Using AMS Data to Model Cosmic Ray Propagation in the Galaxy

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AMS-Italia 28/11/2024 - Nicolò Masi

Explaining Z ≤ 28 CRs physics by means of GALPROP and HelMod

- Thanks to AMS-02 high precision data we can constrain CRs production and propagation **at the % level**;

- AMS-02 published data can be fitted in the combined framework of GALPROP and HelMod **within a single model**, capable of reproducing all primary and secondary spectra at the same time (*see* ApJ **840**:115 No 2, 2017; ApJ **854**:94 No 2, 2018; ApJ **858**:61 No 1, 2018; ApJ 889:167, 2020; ApJS **250** 27, 2020; ApJ **913** 5, 2021; ApJ **925** 108, 2022; ApJ **933** 147, 2022);

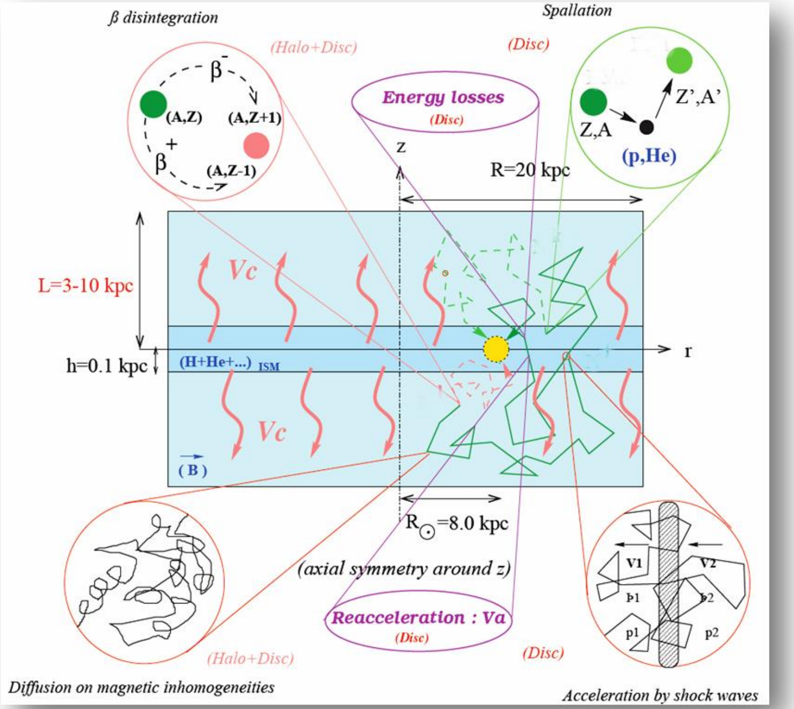
- The 28 proposed LISs fit Voyager-1, ACE-CRIS, HEAO-3-C2, Pamela, AMS-02, CREAM, ATIC-2 and recent NUCLEON, CALET and DAMPE data, from 10 MeV/n up to 200 TeV/n, representing a **forecasting tool for the Collaboration.**

The propagation scheme and the MCMC approach

Diffusion · Reacceleration · Energy Loss in ISM · Fragmentation

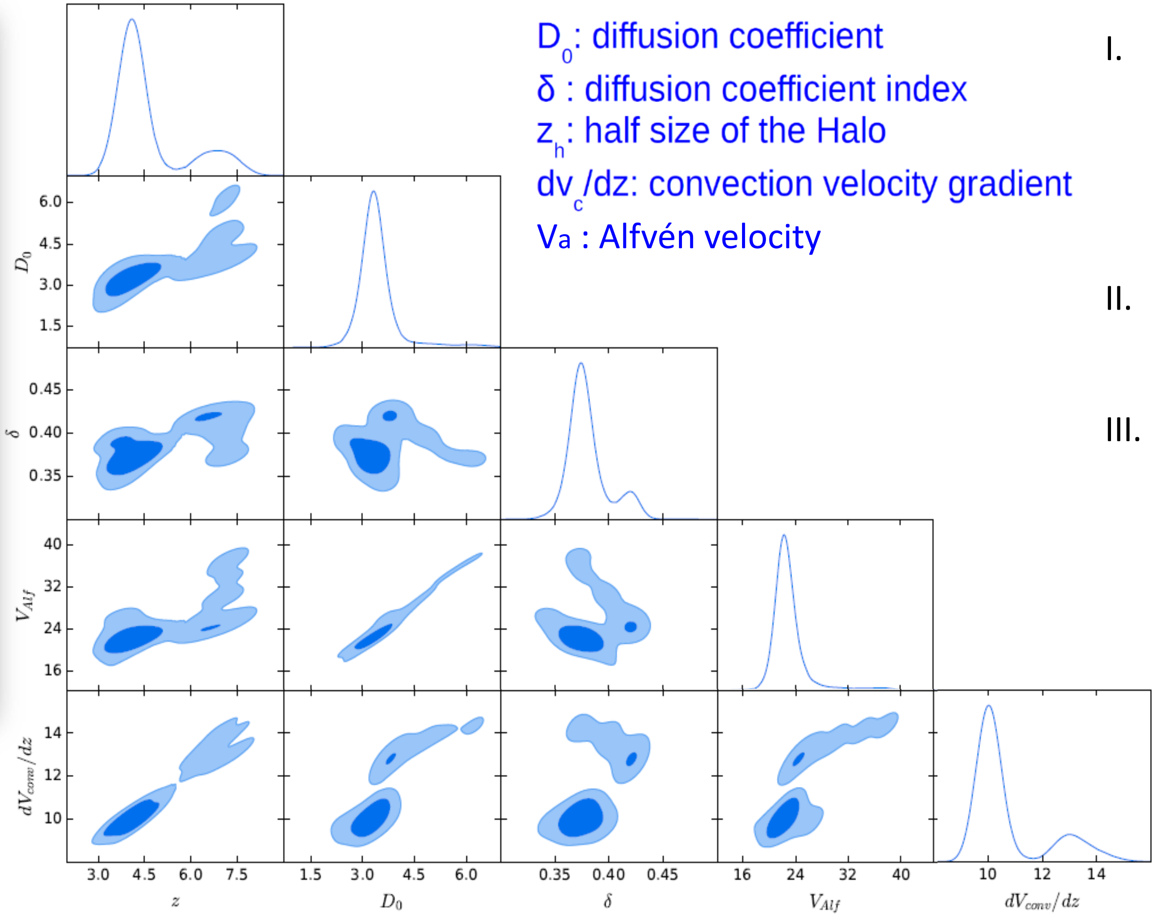
$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot\left(D_{xx}\vec{\nabla}\psi - \vec{V}\psi\right) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Source · Convection · Adiabatic Expansion · Decay



One order of magnitude of improvement for fundamental parameters uncertainties

5 fundamental parameters space to fix CR propagation



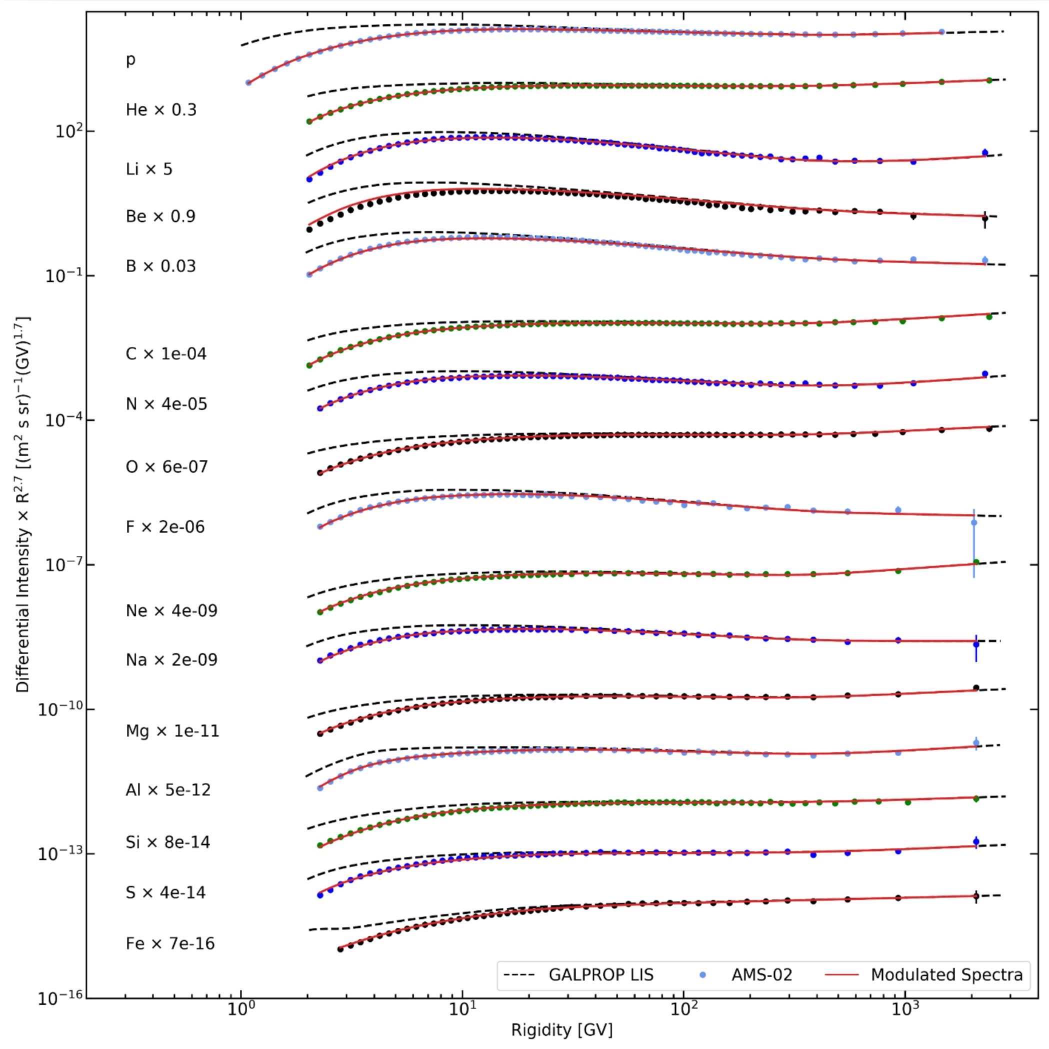
- D_0: diffusion coefficient
- δ : diffusion coefficient index
- z_h: half size of the Halo
- dv_c/dz: convection velocity gradient
- V_a : Alfvén velocity

I. The Monte-Carlo-Markov-Chain interface to **GALPROP** was **developed by AMS-02 Bologna group**;

II. The solar modulation is made using **HelMod**;

III. The experimental observables used in the MCMC scan include **all primary CRs AMS-02 data and B/C ratio, not the secondaries produced by spallation**

M. Boschini, S. della Torre, N. Masi, I. Moskalenko, L. Quadrani, P.G. Rancoita *et al.*,
Solution Of Heliospheric Propagation: Unveiling The Local Interstellar Spectra Of Cosmic Ray Species,
The Astrophysical Journal **840**:115 No 2, 2017

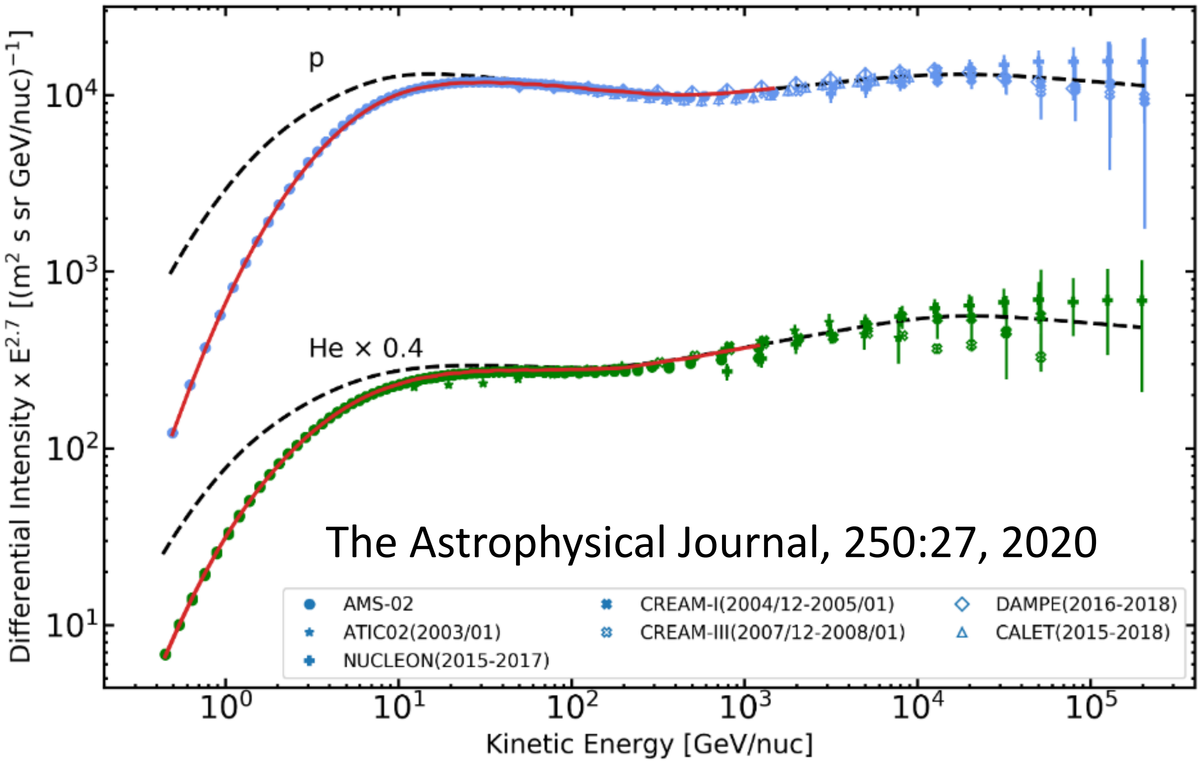


The Model confirms its prediction capability for all AMS-02 species with a single set of propagation parameters

N	Parameter	Units	Best Value	Error
1	z_h	kpc	4.0	0.6
2	D_0	10^{28} cm^2 s^{-1}	4.3	0.7
3[a]	δ_1		0.415	0.025
4	$V_{\rm Alf}$	km s^{-1}	30	3
5	$dV_{\rm conv}/dz$	km s^{-1} kpc^{-1}	9.8	0.8

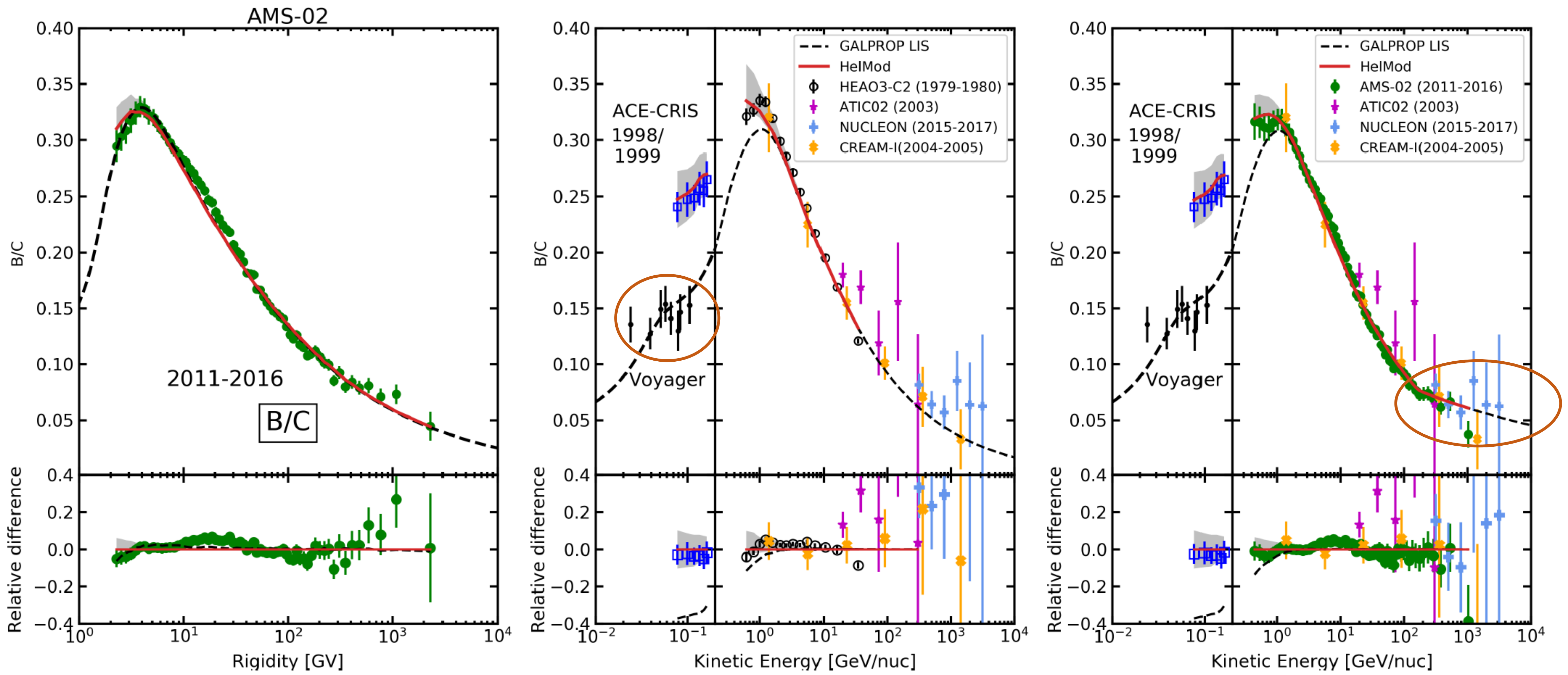
[a] For the *P*-scenario : $\delta_2 = 0.15 \pm 0.03$ for $R \geq 370 \pm 25$ GV.

Fine hardening and softening of primary species:
LISs validity is extended up to tens (and hundreds) TeV/n

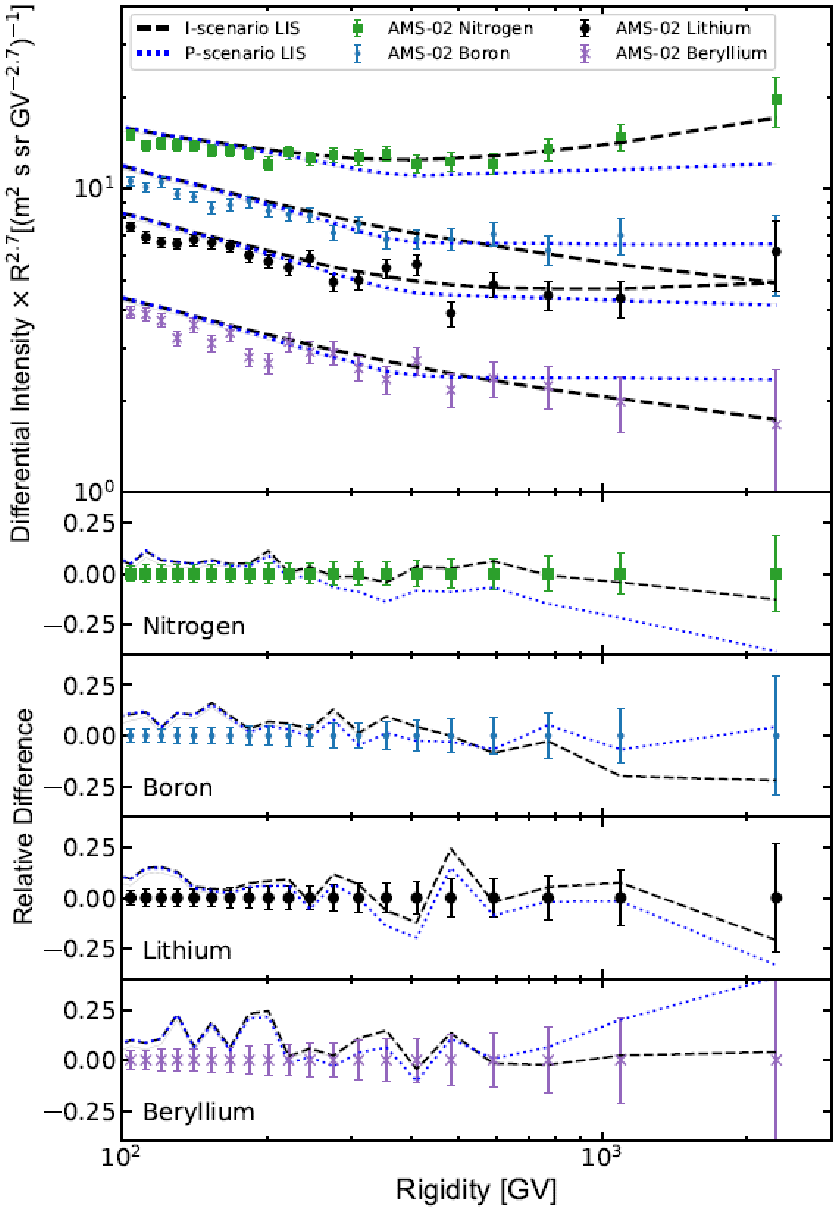


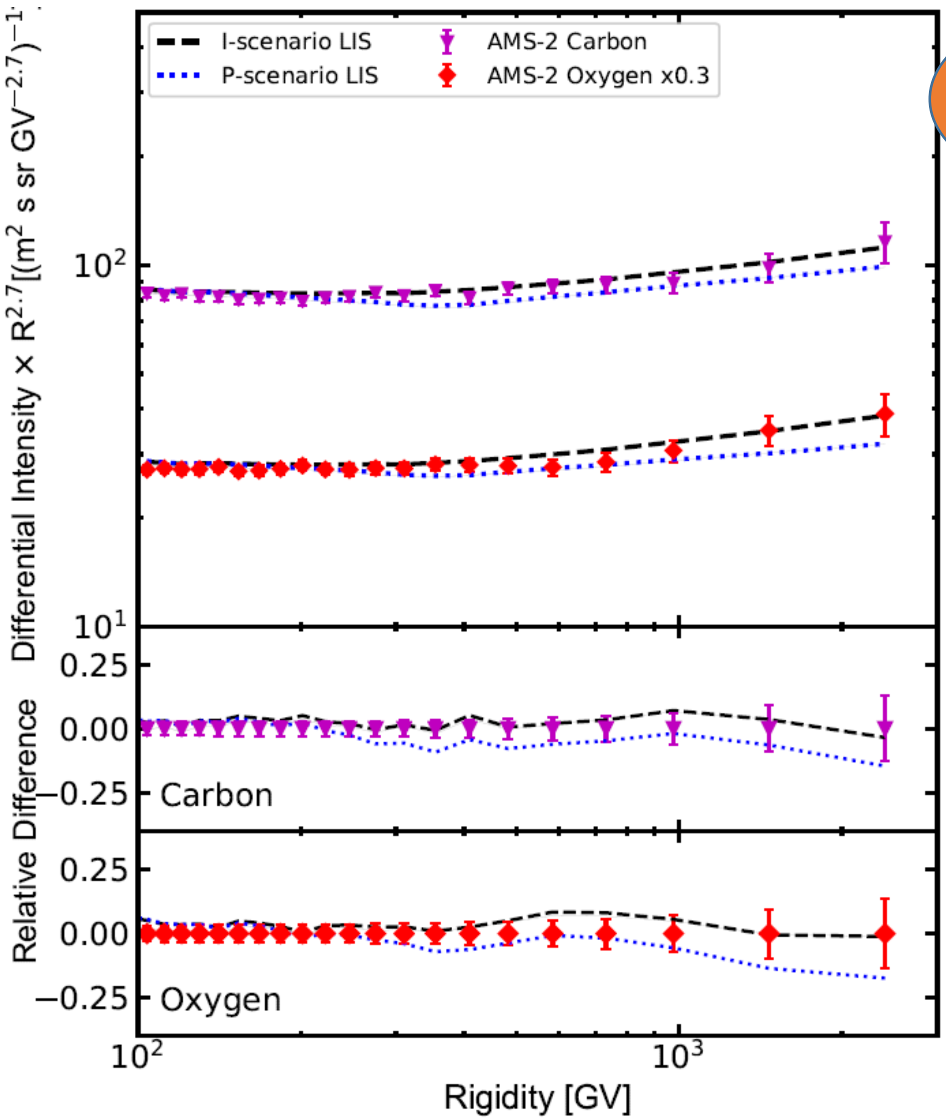
Secondary over primary ratio: B/C

Diffusive break Propagation-scenario



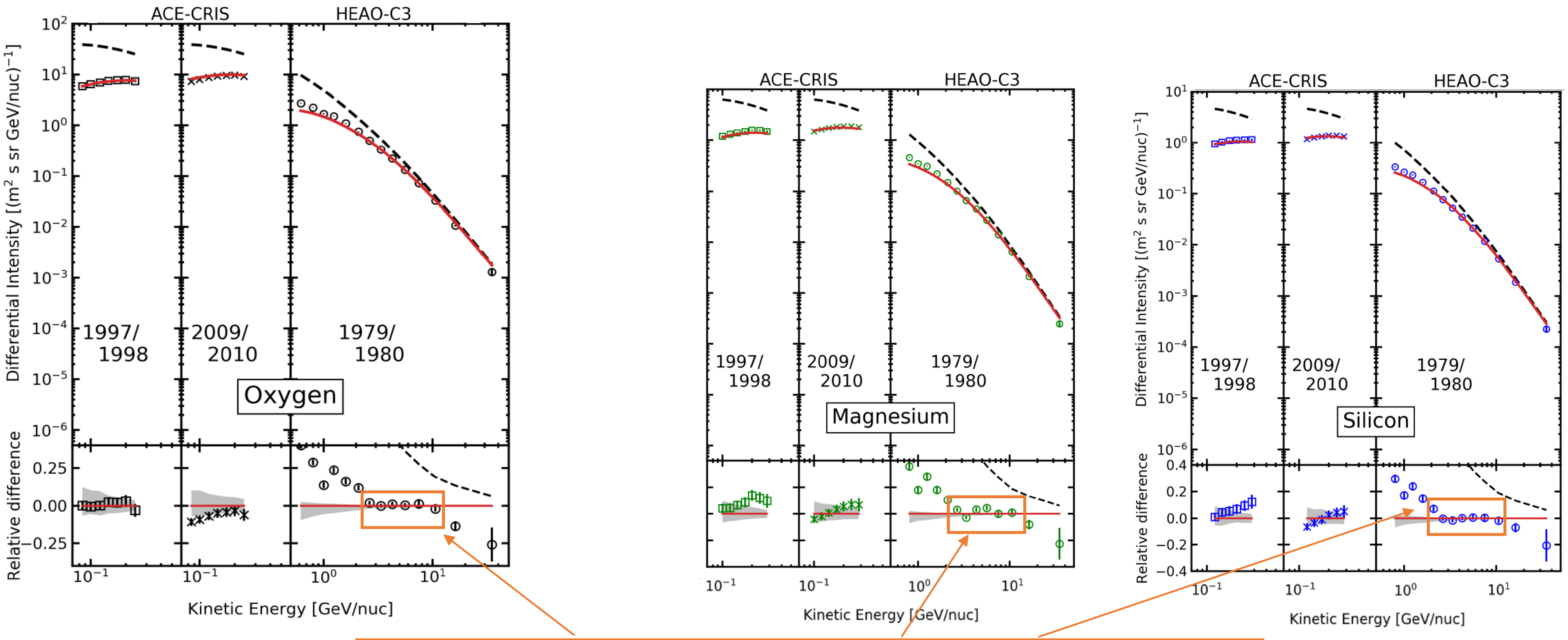
Injection versus Propagation scenarios to explain CRs hardening above 300 GV





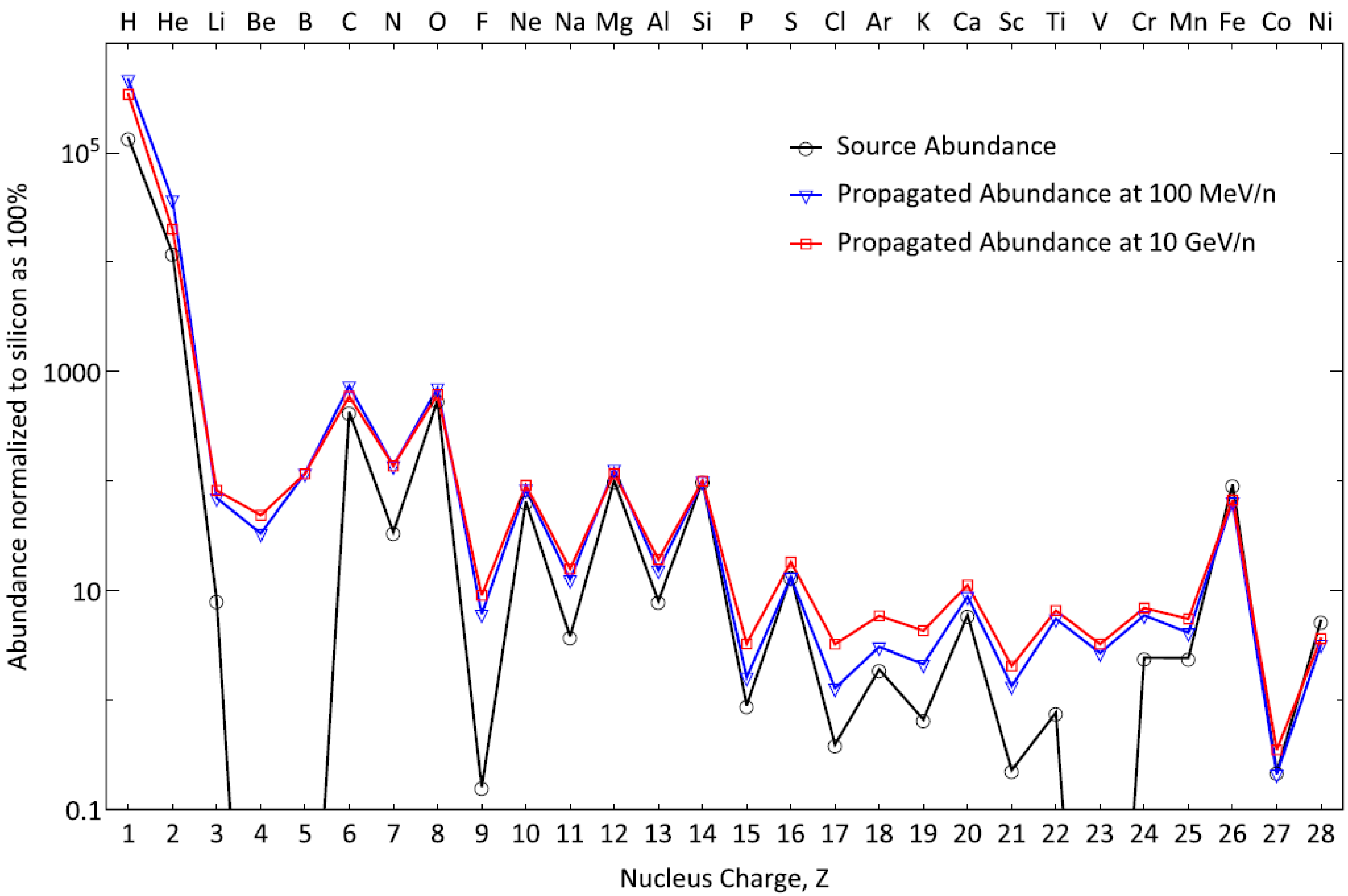
I or P?

HEAO vs AMS-02 normalization to forecast unpublished Z >14 nuclei

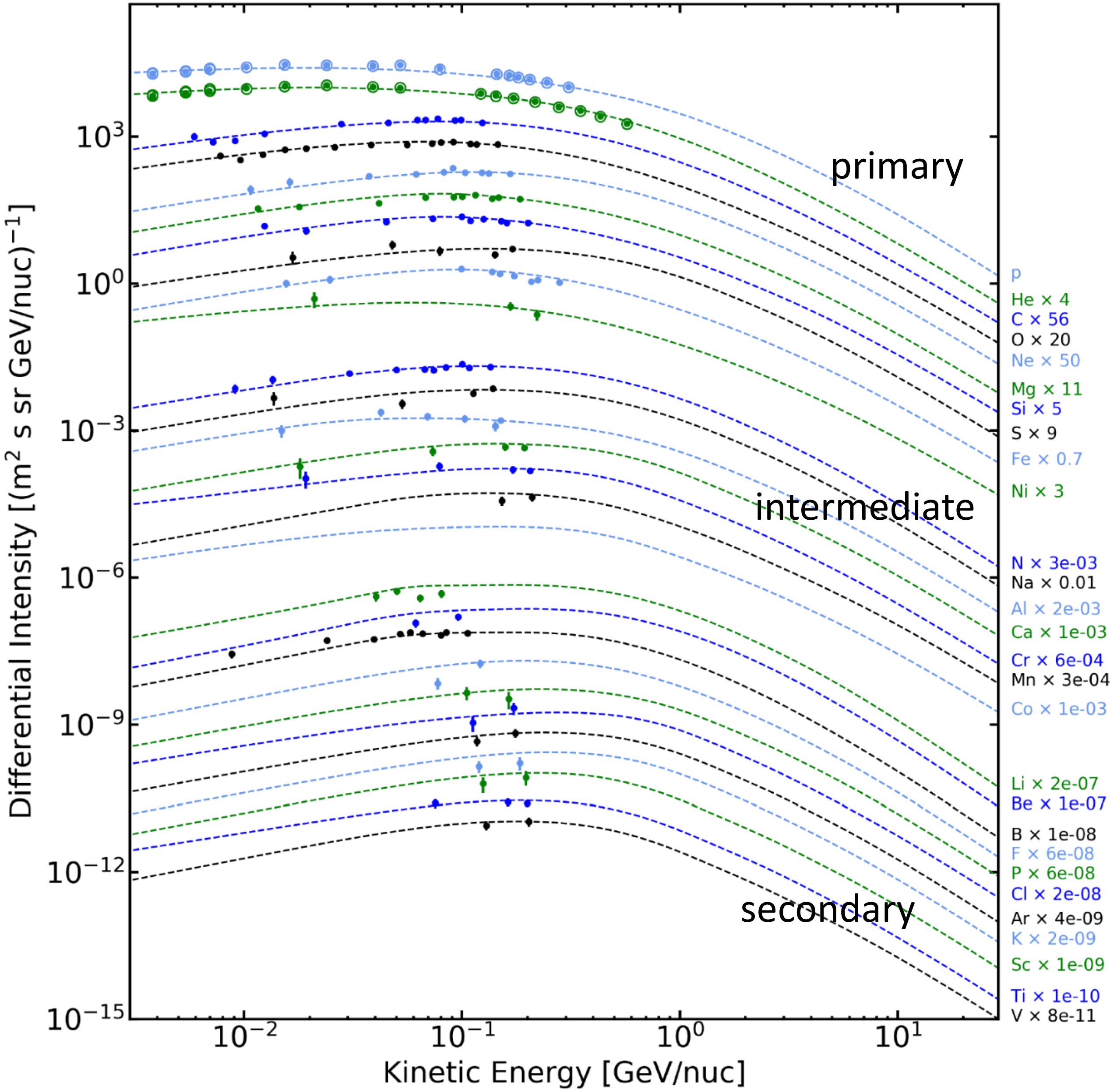


AMS-02 and HEAO normalization coincide at the % level in this region (2.65-10.6 GeV/n) for not to heavy species

CR abundances

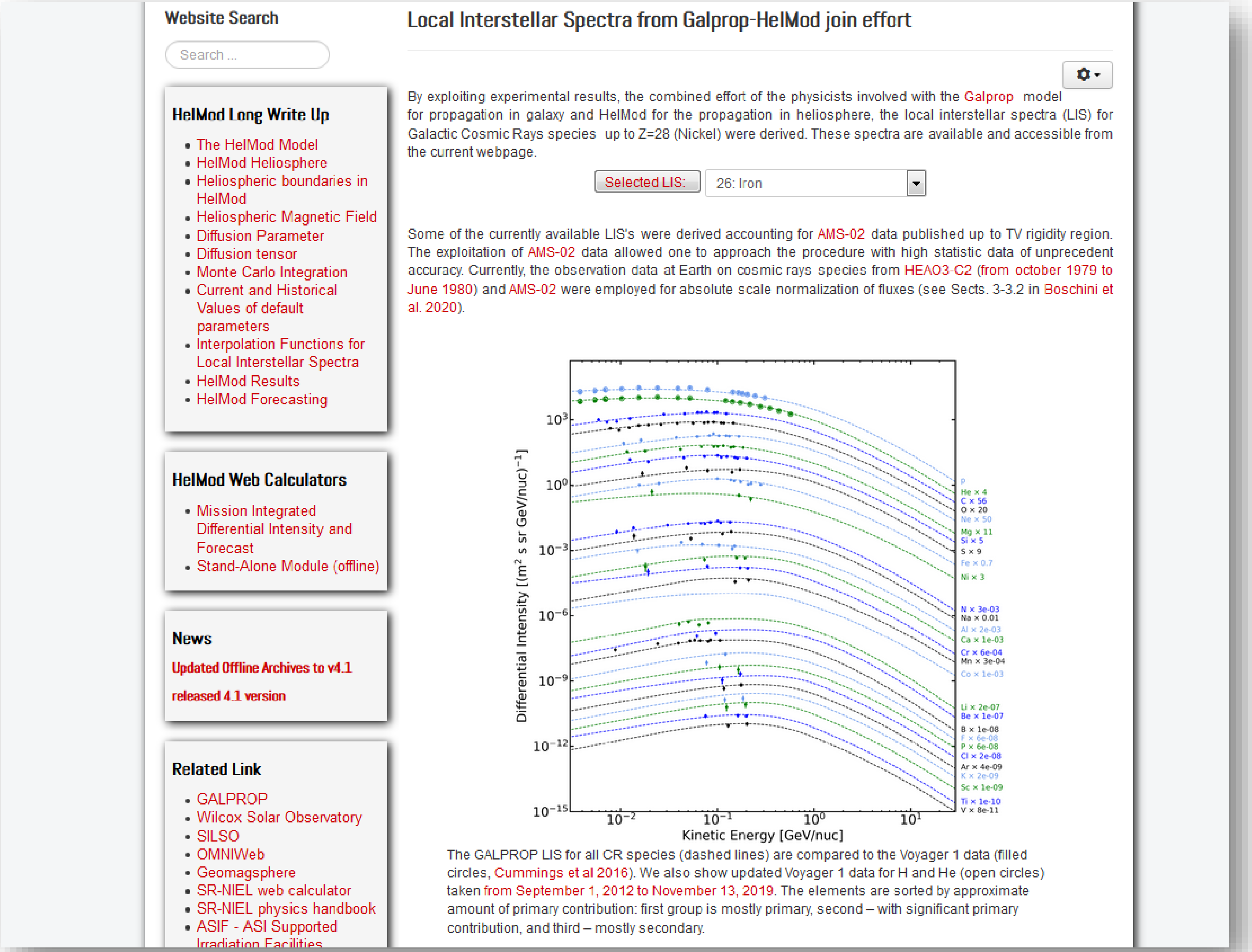


Interstellar spectra measured by Voyager-1



All Z ≤ 28 are well reproduced

Our website provides numerical LISs, formulas and plots


Website Search

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- Interpolation Functions for Local Interstellar Spectra
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Local Interstellar Spectra from Galprop-HelMod join effort

By exploiting experimental results, the combined effort of the physicists involved with the Galprop model for propagation in galaxy and HelMod for the propagation in heliosphere, the local interstellar spectra (LIS) for Galactic Cosmic Rays species up to Z=28 (Nickel) were derived. These spectra are available and accessible from the current webpage.

Selected LIS: 26: Iron

Some of the currently available LIS's were derived accounting for AMS-02 data published up to TV rigidity region. The exploitation of AMS-02 data allowed one to approach the procedure with high statistic data of unprecedent accuracy. Currently, the observation data at Earth on cosmic rays species from HEAO3-C2 (from october 1979 to June 1980) and AMS-02 were employed for absolute scale normalization of fluxes (see Sects. 3-3.2 in Boschini et al. 2020).

The GALPROP LIS for all CR species (dashed lines) are compared to the Voyager 1 data (filled circles, Cummings et al 2016). We also show updated Voyager 1 data for H and He (open circles) taken from September 1, 2012 to November 13, 2019. The elements are sorted by approximate amount of primary contribution: first group is mostly primary, second – with significant primary contribution, and third – mostly secondary.

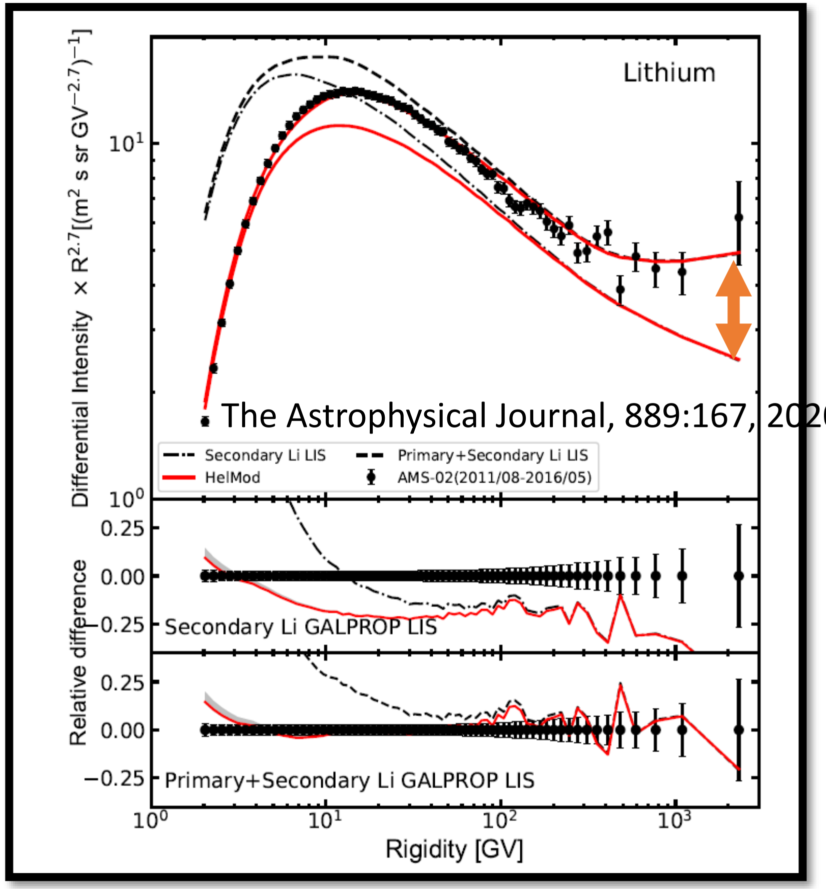
LISs will be futher fine-tuned and updated on the website using incoming AMS-02 measurements

Some CR ions still requires the injection of an additional primary spectrum in some rigidity windows:

- **Lithium**
- **Iron**
- **Fluorine**
- **Aluminum**

CR nuclei anomalies: Lithium and Iron

Li isotopes main production channels (from C and O) are well-constrained and a 20% nuclear error in one of them would correspond to only 2%–3% correction: **primary Lithium from new stars processes seems to be mandatory to explain AMS-02 measurement**

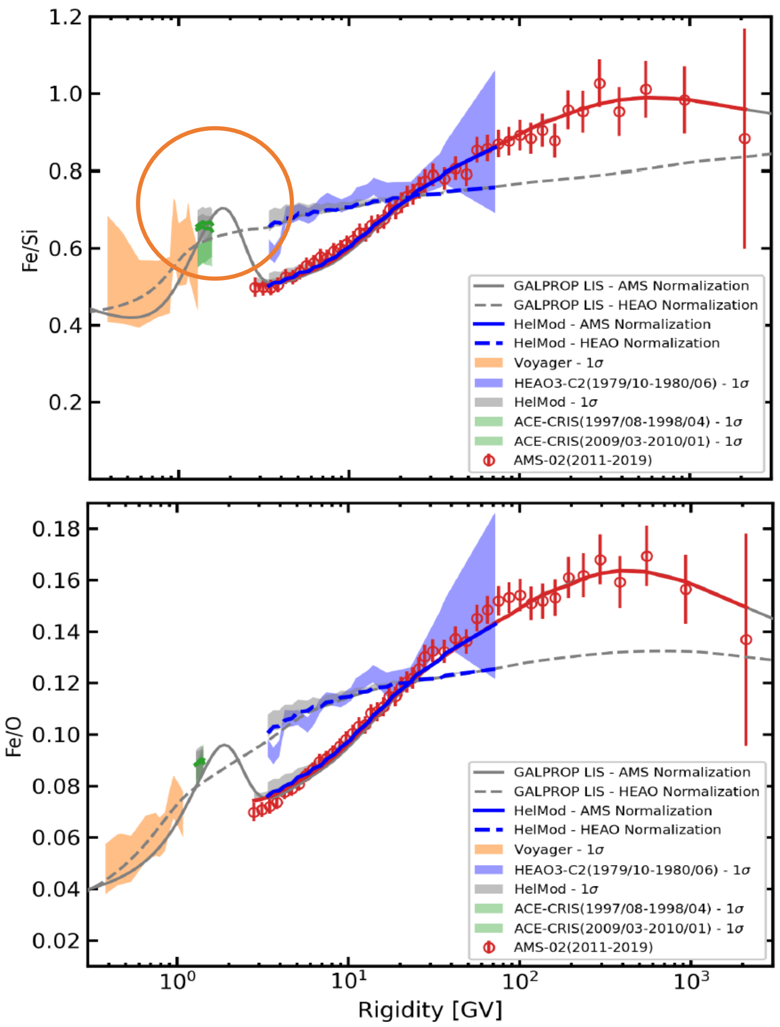


The Astrophysical Journal, 889:167, 2020

I. **Primary ^{7}Li through the Cameron-Fowler mechanism** for intermediate-mass AGB (asymptotic giant branch) stars and Novae: alpha-capture $^3He(\alpha,\gamma)$ ^7Be, transport of ^7Be into cooler layers -> **^{7}Be decay (53.22 days) → ^{7}Li**

II. **Observation of blue-shifted absorption lines of partly ionized ^{7}Be in the spectrum of a classical nova** about 40-50 days after the explosion is the first observational evidence

The Astrophysical Journal, 913:5, 2021



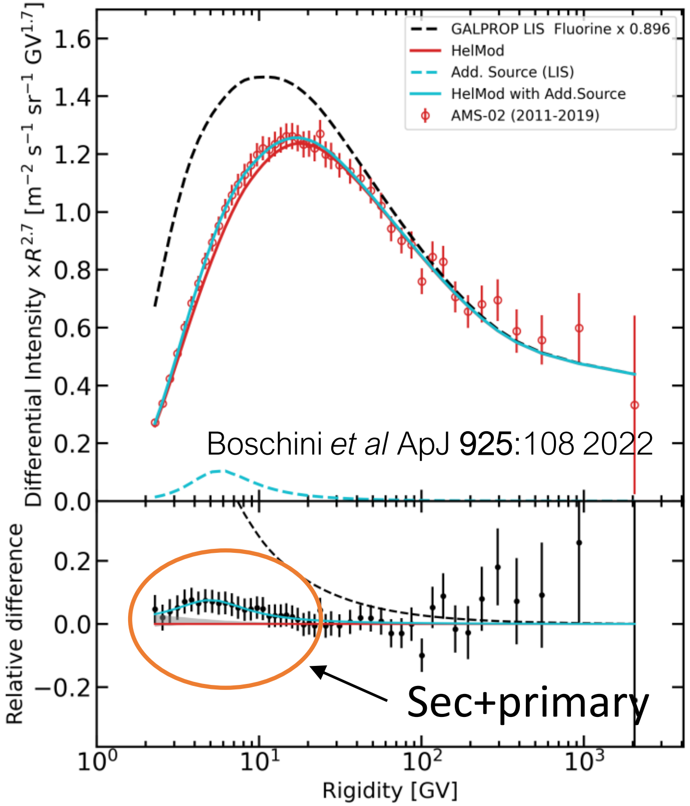
I. Because of the large fragmentation cross section and ionization energy losses, most of **CR iron at low energies is local**

II. **The analysis of AMS-02 iron spectrum together with Voyager-1 and ACE-CRIS data reveals the unexpected necessity of a bump** in the iron spectrum at 1÷3 GV (0.2÷0.7 GeV/n)

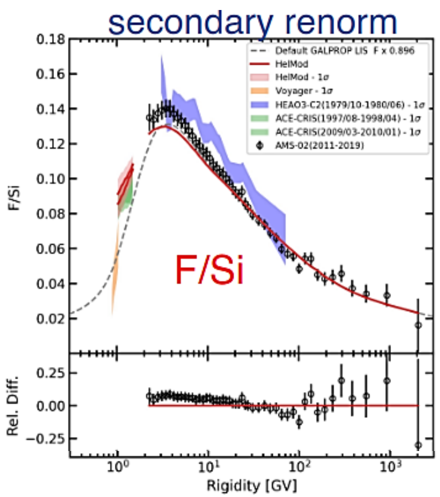
The found excess fits well with recent discoveries of radioactive ^{60}Fe (half-life 2.6 million years) deposits in the deep ocean sediments, in lunar regolith samples and in the Antarctic snow and **in CRs by ACE-CRIS spacecraft:** such deposits can be made by recent SN explosions in the solar neighborhood.

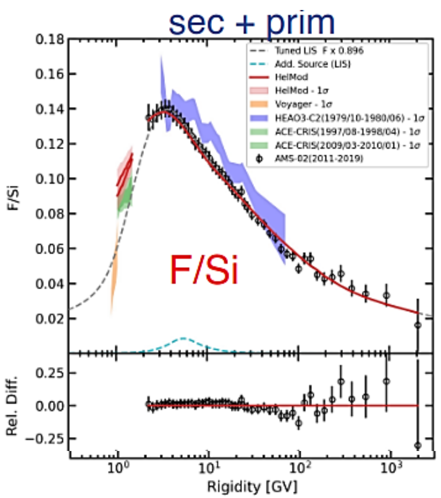
It is hard to establish the number of SNe events and their exact timing, but there could be several events during the last ~10 Myr at distances of up to 100 parsecs

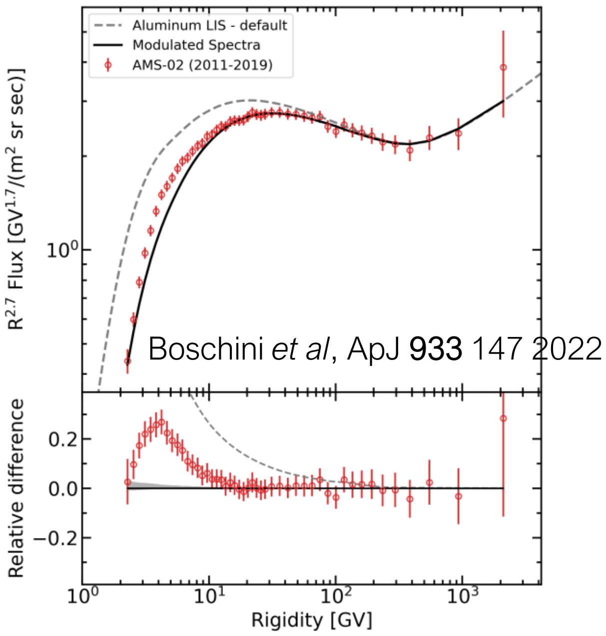
CR nuclei anomalies: Fluorine and Aluminum

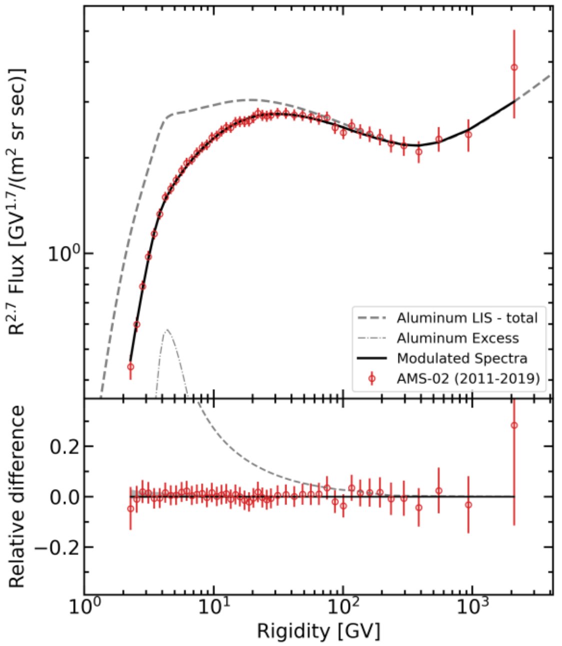


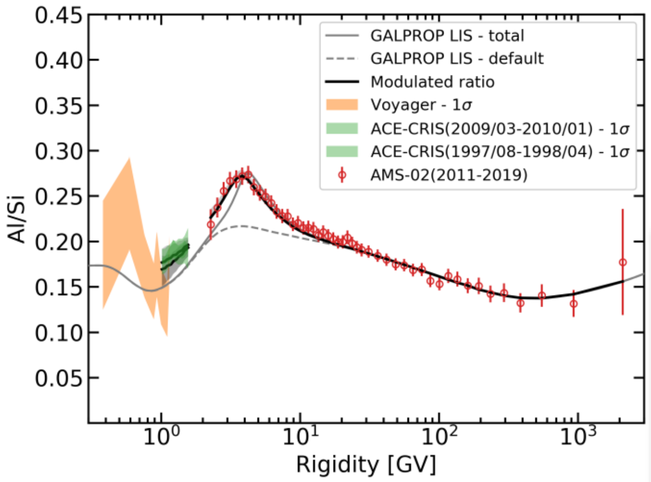
- The origin of cosmic fluorine (from ^{14}N) is still not well constrained: the main astrophysical sources of fluorine are thought to be SNe Type II, Wolf–Rayet stars and intermediate-mass AGB stars
- They could be all important at different stages of chemical evolution of the Galaxy











(i) an incorrect spectrum of ^{28}Si, the major progenitor

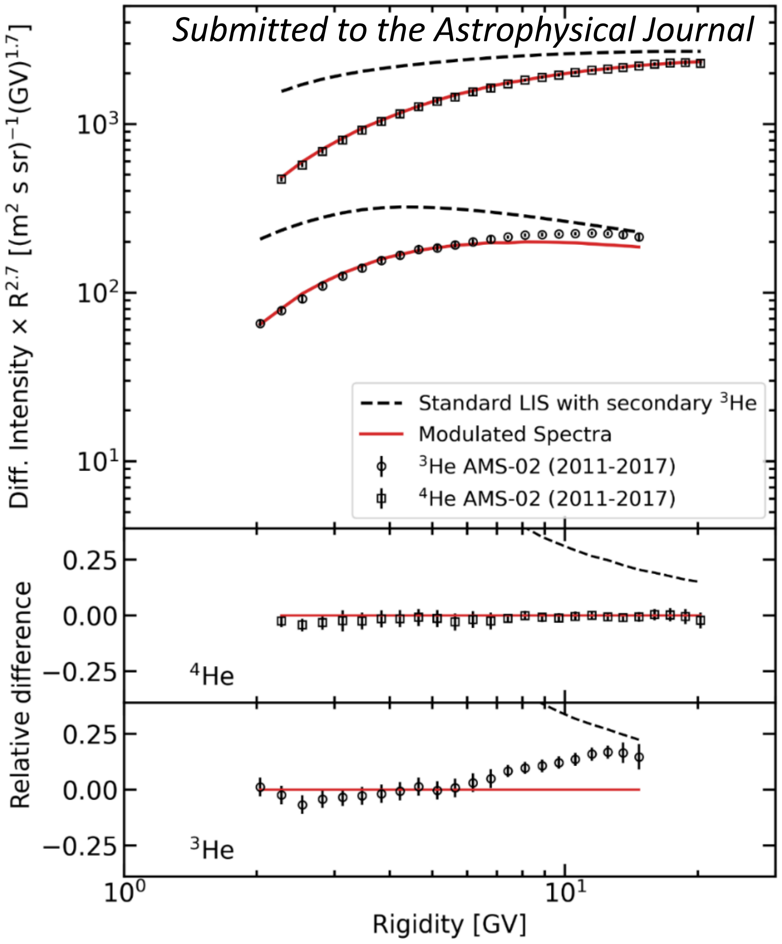
(ii) errors in the total inelastic cross sections of Al

(iii) errors in the isotopic production cross sections

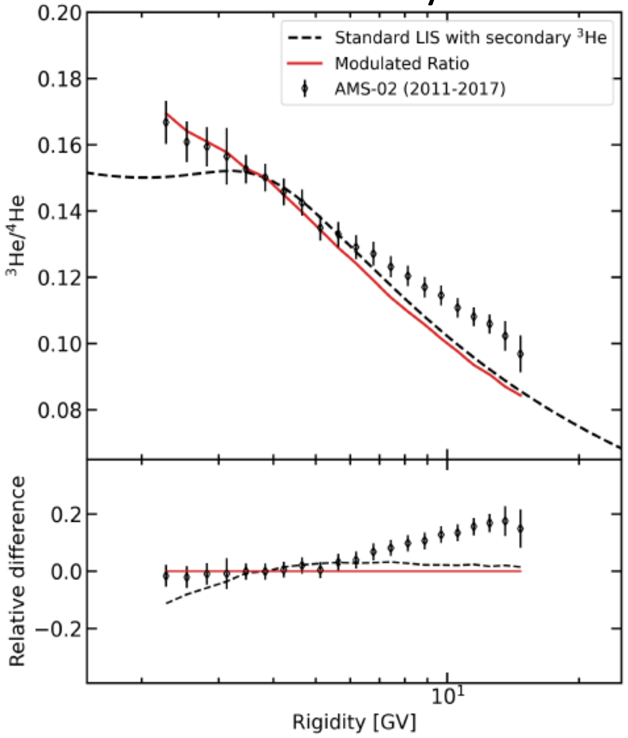
(iv) an additional local component of primary ^{27}Al

- From observations of the distribution of the Galactic 1.809 MeV γ-ray emission line from Al decay, potential sources include AGB stars, novae, core collapse supernovae, and Wolf-Rayet star winds
- The sources of additional Al could be simultaneously also the sources of other rare isotopes, such as ^{7}Li and ^{19}F

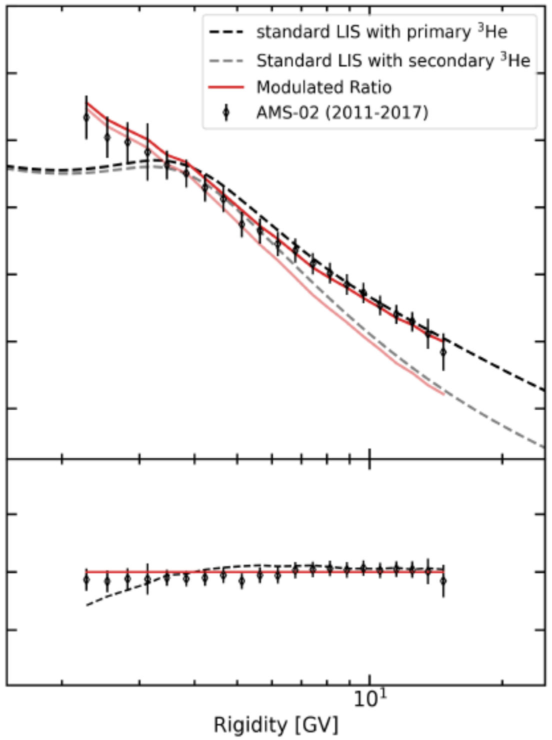
CR isotopes anomalies: the Helium case



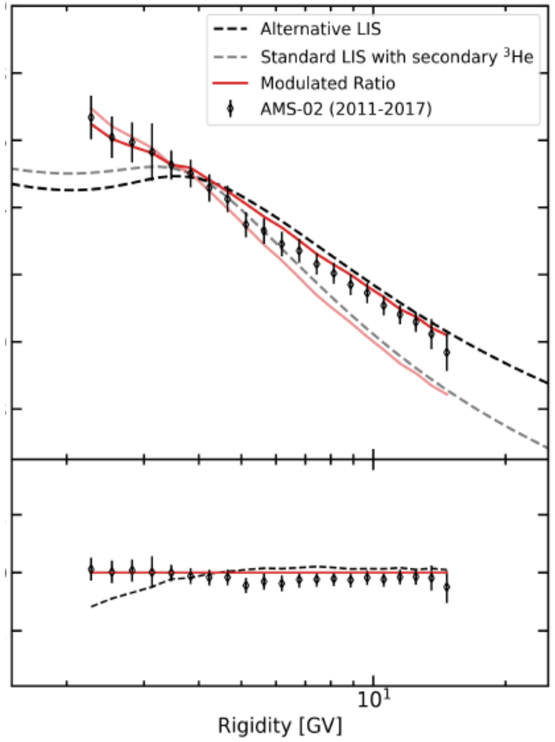
Secondary



Primary



Alternative propagation



The ^3He spectrum obtained in a pure secondary production scenario shows an underestimation w.r.t. AMS-02 data above 7 GV, while ^4He spectrum agrees with AMS-02 data at the % level.

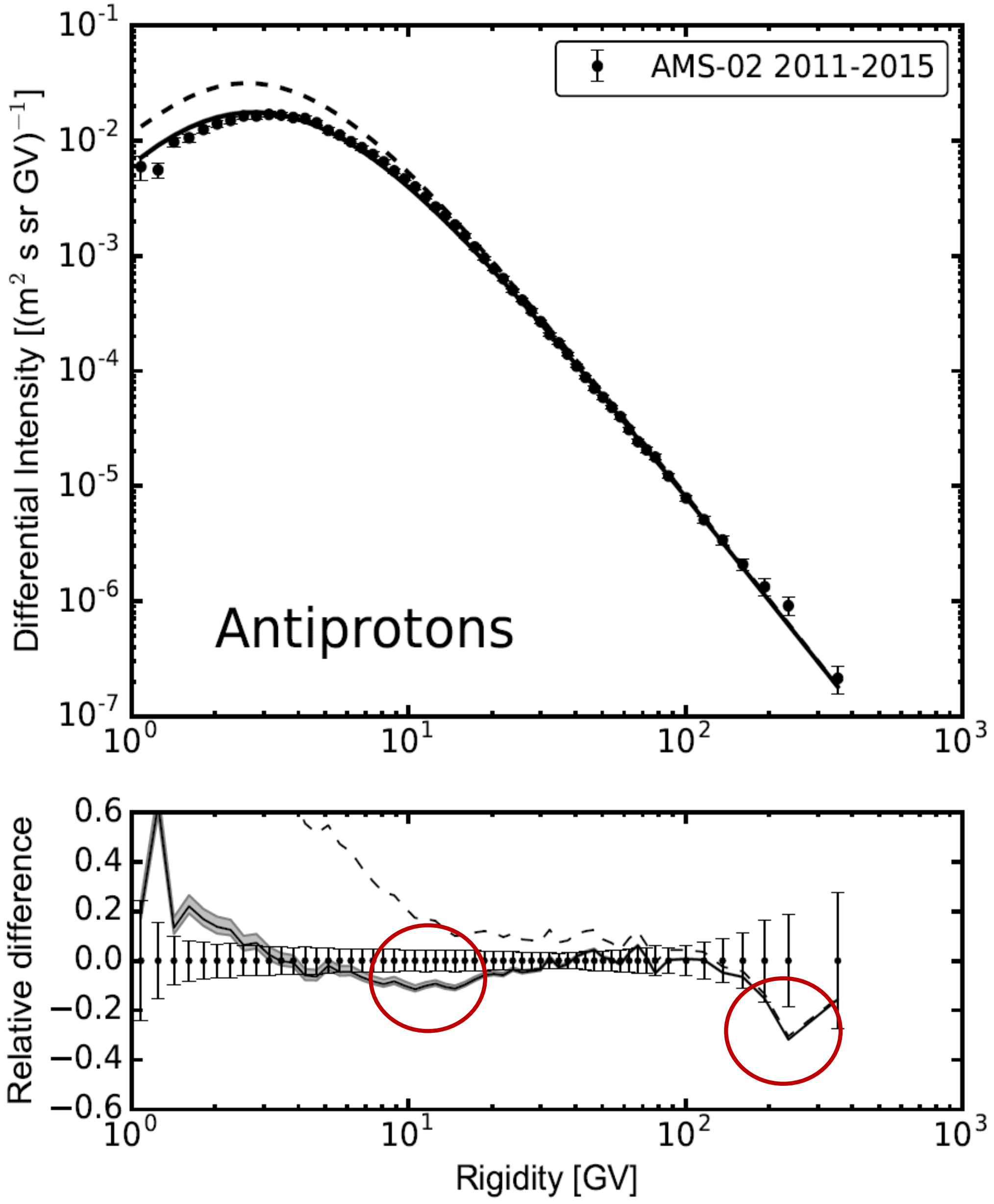
A fundamental property of the production and fragmentation cross sections is their energy independence above ~1÷2 GeV/n. The excess in the ^3He spectrum and the $^3He/^4He$ ratio is observed above 3.8 GeV/n for ^3He: **this could be sufficient to rule out the nuclear hypothesis**

The ^3He "excess" can be fitted adding a new tiny source term (additional primary ^3He) which is few ‰ of ^4He abundance at source.
Solar energetic particle event exhibit **resonant enhancements in the ratio $^3He/^4He$**, that could even make ^3He dominant.

^3He was calculated as a sum of the Z>2 background plus secondary ^3He produced in fragmentation of ^4He with alternative propagation:

D0 = 5.9 x 10^28 cm^2 s^-1
delta = 0.19
dVconv/dz = 2.0 km s^-1 kpc^-1

Antiprotons



ApJ 840:115 No 2, 2017

$$p + ISM \rightarrow \bar{p} \ldots \begin{cases} p + p_{ISM} \rightarrow \bar{p} \ldots \\ p + He_{ISM} \rightarrow \bar{p} \ldots \end{cases}$$

The Antiproton LIS is substantially compatible with AMS-02 within 2σ

Discrepancies w.r.t. AMS-02 high precision data could be due to:

- **nuclear cross section uncertainties**
- peculiar propagation effects
- DM annihilation in the galactic halo (40-90 GeV or 200-400 GeV mass DM)

Thanks to the AMS-02 plus GALPROP/HelMod approach, **propagation uncertainties are now lower than nuclear ones**

Conclusions

- The analysis of nuclei by AMS-02 within the GALPROP–HELMOD framework, together with Voyager-1, HEAO-3-C2 and ACE-CRIS data, provided updated local interstellar spectra up to $Z \leq 28$.

- Al, F, Li and Fe spectra could be examples of excesses in some peculiar rigidity windows: contributions of local new sources are most likely.

- AMS-02 high precision data put realistic models to a severe test, highlighting fine features in nuclei spectra, isotopes and antimatter.

- The helium isotopes and their ratio have been compared with AMS-02: primary ${}^{4}He$ is perfectly described whereas ${}^{3}He$ flux shows an underestimation for R > 7 GV, which points towards a non-nuclear explanation.

- The exploration of fine features in CR species has just begun, thanks to the data from the interstellar probes Voyager 1-2, ACE-CRIS and precise measurements by AMS-02: these features harbor the keys to understanding our local Galactic environment and the history of formation of the Solar System.

- This public framework can be exploited to predict, guide and interpret AMS-02 data.