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Cosmic-ray transport parameters and fluorine source abundance from AMS-02 data of the F/Si flux ratio

E. Ferronato Bueno, L. Derome, Y. Génolini, D. Maurin, V. Tatischeff, M. Vecchi

university of groningen

Scientific goals

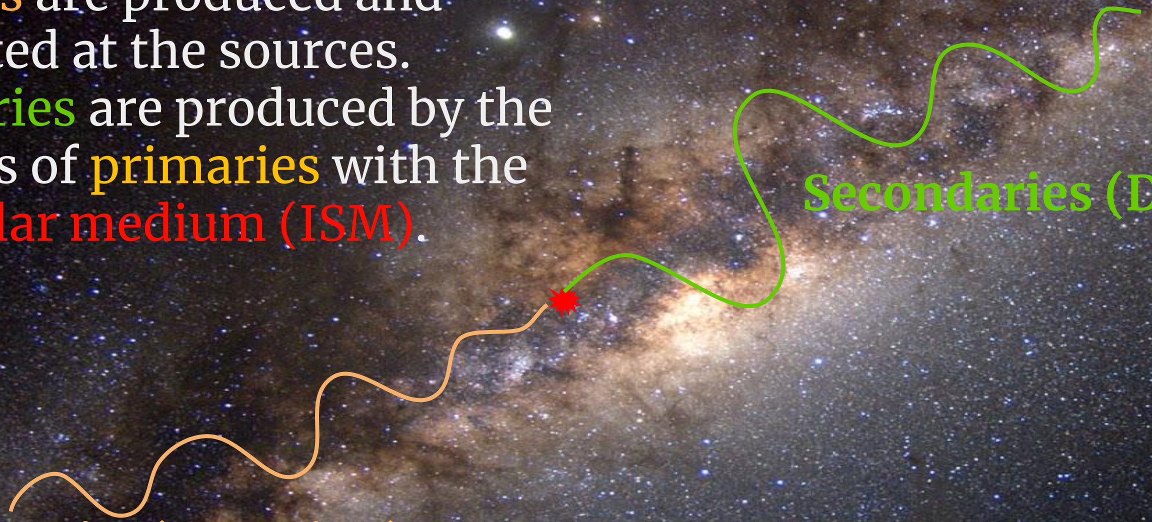
- We study whether F/Si data recently published by AMS-02 [Aguilar et al Phys.Rev.Lett. 126 (2021) 8] can be reproduced by the same propagation models which give a best fit of lighter secondary-to-primary ratios, (Li, Be, B)/C, as derived in Weinrich et al, A&A 639, A131 (2020)
- We investigate whether data allow for primary F component
- We follow the methodology described in Derome et al, A&A 627 (2019) A158

This talk is based on the results presented in *E. Ferronato Bueno et al, on arxiv this week.*

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).



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. Ferronato Bueno

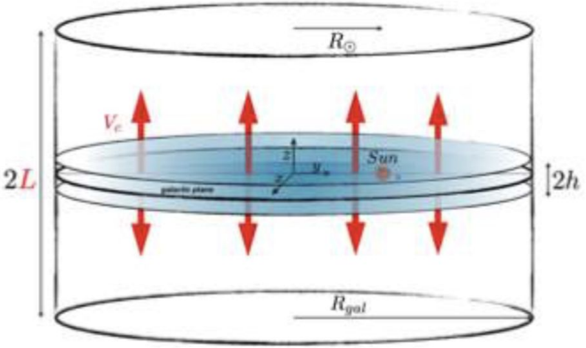
Cosmic-ray transport in the Galaxy

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

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

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

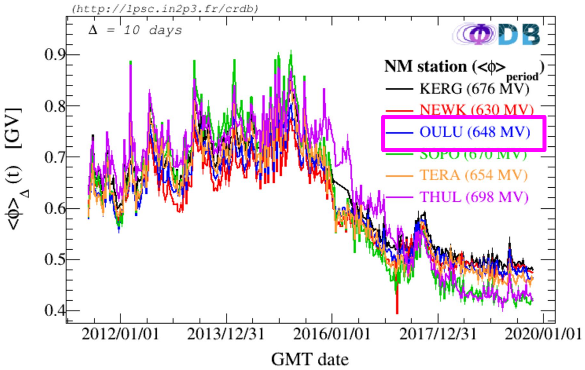
$$
+\sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha + \Gamma_\alpha\,\psi_\alpha = \; q_\alpha + \sum_\beta \left\{\sigma_{\beta\to\alpha}v_\beta n_{\rm ism} \; + \Gamma_{\beta\to\alpha}\right\}\,\psi_\beta
$$

- 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 propagation scenarios described in [Génolini et al Phys.Rev. D99 (2019)], namely BIG, SLIM and QUAINT, which provide an excellent fit to the lighter species measured by AMS-02.

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.

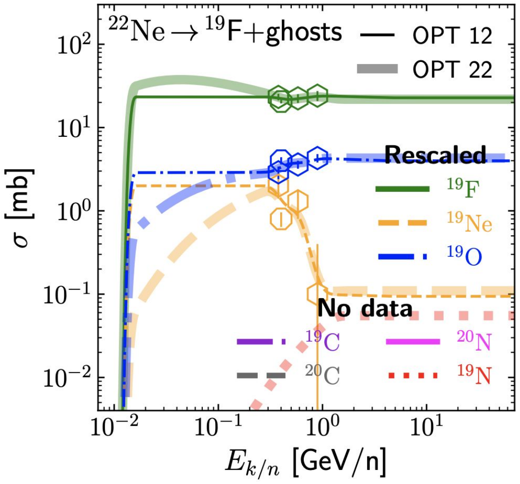


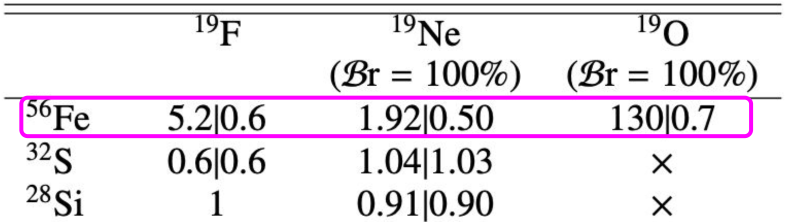
<Φ> from https://lpsc.in2p3.fr/crdb/
based on Ghelfi et al., AdSR 60, 833 (2017)

- The TOA fluxes are compared to the data using a chi2 minimization procedure that accounts for several systematic effects (energy correlation, solar modulation and nuclear x-sections).

Rescaling of F production cross-sections to nuclear data

- We follow the procedure presented in Maurin et al 2022 to update the original GALPROP cross-sections.
- We consider both stable isotopes and short-lived nuclei (*aka* ghosts).
- We retrieve production cross-section for the main progenitors of F from the EXFOR database [Otuka et al Nucl Data Sheets, 120, 272, 2014].



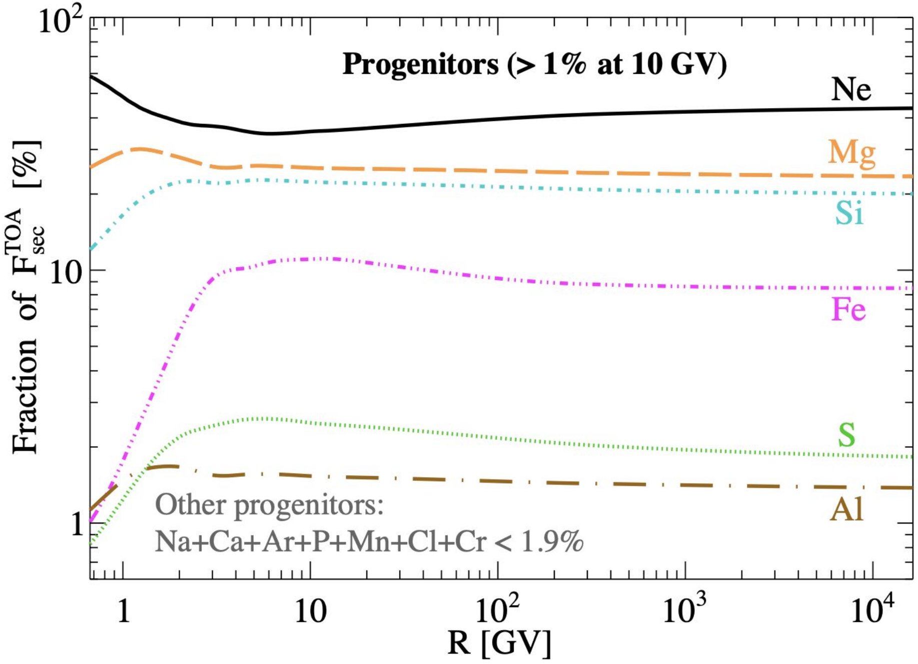


	^{19}F	^{19}Ne ($\mathscr{B}$r = 100%)	^{19}O ($\mathscr{B}$r = 100%)
^{56}Fe	5.2|0.6	1.92|0.50	130|0.7
^{32}S	0.6|0.6	1.04|1.03	×
^{28}Si	1	0.91|0.90	×

Rescaling factor applied for the two parametrizations (OPT12|OPT22) for different fragments.

Progenitors of CR fluorine

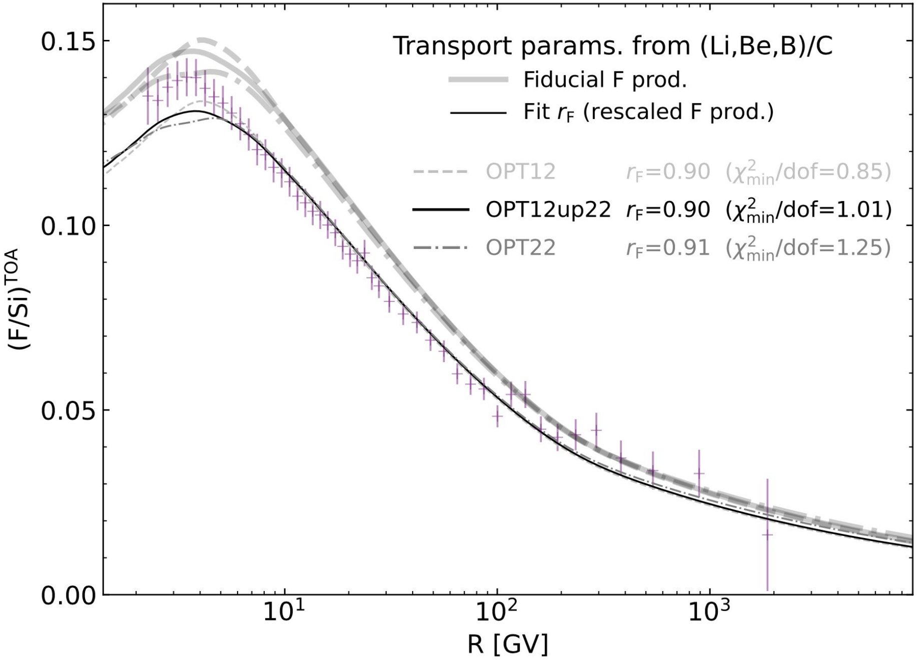
Following the methodology described in Génolini et al *Phys.Rev.C* 98 (2018) 3, 034611



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

Results: F/Si vs B/C (as pure secondaries)

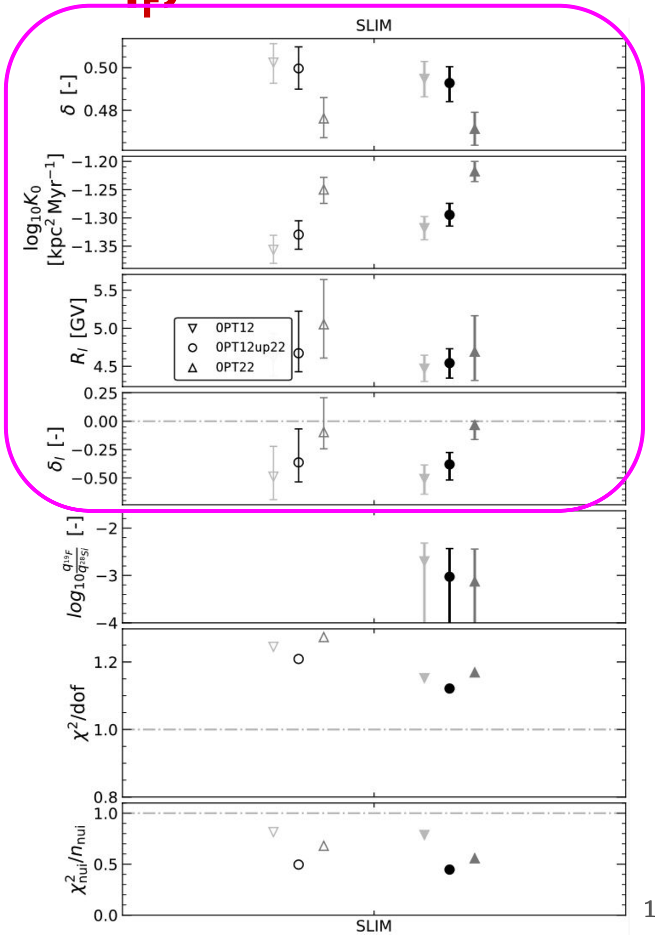
- The model tuned on (Li, Be, B)/C AMS-02 data [Weinrich et al, A&A 639, A131 (2020)] overshoots F/Si data by 10% (consistent with XS uncertainties), similar to M. Boschini et al 2022.
- NB: very good chi2 including the covariance matrix of AMS data systematic uncertainties (correlated low-rigidity data, *a priori* no need for primary F).



Results of F/Si+(Li,Be,B)/C fit (allowing for q_F):

1) Propagation parameters

Propagation parameters

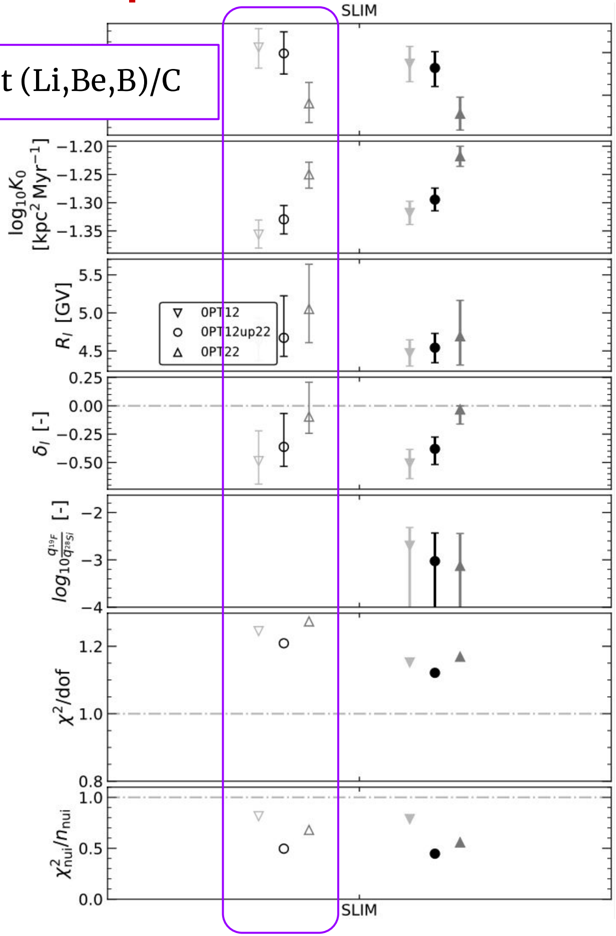


- Very good fit for combined analysis
- Diffusion slope consistent with delta=0.5
- Slight preference for low rigidity break
- Robust result wrt propagation scenarios (see paper)

Results of F/Si+(Li,Be,B)/C fit (allowing for q_F):

1) Propagation parameters

Propagation parameters



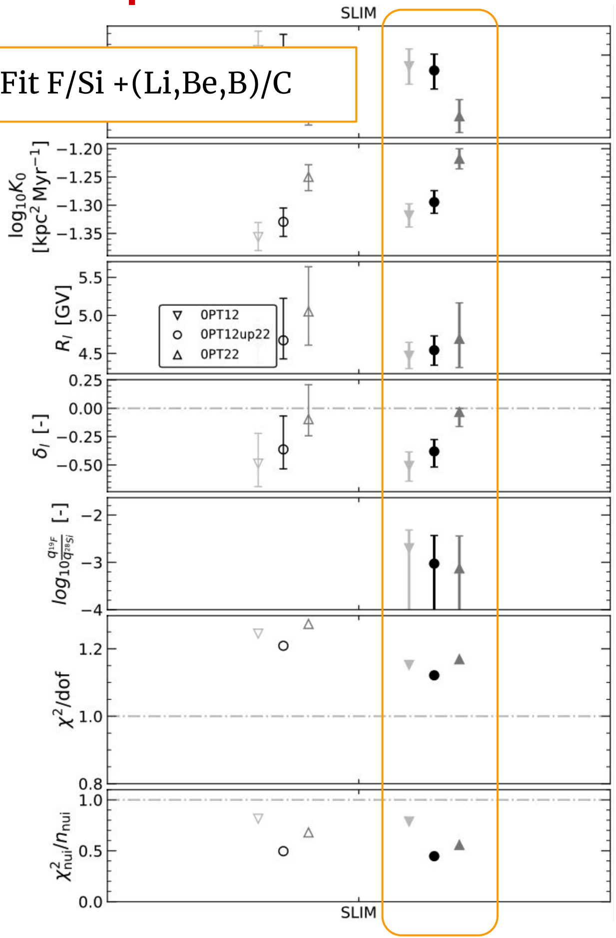
Fit (Li,Be,B)/C

- Very good fit for combined analysis
- Diffusion slope consistent with delta=0.5
- Slight preference for low rigidity break
- Robust result wrt propagation scenarios (see paper)

Results of F/Si+(Li,Be,B)/C fit (allowing for q_F):

1) Propagation parameters

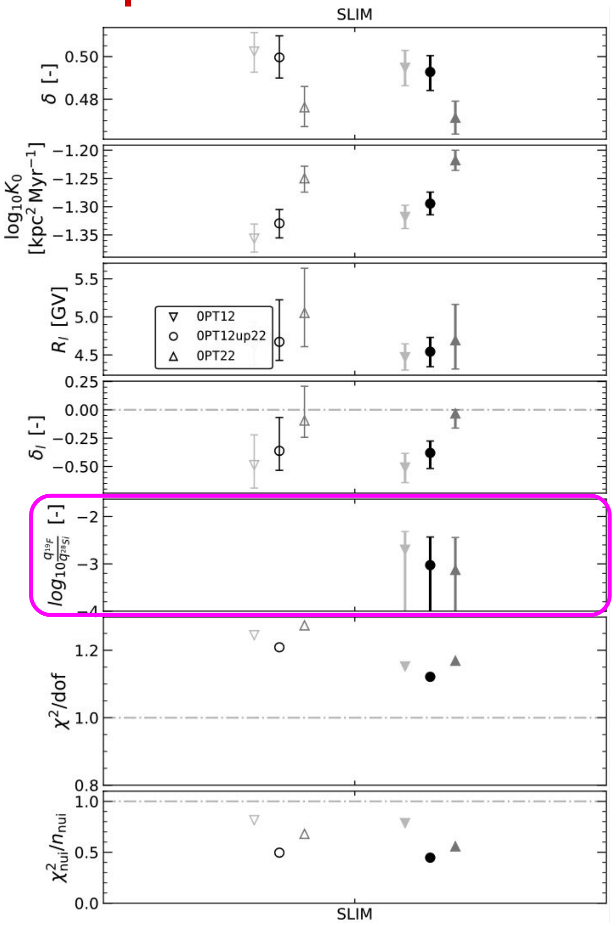
Propagation parameters



Fit F/Si +(Li,Be,B)/C

- Very good fit for combined analysis
- Diffusion slope consistent with delta=0.5
- Slight preference for low rigidity break
- Robust result wrt propagation scenarios (see paper)

Results of F/Si+(Li,Be,B)/C fit (allowing for q_F):
2) Source abundance



- The best fit value is ~ 10^{-3}, and a 1-sigma lower limit consistent with a null value (no primary F).

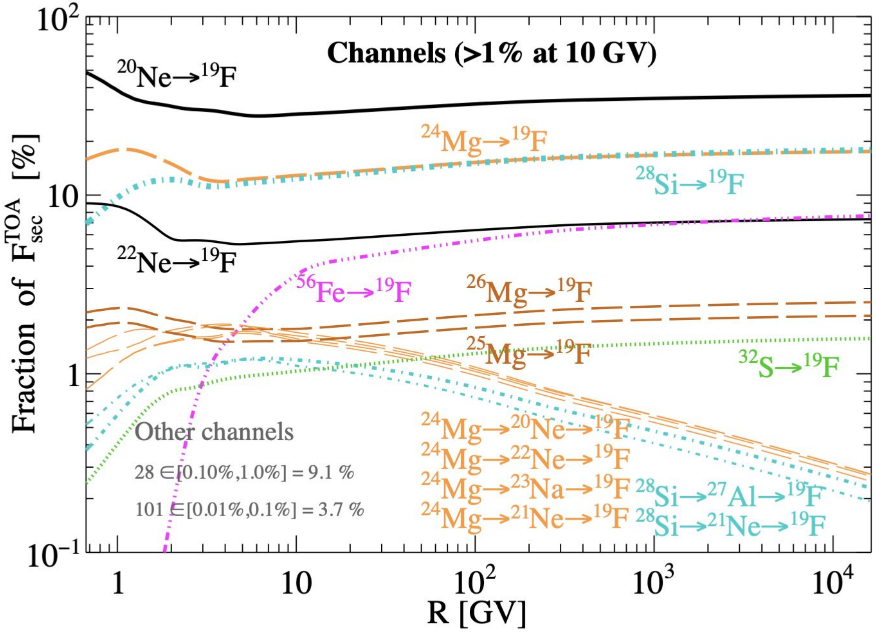
- 1-sigma upper limit on $(^{19}F\ /^{28}Si)_{CR}$ ~ 5 10^{-3} which is significantly higher than $(^{19}F\ /^{28}Si)_{CR}$ ~ 10^{-4} predicted in acceleration models [see Tatischeff et al MNRAS, 508, 2021]

Summary

- The transport parameters obtained from the AMS-02 F/Si are compatible with those obtained from lighter secondary-to-primary ratios.
- The combined fit of all these ratios yields an excellent agreement to the data, with <10% adjustment to the B and F production cross-sections.
- 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, indicating that no primary F component is needed. Our result does not reach the sensitivity needed to test global acceleration models of cosmic-ray nuclei.

backup

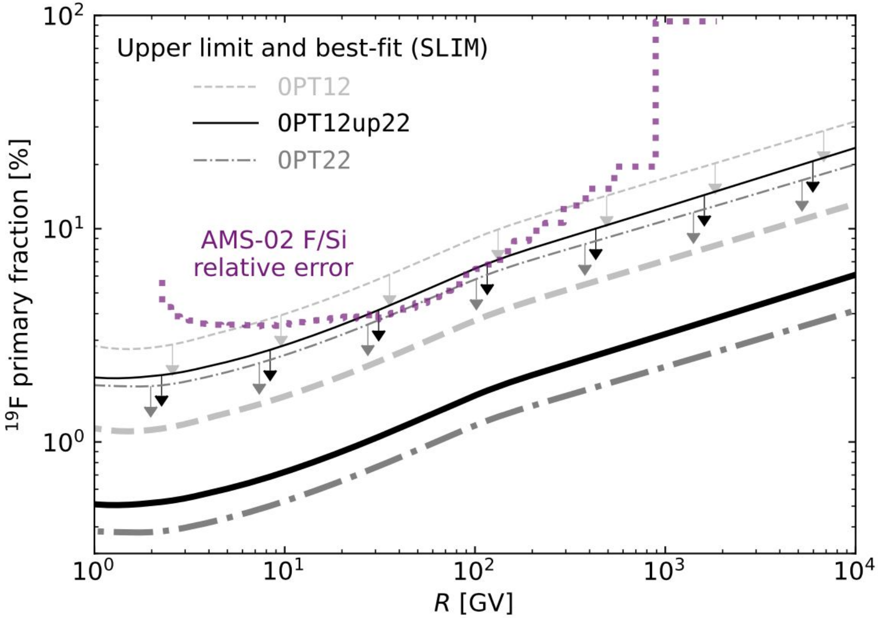
Dominant processes producing CR fluorine



- We have identified **5 channels** which contribute to the F production for~ 62% .
- We find that 1-step channels contribute to ~ 70% of F production, while 2-step production contribute to 20% and multi-steps production contribute to ~10%.
- These numbers only marginally depend on the cross-section set considered.

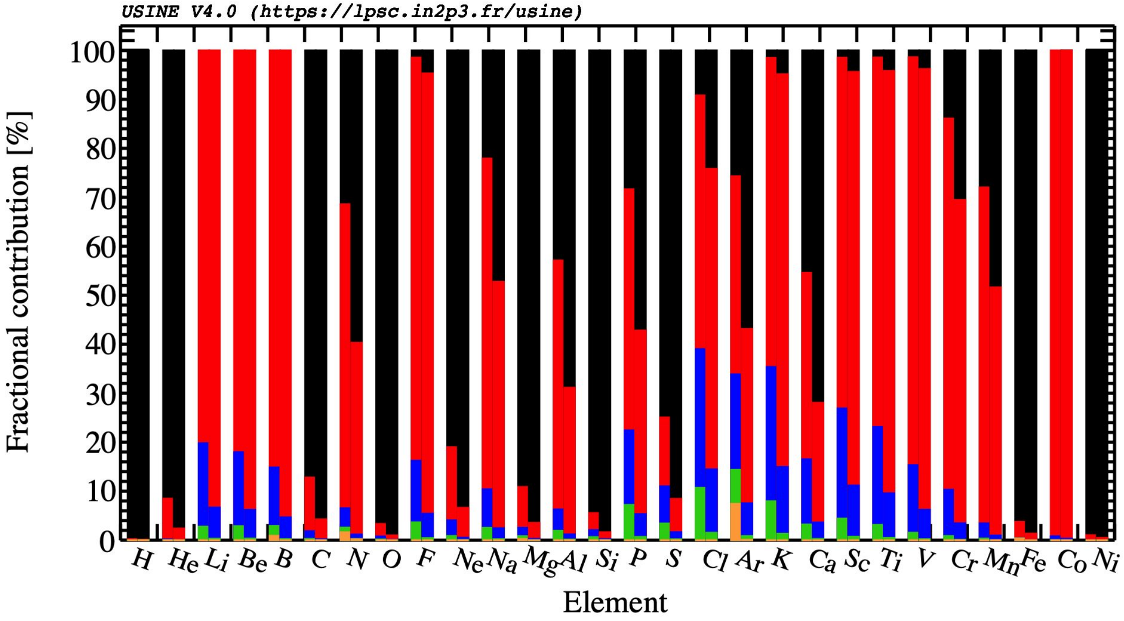
Results: do we need a F primary component ?

- Despite ^{19}F being mostly secondary, we study the effect of a primary component.
- The best fit value is ~ 10^{-3}, which is consistent with a null value, indicating that no primary contribution is necessary to match the data.
- 1-sigma upper limit on $(^{19}F/^{21}Si)_{CR}$ ~ 5 10^{-3} which is significantly higher than the predictions and does not allow to discriminate between different scenarios.



Secondary CR production

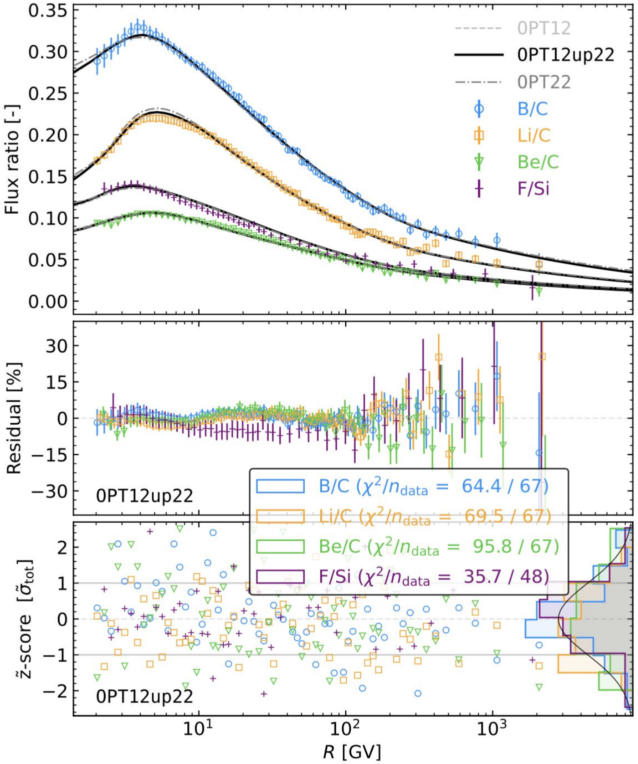
Relative contributions per production process for elemental fluxes
(at 50 GV and 2 TV)



Primary species
Secondary species (1step)
Secondary species (2steps)
Secondary species (>2steps)
Radioactive isotopes

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).

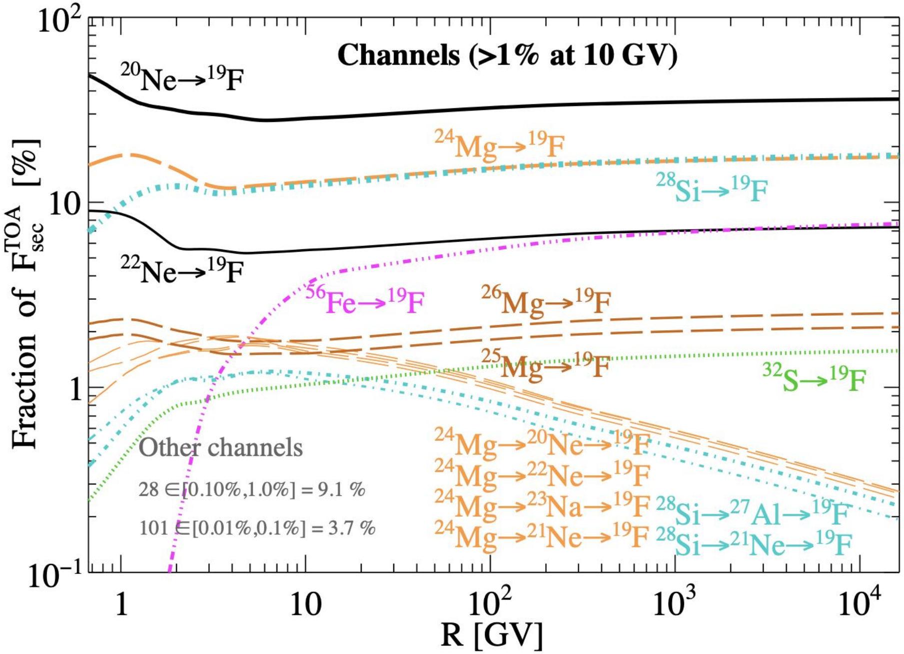
Combined analysis of Li,Be,B/C and F/Si data



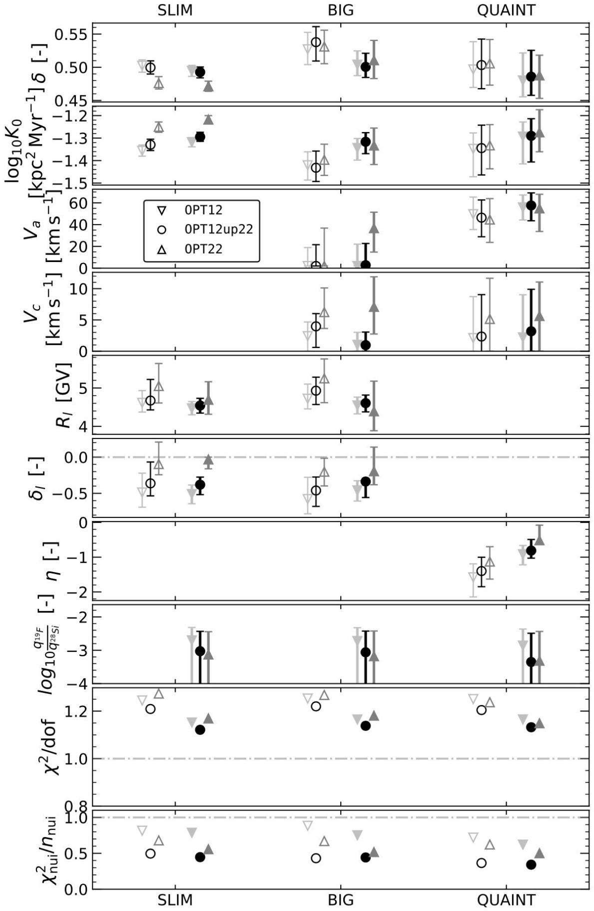
Summary

- 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

Dominant processes producing CR fluorine



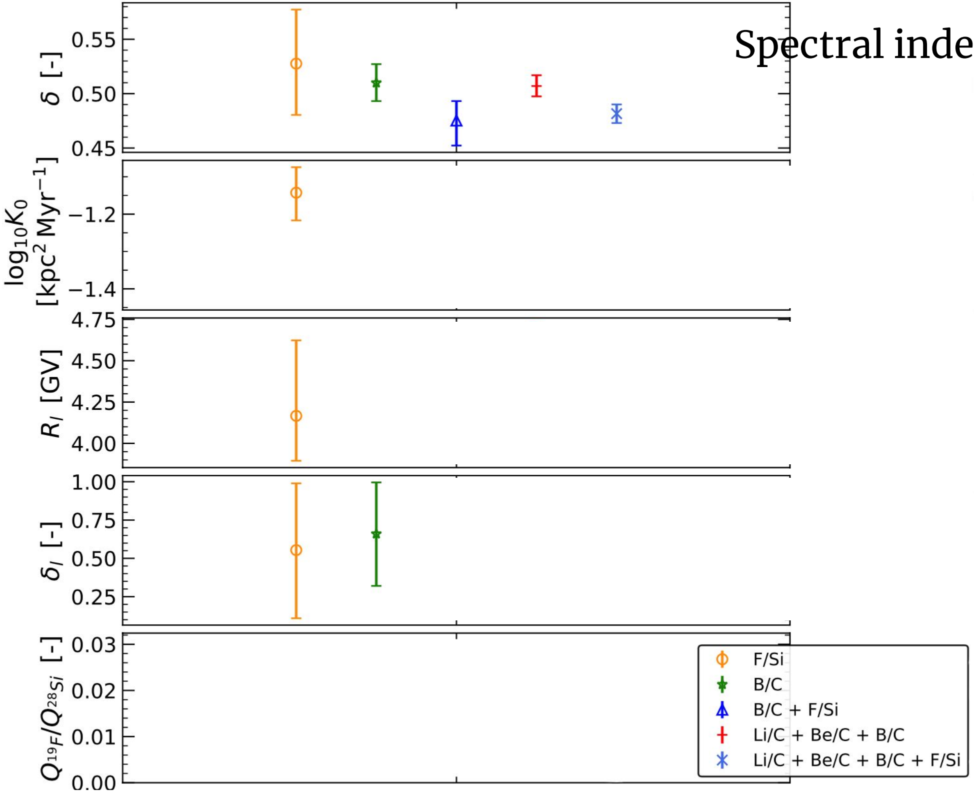
- We have identified **5 channels** contribute to ~ 62% of the total.
- While the ranking of the dominant channels is a robust prediction, the individual numbers are subject to uncertainties due to the cross section and propagation parameters.


SLIM
BIG
QUAINT
δ [-]
0.55
0.50
0.45
log10K0 [kpc² Myr⁻¹]
−1.2
−1.3
−1.4
−1.5
Va [km s⁻¹]
60
40
20
0
OPT12
OPT12up22
OPT22
Vc [km s⁻¹]
10
5
0
Rl [GV]
5
4
δl [-]
0.0
−0.5
η [-]
0
−1
−2
log10 q19F/q28Si [-]
−2
−3
−4
χ²/dof
1.2
1.0
0.8
χ²nui/nnui
1.0
0.5
0.0
SLIM
BIG
QUAINT

Results: propagation parameters (and more)

Effective diffusion coefficient

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

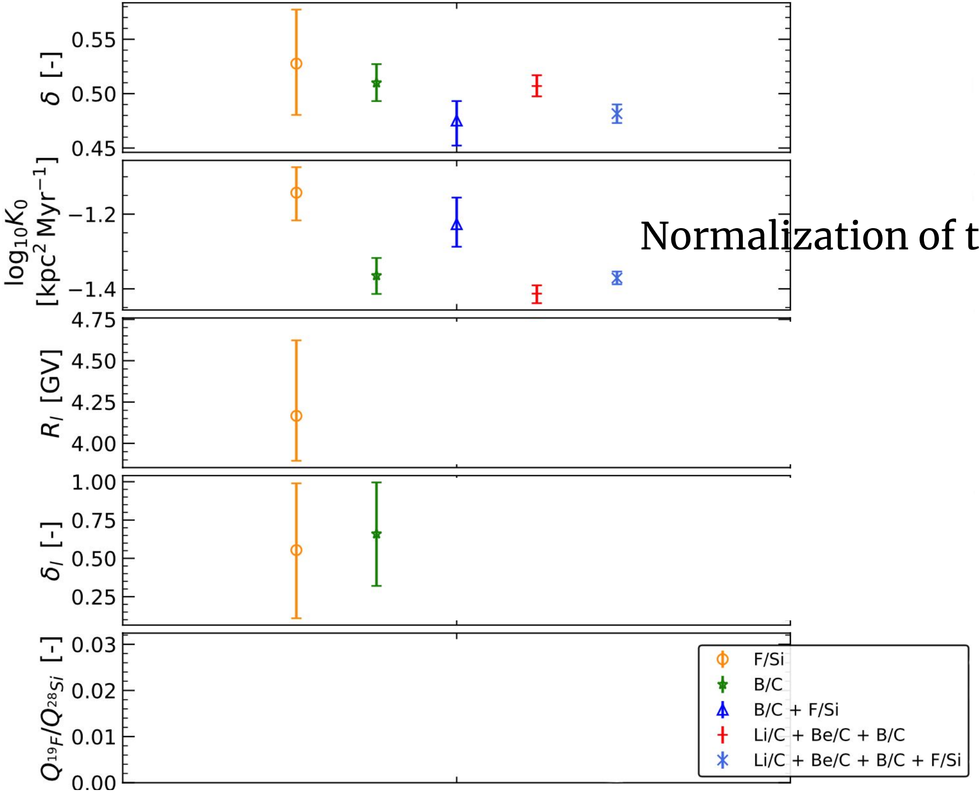


Spectral index of diffusion coefficient

Results: propagation parameters (and more)

Effective diffusion coefficient

$$K(R) = \beta^{\eta} K_0 \left\{ \boxed{1+} \left(\frac{R}{R_{\mathrm{l}}} \right)^{\frac{\delta_{\mathrm{l}}-\delta}{s_{\mathrm{l}}}} \right\}^{s_{\mathrm{l}}} \left\{ \frac{R}{R_0 = 1\,\mathrm{GV}} \right\}^{\delta} \left\{ 1 + \left(\frac{R}{R_{\mathrm{h}}} \right)^{\frac{\delta-\delta_{\mathrm{h}}}{s_{\mathrm{h}}}} \right\}^{-s_{\mathrm{h}}}.$$

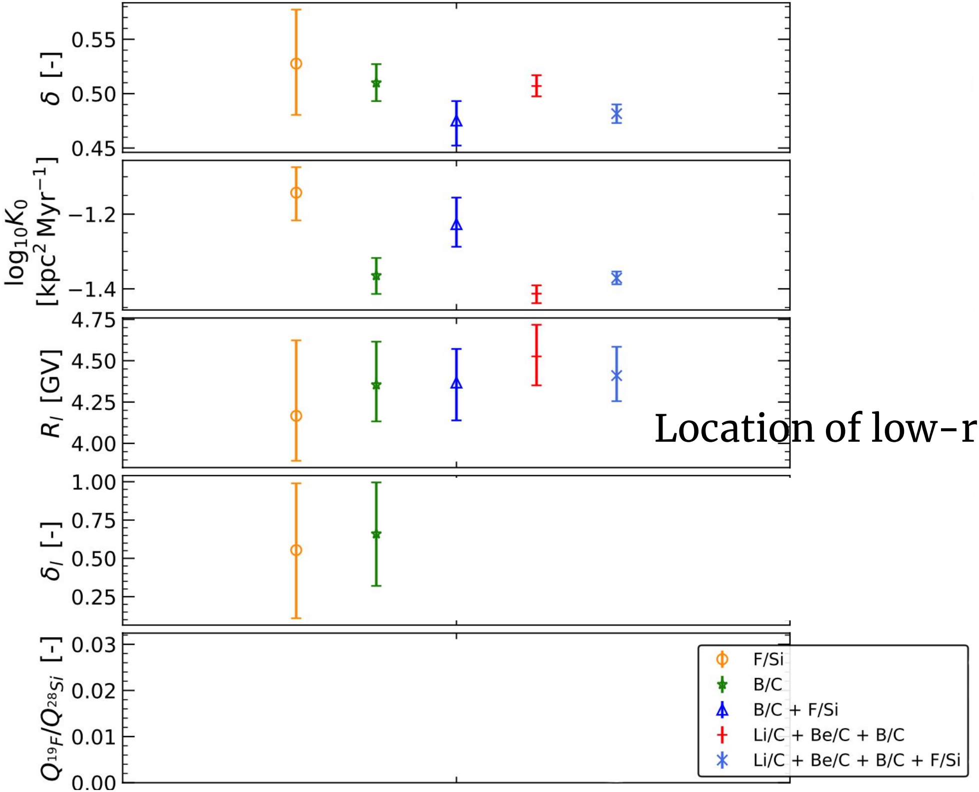


Normalization of the diffusion coefficient

Results: propagation parameters (and more)

Effective diffusion coefficient

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

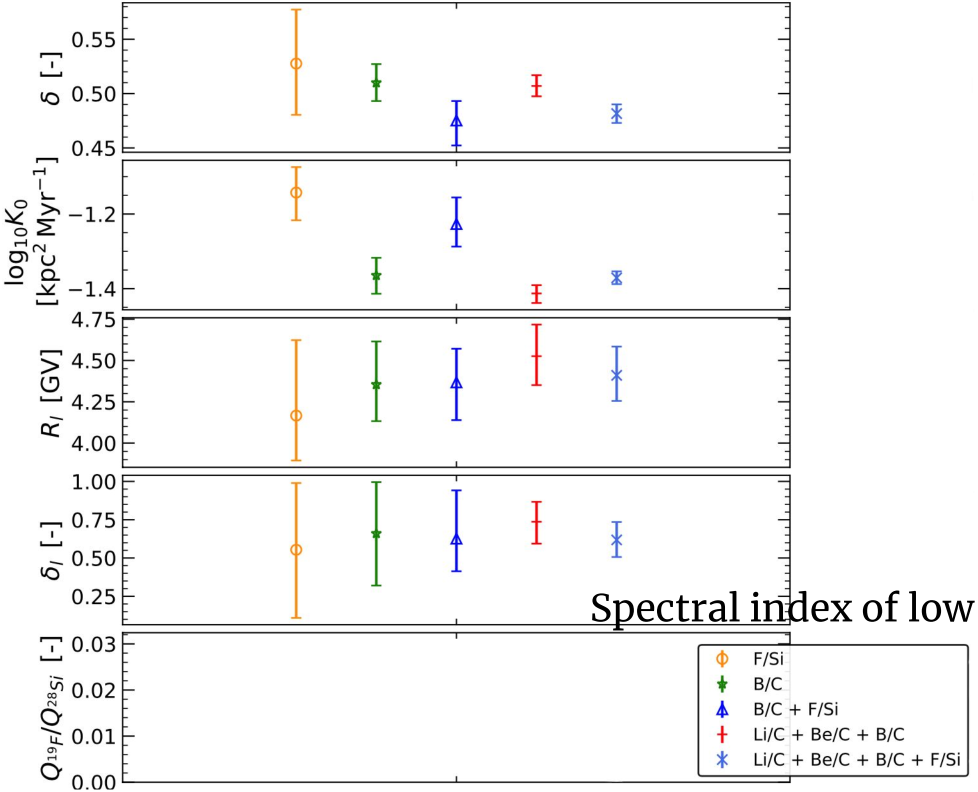


Location of low-rigidity break

Results: propagation parameters (and more)

Effective diffusion coefficient

$$K(R) = \beta^{\eta} K_0 \left\{1+\left(\frac{R}{R_{\mathrm{l}}}\right)^{\frac{\delta_{\mathrm{l}}-\delta}{s_{\mathrm{l}}}}\right\}^{s_{\mathrm{l}}} \left\{\frac{R}{R_0 = 1\,\mathrm{GV}}\right\}^{\delta} \left\{1+\left(\frac{R}{R_{\mathrm{h}}}\right)^{\frac{\delta-\delta_{\mathrm{h}}}{s_{\mathrm{h}}}}\right\}^{-s_{\mathrm{h}}}.$$



Spectral index of low-rigidity diffusion coefficient