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# Results and prospects on registration of reflected Cherenkov light of EAS from cosmic particles above $10^{15}$ eV

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PANIC-2014, Hamburg

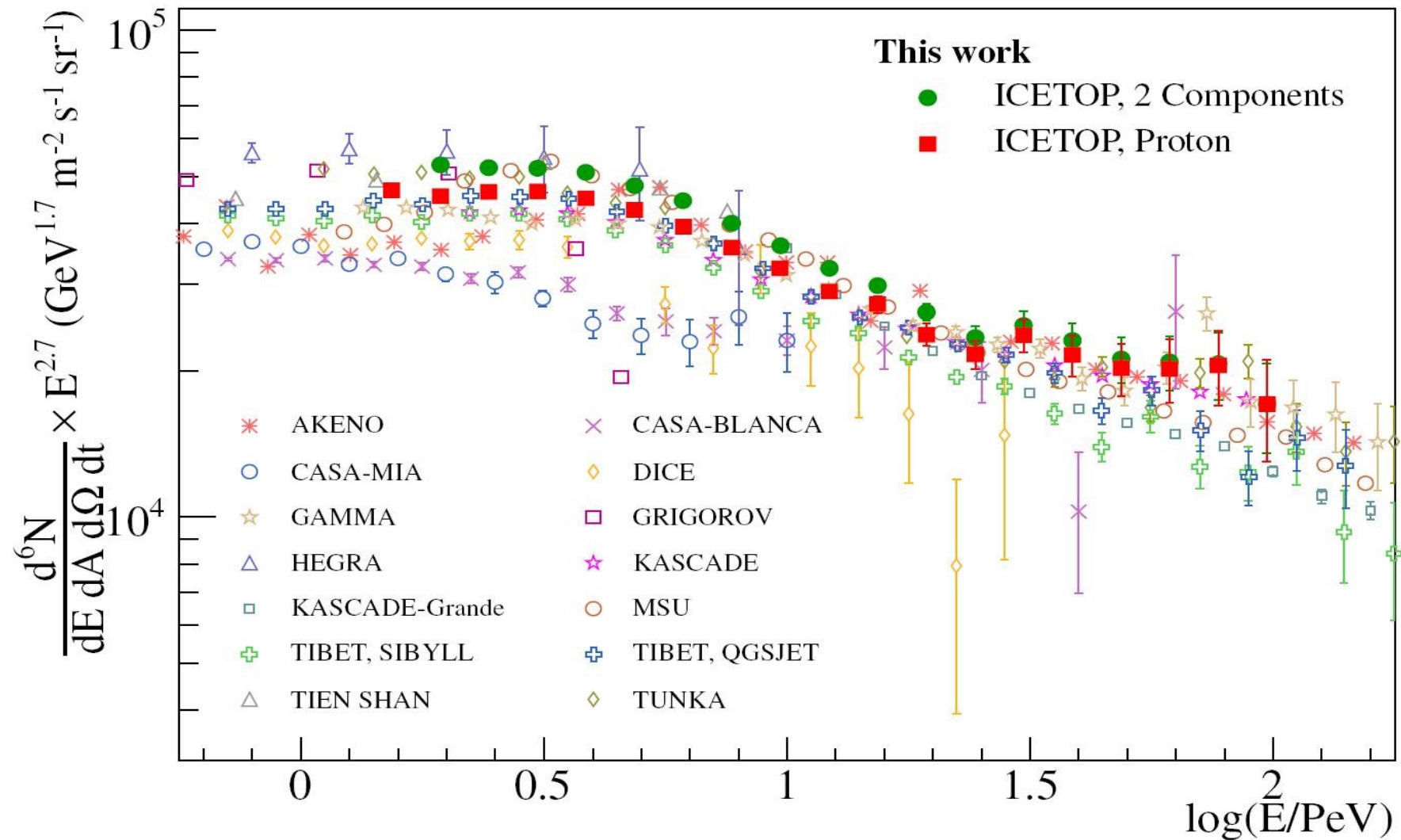


# Contents

1. Some experimental results on the all-particle CR spectrum and nuclear composition.
2. The reflected optical Vavilov-Cherenkov radiation (“Cherenkov light”) method; development of the technique over the last 30 years.
3. The SPHERE-2 detector and the Working Group.
4. Reconstruction of the all-particle spectrum and composition. Systematic uncertainties.
5. Prospects.
6. Conclusions.

This talk is mostly based on the extensive (~60-page) paper: R.A. Antonov et al., Phys. Part. Nucl., **1**, (2015) (In press).

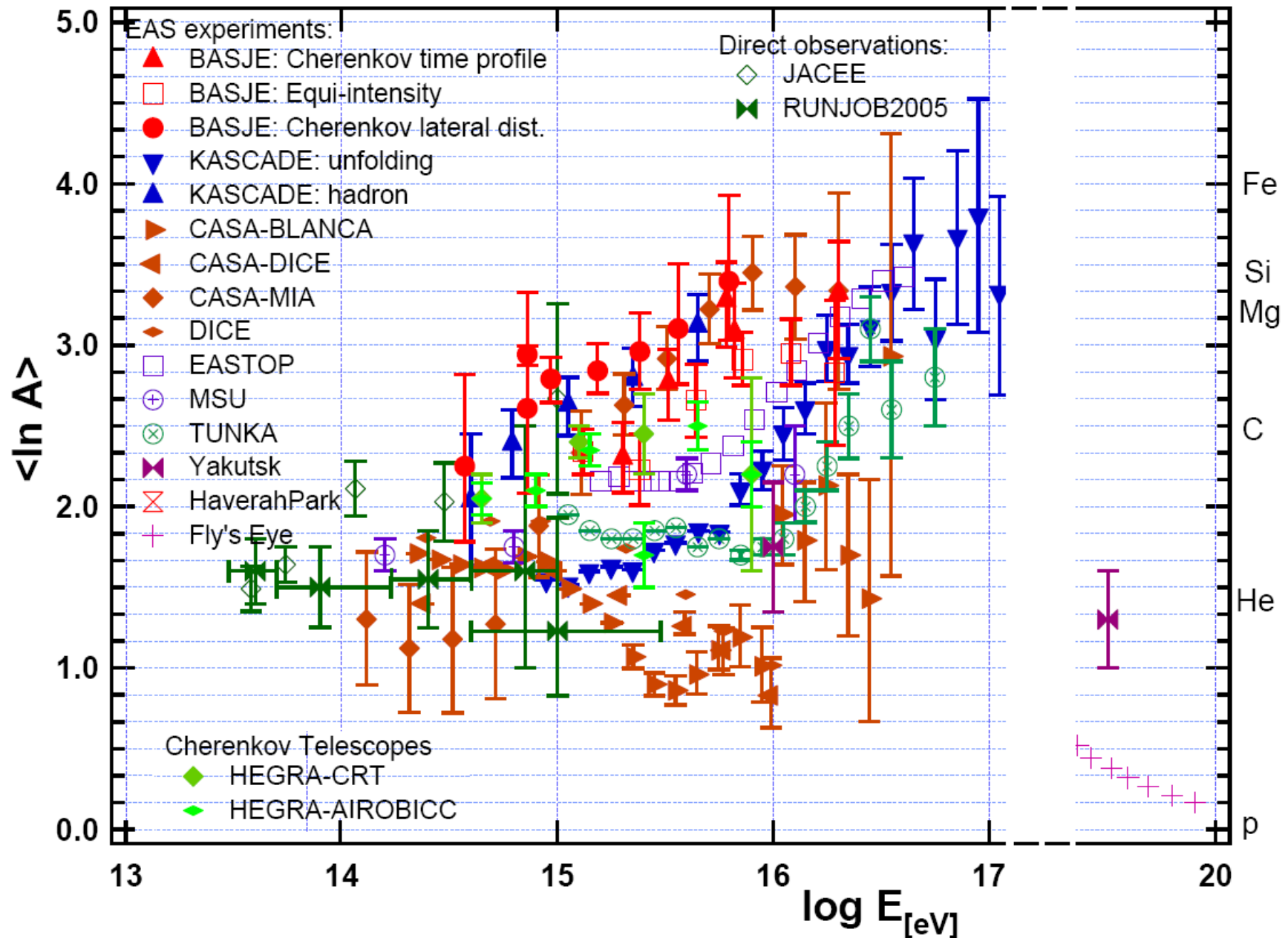
(Some) experimental results on the all-particle CR spectrum  
(R. Abbasi et al. (ICETOP) 2012 (astro-ph/1202.3039))



Dependence of the reconstructed intensity on nuclear composition may introduce systematic uncertainty of the the all-particle CR spectrum.  
For some EAS techniques this uncertainty is up to ~20-30 %.

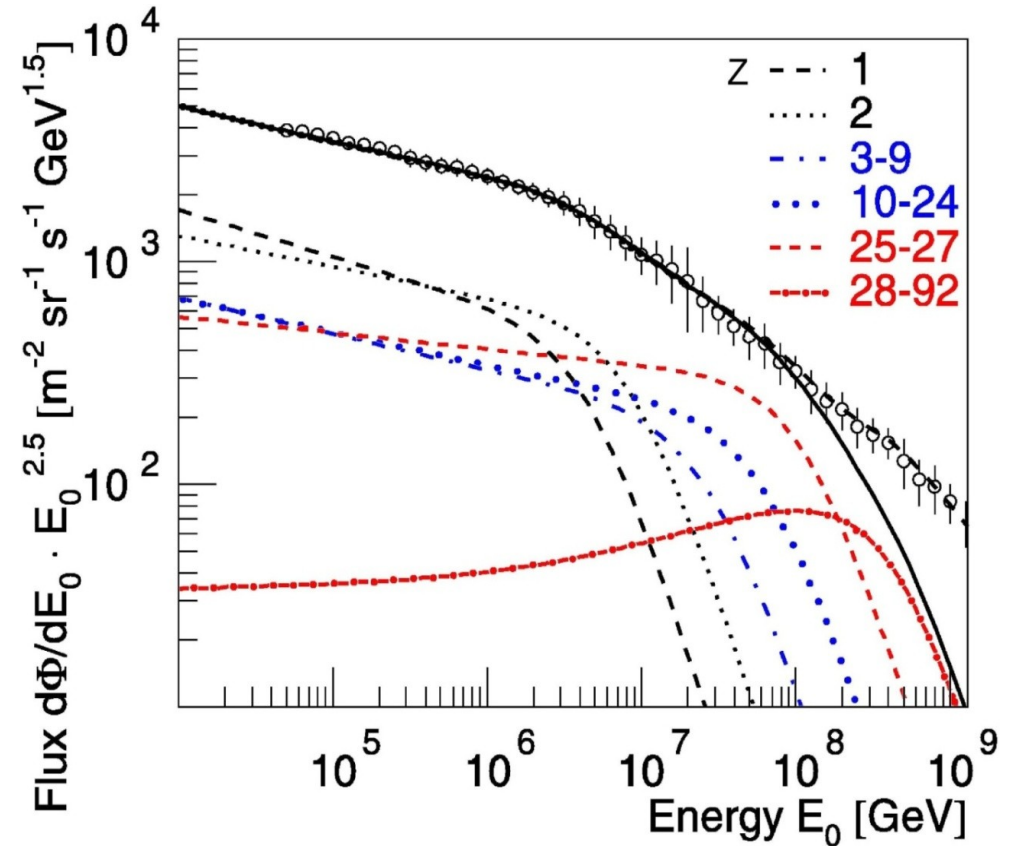
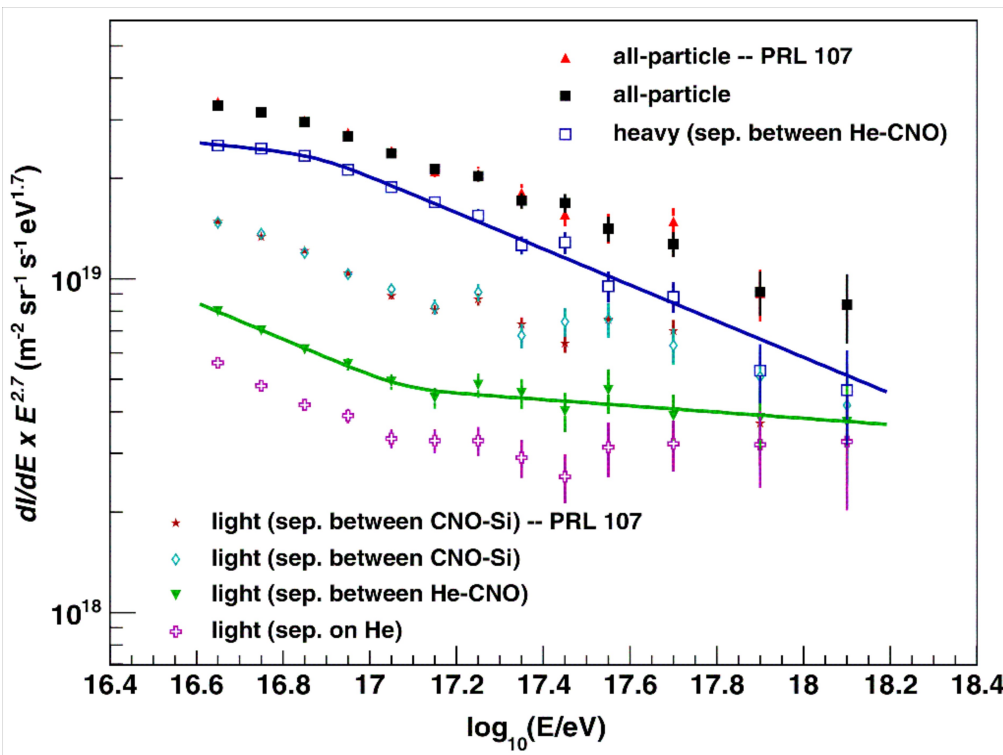


Primary composition (Y. Tsunesada et al. (BASJE),  
 Proc. 30<sup>th</sup> ICRC, 4, 127 (2008)). Newer review: K.-H. Kampert  
 & M. Unger, APh, 35, 660 (2012) (see slides 22-23)



W. D. Apel et al. (KASCADE-Grande),  
Phys. Rev. D 87, 081101(R) (2013)

End of Galactic CR spectrum (model):  
J. Hoerandel, APh, **19**, 193 (2003)



The simplest assumption would be that the extra component above 100 PeV is composed of **extragalactic protons** (e.g. V.S. Berezhinsky et al., Phys. Rev. D 74, 043005 (2006))  
→ very light composition at 1000 PeV

# The reflected Cherenkov light method

Introduced by A.E. Chudakov: Proc. All-USSR Symp. on Exp. Meth. of UHECR (Yakutsk) (In Russian), 69 (1974).

First detection: C. Castagnoli et al., Proc. 17<sup>th</sup> ICRC, **6**, 103 (1981) (experiment in mountains, “sliding geometry”).

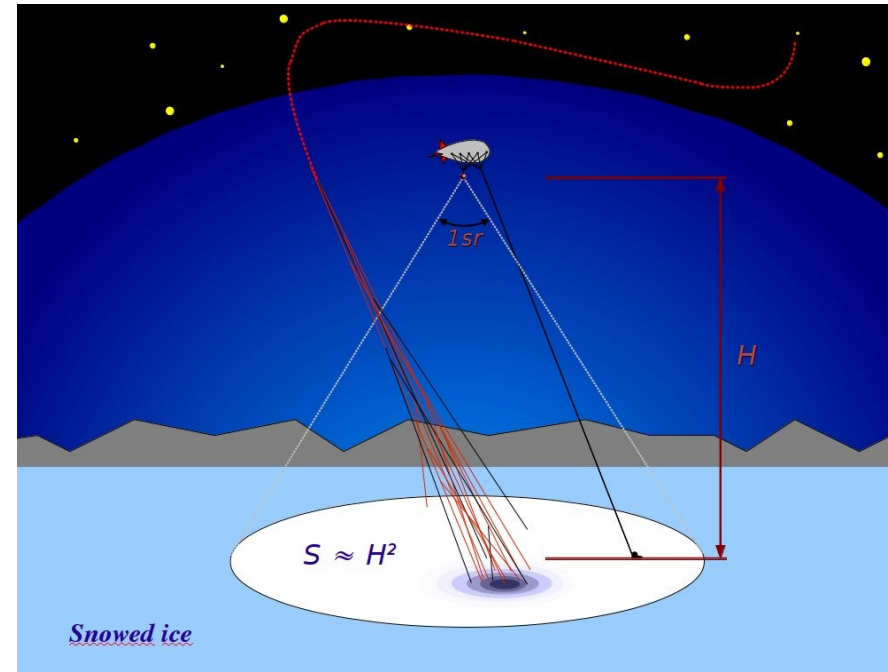
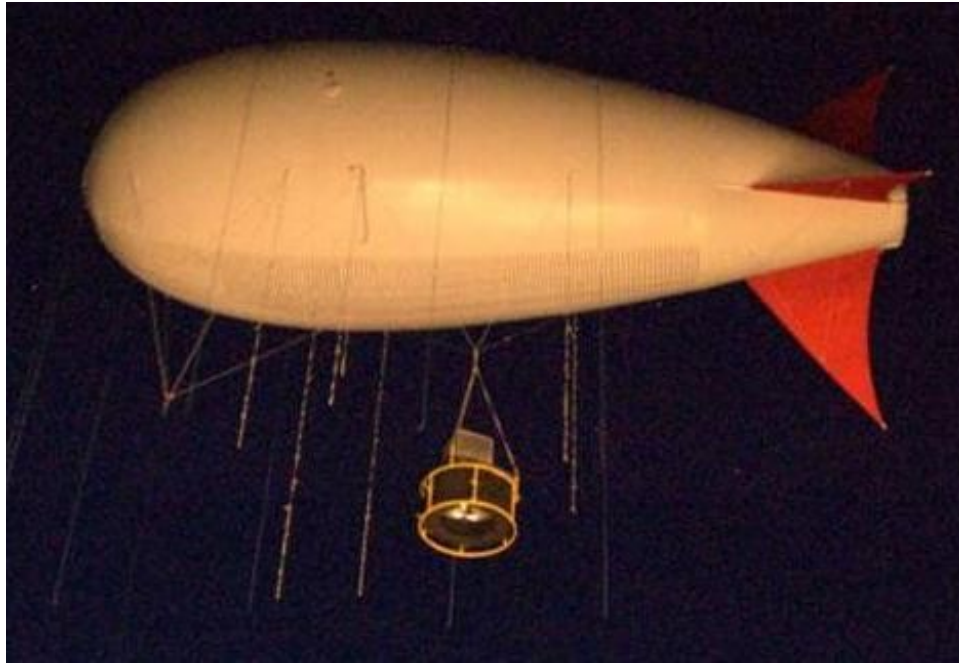
Further development:

1. R.A. Antonov et al., Proc. 14<sup>th</sup> ICRC, **9**, 3360 (1975); R.A. Antonov et al., SINP MSU Preprint (1995) (The SPHERE-1 detector prototype, “sliding geometry”).

2. R.A. Antonov et al., Proc. 27<sup>th</sup> ICRC, **1**, 59 (2001) (The SPHERE-1 balloon-borne experiment with mosaic of 19 PMTs).

3. The SPHERE-2 detector: mosaic of 109 PMTs, 12.5 ns sampling. Currently the most advanced experiment (both hardware and analysis) utilizing the reflected Cherenkov light method.

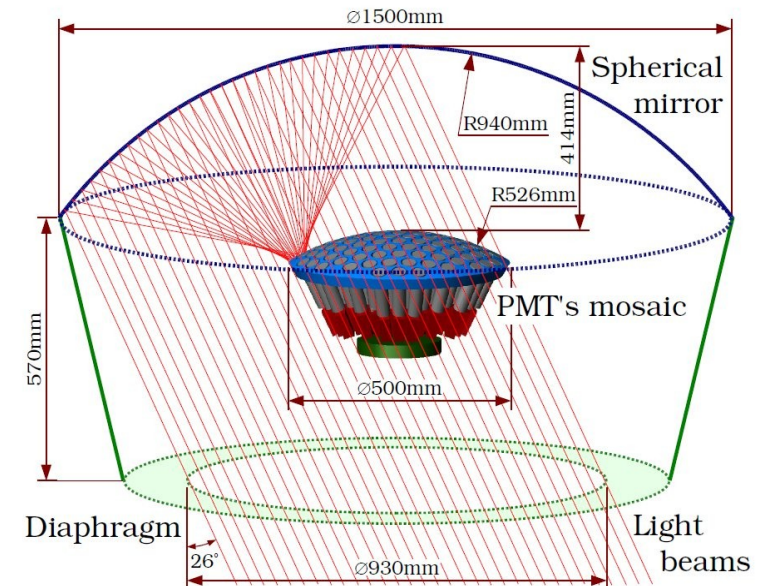
# The SPHERE-2 balloon-borne detector



$H = 200\text{--}900\text{ m}$ ,  $T_{\text{EXP}} \approx 130\text{ h}$

2008-2009: test flights; only sporadic  
EAS observed

2010-2013 (February-March)  
(4 upgrades):  $\sim 30$  hours of  
exposition/year;  
about 1100 EAS in total





# The SPHERE-2 Working Group

Our main task: study of the primary spectrum and composition at  $E = 10 \text{ PeV} - 1 \text{ EeV}$  using Cherenkov light of EAS reflected from the snow surface of Lake Baikal

Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (Moscow):

R.A. Antonov, T.V. Aulova, E.A. Bonvech, D.V. Chernov, T.A. Dzhatdov, T.M. Roganova

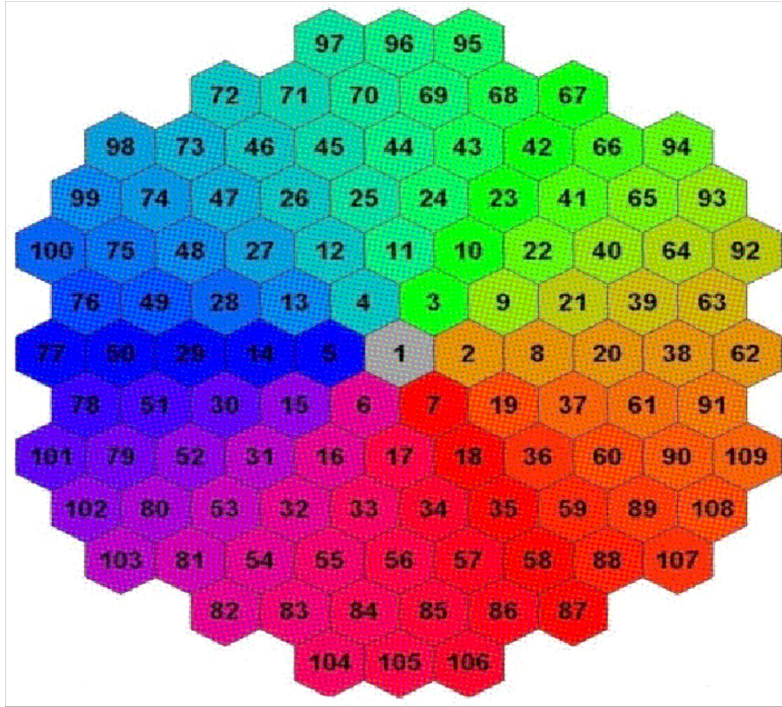
Lebedev Physical Institute of the Russian Academy of Sciences (Moscow): S.P. Beschapov, N.V. Kabanova, A.S. Petkun, S.B. Shaulov, T.I. Sysoeva

Charles University, Prague, Czech Republic: Mir. Finger, Mix. Finger:  
MSU Physics Department (Moscow): V.I. Galkin, D.A. Podgrudkov  
+ valuable contributions from our technical collaborators!

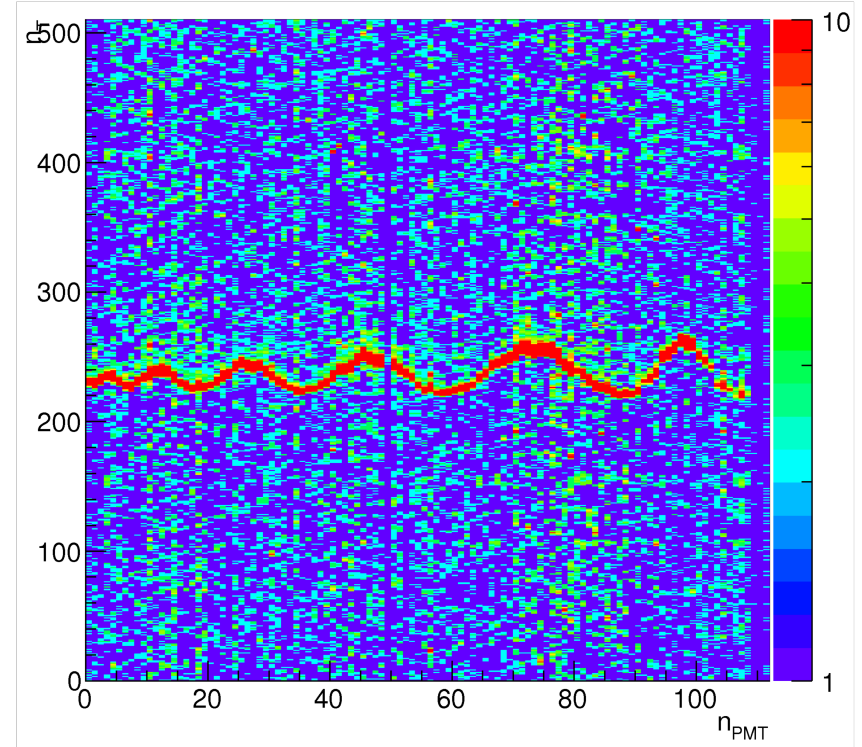
e-mail: [chr@dec1.sinp.msu.ru](mailto:chr@dec1.sinp.msu.ru) (hardware), [timur1606@gmail.com](mailto:timur1606@gmail.com) (analysis)

<http://sphere.sinp.msu.ru/>

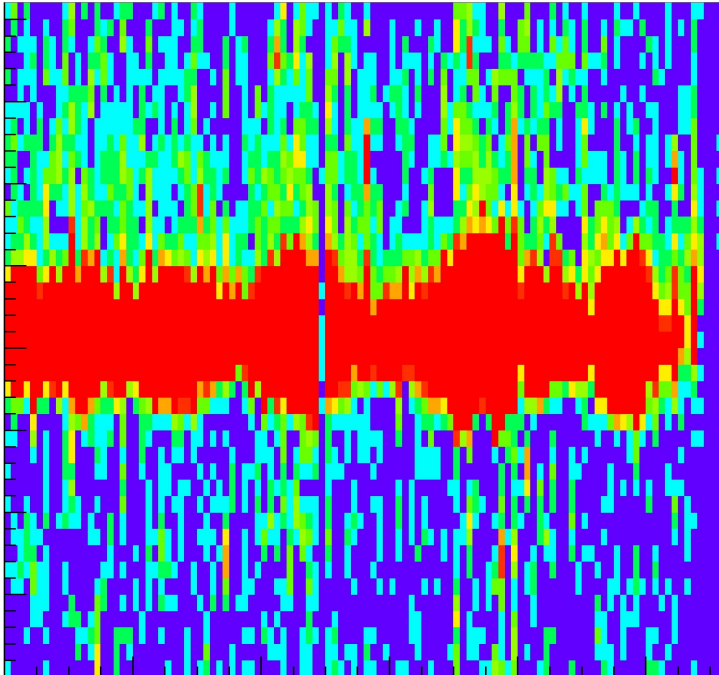
# Low-level experimental data analysis



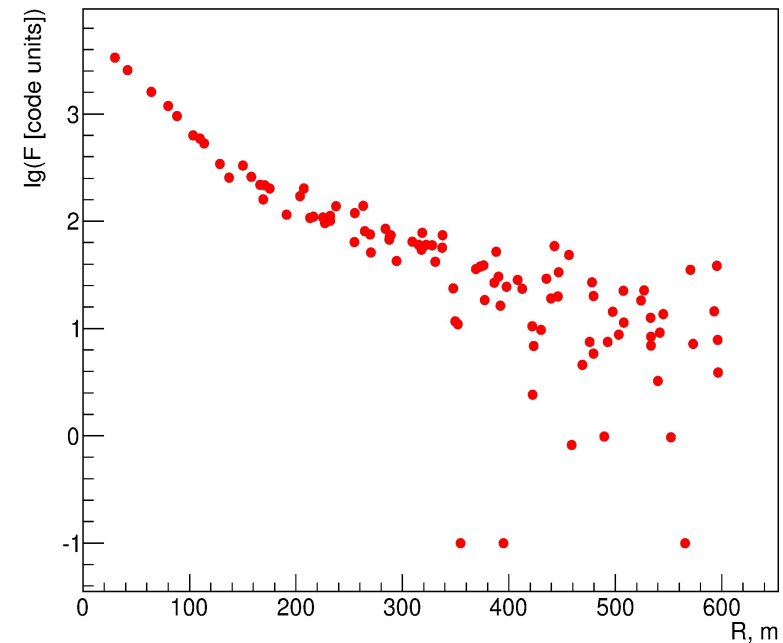
a)



b)

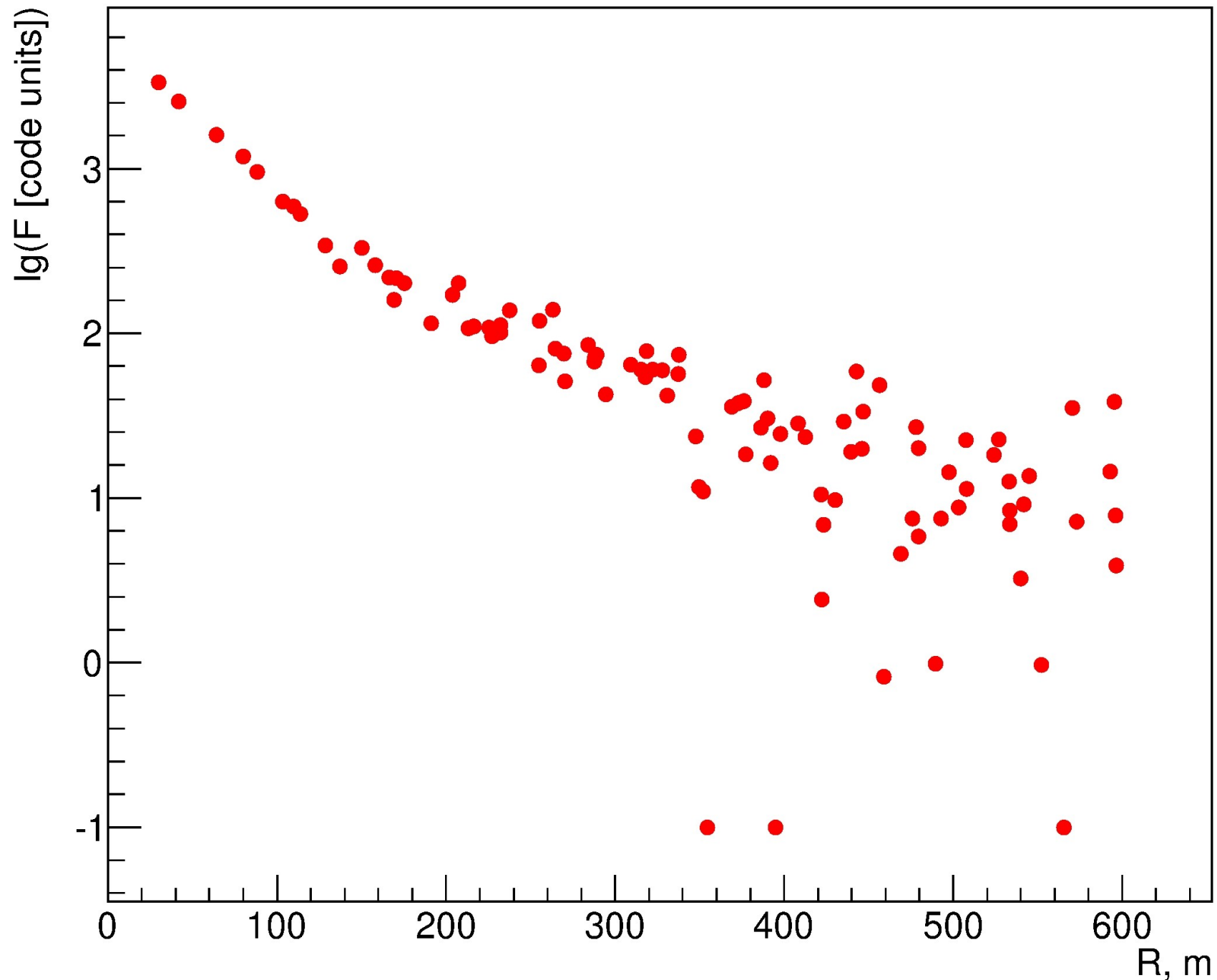


c)

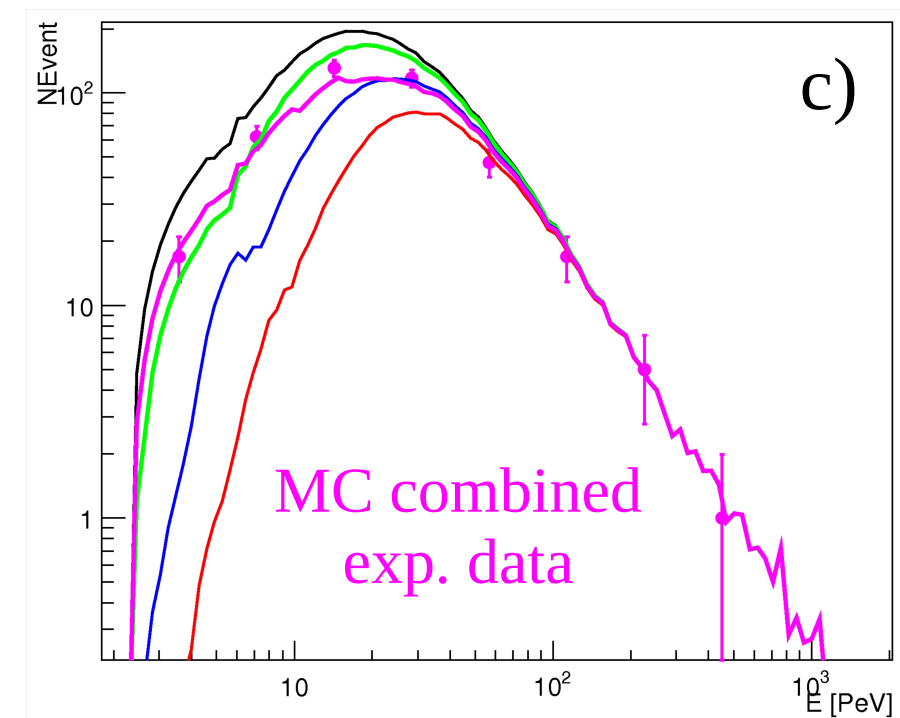
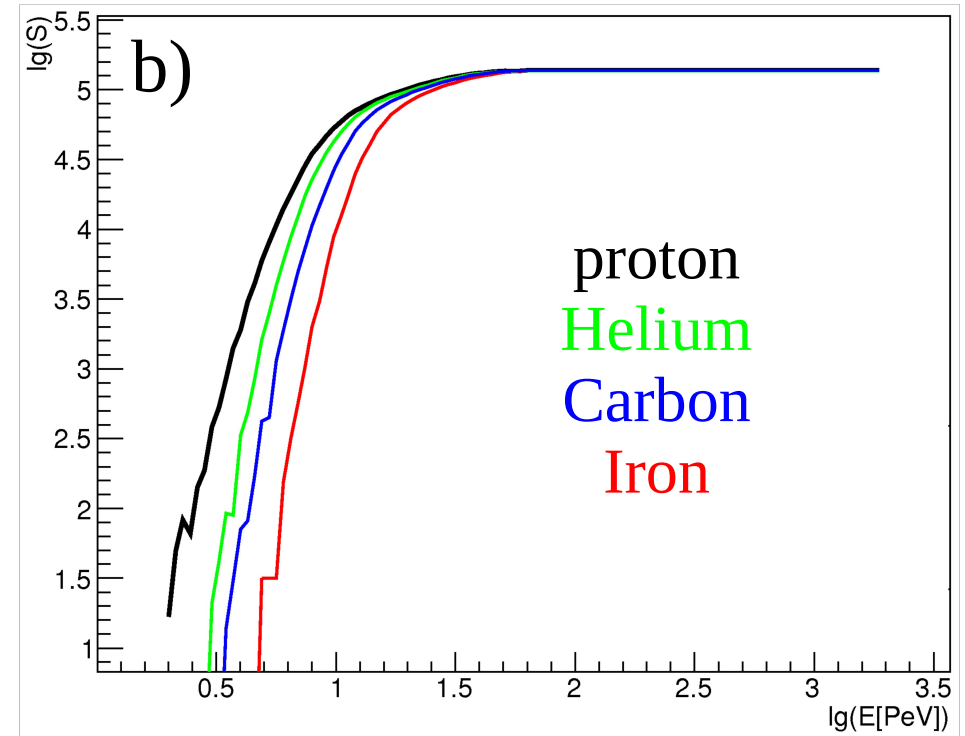
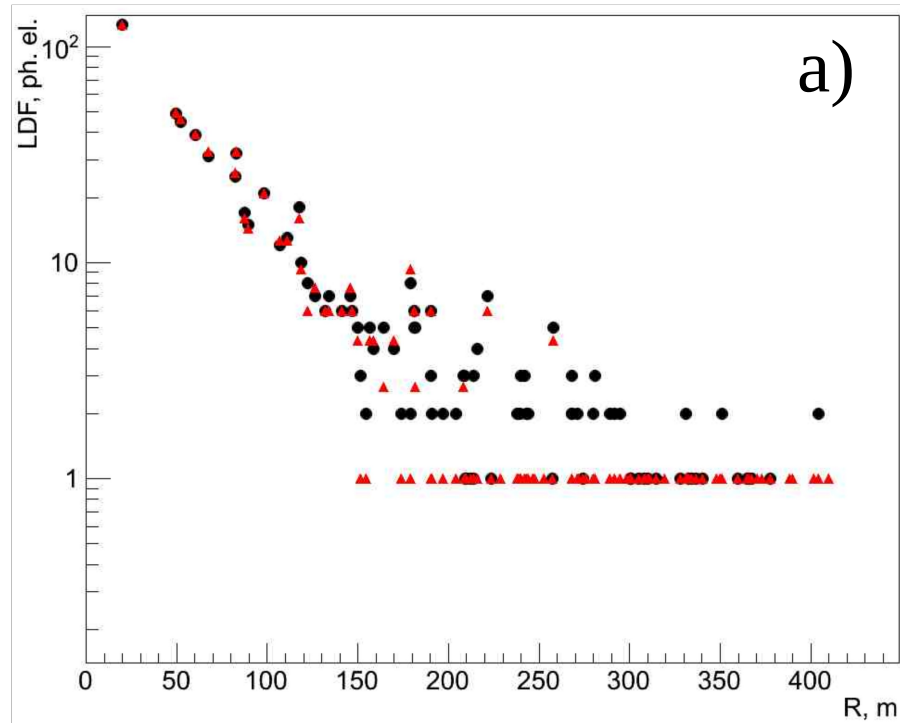


d)

Possible to probe Lateral Distribution Function (LDF) near to the axis ( $<50$  m)  $\rightarrow$  event-by-event sensitivity to nuclear composition!



# Simulations (a,b) and energy distribution data-MC comparison (c)



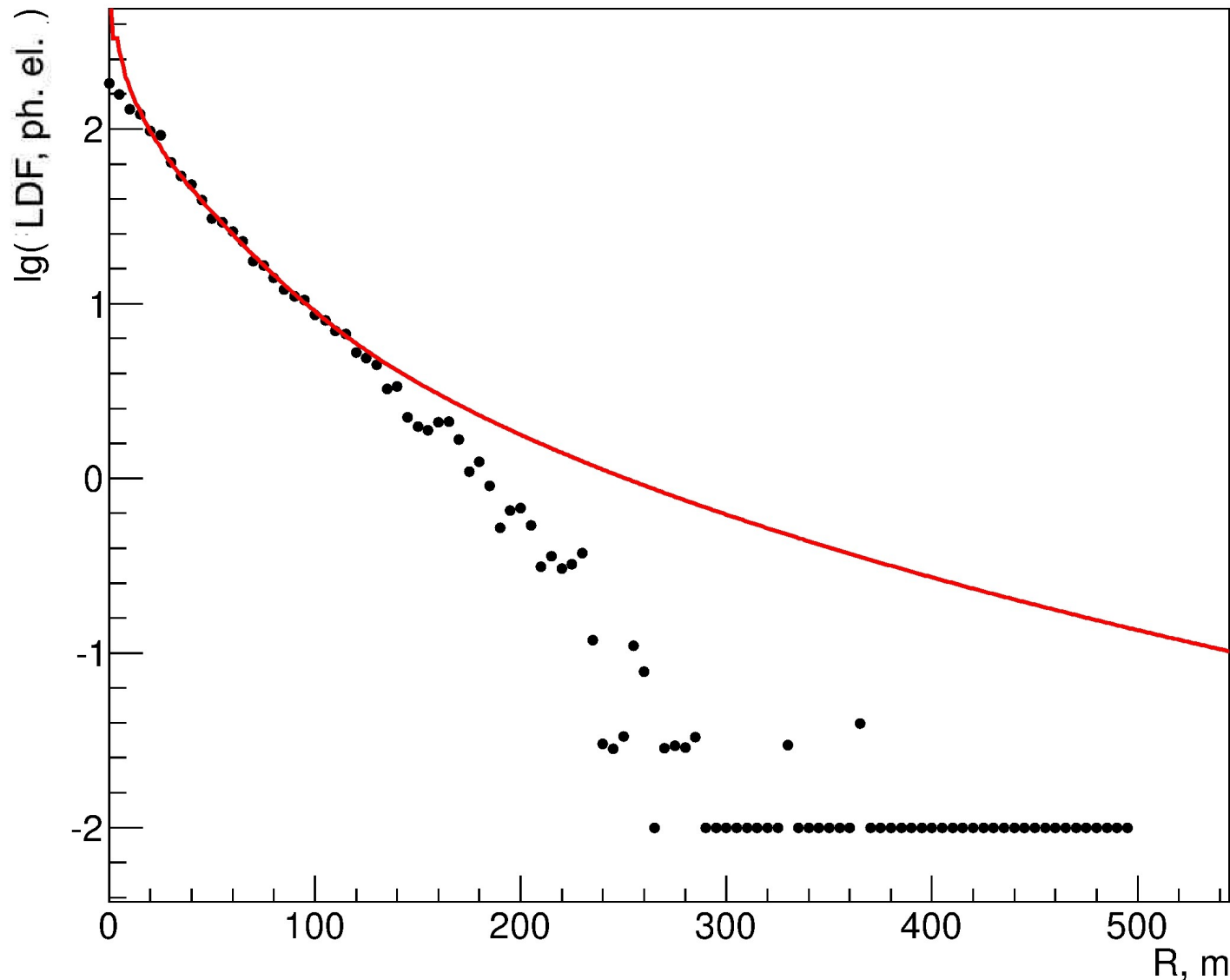
hybrid CORSIKA/Geant4 MC approach  
CORSIKA/(QGSJET-I/II, GHEISHA) [1-4]:  
10, 30, 100 PeV showers (1.5 k). Full direct  
MC! ~1M simulated events.

1. D. Heck et al. FZKA 6019 (1998)
2. N. Kalmykov et al, Nucl. Phys. Proc. Suppl. B, **52**, 17 (1997)
3. H.C. Fesefeldt, Technical Report No. PITHA 85-02 RWTH (1985)
4. S. Agostinelli et al., NIM A, **506**, 250 (2003)



# The “Composite Model LDF” concept

How to deal with geometric smearing over the PMTs field-of-view (FOV)?

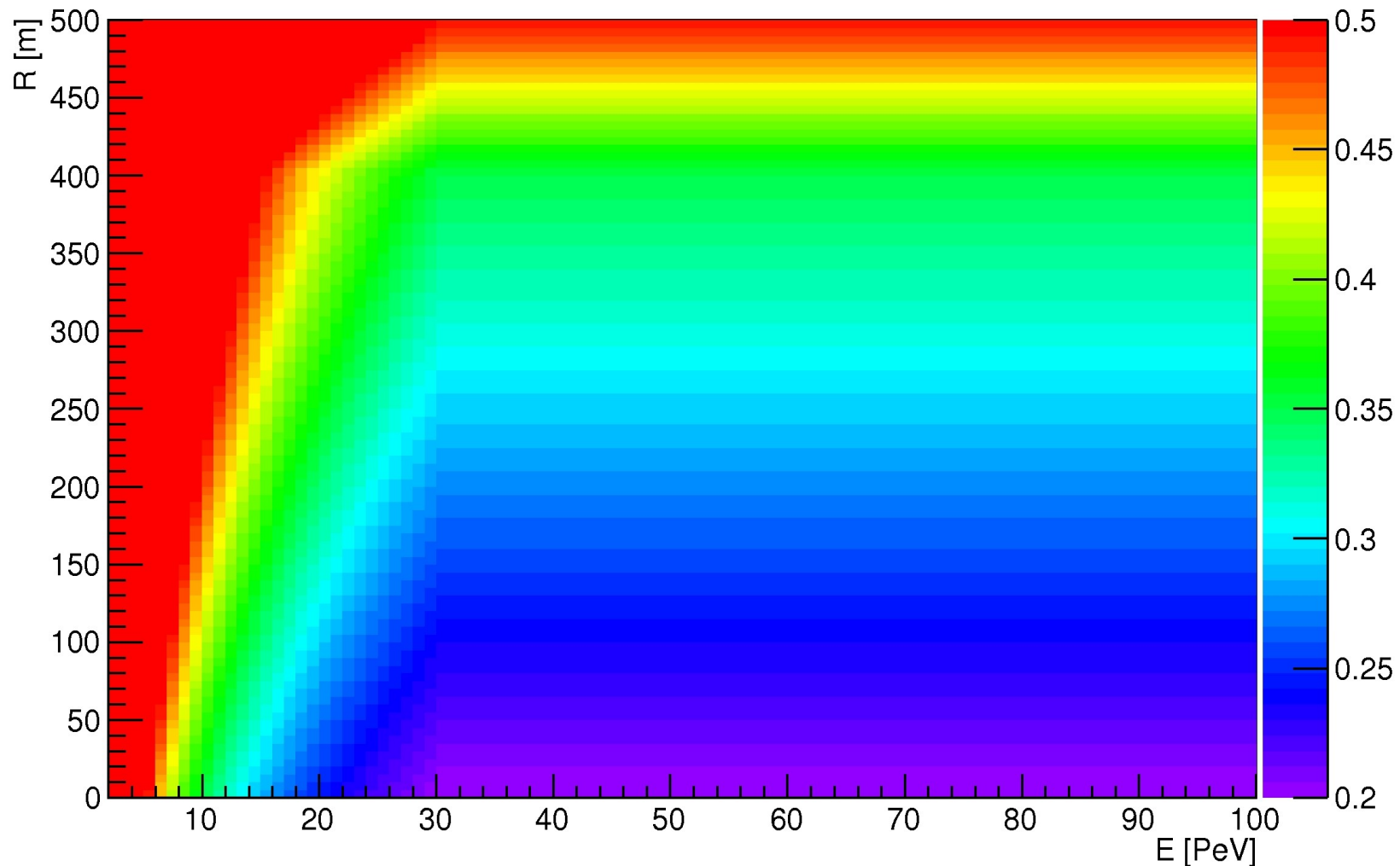


Compensate for geometrical effects and average many model LDFs for one CORSIKA shower. **Red: CORSIKA LDF** Black: “Composite Model LDF” → good agreement except near the axis (optical smearing) and at large distances (digitization effects)

# Energy reconstruction uncertainty (conservative)

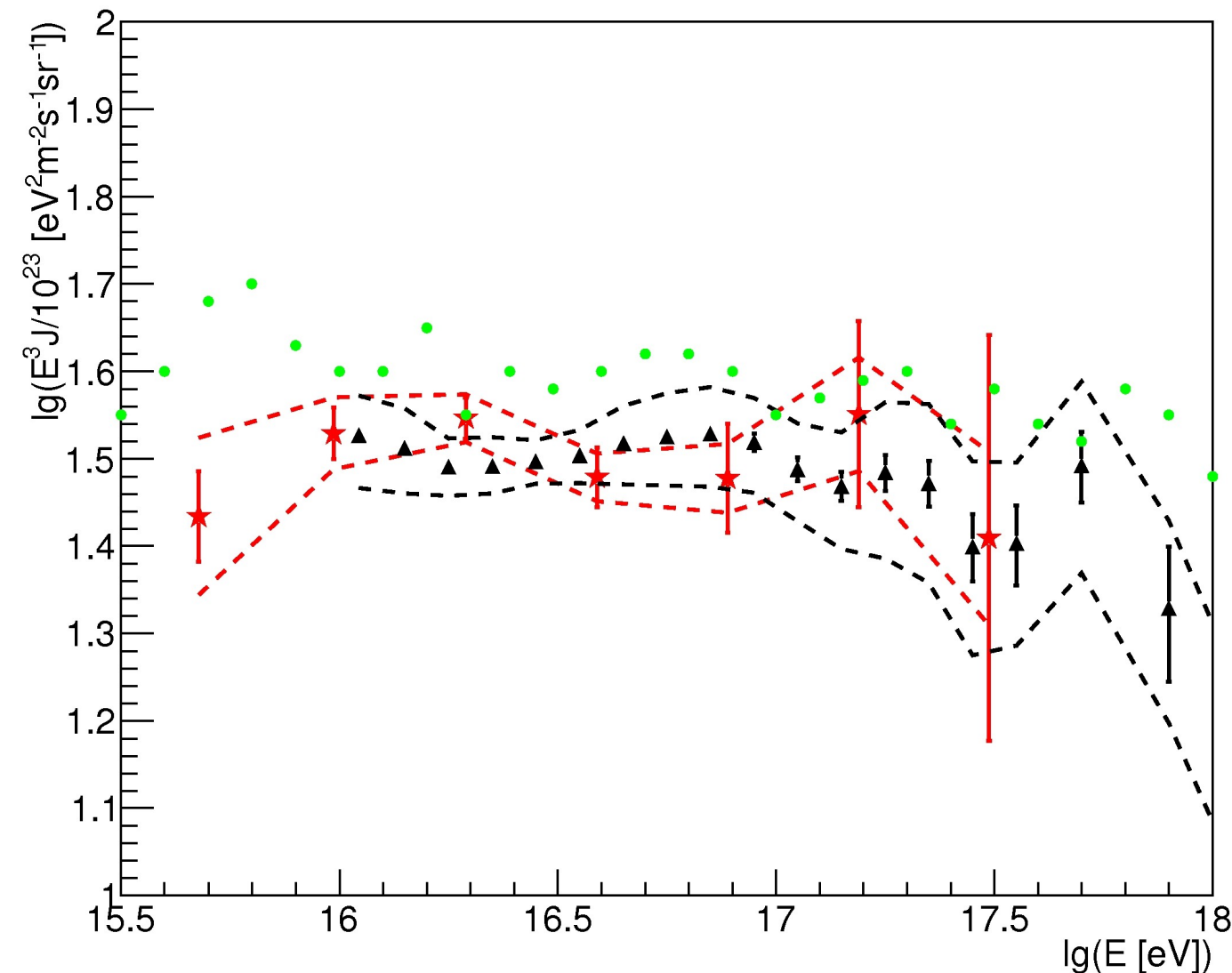
Most of showers in red area are not “seen” by the trigger

$\epsilon(E)$  vs.  $(E,R)$  for  $H=815$  m



Energy reconstruction method: Fit experimental LDF to a sample of “composite model LDFs” with normalization factor  $k$ ;  $E = \text{Const} \cdot k$  (L.G. Dedenko et al., Nucl. Phys. B (Proc. Suppl.), 136, 1217 (2004))

# Reconstructed all-nuclei spectrum



Red: SPHERE-2  
Details on systematics:  
see slide 28

Green: Akeno (M.  
Nagano et al., J. Phys. G,  
**18**, 423 (1992))

Black:  
KASCADE-Grande  
(W.D. Apel et al., Aph,  
**36**, 183 (2012))

Other results include:

ICETOP (M.G. Aartsen et al., Phys. Rev. D, 88, 042004 (2013))

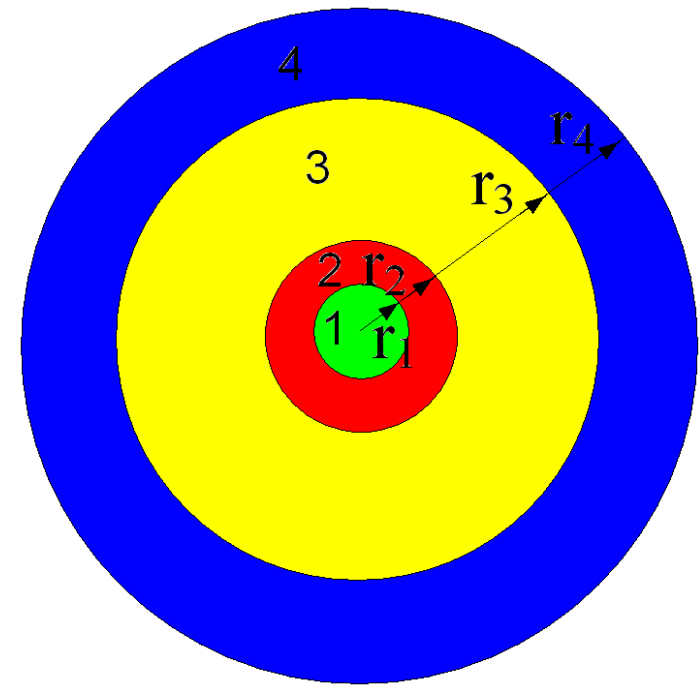
Yakutsk (S.P. Knurenko et al., 33rd ICRC (2013))

# The principle of the primary composition study

$\eta$  = LDF steepness parameter sensitive to composition (\*);

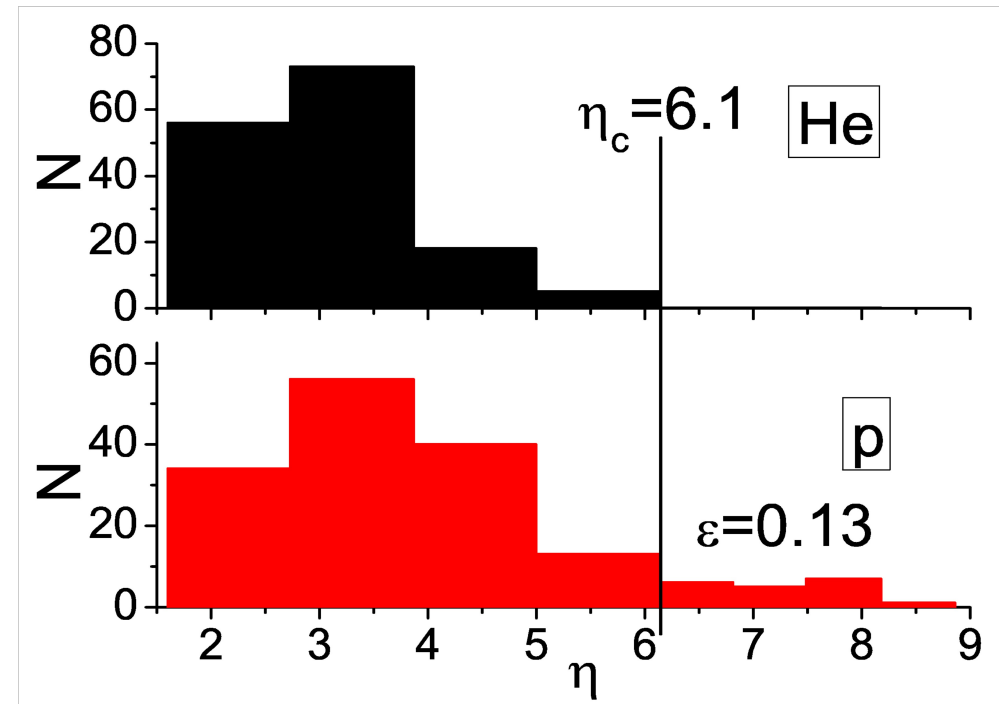
also needed for the acceptance estimation at  $E < 30$  PeV

a fraction  $f(p)$  estimated from fitting of experimental distribution with a weighted sum for p and Fe



$$\eta(r_1, r_2, r_3, r_4) = \frac{\int_{r_1}^{r_2} 2\pi r \cdot \rho(r) dr}{\int_{r_3}^{r_4} 2\pi r \cdot \rho(r) dr}$$

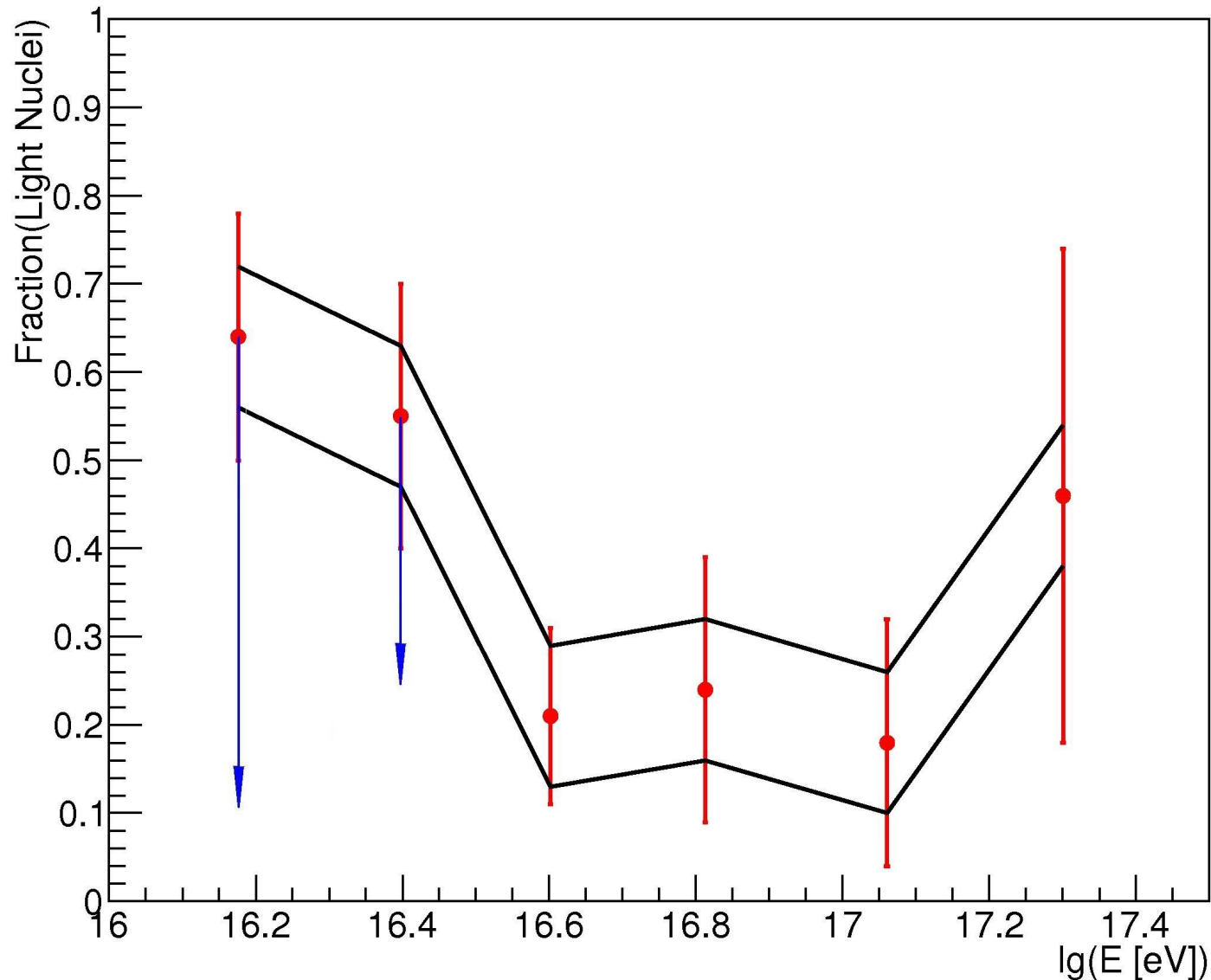
$$r_4 \geq r_3 + \delta r, \quad r_3 \geq r_2, \quad r_2 \geq r_1 + \delta r$$



(\* ) See R.A. Antonov et al, 31<sup>st</sup> ICRC (2009), HE.1.3, id. 434  
for more details



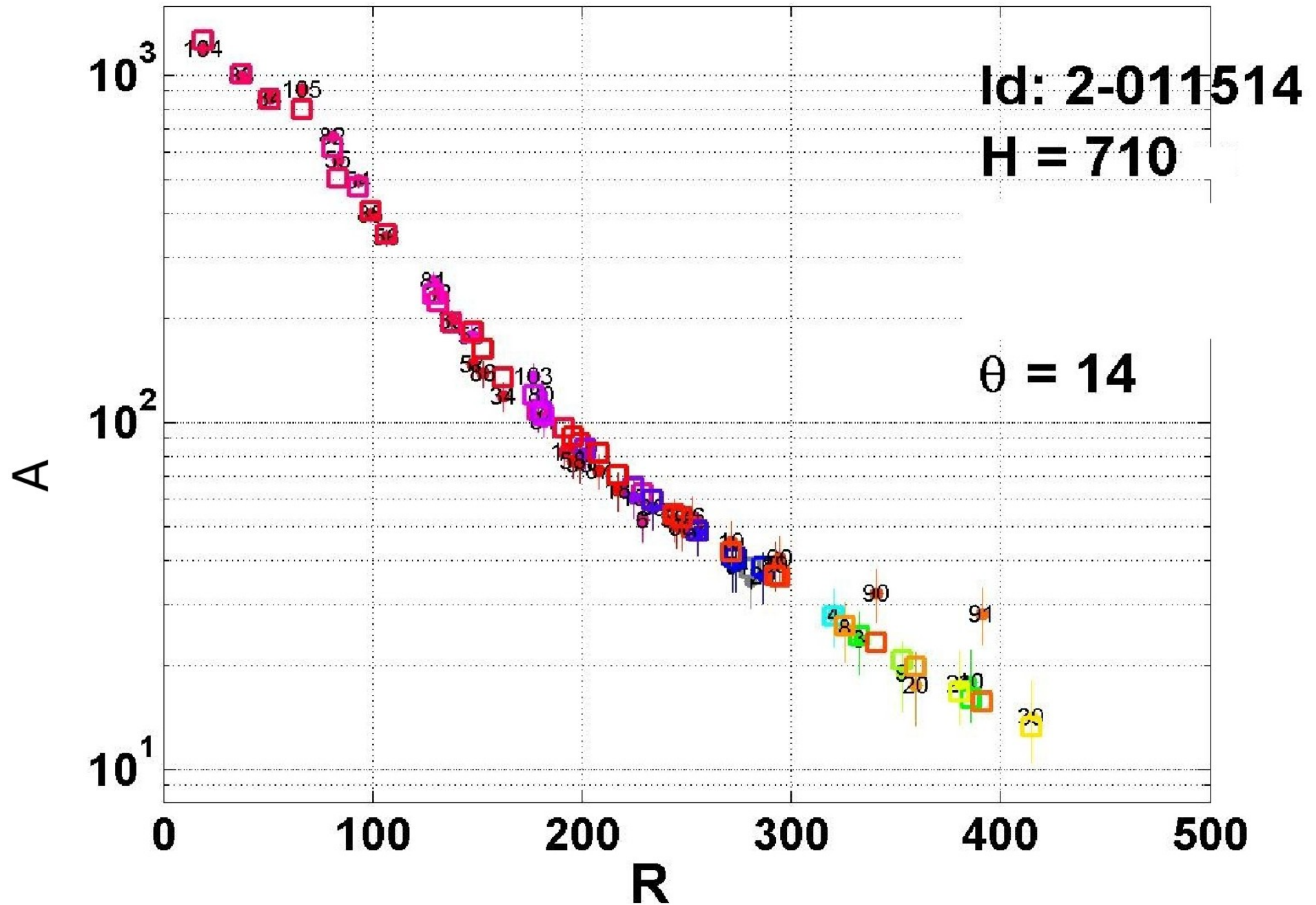
Reconstructed fraction of light nuclei for the 2012 run  
(R.A. Antonov et al., J. Phys. Conf. Ser., **409** 012088 (2013))  
Fraction of light nuclei averaged over 30-150 PeV =  $21 \pm 11$  %



Black lines:  
estimated  
systematics

Blue arrows:  
dependence of the  
primary composition  
vs. acceptance

The second independent analysis is ongoing...



# Prospects

I. Spectrum and composition study at  $E > 50$  PeV with tethered balloon at  $H = 2\text{--}3$  km. SPHERE-type detector with 1000 channels will allow to independently measure the KASCADE-Grande light component “ankle” at 100 PeV with  $\sim 4\sigma$  significance during  $\sim 400$  h exposition (2-3 winter seasons with stable snow cover).  $E_{\text{THR}} < 10$  PeV,  $\sim 100\times$  enhanced statistics w.r.t. the current SPHERE-2 exposition.

II. Measurement of Ultrahigh Energy Cosmic Rays (UHECR) all-nuclei spectrum with SPHERE-type detector during long-duration high-altitude Antarctic flight (R.A. Antonov, Russian Cosmic Ray Conference (2014)).  $E_{\text{THR}} = 100$  PeV (Cherenkov light), 1 EeV (fluorescent light).

# Conclusions

I. The reflected Cherenkov light method is currently mature enough to be competitive with other EAS observation methods, given sufficient observation time.

II. For the first time, a detailed reconstruction of the all-particle CR spectrum at  $E = 3\text{--}300\text{ PeV}$  was performed using reflected Cherenkov light.

III. As well, this technique allows the CR nuclear composition study on event-by-event basis.

IV. Reflected Cherenkov light is a promising signal to study CR at  $E > 100\text{ PeV}$ , either with tethered balloon at  $H = 2\text{--}3\text{ km}$ , or during high-altitude Antarctic flight.



# Acknowledgements

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The Russian Foundation for Basic Research (grant 11-02-01475-a, 12-02-10015-k, 13-02-00470-a); Russian President grants LSS-871.2012.2; LSS-3110.2014.2

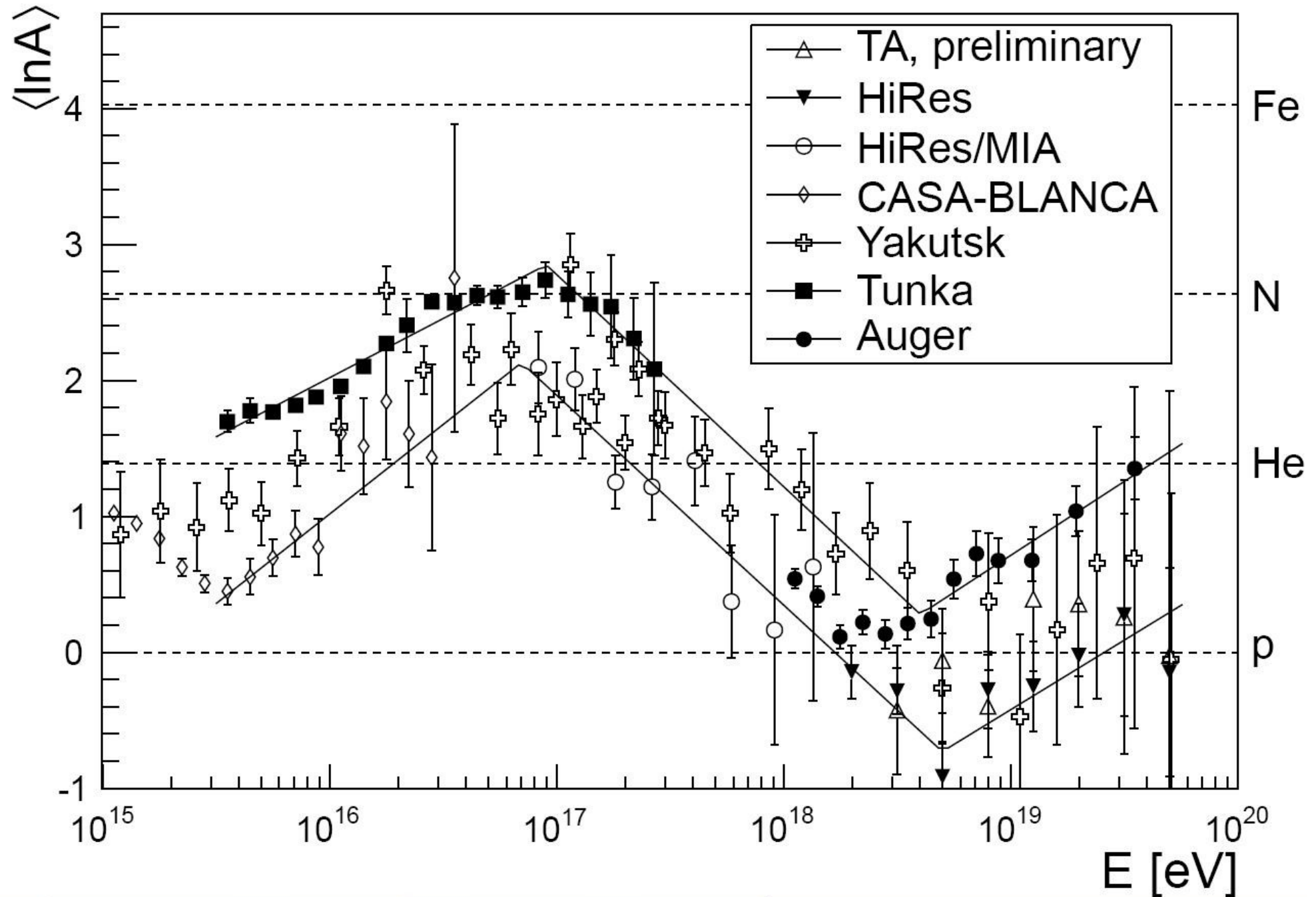
The Program of basic researches of Presidium of Russian Academy of Sciences "Fundamental properties of a matter and astrophysics" for the support;

The technical collaborators of the SPHERE-2 experiment.

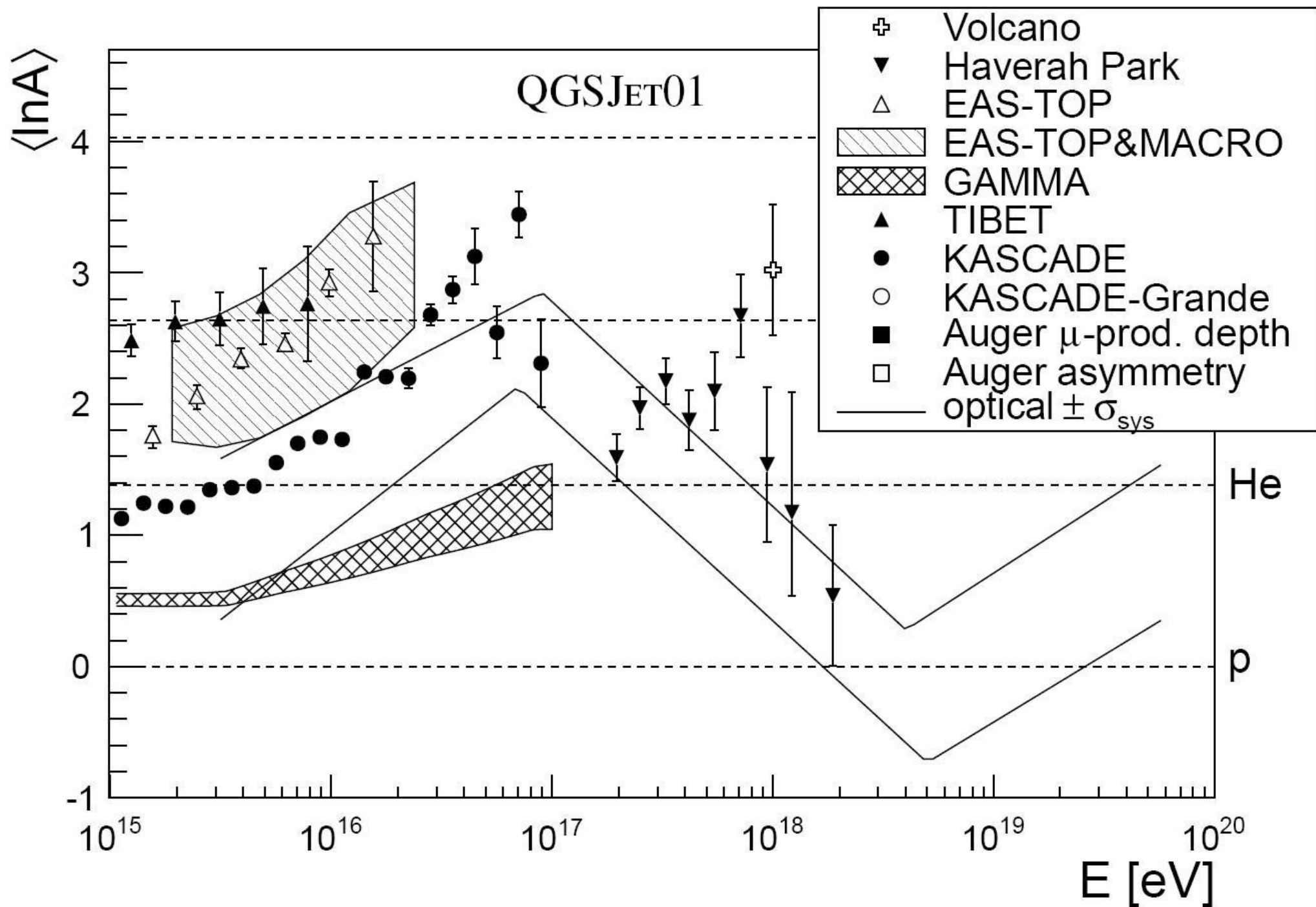
Calculations of the instrumental acceptance were performed using the SINP MSU OKM Center computer cluster. Authors are grateful to V.V. Kalegaev for permission to use the hardware and to V.O. Barinova, M.D. Nguen, D.A. Parunakyan for support.

Additional slides

Measured  $\langle \ln A \rangle$  for (mostly) optical detectors (K.-H. Kampert & M. Unger, APh, 35, 660 (2012))

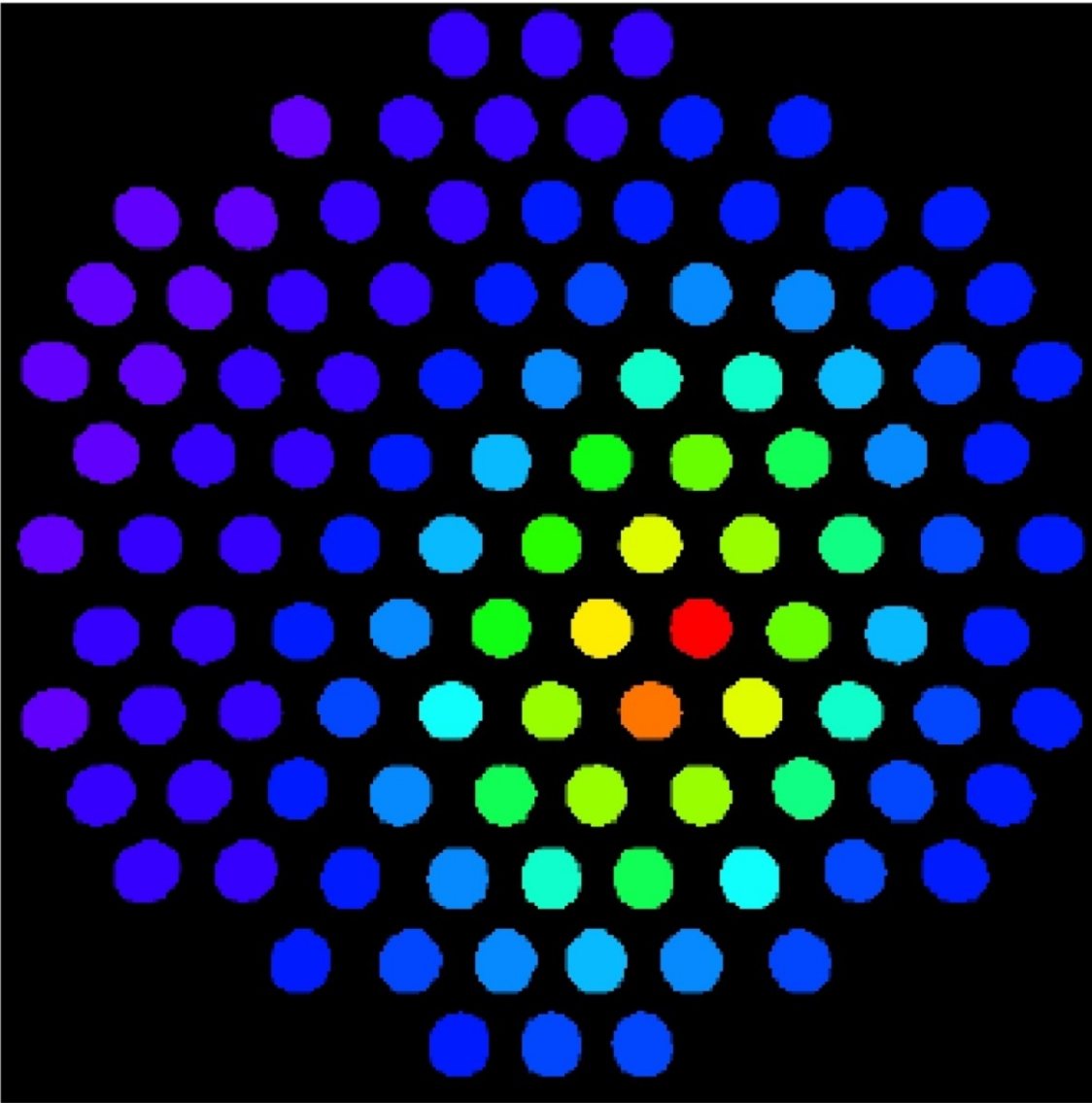


...and for particle detectors





# Simulations



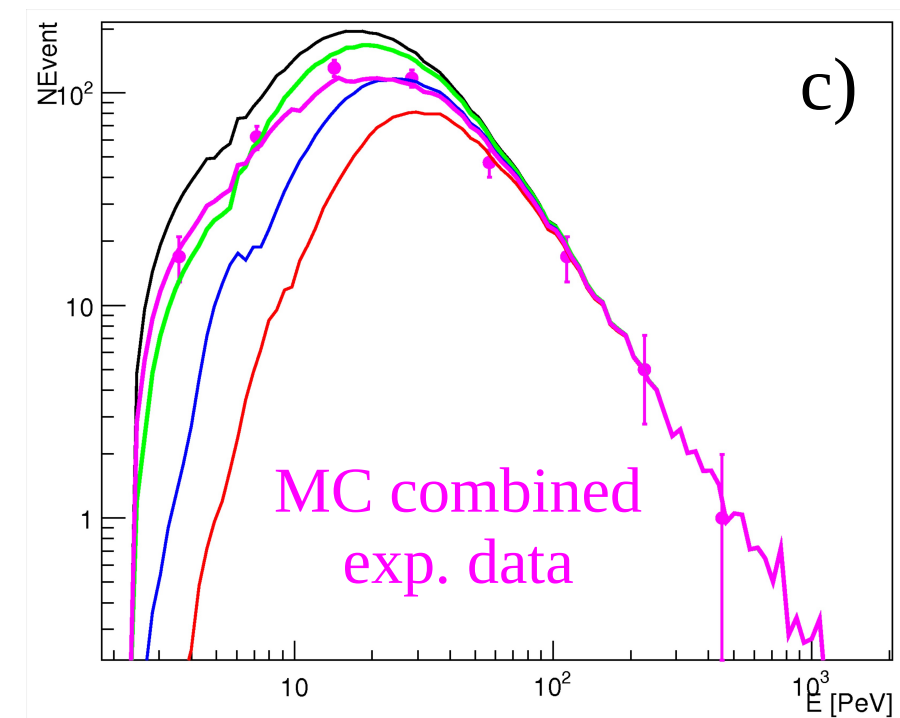
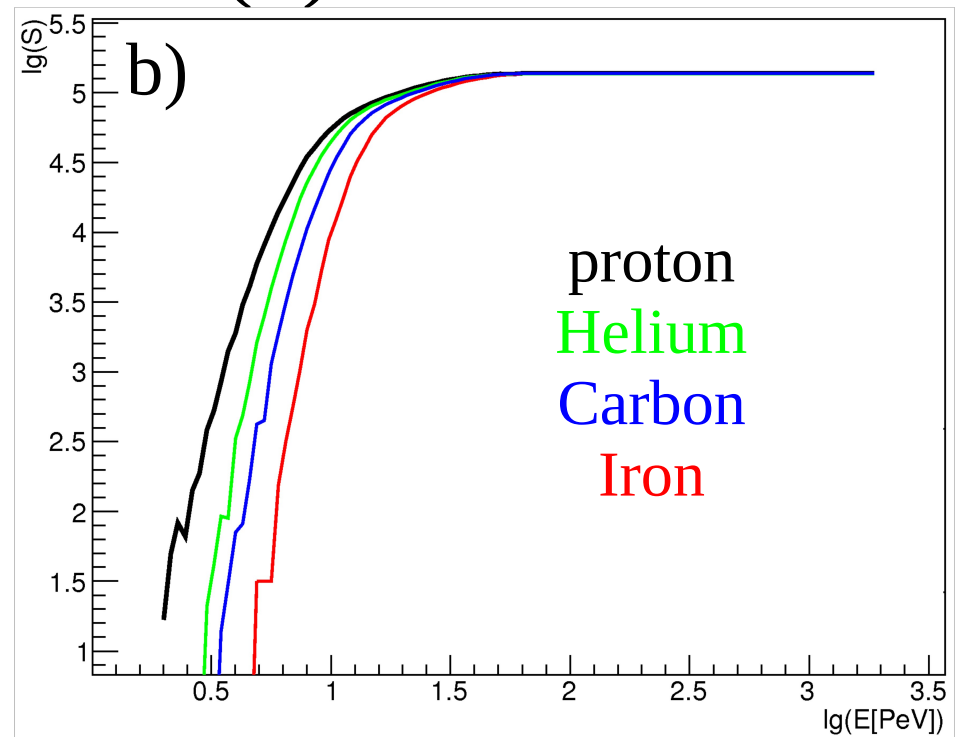
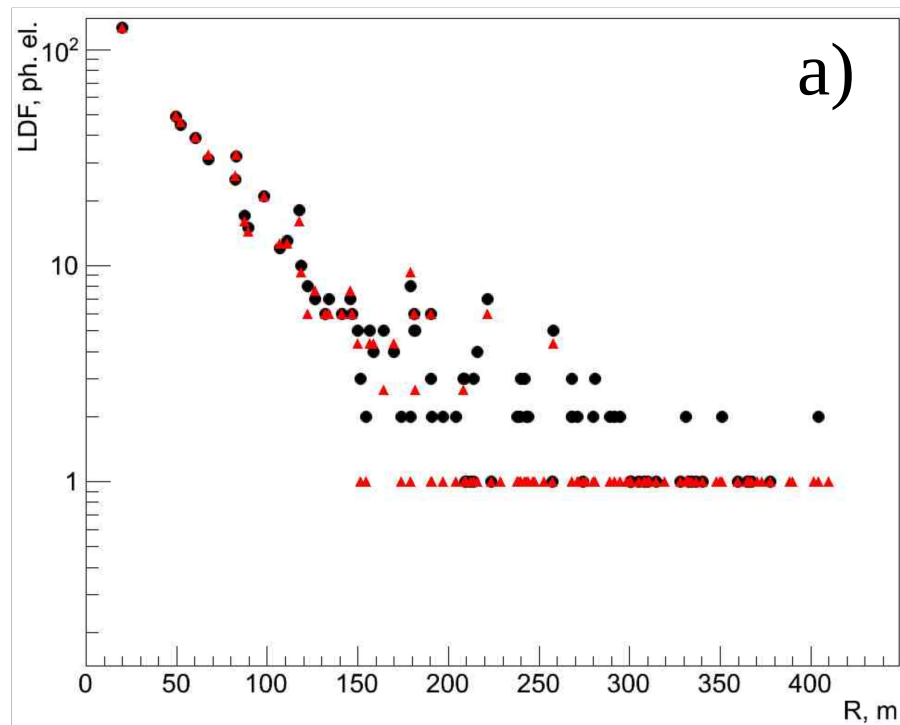
SPHERE-2 field-of-view geometry  
with model LDF superimposed

hybrid MC CORSIKA/Geant4  
approach

CORSIKA/(QGSJET-I/II,  
GHEISHA) [1-4]: 10, 30, 100 PeV  
showers (1.5 k). Full direct MC!  
Geant4 [5]: optical and  
geometrical effects. ~1M  
simulated events.

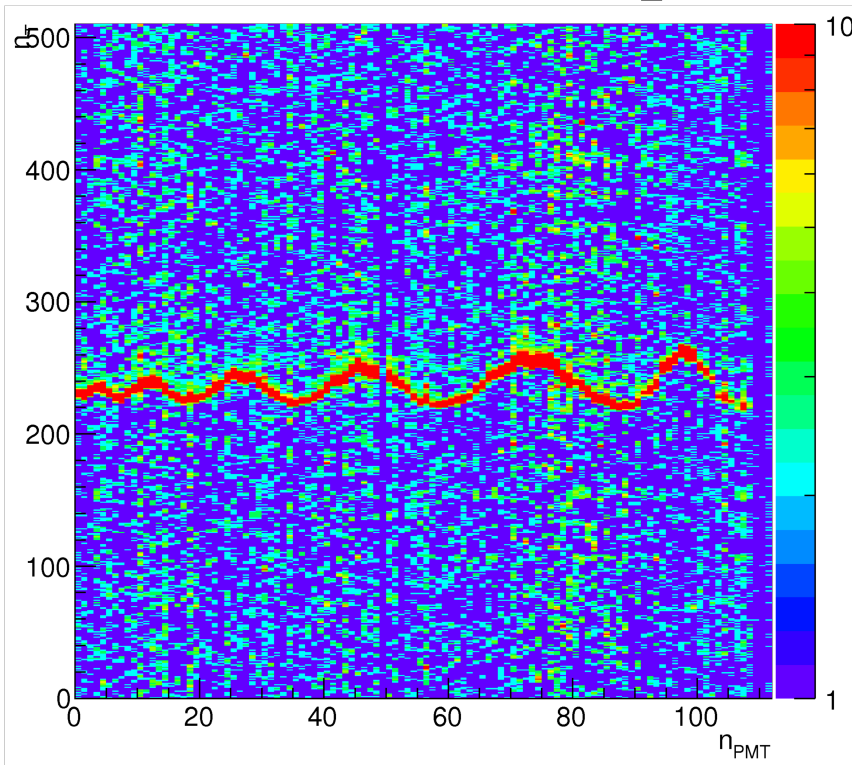
- 1.D. Heck et al. FZKA 6019 (1998)
- 2.N. Kalmykov et al, Nucl. Phys. Proc. Suppl. B, **52**, 17 (1997)
- 3.H.C. Fesefeldt, Technical Report No. PITHA 85-02 RWTH (1985)
- 4.S. Ostapchenko, Nucl. Phys. Proc. Suppl. B, **151**, 143 (2006)
- 5.S. Agostinelli et al., NIM A, **506**, 250 (2003)

# Simulations (2)

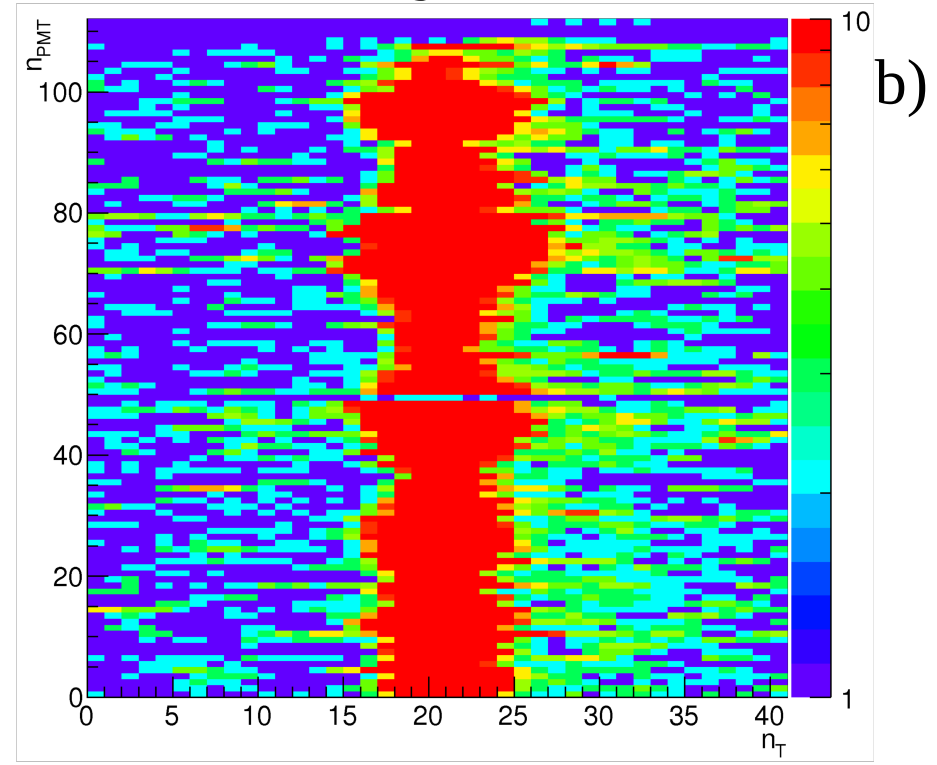


- a) Example of reconstructed LDF for model shower: before (in ph.el., black) and after digitization (in code units, normalized to black points)
- b) Example of simulated instrumental acceptance: proton (black), Helium (green), Nitrogen (blue), Iron (red)
- c) Example of simulated (curves) and experimental (magenta points) energy distributions. Thick magenta curve – model energy distribution for mixed composition.

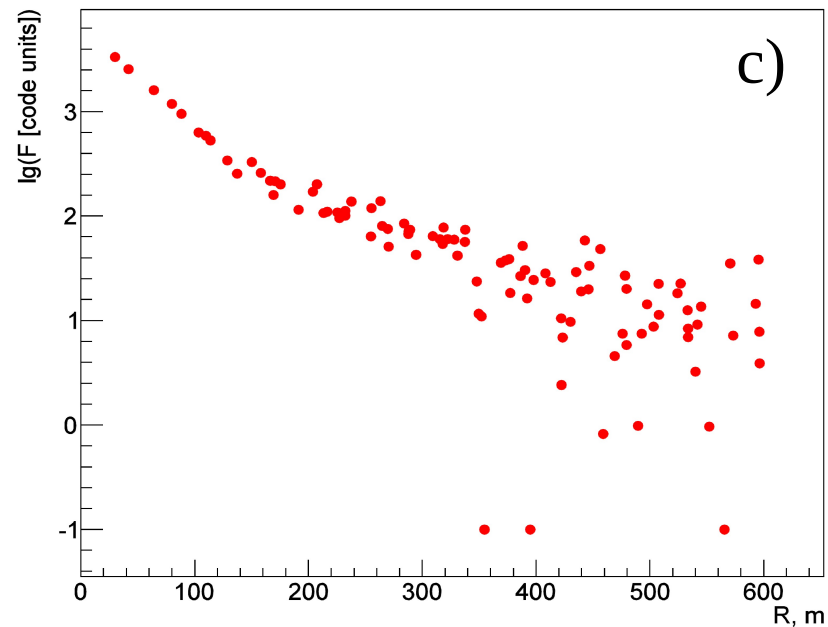
# Experimental data analysis



a)



b)



c)

- a) Example of raw experimental event (bins with  $>10$  code units set to red)
- b) The same event after pattern recognition procedure (subtraction of  $\delta t$  for each channel)
- c) Example of reconstructed lateral distribution function (LDF) of an observed shower

# Experimental data analysis (2)

For the spectrum estimation, we select contained events (CONT)  
(axis within FOV of the detector) + some external events (EXT)  
(distance from the FOV edge to the axis  $R < 100$  m)

For composition reconstruction: the same, but for  $R < 30$  m

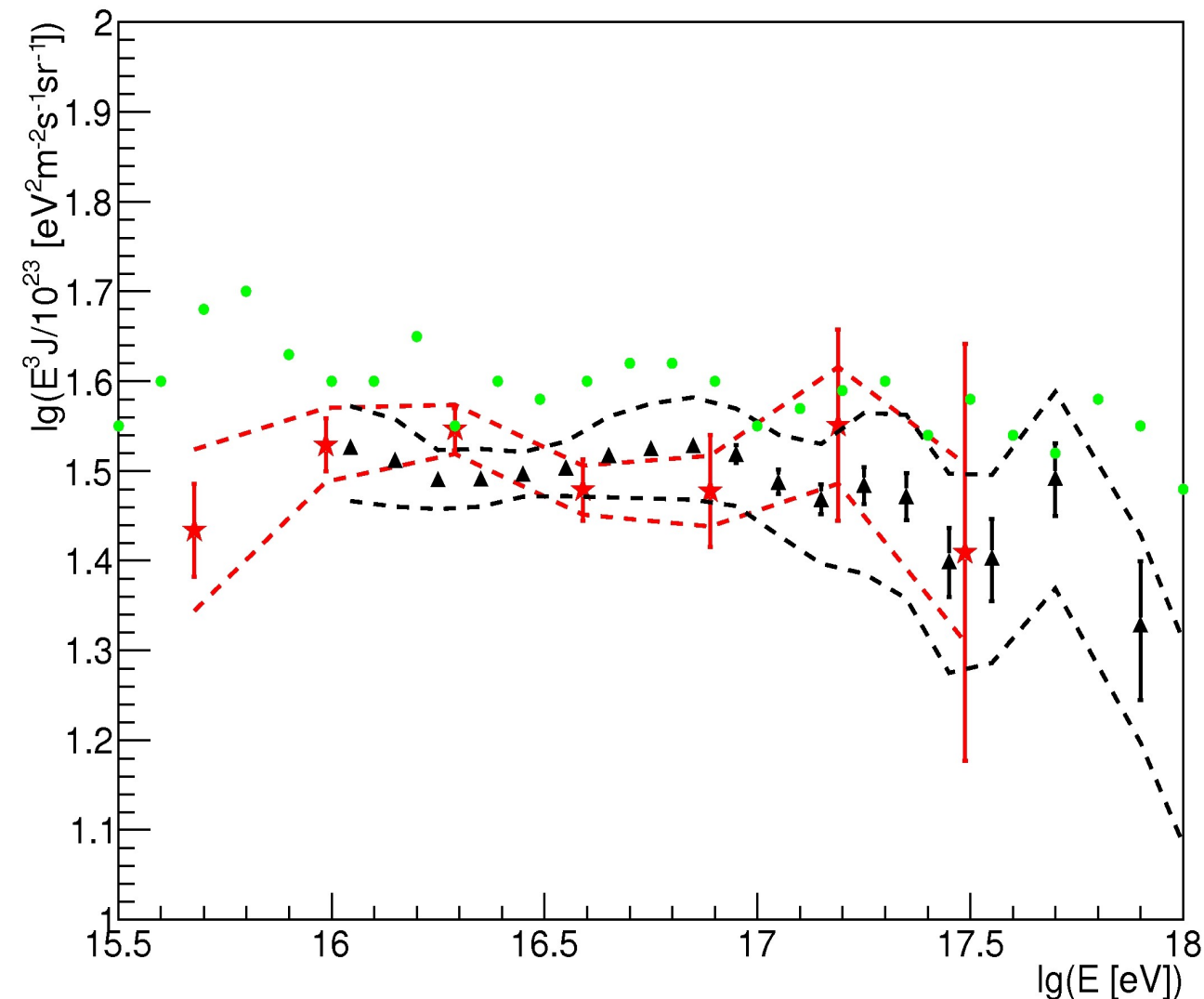
Uncertainties of the parameters estimation:

$$\delta\theta \approx 1.5^\circ \text{ for } \theta < 20^\circ$$

1.  $\varepsilon(E) \approx 20\%$  for  $E > 30 \text{ PeV}$  and axis at (0,0)
2.  $\varepsilon(E) < 30\%$  for  $E > 30 \text{ PeV}$  (conservative estimate for CONT);
3.  $\varepsilon(E) \sim (30 \text{ PeV}/E)^{0.5}$  for  $E < 30 \text{ PeV}$ , CONT
4.  $\varepsilon(E) < 50\%$  for  $R < 100$  m

and EXT events that were seen by the trigger

# The all-nuclei spectrum



## Methodical effects and systematics

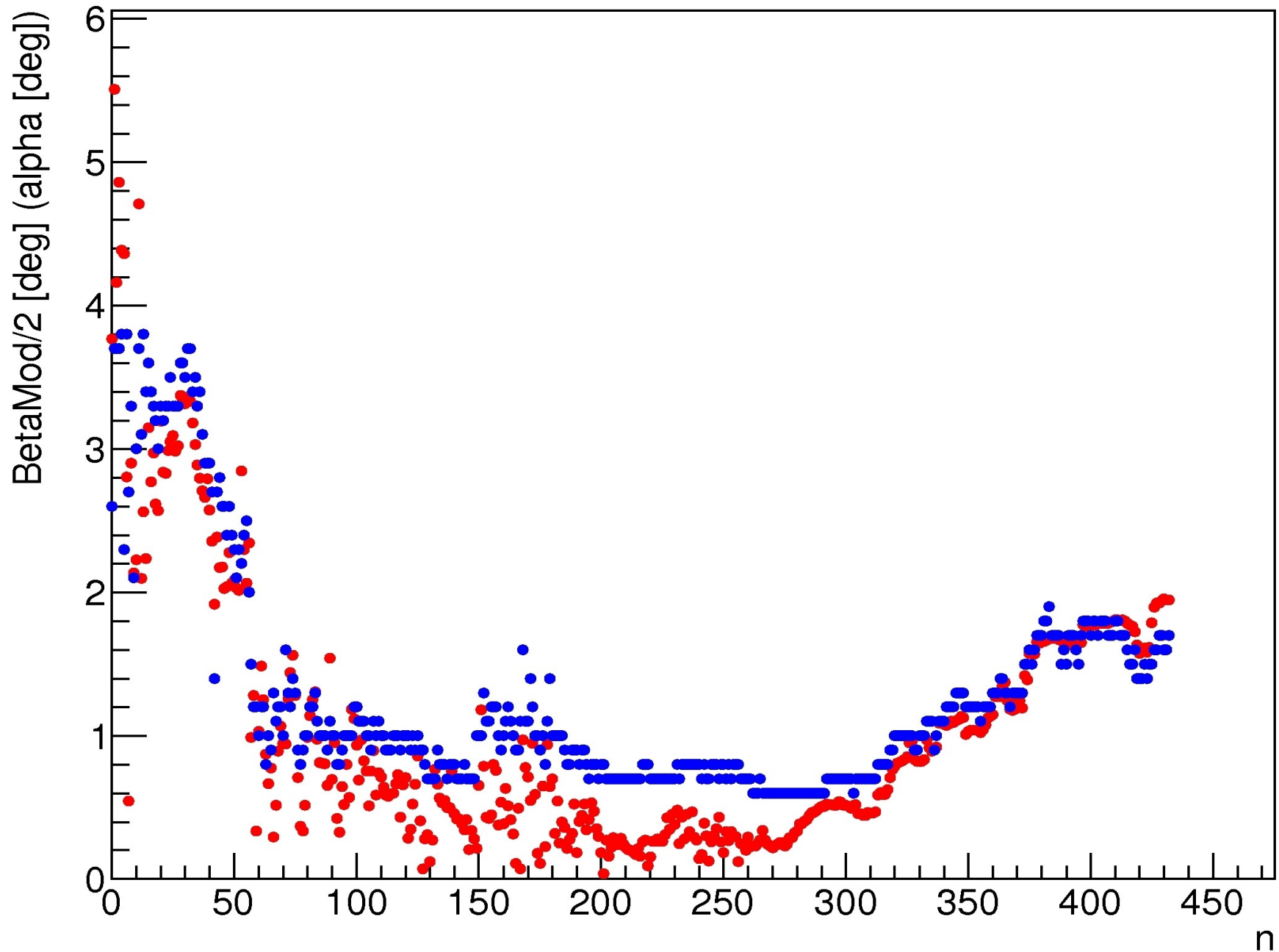
1. Bin-to bin migration: dominant at  $E > 20$  PeV
2. Statistical error of the acceptance evaluation:  $\sim 2\%$  at  $E > 20$  PeV
3. Uncertainty of the primary composition: dominant at  $E < 20$  PeV
4. Discrete model energies: negligible
5. Zenith angle uncertainty: negligible
6. Discrete row of altitudes in calculation: negligible
- Under evaluation: 7. energy vs. composition (under attack)

Under evaluation: 8. acceptance vs. optical axis inclination (mostly due to wind); at  $E > 10$ - $15$  PeV probably second order effect

Under attack: 9. energy vs. composition



# Detector's optical axis inclination reconstructed by two methods



## A short note on the number of observed EAS

Let systematical uncertainty on intensity be  $\sim 15\%$   
 $\sim 40$  events/energy bin would cause the statistical  
fluctuation of  $15\%$

Thus, the total uncertainty of the spectrum  
starts to saturate (2 decades on energy assumed):

For 3 bin/decade of energy: more than  $6 \cdot 40 = 240$  events

For 5 bin/decade of energy: more than  $10 \cdot 40 = 400$  events

For 10 bin/decade of energy: more than  $20 \cdot 40 = 800$  events

In this work we use LDF steepness  
with  $(r_1, r_2, r_3, r_4) = (0, 67, 67, 134)$  m.

For p/Iron selection it is possible to select 40- 60 %  
of protons, depending of the zenith angle range.

This task is simpler than p/Helium classification.