TeV Particle Astrophysics

TeVPA 2022

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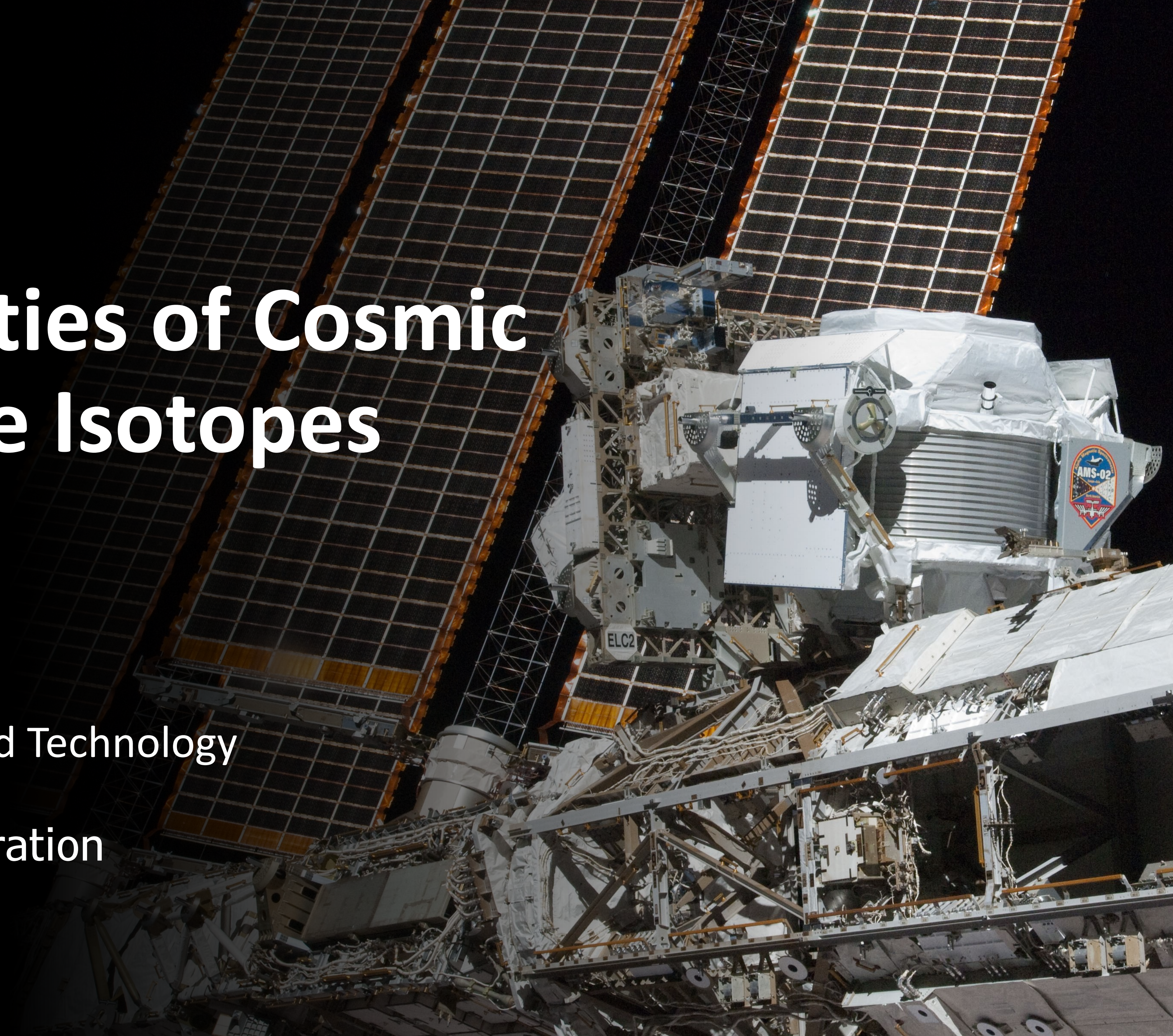
QUEEN'S UNIVERSITY
Kingston, ON

Unique Properties of Cosmic H, He, Li and Be Isotopes



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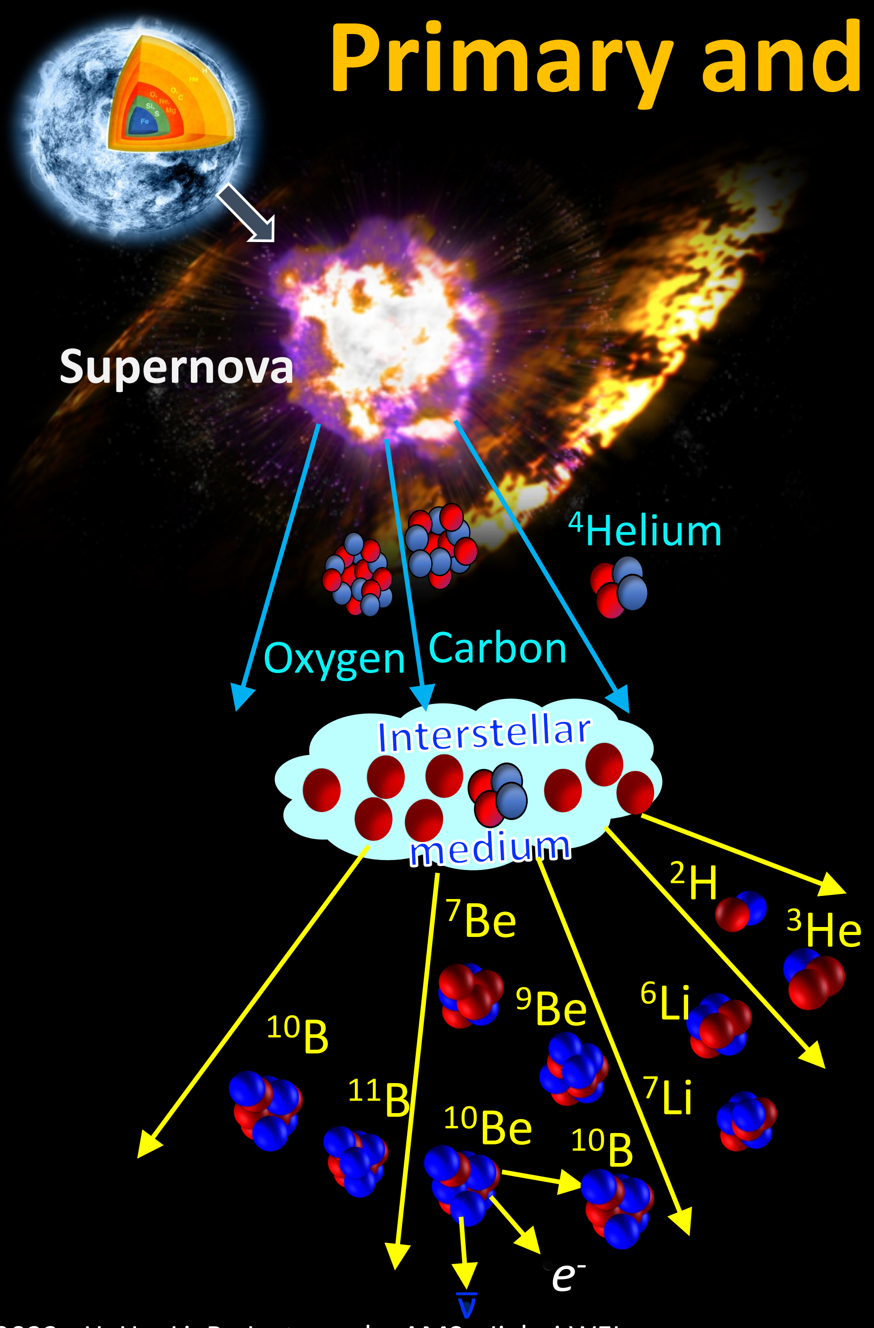
On behalf of the AMS collaboration

09 August 2022

Primary and Secondary Cosmic Rays

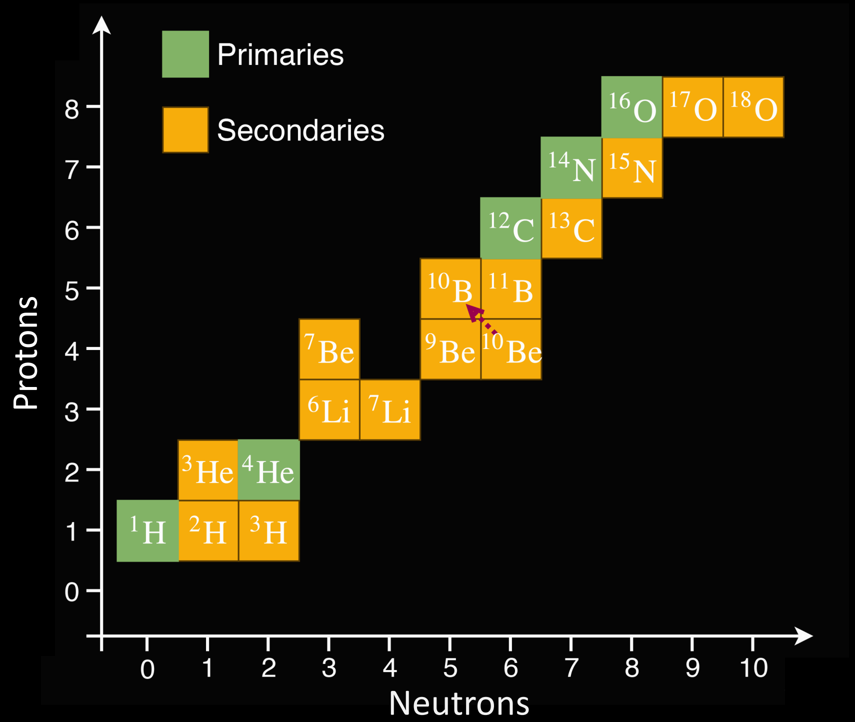


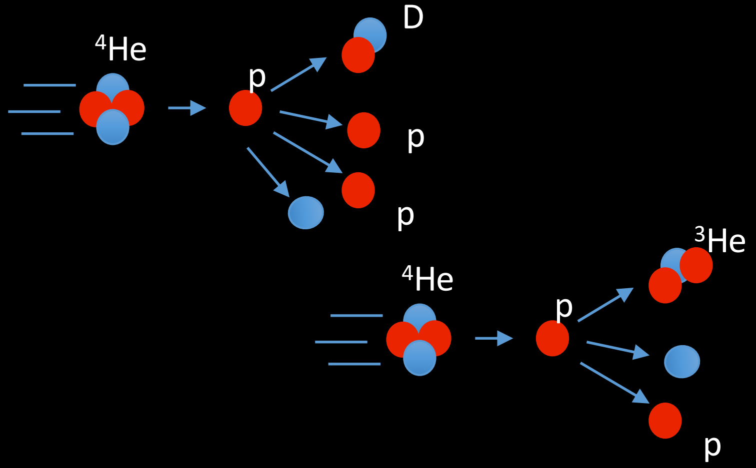
Primary cosmic rays (p, ^{4}He, C, O, ...) are mostly produced during the lifetime of stars and are accelerated in supernovae shocks.

Secondary cosmic rays (D, ^{3}He, Li, Be, B, ...) are produced by the collisions of primary cosmic rays and interstellar medium.

Deuterium and Helium Isotopes

- Helium nuclei are the second most abundant nuclei in cosmic rays.
- D and ^{3}He are mostly produced by the fragmentation of ^{4}He:
  simpler comparison with propagation models than with heavier secondary/primary ratios.
- Smaller cross section of He:
  D/^{4}He and ^{3}He/^{4}He probe the properties of diffusion at larger distances
- Different A/Z ratios of D and ^{3}He allow to disentangle kinetic energy and rigidity dependence of propagation.

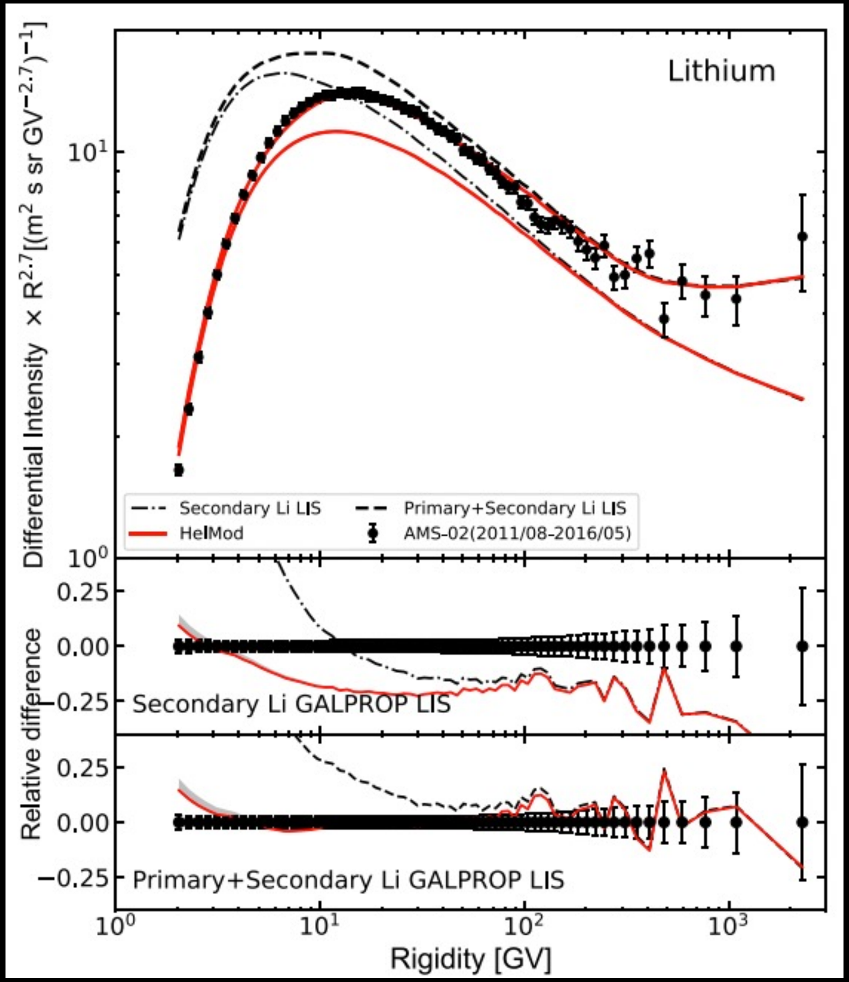




Lithium Isotopes

- Secondary produced by the spallation of heavier nuclei.
- Some studies show lithium flux higher than model prediction:
  - Uncertainty in the production cross-section? (Weinrich et al. A&A, 2020)
  - Primary lithium? (Boschini et al. APJ, 2020)
- Studies of lithium isotopic composition may help to investigate the mechanism.

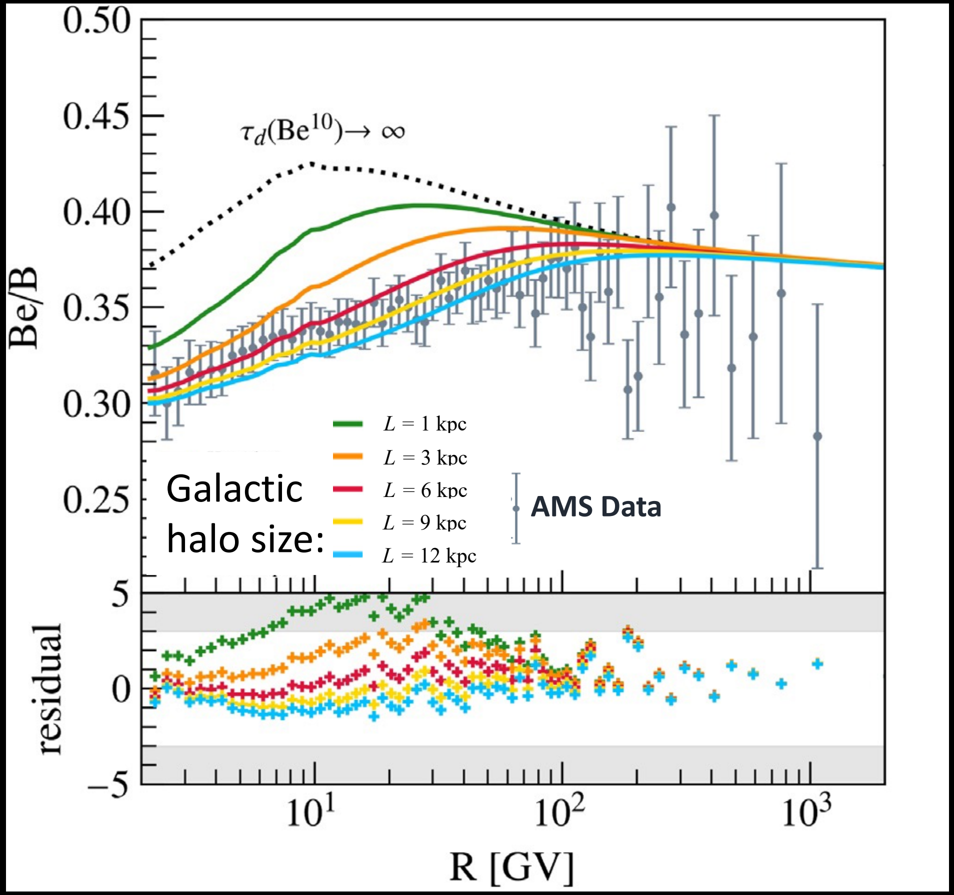
Boschini et al. APJ, 2020



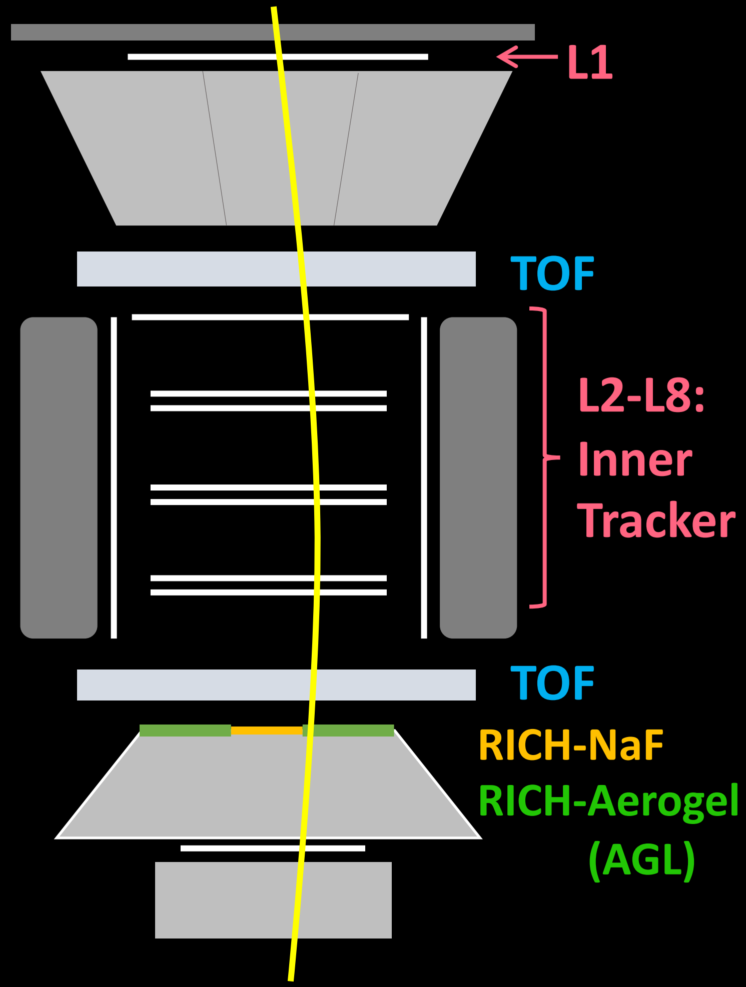
Beryllium Isotopes

- $^{10}Be \rightarrow {}^{10}B$, $t_{1/2} \approx 1.38$ My: "radioactive clock"
- Recent studies of cosmic ray propagation using Be/B flux ratio:
  - Evoli et al. PRD, 2020
  - Weinrich et al. A&A, 2020
- $^{10}Be/^{9}Be$ provides more sensitive measurement of the age of cosmic rays.
- AMS is able to measure Be isotopes up to 12 GeV/n (~30 GV).

Evoli et al. PRD, 2020



Measurement of Isotopes with AMS-02

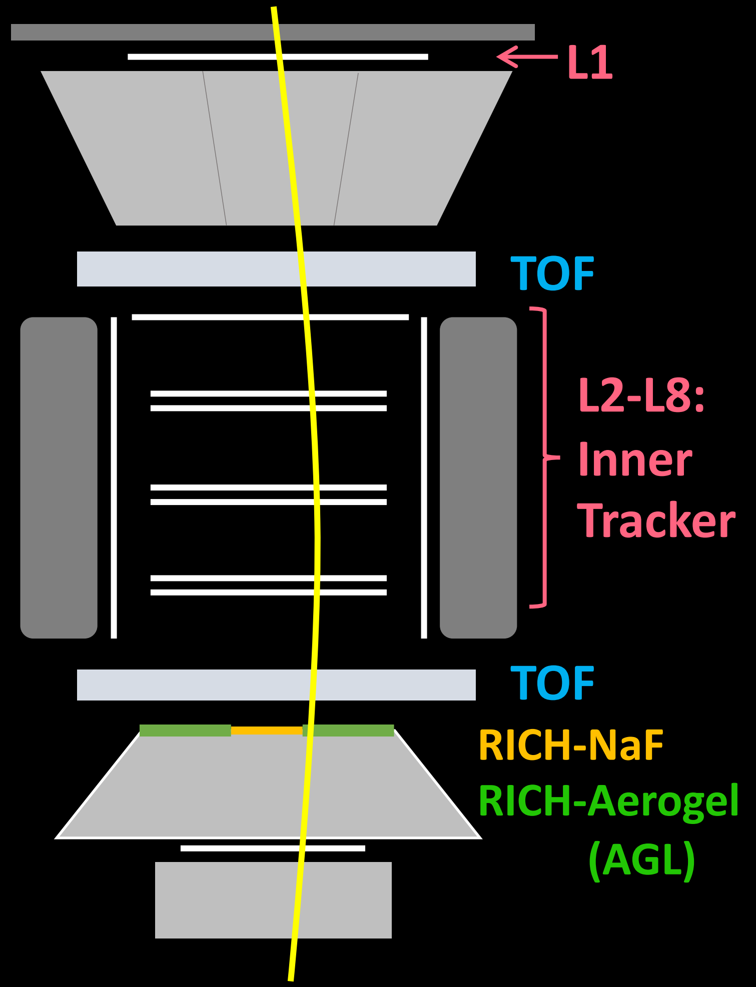


$$M = \frac{RZ}{\beta\gamma}$$

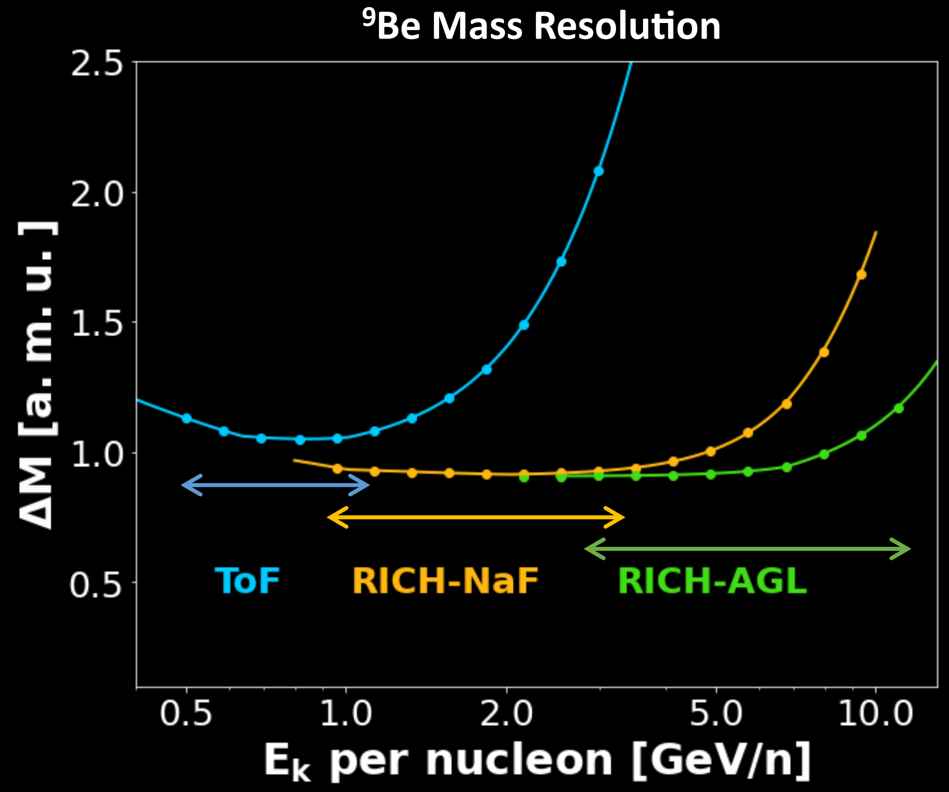
- R measurement :
  - Tracker, $\Delta R/R \sim 10\%$ at 10 GV
- β measurements:

	E_{kn} range (GeV/n)	$\Delta\beta/\beta$ (Z=1)	(Z=4)
TOF	(0.5, 1.2)	~3%	~1.5%
RICH-NaF (n=1.33)	(0.8, 4.0)	~0.3%	~0.15%
RICH-AGL (n=1.05)	(3.0, 12)	~0.1%	~0.05%

Measurement of Isotopes with AMS-02

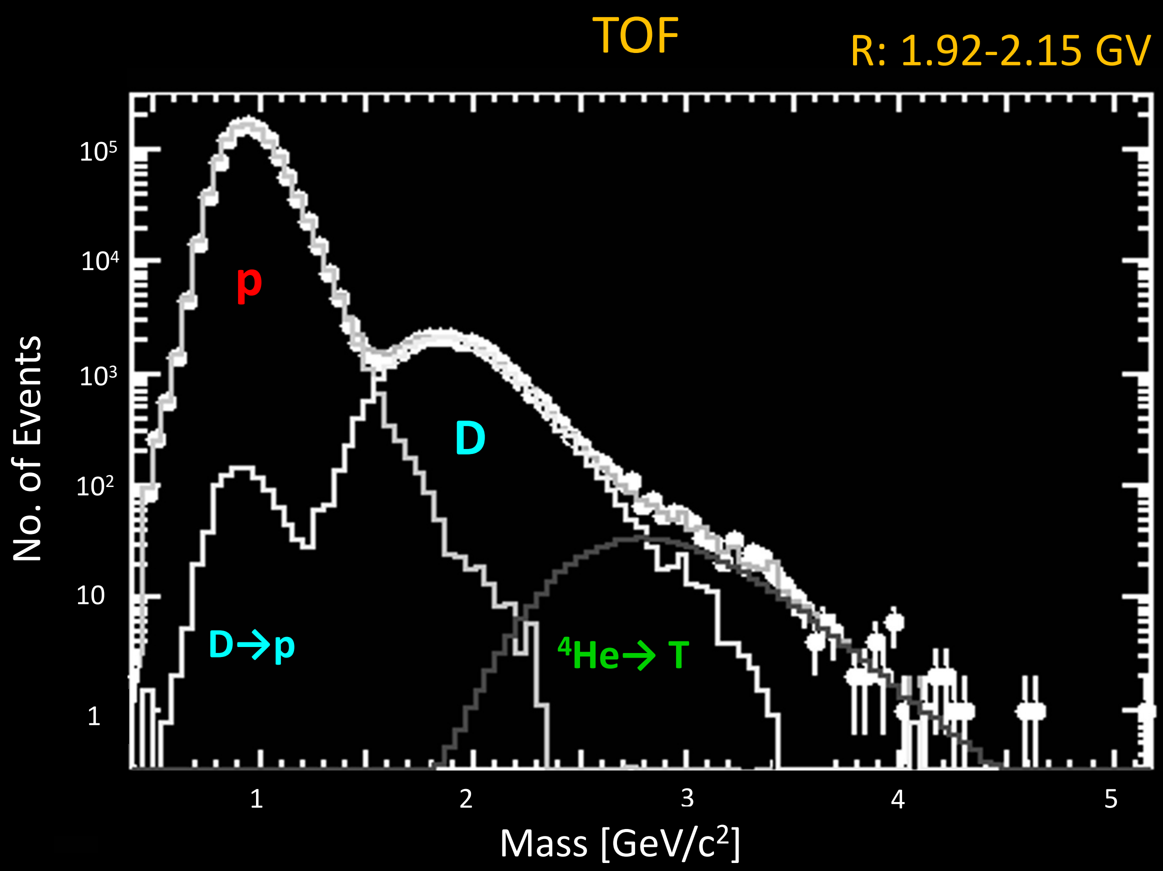


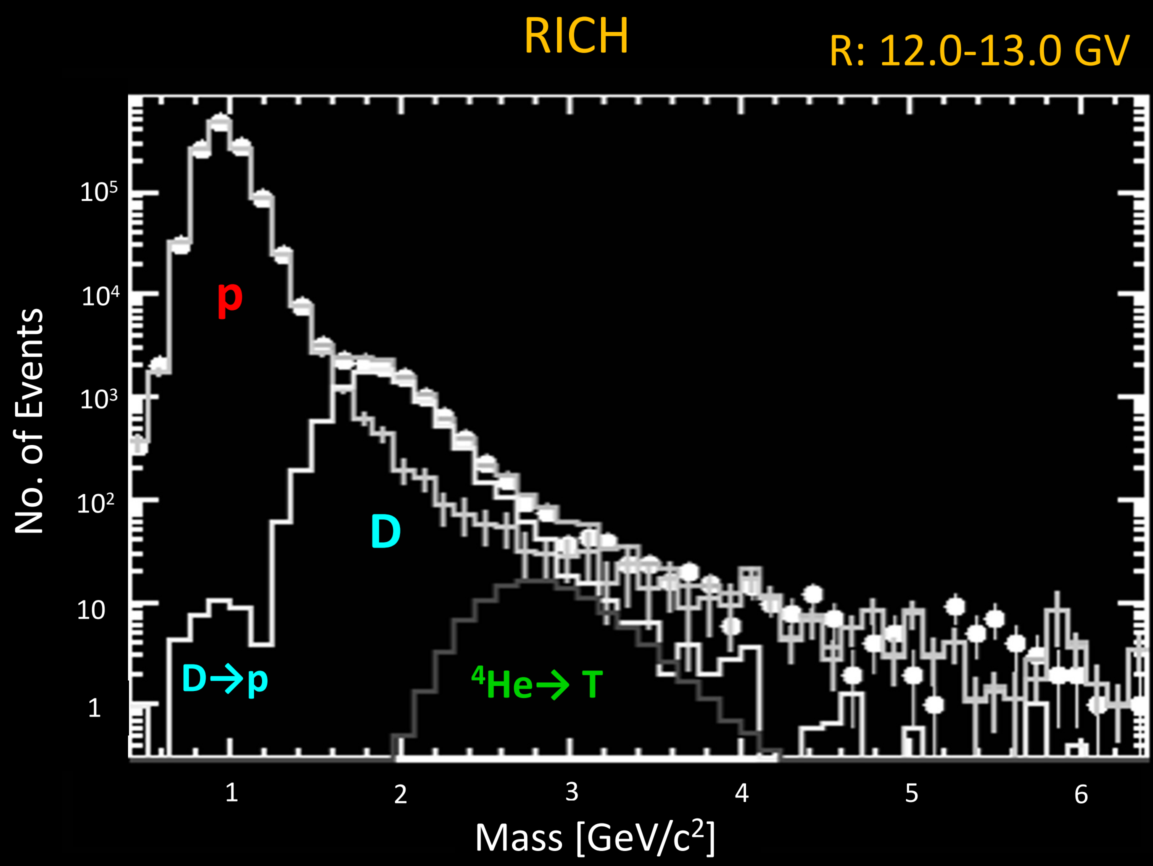
$$\frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta R}{R}\right)^2 + \left(\gamma^2 \frac{\Delta\beta}{\beta}\right)^2}$$



$\Delta M \sim 1$ a.m.u.→ Unable to do event-by-event isotope identification

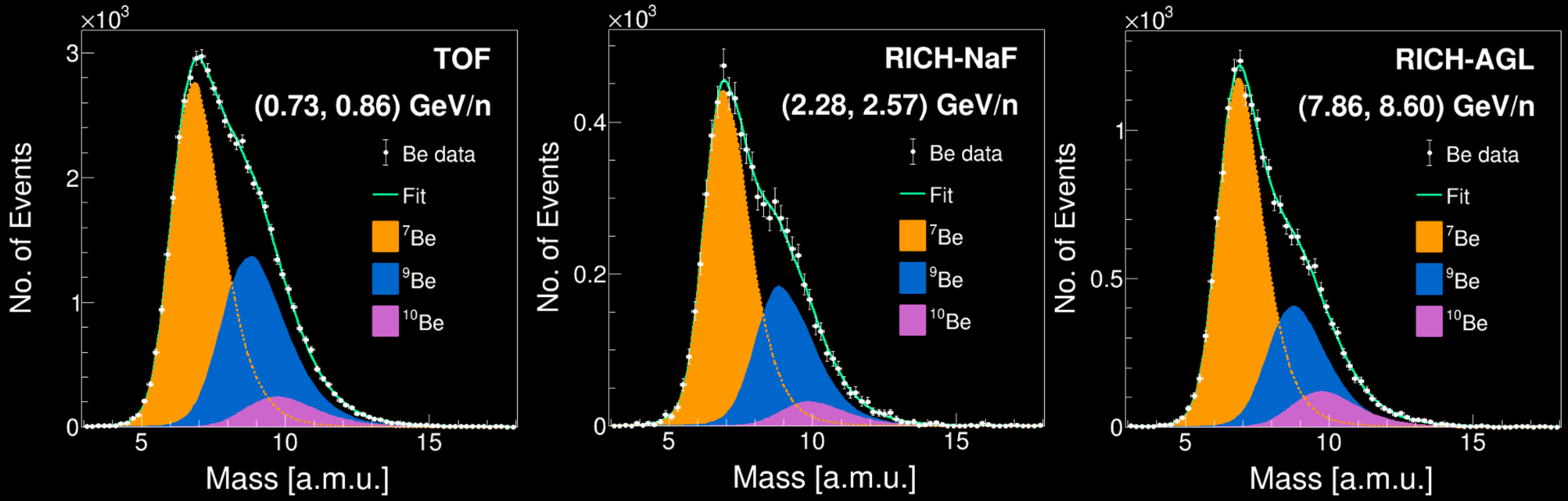
Examples of Mass Template Fit for Z=1





- Isotopic abundances obtained from mass template fit carried out in difference energy ranges.
- Mass templates are based on Monte Carlo simulation validated by data.

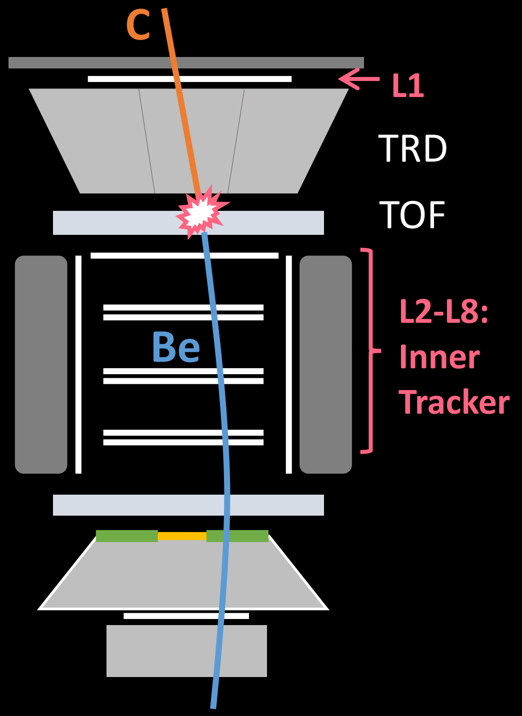
Examples of Mass Template Fit for Z=4



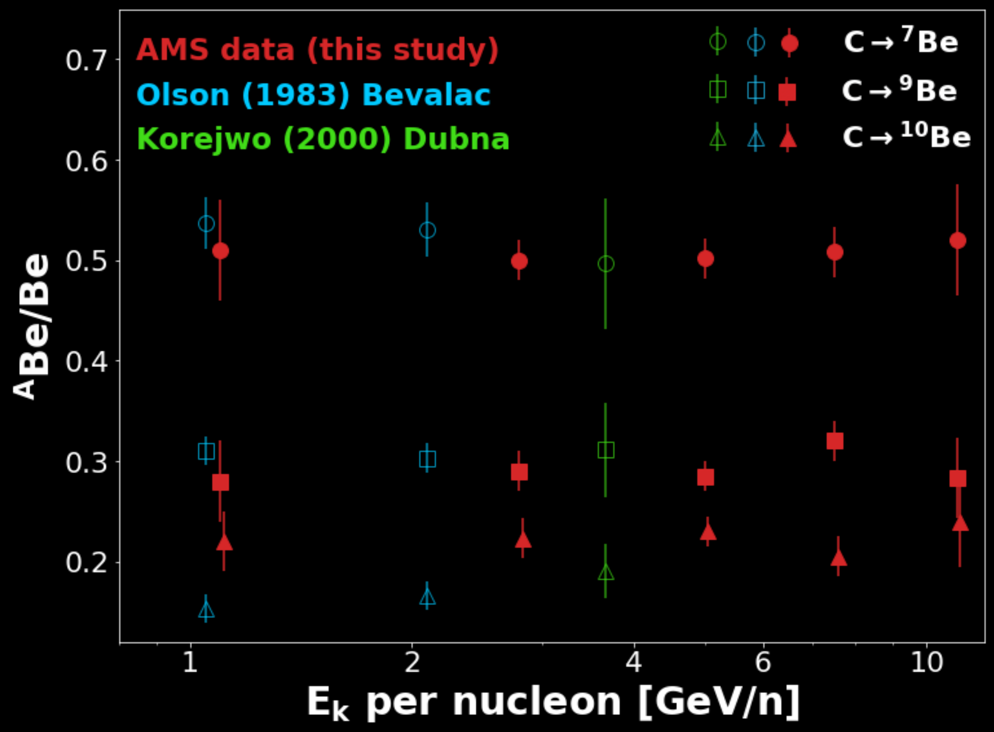
- Isotopic abundances obtained from mass template fit carried out in difference energy ranges.
- Mass templates are based on Monte Carlo simulation validated by data.

Validation of Fragmentation Cross Sections

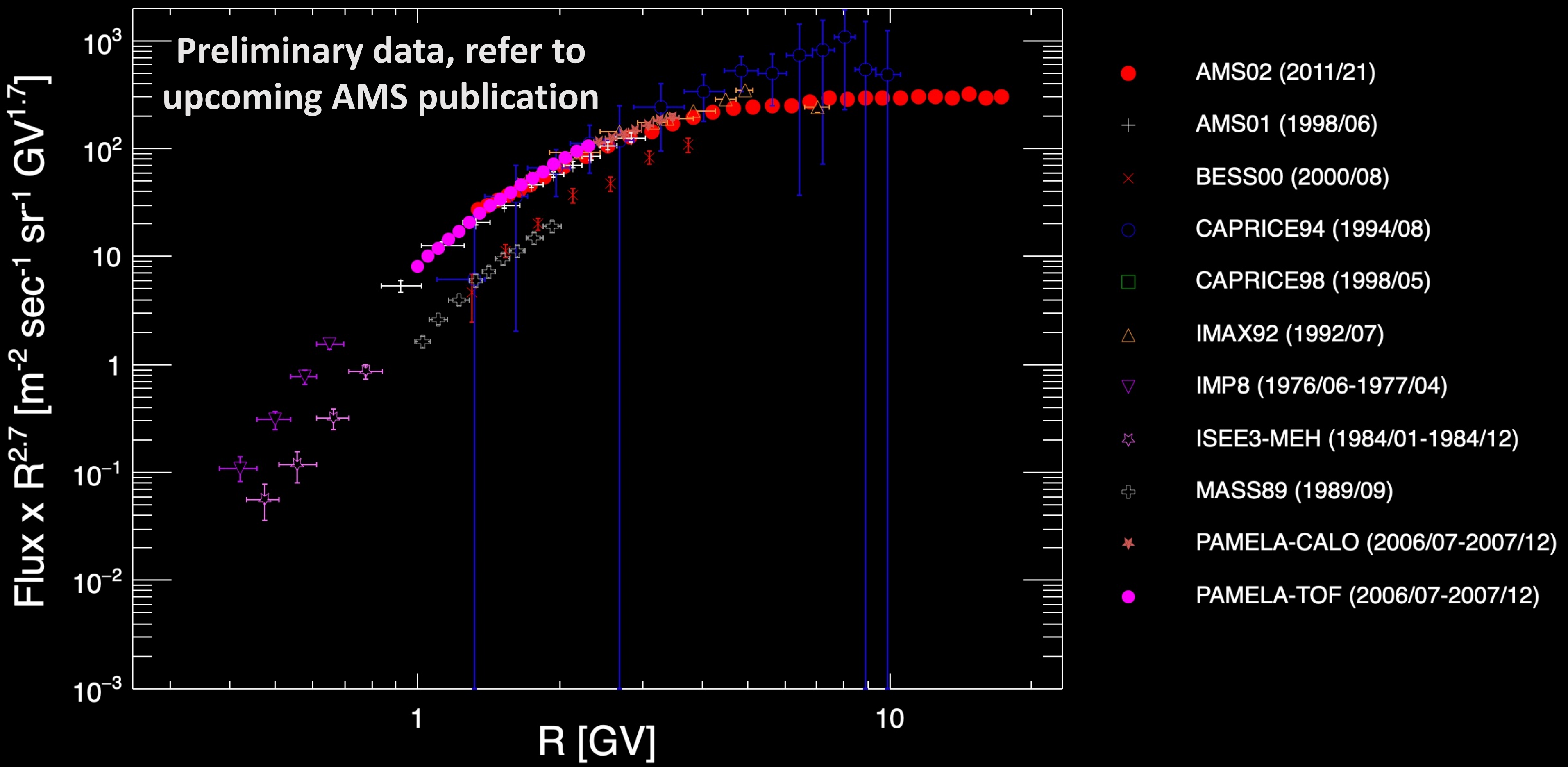
- The fragmentation background is not negligible.
- The knowledge of nuclei interaction cross sections is important.
- Using AMS material as the target, the fragmentation cross sections (Q. Yan et al. 2020) and isotopic cross sections can be validated.



Carbon nuclei fragmenting to beryllium isotopes in TRD+TOF

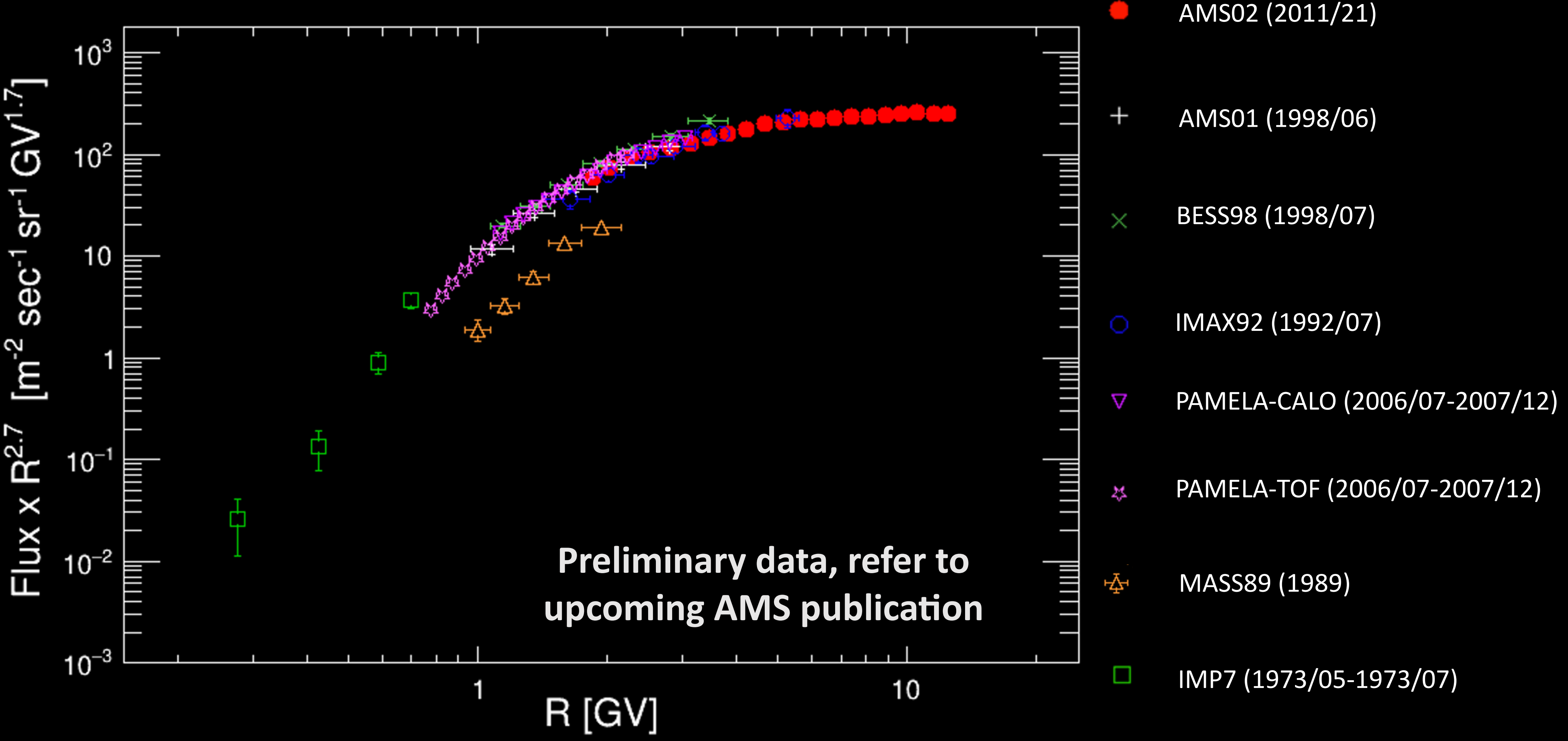


^2H Flux



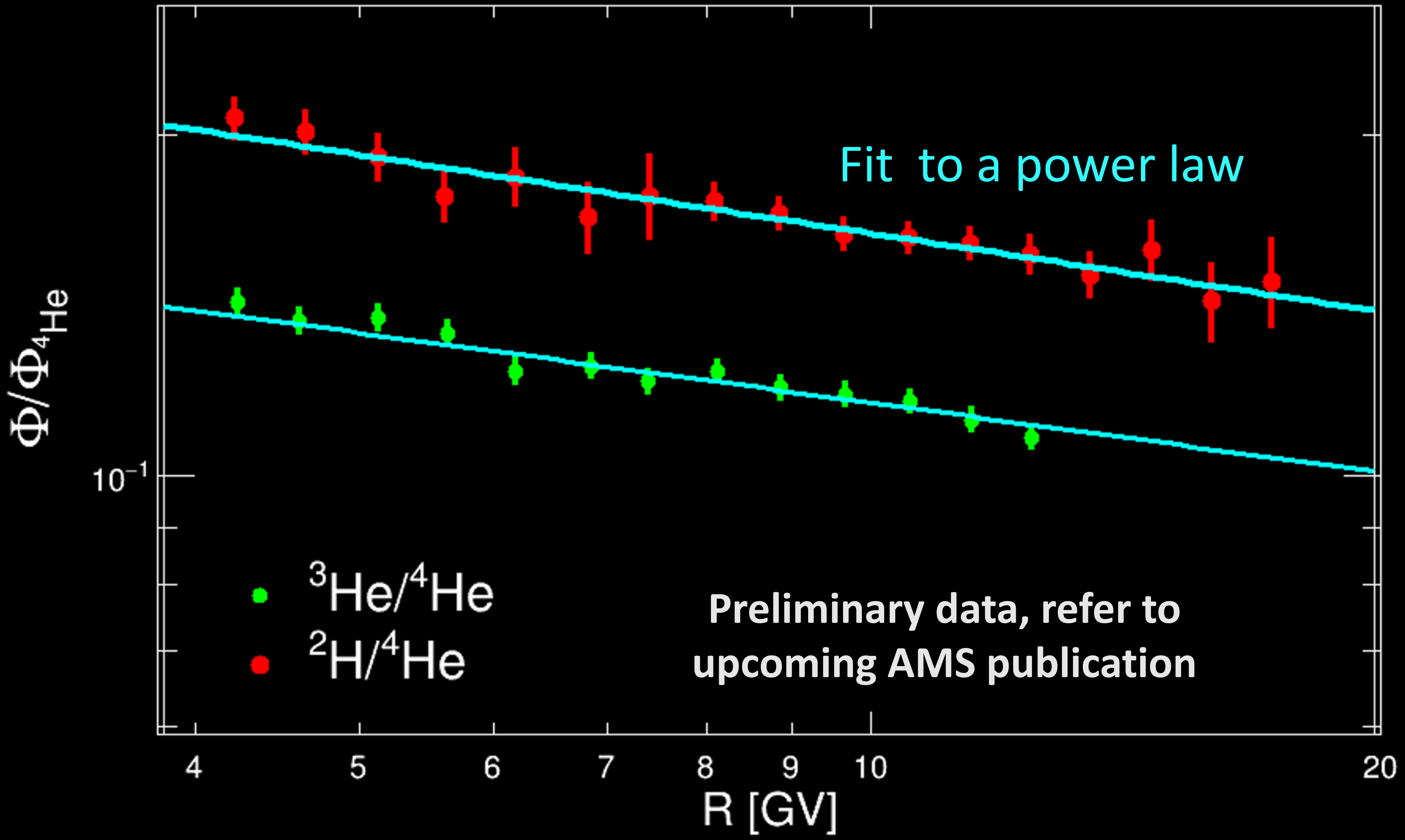
- Based on 9 million deuteron events
- Combined three analyses using TOF, RICH-NaF and RICH-AGL.

^{3}He Flux

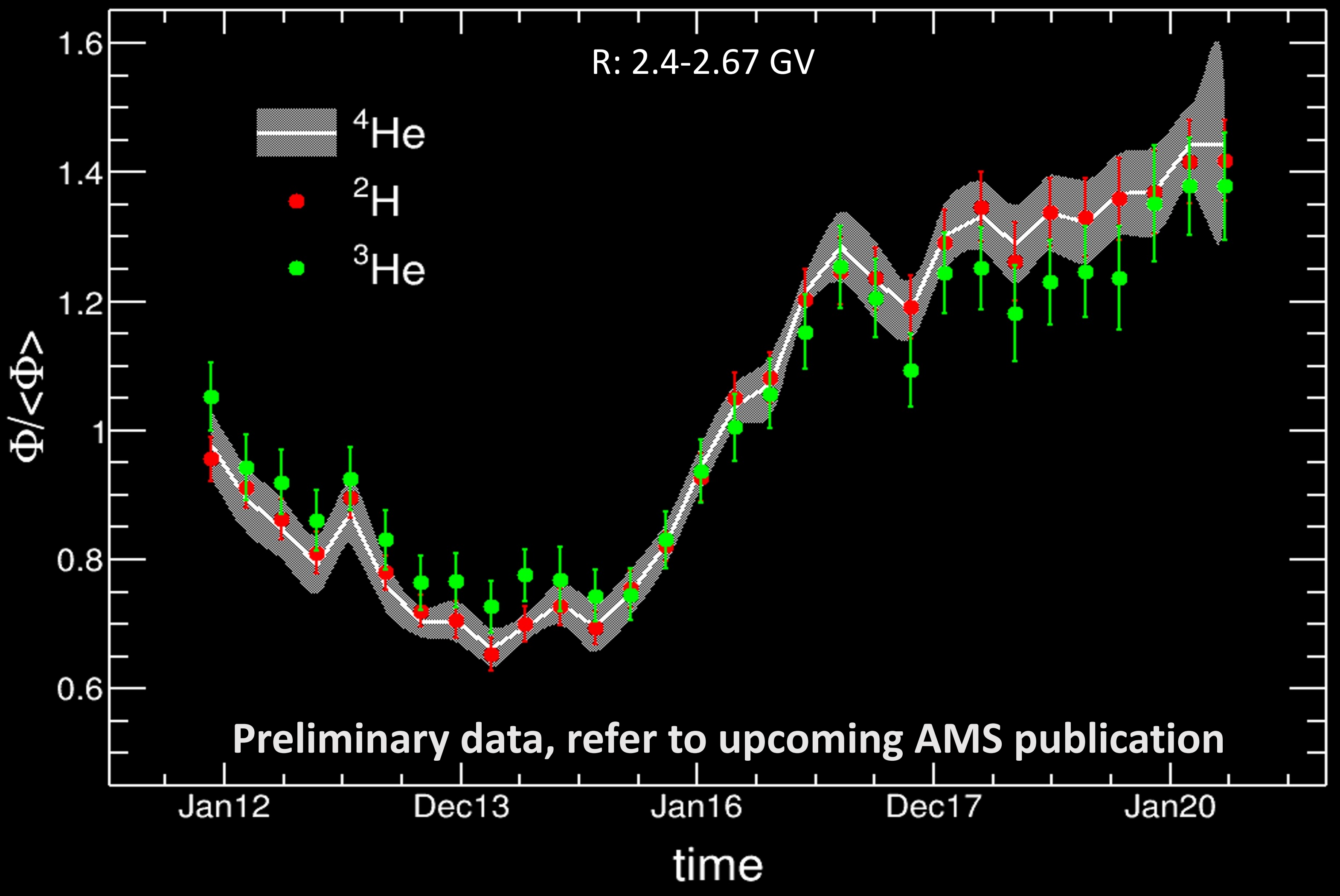


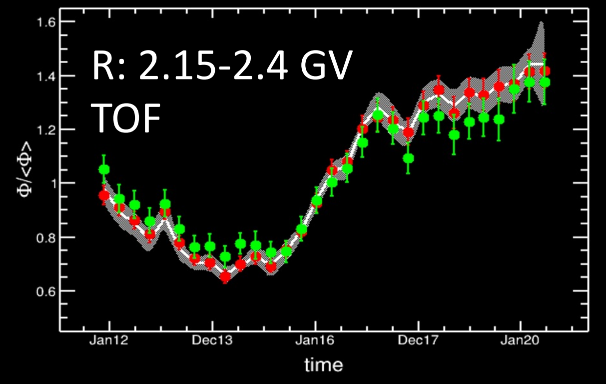
- Based on 60 million ^{3}He events

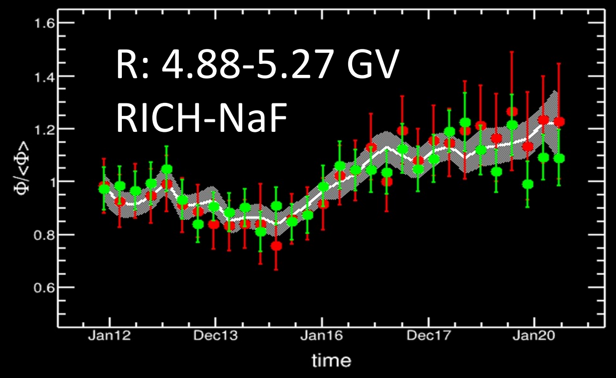
$^2H/^4He$ and $^3He/^4He$ Flux Ratios

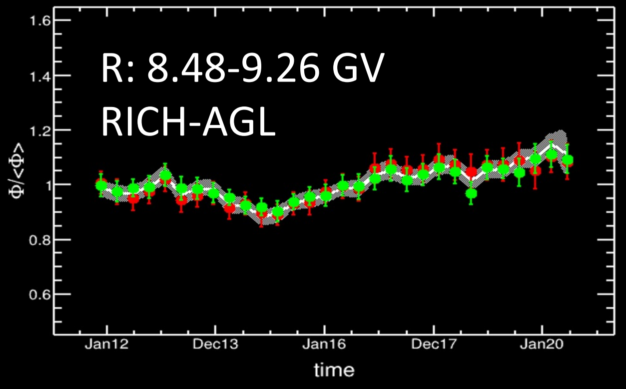


Evolution with Time





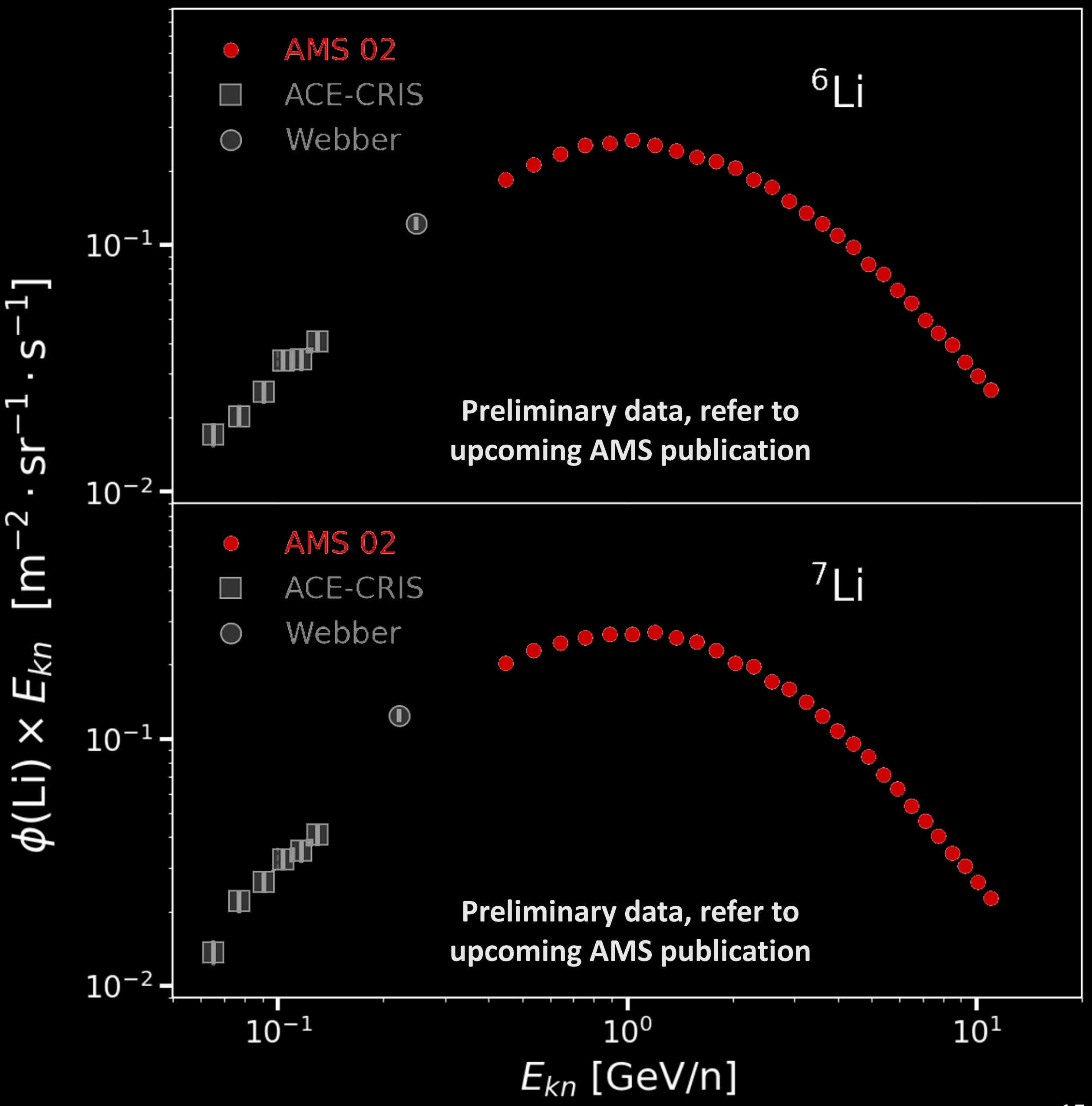




Lithium Isotopic Fluxes

- Based on 0.8 million lithium events.

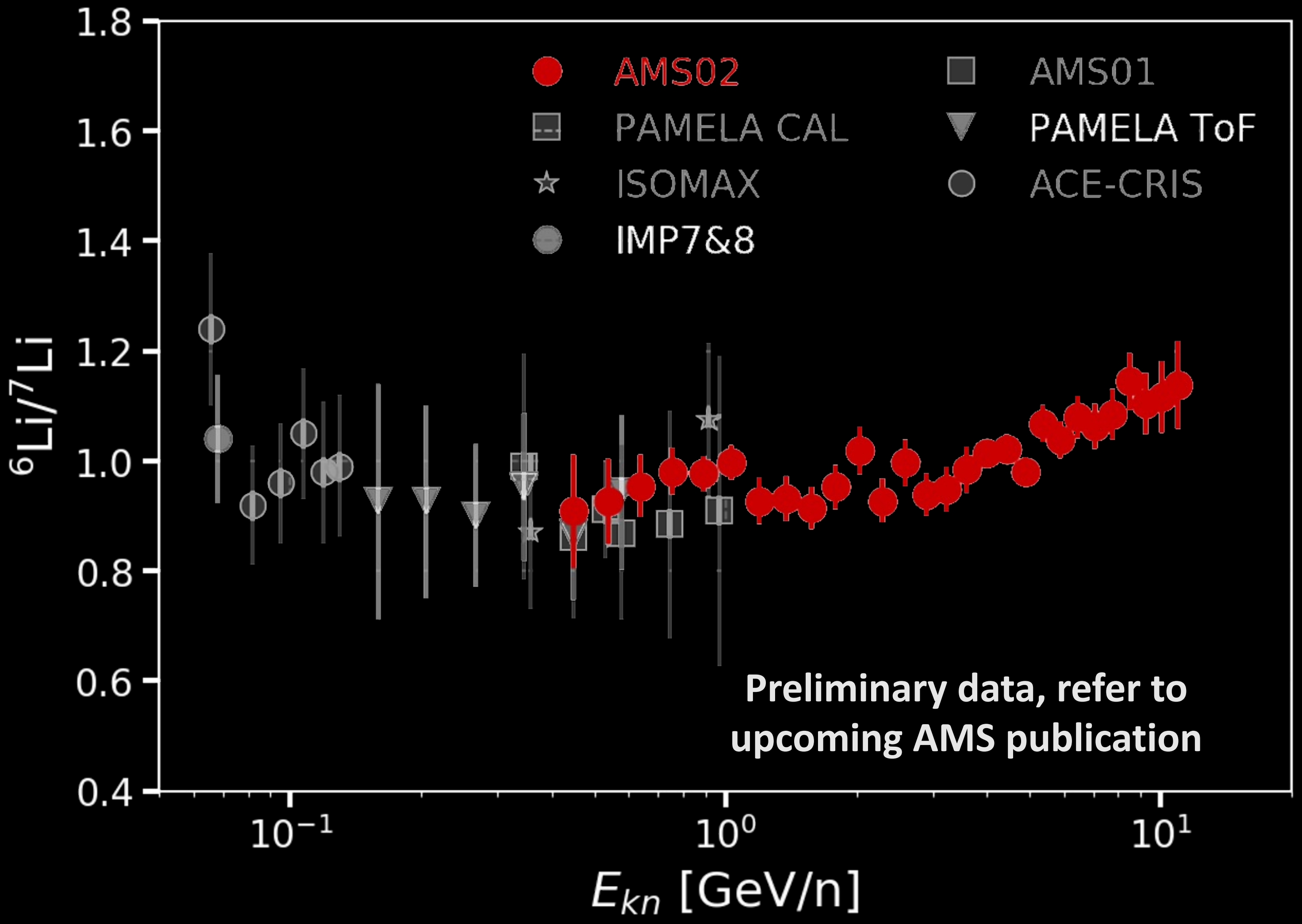
→ First measurement of ^{6}Li and ^{7}Li fluxes above 0.5 GeV/n and up to 12 GeV/n.



Lithium Isotopic Flux Ratios

- $^{6}Li/^{7}Li$ flux ratio and comparison with previous experiments:

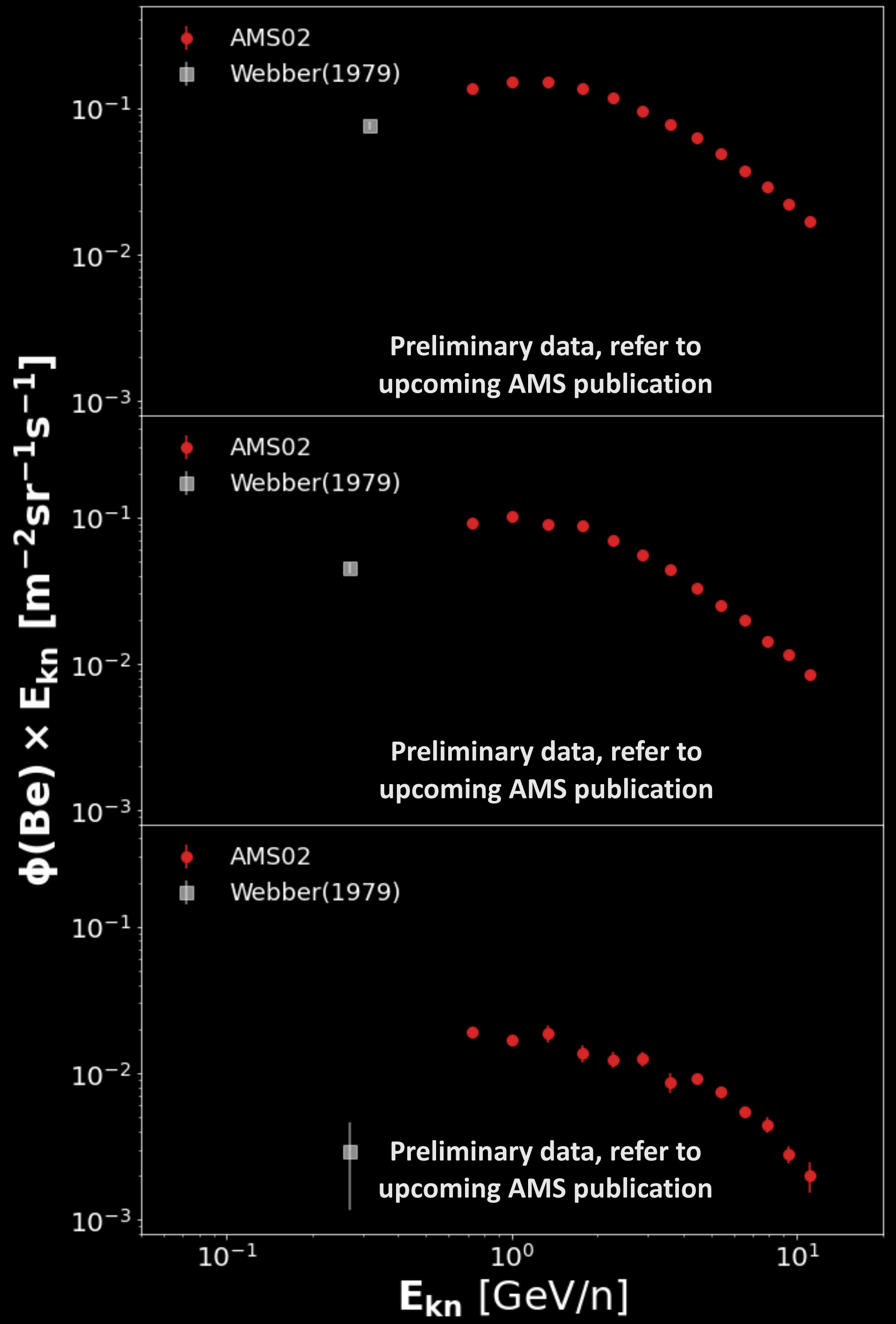
→ **Extend the measurement of $^{6}Li/^{7}Li$ flux ratio above 1 GeV/n to 12 GeV/n**



Beryllium Isotopic Fluxes

- Based on 0.4 million beryllium events.

→ First measurement of ^{7}Be, ^{9}Be and ^{10}Be fluxes above 0.5 GeV/n and up to 12 GeV/n.

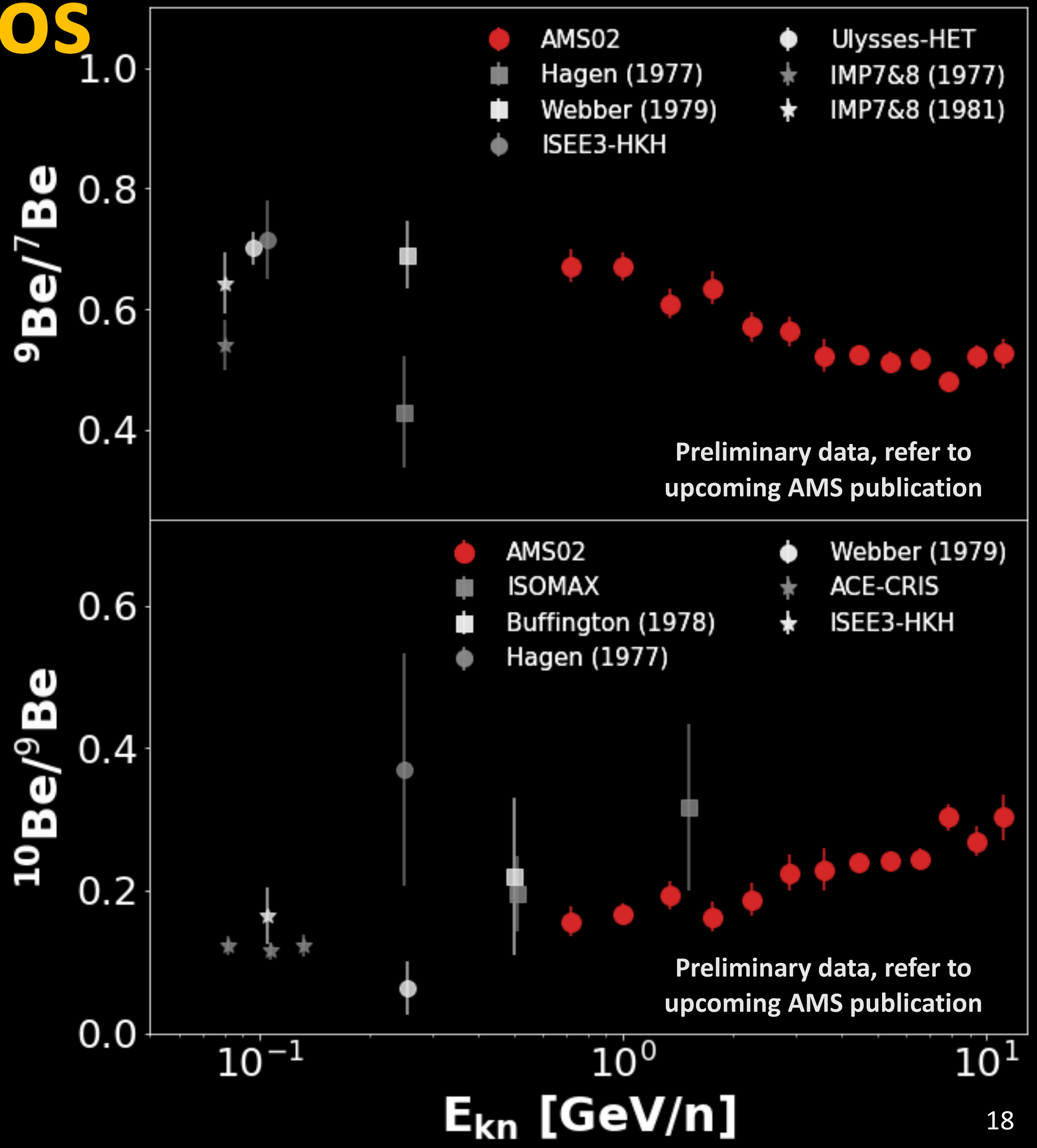


Beryllium Isotopic Flux Ratios

- $^{9}Be/^{7}Be$ and $^{10}Be/^{9}Be$ flux ratios and comparison with previous experiments:

→ First measurement of

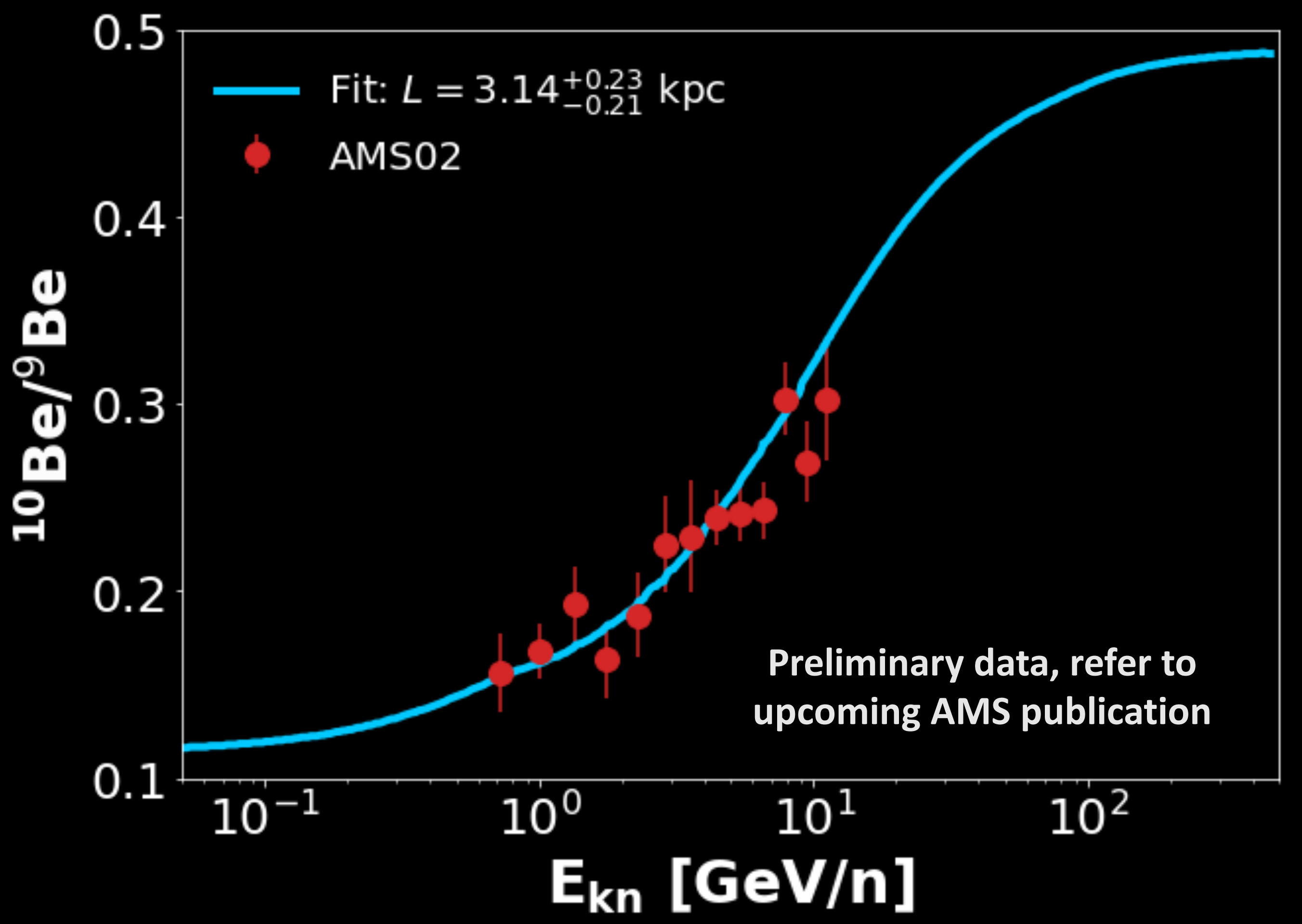
- **$^{9}Be/^{7}Be$ flux ratios above 0.5 GeV/n.**
- **$^{10}Be/^{9}Be$ flux ratios above 2 GeV/n.**



Fitting the $^{10}Be/^{9}Be$ Flux Ratios

- Galactic diffusion halo size L fitted on AMS02 data with an analytical formula:
  (D. Maurin *et al.*, arXiv:2203.07265)

- **Precision on L from AMS02 data $\Delta L_{\mathrm{AMS02}} \sim 0.2$ kpc.**
- Error dominated by uncertainty from production cross-section (1 kpc).



Conclusions

- Isotope studies give unique information on propagation (D, ^{3}He), production mechanism ($^{6,7}Li$, $^{7,9}Be$) and independently measure the age of cosmic rays ($^{9,10}Be$).
- AMS-02 measured cosmic-ray isotopes based on 9M deuteron, 60M ^{3}He, 0.8M lithium and 0.4M beryllium events.
- The following preliminary results were presented:
  - D and ^{3}He fluxes in the rigidity range from 2 GV to 20 GV and 15 GV .
  - The ratio of D and ^{3}He to ^{4}He are compatible with a power law function.
  - Time evolution of D and ^{3}He fluxes, similar to those of ^{4}He.
  - Li and Be isotopic fluxes, and their ratios in the energy range of 0.5 GeV/n to 12 GeV/n.