# EAS phenomenology and cosmic ray spectrum ground based measurements

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## *Starting remarks:*

The problem of ground-based measurements is existence of a thick Earth's atmosphere:

from one side it gives an opportunity to use it as a calorimeter but,

from another side – recovery of primary particle parameters is not a simple task.

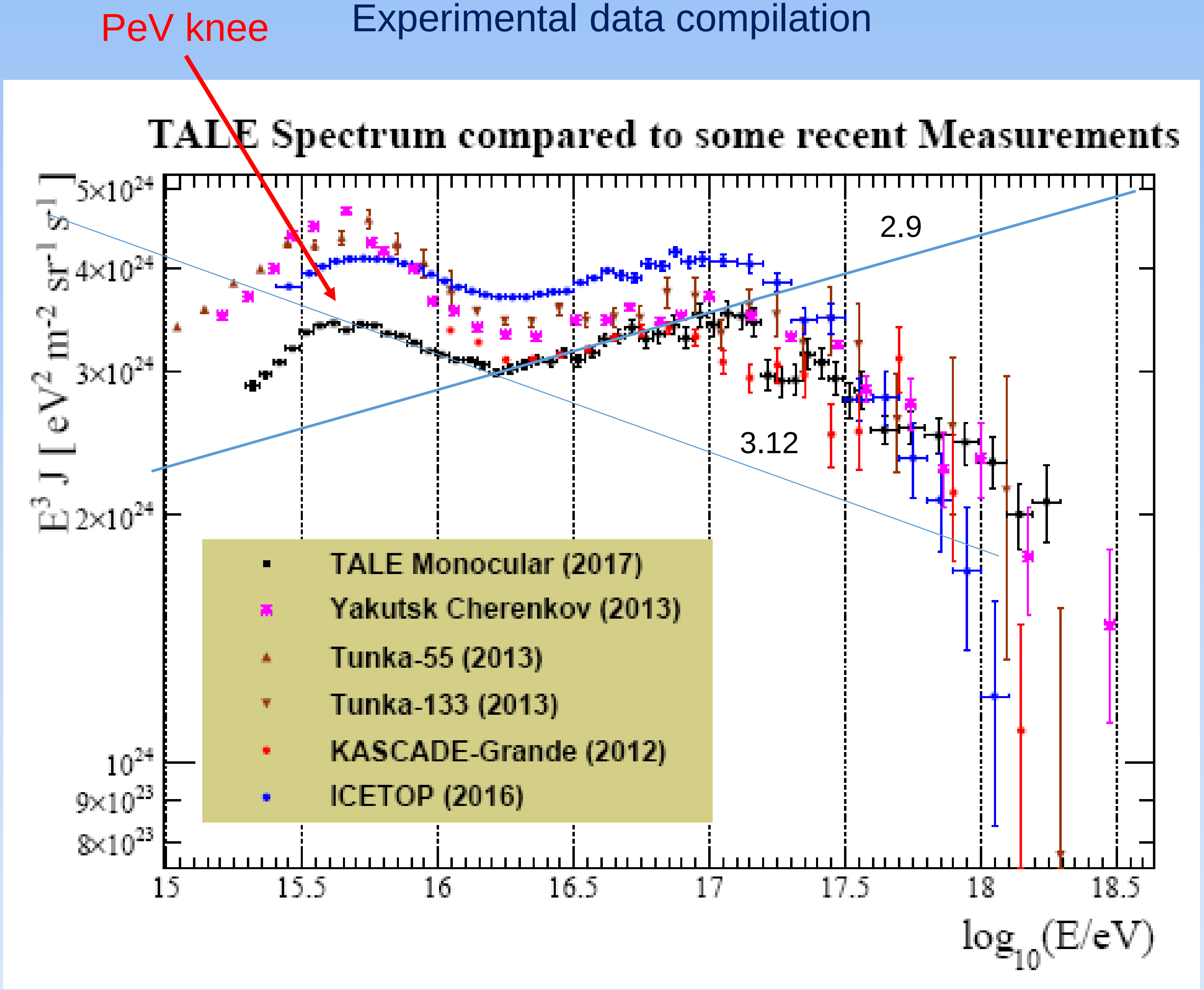
The calorimetric parameter (energy estimator) has to be known with a precise accuracy at every point of the measurable range.

In our case, when we are using a secondary EAS method and have as a rule only one point on a cascade curve, it is especially difficult task.

A question is:

where are the lower and upper energy limits of the EAS method?

# Experimental data compilation



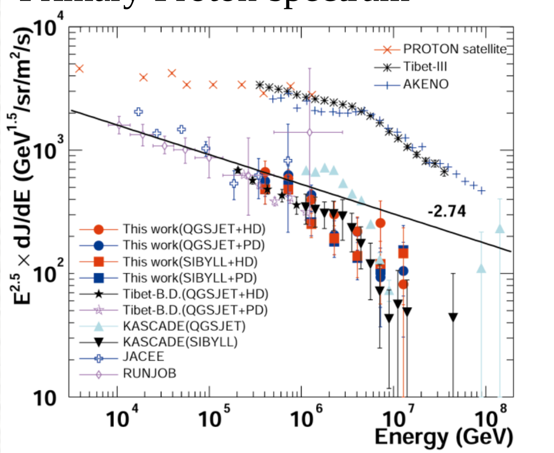

arXiv:1803.01288v1 [astro-ph.HE] 4 Mar 2018

# P, He by Tibet hybrid Experiment

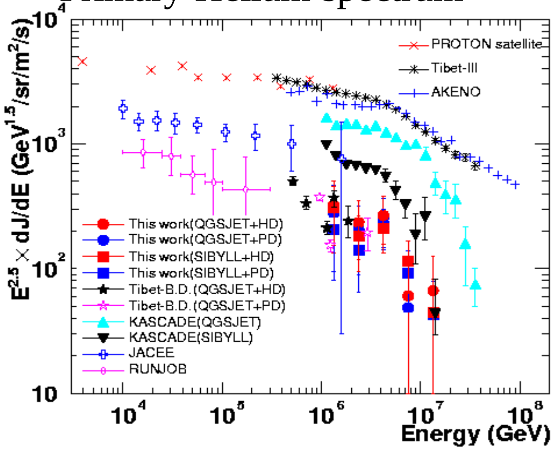


## (Phys. Lett. B, 632, 58 (2006))

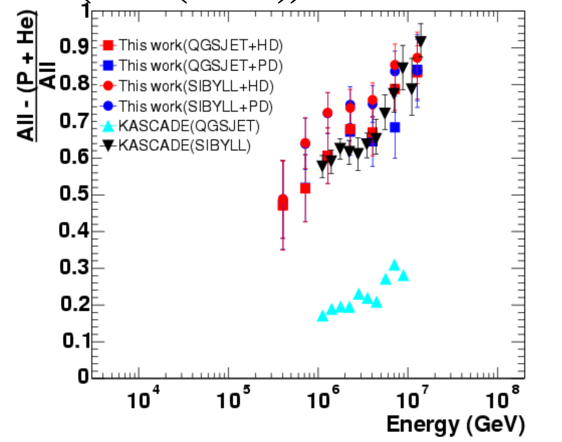
Primary Proton spectrum




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.**

The knee for light components @ 300-400 TeV?

KASCADE conclusion contradicts this:

the knee is caused by proton flux decrease above 3 PeV !

# About the cosmic-ray spectrum around the knee

M. Shibata

TibetASγ knee
for all-particle spectrum

PROCEEDINGS OF THE $31^{st}$ ICRC, ŁÓDŹ 2009

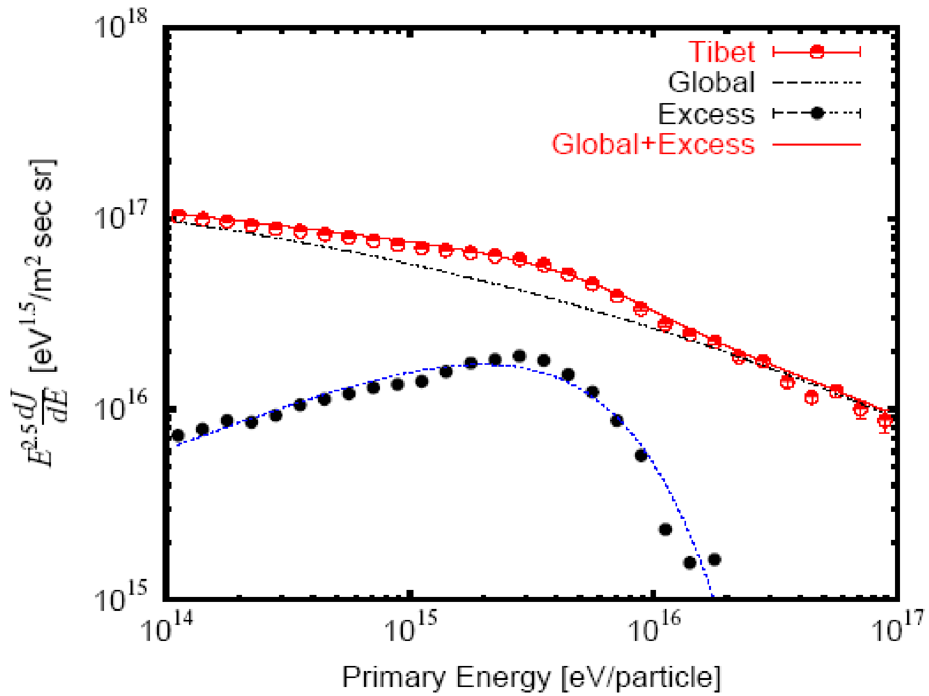



Fig. 2. All-particle spectrum around the knee. Solid line is the global component calculated by present model. Dashed line is the fit to the excess component seen in Tibet 3 data[11] which can be approximated as $f_x(E) \propto E^{-2}\exp(-E/4\mathrm{PeV})$. The dot-chained line is the sum of the global component and $f_x(E)$

# **ARGO** knee @ 700 TeV

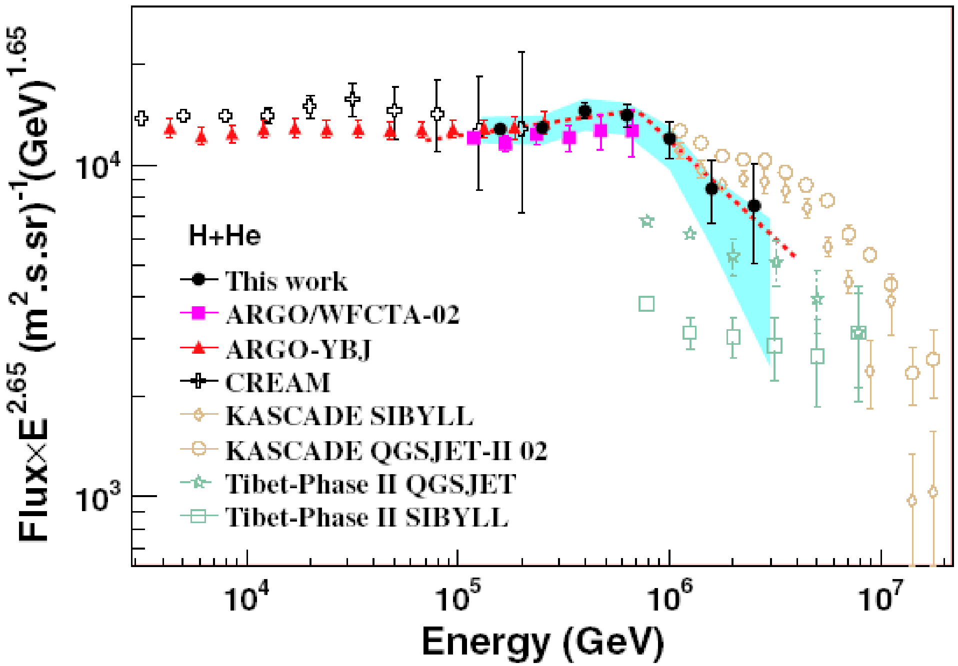



FIG. 10 (color online). H&He spectrum obtained by the hybrid experiment with ARGO-YBJ and the imaging Cherenkov telescope. A clear knee structure is observed around 700 TeV. The H&He spectra by CREAM [7], ARGO-YBJ [16] and the hybrid experiment [18] below the knee, the spectra by Tibet AS$_\gamma$ [9] and KASCADE [10] above the knee are shown for comparison. In our result, the error bar is the statistical error, and the shaded area represents the systematic uncertainty.

B. Bartoli, P. Bernardini, X. J. Bi, Z. Cao, et al.,( ARGO-YBJ Collaboration). *PHYSICAL REVIEW D* 92, 092005 (2015)

# New “knee” at 45 TeV found by **HAWC**?

R. Alfaro, C. Alvarez, J. D. Álvarez,, et al. (HAWC collaboration). *PHYSICAL REVIEW D* 96, 122001 (2017)

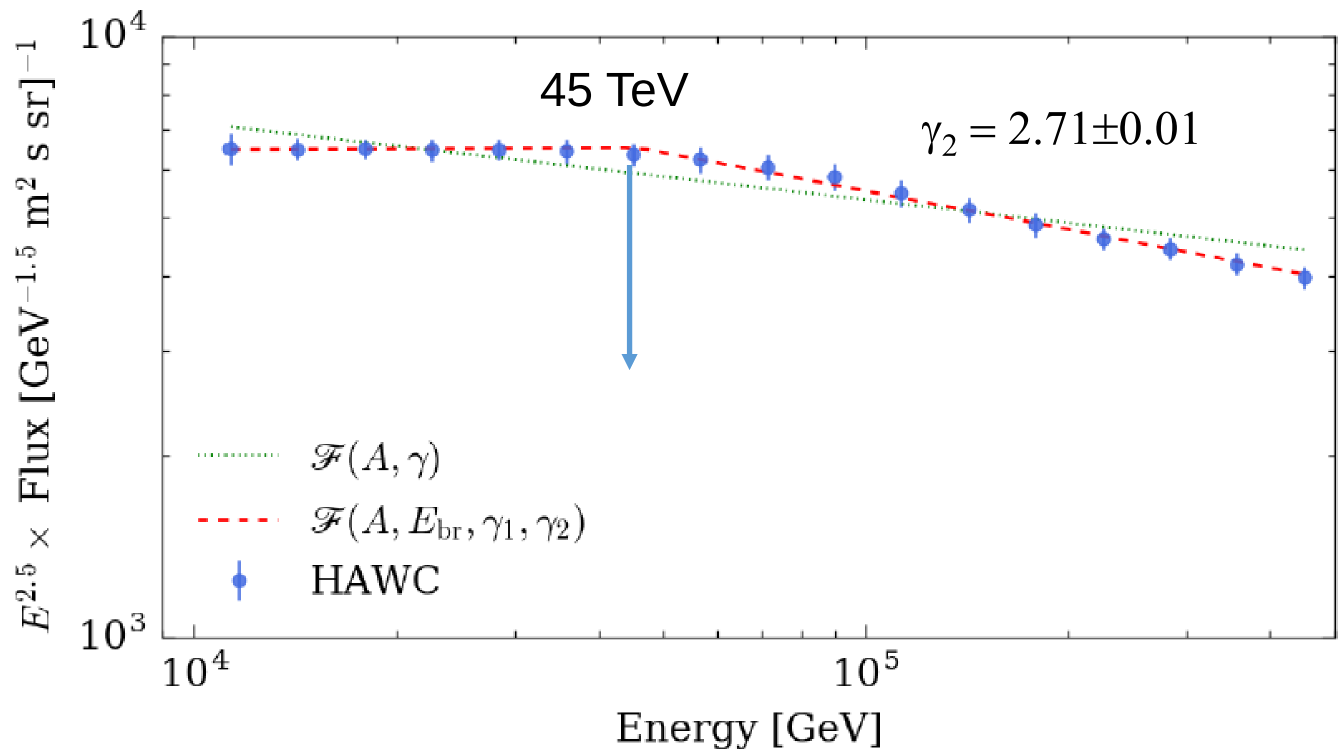



FIG. 9. Unfolded all-particle differential energy spectrum scaled by $E^{2.5}$. The uncertainties visible on the data are the systematic uncertainties from the finite size of the simulated data set, while the statistical uncertainties are smaller than the markersize. Fits to the flux using single $\mathscr{F}(A,\gamma)$ and broken $\mathscr{F}(A, E_{br}, \gamma_1, \gamma_2)$ power law forms are also shown by the dashed lines. The broken power law is favored, as for $\Delta\chi^2 = 29.2$ with a difference of two degrees of freedom gives a p-value of $4.6 \times 10^{-7}$.

# What is origin of all these “knees”?

It would be very difficult to explain the existence of all 4 “knees” between 45 TeV and 5 PeV by astrophysics nor particle interactions changes.

More probably to suppose an existence of methodical “knees” attributed to the EAS method, depending on the array altitude, on trigger conditions and on the data processing procedure.

Phenomenological approach can solve this problem.

# Historical remarks:

Up to 1949, EAS was considered as a pure e-m cascade in atmosphere.

Then George Zatsepin showed that this simplification was not true and EAS is a hadronic cascade while e-m component is produced by $\pi^0$ decays. This results in that the two components are in equilibrium and all EAS features are defined by the hadronic component being a "skeleton" of the shower. (G.T. Zatsepin, DAN SSSR, 67, 993 (1949)).

The latter means one needs to study hadronic component first of all.

But up to date people use e-m theory of cascade development (NKG function, ages, etc.) and measure mostly electronic component, sometimes muonic and very rarely hadronic one.

Up to date nobody put lower limit to primary energy when the EAS method starts working properly.

***K.Greisen. Cosmic Ray Showers. Annu. Rev. Nucl. Sci. 1960.10:63-108***

"The nuclear cascade which is the backbone of a shower is dominated by a very few high-energy particles, **sometimes only one**, in the core of the shower……, and showers of a given size are encountered at a single altitude in all stages of development."

"Since the interactions of the few nuclearactive particles carrying most of the energy are governed by chance, both in location and in distribution of energy among the secondary particles, it is only natural that large fluctuations in the energy balance should occur from one shower to another, particularly among the smaller showers, in which there is often **only a single particle of very high energy in the core**."

"Slow neutrons, from thermal energies up to one Mev, must be very abundant in the showers, but have not yet been measured."

# Therefore, 2 counclusion can be made:

1. The number of high energy hadrons Nh is small – this results in high fluctuatuons;
2. Evaporation neutrons can be measured and serve as an energy estimator.

## A simple question arises:

What will happen when Nh=0?

“Slow neutrons, from thermal energies up to one Mev, must be very abundant in the showers, but have not yet been measured.”

# Phenomenological approach

(proposed in: Yu. Stenkin. Mod. Phys. Lett. A, **18**, 1225 (2003))

The idea is:

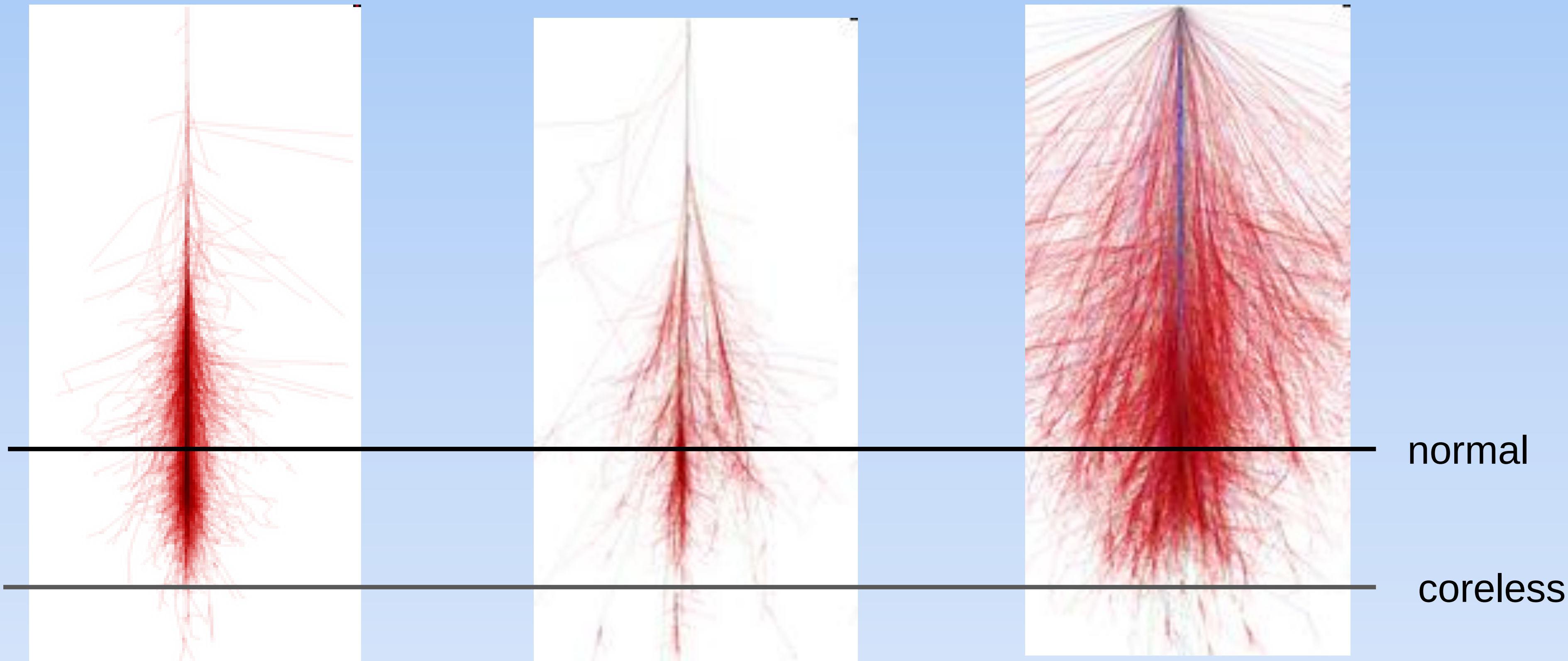
1. Primary spectrum follows power law: $F \sim E^{-\gamma}$ with a constant or smoothly changing $\gamma$.

2. The «knee» ("h-knee") visible in the EAS e-m component ($\sim N_e^{-\gamma/\alpha}$) in PeV region is caused by a break of equilibrium between the main hadronic and secondary e-m components at a point where the number of cascading hadrons becomes close **to 1** and then **to 0**, resulting in a break of $\alpha$ in a function $N_e(E_0) \sim E_0^{\alpha}$ due to changes in EAS structure and its attenuation.

3. The "knees" observed in subPeV region could be explained by the change of $\alpha$ due to different probability for e-m particles to reach the detector level below and above these points depending on mass A.

# CORSIKA showers:

Photon Proton Iron




Compiled by Fabian Schmidt, University of Leeds, UK.

# What do ground based detectors measure?

Primary spectrum $I \sim E^{-\gamma}$

Secondary component (energy estimator) $N_x \sim E^{\alpha}$

→ $I \sim N_x^{-\beta}$

$\beta = \gamma/\alpha$ measured slope

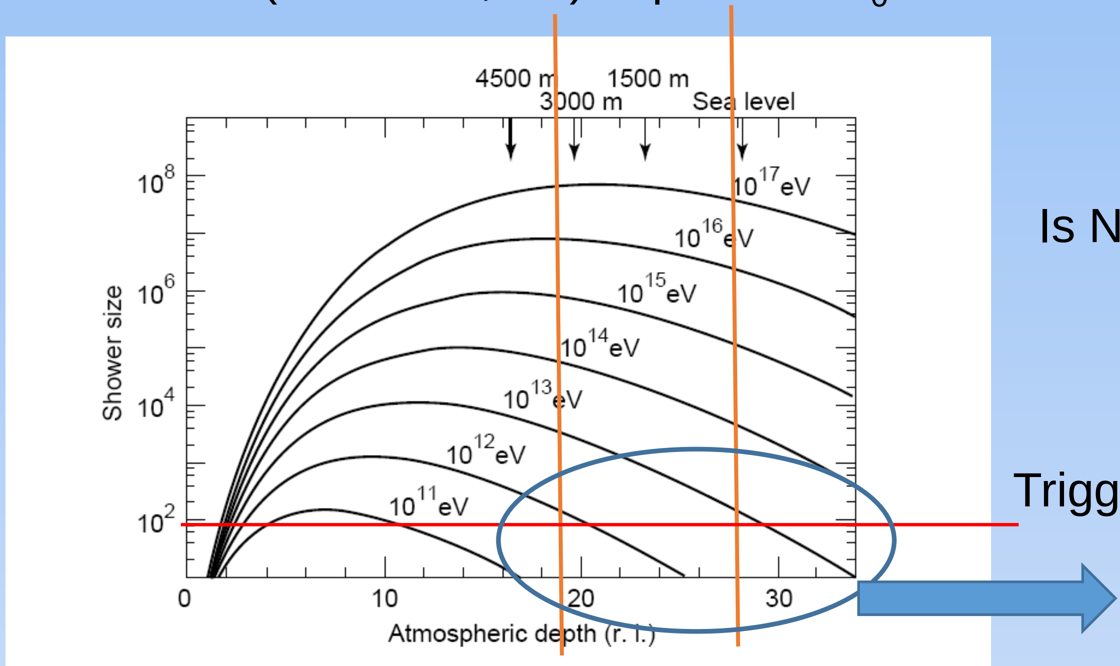
$\beta_e = \gamma/\alpha_e = 1.7/1.1 \approx 1.5$

$\beta_h = \gamma/\alpha_h = 1.7/0.9 \approx 1.9$

Difference between normal and coreless EAS' results in:
"knee", $\Delta\beta \approx 0.4$

Nota bene: $\alpha_\mu = \alpha_h < 1$ while $\alpha_e > 1$
(these parameters depend on experimental details)

How does energy estimator Ne (ionization, etc) depend on $E_0$? – this is the main question




Is Ne ~ $E^\alpha$ or not?

*Stenkin Yu.V. Physics of Atomic Nuclei, 2008, Vol. 71, No. 1, pp. 98–110:*

$$\alpha = d(\ln(N_e(E_0))/d(\ln(E_0)) \approx \delta + 30.5/\Lambda_{att}$$

$\delta$ – slope in $Ne_{max}$ (E0) ~ $(E_0)^\delta$    30.5 – alongation rate  and $\Lambda_{att}$ is attenuation length

*$\alpha$ >1 only after the maximum and $\alpha$<1 before the maximum (at high altitudes)!*

Therefore, *$\alpha \neq$ const in a wide energy range* even if $\Lambda_{att}$ =const

The latter makes the EAS method non universal and depending on many parameters

# M-C simulation made in a wide energy range (CORSIKA 6.90)

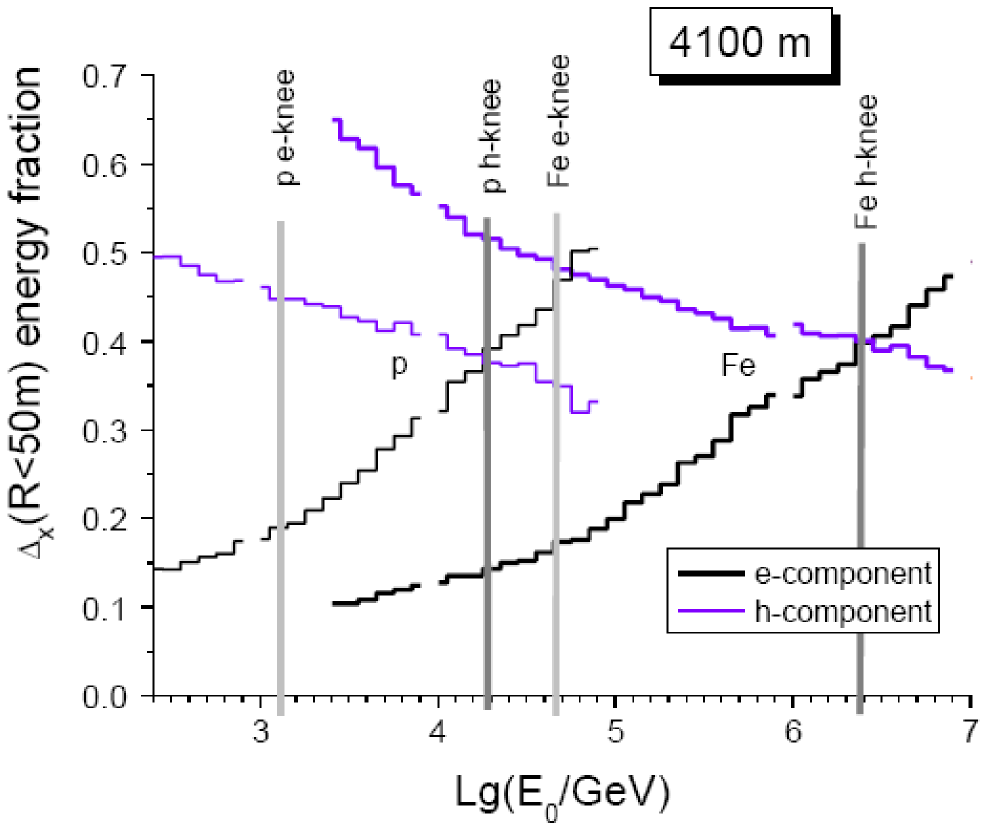



Fig. 1. EAS energy fraction inside a ring of 50 m radius carried by hadronic and electromagnetic components at 4100 m above sea level as a function of primary energy.

# M-C: secondary e-m component vs primary energy (CORSIKA 6.90 + CORSIKA 7.56)

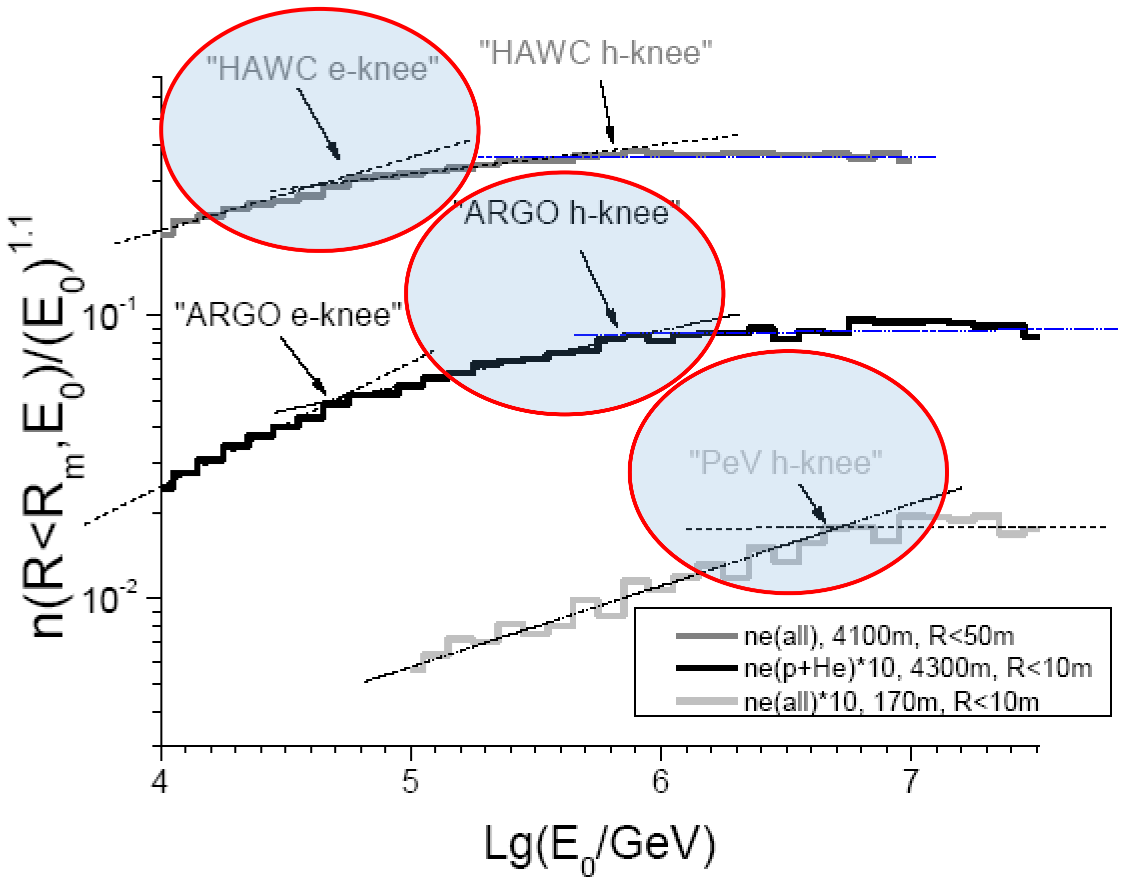
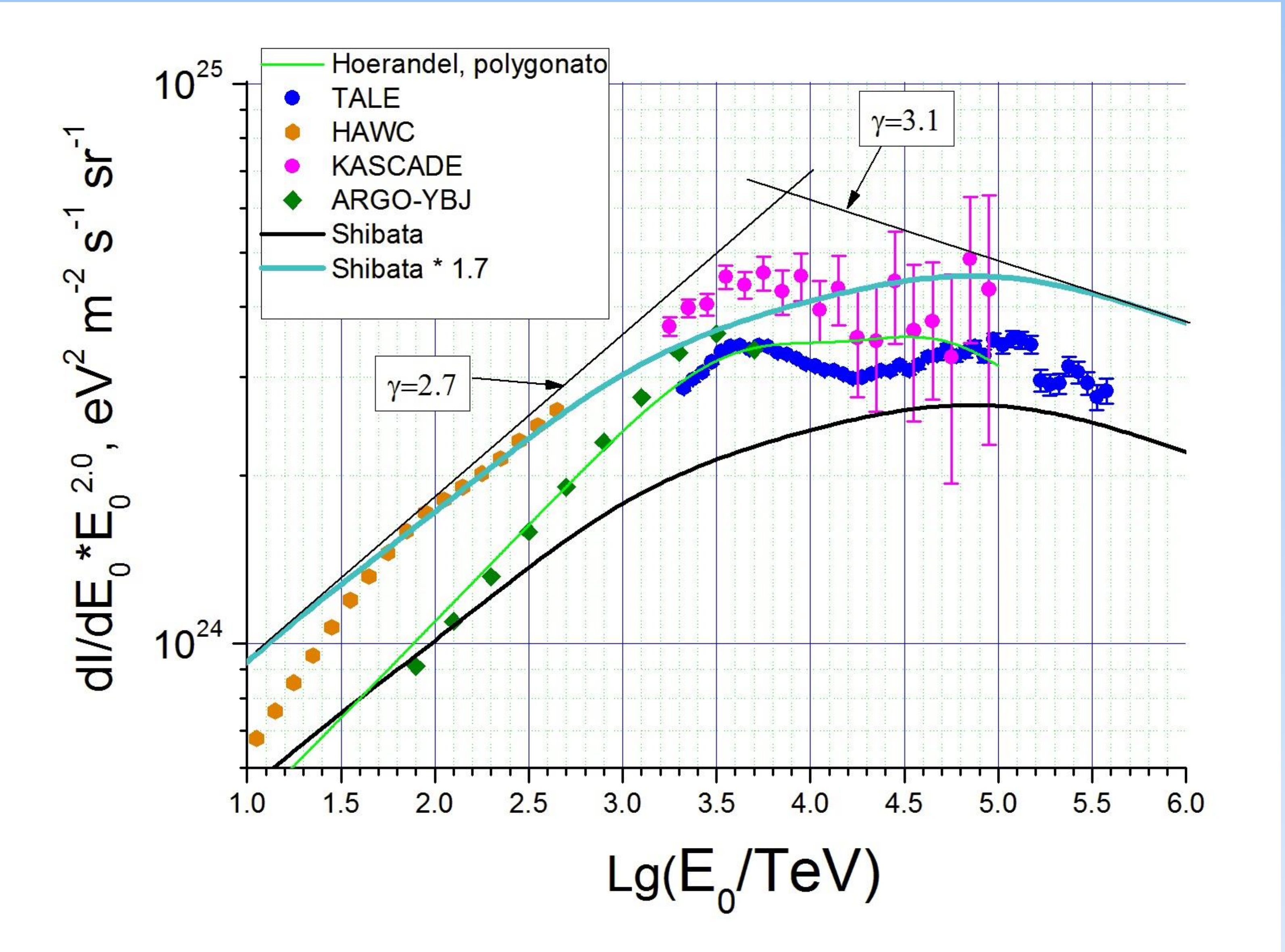


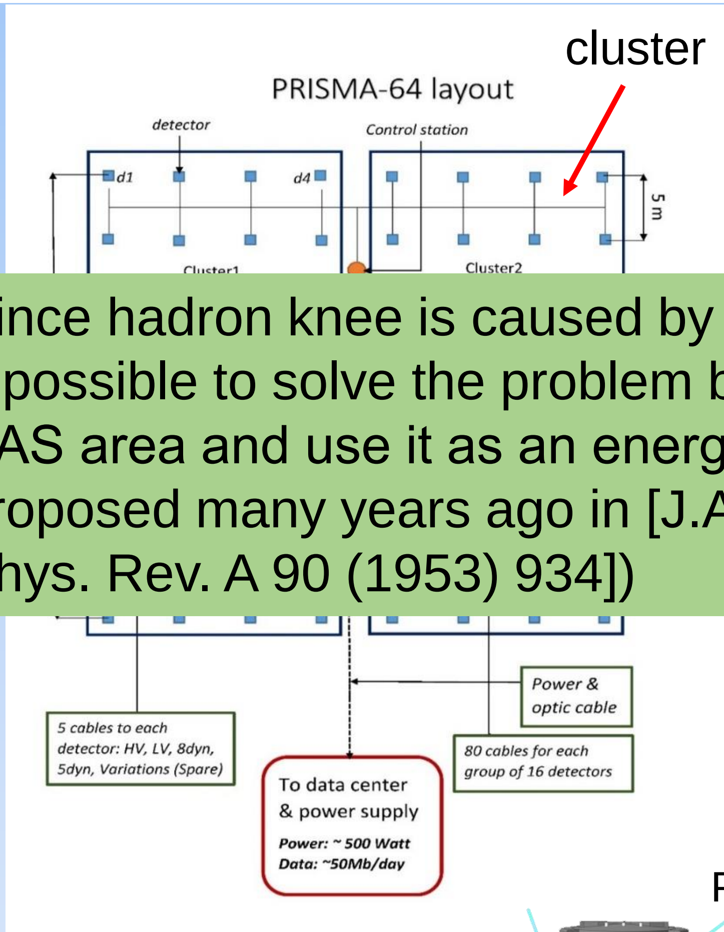

Fig. 2. Number of electromagnetic particles inside a ring of $R_m$ radius divided by $E_0^{1.1}$ as a function of primary energy for 3 different altitudes: sea level, 4100 m and 4300 m.

## Experimental data compilation and expectation

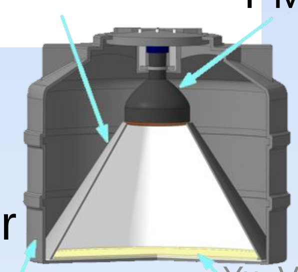


The array of 64 en-detectors (4 clusters) under construction in conjunction with LHAASO project

# PRISMA-LHAASO (ENDA)




Since hadron knee is caused by appearance of hadrons at the detector level, It possible to solve the problem by measuring hadronic component over whole EAS area and use it as an energy estimator (a kind of "Neutron calorimeter" proposed many years ago in [J.A. Simpson, W. Fongen, S.B. Treiman, Phys. Rev. A 90 (1953) 934])

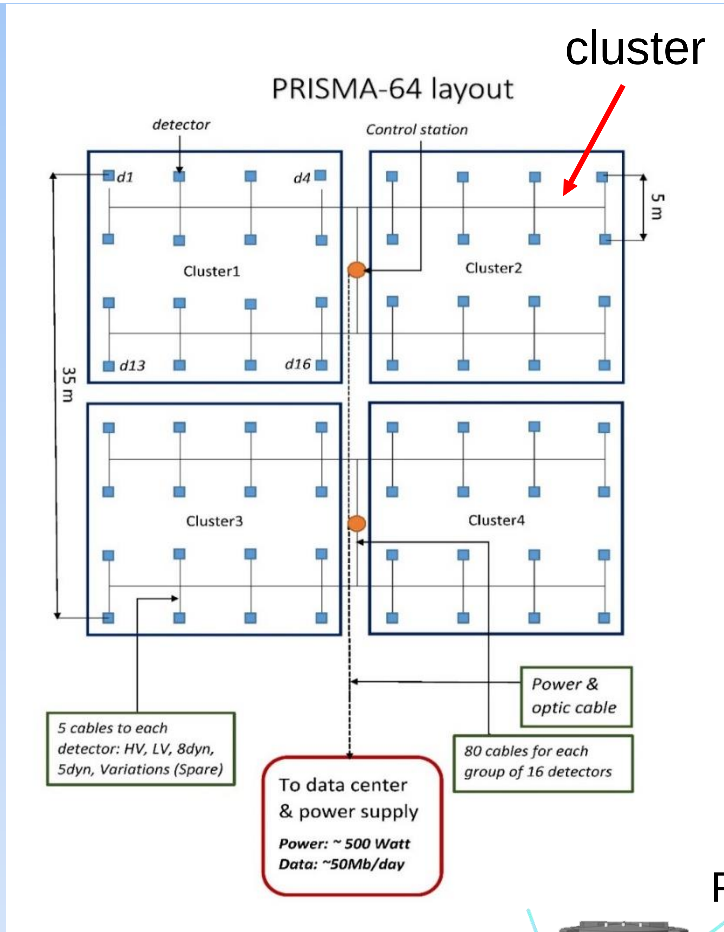



Electron Neutron Detector Array

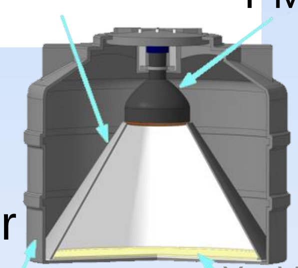
# PRISMA-LHAASO (ENDA)

The array of 64 en-detectors (4 clusters) under construction in conjunction with LHAASO project

cluster




PMT



En-detector

ZnS(Ag)+B2O3

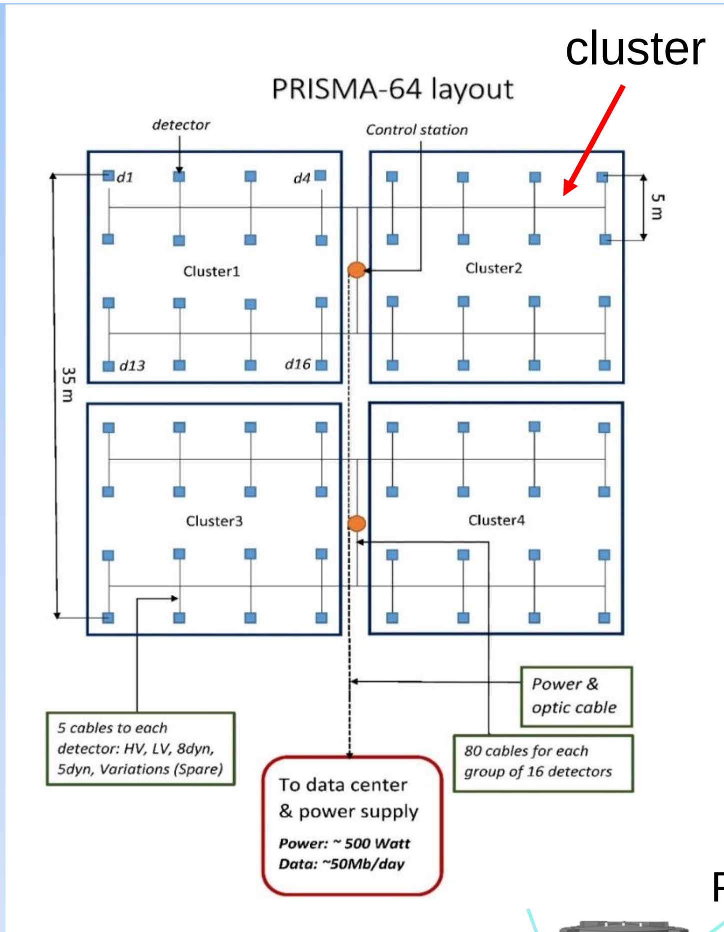
Electron Neutron Detector Array

# PRISMA-LHAASO (ENDA)

The array of 64 en-detectors (4 clusters) under construction in conjunction with LHAASO project

Future plan: 400 en-detectors (25 clusters)

cluster

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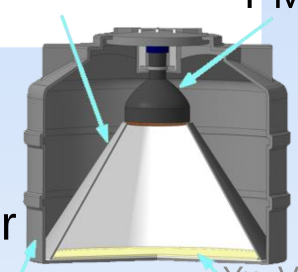
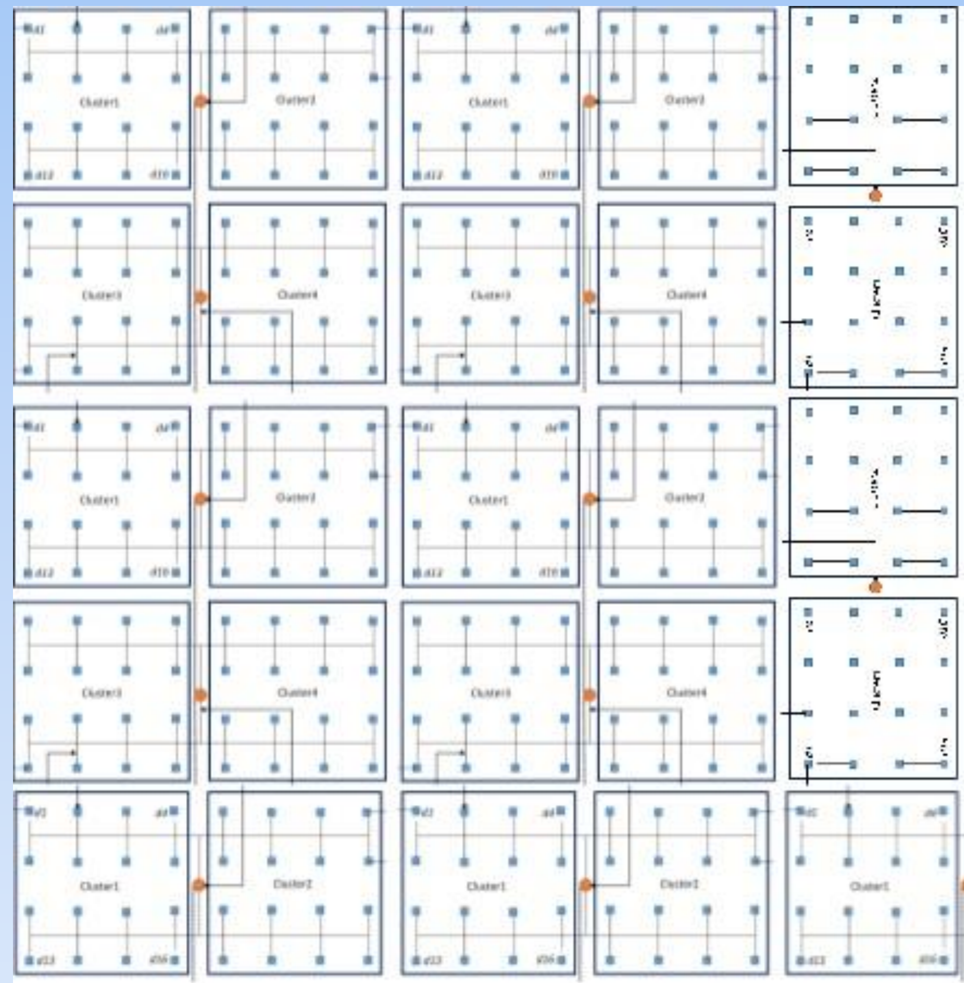


En-detector

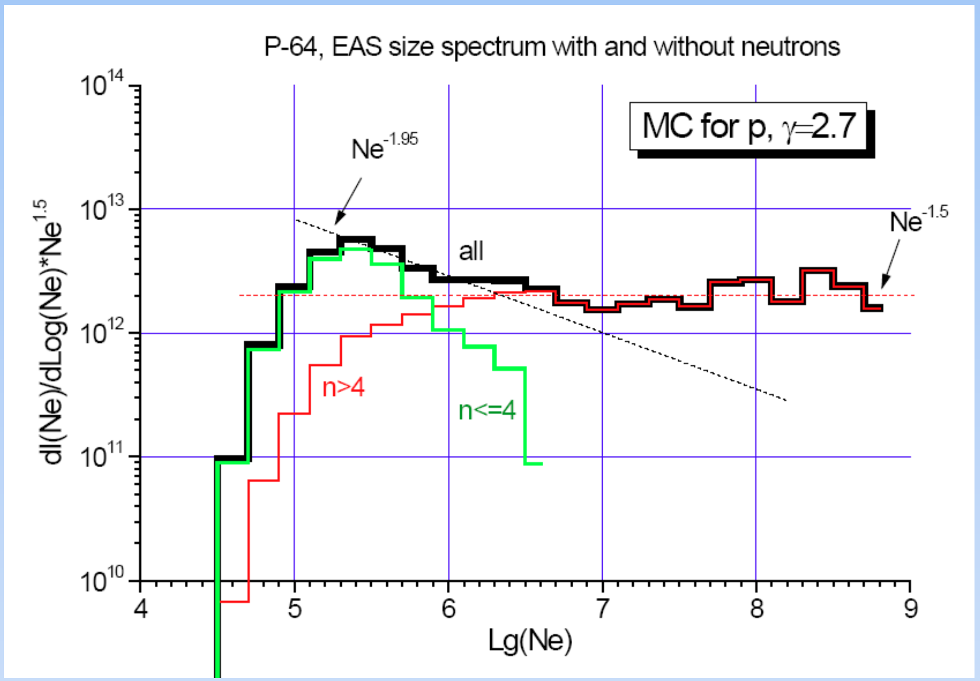
ZnS(Ag)+B2O3

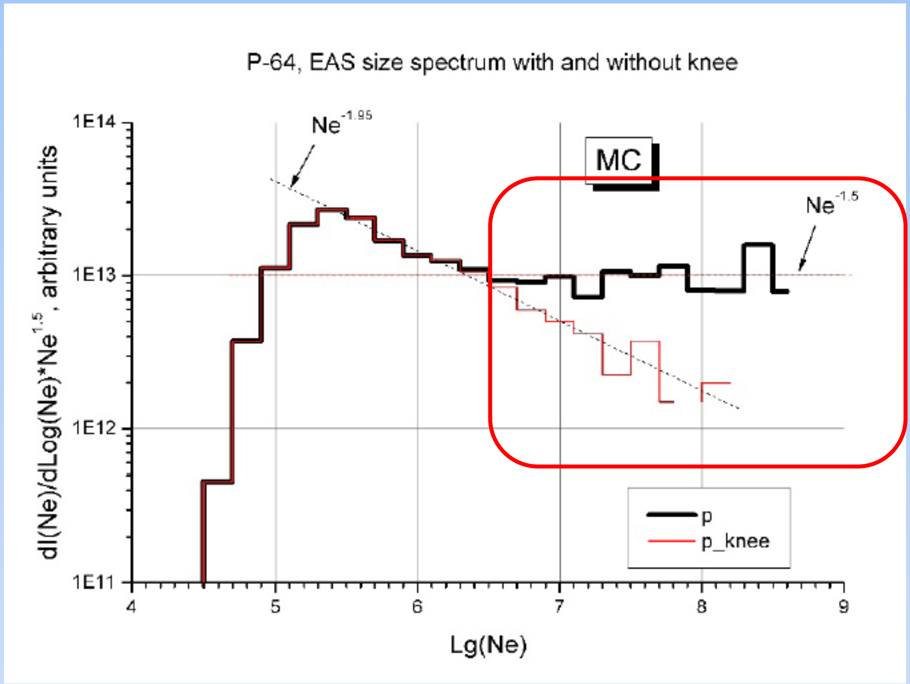


Electron Neutron Detector Array

# Simulation for PRISMA-64: EAS size spectrum for γ=2.7, 4300 m a.s.l.

Yu V Stenkin and O B Shchegolev 2019 *J. Phys.: Conf. Ser.* **1181** 012021




No "knee" in events with neutrons (hadrons). The bump in PeV region Is produced by *coreless* (*neutronless*) showers

Only above Ne~$10^{6.5}$ EAS method gives correct result

# Conclusion

- The “knees” in EAS size spectra are probably the features of EAS phenomenology – even at a power law spectrum, its specific behavior can produce systematic “knees”, depending on altitude of observation and on the experimental conditions.
- Conventional EAS method gives correct result only above Ne ~ $10^{6.5}$, i.e. well above the PeV “knee” where equilibrium between EAS components is reached.
- How to solve the problem:
- 1). in PeV region:
  - ➢ record hadronic component over full array area using it as an energy estimator (the easiest way),
  - ➢ make very careful simulations and take into account that recalculation from Ne (or other secondary parameter) to $E_0$ gives a non power law function. No extrapolations!

2) in TeV region:

➢ ground based: make very careful simulations and take into account that Ne (or other secondary parameter) dependence vs $E_0$ gives a non power law function.

- ➢ make measurements beyond atmosphere using direct methods

# Thank you!

# Simulation for PRISMA-64: EAS size spectrum for γ=2.7, 4300 m a.s.l.

Yu V Stenkin and O B Shchegolev 2019 *J. Phys.: Conf. Ser.* **1181** 012021