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Unified Picture of Galactic CR Transport

Benedikt Schroer

Carmelo Evoli, Pasquale Blasi

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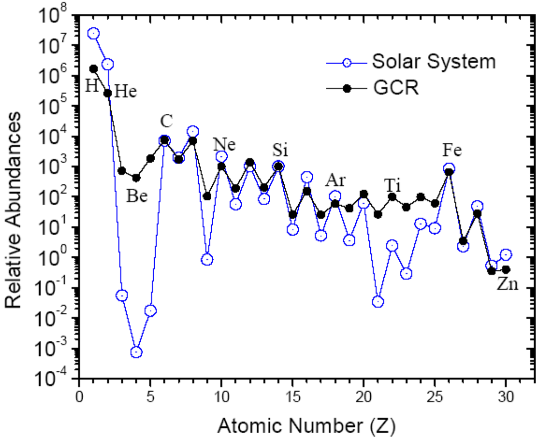
Content

Observations

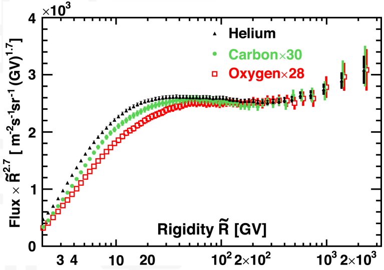
Observations

- Certain Elements are significantly more abundant in CRs compared to their abundances in the solar system

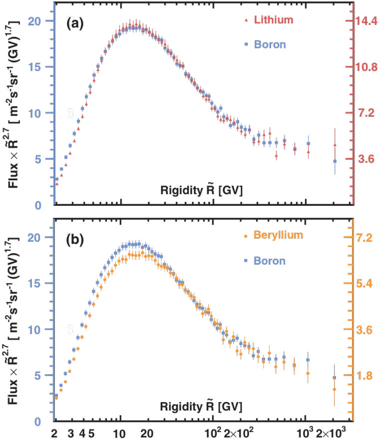


[http://www.srl.caltech.edu]

Observations



- The overabundant elements show also a steeper spectrum than the other nuclei
- Interpretation of these observations: The secondary CRs are produced during CR transport via spallation processes



[AMS Collaboration 2021]

Different Approaches

- Two fundamentally different approaches:

- Significant fraction of secondaries is produced via spallation processes in the source surroundings at high rigidities [D'Angelo et al. 2016; Mertsch et al. 2021]

- Most secondaries are produced via spallation in the Galactic disk during the CR transport [Evoli et al. 2020; Weinrich et al. 2020; Korsmeier, Cuoco 2021; Boschini et al. 2021]

Different Approaches

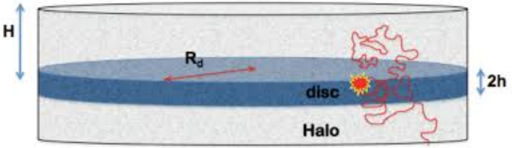
- Two fundamentally different approaches:

- Significant fraction of secondaries is produced via spallation processes in the source surroundings at high rigidities [D'Angelo et al. 2016; Mertsch et al. 2021]
- Naturally explains the observed value and flatness of the positron to antiproton ratio [Lipari 2017]

- Most secondaries are produced via spallation in the Galactic disk during the CR transport [Evoli et al. 2020; Weinrich et al. 2020; Korsmeier, Cuoco 2021; Boschini et al. 2021]
- Successful in explaining many primary and secondary CR fluxes with few free parameters

Weighted Slab Model

Standard Picture of CR Transport



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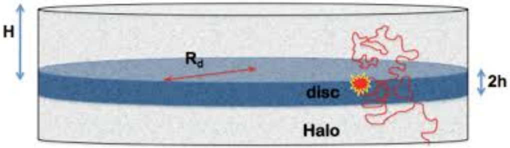

$$-\frac{\partial}{\partial z}\left[D_a\frac{\partial f_a}{\partial z}\right]+v_A\frac{\partial f_a}{\partial z}\quad-\frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_a}{\partial p}\quad-\frac{\partial}{\partial p}p^2D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}f_a$$

$$+\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{a,\mathrm{ion}}f_a\right]+\frac{\mu v(p)\sigma_a}{m}\delta(z)f_a\qquad+\frac{f_a}{\hat{\tau}_{d,a}}$$

$$=\quad 2h_d q_{0,a}(p)\delta(z)\quad+\sum_{a'>a}\frac{\mu\, v(p)\sigma_{a'\to a}}{m}\delta(z)f_{a'}\qquad+\sum_{a'>a}\frac{f_{a'}}{\hat{\tau}_{d,a'}}$$

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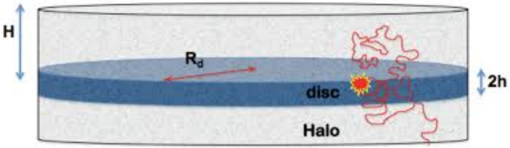

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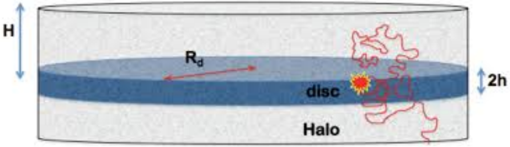

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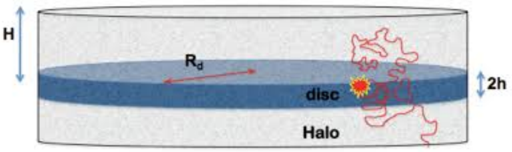

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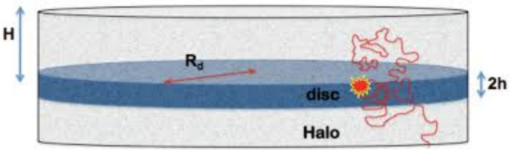

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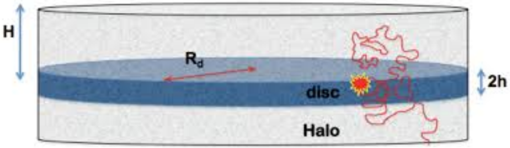

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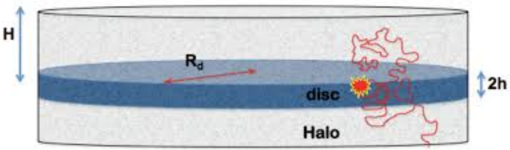

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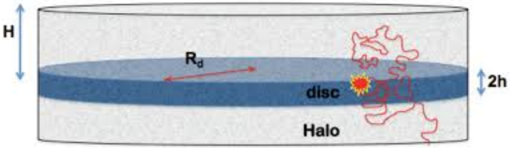

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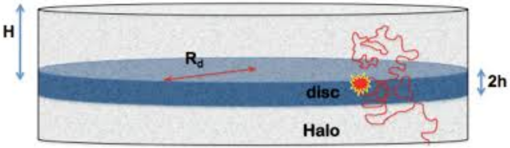

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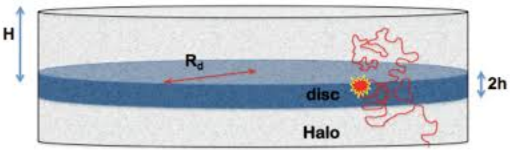

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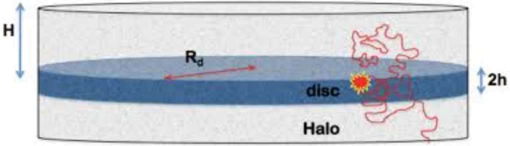

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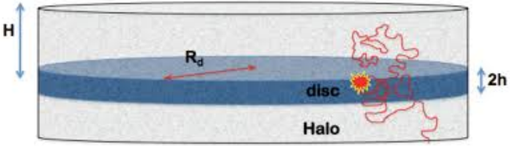
$$= \underbrace{2 h_d q_{0,a}(p)\delta(z)}_{\text{Injection at the sources}} \underbrace{+ \sum_{a' > a} \frac{\mu\, v(p)\sigma_{a' \to a}}{m}\delta(z) f_{a'}}_{\text{Production via Spallation}} \underbrace{+ \sum_{a' > a} \frac{f_{a'}}{\hat{\tau}_{d,a'}}}_{\text{Production due to decay}}$$

Overview

- Same equation used by different groups with different approaches
- E.g. Previous talk $\sim 13-17$ parameters [Korsmeier, Cuoco 2021] to fit light nuclei
- $5-7$ parameters in [Weinrich et al. 2020] to fit light nuclei ratios from $\sim 1-10^3$ GV
- $\gtrsim 100$ parameters for [Boschini et al. 2021] describing all particle spectra from 1 MeV/nucleon to $100-500$ TeV/nucleon
- Large part of these parameters are breaks introduced in the injection spectra of ~ 26 primary nuclei with $2-3$ breaks each $\rightarrow \sim 100$ of parameters
- All models reach reasonable precision at AMS-02 rigidities, though differences arise mainly from different freedom in the cross section parametrisations leading to different conclusions (existence of primary Li vs. no need for it)
- With so many free parameters it is important to keep the underlying physics in mind

Our Model



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$$

Our Model

One can rewrite as equation in terms of grammage and flux $I_a(E) = 4\pi A p^2 f_a(p)$:

$$\frac{I_a(E)}{X_a(E)} + \frac{\mathrm{d}}{\mathrm{d}E}\left(\left[\left(\frac{\mathrm{d}E}{dx}\right)_{ad} + \left(\frac{\mathrm{d}E}{dx}\right)_{ion,a}\right] I_a(E)\right)$$
$$+ \frac{I_a(E)}{X_{\mathrm{cr,a}}} = 2h\frac{A_a p^2 q_a(p)}{\mu v} + \sum_{a'>a} \frac{I_{a'}(E)}{m}\sigma_{a'\to a}$$

- where we introduced the critical grammage $X_{\mathrm{cr,a}} := \frac{m}{\sigma_a}$ and the grammage traversed by nuclei a $X_a(E) := \frac{\mu v}{2 v_A}\left(1 - e^{-\frac{v_A H}{D}}\right)$
- Without energy losses $I_a(E) \propto E^{-\gamma+2}$ for $X_a(E) \gg X_{\mathrm{cr,a}}$ and $I_a(E) \propto E^{-\gamma+2-\delta}$ for $X_a(E) \ll X_{\mathrm{cr,a}}$
- $\Rightarrow$ Secondary over primary ratios flat at low E and $\propto E^{-\delta}$ at high E
- Solutions only sensitive to ratio $\frac{H}{D}$

CRAMS Code

$$\frac{I_a(E)}{X_a(E)} + \frac{\mathrm{d}}{\mathrm{d}E}\left(\left[\left(\frac{\mathrm{d}E}{dx}\right)_{ad} + \left(\frac{\mathrm{d}E}{dx}\right)_{ion,a}\right] I_a(E)\right)$$

$$+\frac{I_a(E)}{X_{\mathrm{cr,a}}} = 2h\frac{A_a p^2 q_a(p)}{\mu v} + \sum_{a'>a}\frac{I_{a'}(E)}{m}\sigma_{a'\to a}$$

$$\Rightarrow \Lambda_{1,a}(E) I_a(E) + \Lambda_{2,a}(E)\partial_E I_a(E) = Q_a(E)$$

Solution:

$$I_a(E) = \int_E dE' \frac{Q_a(E')}{|\Lambda_{2,a}(E')|} \exp\left[-\int_E^{E'} dE'' \frac{\Lambda_{1,a}(E'')}{|\Lambda_{2,a}(E'')|}\right]$$

code solves iteratively this equation starting from the heaviest isotope

$\sim$ 90 different isotopes from Ni-64 to H

Fitting Parameters

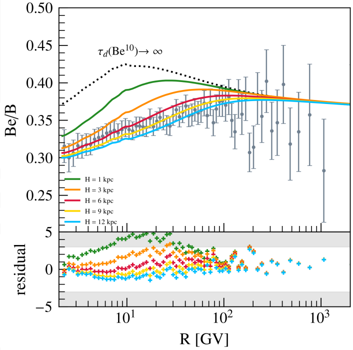
- Spatial transport, including diffusion and advection, comprises 7 free-parameters: D_0, δ, v_A, H, R_b, $\Delta\delta$, s:

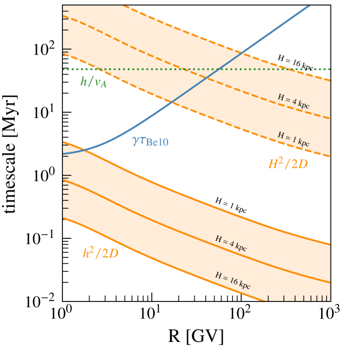
$$D(R) = 2v_A H + \beta D_0 \frac{(R/\mathrm{GV})^{\delta}}{[1 + (R/R_b)^{\Delta\delta/s}]^{s}} \,,$$

  motivated by [Recchia et al. 2016]
- The injection efficiencies ϵ_a of the species H, He, C, N, O, Ne, Mg, Si, S and Fe
- Injection slope γ, assumed to be the same for all of them without any break
- Solar modulation potential ϕ
- Total of 19 parameters
- Restrict ourselves to $R > 10\,\mathrm{GV}$ to reduce the impact of low-energy effects

Lighter Nuclei

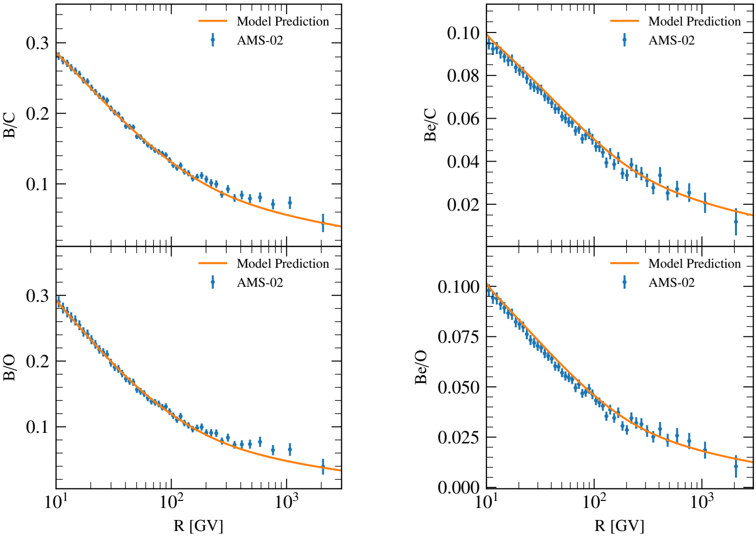
Determining the Halo size





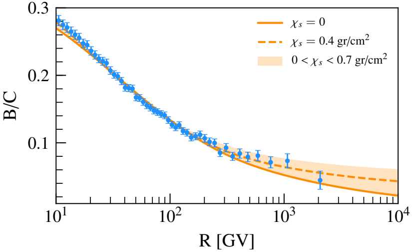
- For radioactive nuclei $X_a(E) \approx \frac{\mu v}{2}\sqrt{\frac{\tau_d}{D}}$ for $\tau_d \ll \min\left(\frac{H^2}{D}, \frac{H}{v_A}\right)$
- With our model a Halo size $H \geq 5$ kpc is preferred [Evoli et al. 2020]
- Influenced by cross section uncertainties
- Compatible with ~ 5 kpc found by [Weinrich et al. 2020] and a bit larger than 4 kpc by [Boschini et al. 2020]
- In the following we fix $H = 7$ kpc in our model

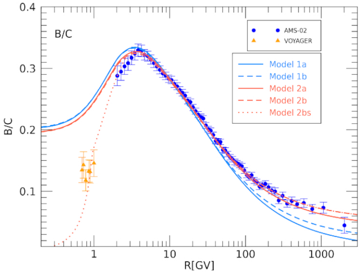
Fit to light Ratios



[Schroer et al. 2021]

Effect of Source Grammage/Reacceleration

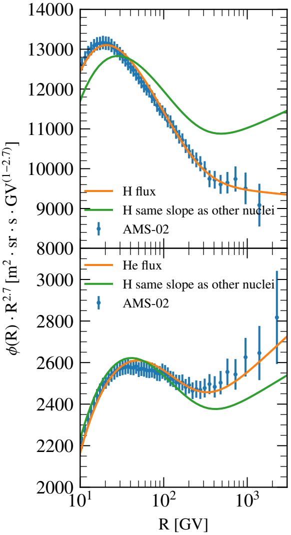




- Neglected effects like source grammage or reacceleration can improve high rigidity agreement

[Evoli et al. 2019], [Bresci et al. 2019]

He and H Results

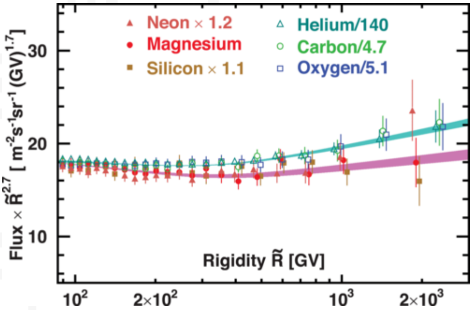


[Schroer et al. 2021]

- H and He require a different slope than other nuclei and each other, confirms result of previous study [Evoli et al. 2019] and independently confirmed by [Weinrich et al. 2020]
- Puzzling result as only theoretical explanation for different slopes is due to different A/Z but then He should have the same slope as other primaries like O
- Raises the question: Is there an observable trend of the acceleration slope with particle mass?

Intermediate-mass and Heavy Nuclei

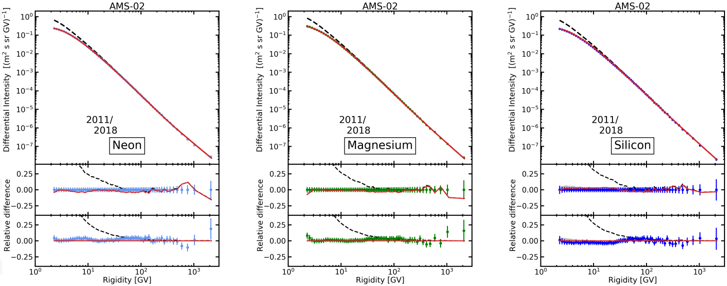
Observation of Intermediate Mass Nuclei



- Note: He has same slope as O but suffers quite different spallation losses $\Rightarrow$ needs to be injected with different slope
- All are primaries, but have different slope than lighter primaries like O
- Is this a confirmation of a mass dependent effect on the injection slope?

[AMS Collaboration 2020]

Intermediate-Mass Nuclei



[Boschini et al. 2020]

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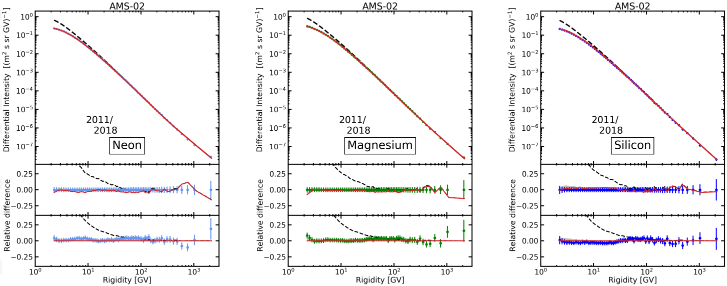
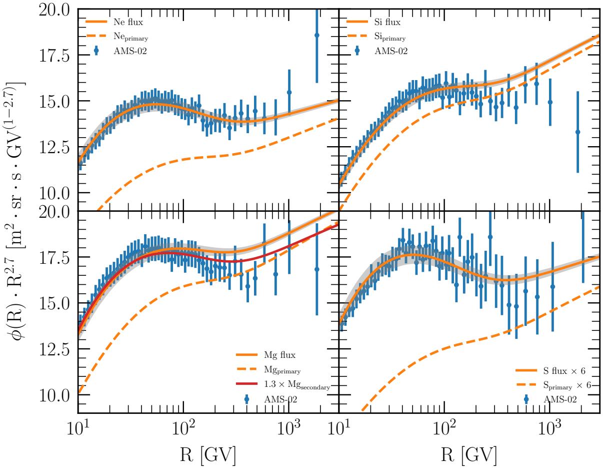


- Fits to intermediate-mass nuclei with different slope for each nuclei (and breaks at R below 10 GV)
- Difference in slope is of the order of ~ 0.04 compatible with the difference between H and He in our model
- Similarly C and O have a different slope of 0.03 to each other in this model

[Boschini et al. 2020]

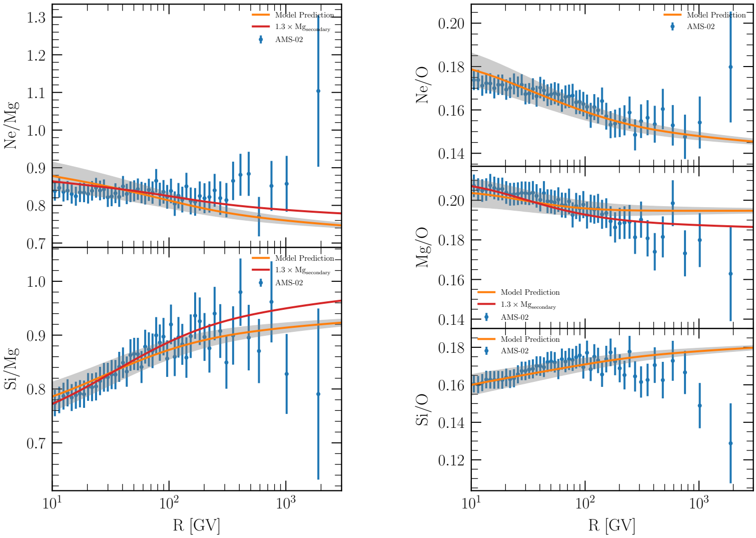
Our Results



- Requiring the same slope leads to reasonably good fits
- Possible tensions can be lifted with cross-section uncertainties (see Mg) and possibly source grammage plays a role as well

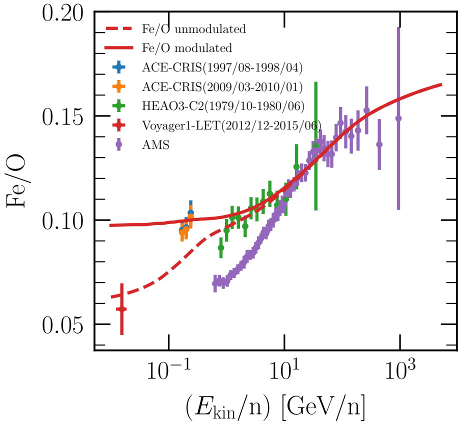
[Schroer et al. 2021]

Fit to the Ratios



[Schroer et al. 2021]

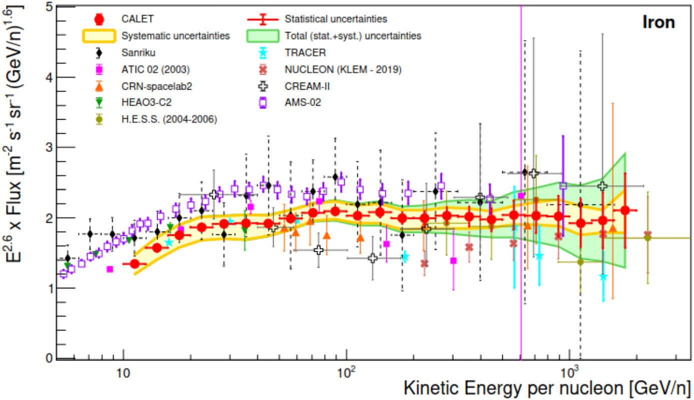
Results



- Our model is compatible with all available data except AMS-02
- Fe data might require to incorporate a new or so far neglected effect into our model

[Schroer et al. 2021]

CALET Fe Measurement



- CALET measurement shows different normalization than AMS-02, but confirms slope
- However does not cover the part of the spectrum where we see the large deviations from our model and other experiments

[CALET Collaboration 2021]

Possible Caveats

So far we tested different possible cavetas of our model:

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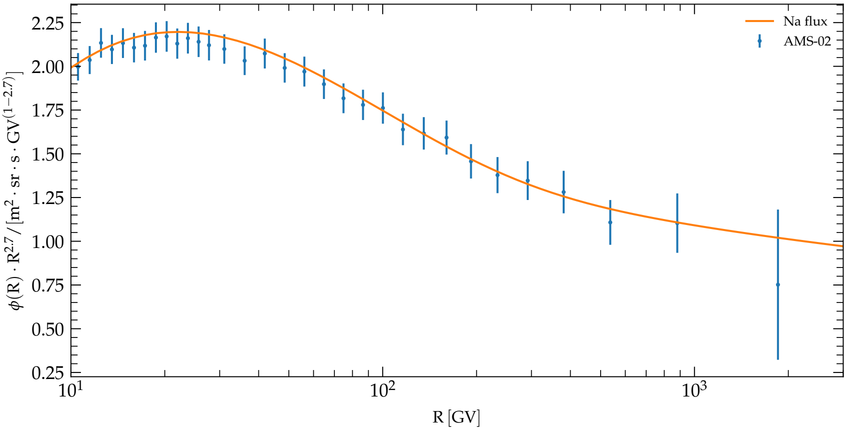
- ~~Iron could have another injection slope~~ Does not give a satisfying fit either, also [Boschini et al. 2021] require a break at 355 GV in the iron injection spectrum in order to fit the data

Preliminary Results



- Prediction for Na flux agrees perfectly

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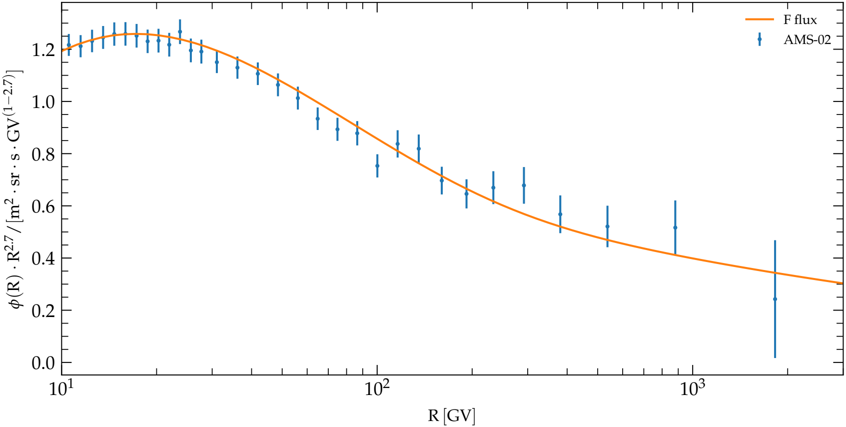

- F flux requires change in cross section of $\sim 15\%$ to reproduce measurement with same parameters

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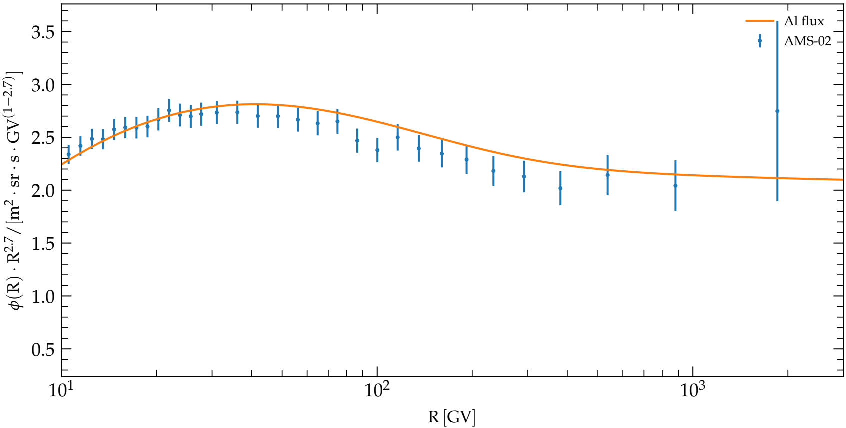

- Al requires slightly different primary injection efficiency

Conclusion

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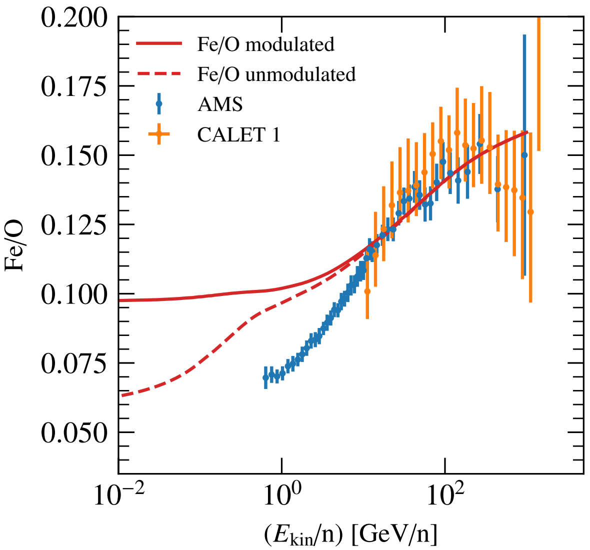
- Many different groups with similar approaches able to fit AMS-02 data of lighter nuclei
- Cross section uncertainties play an important role for dectecting physical anomalies
- Our model is able to reproduce flux of all intermediate-mass to light elements using a single injection slope for all nuclei heavier than He reducing heavily the amount of free parameters compared to other studies like [Boschini et al. 2020] who fit all nuclei simultaneously
- Able to give predictions which are compatible with new data without refitting the model
- There seems to be an issue with Fe, that we still need to understand

Backup Slides

Best fit

v_A 4.4 km/s
D_0 2.48 $\cdot 10^{28}$ cm^2/s
delta 0.56
H slope 4.375
He slope 4.31
nuclei slope 4.33
ϕ 0.49 GV
H 7 kpc
ddelta 0.22
s 0.09
R_b 290 GV

Fe/O CALET



Fe/O modulated
Fe/O unmodulated
AMS
CALET 1
Fe/O
0.200
0.175
0.150
0.125
0.100
0.075
0.050
10^{-2}
10^{0}
10^{2}
$(E_{\mathrm{kin}}/\mathrm{n})$ [GeV/n]