The FLUKA cross sections for galactic cosmic-ray propagation studies

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with

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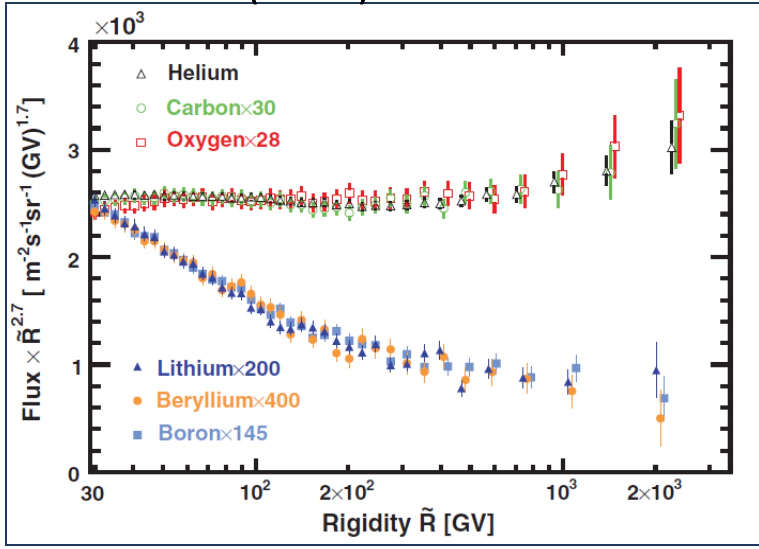
Introduction

- Current measurements of cosmic-ray (CR) fluxes have reached unprecedented accuracy
- Significant progress has been also made in the propagation models of galactic CRs
  - Secondary to primary CR ratios are useful tools to infer the grammage traversed by CR propagating for hundred millions of years in the Galaxy
  - These ratios depend on the cross sections describing the collisions among the various species of CR nuclei (spallation cross sections) with the interstellar medium (ISM)
- Current spallation cross sections models are based on set of parametrizations mixing (few) data points and simulation predictions for those channels with no measurements
- In this talk we present new sets of cross sections of cosmic-ray interactions in the Galaxy computed with the FLUKA simulation code that has been extensively tested against data
- These cross sections (up to iron) have been implemented in the DRAGON2* code to study the main propagation parameters

AMS collaboration, *Phys. Rev. Lett.* **120** (2018) 021101

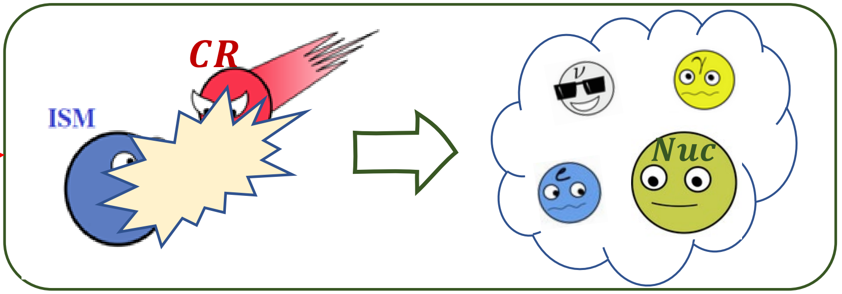


http://www.fluka.org/fluka.php

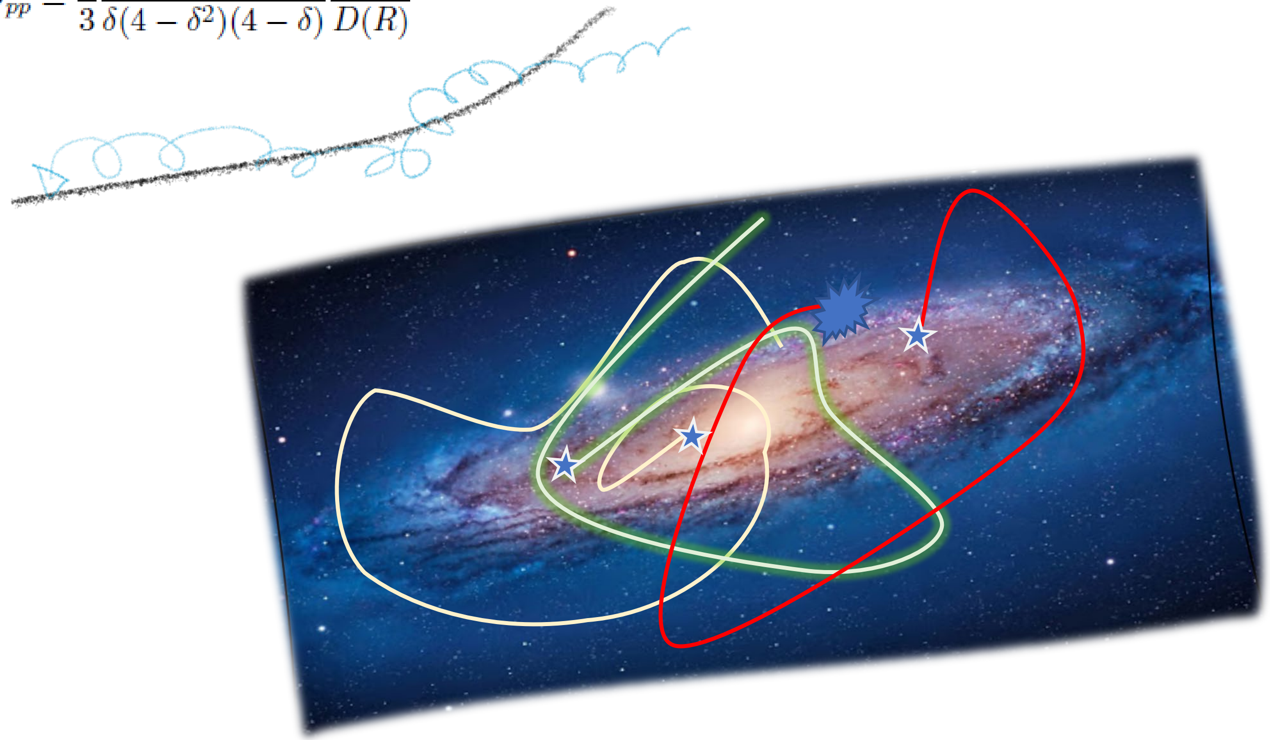
* Available at https://github.com/cosmicrays/DRAGON2-Beta_version

Diffusive transport of Galactic cosmic rays

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



$$D_{pp} = \frac{4}{3}\frac{1}{\delta(4-\delta^2)(4-\delta)}\frac{v_A^2 p^2}{D(R)}$$



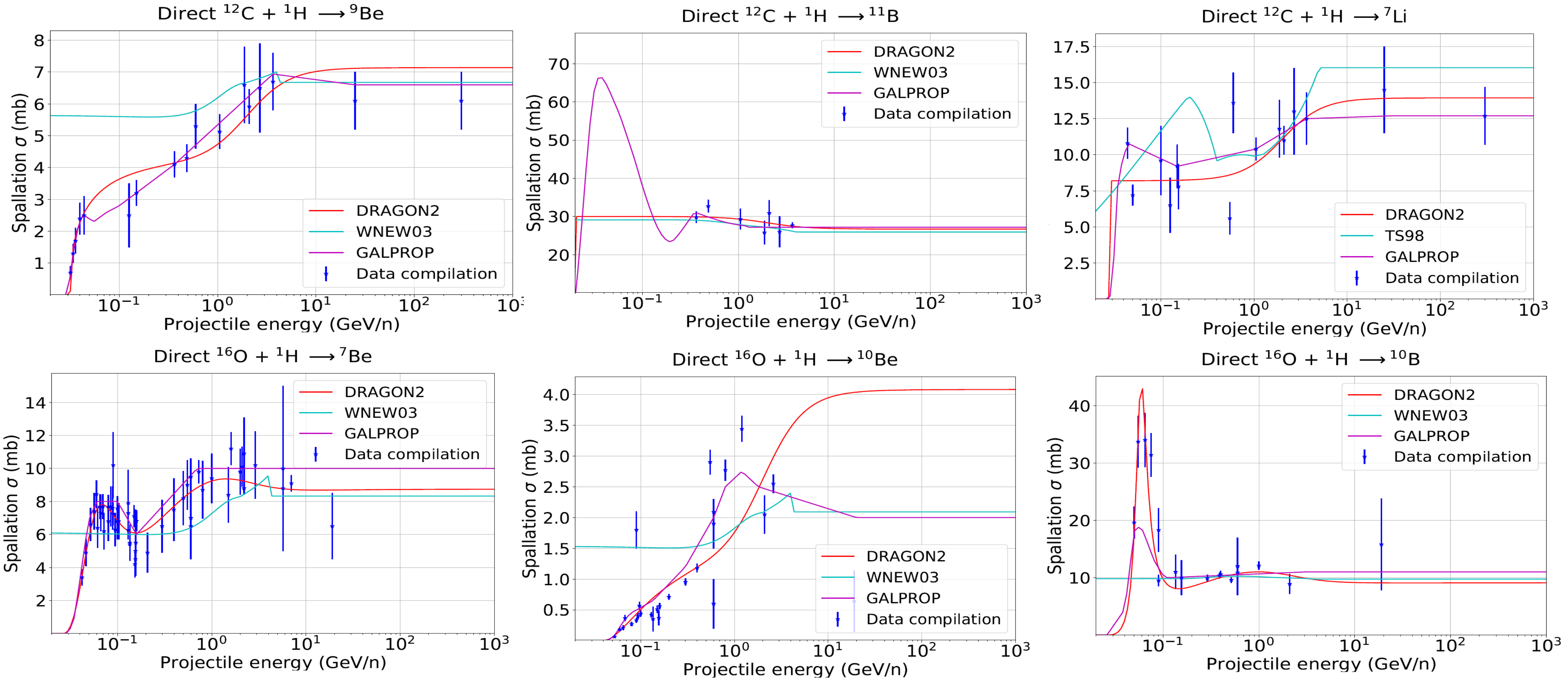
Diffusion coefficient ($D \propto 1/\tau^{\mathrm{diff}}$)

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

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

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

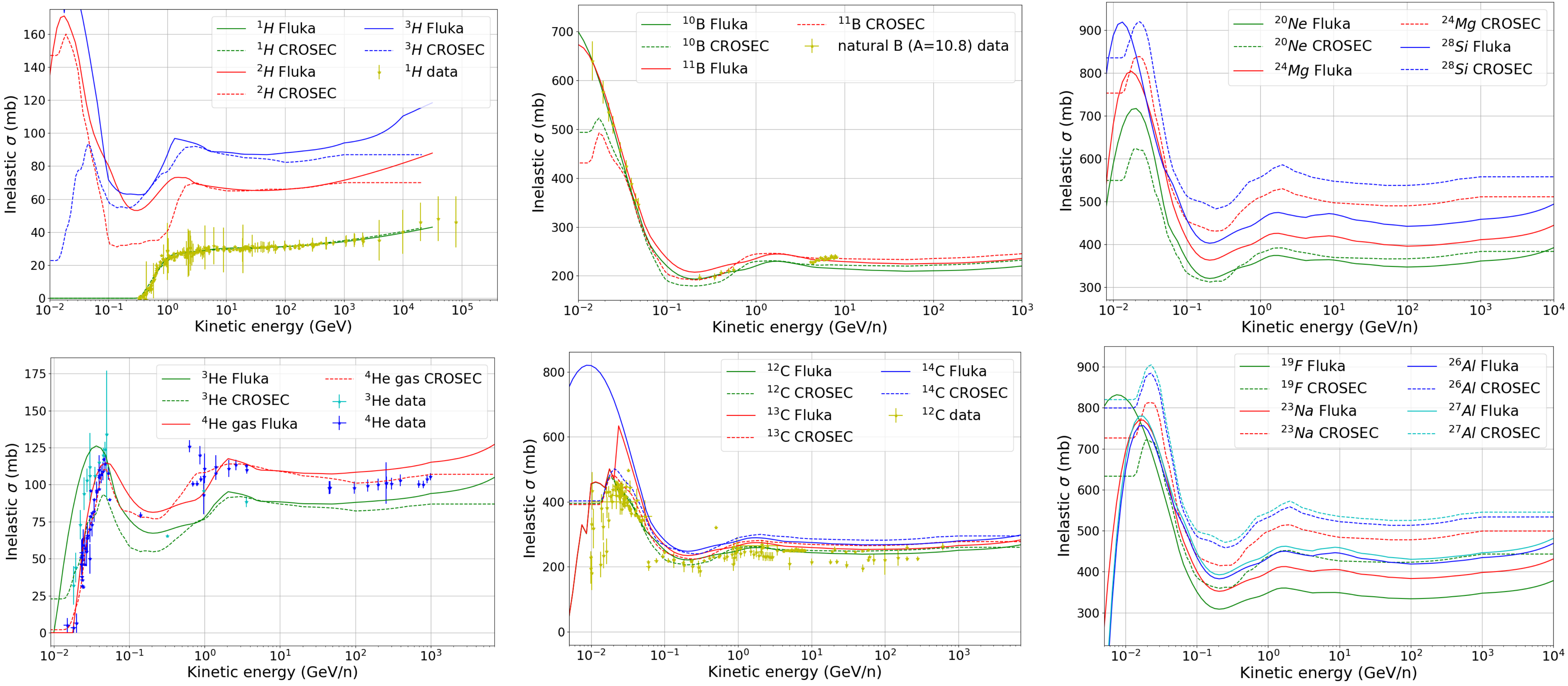
Cross sections parametrizations: need to go beyond!



WNEW3: W. Webber+ *Astrophys. J. Suppl. Ser.* **144** (2003) 153

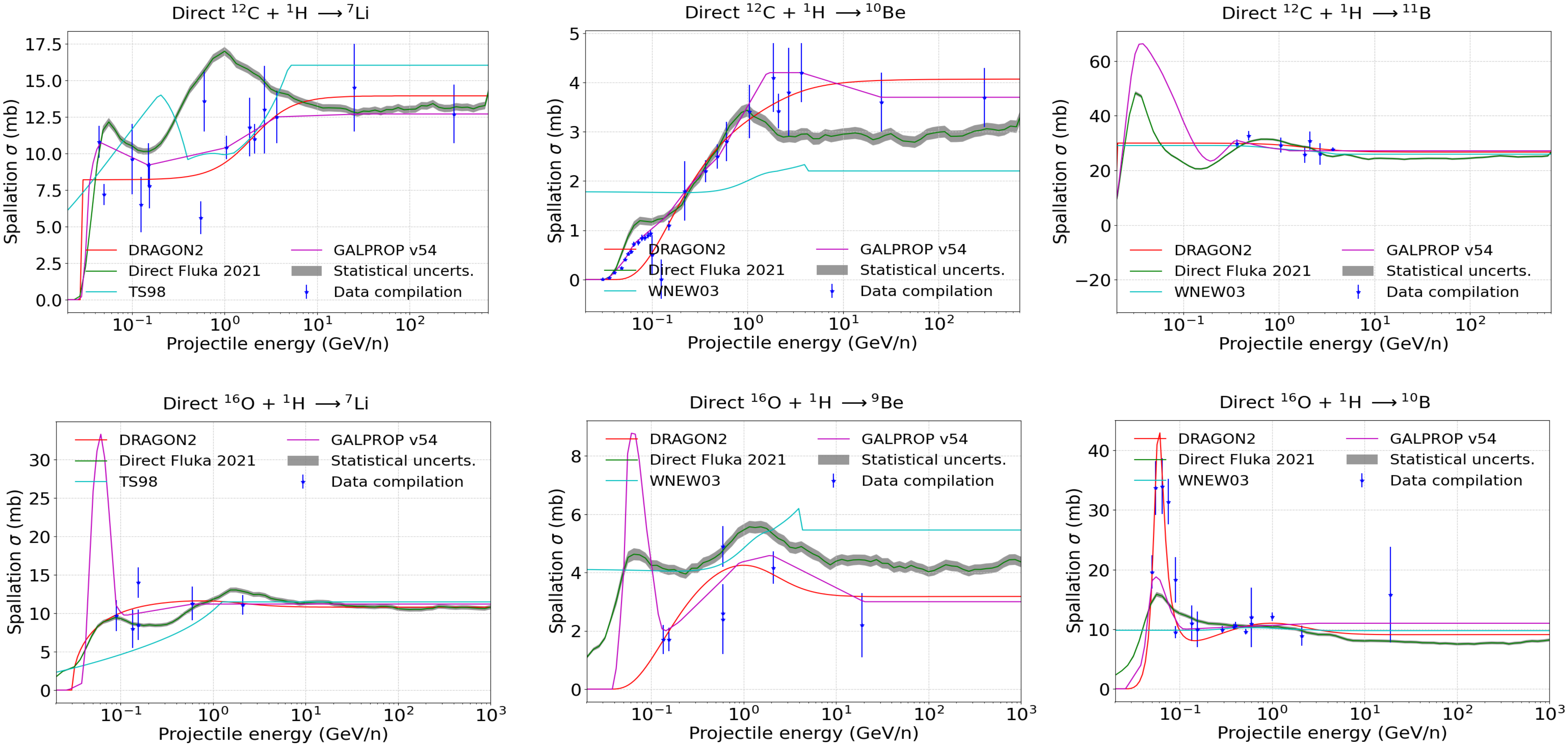
GALPROP: https://galprop.stanford.edu/

FLUKA inelastic cross sections



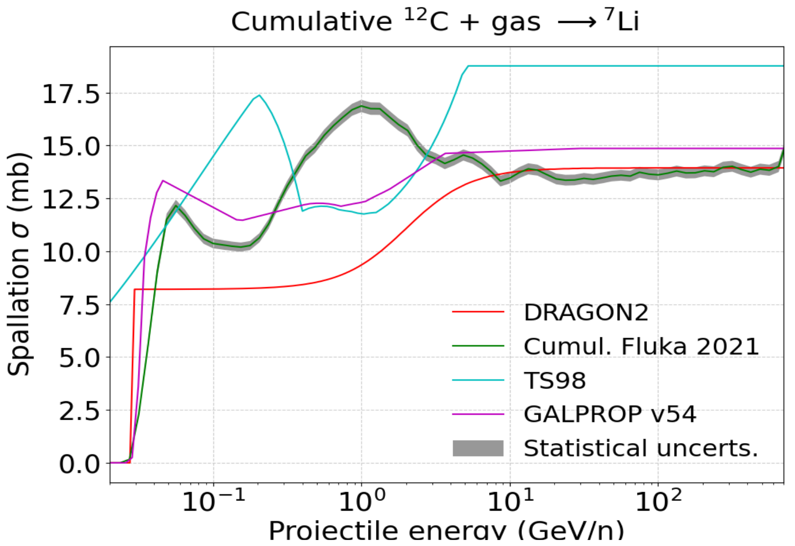
CROSEC: V.S. Barashenkov and A. Polanski E2-94-417, JINR-E2-94-417 (1994) (default option in the DRAGON2)

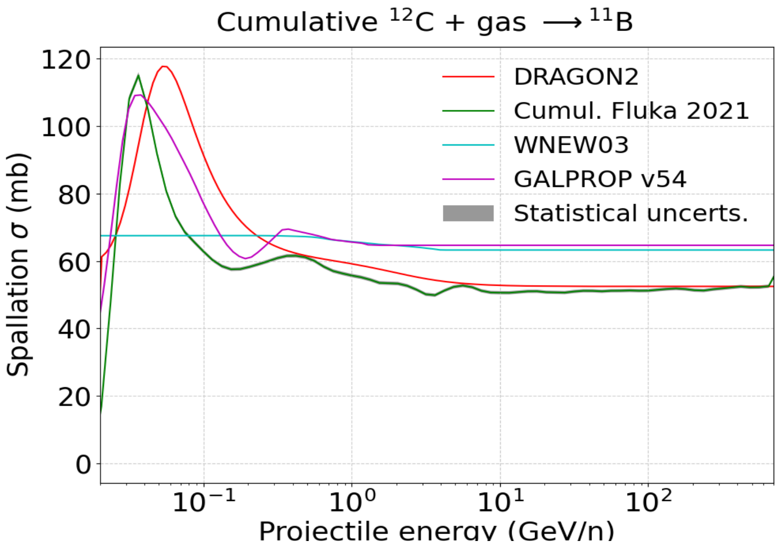
FLUKA (direct) inclusive cross sections

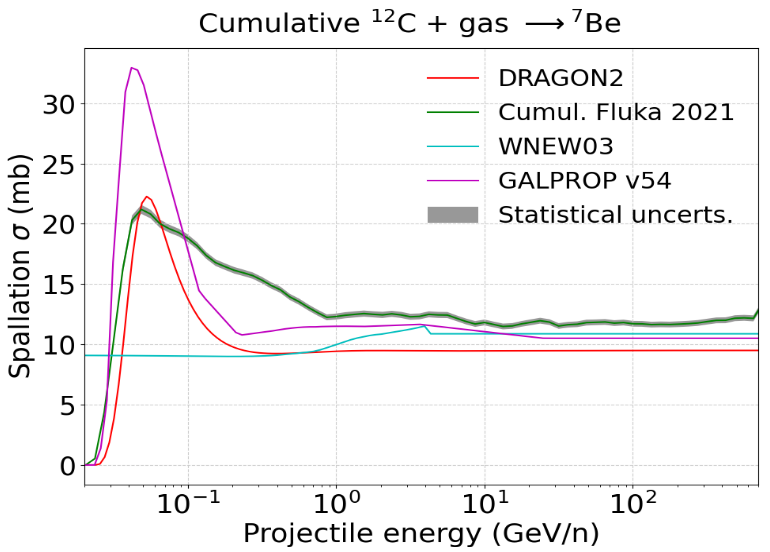


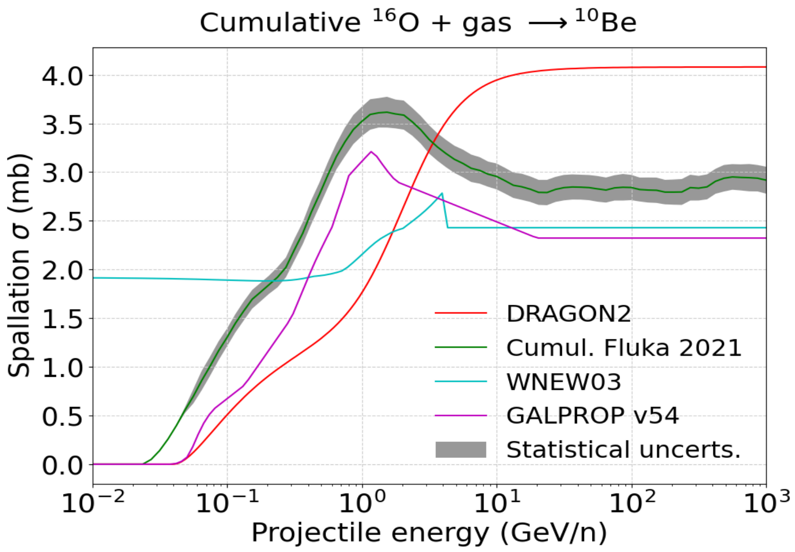
FLUKA cumulative inclusive cross sections

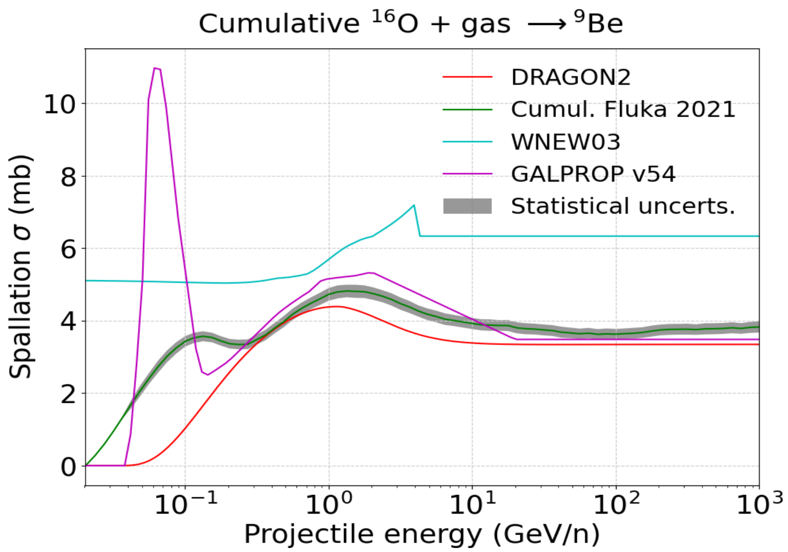
Cumulative: cross sections of interactions with ISM including all the contributions of unstable nuclei for short lifetime decay

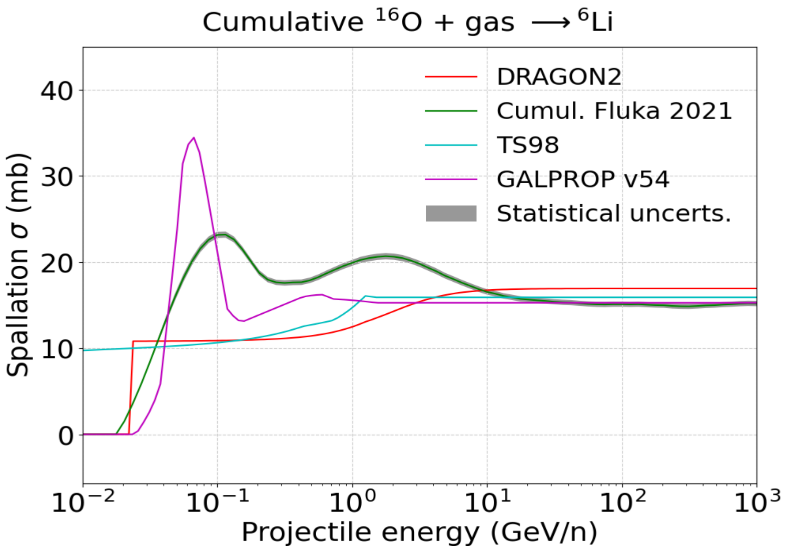






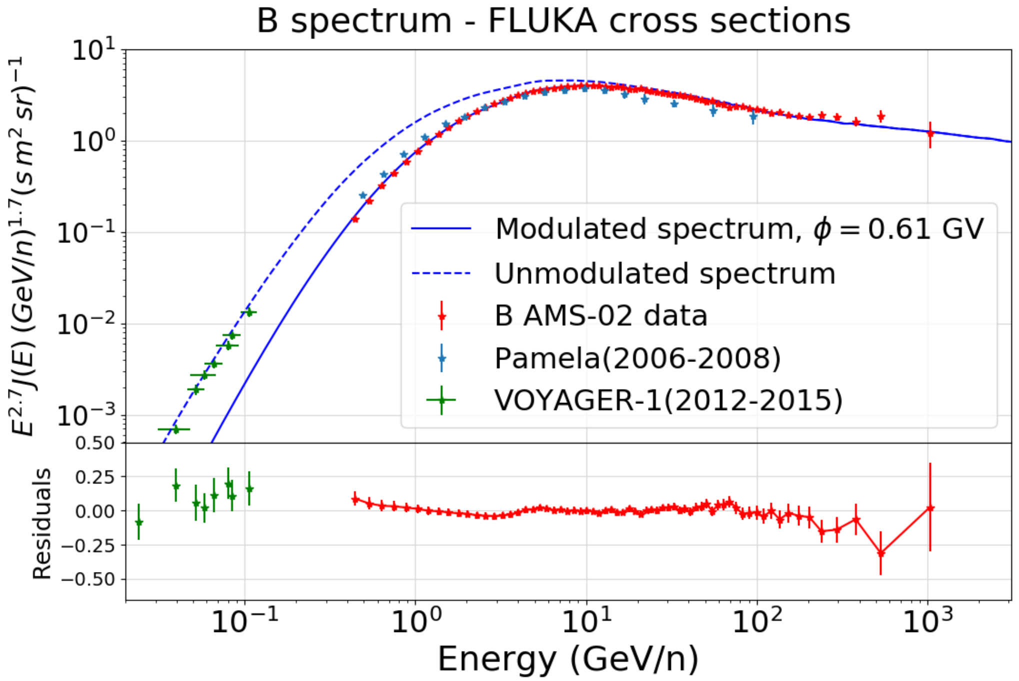


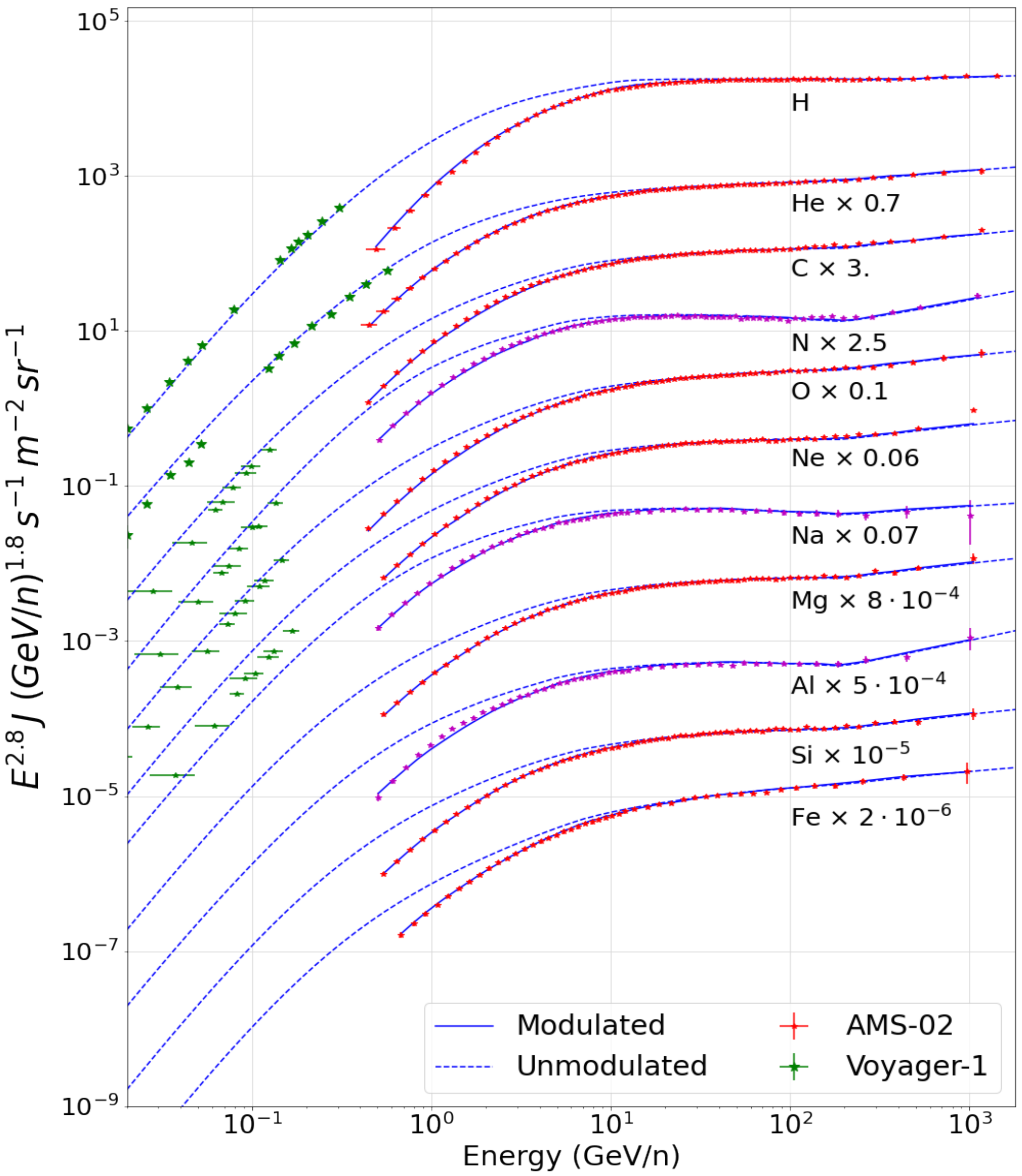




DRAGON2 predictions: fitting B/C

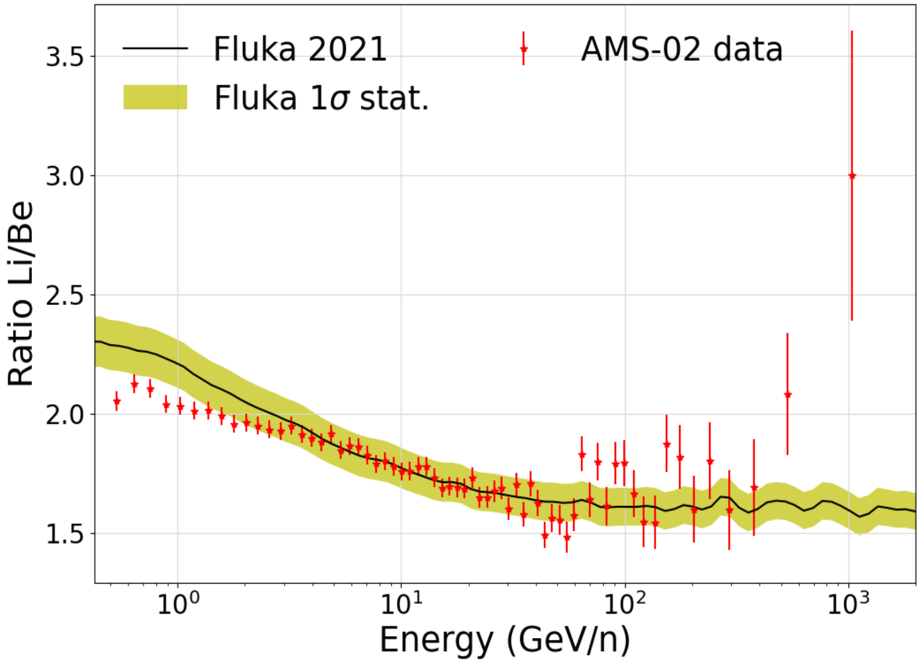
- The cross sections evaluated with FLUKA are implemented in the DRAGON2 code with the aim of studying the production of the secondary CRs B, Be and Li
  - $\delta \approx 0.45$, $D_0/H \approx 0.82 \times 10^{28} cm^2 s^{-1} kpc^{-1}$, $V_A \approx 23$ km/s

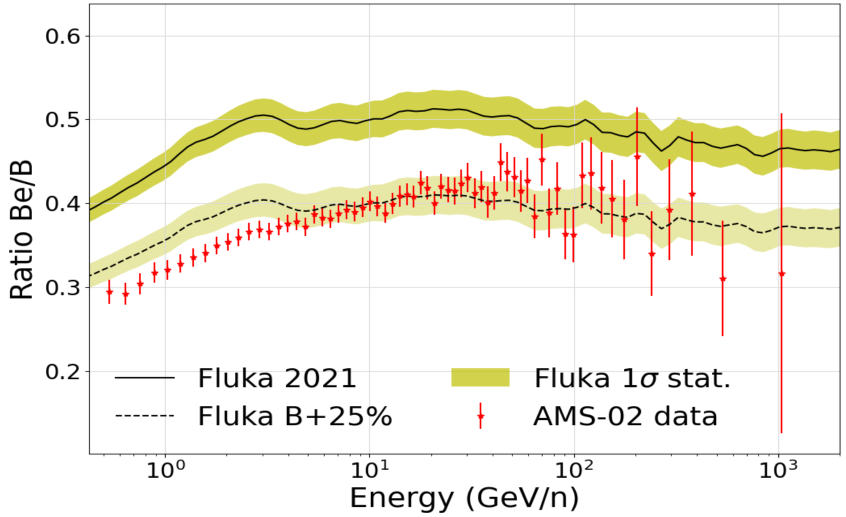


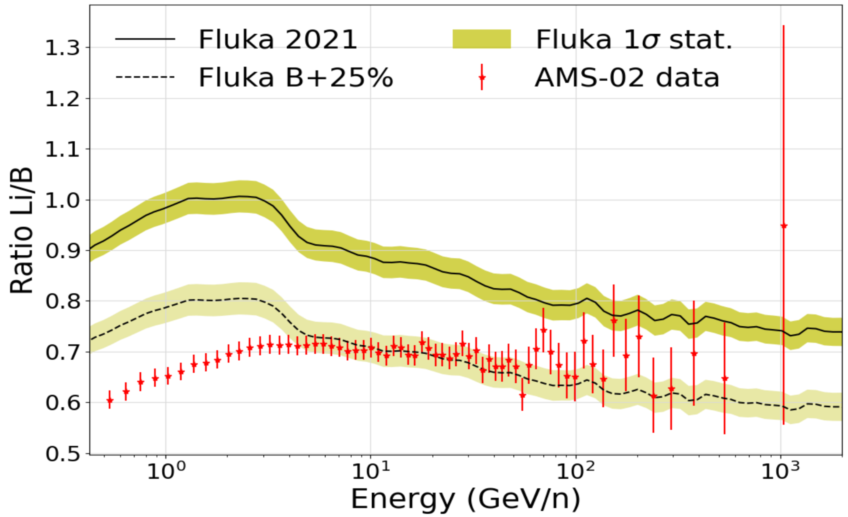


FLUKA cross sections: B, Be and Li ratios

- Energy dependence is greatly reproduced above a few GeV per nucleon
- These ratios match AMS-02 data considering a ~20% scaling of the cross sections

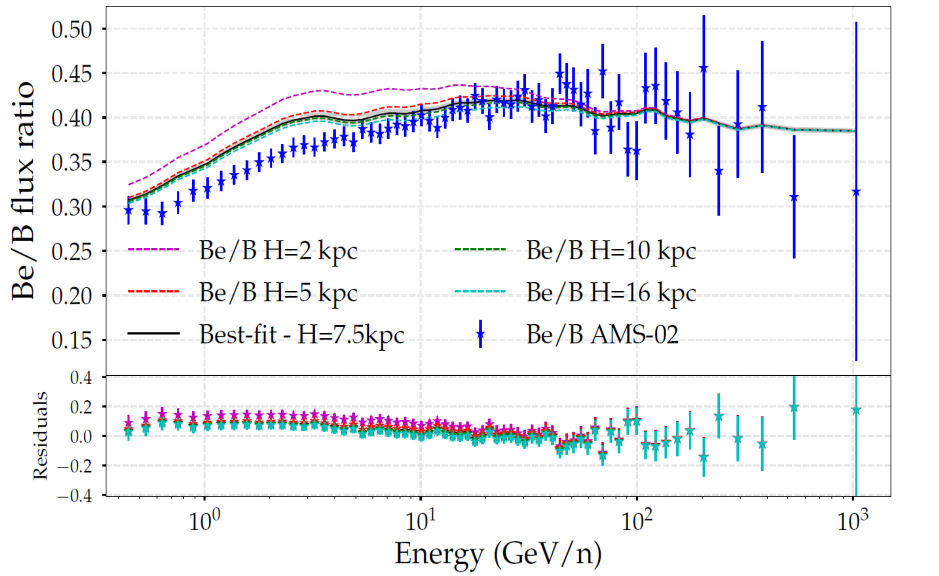


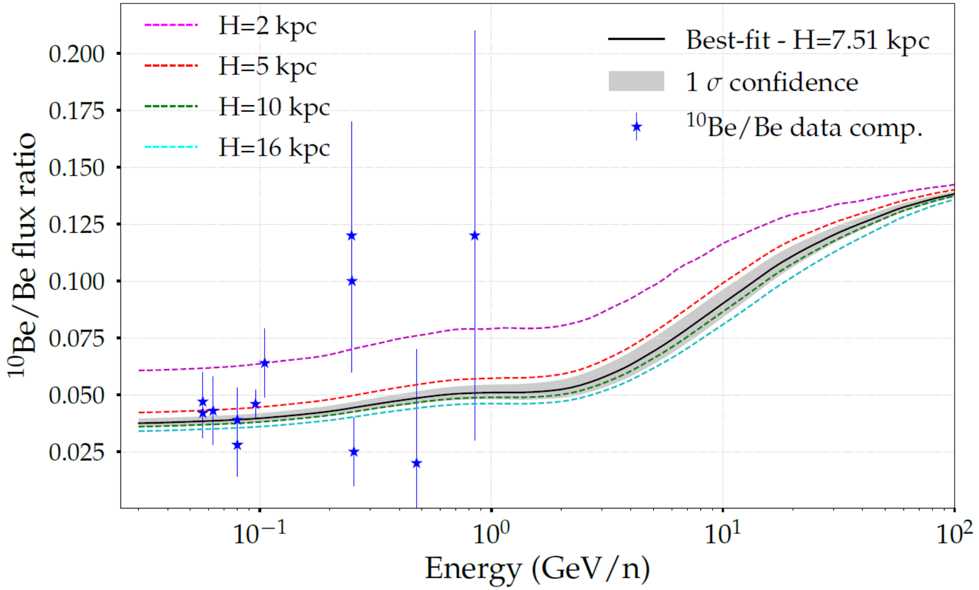




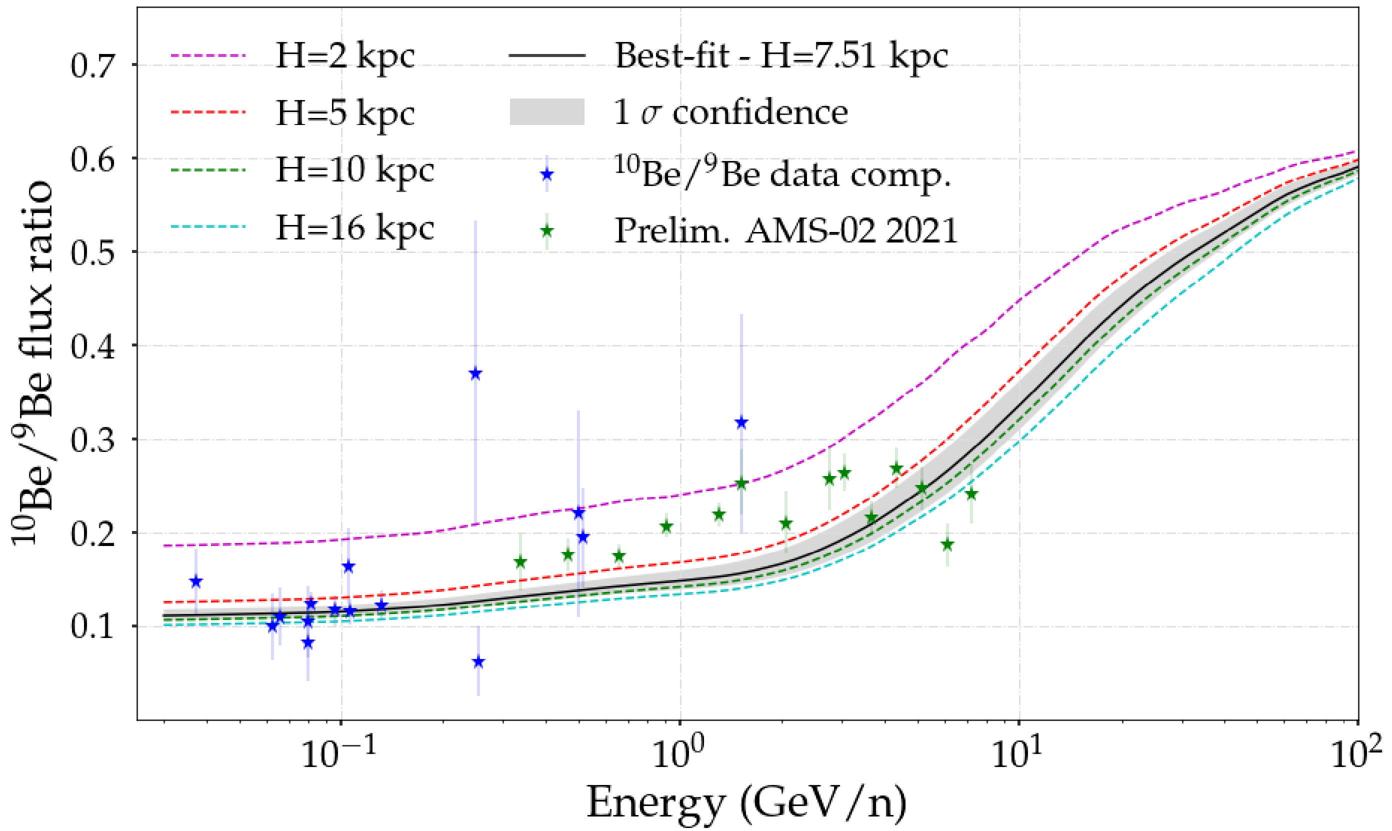
$$\frac{J_k}{J_j}\left(E\right) \propto \frac{\sum^{\alpha\to k} J_\alpha(E)\sigma_{\alpha\to k}(E)}{\sum^{\alpha\to j} J_\alpha(E)\sigma_{\alpha\to j}(E)} \xrightarrow{\text{high energies}} \sim \frac{\sum^{\alpha\to k} C_\alpha E^{-\gamma_\alpha}\sigma_{\alpha\to k}(E)}{\sum^{\alpha\to j} C_\alpha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

The halo size





The halo size can be constrained from the ^{10}Be ratio to the ^{9}Be and Be (=^{9}Be+^{10}Be)



Preliminary AMS-02 data not included in the fit

Combined fit of light secondary CRs (1)

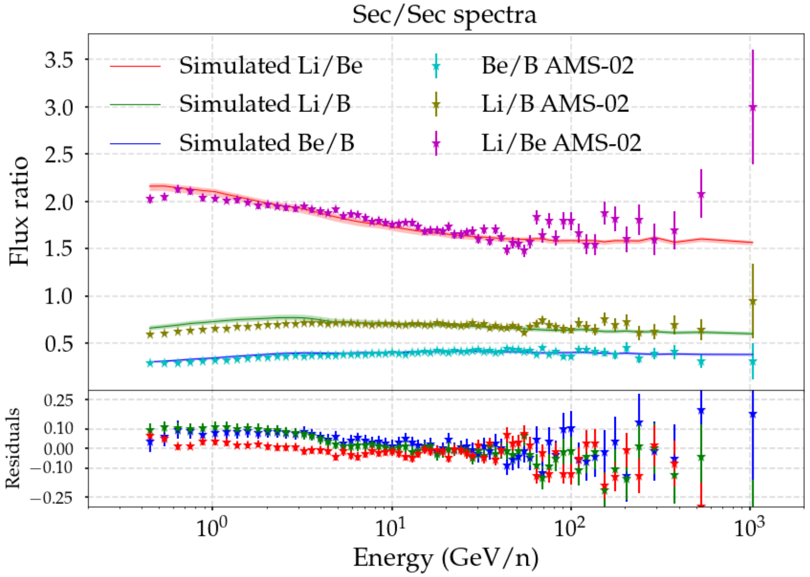
- Markov Chain Monte Carlo analysis:
  - Combination of the ratios of secondary CRs
  - Parameters entering in the diffusion parametrization + Alfven speed included in the fit
  - Nuisance parameters (scale factors, Sx) for renormalizing cross sections
- Injection spectra are left free in the fit, resulting 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 (Halo), Be/B, Li/B, Li/Be (scale factors: Sx, Halo)

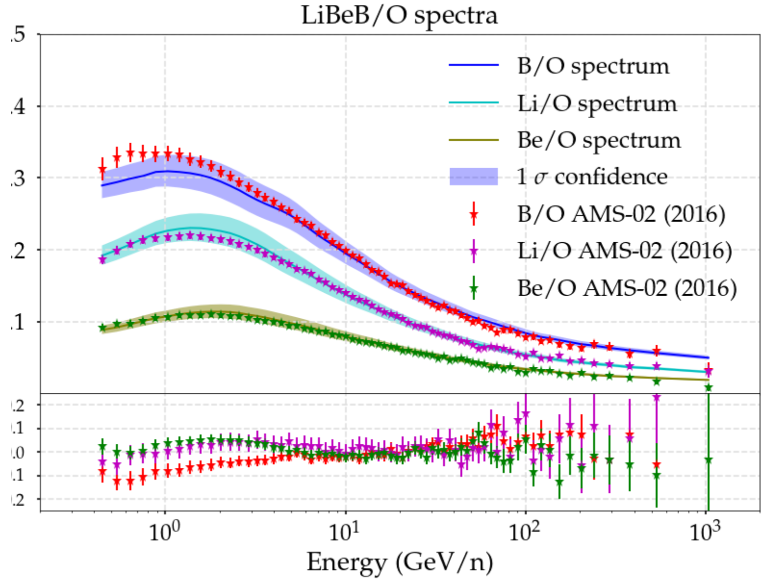
$$\ln \mathscr{L}^{Total} = \sum_{F}^{Li,Be,B/(C,O,Li,Be,B)} \ln(\mathscr{L}(F)) + \sum_{X}^{B,Be,Li} \mathscr{N}_X$$

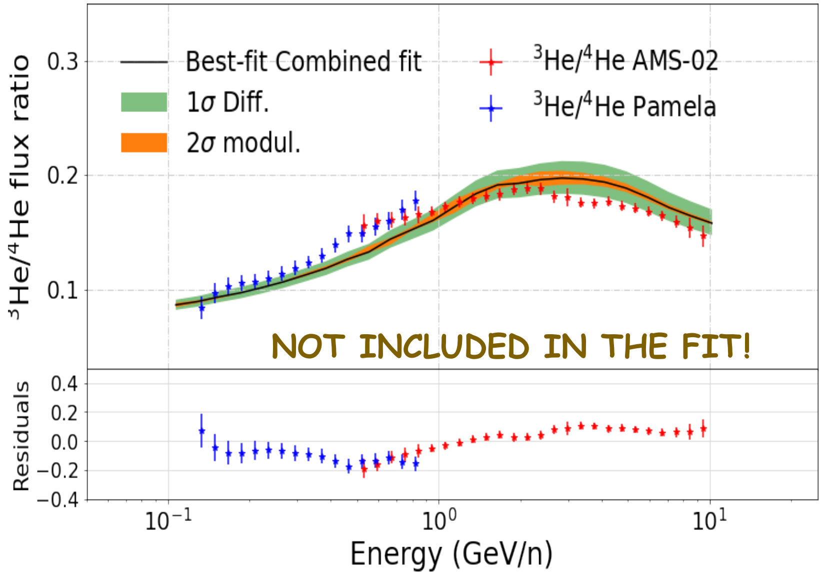
$$D = D_0 \beta^\eta \left(\frac{R}{R_0}\right)^\delta$$ **Source hypothesis**

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

Combined fit of light secondary CRs (2)





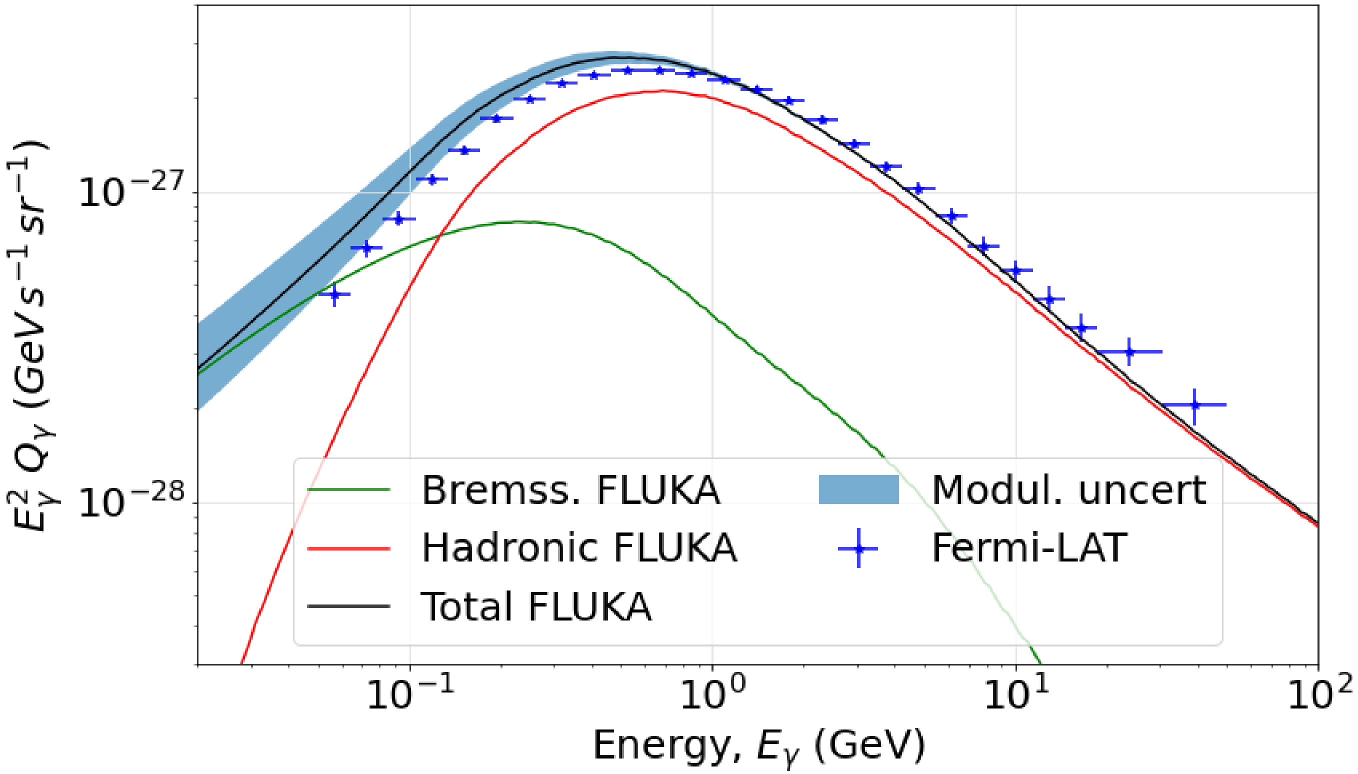


- Combined analysis predicts an energy dependence of the flux ratios in good agreement with AMS-02 data
- Propagation parameters (obtained from Sec/Prim) in good agreement with other cross section parametrizations
  - In the current analysis the scale factors are below 20% (~15% for B, ~5% for Li, Be)

FLUKA cross sections for gamma-ray production

- Study of the local emissivity (at latitudes 10° < |b| < 70°)
  - ISM composition with relative abundances 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}
- This quantity just depends on the cross sections of gamma-ray production and on the spectra of electrons, protons and He
  - Low-energy uncertainties due to solar modulation uncertainties!

$$\frac{Q_S(E_S)}{n_{gas}} = 4\pi \int J(E) \frac{d\sigma(E_S|E)}{dE_S} dE$$



Conclusions

- Cross sections are the main limitation for the studies 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 the AMS-02 data
- 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
  - Well in agreement with the standard theoretical scenarios
- FLUKA helps us in using gamma-ray data to constrain the set-ups of CR propagation
  - Hadronic and leptonic gamma-ray production
- For more details see P. De La Torre Luque *et al* JCAP07(2022)008 arXiv:2202.03559

BACKUP

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-living 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.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

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

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, **rQDM** 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=28 (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.

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

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

- **<u>Resonances</u>** produced in hadron-nucleon inelastic collisions dominate from the MeV up to 3-5 GeV
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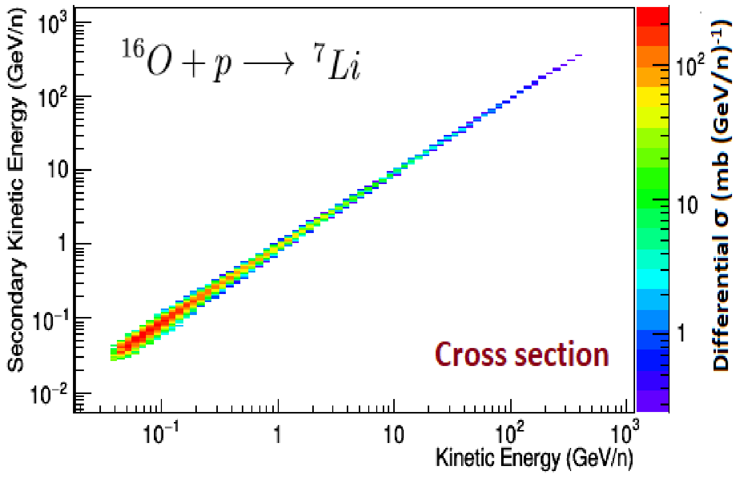
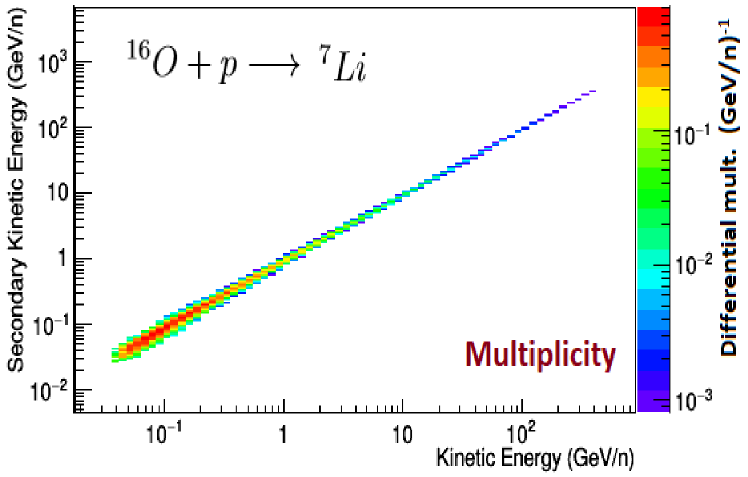
- Nucleus-Nucleus use **Boltzmann thermal equation** at E<0.1GeV/u, **rQDM** model up to 5 GeV/u and **DPMJET** above

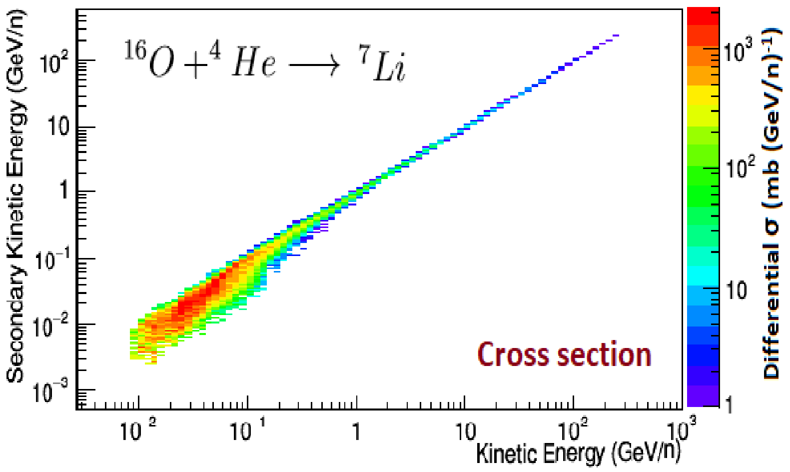
<table>
<tr><td colspan="4">Hadron-Hadron</td></tr>
<tr><td>Elastic,exchange
Phase shifts
data, eikonal</td><td>P<3-5GeV/c
Resonance prod
and decay</td><td>low E π,K
Special</td><td>High Energy
DPM
hadronization</td></tr>
<tr><td rowspan="2">Hadron-Nucleus

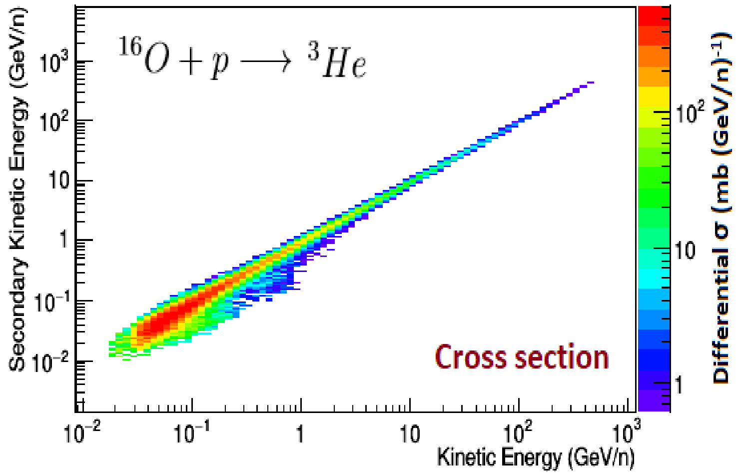
PEANUT
Sophisticated GINC
Gradual onset of Glauber-Gribov multiple interactions
Preequilibrium
Coalescence</td><td colspan="3">Nucleus-Nucleus</td></tr>
<tr><td>E< 0.1GeV/u
BME
Complete fusion+
peripheral</td><td>0.1< E< 5 GeV/u
rQMD-2.4
modified
new QMD</td><td>E> 5 GeV/u
DPMJET
DPM+
Glauber+
GINC</td></tr>
<tr><td colspan="4">Evaporation/Fission/Fermi break-up
γ deexcitation</td></tr>
</table>

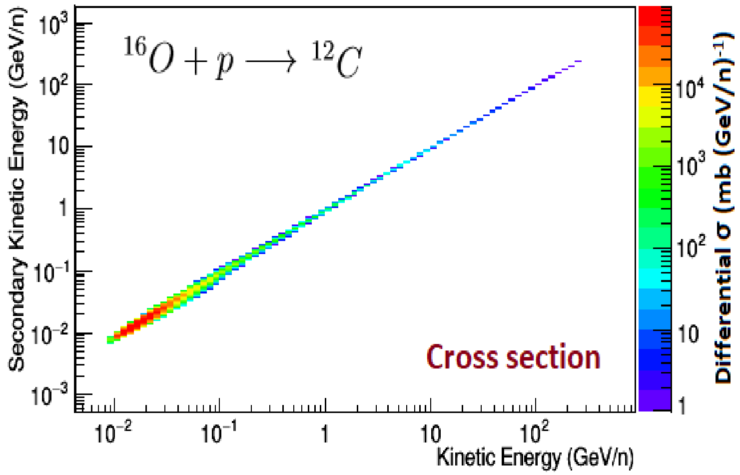
Credit: Paola sala


$^{16}O + p \longrightarrow {}^{7}Li$
Cross section
Secondary Kinetic Energy (GeV/n)
Kinetic Energy (GeV/n)
Differential σ (mb (GeV/n)$^{-1}$)

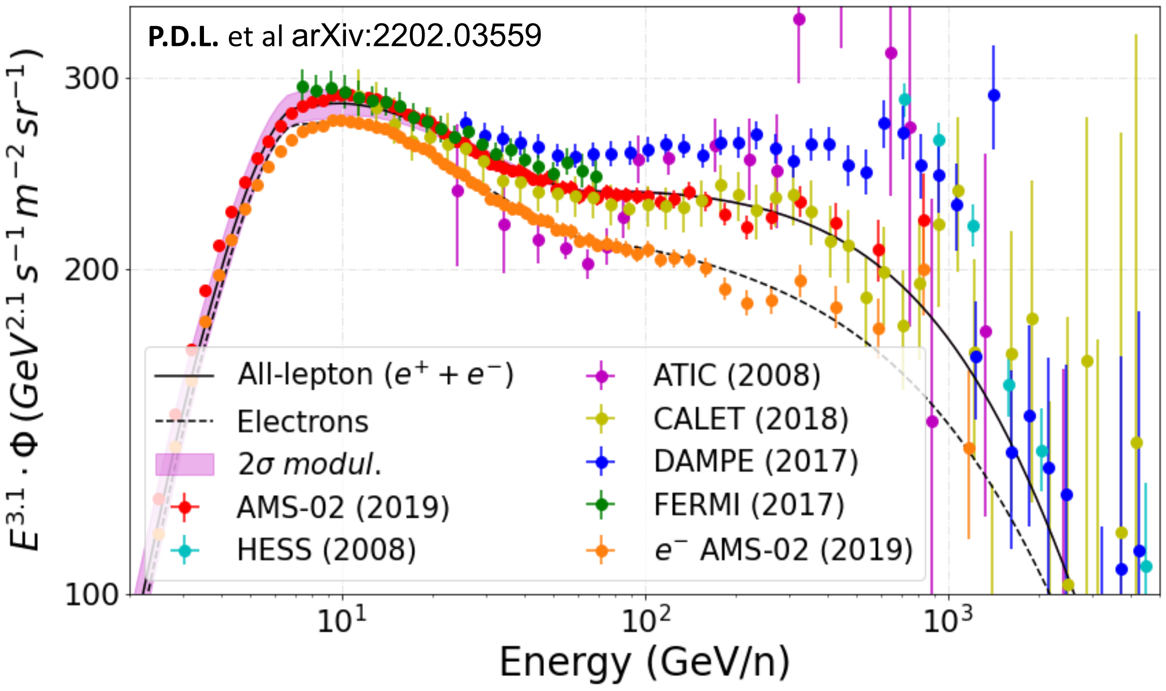

$^{16}O + p \longrightarrow {}^{7}Li$
Multiplicity
Secondary Kinetic Energy (GeV/n)
Kinetic Energy (GeV/n)
Differential mult. (GeV/n)$^{-1}$


$^{16}O + {}^{4}He \longrightarrow {}^{7}Li$
Cross section
Secondary Kinetic Energy (GeV/n)
Kinetic Energy (GeV/n)
Differential σ (mb (GeV/n)$^{-1}$)


$^{16}O + p \longrightarrow {}^{3}He$
Cross section
Secondary Kinetic Energy (GeV/n)
Kinetic Energy (GeV/n)
Differential σ (mb (GeV/n)$^{-1}$)


$^{16}O + p \longrightarrow {}^{12}C$
Cross section
Secondary Kinetic Energy (GeV/n)
Kinetic Energy (GeV/n)
Differential σ (mb (GeV/n)$^{-1}$)

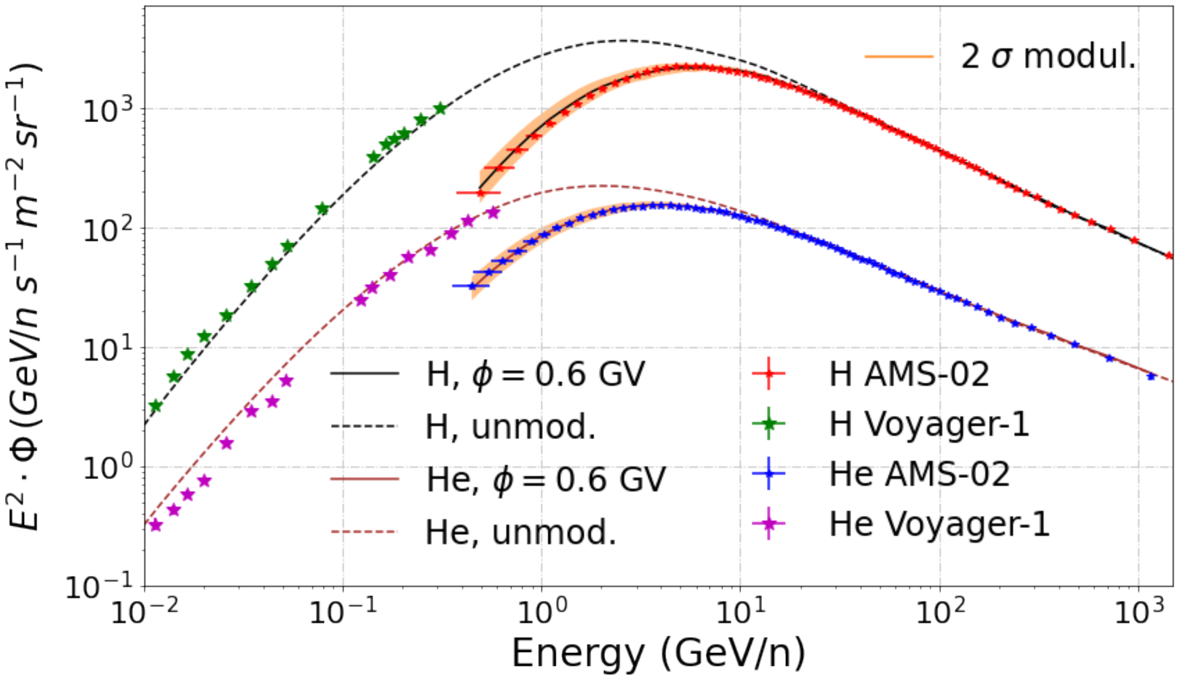
FLUKA cross sections for gamma-ray production



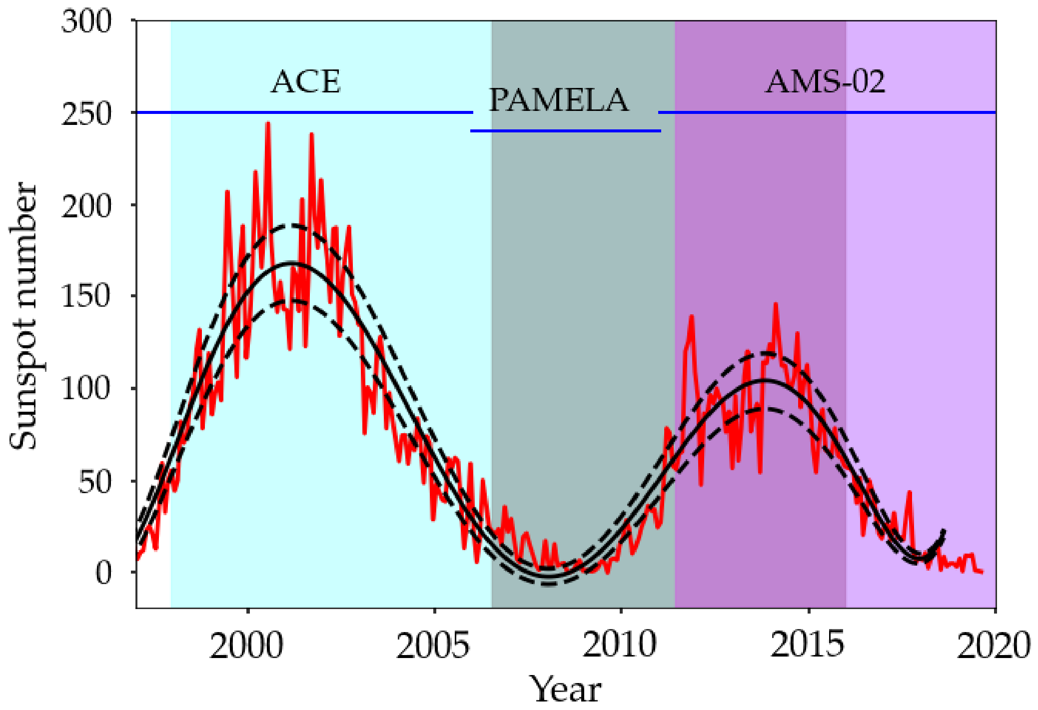
Electrons require a doubly broken power-law in order to reproduce at the same time CR local measurements and **local γ-ray emissivity** at low energies

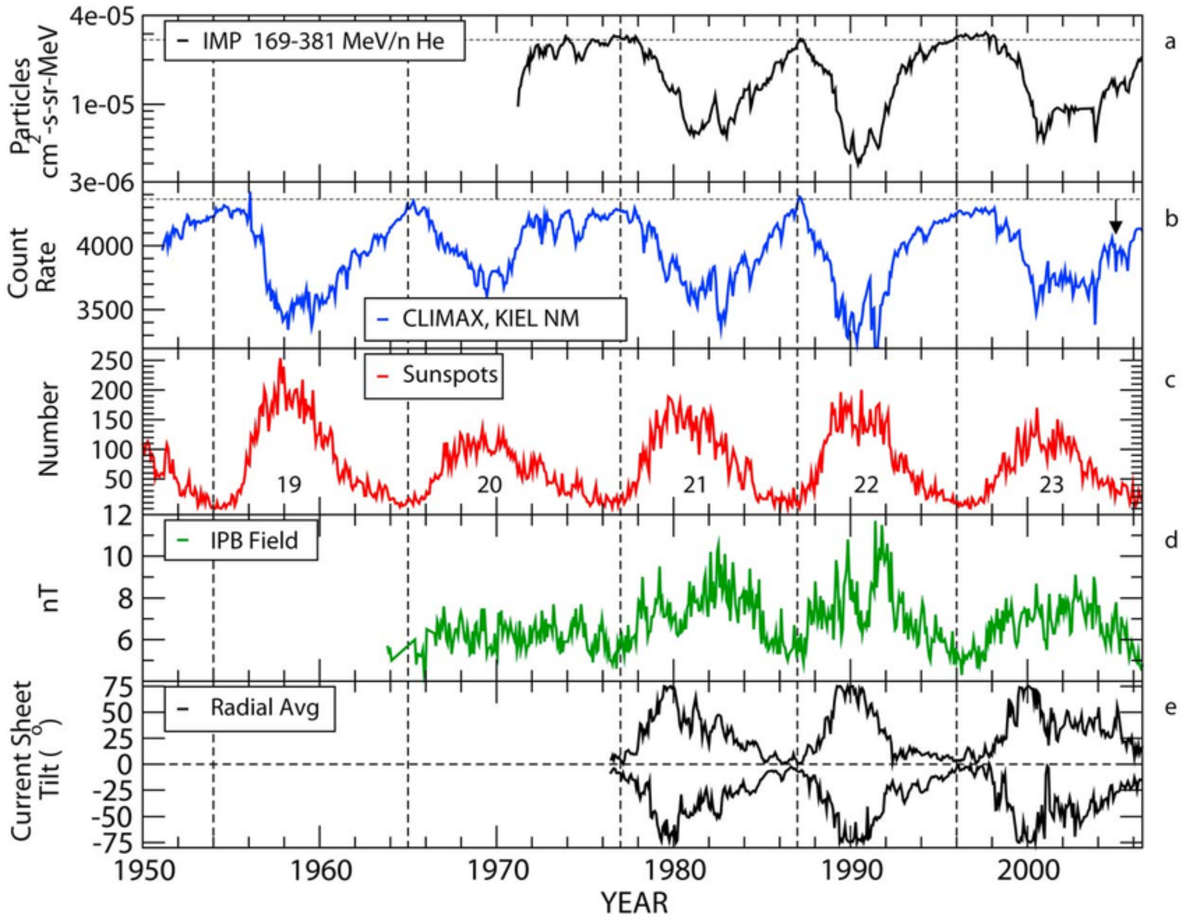
γ-ray production from different gas nuclei

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



SOLAR MODULATION



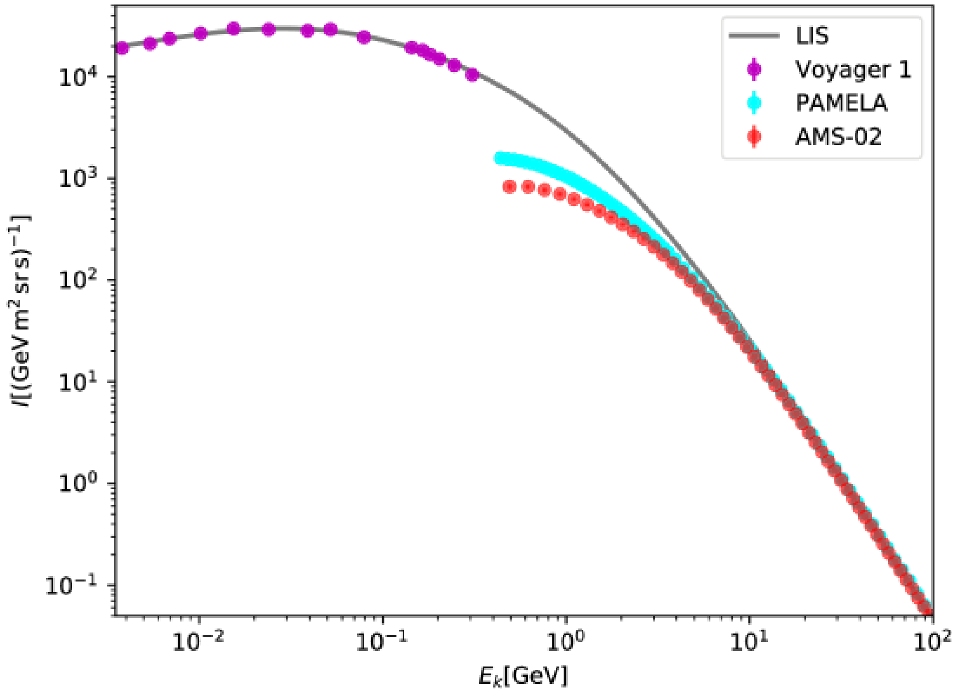


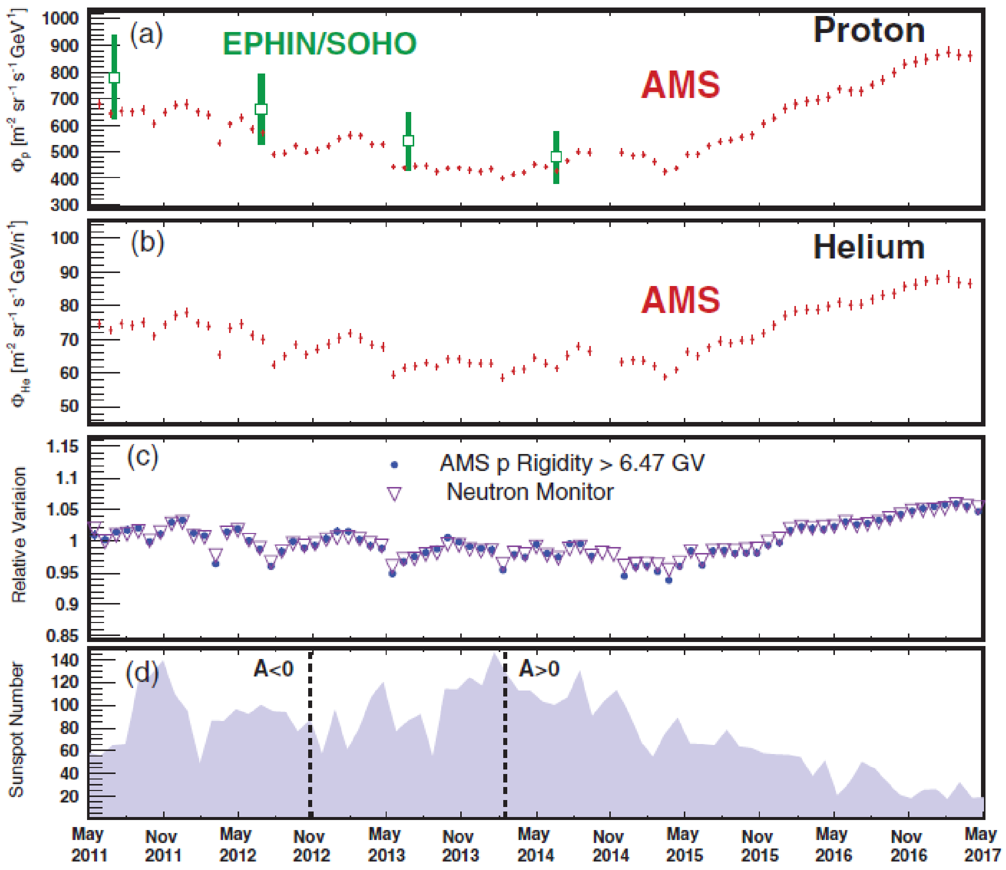
- Force-Field approximation
- Neutron monitor data + Voyager-01 data
- Cholis-Hooper-Linden ([arXiv:1511.01507]) correction

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

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

SOLAR MODULATION





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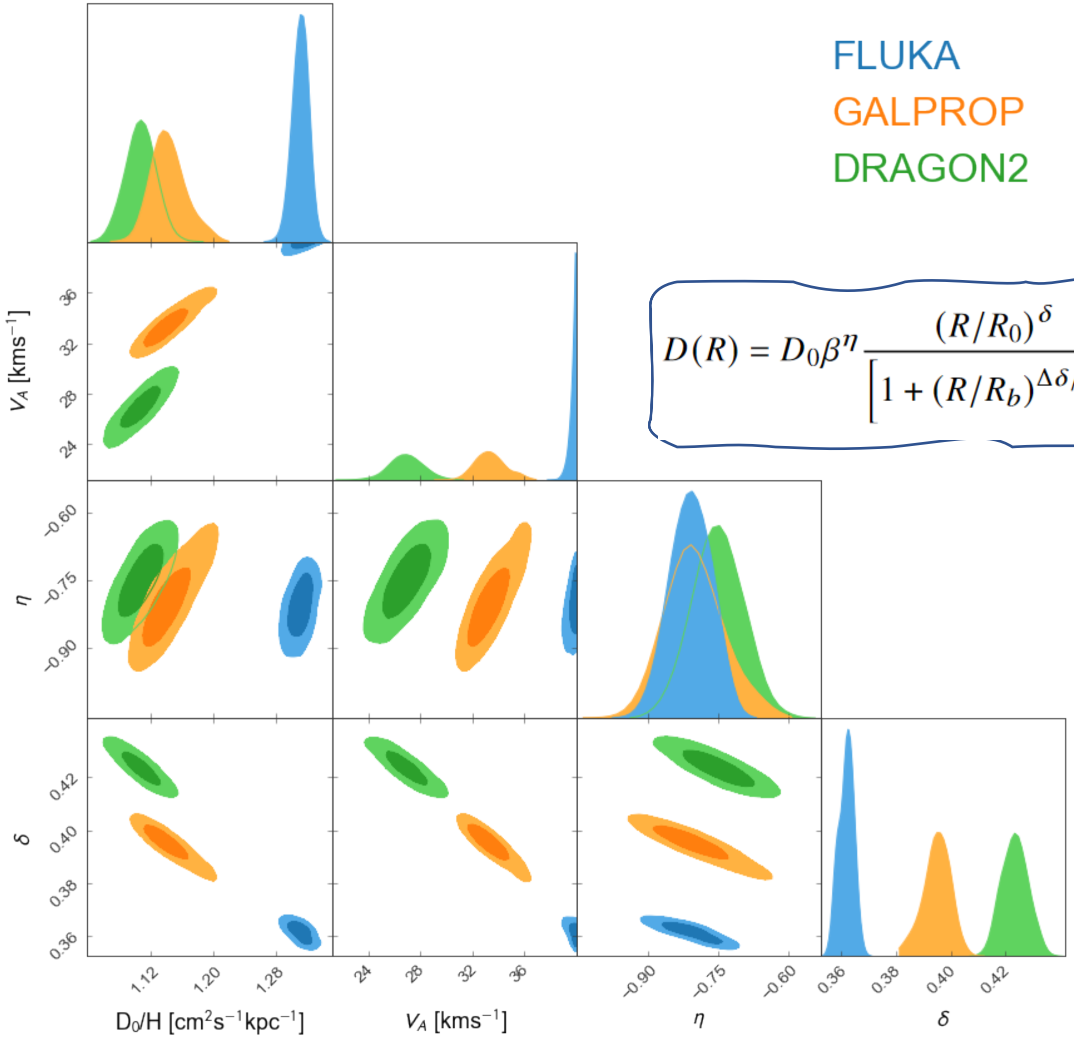
$$\phi^{\pm}(t, \mathcal{R}) = \phi_0(t) + \phi_1^{\pm}(t)\ \mathcal{F}\left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)$$

Combined fit of light secondary CRs (3)

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