Skobeltsyn Institute of Nuclear Physics
Lomonosov Moscow State University

NUCLEON

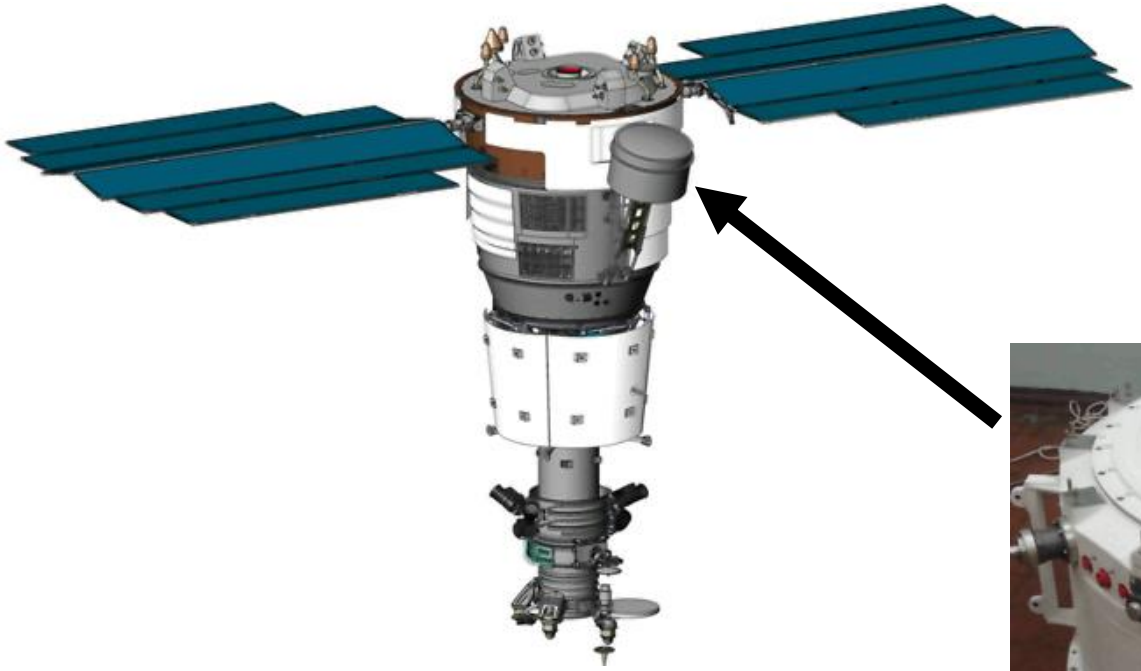
Chemical Composition and Energy Spectra of Cosmic Rays at 1-1000 TeV

D. Podorozhny for "Sources of Galactic cosmic rays"

APC, Paris - December 11-14, 2018

NUCLEON mission

NUCLEON apparatus is placed on board of the RESURS-P regular satellite as an additional payload. The spacecraft orbit is with inclination 97.276° and an average altitude of 475 km.
Lanuched December 28, 2014, Switched on January 11, 2015,
From March 2015 up to now - regular measurements



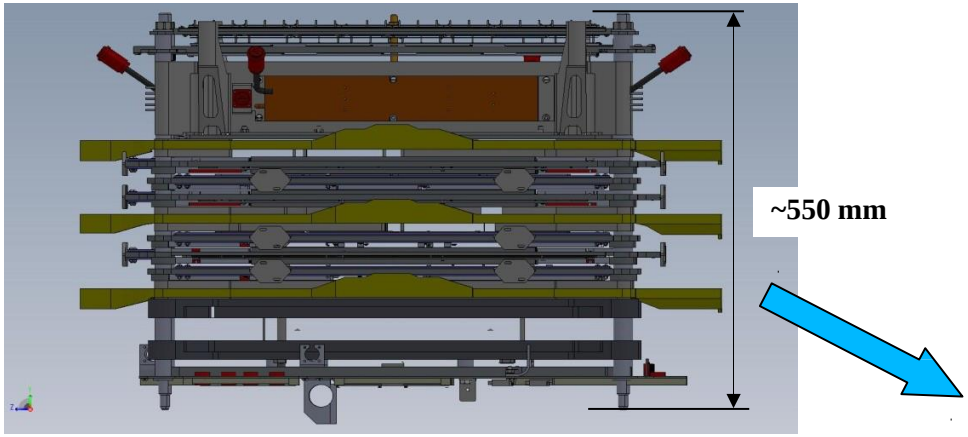
Vessel:

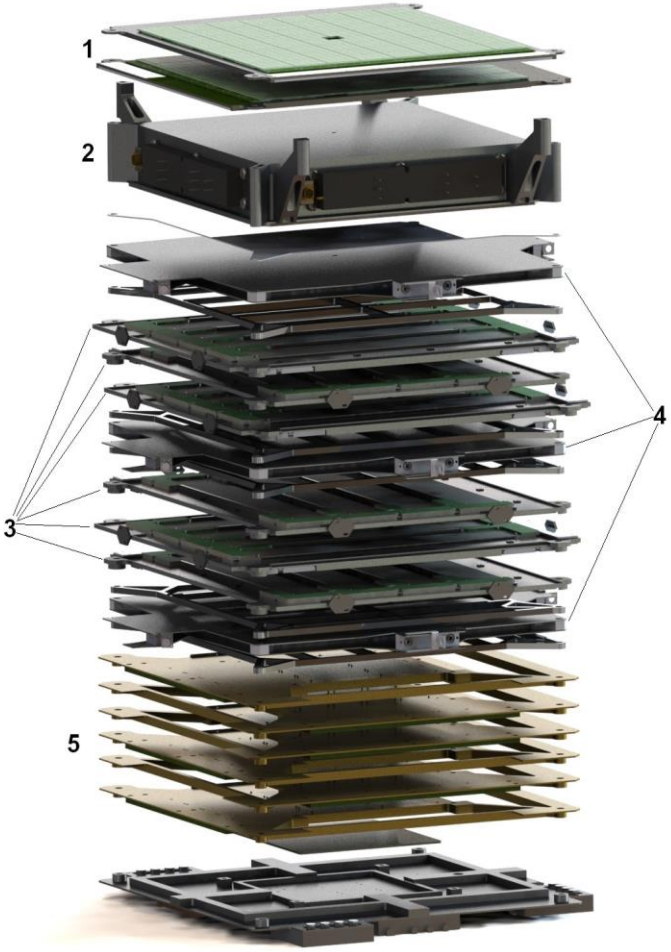
Weight ~360 kg

Power consumption ~160 W

Telemetry ~10 GB/day

The NUCLEON apparatus





- **Charge measurement system** – four planes of pad silicon detectors (1.5×1.5 cm²) (**1**);
- **tracker for KLEM energy measurement** – carbon target of 0.25 proton interaction lengths (**2**) and six planes of microstrip silicon detectors (0.4mm pitch) with tungsten between them (~2mm each, ~3 X-lengths in total) (**3**);
- **trigger sysytem** – three double scintillator planes (**4**).

Active area 500*500 mm².
Geometrical factor ~0.2 m²sr.

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

Active area 250*250mm².

Geometrical factor (together with charge and KLEM systems) ~0.06 m²sr.

10604 independent electronic channels in total

Important Feature of the NUCLEON experiment:

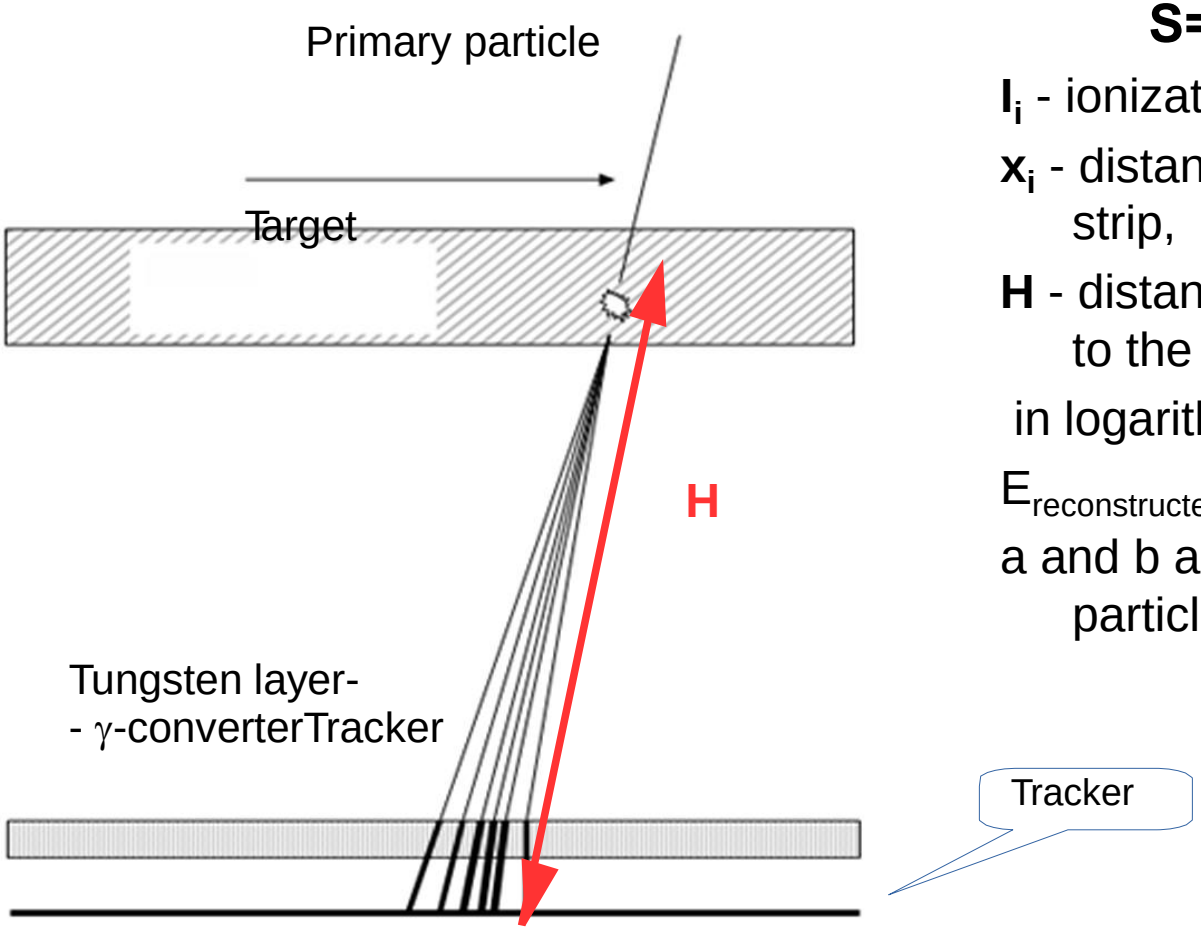
Two different methods of measuring energy of particles are implemented in the NUCLEON experiment at the same time:

1. **The kinematic method KLEM - for the first time**
2. **The calorimetric method - usual and well studied**

KLEM

Kinematic Lightweight Energy Method

is based on measurements of spatial density of secondary particles at beginning stage of development of nuclear and electromagnetic cascades (a combination of kinematic techniques and of ultra-thin calorimeter method)



$$S=\sum \eta_i^2 N_i \sim \Sigma I_i \ln^2(2H/x_i)$$

$\eta_i = -\ln \mathrm{tg}\theta_i/2$

I_i - ionization in a strip,

x_i - distance from the event axis to the strip,

H - distance from the center of the target to the strip plane.

in logarithmic scales

$E_{reconstructed} = aS^b$, $<(E_{rec} / E)> = 1$

a and b are the parameters of the particle (charge) type.

resolution ~60%

Thin Calorimeter

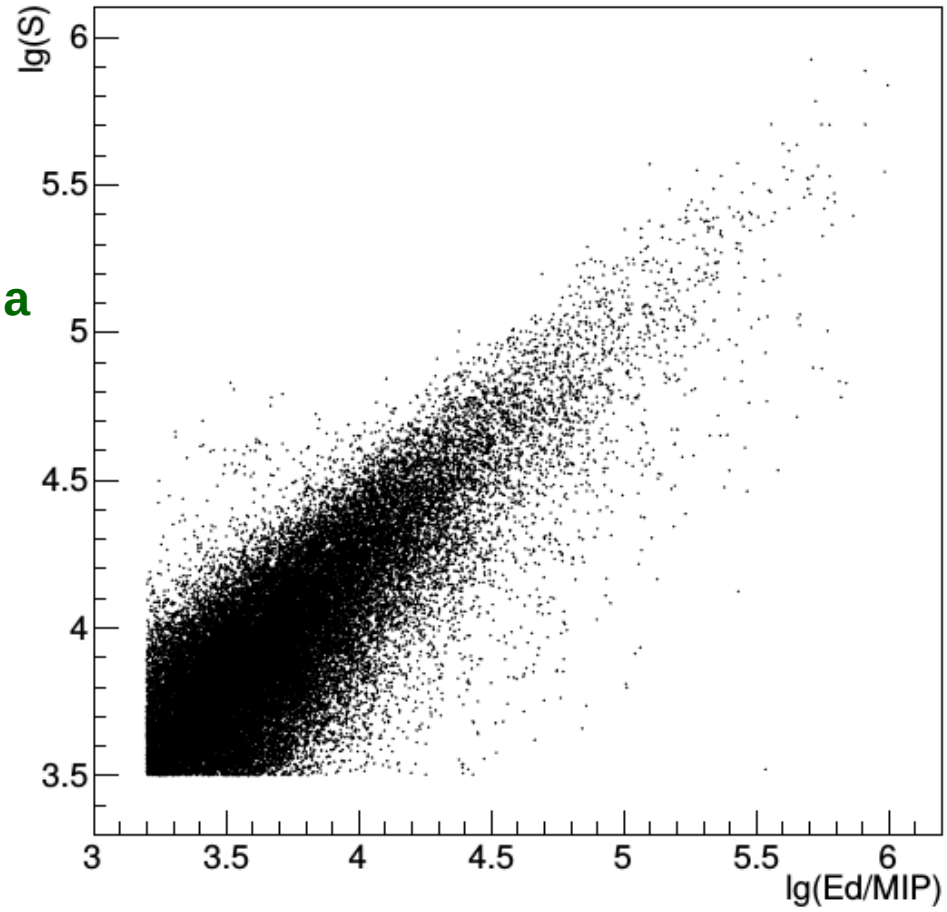
resolution p~45%, Fe ~35%, e^- ~8%

A mini ionization calorimeter (MIC) was added to the NUCLEON apparatus. MIC covers ~ 25% of the aperture of the KLEM spectrometer. The main task is to control the functioning of the KLEM, and, if necessary, to carry out flight calibration. The electron spectrum was determined by MIC

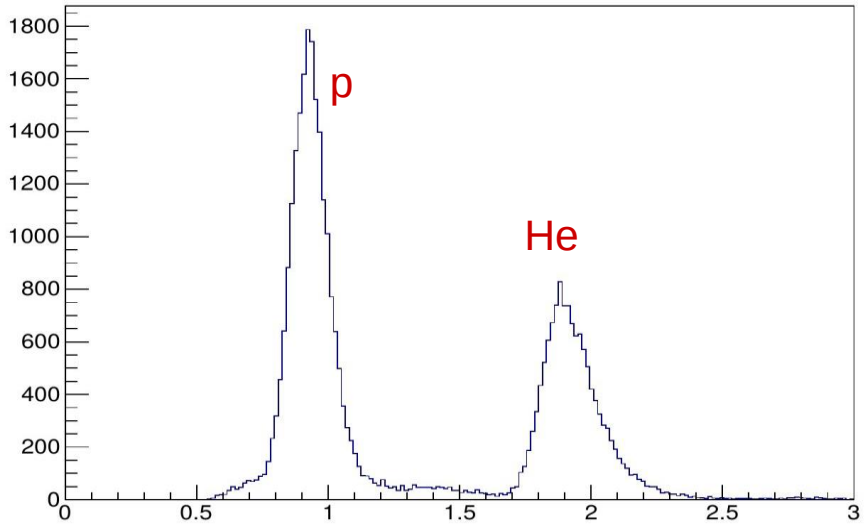
Correlation of the calorimeter energy deposit (Ed) and KLEM parameter (S)

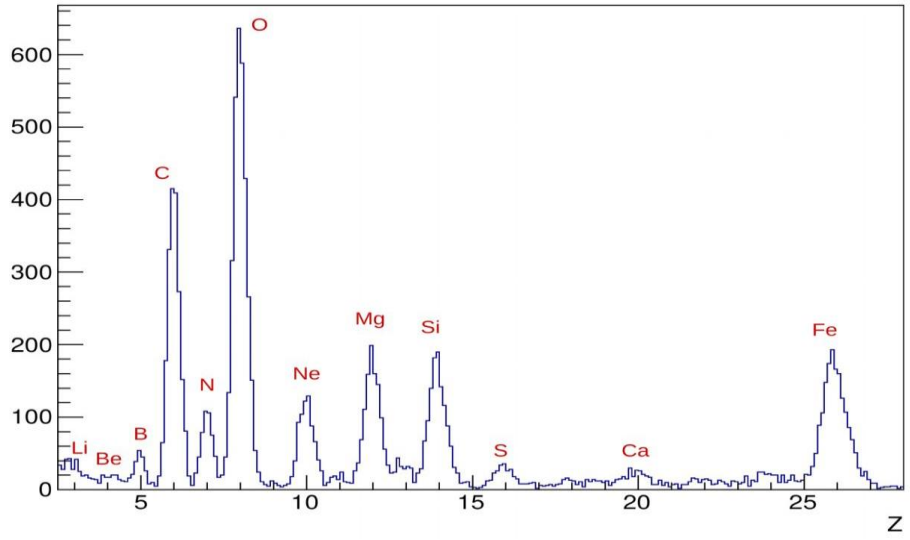
This experimental correlation is a model-independent result

Correlation coefficient ~ 0.9



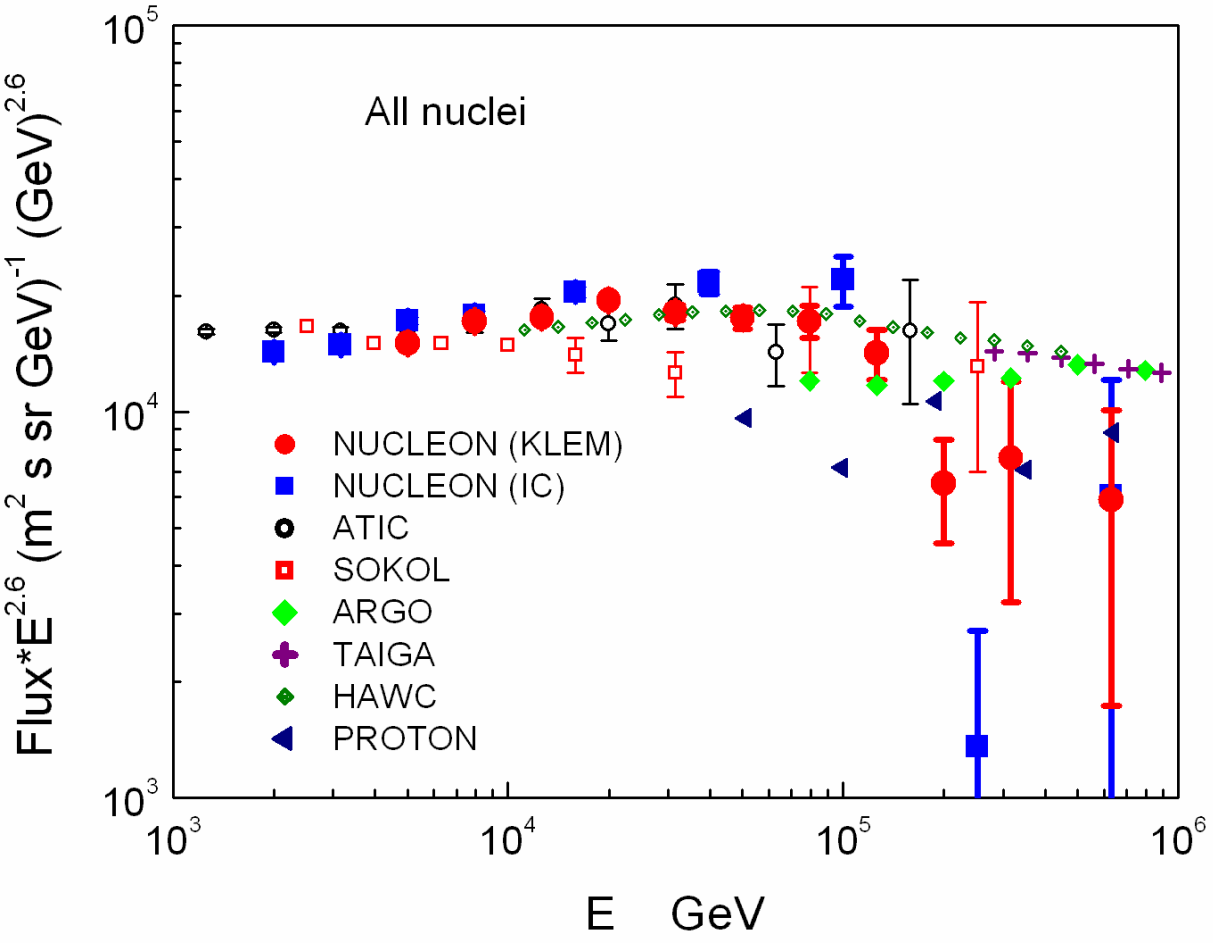
Charge Measurement



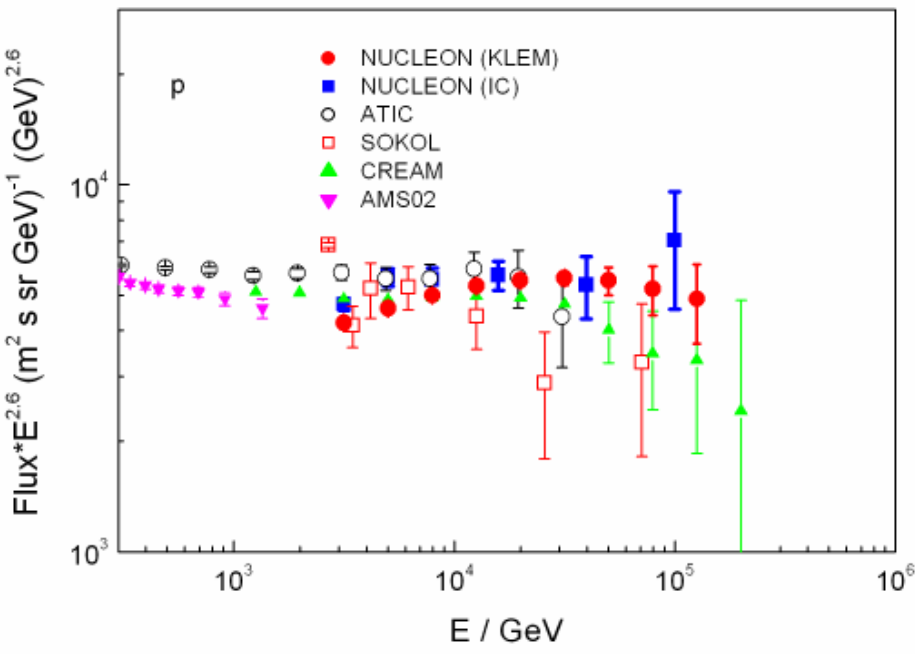


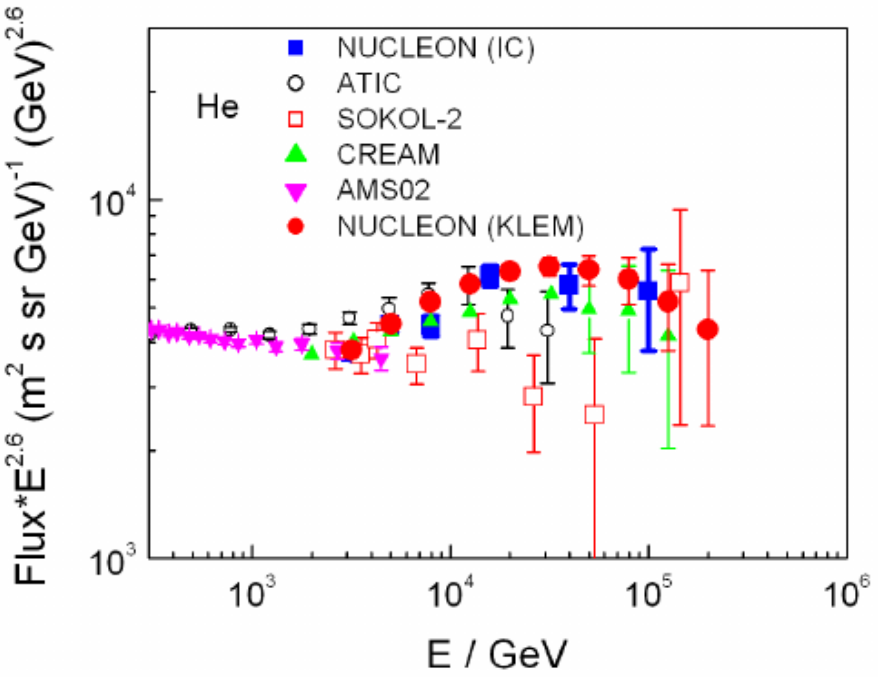
charge resolution in space experiment ~0.2 ch.u.!

The main results of the space experiment NUCLEON (2018)

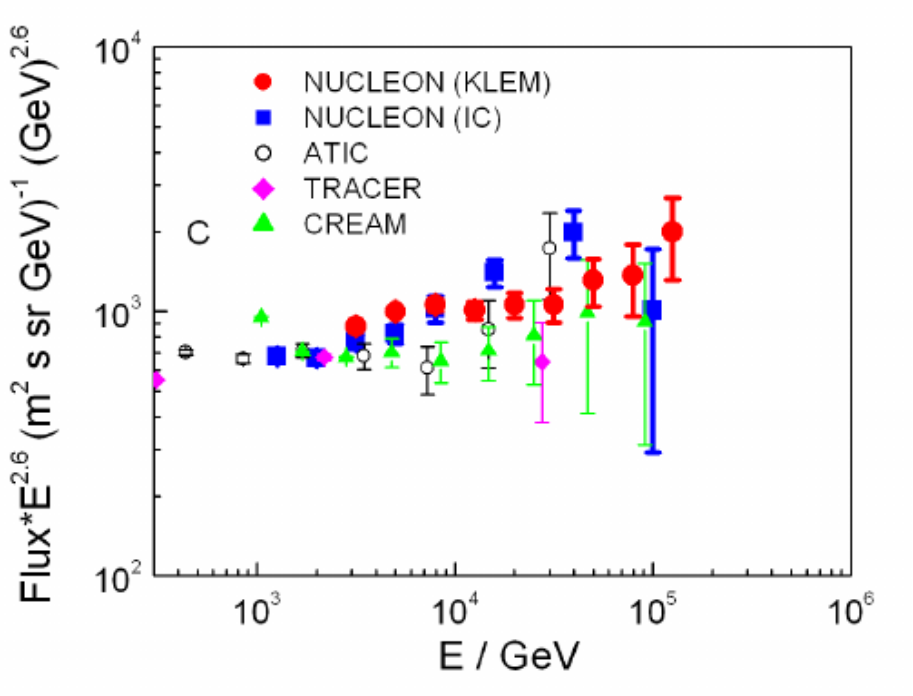

All nuclei
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
SOKOL
ARGO
TAIGA
HAWC
PROTON
Flux*E^2.6 (m^2 s sr GeV)^-1 (GeV)^2.6
E GeV
10^3
10^4
10^5
10^6

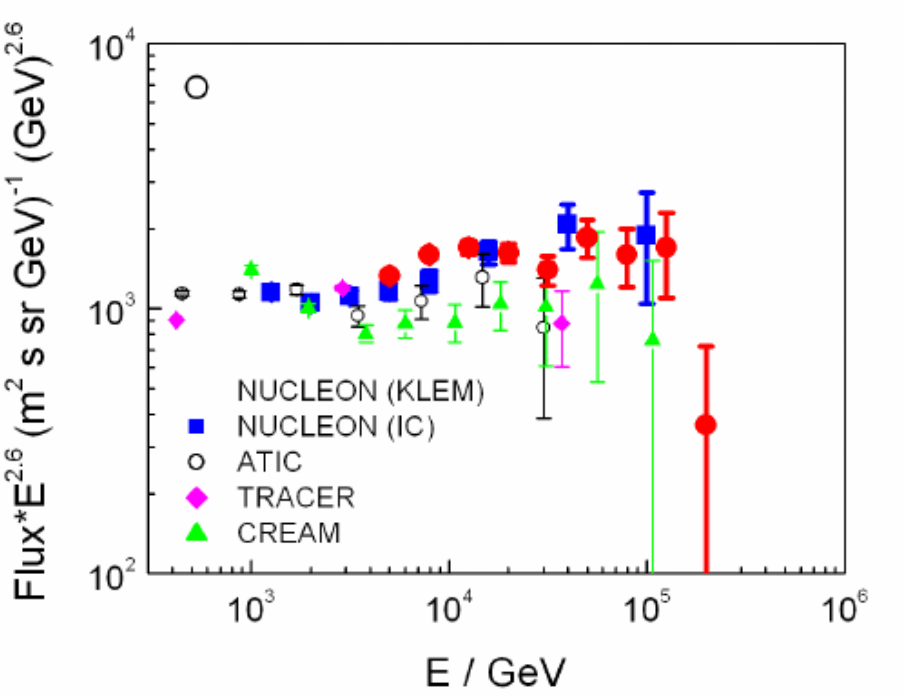
Protons and Helium



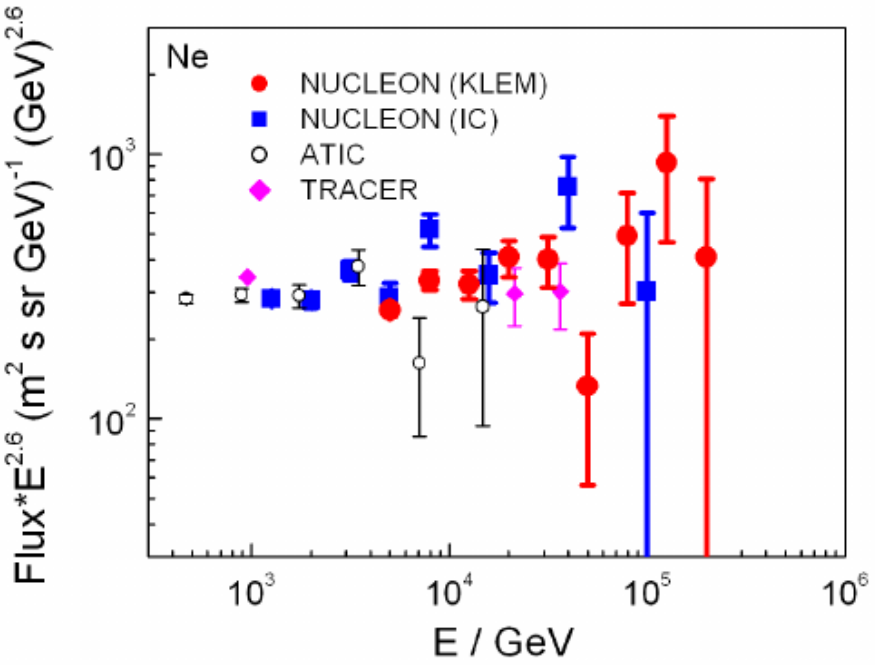


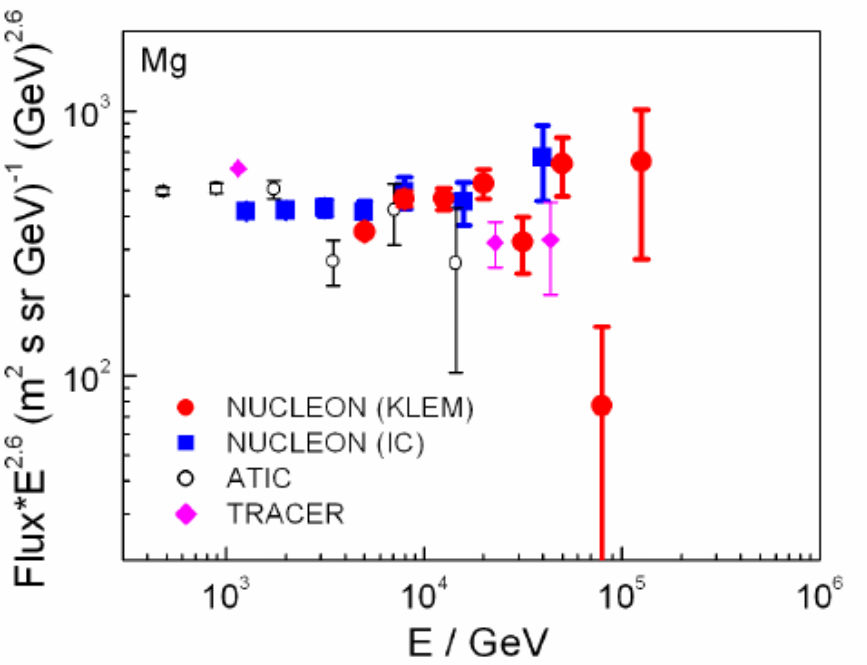
Carbon and Oxygen: hard above ~3 TeV

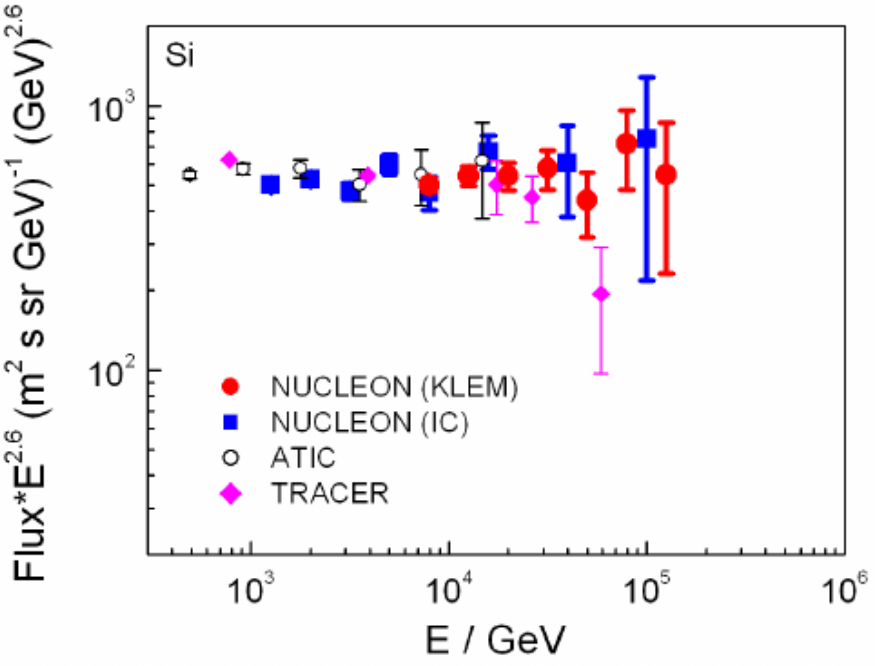




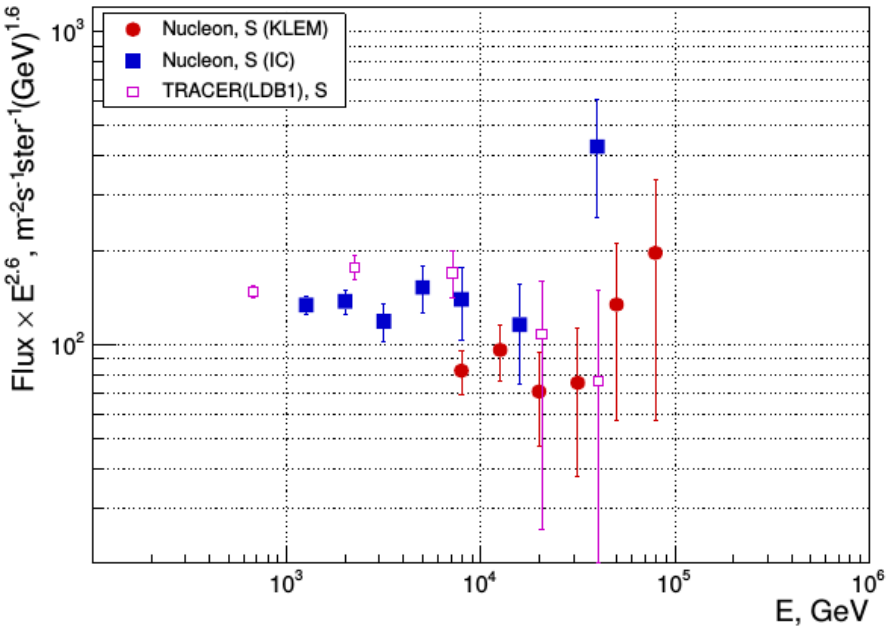
Ne-Mg-Si

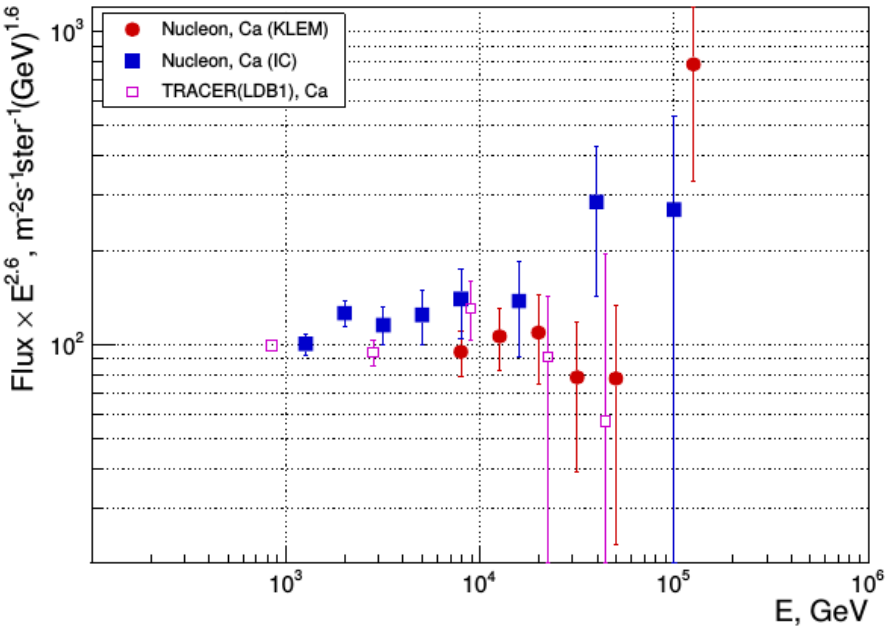

Ne
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
TRACER
Flux*E^2.6 (m^2 s sr GeV)^-1 (GeV)^2.6
E / GeV


Mg
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
TRACER
Flux*E^2.6 (m^2 s sr GeV)^-1 (GeV)^2.6
E / GeV

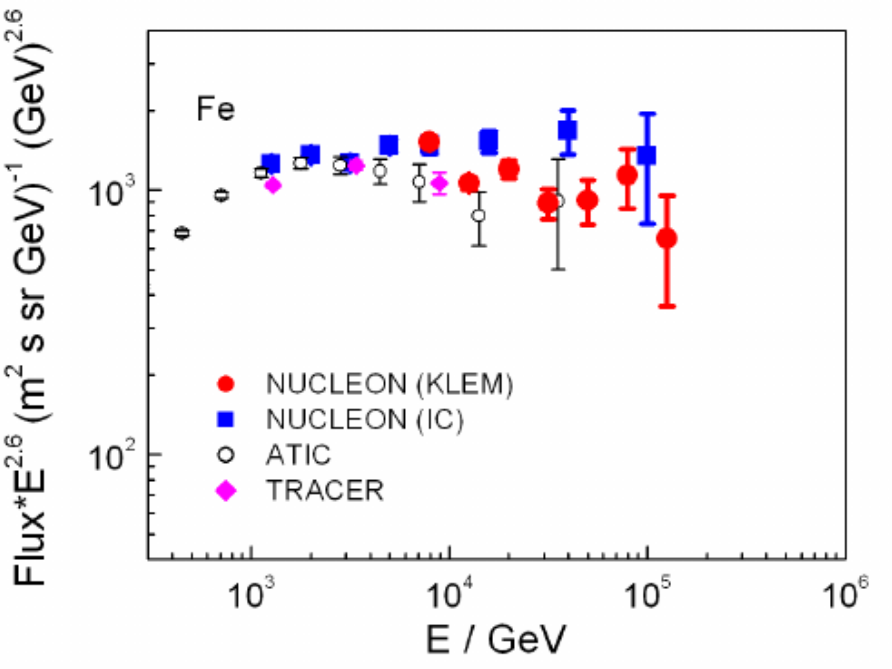

Si
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
TRACER
Flux*E^2.6 (m^2 s sr GeV)^-1 (GeV)^2.6
E / GeV

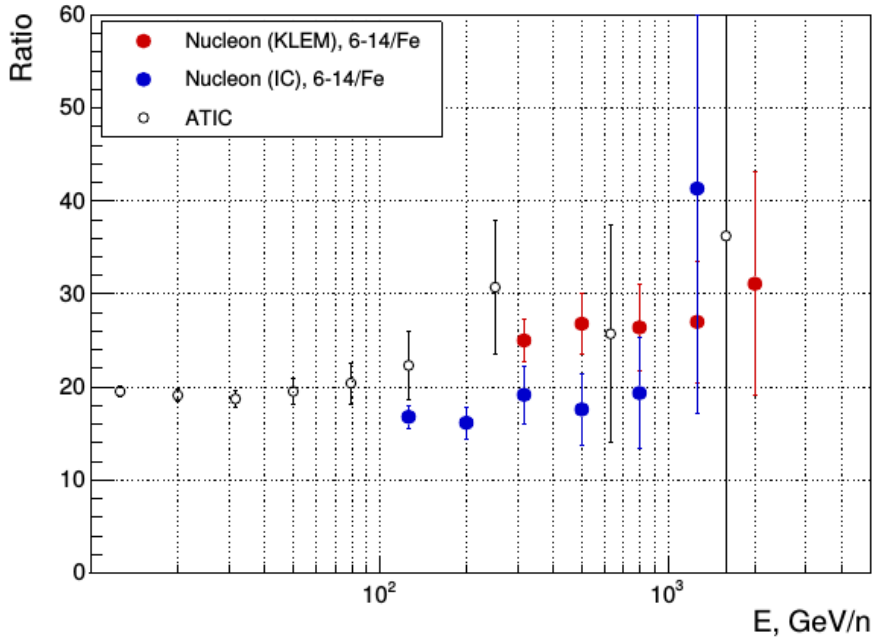
S and Ca - hints of complicated behavior, more statistics are needed





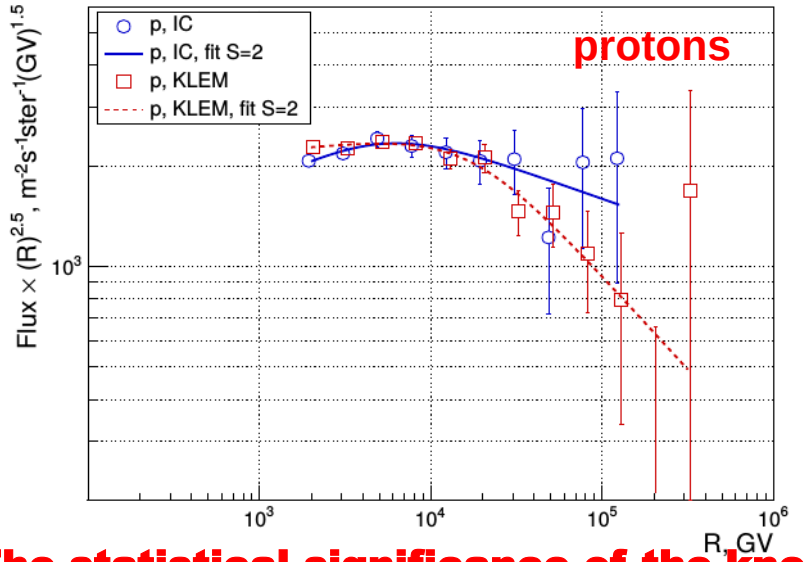
Iron spectrum -
softer, than the spectra of other heavy nuclei?
(Z = 6-14)

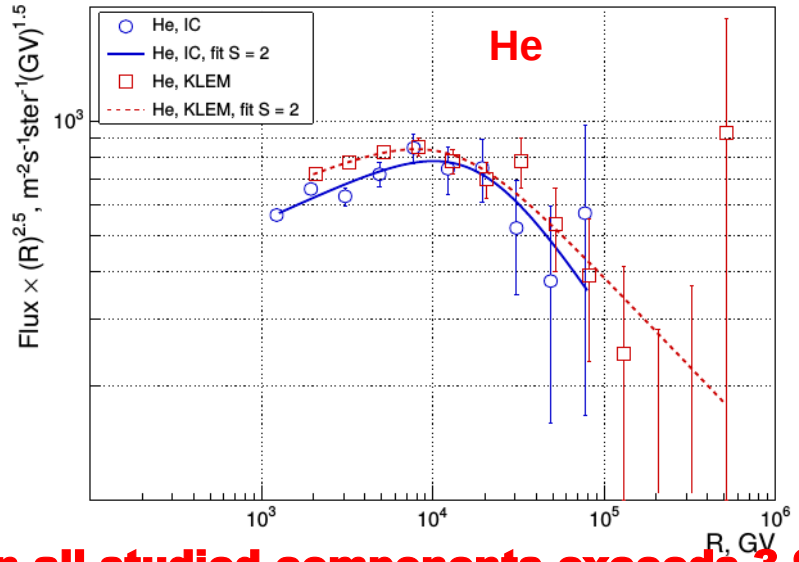




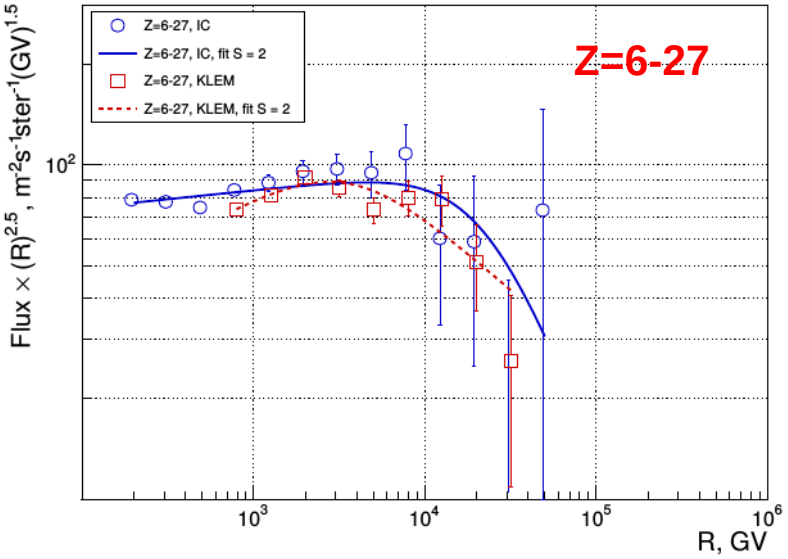
A new universal cosmic-ray knee near the magnetic rigidity 10 TV

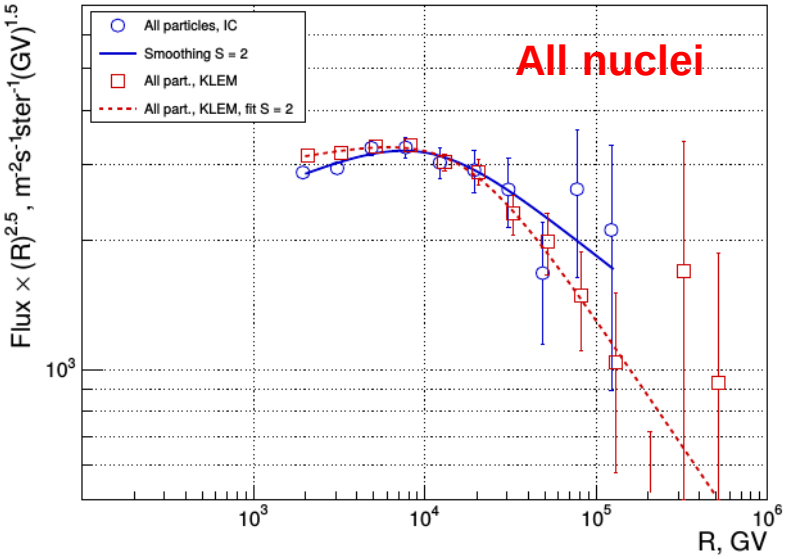
JETP Lett. V.108, No 1, P. 5 (arXiv:1805:07119)



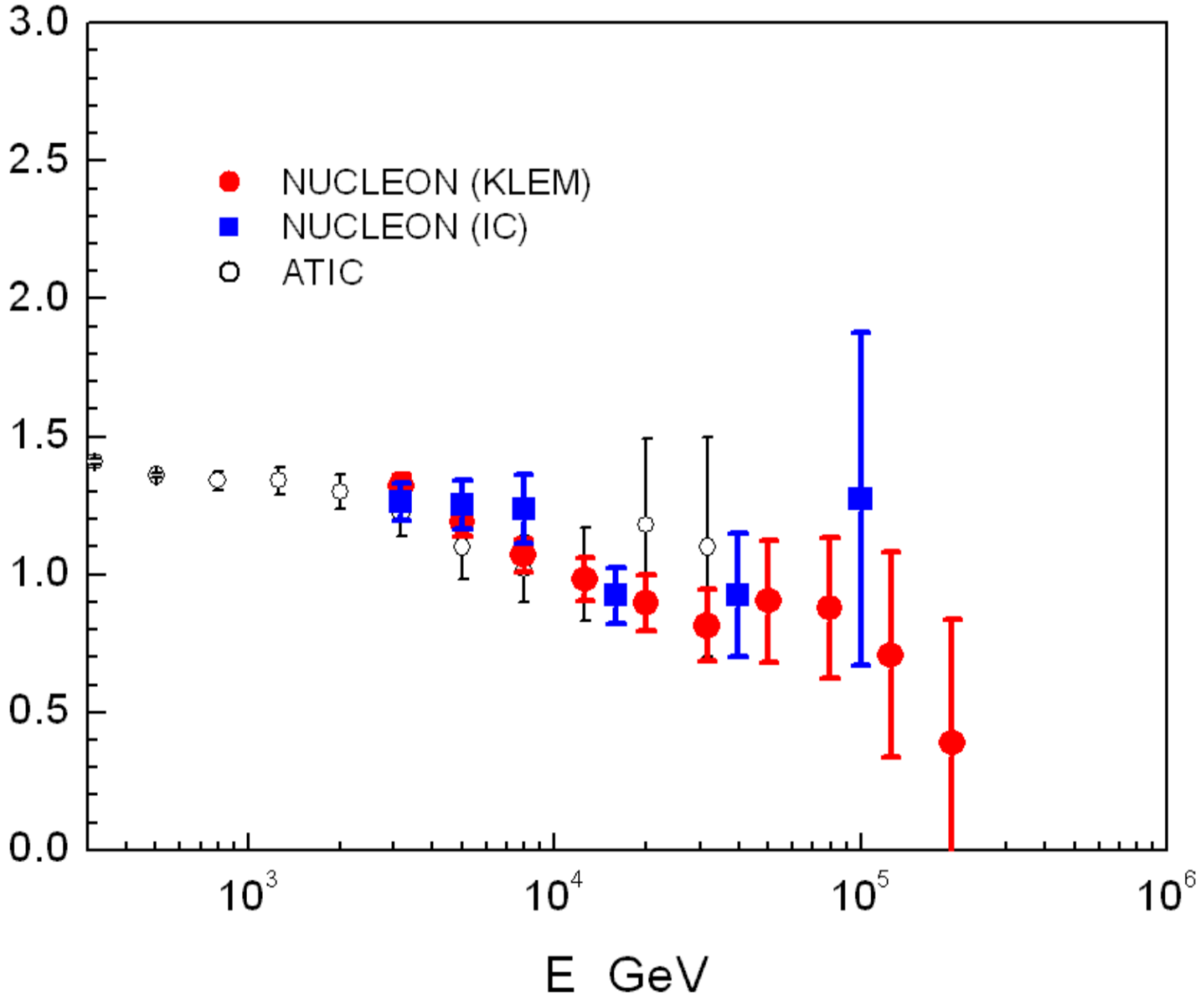


The statistical significance of the knee in all studied components exceeds 3.9 standard deviations.

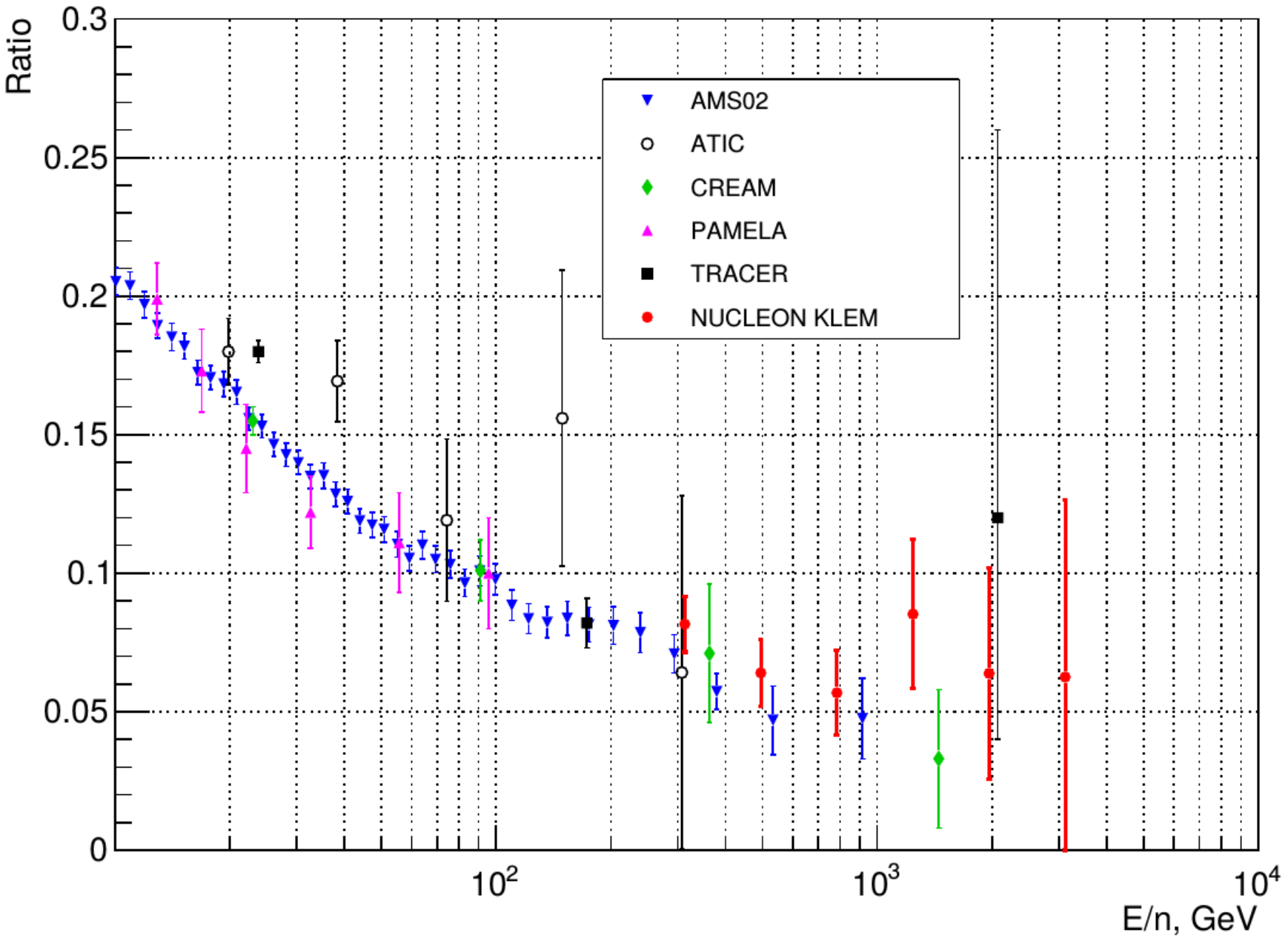


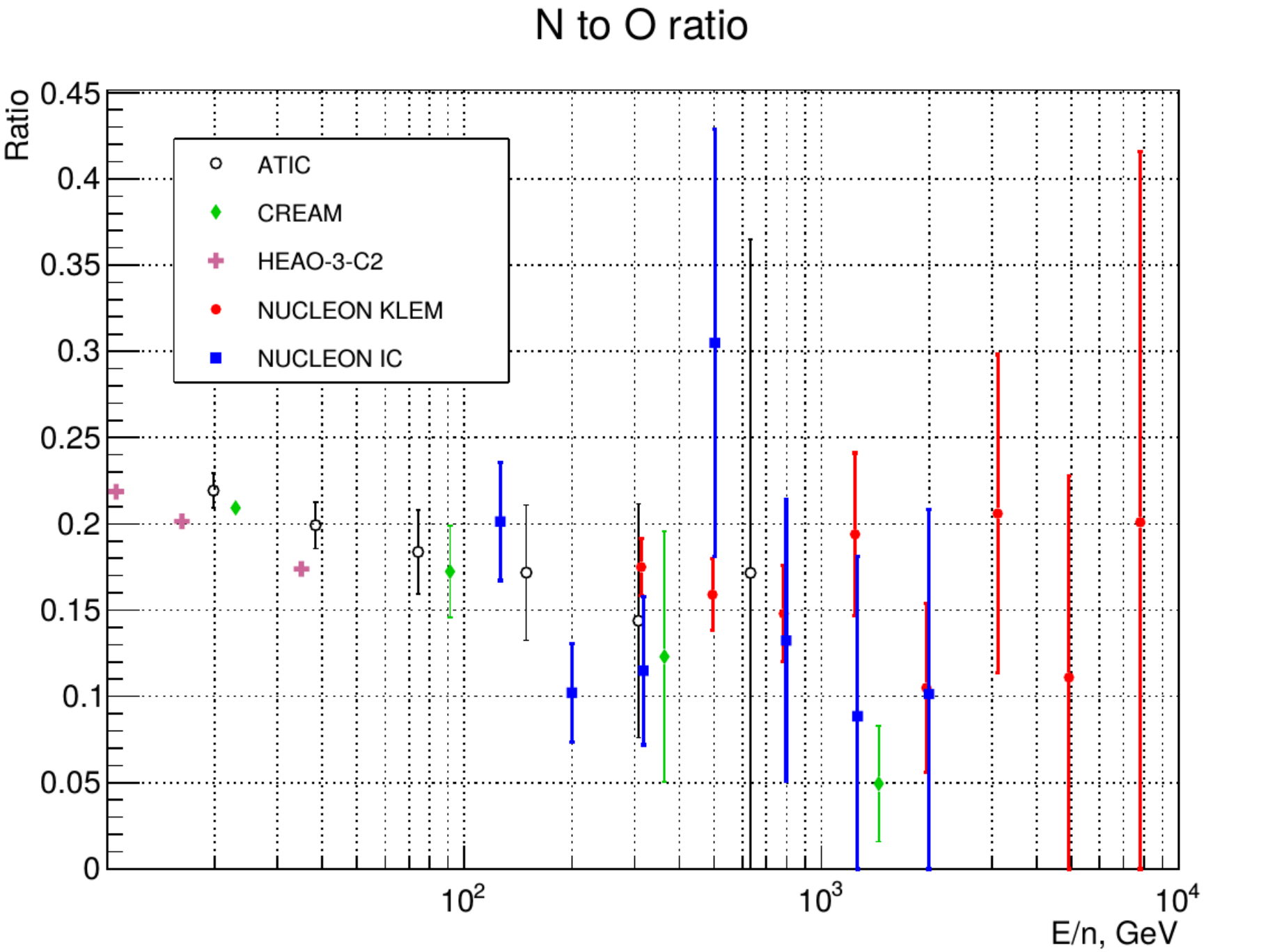


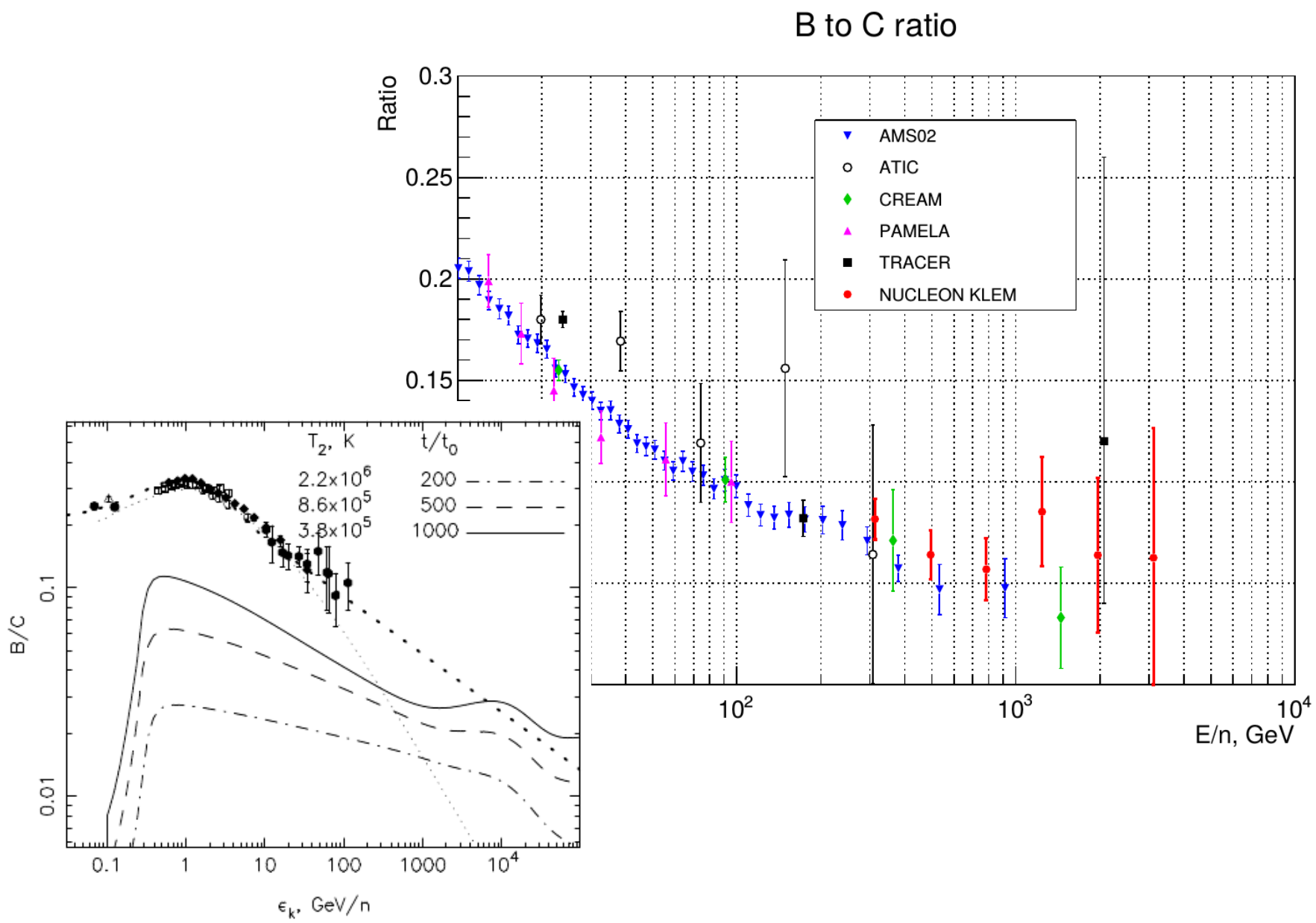
p/He ratio



The protons and helium nuclei fluxes show a steady change in the flux ratio in the energy range from 5 TeV to about 100 TeV/particle. The ratio decreases by ~2 times over this range.


B to C ratio
Ratio
0.3
0.25
0.2
0.15
0.1
0.05
0
AMS02
ATIC
CREAM
PAMELA
TRACER
NUCLEON KLEM
10^2
10^3
10^4
E/n, GeV

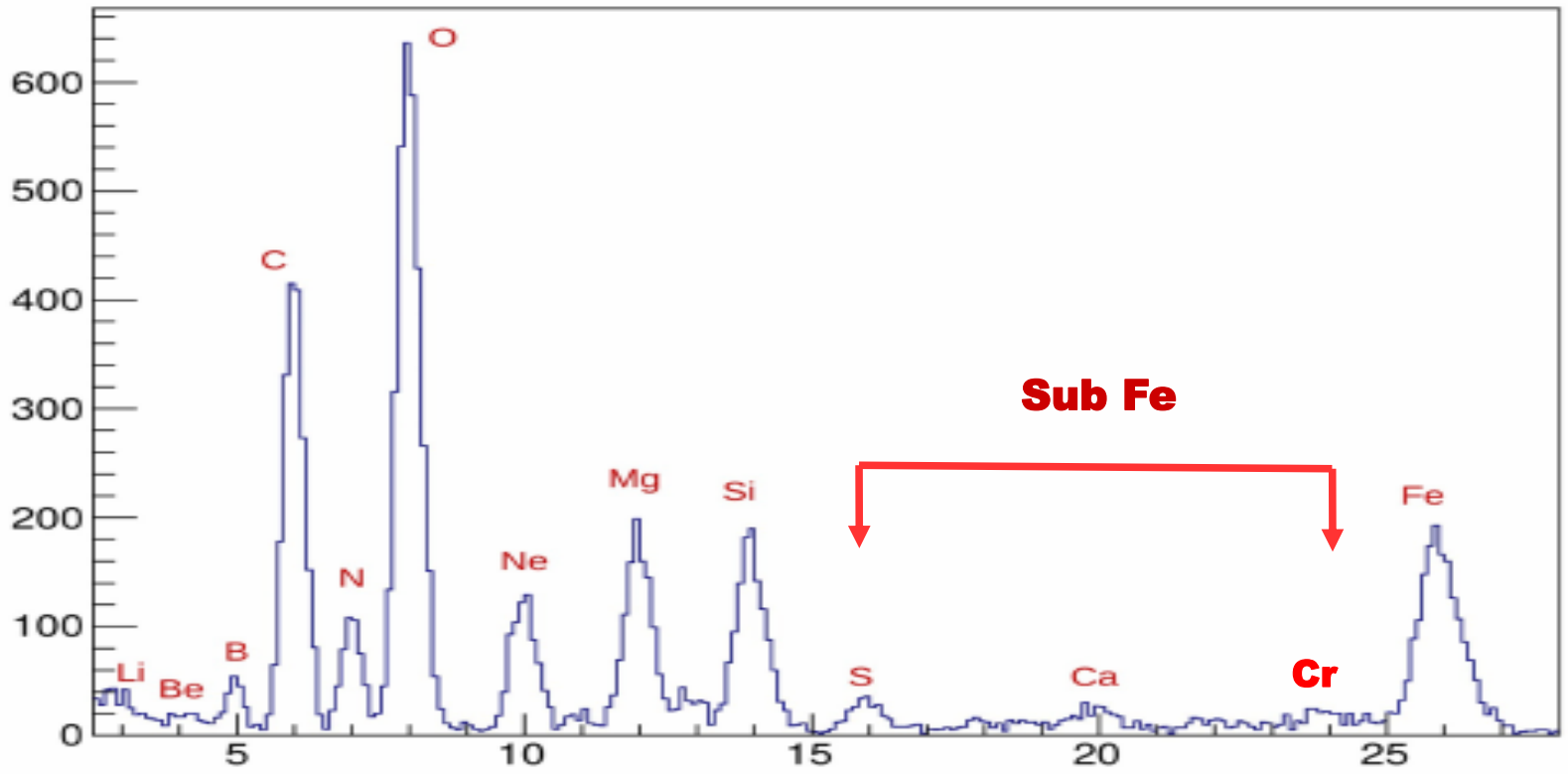

N to O ratio
Ratio
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
ATIC
CREAM
HEAO-3-C2
NUCLEON KLEM
NUCLEON IC
10^2
10^3
10^4
E/n, GeV

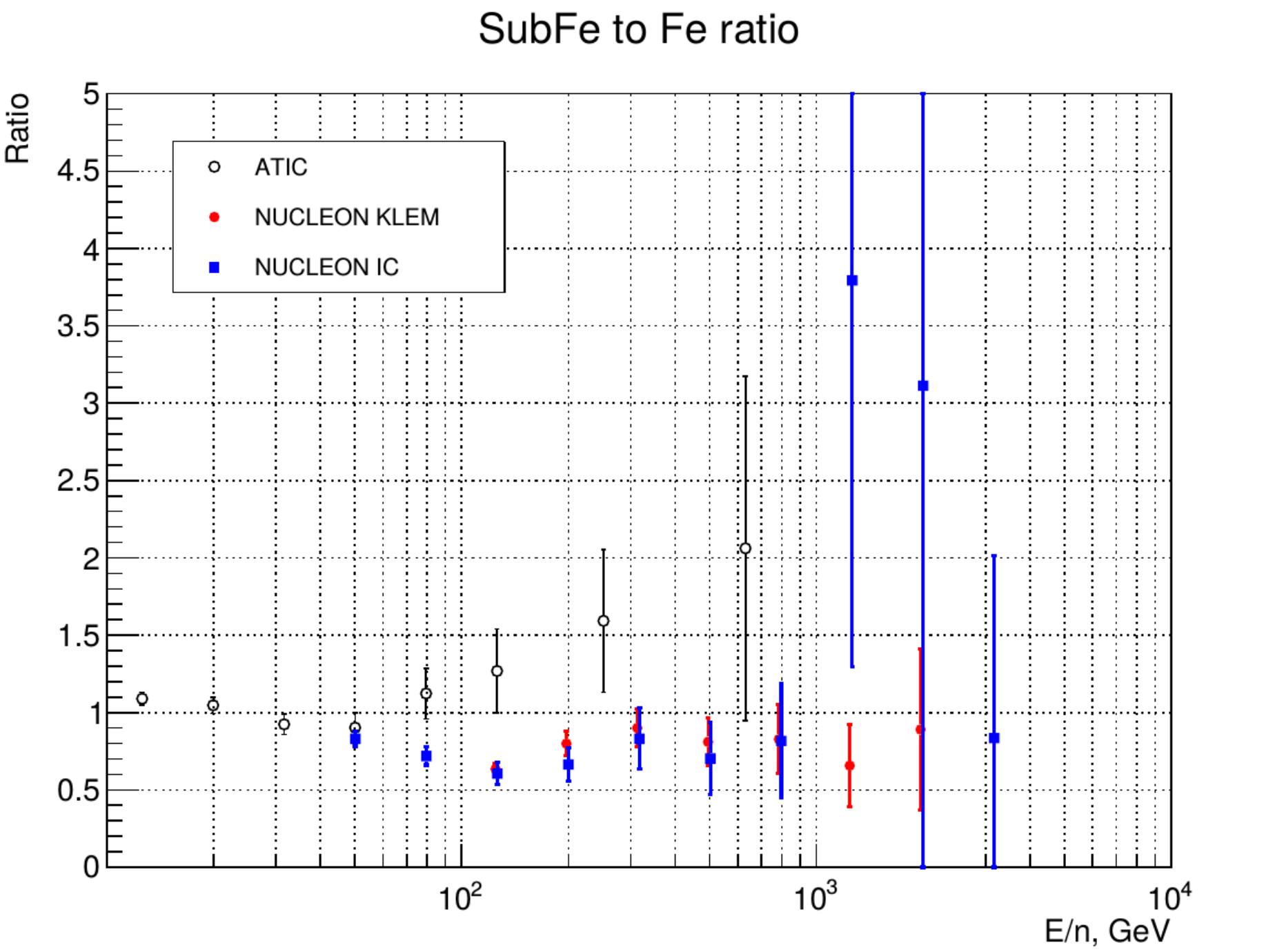


E. G. Berezhko, L. T. Ksenofontov, V. S. Ptuskin, V. N. Zirakashvili, H. J. Voelk. Astron.Astrophys. 410 (2003) 189-198 (arXiv:astro-ph/0308199v1).

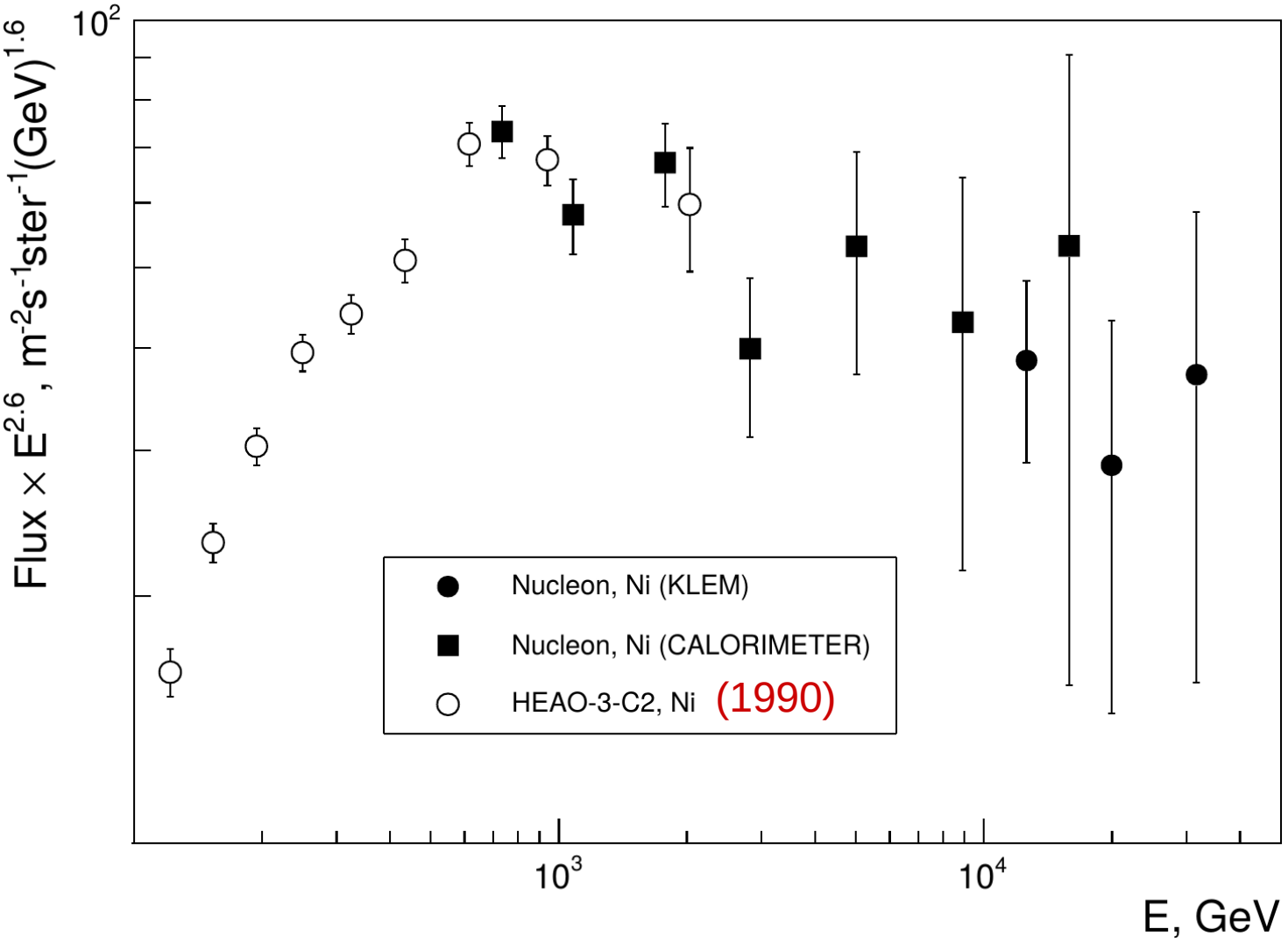
An indication was obtained of the absence of the expected fall in the ratio of the intensity of the flux of the nuclei of the sub-Fe group (where the fraction of secondary nuclei is large) to the flux of the primary Fe nucleus with increasing energy.

This effect can also be associated with the acceleration of secondary nuclei in sources, but has not yet had a widely recognized explanation.

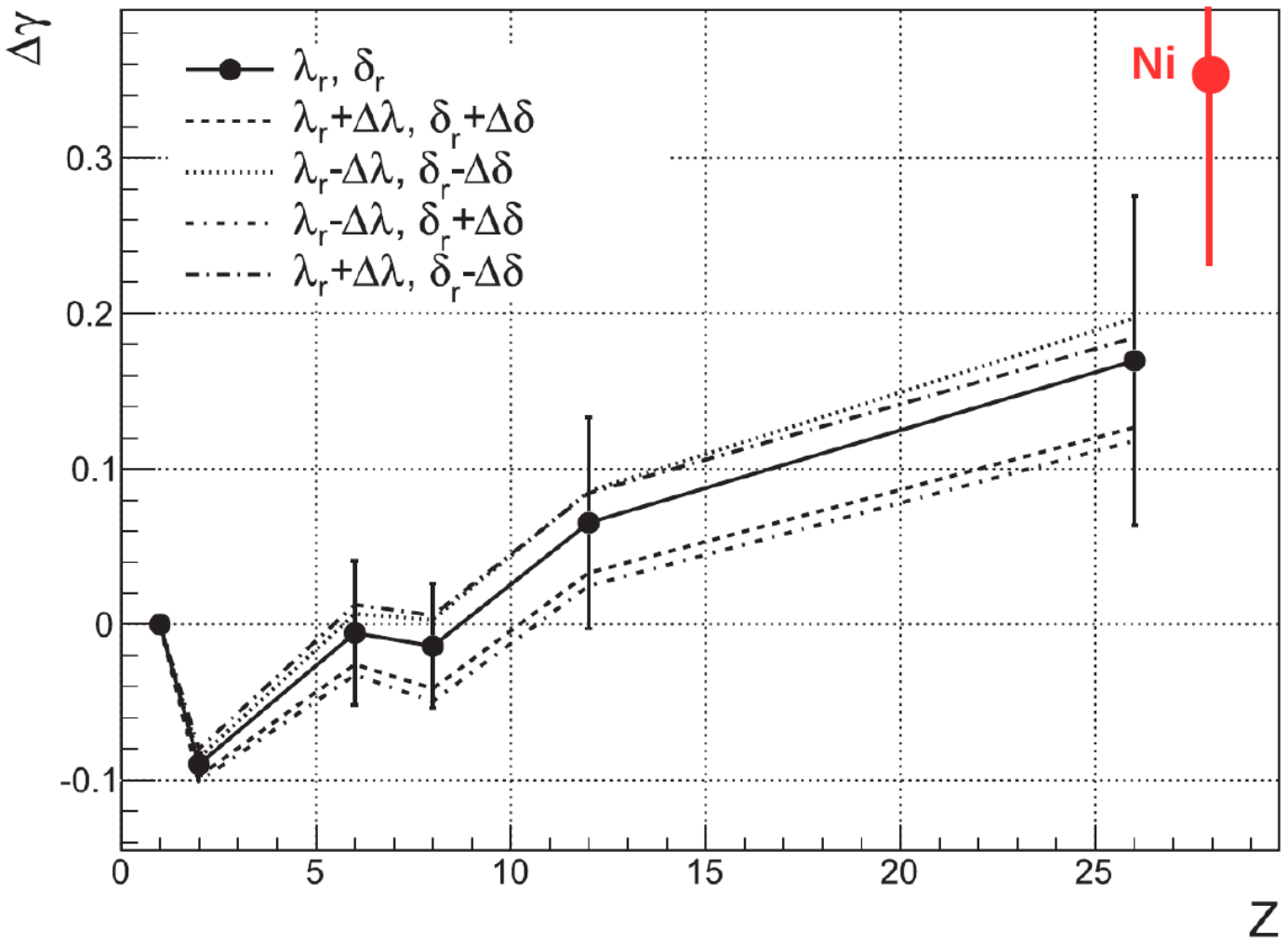



SubFe to Fe ratio
Ratio
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
ATIC
NUCLEON KLEM
NUCLEON IC
10^2
10^3
10^4
E/n, GeV

Nickel (Z=28) spectrum. $\gamma = 2.83 \pm 0.09$

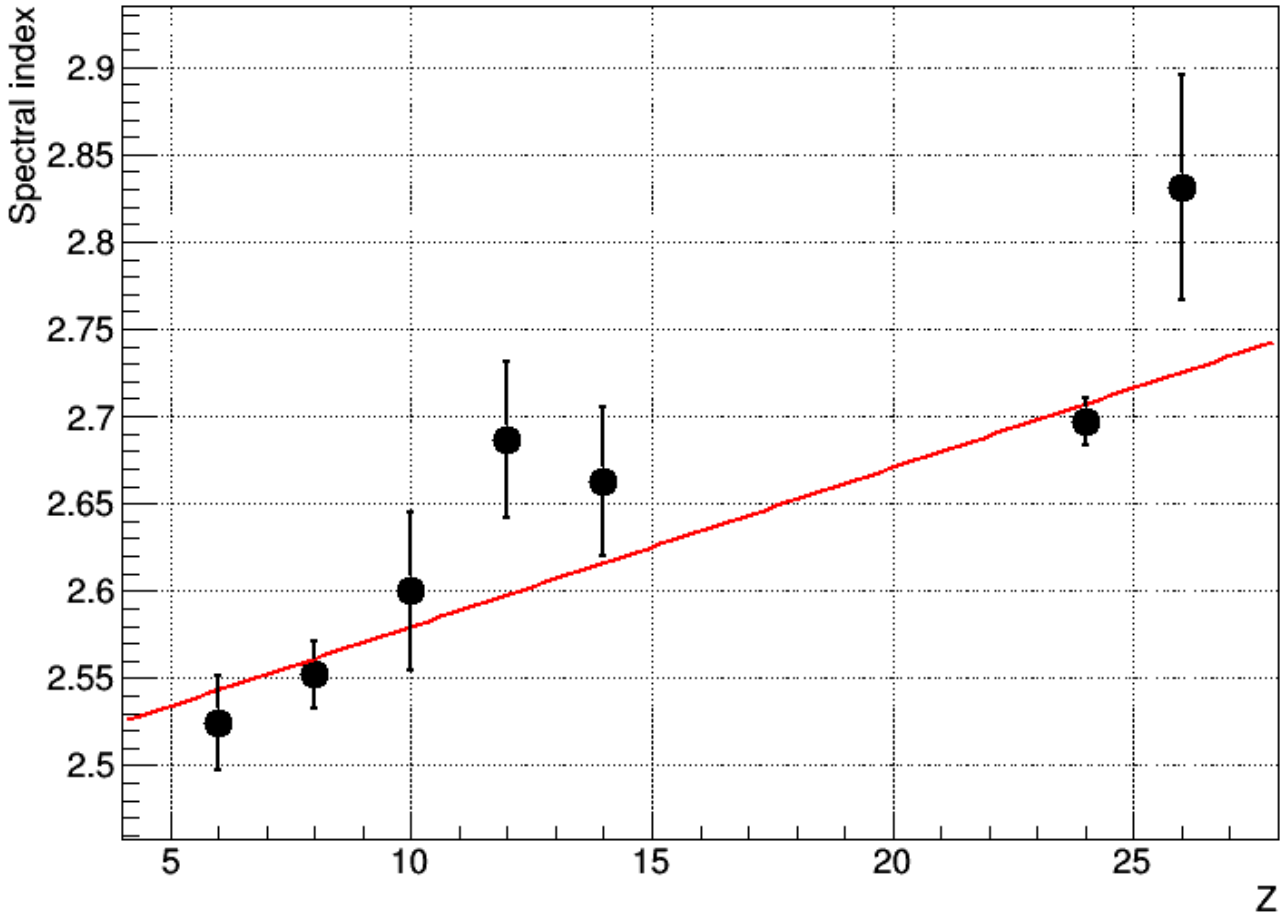


ATIC: the spectra of nuclei in source are softer for higher charges, with new Ni point from NUCLEON



The Astrophysical Journal, V.837, 77 (2017)

Spectral index versus Z



Slope is positive with 7.6♦

Conclusions

- **The analysis of the NUCLEON space experiment data gives 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).**

Thank you!