Boron and Carbon Isotopes in the PAMELA Experiment

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RCRC-2020, 29.09.2020, Dubna

PAMELA Collaboration

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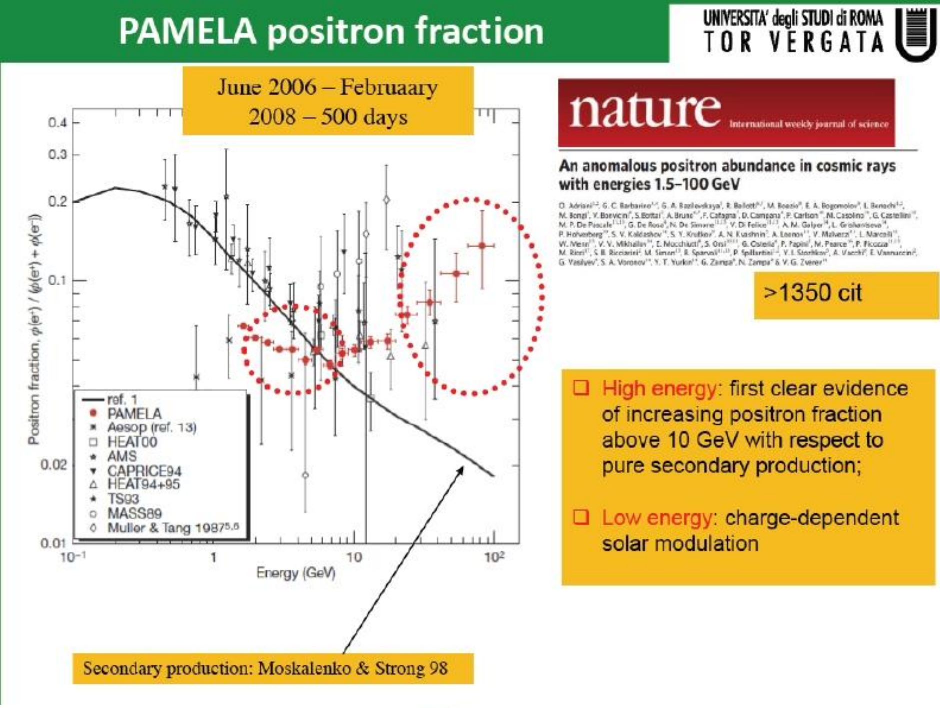
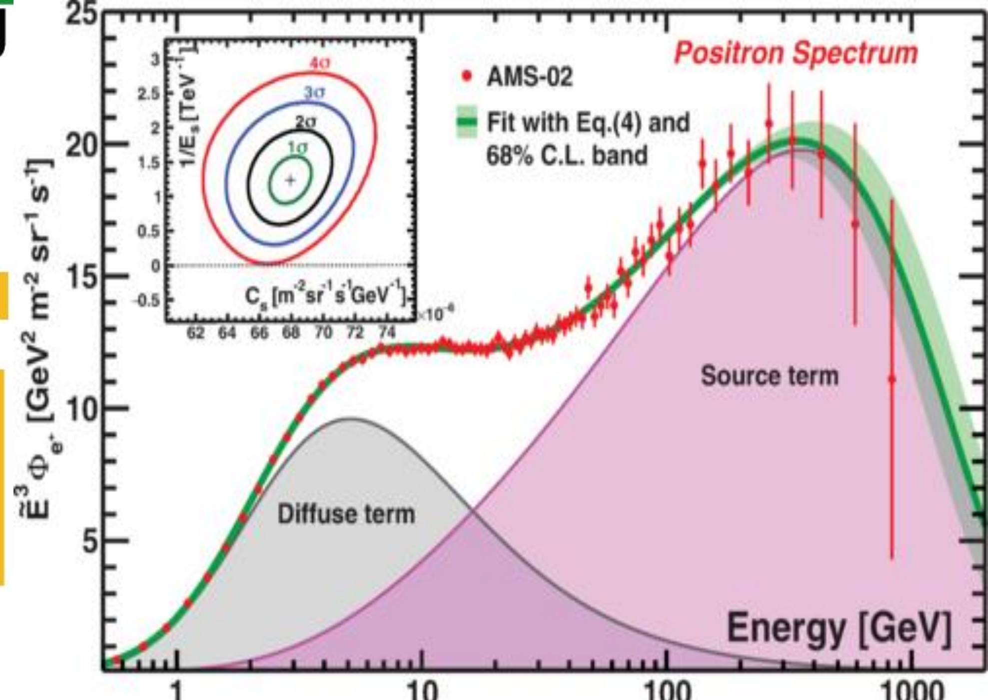
Introduction

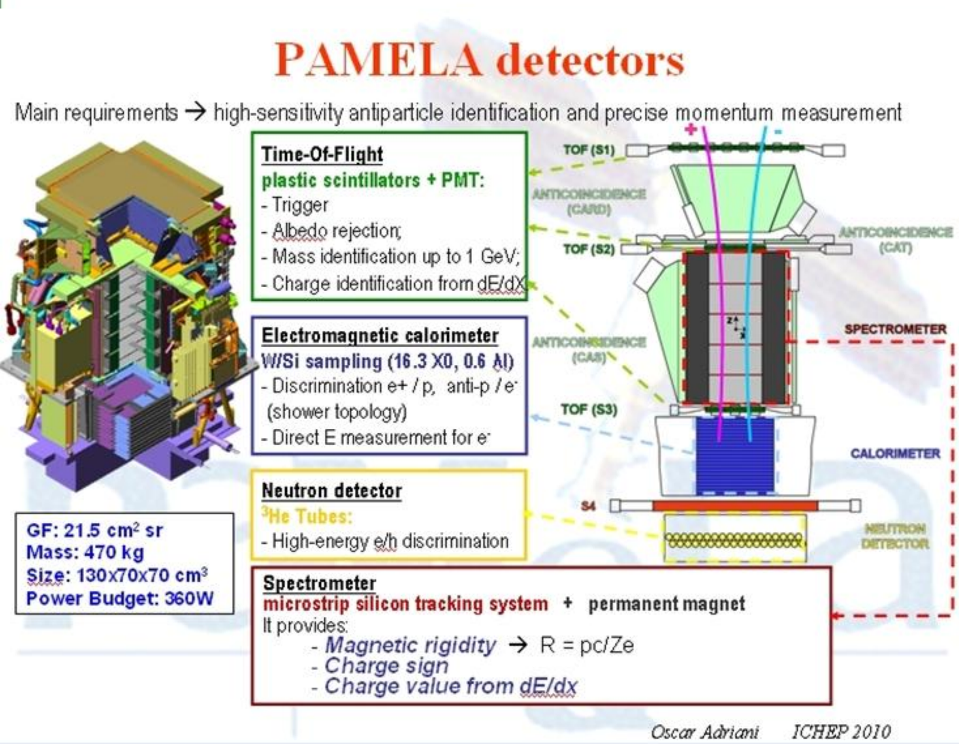
The analysis of the isotopic composition of nuclei in galactic cosmic rays (GCR) in the orbital experiment PAMELA allows one to study the problems of the origin and propagation of cosmic rays in the Galaxy. Due to the high statistical and methodological accuracy, the data of the PAMELA magnetic spectrometer ensured significant progress in the study of the isotopic composition of light nuclei from H to Be in GCR in the energy range of ~ 0.1-1 GeV / nucleon and for the first time made it possible to estimate the contribution to GCR of local sources from close (up to ~ 300 pc) of recent (up to ~ million years) supernova explosions. To date, isotopic analysis of boron nuclei in GCR has been performed only in the energy range of ~ 0.08-0.17 GeV / nucleon in the space experiments Voyager, Ulysses, ACE / CRIS, and the ^{13}C / ^{12}C carbon isotope ratio was measured in the Voyager 1.2 experiment at an energy of 0.05 0.13 GeV / nucleon, and in the ACE / CRIS experiment, the upper limit for the ^{14}C / ^{12}C ratio was estimated at energies of 0.12–0.43 MeV / nucleon. In this work, using PAMELA data from 2006-2014, on the rigidity of the detected nuclei and their velocity (time-of-flight analysis and ionization losses in a multilayer calorimeter), an attempt was made to determine the ^{11}B / ^{10}B ratio in the energy range ~ 0.1-1.0 GeV / nucleon and for the first time to estimate the ^{14}C / ^{12}C ratio at energies of ~ 0.1-1.5 GeV / nucleon using PAMELA boron data. The new PAMELA data expand the energy range of previous measurements, agree with the existing measurements and those expected from modeling, but the statistical and methodological accuracy of measurements does not allow to single out the contribution of local boron sources to GCR, and the data on the ^{14}C / ^{12}C ratio allow us to estimate the lower limits of the distances to possible local sources ^{14}C. The results of isotopic analysis of boron and carbon nuclei in GCR (spectra of ^{12}C, ^{13}C, upper limits of ^{14}C and for the ^{14}C / ^{12}C ratio depending on the rigidities and energy of nuclei) are presented in comparison with the existing measurement and calculation data.



PAMELA positron fraction
UNIVERSITA' degli STUDI di ROMA
TOR VERGATA
June 2006 – Februaary 2008 – 500 days
nature
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV
>1350 cit
Positron fraction, φ(e+) / (φ(e+) + φ(e-))
Energy (GeV)
ref. 1
PAMELA
Aesop (ref. 13)
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987
High energy: first clear evidence of increasing positron fraction above 10 GeV with respect to pure secondary production;
Low energy: charge-dependent solar modulation
Secondary production: Moskalenko & Strong 98



Positron Spectrum
AMS-02
Fit with Eq.(4) and 68% C.L. band
Source term
Diffuse term
Energy [GeV]
$\tilde{E}^3 \Phi_{e^+}$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
1/E$_s$ [TeV^{-1}]
C$_s$ [m^{-2}sr^{-1}s^{-1}GeV^{-1}]
4σ
3σ
2σ
1σ



PAMELA detectors
Main requirements → high-sensitivity antiparticle identification and precise momentum measurement
Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX
Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e-
(shower topology)
- Direct E measurement for e-
Neutron detector
3He Tubes:
- High-energy e/h discrimination
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- Magnetic rigidity → R = pc/Ze
- Charge sign
- Charge value from dE/dx
GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W
TOF (S1)
TOF (S2)
TOF (S3)
S4
ANTICOINCIDENCE (CARD)
ANTICOINCIDENCE (CAT)
ANTICOINCIDENCE (CAS)
SPECTROMETER
CALORIMETER
NEUTRON DETECTOR
Oscar Adriani ICHEP 2010

AMS-02

Antiprotons in GCR

PAMELA, PRL 105(2010)121101

AMS-02, PRL 117(2016)091103

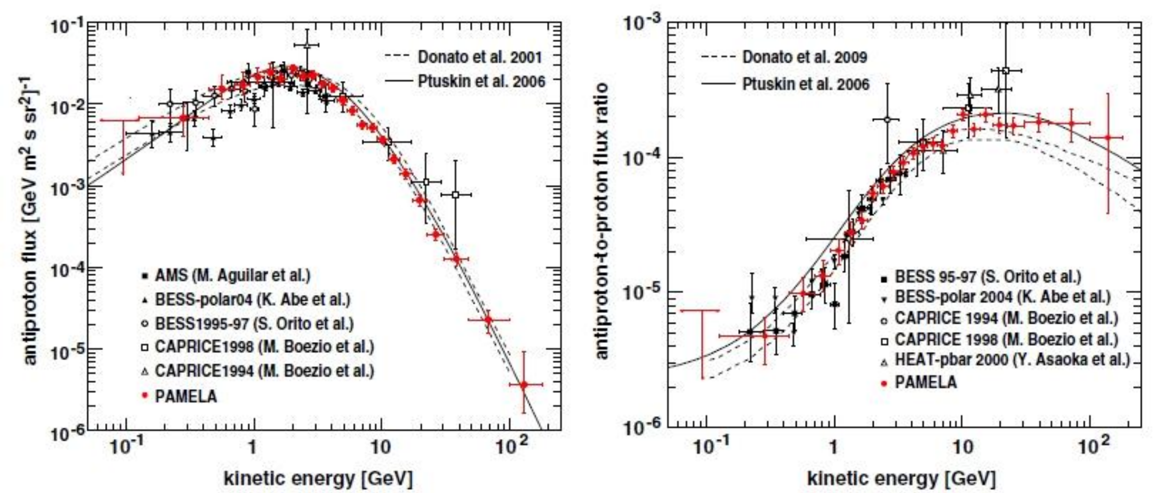
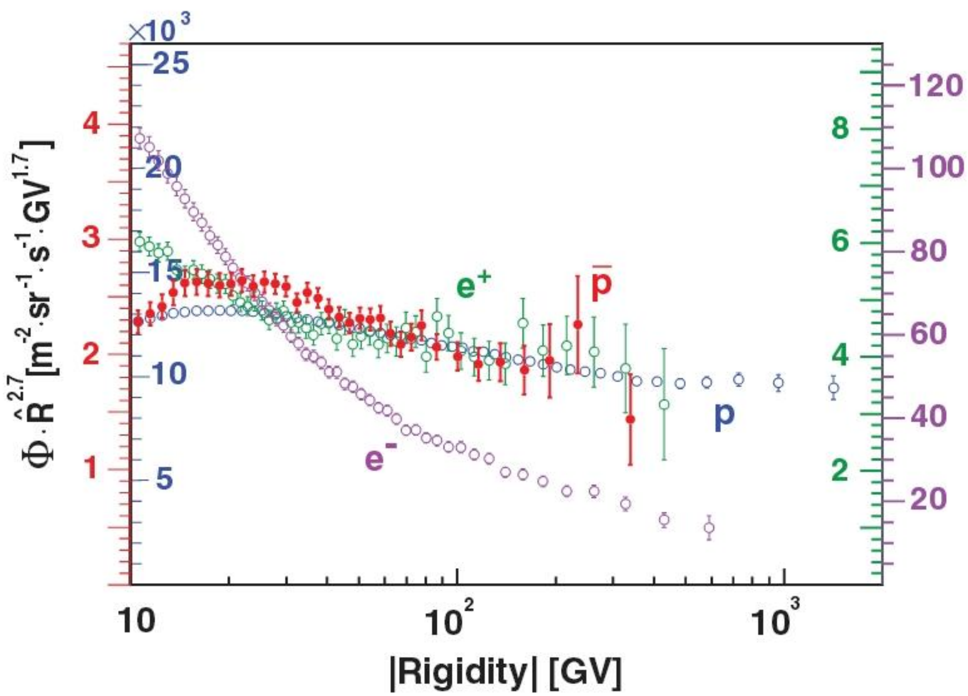
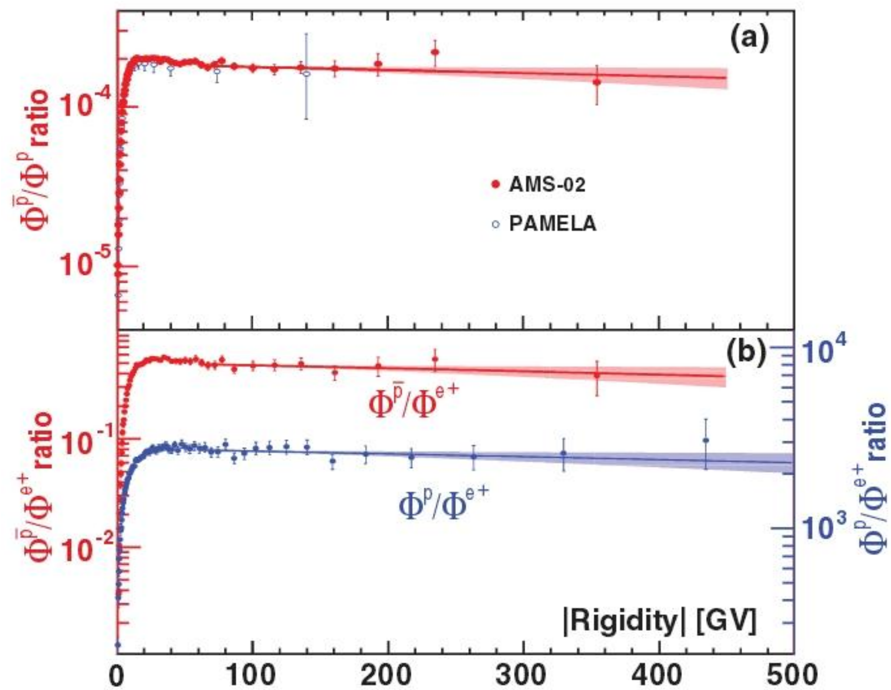


Fig. 2 The $\bar{p}$ spectrum (*left*) and the $\bar{p}/p$ flux ratio (*right*) measured by PAMELA [6], compared with data from other contemporary experiments [8–13] and theoretical calculations for purely secondary production of antiprotons in the Galaxy [14–16]

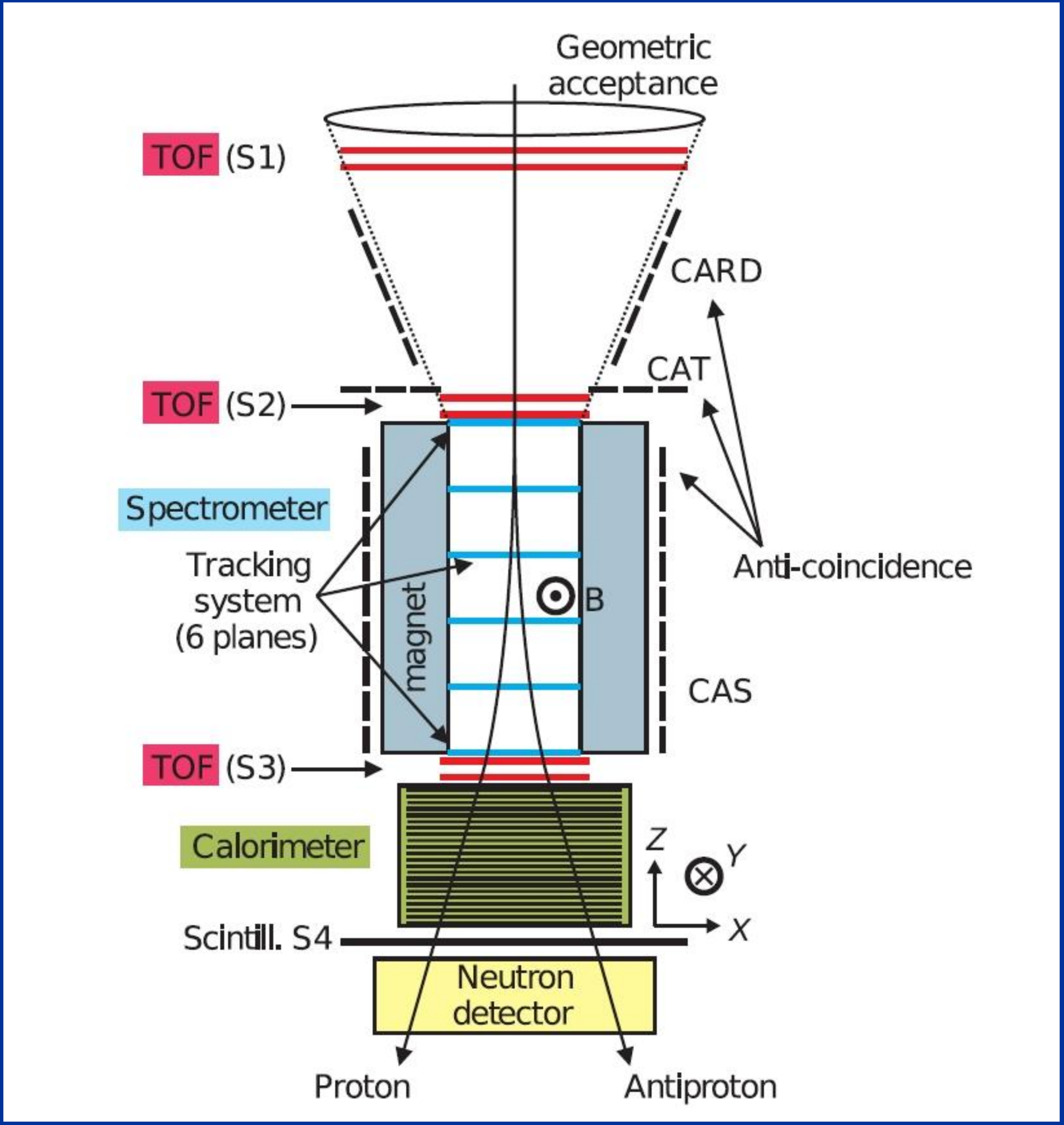




PAMELA

AMS-02

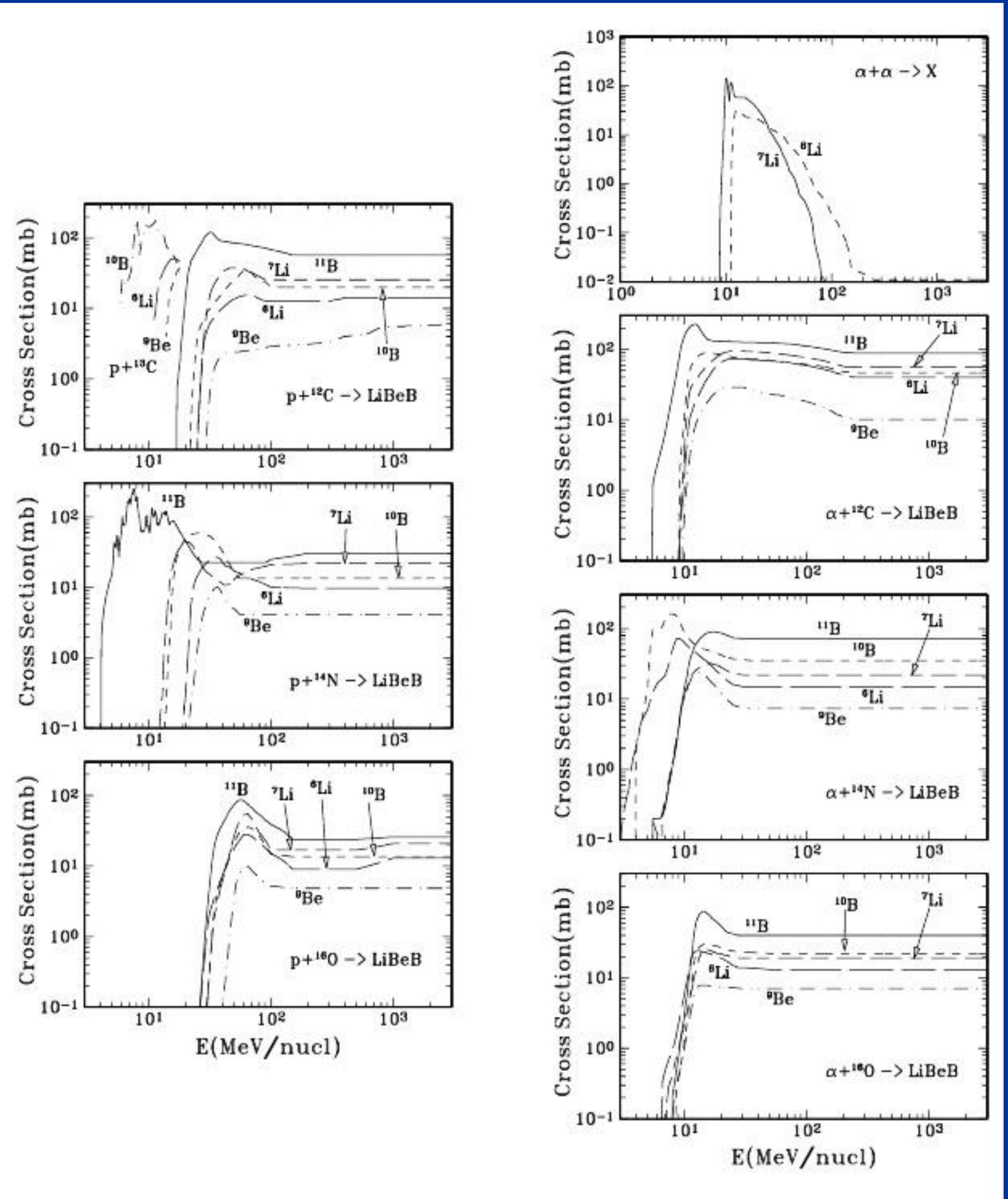
PAMELA Magnetic Spectrometer



Mass: $Mc^2 = RZ/(\beta^{-2} - 1)^{1/2}$

1. Z from S1, S2, S3
2. $\beta = v/c$ from TOF
   Time resolution:
   Z=1 ~ 250 ps
   Z=2 ~ 100 ps
   Z=3 ~ 85 ps
   Z=4 ~ 80 ps
   Z=5 ~ 80 ps
3. R from Tracker
   MDR ~ 1 TV
4. Up to S3 - X~5 g/cm^2
5. Orbit inclination 70^0

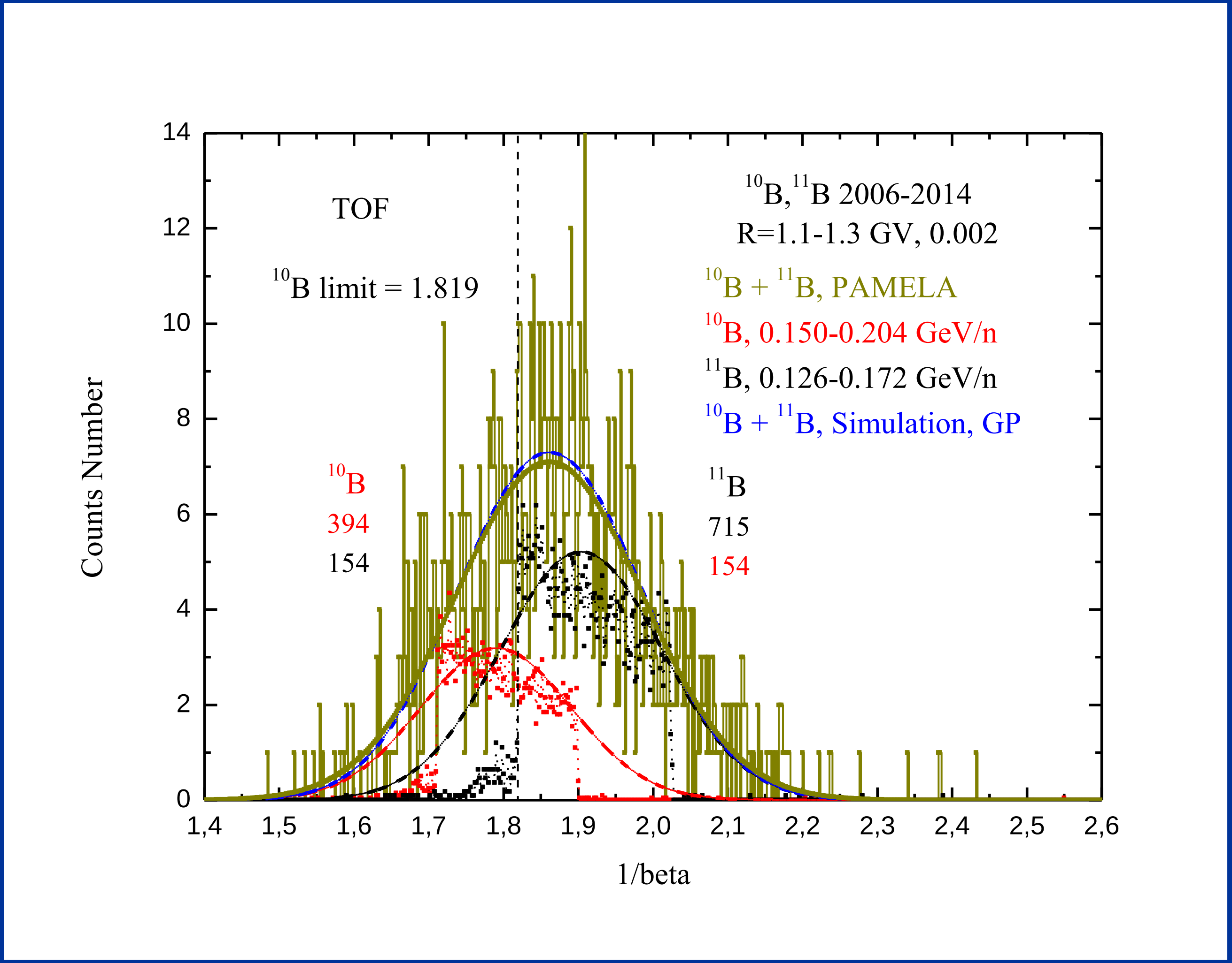
Origin of Li, Be and B Isotopes –
GCR 1H and 4He interactions on He, C, N, O



E. Vangioni-Flam et al.
astro-ph 990717

NB. 6Li, 7Li from He+He by
E = 10-100 MeV/nucl.

Method of limits for isotopes selection (example), TOF

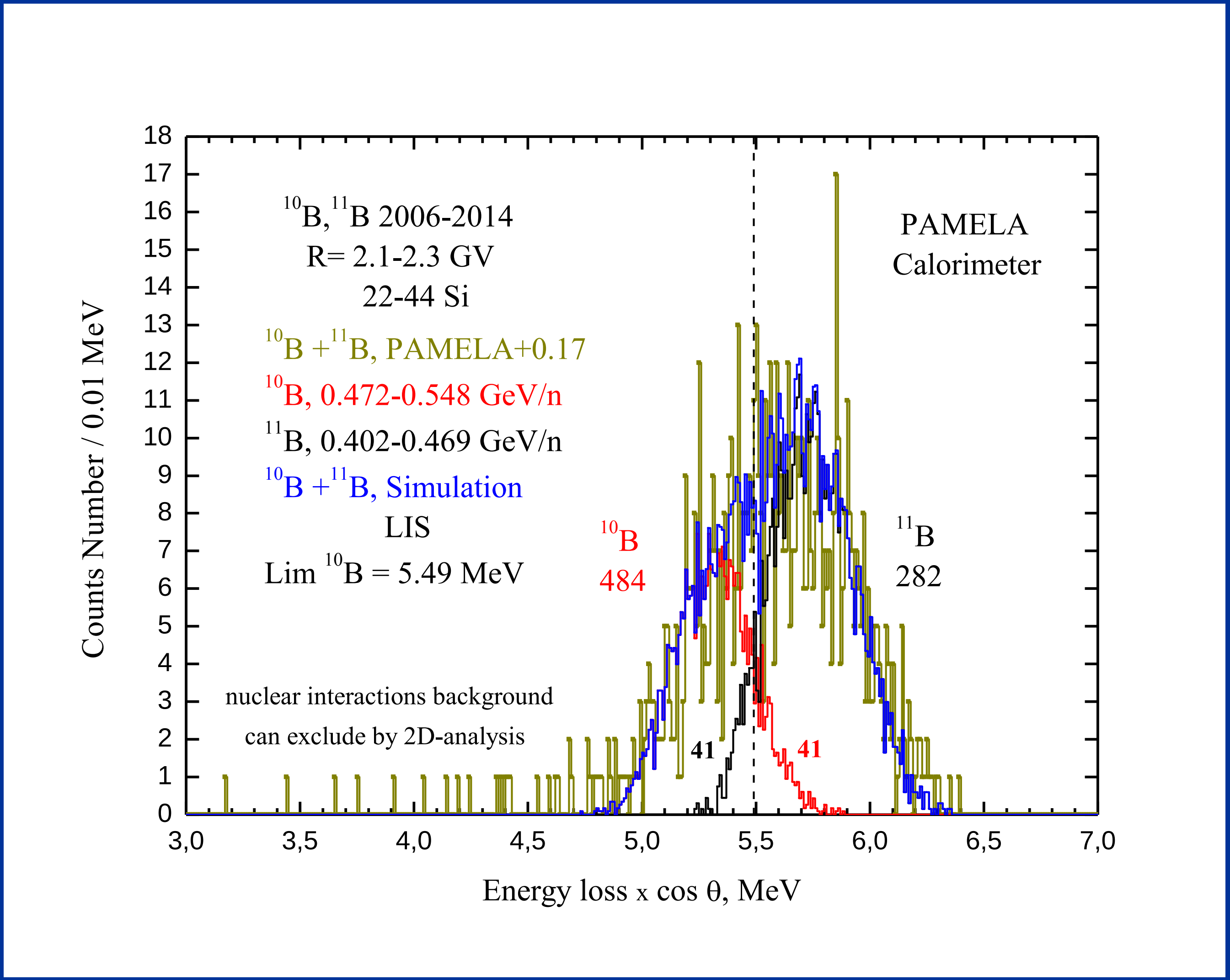


Advantages:

1. Simple
2. Stable to 1/beta distributions and isotope ratio in reasonable limits
3. Precision of data for 1/beta limits ~ 0.002-0.004
4. Good agreement with usual methods by GCR H and He isotopes analysis.

NB. Events in crossing area include in errors of ratio data.

Method of limits for isotopes selection (example), Calorimeter

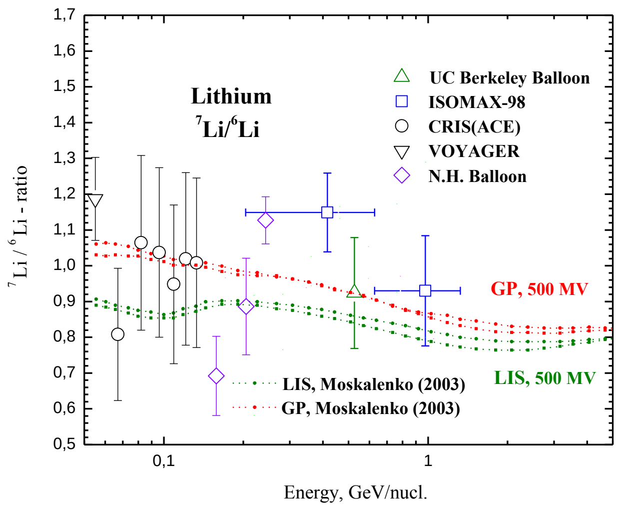


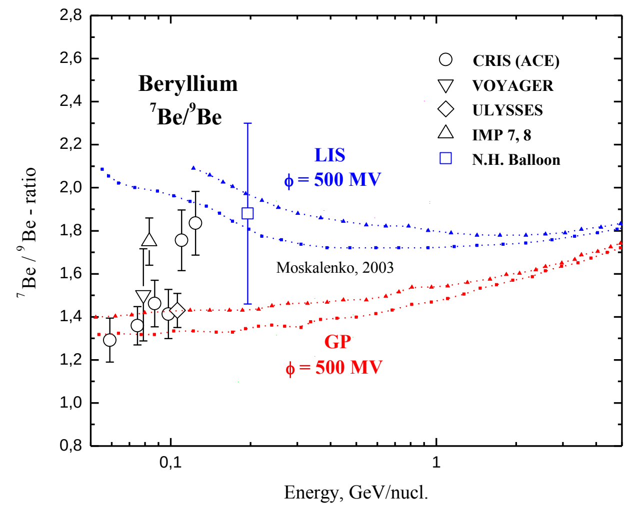
Advantages:

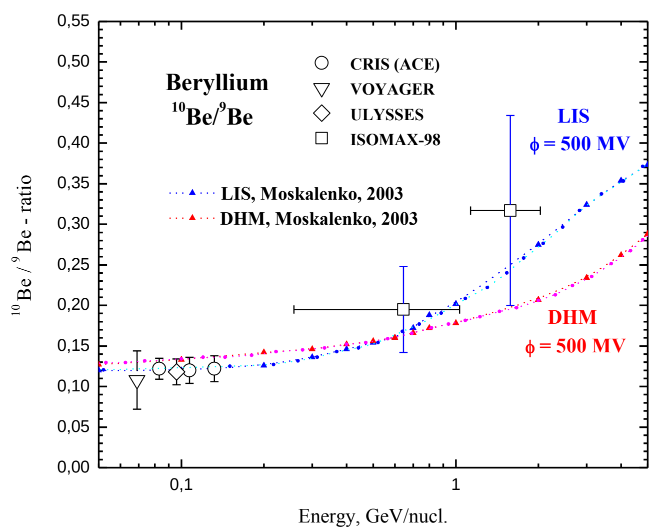
1. Simple
2. Stable to dE/dx distributions and isotope ratio in reasonable limits
3. Precision of data for 10B limits ~ 0.01 MeV
4. Good agreement with usual methods by GCR H and He isotopes analysis.

NB. Events in crossing area include in errors of ratio data.

7Li/6Li, 7Be/9Be, 10B/9Be E-Ratio before PAMELA

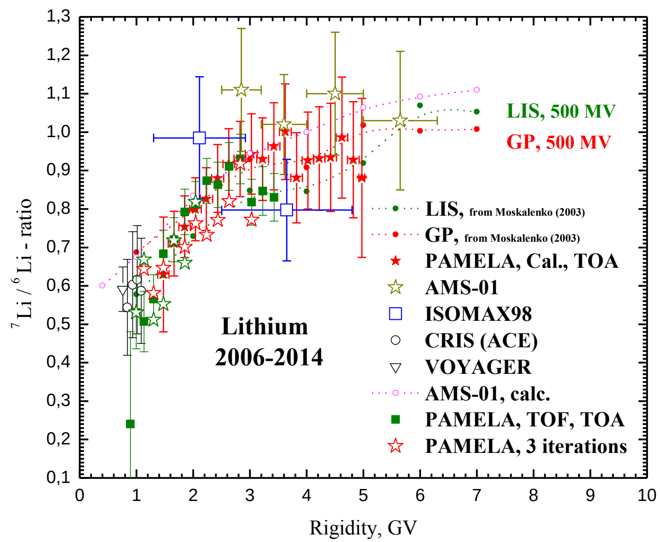


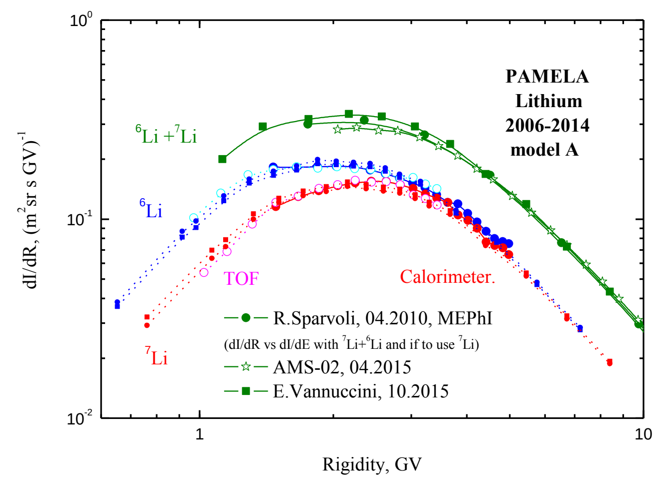


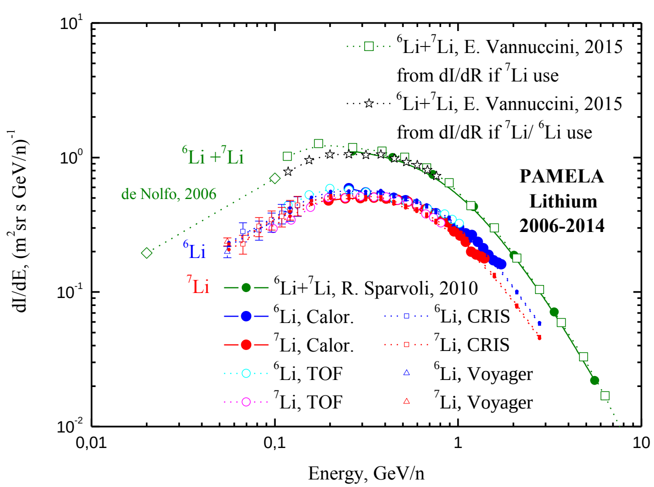


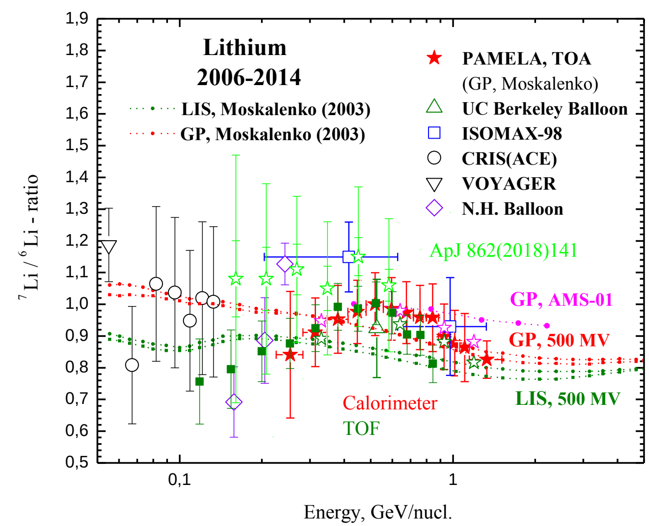
PAMELA, 7Li/6Li-Ratio, R and E-Spectra, 2006-2014 and Local Interstellar Sources (Preliminary data)

Bull.RAS, Physics 83(2019)967



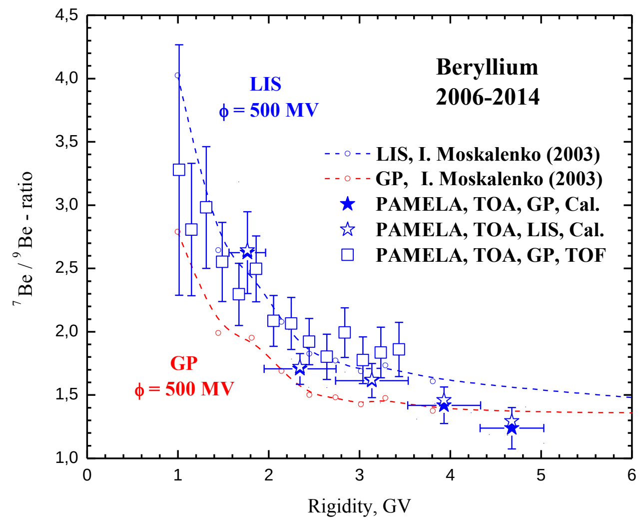


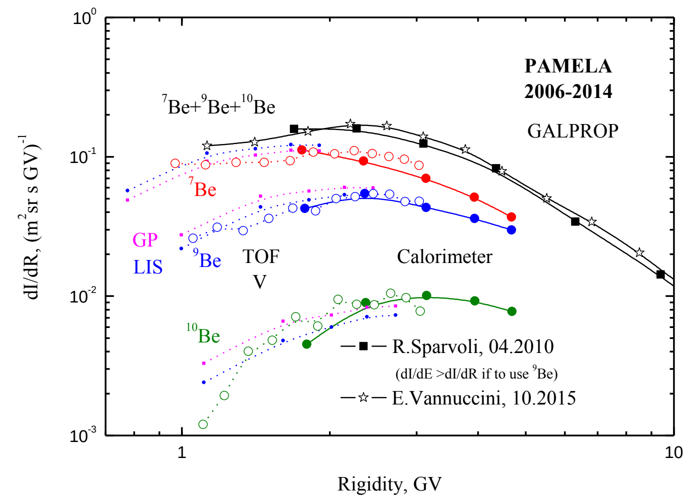


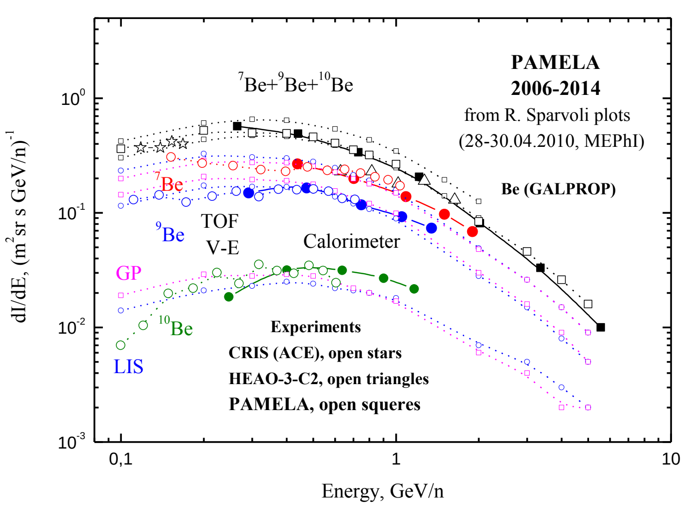


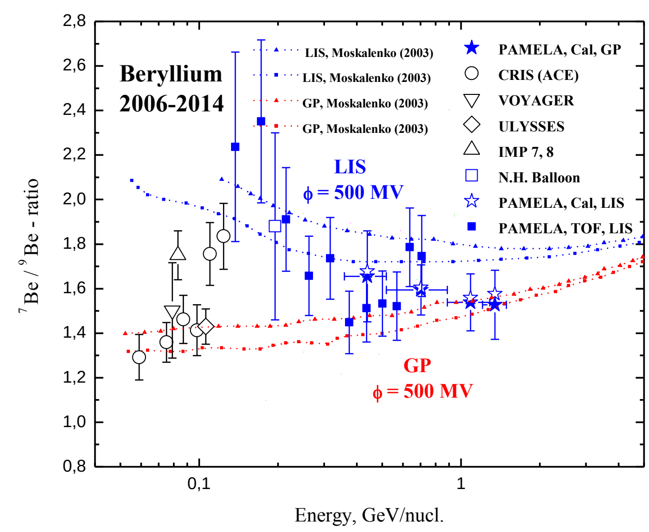
PAMELA, 7Be/9Be-Ratio, R and E-Spectra, 2006-2014
and Local Interstellar Sources (Preliminary data)

Bull. RAS, Physics 83(2019)967



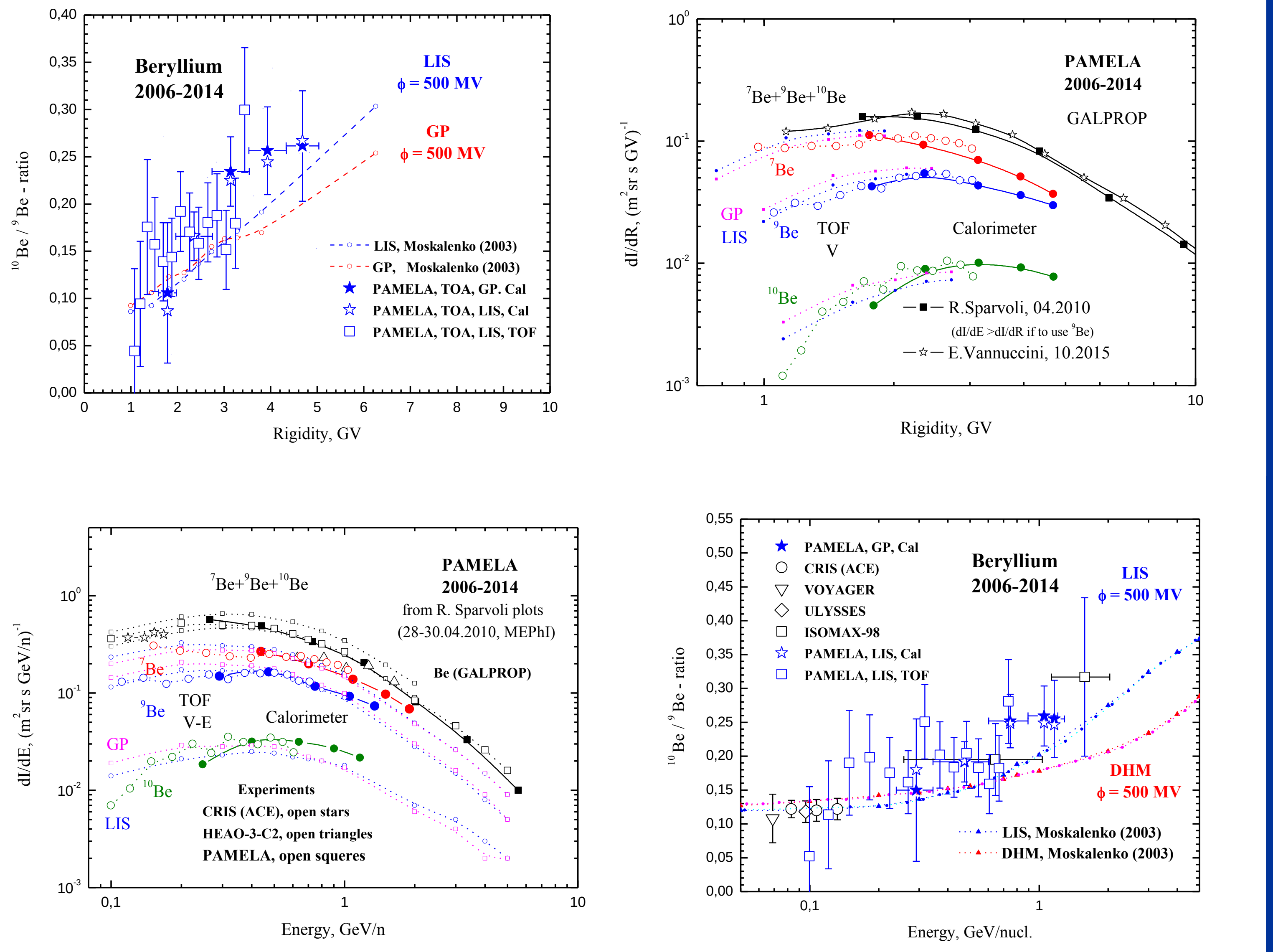




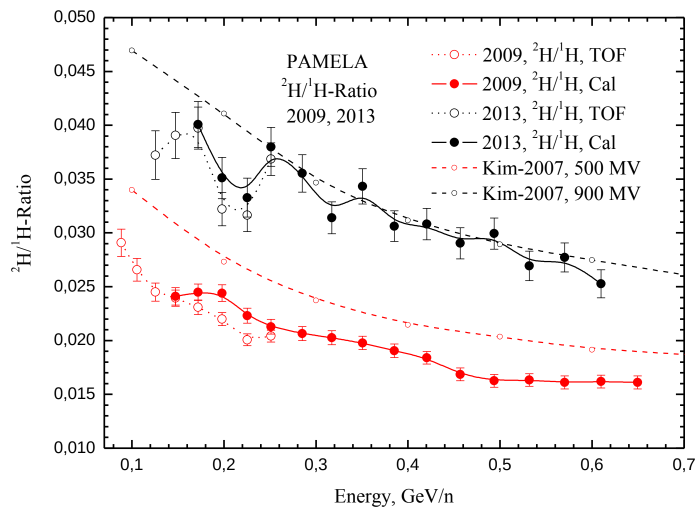


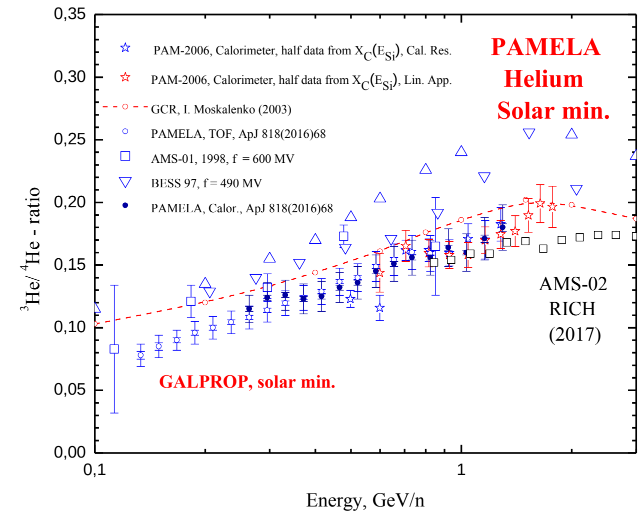
PAMELA, 10Be/9Be-Ratio, R and E-Spectra, 2006-2014 and Local Interstellar Sources (Preliminary data)

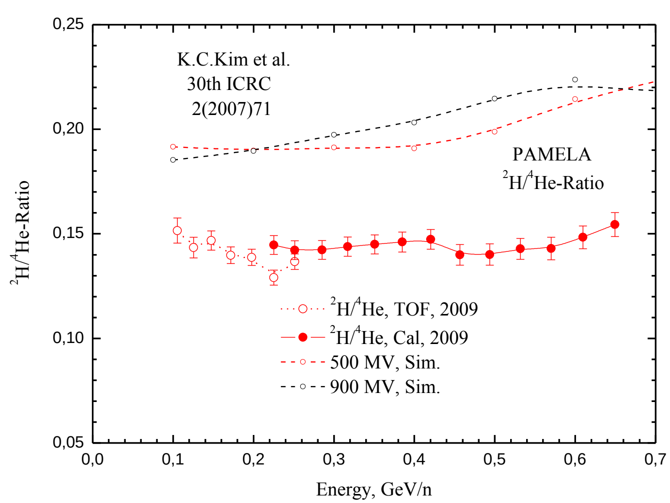
Bull. RAS, Physics 83(2019)967



PAMELA, 2H/1H, 3He/4He, 2H/4He E-Ratio and Local Interstellar Sources







Measured decreasing of 3He/4He, 2H/1H , 2H/4He in comparison with GALPROP simulation can indicate on additional Local Interstellar Sources of 1H and 4He in Cosmic Rays…

7Be/9Be+10Be E-Ratio, PAMELA in ApJ 862(2018)141

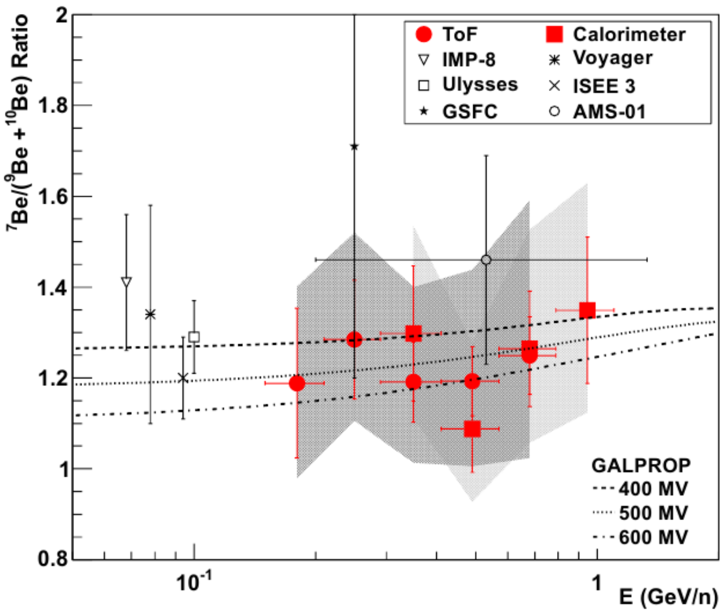
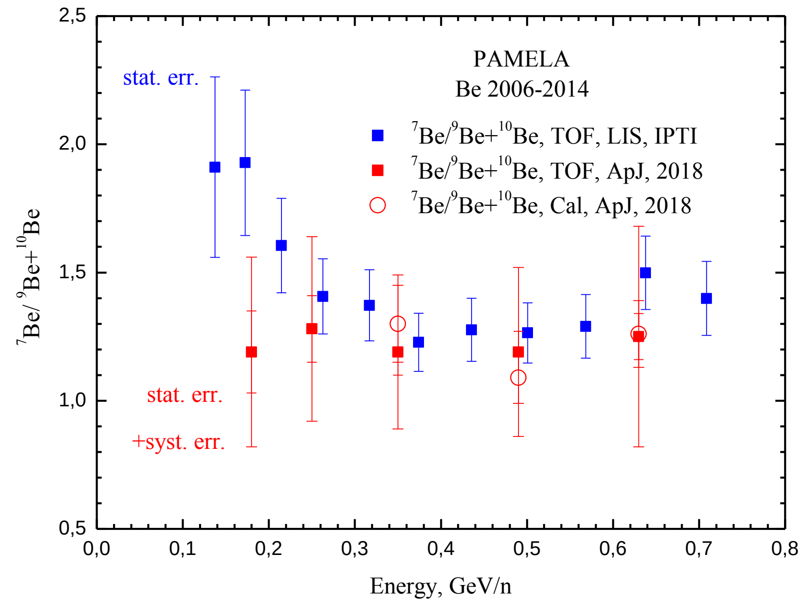
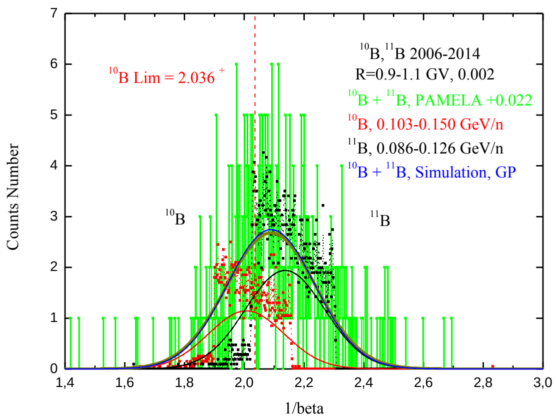


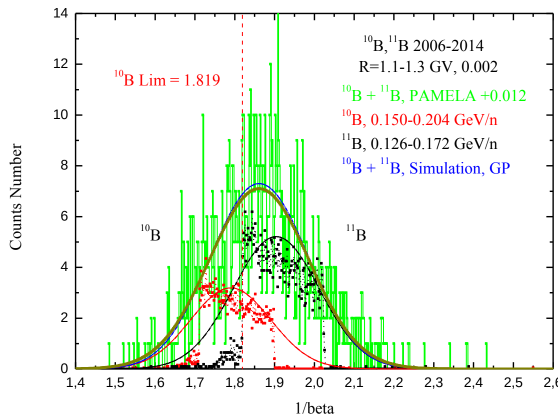
Fig. 11.— Ratio of ^{7}Be/(^{9}Be + ^{10}Be) derived with the PAMELA ToF (circles) or the calorimeter (squares). Error bars show the statistical uncertainty while shaded areas show the systematic uncertainty. Previous experiments are: Voyager (Webber *et al.* 2002), ULYSSES (Connell 1998), ISEE3 (Wiedenbeck & Greiner 1980), IMP7/8 (Garcia-Munoz *et al.* 1977), GSFC (Hagen *et al.* 1977), AMS-01 (Aguilar *et al.* 2011). Also shown are predictions of GALPROP webRun v54.1 (Vladimirov *et al.* 2011) using different solar modulation parameters.

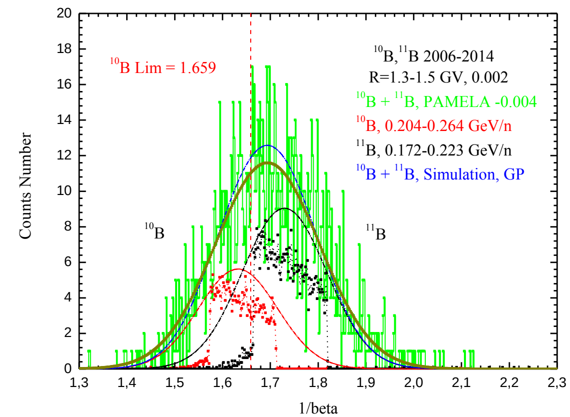


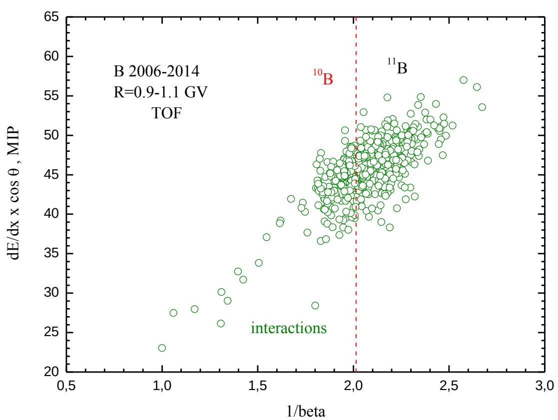
Boron Isotopes In Cosmic Rays

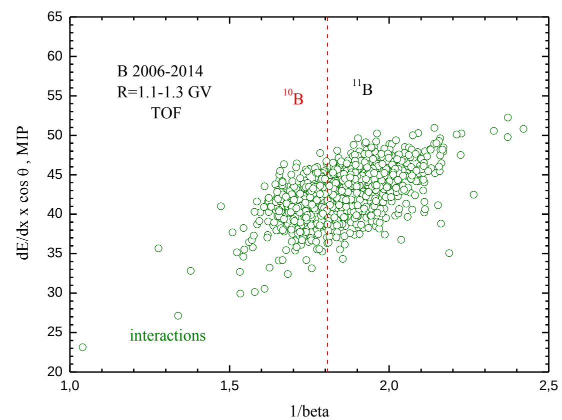
10B and 11B, 0.9-1.5 GV, 2006-2014, TOF

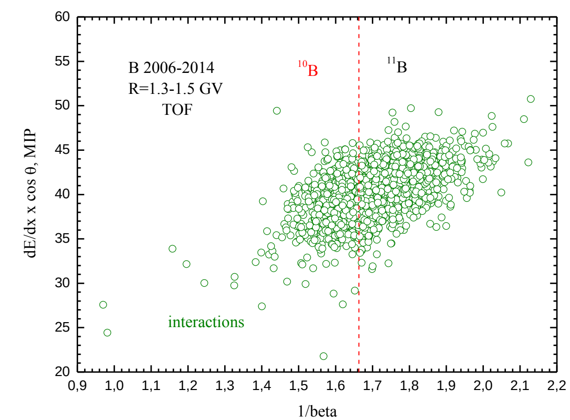






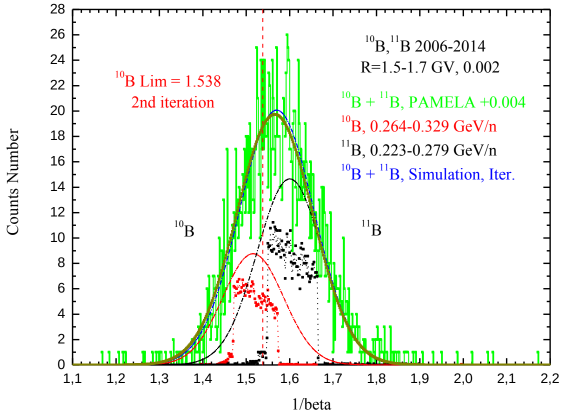


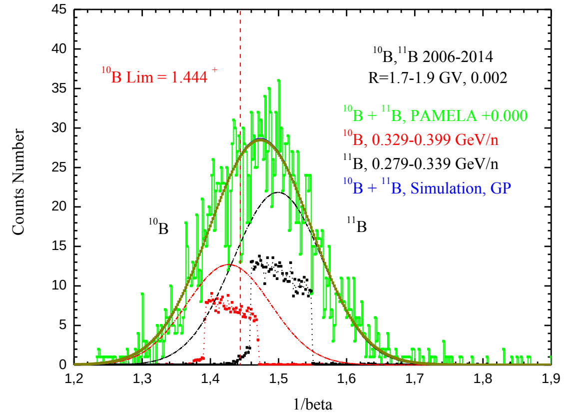


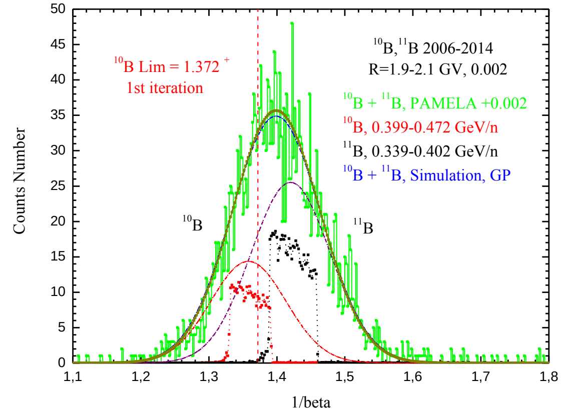


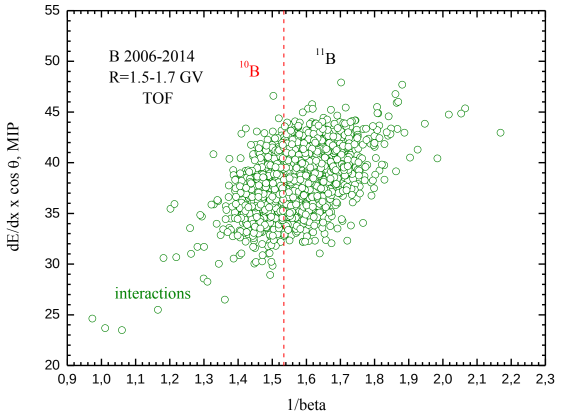
2D-analysis (dE/dx vs 1/beta) can use for background selection of nuclear interactions.

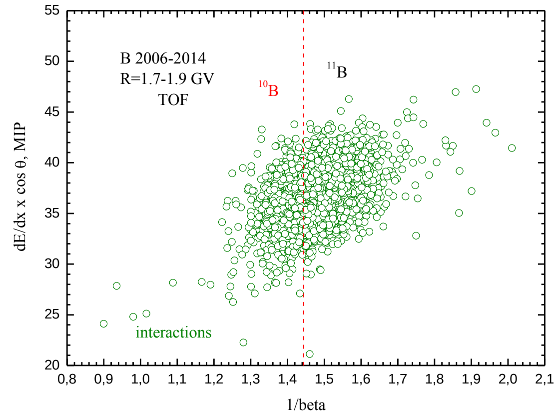
10B and 11B, 1.5-2.1 GV, 2006-2014, TOF

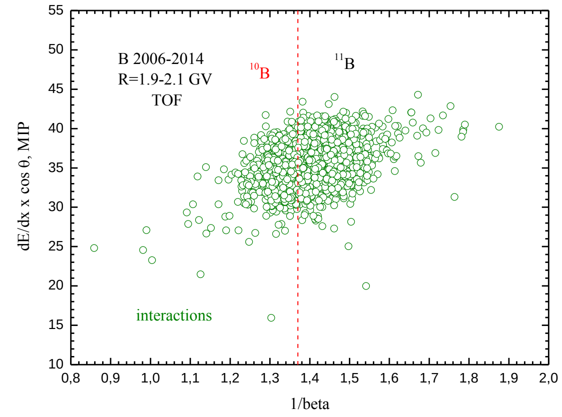






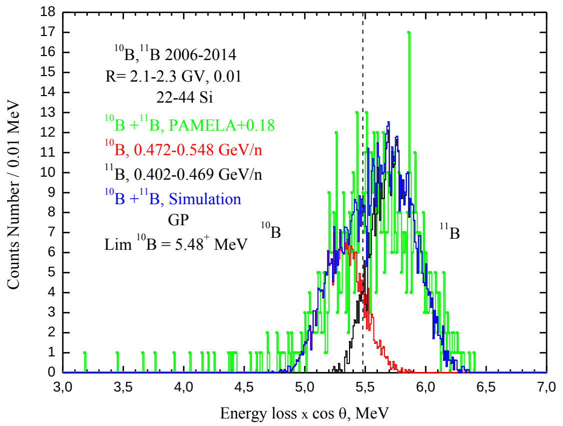


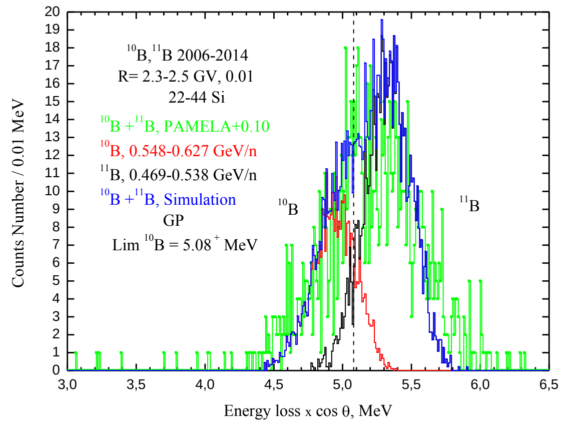


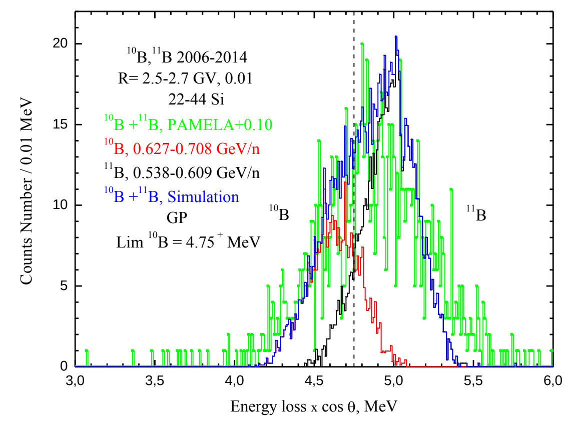


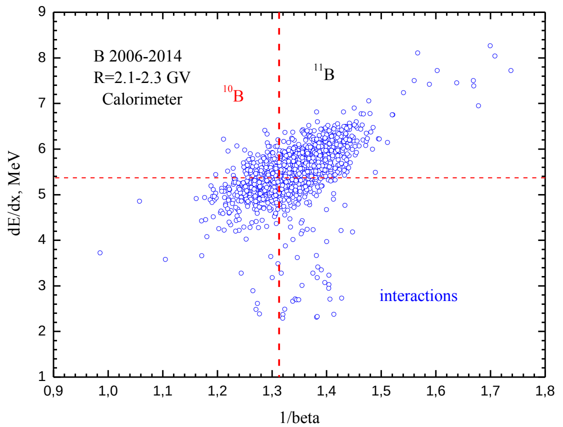
Background of nuclear interactions is not so big in the PAMELA TOF flight data.

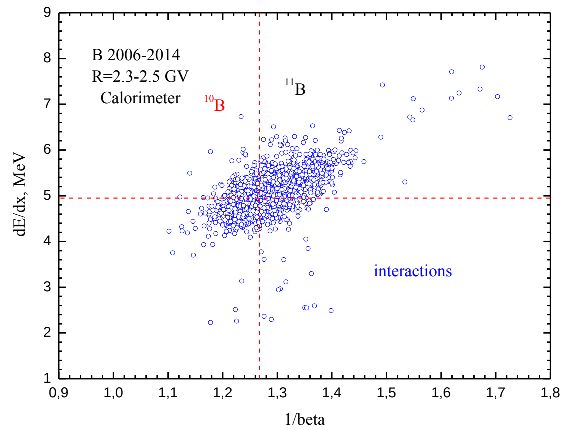
10B and 11B, 2.1-2.7 GV, 2006-2014, Calorimeter

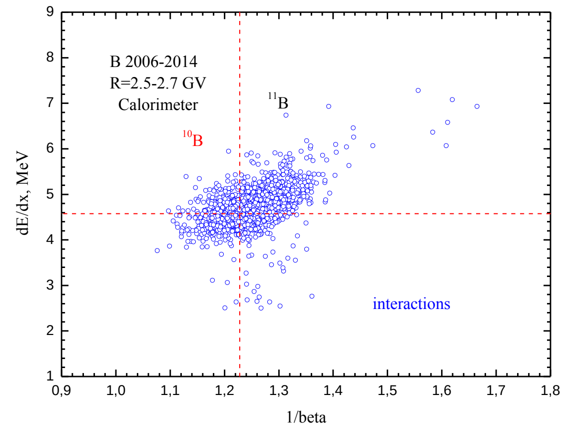






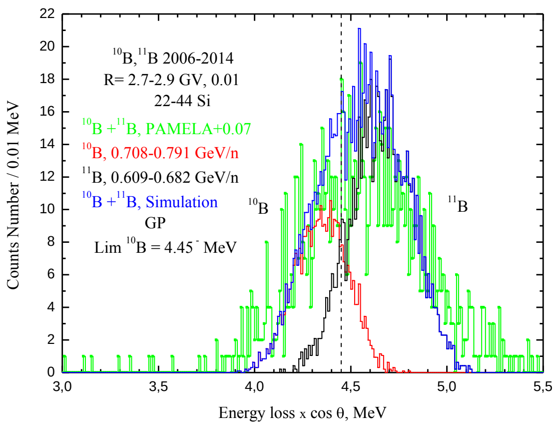


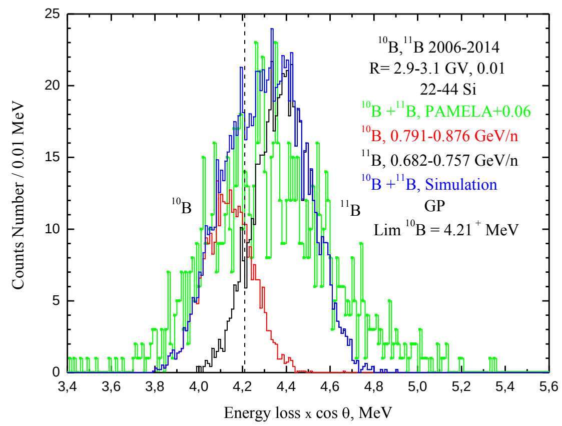


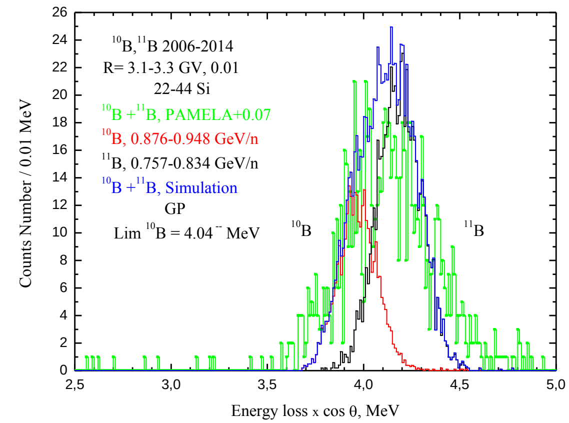


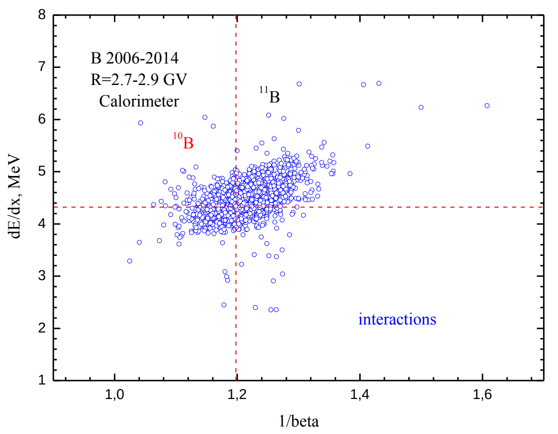
2D-analysis (dE/dx vs 1/beta) can use for background selection of nuclear interactions.

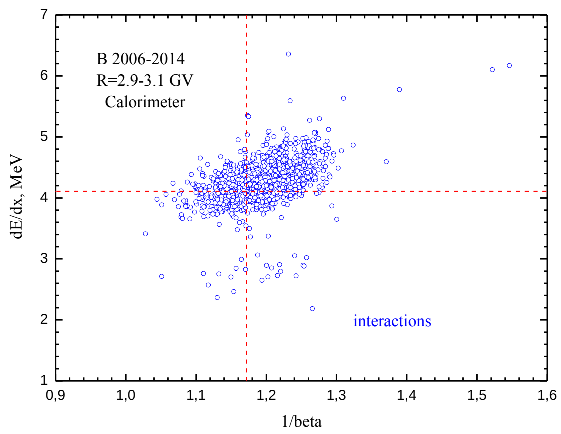
10B and 11B, 2.7-3.3 GV, 2006-2014, Calorimeter

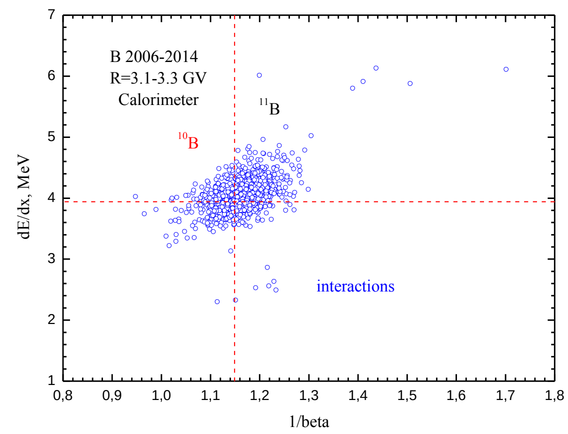




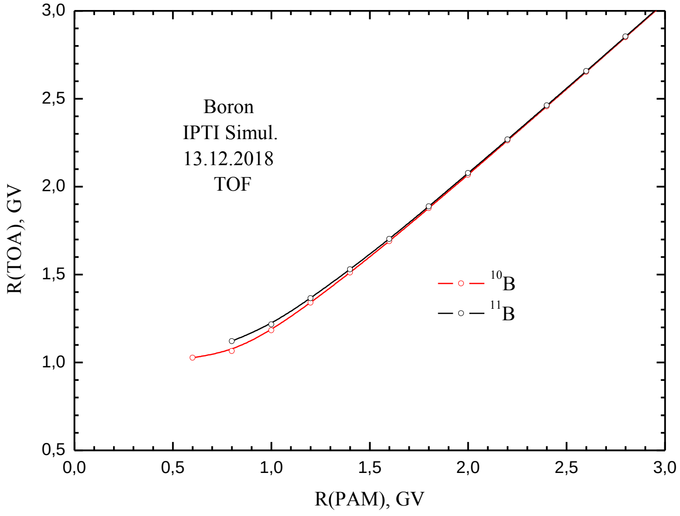


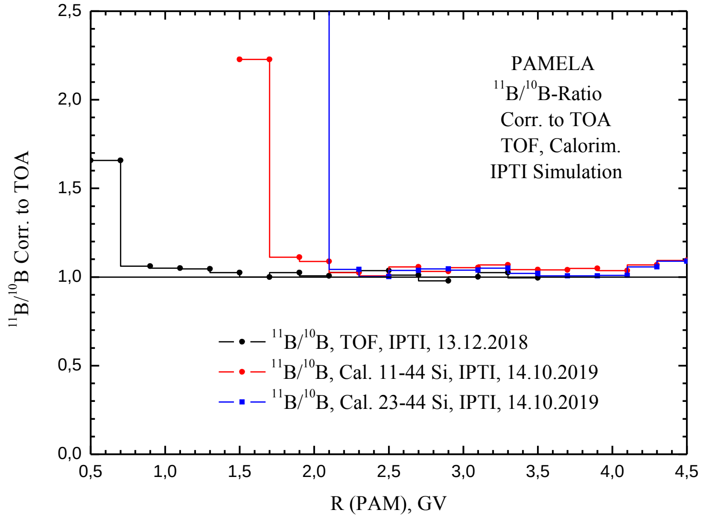


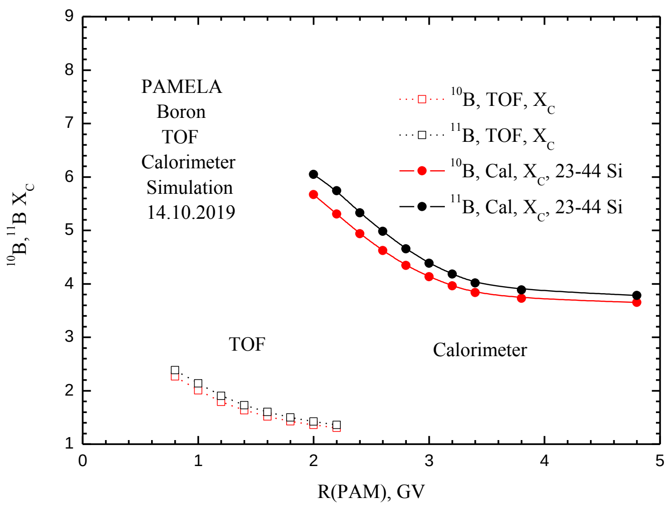


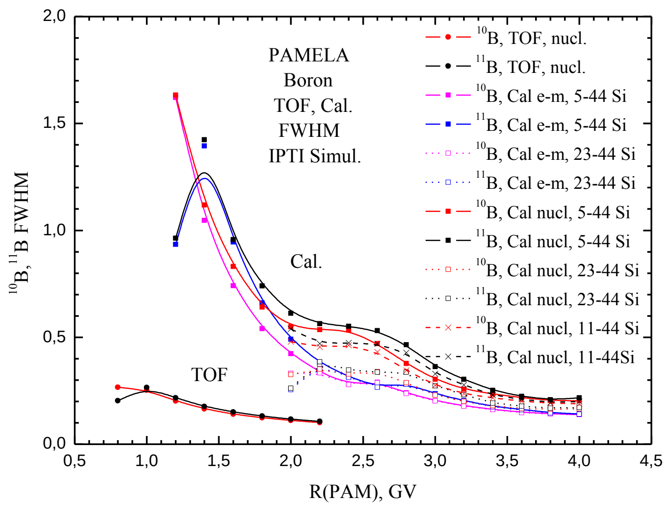


PAMELA. Correction of B data to TOA (Space), Xc, FWHM

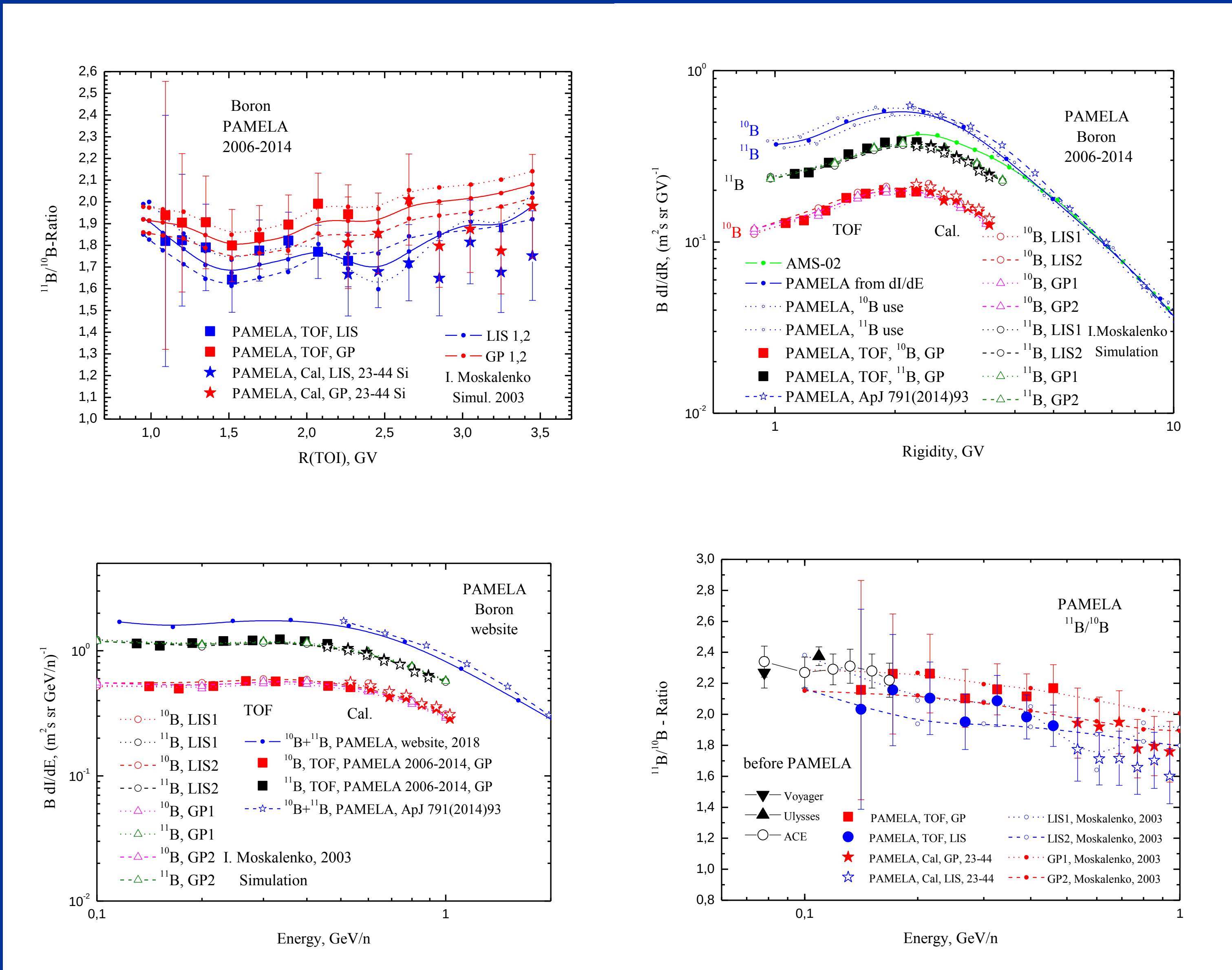








PAMELA, 11Be/10B-Ratio, R and E-Spectra, 2006-2014
GCR and Local Interstellar Sources (Preliminary data)

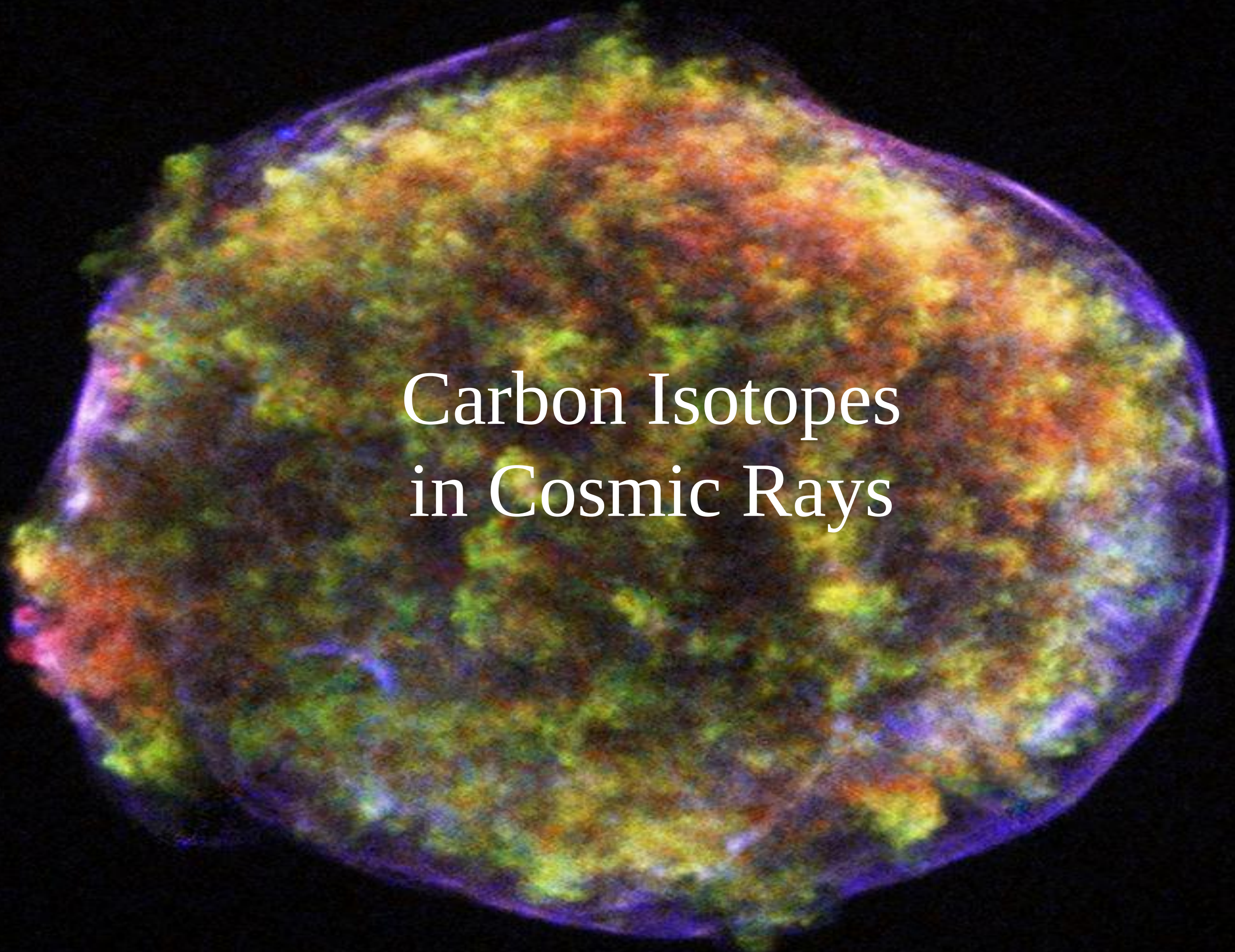


PAMELA a Payload for Antimatter Matter Exploration and Light–nuclei Astrophysics

Conclusion

Analysis of the isotopic composition of nuclei in galactic cosmic rays (GCR) in the PAMELA orbital international experiment allows to study the problems of cosmic ray origin and propagation in our Galaxy. PAMELA magnetic spectrometer data provided the significant progress in the study of the light nuclei isotopic composition of GCR from H to Be in the energy range ~ 0.1–1 GeV/nucl. This makes it possible to estimate the contribution of local (~ 100 pc) young (~ 10^6 years) local interstellar sources (LIS) from supernova explosions into GCR fluxes. The analysis of boron (B) isotope fluxes in the GCR has so far been carried out only in the energy range ~ 0.08–0.17 GeV/nucl. in the space experiments Voyager, Ulysses, ACE. In present contribution the attempt was done to determine the ^{11}B/^{10}B ratio in the energy range ~ 0.1–1.0 GeV/nucl. for the first time on the base of 2006-2014 PAMELA data using the measurements of the detected nuclei rigidities, velocities and ionization losses in a multilayer calorimeter. The new PAMELA results are consistent with existing as experimental data and those expected from simulations. However the statistical and systematic measurement accuracies do not allow us to separate the local boron source contributions into GCR fluxes. The results of the boron isotope flux analysis in GCR (^{10}B, ^{11}B spectra and ^{11}B/^{10}B ratio dependences on the rigidity and energy) are presented as well as the existing measurement data and simulation results. Boron distributions 0f TOF of Calorimeter PAMELA data were used for search of ^{14}C…

Carbon Isotopes in Cosmic Rays

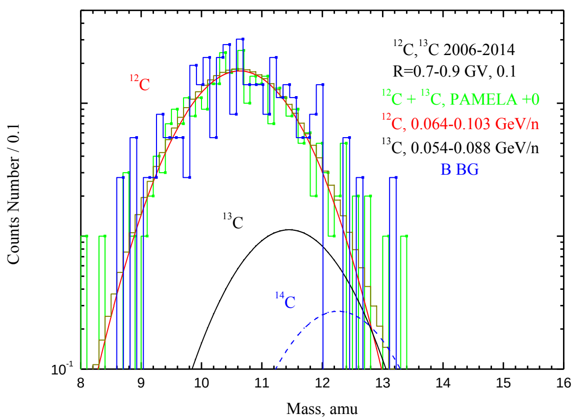


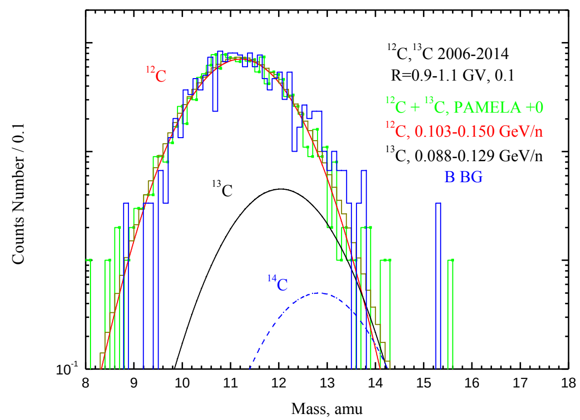
SN 1572 (Tycho Brahe)

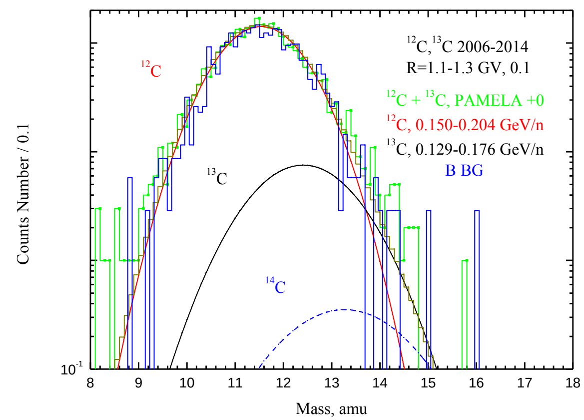
Carbon Isotopes

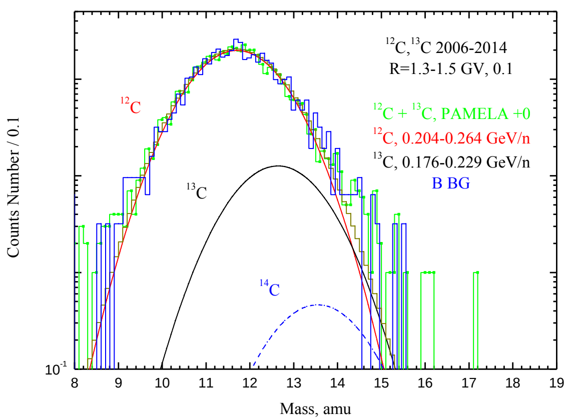
To date, the isotopic composition of carbon nuclei in the GCR has been measured only for the ^{13}C / ^{12}C ratio in the energy region ~ 0.05-0.13 GeV / nucleon in the VOYAGER 1.2 space experiment and the upper limit for the ^{14}C / ^{12}C ratio was estimated in the ACE / CRIS experiment for energies 0.12-0.43 MeV / nucleon. In this work, using PAMELA flight data 2006-2014, on the rigidity of the detected nuclei and their speed (time-of-flight analysis and ionization losses in the multilayer calorimeter of the device), an attempt was made to determine the isotopic composition of carbon nuclei in the energy region of ~ 0.1-1 GeV / nucleon. The half-life of ^{14}C nuclei is 5730 years and can be detected in the case of a supernova explosion in the last ~ $5\ 10^4$ years at a distance of ~ 100 200 pc. The results of isotope analysis of carbon nuclei in GCR (spectra ^{12}C, ^{13}C, ^{14}C and ^{14}C / ^{12}C - ratio depending on the rigidity and energy of the nuclei) in comparison with the existing measurement data will be presented.

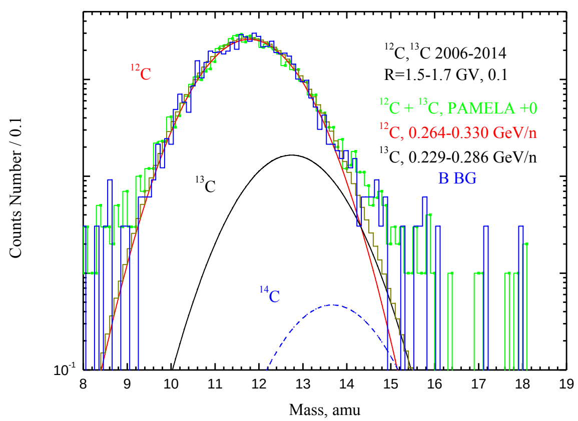
12C+13C. 14C(?) and 10B+11B, 0.7-1.9 GV, 2006-2014, TOF

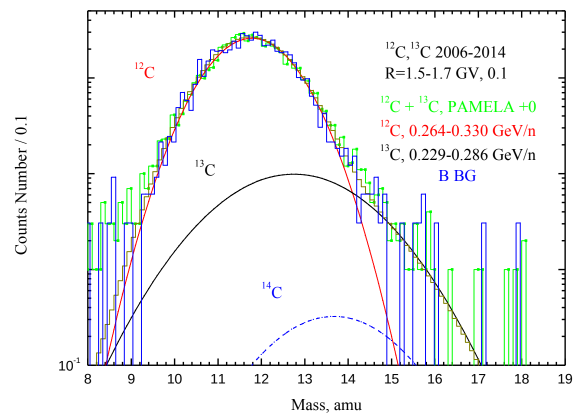




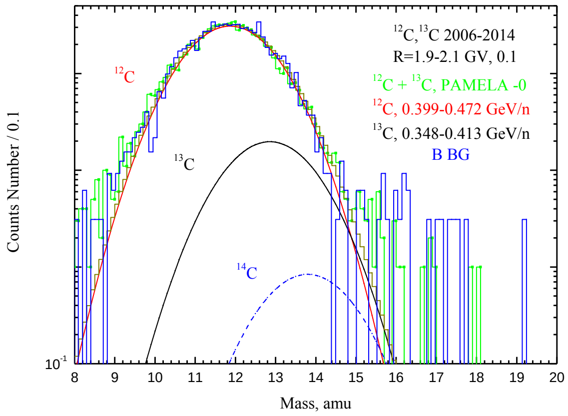


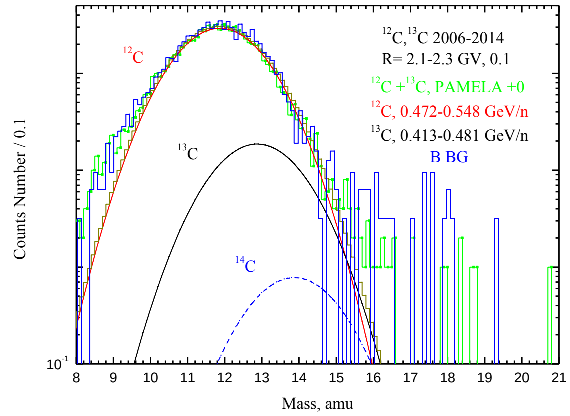


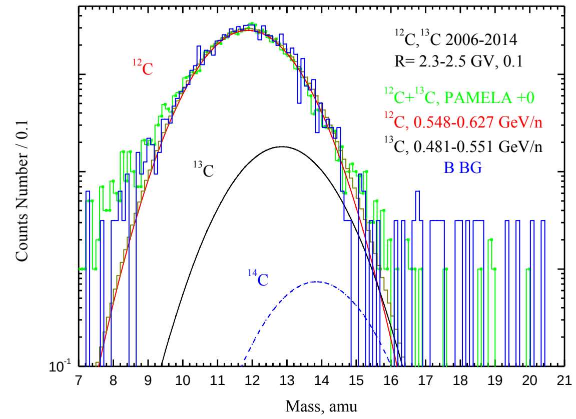


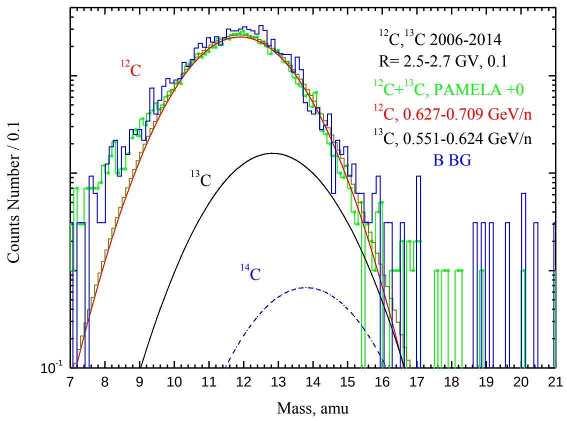


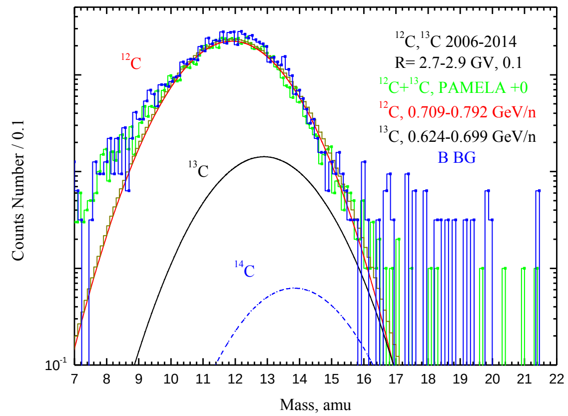
12C+13C. 14C(?) and 10B+11B, 1.9-3.1 GV, 2006-2014, TOF

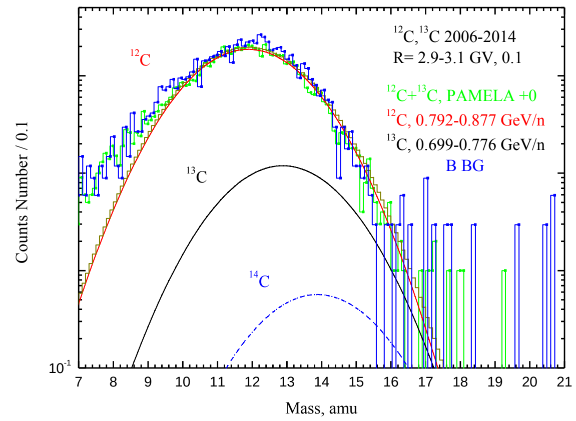




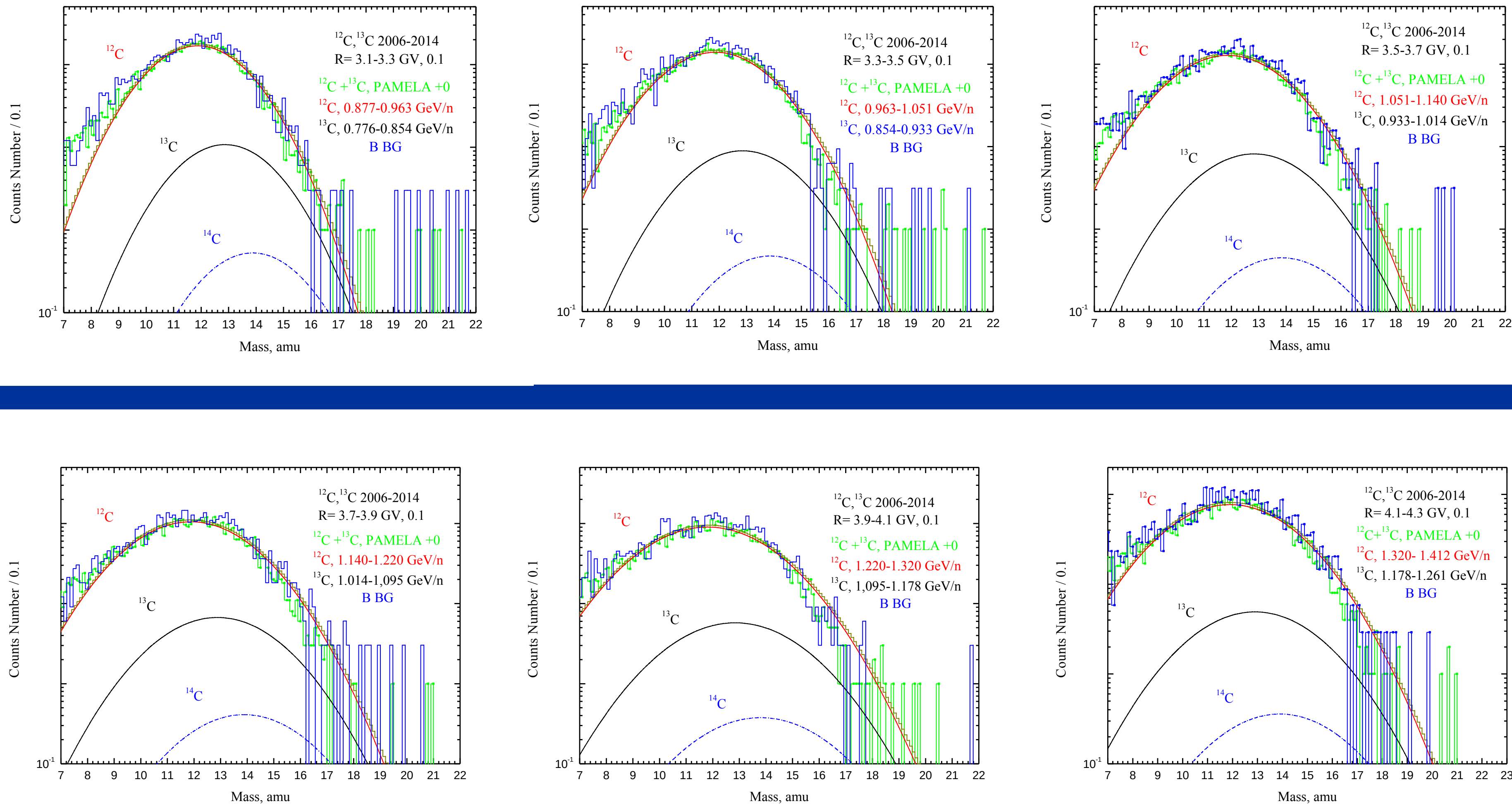




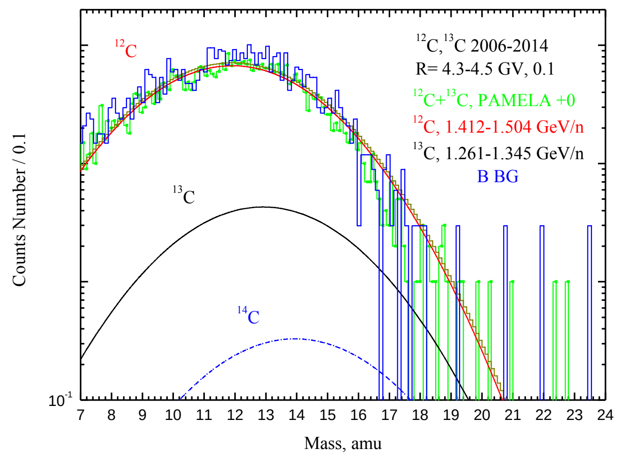


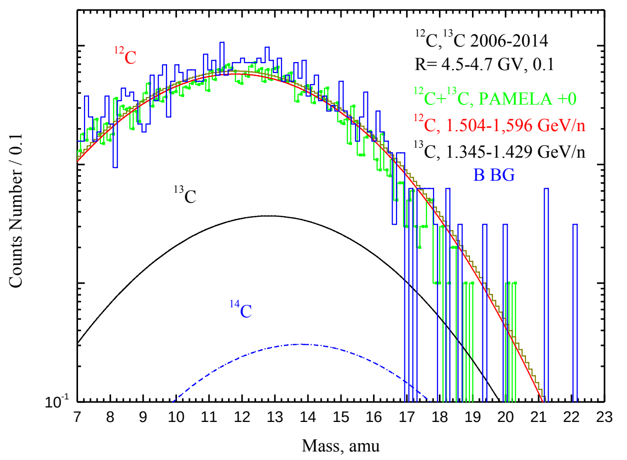


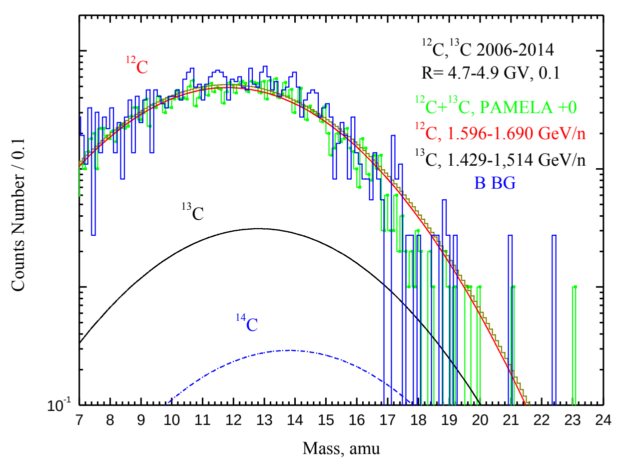
12C+13C. 14C(?) and 10B+11B, 3.1-4.3 GV, 2006-2014, TOF

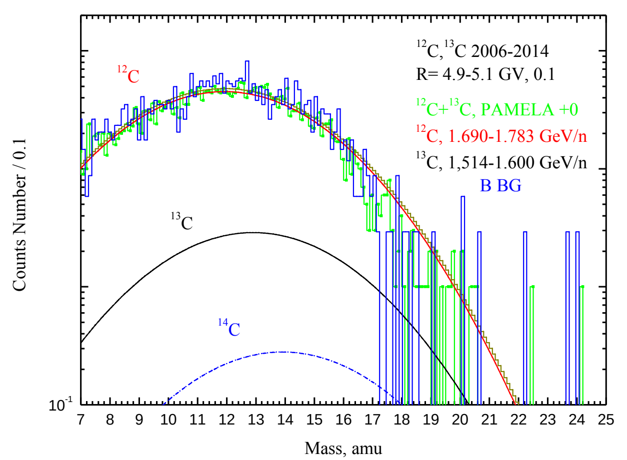


12C+13C. 14C(?) and 10B+11B, 4.3-5.1 GV, 2006-2014, TOF

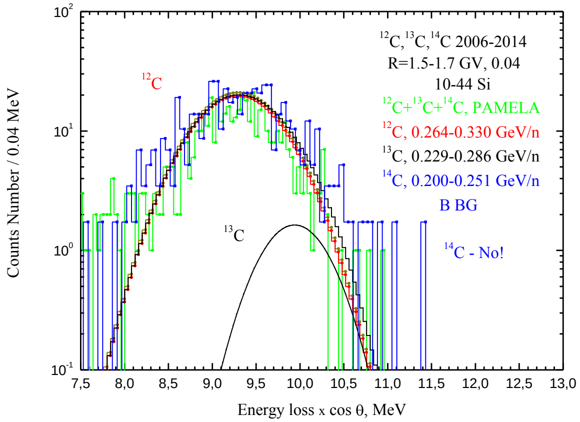


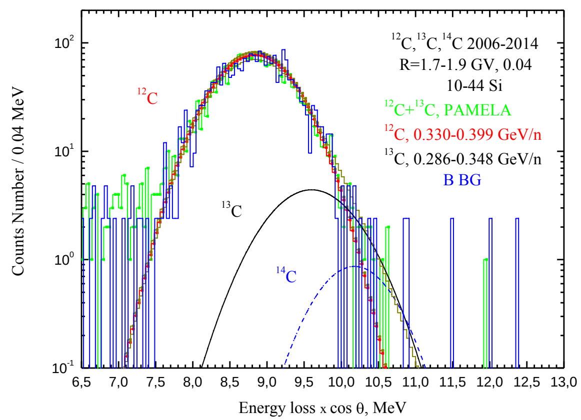


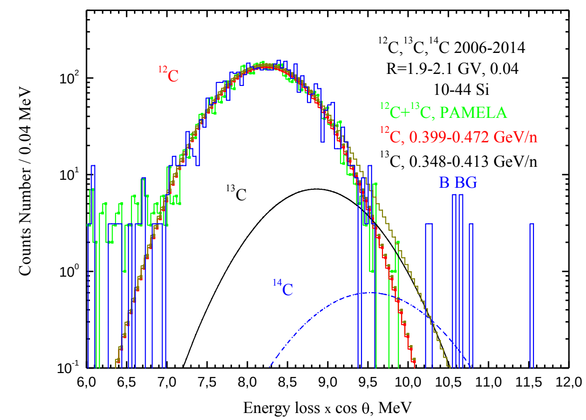


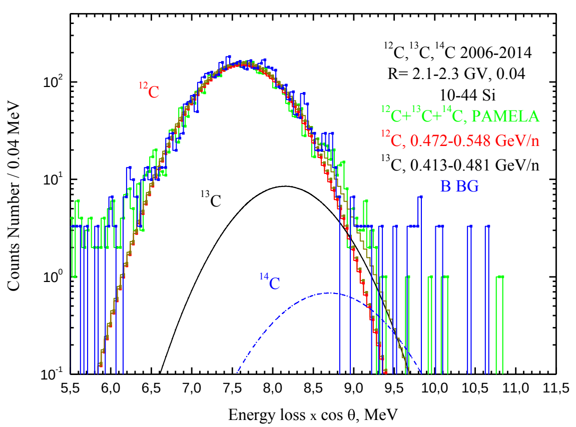


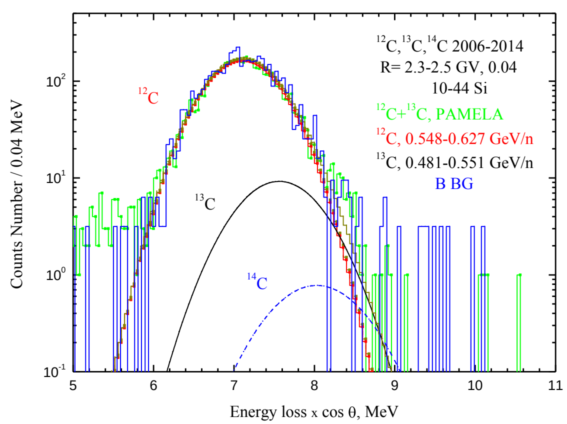
12C+13C. 14C(?) and 10B+11B, 1.5-2.7 GV, 2006-2014, Calorimeter

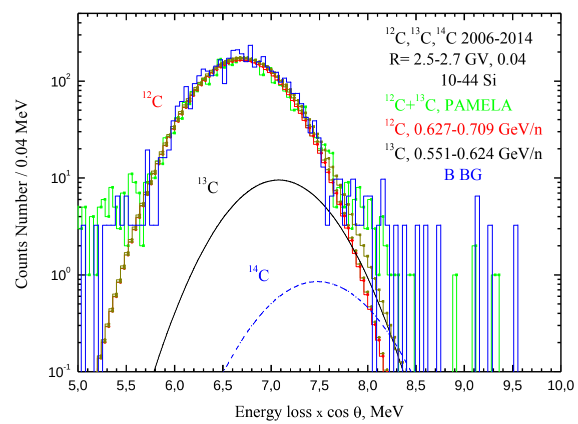




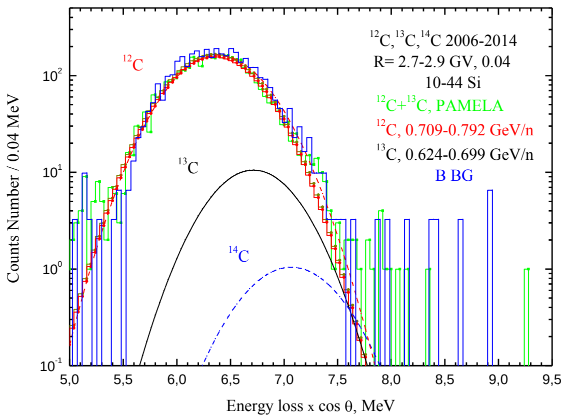


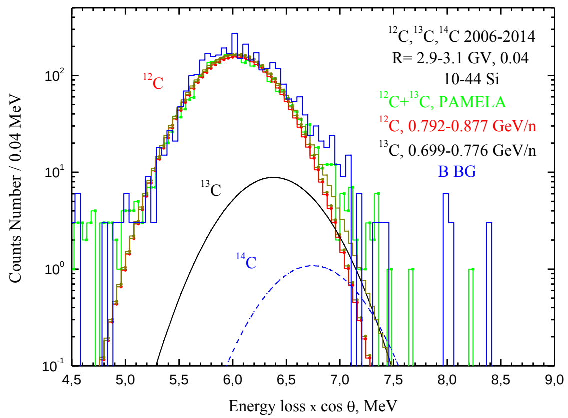


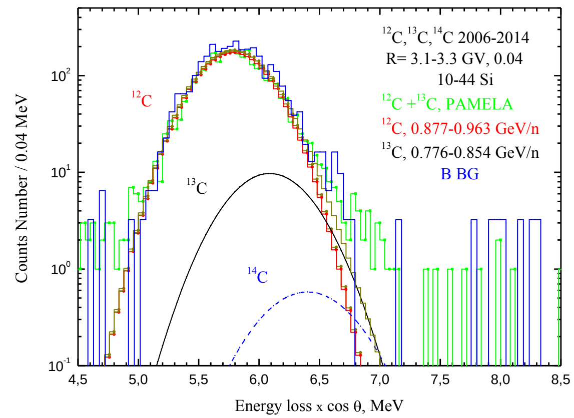


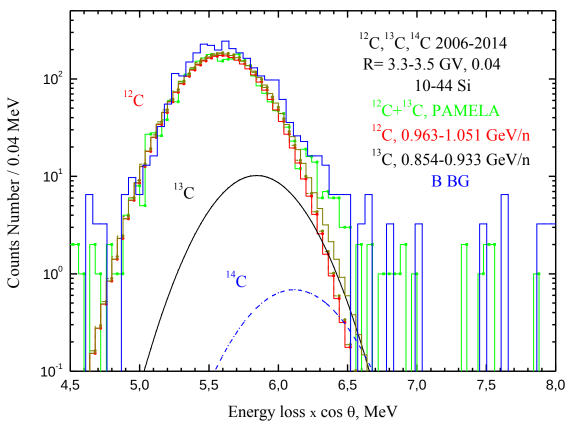


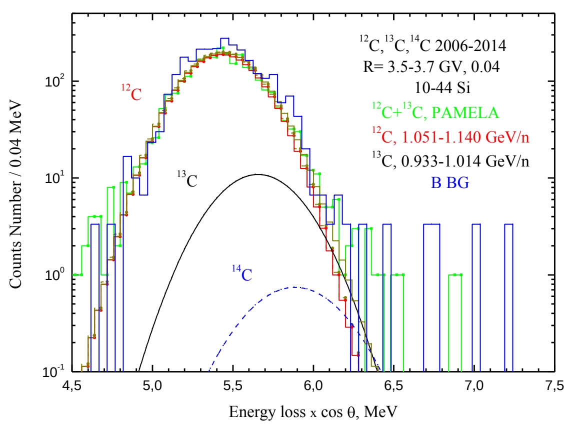
12C+13C. 14C(?) and 10B+11B, 2.7-3.9 GV, 2006-2014, Calorimeter

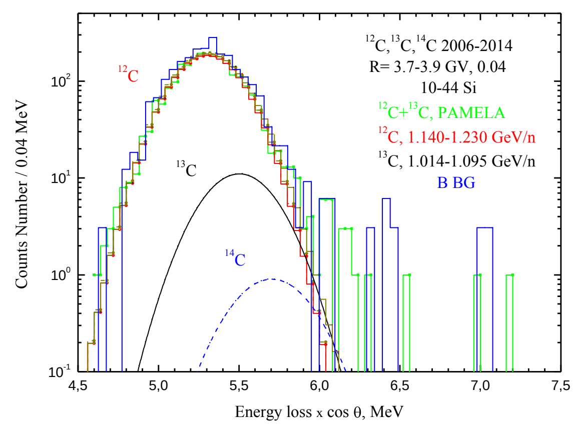




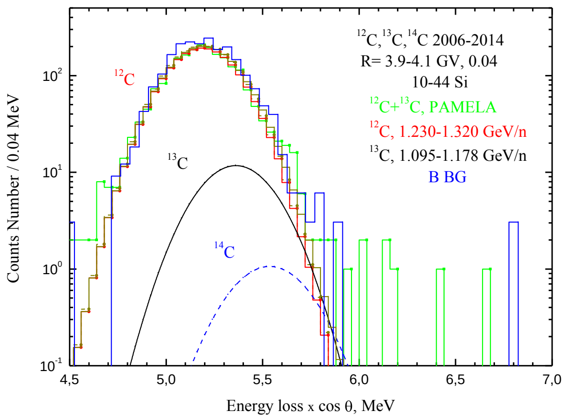


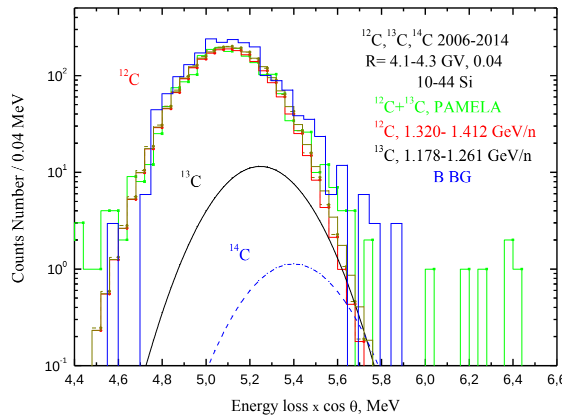


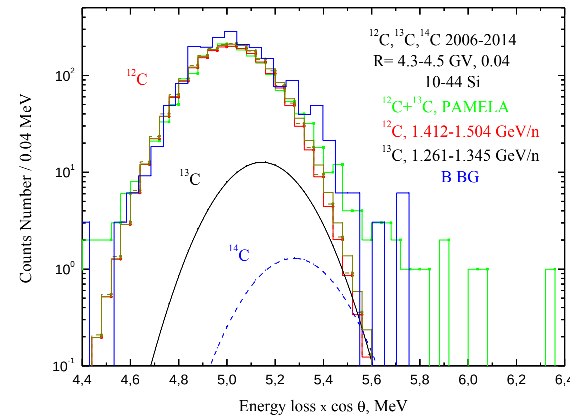


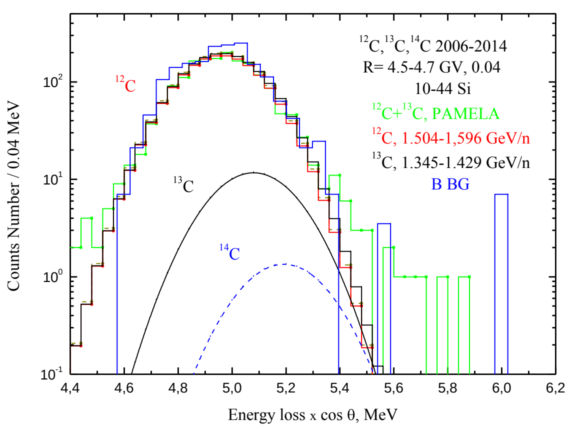


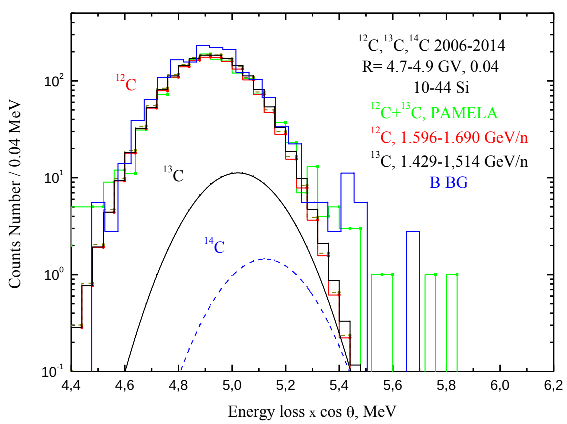
12C+13C. 14C(?) and 10B+11B, 3.9-5.1 GV, 2006-2014, Calorimeter

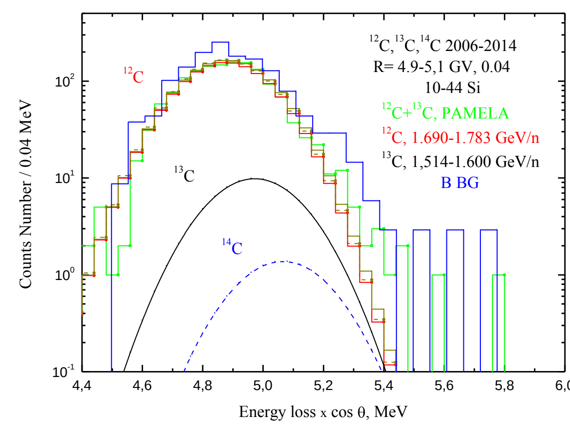




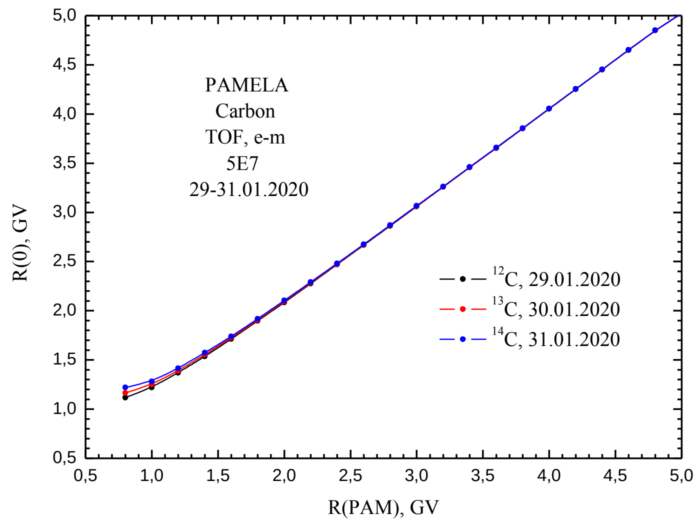


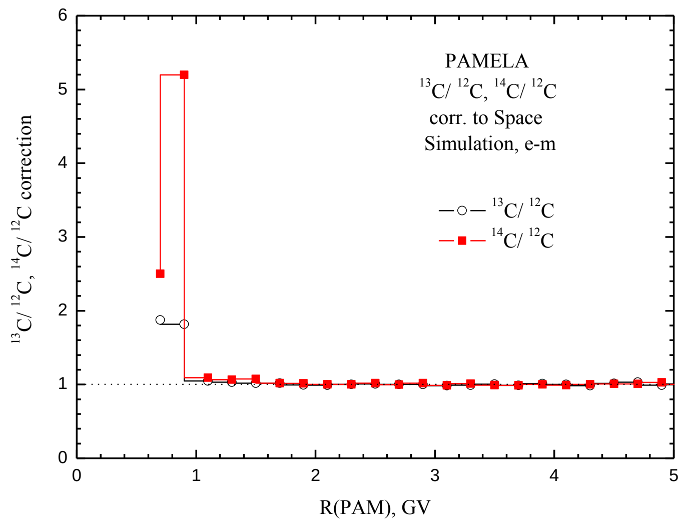


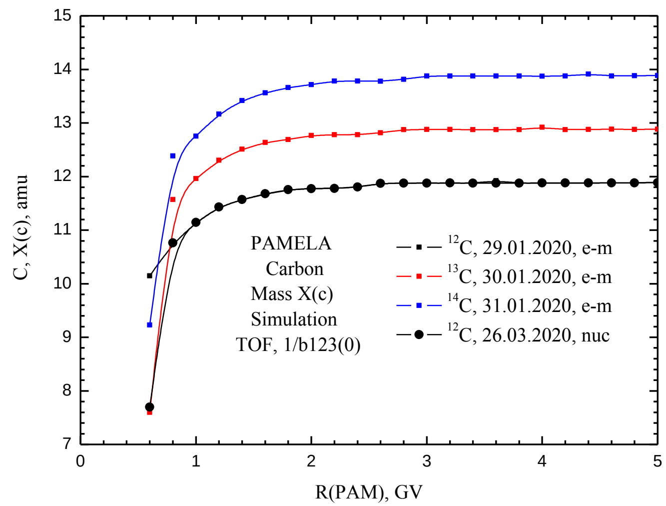


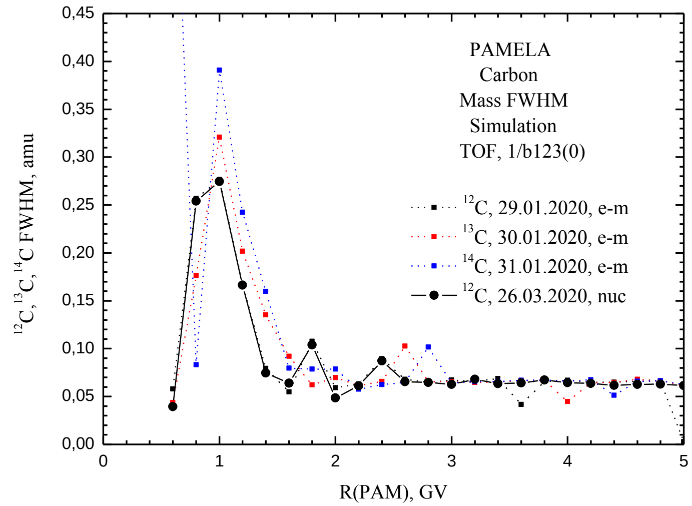


PAMELA. Correction of C isotopes data to TOA (Space), Xc, FWHM

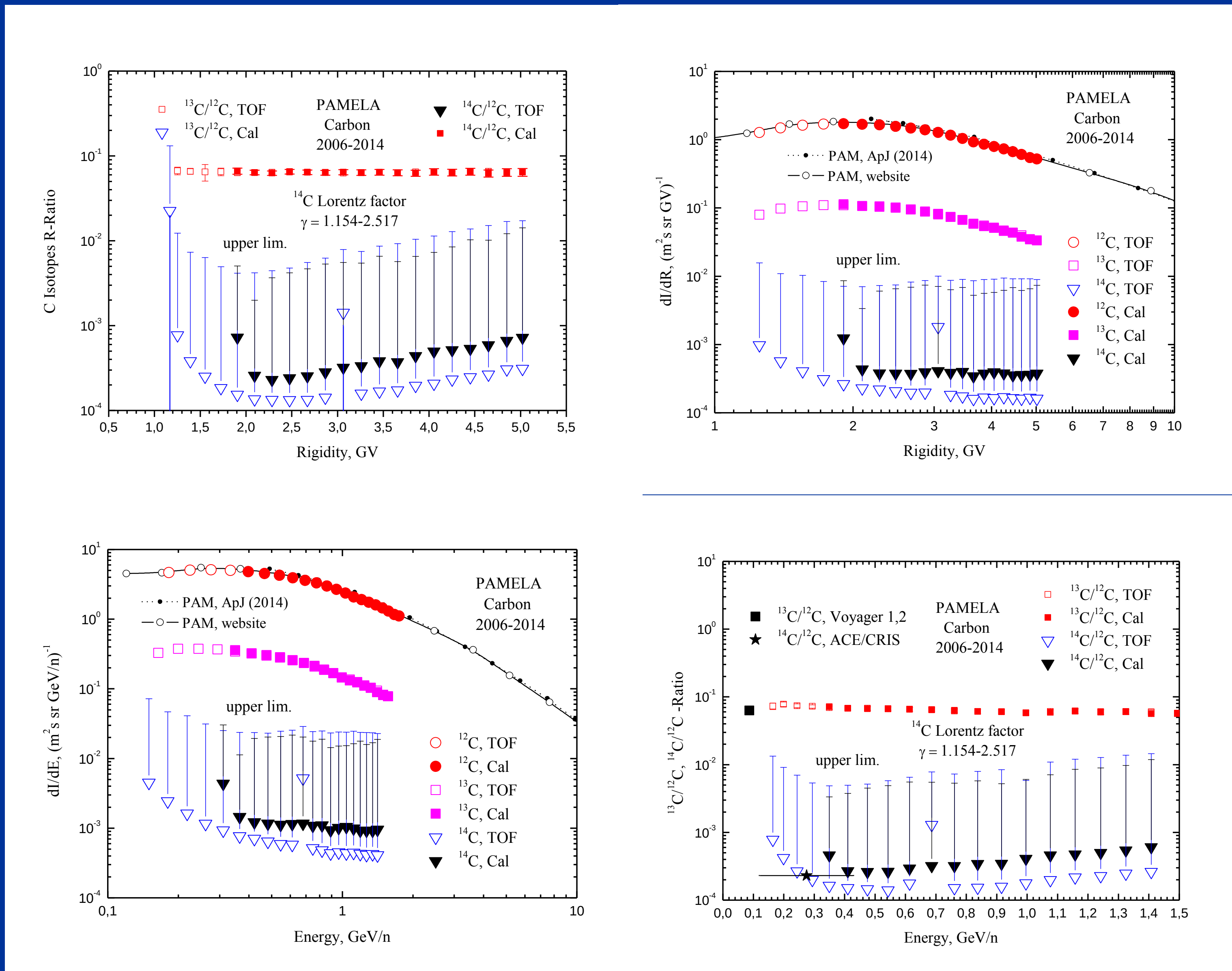




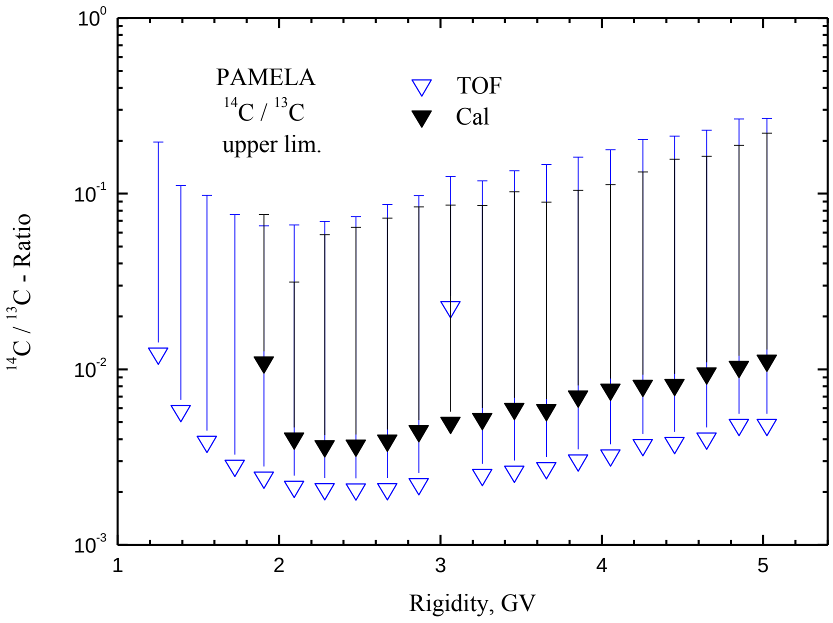


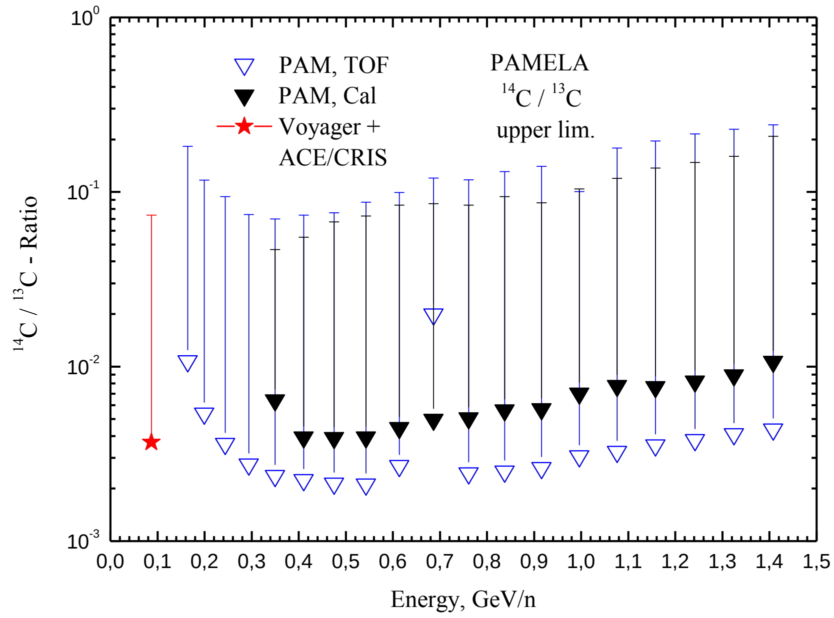


PAMELA, 14C/12C upper limits, 13C/12C-Ratio, C isotopes R and E-Spectra, 2006-2014



PAMELA 2006-2014, 14C/13C R-Ratio, 14C/13C E-Ratio, upper limits





Pulsars and Supernova Remnants

$L = (D\,\gamma\,\tau_{decay})^{1/2}$, $D = 3.3\ 10^{28}\ cm^2\ s^{-1}$, $\tau_{decay} = 5700$ yr or 1,798 10^{11} s, 1 pc = 3.2616 light yr

$L(\gamma=1) = 7.702\ 10^{17}$ m or 23.61 pc, $L(\gamma) = 23.61\ \gamma^{1/2}$ pc, $L(^{14}C$, 5 GV) = 37.39 pc τ_{decay} = 14295 yr

$L(^{14}C$, 3 GV) = 30.82 pc τ_{decay} = 9714 yr

$L(^{14}C$, 1 GV) = 24.66 pc τ_{decay} = 6274 yr

SN: if $^{13}C/^{12}C = 0.01$ and $^{14}C/^{13}C$ (5 GV) < 0.02898, L(total) > 191.0 pc, Age > 73.0 kyr

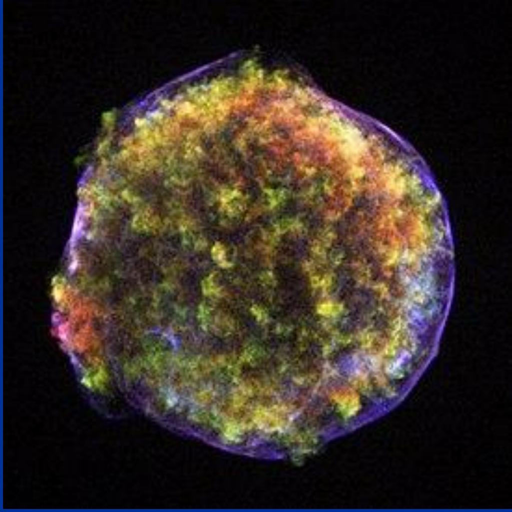
PAMELA $^{14}C/^{13}C$ (3 GV) < 0.01422, L(total) > 189.0 pc, Age > 59.6 kyr

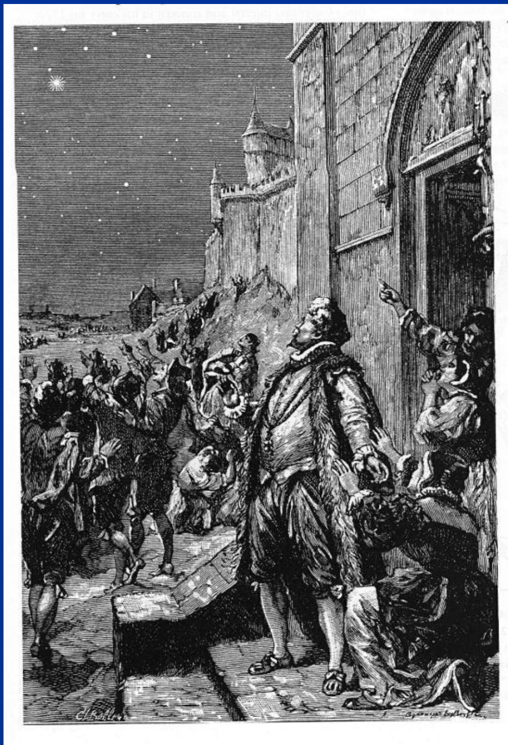
Pulsars			$^{14}C/^{13}C$ (1-3-5 GV)
Geminga Pulsar J 0633+1746	Distance – 190 pc, Age – 342 kyr	3.25 10^{34} erg/s	< (0.8-2.3~4.9) 10^{-3}
Monogem Pulsar B 0656+14	Distance – 290 pc, Age – 111 kyr	3.81 10^{34} erg/s	(0.5-2.5-7.7) 10^{-4}
Vela Pulsar J 0835+4510	Distance – 294 pc, Age – 11.0-12.3 kyr	7 10^{33} erg/s	(3.3-4.2-5.1) 10^{-4}
Crab Pulsar J 0534-5+2201(SN1054)	Distance - ~ 2 kpc, Age - 6.5 kyr	4.6 10^{38} erg/s	(5.5-6.9-8.3) 10^{-4}

SN Remnants

SN 185 (Ia ?) RCW 86 ?	Distance – 919.8 pc, Age – 3.0+1.82 kyr	(8.5-10.7-12.9) 10^{-4}
SN 1006 (Ia) SNR1006	Distance – 2.2 kpc, Age – 7.2+1.00 kyr	(5.0-6.3-7.6) 10^{-4}
SN 1572 (Ia) (Tycho Brahe)	Distance - 2.3 kpc, Age – 7.5 +0.44kyr	(5.2-6.5-7.8) 10^{-4}
SN 1604 (Ia) (Kepler SNR)	Distance – 6.13 kpc, Age – 20+0.40 kyr	(2.0-2.5-3.1) 10^{-4}
Cas A 1630-1680 (IIb), 3C461	Distance – 3.37 kpc, Age – 11+0.33 kyr	(3.6-4.5-5.5) 10^{-4}

AMS-02 carbon nuclei statistics probably allow to detect 14C…
The number of possible CR Local Sources can be about 10.





SN 1572 Tycho Brahe

Conclusion

Presented in this report preliminary data of the analysis of the isotopic composition of carbon nuclei in cosmic rays in the energy range of ~ 0.1-1.0 GeV / nucleus, obtained in the PAMELA experiment during measurements in 2006-2014, agree with the data of measurements on the Voyager 1, 2 spacecraft. and ACE / CRIS, extend the measurement range and PAMELA methodical errors by ~ 3 times less. Estimation of the ratios of ^{14}C isotopes with a half-life of 5700 years (taking into account the Lorentz factor 1.154-2.517 in the PAMELA measurement range of ~ 6600-14300 years) and stable ^{13}C isotopes at a level less than ~ 0.01, taking into account the process of diffusion of nuclei from a possible source at a diffusion coefficient of ~ 3.3 10^{28} cm^2 s^{-1} allow us to conclude that a possible source of ^{14}C nuclei cannot be closer than ~ 190 pc and the birth of a supernova could not have occurred earlier than ~ 73 thousand years ago. Among the known SNs, the closest is Geminga at a distance of ~ 190 pc, but with an age of ~ 342 thousand years ... An analysis of the possible observation of the ^{14}C / ^{13}C ratio from local SN explosions observed on Earth in the last 2 thousand years shows that an increase in the statistics of registering carbon isotopes by about 1-2 orders of magnitude compared to the PAMELA capabilities can lead to the registration of ^{14}C nuclei from local sources ... This problem can be solved by the AMS-02 collaboration due to the huge aperture of the device. The co-authors of the work are naturally the members of the PAMELA collaboration, who provided the initial flight information.

Best wishes in the process of Cognition :~)

Thanks