Summary of Experimental Results

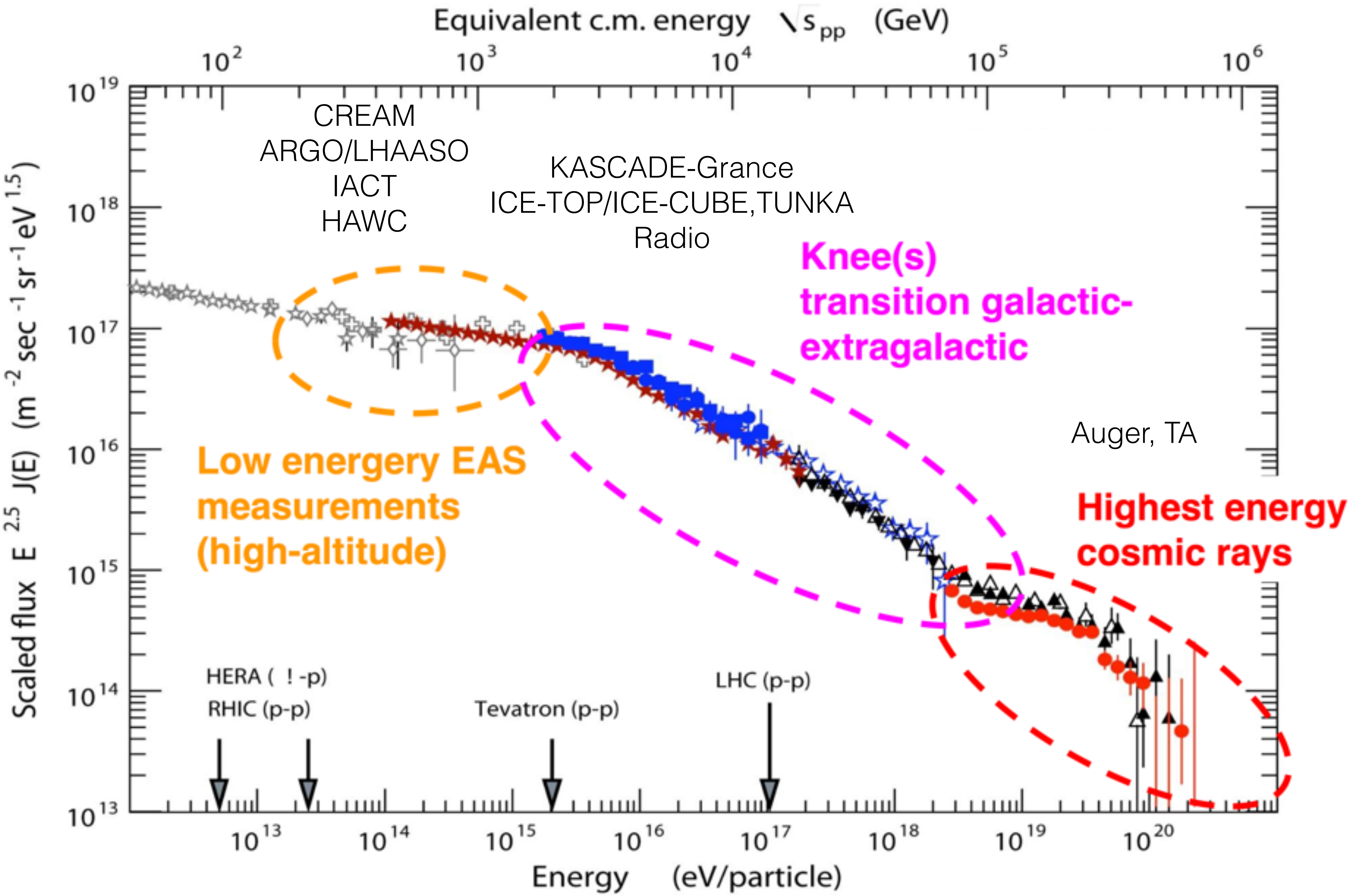
M. Bertaina (University of Torino and INFN)

Standard disclaimer

- Sorry for all those nice results that will not appear on the slides. As usual some selection was needed due to time constraints…..

- I will focus mainly on composition and spectrum.

High-energy cosmic ray spectrum



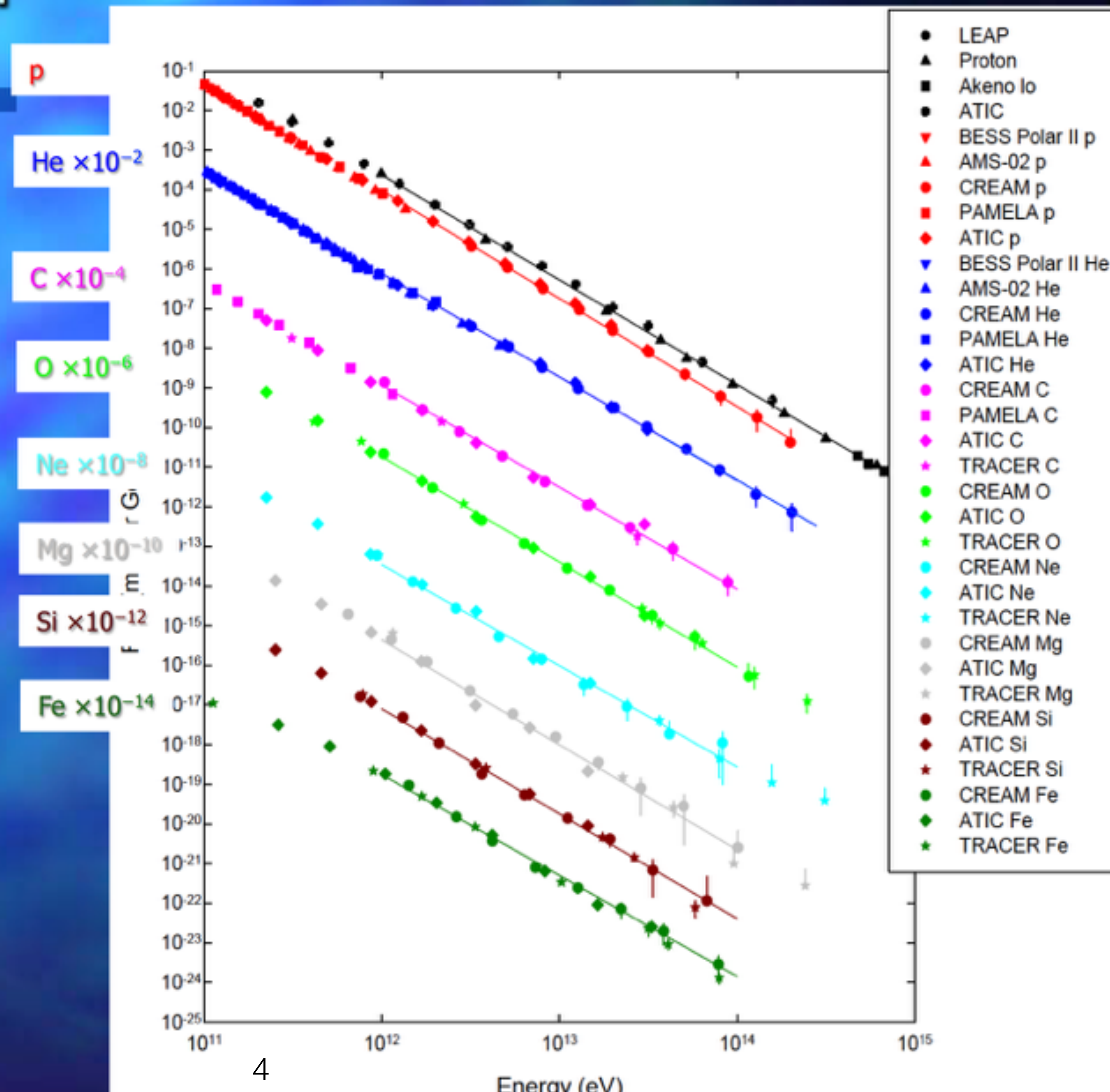
Elemental spectra

Ahn et al., ApJ 707, 593 (2009),
Ahn et al., ApJ 715, 1400 (2010),
Yoon et al., ApJ 728, 122 (2011)

Each component can be fitted to a single power law (CREAM only to avoid different systematics):

- H: $dN/dE \sim E^{-2.66\pm0.02}$
- He: $dN/dE \sim E^{-2.58\pm0.02}$
- C: $dN/dE \sim E^{-2.61\pm0.07}$
- O: $dN/dE \sim E^{-2.67\pm0.07}$
- Ne: $dN/dE \sim E^{-2.72\pm0.10}$
- Mg: $dN/dE \sim E^{-2.66\pm0.08}$
- Si: $dN/dE \sim E^{-2.67\pm0.08}$
- Fe: $dN/dE \sim E^{-2.63\pm0.11}$

The components do add up to the all-particle spectrum!

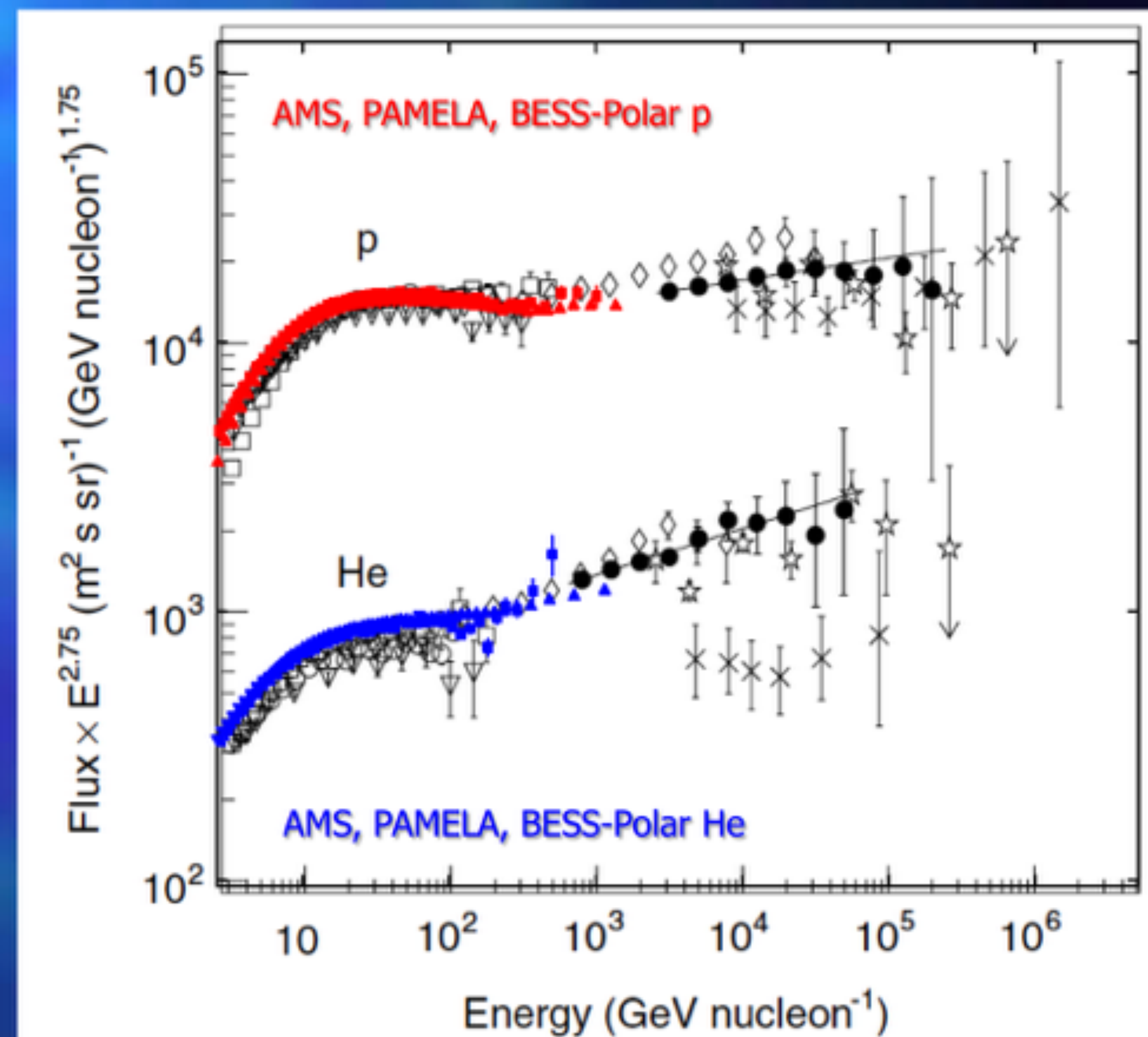


S. Coutu

p vs He

Aguilar et al., PRL 114, 171103 (2015)
Adriani et al., Science 332, 69 (2011)
Abe et al., arXiv: 1506.01267 (2015)

Yoon et al., ApJ 728, 122 (2011)



CREAM measures a statistically different energy spectral index for the first time beyond a few TeV/nucleus:

- H: $dN/dE \sim E^{-2.66\pm0.02}$
- He: $dN/dE \sim E^{-2.58\pm0.02}$

Origin could be non-linear DSA effects in the sources:

- H: reverse shocks in Type II SNRs;
- He: reverse shocks in Type I SNRs;
- both: forward shocks in all SNRs.

(Ptuskin et al., ApJ 763, 47 (2013))

Could be due to non-linear effects in CR transport through the Galaxy;
(Aloisio et al., arXiv:1507.00594)

Could be due to young nearby sources;
(Thoudam & Hörandel, MNRAS 435, 2532 (2013))

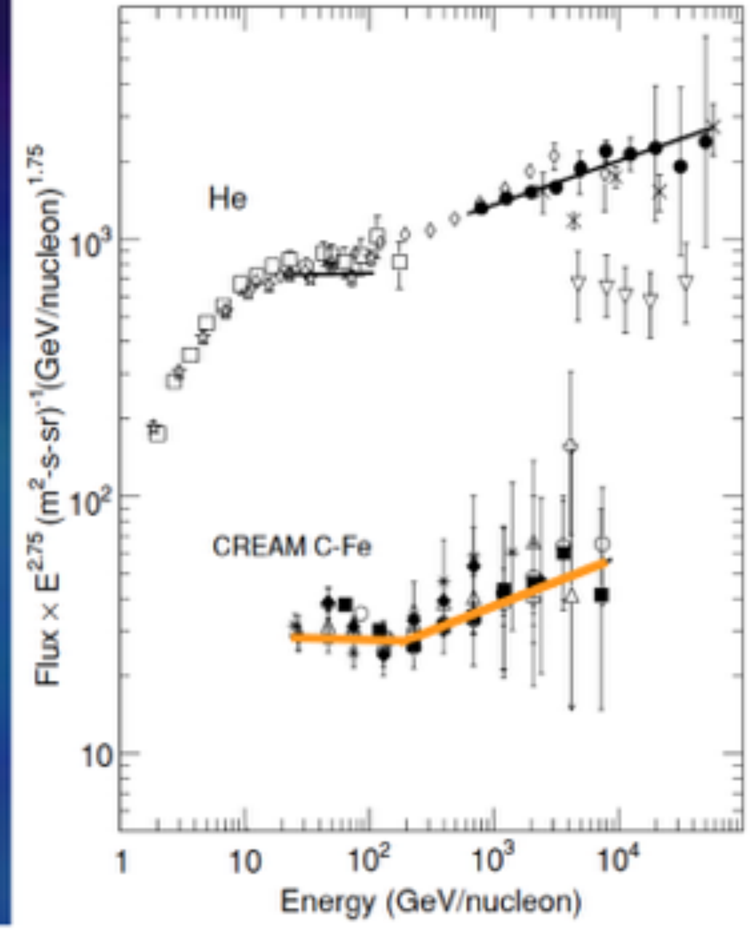
Ahn et al., ApJ 714, L89 (2010)

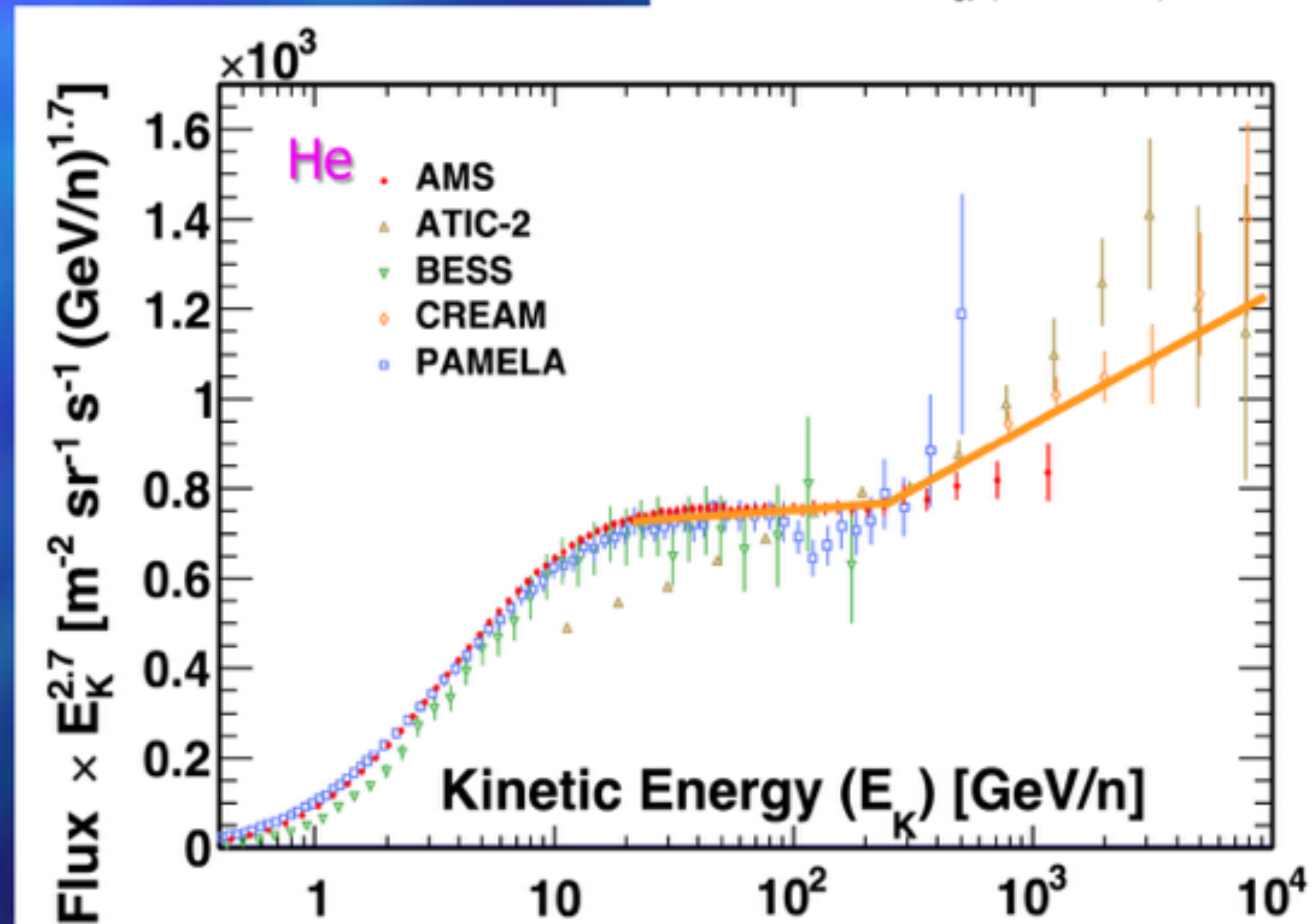
Hardening spectra

CREAM heavy element spectra (2010):
- He to Fe all seem to have similar spectra, same index as He (−2.58±0.02);
- Probably from the same source and acceleration mechanism.

- But at the 4σ level better fit with a broken power law (index change at 200 GeV/n);

- AMS/PAMELA see this in He;





https://indico.cern.ch/event/381134/timetable/#2015041

S. Coutu

Ahn et al., ApJ 714, L89 (2010)

Hardening spectra

CREAM heavy element spectra (2010):

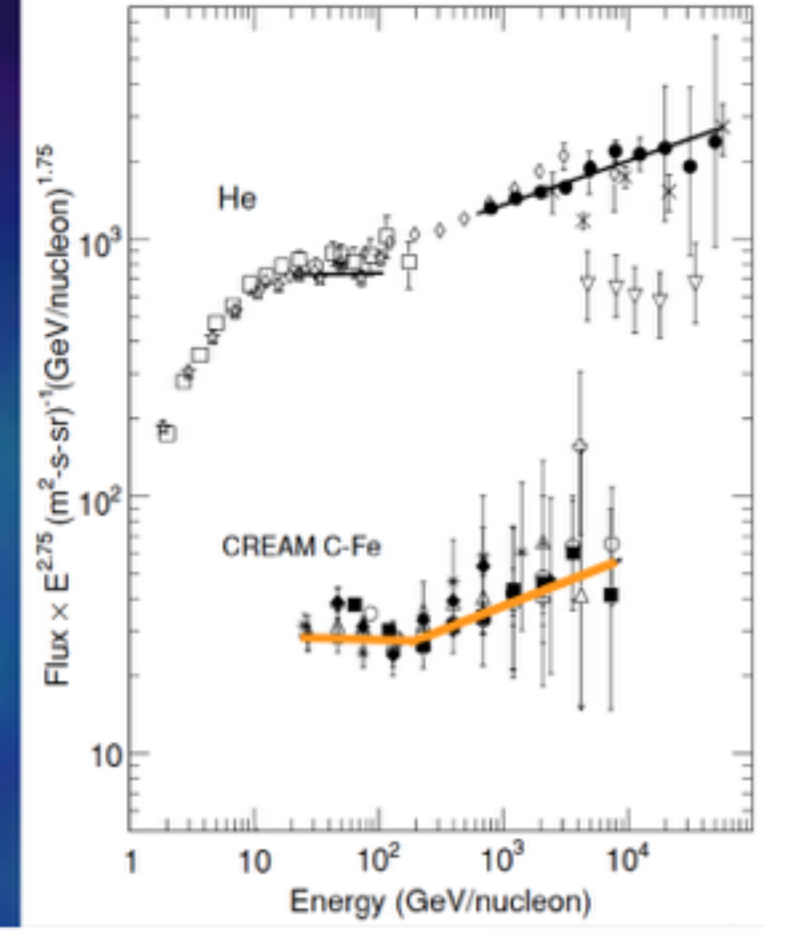
• He to Fe all seem to have similar spectra, same index as He (−2.58±0.02);

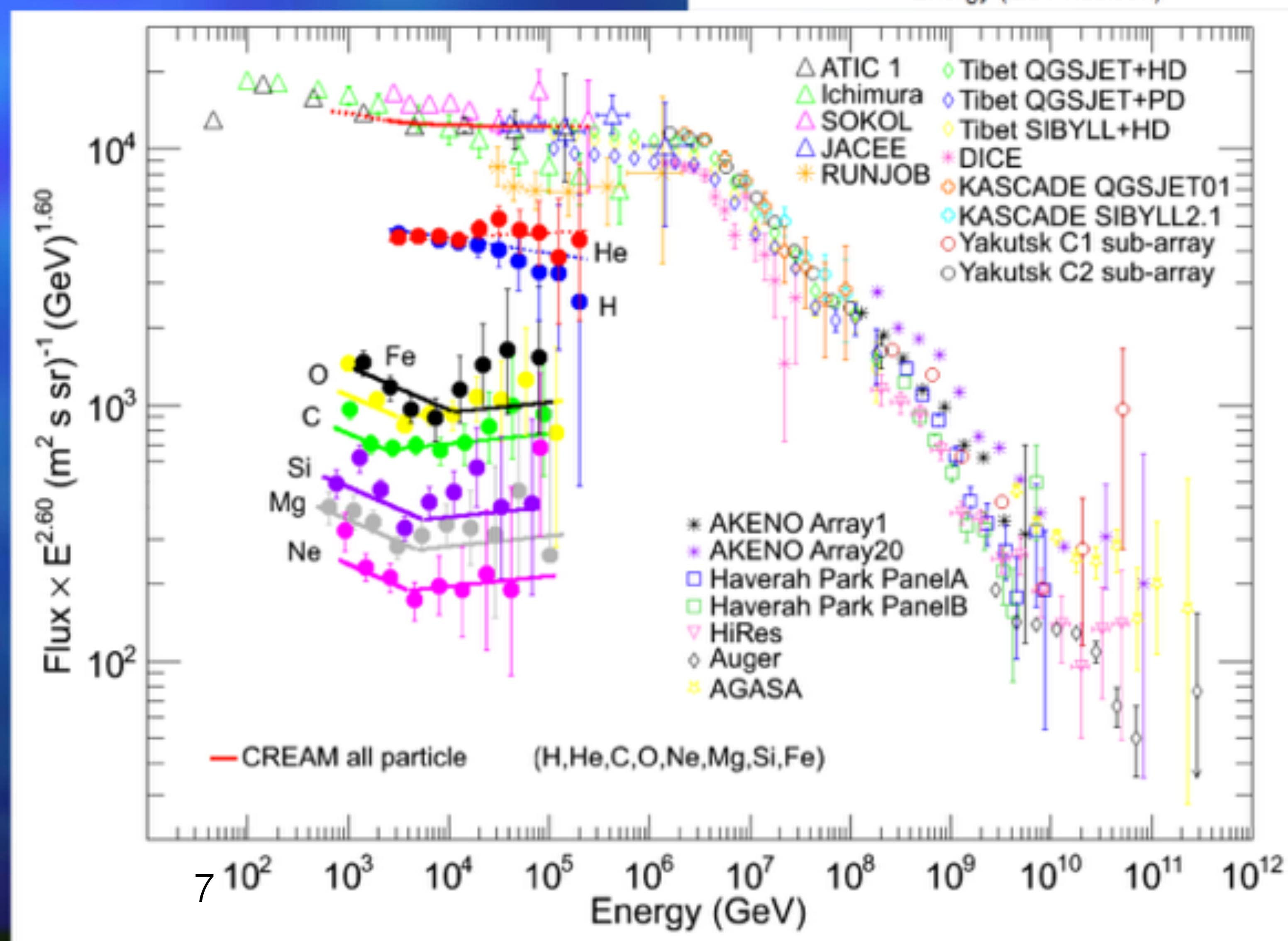
• Probably from the same source and acceleration mechanism.

• But at the 4σ level better fit with a broken power law (index change at 200 GeV/n 2.77±0.03 → 2.56±0.04);

• AMS/PAMELA see this in He;

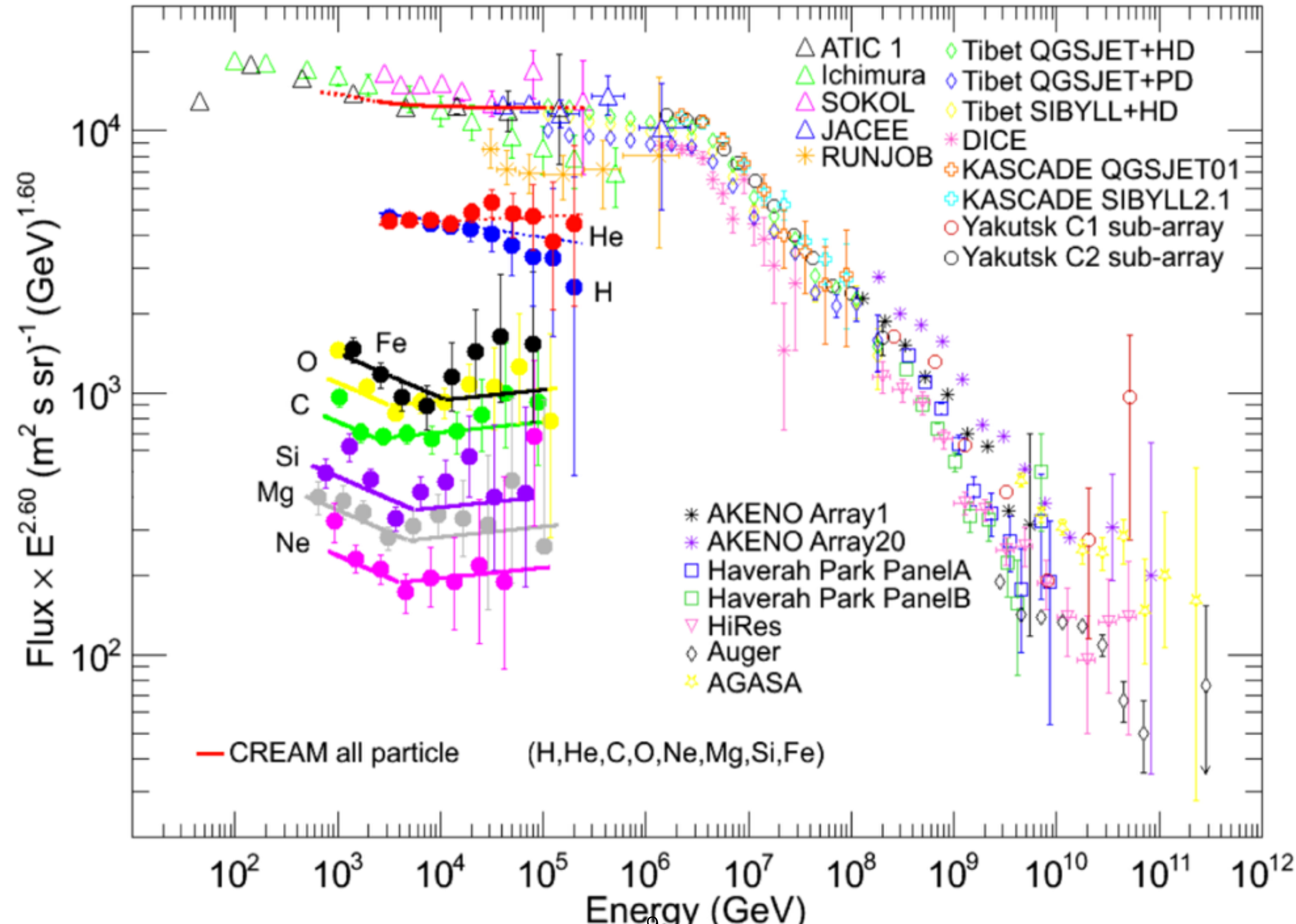
• Detailed source modeling needs to address this, but individual spectra do add up to that measured by air shower arrays.





Next gen instruments

Project	$e^{+}+e^{-}$	CR	UHGCR	gamma	Type/ launch
NUCLEON	100 GeV – 3 TeV	p-Zn 100 GeV – 1 PeV			SAT 26 Dec 2014
CALET	1 GeV – 10 TeV	p-Fe 10 GeV – 1 PeV	Z=26-40 ~ GeV/n	10 GeV – 10 TeV	ISS 16 Aug 2015
ISS-CREAM	100 GeV – 10 TeV	p-Fe 1 TeV – >1 PeV			ISS May/Jun 2016
DAMPE	5 GeV – 10 TeV	p-Ca 100 GeV – 100 TeV		5 GeV – 10 TeV	SAT Dec 2015
HELIX		light isotopes <10 GeV/n			LDB ~2020
SuperTIGER redux			Z=10-40 (→ 60) ~ GeV/n		LDB ~2019?
GAMMA-400	1 GeV – 20 TeV	p-Fe 1 TeV – 3 PeV		20 MeV – 1 TeV	SAT 2023-2025



ATIC 1
Ichimura
SOKOL
JACEE
RUNJOB
Tibet QGSJET+HD
Tibet QGSJET+PD
Tibet SIBYLL+HD
DICE
KASCADE QGSJET01
KASCADE SIBYLL2.1
Yakutsk C1 sub-array
Yakutsk C2 sub-array
He
H
Fe
O
C
Si
Mg
Ne
AKENO Array1
AKENO Array20
Haverah Park PanelA
Haverah Park PanelB
HiRes
Auger
AGASA
CREAM all particle
(H,He,C,O,Ne,Mg,Si,Fe)
$Flux \times E^{2.60}$ $(m^2\ s\ sr)^{-1}$ $(GeV)^{1.60}$
Energy (GeV)

Array	g cm^{-2}	Detector	ΔE [eV]	Area [km^2]
ARGO	600	RPC hybrid (LLASHO)	0.3-5 10^{15}	0.0056
Tibet-ASγ	600	Scintillator/burst detector	1-200 10^{15}	0.0037 [0.5 phase III]
EasTop	820	scintillator/muon	1-100 10^{15}	0.01
GAMMA	700	scintillator/muon	3-200 10^{15}	0.03
KASCADE	1020	scintillator/muon	2-90 10^{15}	0.04
CASA-MIA	860	scintillator/muon	0.1-100 10^{15}	0.25
Kascade-Grande	1020	scintillator/muon	10^{16}-10^{18}	0.49
IceTop	680	ice Cher.tanks	10^{16}-10^{18}	1
Tunka	900	unshielded PMTs	10^{15}-10^{18}	3
Yakutsk	1020	scintillator/ unshielded PMTs	10^{15}-10^{19}	~40
Telescope Array +TALE	880	scintillator+ fluorescence tel.	4 10^{15}-10^{20}	700
Auger +Infill	840	water Cher.tanks fluorescence tel.	10^{17}-10^{20}	3000

High altitude experiments:

- N_{part} ~ indip of composition
- close to maximum of EAS: low fluctuations

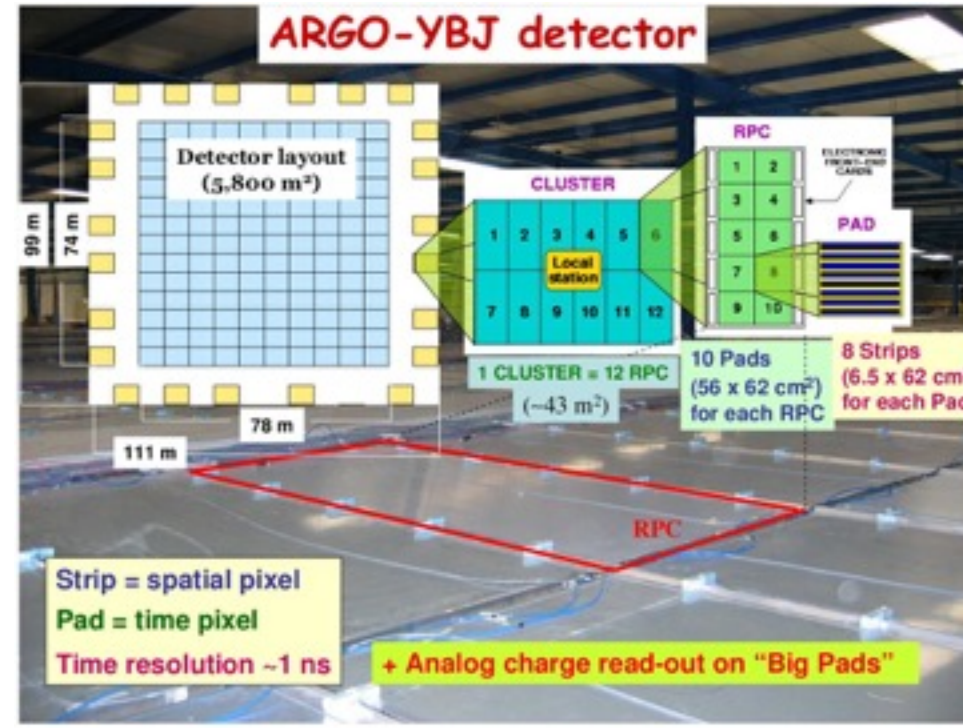
energy resolution

Sea level experiments:

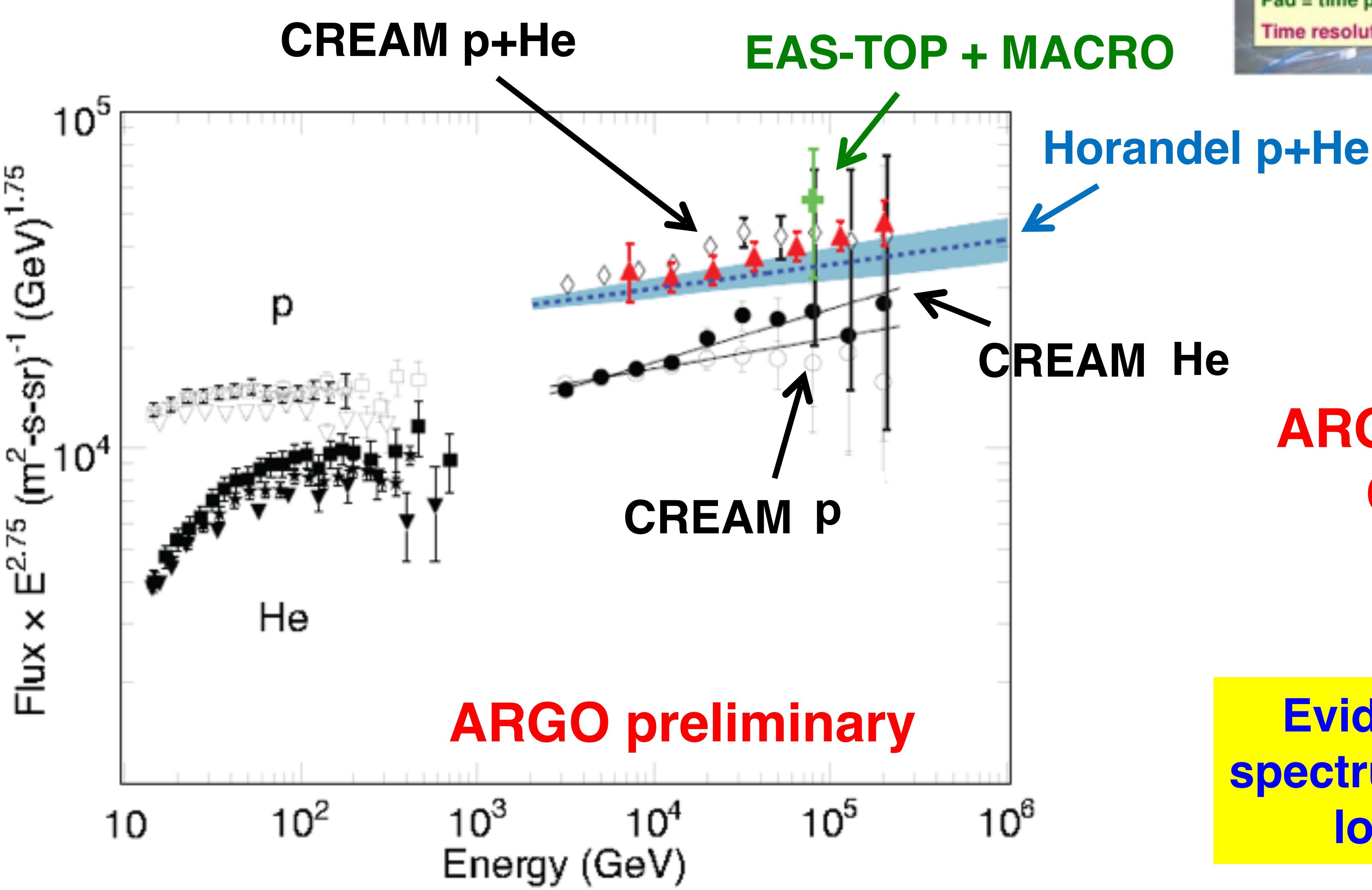
- EAS after maximum
- exploit longitudinal distribution differencies for different primaries

composition

Light-component spectrum of CRs measured by ARGO (5-250 TeV)



Measurement of the *light-component* (p+He) spectrum of primary CRs in the energy region (5 – 250) TeV via a Bayesian unfolding procedure

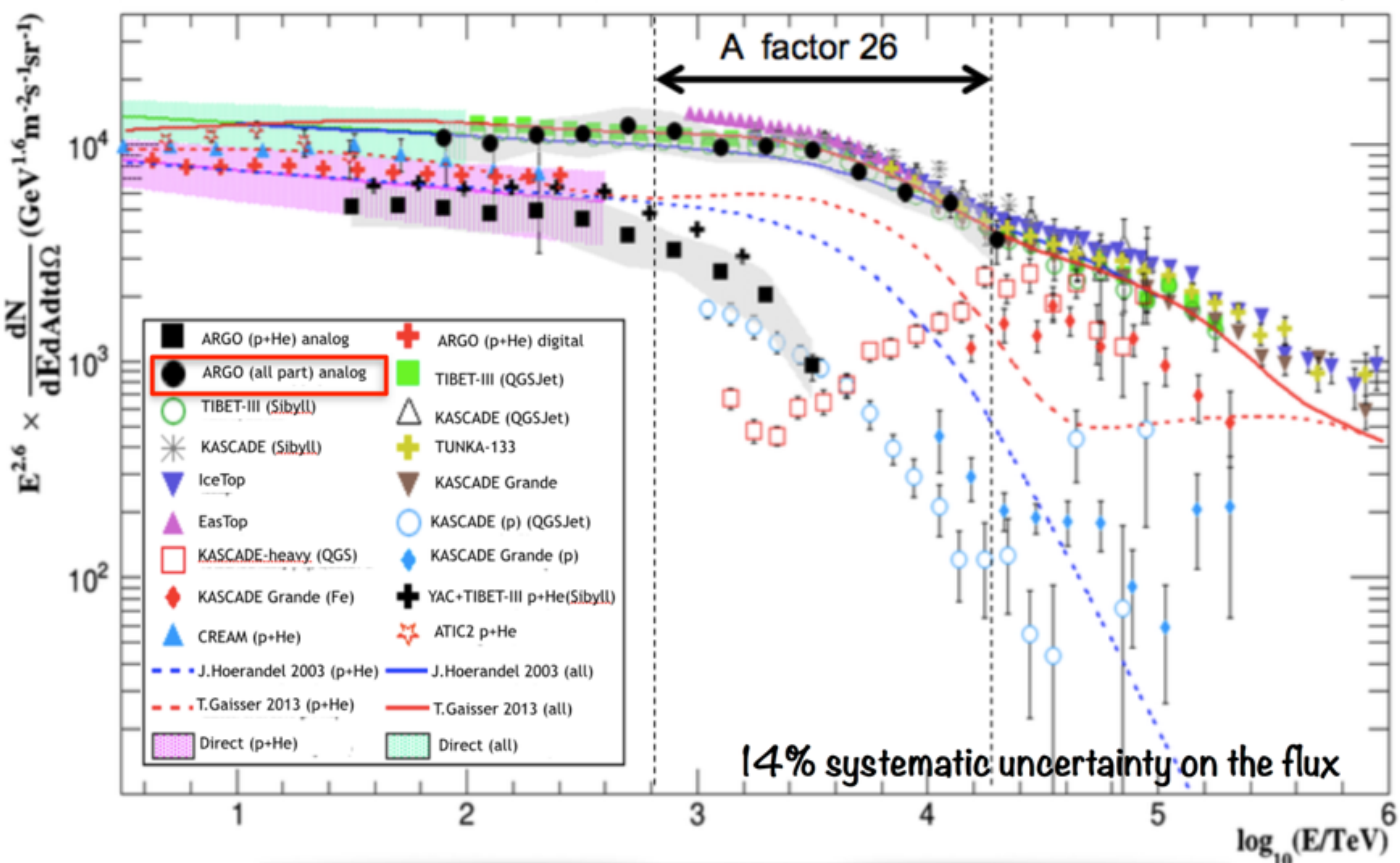


CNO < 2%

ARGO data agree with CREAM results

Evidence that the proton spectrum is flatter than in the lower energy region

ARGO-YBJ all particle spectrum



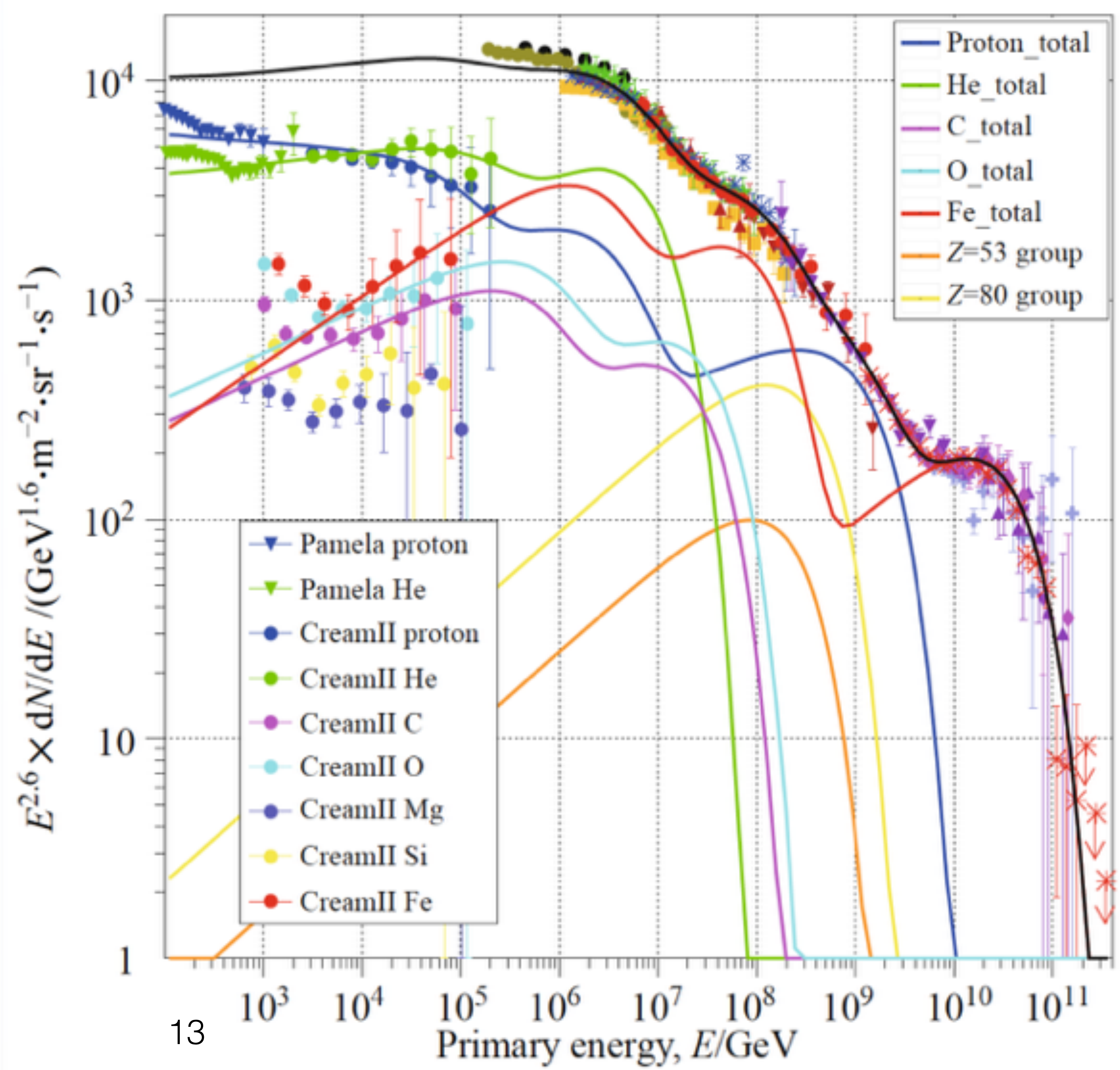
- all particle knee ~ 4 PeV
- consistent with direct and indirect measurements

Beyond the knee

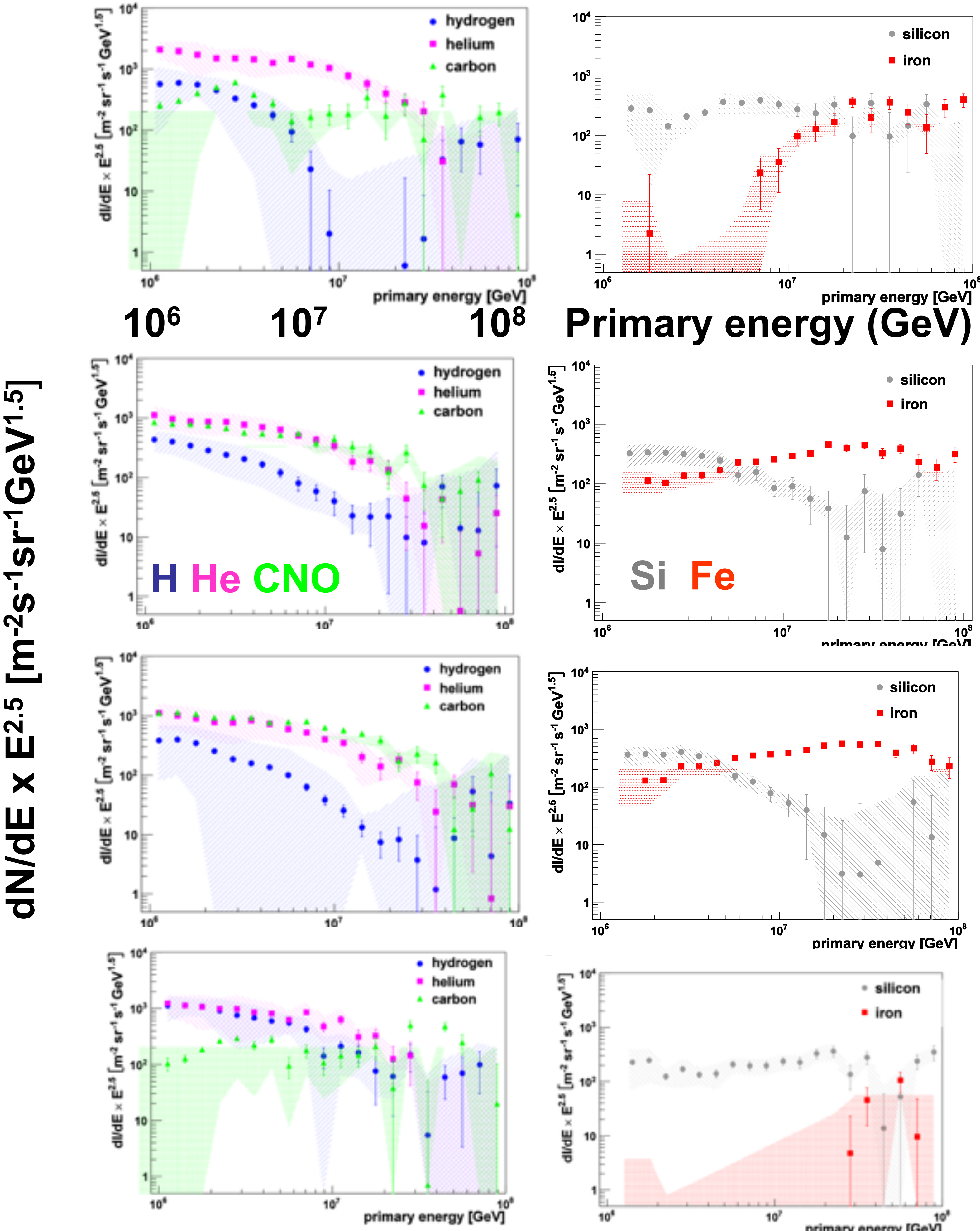
Gaisser, Stanev, Tilav, Front. Phys. 8(6), 748 (2013)

Direct measurements anchor models for composition interpretation of air shower measurements beyond the knee.

Rich phenomenology!



KASCADE



QGSjet01/FLUKA

QGSjetII/FLUKA

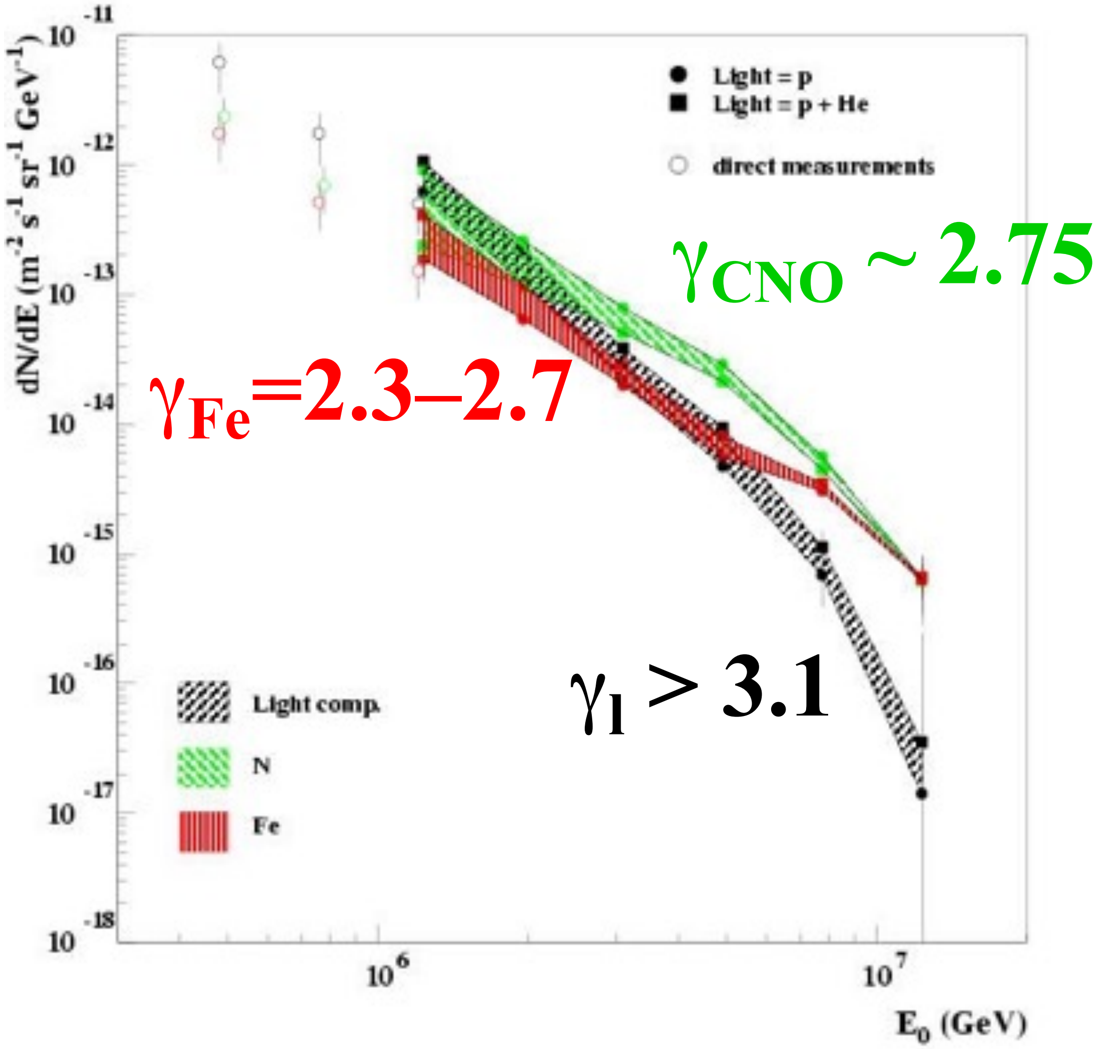
SIBYLL/FLUKA

EPOS1.99/FLUKA

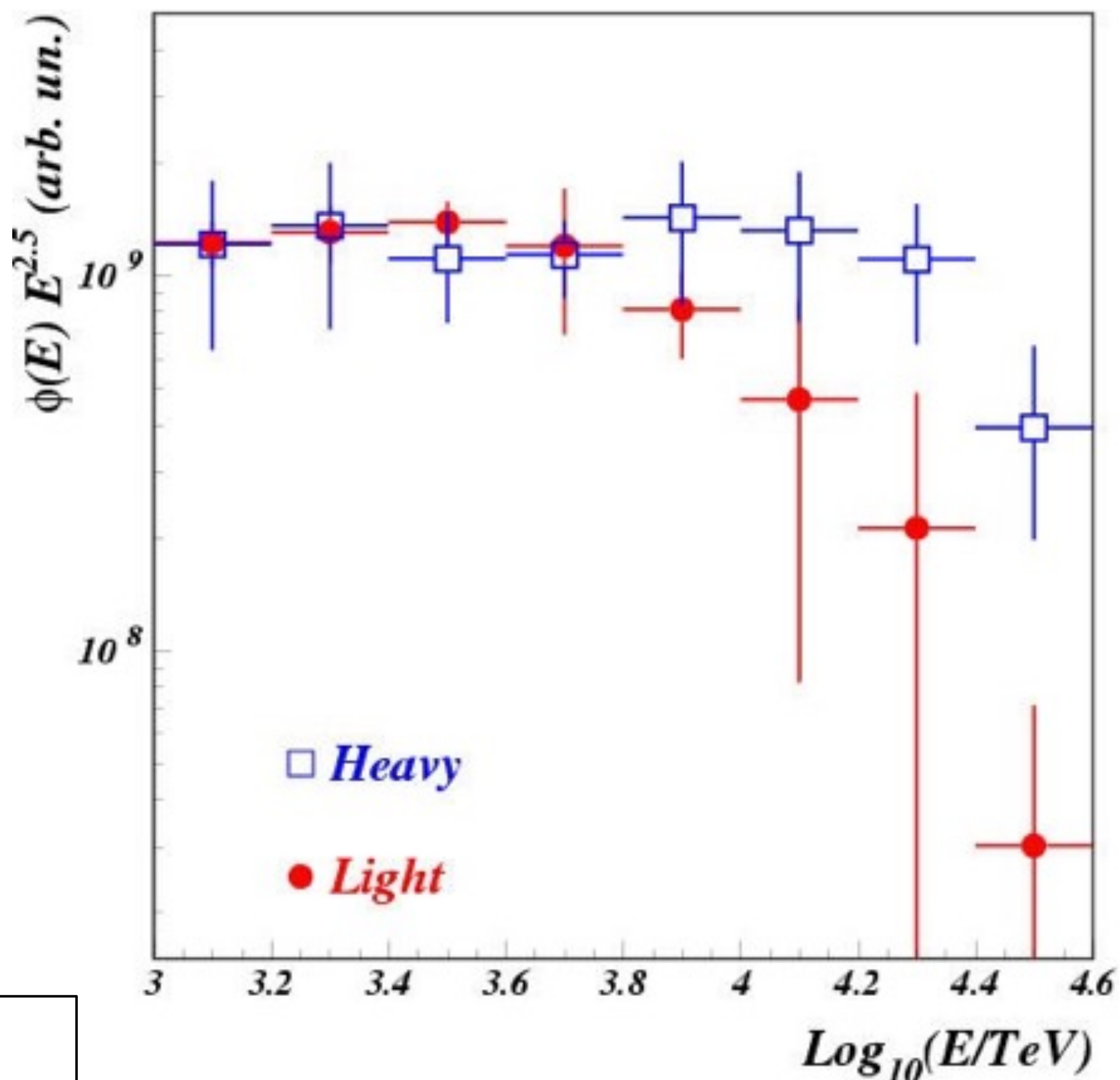
M. Fingler, PhD thesis

EAS-TOP (2005 m a.s.l.) & MACRO

EAS-TOP Ne-Nμ (GeV)



EAS-TOP/MACRO Ne-Nμ (TeV)



Average power low index
of different mass groups (γ)
Heavier primary spectra harder
➔ $E_k \propto Z$?

Astrop. Phys. 21 (2004) 583

L = p + He   H = Mg + Fe

Astrop. Phys. 20 (2004) 641

GAMMA: Mt Aragats, Armenia 3200 m a.s.l. (~700 gr/cm^2)

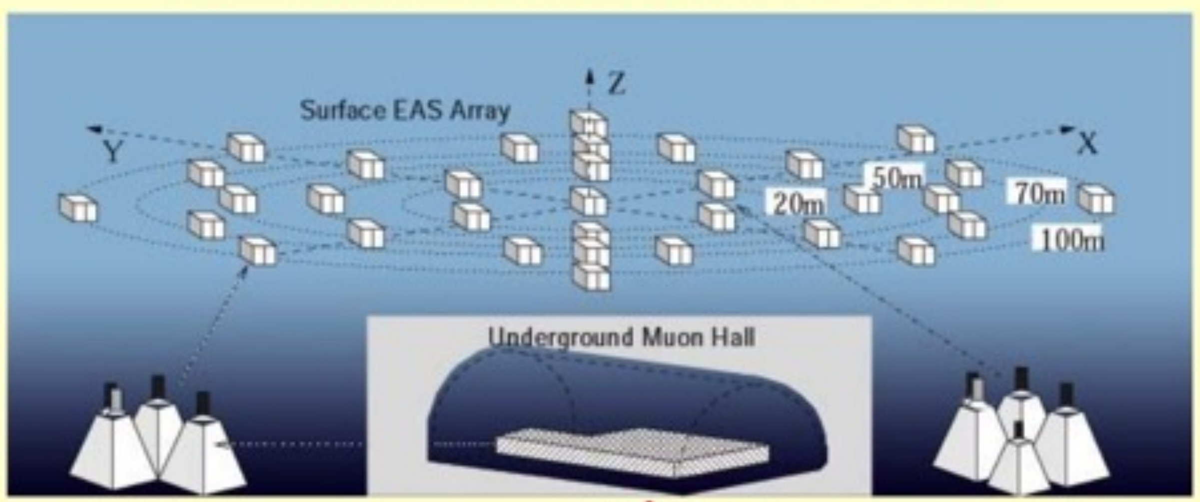
ARAGATS scientific station (late autumn)

Hill sides of the Mt. Aragats, Armenia, 65 km from Yerevan

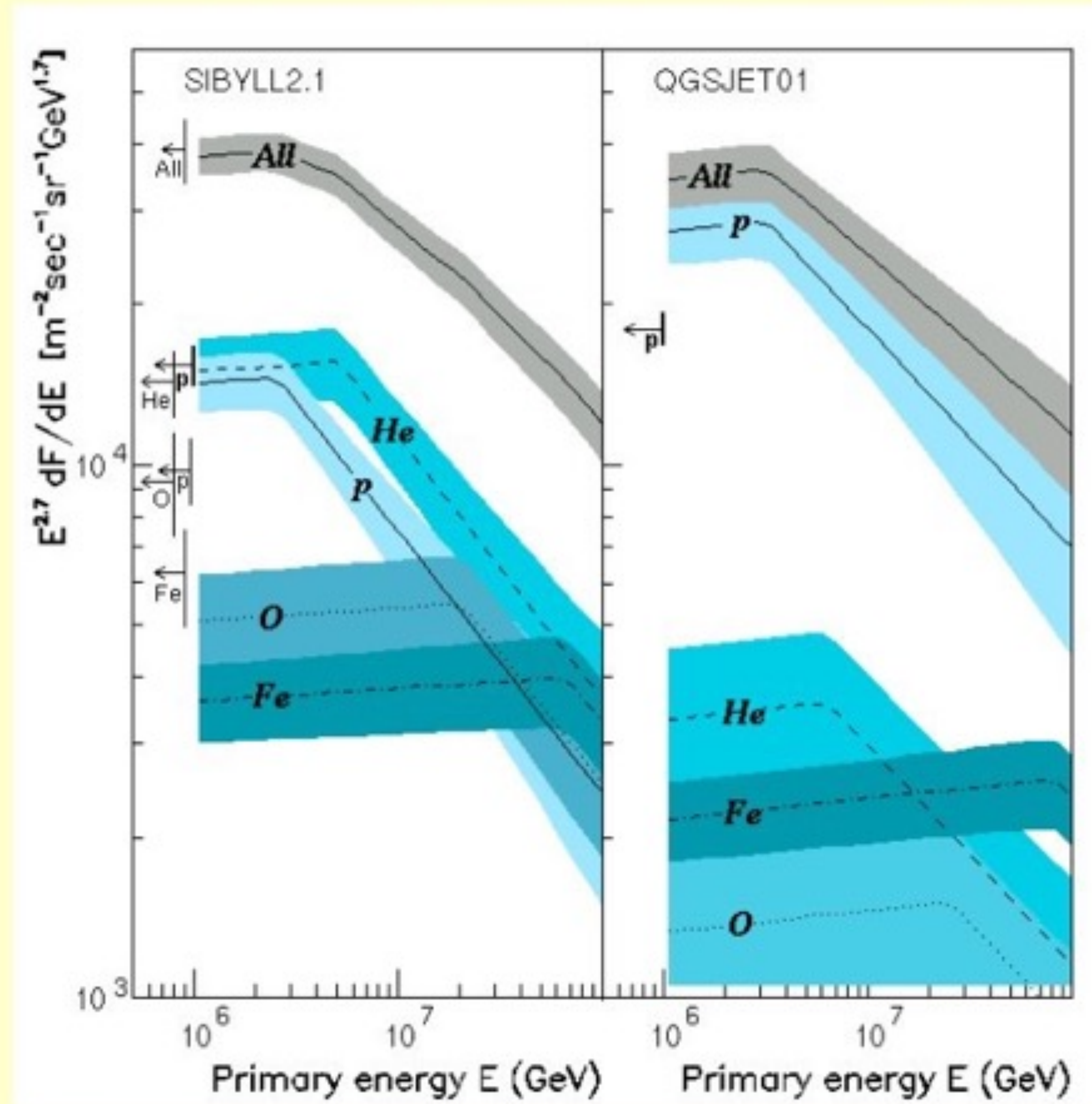
Elevation: 3200 m a.s.l. (700 g/cm^2 of atmospheric depth)

Geographical coordinates: Latitude = 40.470 N, Longitude = 44.180 E

GAMMA facility (2003-2008)



Energy spectra for the primary nuclei groups



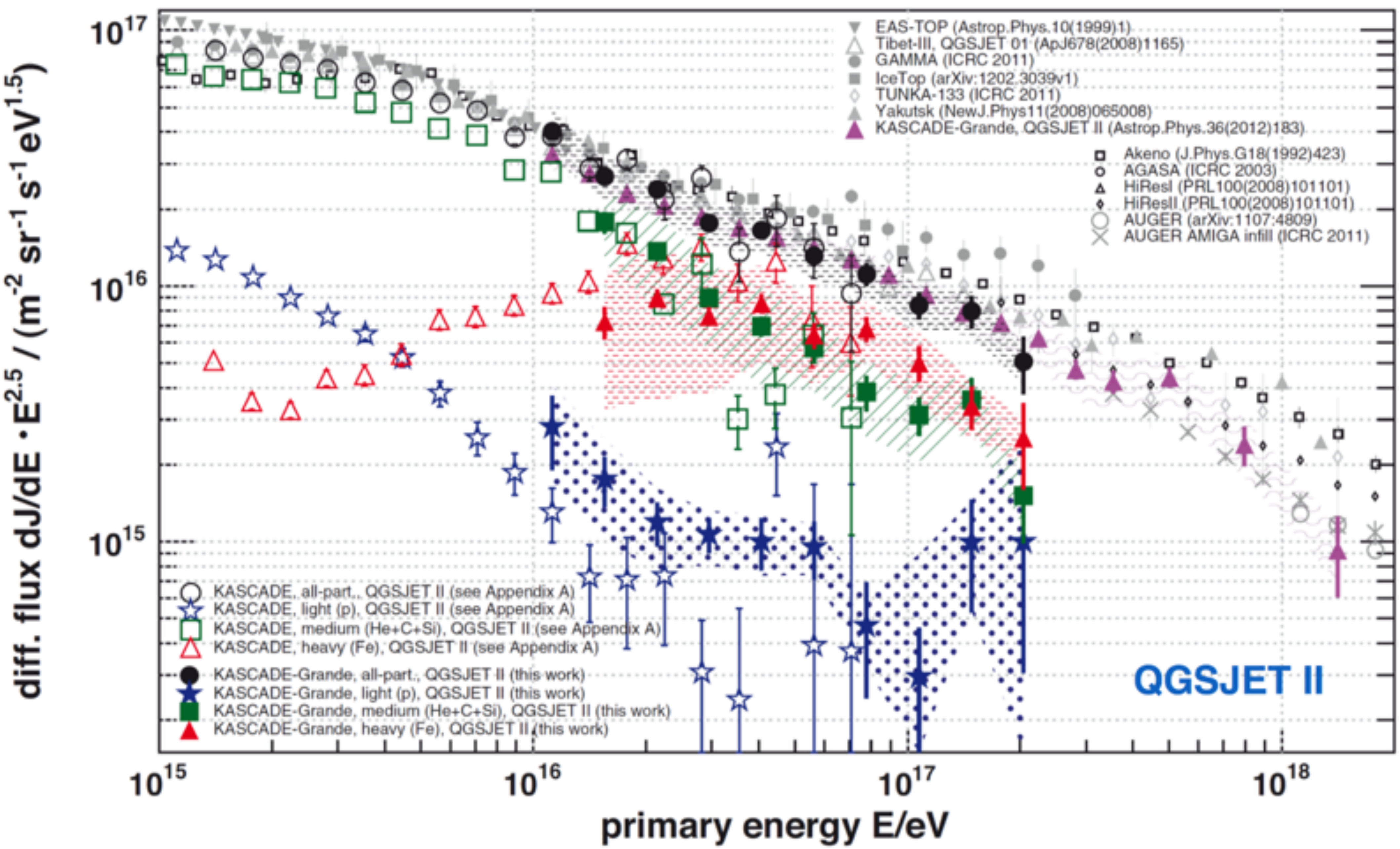
B.Wiebel & P.Biermann, 24th ICRC (1995)

A.Lagutin et al., 29th ICRC (2005)

Knee due to the light elements

Astroparticle Physiscs, 28 (2007) 169

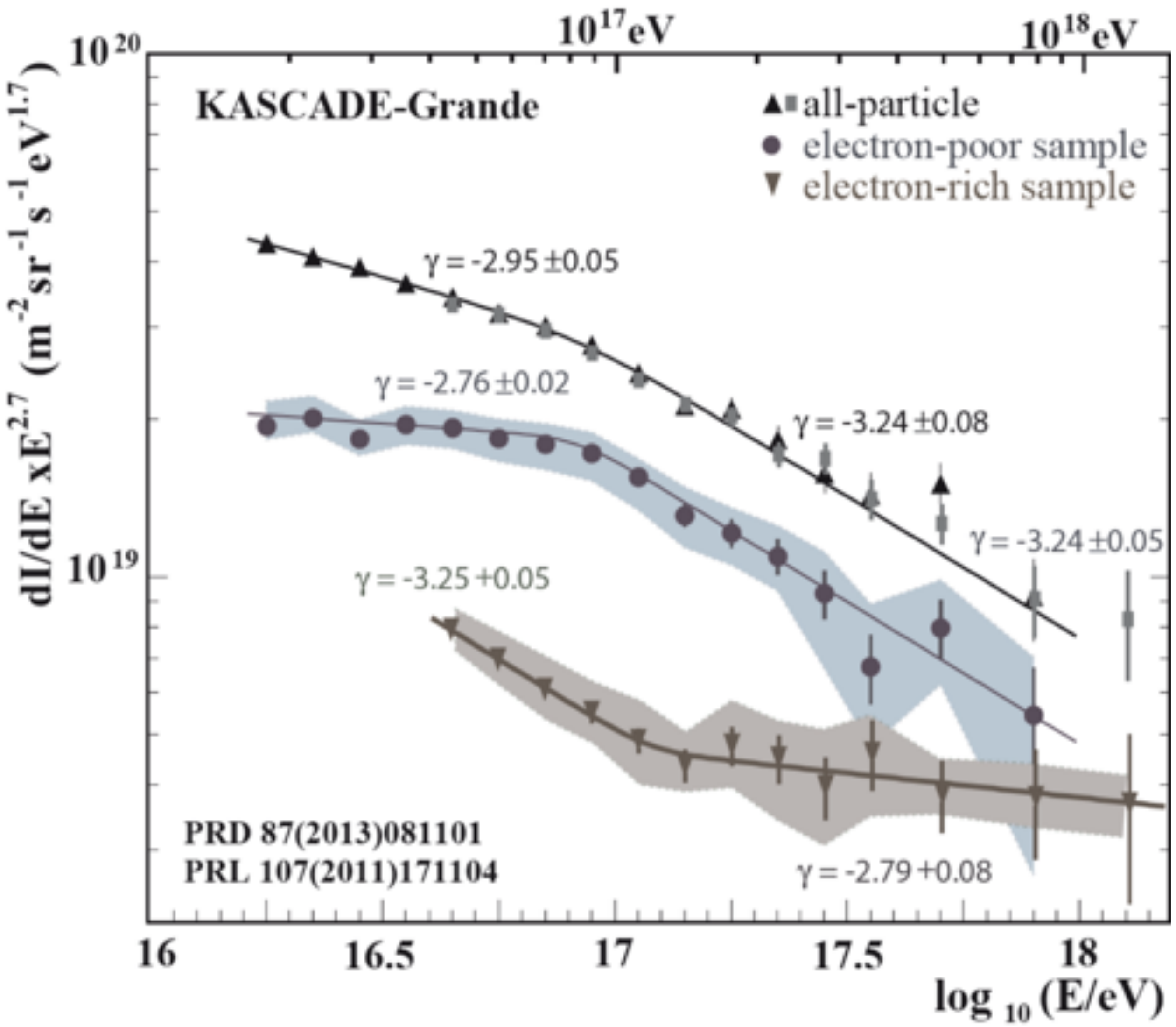
Unfolding results: KASCADE and KASCADE-Grande

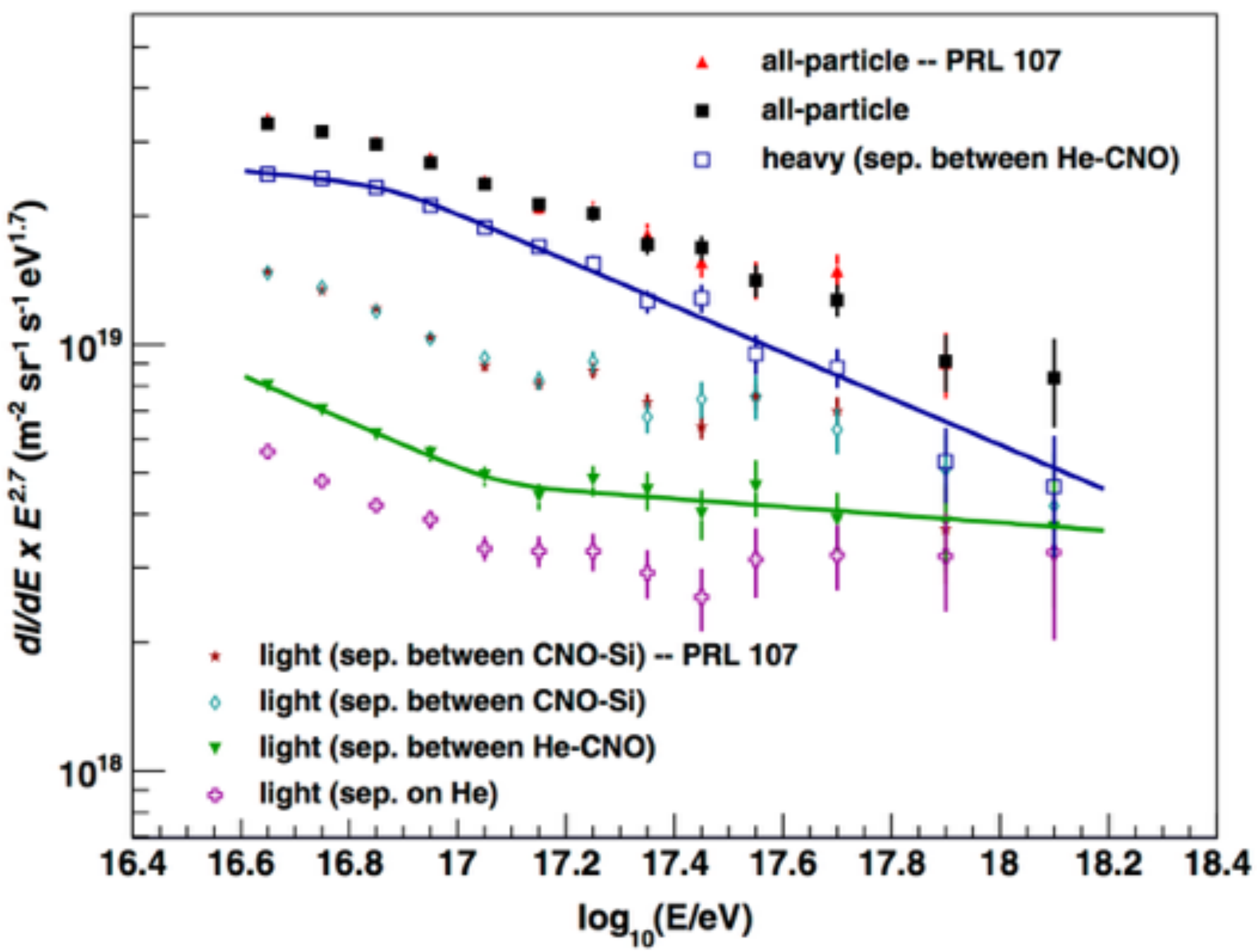


spectra of individual mass groups:
proton medium (He+C+Si) iron
➔ all spectra overlap and agree well!
➔ all three show a knee-like feature!!

Astroparticle Physics 47 (2013) 54

KASCADE-Grande Ankle-like feature on the el. rich sample





Phys.Rev.Lett. 107 (2011) 171104

Phys.Rev.D (R) 87 (2013) 081101

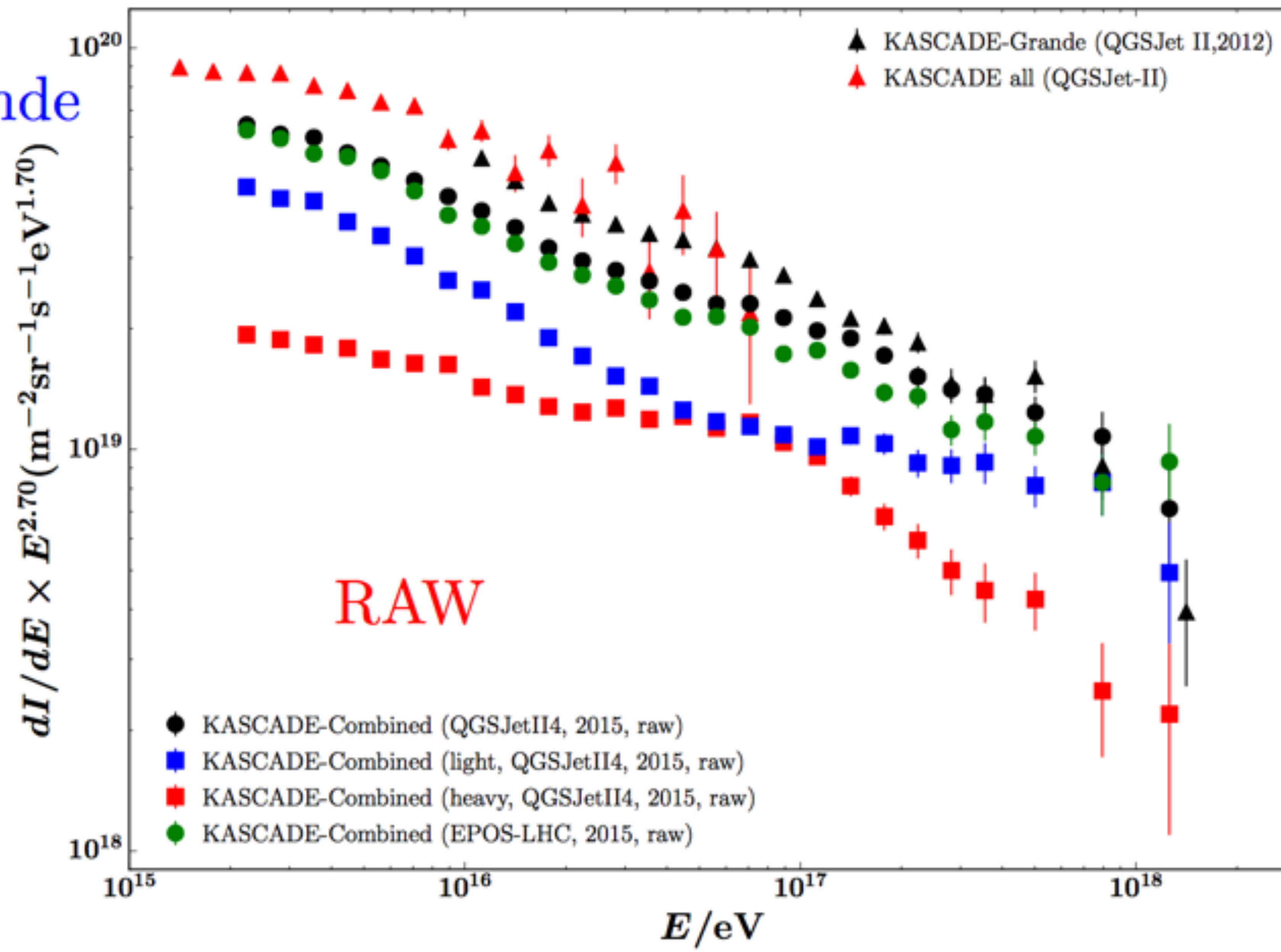
Combined Analysis

New models

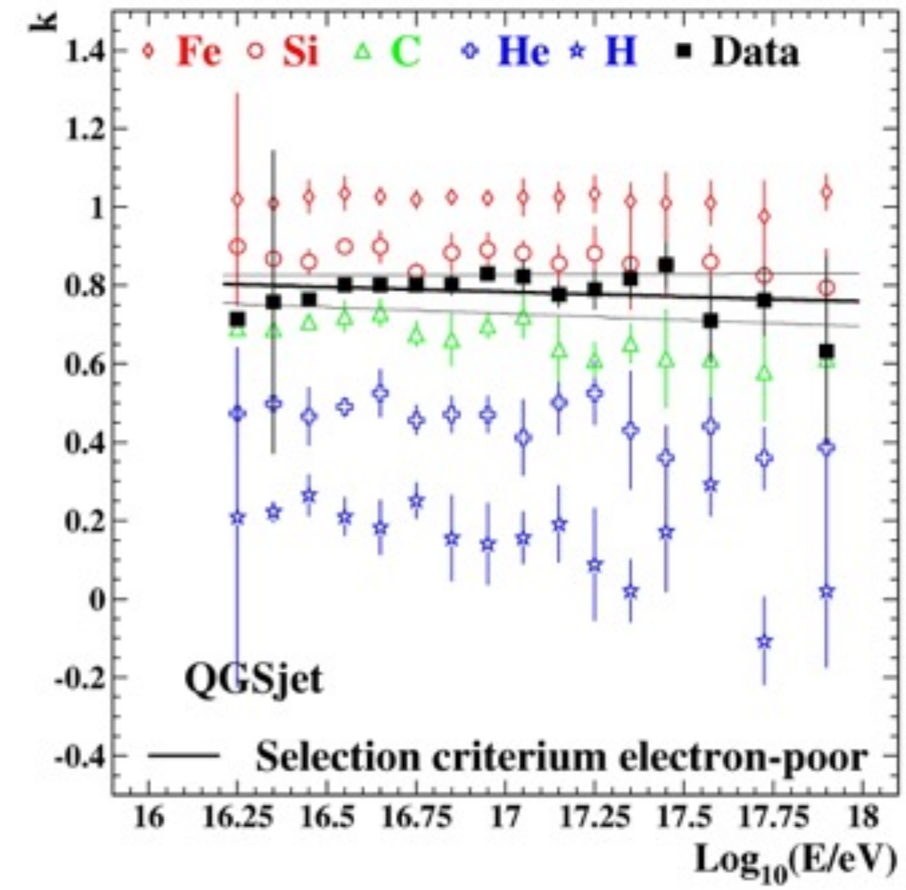
- are consistent with Grande
- agree below 10^{16} eV
- result in a lower flux

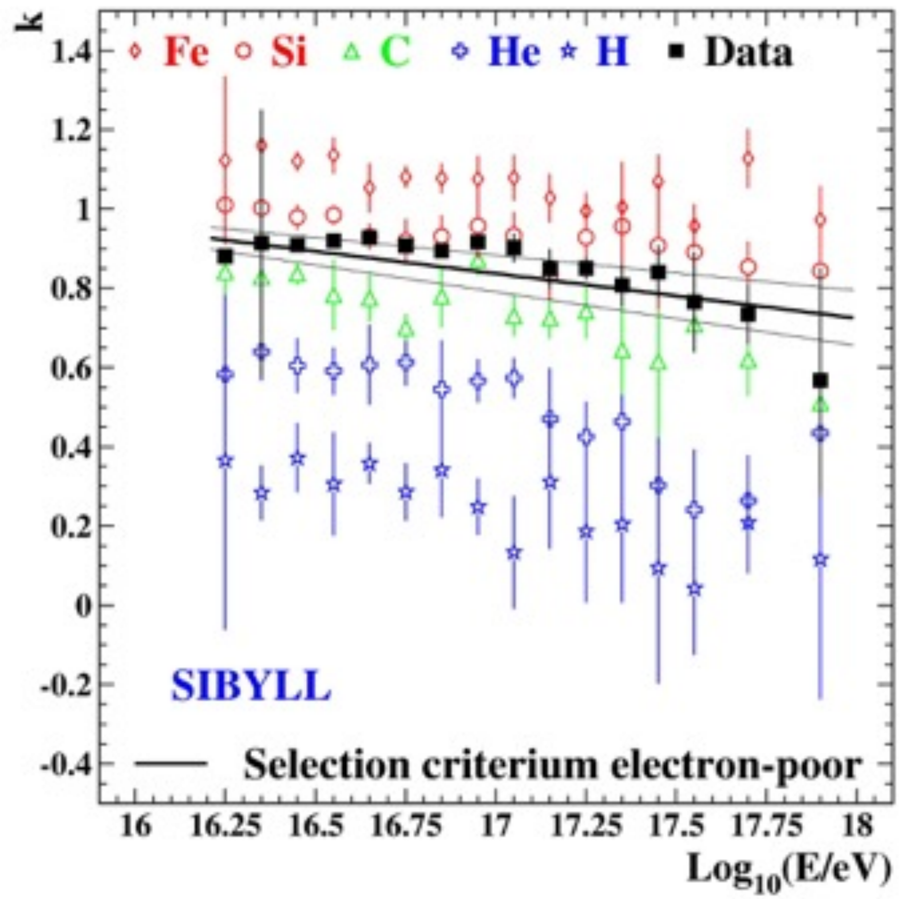
Same features as before

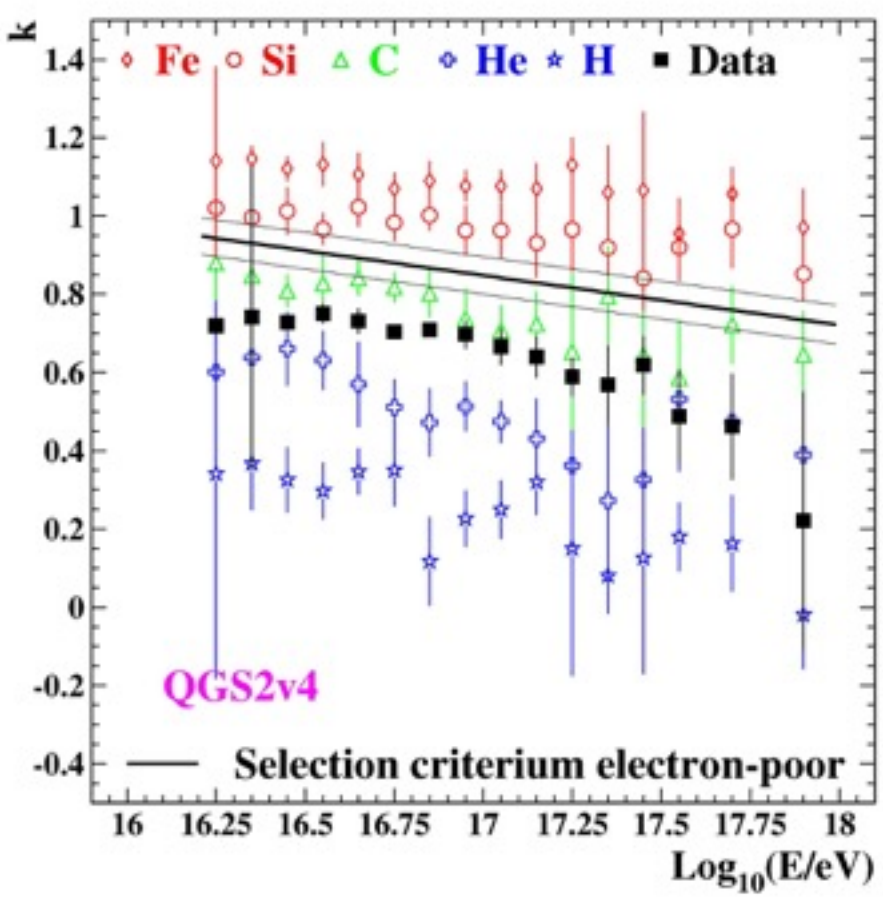
No corrections applied yet
Mass separation kept very simple

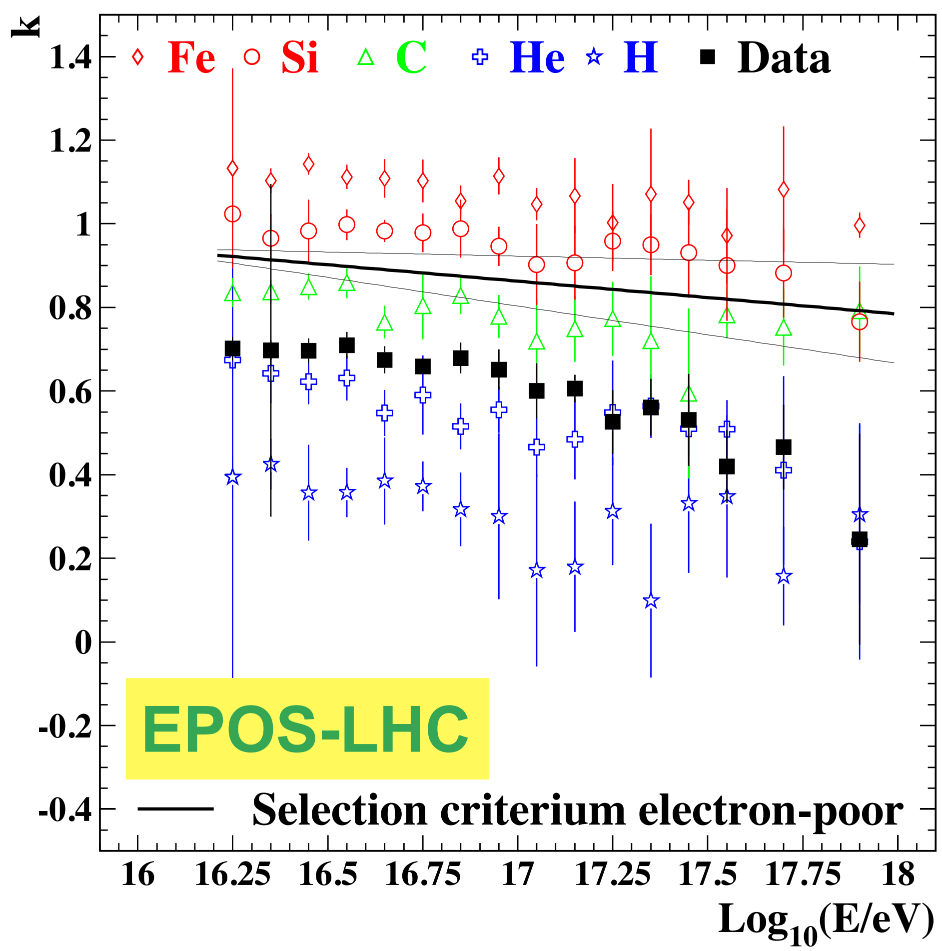


K parameter as a function of Energy (bin 1-2)



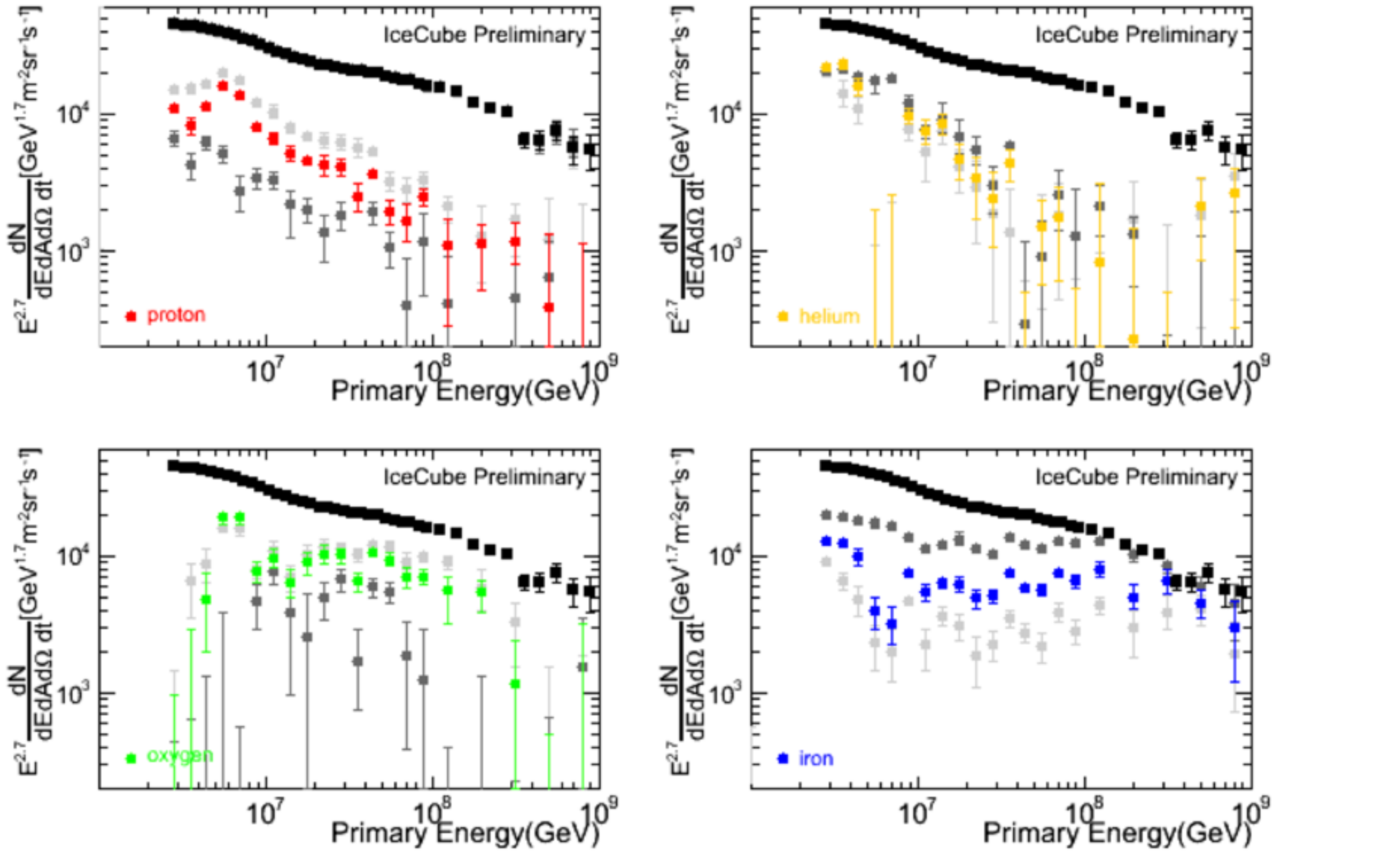




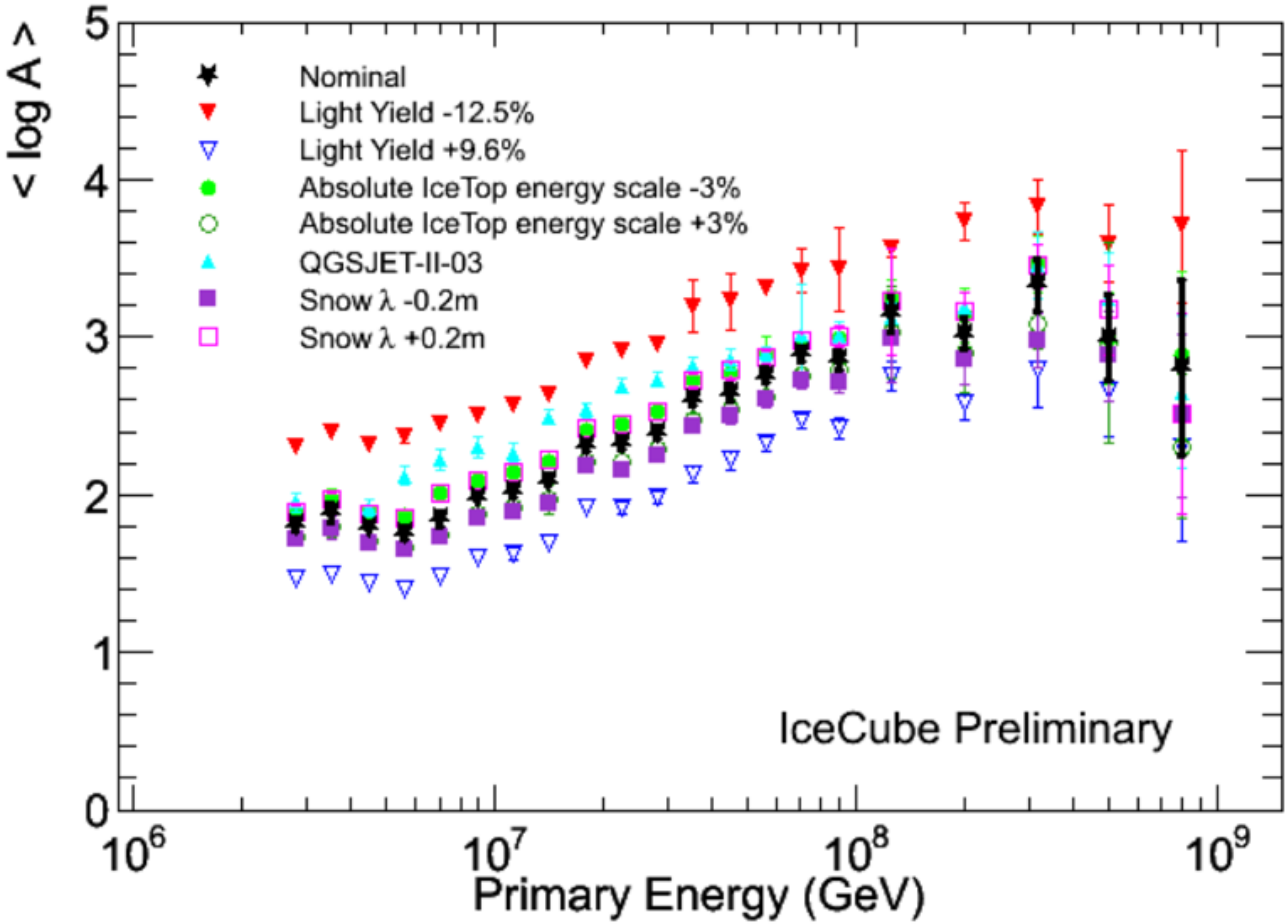


Systematics: Individual energy spectra, In-ice light yield

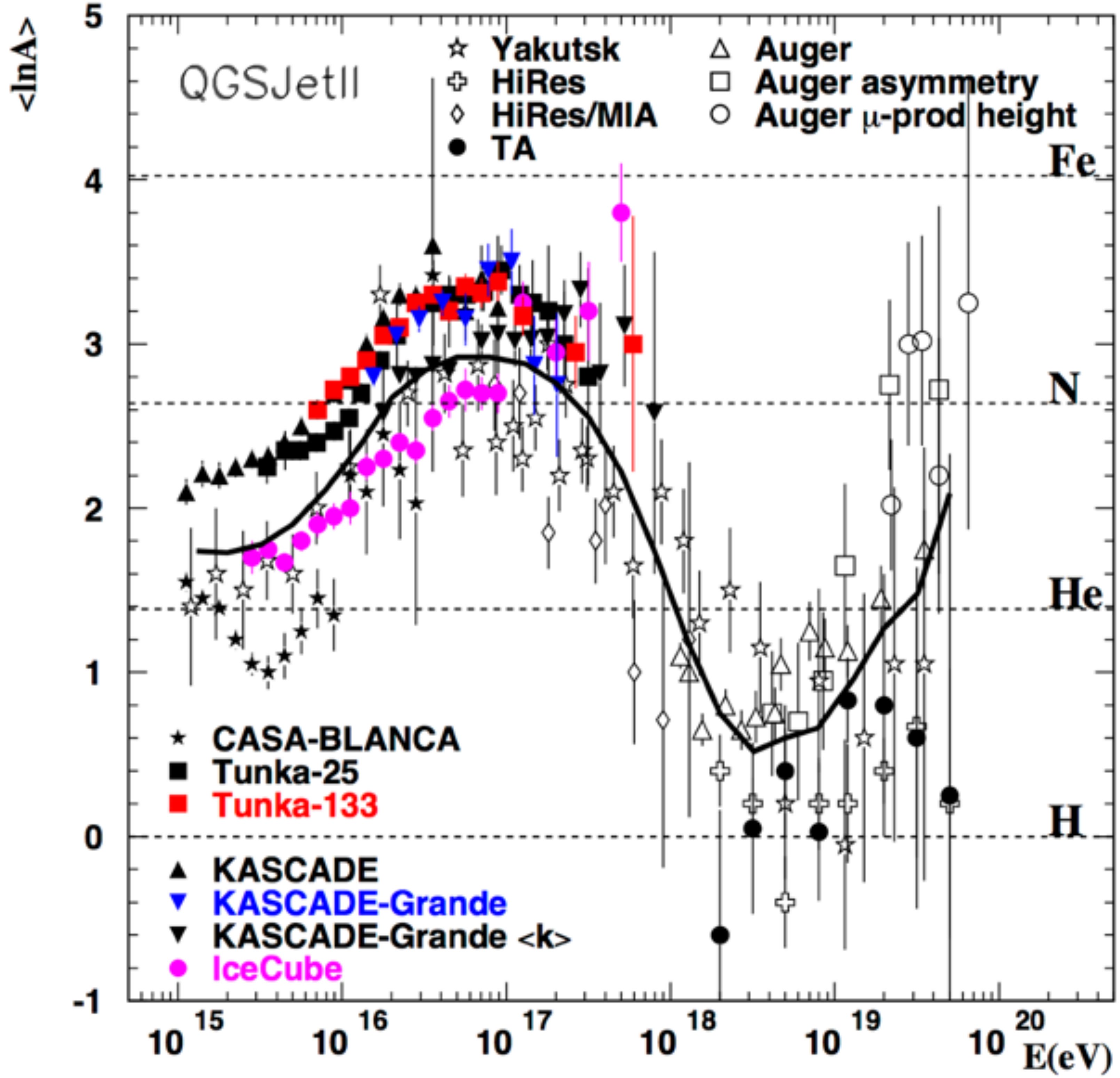
dark gray: -12.5%, light gray: +9.6%



Results: Composition



<lnA> —> A



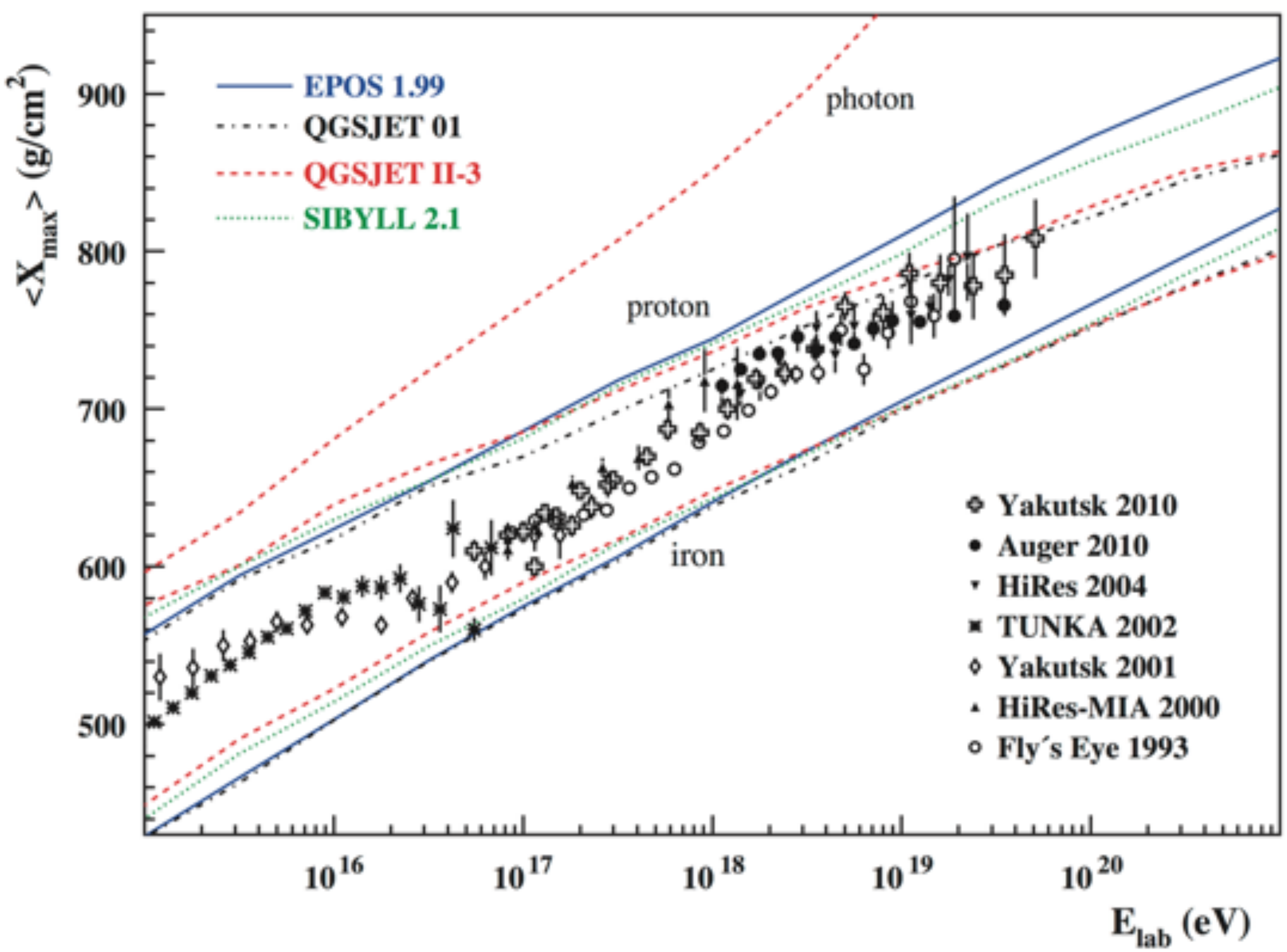
QGSJetII
Yakutsk
HiRes
HiRes/MIA
TA
Auger
Auger asymmetry
Auger μ-prod height
Fe
N
He
H
CASA-BLANCA
Tunka-25
Tunka-133
KASCADE
KASCADE-Grande
KASCADE-Grande <k>
IceCube
<lnA>
E(eV)

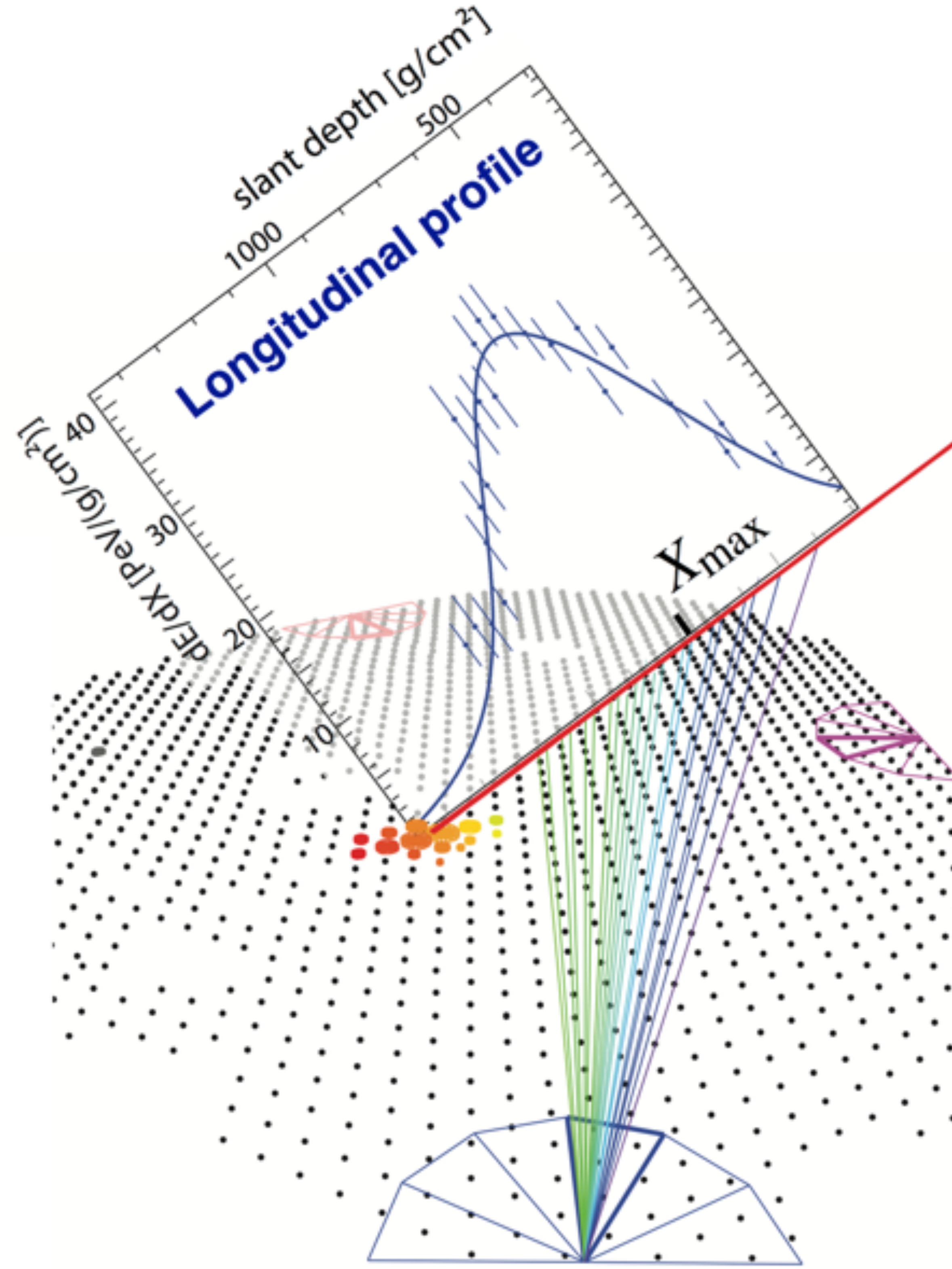
Fluorescence technique

Electrons:

$$E_{\mathrm{em}} = \int \left. \frac{\mathrm{d}E_{\mathrm{ion}}}{\mathrm{d}X} \right|_{\mathrm{meas.+extrap.}} \mathrm{d}X$$

$$E_{\mathrm{tot}} = (1 + f_{\mathrm{cor}}) E_{\mathrm{em}}$$

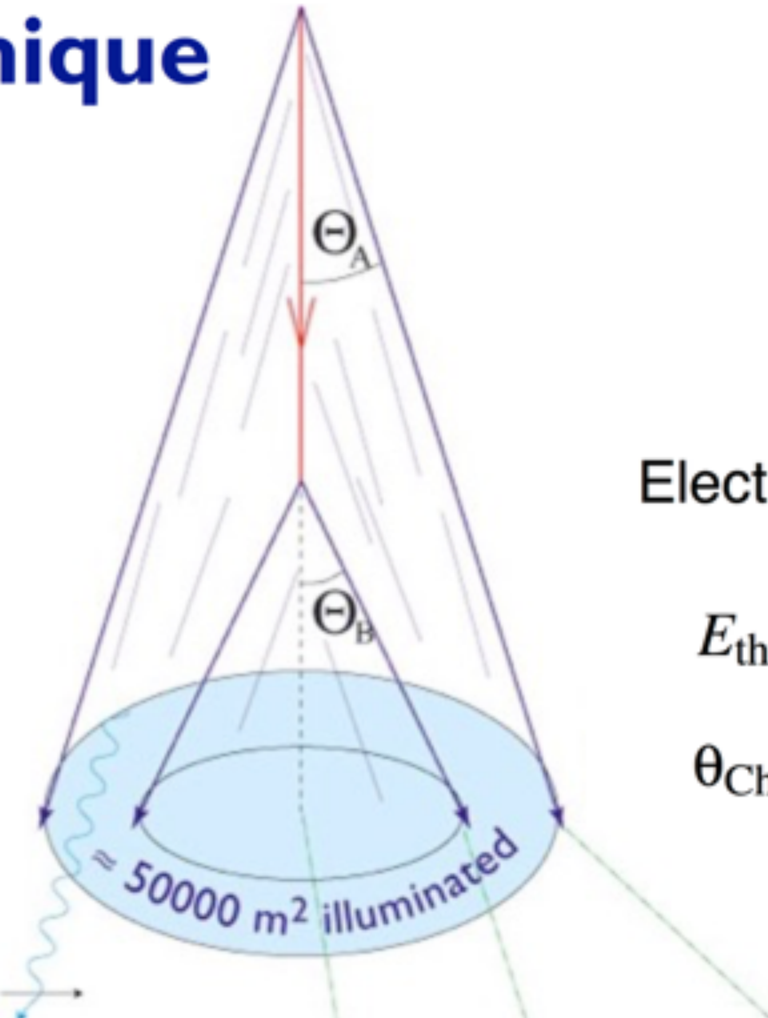




Example: event observed with Auger Observatory

(RE, Pierog, Heck, ARNPS 2011)

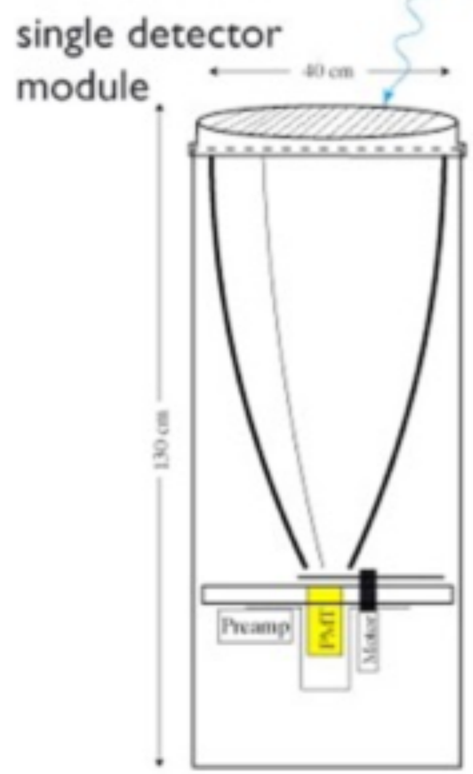
Non-imaging Cherenkov technique

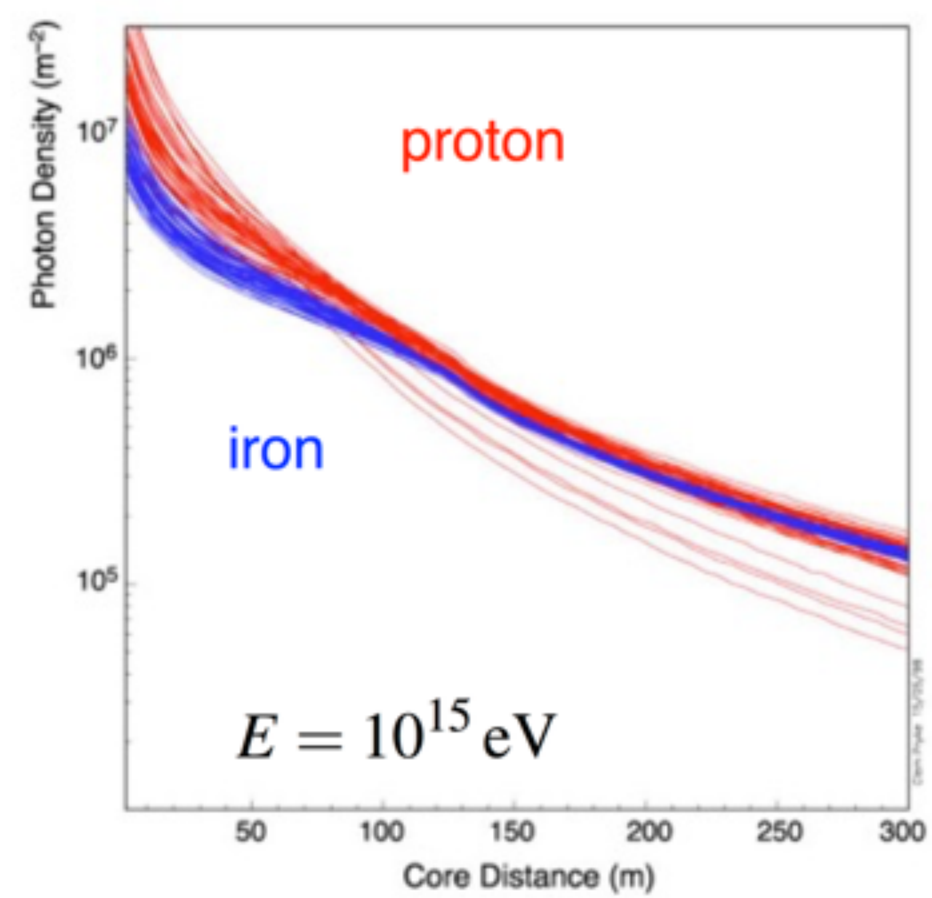


Electrons:

$E_{\rm th} \approx 21\,{\rm MeV}$

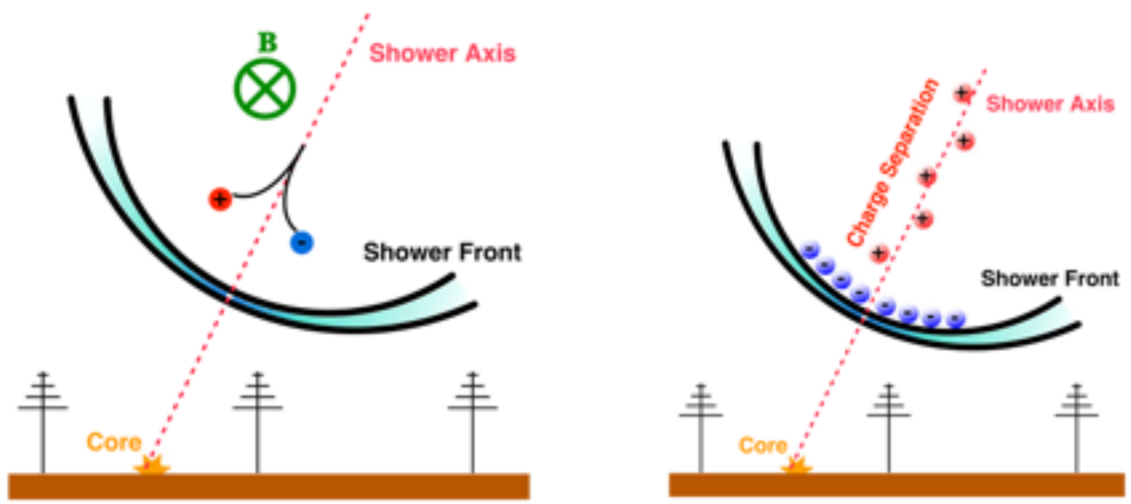
$\theta_{\rm Ch} \approx 1.4^\circ$

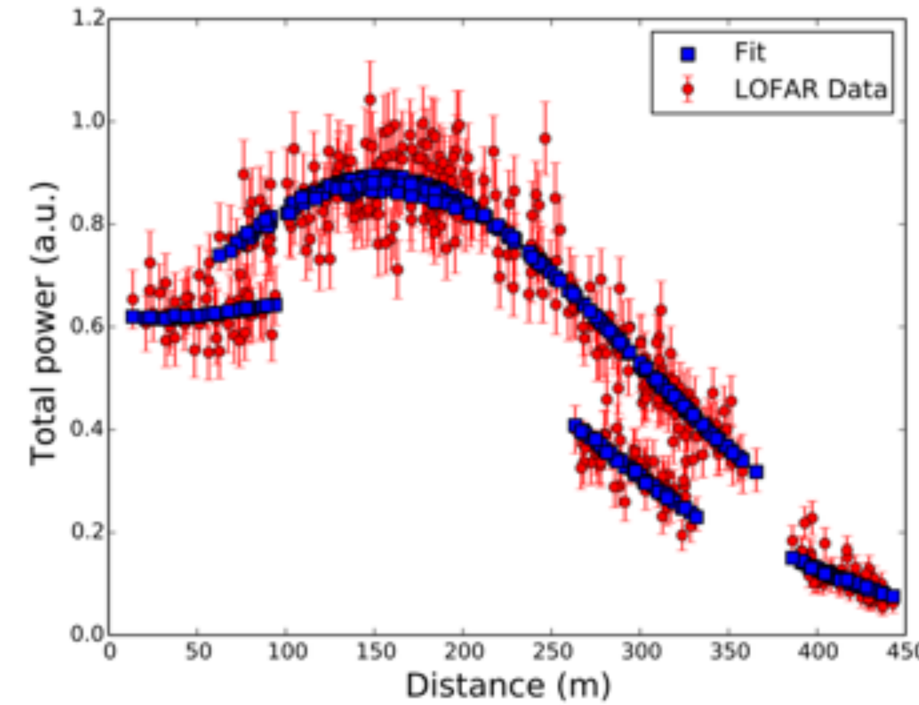




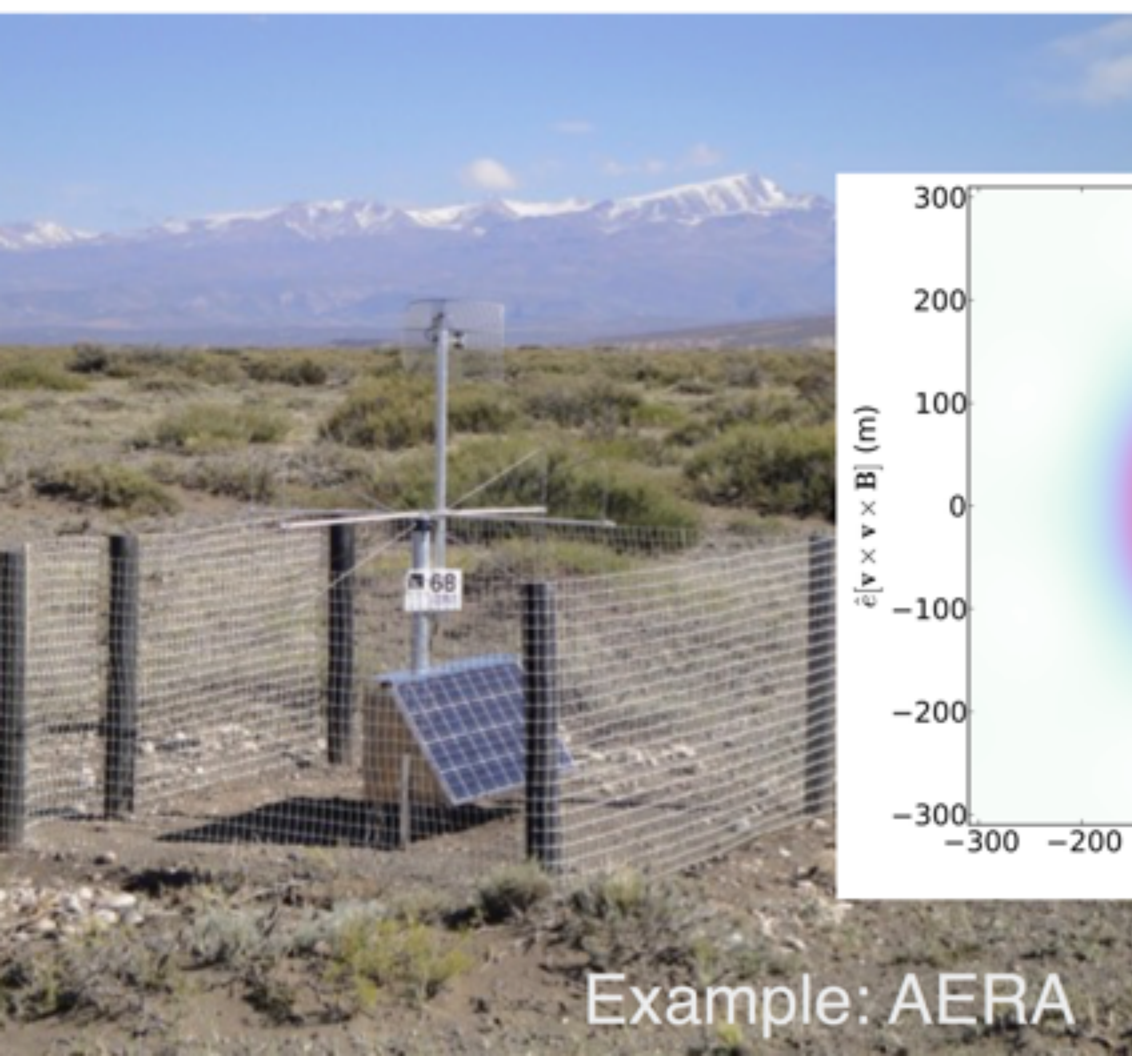
Radio signal measurement

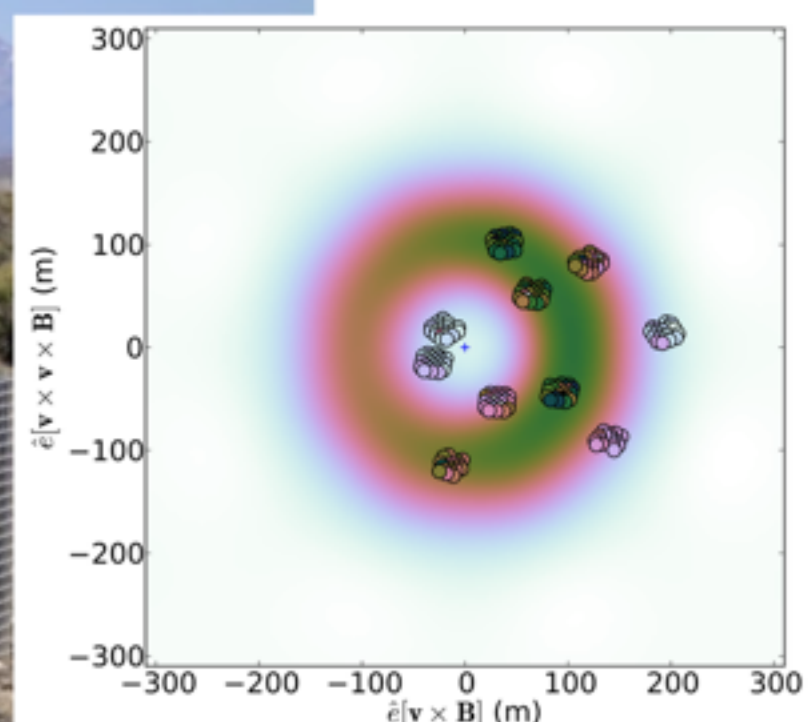
Electrons/positrons

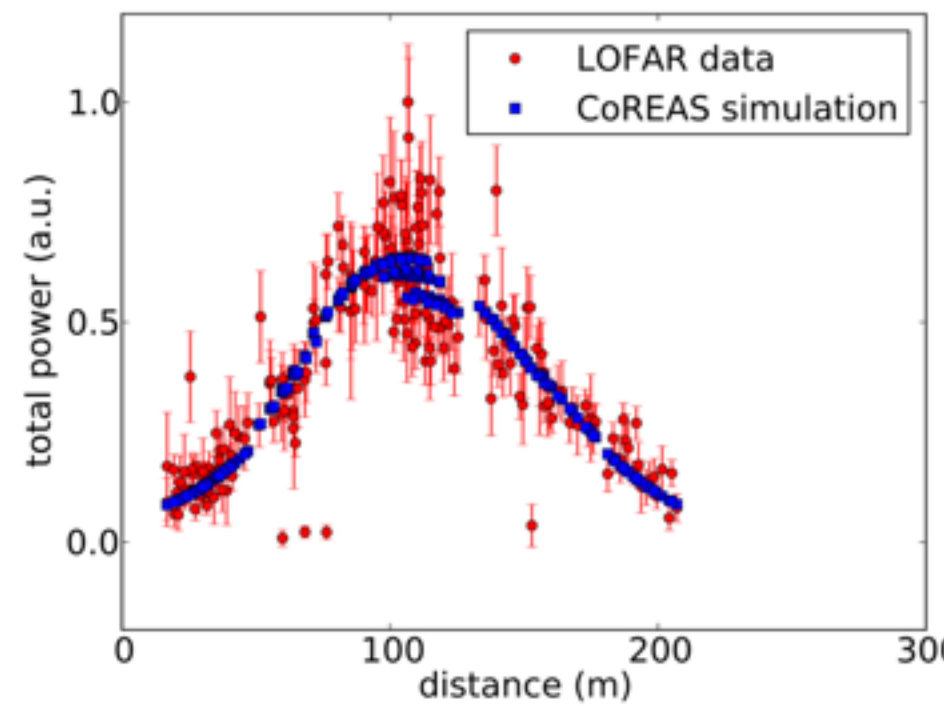




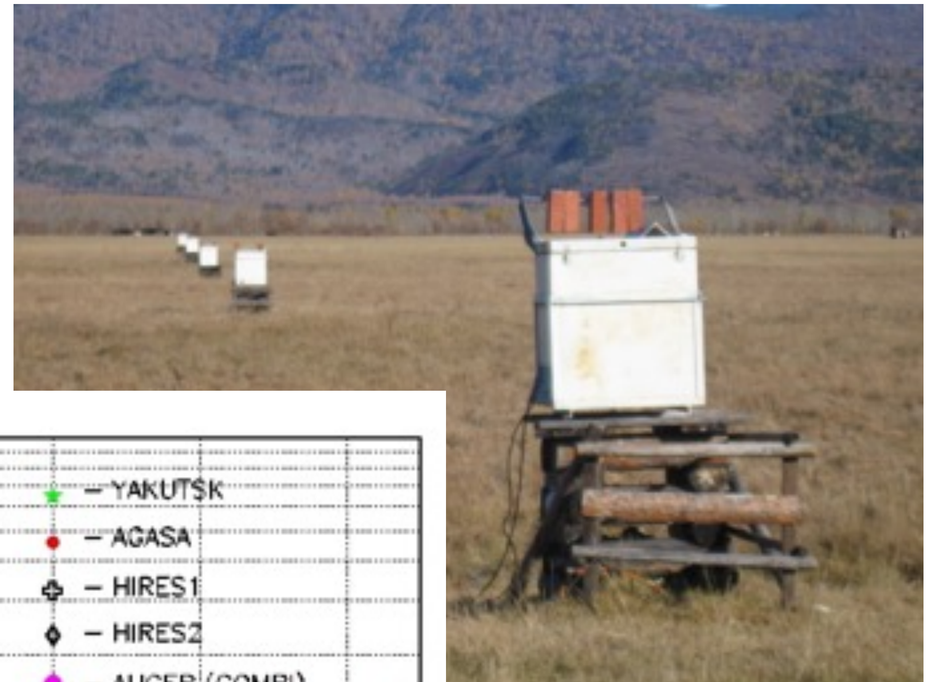
Nelles et al. (LOFAR), ECRS 2014

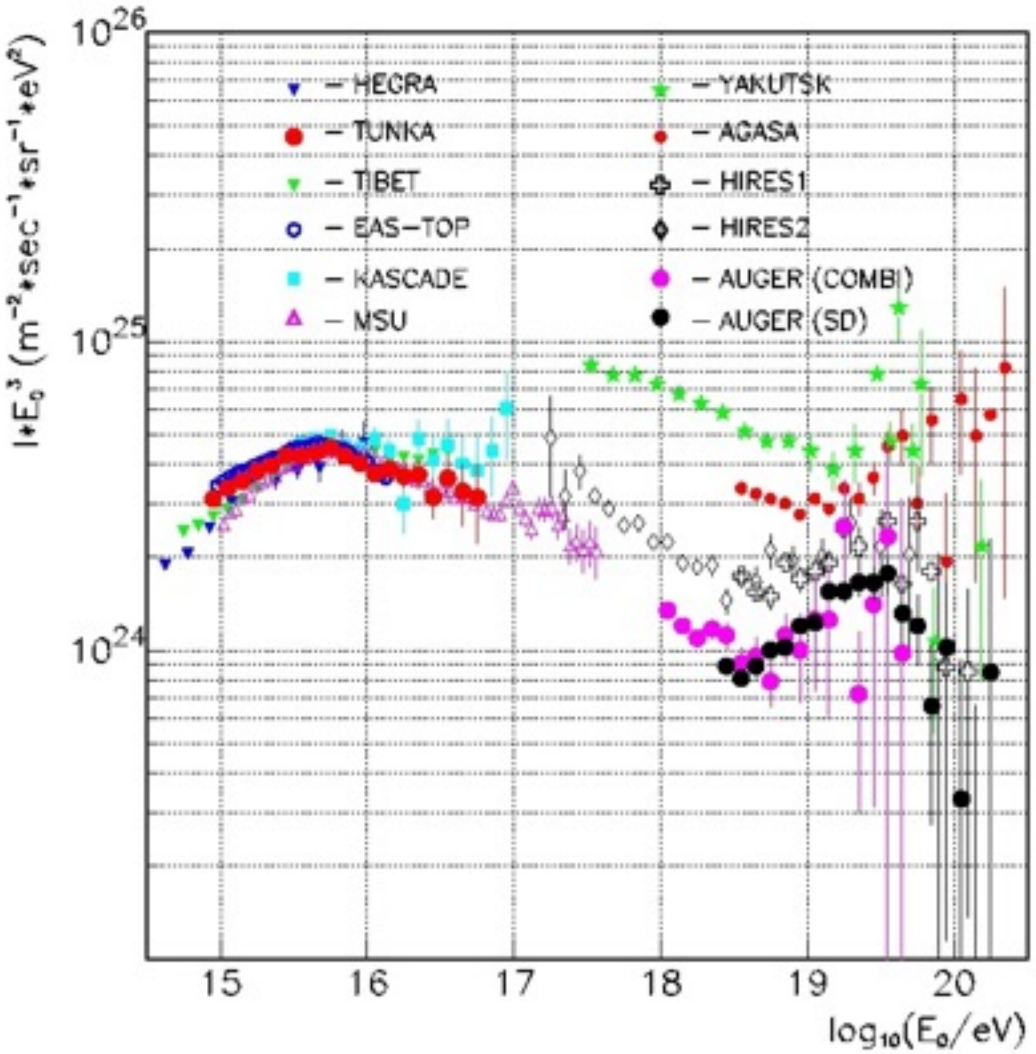


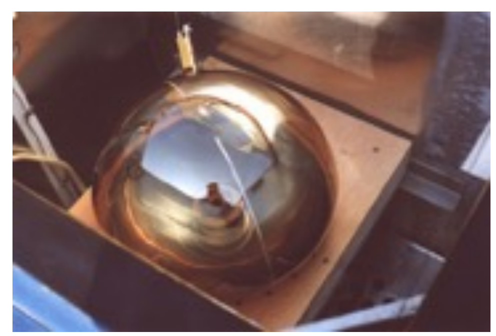




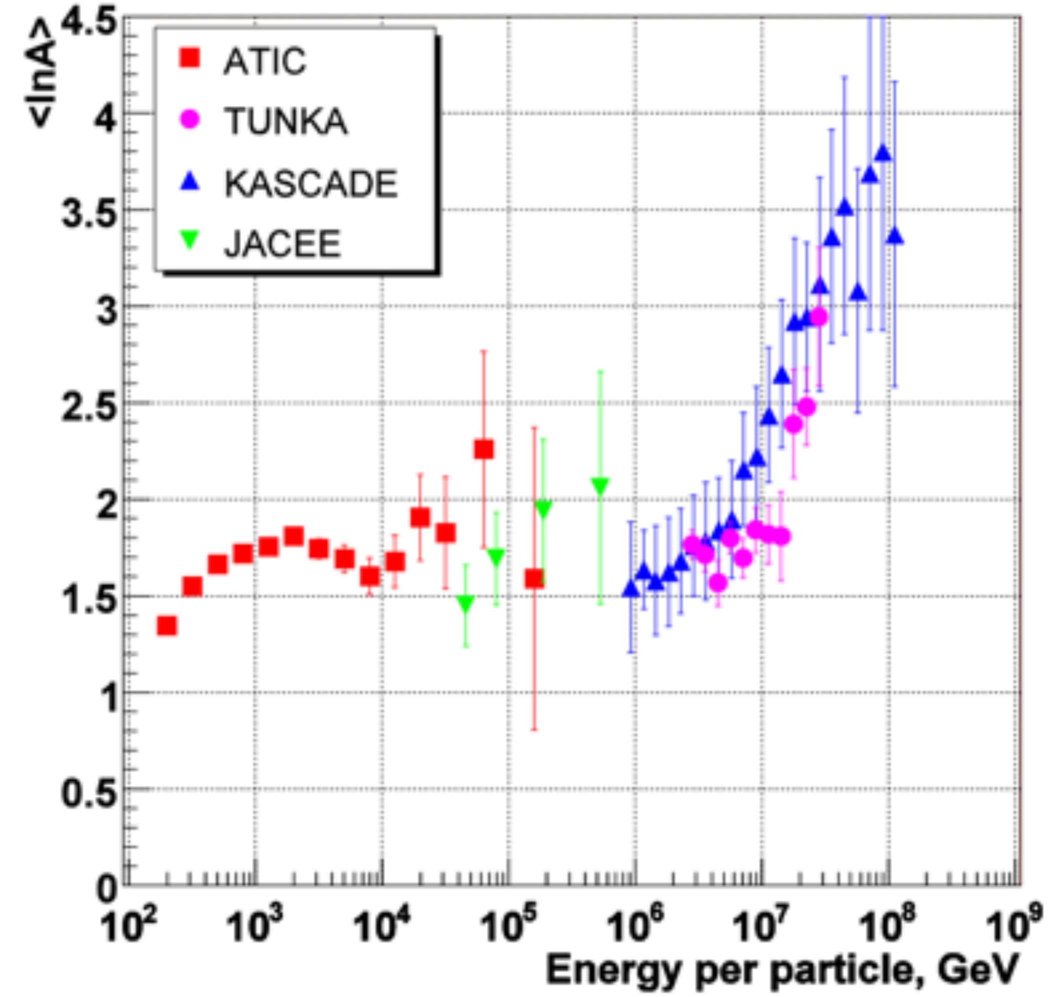
TUNKA-25 Cherenkov array, Siberia 675 m a.s.l.







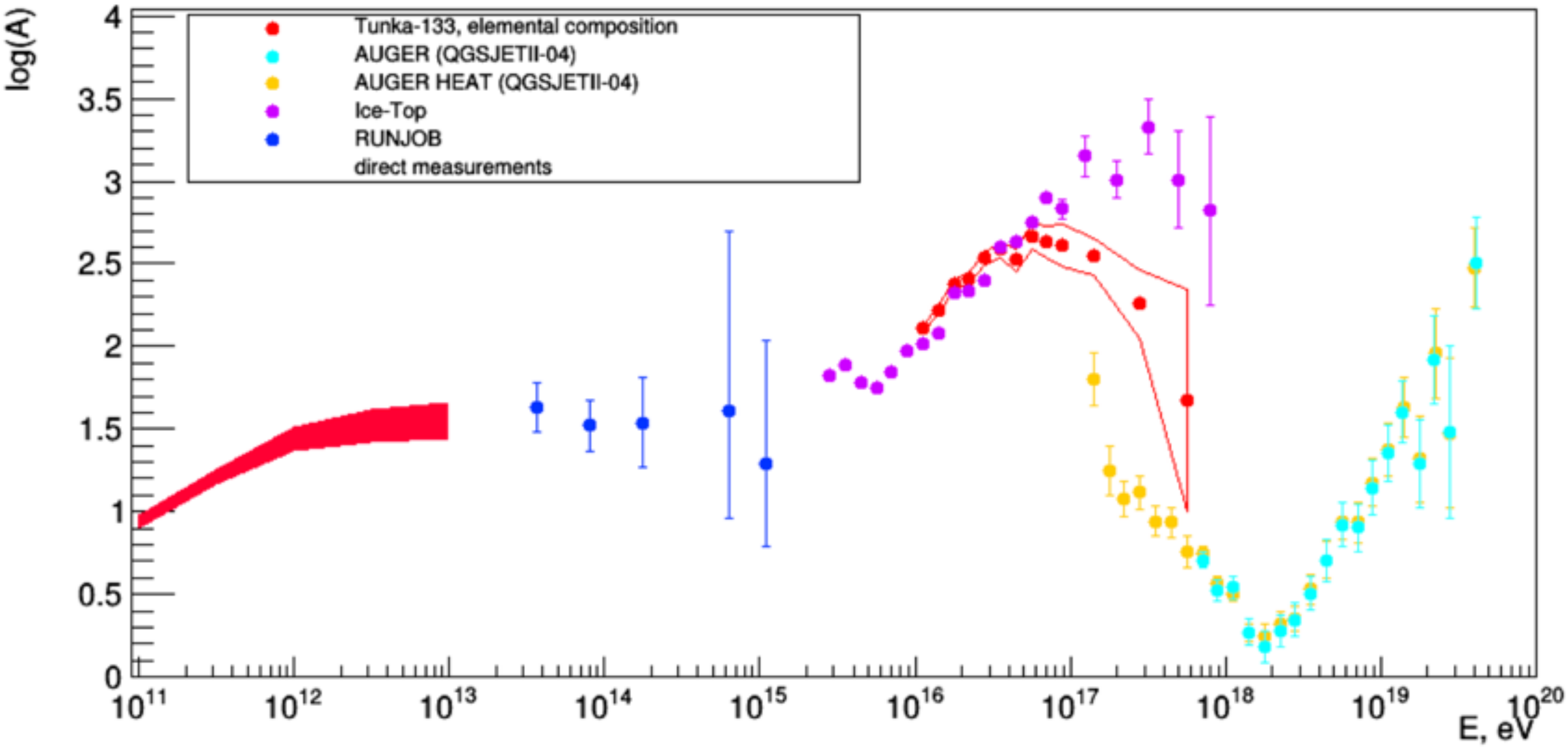
Mean mass composition



V. Prosin, *Highlights of Astroparticle Physics* Torino, 2010

1. Composition before the knee and in the knee is light 70% of p +He, 30% of others.
2. Composition at $3 \cdot 10^{16}$ is heavy 30% of p+He, 70% of others.

Most recent data. Where are we?

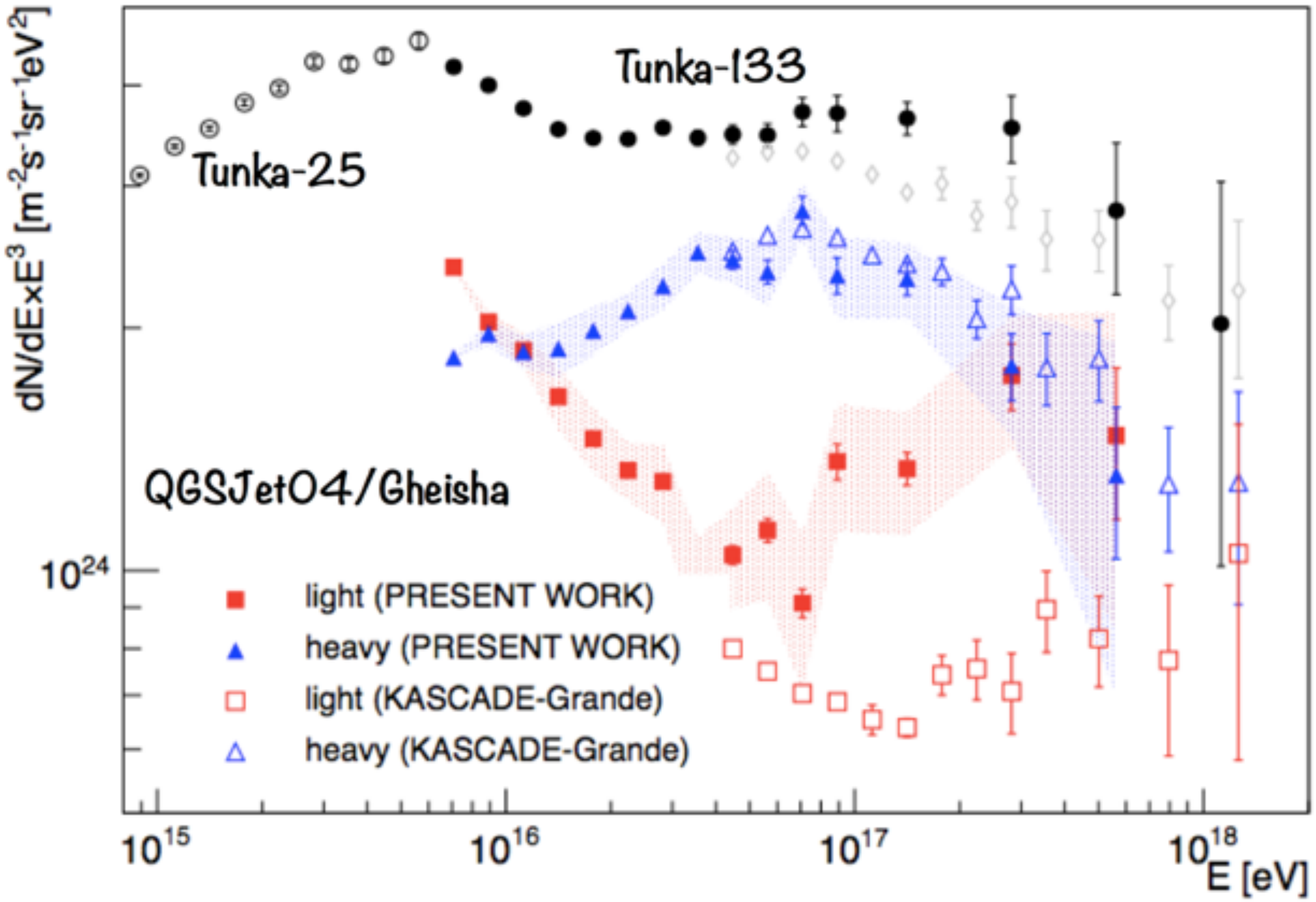


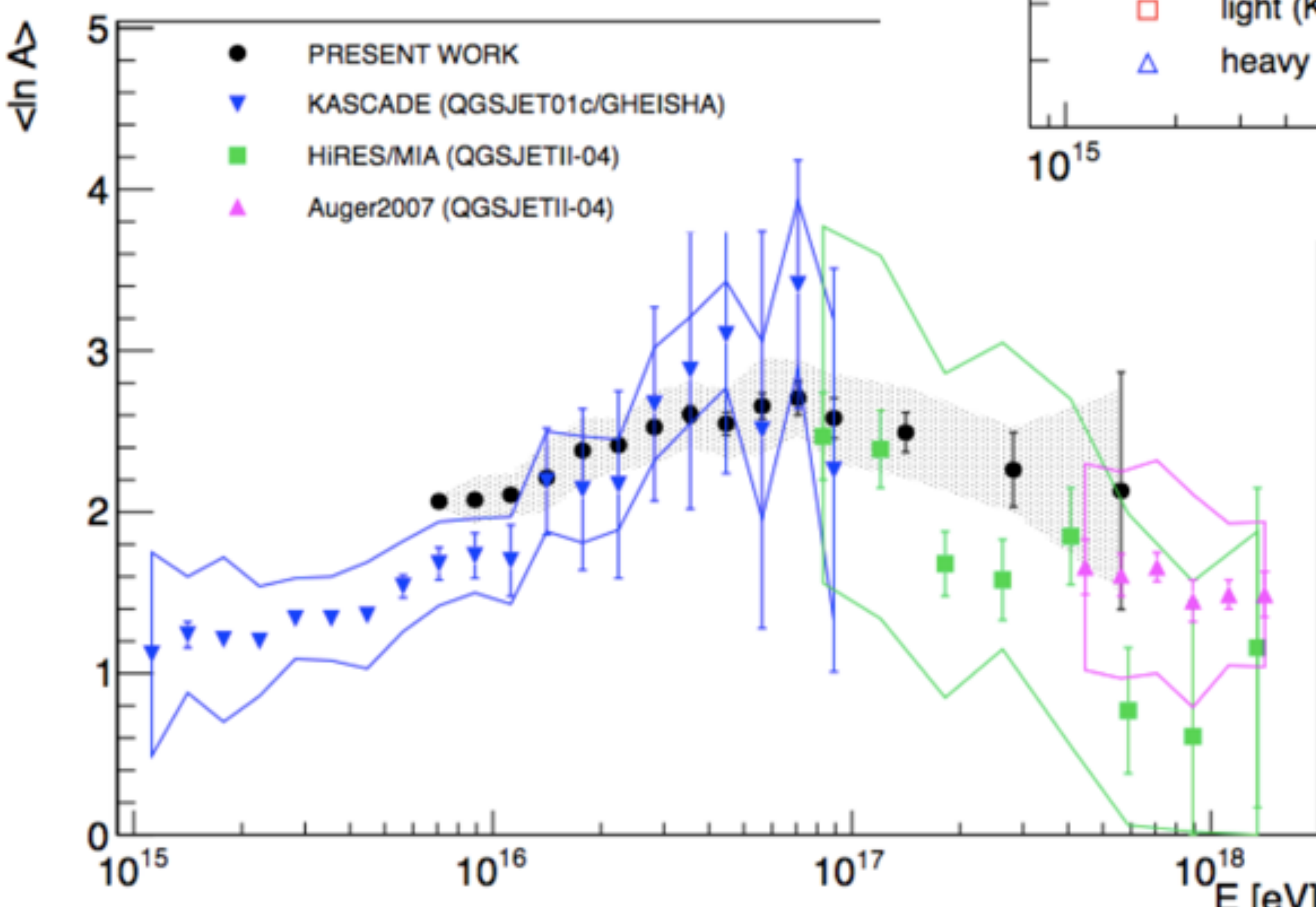
- T-133 and HEAT ?
- T-133 and Ice-Top ?

Tunka Composition

light: p+He

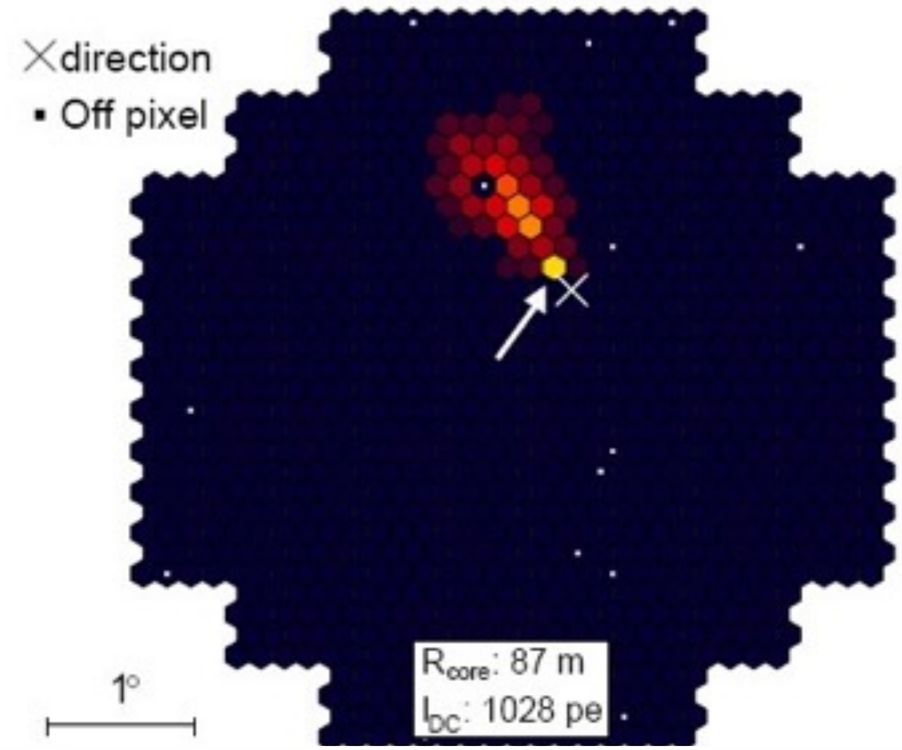
heavy: N+Fe



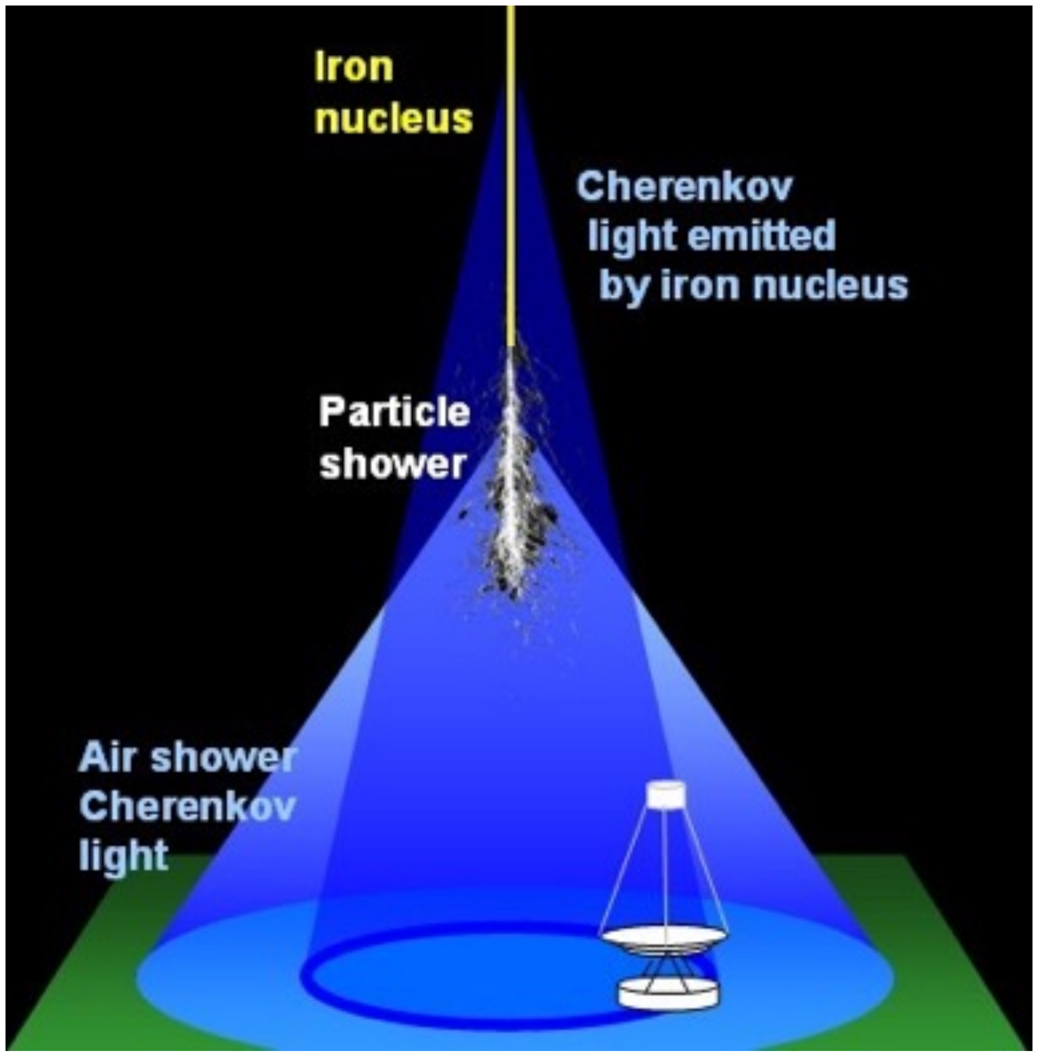


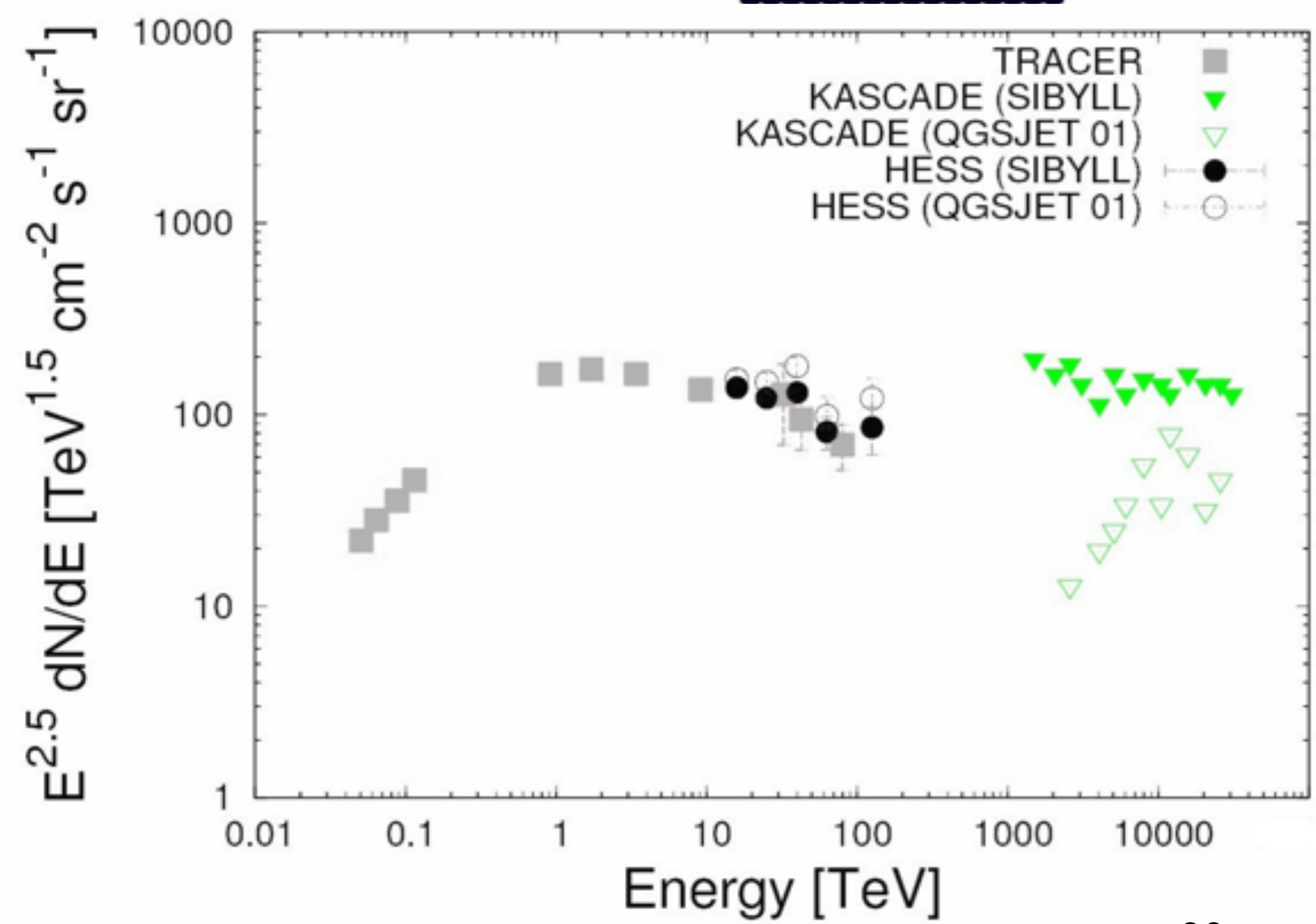
- knee : p, He
- heavy knee at ~ 7 10^{16} eV
- light component growing above 4-5 10^{16} eV
- mean mass getting heavier up to ~ 10^{17} eV, then lighter again

Cherenkov light: H.E.S.S.
Iron: 15 – 150 TeV



Cherenkov Light $\propto Z^2$





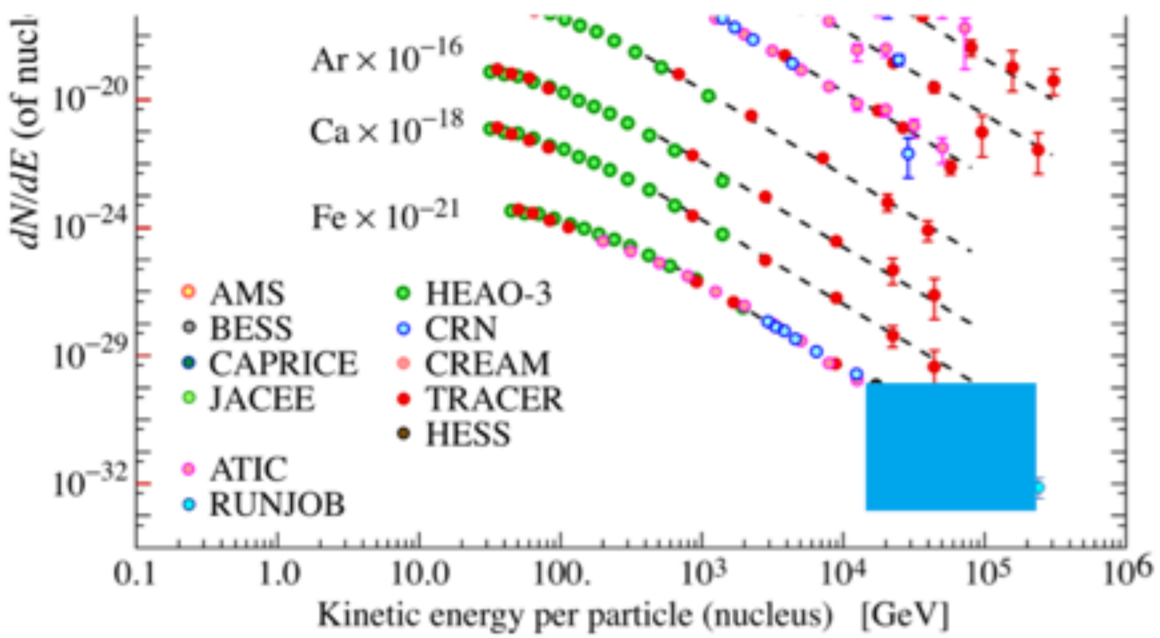
Good agreement with other exper.
- Hadronic model ≈20% on normal.
- Power-law Index

QGSJET= 2.62 +- 0.11
SIBYLL= 2.76 +- 0.11

Aharonian et al., 2007

Previous Results (H.E.S.S. & VERITAS)

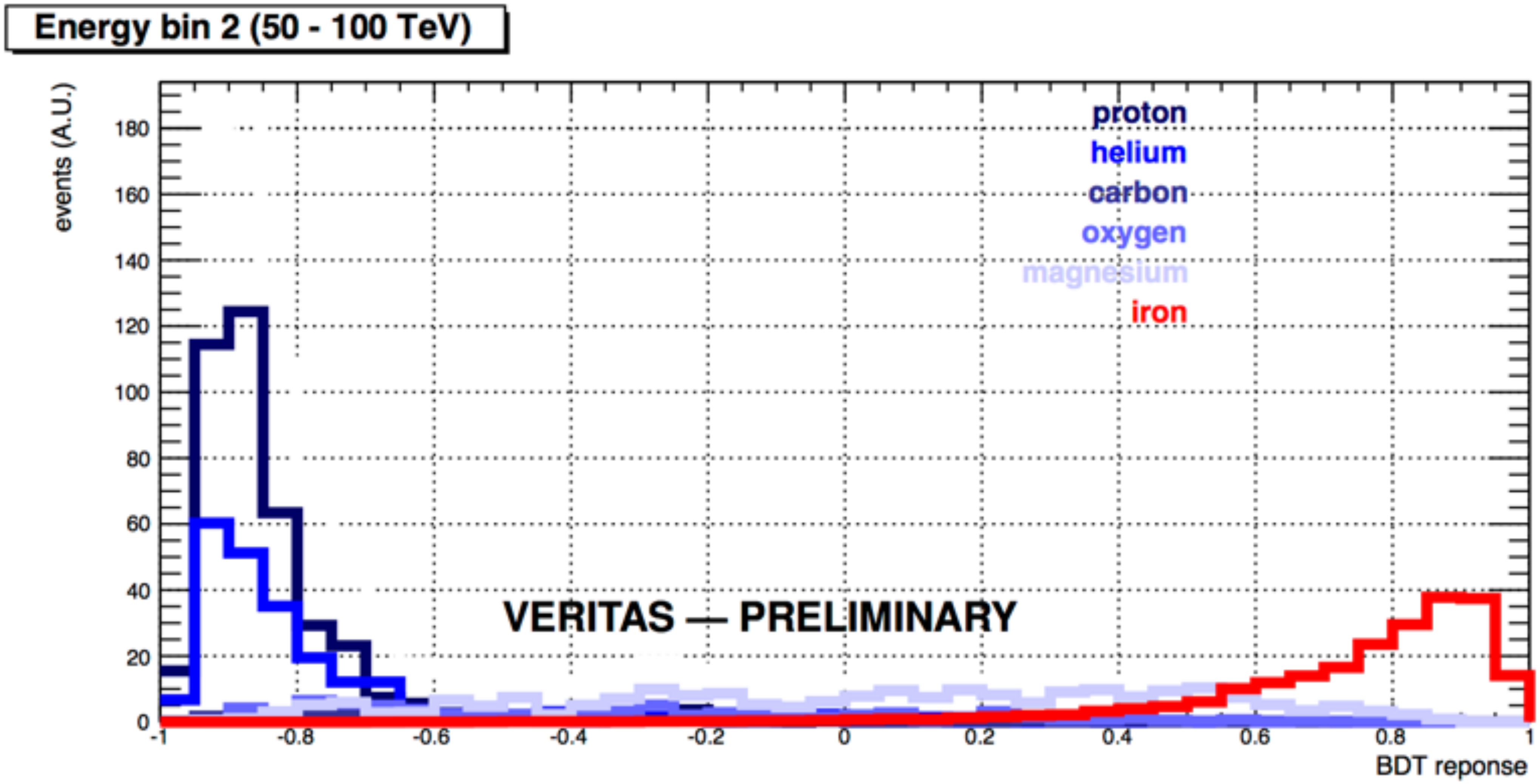
- Aharonian et al. [2007]: 'heavy' elements ($Z = 25 - 28$), 13 – 200 TeV.
- Wissel [2010]: iron, 20 – 140 TeV.
- Spectral shape: $F(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\gamma}$, see below.
- Dominant uncertainties: statistics, atmosphere, hadronic interaction model.
- Can we improve on that?



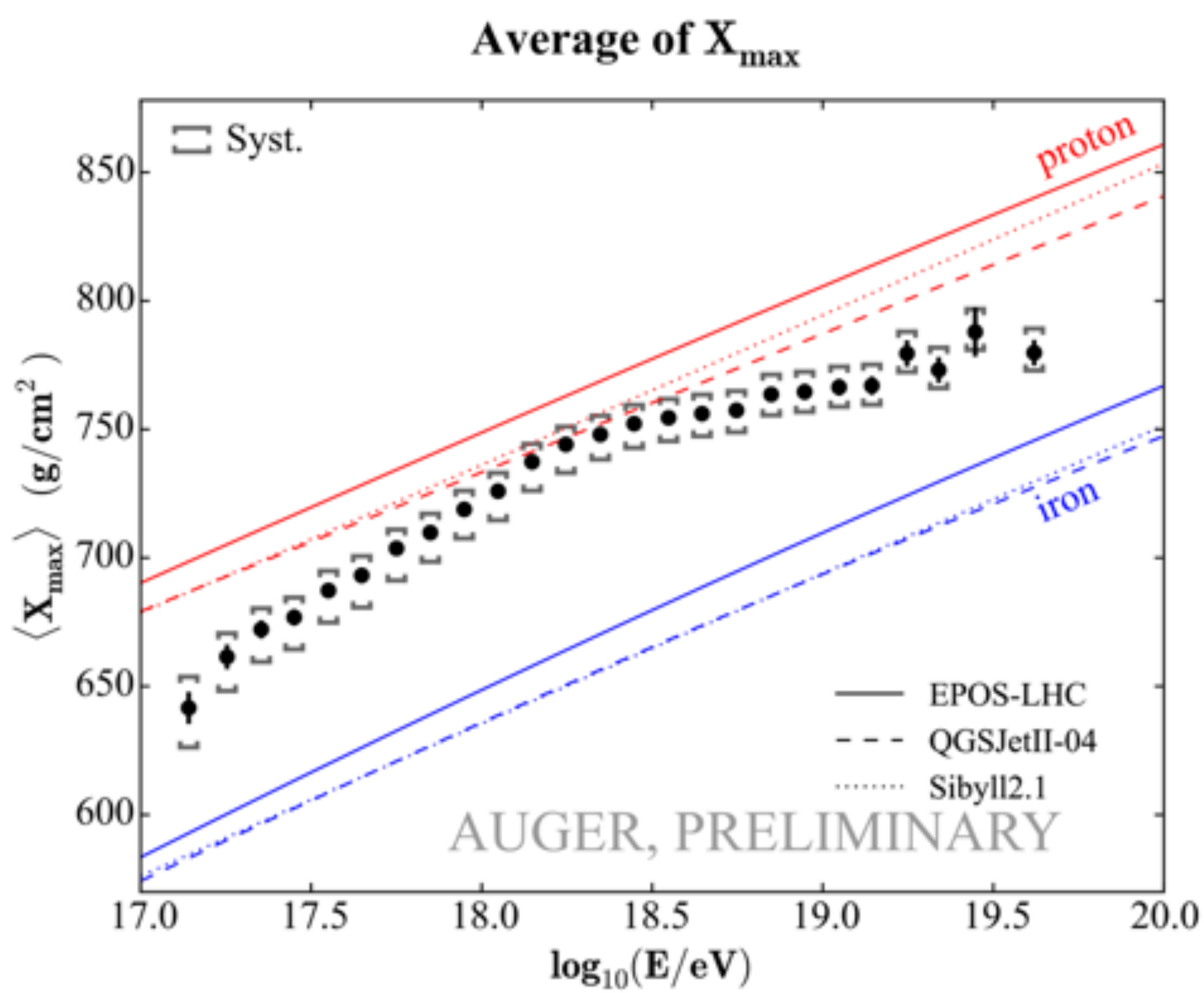
	E_0/TeV	$\phi_0 \cdot (m^2 \cdot s \cdot sr \cdot TeV)$	γ
H.E.S.S. (QGSJET)	1	$(2.2 \pm 0.9 \pm 0.6) \cdot 10^{-2}$	$2.62 \pm 0.11 \pm 0.17$
H.E.S.S. (SYBILL)	1	$(2.9 \pm 1.1 \pm 0.8) \cdot 10^{-2}$	$2.76 \pm 0.11 \pm 0.17$
VERITAS (QGSJET)	50	$(5.8 \pm 0.84 \pm 1.2) \cdot 10^{-7}$	$2.84 \pm 0.3 \pm 0.3$

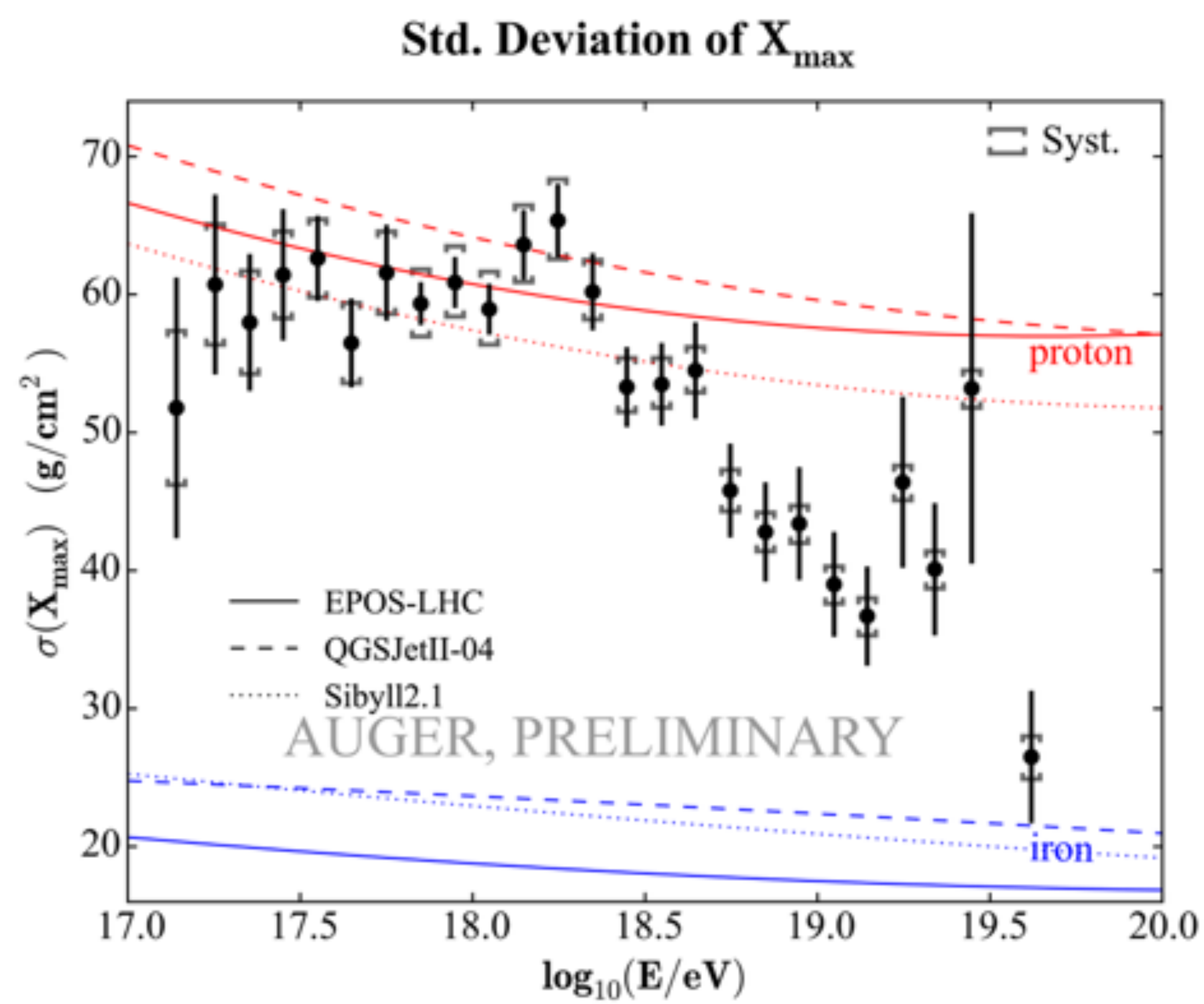
Charge separation

- Multivariate analysis combining DC light, image shape, . . .
- Composition measurement possible with this approach.



Average shower maximum and RMS

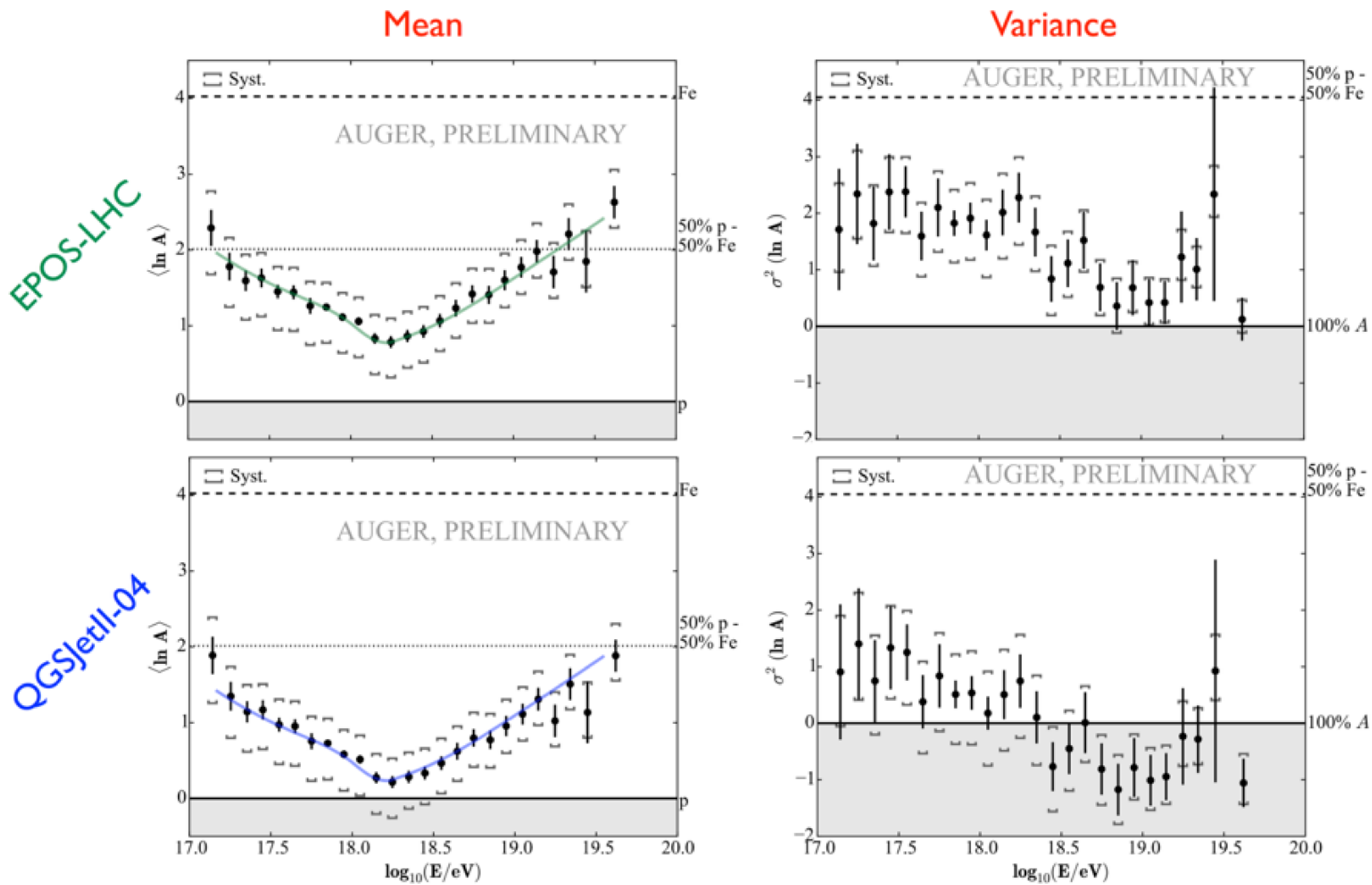




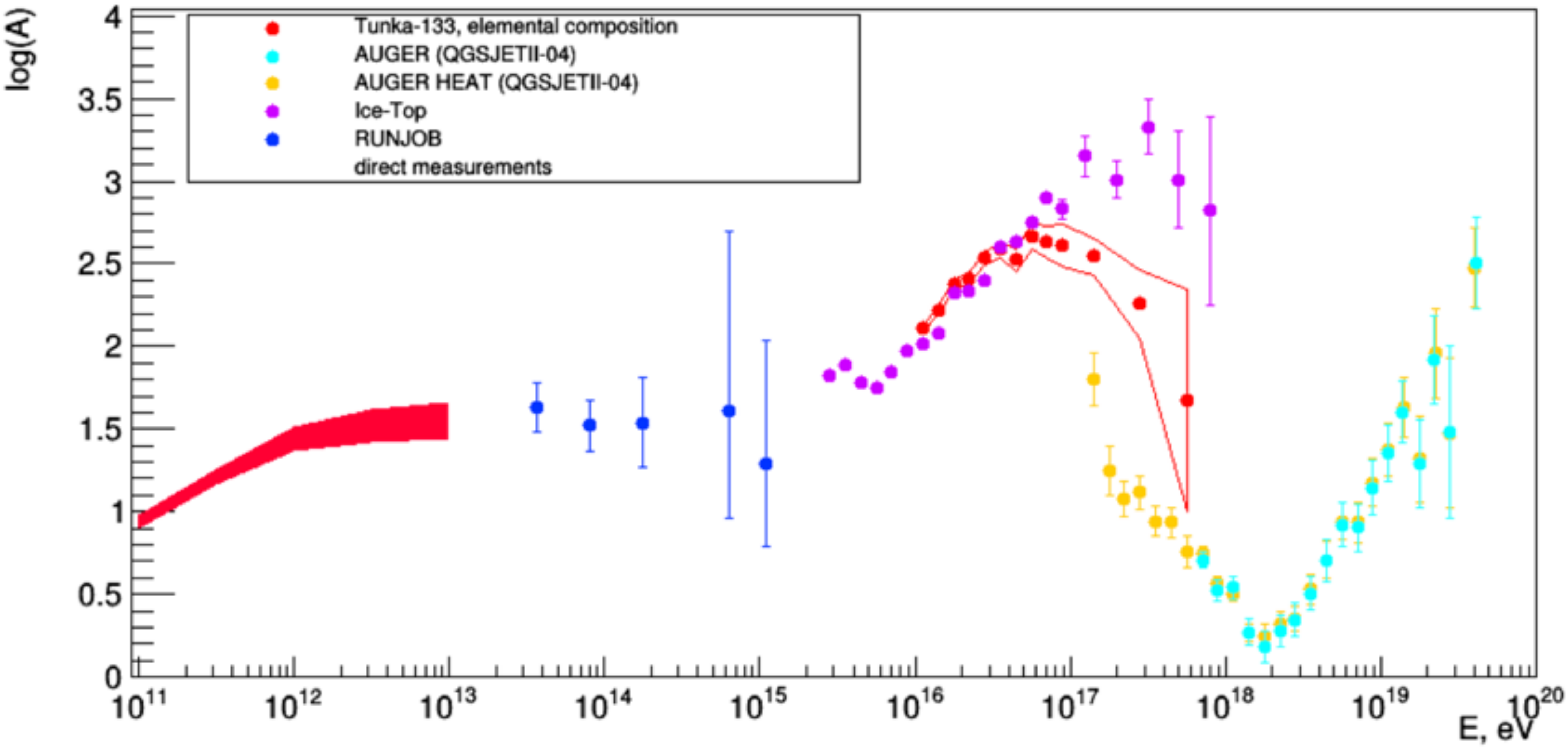
Dip model (ankle due to pure proton flux) seems to be ruled out

Pierre Auger Collaboration, to be presented at ICRC15

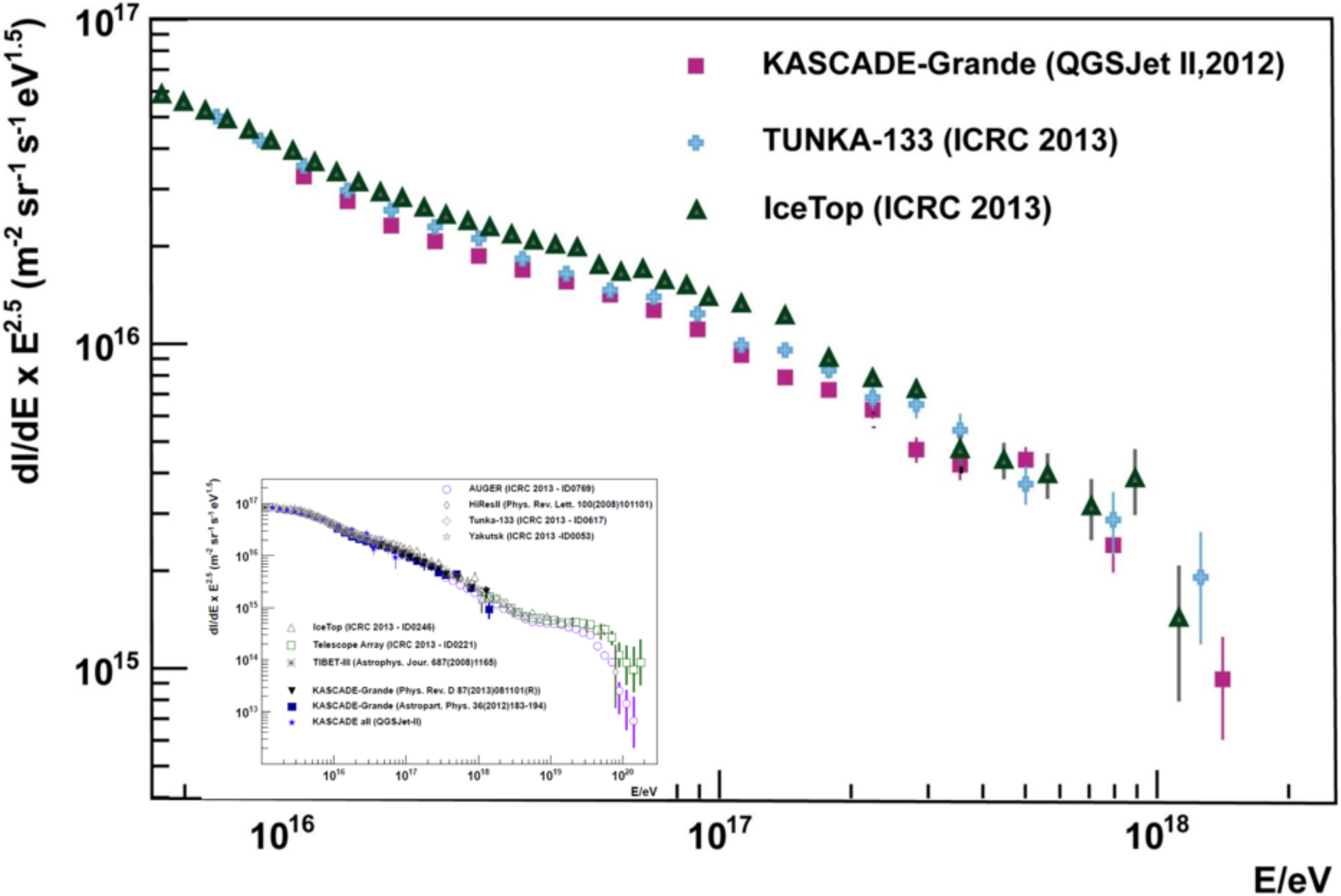
Statistical moments of ⟨ln A⟩



Most recent data. Where are we?

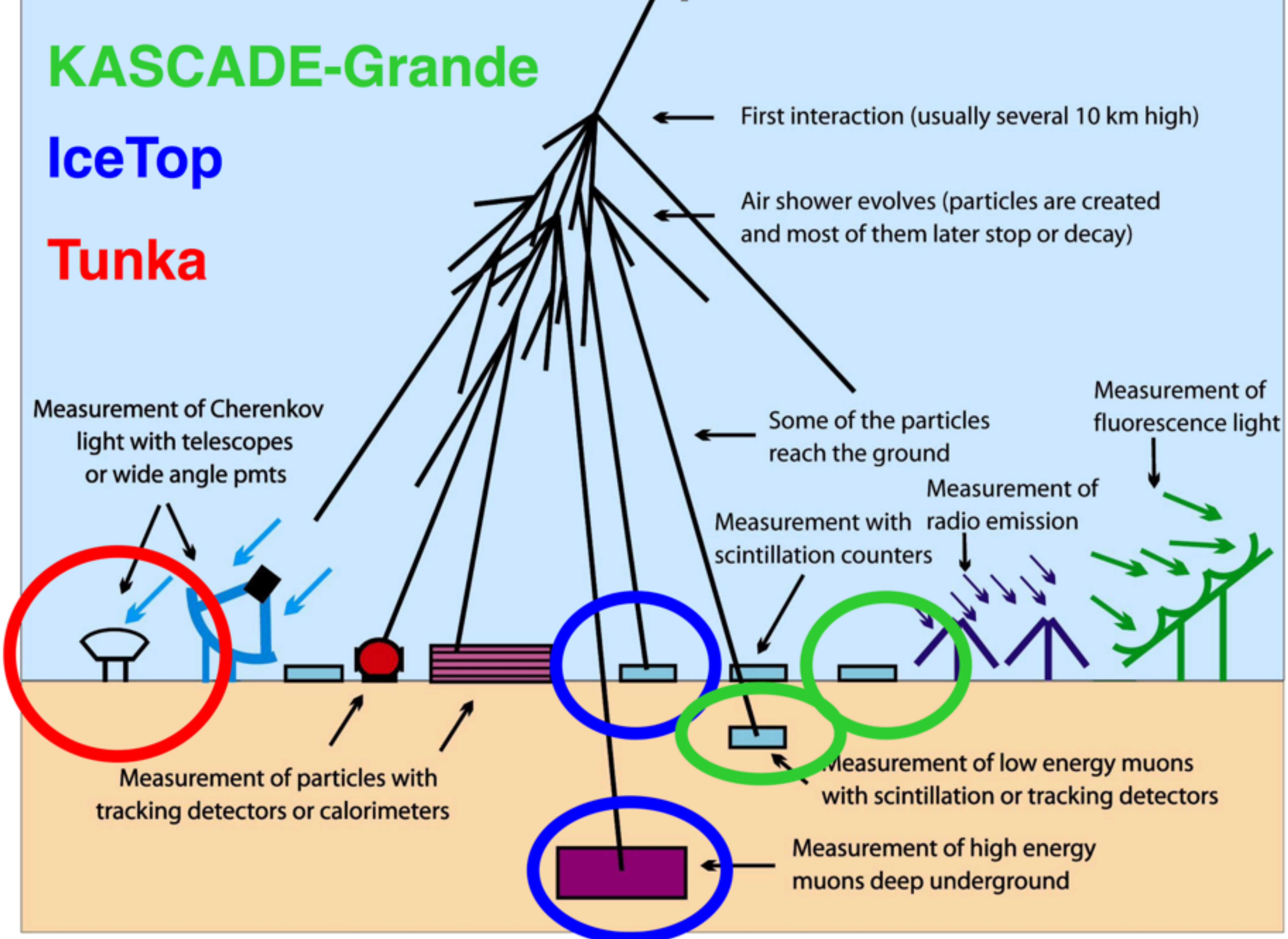


- T-133 and HEAT ?
- T-133 and Ice-Top ?

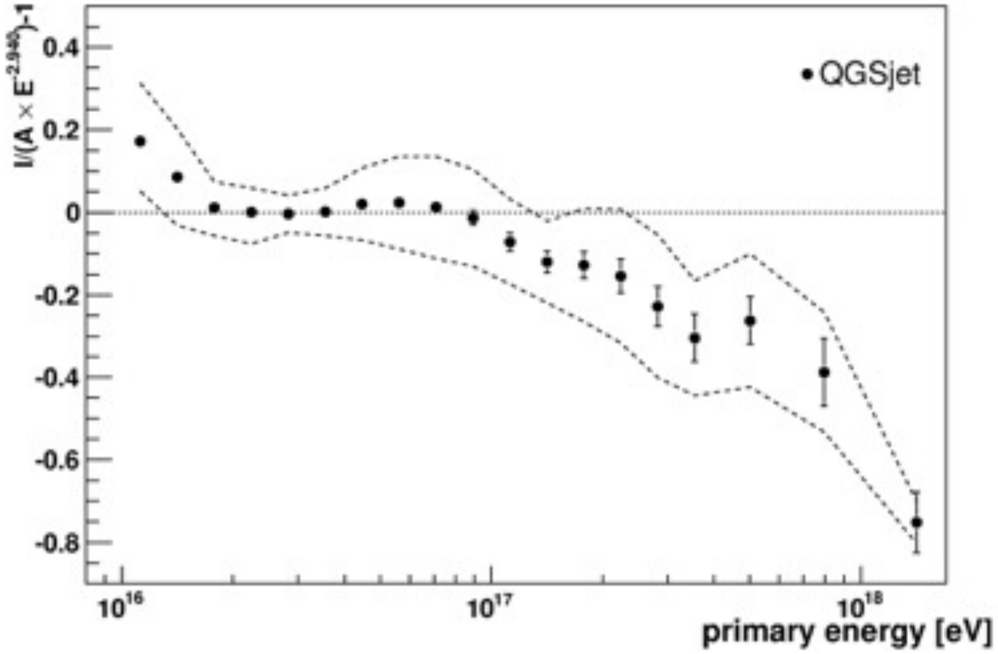


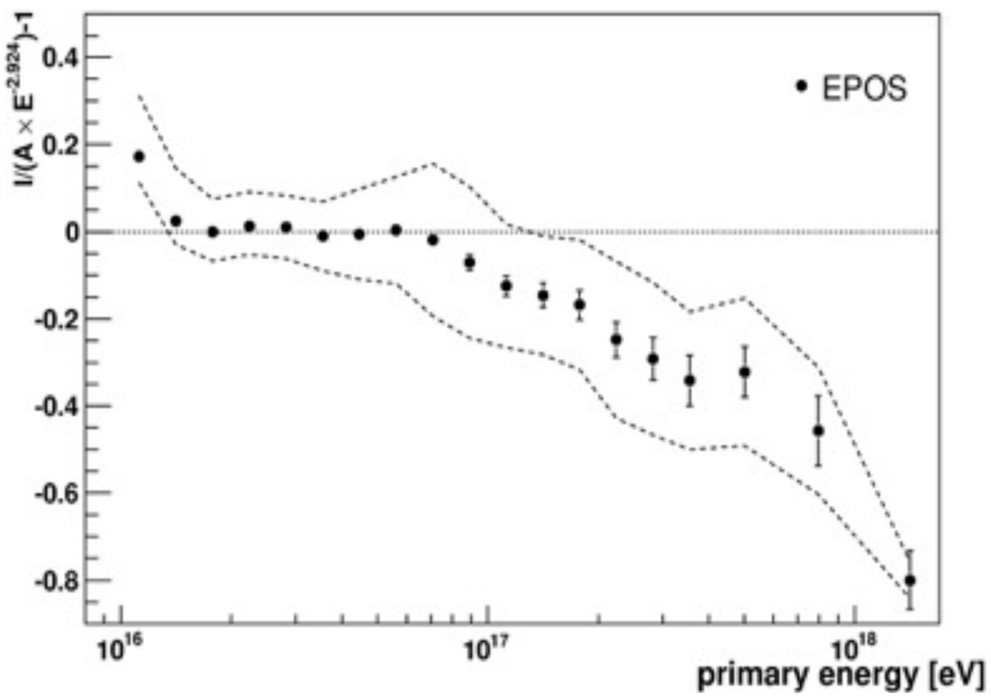
- Structures of all-particle spectra similar (in the level of 15%)

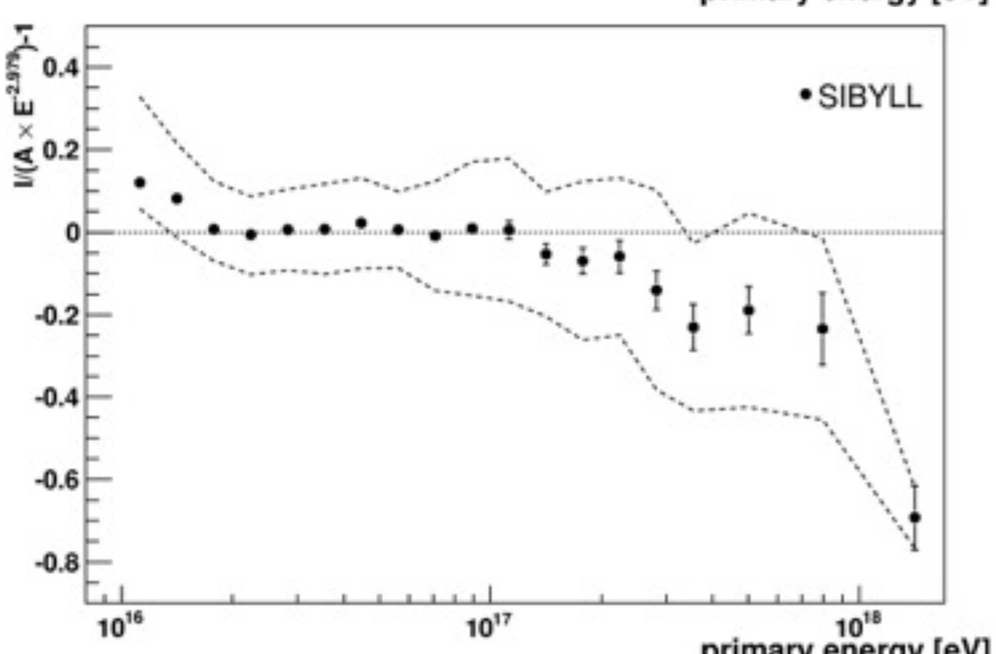
Measurement Techniques of Air Showers

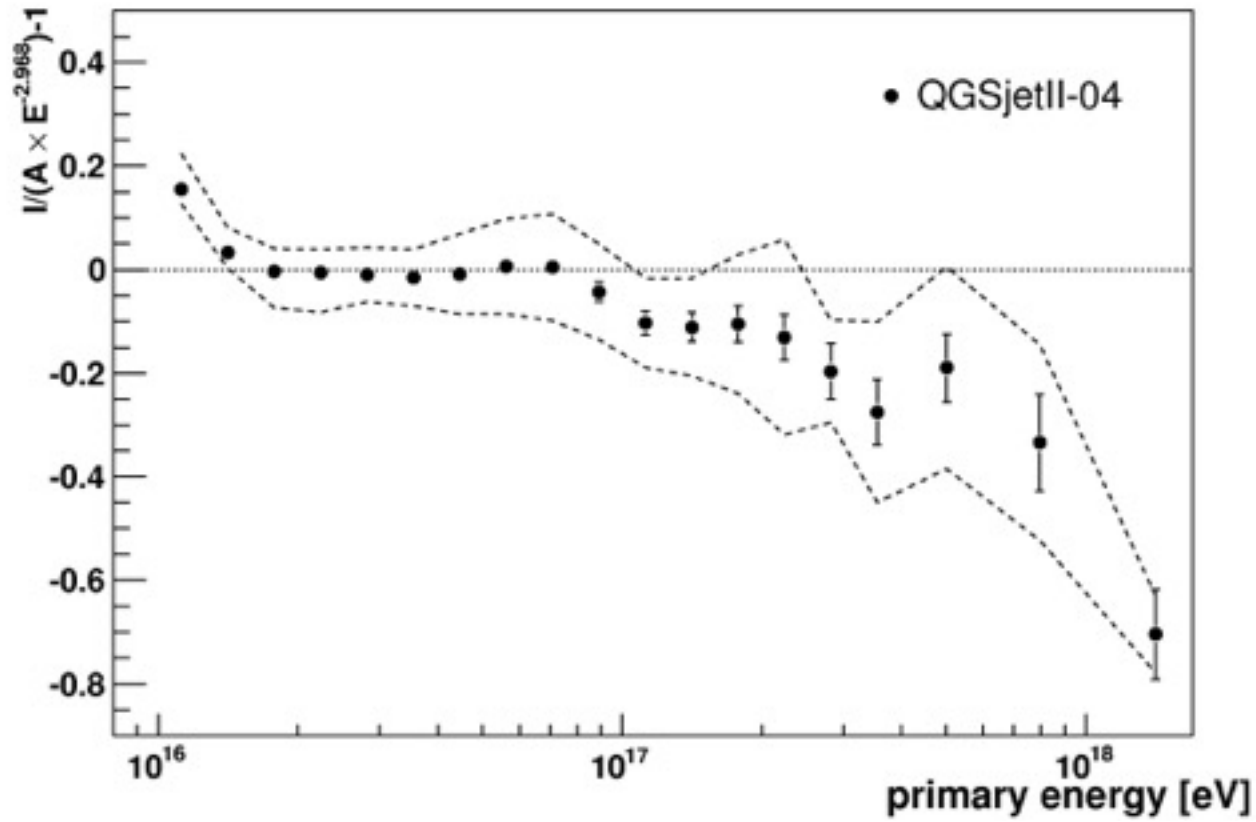


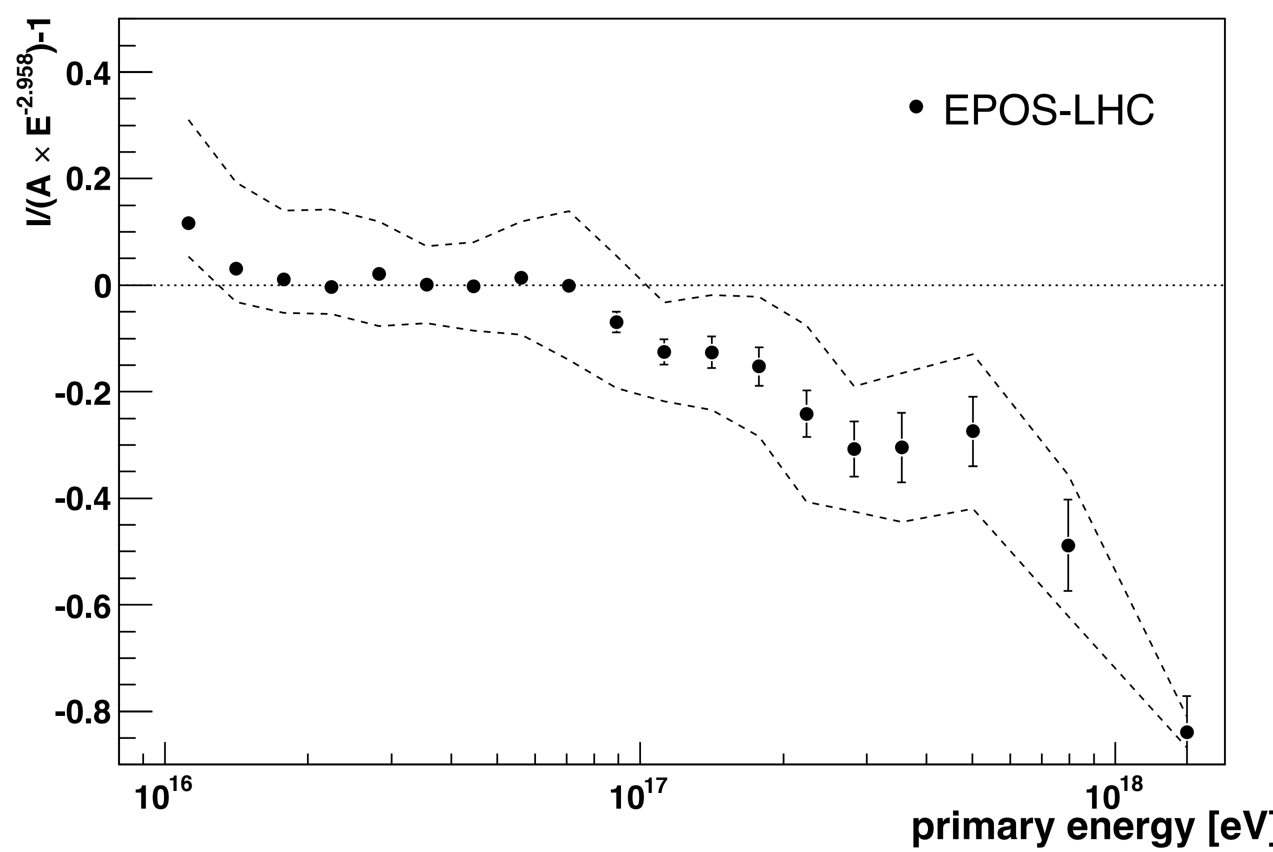
RESIDUAL PLOTS – UNFOLDED DATA



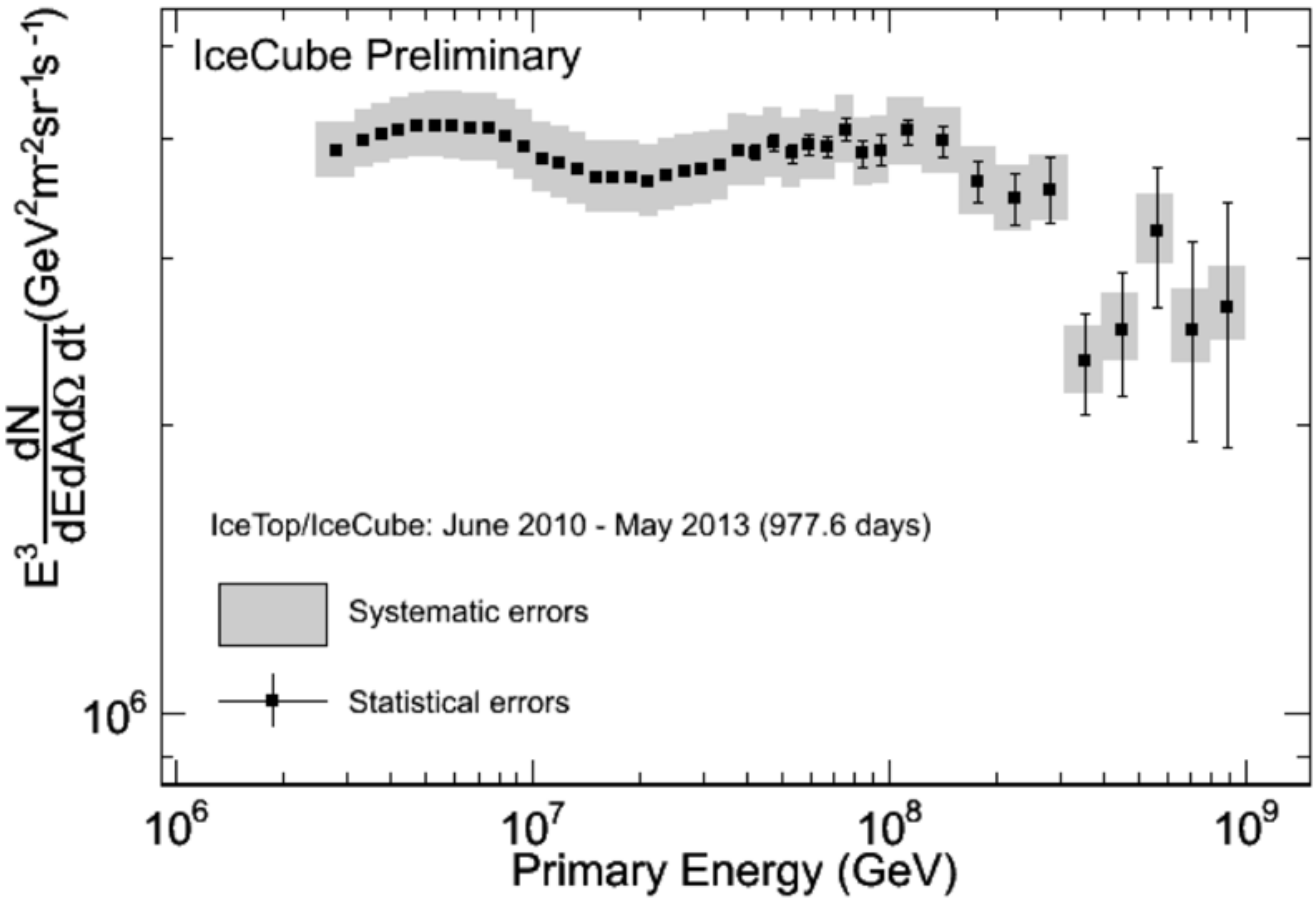




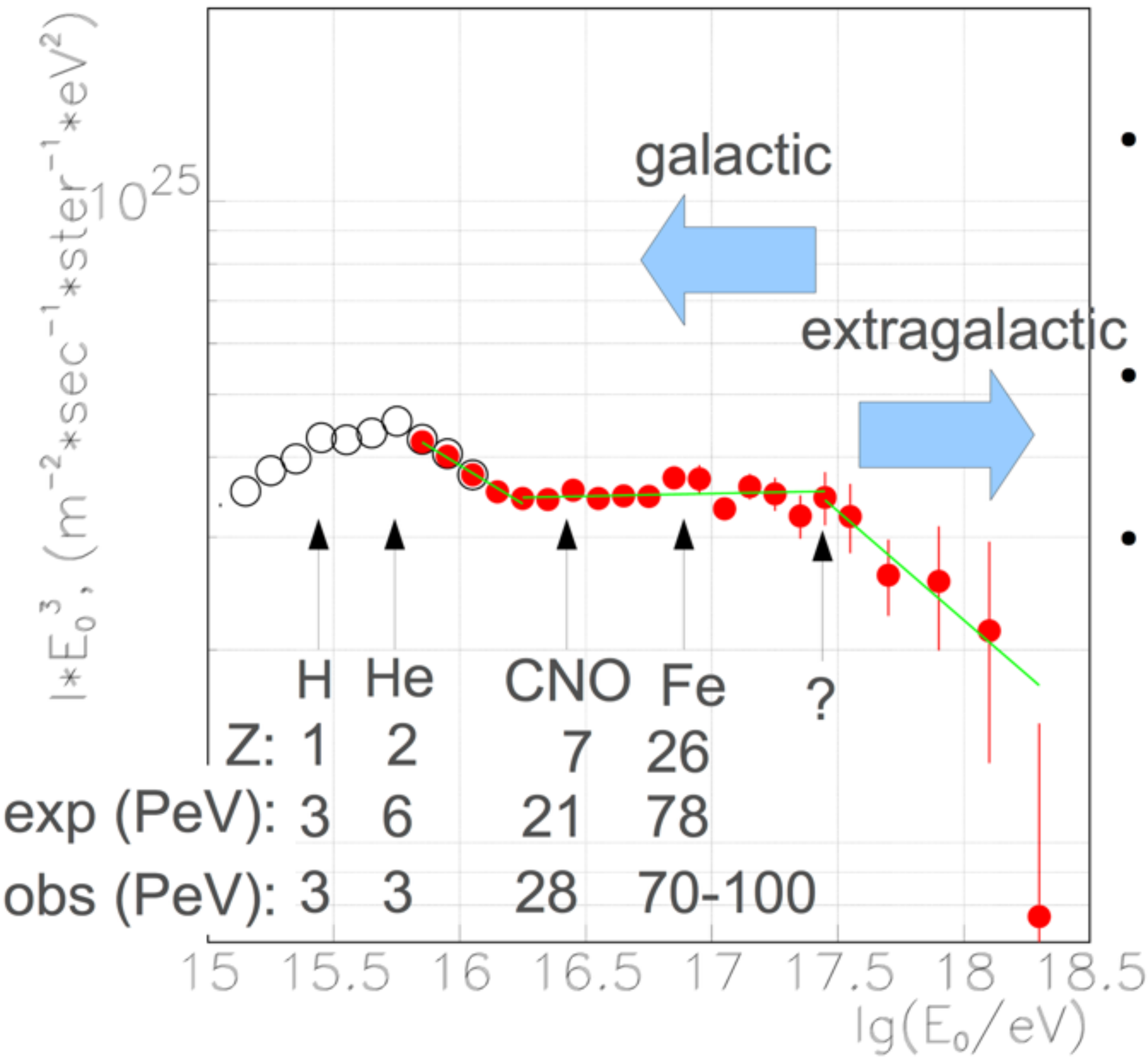




Results: Energy spectrum



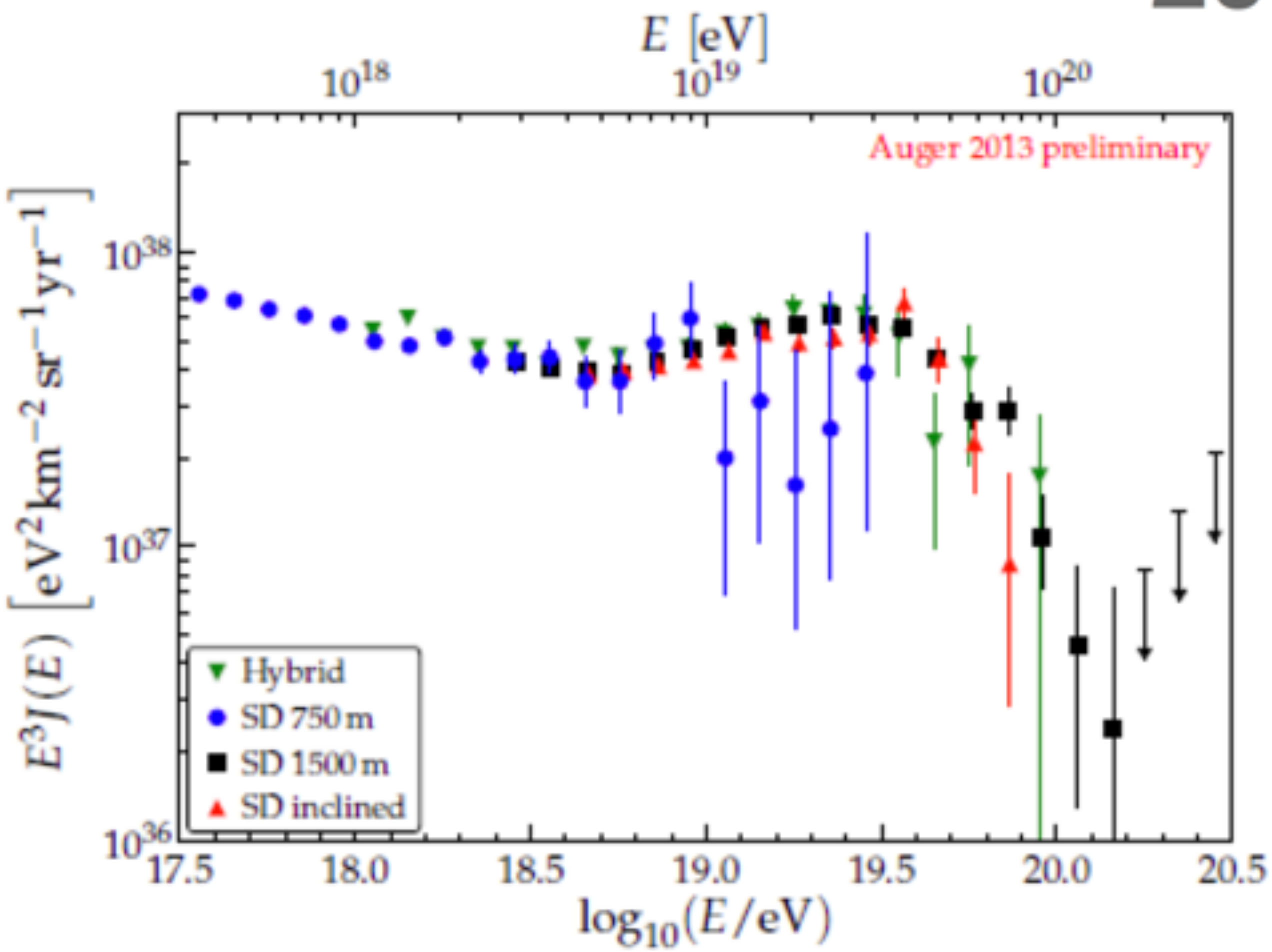
Energy spectrum: interpretation

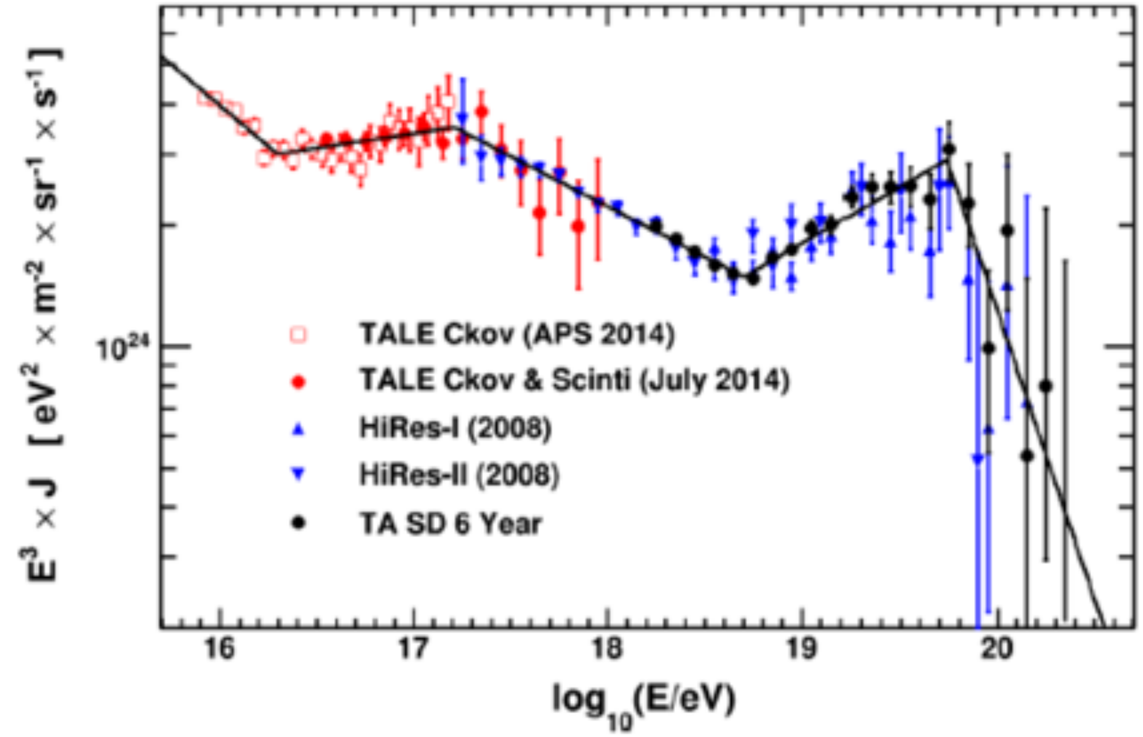


the classical view:

- rigidity dependent cut-offs of different nuclei groups ($E_c \sim Z$)
- the composite knee – hydrogen and helium
- the 2nd knee – acceleration limit of the Galaxy

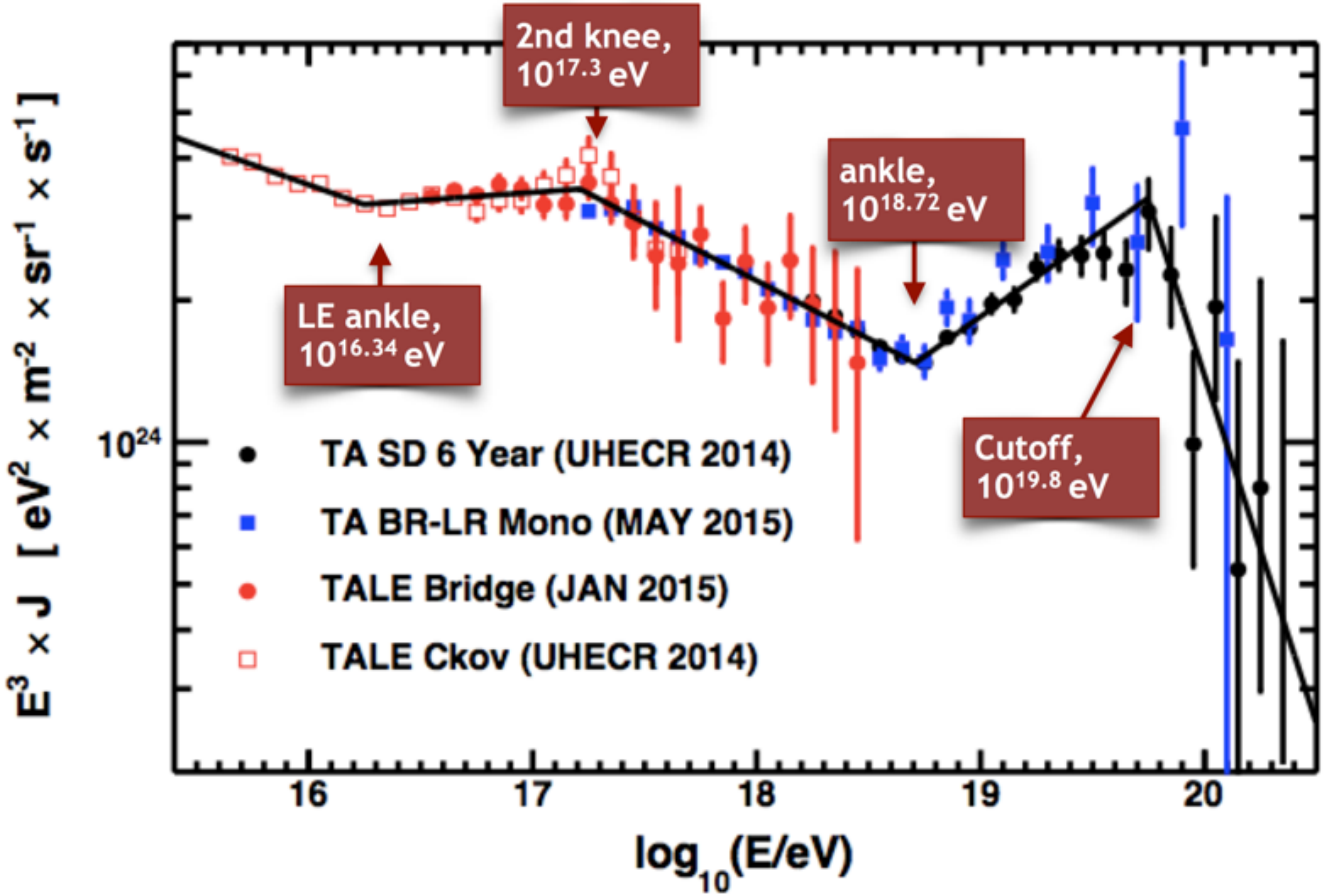
2015


E [eV]
10^18
10^19
10^20
Auger 2013 preliminary
E^3 J(E) [eV^2 km^-2 sr^-1 yr^-1]
10^38
10^37
10^36
Hybrid
SD 750 m
SD 1500 m
SD inclined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
log10(E/eV)


E^3 × J [eV^2 × m^-2 × sr^-1 × s^-1]
10^24
TALE Ckov (APS 2014)
TALE Ckov & Scinti (July 2014)
HiRes-I (2008)
HiRes-II (2008)
TA SD 6 Year
16
17
18
19
20
log10(E/eV)


Pierre Auger
Observatory


Telescope Array



- 4.8 orders of magnitude spectrum, 4 spectral features
- thanks to TALE, a clear 2nd knee is visible at ~1.5 10^{17} eV and a low energy ankle appears at 1.8 10^{16} eV
- ankle at 5.2 10^{18} eV cutoff at 6.3 10^{19} eV (6.5σ)

2^{nd} knee

Table 2. Our broken power law fits to spectrum measurements in the Second Knee energy range. The fit parameters include a normalization (not shown), slope parameters above and below the break and the break point energy for the Second Knee.

Experiment (reference)	χ^2/DOF	Slope below	Break point $\log_{10}\left(\frac{E}{eV}\right)$	Slope above
Akeno (Nagano *et al* 1992)	8.3/13	3.04 ± 0.02	17.8 ± 0.2	3.25 ± 0.12
Fly's Eye (Bird *et al* 1993)	13.7/18	3.04 ± 0.05	17.60 ± 0.06	3.27 ± 0.02
HiRes/MIA (Abu-Zayyad *et al* 2001)	2.5/5	3.02	17.6 ± 0.2	3.23 ± 0.14
Haverah Park (Ave *et al* 2003a)	1.4/5			3.32 ± 0.05
Yakutsk T-500 (Egorova *et al* 2004)	45.2/15			3.213 ± 0.0
HiRes (Abbasi *et al* 2007a)	8.55/15			3.26 ± 0.02
Global fit (at Fly's Eye *E* scale)	109.4/93	3.02 ± 0.01	17.52 ± 0.02	3.235 ± 0.0

K-Grande

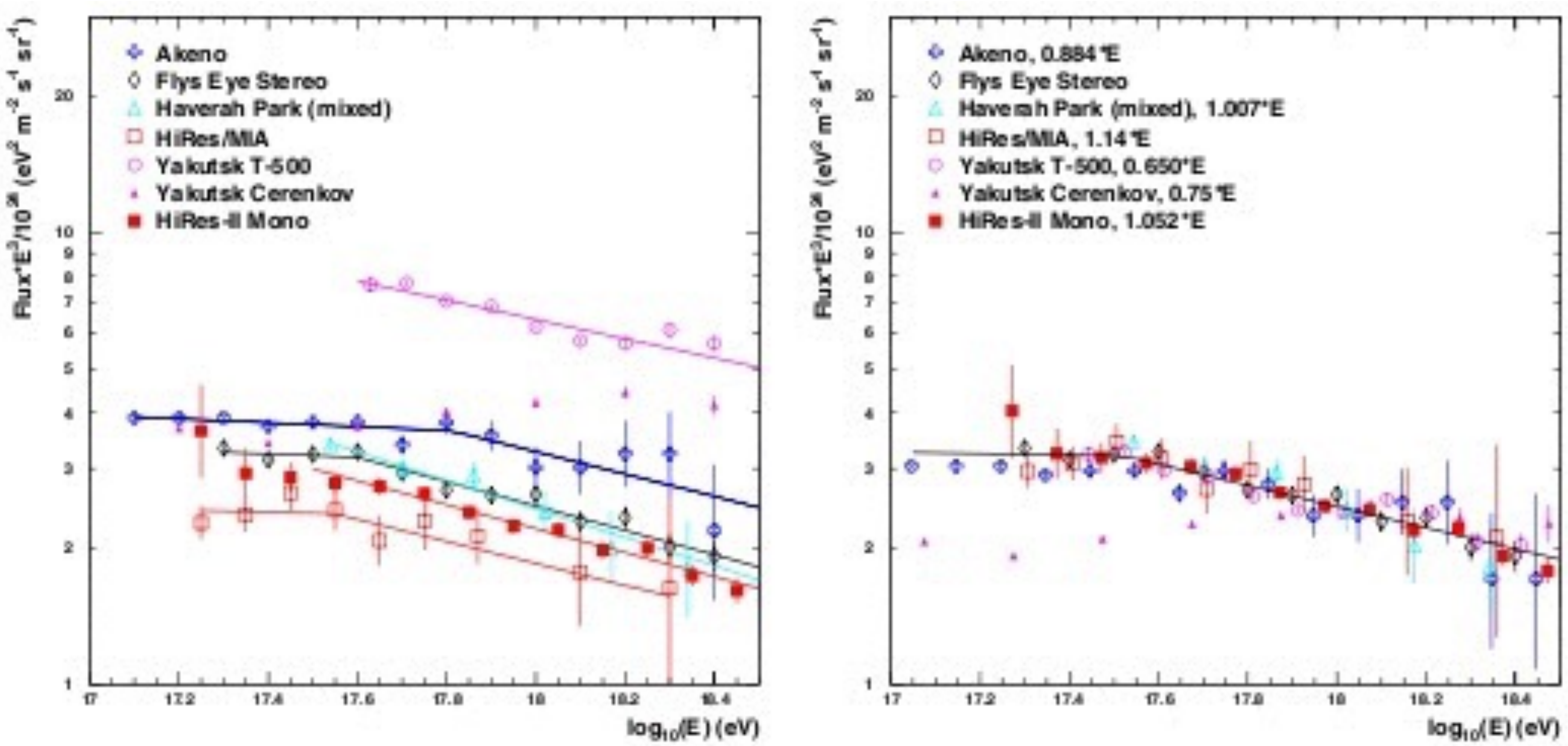
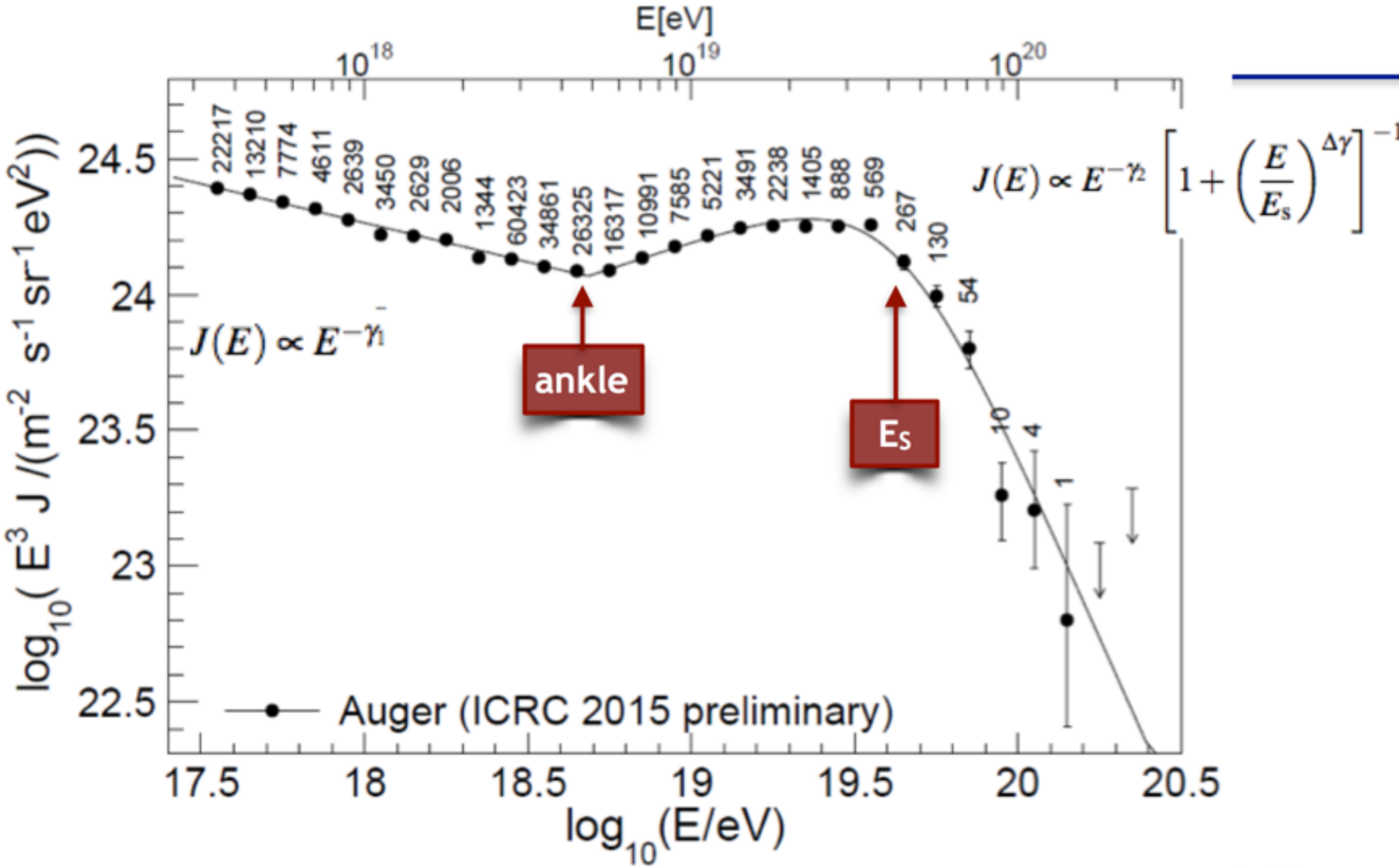


Figure 11. Left: flux measurements in the Second Knee energy range. The shown fits are our calculation. Right: flux measurements in the Second Knee energy range, scaled so that the flux agrees with the Fly's Eye result at 10^{18} eV. The scaled data points were fit to a broken power law spectrum in a global fit, with the result shown.

Global fit Fly's Eye E scale:

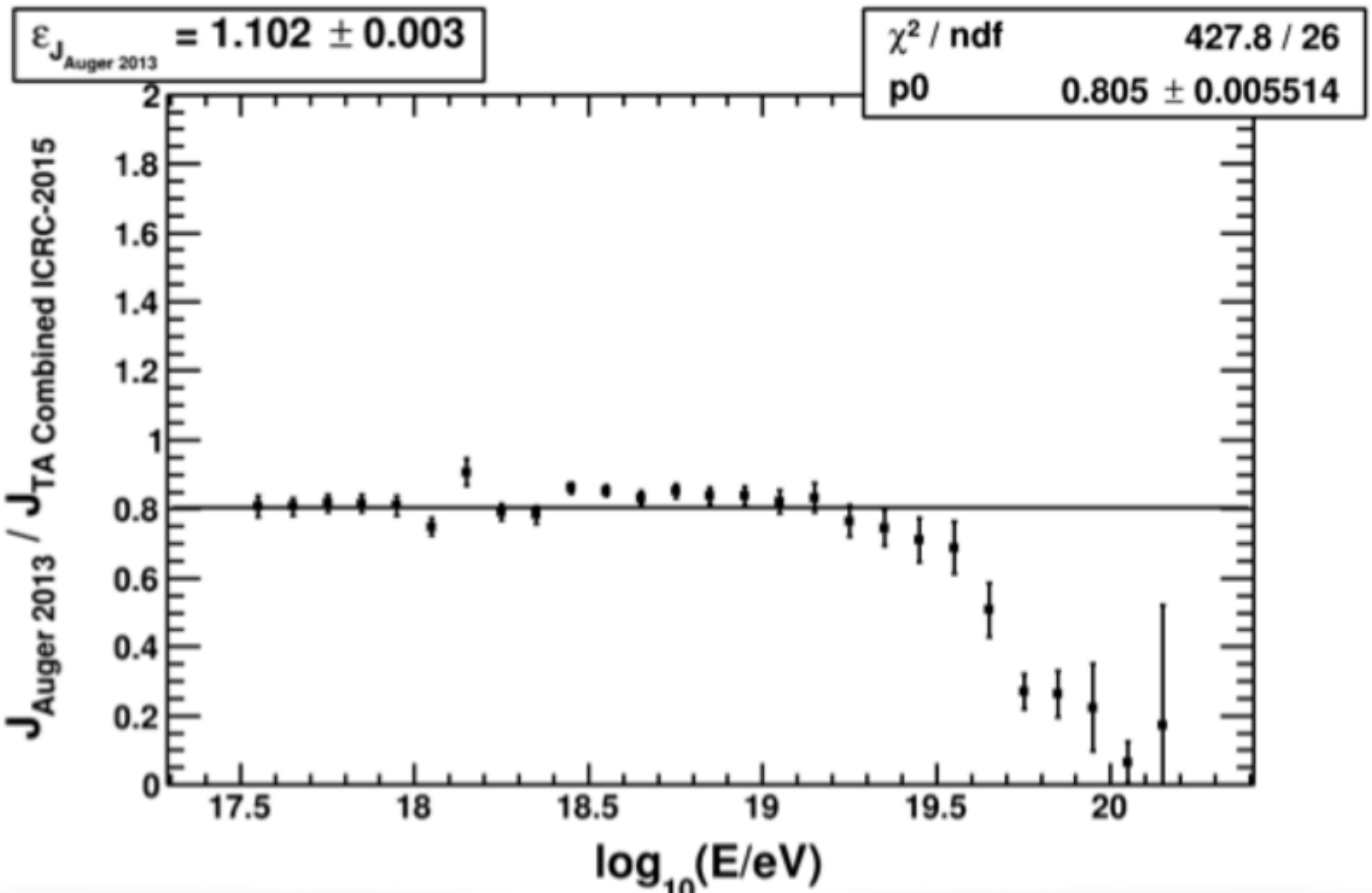
$$\mathrm{Log}_{10}(E/eV) = 17.52 \pm 0.02$$
$$\gamma_{below} = 3.02 \pm 0.01$$
$$\gamma_{above} = 3.235 \pm 0.008$$

D.R. Bergman & J.W. Belz, J. Phys. G: Nucl. Part. Phys. **34** (2007) R359–R400



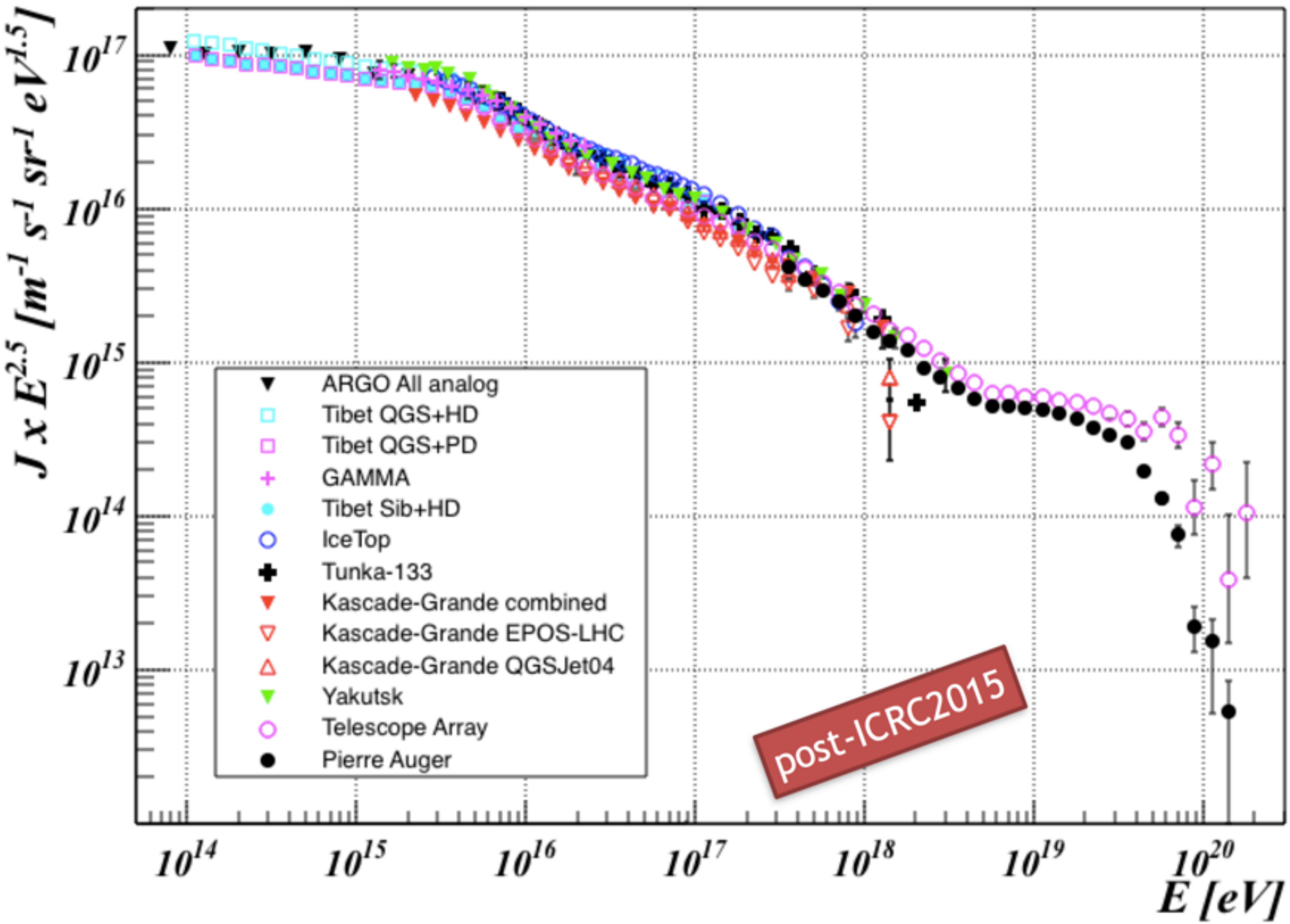
- ankle observed at E_{ankle}= 4.8 10^{18} eV
- cut-off clearly observed (>20σ significance)
- fitting model: power law below the ankle+power law with smooth suppression above
- Es=4.2 10^{19} eV, $E_{1/2} = (2.48 \pm 0.01)\times10^{19}$ eV

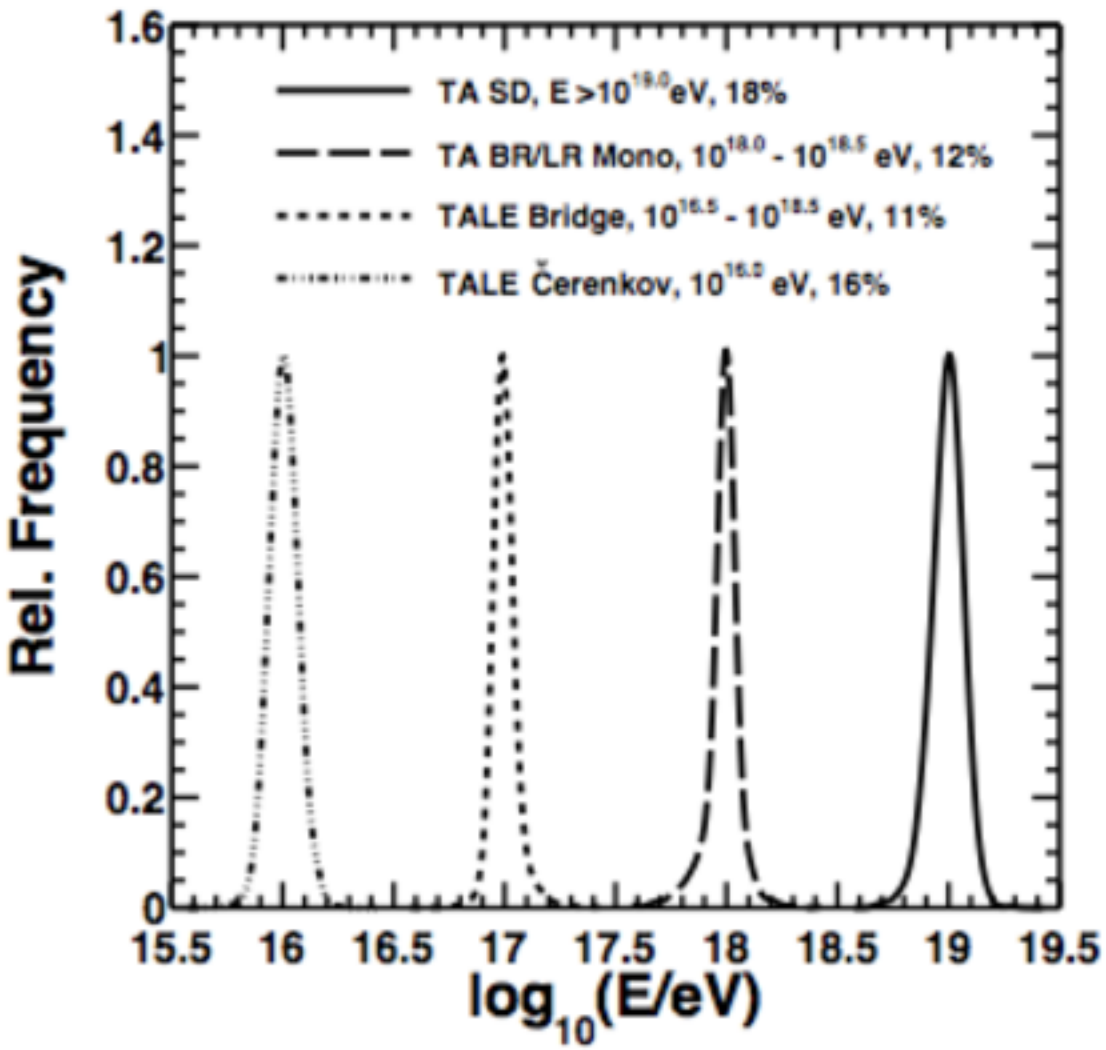
Auger / Telescope Array comparison

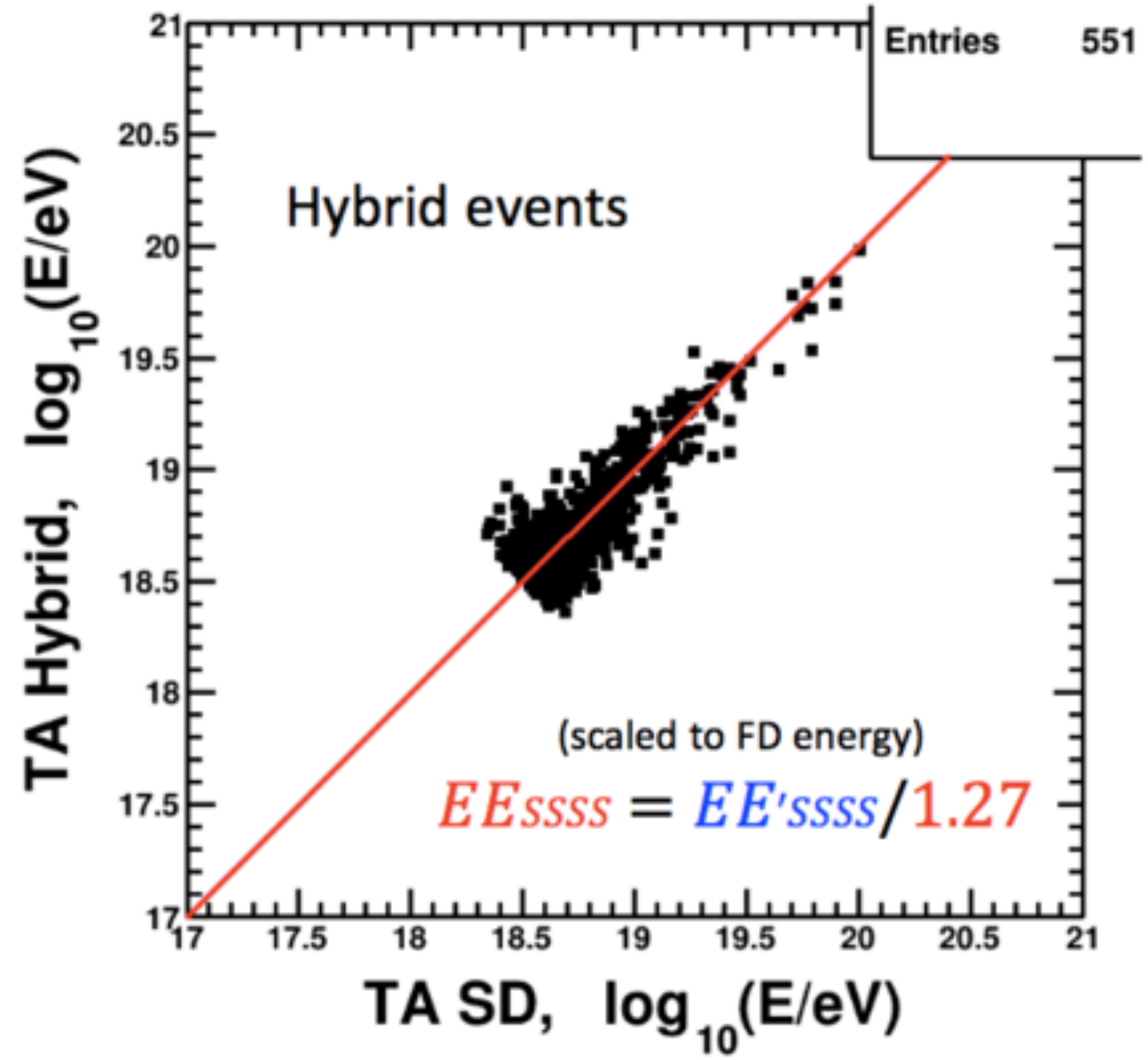


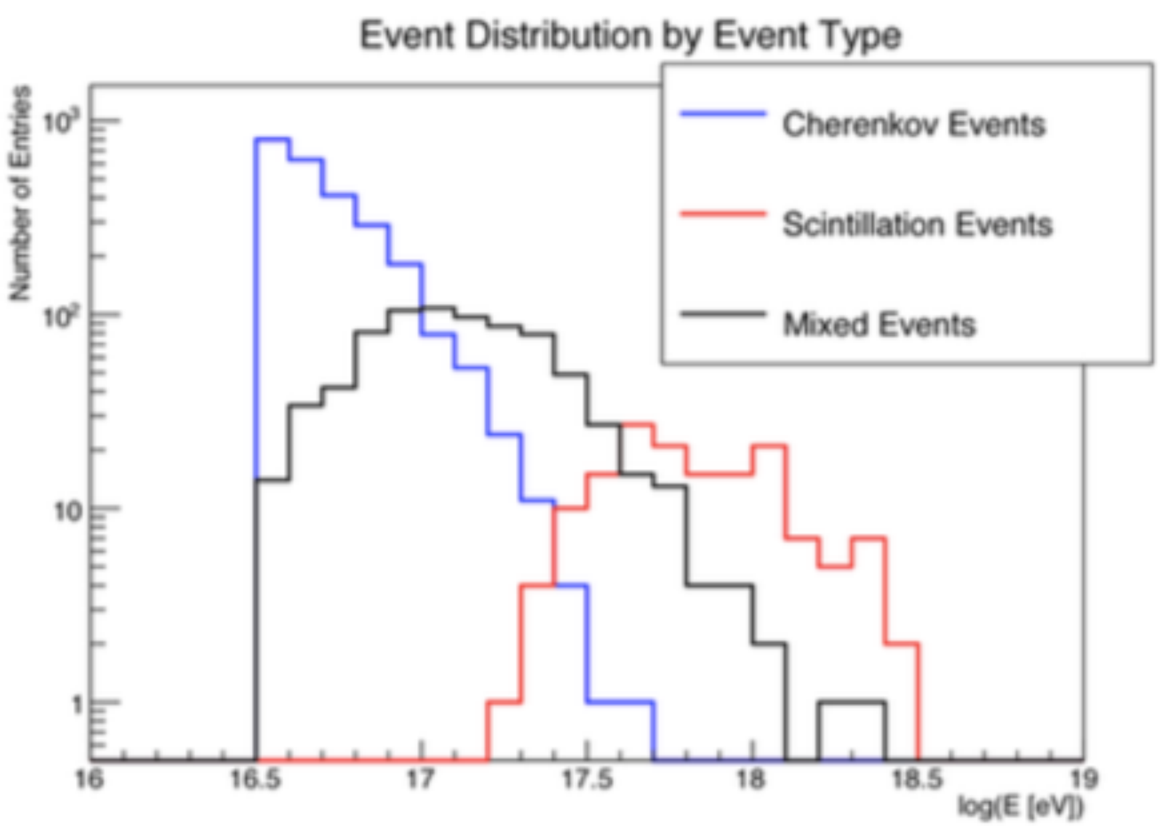
- 10% shift in energy would bring the two in agreement up to $10^{19.3}$ eV
- large discrepancy above

All particle spectrum









4 different data sets

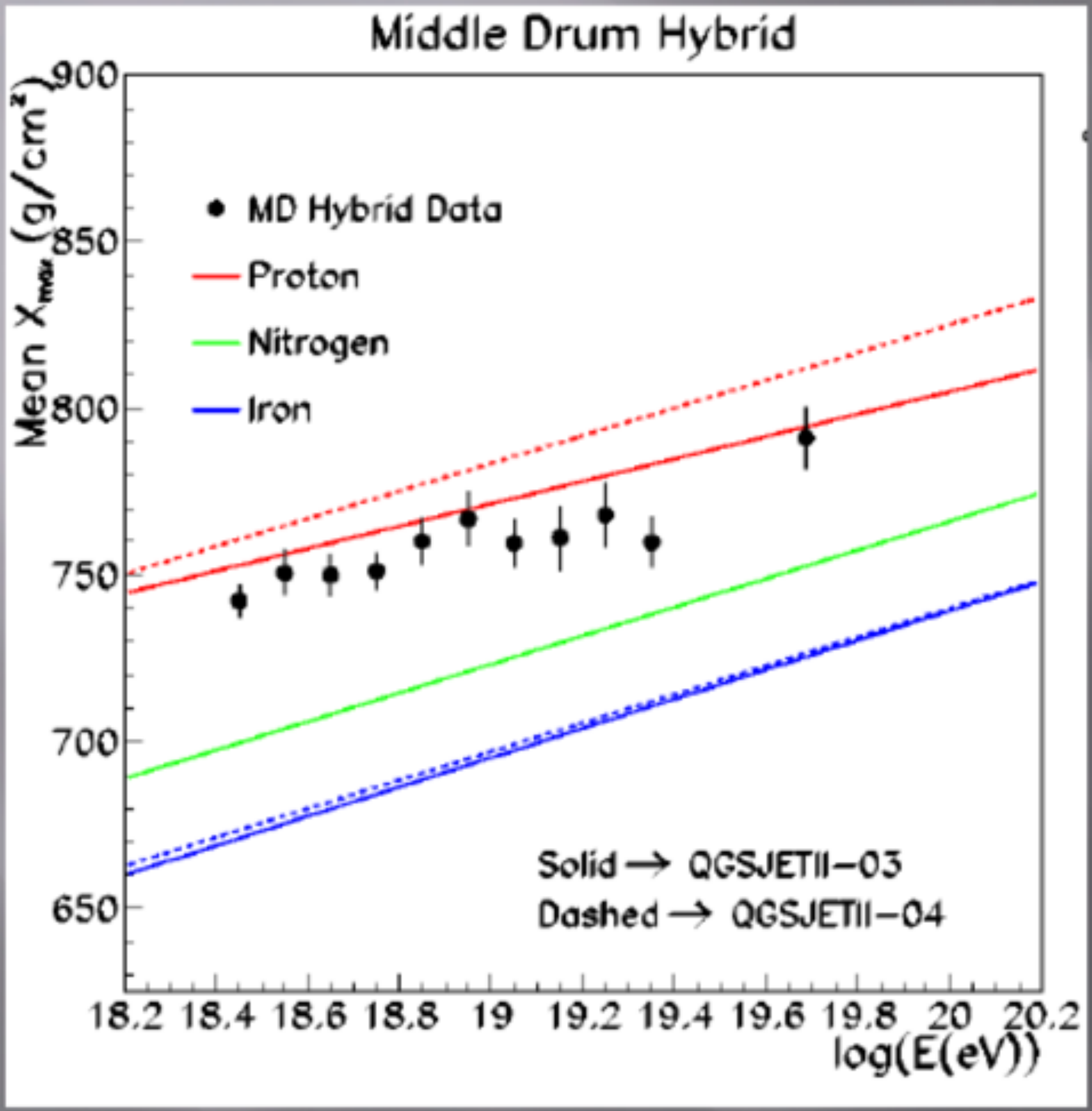
SD alone $>10^{19}$ eV

FD-Mono $>10^{17.2}$ eV

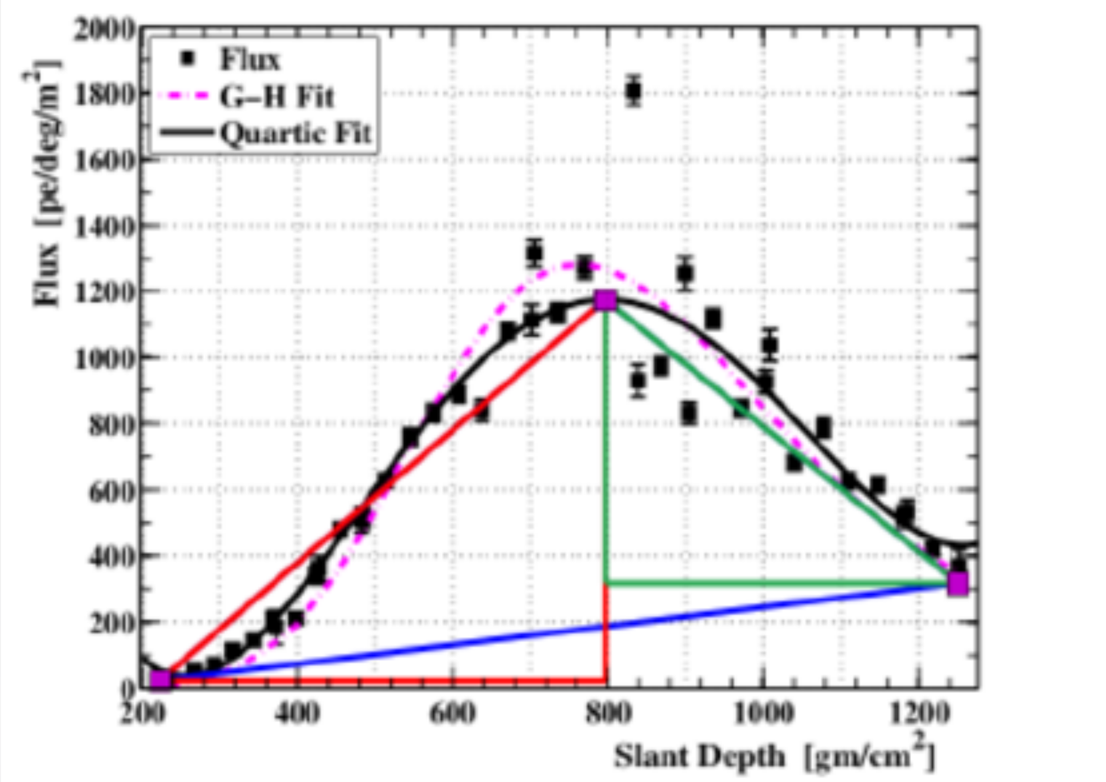
TALE-FD $10^{16.5}$-10^{19} eV

TALE-Ch $10^{15.6}$-$10^{17.7}$ eV

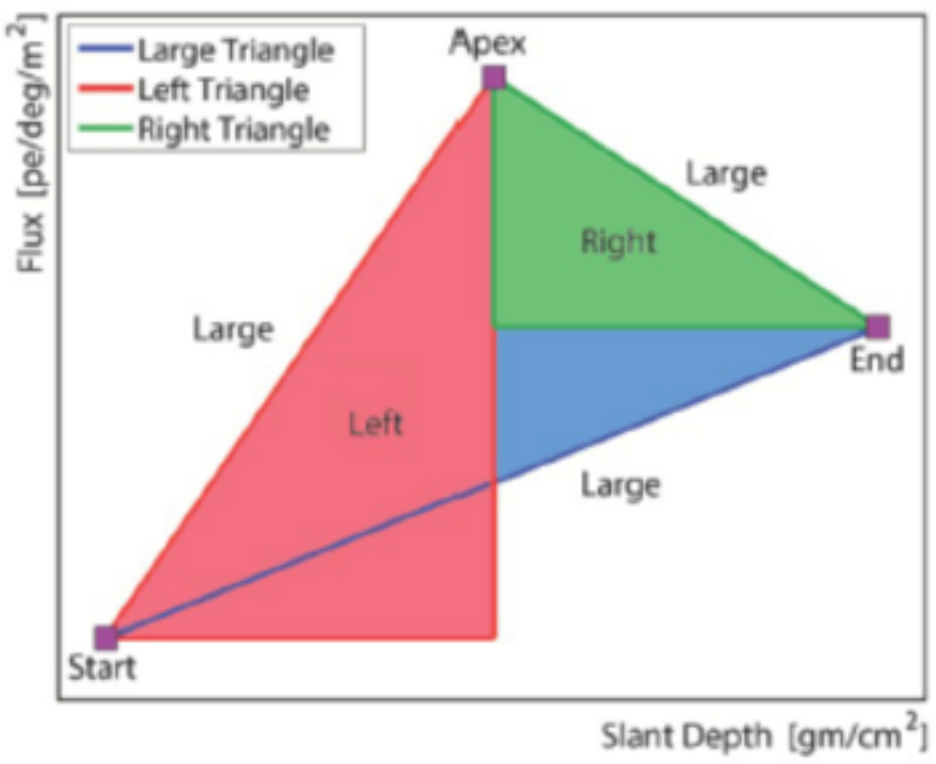
TA MD Hybrid



Middle Drum Hybrid
Mean X_{max} (g/cm²)
MD Hybrid Data
Proton
Nitrogen
Iron
Solid → QGSJETII−03
Dashed → QGSJETII−04
log(E(eV))

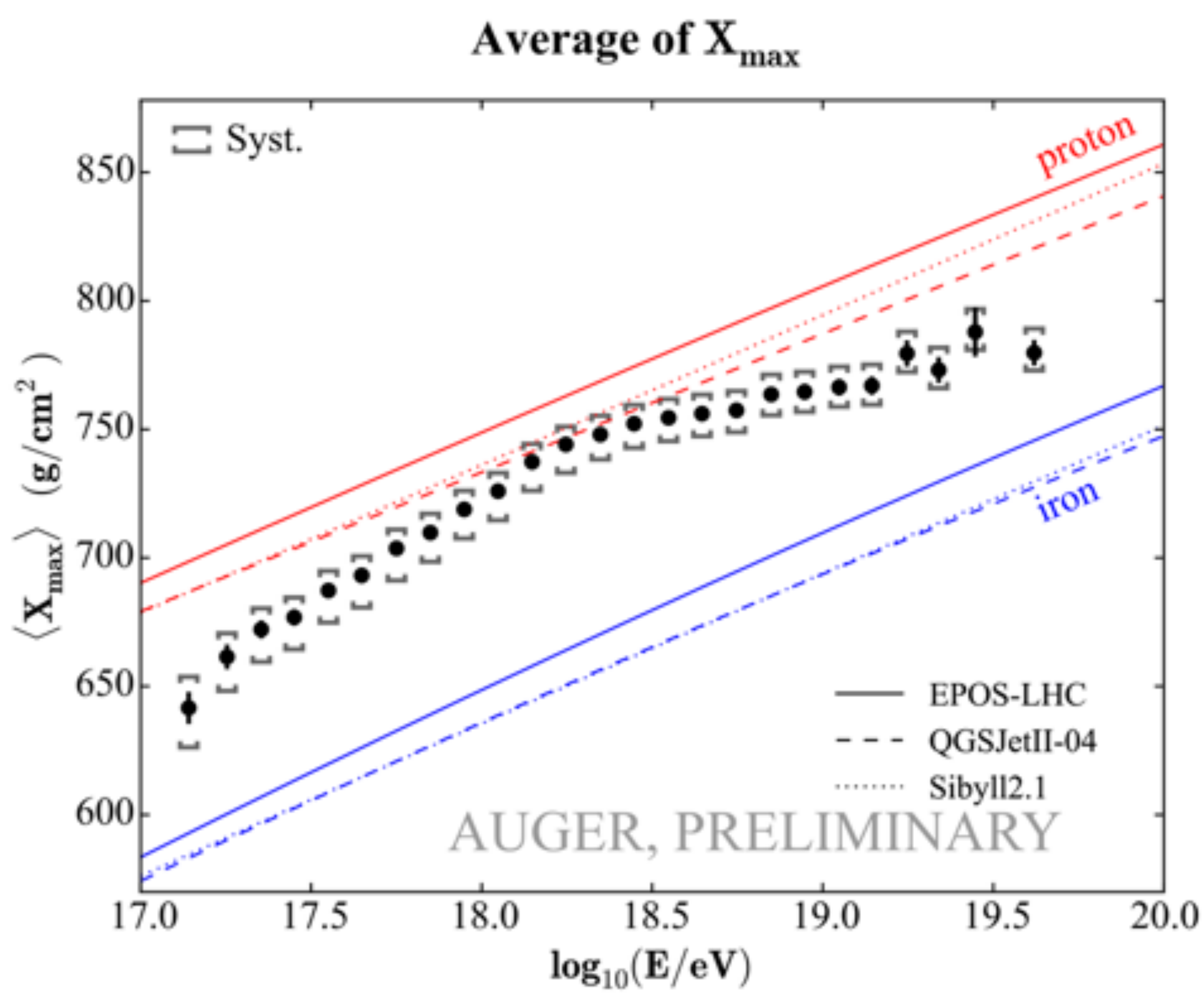


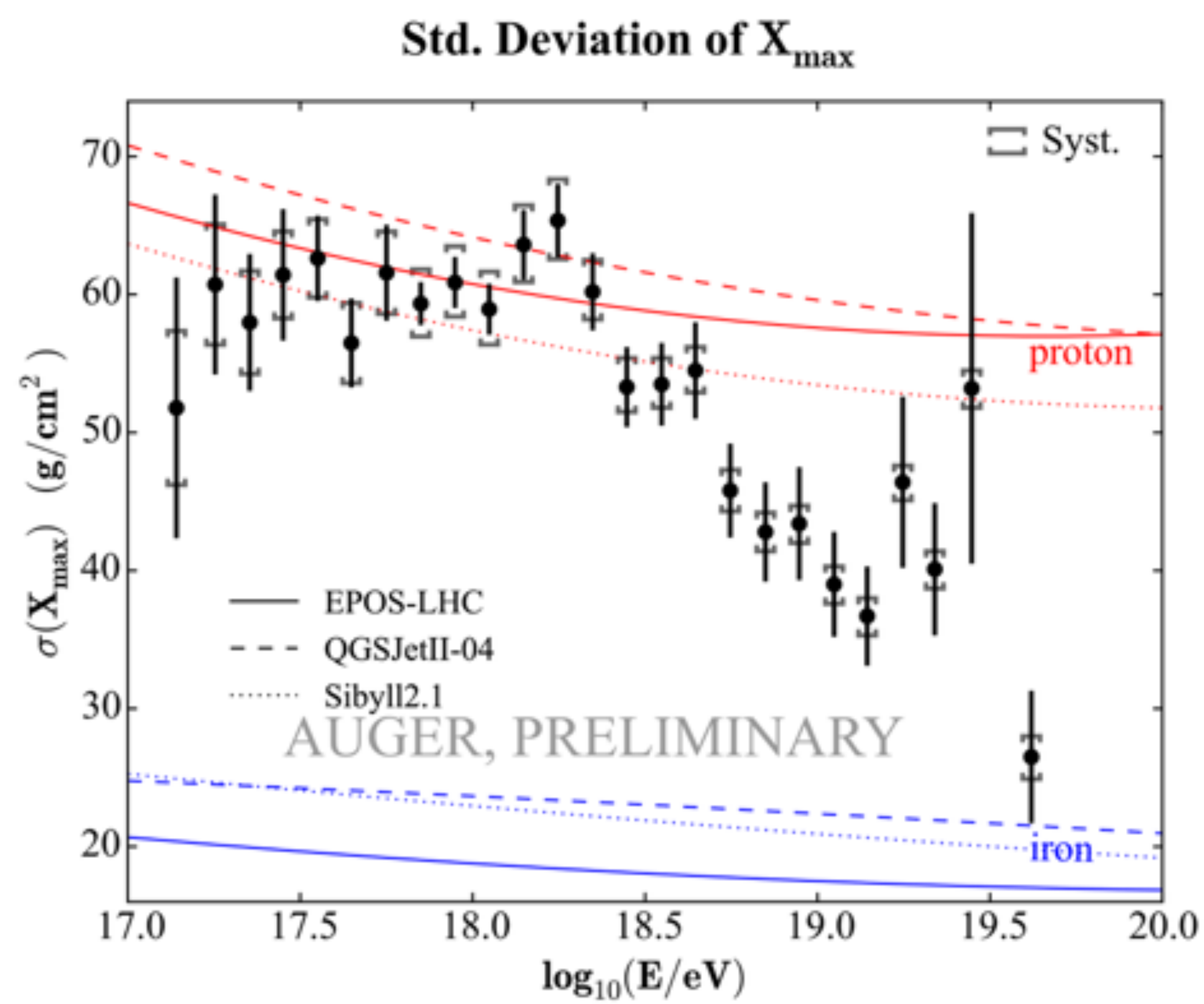
Flux
G–H Fit
Quartic Fit
Flux [pe/deg/m²]
Slant Depth [gm/cm²]



Large Triangle
Left Triangle
Right Triangle
Apex
Large
Right
Large
Left
Large
Start
End
Flux [pe/deg/m²]
Slant Depth [gm/cm²]

Average shower maximum and RMS



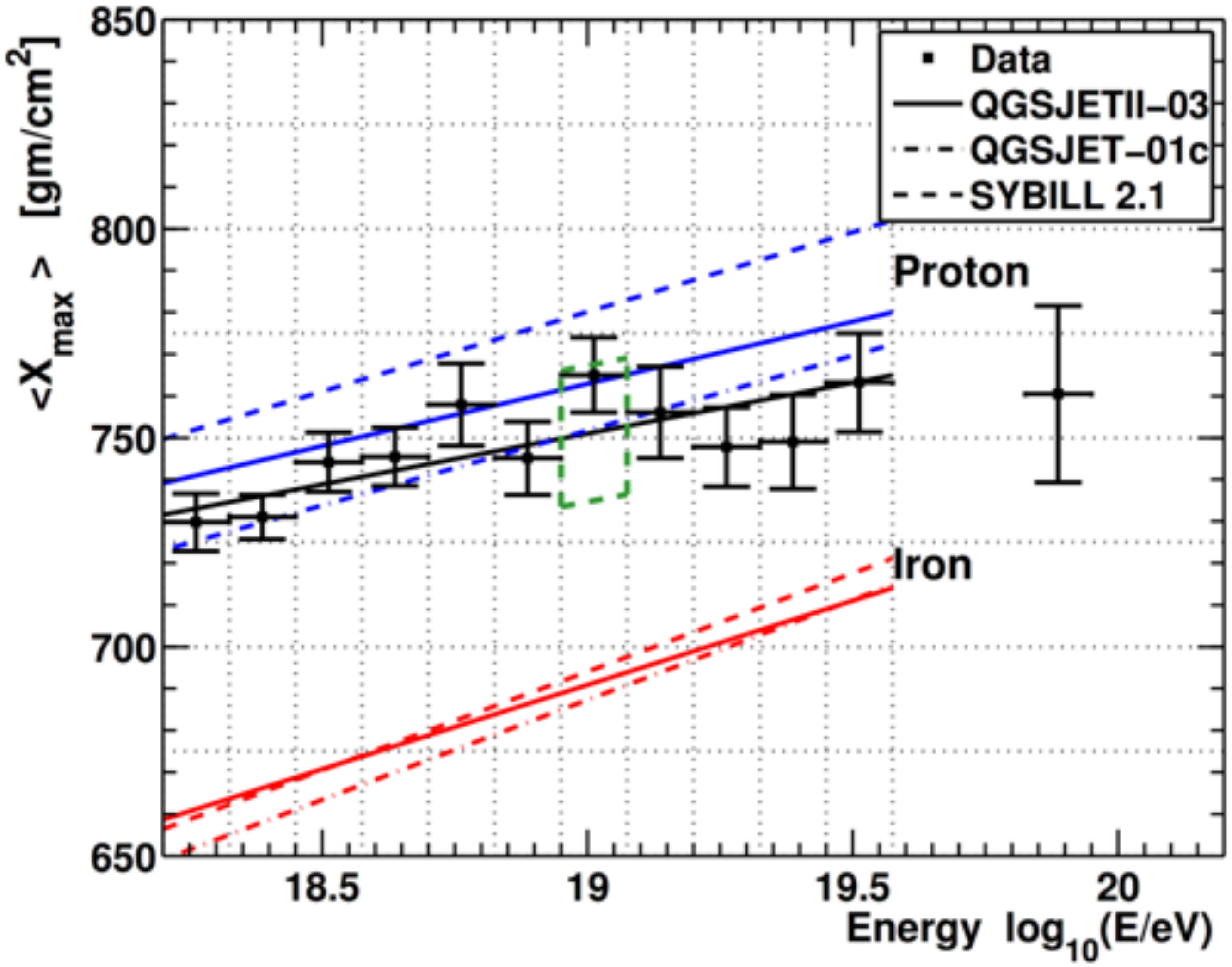


Dip model (ankle due to pure proton flux) seems to be ruled out

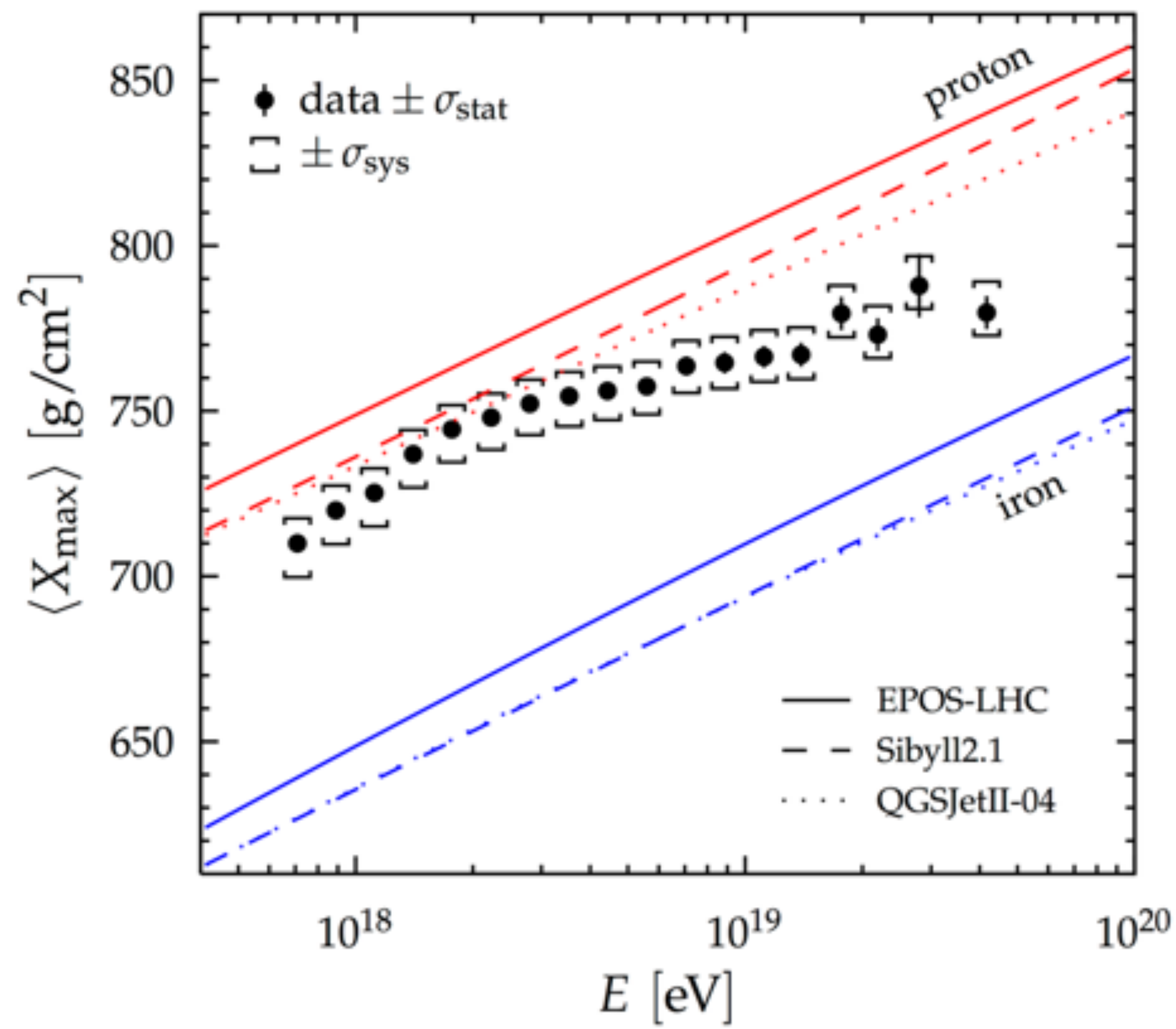
Pierre Auger Collaboration, to be presented at ICRC15

Average shower maximum

Telescope array



Auger



- EAS simulations are folded with detector response (det. resolution and bias introduced)
- Maximized statistics

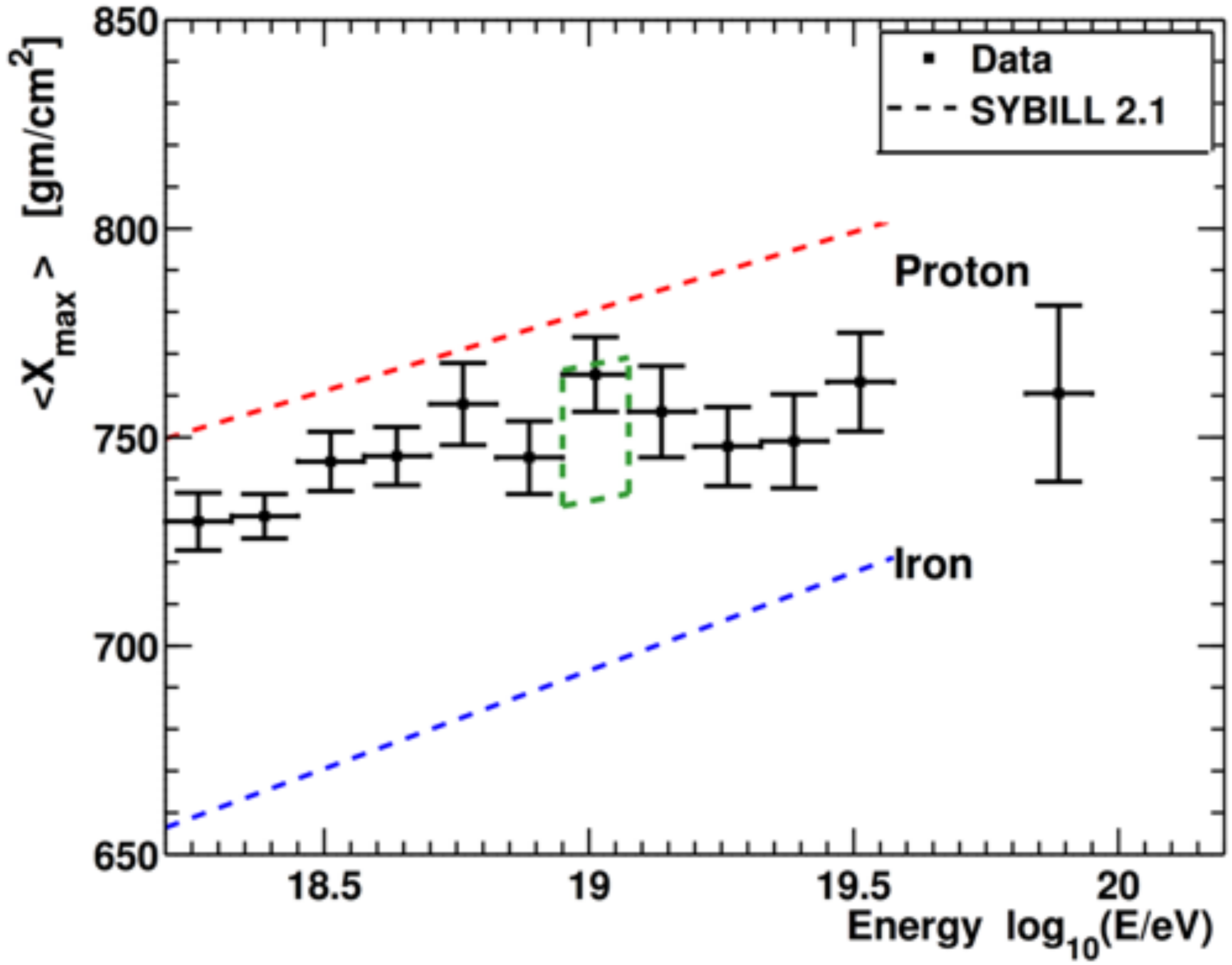
- Unbiased estimate of X_{max} and higher moments
- Reduced statistics

Telescope Array Collaboration, APP 64 (2014) 49

Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

Average shower maximum

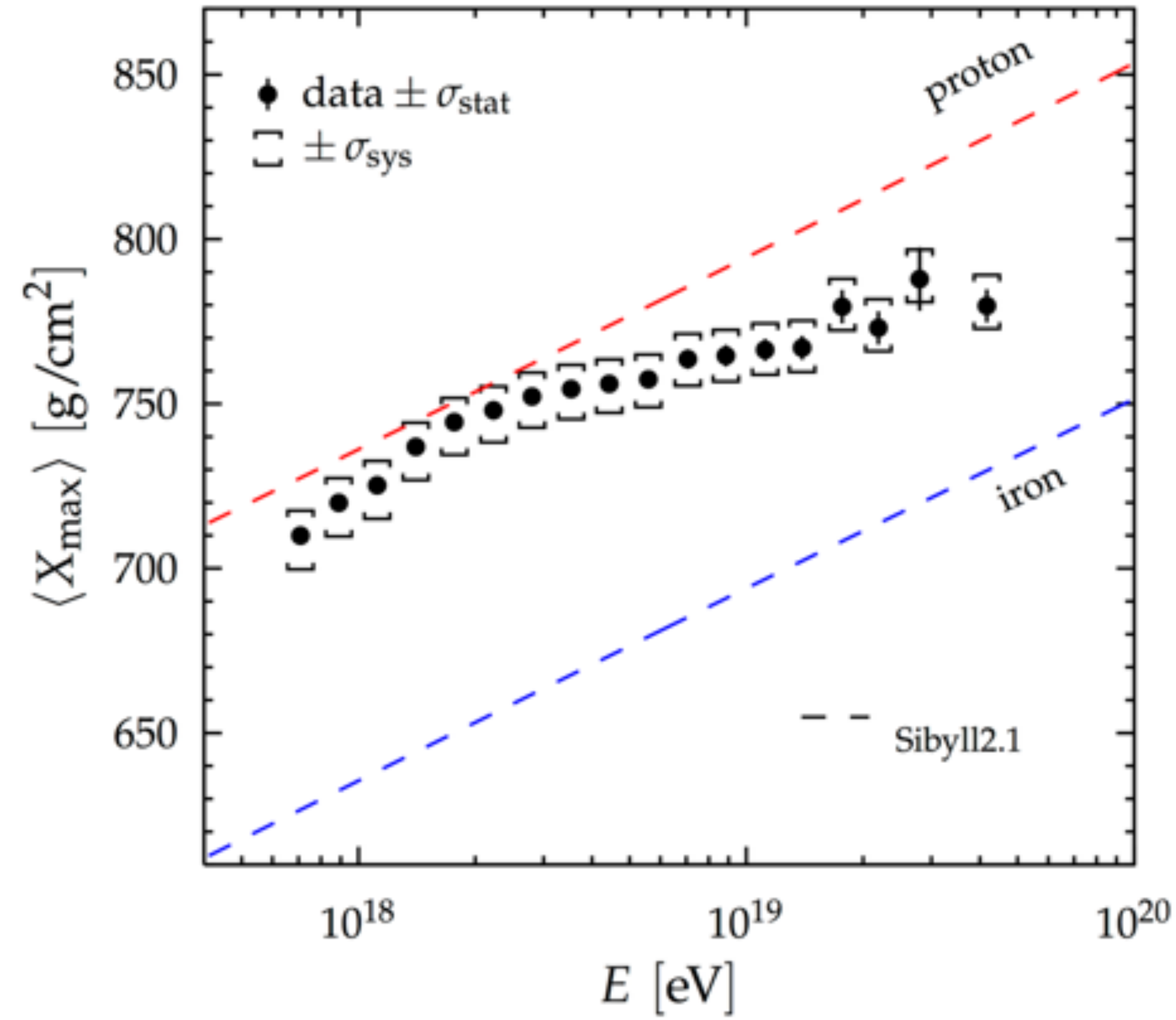
Telescope array



- EAS simulations are folded with detector response (det. resolution and bias introduced)
- Maximized statistics

Telescope Array Collaboration, APP 64 (2014) 49

Auger



- Unbiased estimate of X_{max} and higher moments
- Reduced statistics

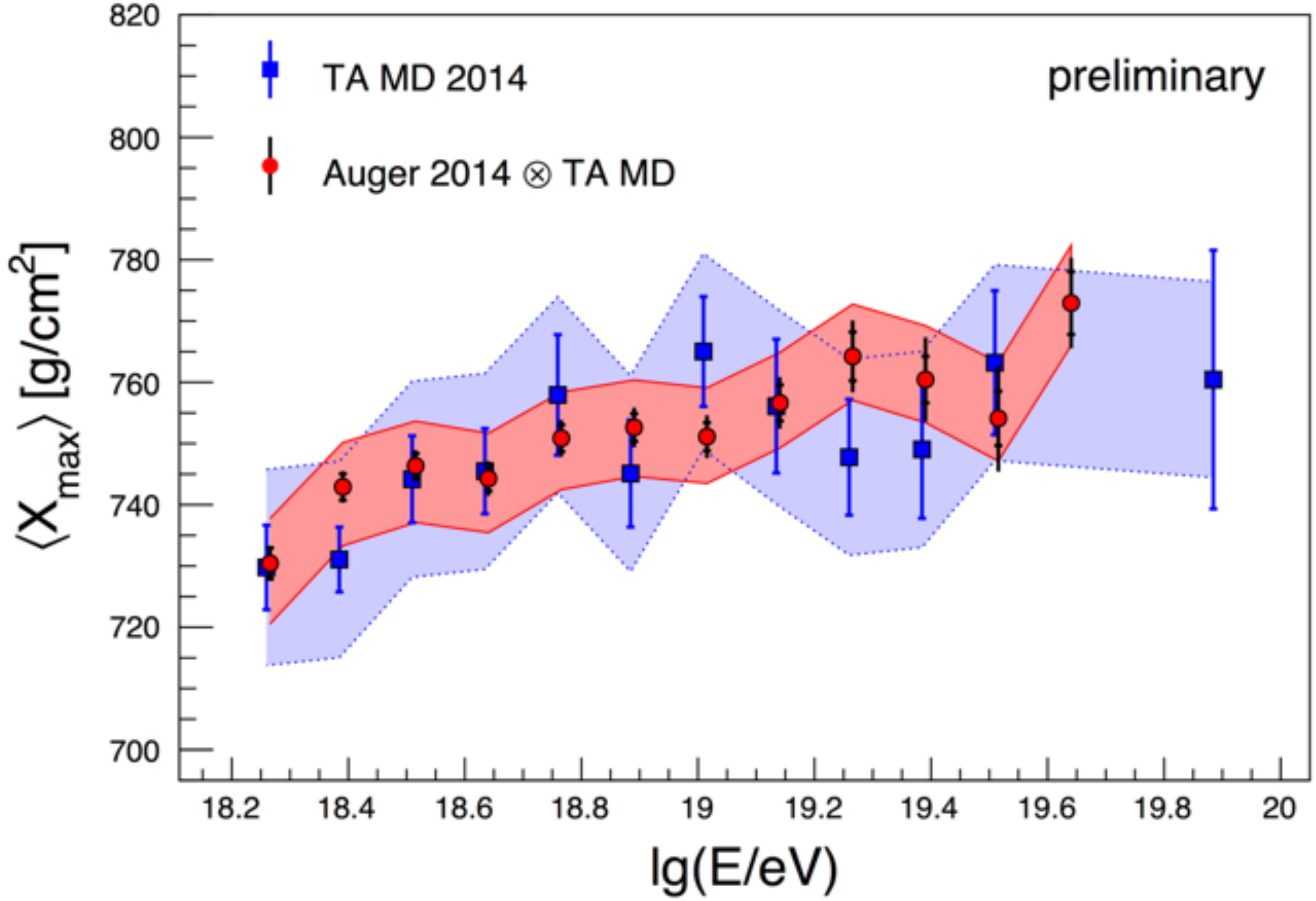
Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

Average shower maximum

TA data from MD telescopes

Parameterized Auger data folded with the MD acceptance

MD = Middle Drum
(site of one telescope station)



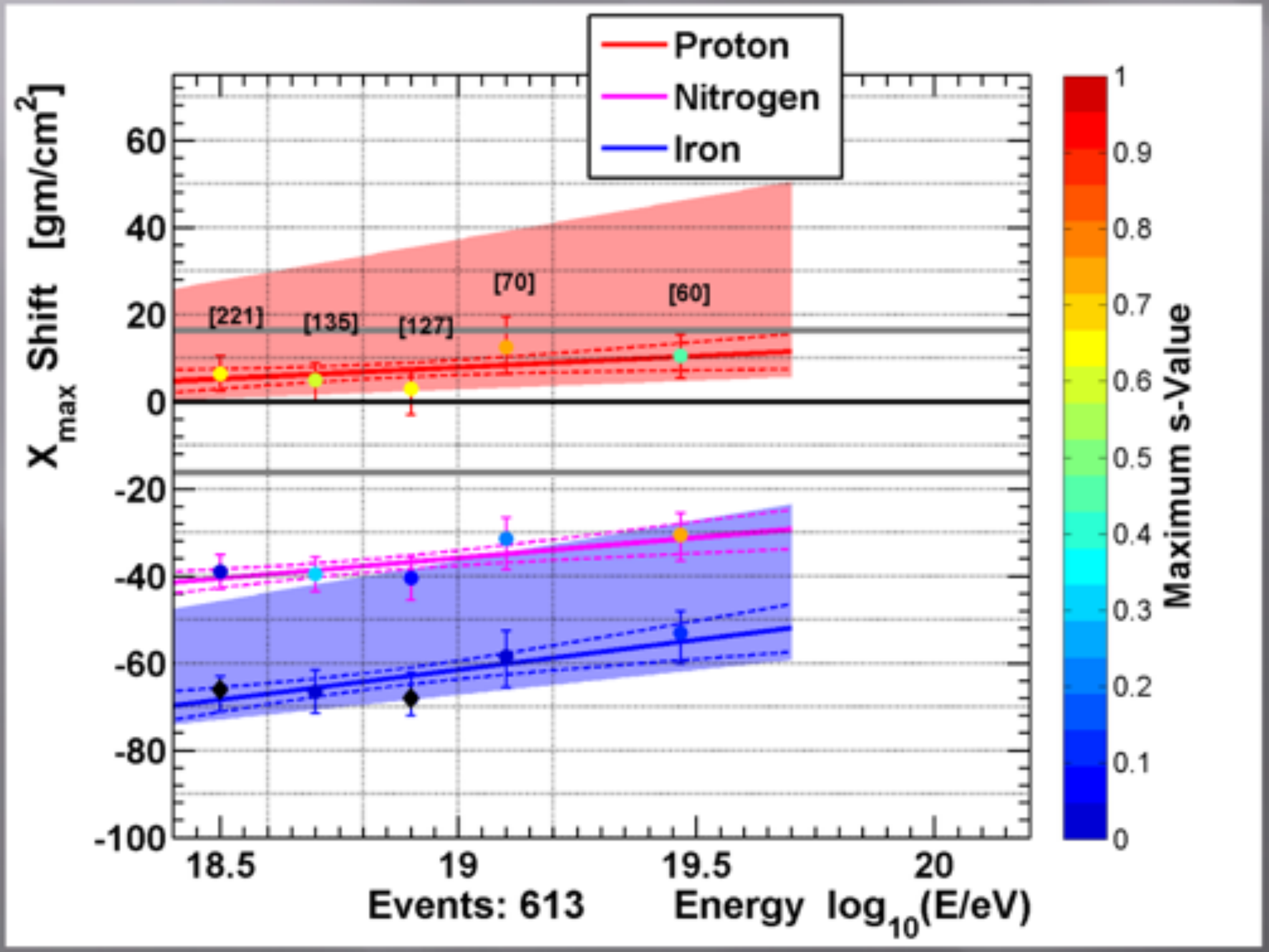
$\langle \Delta \rangle$ = (2.9 ± 2.7 (stat.) ± 18 (syst.)) g/cm^2

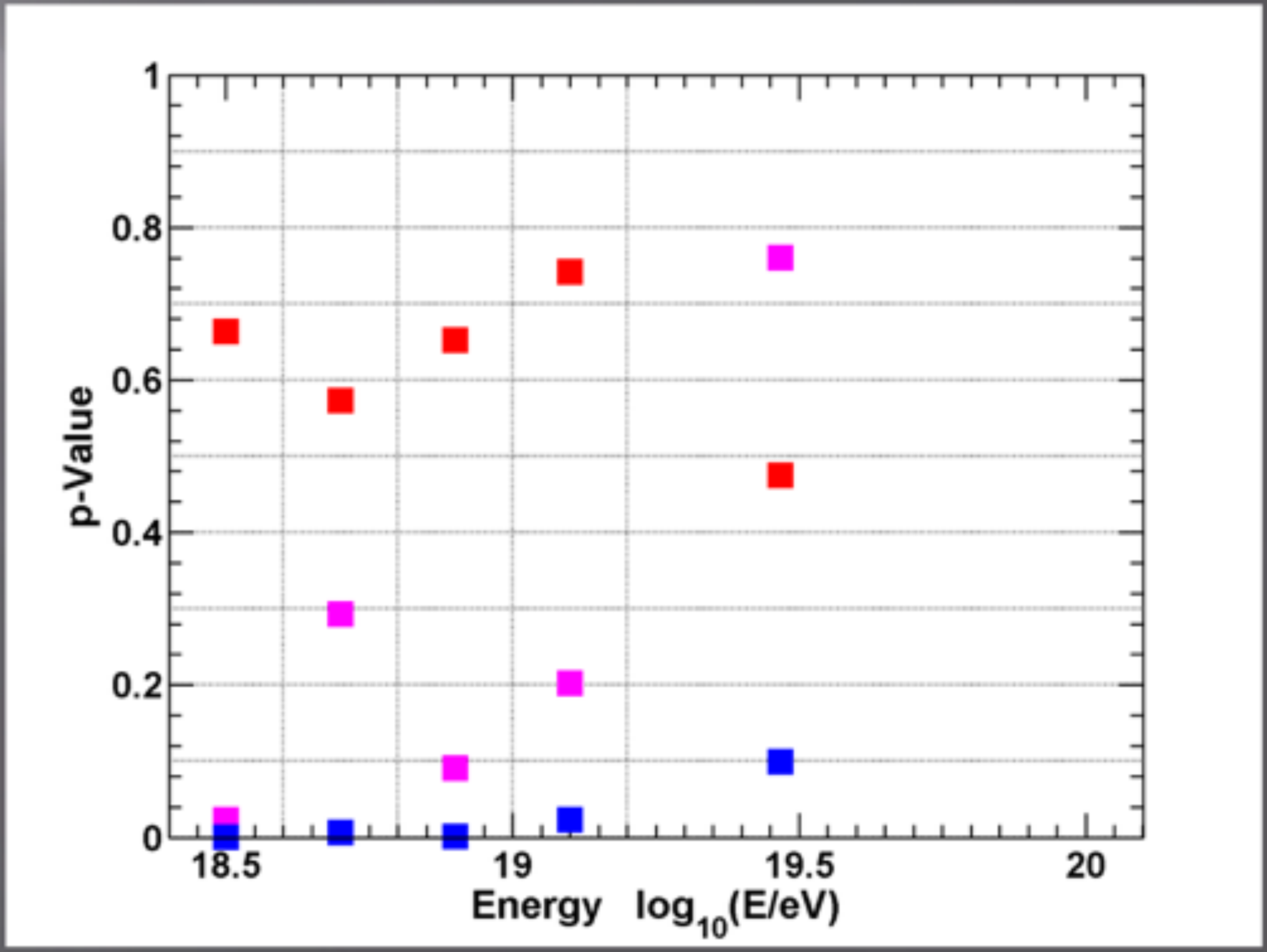
Pierre Auger and TA Collaborations, Proc. UHECR 2014, arXiv:1503.07540

TA MD Composition Result

- The data look like proton
- Nitrogen is disfavored
- Iron is excluded

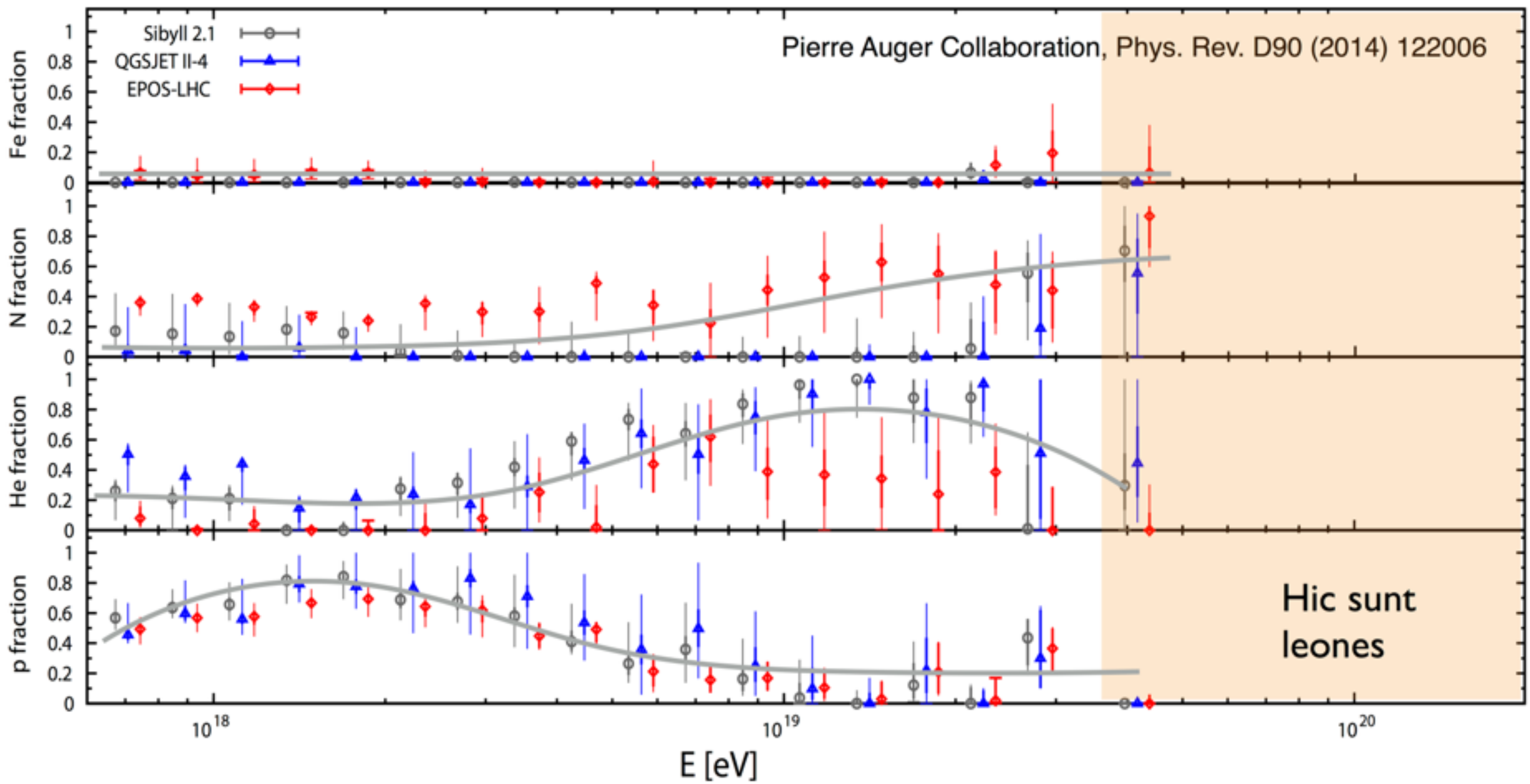
QGSJetII-03





Composition Fit (X_{max} distribution)

Data available only up to < $5x10^{19}$ eV



Pierre Auger Collaboration, PRD 90 (2014) 12, 122006

CONCLUSIONS

The situation of direct measurements seems to be quite consistent (see PAMELA, AMS and CREAM) with very low systematic uncertainty (a few %).

Around the knee experiments tend to say that the knee is due to light elements. May be the knee is more complex than what we imagined (knee of H around 1 PeV and the main knee is more He dominated, or different populations making knees around a few 10^15 eV).

KASCADE-Grande, ICE-TOP/ICE-CUBE and Tunka show that at 10^17 eV we are dominated by heavy particles and show knees in the heavy components.

Light ankle at ~2x10^16 eV is now quite well established (it is something we became aware only a few years ago).

I think we have to pay attention and distinguish between 'heavy-knee' in the all particle spectrum and '2nd knee'.

We have indications of a flattening of the light component around 10^17 eV. May be it is the first sign of an extra-galactic component, but still to be understood.

Still some contradiction on the composition around 10^18eV. HEAT (Auger) indicate a clear transition from heavy to light between 10^17 eV and 10^18 eV while Tunka and IceCube show a less pronounced effect.

CONCLUSIONS

Above between $17.5 < \log E < 19.3$ Auger and TA show very similar spectrum. Above still some differences: a question of statistics, systematics or a real difference in the original spectrum?

It is interesting to observe that the experiments such as ICe-Cube and K-Grande overlap quite well in flux at a few 10^17 eV - 10^18 eV with Auger and TA. Their energy calibrator is MC. On the other hand in Auger and TA is fluorescence and we know that for TA there is a 1.27 energy scaling between MC and fluorescence. Why?

Recent analysis reconcile the composition evolution between Auger and TA. May be still a preference for TA to consider the composition p-like, but not really a tension with Auger.

A lot of progress in Radio observation. The technique is becoming more and more mature.

HOMEWORK

Go back to data analysis…. and continue processing the data looking carefully at the possible systematics in our own analysis methods and detection technique.

Radio technique is promising! Continue full-steam in Radio observation and understanding the methodology.

Build LHAASO, Auger Prime and TAx4!

As it was done between TA and Auger, try to define a common set of simulations to cross-check results of different experiments between 10^{16} to 10^{18} eV (natural choices EPOS-LHC and QGSjetII-04).

Continue the common work between Auger and TA to understand more deeply the remaining differences: are they real or still in the systematics?

THANK YOU