Cosmic rays: air showers from low to high energies

Rapporteur Talk

UNM NUPAC Sept 1, 2015
... slightly revised version ...
John Matthews

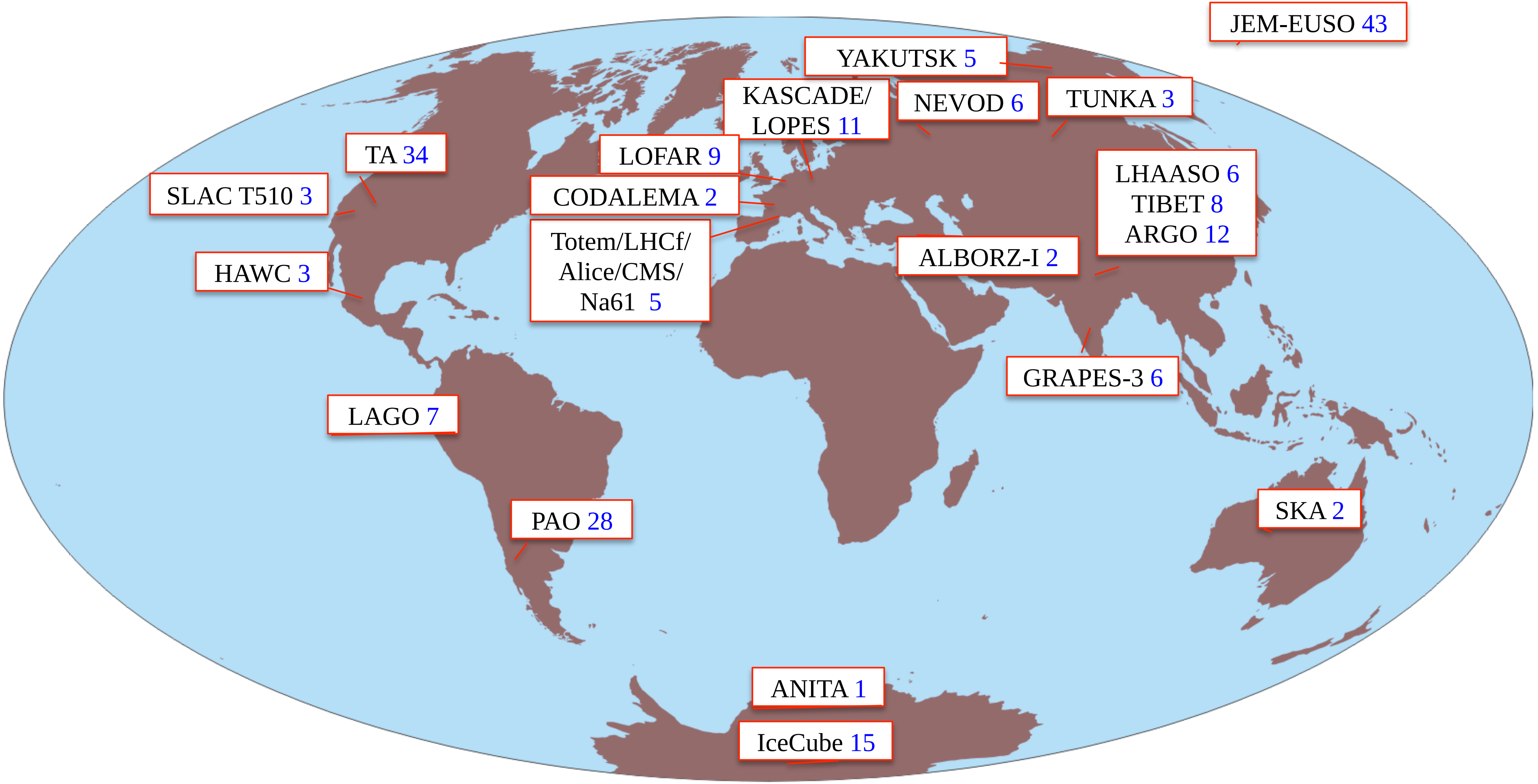
Valerio Verzi

INFN, Sezione di Roma "Tor Vergata"

6th August, 2015

ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

INFN
Istituto Nazionale di Fisica Nucleare

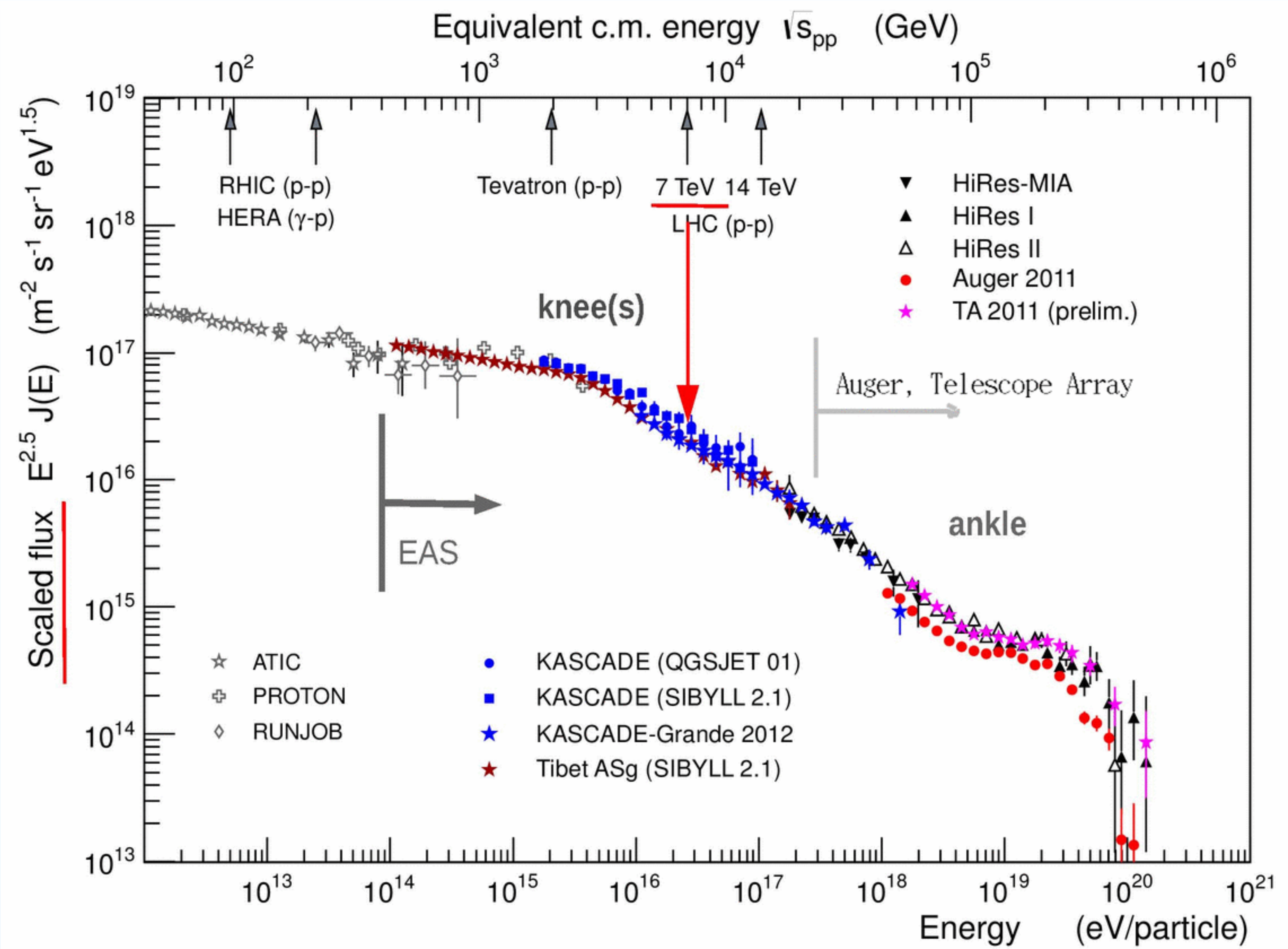


# of contributions/experiment

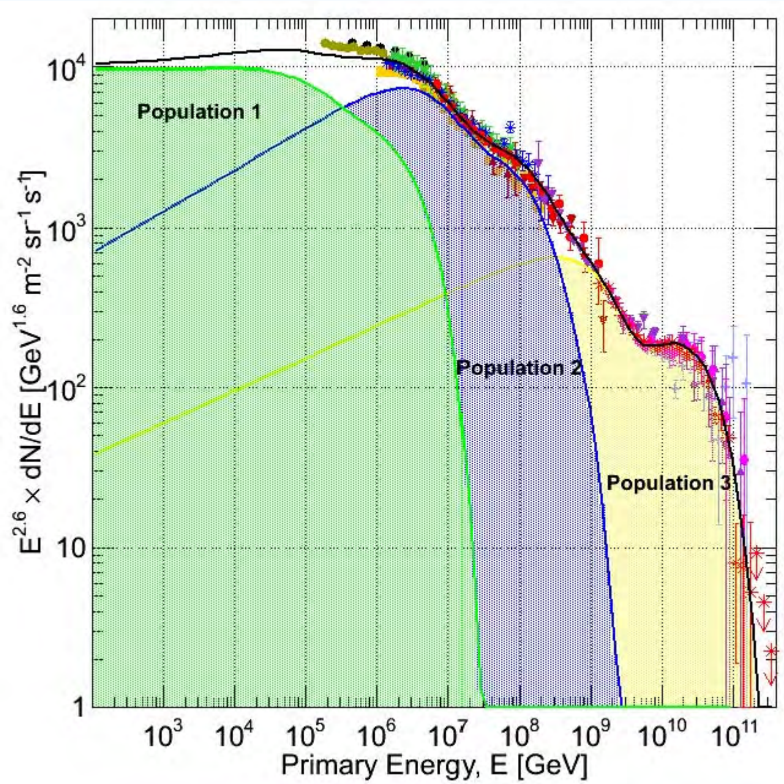
1) **ENERGY SPECTRUM**
2) **MASS COMPOSITION**
3) **ANISOTROPY**
4) **HADRONIC INTERACTIONS**
5) **RADIO**
6) **FUTURE**

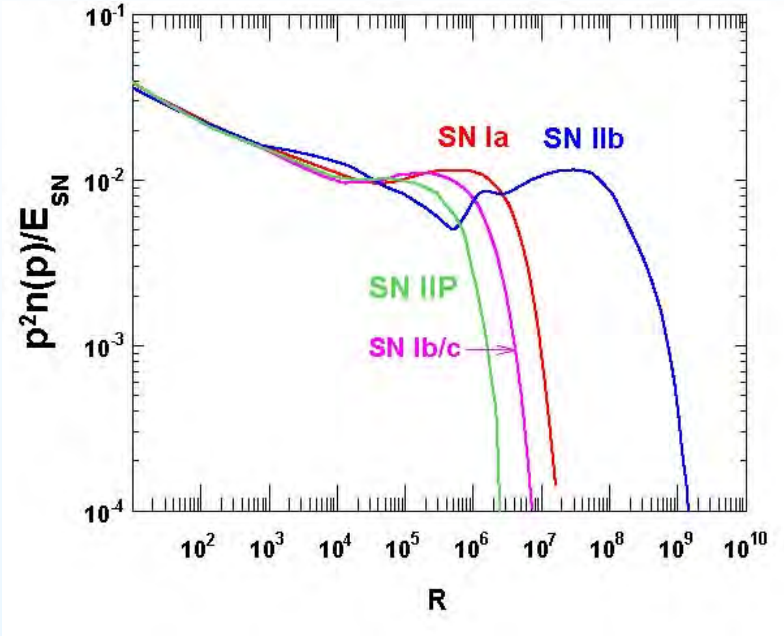
references in the talk
PoS number

Spectrum of high energy cosmic rays (CR)



Possible CR *source populations*





- Left: Gaisser, Stanev and Tilav's 2013 review article suggests several source populations
- Above: Ptuskin, Zirakashvili and Seo (2010) propose a cocktail of supernova types and environments as candidate population 1,2 sources. (R-scale assumes only protons.)
- *rigidity* $R = (pc)/(Zm_N c^2)$ is natural for mixed cosmic ray composition

ARGO-YBJ

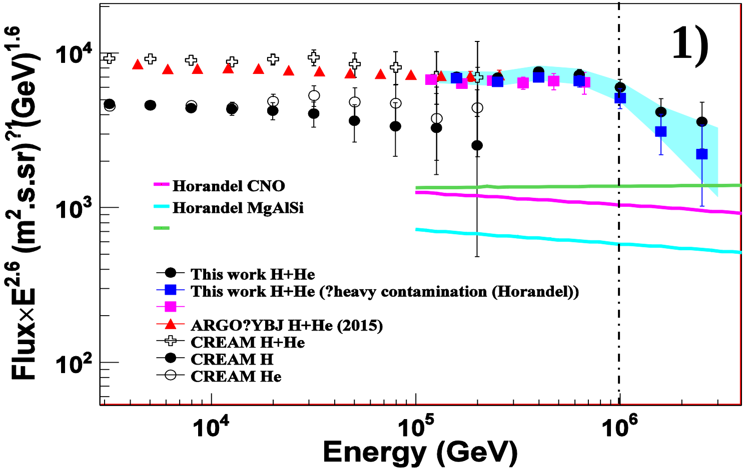
p/He spectrum bending below 1 PeV

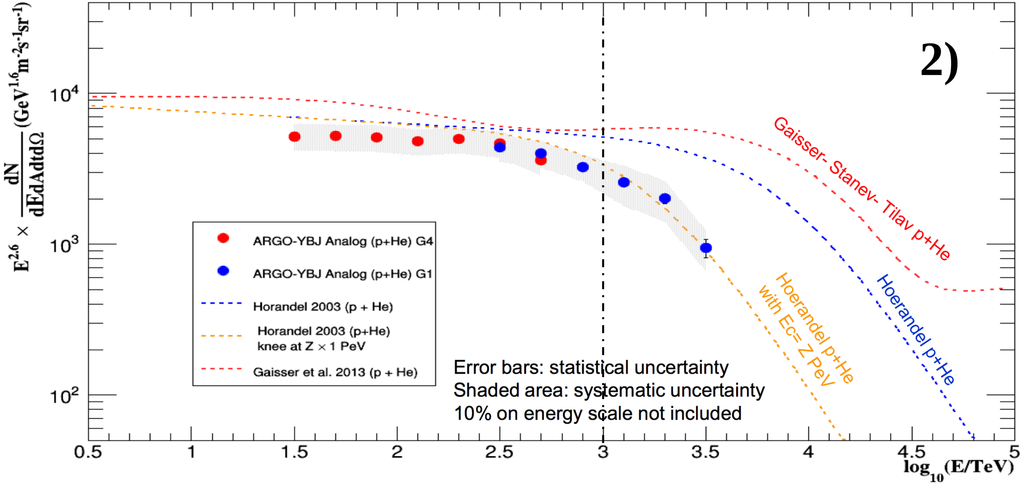
benefit of analog charge readout very close to the core

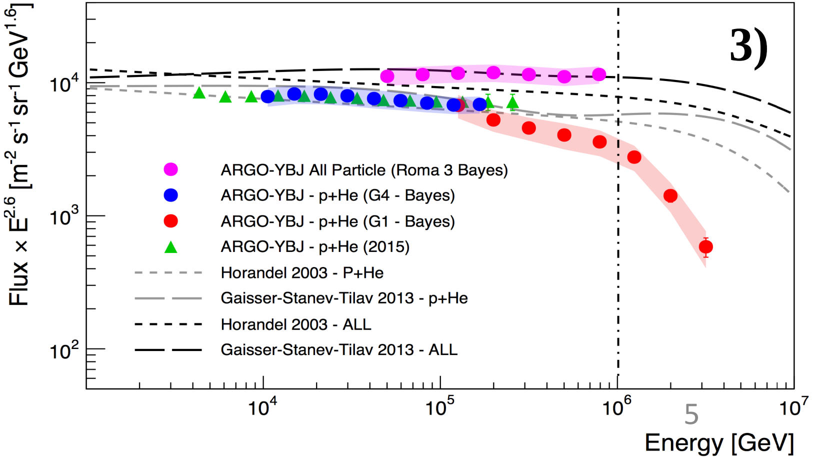
1) **'Hybrid' (LHAASO cher. Tel.)** *Z.Cao, 261*

2) **'Analog'** *I. De Mitri, 366*

3) **'Analog-bayesan'** *P. Montini, 371*



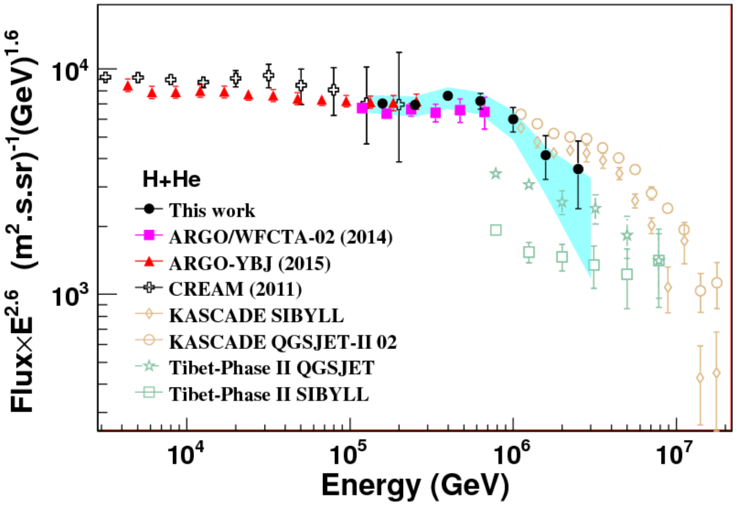




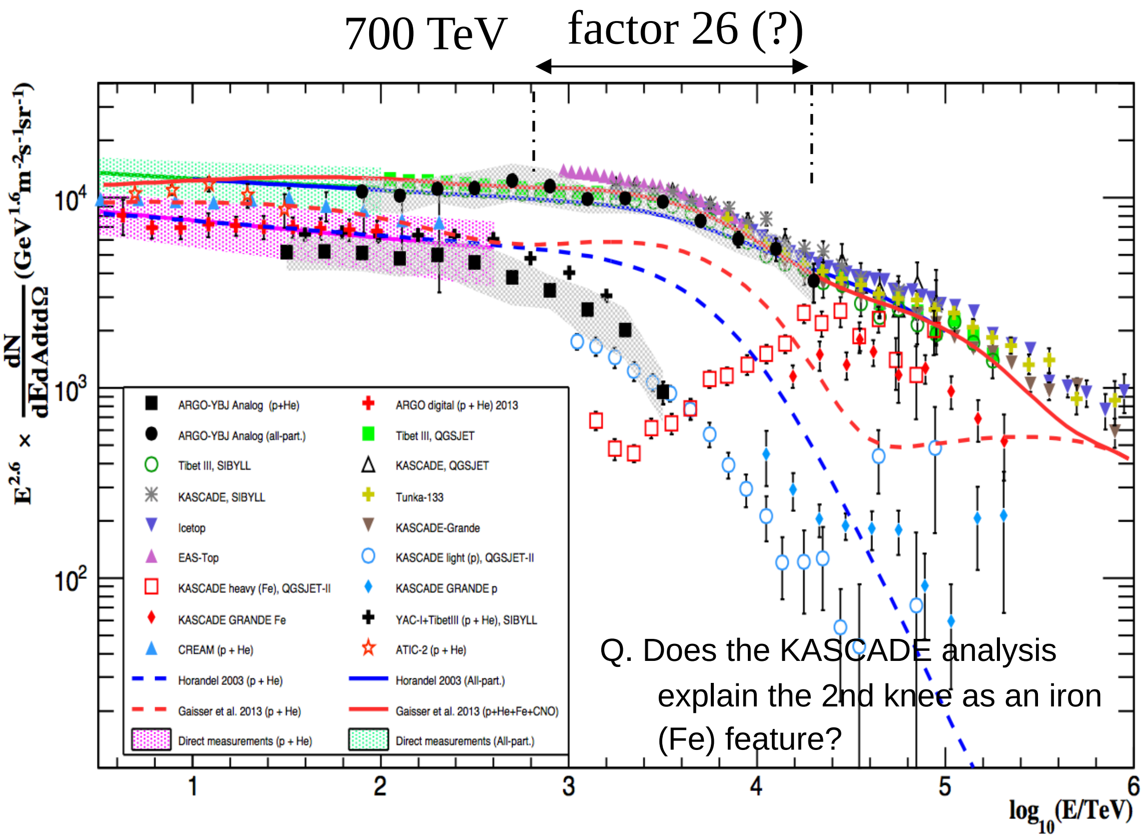
ARGO-YBJ

p/He spectrum bending below 1 PeV

- p/He and all particle spectrum
- consistency with direct and indirect experiments



Z.Cao, 261

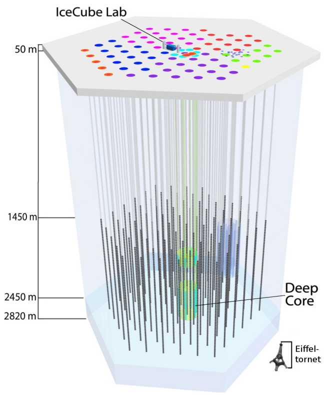


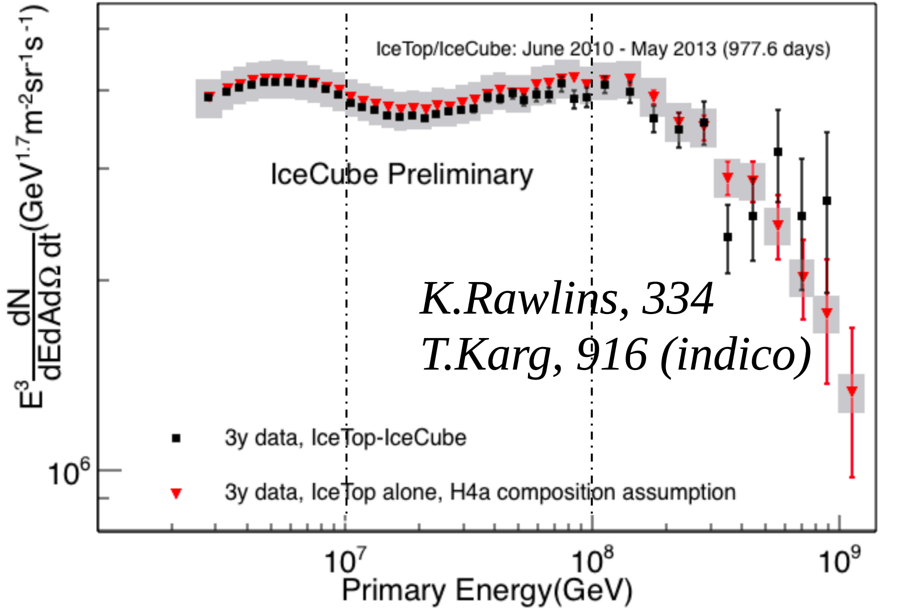
I. De Mitri, 366

above the knee

IceCube

spectrum for p, He, O, Fe

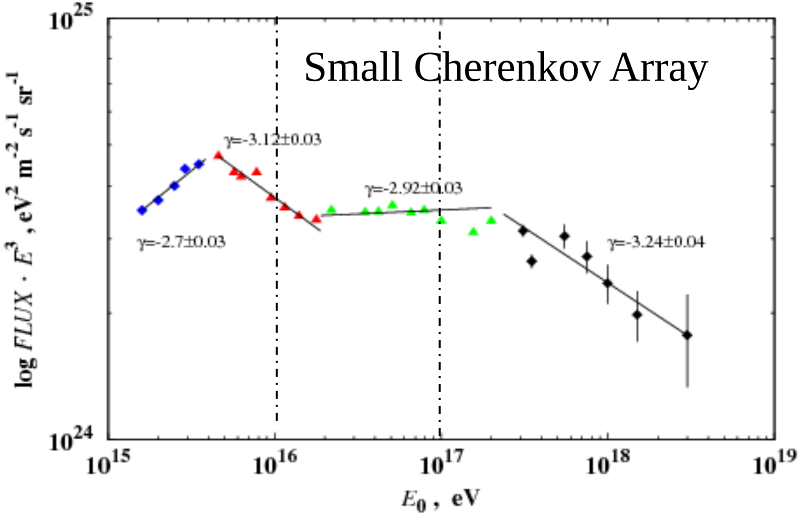




K.Rawlins, 334
T.Karg, 916 (indico)

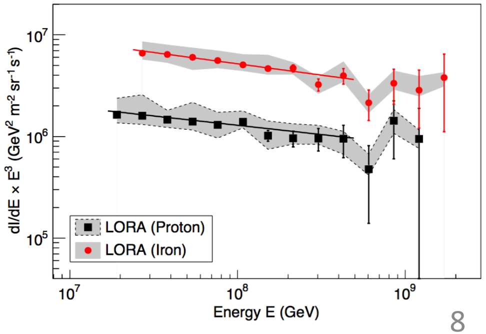
Yakutsk

I.Petrov, 252



LORA

S.Thoudam, 327

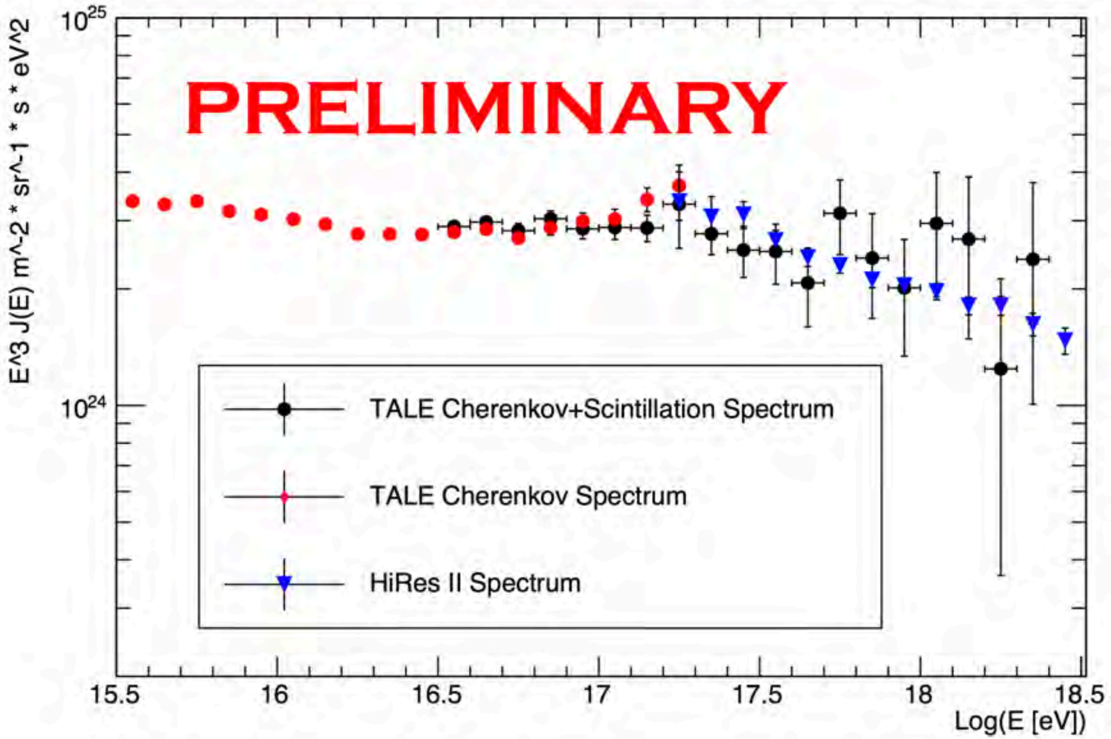


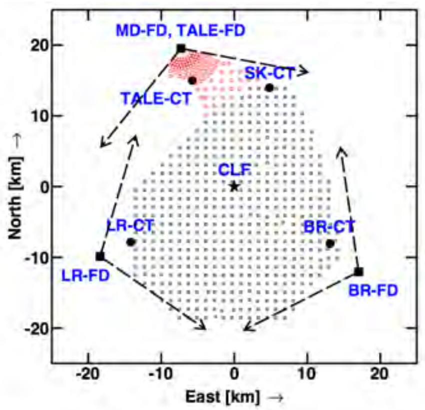
above the knee

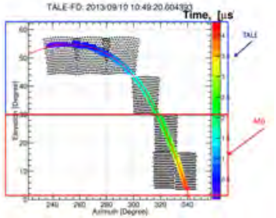
TALE (TA)

Telescope Array Low Energy Estimation

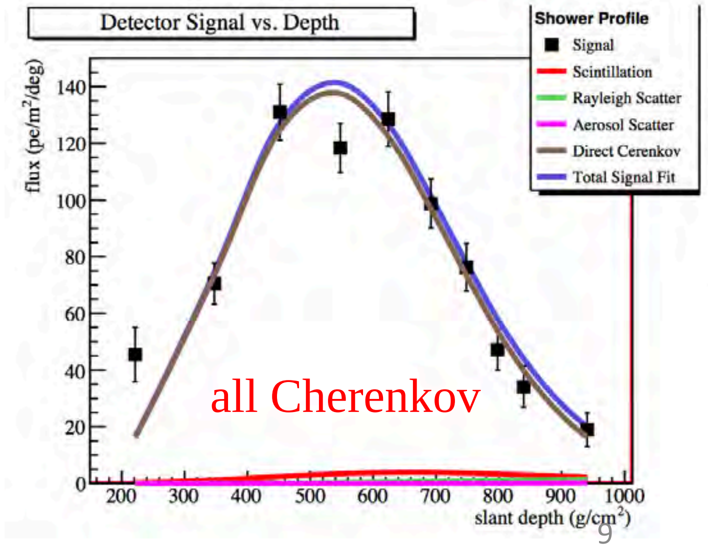
T. AbuZayyad, 422   *Z. Zundel, 445*







Profile Constrained Geometry Fit



all Cherenkov

Toward the highest energies

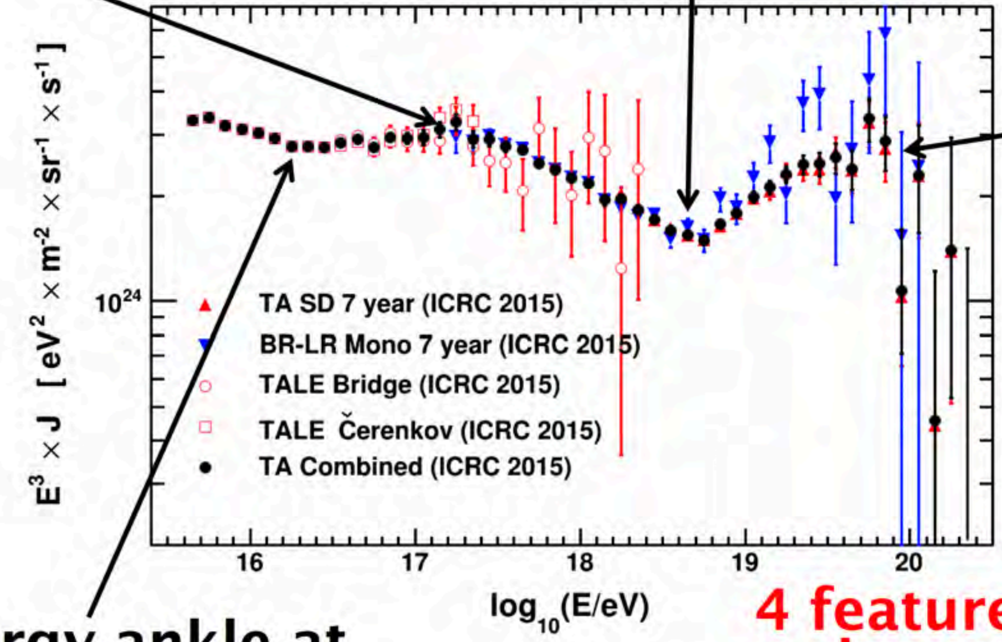
Telescope Array

D. Ivanov, 349

C. Jui, highlight

Second knee at E = $10^{17.3}$ eV

Ankle at E = $10^{18.72}$ eV



Break at $10^{19.8}$ eV

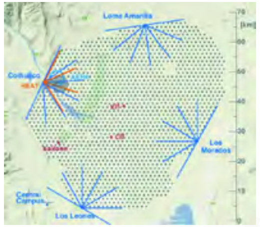
Z. Zundel, 445
T. AbuZayyad, 422
T. Fujii, 320
FD BR-LR Mono
D. Ikeda, 362 Hybrid

Low energy ankle at $10^{16.34}$ eV

4 features over 4.7 orders of magnitude in energy

Q. Are knee 1 and 2 related to p,Fe spectral cutoffs OR to two different source populations (and compositions) OR ??

Toward the highest energies

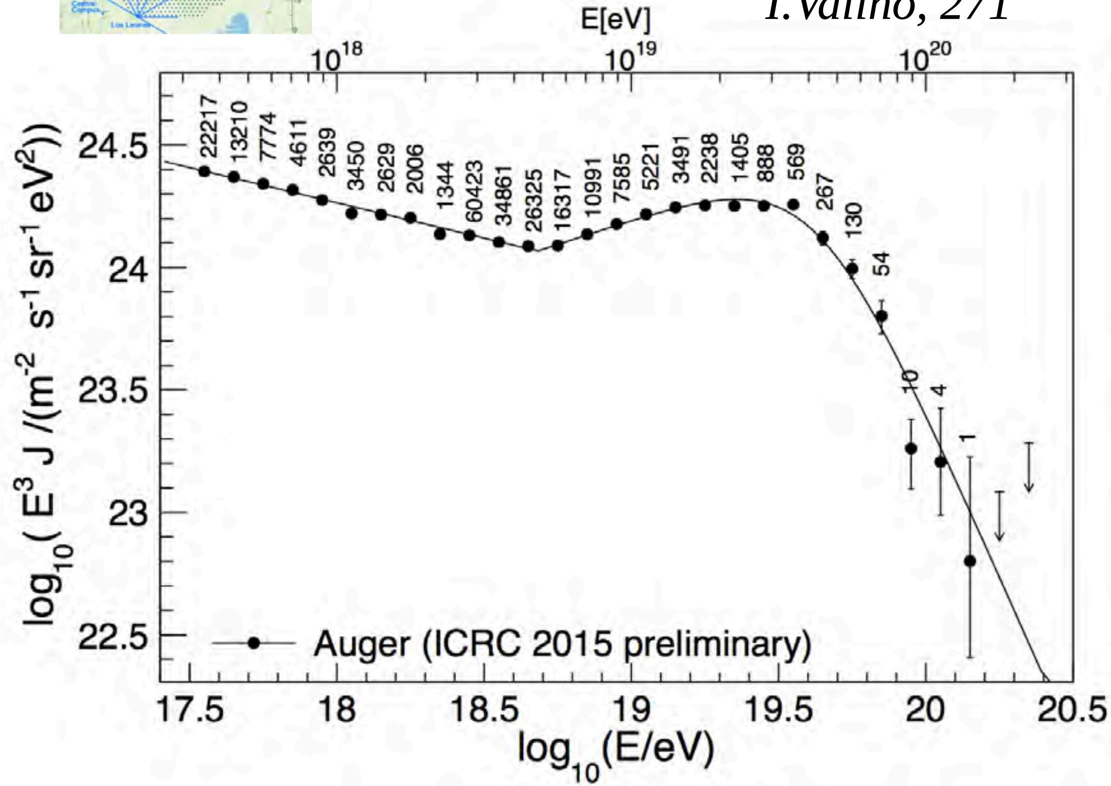


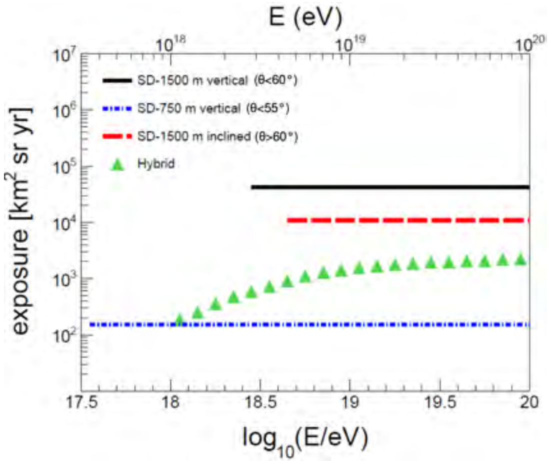
Auger

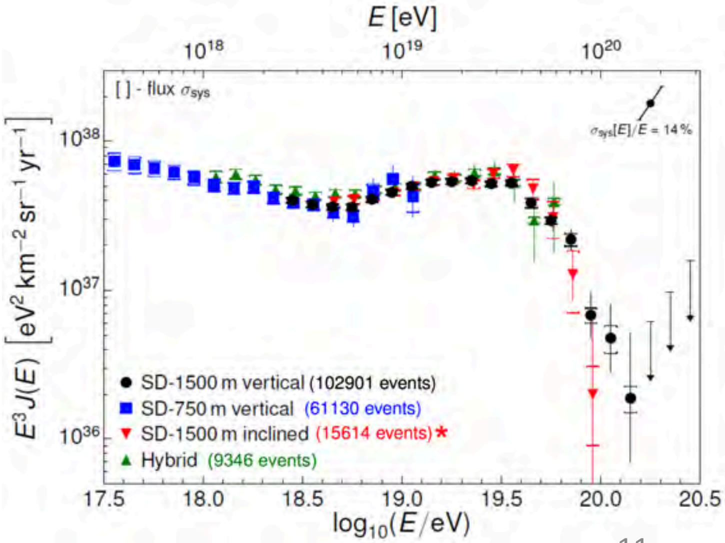
50,000 km^2 sr yr

P.Ghia, highlight

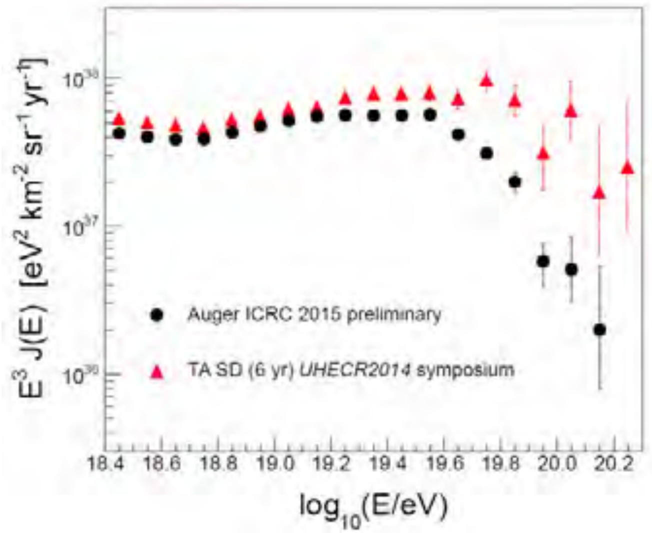
I.Valino, 271







Auger vs TA

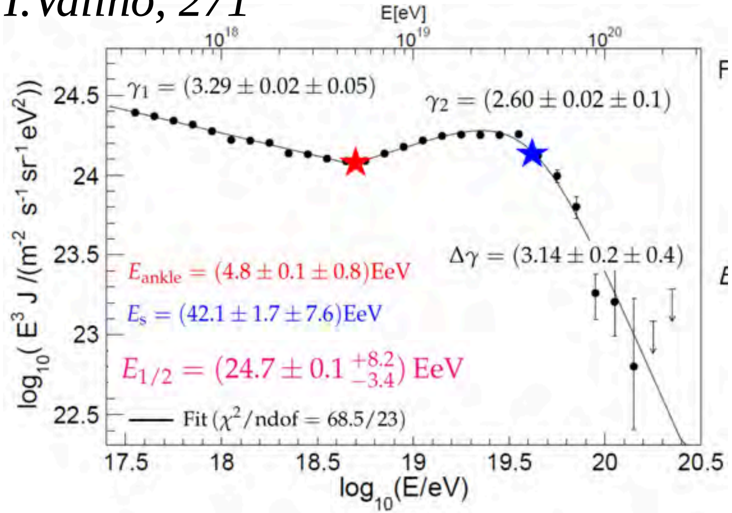


	Auger	TA
E_{ankle} (EeV)	≈ 4.8	≈ 5.2
$E_{1/2}$ (EeV)	**≈ 25**	**≈ 60**

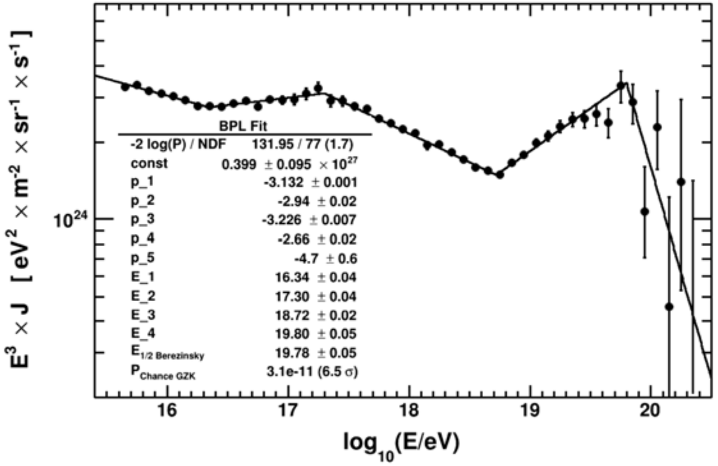
TA:Auger E_ankle compatible with energy scale uncertainties (10%)

TA:Auger E_1/2 (cutoff) energies are INcompatible! (expt'l bias??)

I.Valino, 271

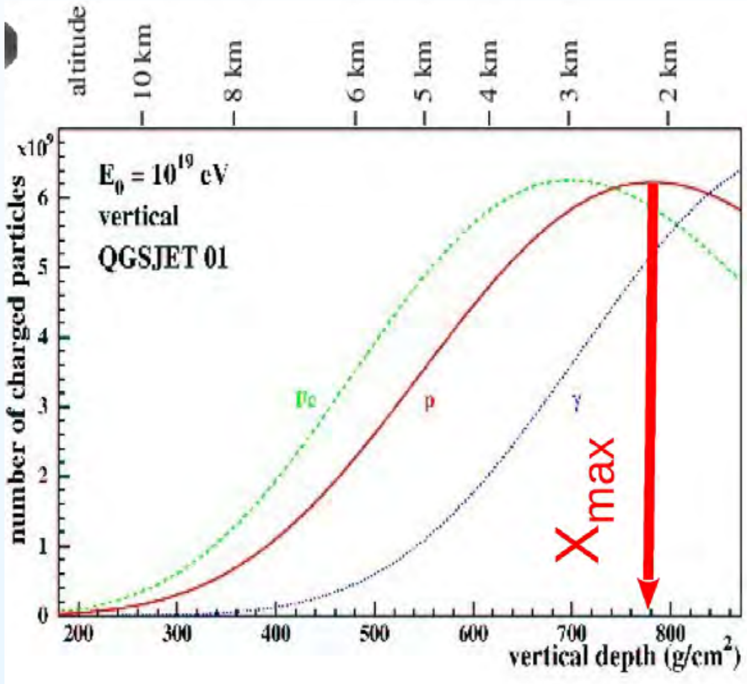


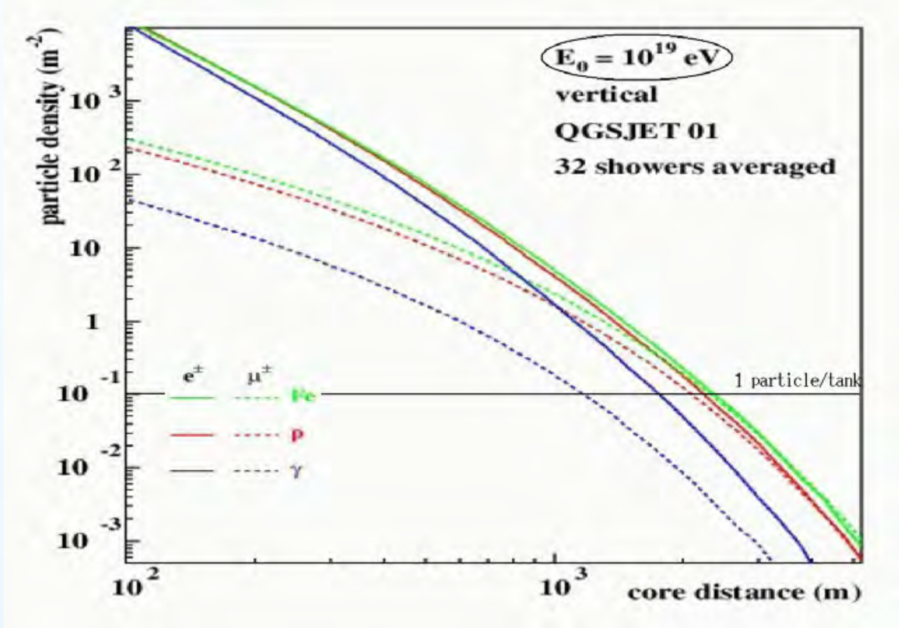
D.Ivanov, 349



1) ENERGY SPECTRUM
2) **MASS COMPOSITION**
3) ANISOTROPY
4) HADRONIC INTERACTIONS
5) RADIO
6) FUTURE

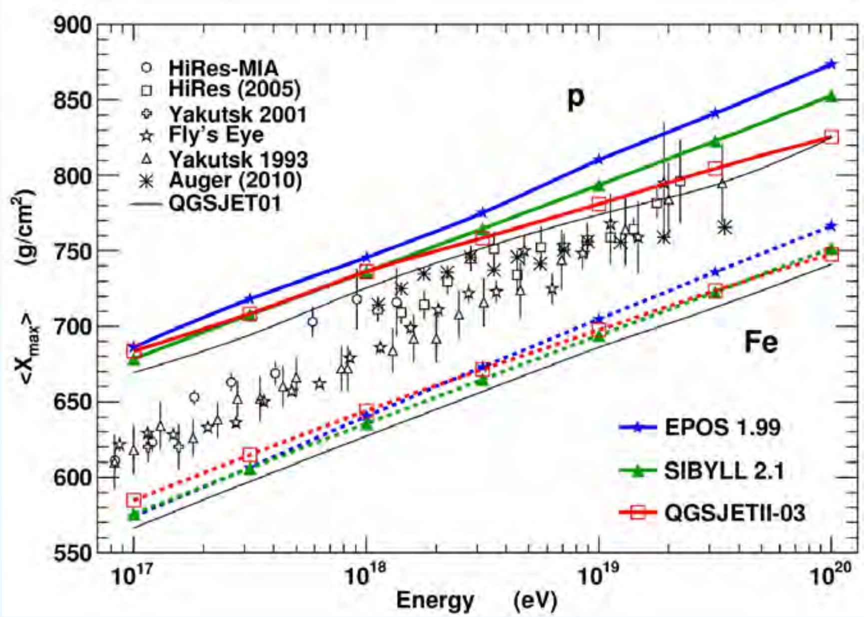
Experimental sensitivity to CR composition

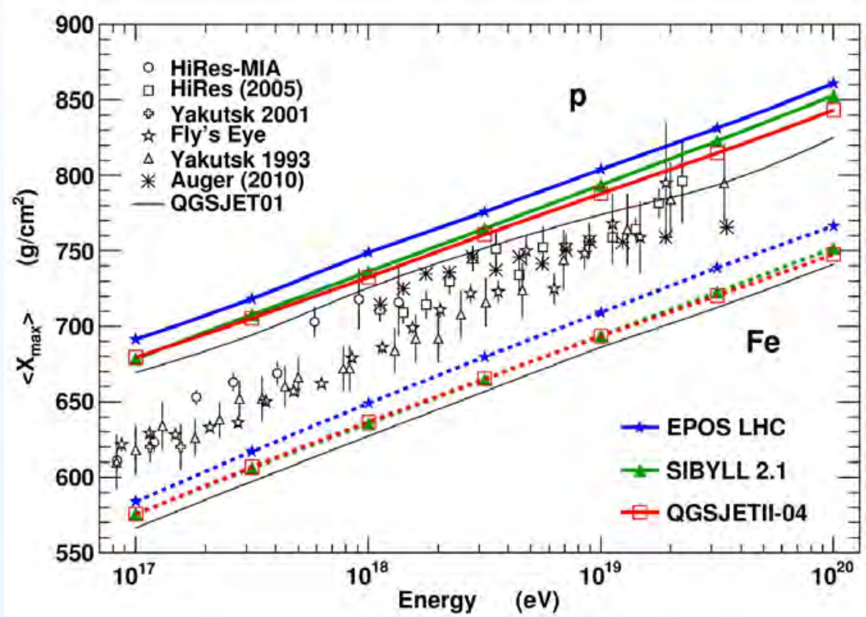




- Extensive air showers differ for iron(Fe), proton(p) and photon(γ) primaries.
- (Left:) The position of shower maximum, X_{max}, is measured by fluorescence telescopes.
- (Right:) The radial densities of muons(μ) and electro-magnetic($e^{\pm}$) particles from the shower core are measured by the Auger surface detectors.

Shower Monte Carlo (MC) predictions



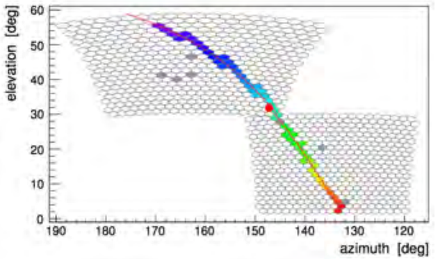


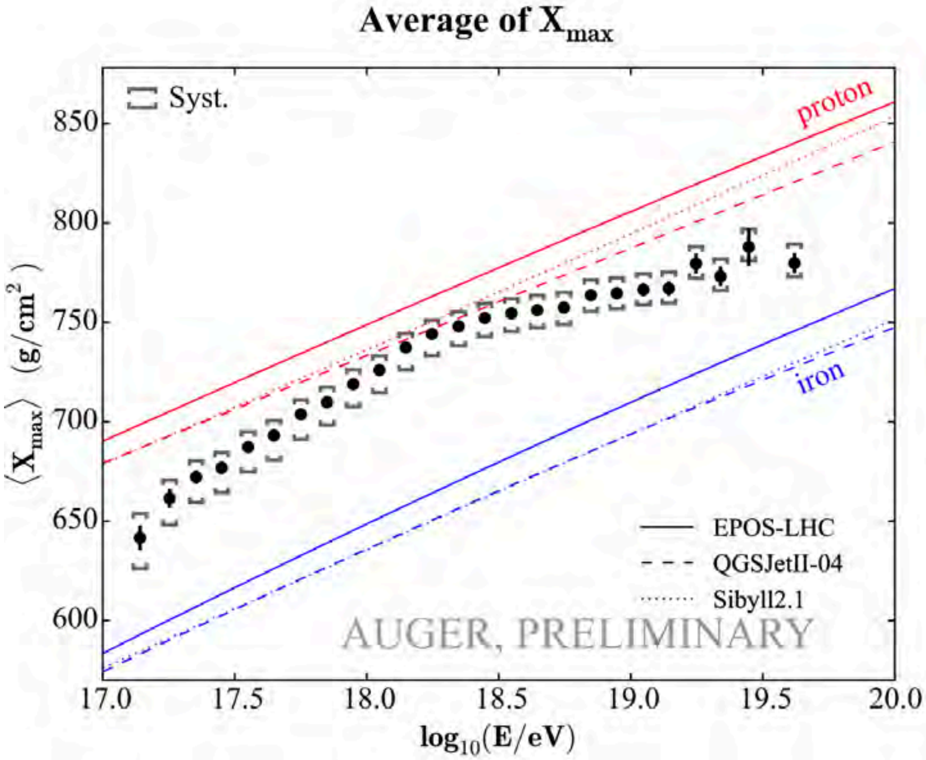
- Shower MCs include known particle physics plus phenomenological models to extend to Auger/TA CR energies but not "1σ" possibilities ...
- (Left:) Predictions for X_{max} for p and Fe primaries from MC version "n".
- (Right:) Predictions from MC version "n+1" tuned to the latest collider data.
- MC differences may under (or over) estimate systematic uncertainties.
- Experimental data are "noisy" but MC predictions disfavor pure proton composition!

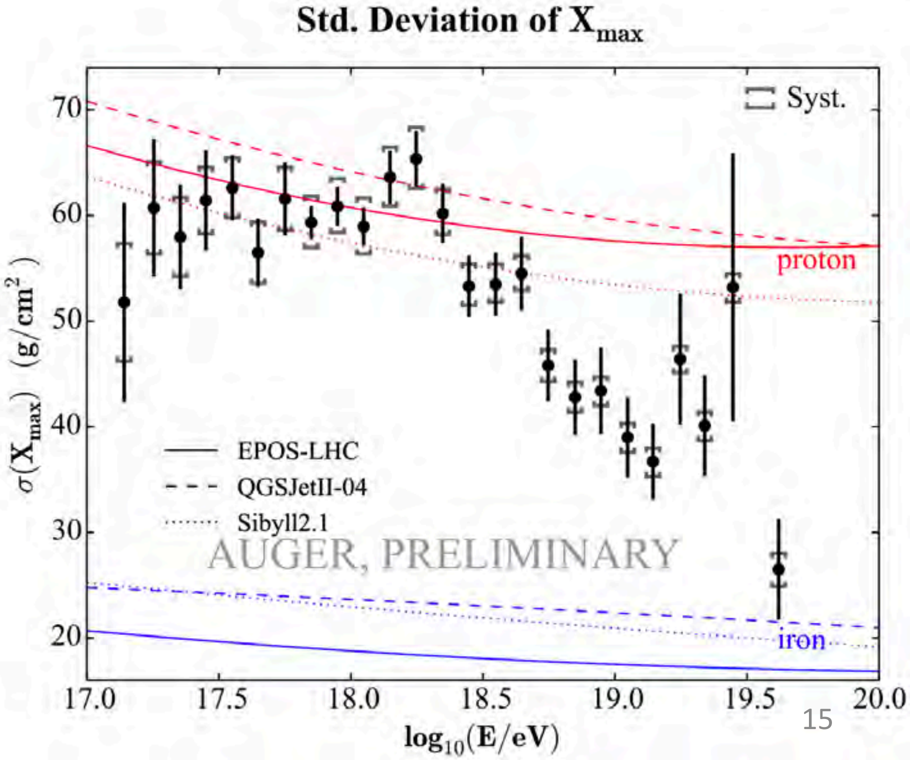
Auger

A.Porcelli, 420

down to 10^{17} eV using HEAT







Auger

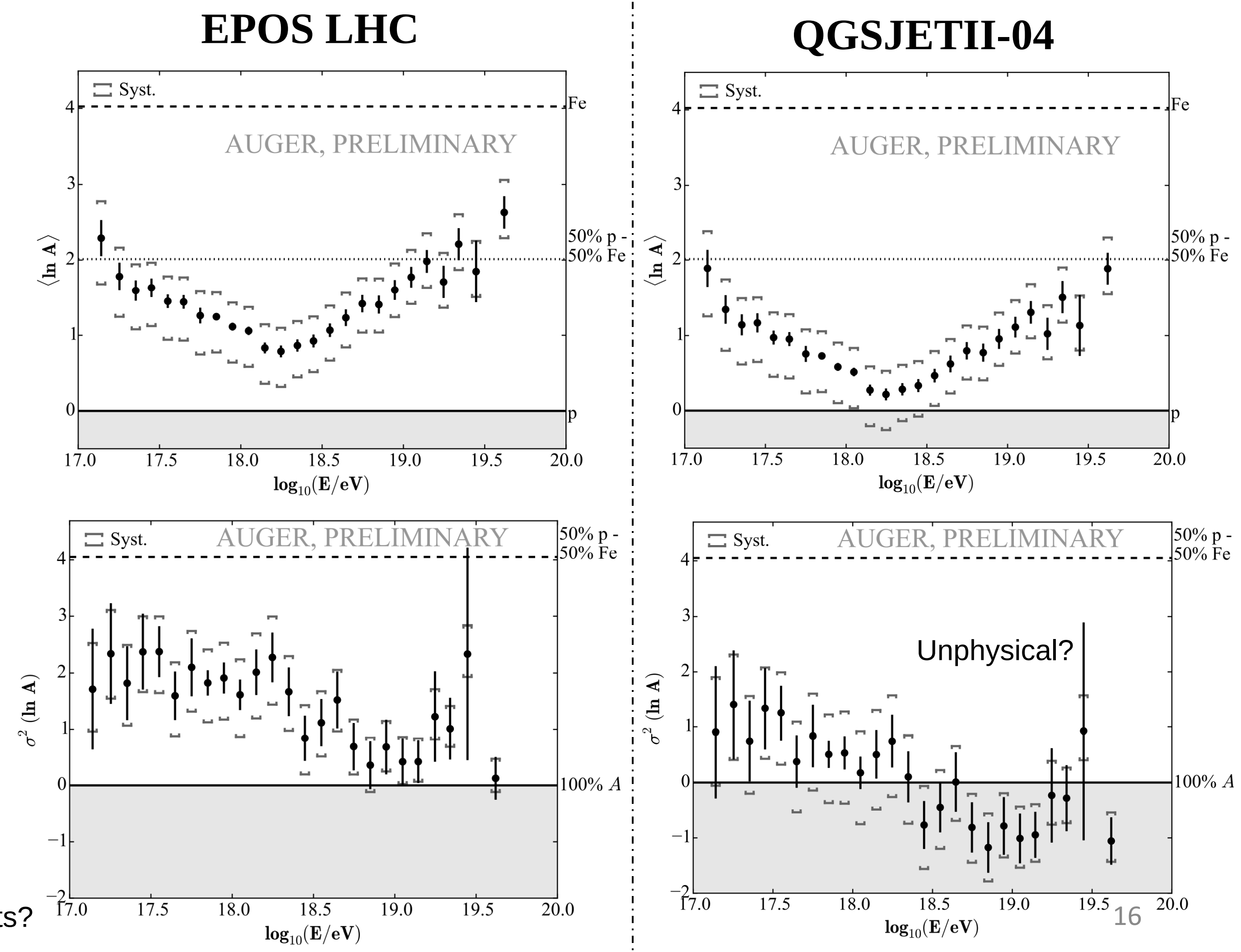
A.Porcelli, 420

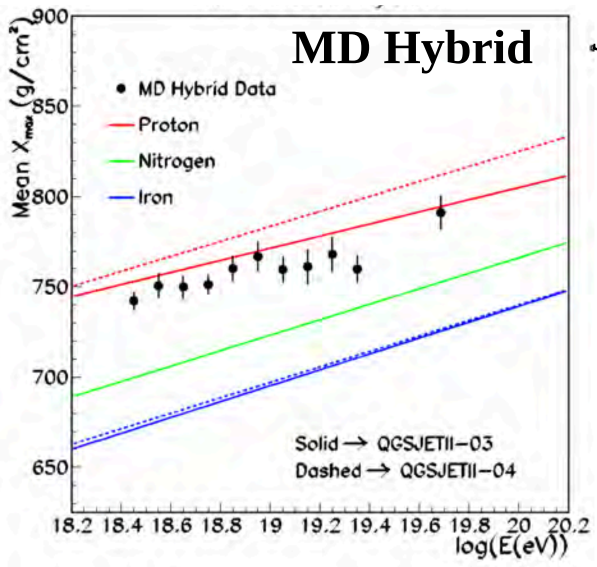
lightest composition at ~2 × 10^{18} eV

heavier at lower and at higher energies

NB the analyses "assume" the correctness of the shower MC simulations + model to extract <lnA> and lnA RMS.

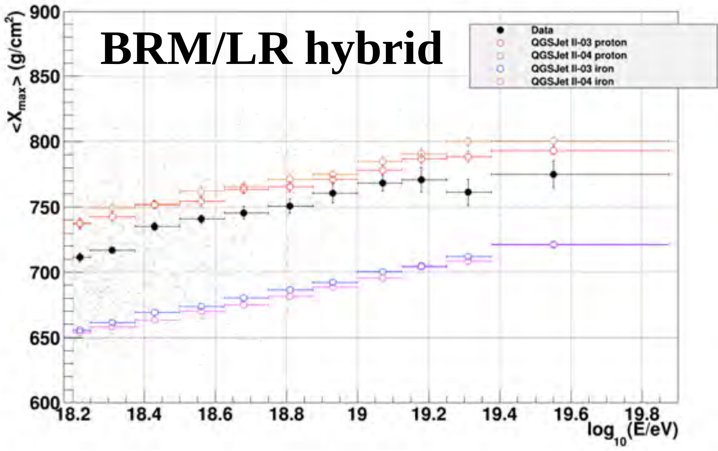
What should we then question when there is a region of Unphysical results?





J.P.Lundquist, 441, 442

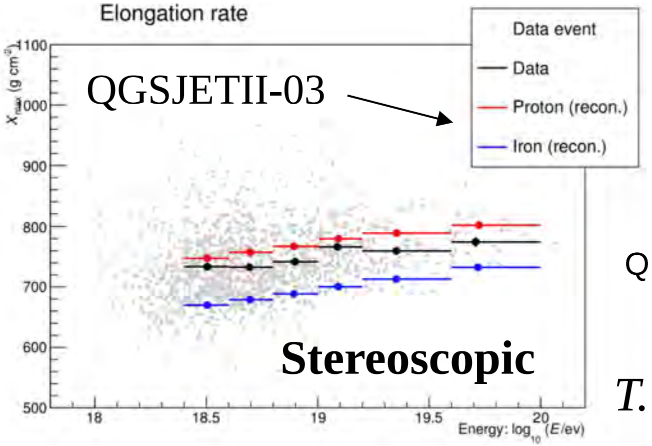
D. Ikeda, 362



TA

multiple X_{max} measurements

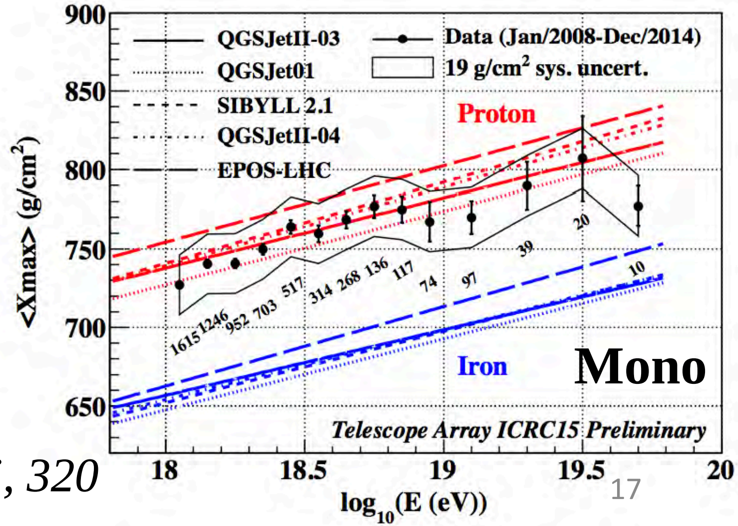
allows a check of systematic uncertainties

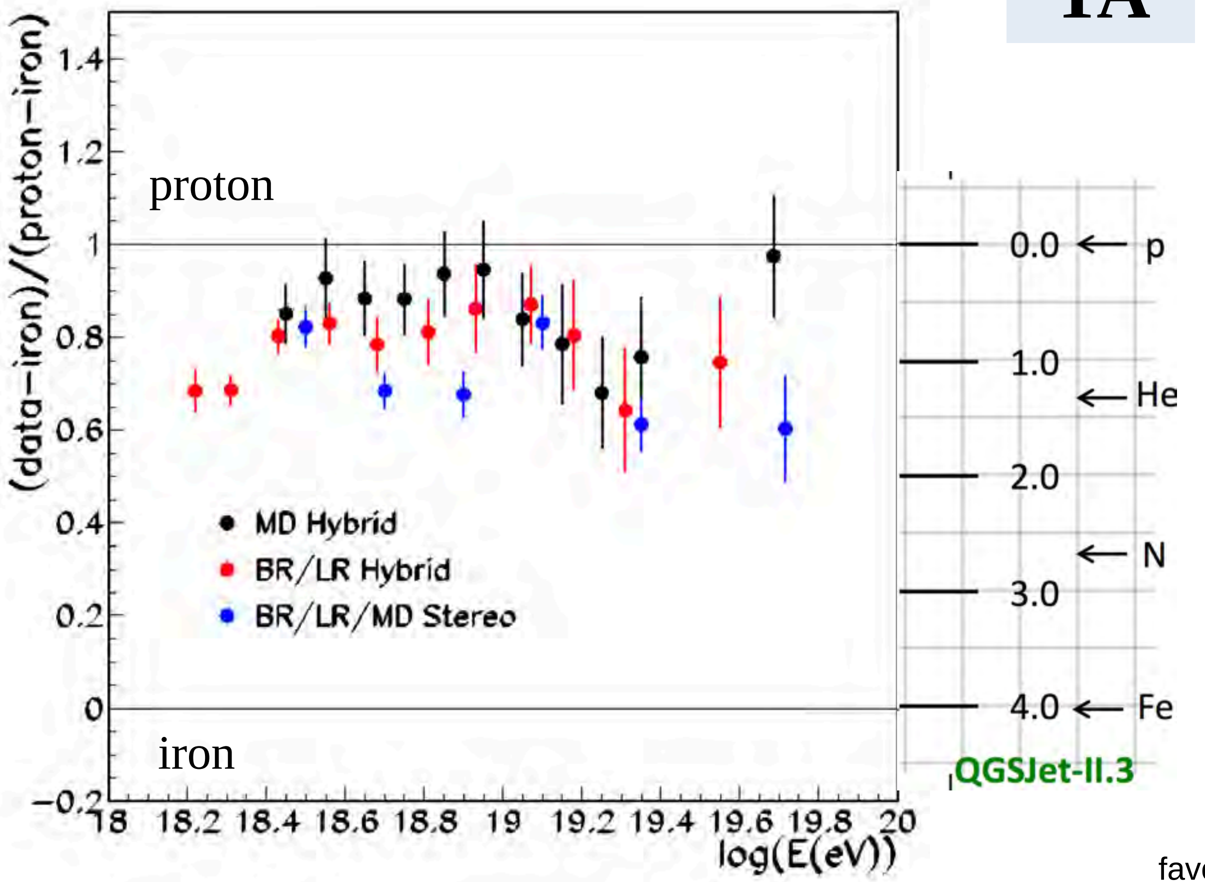


Q. But what if using QGSJetII-03 provides a BIASED physics interpretation?

T. Stroman, 361

T.Fujii, 320





TA

C.Jui, Highlight
J.Belz, 349

X_{max} measurements vs **QGSJETII-03**

Reasonable agreement within systematic uncertainties

“Light” (< CNO) composition within this model

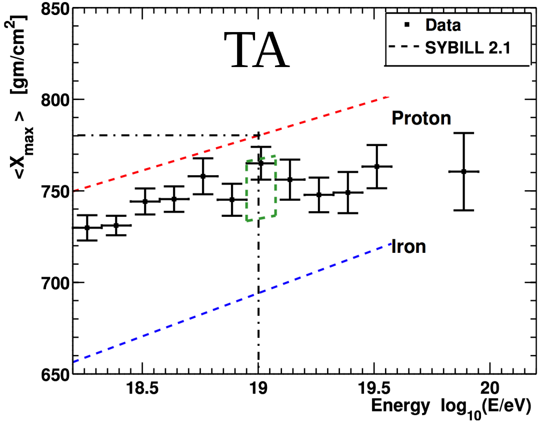
NB: "newer" eg QGSJetII-04 models favor heavier composition (R. Engel review talk)

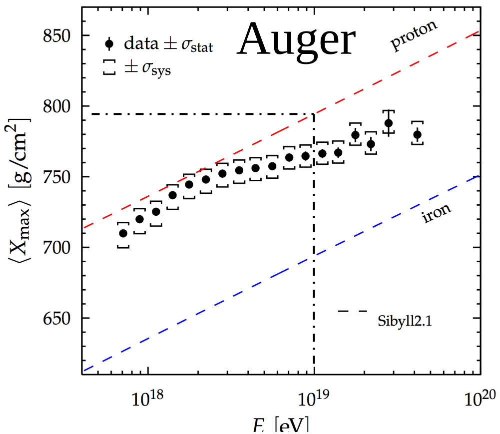
AUGER/TA WG

M.Unger, 307

TA folded with detector

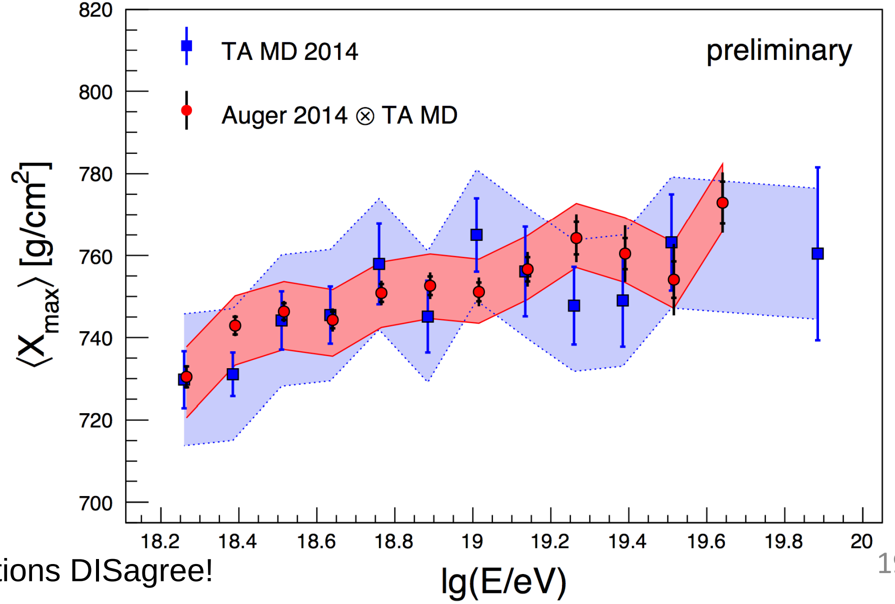
Auger unbiased





TA: reconstruct simulated events compatible with X_{max} distribution from Auger

compare above simulation with data



very good agreement!

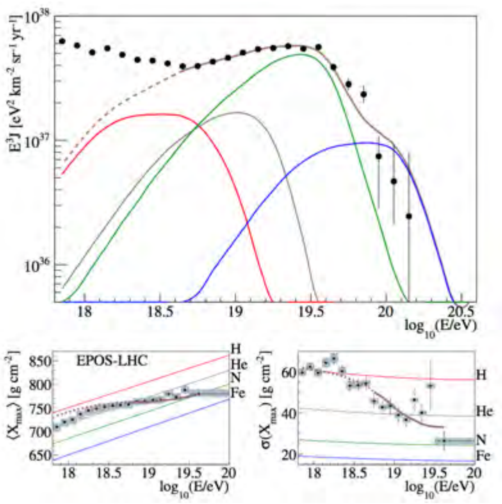
NB Auger and TA data agree ... but the MC based interpretations DISagree!

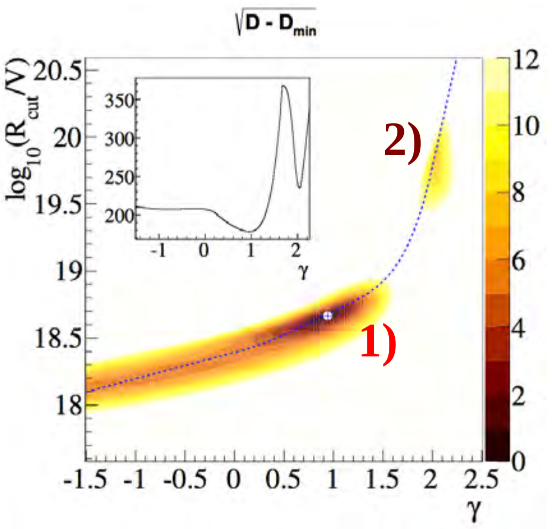
Auger

A. Di Matteo, 249

combined fit spectrum and composition

maximum rigidity (1) favored over photo-disintegration (2)





TA

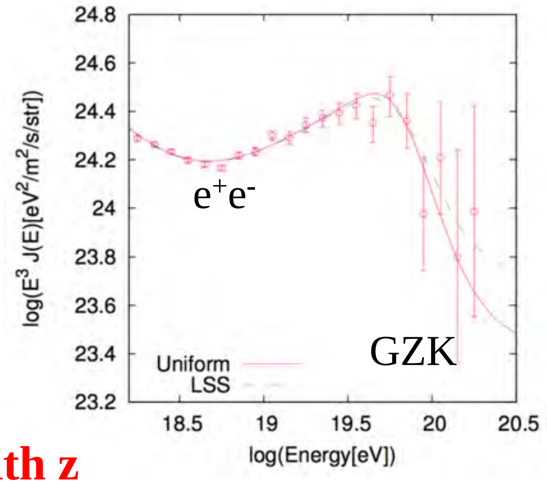
E. Kido, 258

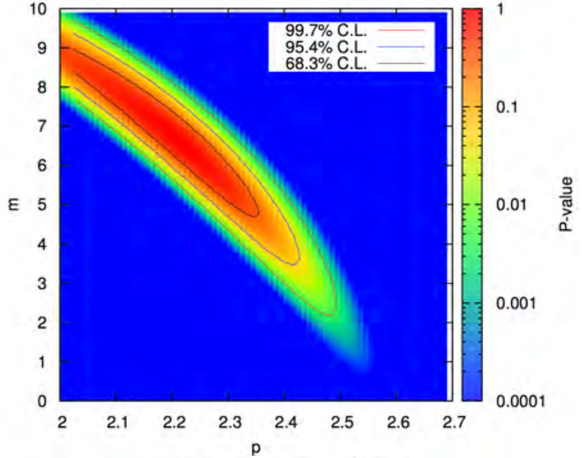
fit spectrum with a pure p composition

"no cut-off " at the source

"dip" scenario

strong evolution of sources with z





$\alpha E^{-p}(1+z)^{3+m}$

ankle 5×10^{18} eV

"dip" scenario requires extragal. protons (>85%)

TA *D.Ivanov, 249*

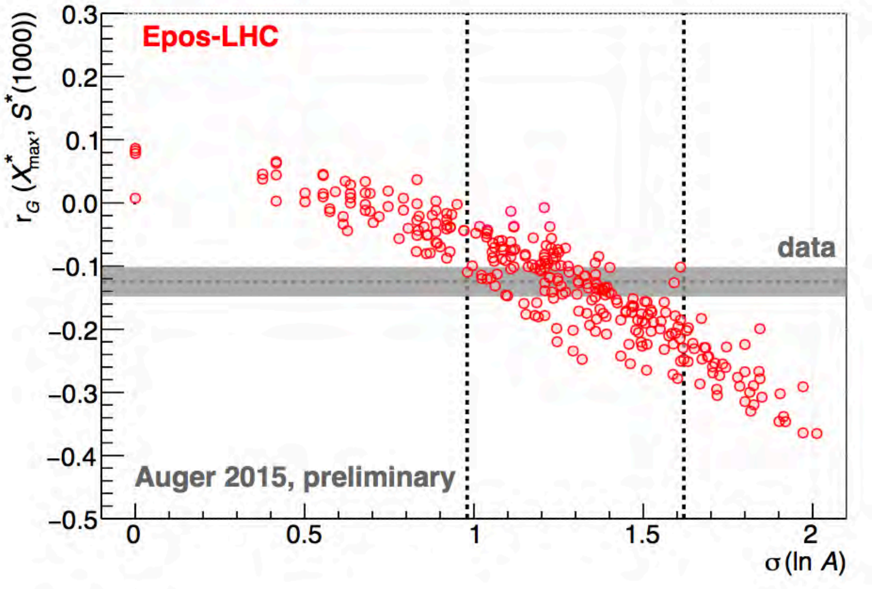
✔ isotropy at $\sim10^{18}$ eV

→ GCR< 1% at 90% C.L.

Auger *A.Yushkov, 335*

? mixed composition at the ankle

correlation X_{max} vs S(1000)



attempt for an overall description of specrtum/comp. vs E → no "dip" scenario

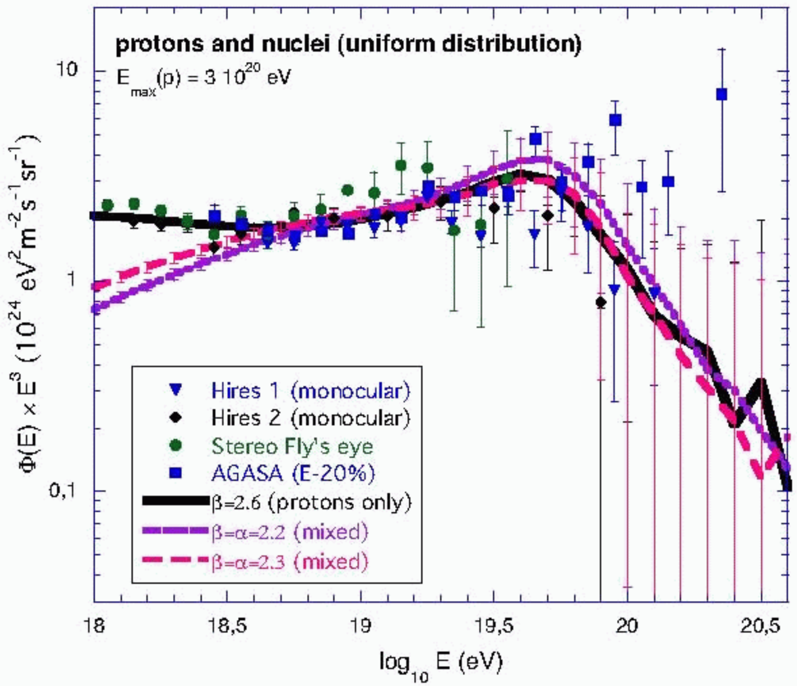
N.Globus, 515 only two components

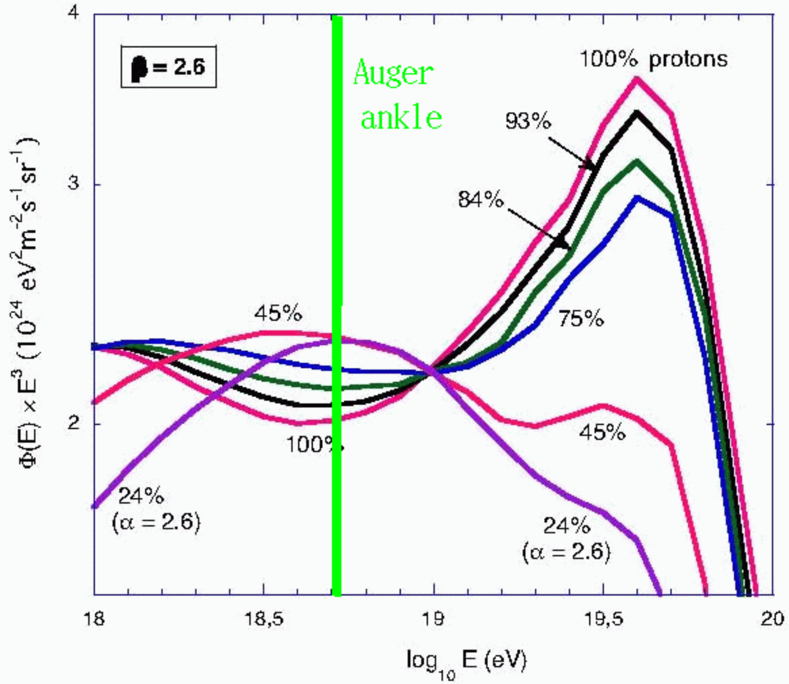
1) GCR/rigidity 2) EGCR/acceleration at mildly relativistic internal shocks of GRBs

G.Farrar, 513

photo-disintegration in the vicinity of the accelerator before escaping

Spectrum analysis for *mixed* composition





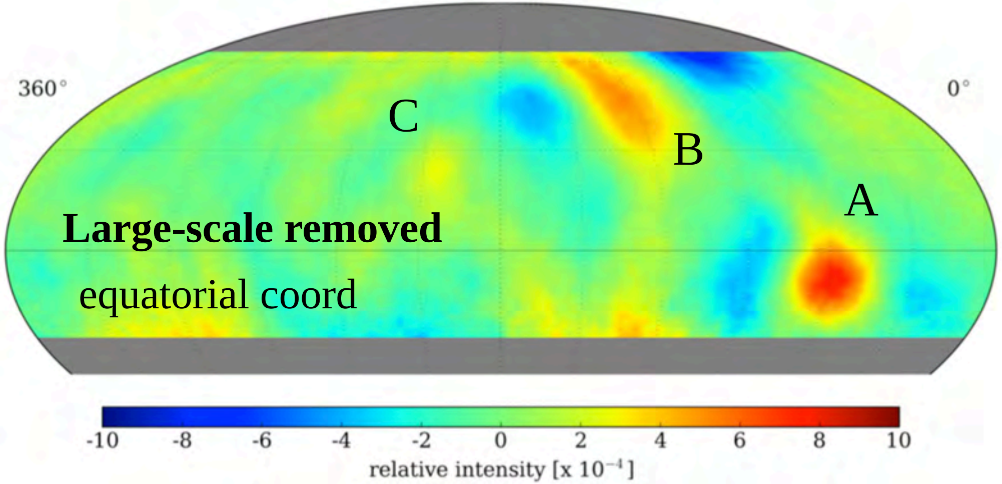
- Population 1 and 2 have mixed composition: p, He, ... Fe; why not population 3?
- (Right plot:) Allard, Parizot, Khan, Goriely and Olinto (2008) found that only almost pure protons have a distinct ankle. Left plot confirms that only almost pure protons model the flux over essentially all of the population 3 energy range.
- Does the clear ankle, in Auger/TA data, favor mostly ($> 75\%$) proton composition?

1) ENERGY SPECTRUM
2) MASS COMPOSITION
3) **ANISOTROPY**
4) HADRONIC INTERACTIONS
5) RADIO
6) FUTURE

Anisotropy - TeV

A – strongest, harder than bkg
B – most extended
C – confirms ARGO-YBJ observation

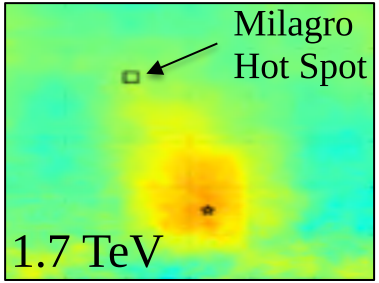
HAWC *D.W.Fiorino, 241*

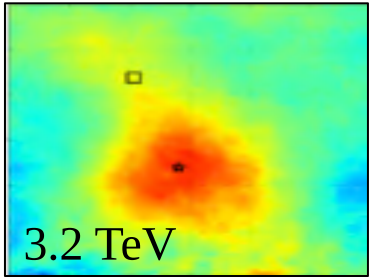


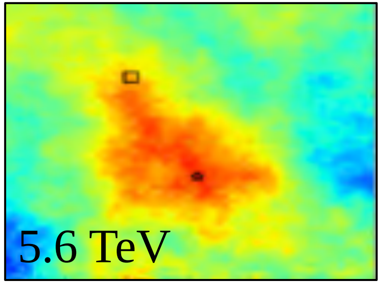
HACW-111

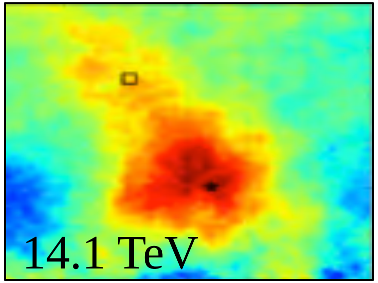
86 billion events in 181 days

NB the anisotropy results are over a much larger CR energy range than previous (spectrum, composition) results!









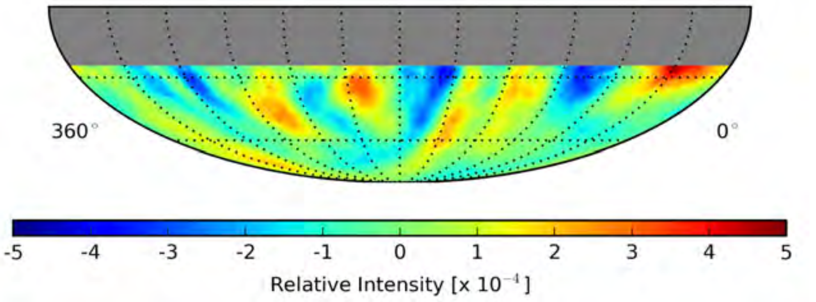
Anisotropy in the Southern Hemisphere

IceCube

S.Westerhoff, 274

small scale structure

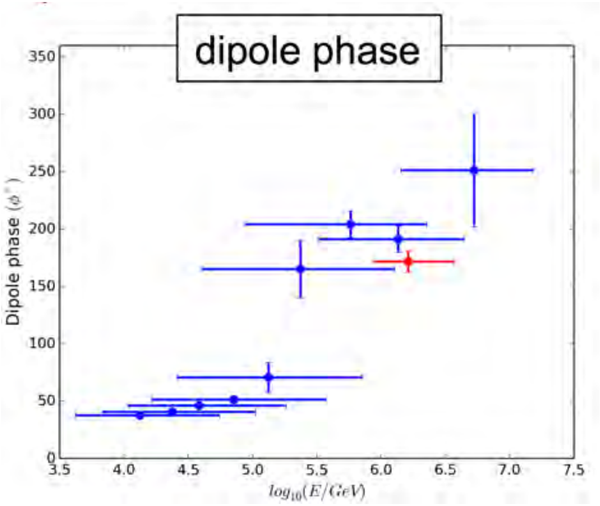
equatorial coordinates

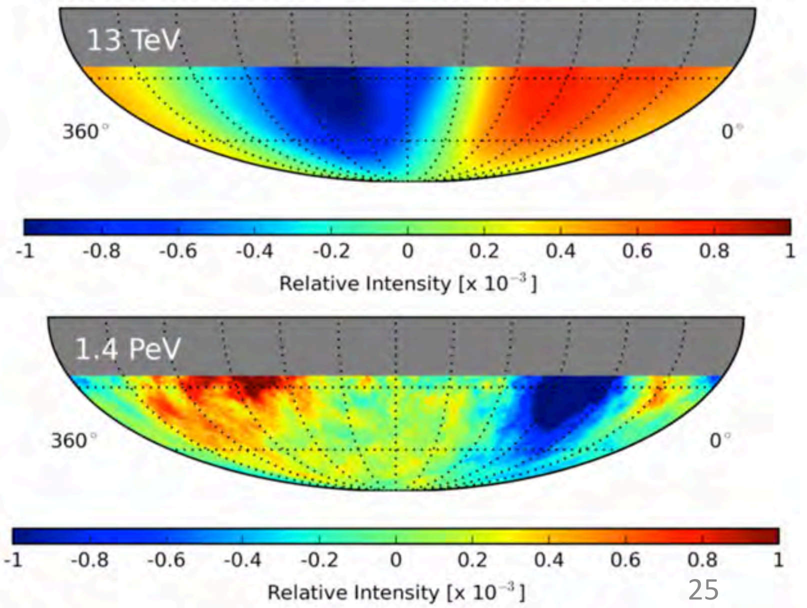


250 billion events in 5 years

harmonic analysis in RA

abrupt change at 100 TeV





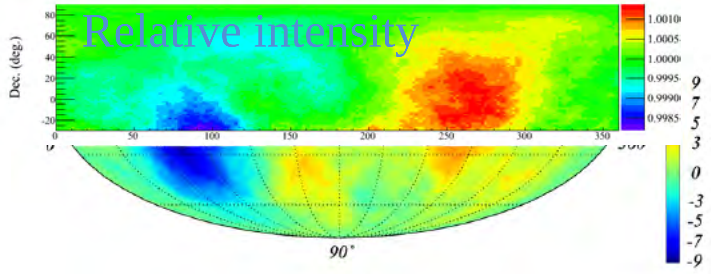
M.Sutherland, 274 **first PeV neutron flux limits**

Tibet Air Shower Array

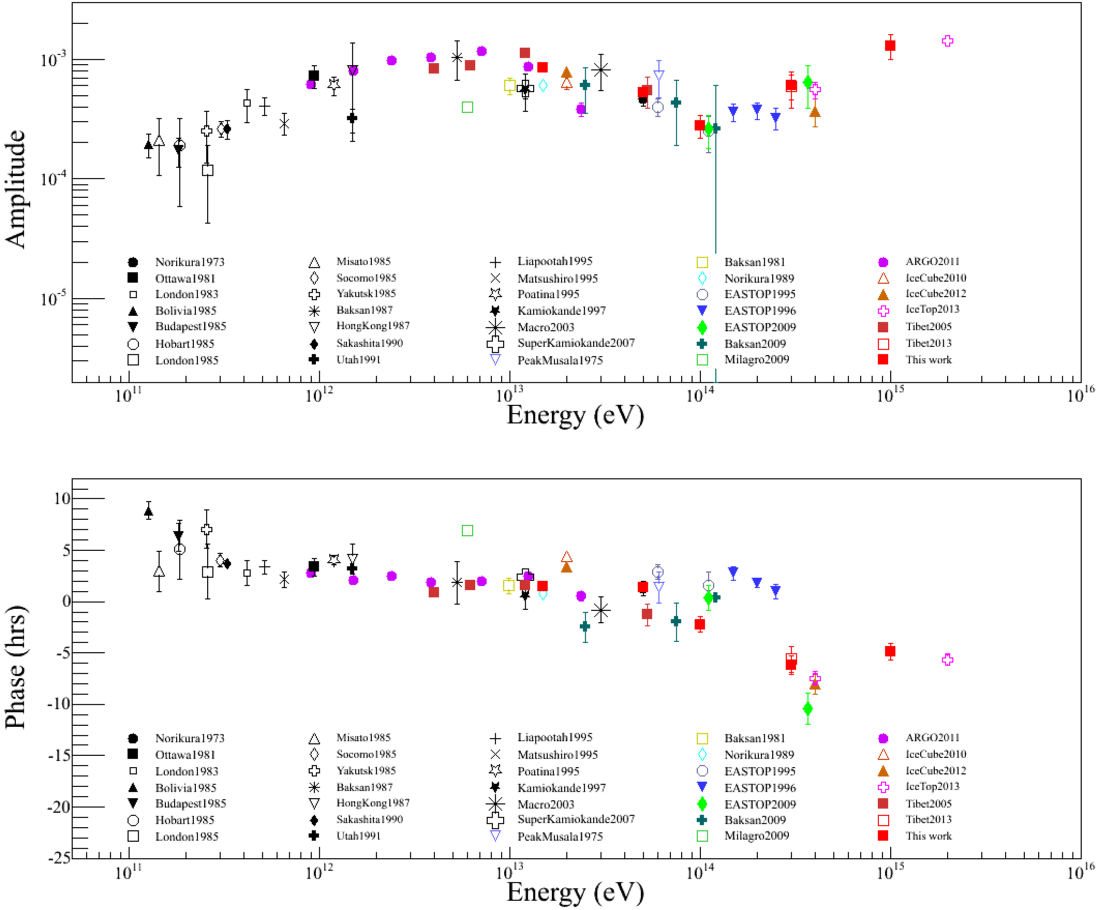
Z.Feng, 372

New structure on the energy dependence of first harmonic above 100 TeV

Northern sky
Tibet AS array 300TeV



Southern sky (b)
IceCube 400TeV



See also K.Munakata, 372

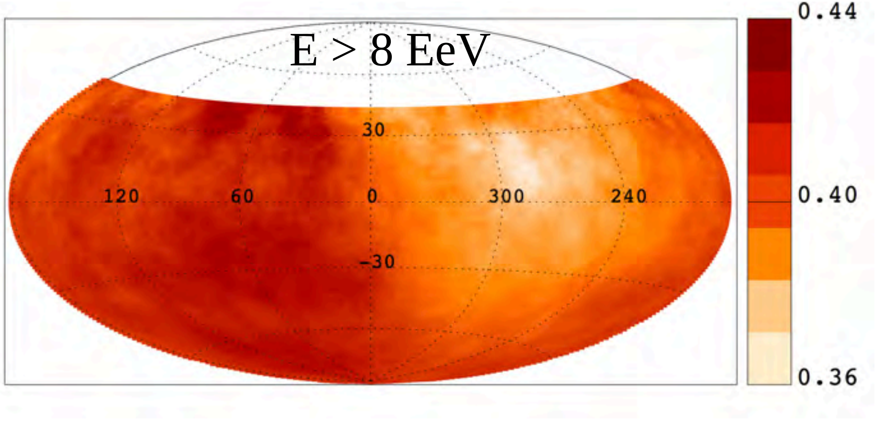
Large scale anisotropy at the highest energies

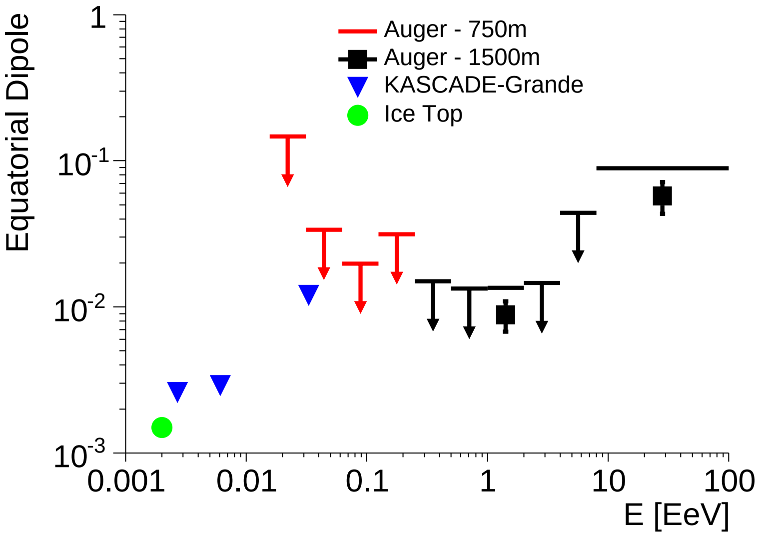
Auger

I. Al Samarai, 372

Rayl. analysis in RA and azimuth

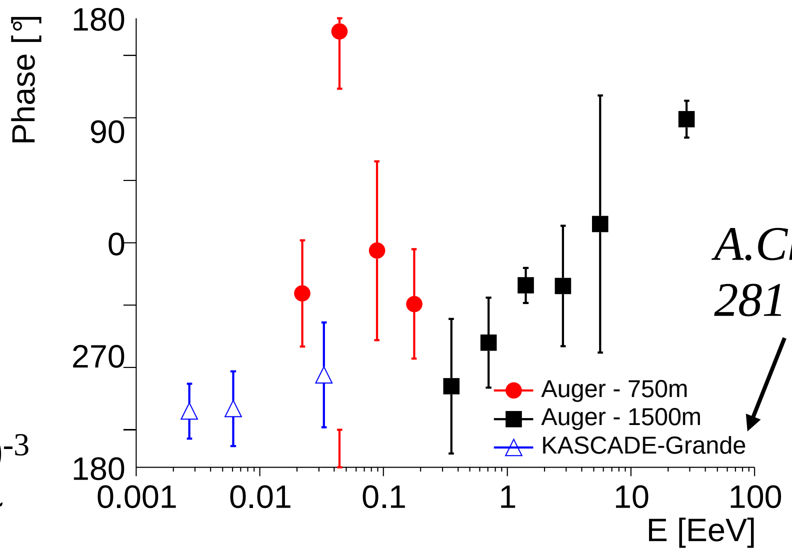
E(EeV)	d	δ_d	α_d
4-8	0.027 ±0.012	-81°± 17°	15°± 115°
>8	0.073 ± 0.015	-39°±13°	95°± 13°





$<10^{-3}$

4σ



A.Chiavassa, 281

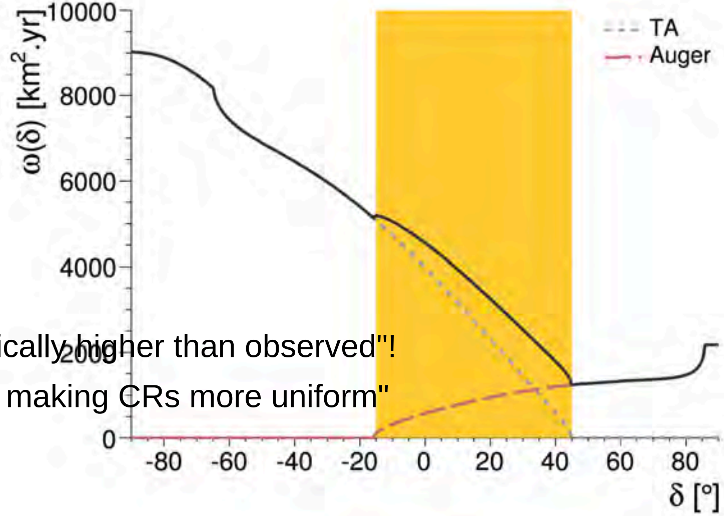
Auger and TA full sky coverage

O.Deligny, 395

Zenith up to
80^0 Auger
55^0 TA

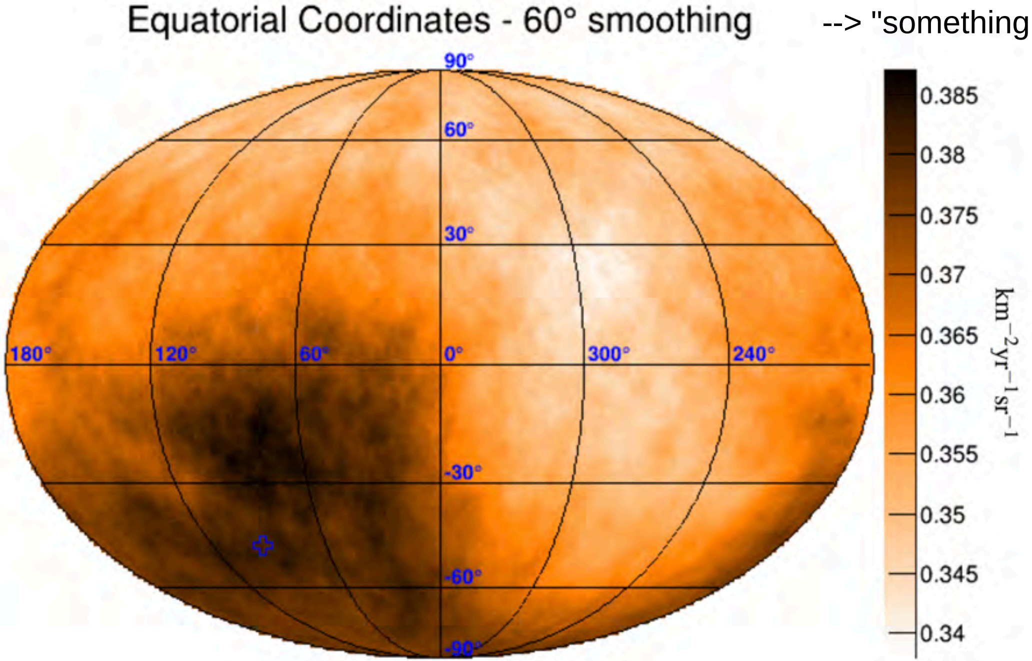
$$\omega(\mathbf{n};b) = \omega_{\mathrm{TA}}(\mathbf{n}) + b\,\omega_{\mathrm{Auger}}(\mathbf{n})$$

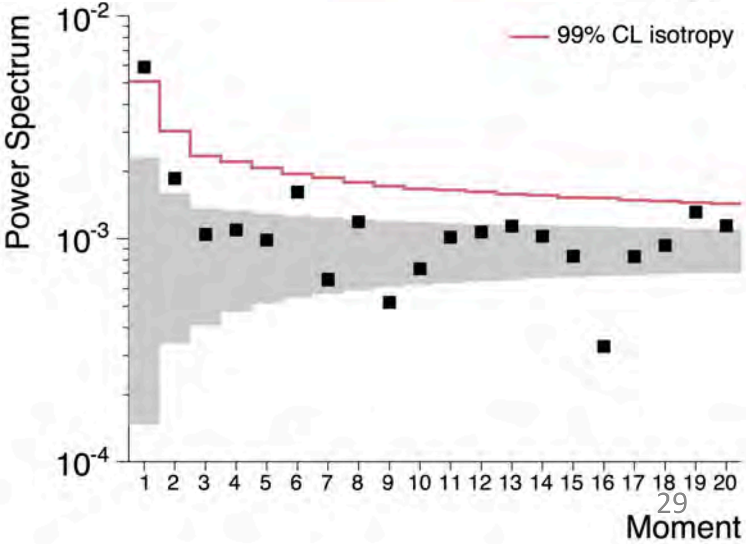
$> 10^{19}$ eV



Tinyakov & Urban: "predicted (low) multipoles assuming protons are systematically higher than observed"!

--> "something is making CRs more uniform"





Other anisotropy tests

Auger

J.Aublin, 310

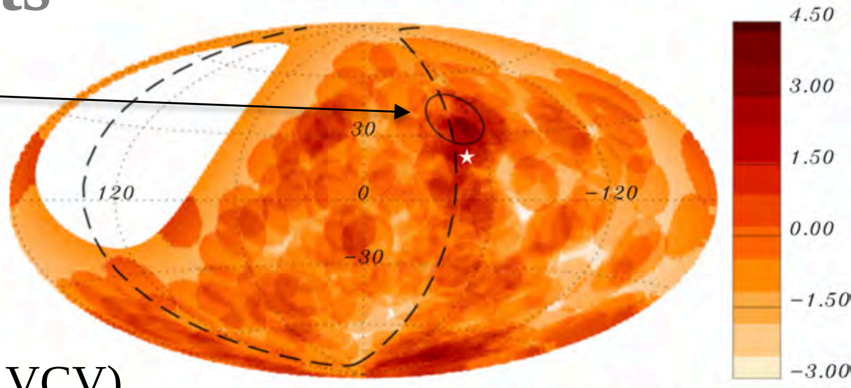
66500 km^2 sr yr

602 ev. E>40 EeV

Most significant excess
E_{th}=54 EeV $\psi=12^0$
Post trial prob. 69%

compatible with isotropy

(Cen A. indicated as a white star)



Li-Ma significance map (galactic coordinates)

- No significant correlation with catalogs (including VCV).
- Post trial prob. of 1.4% for E_{th}=58 EeV $\psi=15^0$ around CenA

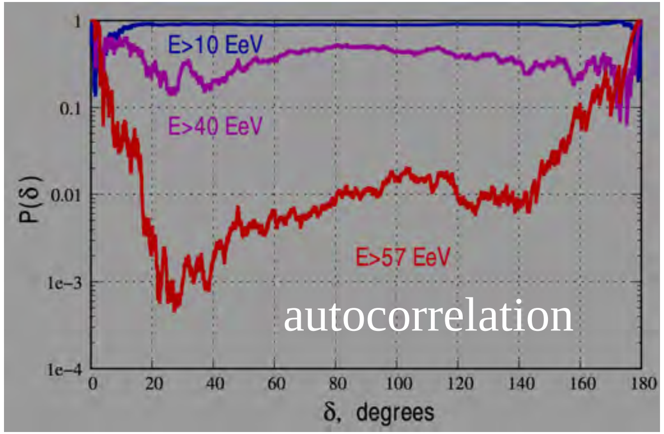
TA

P.Tinyakov, 326

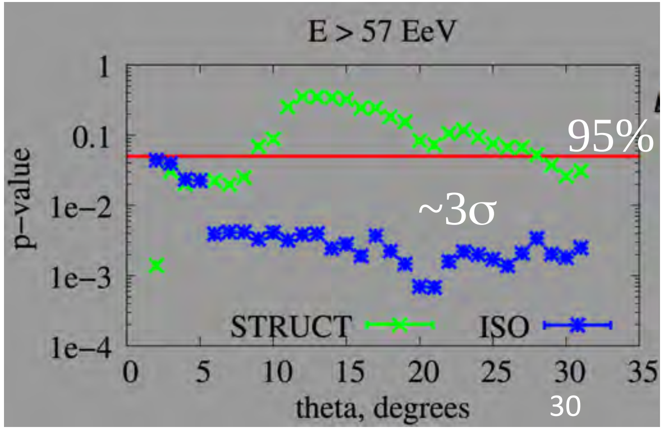
8600 km^2 sr yr

Events
2996 E>10 EeV
201 E>40 EeV
83 E>57 EeV

tension E>57 EeV



2MASS Galaxy Redshift Catalog



Hot Spot with 2 additional years

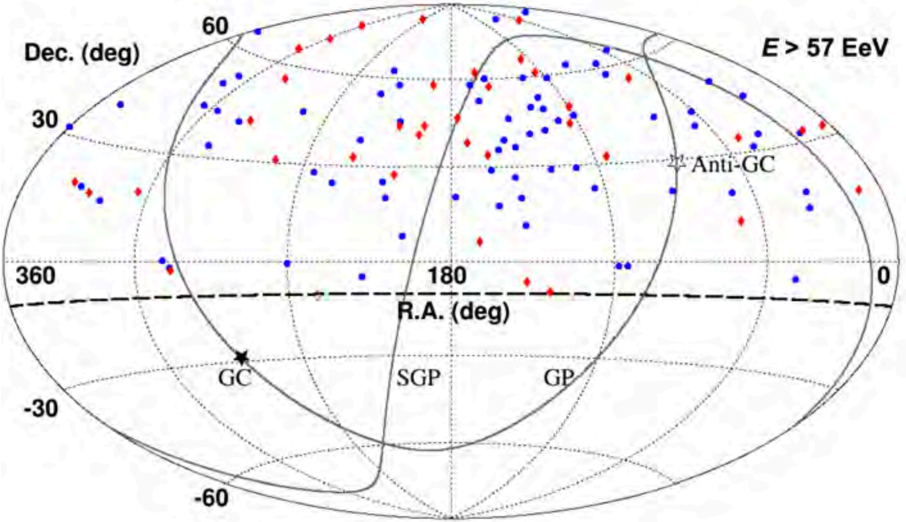
TA

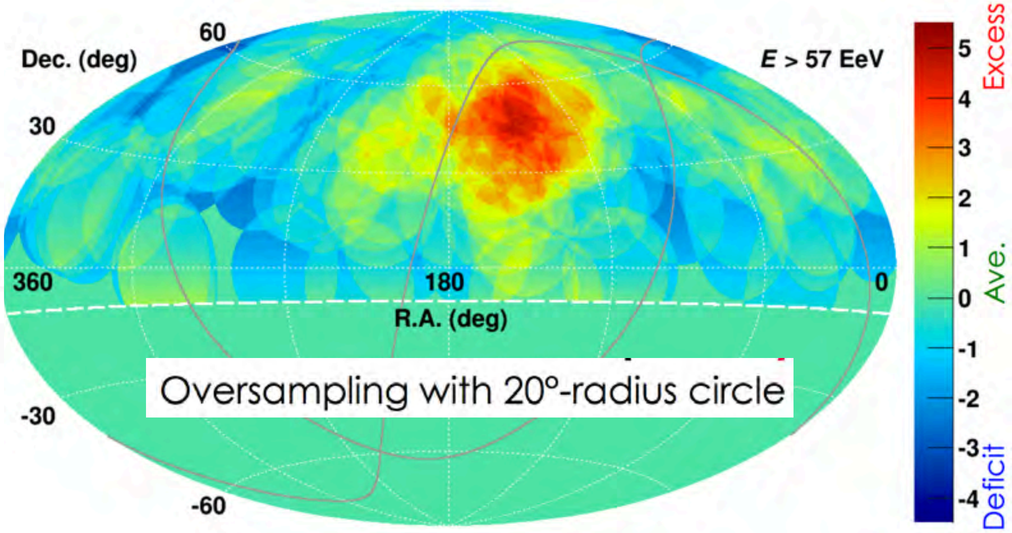
P.Tinyakov, 326

20^0 around RA=148.4^0 Dec=44.5^0

E > 57 EeV 24 events N_{bkg} = 6.88

7 yr: chance probability 3.7×10^{-4} 3.4σ





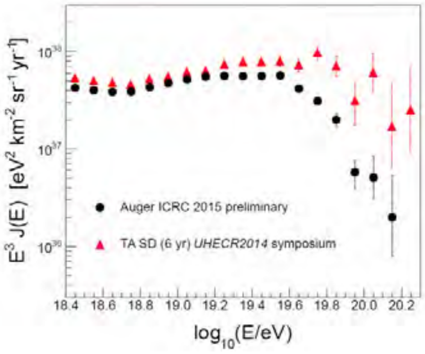
Very difficult to confirm "extended" regions of excess CRs!

Period	Total (>57EeV)	Hotspot Signals	B.G.	Chance Prob.	Center position (RA., Dec.)
6-th year	15	3	0.94	7%	146.7°, 43.2°
7-th year	22	1	1.37	74%	146.7°, 43.2°
6 & 7-th year	37	4	2.31	20%	146.7°, 43.2°

- Hot Spot near to Ursa Major Cluster (20 Mpc)
- shifted from SGP by 17^0

See also *Haoning He, 325* for the interpret.

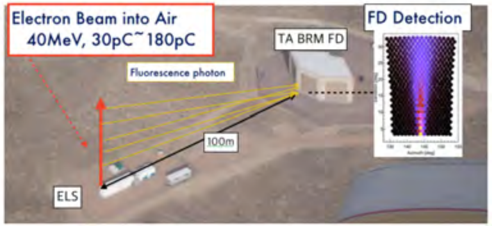
north/south spectrum



FD energy scale

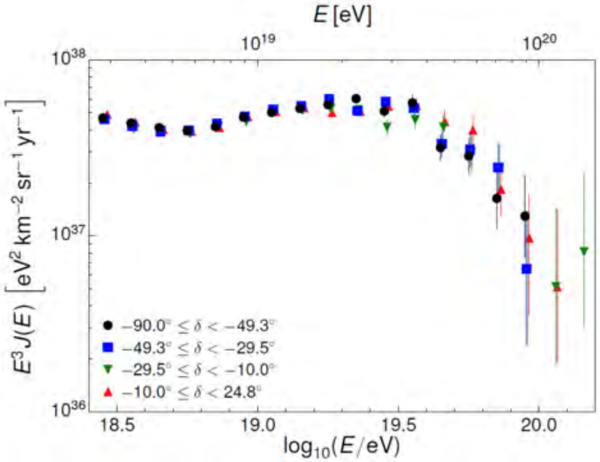
systematics uncertainties →

- **TA cal. with elec. beam** *B.Shin, 325*



- TA Octocopter *M.Hayashi, 692*
- Auger FD cal *G.Salina, 325*
- Auger atmosphere *C.Medina-H., 624*
- Auger tanks *P.Assis, 620*

P.Ghia, highlight



Auger

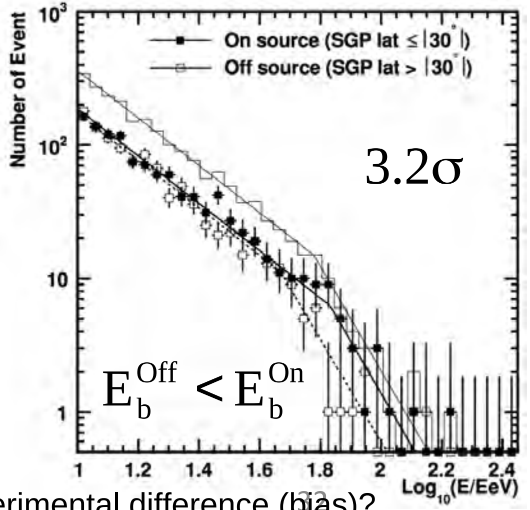
I.Valino, 271

no declination dependence

TA

T.Nonaka, 384

"On source" ≠ "Off source"



3.2σ

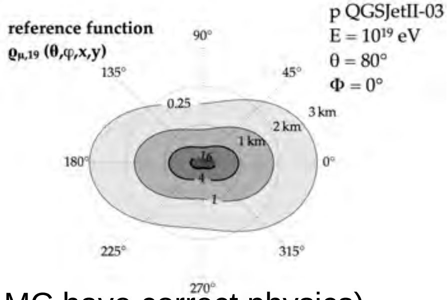
$E_b^{Off} < E_b^{On}$

Q. IF Auger data show NO declination dependence, then is the North/South difference an experimental difference (bias)?

1) ENERGY SPECTRUM
2) MASS COMPOSITION
3) ANISOTROPY
4) **HADRONIC INTERACTIONS**
5) RADIO
6) FUTURE

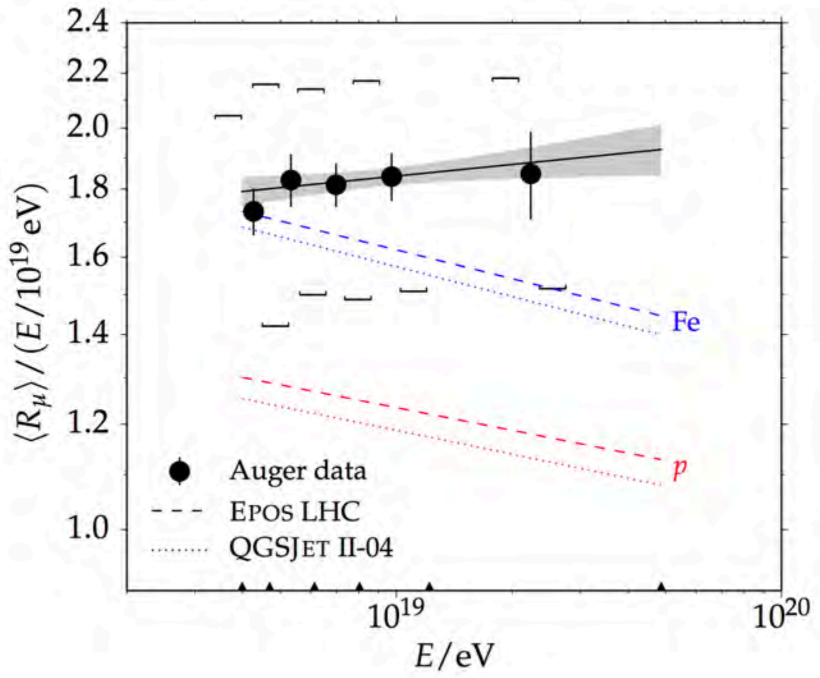
μ - Auger

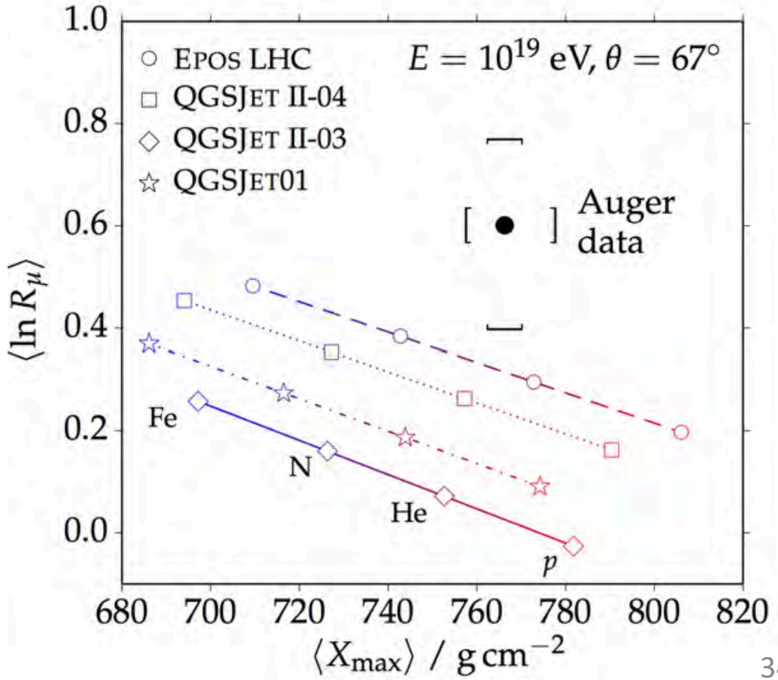
L. Collica, 336



Excess of muons in highly inclined events

NB rising muon fraction with energy is INcompatible with fixed composition (assuming shower MC have correct physics).





Hadronic interactions

- X_{max}
- Auger $\sigma^2_{\ln A}$ QGSJet II.04
- Auger/TA energy scale
- too few muons
- X^{μ}_{max}

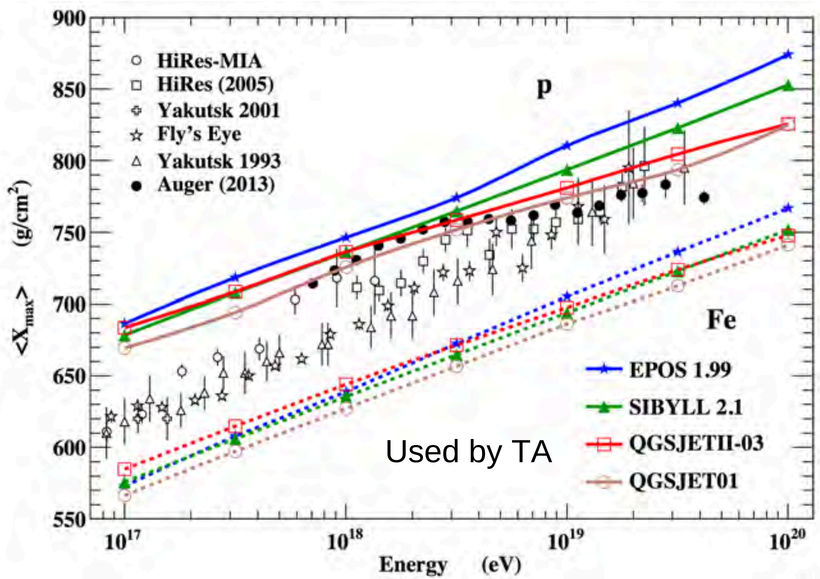
R. Engel, review talk

extrapolation beyond

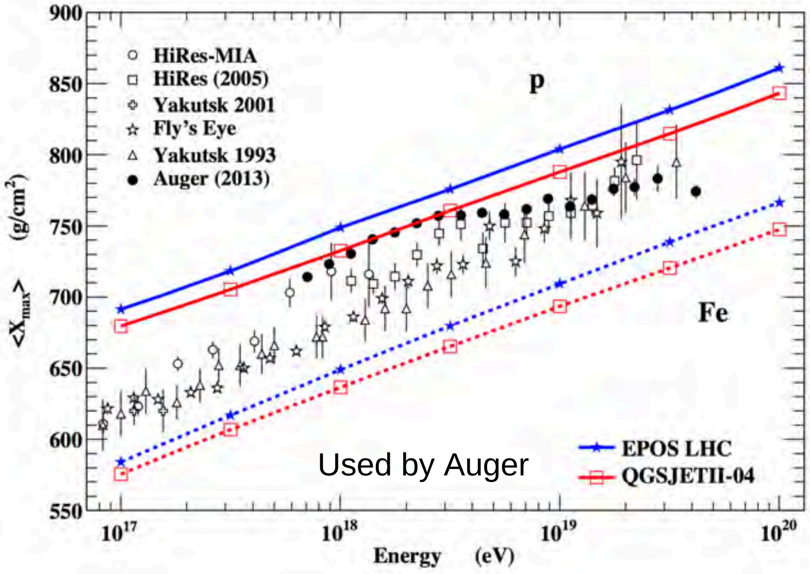
$\sqrt{s_{LHC}} \sim 10^{17}$ eV

New models favour interpretation as heavier composition than before

pre-LHC



post-LHC



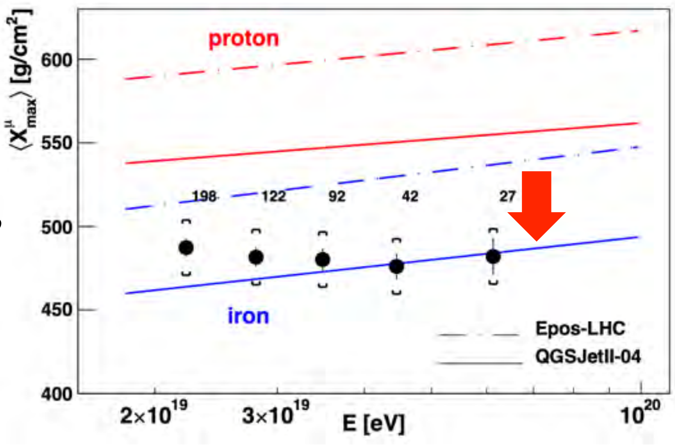
Constraints on hadronic int. models ?

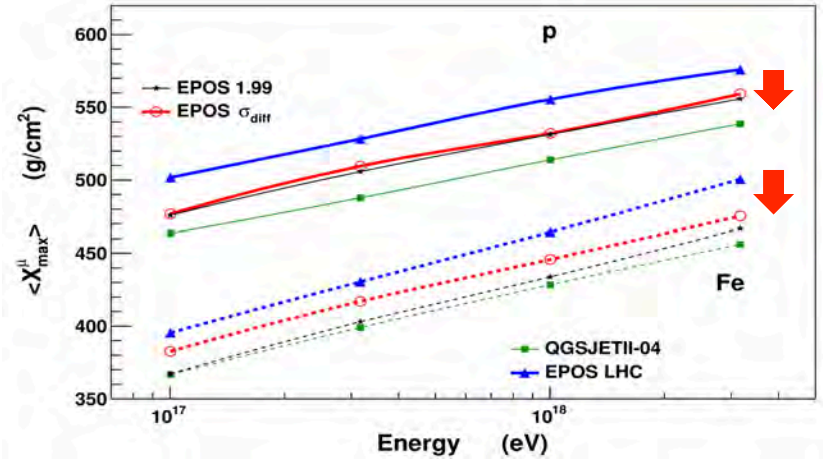
EPOS-LHC inconsistent with Auger Muon Production Depth

reduce elasticity in π-air by -10% with minor modification to X_{max}

T.Pierog, 337

L.Collica, 336

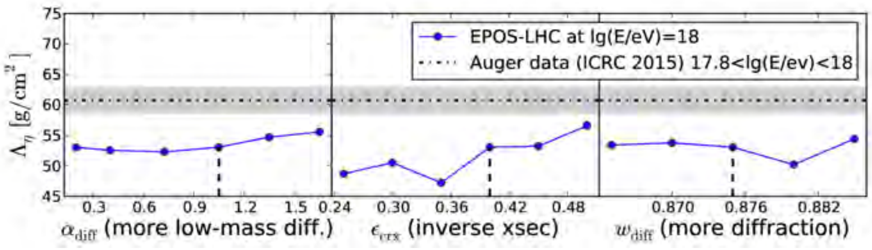




-30 g/cm²

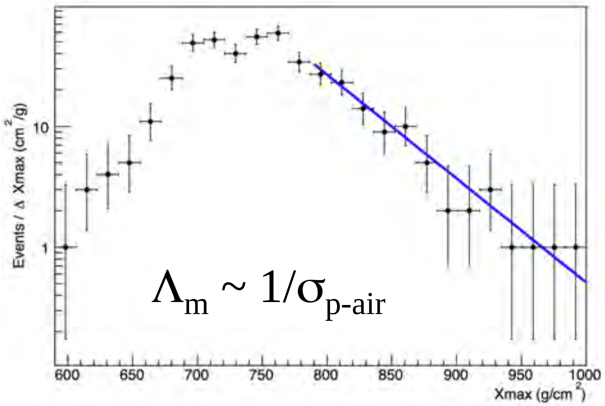
C.Baus et al., 418

technique to tune hadronic interaction parameters



$\sigma_{p\text{-}air}$ (inelastic) from FD

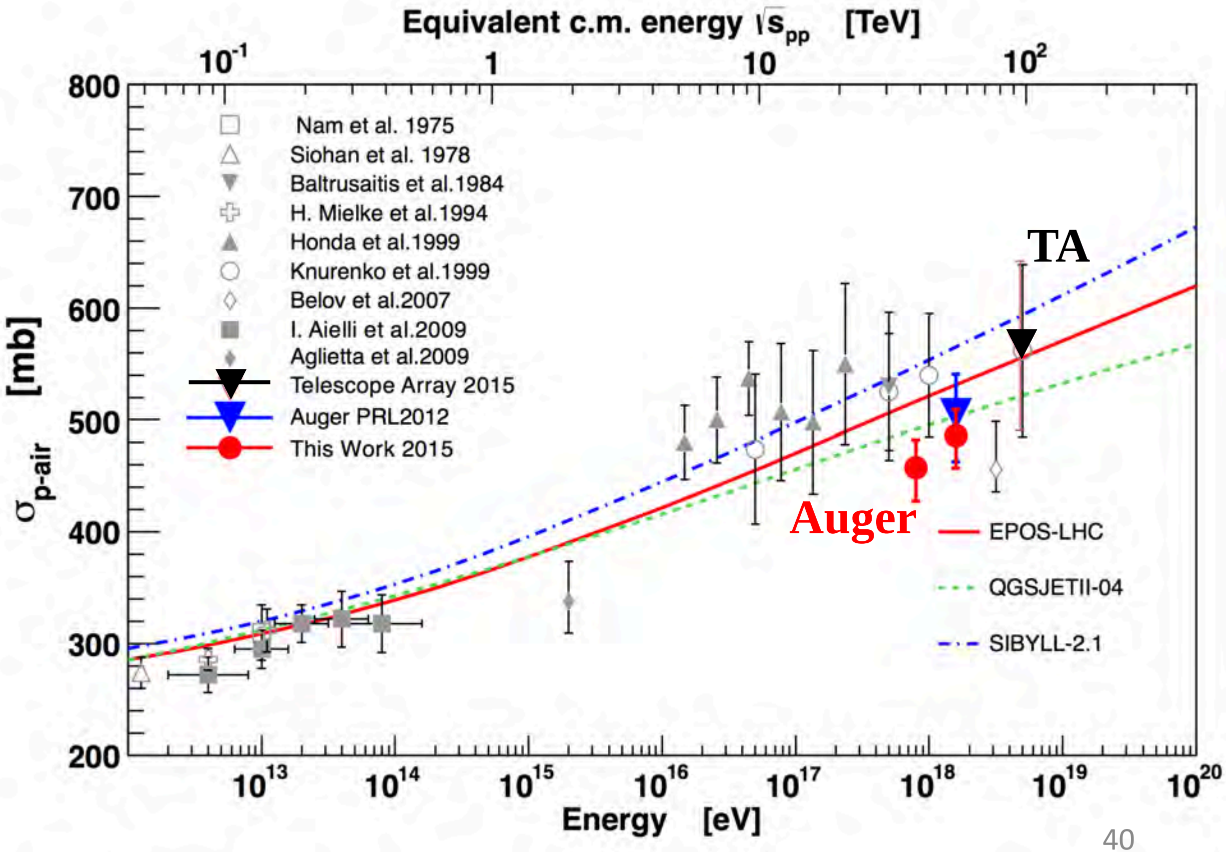
AUGER: R. Ulrich, 401
TA: R. Abbasi, 402



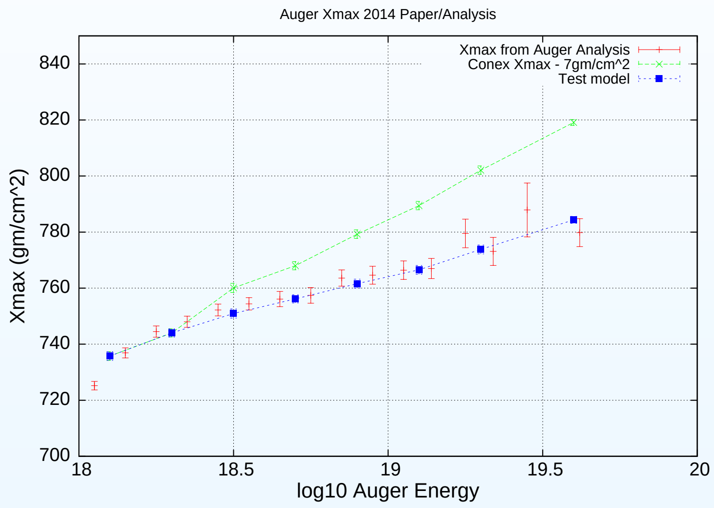
GH profiles and hadronic interaction

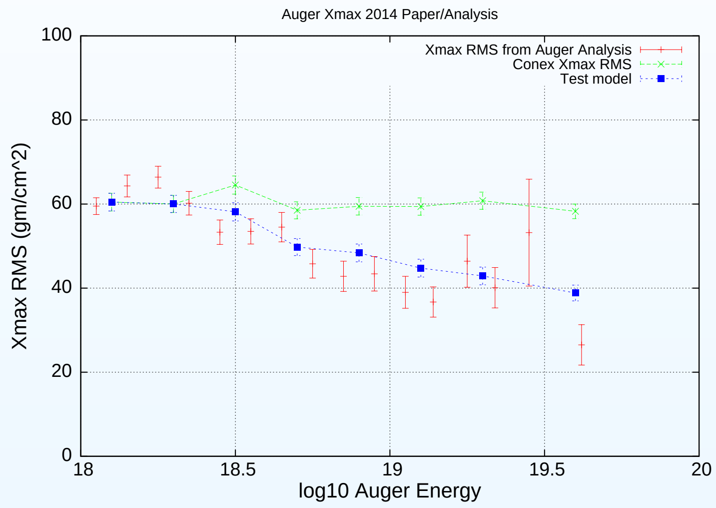
D.R.Bergman, 339

F.Diogo, 413



Simple modifications to *first* p-air interaction - I

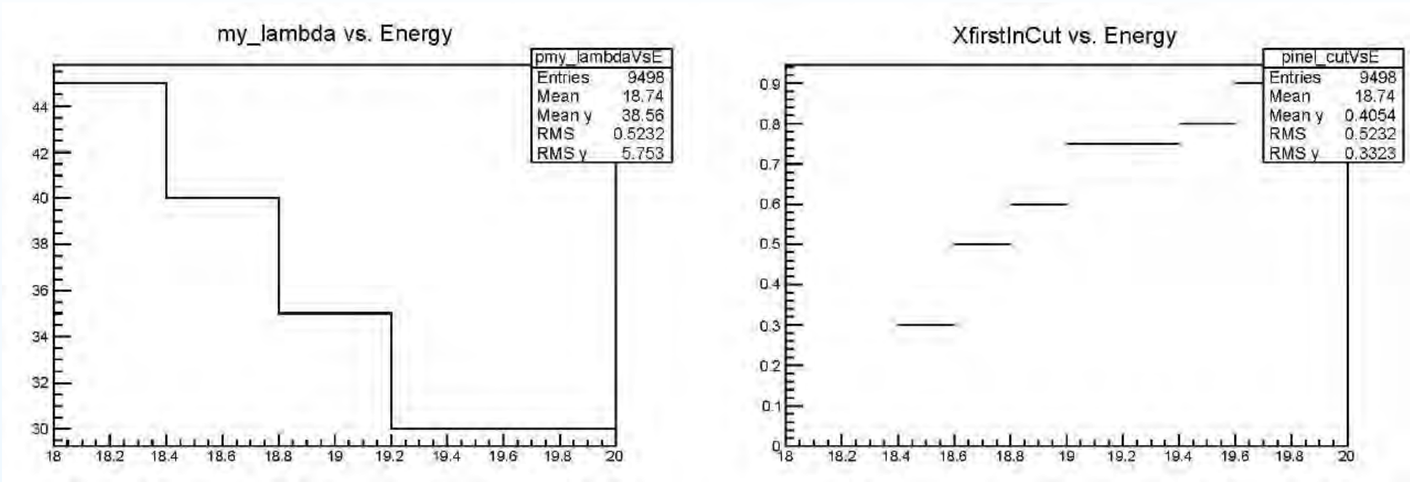




- Auger PRD results compared to a UNM toy model assuming only proton primaries: (Top Left) for X_{max} and (Top Right) for $X_{max} RMS$.
- The green points are QGSJetII shower predictions.
- The blue points include two modifications to the *first* p-air interaction:
  - increase the p-air cross section for $log_{10}E > 18.4$
  - retain the *more-INelastic* scatters for $log_{10}E > 18.4$

chosen to follow the X_{max} data [that are now in agreement with TA/HiRes]. Curiously the agreement of the toy model with $X_{max} RMS$ data is quite good.

Simple modifications to *first* p-air interaction - II



- Top Left: UNM toy model increases the effective p-air cross section by modifying the exponential distribution of atmospheric depth, X_{first}, of the *first* interaction:

$$dN/dX_{first} \propto exp(-X_{first}/my\_lambda)$$

- Top Right: UNM toy model accepts only simulated showers with *inelasticity* above some energy dependent threshold: $XfirstInCut$.
- Both my_lambda and $XfirstInCut$ depend on shower energy as shown.
- While the toy model describes X_{max} and $X_{max}RMS$, what other details of UHECR air showers are in agreement (or not) with model predictions?

Curiously "this" model is in excellent agreement with the TA Xmax data (in their p-air cross section paper)!

1) ENERGY SPECTRUM

2) MASS COMPOSITION

3) ANISOTROPY

4) HADRONIC INTERACTIONS

5) **RADIO**

a) R&D at several sites/experiments [LOPES/Kascade, LOFAR, AERA/Auger ...] on radio detection and optimization of extensive air showers

6) FUTURE

b) Ultimate goal is to instrument a much larger area with better duty factor than eg air fluorescence telescope based experiments

1) ENERGY SPECTRUM

2) MASS COMPOSITION

3) ANISOTROPY

4) HADRONIC INTERACTIONS

5) RADIO

6) FUTURE

All major experiments are planning upgrades

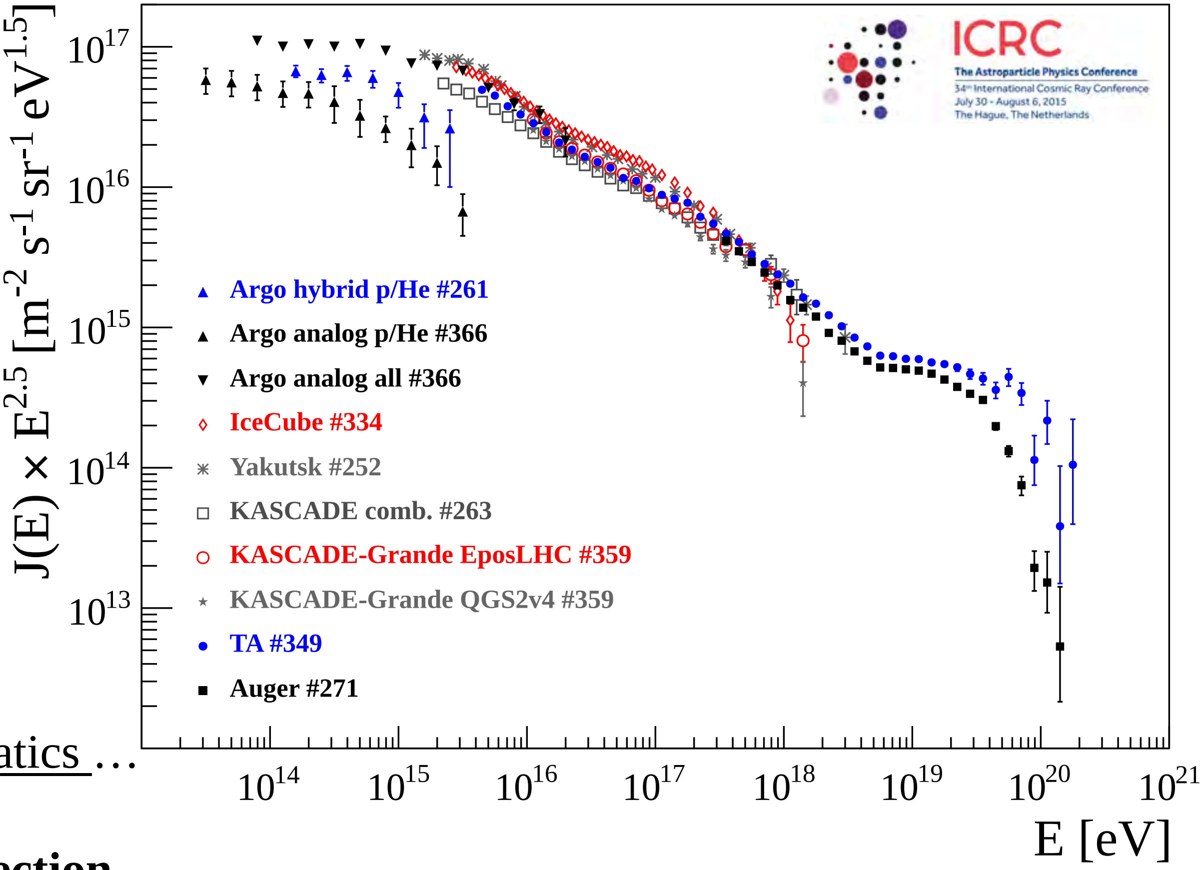
a) IceCube-Gen2 "to deliver statistically significant samples of VHE astrophysical neutrinos"

b) AugerPrime "addition of ~4m^2 scintillators above each WCD to provide primary CR mass sensitivity above the GZK cutoff"
(ie select p-showers over Fe-showers for better point source searches)

c) TA x 4 "increase the area of the TA experiment to enhance the sensitivity to the TA-hot spot"

d) LHAASO for gamma-ray astronomy and precise CR physics (China) thanks to all for providing the data

- **light knee below PeV to be confirmed**
- **low E ankle and second knee evident**
- **interpretation of the ankle difficult**
- **end of cosmic rays: propagation or cut-off at the sources ???**
- **TA Hot Spot exciting**



more statistics - composition
- hadr. int. mod., detector systematics …

new projects go in the right direction

THANKS