Skobeltsyn Institute of Nuclear Physics
Lomonosov Moscow State University

Review of the NUCLEON space experiment

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D. Podorozhny, D. Polkov, S. Porokhovoy, V. Shumikhin,
A. Tkachenko, L. Tkachev, A. Turundaevskiy, O. Vasiliev,
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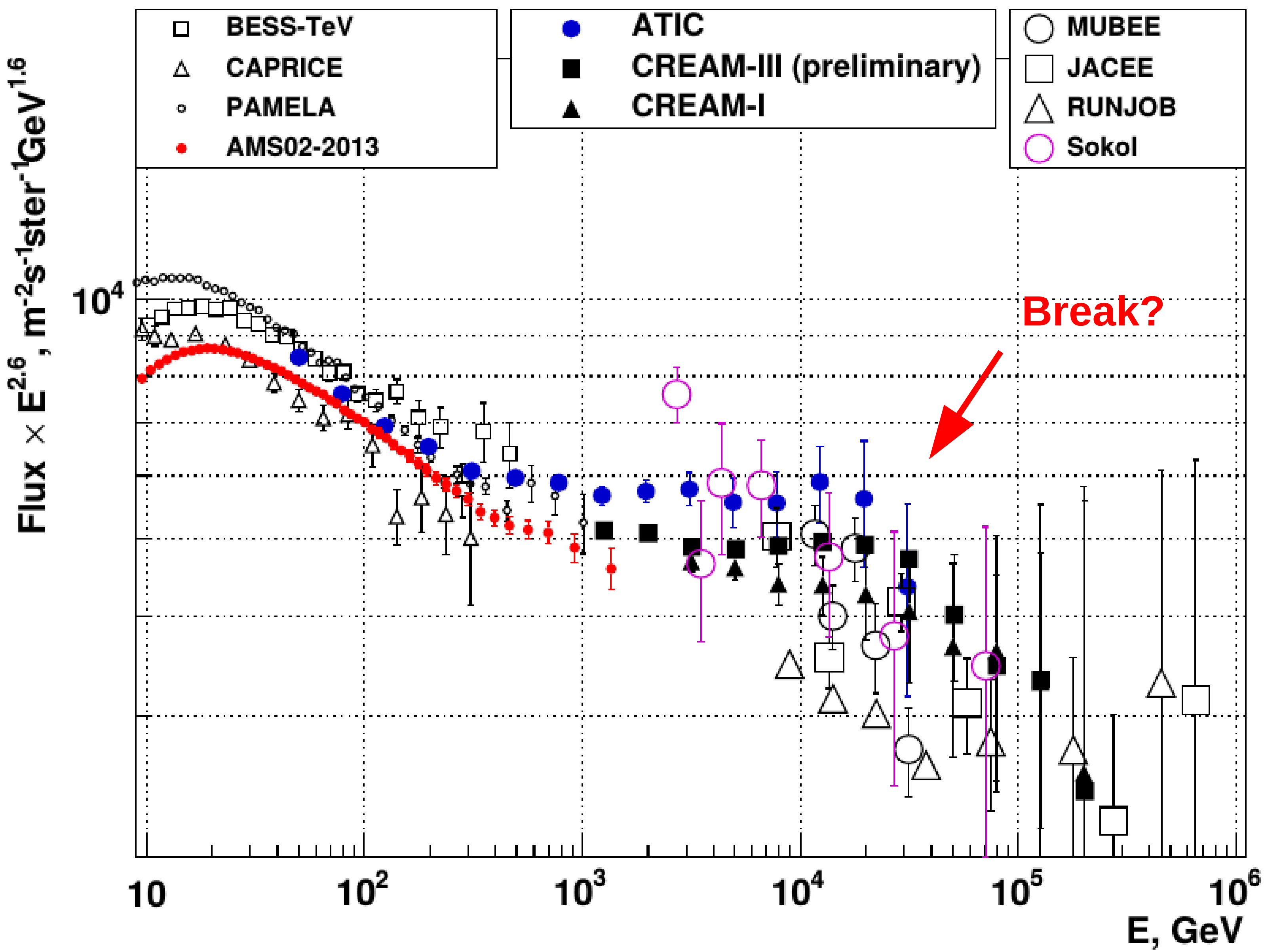
NextGAPES-2019

Approaching the knee area.

Problems in cosmic-ray spectra at energies 10 TeV - 1PeV per particle.

An example: proton spectra before NUCLEON.



The objectives of NUCLEON space experiment

Priority: experimental study of cosmic ray spectra in the energy range from a few TeV - 1 PeV per particle with elemental charge resolution.

Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow,

Joint Institute for Nuclear Research, Dubna, Russia

National Research Nuclear University "MEPhI", Moscow

SDB Automatika, Ekaterinburg, Russia

ROSKOSMOS, Russia

JSC SRC "Progress"

Russian Academy of Sciences

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.

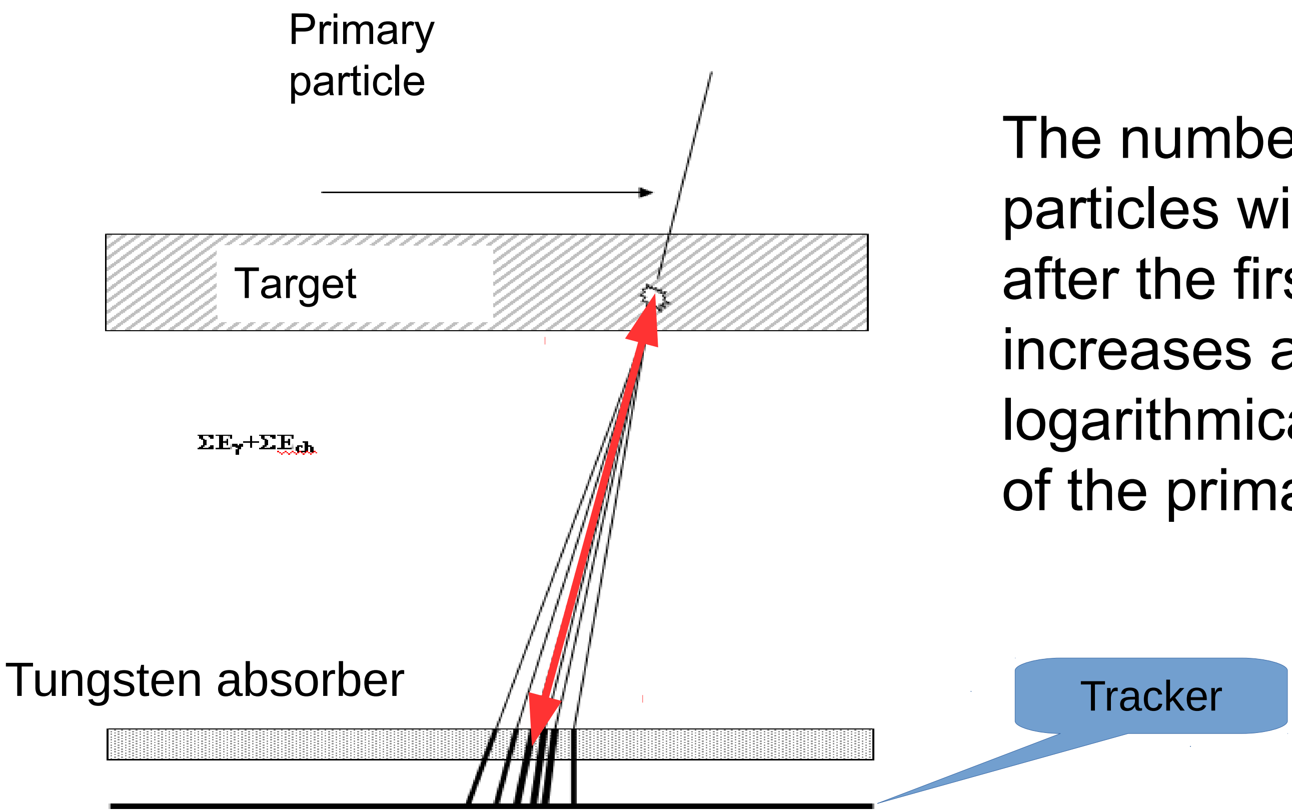
- The experiment was stopped in December 2017 due to Resource-2P satellite problems.
- From 2015 to 2017 about 20 million scientific events were collected.
- The processing and interpretation of the NUCLEON experiment data continues.

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

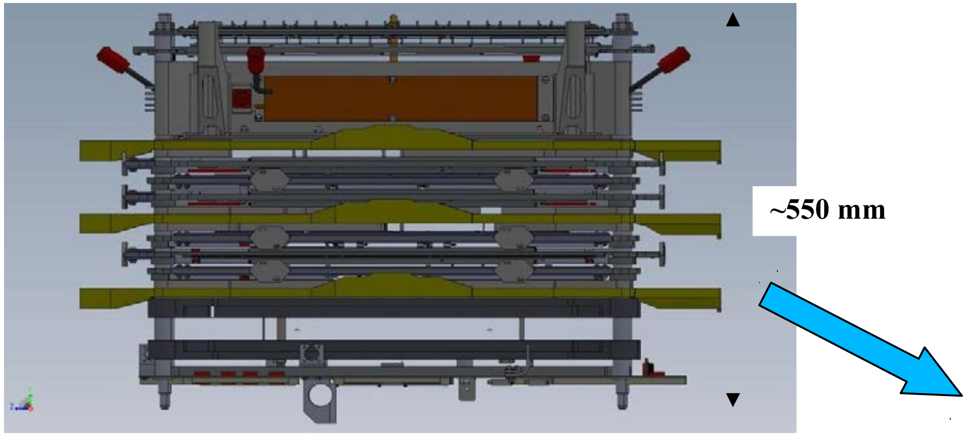


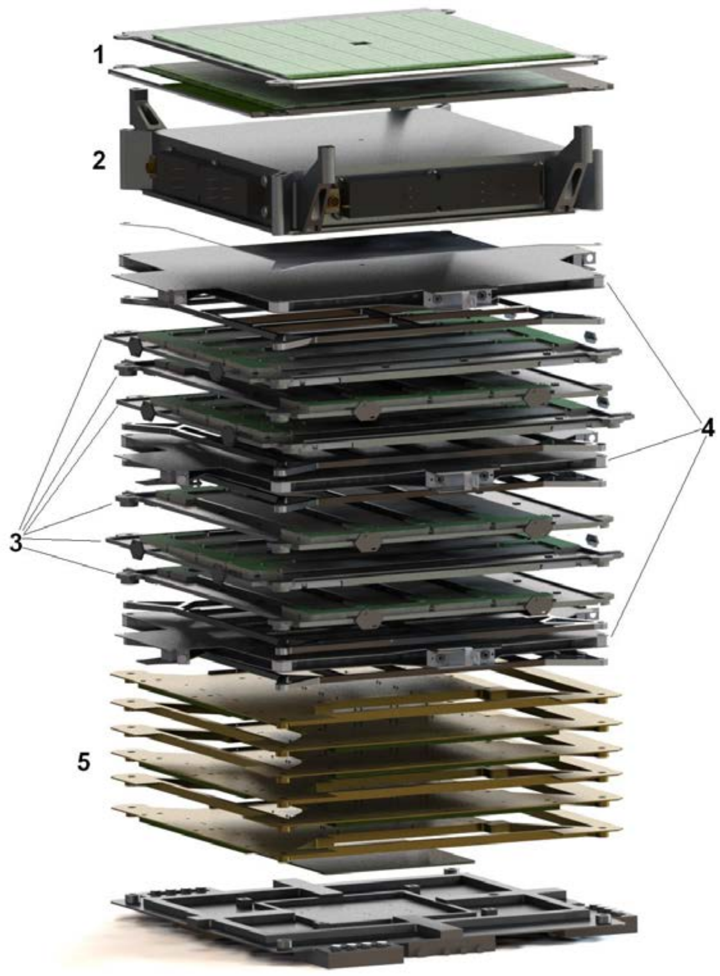
The number of secondary particles with high pseudorapidity after the first interaction increases approximately logarithmically along increasing of the primary energy of particle

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;

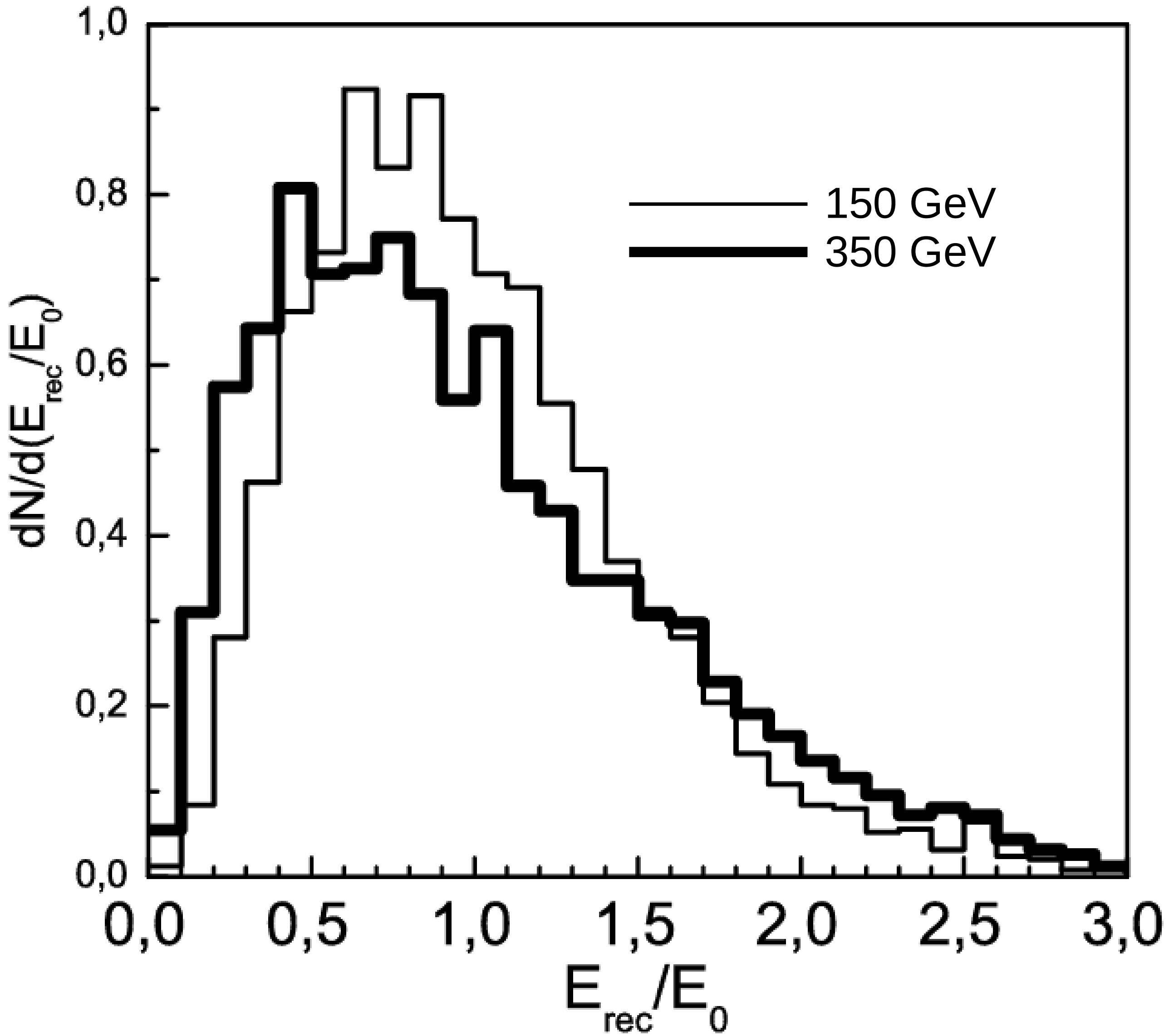
(3) KLEM tracker – six planes of microstrip silicon detectors (400 mkm step) with tungsten between them (~2mm each, ~3 X-lengths summary).
Active square 500*500 mm^2.
KLEM geometrical factor 0.24m^{2}sr.

(4) Trigger system – tree double sntillator planes;

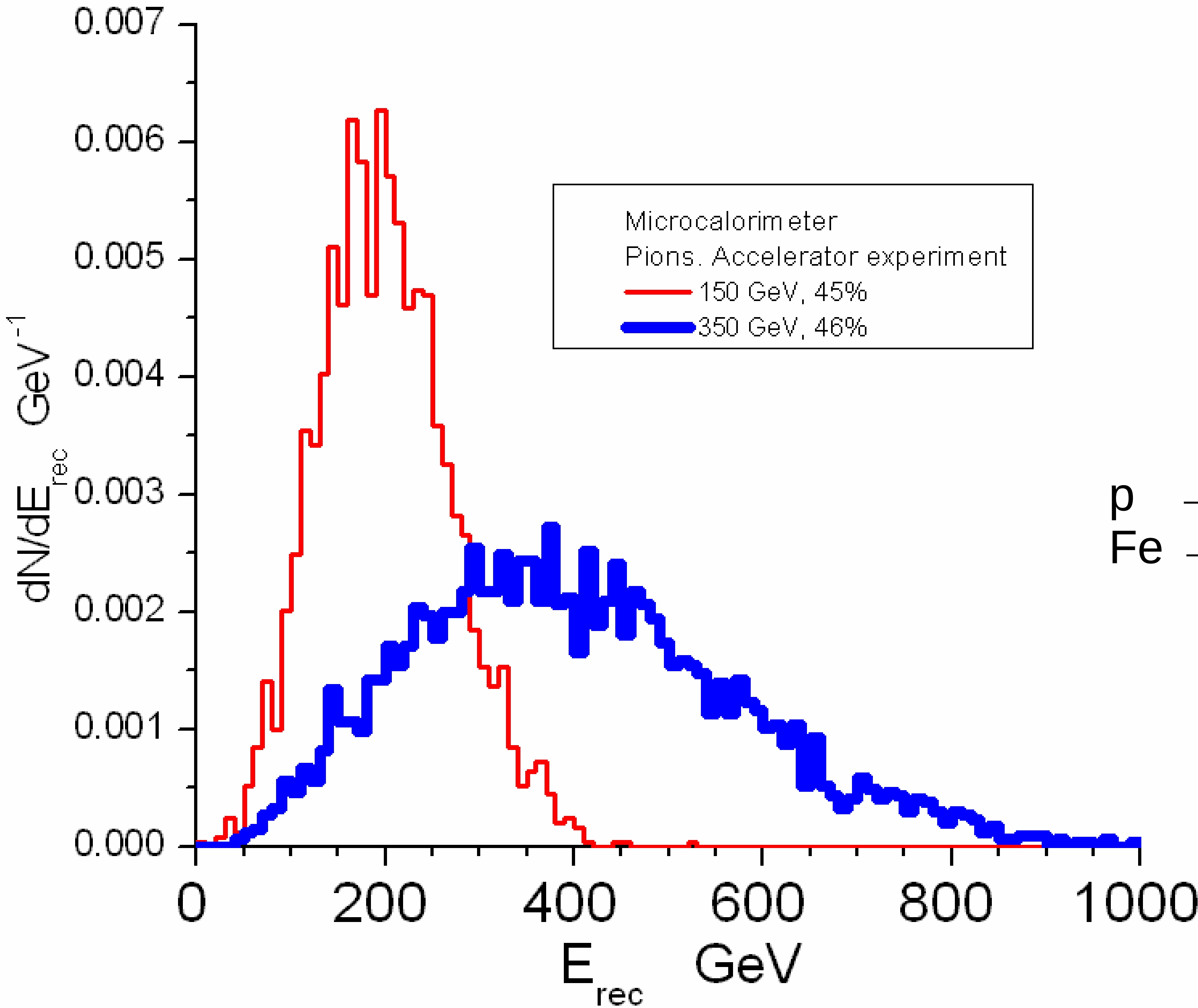
(5) Ionization calorimeter (IC) – six planes of tungsten absorber (~8mm each, ~12 X-lengths summary) with silicon strip detectors (1mm step).
Active square 250*250mm^2.
IC geometrical fact 0.06m^{2}sr

10604 independent electronic channels in total

KLEM, CERN test for π^-, resolution ~60%



Calorimeter, CERN test for π^-, resolution ~45%

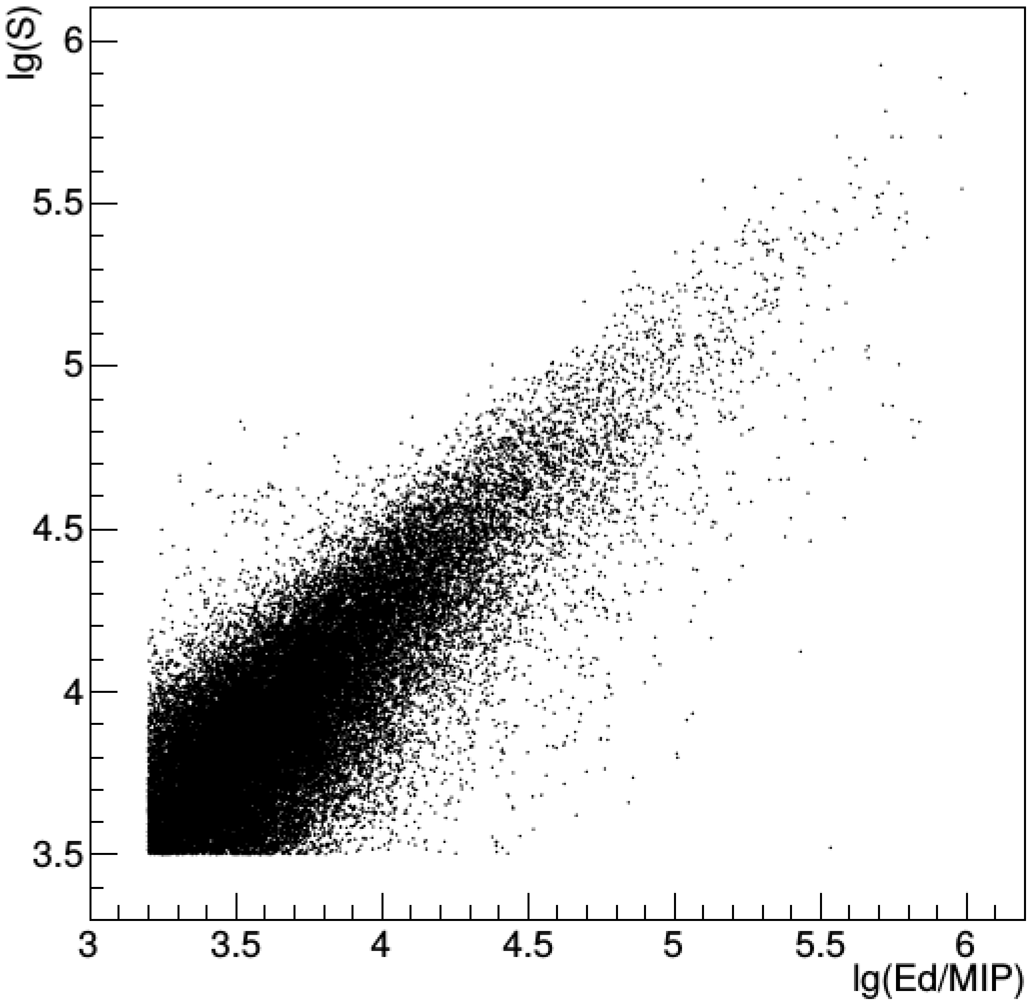


p → ~45%
Fe → ~35%

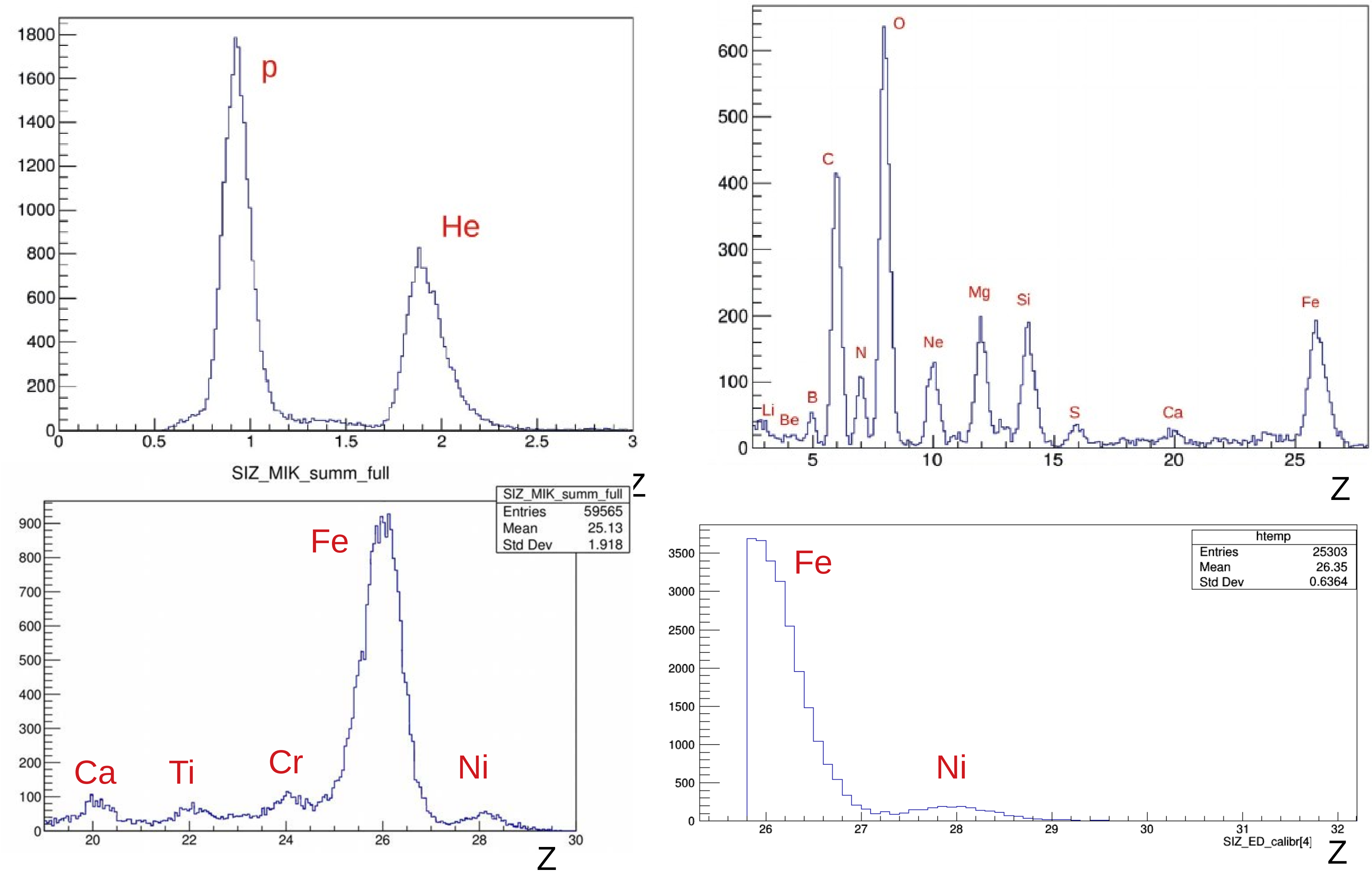
Model-independent evidence that the KLEM method may be used to measure energy of particles

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

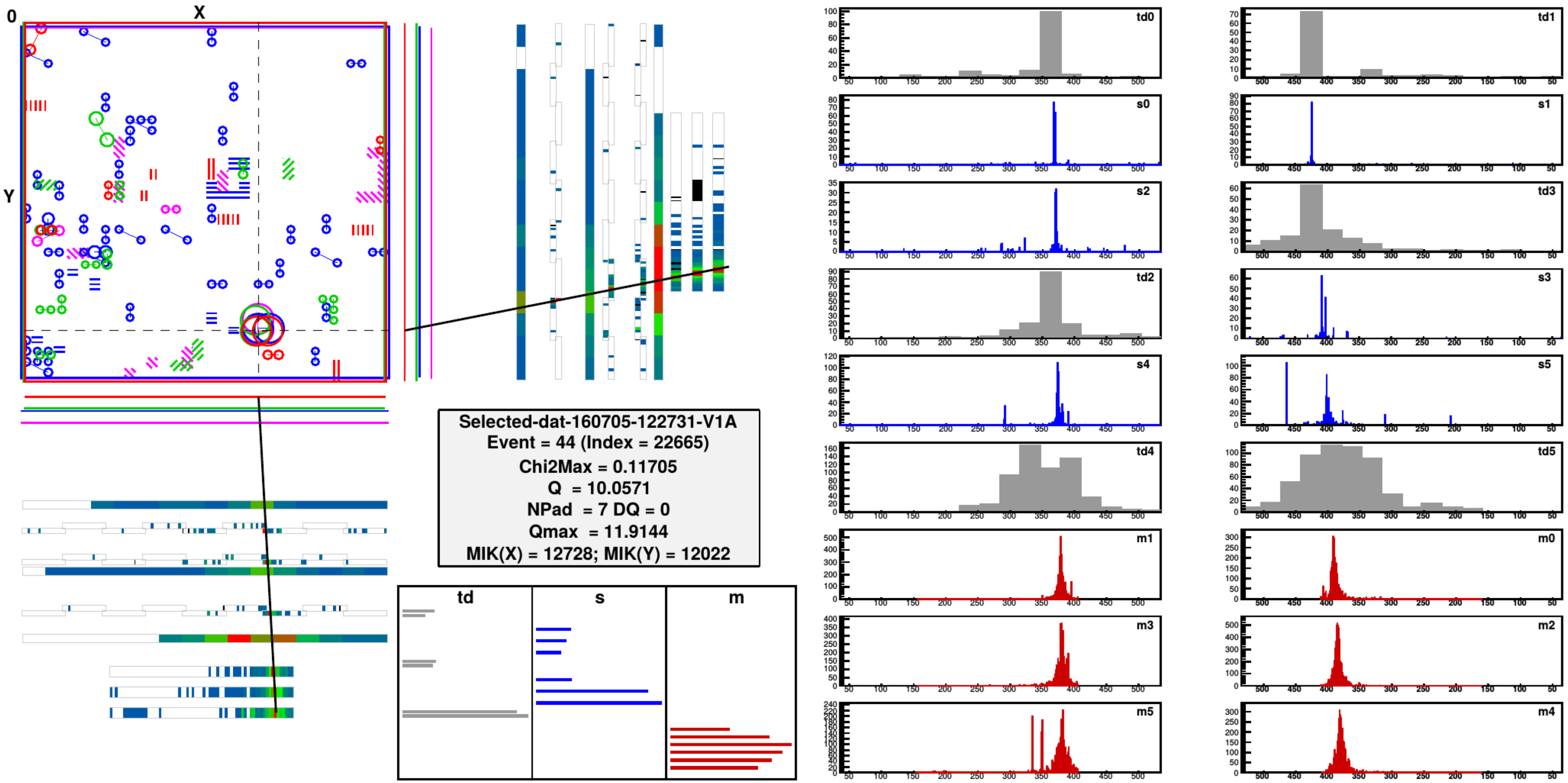
This correlation is a model-independent result



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

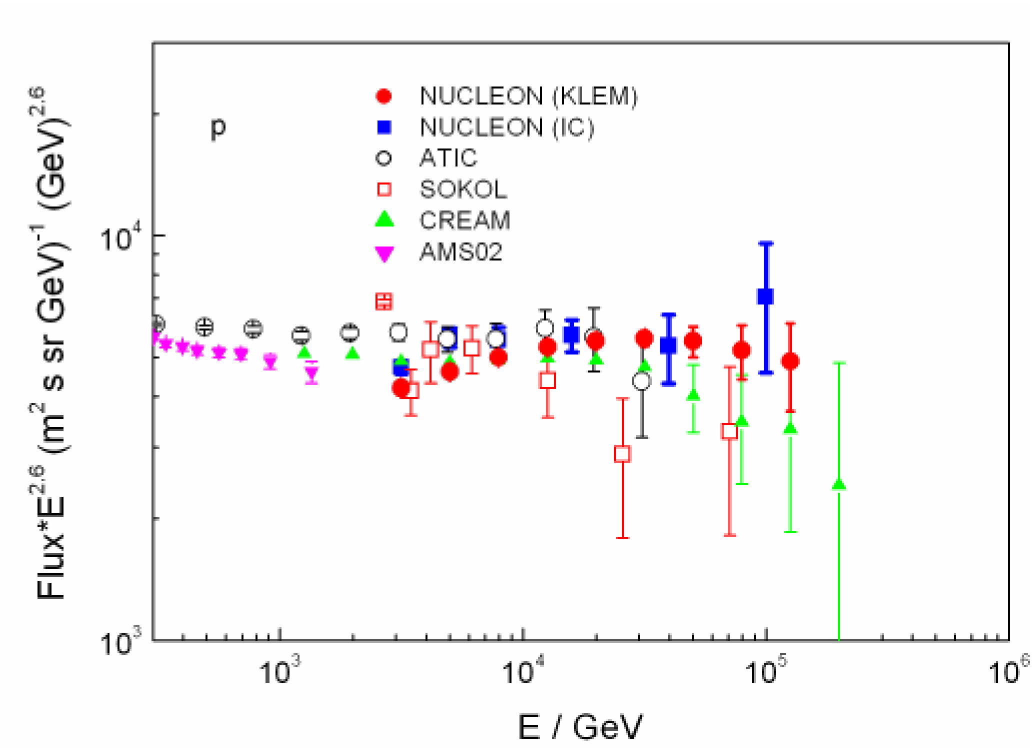


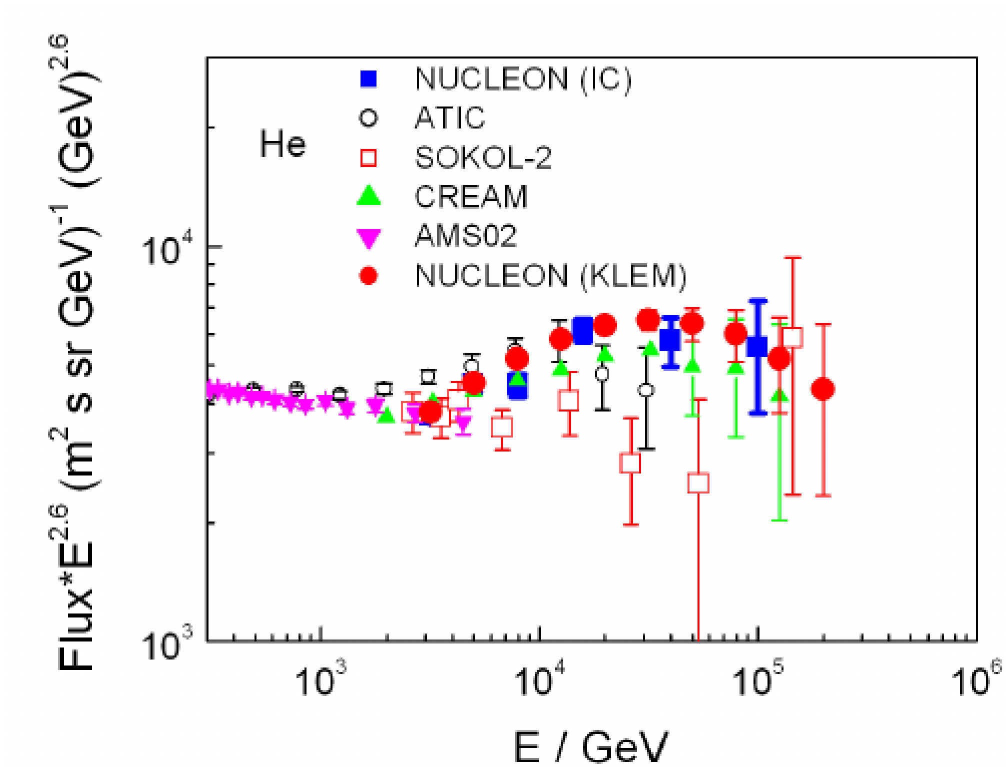
An example of an event «portrait»



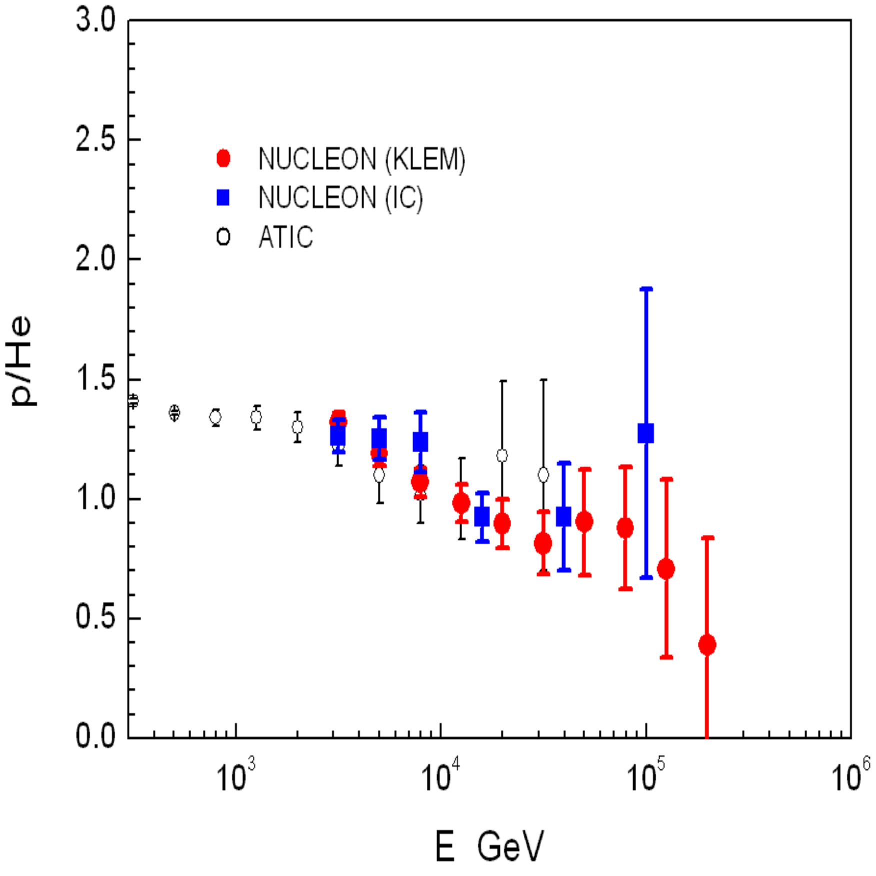
Main data

Protons and Helium

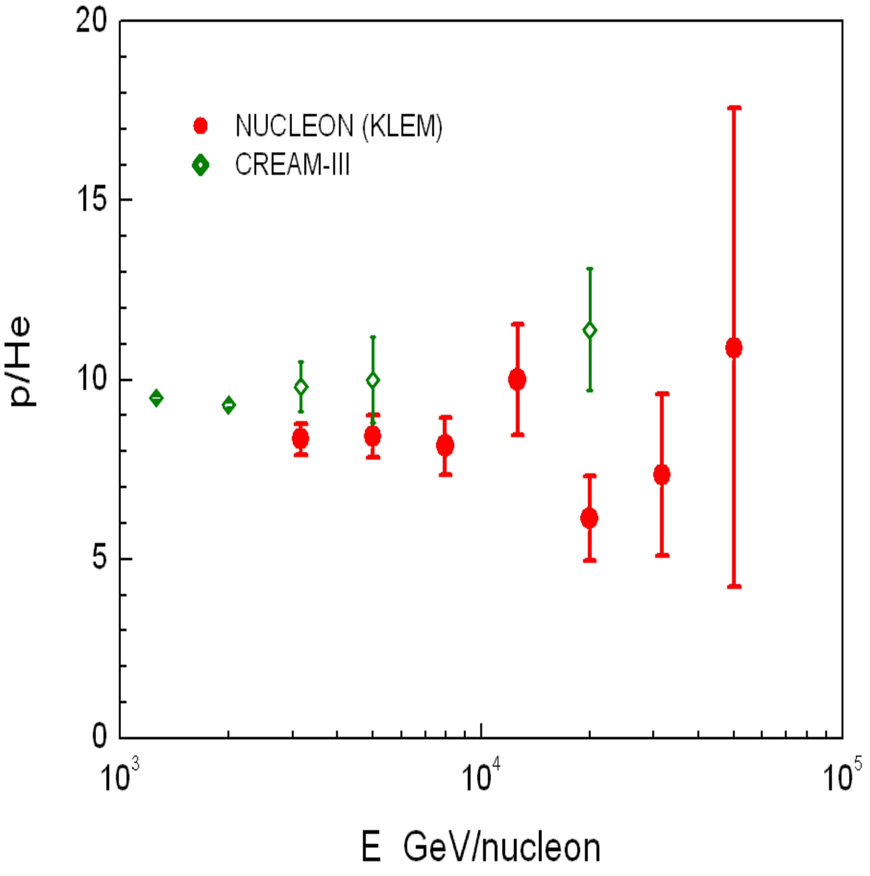




p/He ratio

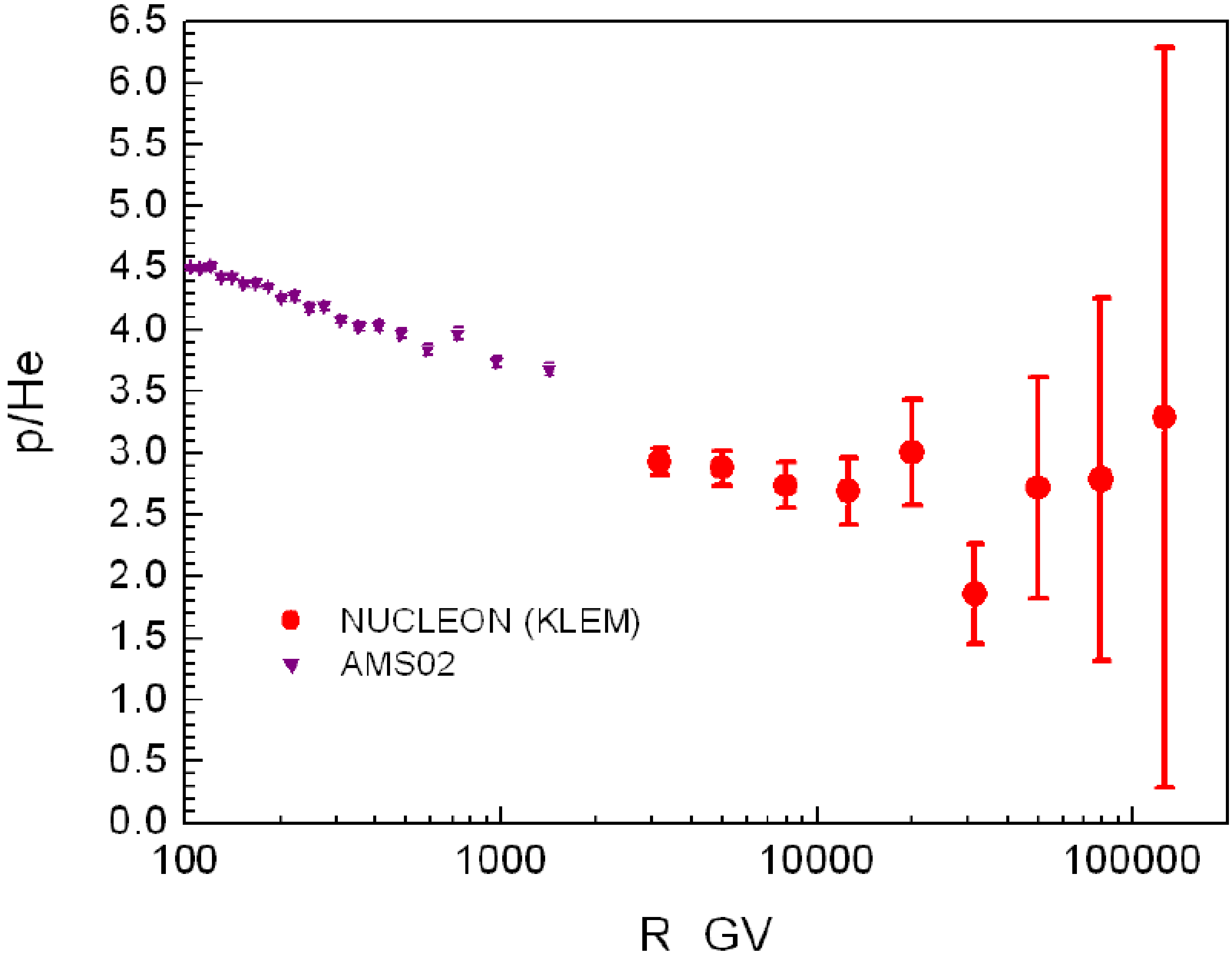


3.0
2.5
2.0
1.5
1.0
0.5
0.0
p/He
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
10^3
10^4
10^5
10^6
E GeV

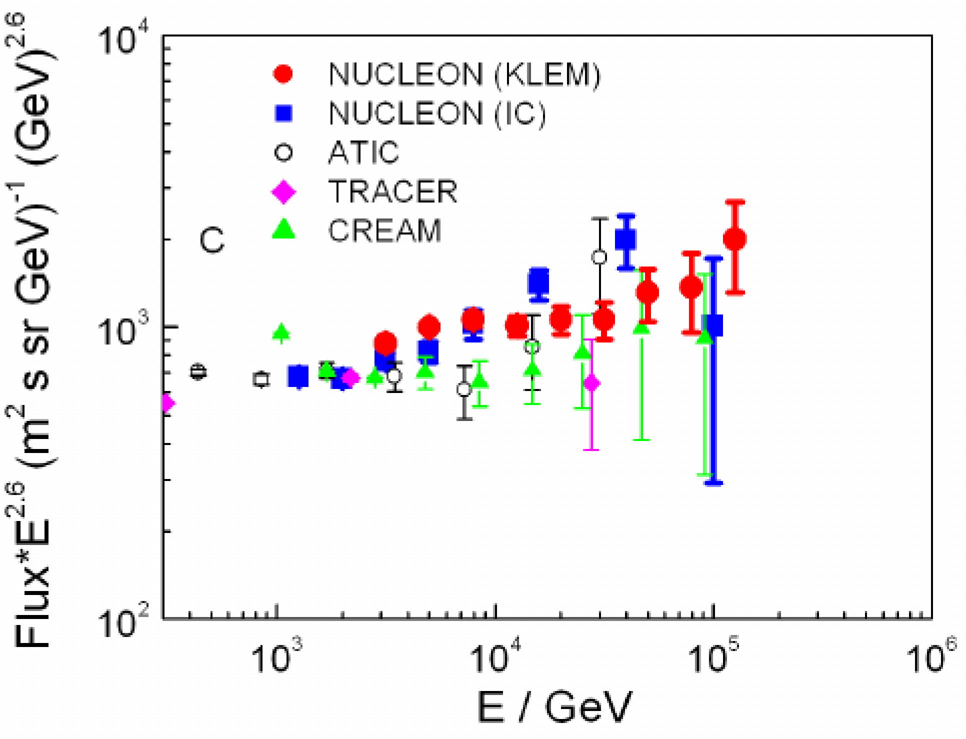


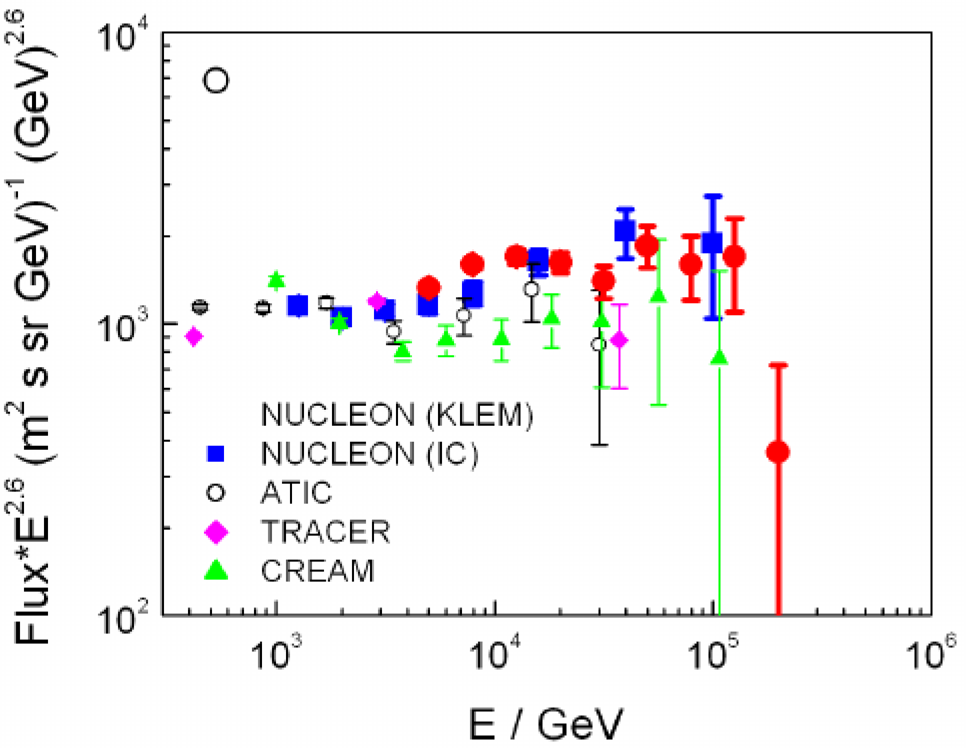
20
15
10
5
0
p/He
NUCLEON (KLEM)
CREAM-III
10^3
10^4
10^5
E GeV/nucleon

p/He ratio in terms of magnetic rigidity

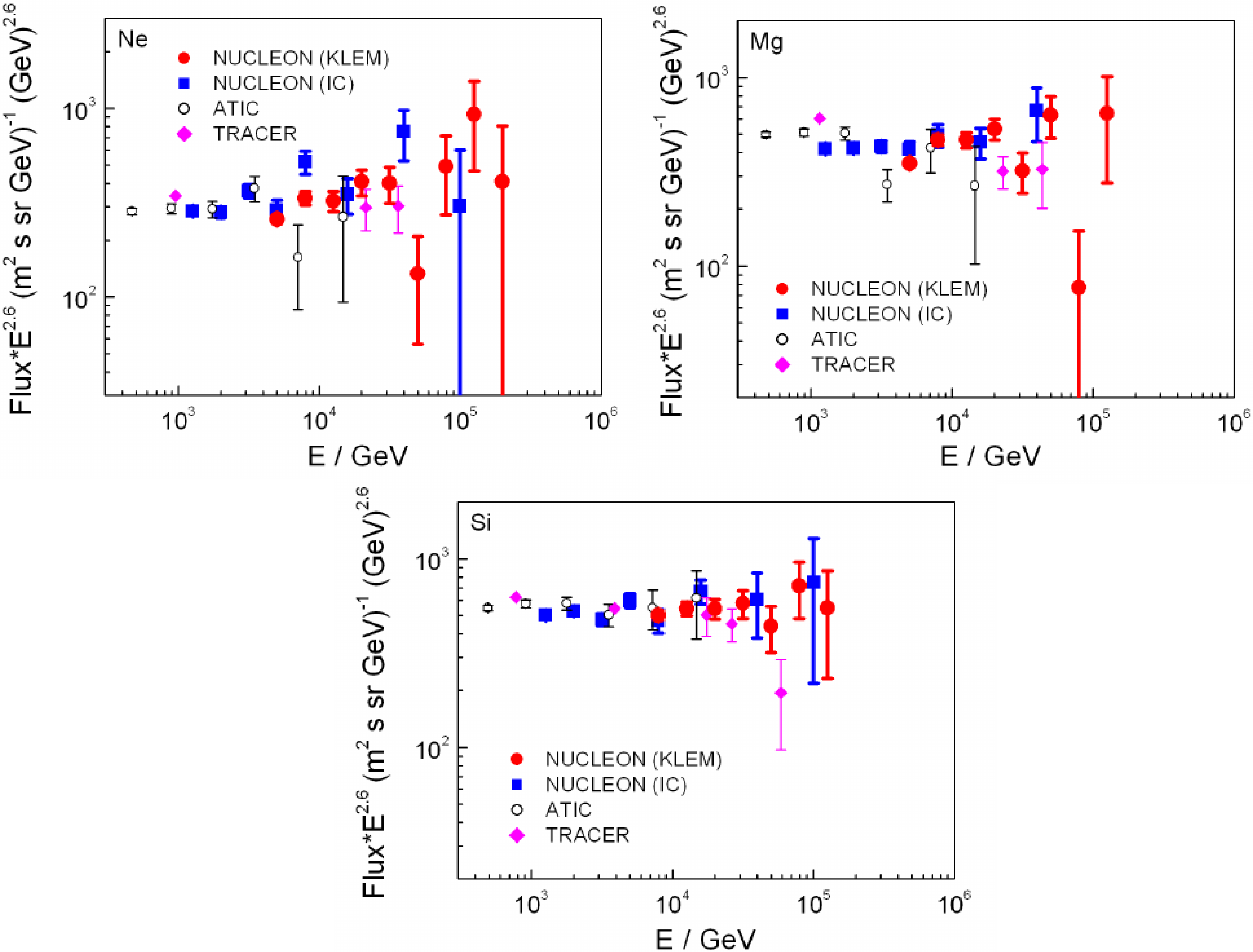


Carbon and Oxygen: hard (γ≈2.4) above ~3 TeV



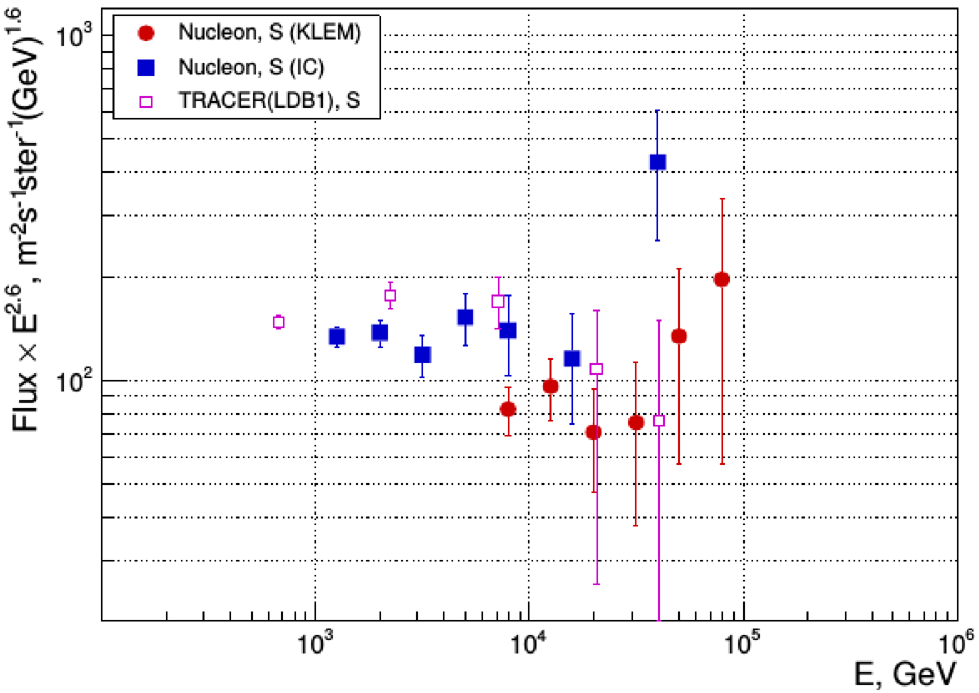


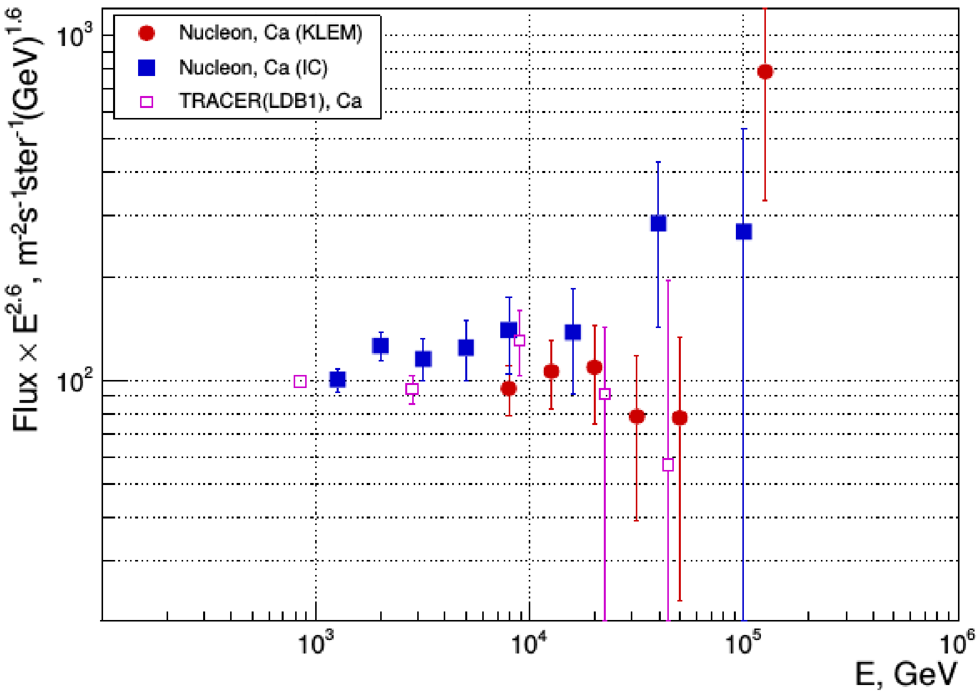
Ne-Mg-Si



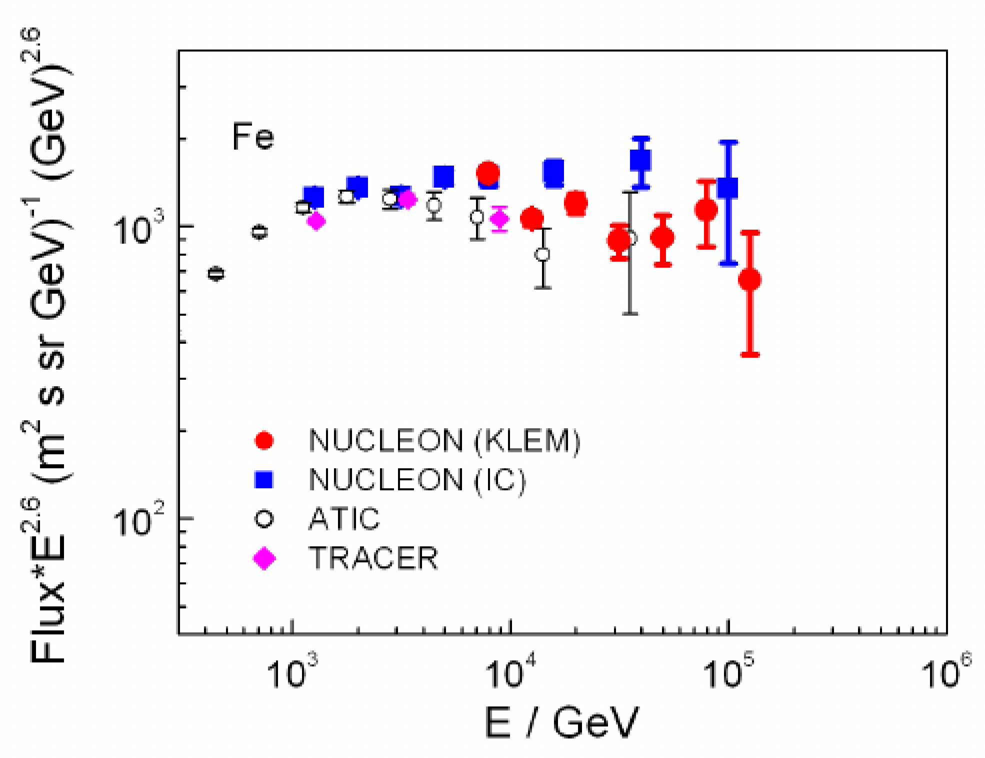
Ne
Mg
Si
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
TRACER
Flux*E$^{2.6}$ (m^2 s sr GeV)$^{-1}$ (GeV)$^{2.6}$
E / GeV
10^2
10^3
10^4
10^5
10^6

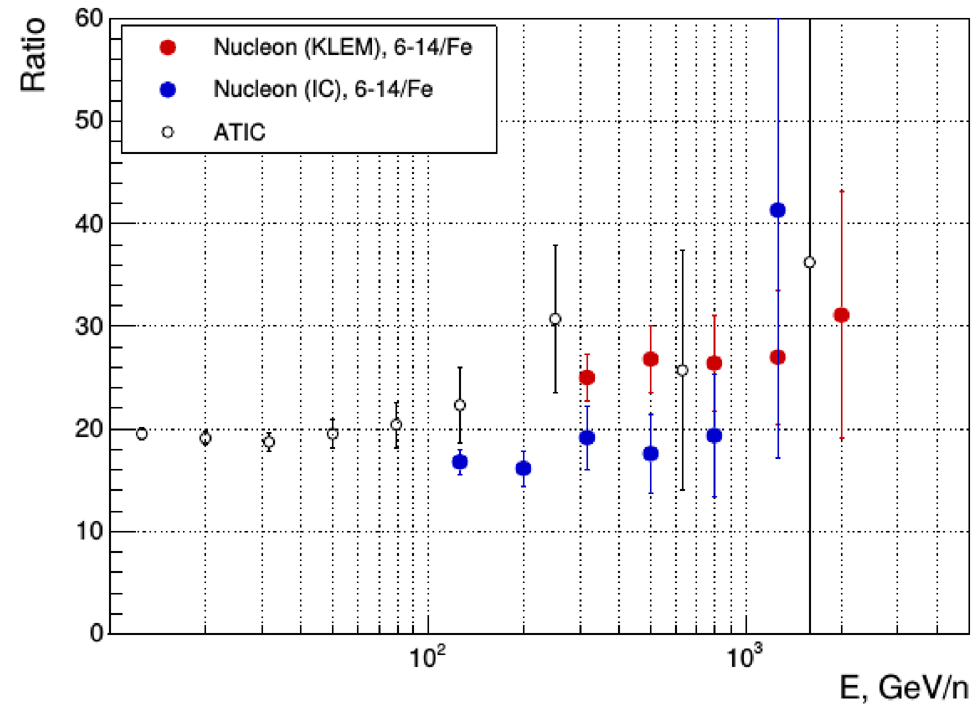
S and Ca - hints of complicated behavior, more statistics are needed





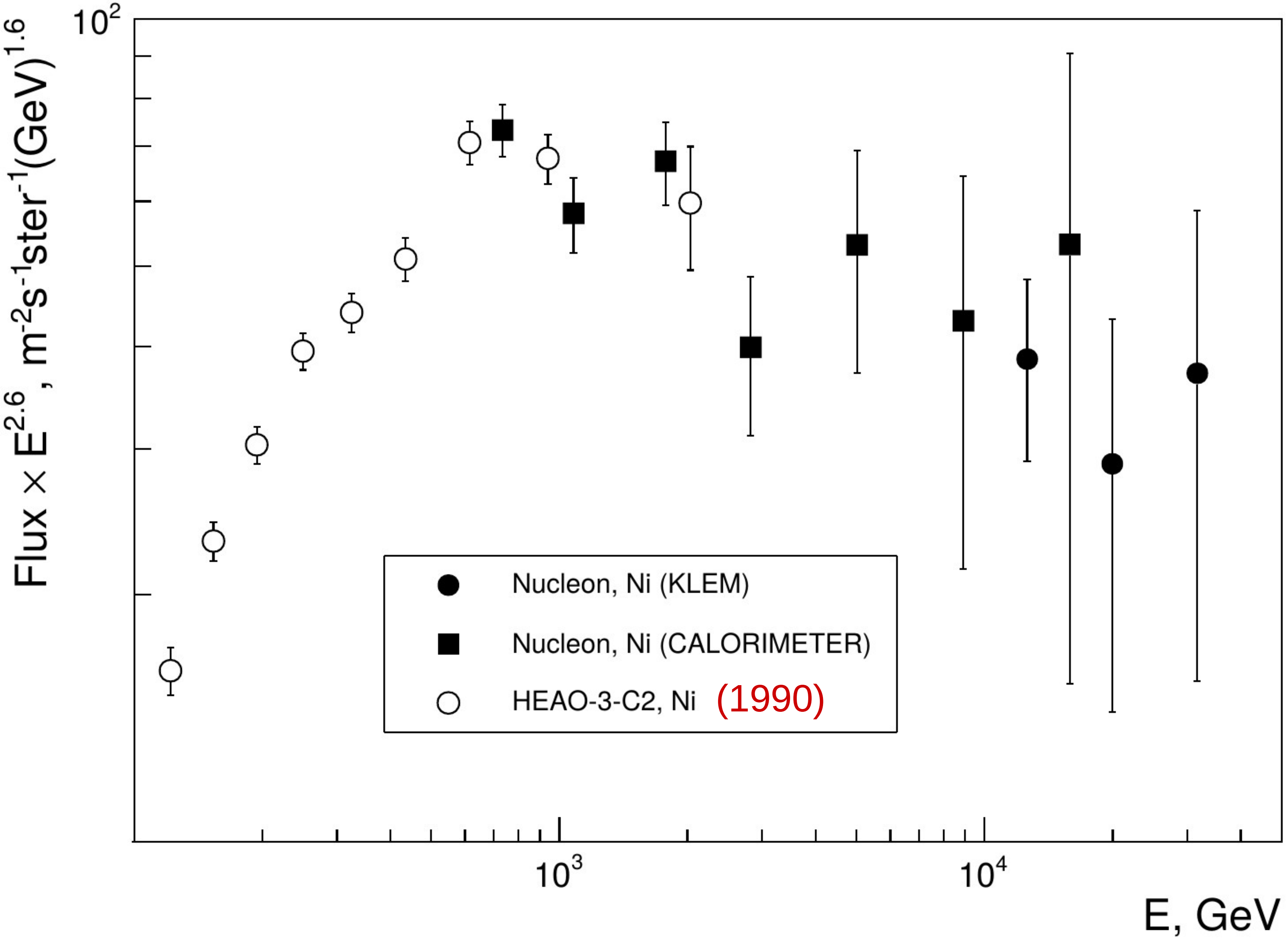
Iron spectrum ($\gamma \approx 2.6$) - softer, than the spectra of other heavy nuclei? (Z = 6-14)



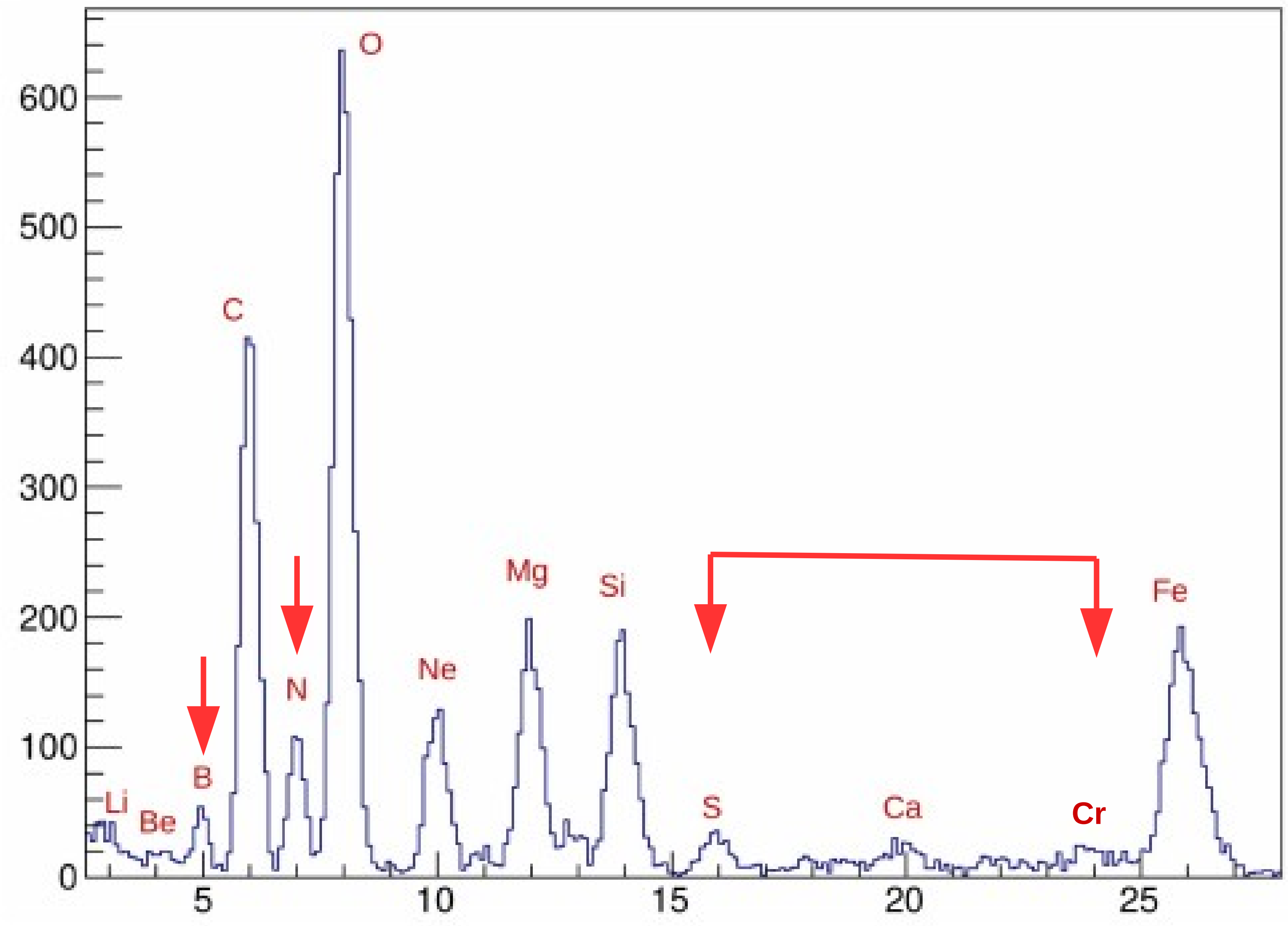


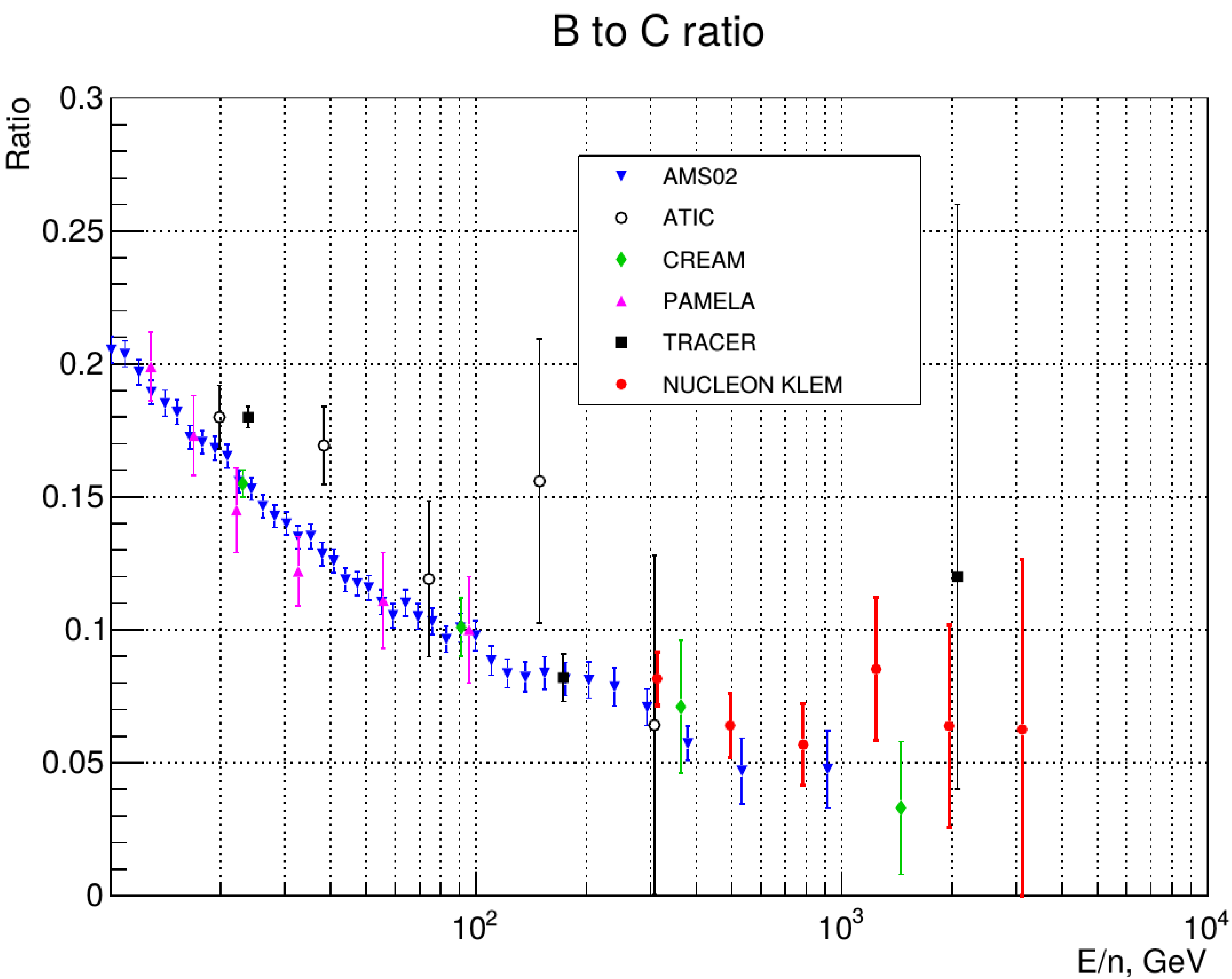
Nickel (Z=28) spectrum. γ = 2.83 ± 0.09

γ_{Fe}= 2.64 ± 0.02

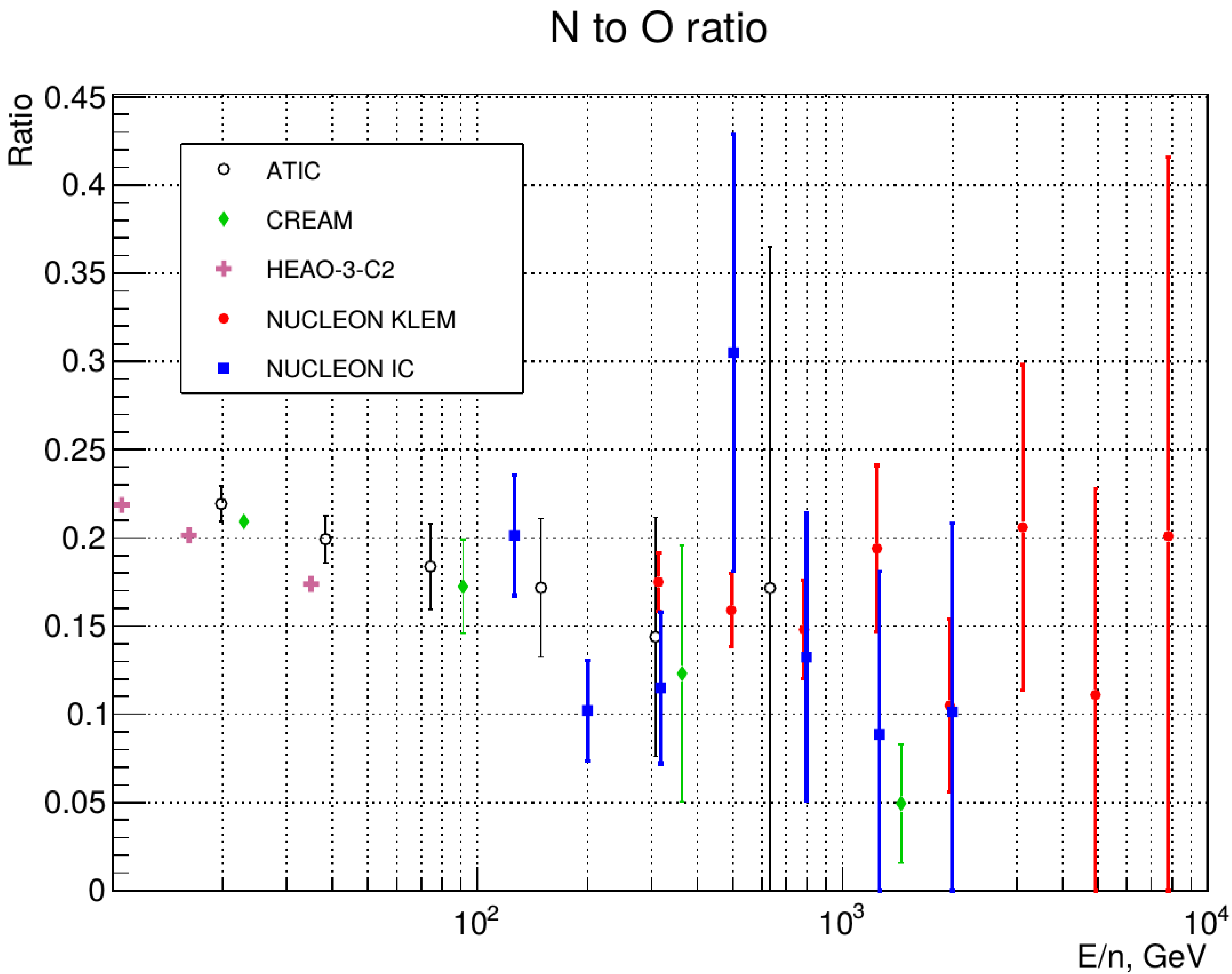


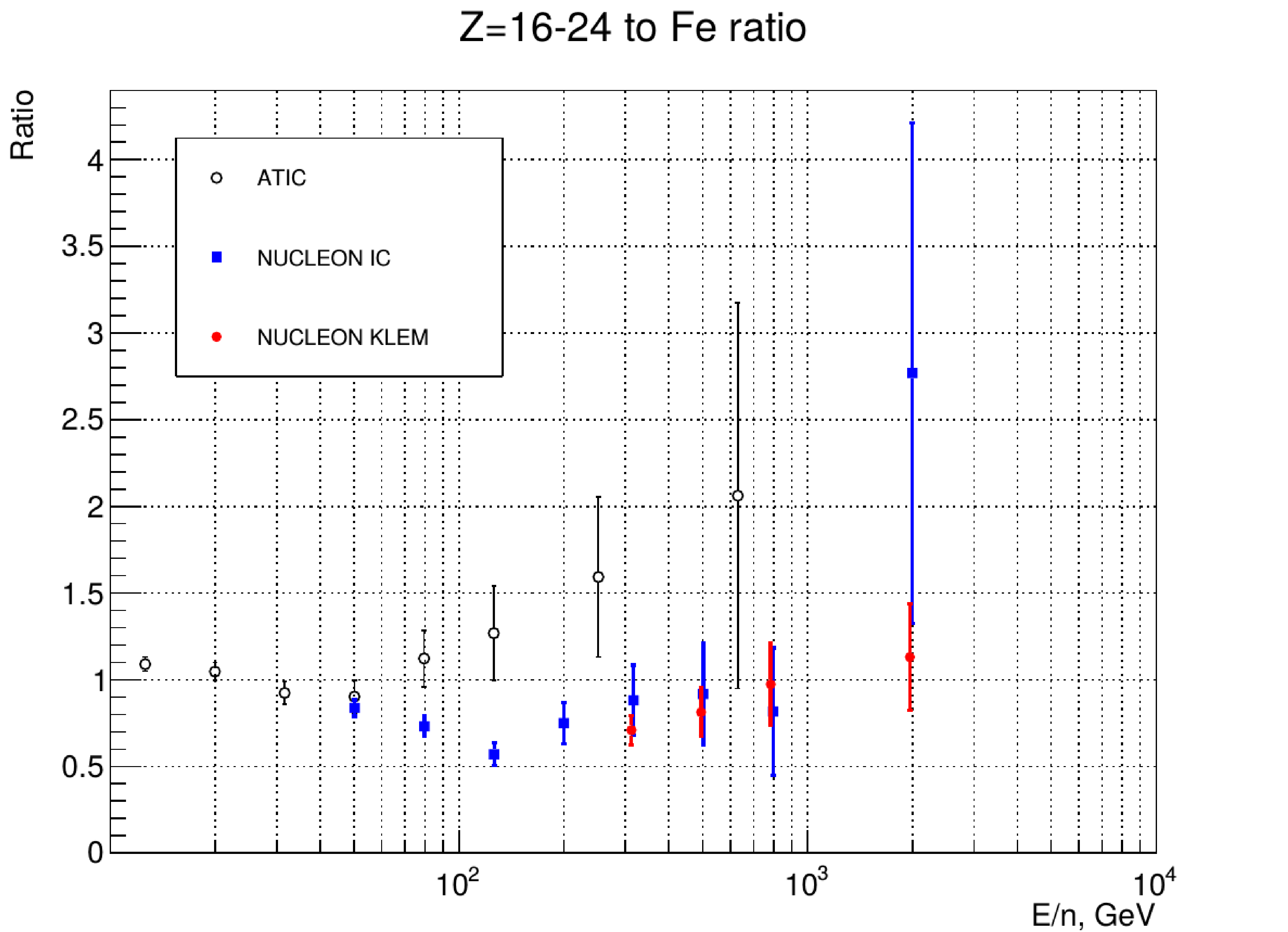
Spectra of secondary nuclei



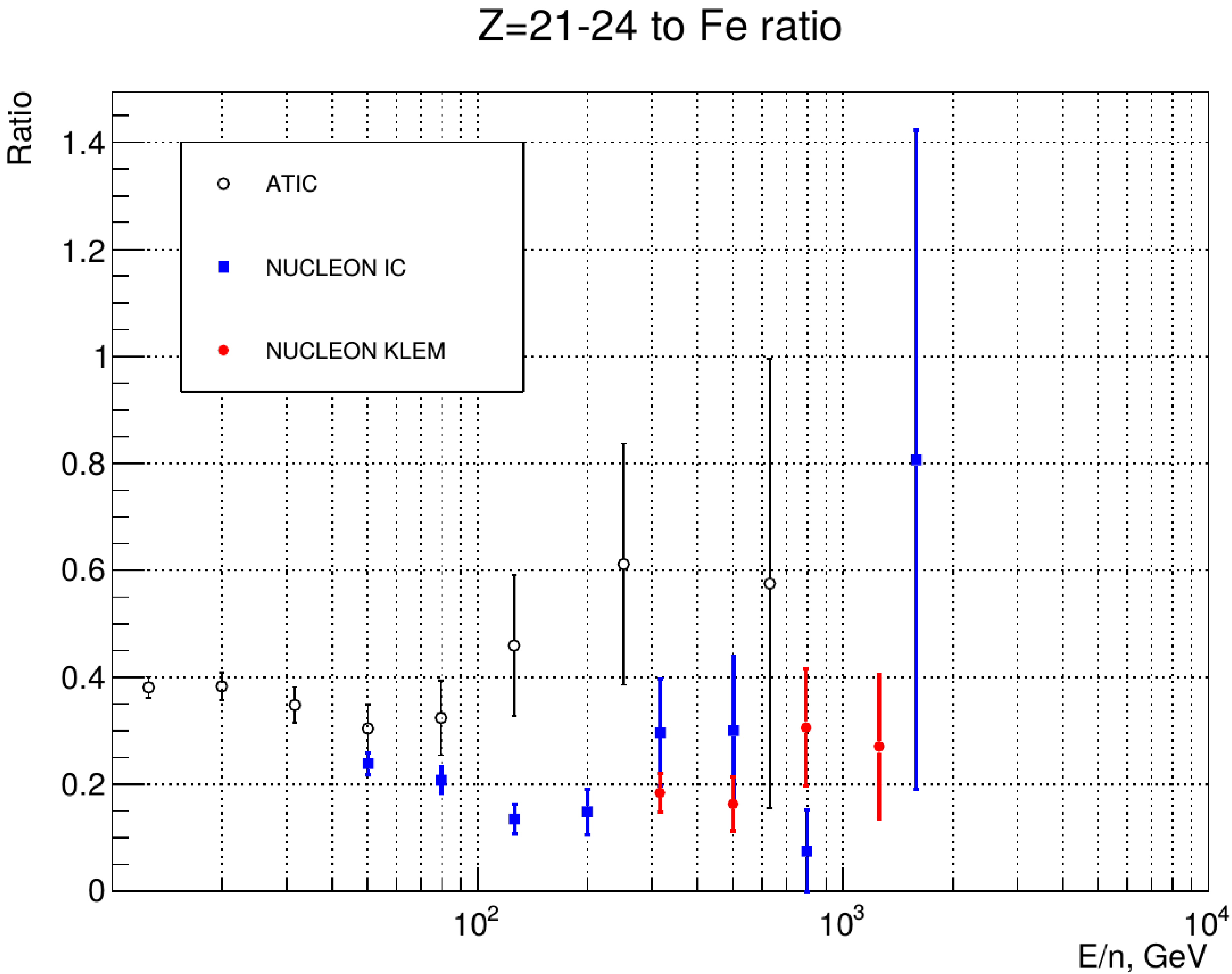


B to C ratio
Ratio
0.3
0.25
0.2
0.15
0.1
0.05
0
10^2
10^3
10^4
E/n, GeV
AMS02
ATIC
CREAM
PAMELA
TRACER
NUCLEON KLEM


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

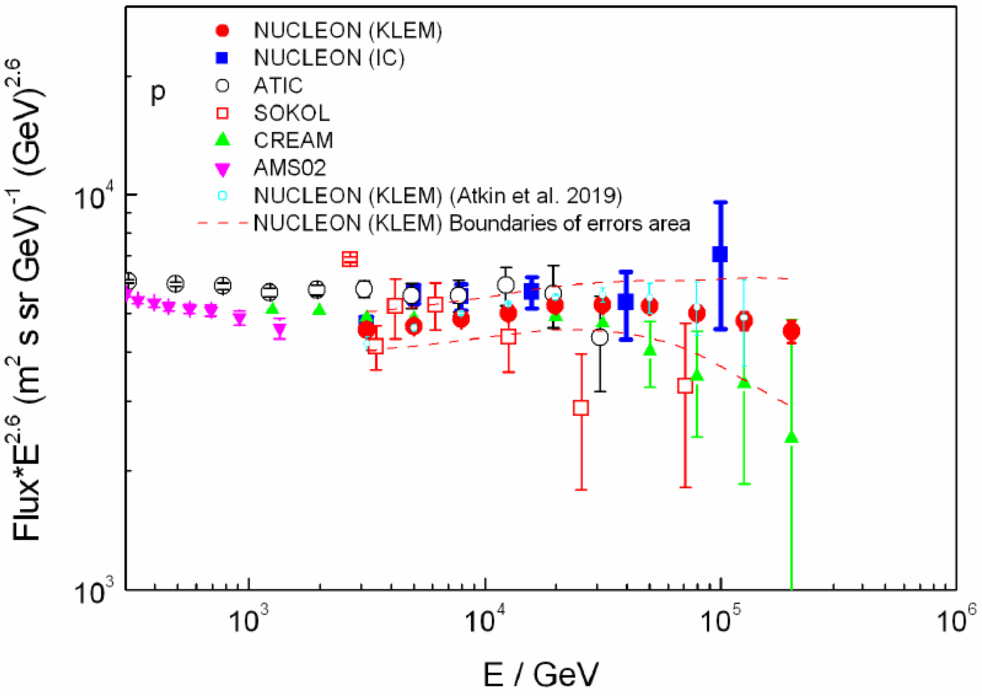


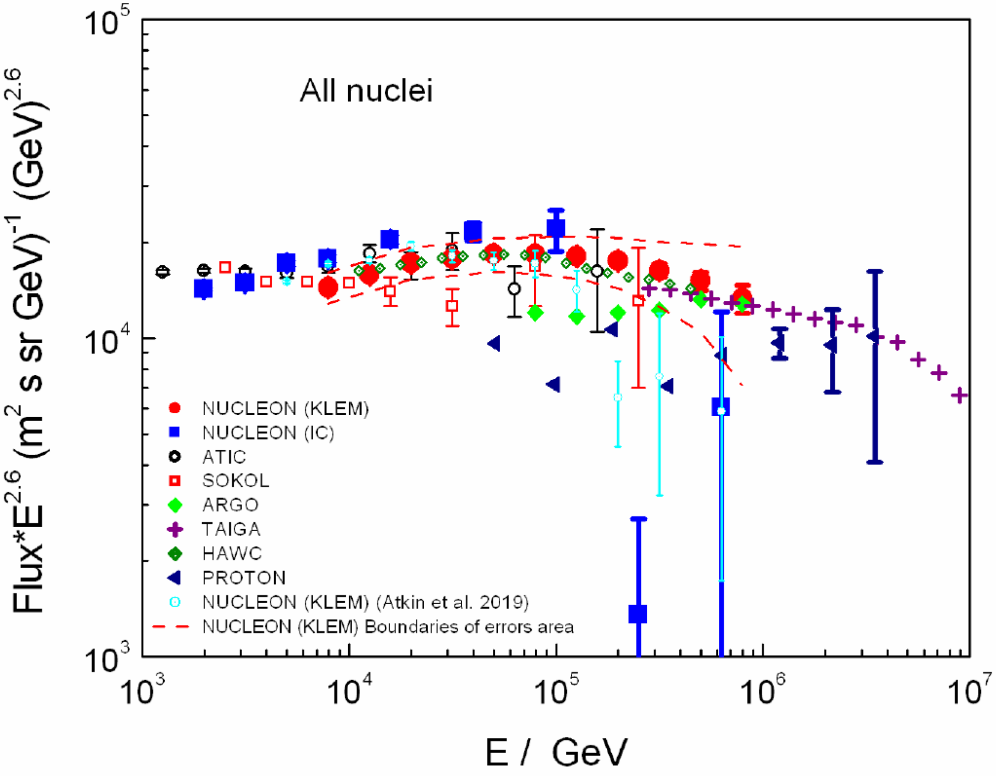
Z=16-24 to Fe ratio
Ratio
ATIC
NUCLEON IC
NUCLEON KLEM
0
0.5
1
1.5
2
2.5
3
3.5
4
10^2
10^3
10^4
E/n, GeV



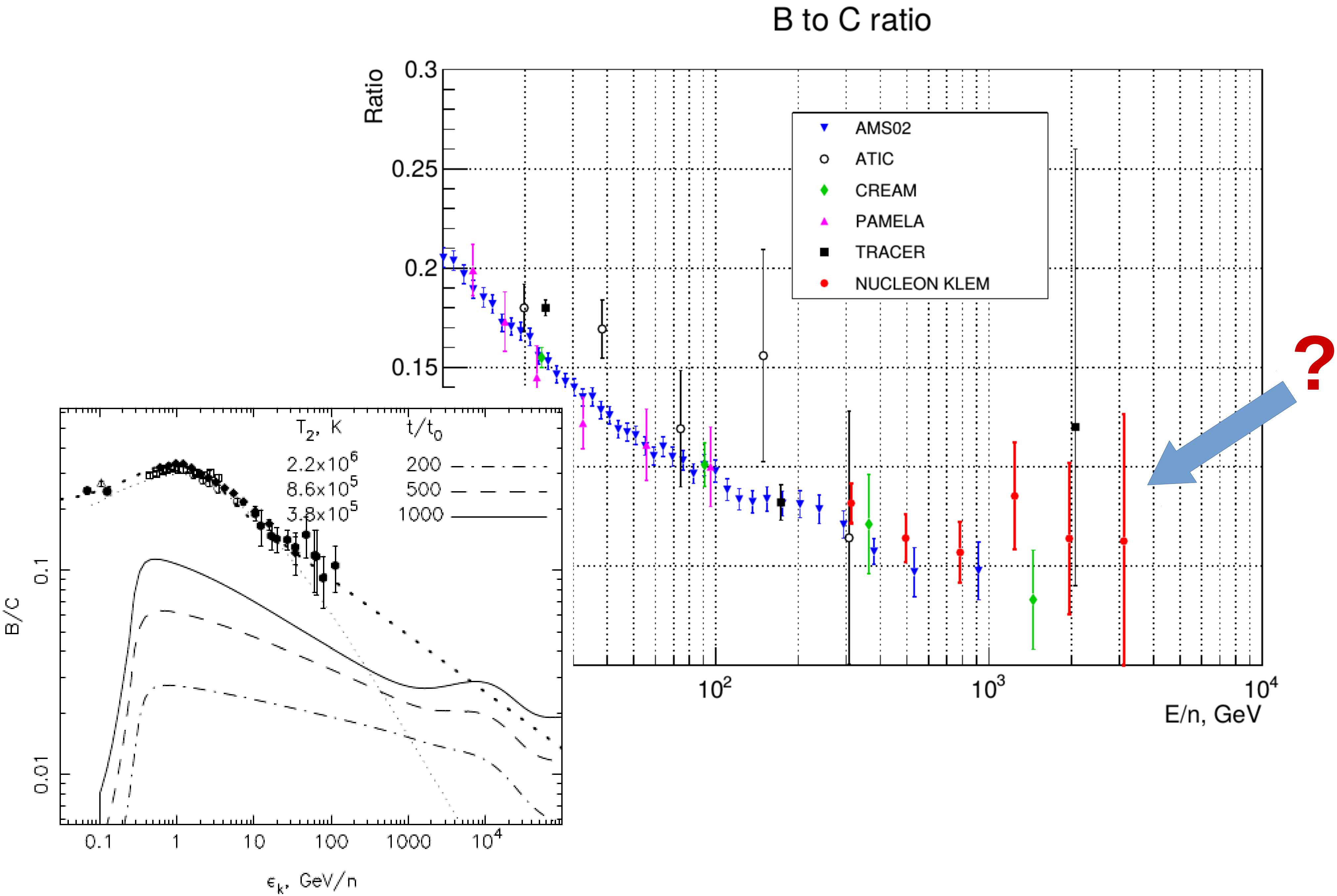
Z=21-24 to Fe ratio
Ratio
1.4
1.2
1
0.8
0.6
0.4
0.2
0
ATIC
NUCLEON IC
NUCLEON KLEM
10^2
10^3
10^4
E/n, GeV

The work is in progress: systematics, deconvolution etc...





Some interesting physics

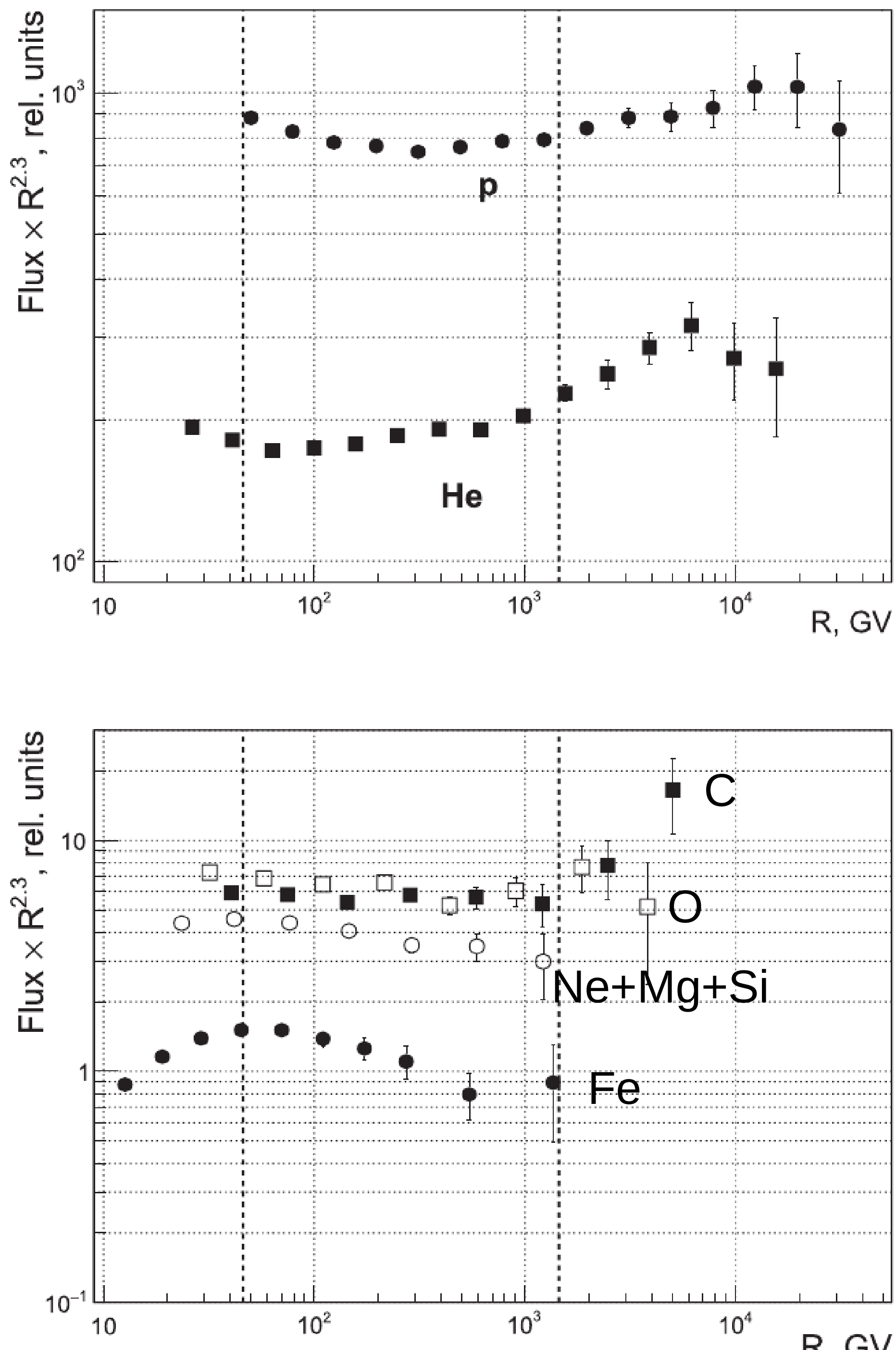


E. G. Berezhko, L. T. Ksenofontov, V. S. Ptuskin, V. N. Zirakashvili, H. J. Voelk. Astron.Astrophys. 410 (2003) 189-198 (arXiv:astro-ph/0308199v1).

ATIC:

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

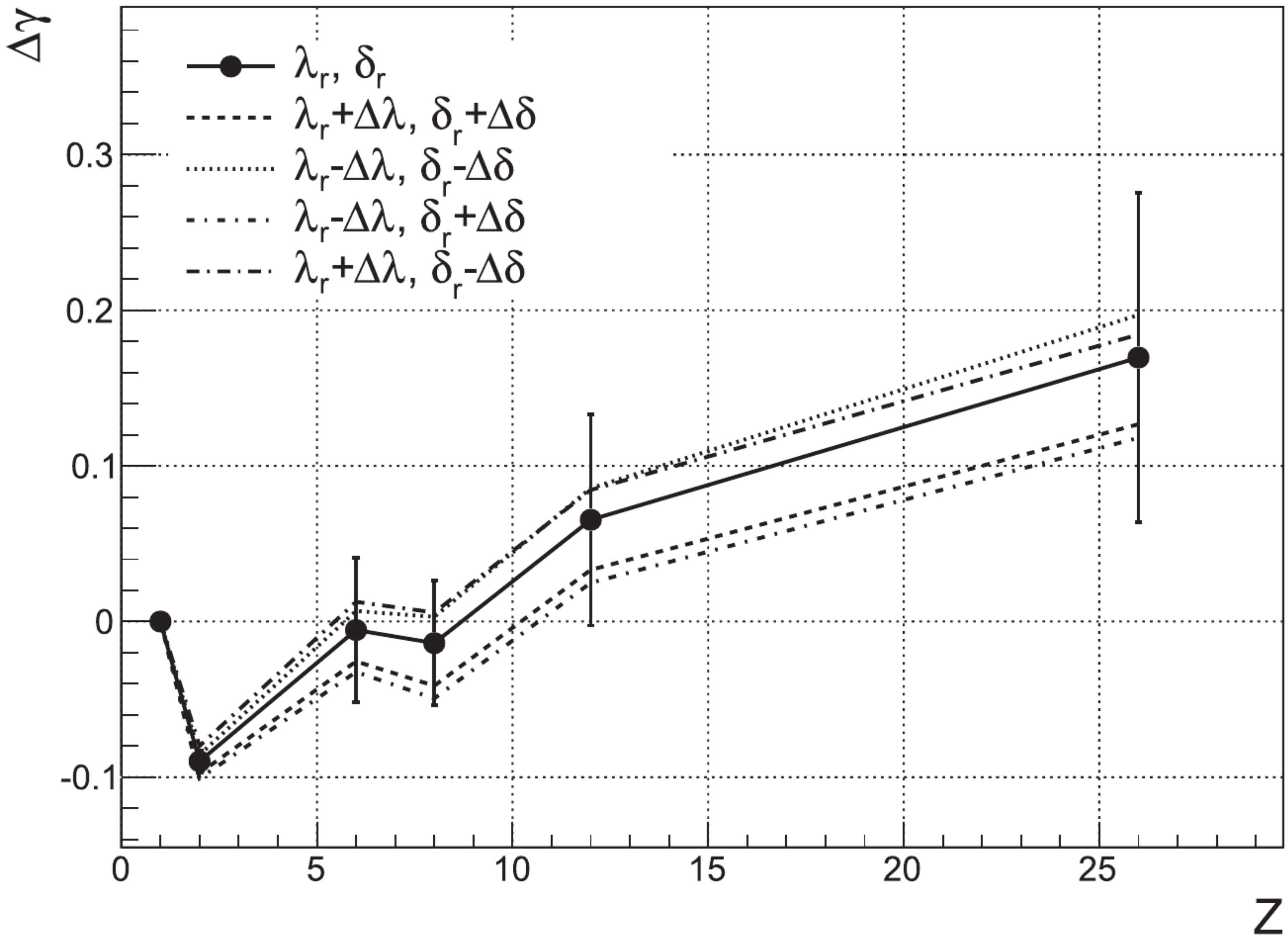
- Same rigidity region for different nuclei
- Back propagation problem is solved



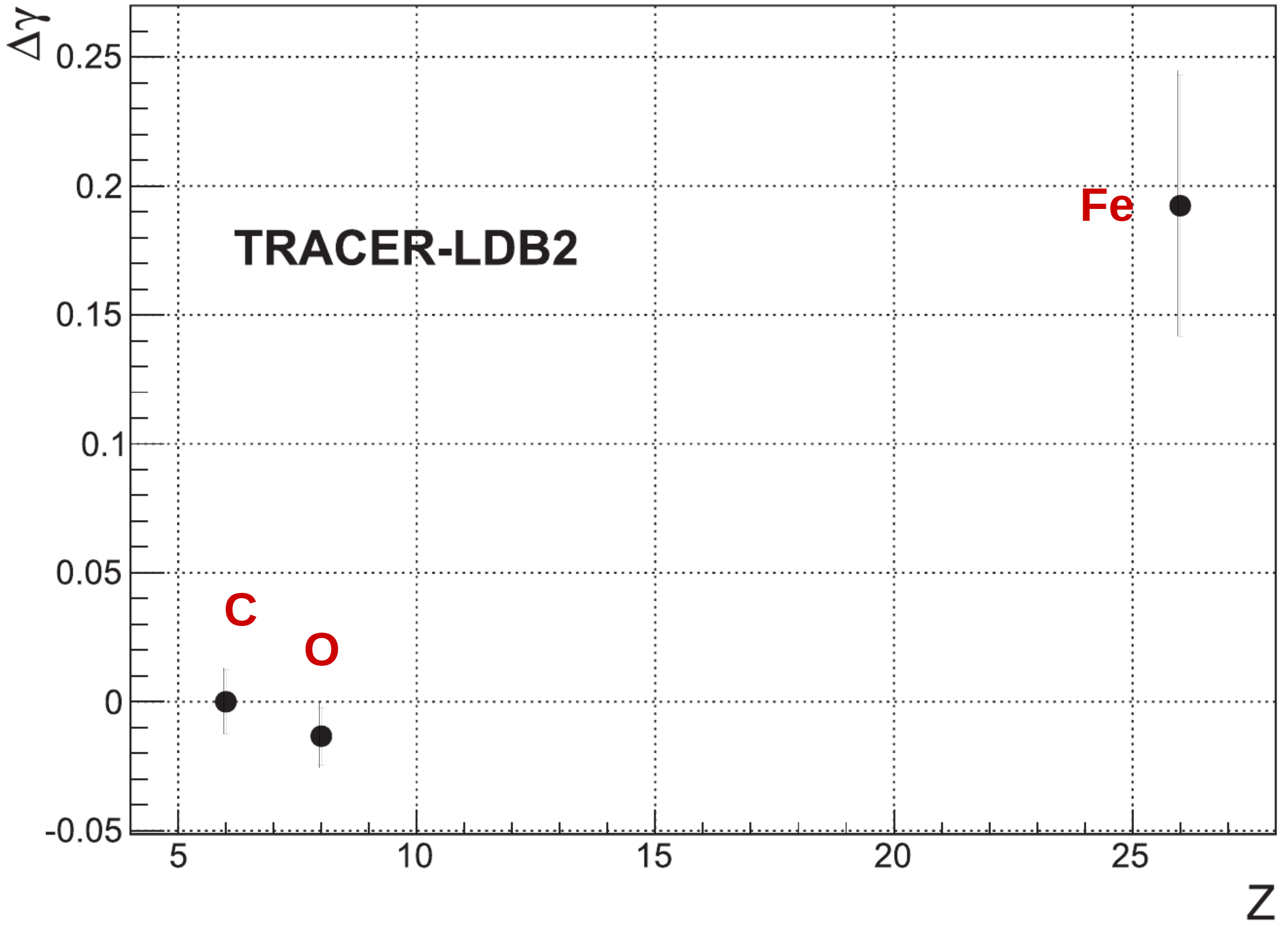
45–1300 GV

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

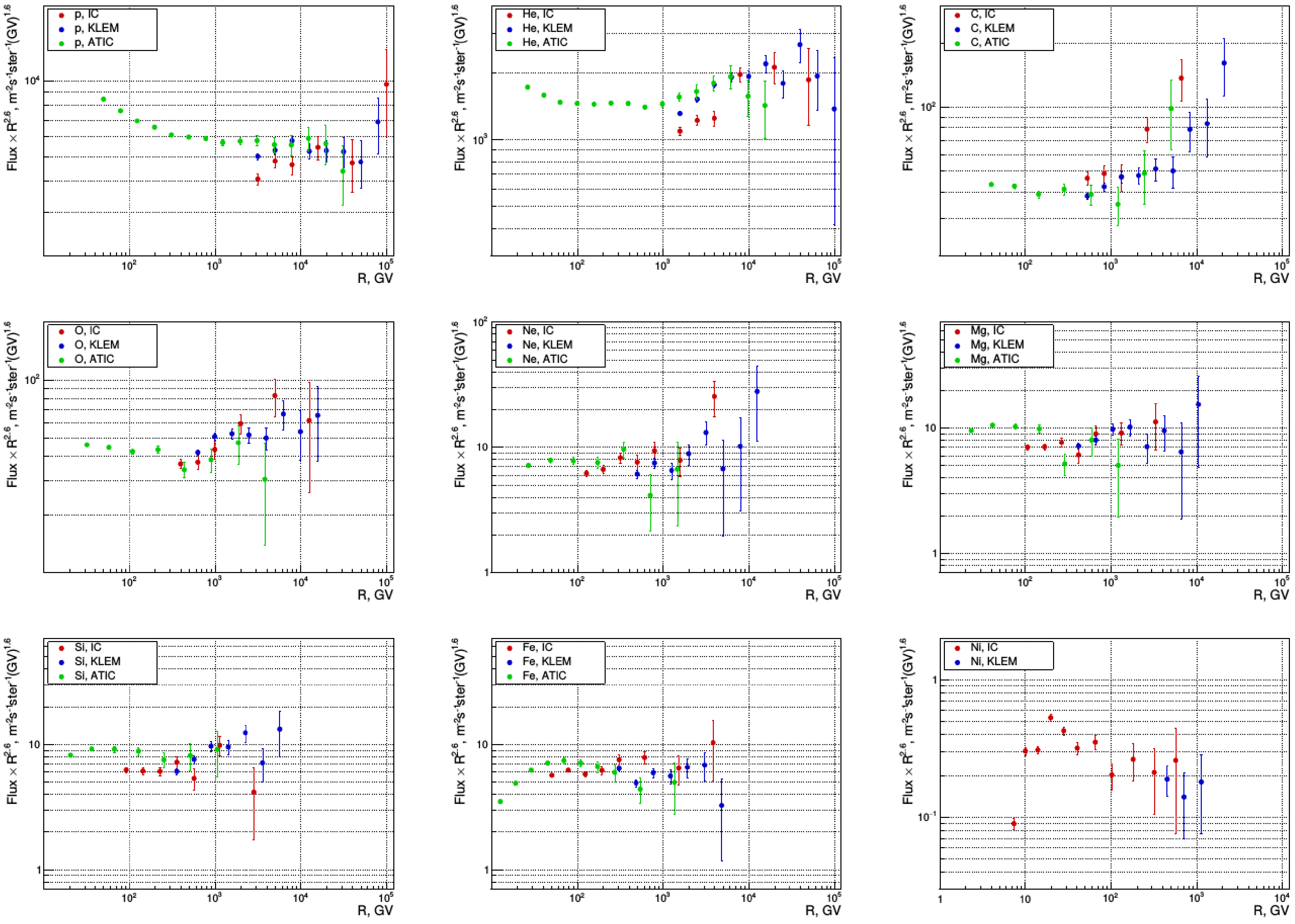
ATIC: ApJ, V.837, 77 (2017)



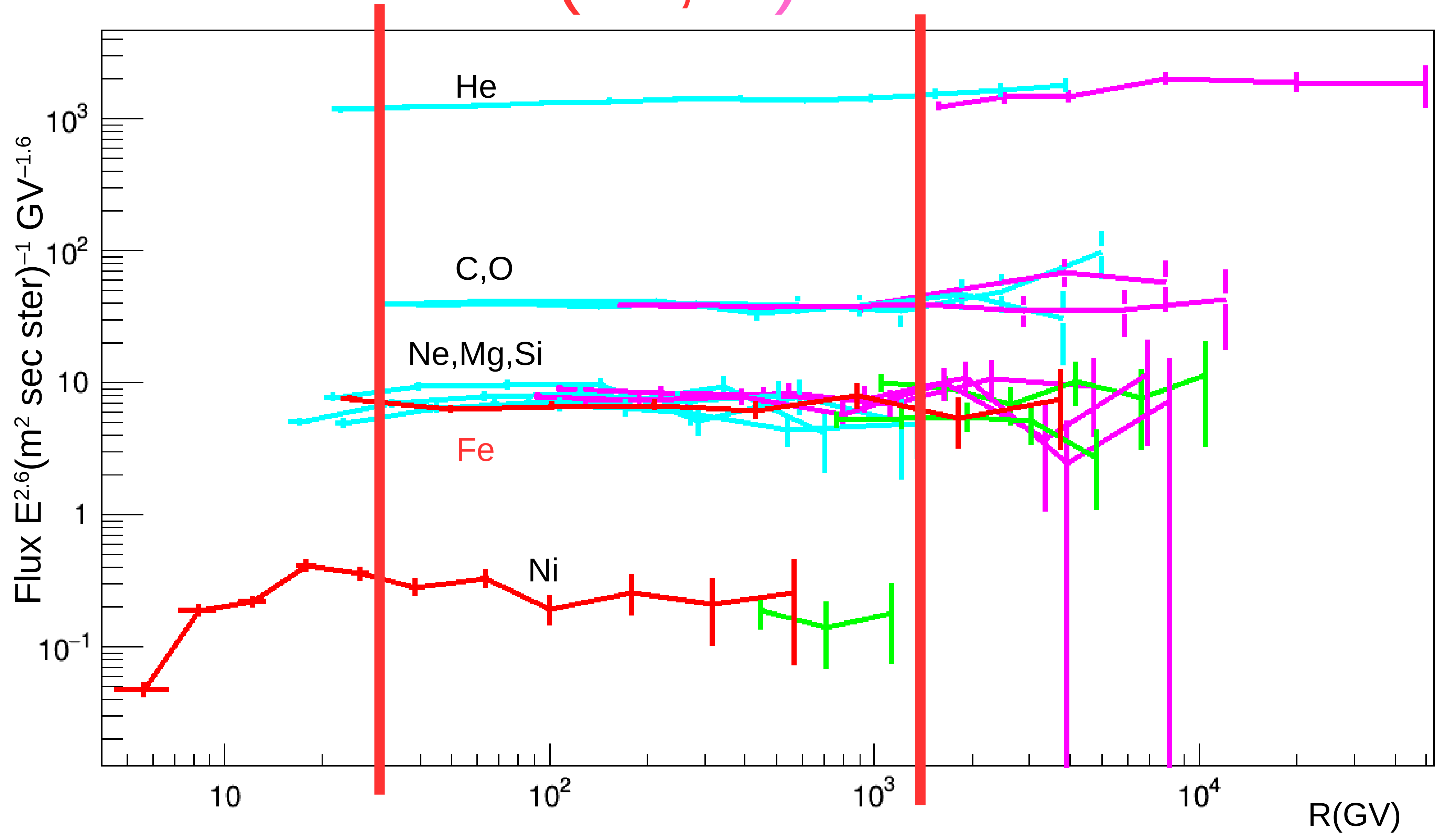
ATIC: ApJ, V.837, 77 (2017)
TRACER: ApJ, V.742, 14 (2011)



Rigidity spectra of nuclei in ATIC and NUCLEON experiments



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



30GV – 1300GV

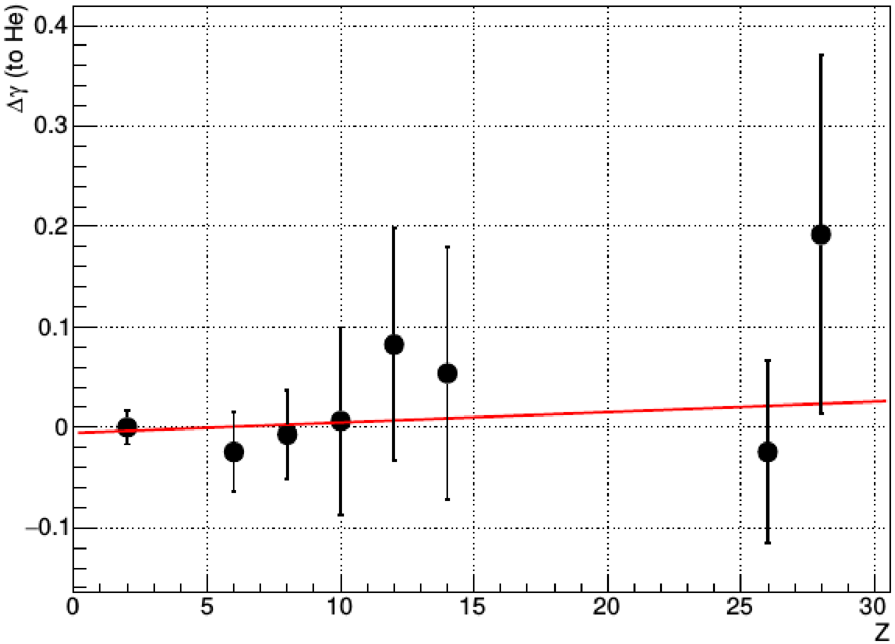
Solution of the back propagation problem:
GALPROP +
parameters based on AMS-02 data

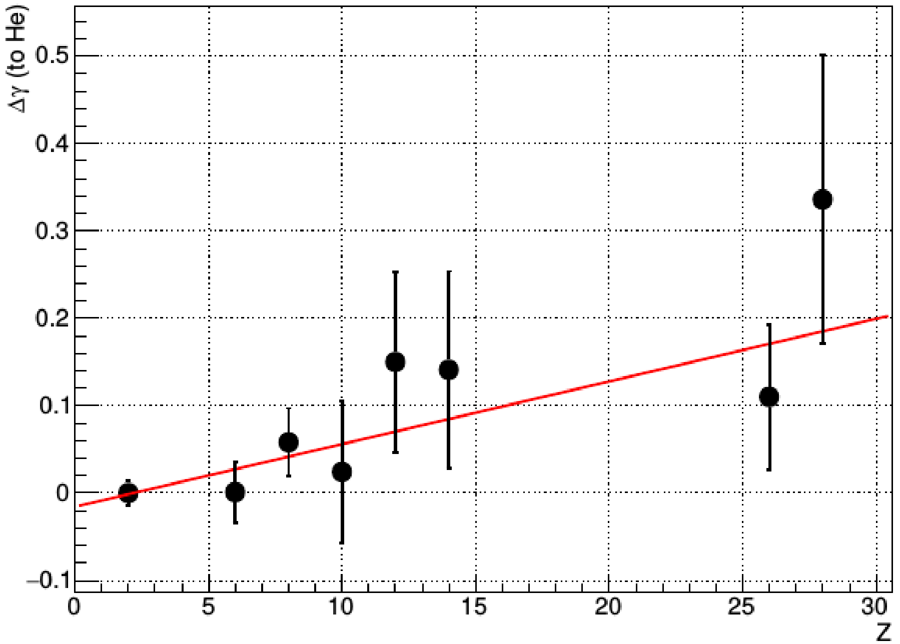
[M.J. Boschini, et. al. ApJ, 858:61 (2018)]:

$D = D_0 \times (R/R0)^{-\delta}$

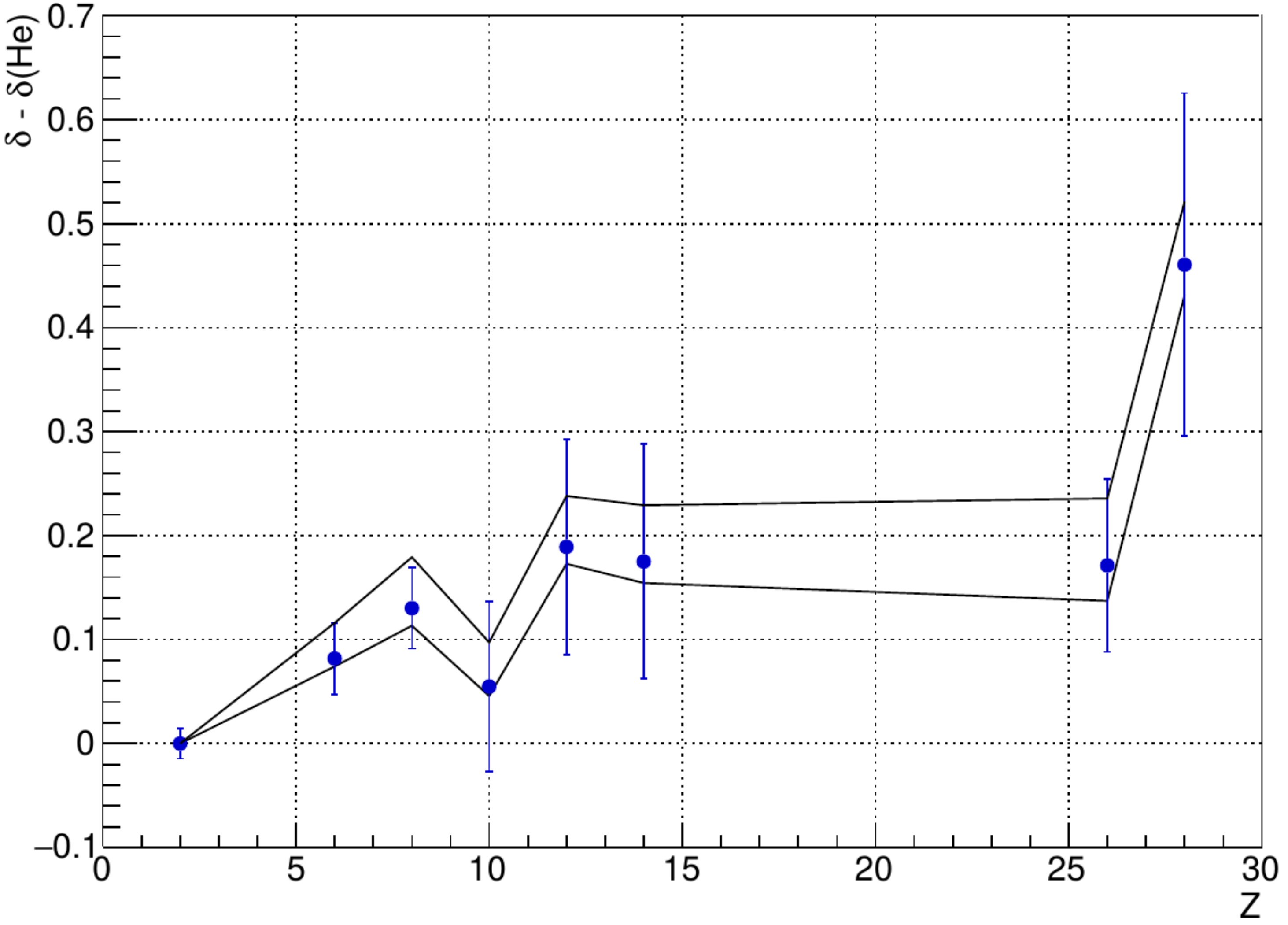
$D_0 = (4.3 \pm 0.6) \times 10^{28}\ cm^2 s^{-2}\ (R_0 = 4\ GV)$

$\delta = 0.415 \pm 0.025$





Systematic errors corridor: 3 standard deviations on D_0 and δ



Statistical significance of the positive slope:
not less than 3.2σ (Systematics included)

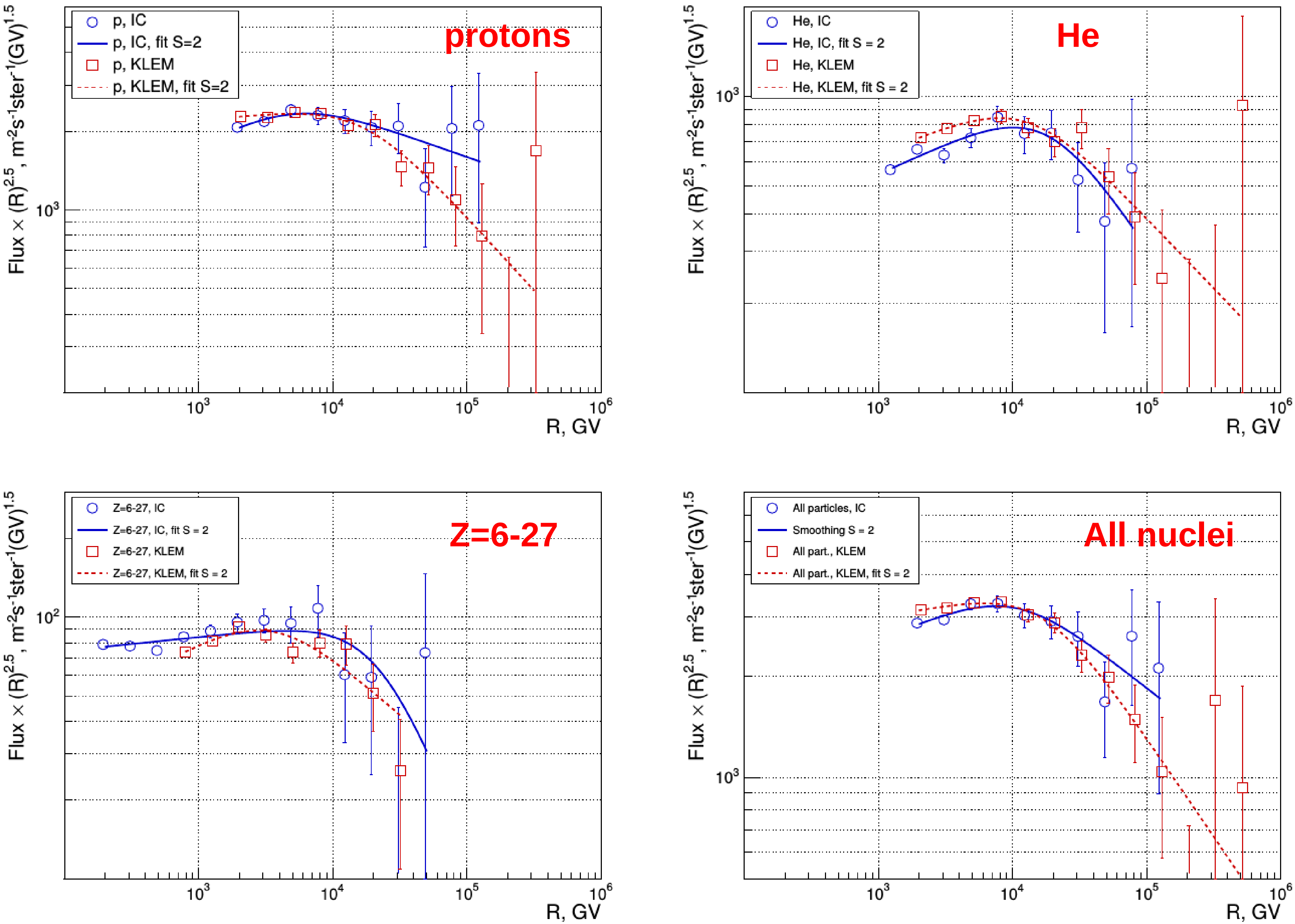
What can it be?

- 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”.

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

JETP Lett. V.108, No 1, P. 5 (2018) [arXiv:1805:07119]



Statistical significance of the 10 TV - knee: Monte Carlo method 10000 MC tests

S = 2 - smooth link
S = ∞ - point- like link.

JETP Lett. V.108, No 1, P. 5 (2018)
[arXiv:1805:07119]

nucl. group	$S = 2$ percents(σ)	$S = \infty$ percents(σ)	single γ percents(σ)
1	2	3	4
IC			
p	99.31(2.70)	98.49(2.43)	53.17(0.73)
He	99.85(3.25)	99.45(2.78)	90.13(1.65)
$6 \div 27$	95.94(2.05)	97.93(2.31)	90.00(1.64)
All	99.97(3.62)	99.89(3.26)	91.07(1.70)
KLEM			
p	>99.99(3.9)	>99.99(3.9)	98.67(2.47)
He	>99.99(3.9)	>99.99(3.9)	99.59(2.93)
$6 \div 27$	>99.99(3.9)	>99.99(3.9)	>99.99(3.9)
All	>99.99(3.9)	>99.99(3.9)	>99.99(3.9)

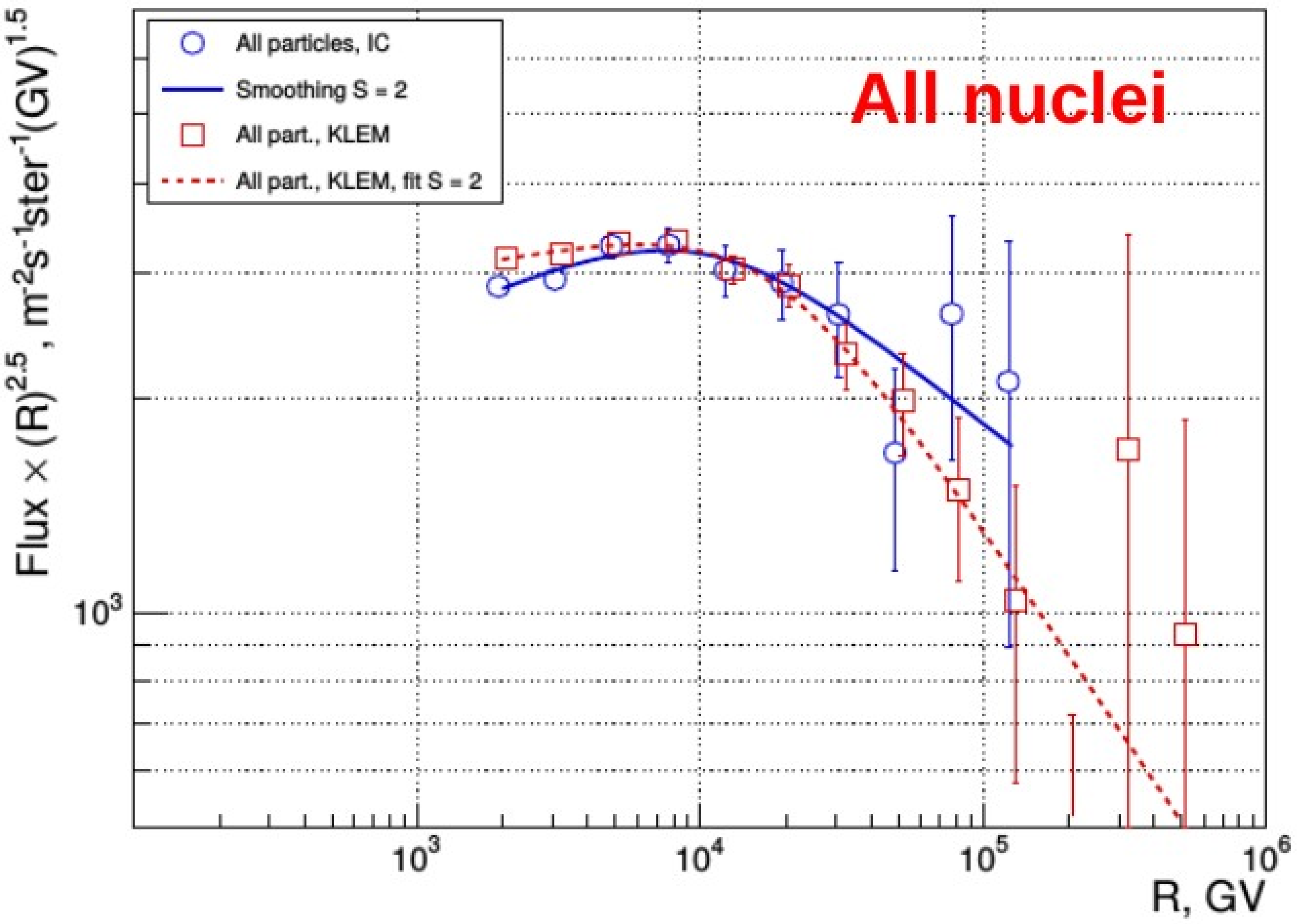
Now we have significance >= 4.2σ for all nuclei groups

The simplest possible explanation of 10TV-knee:

10TV is a limit of acceleration of some kind
of CR source - a single nearby one (?) or generic (?)

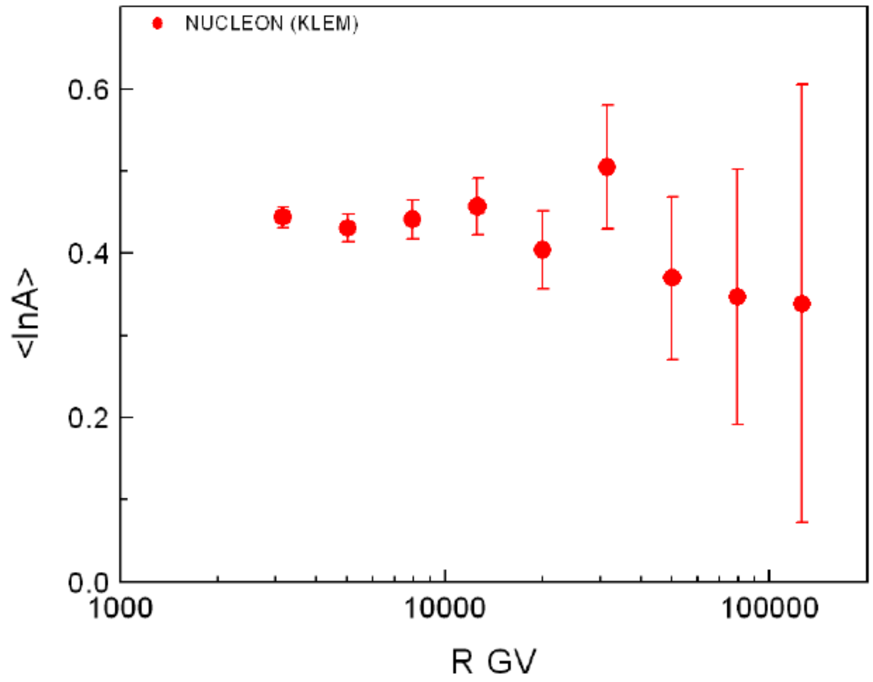
Argument for a single source No 1:

The knee is very sharp to be from multiple sources

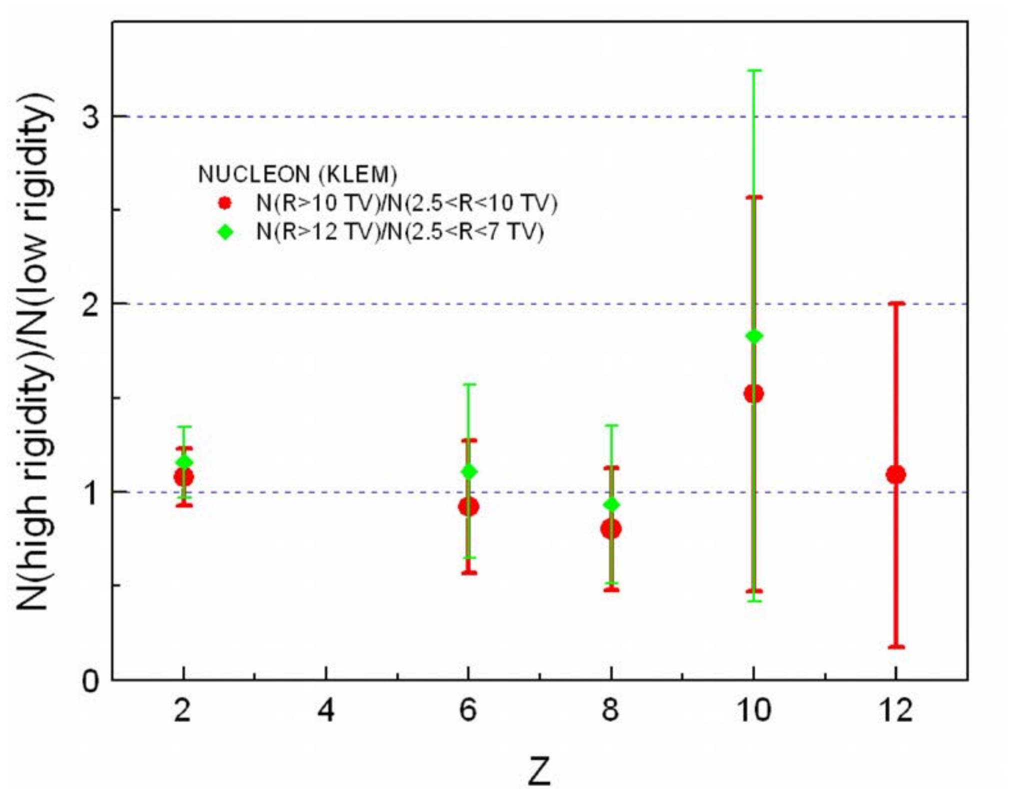


Argument for a single source No 2:

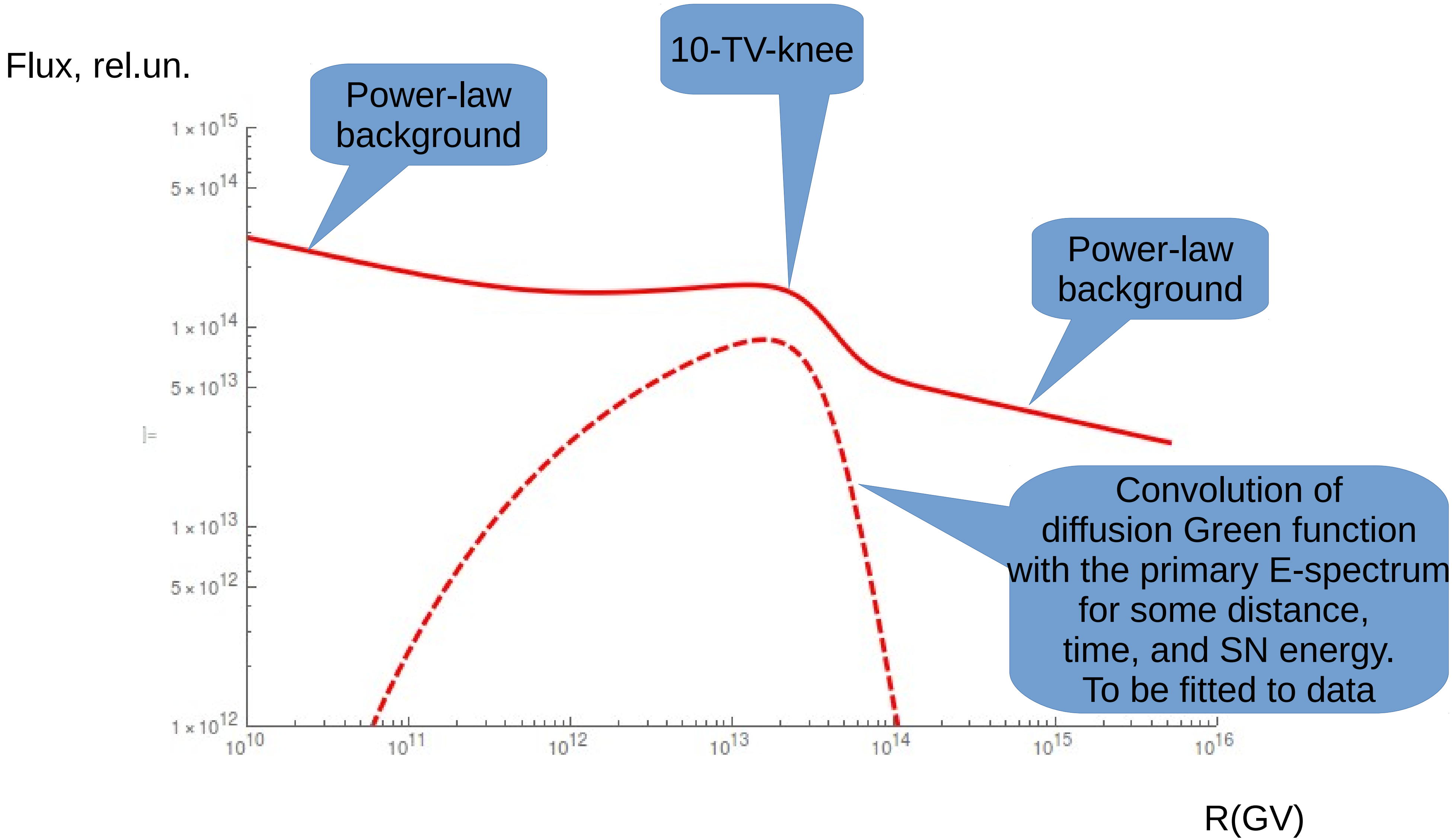
The chemical composition is approximately constant around the knee



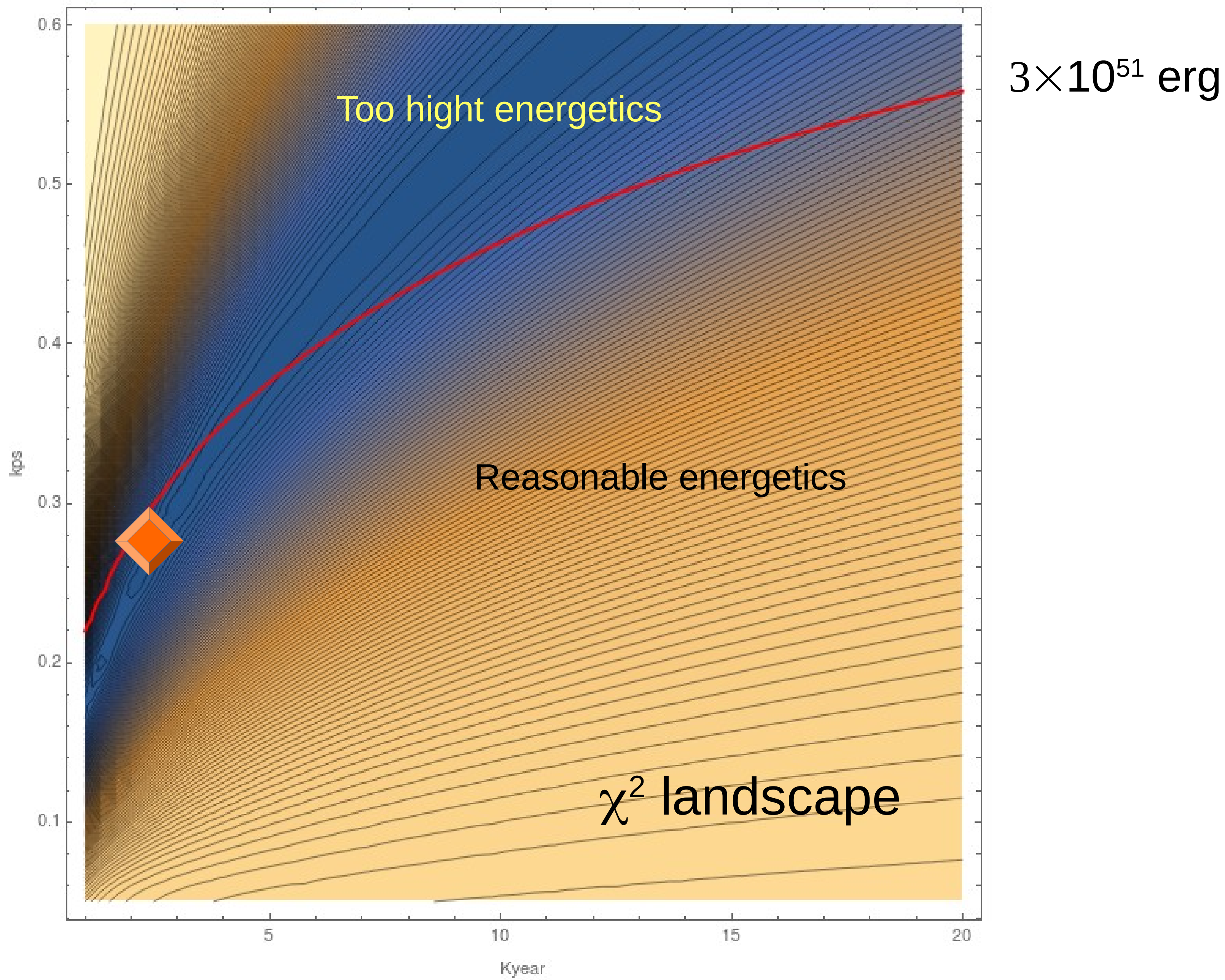
N – nucleus flux / protons flux



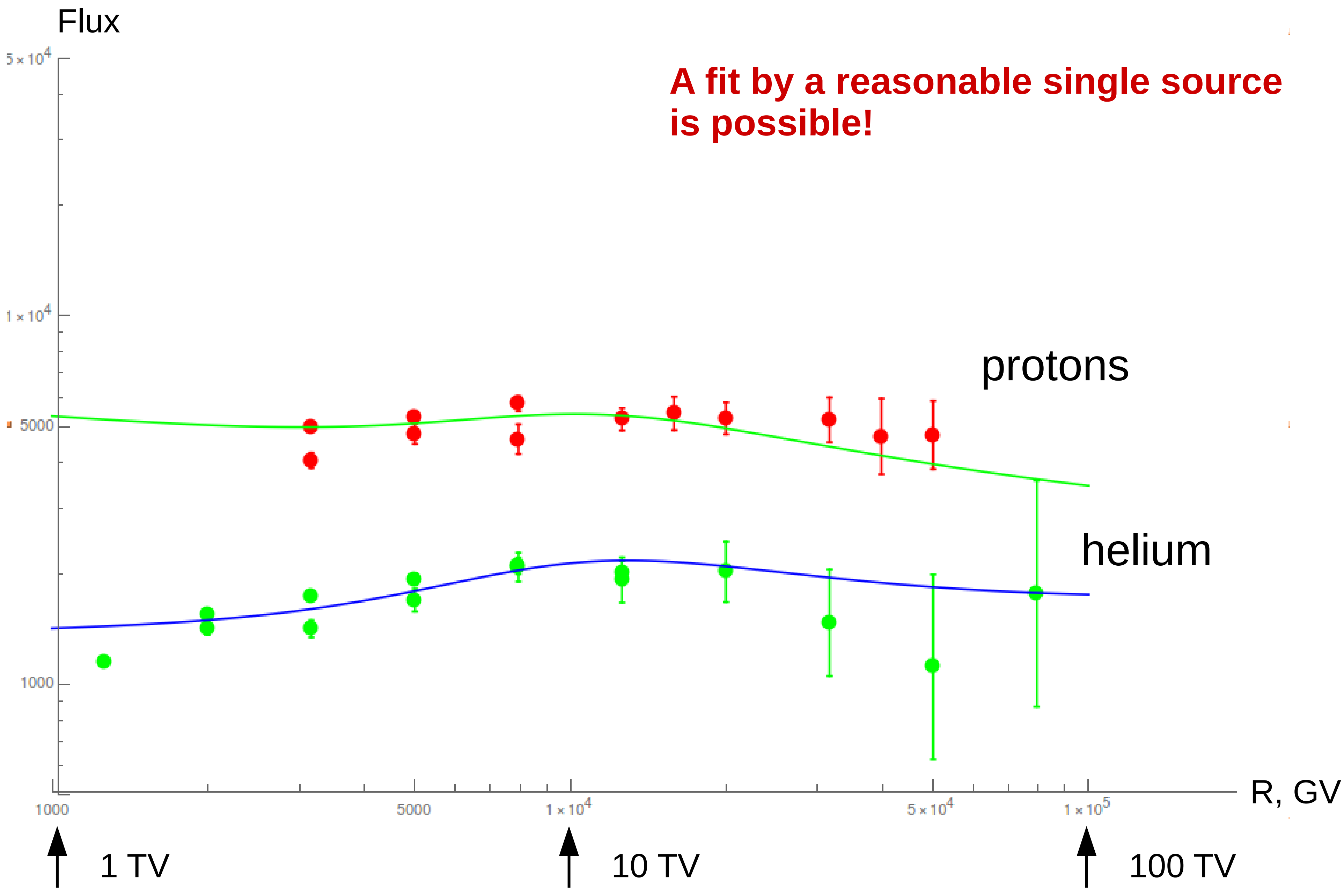
A single source model:
Duffusion model in the background + “Flash lamp” approximation



The best fit:
t = 3 ky, L = 0.3 kpc, W = 1.6×10^{51} erg (10% in the cosmic rays)

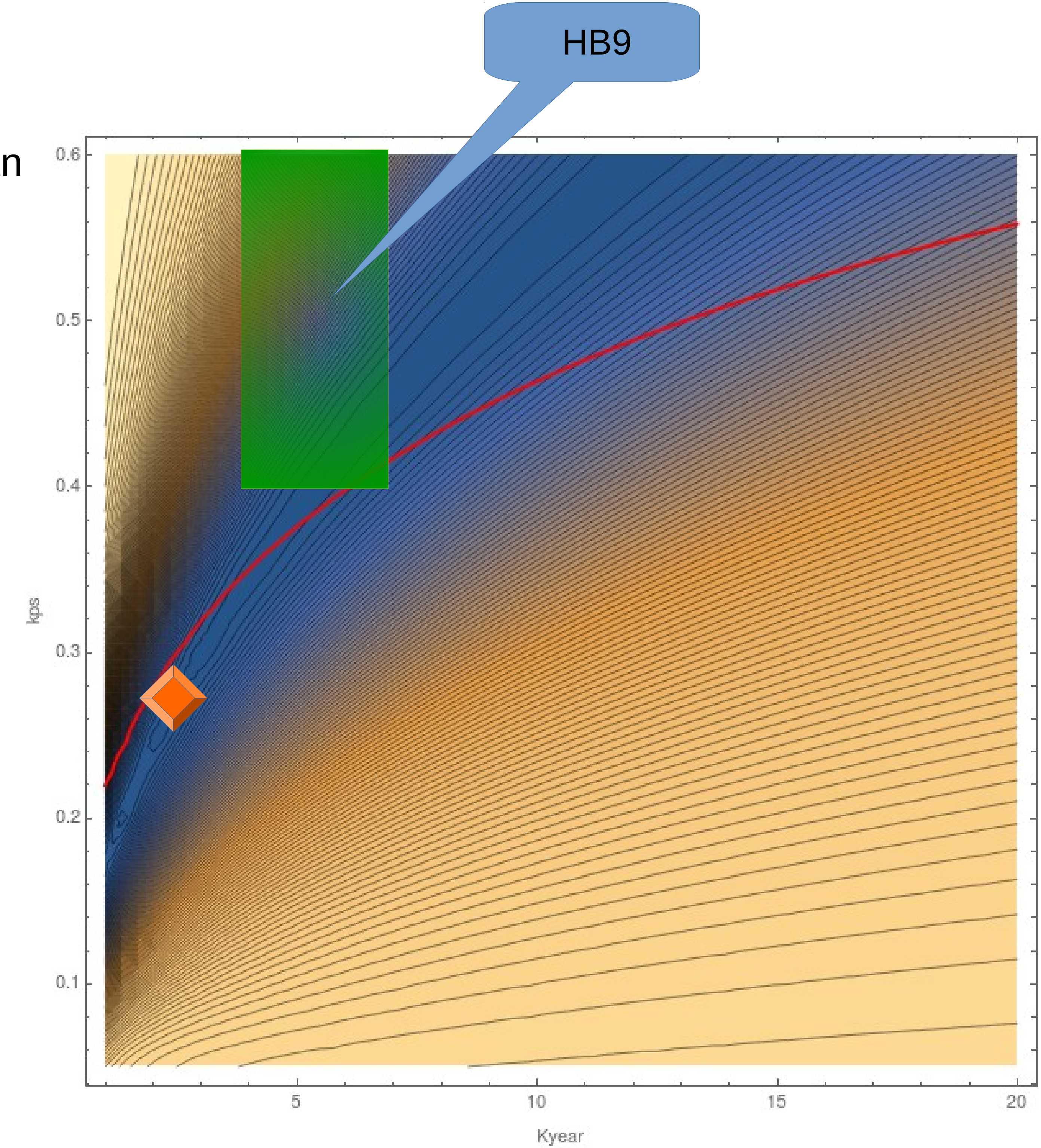


All nuclei groups are fitted by the same single source separately

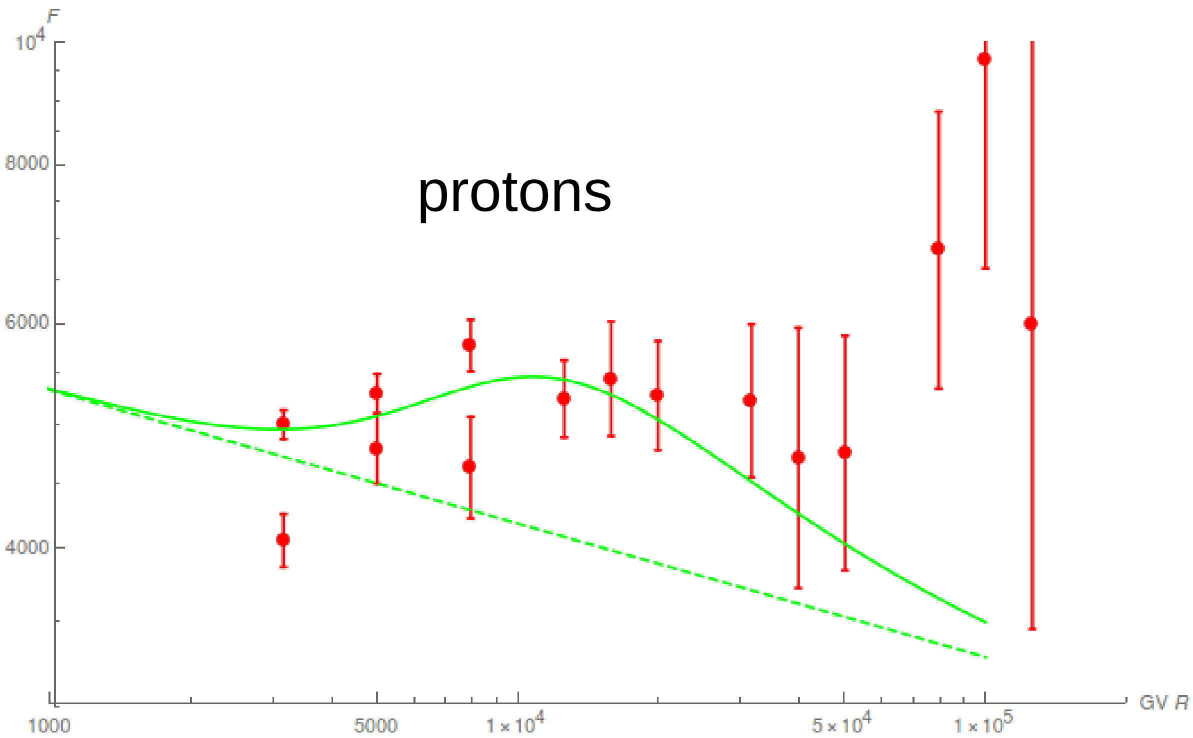


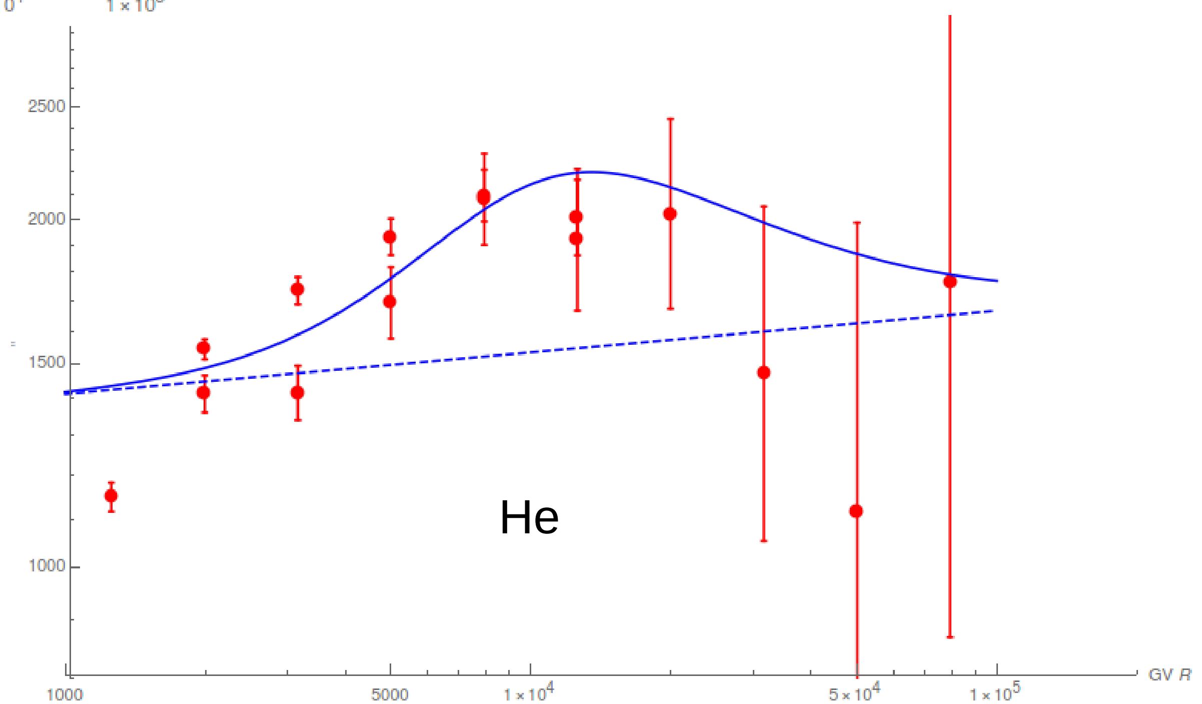
D. A. Leahy and W. W. Tian
A&A, V.461, 1013 (2007)

L = 0.4 – 1.2 kpc
t = 4 – 7 ky



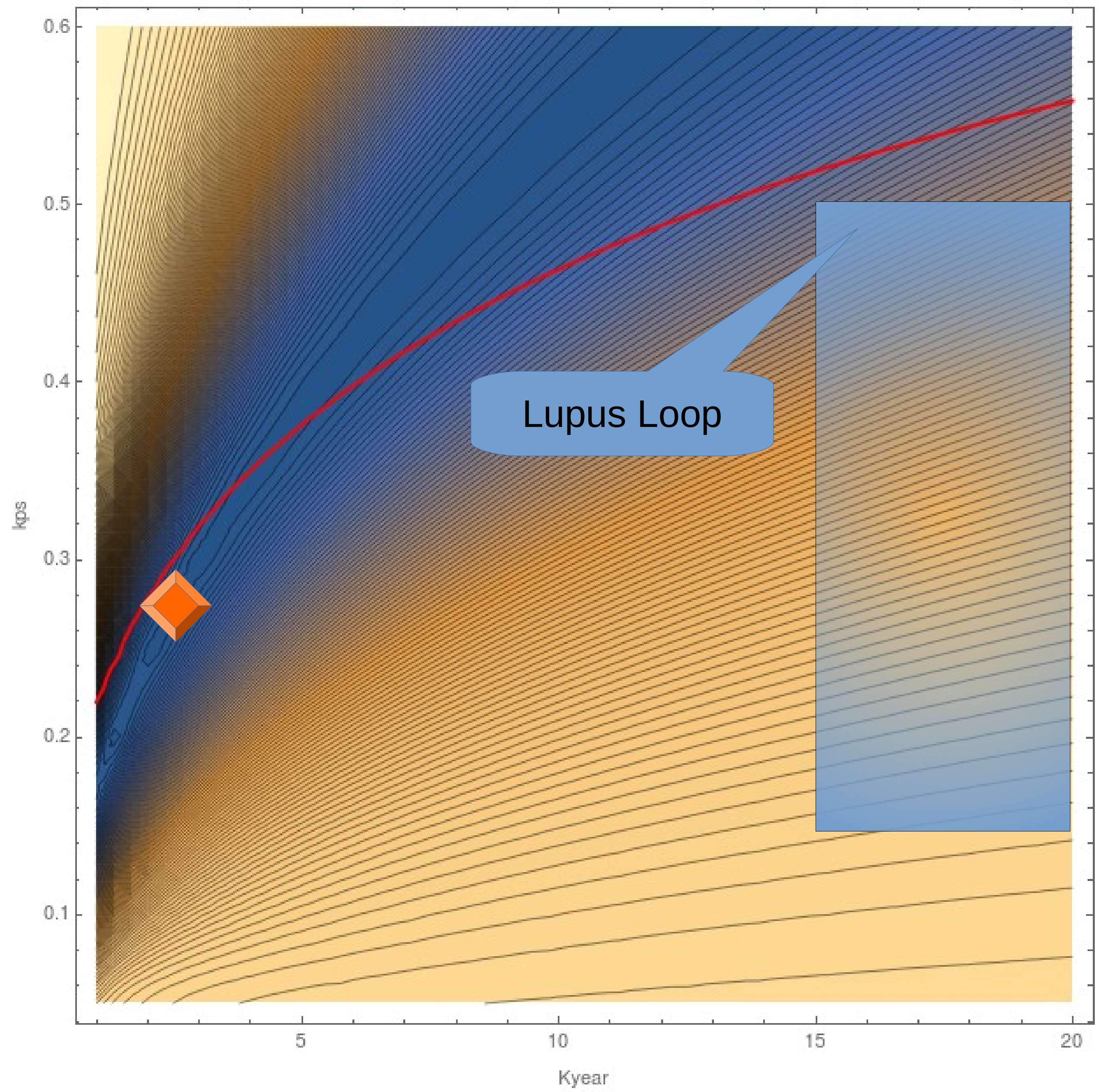
HB9


F
10^4
8000
6000
4000
protons
1000
5000
1 × 10^4
5 × 10^4
1 × 10^5
GV R


2500
2000
1500
1000
He
1000
5000
1 × 10^4
5 × 10^4
1 × 10^5
GV R

Lupus Loop:

L = 0.15 – 0.5 kpc
t = 15 – 30 ky



- There are several of SNR candidates to fit 10TV-knee
- There may be several SNR that are invisible to us
- The work is in progress

Conclusions

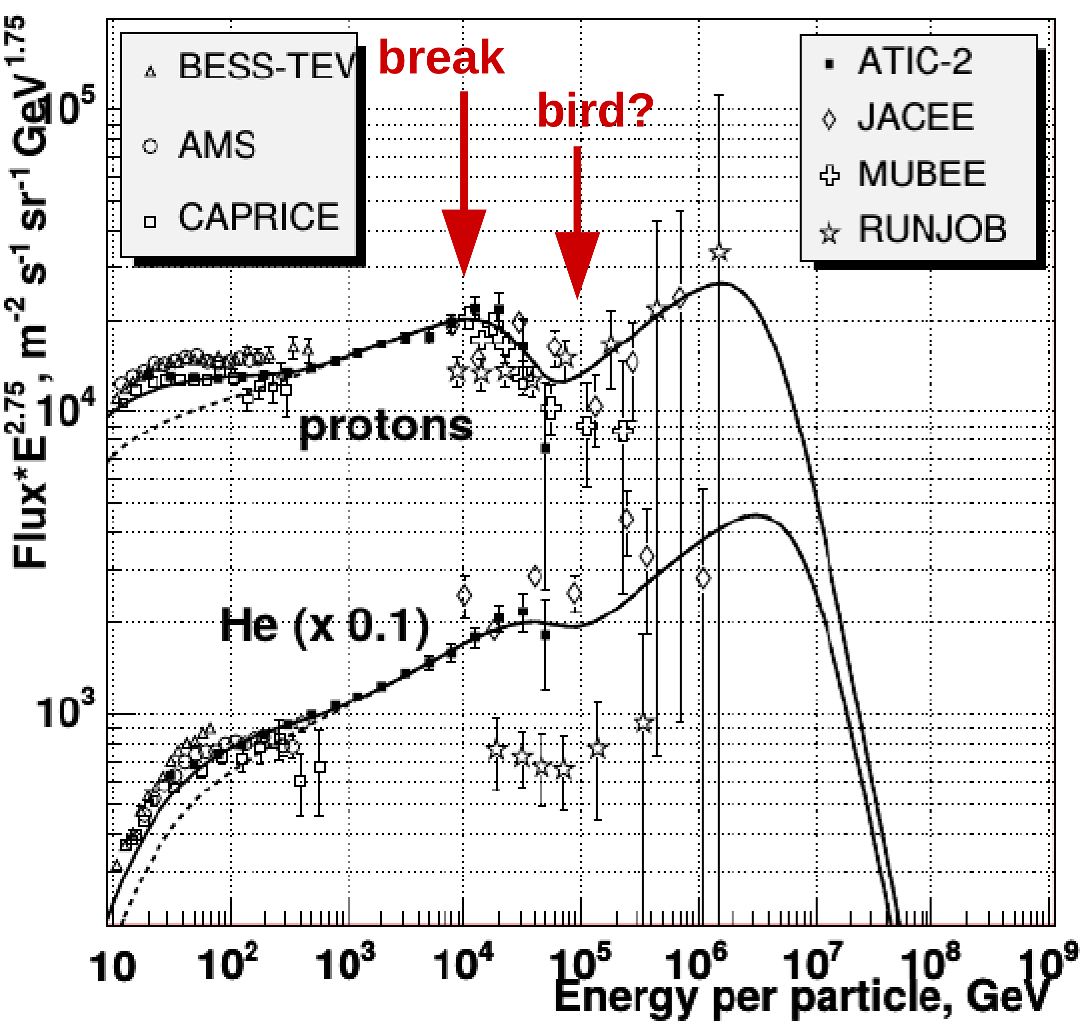
- **The preliminary analysis of the NUCLEON space experiment data gives indications of the existence of a number of features in the energy spectra of cosmic ray nuclei at energies from few TeV to ~100 TeV (per particle).**

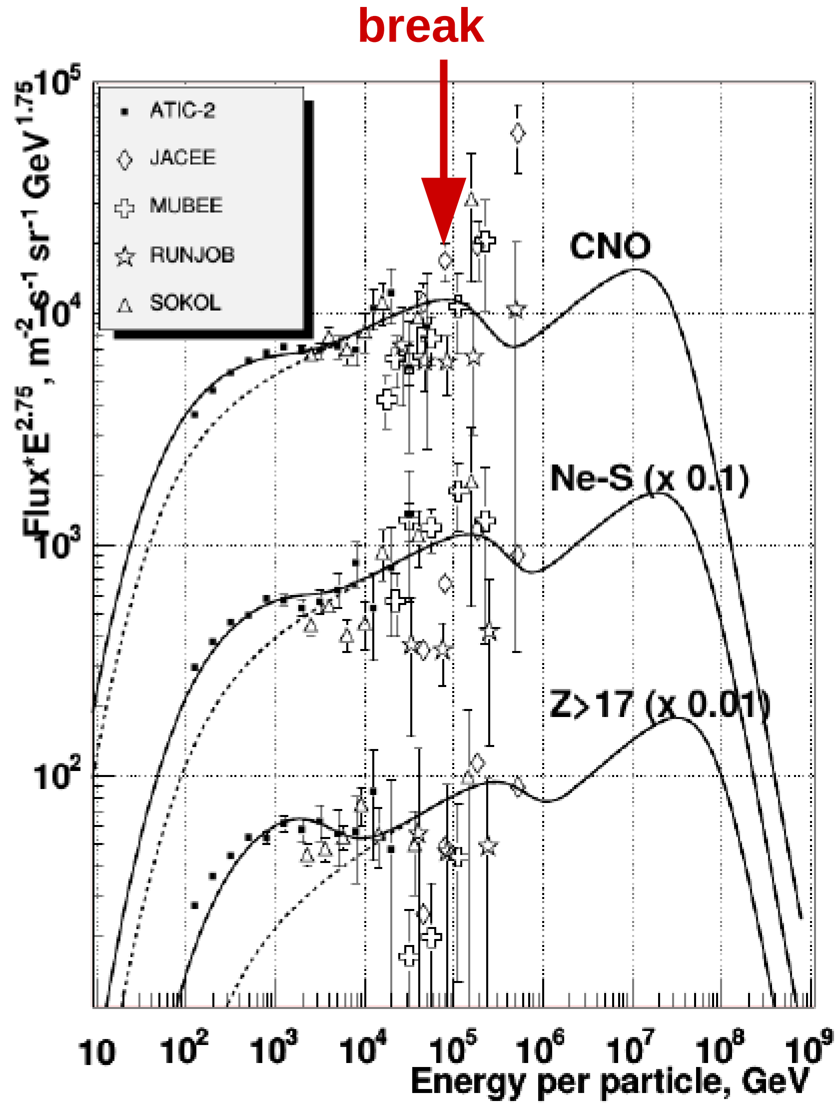
- **Interesting physics may be associated with these features of the spectra**

- **The processing of the NUCLEON data continues.**

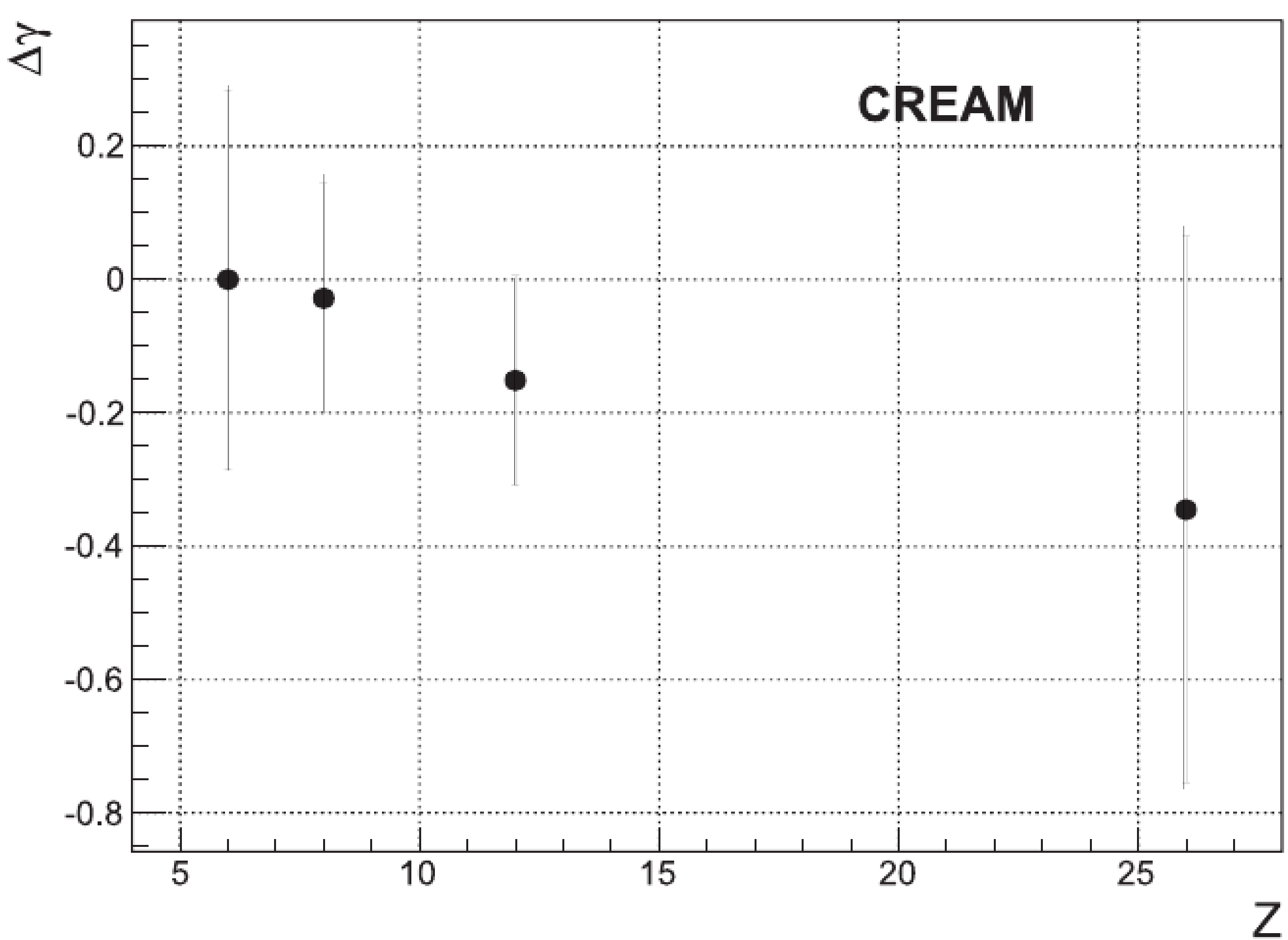

Thank you
for attention!

Zatsepin & Sokolskaya model predicts breaks near R = 10 TV both in spectra of protons and helium, and in spectra of heavy nuclei





V.I. Zatsepin and N.V. Sokolskaya.
A&A, V.458, 2006, pp.1-5


Δγ
CREAM
0.2
0
-0.2
-0.4
-0.6
-0.8
5
10
15
20
25
Z