Understanding Galactic Cosmic Rays: The Critical Role of Nuclear Cross-Sections

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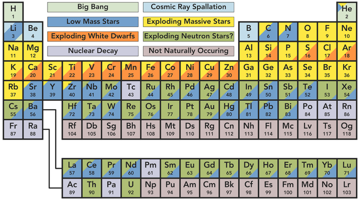
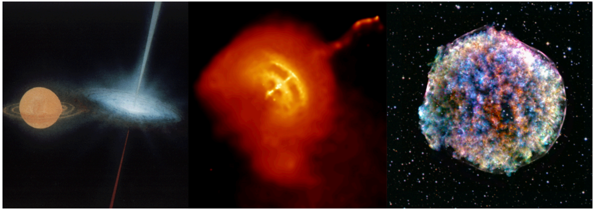
Why Should We Be Interested in Galactic Cosmic Rays?

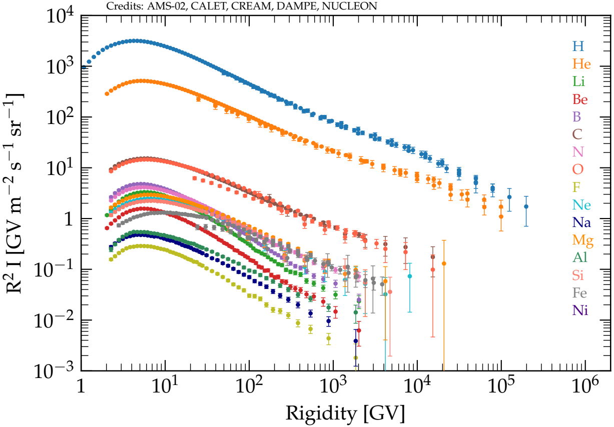




- **Probing the Universe's Most Energetic Phenomena:**
  GCRs originate from some of the most extreme environments in the universe, such as supernovae and other high-energy astrophysical sources, providing insight into processes we cannot (yet) replicate on Earth.
- **Natural Probes of the Galaxy:**
  By studying how GCRs propagate through the Galaxy, we gain valuable knowledge about magnetic fields, gas distributions, and the overall structure of the Milky Way.
- **A Window into Dark Matter:** (see Di Mauro's talk)
  Certain GCR interactions may reveal indirect evidence about the nature of dark matter, helping us study this mysterious component of the Universe.
- **Origins of Elements:**
  Fragile nuclei between helium and carbon are rarely formed in stars. Significant contributions from interactions of primordial cosmic rays in early galaxies.

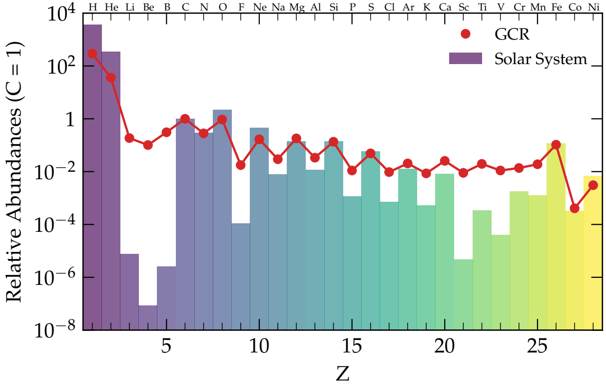
Unprecedented Measurements of GCR Flux and Composition Below the Knee

- Direct measurements are now exploring the **multiple TeV** scale
- The spectrum **of each isotope** includes contributions from various parents - both in terms of **fragmentation** and **decays** - resulting in a very complex history for each observed element
- **How do we combine all this information to tell a coherent story?**



Acknowledgments: All plots in this presentation were made easier thanks to the CRDB database https://lpsc.in2p3.fr/crdb/.

The Cosmic-Ray Composition as a Measure of the Galactic Grammage



- Thermal particles in the average ISM are somehow accelerated to relativistic energies, becoming cosmic rays (CRs) → primary CRs
- A secondary population is produced during propagation by the spallation of primary CRs → secondary CRs
- The average Galactic Grammage $\chi_{\rm gal}$ can be directly inferred from this plot ($E \sim$GeV) provided we know the relevant cross-section:

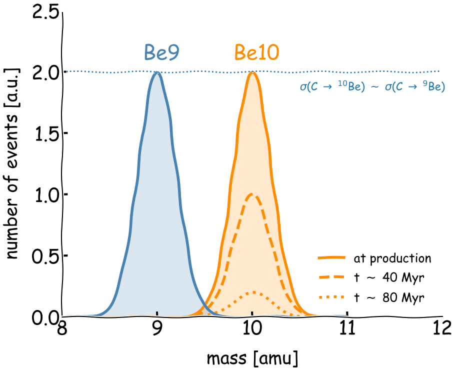
$$\frac{\mathrm{B}}{\mathrm{C}} \sim \chi_{\rm gal} \frac{\sigma_{\rm C \to B}}{\langle m \rangle_{\rm ISM}} \sim 0.3 \longrightarrow \chi_{\rm gal} \sim 5\ \mathrm{g\,cm}^{-2}$$

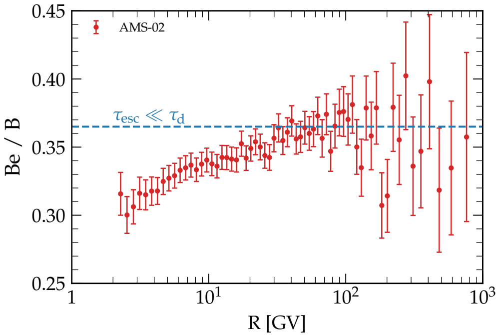
- This should be compared with the grammage χ_d accumulated at each crossing of the gas disk $h \sim 100$ pc:

$$\chi_d \sim m_p n_{\rm gas} h \sim 10^{-3}\ \mathrm{g\,cm}^{-2} \ll \chi_{\rm gal}$$

Accurate determination of grammage is crucial for any cosmic ray propagation model → microphysics

The Cosmic-Ray Isotopic Ratio and the Galactic Lifetime

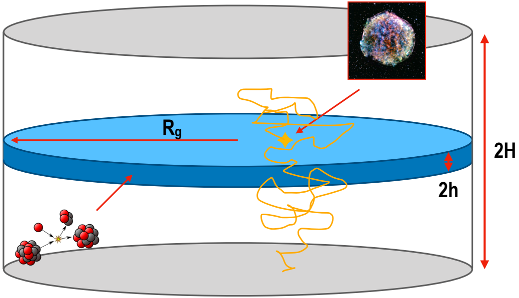




- ^{10}Be is a β^- unstable isotope that decays into ^{10}B with a half-life of approximately 1.5 Myrs
- ^{9}Be and ^{10}Be have similar production rates $\sigma_{\rm Be9} \sim \sigma_{\rm Be10}$
- Traditionally, the ^{9}Be/^{10}Be ratio has been used as a cosmic ray clock; however, there are only poor measurements of this ratio at $E \gtrsim 1$ GeV/n
- The observed Be/B ratio is affected twice by this effect hinting a galactic lifetime of $t_{\rm esc} \sim \mathcal{O}(100)$, Myr $\gg \frac{R_{\rm G}}{c}$

The Galactic Halo Model

Morrison, Olbert, and Rossi, Phys. Rev (1954); Ginzburg and Syrovatskii (1964)



- GCRs are accelerated within the disk h by SNRs and subsequently injected with a universal spectrum $Q_s \propto E^{-\alpha}$ where $E \gtrsim 2$.
- Post-injection, CRs propagate diffusively throughout the Galactic halo (approximately 1-D) with a diffusion coefficient $D \propto E^{\delta}$, where $\delta \sim 1/3 - 1/2$ depending on the turbulence model.
- Secondary production, such as Li, Be, and B, occurs predominantly in the disk h where all the gas is concentrated.
- H represents the diffusive halo height (free escape boundary) and R_d denotes the radius of the Galactic disk.
- All these parameters have profound implications for the microphysics of cosmic ray acceleration and transport!

Main Galactic Halo Model Predictions

Evoli & Dupletsa, arXiv:2309.00298

- Focus on a simplified case with only one secondary species and one parent nucleus: C⟶B.
- For Carbon (primary), source term is proportional to SN rate R_{SN} and spectrum $N_{\mathrm{SN}}(p) \propto E^{-\alpha}$:

$$Q_{\mathrm{C}} = \frac{N_{\mathrm{SN}}(E)\mathcal{R}_{\mathrm{SN}}}{\pi R_d^2 H} \Rightarrow f_{\mathrm{C}}(E) = \overset{\text{injection}}{\boxed{\frac{N_{\mathrm{SN}}(E)\mathcal{R}_{\mathrm{SN}}}{\pi R_d^2 H}}} \overset{\text{escape}}{\boxed{\frac{H^2}{D(E)}}} \propto E^{-\alpha-\delta}$$

- While for Boron (secondary), source term is proportional to production cross-section $\sigma_{\mathrm{C}\to\mathrm{B}}$ and mean target density $\bar{n}$:

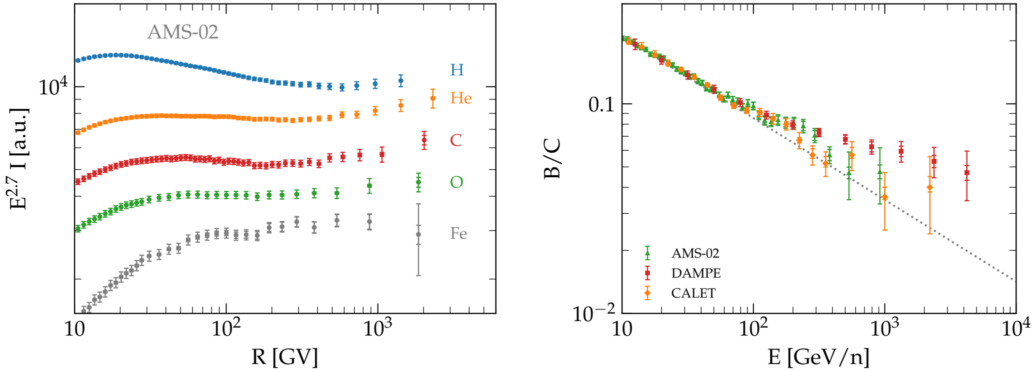
$$Q_{\mathrm{B}} = v\bar{n}\,\sigma_{\mathrm{C}\to\mathrm{B}}\, f_{\mathrm{C}}(E) \Rightarrow f_{\mathrm{B}}(E) = \overset{\text{injection}}{\boxed{v\bar{n}\,\sigma_{\mathrm{C}\to\mathrm{B}} f_{\mathrm{C}}(E)}} \overset{\text{escape}}{\boxed{\frac{H^2}{D(E)}}} \propto E^{-\alpha-2\delta}$$

- The ratio between the two becomes:

$$\boxed{\frac{\mathrm{B}}{\mathrm{C}} = v\bar{n}\,\sigma_{\mathrm{C}\to\mathrm{B}} \frac{H^2}{D(E)} \propto \frac{H}{D_0} E^{-\delta}}$$

Notice however that $\bar{n} = n_d \frac{h}{H}$ so that B/C is sensitive only to the H/D ratio

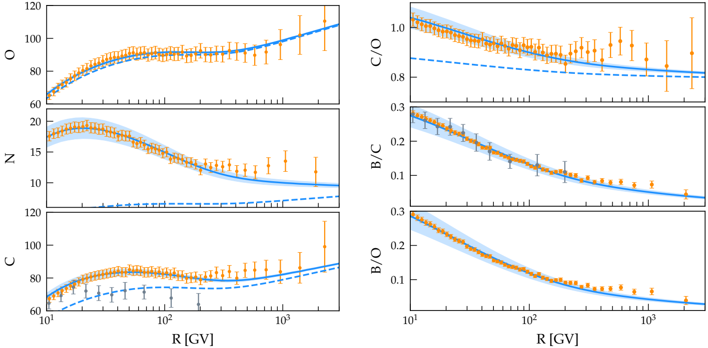
A remarkable hardening at $R \gtrsim 300$ GV



- A break was first identified by the experiments ATIC-2 [Panov et al. 2009], CREAM [Ahn et al. 2010], and PAMELA [Adriani et al. 2011].
- The CR spectrum cannot be described by a single power law.
- Spectral break indicates that at least one process among acceleration, escape, or transport cannot be described by a single power law
- The same break observed in the B/C ratio suggests an explanation involving the diffusion coefficient → changes in transport

The Galactic Halo Model confront measurements: secondary-over-primary ratios

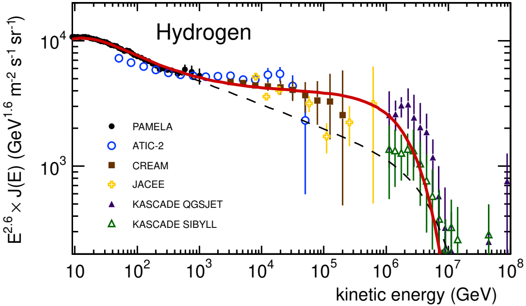
Evoli+, PRD 99, 2019; Weinrich+, A&A 639, 2020; Vecchi+, arXiv:2203.06479

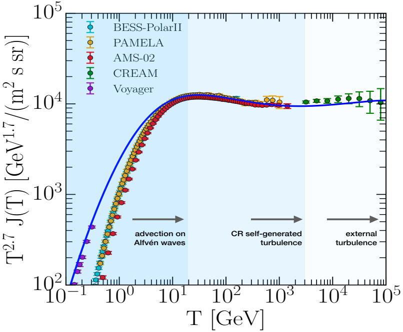


- By fitting primary and secondary/primary measurements we found: $\delta \sim 0.54$, $D_0/H \sim 0.5 \times 10^{28}$ cm/s^2/kpc, $\Delta\delta \sim 0.2$, $v_A \sim 5$ km/s
- All nuclei injected with $\alpha \sim 2.3$ - It remains true even for intermediate mass elements Ne, Si, Mg, and S [Schroer, CE, and Blasi, PRD 2021]
- Oxygen - alongside H - is the only pure primary species
- Shaded areas shows uncertainty from cross sections still the largest ones

Secondary-to-Primary Ratios and the Origin of the Hardening

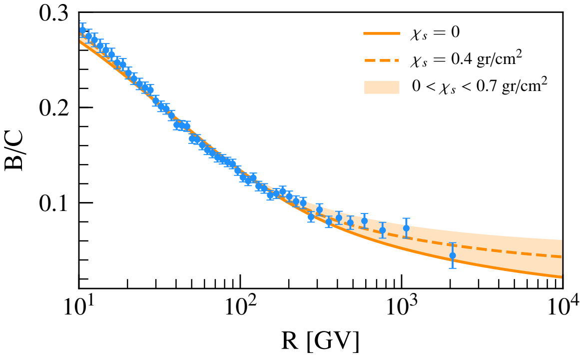
Blasi+, PRL 2012; Tomassetti, A&A 2012; Evoli+, PRL 2018





- At ~ 300 GV, a similar break is detected in the secondary-to-primary ratios → a change in CR transport within the Galaxy.
- Currently, two physical interpretations are proposed:
  - It marks the transition between the self-generation of turbulence by CRs themselves and the large-scale turbulence
  - The transition results from differing turbulence conditions in the disk and halo
- It remains unclear if these interpretations fully reproduce the sharpness of the observed feature

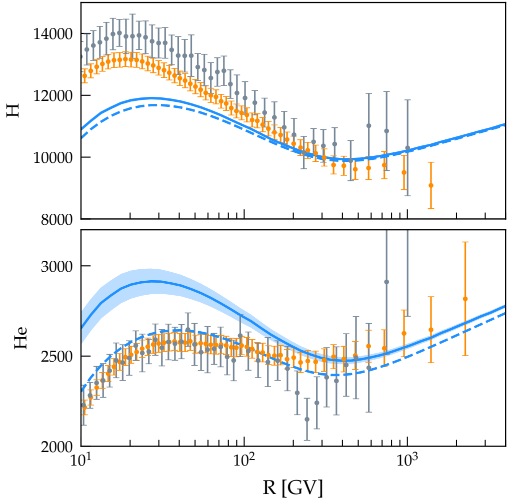
Beyond the Standard Halo Model: Grammage at Source?



- Growing evidence suggests the presence of low-diffusion regions around cosmic-ray sources [Hanabata+, ApJ 2014; Aharonian+, Nature Ast. 2019; Abeysekara+, Science 2017].
- At high energies, the secondary-to-primary ratio is likely influenced by the grammage accumulated near the source environment [Malkov+, ApJ 2013; D'Angelo+, PRD 2016; Nava+, MNRAS 2016; Jacobs+, JCAP 2022].
- This effect leads to a flattening of the secondary-to-primary ratio at energies $\gtrsim$ TeV/n.
- Hints of this phenomenon are observed in high-energy Boron-to-primaries measurements by DAMPE and NUCLEON.
- Identifying these effects requires grammage estimates with precision far beyond current limitations imposed by cross-section uncertainties.

The Injection of Light Nuclei: Proton and Helium

Evoli et al., PRD 99, 2019

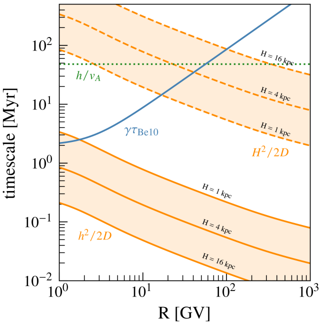


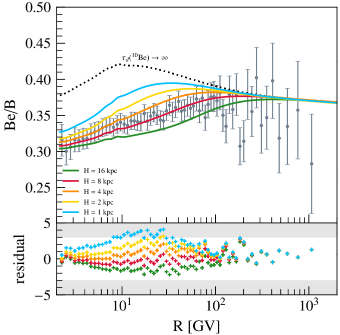
Predictions assuming $\gamma \sim 4.3$ for both protons and Helium

- Hydrogen is softer than nuclei, while helium is comparatively harder: $\Delta\gamma \sim \pm 0.05$
- This is clearly inconsistent with expectations from pure rigidity-dependent acceleration [Serpico, ICRC 2015]
- This discrepancy poses challenges even for models attributing differences in proton and helium injection to variations in A/Z ratios at shocks [Hanusch+, Apj 2019]
- For He, the issue stems from the secondary production of ^{3}He, which influences the low-energy spectrum.

The Beryllium-to-Boron Ratio and Cosmic Ray Escape Time

Evoli et al., PRD 101, 2020; Weinrich et al., A&A 2020

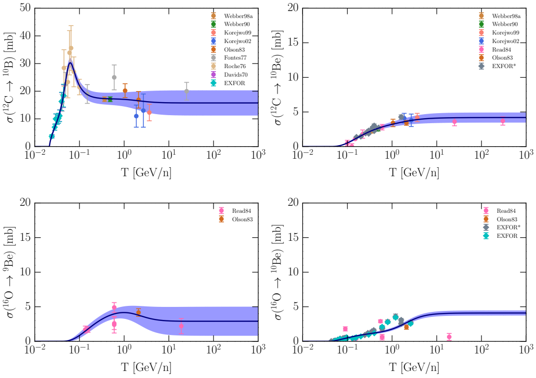


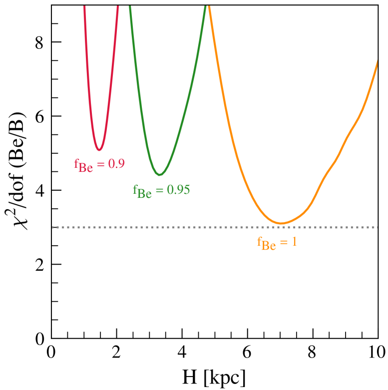


- It's crucial to ensure that ^{10}Be decays outside the Galactic disc (which may be hostile to transport) → $E \gtrsim$ few GeV
- A preference emerges for large halos ($H \gtrsim 5$ kpc), which may be in tension with the typical scale of other galactic magnetic fields.
- Note that H (halo height) and $\tau_{\rm esc}$ (escape time) are directly correlated:

$$\boxed{\tau_{\rm esc}(10\,\text{GV}) \sim \frac{H^2}{2D} \sim 20\,\text{Myr}\left(\frac{H}{\text{kpc}}\right)\left(\frac{0.25\times10^{28}\,\text{cm}^2/\text{s/kpc}}{D_0/H}\right)}$$

Determination of Cosmic Ray Lifetime: The Cross-Section Bottleneck

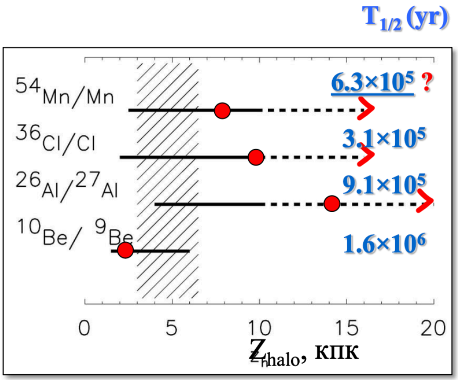




- The determination of the Halo size from the Be/B ratio is a key example of the cross-section bottleneck.
- Secondary production uncertainties critically impact results, even when measurement precision reaches 1–3%.
- For more details, see Maurin et al., A&A 667, A25, 2022.

Key Indicators of Diffusive Transport: Unstable Elements

Credit: Igor Moskalenko



- Significant variability observed among different isotopes
- Potential contributing factors:

☞ Instrumentation and/or data analysis errors

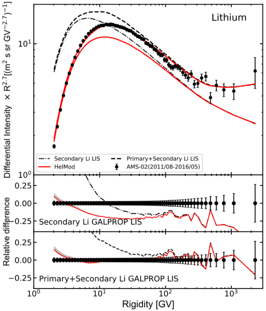
☞ Inaccuracies in cross-section calculations

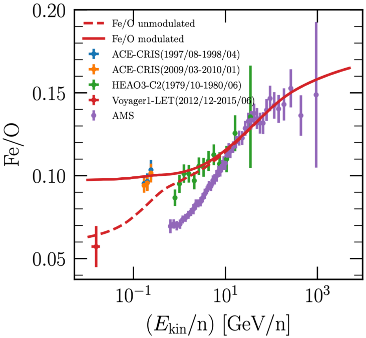
☞ Uncertainties in lifetime estimates

☞ Varying origins of elements (local vs. global sources)

Additional Anomalies in Galactic Cosmic Ray Species

Boschini+, ApJ 889, 2020; Maurin+, A&A 668, 2022

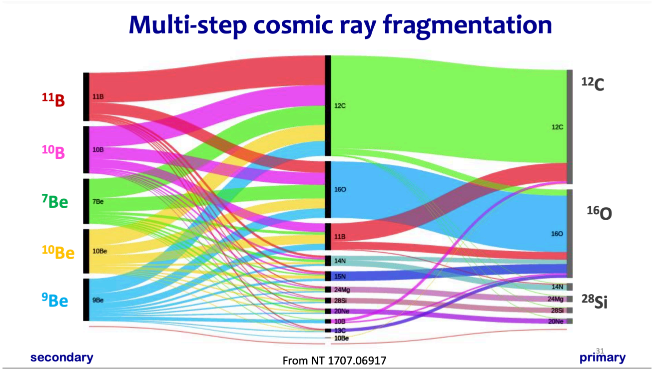




- Li spectrum appears somewhat flatter at high energies, potentially indicating a primary Lithium component ⟶ Could this imply new sources?
- Uncertainties in production cross-sections might be responsible for this discrepancy ⟶ urge measuring these channels [Maurin+, A&A 668, 2022].
- Iron anomaly: Fe and O are both pure primaries, reducing theoretical uncertainties [B. Schroer+, PRD, 2023].
- Significant disagreement persists between calorimeters (e.g., CALET/DAMPE) and spectrometers (e.g., AMS-02) for nearly all nuclei

The Nuclear Reaction Network: A Critical Bottleneck

Evoli+, JCAP 2018; Evoli+, PRD 2019; Tomassetti, PRD 2012; Genolini+, PRC 2018

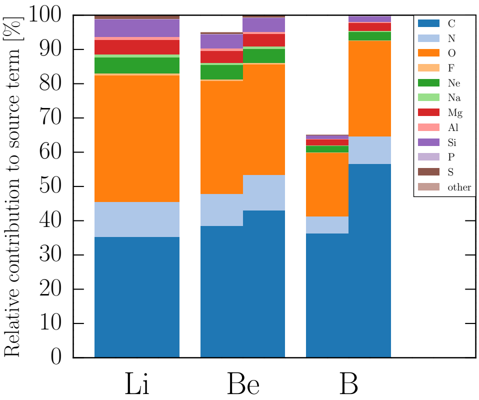


Multi-step cosmic ray fragmentation

From NT 1707.06917

- In practical simulations, we must solve a system of approximately 80 coupled partial differential equations
- Poorly understood cross-sections for spallation reactions are the primary limitation in extracting valuable information from data
- There is an urgent need for a comprehensive campaign of high-precision measurements of spallation xsecs (e.g. NA61/SHINE)

The role of intermediate lived species



- We define intermediate lived species those with half-life longer than 1 ms and shorter than $\sim 10^3$ years.
- For example, production of Be9 takes place trough the reaction:

$$
\begin{aligned}
N_i + p &\rightarrow {}^{9}\mathrm{Li}(t_{1/2} = 178\,\mathrm{ms}) \rightarrow {}^{9}\,\mathrm{Be}(\mathrm{br} = 49.2\%) \\
N_i + p &\rightarrow {}^{11}\mathrm{Li}(t_{1/2} = 8.6\,\mathrm{ms}) \rightarrow {}^{9}\,\mathrm{Be}(\mathrm{br} = 4.1\%)
\end{aligned}
$$

- The cumulative cross section of fragmentation in ^{9}Be from a primary i is:

$$\sigma^{\mathrm{effective}}_{i\rightarrow {}^9\mathrm{Be}} = \sigma^{\mathrm{direct}}_{i\rightarrow {}^9\mathrm{Be}} + 0.492 \times \sigma_{i\rightarrow {}^9\mathrm{Li}} + 0.041 \times \sigma_{i\rightarrow {}^{11}\mathrm{Li}}$$

- There are almost NO measurements for these processes.
- We need $\gtrsim$ three steps to achieve 1% accuracy![a]
- No reliable theoretical models to compute these channels → AI?

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[a] https://github.com/carmeloevoli/XS4GCR

Conclusions

- In the past two decades, charged cosmic-ray measurements below the knee have challenged many of the foundational ideas in cosmic ray physics.

- The standard model of cosmic ray acceleration at sources and their transport through interstellar and intergalactic space requires updates → several new ideas are being explored!

- A significant issue raised by the community: Cross-sections are a major limitation in discriminating between competing models!

- Pivotal results in Genolini+, PRC 2023, 2024 to rank the relevant channels of secondary production

- What can we do beyond measuring them? A wish-list:
  - A reliable (and reproducible) cross-section measurement database,
  - Open-source libraries to compute cumulative cross-sections,
  - Improved parameterizations of unmeasured reaction channels (benchmarking nuclear codes?),
  - More collaboration (alike this conference!) aimed at comparison between different approaches.

Thank you!

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- slides available at: https://zenodo.org/communities/carmeloevoli_talks