A Model for Propagation of Cosmic Rays from Nuclei Spectra Measurements

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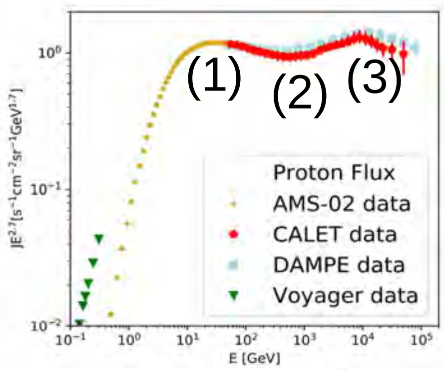
Introduction

- Motivation: Suitable propagation conditions needed to use electron/positron cosmic rays for studying individual astrophysical sources (nearby SNR) and indirect search for dark matter signatures.
- Nuclei cosmic rays experience much less energy loss than electrons
  - → Longer propagation distances and times
  - → Sources distributed throughout the galaxy and over millions of years
  - → O 3 SN/100 yr: individual source positions and ages less important for observed nuclei spectra at Earth
- Relations between nuclei spectra can reveal propagation conditions:
  - → Production of secondary cosmic rays depends on amount of ISM encountered
  - → Unstable nuclei and their decay products depend on the residence time

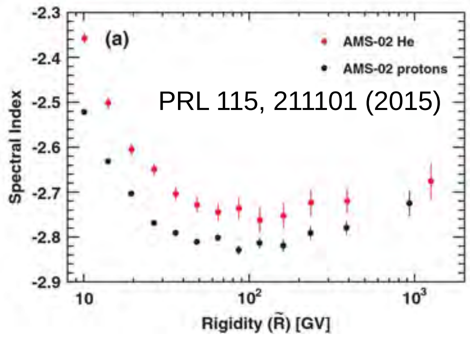
Goal: Find propagation conditions explaining the current nuclei spectra measurements assuming a common source spectrum for all primary nuclei

Hypothesis: Differences in Nuclei Spectra Caused by Propagation



- Observed spectra are power laws but the index changes with rigidity at several points: (1) Softening @ O 10 GV, (2) Hardening @ O 100 GV – 1 TV, (3) Softening @ O 10 TV

- Indices and break positions different between proton and He (and other nuclei, but less significant)



- Possible Explanations:
  - Source spectrum different for each nuclei species
  - **Propagation causes differences in spectal shape**

→ Assumed common source spectrum: power law with index γ_l below, and γ_h above the break at R_{bi} with softness s_{bi} , and with an exponential cut-off at R_{cut}

Diffusion Coefficient Structure

- Further spectral changes of the nuclei spectra are modeled by two breaks in the rigidity dependence of the diffusion coefficient, softening from δ_l to δ at R_{bl} with softness s_l , then hardening again to δ_h at R_{bh} with softness s_h
- Diffusion coefficient depends on position – exponential increase with galactic radius r, distance from galactic plane z – constant central zones: galactic center $r_n = 2$ kpc, galactic disc $z_n = 0.15$ kpc

$$D(r,z,D) = D_0 max\left(e^{(r-r_n)/r_s}, 1\right) max\left(e^{(z-z_n)/z_s}, 1\right) \left(\frac{R}{4\,GV}\right)^{\delta_l} \left(1+\left(\frac{R}{R_{bl}}\right)^{\frac{\delta_l-\delta}{s_l}}\right)^{-s_l} \left(1+\left(\frac{R}{R_{bh}}\right)^{\frac{\delta-\delta_h}{s_h}}\right)^{-s_h}$$

- Motivation: Sources concentrated in galactic center and disk cause magnetic field turbulence, influence decreasing with distance – different propagation conditions for nuclei species depending on how far they propagate out into the halo and back based on nuclei mass and A/Z

Used Tool: DRAGON

- Publicly available program for numercial calculation of CR propagation on grid in space and momentum D. Gaggero et al., Phys.Rev.Lett. 111(2), 021102 (2013)
- Important features:
  - Spiral arm structure of source distribution & gas
  - Non-equidistant grid in space – 0.5 kpc in halo reduced to 0.05 kpc near galactic plane to allow for gradual diffusion coefficient change
- Own modifications:
  - Soft breaks in source spectrum and diffusion coefficient function
  - Double exponential spatial dependence of the diffusion coeffient

The Parameter Space

Sources	Low rigidity index	Break rigidity	Break softness	High rigididty index	Cut-off rigidity	Spiral arm width
	γ_l	R_{bi}	s_{bi}	γ_h	R_{cut}	w_{sa}
Diffusion	Diffusion coefficient normalization	Radial scale distance	Exponential scale height	Low rigidity index	Low break rigidity	Low break softness
	D_0	r_s	z_s	δ_l	R_{bl}	s_l
	Mid rigidity index	High break rigidity	High break softness	High rigidity index	Alven velocity	**17 free parameters in total**
	δ	R_{bh}	s_h	δ_h	v_a	

Experimental Data Used (Spectra)

- **Proton Flux**

  0.13 – 0.35 GeV: Voyager APJ 831(1), 18 (2016)

  5 GeV – 1 TeV: AMS-02 PRL 114, 171103 (2015)

  1 – 60 TeV : CALET PRL 129, 101102 (2022)

- **Helium Flux**

  0.11 – 0.66 GeV: Voyager APJ 831(1), 18 (2016)

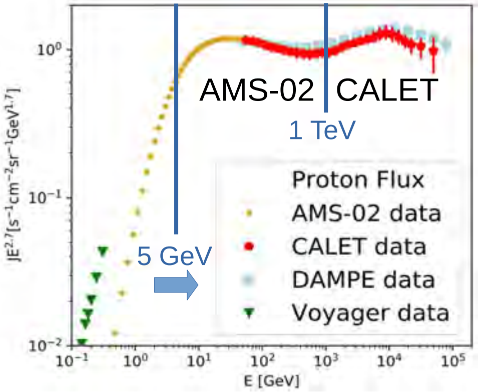
  11 GV – 3 TV: AMS-02 PRL 115, 211101 (2015)

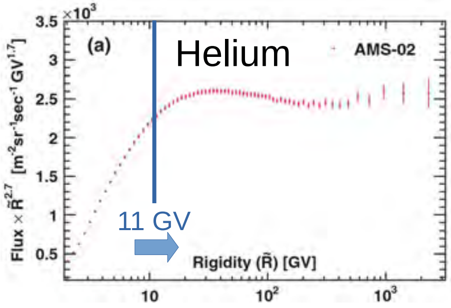
- **Carbon Flux**

  10 GeV – 2.2 TeV: CALET PRL 125, 251102 (2020)

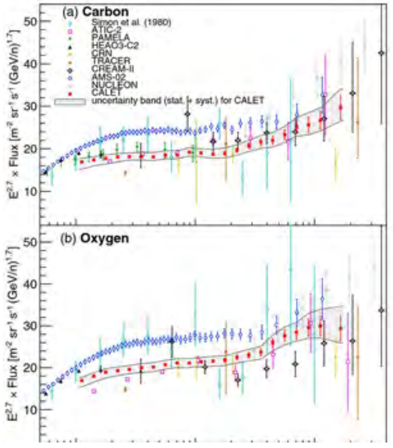
- **Oxygen Flux**

  10 GeV – 2.2 TeV: CALET PRL 125, 251102 (2020)





Using data above 5 GeV/nucleon or equivalent rigidity – solar modulation difficult to model below this energy → Voyager data for lower energy range



Experimental Data Used (Ratios)

- **Antiproton fraction**

  5 – 450 GV: AMS-02 PRL 117, 091103 (2016)

- **$^{3}He/^{4}He$ ratio**

  5 – 10 GeV: AMS-02 PRL 123, 181102 (2019)

- **B/C ratio**

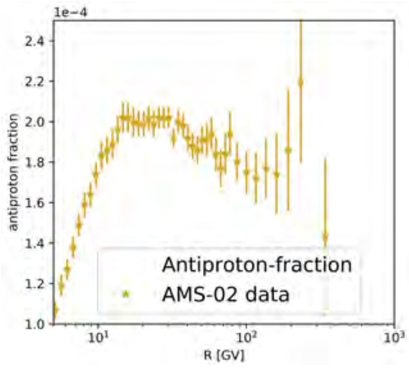
  5 GeV – 1.3 TeV: AMS-02 PRL 117, 231102 (2016)

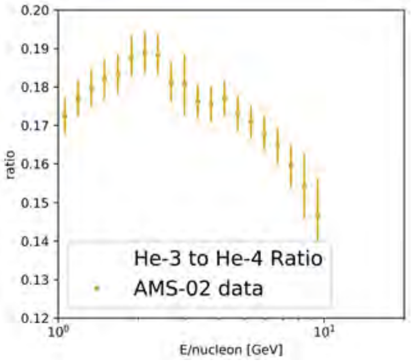
- **$^{7}Be/Be$ ratio**

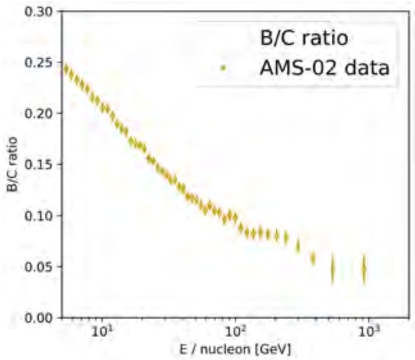
  0.25 – 0.85 GeV: PAMELA Universe 7 (2021) 6, 183

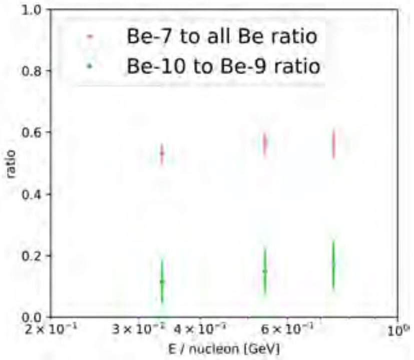
- **$^{10}Be/^{9}Be$ ratio**

  0.25 – 0.85 GeV: PAMELA Universe 7 (2021) 6, 183





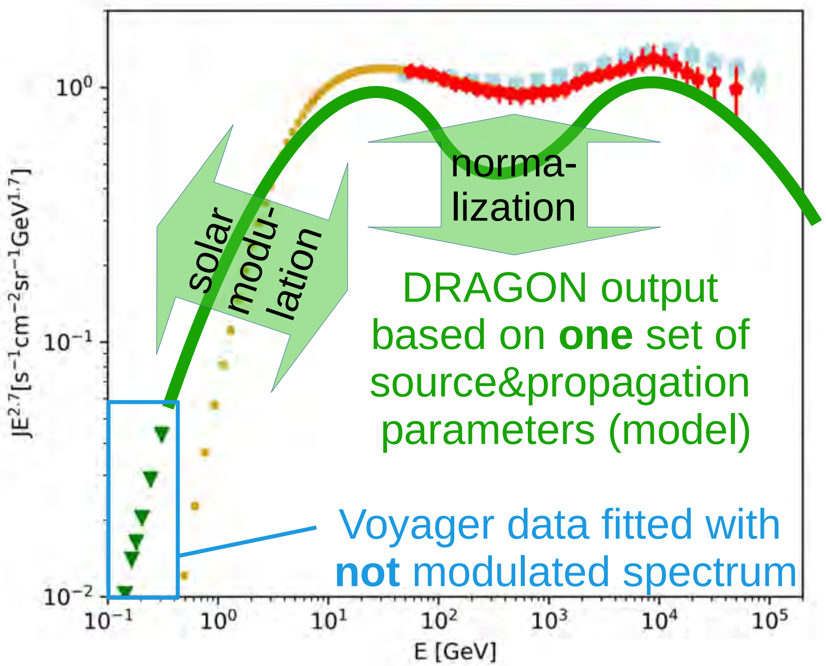




Universe 7 (2021) 6, 183
Beryllium Radioactive Isotopes as a Probe to Measure the Residence Time of Cosmic Rays in the Galaxy and Halo Thickness: A "Data-Driven" Approach, Francesco Nozzoli, Cinzia Cernetti

Fitting the Spectra to the Data

- Parameters fitted by minimizing total χ^2 of all experimental data
  - Normalization correction factors
    - Proton
    - Helium
    - Carbon
    - Oxygen
  - Solar modulation potential parameters
    - Φ_0
    - Φ_{1+} (positive charge)
    - Φ_{1-} (negative charge)
    - R_0



Charge sign and rigidity dependent solar modulation potential:

$$\Phi = \Phi_0 + \Phi_{1\pm} \left(\frac{1 + (R/R_0)^2}{((R/R_0)^3)} \right)$$

based on
Ilias Cholis, Dan Hooper, Tim Linden
Phys. Rev. D 93, 043016 (2016)
"A Predictive Analytic Model for the Solar Modulation of Cosmic Rays"

Optimizing DRAGON Parameters

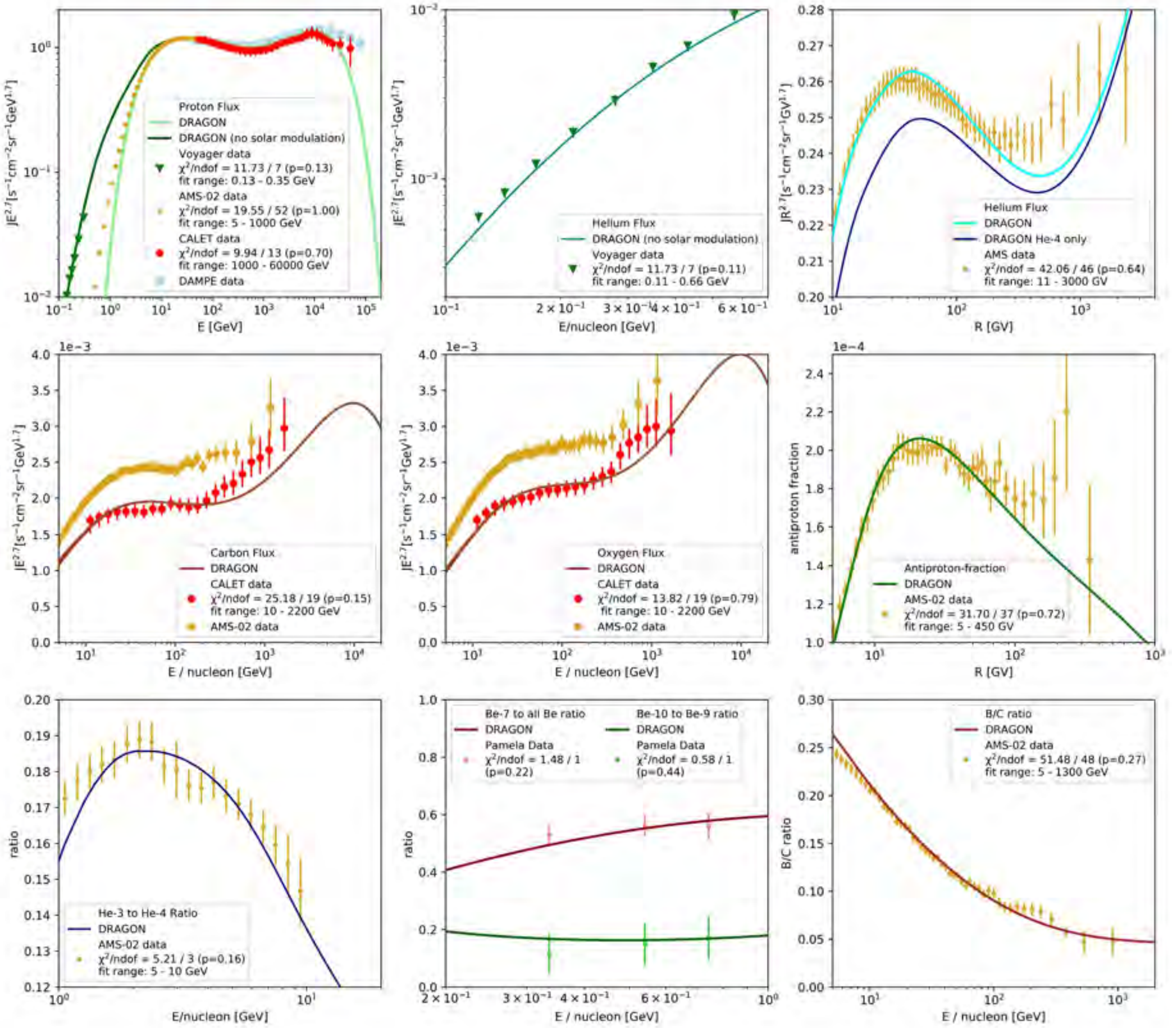
- Model quality parameters extracted from fit to data
  - Total χ^2 of all experimental data
  - Reduced χ^2 (single experiment), summed over experiments
  - Likelihood (p-value, single experiment), log-summed over experiments
  - Combinations of the above quality parameters
    (used in final step: log-sum of p-values, worst experiment doubled)

- Parameter space probed by “random” walk, combination of different methods used to select next model to calculate:
  - randomly within a given step size
  - following the negative gradient calculated from neigboring models
  - by interpolating/extrapolating parameters of already calculated models

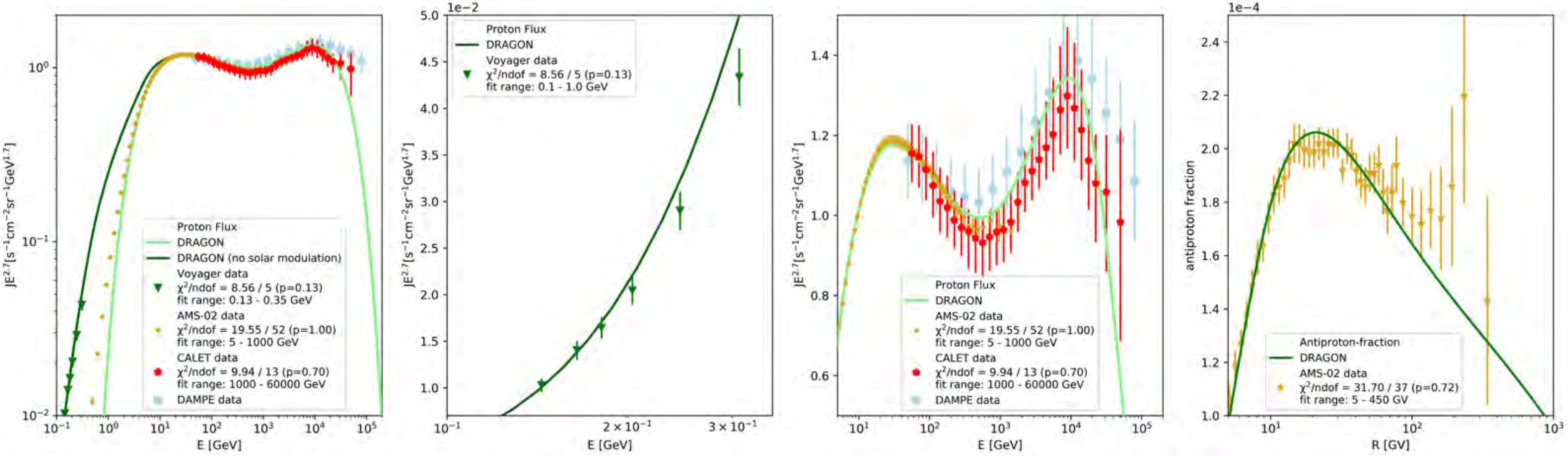
- Initially optimization of helium-proton (with antiproton), and oxygen-beryllium separately, then combined by calculating silicon-proton and finally iron-proton (correction factor for influence of heavier nuclei used in partial calculations)

Current Best-fit Model

γ_l	R_{bi}	s_{bi}	γ_h	R_{cut}	w_{sa}
2.001	11.92 GV	0.213	2.345	27.91 TV	0.401 kpc
D_0	r_s	z_s	δ_l	R_{bl}	s_l
2.809×10^{28} cm^2/s	9.84 kpc	4.20 kpc	0.246	7.732 GV	0.050
δ	R_{bh}	s_h	δ_h	v_a	total χ^2/ndof: 221/274
0.504	911.8 GV	0.369	0.003	15.93 m/s	



Proton & Antiproton

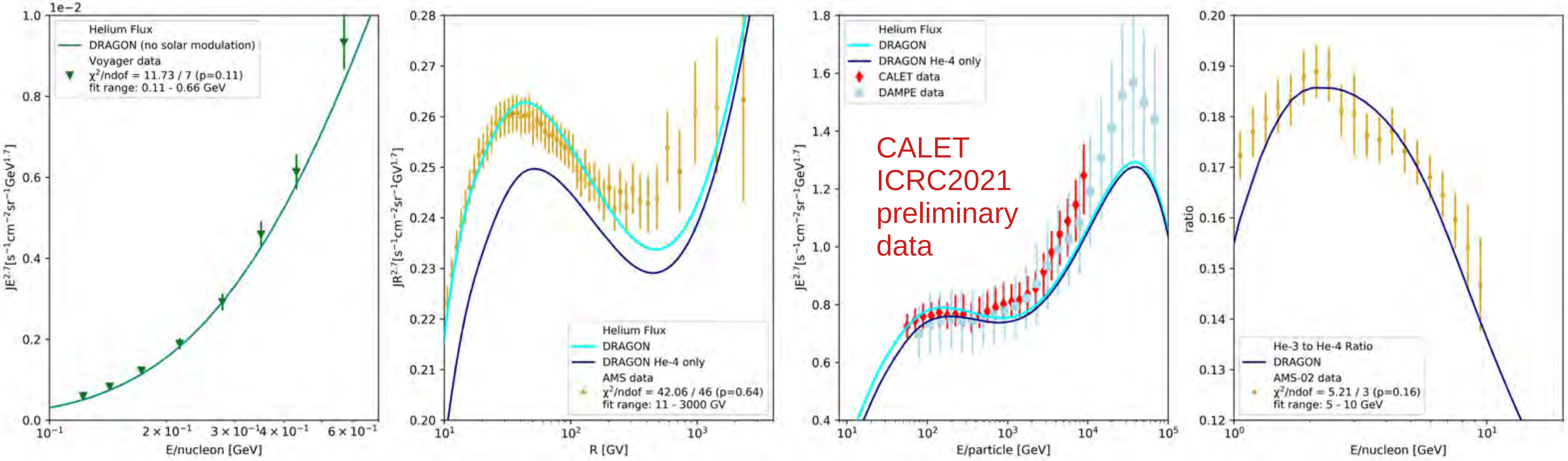


DAMPE proton:
Sci.Adv. 5 (2019) 9

The exponential cut-off of the source spectrum at ~28 TV well reproduces the sudden softening of the CALET proton data

AP “excess” above 100 GV visible by eye but not significant (χ^2 /ndof < 1)

Helium

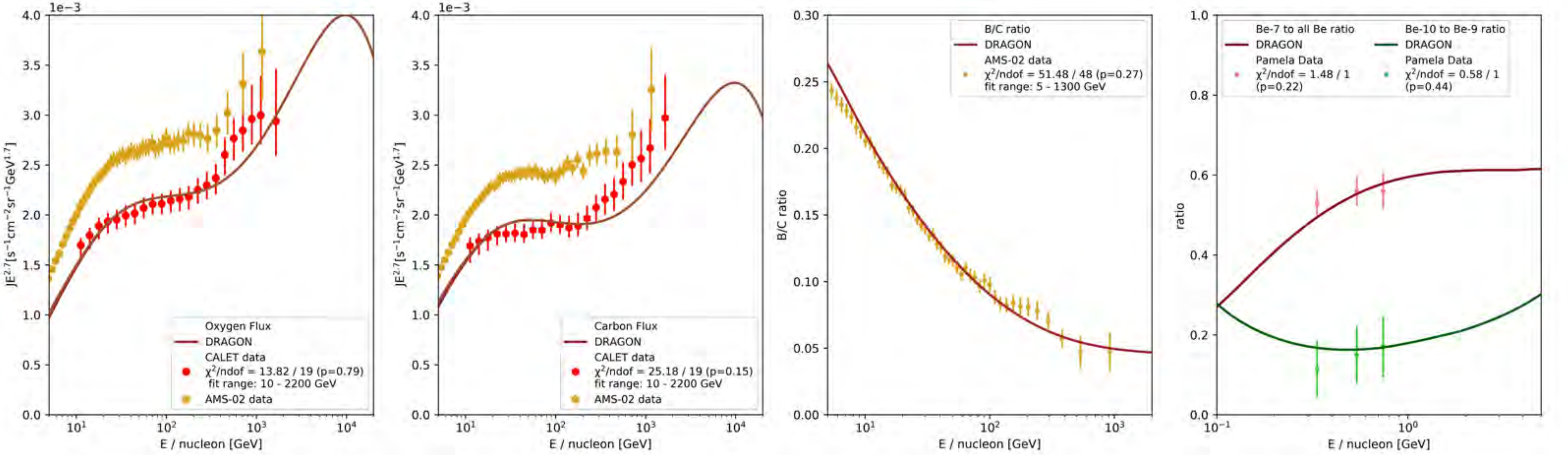


Secondary He-3 contributes significantly to the He spectrum → influence of propagation conditions on spectral shape

CALET/DAMPE helium data not used in fitting, but in general agreement

DAMPE helium:
PRL 126, 201102 (2021)
CALET helium:
PoS ICRC2021 (2021) 101

Oxygen,Carbon,Boron,Beryllium



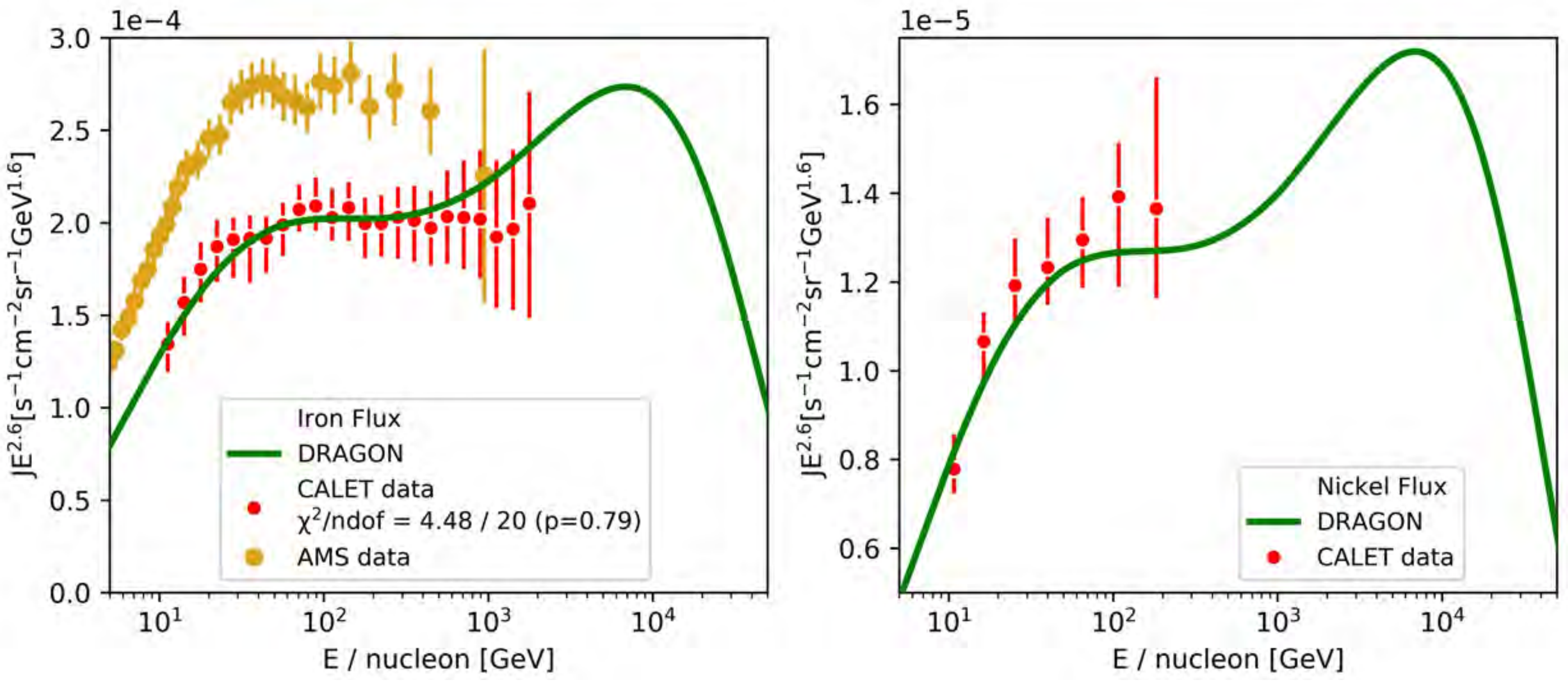
Normalization difference for C and O spectra between AMS-02 and CALET but general shape matches both datasets in general

AMS-02 C and O:
PRL 119, 251101 (2017)

Model predicts B/C ratio to become flat in the TeV region

Expoential increase of the diffusion coefficient with z reproduces ratios of instable beryllium isotopes – correct effective diffusion zone height

Iron,Nickel



Iron & nickel not used to optimize DRAGON parameters, separate normalization factor for iron fitted afterwards.
Very good agreement with CALET data.

CALET iron:
PRL 126, 241101 (2021)
CALET nickel:
PRL 128, 131103 (2022)
AMS-02 iron:
PRL 126, 041104 (2021)

Conclusions / Outlook

- The presented model with a common source spectrum for all primary nuclei shows that explaining the current nuclei measurement data within experimental uncertainty based on propagation effects is possible.
- Differences in the spectral structures depending on the nuclei species could be caused by the propagation throughout the galactic halo with a diffusion coefficient which depends on both position and momentum.
- The presented model is the current best fit from the parameter space scan – further optimization is ongoing and new experimental data will be added.
- These detailed propagation conditions represent a huge parameter space which cannot easily be scanned to find allowed regions due to the time/resource requirements of the numerical calculation – preselection of models by machine learning algorithms might improve efficiency – future work.

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