Energy spectra of nuclei from protons to iron in sources, according to the ATIC experiment

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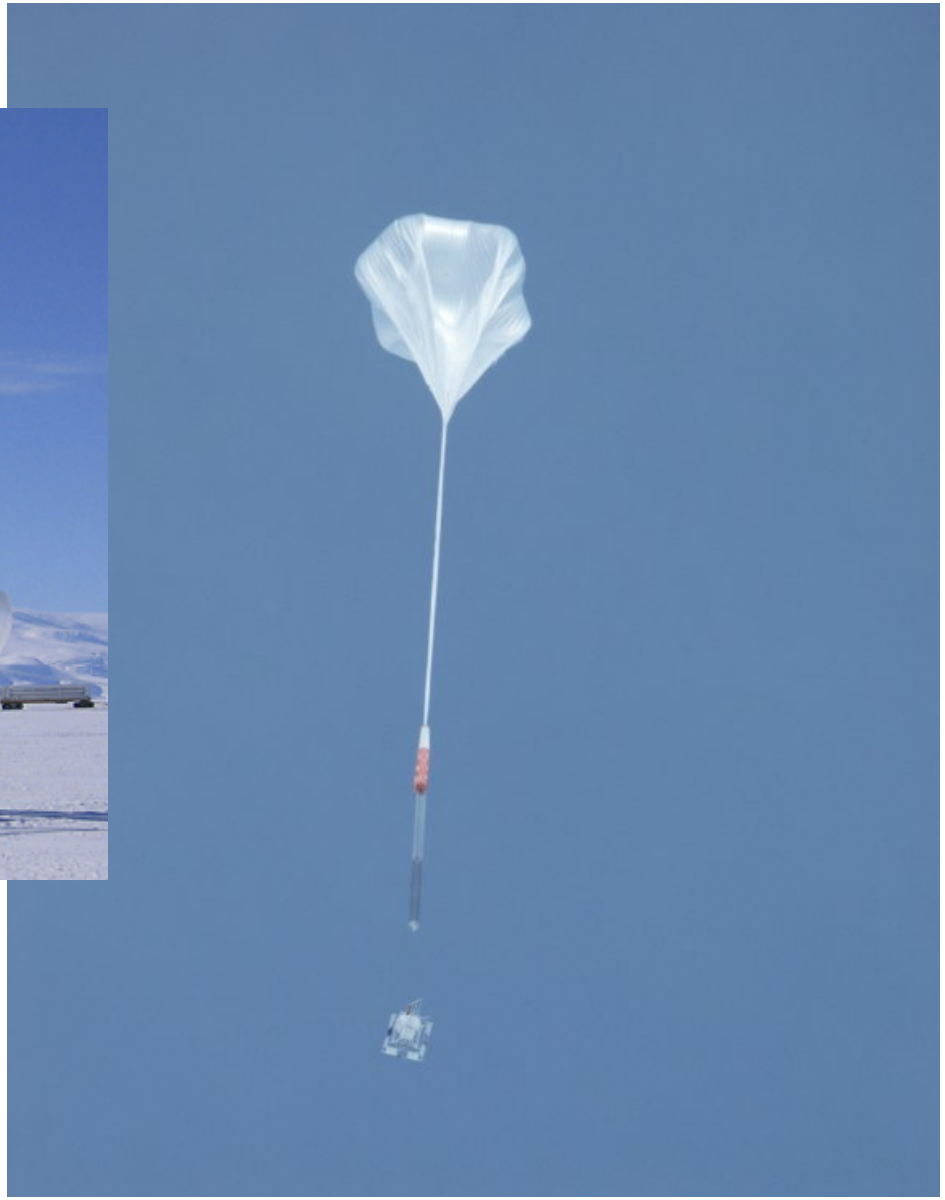
ICRC2015, Hague

The ATIC spectrometer

At the start position



In the flight

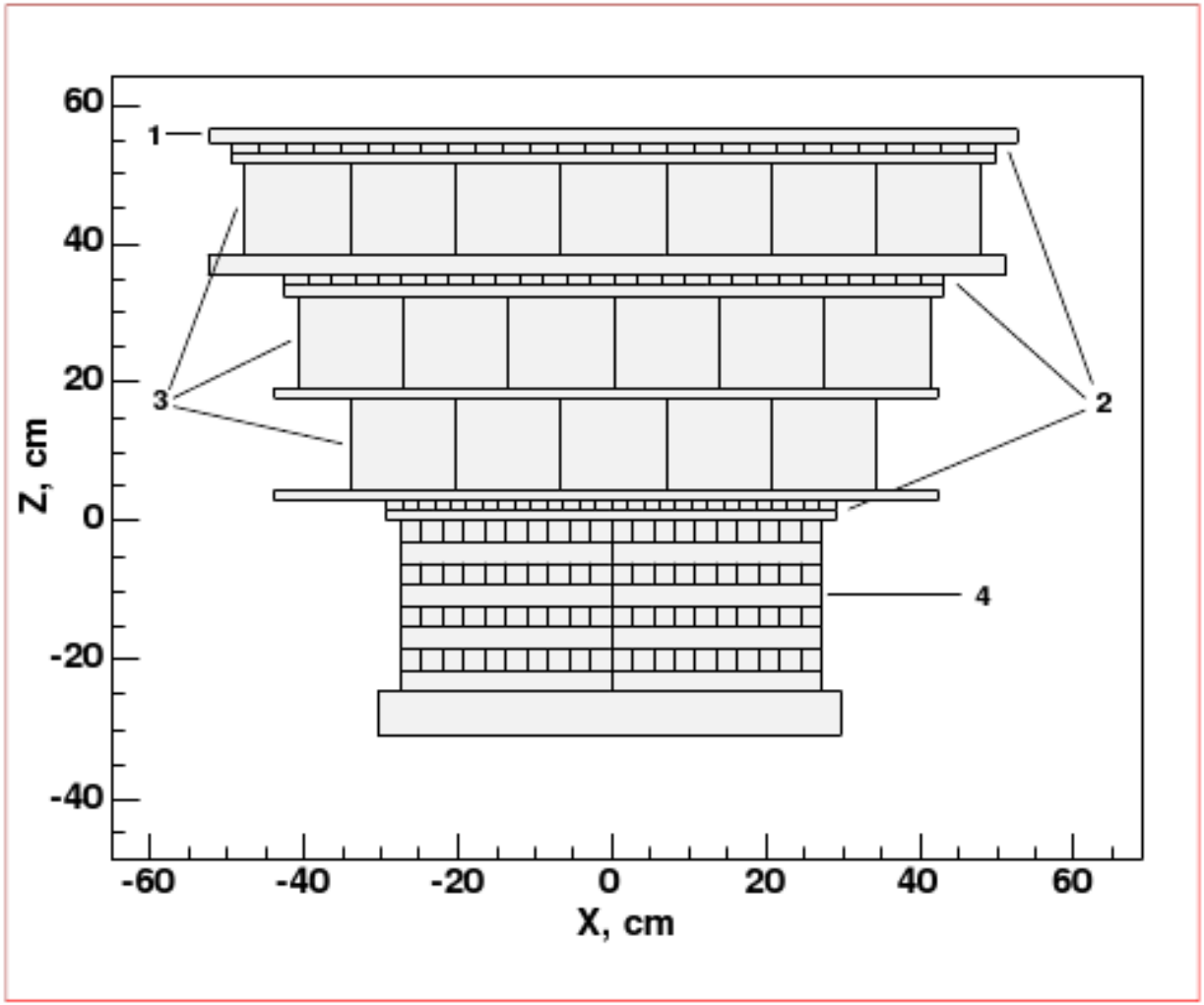
Protons and nuclei — 30 GeV - 100 TeV
$e^- + e^+$ — 30 GeV - 2-3 TeV

ATIC (Advanced Thin Ionization Calorimeter)

ATIC collaboration:

1. Skobeltsyn Institute of Nuclear Physics,
   Moscow State University, Moscow, Russia
2. Marshall Space Flight Center, Huntsville, AL, USA
3. University of Maryland, Institute for Physical Science & Technology,
   College Park, MD, USA
4. Purple Mountain Observatory, Chinese Academy of Sciences, China
5. Max-Planck Institut for Solar System Research,
   Katlenburg-Lindau, Germany
6. Southern University, Department of Physics, Baton Rouge, LA, USA
7. Louisiana State University, Department of Physics and Astronomy,
   Baton Rouge, LA, USA

ATIC (Advanced Thin Ionization Calorimeter)



1 — **Silicon matrix**

80×56 pixels, 1.5×2cm

2 — **Scintillator hodoscopes**

3 — **Carbon target**

$(1.5\ X_0)$

4 — **BGO-calorimeter (thin)**

Top view:

50×50 cm

BGO crystal:

$2.5 \times 2.5 \times 25$ cm

8 layers in ATIC-2

$(18\ X_0)$

The ATIC flights

ATIC-1 28.12.2000–13.01.2001

Test flight, 0.6 m^2 sr days

ATIC-2 29.12.2002–18.01.2003

First science flight, 2.5 m^2 sr days

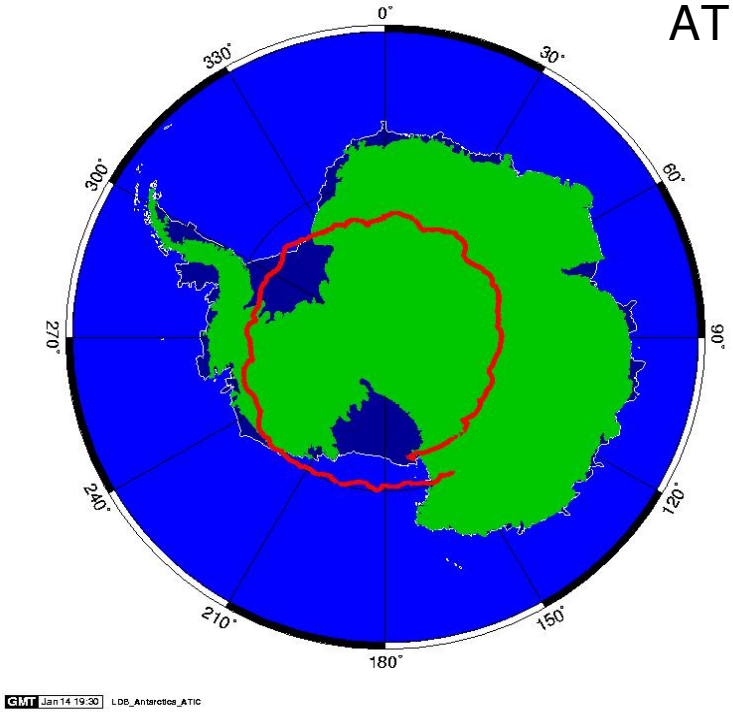
ATIC-3 2005

failed to rich altitude

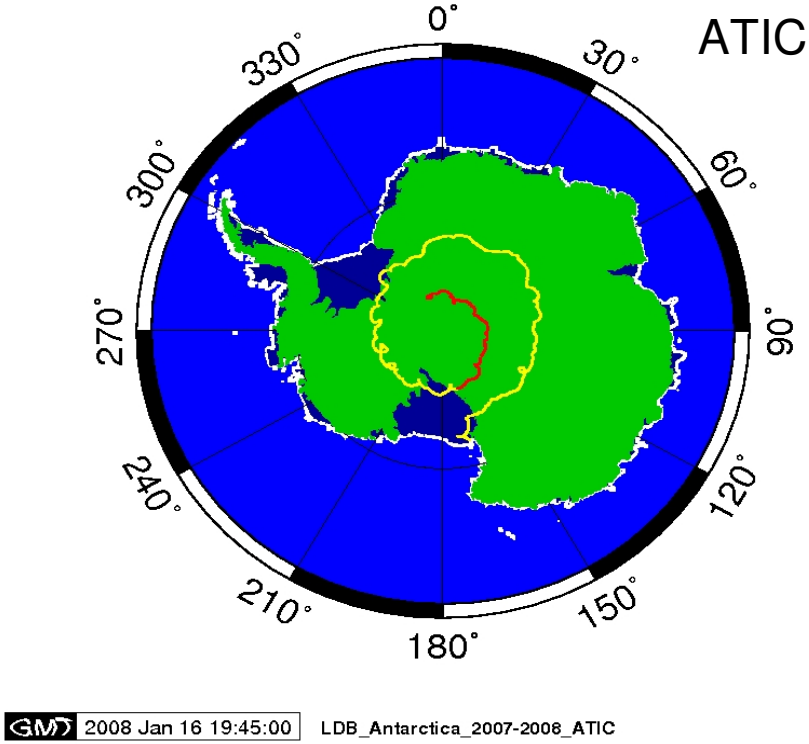
ATIC-4 26.12.2007–15.01.2008

Second science flight,
2.2 m^2 sr days

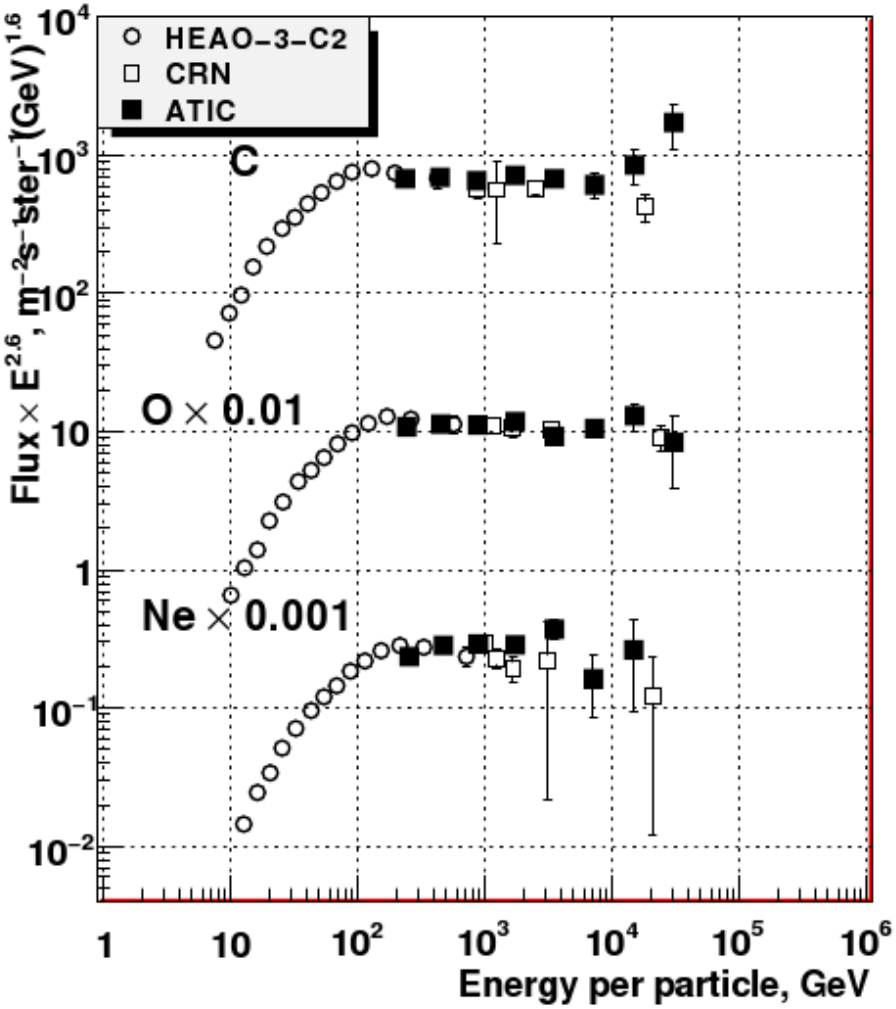
ATIC-2

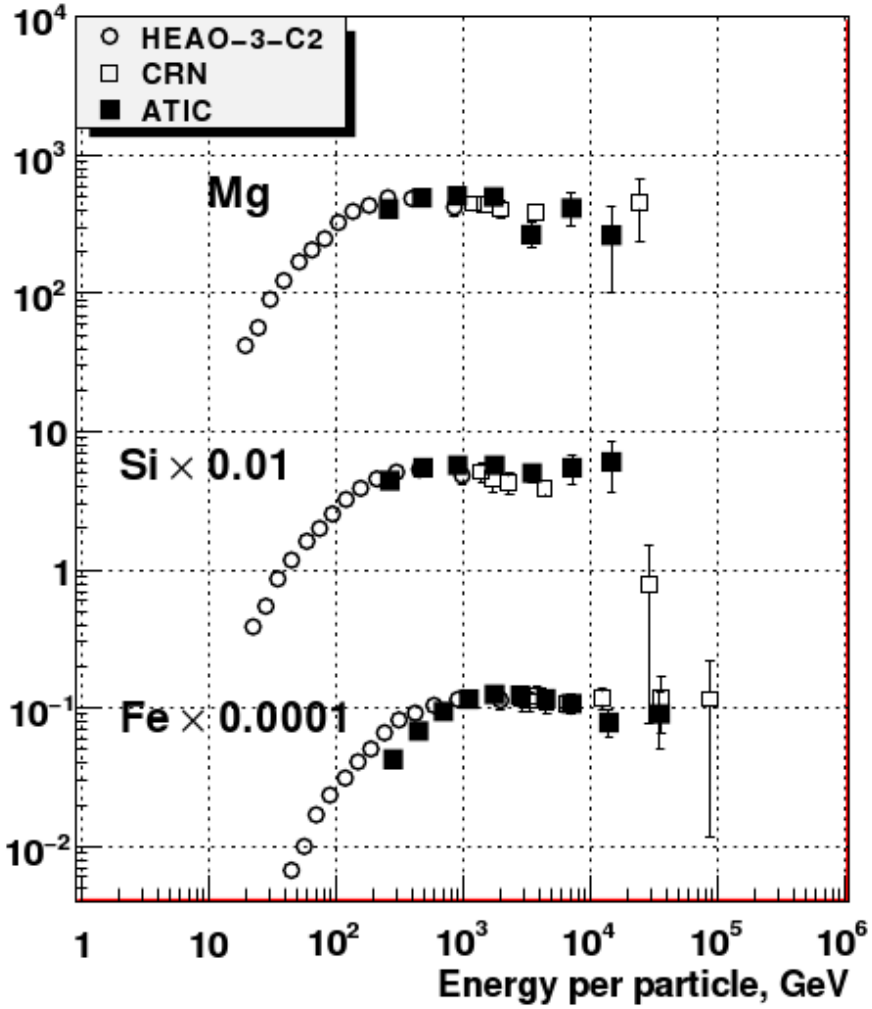


ATIC-4

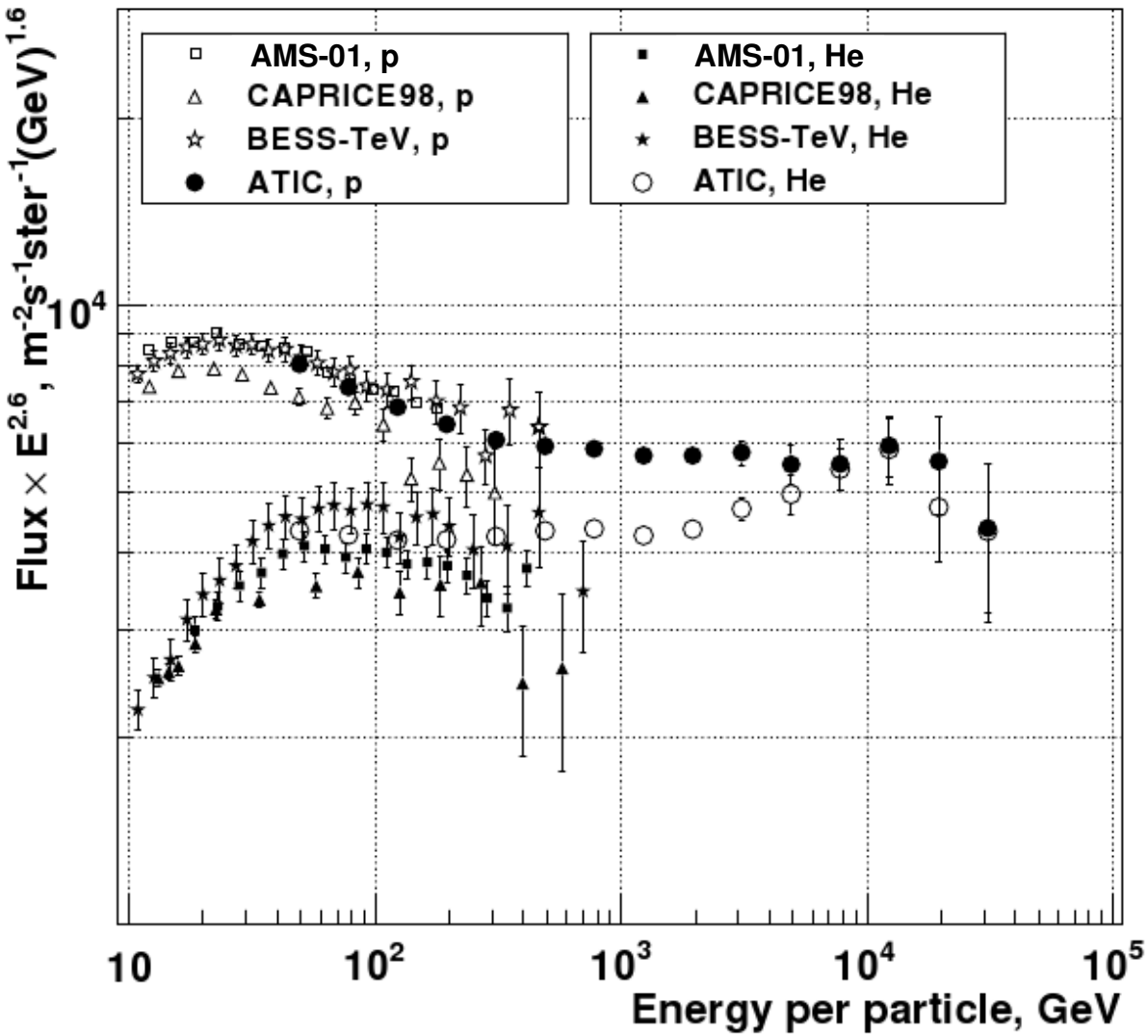


ATIC results for energy spectra of abundant nuclei: heavy nuclei (energy per particle)





ATIC results for energy spectra of abundant nuclei: protons and helium (energy per particle)



The difference of measured proton and helium spectra means also the difference of spectra in the source due to similarity of propagation.

What can ATIC data say about the source spectra of heavy nuclei?

To magnetic rigidity spectra of nuclei in the sources

$$M(E) \Rightarrow M(R) \quad \text{– trivial transformation}$$
$$M(R) = \hat{P}Q(R) \quad \text{– integral operator}$$
$$Q(R) = \hat{P}^{-1}M(R) \quad \text{– solution of integral equation}$$

Class of models: homogeneous magnetic halo

Leaky-box model (approximation) <u>for abundant nuclei</u>

$$M(R) = \frac{1}{\rho v}\frac{1}{1/\lambda_{esc}(R) + 1/\lambda_N}Q(R)$$

$$Q(R) = \rho v\left(\frac{1}{\lambda_{esc}(R)} + \frac{1}{\lambda_N}\right)M(R)$$

$$\lambda_{esc}(R) = 34.1R^{-0.6}$$

J.J. Engelmann, et al. A&A, 233(1990)96
HEAO-3-C2, experiment, B/C

$$\lambda_{esc}(R) = 4.2(R/R_0)^{-1/3}[1 + (R/R_0)^{-2/3}], \;\; R_0 = 5.5\,\Gamma\mathrm{B}$$

J. L. Osborne, V. S. Ptuskin, Sov. Astron. Lett. V.14(2), 1988, P.132-134
approximation of analytical solution of diffusion equation
with weak reacceleration and Kolmogorov turbulence

Approximation of numeric GALPROP solution by leaky-box model

V. Ptuskin, O. Strelnikova and L. Sveshnikova. Astropart. Phys. 31(2009)284

$$\lambda_{esc} = 19\beta^3 (R/3\,\mathrm{GV})^{-0.6}, \quad R > 3\,\mathrm{GV}$$

Simplest power-law model (plain model)

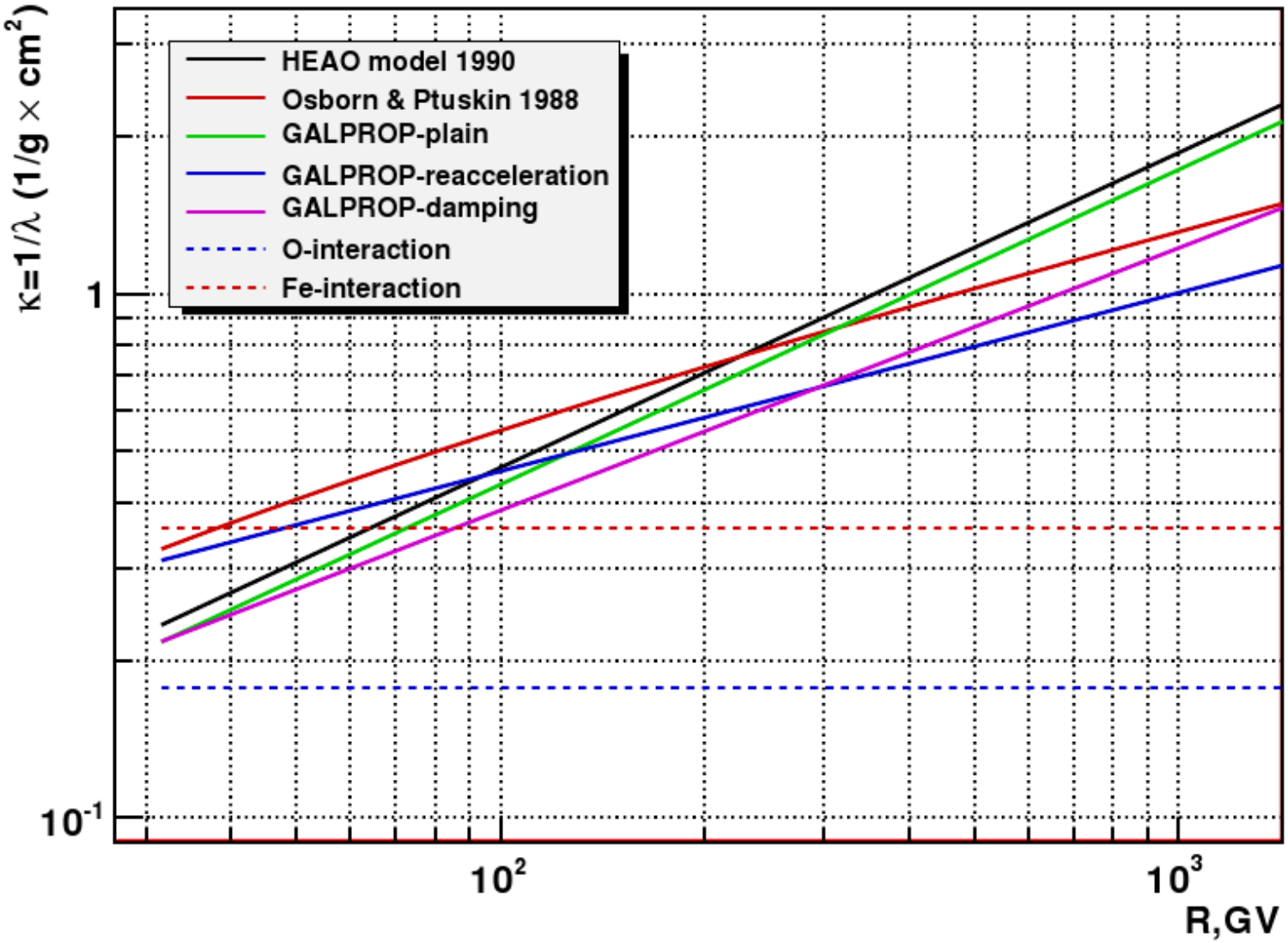
$$\lambda_{esc} = 7.2\beta^3 (R/3\,\mathrm{GV})^{-0.34}, \quad R > 40\,\mathrm{GV}$$

Reacceleration model

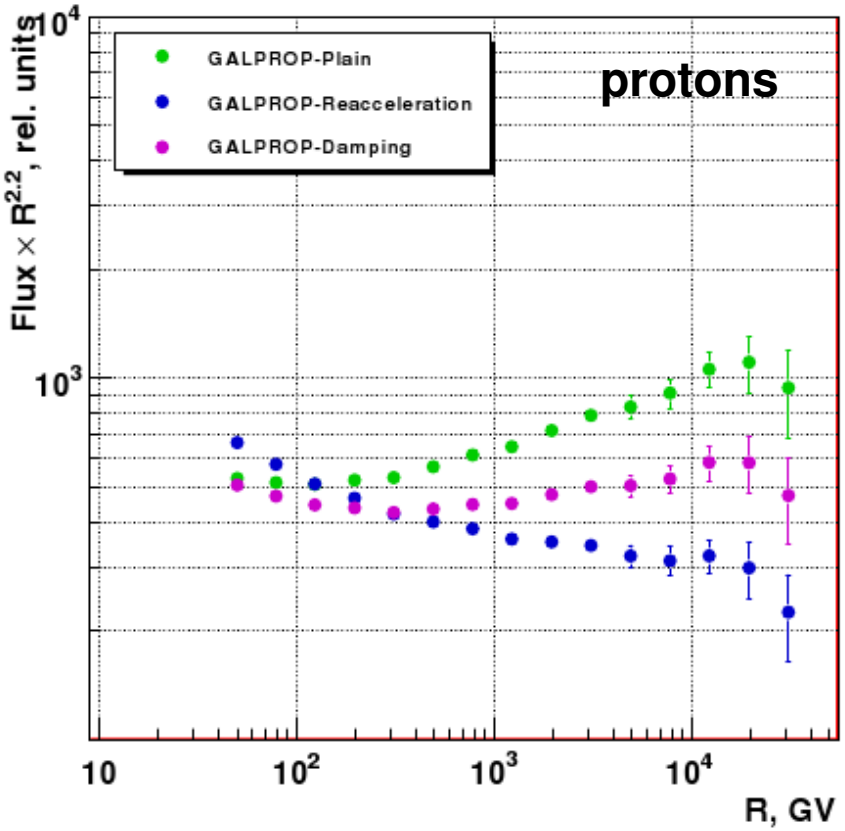
$$\lambda_{esc} = 13\beta^3 (R/3\,\mathrm{GV})^{-0.5}, \quad R > 10\,\mathrm{GV}$$

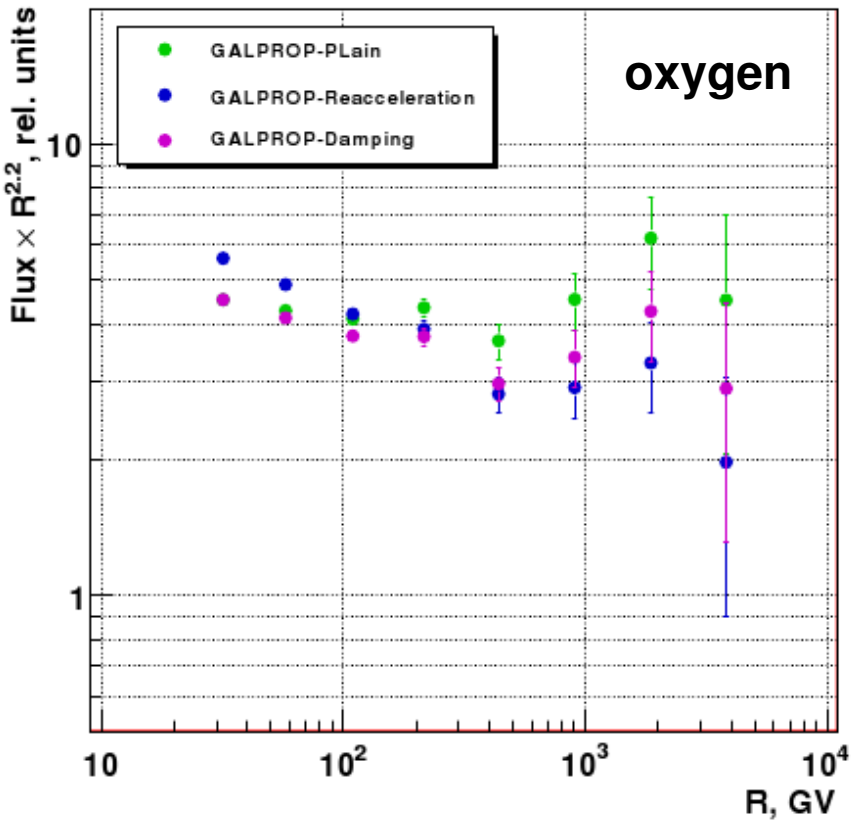
Non-linear damping model

Different models of propagation - escape length

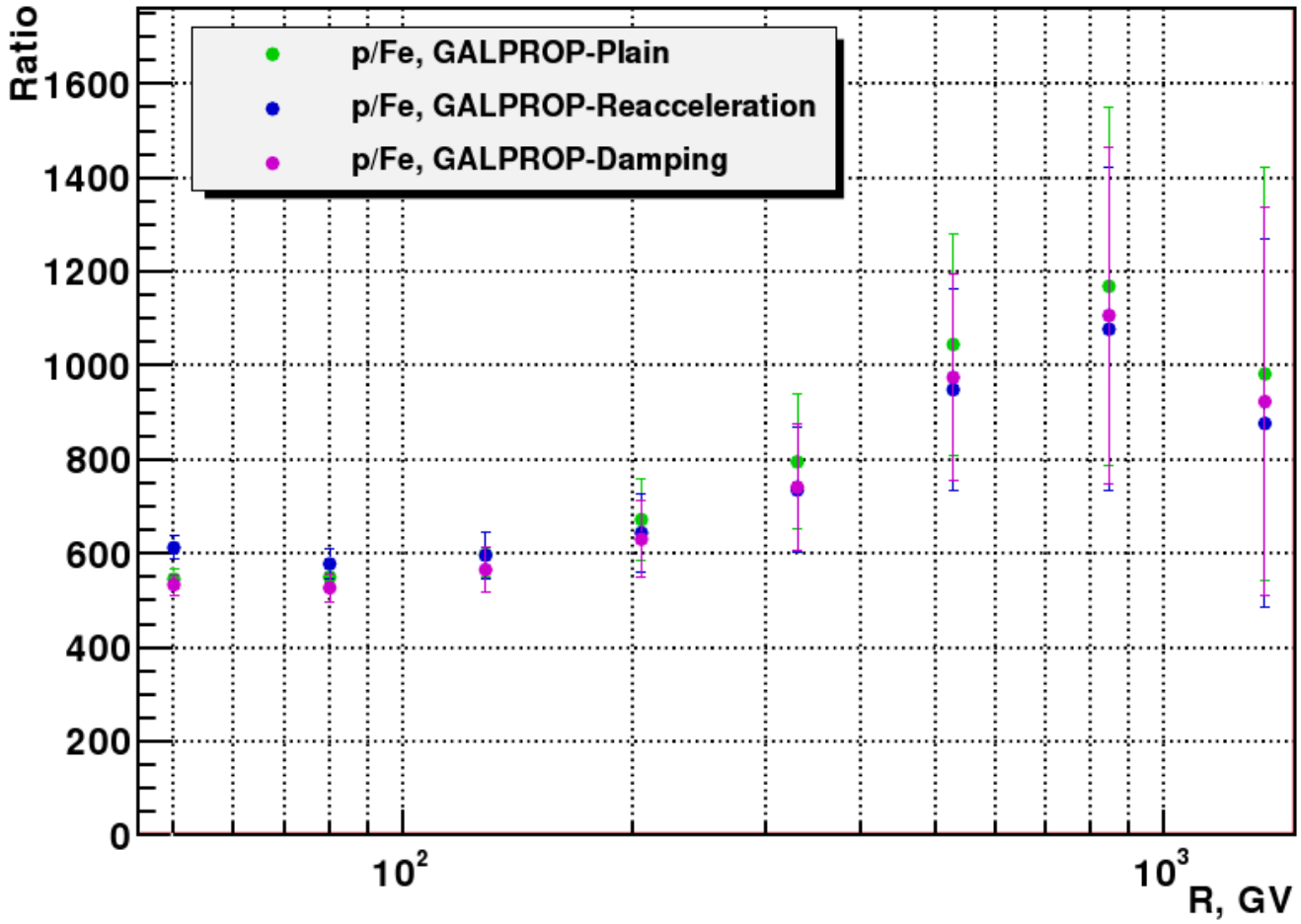


Solution of back propagation problem is strongly model dependent



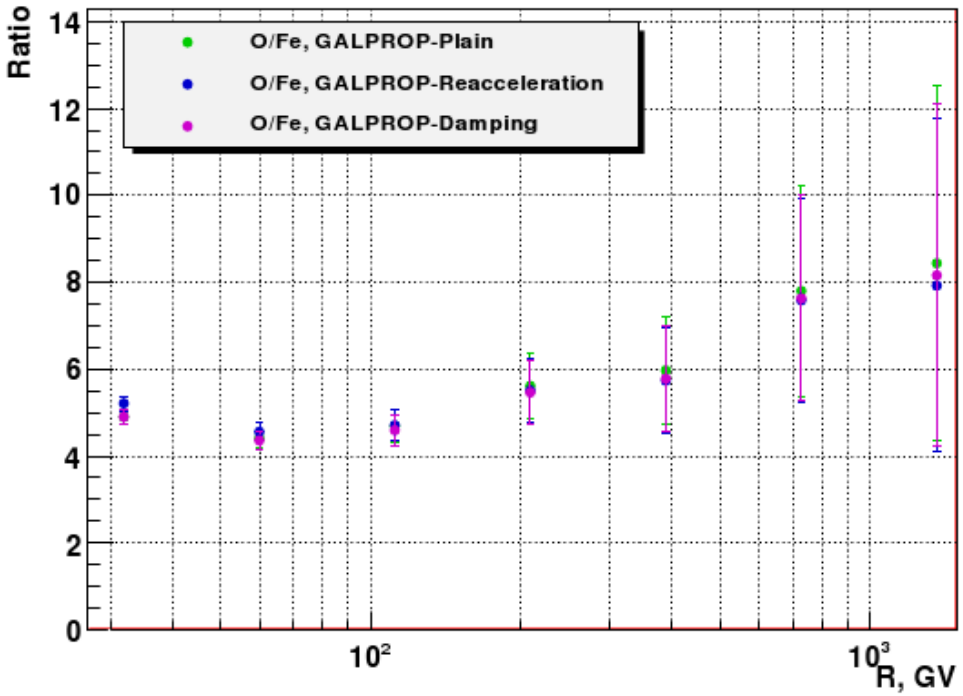


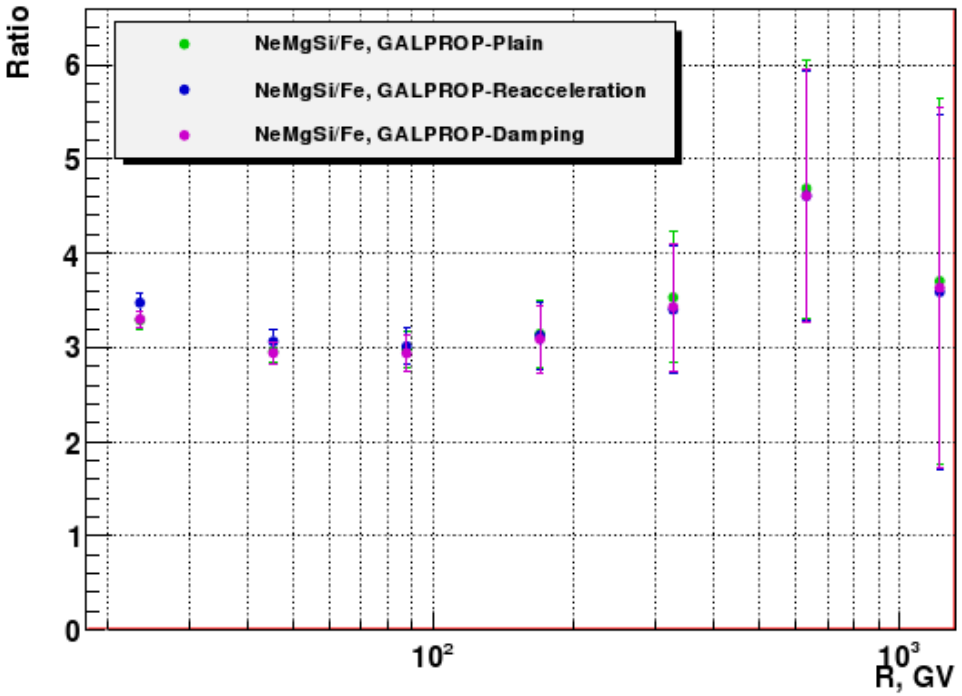
Comparison of shapes of rigidity spectra in the source is almost model-independent



The p/Fe ratio is the most model-dependent compare with other pairs of nuclei

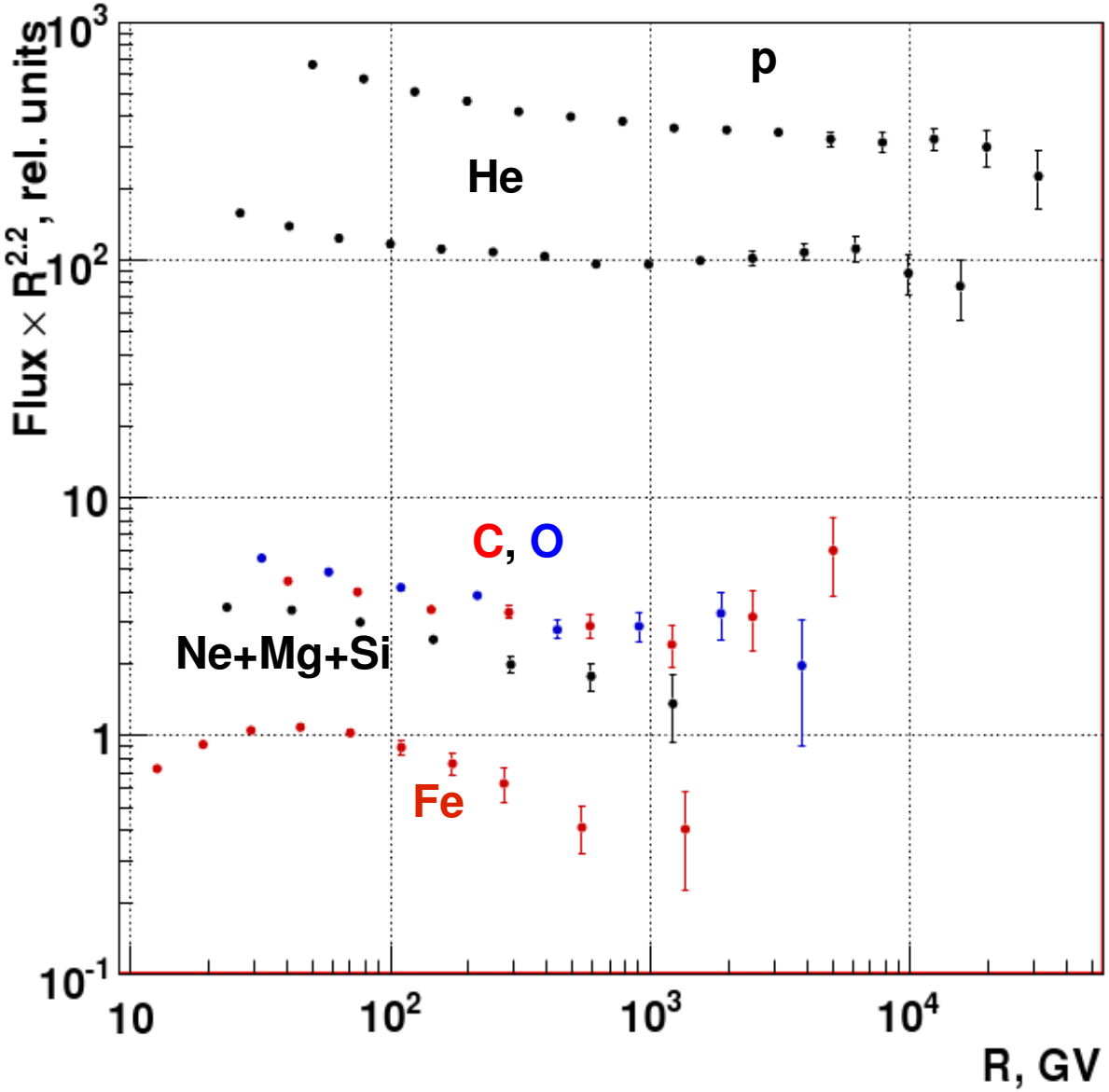
The smaller charge difference, the smaller model dependence of the ratio





All spectra measured in a single experiment *by the same method*
⇒ *comparison* of the spectra is methodically reliable

Spectra p, He, C, O, Ne, Mg, Si, Fe in the source in the model GALPROP-Reacceleration. Ne, Mg, Si are combined



There are totally 6×(6-1)/2 = 15 ratios of spectra

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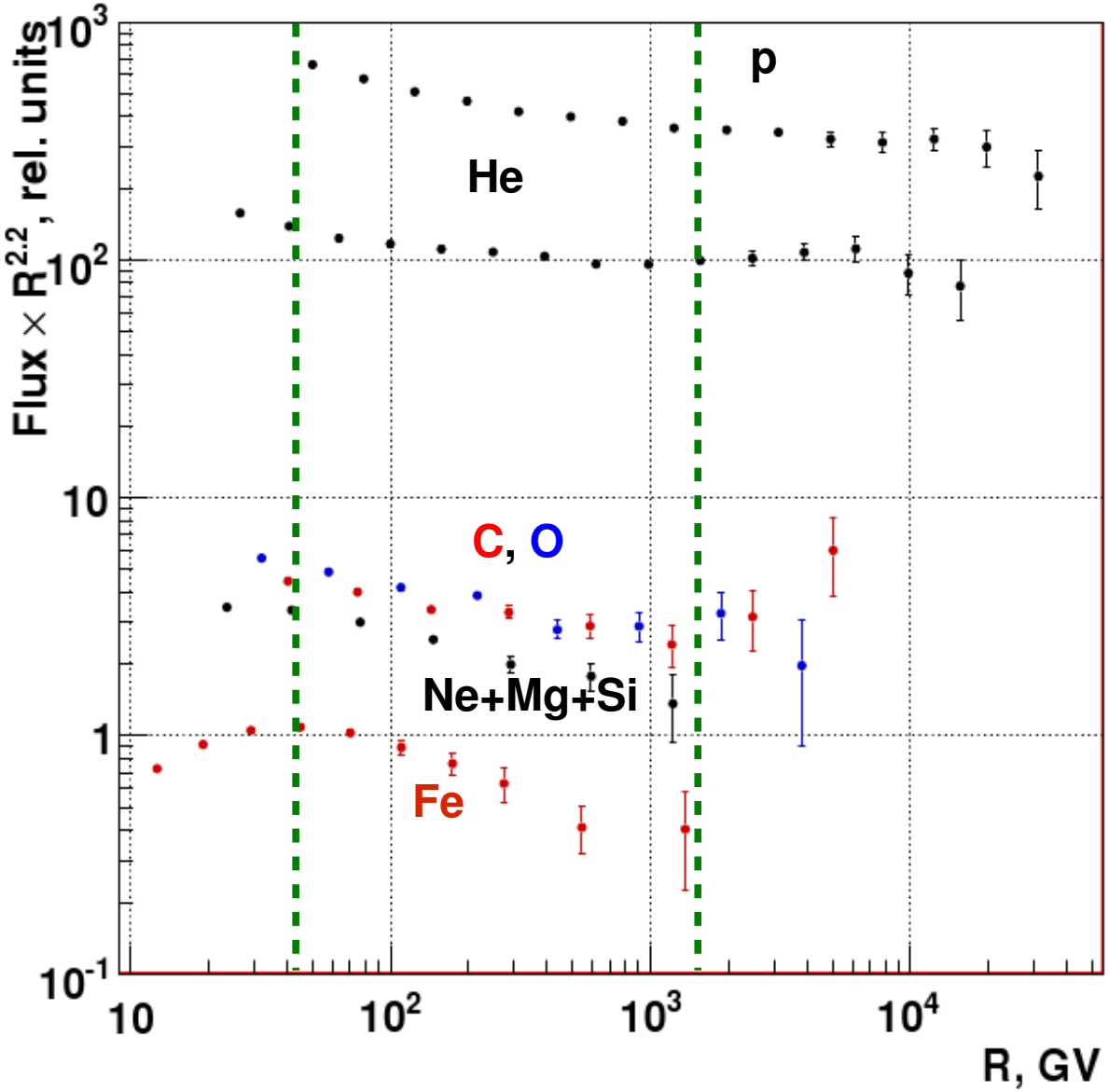
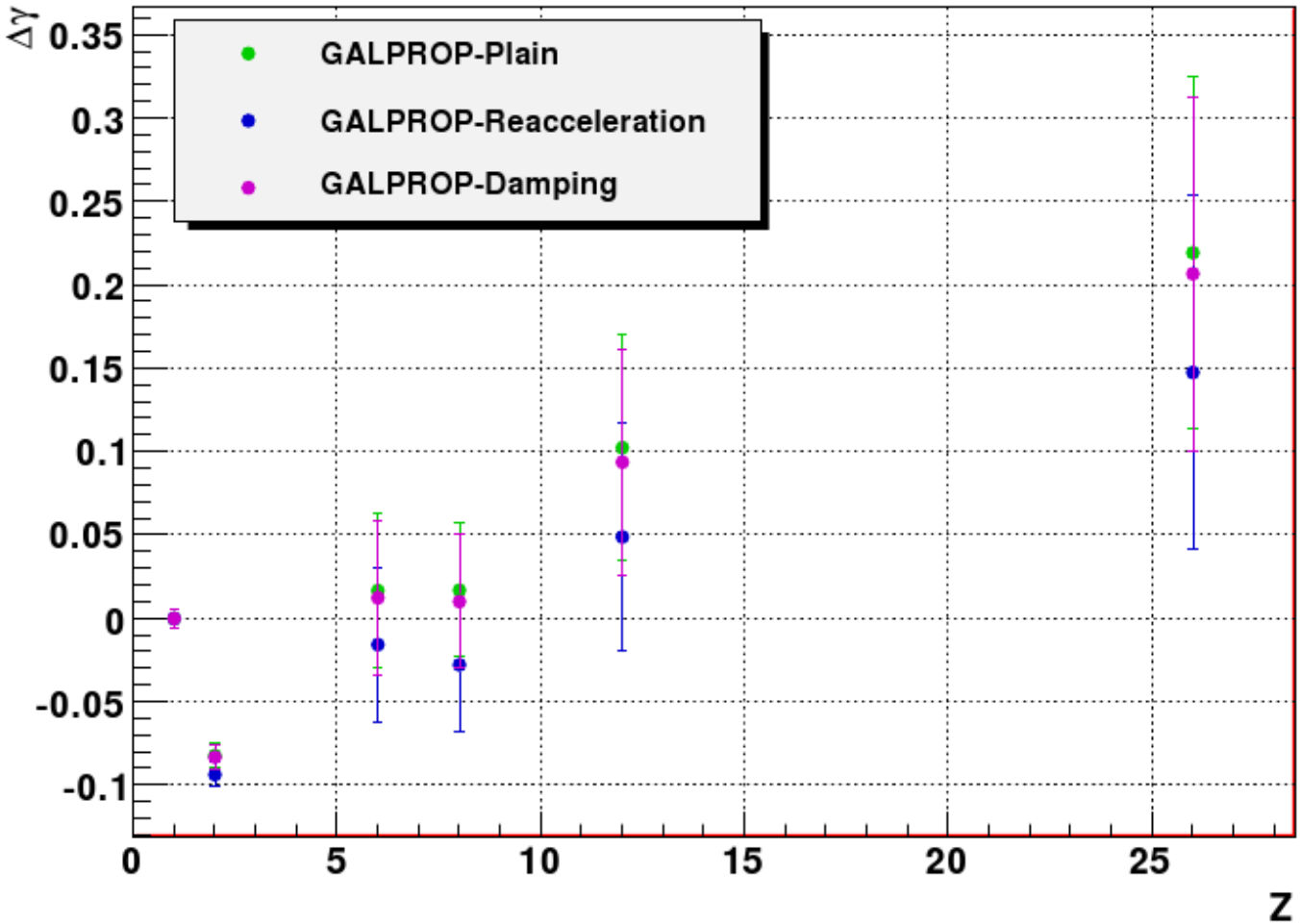


Common magnetic ridigity region for all nuclei is 50-1350 GV

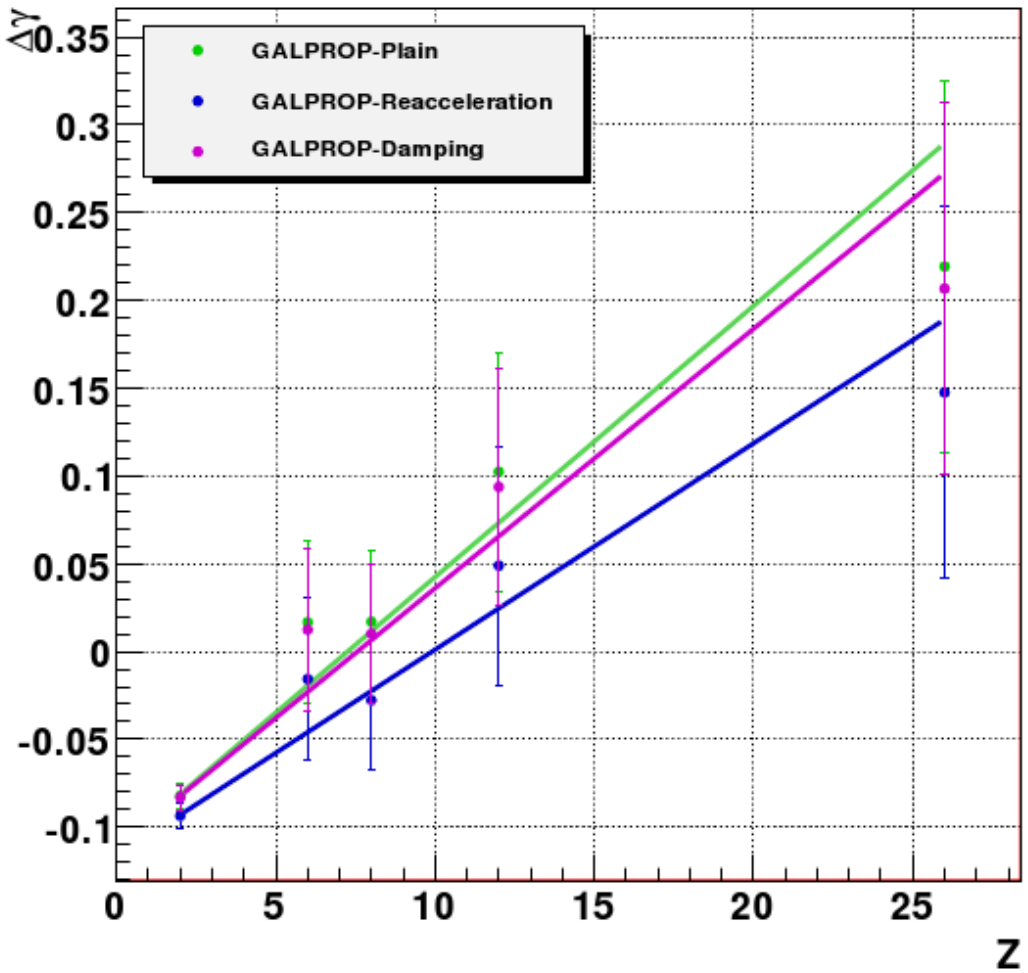
Spectral indexes relative to protons have weak model dependence



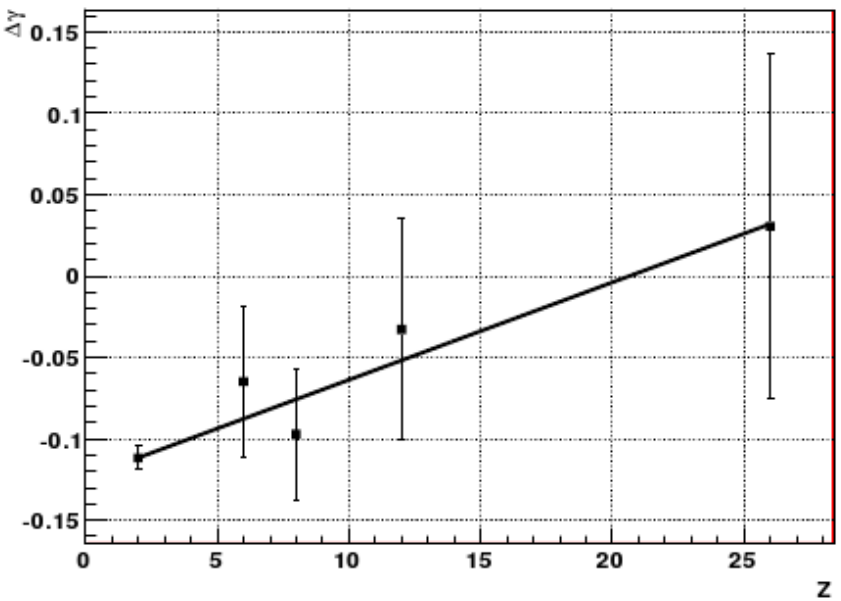
1. Spectra of protons and helium have significantly different slopes in the sources, the result is model independent, statistical significance is very high.

$$\Delta\gamma \approx 0.09 \pm 0.01, \text{ for } 50\,\mathrm{GV} < R < 1350\,\mathrm{GV}$$

The trend in spectral indexes for nuclei from helium to iron



There is no statistically significant trend in the observed rigidity spectra

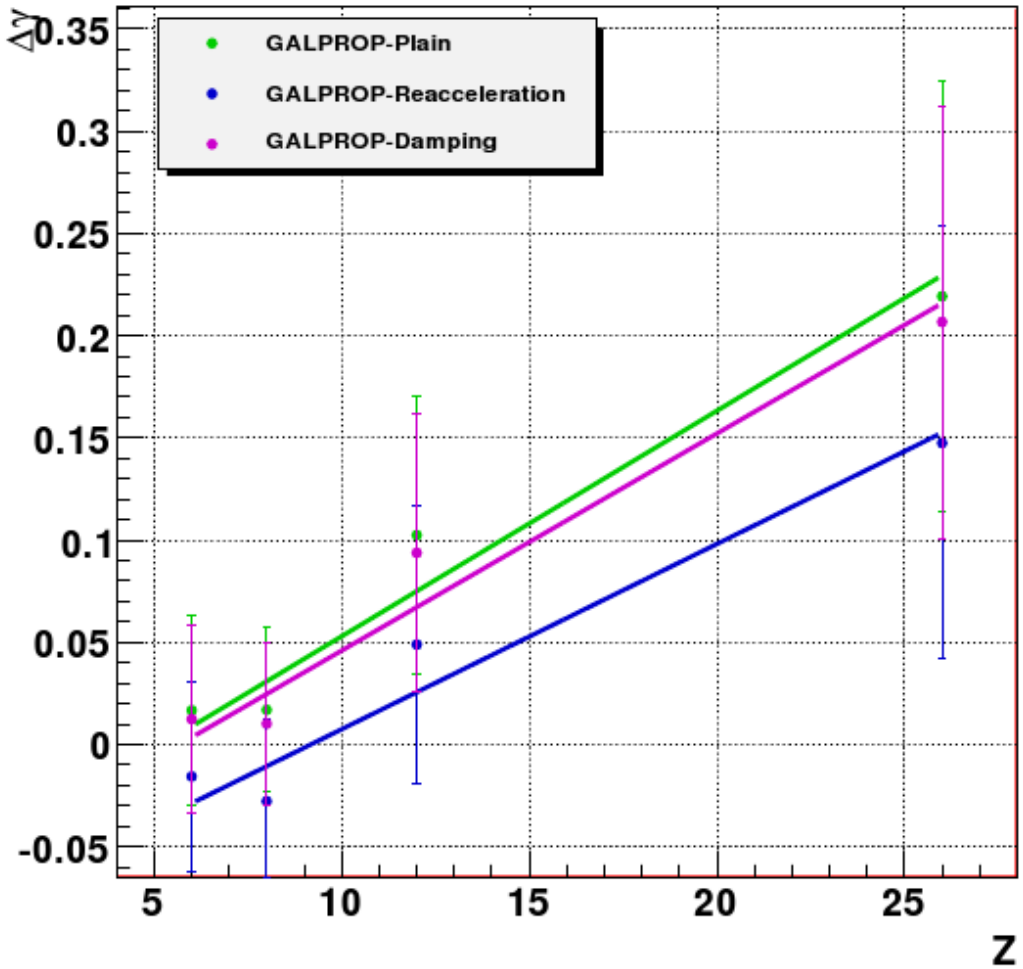


$$k = (5.99 \pm 3.19) \times 10^{-3} \approx 1.9\sigma$$

2. There is statistically significant trend in spectral indexes for nuclei from He to Fe from 3.7σ to 4.8σ (for different models).

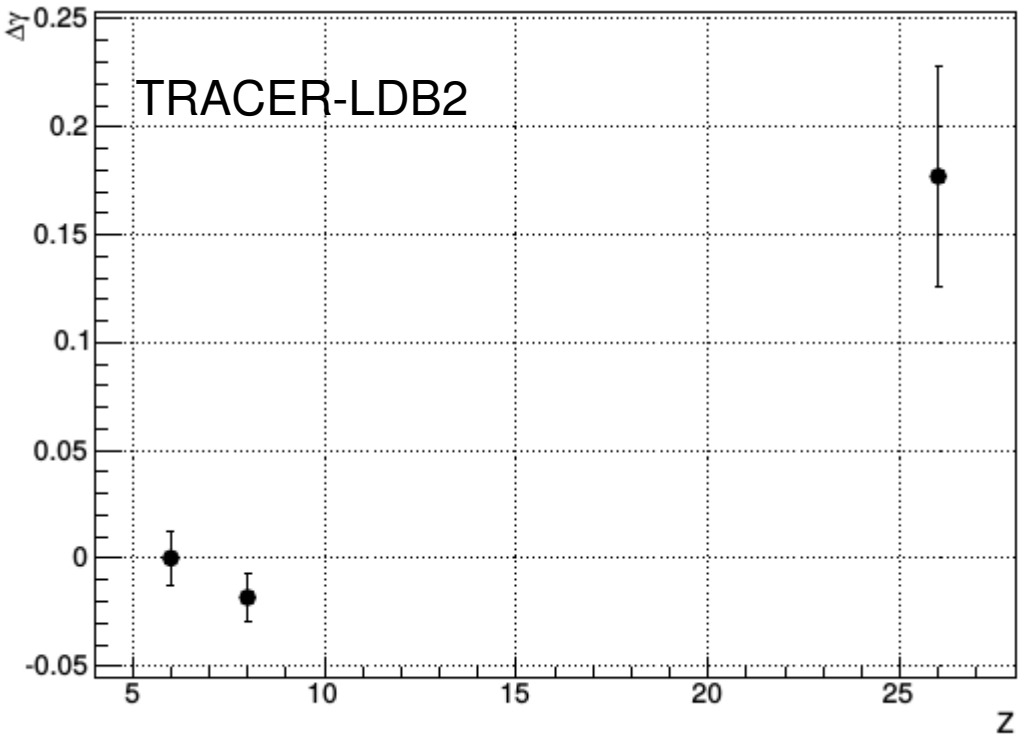
Is there a physical meaning in the data approximation from helium to iron?

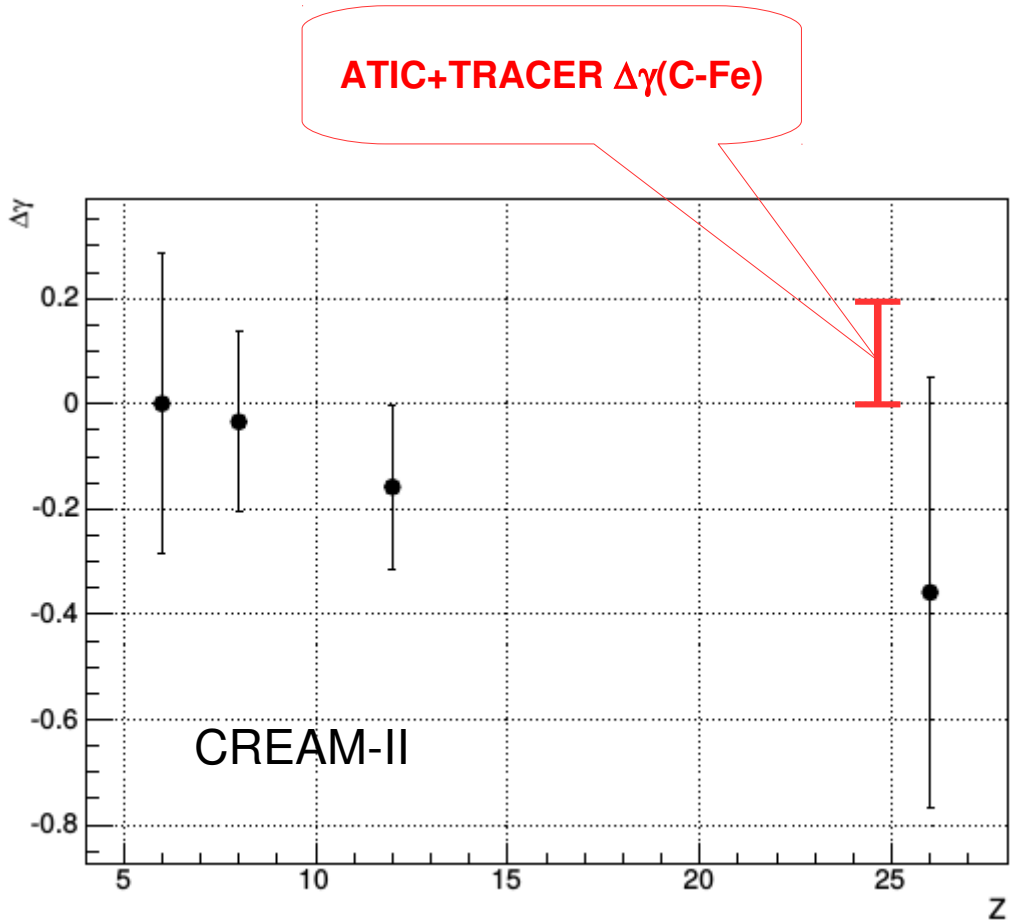
More “natural” plot:
The trend in spectral indices for nuclei from carbon to iron



3. The statistical significance for nuclei from C to Fe
   is from 1.63σ to 1.99σ (for different models):
   There is an evidence for a trend, but it should be checked.

Other experiments





Spectrum of iron is statistically significant steeper than carbon and oxygen (3.5σ for C-Fe difference)

No result (errors too large)

Confirms the ATIC's trend (1.63σ to 1.99σ) [50 GV – 1350 GV]

TRACER & CREAM [50 GV – 400 GV]

Summary and discussion

1. There is the differences between mean spectral indices of protons and helium in the sources 0.09 ± 0.01 (9 standard deviations) in the rigidity region of 50–1350 GV

2. There are certain evidences for a trend in a source spectrum slopes from helium to iron or even only in group of heavy nuclei - from carbon to iron (the steepness grows with Z in the rigidity region of 50–1350 GV)

Possible causes:

1. Different sources (different chemical composition and different slopes)
2. Heterogeneous sources (different nuclei with different spectra are accelerated at different stages of supernova explosion)

Thank you for attention!

Addenda

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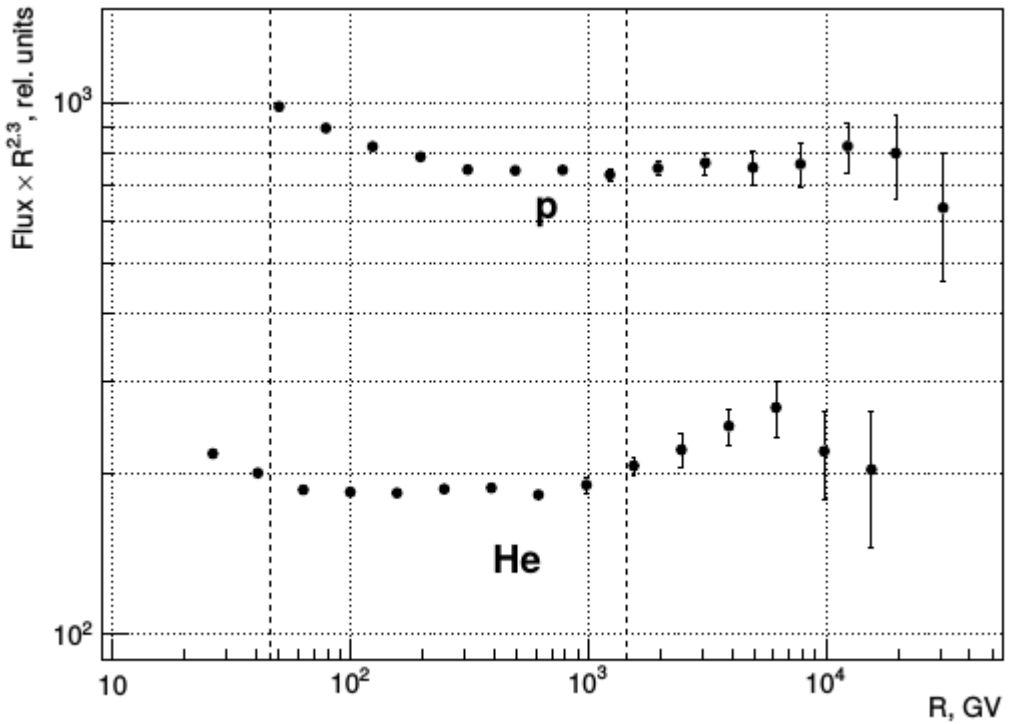

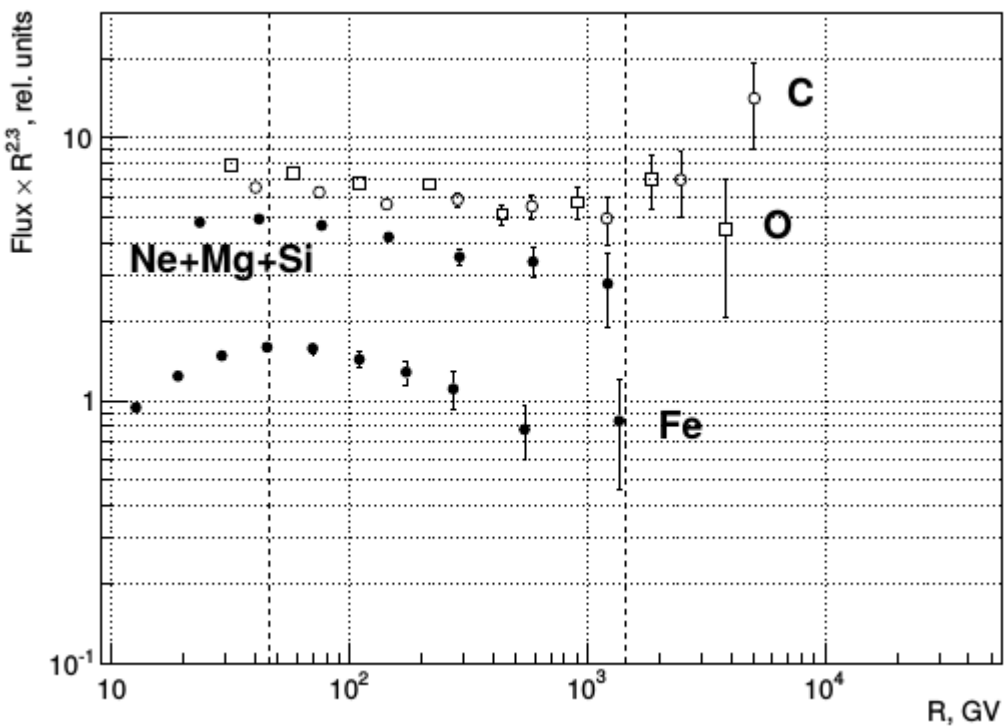

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