Updated Predictions for Cosmic-Ray Beryllium Isotopes

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Outline

- **Cosmic Rays:** origin, propagation, and spallation
- **Observable:** the ^{10}Be/^{9}Be radioactive clock
- **Modeling tools:** GALPROP transport + HelMod and FFA modulation
- **Analysis strategy:** baseline validation $\rightarrow$ elemental fluxes $\rightarrow$ isotope ratios
- **Results:** beryllium fluxes, isotopic ratios, radioactive clock
- **Conclusions & Outlook**

Cosmic Rays

- High Energy charged particles arriving isotropically at Earth ($\sim$90% protons, $\sim$9% helium, $\sim$1% heavier nuclei and electrons)
- Discovered by Victor Hess (1912, balloon experiments)
- Observed energy range: 10^9–10^{20} eV per particle
- Magnetic rigidity $\rho = pc/Ze$, governing motion in magnetic fields
- Only direct sample of million-year-old Galactic matter

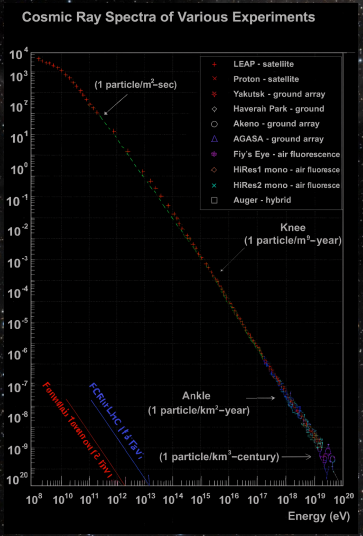
Cosmic Rays: Origin & Propagation

- **Origin:** Powered by astrophysical accelerators (e.g. Supernova Remnants)
- **Maximum Energy:** $E_{\max} \propto ZBR$
- **Diffusion:** Scattering on magnetic turbulence dominates
- **Coefficient:** $D_{xx} \propto R^{\delta}$ with $\delta \approx 0.5$
- **Residence Time:** Confined for $\sim$10–20 Myr before escaping

Cosmic Rays: Spallation

- **Spallation:** Primaries (C, O) fragment on Interstellar medium (ISM) (H, He) and produce secondaries (Li, Be, B)
- **Secondary-to-Primary Ratio**: Directly encode the amount of grammage traversed by the CRs
- **Grammage:** $\langle X \rangle = \rho c \tau_{\text{esc}}$ traced by B/C

All-Particle Cosmic-Ray Spectrum



- Nearly perfect **power law** over many decades
- **Knee** ($\sim$ 3 PeV): steepening, marks limit of Galactic accelerators
- **Ankle** ($\sim$ 10 EeV): transition to extragalactic sources
- **This work:** isotopes studied in the **GeV–TeV regime**, well below the knee, where transport and spallation dominate

Observable: The ^{10}Be/^{9}Be "Radioactive Clock"

- **^{9}Be:** stable; **^{10}Be:** radioactive with $t_{1/2} \approx 1.39\,\mathrm{Myr}$

$$\frac{N_{10}}{N_9} = \frac{q_{10}}{q_9} \tanh\left(\frac{h}{\lambda_d}\right) \frac{\lambda_d}{h}, \qquad \lambda_d = \sqrt{\frac{D\tau}{1+\tau/\tau_\beta}}$$

λ_d encodes diffusion; h is halo height; $\tau_\beta = 3.8$ Myr fixed by nuclear physics.

- **Clock:** ^{10}Be/^{9}Be $\leftrightarrow$ residence time
- Low energy $\rightarrow$ long path $\rightarrow$ more decay $\rightarrow$ ratio drops
- High energy $\rightarrow$ fast escape $\rightarrow$ ratio saturates

Modeling Propagation with GALPROP

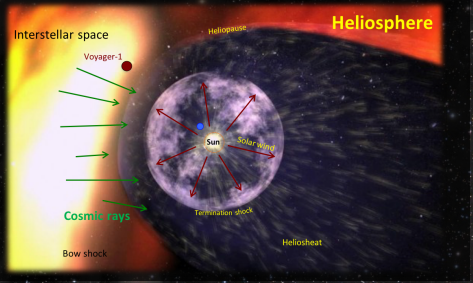
The transport of Galactic cosmic rays is described by the Cosmic Ray Transport Equation (CRTE):

$$\frac{\partial \psi(\mathbf{r}, p, t)}{\partial t} = \underbrace{q(\mathbf{r}, p)}_{\text{source term}} + \underbrace{\nabla \cdot (D_{xx} \nabla \psi - \mathbf{V}\psi)}_{\text{spatial diffusion \& convection}} + \underbrace{\frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{\psi}{p^2}\right)\right]}_{\text{diffusive reacceleration}} - \underbrace{\frac{\partial}{\partial p}\left(\dot{p}\,\psi - \tfrac{p}{3}(\nabla \cdot \mathbf{V})\psi\right)}_{\text{energy losses \& adiabatic effects}} - \underbrace{\frac{\psi}{\tau_f}}_{\text{fragmentation}} - \underbrace{\frac{\psi}{\tau_r}}_{\text{radioactive decay}} . \quad (1)$$

- GALPROP v57 numerically solves the full CRTE on a 3D galactic grid.
- Produces Local Interstellar Spectra (LIS) for primaries and secondaries.
- These LIS form the input for isotopic predictions in this work.

Solar Modulation: The Sun's Influence

- Solar wind and the heliospheric magnetic field reduce CR energy below $\sim$20–30 GeV/n.
- Key processes: convection, diffusion, adiabatic cooling, drifts, and reacceleration.
- Modulation varies with the $\sim$11-year solar cycle.
- CRs measured at Earth (1 AU); GALPROP spectra (interstellar space) need modulation correction.



Modulation Tools: HelMod vs. FFA

- **Heliospheric Modulation (HelMod):** 3D, time-dependent; includes drifts and solar-cycle effects.
- **Force-Field Approximation (FFA):** 1-parameter (ϕ), $\sim 10^4\times$ faster, but drift-free.
- Identical A/Z in isotopes modulation largely cancels in ratios.
- **Usage:** HelMod for elemental fluxes; FFA for isotopic ratios ($< 1\%$ bias).

The Alpha Magnetic Spectrometer (AMS-02)

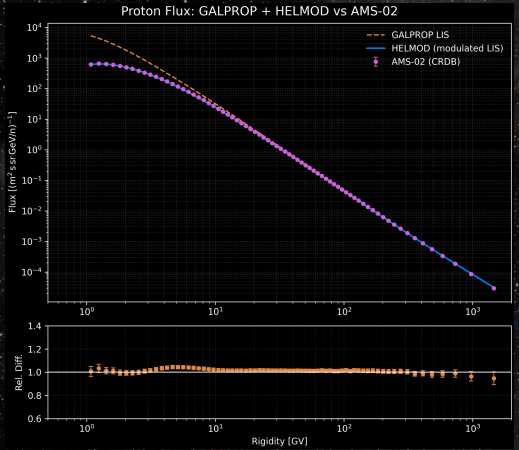
- **AMS-02:** Precision CR spectrometer operating on the International Space Station (ISS) since 2011.
- 253 billion triggered events (largest precision CR sample to date).
- 0.9 T magnet cooled to 1.8 K; the coldest persistent object in space.
- Has provided the most accurate CR spectra (p, He, B/C, Li, Be) over more than a decade.

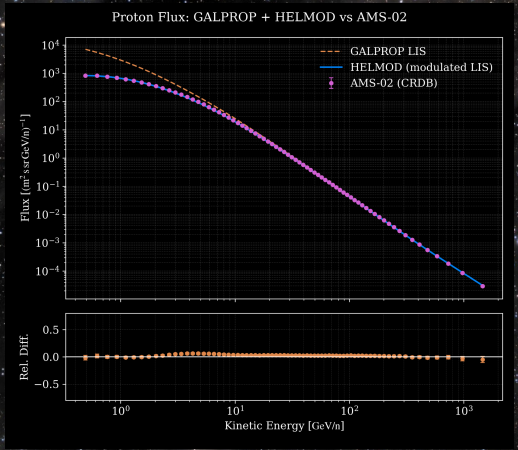
AMS-02 on the ISS (NASA)

Analysis Strategy

- **Step 1:** Validate GALPROP+HelMod fluxes (p $\rightarrow$ Fe) vs. AMS-02 (KE & Rigidity).
- **Step 2:** Benchmark secondary ratios (B/C, Be/C, Be/B) with FFA modulation.
- **Step 3:** Predict Be isotopes (^{7}Be/Be, ^{9}Be/Be, ^{10}Be/^{9}Be) using HelMod; compare with pre-AMS data.
- **Step 4:** Propagate uncertainties (propagation, solar modulation, nuclear cross-sections).

Baseline Validation (Proton Flux)

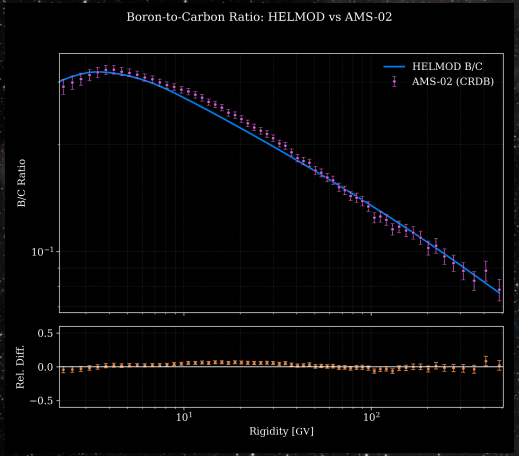


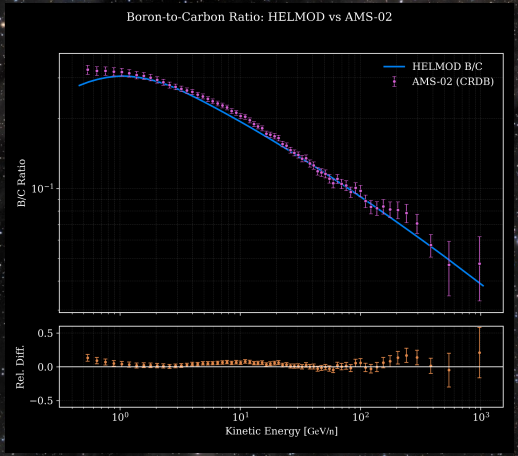


Rigidity [GV] Kinetic Energy [GeV/n]

- Agreement within ∼5% above 2 GV in both rigidity and kinetic-energy space.

Validation of Key Ratio (B/C)



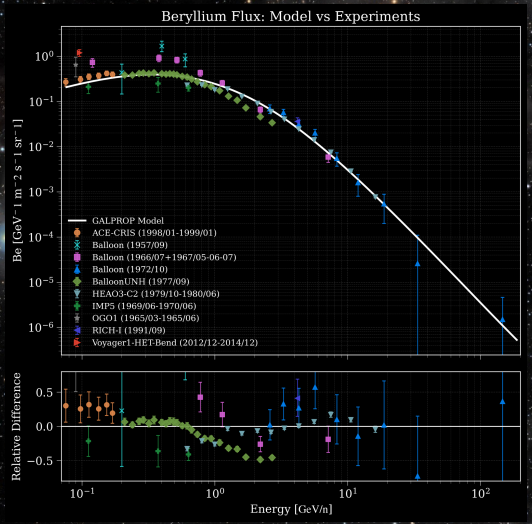


Rigidity [GV]

Kinetic Energy [GeV/n]

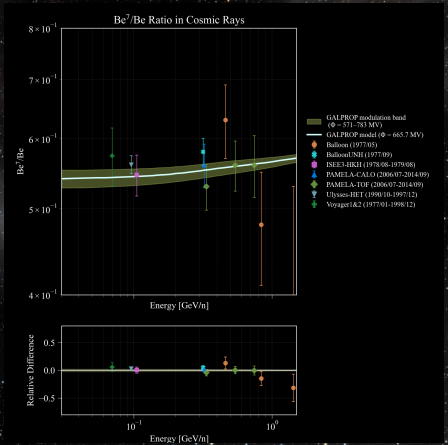
- Model reproduces classic secondary-to-primary ratio within ∼5%.

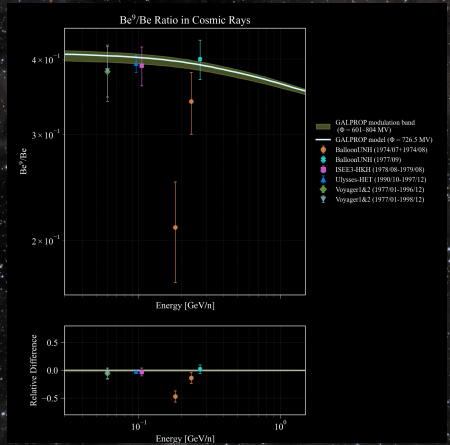
Total Beryllium Flux



- Agreement within ∼15%.
- Absolute beryllium production scale correctly captured.

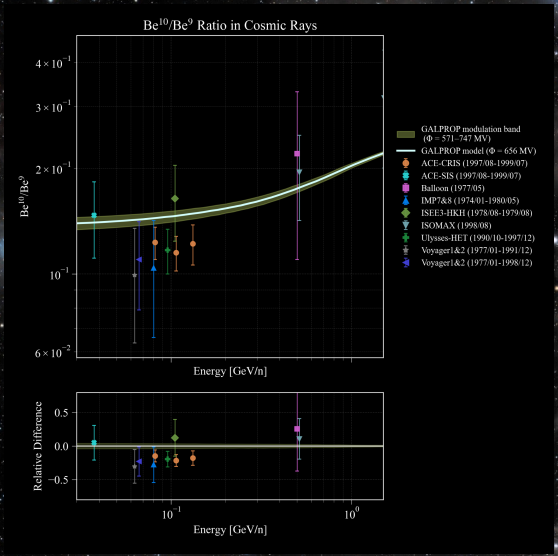
Isotopic Ratios ^{7}Be/Be & ^{9}Be/Be





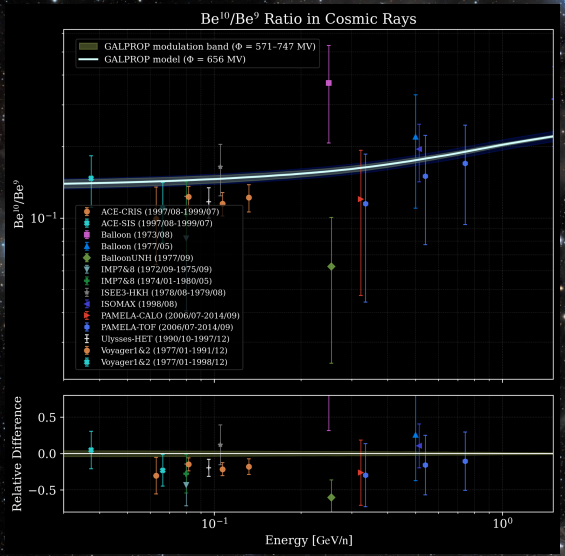
- Model reproduces spectral shapes within ±6.

The ^{10}Be/^{9}Be Radioactive Clock



- Concave-up trend reproduced without re-tuning.
- Data lie within $\varphi = 571$–747 MV band; $< 5\%$ mean offset above 0.5 GeV n^{-1}.
- $\chi^2/\mathrm{ndf} \approx 1.2 \Rightarrow 10\%$ agreement, scatter dominated by balloon/detector legacy systematics.

Uncertainty Analysis & Systematic Limitations



- Total band: $\pm 11\%$.
- Propagation: $\pm 5\%$.
- Solar modulation (ϕ range): $\pm 4\%$.
- Nuclear cross-sections: $\pm 8\%$ (dominant).
- Procedural XS-flag degeneracy $\Rightarrow$ main precision bottleneck.

Conclusions

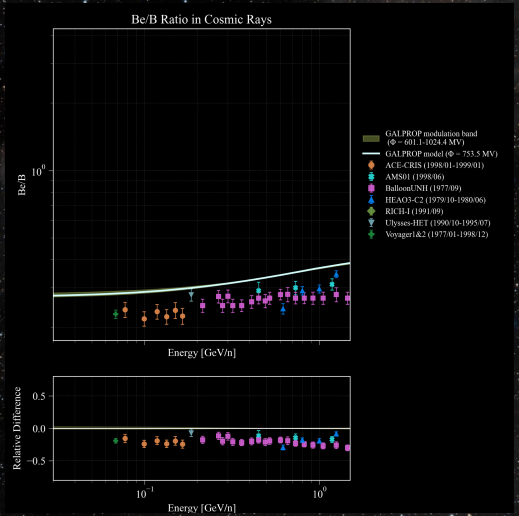
- GALPROP baseline (p, He, B/C) reproduced within 5–10%.
- Light beryllium isotope ratios consistent with the tuned model; ^{10}Be/Be curvature confirms the diffusion–decay framework at $\sim$10% precision.
- Total uncertainty budget $\approx$10%: $\pm$5% from propagation, $\pm$10–12% from nuclear cross sections and solar modulation.
- Further progress requires (i) high-statistics AMS-02 isotope data and (ii) improved fragmentation cross-section libraries.
- Developed pipeline is prepared for future joint cross-section + propagation likelihood analyses.


Thank you!

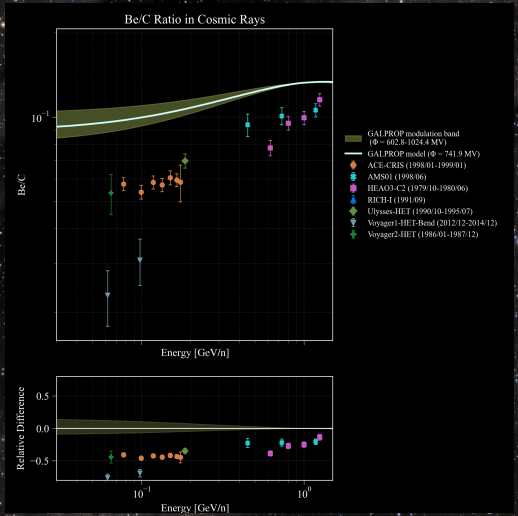
References

- **GALPROP v57:** Strong, Moskalenko & Ptuskin, *ApJ* **722** (2010) L58; `galprop.stanford.edu`
- **HelMod:** Bobik et al., *JGR* **123** (2018) 12345; `helmod.org`
- **AMS-02 performance:** Aguilar et al., *Phys. Rep.* **894** (2022) 1
- **Be-isotope data compilation:** Maurin et al., *A&A* **640** (2020) A67; `crdb.us`
- **Nuclear cross-section uncertainties:** Genolini et al., *A&A* **642** (2020) A15
- **All-particle spectrum & knee:** Picozza et al., *Cosmic Rays under the Knee*, arXiv:1402.4311
- **Auger spectrum data:** Pierre Auger Collab., *Phys. Rev. D* **102** (2020) 062005; `auger.org/spectrum`

Backup: Be/B and Be/C Ratios

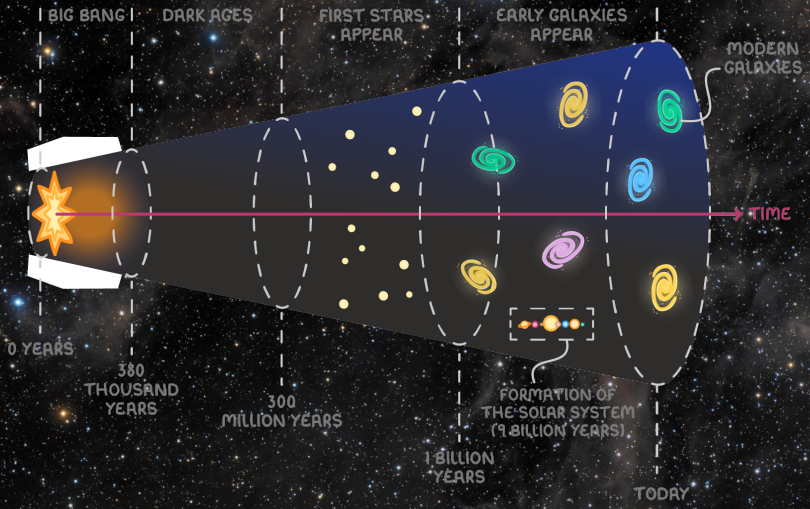


Be/B Ratio

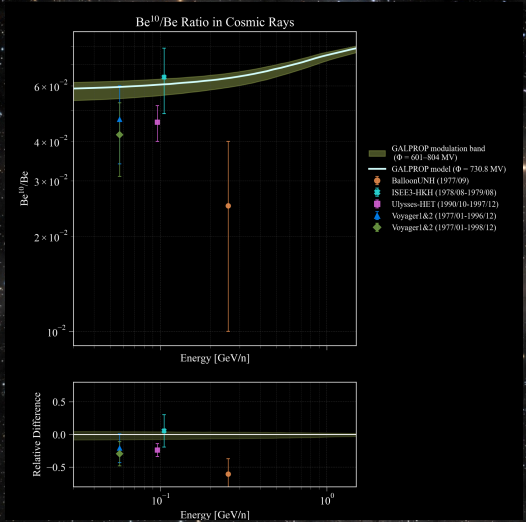


Be/C Ratio

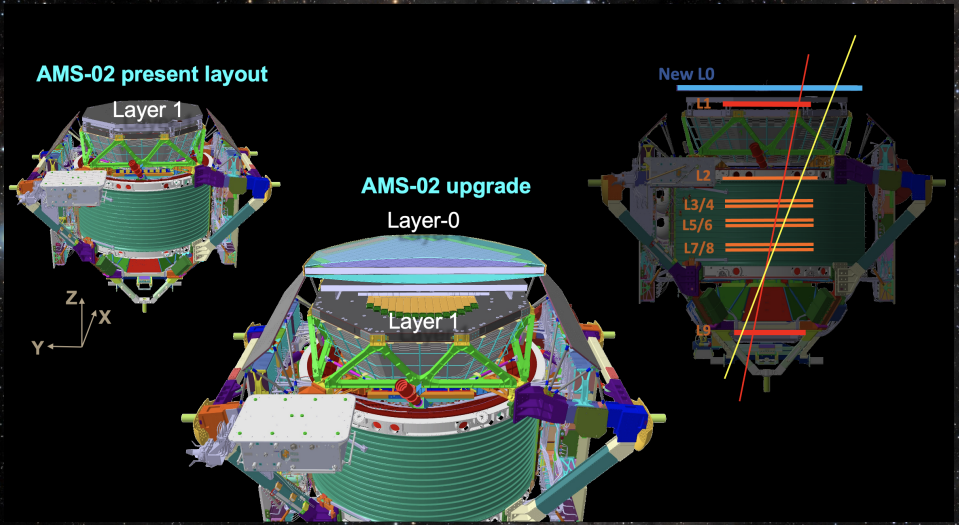
Backup


BIG BANG
DARK AGES
FIRST STARS APPEAR
EARLY GALAXIES APPEAR
MODERN GALAXIES
TIME
0 YEARS
380 THOUSAND YEARS
300 MILLION YEARS
1 BILLION YEARS
FORMATION OF THE SOLAR SYSTEM (9 BILLION YEARS)
TODAY

Backup


Be10/Be Ratio in Cosmic Rays
6 × 10−2
4 × 10−2
3 × 10−2
2 × 10−2
10−2
Be10/Be
Energy [GeV/n]
GALPROP modulation band
(Φ = 601–804 MV)
GALPROP model (Φ = 730.8 MV)
BalloonUNH (1977/09)
ISEE3-HKH (1978/08–1979/08)
Ulysses-HET (1990/10–1997/12)
Voyager1&2 (1977/01–1996/12)
Voyager1&2 (1977/01–1998/12)
0.5
0.0
−0.5
Relative Difference
10−1
100
Energy [GeV/n]

Backup


AMS-02 present layout
Layer 1
Z
X
Y
AMS-02 upgrade
Layer-0
Layer 1
New L0
L1
L2
L3/4
L5/6
L7/8
L9