The need for Cross Section Measurements for the Interpretation of Cosmic-ray Data

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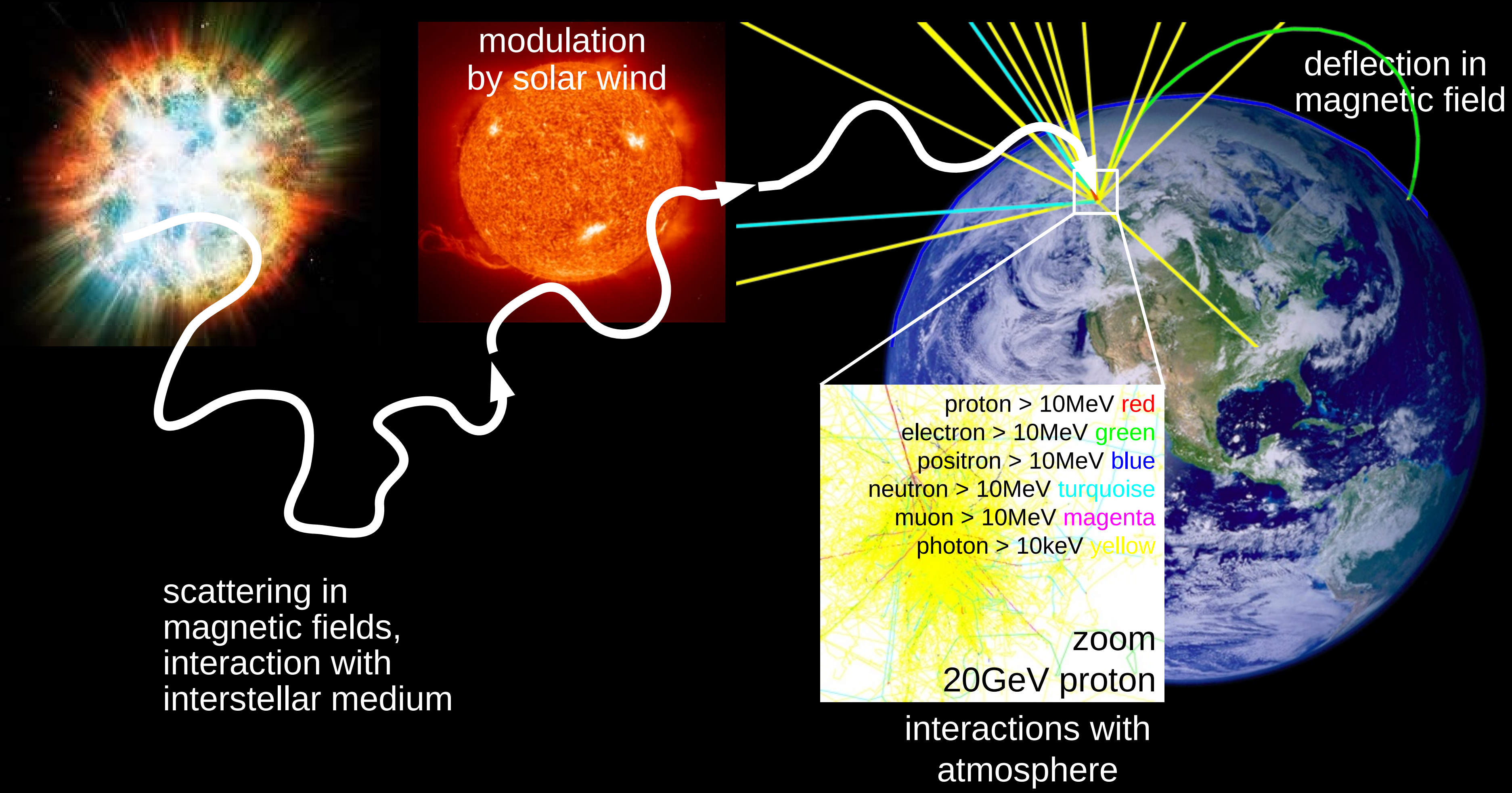
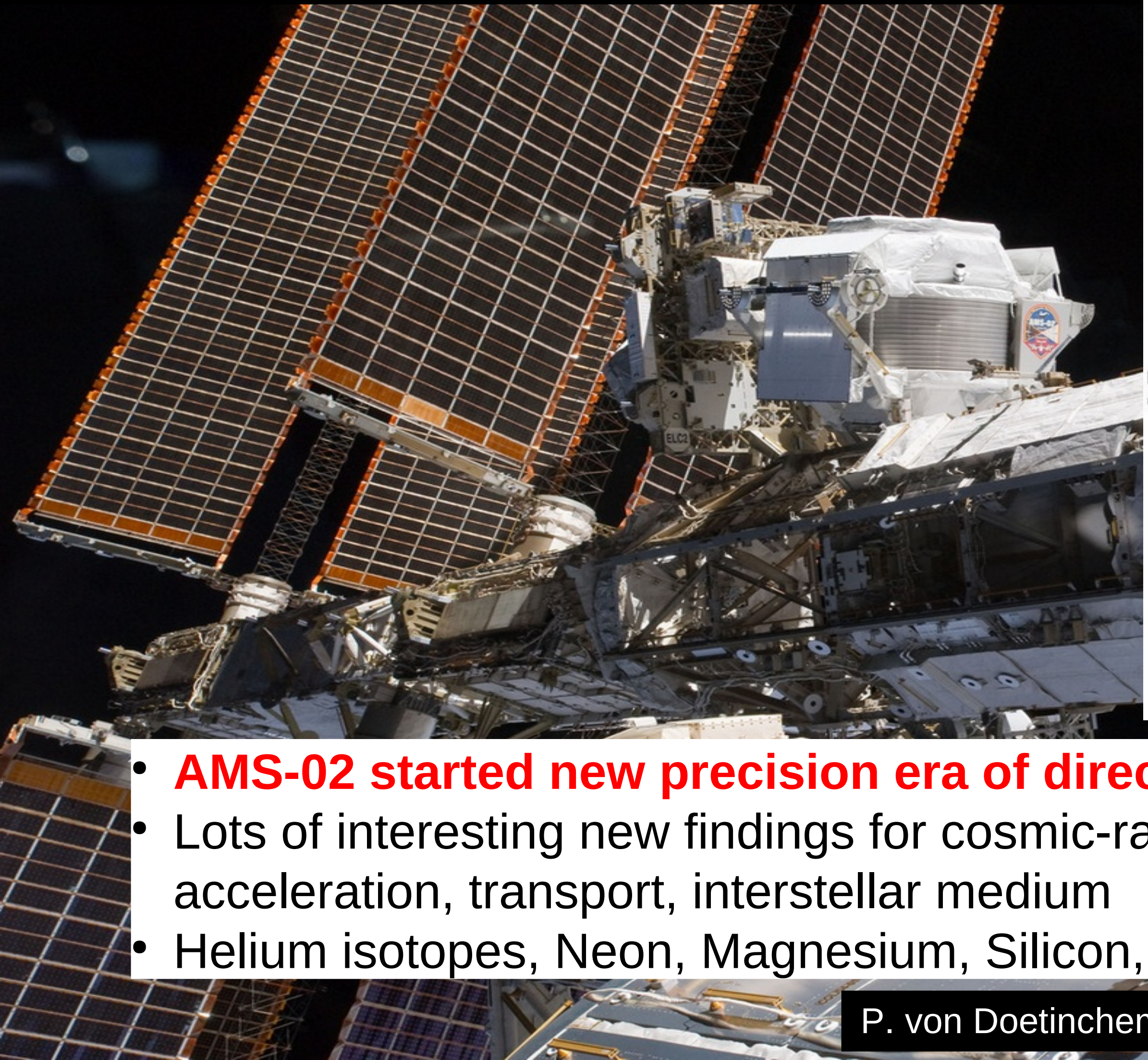
Philip von Doetinchem

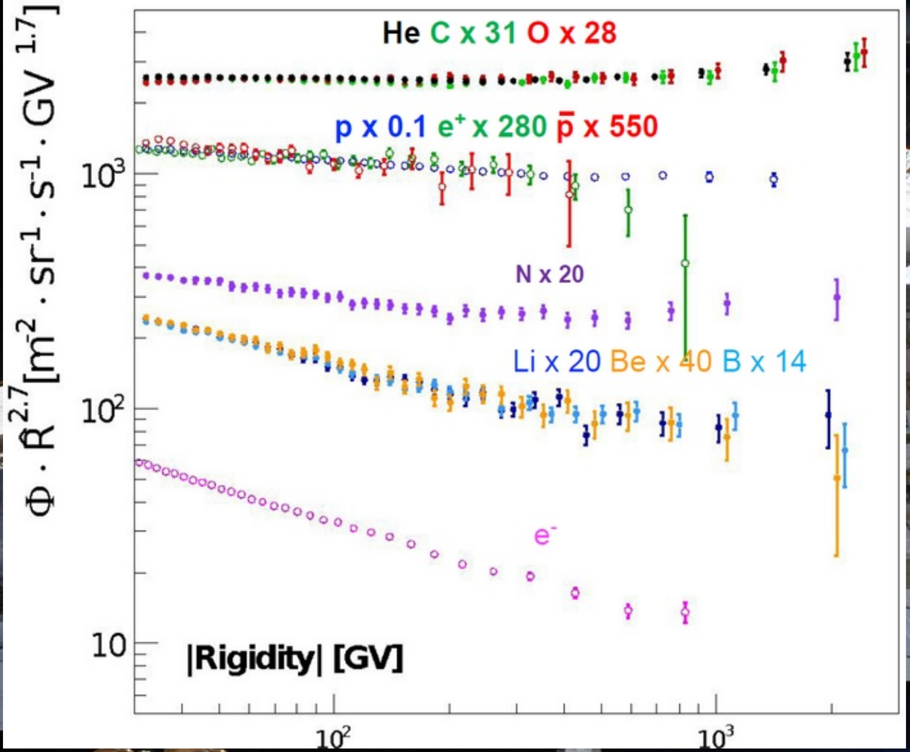
Department of Physics & Astronomy
University of Hawaii at Manoa
philipvd@hawaii.edu
https://www.phys.hawaii.edu/~philipvd

Cosmic rays as messengers



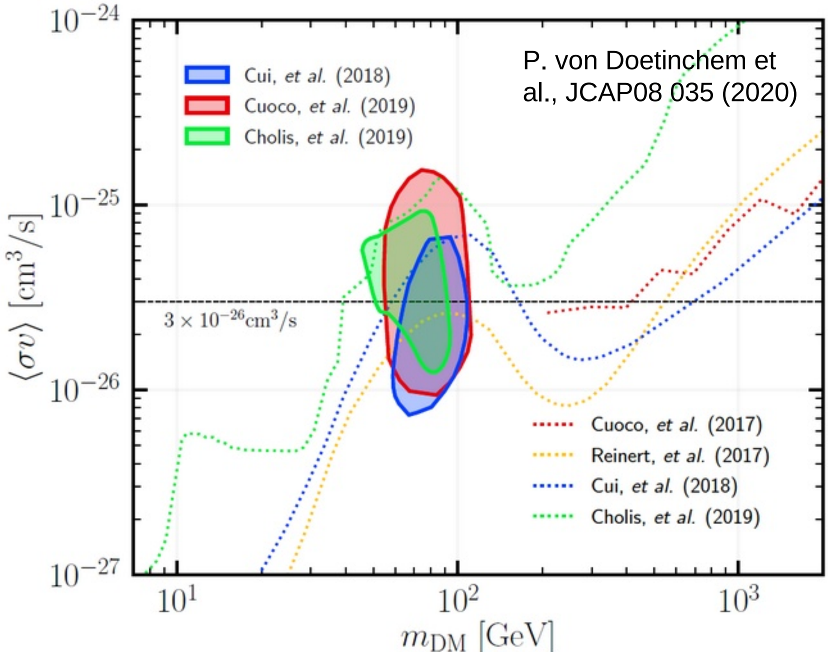
AMS-02 on the International Space Station

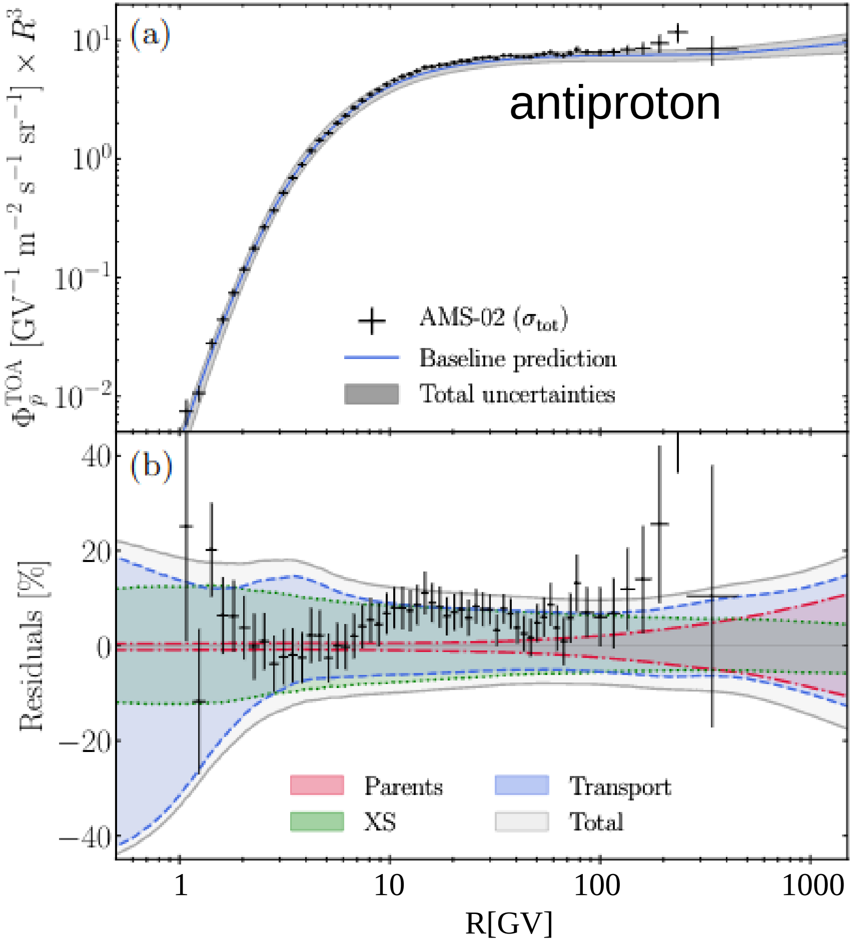




- **AMS-02 started new precision era of direct cosmic-ray measurements**
- Lots of interesting new findings for cosmic-ray physics concerning sources, acceleration, transport, interstellar medium
- Helium isotopes, Neon, Magnesium, Silicon, Sulfur Iron, Deuterium, etc.

Unexplained features in cosmic antiparticles?



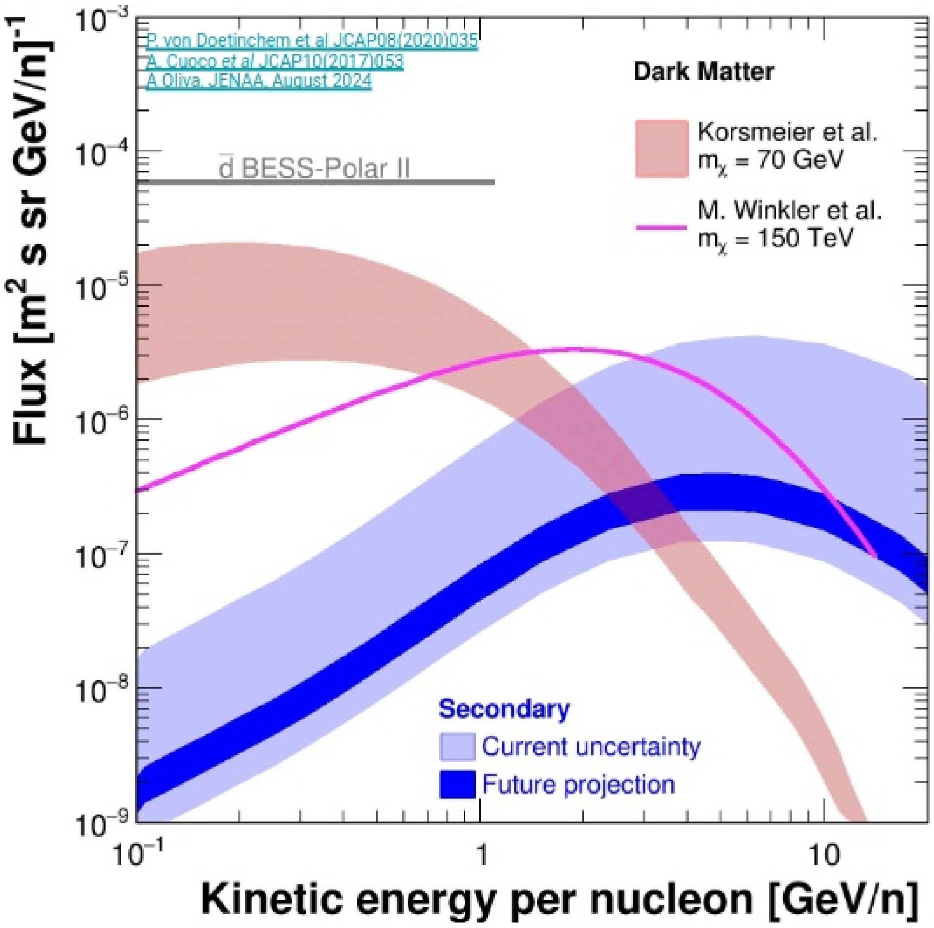


- combined fit with antiproton and diffuse gamma-rays from the Galactic Center → 70-80GeV DM particle? (ongoing debate)
- unexplained feature in positrons:
  - astrophysical origin → pulsars
  - SNR acceleration
  - dark matter annihilation
- **understanding astrophysics background is a challenge** → better constraints on cosmic-ray propagation and production needed

Cosmic Antinuclei

- Antideuterons are unexplored probes for indirect dark matter (DM) detection:
  - Predicted in a broad range of dark matter models
  - Expected astrophysical background at low energies is many orders of magnitude lowe
- Antihelium candidates have also been announce by AMS-02 (~1/year):
  - Astonishing on multiple levels
  - No current theory predicts this level of abundance
  - Secondaries, DM, or even nearby antistars‘

Large uncertainties in both astrophysical antinuclei production and Galactic transportation.

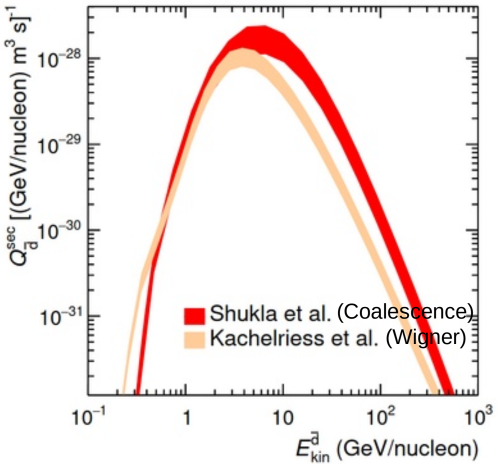


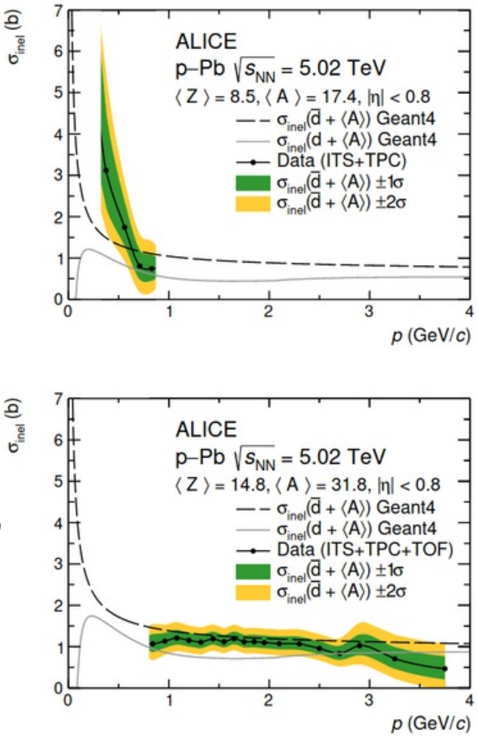
From production to flux at Earth

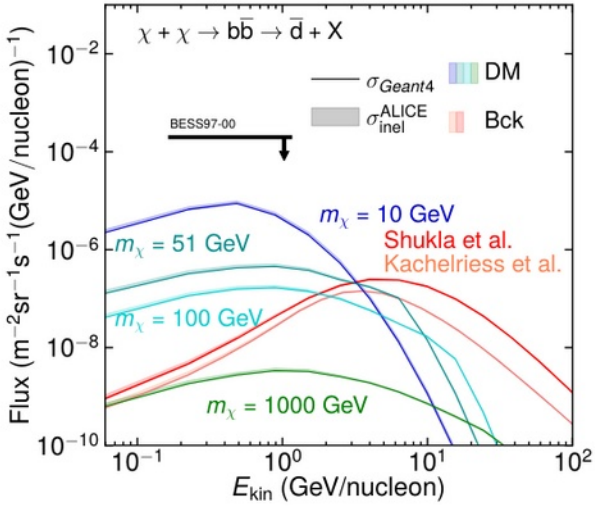
Šerkšnytė et al., Phys. Rev. D 105, 083021 (2022)

Propagation equation:

$$\frac{\partial\psi}{\partial t} = Q(\boldsymbol{r},p) + \mathbf{div}(D_{\rm xx}\mathbf{grad}\psi - \boldsymbol{V}\psi) + \frac{\partial}{\partial p}p^2 D_{\rm pp}\frac{\partial}{\partial p}\frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi\frac{{\rm d}p}{{\rm d}t} - \frac{p}{3}(\mathbf{div}\cdot\boldsymbol{V})\psi\right] - \frac{\psi}{\tau},$$



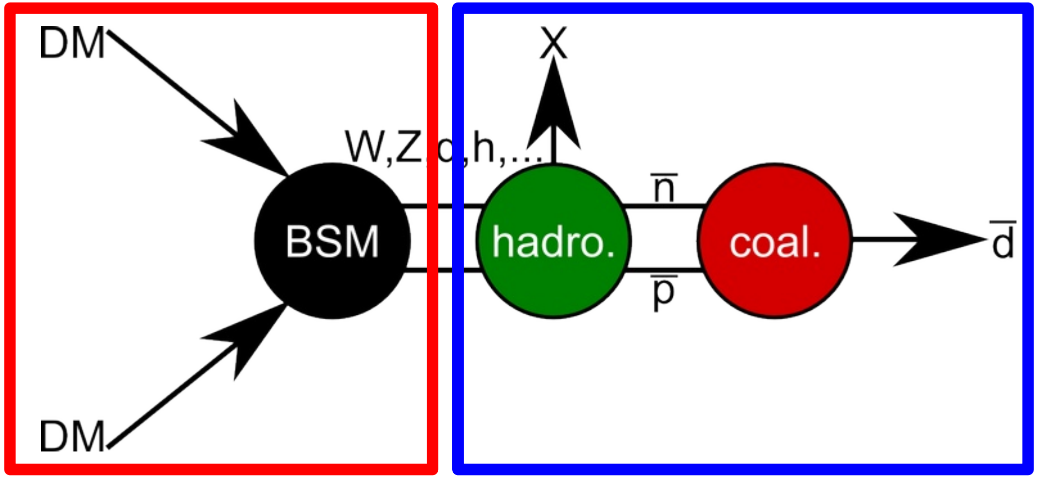




Antideuteron flux at the top of the atmosphere

- D_{xx}, V, and D_{pp} are the spatial diffusion coefficient, the convection velocity, and the diffusive re-acceleration coefficient, respectively.
- ψ/τ accounts for particles lost via decay, fragmentation and inelastic interactions in the Galaxy

(Anti)nuclei coalescence



dark matter

conventional production (e.g., p+ISM) & dark matter

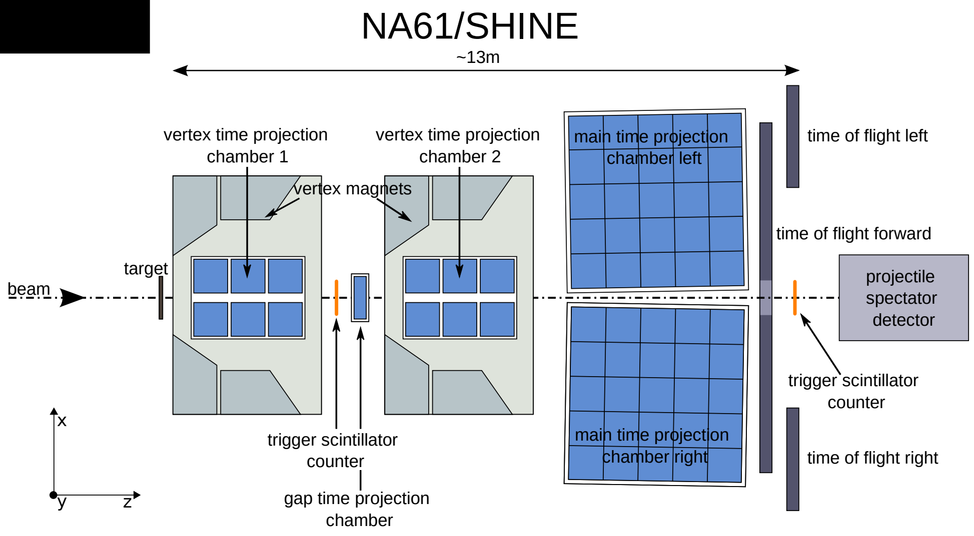
- (Anti)nuclei yield:

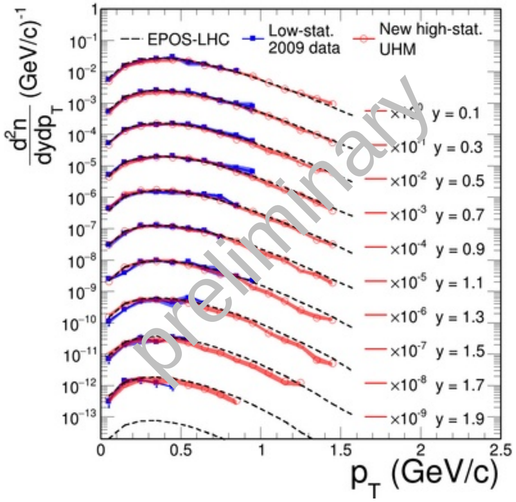
$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3}\right)^Z \left(E_n \frac{\mathrm{d}^3 N_n}{\mathrm{d}p_n^3}\right)^N \quad \text{with } B_A = A\left(\frac{4\pi}{3}\frac{p_0^3}{m_p}\right)^{A-1}$$

Work toward a data-driven quantum-mechanical description of coalescence with data in the right energy range with new data

Future measurements

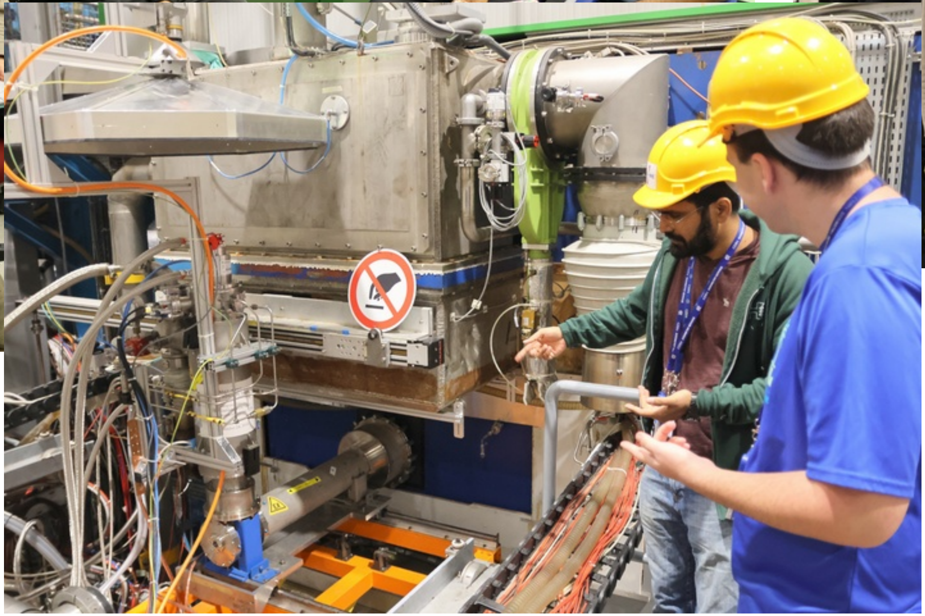
- NA61/SHINE at CERN SPS:
  - Fixed target experiment
  - High statistics $\bar{p}$ studies
  - C-p fragmentation cross section measurements
  - Deuteron production cross section, d/p ratio
  - Antiparticle correlation studies
- LHCb at LHC:
  - Antideuteron production in heavy hadron decays and in fixed-target collisions
  - Antihelium-3 from antilambda-b decays
- ALICE at LHC
  - Antinuclei production
  - Antinuclei inelastic cross sections
- AMBER at CERN SPS (upgraded COMPASS):
  - Fixed target experiment
  - High-statistics antiproton production cross section measurements





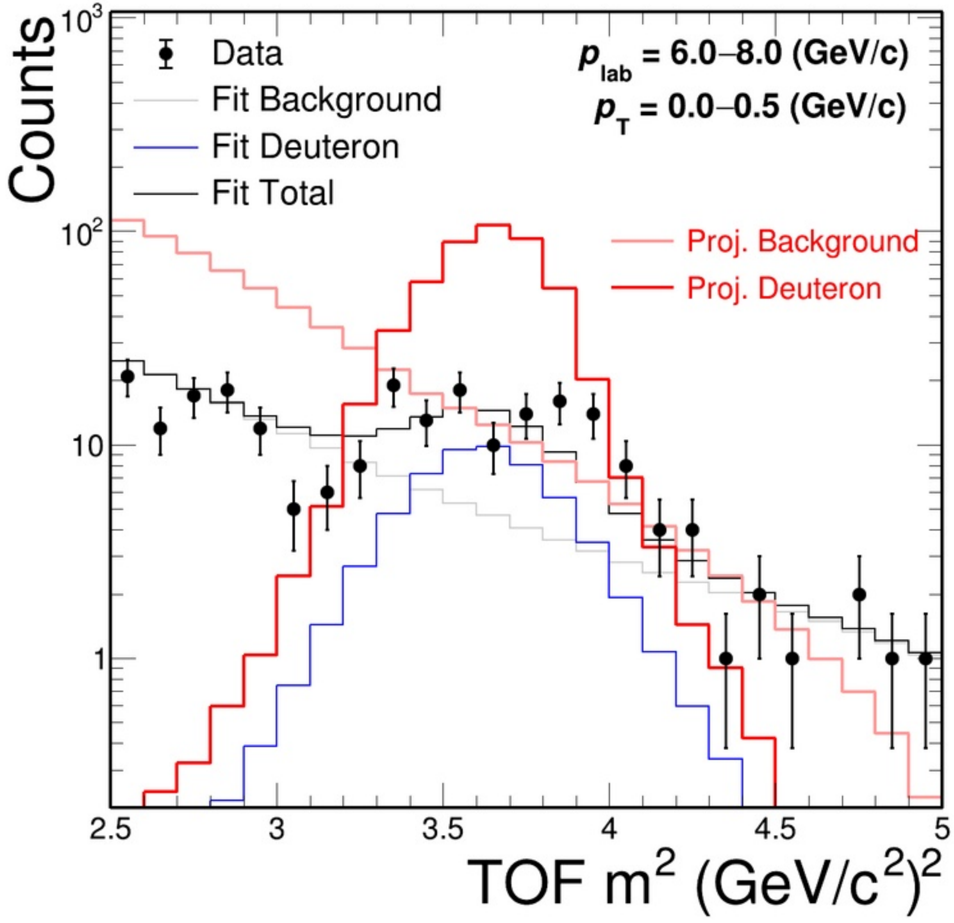
New NA61/SHINE data in 2025/26

Only UH group shown, many other NA61/SHINE collaborators were crucial

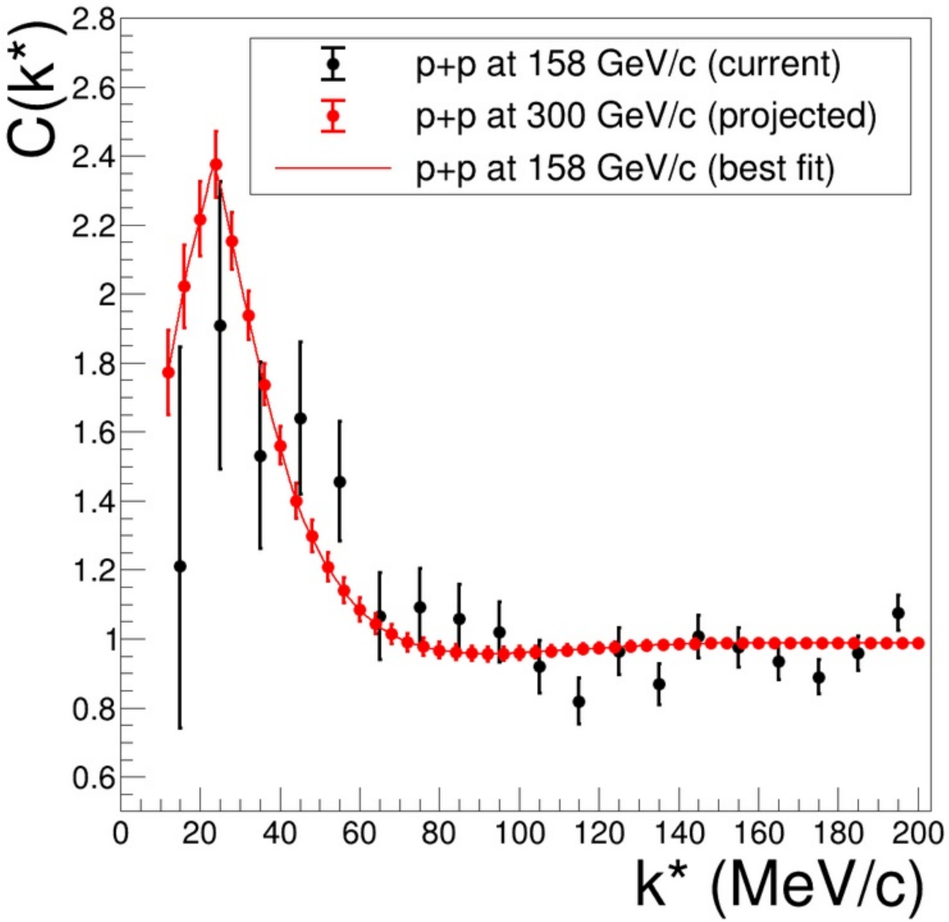


- New data proton+liquid hydrogen at 300GeV/c collected in fall 2025 and spring 2026
- 0.75B events → largest data set for antideuteron production measurement in the right energy range

New NA61/SHINE data in 2025/26

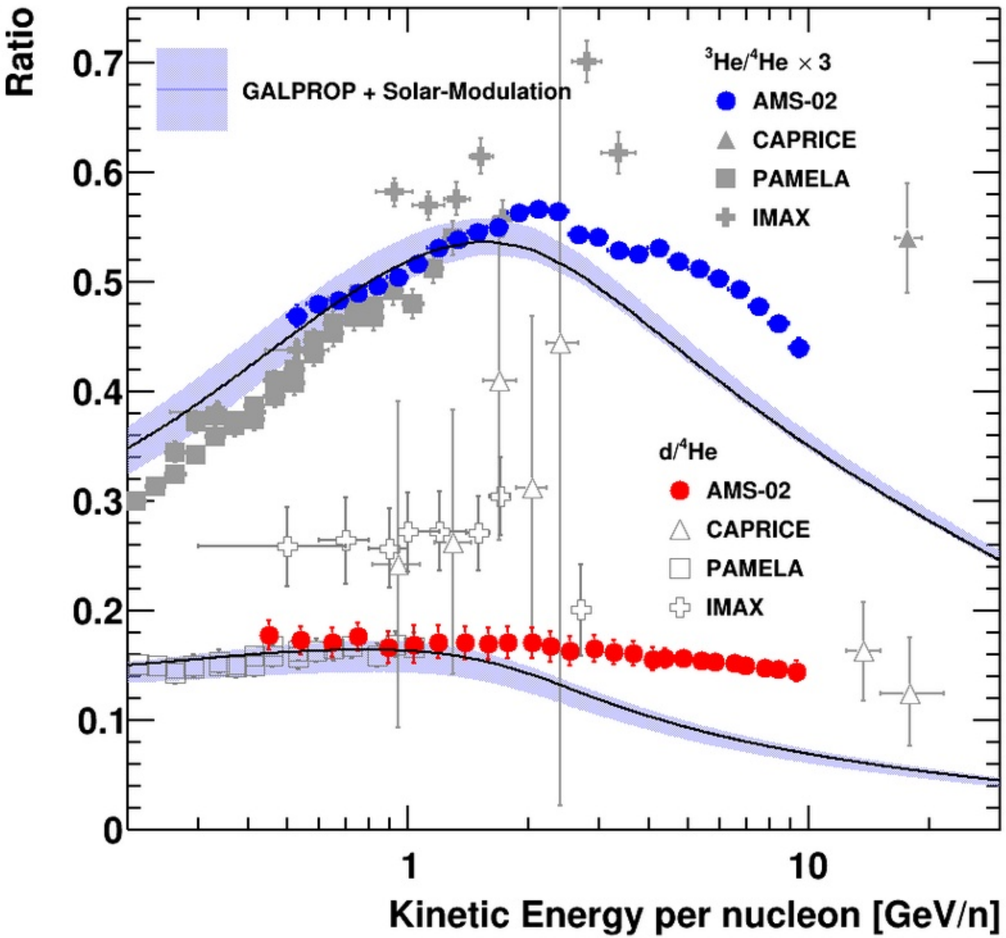


Deuterons



pp correlations

Cosmic deuterons

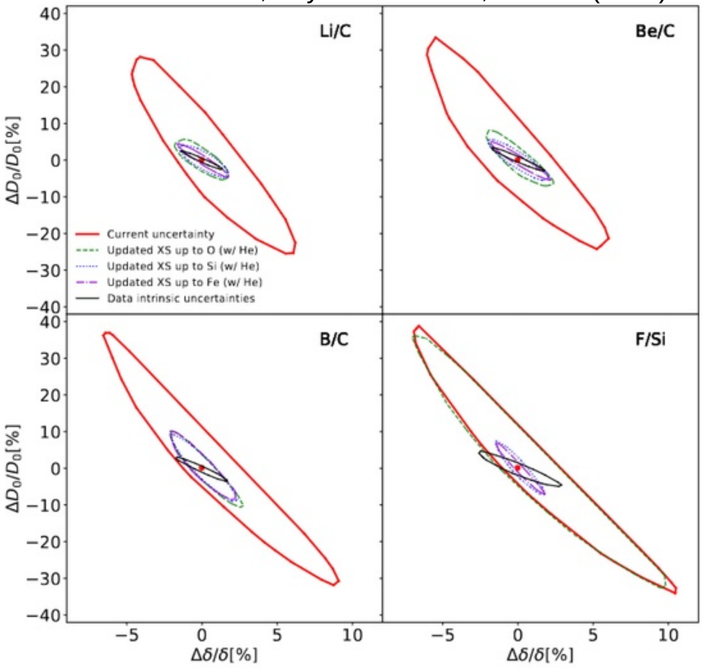


- Recent AMS-02 results show potentially more deuterons than anticipated
  - Primary deuteron component?
  - Underestimation of traversed material?
  - Problem with production cross sections?

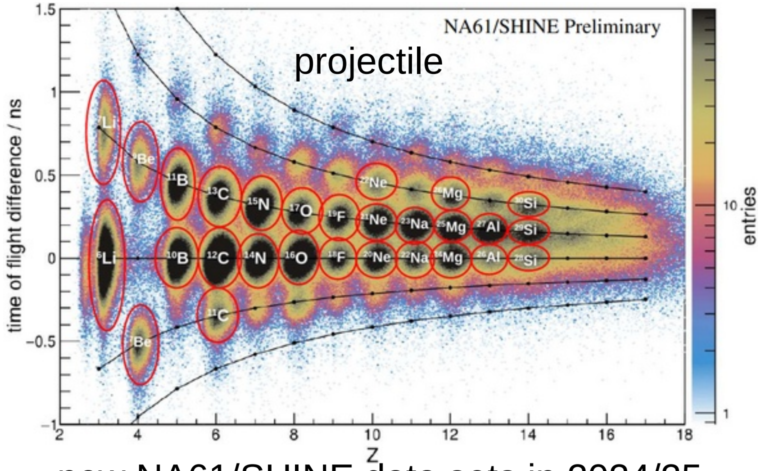
→ **Important impact on antiproton flux prediction**

Propagation uncertainties

Génolini et al., Phys. Rev. C 109, 064914 (2024)



- An important constraint for antinuclei flux from dark matter annihilations is the Galactic halo size, which directly scales the observable flux
- Amount of particle production in the Galaxy depends on the integrated traversed matter density
  → ratio of secondary-to-primary cosmic rays, e.g., Lithium/Carbon, Boron/Carbon or Deuteron/Helium
- Need to know fragmentation cross sections from laboratory measurements
  → **limitation:** cross sections are currently only known on the 10-20% level



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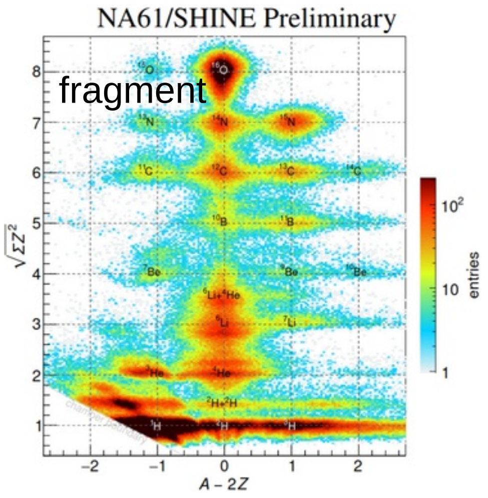


new NA61/SHINE data sets in 2024/25
^{12}C+PE/C at 12.5GeV/c ~50M event

XSCRC Effort

D. Maurin, L. Audouin, E. Berti, et al.,
PHYS REP 1161, 1 (2026), arXiv:2503.16173

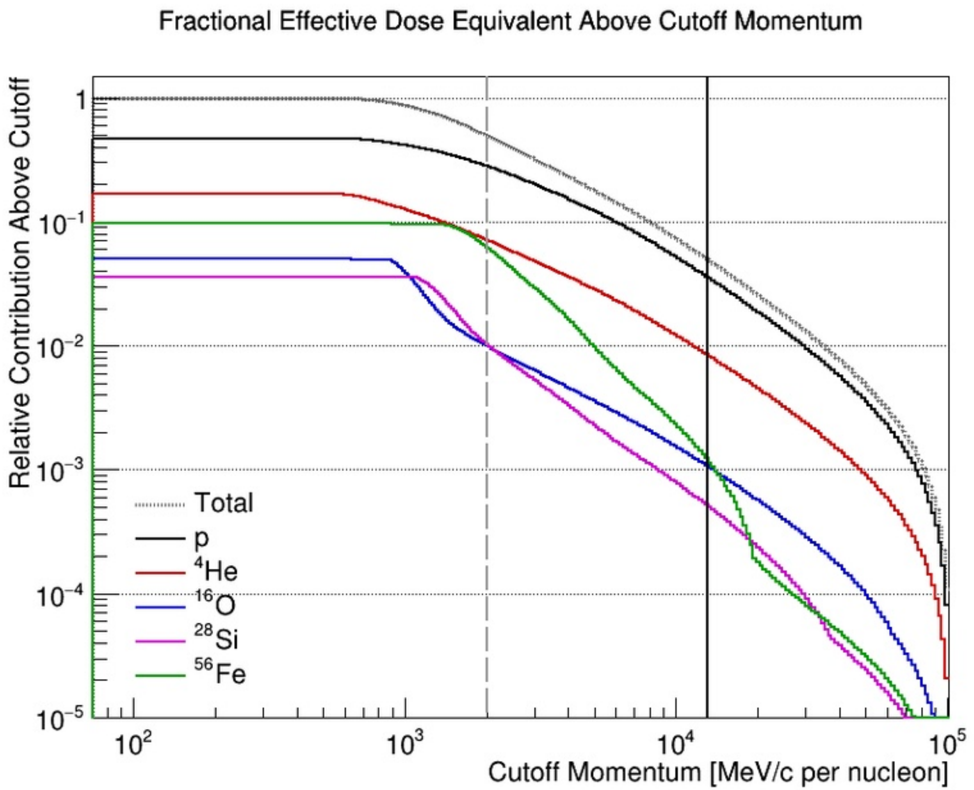
Requirements for XS improvements were formulated.,
e.g. for improvement of the understanding of dark matter

Particle	Reaction	Measurement	$\sqrt{s}$	Sought precision
$\overline{\mathrm{p}}$	$\mathrm{p}+\mathrm{p}\rightarrow\overline{\mathrm{p}}+\mathrm{X}$	σ_{inv}	5 to 100 GeV	$< 3\%$
	$\mathrm{p}+\mathrm{He}\rightarrow\overline{\mathrm{p}}+\mathrm{X}$			$< 5\%$
	$\mathrm{p}+\mathrm{p}\rightarrow\overline{\Lambda}+\mathrm{X}$			$< 10\%$
	$\mathrm{p}+\mathrm{He}\rightarrow\overline{\Lambda}+\mathrm{X}$			$< 10\%$
	$\mathrm{p}+\mathrm{p}\rightarrow\overline{\mathrm{n}}+\mathrm{X}$			$< 5\%$
	$\mathrm{p}+\mathrm{n}\rightarrow\overline{\mathrm{p}}+\mathrm{X}$			$< 5\%$
$\overline{\mathrm{d}}$	$\mathrm{p}+\mathrm{p}\rightarrow\overline{\mathrm{d}}+\mathrm{X}$	$\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$	5 to 100 GeV	(any data)
	$\mathrm{p}+\mathrm{He}\rightarrow\overline{\mathrm{d}}+\mathrm{X}$	$\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$	5 to 100 GeV	(any data)
	$\overline{\mathrm{p}}+\mathrm{p}\rightarrow\overline{\mathrm{d}}+\mathrm{X}$	σ_{inv}	2 to 10 GeV	(any data)
$\overline{\mathrm{He}}$	$\mathrm{p}+\mathrm{p}\rightarrow\overline{\mathrm{He}}+\mathrm{X}$	$\sigma_{\mathrm{inv}}/n_{\mathrm{tot}}$	5 to 100 GeV	(any data)
$e^{\pm}$	$\mathrm{p}+\mathrm{He}\rightarrow\pi^{\pm}+\mathrm{X}$	σ_{inv}	5 to 100 GeV	$< 5\%$
	$\mathrm{p}+\mathrm{He}\rightarrow K^{\pm}+\mathrm{X}$			$< 5\%$
γ	$\mathrm{p}+\mathrm{p}\rightarrow\pi^{0}+\mathrm{X}$	σ_{inv}	5 to 1000 GeV	$< 5\%$
	$\mathrm{p}+\mathrm{He}\rightarrow\pi^{0}+\mathrm{X}$			$< 5\%$

2024 conference website: https://indico.cern.ch/event/1377509/

2027 planning just started

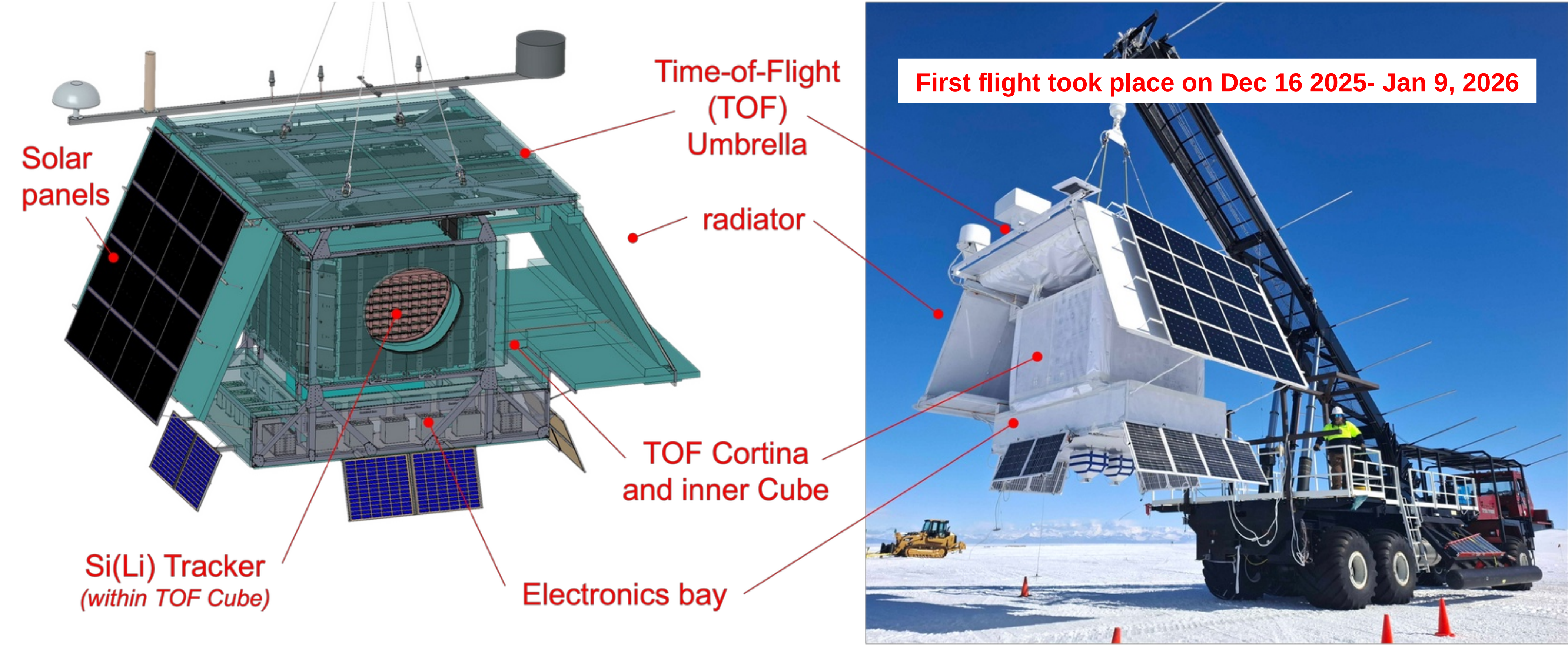
XS Measurement for Space Travel



Relative contribution to dose due to cosmic raysi mpinging on Al spacecraft shield

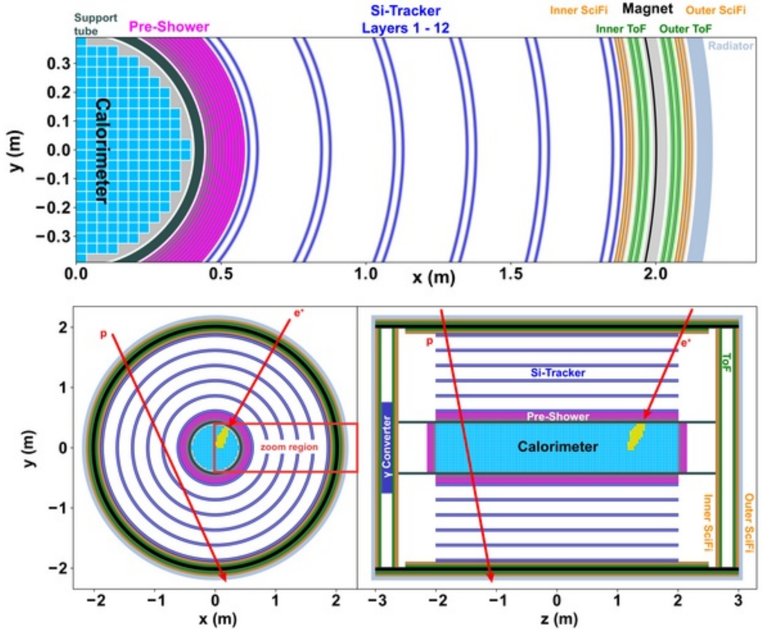
- Radiation dose calculation for space radiation protection depends on XS knowledge
- Large uncertainties in relevant cross sections exist
- Relevant for Moon or Mars missions

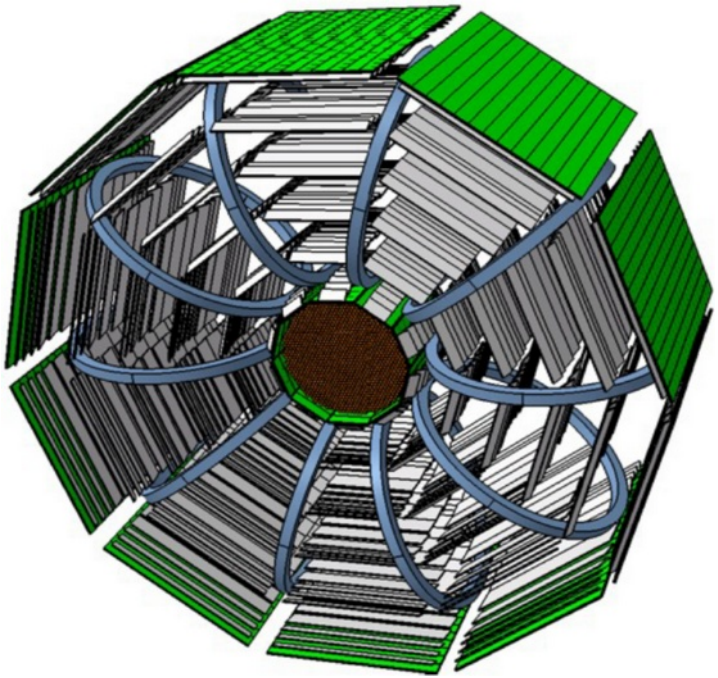
GAPS Experiment



- The **G**eneral **A**nti**P**article **S**pectrometer will deliver:
  - A precision antiproton measurement in an unexplored energy range <0.25 GeV/n
  - Antideuteron sensitivity 2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
  - Leading sensitivity to low-energy cosmic antihelium nuclei

Future beyond AMS-02 and GAPS





- AMS-100 a space-based platform (10-year oepration at Sun-Earth Lagrange Point 2) using a thin, large-volume, high-temperature superconducting solenoid magnet
- large geometrical acceptance of 100 m^2sr will measure the antideuteron spectrum, test heavier cosmic antimatter ($Z \leq -2$)

- ALADino: large accpetance, superconducting magnet
- Operation at Langrange Point 2

Nuclear antimatter up to 1000 GV, dark matter at the multi TeV/c^2, composition of CR in the multi 10 TV

NASA Ad Astra 2030 planning exercise is happening

Conclusion & Outlook

- ***Cosmic-ray antinuclei are important means to the study new physics***

- Uncertainties need to be reduced:
  - Antideuteron and antihelium formation are not well understood
  - Cross section measurements need to be conducted for interpretation
  - **Collider experiments make important contributions**

- Cosmic ray missions:
  - AMS-02 continues collecting data, and will be upgraded
  - GAPS had its first successful flight during the 2025/26 season
  - Planning for next-generation magnetic spectrometers has to start now