An Indirect Dark Matter Search Using Cosmic Ray Antiparticles with GAPS

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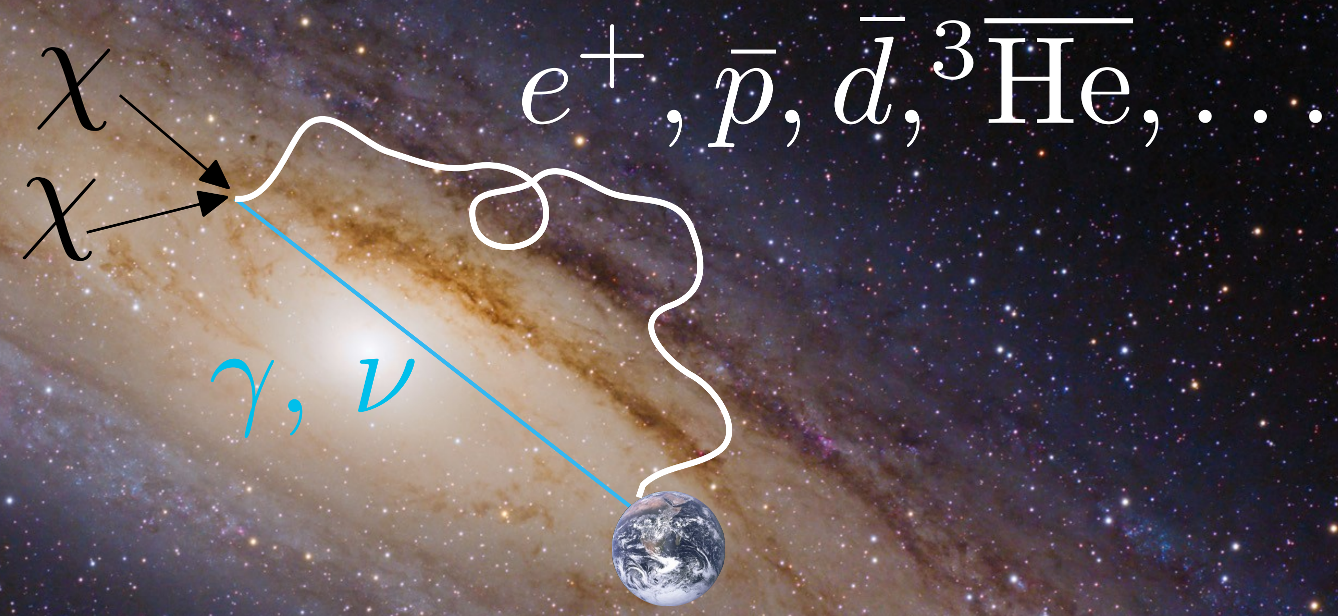
on behalf of the GAPS Collaboration

Indirect Searches for Dark Matter in Cosmic Rays



- Indirect searches complement direct and collider searches for DM
- DM particles in the Galactic DM halo annihilate or decay and produce SM particles
- Gammas and neutrinos point back to the source
- Charged SM particles undergo complex transport through ISM and Galactic/solar B fields before arriving at Earth

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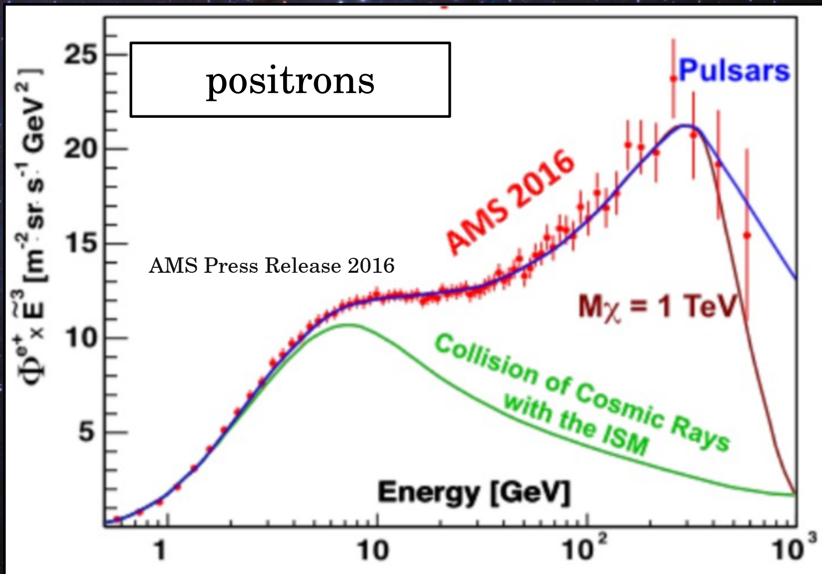
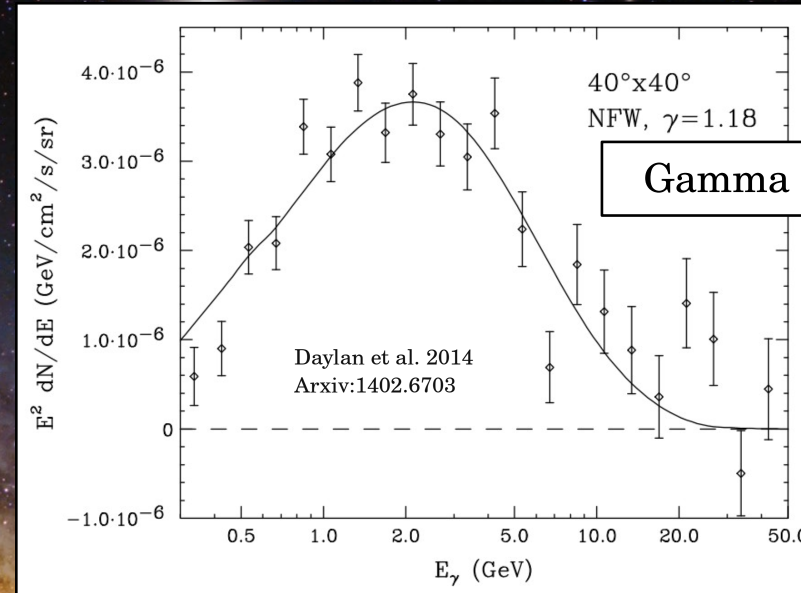
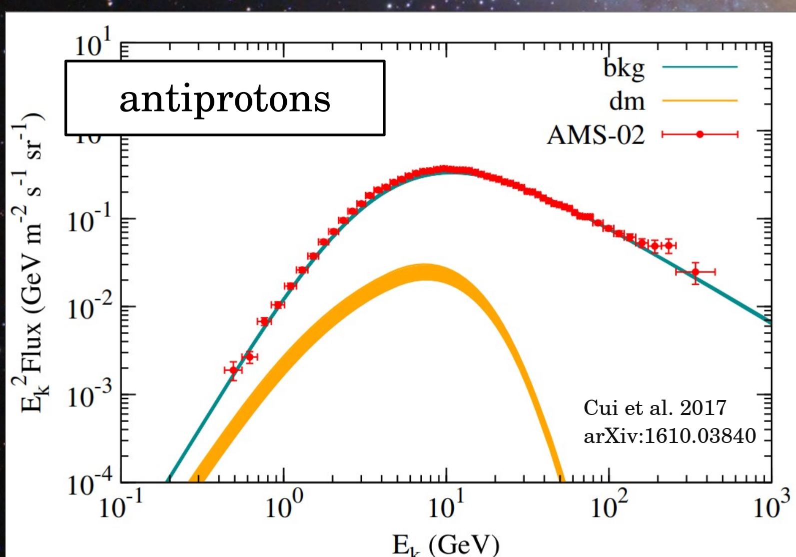


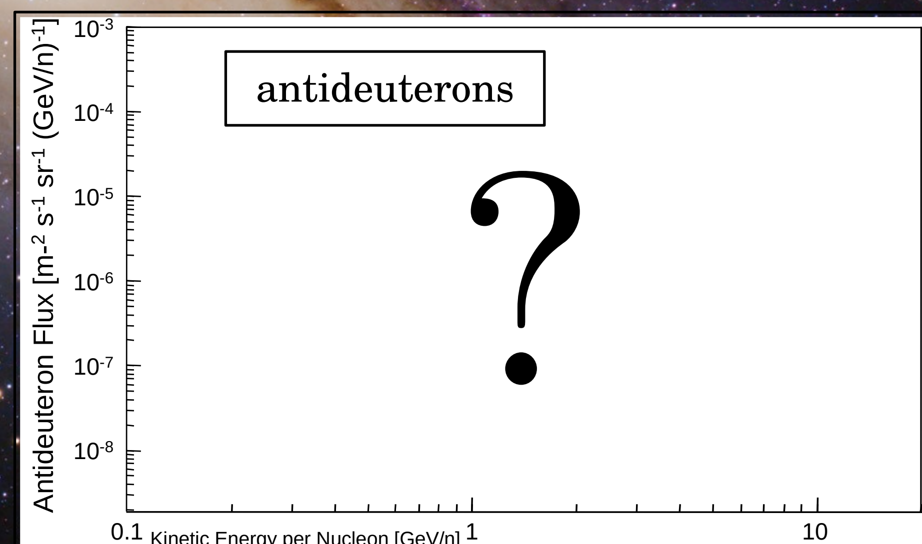
Positron excess consistent with ~1 TeV/c² DM, but can be explained by a local pulsar contribution or SNR acceleration



Fermi GeV excess from GC consistent with ~30 GeV/c² DM, but can be explained with unresolved pulsar population



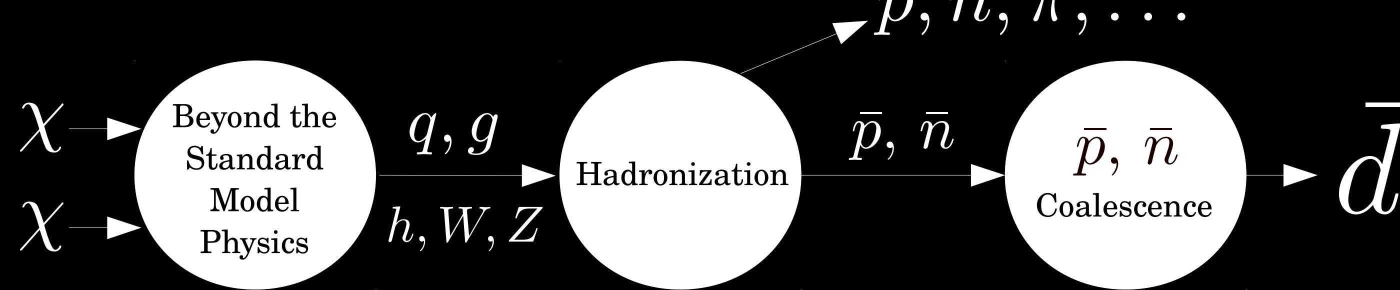
Possible excess in AMS antiproton spectrum favoring ~10 GeV/c² DM, although analyses are sensitive to large uncertainties in CR propagation



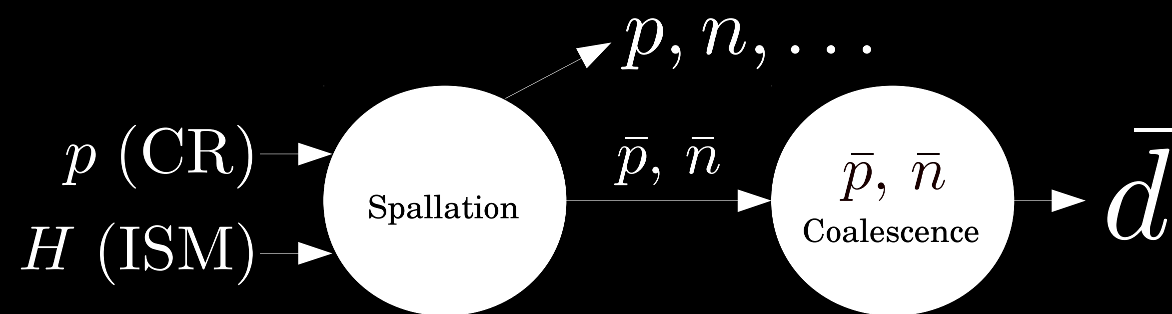
- **Antideuterons not yet detected in CRs**
- **Very low expected astrophysical background**

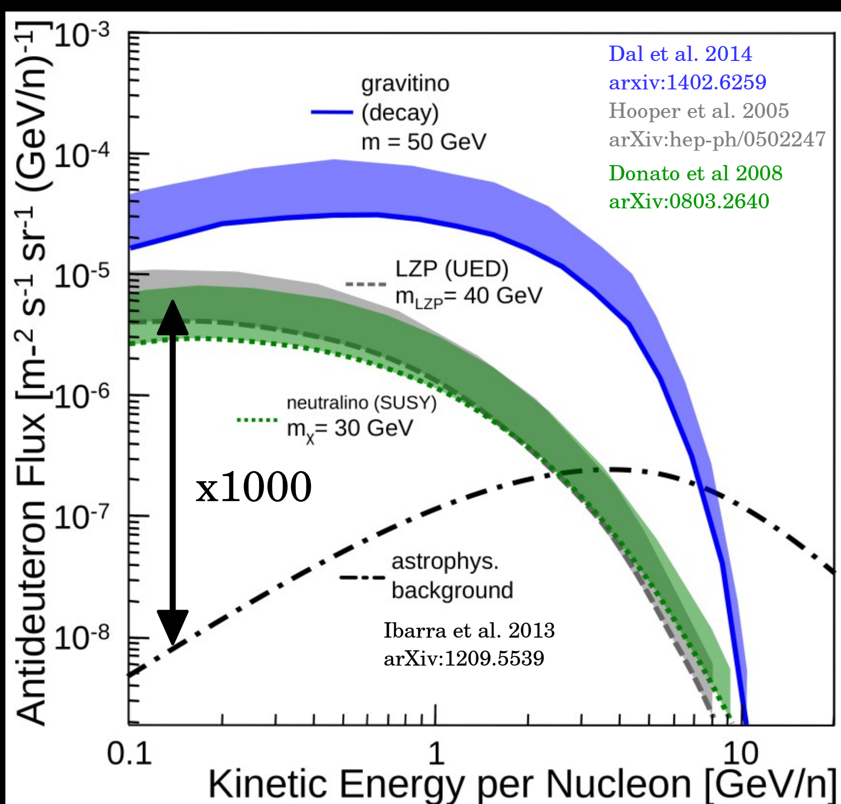
Cosmic Ray Antideuterons as Probes of Dark Matter

$\bar{d}$ from DM:



$\bar{d}$ from CR/ISM interactions:

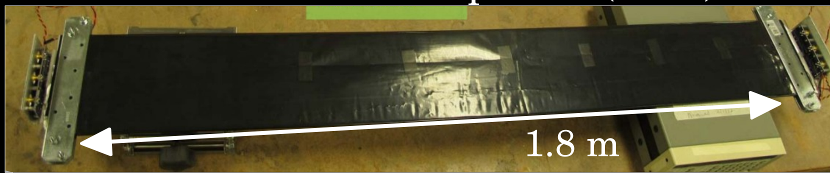




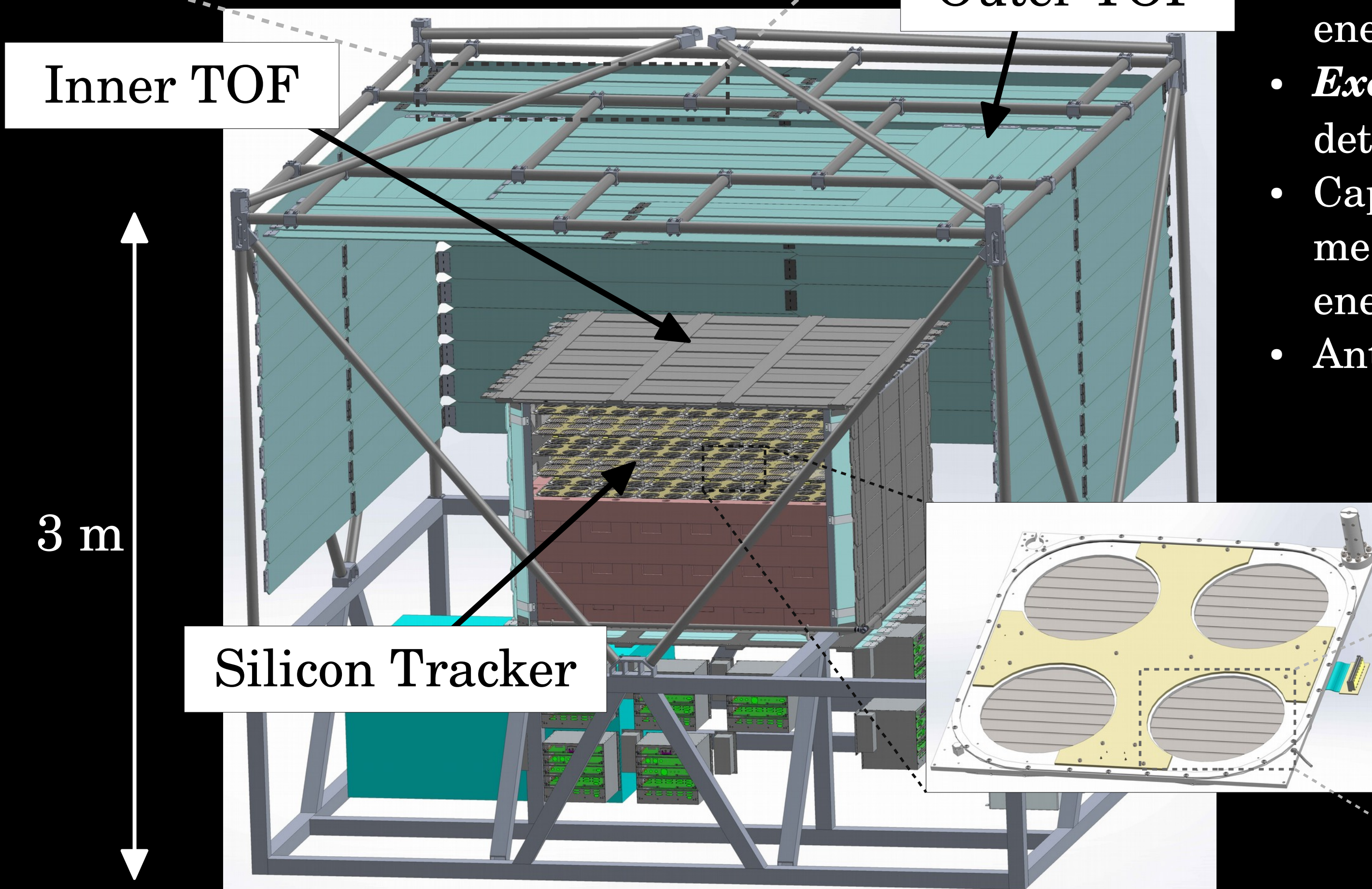
- Background processes inefficient at producing < 1 GeV/n antideuterons
- Well-motivated WIMP DM scenarios predict an antideuteron signal which can exceed the background by 10^2-10^3 at low energies
- Low energy antideuterons are an important, unexplored probe of DM physics!

The General Antiparticle Spectrometer (GAPS)

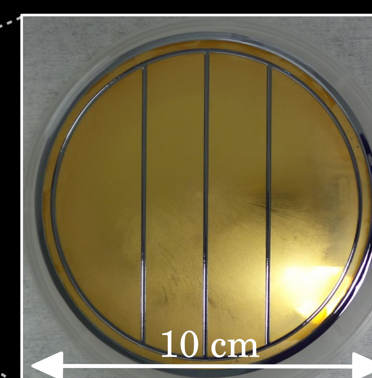
Plastic scintillator paddle (x202)



- GAPS is a balloon borne detector of cosmic ray antiparticles
- First experiment optimized for low energy antideuterons (<0.25 GeV/n)
- ***Exotic atom*** technique for particle detection and identification
- Capable of precision antiproton measurement in unexplored energy range
- Antihelium detection capability



Si(Li) Detector (x1000)

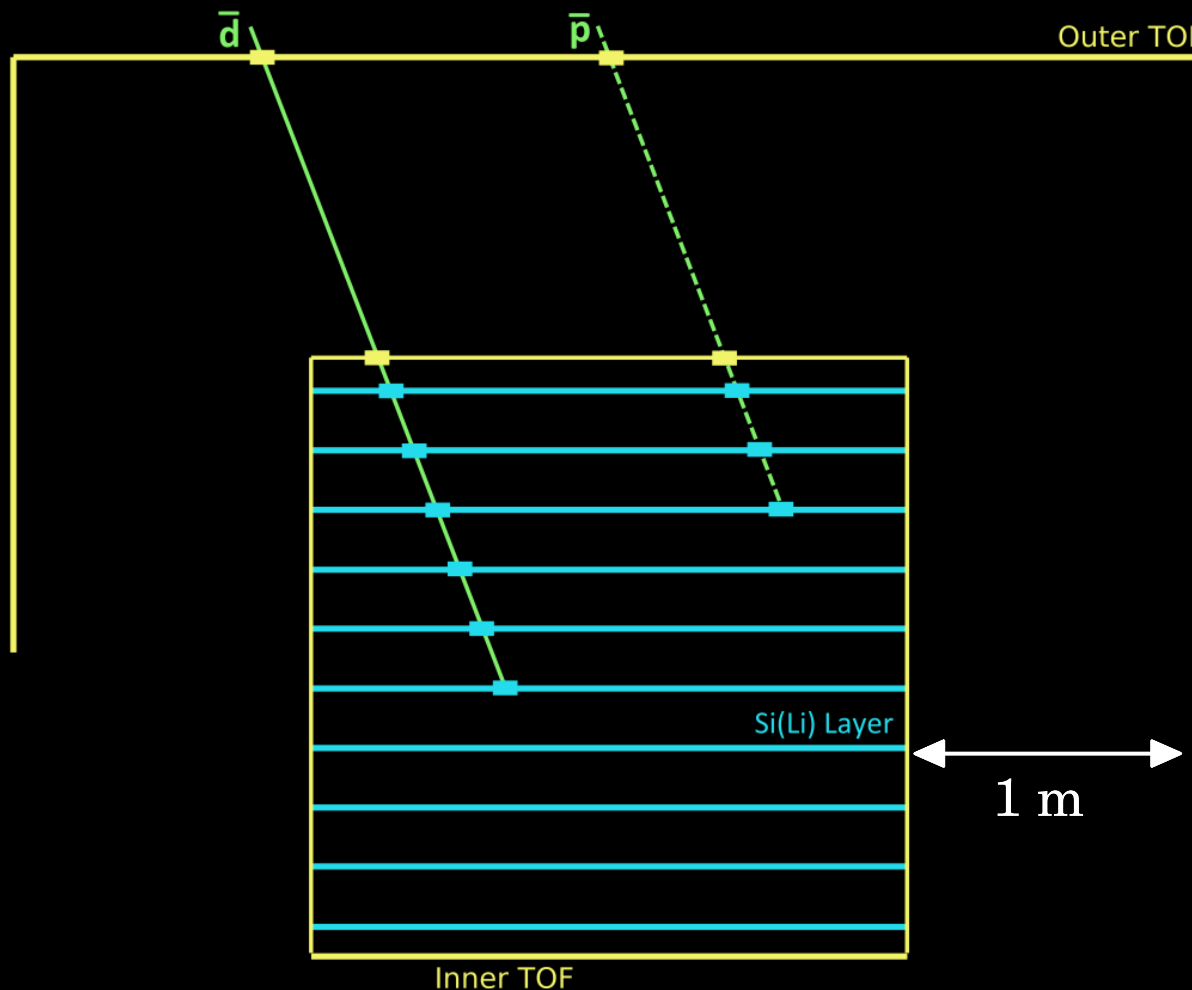


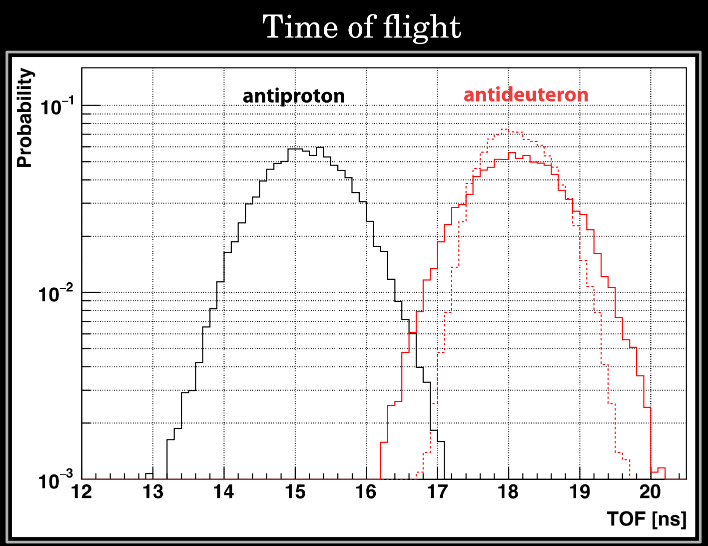
GAPS gondola (mass: 1700 kg, power: 1400 W)

Detector systems:

- Time of Flight (TOF): Particle velocity, dE/dx, tracking, incidence angle, trigger
- Si(Li) Tracker: Tracking, dE/dx, stopping depth, X-ray spectroscopy

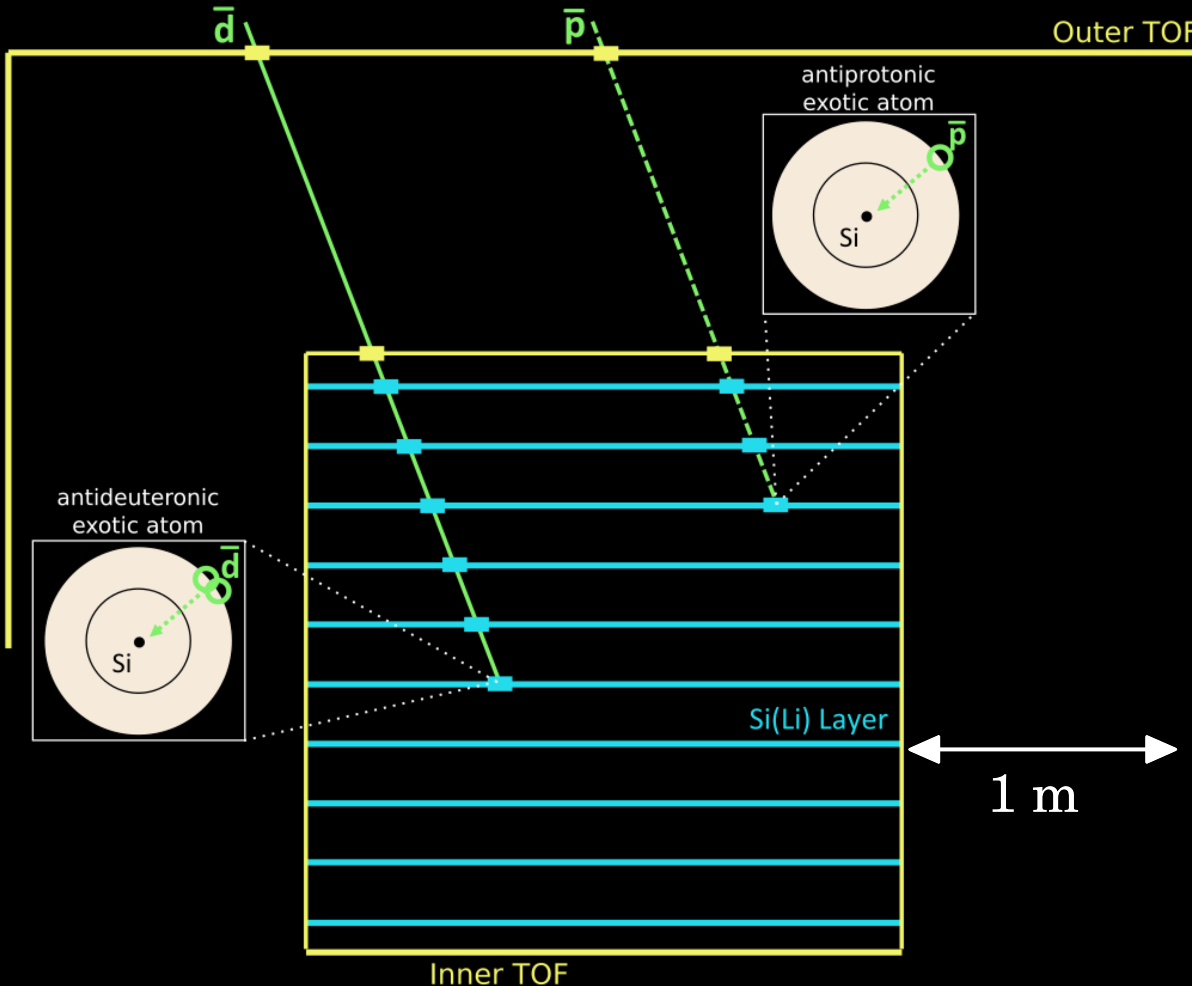
GAPS Operating Principle



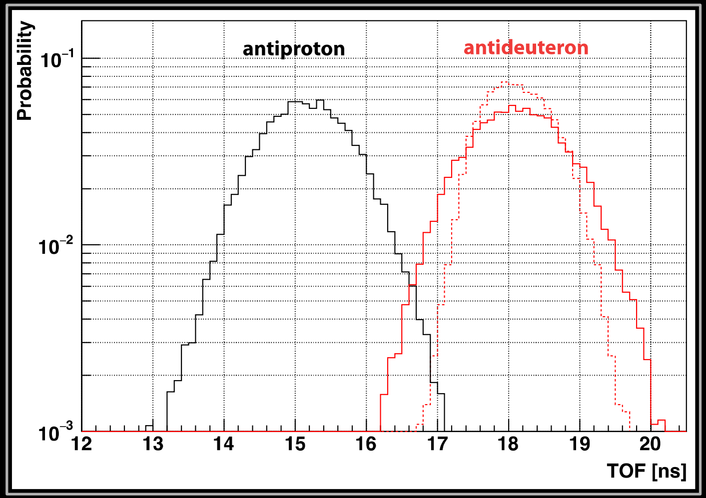


- Antiparticle strikes inner and outer TOF, and stops in tracker
  ➔ TOF vs. stopping depth for antiparticle identification

GAPS Operating Principle

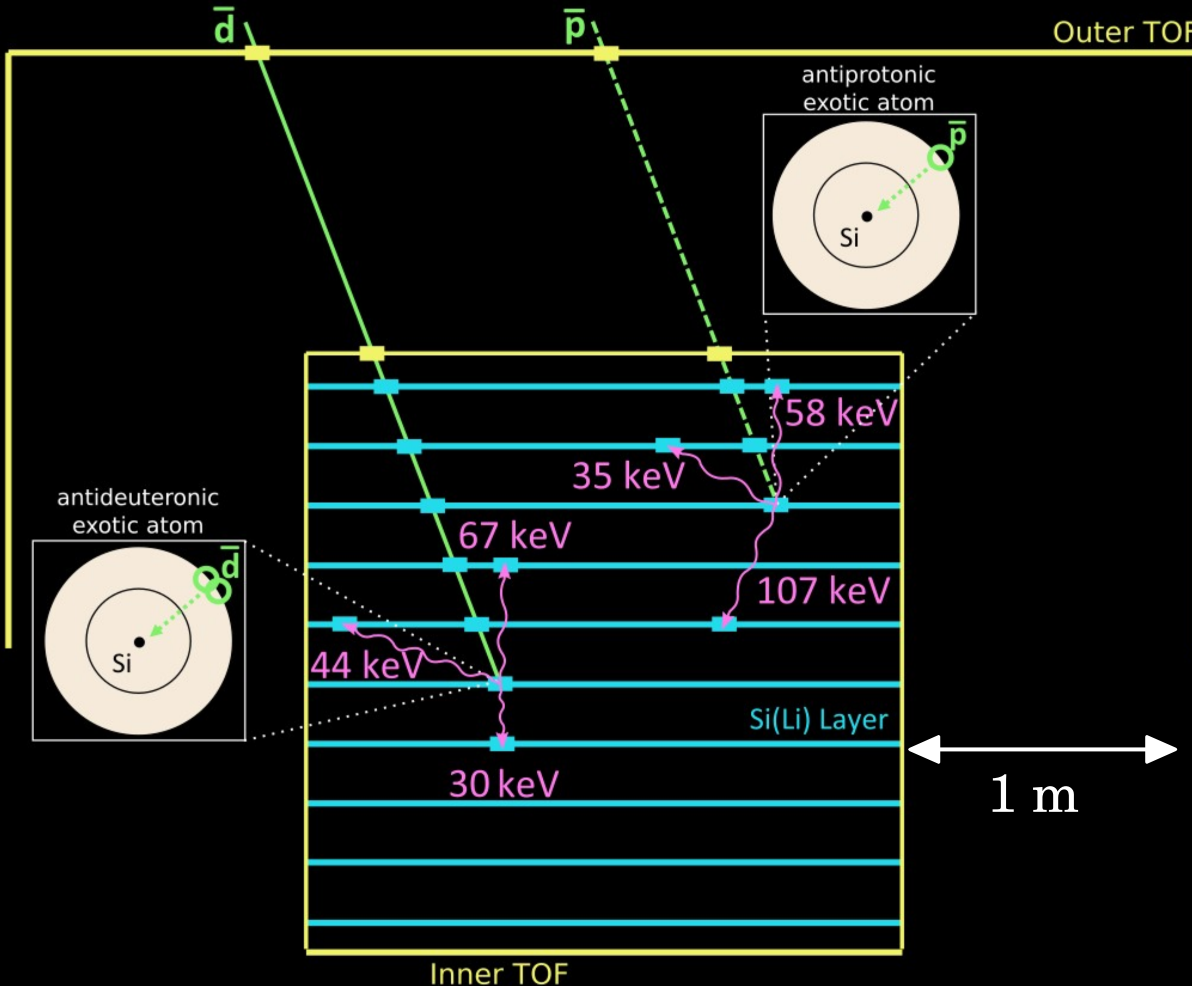


Time of flight

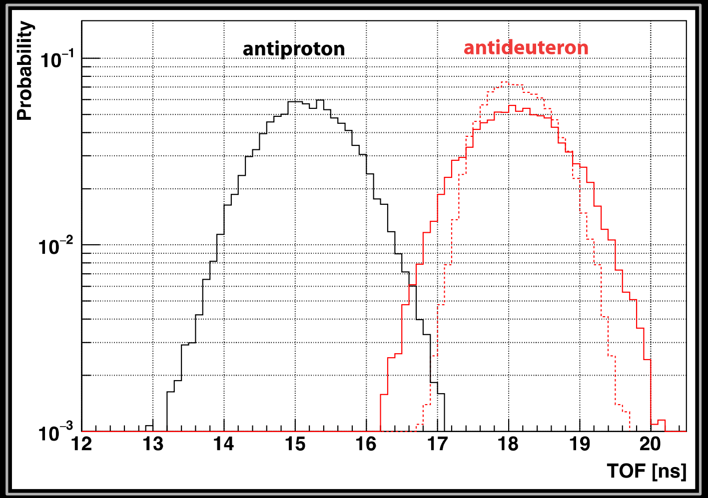


- Antiparticle strikes inner and outer TOF, and stops in tracker
  ➔ TOF vs. stopping depth for antiparticle identification
- Stopped antiparticle forms excited exotic atom with Si nucleus

GAPS Operating Principle



Time of flight



X-ray yields

$\bar{d}$	X-ray yield	$\bar{p}$	X-ray yield
30 keV	80%	35 keV	73%
44 keV	92%	58 keV	84%
67 keV	96%	107 keV	70%

- Antiparticle strikes inner and outer TOF, and stops in tracker
  ➔ TOF vs. stopping depth for antiparticle identification
- Stopped antiparticle forms excited exotic atom with Si nucleus
  ➔ Deexcitation X-ray energies discern between antiparticle species

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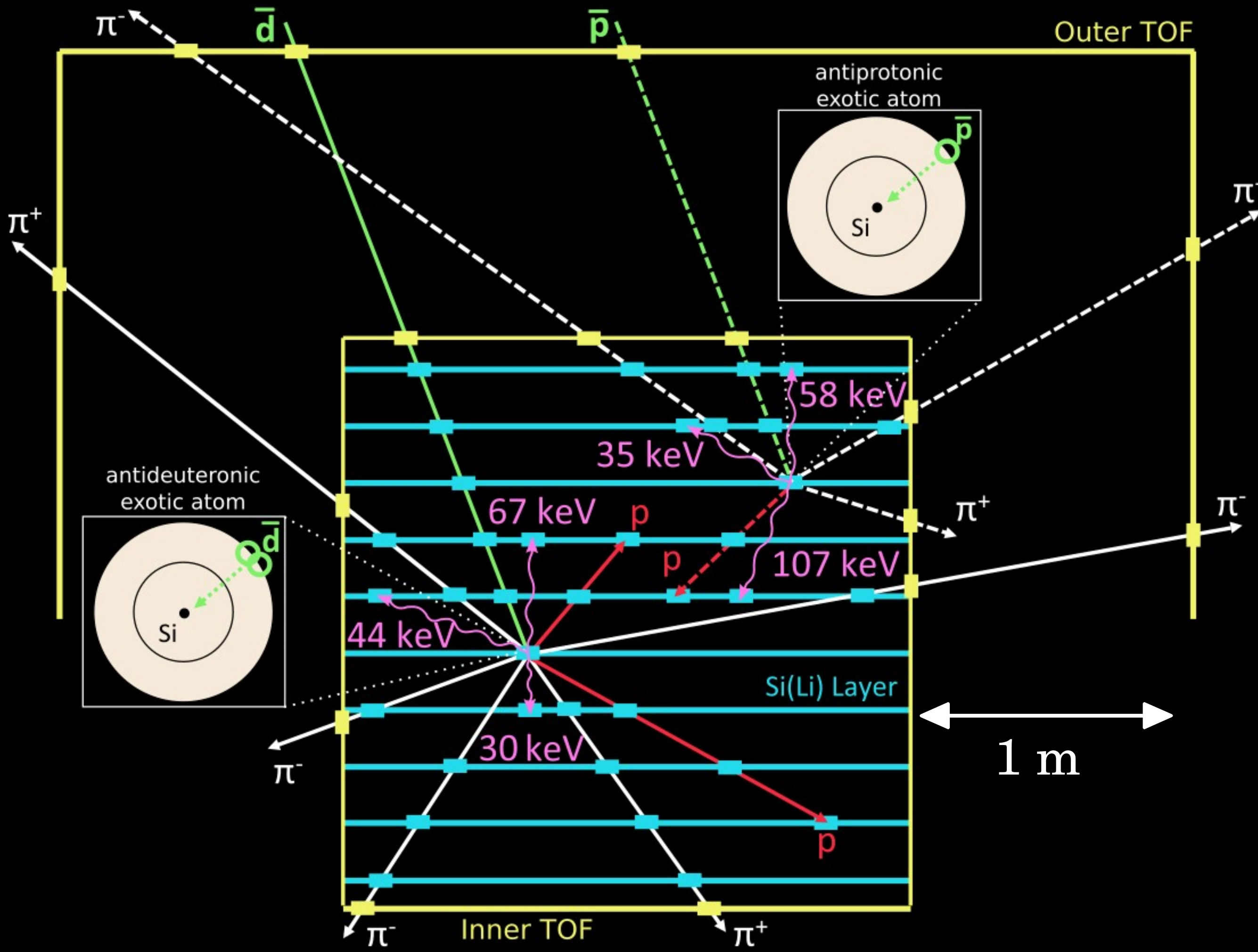
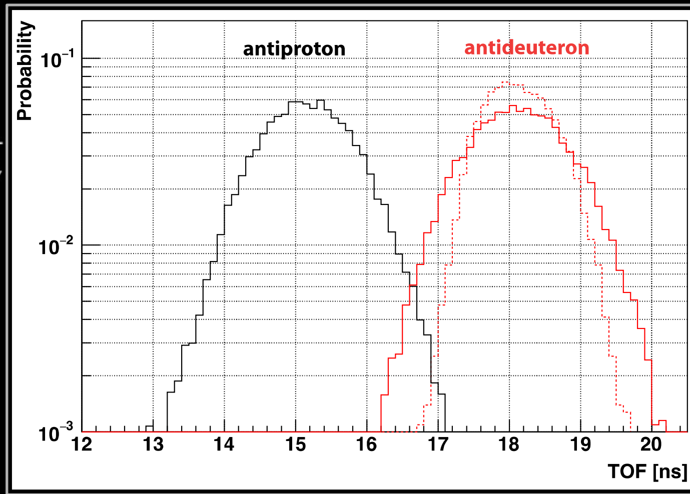


Time of flight



X-ray yields

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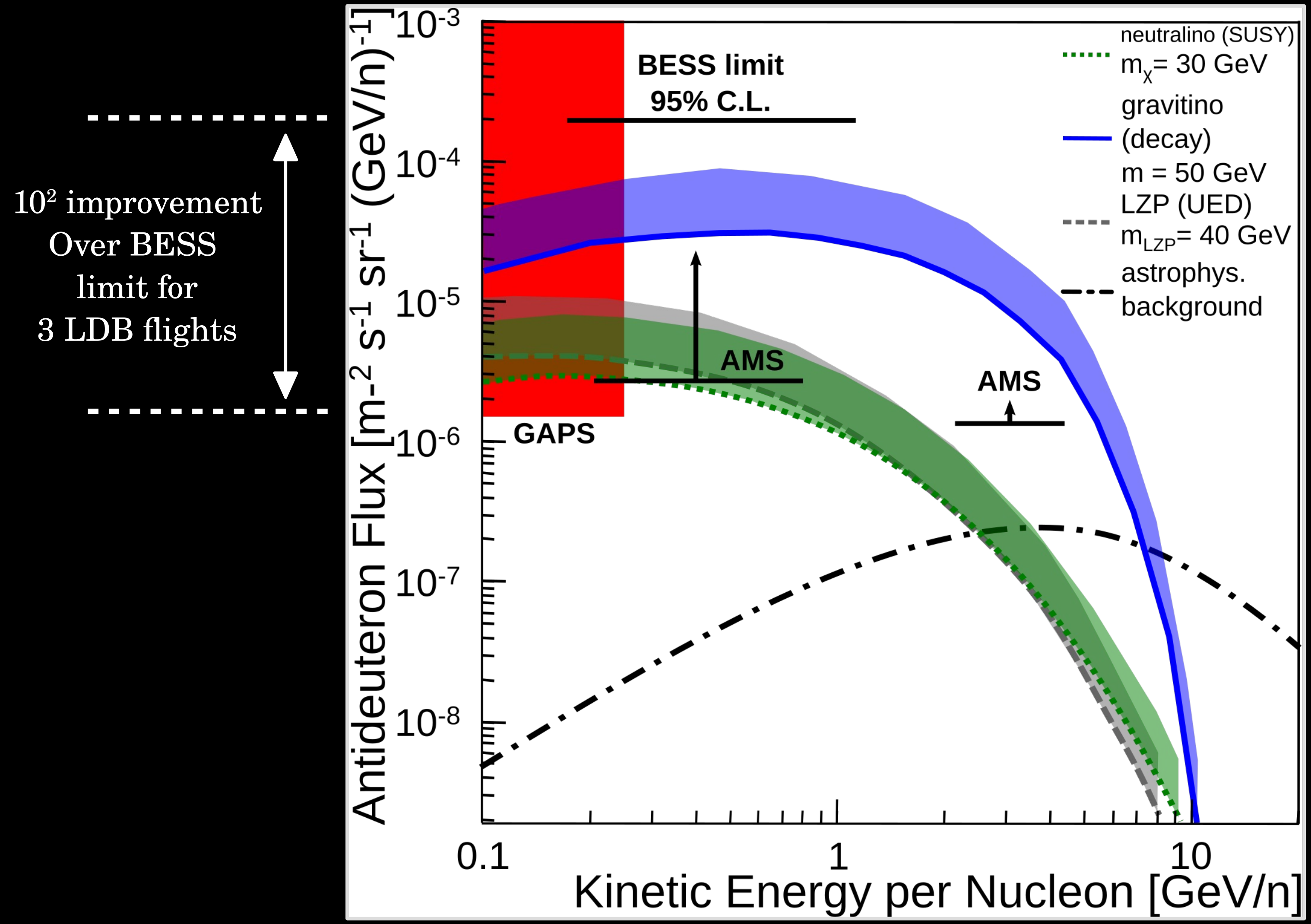
Pion and proton multiplicities

$\bar{d}$ multiplicities		$\bar{p}$ multiplicities	
$>5\pi^{\pm}$	62%	$>5\pi^{\pm}$	7%
$>2p$	60%	$>2p$	5%

- Antiparticle strikes inner and outer TOF, and stops in tracker
  ➔ TOF vs. stopping depth for antiparticle identification
- Stopped antiparticle forms excited exotic atom with Si nucleus
  ➔ Deexcitation X-ray energies discern between antiparticle species
- Antinucleon annihilation produces pions and protons (tracks)
  ➔ Pion and proton multiplicities further distinguish between antiparticle species

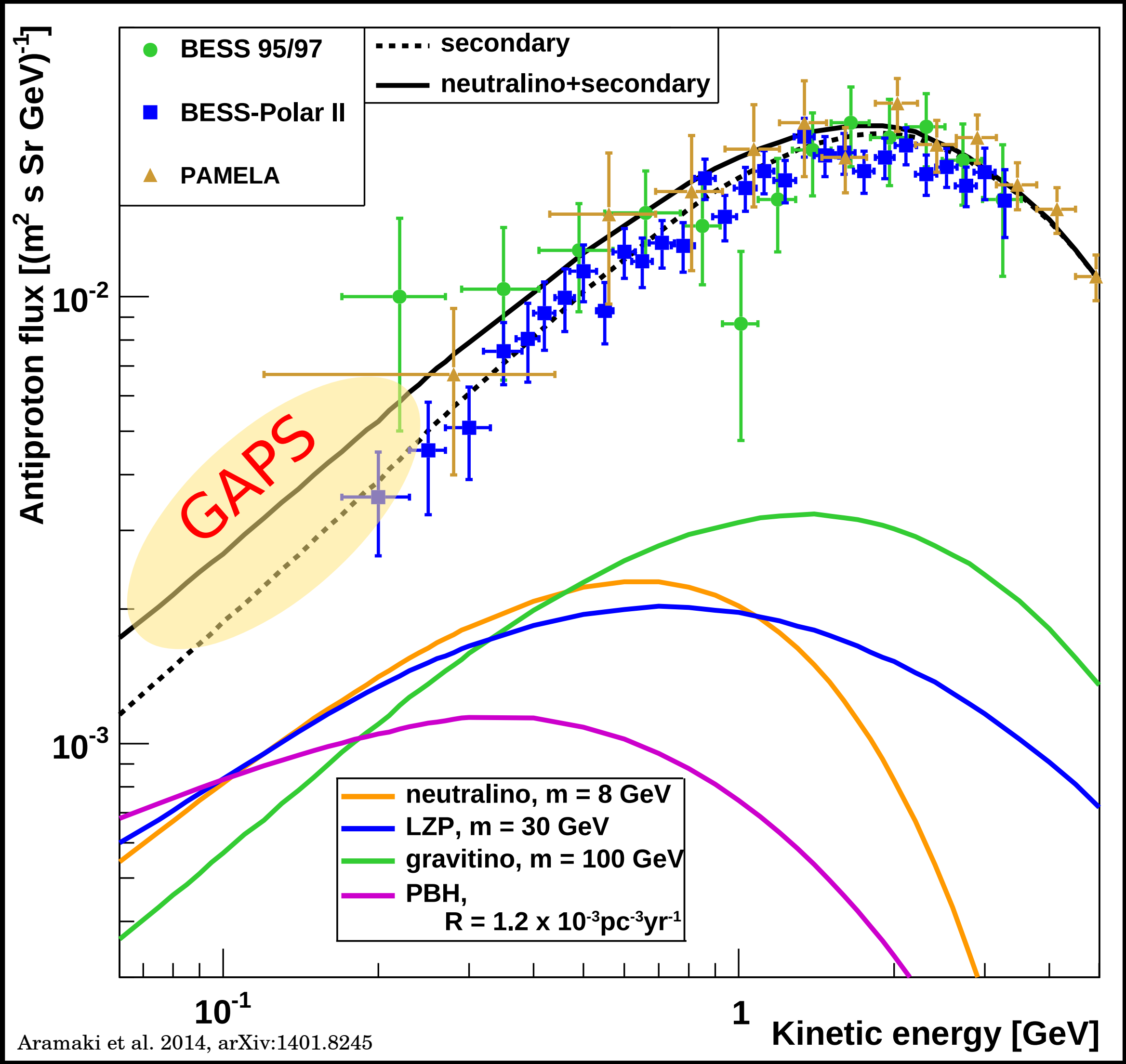
Exotic atom technique validated at KEK
Aramaki et al. 2013, arXiv:1303.3871

GAPS Antideuteron Sensitivity



- Antiprotons are the dominant background for the antideuteron measurement
- 1 (3) LDB flight 99% CL sensitivity: 4.5 (1.5) x 10^{-6} $m^{-2}s^{-1}sr^{-1}$ $(GeV/n)^{-1}$
- Depending on DM scenario, up to ~10 antideuterons may be detected throughout 3 LDB flights
- GAPS will also be sensitive to antihelium, sensitivity analysis is ongoing

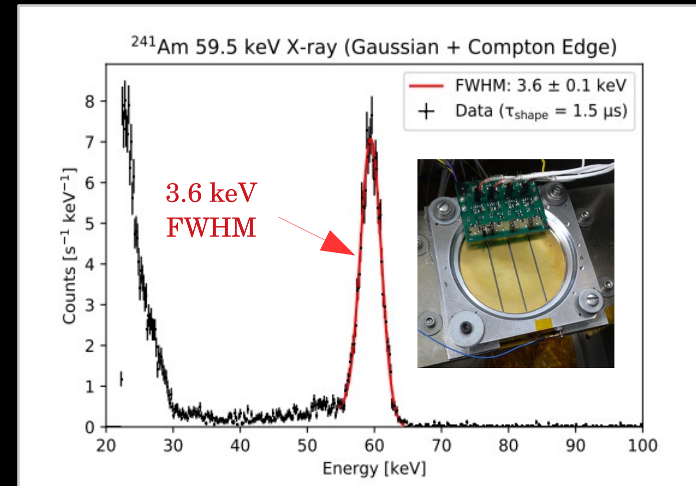
GAPS Antiproton Measurement



- In just 1 LDB flight, GAPS will detect > 1000 antiprotons in an unexplored energy range, constraining light (< 10 GeV mass) DM models
- Antiprotons will be used to validate the exotic atom detection scheme in flight
- Bonus: GAPS will set leading limits on primordial black hole evaporation

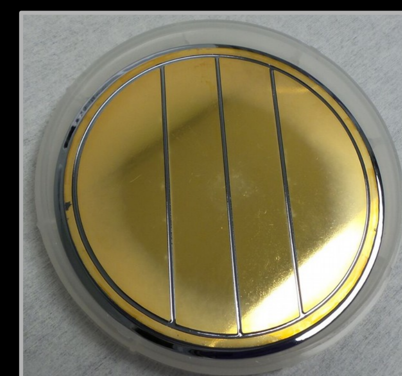
Si(Li) Detector System: Design and Progress

- 10 cm x 0.25 cm Si(Li) detectors developed with Shimadzu
  - ➔ Low cost production scheme
  - ➔ 4 strip design meets 4 keV FWHM energy resolution requirement for X-ray identification



Shimadzu Si(Li) detector line width measurement

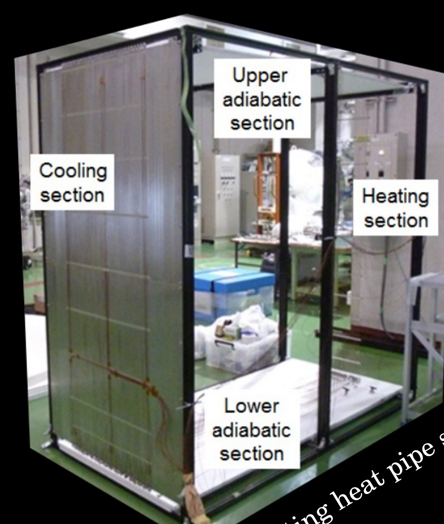
- 32 channel readout ASIC
  - ➔ Integrated low noise preamplifer
  - ➔ Dynamic range compression: 20 keV to 50 MeV
  - ➔ Design in final stages of validation



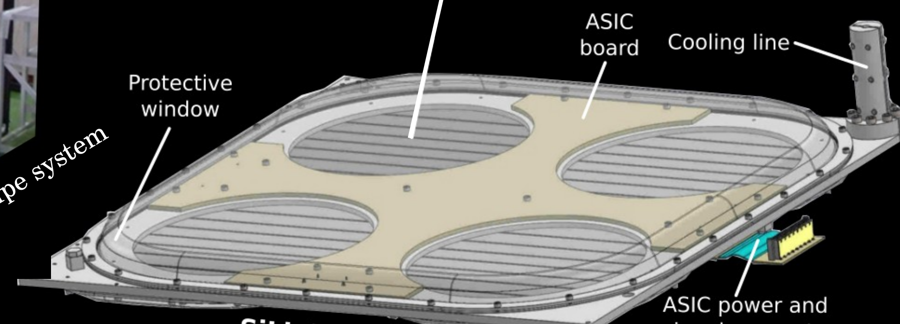
Si(Li) detector

- Oscillating heat pipe system
  - ➔ Cools Si(Li) detectors to -40C for better noise performance

Okazaki et al. 2018 Applied Thermal Engineering 141



Oscillating heat pipe system

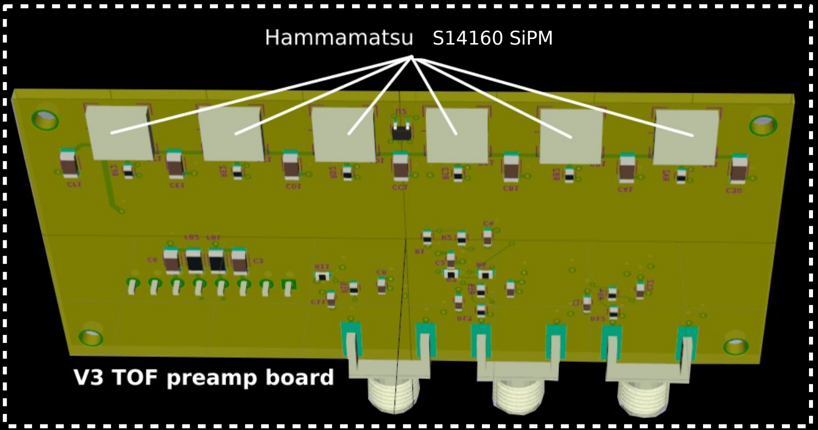


SiLi detector module

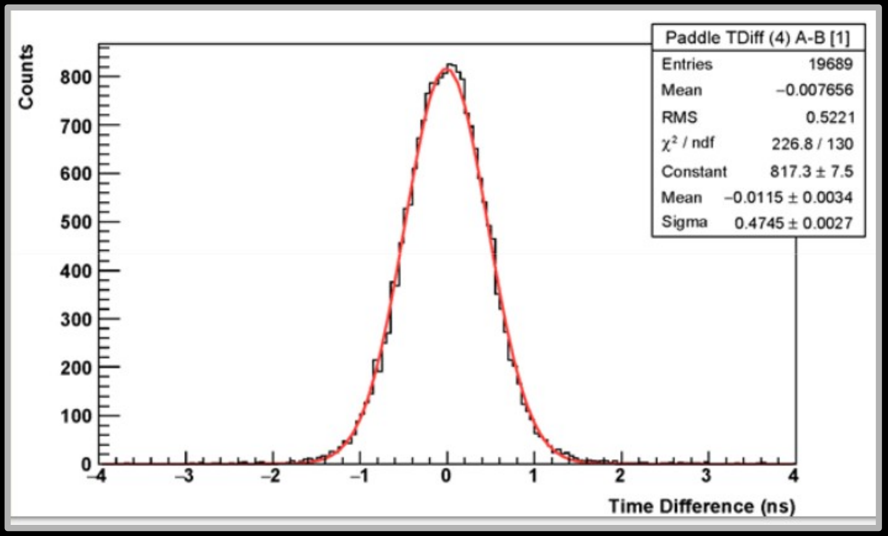
TOF System: Design and Progress

- EJ-200 plastic scintillator paddles
  - ➔ 16 cm by 0.6 cm,
    two lengths: 1.6 m and 1.8 m
  - ➔ SiPM readout
  - ➔ Traces digitized with DRS4 ASIC
  - ➔ Better than 500 ps timing resolution demonstrated
- Trigger design
  - ➔ TOF system provides trigger for tracker
  - ➔ Trigger accepts ~80% of antinuclei while reducing proton/alpha rate by 10^3-10^4

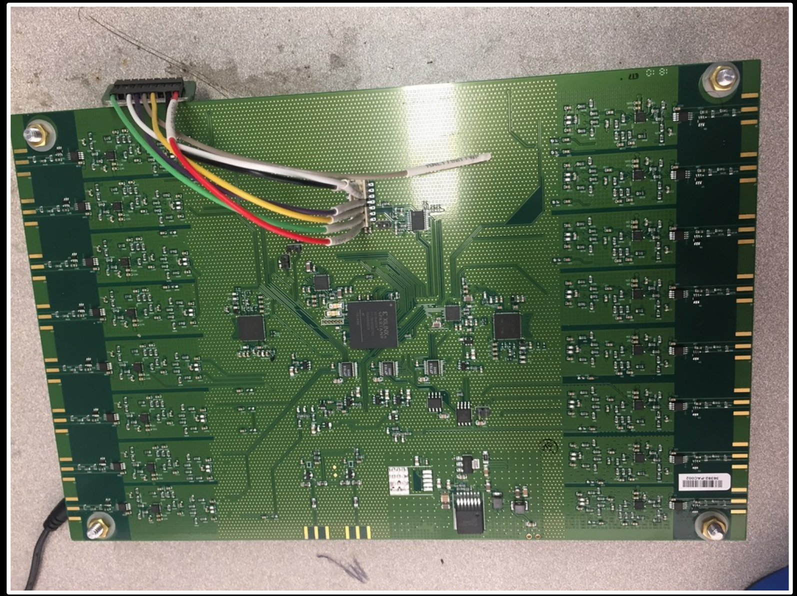
TOF paddle (202 total)



TOF preamp board (404 total)

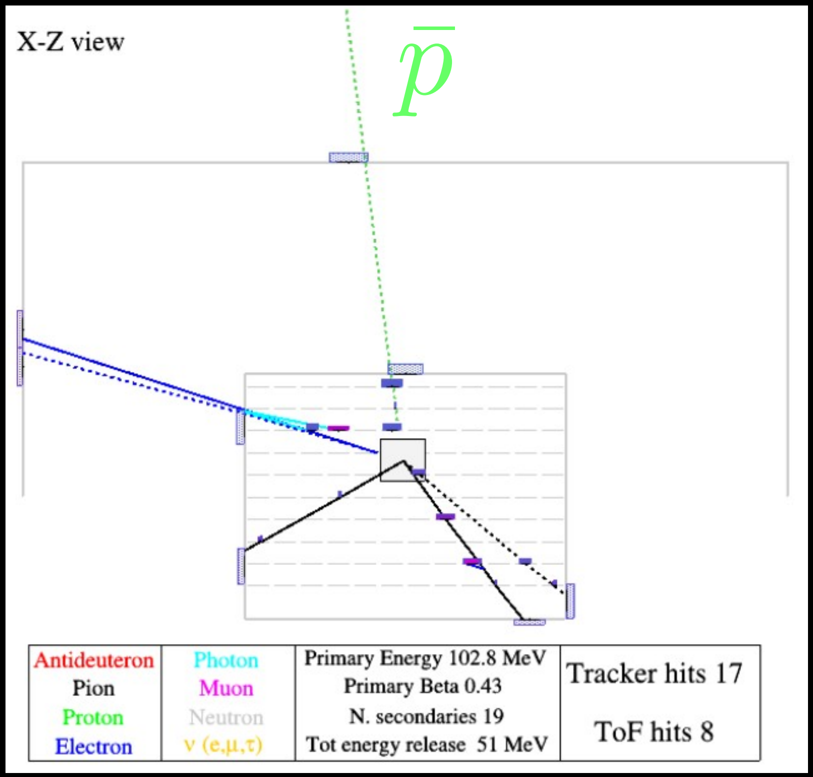


End to end TOF paddle time difference measurement

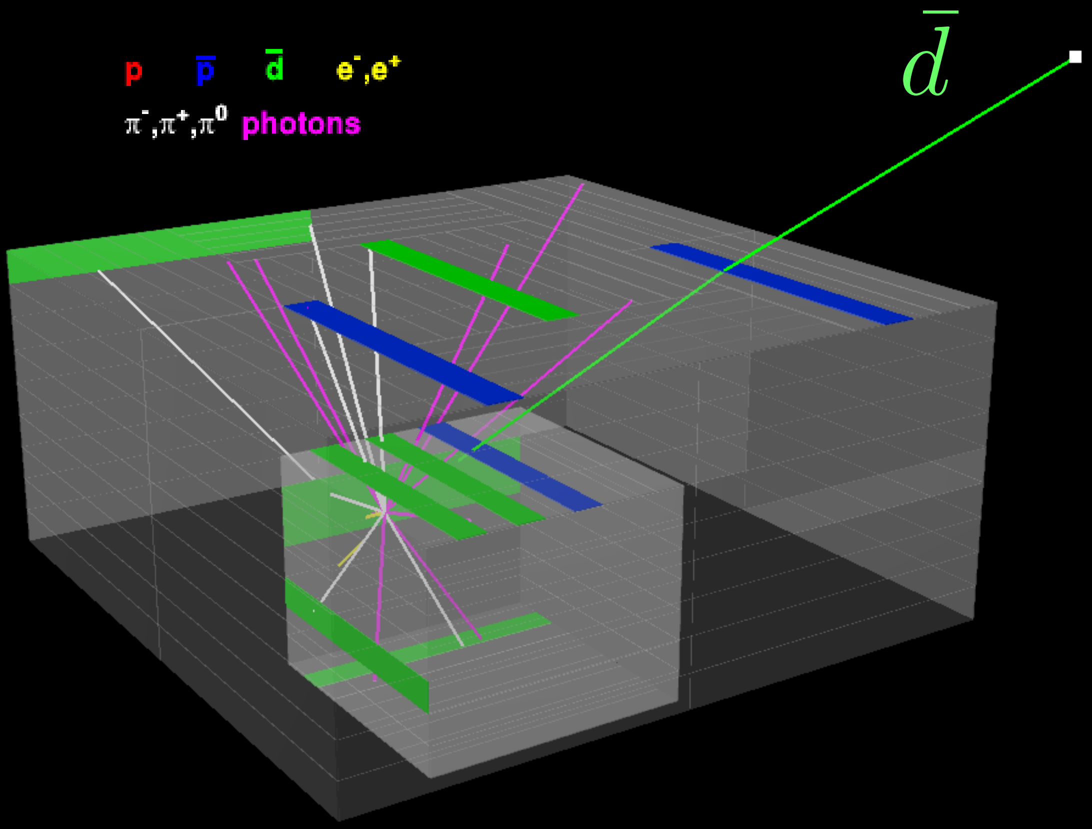


DRS4 board (27 total)

Simulations



2D viewer



3D viewer

- Comprehensive Geant4 based simulation framework developed for GAPS
- Realistic mass model closely following ongoing mechanical design
- Simulation framework continues to be used successfully to:
  - Study particle identification and track reconstruction algorithms
  - Design and validate trigger concept
  - Optimize geometrical configuration
  - Compute sensitivities, rejection power, etc.

GAPS Balloon Campaigns

von Doetinchem et al. 2014, arXiv:1303.1615
Mognet et al. 2014, arXiv:1303.1615

- 2012 prototype GAPS flight with JAXA from Taiki, Japan
  - ➔Successful 6 hour flight with background measurement
  - ➔Verified functioning of Si(Li) and TOF prototypes at 33 km float altitude
  - ➔OHP prototype and thermal model also validated

- GAPS is funded (NASA) and on track for 1st LDB flight from McMurdo Station, Antarctica in 2020/2021
  - ➔Antideuteron sensitivity will exceed BESS limit by ~1.5 orders of magnitude
  - ➔Precision antiproton spectrum measurement with >1000 antiprotons
- Two more follow up flights are planned for the mid 2020s to further science goals

Summary

- Antideuterons are a promising avenue for indirect DM searches
- GAPS, the first instrument optimized for low energy antideuterons, is well poised to detect or set deeper limits on the cosmic antideuteron flux
- Antiproton and antihelium measurements further the GAPS science reach
- Si(Li) and TOF detector systems are at a mature stage, full scale production to start promptly
- GAPS is on track for an LDB flight in 2020/2021 from Antarctica, with follow-up flights planned for the mid 2020s

GAPS Collaboration