Inference of the Local Interstellar Spectra of Cosmic-Ray Nuclei $Z \leq 28$ with the GALPROP–HELMOD Framework: Prediction Capability and Hints of Excesses

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

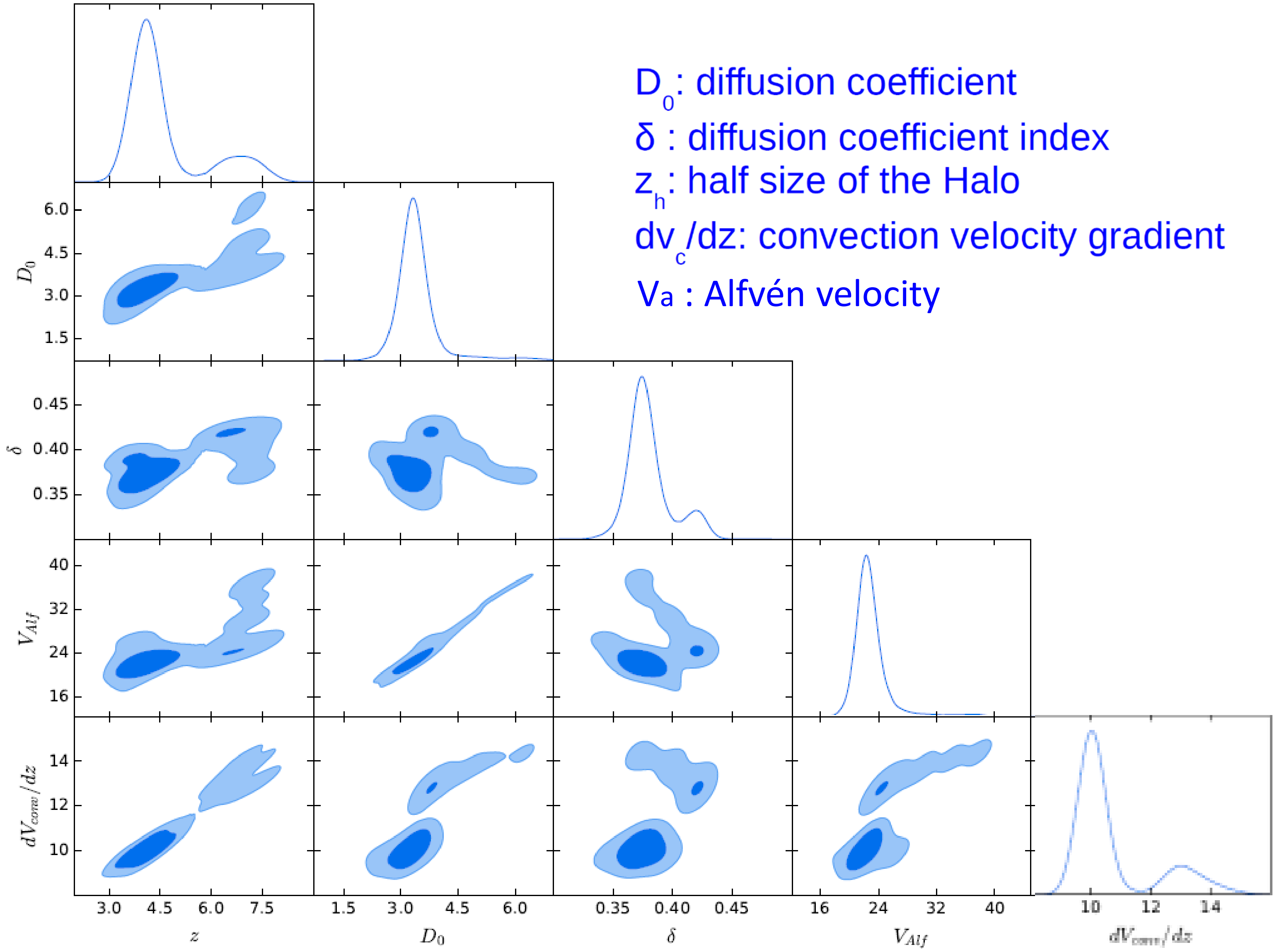
- Thanks to AMS-02 high precision data we can constrain CRs production and propagation **at the % level**;

- AMS-02 published data can be fitted in the combined framework of GALPROP and HelMod (for Galactic and Heliosphere propagation, respectively) **with 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 astroparticle and solar physics.**

MCMC Matrix Approach

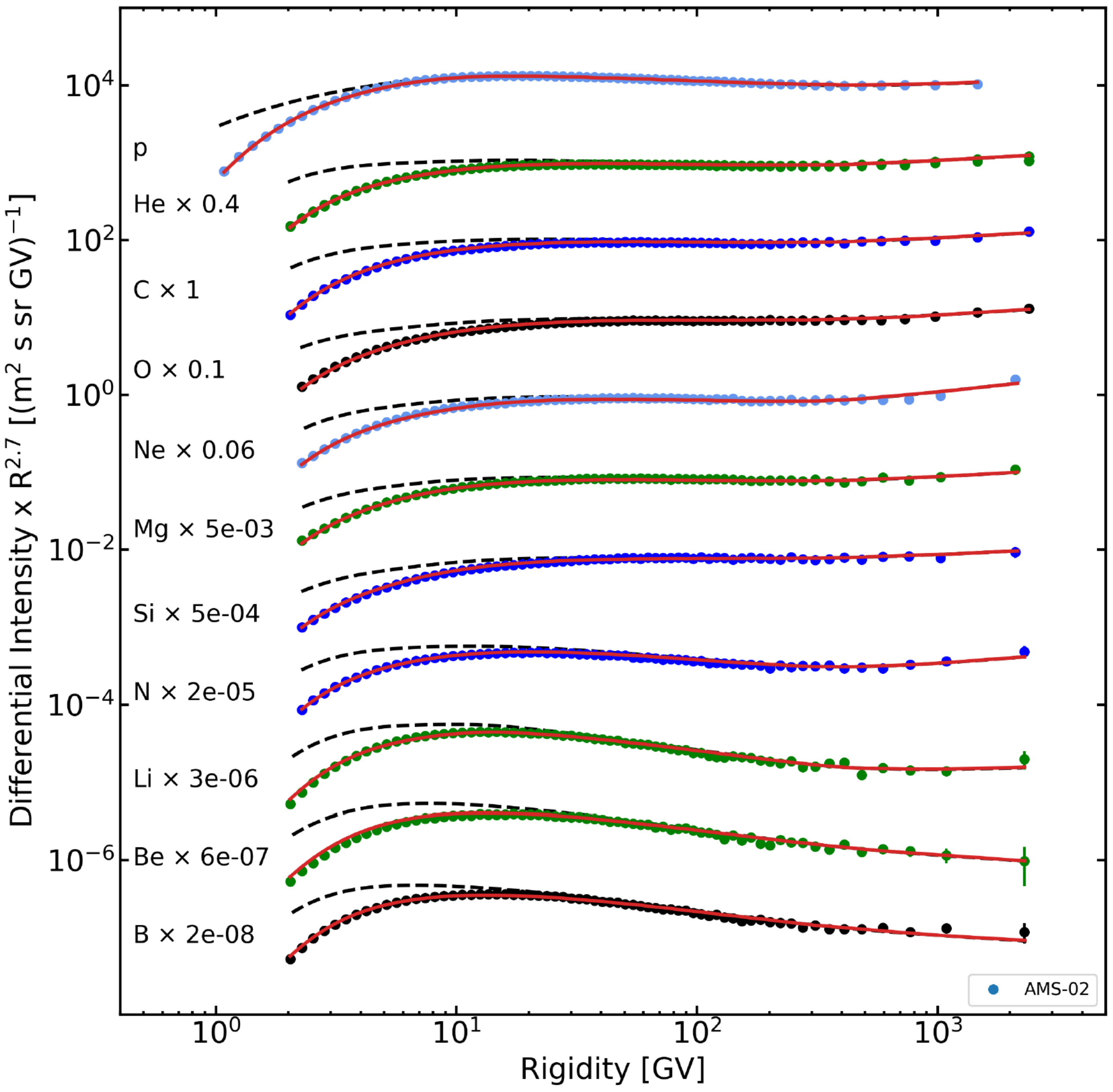
Solution Of Heliospheric Propagation: Unveiling The Local Interstellar Spectra Of Cosmic Ray Species,
The Astrophysical Journal **840**:115 No 2, 2017



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

1. The Monte-Carlo-Markov-Chain interface to **GALPROP** was **developed in Bologna** from CosRay-MC and COSMOMC package, embedding GALPROP framework into the MCMC scheme;
2. The solar modulation is made using **HelMod**;
3. The experimental observables used in the MCMC scan include all primary CRs AMS-02 data and B/C ratio.

One order of magnitude of improvement for fundamental parameters uncertainties



M. J. Boschini *et al* 2020 ApJS **250** 27

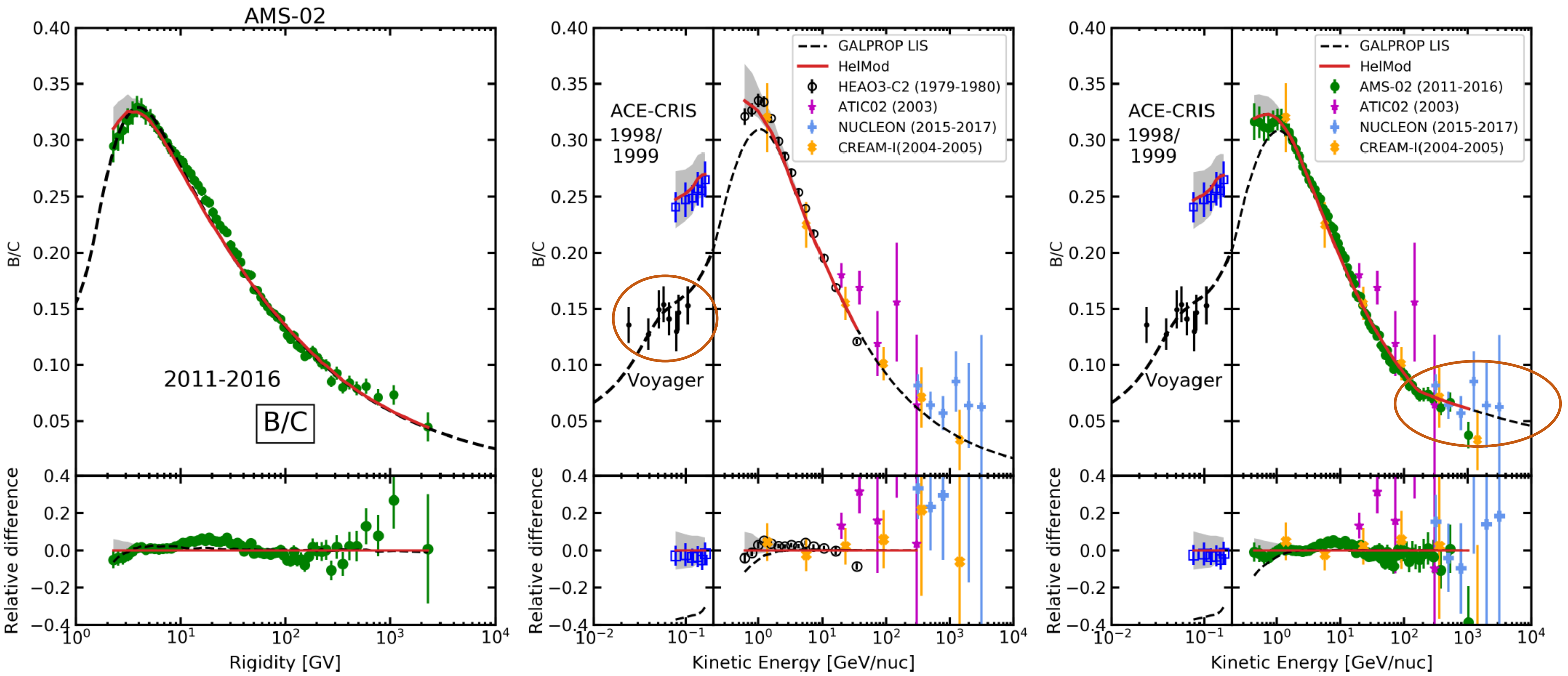
Parameter	Units	Best Value
z_h	kpc	4.0
$D_0(R = 4\ \mathrm{GV})$	cm^2 s^{-1}	4.3×10^{28}
δ^a		0.415
V_{Alf}	km s^{-1}	30
dV_{conv}/dz	km s^{-1} kpc^{-1}	9.8

[a] The *P*-scenario assumes a break in the diffusion coefficient with index $\delta_1 = \delta$ below the break and index $\delta_2 = 0.15 \pm 0.03$ above the break at $R = 370 \pm 25$ GV (for details see

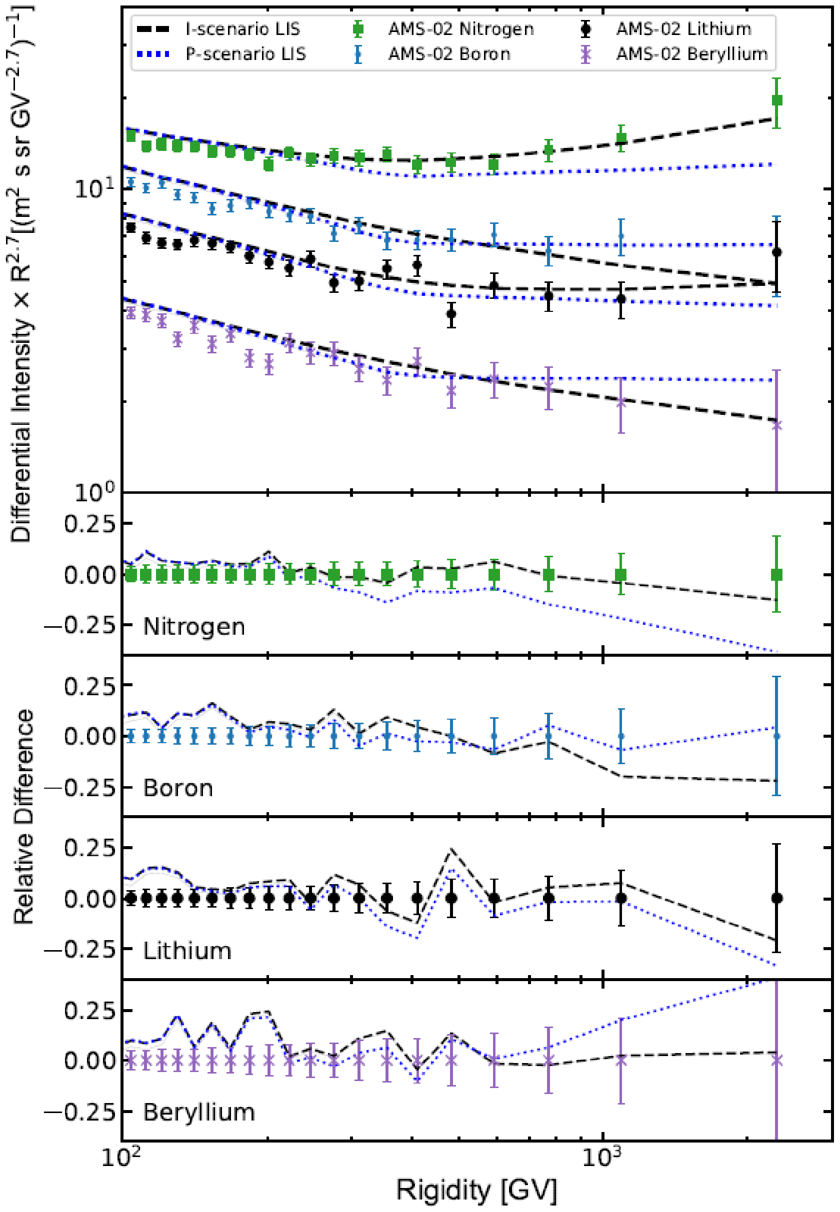
The Model confirms its prediction capability for all AMS-02 species with a single set of parameters

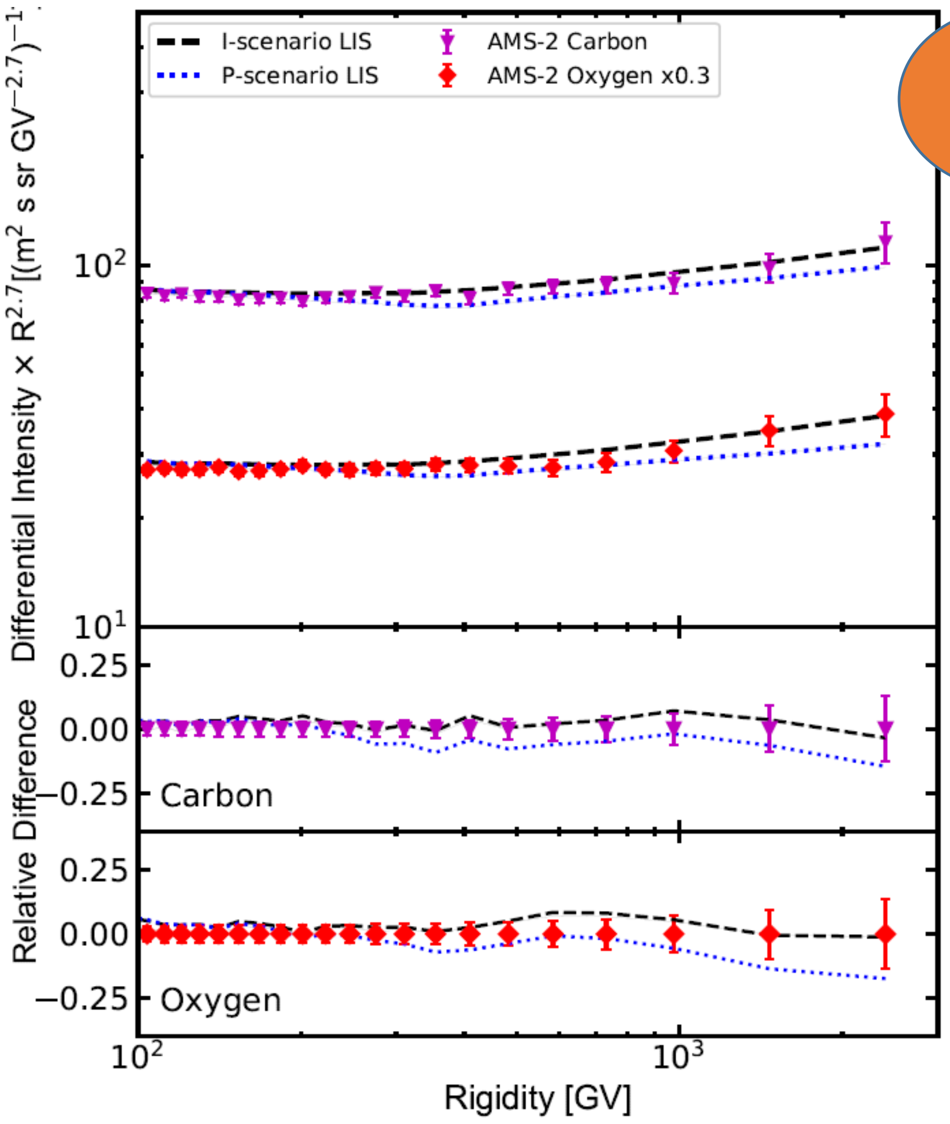
Secondary over primary ratio: B/C

Diffusive break Propagation-scenario



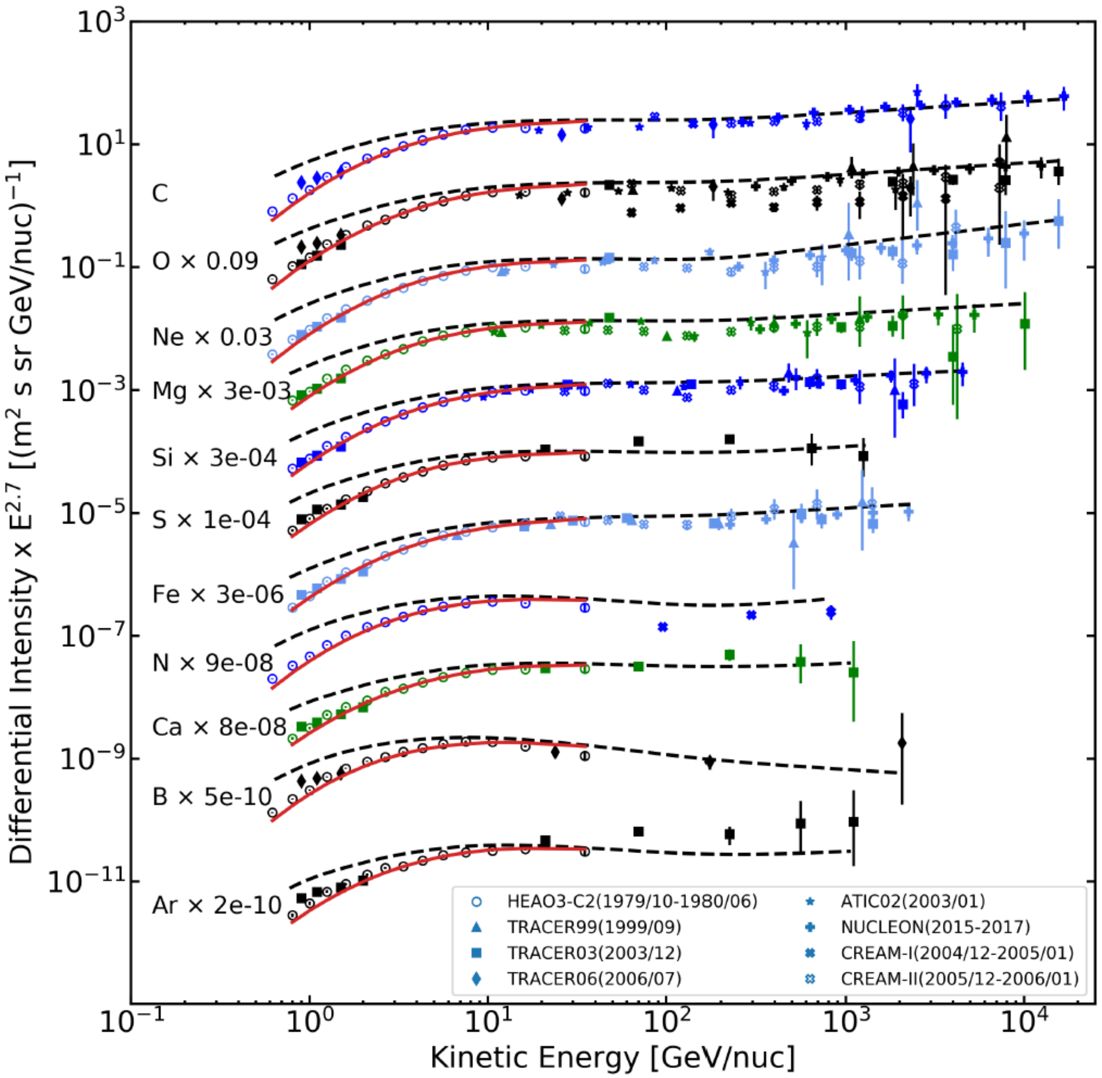
Injection versus Propagation scenarios to explain CRs hardening above 300 GV

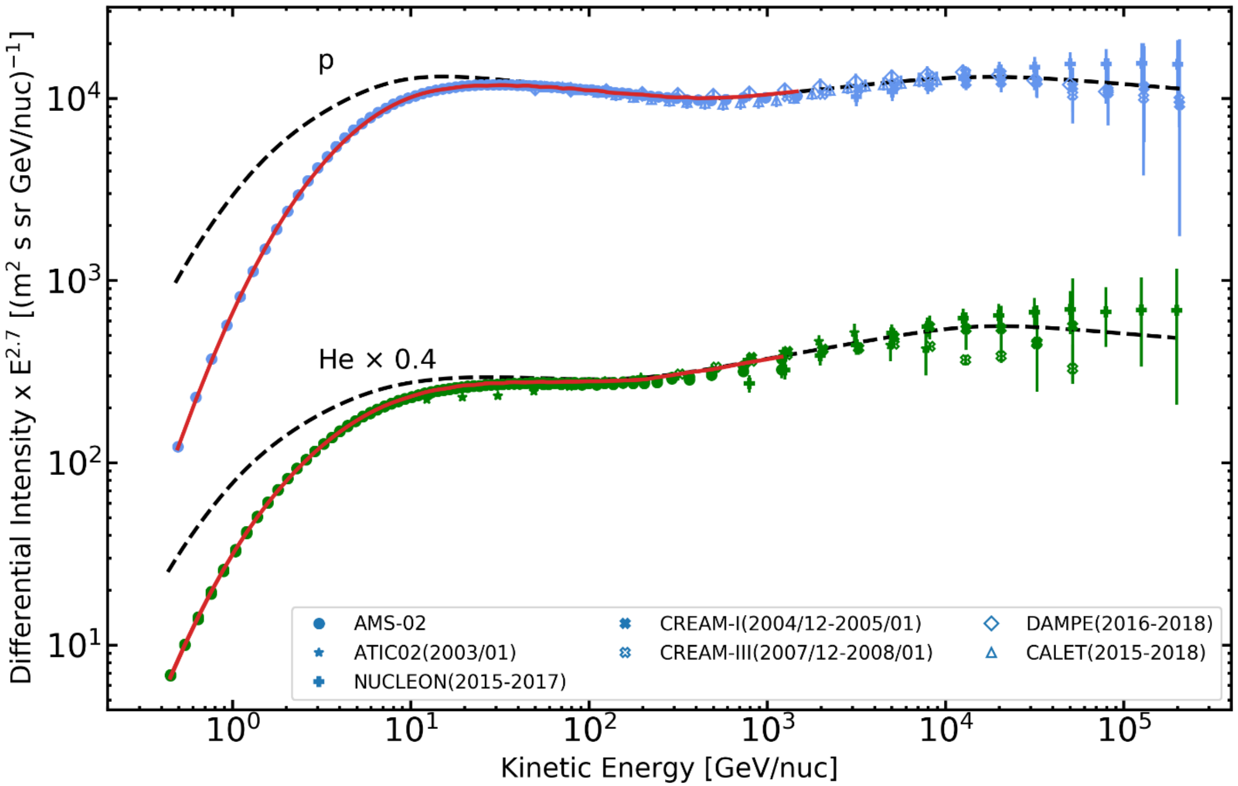




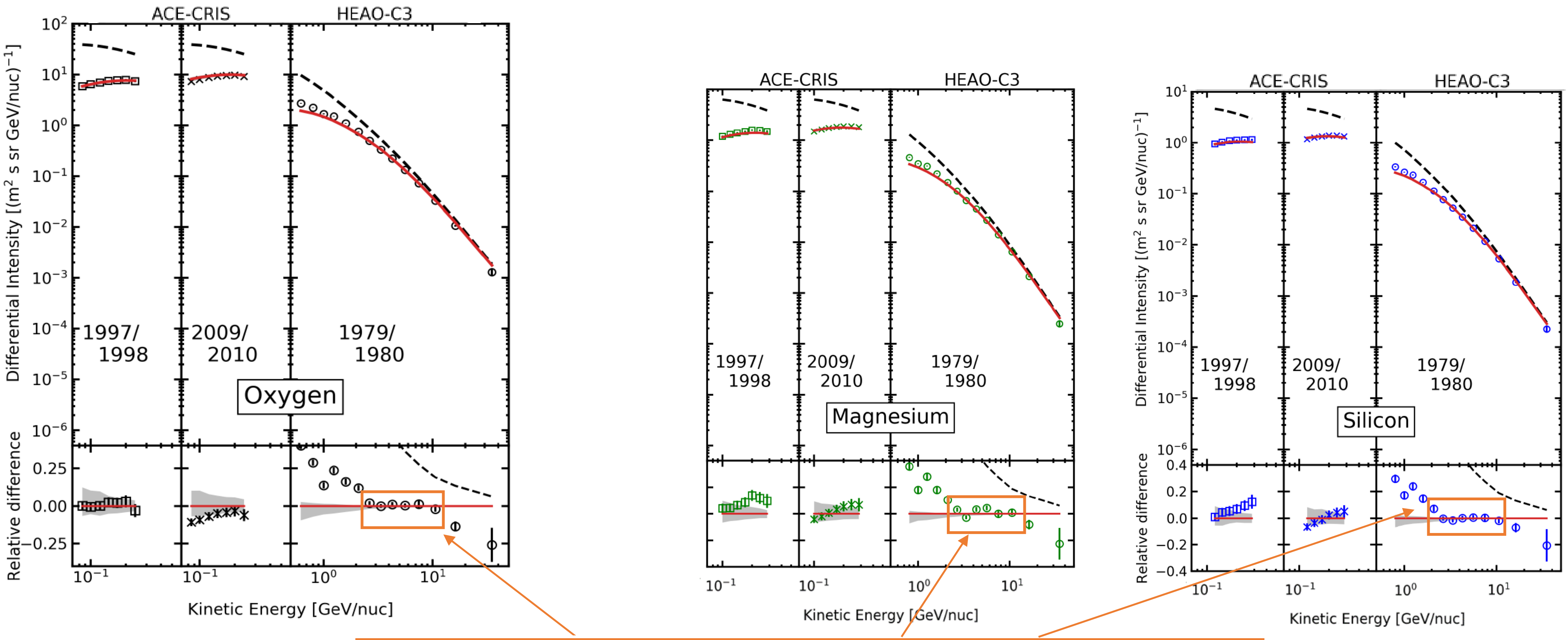
I or P?

LISs validity is extended up to tens (and hundreds) TeV/n



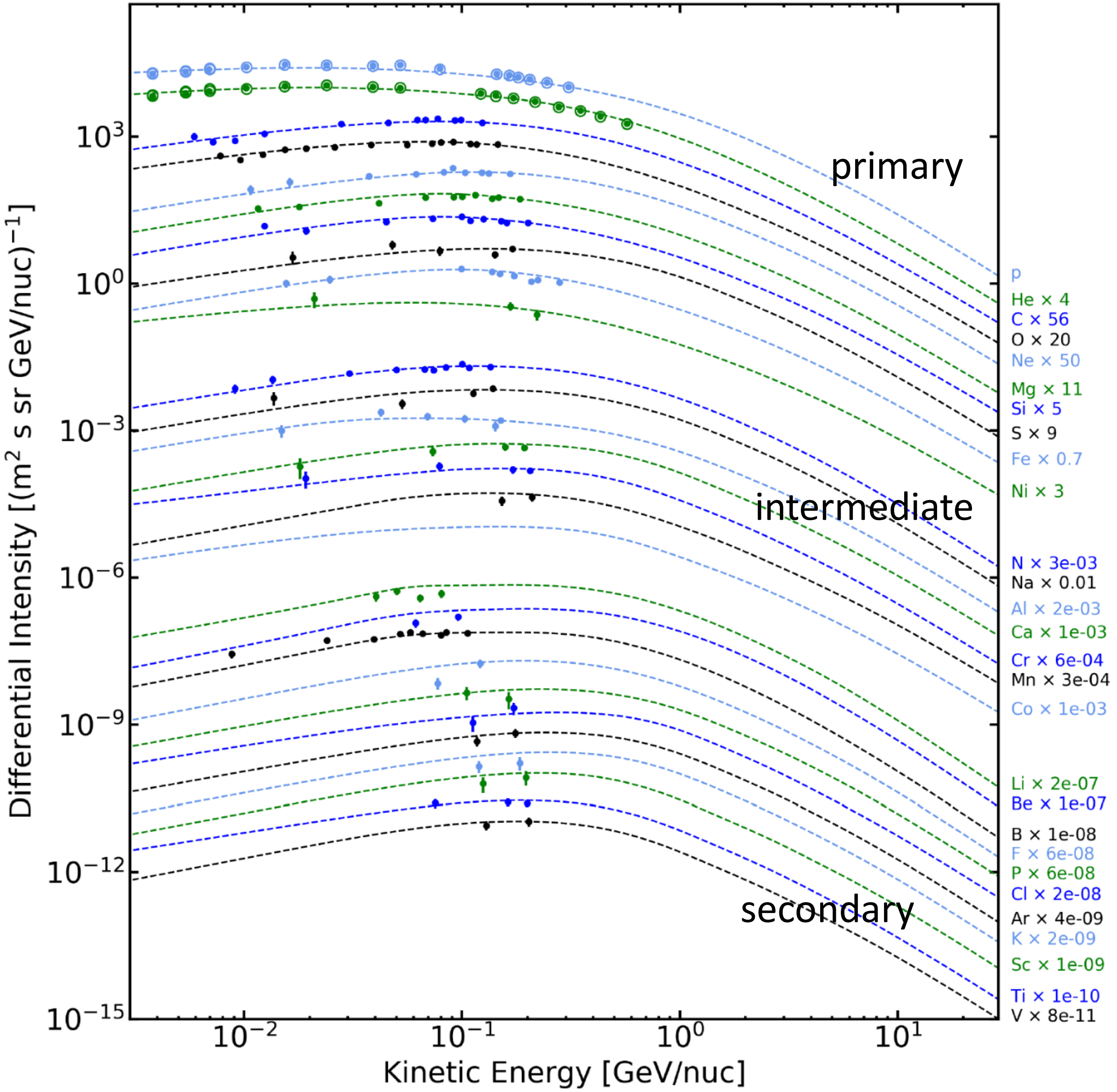


HEAO vs AMS-02 normalization to forecast Z >14 nuclei



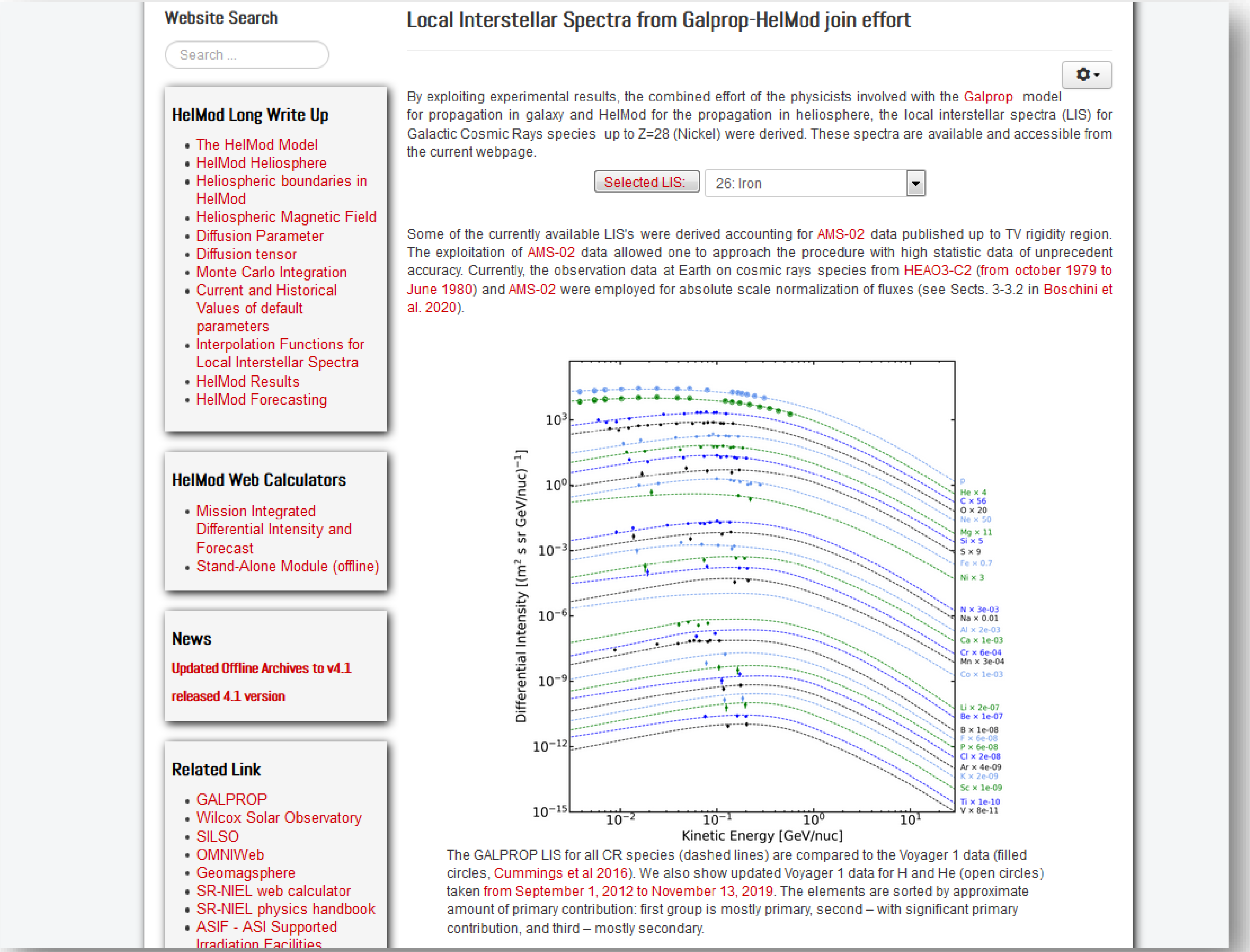
AMS-02 and HEAO normalization coincide at the % level in this region (2.65-10.6 GeV/n) for not to heavy species

Interstellar spectra measured by Voyager-1



All $Z \leq 28$ are well reproduced

Our website provides numerical LISs, formulas and plots



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- Interpolation Functions for Local Interstellar Spectra
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Updated Offline Archives to v4.1

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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.

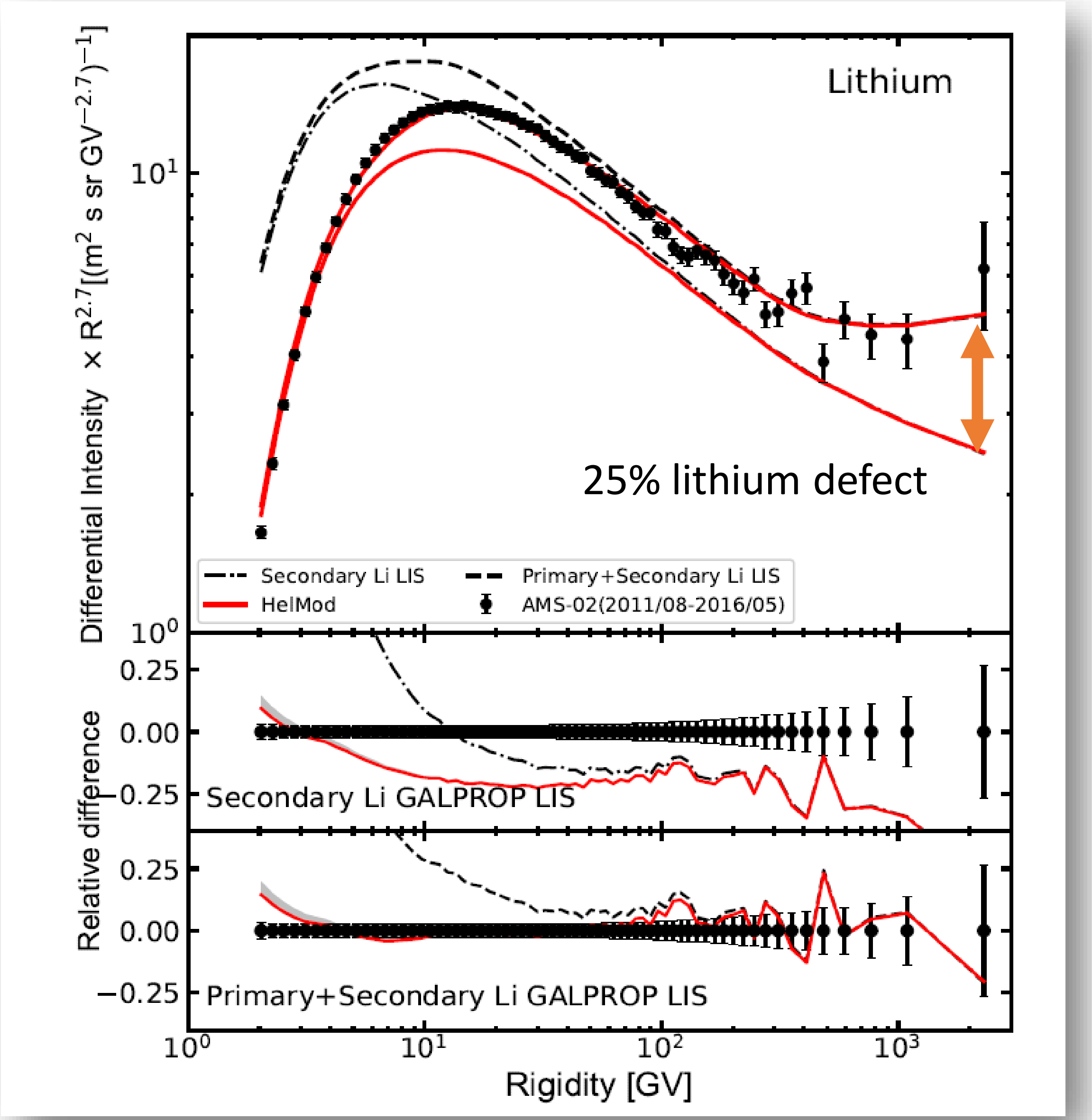
LISs will be futher fine-tuned and updated on the website using incoming AMS-02 measurements

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

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

Primary Lithium

Boschini *et al* ApJ **889**:167 2020



Li isotopes main production channels (from C and O) are well-constrained and a 20% error in one of them would correspond to only 2%–3% correction.
It is rather unlikely that cross-section errors are all biased on the same side leading to the observed 25% excess.

Primary ^{7}Li through the Cameron-Fowler mechanism for intermediate-mass AGB (asymptotic giant branch) stars and Novae:

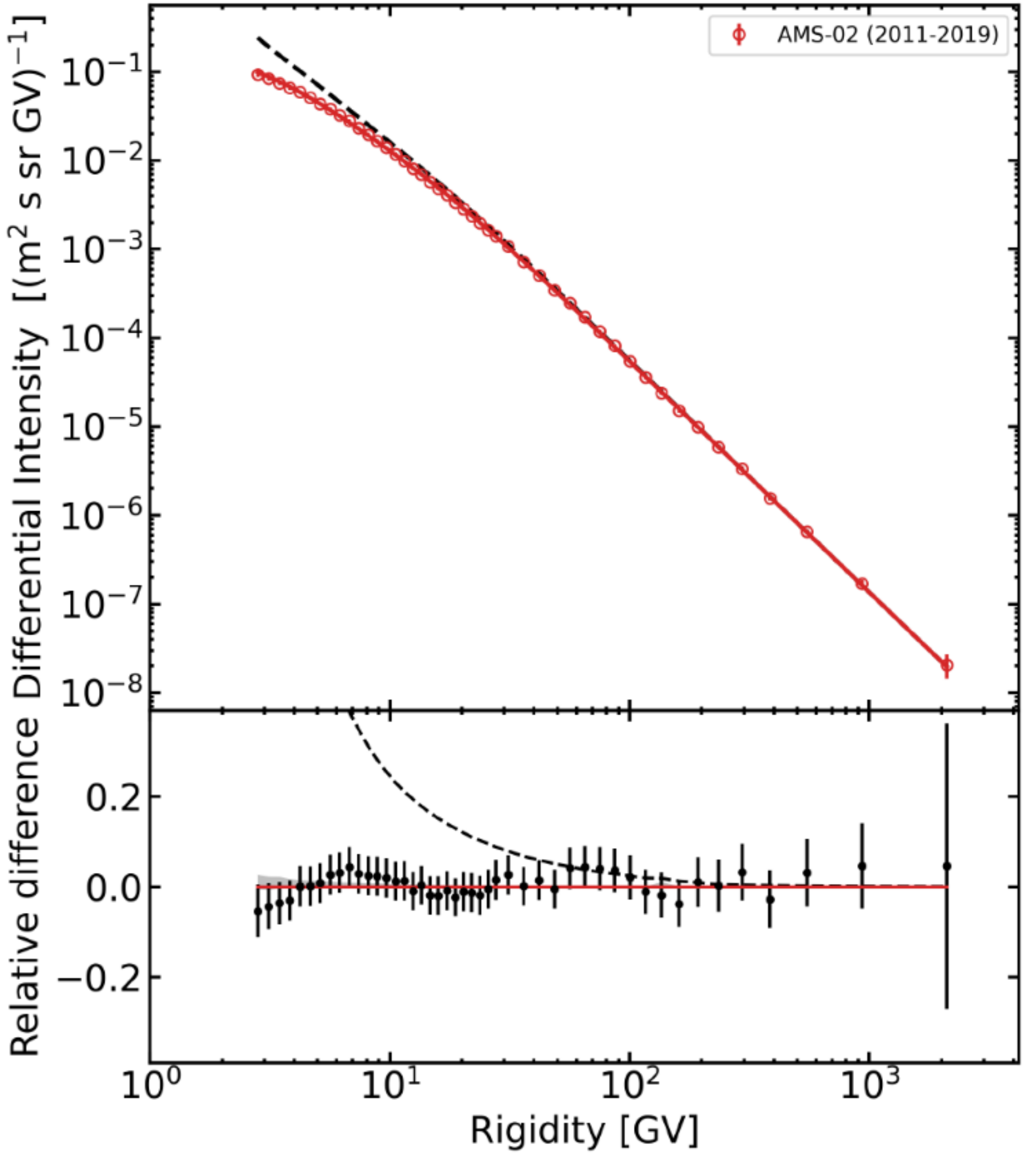
- alpha-capture ^{3}He(α,γ) ^{7}Be
- transport of ^{7}Be into cooler layers
- **^{7}Be decay (53.22 days) → ^{7}Li**

- **Observation of blue-shifted absorption lines of partly ionized ^{7}Be in the spectrum of a classical nova V339 Del** about 40-50 days after the explosion is the first observational evidence that the mechanism proposed in 1970s is working indeed

- **Consequent observations of other stars** (V1369 Cen, V5668 Sgr and V2944 Oph, ASASSN-16kt [V407 Lupi], V838 Her) **also reveal the presence of ^{7}Be lines**

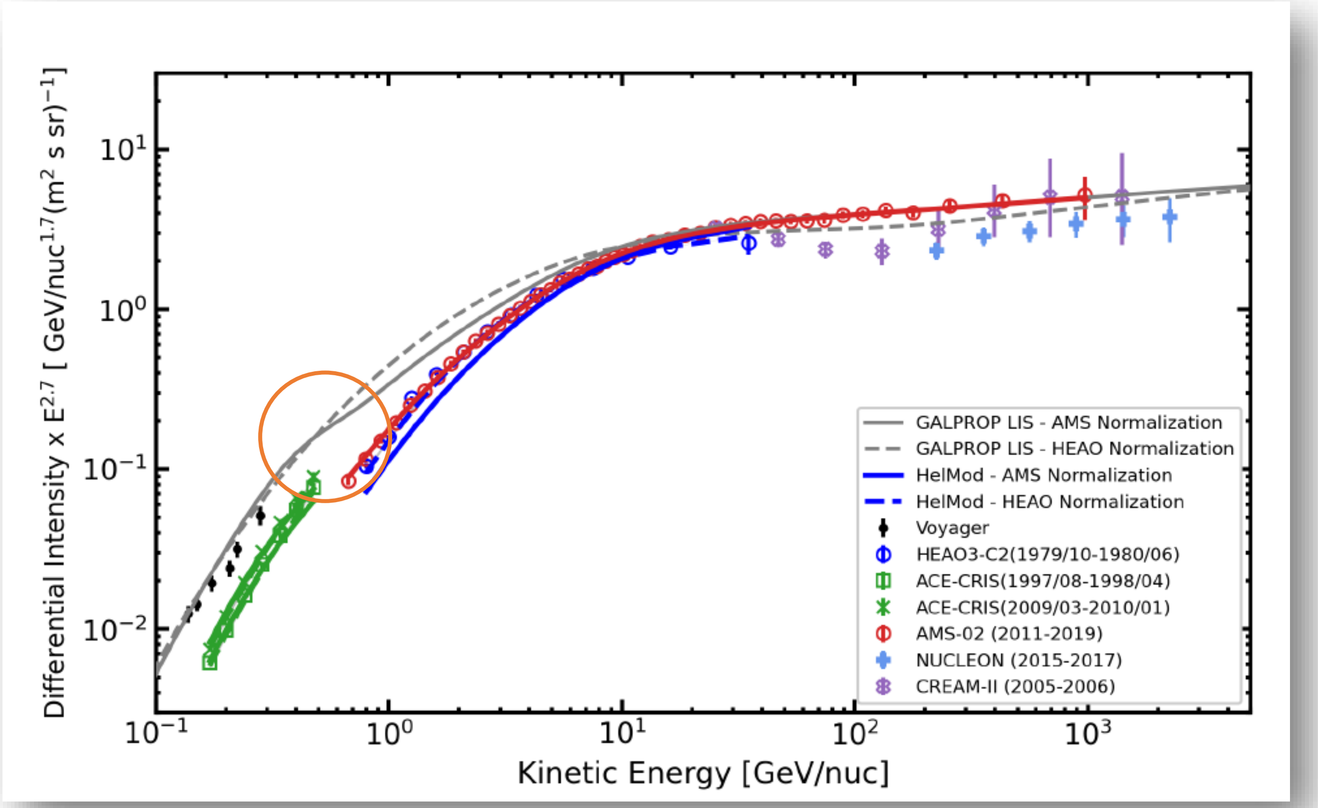
- Primary Lithium from new stars processes is mandatory to explain AMS-02 measurement

The new iron from AMS-02

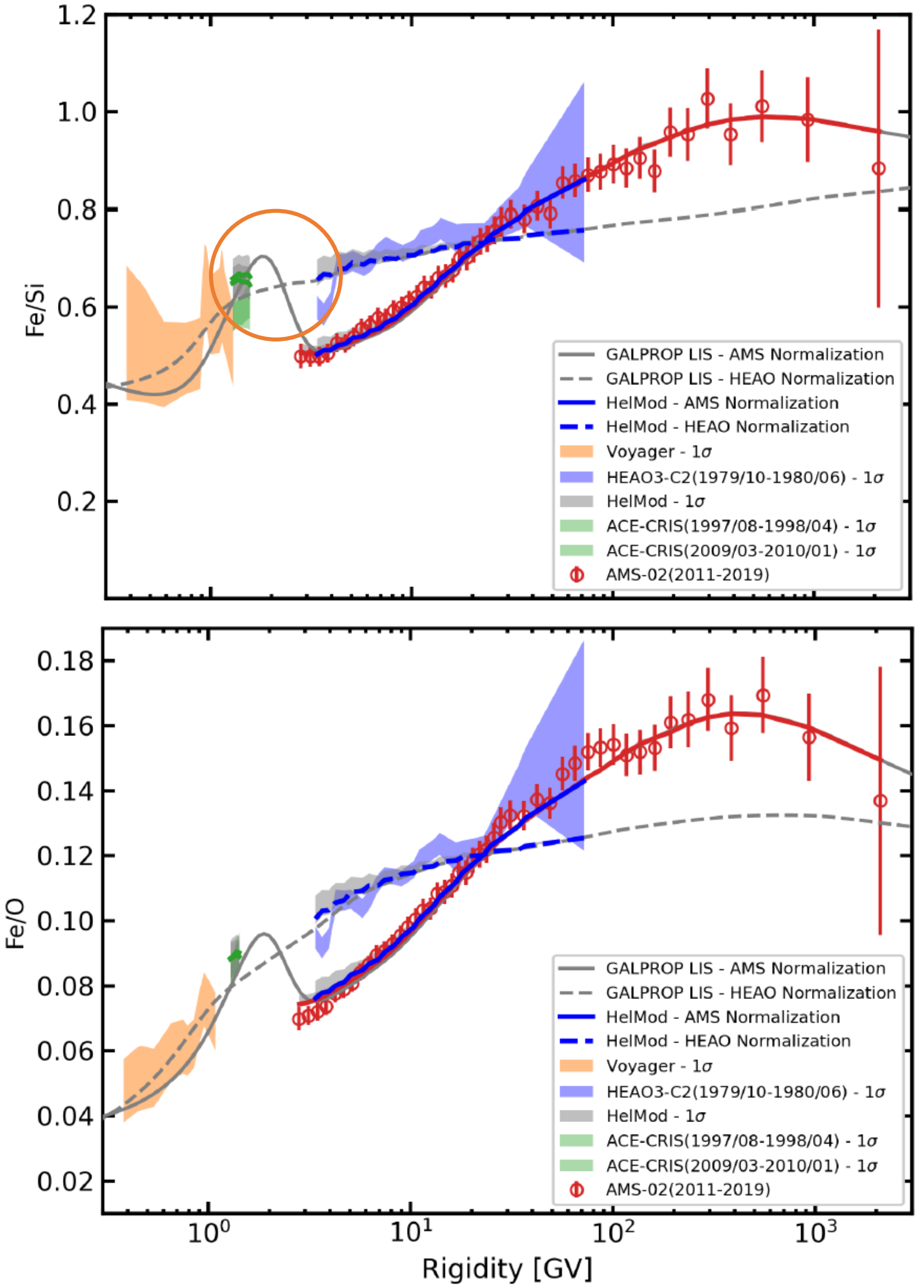


Boschini *et al* ApJ **913**:5 (2021)

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



Iron to primaries ratios

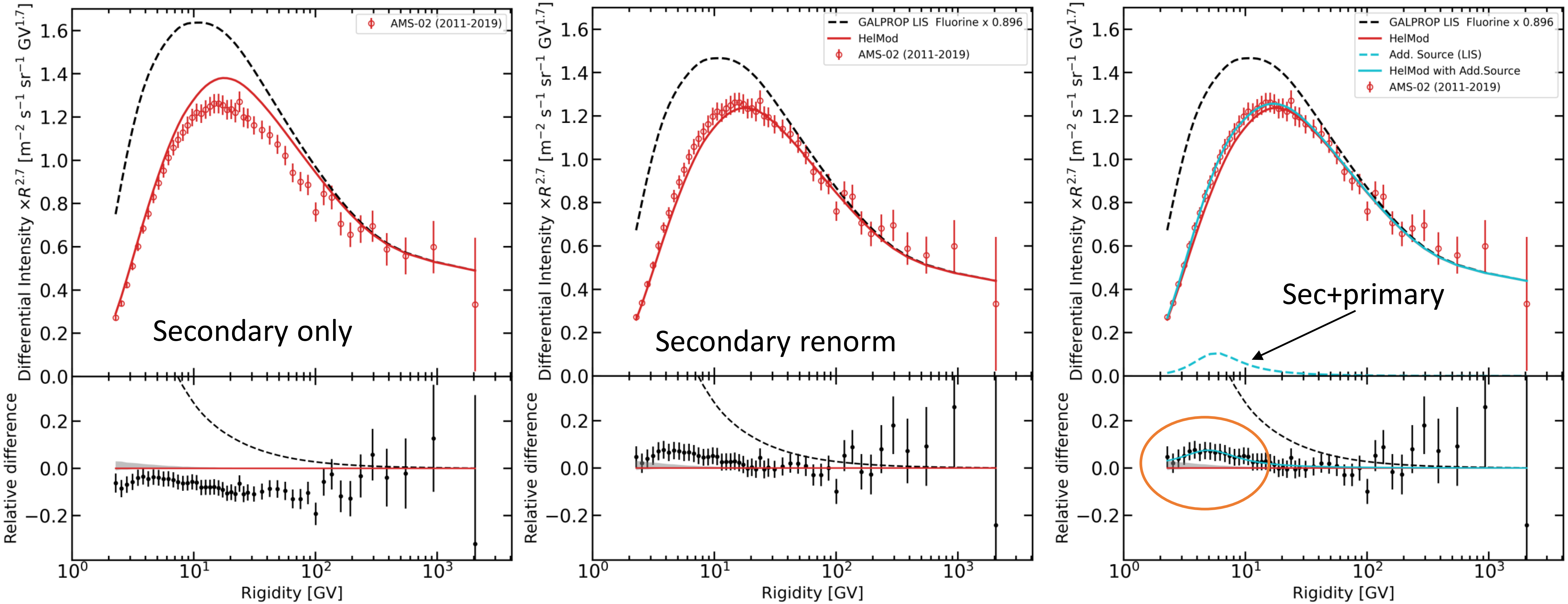


The found excess fits well with recent discoveries of radioactive ^{60}Fe (half-life 2.6 million years) deposits in the deep ocean sediments, in lunar regolith samples and in the Antarctic snow. Such deposits can be made by SN explosions in the solar neighborhood.

Recent observation of ^{60}Fe in CRs by ACE-CRIS spacecraft implies that the low-energy CRs from the most recent SN are still around.

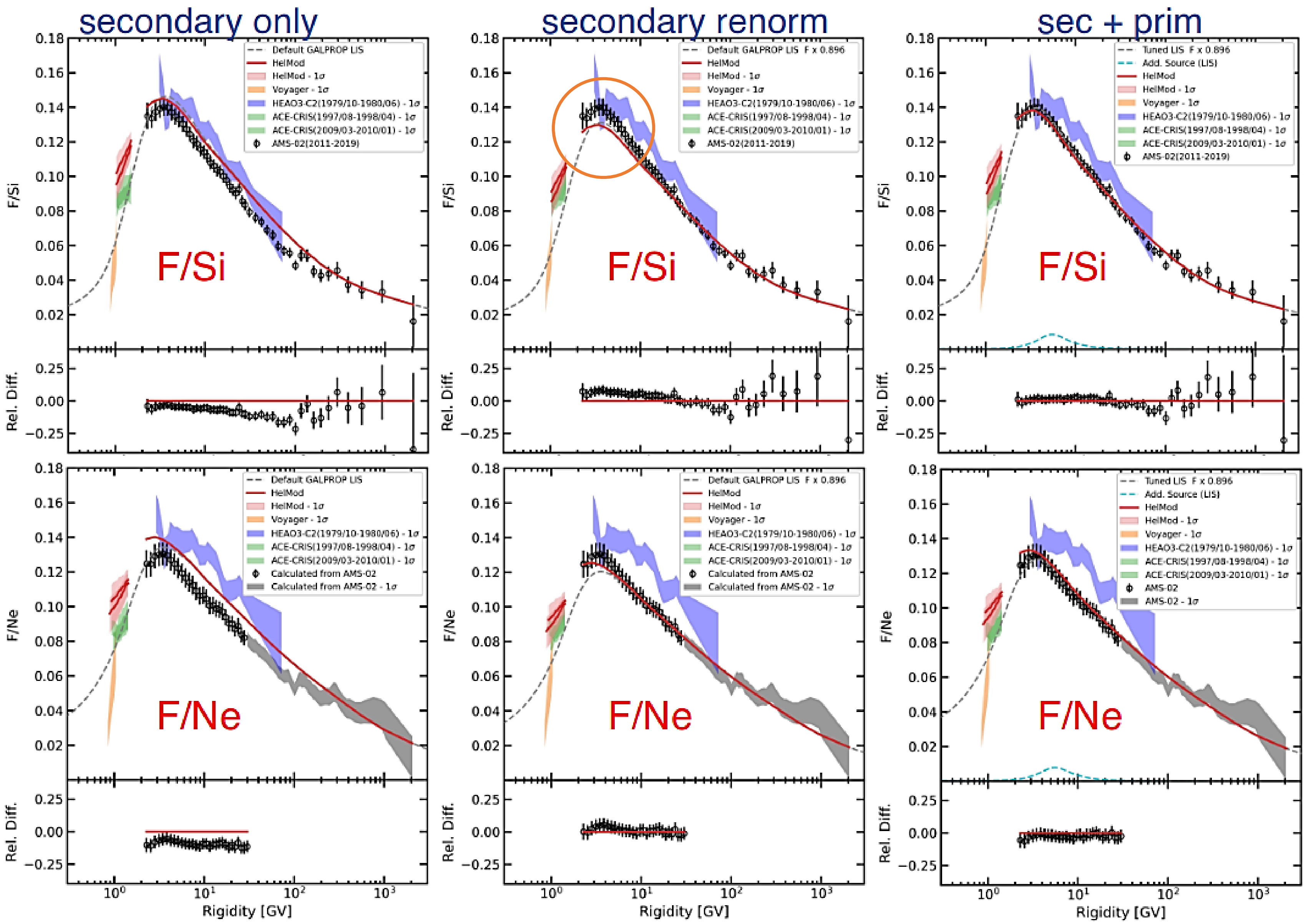
It is hard to establish the number of SNe events and their exact timing, but there could be several events during the last ~10 Myr at distances of up to 100 parsecs (most likely in the **Tucana-Horologium** stellar group).

Fluorine spectrum



- Overall normalization (x 0.9) due to possible errors in the production cross sections (~ constant)
- Remaining excess < 10 GV is treated as a primary component

Boschini *et al* ApJ **925**:108 2022



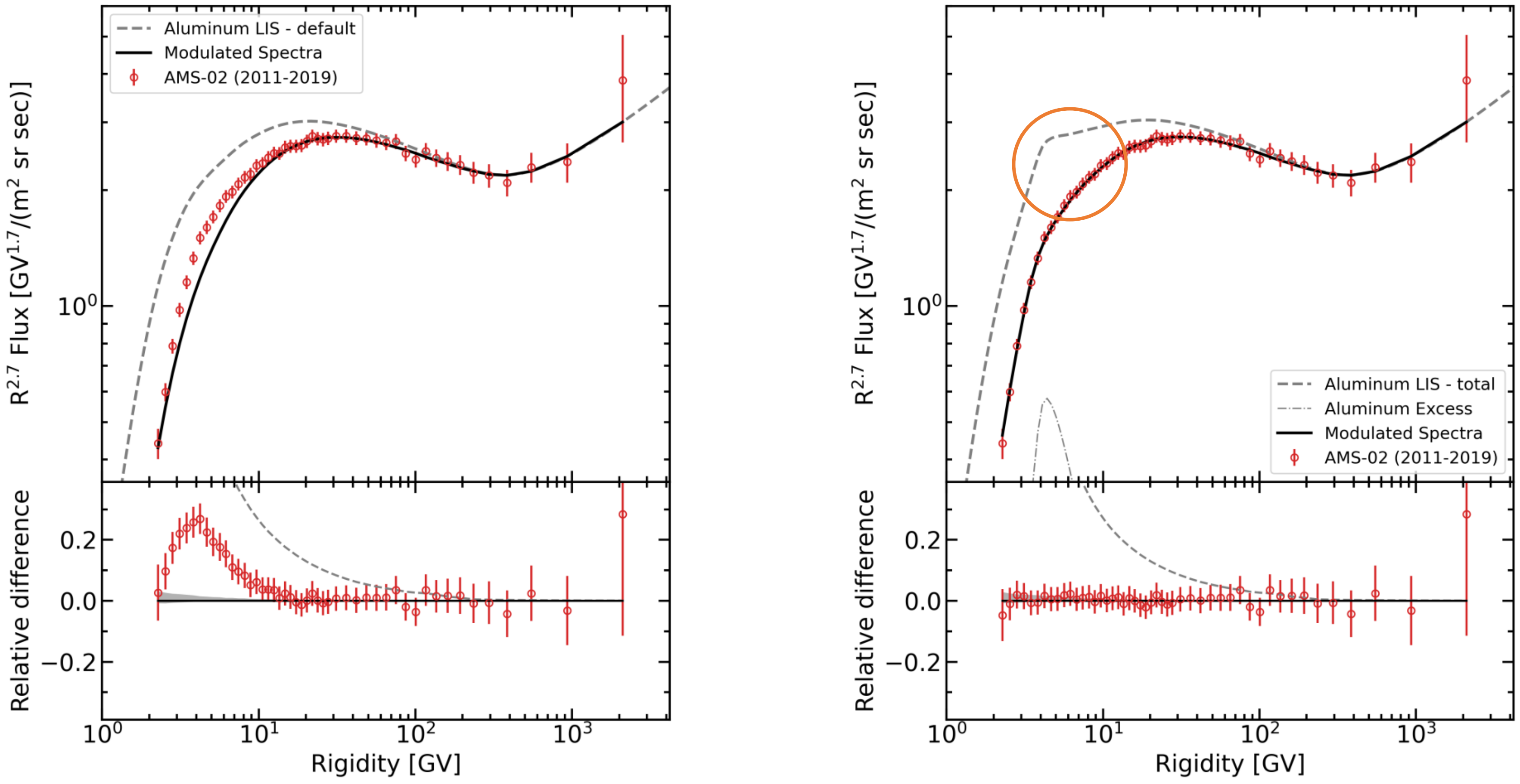
The origin of cosmic fluorine (from ^{14}N) is still not well constrained: the main astrophysical sources of fluorine are thought to be SNe Type II, Wolf–Rayet stars and intermediate-mass AGB stars

They could be all important at different stages of chemical evolution of the Galaxy

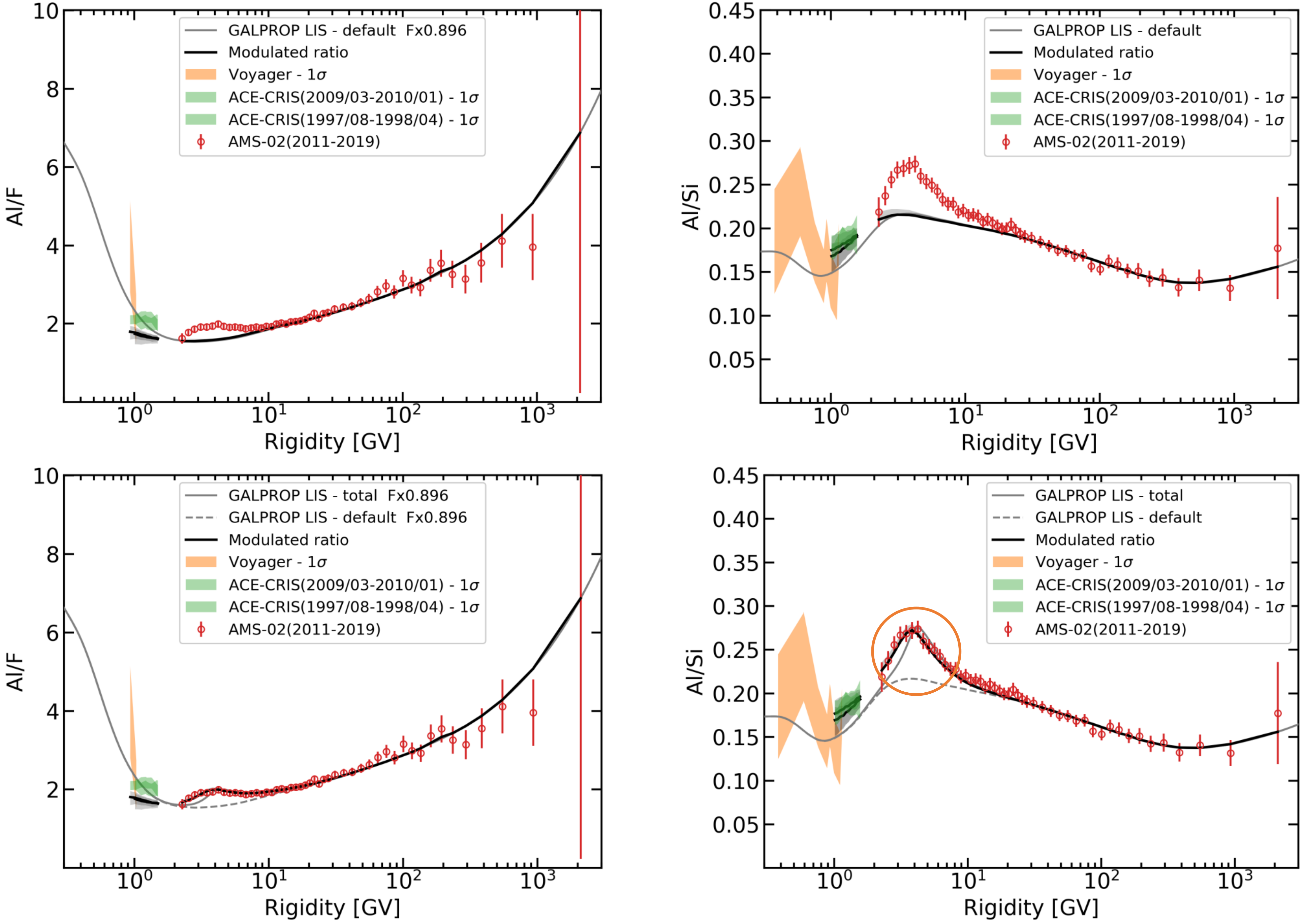
Recent AMS-02 spectra: Sodium and Aluminum

Aluminum

Boschini *et al*, ApJ **933** 147 2022



There is no viable reason of why the Al injection spectrum in the 2–10 GV range should be different from its neighbors in the Si group



Without signal

With signal

Aluminum Excess

There are four possible physical reasons for the observed excess in the Al spectrum:

(i) an incorrect spectrum of ^{28}Si, the major progenitor of $^{26,27}Al$

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

(iii) errors in the isotopic production cross sections of $^{26,27}Al$

Hardly account for such excess

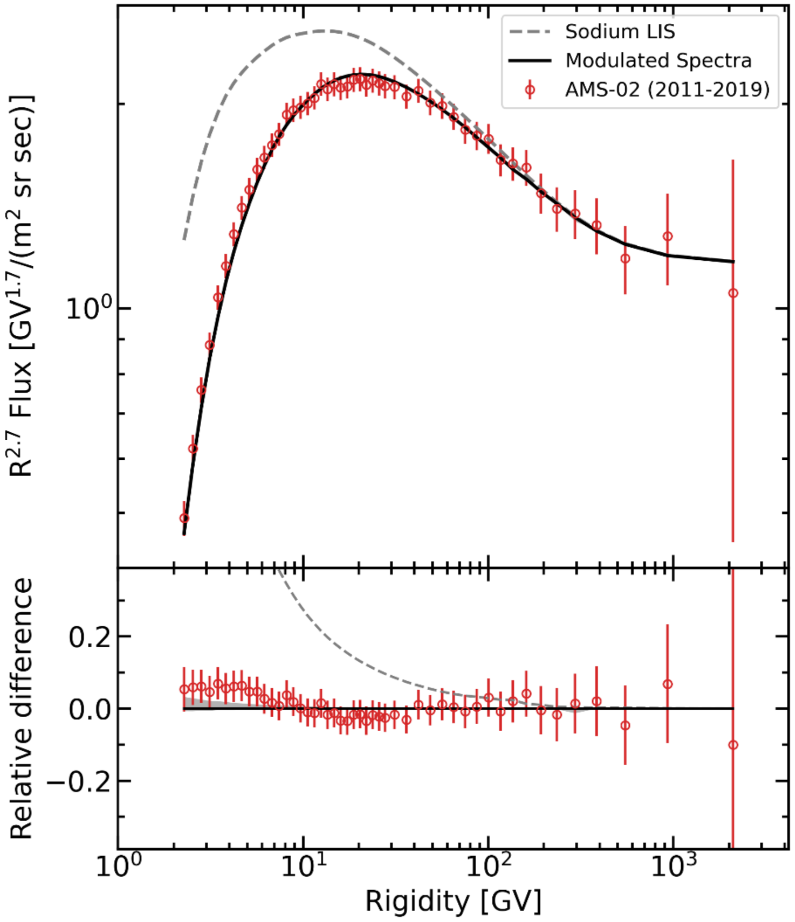
(iv) an additional local component of primary ^{27}Al

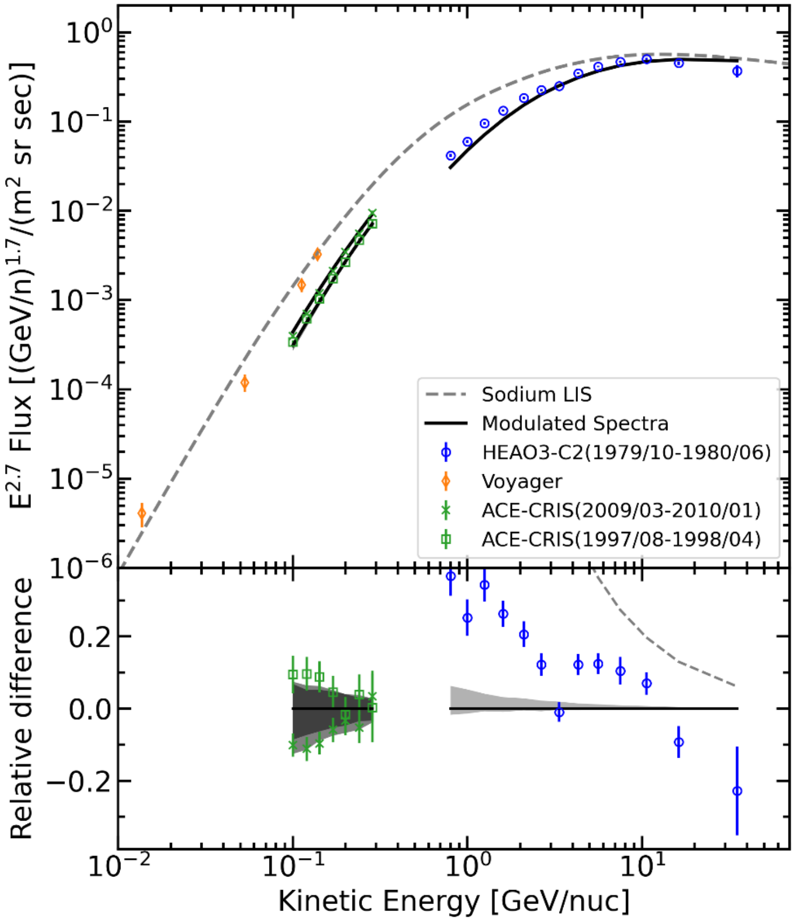
- From **observations of the distribution of the Galactic 1.809 MeV γ-ray emission line from ^{26}Al decay**, potential sources include AGB stars, novae, core collapse supernovae, and Wolf-Rayet star winds
- **The sources of additional Al could be simultaneously also the sources of other rare isotopes, such as ^{7}Li and ^{19}F**

- WR stars were already proposed to explain the observed anomalous $^{22}Ne/^{20}Ne$, $^{12}C/^{16}O$, $^{58}Fe/^{56}Fe$ ratios
- All isotopic ratios measured with ACE-CRIS are consistent with ~20% of WR material mixed with ~80% material with solar-system composition
- Since most of WR stars are found in the **OB associations**, they **are the likely sources of a substantial fraction of CRs** (Scorpius–Centaurus is located about 400 light-years from the Sun)

Recent AMS-02 spectra: Sodium and Aluminum

Sodium





No excess found

Regarding the spectrum of sodium, we note the absence of a similar low-energy excess. An interesting analysis using the Gaia-ESO Survey to study sodium and aluminum abundances in giants and dwarfs and its implications for stellar and Galactic chemical evolution can be found in Smiljanic et al. (2016). WR stars do not seem to be a significant source of sodium. Absence of the excess in the sodium spectrum apparently supports the hypothesis of the origin of the observed excesses in the local OB associations. Meanwhile, studies of sodium nucleosynthesis in different stellar environments are desirable as they may help to discriminate between possible scenarios of the origin of the observed excesses.

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 show significant excesses in some peculiar rigidity windows**: contributions of local new sources are most likely.

- The **WR hypothesis**, that was invoked to reproduce the observed isotopic ratios, **could be also consistent with the observed excesses in Li, F and Al, while excess in primary Fe should be connected with a past SN activity in the Local Bubble.**

- Absence of a corresponding excess in sodium supports this hypothesis, as the WR winds are not a significant source of sodium.

- 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.**