Skobeltsyn Institute of Nuclear Physics

Lomonosov Moscow State University

Galactic cosmic rays from NUCLEON to HERO

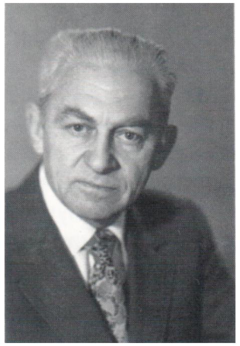
(in Moscow State University)

D. Podorozhny for "Sources of Galactic cosmic rays"

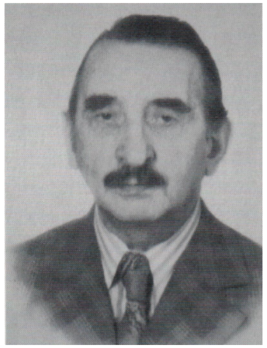
APC, Paris - December 7-9, 2016

Ionization Calorimeter - main detector for high-energy particles

1957

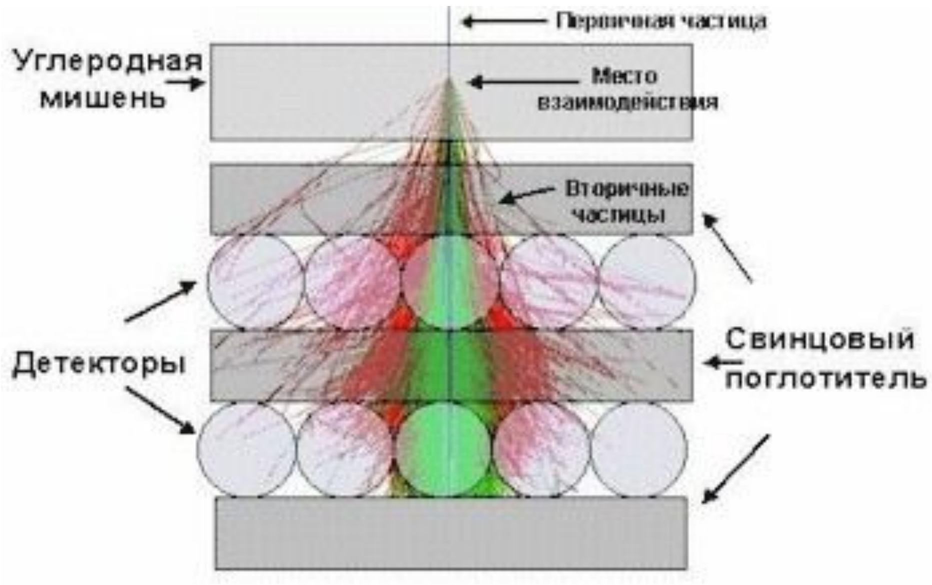


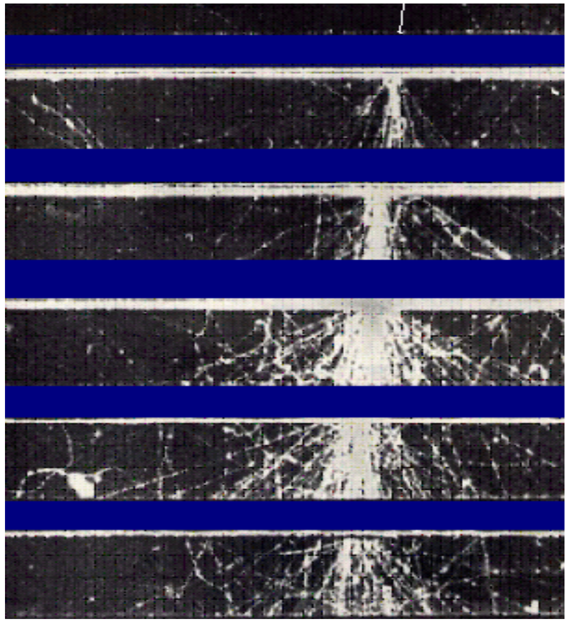
N.L.Grigorov



I.D.Rapoport

V.S.Murzin



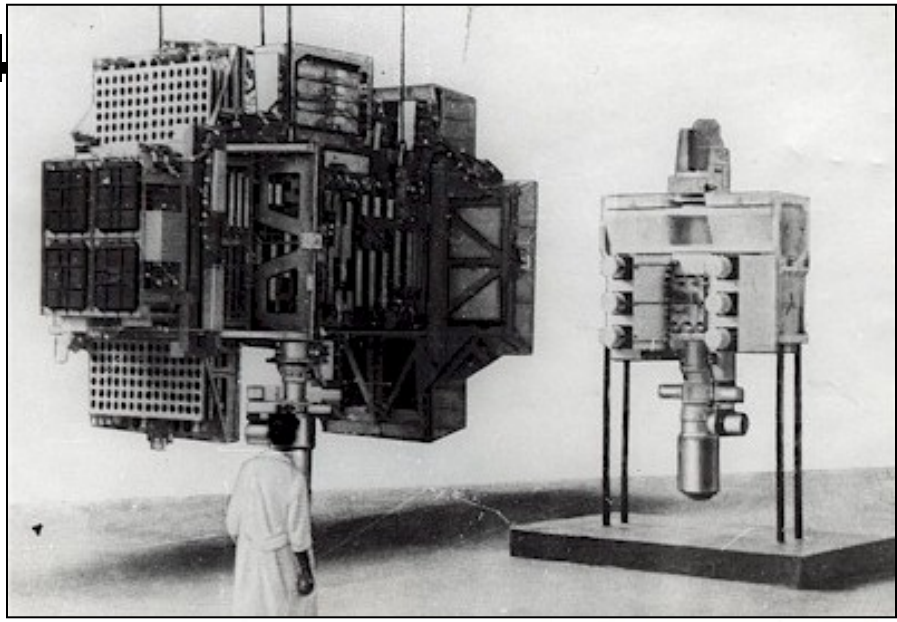


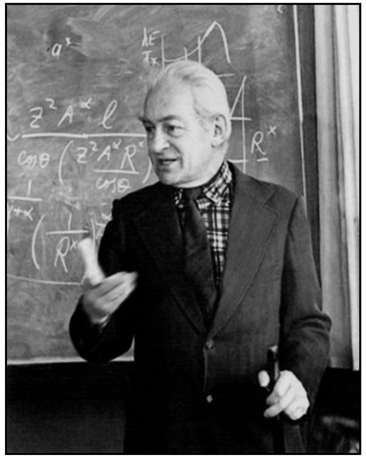
"Proton" Experiments
1965 – 1968

Proton 4

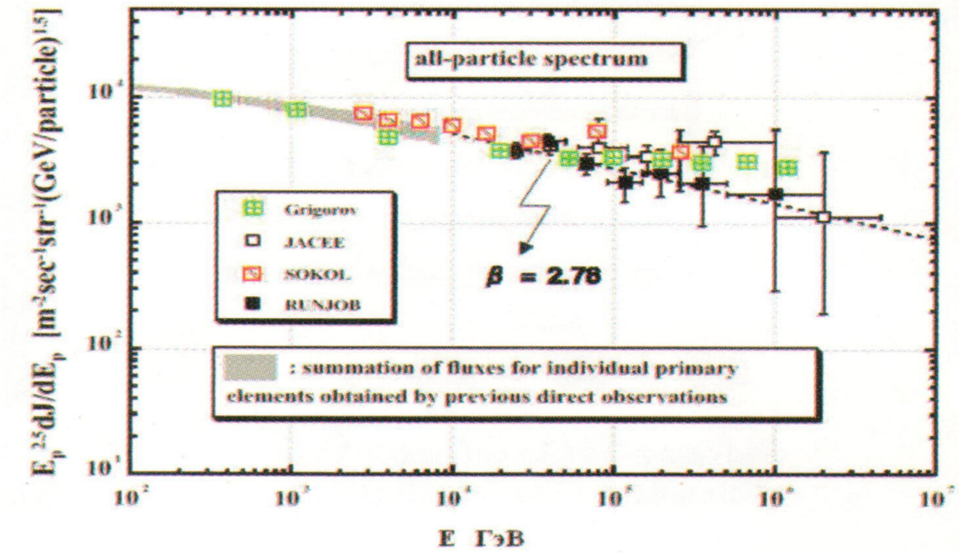
3

S.N.Vernov

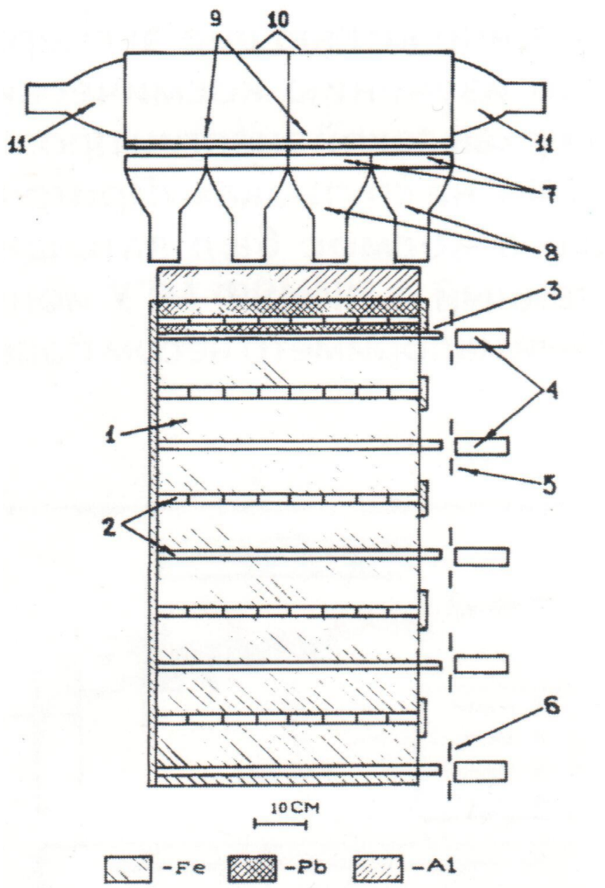


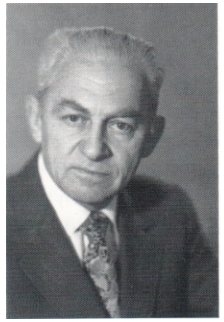


N.L.Grigorov



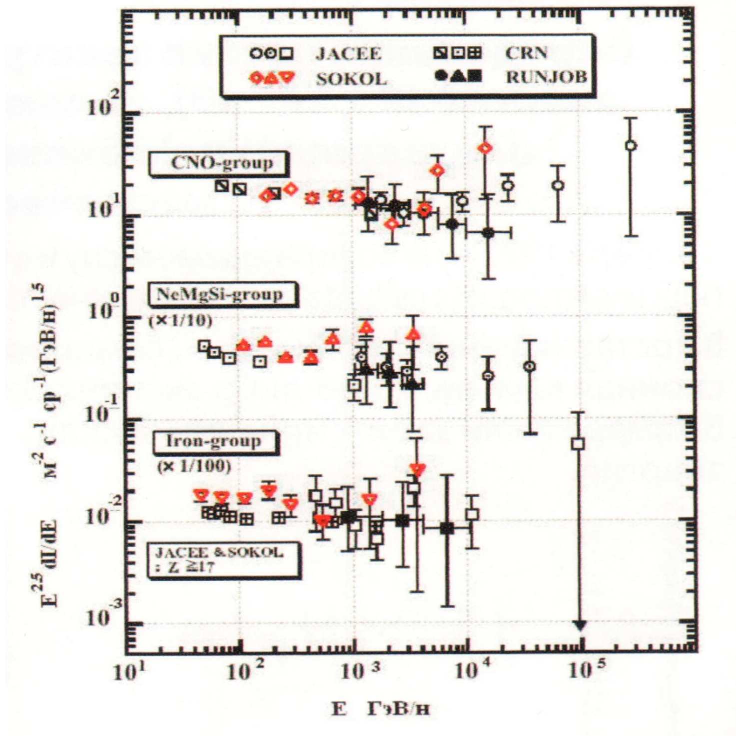
The composition of cosmic rays experiment SOKOL





N.L.Grigorov **I.P.Ivanenko** **V.Ya.Shestoperov**

“Kosmos -1543” SOKOL-1
“Kosmos -1713” SOKOL-2



Now in Russian Federal Space Program 2016-2025

3 projects for Galactic cosmic rays exploring

NUCLEON - experimental study of cosmic ray spectra
in energy range 1 TeV-1 PeV per particle
with element charge resolution.
2007-2014 - Constructor stage
2015-2020 (+?) - Exposure stage

NUCLEON-2 - experimental study of Isotopic Composition: Z = 7-66
Charge composition: Z = 7-94 (+?)
In the energy range E = 0.1-1.0 GeV / nucleon
2015-2020 - Constructor stage
2021-2026 (+?) - Exposure stage

HERO - (High-Energy Ray Observatory)
- experimental study of high-energy astroparticle composition
in energy range 1 TeV-10 PeV per particle
2017-2019 - R&D stage
2025-2025 - Constructor stage
Launch after 2025 before 2030

NUCLEON mission

NUCLEON apparatus is placed on board of the RESURS-P regular satellite as an additional payload. The spacecraft orbit is a Sun-synchronous one with inclination 97.276° and an average altitude of 475 km.

Lanched December 28, 2014.

Switched on January 11, 2015.

Flight test January-February 2015

From March 2015 up to now - regular measuremetns

The planned exposition time is more than 5 years.

Vessel:

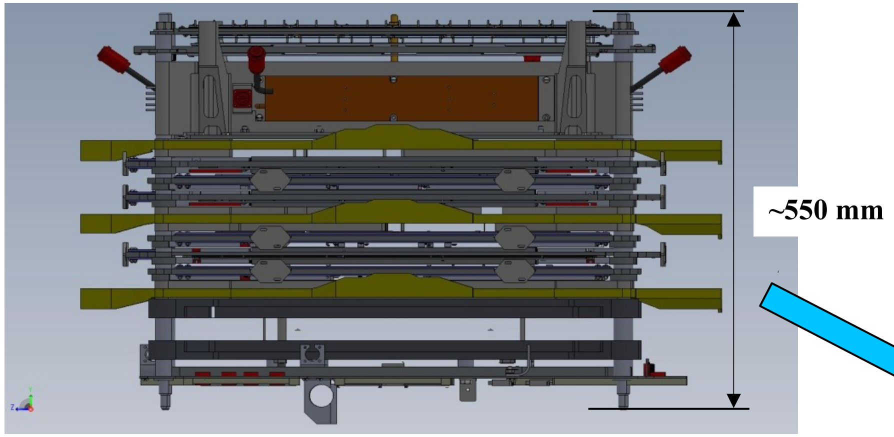
Weight ~360 kg

Power consumption ~160 W

Telemetry ~10 GB/day

The NUCLEON detector on board of the satellite RESURS-P N2.

The NUCLEON apparatus



❖ **system of charge measurements** – four planes of pad silicon detectors (1.5×1.5 cm^2) (**1**);

❖ **tracker for KLEM energy measurement** – carbon target of 0.25 proton iteraction lengths (**2**) and six planes of microstrip silicon detectors (0.4mm step) with tungsten between them (~2mm each,

~3 X-lengths summary) (**3**);

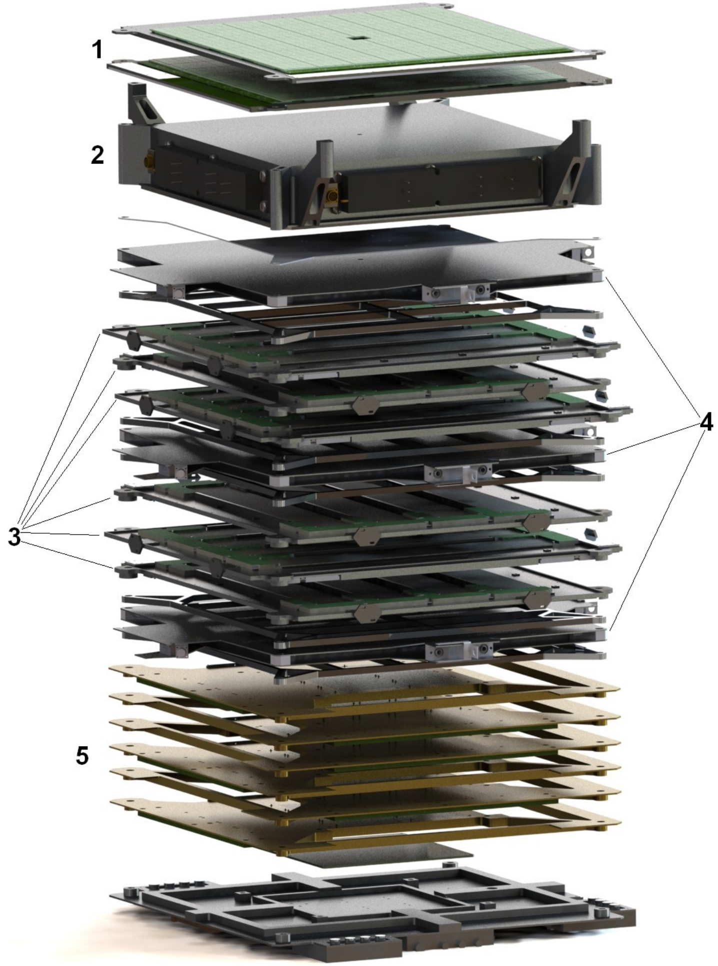
❖ **trigger sysytem** – tree double sntillator planes (**4**).

Active square 500*500 mm^2.
Geometrical factor 0.24m^{2}sr.

ϖ **Ionization calorimeter (IC)** (**5**) – six planes of tungsten absorber (~8mm each, ~12 X-lengths suumary) with silicon strip detectors (1mm step).

Active square 250*250mm^2.

Geometrical factor (together with charge and KLEM systems) ~0.06m^{2}sr..



10604 independent electronic channels in total

IMPORTANT FEATURE OF THE EXPERIMENT:

Two different methods of measuring of the energy of particles are implemented in the NUCLEON experiment:

1. The kinematic method KLEM

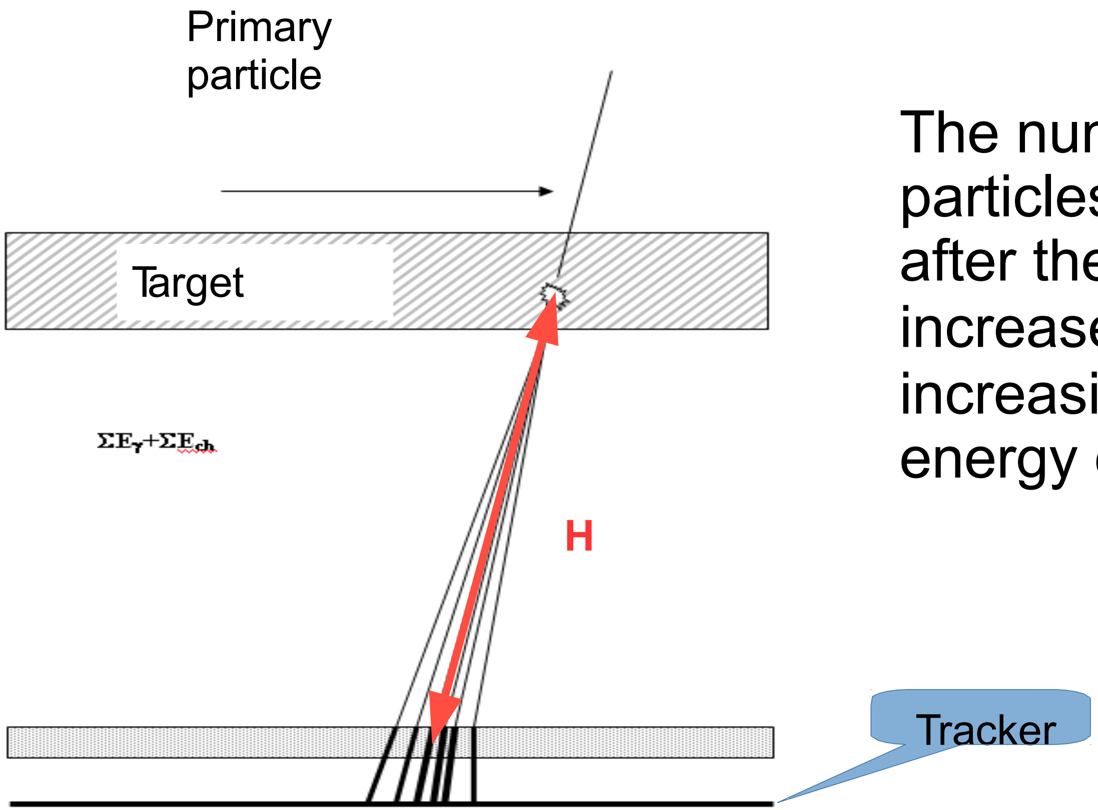
   (Kinematic Lightweight Energy Meter)

   -for the first time

2. The calorimatric method

   -usual and well studied

The kinematic method KLEM



The number of secondary particles with high pseudorapidity after the first interaction increases logarithmically along increasing of the primary energy of particle

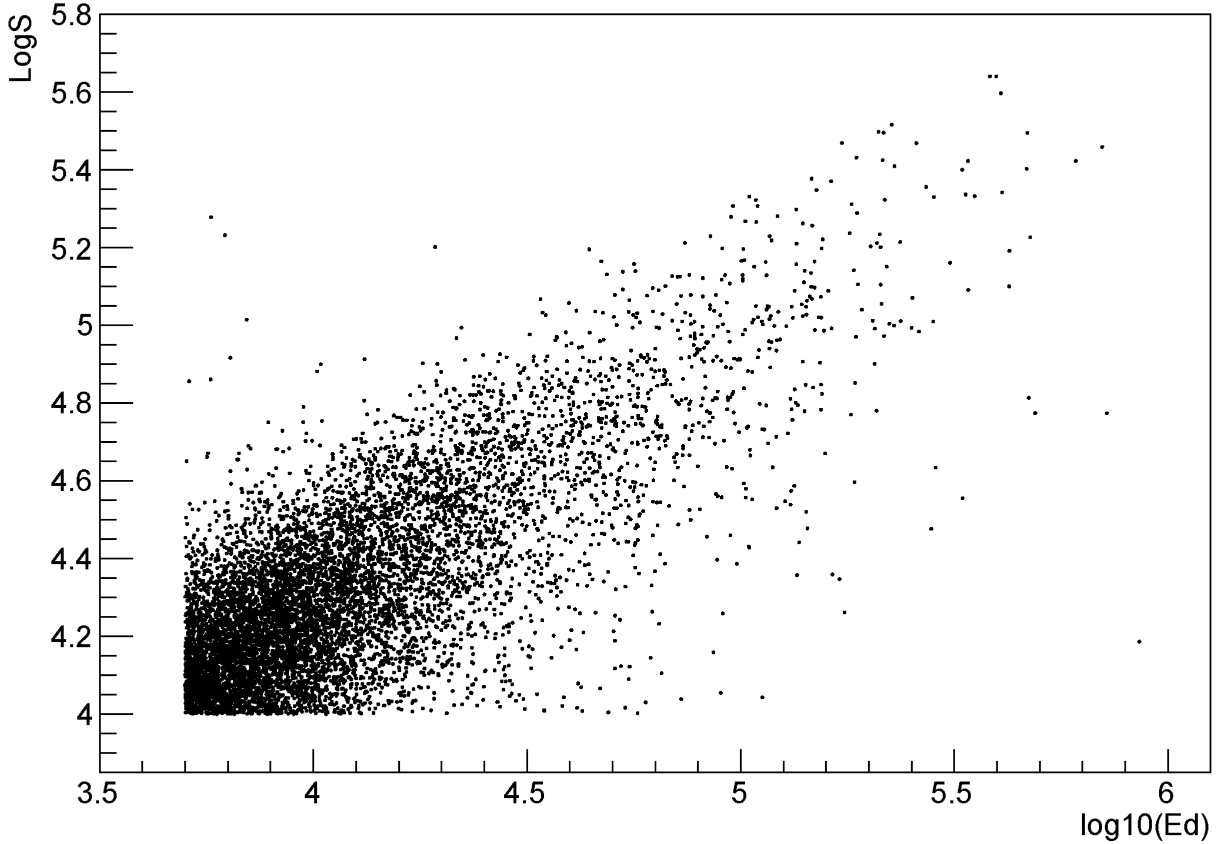
The energies are reconstructed by S-parameter -

$$S=\Sigma(I_i * \ln^2(2H/x_i))$$

KLEM energy resolution ~60% for all nuclei

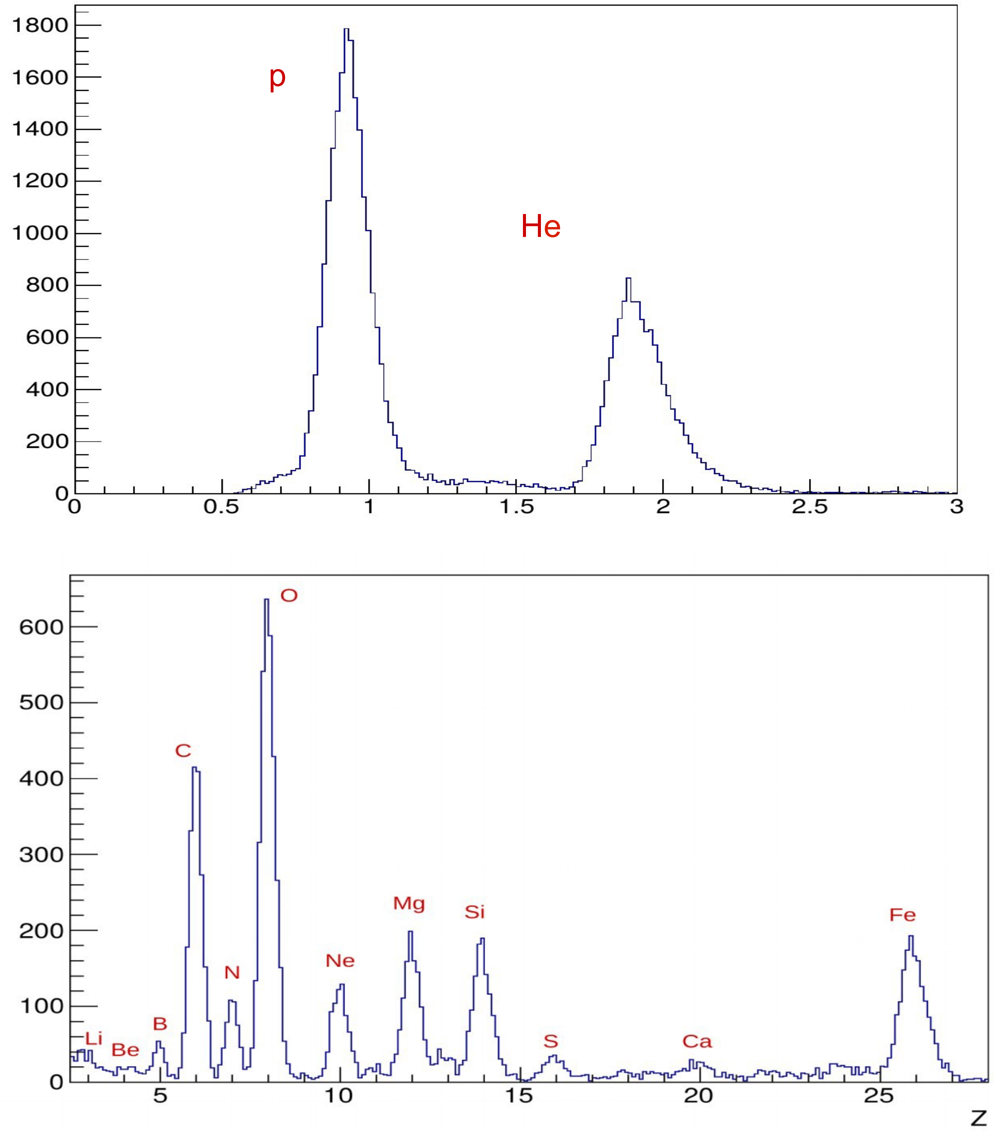
calorimeter energy resolution ~50% for p
~30% for Fe
~8% for e

Correlation of the calorimeter energy deposit (Ed) and KLEM parameter (S) ~90%

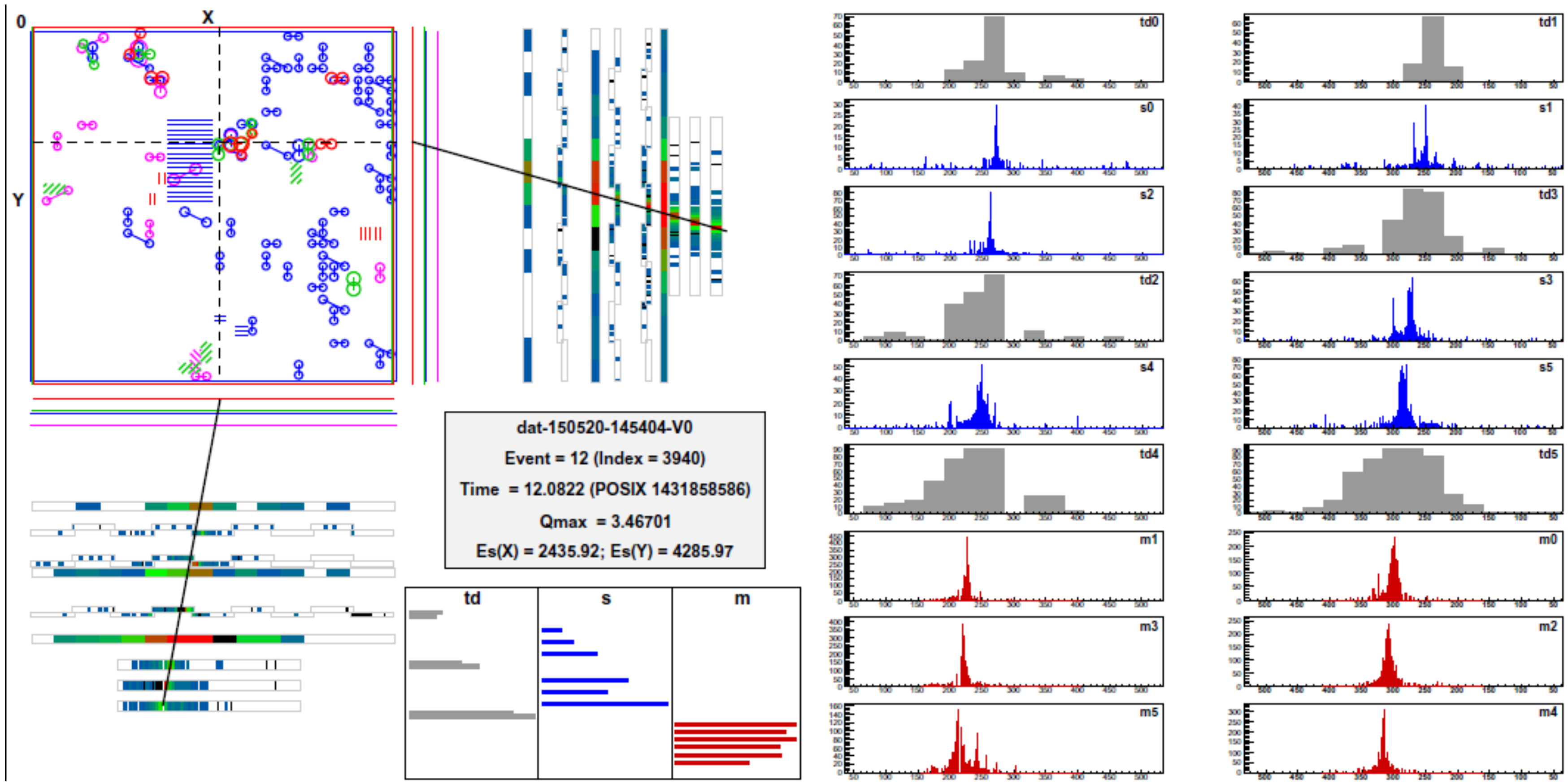


This correlation is a model-independent result

Charge resolution of four silicon planes detector ~0.2 charge units



An example of an event «portrait»



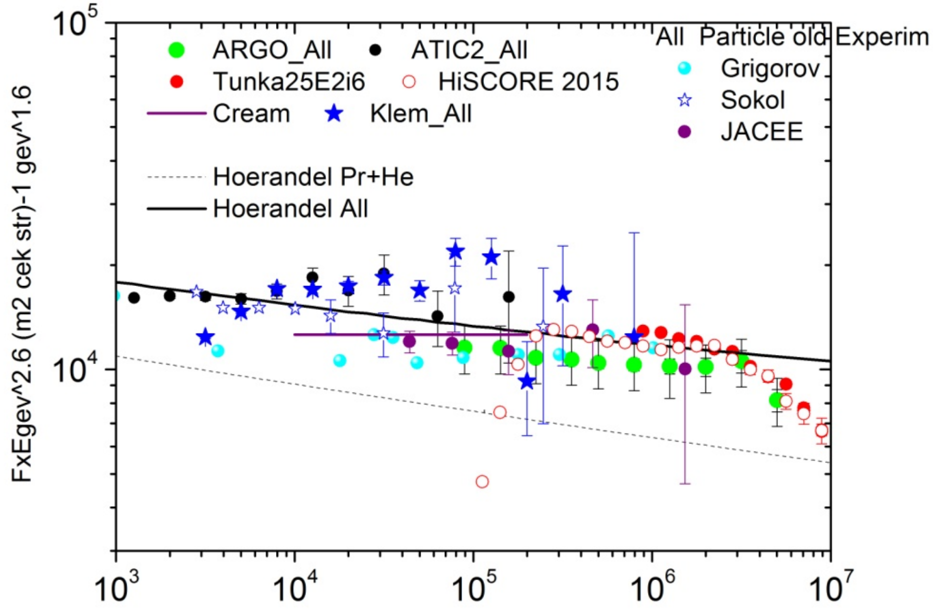
Preliminary results[1]

March 2015 -June 2016

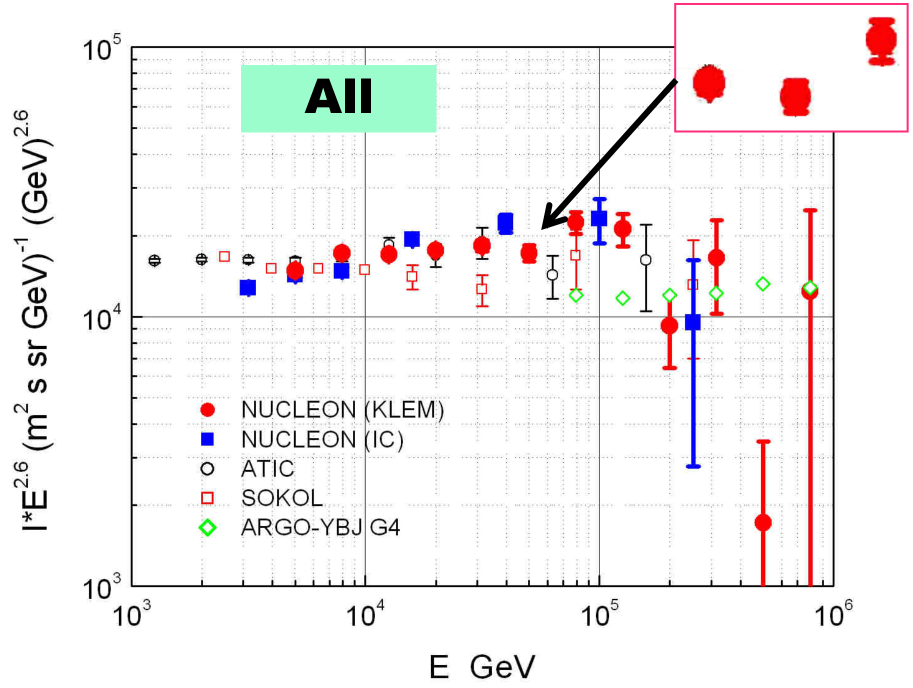
~1/5 expected statistics

[1]The results are preliminary!

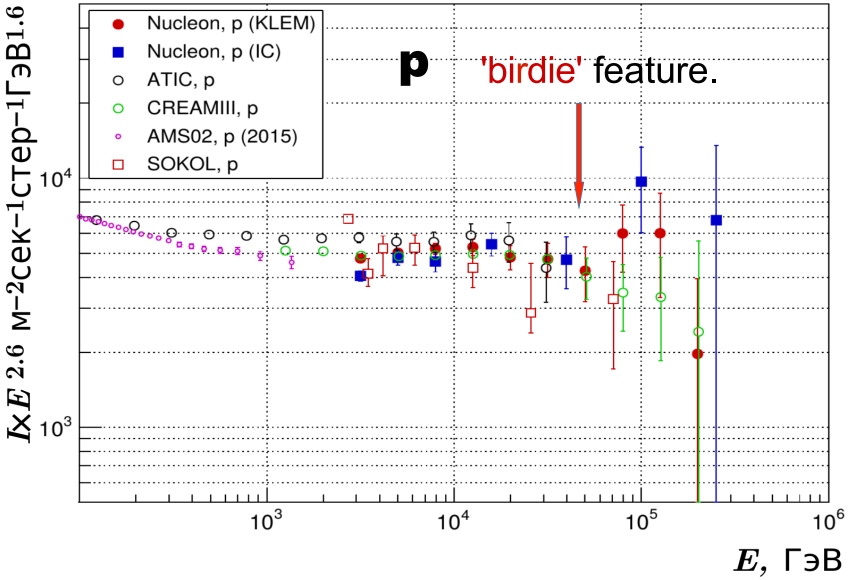
It is measured the all particles energy spectrum in the range of 3-1000 TeV by unified procedure.

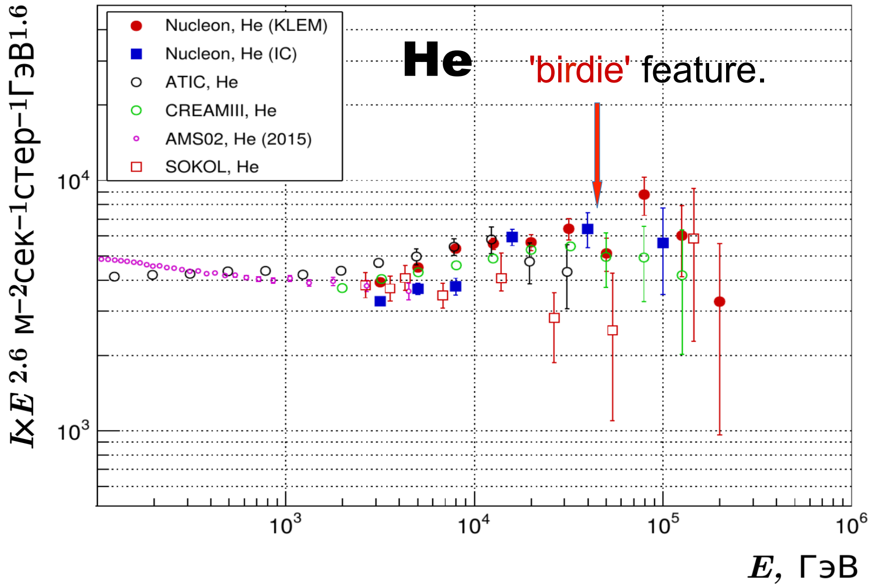


There is an indication of the feature at 30 TeV (~2.8σ)



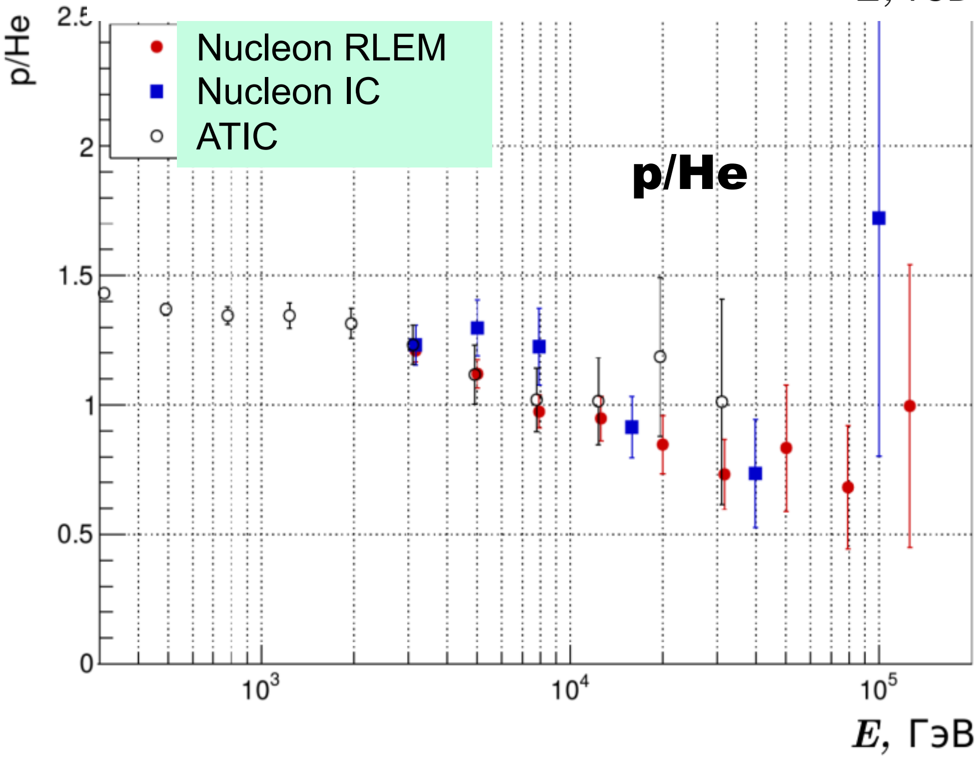
"birdie" feature.

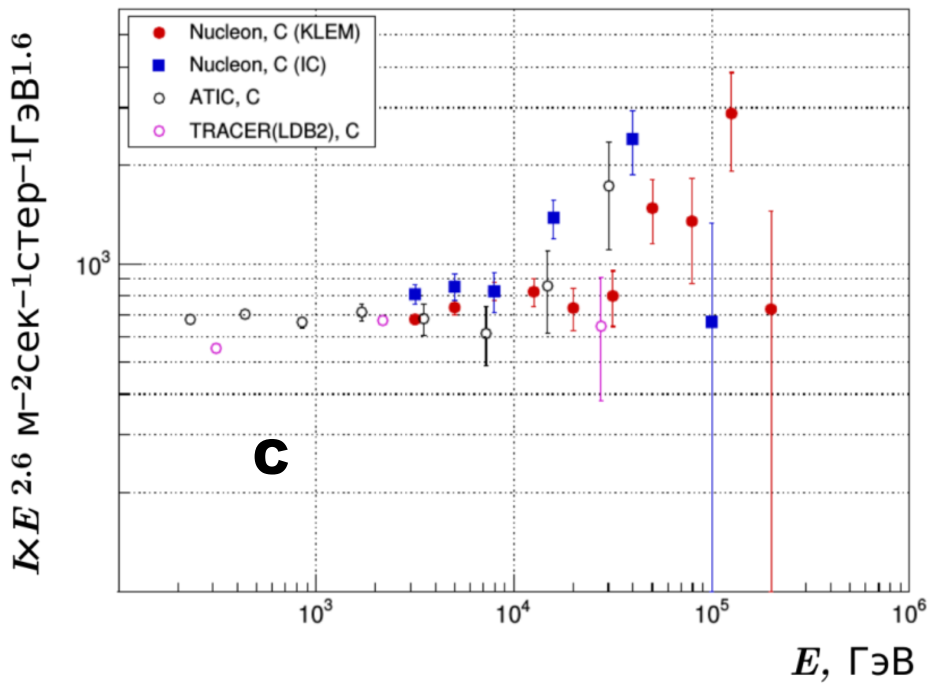


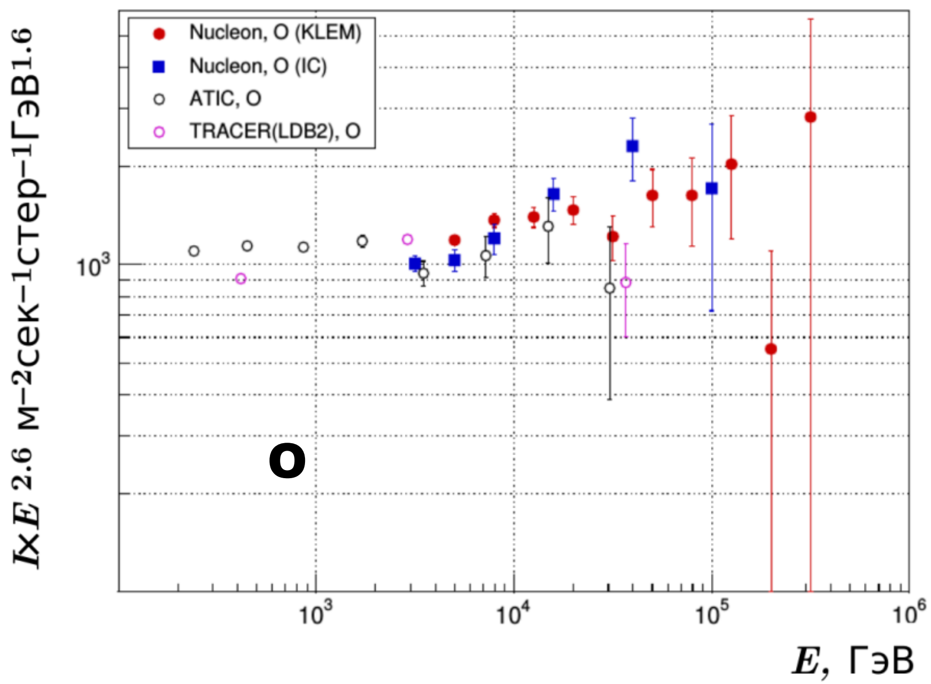


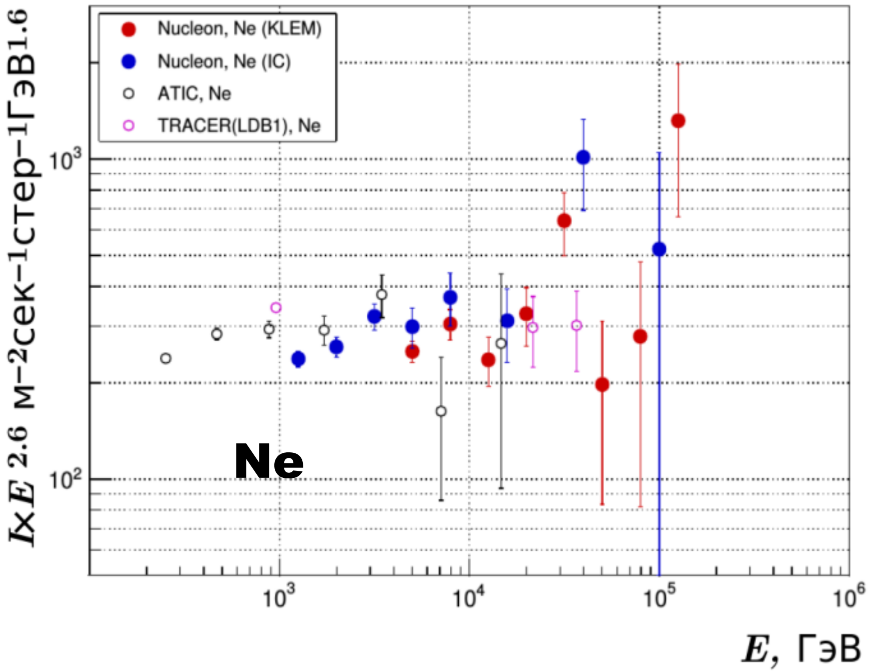
It is flatting spectrum of helium compared with the spectrum of protons.

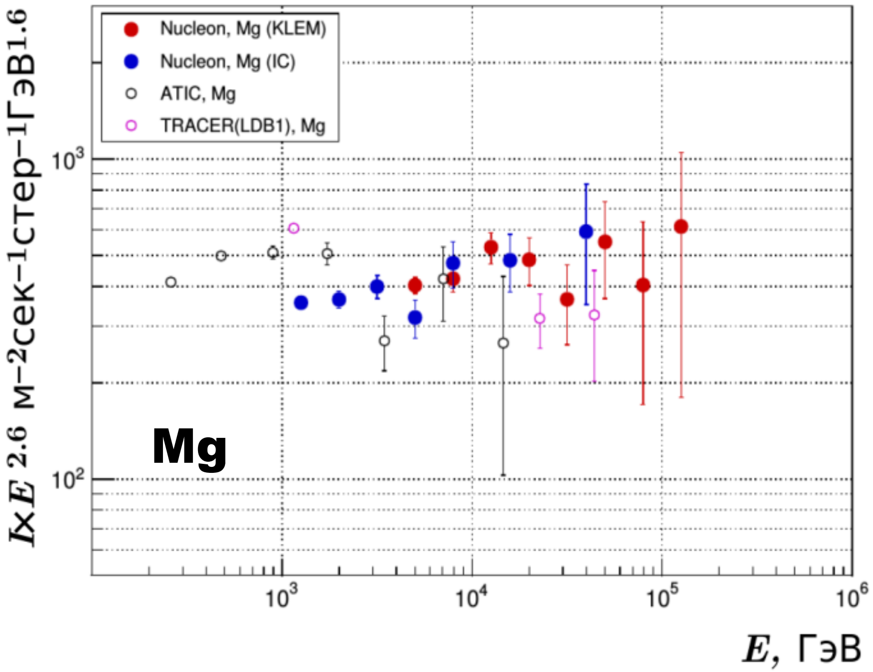
There is an indication that at energies above 100 TeV, the ratio of the slopes is reversed, but statistics is low.

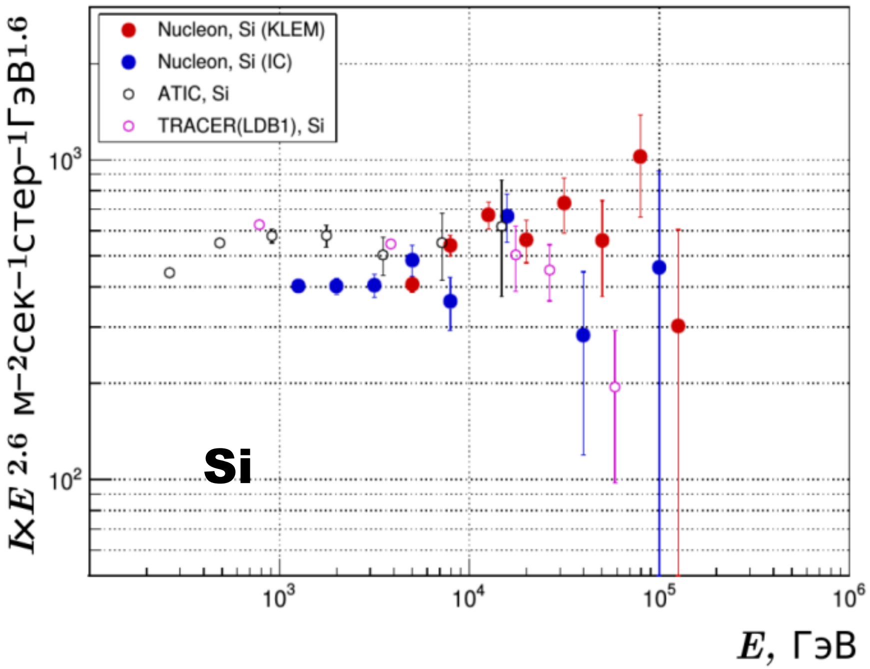


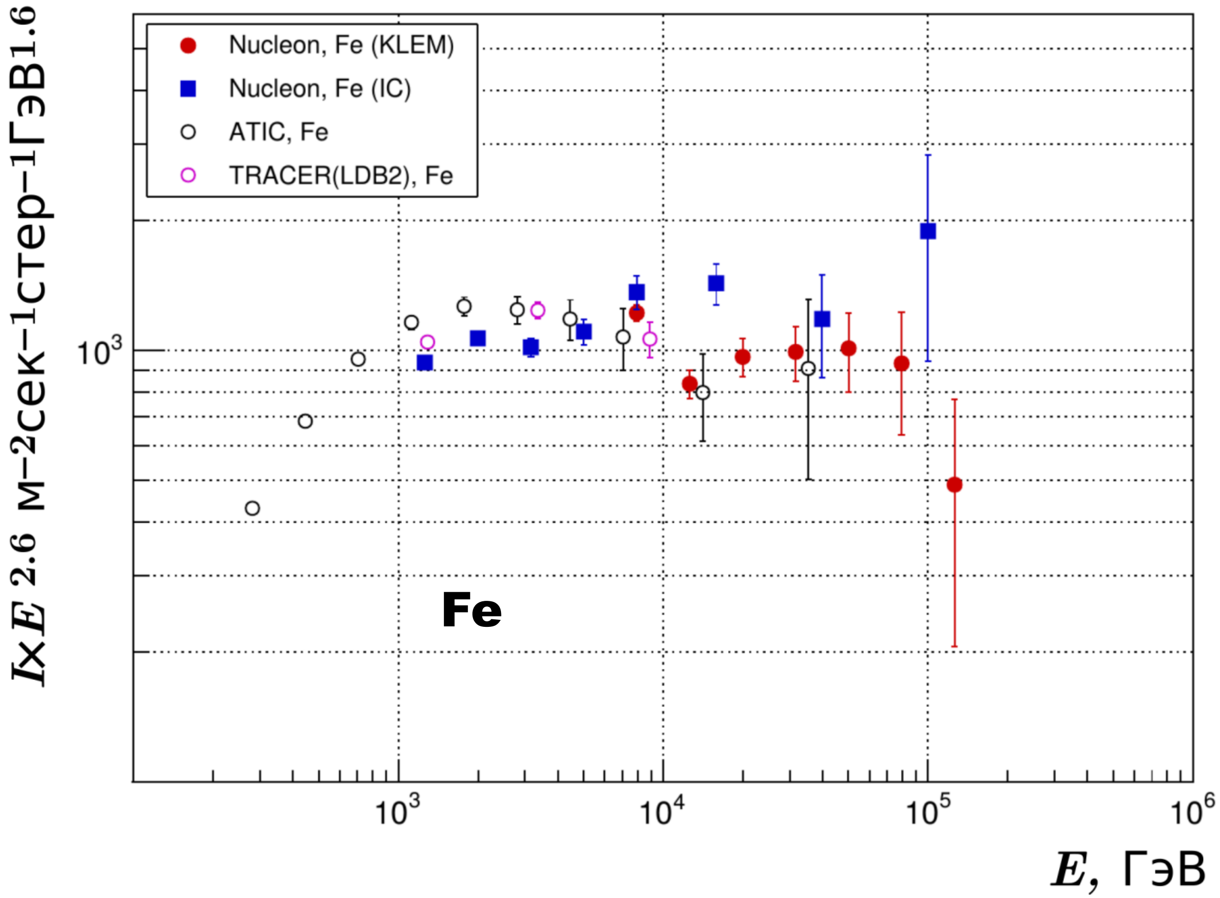

Nucleon, C (KLEM)
Nucleon, C (IC)
ATIC, C
TRACER(LDB2), C
C
$I \times E^{2.6}$ м$^{-2}$сек$^{-1}$стер$^{-1}$ГэВ$^{1.6}$
10^3
10^4
10^5
10^6
E, ГэВ


Nucleon, O (KLEM)
Nucleon, O (IC)
ATIC, O
TRACER(LDB2), O
O
$I \times E^{2.6}$ м$^{-2}$сек$^{-1}$стер$^{-1}$ГэВ$^{1.6}$
10^3
10^4
10^5
10^6
E, ГэВ


Nucleon, Ne (KLEM)
Nucleon, Ne (IC)
ATIC, Ne
TRACER(LDB1), Ne
Ne
$I \times E^{2.6}$ м$^{-2}$сек$^{-1}$стер$^{-1}$ГэВ$^{1.6}$
10^2
10^3
10^3
10^4
10^5
10^6
E, ГэВ


Nucleon, Mg (KLEM)
Nucleon, Mg (IC)
ATIC, Mg
TRACER(LDB1), Mg
Mg
$I \times E^{2.6}$ м$^{-2}$сек$^{-1}$стер$^{-1}$ГэВ$^{1.6}$
10^2
10^3
10^3
10^4
10^5
10^6
E, ГэВ

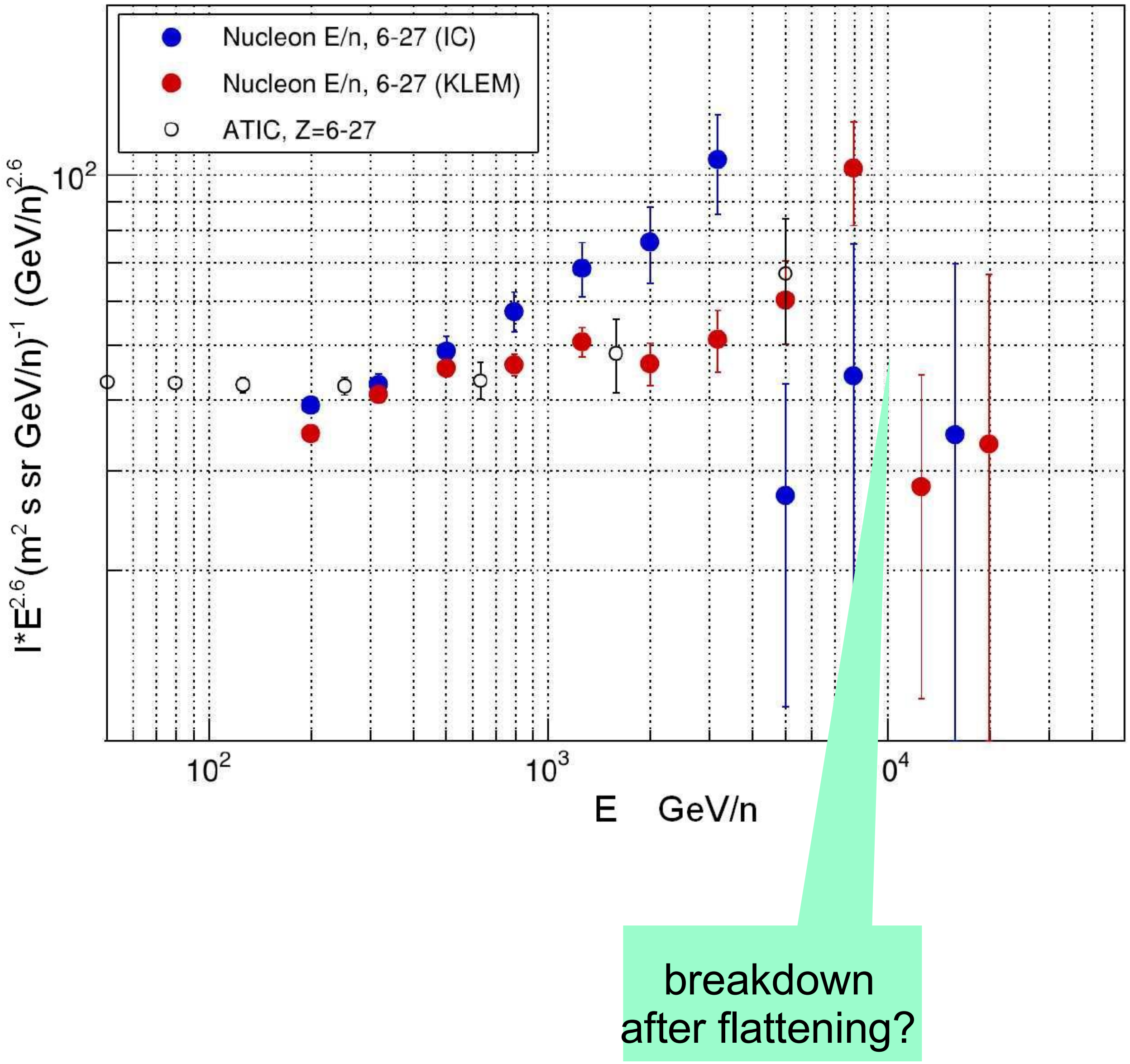

Nucleon, Si (KLEM)
Nucleon, Si (IC)
ATIC, Si
TRACER(LDB1), Si
Si
$I \times E^{2.6}$ м$^{-2}$сек$^{-1}$стер$^{-1}$ГэВ$^{1.6}$
10^2
10^3
10^3
10^4
10^5
10^6
E, ГэВ



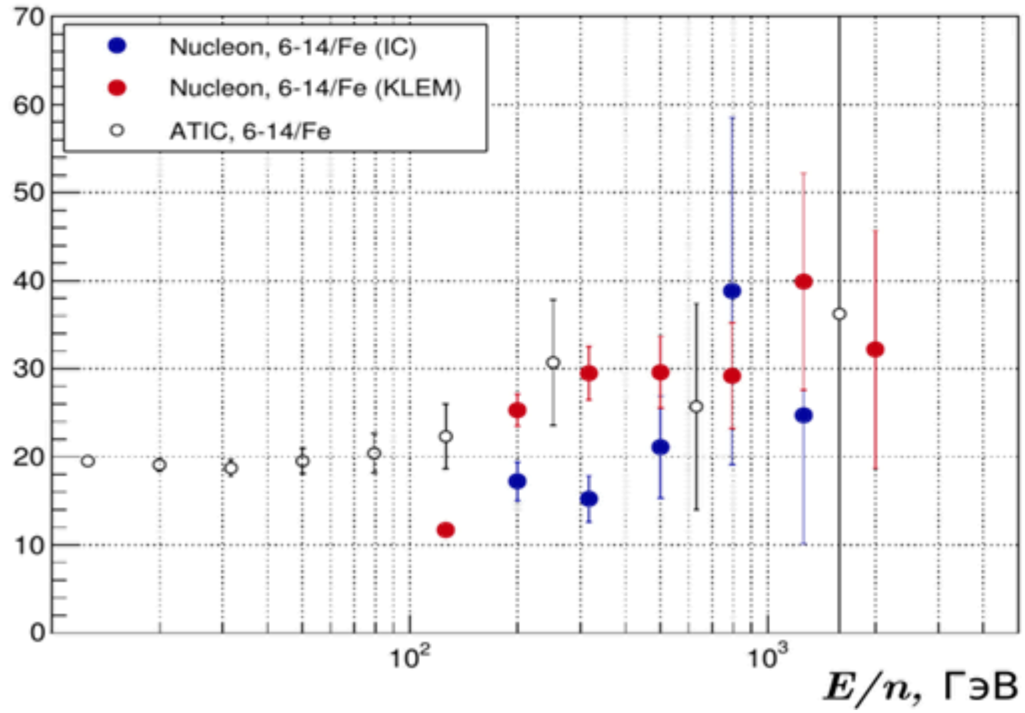
Nucleon, Fe (KLEM)
Nucleon, Fe (IC)
ATIC, Fe
TRACER(LDB2), Fe
Fe
10^3
10^4
10^5
10^6
$I \times E^{2.6}$ м$^{-2}$сек$^{-1}$стер$^{-1}$ГэВ$^{1.6}$
E, ГэВ

Spectra of heavy nuclei (except iron) at energies above 500 GeV per nucleon is hard flat (spectral index ~ 2.4).

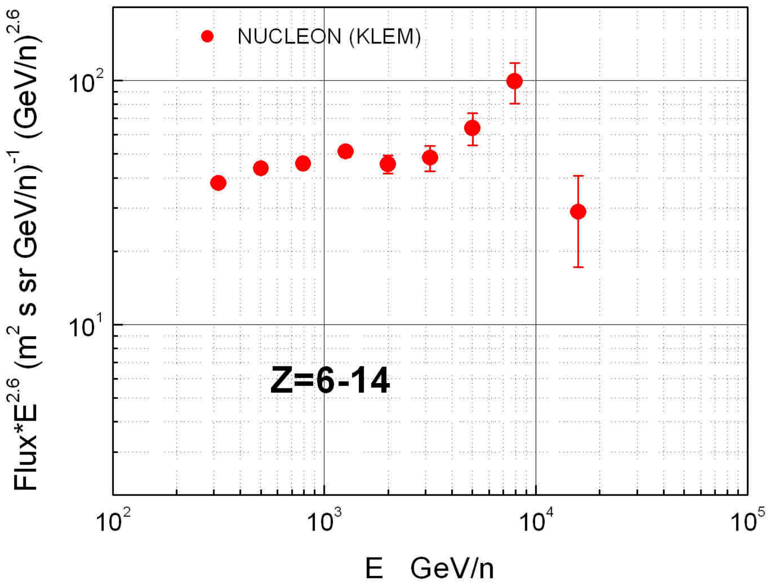
There is an indication that at energies of 5-10 TeV per nucleon this is a spectra break, but statistics is low.



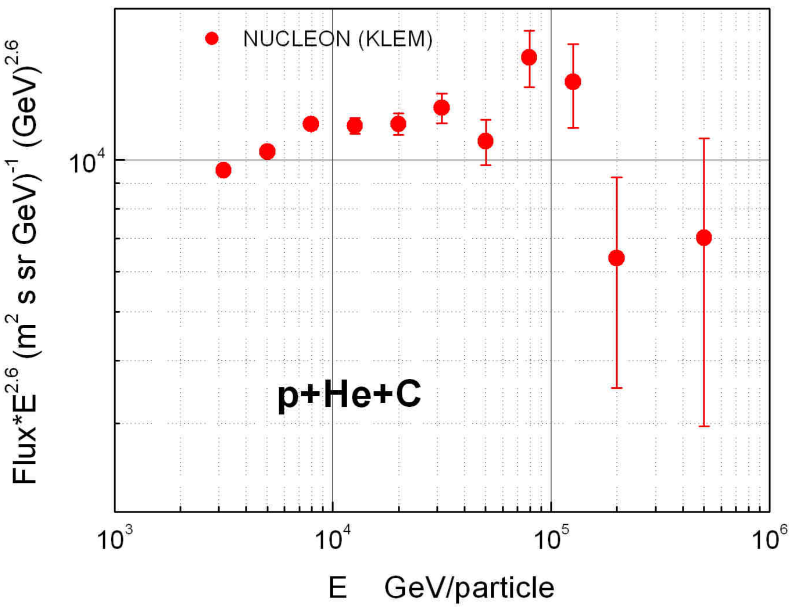
The iron spectrum is steeper than the other spectra of heavy nuclei at energies above 100 GeV per nucleon (~ 4 σ).



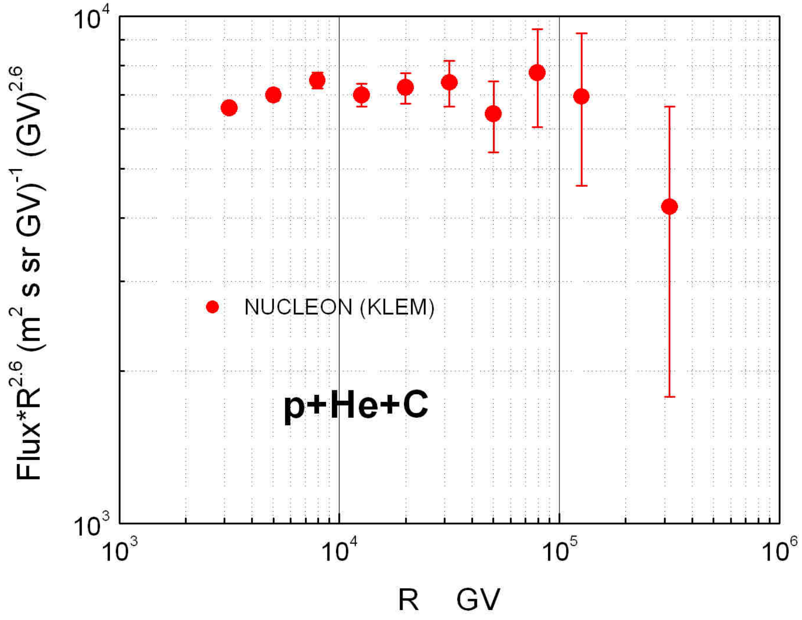
According to the experiment data NUCLEON this effect exists up to energies of 2 TeV/n



all particles spectrum "birdie" feature is stronger in (p+He+C) per particle spectrum (~ 3.2 σ)



And it is loose in (p+He+C) per rigidity (nucleon) spectrum (~ 1.8 σ)



Conclusions

- The preliminary analysis of the NUCLEON space experiment data gives multiple indications of the existence of a number of features in the energy spectra of cosmic ray nuclei at energies from few TeV to ~100 TeV (per particle).

- NUCLEON space experiment is continuing……

NUCLEON-2

The isotopic composition: Z = 7-66

Charge composition: Z = 7-94 (+?)

Energy range E = 0.1-1.0 GeV / nucleon

Basic requirements for apparatus:

The geometrical factor should be at least 1.2 m^2 sr;

Orbital lifetime apparatus should be at least 5 years;

NUCLEON-2 spectrometer measurements fccuracy should be not less than 0.4%;

Energy area UHIS spectrometer should be

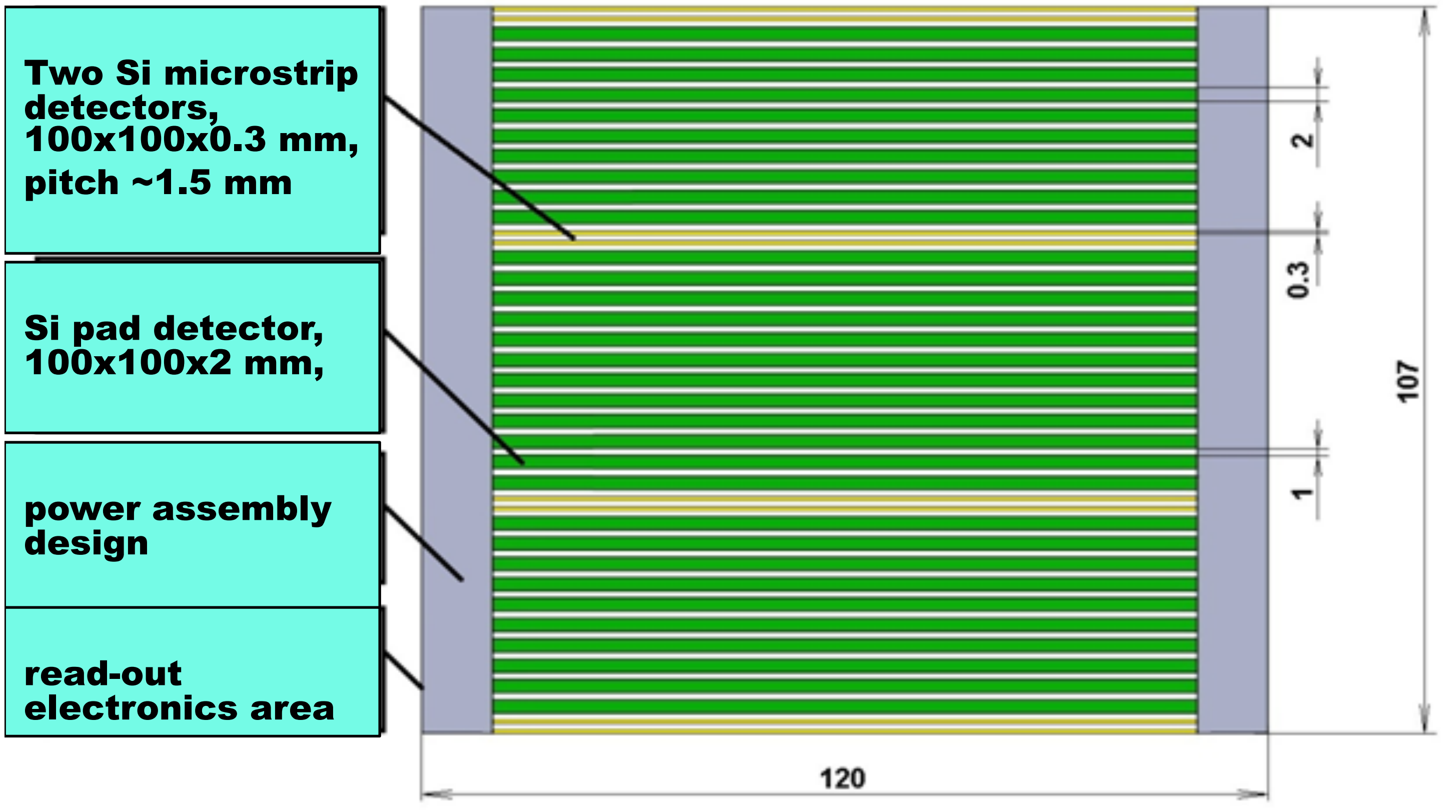
100-1000 MeV/nucleon

It is planned NUCLEON-2 apparatus will be placed on board of some regular satellite as an additional payload.

It is planned that the NUCLEON-2 will be consisting of separated towers.

Every HICRS tower (Heavy Isotopes Cosmic Rays Spectrometer) is independent for controlling

HICRS project design



HICRS has two symmetrical input windows

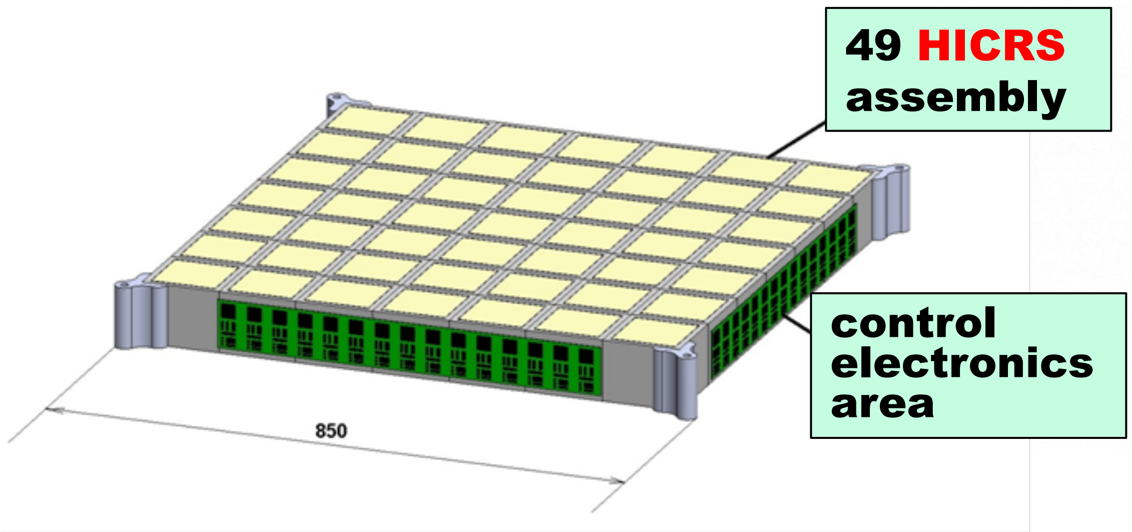
HICRS has «self trigger» system

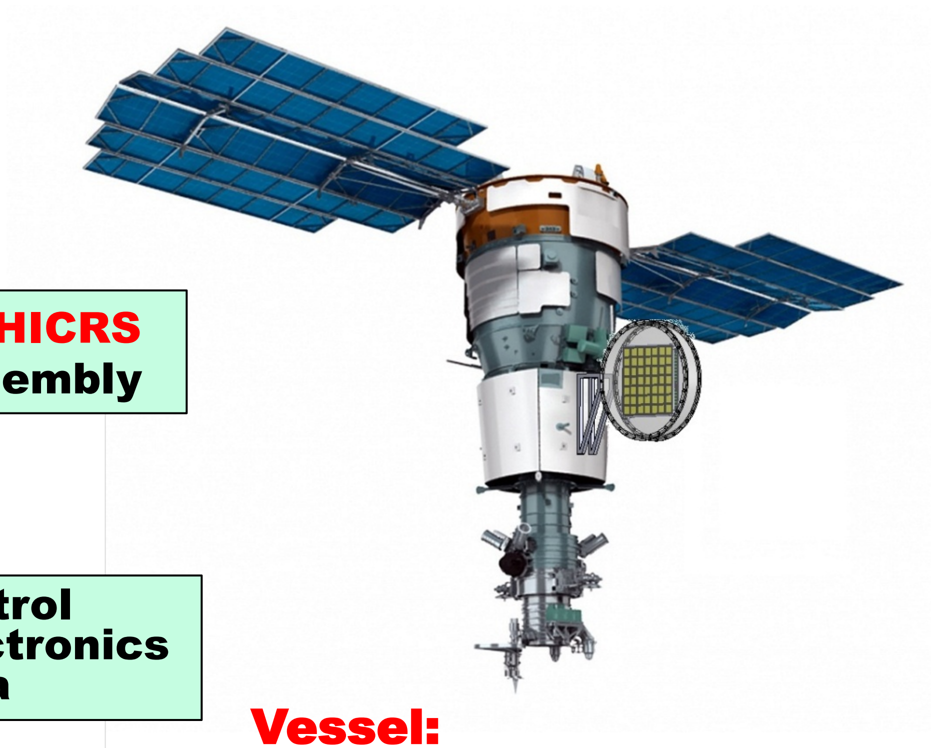
Weight <3 kg

Power consumption ~3 W

544 independent electronic channels

NUCLEON-2 project design





Vessel:

Weight ~ 220 kg

Power consumption ~220 W

Telemetry ~10 GB/day

27 000 independent electronic channels in total

Expected results for 5 years

(by estimation of HEAO-3-C3 and SuperTIGER data)

Isotopic resolution (green) | Charge resolution (yellow)

Nucleus, Z	N	Nucleus, Z	N
Fe 26	$3 \cdot 10^7$	Ho, 67	24
Co 27	$1.4 \cdot 10^5$	Er, 68	100
Ni 28	$1.1 \cdot 10^6$	Tm, 69	29
Cu 29	$1.6 \cdot 10^4$	Yb, 70	110
Zn 30	$1.6 \cdot 10^4$	Lu, 71	45
Ga 31	2000	Hf, 72	90
Ge 32	2300	Ta, 73	53
As 33	350	W, 74	100
Se 34	1400	Re, 75	78
Br 35	200	Os, 76	140
Kr 36	830	Ir, 77	145
Rb 37	250	Pt, 78	220
Sr 38	1000	Au, 79	160
Y 39	250	Hg, 80	150
Zr 40	500	Tl, 81	85
Nb 41	150	Pb, 82	155
Mo 42	230	Bi, 83	62
Ru 44	100	Po, 84	75
Ag 47	140	At, 85	76
Cd 48	120	Rn,86	30
Sn 50	120	Fr, 87	3
Te 52	140	Ra, 88	12
Xe 54	80	Ac, 89	3
Ba 56	180	Th, 90	13
Ce 58	50	Pa, 91	2
Nd 60	40	U, 92	53
Dy 66	180	???	???

by simulation (GEANT-3, GEANT-4, FLUKA)

Neural network analysis

Multivariate statistical technique with maximum likelihood method

HERO (High-Energy Ray Observatory)

>E eV	10^{14}	10^{15}	10^{16}
N m^2sr year	2100	46	0.8

General requirements:

for solving 10^{14} - 10^{16} eV range problems it is necessary at least 100 m^2sr year exposure !

For peculiarities spectra - High energy resolution
High charge resolution
High rejection level: Protons/electrons+γ
High rejection level: Gamma/electrons

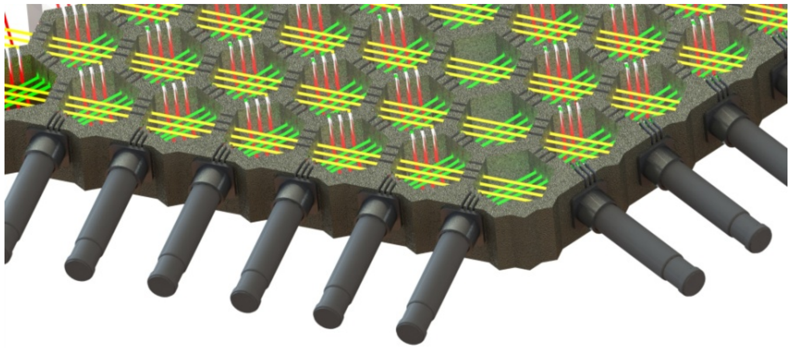
HERO pre-project design

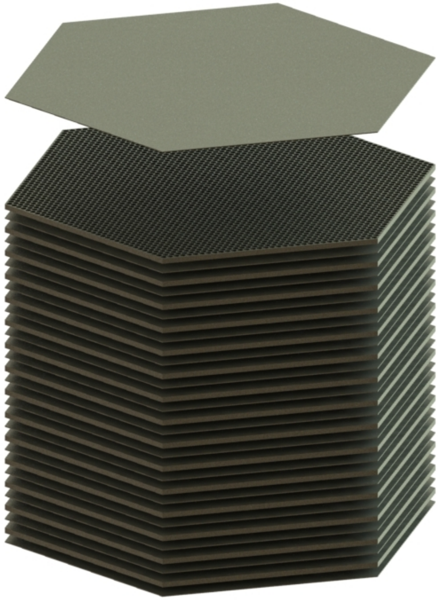
Ionization calorimeter consisting of 15 identical layers.

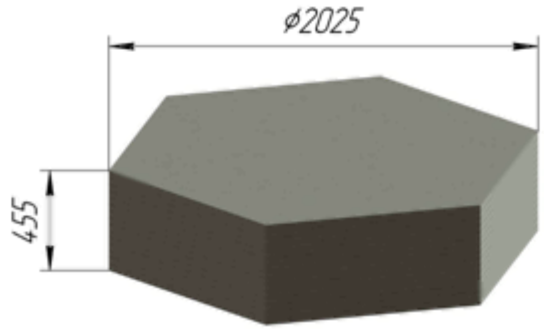
Each layer consists of a hexagonal plane, 25 mm thick and 2025 mm the diameter of the circle

Active medium in a layer - scintillator (ρ~1.0 g/cm^3)

Absorber - tungsten-copper-nickel alloy (ρ~16.0 g/cm^3).







In each direction - 3 fiber

The light signal of each fiber are recorded PMT

3060 - number of registration channels

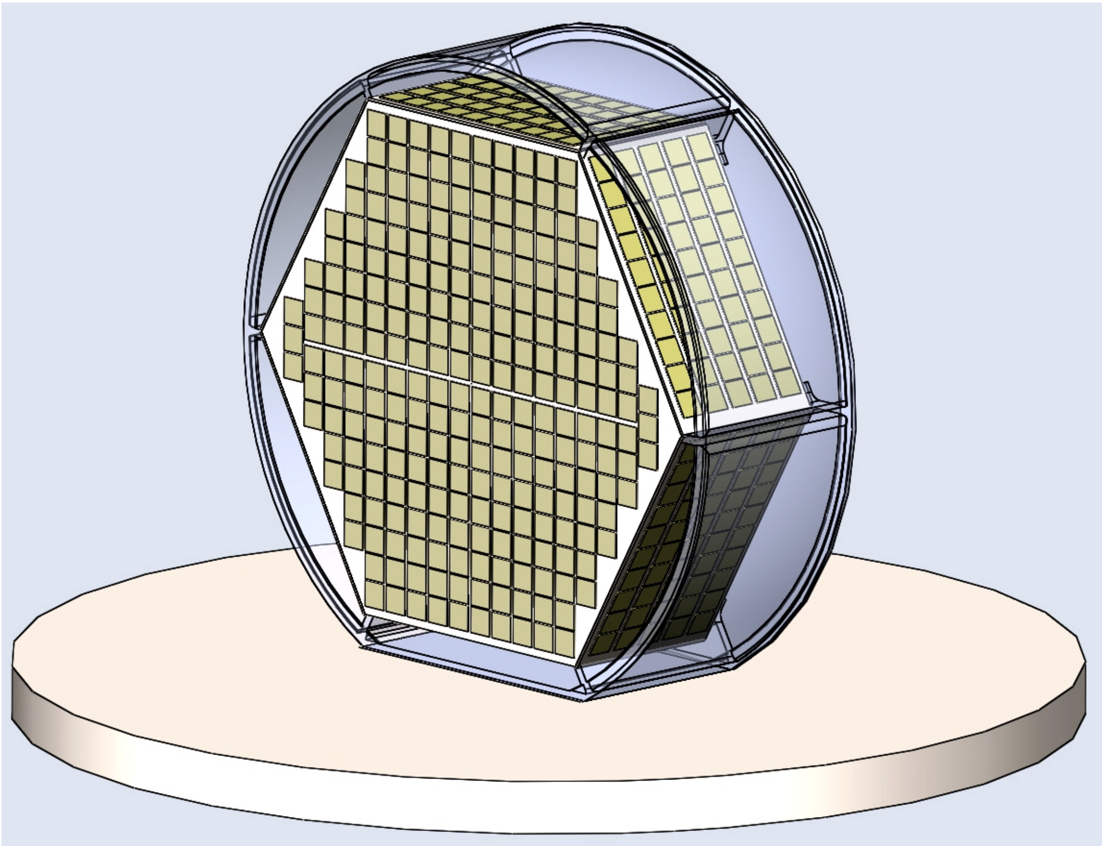
~ 10 tons - Weight

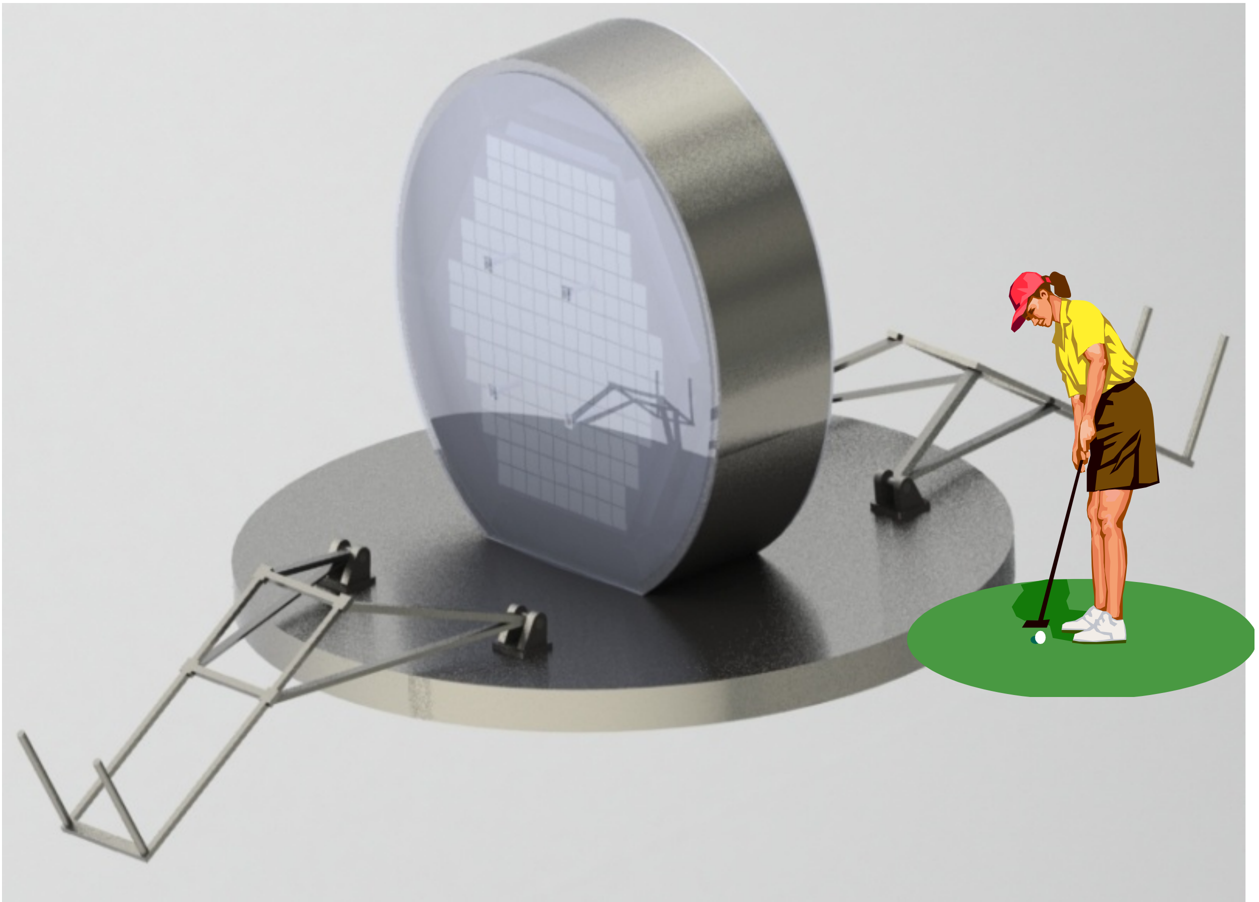
~40 - X-lengths

~ 4 λ_p - proton inelastic interaction length

IC is surrounded by a four laies silicon detectors (like NUCLEON)

~2x10^5 - number of registration channels





HERO exposure – on Low Earth Orbit (weight saving)
Optimization in low Earth orbit - to orient the device by one of the six side surfaces to the Earth. (~ 50% increase in the geometric factor).
Total weight 12.5 tones

HERO general characteristics
(by simulation)

Effective geometrical factor: Protons ~ 9 m^2sr
Nuclei ~ 14 m^2sr
Electrons and gamma ~ 16 m^2sr

Exposition factor: Protons ~ 90 m^2sr year
(10 years flight) Nuclei ~ 140 m^2sr year
Electrons and gamma ~ 160 m^2sr year

Energy resolution: Protons - ~ 20%
Nuclei- ~ 10-15%
Electrons and gamma ~ 5%.

Charge resolution: 0.2 charge unit.

Rejection level: Protons/electrons 10^5-10^6
Gamma/electrons $>10^3$