014

$R_{Sampling}$ = 20º

$Significancia_{LM} = 5.1\sigma$ sin penalizar

Significancia = 3.4σ (3.7×10^{-4})

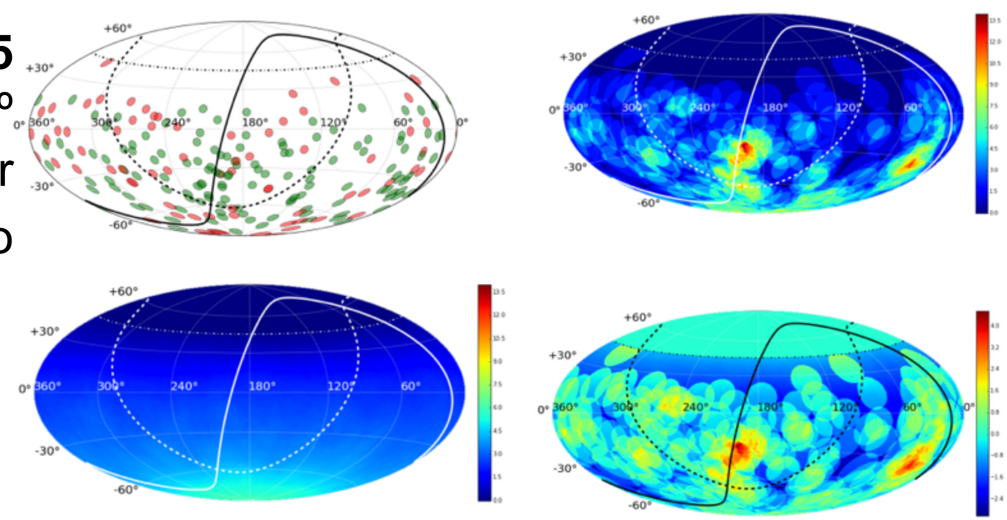
penalizando con R = 15°, 20°, 25°, 30°, and 35°

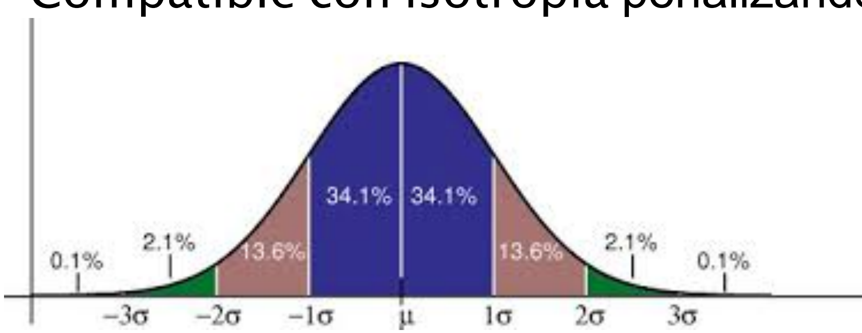
Auger, 2015

$R_{Sampling}$ = 12º

$Significancia_{LM} = 4.6\sigma$ sin penalizar

Compatible con isotropía penalizando





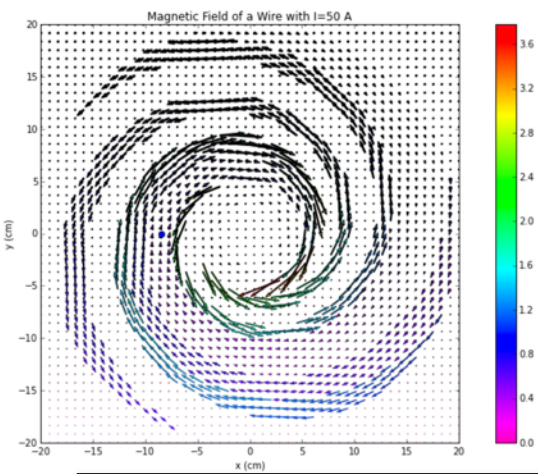
Where do cosmic rays come from?

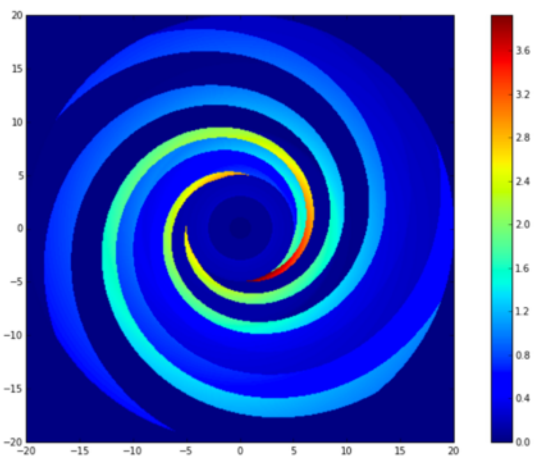
Problem: Sources of cosmic rays with E < 10^{18} eV cannot be determined because of their deflection in the galactic magnetic field.

Solution (?): But UHECRs (with E > 10^{18} eV) are much less deflected (travel straighter) and their direction should point towards their origin

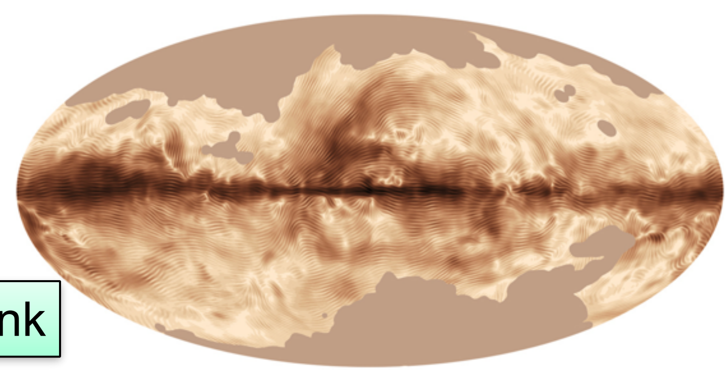
This has turned out to be **FALSE**

Galactic and extragalactic magnetic fields need to be better understood!



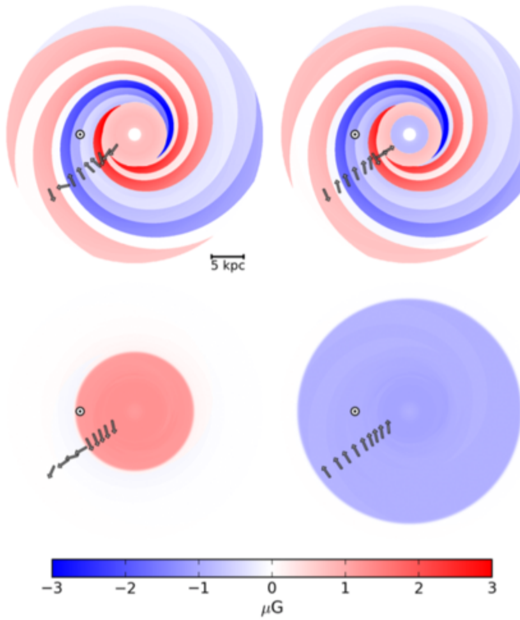


Disk in the JF 2012 Model



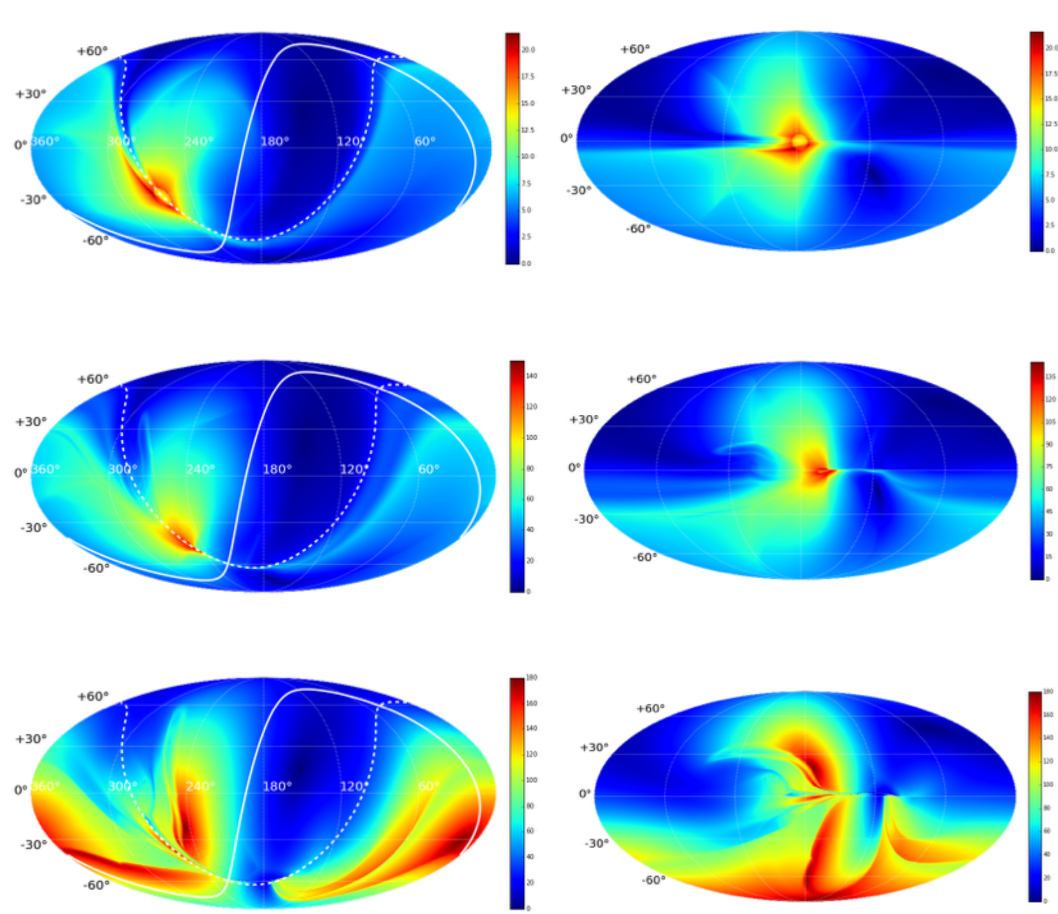
Polarisation data from Plank

Galactic Magnetic Field Model



Deflections of p, O and Fe nuclei with E=60 EeV in regular field of JF2012 GMF model

Equatorial Coords **Galactic Coords**



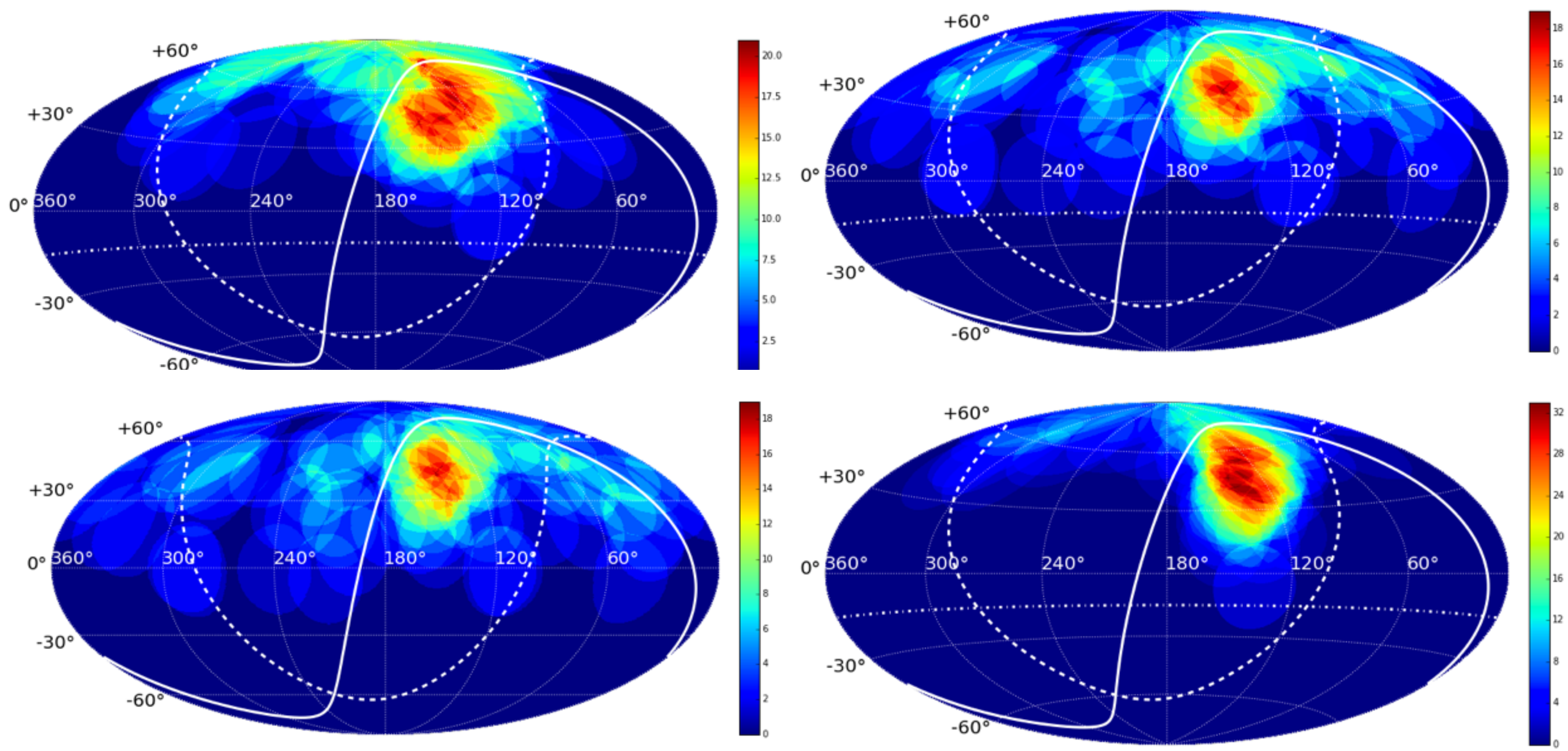
A NEW MODEL OF THE GALACTIC MAGNETIC FIELD, R. Jansson and G. R. Farrar, 2012

21-parameter GMF model fitted to WMAP7 Galactic Synchrotron Emission map and 40403 extragalactic rotation measures

Galactic Magnetic Field Model

TA events deflected assuming p, O and Fe nuclei in regular field of F2012 GMF model

Original **p**



O **F**

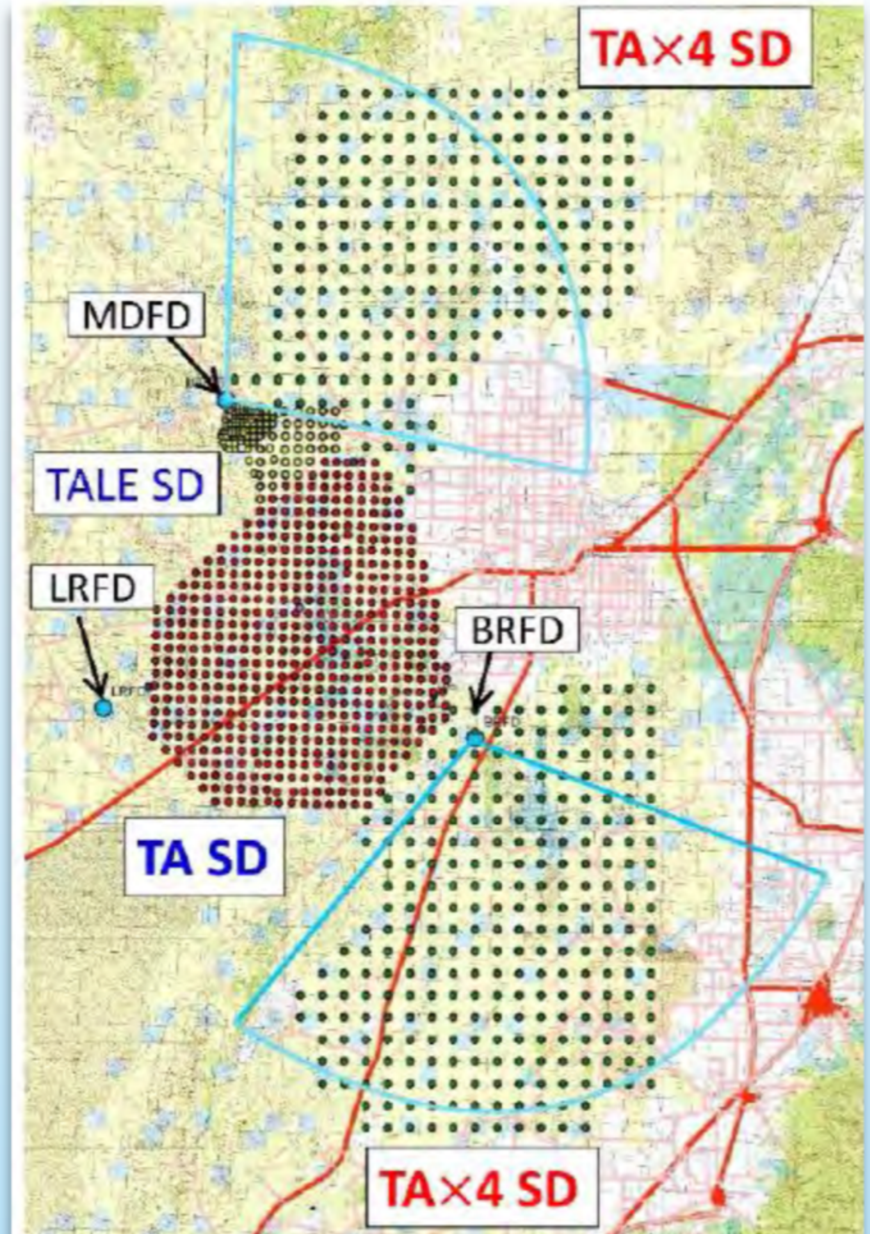
Faraday RM of extragalactic sources indicate that the extragalactic magnetic fields are smaller than ~ 10^{-9} G, for correlation length smaller than 1 Mpc, the deflections of protons of energy 10^{20} eV over a distance of 50 Mpc are smaller than 2°.

Upgrade of Telescope Array

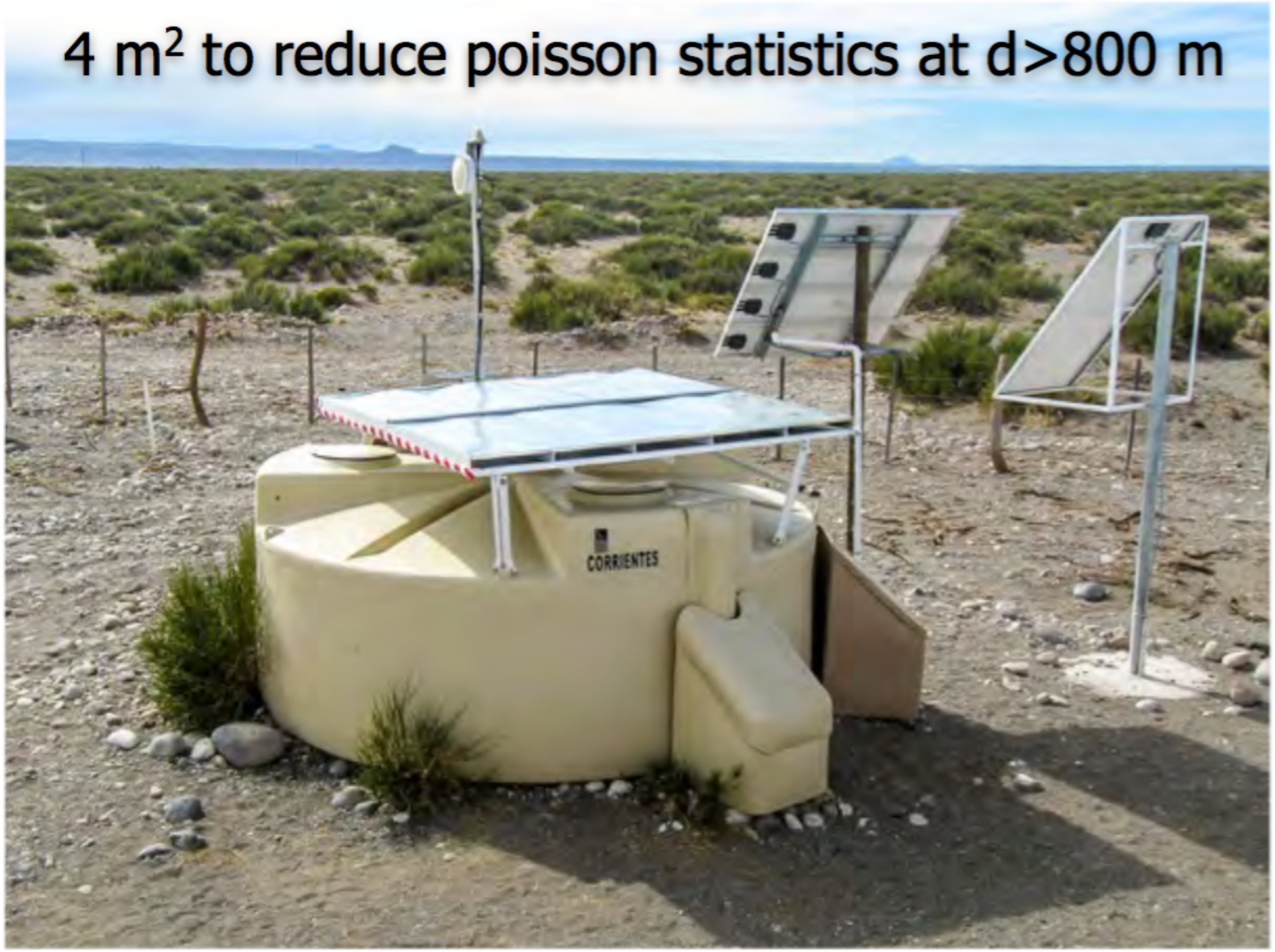
500 more SDs

2 more FD stations

- SD: 700 → **2800 km²**
- Hybrid: x3 acceptance
- Optimized for UHECR above cutoff (fully efficient above ~60 EeV)

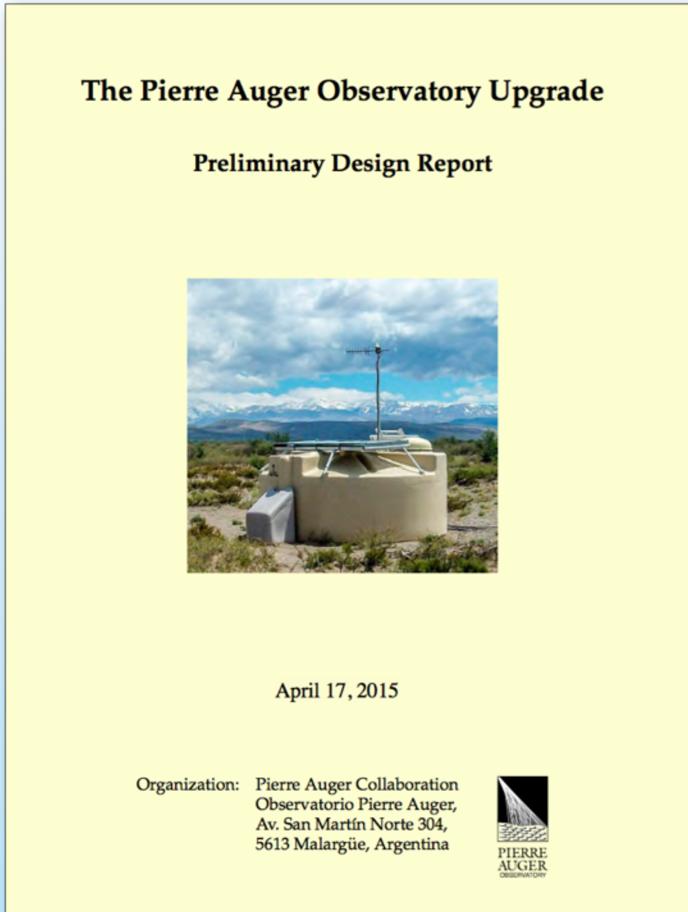


Upgrade of Auger (AugerPrime)



Replacement of electronics with faster data sampling

Upgrade of Auger (AugerPrime)


The Pierre Auger Observatory Upgrade

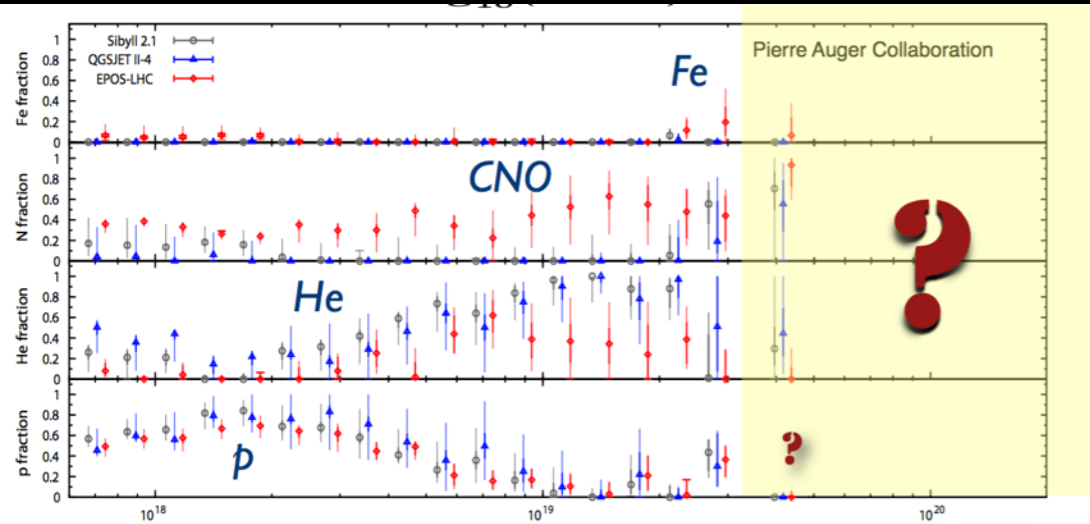
Preliminary Design Report

April 17, 2015

Organization: Pierre Auger Collaboration
Observatorio Pierre Auger,
Av. San Martín Norte 304,
5613 Malargüe, Argentina

- positively evaluated by International Advisory Committee
- endorsed by International Finance Board
- R&D well advanced, prototypes running
- engineering array 03/2016
- construction 11/2016 - 2018
- data taking into 2024
- costs: 12.5 M€
- funding: some positive signs, but not yet approved

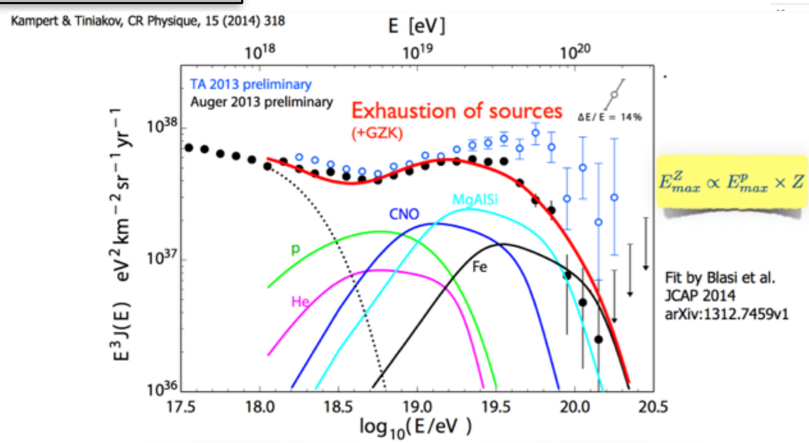
Upgrade of Auger (AugerPrime)

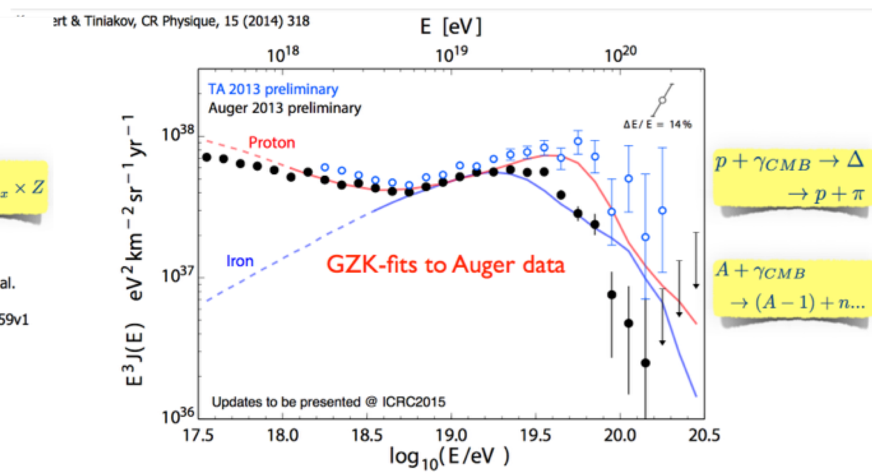


Exhaustion of sources or GZK suppression?

Cosmogenic neutrinos and photons suppressed

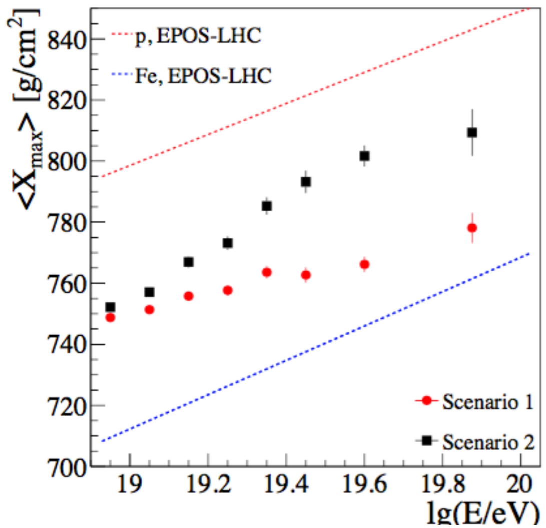
Expect cosmogenic neutrinos and photons

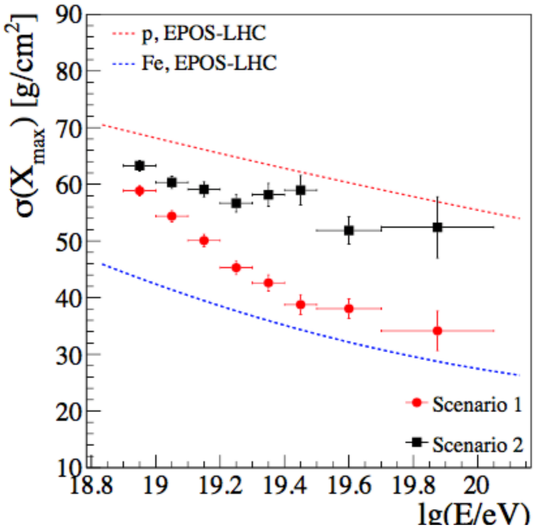


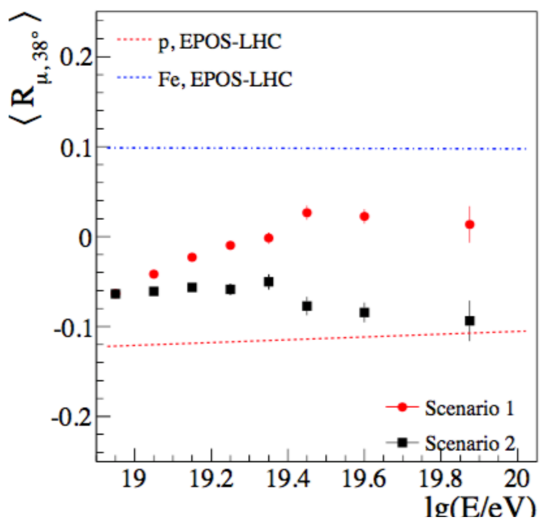


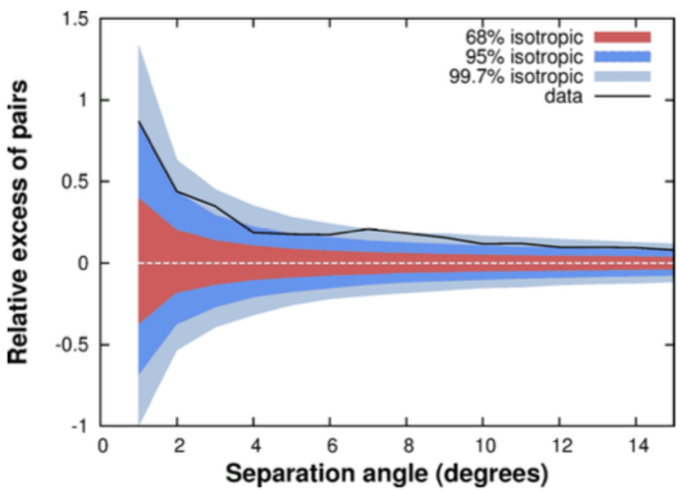
Together with better limits on cosmogenic neutrinos and photons from other experiments

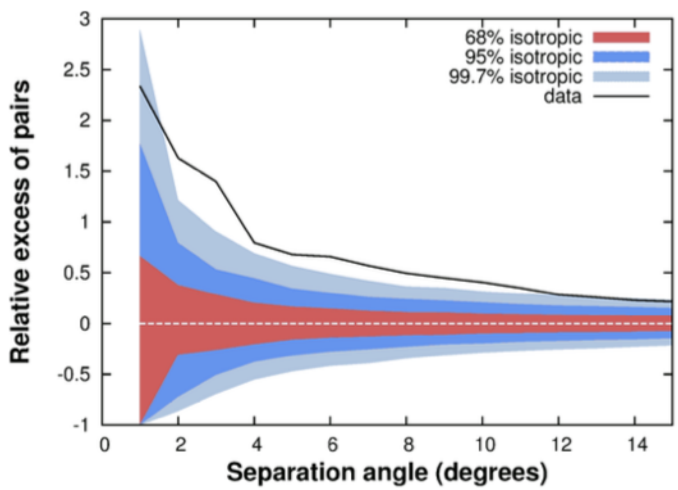
Upgrade of Auger (AugerPrime)







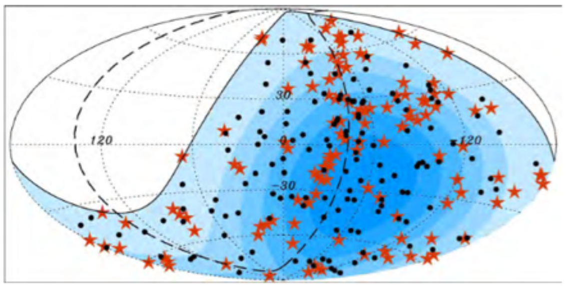


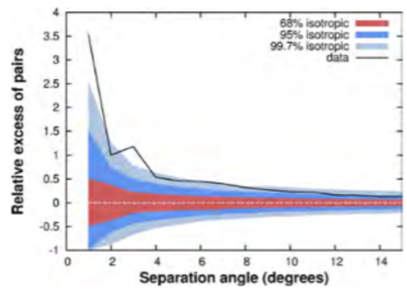


Upgrade of Auger (AugerPrime)

Finally astronomy with charged particles

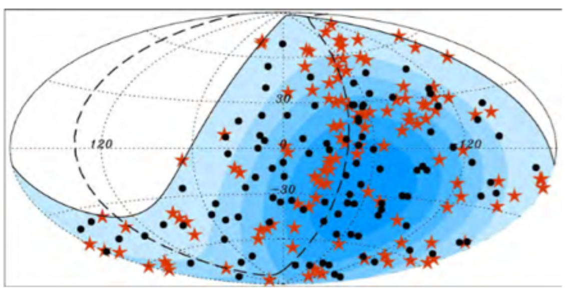
use arrival directions of 141 measured events with $\theta < 60°$ and $E > 5.5 \cdot 10^{19}$ eV
and randomly assign X_{max} according to maximum rigidity model with 10% p-like at high E
and let 50% of p-like events correlate with Swift-BAT sources

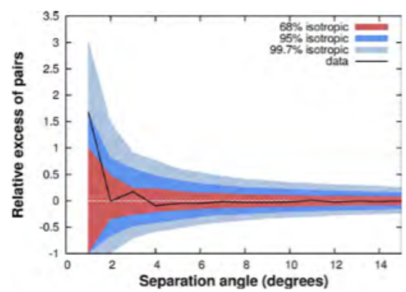




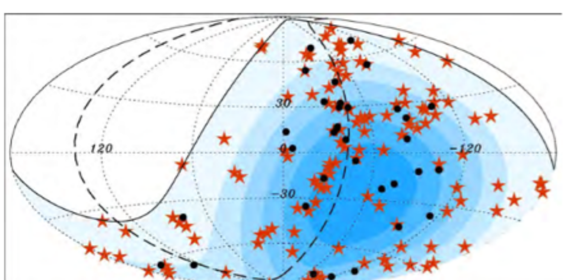
this reproduces well
the present situation

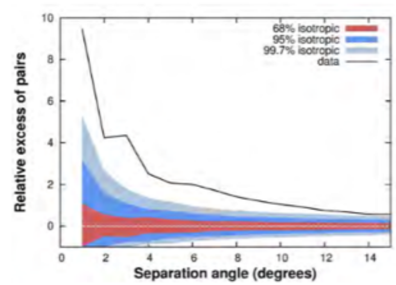
~ 3σ effect





p-like events are removed



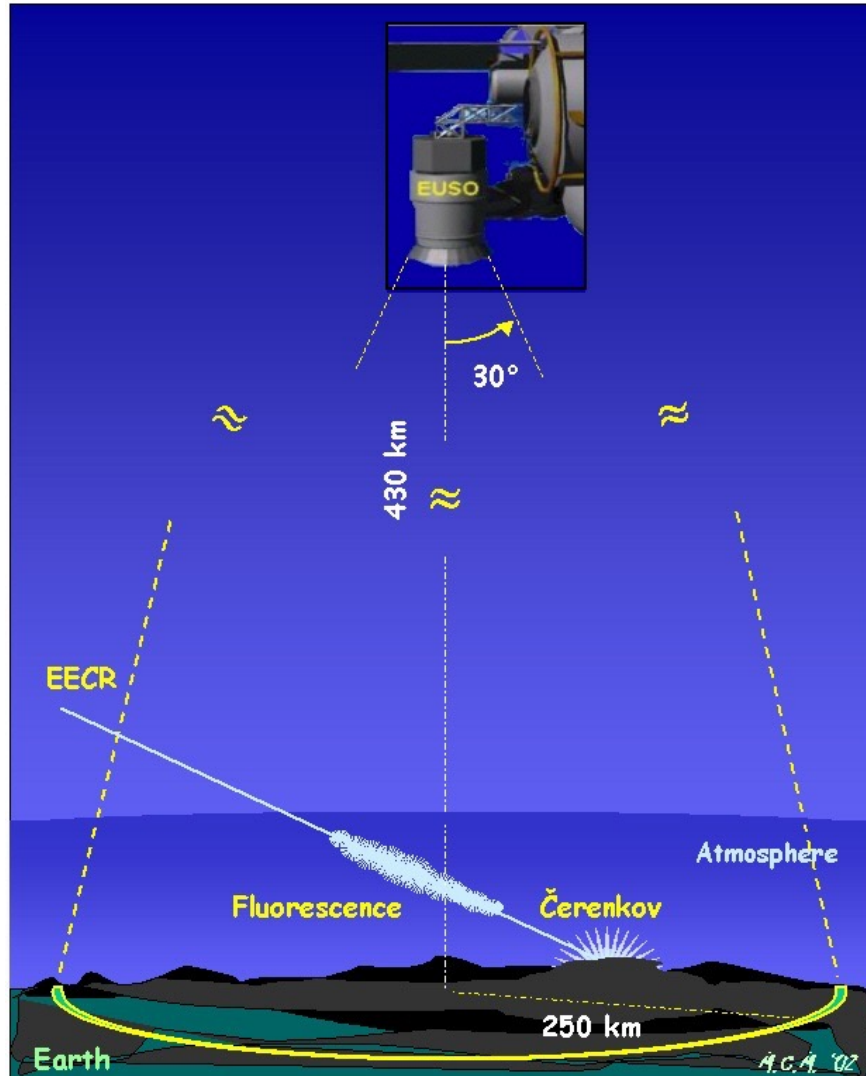


only p-like events included

~ 5σ effect

Next Generation UHECRs Experiments

JEM-EUSO (Extreme Universe Space Observatory onboard the ISS Japanese Experimental Module) concept:
Detecting air showers from space
FoV x10 wrt Auger



Conclusions

- Auger and Telescope Array have made significant contributions to the UHECR field with
- Accurate measurements of CR properties above 10^{17} eV and unprecedented statistics
- Precise determination of the "Ankle" and "GZK" suppression
- Excess of muons wrt hadronic int. models
- Indication that mass gets heavier
  - but <u>Need better mass composition to understand their origins</u>
  - GZK-effect or Exhaustion of Sources

- Indication of large scale anisotropy
  - but <u>No point sources yet</u>
- Better mass composition and larger statistics in the next years will help us resolve these open questions

Together with:

- Better constrains on cosmogenic neutrinos and photons
- Better understanding of galactic and extragalactic magnetic fields

Thank You