In Search of Cosmic-Ray Anti-nuclei from Dark Matter with the GAPS Experiment

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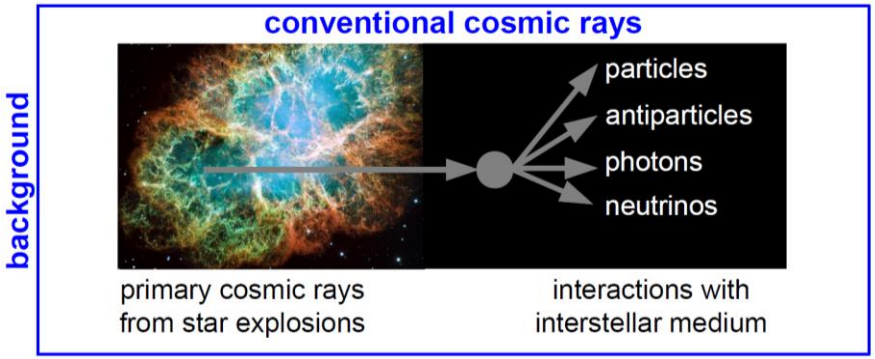
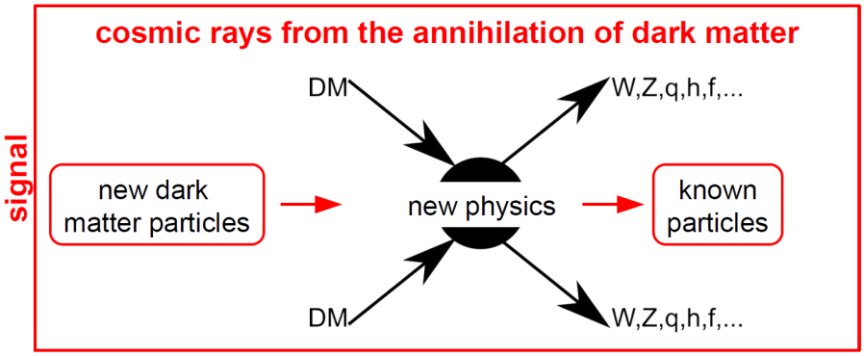
(On behalf of the GAPS Collaboration)

Photo from 33 km up in the air! Prototype GAPS (pGAPS) balloon flight from Taiki, Japan in June 2012

Cosmic Rays as DM Messengers

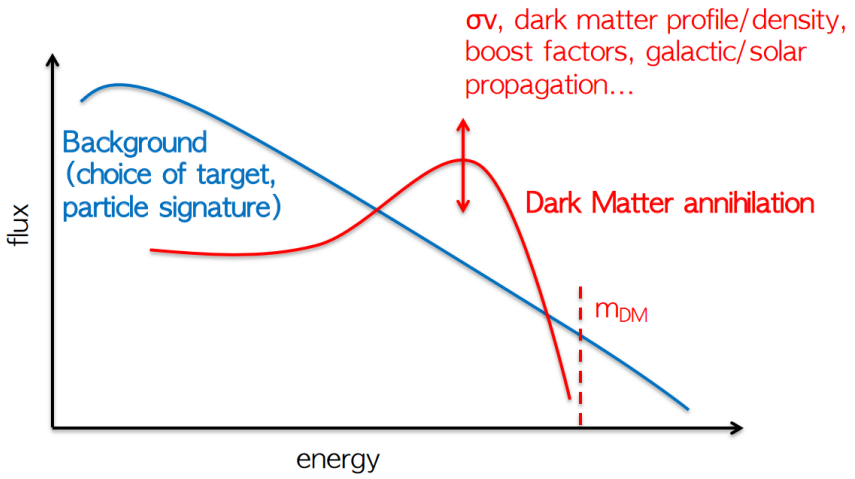
- ***Assumption:*** cosmic rays from dark matter annihilation/decay follow different kinematics than conventional production.





- ***Typical astroparticle DM searches:*** DM signal: peak/bump/shoulder on top of conventional spectrum.

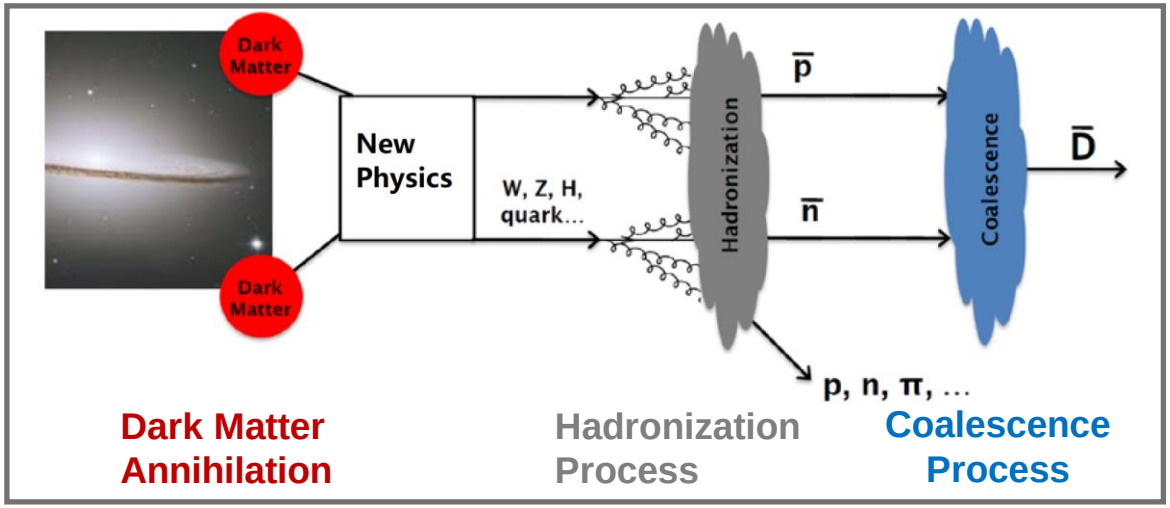
- ***Antideuteron/antihelium DM searches:*** DM signal is orders of magnitude above background, essentially background-free.



➢ *Any detection of cosmic-ray antideuteron/antihelium is new physics!*

Low-energy Cosmic ***antideuterons***

- **Primary flux**: DM annihilation/decay



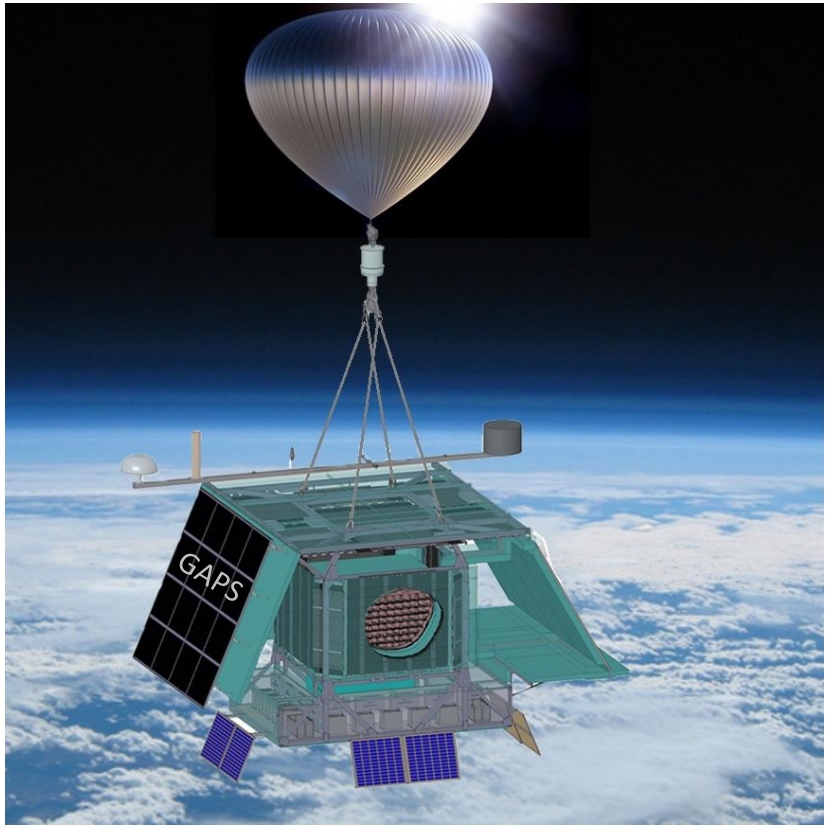
- **Secondary/tertiary**: Cosmic-ray (CR) interactions with interstellar medium (ISM)
  - Much lower (> 2 orders of magnitude) than the primary due to collision kinematics and steeply falling primary proton spectrum

$$p\ (CR) + H\ (ISM) \rightarrow p + H + p + n + \bar{p} + \bar{n}\ \bar{d}$$

✓ ***GAPS experiment is optimized for low-energy cosmic antideuteron searches***
  - *Observation of one antideuteron event is sufficient to claim a discovery → new physics!*

The GAPS Experiment

- **GAPS=G**eneral **A**nti**p**article **S**pectrometer
  - Balloon-borne experiment
  - Instrument size: ~3.6 m × 3.6 m × 3.6 m
  - Flight from Antarctica
- Uniquely characterized atomic X-rays and charged particles from the decay of exotic atoms to identify cosmic anti-nuclei.
- Primary goal: search for low-energy (kinetic energy <**0.25 GeV/n**) ***Antideuteron*** *as signature of new physics*.
  - Can probe various dark matter models.



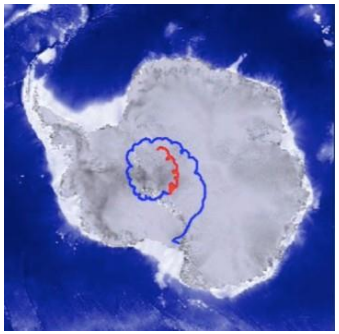
*Balloon photo from Word View

- High statistics measurement of low-energy ***Antiproton*** and leading sensitivity to ***Antihelium.***

➢ The first of a series of flights is planned for **late 2022.**

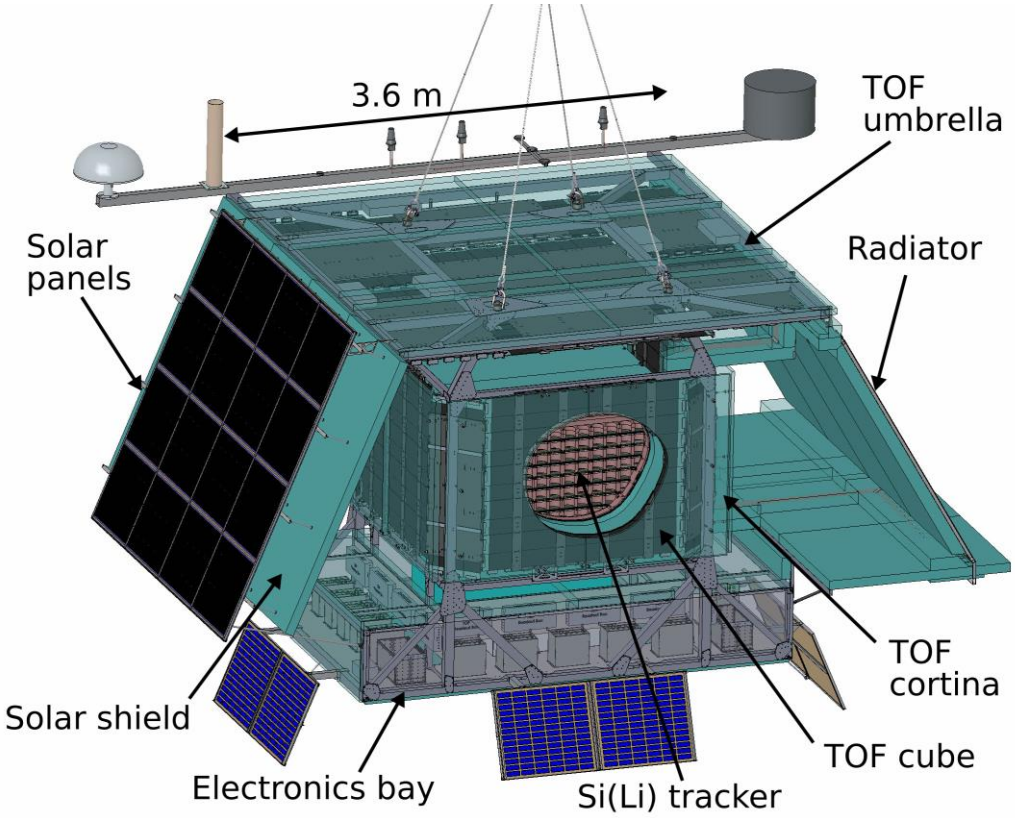
GAPS Detector Design

- **Time of Flight (TOF)**
  - Velocity measurement
  - High-speed trigger and veto
  - dE/dx measurement
- **Si(Li) Tracker**
  - Stopping depth, dE/dx
  - Charge particle multiplicity
  - X-ray identification
  - Vertex reconstruction
- **Thermal system: oscillating heat pipe (OHP)**
  - Cools Si(Li) detectors to ~ -40 ℃



*Photos from NASA.ORG

See S. Quinn's talk (No.101811) in CRD session



Total mass: ~2500 kg, Power: 1.3 kW

- Service for series of Antarctica long-duration balloon (~35 days each LDB) flights.

GAPS Detection Principle

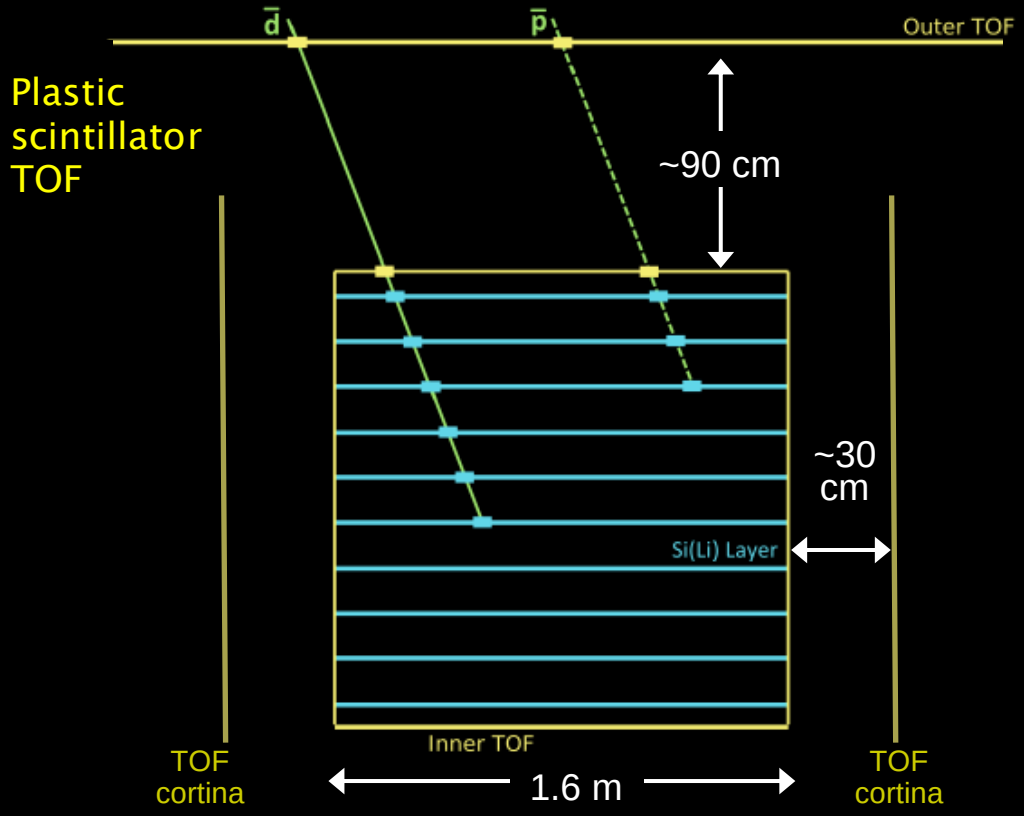
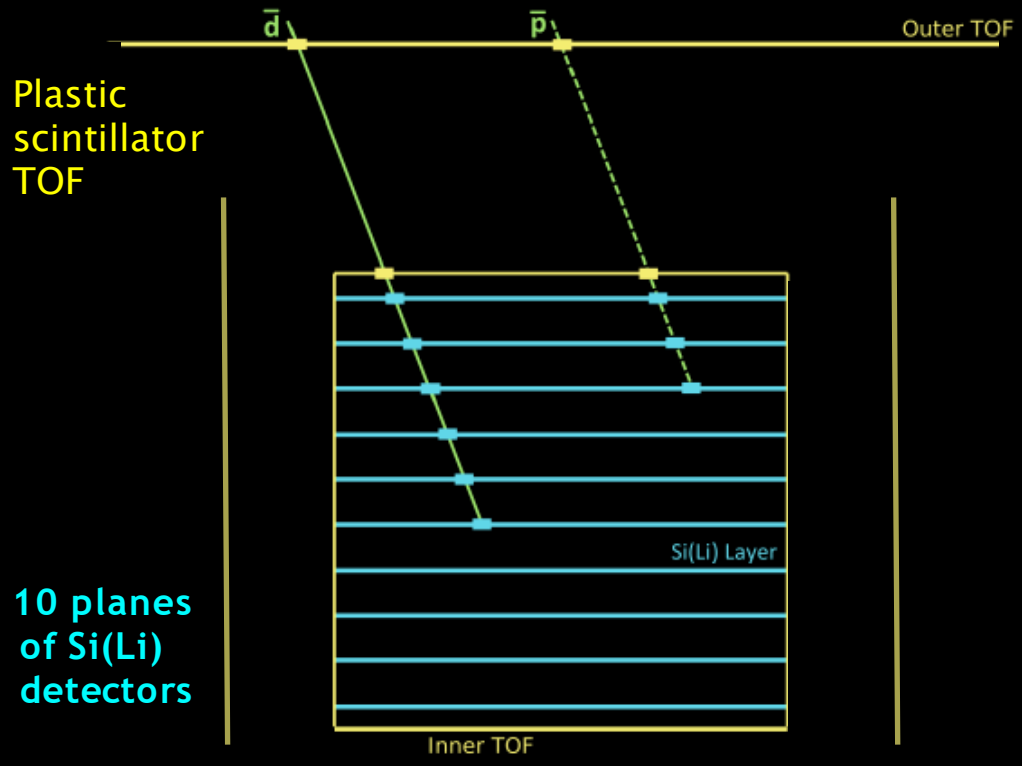


Illustration credit: A. Lowell (UCSD)

Time-of-flight system measures velocity, incoming angle and dE/dx

GAPS Detection Principle



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Time-of-flight system measures velocity, incoming angle and dE/dx

Si(Li) tracker acts as:

- ***target*** to slow and capture an incoming antiparticle

Extoic atom technique verified at KEK: Aramaki+ Astropart.Phys. 49, 52-62 (2013)
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)
GAPS sensitivity to antiprotons: Aramaki+ Astropart.Phys. 59, 12-17 (2014)

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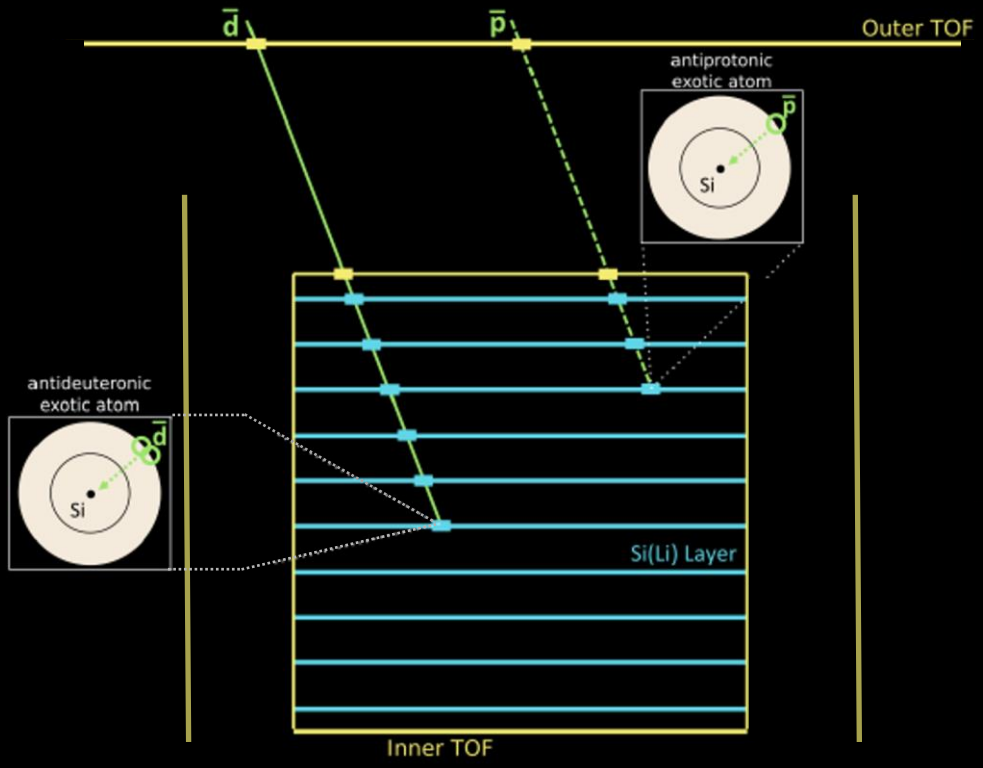

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Time-of-flight system measures velocity, incoming angle and dE/dx

Si(Li) tracker acts as:

- ***target*** to slow and capture an incoming antiparticle into an ***exotic atom***

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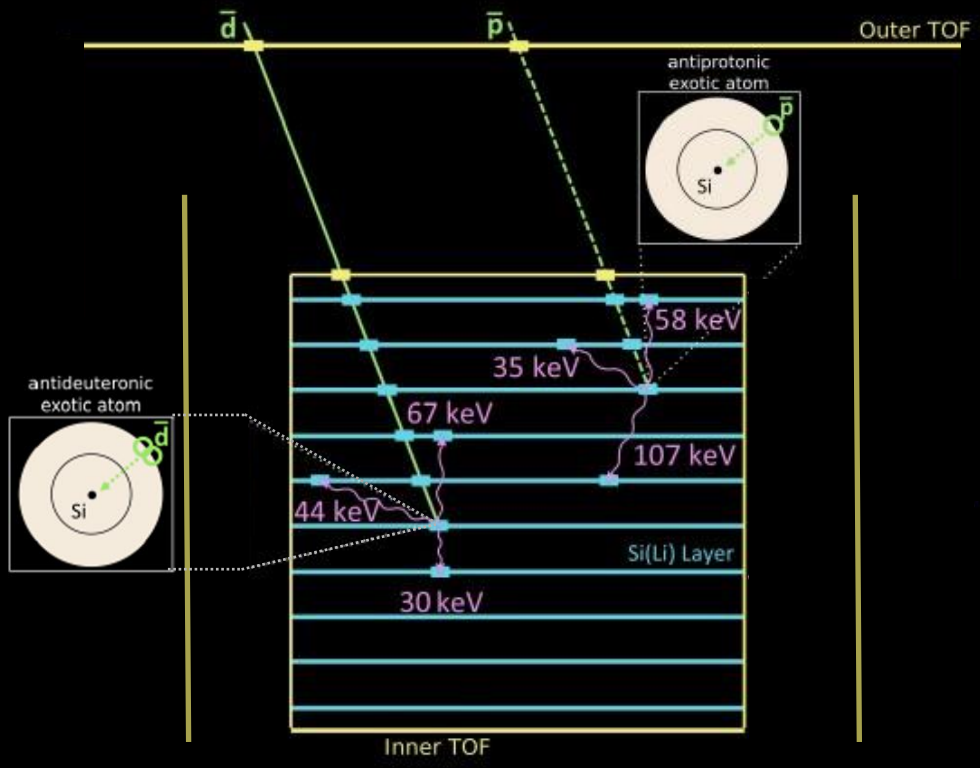

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Time-of-flight system measures velocity, incoming angle and dE/dx

Si(Li) tracker acts as:

- ***target*** to slow and capture an incoming antiparticle into an *exotic atom*
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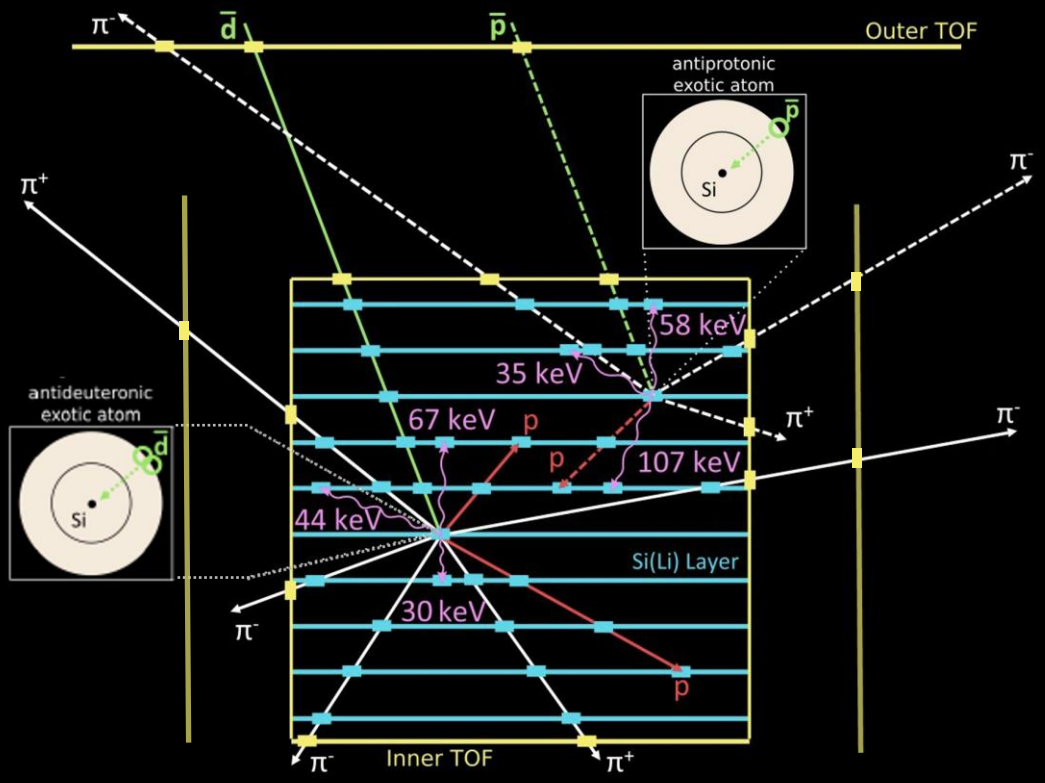

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Time-of-flight system measures velocity, incoming angle and dE/dx

Si(Li) tracker acts as:

- ***target*** to slow and capture an incoming antiparticle into an *exotic atom*
- ***X-ray spectrometer*** to measure the decay *X-rays*
- ***particle tracker*** to measure the resulting dE/dX, stopping depth and annihilation products

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GAPS "Background" Rejection

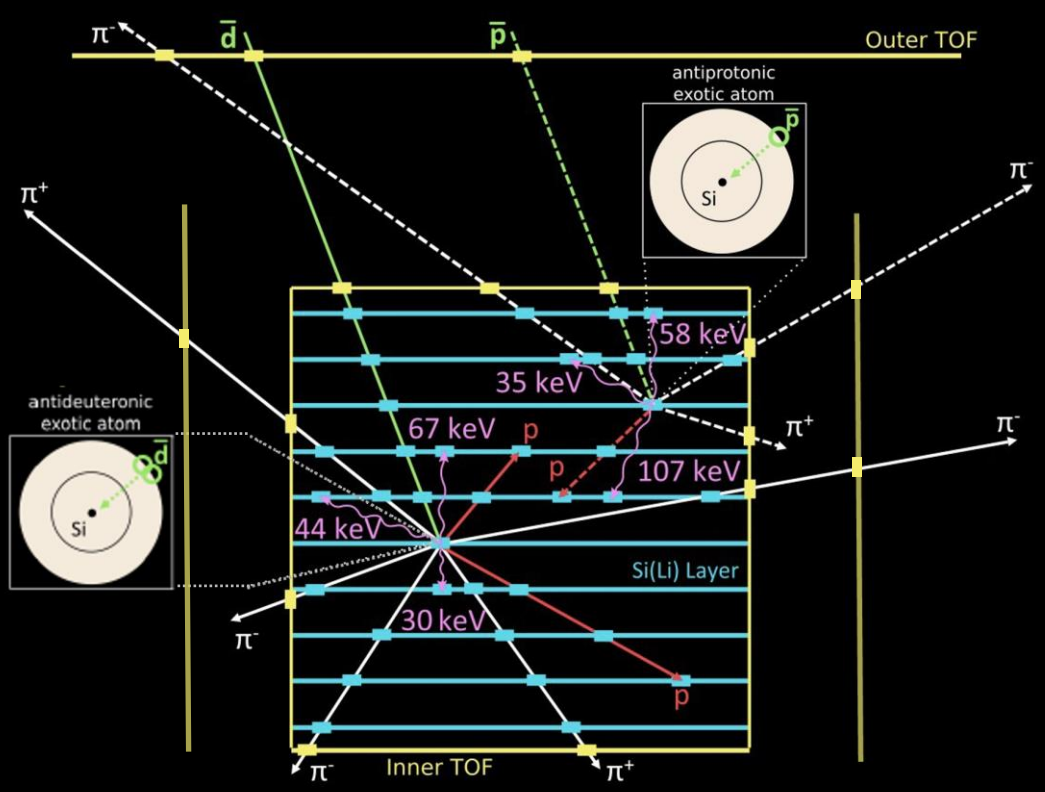

Illustration credit: A. Lowell (UCSD)

- TOF system helps select antinuclei ($\bar{p}$ and $\bar{d}$)
  - Combined with the simultaneous detection in tracker
- Antiparticle ($\bar{p}/\bar{d}$) identification:
  - Stopping range, dE/dx
  - Pion & proton multiplicity
  - Unique atomic X-rays

⇩

➢ "Background" for antideuteron searches ($\bar{p}$ mis-identification) *rejection power* >10^6 *!*

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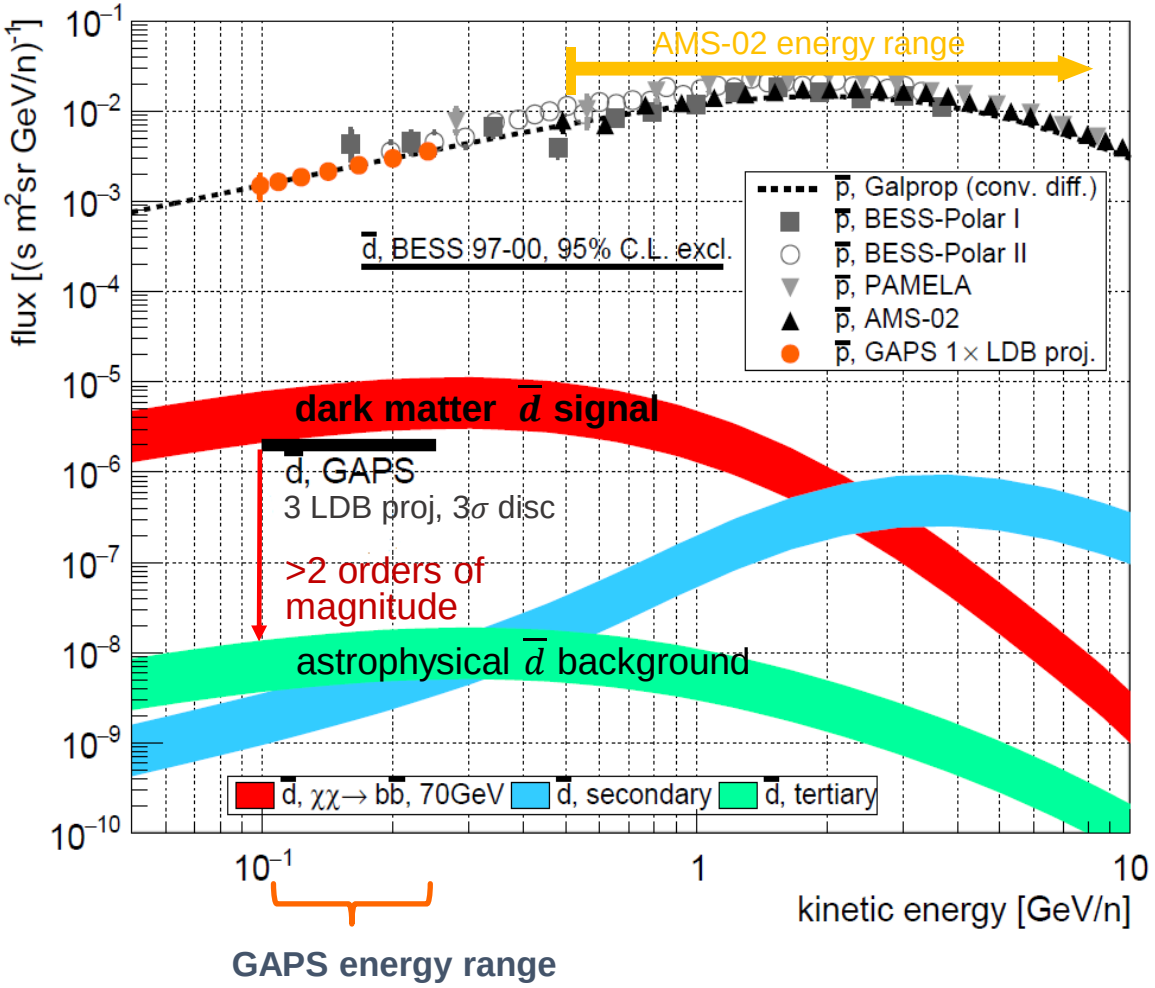
GAPS Sensitivity: cosmic ***antideuterons***

Cosmic-ray antinuclei as messengers of new physics: status and outlook for the new decade: JCAP08 (2020) 035



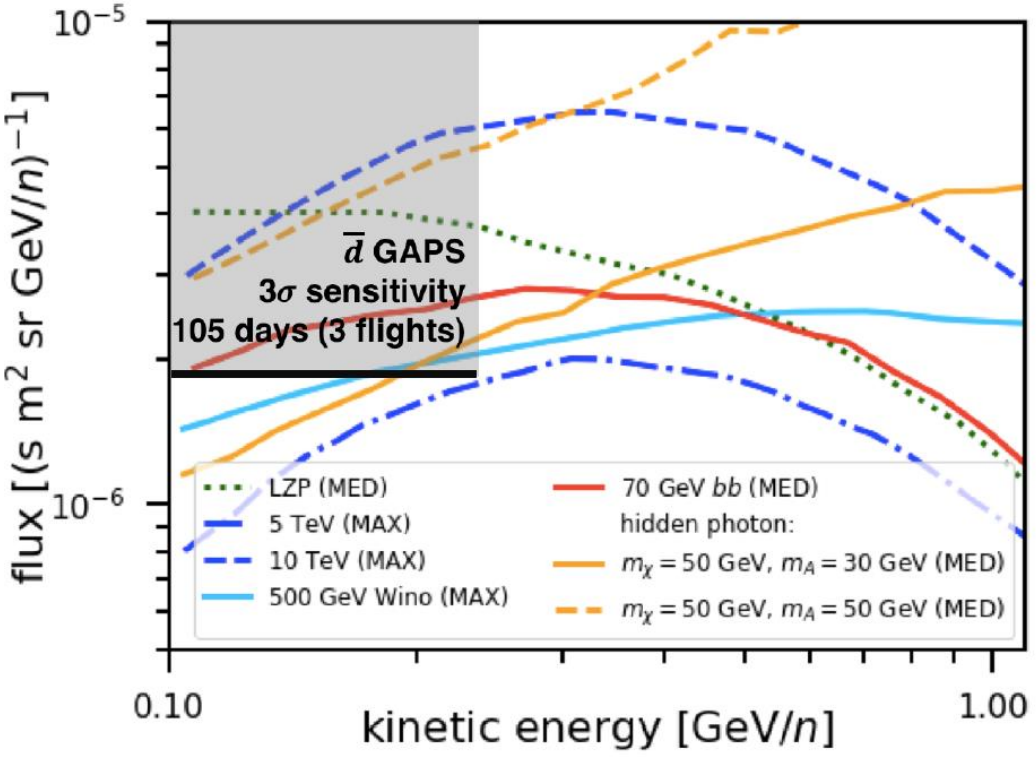
GAPS antideuterons: A generic ***new physics*** signature with *essentially zero* conventional astrophysical background!

sensitivity will be 1-2 orders of magnitude below the current best limits.

GAPS cosmic ***antideuteron*** science

- The GAPS antideuteron search is sensitive to a wide range of dark matter models, e.g.:

- Generic 70-GeV WIMP annihilation model that explains antiproton excess and γ-rays from the Galactic Center
- Dark matter gravitino decay
- Extra dimensions
- Dark photons
- Heavy DM models with Sommerfeld enhancement



Any antideuteron signal needs to be compatible with antiproton constraints!

GAPS Sensitivity: cosmic *antiprotons*

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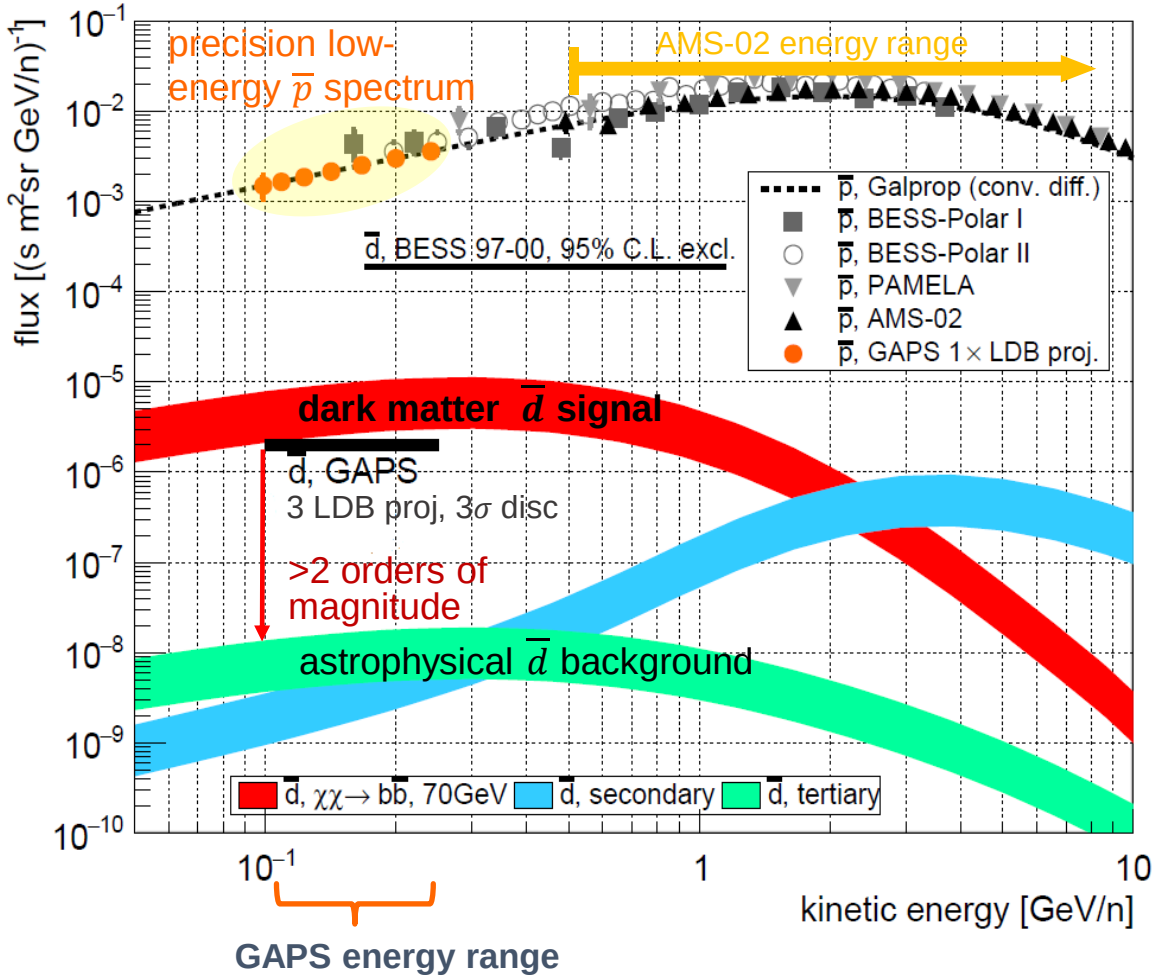
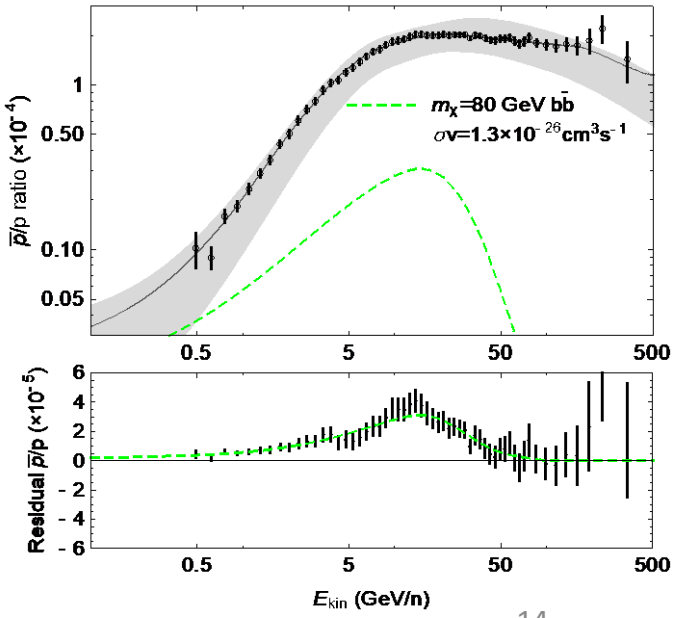


See more discussion in F. Roger's contribution: No. 101833

Precision antiproton spectrum in unexplored low-energy range (<0.25 GeV/n)

- >1000 antiprotons for each long-duration balloon flight.
  - BESS : 29 at ~0.2 GeV
  - PAMELA: 7 at ~0.25 GeV
  - AMS-02: E>0.25 GeV

Cuoco+(2016), Cui+(2016), Cui+ (2018), Cuoco+ (2019), Cholis+ (2019)

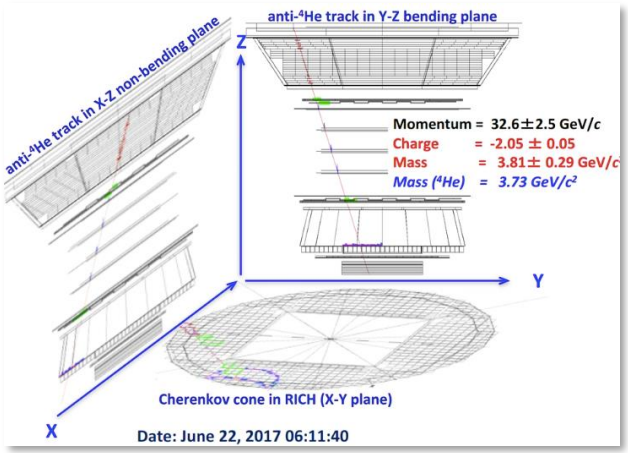


GAPS Sensitivity: cosmic ***antihelium***

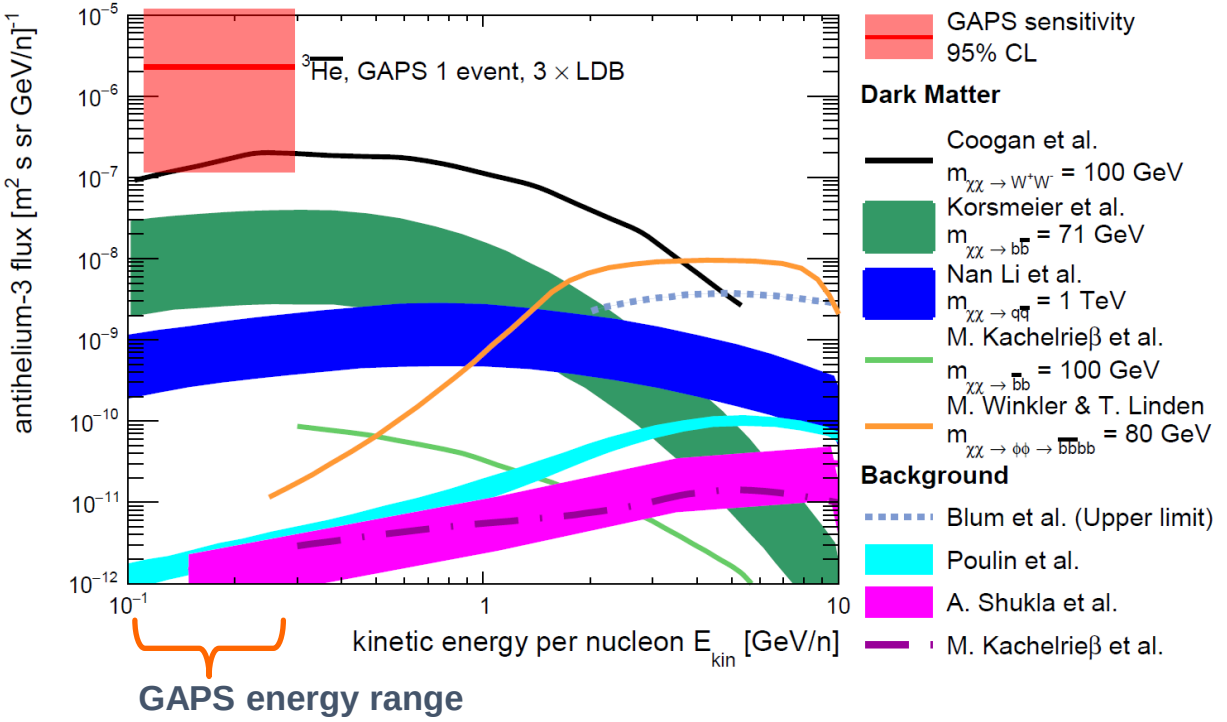
GAPS flux sensitivity to antihelium-3 (three 35-day long duration flights):

- **2018:** "To date, we have observed eight events…with Z = -2. All eight events are in the helium mass region."
  – S. Ting (La Palma, AMS overview)

AMS Candidate Anti-He4 event (p = 32.6 GeV/c)



N. Saffold et al. Astropart. Phys. 102580 (2021).



also see A. Stoessl 's contribution: No. 101701

- *GAPS extends to lower energies (0.11-0.3 GeV/n), complementary to AMS-02.*
  - *Capable of confirming signal, orthogonal detection technique, uniquely low bkg.*

Summary & Conclusions

- GAPS is the first experiment optimized specifically for low-energy (<0.25 GeV/n) antiprotons, antideuterons, and anti-He.
- **GAPS aims to deliver:**
  - *first-time detection of cosmic antideuterons with* sensitivity 1-2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range.
  - *a precision antiproton measurement in an unexplored energy range*, permitting leading constraints on light DM, the best limits on primordial black hole evaporation on Galactic length scales, and novel insight on cosmic-ray propagation models.
  - *open sensitivity to low-energy cosmic anti-He*, in particular to investigate the candidate antihelium events reported by AMS-02
- GAPS instrument integration has begun, on schedule for the ***first science flight from Antarctica in late 2022!***

GAPS Collaboration

NASA

Columbia University

Massachusetts Institute of Technology

UCLA

University of Hawai'i Mānoa

UC San Diego

Northeastern University

Oak Ridge National Laboratory

SSL UC Berkeley

JAXA Japan Aerospace Exploration Agency

INFN Istituto Nazionale di Fisica Nucleare

科研費 KAKENHI

HEISING-SIMONS FOUNDATION

NSF


Thank you!