The FLUKA cross sections for cosmic-ray propagation studies

***Based on ArXiv:* 2202.035559 (*JCAP* 07 (2022) 07, 008)**

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TeV Particle Physics – TeVPa 2022

Talk's outline

The FLUKA cross sections for cosmic-ray propagation studies

(i) The need of refined cross sections sets for CR studies

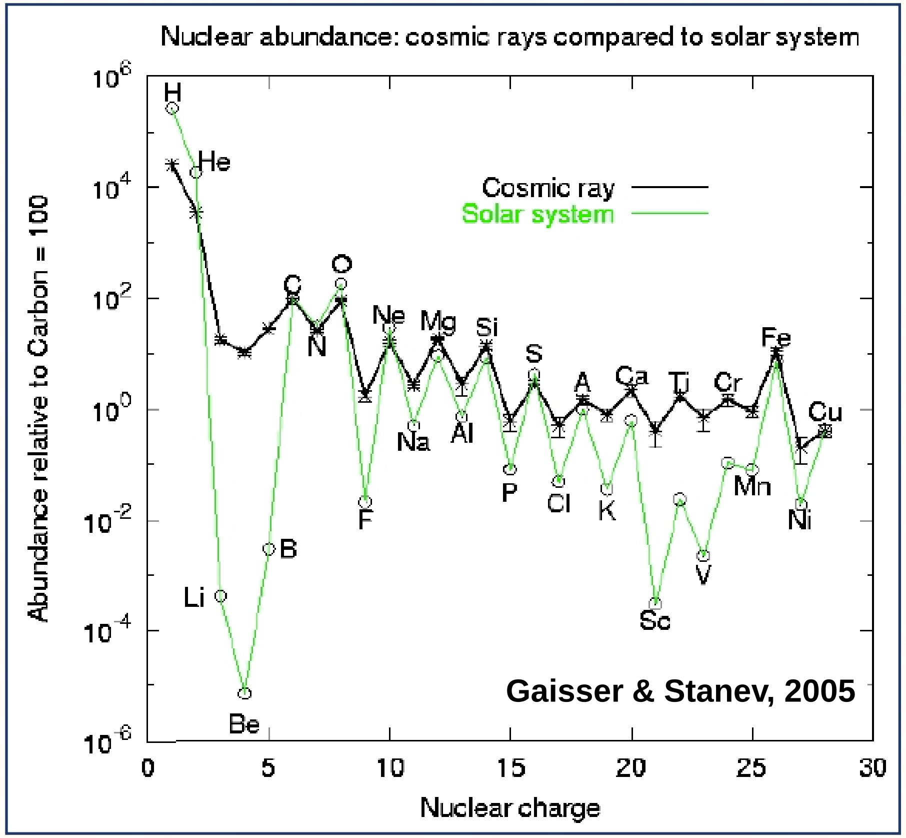
(ii) FLUKA as a solution beyond parameterizations

(iii) The new inelastic and inclusive cross sections sets

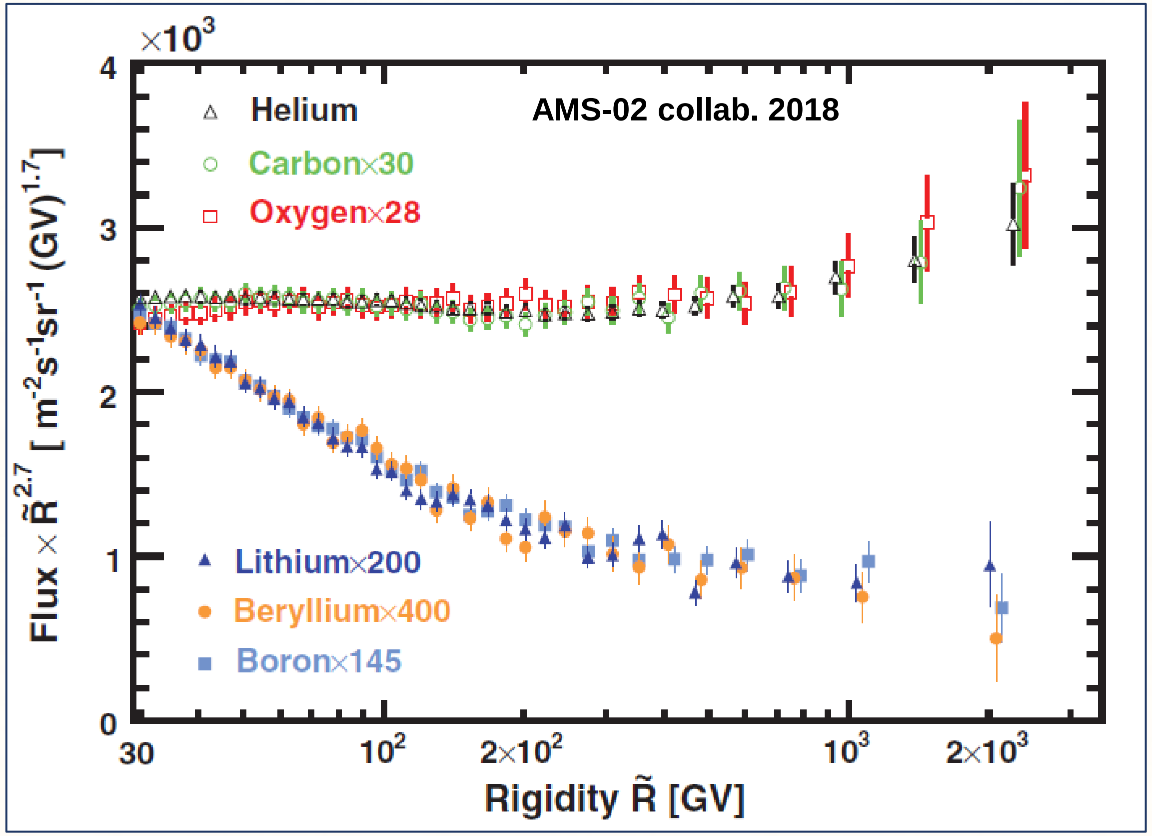
(iv) CR propagation with the FLUKA cross sections

Galactic cosmic rays are accelerated in astrophysical sources (presumably SNRs) and propagate throughout the Galaxy for millions of years due to scattering with plasma waves. Occasionally they interact with ISM gas producing secondary nuclei through spallation.

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

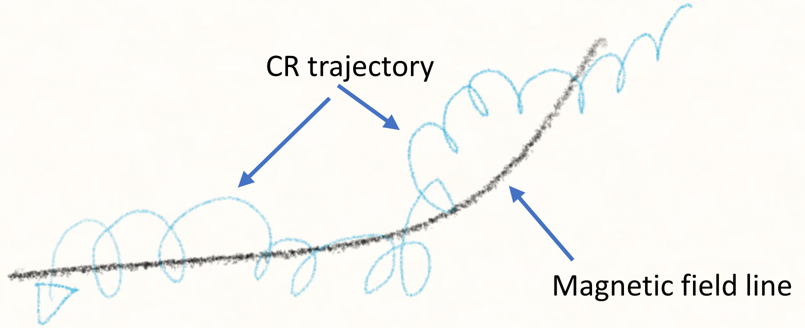


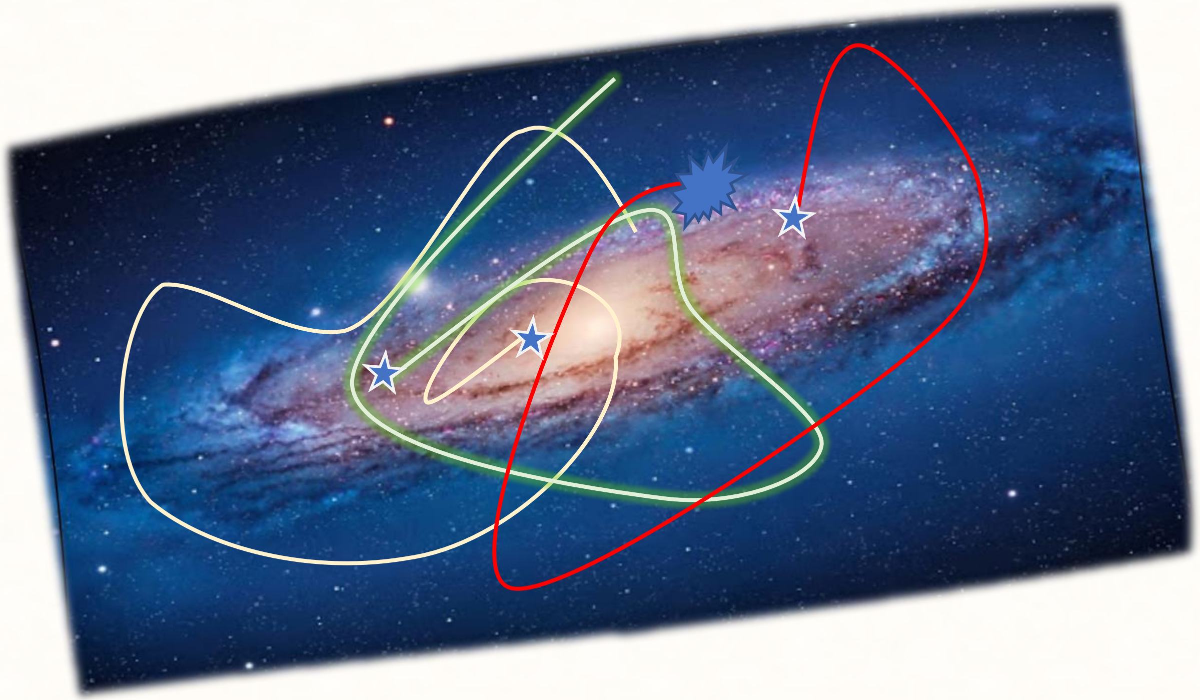
Secondary CRs offer a sensitive tool to infer the grammage traversed by these particles



Diffusive transport of Galactic cosmic rays

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





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

$$D(E) \propto \left(\frac{E}{E_0}\right)^{\delta}$$

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

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

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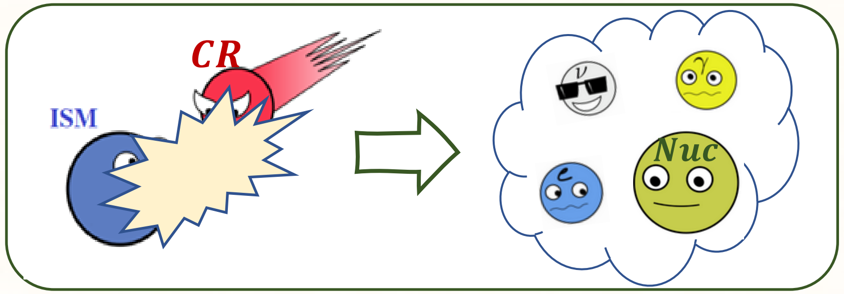

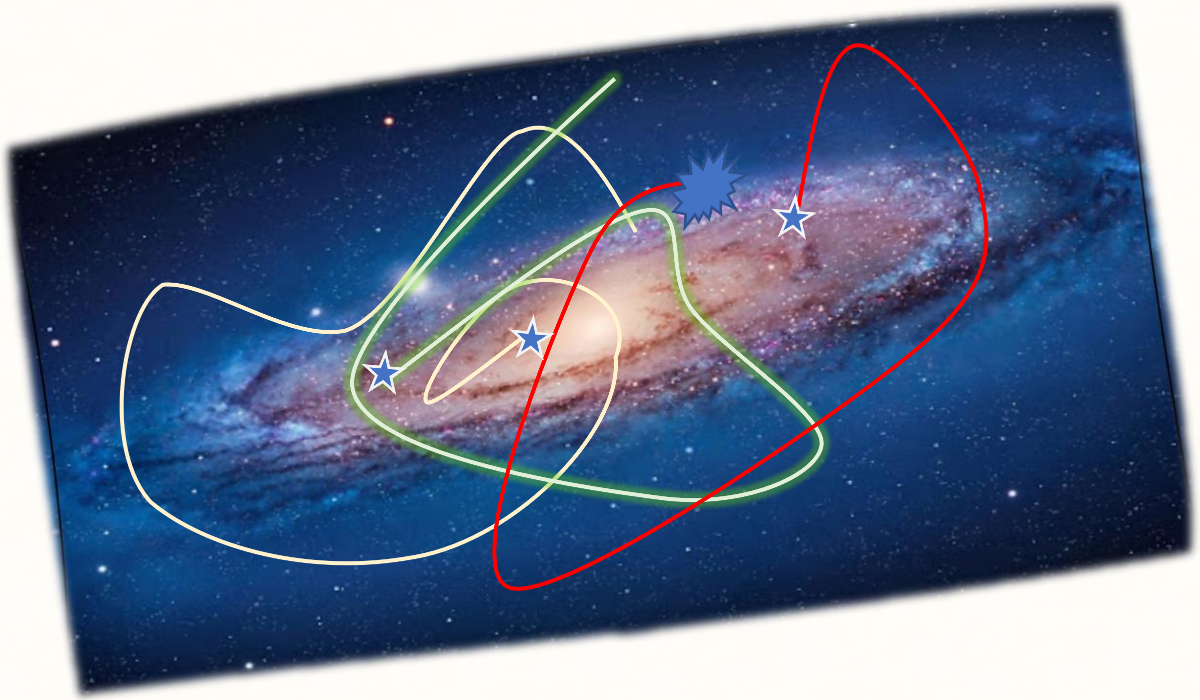

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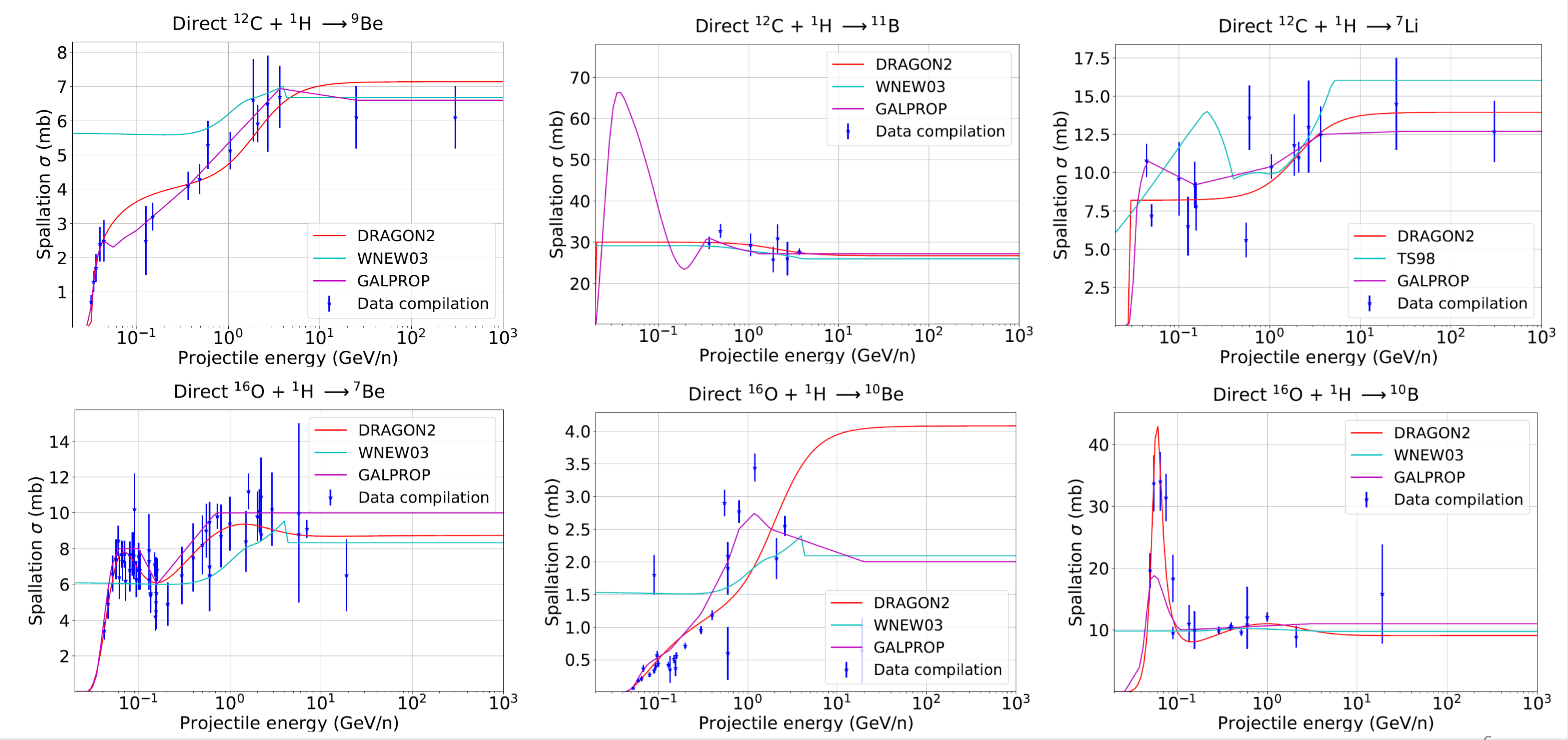
Cross sections parametrizations

Need to go beyond parametrizations !!



The FLUKA toolkit and the evaluation of cross sections for CR interactions

http://www.fluka.org/fluka.php

- **FLUKA** is a general purpose tool that can be used to study electromagnetic and hadronic interactions of particles and their transport in arbitrarily complex geometries.

- Nuclear interactions are optimized in the range from the MeV up to tens of TeV and are treated in a Monte Carlo fashion.

- A code such as FLUKA allows us to precisely study the cross sections of any CR interacting with **any gas nucleus** and the formation of **long and short-lived particles produced**, in the whole energy range for which we have experimental CR data.

- FLUKA has been used in other CR studies as in Mazziotta, **P.D.T.L**. et al PRD 101(8):083011 (2020), as well as for other astrophysical applications as atmospheric neutrino studies (Astropart. Phys., 23:526–534, 2005) or gamma-ray flares from the Sun (Solar Phys., 294(8):103, 2019).

The FLUKA toolkit and the evaluation of cross sections for CR interactions

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Nucleus-nucleus hadronic interactions are treated as following in FLUKA:

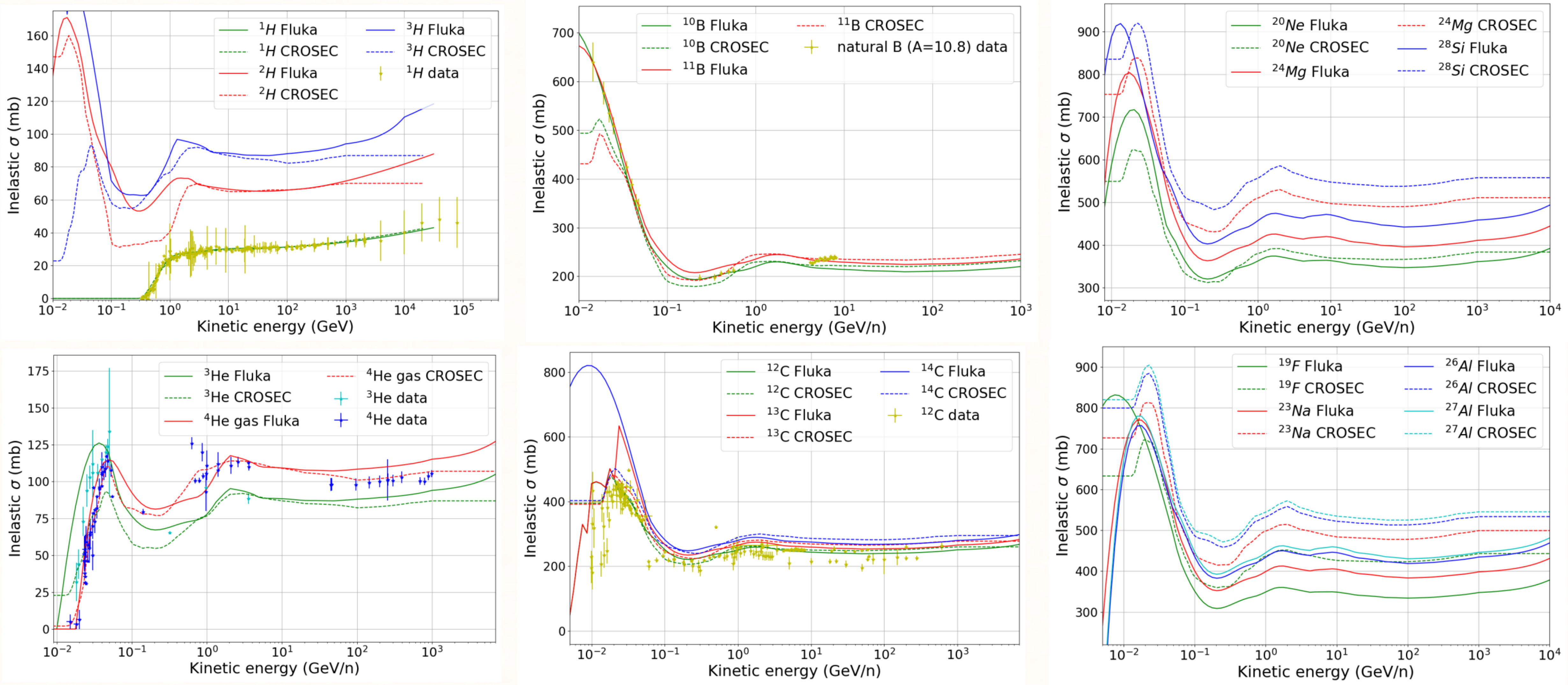
- **Resonances** produced in hadron-nucleon inelastic collisions dominate from the MeV up to 3-5 GeV
- Above 3-5 GeV hadronizations through Dual Parton Model (**DPMJET-3**) takes over
- Extension to hadron-nucleus collisions is achieved through the **PEANUT** model (GINC) + relaxation
- Nucleus-Nucleus use **Boltzmann thermal equation** at E<0.1GeV/u, **rQMD** model up to 5 GeV/u and **DPMJET** above

We have computed inelastic and inclusive cross sections of interactions of all isotopes of the CR nuclei up to Z=26 (Iron) with protons and helium, including a careful analysis of those short-living particles produced (ghost nuclei) from 1 MeV/n to 35 TeV/n.

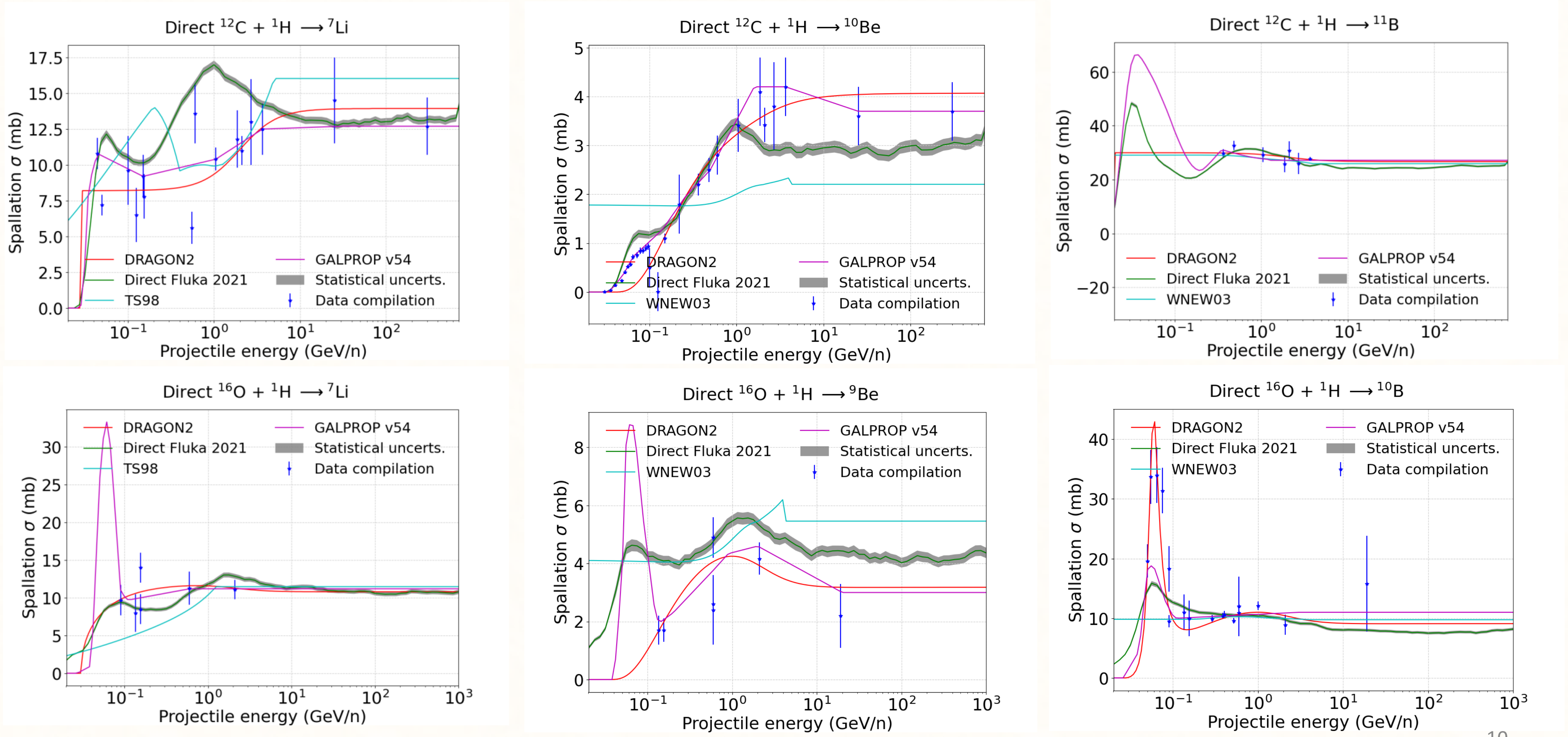
The result is a set a cross sections of secondary CRs that can be used in CR propagation codes. We have also computed cross sections for gamma-ray production and those for secondary leptons, neutrinos and antiproton production will be soon investigated.

FLUKA inelastic cross sections

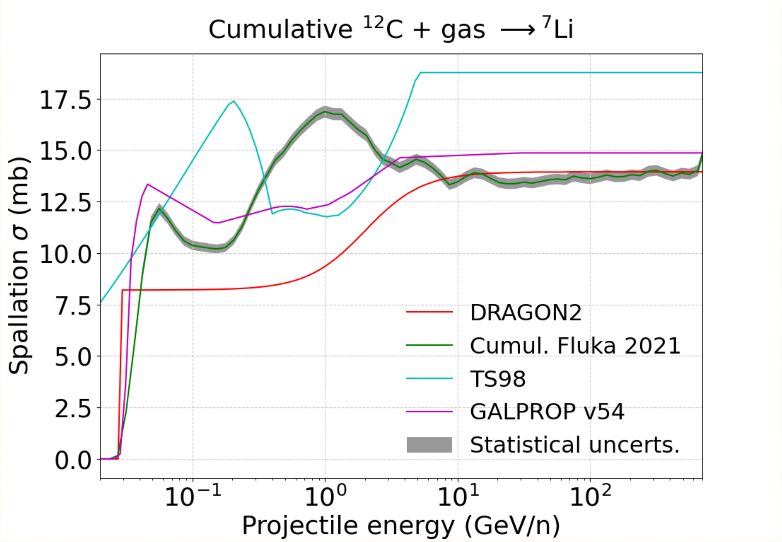
P.D.T.L.+ *JCAP* 2022

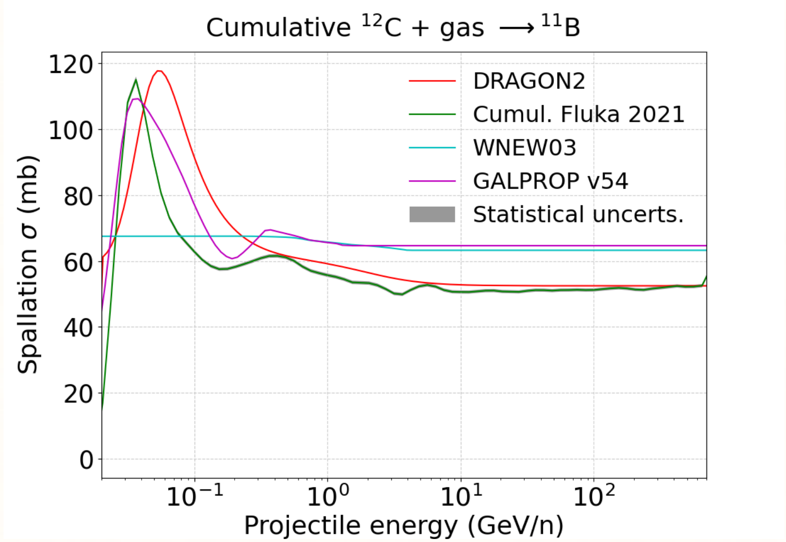


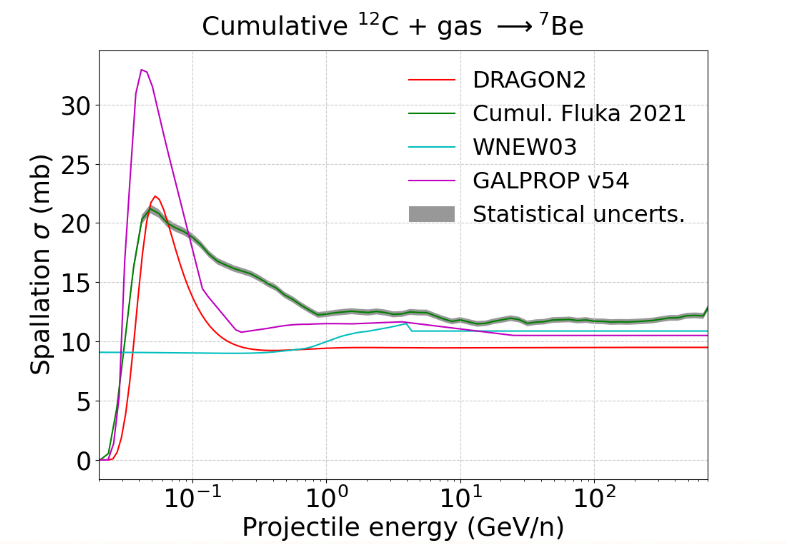
FLUKA (direct) inclusive cross sections

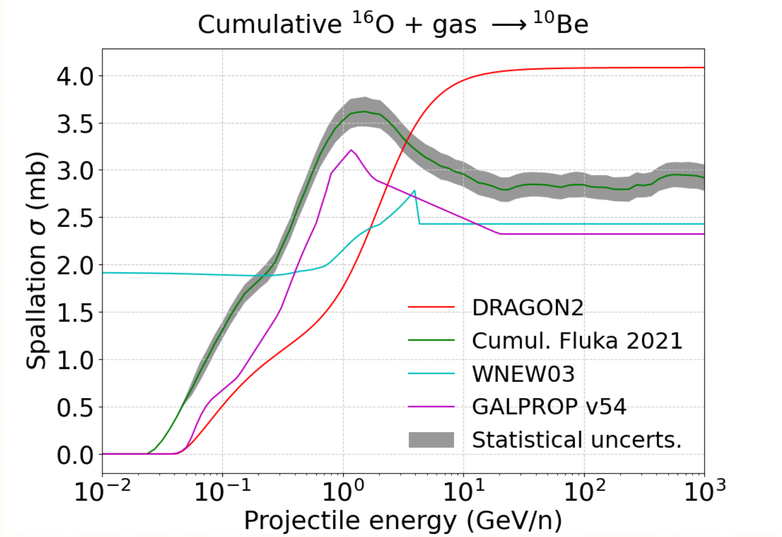


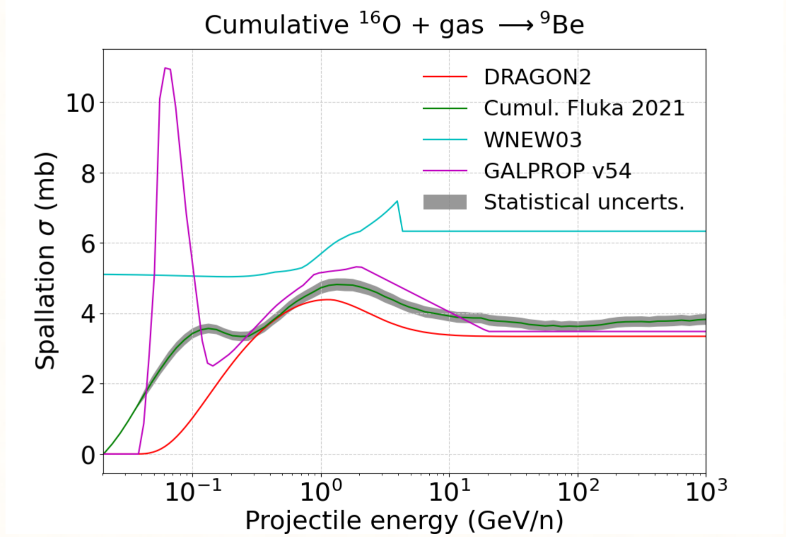
FLUKA (cumulative) inclusive cross sections

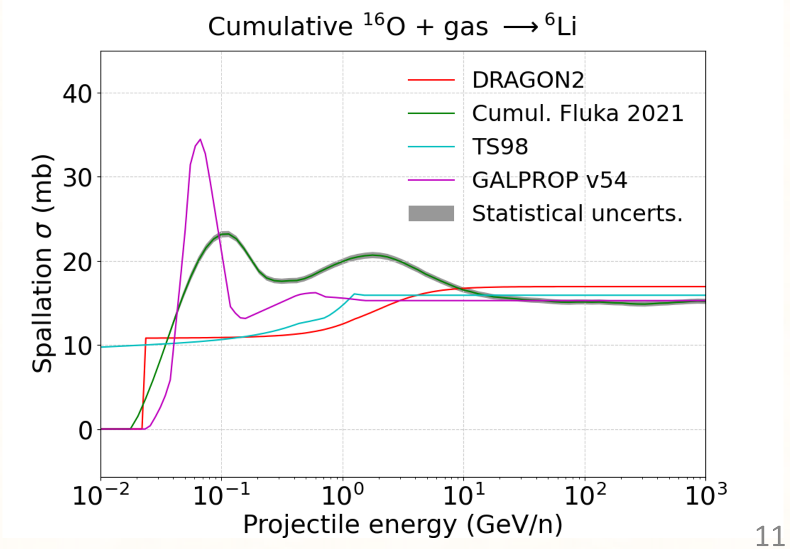












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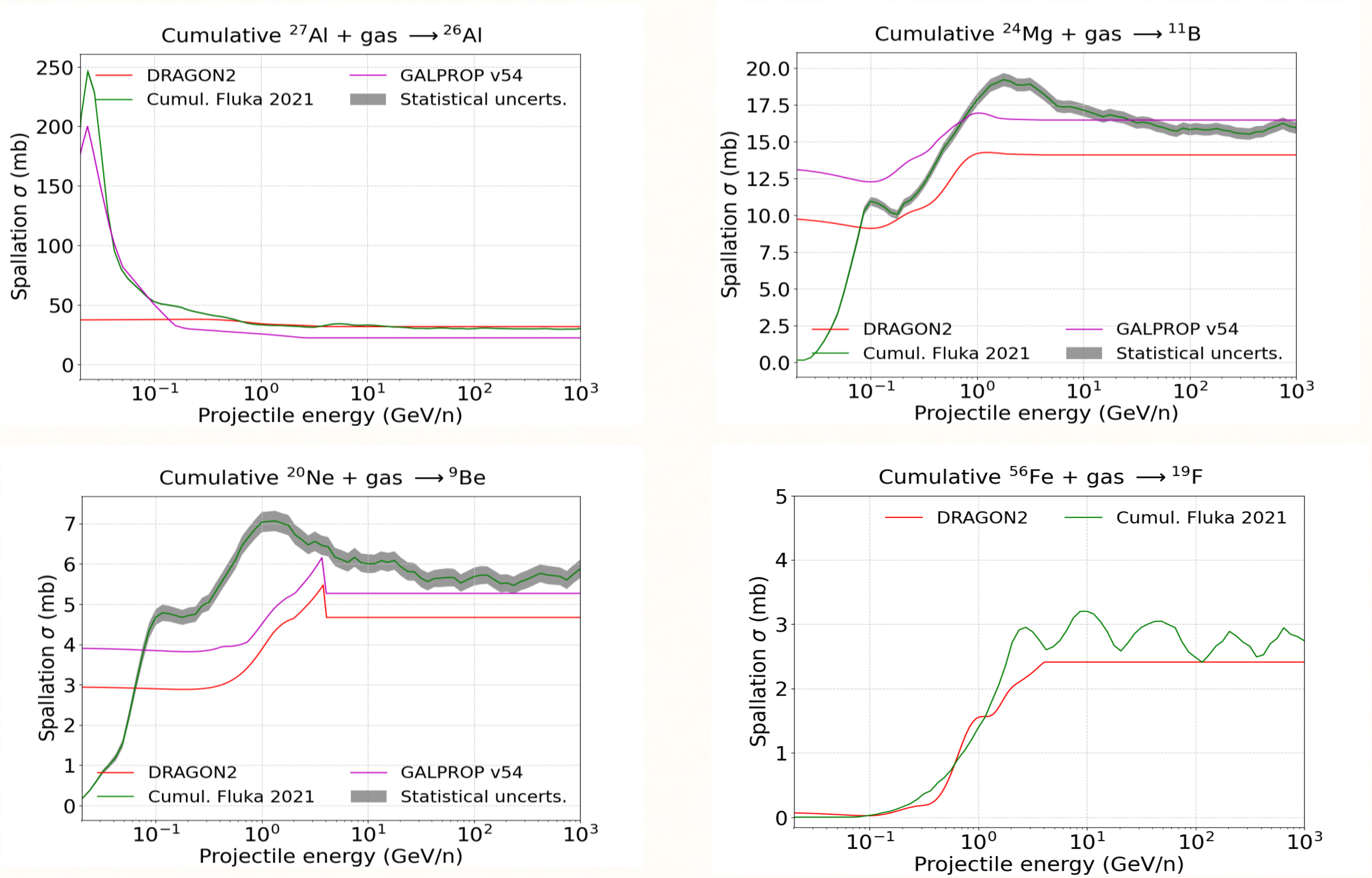


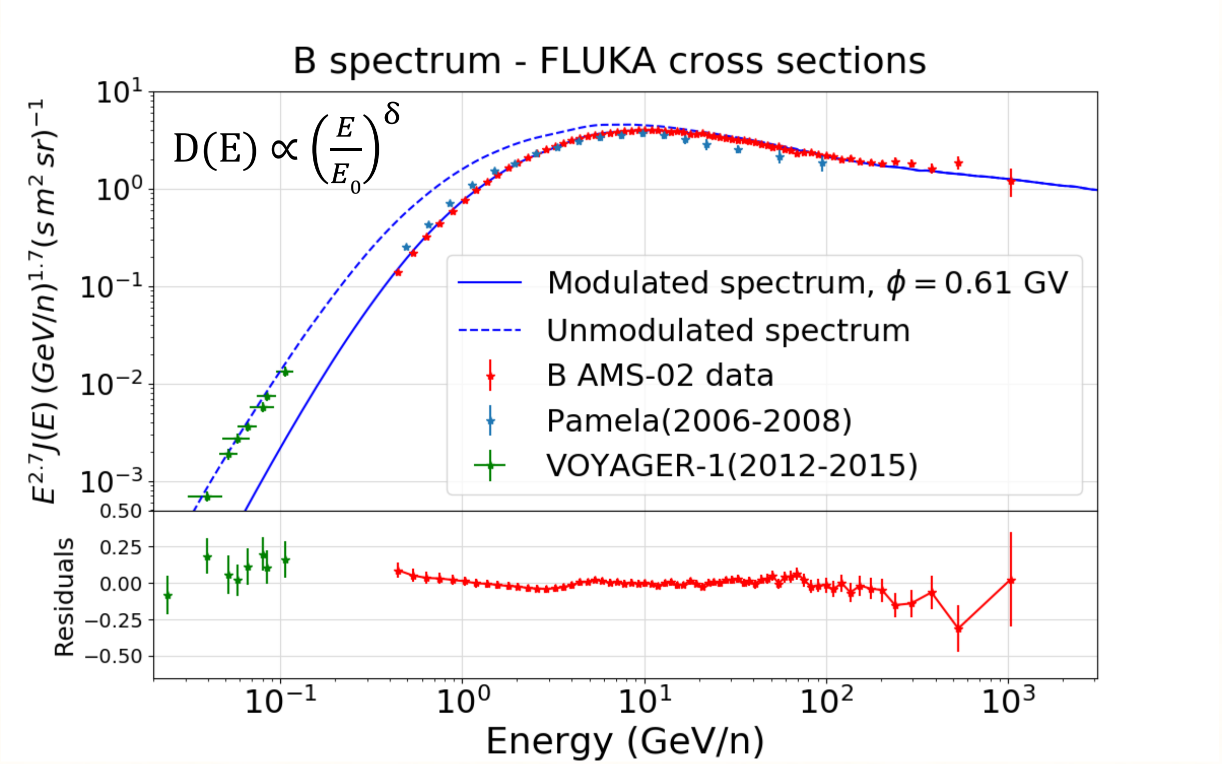
These cross sections are implemented in the DRAGON2 code with the aim of studying the production of the secondary CRs B, Be and Li

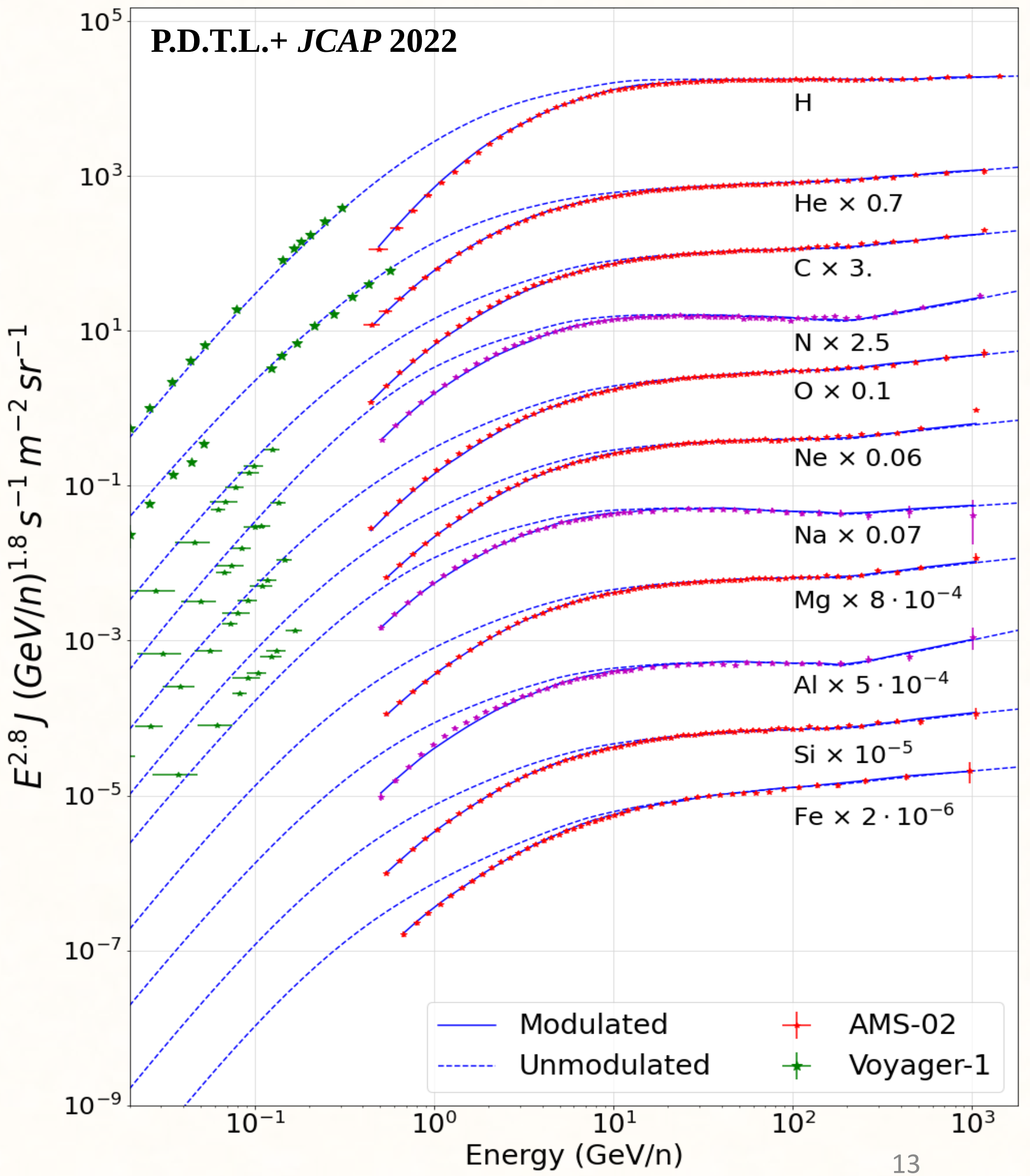
B/C

DRAGON2 δ ~0.44, Galprop δ ~ 0.45, **FLUKA δ ~0.45**

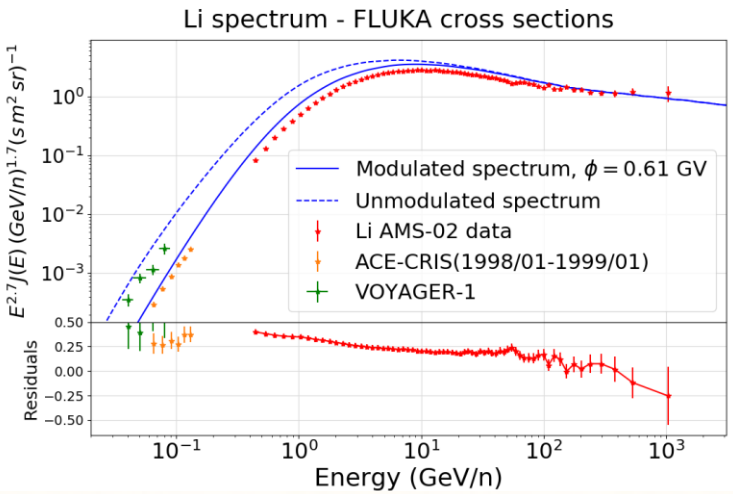
D_0/H : DRAGON2 ~ 0.97, Galprop ~ 0.94, **FLUKA ~ 0.82**

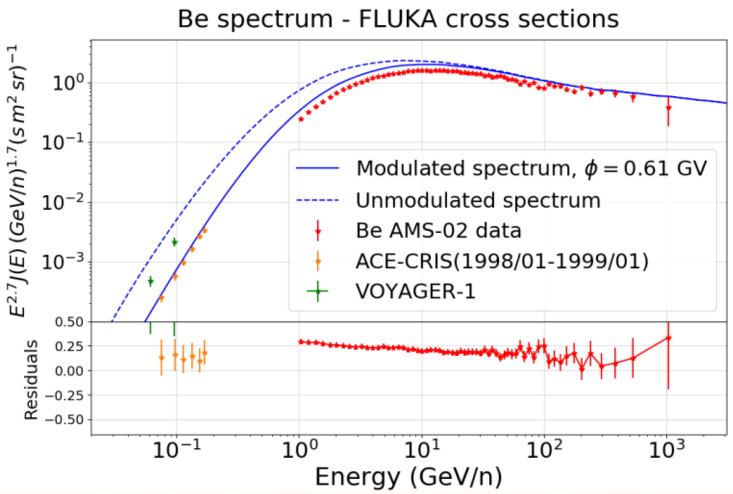
V_A ~23 km/s for all and compatible with **no advection**



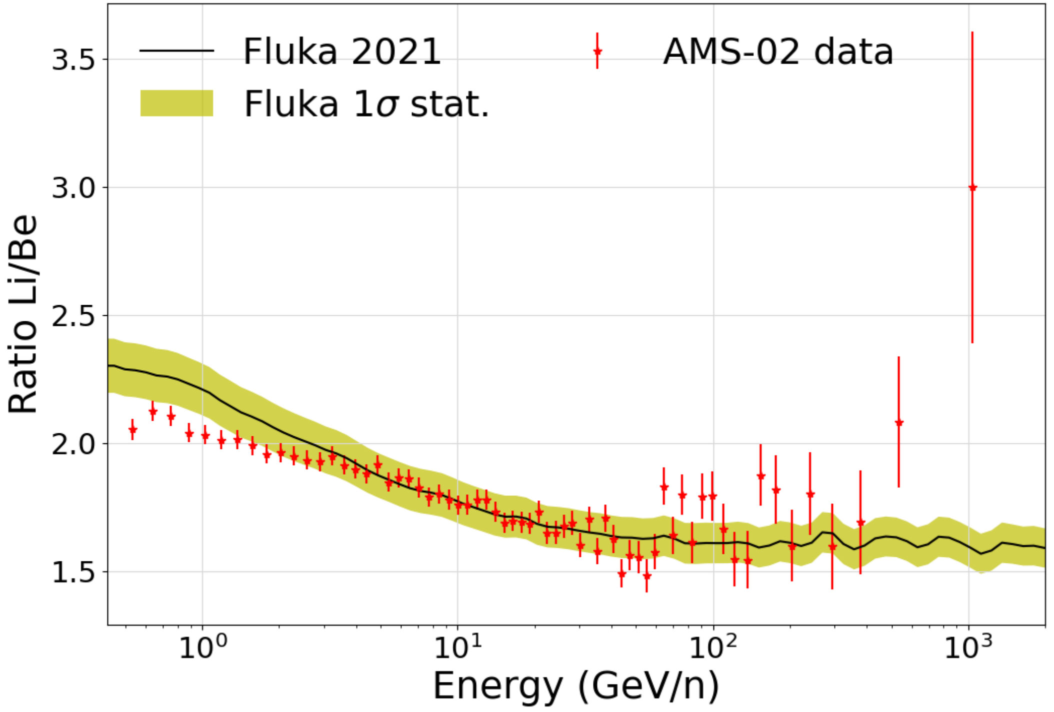


FLUKA cross sections: B, Be and Li ratios



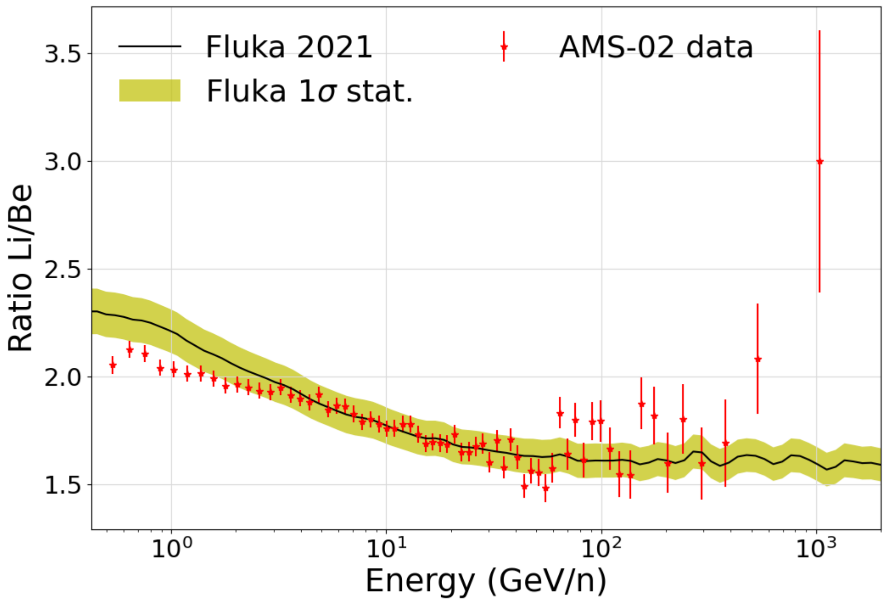


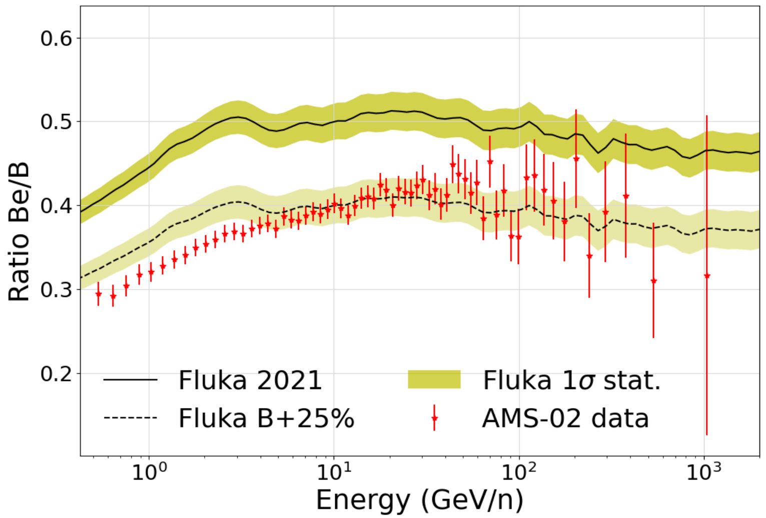
$$\frac{J_k}{J_j}(E) \propto \frac{\sum^{\alpha\to k} J_\alpha(E)\sigma_{\alpha\to k}(E)}{\sum^{\alpha\to j} J_\alpha(E)\sigma_{\alpha\to j}(E)} \xrightarrow{\text{high energies}} \sim \frac{\sum^{\alpha\to k} C_\alpha E^{-\gamma_\alpha}\sigma_{\alpha\to k}(E)}{\sum^{\alpha\to j} C_\alpha E^{-\gamma_\alpha}\sigma_{\alpha\to j}(E)}$$

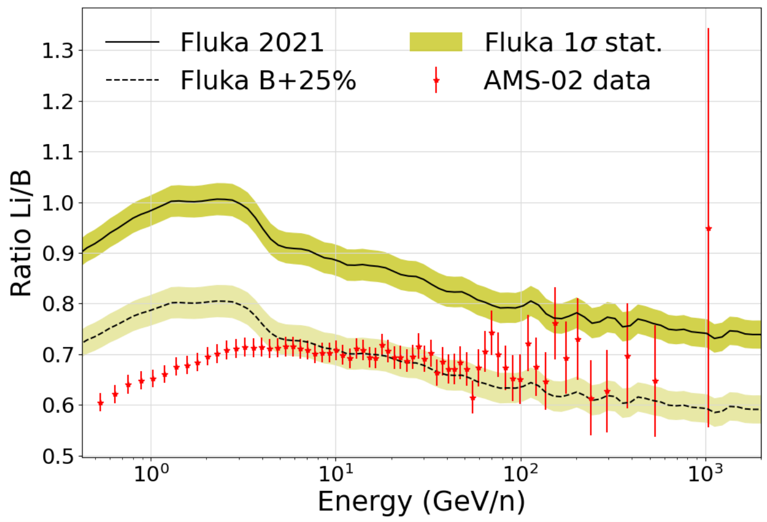


FLUKA cross sections: B, Be and Li ratios

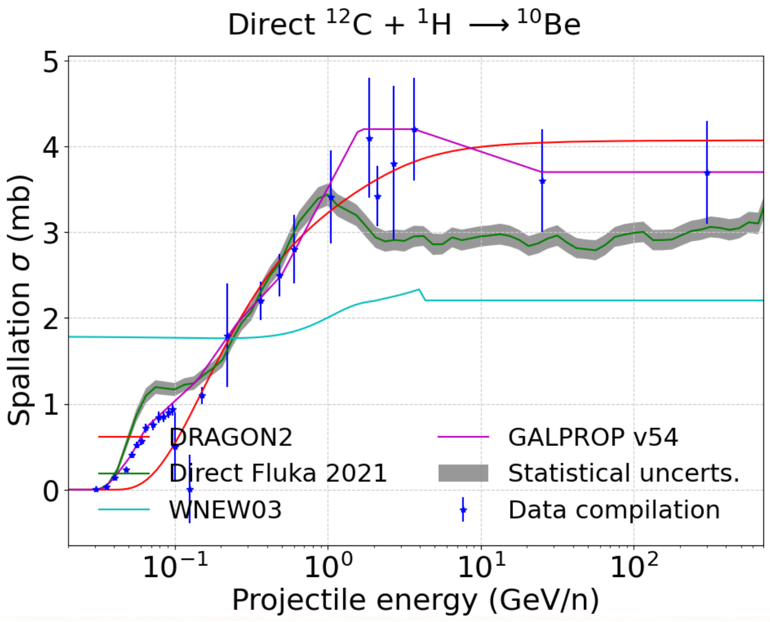
Energy dependence is greatly reproduced above a few GeV per nucleon
These ratios match AMS-02 data considering a ~25% scaling of the cross sections

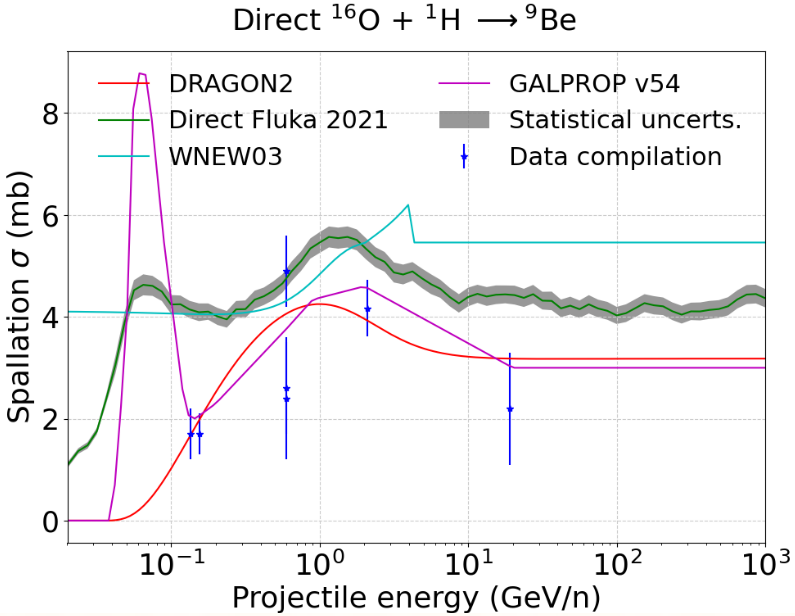


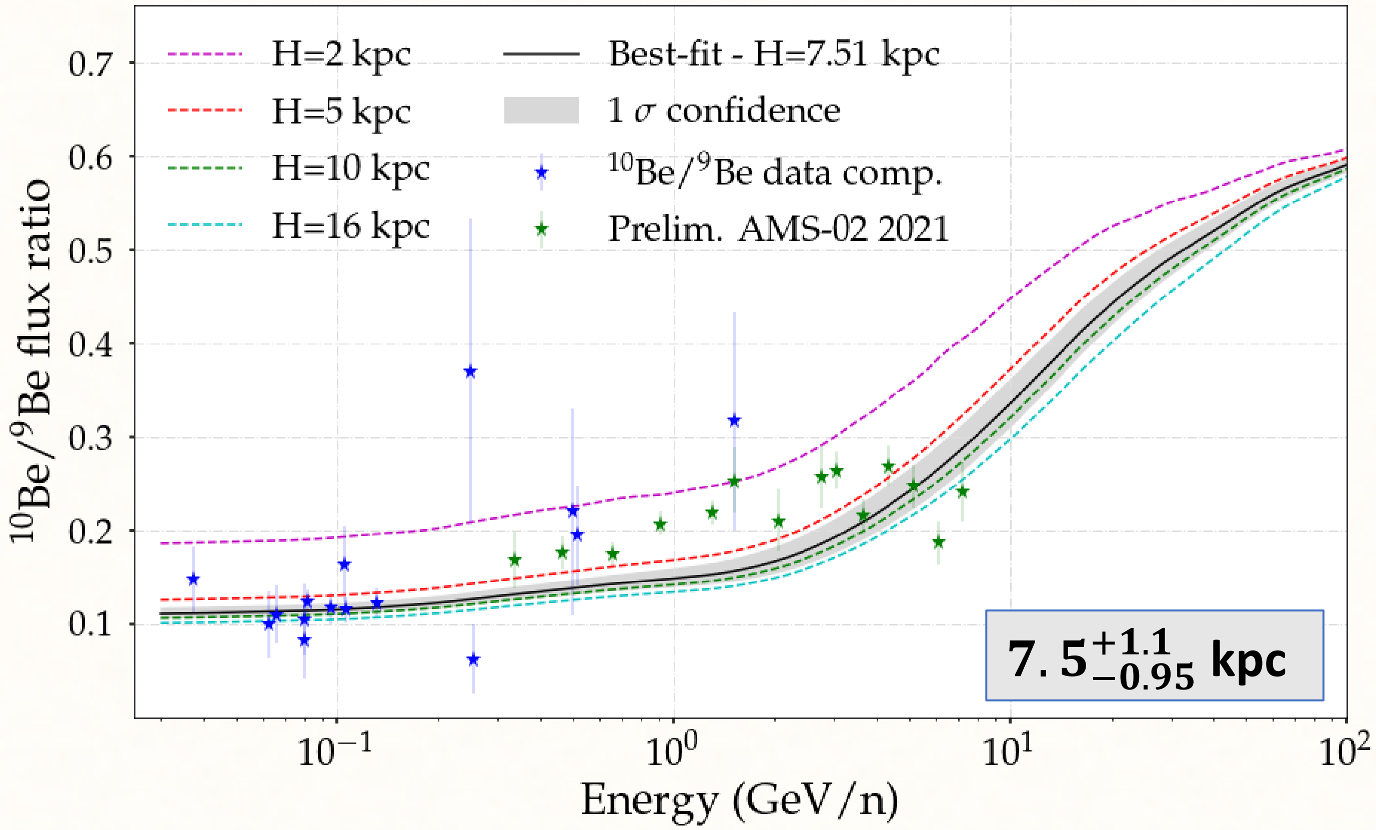




FLUKA cross sections: The halo size







See also P.D.T.L.+ *JCAP* 03 (2021) 099

Combined fit of light secondary CRs

MC Monte Carlo analysis: Combination of the ratios of secondary CRs (see **P.D.T.L.**+ *JCAP*07(2021)010)

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

$$D = D_0 \beta^\eta \left(\frac{R}{R_0}\right)^\delta$$ **Source hypothesis**

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

FLUKA cross sections for spallation interactions and fragmentation of CRs

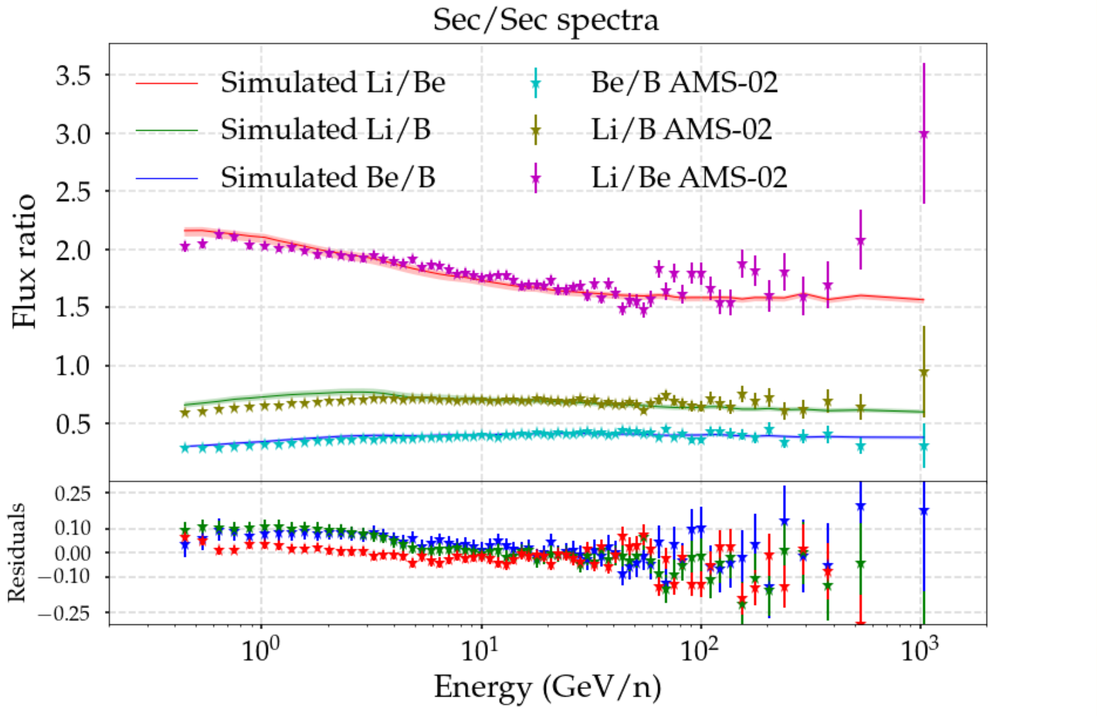
- Parameters entering in the diffusion parametrization + Alfven speed included in the fit
- Nuisance parameters (Scale factors) for renormalizing FLUKA cross sections
- Injection spectra are left free in the fit, resulting in different groups of primary elements (p, He, C-O, N-Na-Al, Ne-Mg-Si, Fe)

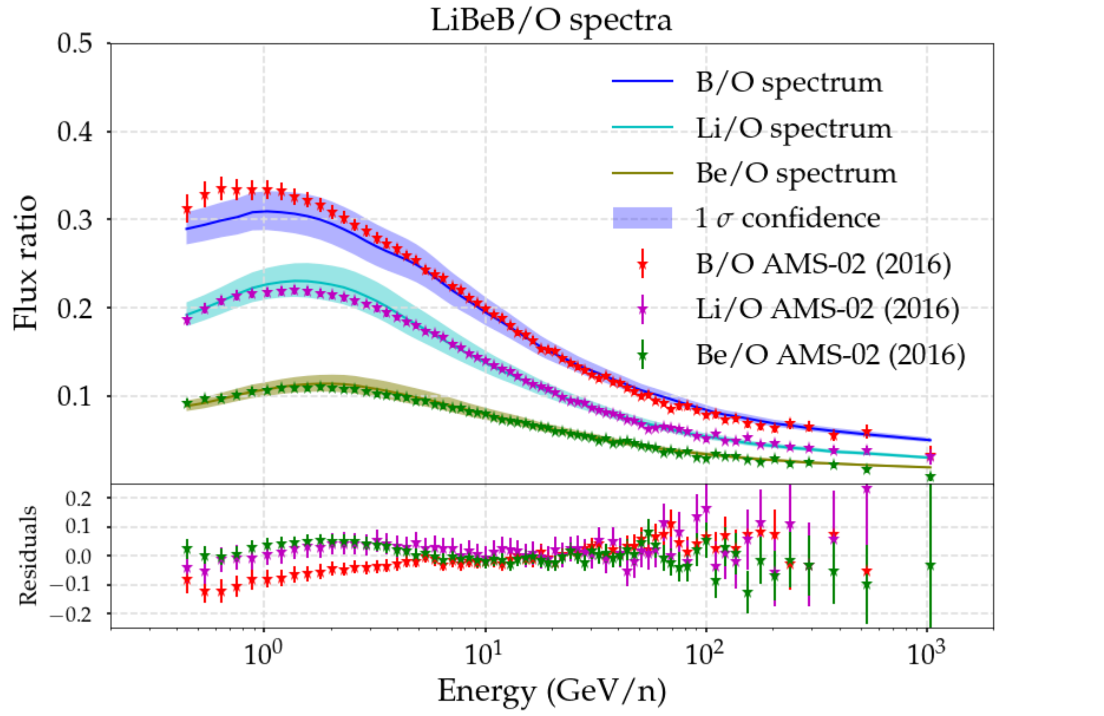
B/C, B/O, Be/C, Be/O, Li/C, Li/O (Propagation parameters)

^{10}Be/^{9}Be, ^{10}Be/Be (H), **Be/B, Li/B, Li/Be** (Scale factors: S_X, H)

Combined fit of light secondary CRs

Combined analysis predicts an **energy dependence** of the **flux ratios** in good **agreement with AMS-02 data**. **Propagation parameters** (obtained from Sec/Prim) in **good agreement with other dedicated parametrizations (δ~0.37)**. Scale factors below 20% (~15% for B, ~5% for Li, Be)





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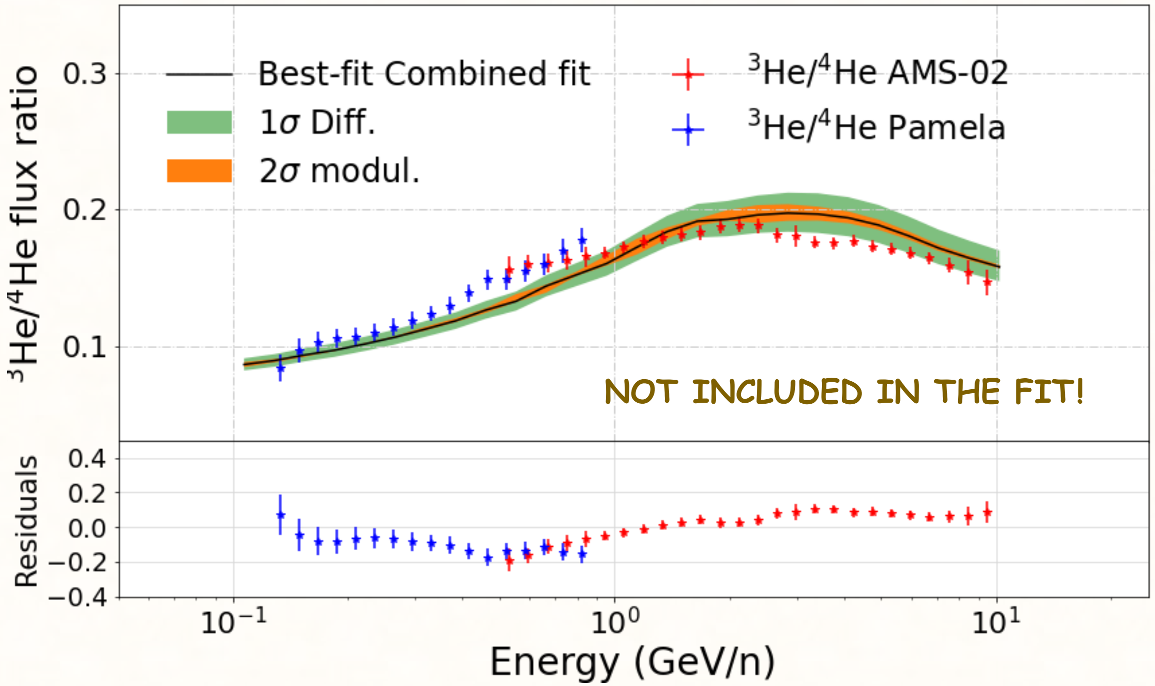
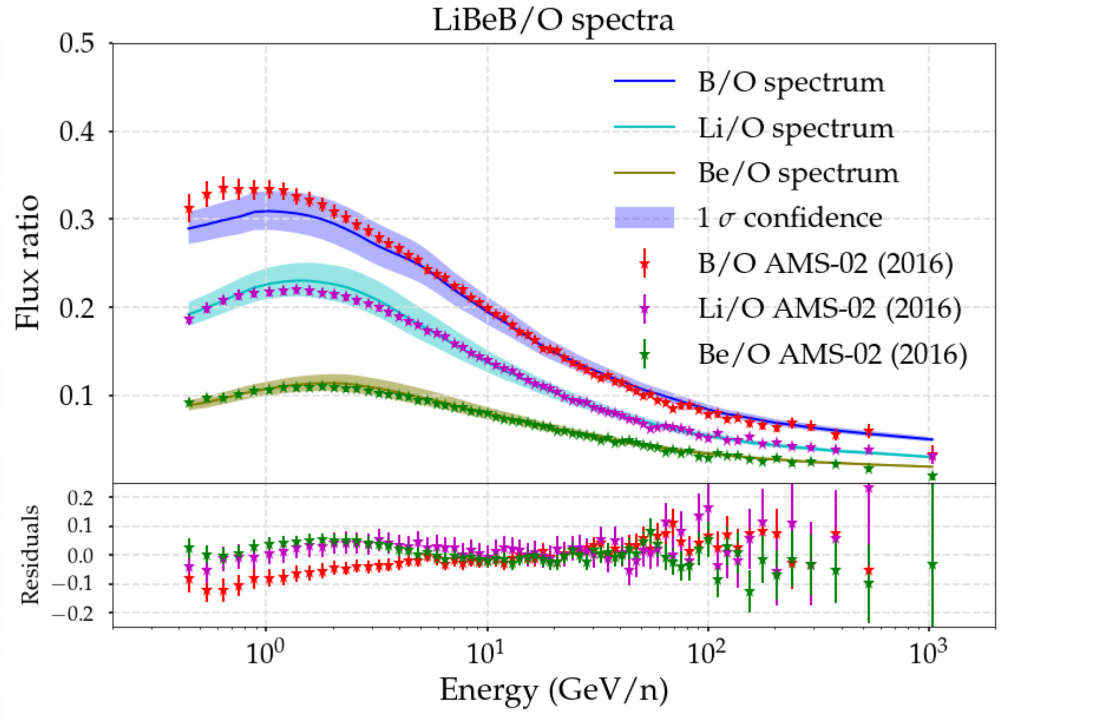




Conclusions

- Cross sections are our main limitation for most of the analyses of propagation of charged particles in the Galaxy: **FLUKA is optimized to improve our predictions on CR interactions cross sections over a wide energy range and for every isotope**

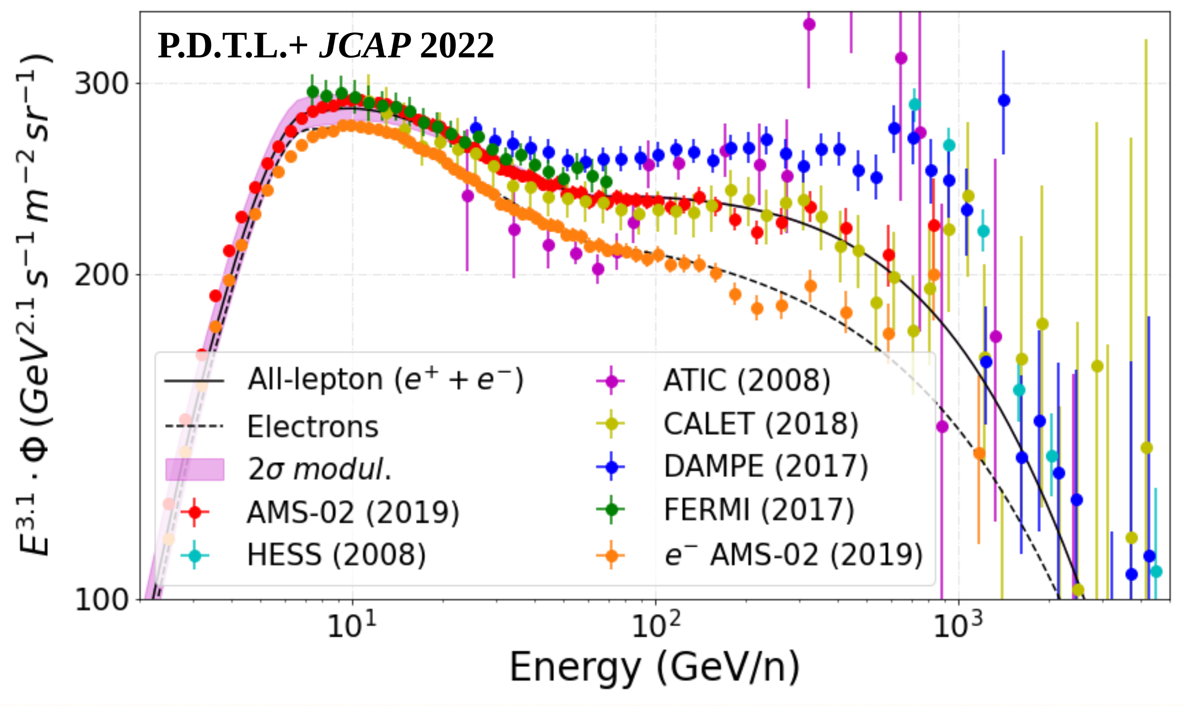
- The **energy dependence** of the B, Be and Li ratios predicted using the FLUKA cross sections is in **good agreement with AMS-02**

- These cross sections allow us to **simultaneously reproduce** the different ratios of **B, Be and Li and ^{3}He** within a set of propagation parameters perfectly in agreement with the standard theoretical scenarios

- FLUKA helps us in using gamma-ray data in order **to constrain** our set-ups of **CR propagation**: Hadronic and leptonic gamma-ray production

BACK UP

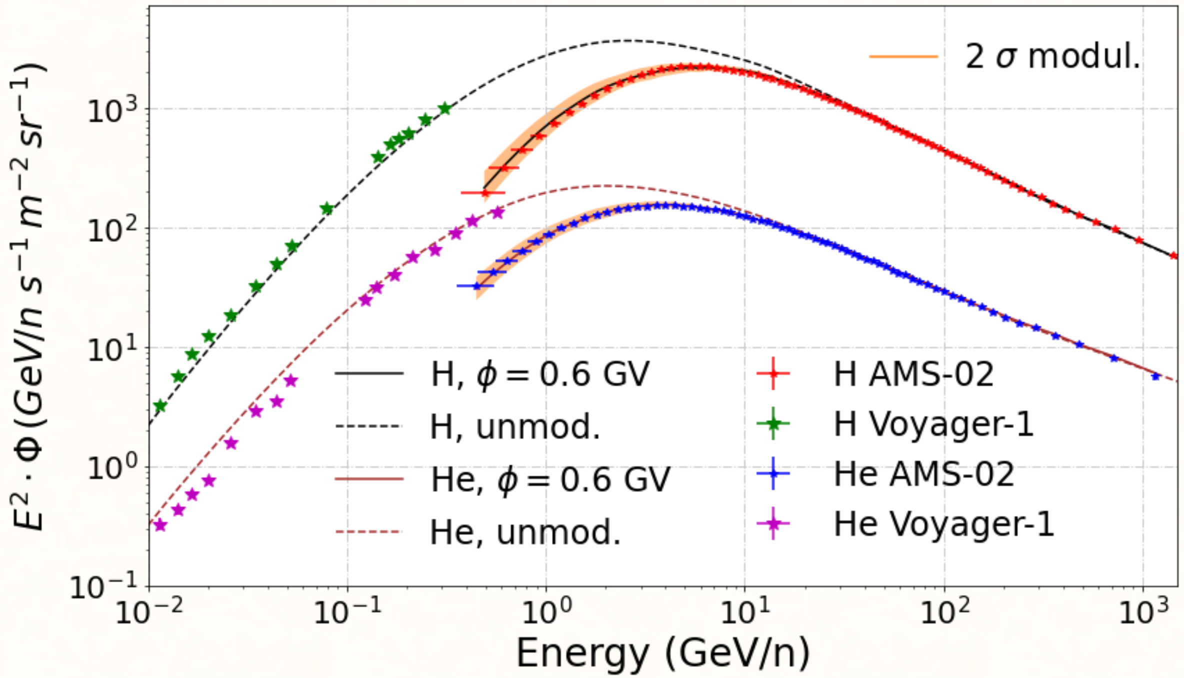
FLUKA cross sections for gamma-ray production



Electrons require a doubly broken power-law in order to reproduce at the same time local CR measurements and **local γ-ray emissivity** at low energies

γ-ray production from different gas nuclei

Protons, He and electrons are treated with the *Force field* approximation and need a break at around 8 GeV/n to fit well experimental data

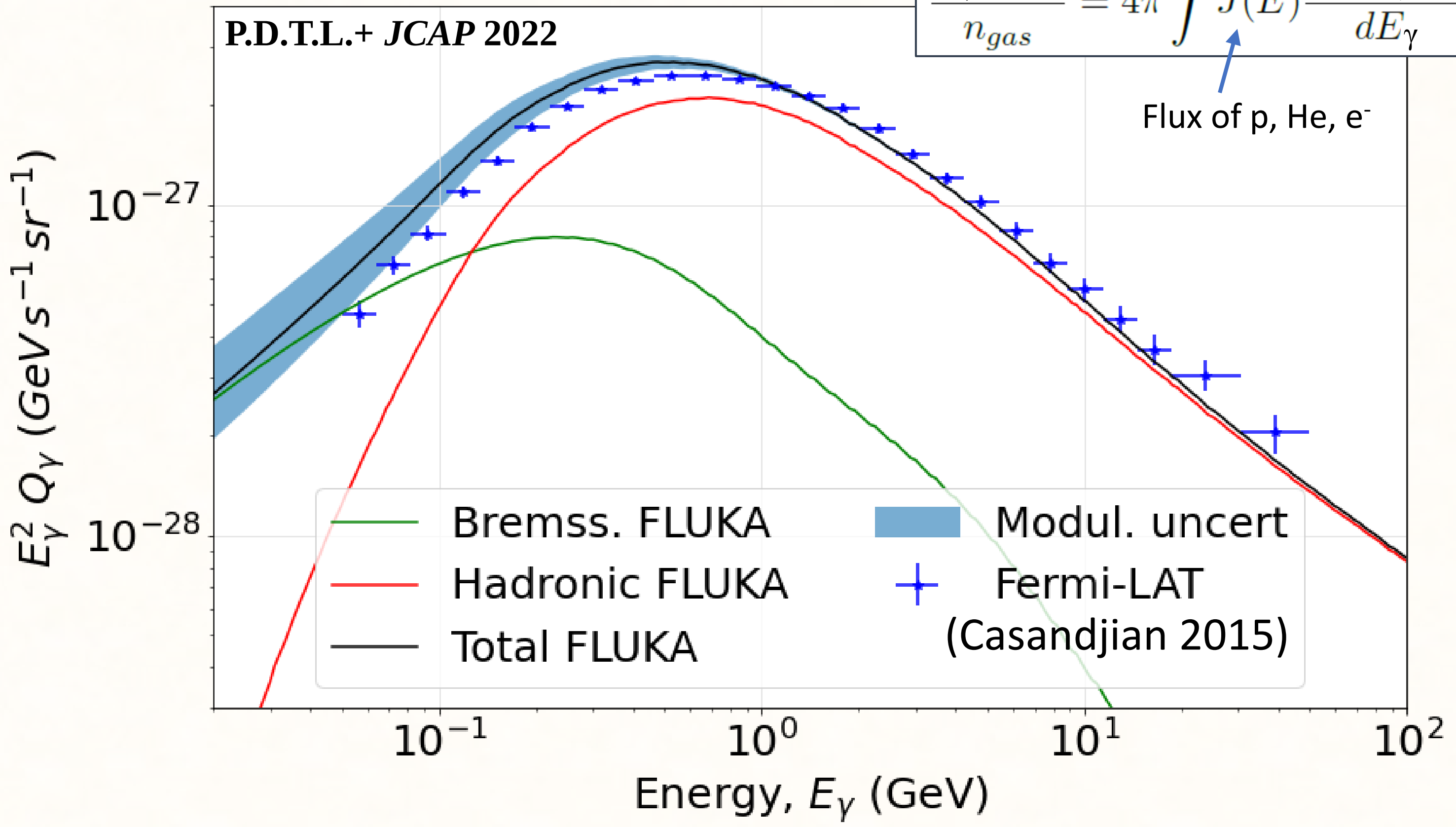


FLUKA cross sections for gamma-ray production

Study of the **local emissivity** (at latitudes 10° < |b| < 70°) ISM composition with relative abundance of H : He : C : N : O : Ne : Mg : Si = 1:0.096 : 4.65 10^{-4} : 8.3 10^{-5} : 8.3 10^{-4} : 1.3 10^{-4} : 3.9 10^{-5} : 3.69 10^{-5}.

$$\frac{Q_\gamma(E_\gamma)}{n_{gas}} = 4\pi \int J(E) \frac{d\sigma(E_\gamma|E)}{dE_\gamma} dE$$

Flux of p, He, e^-

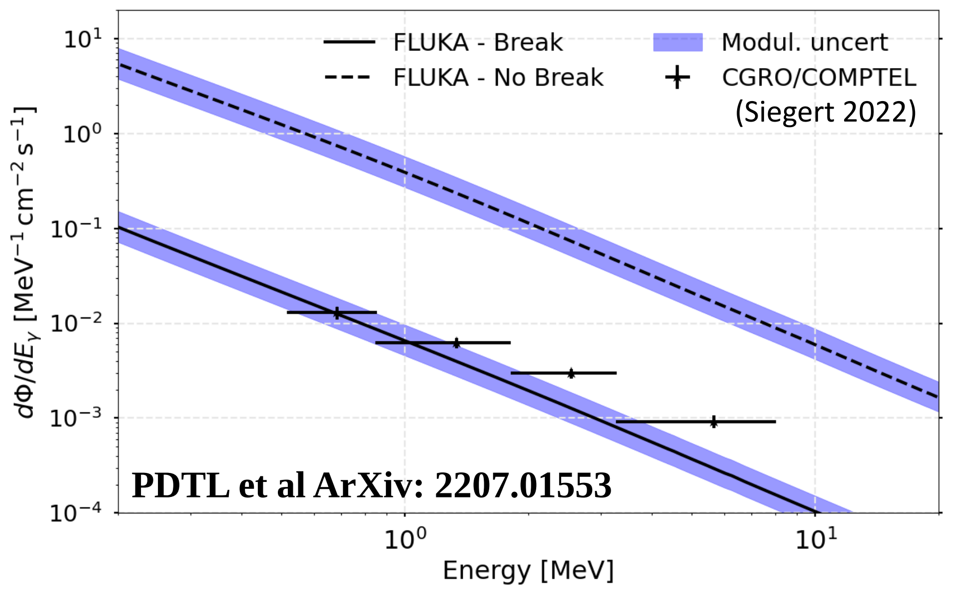


This quantity just depends on the cross sections of gamma-ray production and the spectrum of electrons, protons and He (**low-energy specially uncertain due to solar modulation uncertainties!**)

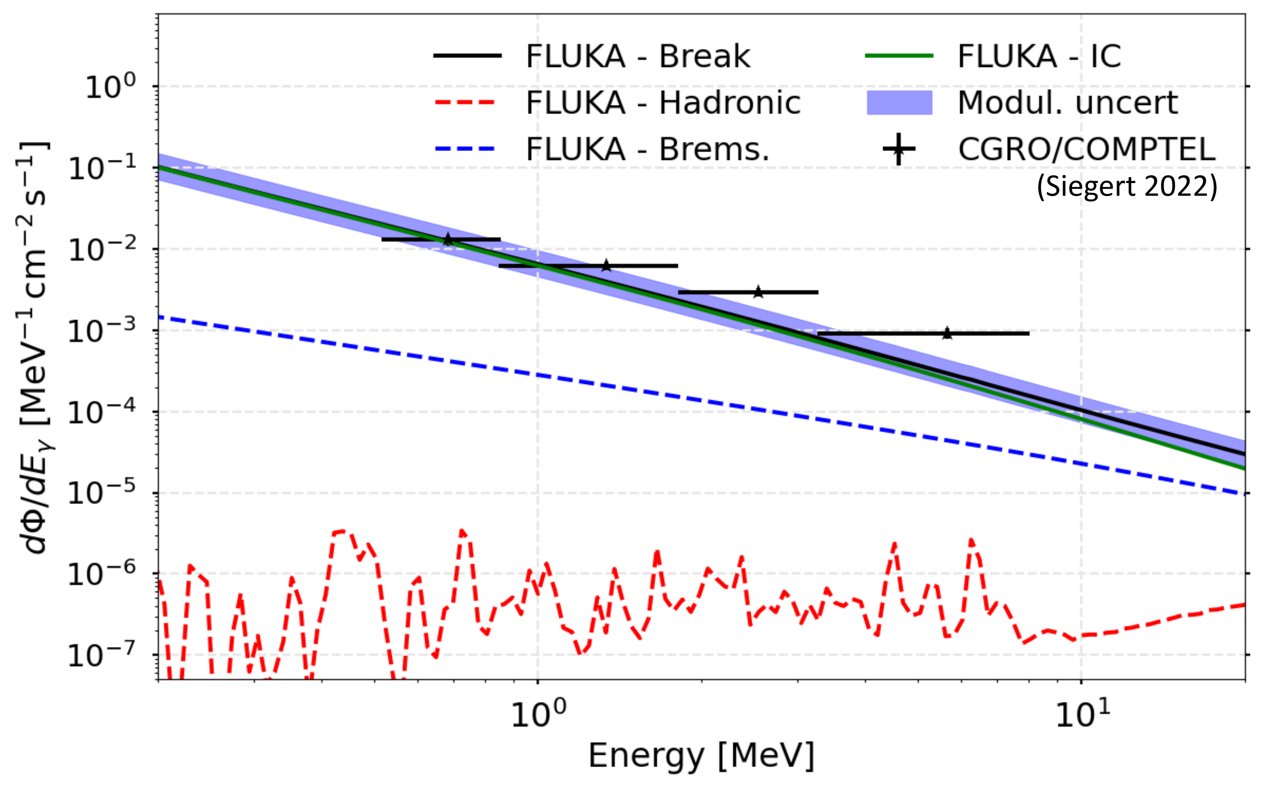
Cross sections implemented in the *GammaSky* code

FLUKA cross sections for gamma-ray production

Probing the low-energy break of e⁻ with measurements from the Compton Gamma-ray Observatory (Siegert et al. 2022).
This data clearly supports the “low-E break” hypothesis, but this is subject to many uncerts.



FLUKA allows us to also study nuclear lines!

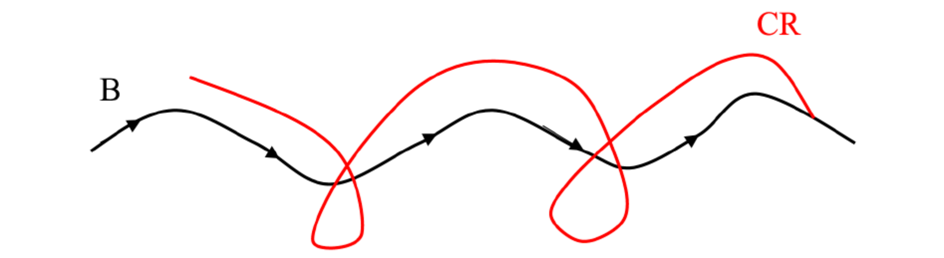


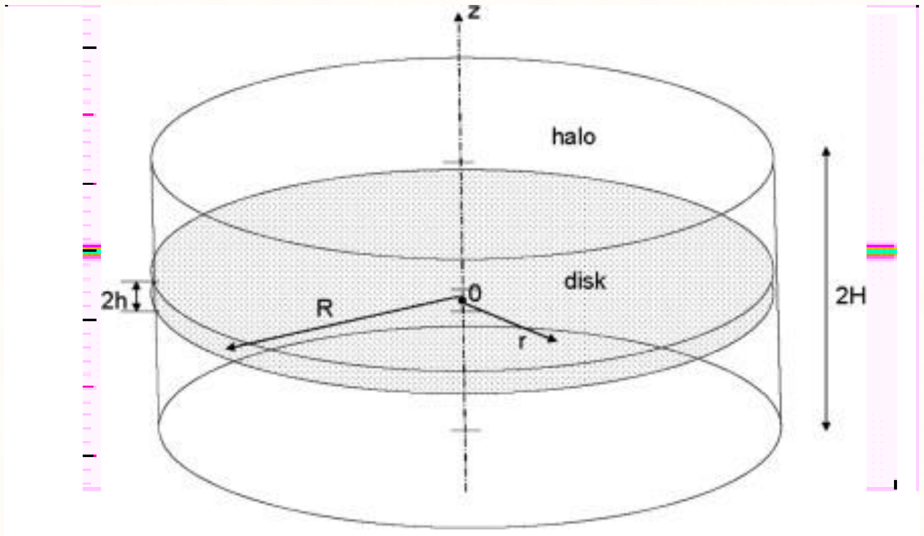
What can we do with *DRAGON*?

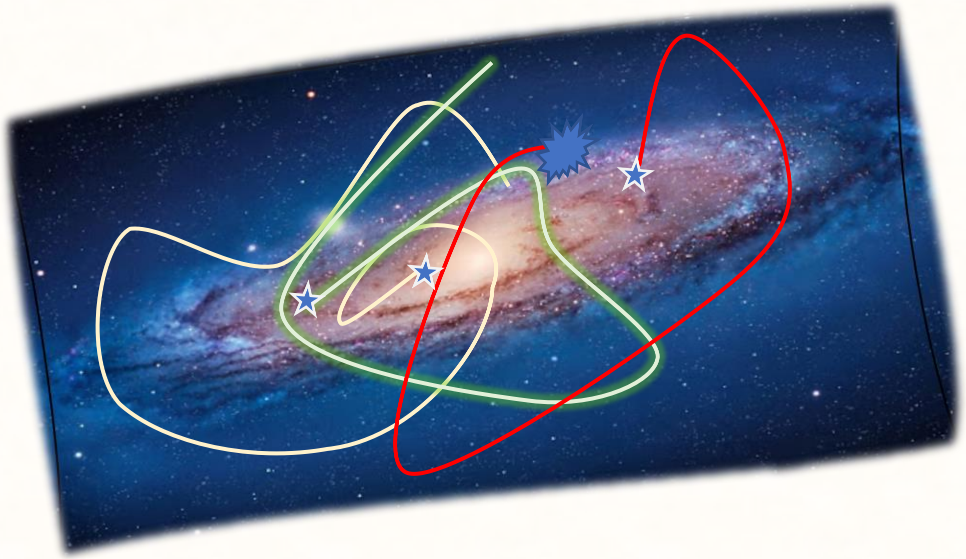
The background

Propagation of **Galactic CRs** is governed by their interaction with **plasma waves**, generated from instabilities in the ISM.

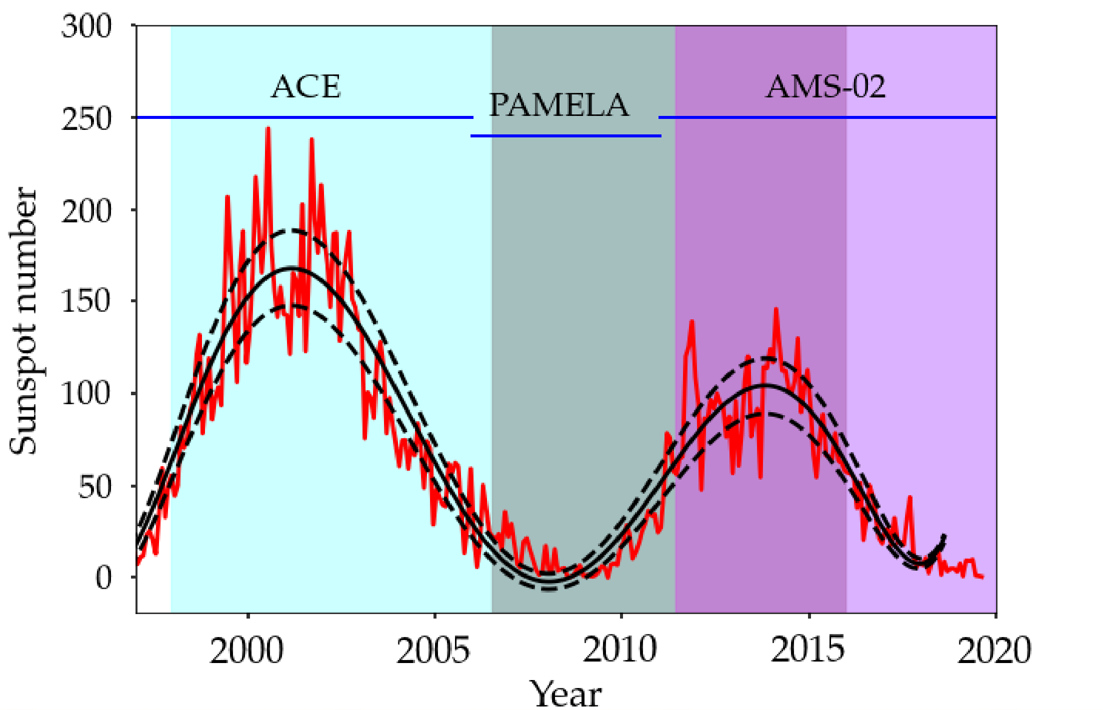
CR pitch-angle scattering on MHD turbulent fluctuations

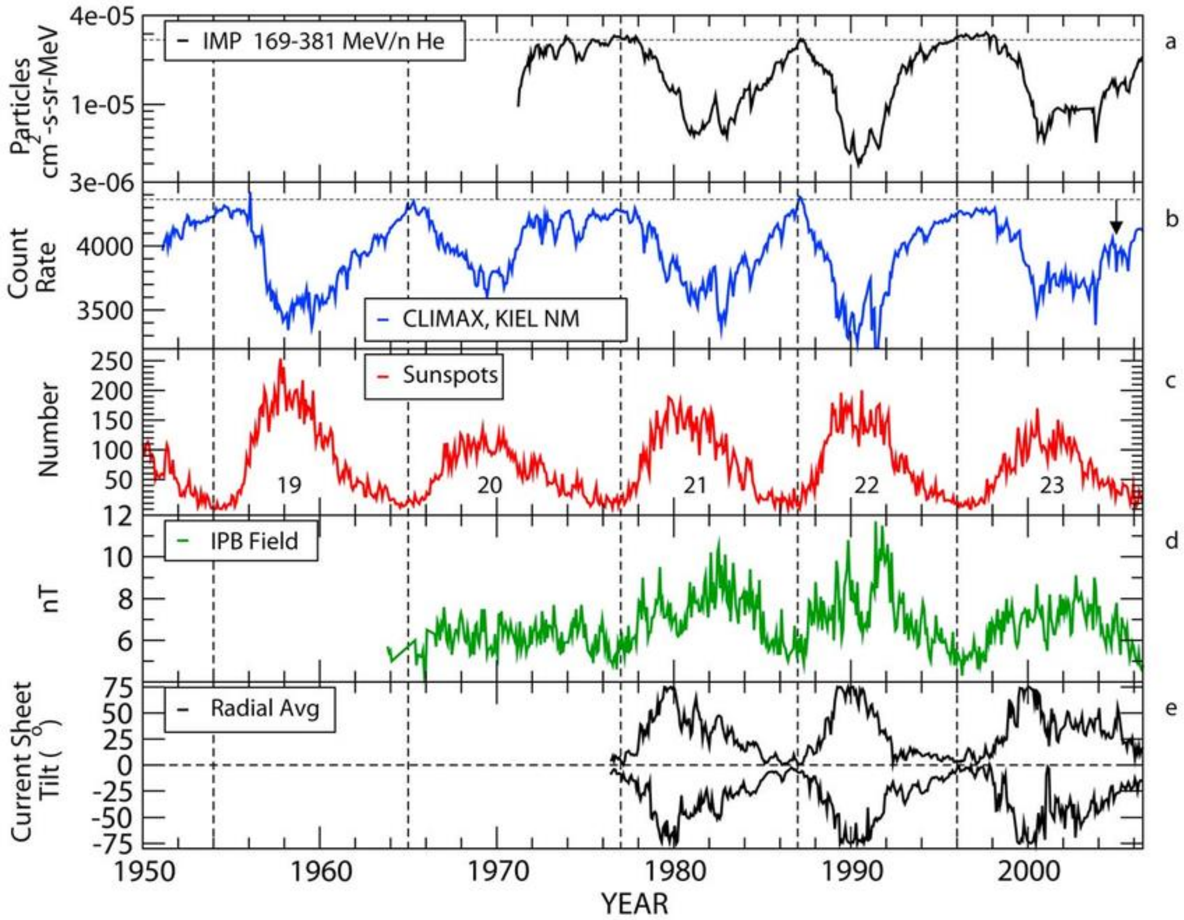






SOLAR MODULATION





- Force-Field approximation
- Neutron monitor data + Voyager-01 data
- Cholis-Hooper-Linden (arXiv:1511.01507) correction

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

$$\phi^{\pm}(t, \mathcal{R}) = \phi_0(t) + \phi_1^{\pm}(t)\,\mathcal{F}\left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)$$

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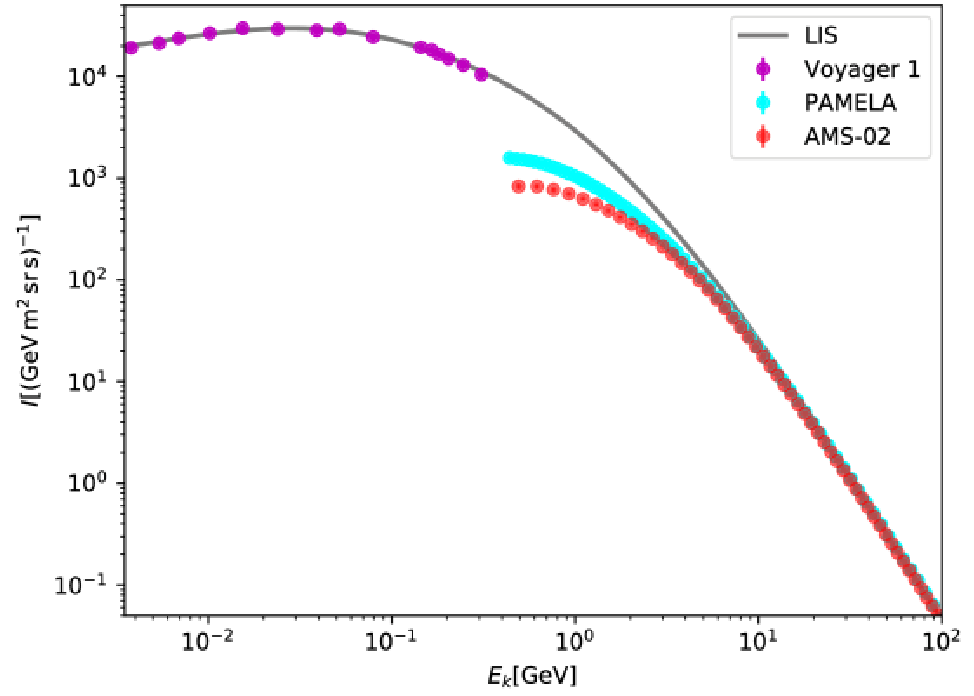

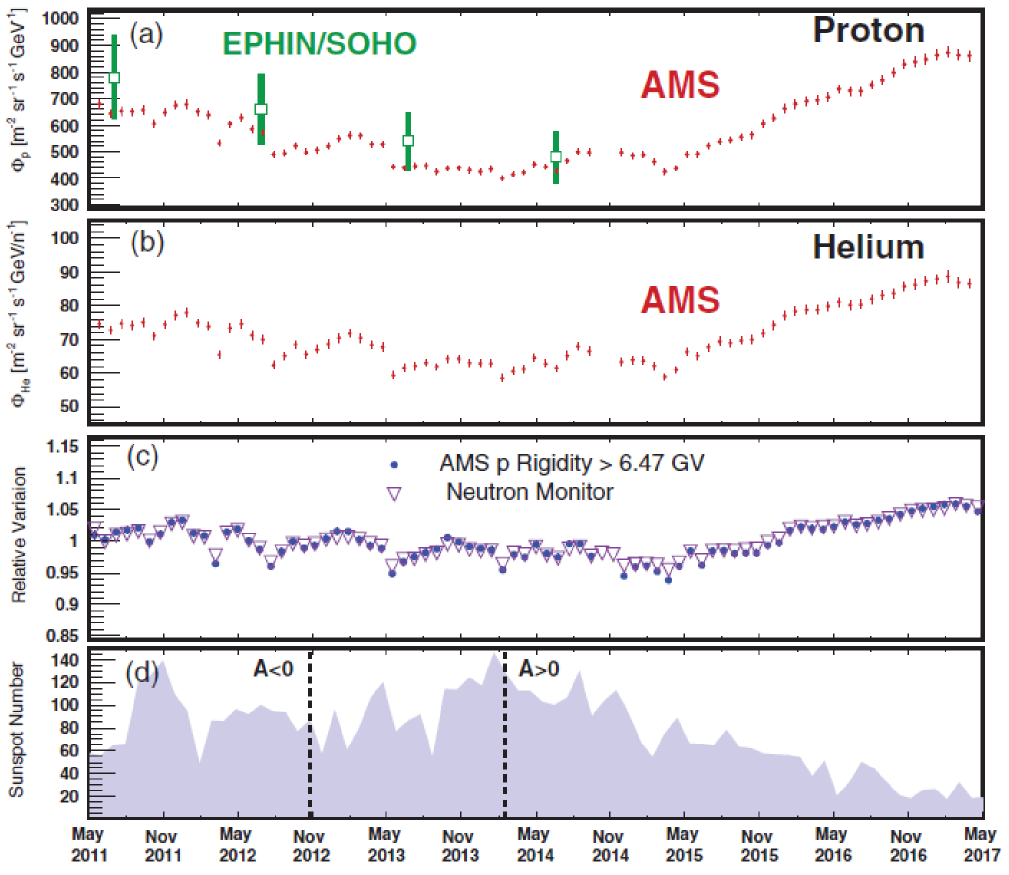

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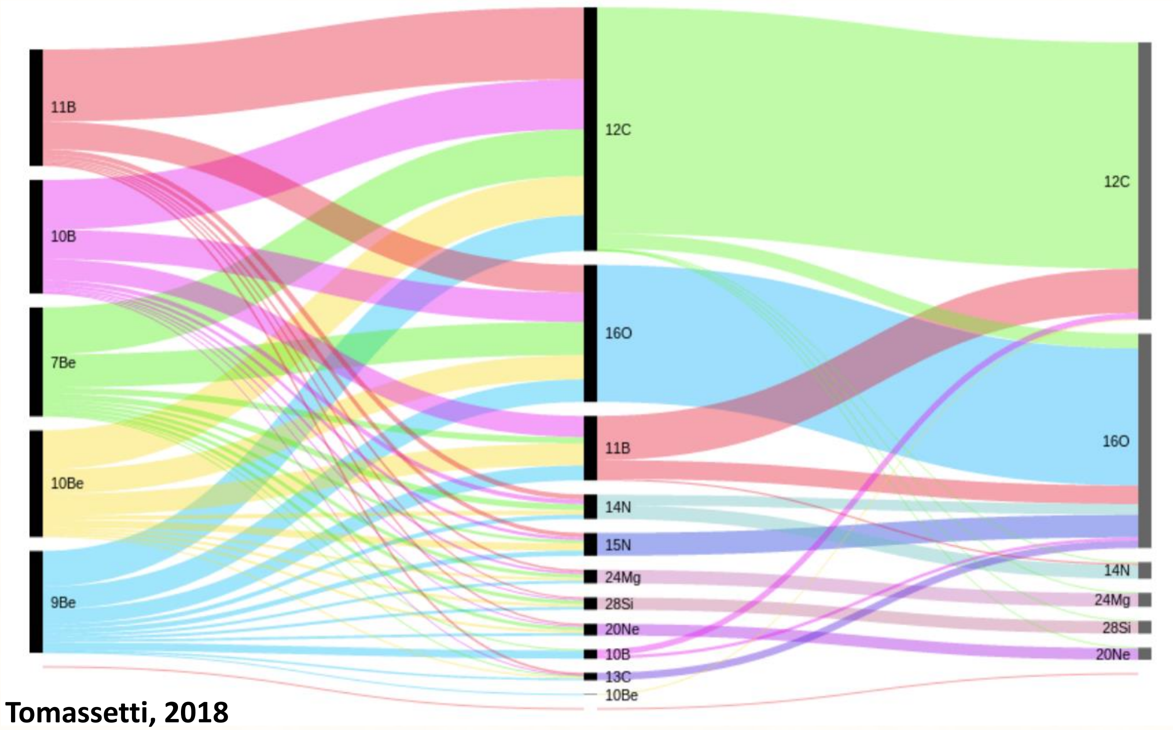
Cross sections → Secondary CRs

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

Complexity of the CS network



Tomassetti, 2018

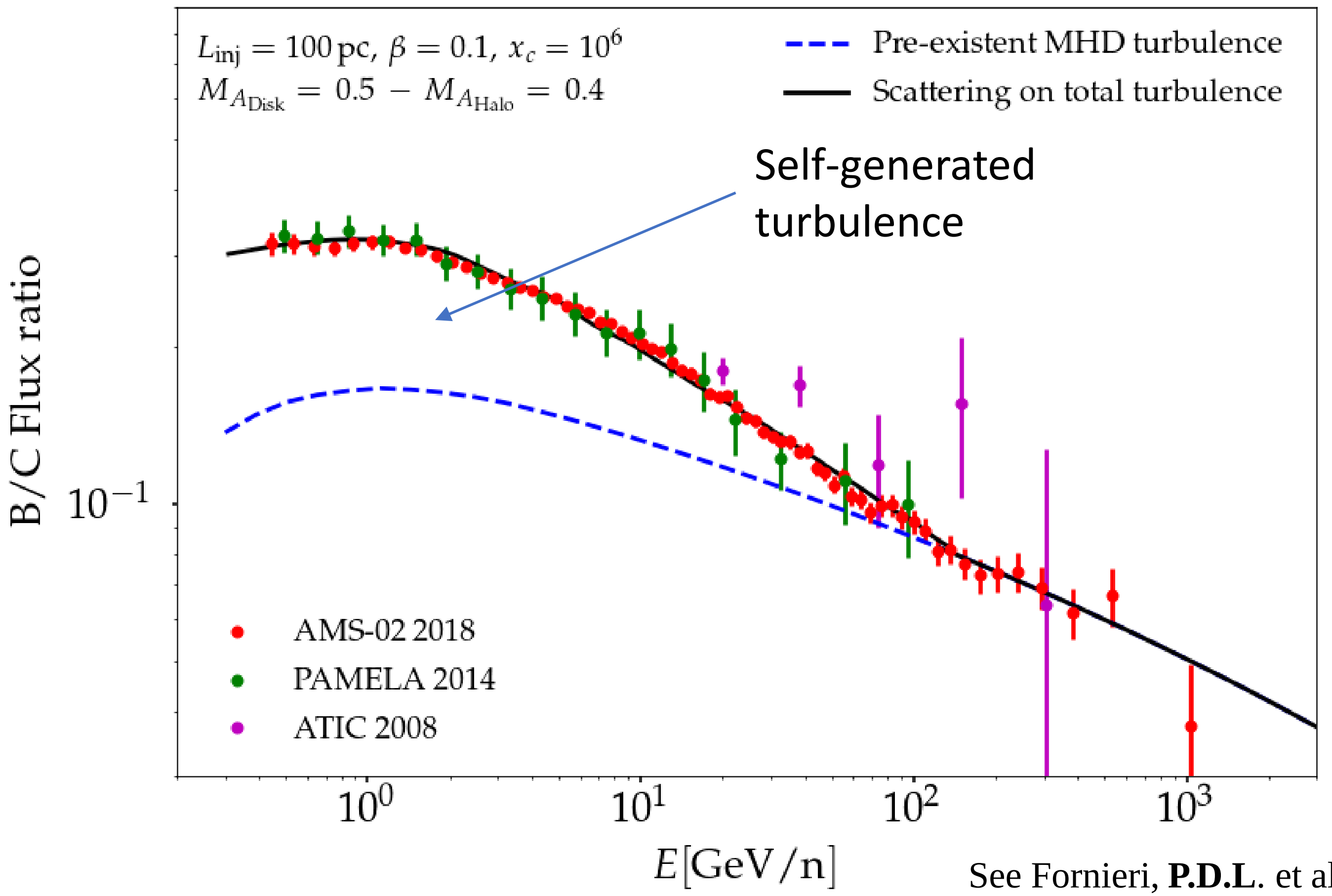
Production of secondary CRs

- 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]

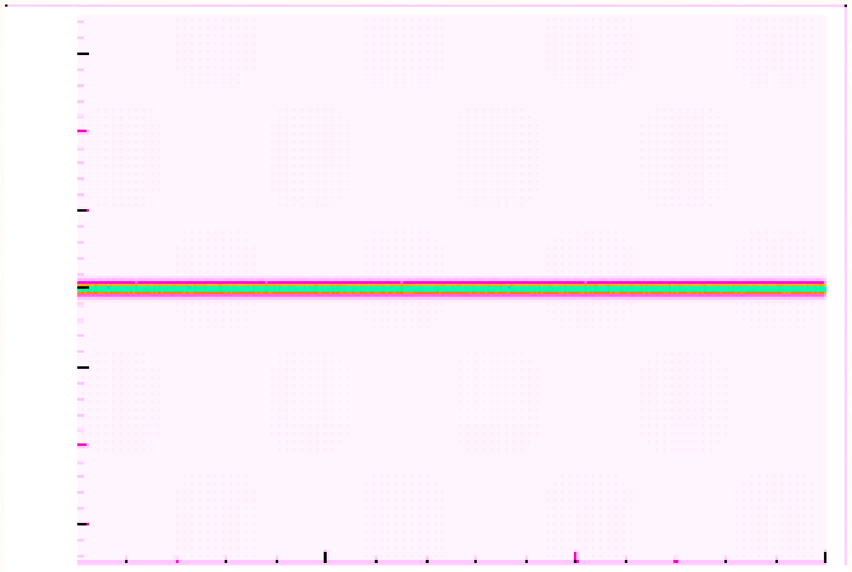
Secondary-to-primary CR flux ratios allow us to constrain the properties of the plasma where the turbulence is generated

CRs trigger instabilities in the plasma that lead to further confinement of cosmic rays in the Galaxy



See Fornieri, **P.D.L.** et al. 2020

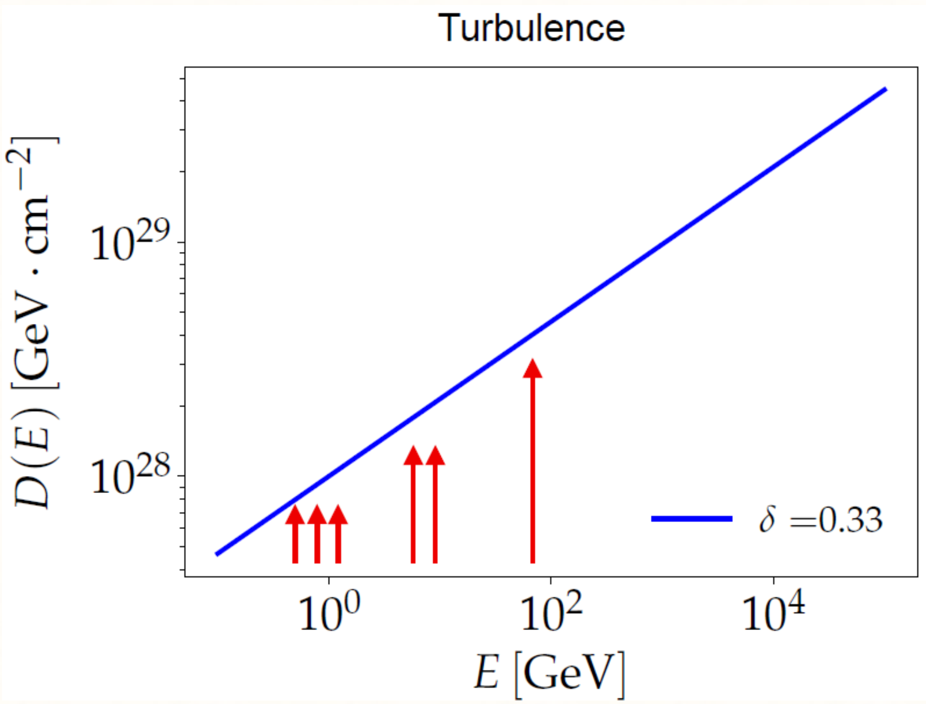
$$\frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \Gamma_{\rm CR} W = q_W(k)$$

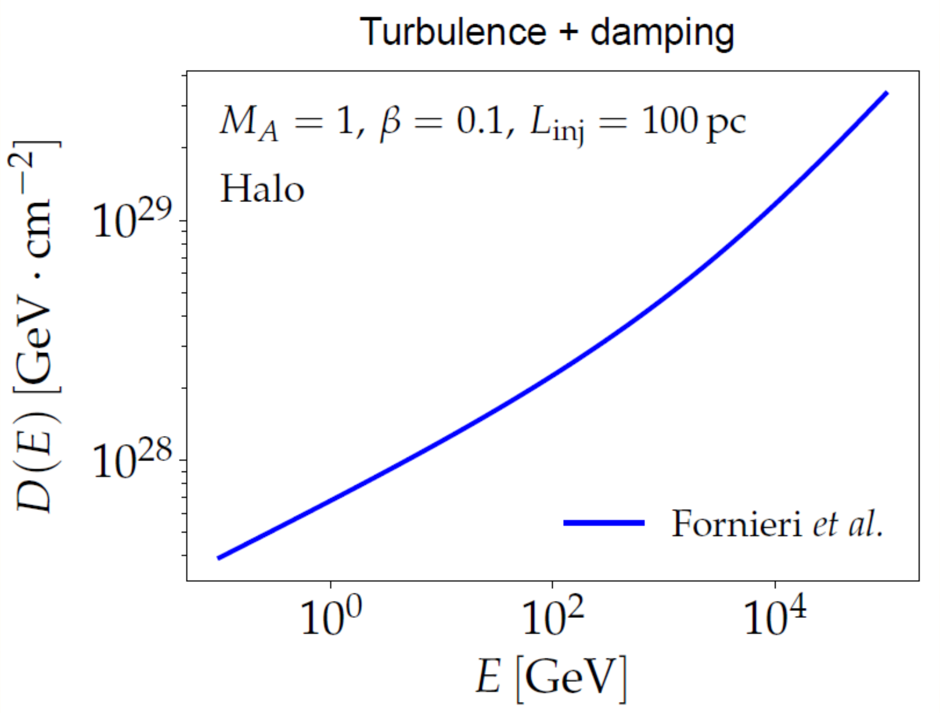


Non-uniform diffusion:
Inhomogeneous diffusion

Importance of the implementation of diffusion coefficients which are calculated in different ways, beyond standard parametrizations

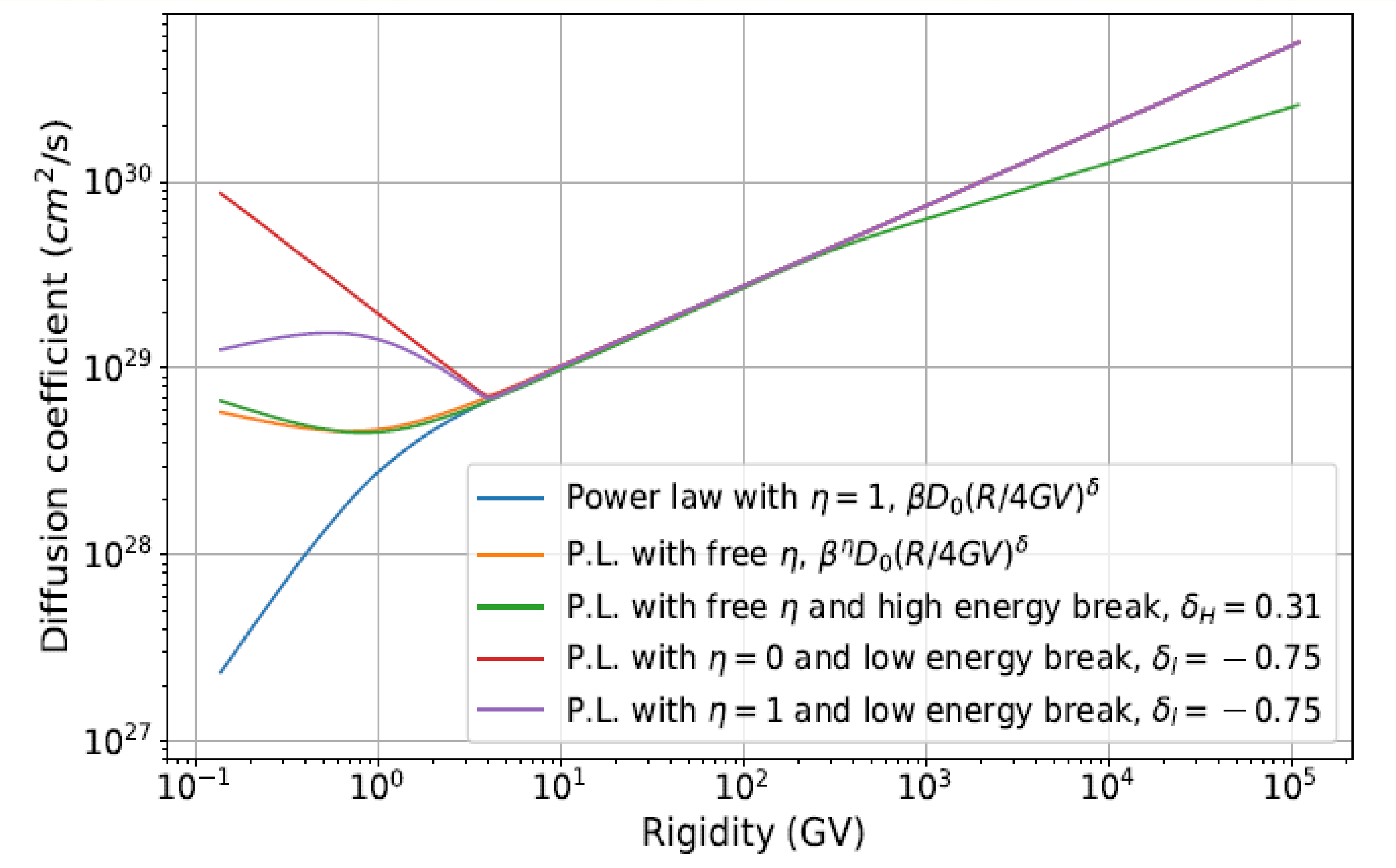
Change in the slope of D at low energies revealed by different analyses of AMS-02 data





Fornieri, **P.D.L.** et al *MNRAS* 502 (2021) 4, 5821-5838

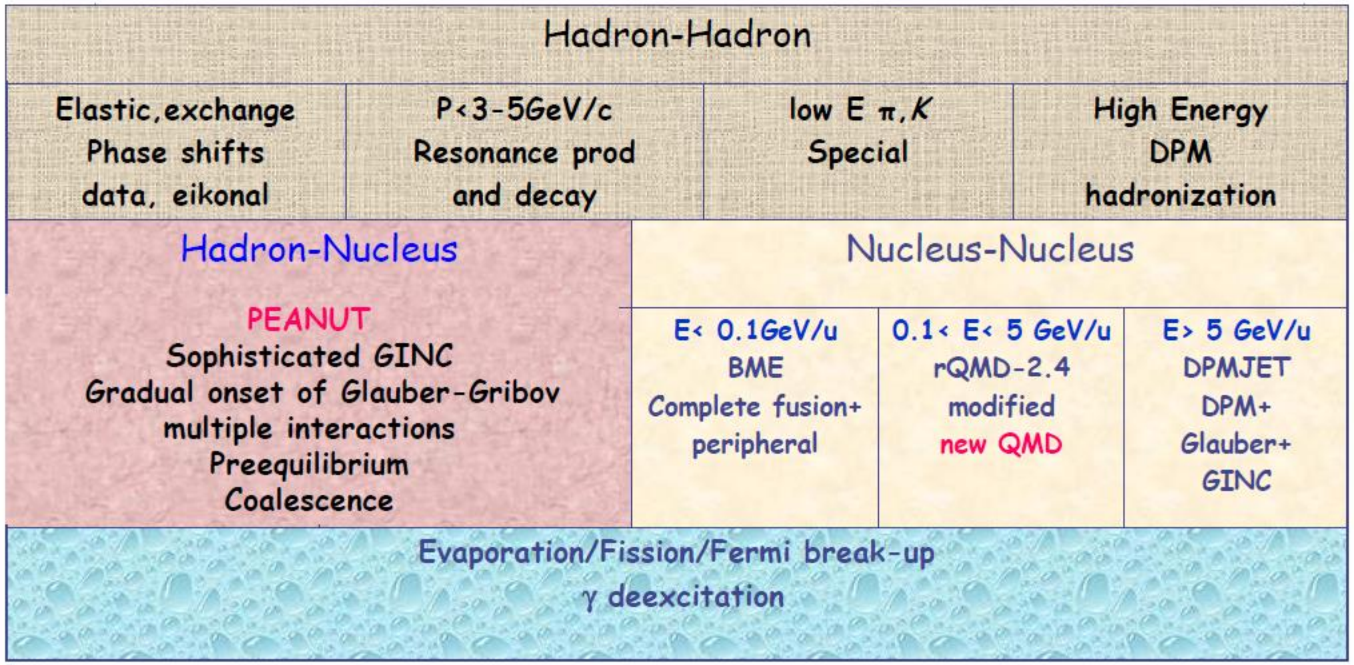
Diffusion coefficient parametrization



The FLUKA toolkit and the evaluation of cross sections for CR interactions

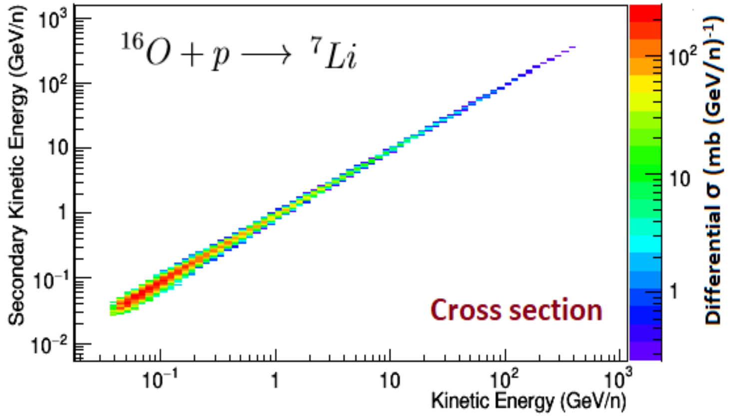
http://www.fluka.org/fluka.php

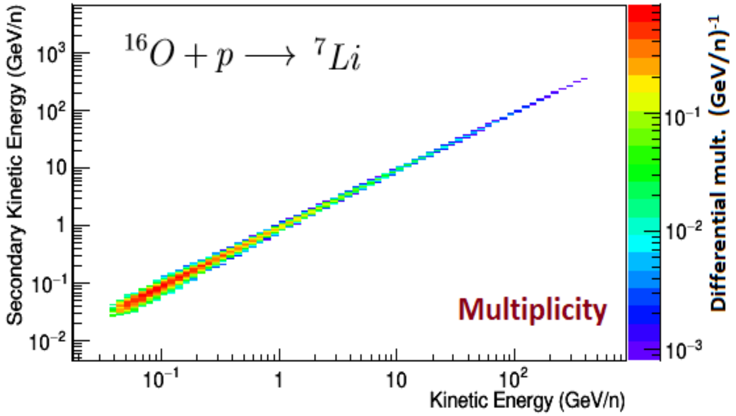
- **Resonances** produced in hadron-nucleon inelastic collisions dominate from the MeV up to 3-5 GeV
- Above 3-5 GeV hadronizations through Dual Parton Model (**DPMJET-3**) takes over
- Extension to hadron-nucleus collisions is achieved through the **PEANUT** model (GINC) + relaxation
- Nucleus-Nucleus use **Boltzmann thermal equation** at E<0.1GeV/u, **rQDM** model up to 5 GeV/u and **DPMJET** above

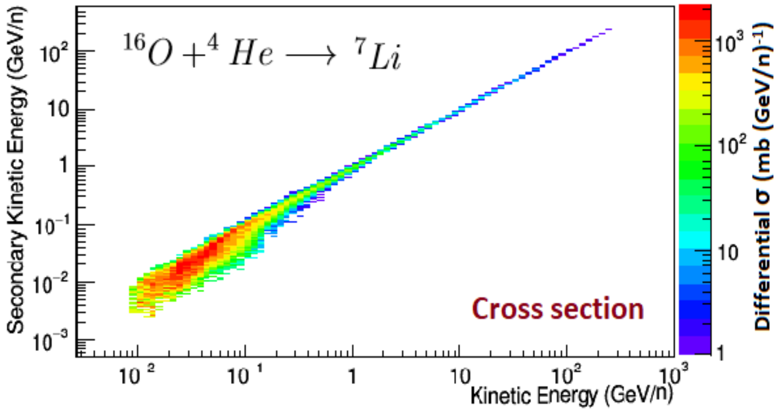


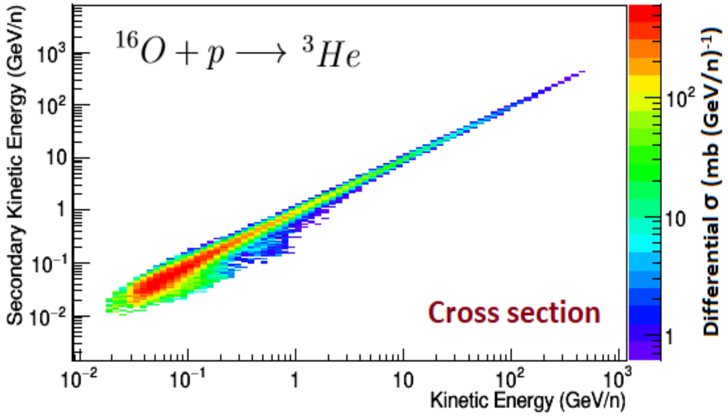
Credit: Paola sala

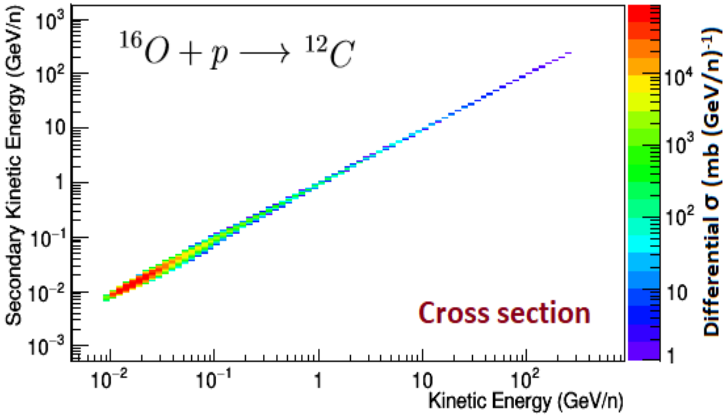
How valid is the head-on approximation below Li?

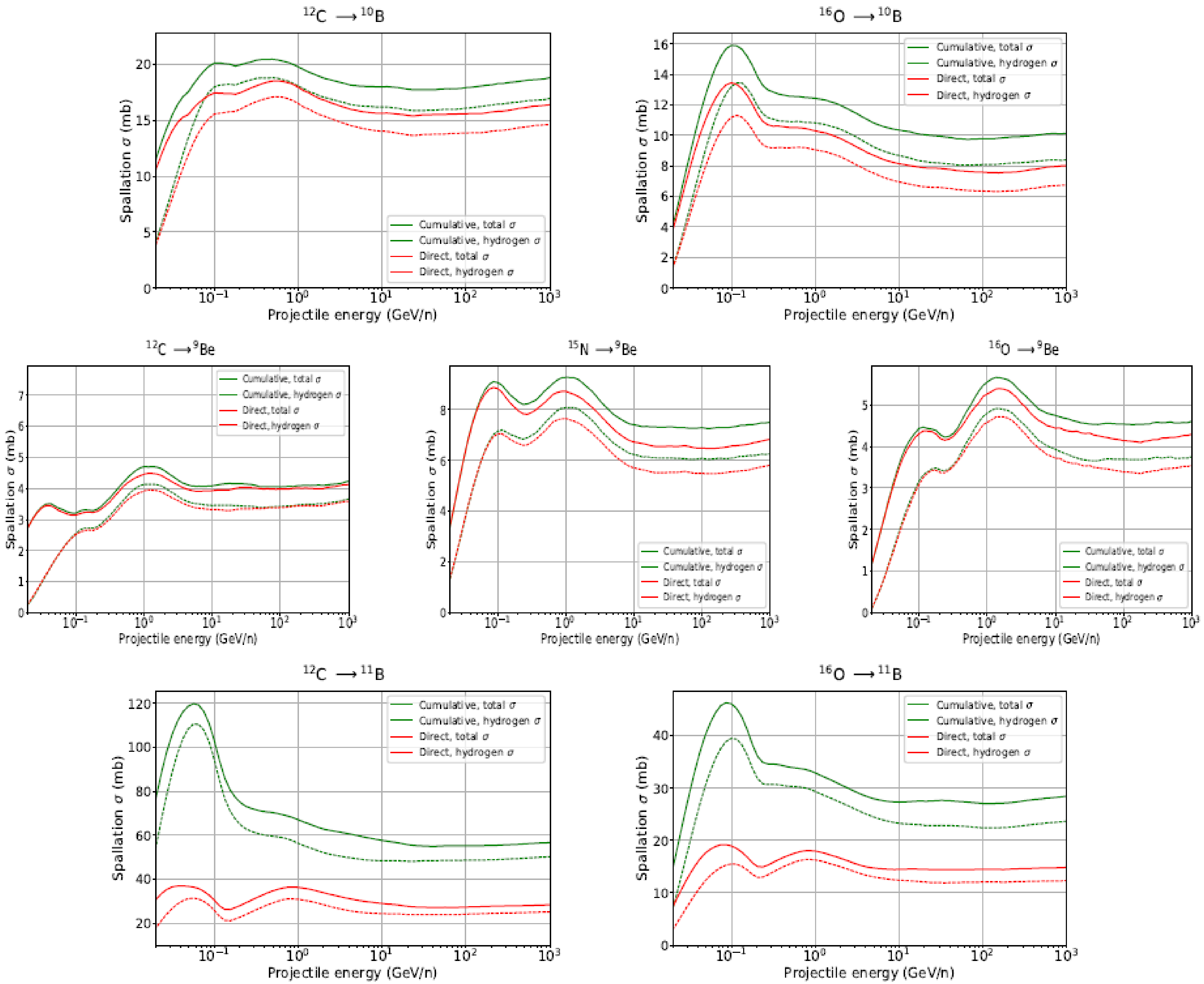






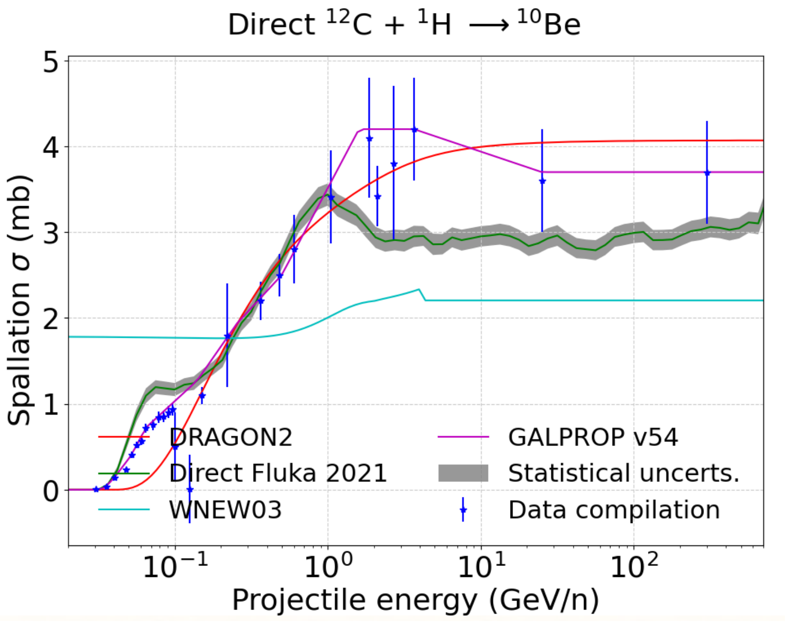


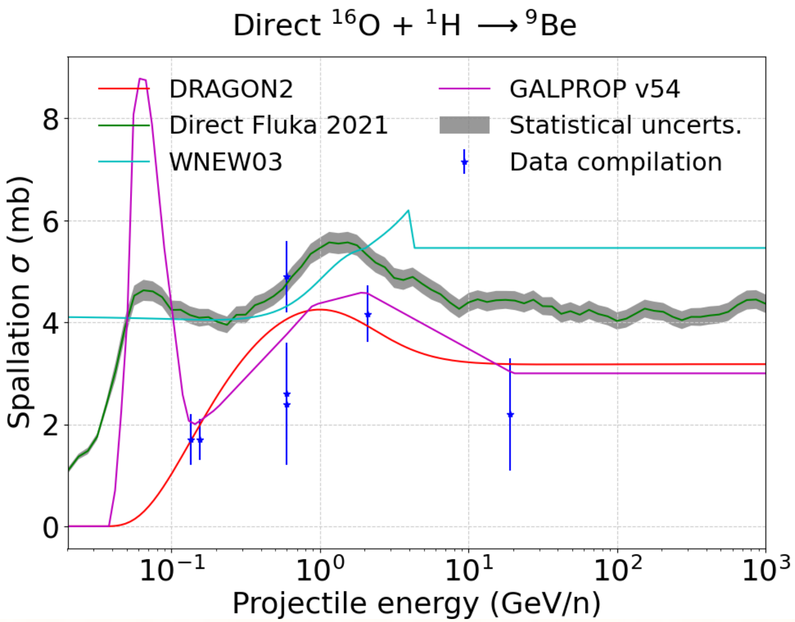




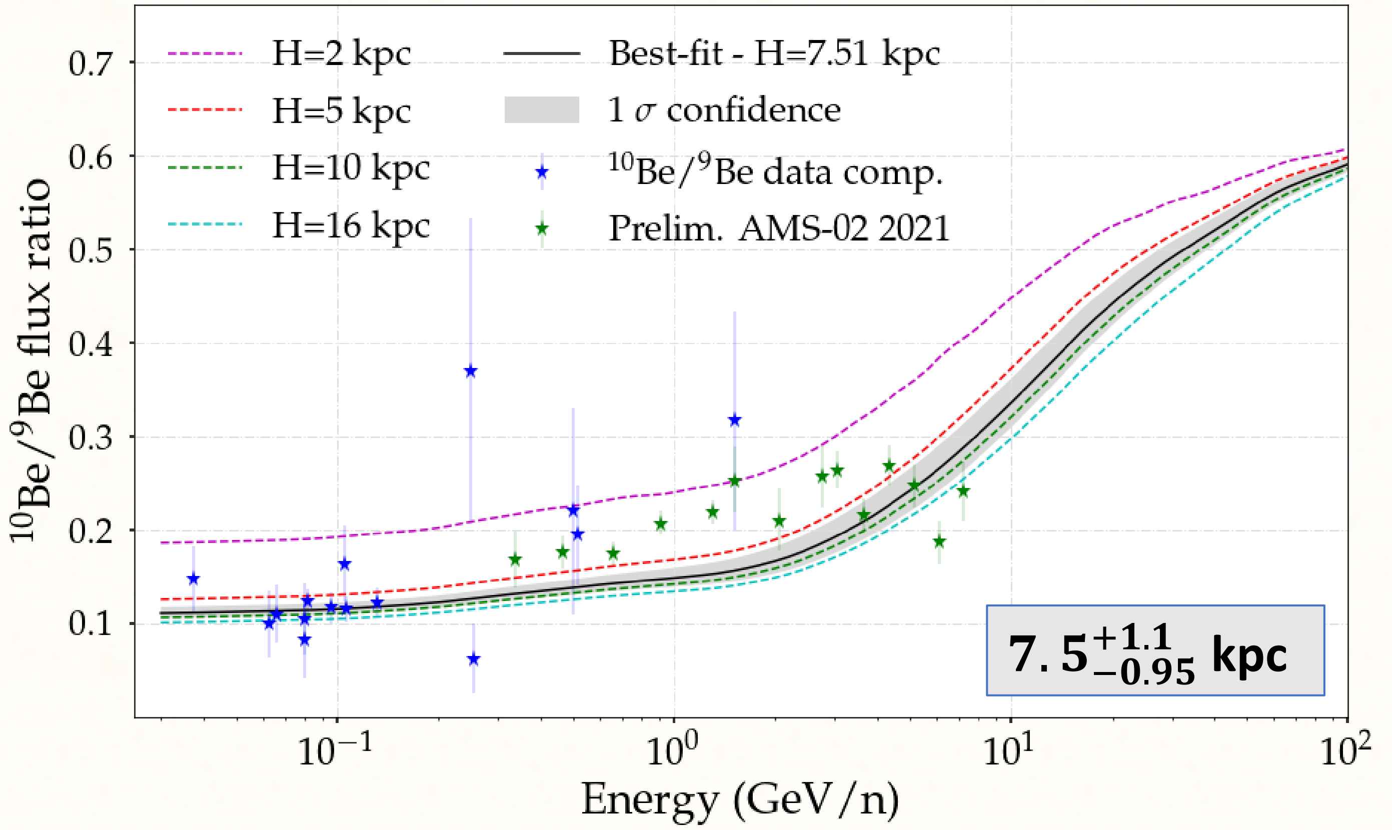
$^{12}C \longrightarrow {}^{10}B$
$^{16}O \longrightarrow {}^{10}B$
$^{12}C \longrightarrow {}^{9}Be$
$^{15}N \longrightarrow {}^{9}Be$
$^{16}O \longrightarrow {}^{9}Be$
$^{12}C \longrightarrow {}^{11}B$
$^{16}O \longrightarrow {}^{11}B$
Cumulative, total σ
Cumulative, hydrogen σ
Direct, total σ
Direct, hydrogen σ
Spallation σ (mb)
Projectile energy (GeV/n)

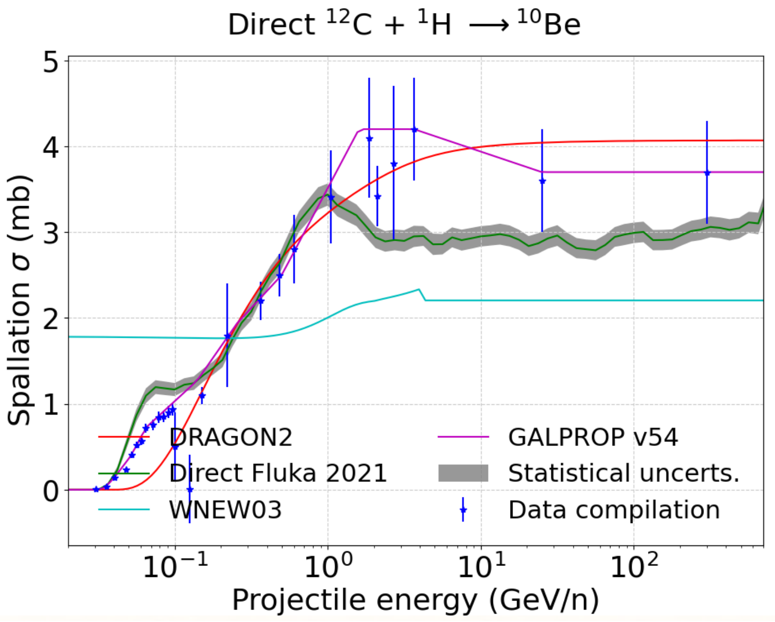
FLUKA cross sections: The halo size

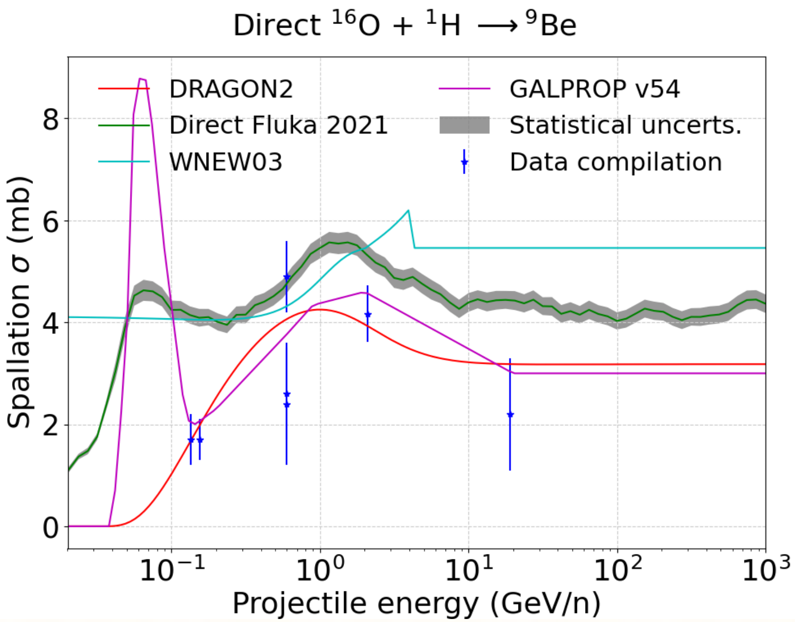




P.D.L. et al arXiv:2202.03559

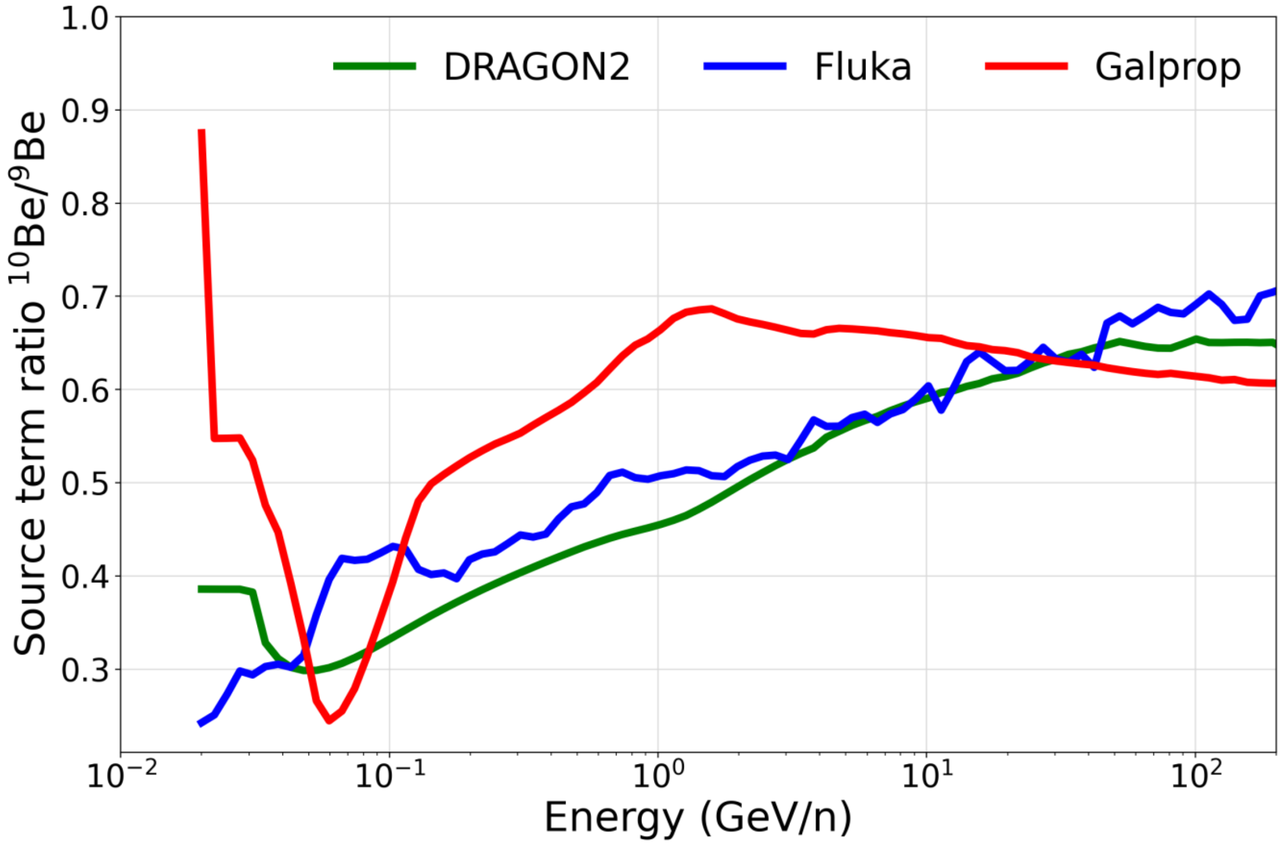






FLUKA cross sections: The halo size

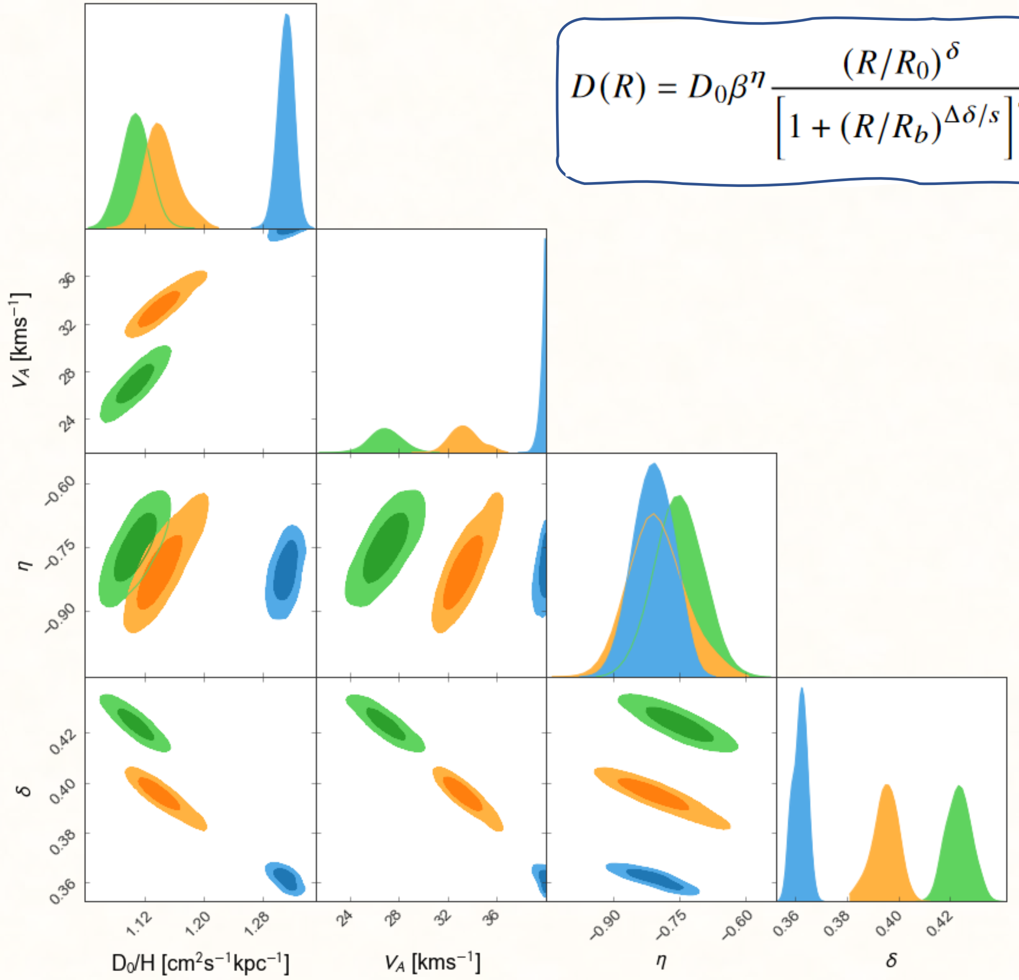
$$Q^{Be}\,(E_{Be}) = \sum_{i=p,He}^{Gas} \sum_{k}^{Prim} 4\pi n_i \int_{E^{kmin}}^{\infty} \left(\frac{d\sigma}{dE_{Be}}\right)_{ik} \Phi_k(Ek)\; dEk$$



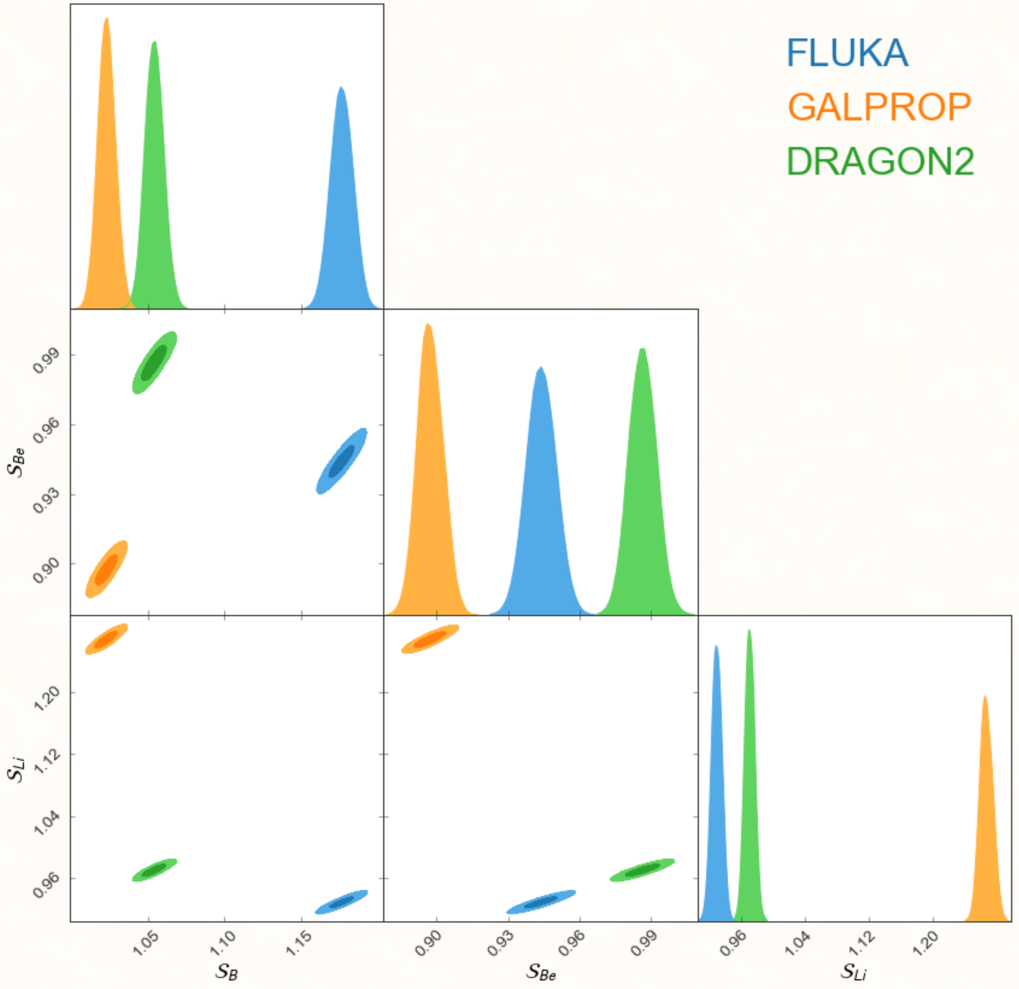
Combined fit of light secondary CRs

Main propagation parameters

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

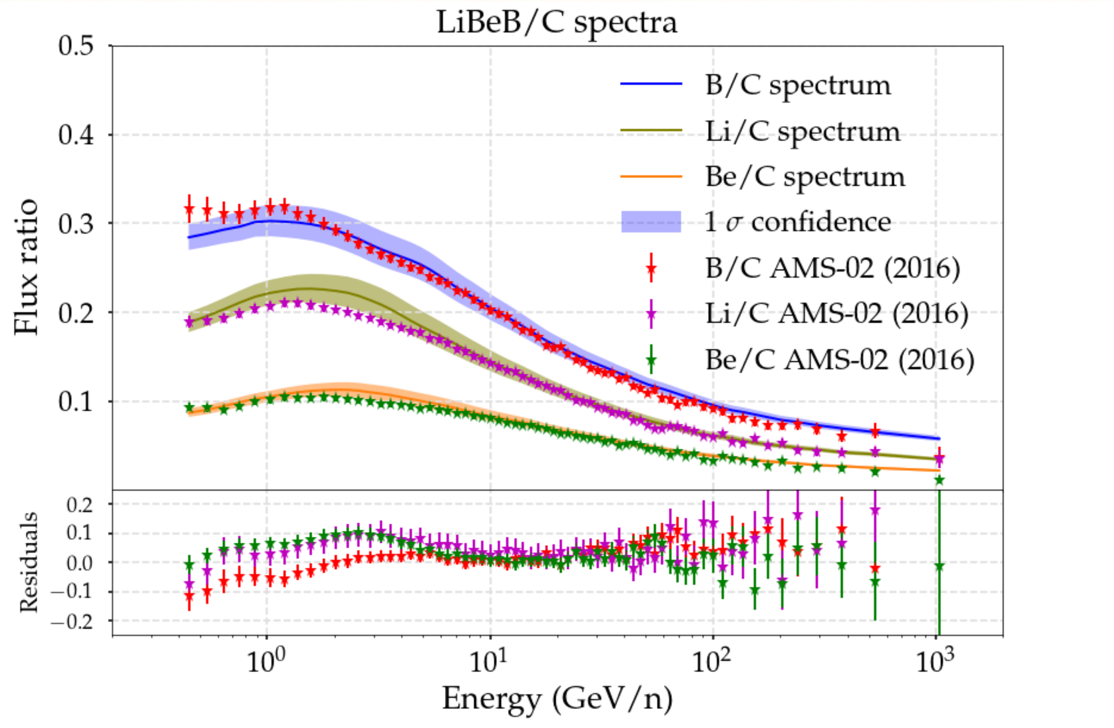


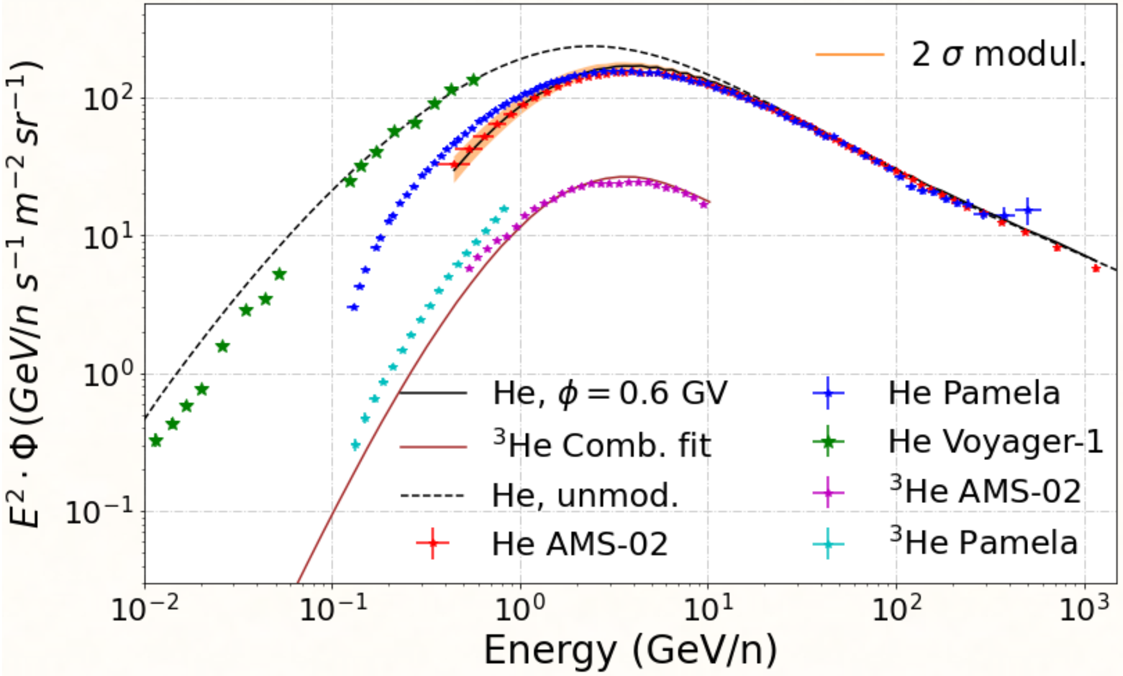
Scale factors



Combined fit reproduces all light secondary CRs

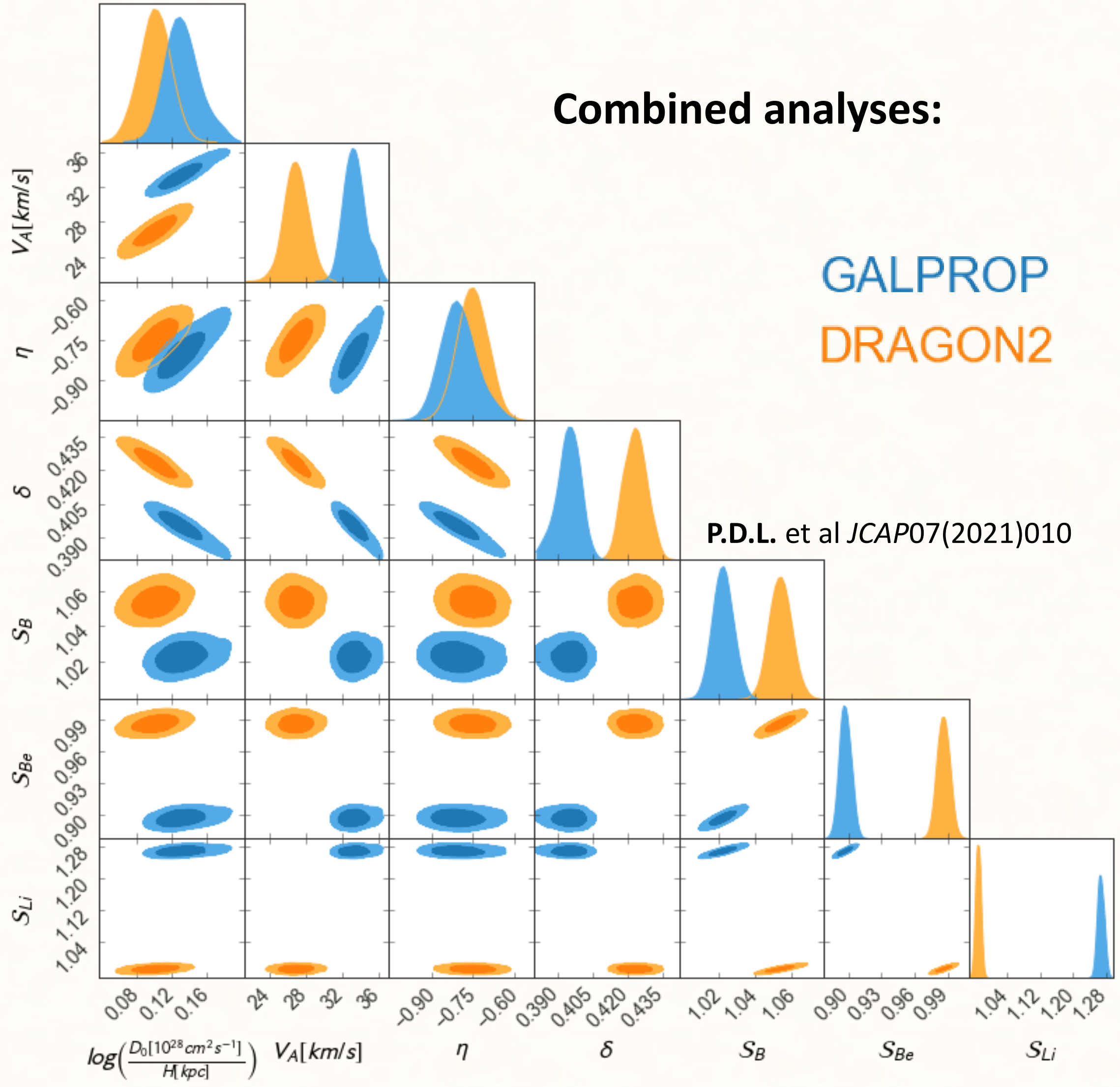
B, Be, Li and ^{3}He in good agreement with AMS-02 data for a diffusion coefficient well compatible with theoretical expectations on CR-waves interactions





Precise studies of secondary CRs: Current parametrizations

Combined analyses:



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- ➢ **Propagation parameters seem to be compatible for different cross sections parametrizations**
- ➢ **These ratios are compatible (within 1 σ) with experimental data for < 6% scaling**