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Combined analysis of AMS-02 secondary-to-primary ratios: universality of cosmic-ray propagation and consistency of nuclear cross sections

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Scientific goals

- We study whether F/Si data recently published by AMS-02 [Aguilar et al Phys.Rev.Lett. 126 (2021) 8] can be reproduced by the same propagation models which give a best fit of lighter secondary-to-primary ratios, as derived in Weinrich et al, A&A 639, A131 (2020)

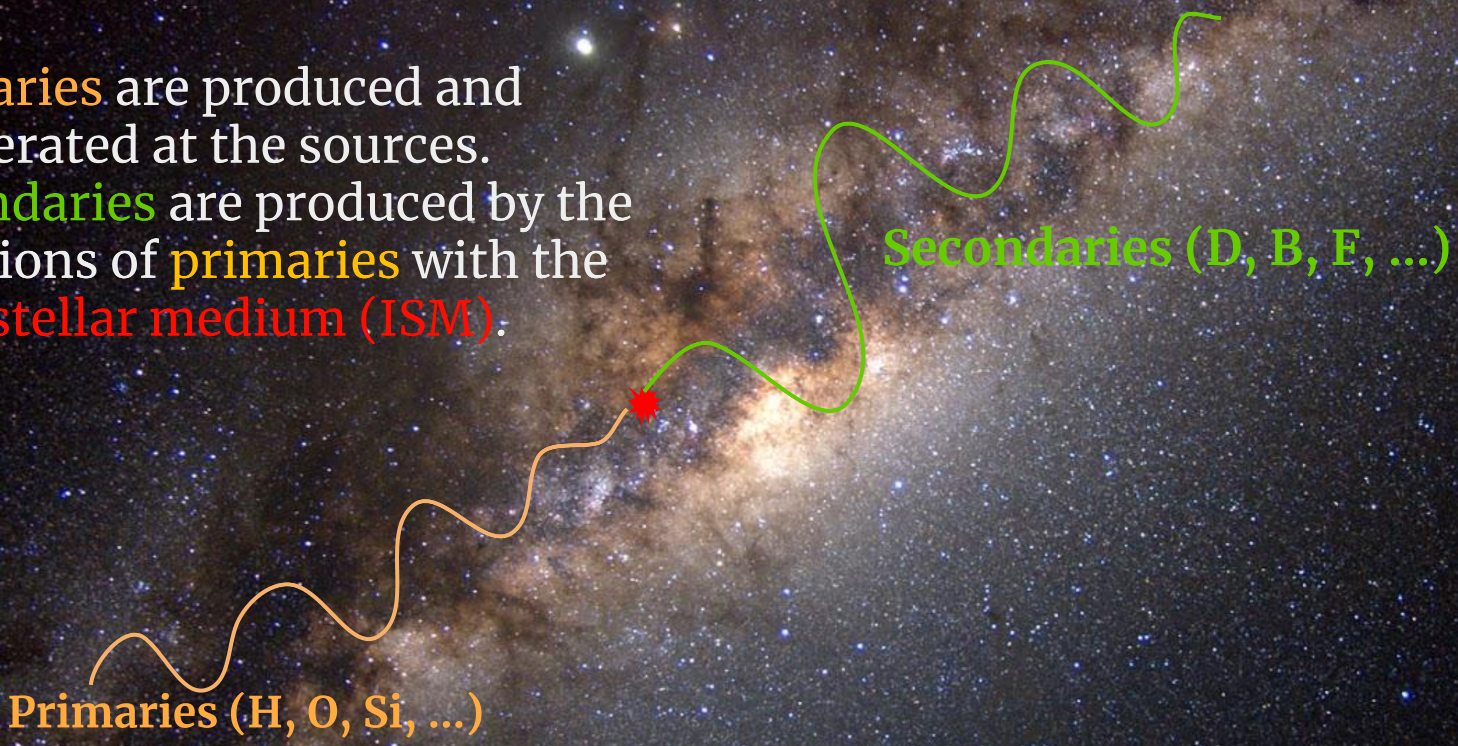
- We follow the methodology described in Derome et al, A&A 627 (2019) A158

- We investigate whether data allow for primary F component

NB: CR fluorine is purely composed of (stable) ^{19}F

Cosmic-ray nuclei

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

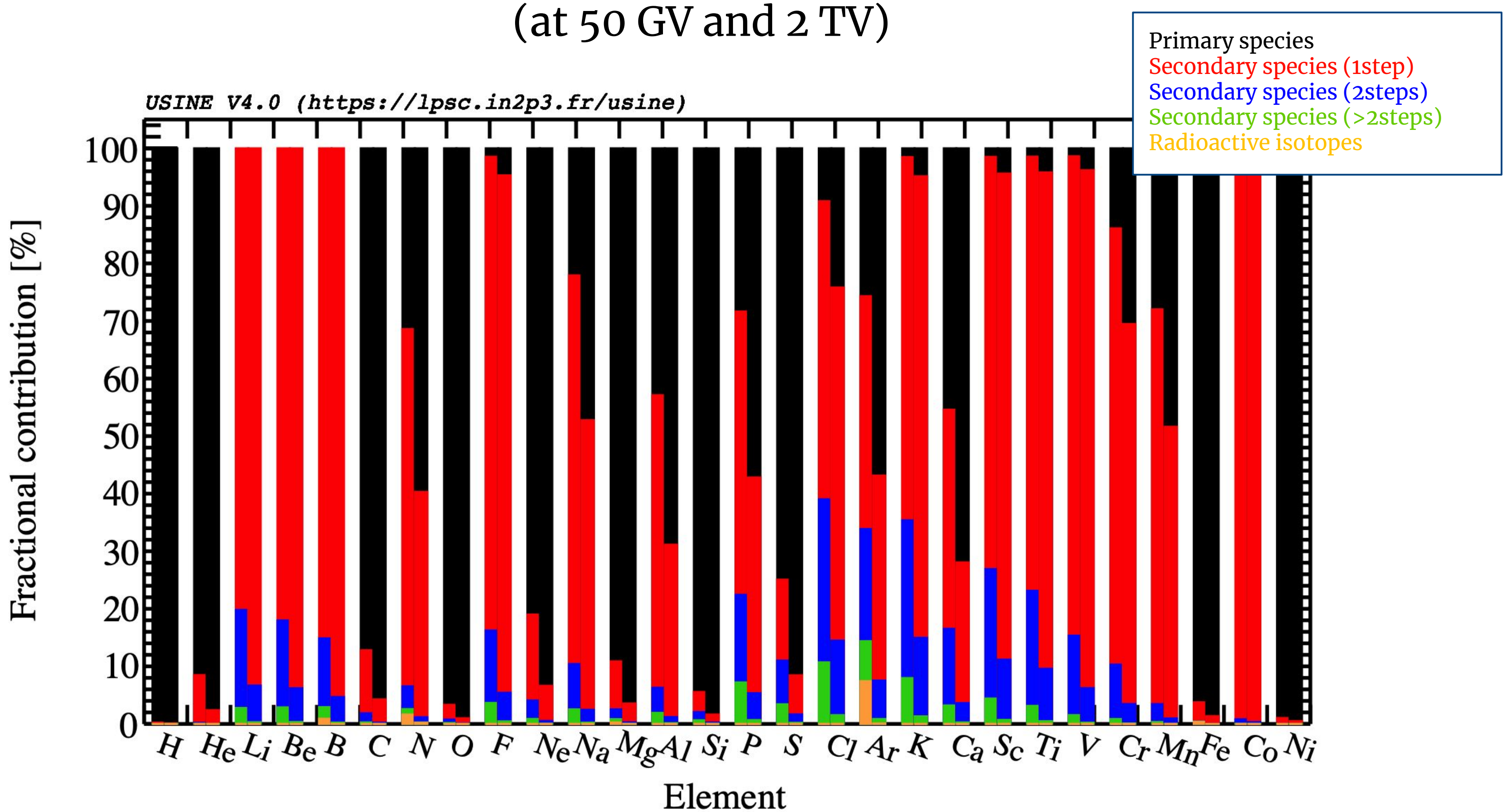


Secondary-to-primary flux ratios, such as B/C or F/Si, are key observables to constrain the propagation processes in the Galaxy.

Slide E. F. Bueno

Secondary CR production

Relative contributions per production process for elemental fluxes
(at 50 GV and 2 TV)



The species with the highest primary content include H, O, Si, and Fe (black), while Li, Be, B, F, and Cl to V have the highest secondary component from both single (red) and multi-step production (blue and green).

Cosmic-ray transport in the Galaxy

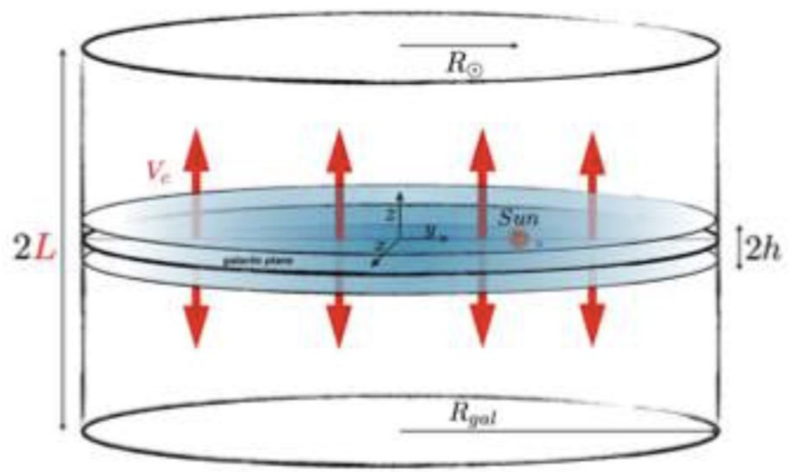
$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha-\vec{V}_c\psi_\alpha\right\}+\frac{\partial}{\partial E}\left\{b_{\rm tot}(E)\;\psi_\alpha-\beta^2\,K_{pp}\,\frac{\partial\psi_\alpha}{\partial E}\right\}$$

$$+\sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha+\Gamma_\alpha\,\psi_\alpha=q_\alpha+\sum_\beta\left\{\sigma_{\beta\to\alpha}v_\beta n_{\rm ism}+\Gamma_{\beta\to\alpha}\right\}\,\psi_\beta$$

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 universal 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

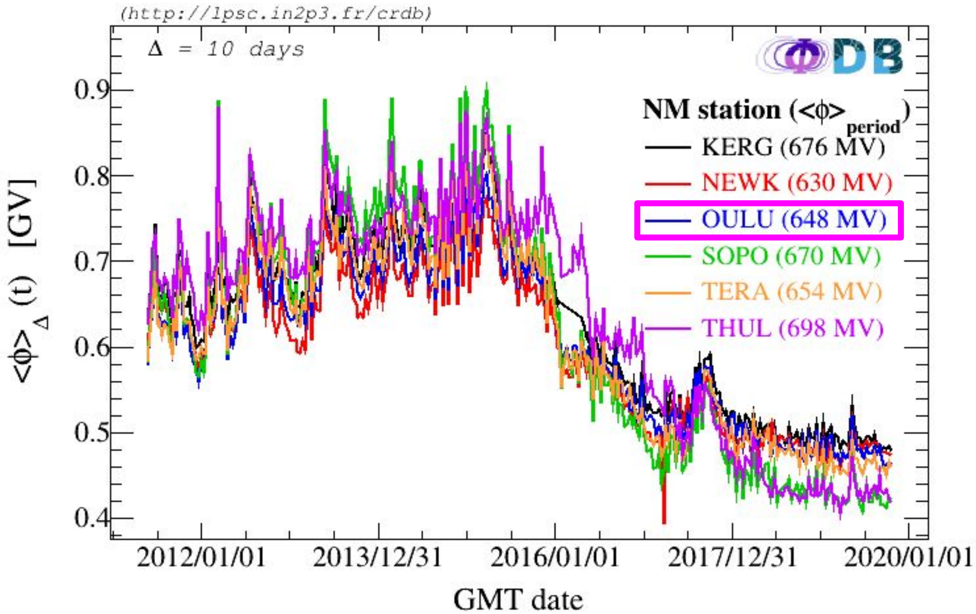
$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha-\vec{V}_c\psi_\alpha\right\}+\frac{\partial}{\partial E}\left\{b_{\rm tot}(E)\,\psi_\alpha-\beta^2\,K_{pp}\,\frac{\partial\psi_\alpha}{\partial E}\right\}$$
$$+\sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha+\Gamma_\alpha\,\psi_\alpha=\;q_\alpha+\sum_\beta\left\{\sigma_{\beta\to\alph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

- 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.
- We use the SLIM propagation scenario [Génolini et al Phys.Rev. D99 (2019)], with 4 free propagation parameters (K_0, δ, R_l, δ_l)

Methodology

- In order to reduce biases in the transport parameter determination, it is crucial to use nuisance parameters for the nuclear production cross sections, and a covariance matrix for the data systematic uncertainties, as described in Derome et al, A&A 627 (2019) A158

- The force-field approximation is used to compute the top-of-atmosphere (TOA) fluxes, using the Fisk potential as a nuisance parameter.

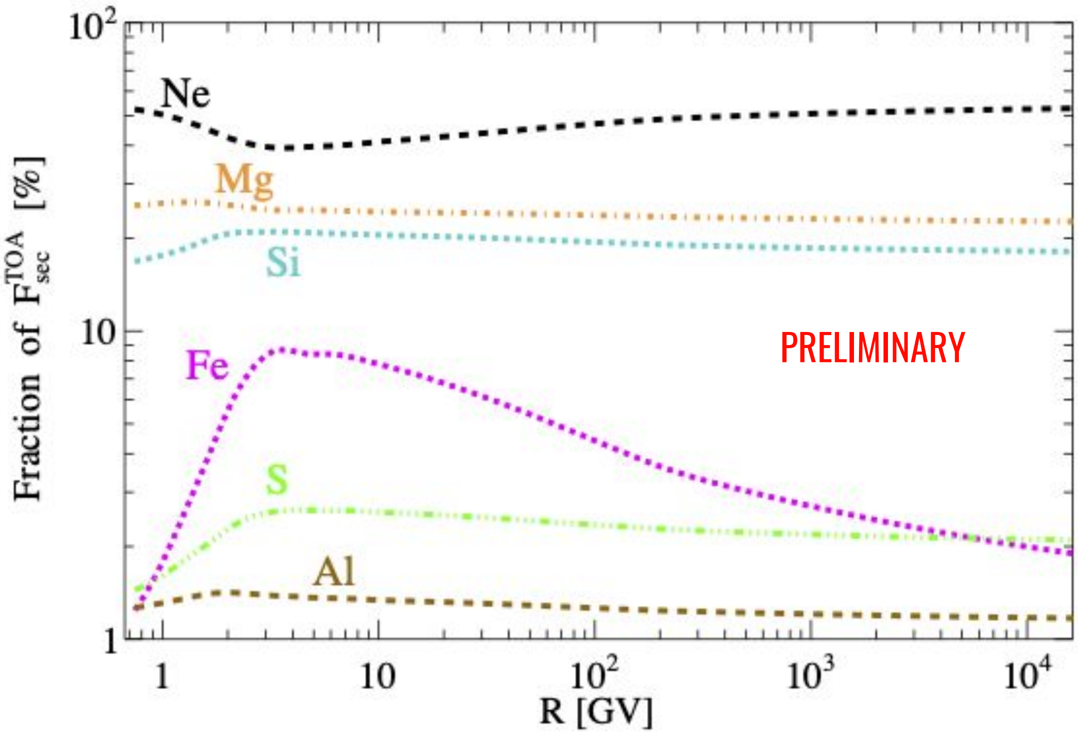


<Φ> from https://lpsc.in2p3.fr/crdb/ based on Ghelfi et al., AdSR 60, 833 (2017)

- The TOA fluxes are compared to the data using a chi2 minimization procedure

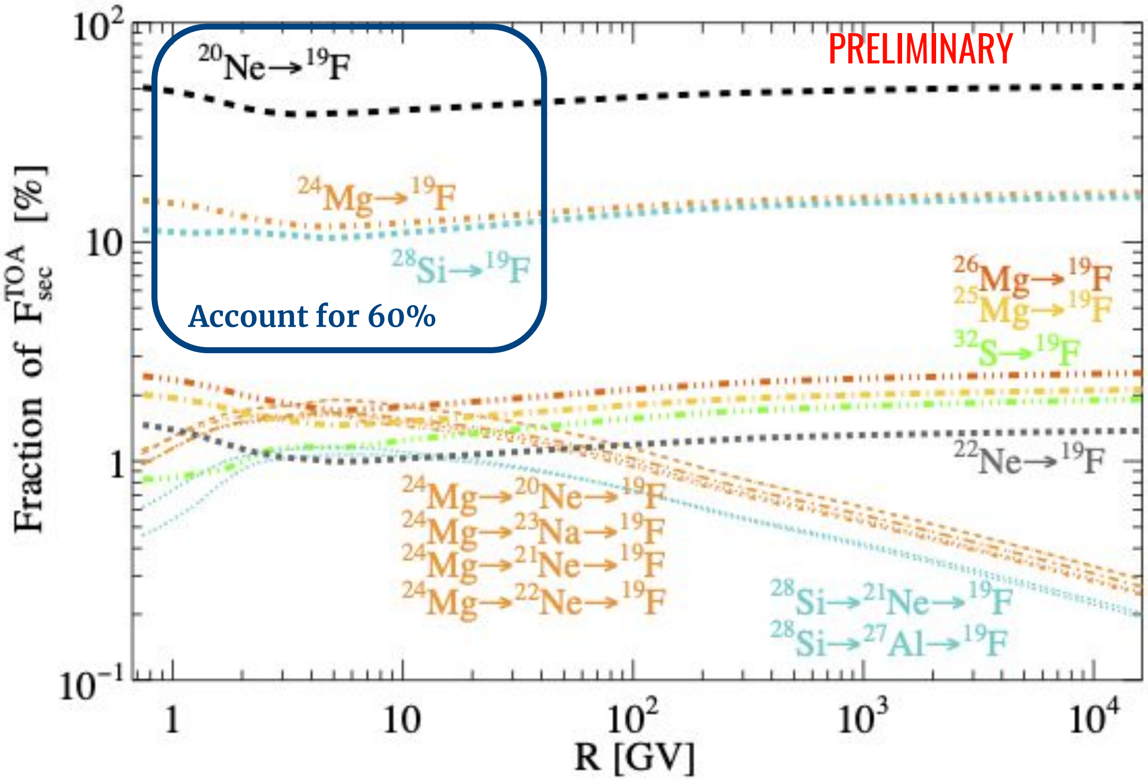
Progenitors of CR fluorine

Following the methodology described in Génolini et al *Phys.Rev.C* 98 (2018) 3, 034611



Ne, Mg, Si and Fe are the main progenitors of F.

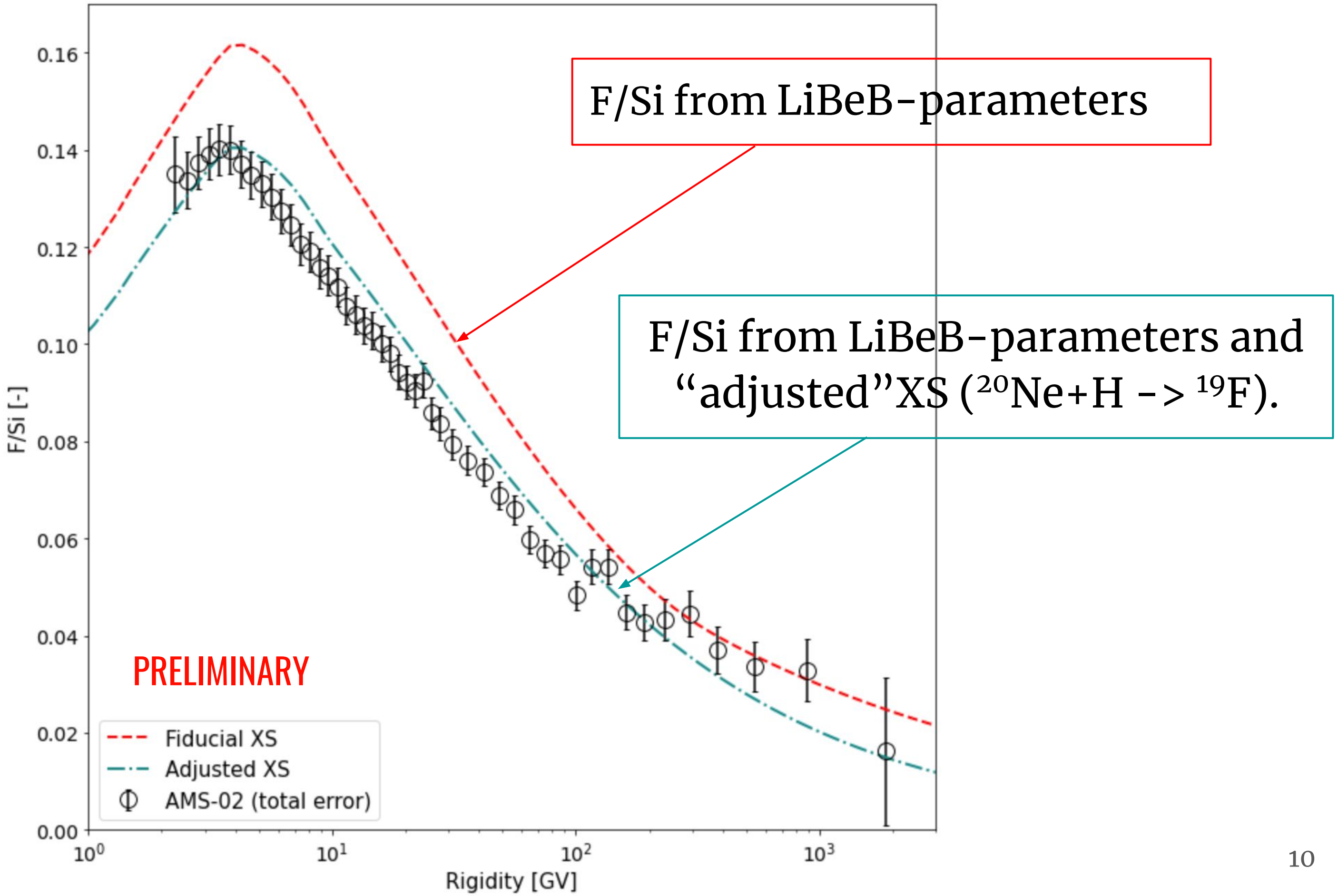
Dominant processes producing CR fluorine



- We have identified **35 channels** whose individual contribution is in the range [0.1-2%] and contribute to ~ 22% of the total.
- While the ranking of the dominant channels is a robust prediction, the individual numbers are subject to uncertainties due to the cross section and propagation parameters.

Results

- The model tuned on light nuclei AMS-02 data [Weinrich et al, A&A 639, A131 (2020)] overshoots F/Si data by 10% - 15%, similar to M. Boschini et al, arXiv:2106.01626
- o(15%) reduction in the XS normalization to recover the difference, in the range of expected XS uncertainties

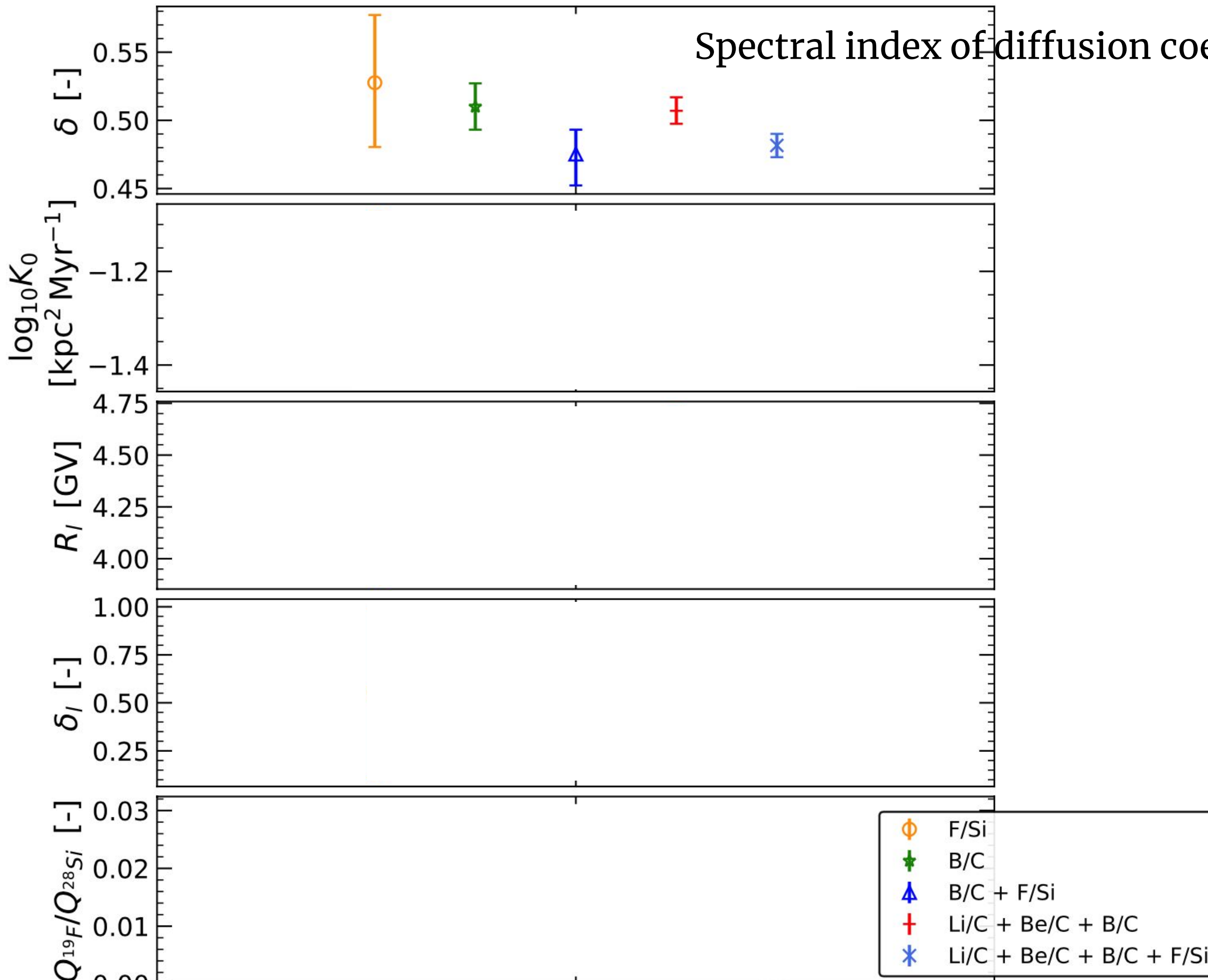


Results: propagation parameters (and more)

Effective diffusion coefficient

$$K(R) = \beta^{\eta} K_0 \left\{1+\left(\frac{R}{R_l}\right)^{\frac{\delta_l-\delta}{s_l}}\right\}^{s_l} \left\{\frac{R}{R_0 = 1\,\mathrm{GV}}\right\}^{\delta} \left\{1+\left(\frac{R}{R_h}\right)^{\frac{\delta-\delta_h}{s_h}}\right\}^{-s_h}$$

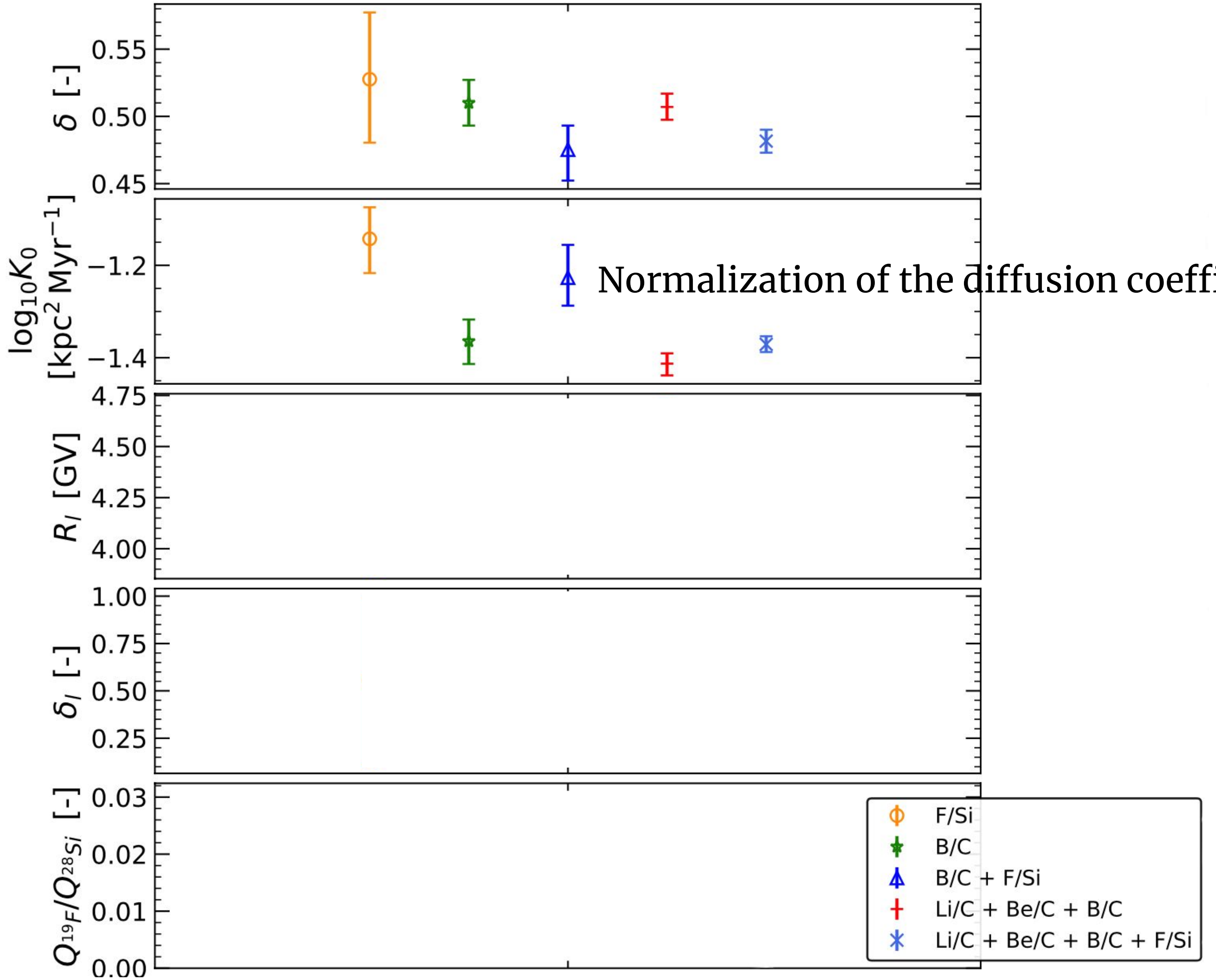
Spectral index of diffusion coefficient



Results: propagation parameters (and more)

Effective diffusion coefficient

$$K(R) = \beta^{\eta} K_0 \left\{1+\left(\frac{R}{R_l}\right)^{\frac{\delta_l-\delta}{s_l}}\right\}^{s_l} \left\{\frac{R}{R_0 = 1\,\mathrm{GV}}\right\}^{\delta} \left\{1+\left(\frac{R}{R_h}\right)^{\frac{\delta-\delta_h}{s_h}}\right\}^{-s_h}$$

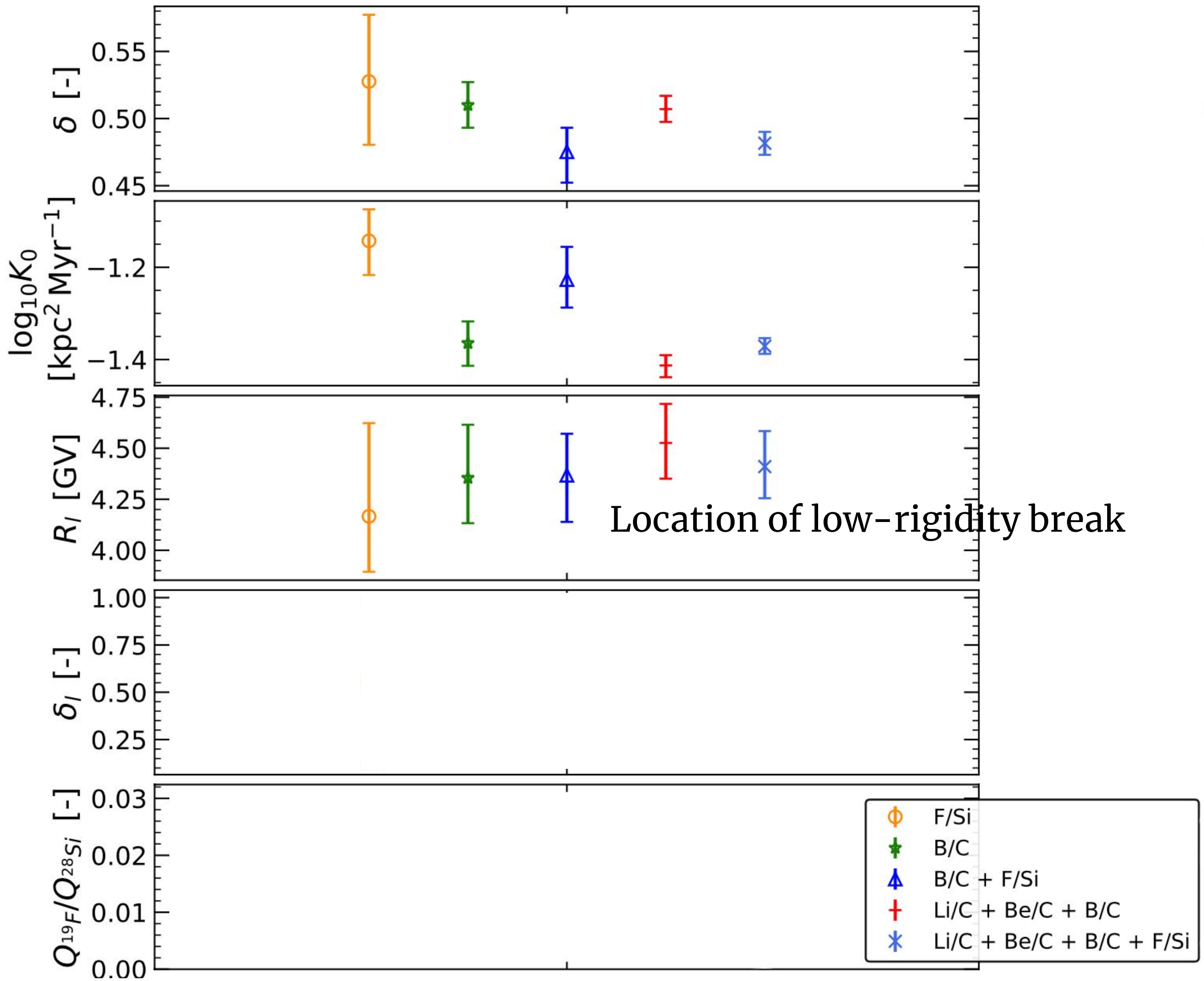


Normalization of the diffusion coefficient

Results: propagation parameters (and more)

Effective diffusion coefficient

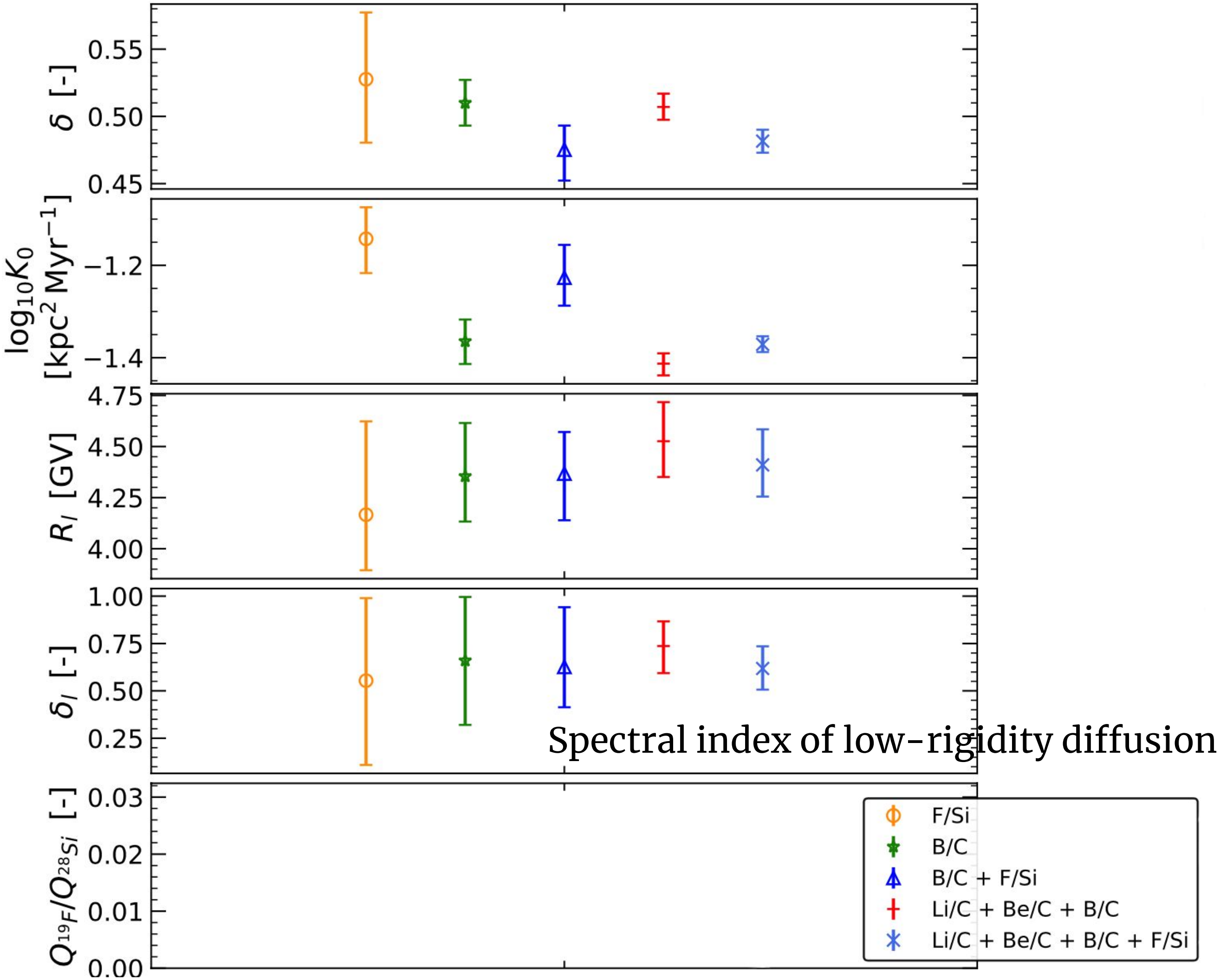
$$K(R) = \beta^\eta K_0 \left\{1+\left(\frac{R}{R_l}\right)^{\frac{\delta_l-\delta}{s_l}}\right\}^{s_l} \left\{\frac{R}{R_0=1\,\mathrm{GV}}\right\}^{\delta} \left\{1+\left(\frac{R}{R_h}\right)^{\frac{\delta-\delta_h}{s_h}}\right\}^{-s_h}$$



Results: propagation parameters (and more)

Effective diffusion coefficient

$$K(R) = \beta^{\eta} K_0 \left\{1+\left(\frac{R}{R_l}\right)^{\frac{\delta_l-\delta}{s_l}}\right\}^{s_l} \left\{\frac{R}{R_0=1\,\mathrm{GV}}\right\}^{\delta} \left\{1+\left(\frac{R}{R_h}\right)^{\frac{\delta-\delta_h}{s_h}}\right\}^{-s_h}$$

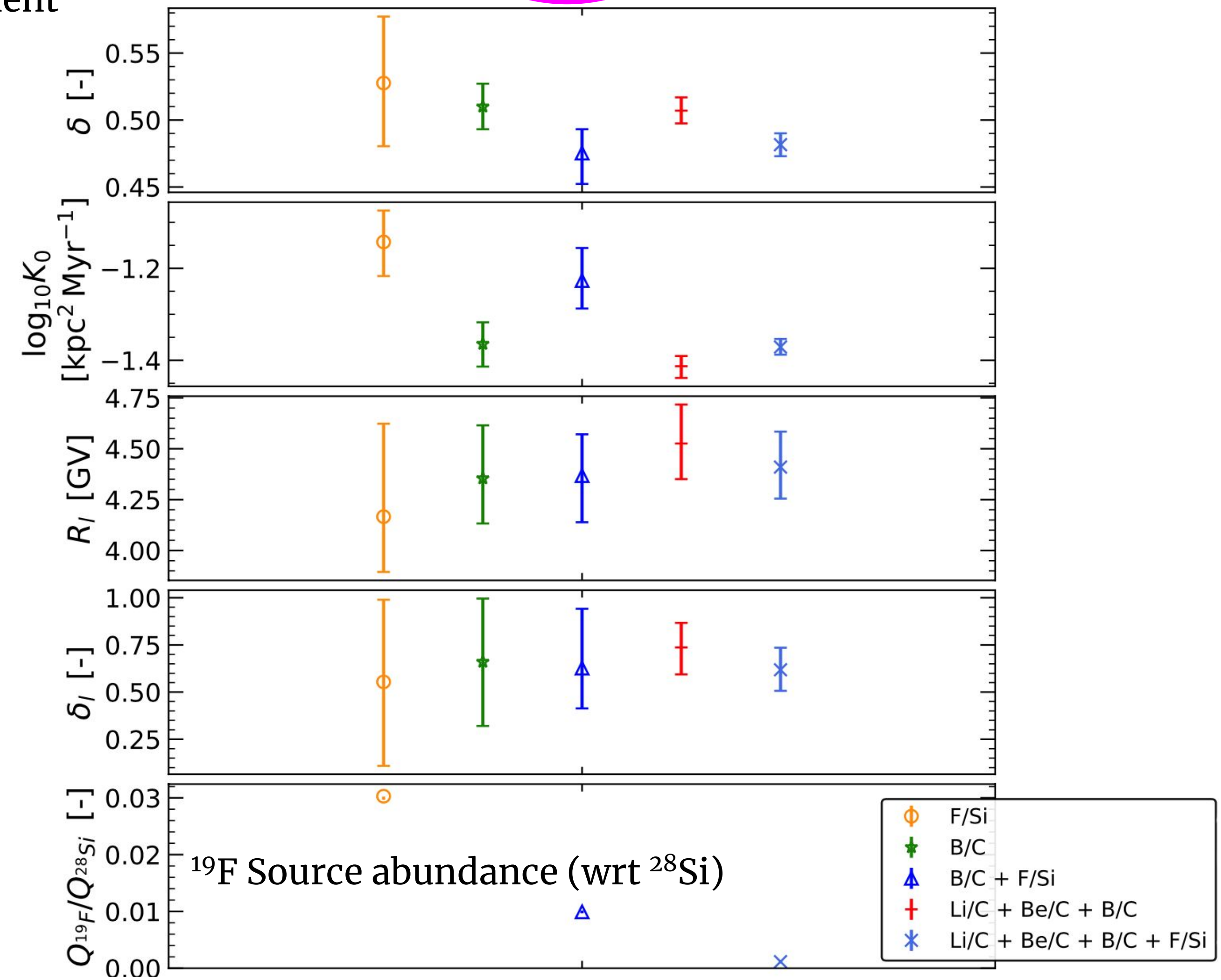


Spectral index of low-rigidity diffusion coefficient

Results: a F primary component ?

Despite ^{19}F being mostly secondary, we study the effect of a primary component

$$Q(R) = Q_{19F} \beta^{\eta_S} R^{-\alpha}$$



Conclusions

- Using the propagation parameters which give a best fit of lighter secondary-to-primary ratios, our model overestimates the data by 10% - 15%. However, this difference can be explained by the F production cross-sections uncertainties
- We conclude that all secondary species from Li to F can be explained by the same transport parameters
- Combined analysis of Li/C, Be/C, B/C and F/Si gives an upper limit on the F source abundance
- Next steps:
  - Final check on the x-sections
  - Interpret the limit on the F source abundance