Studying the low-energy excess in cosmic ray iron: a possible evidence of a massive supernova activity in the solar neighborhood

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

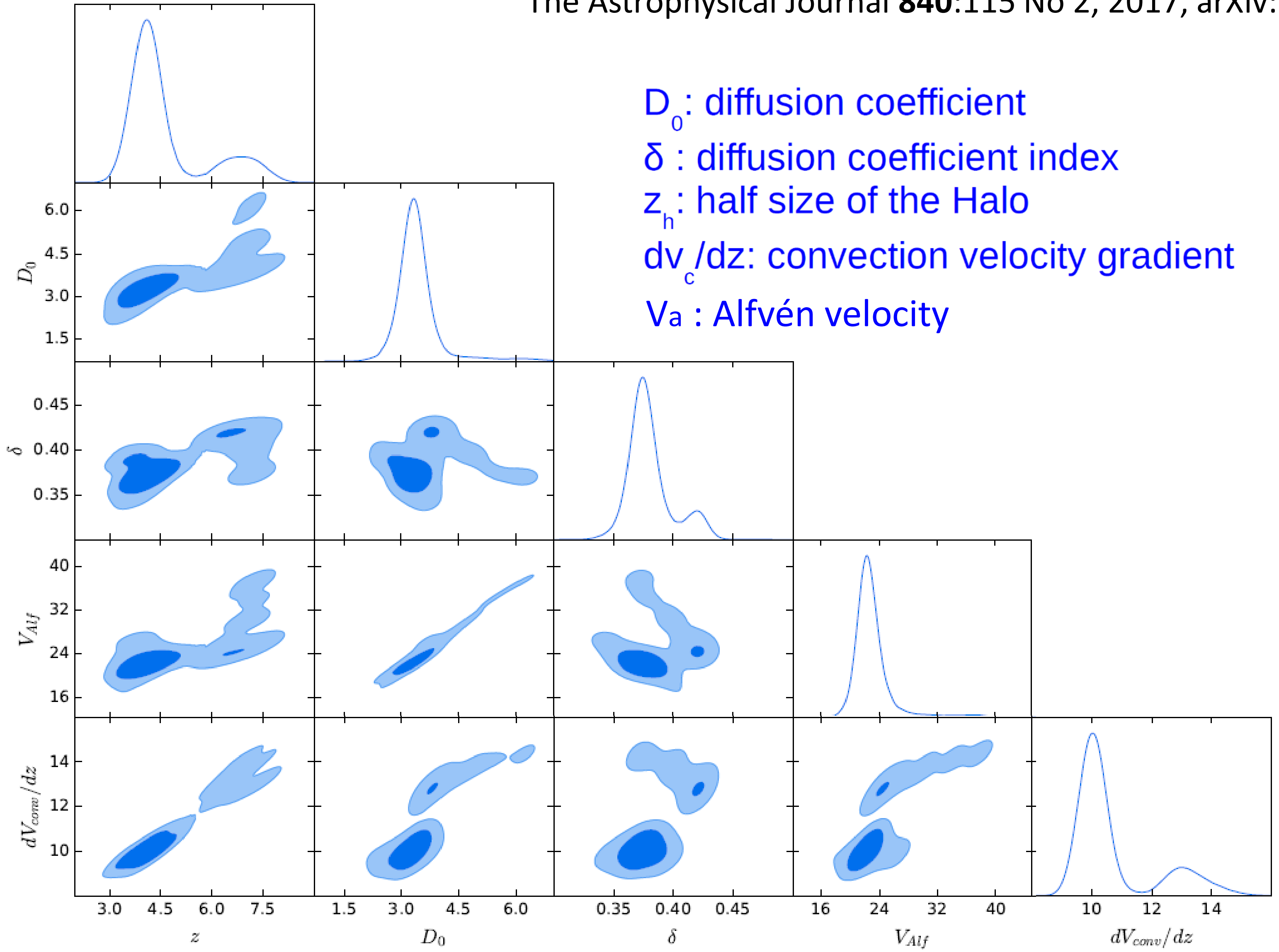
- Thanks to AMS-02 high precision data we can constrain CRs production and propagation **at the % level**;

- 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);

- 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

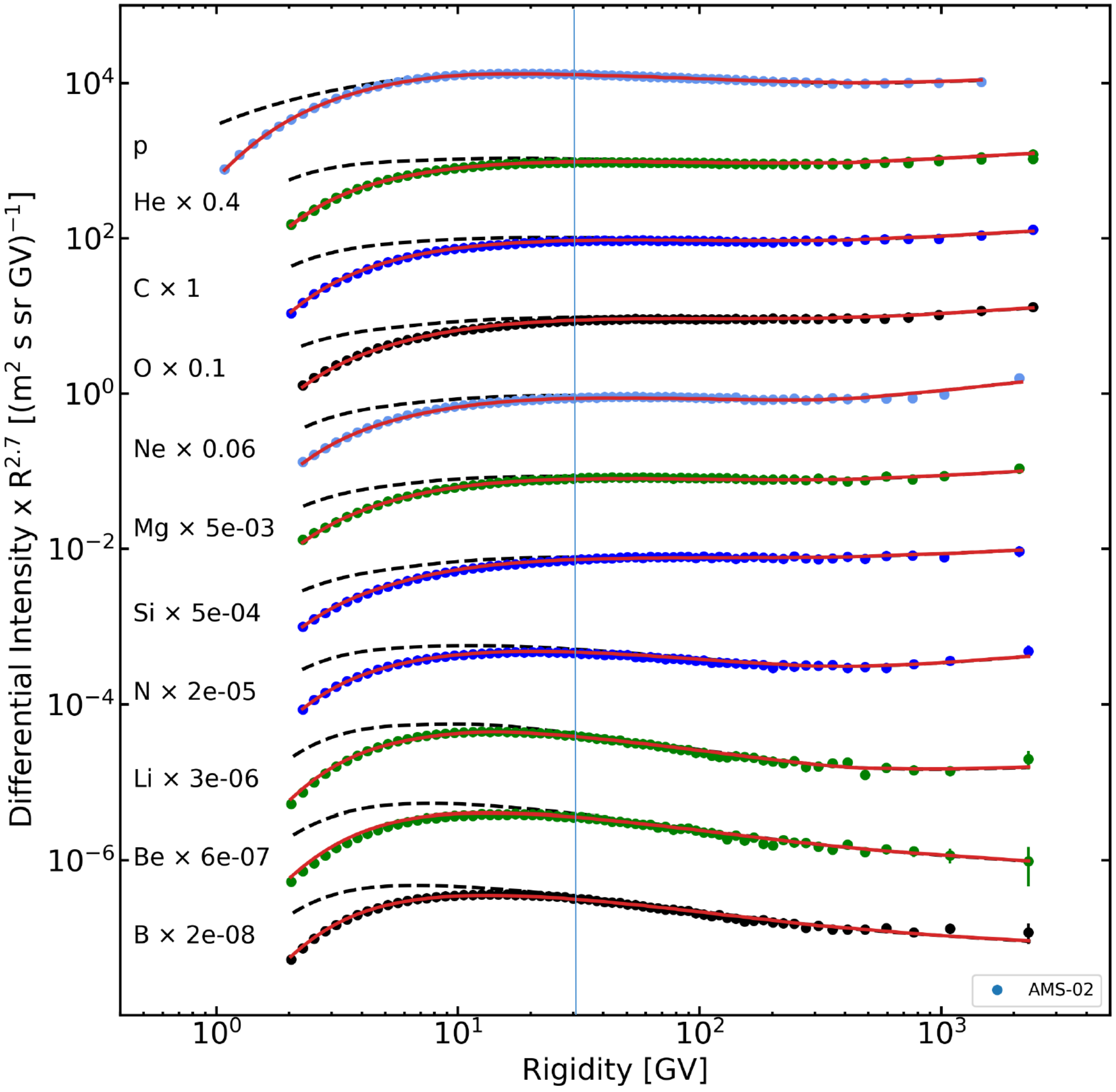
M. Boschini, S. della Torre, N. Masi, I. Moskalenko, L. Quadrani, P.G. Rancoita *et al.*,
Solution Of Heliospheric Propagation: Unveiling The Local Interstellar Spectra Of Cosmic Ray Species,
The Astrophysical Journal **840**:115 No 2, 2017, arXiv:1704.06337



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 v56** 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



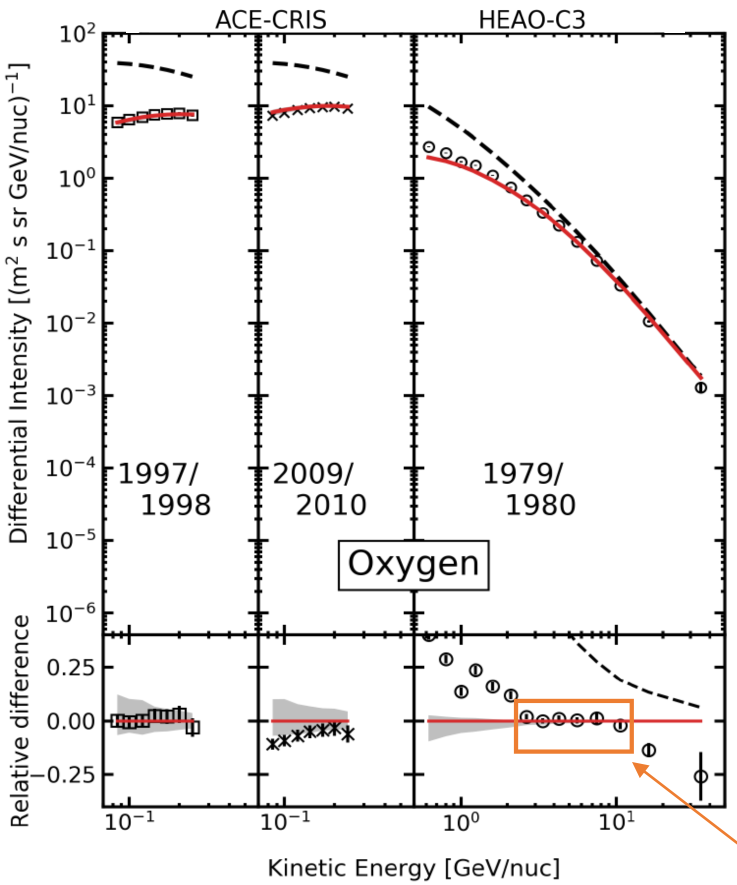
Best-fit propagation parameters for I- and P-scenarios

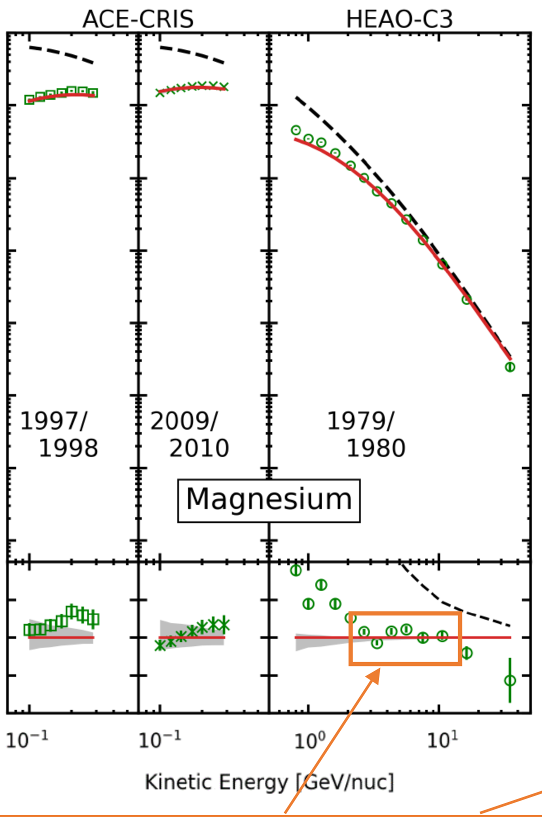
Parameter	Units	Best Value	Error
z_h	kpc	4.0	0.6
$D_0(R = 4\ \mathrm{GV})$	$\mathrm{cm^2\ s^{-1}}$	4.3×10^{28}	0.7
δ^a		0.415	0.025
V_{Alf}	$\mathrm{km\ s^{-1}}$	30	3
dV_{conv}/dz	$\mathrm{km\ s^{-1}\ kpc^{-1}}$	9.8	0.8

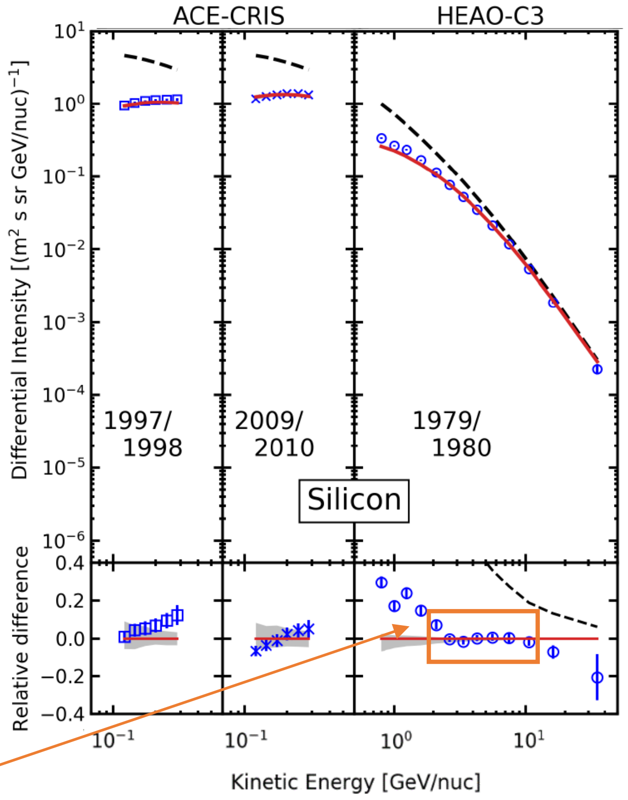
[a] The P-scenario assumes a break in the diffusion coefficient with index $\delta_1 = \delta$ below the break and index $\delta_2 = 0.15 \pm 0.03$ above the break at $R = 370 \pm 25$ GV

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

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

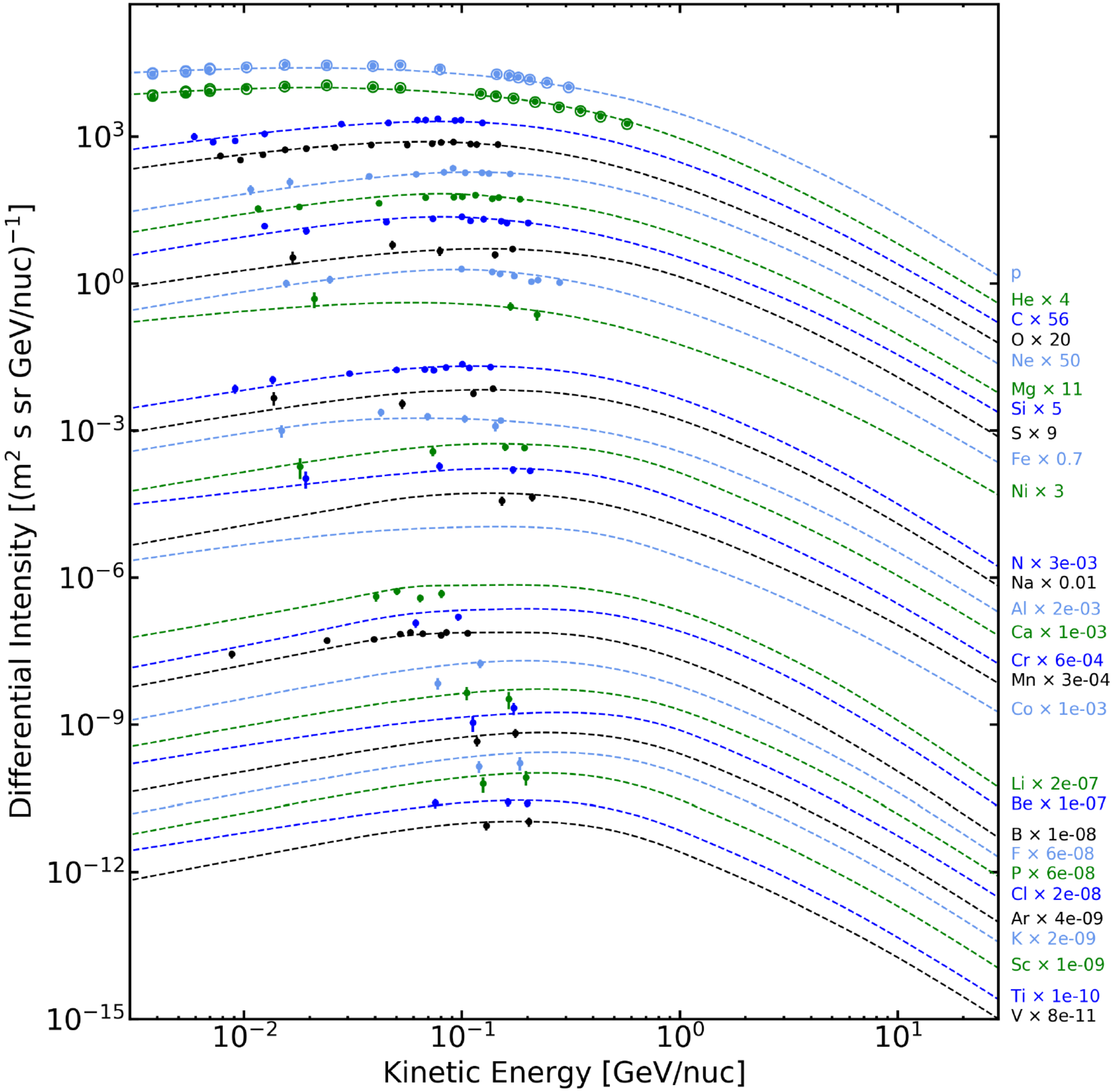






AMS-02 and HEAO normalization coincide at the % level in this region (2.65-10.6 GeV/n) for not to heavy species

Interstellar spectra measured by Voyager-1



All Z ≤ 28 are well reproduced

Our website provides numerical LISs, formulas and plots

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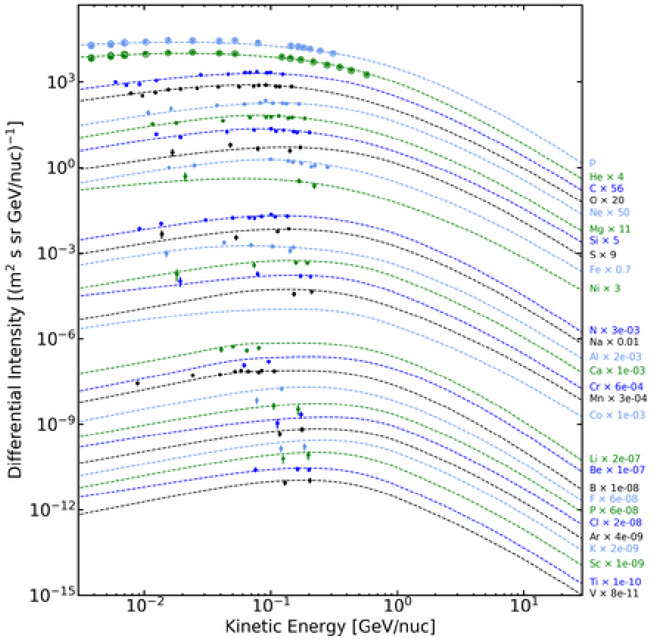
Local Interstellar Spectra from Galprop-HelMod join effort

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

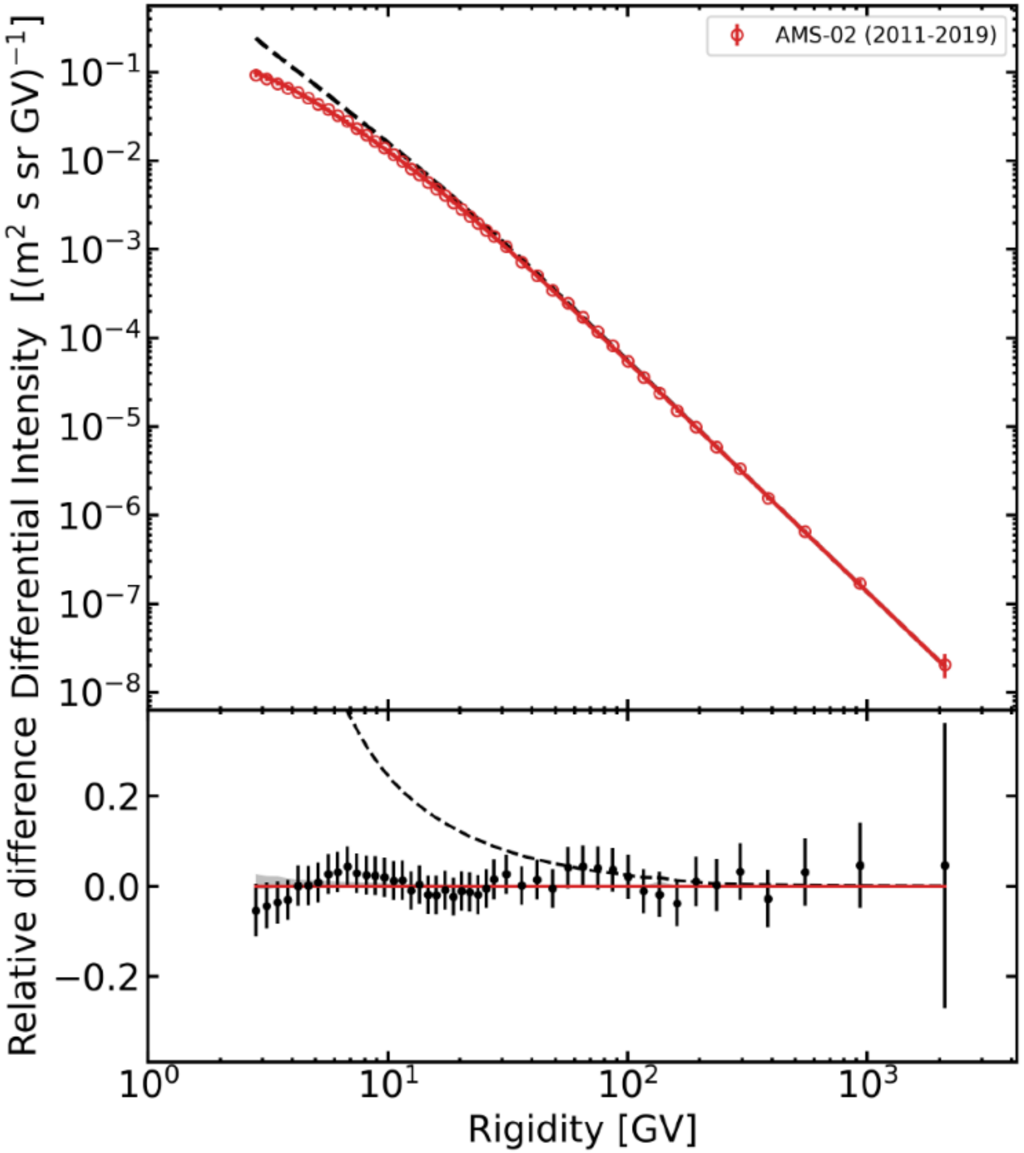
Some of the currently available LIS's were derived accounting for AMS-02 data published up to TV rigidity region. The exploitation of AMS-02 data allowed one to approach the procedure with high statistic data of unprecedent accuracy. Currently, the observation data at Earth on cosmic rays species from 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).



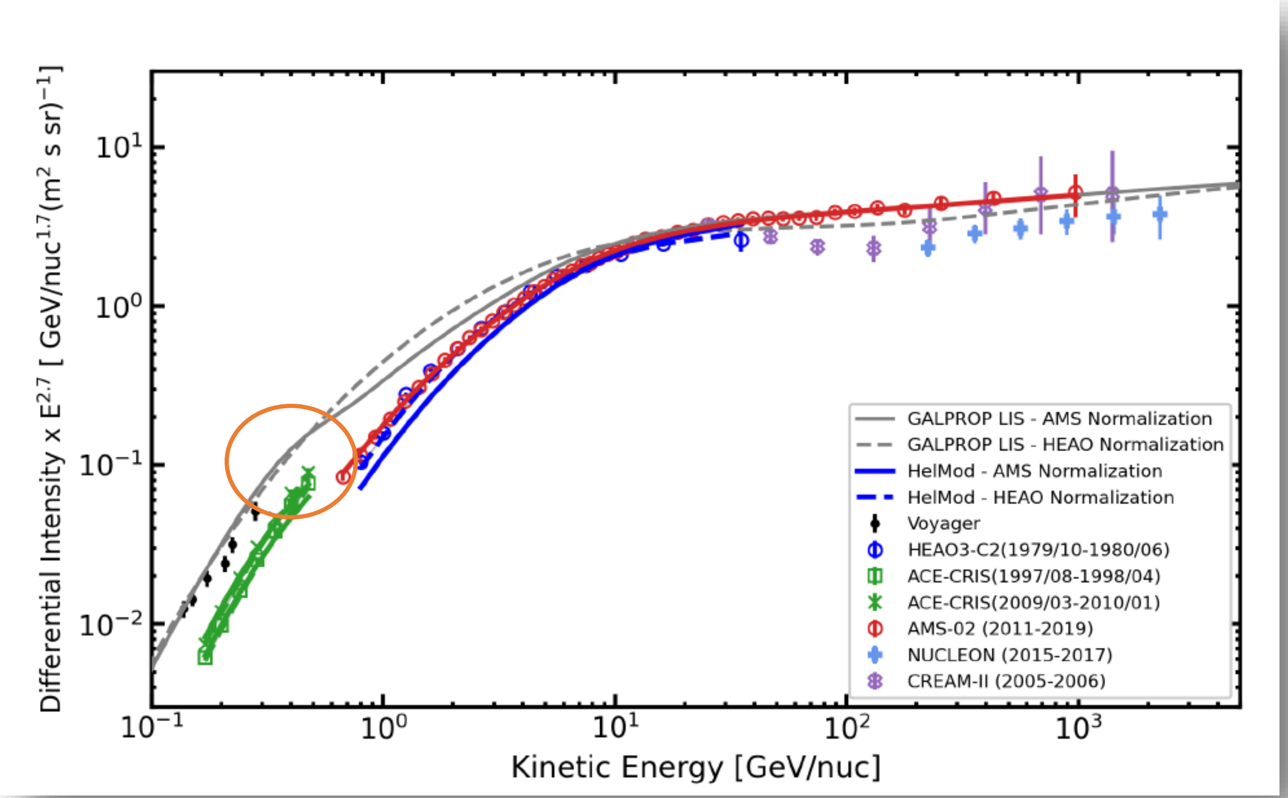
The GALPROP LIS for all CR species (dashed lines) are compared to the Voyager 1 data (filled circles, Cummings et al 2016). We also show updated Voyager 1 data for H and He (open circles) taken from September 1, 2012 to November 13, 2019. The elements are sorted by approximate amount of primary contribution: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

The new iron from AMS-02



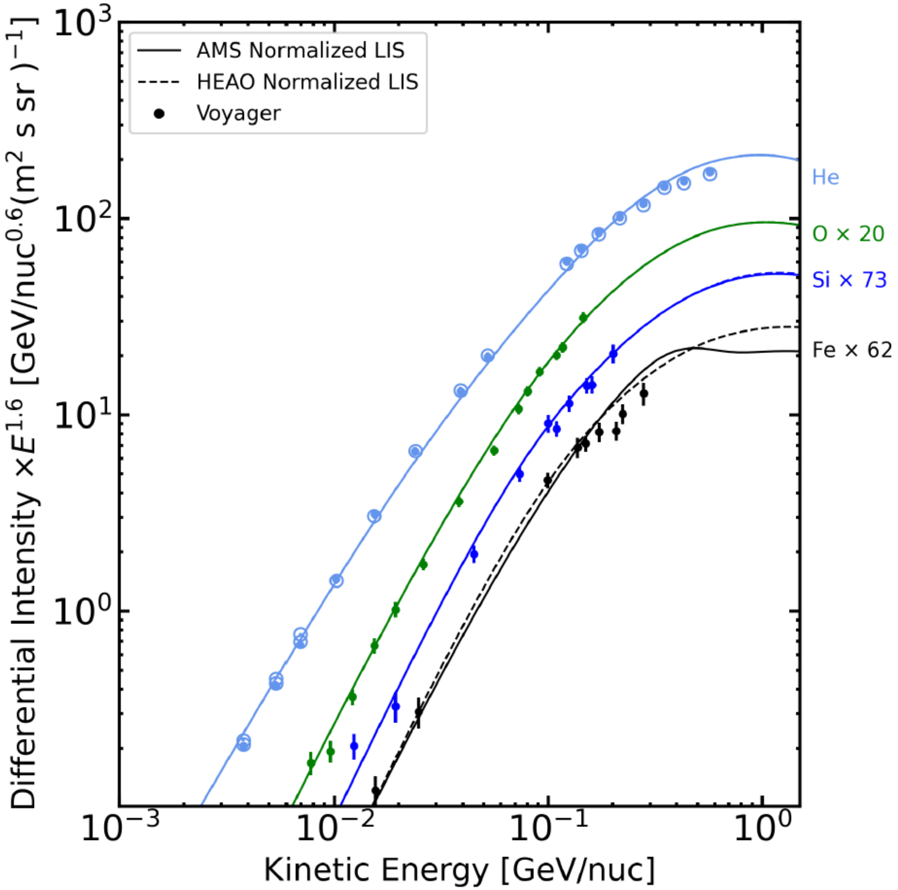
- Because of the large fragmentation cross section and large ionization energy losses, most of CR iron at low energies is local, and may harbor some features associated with supernova activity inside the Local Bubble
- **The analysis of iron spectrum together with Voyager-1 and ACE-CRIS data reveals the unexpected necessity of a bump** in the iron spectrum at 1÷3 GV (0.2÷0.7 GeV/n)



AMS-02 driven Fe LIS

The injection spectrum of iron

	Spectral parameters												
Nucleus	γ_0	R_0 (GV)	s_0	γ'	R' (GV)	s'	γ_1	R_1 (GV)	s_1	γ_2	R_2 (GV)	s_2	γ_3
Old $_{26}$Fe	0.27	1.04	0.18	...	...	...	1.99	7.00	0.20	2.51	355	0.17	2.19
New $_{26}$Fe	0.95	2.00	0.20	3.62	2.94	0.10	2.05	17.0	0.18	2.452	355	0.17	2.23



$$F_{\rm Fe}(R) = \begin{cases} R^{-2.7}\left[a - bR + cR^2 - dR^3 + f\tanh\left(\tanh\left(RG(-gR)\right)\right) - hG(iR^2)\right], & R \le 2.8\,\text{GV}, \\ R^{-2.7}\left[l - mR - n\tilde{R} + o\dfrac{\tilde{R}}{R^2} - \dfrac{p}{\tilde{R}} + \dfrac{q}{R^2\tilde{R}} + r\log\left(s+R\right) + \dfrac{t}{\tilde{R}\log\left(s+R\right)}\right], & R > 2.8\,\text{GV}, \end{cases}$$

$$\tilde{R} = \log R,$$

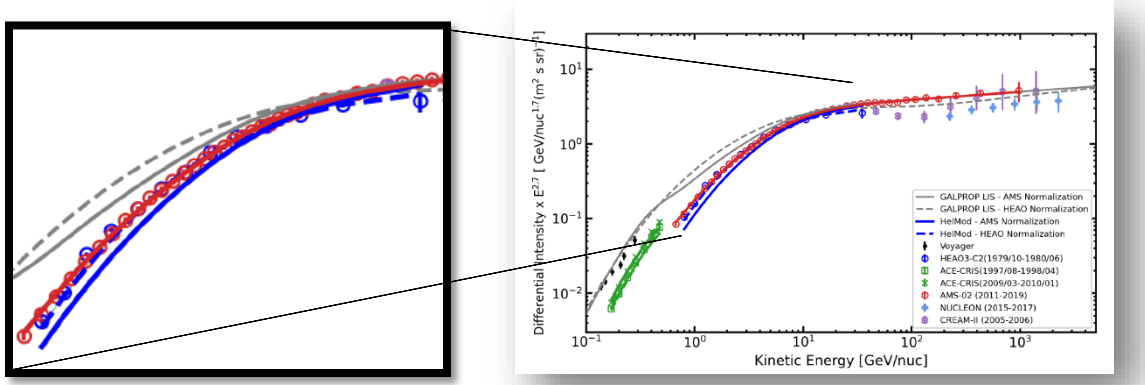
$$G(x) = e^{-x^2}.$$

Analytical formulas and numerical LIS are provided in ApJ 913 5, 2021

Discrepancy between HEAO and AMS

- Previous analysis has shown that the middle range of the HEAO-3-C2 data agrees well with AMS-02 data for light and medium nuclei.
- All **HEAO-3-C2 data points for Fe overlap with AMS-02 data**, but the solar modulation levels during their data taking are dramatically different: HEAO was launched on 1979 September 20 and ended on 1981 May 29 and took the data during the solar maximum conditions, while the AMS-02 data were taken from 2011 to 2019, i.e., through almost the entire Cycle 24, where the solar activity was moderate. Therefore the LISs derived from these two data sets are also quite different.
- Possible sources of errors for HEAO:

  1. technology gap and lack/poor rigidity calibration;
  2. incorrect evaluation of nuclear fragmentation.

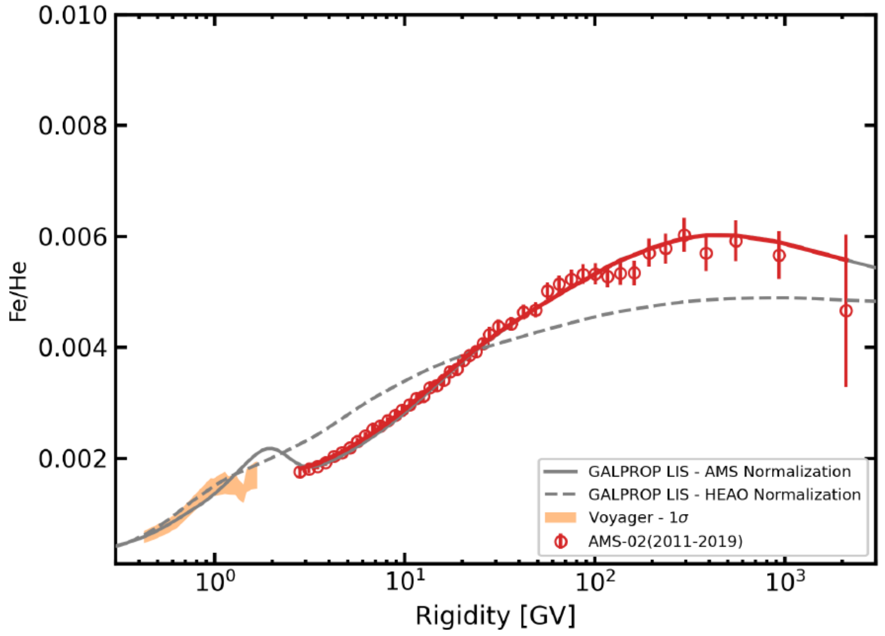


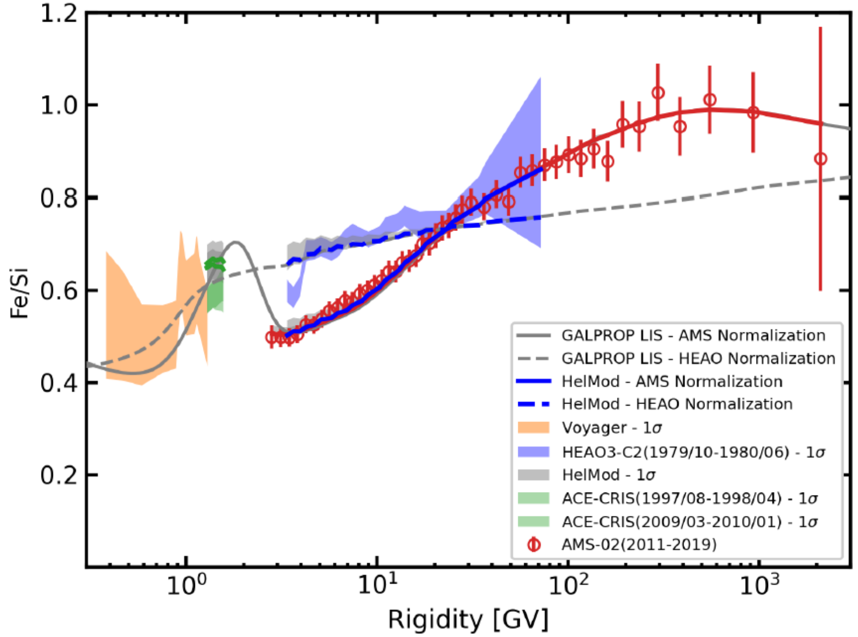
- In HEAO data analysis, the charge-changing cross section was assumed to be energy independent:

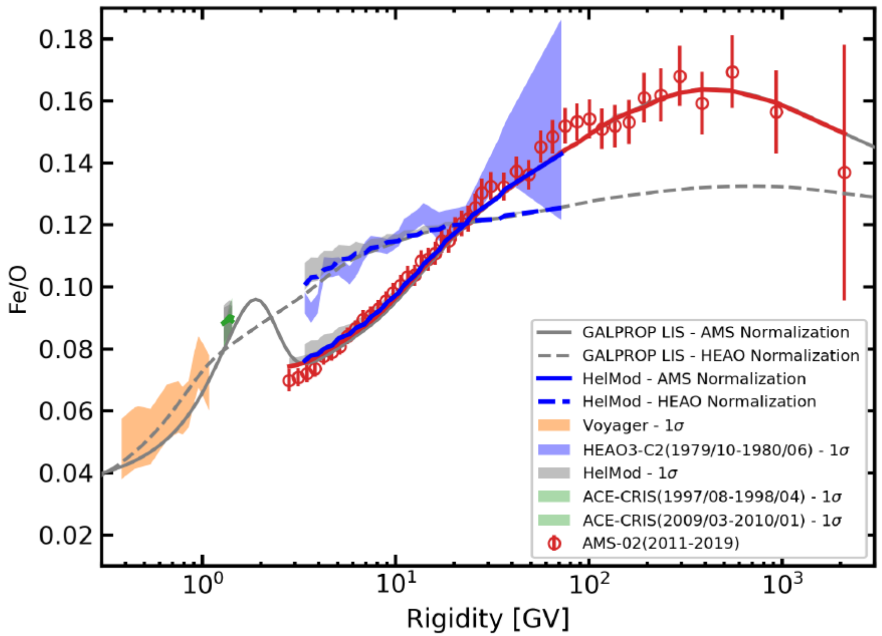
$$\sigma = 57.3(A_t^{1/3} + A_p^{1/3} - 0.83)^2$$

- If our conclusion is correct, we should see a gradual increase in the discrepancy between the HEAO-3-C2 “plateau” data and AMS-02 data as the mass number increases from Si to Fe.

Iron to primaries ratios

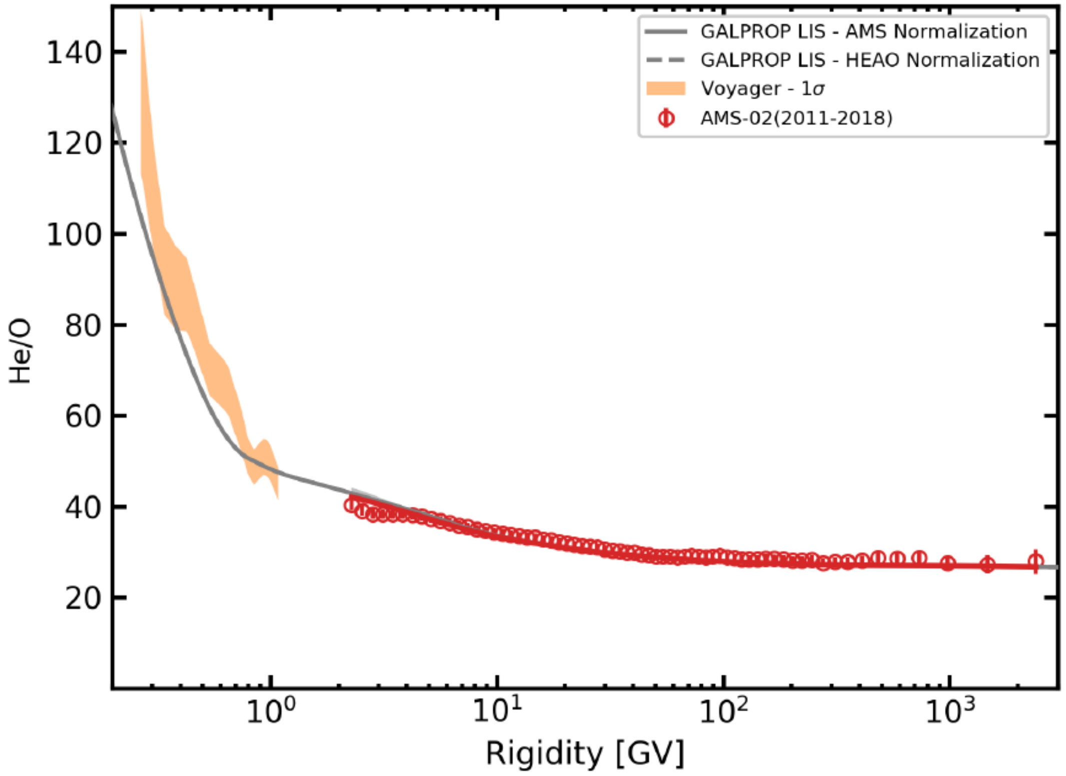


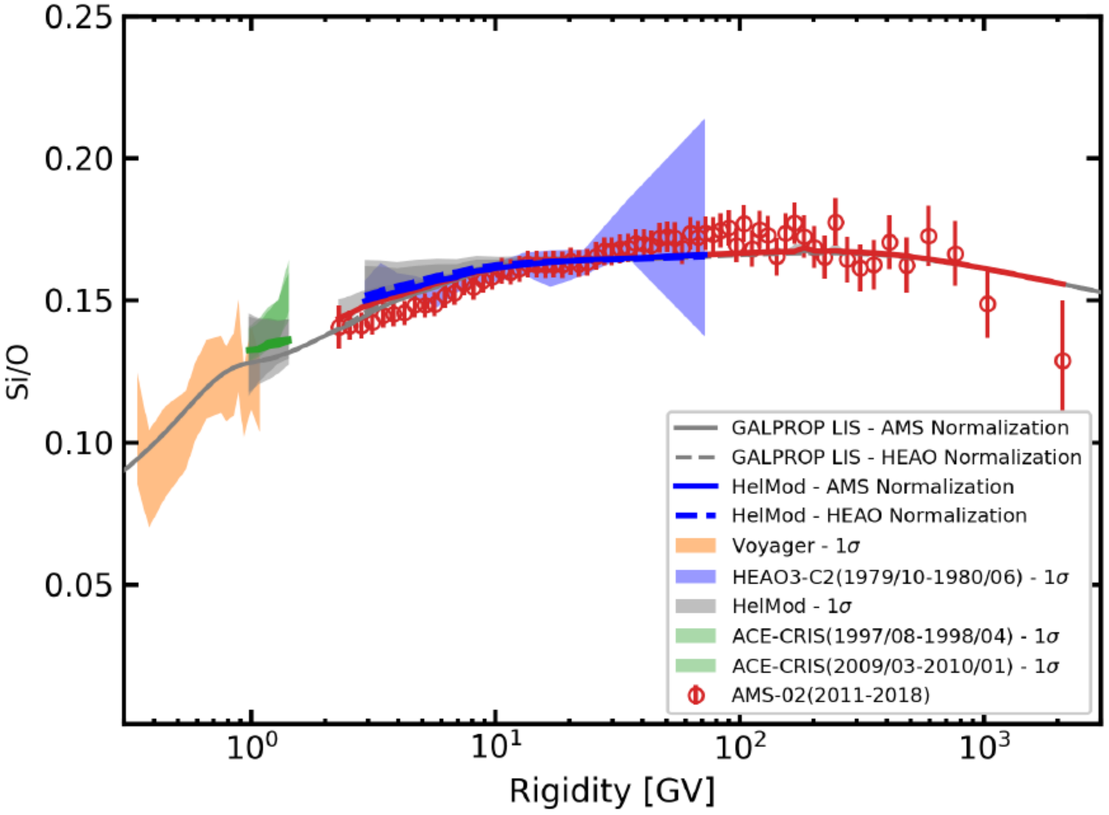




HEAO and AMS-02 data are not compatible, so we had to renormalize Iron to AMS-02: the only way to recover ACE and Voyager-1 data is to introduce a bump peaked at 2 GV.

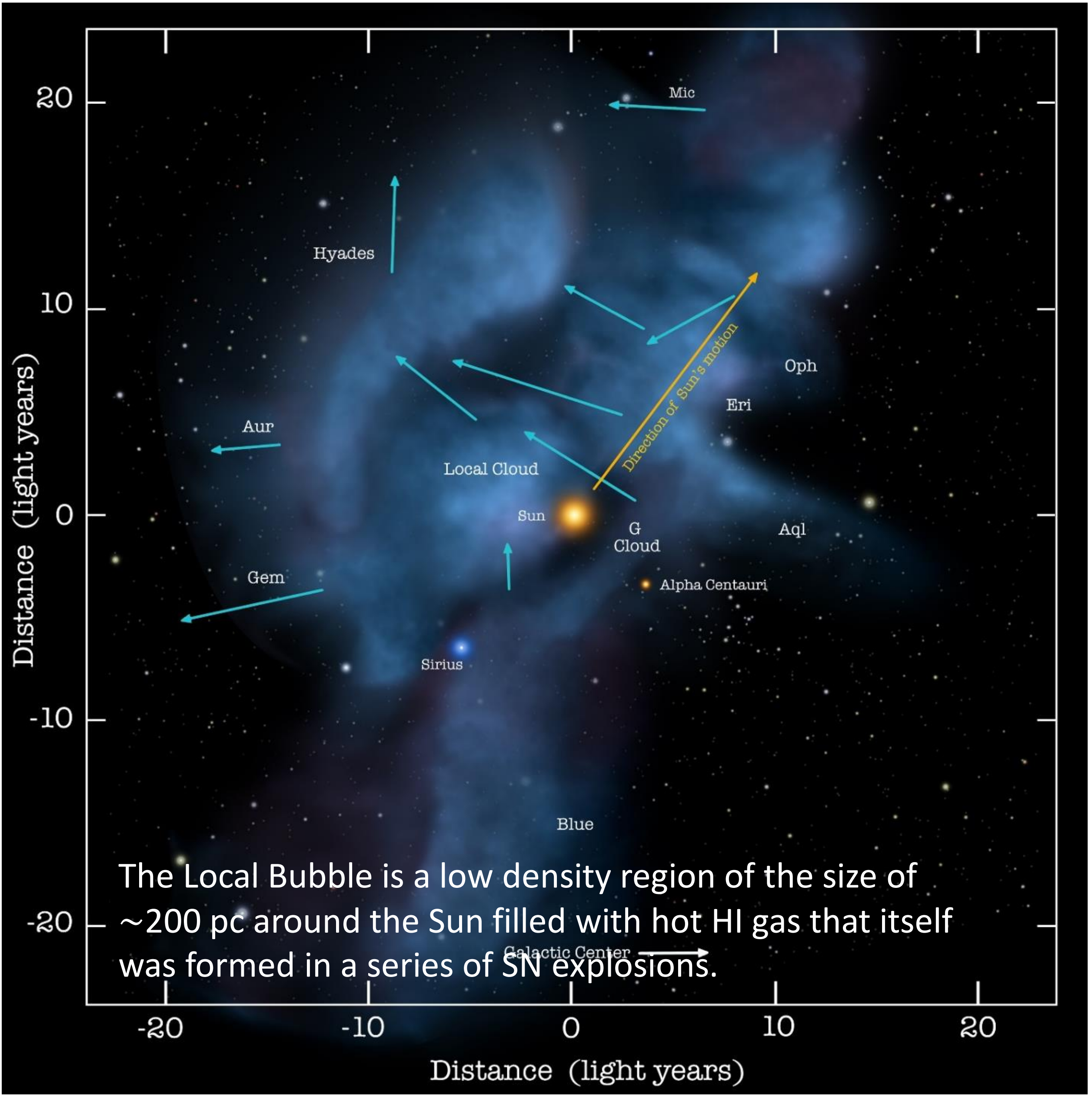
No signs in He, O, Si





A similar feature in the spectra of He, O, Si, and in their ratios is absent, hinting at a local source of low-energy CRs.

A local SNe event and Sne remnants



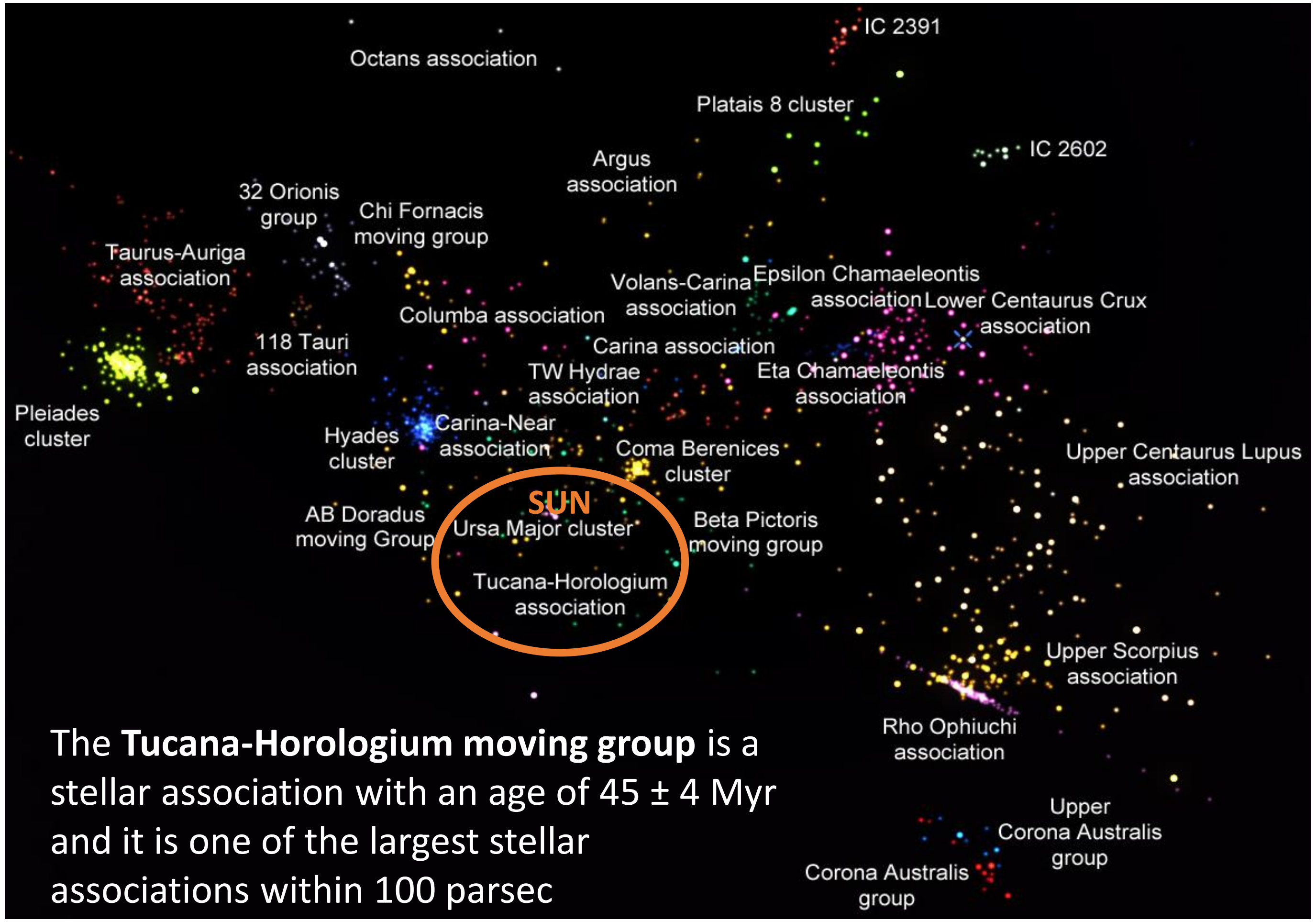
The Local Bubble is a low density region of the size of ~200 pc around the Sun filled with hot HI gas that itself was formed in a series of SN explosions.

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. ACE-CRIS experiment measured a $^{60}Fe/^{56}Fe$ ratio of (4.6±1.7)·10^-5 near Earth.

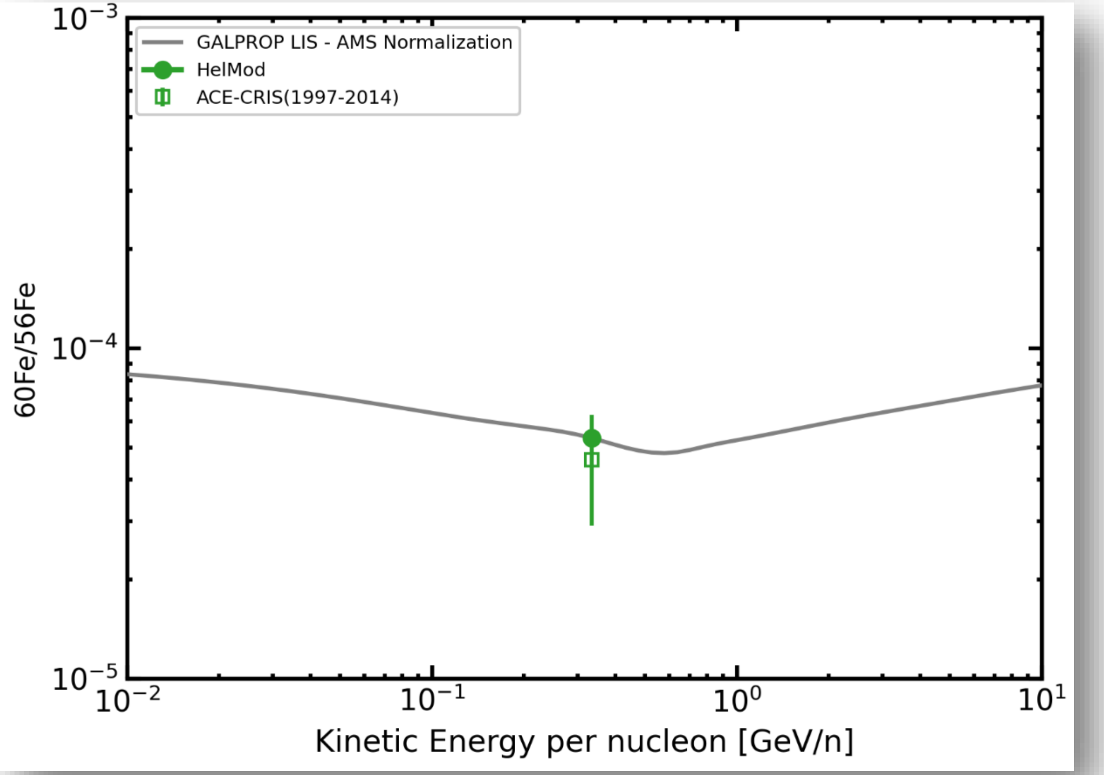
It is hard to establish the number of SNe events and their exact timing, but it is clear that there could be several events during the last ~10 Myr at distances of up to 100 parsecs.

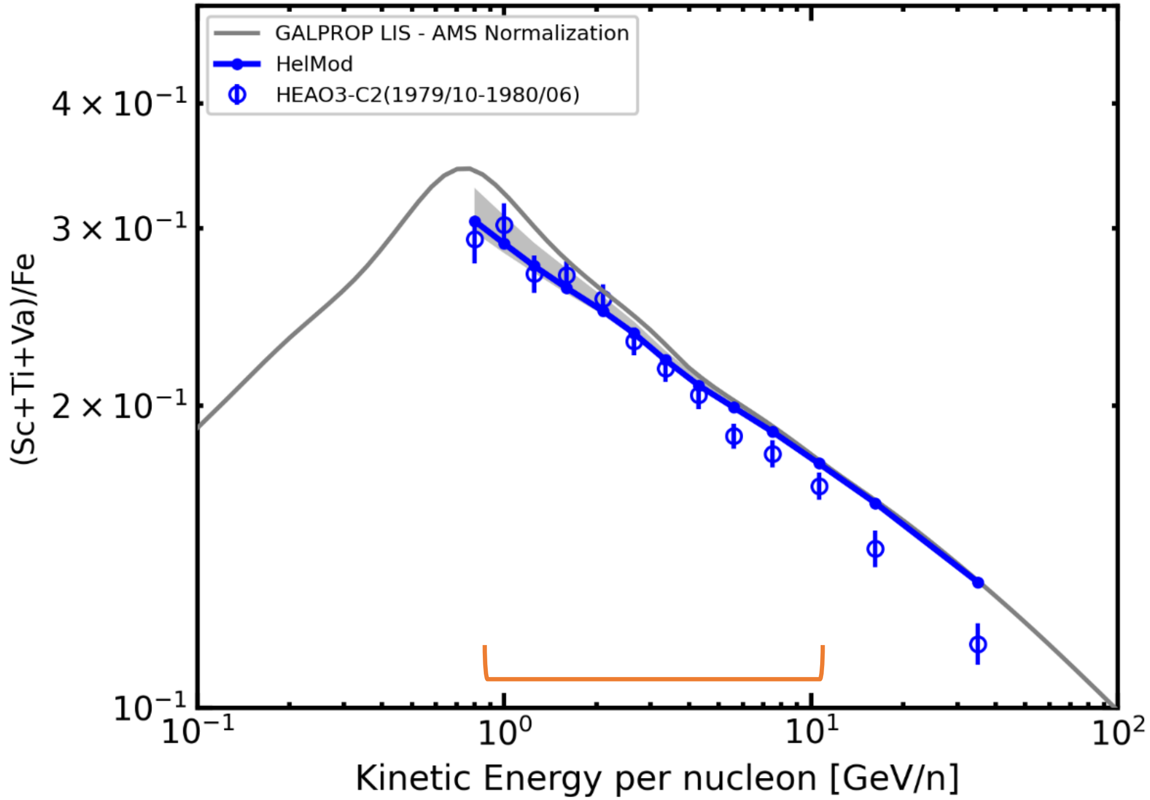
- The most recent SN events in the solar neighborhood were 1.5–3.2 Myr and 6.5–8.7 Myr ago
- *Breitschwerdt et al.* indicates two SNe 90–100 pc away with the closest occurred 2.3 Myr ago and the second exploded about 1.5 Myr ago, both with stellar masses of $\sim 9M_{\odot}$.
- *In Fry et al.* the authors infer from lunar ^{60}Fe deposition a possible progenitor SN occurring 2.8 Myr ago within the **Tuc-Hor stellar group**, at a distance of $\sim$ 50 pc and 8 ÷ 10 $M_{\odot}$.
- ^{60}Fe/^{56}Fe yield at source suffers at least one order of magnitude of uncertainty as a function of the ^{59}Fe(n, γ) ^{60}Fe cross section in the C-burning and He-burning shells of the star.
- Having no ^{60}Co isotope data available to correlate ^{60}Fe to its $\beta-$ decay product, it is hard to characterize present ^{60}Fe abundance in CRs: X-rays emission from ^{60}Co atomic transitions will be an interesting prospect for future missions, along with gamma lines from ^{60}Fe itself in nearby SN remnants.



The **Tucana-Horologium moving group** is a stellar association with an age of 45 ± 4 Myr and it is one of the largest stellar associations within 100 parsec

Rare isotope composition and SubFe/Fe ratio





- The correct ACE-CRIS $^{60}Fe/^{56}Fe$ ratio could be reproduced within our model only assuming a primary ^{60}Fe component, with a normalized abundance at sources of about 0.05 w.r.t. 577 for ^{56}Fe: (8.7·10^-5)
- This is fully consistent with the (7.5±2.9)·10^-5 ACE-CRIS prediction at source.

Good agreement in the 1÷10 GeV/n range

Conclusions

- Since its launch the Alpha Magnetic Spectrometer-02 has delivered outstanding quality measurements of the spectra of cosmic-ray.
- The analysis of new iron spectrum by AMS-02 within the GALPROP–HELMOD framework, together with Voyager-1 and ACE-CRIS data, provided an updated local interstellar spectrum in the energy range from 1 MeV/n to 10 TeV/n: it revealed an unexpected bump both in iron and in the Fe/He, Fe/O and Fe/Si ratios at 1–3 GV.
- This was the first time such an excess was found in the spectrum of an element that is dominated by stable species: it will be fundamental to measure the spectra of other heavy CR species to see if a similar spectral feature is present.
- The new-found excess in the Fe spectrum around 2 GV is falling in line with other excesses in iron rare isotope ^{60}Fe, which is likely connected to the past SN activity in the Local Bubble.
- Starting from this LIS and the $^{60}Fe/^{56}Fe$ abundance measured by ACE-CRIS, ^{60}Fe primary component was estimated, along with the prediction of the important SubFe/Fe ratio.
- To further constrain the ^{60}Fe yield from SNe and interpret the 1.5 ÷ 3 Myr ago progenitor event, it will be useful to study the possible associate production of the long-lived radioactive ^{26}Al isotope.