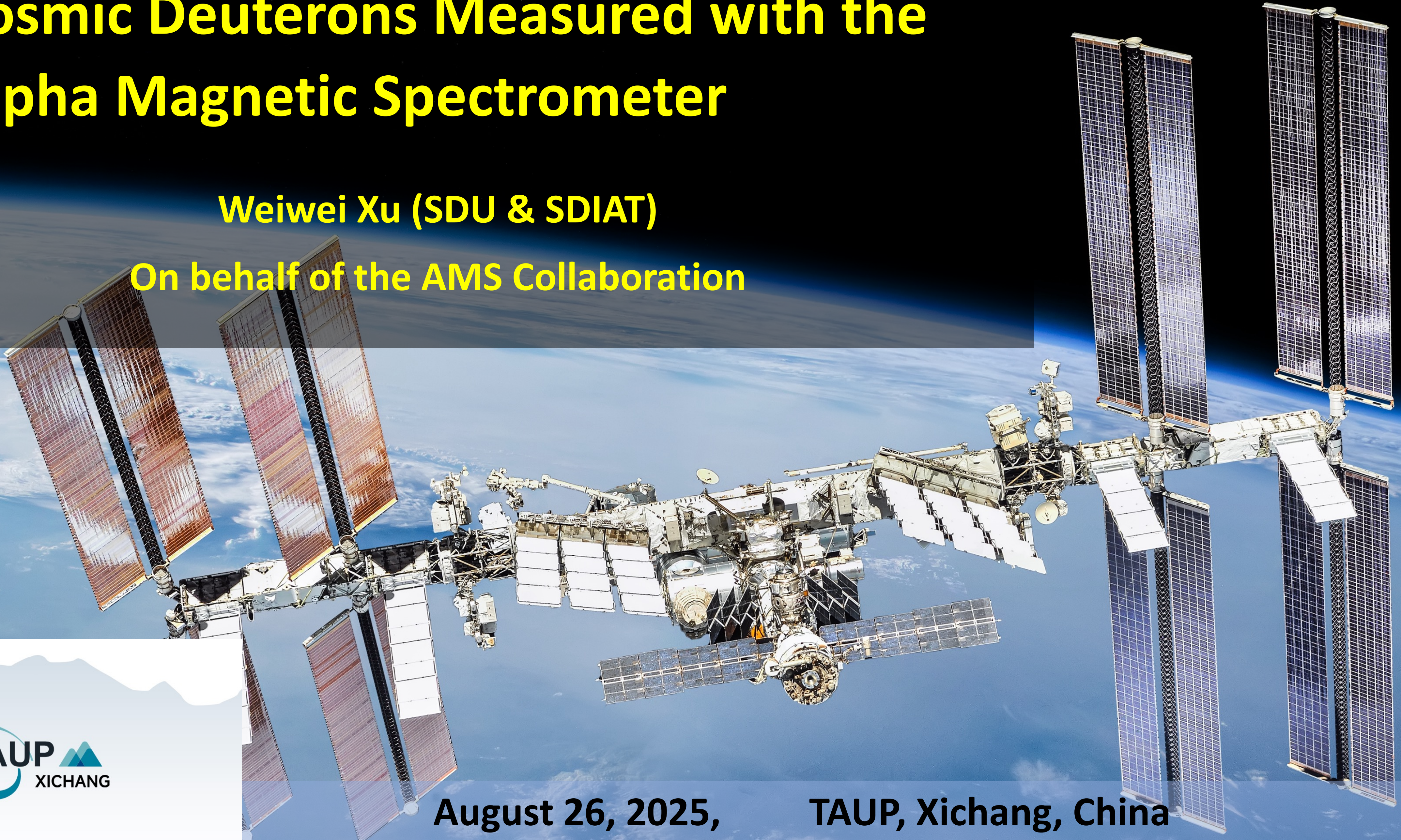
Cosmic Deuterons Measured with the Alpha Magnetic Spectrometer

Weiwei Xu (SDU & SDIAT)

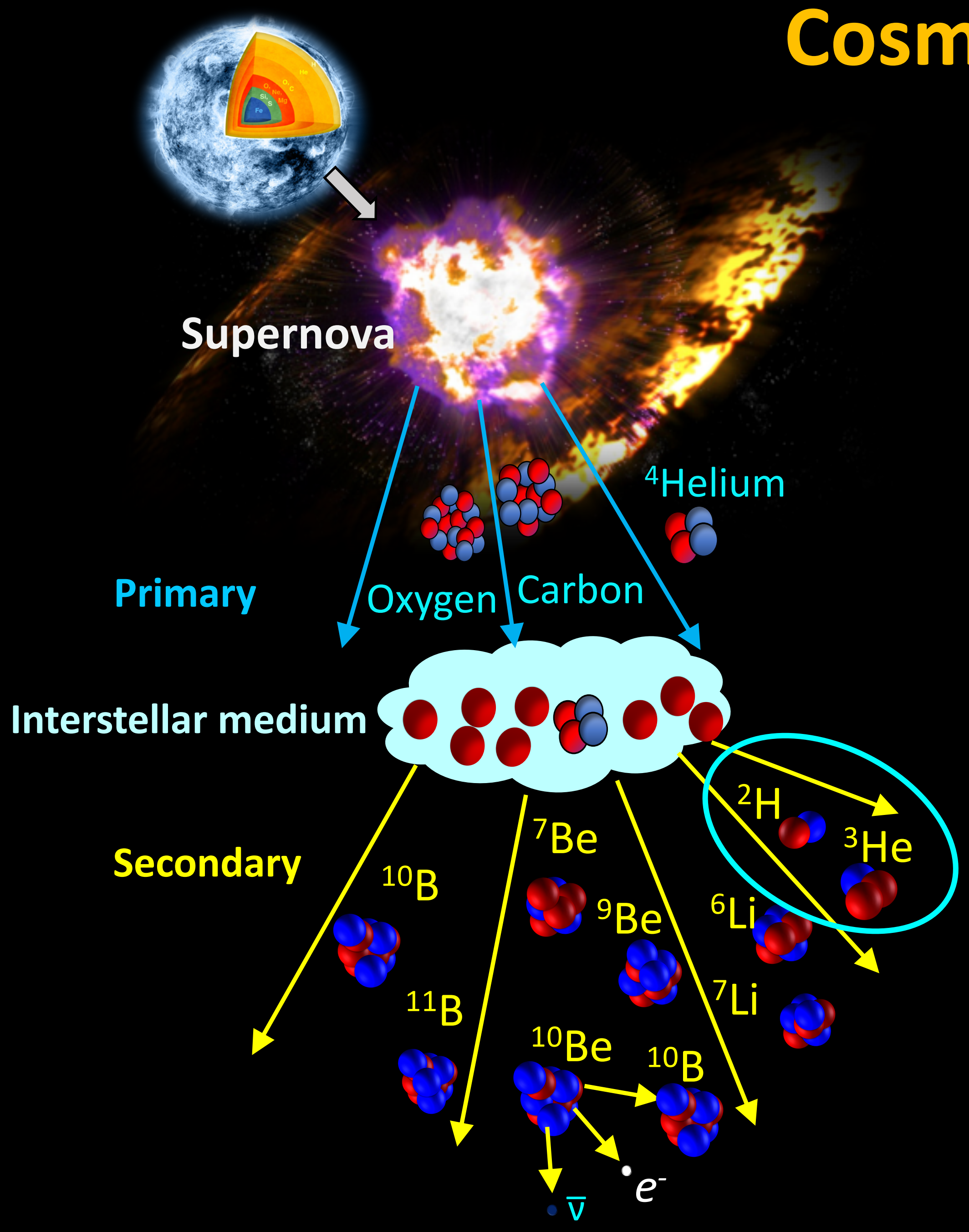
On behalf of the AMS Collaboration

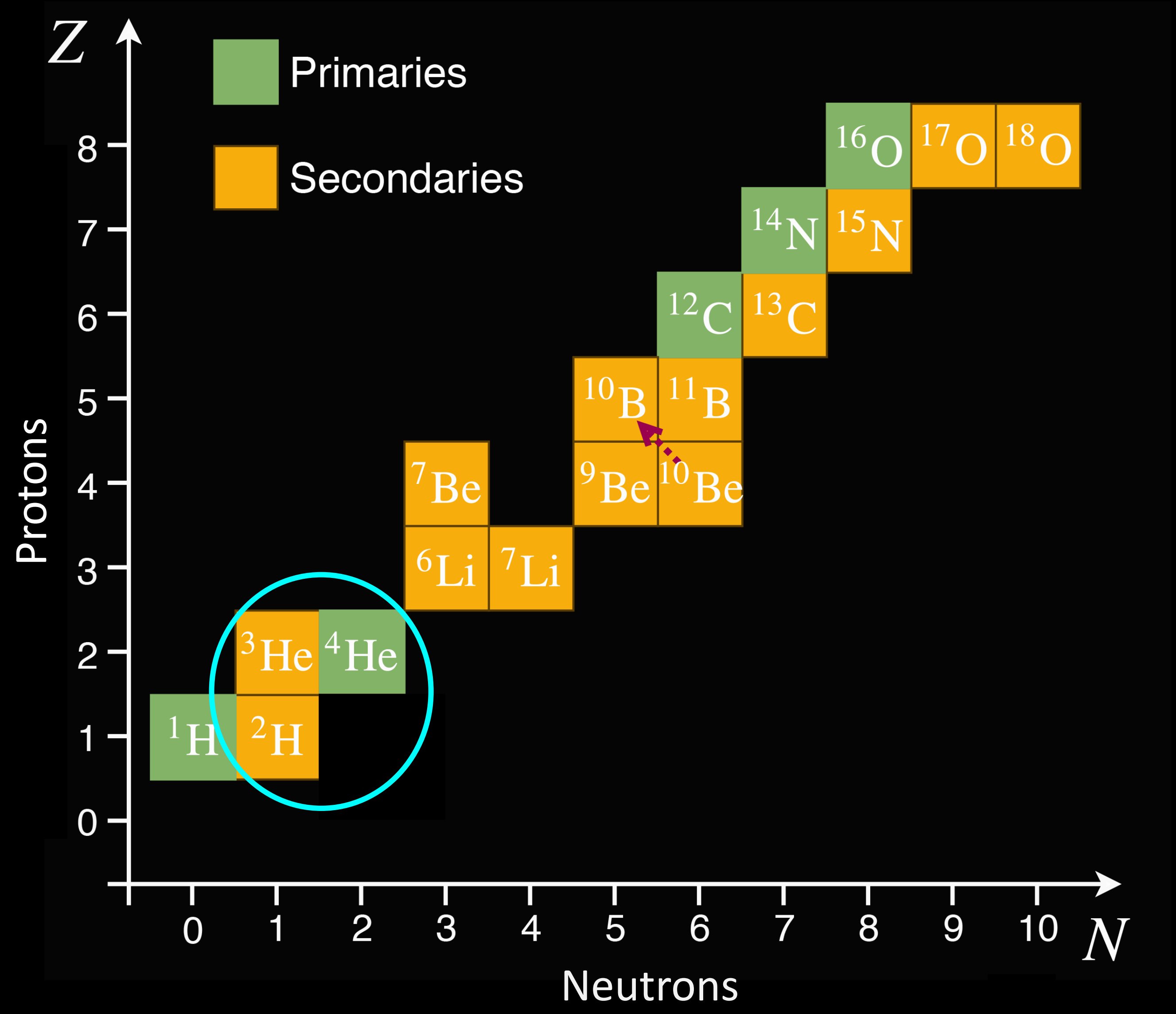


TAUP XICHANG

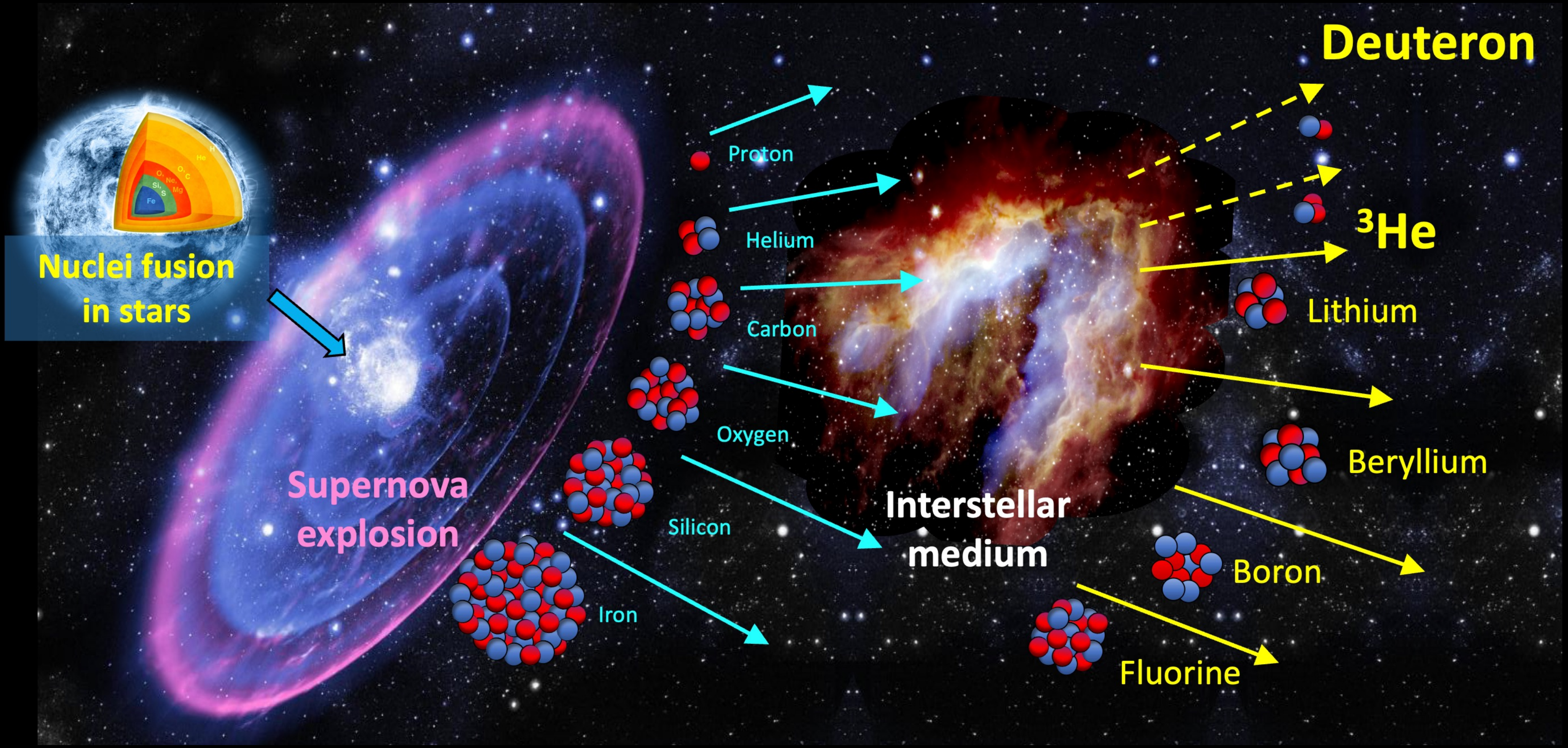
August 26, 2025, TAUP, Xichang, China

Cosmic Ray Isotopes





Physics of Cosmic Deuterons D



Primary Cosmic Rays (^{4}He, C, O, …) + Interstellar Media → (D, ^{3}He,…) + X

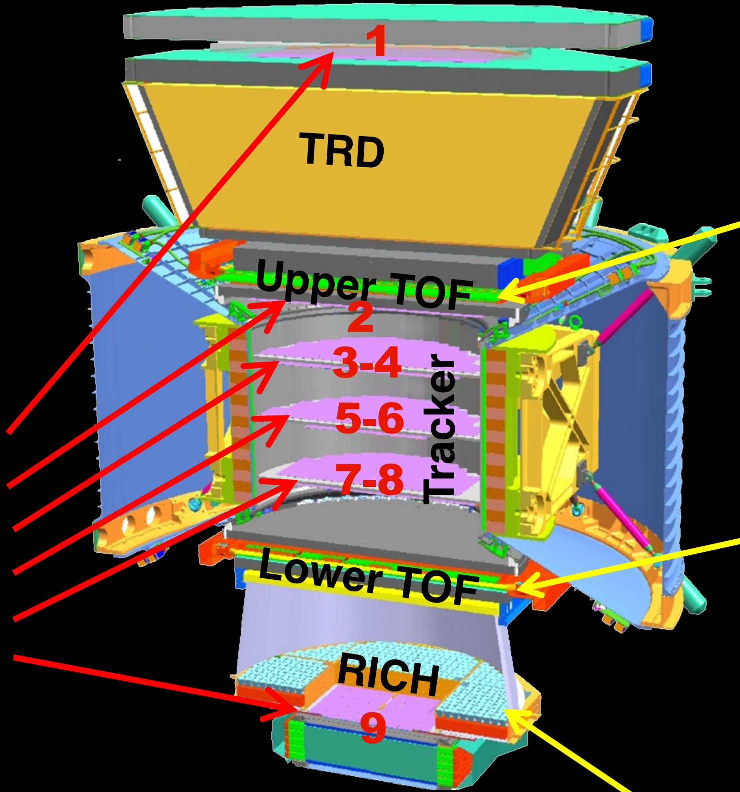
D and ^{3}He are thought to be both secondary cosmic rays,
produced by the collision of primary cosmic rays with the interstellar medium.

Measurement of Isotopes: Cosmic rays with *same Z, different m*

$P = m\beta\gamma$

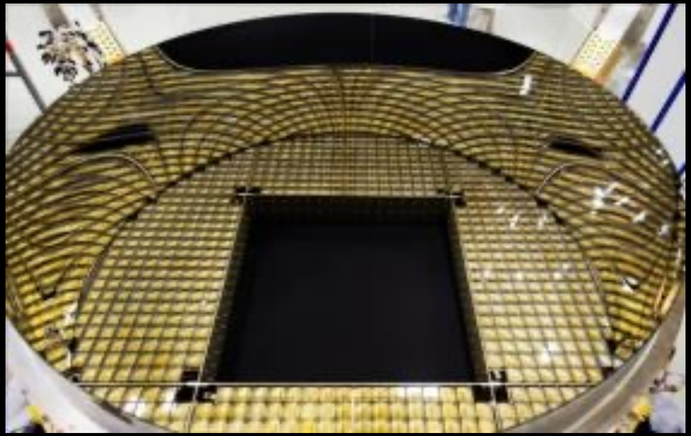
Measurement of P and β determine the mass *m* (isotope)

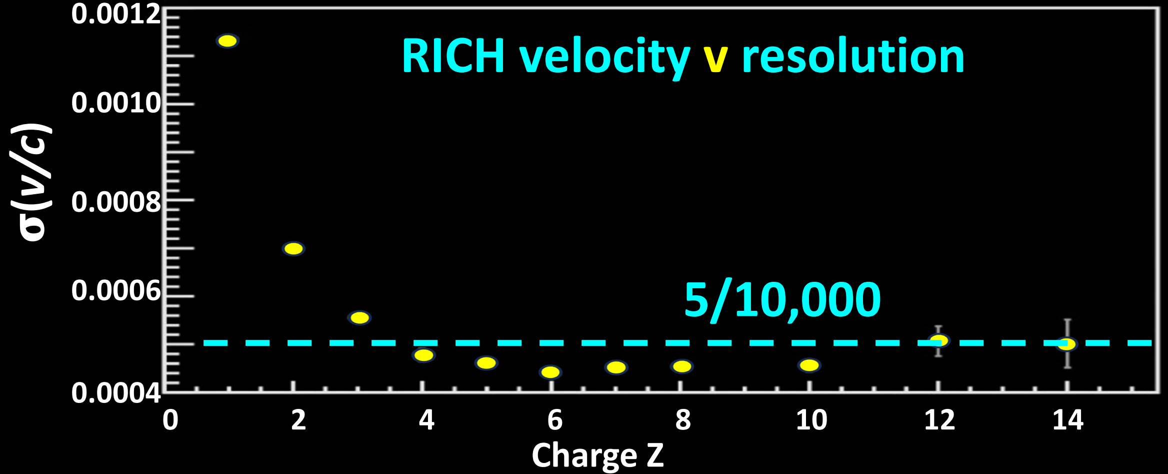
Silicon Tracker + Magnet
Measurement of P and Z



Time-of-Flight
Measurement of β and Z

Ring Imaging Cerenkov (RICH)
Measurement of β and Z





Isotope Fluxes

Isotropic isotope flux

Isotope event number after background subtraction and bin-to-bin migration correction.

$$\Phi_i^a = \frac{N_i^a}{A_i^a \times \varepsilon_i^{\text{trigger}} \times T_i^a \times \Delta E_{k,i}}$$

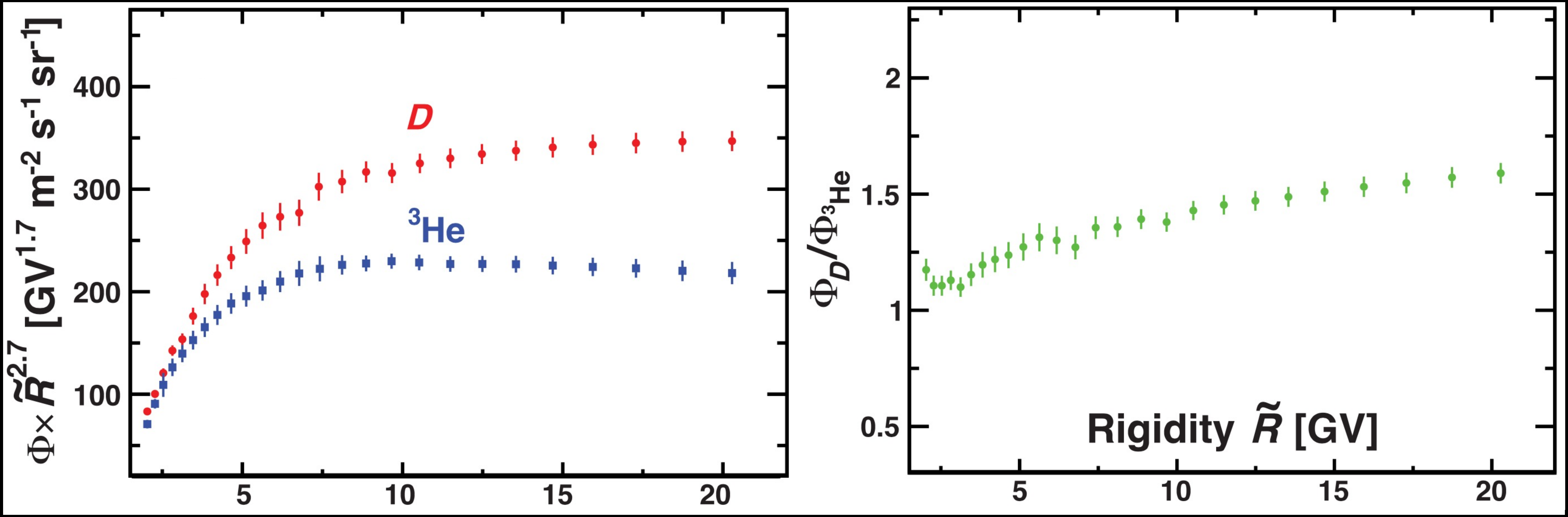
Effective acceptance calculated using MC and corrected for data/MC efficiency difference

Trigger efficiency

Exposure time

Bin width

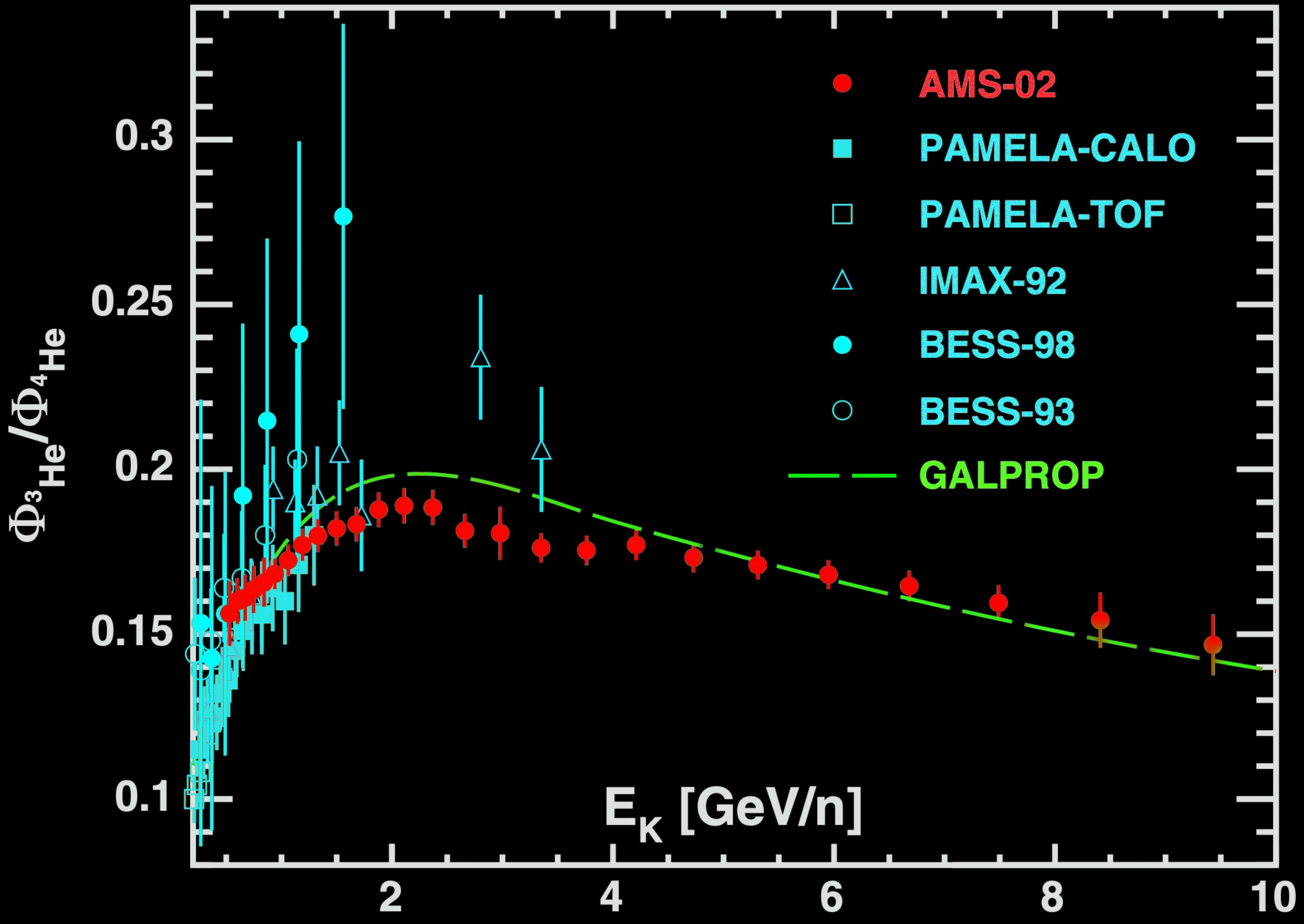
AMS Deuteron and ^3He



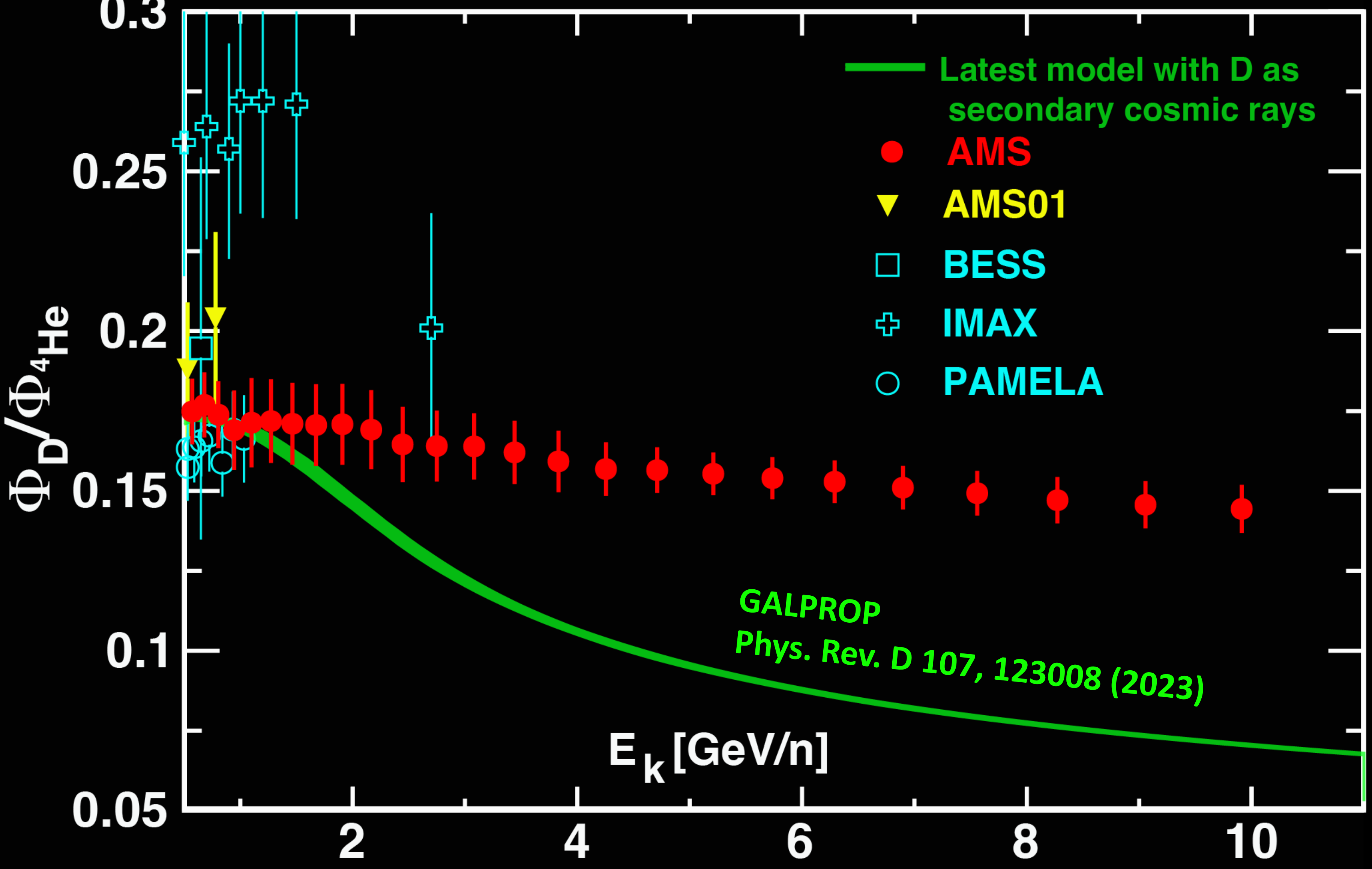
D flux is harder than ^3He

D/^{3}He flux ratio increases with rigidity

AMS Helium Isotopes: consistent with secondary ^{3}He

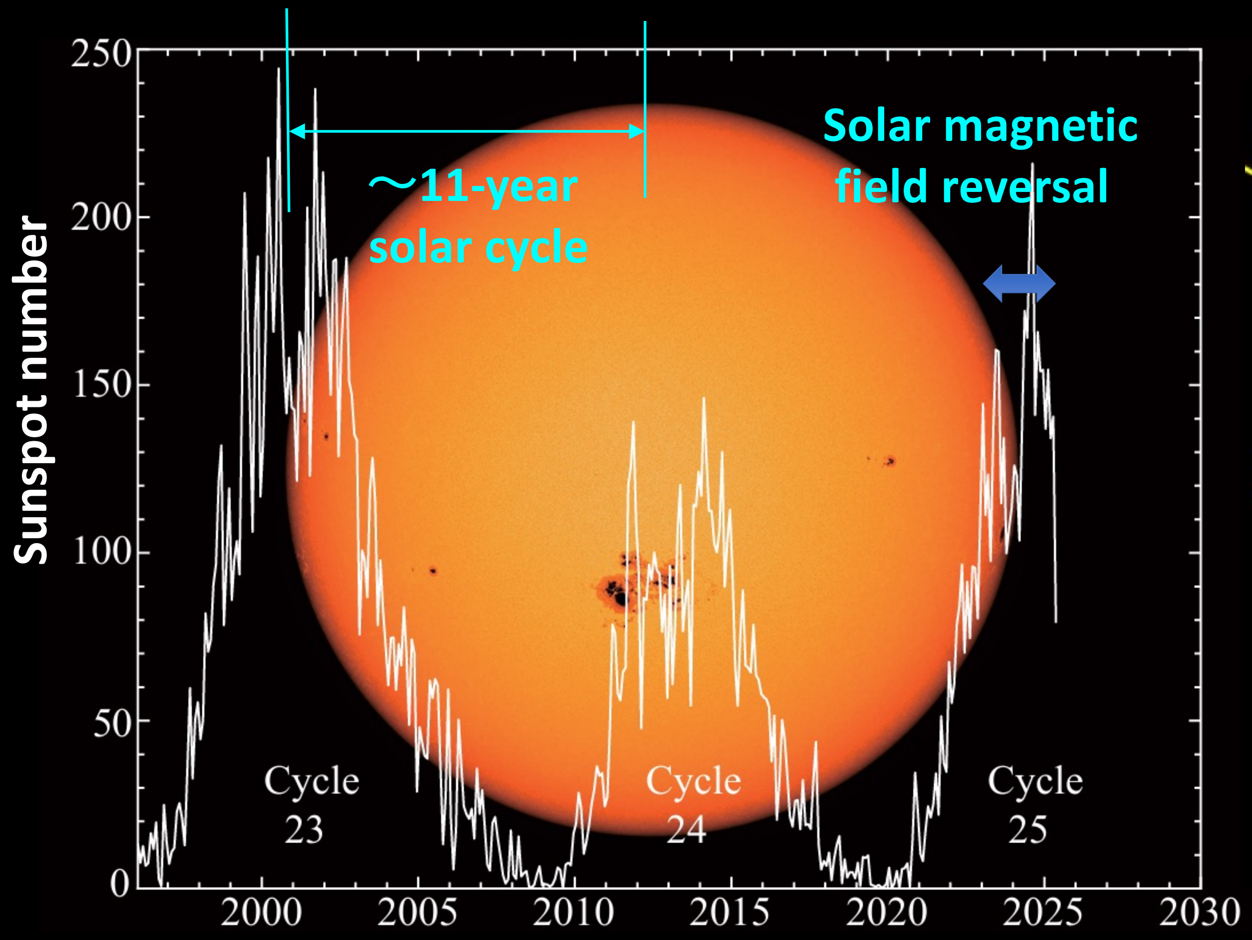


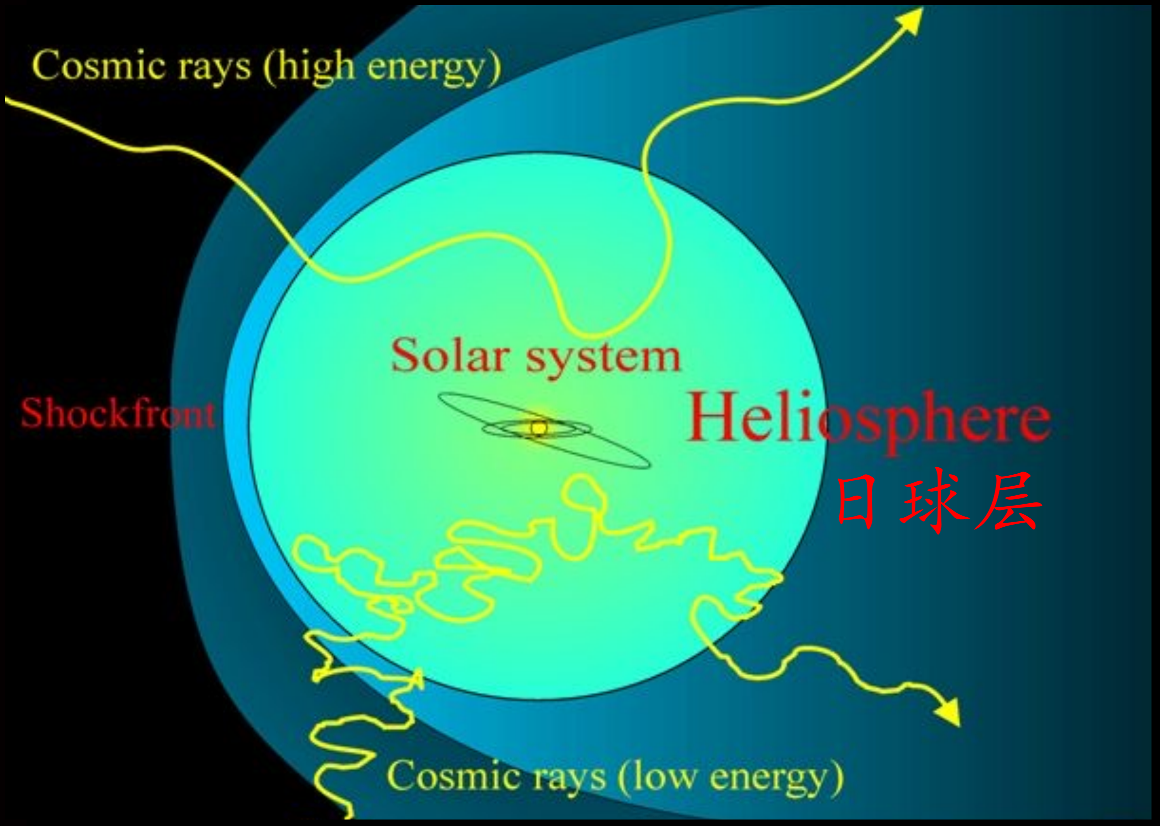
Origin of Cosmic Deuterons D



AMS results disagree with the latest model with D as secondary cosmic rays

Propagation of cosmic rays in the heliosphere



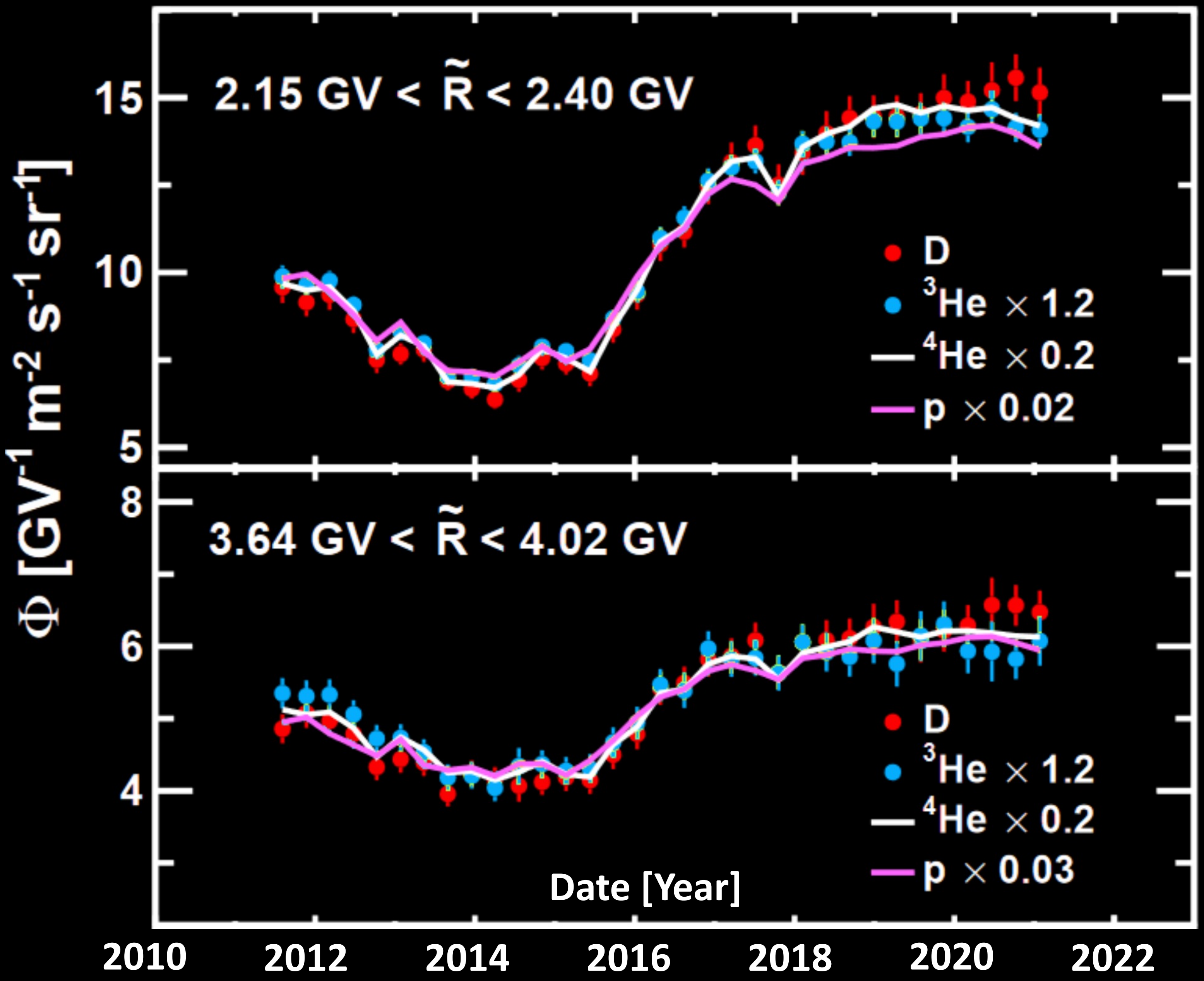


Due to the solar activities and solar magnetic field, cosmic rays spectrum change with time.

D and ^{4}He carry the same A/Z ratio.

D/^{4}He ratio is expected to be less affected by the solar modulation.

Time variation of Deuteron Fluxes



Over the entire rigidity range, the Deuteron flux exhibits similar time variations with the *proton*, ^{3}He, and ^{4}He fluxes.

Relative magnitude of time variation

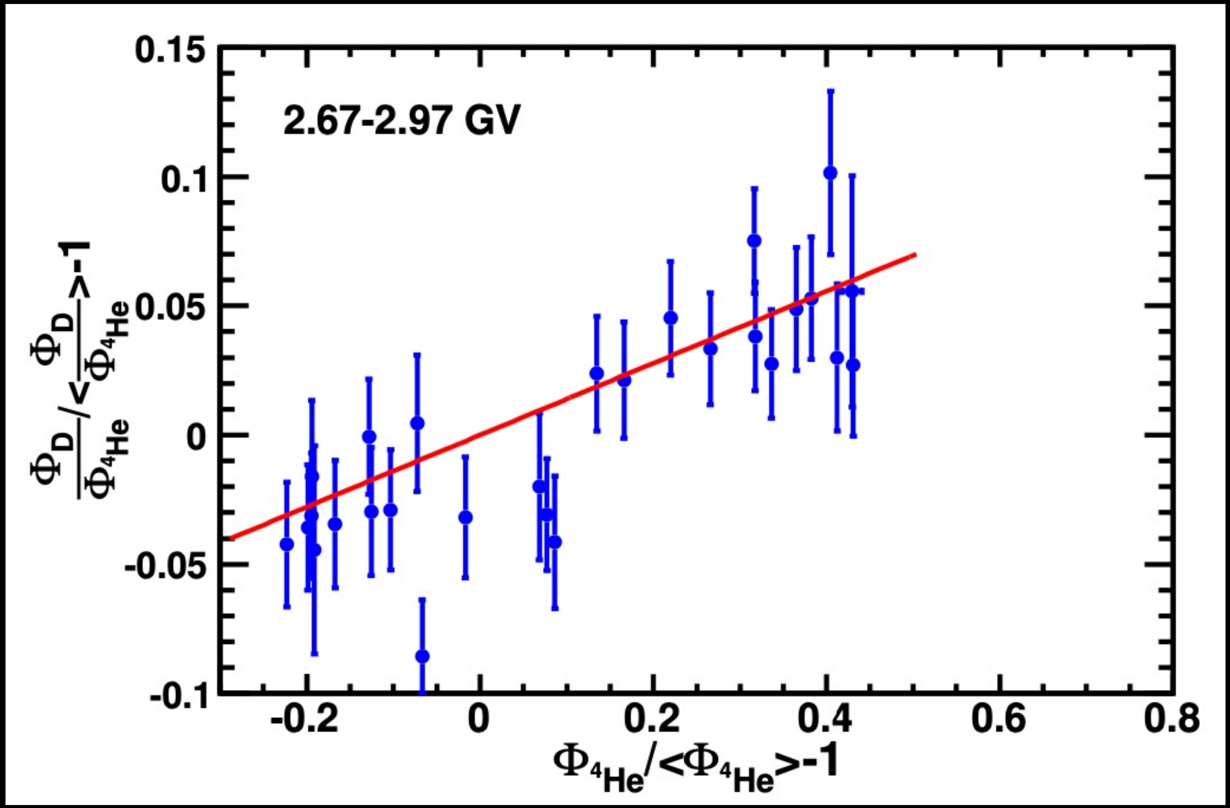
To study the difference of solar modulation effects on D and ^{4}He, the relation of $\Phi_{\mathrm{D}}^{i}/\Phi_{4_{\mathrm{He}}}^{i}$ ratio and $\Phi_{4_{\mathrm{He}}}^{i}$ is fit by the linear function:

$$\frac{\Phi_{\mathrm{D}}^{i}/\Phi_{4_{\mathrm{He}}}^{i}}{\left\langle \Phi_{\mathrm{D}}^{i}/\Phi_{4_{\mathrm{He}}}^{i} \right\rangle} - 1 = k_D^i \left(\frac{\Phi_{4_{\mathrm{He}}}^{i}}{\left\langle \Phi_{4_{\mathrm{He}}}^{i} \right\rangle} - 1 \right)$$

$k_{\mathrm{D}} > 0$, Φ_{D} exhibit more variation than $\Phi_{4_{\mathrm{He}}}$

$k_{\mathrm{D}} = 0$, Φ_{D} exhibit same variation as $\Phi_{4_{\mathrm{He}}}$

$k_{\mathrm{D}} < 0$, Φ_{D} exhibit less variation than $\Phi_{4_{\mathrm{He}}}$

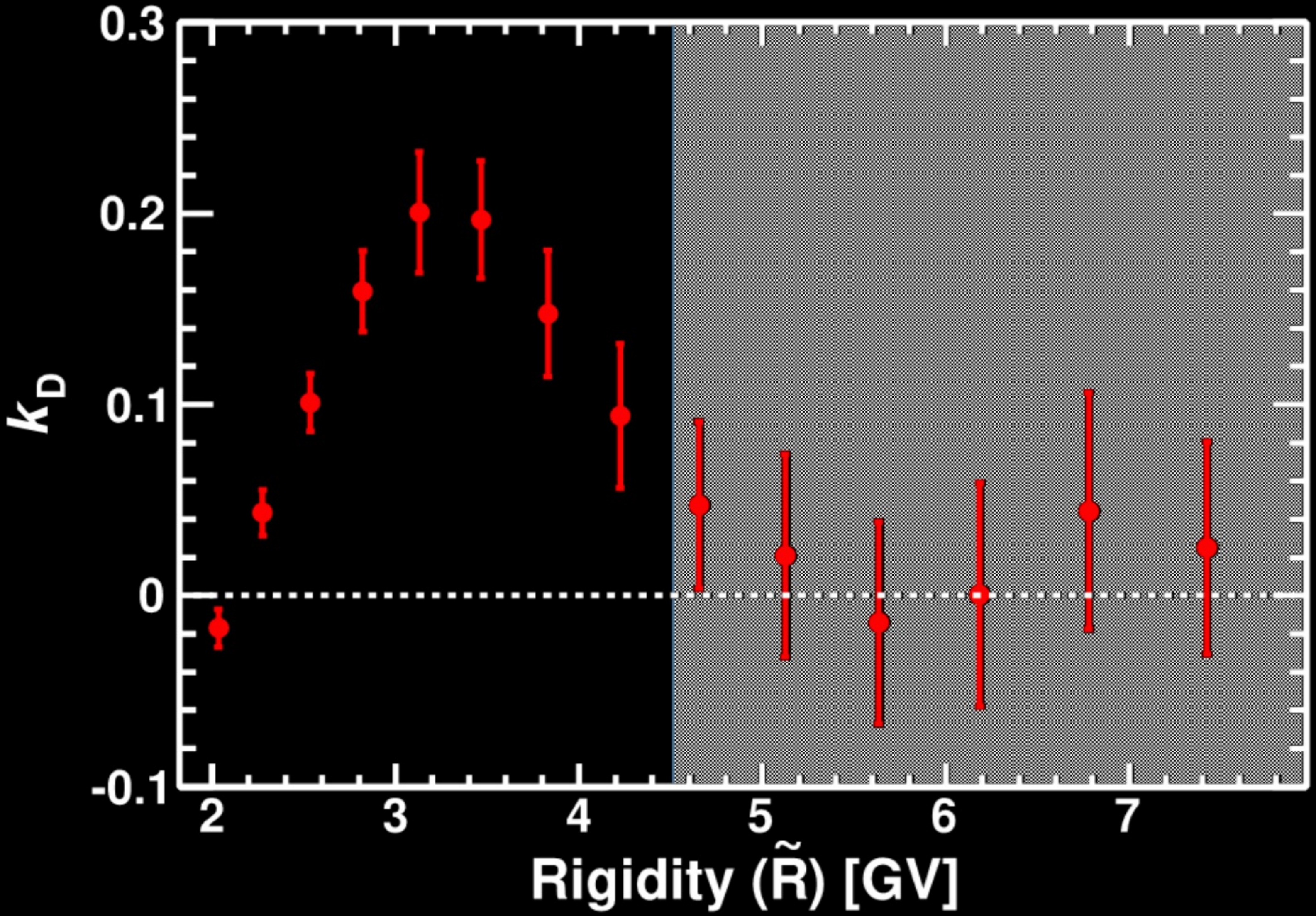


Time variation of Deuteron Fluxes

$$\frac{\Phi_{\rm D}^{i}/\Phi_{\rm ^4He}^{i}}{\langle \Phi_{\rm D}^{i}/\Phi_{\rm ^4He}^{i}\rangle} - 1 = k_D^i \left(\frac{\Phi_{\rm ^4He}^{i}}{\langle \Phi_{\rm ^4He}^{i}\rangle} - 1 \right)$$

Below 4.5 GV, D flux $\Phi_{\rm D}$ exhibit more variation then ^{4}He;

Above 4.5 GV, $\Phi_{\rm D}/\Phi_{\rm ^4He}$ is independent of time.

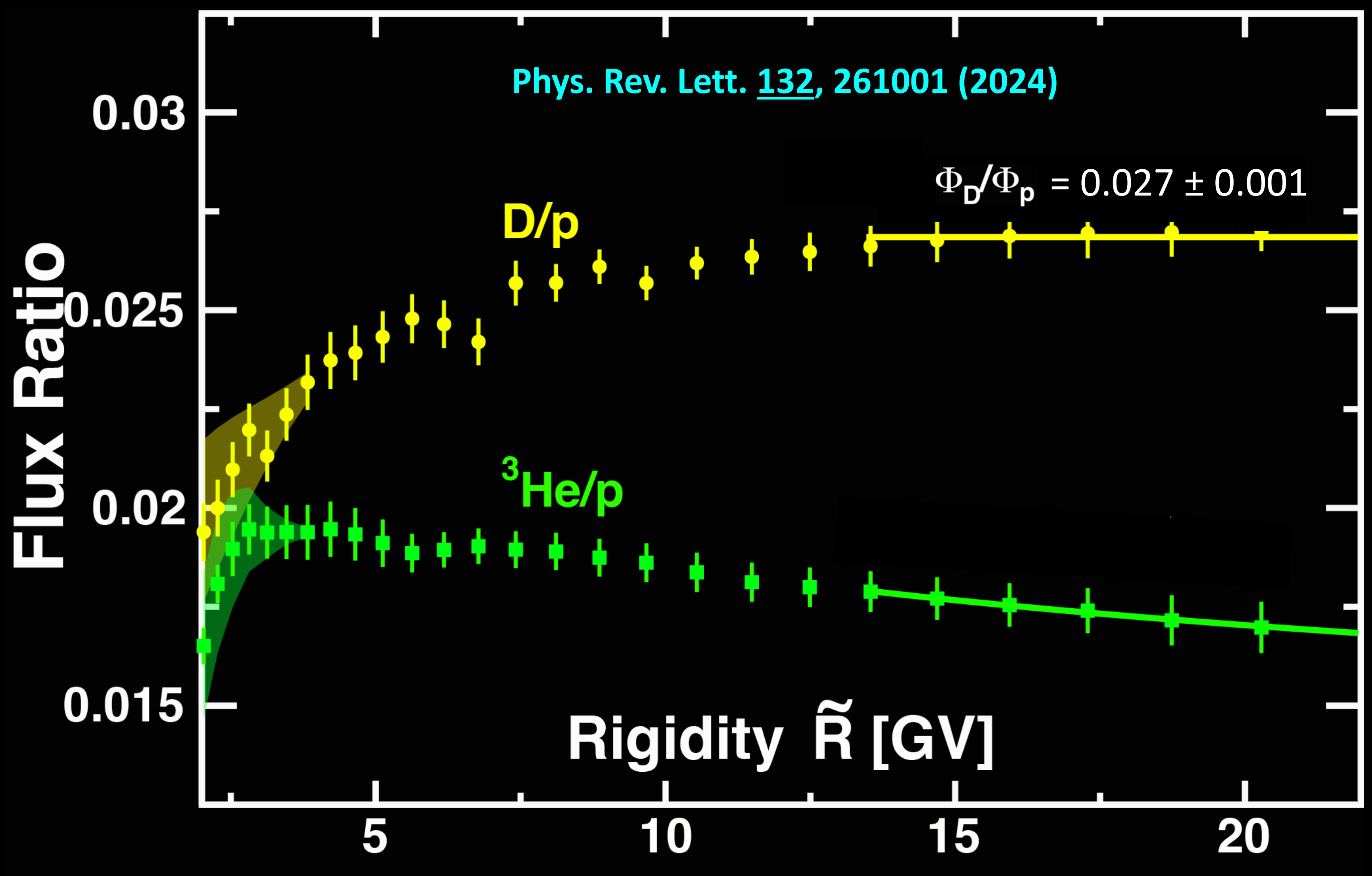


The flux ratio of $^3He/p$ decreases with rigidity above 4 GV.

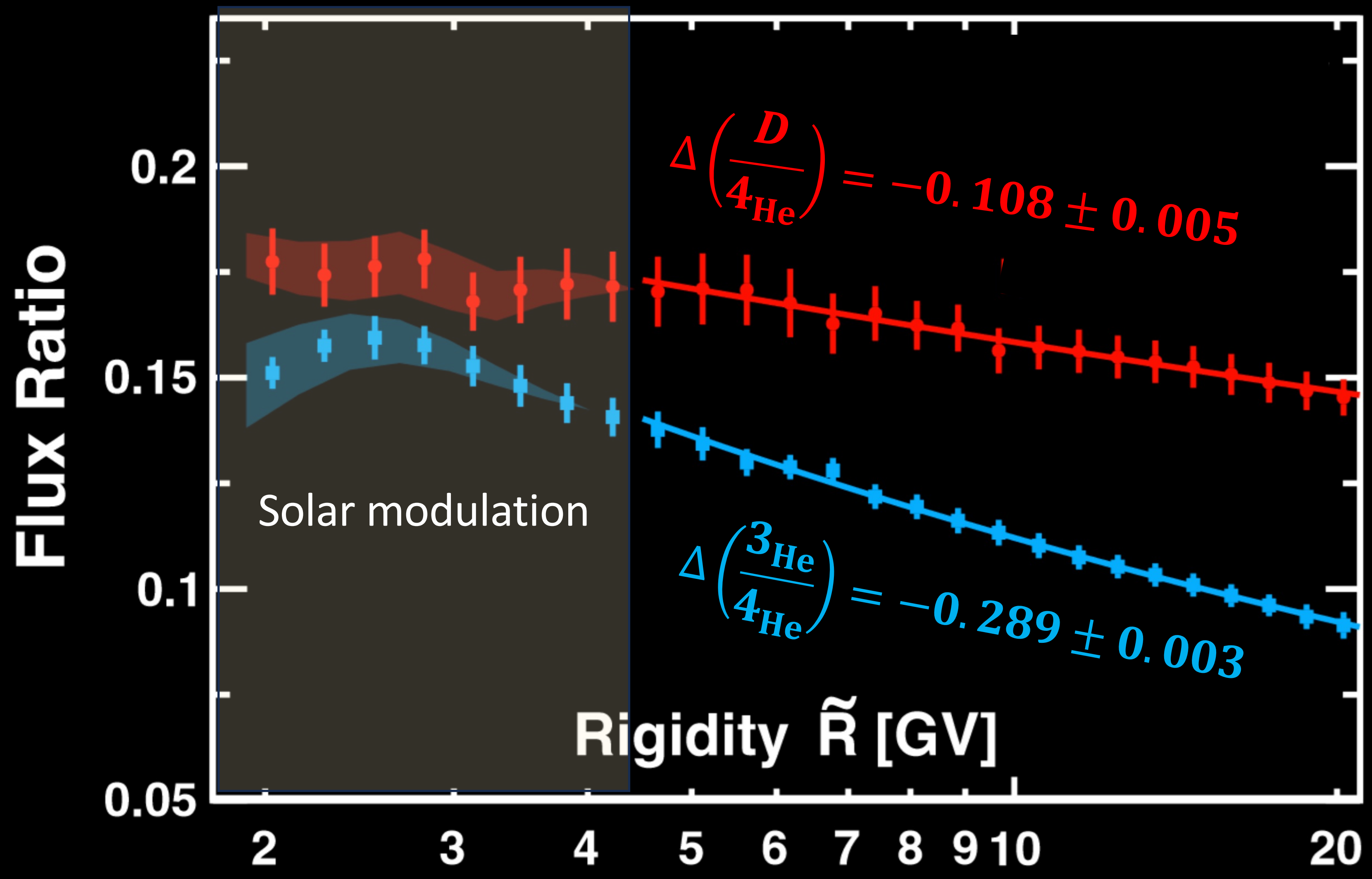
If D is pure secondary, the flux ratio of D/p must also decrease with rigidity above ~4 GV

The flux ratio of D/*p* increases with rigidity and is constant above 13 GV.

D must have an additional primary source



Rigidity dependence of D/^{4}He and ^{3}He/^{4}He



D/^{4}He and ^{3}He/^{4}He exhibit single power law dependence ($\propto R^{\Delta}$) above 4.5 GV。

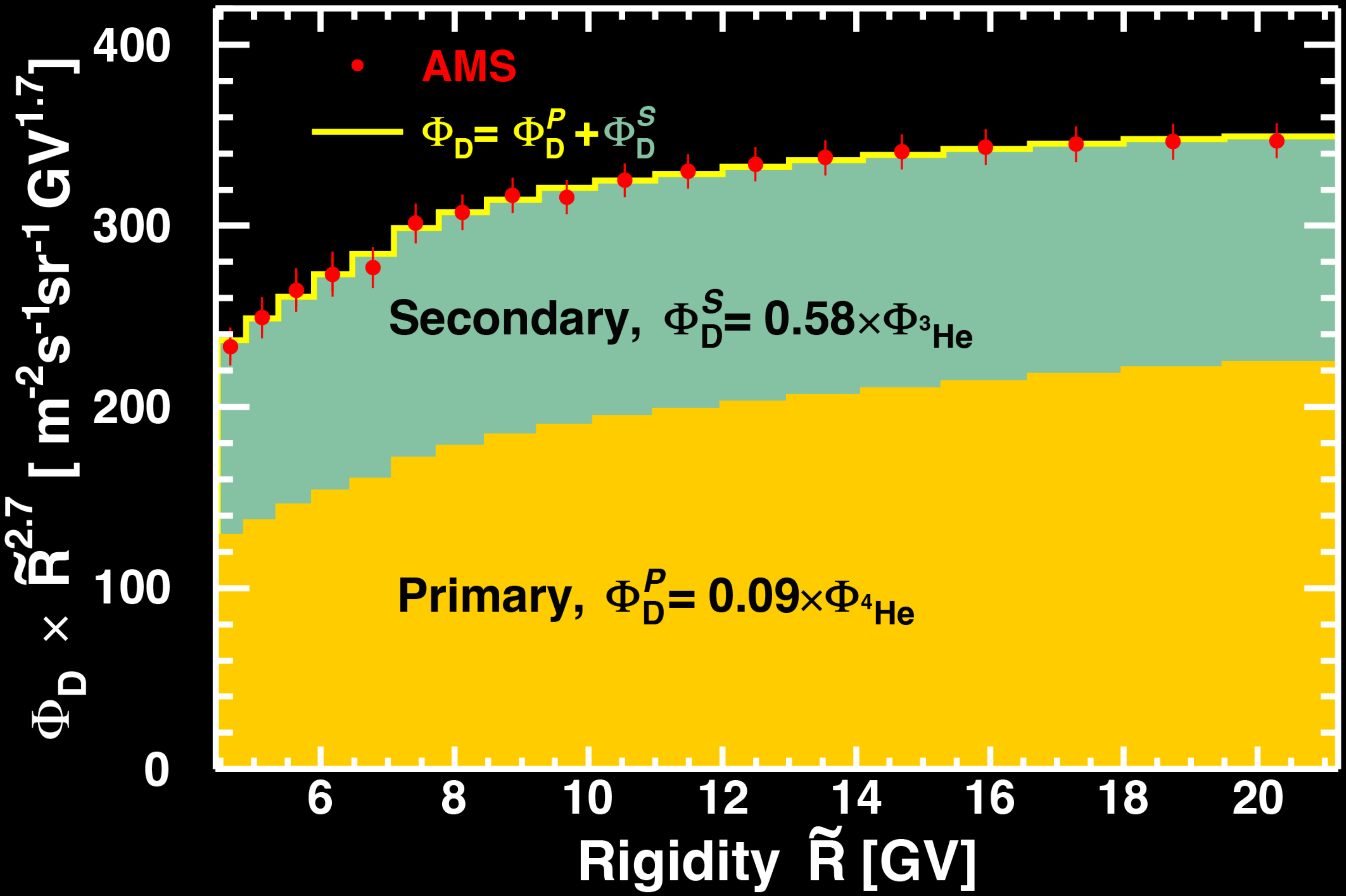
$\Delta\left(\frac{D}{^4He}\right) > \Delta\left(\frac{^3He}{^4He}\right)$

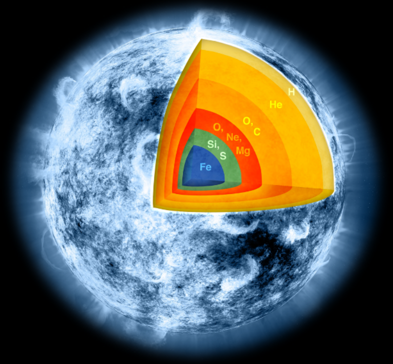
D spectrum is harder than ^{3}He with a significance >10σ

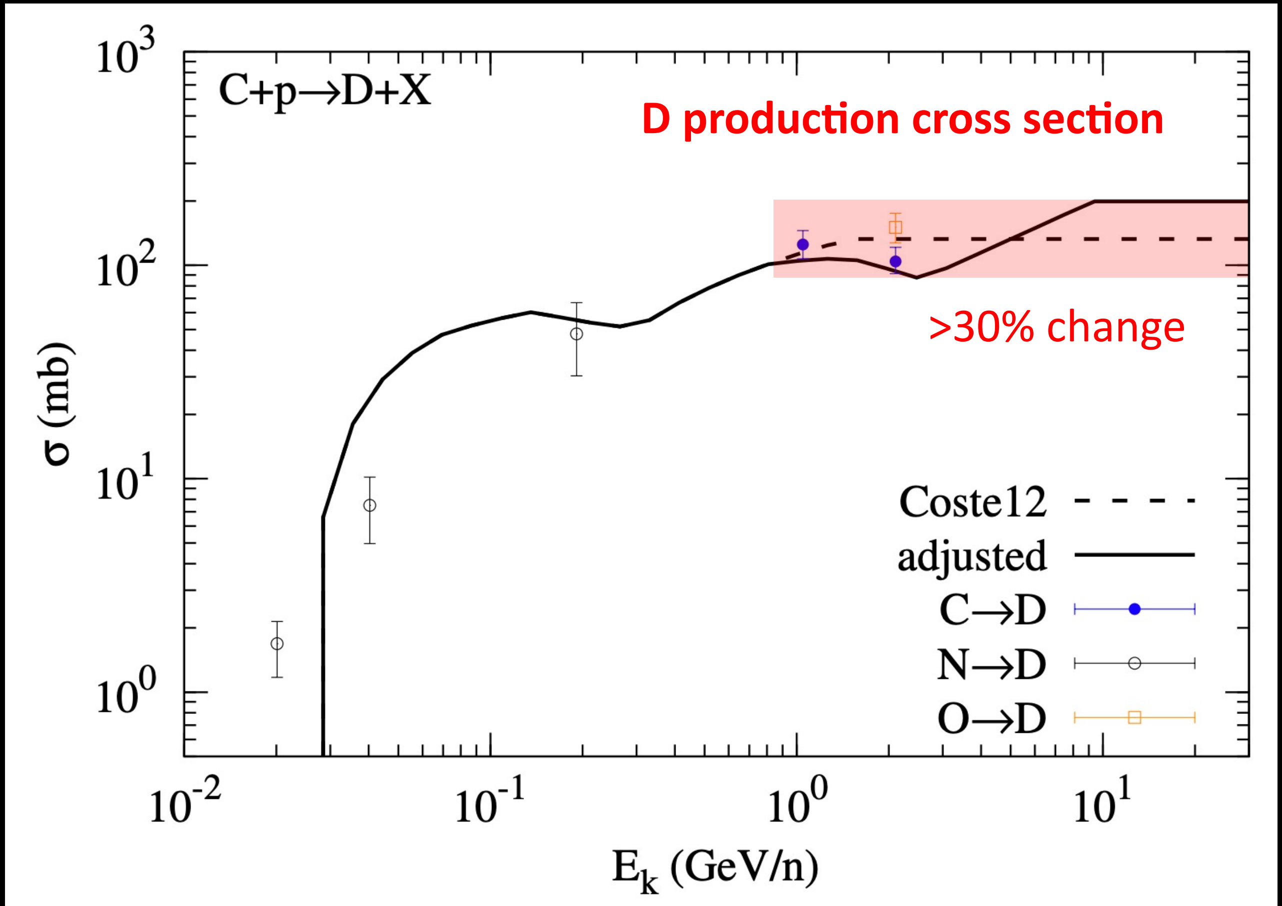
^{3}He is secondary.

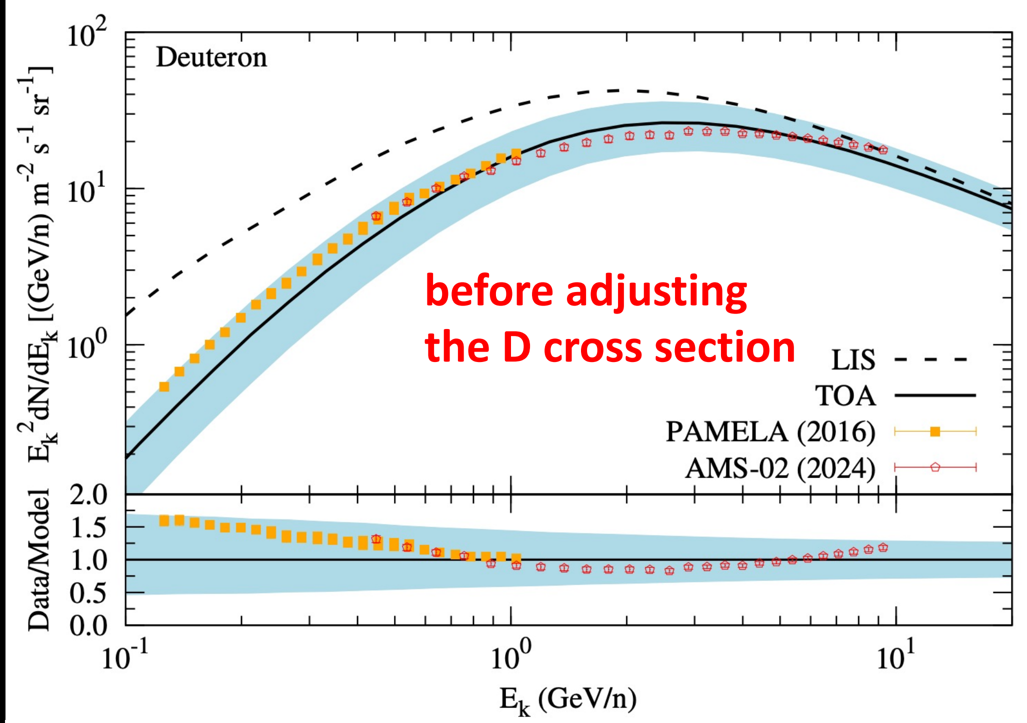
How much primary component does D contain?

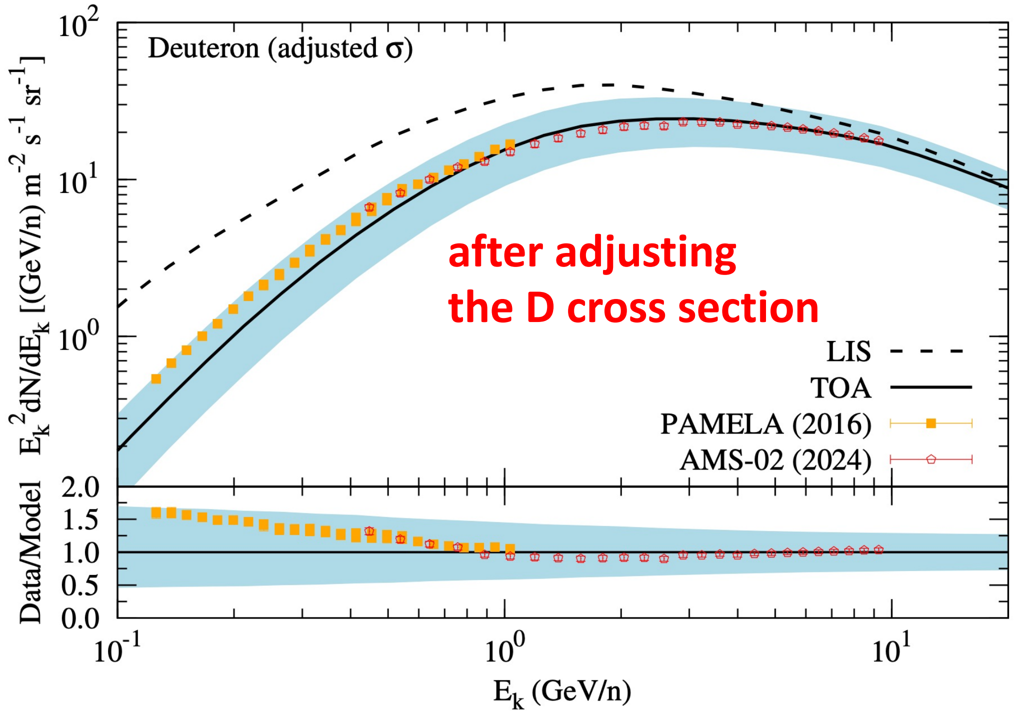
Deuterons have a significant primary component







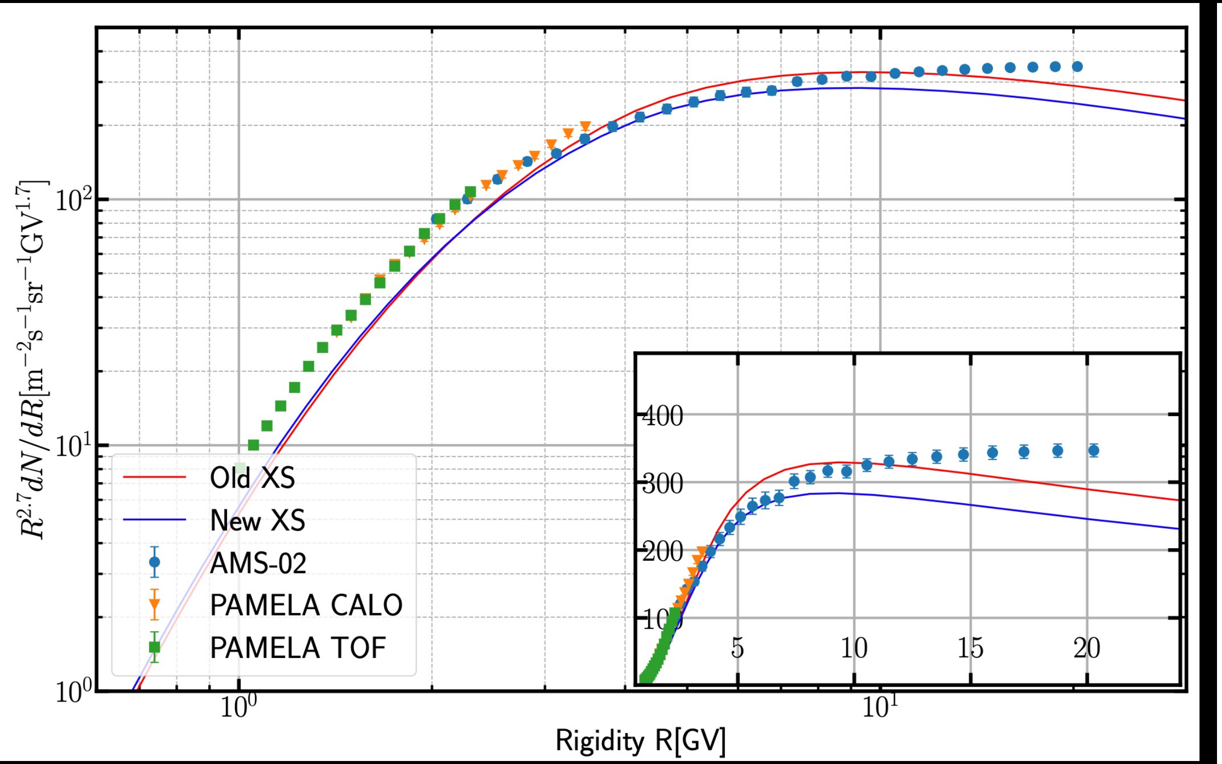




Model uncertainty 20% - 50%

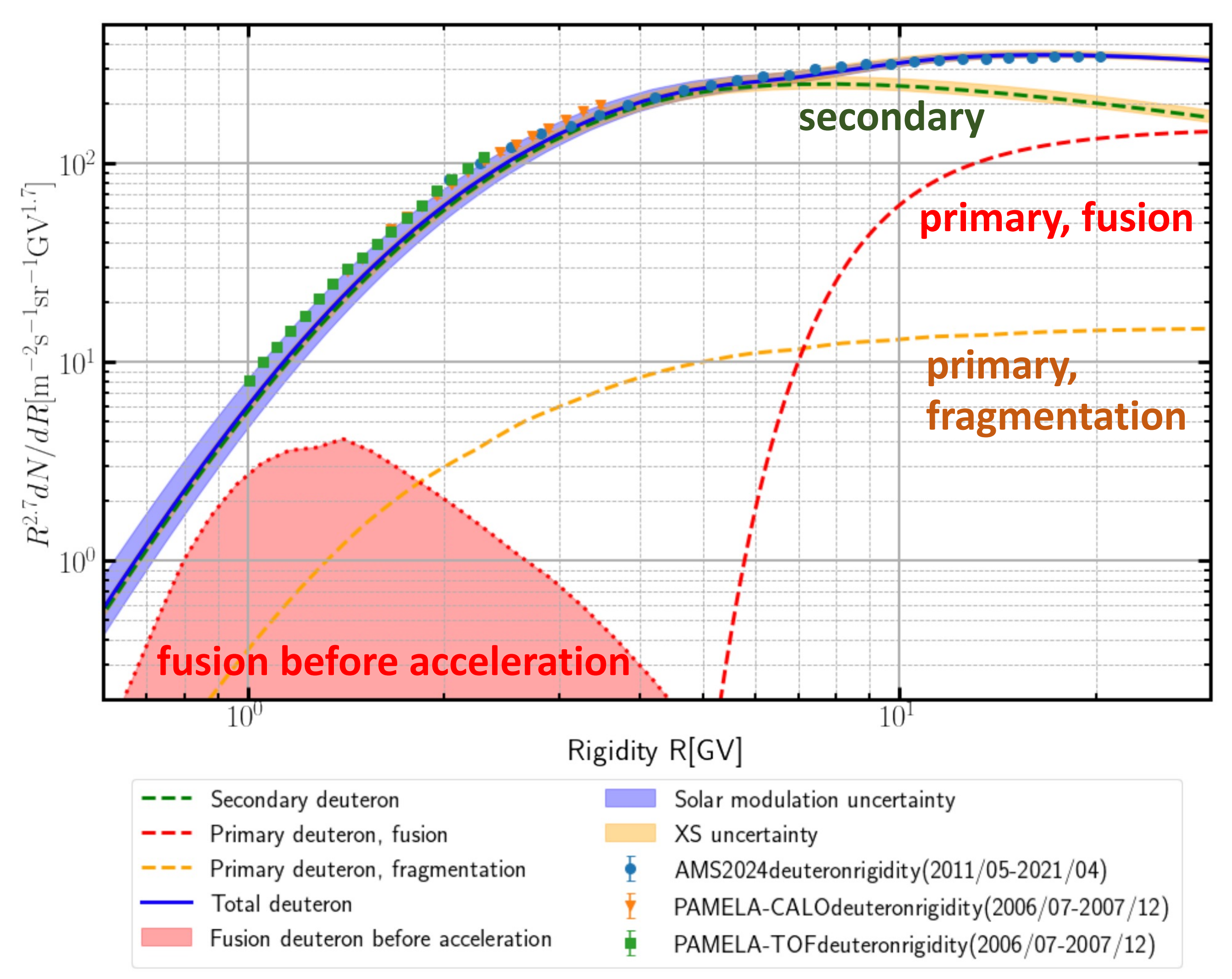
The AMS-02 Cosmic-Ray Deuteron Flux is Consistent with a Secondary Origin, Qiang Yuan and Yi-Zhong Fan, Astrophys.J.Lett. 974 (2024) 1

Secondary Deuteron



Cosmic-ray deuteron excess from a primary component,
Xing-Jian Lv, Xiao-Jun Bi, Kun Fang, Peng-Fei Yin, and Meng-Jie Zhao
arXiv:2409.07139,
Phys.Rev.D 110 (2024) 12, 123030

Multiple Components of Cosmic Deuteron

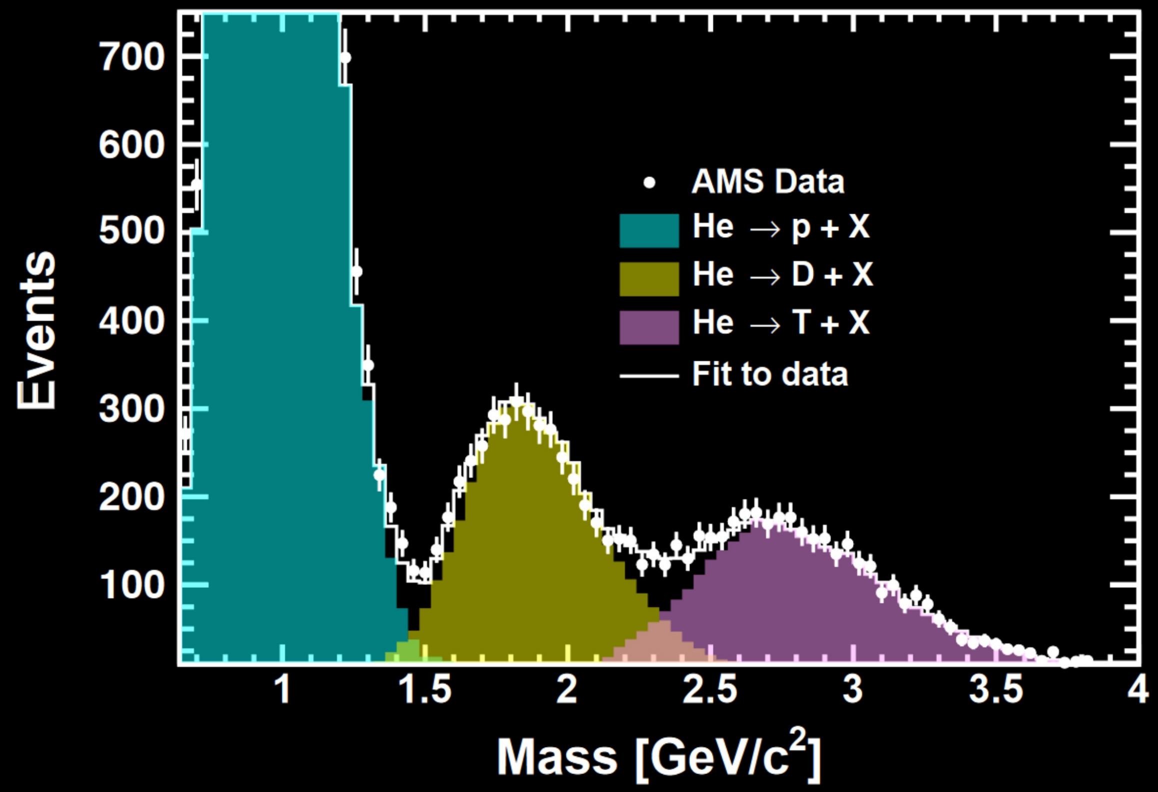


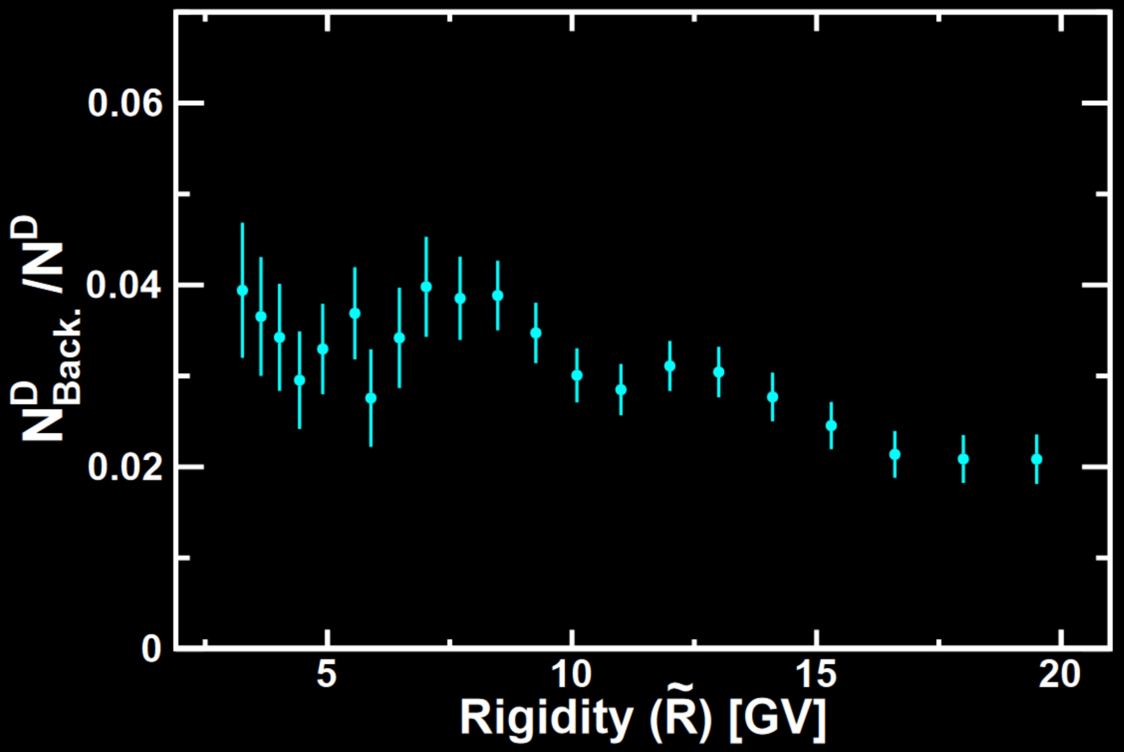
Summary

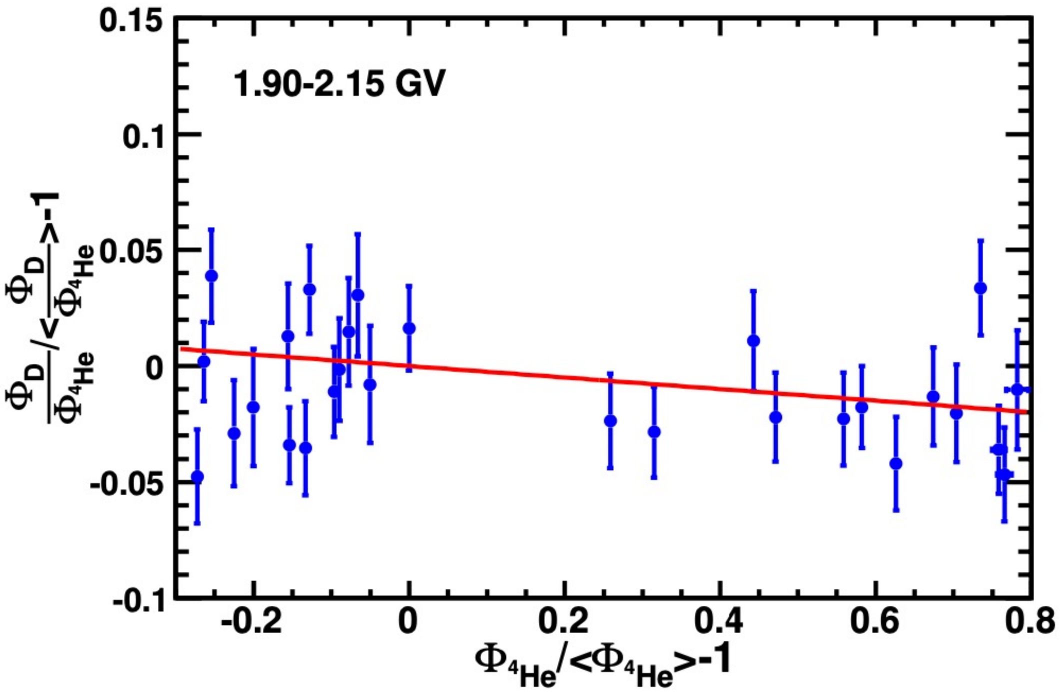
- AMS Precision measurements of the deuteron (D) flux, based on 21 million D nuclei in the rigidity range from 1.9 to 21 GV, are presented.
- Over the entire rigidity range, the D flux exhibits similar time variations with the p, ^{3}He, and ^{4}He fluxes. Yet below 4.5 GV, D shows larger variation (more modulated) than ^{4}He.
- Above 4.5 GV, the D/^{4}He flux ratio is time independent and its rigidity dependence is well described by a single power law ($\propto R^{\Delta}$) with $\Delta_{D/4He} = -0.108 \pm 0.005$,

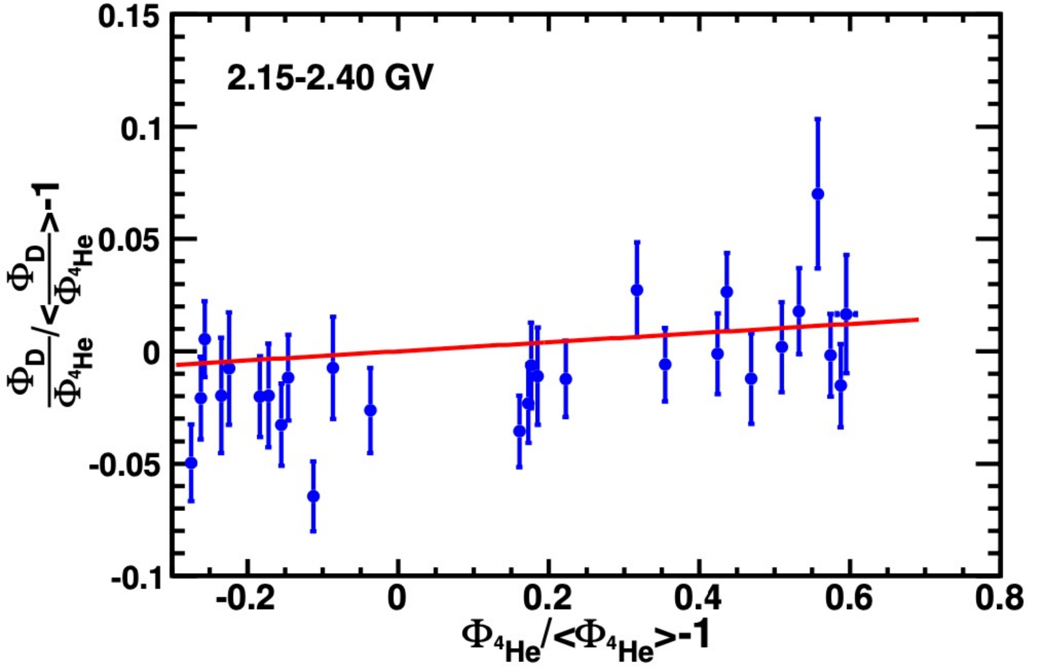
  in contrast with the ^{3}He/^{4}He flux ratio $\Delta_{3He/4He} = -0.289 \pm 0.003$.
- Above ~13 GV, D and p fluxes exhibit identical rigidity dependence with a D/p = 0.027 ± 0.001.
- These unexpected observations show that cosmic deuterons have a sizable primary like component. With a method independent of cosmic ray propagation, we obtain
  - The primary component of the D flux equal to (9.4 ± 0.5)% of the ^{4}He flux
  - The secondary component of the D flux equal to (58 ± 5)% of the ^{3}He flux.
- Current model have large uncertainty and new developments are needed.

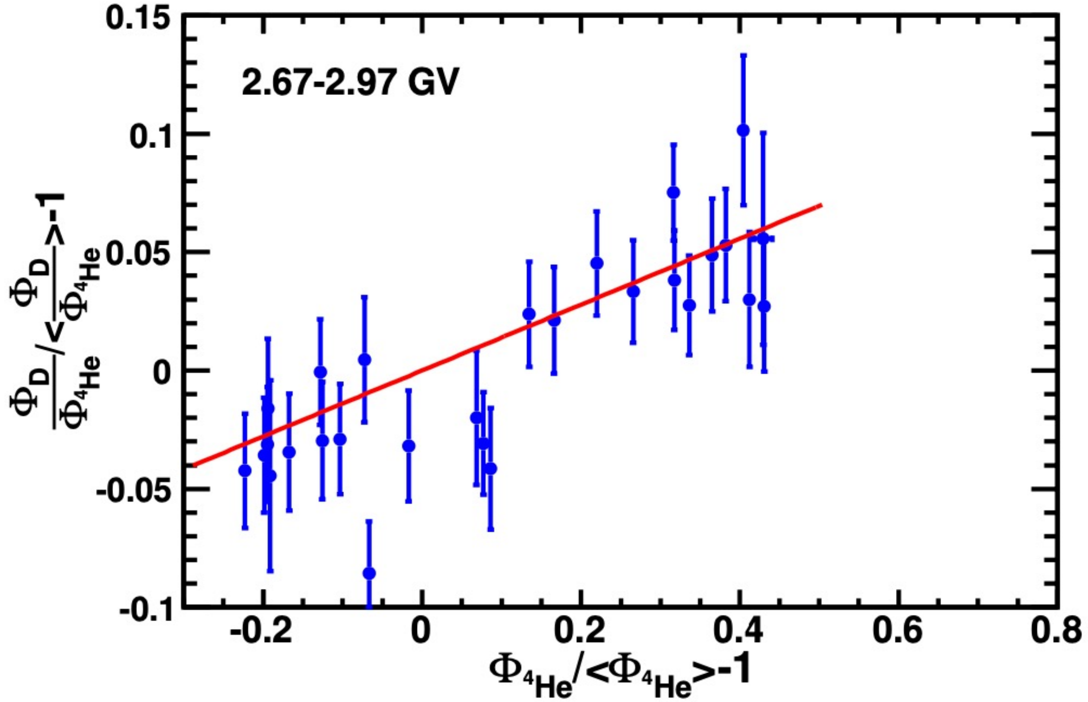
Estimation of ToI background











$$\frac{\Phi_{\mathrm{D}}^{i}/\Phi_{4_{\mathrm{He}}}^{i}}{\left\langle \Phi_{\mathrm{D}}^{i}/\Phi_{4_{\mathrm{He}}}^{i}\right\rangle}-1 = k_{D}^{i}\left(\frac{\Phi_{4_{\mathrm{He}}}^{i}}{\left\langle \Phi_{4_{\mathrm{He}}}^{i}\right\rangle}-1\right)$$