Skobeltsyn Institute of Nuclear Physics

Lomonosov Moscow State University

Spectral indexes of abundant cosmic ray heavy nuclei in sources as measured by the NUCLEON and the ATIC experiments

A. Panov, for the NUCLEON collaboration

ISCRA-2019, June 26

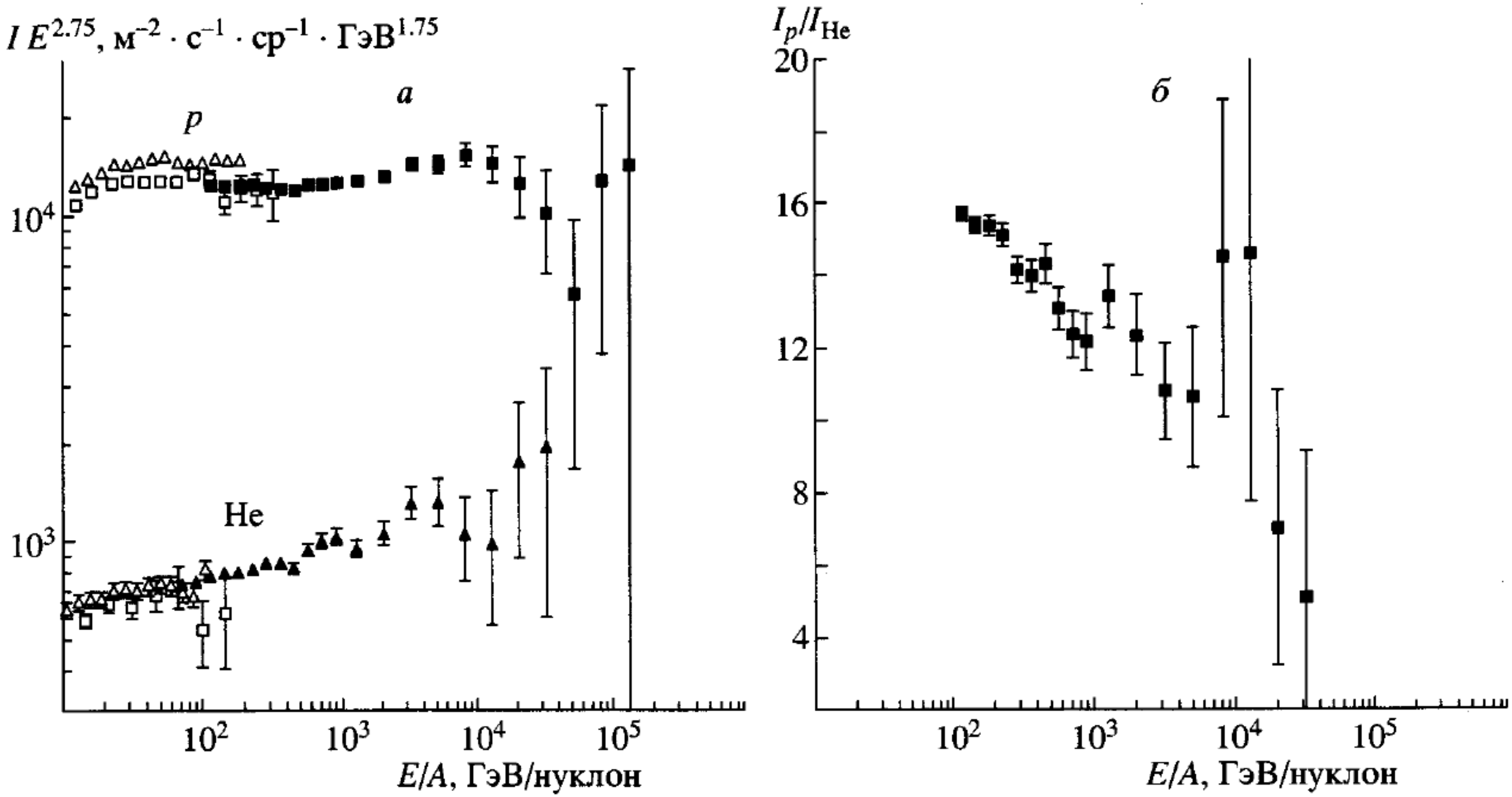
Cosmic rays acceleration physics

- SN shocks are main sources of high-energy CR
- Acceleration of CR is a result of interaction of CR and magnetic fields of SN shock and IS medium
- The most natural description of the acceleration – in the terms of magnetic rigidity R = E/Z.
- G.F. Krymsky (1977), A.R. Bell (1978): Different nuclei have the same R-spectrum with $\gamma \approx 2.0$ independently of Z
- The same acceleration cut-off rigidity for nuclei with different Z etc.

- If one discovers that different Z nuclei have different primary R-spectra (before propagation!) than one has to conclude that the acceleration conditions are different for different Z:

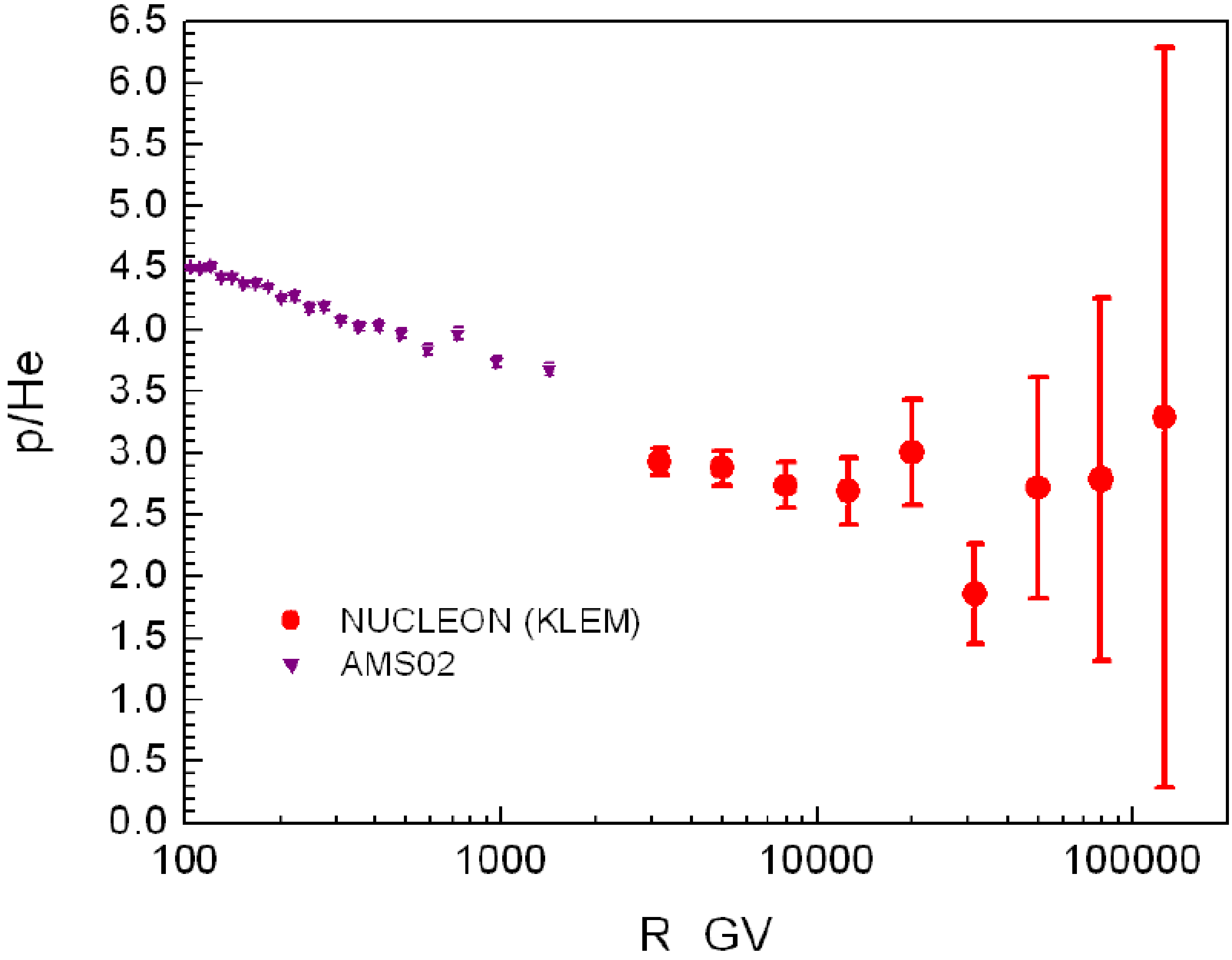
1. There exist different sources with different γ and different chemical composition
2. There exist heterogeneous sources with different acceleration conditions and chemical composition in different places or different times
3. The idea about universal mechanisms of CR acceleration is too rough approximation

Different slopes of proton and He spectra -
well-known from ATIC, 2004 (Bul.Rus. Acad.Sc. Physics, 68, P.1780)



- To compare spectra in the source, solution of back propagation problem is needed.
- No solution of back propagation problem here.
- I_p/I_{He} in the source is approximately the same as in the experimental data due to very large nuclear interaction length in the ISM

p/He ratio in terms of magnetic rigidity – the latest data

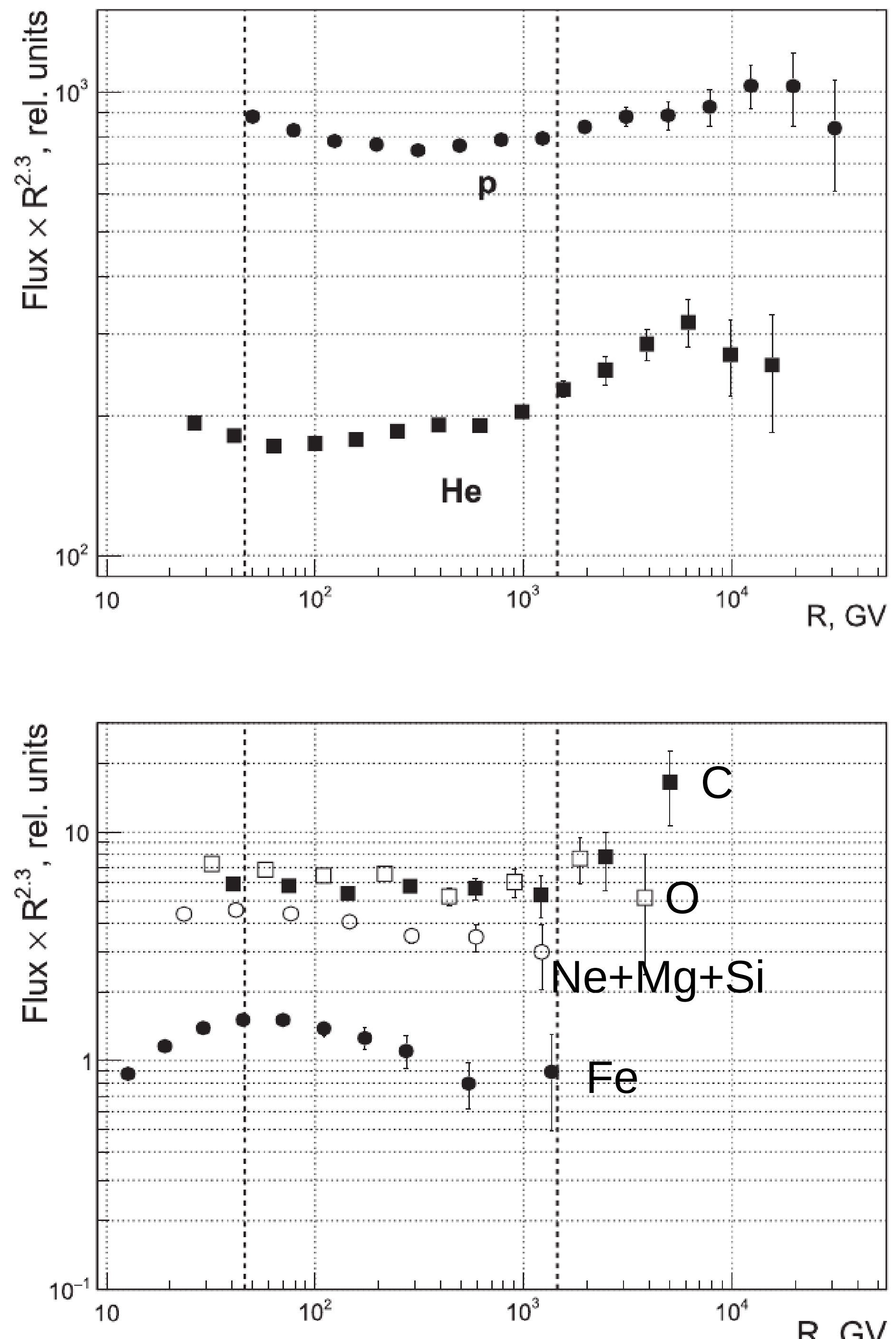


Heavy nuclei

ATIC:

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

- Same rigidity region for different nuclei
- Back propagation problem is solved



45–1300 GV

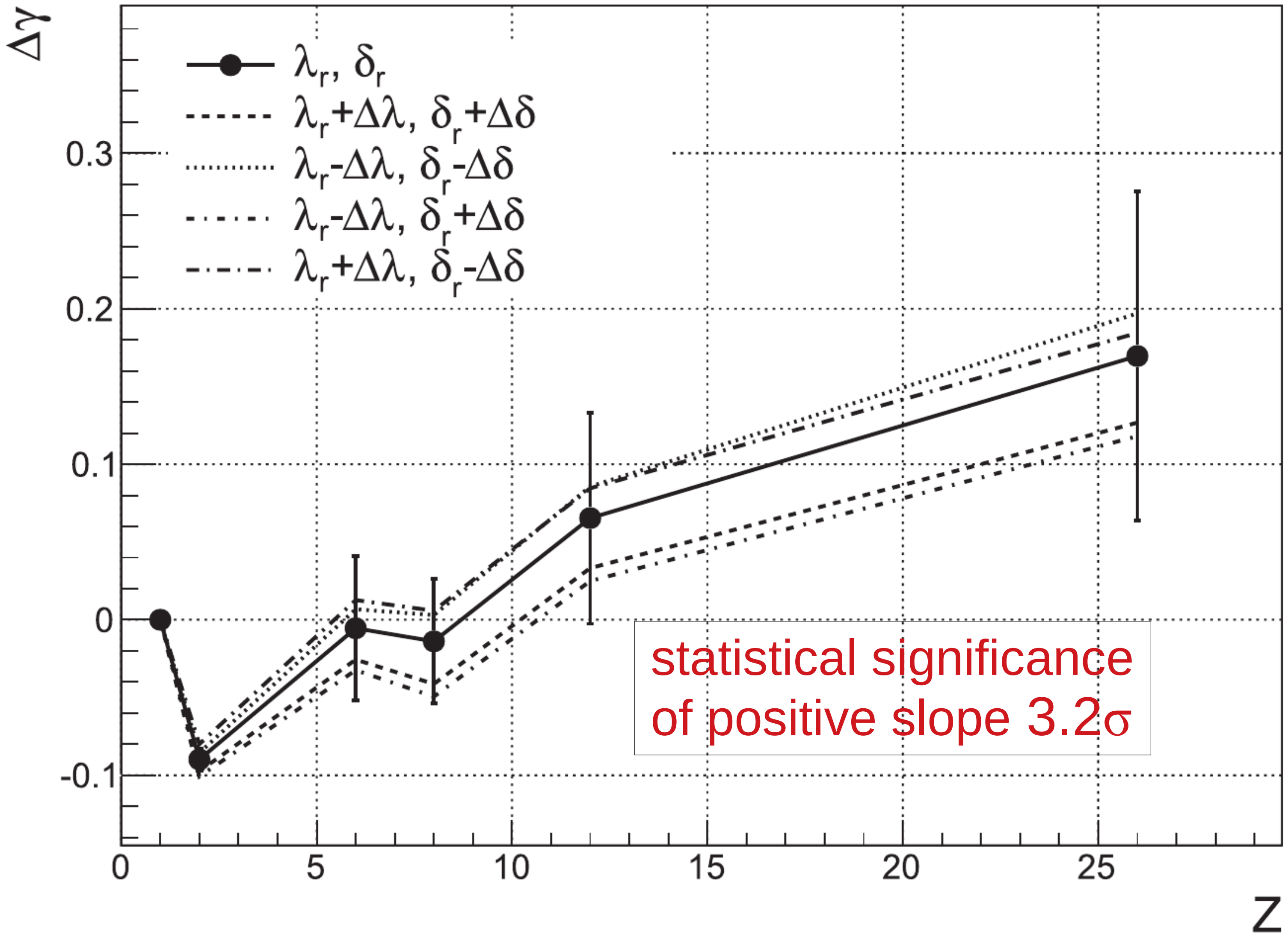
- Absolute spectral indexes in the source can not be obtained reasonably by solution of the back propagation problem due to large systematic uncertainties in the diffusion model

- However, the differences of the spectral indexes for different nuclei are much more stable against systematic uncertainties in the diffusion model

ATIC: the spectra of nuclei in source are softer for higher charges He-Fe

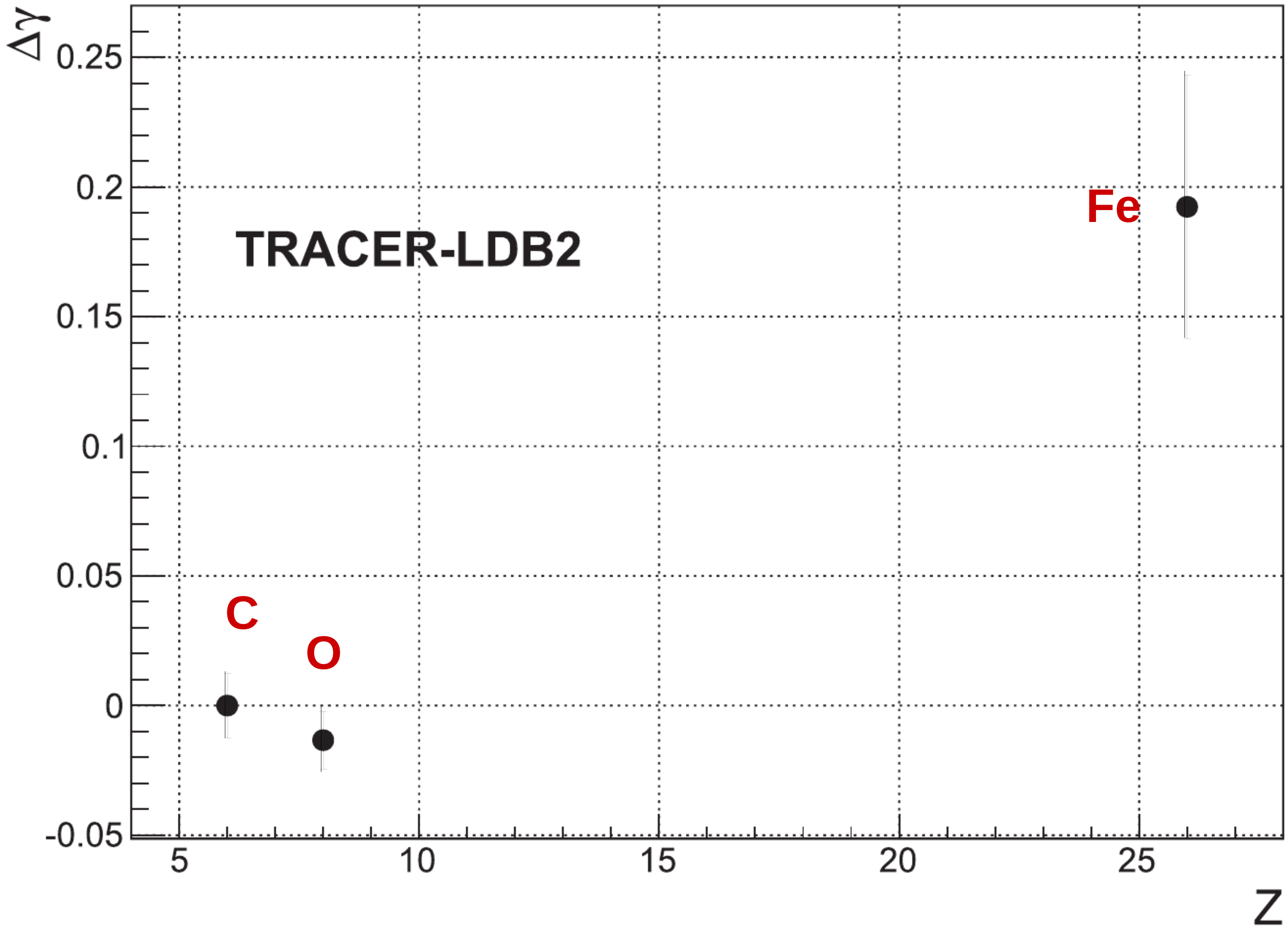
ATIC: ApJ, V.837, 77 (2017)

Back propagation problem was solved for all nuclei



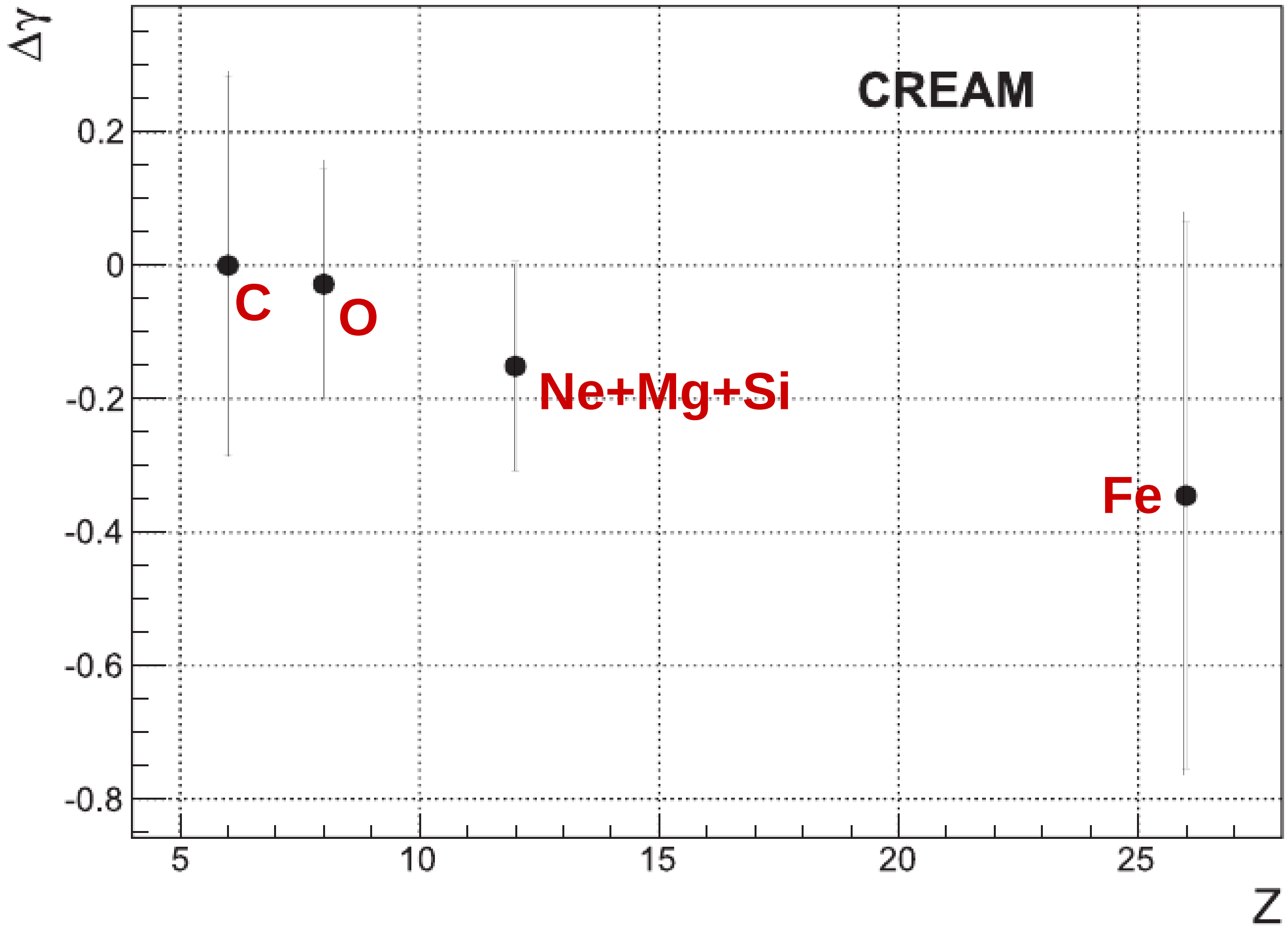
TRACER – Back propagated data

ATIC: ApJ, V.837, 77 (2017)
TRACER: ApJ, V.742, 14 (2011)



CREAM – Back propagated data

Too large statistical errors



NUCLEON mission

NUCLEON apparatus is placed on board of the **RESURS-P** regular satellite as an additional payload.

Lanched **December 28, 2014**.

The spacecraft orbit is a Sun-synchronous one with inclination **97.276°** and an average altitude of **475 km**.

Vessel:

Weight ~360 kg

Power consumption ~160 W

Telemetry ~10 GB/day

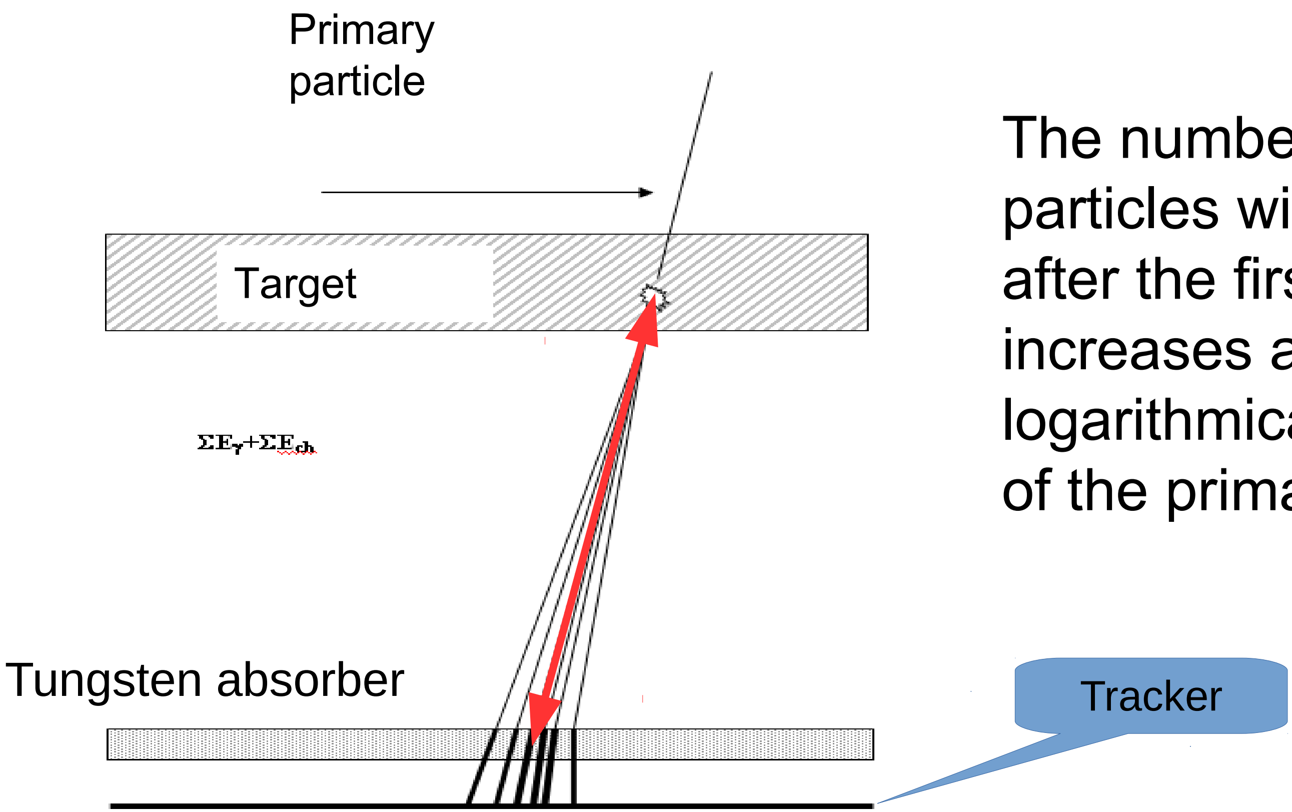
The NUCLEON detector on board of the satellite RESURS-P N2.

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 (main)
2. The calorimetric method
   -usual and well studied

The kinematic method KLEM

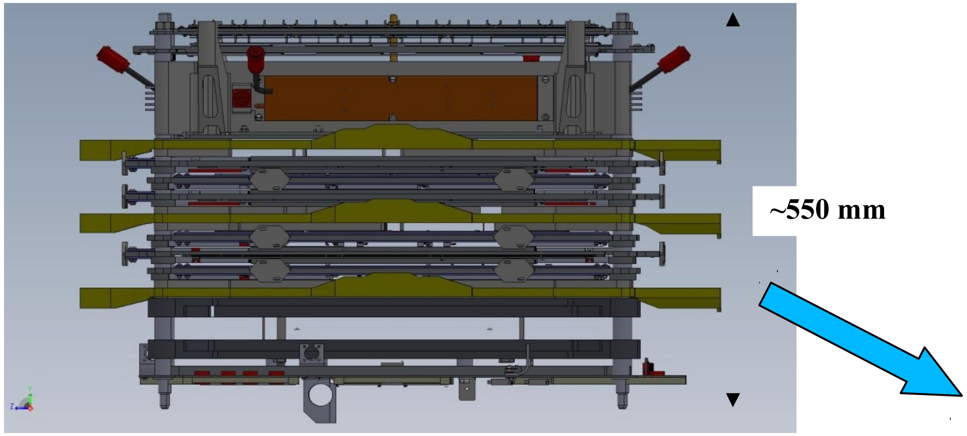


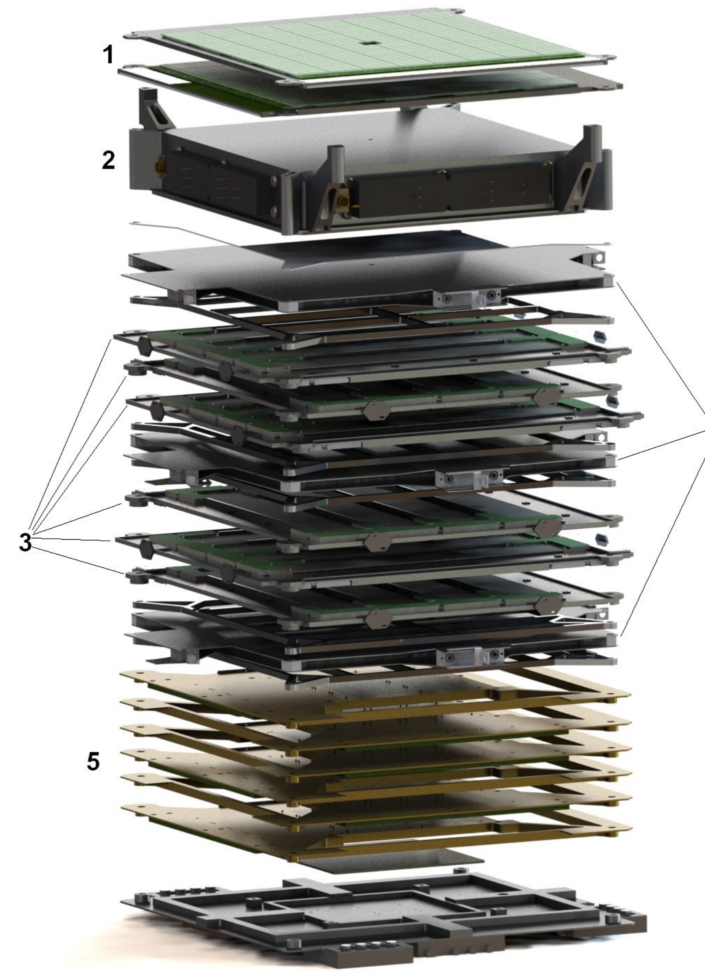
The number of secondary particles with high pseudorapidity after the first interaction increases approximately logarithmically along increasing of the primary energy of particle

The energies are reconstructed by S-parameter -

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

The NUCLEON apparatus





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

(2) Carbon target of 0.25 proton interaction lengths;

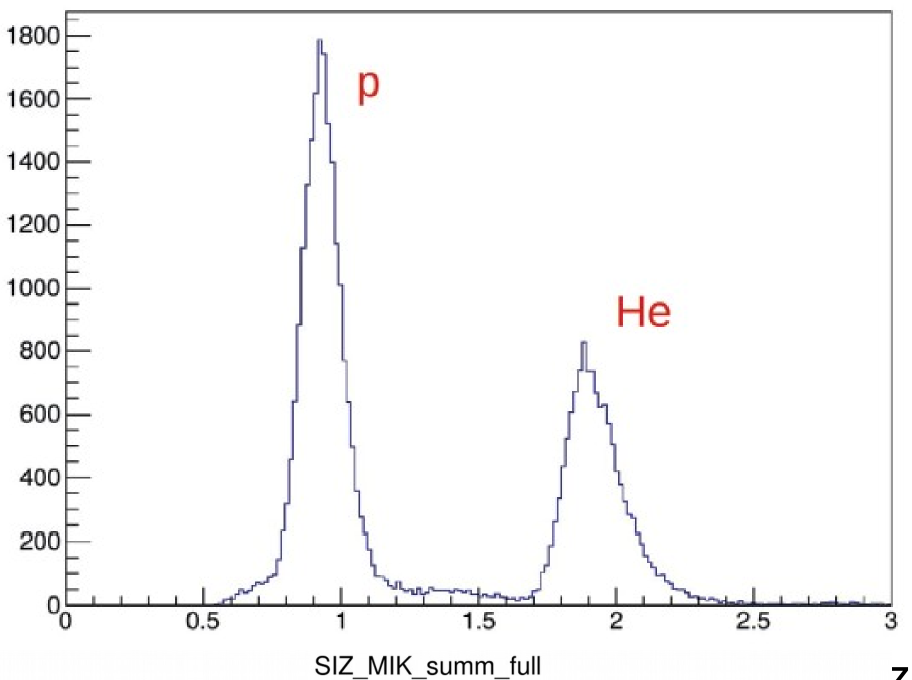
(3) KLEM tracker – six planes of microstrip silicon detectors (400 mkm step) with tungsten between them (~2mm each, ~3 X-lengths summary).
Active square 500*500 mm^2.
KLEM geometrical factor 0.24m^2sr.

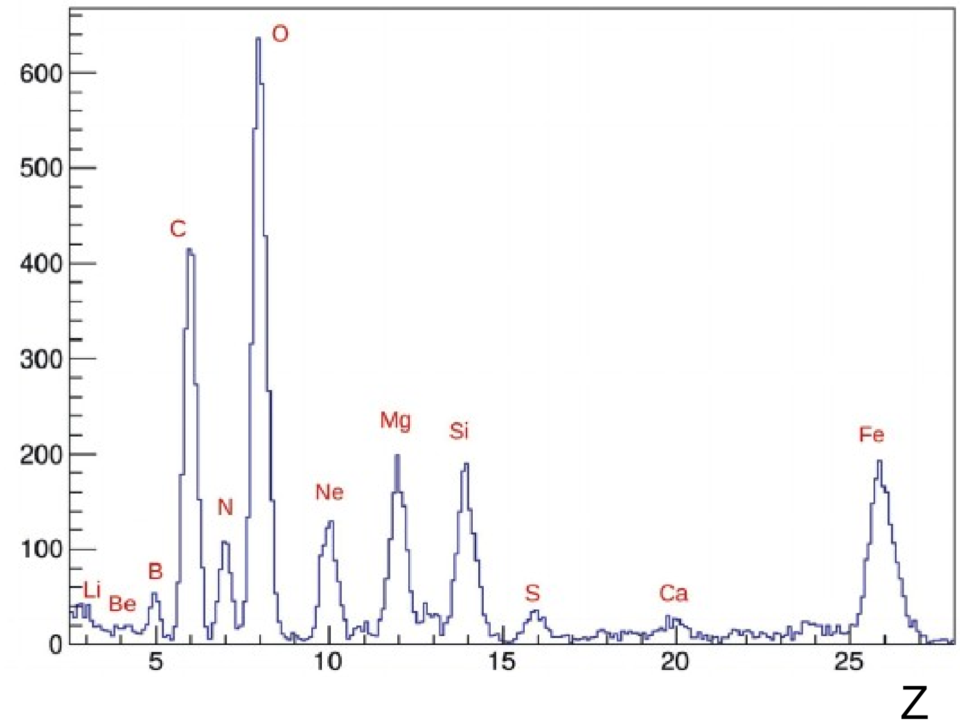
(4) Trigger system – tree double sntillator planes;

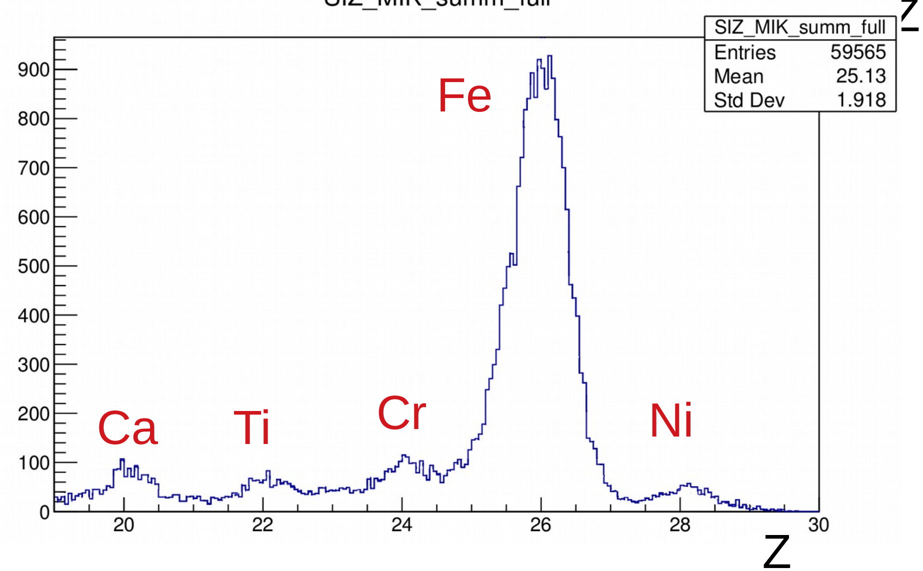
(5) Ionization calorimeter (IC) – six planes of tungsten absorber (~8mm each, ~12 X-lengths summary) with silicon strip detectors (1mm step).
Active square 250*250mm^2.
IC geometrical fact 0.06m^2sr

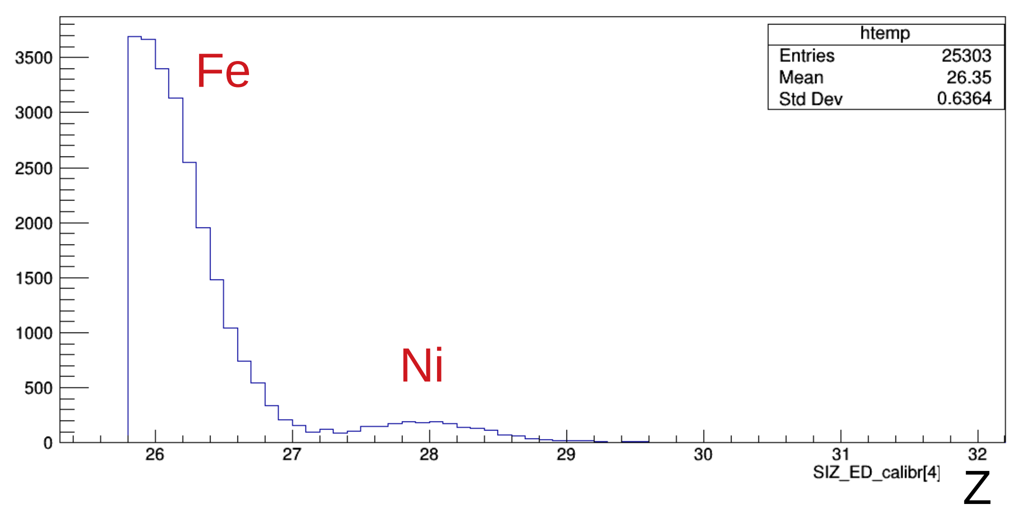
10604 independent electronic channels in total

Charge resolution of four silicon planes detector better than 0.2 charge units near CNO group

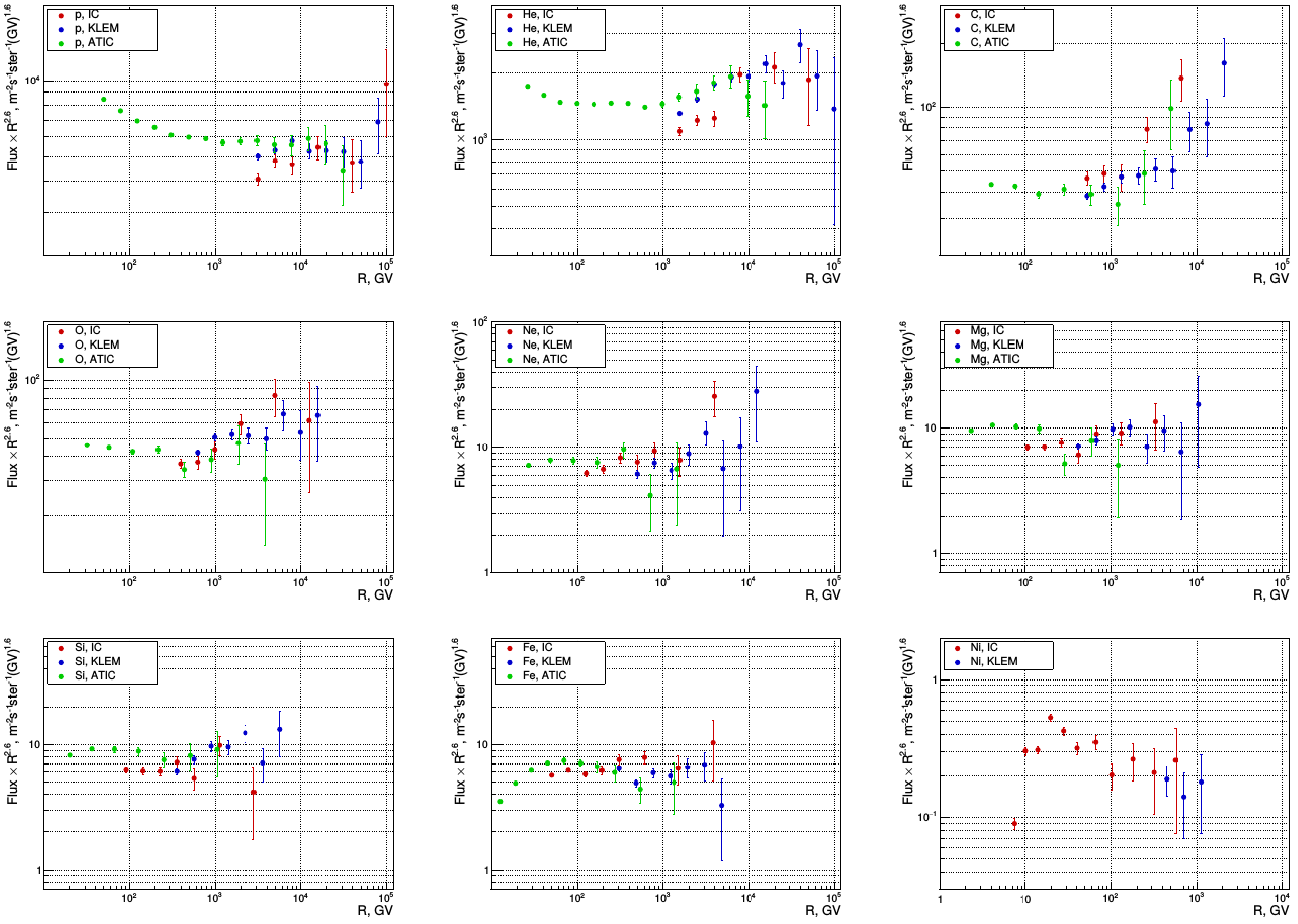






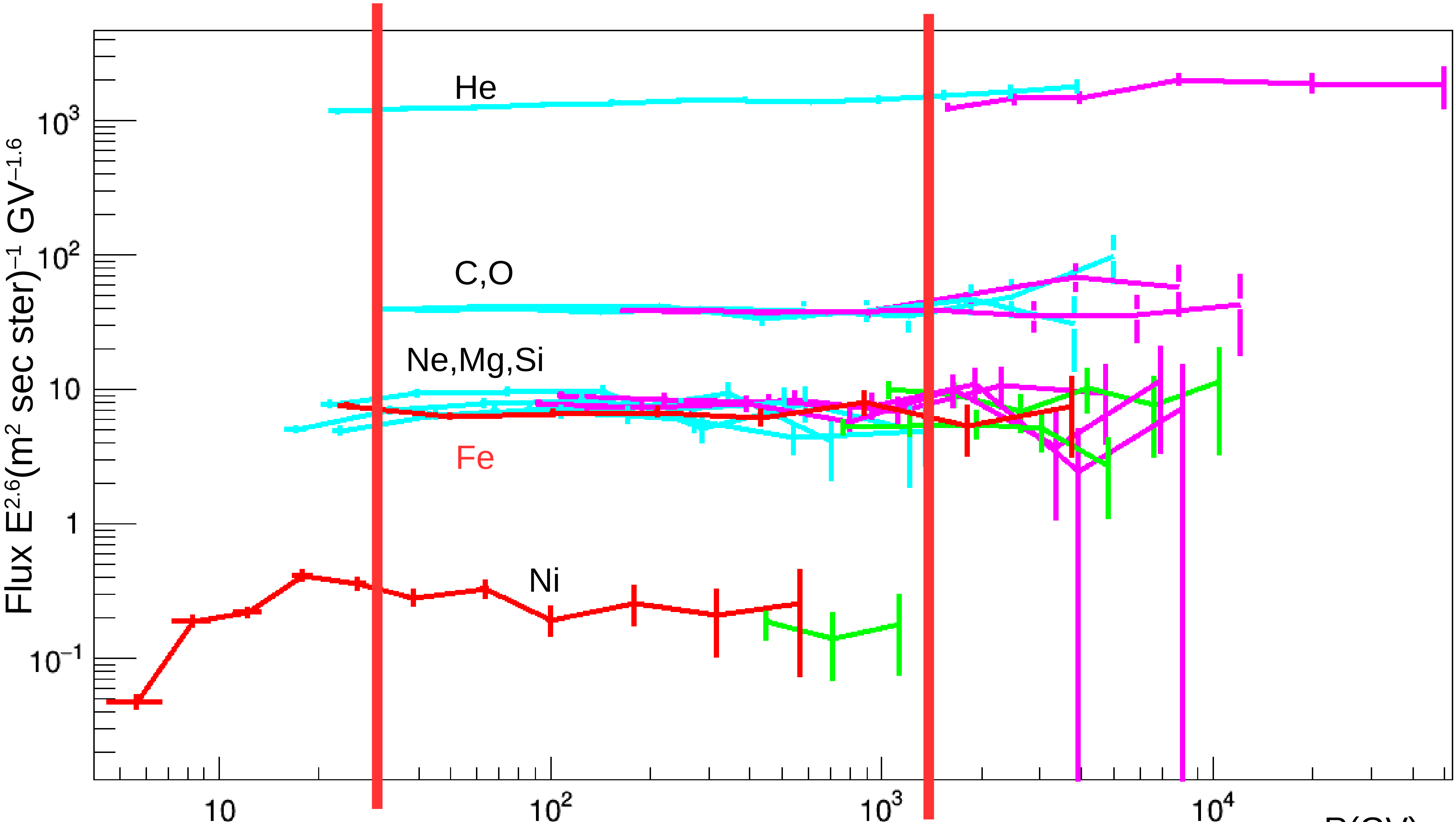


Rigidity spectra of nuclei in ATIC and NUCLEON experiments



ATIC+MIK(C,O,Ne,Mg,Si)+MIK(Fe,Ni)+KLEM

There is no common rigidity region for all NUCLEON data → to join NUCLEON with ATIC



30GV – 1300GV

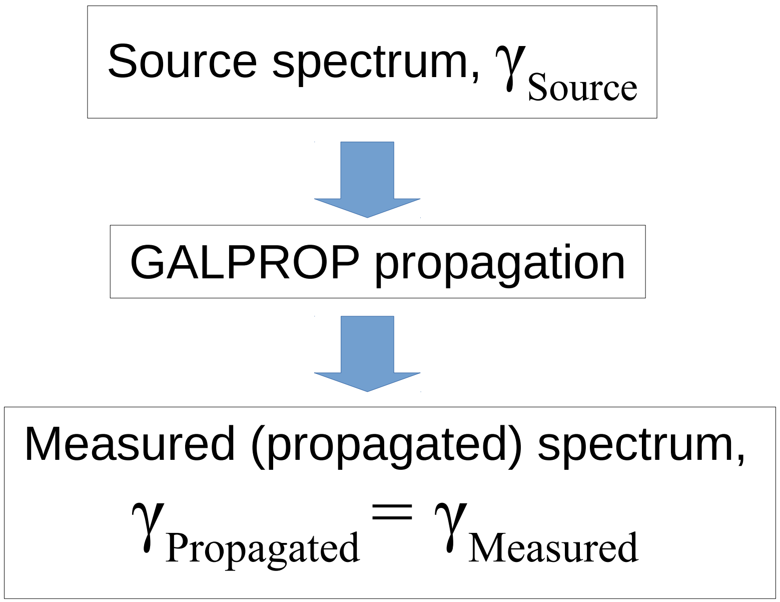
Solution of the back propagation problem for joint ATIC + NUCLEON data + Ni: GALPROP + parameters based on AMS-02 data

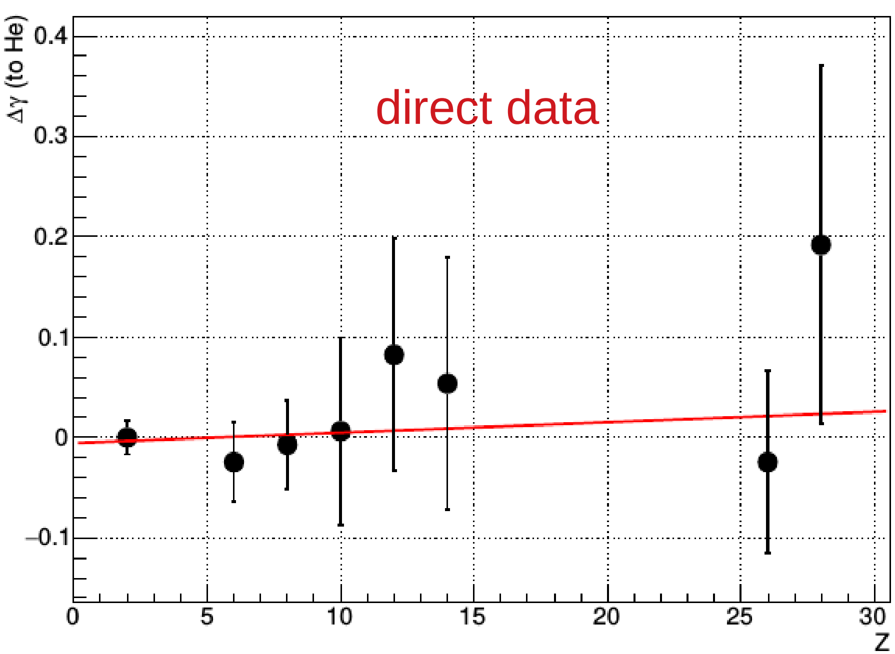
[M.J. Boschini, et. al. ApJ, 858:61 (2018)]:

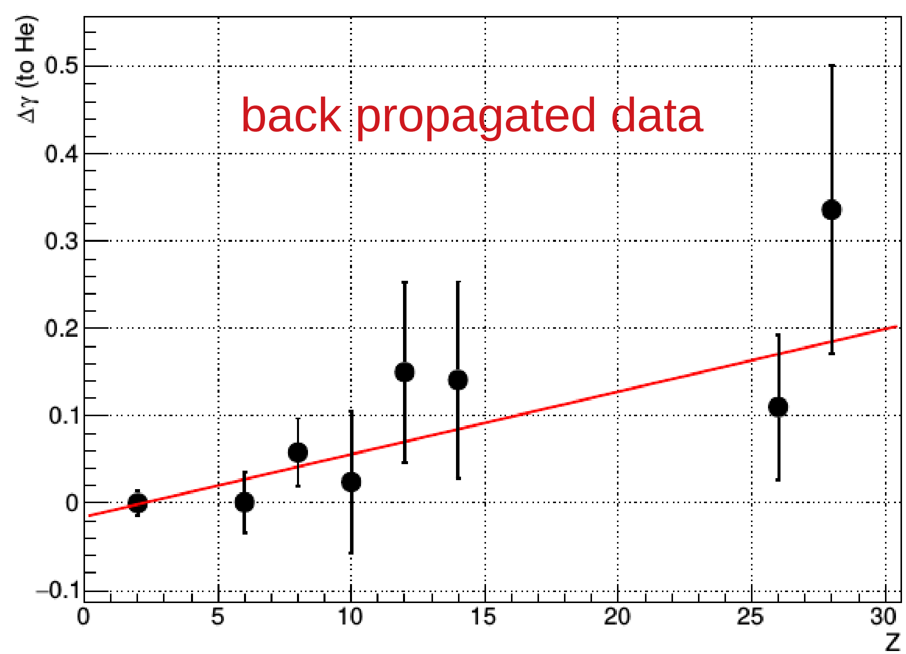
$D = D_0 \times (R/R_0)^{-\delta}$

$D_0 = (4.3 \pm 0.6) \times 10^{28}\ cm^2 s^{-2}\ (R_0 = 4\ GV)$

$\delta = 0.415 \pm 0.025$

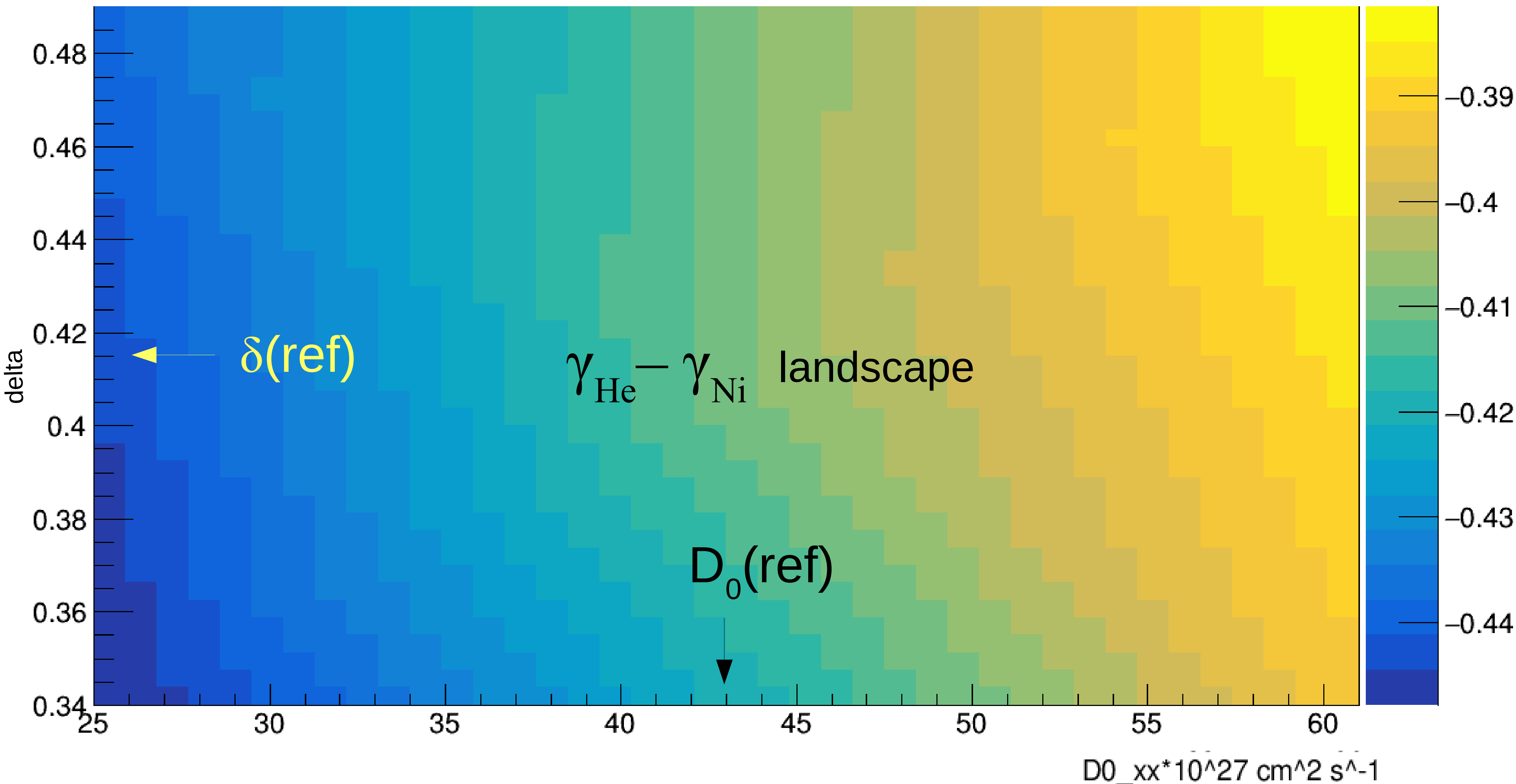




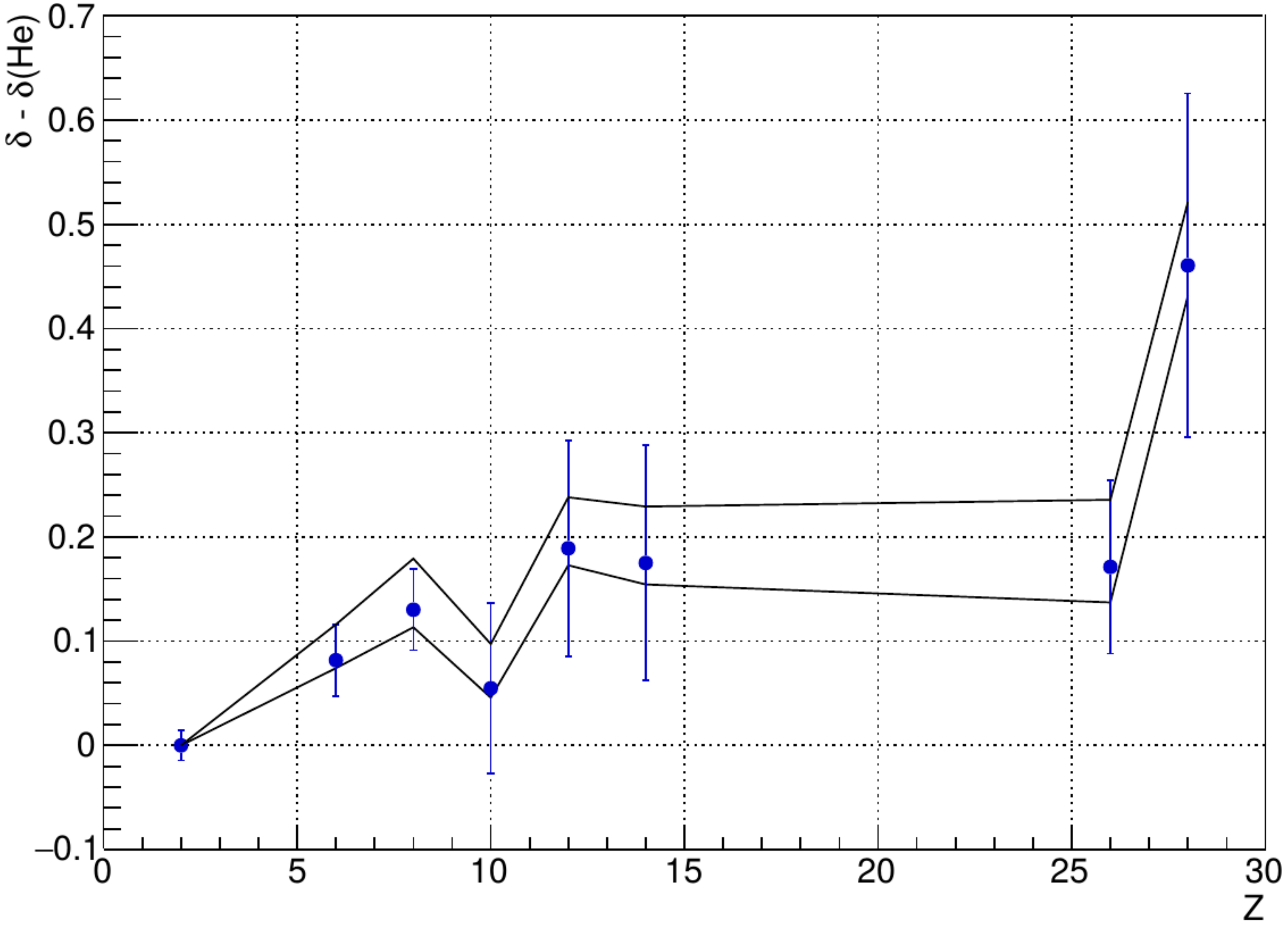


±3σ propagation model systematics

Example: $\gamma_{He} - \gamma_{Ni}$



Systematic errors corridor: 3 standard deviations on D_0 and δ



Statistical significance of the positive slope:
not less than 4.6σ (Systematics included)

What can it be?

- Nobody knows exactly
- A hypothesis:
  Giovanni Morlino
  The role of ionization in the shock acceleration theory
  MNRAS V.412, 2333 (2011)

> “Some dependence of acceleration process on the type of nuclei is indeed expected. The matter is that nuclei are partially ionized in the beginning of the diffusive shock acceleration process. Most of ionization occurs when nuclei are ultrarelativistic and are ionized by background infra red, optical and microwave photons. It is more difficult to ionize heavier nuclei because of smaller ionization cross-sections. Therefore it is expected that the maximum magnetic rigidity of heavy nuclei is smaller than the magnetic rigidity of the light nuclei”.

Conclusions

- **The data of ATIC + NUCLEON experiments give strong indication to systematic increasing of spectral indexes of nuclei in the rigidity range 30-1300 GV with Z from He to Ni**

- **The origin of this phenomenon is still unknown, but it might be related to different ionization state of different nuclei at the beginning of the acceleration process**

- **Further both experimental and theoretical study are needed**

Thank you for attention!