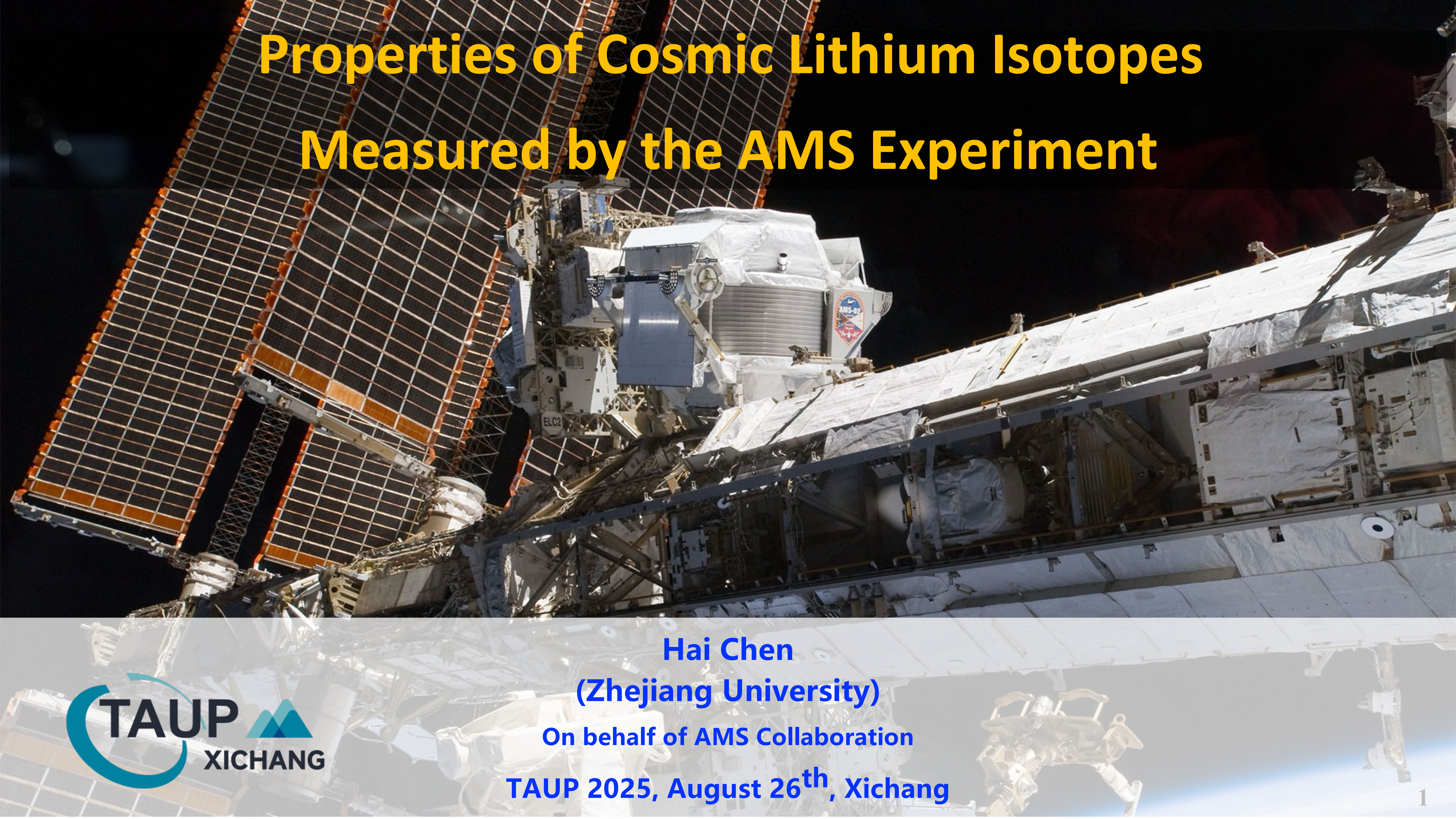

Properties of Cosmic Lithium Isotopes Measured by the AMS Experiment

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(Zhejiang University)

On behalf of AMS Collaboration

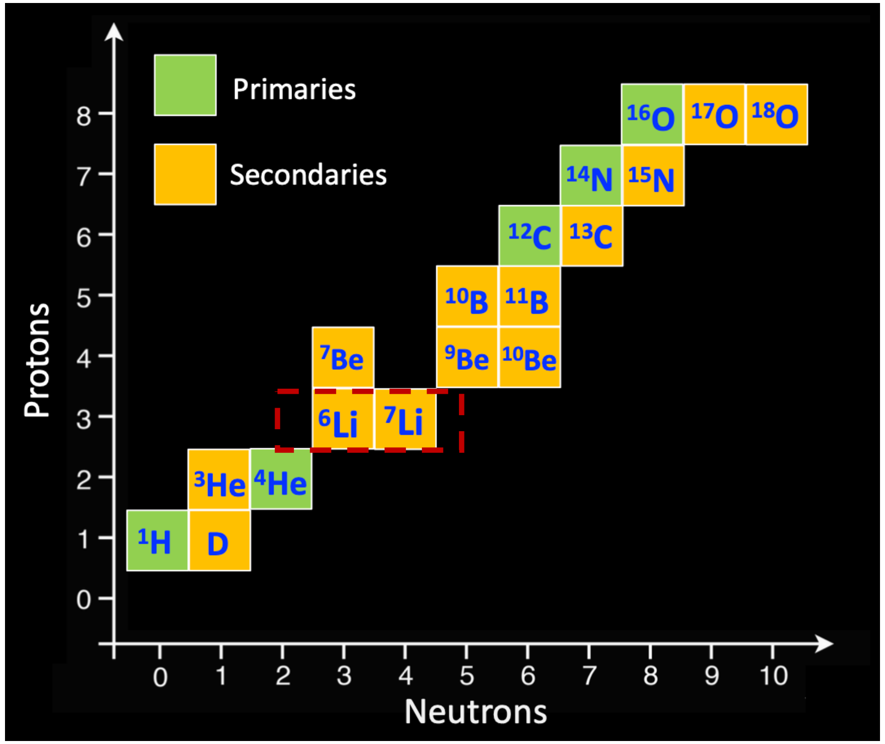
TAUP 2025, August 26th, Xichang

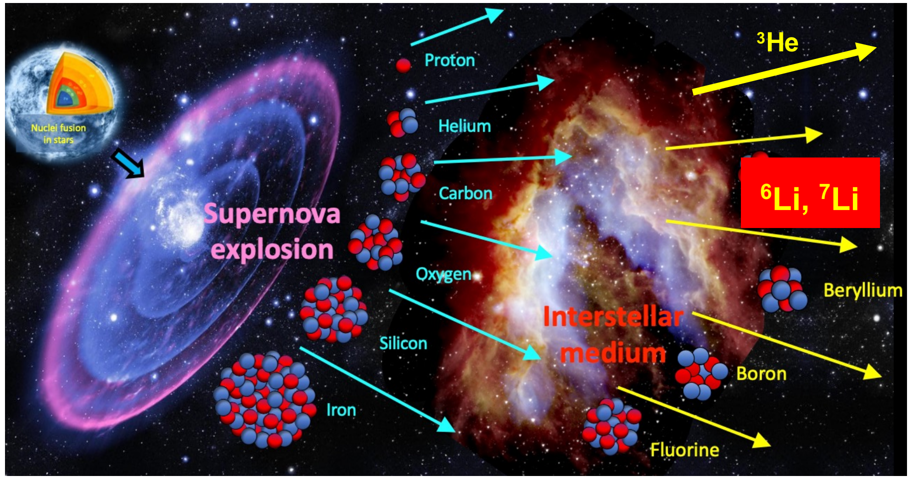
TAUP XICHANG

Lithium Isotopes in Cosmic Rays

- Lithium nuclei are among the rarest in the Solar System (Li/Si~10^{-4}), yet they are relatively common in cosmic rays (Li/Si~1);
- They consist of two stable isotopes, ^{6}Li and ^{7}Li;
- Both ^{6}Li and ^{7}Li are thought to be produced by collisions of heavier cosmic-ray nuclei with the interstellar medium;
- They are called secondary cosmic rays.
- The total Lithium flux has been presented by AMS in 2018. (*Phys. Rev. Lett. 120, 021101*)

Precise measurement of the cosmic-ray ^{6}Li and ^{7}Li isotope fluxes provides insights into the origin and propagation of lithium nuclei.

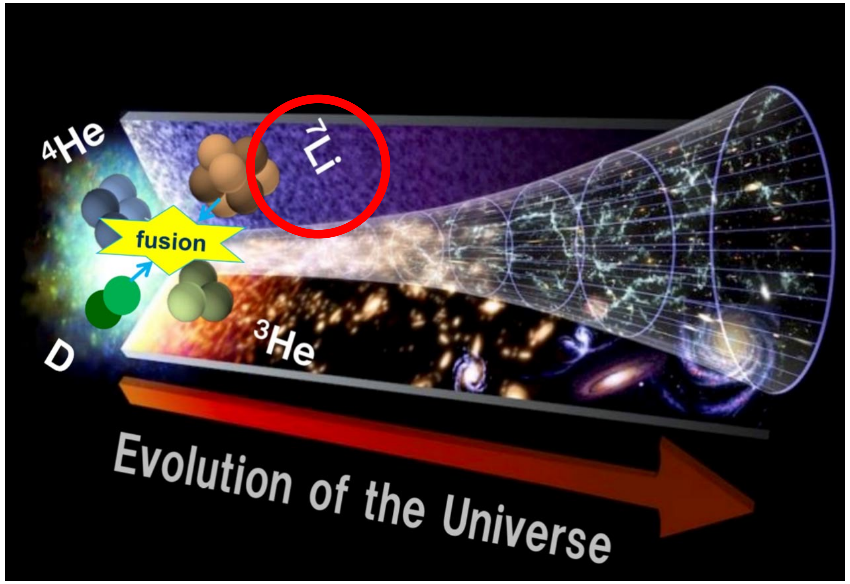


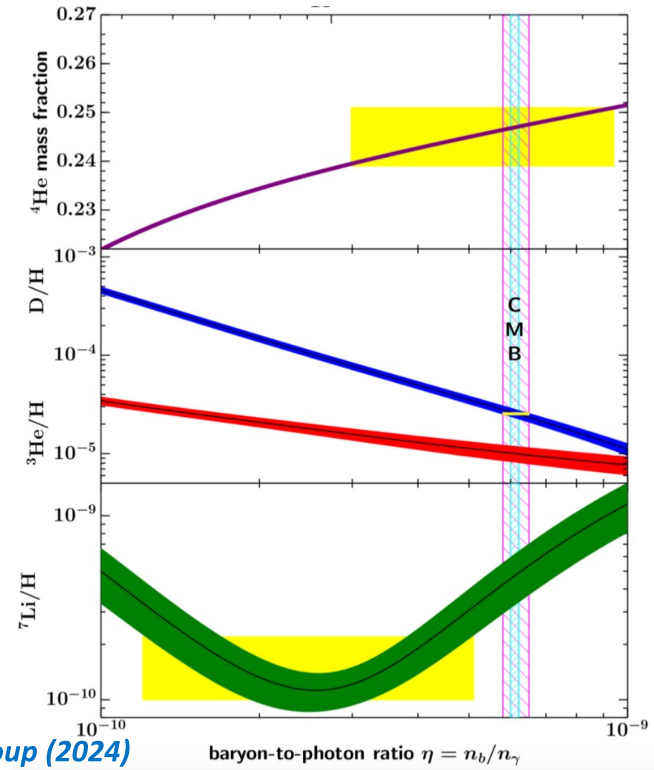


On the Origin of ^{7}Li

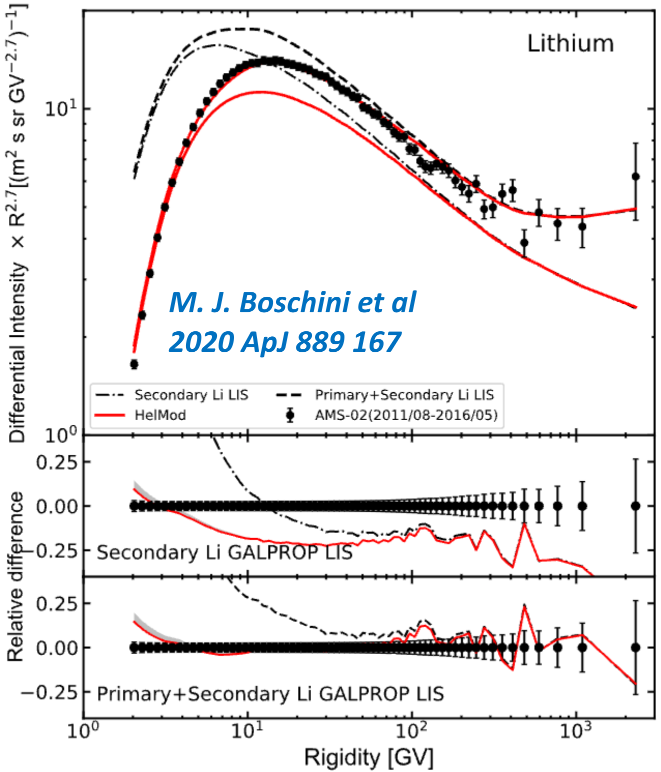
The origin of ^{7}Li is still not yet well understood:

1) ^{7}Li may contain a primordial component from Big Bang Nucleosynthesis, and its predicted abundance from BBN does not match the value inferred from stellar and cosmological observations, or cosmic-ray data (*Lithium problem*).
2) Another ^{7}Li primary component can be produced from ^{7}Be decay by electron capture at astrophysical sources.
3) The AMS total lithium flux (^{6}Li+^{7}Li) measurement could not be described by secondary lithium propagation models, possibly due to the presence of a primary component in the ^{7}Li flux.





Particle Data Group (2024)



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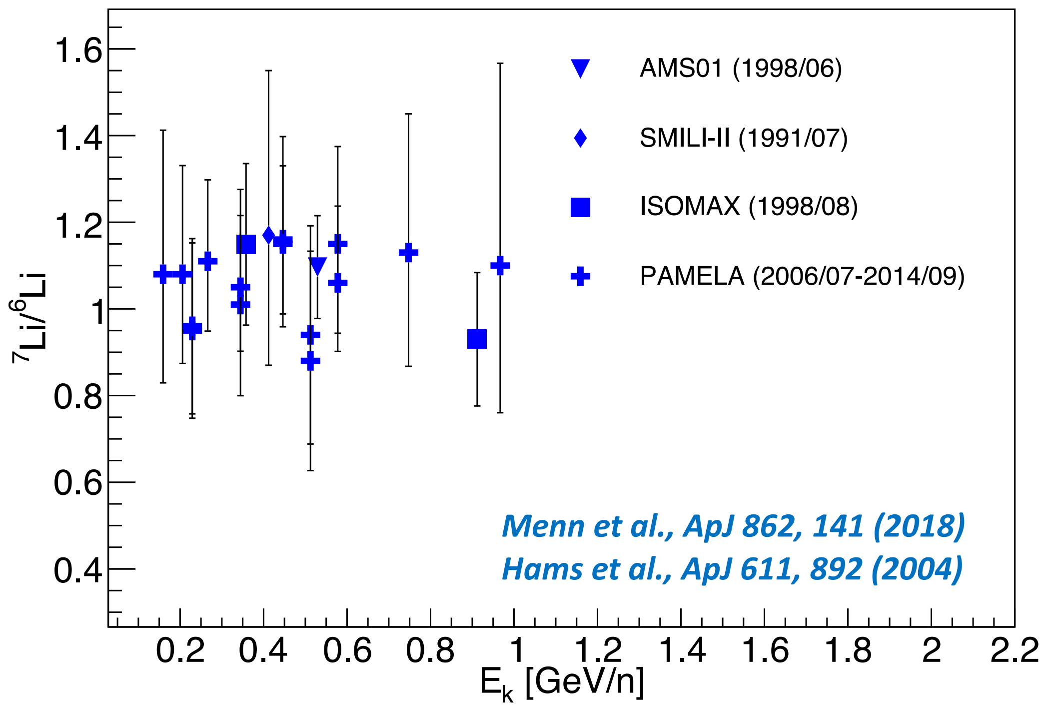
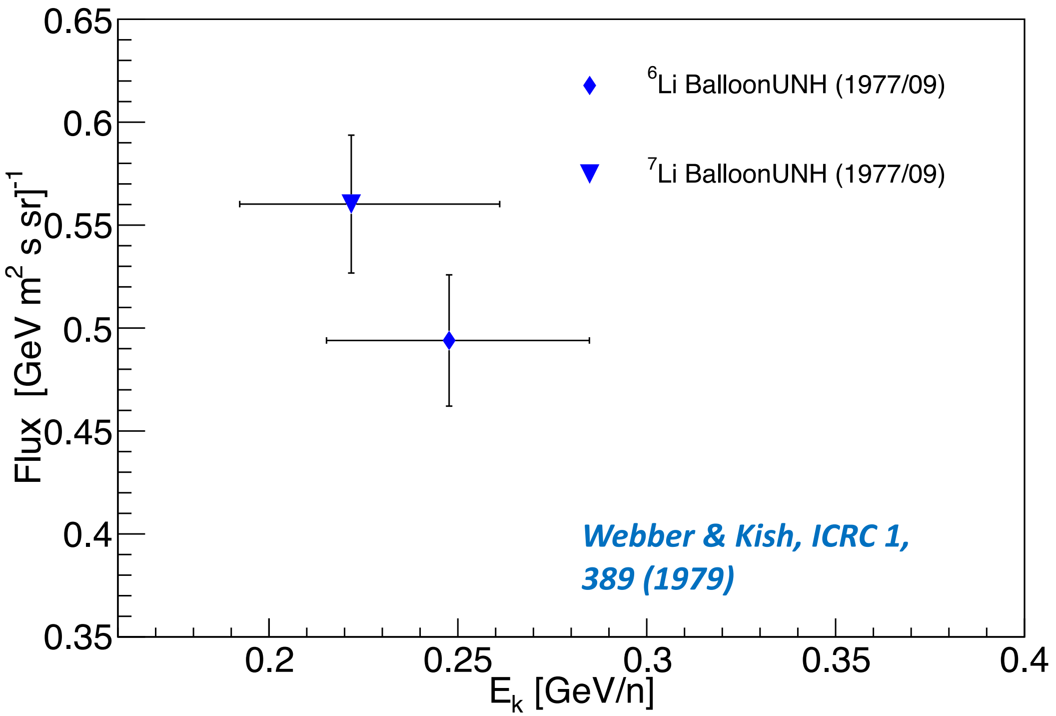
Lithium Measurement Before AMS

- Over the last 50 years, several experiments have measured the $^7Li/^6Li$ ratio as a function of kinetic energy per nucleon only below 1.2 GeV/n with ~20% errors, or as a function of rigidity below 6.3 GV with ~15% uncertainties.
- The Lithium isotope fluxes have been measured only below 0.3 GeV/n (below ~1.9 GV in rigidity) in 1979.

In this talk, we present the unique and precision measurements of the ^6Li and ^7Li fluxes in the rigidity range from 1.9 to 25 GV.

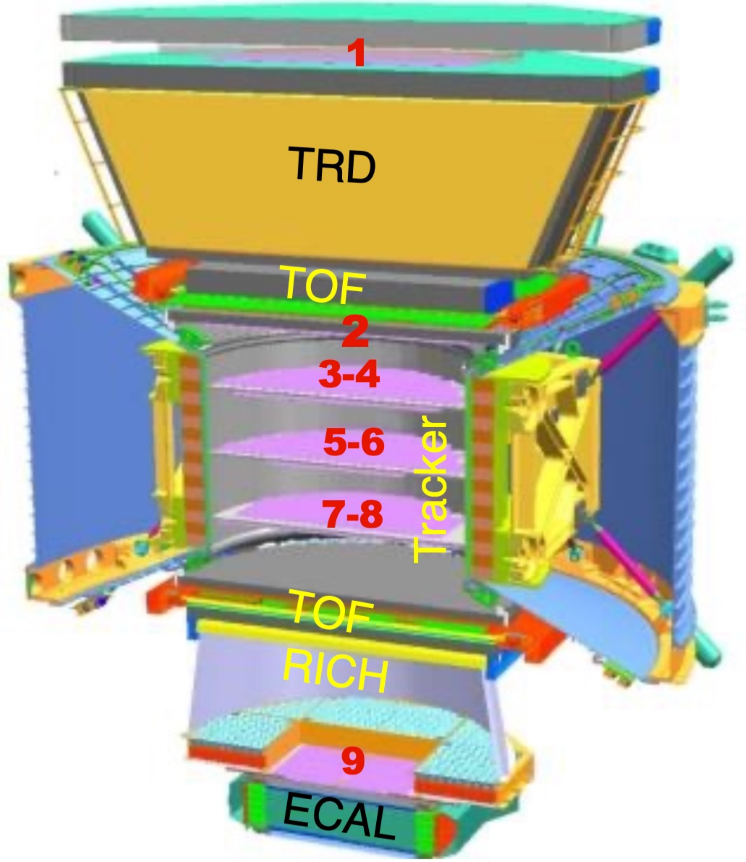


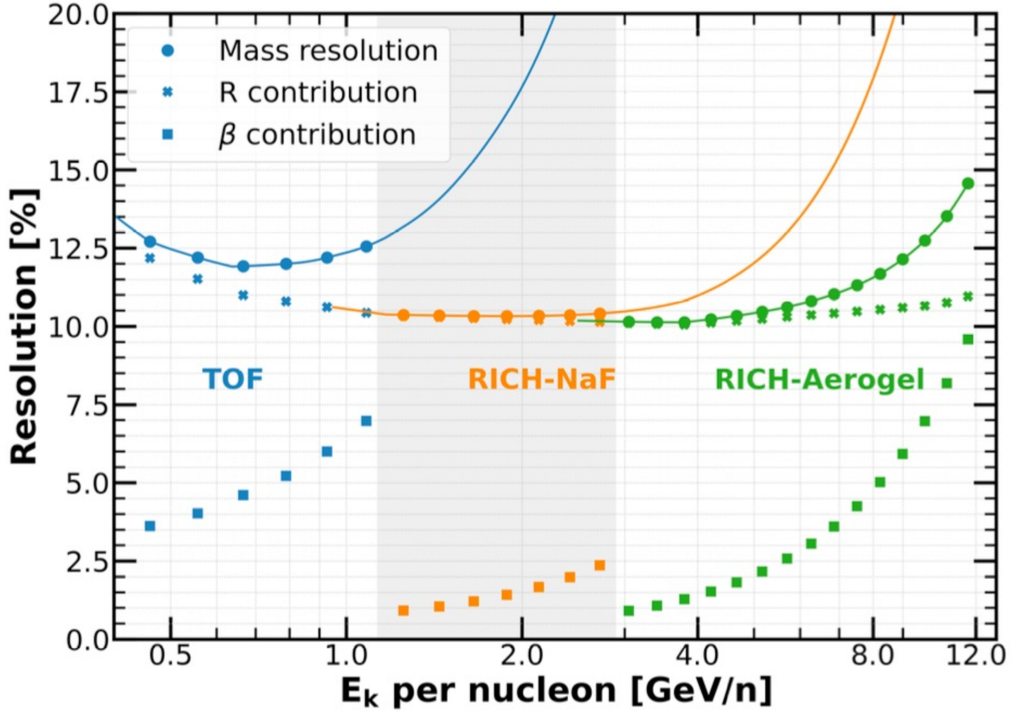


Mass Measurement in AMS

In AMS, mass is determined by simultaneous measurements of Charge Z (Tracker, TOF, RICH), Rigidity R (Tracker), and Velocity β (TOF, RICH-NaF, RICH-Aerogel):

$$M = \frac{ZR}{\beta\gamma} \qquad \frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta R}{R}\right)^2 + \left(\gamma^2 \frac{\Delta\beta}{\beta}\right)^2}$$





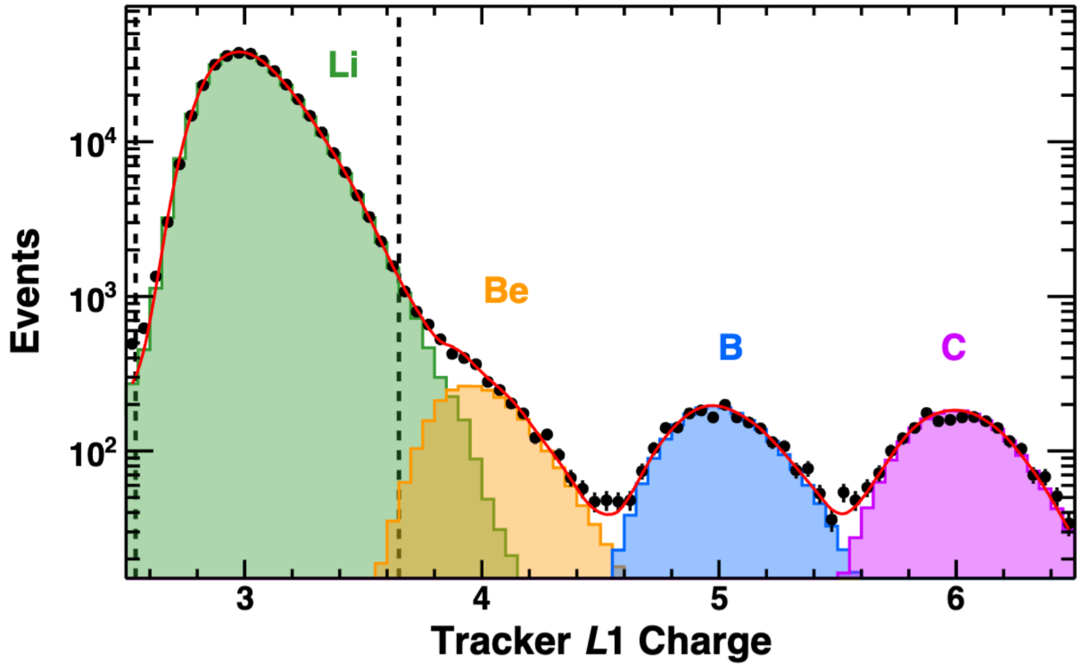
$\Delta M/M$

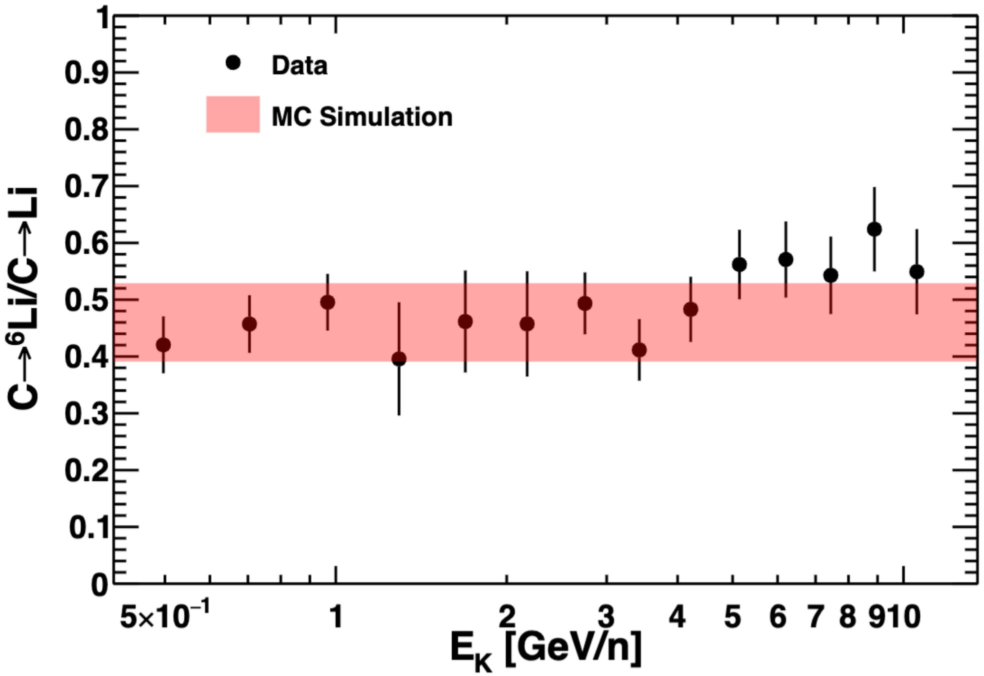
$\Delta R/R$

$\gamma^2 \Delta\beta/\beta$

Lithium Event Selection

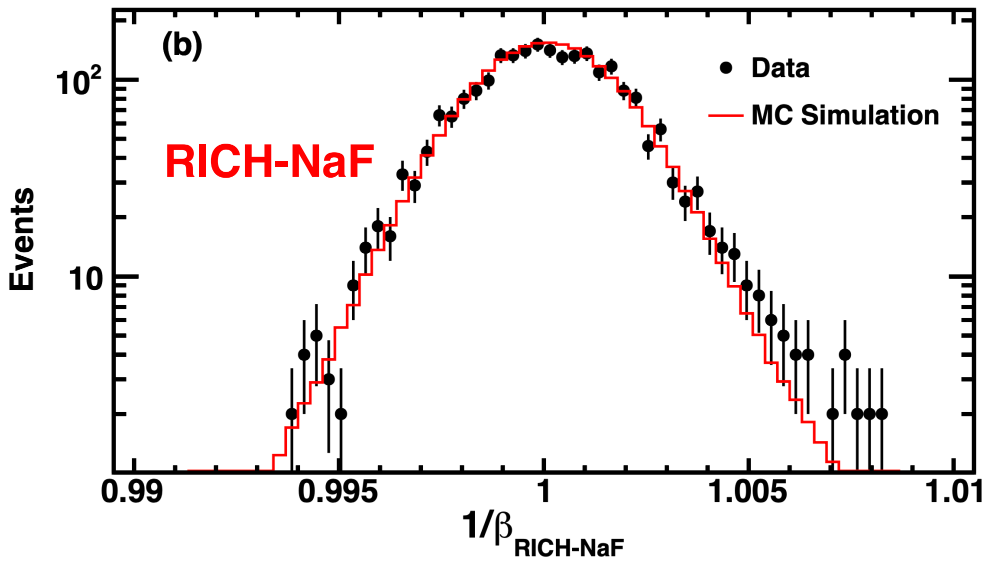
- **Charge measurements** on Tracker L1, TOF, and Inner Tracker are required to be compatible with Z = 3.
  - The background from interactions in the material **between Tracker L1 and L2** is evaluated by fitting the charge distribution of Tracker L1 with templates of Li, Be, B, and C (negligible <0.1%).
  - The background from interactions in materials **above Tracker L1** has been estimated from simulation using MC samples generated according to AMS flux measurements.

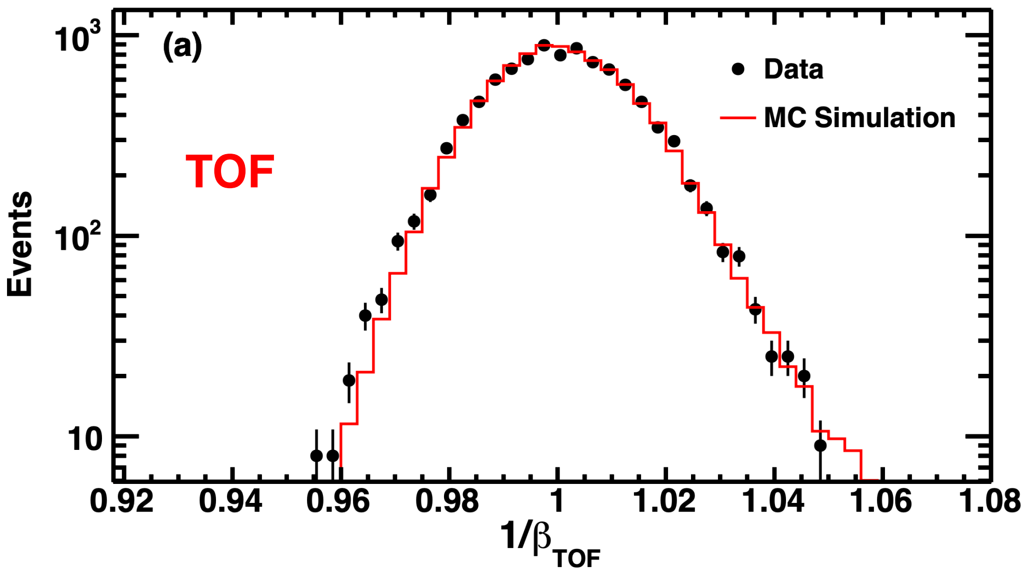


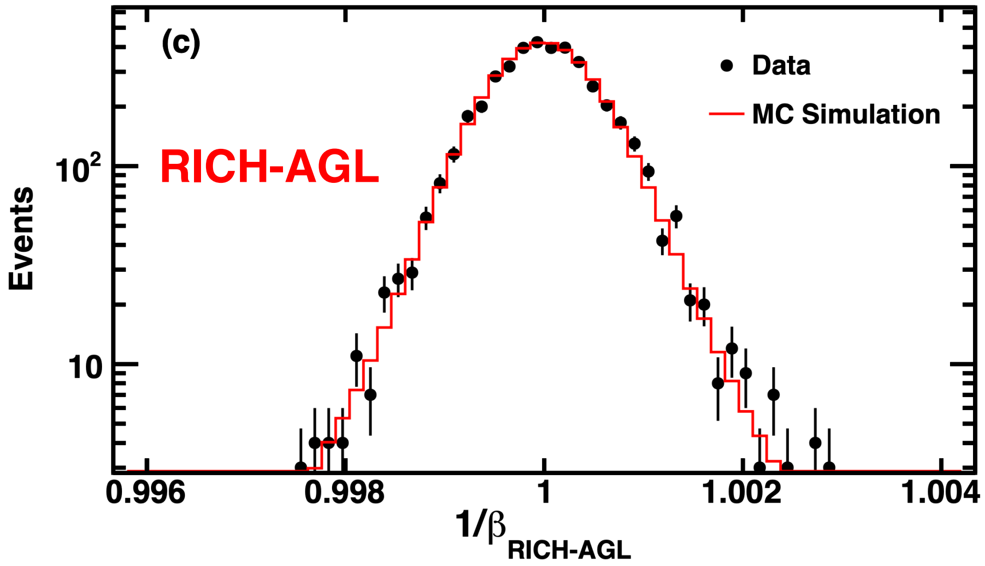


Velocity Resolution

- The rigidity resolution function, determined from MC simulations, has been extensively verified with the data in previous studies.
- The **Lithium velocity resolution functions** of TOF and RICH are determined from MC simulation and verified with data with **$\beta \simeq 1$ events** by selection on Rigidity > 100 GV.
- As seen, the MC simulation agrees well with the data.



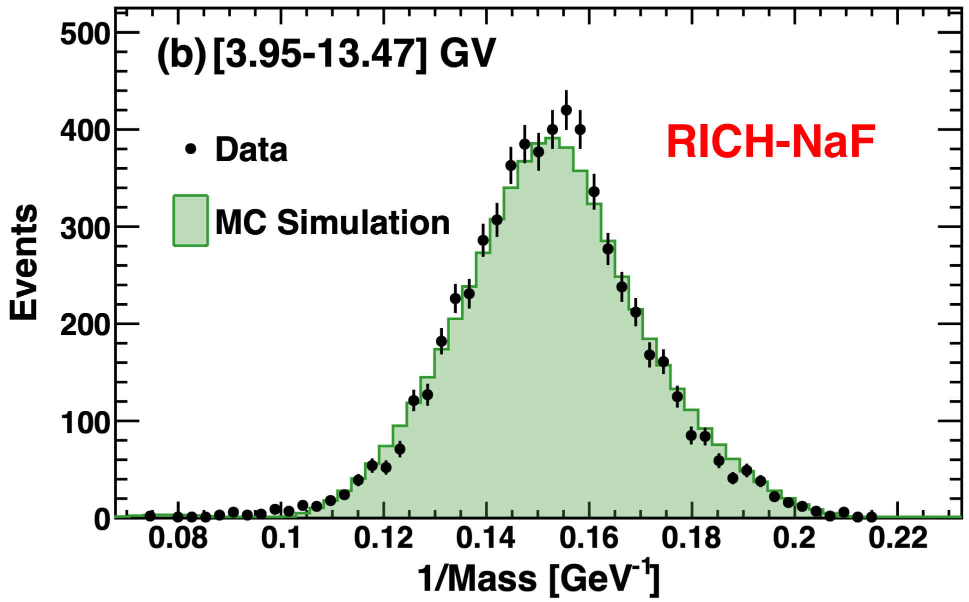


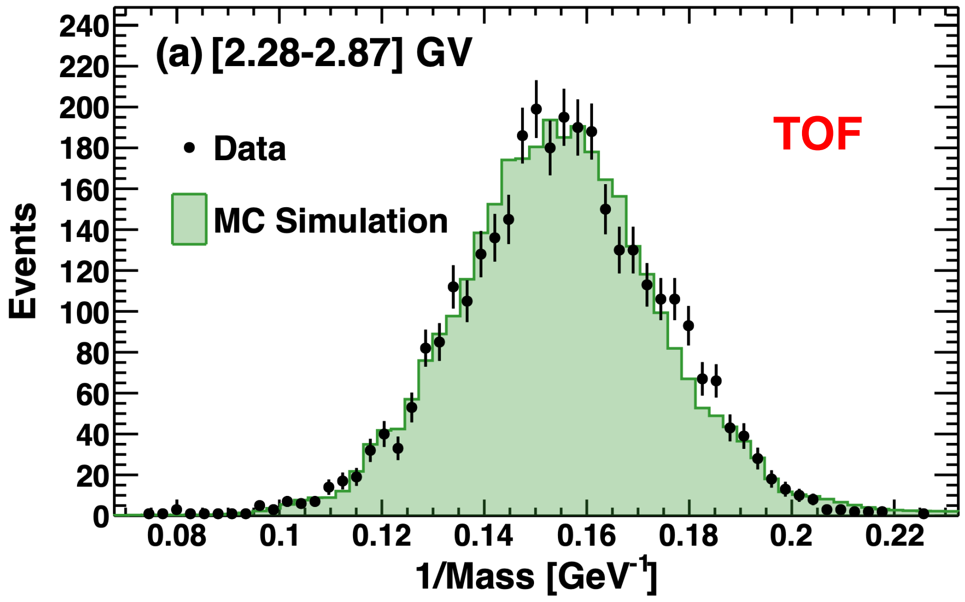


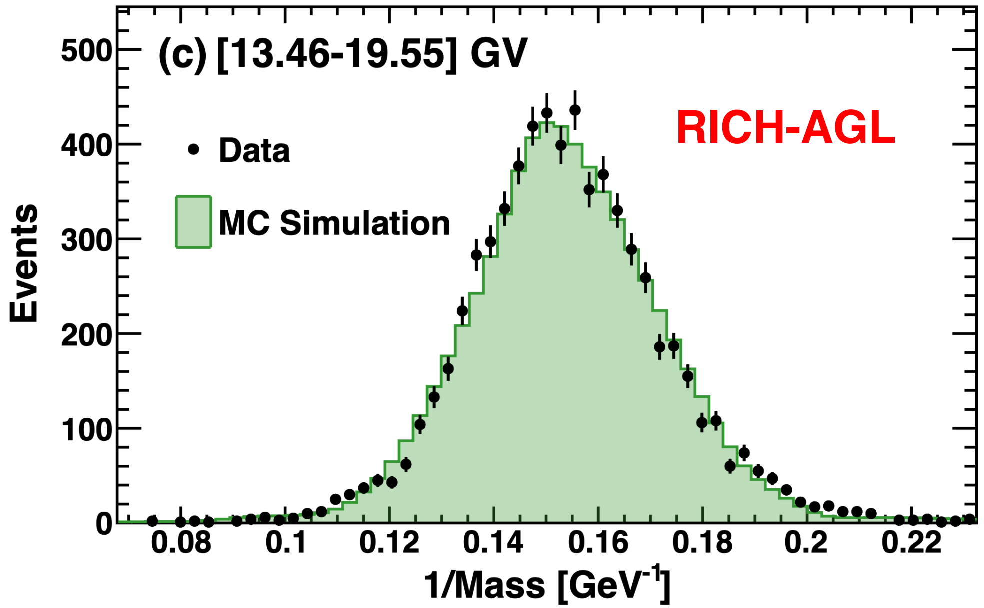
Inverse Mass Template

The event number of Lithium isotopes are obtained by fitting the measured inverse mass distribution 1/M with ^{6}Li and ^{7}Li inverse mass templates.

- The MC inverse mass templates have been verified with the ^{7}Li data using the geomagnetic cutoff as a filter.
- As seen, the MC simulation also agrees well with the data.



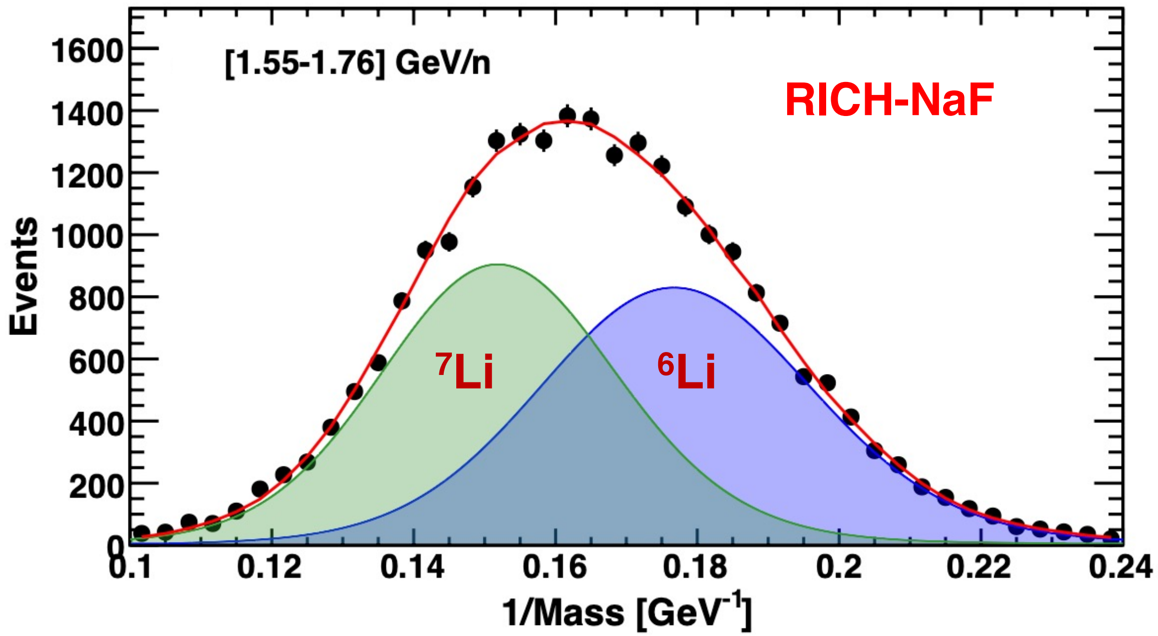


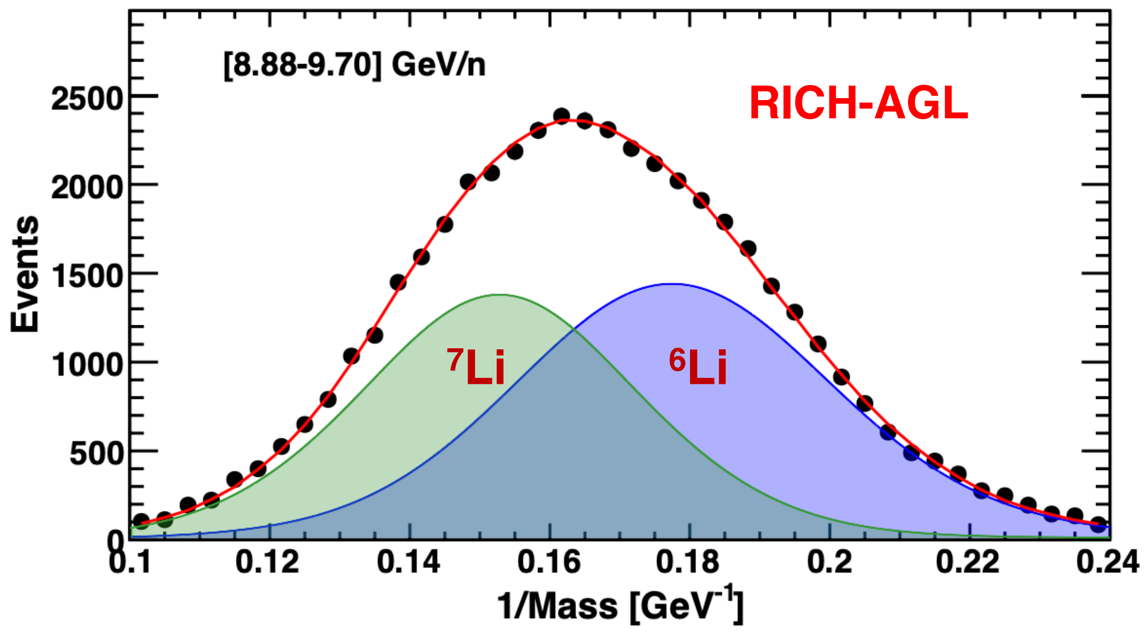


Inverse Mass Template Fitting

As an example, inverse mass distributions for $^{6}Li+^{7}Li$ data (black points) for two E_K bins for the RICH-NaF and the RICH-Agl are shown below.

- These E_K bins correspond to ^{7}Li rigidity bins of [5.37-5.90] GV, and [22.8-24.7] GV, respectively;
- The mass peak of ^{6}Li (purple) and ^{7}Li (green) are clearly separated;
- The red curves show the fits of the sum of the ^{6}Li and ^{7}Li MC templates to the data with good agreement.

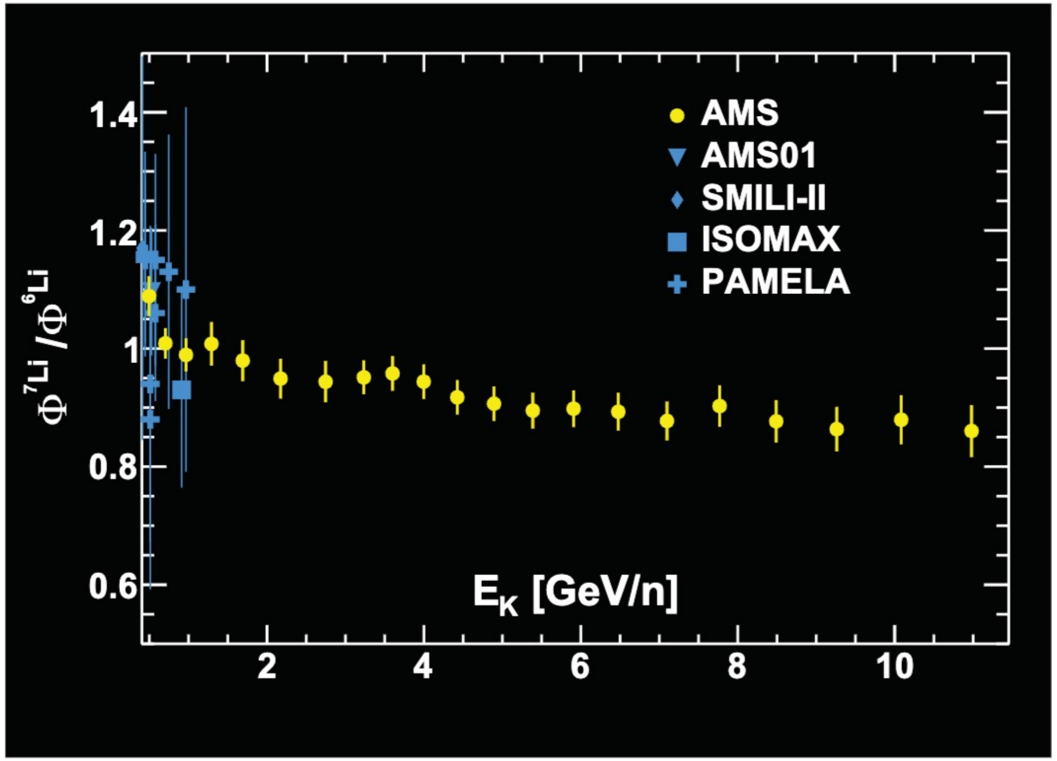




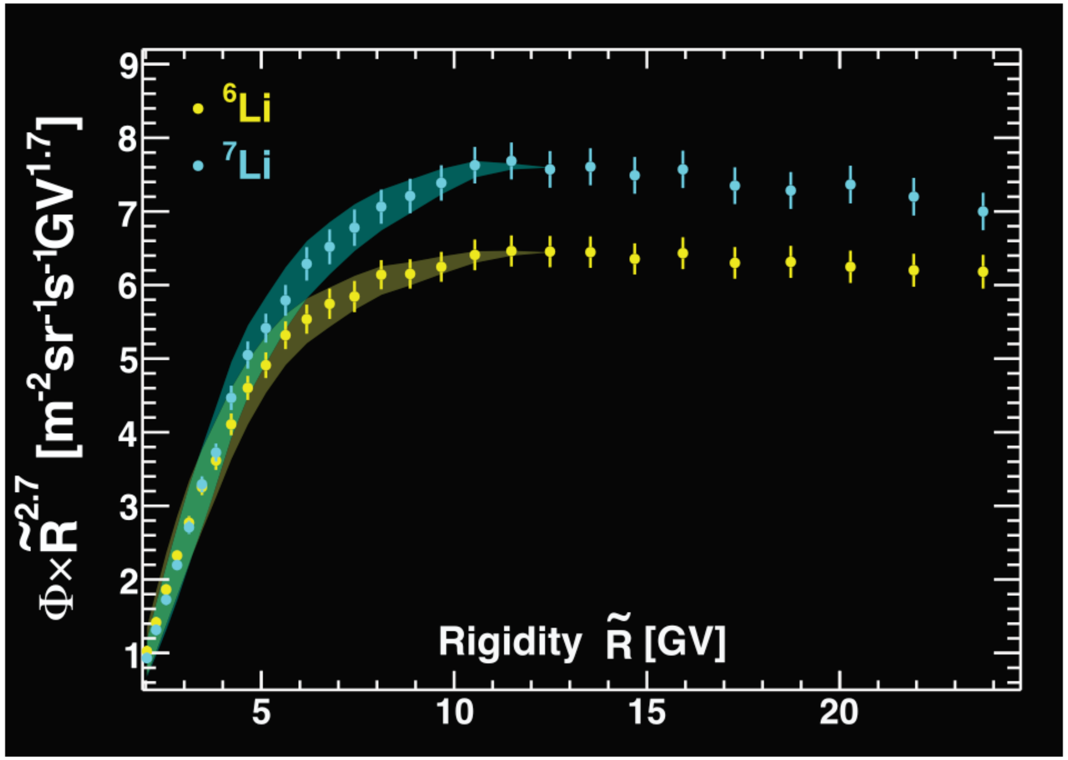
AMS ^{7}Li/^{6}Li Ratio and Flux

Based on 9.7 × 10^5 ^{6}Li and 1.04 × 10^6 ^{7}Li nuclei collected by AMS from May 2011 to October 2023.

- AMS $\Phi(^7Li)/\Phi(^6Li)$ ratio as a function of kinetic energy per nucleon, together with earlier measurements.
- First result in the energy range above 1 GeV/n.



- AMS individual $\Phi(^7Li)$ and $\Phi(^6Li)$ as functions of rigidity, together with time variation (color band).
- First result as a "flux" form of Lithium isotopes.



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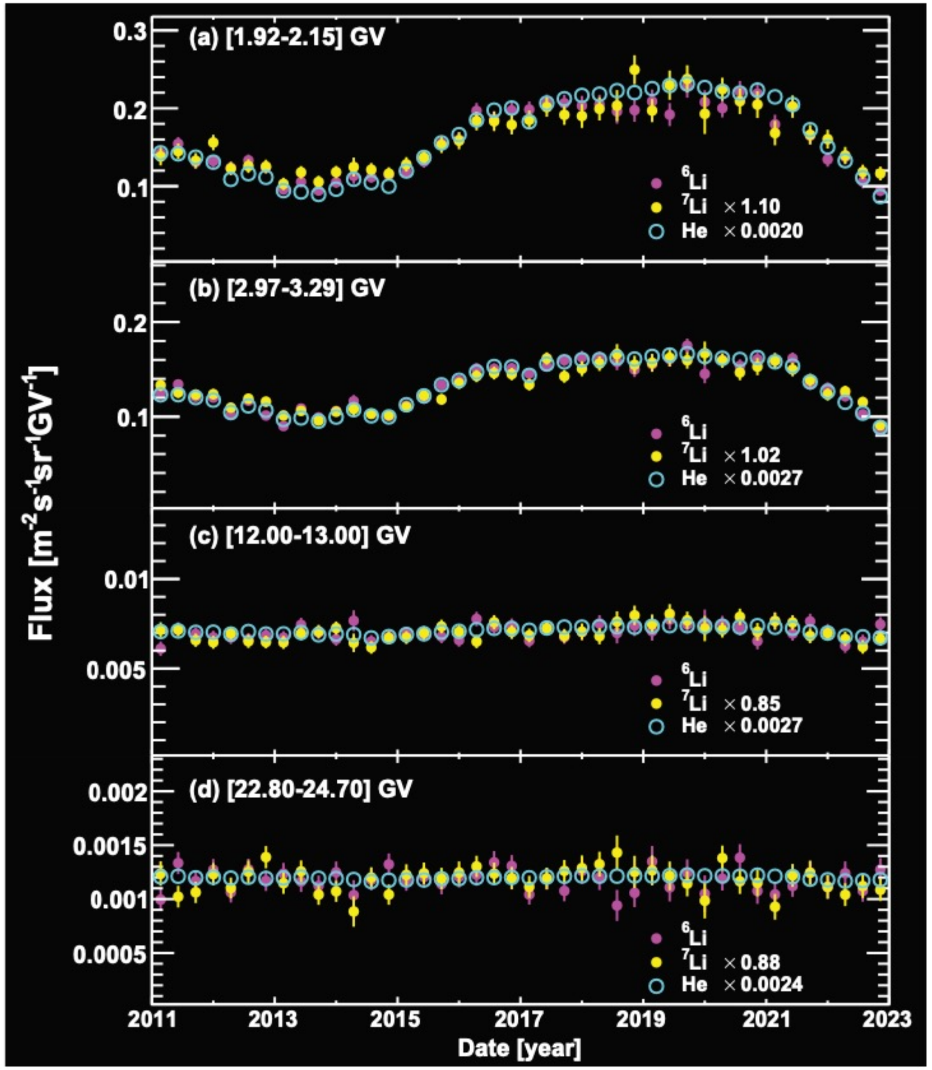
^{7}Li and ^{6}Li Flux Time Variation

- The AMS ^{6}Li, ^{7}Li, and He as functions of time for four characteristic rigidity bins.
- As seen, in each rigidity bin the three fluxes exhibit a nearly identical time behavior, and the relative magnitude of the variations decreases with increasing rigidity.

To study the differences in time variation for $\Phi(^6\mathrm{Li})$, $\Phi(^7\mathrm{Li})$, and $\Phi(\mathrm{He})$ in detail, we define a *k factor* to demonstrate the slopes of the linear dependence between nuclei:

$$\frac{\Phi_i^{^6\mathrm{Li}}/\Phi_i^{\mathrm{He}} - \langle \Phi_i^{^6\mathrm{Li}}/\Phi_i^{\mathrm{He}} \rangle}{\langle \Phi_i^{^6\mathrm{Li}}/\Phi_i^{\mathrm{He}} \rangle} = k_i^{^6\mathrm{Li}} \frac{\Phi_i^{\mathrm{He}} - \langle \Phi_i^{\mathrm{He}} \rangle}{\langle \Phi_i^{\mathrm{He}} \rangle},$$

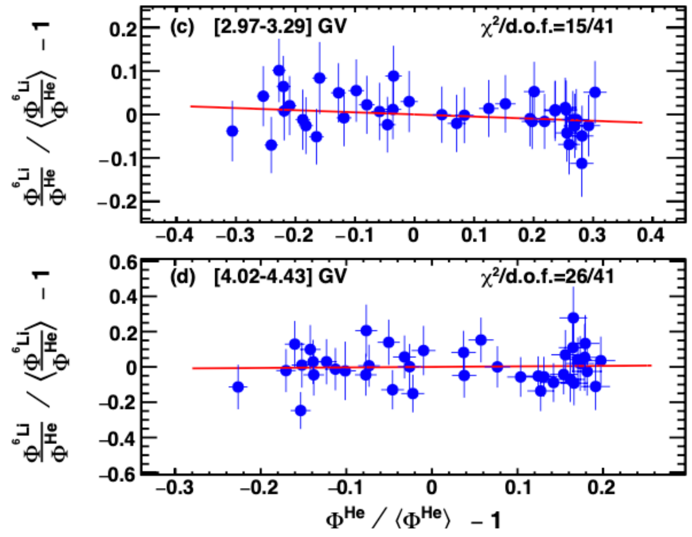
$$\frac{\Phi_i^{^7\mathrm{Li}}/\Phi_i^{\mathrm{He}} - \langle \Phi_i^{^7\mathrm{Li}}/\Phi_i^{\mathrm{He}} \rangle}{\langle \Phi_i^{^7\mathrm{Li}}/\Phi_i^{\mathrm{He}} \rangle} = k_i^{^7\mathrm{Li}} \frac{\Phi_i^{\mathrm{He}} - \langle \Phi_i^{\mathrm{He}} \rangle}{\langle \Phi_i^{\mathrm{He}} \rangle},$$

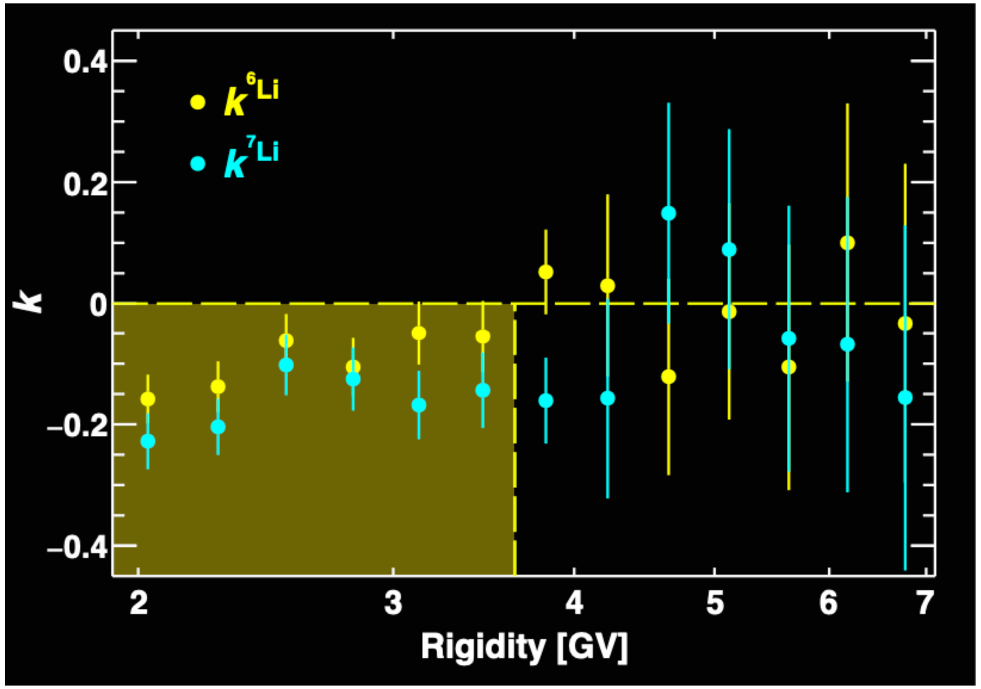


^{7}Li and ^{6}Li Modulation

As can be seen from the ***k factor*** of 6Li and 7Li isotopes as a function of rigidity:

- From 1.9 to 3.6 GV, both k(^{6}Li) and k(^{7}Li) are below zero, showing that **Φ(^{7}Li) and Φ(^{6}Li) are less modulated than Φ(He)** in this rigidity range;
- From 1.9 to 4.0 GV, k(^{7}Li) is smaller than k(^{6}Li), indicating that **Φ(^{7}Li) is less modulated than Φ(^{6}Li)** in this rigidity range;
- Above 4.0 GV, k(^{6}Li) and k(^{7}Li) are both compatible with zero, showing that **Φ(^{6}Li), Φ(^{7}Li), and Φ(He) exhibit identical variations higher than ~4 GV.**

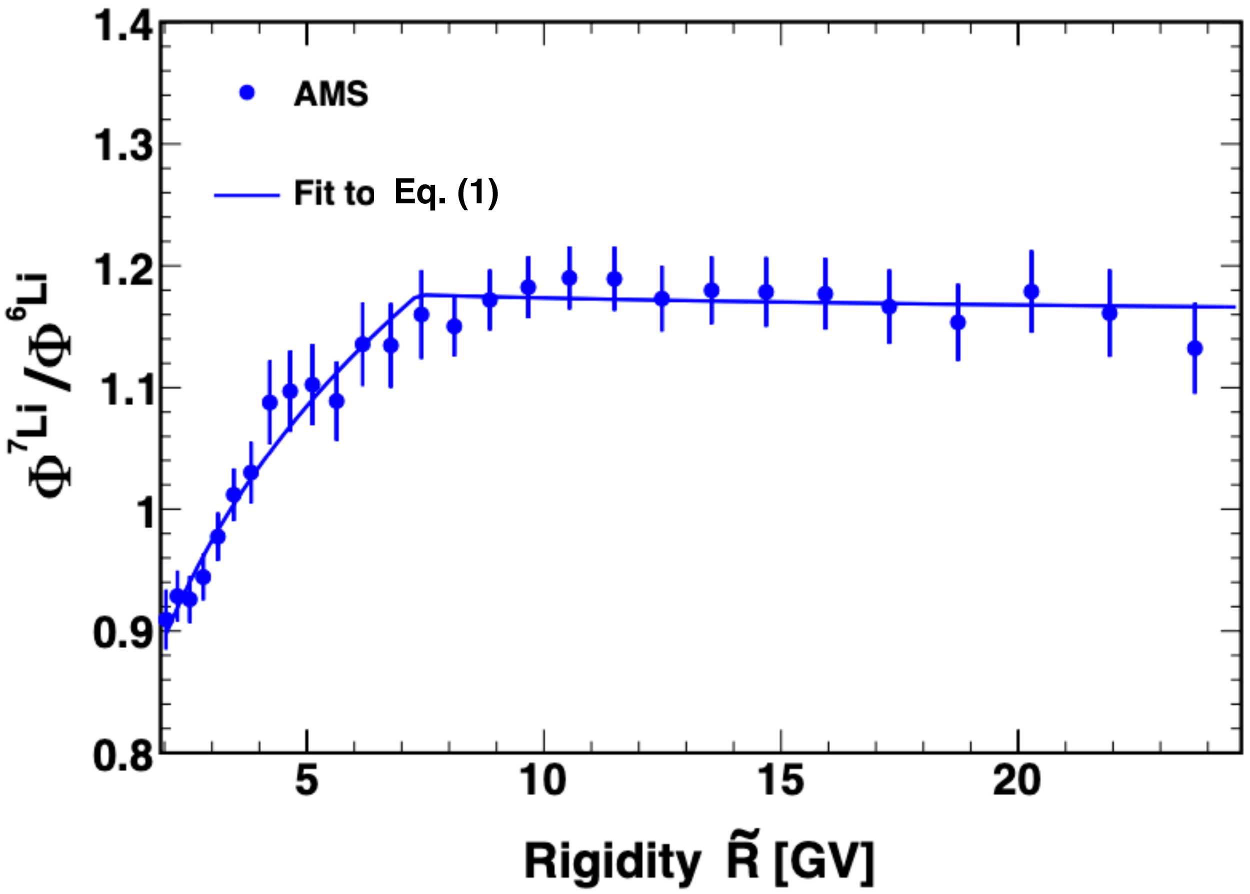




Analysis on $^7Li/^6Li$ Ratio

To study the rigidity dependence of $\Phi(^7Li)/\Phi(^6Li)$ ratio, it has been fitted over the entire rigidity range with power law:

$$\Phi^{^7\mathrm{Li}}/\Phi^{^6\mathrm{Li}} = \begin{cases} K\,(R/R_0)^{\Delta_1}, & R \le R_0, \\ K\,(R/R_0)^{\Delta_2}, & R > R_0. \end{cases} \qquad (1)$$

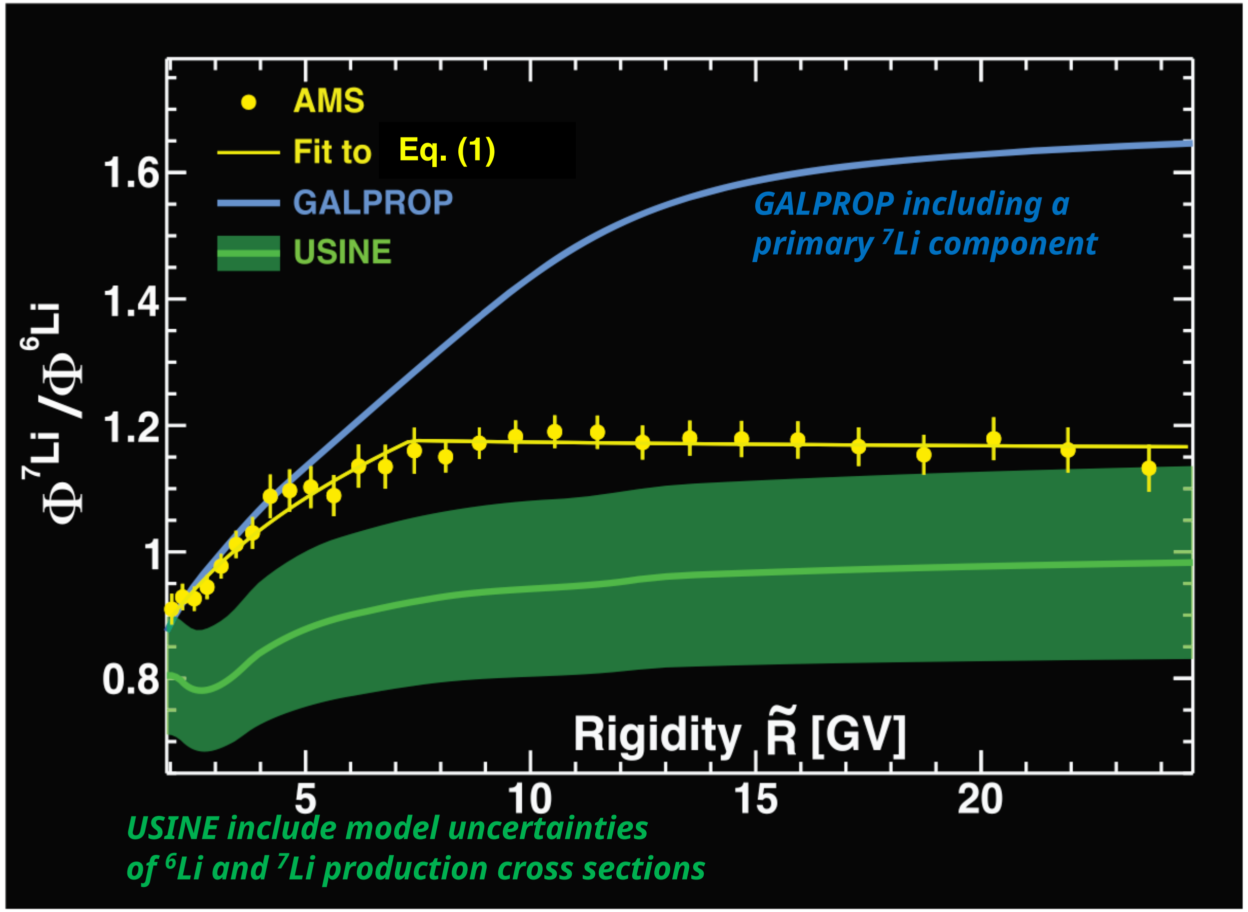


- The fit yields R_0 = 7.2 ±0.4 GV, Δ_1 = 0.21 ±0.01, and $\Delta_2 = -0.002 \pm 0.011$ with a χ^2/d.o.f. of 23.8/24.
- Δ_2 is consistent with zero, which confirms that $\Phi(^6Li)$ and $\Phi(^7Li)$ have an identical rigidity dependence above R_0~7 GV.

Models on ^{7}Li/^{6}Li Ratio

The time-averaged $\Phi(^7\text{Li})/\Phi(^6\text{Li})$ ratio is compared with the predictions of propagation models GALPROP and USINE based on AMS total Lithium flux measurement.

- As seen, both models fail to describe the AMS result on $\Phi(^7\text{Li})/\Phi(^6\text{Li})$;
- GALPROP with a primary ^{7}Li component deviates from AMS data with excess of ^{7}Li above a few GV;
- The USINE model prediction, which assumes pure secondary origin of ^{6}Li and ^{7}Li, does not agree with the AMS measurements neither, within the model uncertainties that are related to the production cross sections from heavier nuclei.



Estimation of Primary ^{7}Li Fraction

Using the AMS Oxygen flux, Φ(O), as an estimator of the primary ^{7}Li flux contribution, and the AMS ^{6}Li flux, Φ(^{6}Li) for the secondary ^{7}Li flux contribution:

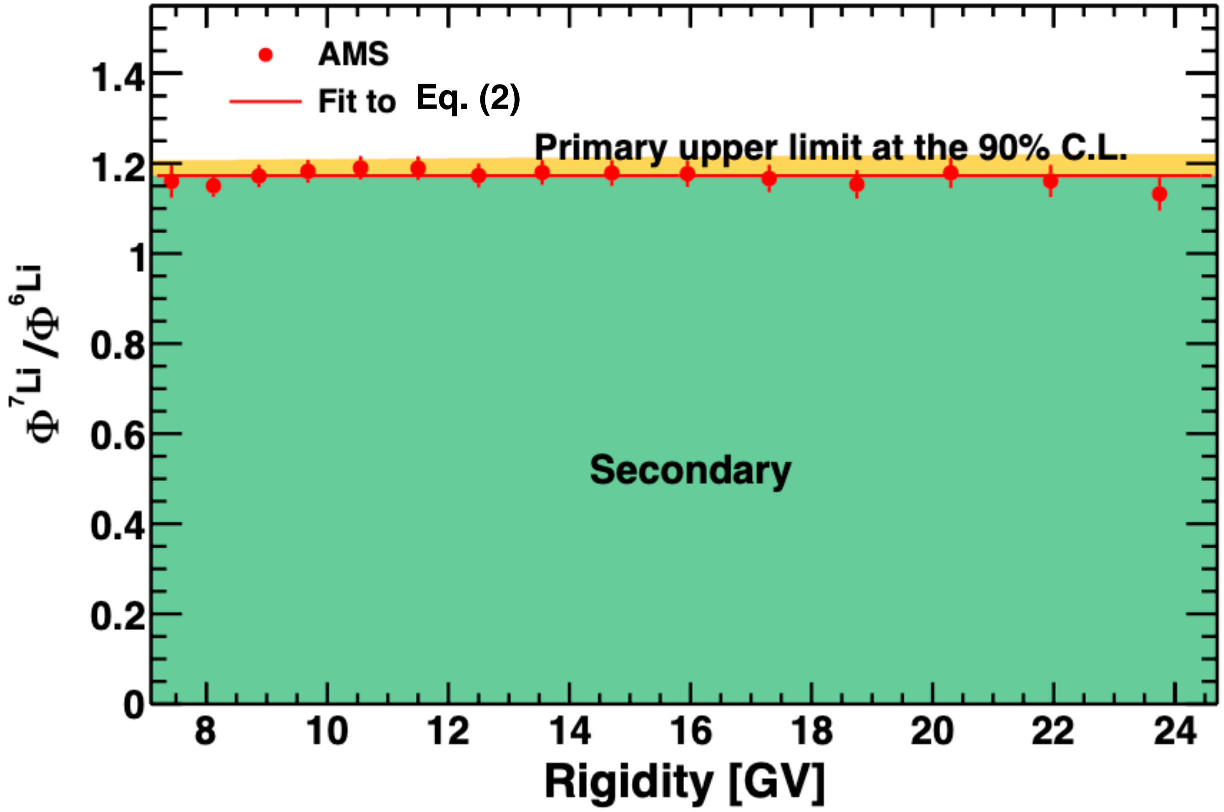
$$\Phi^{^7\mathrm{Li}} = \Phi^{^7\mathrm{Li}}_{\mathrm{primary}} + \Phi^{^7\mathrm{Li}}_{\mathrm{secondary}}$$

$$\Phi^{^7\mathrm{Li}}_{\mathrm{primary}} = f_{\mathrm{O}} \times \Phi^{\mathrm{O}}$$

$$\Phi^{^7\mathrm{Li}}_{\mathrm{secondary}} = c \times \Phi^{^6\mathrm{Li}}$$

$$\frac{\Phi^{^7\mathrm{Li}}}{\Phi^{^6\mathrm{Li}}} = c + \frac{f_{\mathrm{O}} \times \Phi^{\mathrm{O}}}{\Phi^{^6\mathrm{Li}}} \qquad (2)$$

- **The fit yields $c = 1.17^{+0.02}_{-0.03}$ and $f_O = 0^{+0.0027}_{-0}$, with a χ^2/d.o.f. of 12/13.**
- **This corresponds to a fraction of the primary ^{7}Li flux of <3% at the 90% C.L.**



Summary

- Precision measurements of the cosmic-ray ^{6}Li and ^{7}Li fluxes have been presented in the rigidity range from 1.9 to 25 GV.
  - We observed that over the entire rigidity range the ^{6}Li and ^{7}Li fluxes exhibit nearly identical time variations;
  - Above ~4 GV, the time variations of ^{6}Li, ^{7}Li, He fluxes are identical;
- Above ~7 GV, we found an identical rigidity dependence of the ^{6}Li and ^{7}Li fluxes.
- These results show that both ^{6}Li and ^{7}Li are produced by collisions of heavier cosmic-ray nuclei with the interstellar medium, and excludes the existence of a sizable primary component in the ^{7}Li flux.