Observation of high energy cosmic rays below 10^{17} eV

M. Bertaina

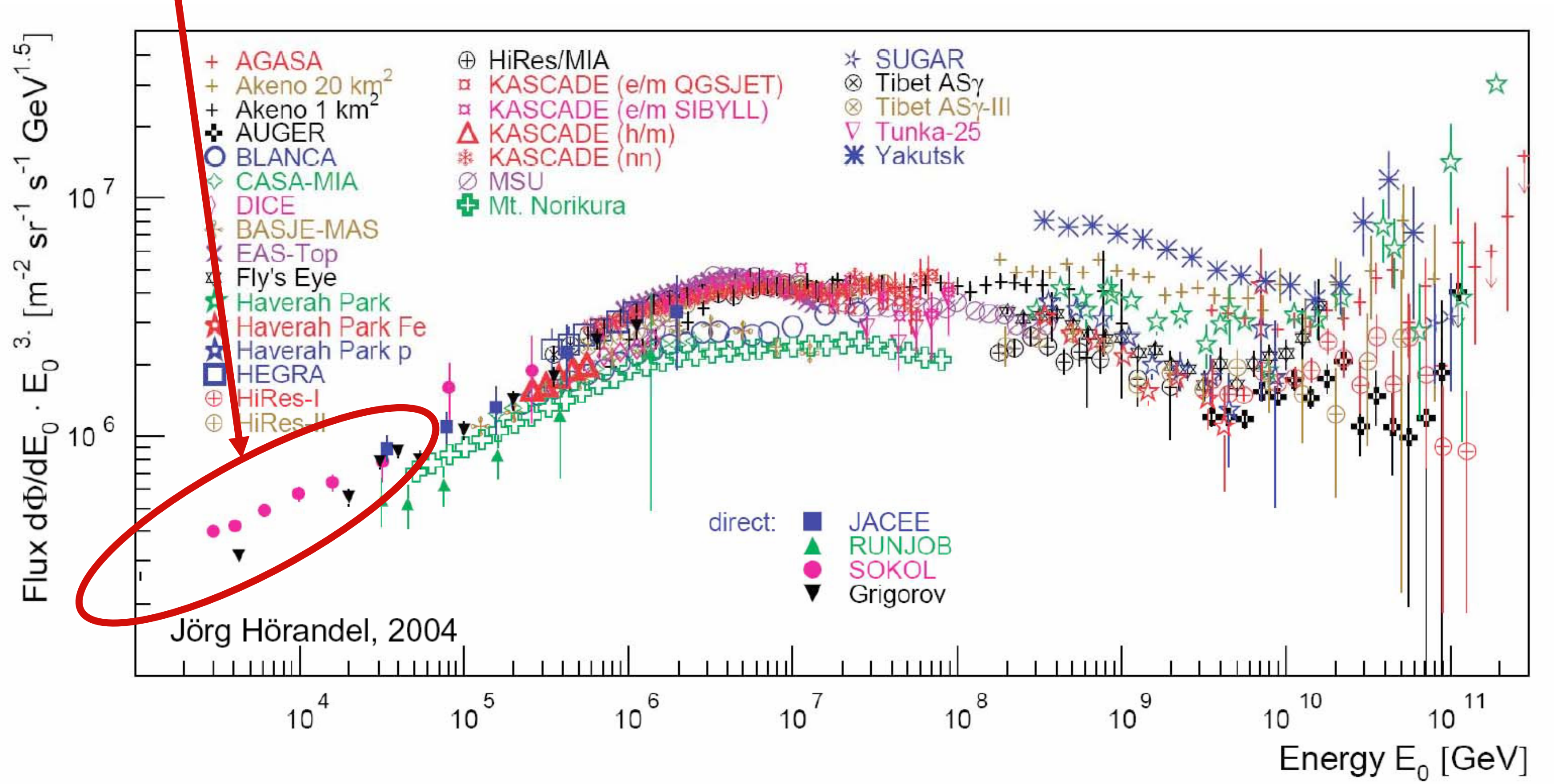
Torino University and INFN

Symposium on "The Recent Progress of Ultra-high Energy Cosmic Ray Observation"

2010/12/10-12, Nagoya, JAPAN

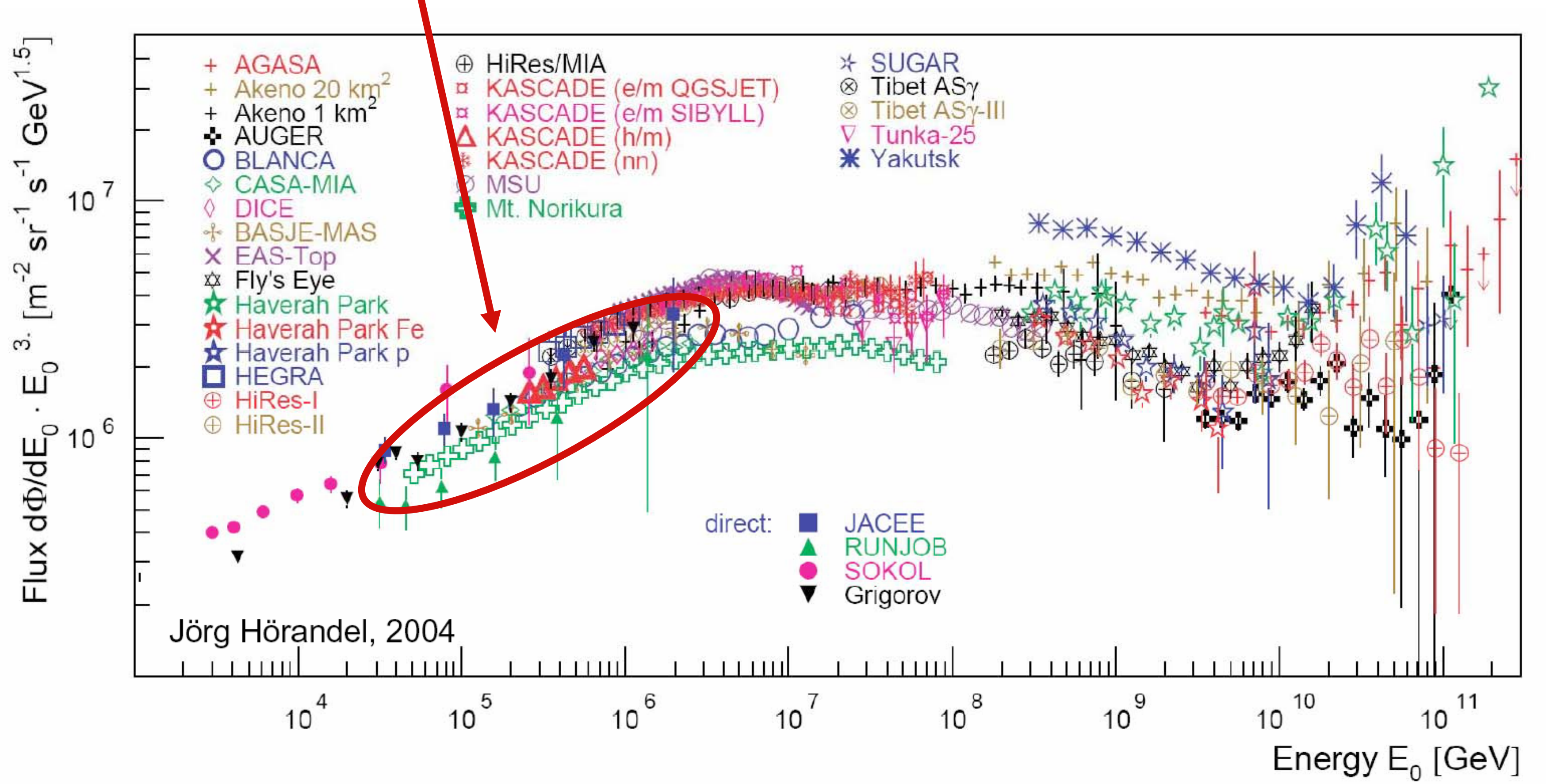
Features and problems: $S(E_0)*E_0^3$

Interpretation of the new results from direct experiments

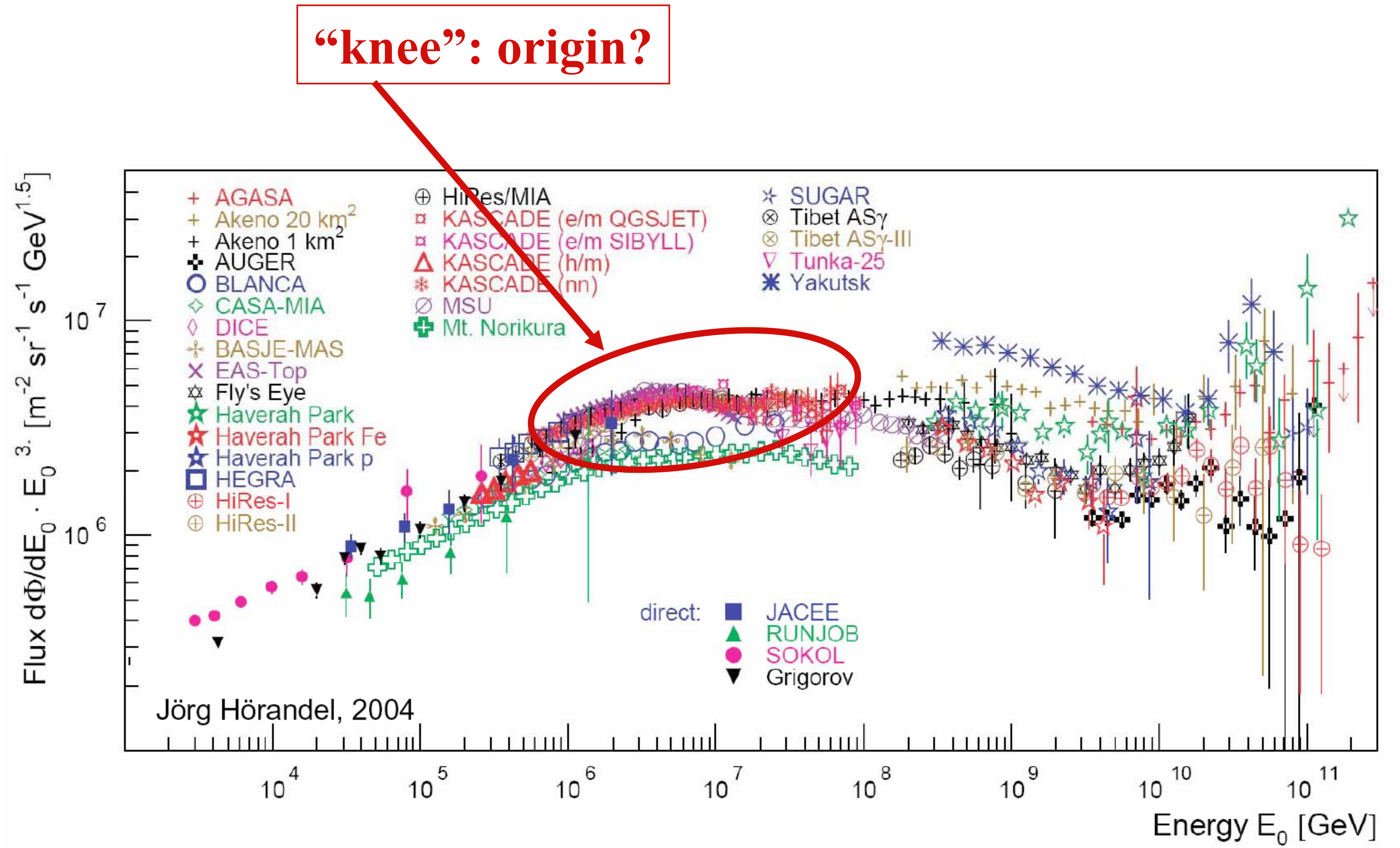


Features and problems: $S(E_0)*E_0^3$

Technical: direct to ground based experiments

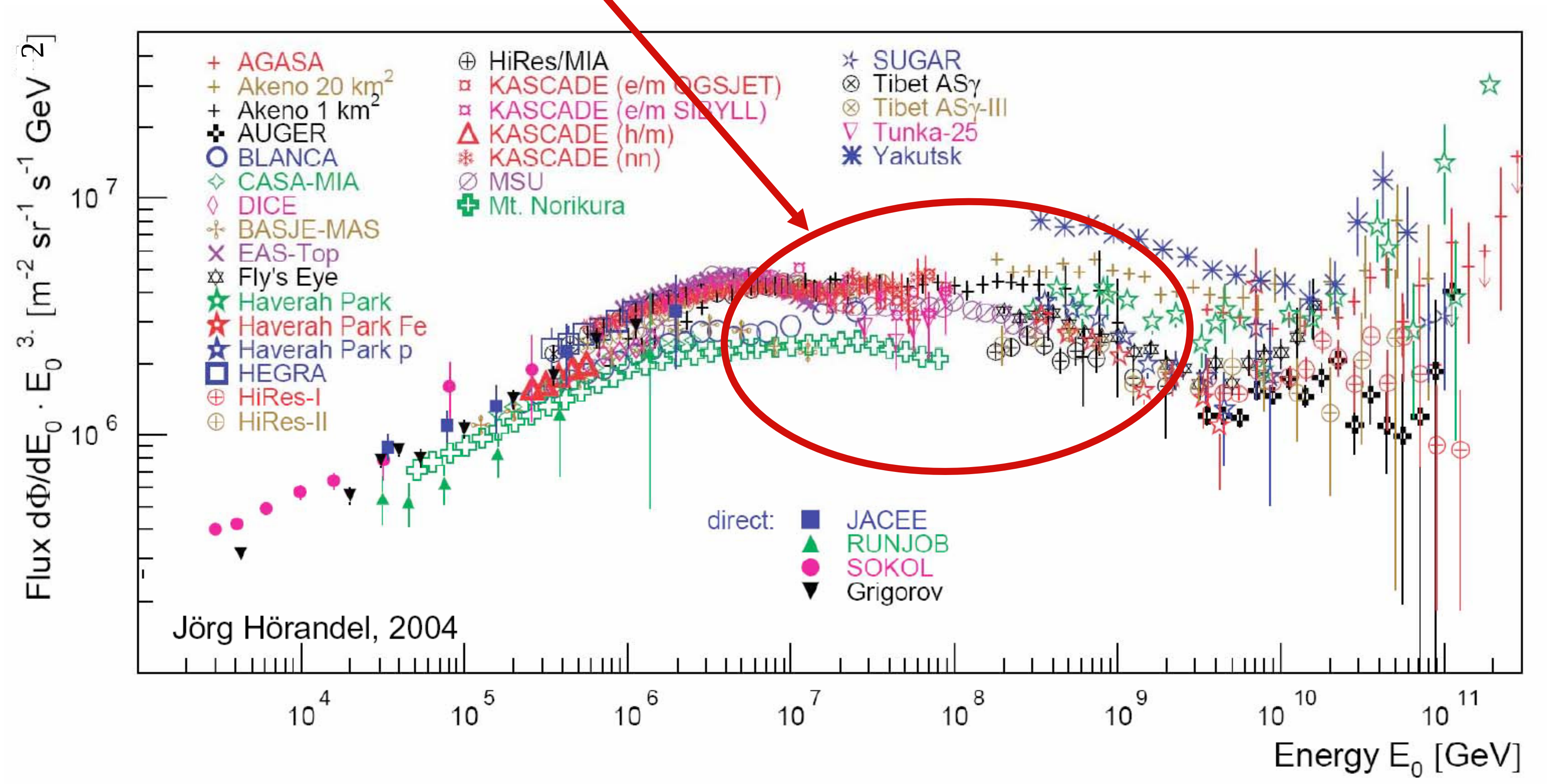


Features and problems: $S(E_0)*E_0^3$



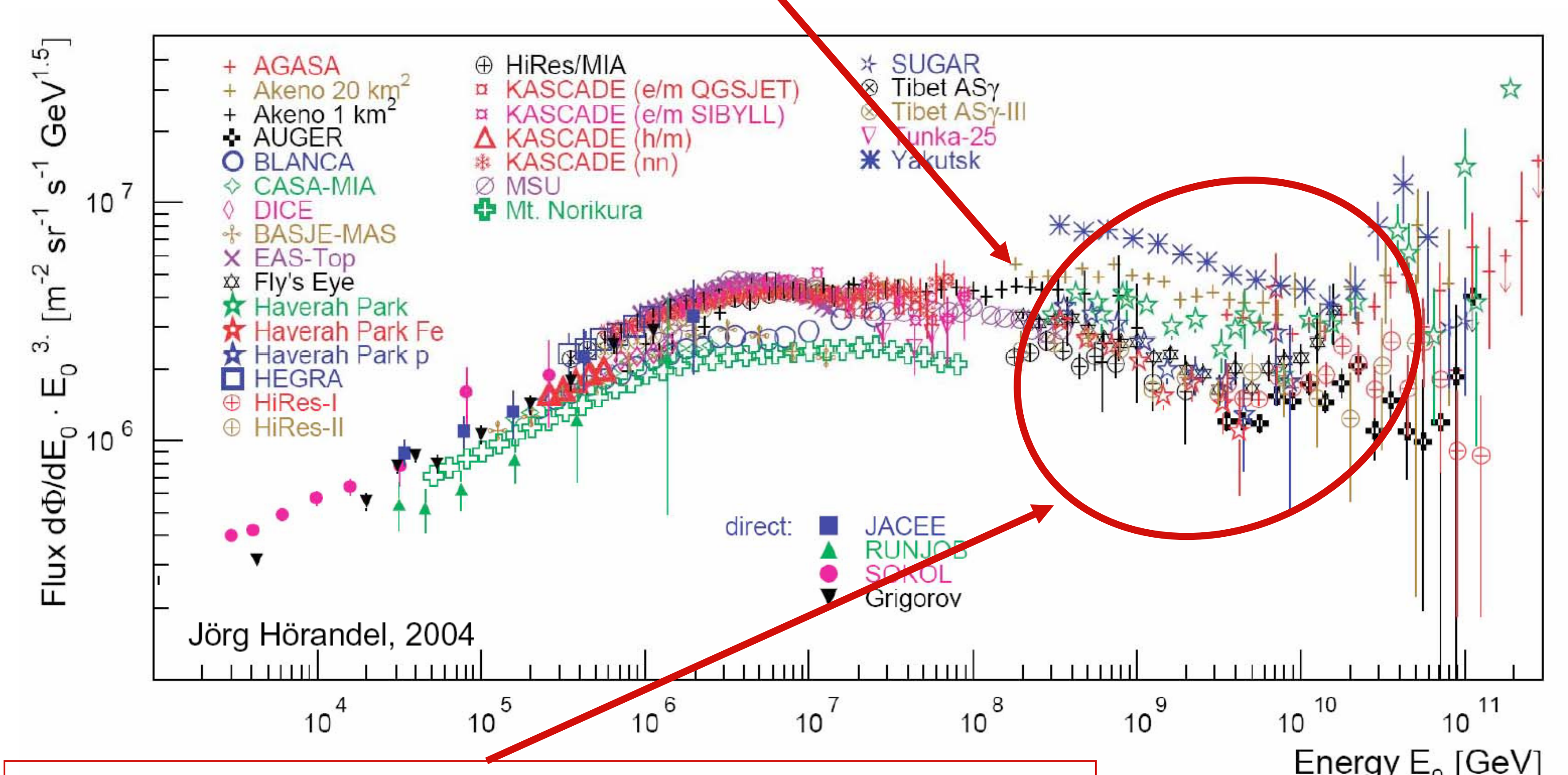
Features and problems: $S(E_0)*E_0^3$

Composition / Hadronic interactions



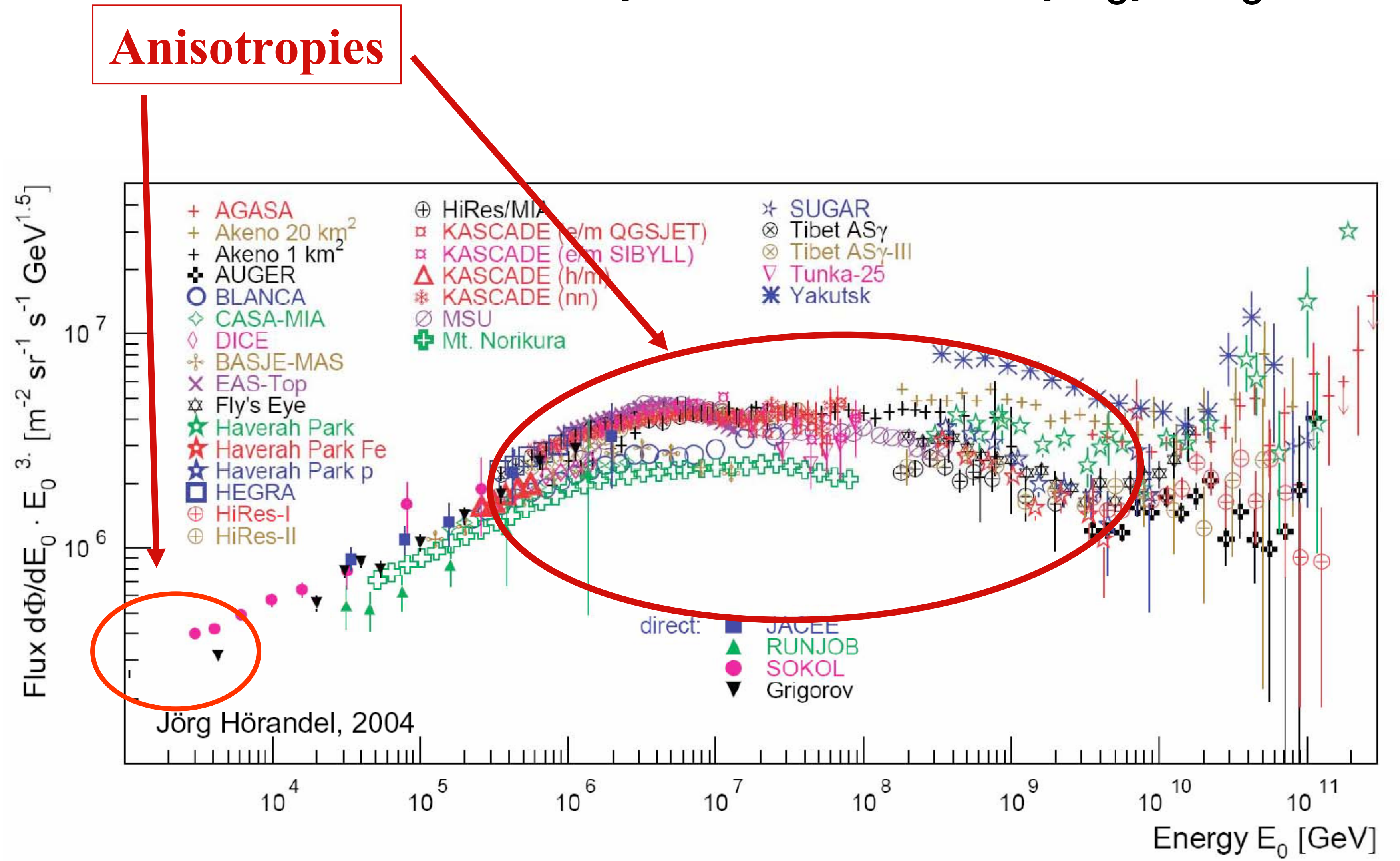
Features and problems: $S(E_0)*E_0^3$

Technical: energy calibration



Sources: galactic to extragalactic? “ankle”?

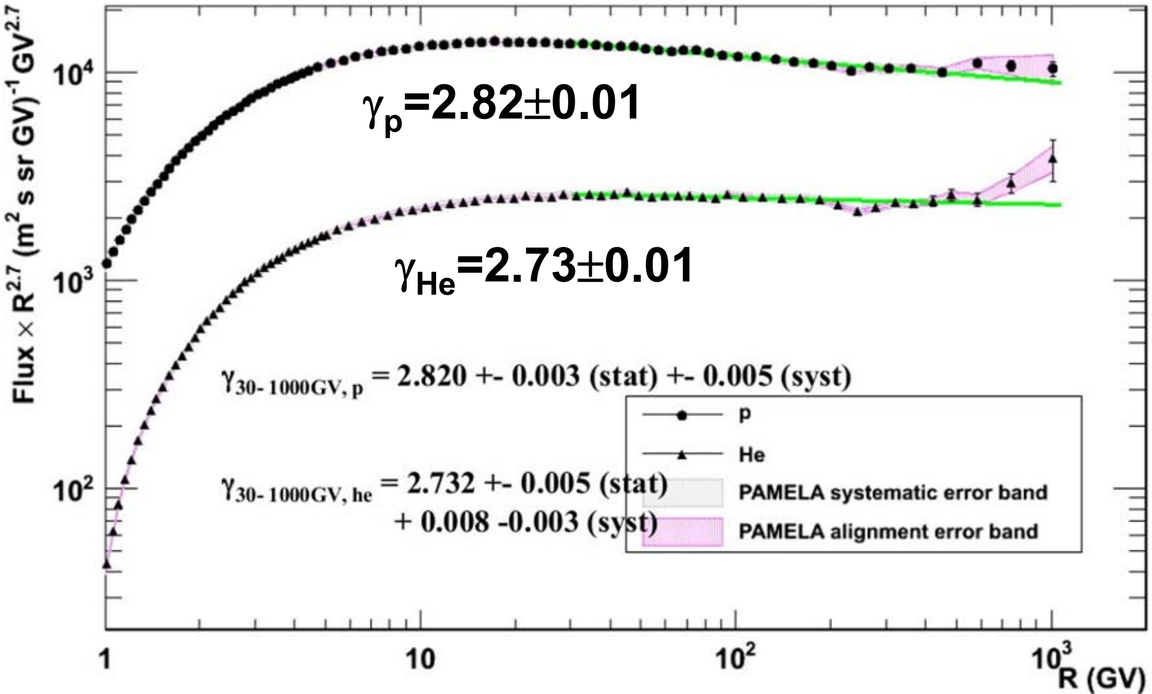
Features and problems: $S(E_0)*E_0^3$

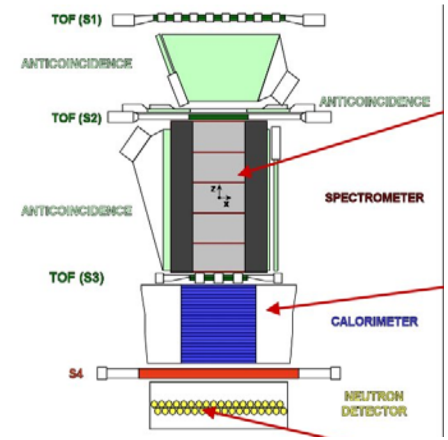


Techniques ($E < 10^{16}$ eV)

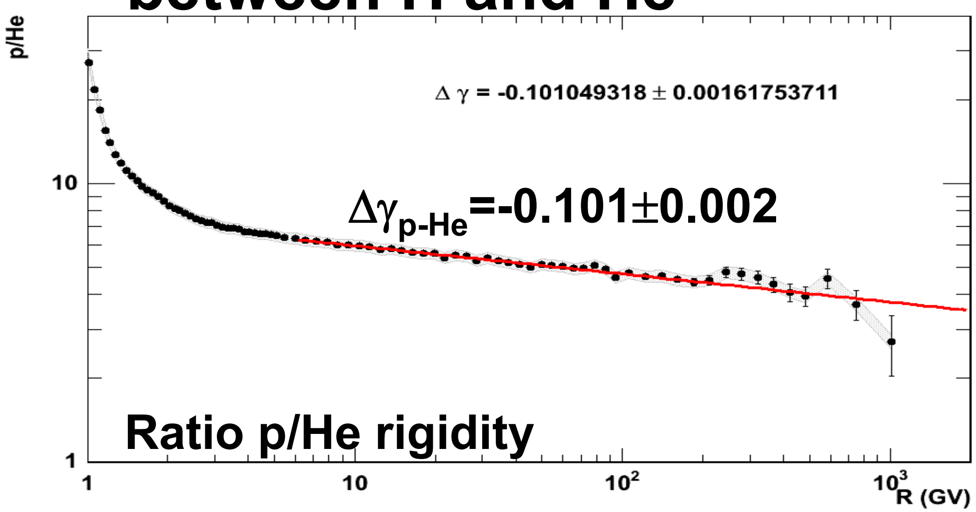
Type	Technique	Energy Range	Example of experiments & sensitive components
direct	spectrometer	1 - 1000 GeV	AMS (p,He), BESS (p,He), HEAO (CNO,Fe), PAMELA (p,He)
direct	calorimeter	30 GeV – 500 TeV	ATIC (all), CREAM (all), TRACER (O-Fe)
direct	emulsion chambers	10 – 500 TeV	JACEE, RUNJOB (all)
indirect	hadron calorimeter	500 GeV – 1 PeV	KASCADE, EAS-TOP (p)
indirect	muon spectrometer	100 GeV – 10 TeV	L3+C (mostly p & He)
indirect	Cherenkov	15 – 150 TeV	Hess (Fe)
indirect	Cherenkov + TeV μ	50 – 300 TeV	EAS-TOP/MACRO (p,He,CNO)
indirect	emulsion chambers, burst detectors	5 – 300 TeV	Tibet ASγ (p,He)
indirect	RPC carpet	5-250 TeV	ARGO (p+He)
indirect	Cherenkov	1PeV – 10 PeV	TUNKA-25 (all)
indirect	N_e-N_μ(GeV)	100 TeV – 10 PeV	GRAPES,EAS-TOP,KASCADE (all)

PAMELA $10^9<E<10^{12}$ eV

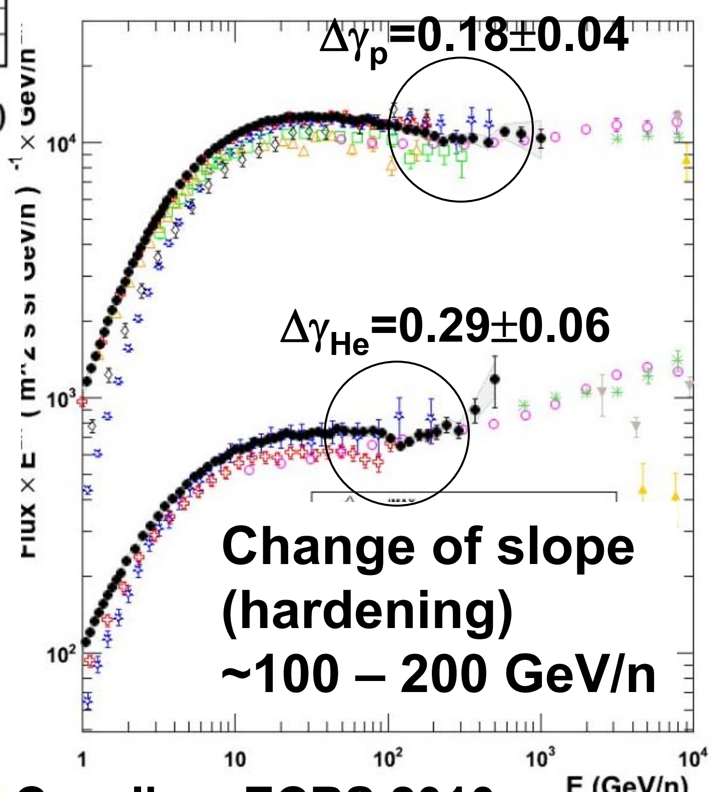




Different spectral index between H and He



Comparison with previous experiments



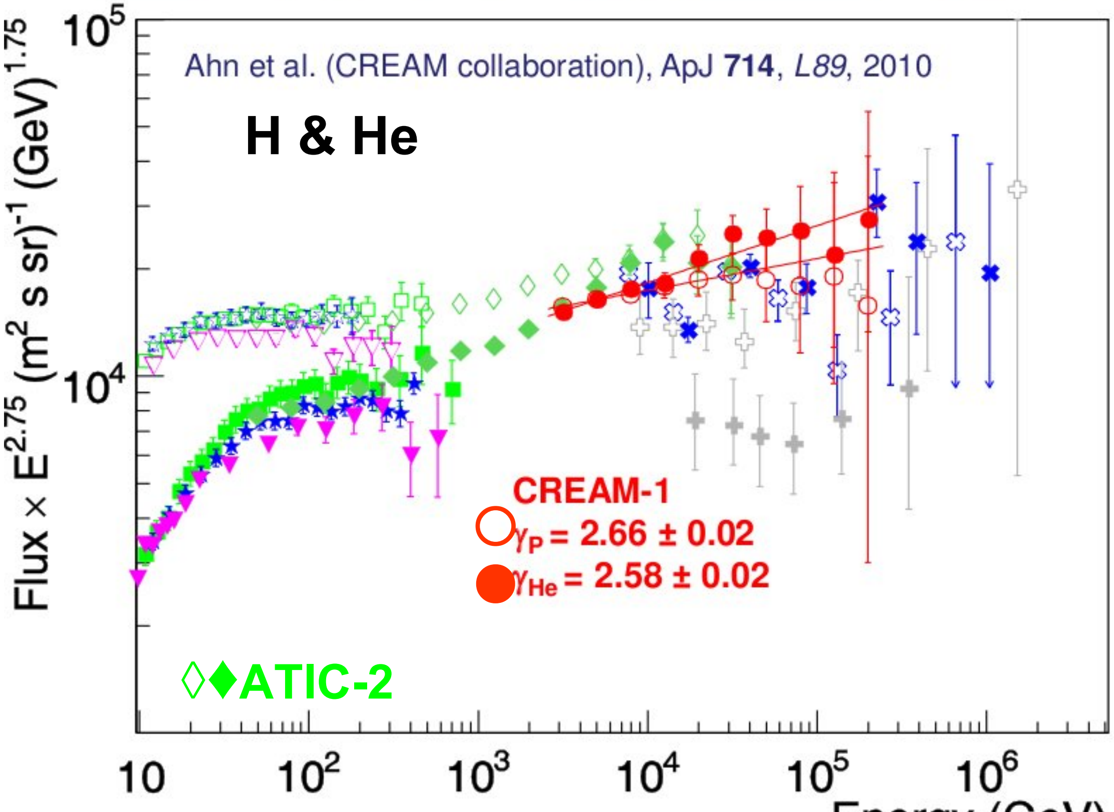
Change of slope (hardening) ~100 – 200 GeV/n

M.Casolino, ECRS 2010

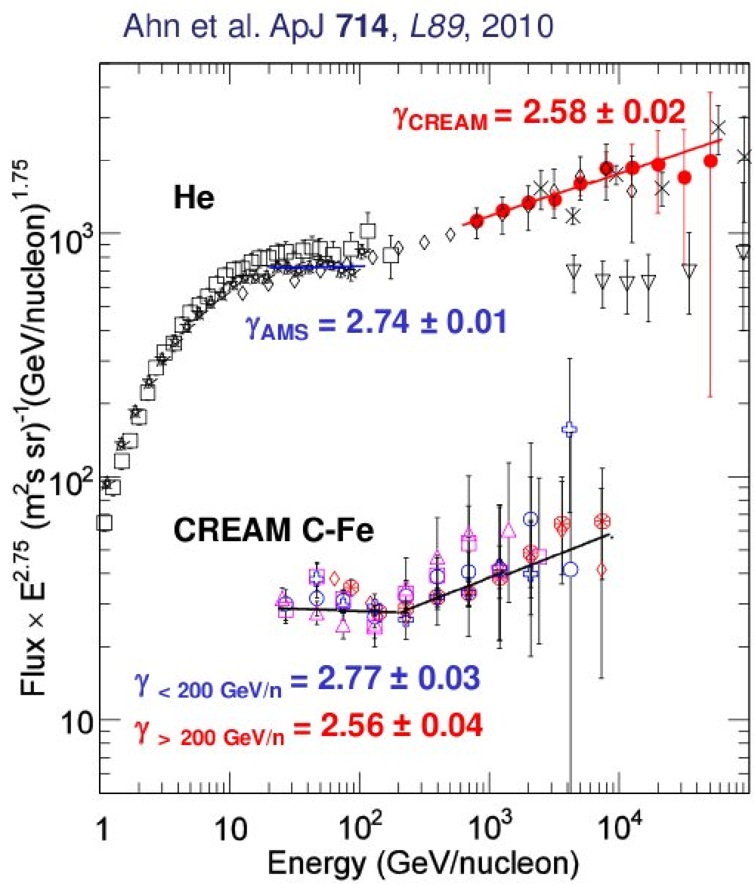
CREAM $10^{12}<E<10^{14}$ eV

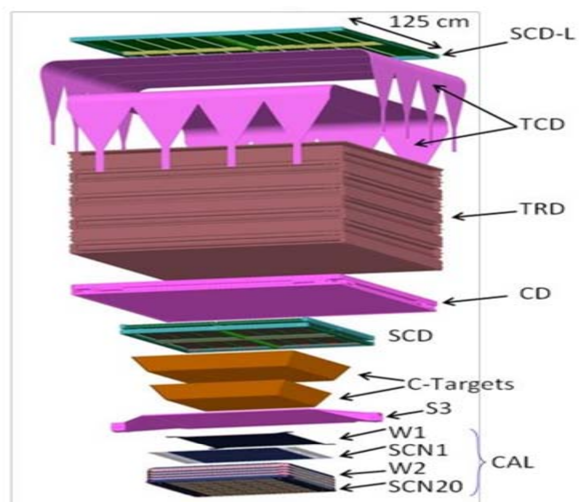
also sees different spectral index between H and the other elements

The change of spectral index occurs also for C-Fe in the same energy range (100-200 GeV/n) as for PAMELA

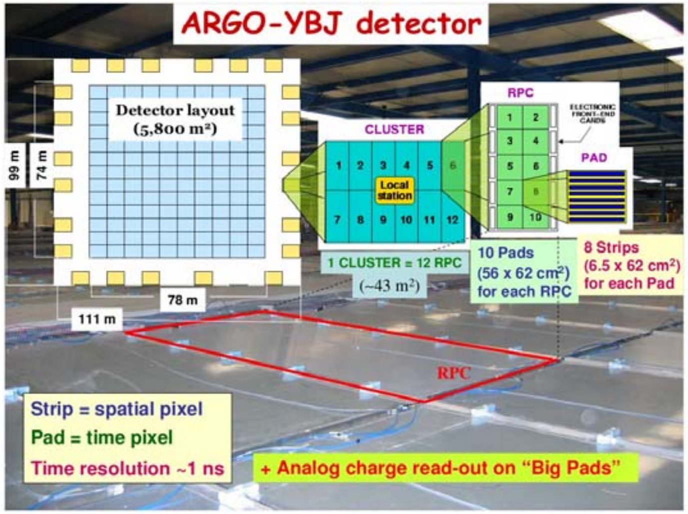


E.Seo, ISVHECRI 2010

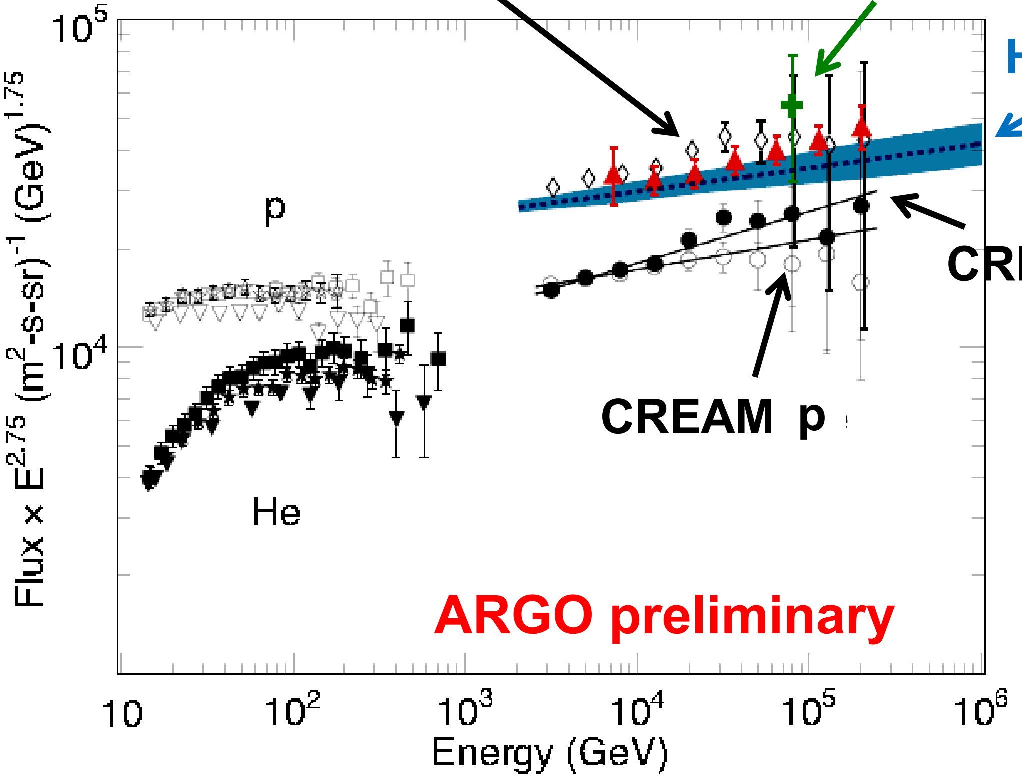




Light-component spectrum of CRs measured by ARGO (5-250 TeV)



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

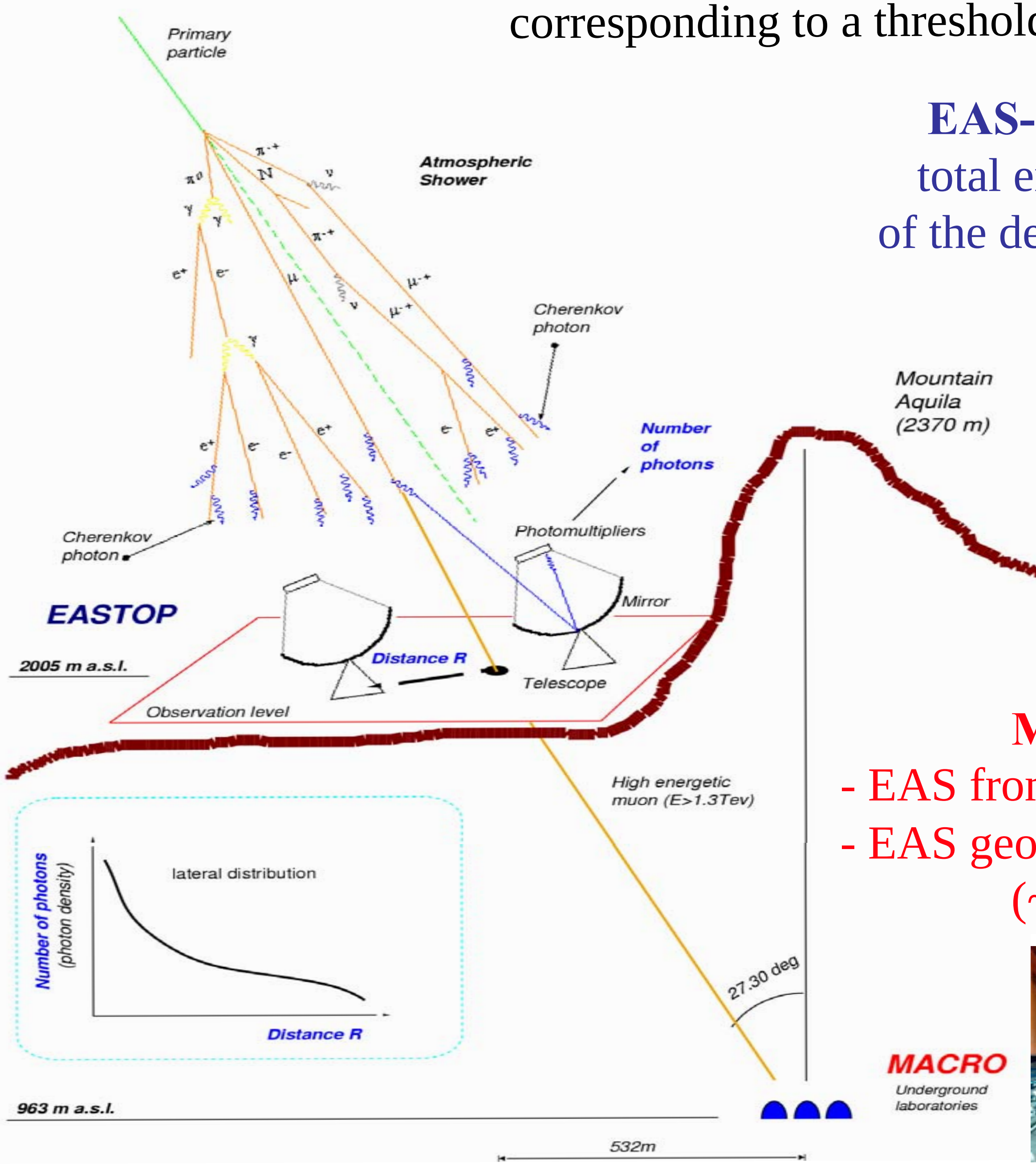


CNO < 2%

ARGO data agree with CREAM results

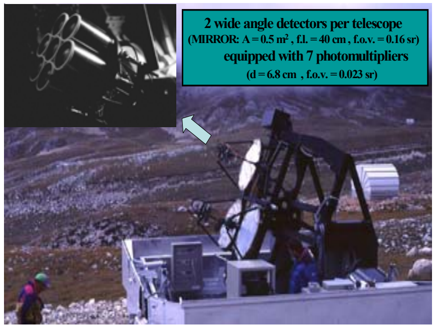
Evidence that the proton spectrum is flatter than in the lower energy region

MACRO and EAS-TOP are separated by 1100 - 1300 m of rock corresponding to a threshold $E_\mu \approx 1.3 - 1.6$ TeV.



EAS-TOP (Cherenkov detector):
total energy through the amplitude
of the detected Cherenkov light signal.

THE EAS-TOP CHERENKOV DETECTOR



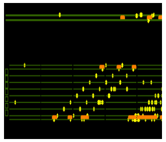
Trigger threshold: $N_{phe,th} = 120$ phe / mirror ($E_{thr} \approx 40$ TeV at r = 130 m)
Trigger rate: 7 Hz/telescope
Cherenkov event: coincidence in $\Delta T = 30$ ns , between any 2 corresponding PMs.

5

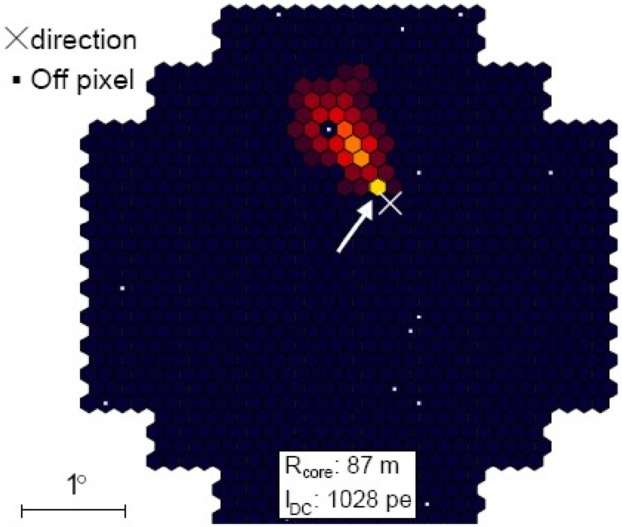
MACRO (as a μ detector):

- EAS from primaries with $E_n > 1.3$ TeV/n
- EAS geometry through the μ track (~20 m uncertainty) .

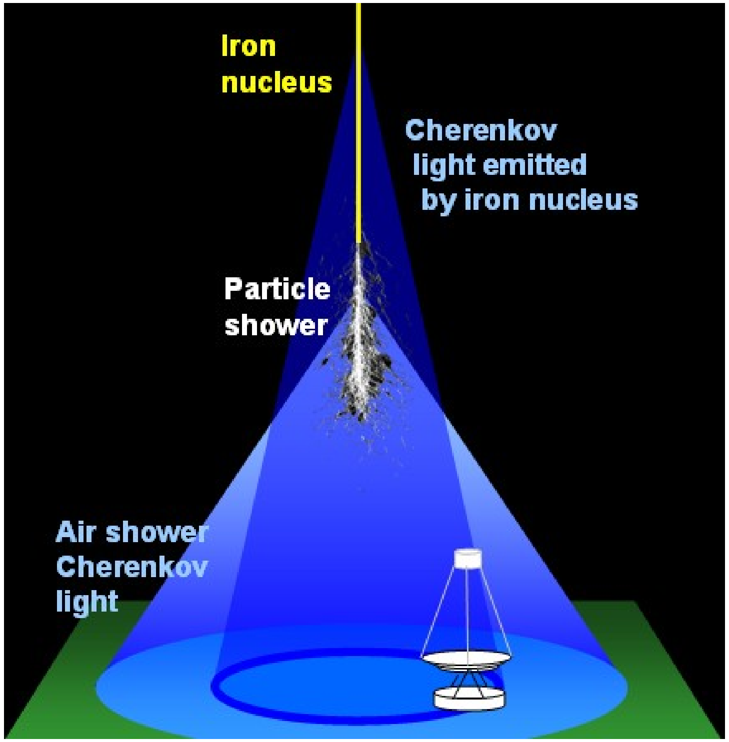
$E\mu^{th} \sim 1.3$ TeV
76.6 x 12 x 4.8 m^3
$\sigma_\theta < 1^o$
20 m at surface level



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



Cherenkov Light ∝ Z^2

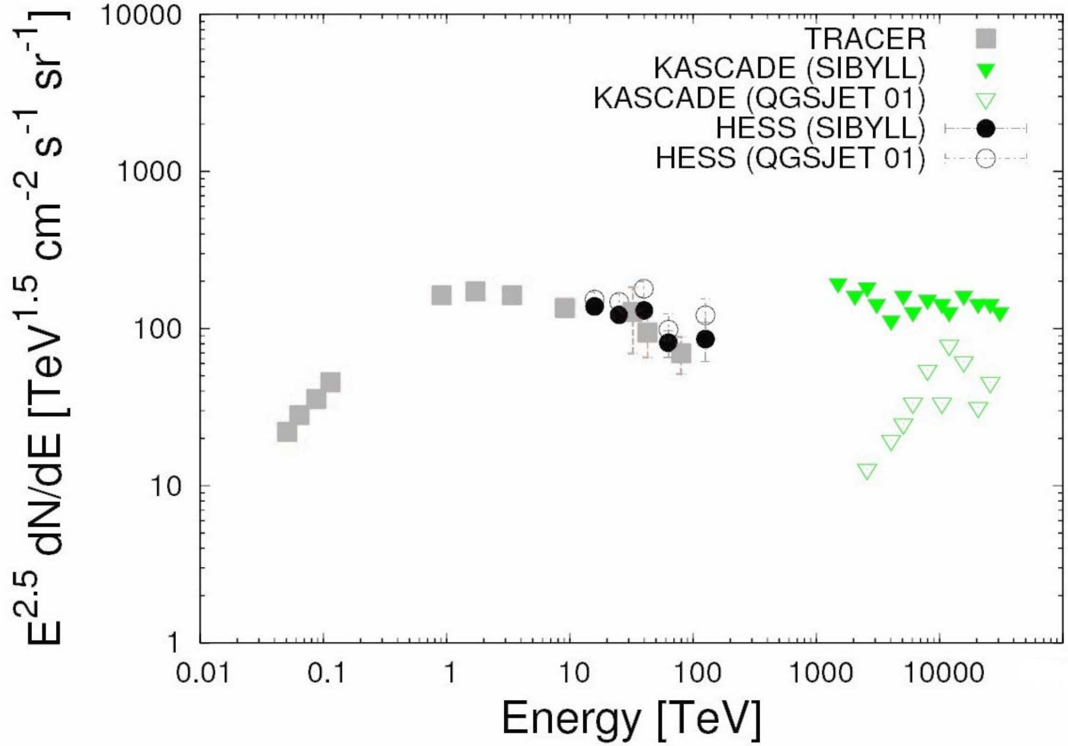


Good agreement with other exper.

- Hadronic model ≈20% on normal.
- Power-law Index

QGSJET= 2.62 +- 0.11

SIBYLL= 2.76 +- 0.11

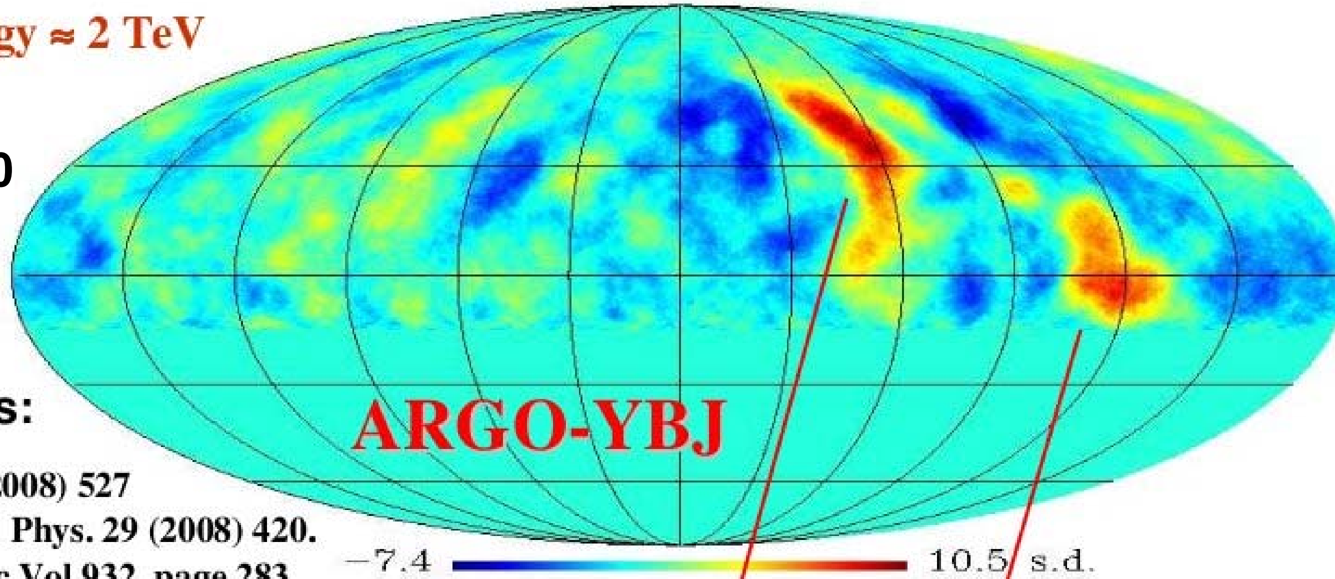


Aharonian et al., 2007

TeV anisotropy

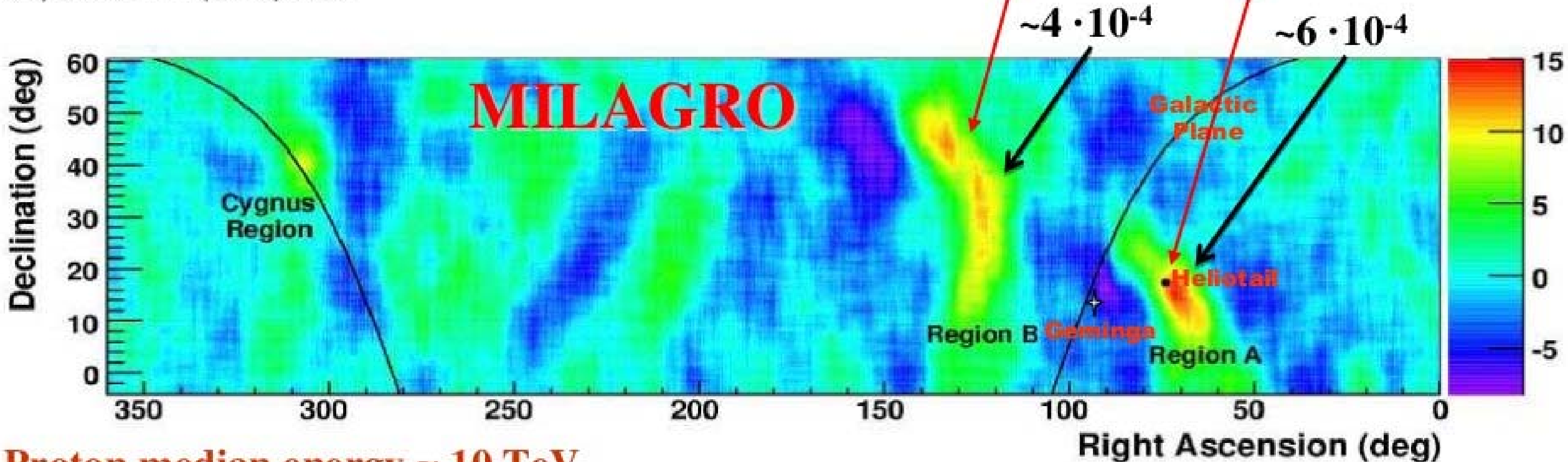
Proton median energy ≈ 2 TeV

A.Surdo, ECRS2010



Several explanations:

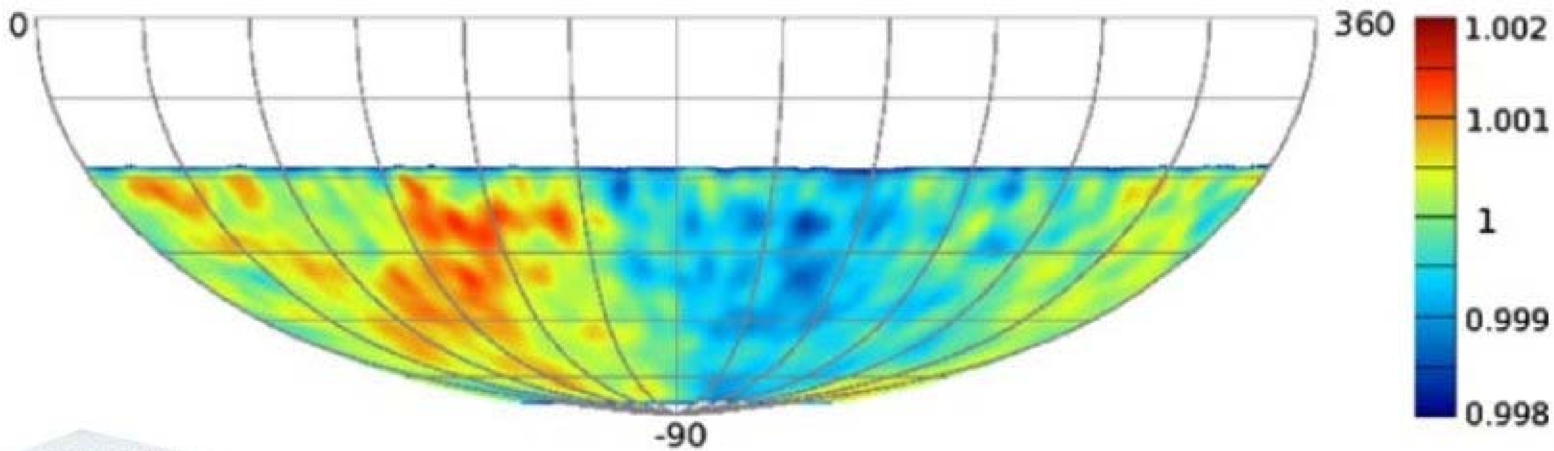
Salvati & Sacco, A&A 485 (2008) 527
Drury & Aharonian, Astrop. Phys. 29 (2008) 420.
K. Munakata ,AIP Conf Proc Vol 932, page 283
Salvati, A&A 513 (2010) A28

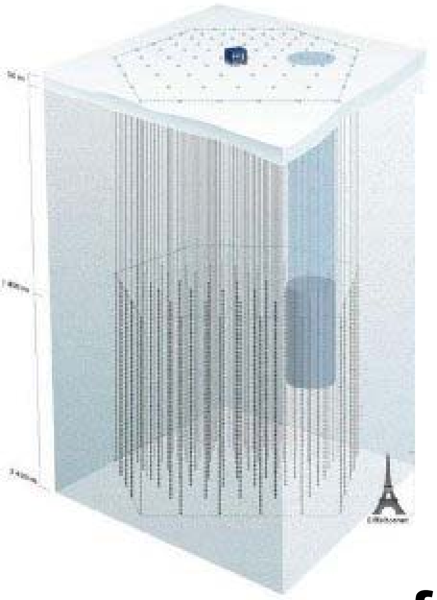


Proton median energy ≈ 10 TeV

A. A. Abdo et al, Phys. Rev. Letters 101 (2008) 221101

ICECUBE





Primary energy around 20 TeV

Which is the reason of MILAGRO-ARGO and ICECUBE anisotropies?
a) Nearby accelerators?
b) Local magnetic fields?

Is this connected somehow with the change of spectral indexes seen by PAMELA and CREAM?

Abbasi, R. et al, The Astrophysical Journal Letters 718, L194, 2010

Summary

Is the spectral difference between H and He an indication that there are different types of sources or mechanisms of acceleration?
(Biermann, *A&A* **271**, *649*,1993;Biermann et al. PRL **103**, *061101*, 2009; ApJ **710**, *L53*,2010)

The flattening of the elemental spectra is an indication that:
The source spectra are harder than previously thought?
If it is not acceleration or propagation related, are we seeing a local source? (Erlykin & Wolfendale *A&A* **350**)

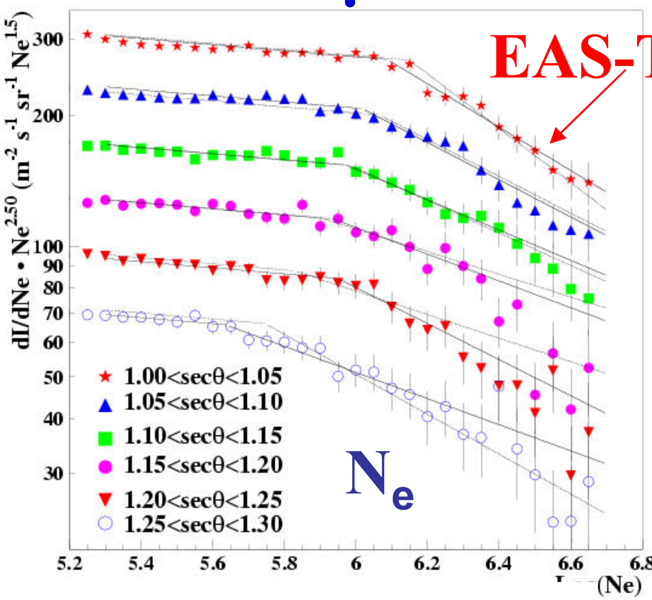
Is the TeV anisotropy connected with what is observed by direct experiments?

Different techniques can be employed by ground based experiments to study cosmic ray flux and composition in the TeV region.
The results are in a general agreement with the measurements performed by balloons and satellites.

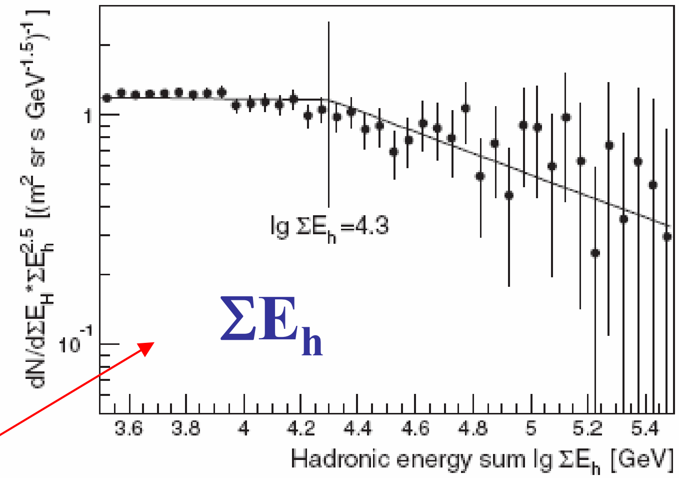
Experimental results at knee energies

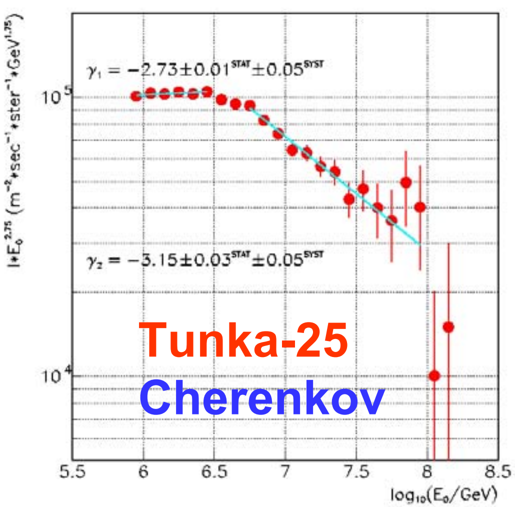
The change of slope is observed in the spectra of all EAS components

EAS-TOP

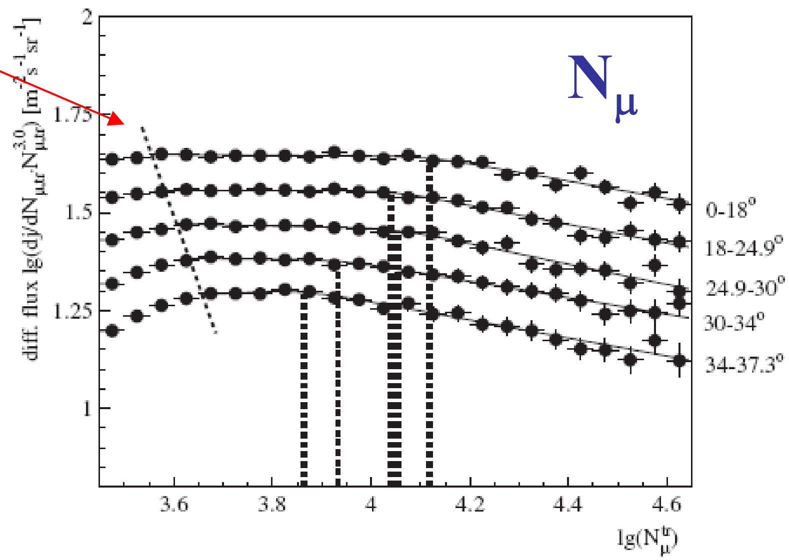


KASCADE





E

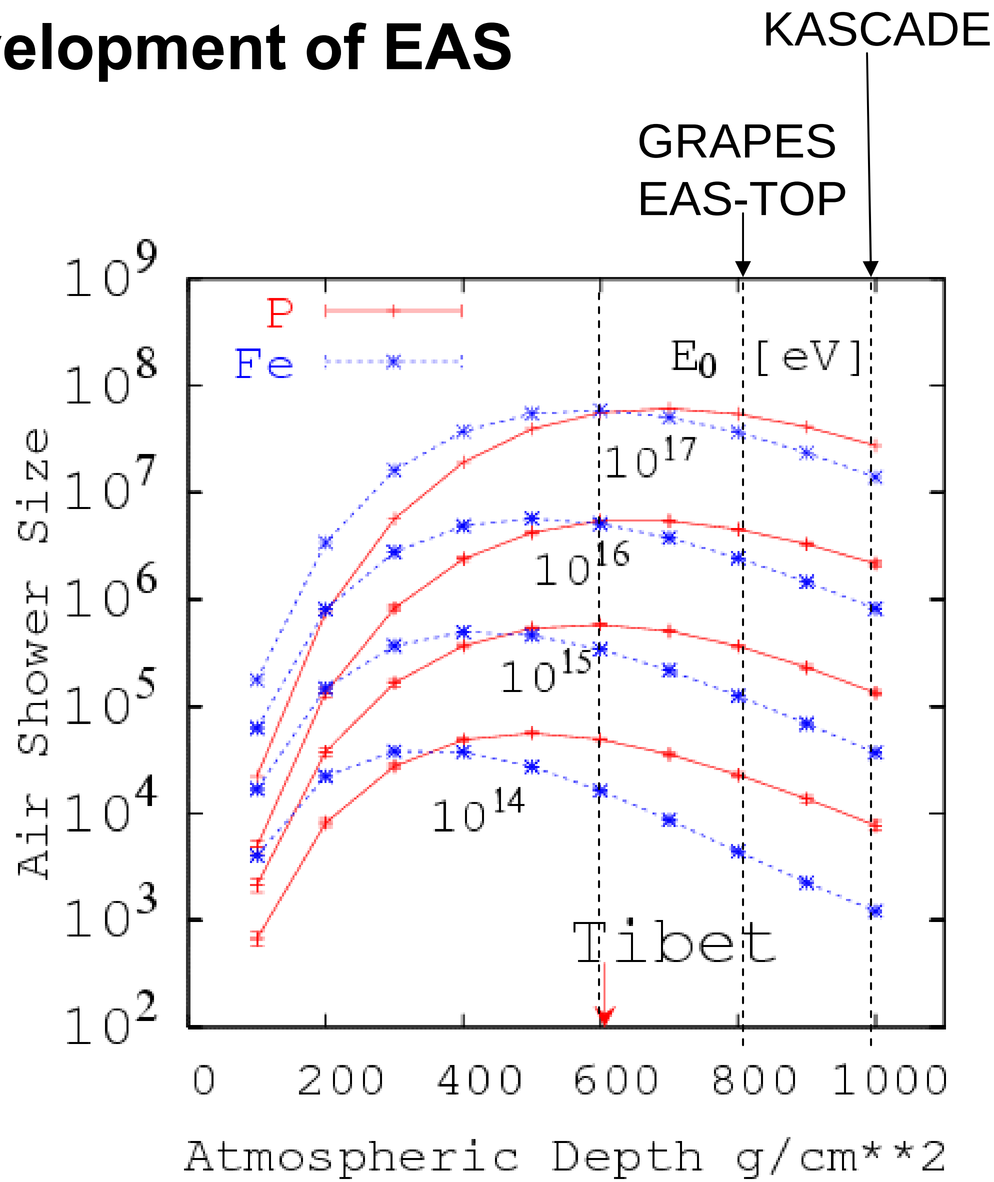


Longitudinal development of EAS

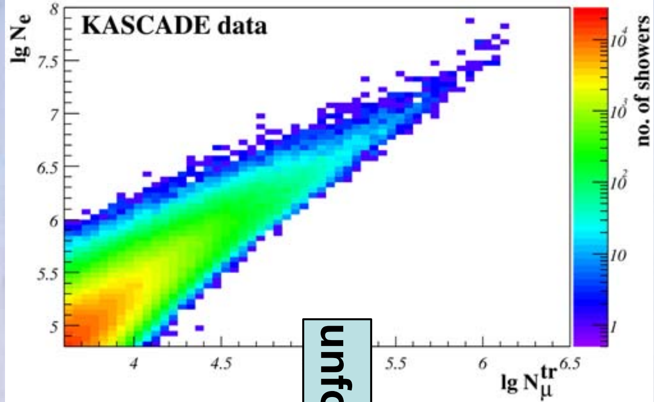
In the knee region:

At **high mountain** the shower is at maximum **less fluctuations**

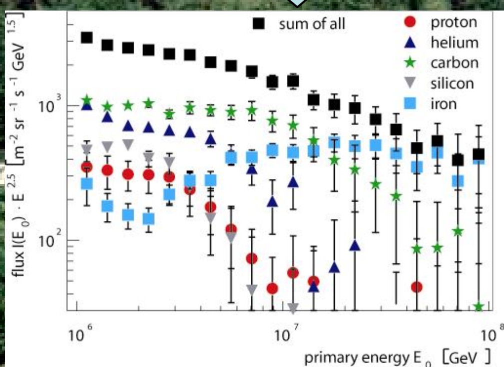
Sea level is better for composition studies because **H – Fe separation is easier**



M. Shibata, CRHEU 2007.3.8.



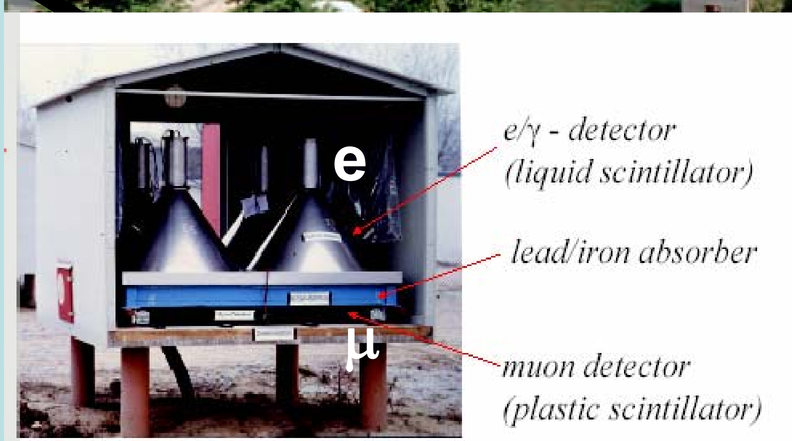
unfolding



Mass group spectra from Ne – Nμ (GeV): E = 1 - 30 PeV

KASCADE (110 m a.s.l.)

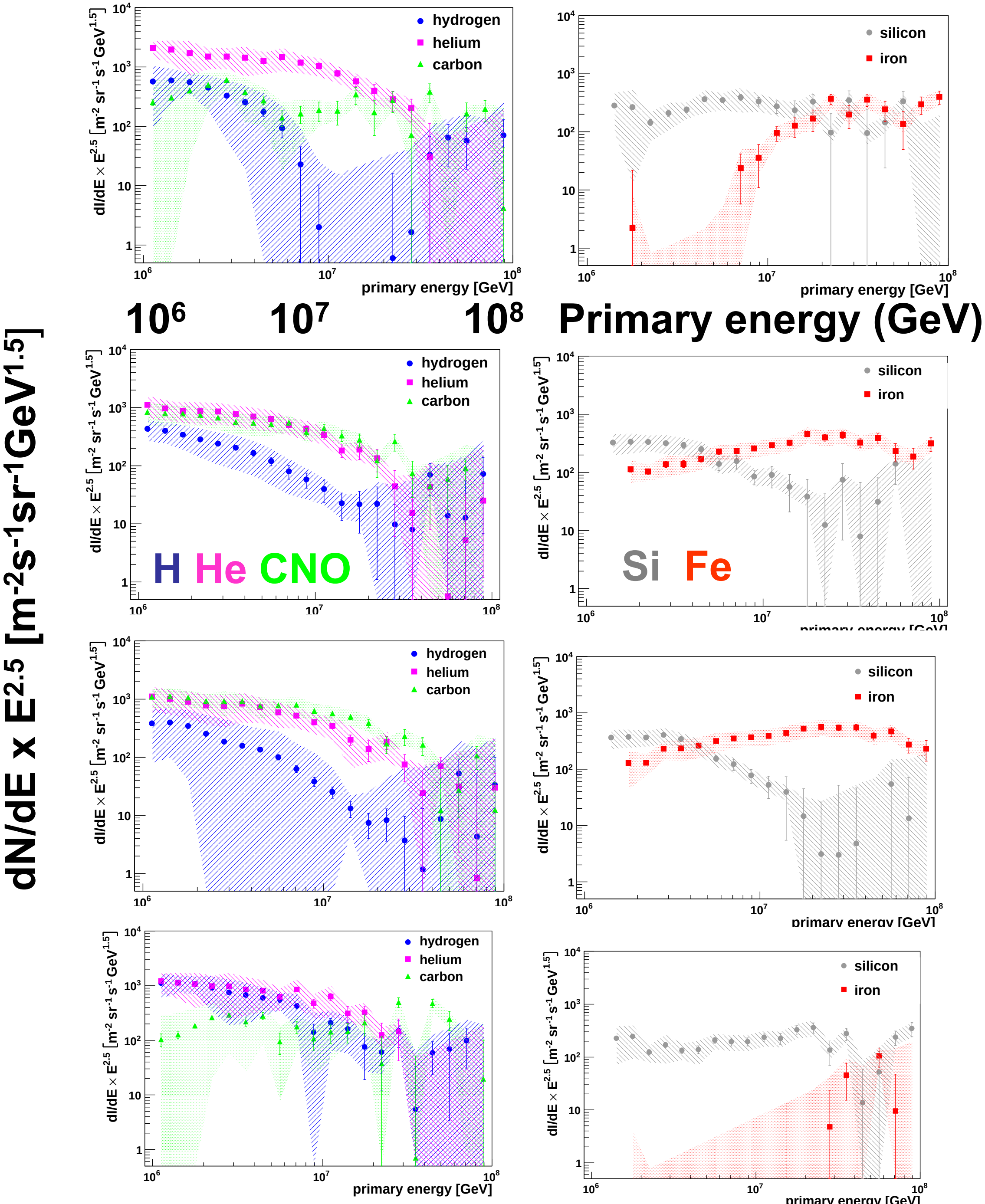
Composition studies by KASCADE collaboration:
Astrop.Phys. 24 (2005) 1 , Astrop.Phys. 31 (2009) 86



Searched:
E and A of the Cosmic Ray Particles
Given:
N_e and N_μ for each single event
➔ solve the inverse problem

$$g(y) = \int K(y,x)p(x)dx$$

with $y=(N_e, N_\mu^{tr})$ and $x=(E,A)$



KASCADE

QGSjet01/FLUKA

Knee H ~ (3 – 4 × 10^{15}eV)

Knee He ~ 8 × 10^{15}eV

No knee in other spectra

QGSjetII/FLUKA

Knee H ~ (3 – 4 × 10^{15}eV)

Knee He ~ 8 × 10^{15}eV

Knee CNO ~ (2-3 x 10^{16} eV)

Knee Si ~ 4x10^{15} eV

SIBYLL/FLUKA

Knee H ~ (3 – 4 × 10^{15}eV)

Knee He ~ 8 × 10^{15}eV

Knee CNO ~ (2-3 x 10^{16} eV)

Knee Si ~ 4x10^{15} eV

EPOS1.99/FLUKA

Knee H ~ (6 – 7 × 10^{15}eV)

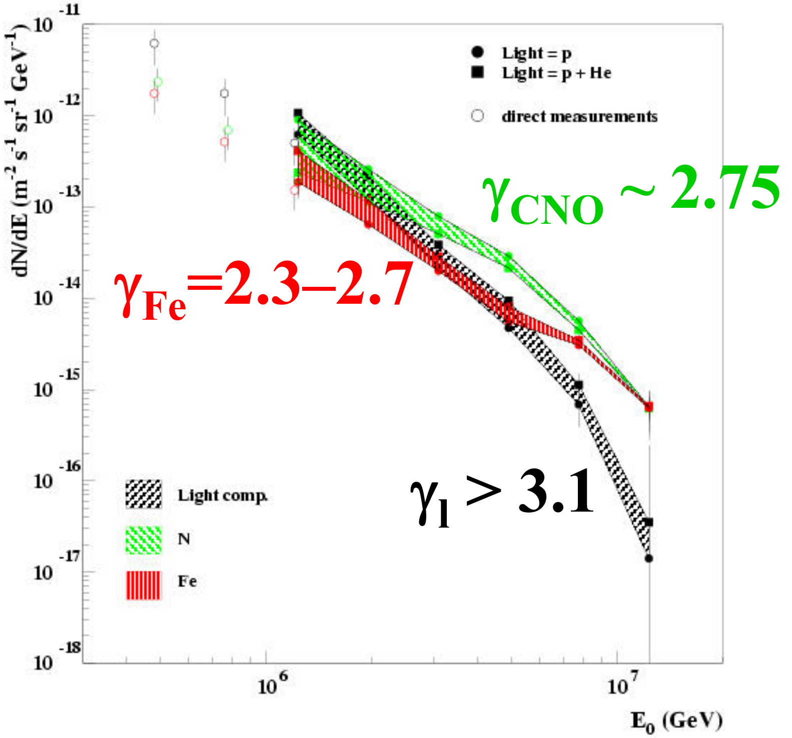
No knee in other spectra

Almost no Fe

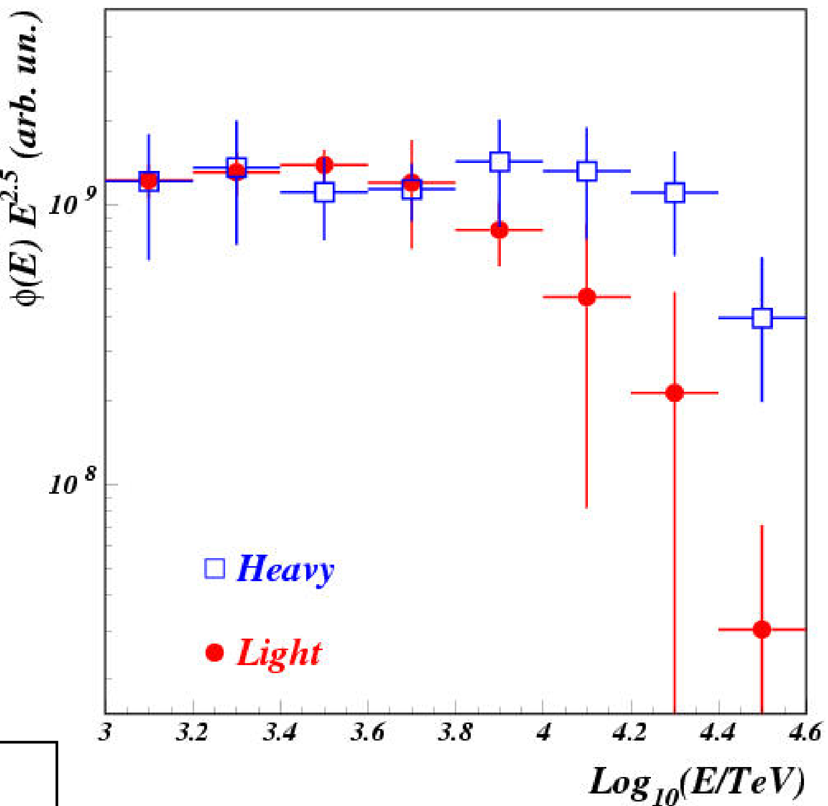
M. Fingler, PhD thesis in preparation

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
➔ $E_k \propto Z$?

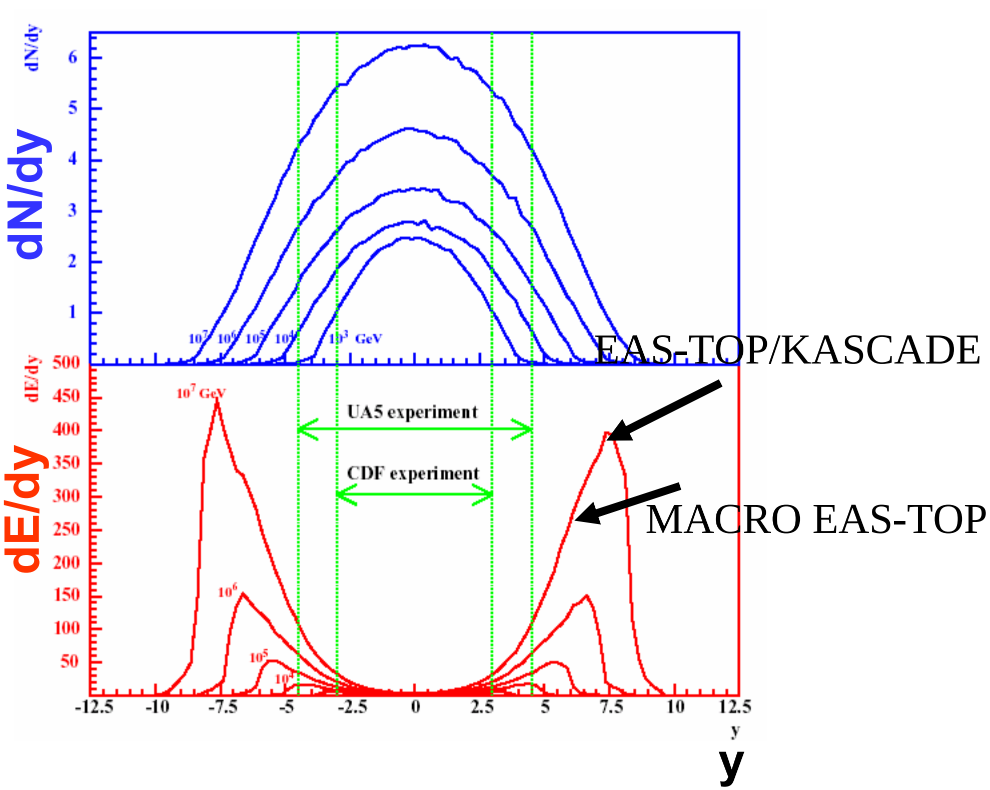
Astrop. Phys. 21 (2004) 583

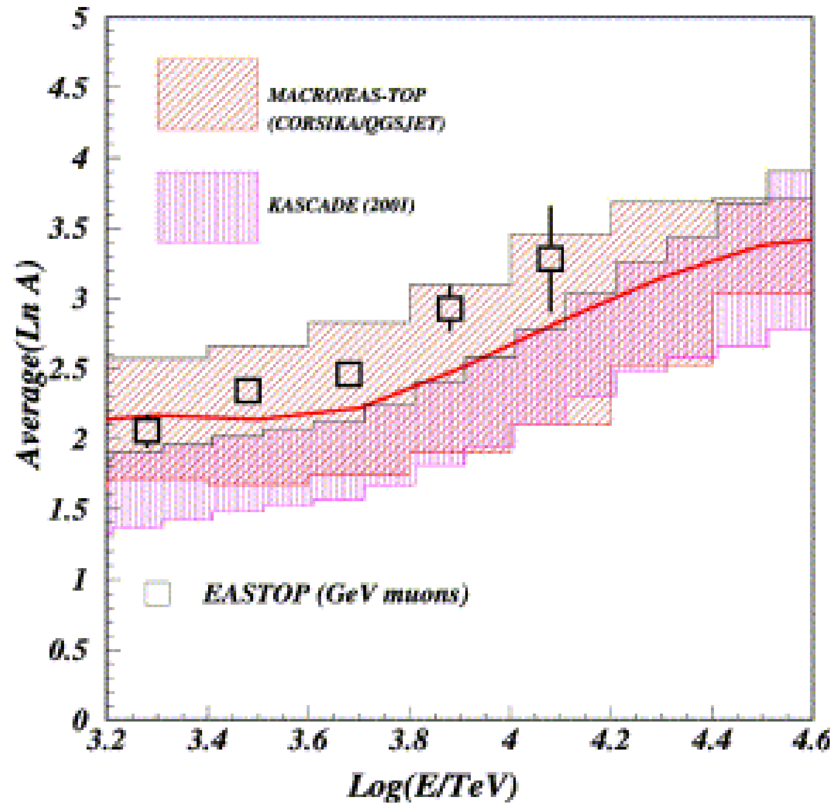
L = p + He   H = Mg + Fe

Astrop. Phys. 20 (2004) 641

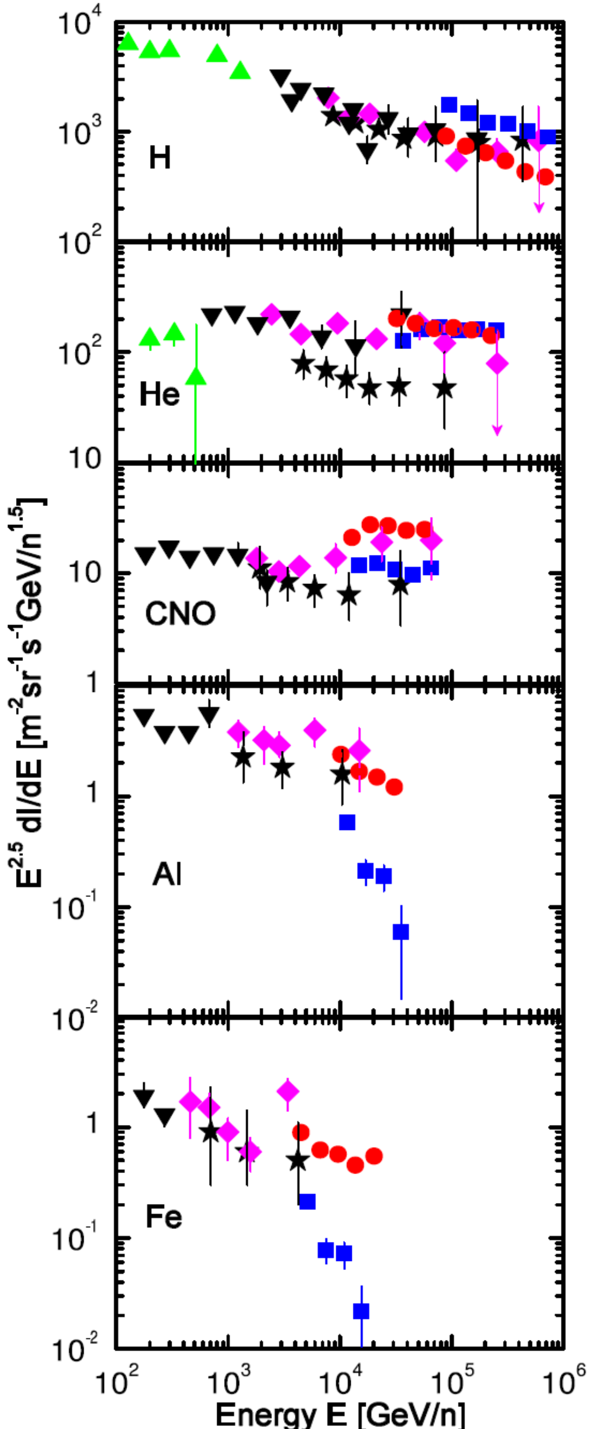
EAS-TOP & MACRO (TeV μ)

particle and energy flux in p-p̲

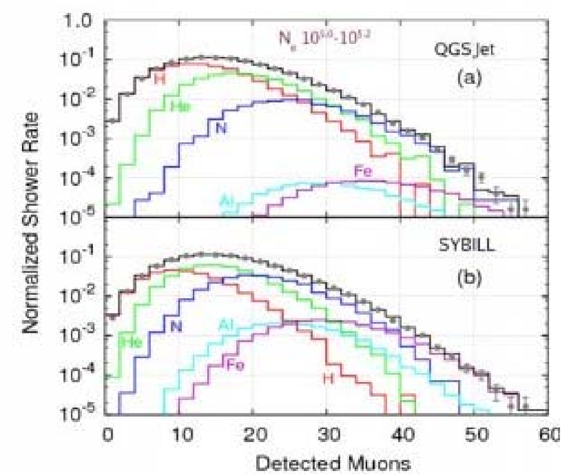




GRAPES-3 (Ooty, India 2200 m a.s.l.)



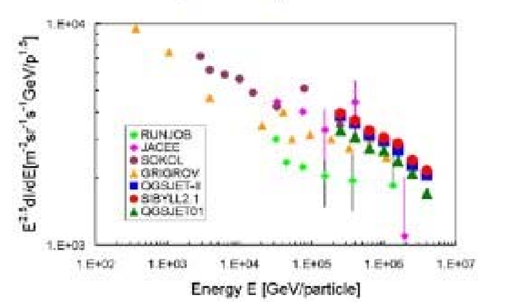
400 scintillators
560 m² tracking μ detector
(Eμ > 1 GeV)
3×10^{13} eV < E < 3×10^{16} eV



Overlap with direct meas.
Knee by light primaries

SIBYLL
QGSjet

All-particle Spectrum



Diamonds: JACEE
Stars: RUNJOB
Triangles: Ryan/SOKOL

Sunil Gupta, ISVHECRI 2010

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

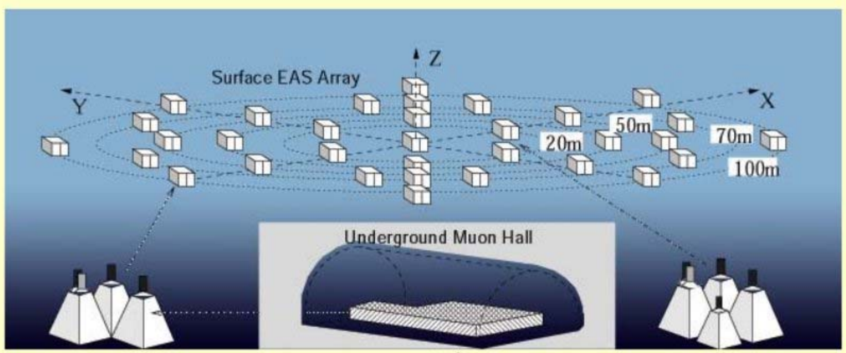
ARAGATS scientific station (late autumn)

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

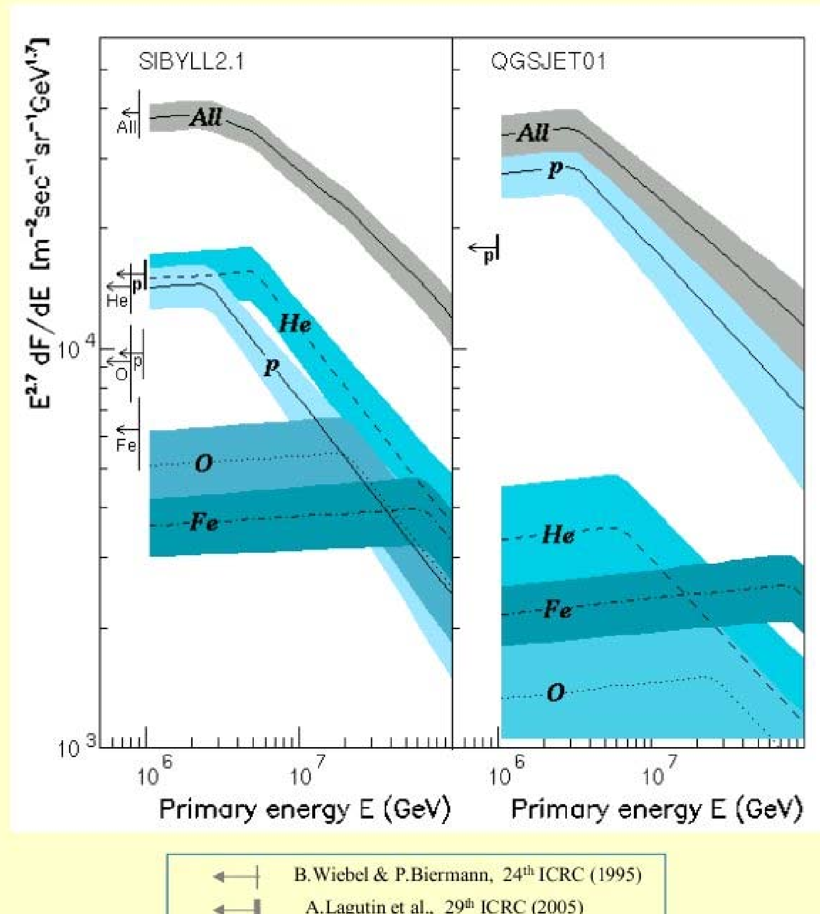
Elevation: 3200 m a.s.l. (700 g/cm^2 of atmospheric depth)

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

GAMMA facility (2003-2008)



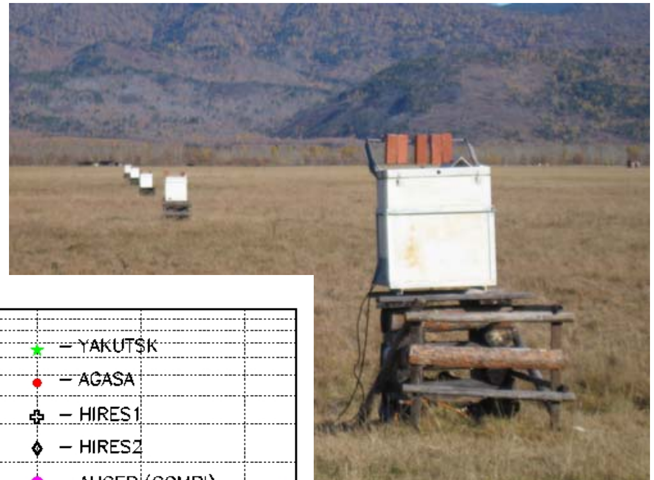
Energy spectra for the primary nuclei groups

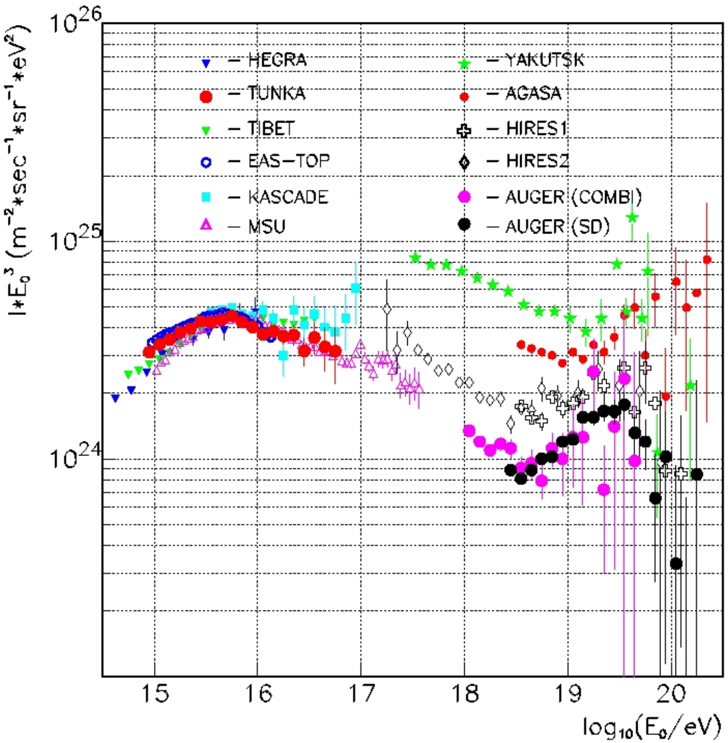


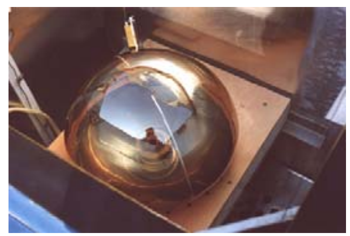
Knee due to the light elements

Astroparticle Physiscs, 28 (2007) 169

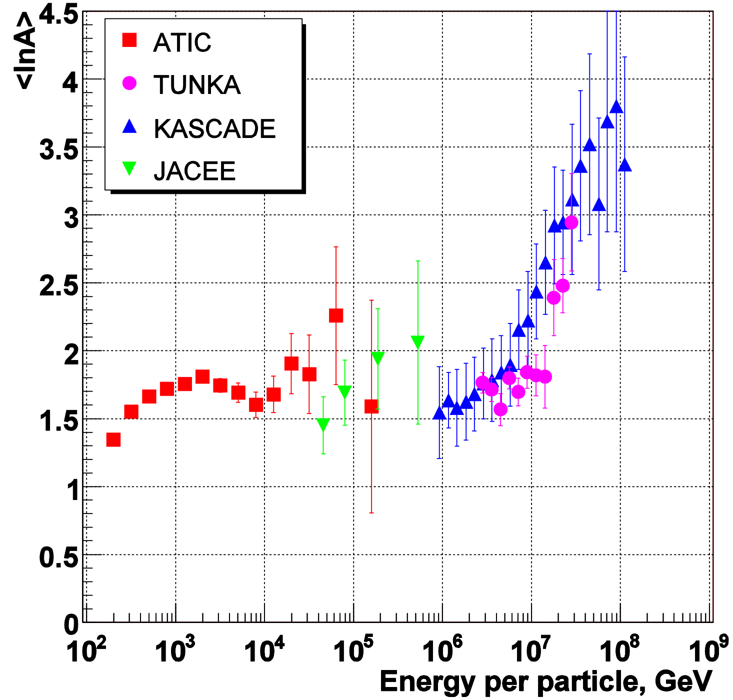
TUNKA-25 Cherenkov array, Siberia 675 m a.s.l.







Mean mass composition



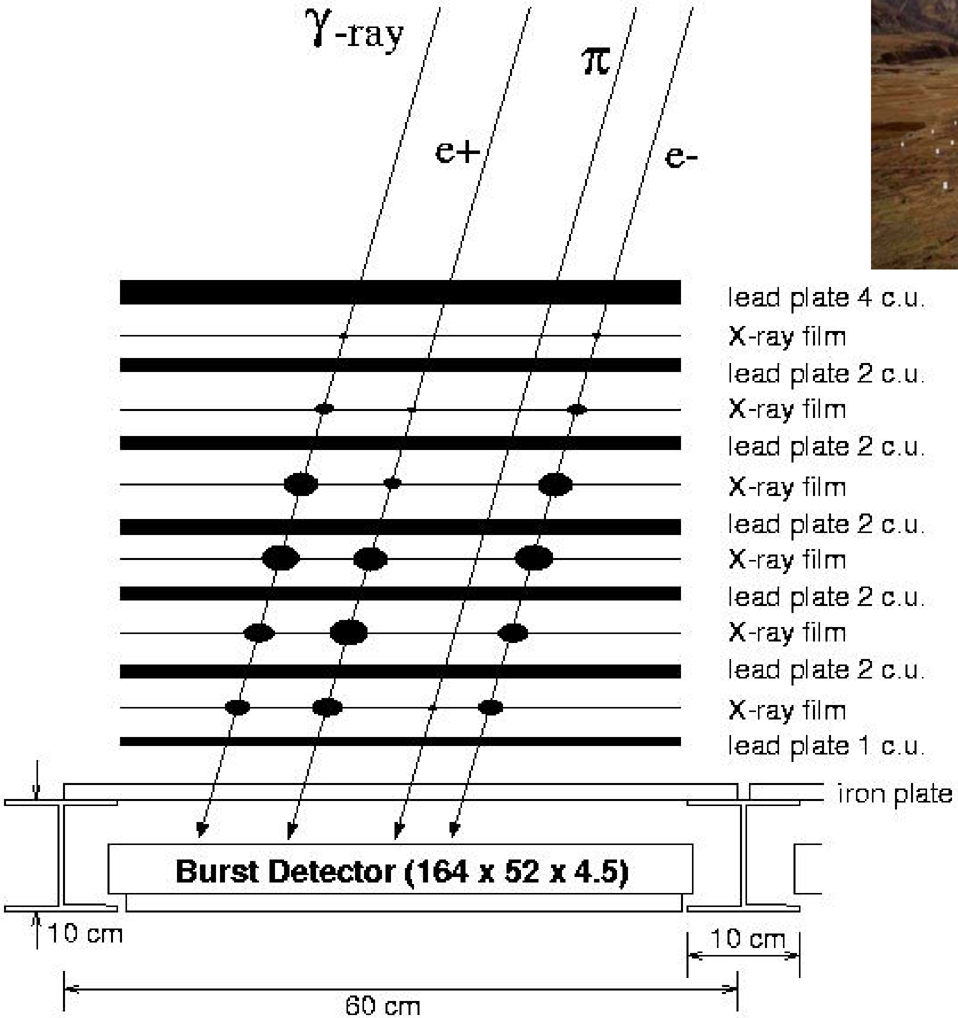
V. Prosin, *Highlights of Astroparticle Physics* Torino, 2010

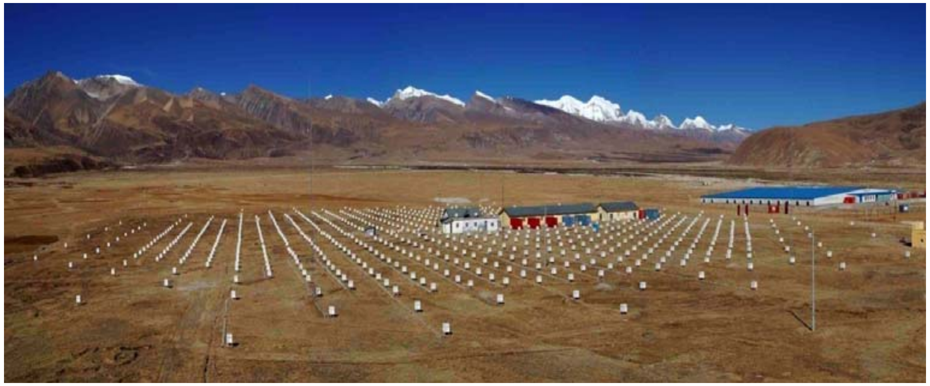
1. Composition before the knee and in the knee is light 70% of p+He, 30% of others.

2. Composition at $3{\cdot}10^{16}$ is heavy 30% of p+He, 70% of others.

Tibet ASγ – 4300 m a.s.l. Yangbaijing

Design of Emulsion Chamber and Burst Detector





γ families

γ and e (> TeV) enter to EC with lateral spread of several cm.

They develop into cascade showers and shower spots are registered by X-ray films which consist of 6 layers.

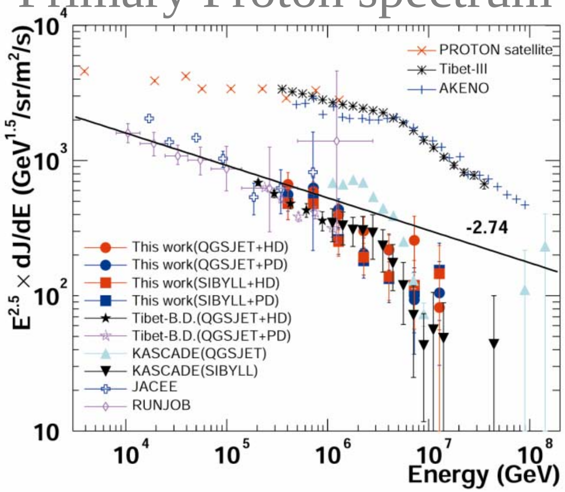
Burst Detector below EC records the burst size, the position and arrival time stamp.
(4 PD are equipped at each corner of the BD.)

M. Shibata, CRHEU 2007.3.8.

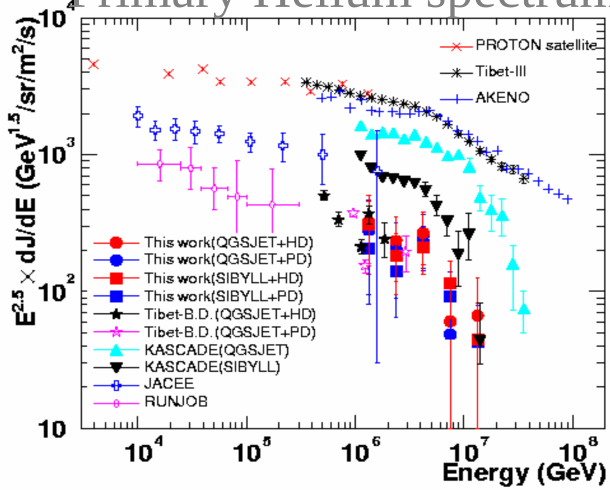
P, He by Tibet hybrid Experiment

(Phys. Lett. B, 632, 58 (2006))

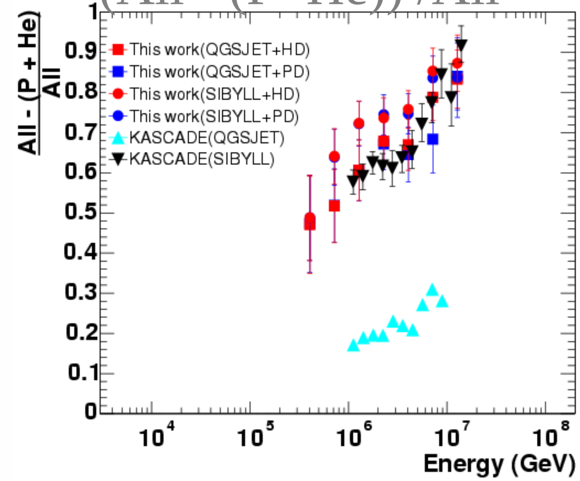
Primary Proton spectrum



Primary Helium spectrum



(All - (P+He)) /All



1) Our results shows that the main component responsible for the knee structure of the all particle spectrum is heavier than helium nuclei.

2） The absolute fluxes of protons and helium nuclei are derived within 30% systematic errors depending on the hadronic interaction models.

SYBILL works better when comparing Tibet and Kascade!

Jing Huang (ISVHECRI 2008-PARIS)

In this analysis the fit of the data is done in the following way:

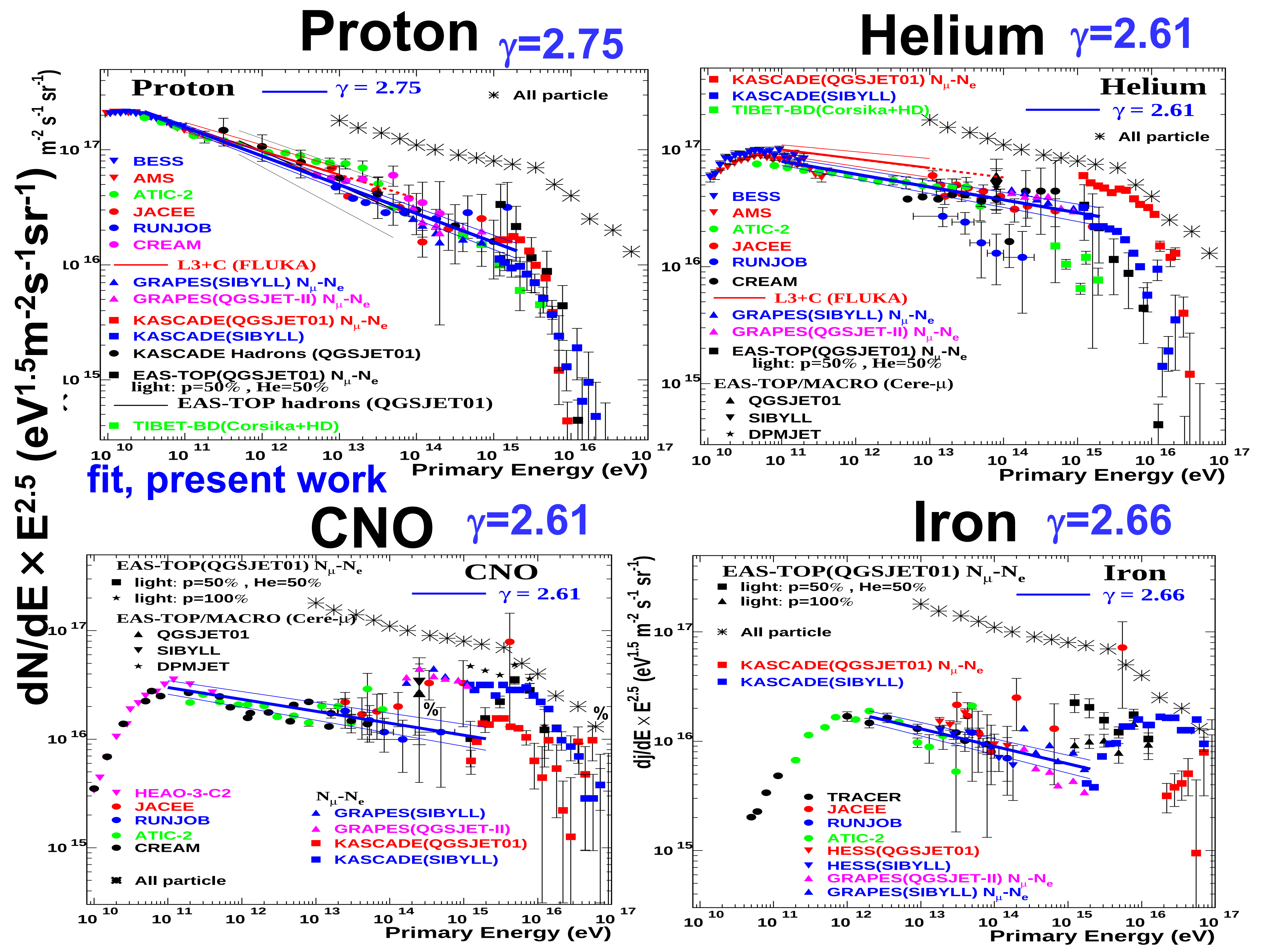
$$dN/dE = N_0 E^{-\gamma}$$

- The flux in the hundreds GeV region, as measured by spectrometers, provides the N_0 parameter. The uncertainty on N_0 is given by the discrepancy on the flux measured by different experiments (AMS, BESS, etc..).

- The slope γ of the spectrum is obtained through the fit of the experimental data in the TeV region (1 – 1000 TeV) which is dominated by the results of the direct measurements.

- Data of the EAS arrays in the PeV region are used only as a guidance to operate selections on the data to be fitted in the TeV region, if needed (like for the He spectrum where results of the experiments do not fully agree among each others).

More details in: **M. Bertaina et al., Journal of Physics: Conference Series, 120 (2008) 062023**



Proton γ=2.75
Helium γ=2.61
CNO γ=2.61
Iron γ=2.66
fit, present work
dN/dE × E^2.5 (eV^1.5 m^-2 s^-1 sr^-1)
Proton
γ = 2.75
All particle
BESS
AMS
ATIC-2
JACEE
RUNJOB
CREAM
L3+C (FLUKA)
GRAPES(SIBYLL) Nμ-Ne
GRAPES(QGSJET-II) Nμ-Ne
KASCADE(QGSJET01) Nμ-Ne
KASCADE(SIBYLL)
KASCADE Hadrons (QGSJET01)
EAS-TOP(QGSJET01) Nμ-Ne
light: p=50% , He=50%
EAS-TOP hadrons (QGSJET01)
TIBET-BD(Corsika+HD)
Primary Energy (eV)
KASCADE(QGSJET01) Nμ-Ne
KASCADE(SIBYLL)
TIBET-BD(Corsika+HD)
Helium
γ = 2.61
All particle
BESS
AMS
ATIC-2
JACEE
RUNJOB
CREAM
L3+C (FLUKA)
GRAPES(SIBYLL) Nμ-Ne
GRAPES(QGSJET-II) Nμ-Ne
EAS-TOP(QGSJET01) Nμ-Ne
light: p=50% , He=50%
EAS-TOP/MACRO (Cere-μ)
QGSJET01
SIBYLL
DPMJET
Primary Energy (eV)
EAS-TOP(QGSJET01) Nμ-Ne
light: p=50% , He=50%
light: p=100%
EAS-TOP/MACRO (Cere-μ)
QGSJET01
SIBYLL
DPMJET
CNO
γ = 2.61
HEAO-3-C2
JACEE
RUNJOB
ATIC-2
CREAM
All particle
Nμ-Ne
GRAPES(SIBYLL)
GRAPES(QGSJET-II)
KASCADE(QGSJET01)
KASCADE(SIBYLL)
Primary Energy (eV)
dj/dE × E^2.5 (eV^1.5 m^-2 s^-1 sr^-1)
EAS-TOP(QGSJET01) Nμ-Ne
light: p=50% , He=50%
light: p=100%
Iron
γ = 2.66
All particle
KASCADE(QGSJET01) Nμ-Ne
KASCADE(SIBYLL)
TRACER
JACEE
RUNJOB
ATIC-2
HESS(QGSJET01)
HESS(SIBYLL)
GRAPES(QGSJET-II) Nμ-Ne
GRAPES(SIBYLL) Nμ-Ne
Primary Energy (eV)

Assumptions

How well do these fits of the mass groups reproduce the all particle spectrum?

•The spectra of H, He, CNO and Fe groups are given by the fits here presented (tuned inside their uncertainties).

•The spectra of the other elements are taken from: Wiebel-Sooth et al., Astron. Astrophys. 330 (1998) 389.

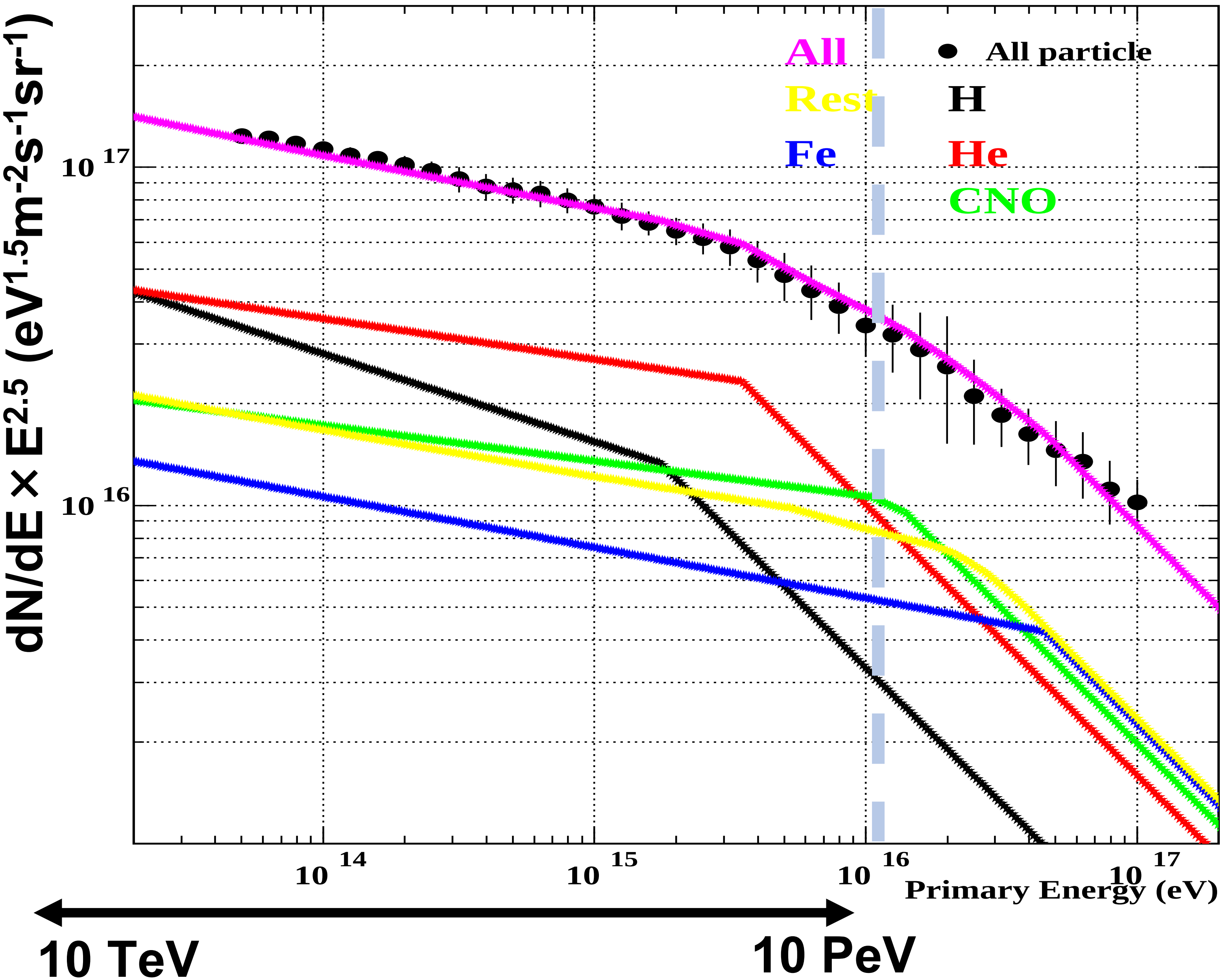
•The all particle spectrum is taken from the following compilation: J. Hörandel, Astroparticle Physics 19 (2003) 193.

•The knee of the He component (the dominant one at the knee) is set at $E_{k,He}=3.5\cdot10^{15}$eV (coincident with the knee in the all particle spectrum).

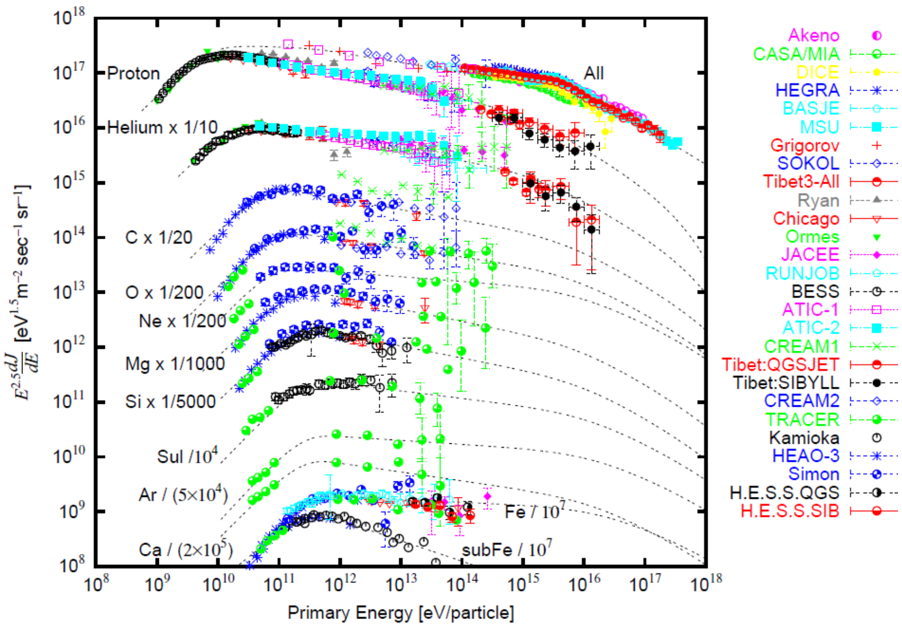
•The knees of the single mass groups follow a rigidity dependence $E_{k,Z}=Z\cdot E_{k,p}$.

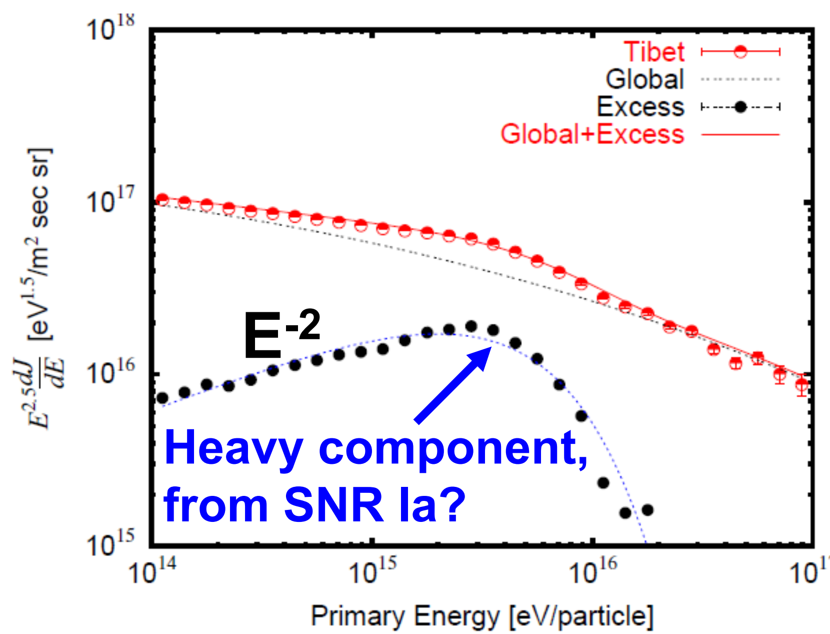
•All the components have a common γ after the knee: $\gamma = 3.3$.

All particle spectrum (10 TeV – 10 PeV)



Sharp knee from AS γ and single source interpretation





$$\frac{dj}{dE} = j_0 E^{-\gamma}(1 + E/\varepsilon_b)^{-\Delta\gamma} h(E)$$

$$\varepsilon_b(z) = z \times \varepsilon_b(p)$$ $\varepsilon_b(p) = 7 \times 10^{14}$ eV

$$h(E) = 1 - \exp[-(\frac{E}{a})^{1.3}]$$

$$\Delta\gamma = 0.4 \pm 0.1$$

Fig. 4. All-particle spectrum around the knee. Solid line is the global component calculated by present model. Dashed line is the fit to the excess component seen in Tibet 3 data [5] which can be approximated as $f_x(E) \propto E^{-2} \exp(-E/4\mathrm{PeV})$. The dot-chained line is the sum of the global component and $f_x(E)$

M.Shibata et al, The Astrophysical Journal, 716 (2010) 1076

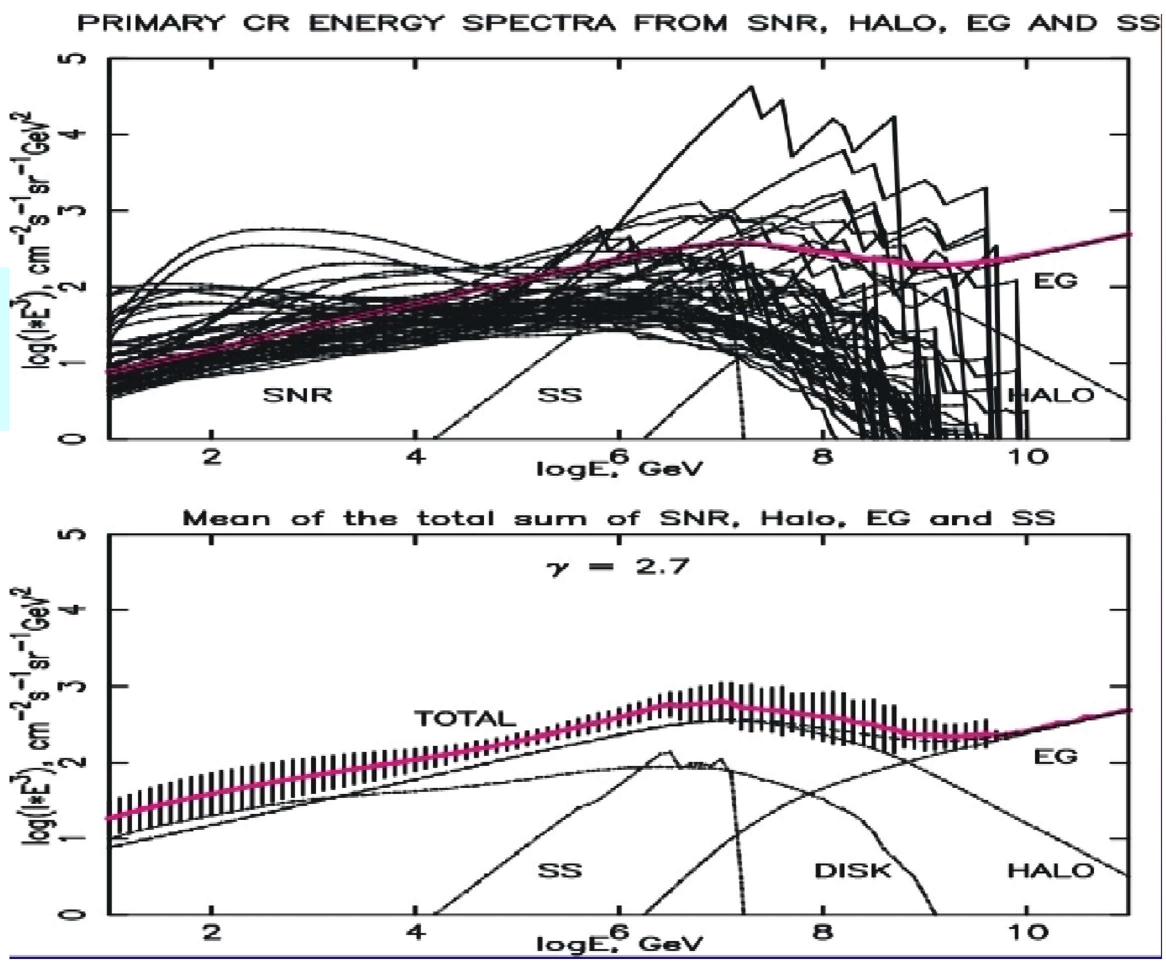
The Single Source Model

The essence of the Single Source Model of the knee is the non-uniform, stochastic distribution of CR sources in space and time.
The knee is due to the contribution of the nearby and recent supernova explosion.

Sharpness of the knee:

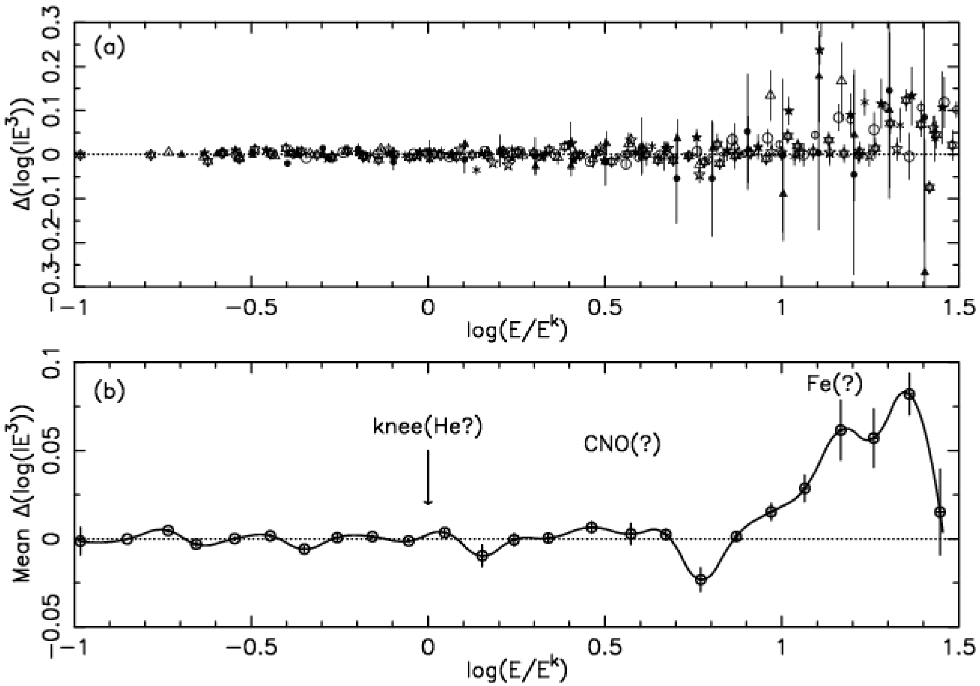
$$S = \frac{d\gamma}{d(\log E)} = -\frac{d^2(\log I)}{d(\log E)^2}$$

S does not depend on absolute values of I and γ

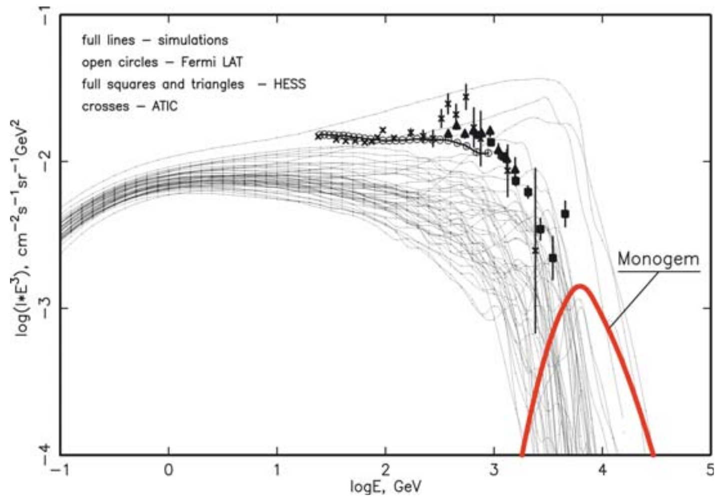


A. Erlykin & A. Wolfendale
B. A&A **350, L1,** 1999

Deviations from the smooth fit in the new data confirm the irregularity at log(E/Ek)=0.5-0.6 ('CNO peak') and reveal the possible existence of the peak at log(E/Ek)=1-1.2 ('Fe peak')



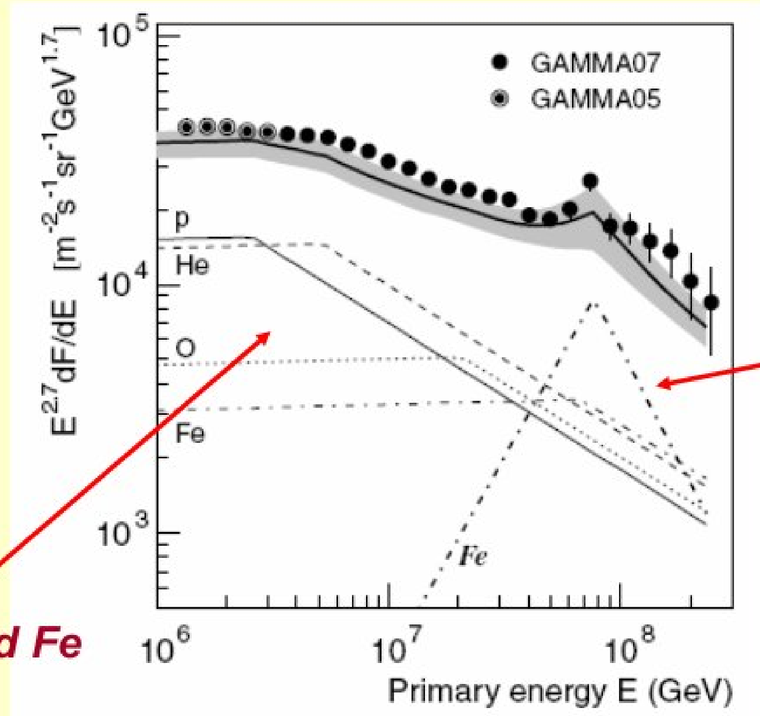
Primary electron energy spectrum



General Conclusion (A. Erlykin, ECRS2010)

New data manifest substantial non-uniformity of the CR source distribution in space and time and the evidence in favor of the presence of a 'Single Source' is even stronger than before

All-particle spectra and pulsar *Fe* component



Fe component from compact objects

Galactic p, He, O and Fe components

All-particle energy spectrum and expected energy spectra obtained from EAS inverse problem solution for p, He, O and Fe primary nuclei using two-component parametrization along with energy spectra of Galactic p, He, O and Fe components and with additional Fe component from compact objects

!!! Two-component all-particle spectrum (bold line with shaded area) agree within the errors with the results of the event-by-event analysis !!!

- Knee is not related to a change in the interaction mechanism.
- Knee can be interpreted as the maximum energy for acceleration in SNR and/or diffusion in the galaxy.
- Spectra of different elements change the slope at energy $E^{knee}_{Z} = Z\, E^{Knee}_{p}$
- The SNR spectrum would extend to a maximum energy for iron $E^{max}_{Fe}=26E^{max}_{p}$

AND

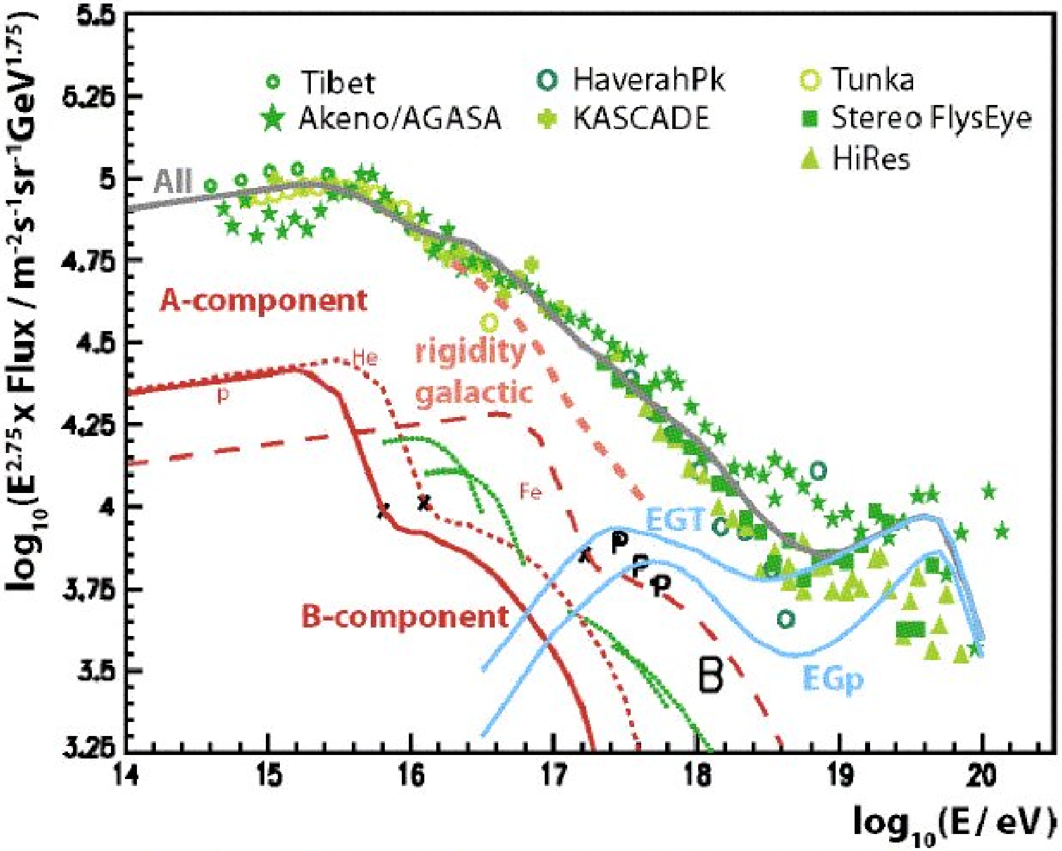
Single source model(s)?

Need to precisely measure the spectrum & composition at 10^{16} eV<E<10^{17} eV

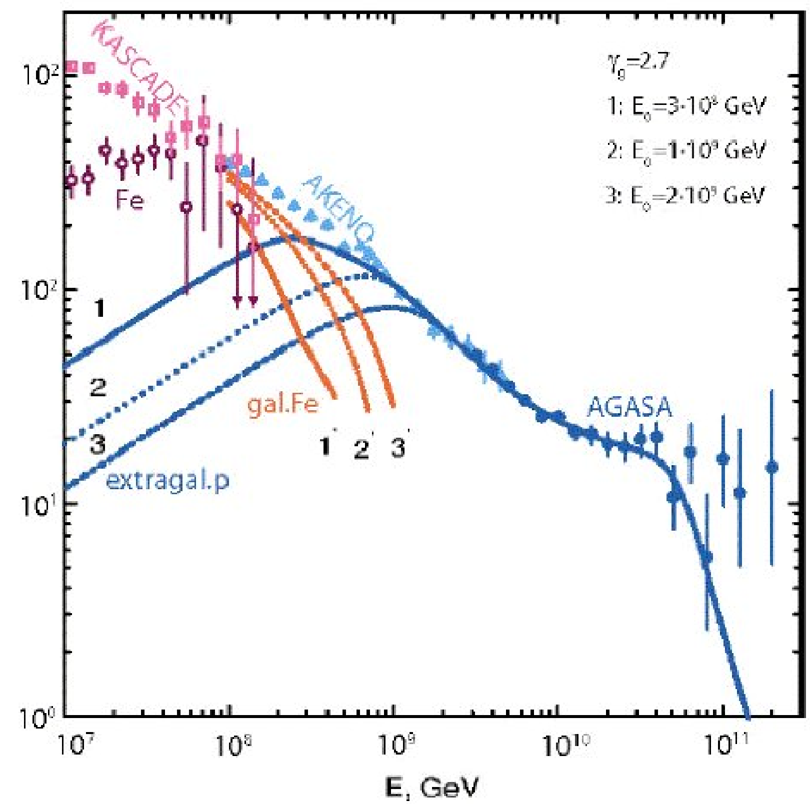
The transition from galactic to extra-galactic radiation

★ "mixed composition model" (Hillas, Allard, et al.)
→ in the field of the SM,
extra contribution of galactic CRs up to $E > 10^{18}$ eV
→ raise of extragalactic component just at the highest energies, from early active sources, with spectrum $E^{-2.3}$

★ "dip model" (Berezinsky et al.)
→ break of galactic component at ~ 10^{17} eV
→ raise of purely extragalactic p
→ AGNs as sources, spectrum $E_0^{-2.7}$



A.M.Hillas, J. Phys. G: Nucl. Part. Phys. 31 (2005) R95



V.Berezinsky, astro-ph/0403477

Experiments Operating in the $10^{16}<E<10^{18}$ eV energy range (a bridge towards UHECR experiments)

- KASCADE-Grande (Nch – Nμ)
- IceTop/ICECUBE (Nch – TeV μ)
- Tunka-133 (Cherenkov)
- HEAT+Infill+Amiga (Fluo,Nch,μ)

operating, established techniques

- LOPES, Codalema, AERA (Radio)

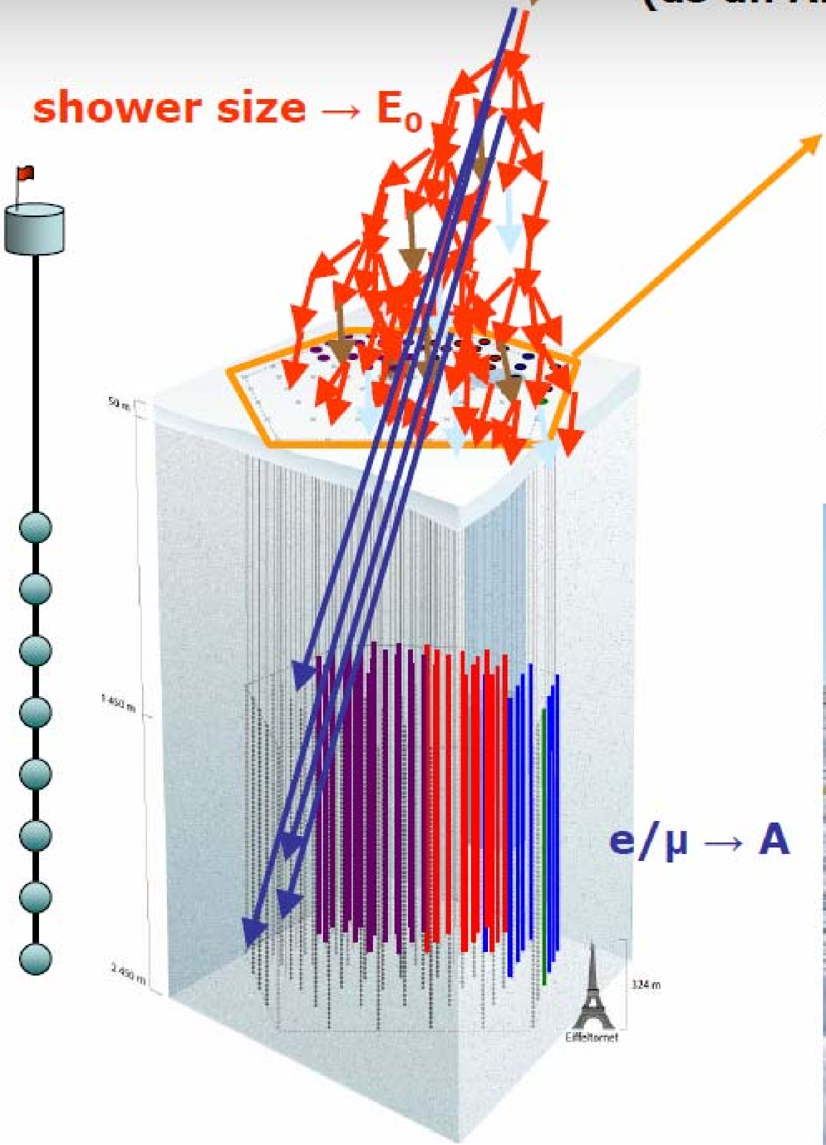
test of principle, hopefully physics

- TALE (Fluorescence)

planned

The IceCube Observatory

(as an Air Shower Detector)



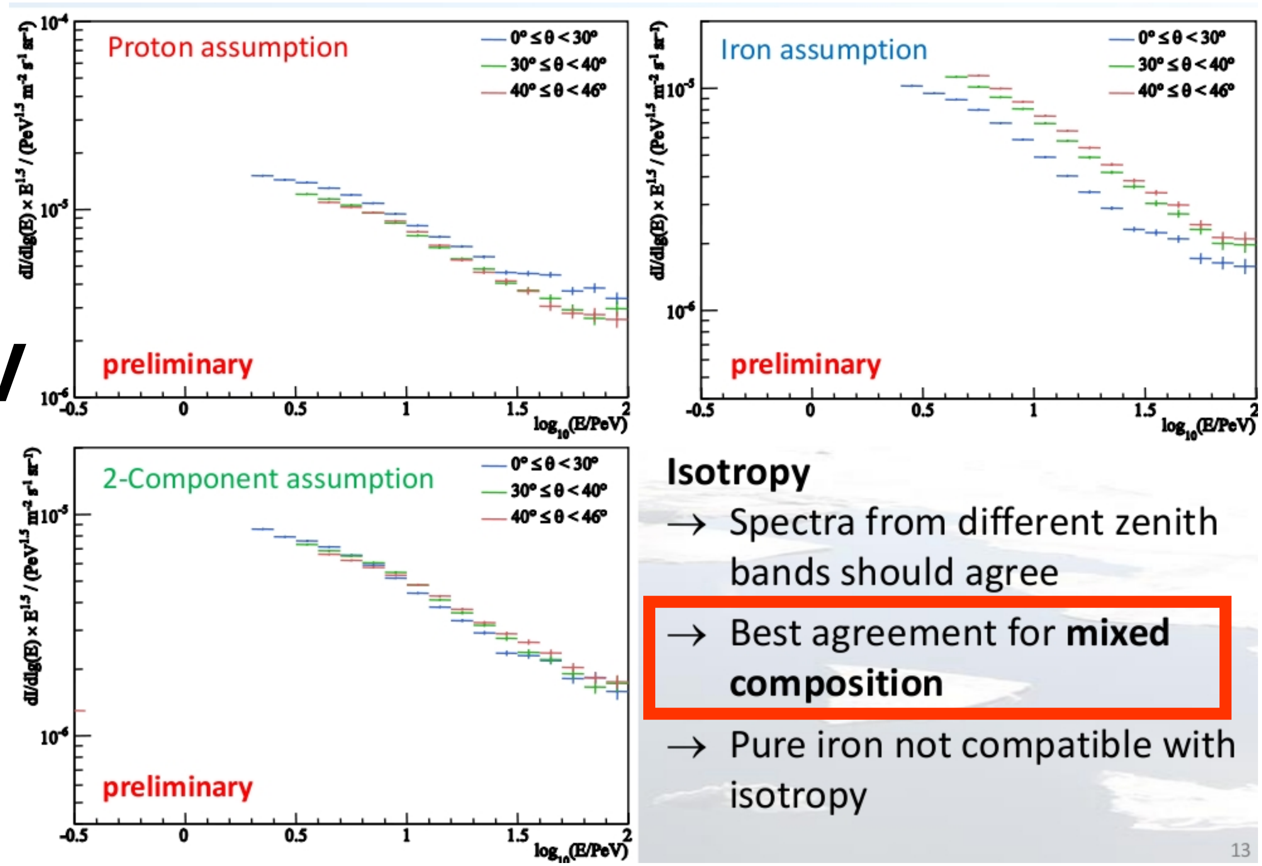
IceTop → Shower Detection

- 80 Stations à 2 Ice-Č-Tanks (40 in 2008!)
- 2830 m altitude
- 125 m spacing
- $3 \cdot 10^{14} < E < 10^{18}$ eV
- $A_{tot} \sim 1$ km^2

- Construction Completed in 2011
- Ice Top resolutions (0° <θ<30°)
  - Core position ~9m, Arrival direction ~1.5°
  - Energy (E>3PeV) ~16% in E,

  Full Efficiency >1PeV

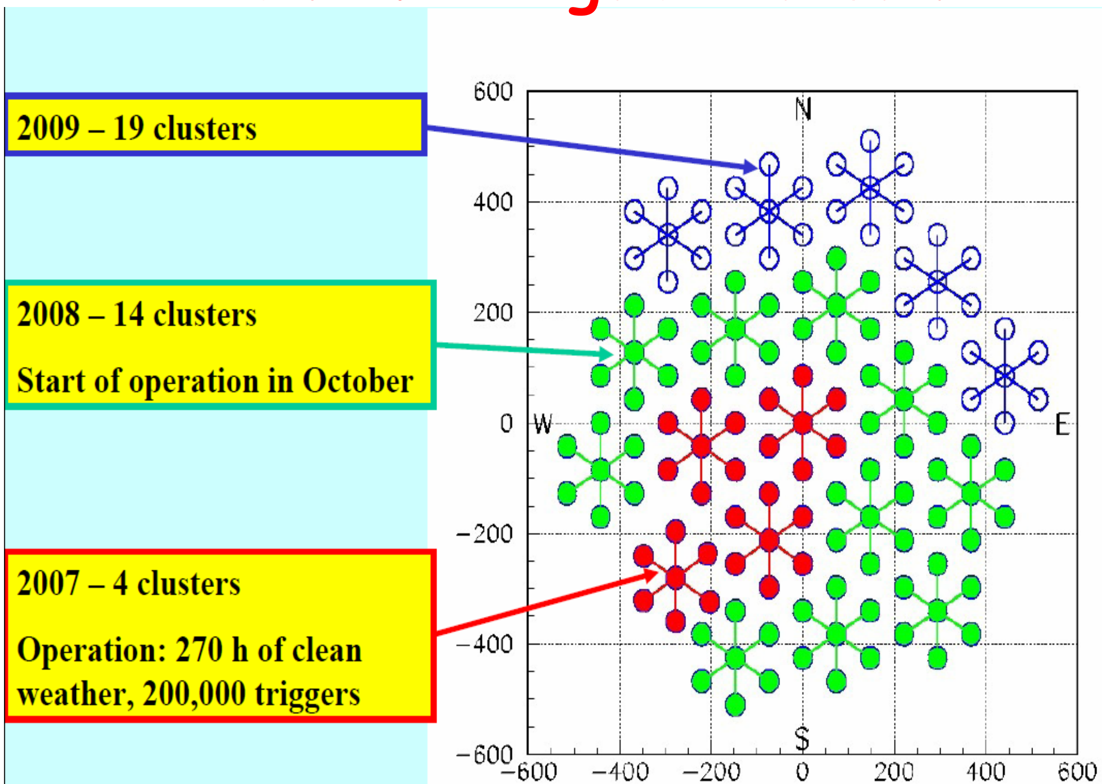
Unfolded energy spectra 10^{15}eV<E<10^{17}eV



F.Kislat, ECRS2010

TUNKA 133

Cherenkov ligth detector



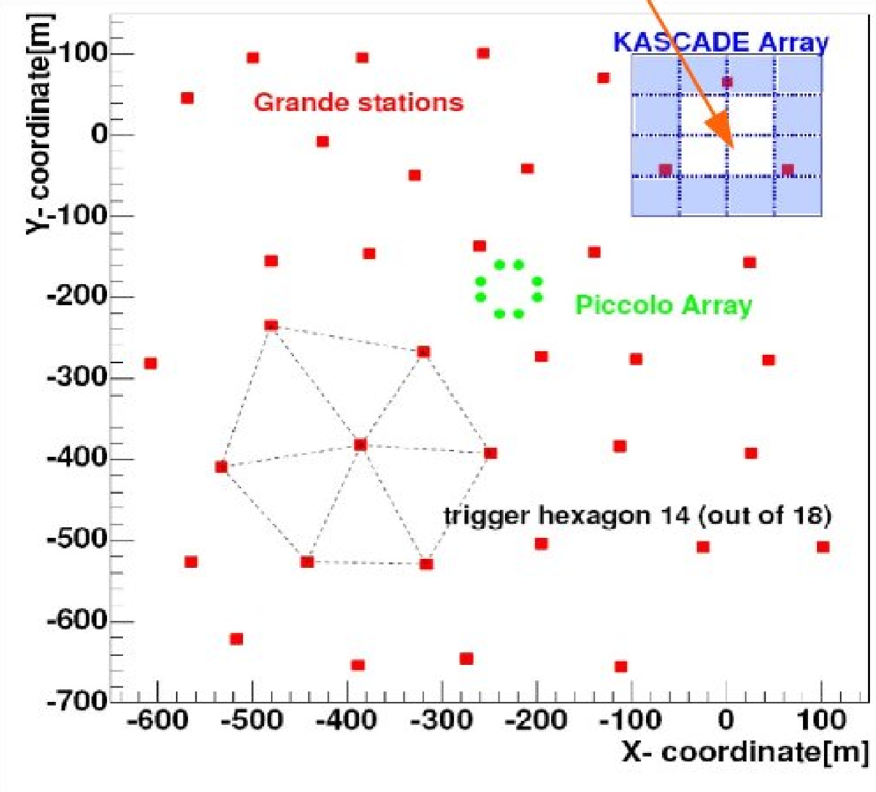
20cm diameter PMT
Angular aperture ≤45°
Area ~1 km²
Full Efficiency E>2x10^{15} eV
Expected Accuracy:
15% energy
~25 g cm^{-2} X$_{max}$

Preliminary results on energy spectrum expected in 2011

KASCADE-Grande features and performances

- KASCADE:
  → energy range $10^{14} – 10^{16}$ eV
  → 252 detector stations over 200x200 m^2
  → in a station: measurement of e and μ separately with two co-located types of detector scintillators

- Grande:
  → 37 detector stations 10 m^2 each spread over 700 x 700 m^2
  → in a station: measurement of all-charged e + μ
  → 18 hexagonal clusters. 7 out-of-7 coincidence triggers data acquisition

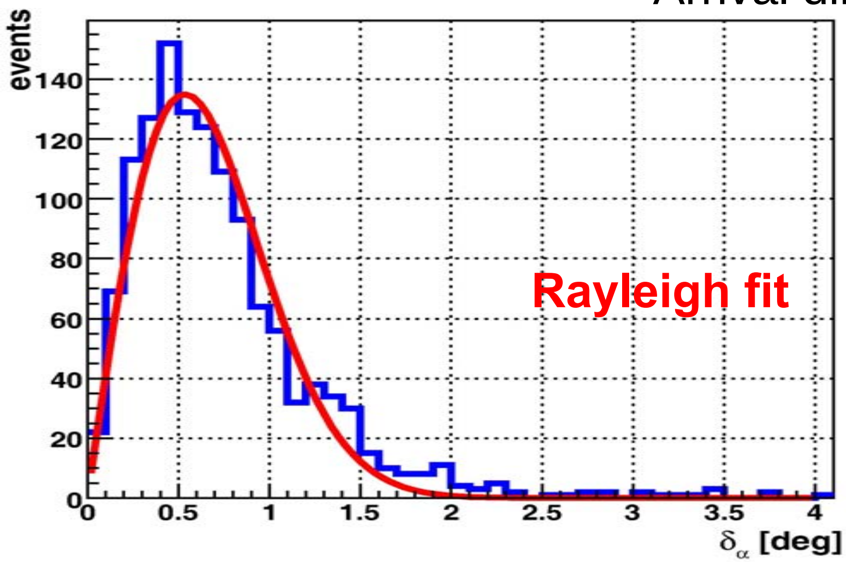


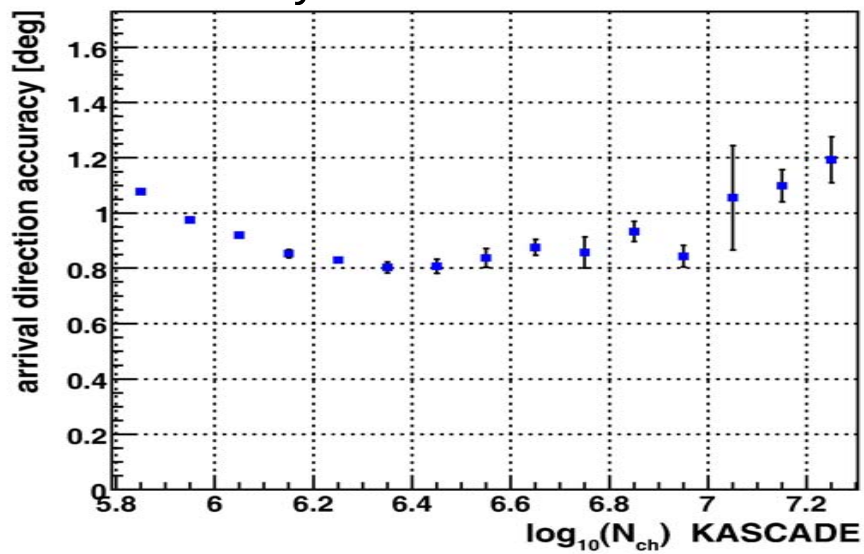
Upper view and Bottom view of a Grande station

Good agreement between the reconstruction accuracies of the 2 detectors

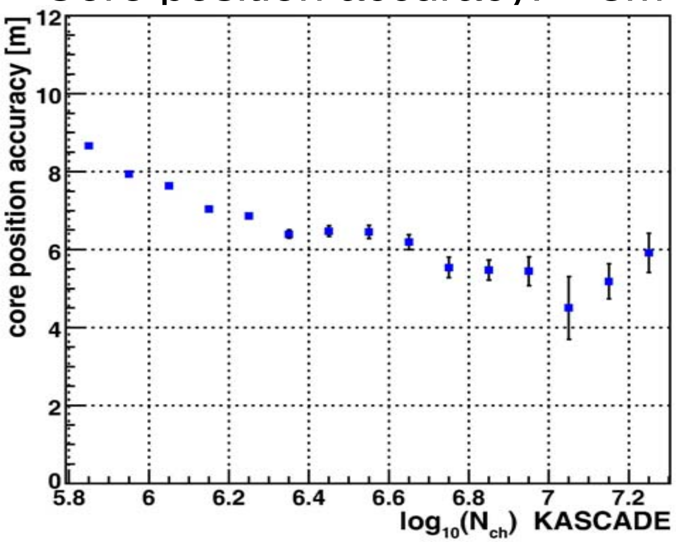
Arrival direction accuracy <1°

DATA

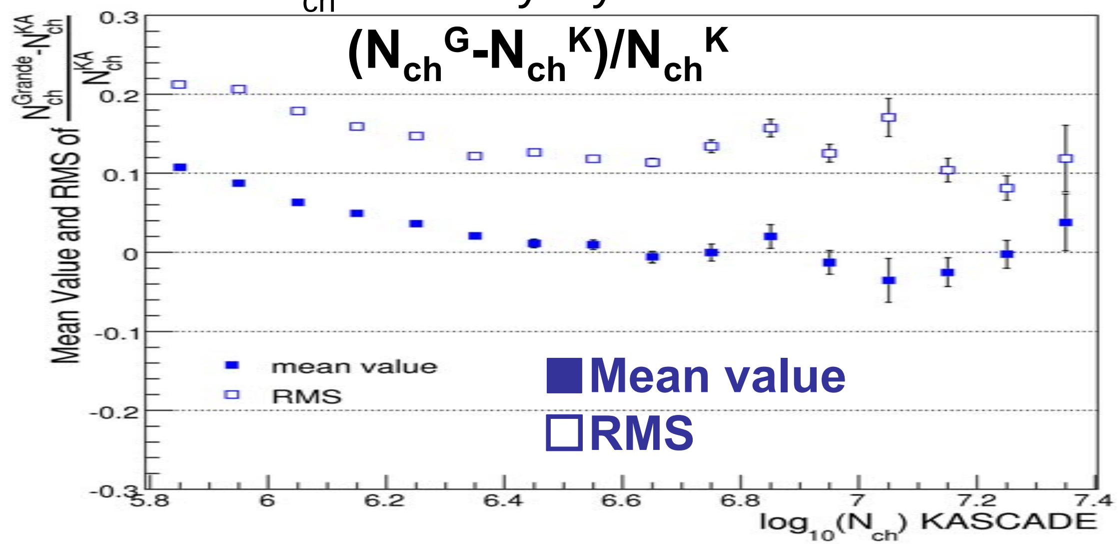




Core position accuracy: < 8m



N_{ch} accuracy: systematics < 10%



Apel et al. NIMA 620 (2010) 202-216

Reconstruction of the energy spectrum

We use three different methods:

- N_{ch} as observable
- N_{μ} as observable
- Combination of N_{ch} and N_{μ} as observables

↓

- Cross check of reconstruction procedures
- Cross check of systematic uncertainties
- Test sensitivity to composition
- Cross check of validity of hadronic interaction models

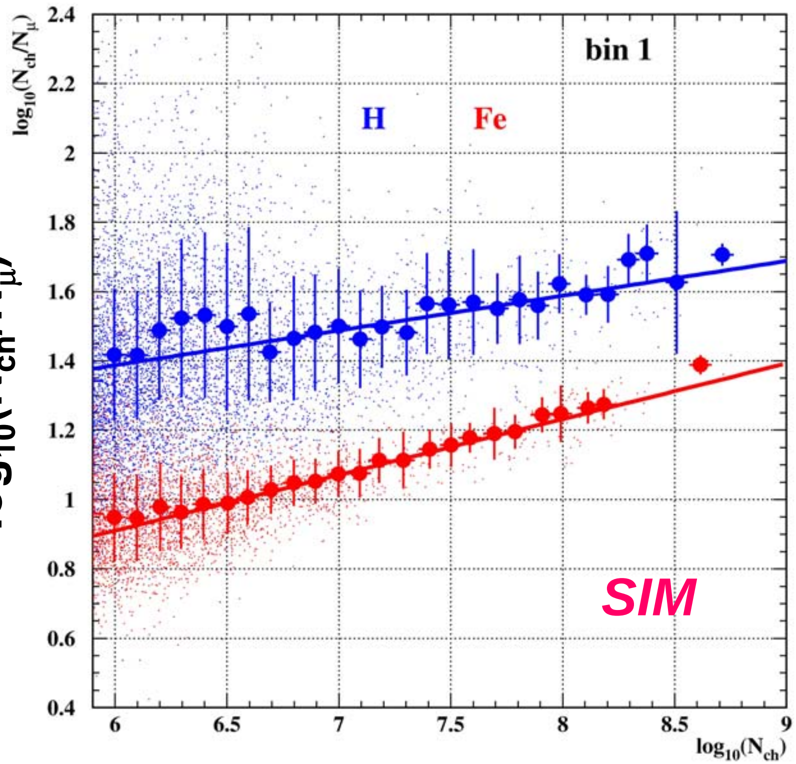
If not explicitly mentioned in the following CORSIKA QGSjetII/FLUKA interaction model is used

***additional method to reconstruct the energy spectrum employs the particle density at 500 m (S500)**

$N_{ch} - N_{\mu}$ technique

5 angular bins treated independently

$$\log_{10}(N_{ch}/N_{\mu})_{p,Fe} = c_{p,Fe}\log_{10}N_{ch} + d_{p,Fe}$$

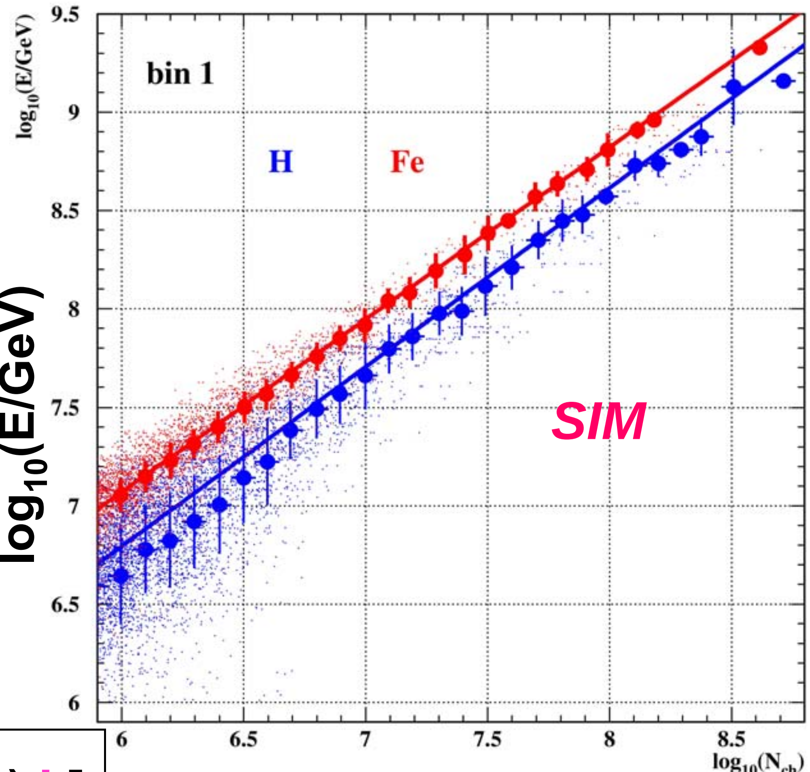


$\log_{10}(N_{ch}/N_{\mu})$

$\log_{10}(N_{ch})$

*error bars=
RMS of distributions

$$k = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_p}{\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_p}$$



$\log_{10}(E/GeV)$

$\log_{10}(N_{ch})$

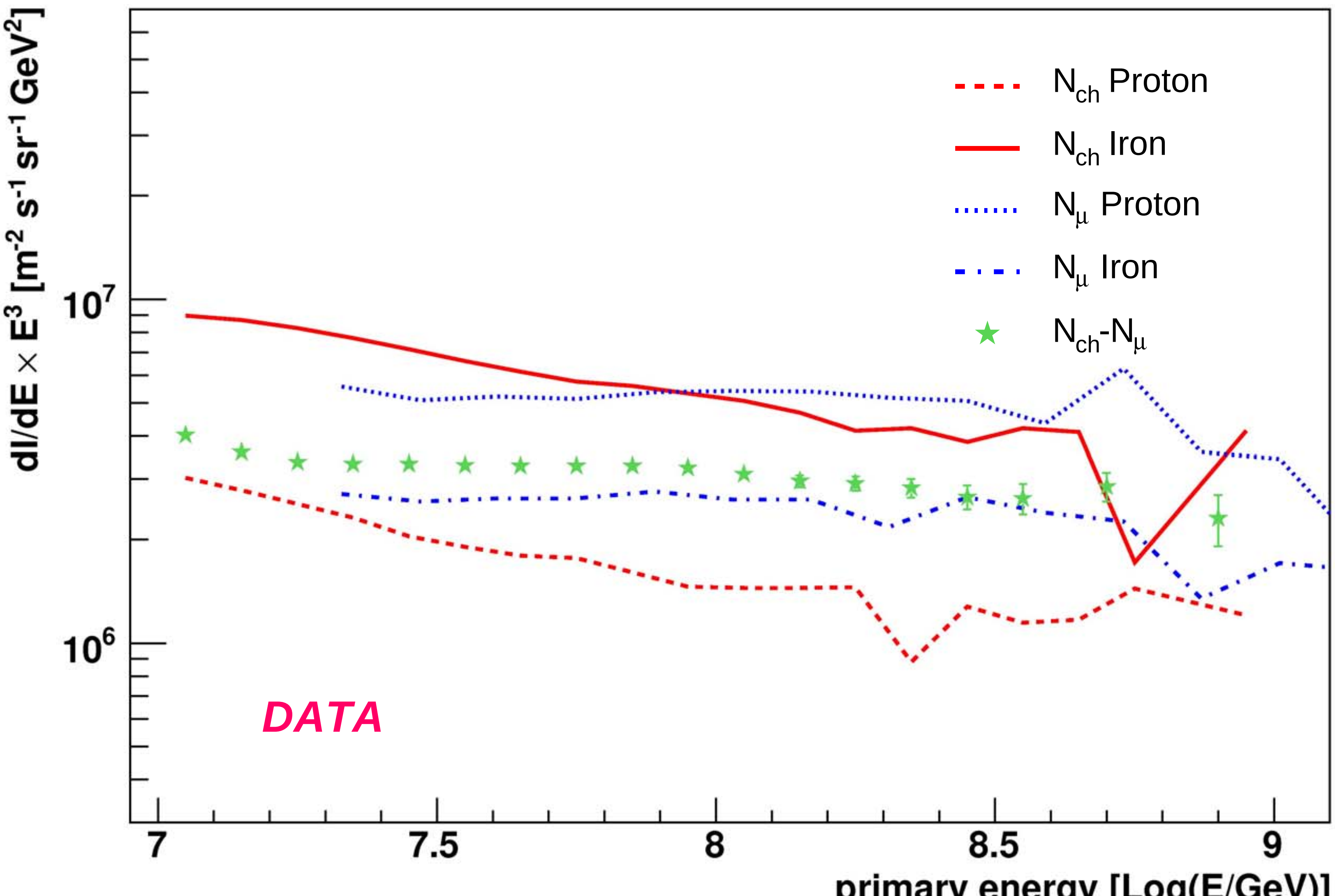
$$\log_{10}E_{p,Fe} = a_{p,Fe}\log_{10}N_{ch} + b_{p,Fe}$$

$$\log_{10}E = [a_p + (a_{Fe} - a_{,p})\cdot k]\cdot\log_{10}(N_{ch}) + [b_p + (b_{Fe} - b_p)\cdot k]$$

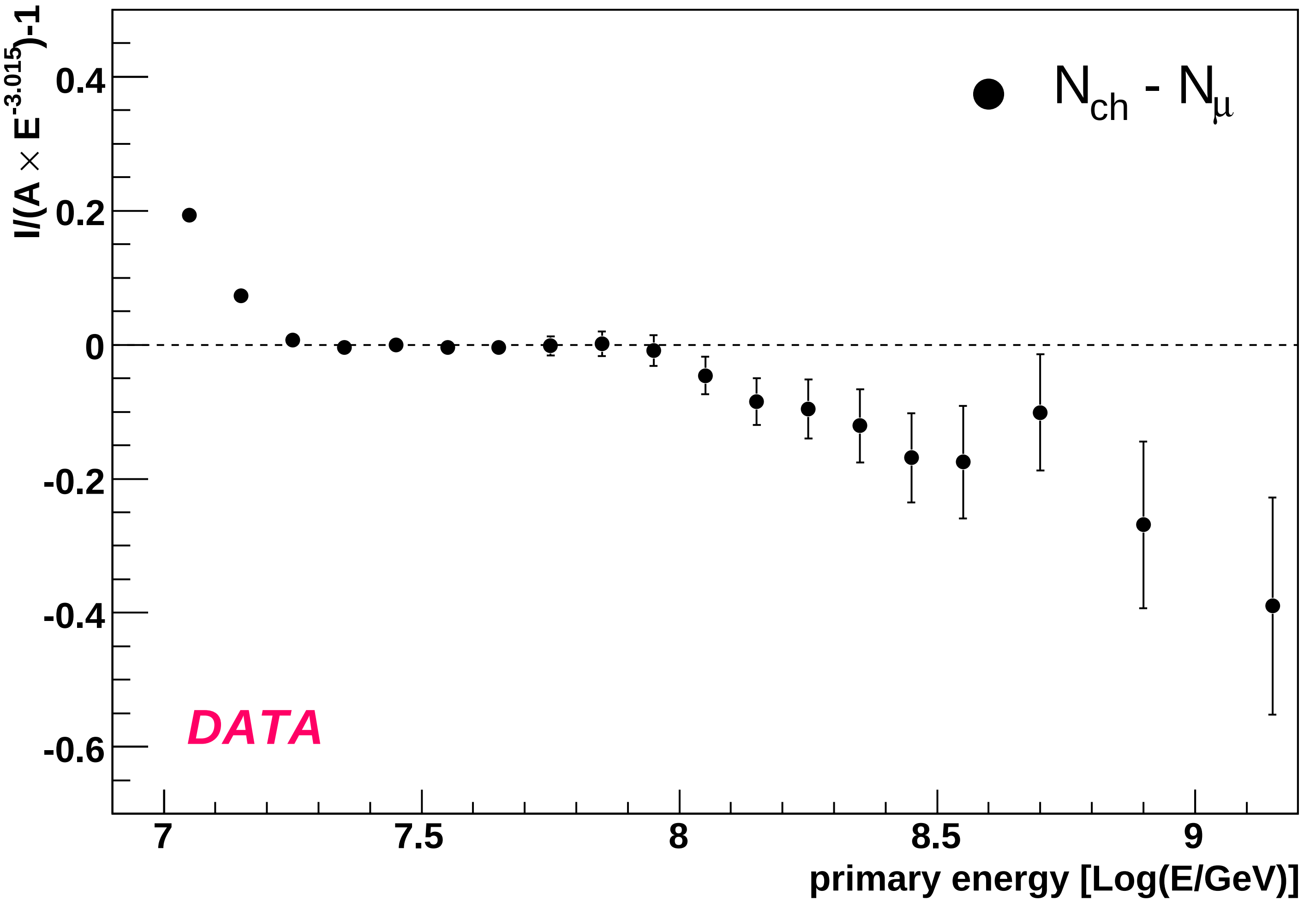
Table of systematics on the flux

Source of uncertainty	**10^{16}eV (%)**	**10^{17}eV (%)**	**10^{18}eV (%)**
Intensity in different angular bins (attenuation)	10.2	9.3	13.0
Calibration & composition	10.8	7.8	4.4
Slope of the primary spectrum	4.0	2.0	2.1
Reconstruction (shower sizes)	0.1	1.3	6.6
TOTAL	**15.4**	**12.4**	**14.7**
Other uncertainties	**%**	**%**	**%**
Sudden knee structures (extreme cases)		<10	
Hadronic interaction model (EPOS-QGSjet)	-5.4	-12.3	-9.5
Statistical error	**0.6**	**2.7**	**17.0**
Energy resolution (mixed primaries)	**24.7**	**18.6**	**13.6**

Comparing the 3 methods (dI/dE x E^3)



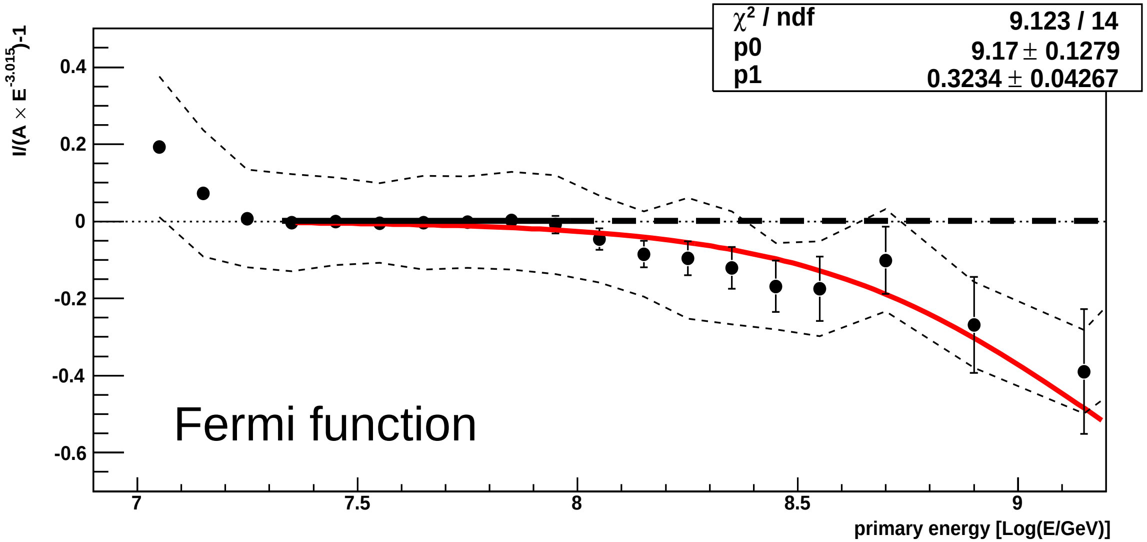
Residual plot



$F_{test} = (\chi^2_{single\ power\ law} / m) / (\chi^2_{function} / n)$, with m,n = ndf single power-law, function

$\text{Variance} = 2n^2(m+n-2) / m(n-2)^2(n-4)$

Significance in units of the standard deviation = $F_{test} / \sqrt{\text{Variance}}$



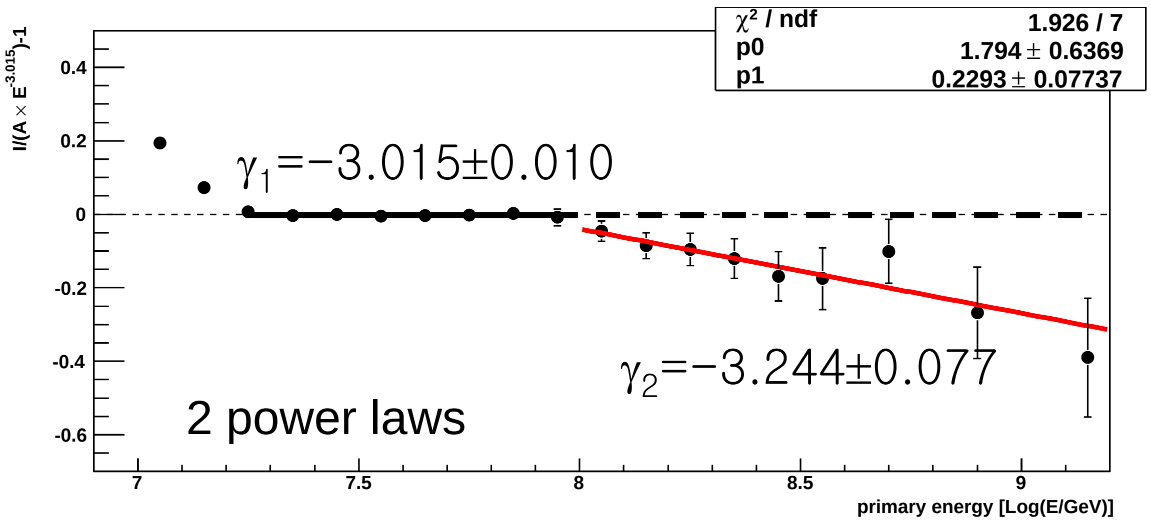
$\chi^2_{single\ power\ law}$ / ndf =2.97

χ^2_{fermi} / ndf =0.65

F_{test} = 4.56

Variance = 0.51

Significance = 6.4 σ



$\chi^2_{single\ power\ law}$ / ndf =2.97

$\chi^2_{2\ power\ laws}$ / ndf =0.49

F_{test} = 6.09

Variance = 0.62

Significance = 7.7 σ

2^{nd} knee

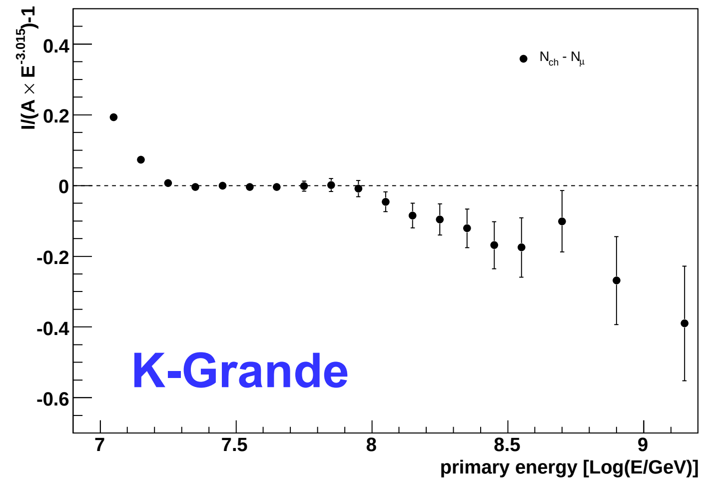


Table 2. Our broken power law fits to spectrum measurements in the Second Knee energy range. The fit parameters include a normalization (not shown), slope parameters above and below the break and the break point energy for the Second Knee.

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

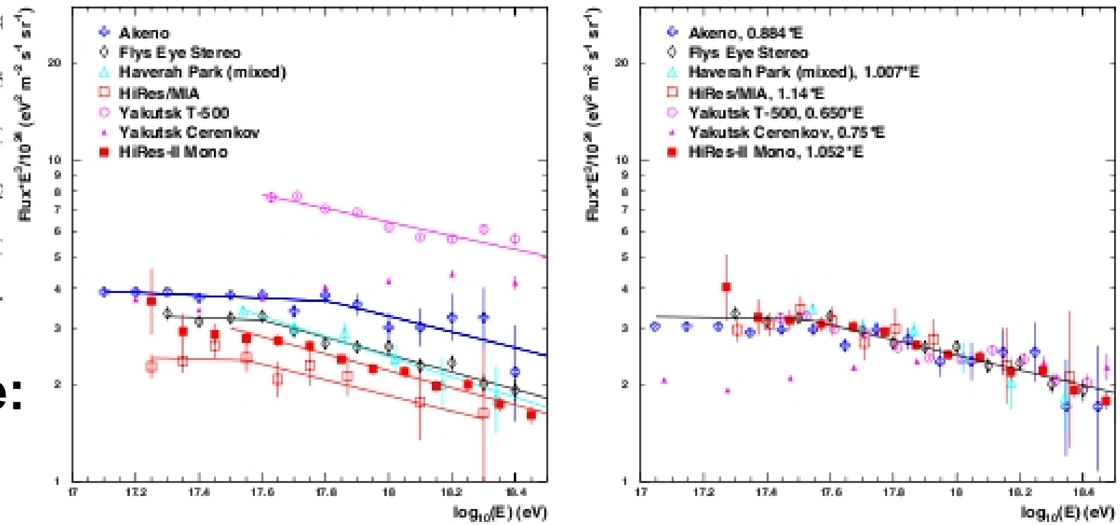


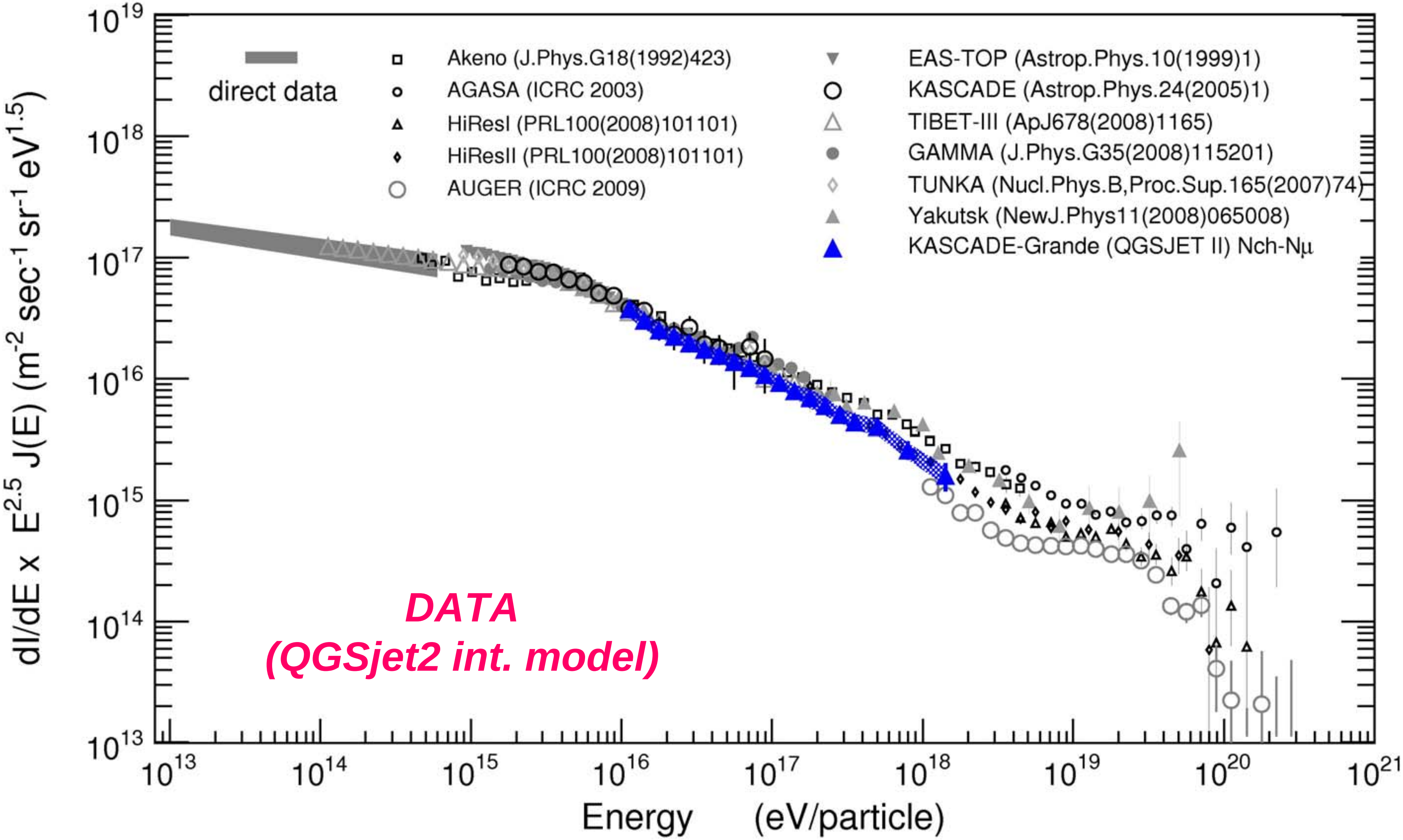
Figure 11. Left: flux measurements in the Second Knee energy range. The shown fits are our calculation. Right: flux measurements in the Second Knee energy range, scaled so that the flux agrees with the Fly's Eye result at 10^{18} eV. The scaled data points were fit to a broken power law spectrum in a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

The all-particle energy spectrum



The spectrum is nicely connected at the knee with other experiments and points naturally to HiRes and Auger spectra at UHECR energies

Conclusions

- Different spectral indexed between H and the other elements. Change of slope for all elements around 100-200 GeV/n.What does it mean?
- Anisotropy @ TeV energies, why?
- Fairly well agreement between direct and indirect measurements in the TeV region.
- The majority of experiments show a dominance of light primaries at the knee and He main candidate for it. However, still source of debate – see e.g.Tibet ASγ.
- Rigidity dependent knees.
- Single Source model(s)?
- Where does the transition between galactic and extra-galactic components occur?

What can we learn at E<10^{17} eV in the near future?

- Extension of the direct measurements up to 10^{15} eV (ex. CALET on ISS)
- Better understanding of the interaction models from accelerators (ex. LHCf, TOTEM)
- Composition studies by YAC/MD Tibet ASγ (main knee), KASCADE-Grande, ICECUBE, Tunka-133, GRAPES (10^{16} – 10^{18} eV)

THE END

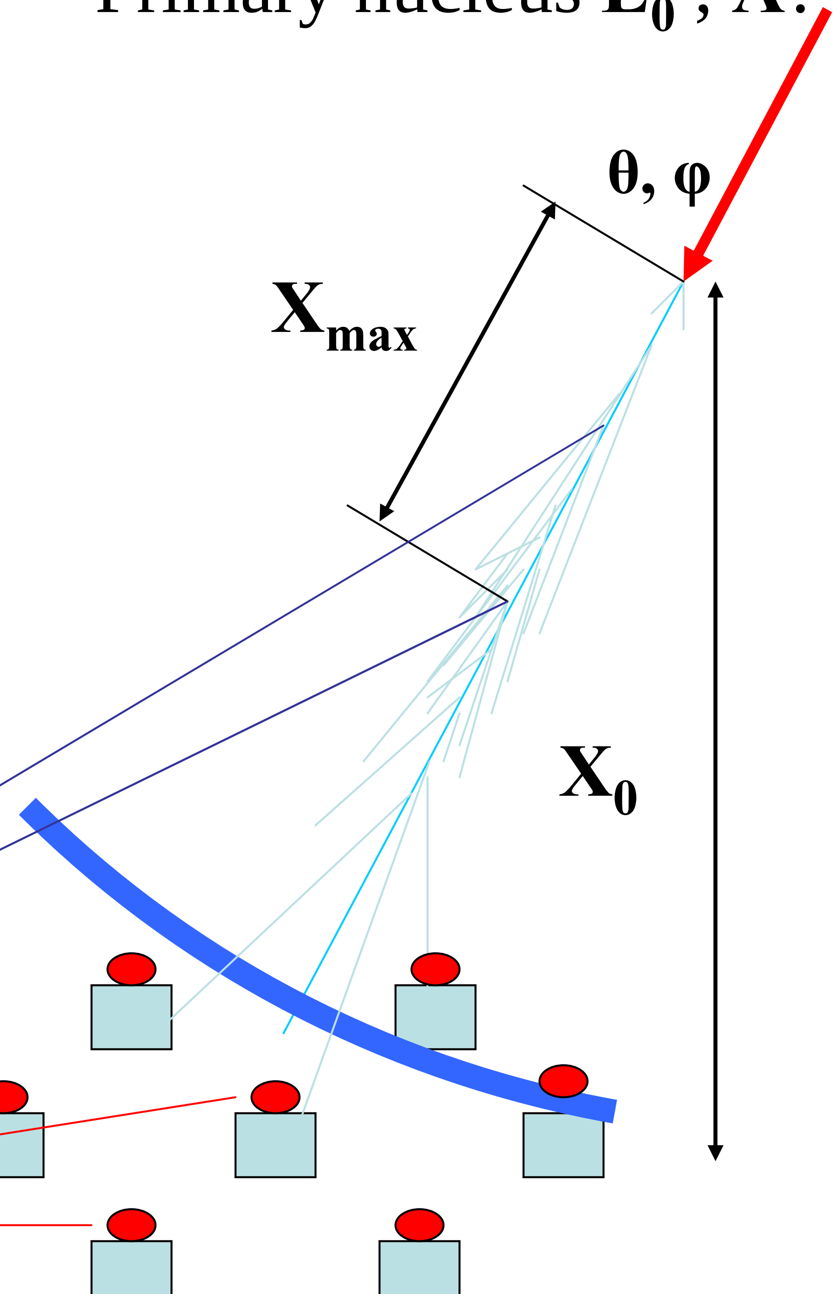
Primary nucleus $\mathbf{E_0}$, **A**?

1. $\mathbf{E_0 \sim Q_{175}}$ – Cherenkov light flux

2. $\mathbf{X_{max}}$(model independent):

$\underline{X_{max}} = Xp - \delta X_{max}/\delta \ln E \cdot \underline{\ln A}$

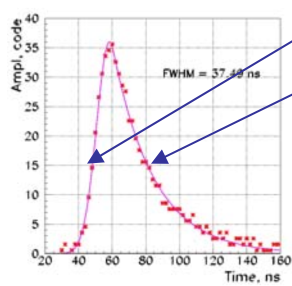
Two methods:



Pulse width:

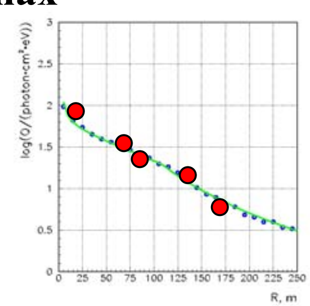
$\Delta X = a - b \cdot FWHM$ **[g/cm²]**

$\Delta X = X_0/\cos\theta - X_{max}$



LDF steepness P:

$H_{max} = c - d \cdot P$



$H_{max} = (T_0/grad(T)((X_{max}\cos\theta\ /X_0)^{C/grad(T)} - 1) -$

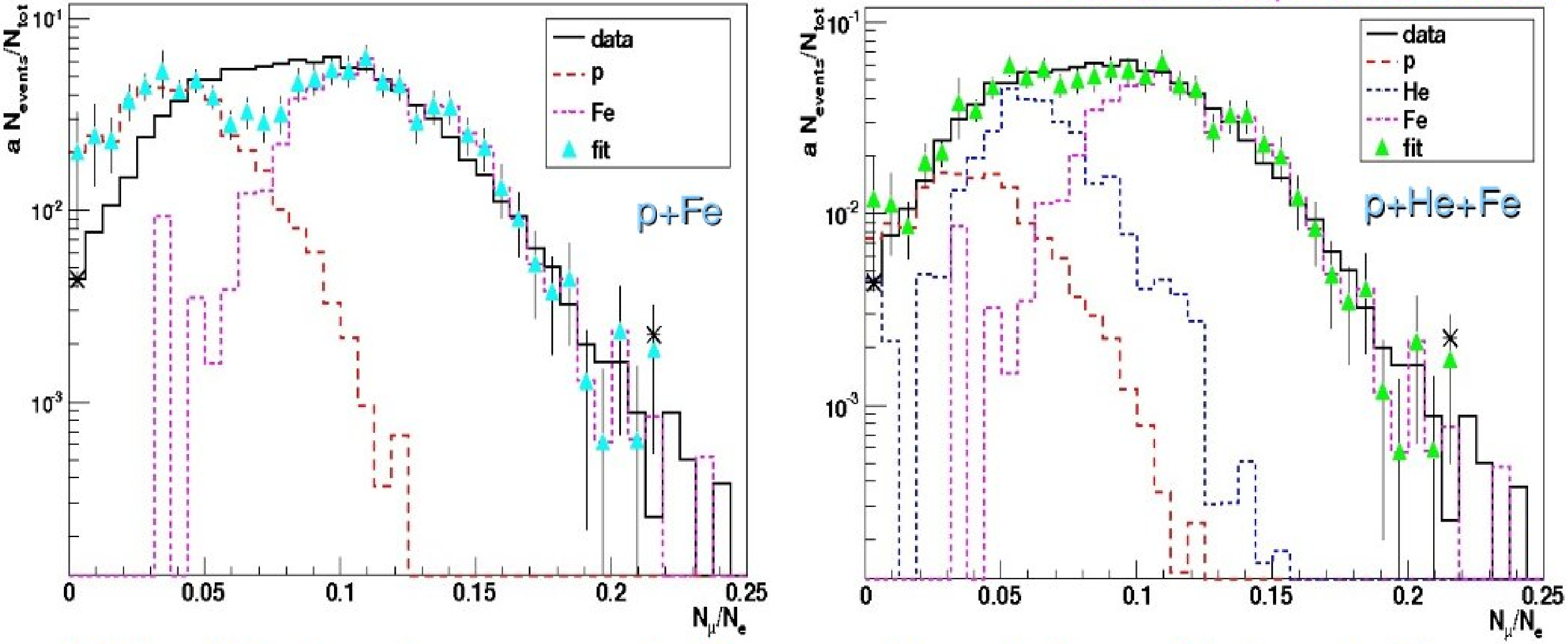
Towards the composition

- The Energy spectrum shows interesting structures.
- The composition analysis is crucial to try to understand their origin.
- The composition analysis is under study using different approaches (all based on N_{ch}-N_{μ} observables and QGSjet model) like we did for the Energy spectrum to have a coherent result and check systematics for each technique:
  - K parameter
  - Separation in light & heavy spectra
  - KNN technique
  - N_{μ}/N_{ch} distributions in bins of N_{ch}
  - unfolding

N_{ch}/N_μ distributions

- The sensitivity to primary composition: data, in different arrival directions and charged size intervals, are compared with simulations, performing a χ^2 fit with a linear combination of different primary contributions
  - first step for further composition studies
  - perform a check on used interaction model

E. Cantoni et al., Proc. ICRC 2009

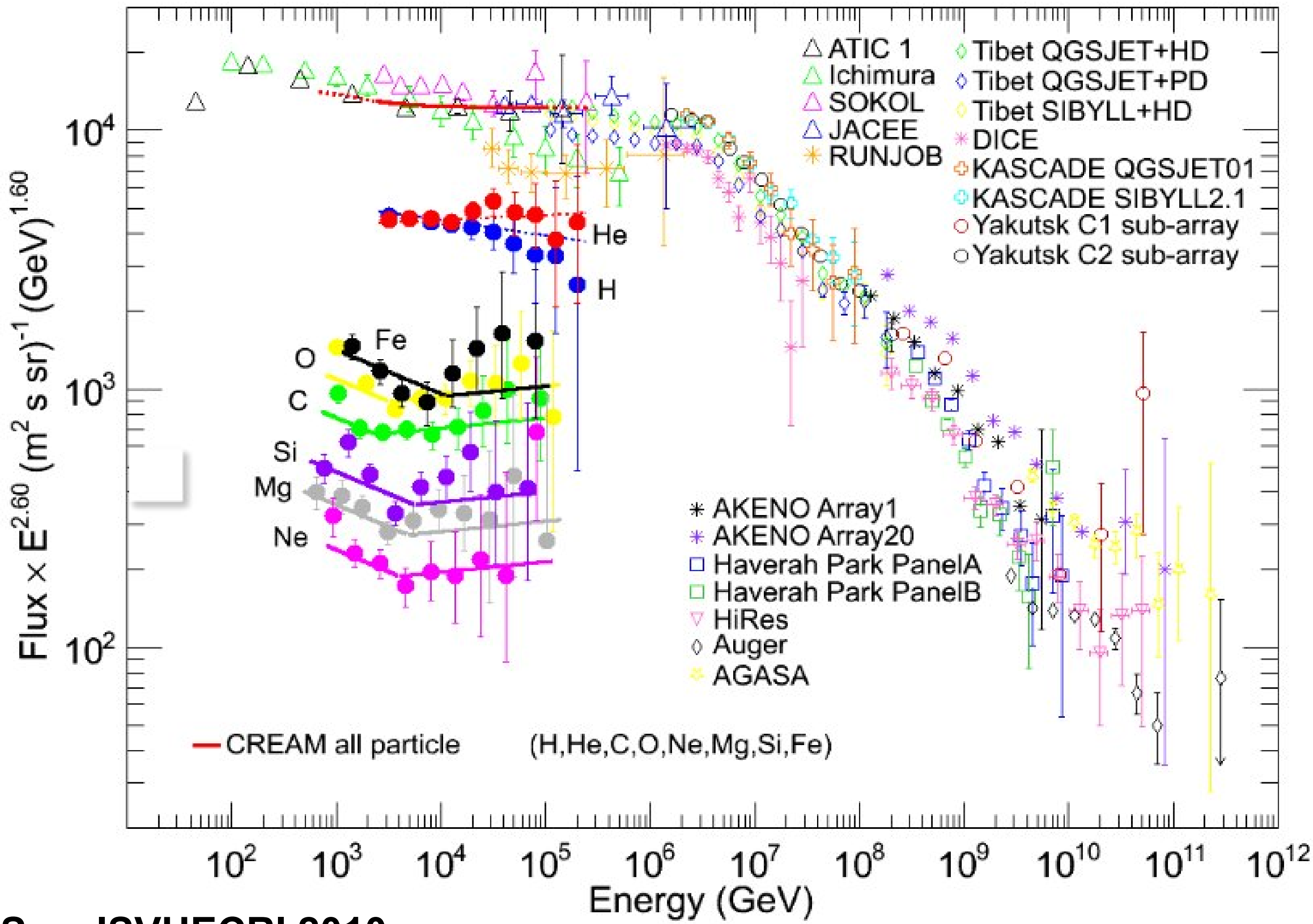


→ At least 3 primaries are needed for good description of data selections

E. Cantoni, CRIS 2010

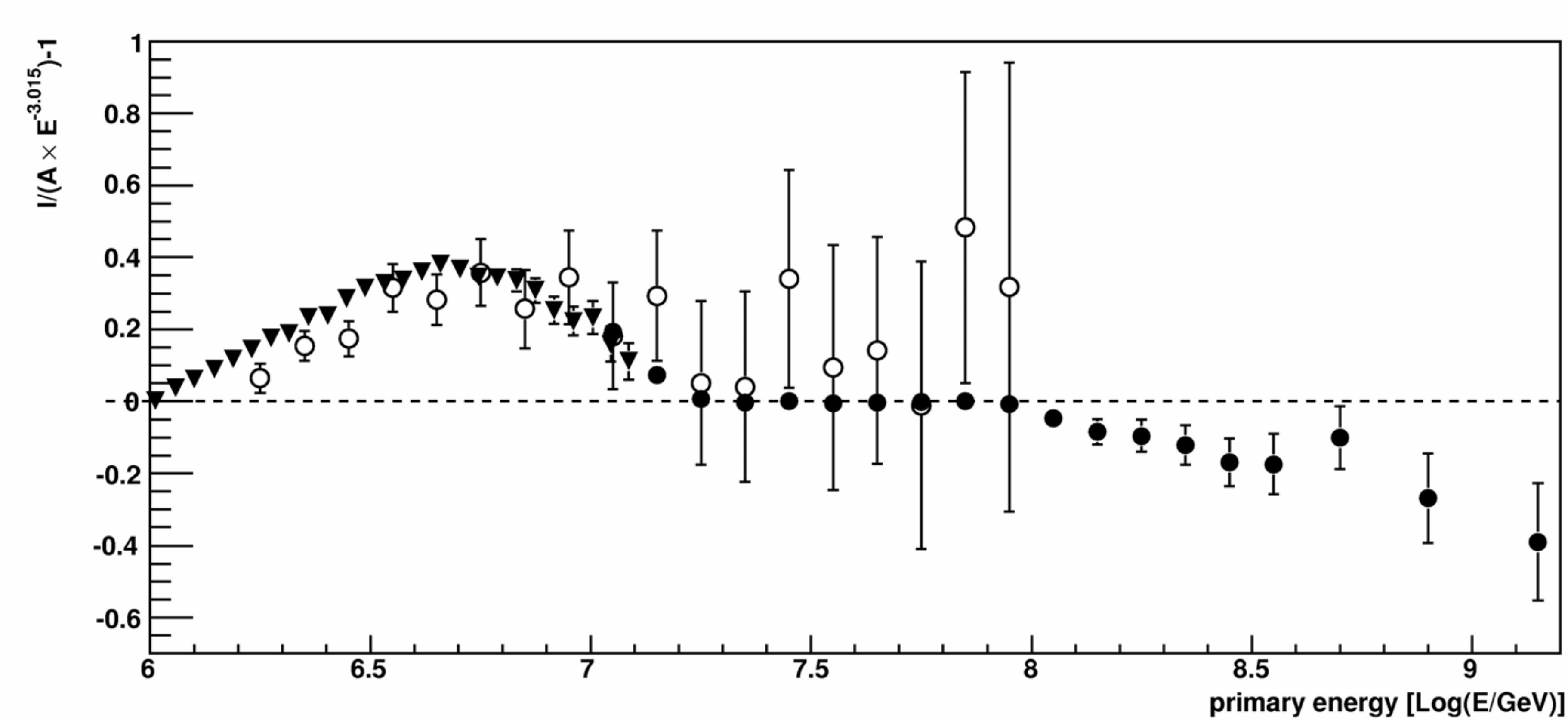
DATA

Single and All-particle spectra by CREAM



E.Seo, ISVHECRI 2010

Comparison with KASCADE & EAS-TOP



○ KASCADE QGSjet01
▼ EAS-TOP
● KASCADE-Grande QGSjet2