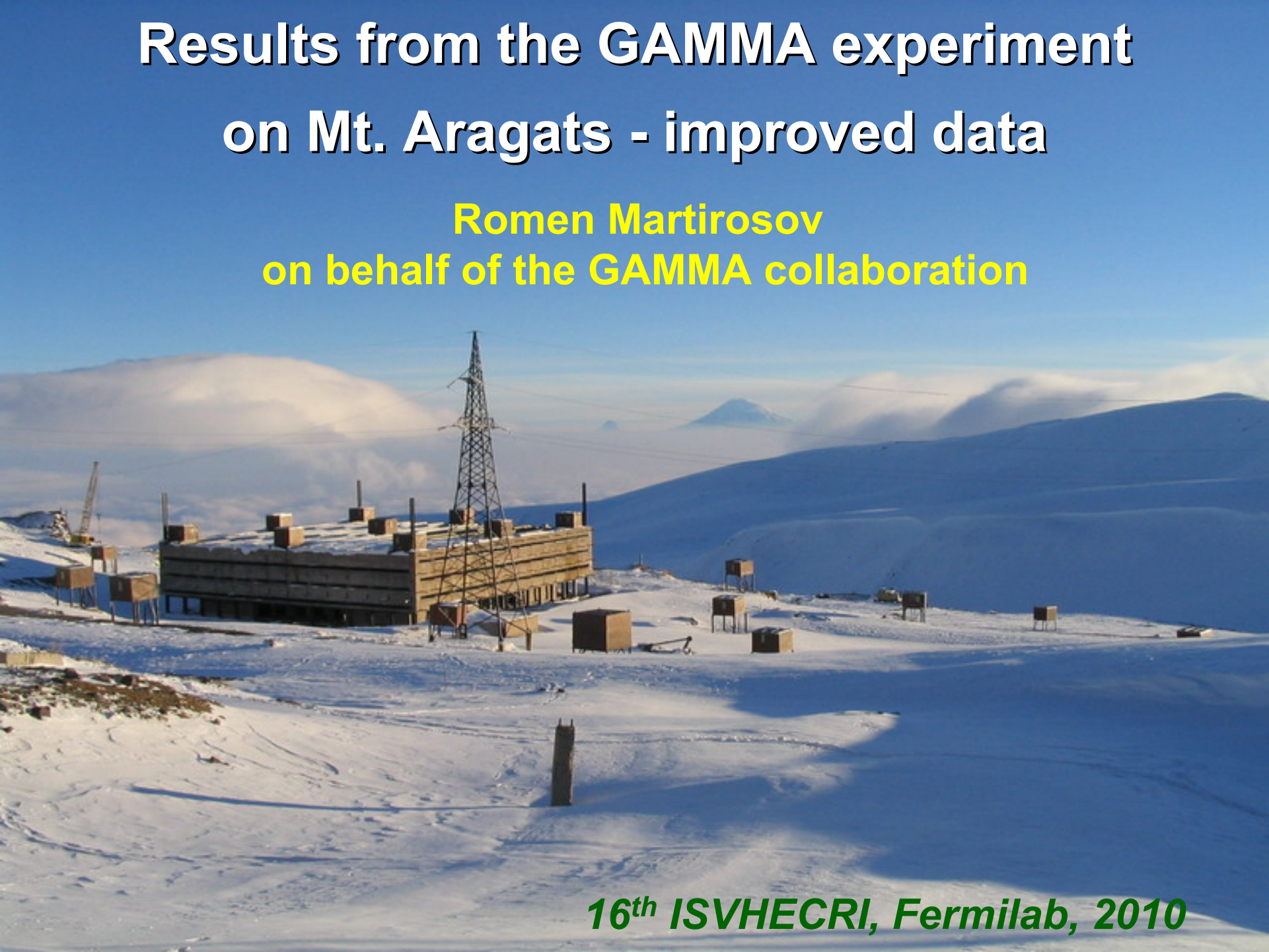
Results from the GAMMA experiment on Mt. Aragats - improved data

Romen Martirosov
on behalf of the GAMMA collaboration



16th ISVHECRI, Fermilab, 2010

GAMMA Collaboration

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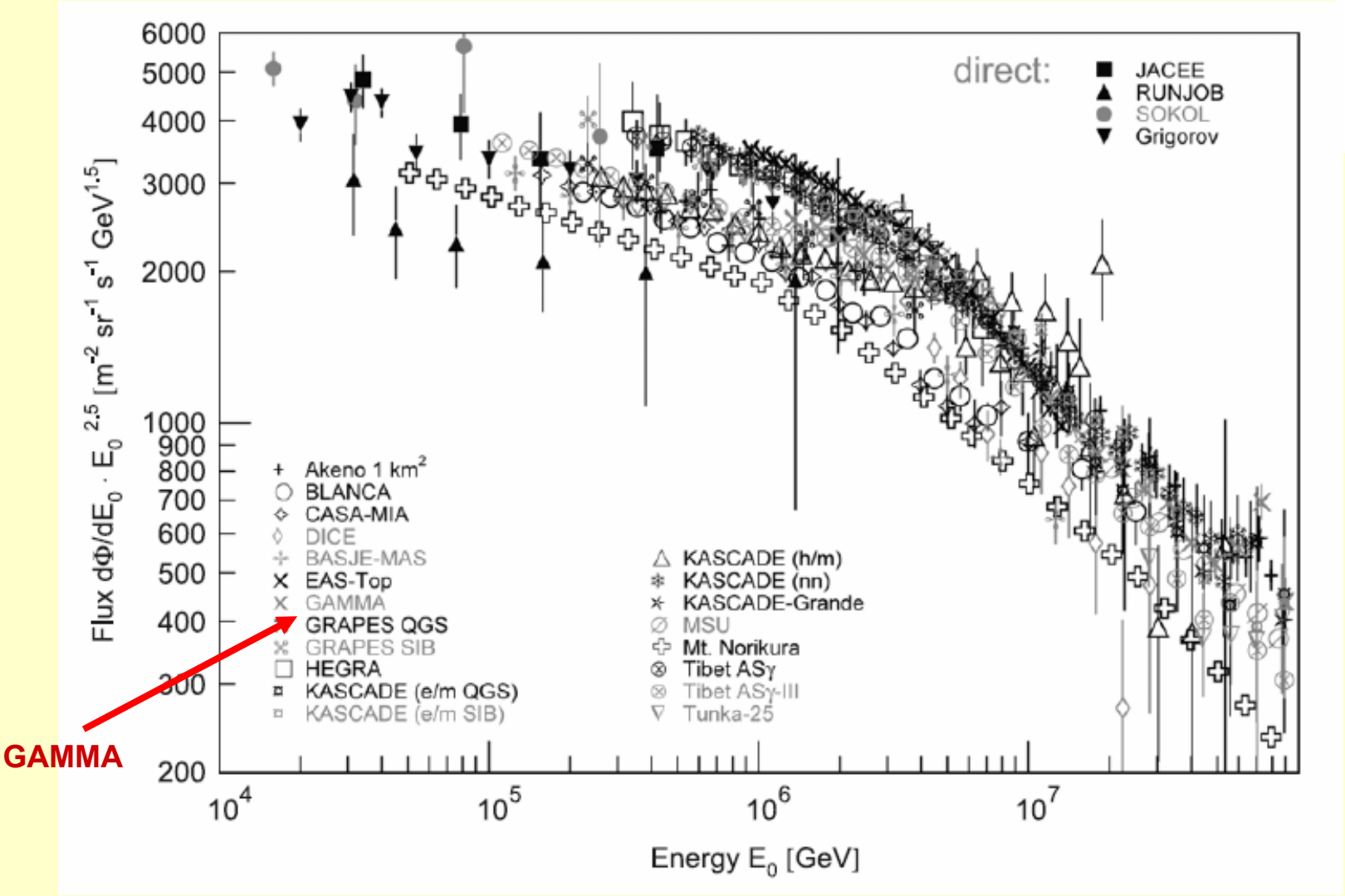
Outline

- Introduction (1 – 100 PeV)
- GAMMA experiment – Status 2010 and main topics
- Irregularities in 10-100 PeV (results from GAMMA and other experiments)
- Galactic diffuse gamma-ray flux (preliminary result)
- Near perspective

Recent large-scale experiments at 1-100 PeV

	Elevation		
CASA-MIA	1435 a.s.l.	USA	Terminated
EAS-TOP	2005 a.s.l.	Italy	Terminated
TIBET- III	4300 a.s.l.	China	Operating
TIEN SHAN	3300 a.s.l.	Kazakhstan	Under modernization
KASCADE	110 a.s.l.	Germany	Terminated
KASCADE-Gr.	110 a.s.l.	Germany	Terminated *not fully*
GRAPES - III	2200 a.s.l.	India	Operating
TUNKA	675 a.s.l.	Russia	Operating
ICE TOP	3300 a.s.l.	South Pole	Operating
MAKET-ANI	3250 a.s.l.	Armenia	Terminated
GAMMA	*3250 a.s.l.*	*Armenia*	*Operating*

All-Particle energy spectra



! It is necessary an individual analysis and comparisons of spectra !

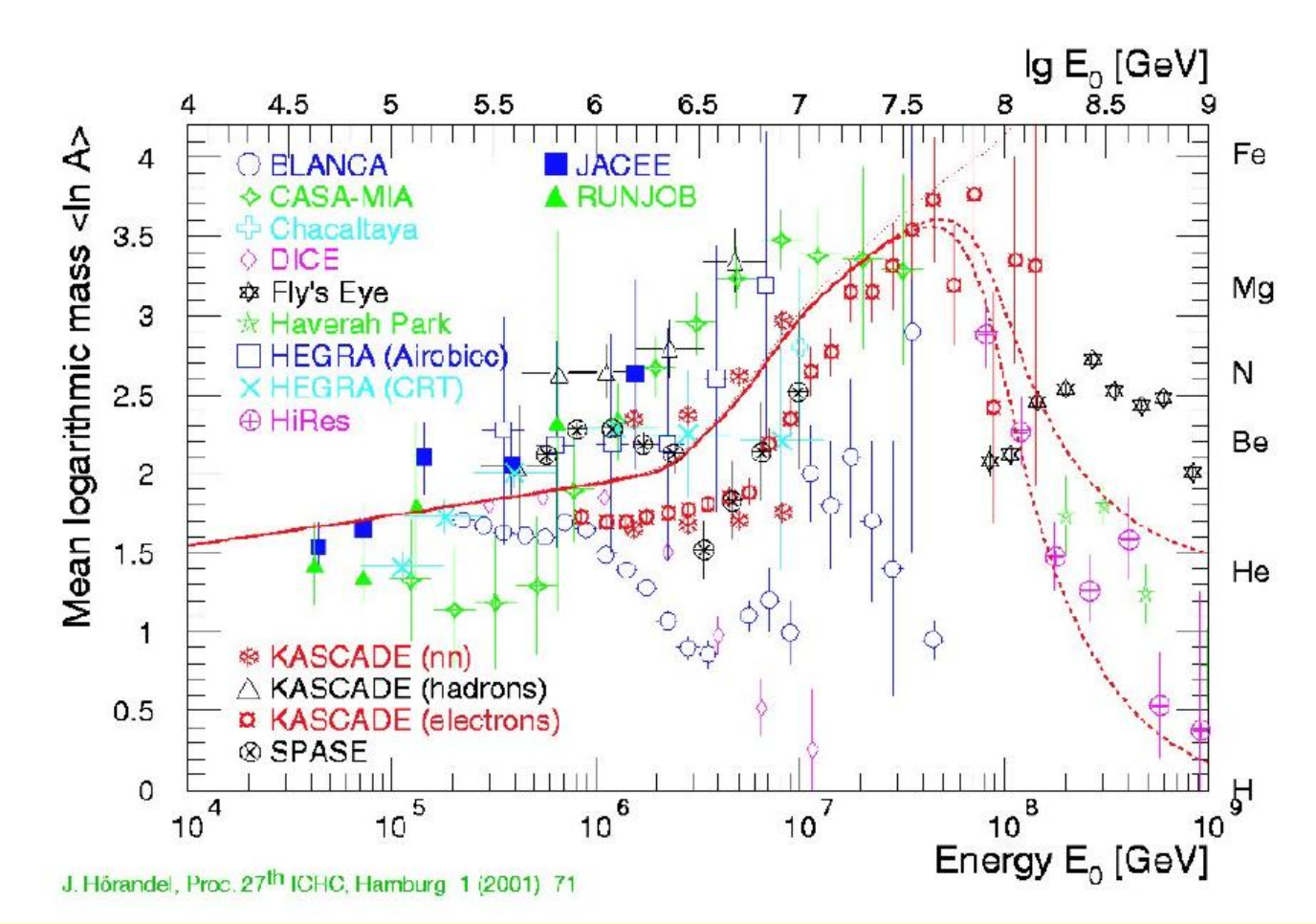
Common resume (in near past):

- Global characteristics of the all-particle spectrumagree within of about 20-30% of the systematic errors.

- Changing of slope of the all-particle energy spectrum from about -2.7 below the “knee” to about -3.1 after the “knee” may be considered as an experimentally established fact;

?

In spite of so many experiments there are still serious disagreements in the chemical composition estimations. !MOST IMPORTANT FOR UNDERSTANDING OF THE KNEE ORIGIN!



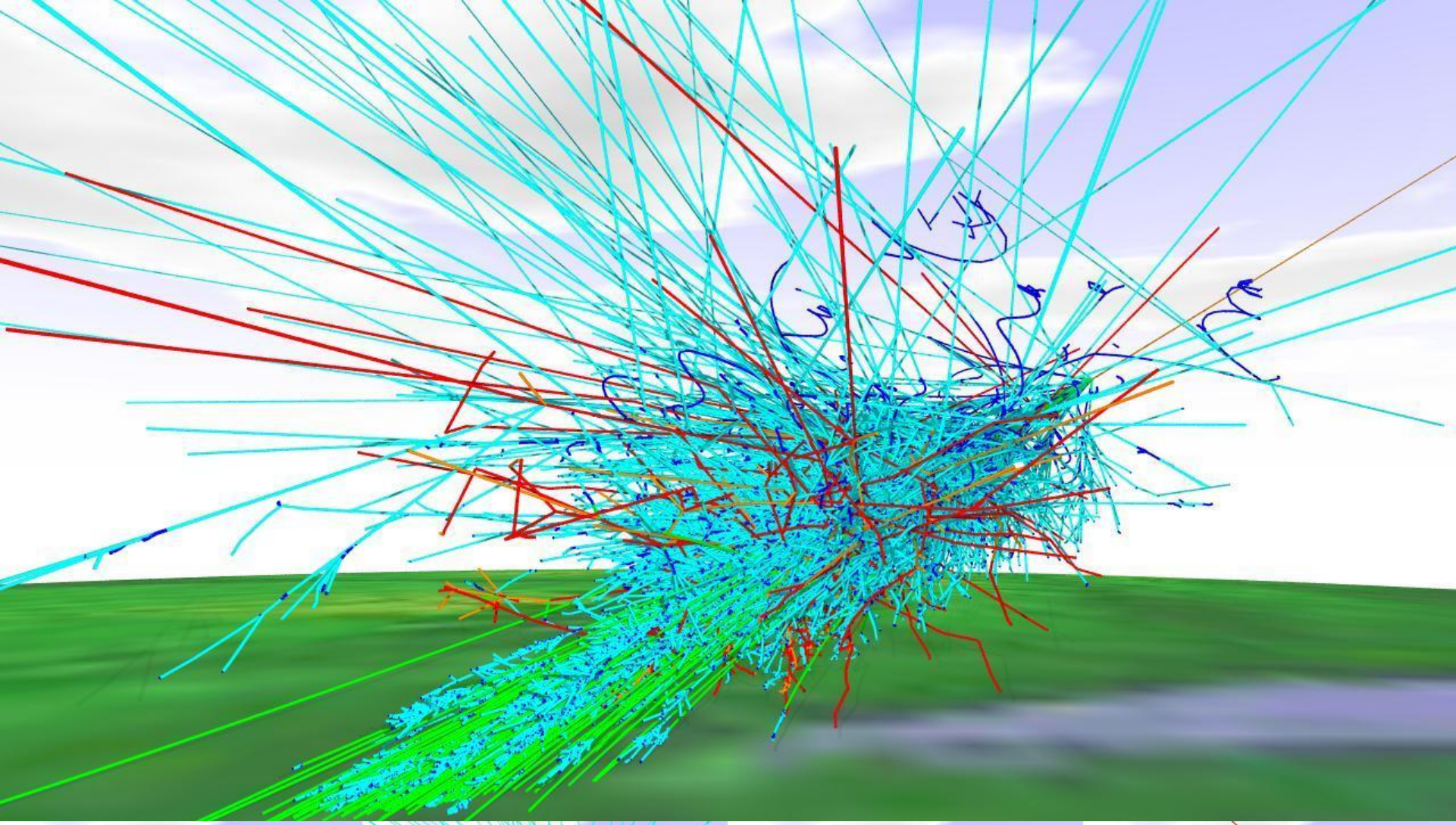
J.Hoerandel, ICRC, Hamburg, 2001

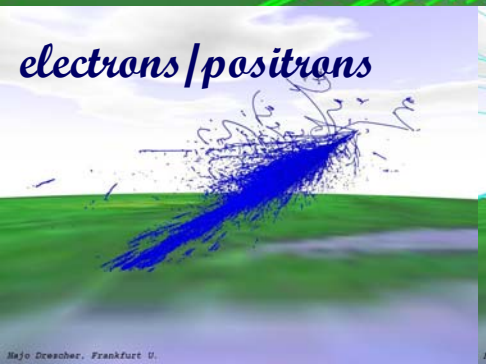
Sources of these uncertainties may be found:

- **in the big fluctuations of showers deeper in the atmosphere;**

- **in different assumption concerning the primary interaction and cascade development models used in data analysis;**

- **and/or in energy normalization uncertainty.**

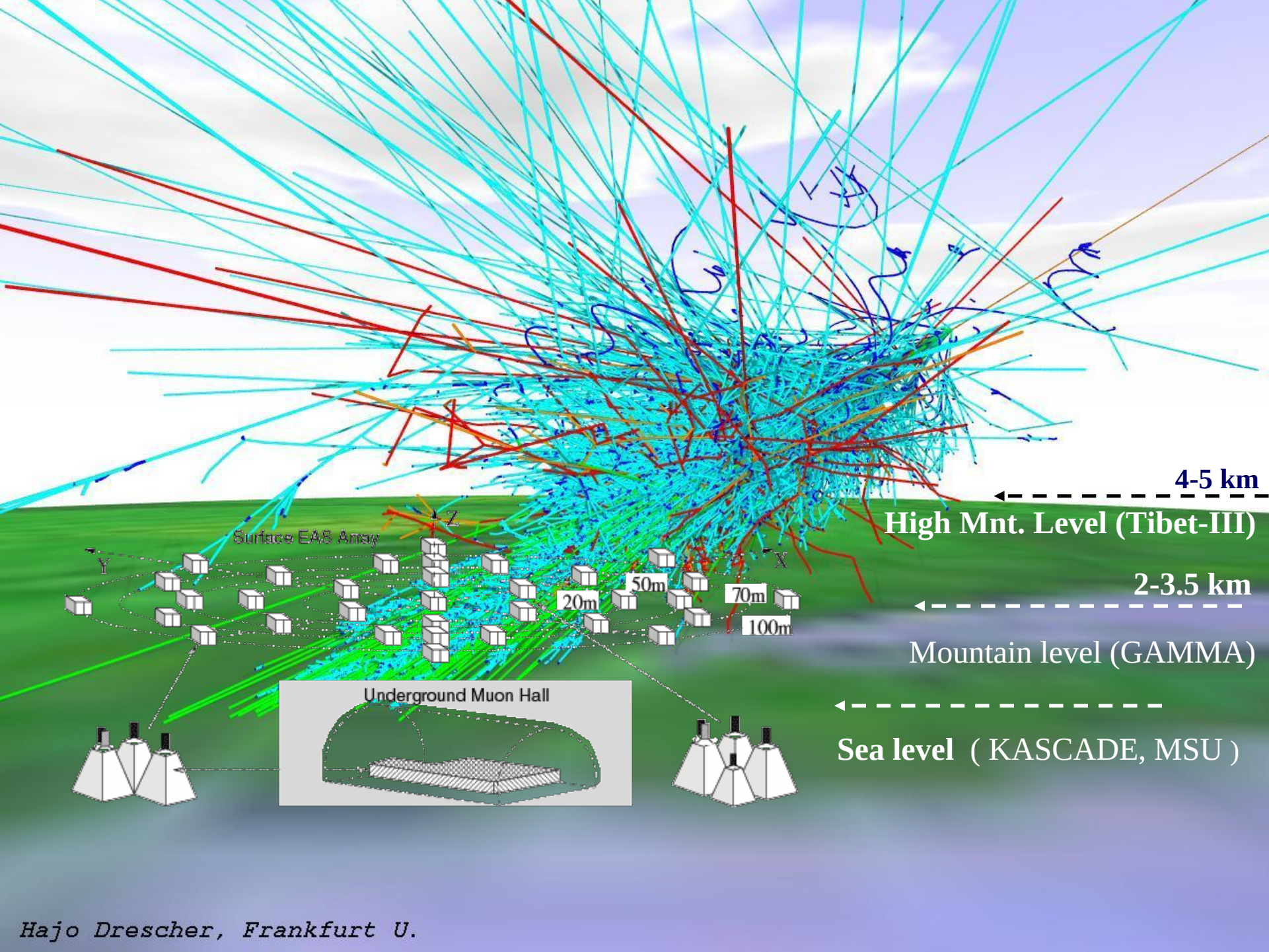



electrons/positrons
Hajo Drescher, Frankfurt U.


photons
Hajo Drescher, Frankfurt U.


muons
Hajo Drescher, Frankfurt U.


neutrons
Hajo Drescher, Frankfurt U.


4-5 km
High Mnt. Level (Tibet-III)
2-3.5 km
Mountain level (GAMMA)
Sea level (KASCADE, MSU)
Surface EAS Array
Z
Y
X
20m
50m
70m
100m
Underground Muon Hall
Hajo Drescher, Frankfurt U.

!Primary spectrum above the knee is not smooth!

It is necessary to pay special attention to the energy region of 10 - 100 PeV, where experimental results are still very limited.

Small irregularities in energy spectrum in this energy region are in

AKENO experiment (more than 20 years ago)

! Never discussed !

GAMMA experiment – old results (2002)

GAMMA experiment (recent result): visible ‘bump’ (~ 4 standard deviations)

OTHER EXPERIMENTS (will be shown)

At the same time (experimental results):

the behavior of the age parameter of EAS and muon component characteristics point out that the primary mass composition above the knee becomes significantly heavier.

Based on these indications, additional investigations of the fine structure of the primary energy spectrum at 10 - 100 PeV have a special interest.

Primary γ-rays

One of the main topics at the knee energy region:

study a diffuse flux γ-rays of and search of sources (gamma-astronomy)

In spite of many attempts, there are still not reliable confirmations of the observed sources of γ-rays at energies around PeV.

GAMMA experiment is fully in line for studies of primary energy spectrum and mass composition at 1 – 100 PeV as well as for investigation of high-energy primary γ-rays.

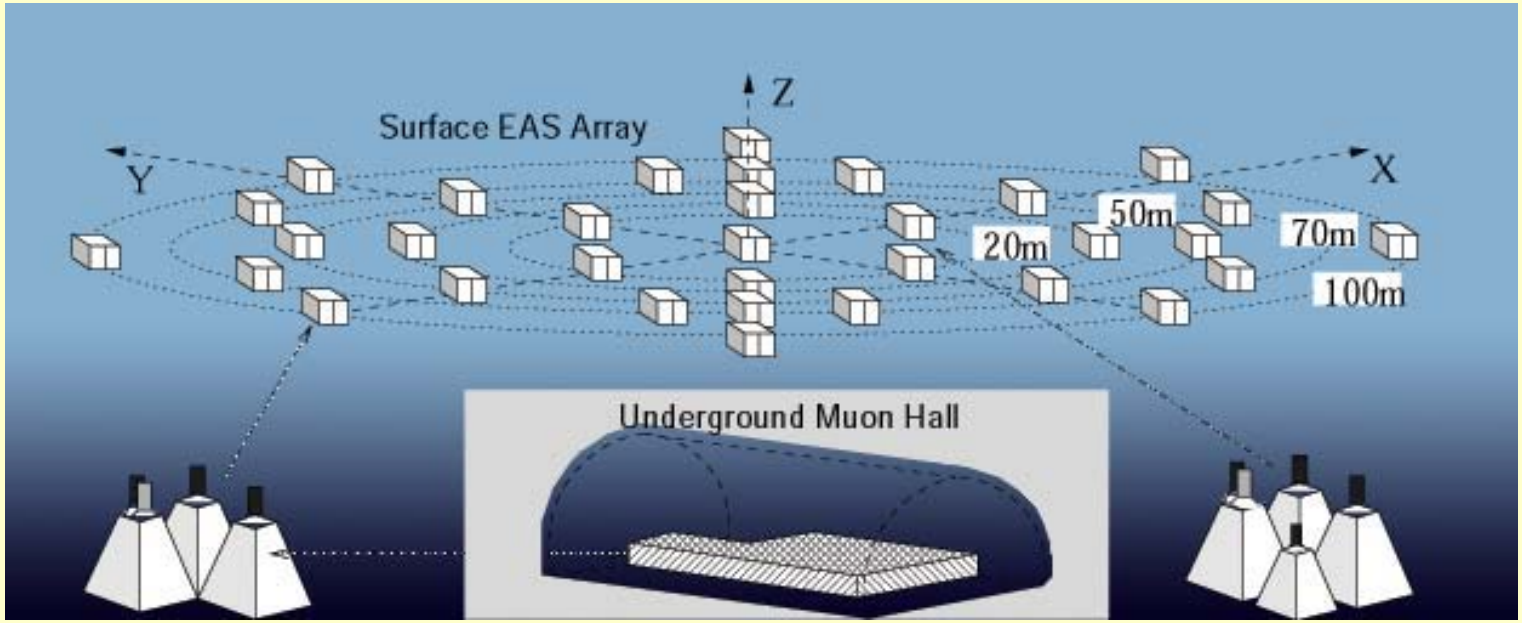
ARAGATS scientific station (late autumn)

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)



GAMMA (2003-2008)

(after several modifications)

Surface part (electromagnetic component)

33 stations on R = 0, 18, 28, 50, 70 and 100 meters with 3 plastic scintillation detectors (S=1m^2) in each station. Total number (including 9 small detectors) – 108

The area – ~ 30.000 m^2

33 fast-timing channels for estimation of the EAS angular characteristics

Underground part (muon component)

Carpet of muon scintillation detectors with total number – 150 and energy threshold E_μ > 5 GeV)

GAMMA (2003-2008)

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Surface part (electromagnetic component)

- **33 stations on R = 0, 18, 28, 50, 70 and 100 meters with 3 plastic scintillation detectors ($S=1m^2$) in each station. Total number (including 9 small detectors) – 108**

  The area – ~ 30.000 m^2
- **33 fast-timing channels for estimation of the EAS angular characteristics**

Underground part (muon component)

- **Carpet of muon scintillation detectors with total number – 150 and energy threshold $E_\mu > 5$ GeV)**

GAMMA (from 2009)

Surface part

8 additional stations in the central surface part on R = 14 and 30 meters with 1 plastic scintillation detectors ($S=1m^2$) in each station.

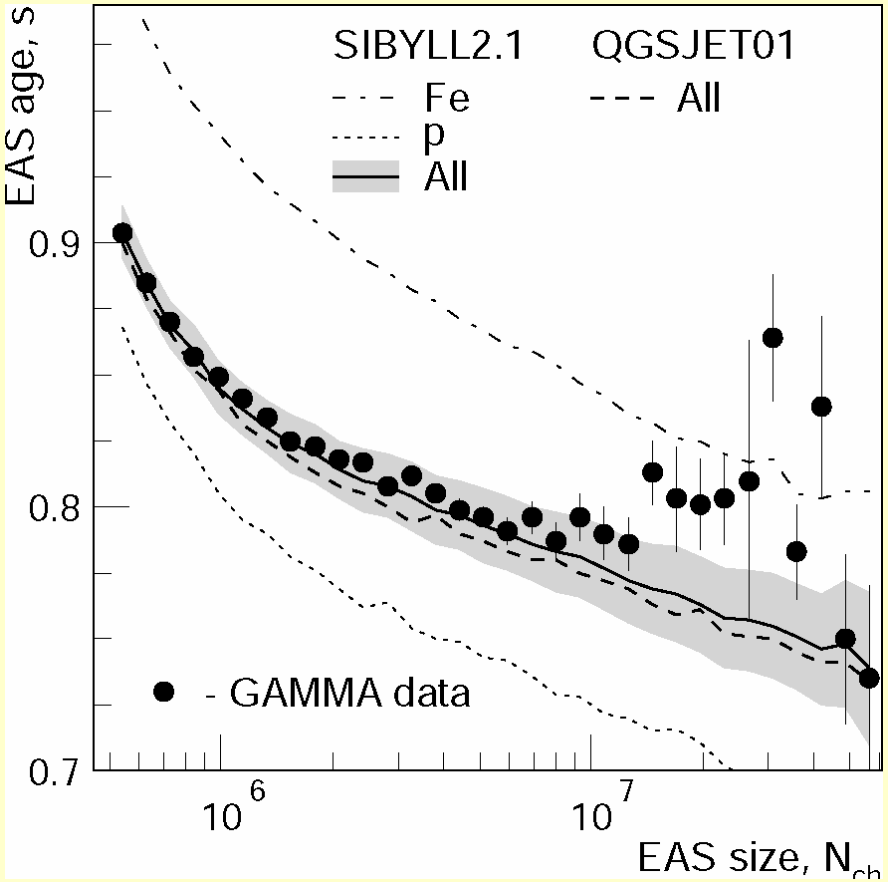
Increasing density of surface points and decreasing threshold up to ~500 TeV

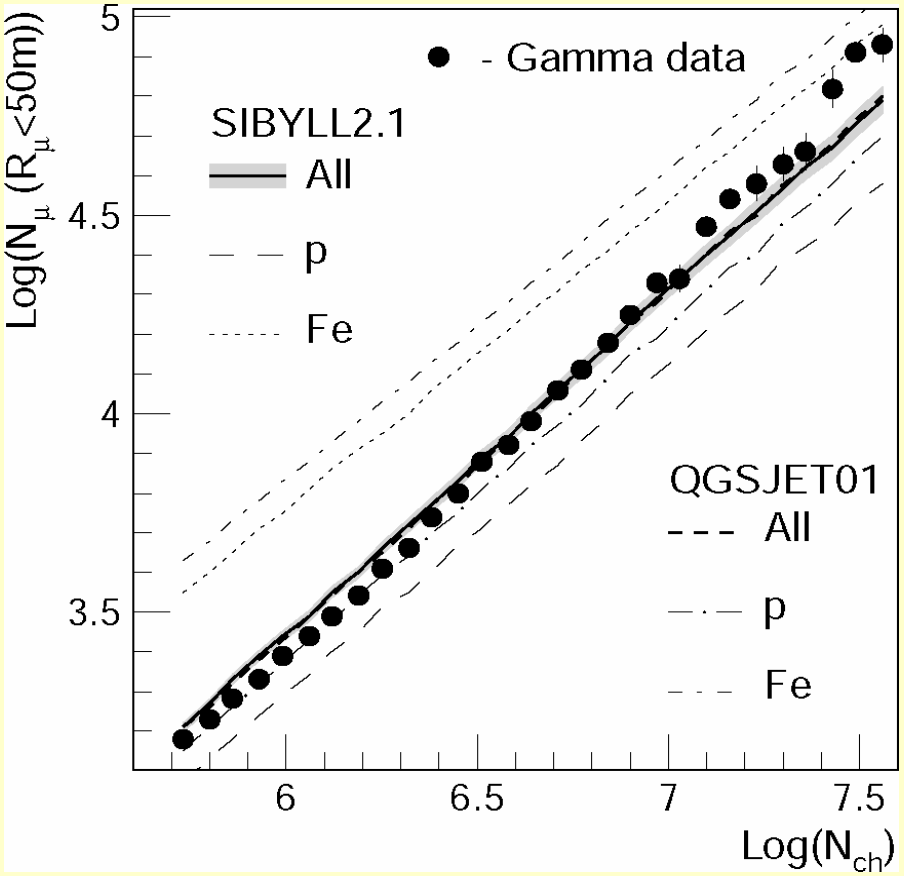
Results (2007)

Rigidity-dependent CR energy spectra in the knee region

[*Astroparticle Physiscs, 28 (2007) 169*]

On the base of EAS data the energy spectra and elemental composition of the PCR are derived in the 1 – 100 PeV. The reconstruction of spectra carried out using an EAS inverse approach in the frameworks of the SIBYLL2.1 and QGSJET0.1 interaction models and the hypothesis of power-law primary energy spectra with rigidity-dependent knees.

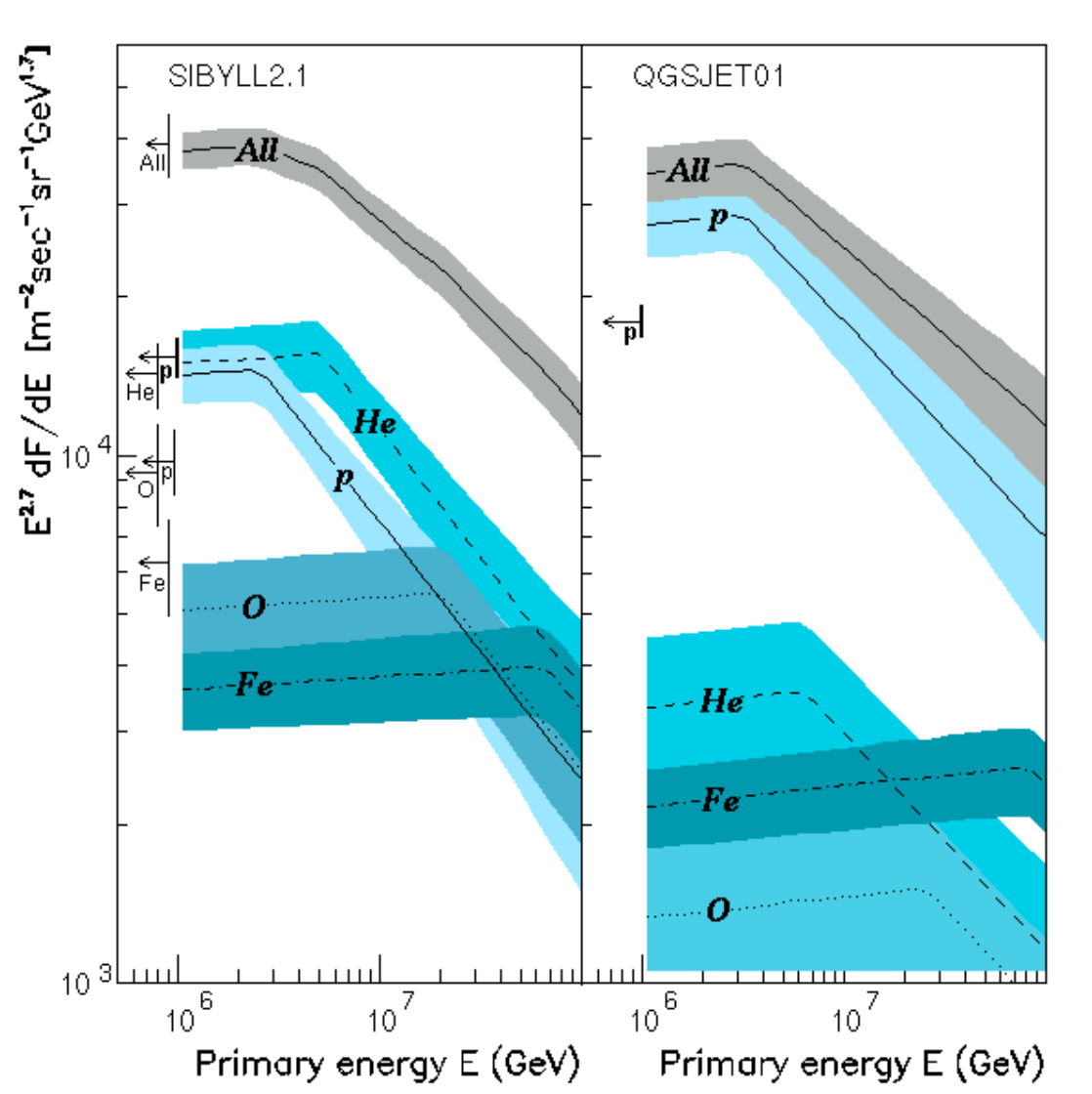




Dependence of the average EAS age parameter on EAS size

Average EAS truncated muon size versus EAS size

Energy spectra for the primary nuclei groups



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

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

Conclusion (2007)

- Rigidity-dependent spectra describe the EAS data at least up to E~100 PeV.
- The abundances and energy spectra obtained for primary p, He, O-like and Fe-like nuclei strongly depend on interaction model.
- The SIBYLL interaction model is preferable in terms of consistency of the extrapolation of obtained primary spectra with direct measurements in the energy range of satellite and balloon experiments.
- ! The derived all-particle primary energy spectra only weakly depend on interaction model. !
- An anomalous behavior of the muon size and density spectra and age parameter for EAS size $N_{ch} > 10^7$ is observed and requests additional analysis.

Results (2008)

An all-particle primary energy spectrum in the 3-200 PeV energy range

[*J.Phys. G: Nucl. Part. Phys. 35 (2008) 115201*]

On the basis of extended EAS data set from the GAMMA experiment an all-particle primary CR energy spectrum in the 3-200 PeV energy range was obtained by a multi-parametric event-by-event evaluation of the primary energy.

The energy evaluation method has been developed using the EAS simulation with the SIBYLL interaction model taking into account the response of the GAMMA detectors and reconstruction uncertainties of EAS parameters.

Energy estimator

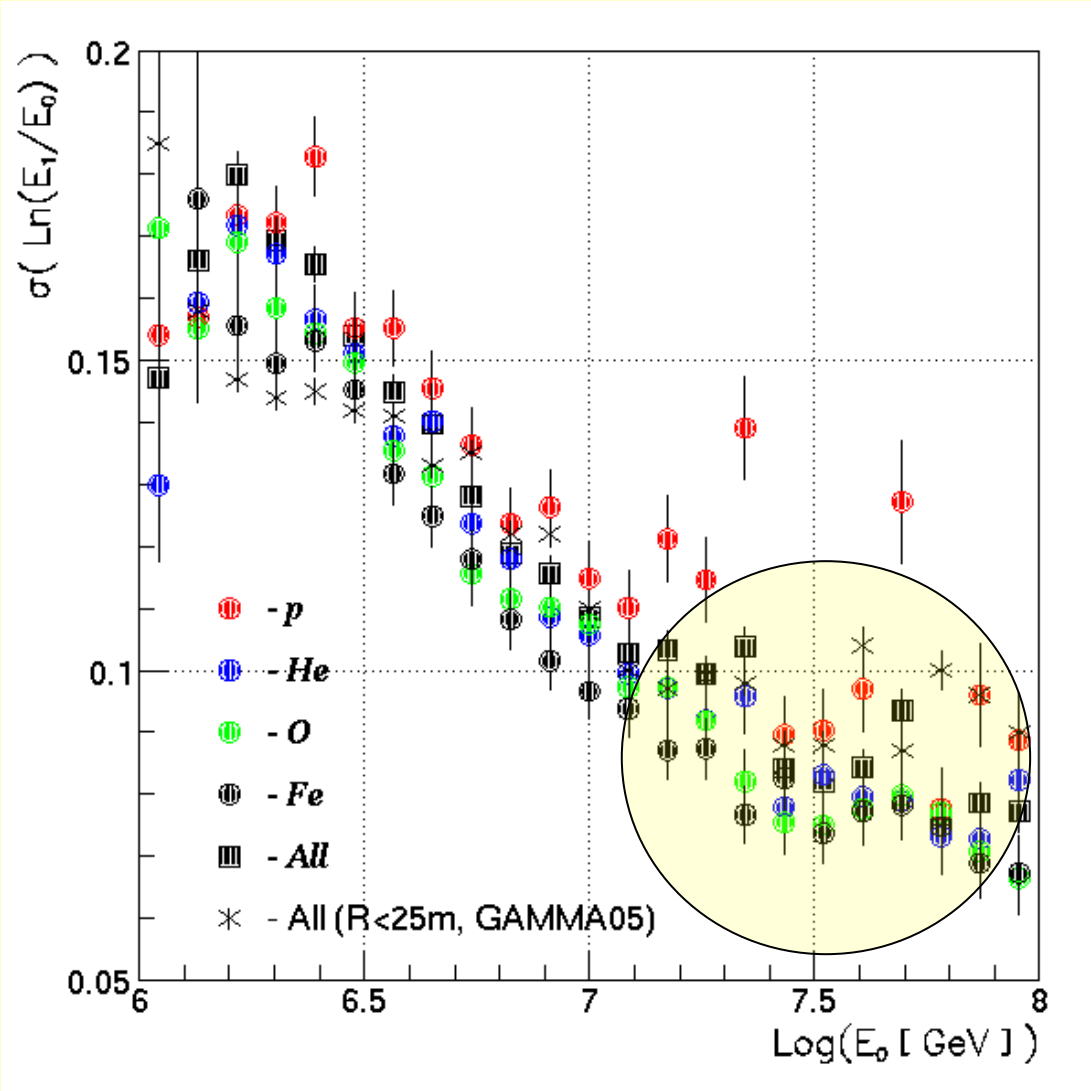
$$Ln(E_0) \approx Ln(E_1) = f(N_{ch}, N_\mu, s, cos\theta)$$

where N_{ch}, N_μ, s, cos θ – ! experimentally measured parameters !

The best energy estimations as a result of $\chi^2_{min}(E_0,E_1)$ were achieved for the 7-parametric fit:

$$LnE_1 = a_1 x + a_2 \sqrt{s}/c + a_3 c + a_4 + a_5/(x - a_6 y) + a_7 y e^s$$

where $x = LnN_{ch}$, $y = LnN_\mu$ (R<50m), $c = \cos(\theta)$

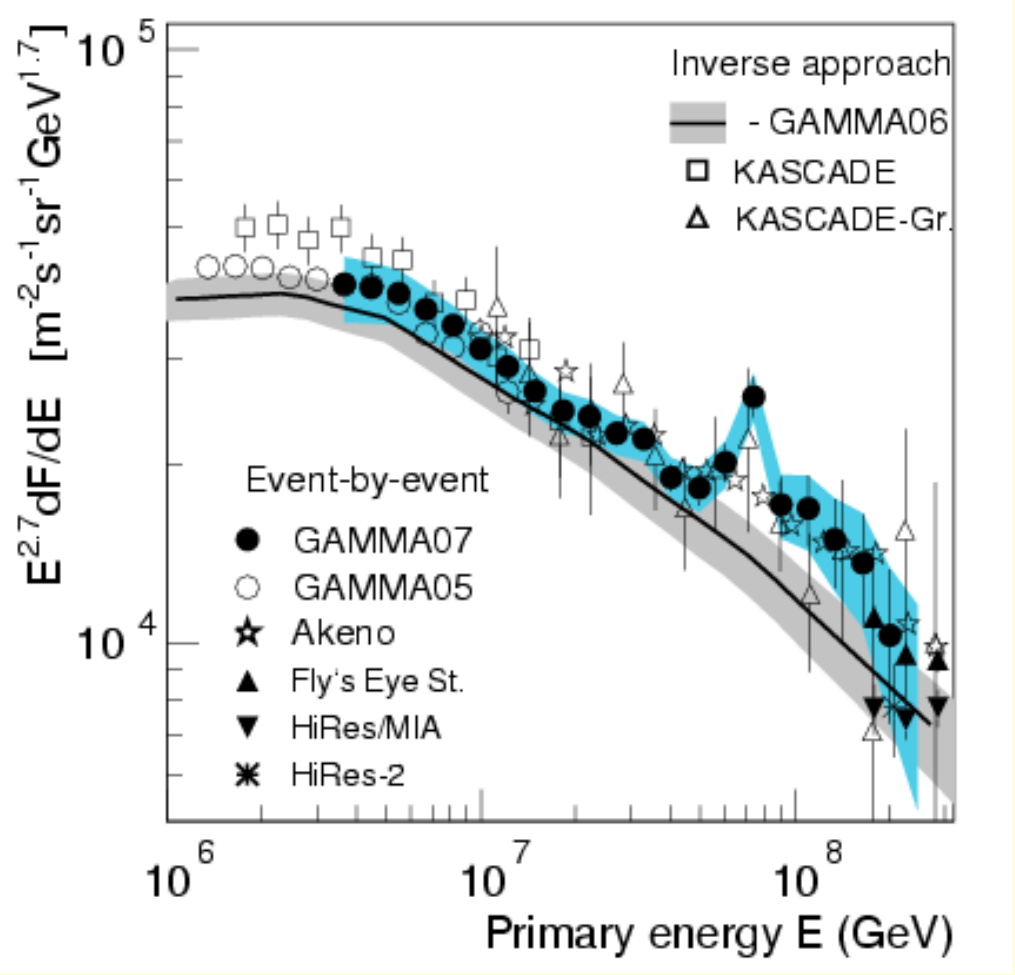


Errors of the energy estimator versus primary energy E_0 for 4 primary nuclei and uniformly mixed (All) composition.

Such high accuracy of the energy evaluation independently of primary nuclei is a consequence of the high mountain location of the GAMMA facility (700 g/cm^2), where the correlation of primary energy with the detected EAS size is about 0.95-0.97

All-Particle Energy Spectrum

GAMMA05: R < 25m; Q < 30^0
GAMMA07: R < 50m; Q < 45^0



All-particle energy spectrum in comparison with the results of EAS inverse approach (GAMMA-06, KASCADE, KASCADE-Grande), our preliminary data and results of other experiments

All-Particle Energy Spectrum

GAMMA05: R < 25m; Q < 30⁰
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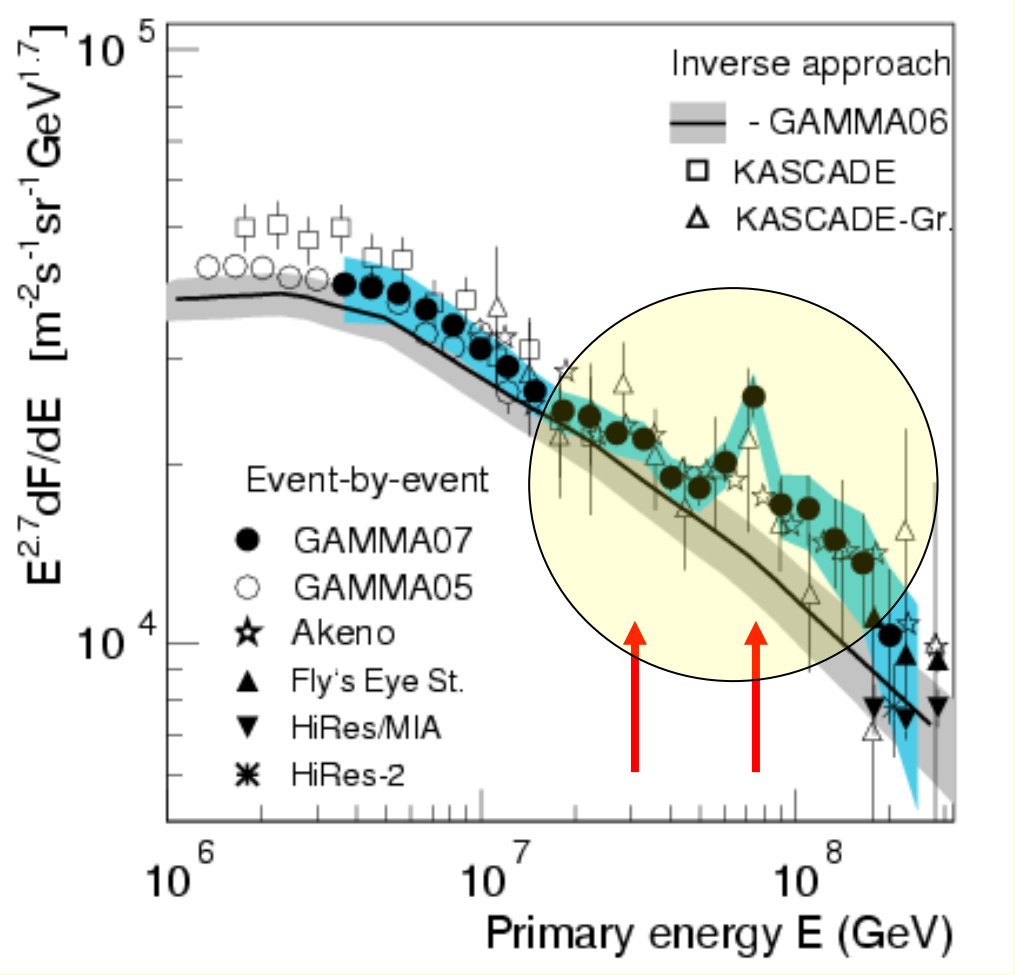
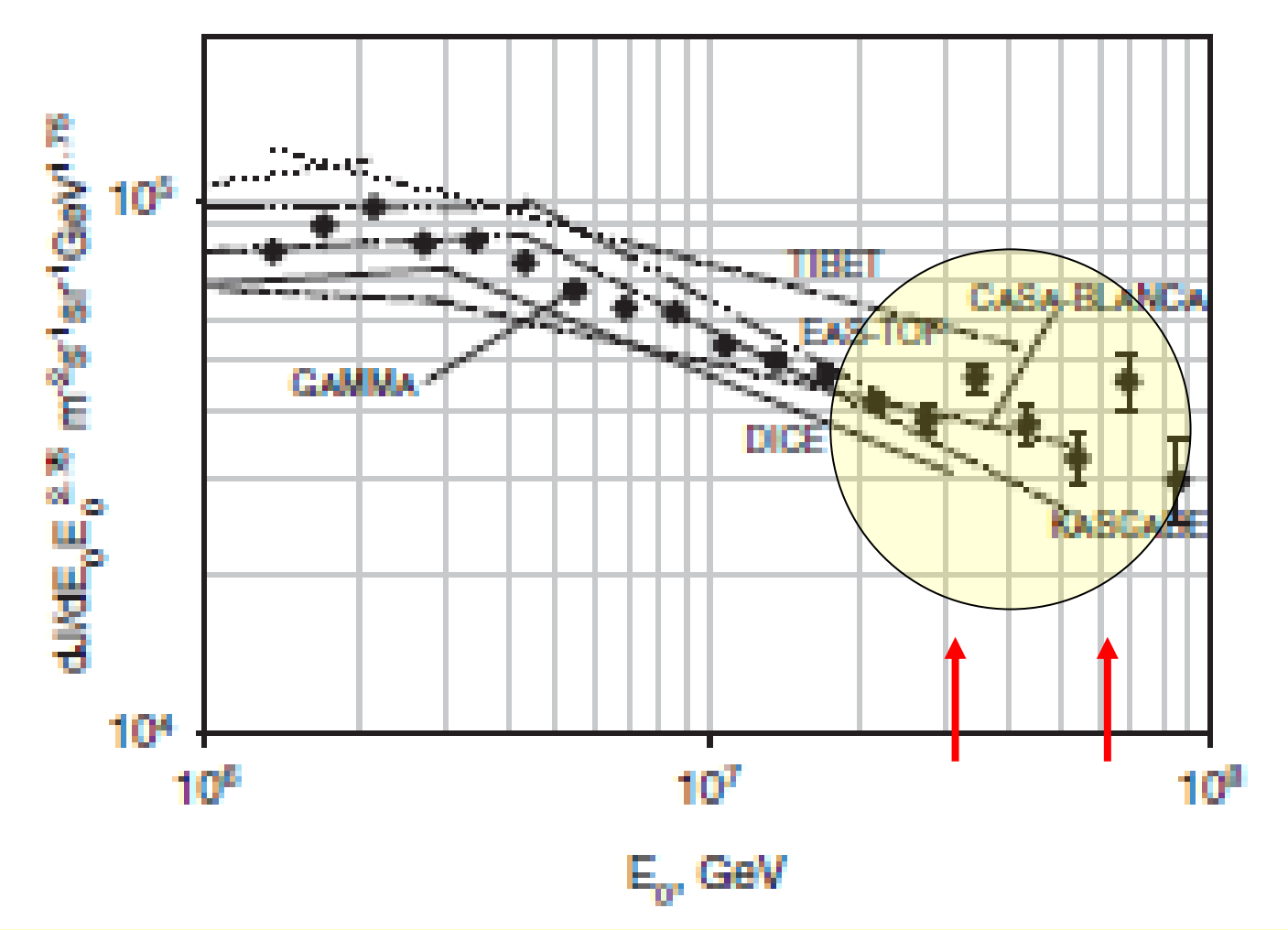


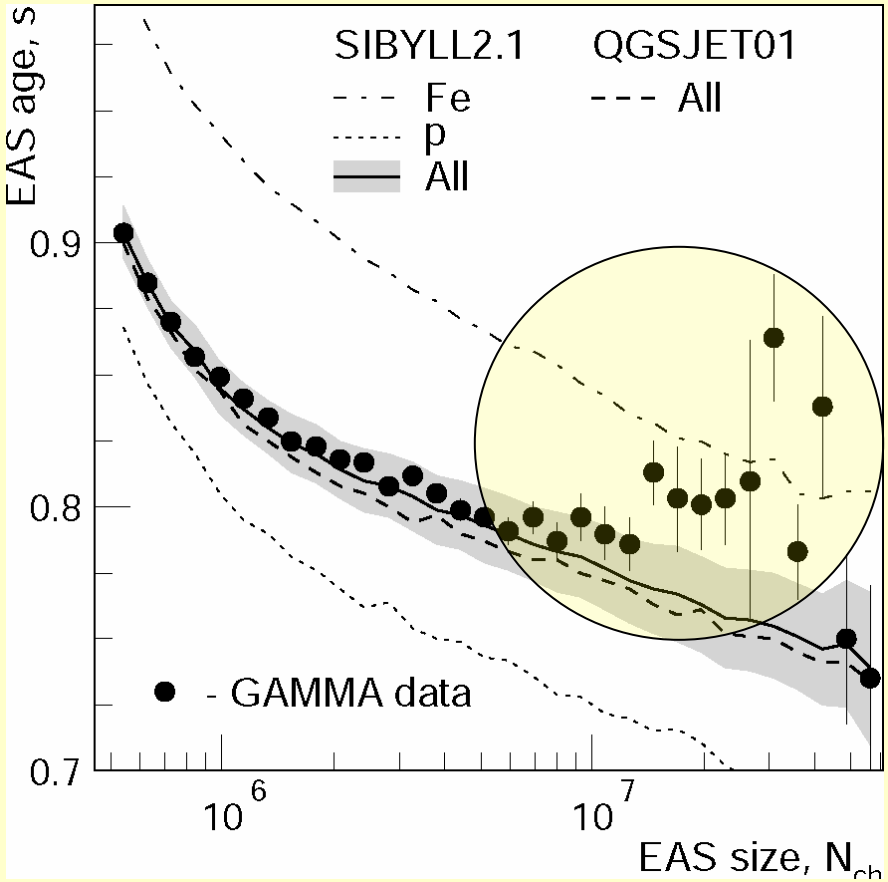
All-particle energy spectrum in comparison with the results of EAS inverse approach (GAMMA-06, KASCADE, KASCADE-Grande), our preliminary data and results of other experiments

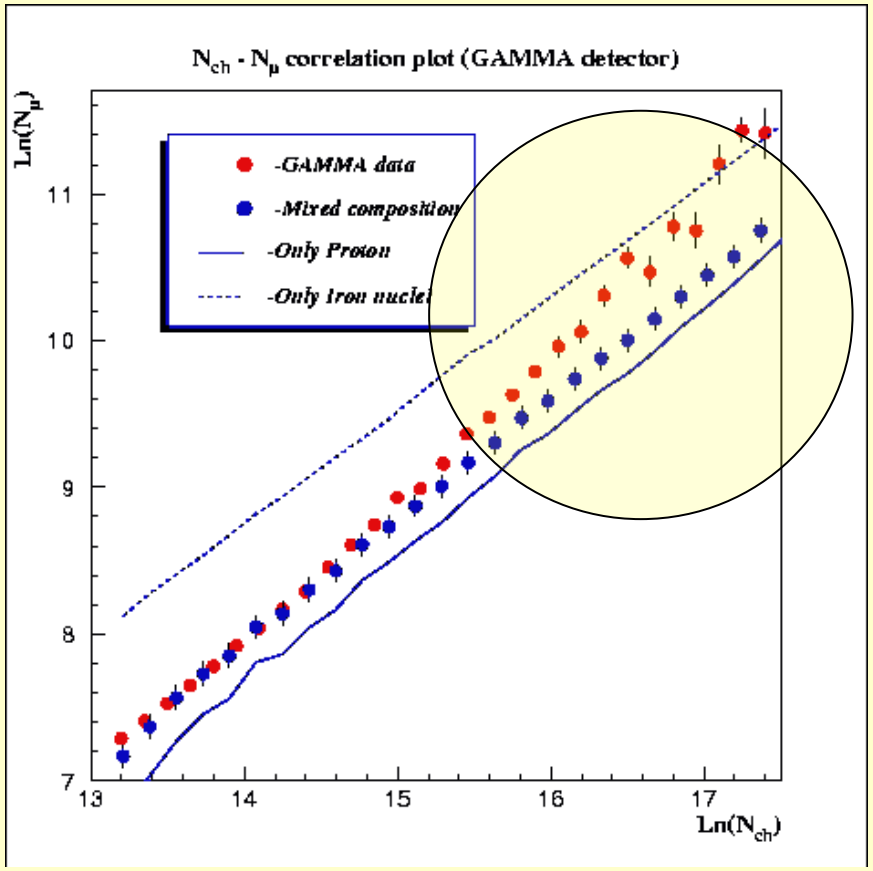
GAMMA data 2002 (using only surface detectors)

[*J.Phys. G: Nucl. Part. Phys. 28 (2002)*]



! "We would like to underline that the bump observed at E_0 ~ 3x10^7 GeV is not connected to any methodical effects." !

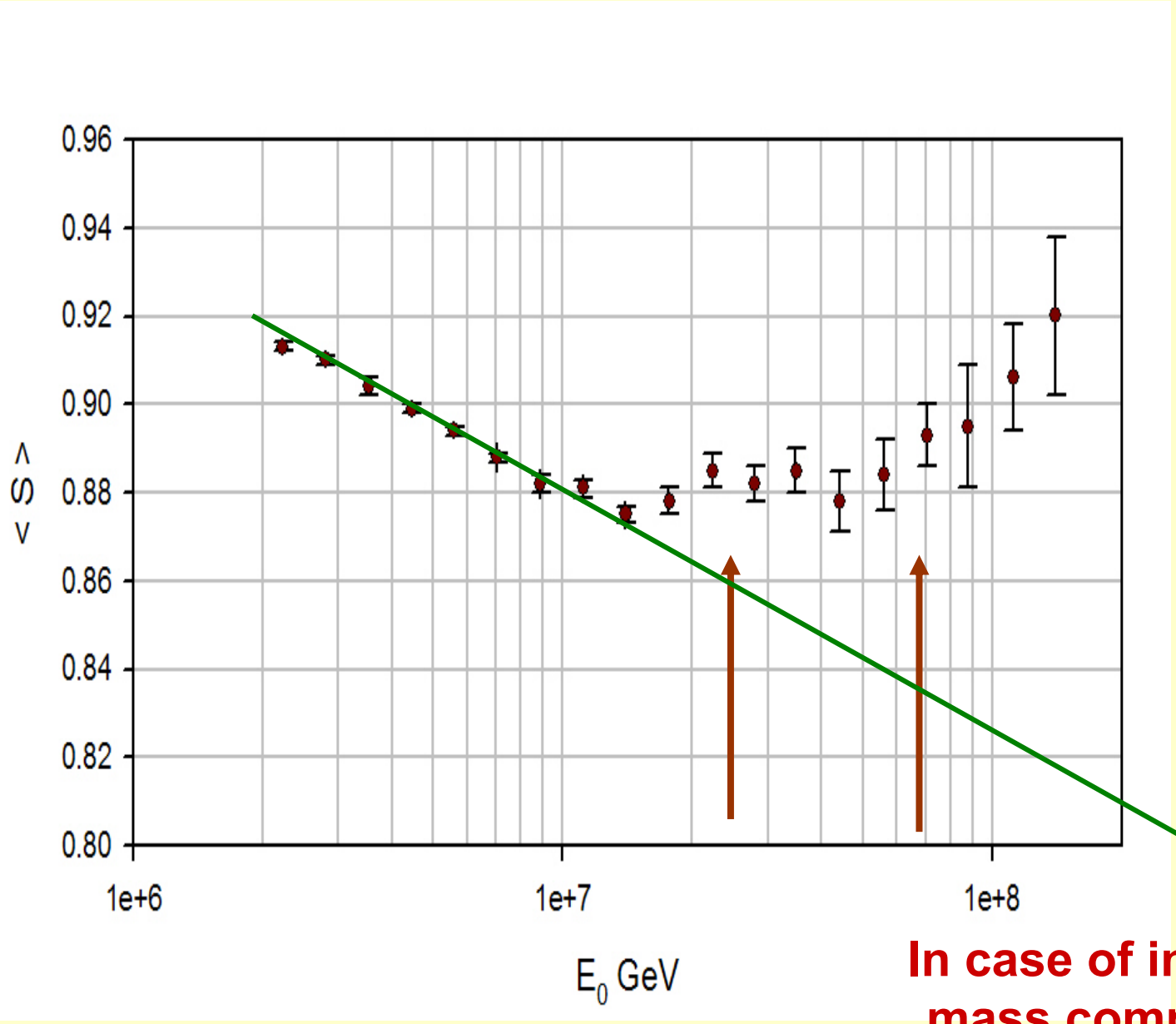




Dependence of the average EAS age parameter on EAS size

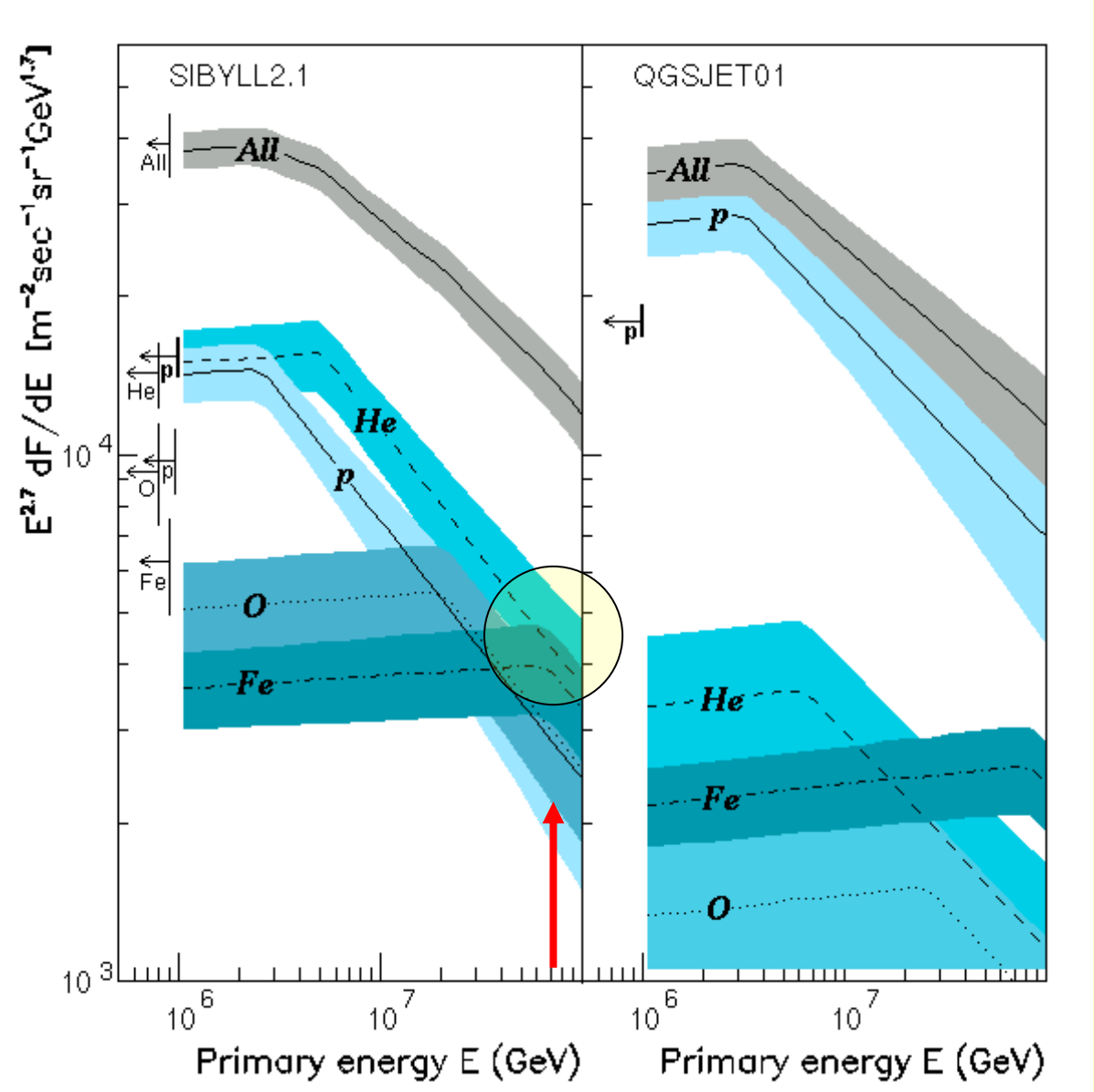
Average EAS truncated muon size versus EAS size

$S = f(E_0)$



In case of invariable mass composition

Results from 2007



On the assumtion of these indications

! Possible origin of irregularities !

Rigidity-dependent primary-energy spectra cannot describe the phenomenon of ageing of EAS at energies above the knee which was observed in mountain-altitude experiments.

! It is reasonable to assume that an additional flux of heavy nuclei (Fe-like) is responsible for the bump at these energies. !

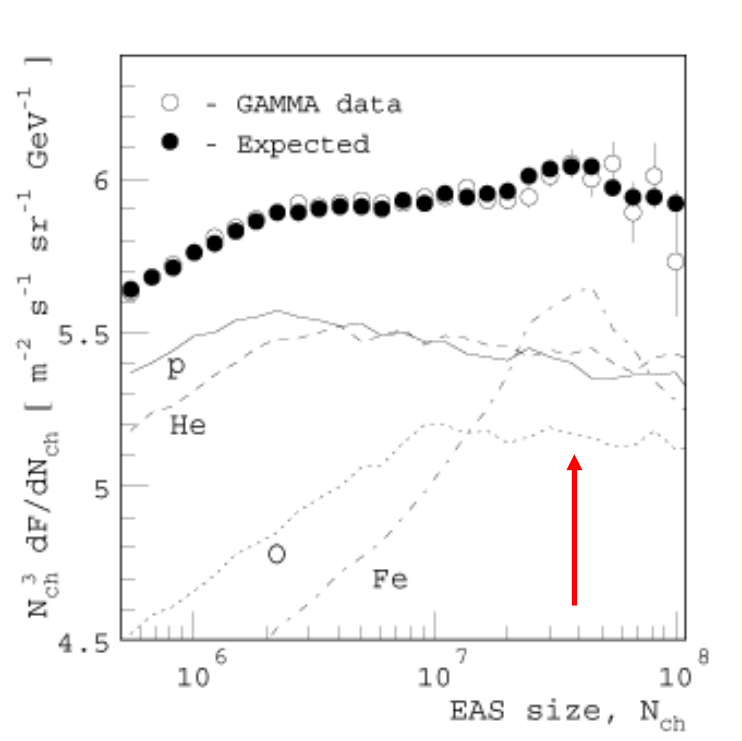
In addition, the sharpness of the bump points out the local origin of this flux from compact object.

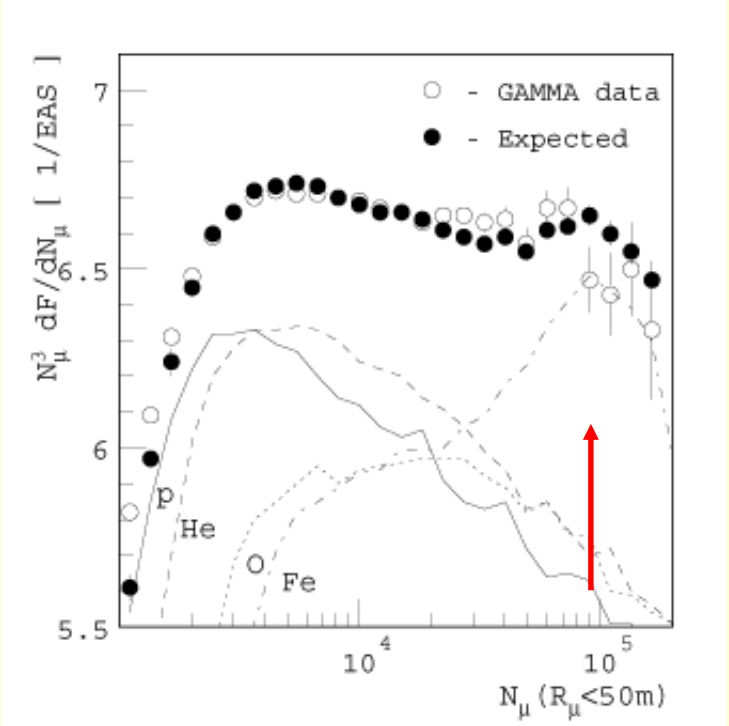
We carried out the test of this assumption using the inverse approach on the base of GAMMA data and the hypothesis of two-component origin of cosmic ray flux:

so-called Galactic component is the power-law energy spectra with rigidity-dependent knees at energies $E_k=E_R \cdot Z$ and power indices $\gamma = \gamma_1$ and $\gamma= \gamma_2$ for $E < E_k$ and $E > E_k$ respectively;

so-called pulsar component is an additional power-law energy spectrum with cut-off energies $E_{c,Fe}$ and indices $\gamma_p= \gamma_{1,p}$ and $\gamma_p= \gamma_{2,p}$ for $E < E_{c,Fe}$ and $E > E_{c,Fe}$ respectively.

Shower Spectra
for electromagnetic and muon components

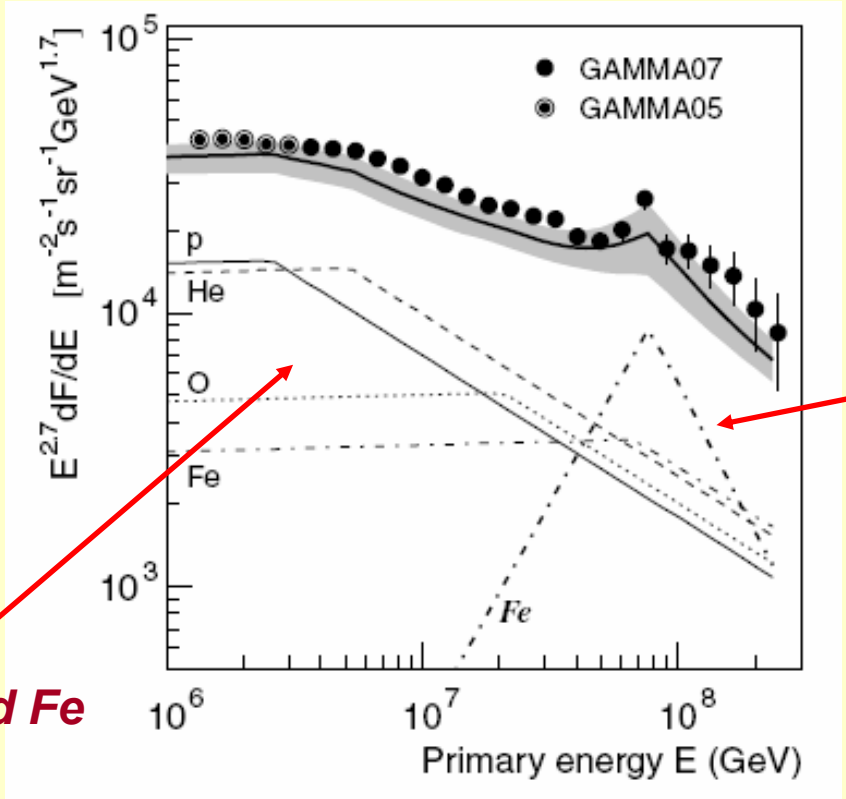




EAS size (on the left) and truncated muon size spectra and corresponding expected spectra computed in the framework of the SIBYLL interaction model and the two-component parametrization of primary spectra.

The lines correspond to expected spectra computed for each of the primary nuclei.

All-particle spectra and pulsar *Fe* component



Fe component from compact objects

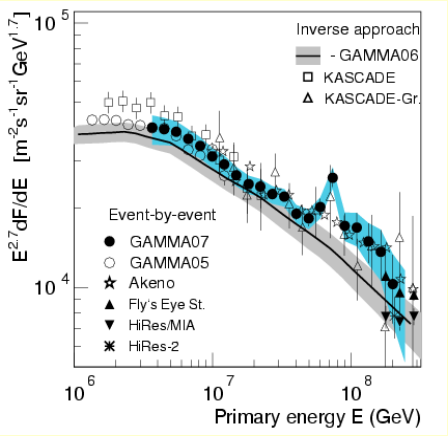
Galactic p, He, O and Fe components

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

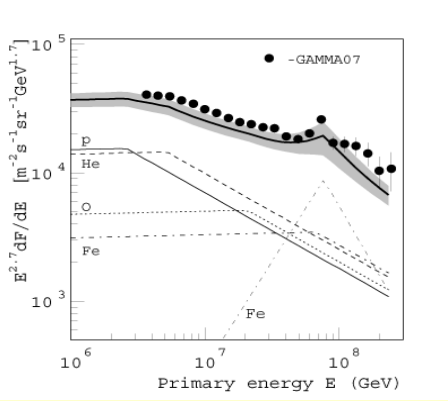
!!! Two-component all-particle spectrum (bold line with shaded area) agree within the errors with the results of the event-by-event analysis !!!

Conclusion (2008)

- All-particle energy spectrum are obtained using GAMMA facility EAS database. The all-particle spectrum in the range of statistical and methodical errors agrees with the same spectrum obtained using EAS inverse approach in 5-70 PeV energy region. High accuracies of energy evaluations and small statistical errors point out to the existence of explicit irregularity (bump) of energy spectrum in the 60-80 PeV region.

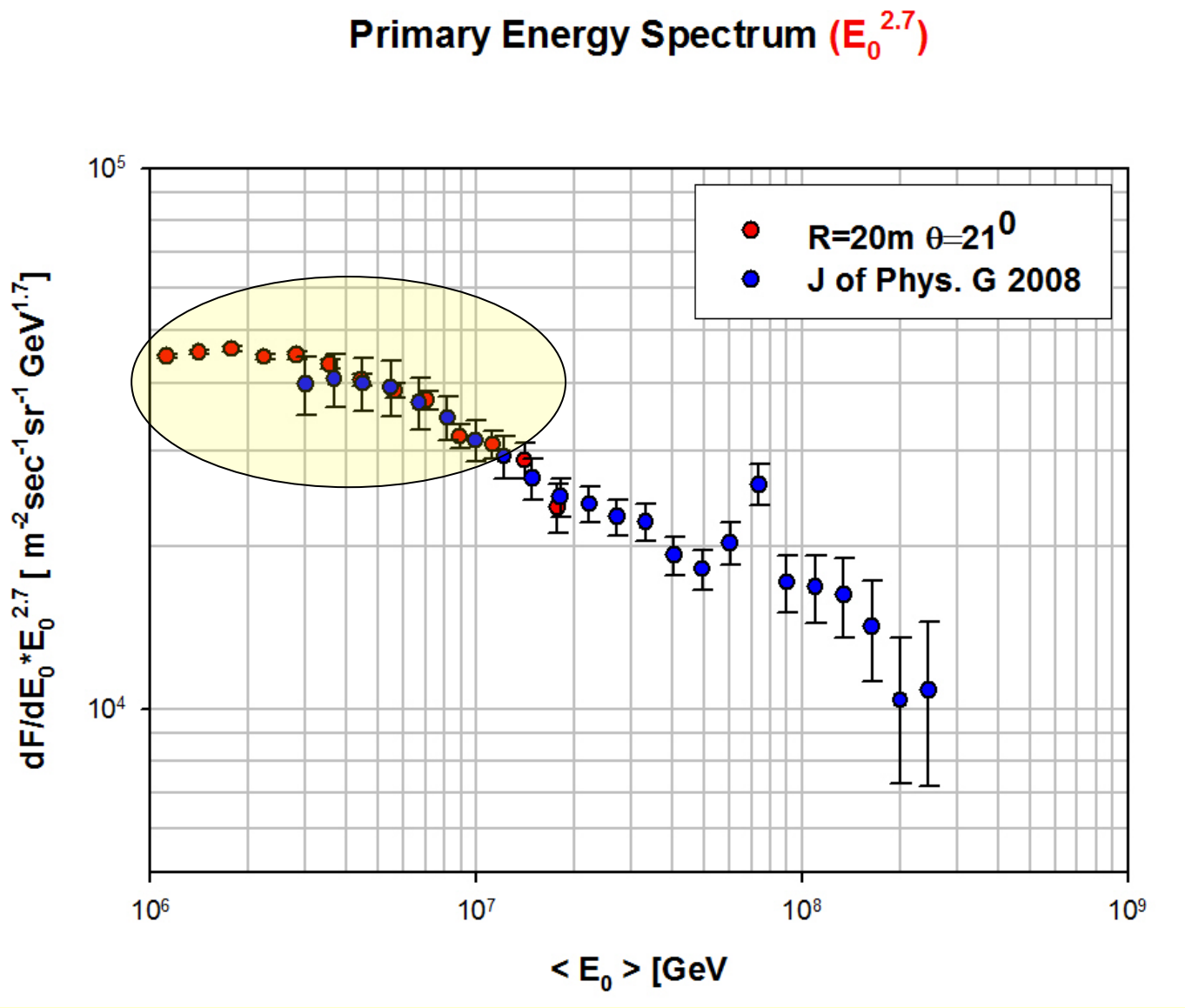


- The bump can be described by a two-component model of primary CR origin with additional (pulsar) Fe component.

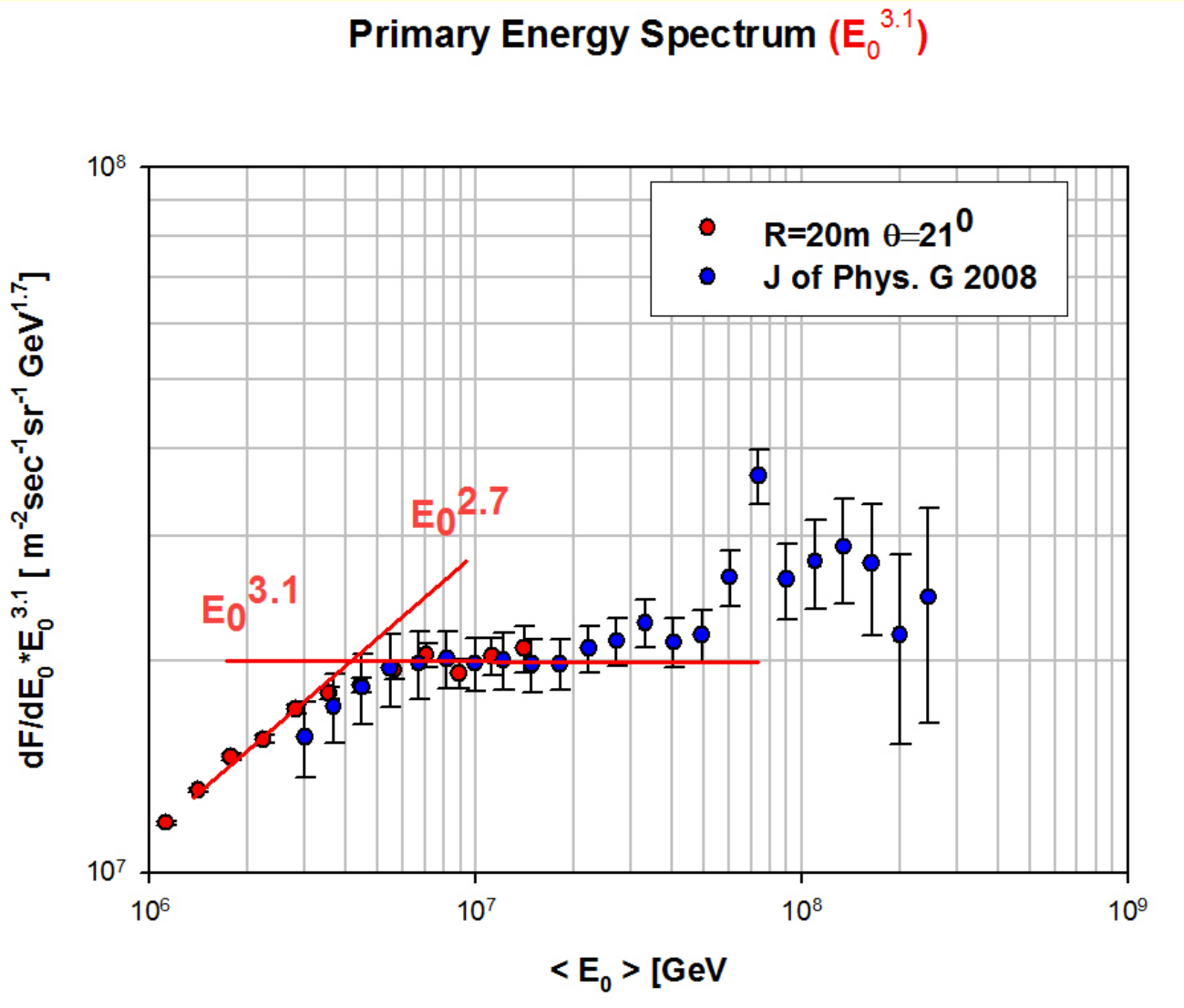


! This interesting phenomenon needs for additional study and interpretation !

Last results 2010



Last results 2010 (preliminary)



Irregularity in the energy range 10 – 100 PeV

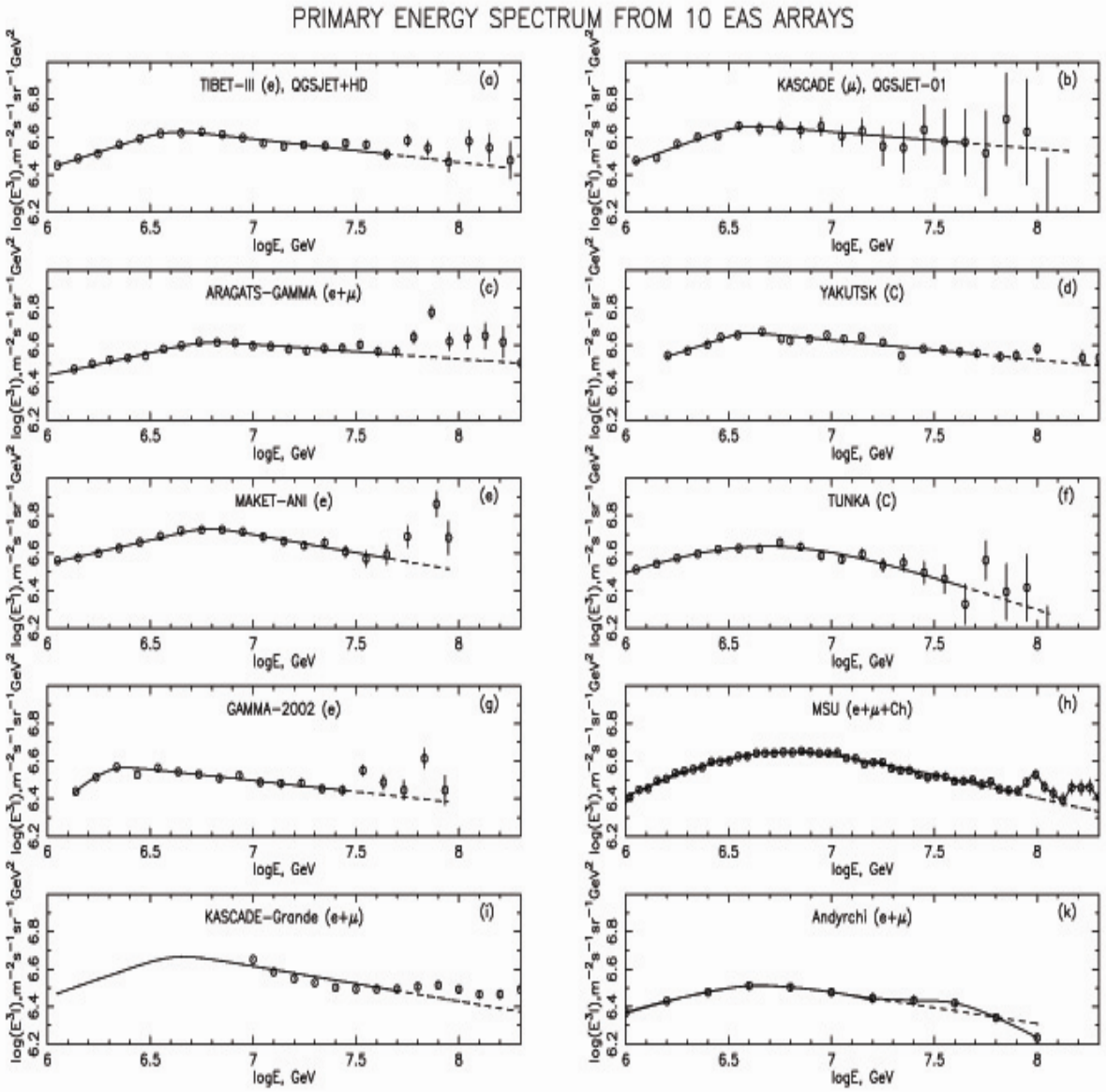
TIBET -III

GAMMA-2008

MAKET-ANI

GAMMA-2002

KASCADE - GRANDE



KASCADE

YAKUTSK

TUNKA

MSU

ANDYRCHI - BAKSAN

Erlykin, Wolfendale, ESCR, Turku, 2010

Do we see an 'Iron Knee' ?

Part of conclusion
(Erlykin, Wolfendale)

The advance to the higher energy of about 10^8 GeV lead us to the existence of a new feature – another irregularity in the spectrum at energies of 50-80 PeV, claimed first in GAMMA experiment, 2008. If the dominant contribution to the knee is due to primary He-nuclei, this new irregularity is just where primary iron nuclei should appear and create so-called the 'Iron knee'.

SUMMARY COMMENTS to energy spectrum

There is an obvious and strong irregularity at energies 50-80 PeV confirmed by many experiments.

It points out on changing the mass composition after the knee to heavier (Fe-like) nuclei.

It is necessary to continue investigations in this energy region, especially using facilities located at mountain elevations, where fluctuations of the detected EAS are significantly smaller in comparison with experiments at sea level.

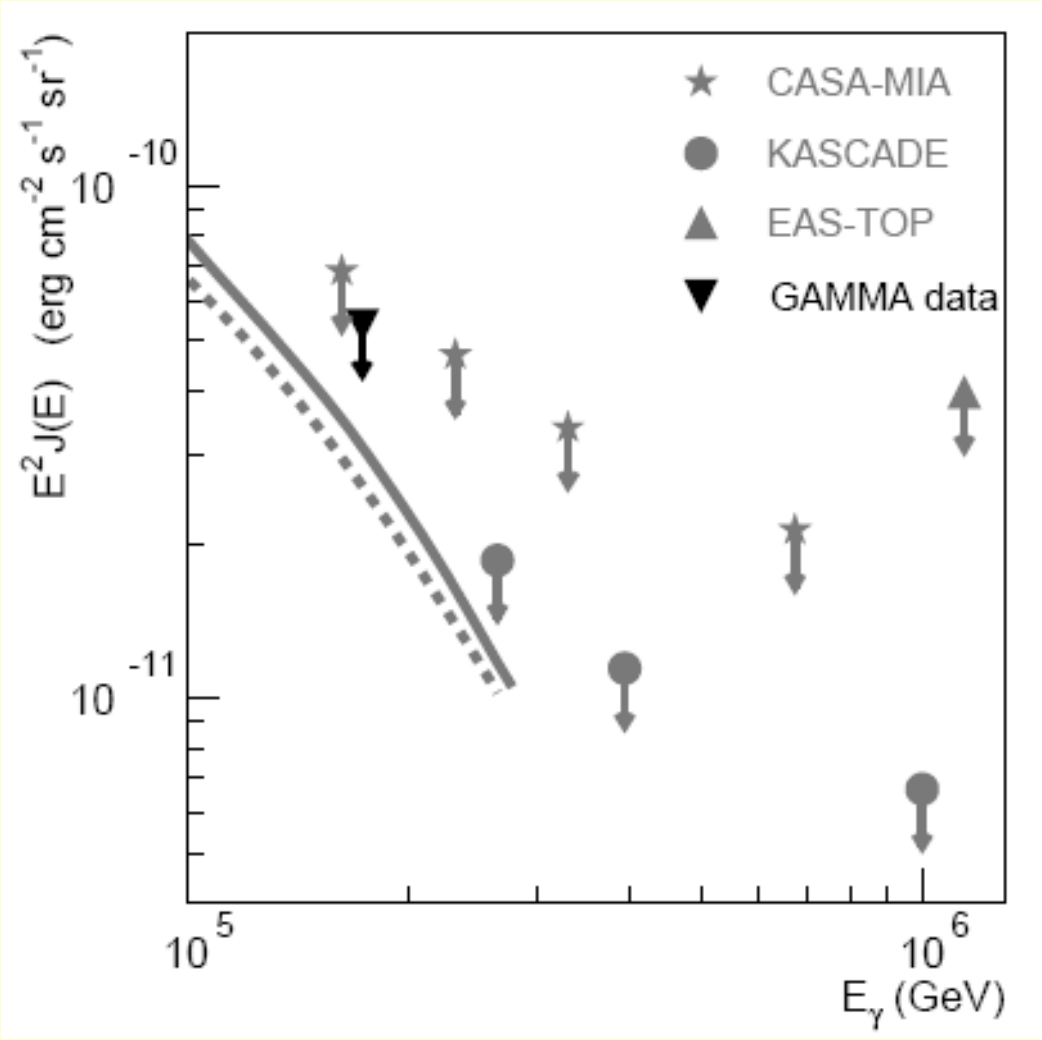
Recent results 2009

Galactic diffuse gamma-ray flux at the energy about 175 TeV

[*Proc. of the 31st ICRC, Lodz, 2009*]

Discrimination of the γ-showers from primary induced showers is performed on the basis of following 6 conditions:

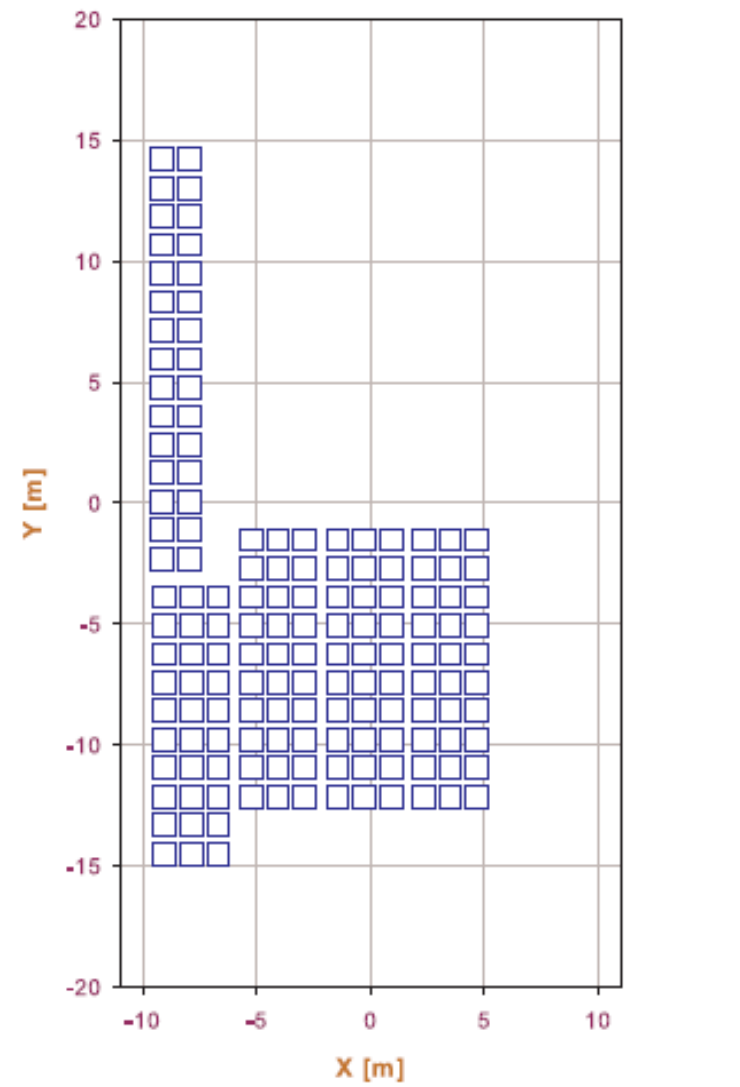
1) the reconstructed shower core coordinates is distributed within radius of $R < 15$m;
2) shower zenith angles $\theta < 30^0$;
3) reconstructed shower size $Nch > 10^5$;
4) reconstructed shower age parameters (s) is distributed within $0.4 < s < 1.5$;
5) goodness-of-fit test for reconstructed showers $\chi 2 < 2.5$;
6) no-muon signal is recorded for detected showers satisfying the previous 5 conditions.



Upper limit of gamma ray flux derived from detected no-muon showers (black triangle symbol). The gray symbols are the CASA-MIA [11], KASCADE [13] and EAS-TOP [12] data taken from [13]. The lines are expected Galactic diffuse background flux from [Aharonian, F. A., A. M. Atoyan 2000, Astron. Astrophys. 362, 937].

Near perspectives

Muon carpet at present



Muon detectors disposition in the underground hall

150 - sq. meters

Increasing in 2010 effective area of muon carpet up to 250 sq. m using both scintillation detectors and Geiger counters

1. **To improve the gamma-proton showers discrimination efficiency**
2. **To improve primary energy estimation using multi-parametric analysis**


Thanks
http://gamma-armenia.org

Measurement errors

$\Delta\theta \sim 1.5^0$;

$\Delta N_{ch}/N_{ch} = 0.05 - 0.15$;

$\Delta s = 0.05$

ΔX and $\Delta Y = 0.7 – 1.0$ m

INTRODUCTION

The investigation of the energy spectra and elemental composition of primary cosmic rays in the “knee” region (1 - 100 eV) and above remains one of the intriguing problems of the modern VHE cosmic-ray physics

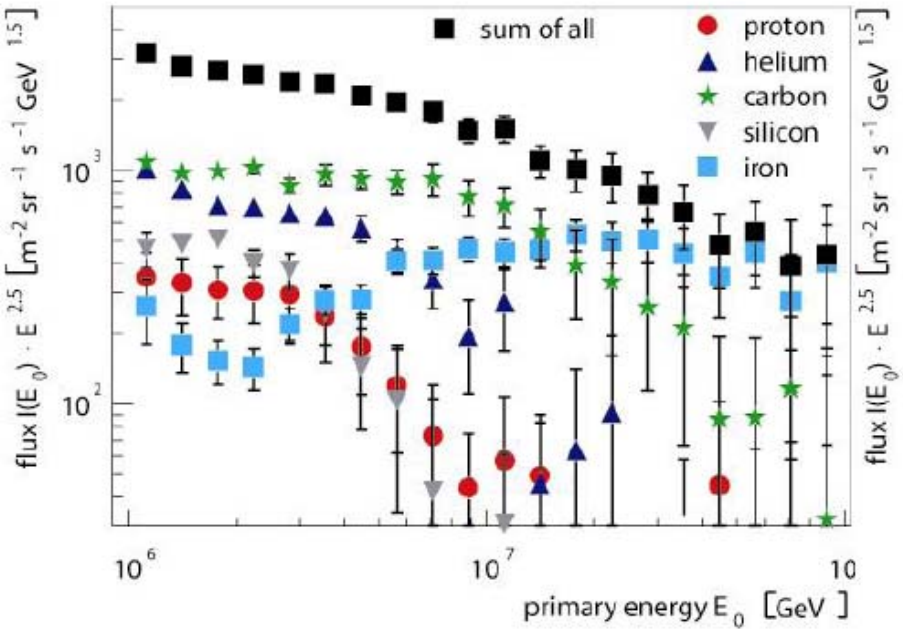
There are not still common arguments on origin of knee in spite of many astrophysical scenarios like:

- **change of acceleration mechanisms at the sources of cosmic rays (supernova remnants, pulsars, etc.);**
- **the single source assumption;**
- **effects due to the propagation inside the galaxy (diffusion, drift, escape from the Galaxy);**
- **particle-physics models like the interaction with relic neutrinos during transport or new processes in the atmosphere during air-shower development**

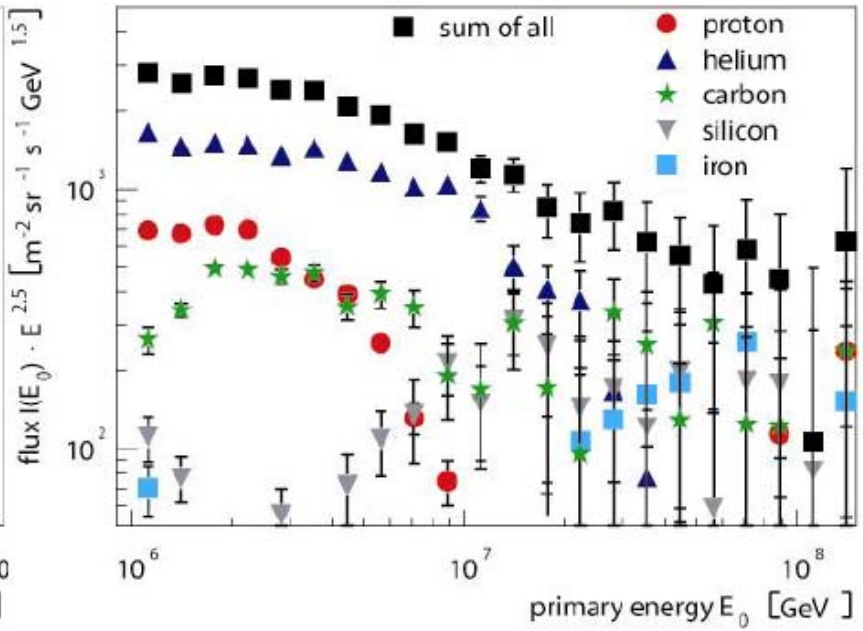
KASCADE results

- same unfolding but based on two different interaction models:
- SIBYLL 2.1 and QGSJET01 (both with GHEISHA 2002) all embedded in CORSIKA

SIBYLL



QGSJet

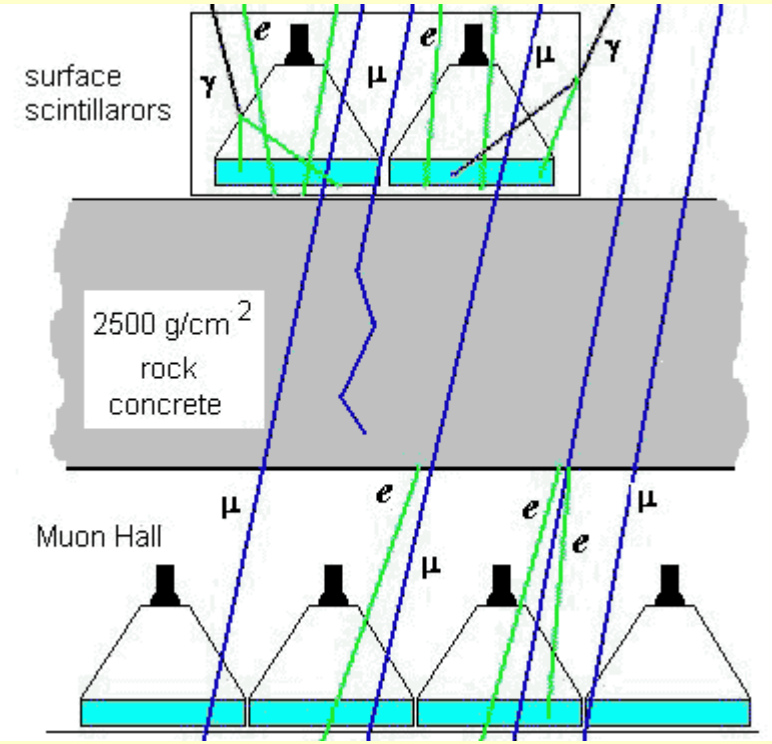


KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25, astro-ph/0505413

! All-particle spectra are practicallly identical for both models !

EAS Simulations

CORSIKA6.031(NKG)



Simulated database: $W_A(E_A, \boldsymbol{X})$

$$\{A, E_A\} \Rightarrow \mathbf{X}(N_e, N_\mu, N_h, s, x_0, y_0, \theta, \varphi)$$

A	SIBYLL2.1	QGSJET01	E_{min} [PeV]
P	$1.0 \cdot 10^5$	$1.0 \cdot 10^5$	0.5
He	$7.1 \cdot 10^4$	$6.0 \cdot 10^4$	0.7
O	$4.6 \cdot 10^4$	$4.4 \cdot 10^4$	1.0
Fe	$4.8 \cdot 10^4$	$4.0 \cdot 10^4$	1.2

$E_{max} = 500$ PeV

$\gamma = -1.5$

$\theta < 30^0$

$R < 25$m

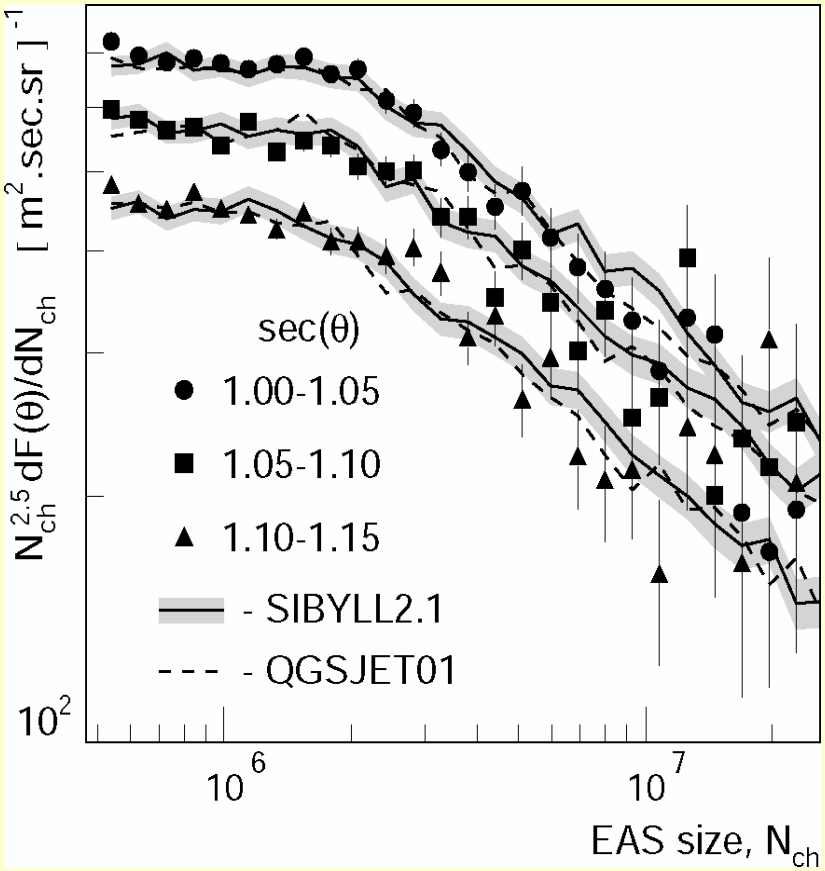
$E_{e,\gamma} > 1$ MeV

$E_\mu > 150$ MeV

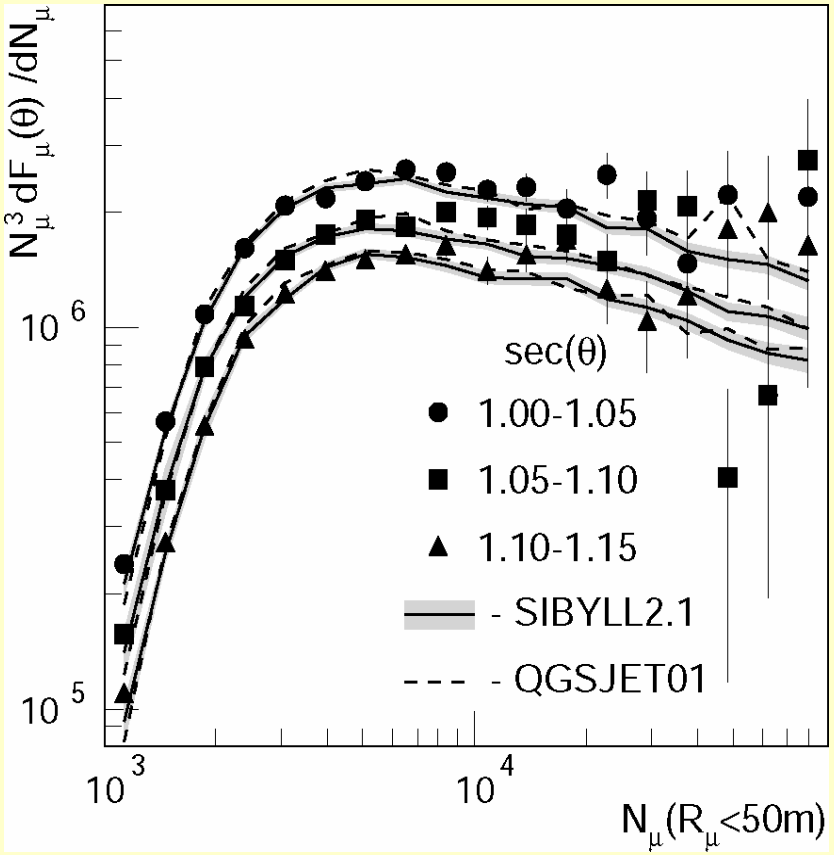
Muon hall:

$E_\mu > 4$ GeV ($e^{\pm}$,FLUKA)

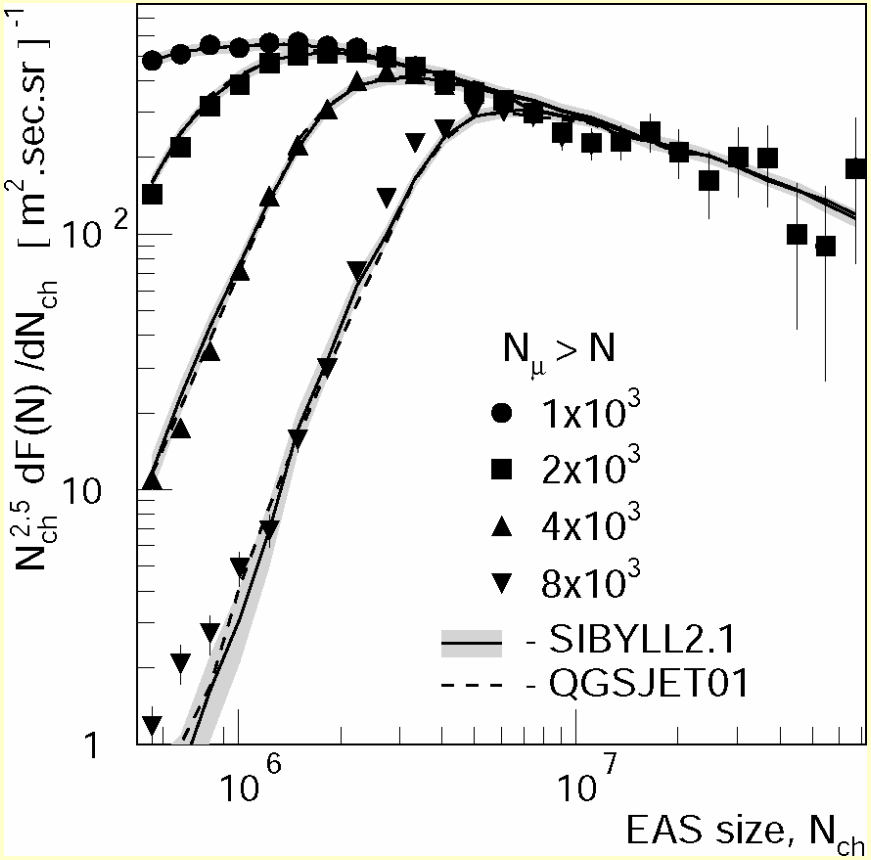
The measured variable distributions in comparison with expected dependences from SIBYLL and QGSJET interaction models

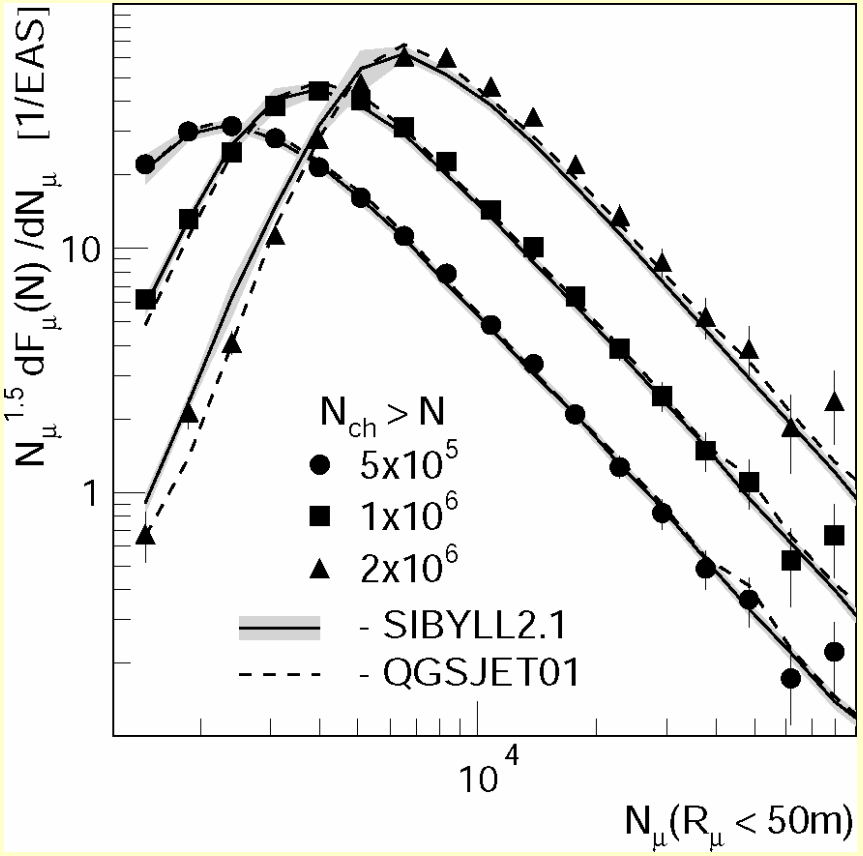


EAS size spectra for three zenith angle intervals



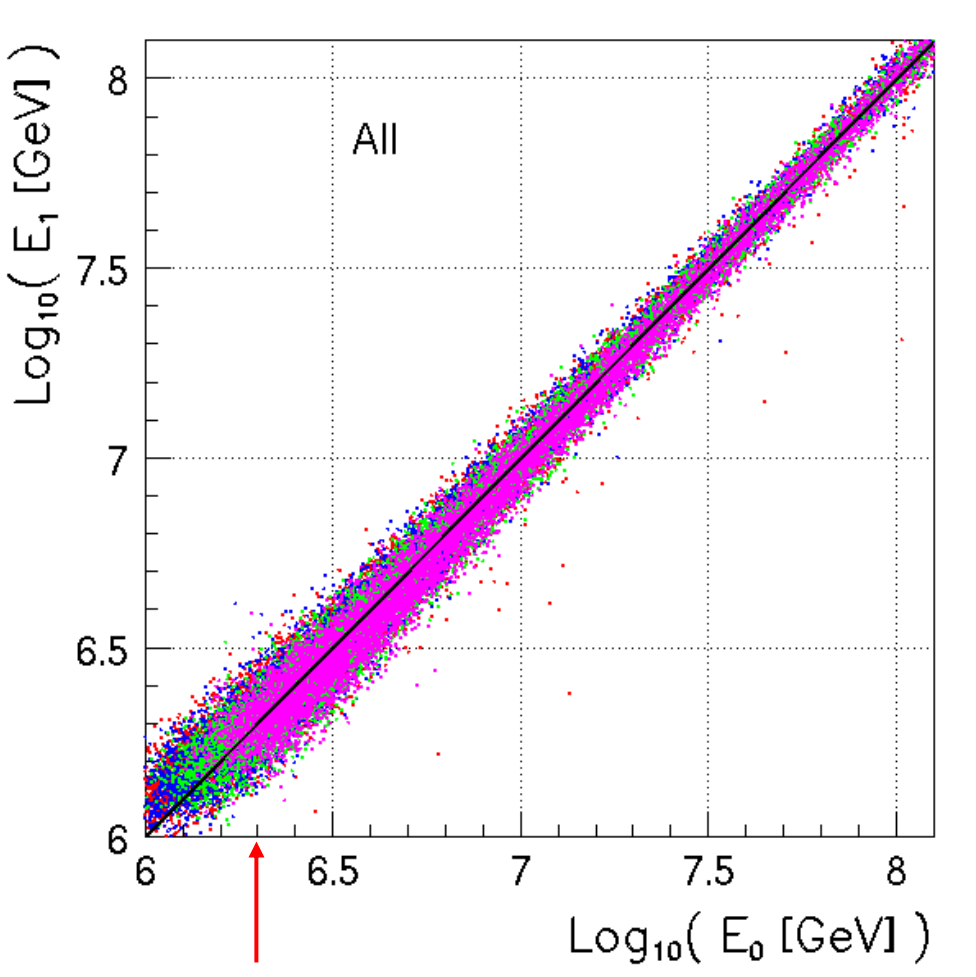
EAS truncated muon size spectra for three zenith angle intervals





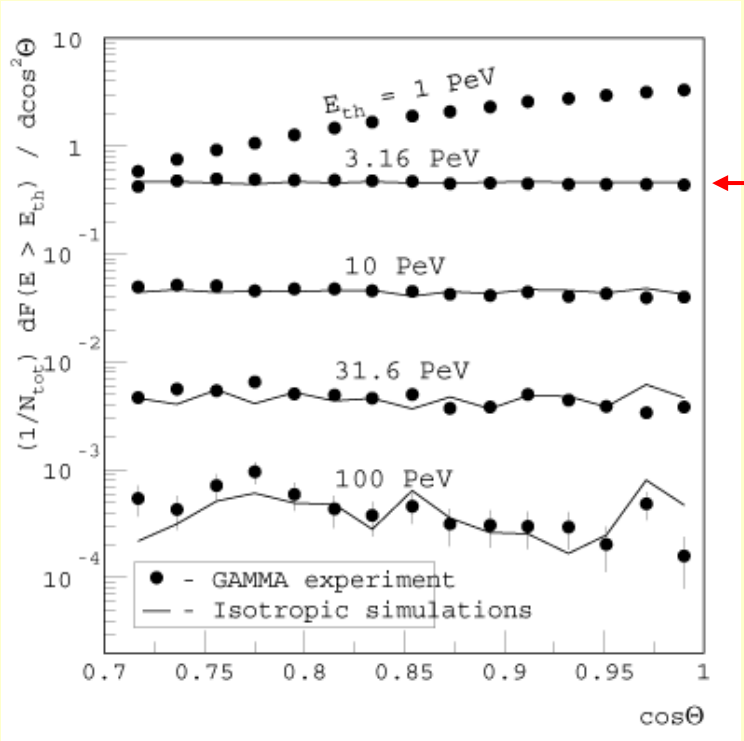
EAS size spectra for different truncated muon size thresholds

EAS truncated muon size spectra for different shower size thresholds



E_0-E_1 scatter plots of simulated primary energy E_0 and estimated energy $E_1(N_{ch},N_\mu,s,\theta)$ for 4 primary nuclei

Zenith Angular Distribution



R<50m, $\theta<45^0$

Detected zenith angular distributions for different energy thresholds. The lines correspond to simulated distributions with the same statistics.

The agreement of detected and simulated distributions gives an additional support to the consistency of energy estimations in the whole measurement range.

The anisotropic spectral behavior at low energy (less than 3 PeV) is explained by the lack of heavy nuclei at larger zenith angles.