Status of cosmic-ray antinuclei searches

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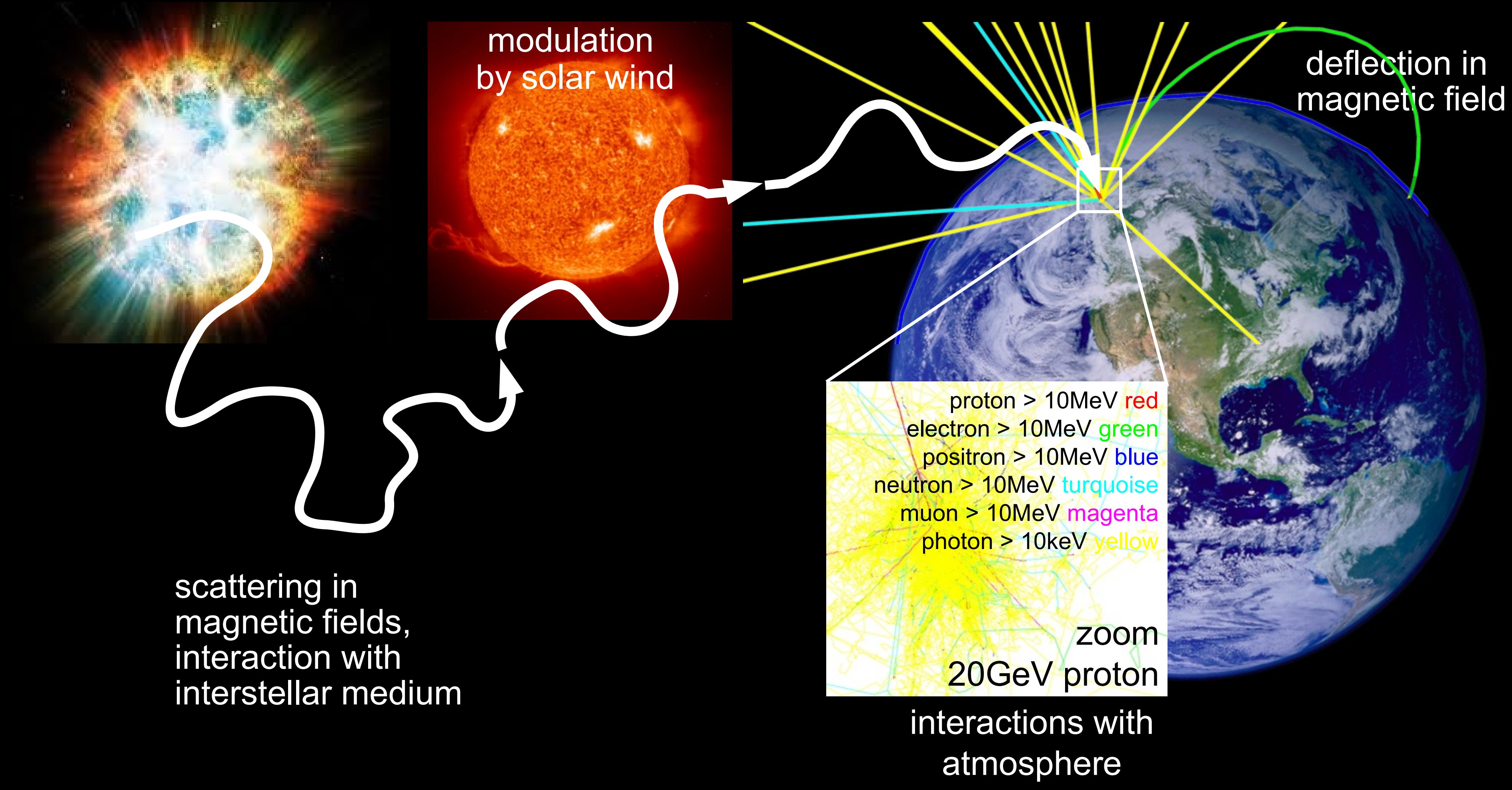
Cosmic antinuclei

Measurement of cosmic-ray antinuclei (antiproton, antideuteron, antihelium) is an exciting way to search for new physical phenomena:

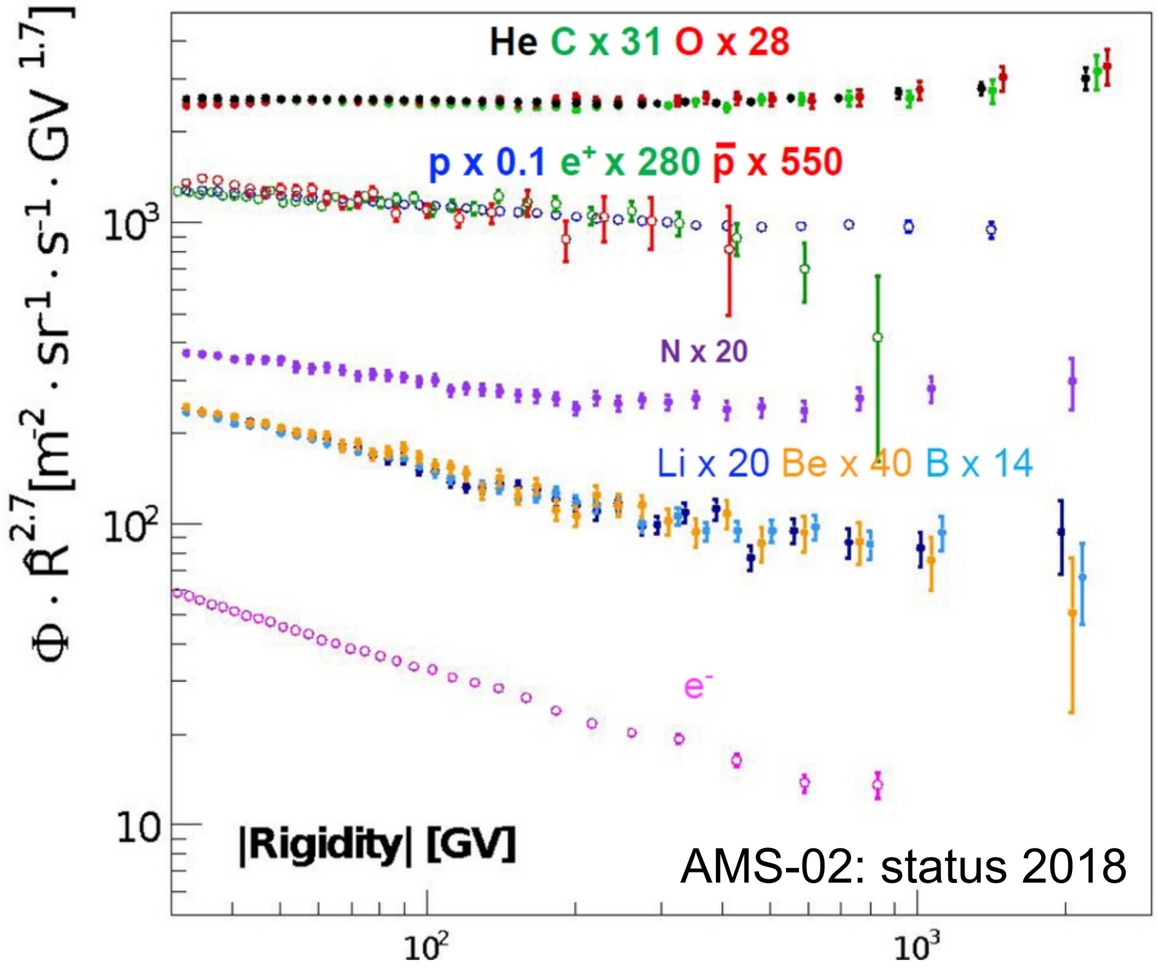
Talk outline:

- Cosmic rays as messengers
- Potential primary sources of antinuclei
- Uncertainties of production and propagation in our Galaxy
- Experimental cosmic-ray search updates
- Path forward

Cosmic rays as messengers



Snapshot of cosmic-ray status



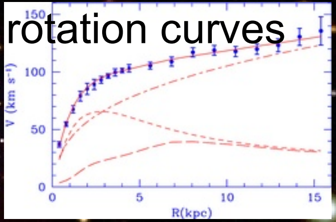
- **AMS-02 started new precision era of direct cosmic-ray measurements**
- Lots of interesting new findings for cosmic-ray physics concerning sources, acceleration, transport, interstellar medium
- Also available: helium isotopes, Neon, Magnesium, Silicon, Sulfur Iron, Deuterium
- Focus of this talk: **antinuclei**

Existence of dark matter

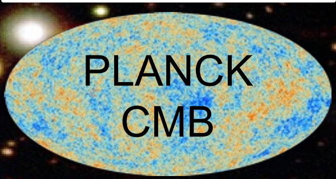
Bullet cluster
red: hot X-ray emitting gas
blue: distribution of dark matter

- **dark matter exists, but nature remains unknown!**
- luminous matter cannot describe the structure of the Universe
- evidence for dark matter comes from many different type of observations on different distance scales

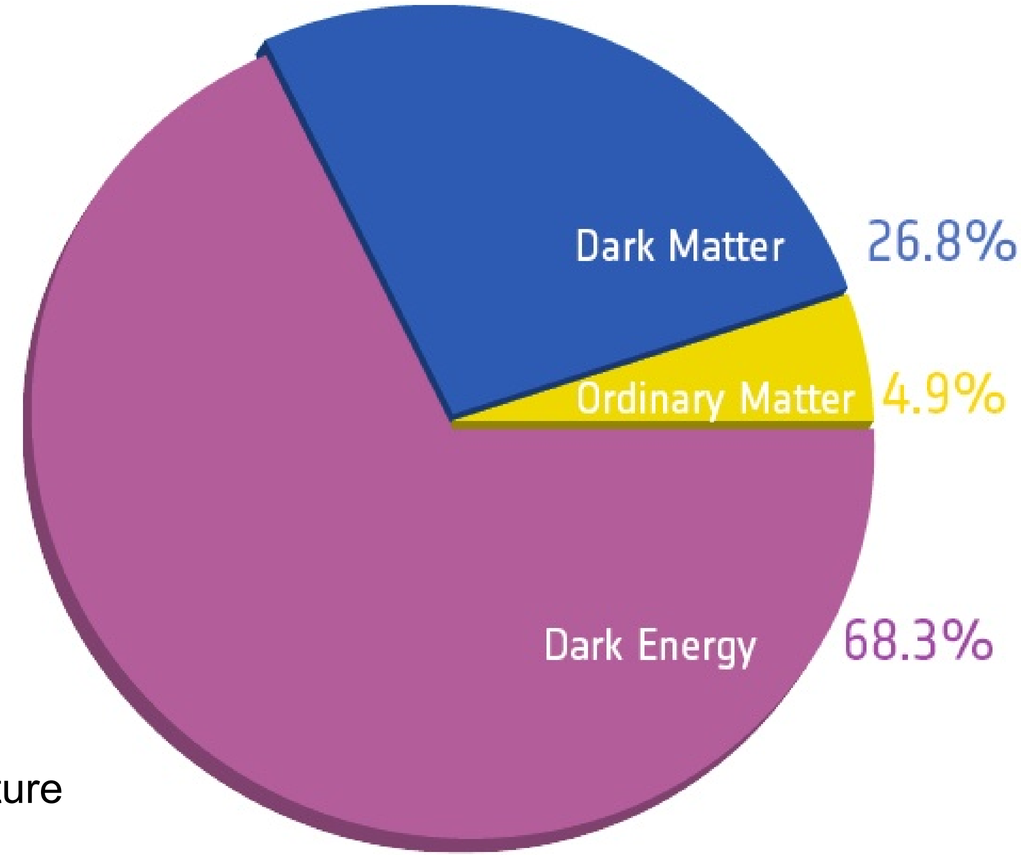
rotation curves



Abell 1689: gravitational lensing



Why do we need something new?



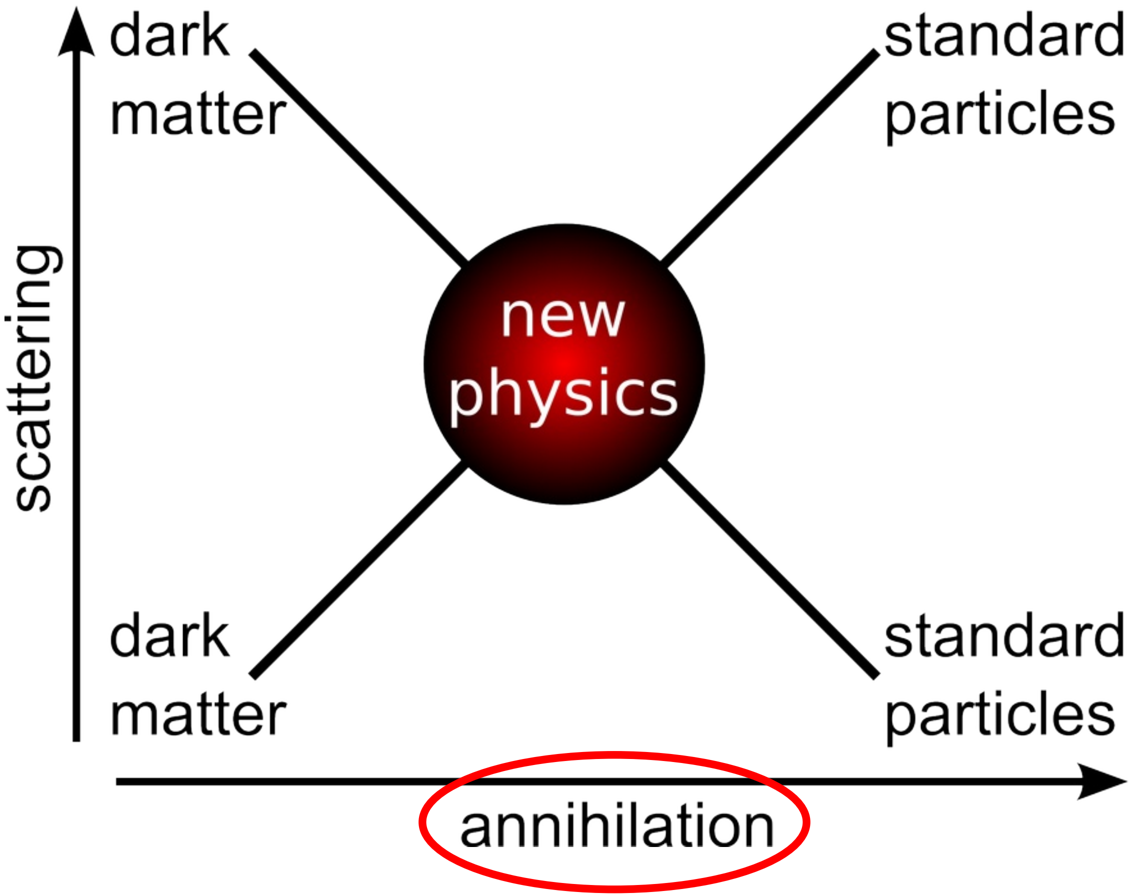
- dark matter is so far only gravitationally visible and must be a **new non-baryonic type of particle**
  - neutral
  - with relatively high mass to explain the structure formation of the universe
  - with only very weak interactions with standard particles (if at all)
- **discovering the nature of dark matter is one of the most striking problems in physics**

How is dark matter interacting?

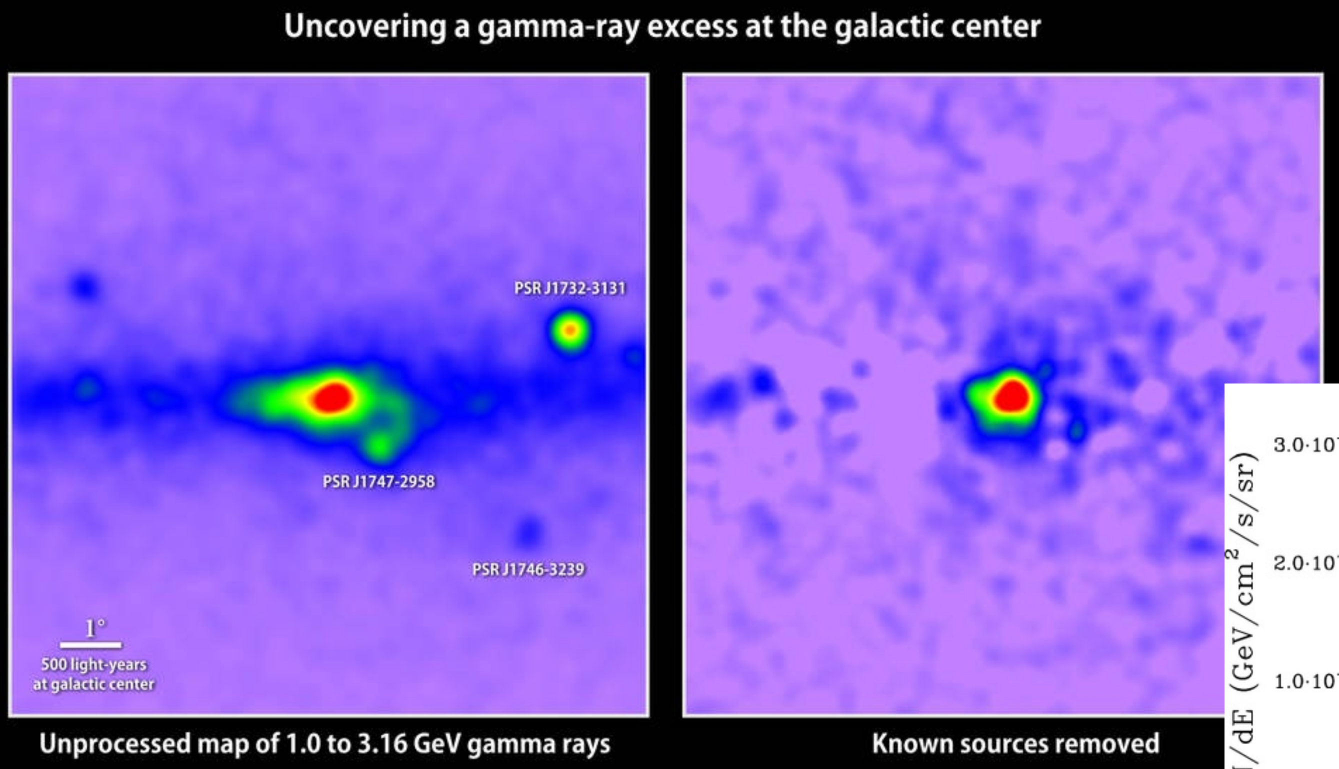
- **natural assumption:** dark matter was in thermal equilibrium in the early universe expansion led to dark matter freeze-out
- **WIMP miracle (?):** weak-scale particles are ideal candidates (~100-1000GeV) to reproduce observed relic dark matter density

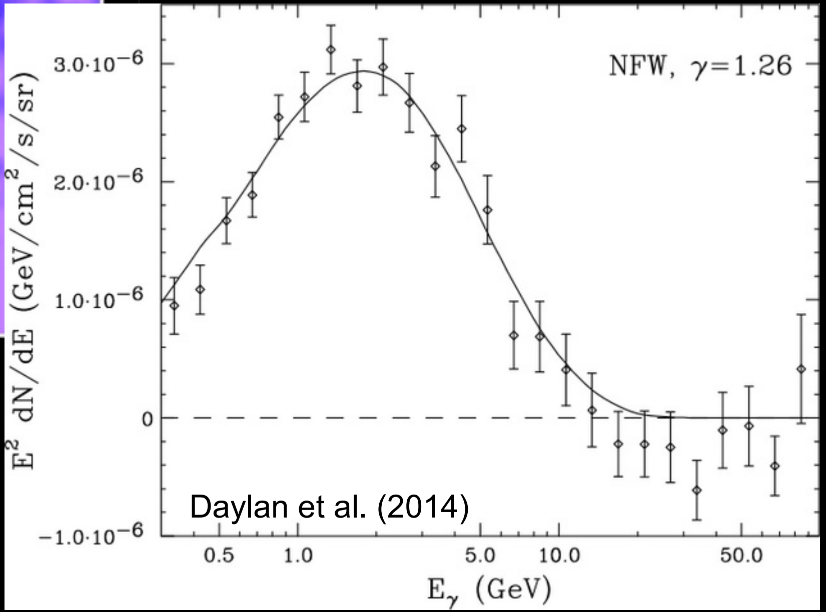
  → dark matter must be able to interact with standard model particles?

- Situation is complicated and dark matter particle searches have not been conclusive so far



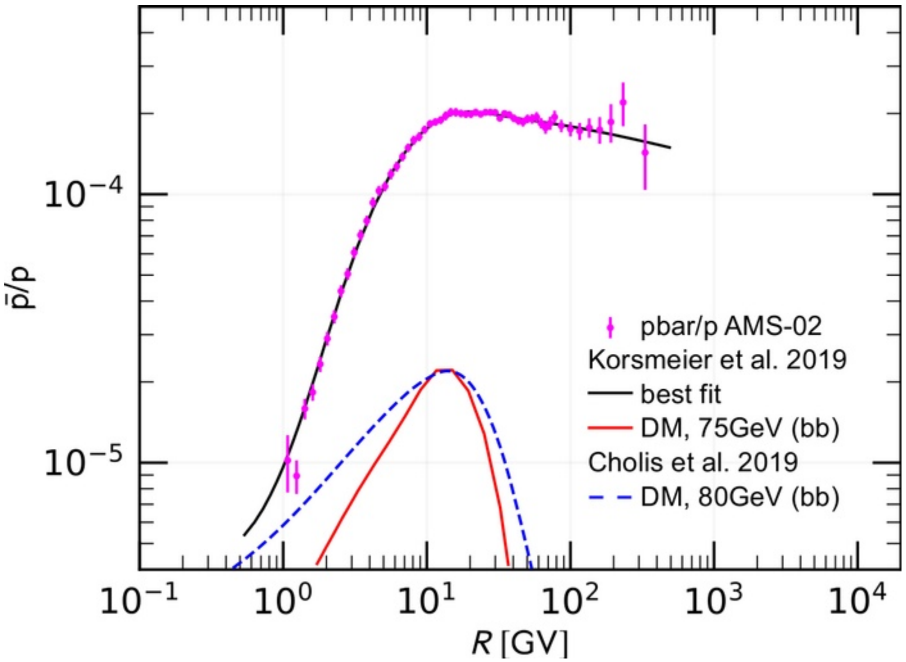
Diffuse Galactic γ-ray excess?

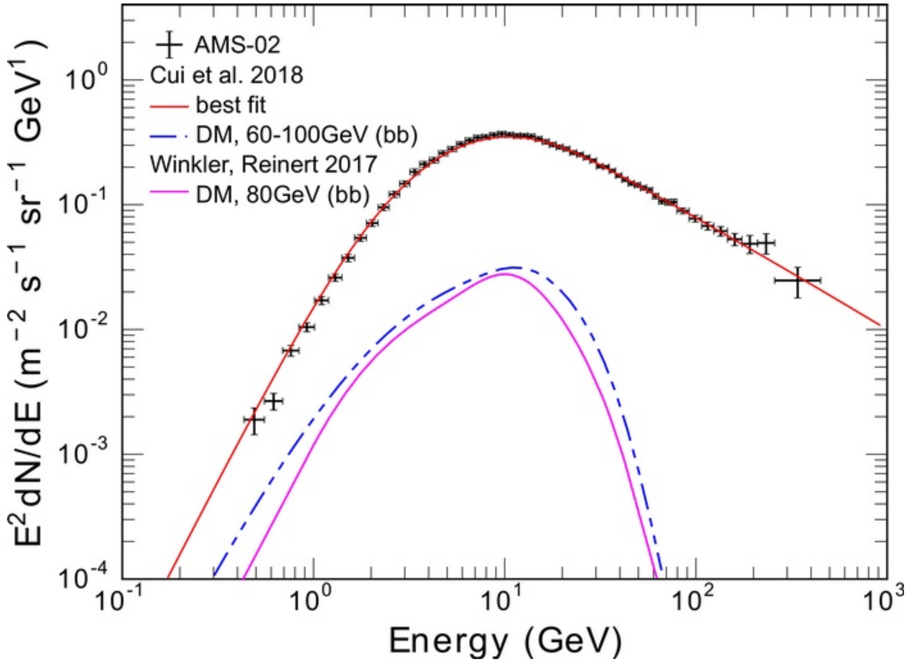




- gamma-ray excess at the galactic center → ~30GeV dark matter particle?
- unresolved millisecond pulsars?
- pion production in molecular clouds
- tension with dwarf galaxies

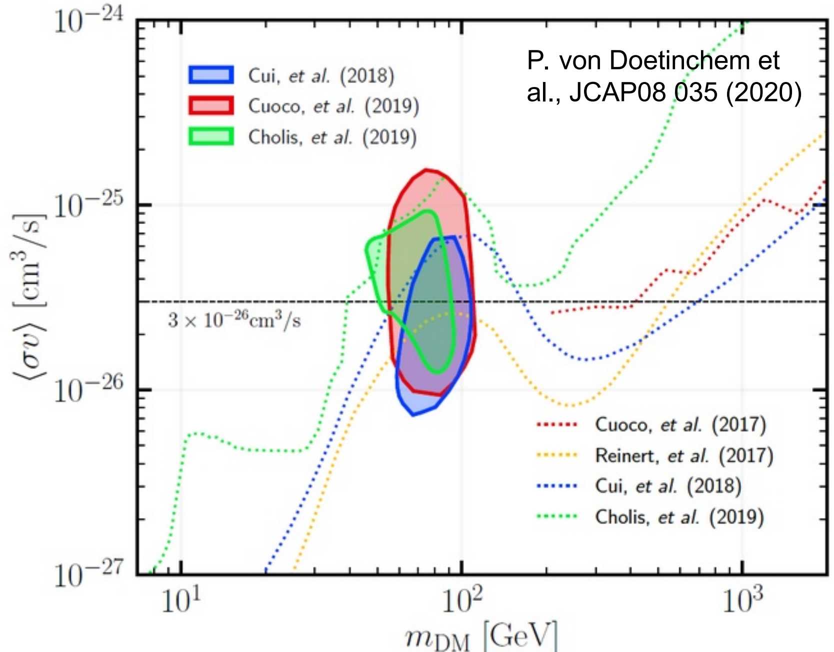
Low-energy antiproton excess



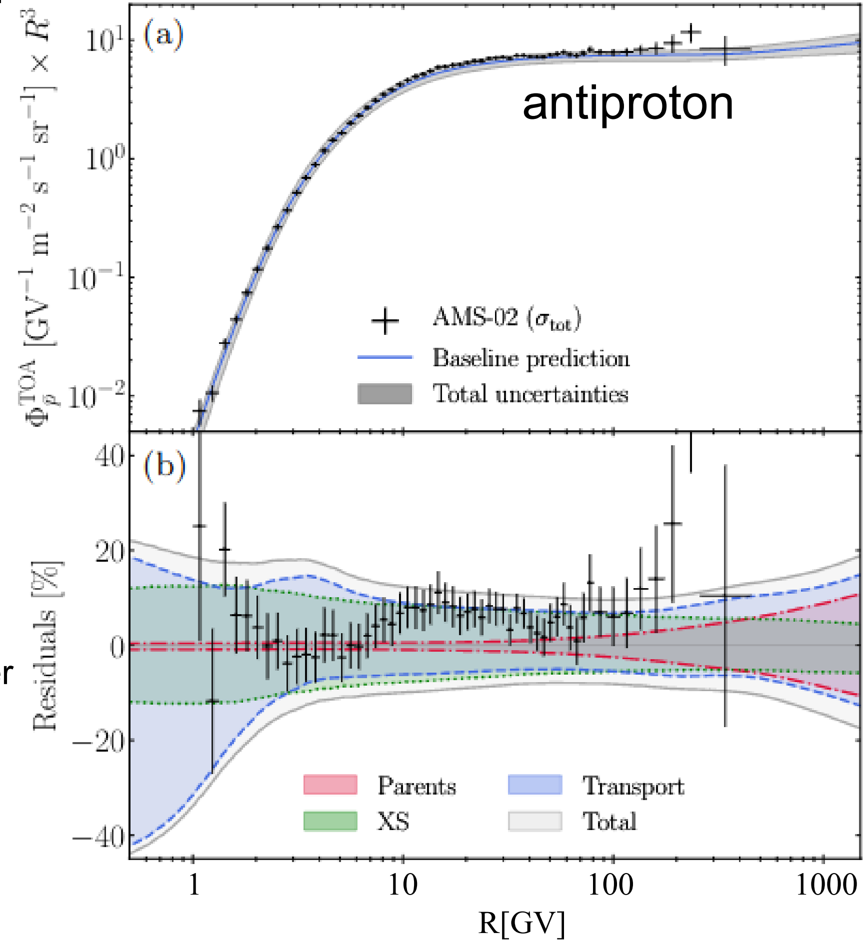


- A small $\bar{p}$ excess in AMS-02 data above secondary background predictions at R~10 GV was reported in various studies → significance level unclear
- This excess is in agreement with explaining the γ-ray excess at the Galactic Center with a signal from dark matter annihilation

Unexplained features in cosmic antiparticles?



M. Boudaud et al., Phys. Rev. Research 2, 023022 (2020)



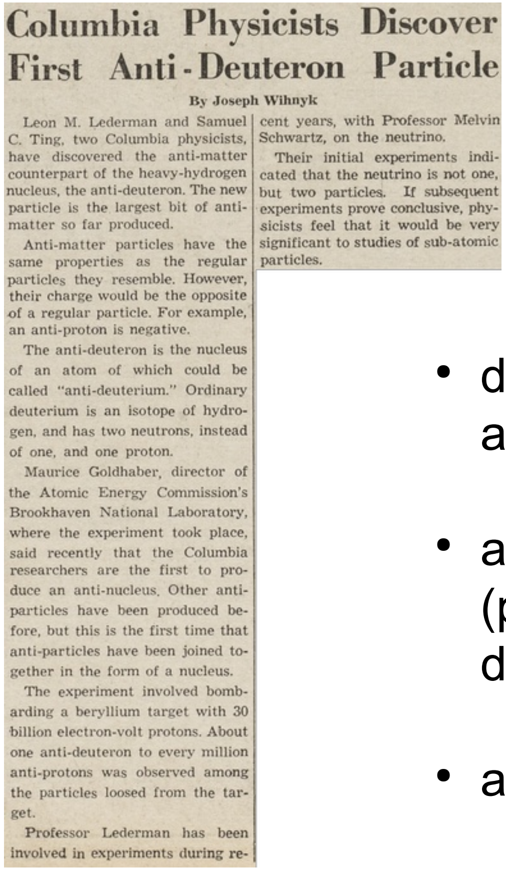
- combined fit with antiproton and diffuse gamma-rays from the Galactic Center → 70-80GeV DM particle? (ongoing debate)
- unexplained feature in positrons:
  - astrophysical origin → pulsars
  - SNR acceleration
  - dark matter annihilation
- **understanding astrophysics background is a challenge** →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

Antideuteron discovery

COLUMBIA DAILY SPECTATOR

FOUNDED 1877

Vol. CIX—No. 85 NEW YORK, N.Y., THURSDAY, MARCH 11, 1965 401 FIVE CENTS



Columbia Physicists Discover First Anti-Deuteron Particle

By Joseph Wihnyk

Leon M. Lederman and Samuel C. Ting, two Columbia physicists, have discovered the anti-matter counterpart of the heavy-hydrogen nucleus, the anti-deuteron. The new particle is the largest bit of anti-matter so far produced.

Anti-matter particles have the same properties as the regular particles they resemble. However, their charge would be the opposite of a regular particle. For example, an anti-proton is negative.

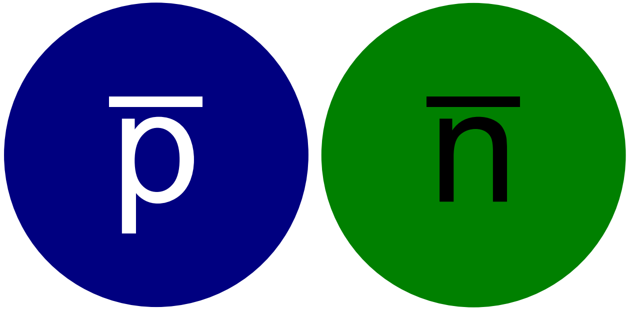
The anti-deuteron is the nucleus of an atom of which could be called "anti-deuterium." Ordinary deuterium is an isotope of hydrogen, and has two neutrons, instead of one, and one proton.

Maurice Goldhaber, director of the Atomic Energy Commission's Brookhaven National Laboratory, where the experiment took place, said recently that the Columbia researchers are the first to produce an anti-nucleus. Other anti-particles have been produced before, but this is the first time that anti-particles have been joined together in the form of a nucleus.

The experiment involved bombarding a beryllium target with 30 billion electron-volt protons. About one anti-deuteron to every million anti-protons was observed among the particles loosed from the target.

Professor Lederman has been involved in experiments during recent years, with Professor Melvin Schwartz, on the neutrino.

Their initial experiments indicated that the neutrino is not one, but two particles. If subsequent experiments prove conclusive, physicists feel that it would be very significant to studies of sub-atomic particles.

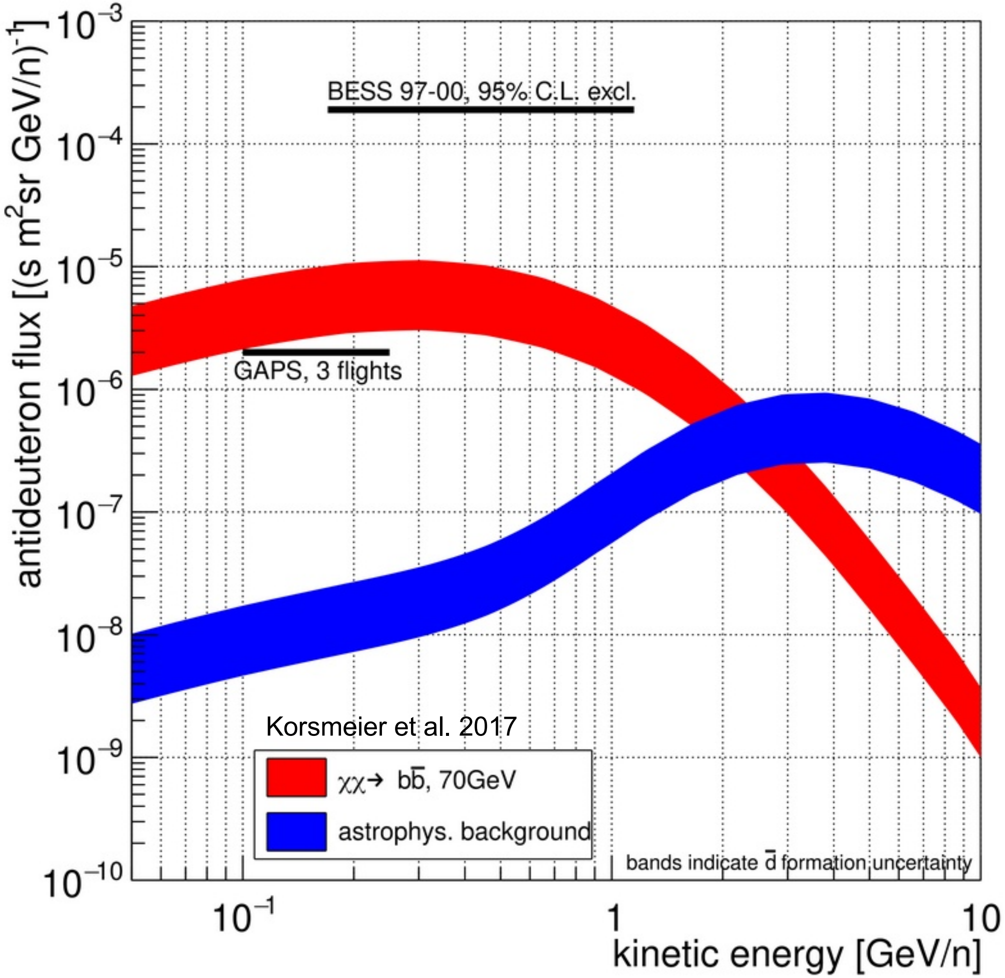


- deuterons are the nuclei of heavy water and antideuterons are the corresponding antimatter (Z=-1,m=1876MeV, s=1)

- antideuterons were discovered in 1965 at Brookhaven (p+Be) and CERN and were the first bound antimatter ever discovered

- antideuterons have not been detected in cosmic rays

Antideuterons as a probe of dark matter

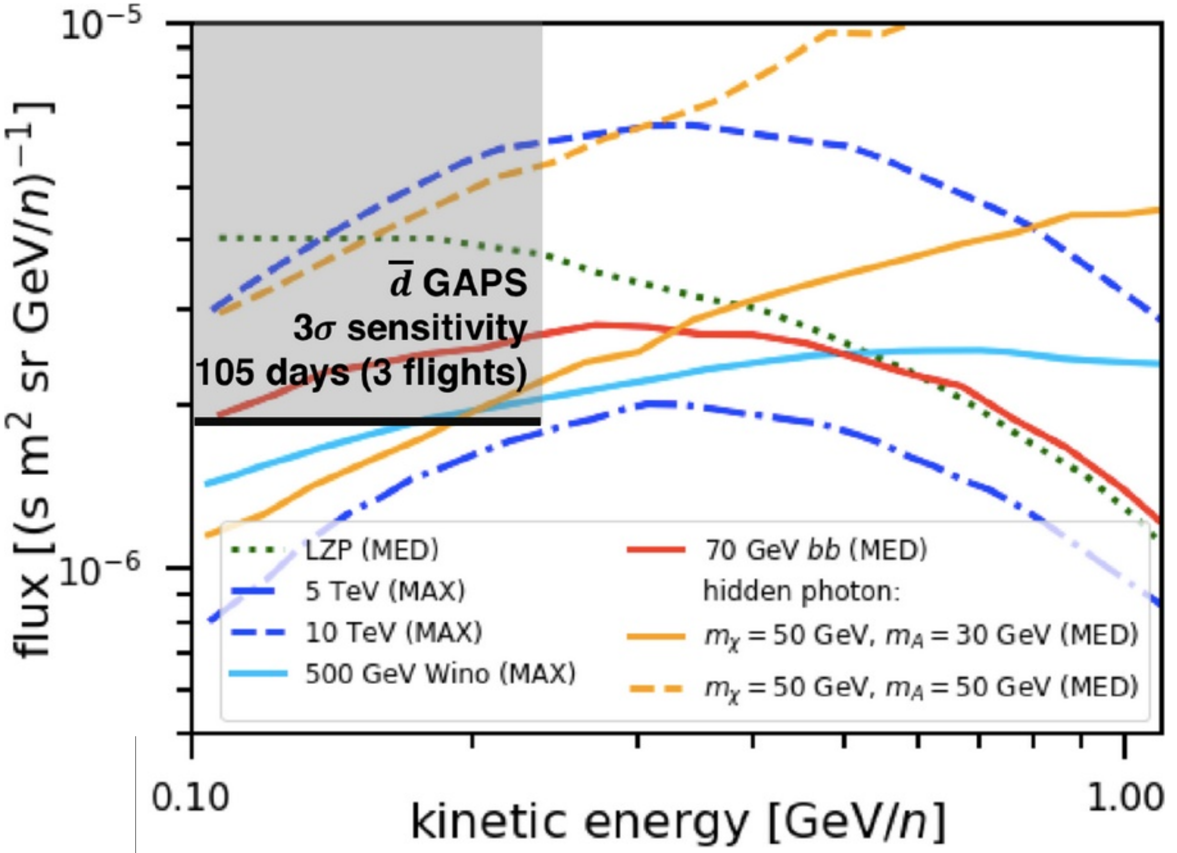


- Low-energy antideuterons from dark matter annihilation or decay can be orders of magnitude above the astrophysical background.
- Antideuterons are an important dark matter search technique that needs to be explored much more!

Antideuteron model sensitivity

T. Aramaki et al., Astropart. Phys. 74, 6 (2016)

- **Low-energy antideuterons are essentially free of astrophysics background**
- **Wide range of dark matter models**, e.g.:
  - Generic 70GeV WIMP annihilation model that explains antiproton excess and γ-rays from Galactic center
  - Dark matter gravitino decay
  - Extra dimensions
  - Heavy DM models with Sommerfeld enhancement
  - Dark photons (inaccessible to other techniques)
  - Selection of publications:
    Braeuninger et al. Physics Letters B 678, 20–31 (2009)
    Cui et al, JHEP 1011, 017 (2010)
    Hryczuk et al., JCAP 1407, 031 (2014).
    Korsmeier et al., Physical Review D 97, 103011 (2018)
    Randall & Xu, JHEP (2020)



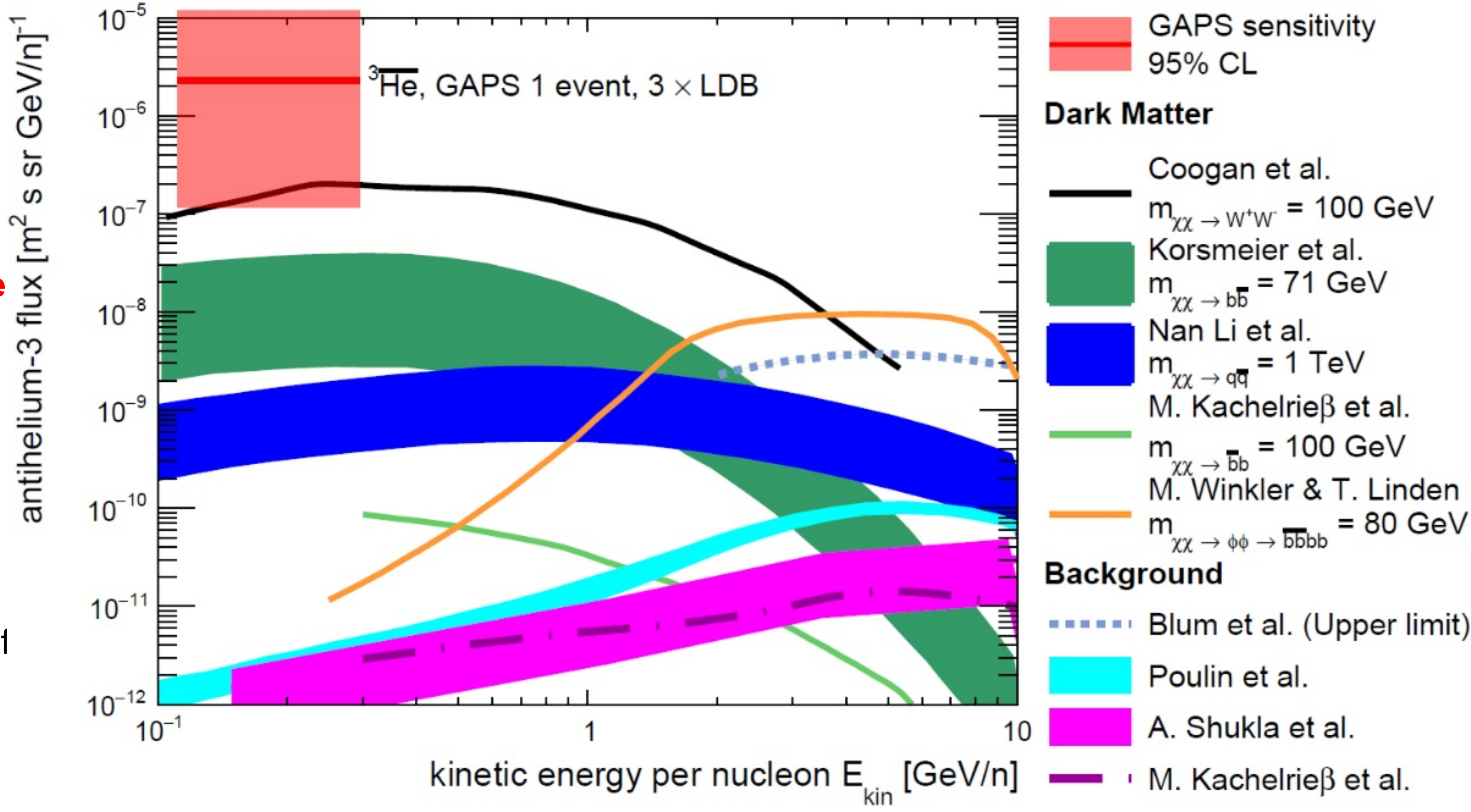
astrophysics background at ~10^{-7}–10^{-8}(s m^2 sr GeV/n)$^{-1}$

Cosmic-ray antihelium

- AMS-02 reported that **several He candidate events have been observed**
  → interpretations are actively ongoing

- **Possible antihelium candidate explanations include:**
  - Secondary astrophysical background
  - Dark matter annihilation or decay
  - Nearby antistar: at distance of ~1pc

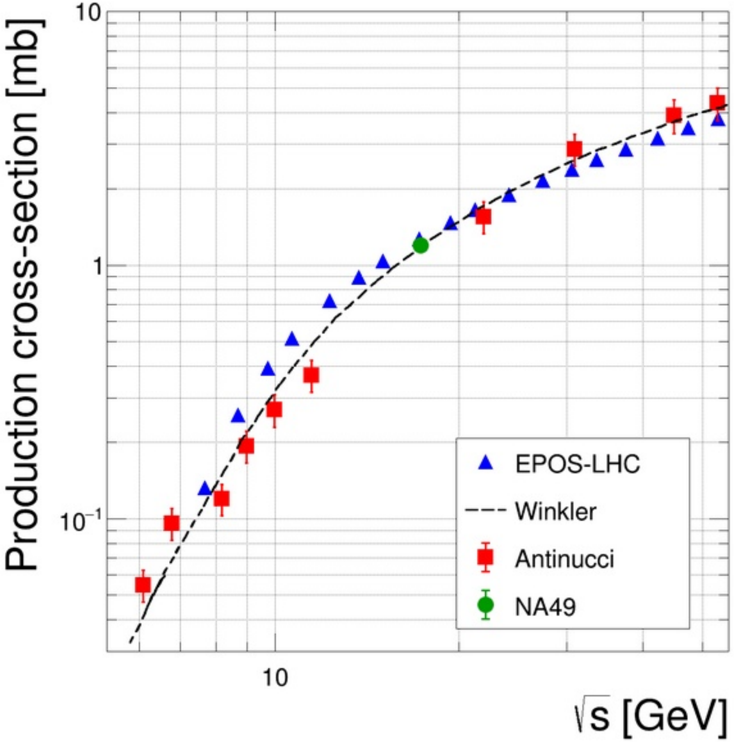
- **No explanation of antiproton nor antihelium should overproduce antideuterons relative to existing limits**



Review based on 2nd Cosmic-ray Antideuteron Workshop: JCAP08(2020)035, arXiv:2002.04163

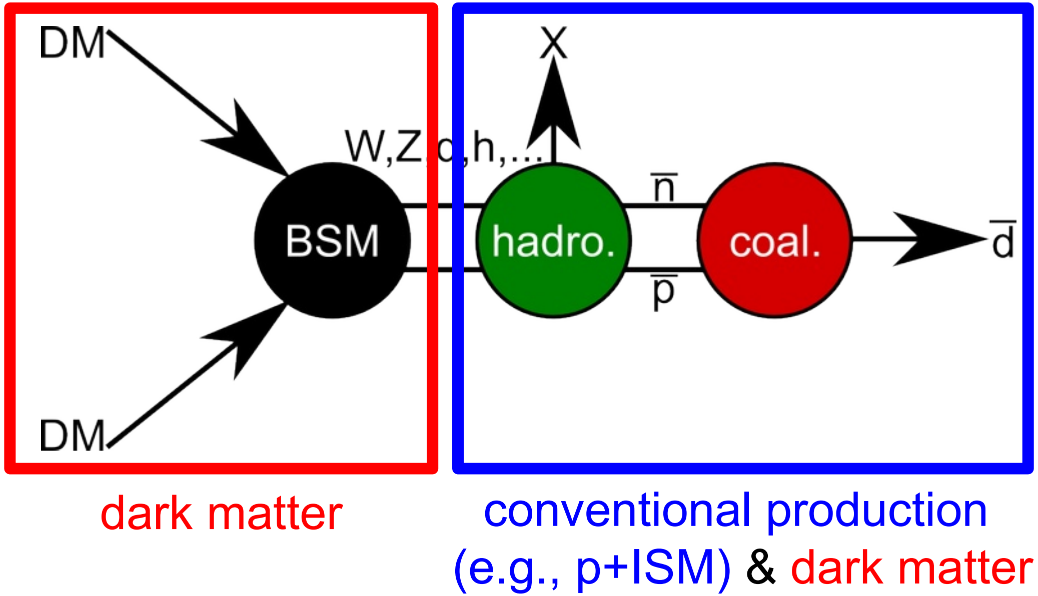
Uncertainties

- **Cosmic-ray propagation**:
  - Fits of cosmic-ray nuclei data are very important to constrain cosmic-ray propagation models (e.g., B/C, d/α, Li/C, Li/O, Be/C, Be/O, B/O) and models depend on production cross sections of primary cosmic rays with the interstellar medium
  - Inelastic interactions of antinuclei in the Galaxy
    → ALICE conducted cross section measurements
- **Antinuclei formation** process breaks the degeneracy between heavier antinuclei and antiprotons:
  - Antiproton production cross section not very well known
  - Coalescence: $\bar{d}$ can be formed by an $\bar{p}$-$\bar{n}$ pair if relative momentum is small compared to coalescence momentum p_0
  - Thermal model: Antinuclei directly formed at hadronization stage
  - Wigner-function based, semi-classical model has been developed



→ Measurements of relevant primary cosmic ray and interstellar medium cross sections are important

(Anti)nuclei coalescence



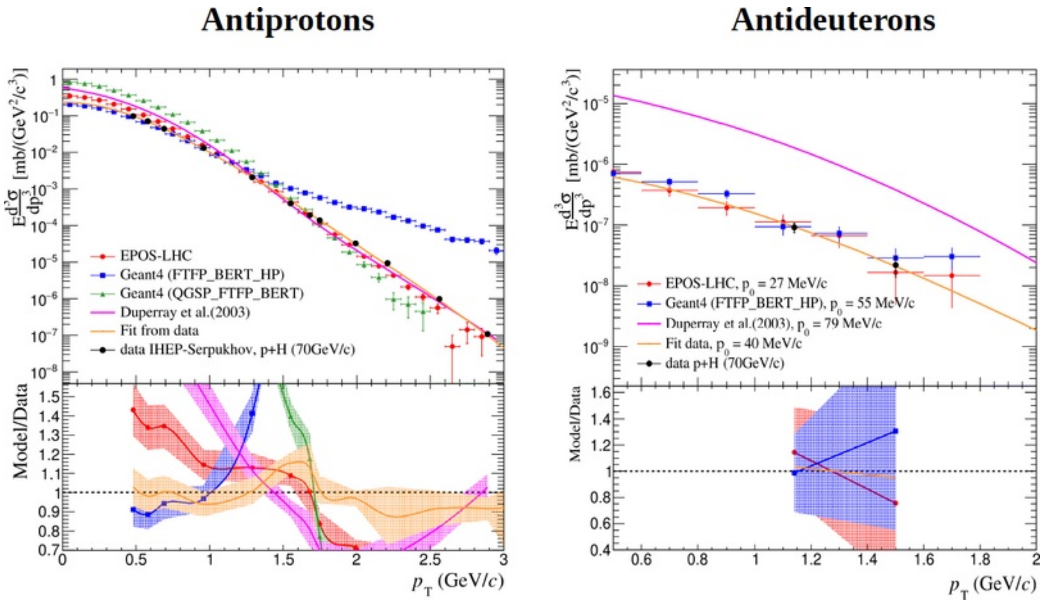
- (Anti)nuclei yield:

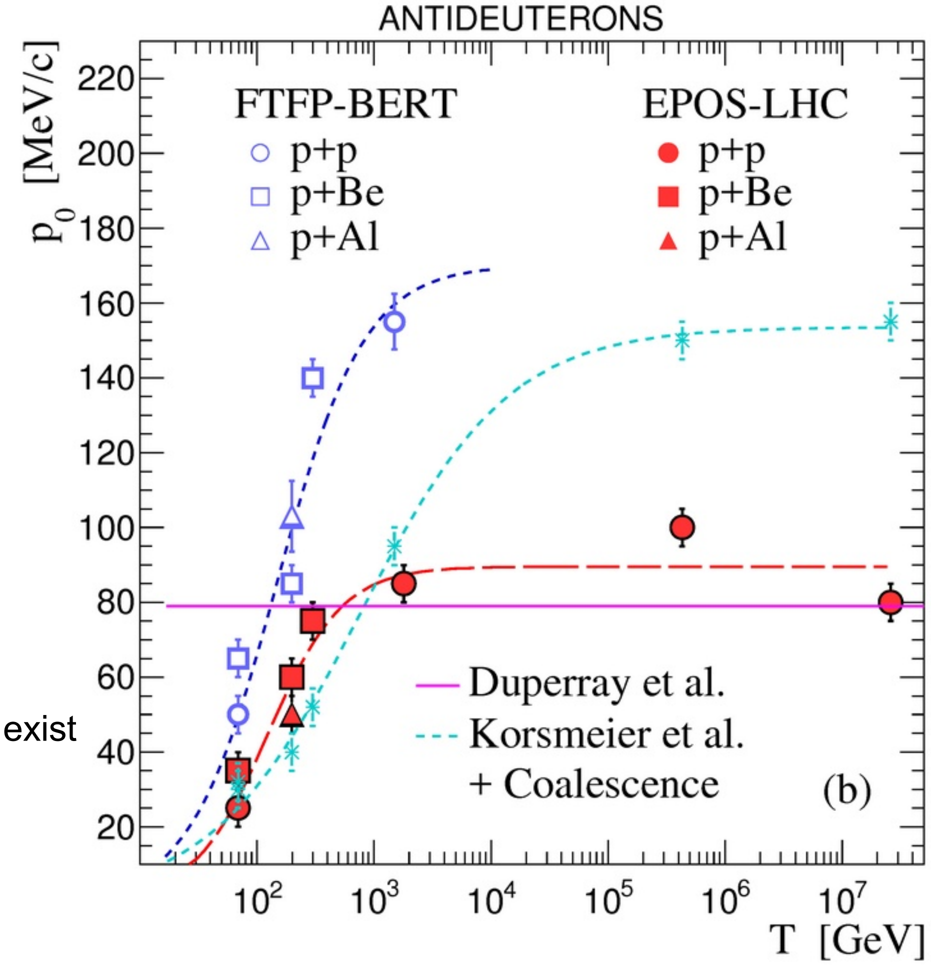
$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3} \right)^Z \left(E_n \frac{\mathrm{d}^3 N_n}{\mathrm{d}p_n^3} \right)^N \quad \text{with } B_A = A \left(\frac{4\pi}{3} \frac{p_0^3}{m_p} \right)^{A-1}$$

- use an event-by-event coalescence approach with hadronic generators

Coalescence modeling

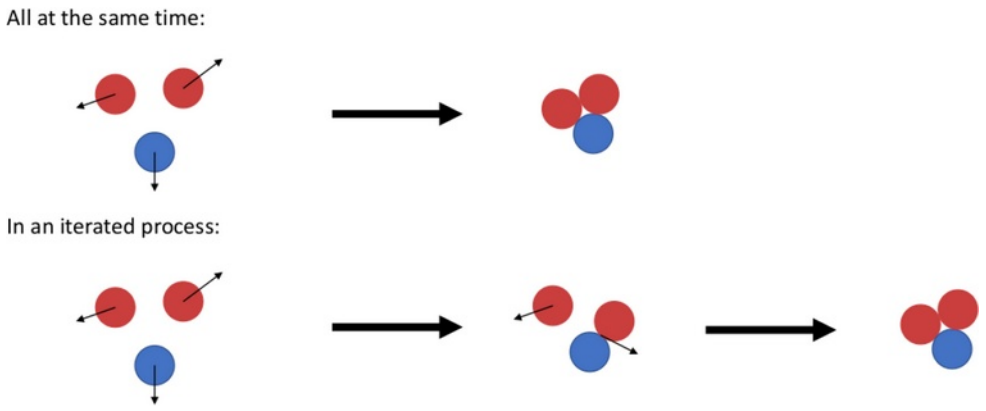
D. Gomez-Coral et al., Phys Rev D 98, 023012 (2018)





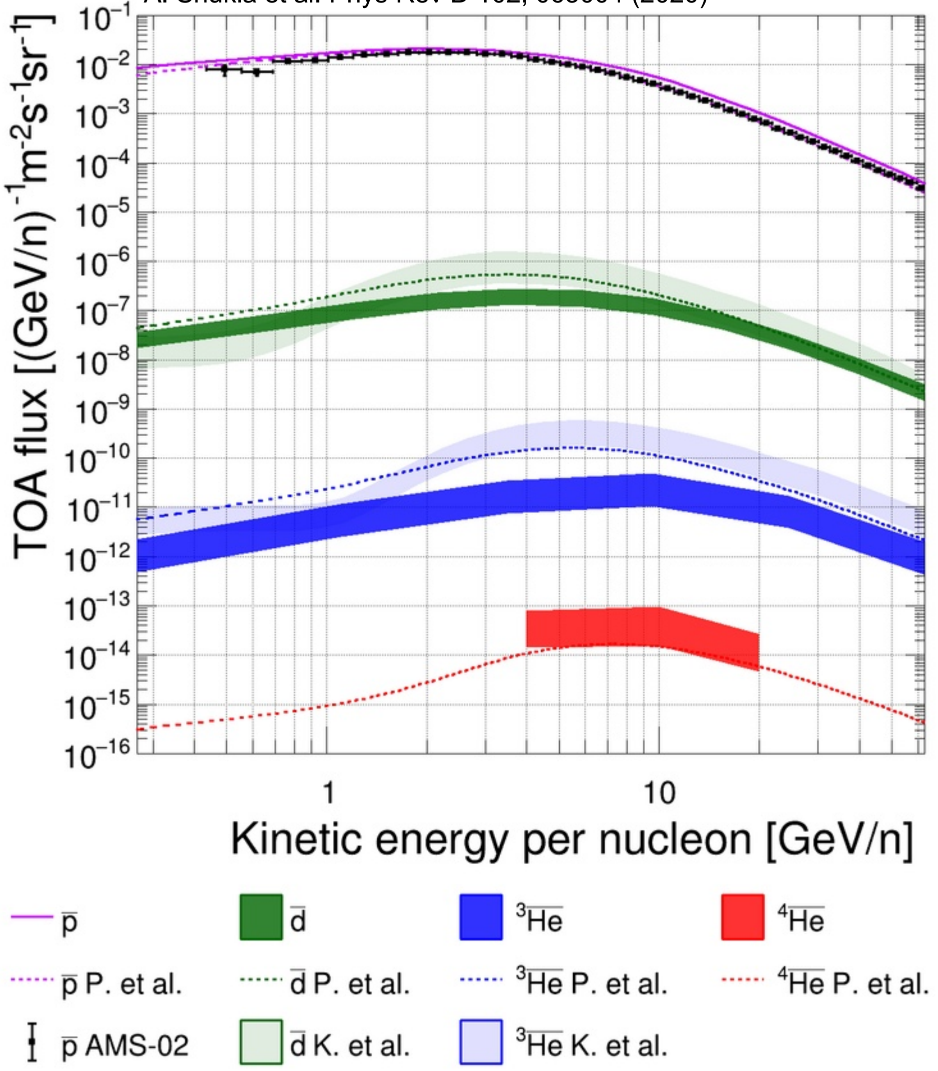
- Event-by-event approach with hadronic generators
- find p_0 for each data set where antiproton and antideuteron results exist
- p_0 show strong energy depedence in the range most important for cosmic rays
- **more high-statistics p-p data needed to constrain antinuclei formation models**

Antihelium coalescence



- expanded modified MC coalescence model to merging multiple antinucleons from p-p interactions
  → requires quite a bit of computing power (~**5,000 years**)
- use the p_0 behavior from antideuterons
- Very good agreement with ALICE antihelium-3 data (p-p at √s=7TeV)

A. Shukla et al. Phys Rev D 102, 063004 (2020)



Issues of the coalescence model

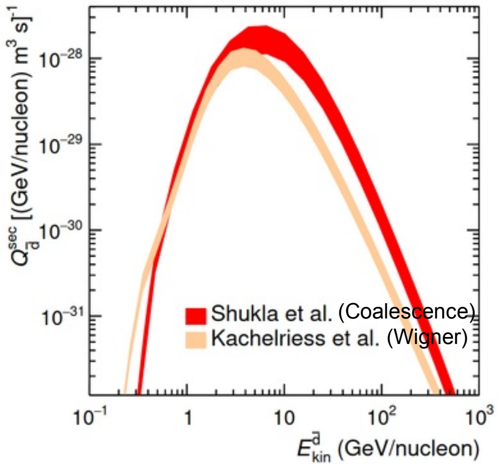
- **phase space** for ion production depends on the available energy in the formation interaction
- highly sensitive to **two-particle correlations** between the participating (anti)nucleons
- (anti)neutron spectra are challenging to access experimentally, potential asymmetries should be evaluated
- hadronic generators failing to describe (anti)proton and (anti)neutron spectra automatically result in a shift of p_0
- **spin** is not considered
- not a QM model
- generators not really tuned for antiparticle production
  → use dedicated antiproton, deuteron, and antideuteron data

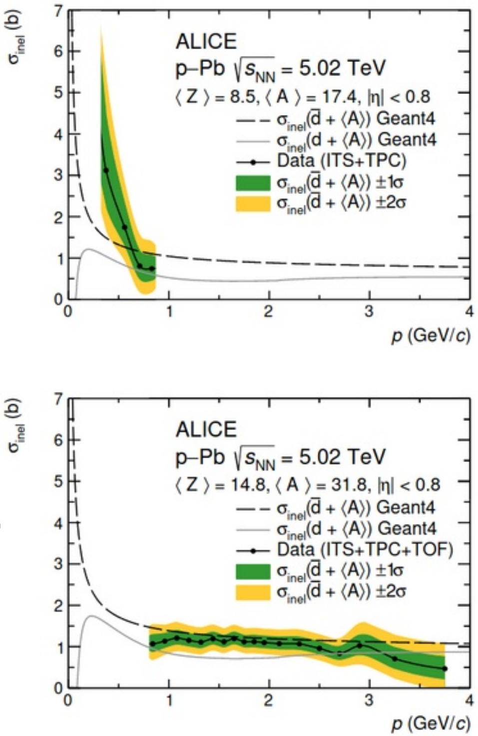
From production to flux at Earth

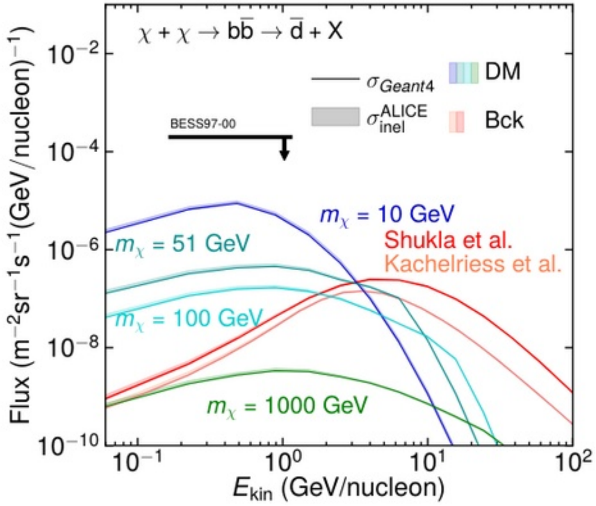
Šerkšnytė et al., Phys. Rev. D 105, 083021 (2022)

Propagation equation:

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







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

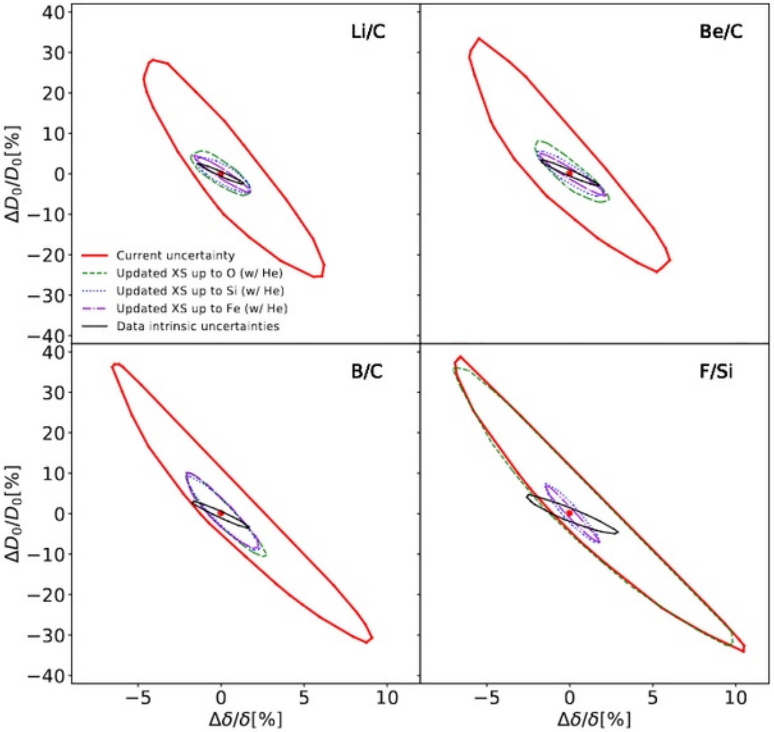
Propagation uncertainties

- 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

Génolini et al., arXiv:2307.06798

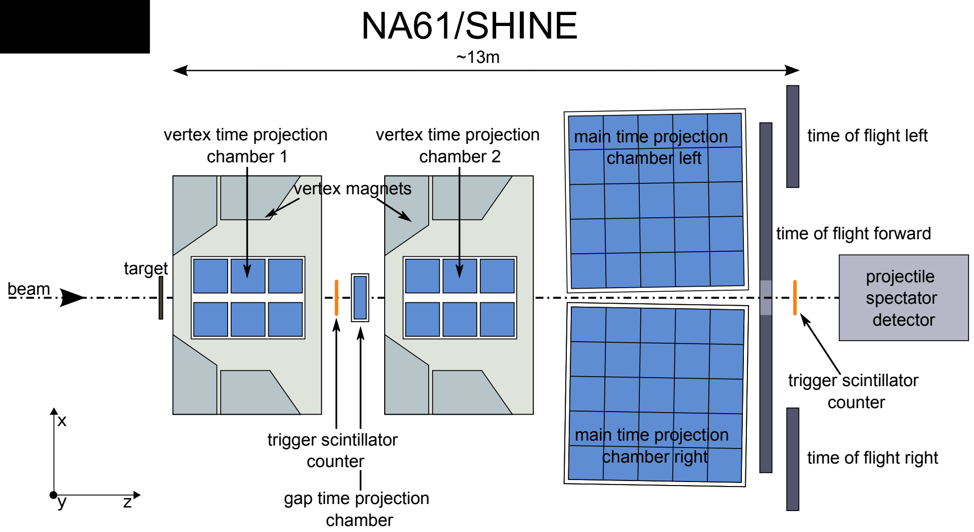


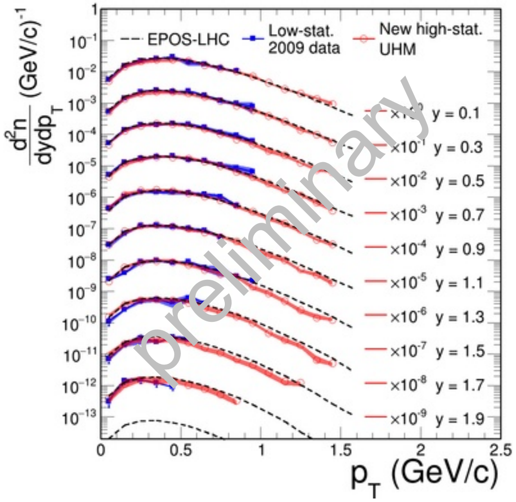
Proposed number of interactions

reaction	N_{int}
^{16}O+H	60k
^{12}C+H	50k
^{16}O+He	20k
^{11}B+H	10k
^{15}N+H	10k
^{14}N+H	10k
^{12}C+He	10k
^{10}B+H	5k
^{13}C+H	5k
^{7}Li+H	5k
	$N(\leq \mathrm{O}) = 1.9 \times 10^5$
^{28}Si+H	50k
^{24}Mg+H	50k
^{20}Ne+H	50k
^{22}Ne+H	20k
^{28}Si+He	10k
^{27}Al+H	10k
^{26}Mg+H	10k
^{24}Mg+He	10k
^{23}Na+H	10k
^{25}Mg+H	10k
^{21}Ne+H	10k
^{20}Ne+He	10k
^{32}S+H	5k
^{29}Si+H	5k
^{22}Ne+He	5k
	$N(\leq \mathrm{Si}) = 3.8 \times 10^5$
^{56}Fe+H	30k
^{56}Fe+He	10k
	$N(\leq \mathrm{Fe}) = 4.2 \times 10^5$

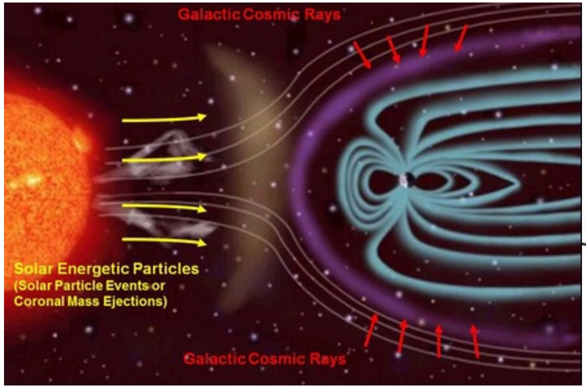
Future measurements

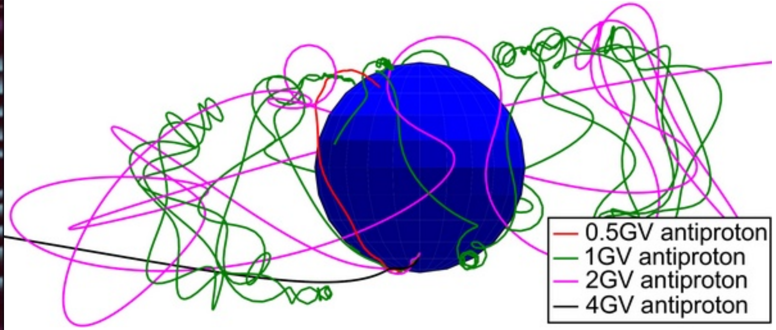
- NA61/SHINE at CERN SPS:
    - Fixed target experiment
    - High statistics $\bar{p}$ studies
    - C-p fragmentation cross section measurements
    - Deuteron production cross section, d/p ratio
    - Antiparticle correlation studies
- LHCb at LHC:
    - Antideuteron production in heavy hadron decays 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

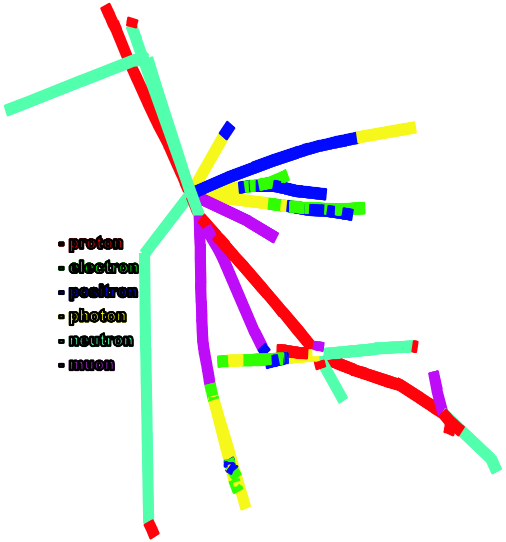




Last bit of the way for cosmic rays







- Solar energetic particles interact with Galactic cosmic rays and modify the cosmic flux

- Charged low-energy particles can be strongly deflected by the magnetosphere
- reverse computation of cosmic-ray trajectories to investigate which particles can make it through to the detector

- Interactions of cosmic rays with the atmosphere alter the detectable flux
- grammage of matter in front of 37km: ~6g/cm^2 (typical balloon altitude, cosmic ray traverse about 6-10g/cm^2 in the Galaxy)

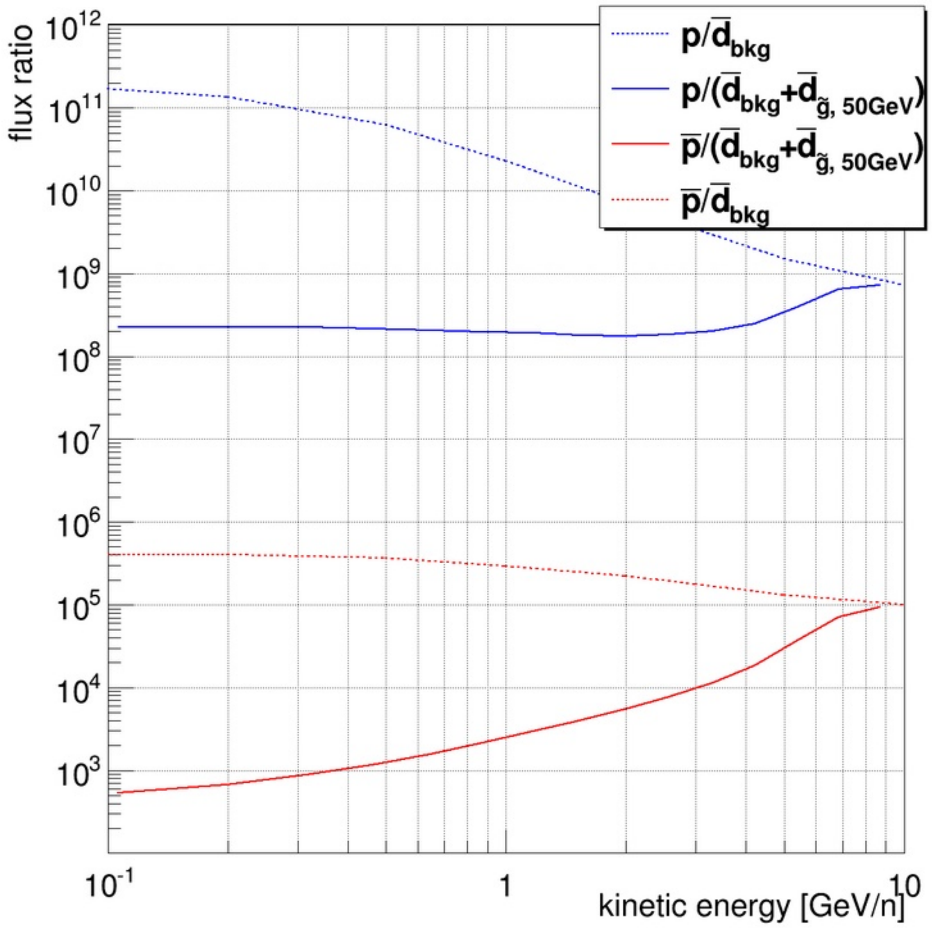
Identification challenge

Required rejections for antideuteron detection:

- **protons**: > 10^8 - 10^{10}
- **He-4**: > 10^7 - 10^9
- **electrons**: > 10^6 - 10^8
- **positrons**: > 10^5 - 10^7
- **antiprotons**: > 10^4 - 10^6

Antideuteron measurement with balloon and space experiments require:

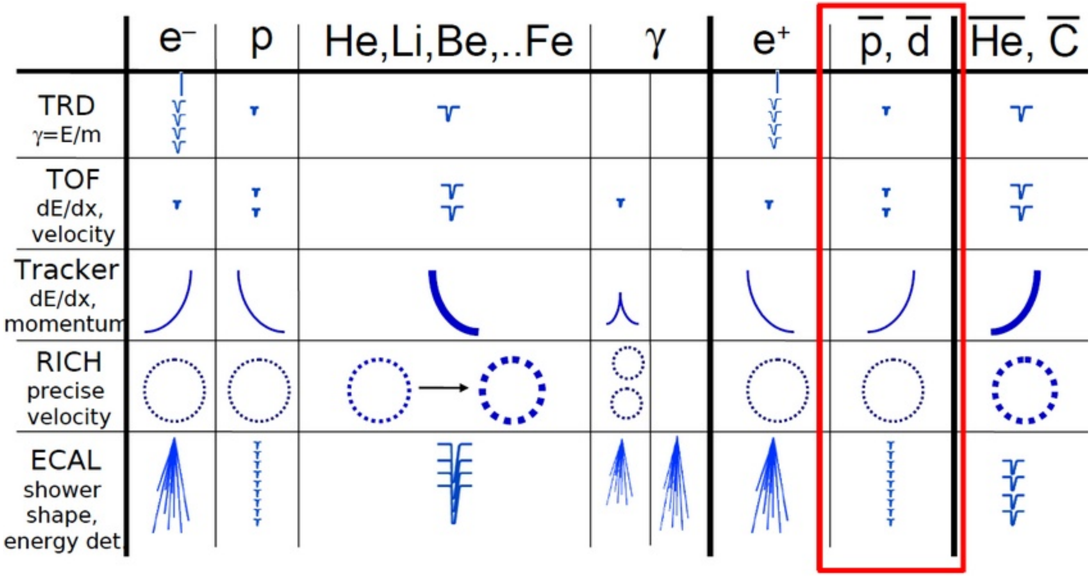
- **strong background suppression**
- **long flight time and large acceptance**

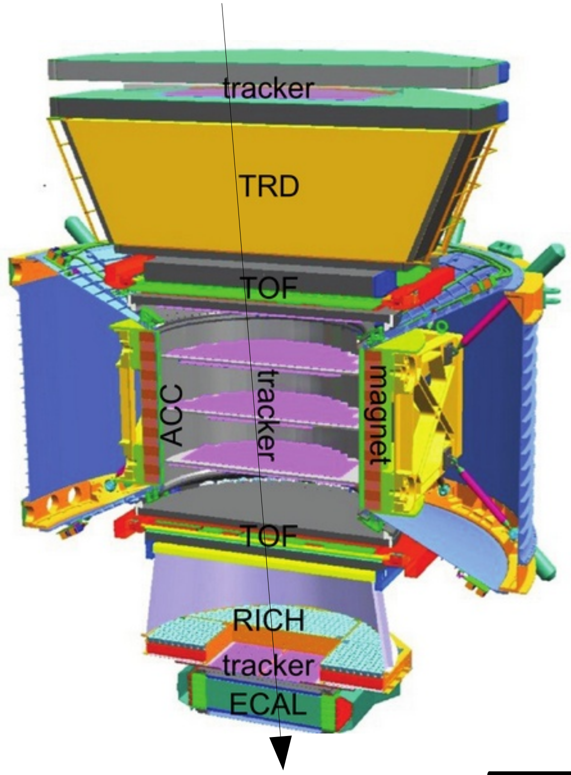


AMS-02 on the International Space Station

- AMS is a multi-purpose particle physics detector installed on the International Space Station
- large international collaboration (~600 people from 60 countries involved)
- AMS collected more than100 billion of events since May 2011

AMS-02 antinuclei analyses

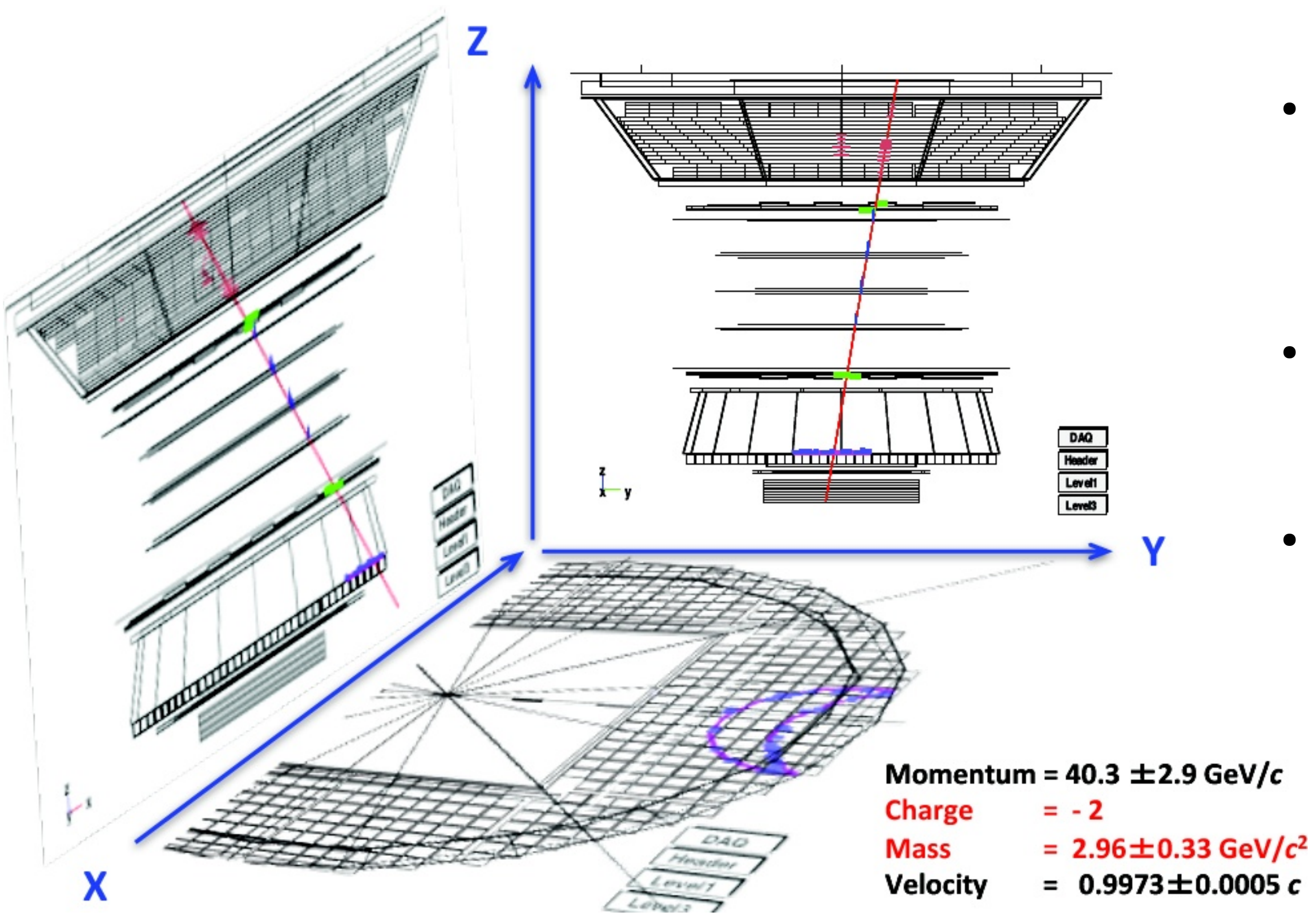




- **antinuclei identification:**
  - momentum measured in the form of rigidity
  - charge from TOF, TRD, tracker
  - lower velocities: **T**ime **O**f **F**light scintillator system
  - higher velocities: **R**ing **I**mage **Ch**erenkov detector

$$m = R \cdot Z \sqrt{\frac{1}{\beta^2} - 1}$$

Antihelium candidates by AMS-02



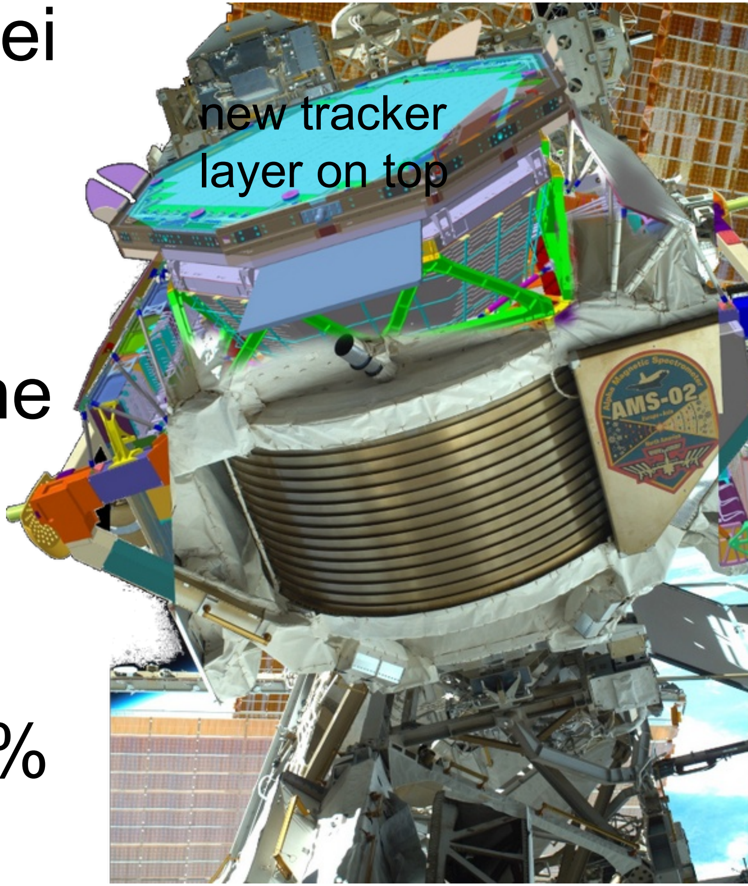
- antihelium-3 and antihelium-4 candidates have been identified **→ would be a very transformative finding**
- massive background simulations are carried out to evaluate significance
- more data are needed

AMS-02 status and outlook

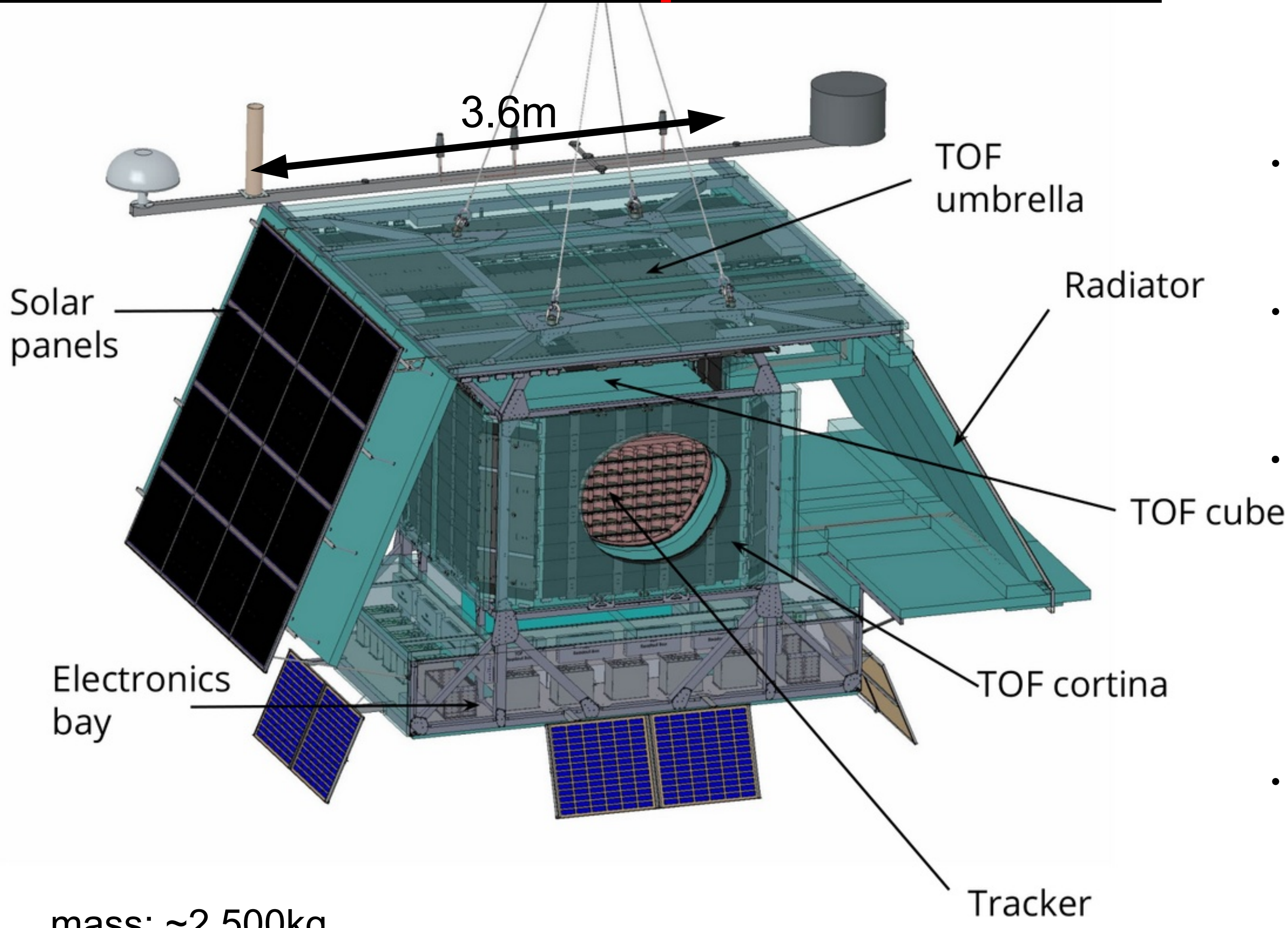
- A few antideuteron and antihelium nuclei candidates have been observed by AMS-02

- AMS-02 will continue to take data for the ISS lifetime

- AMS-02 tracker upgrade:
  - Increase detector acceptance by 300%
  - Ready to deliver to NASA in 2025



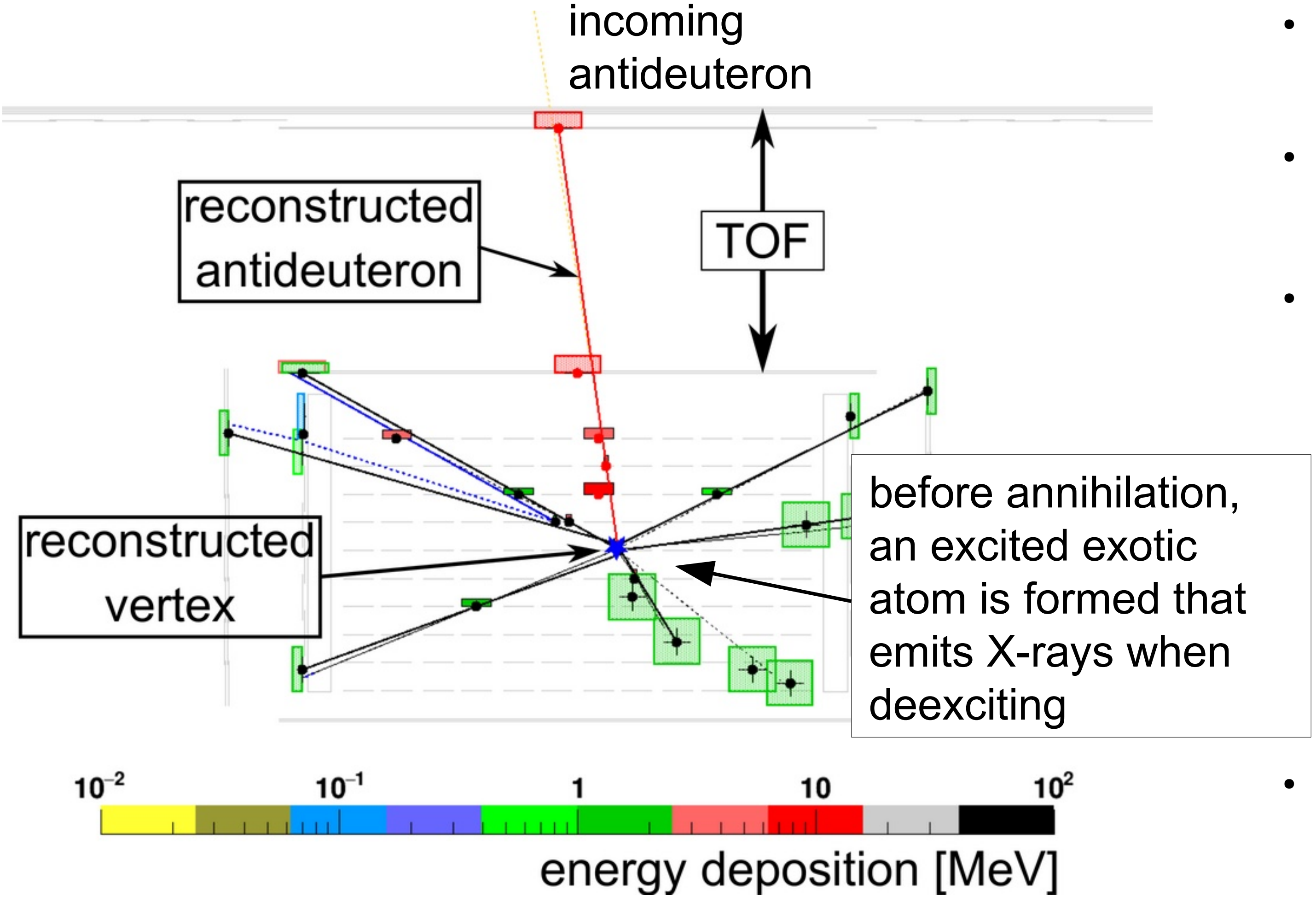
The GAPS experiment



mass: ~2,500kg
power: 1.3kW

- The **G**eneral **A**nti**P**article **S**pectrometer is the first experiment dedicated and optimized for low-energy cosmic-ray antinuclei search
- Requirements: long flight time, large acceptance, large identification power, flight at low-geomagnetic cutoff location
- **GAPS 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
- **GAPS is under construction, preparing for first Antarctic Long Duration Balloon flight in December 2024**

GAPS principle



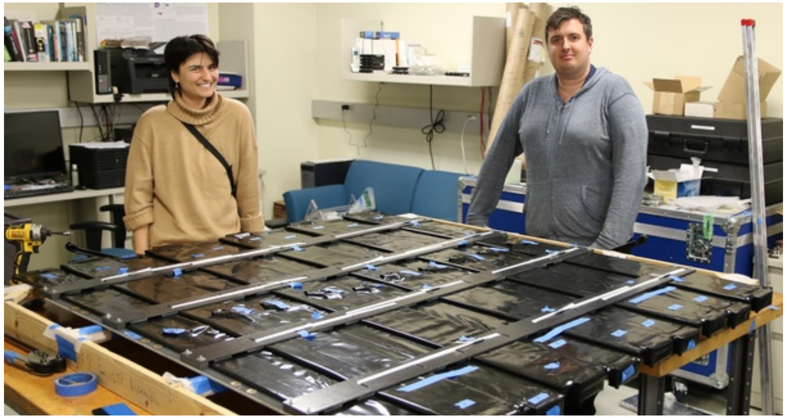
- antiparticle slows down and stops in material
- near-unity chance for creation of an excited exotic atom (E_{kin}~E_{I})
- deexcitation:
  fast ionization of bound electrons (Auger)
  → complete depletion of bound electrons
  Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic X-ray transitions depending on antiparticle mass
- Nuclear annihilation with characteristic number of annihilation products

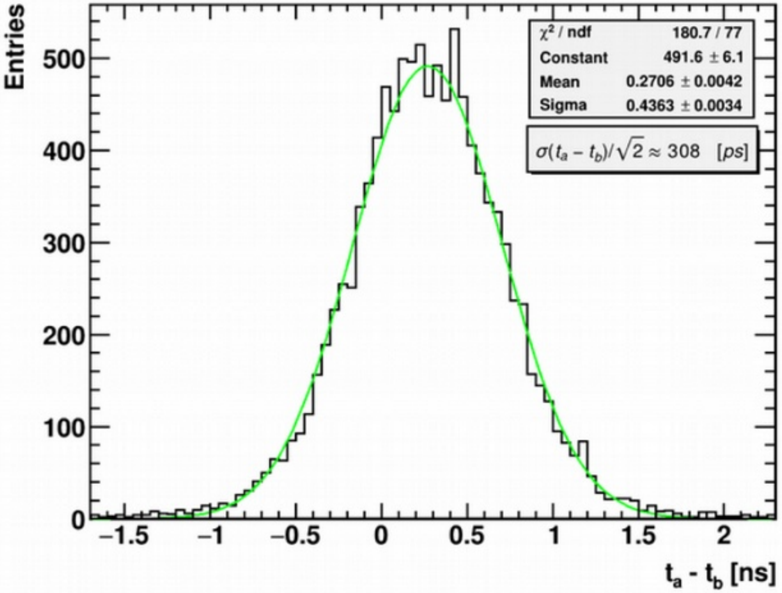
Time-of-Flight

- Tasks:
  - Main trigger system, special antinuclei trigger achieves a manageable rate of ~500 Hz (down from 200 kHz individual TOF paddle rate)
  - Tracking of incoming (anti)particles and outgoing secondary particles
  - Particle velocity measurement

- Plastic scintillator (Eljen EJ-200: 160-180cm long, 0.6 cm thick) with 6 SiPMs per end (Hamamatsu S13360-6050VE)

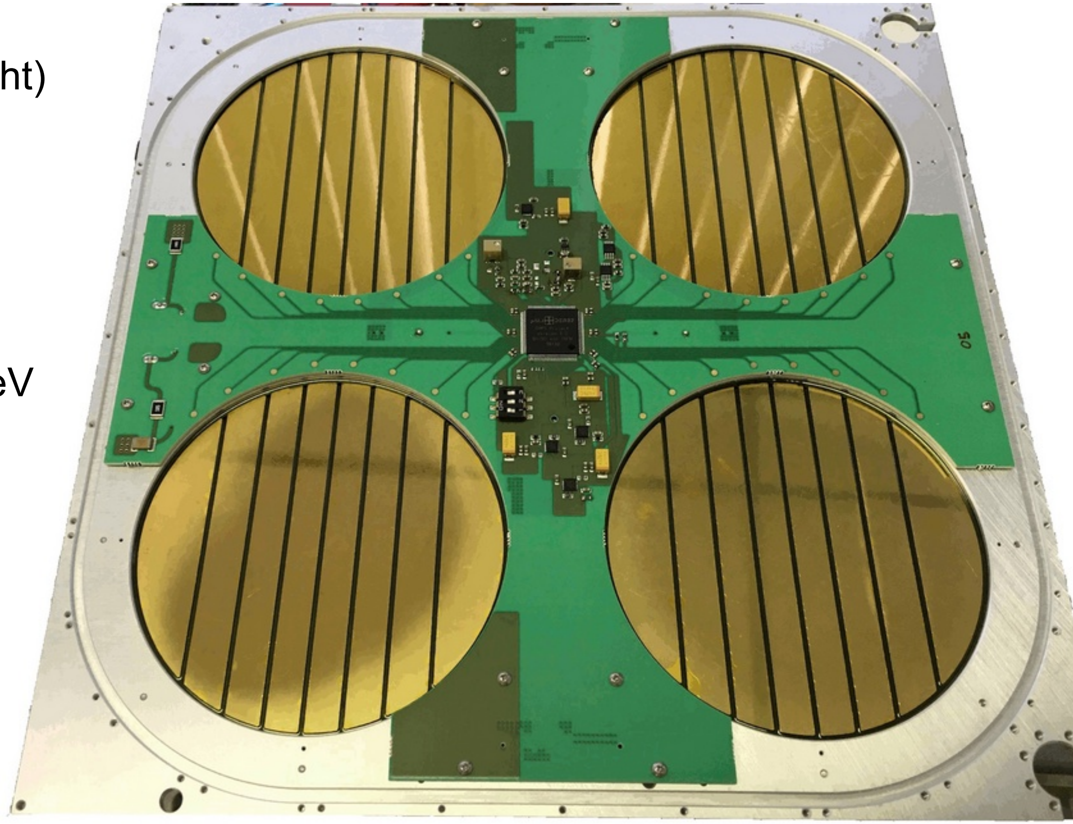
- fast sampling with custom-made readout board, based on the DRS-4 ASIC: <400ps timing resolution achieved in test paddles (end-to-end time difference) and in GAPS functional prototype (GFP).



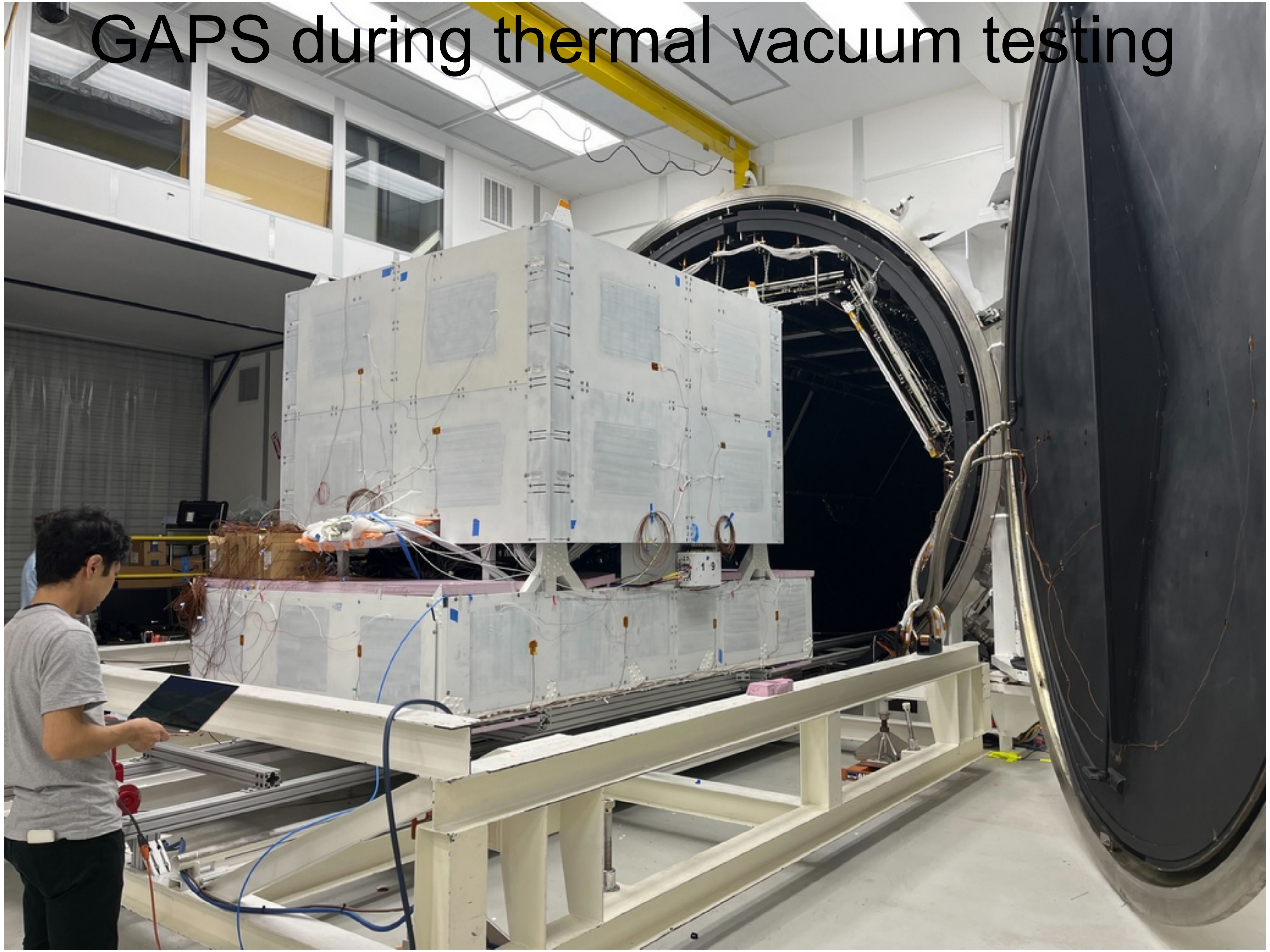


Tracker

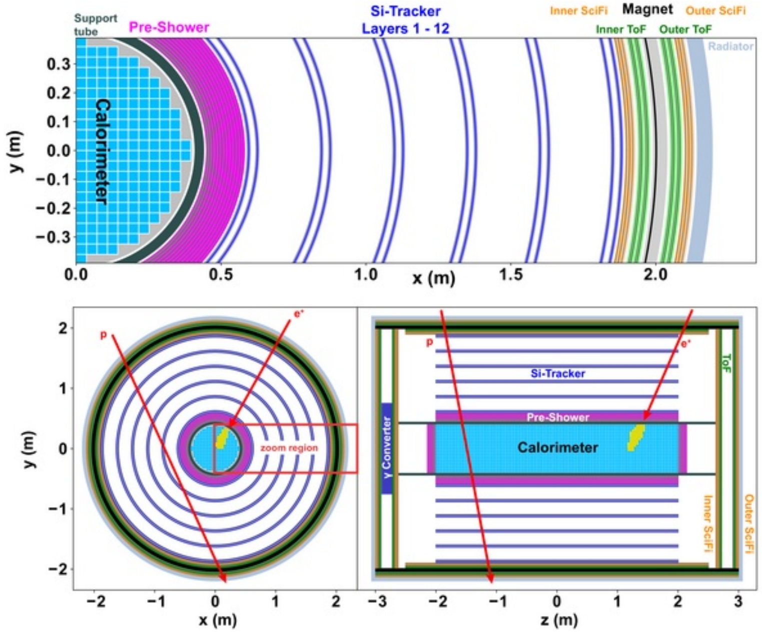
- Tracker acts as target and tracking device
- GAPS can accommodate 1,440 4” Si(Li) detectors, 2.5mm thickness (1109 detectors calibrated for first flight)
- Operation at temperature of –35C to –45C, cooling system will use novel OHP approach
- Readout via custom ASIC: integrated low-noise preamplifier with large dynamic range: 10keV to 100MeV
- Publications:
  - Perez et al., NIM A 905, 12 (2018)
  - Kozai et al., NIM A 947, 162695 (2019)
  - Rogers et al., JINST 14, P10009 (2019)
  - Saffold et al., NIM A 997, 165015 (2021)
  - Manghisoni et al., IEEE 68 (11), 2661 (2021)
  - Kozai et al., NIM A 1034, 166820 (2022)
  - Xiao et al., in preparation (2023)
  - Roach et al., in preparation (2023)

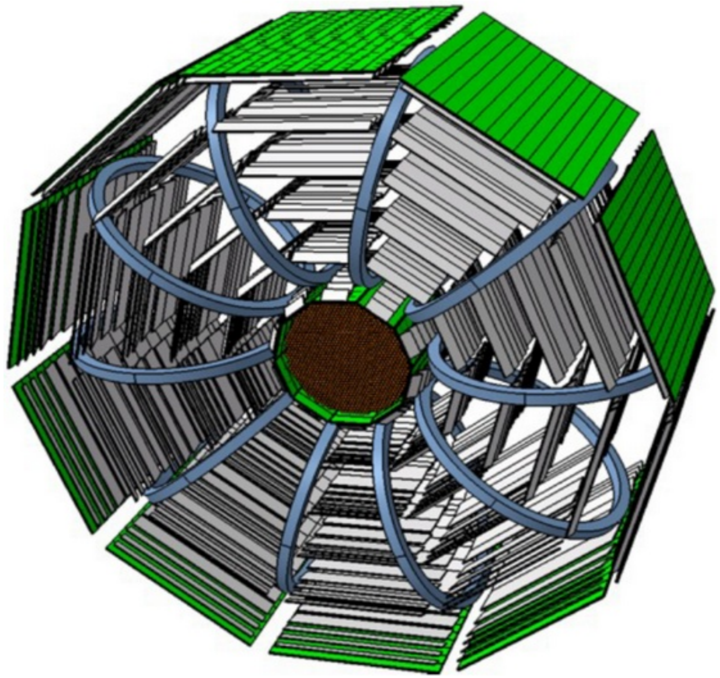


GAPS Vacuum Testing



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 ($Z\leq-2$).
- NIM A 944 162561 (2019)

- 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

Conclusion & Outlook

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

- All antinuclei species need to be explained together

- Uncertainties need to be reduced:
  - Antideuteron and antihelium formation are not well understood
  - Cross section measurements need to be conducted on for the interpretation

- AMS-02 continues collecting data

- GAPS will have first flight in two years

Next step: coalescence improvements

- Following the ALICE approach, studiyng two-nucleon correlations in p-p data allows for extracting the size of the formation region $R(p_T)$:

$$\mathcal{C}(k) = \mathcal{N}\frac{N_{\mathrm{same}}(k)}{N_{\mathrm{mixed}}(k)} = \int \mathrm{d}^3 r S(r) |\Psi(r,k)|^2$$

- **Data-driven** quantum-mechanical description of coalescence:

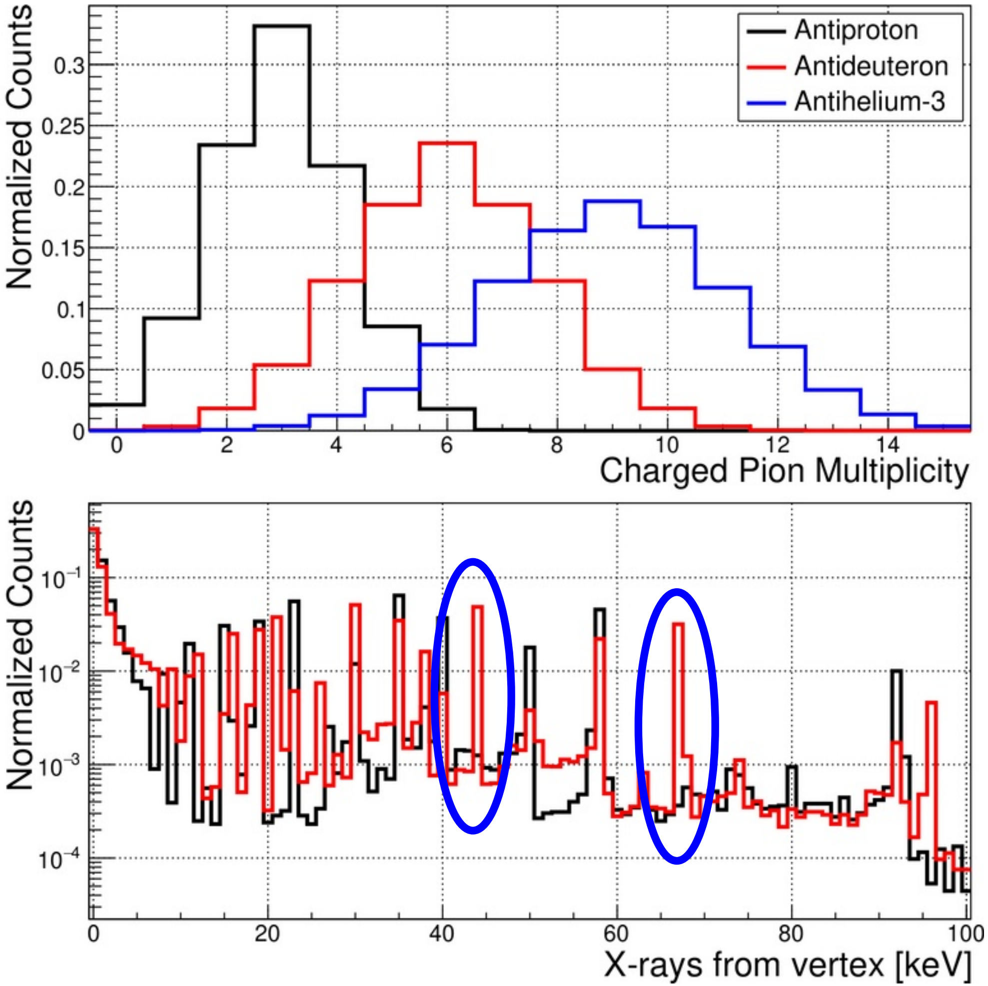
$$B_2(p_T) \approx \frac{3}{2m} \int \mathrm{d}^3 q D(q) \exp\left(-R(p_T)^2 q^2\right) \text{ with } D(q) = \int \mathrm{d}^3 r |\varphi_d(r)|^2 \exp(-iqr)$$

S: emission source function, ψ 2-(anti)nucleon wave function,
φ internal (anti)deuteron wave function

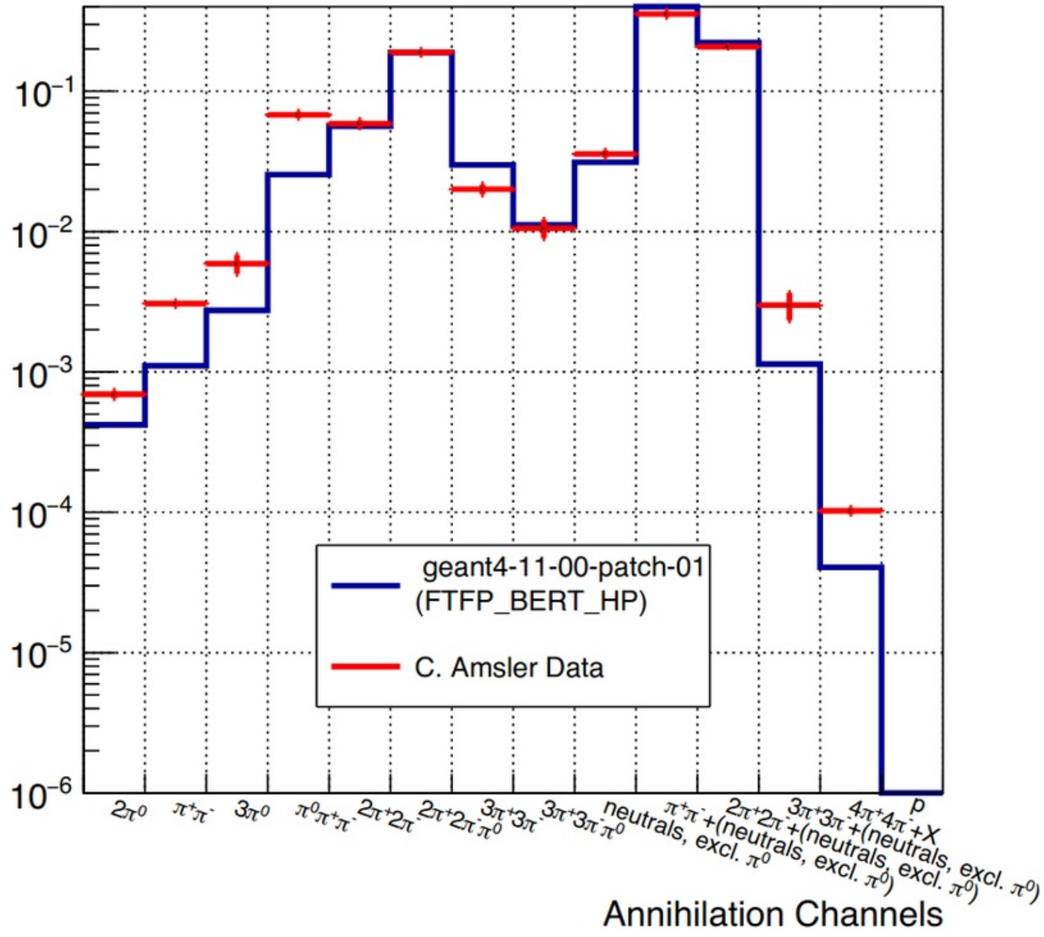
GAPS identification technique

GAPS identification technique uses:

- Energy loss in the detector of the antinucleus (depends on Z and β)
- Deexcitation X-rays from exotic atom
- Multiplicity of charged annihilation products



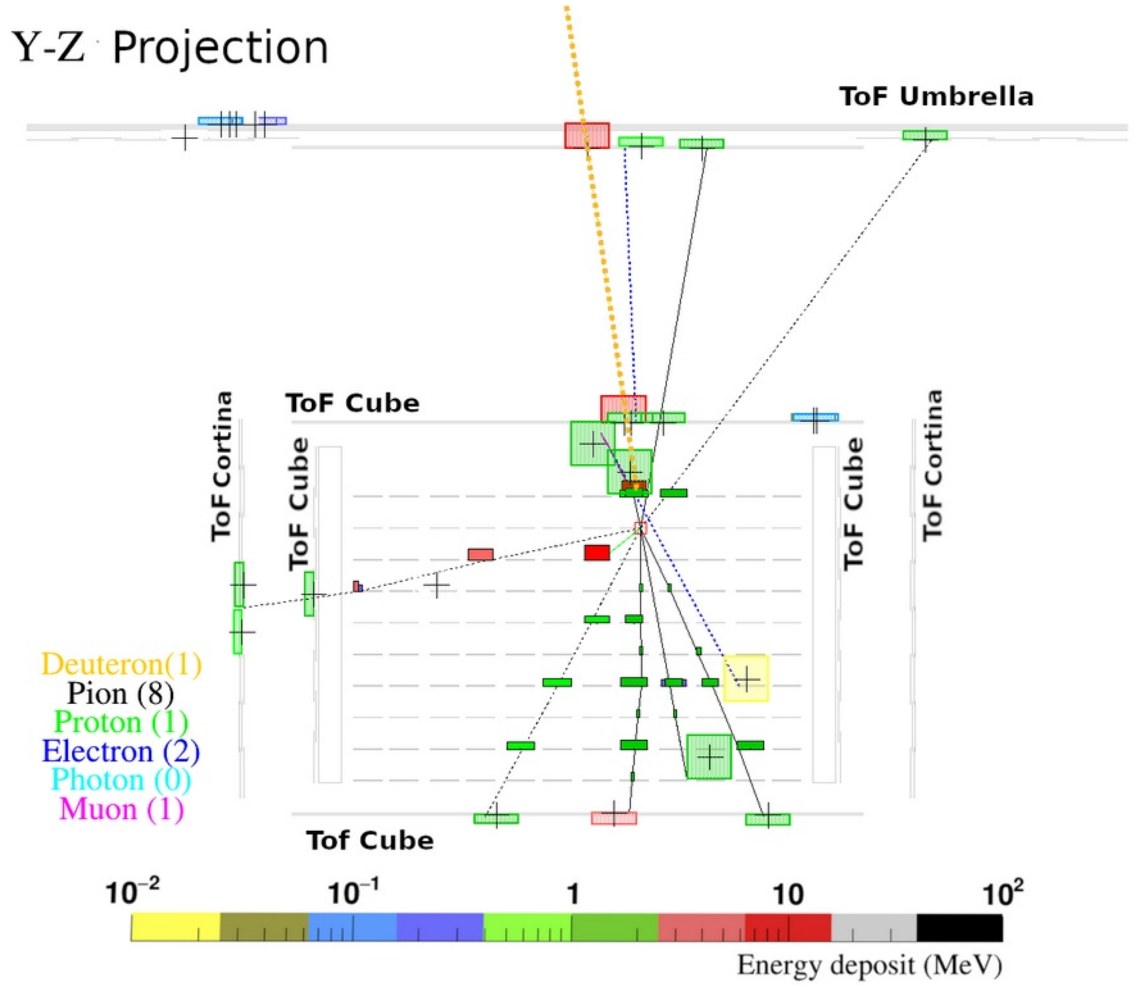
$\bar{p}$+p annihilation at rest



- test of annihilation physics in Geant4 is ongoing
- use antiproton data for validation
- work with Geant4 developers

Event reconstruction

R. Munini et al., Astropart. Phys. 133, 102640 (2021)



- For the event reconstruction it is critical to identify a well defined primary track $\rightarrow \beta$ measurement, energy deposition, column density
- The primary track is used as a seed for the determination of the stopping vertex with the corresponding secondary tracks