Explaining the Measured Cosmic-Ray Nuclei Spectra with a Dual Source-category Model

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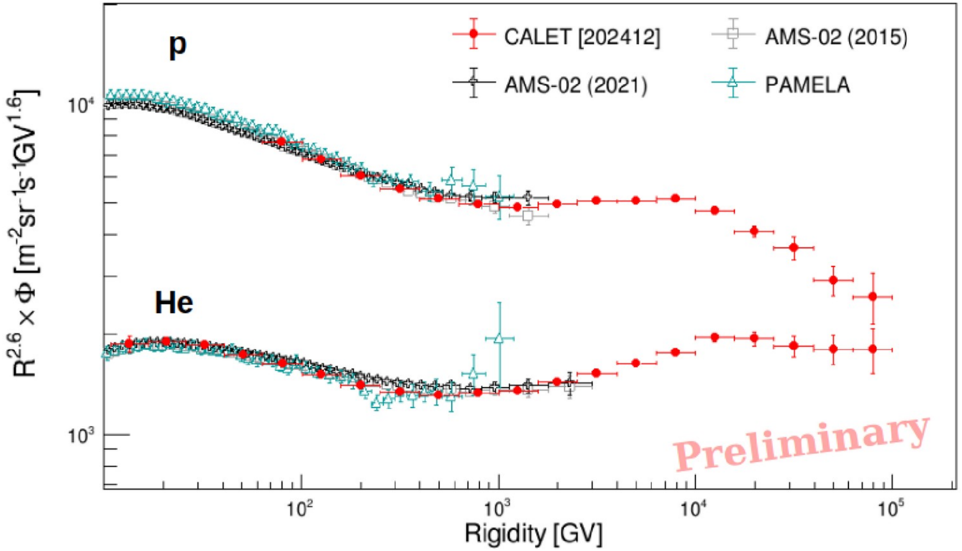
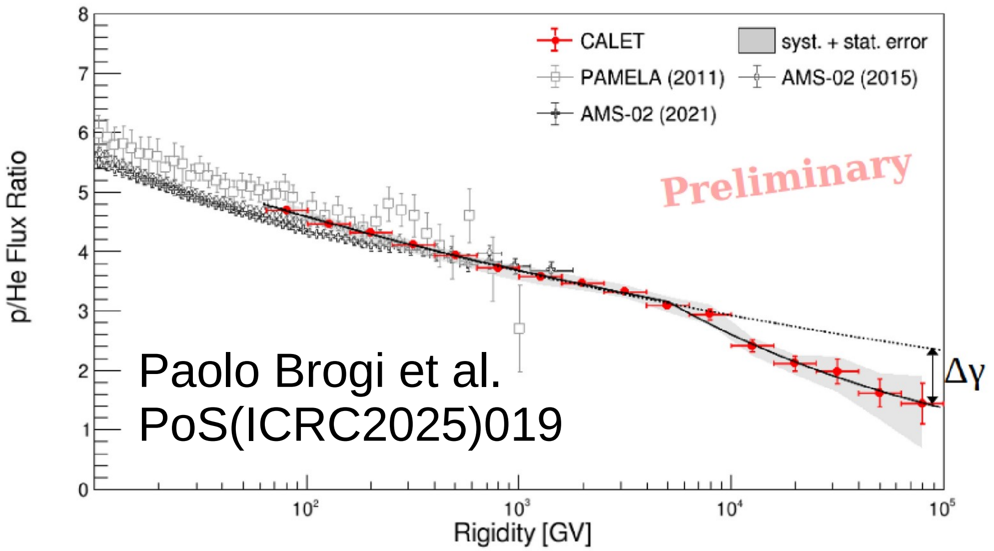
Motivation: ICRC2025 CALET p/He





Acceleration in supernova remnant (SNR) source depends on rigidity:
→ Initial (before propagation) spectral shape for all nuclei species should be the same

- Helium and proton spectra show hardening around R = 1 TV → could be a propagation effect: change of diffusion coefficient power law index
- Helium power law (after propagation) is harder than for proton → difficult to explain by propagation, but spatial dependence of diffusion coefficient may work
- Helium and Proton spectra show softening around 10 TV (source maximum rigidity ?) **AND** Proton to Helium ratio has a softening at the same rigidity → **not a propagation effect**

Tested Hypothesis

- **Assume same acceleration conditions for all nuclei species**
  → common source power law index and cut-off rigidities

- But abundance for primary nuclei species could vary between sources
  → Introduce **two source categories** with **adjustable abundances**:

    (1) softer spectrum with lower cut-off, lower Helium abundance

    (e.g. later phase SNRs which accelerate ISM matter)

    (2) harder spectrum with higher cut-off, larger Helium abundance

    (e.g. early phase SNRs accelerating progenitor star matter, or SNRs of Wolf-Rayet stars which have lost their hydrogen envelope)

- Can this two-source modelling explain the break in the proton-helium ratio and simultaneously match the constraints on cosmic ray propagation from the shape of the primary nuclei spectra and secondary to primary ratios?

Calculation with DRAGON

- DRAGON calculation done independently for the two source types, abundance adjustment for the primary nuclei is done in a fit to the measured nuclei spectra by using separate normalization for each source type and primary species

- Common injection spectrum for all primary nuclei species:
  Two power laws with index γ_1 / γ_2 and exponential cut-off at R_{cut1} / R_{cut2}

- Diffusion coefficient depending on position and with two breaks in rigidity dependence (motivated by breaks in secondary/primary CR ratios):

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

- Further parameters: Spiral arm width w_a, Alfven velocity v_a

- 16 parameters total: 4 for the source spectra, 12 for propagation and environment

Experimental Data Used (Spectra)

Common

- **Proton Flux**

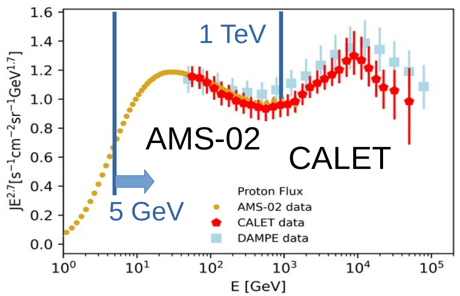
5 GeV – 1 TeV: AMS-02 PRL 114, 171103 (2015)

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

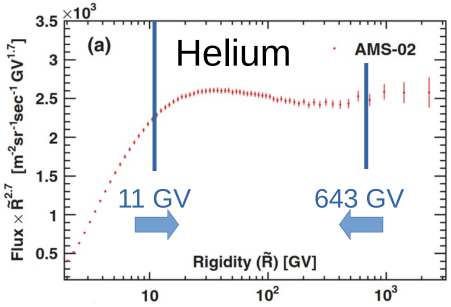
- **Helium Flux**

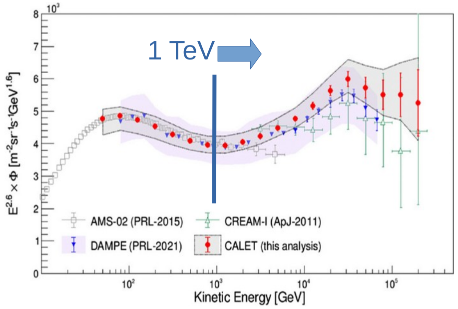
11 GV – 643 GV: AMS-02 PRL 115, 211101 (2015)

1 TeV – 250 TeV: CALET PRL 130, 171002 (2023)



Using data above 5 GeV/nucleon or equivalent rigidity – solar modulation difficult to model below this energy





CALET-focus model

- **Carbon & Oxygen Flux**

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

- **Iron Flux**

10 GeV – 1.6 TeV: CALET PRL 135, 021002 (2025)

- **Nickel Flux**

8.8 GeV – 240 GeV: CALET PRL 128, 131103 (2022)

AMS-focus model

- **Carbon & Oxygen Flux**

11 GV – 3.0 TV: AMS-02 PRL 119, 251101 (2017)

- **Silicon Flux**

11 GV – 3.0 TV: AMS-02 PRL 124, 211102 (2020)

- **Iron Flux**

11 GV – 3.0 TV: AMS-02 PRL 126, 041104 (2021)

Experimental Data Used (Ratios)

Common

- **Antiproton fraction**

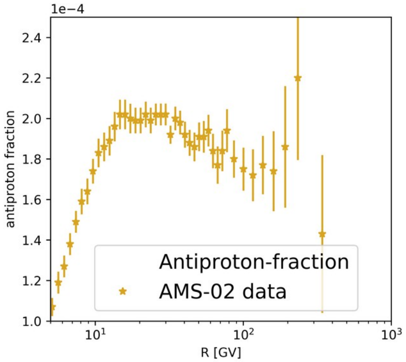
5 GV – 450 GV: AMS-02 PRL 117, 091103 (2016)

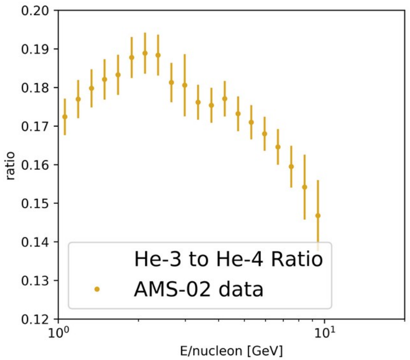
- **^{3}He/^{4}He ratio**

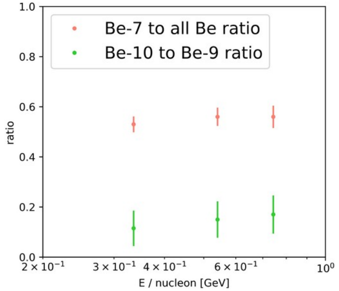
5 GV – 10 GeV: AMS-02 PRL 123, 181102 (2019)

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

CALET-focus model

- **B/C ratio**

8.4 GeV – 3.9 TeV: CALET PRL 129, 251103 (2022)

AMS-focus model

- **B/C ratio**

11 GV – 3.3 TV: AMS-02 PRL 120, 021101 (2018)

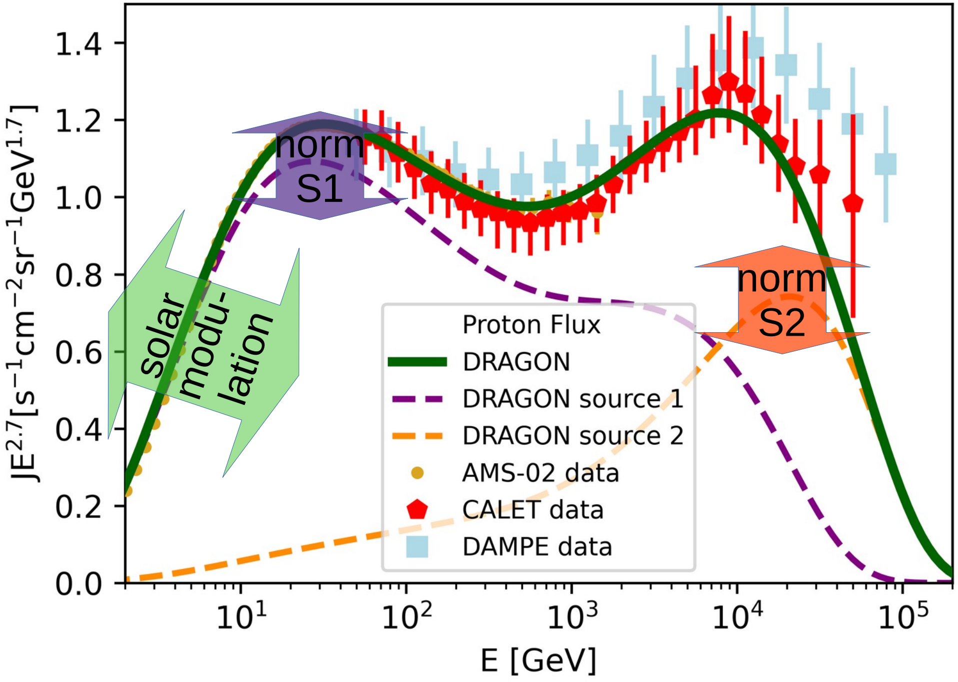
- **B/O ratio**

11 GV – 3.3 TV: AMS-02 PRL 120, 021101 (2018)

Fitting DRAGON Spectra to Data

Fit of **each DRAGON prediction** to the data by minimizing total χ^2 of all experimental data-sets

- Normalization correction factors
  - Proton Source 1 , Proton Source 2
  - Helium Source 1 , Helium Source 2
  - Carbon Source 1 , Carbon Source 2
  - Oxygen Source 1 , Oxygen Source 2
  - Silicon Source 1 , Silicon Source 2
  - Iron Source 1 , Iron Source 2
  - Nickel Source 1 , Nickel Source 2
- 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”

DRAGON Parameter Optimization

- Explore the 16-dimensional parameter space and search for best fitting parameters using:
  - machine learning assisted random walk – train an ANN on already calculated data-points to predict the fit-quality in not yet explored regions of parameter space – pick next point in Markov-Chain MC as best one from a large number of ANN-evaluated candidate points
  - Linear Interpolation/Extrapolation – take composite flux from up to five already calculated data-points and adjust weights for best fit to data – apply same weights to superposition of the parameters to find the next point to calculate (if negative weights → extrapolation)
- Final model quality parameter: likelihood (p-value) of the worst fitting experiment → focus is on agreement with all experimental data-sets

Best Fitting Parameter Sets

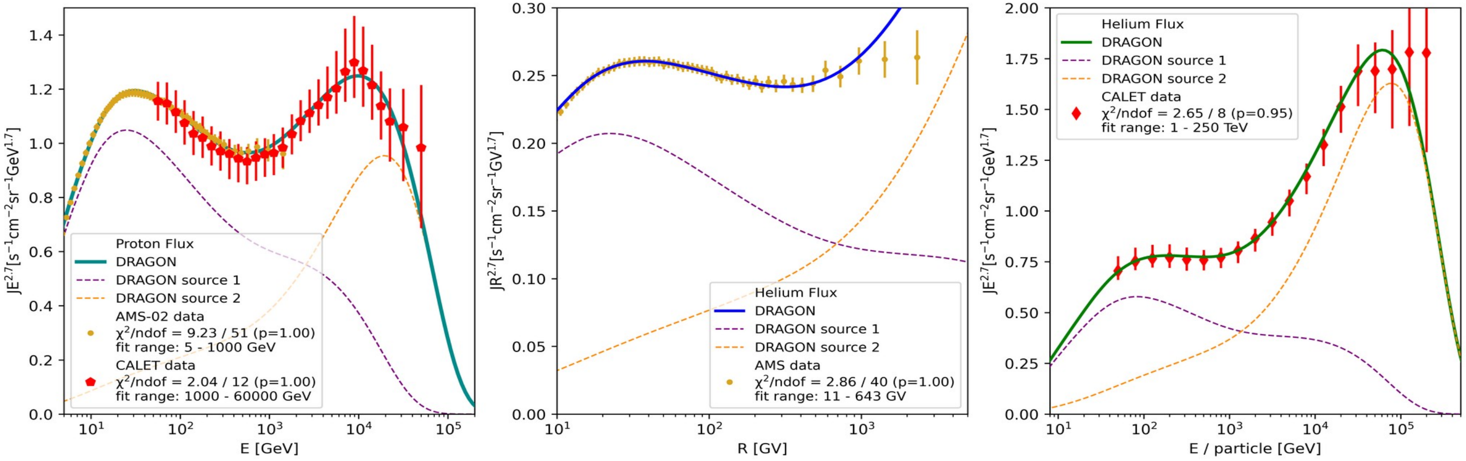
- Best fitting parameters for **CALET-focus model**:

γ_1	γ_2	R_{cut1} [TV]	R_{cut2} [TV]	w_{sa} [kpc]	D_0 [10^{28}cm^2/s]	z_s [kpc]	r_s [kpc]
2.3984	1.9777	15.7736	39.4342	0.2726	1.0045	2.2432	4.8984
δ_l	R_{bl} [GV]	s_l	δ	R_{bh} [GV]	s_h	δ_h	v_a [km/s]
0.1211	5.2354	0.1222	0.5675	684.4285	0.195	0.2321	9.1825

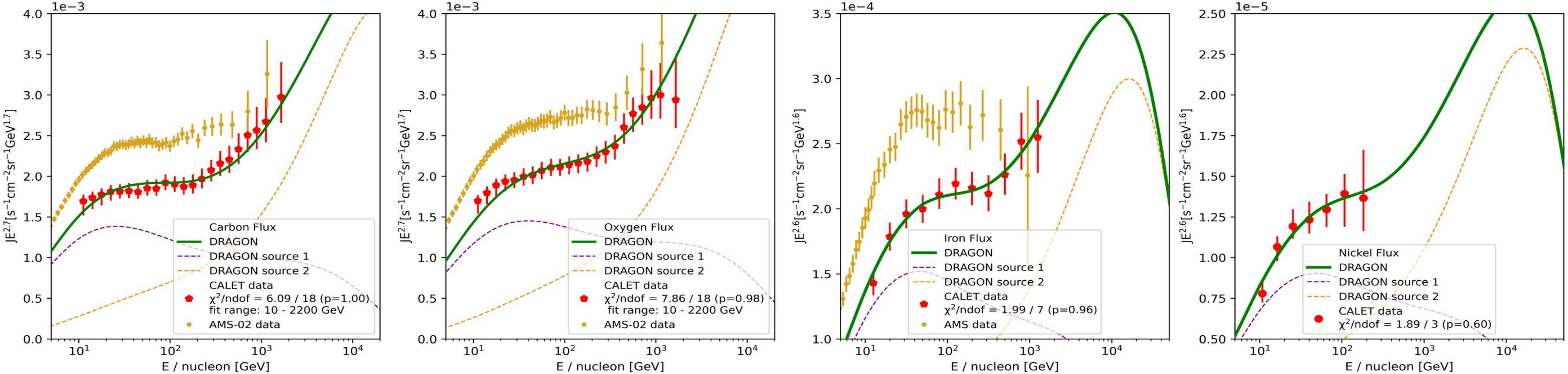
- Best fitting parameters for **AMS-focus model**:

γ_1	γ_2	R_{cut1} [TV]	R_{cut2} [TV]	w_{sa} [kpc]	D_0 [10^{28}cm^2/s]	z_s [kpc]	r_s [kpc]
2.3139	1.952	20.3496	42.7679	1.8441	0.852	1.932	4.4135
δ_l	R_{bl} [GV]	s_l	δ	R_{bh} [GV]	s_h	δ_h	v_a [km/s]
0.1641	8.2525	0.1083	0.5751	745.0963	0.264	0.1342	8.6837

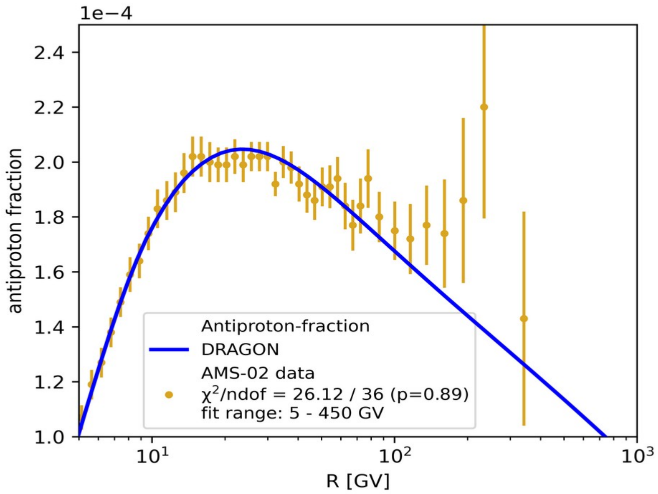
Primary Spectra Fit (CALET-focus)

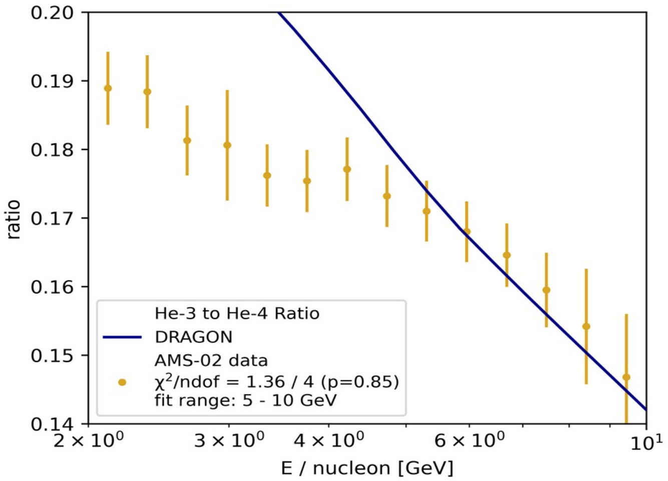


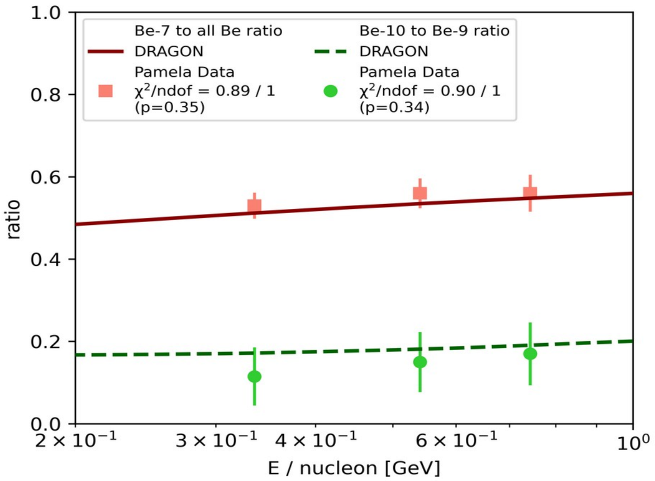
- Overall fit quality:
  χ / ndof = 85.9 / 247
- The model fits all primary spectra well
- Harder high-energy source causes the hardening at R ~ 1 TV mostly, propagation effect is secondary

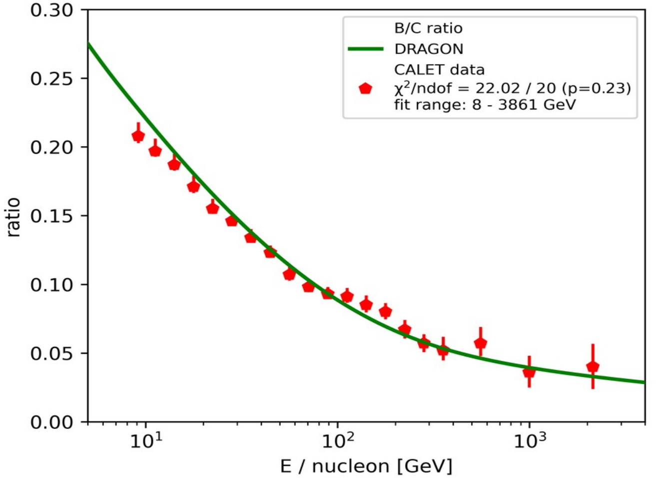


Secondary Ratios Fit (CALET-focus)



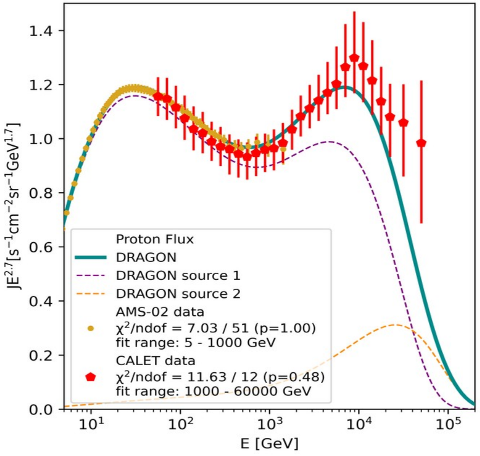


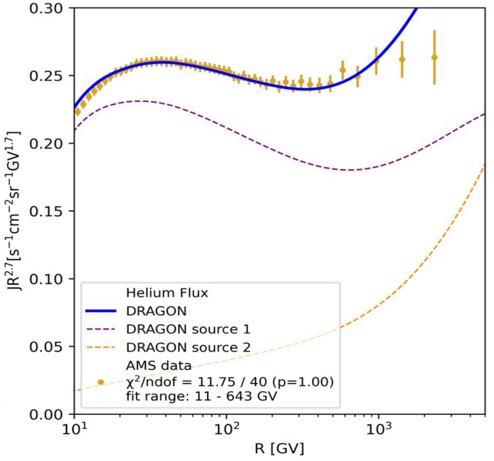


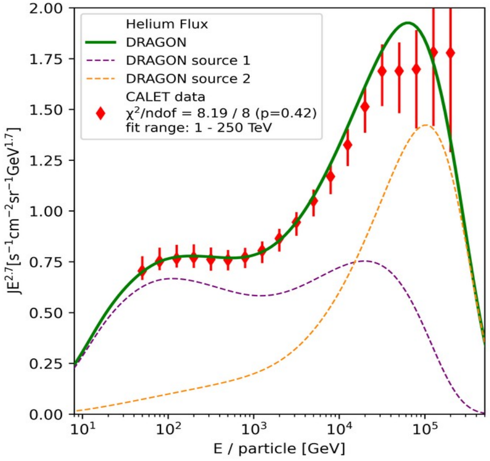


Worst likelihood p=0.23 for B/C ratio →
Model not excluded by any of the data-sets
(Main constraint is conflict between low-energy B/C ratio and He-3 to He-4 ratio)

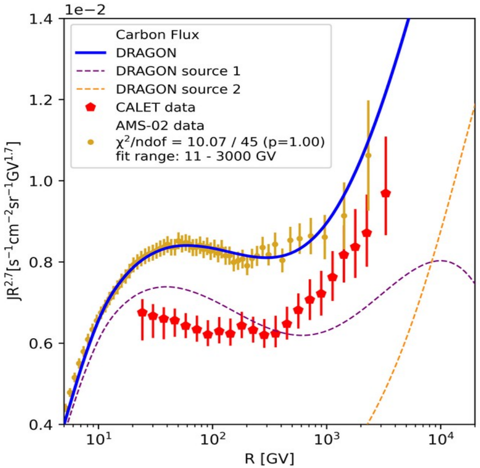
Primary Spectra Fit (AMS-focus)

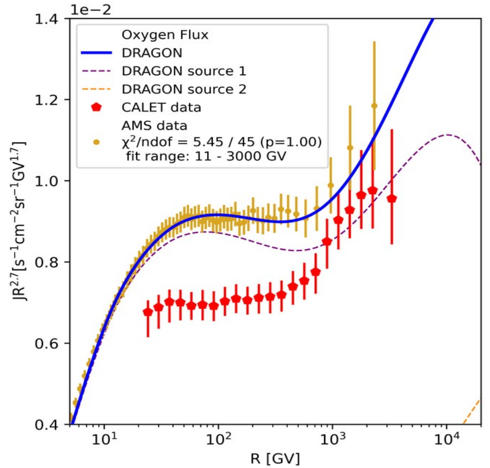


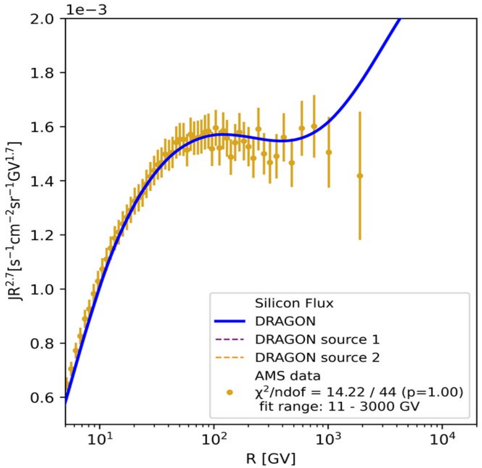


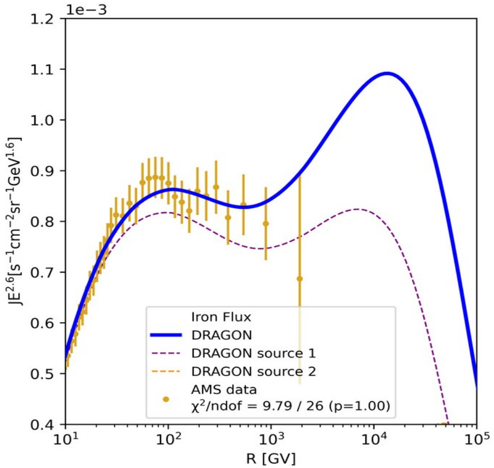


- Overall fit quality: χ / ndof = 232.0 / 437
- The model fits all primary spectra well
- Diffusion coefficient slope change and high-energy source together explain the hardening at R ~ 1 TV

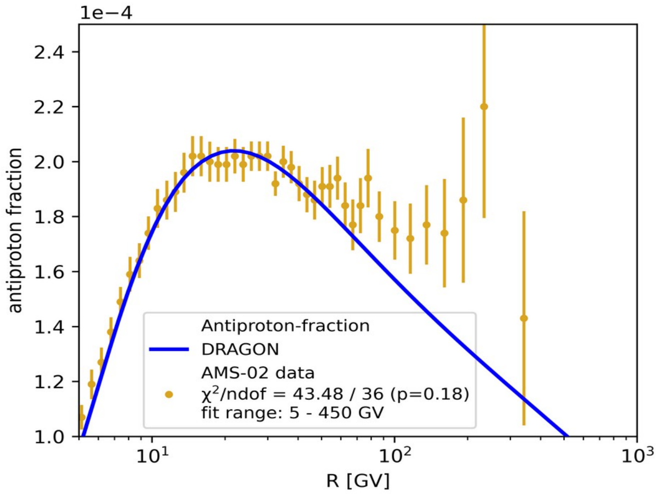


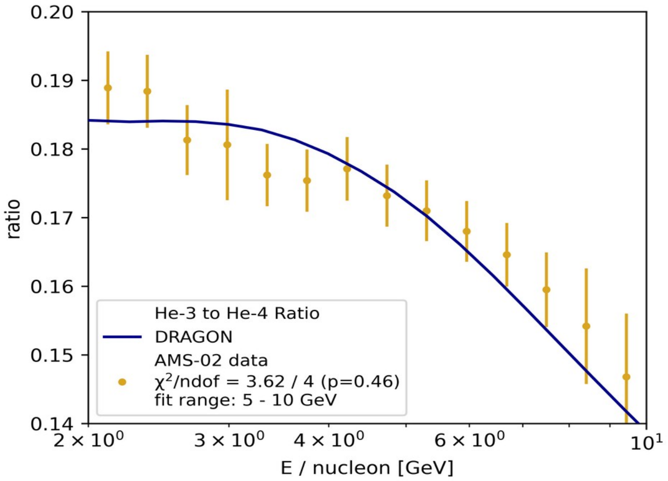


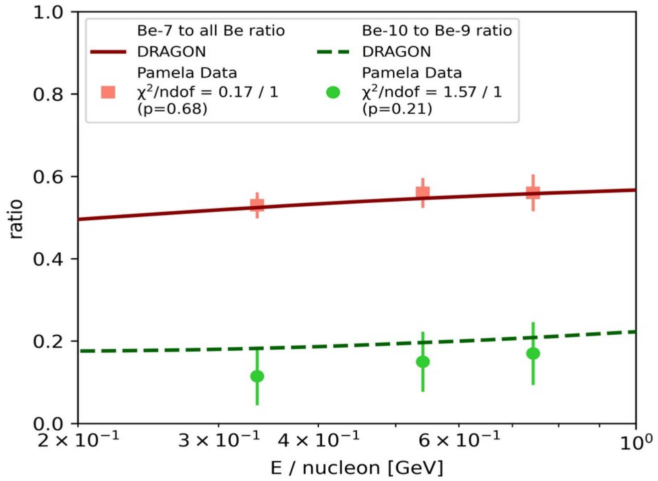


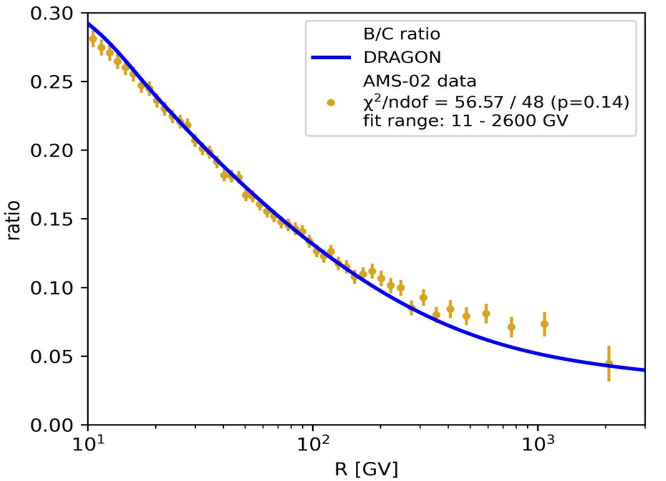


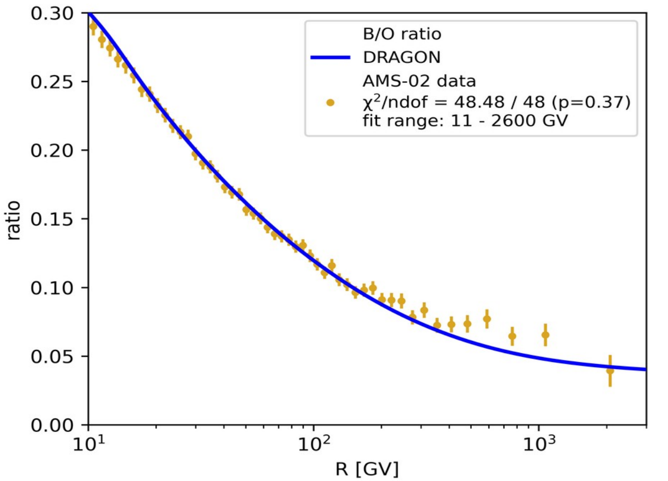
Secondary Ratios Fit (AMS-focus)







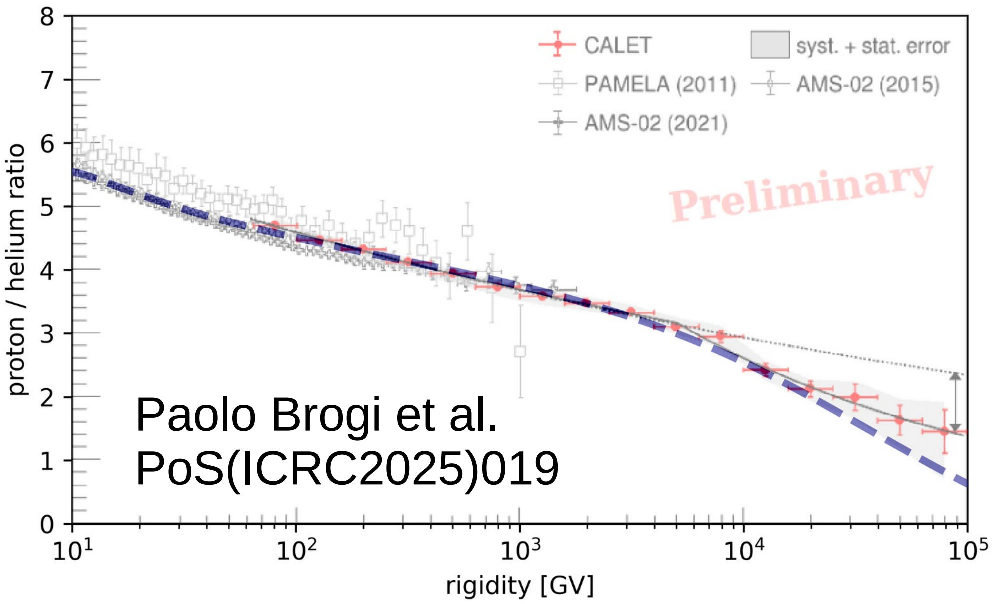




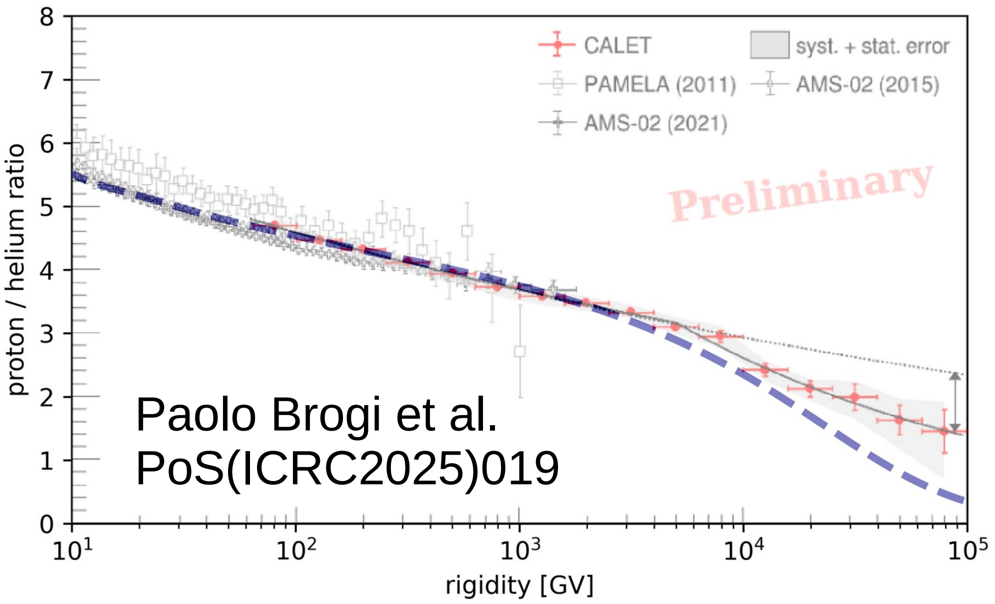
Worst likelihood p=0.14 for B/C ratio
→ Model not excluded by any of the data-sets
(Main constraint is conflict between low-energy B/C ratio and He-3 / He-4 ratio & AP fraction)

p/He Ratio

CALET-focus model



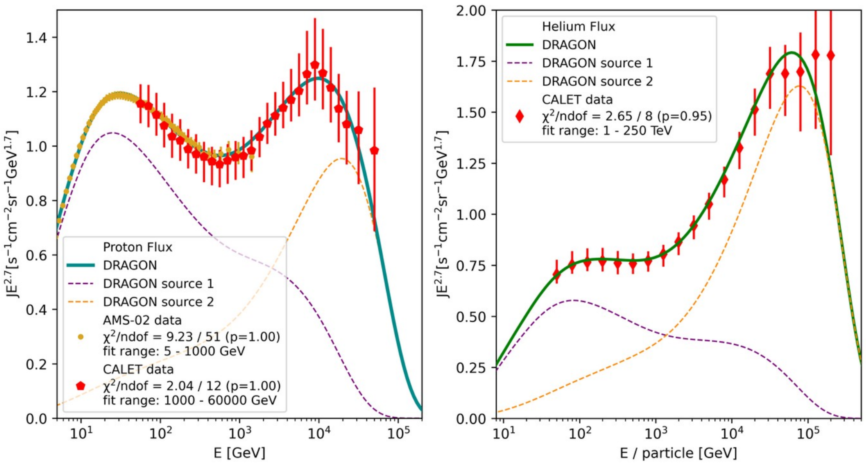
AMS-focus model

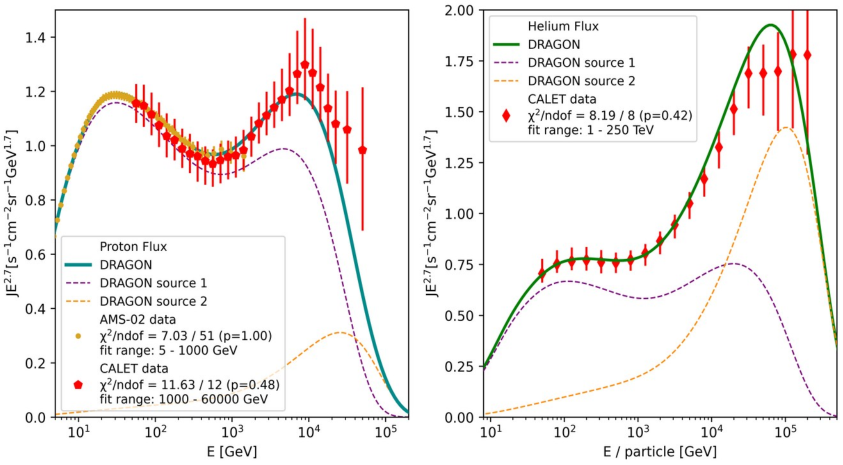


Preliminary, numerical data not published
→ p/He ratio not fitted directly, only qualitative comparison

The two-source model matches the observed change in slope of the p/He ratio

Helium Abundance Ratios





CALET-focus model

Helium / Hydrogen
abundance ratios:
Source 1: 7.76 %
Source 2: 19.0 %

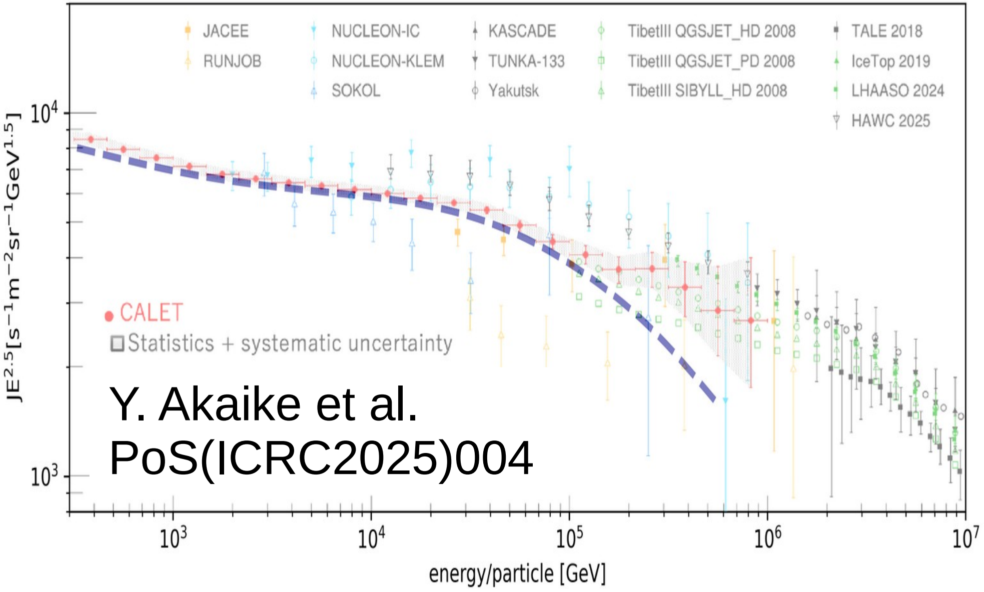
AMS-focus model

Helium / Hydrogen
abundance ratios:
Source 1: 7.76 %
Source 2: 47.9 %

→ helium rich high-energy source explains stronger hardening of Helium spectrum
→ overall lower contribution of this source to the hardening in AMS-focus model
→ larger helium abundance needed

All-nuclei Spectrum

CALET-focus model



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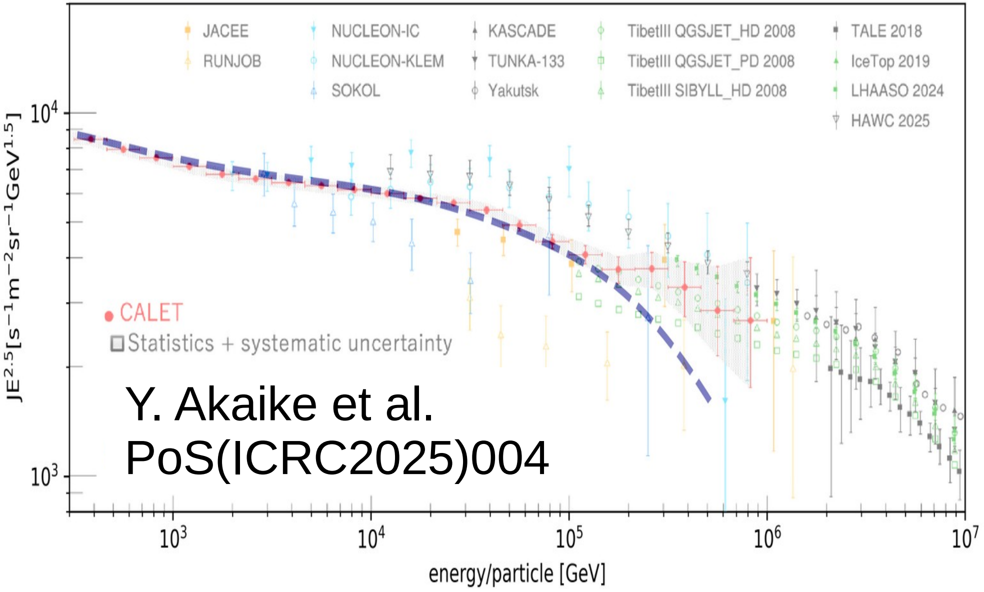


Preliminary, numerical data not published

→ all-nuclei flux not fitted directly, only qualitative comparison

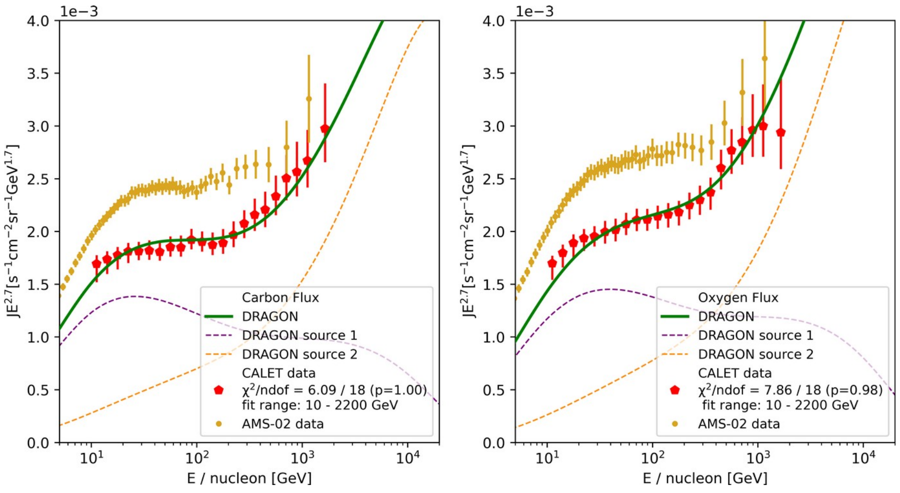
The two-source model matches the observed spectrum up to about 100 TeV and reproduces the softening between 10 and 100 TeV, indicating that the re-hardening near 200 TeV would correspond to another, higher-energy source category.

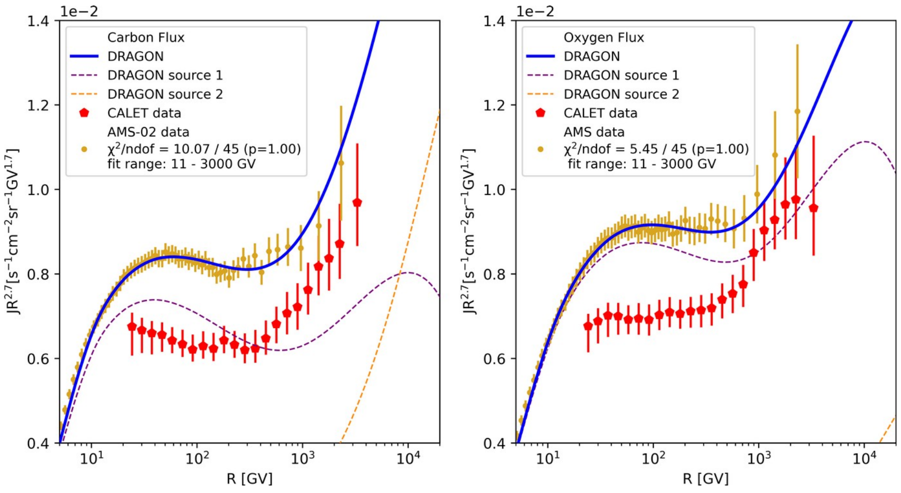
Conclusion and Outlook

- A two source category model with a helium-rich high energy source has been implemented in DRAGON and it is shown that it can
  - explain the observed break in the proton to Helium ratio
  - explain the harder spectrum of Helium compared to other nuclei
  - fit the most important nuclei spectra and primary to secondary ratios (for two models focusing on CALET and AMS-02 data respectively)
- Mapping of “allowed” parameter space and optimization continues
- Voyager data at very low energy outside heliosphere to be included

Backup Slides

Other Abundance Ratios





CALET-focus model

Carbon / Oxygen abundance ratios:

Source 1: 78.5 % ; Source 2: 79.8 %

Nickel / Iron abundance ratios:

Source 1: 6.10 % ; Source 2: 7.64 %

AMS-focus model

Carbon / Oxygen abundance ratios:

Source 1: 68.8 % ; Source 2: 244 %

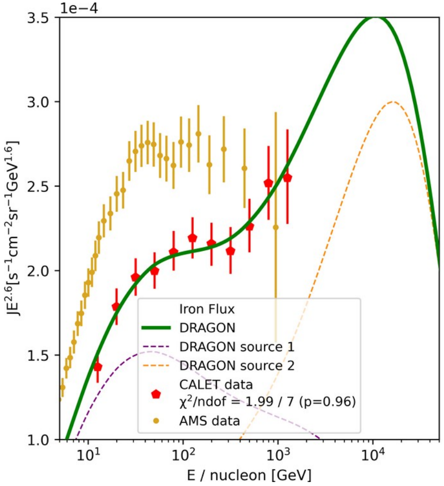
Iron / Silicon abundance ratios:

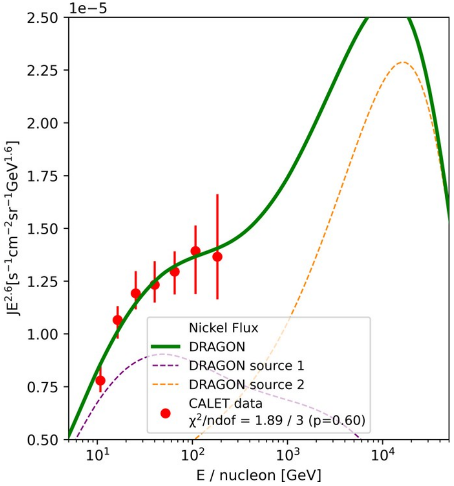
Source 1: 89.2 % ; Source 2: $5 \cdot 10^8$ %

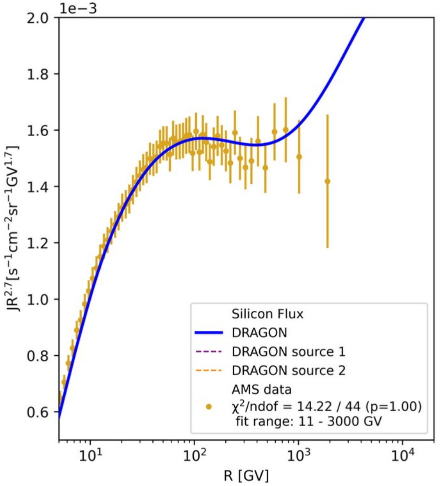
(source 2 has negligible silicon)

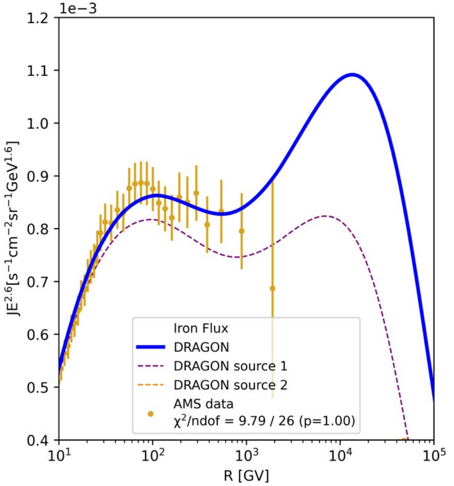
→ parameter optimization yields partly strange results but there is no strong constraint on the second source abundance for heavy elements from the observation data

Other Abundance Ratios









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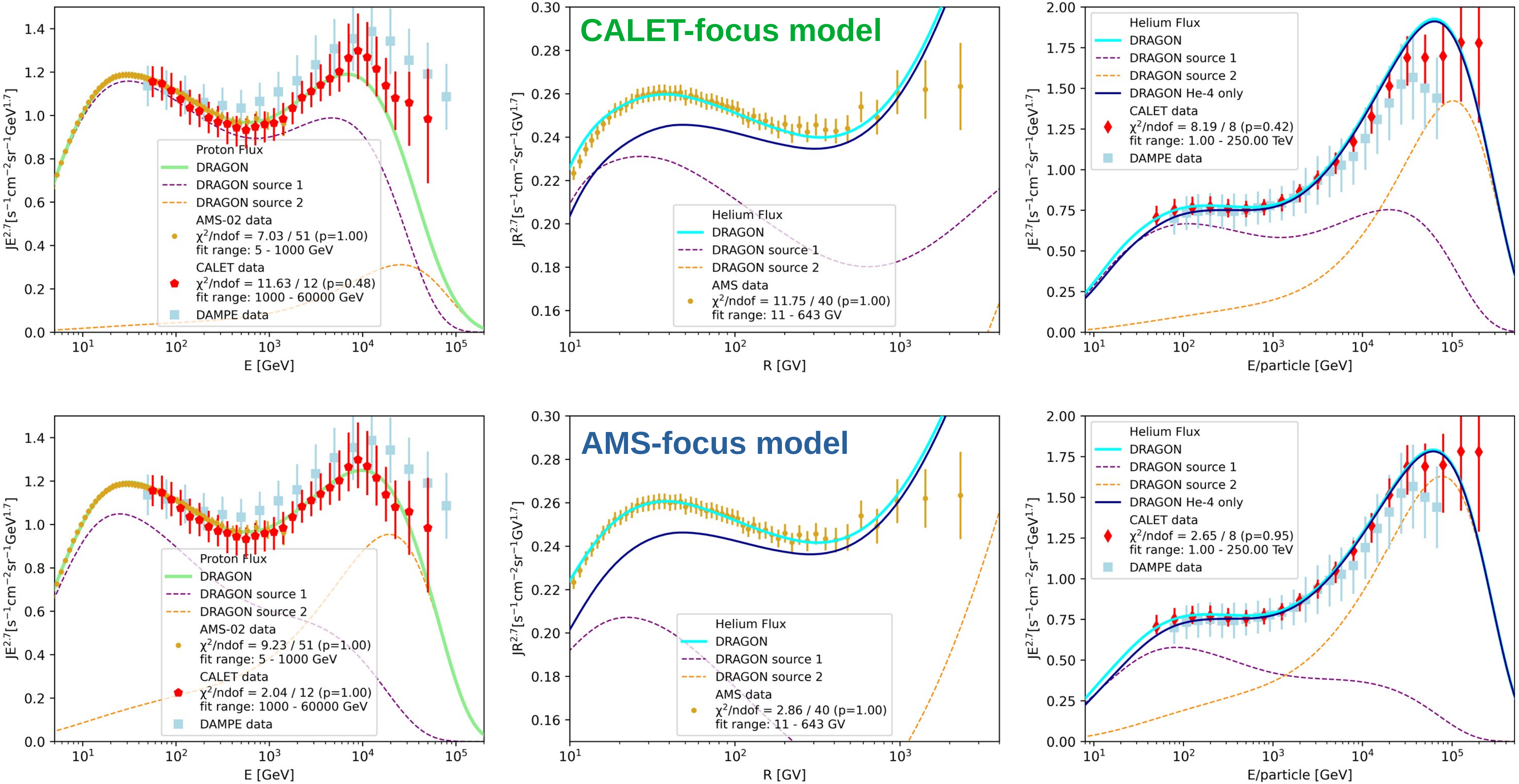
Comparison to DAMPE Data and He-3 Influence on He-spectrum



Details of Parameter Optimization

- Initially optimization of helium-proton (with antiproton) range. After convergence to a well-fitting model calculation is extended to silicon-proton range. Finally nickel-proton range is calculated for confirmation (a correction factor for influence of heavier nuclei is used in partial calculations)

- Model quality parameters change during the optimization
  - Initially used for coarse optimization: total χ^2 , sum of reduced χ^2 over all experiments, squared sum of reduced χ^2 over all experiments, total χ^2 for fit of ratios, sum of reduced χ^2 over all experiments plus total χ^2 , maximum reduced χ^2 out of all experiments
  - Finally used for fine tuning: sum of negative log-likelihoods over all experiments, squared sum of negative log-likelihoods over all experiments, sum of negative log-likelihoods over ratio experiments, sum of negative log-likelihoods over all experiments counting the largest double, maximum negative log-likelihoods out of all experiments

Details of Fitting to Data

- Helium normalization for source 1 is not only fitted as a correction factor, but iteratively interpolated between two DRAGON calculations with 5% and 10% Helium (relative to proton) abundance, as it was found that the initial helium abundance influences the fit slightly. Helium abundance for source 2 is set to 20% of proton initially.
- Normalization correction factor for boron is calculated as 0.6 times normalization factor of carbon plus 0.4 times normalization factor of oxygen (assuming 60% of boron originate from carbon, and 40% from oxygen)