The rigidity dependence of galactic cosmic-ray fluxes and its connection with the diffusion coefficient

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Scientific motivations

- The logarithmic slope of galactic CR is connected to the diffusion properties and the *primary* or *secondary* nature of the different species.
- The measured slopes are sometimes interpreted in the pure diffusive regime, implying that additional effects at play (convection, reacceleration, and destruction) can be neglected. This assumption leads to misleading conclusions.

This talk is based on *M. Vecchi et al*, *Front. Phys., 24 March 2022 Sec.High-Energy and Astroparticle Physics (open access)*

Scientific motivations and goals

- The logarithmic slope of galactic CR is connected to the diffusion properties and the *primary* or *secondary* nature of the different species.
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Using the code USINE for CR propagation and taking into account all relevant processes, we study:

- the slope of the B/C in different propagation scenarios, and compare to the B/C data from AMS-02.
- the flux slope for different CR species from H to Fe.

Cosmic-ray nuclei

Primaries are produced and accelerated at the sources. Secondaries are produced by the collisions of primaries with the interstellar medium (ISM).

Secondaries (D, B, F, ...)

Primaries (H, O, Si, ...)

Secondary-to-primary flux ratios, such as B/C or F/Si, are key observables to constrain the propagation processes in the Galaxy.

Slide E. F. Bueno

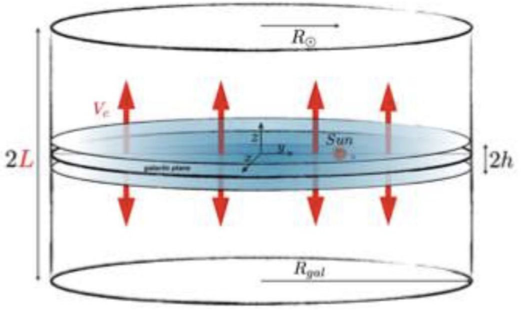
Cosmic ray transport in the galaxy

$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha - \vec{V}_c\psi_\alpha\right\} + \frac{\partial}{\partial E}\left\{b_{\rm tot}(E)\,\psi_\alpha - \beta^2\,K_{pp}\,\frac{\partial\psi_\alpha}{\partial E}\right\}$$
$$+\sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha + \Gamma_\alpha\,\psi_\alpha = \;q_\alpha + \sum_\beta\left\{\sigma_{\beta\to\alpha}v_\beta n_{\rm ism}\;+\Gamma_{\beta\to\alpha}\right\}\,\psi_\beta$$

K(E): A two-break diffusion coefficient is used

Génolini et al PRL 119, 241101 (2017), Génolini et al Phys.Rev. D99 (2019)

q_α: A single power-law is used for the source term.



1D model and semi-analytic approach with the USINE code

[Maurin CPC 247 (2020) 106942, https://dmaurin.gitlab.io/USINE/

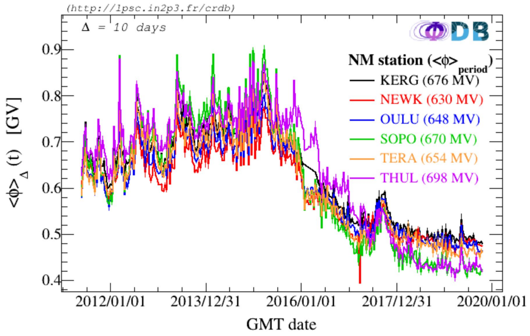
Cosmic-ray transport in the Galaxy

$$
\begin{aligned}
- \vec{\nabla}_{\mathbf{x}} \left\{ K(E)\, \vec{\nabla}_{\mathbf{x}} \psi_\alpha - \vec{V}_{\rm c} \psi_\alpha \right\} + \frac{\partial}{\partial E} \left\{ b_{\rm tot}(E)\, \psi_\alpha - \beta^2\, K_{pp}\, \frac{\partial \psi_\alpha}{\partial E} \right\} \\
+ \sigma_\alpha\, v_\alpha\, n_{\rm ism}\, \psi_\alpha + \Gamma_\alpha\, \psi_\alpha = \; q_\alpha + \sum_\beta \left\{ \sigma_{\beta\to\alpha} v_\beta n_{\rm ism} + \Gamma_{\beta\to\alpha} \right\} \psi_\beta
\end{aligned}
$$

- This equation couples about a hundred CR species (for $Z < 30$) over a nuclear network of more than a thousand reactions.
- To solve this diagonal matrix of equations, we start with the heaviest nucleus, which is always assumed to be a primary species, and then proceed down to the lightest one.

Methodology

- We use the **propagation scenarios** described in [Génolini et al 2019], namely BIG, SLIM and QUAINT, which provide an excellent fit to accurate description of the (Li, Be, B)/C data from AMS-02 [Weinrich et al 2020].
- For the **nuclear production and spallation cross-sections**, we use as reference the set of tables from the *Galprop* package, following the approach described in [Génolini et al 2018] and recently updated as in [Maurin et al. 2022].
- The calculated fluxes are **Top-of-Atmosphere quantities** modulated with the force field approximation. We obtain the **modulation potential** ϕ = 670 MV from https://lpsc.in2p3.fr/crdb/ based on [Ghelfi et al. 2017]



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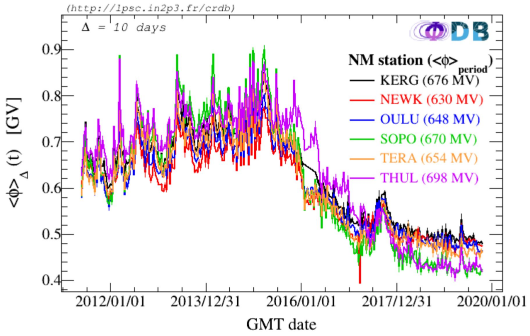

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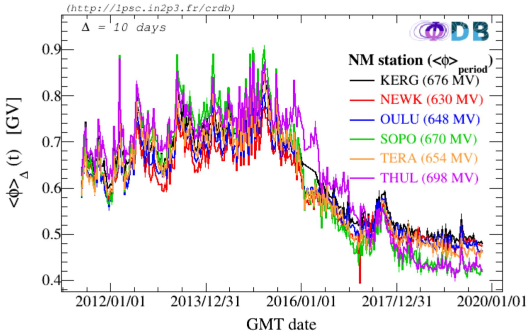
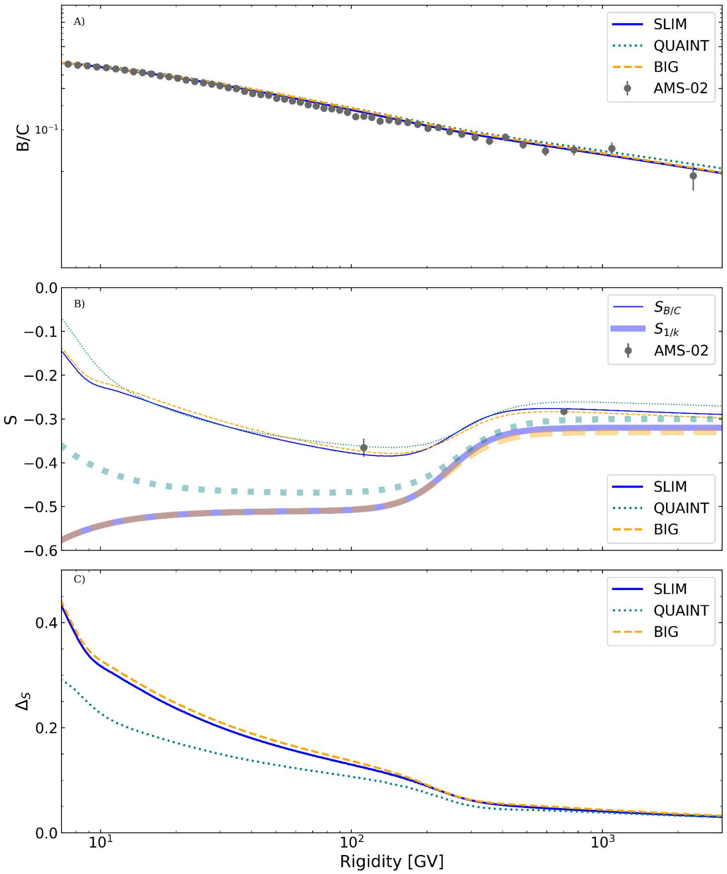


B/C slope vs diffusion slope

The SLIM, QUAINT and BIG propagation scenarios fit well the AMS-02 B/C data.

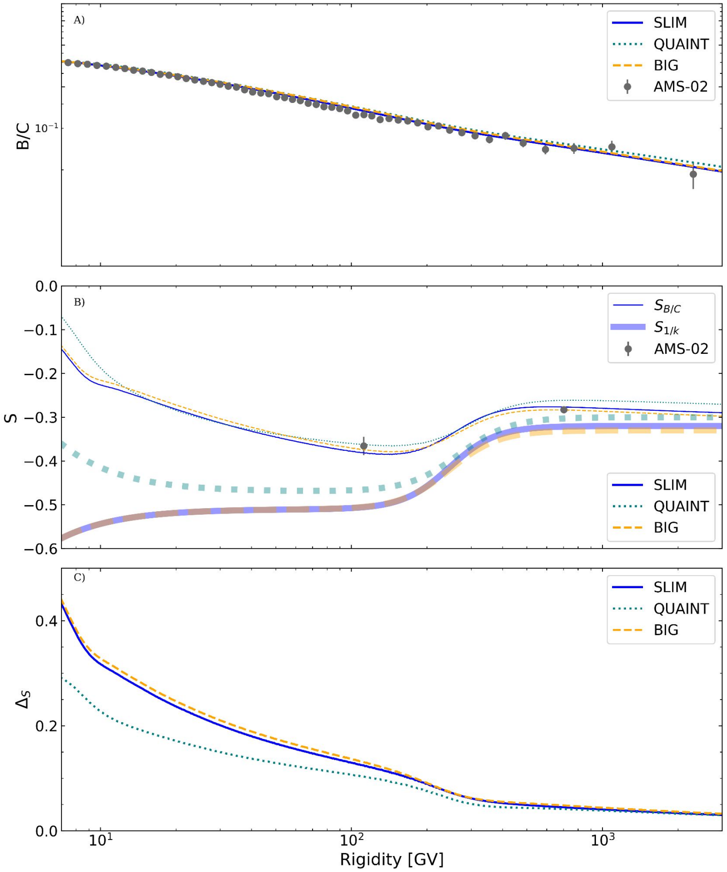


B/C slope vs diffusion slope

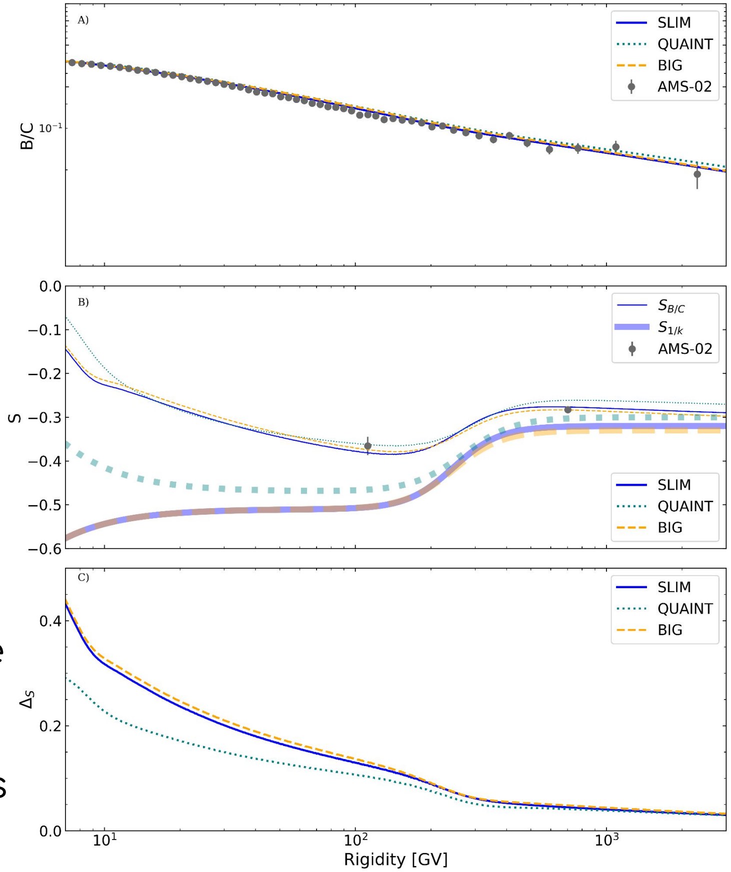
$$S_\Phi = \mathrm{d}\left[\log \phi\right] / \mathrm{d}\left[\log R\right]$$

$$S_K = \mathrm{d}\left[\log K(R)\right] / \mathrm{d}\left[\log R\right] = -S_{1/K}$$

The diffusion coefficient slope never matches the B/C slope, except at the highest rigidities



B/C slope vs diffusion slope

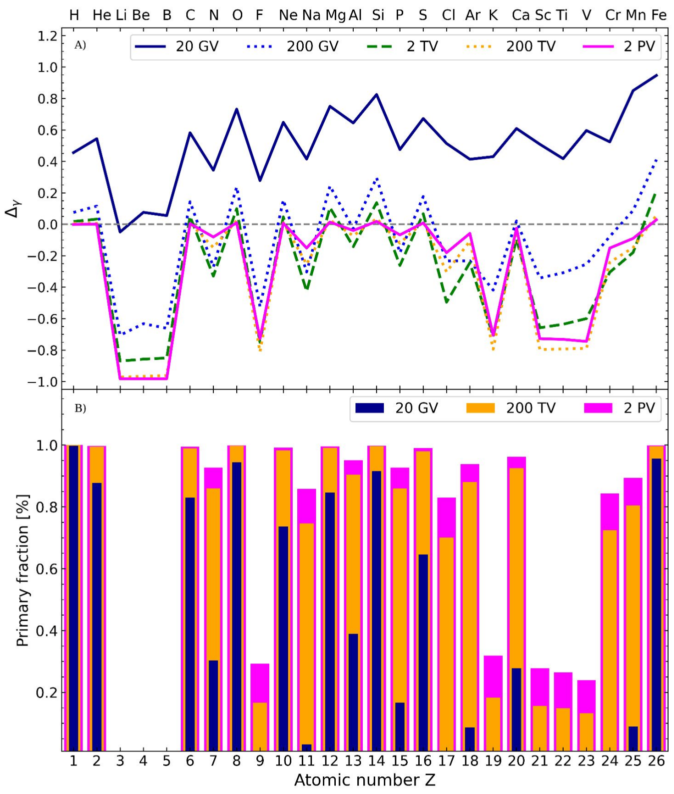


$$\Delta_S = S_{B/C} - S_{1/K}$$

- Slow convergence to the pure diffusive regime only above 200 GeV.
- Assuming the B/C slope directly provides the slope of the diffusion coefficient strongly biases the conclusions drawn on the turbulence type.

Understanding the slopes' behavior

$$\Delta_\gamma = \frac{S_\Phi - (\alpha(Z) + S_{1/K})}{S_{1/K}}$$



In the purely diffusive regime

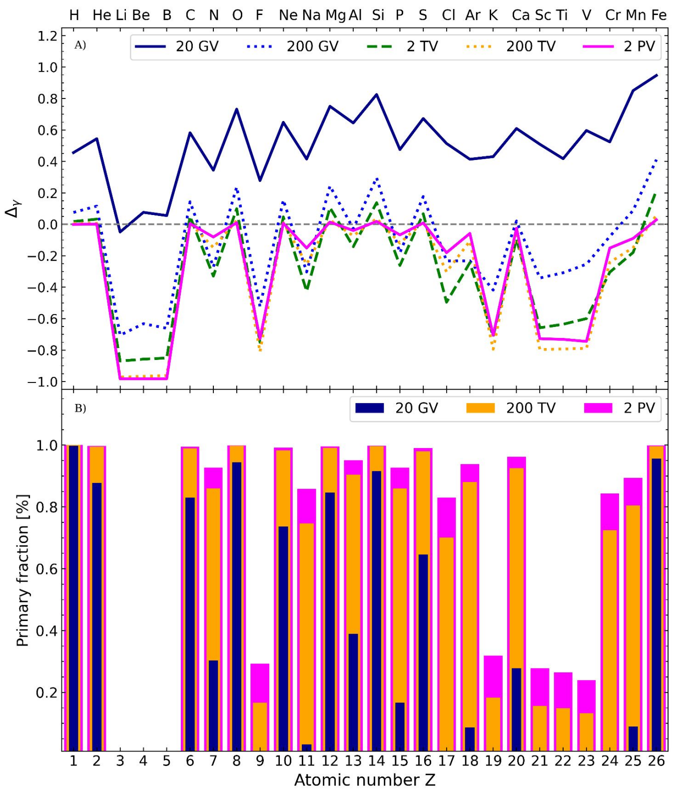
- $\Delta_\gamma = 0$ for primary species
- $\Delta_\gamma = -1$ for secondary species

- Source slope for H and He are taken to be different from that of all other nuclei
- Slope of the diffusion coefficient for SLIM scenario

Understanding the slopes' behavior

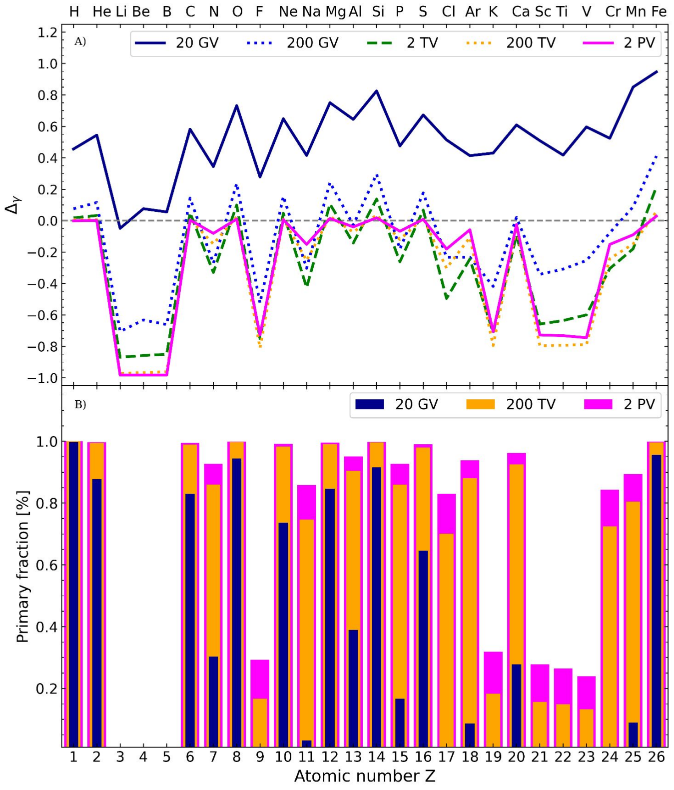
$$\Delta_\gamma = \frac{S_\Phi - (\alpha(Z) + S_{1/K})}{S_{1/K}}$$

- Slopes at 20 GV: $\Delta_\gamma > 0$ for all species.
- The slopes of the measured fluxes are always softer than those expected in the purely diffusive regime.
- For growing Z, the impact of inelastic cross-sections is also rising (growing Δ_γ) and causing an increasing difficulty to identify which species are of primary or secondary origin.



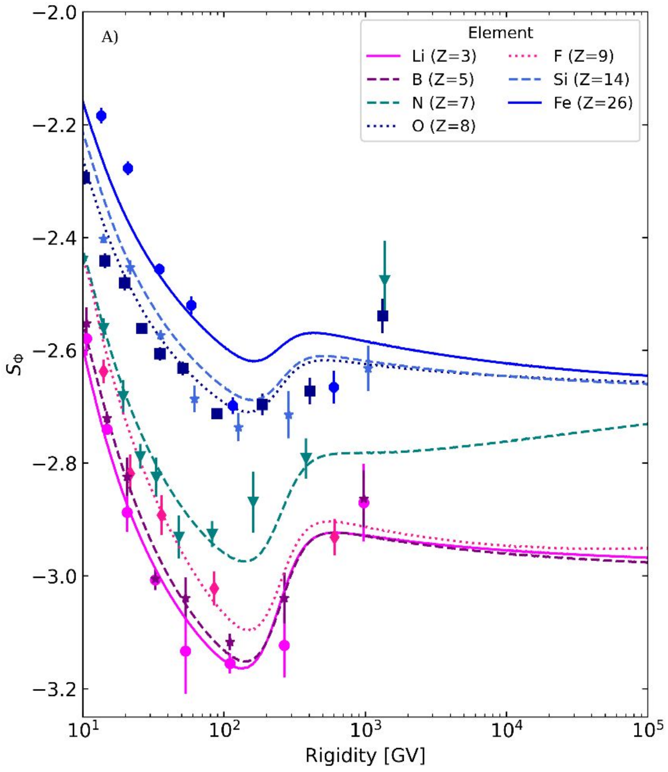
Understanding the slopes' behavior

- Pure diffusion reached above 200 GV: primary species have $\Delta_\gamma = 0$ and secondary species on $\Delta_\gamma = -1$
- For $Z \gtrsim 20$ where inelastic interactions still have a significant impact even at 200 GV.
- In principle, for the highest rigidity shown, i.e., 2 PV (where the asymptotic diffusive regime holds), the heavy species should also converge to 0 or −1.



Comparison to AMS-02 data

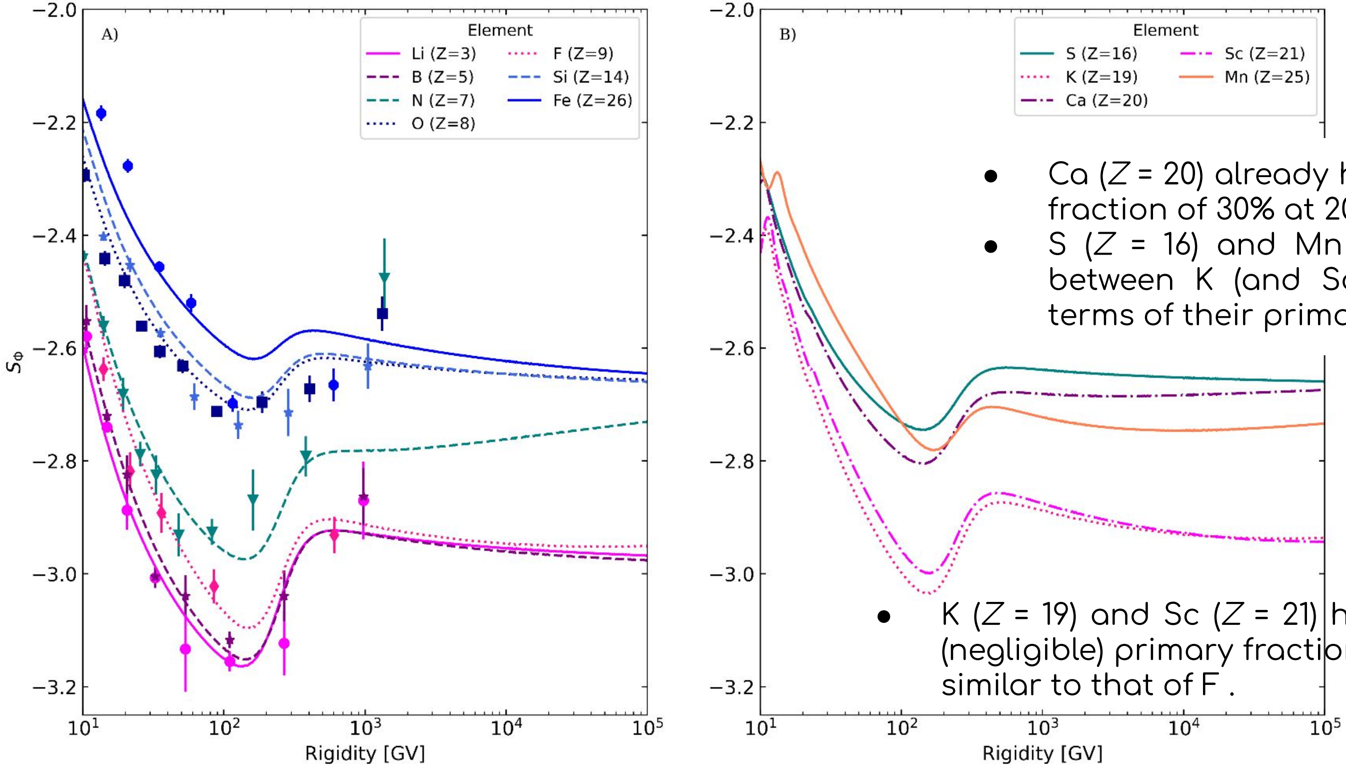
$$S_\Phi = \mathrm{d}[\log \phi]/\mathrm{d}[\log R]$$



- Li ($Z = 3$), B ($Z = 5$) and F ($Z = 9$), which have $f_{prim} < 5\%$ up to tens of TV, are ordered and shifted according to their growing destruction cross-section, before all slopes converge to the "universal" secondary flux slope;
- the same ordering is observed for O ($Z = 8$), Si ($Z = 14$), and Fe ($Z = 26$), though these species now converge towards the "universal" primary flux slope in our model;
- N ($Z = 7$) is a mixed species: its flux slope starts close to the "pure secondary" group and ends up close to the "pure primary" group.

... and expectations for Z=15-25 elements

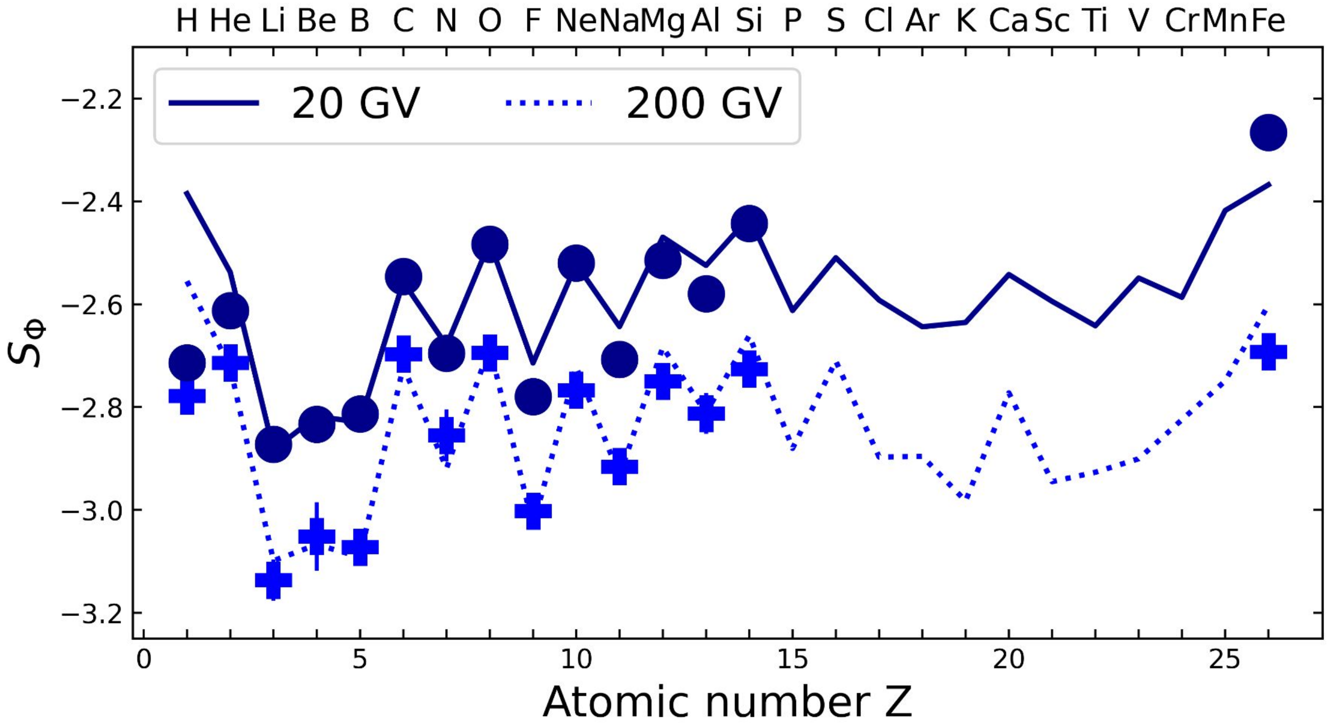
Z>14 elements have not yet been measured by AMS-02



- Ca (Z = 20) already has a primary fraction of 30% at 20 GV.
- S (Z = 16) and Mn (Z = 25), fall between K (and Sc) and Ca in terms of their primary content
- K (Z = 19) and Sc (Z = 21) have a (negligible) primary fraction very similar to that of F .

Slope dependence on Z

We find a very good agreement between the modelled slopes and the measured ones (except for H and Fe).



Summary

- To conclude on the source slope or diffusion slope, the AMS-02 data should be used together with an underlying propagation model, since the purely diffusive propagation regime is only reached above hundreds of TV.

- The competition between inelastic interactions (growing with Z) and primary content of the elements (growing with R) leads to non-trivial dependencies of the flux slopes.

- Despite the non-trivial behavior, slopes are a useful tool to obtain information on breaks, CR primary or secondary origin, and on whether the measured slopes reach the expected asymptotic regime.