# Precision Measurement of Cosmic Ray Deuterons with the Alpha Magnetic Spectrometer on the ISS

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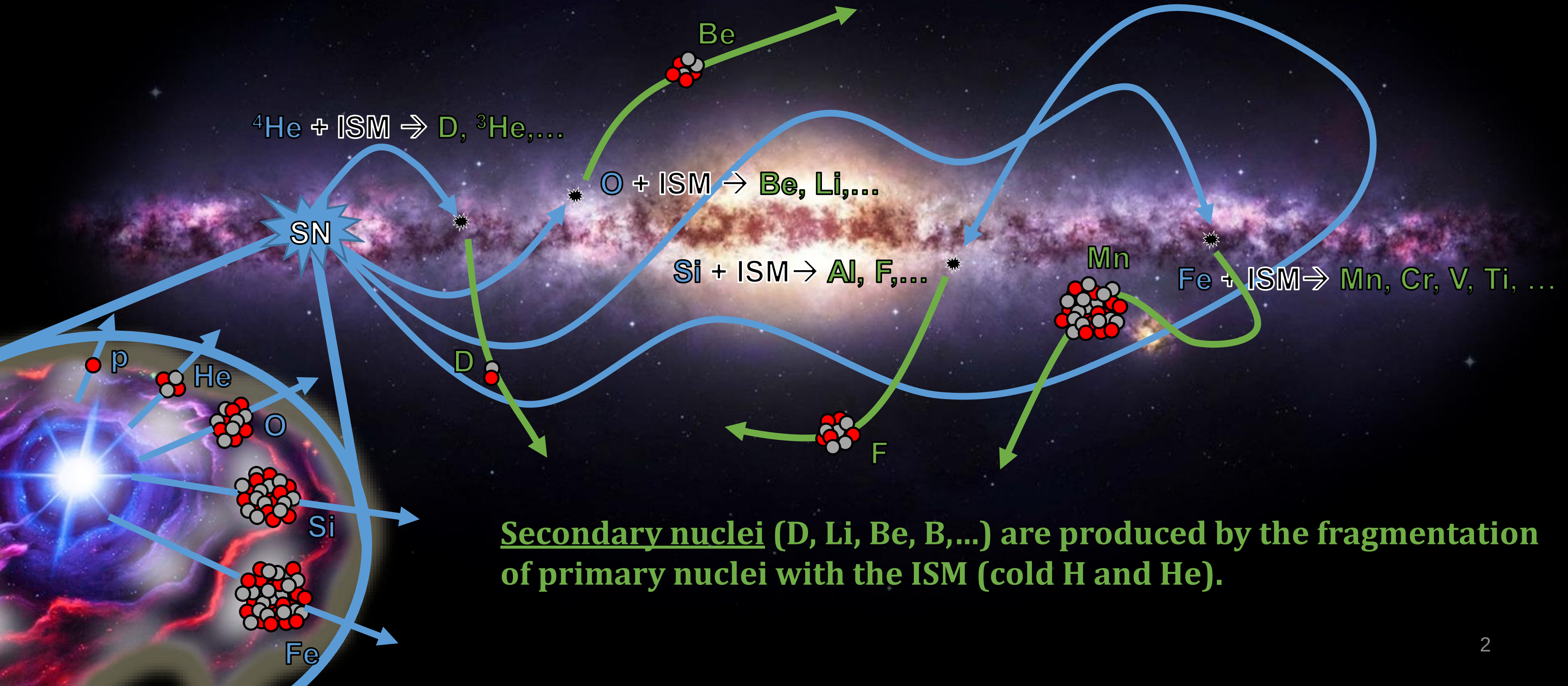
# Primary and Secondary nuclei in Cosmic Rays

Primary nuclei (He, C, O, Ne, Mg, Si, Fe) are fused in stars and injected into the galaxy in a supernova explosion.

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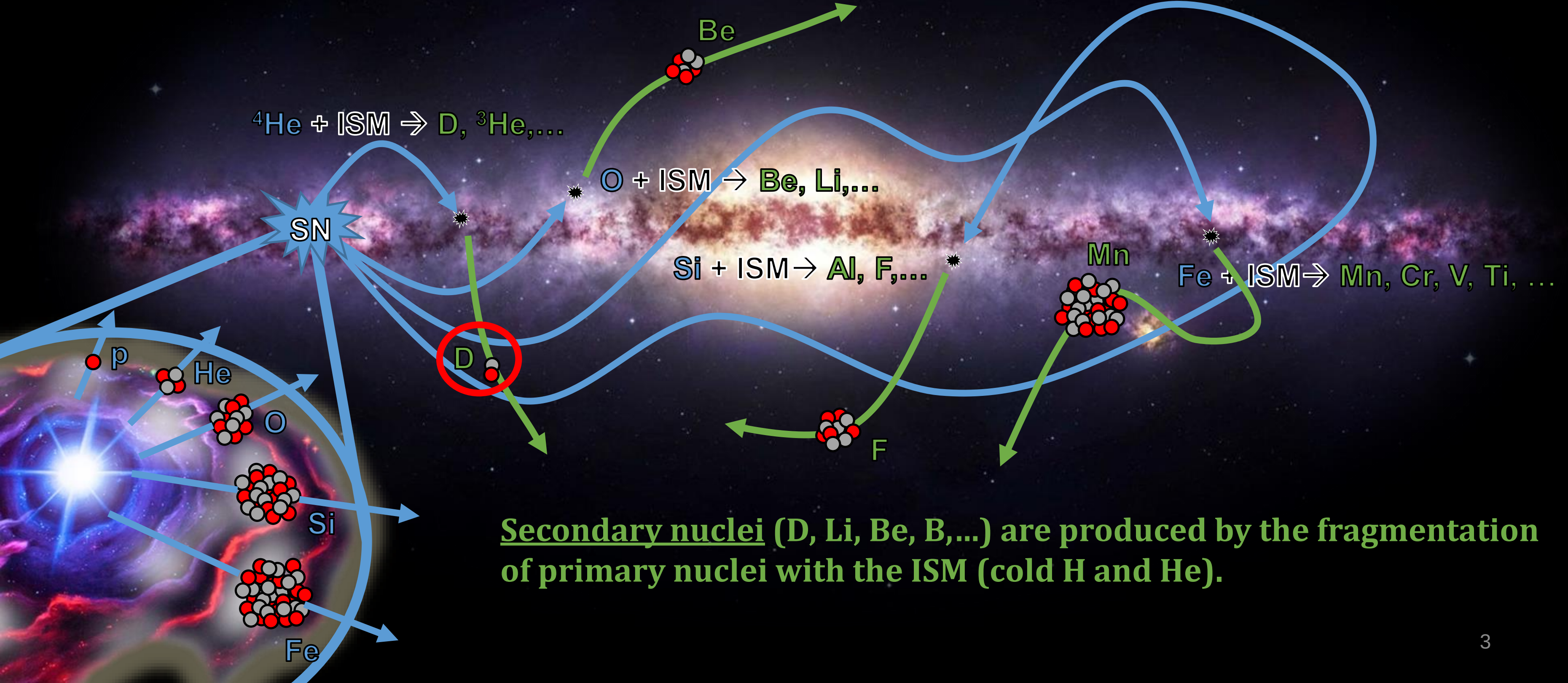


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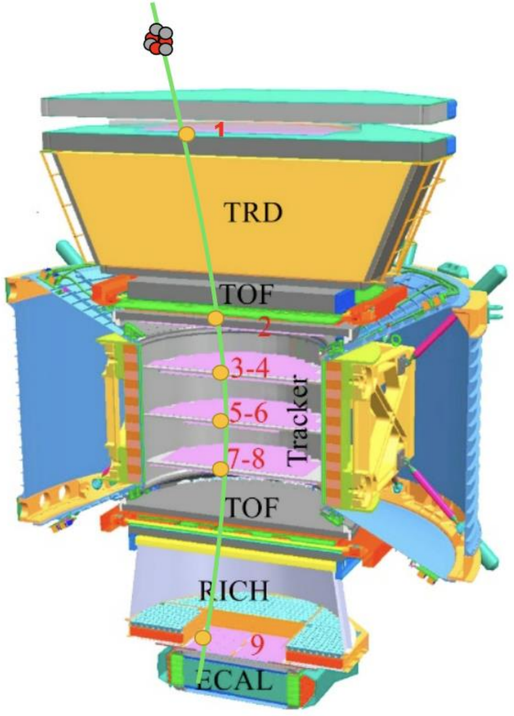
# Deuterons in cosmic rays

- Deuterons (D), just like $^3$He, **are believed to be secondary nuclei**, which are produced mainly by $^4$He fragmentation.
- The measurement of cosmic deuterons fluxes is of **great importance** for the study of the properties of the galaxy:
  - The **smaller interaction cross section of He** with respect heavier nuclei, allows to study the **properties of diffusion at larger distances** than other nuclei.
  - The **different A/Z ratios** of D and $^3$He could allow to **disentangle kinetic energy and rigidity dependence** in propagation models.
  - For the **D/$^4$He ratio**, since their kinetic energy per nucleon is the same for equal rigidity, **the effect of modulation is expected to be reduced** compared with other nuclei ratios.

# Isotope identification in AMS




$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta R}{R}\right)^2 + \gamma^4 \left(\frac{\Delta \beta}{\beta}\right)^2$$

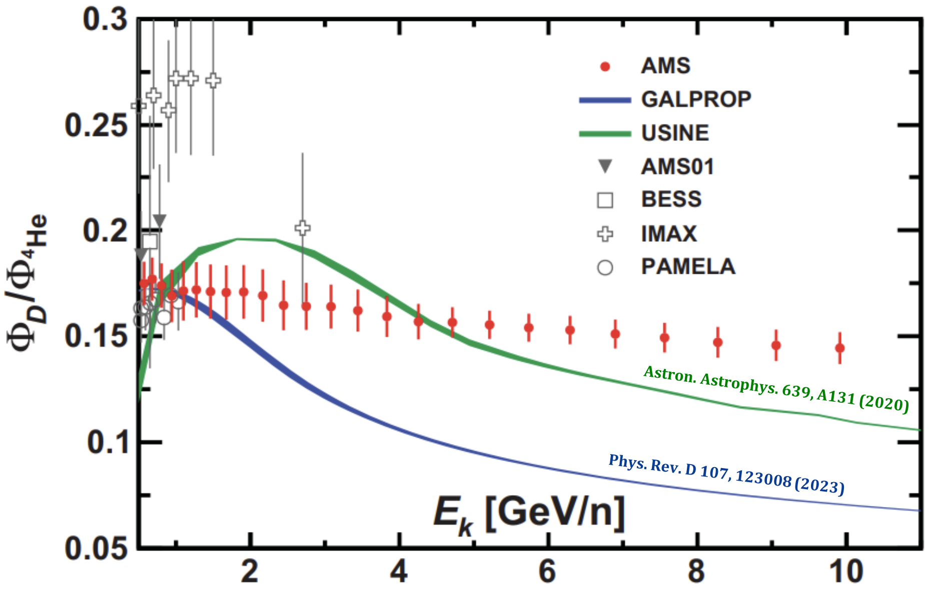
- **Nuclei mass is reconstructed** from the combination of the **rigidity** measured by the Tracker and the **velocity** measured either by the TOF or the RICH.
- **Separation power depends on rigidity and velocity resolutions.**
- **Rigidity resolution function** is determined from MC simulation, with **ΔR/R ~ 10%** @10GV.
- The **inverse velocity (1/$\beta$) resolution** functions for both the TOF and the RICH are modeled and fitted to data.

| | Δβ/β (Z=1, β=1) | Δβ/β (Z=2, β=1) | $E_k$/n range (GeV/n) |
|---|---|---|---|
| **TOF** | 4% | 2% | (0.42, 1.2) |
| **RICH-NaF** | 0.35% | 0.25% | (0.8, 4.0) |
| **RICH-Aerogel** | 0.12% | 0.07% | (3.0, 12) |

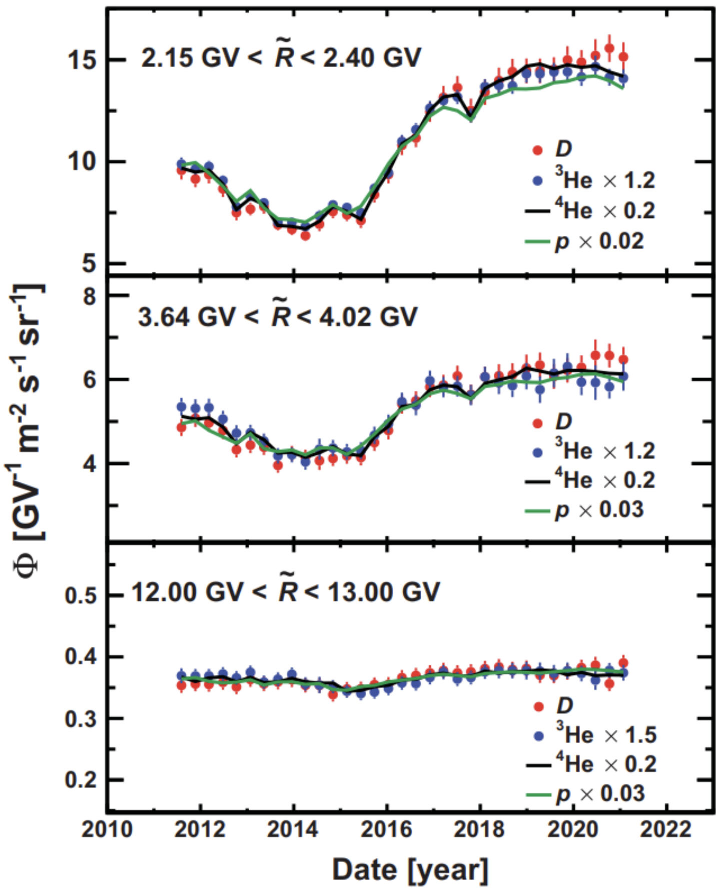
# Properties of Cosmic Deuterons Measured by the Alpha Magnetic Spectrometer

- The measurement is based on **21 million D nuclei collected by AMS** in the rigidity range from 1.9 GV to 21 GV from May 2011 to April 2021.

- The **AMS results** on the D/$^4$He flux ratios **disagree with GALPROP and USINE predictions,** which include **only secondary deuteron contribution,** and show a significantly harder spectrum.



# Fluxes Time Dependence

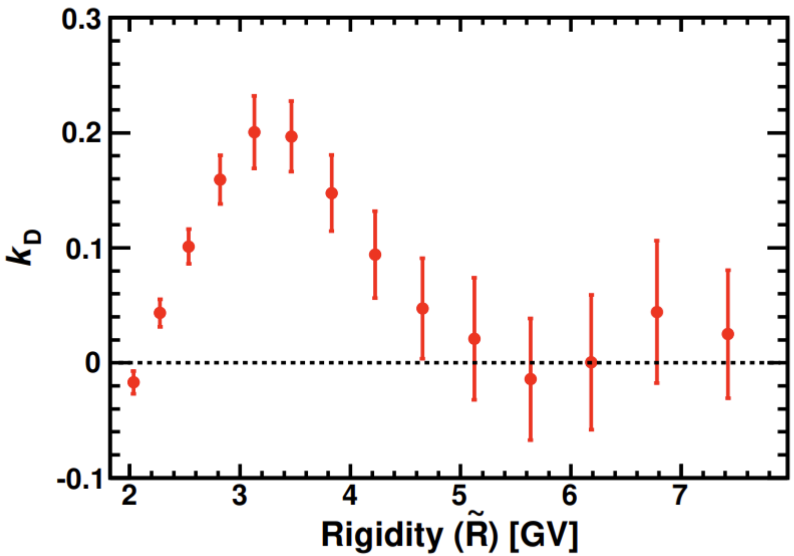



- Since we are considering **time-averaged ratios**, we must study **possible differences in fluxes time dependence** that would have an impact in the results.
- In each rigidity bin, **D, p, $^4$He and $^3$He fluxes exhibit a similar time behavior**.
- The relative magnitude of the variations **decrease with increasing rigidity**.

# Fluxes Time Dependence

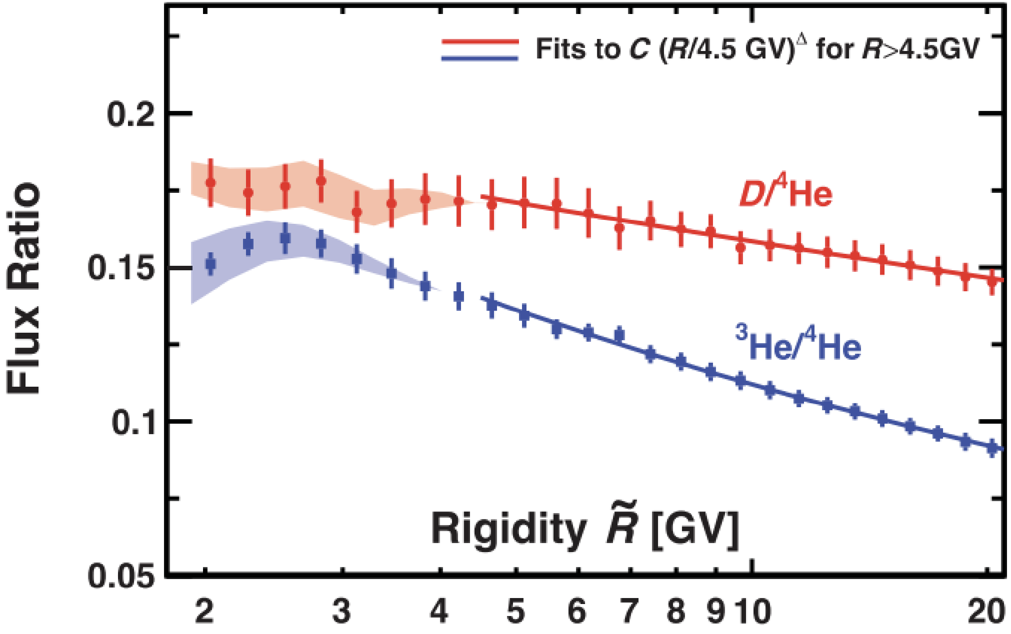
- To further study the differences in time variation, we fit a **linear relation between the relative variations** of D/$^4$He ratio and $^4$He flux for each bin.
- $\boldsymbol{k_D}$ is **significantly above zero** from rigidities 2.1 to 4.5 GV, showing that the **D flux is more modulated** than the $^4$He flux in this rigidity range.
- Above 4.5 GV, the **D/$^4$He flux ratio is time independent.**

$$\frac{\Phi^i_D/\Phi^i_{^4\mathrm{He}} - \langle \Phi^i_D/\Phi^i_{^4\mathrm{He}} \rangle}{\langle \Phi^i_D/\Phi^i_{^4\mathrm{He}} \rangle} = k^i_D \frac{\Phi^i_{^4\mathrm{He}} - \langle \Phi^i_{^4\mathrm{He}} \rangle}{\langle \Phi^i_{^4\mathrm{He}} \rangle}$$



# Time-averaged D/$^4$He and $^3$He/$^4$He flux ratios

- Above 4.5 GV, D/$^4$He and $^3$He/$^4$He flux ratios are **well described by a single power law**.
- Unexpectedly, **their spectral indexes are different**, showing that **cosmic deuterons have a sizeable primary-like component.**




Shaded areas show time variations at low rigidities

$$\Delta_{D/^4He} = -0.108 \pm 0.005$$

$$\Delta_{^3He/^4He} = -0.289 \pm 0.003$$

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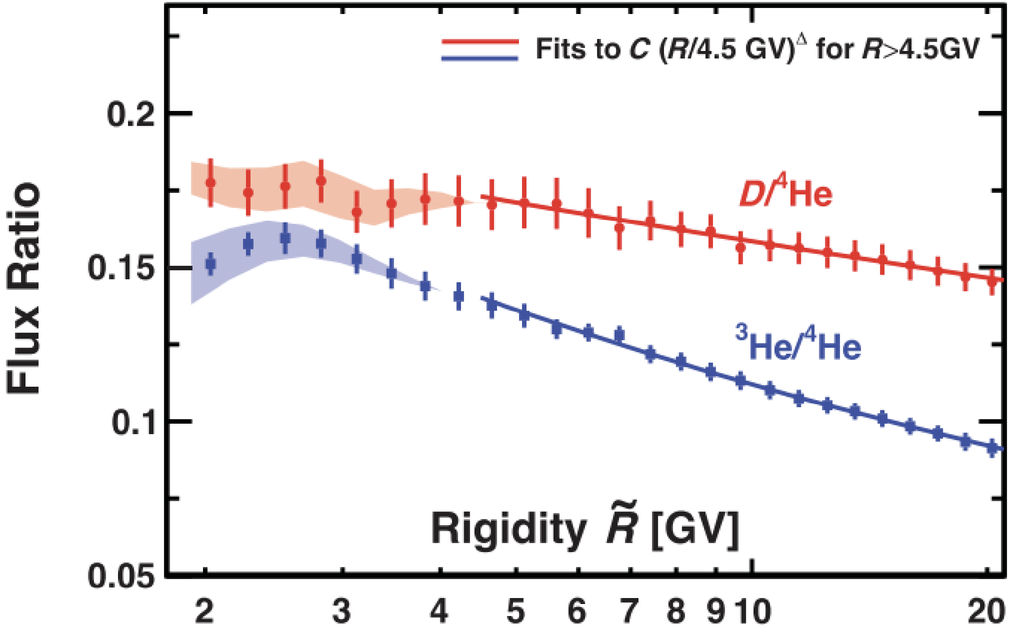


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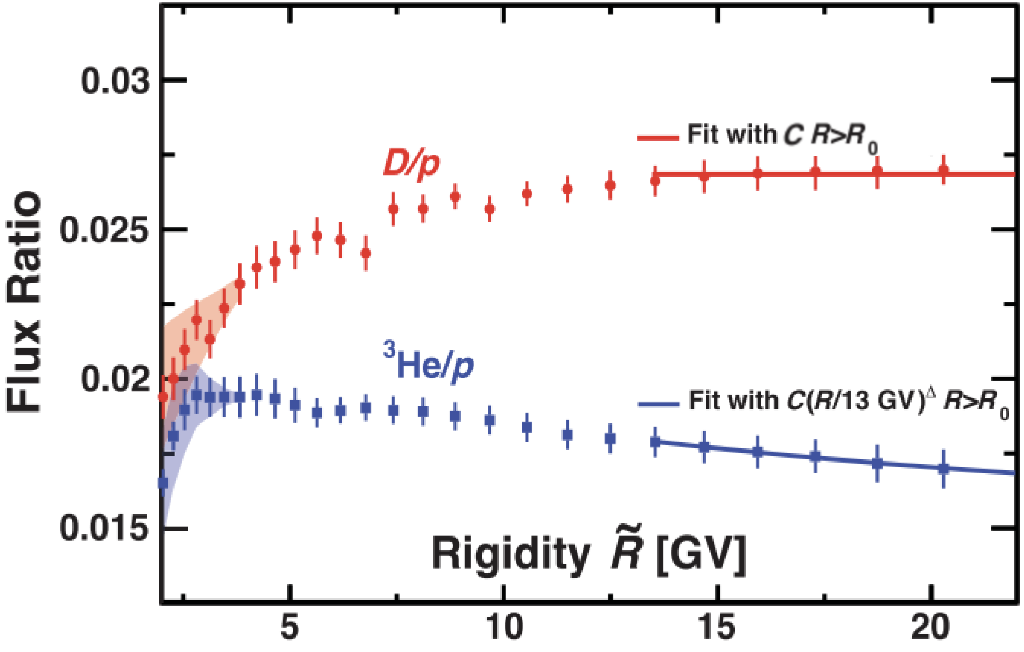
**More than 10σ difference significance**

# Time-averaged D/p and $^3$He/p flux ratios

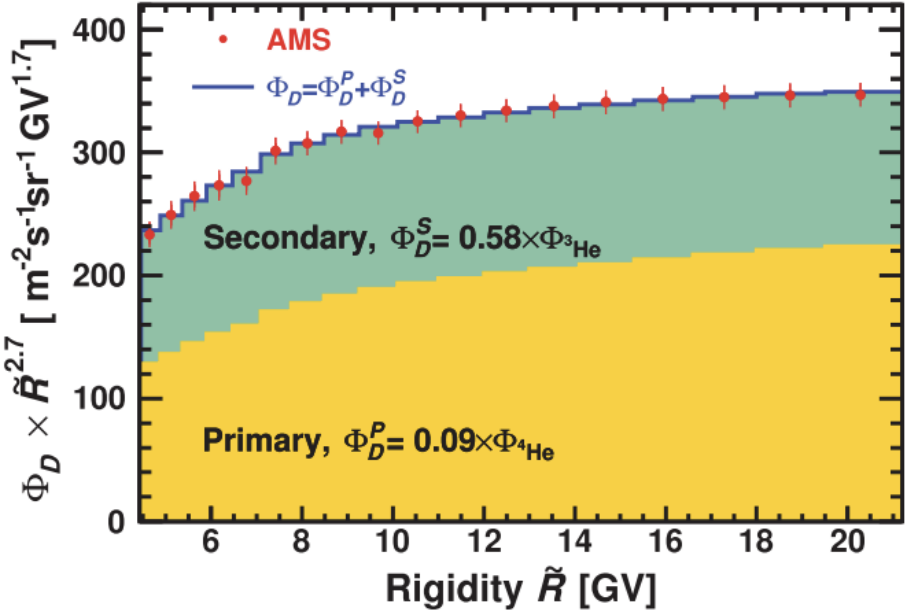
- **D and p fluxes are nearly identical above ~13 GV**, further supporting the conclusion of the primary-like component.
- The rigidity dependence of the **D/p and $^3$He/p flux ratios are very different.**




Shaded areas show time variations at low rigidities

# D primary and secondary components

- We determine the **amount of primary and secondary components** using a **cosmic ray propagation independent method.**
- Above 4.5 GV, we fit the **D flux as a weighted sum** of a characteristic **primary flux ($^4$He)** and a characteristic **secondary flux ($^3$He).**




$$\Phi_D^P = (0.094 \pm 0.005) \times \Phi_{^4\mathrm{He}}$$

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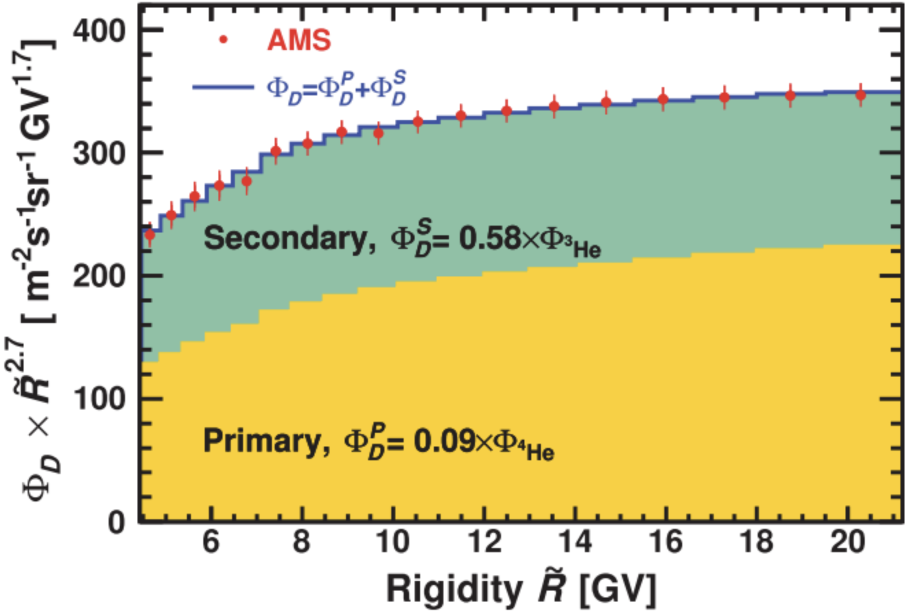


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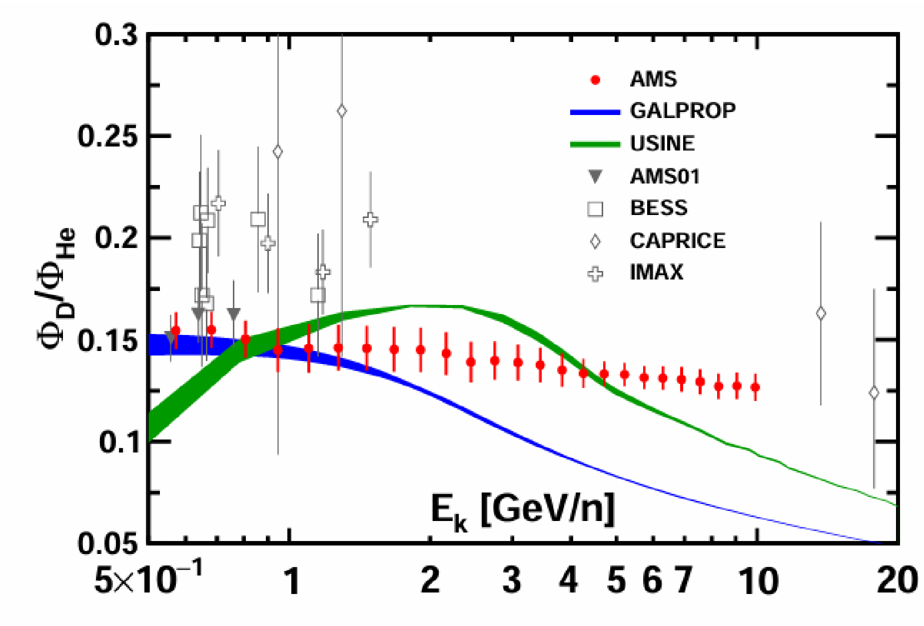
We obtain a **primary component** of the D flux equal to **9.4 ± 0.5% of the $^4$He flux.**

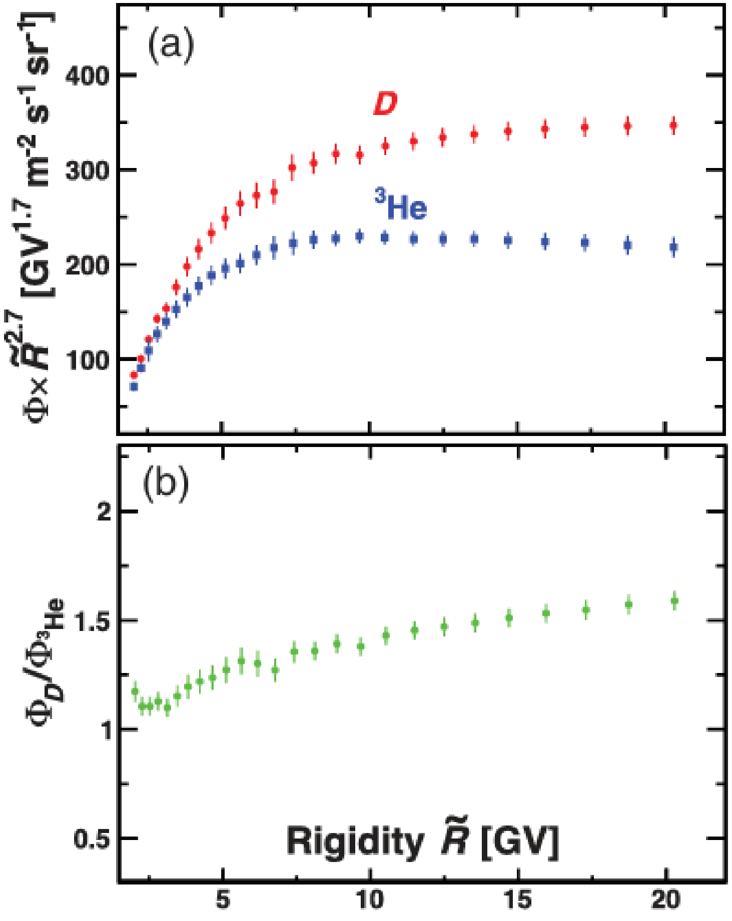
# Conclusions

- Over the entire rigidity range, **D flux exhibits nearly identical time variations with the p, $^3$He and $^4$He fluxes.**
- Above 4.5 GV, the **D/$^4$He and $^3$He/$^4$He flux ratios are time independent** and their rigidity dependence is well described by **power laws with spectral indexes that differ > 10 $\sigma$ level, indicating a sizable primary-like component.**
- Above ~13 GV the **rigidity dependence of the D and p fluxes is nearly identical**, further supporting the conclusion of a **primary-like component**.
- Above 4.5 GV, we obtain a **primary component of the D flux equal to 9.4 ± 0.5% of the $^4$He flux.**
- These unexpected observations show that contrary to traditional expectations, **deuterons must have a primary-like component.**

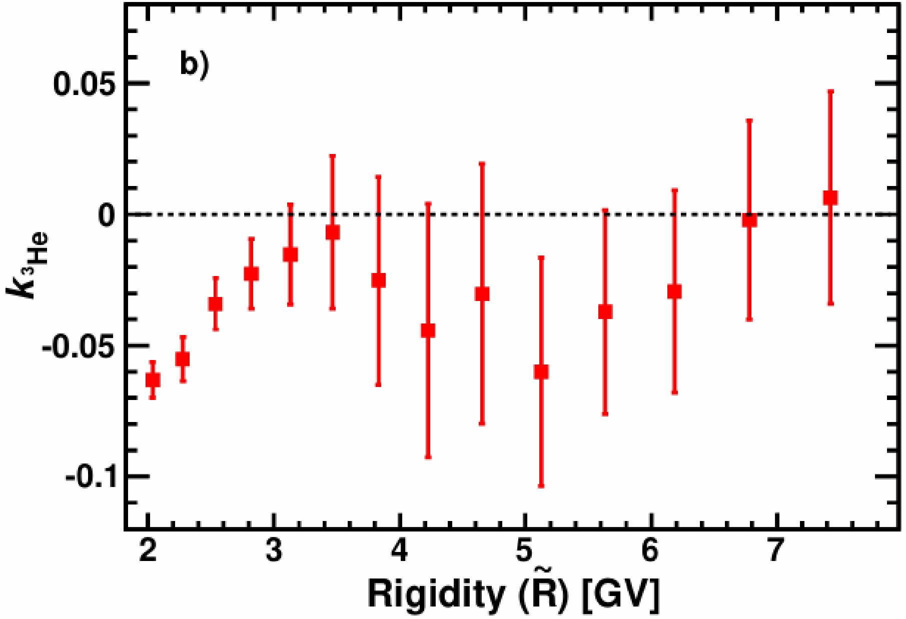
# BACKUP

# Time-Averaged Flux Ratio



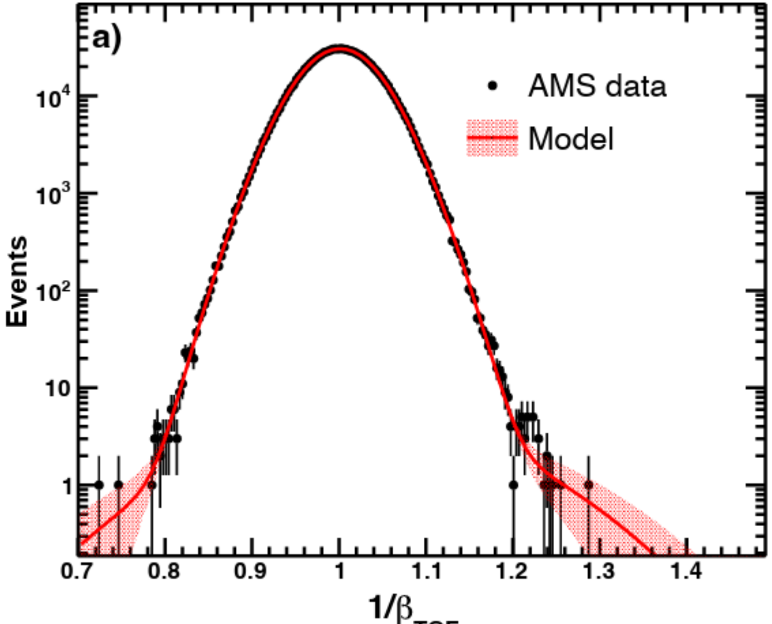



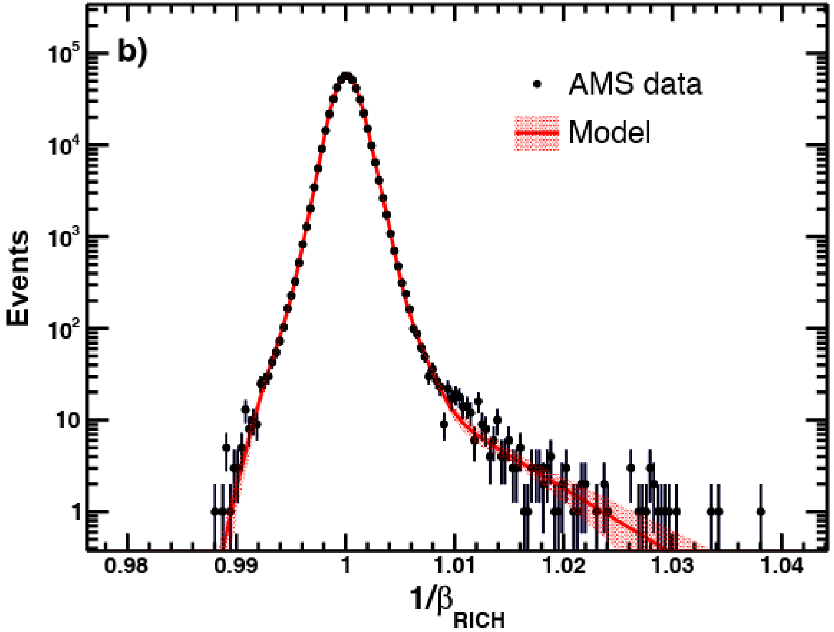
# $^{3}$He Time Dependence



# Beta Resolution

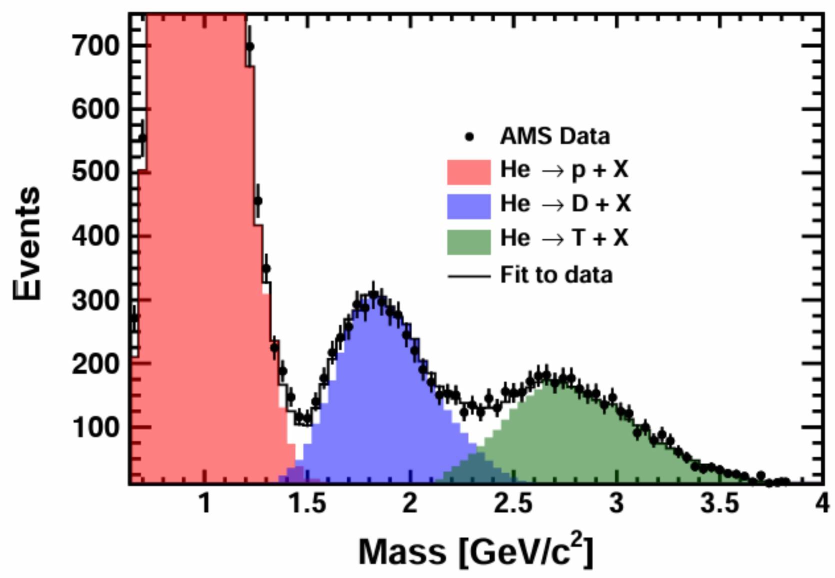
- Resolution functions are modeled and fitted at $\beta \simeq 1$ for Z=1 events.
- The dependence on $\beta$ was obtained from MC simulation and corrected with data.
- Corrections of <5% for TOF and RICH.

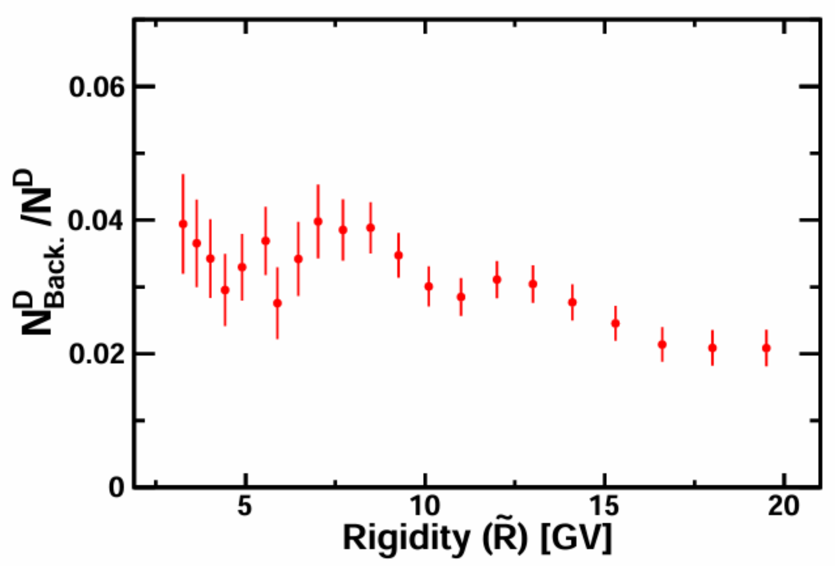


# Background Subtraction

- Background comes mostly from He fragmentation with AMS materials above L1.
- We estimate the background measuring the different branching ratios using data with Z=2 measured in L1 and Z=1 in the inner tracker.



# Isotope Identification

- Rigidity unfolded event count distribution for β>0.952.