

Analyzing Cosmic Ray Spectral Features: A Numerical Investigation

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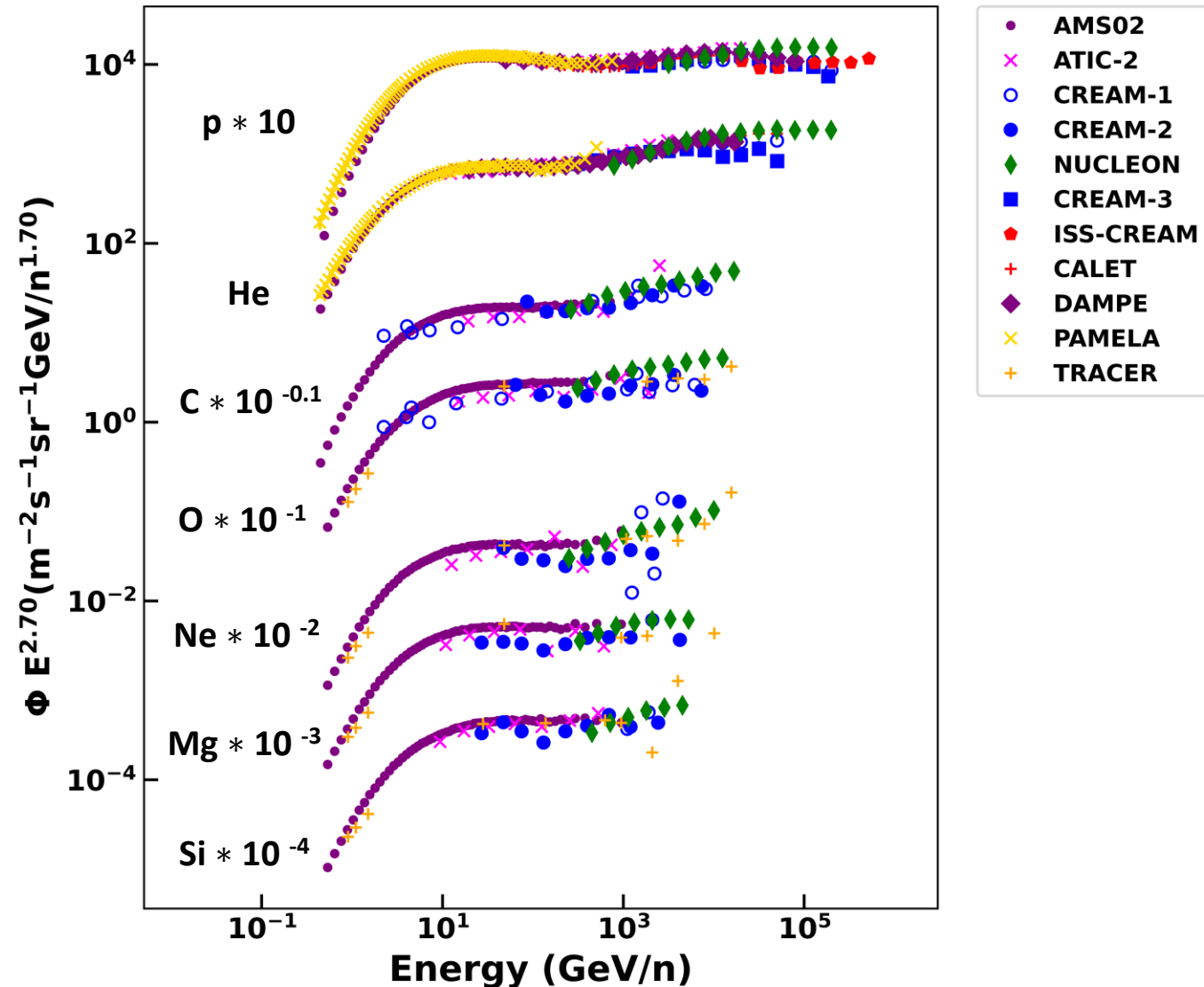
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Cosmic Ray Spectra

- Spectral features can be seen from compiled cosmic ray data (Seo 2021 and references therein).
 - Spectral hardening of cosmic ray elemental data can be seen above ~ 200 GV.
 - A softening in the proton spectrum can be seen above ~ 10 TV.
 - A softening in the helium spectrum can be seen above ~ 34 TeV.
 - A positron excess can be seen above ~ 25 GeV.
- What effects could be producing these spectral features?



GALPROP

- GALPROP numerically solves the transport equation down below (Strong *et al.* 2013 and references therein):

$$\begin{aligned}
 \frac{\partial \psi(\vec{r}, p, t)}{\partial t} &= \underbrace{q(\vec{r}, p, t)}_{\text{Sources}} + \underbrace{\vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi)}_{\text{Diffusion}} \\
 &+ \underbrace{\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi}_{\text{Diffusive reacceleration}} - \underbrace{\frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right]}_{\text{Energy loss}} - \underbrace{\frac{1}{\tau_f} \psi}_{\text{Fragmentation}} - \underbrace{\frac{1}{\tau_r} \psi}_{\text{Decay}}
 \end{aligned}$$

D_{xx} : spatial diffusion coefficient
 τ_f : time
 τ_r : time
 $\dot{p}$: Momentum
 CR density per unit

Methodology

- A diffusion model with reacceleration and convection effects serves as a base model.
- GALPROP v57's (Porter *et al.* 2022) parameter optimization routine, utilizing MINUIT2, is used to tune the model's free parameters and obtain parameter errors.
- In this work, we add in new heavy element data, introduce a charge-symmetric primary positron source, and obtain errors for propagation parameters (Chen *et al.* 2023).
- For work on data below ~ 200 GV, please refer to E1.1 Presentation No. 38 by Z. M. Dorris.
- Input Data for Fitting **Hardening**: p , $\bar{p}$, He, C, N, O, Be, B, B/C, B/O, Ne, Mg, Si, S, Fe, e^+ , and e^-
 - AMS-02 (Aguilar *et al.* 2023, Aguilar *et al.* 2021, Aguilar *et al.* 2020), CALET (Adriani *et al.* 2021, Adriani *et al.* 2023), CREAM-I+III (Yoon *et al.* 2017), DAMPE (An *et al.* 2019, Alemanno *et al.* 2021), ISS-CREAM (Choi *et al.* 2022), NUCLEON-KLEM (Grebenyuk *et al.* 2019)
- Input Data for Fitting **Softening** for p and He: p and He
 - CALET (Adriani *et al.* 2021, Adriani *et al.* 2023), CREAM-I+III (Yoon *et al.* 2017), DAMPE (An *et al.* 2019, Alemanno *et al.* 2021), ISS-CREAM (Choi *et al.* 2022), NUCLEON-KLEM (Grebenyuk *et al.* 2019)
- Input Data for Fitting **Positron Excess**: e^+ and e^-
 - AMS-02 (Aguilar *et al.* 2021)

GALPROP (Cont.)

		Case 1	Case 2	Case 3
Diffusion Coefficient: $D_{xx} \propto \beta D_0 \left(\frac{\rho}{\rho_0} \right)^\delta$	$D_0 (10^{28} \text{cm}^2 \text{s}^{-1})$ ($R = 10 \text{ GV}$)	7.81 ± 0.04	7.81 ± 0.04	7.81 ± 0.04
	δ_1	0.101 ± 0.005	0.101 ± 0.005	0.101 ± 0.005
	$\rho_0 \text{ (GV)}$	6.78 ± 0.06	6.78 ± 0.06	6.78 ± 0.06
	δ_2	0.493 ± 0.001	0.493 ± 0.001	0.493 ± 0.001
	$\rho_1 \text{ (GV)}$	226 ± 9	-----	201.8 ± 0.3
	δ_3	0.382 ± 0.003	-----	0.446 ± 0.004

- Using rigidity-dependent parameters, three cases were considered to study the spectral hardening (Wu *et al.* 2021):

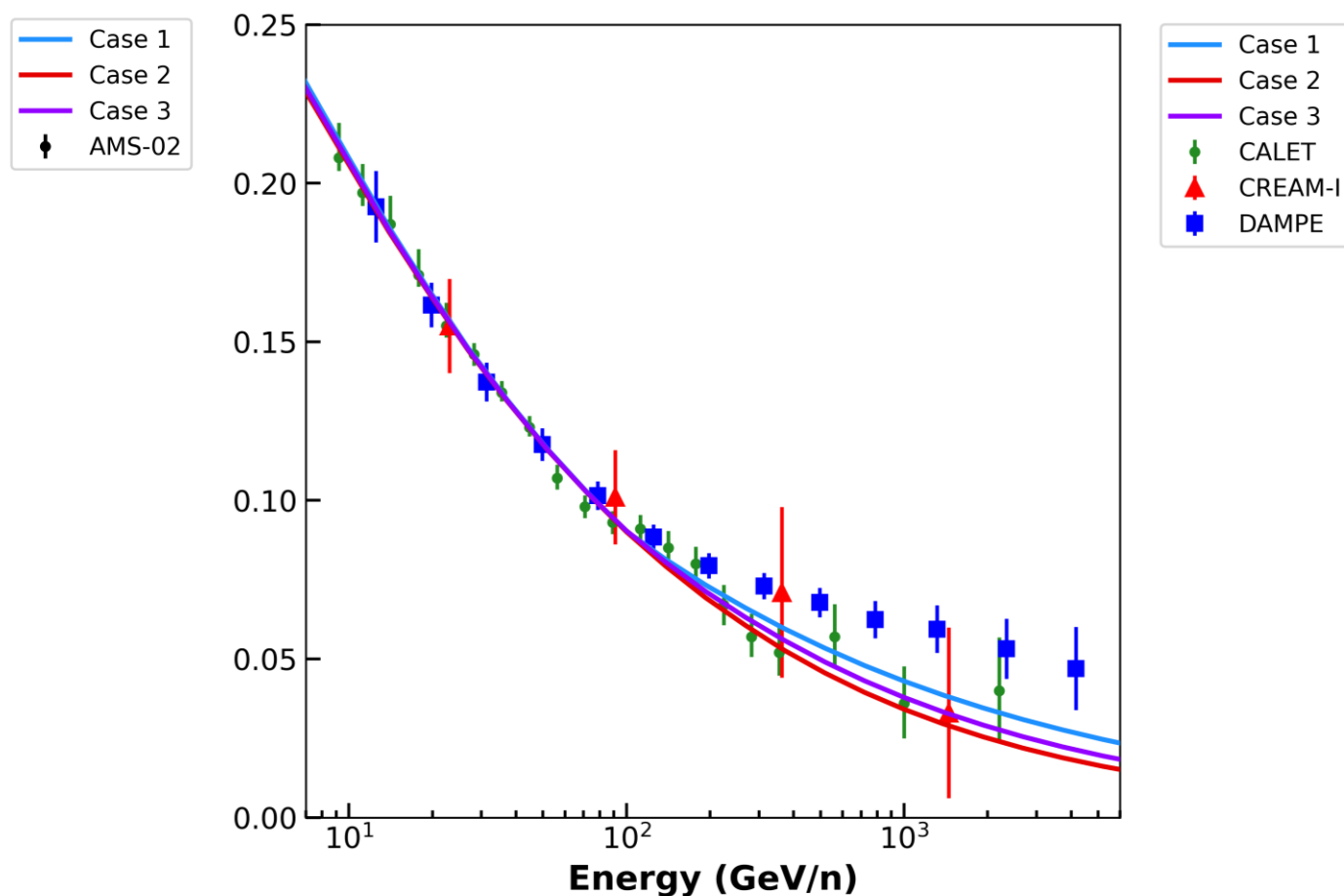
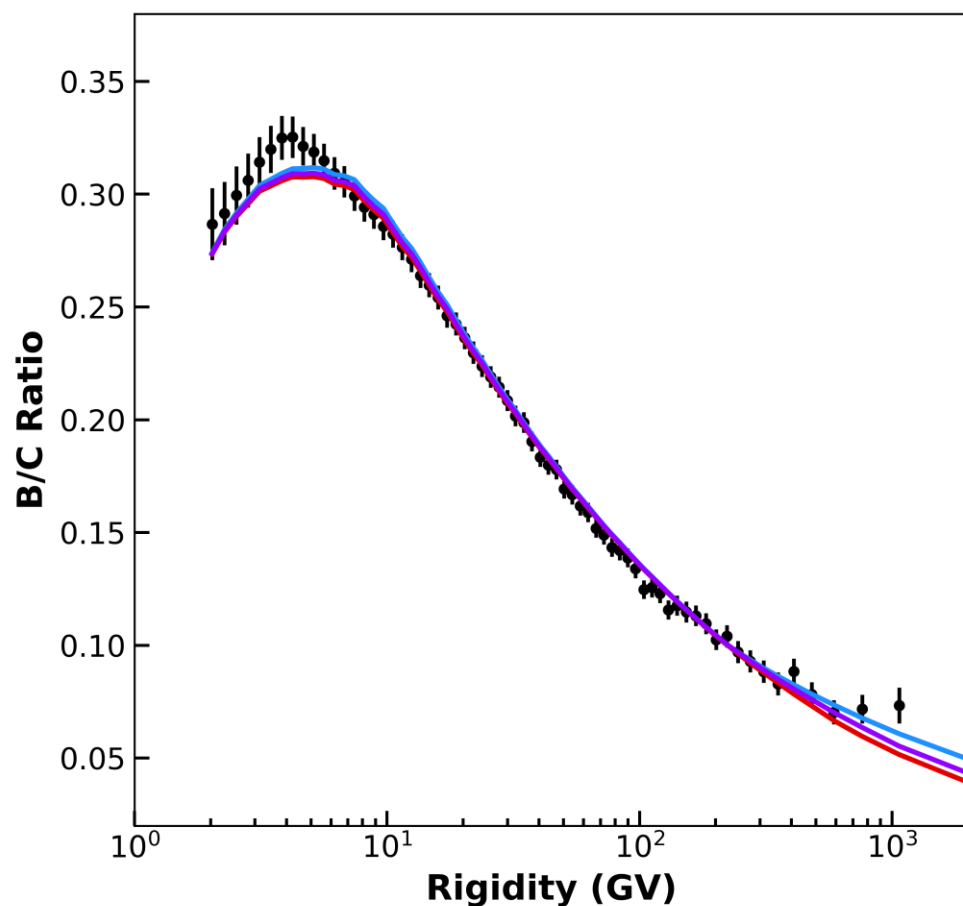
Case 1: One with a diffusion coefficient break

Case 2: One with source spectrum breaks

Case 3: One with a combination of both effects

- Across all three cases,
 - The galactic halo half-width $z_h = 7.5 \text{ kpc}$
 - The Alfvén velocity
 $v_{\text{Alfvén}} = 16.9 \pm 0.2 \text{ km s}^{-1}$
 - The gradient of convection velocity
 $dV_{\text{Conv}}/dz = 3.9 \pm 0.2 \text{ km s}^{-1} \text{ kpc}^{-1}$
 is set.

B/C Ratio

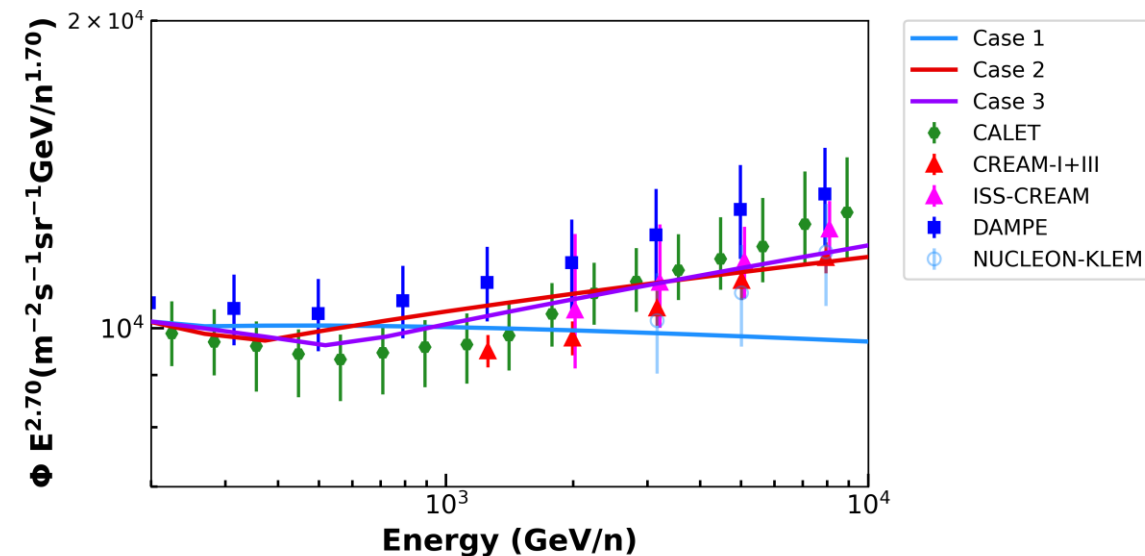
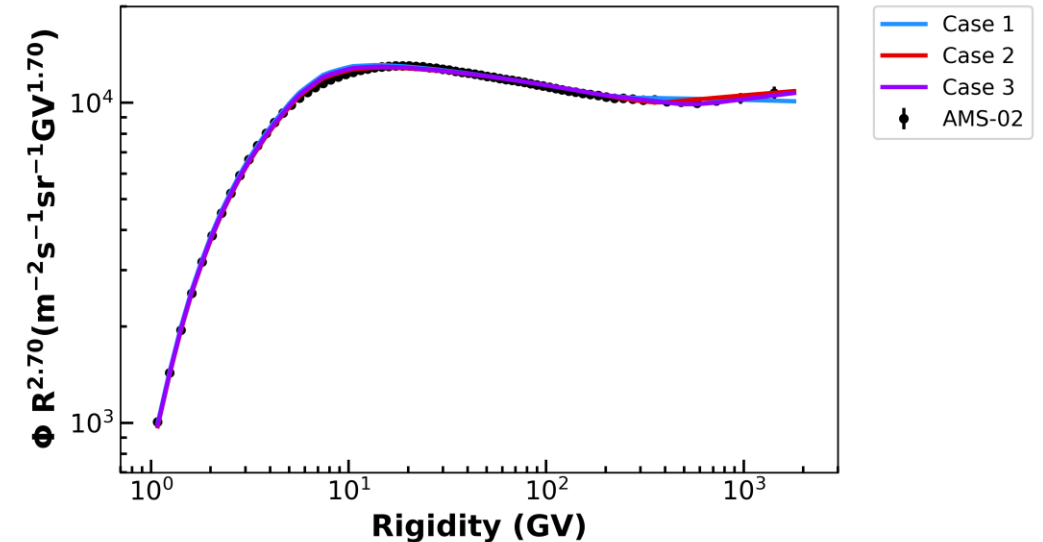


- All three cases produce an acceptable B/C ratio.

Proton Spectrum

		Case 1	Case 2	Case 3
p Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.690 ± 0.004	1.690 ± 0.004	1.690 ± 0.004
	R_1 (GV)	1.93 ± 0.03	1.93 ± 0.03	1.93 ± 0.03
	γ_2	2.3417 ± 0.0002	2.3417 ± 0.0002	2.3417 ± 0.0002
	R_2 (GV)	-----	338 ± 20	553 ± 30
	γ_3	-----	2.163 ± 0.007	2.186 ± 0.008

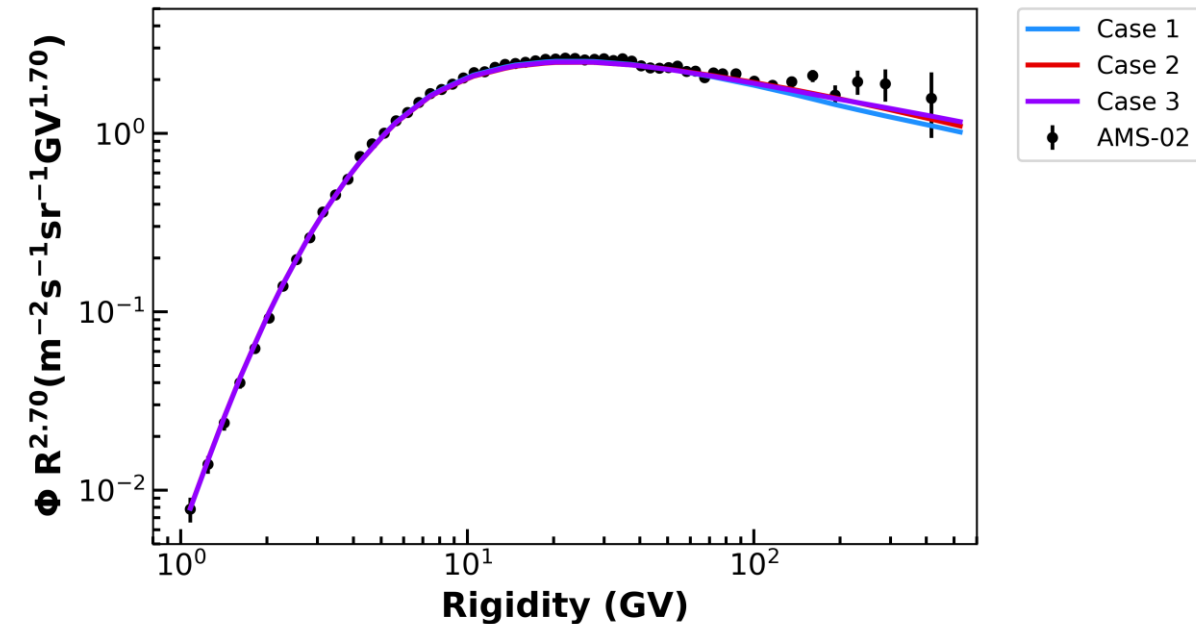
- Considering only a diffusion coefficient break results in insufficient hardening for p.
- GALPROP produces spectral hardening in agreement with p when including a source spectrum break.



Antiproton Spectrum

		Case 1	Case 2	Case 3
p Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.690 ± 0.004	1.690 ± 0.004	1.690 ± 0.004
	R_1 (GV)	1.93 ± 0.03	1.93 ± 0.03	1.93 ± 0.03
	γ_2	2.3417 ± 0.0002	2.3417 ± 0.0002	2.3417 ± 0.0002
	R_2 (GV)	-----	338 ± 20	553 ± 30
	γ_3	-----	2.163 ± 0.007	2.186 ± 0.008

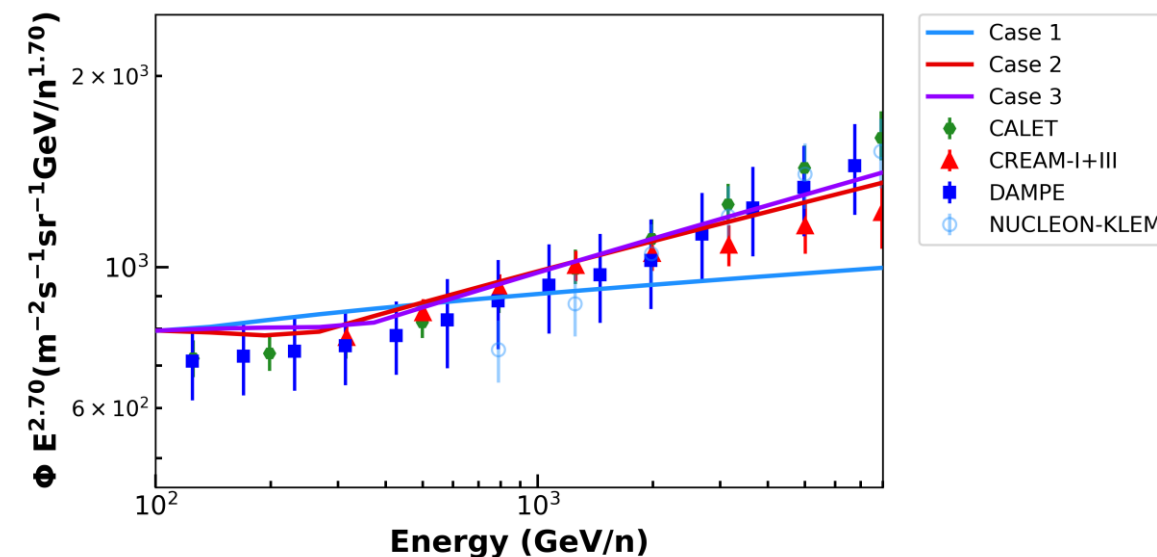
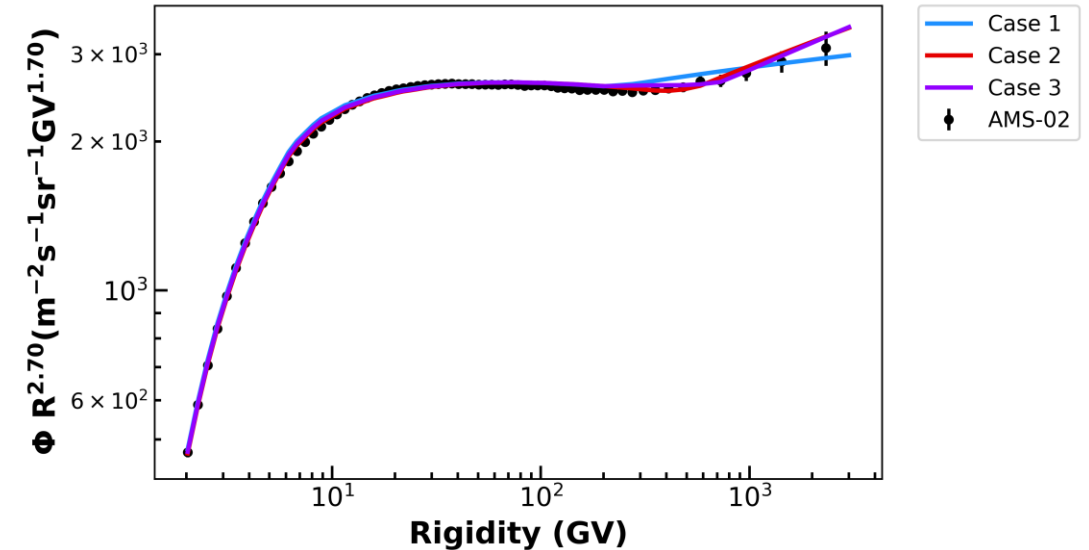
- Neither a diffusion break, source break, or a combination of both breaks can describe the hardening seen in the $\bar{p}$ data.



Helium Spectrum

		Case 1	Case 2	Case 3
He Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.565 ± 0.009	1.565 ± 0.009	1.565 ± 0.009
	R_1 (GV)	2.44 ± 0.03	2.44 ± 0.03	2.44 ± 0.03
	γ_2	2.2799 ± 0.0006	2.2799 ± 0.0006	2.2799 ± 0.0006
	R_2 (GV)	-----	478 ± 23	687 ± 49
	γ_3	-----	2.059 ± 0.010	2.087 ± 0.009

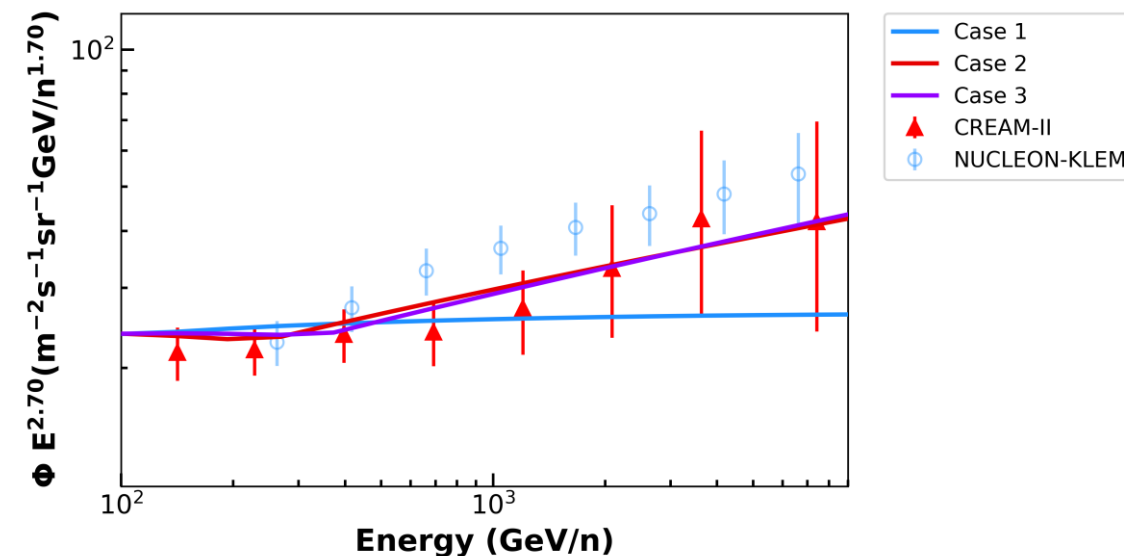
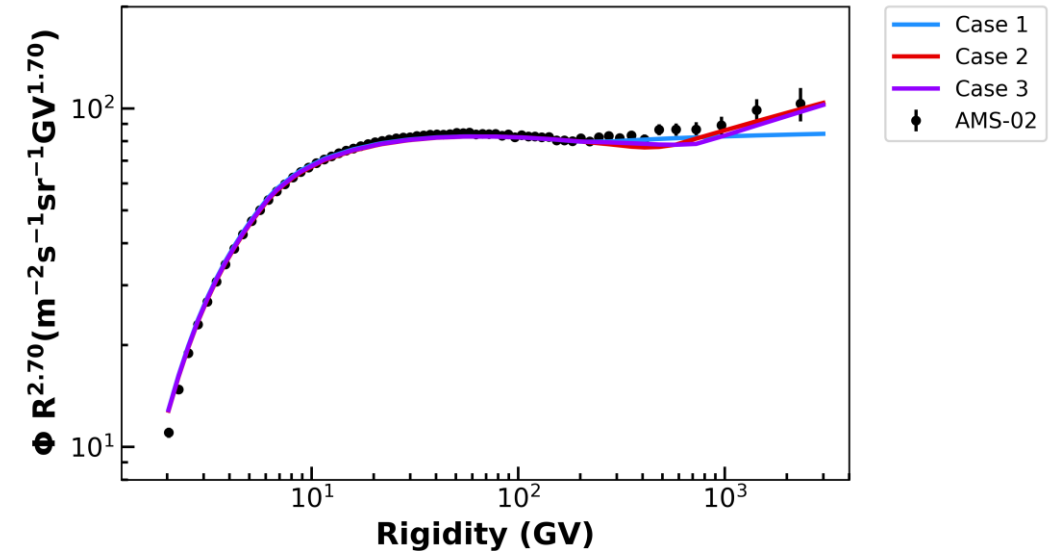
- Only having a diffusion coefficient break results in insufficient hardening for He.
- GALPROP produces spectral hardening in agreement with He when including a source spectrum break.



Carbon Spectrum

		Case 1	Case 2	Case 3
C, N, O Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.137 ± 0.022	1.137 ± 0.022	1.137 ± 0.022
	R_1 (GV)	2.01 ± 0.03	2.01 ± 0.03	2.01 ± 0.03
	γ_2	2.3234 ± 0.0005	2.3234 ± 0.0005	2.3234 ± 0.0005
	R_2 (GV)	-----	478 ± 23	687 ± 49
	γ_3	-----	2.059 ± 0.010	2.087 ± 0.009

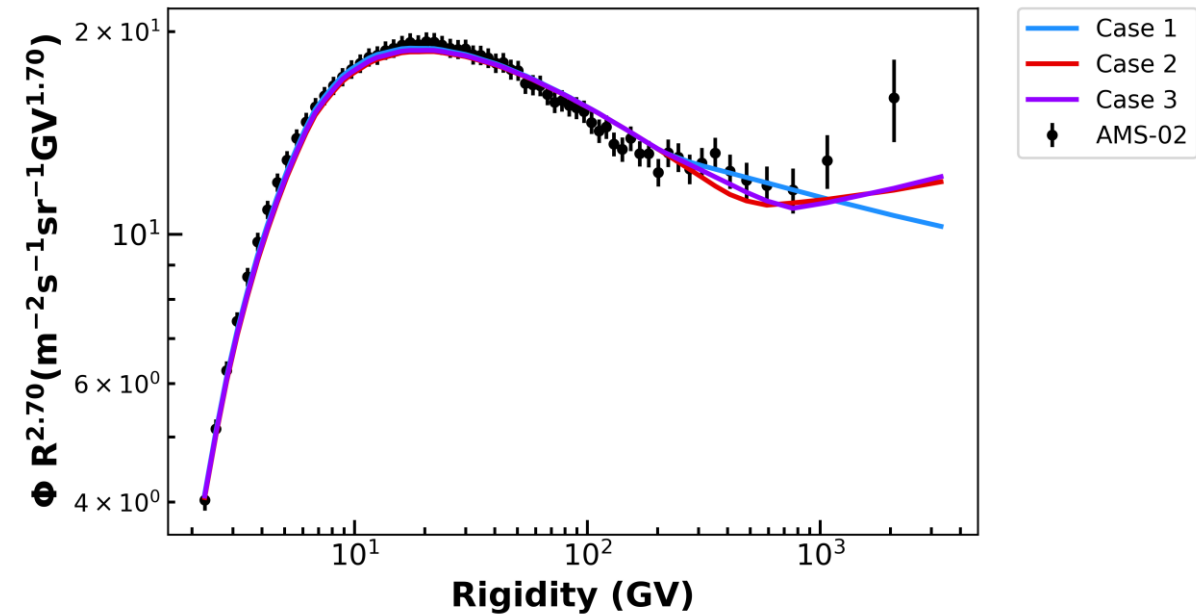
- The spectral hardening from only considering diffusion coefficient effects is not sufficient for the C data.
- Considering a source spectrum break creates spectral hardening sufficient for the C data.



Nitrogen Spectrum

		Case 1	Case 2	Case 3
C, N, O Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.137 ± 0.022	1.137 ± 0.022	1.137 ± 0.022
	R_1 (GV)	2.01 ± 0.03	2.01 ± 0.03	2.01 ± 0.03
	γ_2	2.3234 ± 0.0005	2.3234 ± 0.0005	2.3234 ± 0.0005
	R_2 (GV)	-----	478 ± 23	687 ± 49
	γ_3	-----	2.059 ± 0.010	2.087 ± 0.009

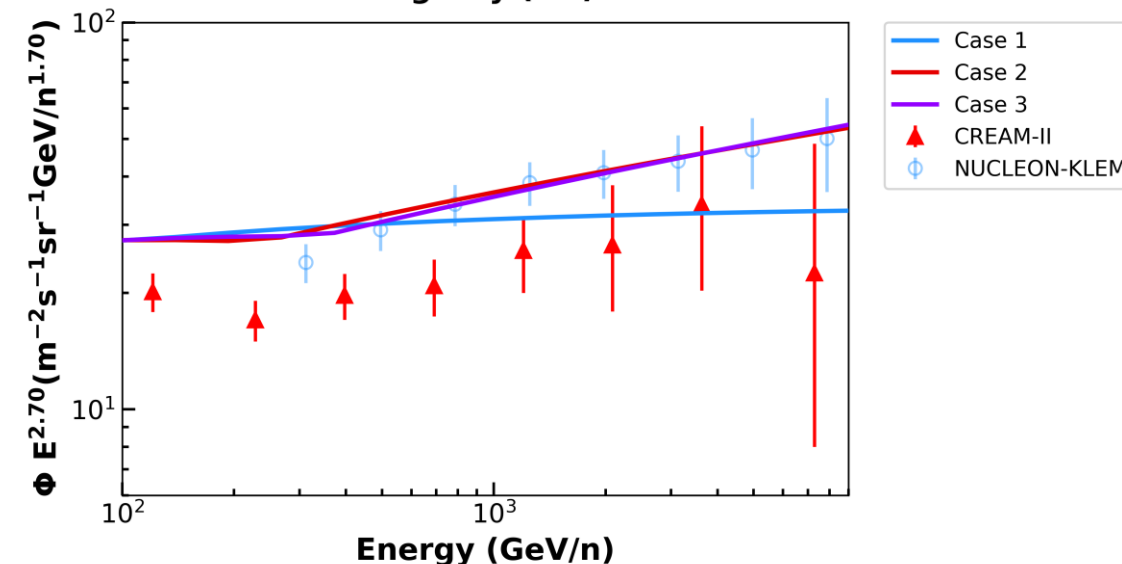
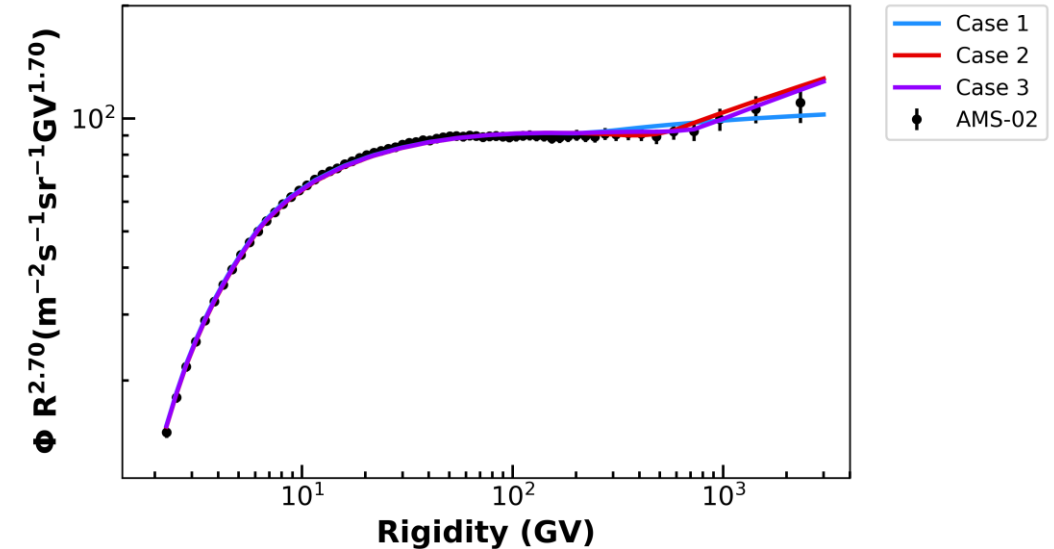
- Spectral hardening from only diffusion effects does not cause sufficient hardening to follow the N data.
- A source break is necessary to follow the hardening of the N data.



Oxygen Spectrum

		Case 1	Case 2	Case 3
C, N, O Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.137 ± 0.022	1.137 ± 0.022	1.137 ± 0.022
	R_1 (GV)	2.01 ± 0.03	2.01 ± 0.03	2.01 ± 0.03
	γ_2	2.3234 ± 0.0005	2.3234 ± 0.0005	2.3234 ± 0.0005
	R_2 (GV)	-----	478 ± 23	687 ± 49
	γ_3	-----	2.059 ± 0.010	2.087 ± 0.009

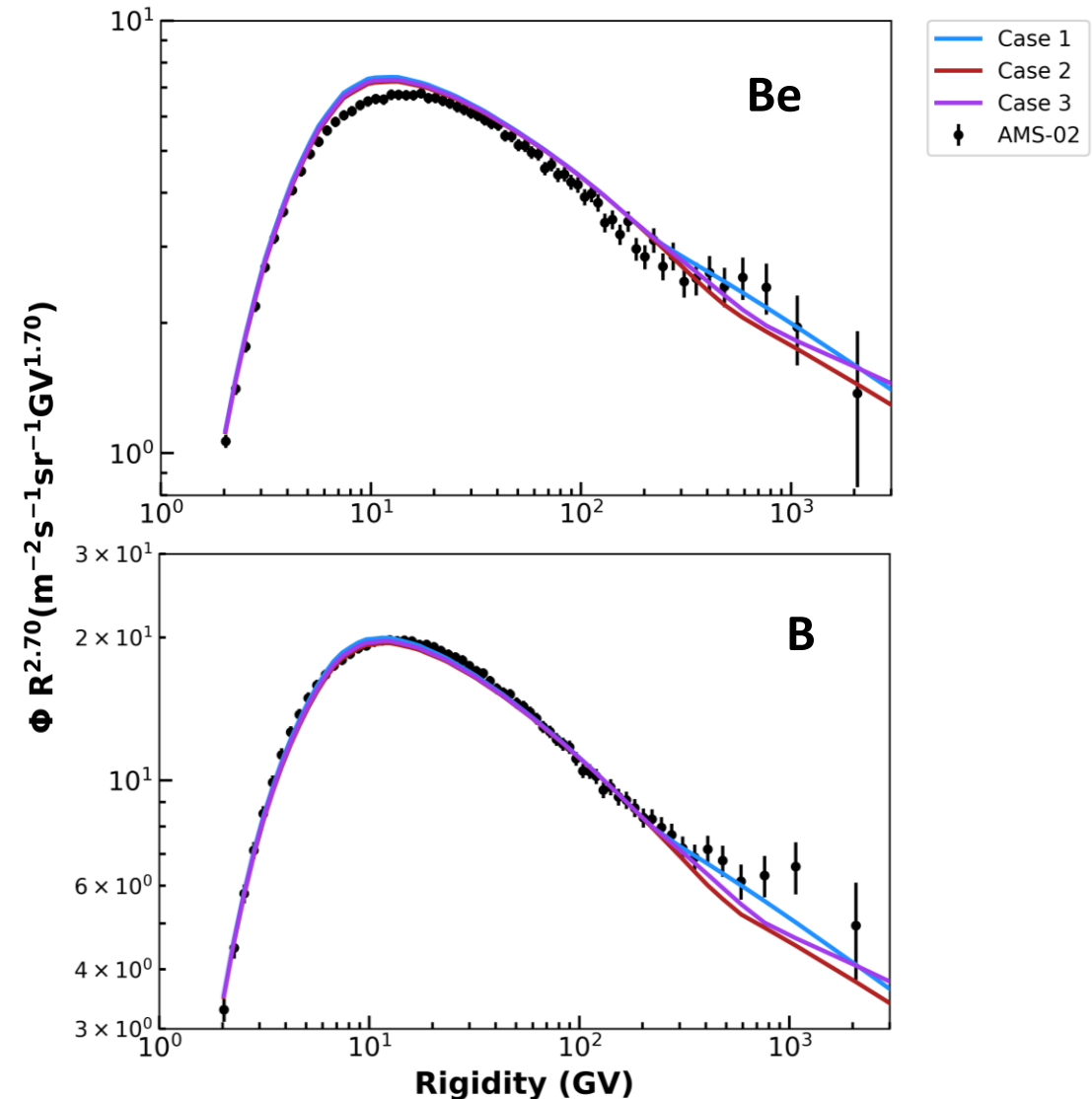
- The spectral hardening from only considering diffusion coefficient effects is not sufficient for the O data.
- Considering a source spectrum break creates spectral hardening sufficient for the O data.



Beryllium and Boron Spectra

		Case 1	Case 2	Case 3
C, N, O Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.137 ± 0.022	1.137 ± 0.022	1.137 ± 0.022
	R_1 (GV)	2.01 ± 0.03	2.01 ± 0.03	2.01 ± 0.03
	γ_2	2.3234 ± 0.0005	2.3234 ± 0.0005	2.3234 ± 0.0005
	R_2 (GV)	-----	478 ± 23	687 ± 49
	γ_3	-----	2.059 ± 0.010	2.087 ± 0.009

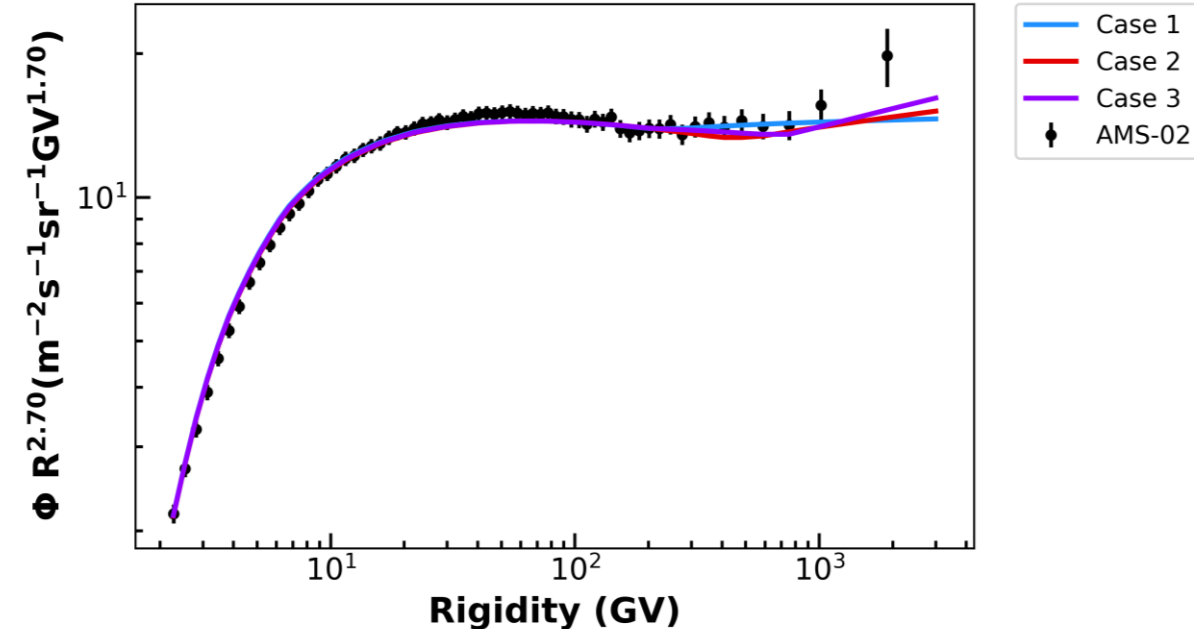
- Considering only a source spectrum break does not sufficiently describe the hardening for the Be and B data.
- A diffusion coefficient break is necessary to create sufficient hardening for both elements, as in Case 1 or Case 3.



Neon Spectrum

		Case 1	Case 2	Case 3
Ne, Si, S Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.570 ± 0.023	1.570 ± 0.023	1.570 ± 0.023
	R_1 (GV)	3.87 ± 0.10	3.87 ± 0.10	3.87 ± 0.10
	γ_2	2.322 ± 0.002	2.322 ± 0.002	2.322 ± 0.002
	R_2 (GV)	-----	463 ± 95	714 ± 99
	γ_3	-----	2.157 ± 0.064	2.148 ± 0.067

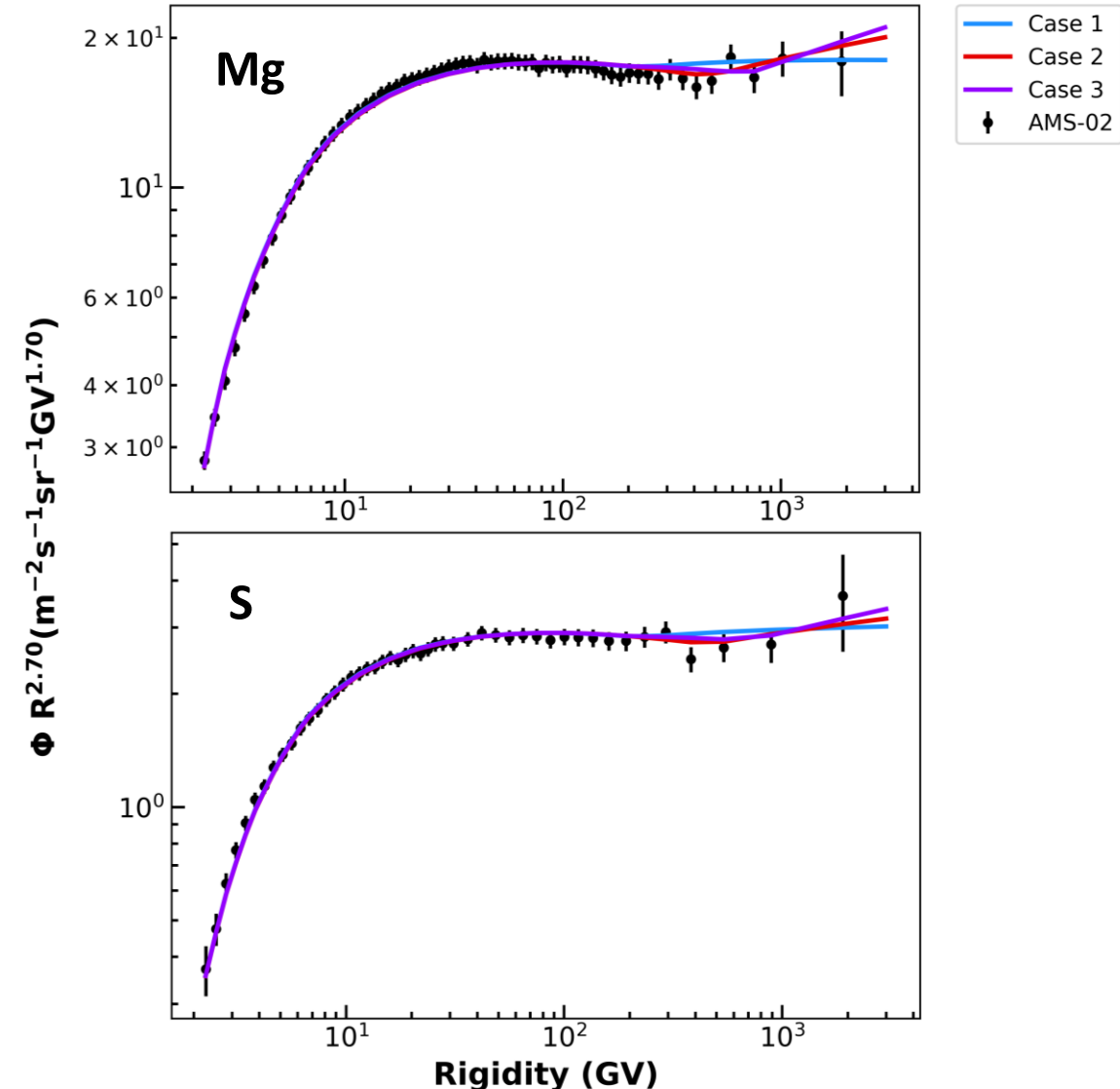
- Only having a diffusion break does not produce sufficient hardening for the Ne data.
- GALPROP produces spectral hardening in agreement with Ne when including a source break.



Magnesium and Sulfur Spectra

		Case 1	Case 2	Case 3
Ne, Si, S Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.570 ± 0.023	1.570 ± 0.023	1.570 ± 0.023
	R_1 (GV)	3.87 ± 0.10	3.87 ± 0.10	3.87 ± 0.10
	γ_2	2.322 ± 0.002	2.322 ± 0.002	2.322 ± 0.002
	R_2 (GV)	-----	463 ± 95	714 ± 99
	γ_3	-----	2.157 ± 0.064	2.148 ± 0.067
		Case 1	Case 2	Case 3
Mg Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.463 ± 0.041	1.463 ± 0.041	1.463 ± 0.041
	R_1 (GV)	3.15 ± 0.15	3.15 ± 0.15	3.15 ± 0.15
	γ_2	2.355 ± 0.003	2.355 ± 0.003	2.355 ± 0.003
	R_2 (GV)	-----	463 ± 95	714 ± 99
	γ_3	-----	2.157 ± 0.064	2.148 ± 0.067

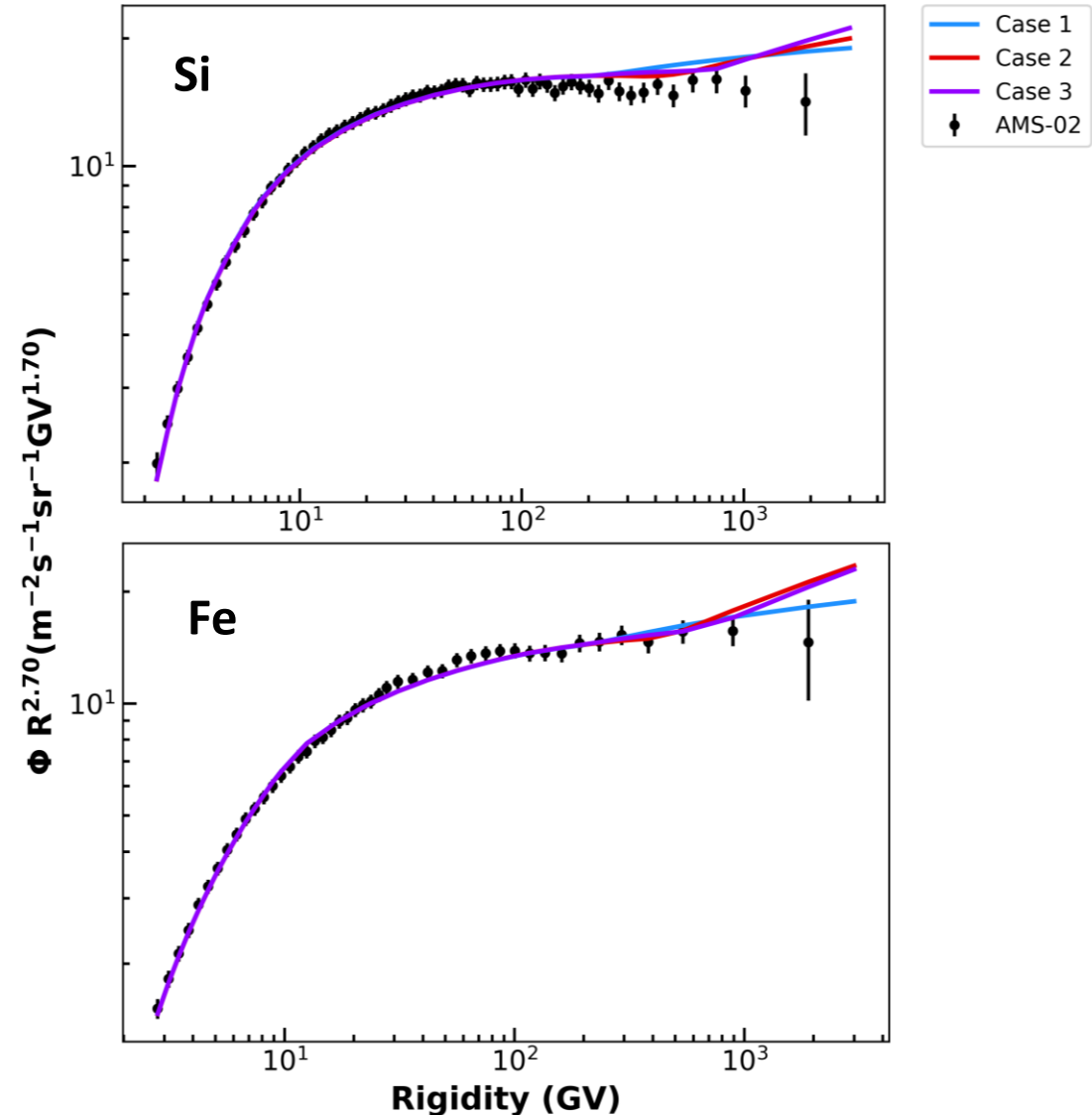
- Including a diffusion break, source breaks, or combination of both breaks produces hardening that is in agreement with the Mg and S data.



Silicon and Iron Spectra

		Case 1	Case 2	Case 3
Ne, Si, S Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.570 ± 0.023	1.570 ± 0.023	1.570 ± 0.023
	R_1 (GV)	3.87 ± 0.10	3.87 ± 0.10	3.87 ± 0.10
	γ_2	2.322 ± 0.002	2.322 ± 0.002	2.322 ± 0.002
	R_2 (GV)	-----	463 ± 95	714 ± 99
	γ_3	-----	2.157 ± 0.064	2.148 ± 0.067
		Case 1	Case 2	Case 3
Fe Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.986 ± 0.014	1.986 ± 0.014	1.986 ± 0.014
	R_1 (GV)	11.4 ± 0.5	11.4 ± 0.5	11.4 ± 0.5
	γ_2	2.311 ± 0.006	2.311 ± 0.006	2.311 ± 0.006
	R_2 (GV)	-----	478 ± 23	687 ± 49
	γ_3	-----	2.059 ± 0.010	2.087 ± 0.009

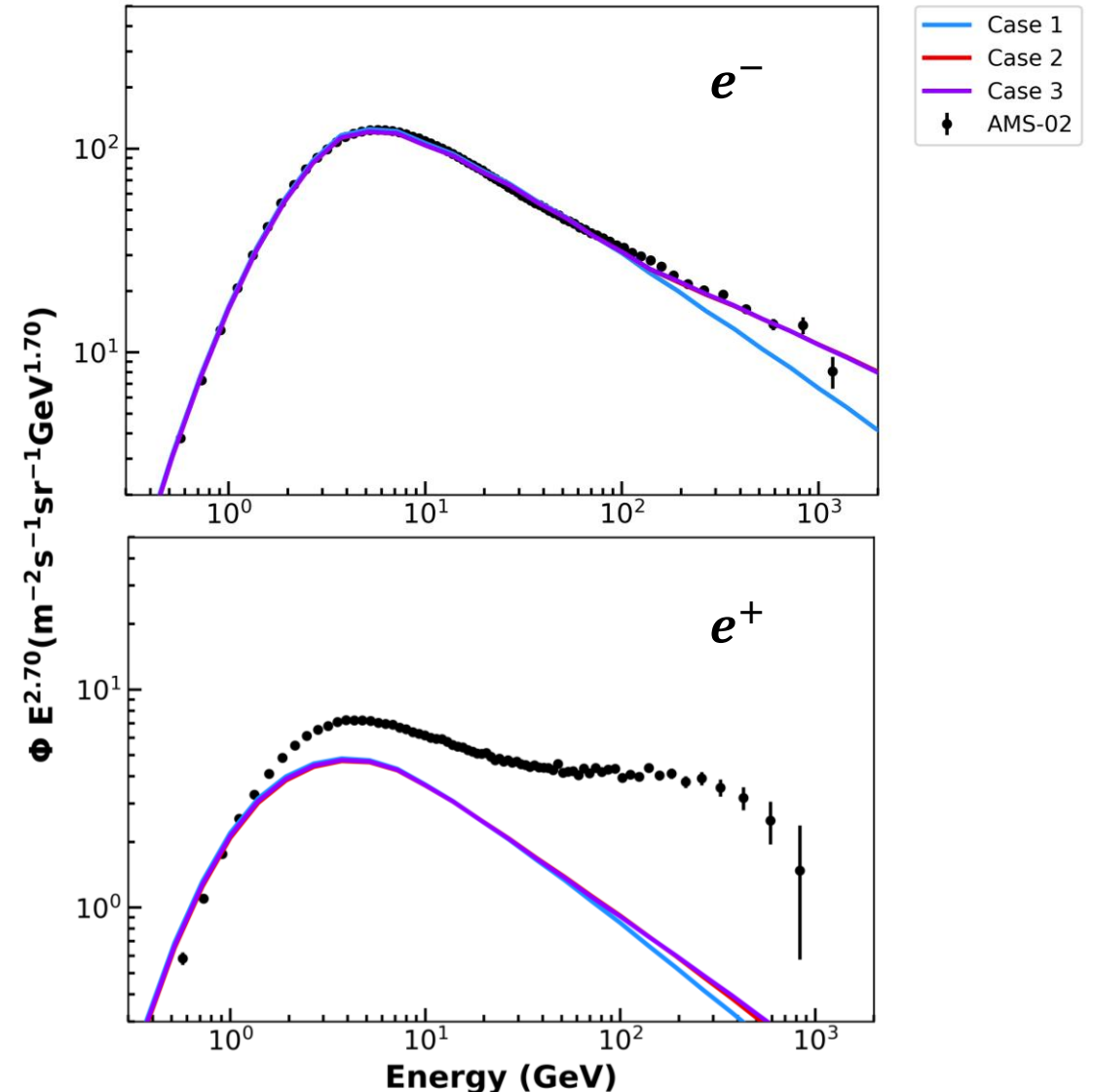
- Including a diffusion break, source breaks, or combination of both breaks is found to be consistent with the Si and the Fe data.



e^- and e^+ Spectra

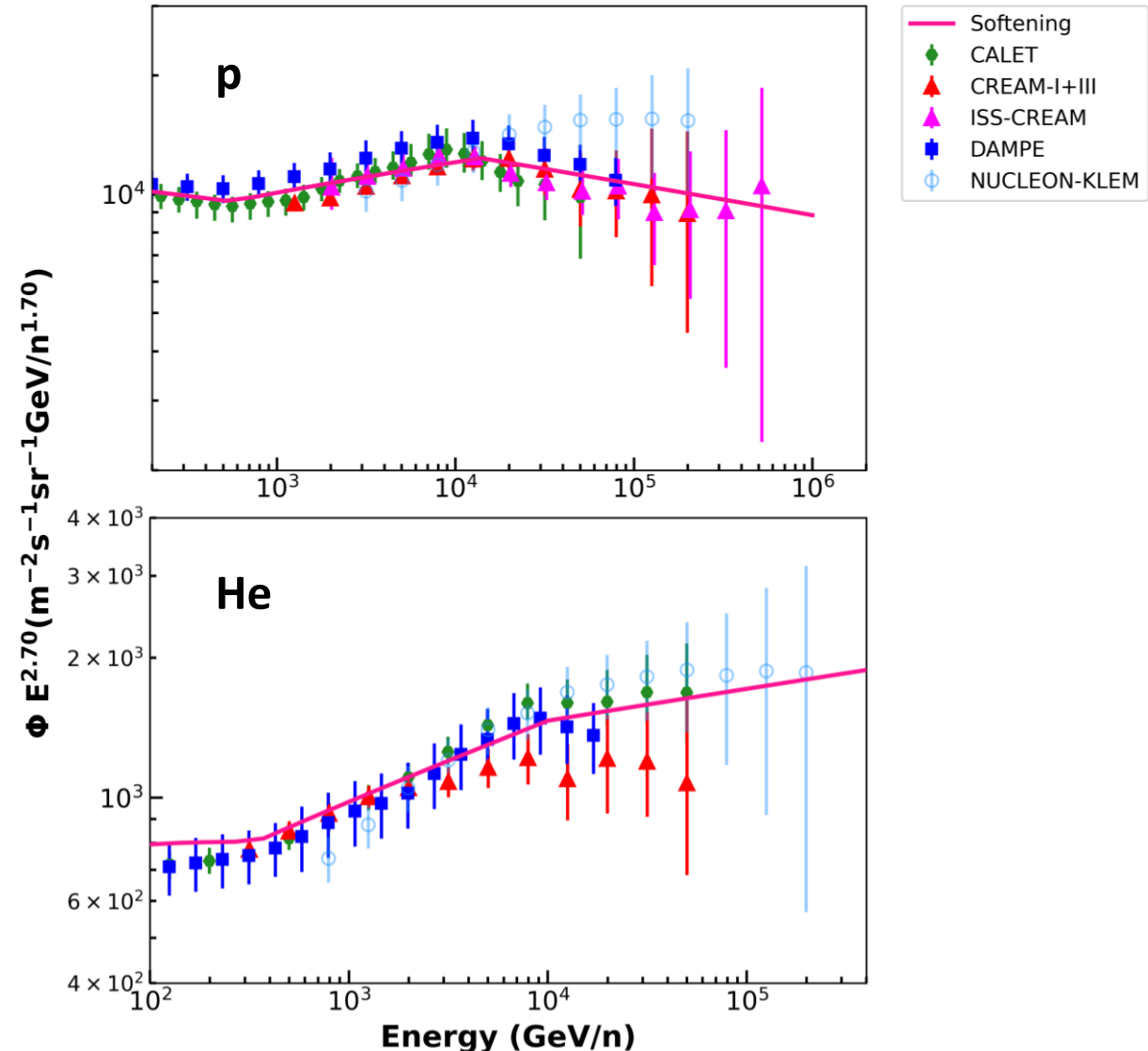
		Case 1	Case 2	Case 3
e^- Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.474 ± 0.015	1.474 ± 0.015	1.474 ± 0.015
	R_1 (GV)	4.21 ± 0.03	4.21 ± 0.03	4.21 ± 0.03
	γ_2	2.6552 ± 0.0007	2.6552 ± 0.0007	2.6552 ± 0.0007
	R_2 (GV)	-----	169 ± 17	156 ± 6
	γ_3	-----	2.378 ± 0.035	2.405 ± 0.012

- Considering only diffusion effects does not sufficiently describe the hardening in the e^- data.
- Incorporating a source break is necessary for sufficient hardening for the e^- data.
- Neither a diffusion break, a source break, or a combination of both breaks can fit the positron excess.



Proton and Helium Spectra

- Results of the p and He softening are built off Case 3 due to its sufficient fit to different elemental spectra and e^- data simultaneously.
- An additional source break at $R_3 = 13.89 \pm 0.02$ TV with an index of $\gamma_3 = 2.186 \pm 0.008$ and $\gamma_4 = 2.334 \pm 0.029$ below and above the break is consistent with the softening in p.
- An additional source break at $R_3 = 20 \pm 1$ TV with an index of $\gamma_3 = 2.087 \pm 0.009$ and $\gamma_4 = 2.188 \pm 0.049$ below and above the break is consistent with the softening in He.
- He is harder than p by ~ 0.1 from 687 GV to 13.89 TV.

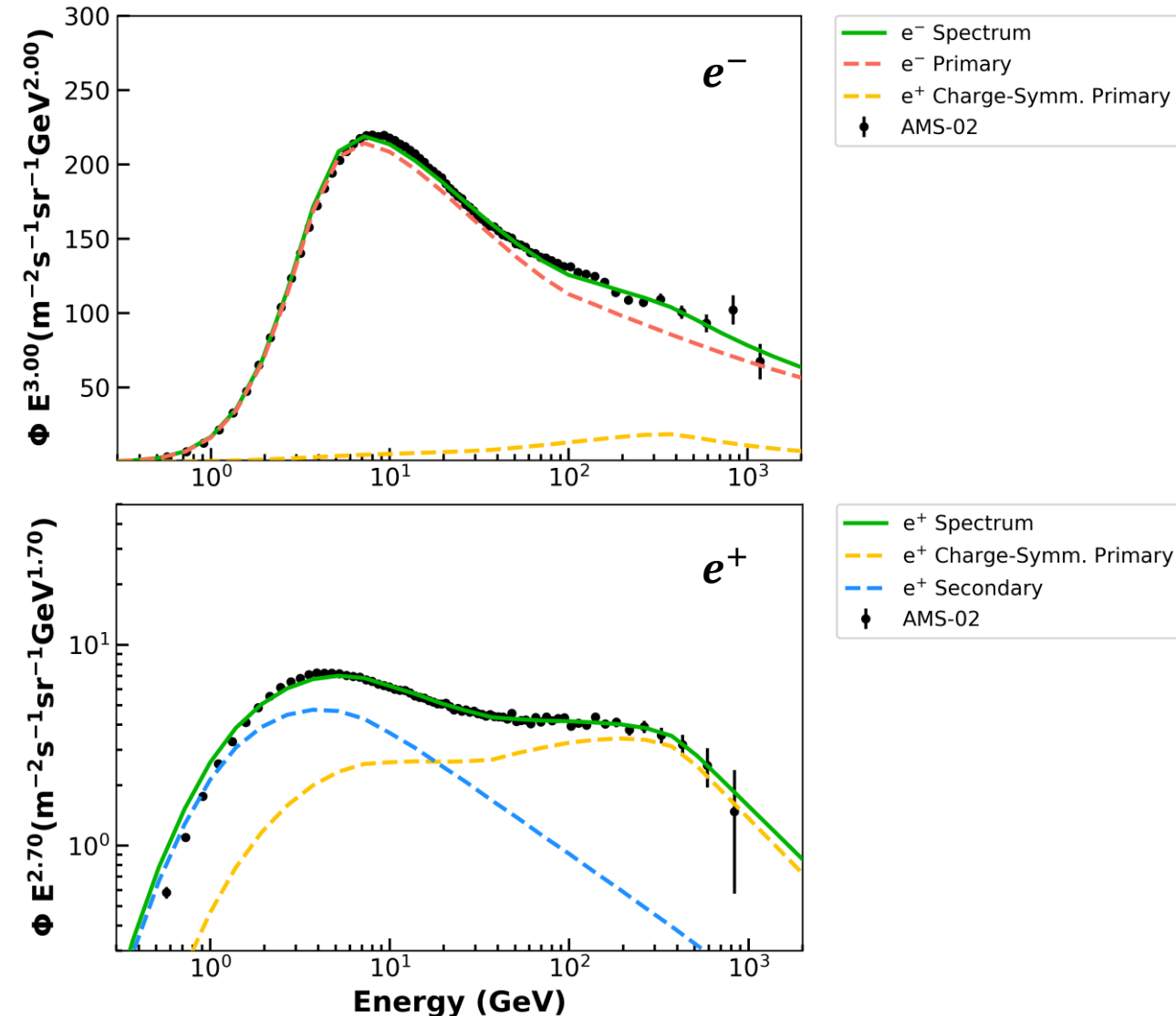


e^- and e^+ Spectra

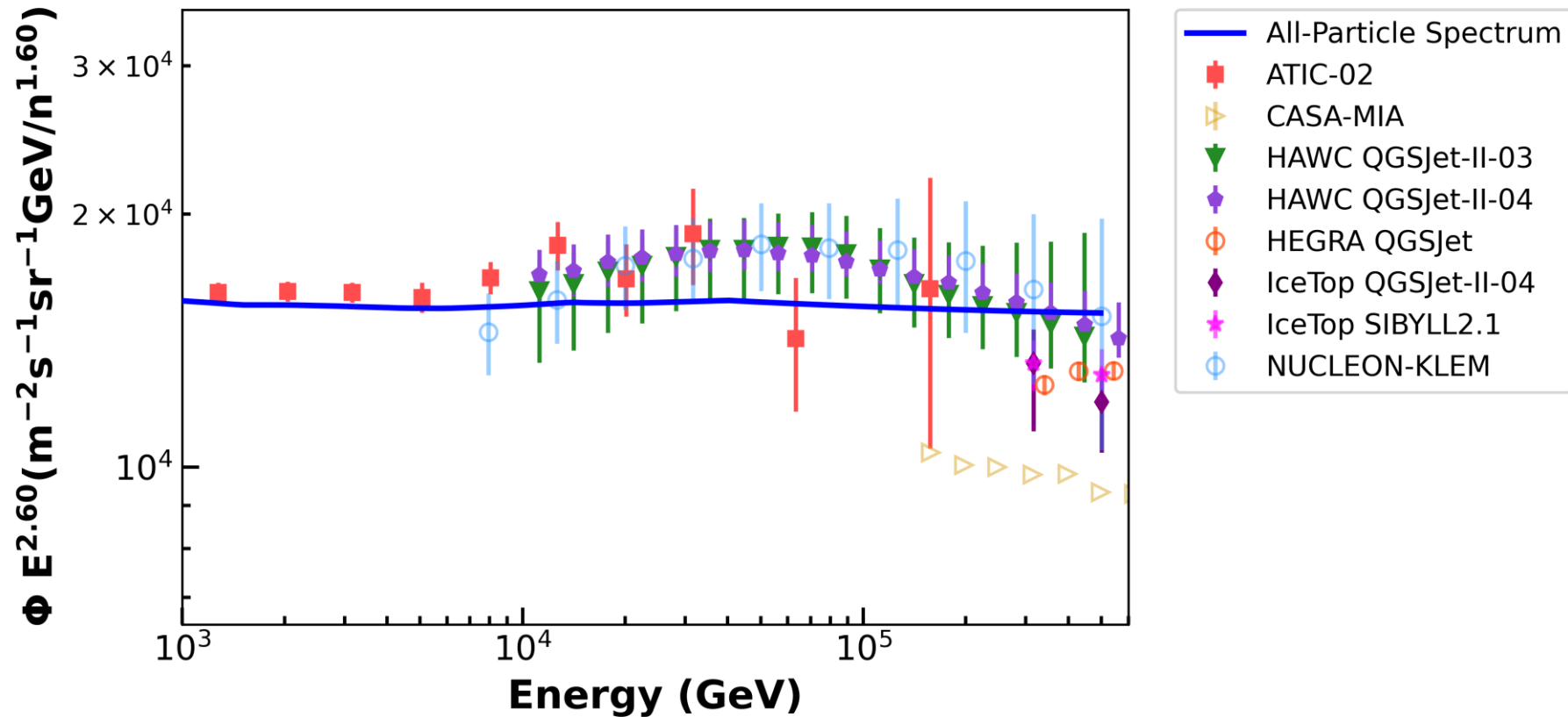
		e^- Primary
e^- Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.492 ± 0.026
	R_1 (GV)	4.48 ± 0.06
	γ_2	2.703 ± 0.006
	R_2 (GV)	99 ± 3
	γ_3	2.504 ± 0.012

		Charge-Symm.
e^+ Source Injection: $\phi \propto R^{-\gamma}$	γ_1	2.258 ± 0.010
	R_1 (GV)	38 ± 4
	γ_2	1.801 ± 0.038
	R_2 (GV)	412 ± 178
	γ_3	2.862 ± 0.630

- Results are built off Case 3 due to its sufficient fit to different elemental spectra and e^- data simultaneously.
- Adding a charge-symmetric primary e^+ source, with an abundance of 97.2 ± 0.9 relative to the primary e^- abundance of $1.06 \cdot 10^3$, can better fit the e^+ data.
- This charge-symmetric primary e^+ source can also be incorporated into the e^- data.



All-Particle Spectrum



- The spectral hardening from both diffusion and source effects, softening from p and He spectra, and primary charge-symmetric e^+ source are compatible with the all-particle spectrum.

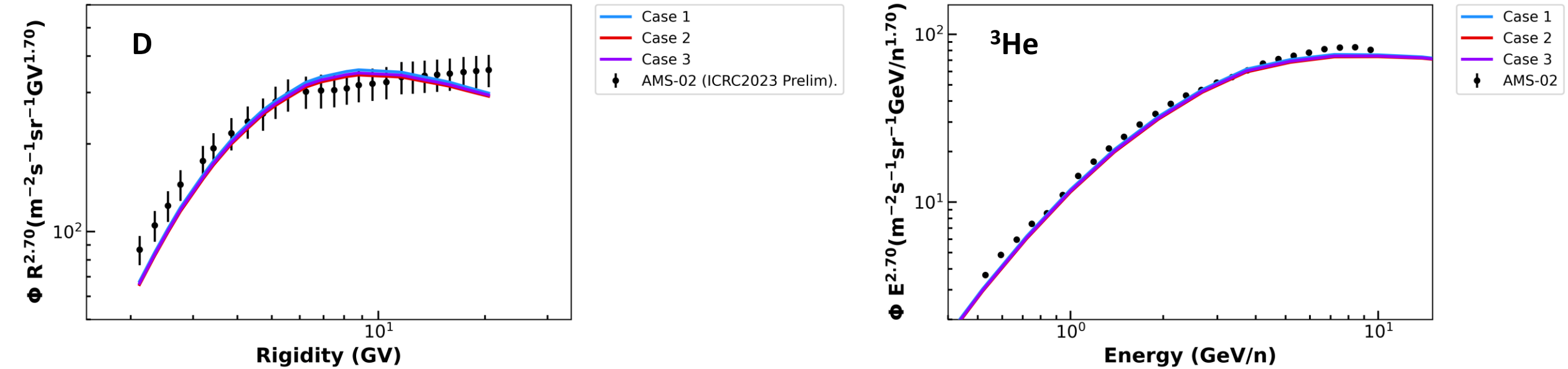
Conclusions

- While a diffusion coefficient break could fit the secondary spectra (Be, B), a combination of both a diffusion coefficient break and source spectrum breaks fits the primary light elements (p, He, C, O), nitrogen, primary heavy elements (Ne, Mg, Si, S, Fe), secondary spectra, and e^- data simultaneously.
- An additional source break at 13.89 ± 0.02 TV and 20.0 ± 1 TV is found to fit the softening of p and He, respectively.
- He is harder than p by ~ 0.1 from 687 GV to 13.89 TV.
- A primary charge-symmetric e^+ source is found to fit the positron excess.
- These spectral features are compatible with the all-particle spectrum.
- Next Steps:
 - Fitting the excess seen in the $\bar{p}$ data above ~ 100 GeV.
 - Fitting the fluorine data and its hardening above ~ 200 GV.

Appendix

D and ^3He Spectra, $\bar{p}/p$ Ratio

D and ^3He Spectra

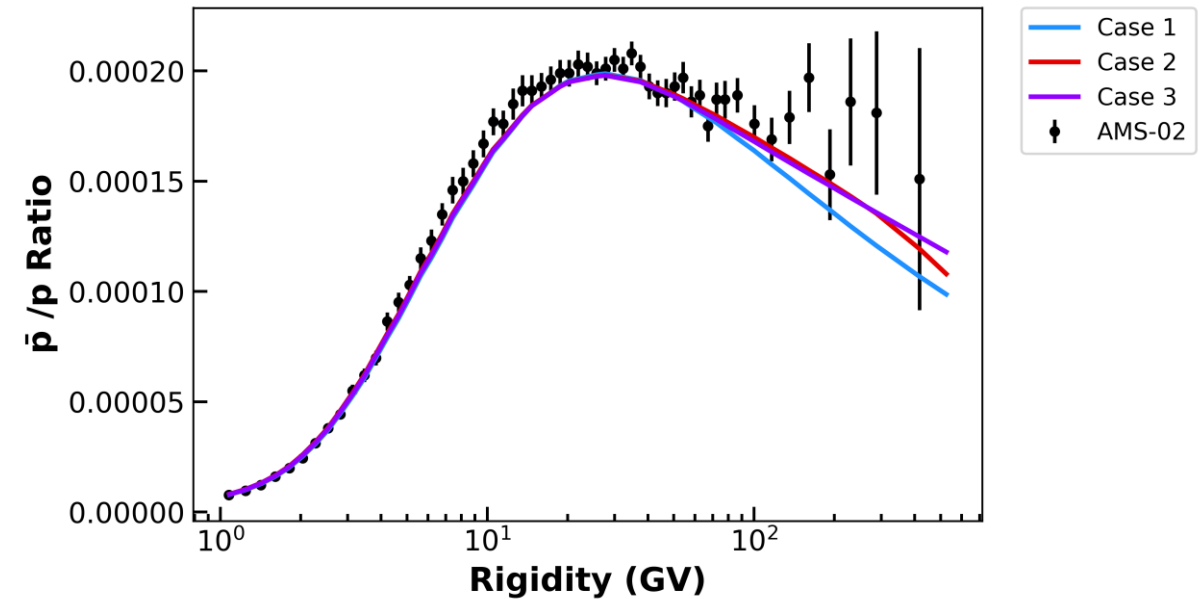


- All three cases produce acceptable D and ^3He spectra.

$\bar{p}/p$ Ratio

		Case 1	Case 2	Case 3
p Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.690 ± 0.004	1.690 ± 0.004	1.690 ± 0.004
	R_1 (GV)	1.93 ± 0.03	1.93 ± 0.03	1.93 ± 0.03
	γ_2	2.3417 ± 0.0002	2.3417 ± 0.0002	2.3417 ± 0.0002
	R_2 (GV)	-----	338 ± 20	553 ± 30
	γ_3	-----	2.163 ± 0.007	2.186 ± 0.008

- Neither a diffusion break, source break, or a combination of both breaks can describe the hardening seen in the $\bar{p}$ spectrum.



Silicon and Iron Spectra

		Case 1	Case 2	Case 3
Ne, Si, S Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.570 ± 0.023	1.570 ± 0.023	1.570 ± 0.023
	R_1 (GV)	3.87 ± 0.10	3.87 ± 0.10	3.87 ± 0.10
	γ_2	2.322 ± 0.002	2.322 ± 0.002	2.322 ± 0.002
	R_2 (GV)	-----	463 ± 95	714 ± 99
	γ_3	-----	2.157 ± 0.064	2.148 ± 0.067
		Case 1	Case 2	Case 3
Fe Source Injection: $\phi \propto R^{-\gamma}$	γ_1	1.986 ± 0.014	1.986 ± 0.014	1.986 ± 0.014
	R_1 (GV)	11.4 ± 0.5	11.4 ± 0.5	11.4 ± 0.5
	γ_2	2.311 ± 0.006	2.311 ± 0.006	2.311 ± 0.006
	R_2 (GV)	-----	478 ± 23	687 ± 49
	γ_3	-----	2.059 ± 0.010	2.087 ± 0.009

- Including a diffusion break, source breaks, or combination of both breaks is found to be consistent with the Si and the Fe data.

