

# Impacts of Propagation on Cosmic-Ray Isotopic Composition

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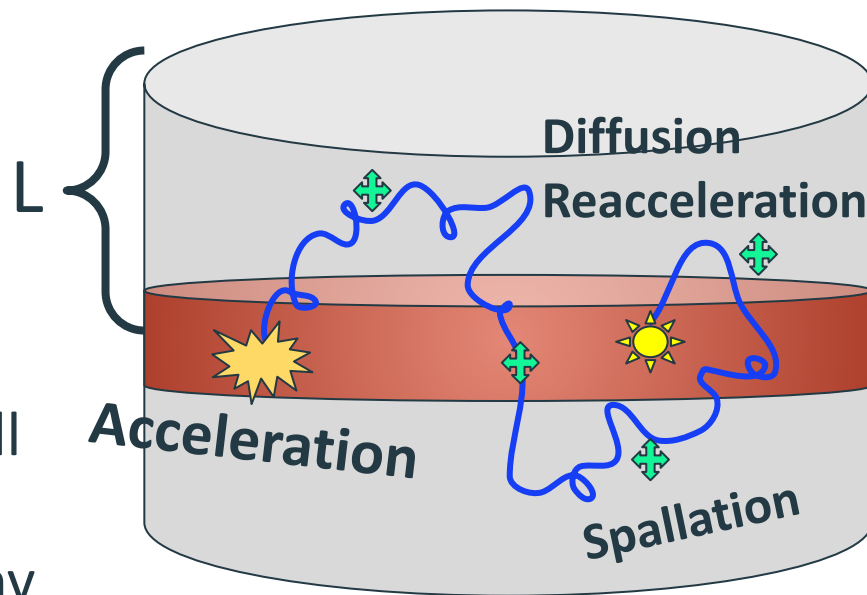
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Technology

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# Cosmic-Ray Propagation

- Cosmic rays undergo many processes before detection
  - Acceleration
  - Diffusion
  - Reacceleration
  - Modulation
  - Fragmentation, etc . . .
- Many processes **identical** for all cosmic ray species
- Simultaneous modeling of many species constrains models



# Modeling Cosmic-Ray Processes

- Diffusion assumed to result from scattering against magnetic field irregularities  $\rightarrow D_{xx} \propto D_0 \beta R^\delta$
- Injection of particles at sources similarly taken as a power law in rigidity  $\rightarrow q \propto R^{-\gamma}$ 
  - $\gamma$  is different for 1)  $Z=1$  2)  $Z=2$  3)  $Z>2$  nuclei
  - The slopes  $\delta$  and  $\gamma$  are permitted to break at a specified rigidity value
- Solar modulation is modeled using the force-field approximation (*ApJ* **154**, 1968)

# Numerical Solution of Cosmic-Ray Processes

$$\frac{\partial \psi}{\partial t} = \underbrace{q(\vec{r}, p)}_{\text{sources}} + \underbrace{\vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi)}_{\text{spatial diffusion}} + \underbrace{\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi}_{\text{reacceleration}} - \underbrace{\frac{\partial}{\partial p} \left[ \dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right]}_{\text{energy loss}} - \underbrace{\frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi}_{\text{fragmentation \& decay}}$$

- Three cases are considered to reproduce cosmic-ray data below  $\sim 200$  GV (*see E1.1-0037-24 for work  $>200$  GV*)
  - **Source breaks** only at low rigidities (SB)
  - **Diffusion break** only at low rigidities (DB)
  - **Source and diffusion breaks** at low rigidities (CB)
  - *(three cases studied for high rigidity data in PoS(ICRC2021)155)*



(Strong et. al. 2013)

# Methodology

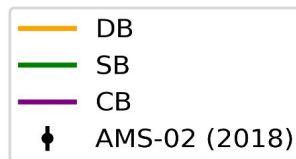
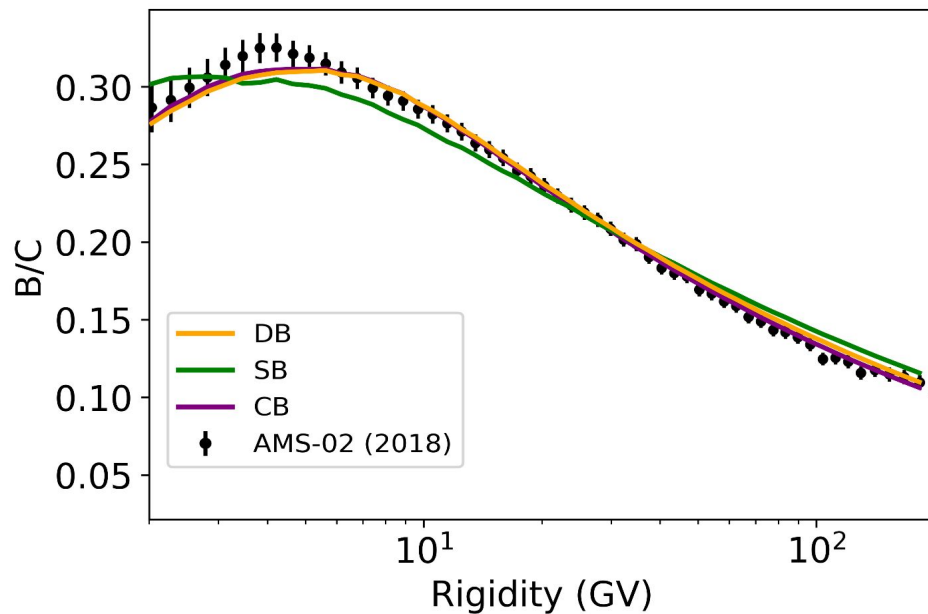
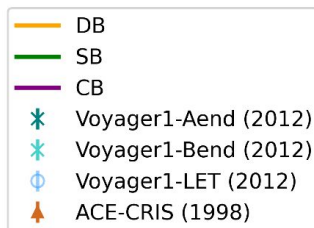
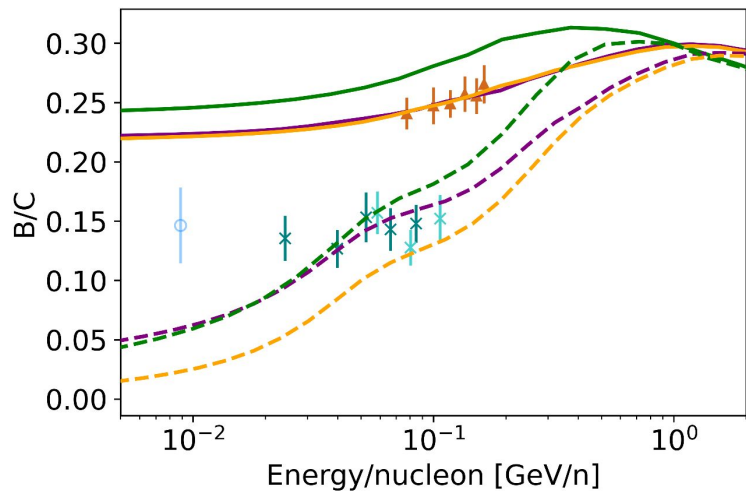
- Datasets considered: H, He, Be, B, C, N, O, B/C, B/O, e<sup>+</sup>, p<sup>-</sup>, <sup>2</sup>H, <sup>3</sup>He, <sup>4</sup>He, <sup>10</sup>Be/<sup>9</sup>Be
  - AMS02 (*PhR* **894** 1, 2021), (*ICRC2023*), (*PRL* **123** 181102, 2019), (*APS April Meeting 2024*)
  - ACE-CRIS (*AdSR* **38** 1558, 2006)
  - Interstellar Voyager (*ApJ* **831** 18, 2016), (*NatAs* **3** 1013, 2019)
- The optimization library MINUIT2 (*Comput. Phys. Commun.* **10**, (1975)) is used to minimize  $\chi^2$  with respect to model parameters
- Voyager data not included for **DB** case due to inability to produce acceptable fits to the data

# Results

|                            | SB             | DB             | CB             |
|----------------------------|----------------|----------------|----------------|
| $v_{\text{alfven}}$ (km/s) | $14.9 \pm 0.1$ | $23.7 \pm 0.1$ | $18.2 \pm 0.1$ |
| $dV/dz$ (km/s/kpc)         | $5.9 \pm 0.1$  | $12.3 \pm 0.3$ | $5.4 \pm 0.1$  |
| $\phi_{\text{AMS}}$        | $471 \pm 2$    | $540 \pm 2$    | $546 \pm 1$    |
| $\phi_{\text{ACE}}$        | $440 \pm 5$    | $489 \pm 6$    | $446 \pm 3$    |

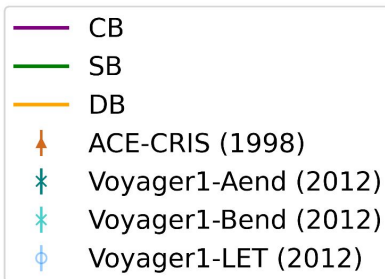
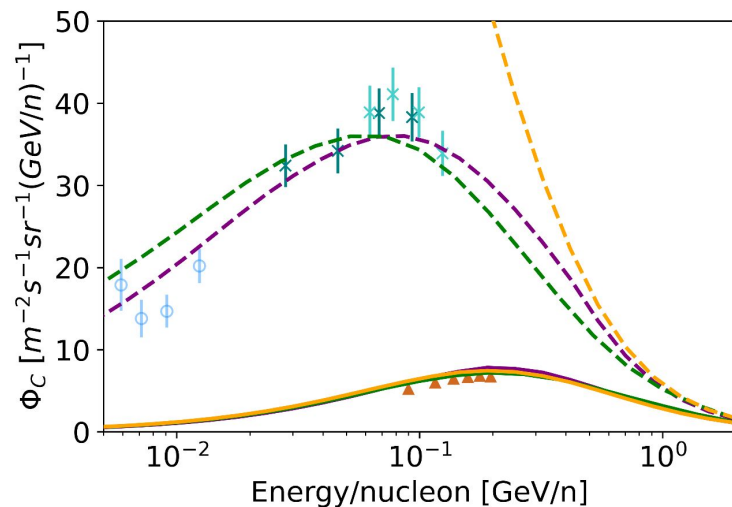
Uncertainties are reported by the MINUIT minimization algorithm

# B/C Ratio

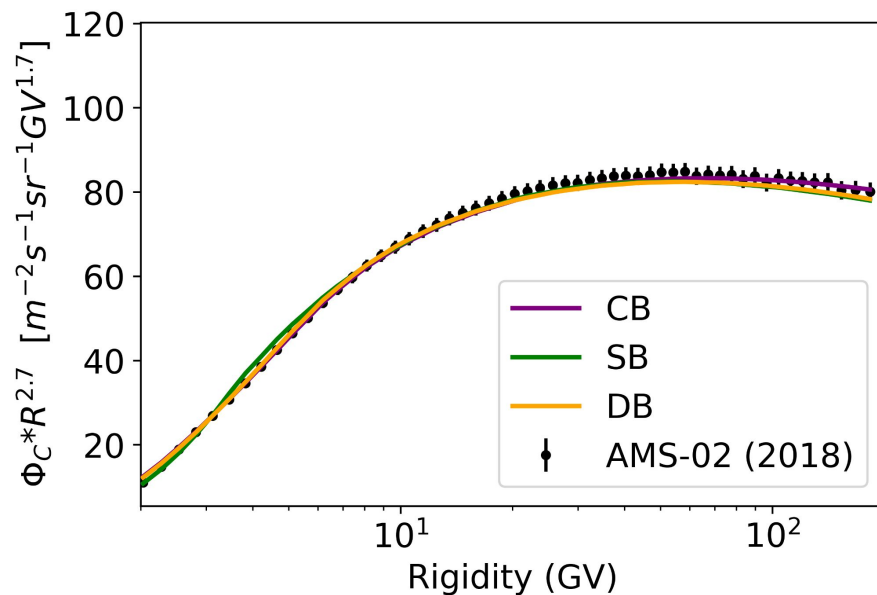


| $D_0 \beta R^\delta$ | SB                   | DB                   | CB                   |
|----------------------|----------------------|----------------------|----------------------|
| $\delta_1$           |                      | 0.136<br>$\pm 0.005$ | 0.142<br>$\pm 0.004$ |
| $R_{br}$ (GV)        |                      | 5.9<br>$\pm 0.1$     | 6.3<br>$\pm 0.1$     |
| $\delta_2$           | 0.485<br>$\pm 0.003$ | 0.561<br>$\pm 0.002$ | 0.535<br>$\pm 0.002$ |

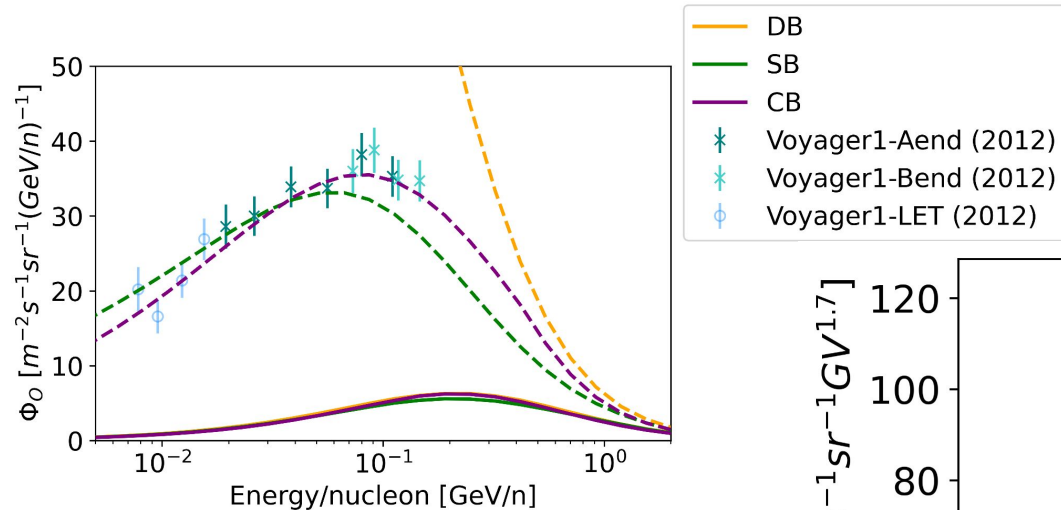
# Carbon



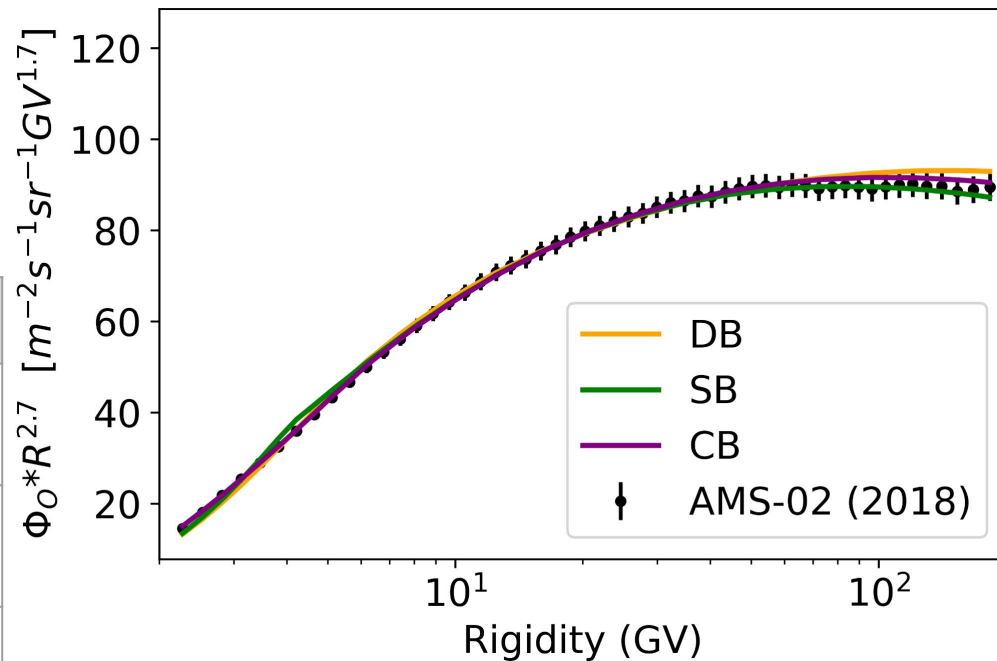
| $\propto R^{-\gamma} (Z>2)$ | SB                   | DB                   | CB                   |
|-----------------------------|----------------------|----------------------|----------------------|
| $\gamma_1$                  | 1.55<br>$\pm 0.01$   |                      | 1.14<br>$\pm 0.05$   |
| $R_{br} \text{ (GV)}$       | 4.4<br>$\pm 0.2$     |                      | 2.03<br>$\pm 0.07$   |
| $\gamma_2$                  | 2.383<br>$\pm 0.002$ | 2.346<br>$\pm 0.001$ | 2.320<br>$\pm 0.001$ |



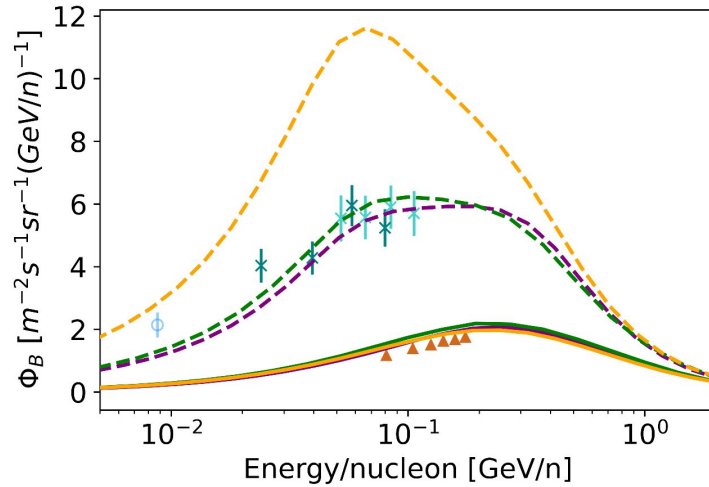
# Oxygen



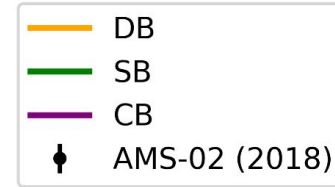
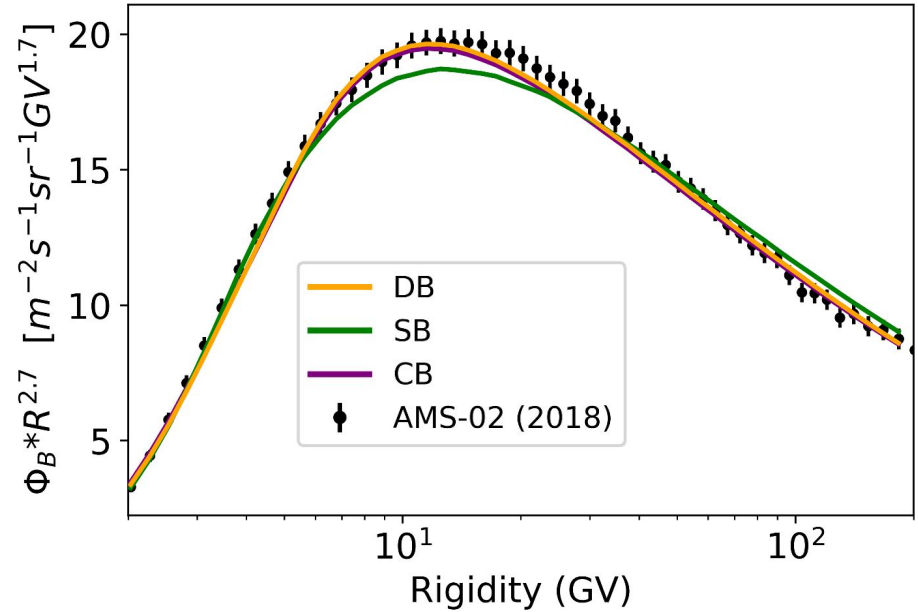
| $\propto R^{-\gamma} (Z>2)$ | SB                   | DB                   | CB                   |
|-----------------------------|----------------------|----------------------|----------------------|
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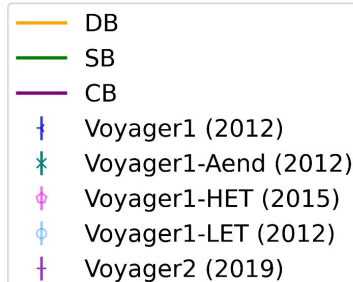
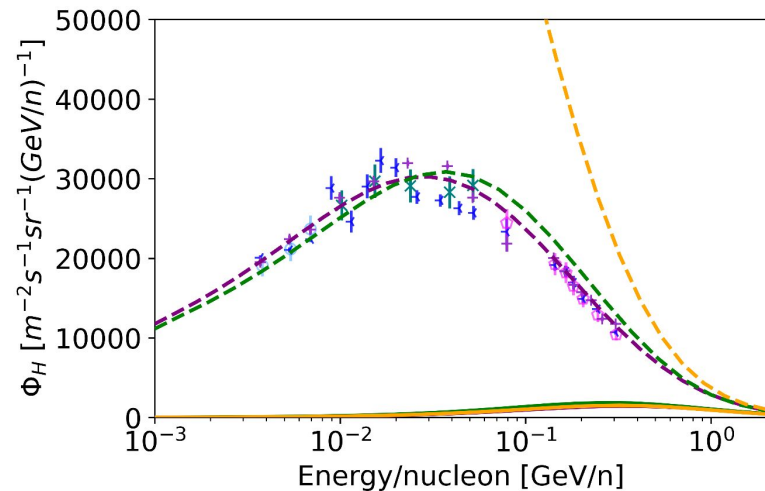


# Boron

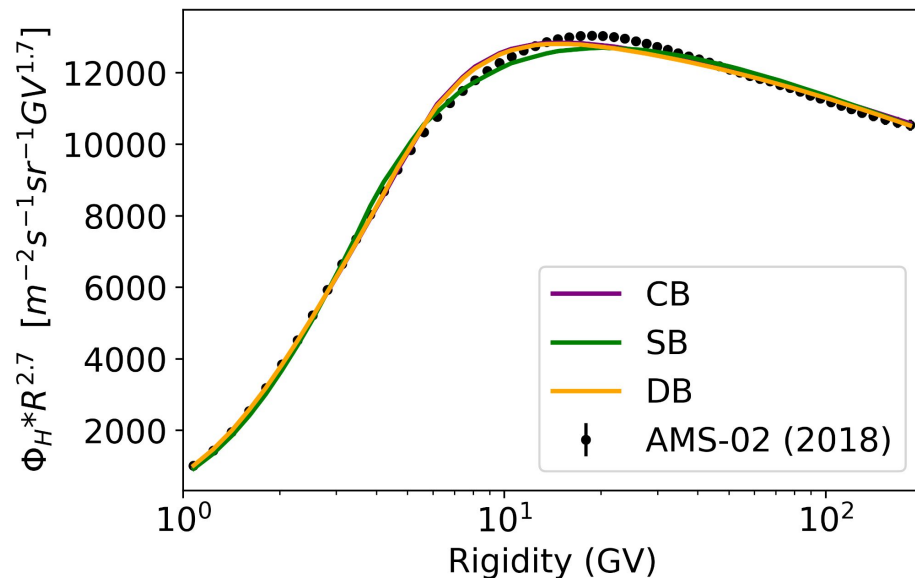


| $D_0 \beta R^\delta$ | SB               | DB               | CB               |
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| $\delta_1$           |                  | 0.136<br>± 0.005 | 0.142<br>± 0.004 |
| $R_{br}$ (GV)        |                  | 5.9<br>± 0.1     | 6.3<br>± 0.1     |
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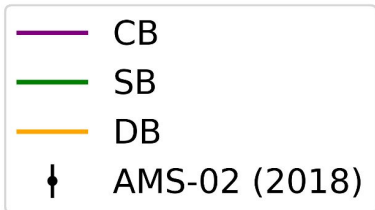
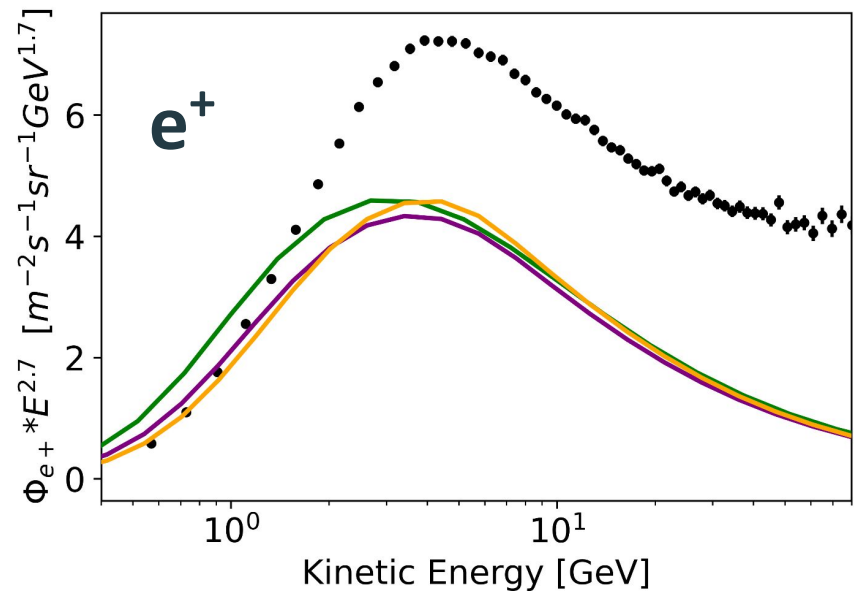




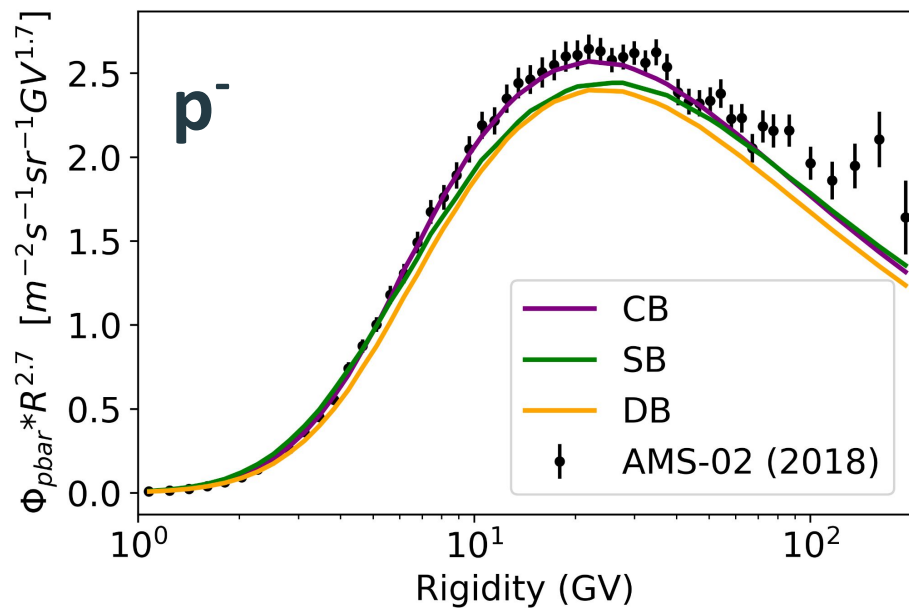
# Hydrogen



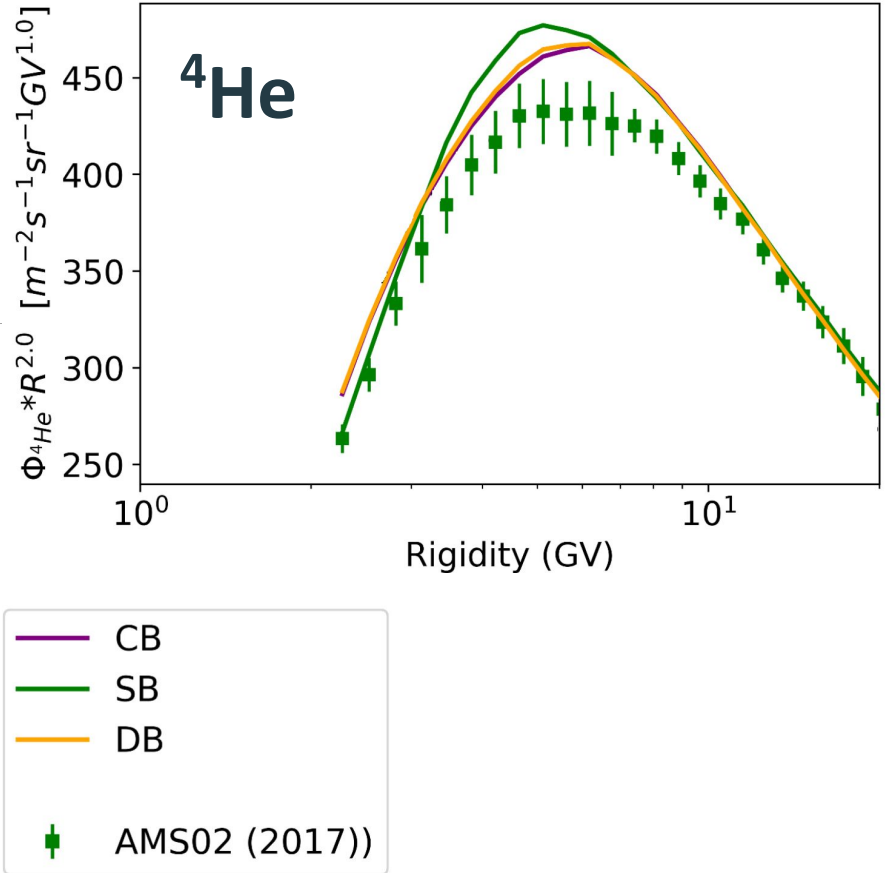
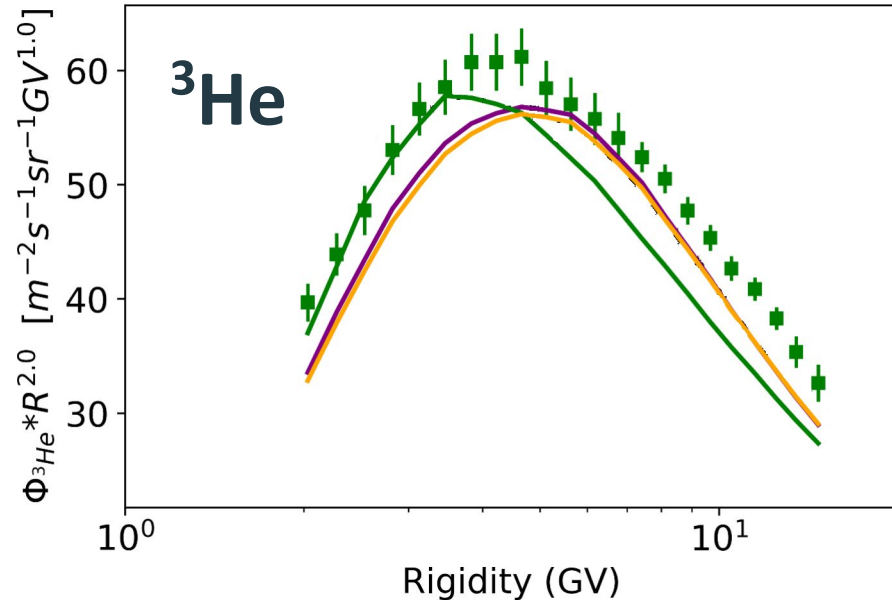
| $\propto R^{-\gamma} (Z=1)$ | SB                   | DB                   | CB                   |
|-----------------------------|----------------------|----------------------|----------------------|
| $\gamma_1$                  | 1.790<br>$\pm 0.002$ |                      | 1.698<br>$\pm 0.001$ |
| $R_{br} \text{ (GV)}$       | 4.80<br>$\pm 0.04$   |                      | 1.91<br>$\pm 0.06$   |
| $\gamma_2$                  | 2.396<br>$\pm 0.001$ | 2.354<br>$\pm 0.001$ | 2.337<br>$\pm 0.001$ |



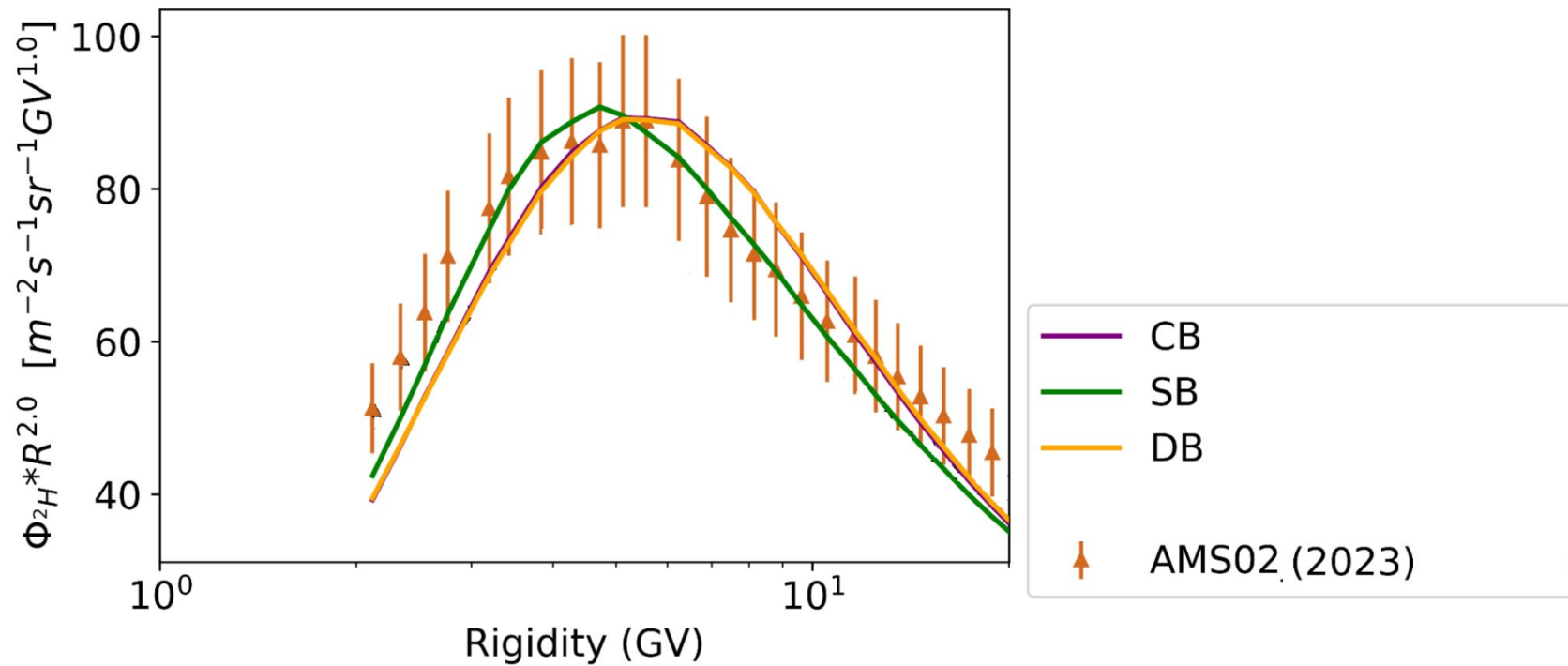
## Positron and Anti-proton



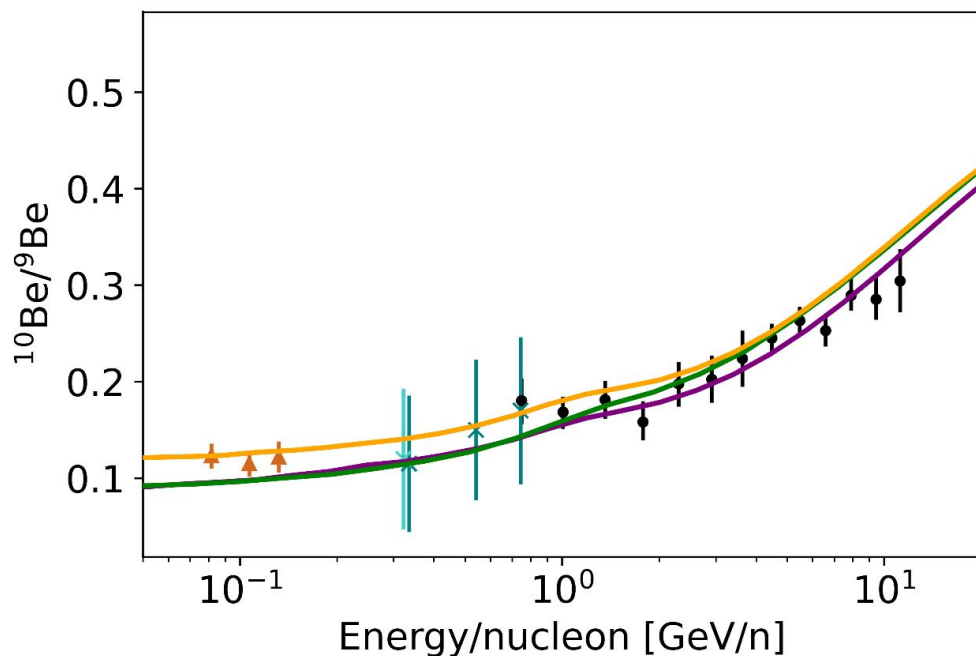
# Helium Isotopes



# Deuteron



# $^{10}\text{Be}/^9\text{Be}$



|         | SB   | DB   | CB   |
|---------|------|------|------|
| L (kpc) | 14.9 | 14.9 | 14.9 |

Note: L was not allowed to exceed 15 kpc

- CB
- SB
- DB
- ◻ AMS-02 APS April (2024)
- \* PAMELA-TOF (2014)
- \* PAMELA-CALO (2014)
- ▲ ACE-CRIS (1997)

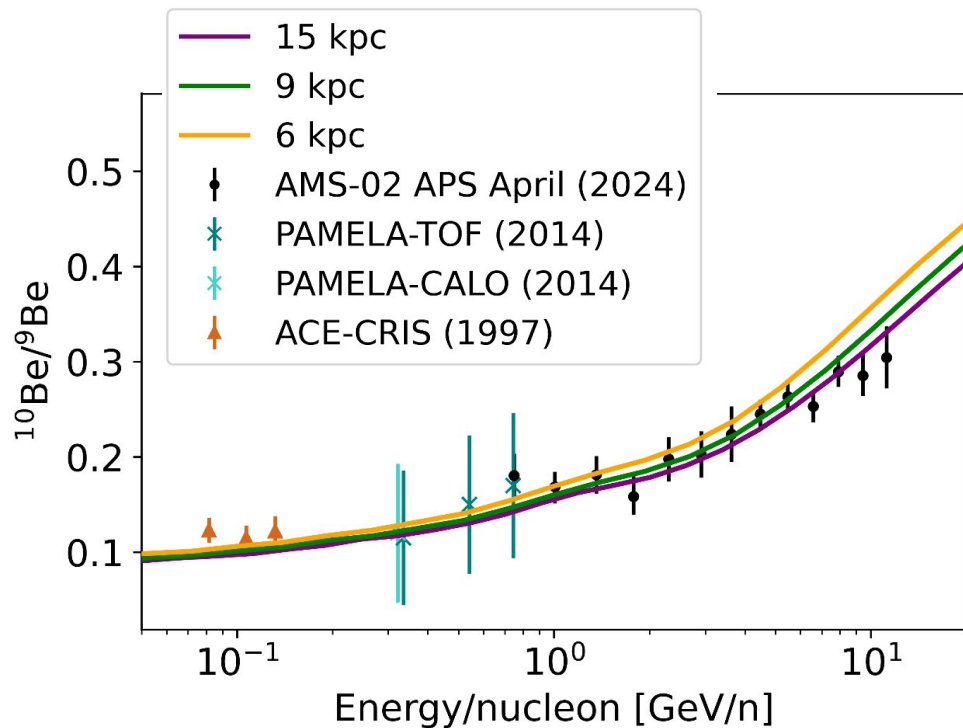
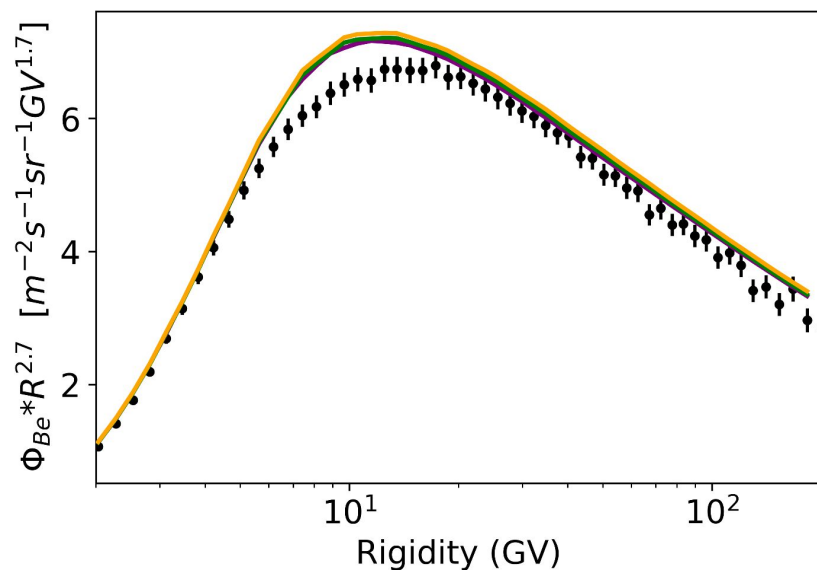
# Investigating Halo Size Results

We focus on the **CB** case and fix the halo size to test values, re-performing the minimization procedure for each

| L (kpc)                                         | 15                | 9               | 6               |
|-------------------------------------------------|-------------------|-----------------|-----------------|
| $D_0$ ( $10^{28} \text{ cm}^2 \text{ s}^{-1}$ ) | $8.580 \pm 0.018$ | $7.80 \pm 0.02$ | $6.44 \pm 0.03$ |
| $\chi^2$ (Be)                                   | 178               | 215             | 286             |
| $\chi^2$ ( $^{10}\text{Be}/^9\text{Be}$ AMS)    | 7.9               | 11.6            | 31.8            |

# Investigating Halo Size Results

Cross-section issues may bias our estimation of  $L$  in this instance



# Conclusions

- We fit three cases for diffusion and source breaks to a wide set of elemental and isotopic cosmic-ray data
- A low-rigidity diffusion break significantly improved the fit to secondary B and  $e^+$ , and a low-rigidity source break was necessary to fit the interstellar spectra together with AMS and ACE data
- The  $^{10}\text{Be}/^9\text{Be}$  and D data is fit across all cases, while the He isotope data shows deficiencies in all cases
- Future work will focus on a repeated assessment with updated data and marginalization across cross-section uncertainties