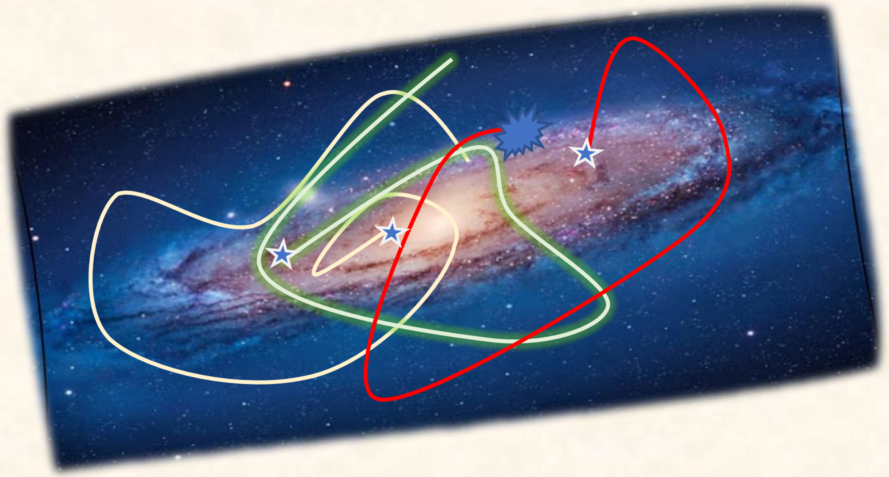
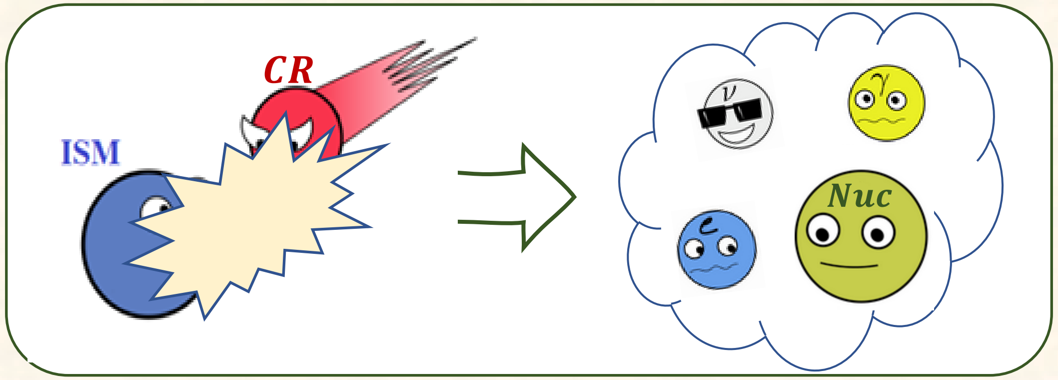
Impact of cross sections uncertainties on the study of galactic cosmic-ray propagation





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Presentation outline

Secondary cosmic rays to study propagation

Flux ratios of secondary cosmic rays from different cross sections parametrizations

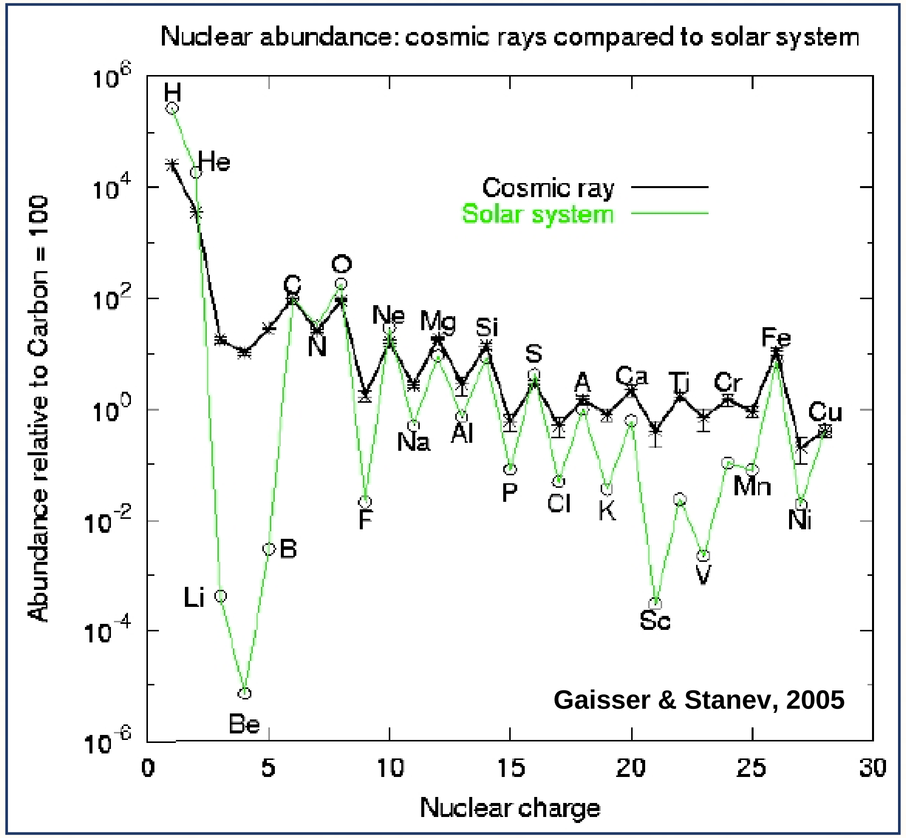
- Hints of primary component of B, Be or Li?
- Constraints on the halo height?
- Primary component of fluorine?

Propagation parameters inferred from different flux ratios and cross sections

- Is it possible to reproduce simultaneously all secondary CRs?

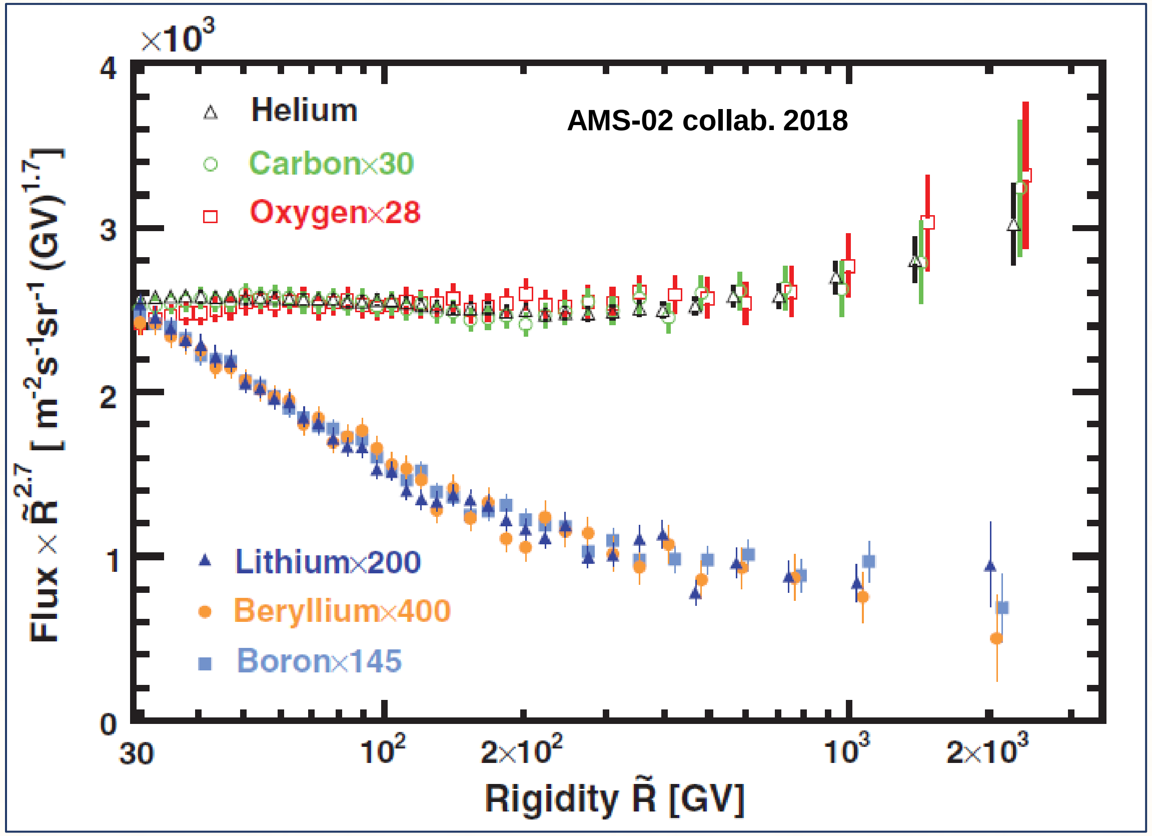
Primary CRs are accelerated in astrophysical sources (presumably SNRs) and propagate throughout the Galaxy, occasionally interacting with gas in the disc of the Galaxy, and there they produce secondary nuclei through spallation.

Abundance of secondary nuclei explained if CRs propagate for hundred millions of years



Gaisser & Stanev, 2005

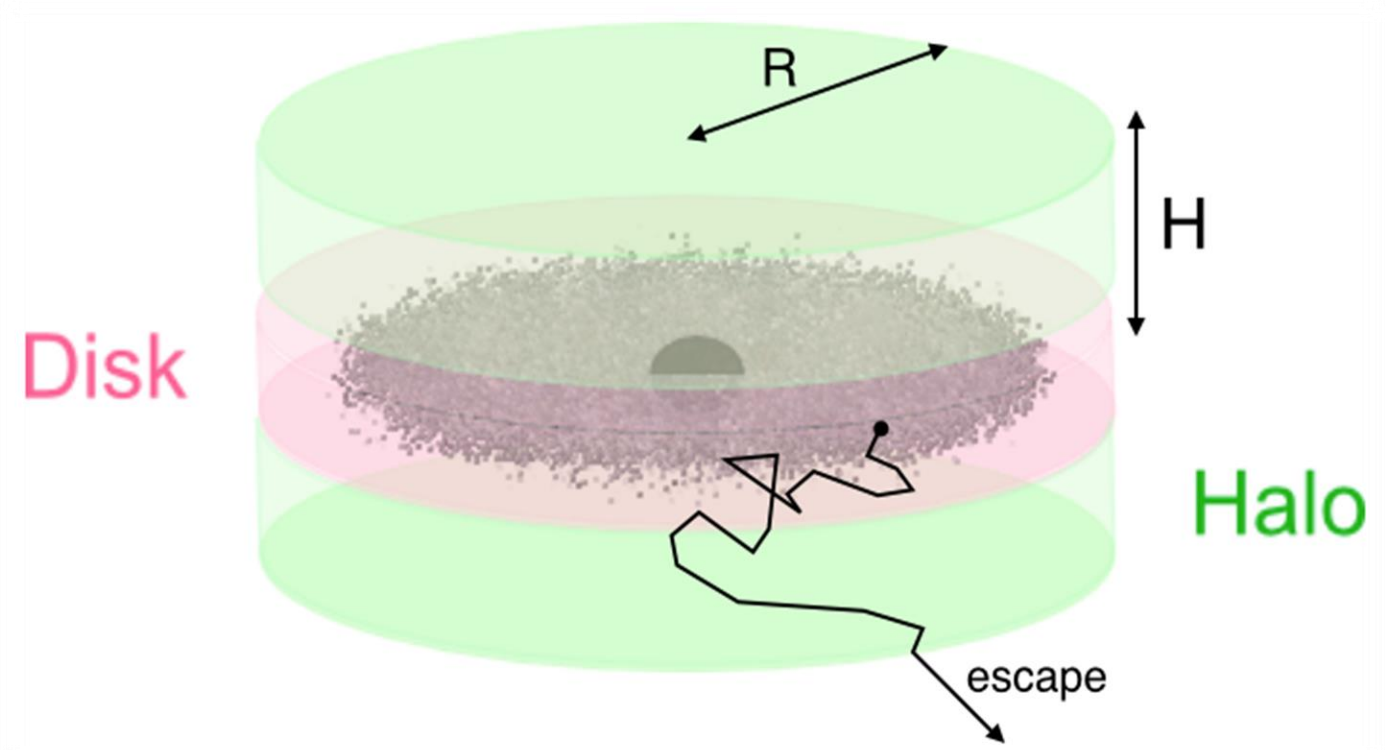
Secondary CRs offer a sensitive tool to infer the grammage traversed by these particles



AMS-02 collab. 2018

Diffusive transport of Galactic cosmic rays

$$\vec{\nabla}\cdot(-D\nabla N_i - \vec{v}_\omega N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] = Q_i + \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_\omega N_i\right)\right]$$
$$-\frac{N_i}{\tau_i^f} + \sum\Gamma^s_{j\to i}(N_j) - \frac{N_i}{\tau_i^r} + \sum\frac{N_j}{\tau^r_{j\to i}}$$



Secondary-to-primary ratios are key to evaluate the diffusion coefficient

Diffusion coefficient ($D \propto 1/\tau^{\mathrm{diff}}$)

$$N_{pr} \propto Q_{pr}(E)/D(E)$$

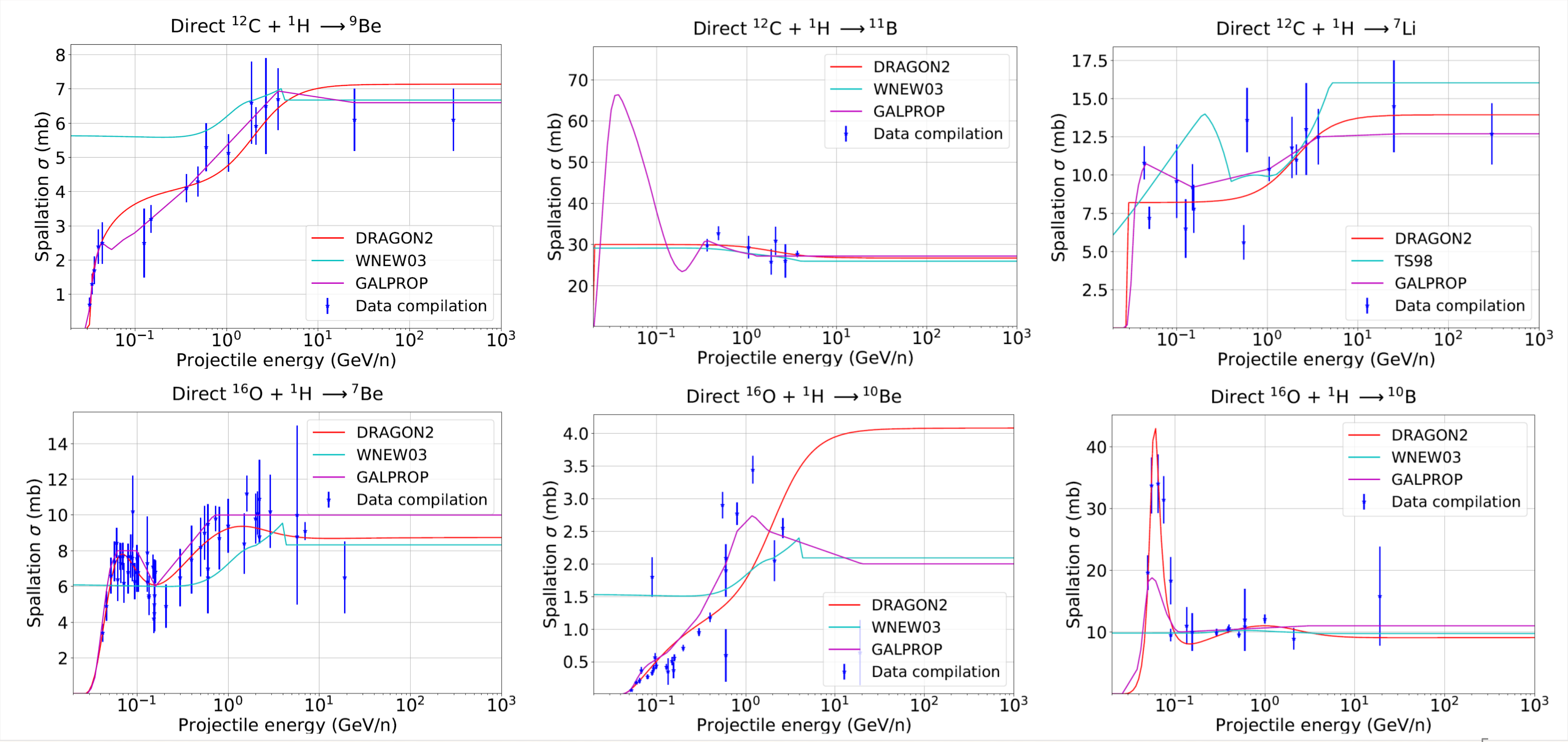
$$N_{sec} \propto Q_{sec}(E)/D(E)$$

$$Q_{sec} \propto N_{pr}(E)\,\sigma(E)$$

$$\frac{N_{sec}}{N_{pr}} = \frac{Q_{sec}}{Q_{pr}} \sim \sigma(E)/D(E)$$

Complexity of cross sections measurements and the amount of interaction channels involved in the CR network obey us to employ <u>parametrizations</u>

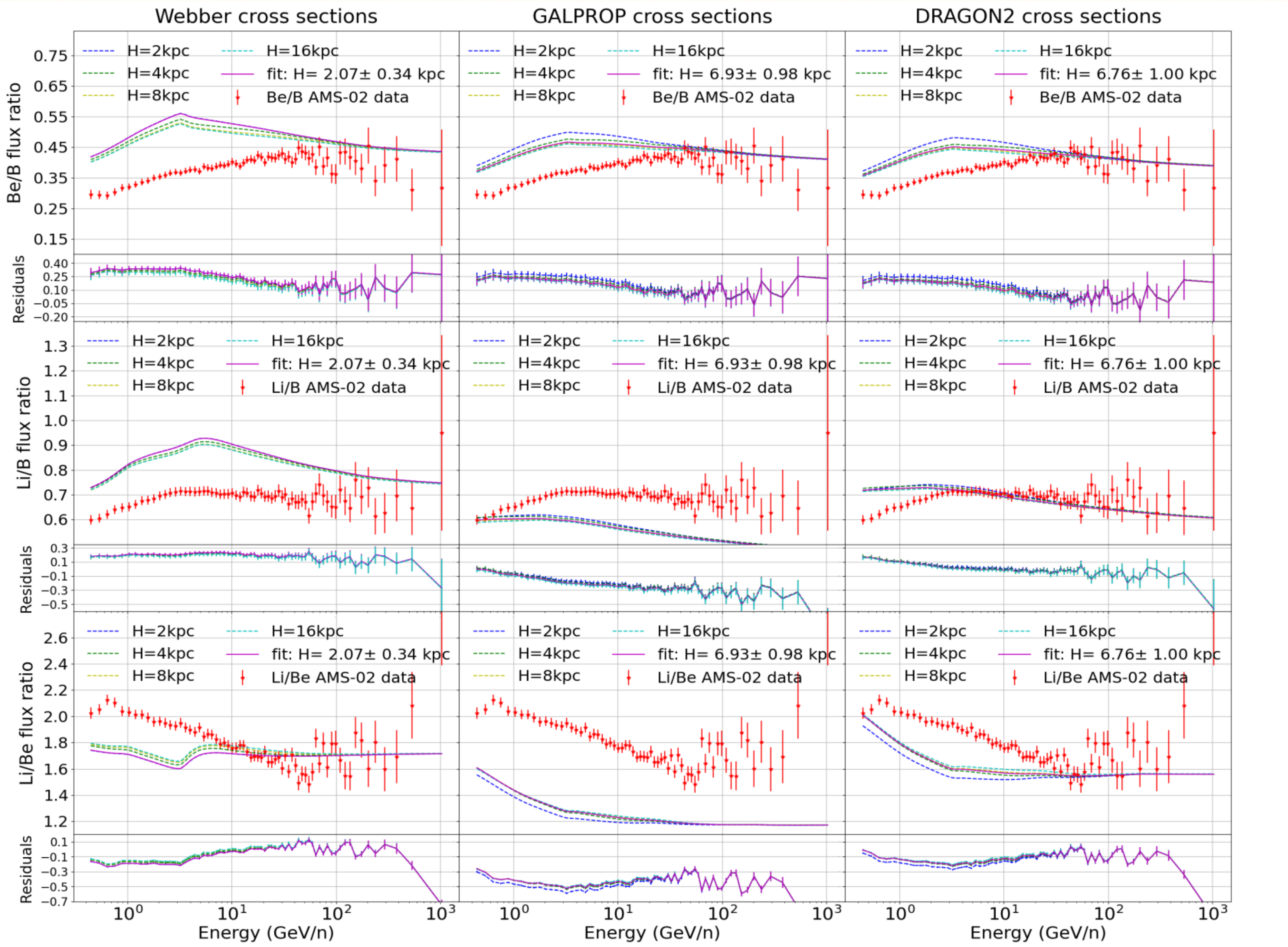
Cross sections parametrizations



Flux ratios of CR B, Be and Li

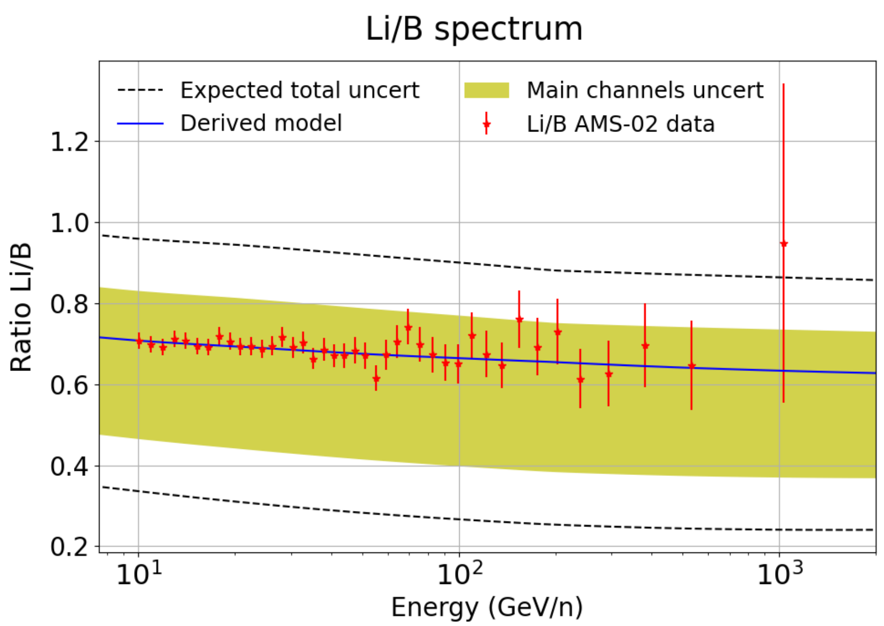
- **Ratios among secondary cosmic rays offer a sensitive tool to compare between different cross sections models**
- Combination of different CR species provide a way to reduce the effect of uncertainties
- Li flux ratios predictions from GALPROP seem to be significantly discrepant with other parametrizations: **Li problem**
- **Primary origin of Li?**

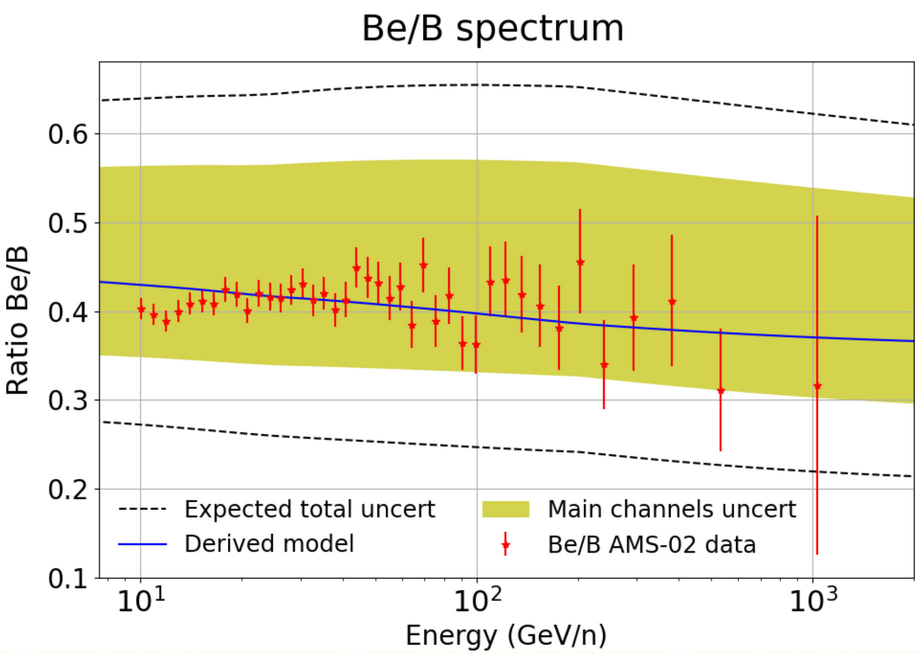
De la Torre et al. JCAP 03, 099 (2021)

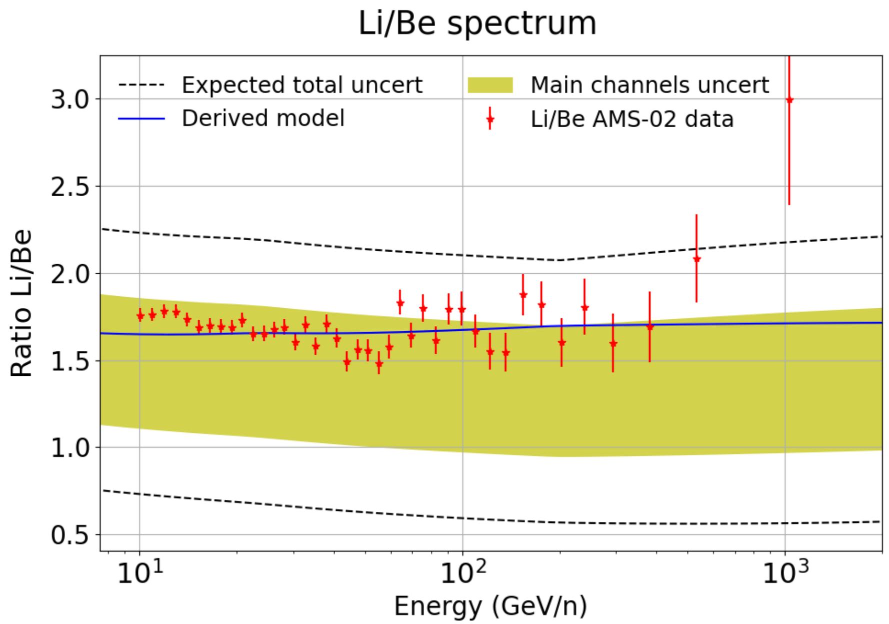


Secondary-over-secondary ratios allow us to easily propagate the cross sections uncertainties revealing that Li, Be and B can be explained at the same time without need of any (extra) primary sources

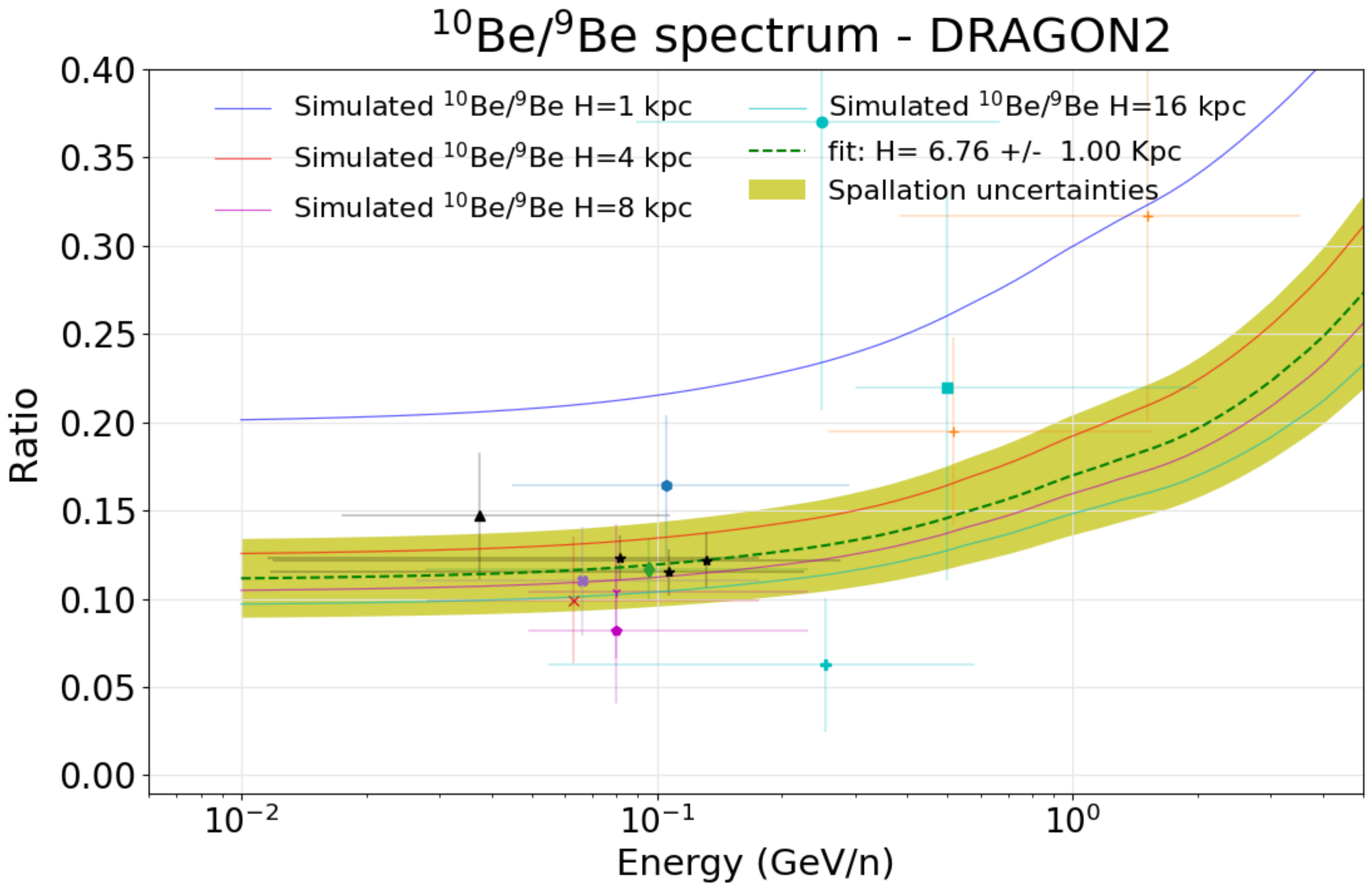
Combination of secondary-over-secondary flux ratios and cross sections measurements can help improving the current parametrizations

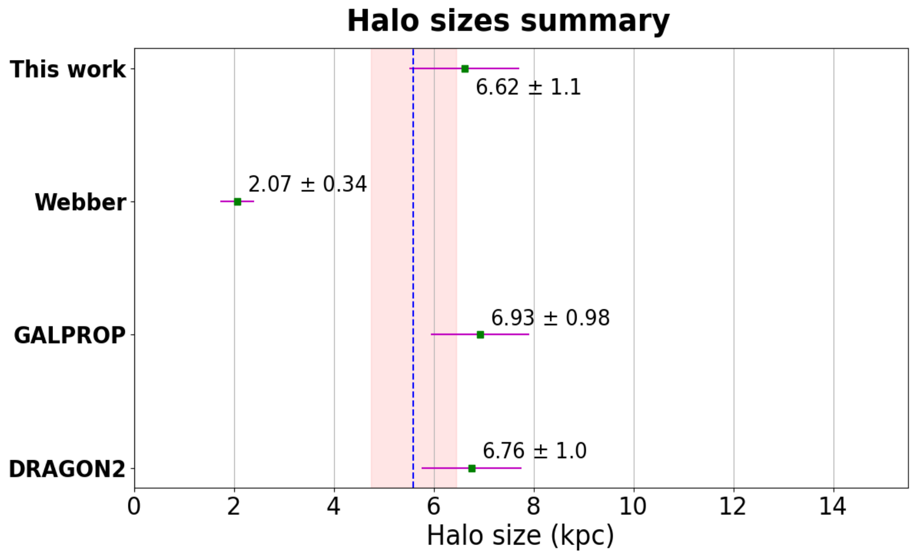






Impact of spallation uncertainties on the halo height determination





Best combined fit: H = 6.8 ± 1 kpc

Spallation uncertainties imply uncertainties around 40% in this ratio

Including these uncertainties we can only constraint the value of the halo height to be **3 kpc < H < 20 kpc**

Fluorine spectra

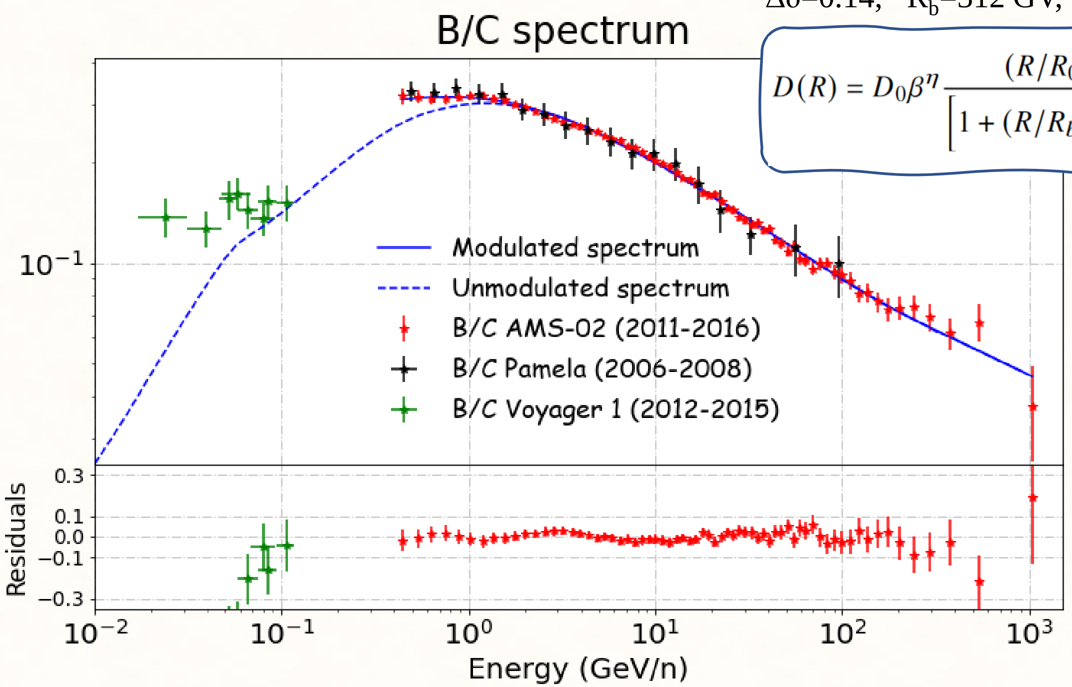
^{19}F mainly produced from Ne, Mg, Si group

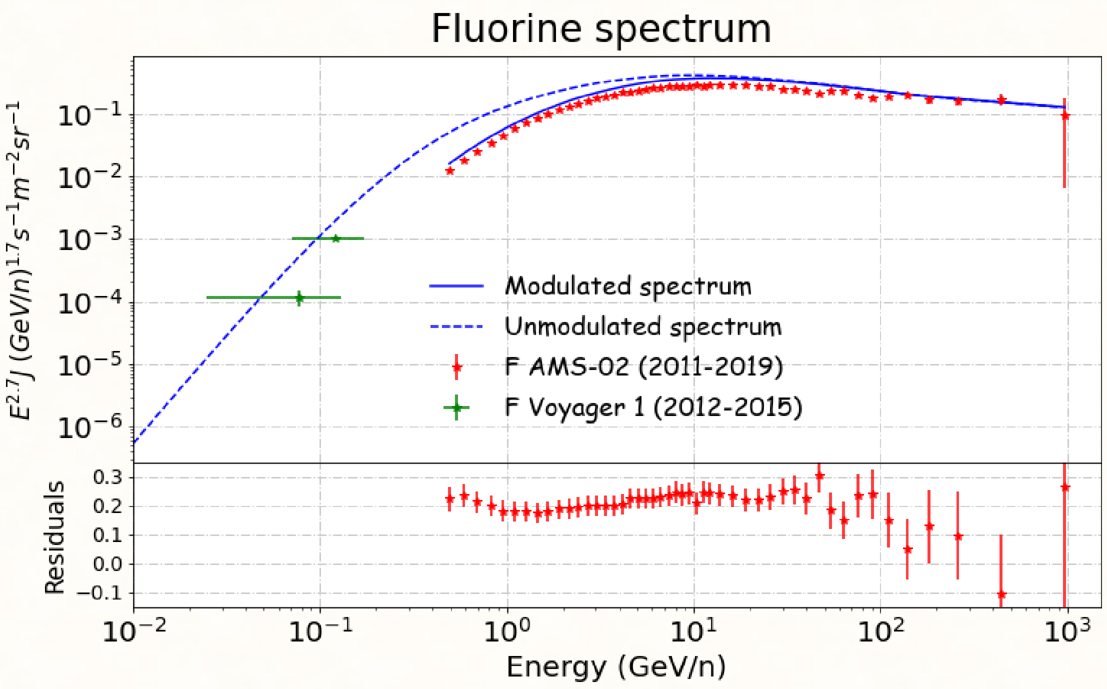
Uncertainties are higher and difficult to quantify

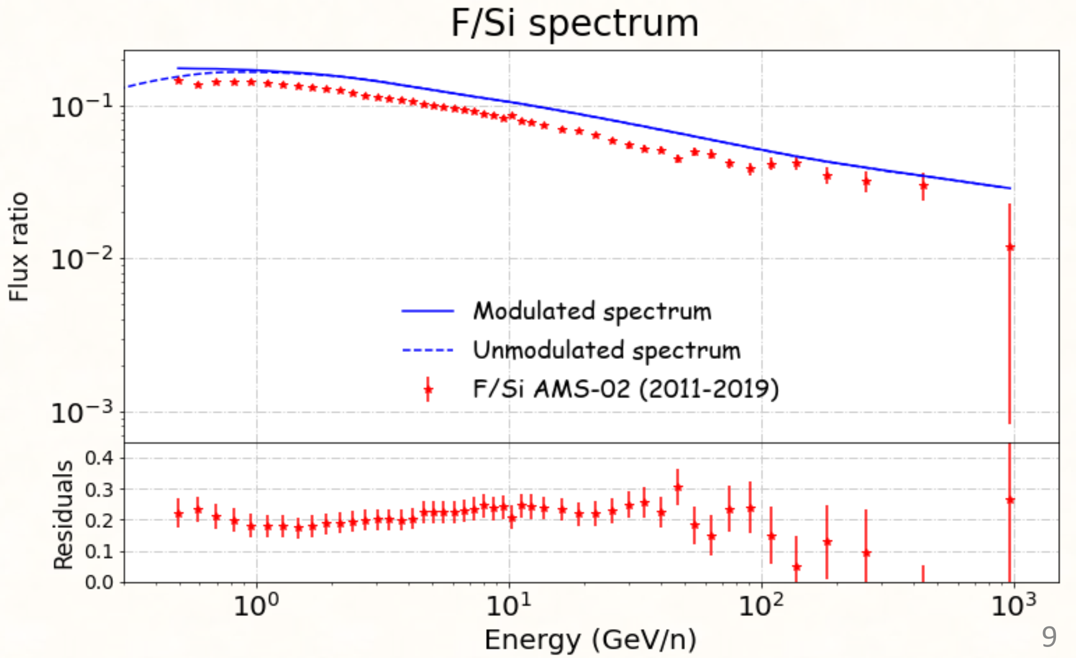
Compatible with AMS-02 data considering a cross sections scaling of ~20%

H=6.8 kpc, $D_0=7.1\cdot10^{28}$ cm^2/s,
V_A=27.7 km/s, η=-0.6, δ=0.42
Δδ=0.14, R_b=312 GV, R_0=4GV

$$D(R) = D_0\beta^{\eta}\frac{(R/R_0)^{\delta}}{\left[1+(R/R_b)^{\Delta\delta/s}\right]^{s}}$$







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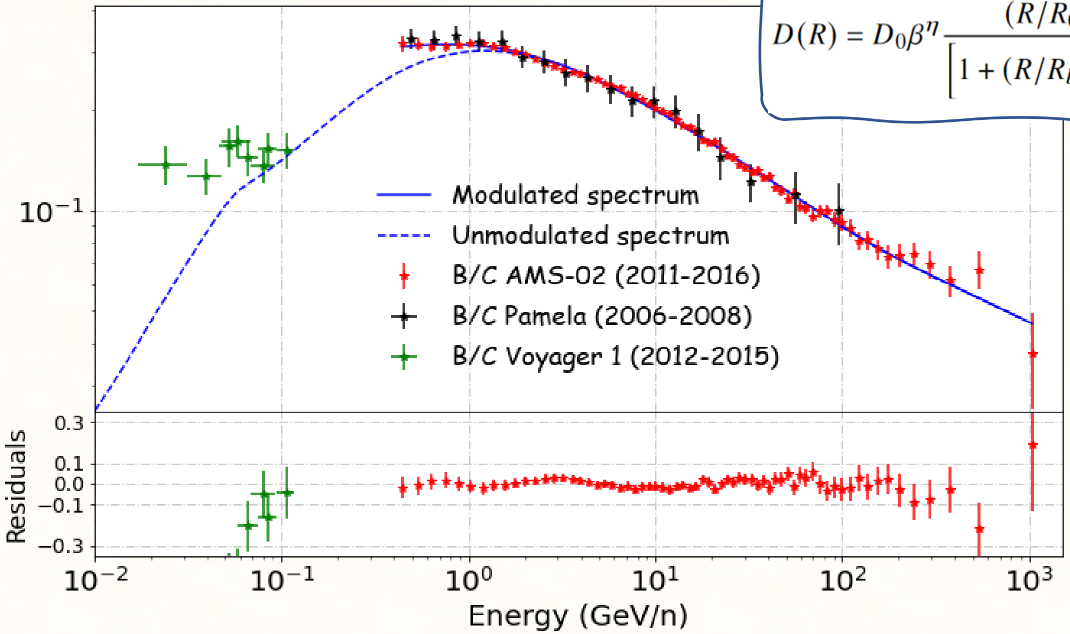
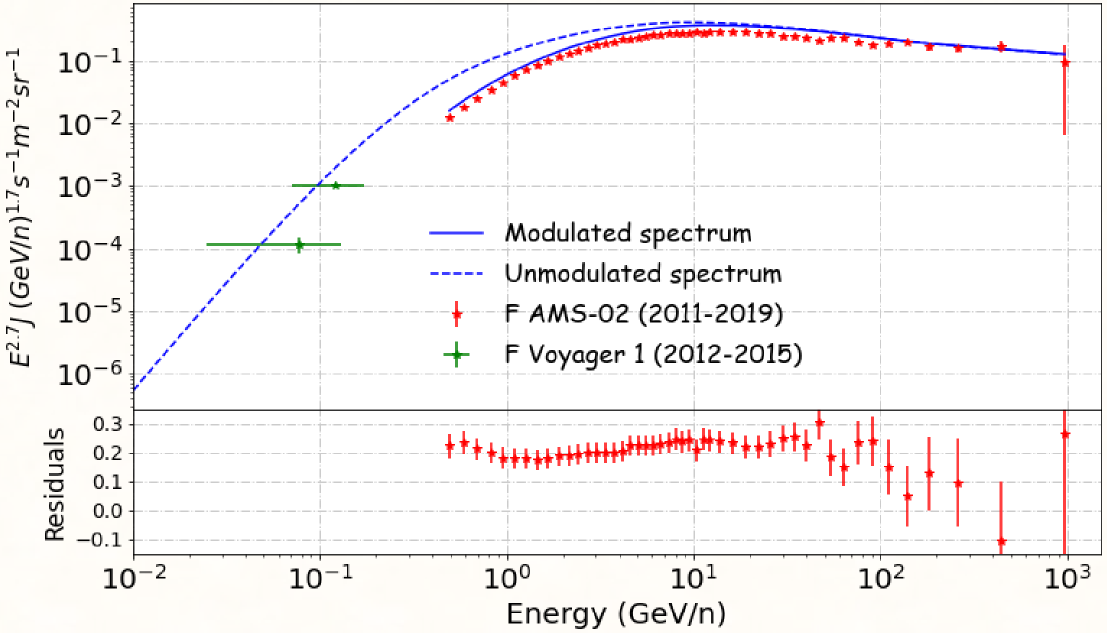
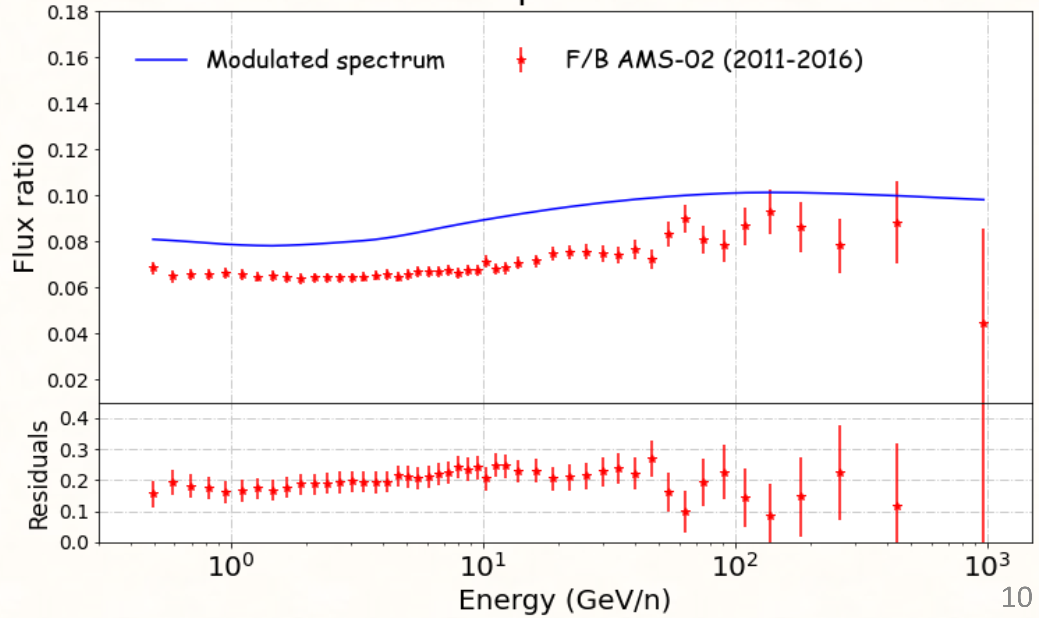
B/C spectrum



Fluorine spectrum

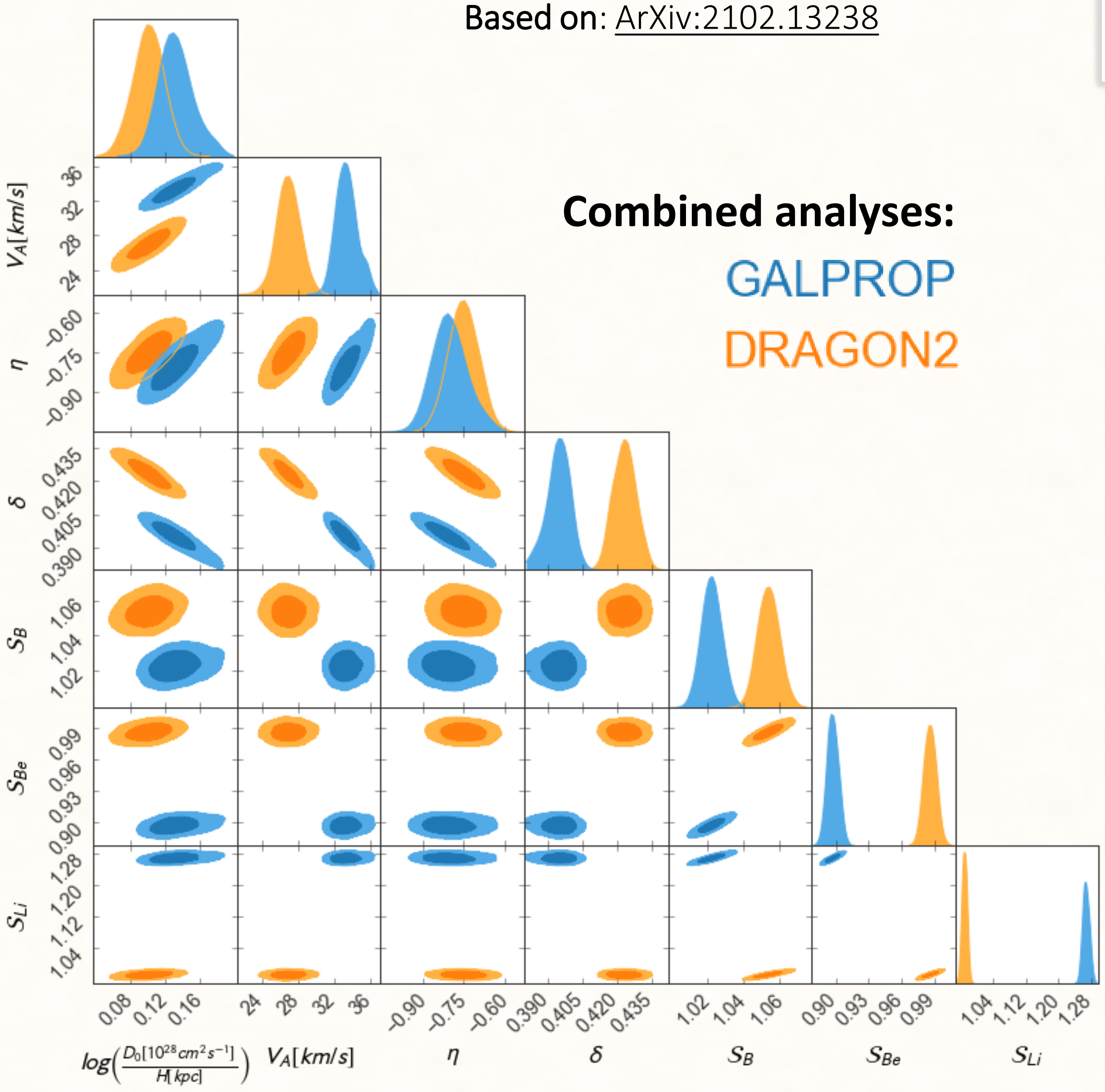


F/B spectrum



Analyses of the diffusion parameters

Based on: ArXiv:2102.13238



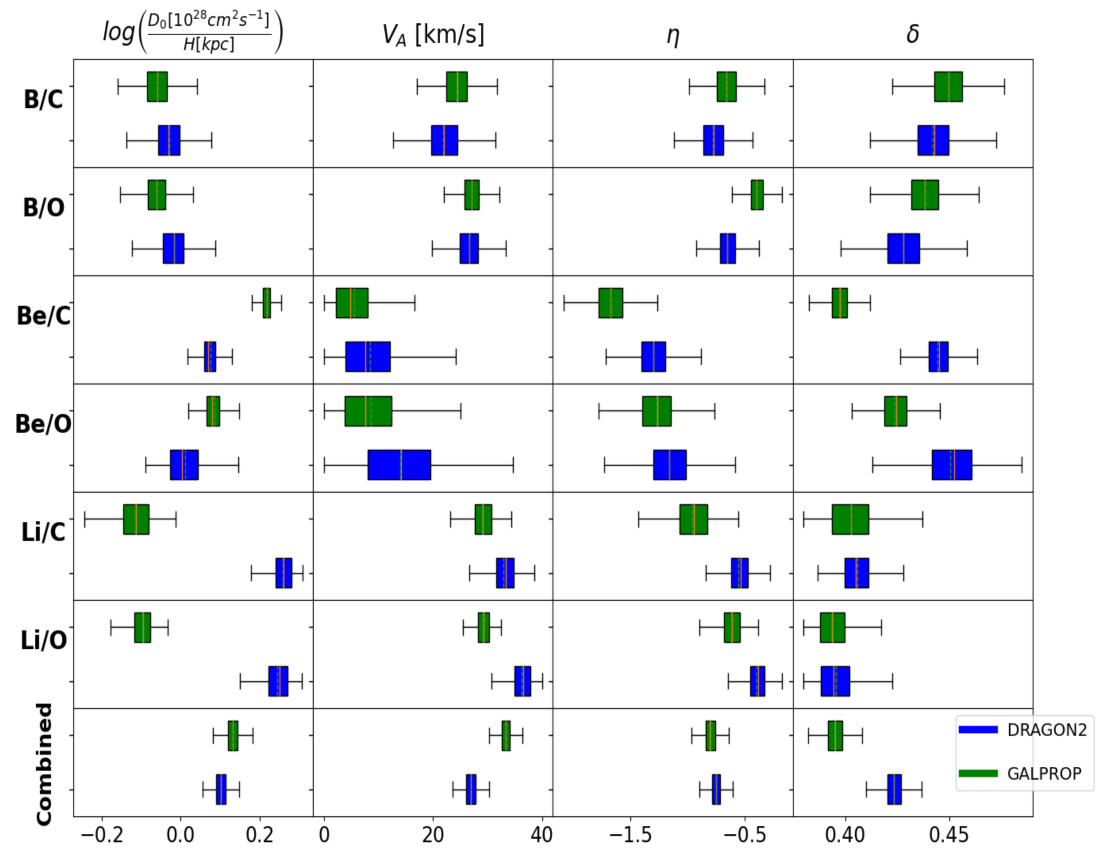
Combined analyses:

GALPROP

DRAGON2

Monte Carlo analysis: Combination of the ratios of secondary CRs

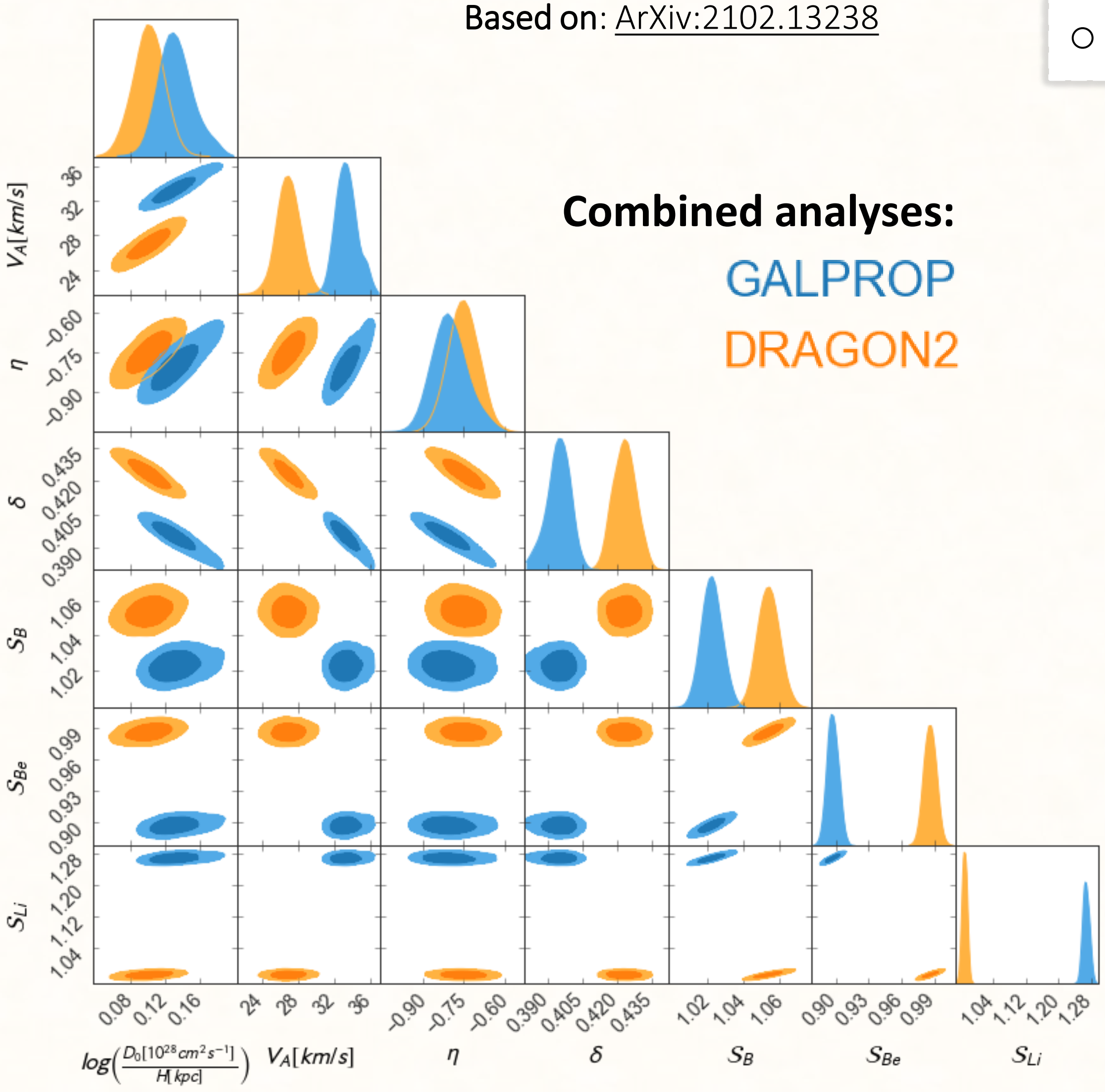
$$\ln \mathscr{L}^{Total} = \sum_{F}^{Li,Be,B/(C,O,Li,Be,B)} \ln(\mathscr{L}(F)) + \sum_{X}^{B,Be,Li} \mathscr{N}_X$$



Analyses of the diffusion parameters

- ○ Negative η values → Wave dissipation
- ○ V_A compatible with ~ 30 km/s
- ○ Large dispersion of δ: 0.37 – 0.46, specially hard for Li ratios

Based on: ArXiv:2102.13238



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GALPROP

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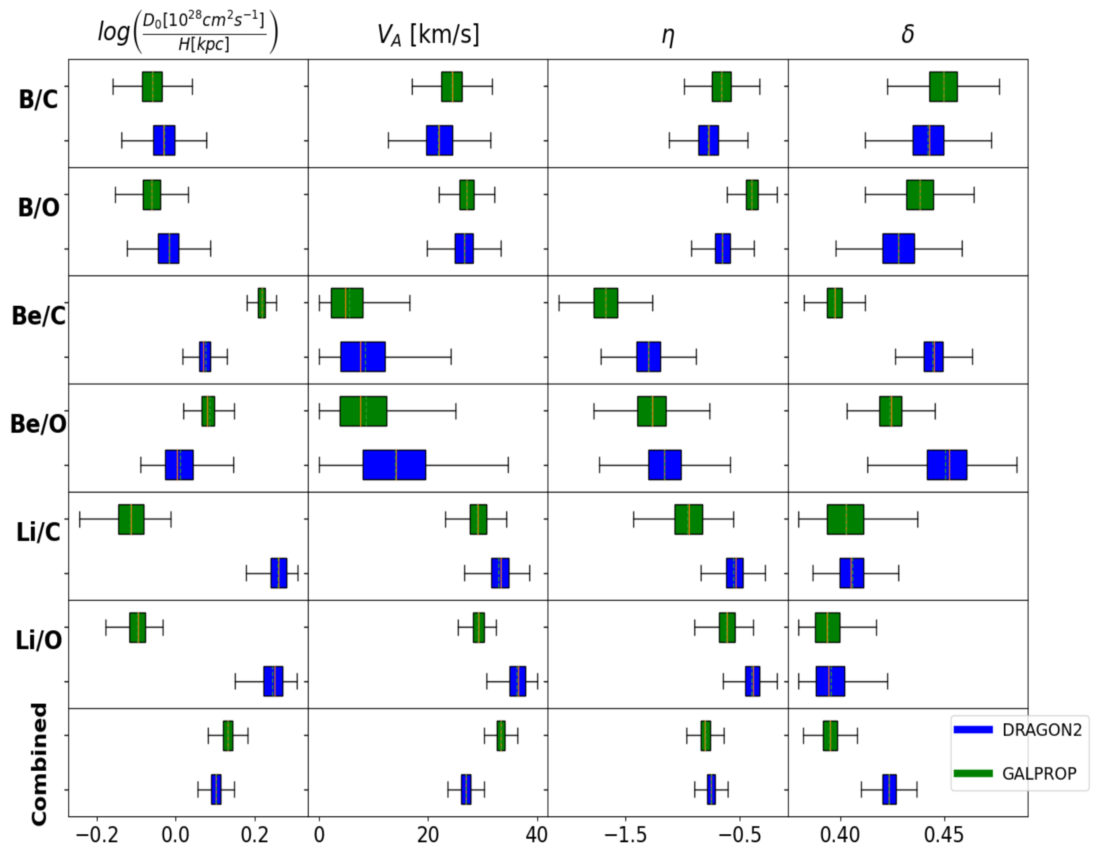
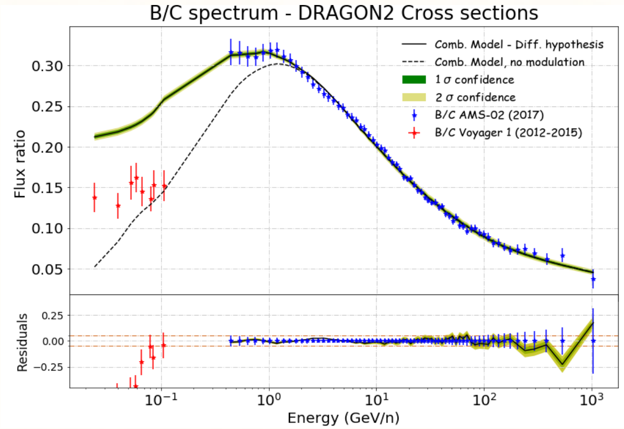
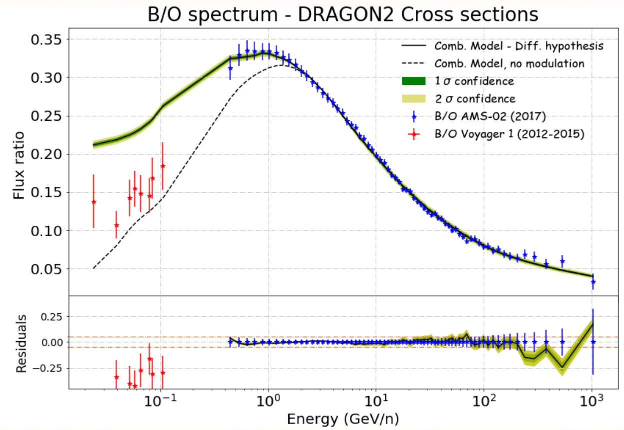
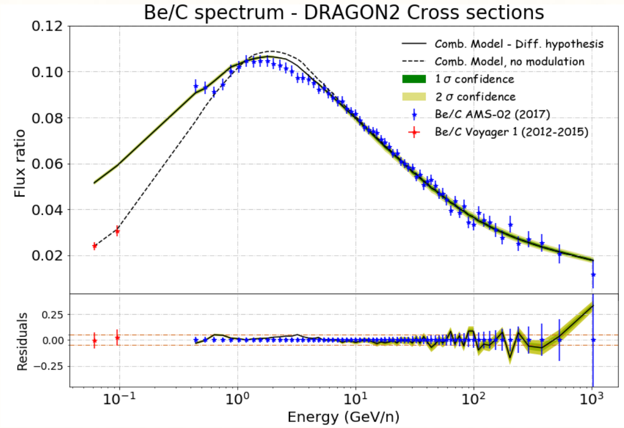
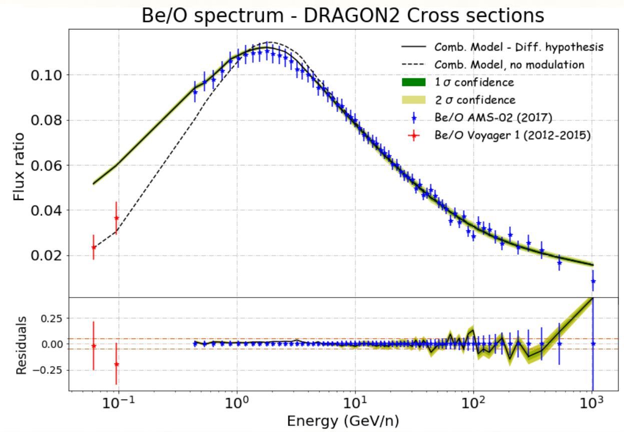


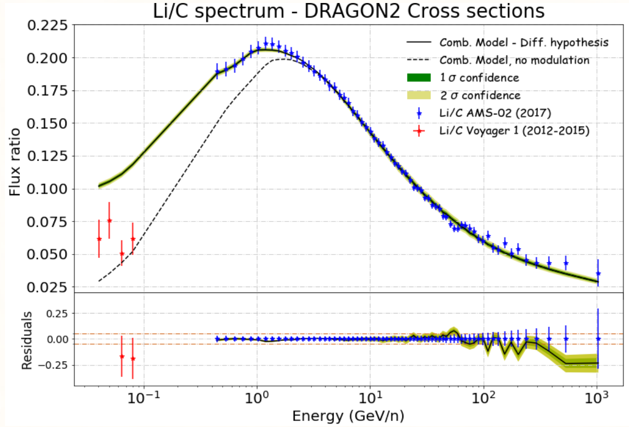
Combined DRAGON2

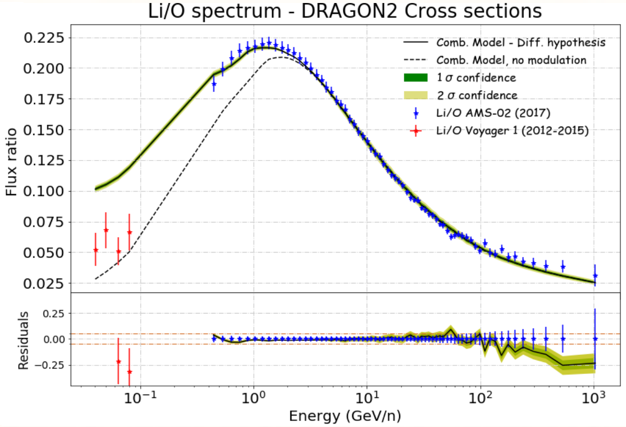

B/C spectrum - DRAGON2 Cross sections


B/O spectrum - DRAGON2 Cross sections


Be/C spectrum - DRAGON2 Cross sections

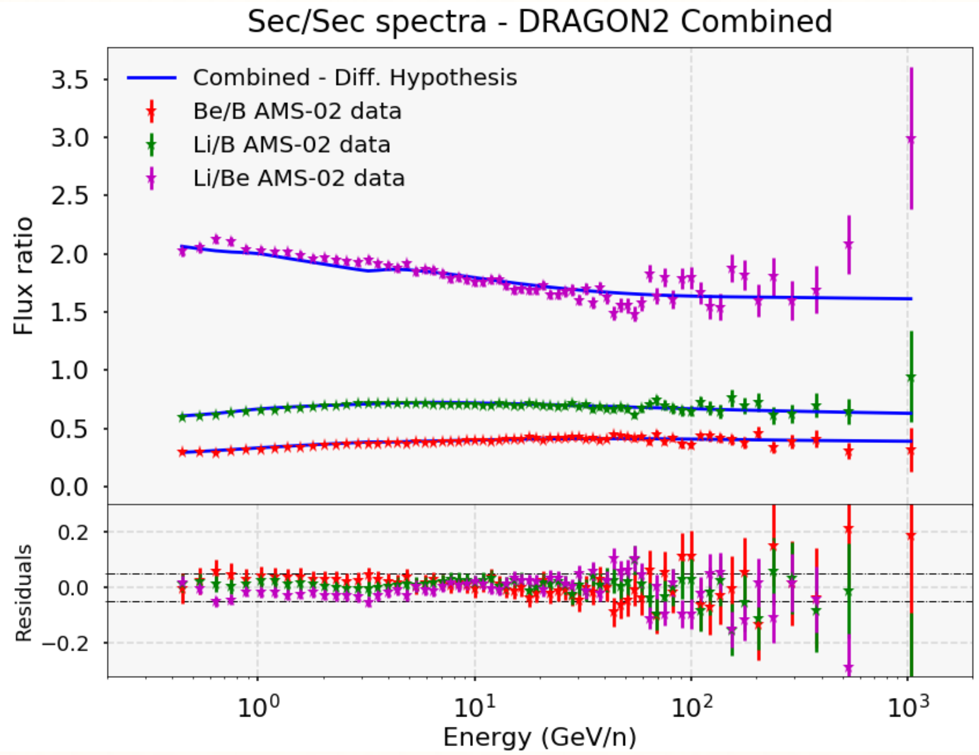

Be/O spectrum - DRAGON2 Cross sections


Li/C spectrum - DRAGON2 Cross sections


Li/O spectrum - DRAGON2 Cross sections

Compatible with all ratios for scale factors $S_X < 1.06$ (< 6% scale)

Predicted **δ = 0.42 (0.38-0.44)**

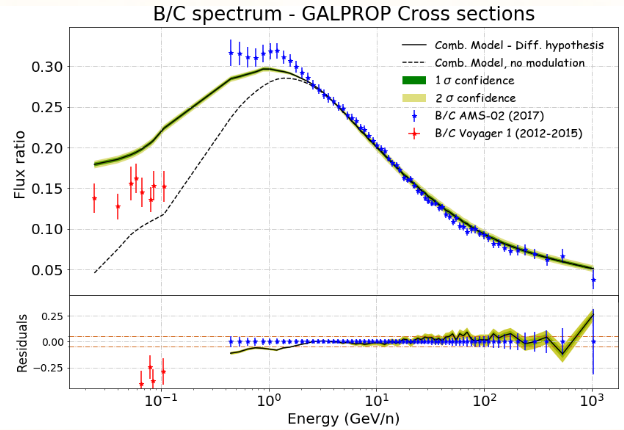

Sec/Sec spectra - DRAGON2 Combined

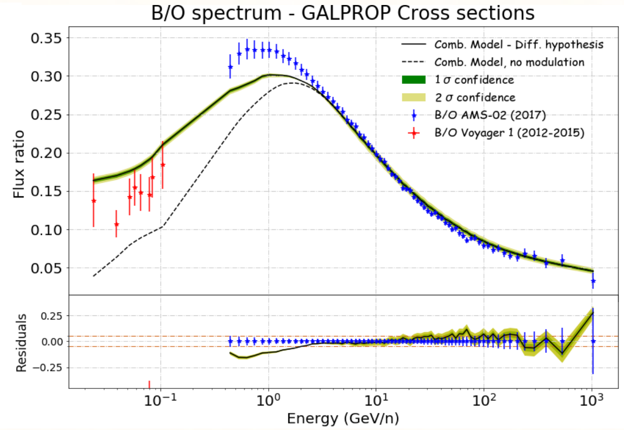
Combined GALPROP

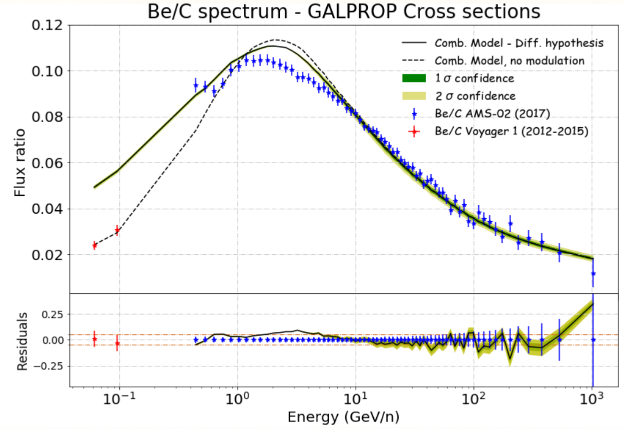
Need of more degrees of freedom

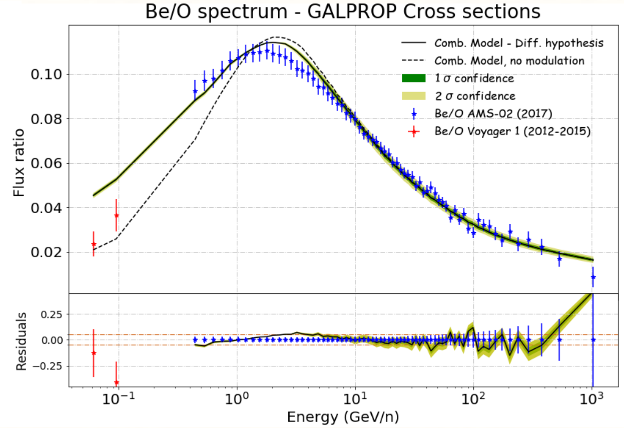
$S_B = 1.01$, $S_{Be} = 0.9$, $S_{Li} = 1.25$ (±1%)

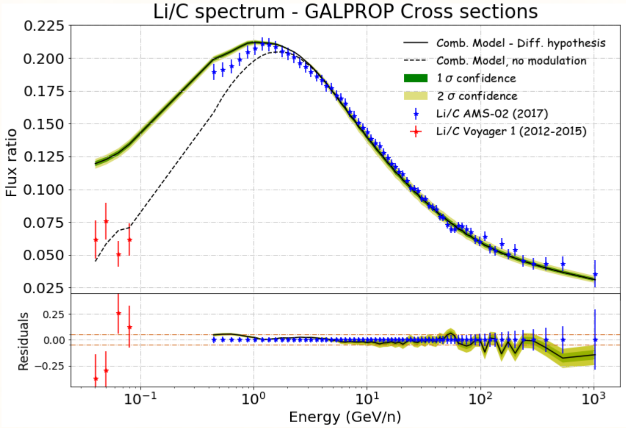
Predicted **δ = 0.39 (0.35-0.42)**

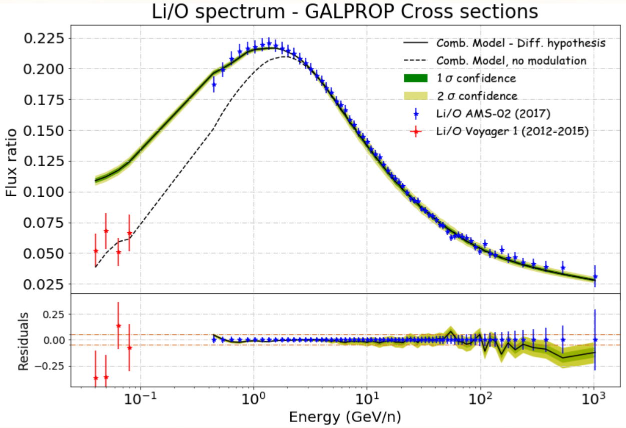

B/C spectrum - GALPROP Cross sections

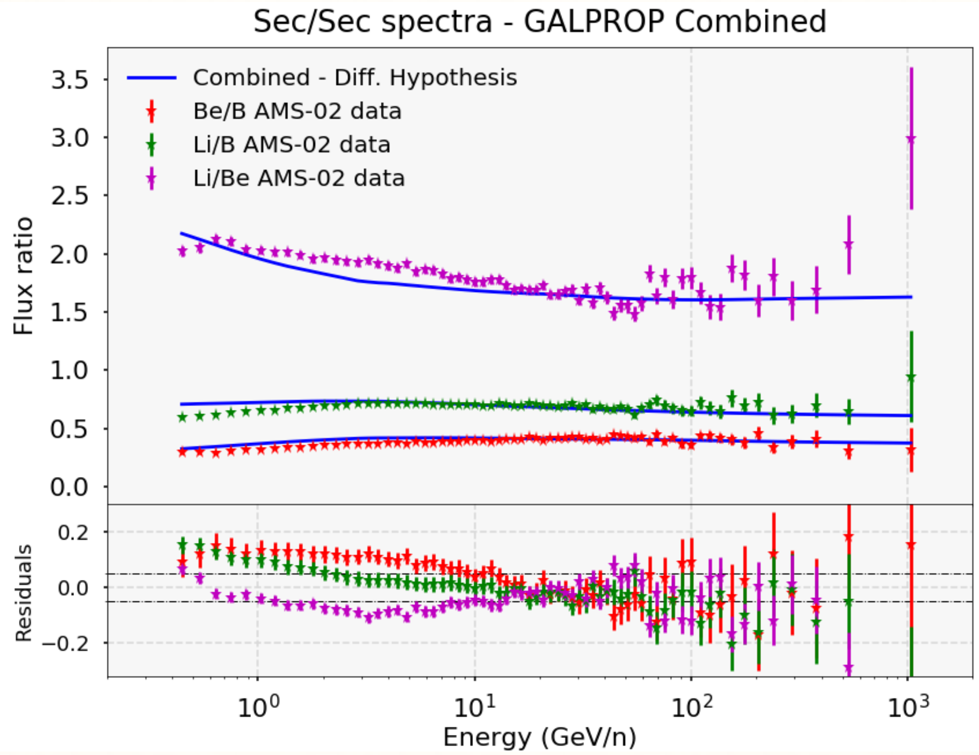

B/O spectrum - GALPROP Cross sections


Be/C spectrum - GALPROP Cross sections


Be/O spectrum - GALPROP Cross sections


Li/C spectrum - GALPROP Cross sections


Li/O spectrum - GALPROP Cross sections


Sec/Sec spectra - GALPROP Combined

TO SUMMARIZE...

- **The spallation cross sections are the main concern for precise studies on CR propagation.** These uncertainties significantly affect our conclusions on the nature and production of secondary CRs, as well as our evaluation of the diffusion process.

- **The most updated parametrizations are able to reproduce all the spectra of secondary CRs simultaneously, just scaling the cross sections below 6%.** This combination of secondary CRs reduce the effect of systematic uncertainties.

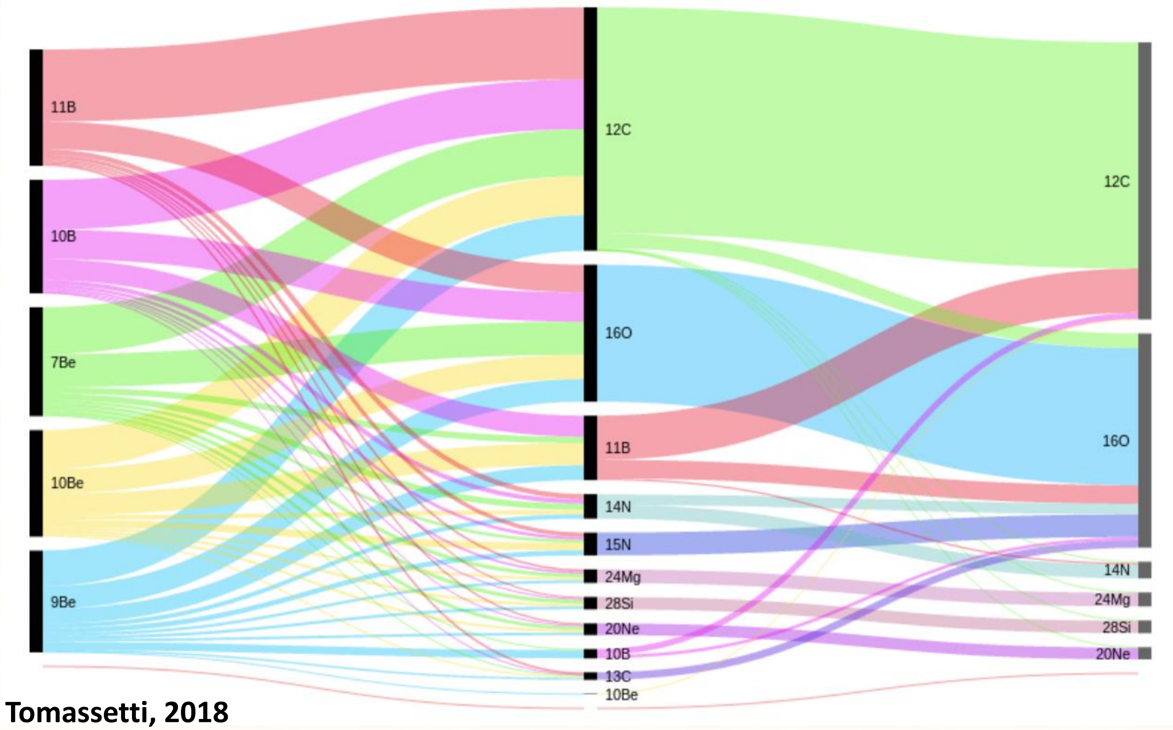
- New and more precise cross sections measurements for the production of the isotopes involved in galactic cosmic-ray studies are wanted! Also isotopic measurements of CRs would allow us improve the current parametrizations.

BACK UP

High uncertainties in XSecs → High uncertainties in the secondary CRs

$$Q_{sec}(E) \propto \sum^{pr} J_{pr}(E)\, \sigma_{pr \rightarrow sec}(E)$$

Complexity of the XS network



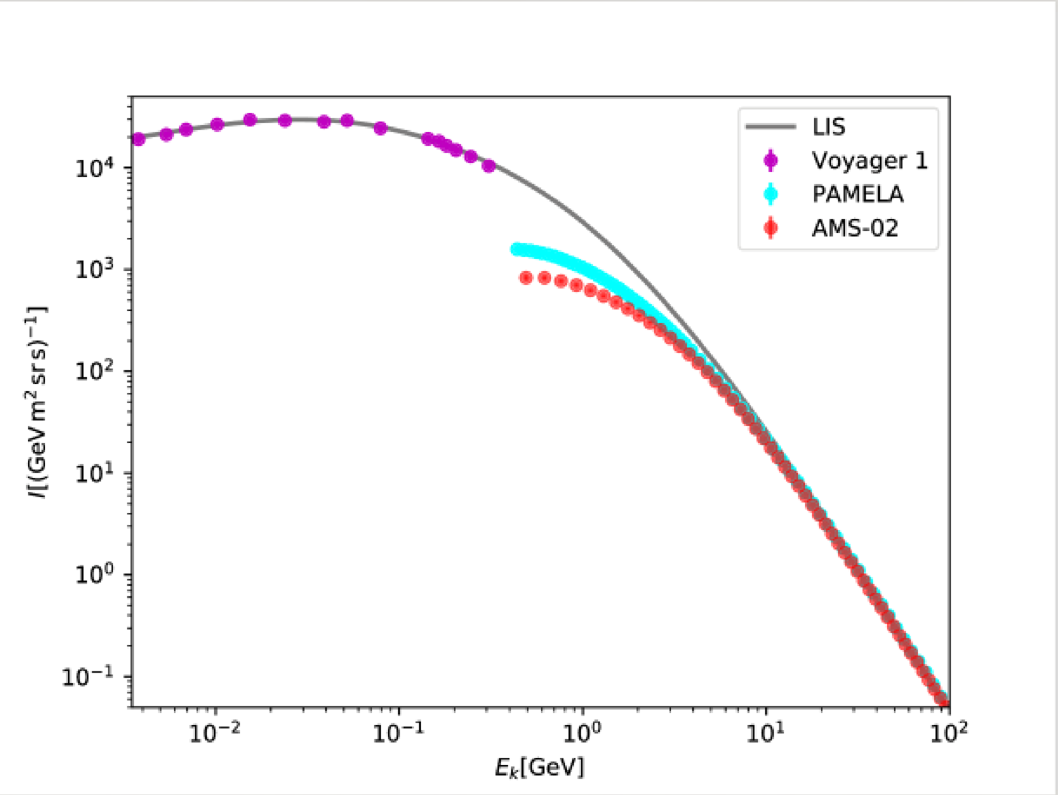
Tomassetti, 2018

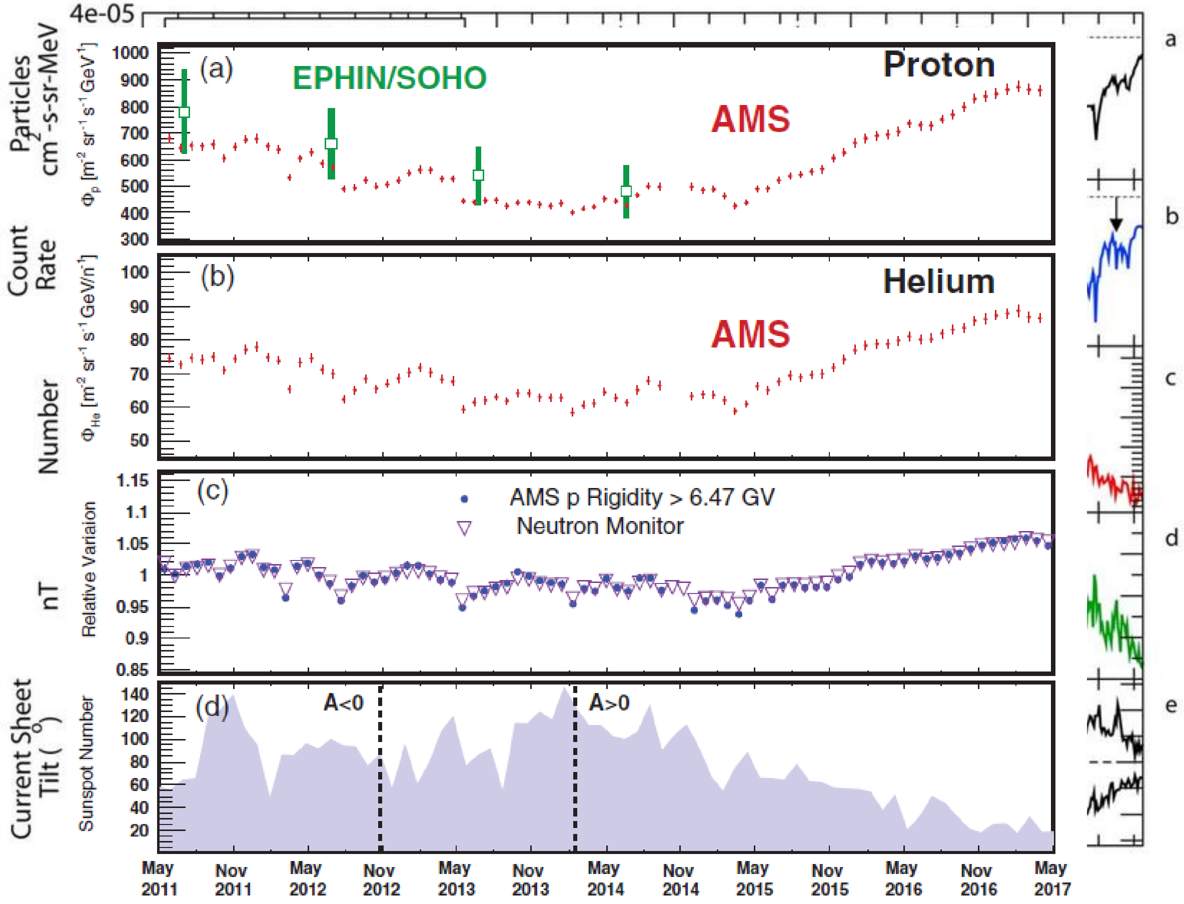
Assessment of XSec errors in sec. CRs

- Main spallation channels: O and C
- Secondary channels (N, Ne, Mg, Si & Fe) are very important for Li and Be (< 50%)
- Tertiary channels also matter:
  e.g. ^{11}B + gas → ^{10}B + X

Genolini et al. 2019 ; arXiv:1803.04686
Tomassetti, 2018 ; arXiv:1707.06917

Solar modulation





$$\Phi^{\mathrm{TOA}}(T) = \frac{2mT + T^2}{2m\,(T + \frac{Z}{A}\phi) + (T + \frac{Z}{A}\phi)^2}\,\Phi^{\mathrm{IS}}(T + \tfrac{Z}{A}\phi)$$

- Detailed heliospheric simulations or Force-Field approximation
- Neutron monitor experiments + Voyager-01 data

Diffusive transport of Galactic cosmic rays

Propagation equation is solved with the DRAGON2 code
https://github.com/cosmicrays/DRAGON2-Beta_version

$$\vec{\nabla}\cdot\left(-D\,\nabla N_i-\vec{v}_{\omega}N_i\right)+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right]=Q_i+\frac{\partial}{\partial p}\left[\dot{p}N_i-\frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_{\omega}N_i\right)\right]$$

$$-\frac{N_i}{\tau_i^f}+\sum\Gamma^s_{j\to i}(N_j)-\frac{N_i}{\tau_i^r}+\sum\frac{N_j}{\tau^r_{j\to i}}$$

$$D=D_0\beta^{\eta}\left(\frac{R}{R_0}\right)^{\delta}F(\vec{r},z)$$

$$\frac{J_{\mathrm{sec}}}{J_{\mathrm{pr}}}\sim\sigma(\mathrm{E})/\,D(E)$$

$$\Gamma^s_{j\to i}=\beta_j c n_t \sigma_{j\to i}N_j$$