GAPS: Searching for Dark Matter using Antinuclei in Cosmic Rays

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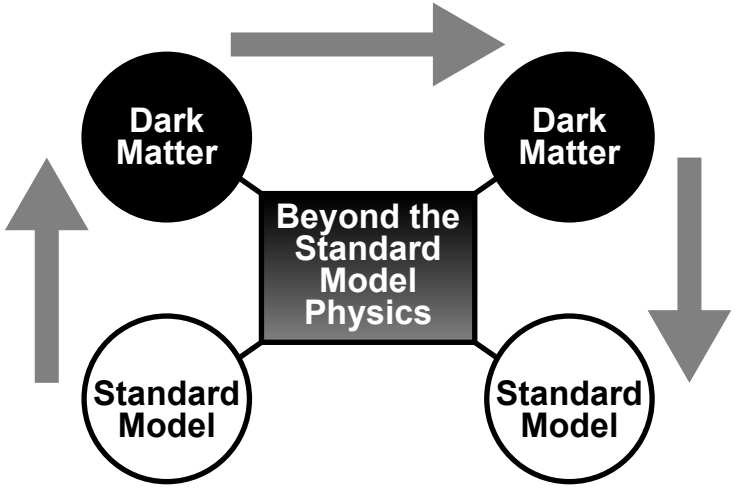
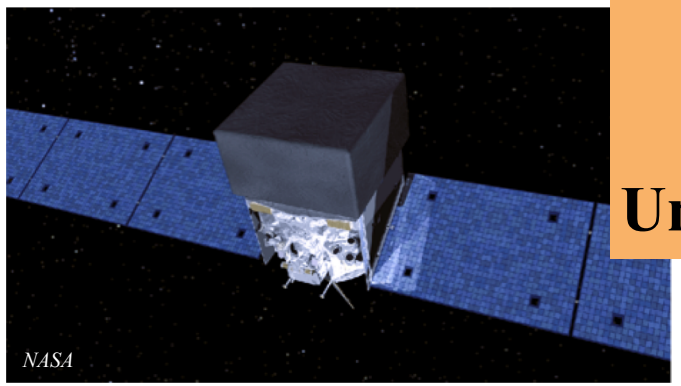
for the GAPS Collaboration
https://gaps1.astro.ucla.edu/gaps/people.php

Multimessenger Searches for Dark Matter

Goal:
Find evidence for dark matter

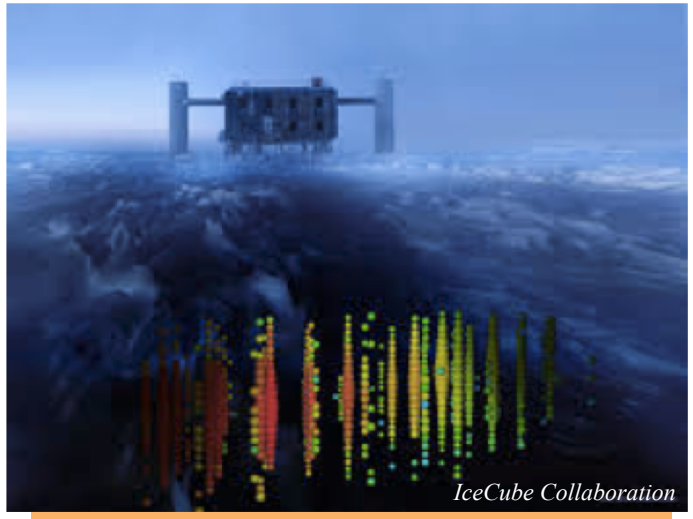


Need:
High signal-to-background
Good control of systematics



Photons:
Strong Signal
Unknown Background

Cosmic Rays:
Strong Signal
Uncertain Background

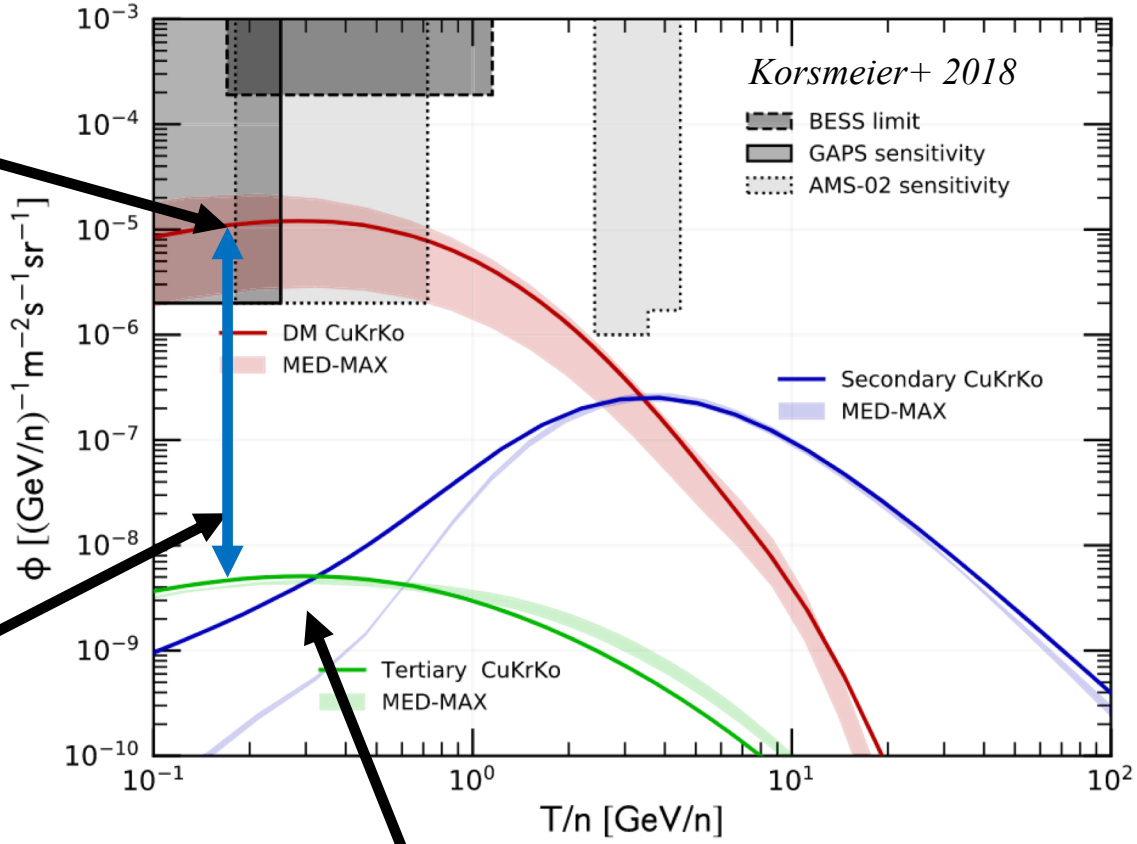


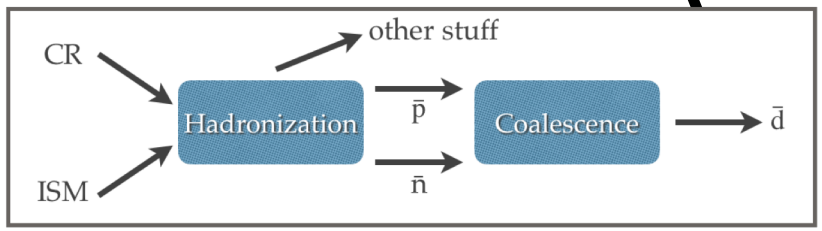
Neutrinos:
Weak Signal
Low Background

Antinuclei as Dark Matter Signatures

Antideuterons from dark matter model fit too AMS-02 antiproton excess.

High Signal-to-Background ratio = good channel for search.

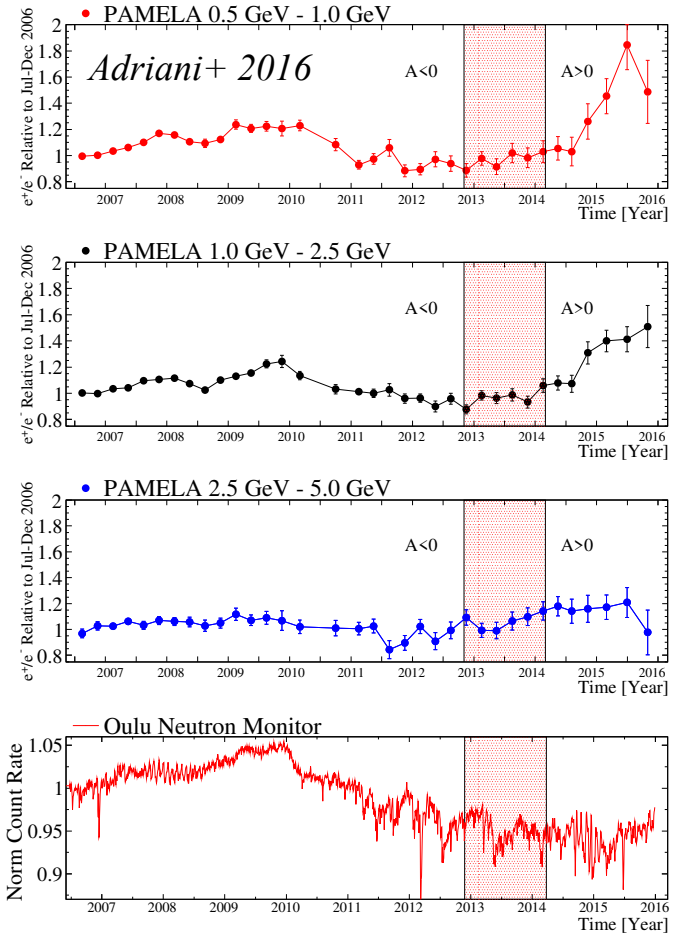




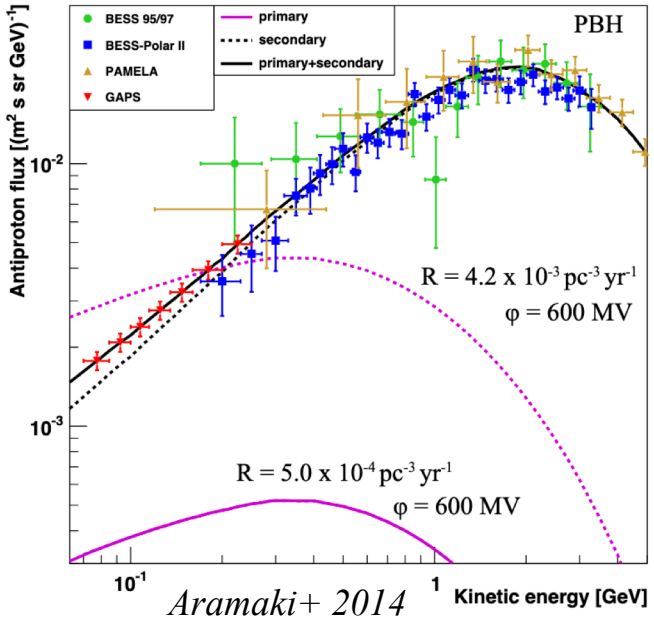
Low energy antinuclei are hard to produce due to kinematic effects

Science with Antiprotons

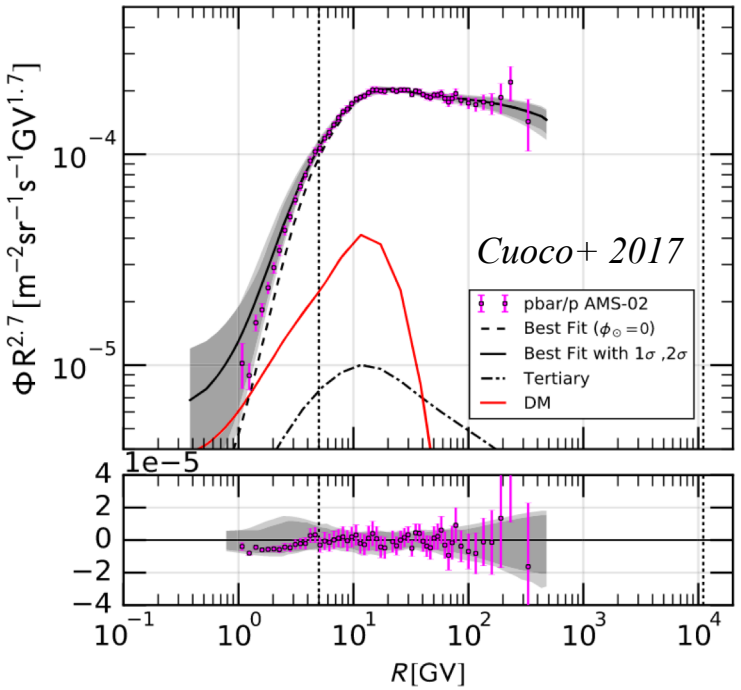
Solar modulation studies comparing proton / antiproton & electron / positron



Primordial black hole search



Antiproton excess fit with dark matter component. Low energy antiprotons will help clarify.



PAMELA and AMS-02 data have enabled detailed studies beyond the force field model. Charge and mass both important!

AMS-02 has a possible excess of antiprotons

GAPS: The General Antiparticle Spectrometer

- Antinuclei provide an excellent window for dark matter searches.
- With an almost background free signal they provide a very clean window.
- However, existing techniques (magnetic spectrometers) have challenges:
  - Energy threshold : not optimized for the low energies where dark matter signal dominates.
  - Background events : difficult to suppress (anti)protons to a low enough level.
- Solution:
  - Exotic atom technique → no background.
  - Dedicated Antarctic balloon → low energy threshold.

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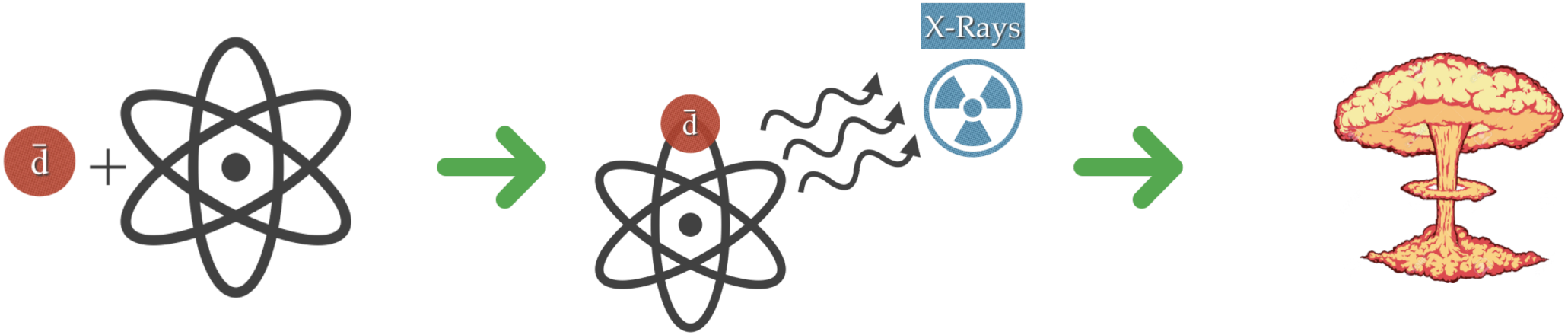
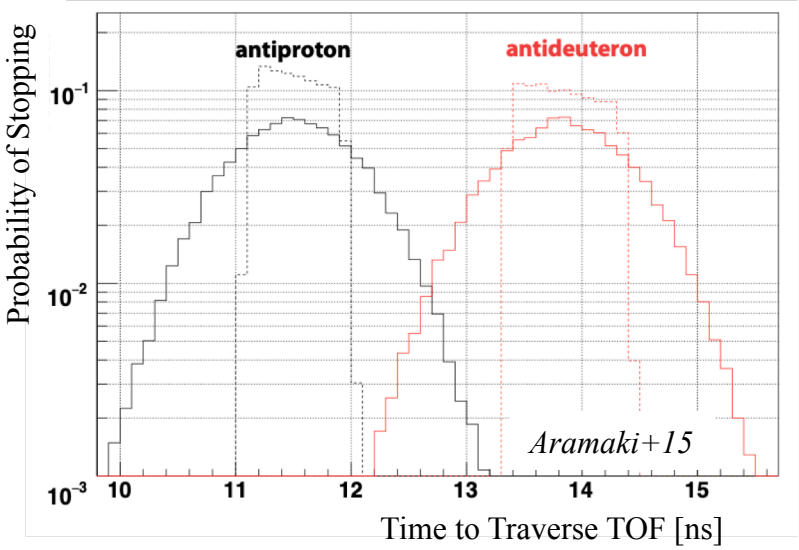
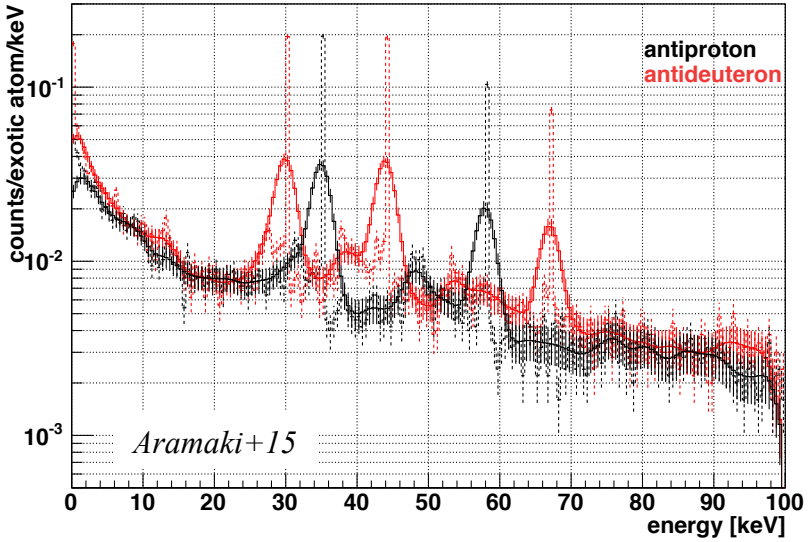
Exotic Atom Technique



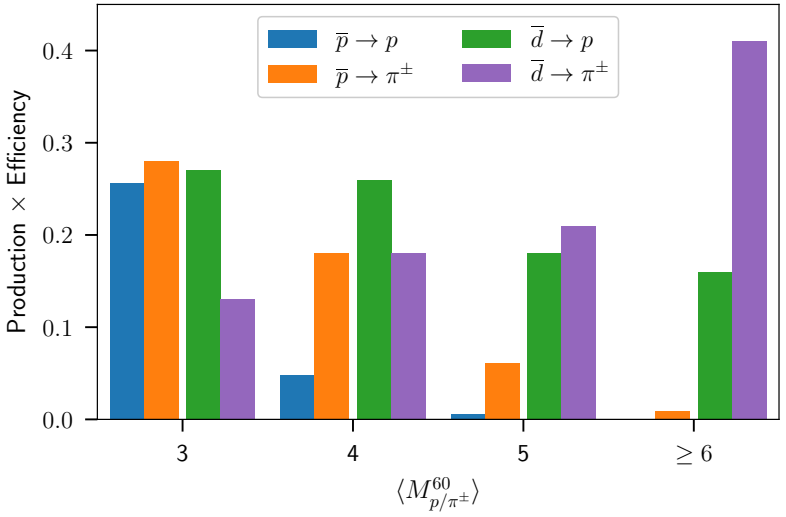
Stopping Depth



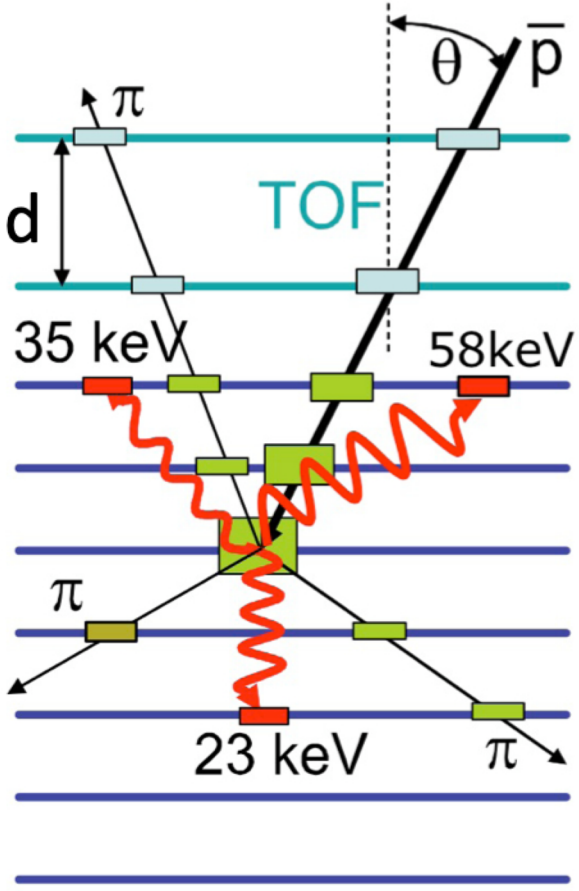
X-Rays



Number of Particles



From Concept to Detector



Shallow stopping depth
23, 35 & 58 keV X-rays
3 pions

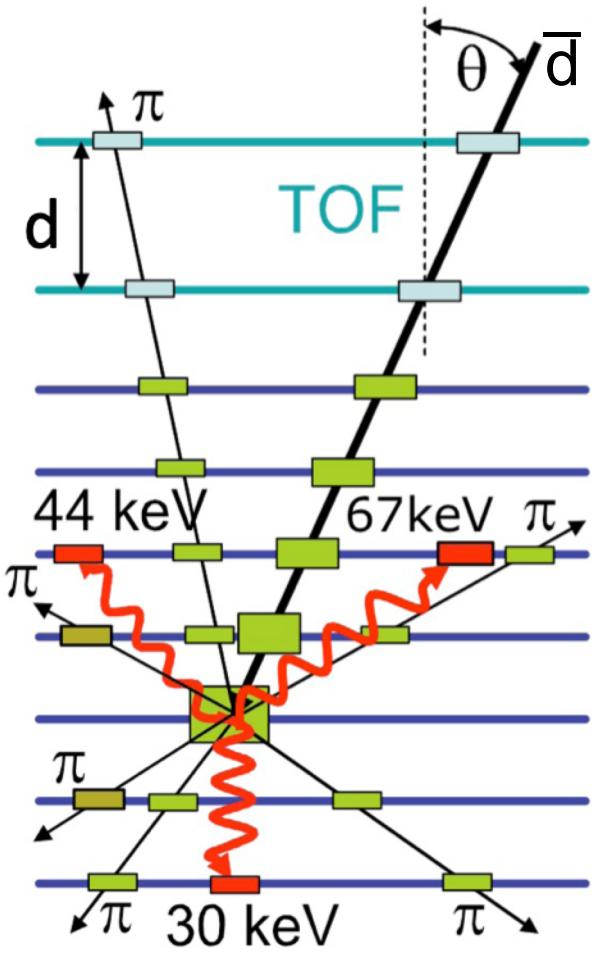
Aramaki+15

Plastic scintillator time of flight (TOF) measures primary velocity (β)

Si(Li) tracker slows primary measuring dE/dx

Primary stops, is captured and gives off X-rays which are measured by Si(Li).

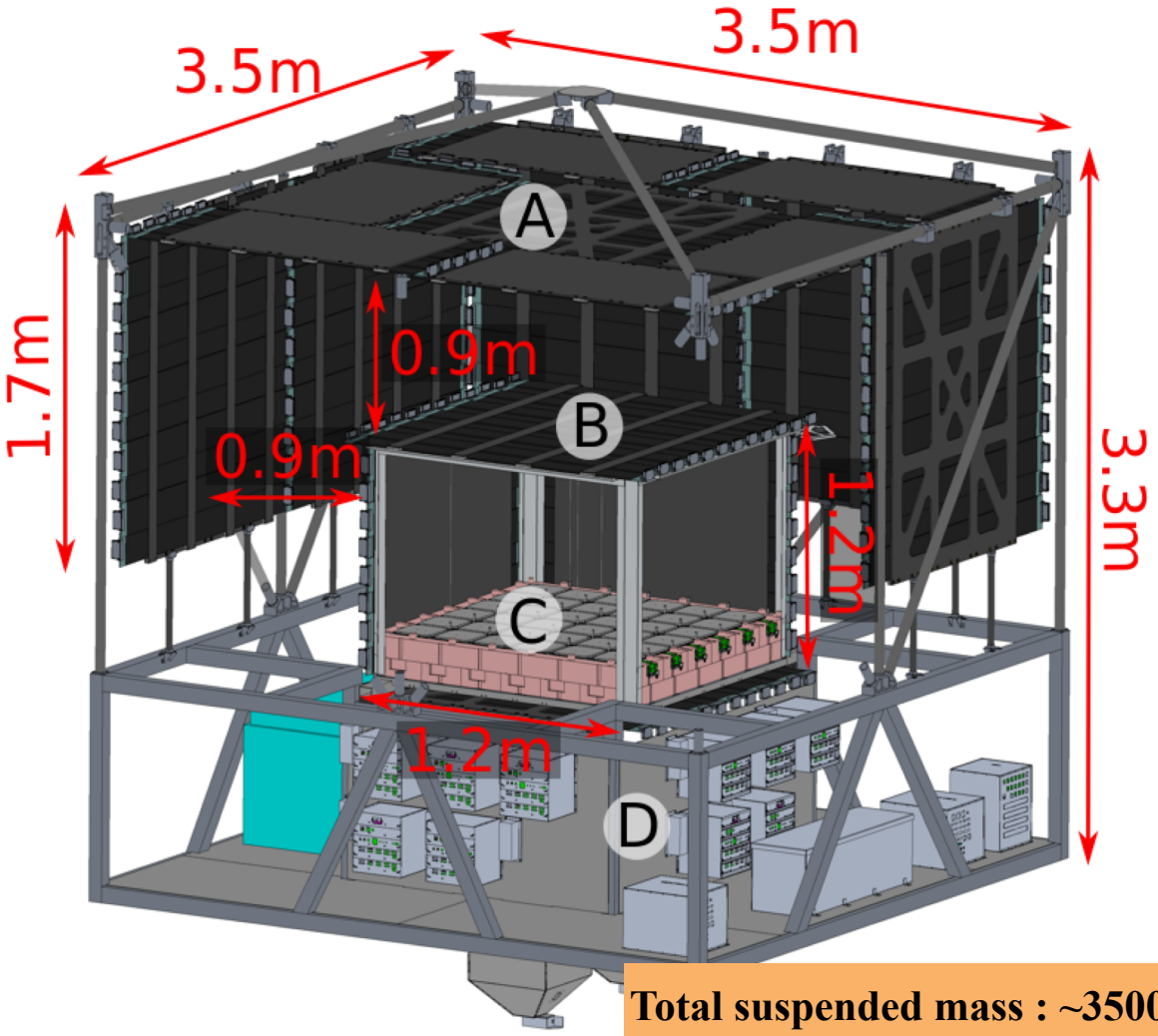
Primary annihilates, producing pions and protons, which are recorded by tracker and TOF.



Deep stopping depth
30, 44 & 67 keV X-rays
6 pions

GAPS Detector – Overview

- The detector consists of 2 instruments.
  - Si(Li) Tracker (C):
    - 1440 10 cm-diameter Si(Li) detectors over 10 layers.
    - Stops primary, detects X-rays, tracks secondaries
  - Time-Of-Flight (A, B):
    - Two layers of plastic scintillator paddles providing near 100% coverage.
    - Characterizes primary, counts secondaries, provides trigger
- In addition:
  - Cooling, power & thermal insulation (not shown)
  - Support systems (D)

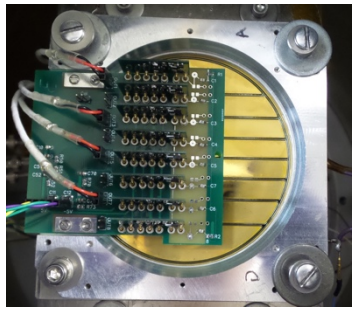


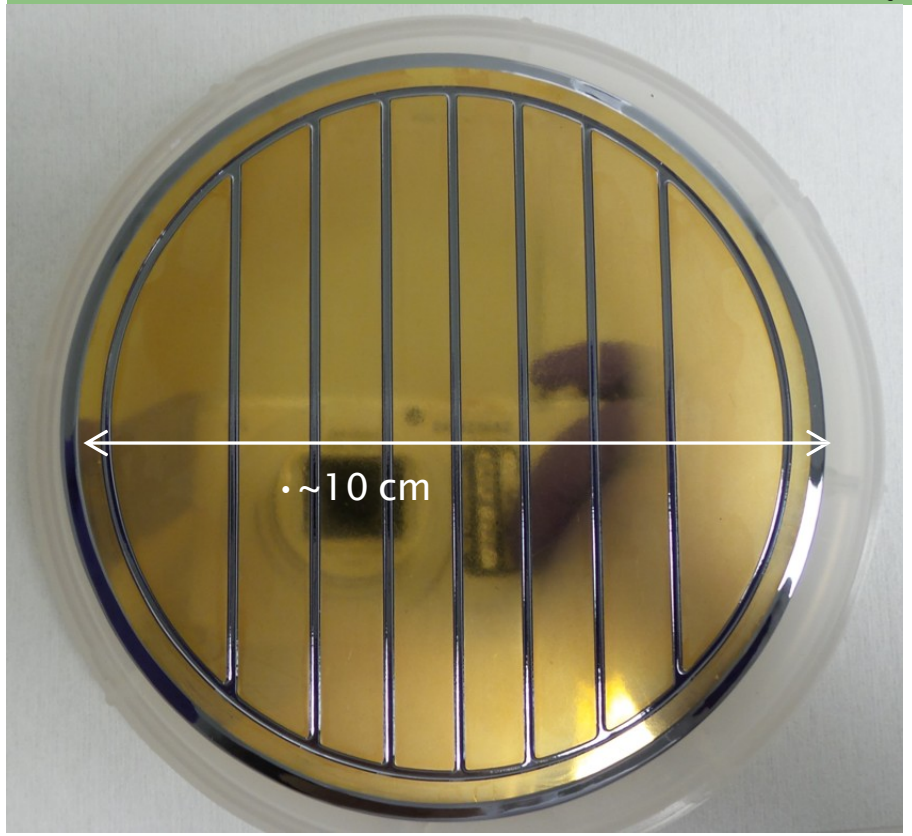
Total suspended mass : ~3500 kg
Total power generated : ~1.5 kW

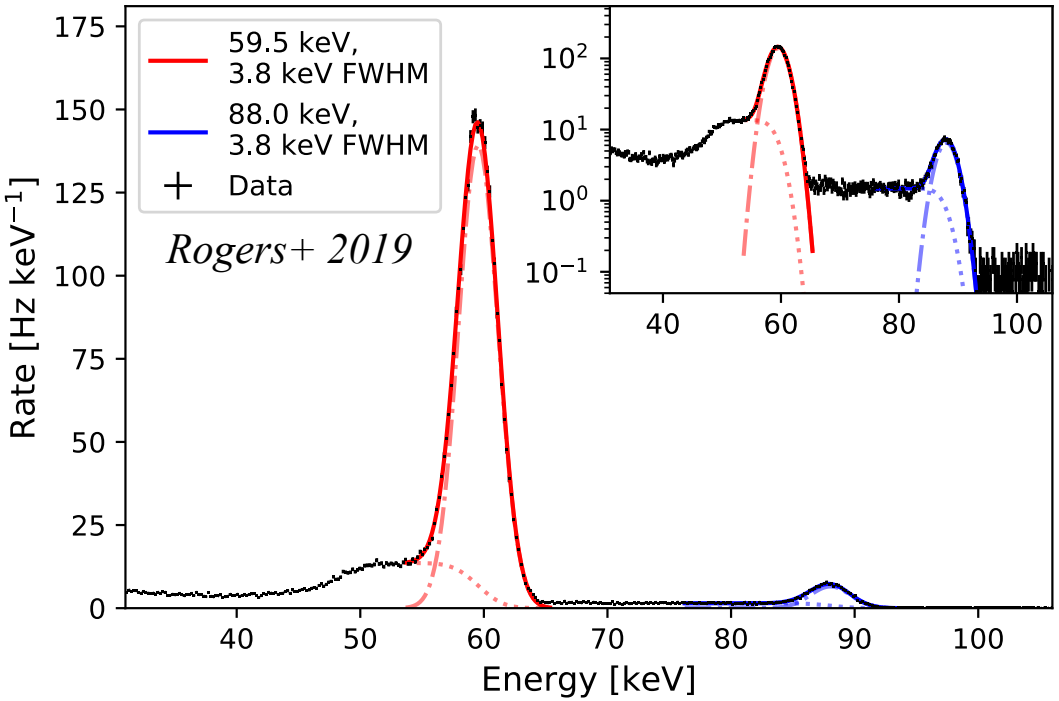
The GAPS Detector – Tracker

Large area, high temperature (< -45°C) detector system sensitive to X-rays and ionizing particles (~10 keV to 100 MeV).

Production method for 10 cm, 8 strip Si(Li) detectors developed. 350/1,440 detectors delivered by Shimadzu Corp.







4 strip detector with discrete component preamplifier. Noise in agreement with model to meet targets.

The GAPS Detector – Tracker Electronics

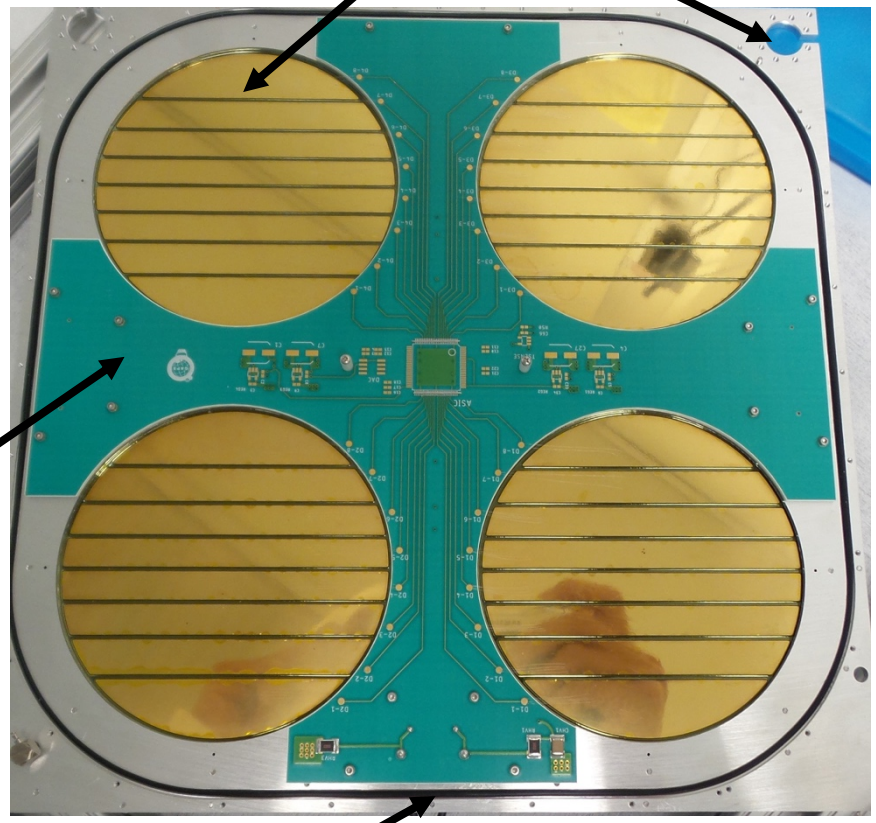
Silicon-Lithium Detector Readout (SLIDER) ASIC

32 analog readout channels

11 bits ADC with high dynamic range (10 keV to 100 MeV)

High resolution at X-ray energies (4 keV)

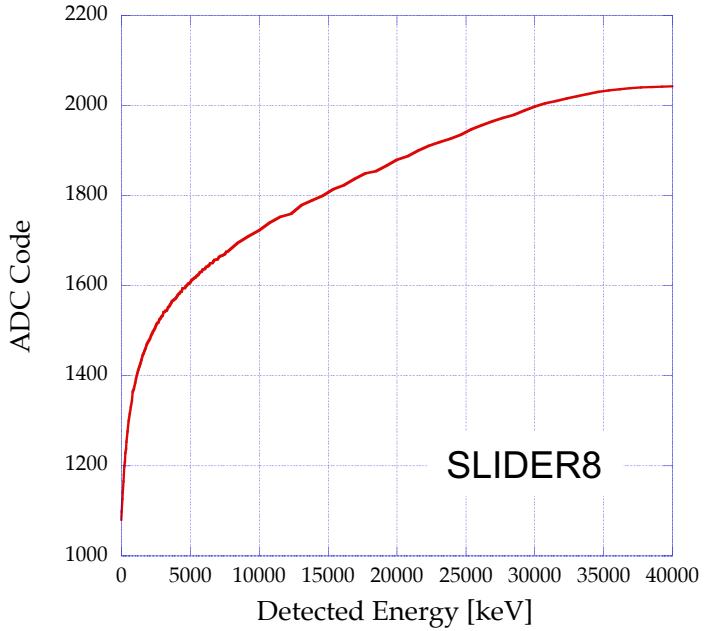
High-voltage power for detector modules and low-voltage power for front-end electronics.



8 channel prototype (SLIDER8) constructed and tested.

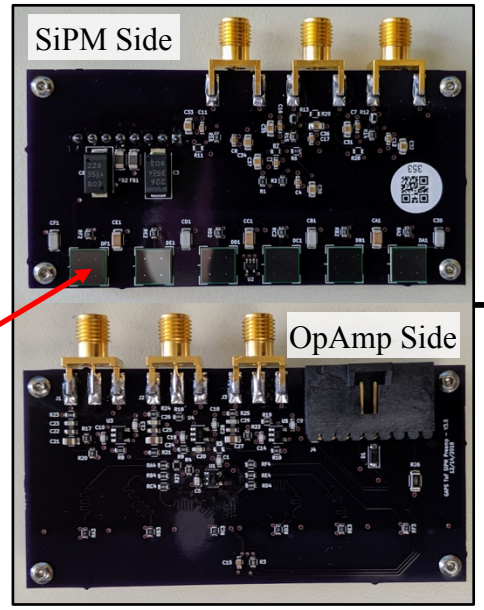
Full flight prototype (pSLIDER32) in production.

Dynamic signal compression provides high dynamic range

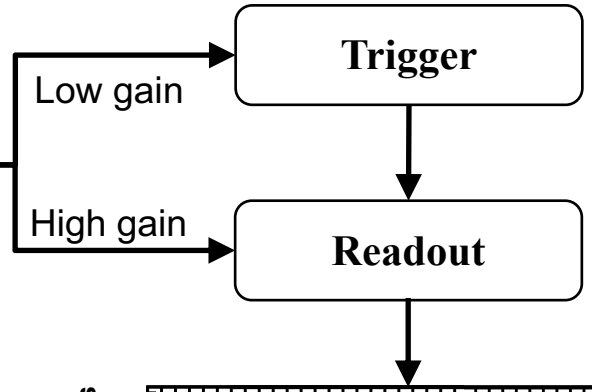


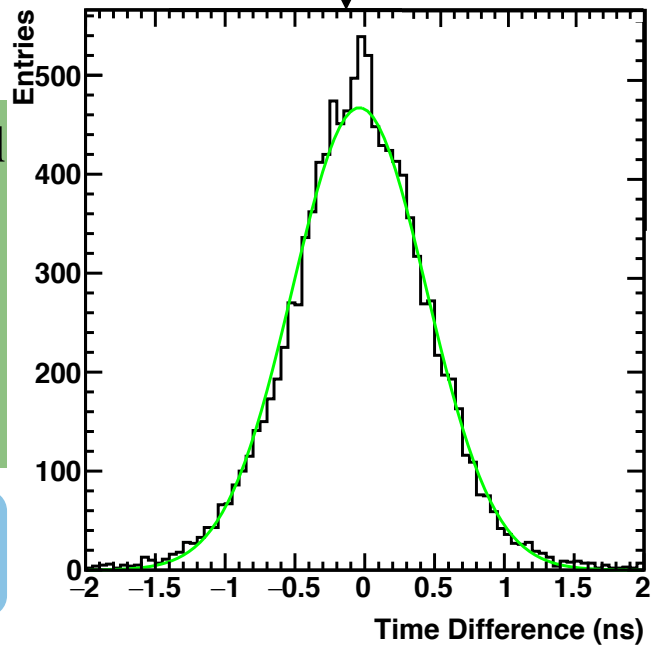
See Poster By V. Scotti for more details on the front end electronics.

The GAPS Detector – Time-Of-Flight



6x Hammamatsu S13360-6050VE





2 layers TOF:

Cube – inner layer that provides near 100% hermeticity around tracker.

Umbrella – outer layer that covers all tracks with an incident zenith angle <60º.

Hierarchical trigger detects low velocity primaries with multiple secondaries.

Triggered signals digitized using DRS4 readout board

Lab testing using vertical, central muons

Timing Resolution = $\sigma(t_A - t_B)/\sqrt{2}$ = 340 ps

Requirement = 500 ps

See Poster By S. Quinn for more details on the TOF development.

The GAPS Detector – Cooling

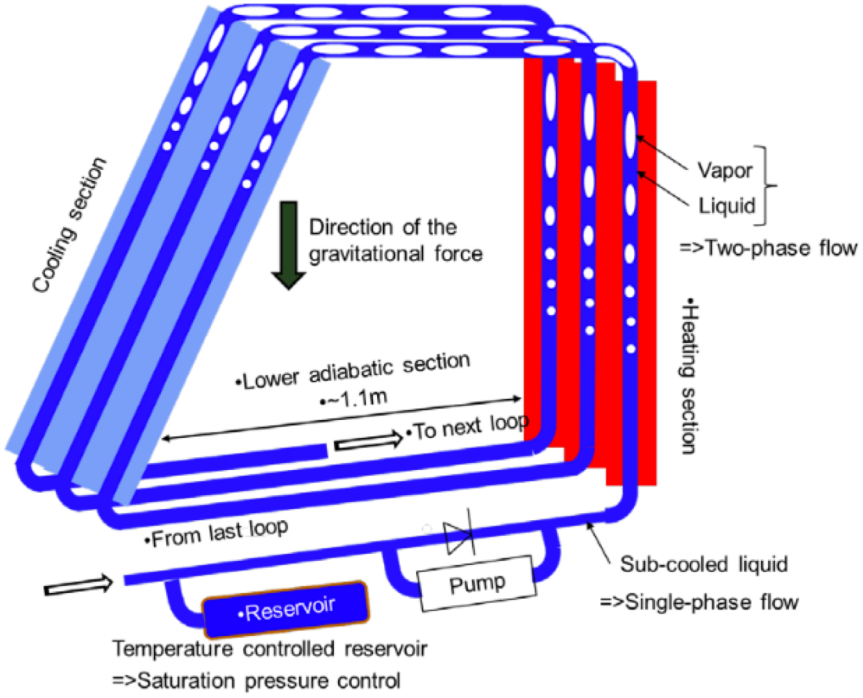
GAPS will use a novel oscillating heat pipe (OHP) cooling system.

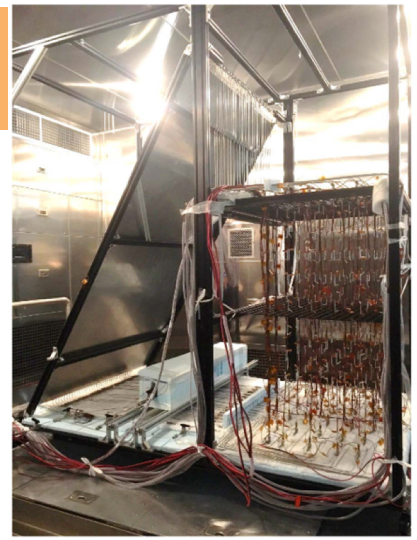
A two-phase working fluid will transfer the heat using passive circulation and self-oscillation around 36 loops connected in series.

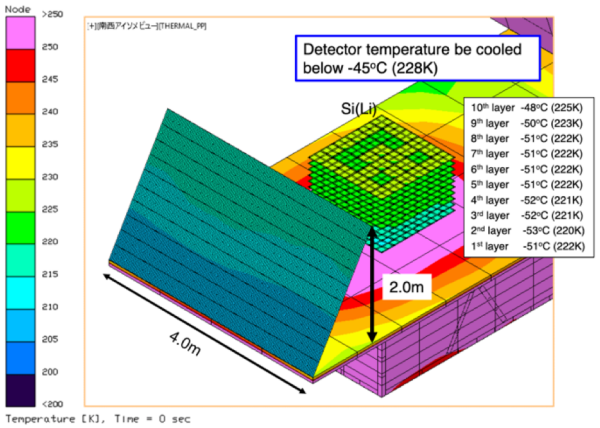
Additional active components are included for system robustness

A scaled radiator was flown piggyback on the NASA/BPO #689 (SIFT) payload in Fall 2018.

Lab engineering models have verified the operation of a large scale system







Full thermal modelling shows achieving required temperatures throughout flight.

Analysis and Reconstruction

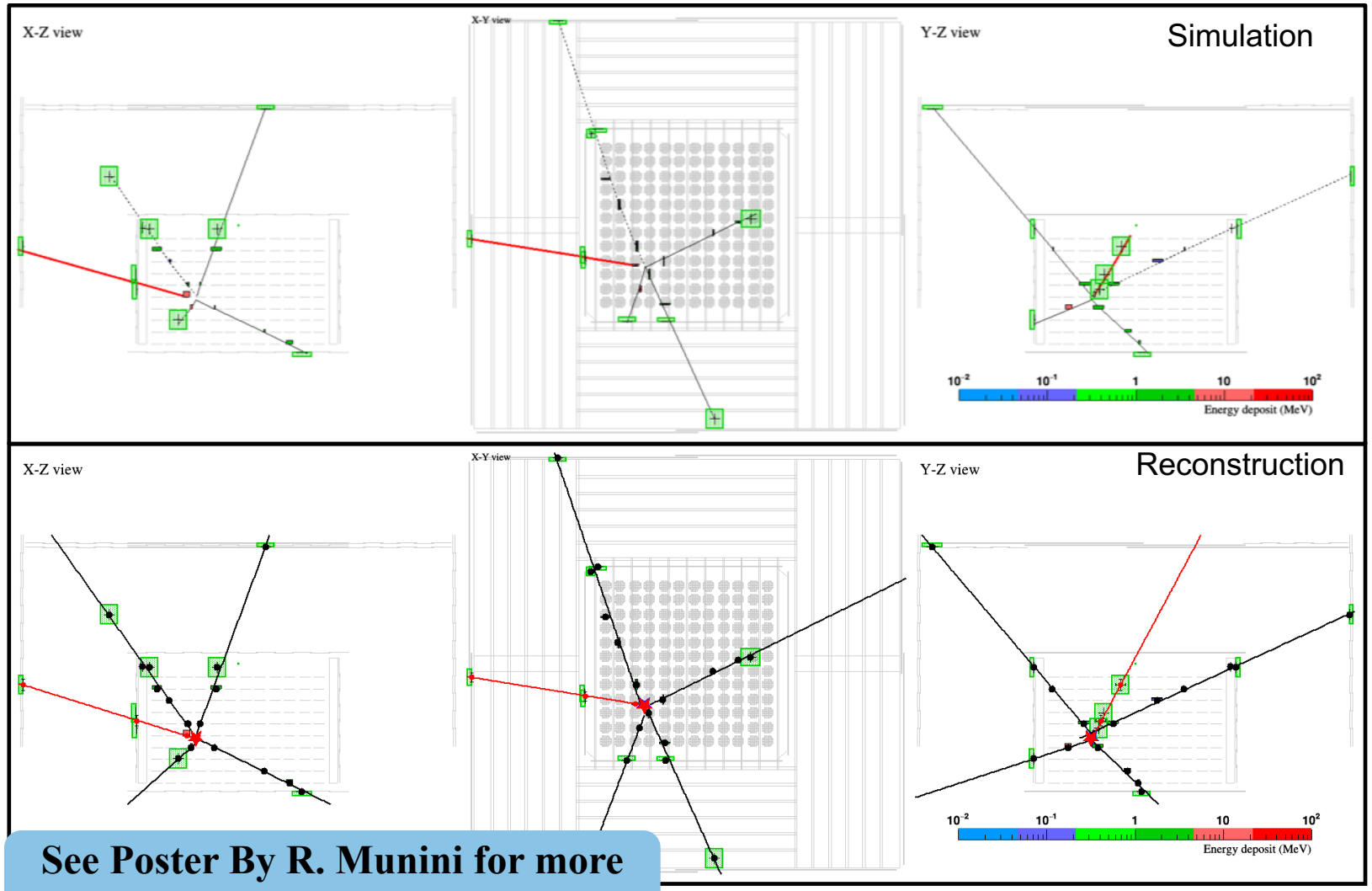
Testing of GEANT4 has identified improvements in the handling of antinuclei. Results cross checked against beam test data (KEK 2004, *Aramaki+13*).

Analysis will require effective background rejection.

Existing methods meeting requirements, further work ongoing.

Reconstructing events with unknown vertex at > 60% reconstruction efficiency with an error on reconstructed position < 70mm (68% containment)

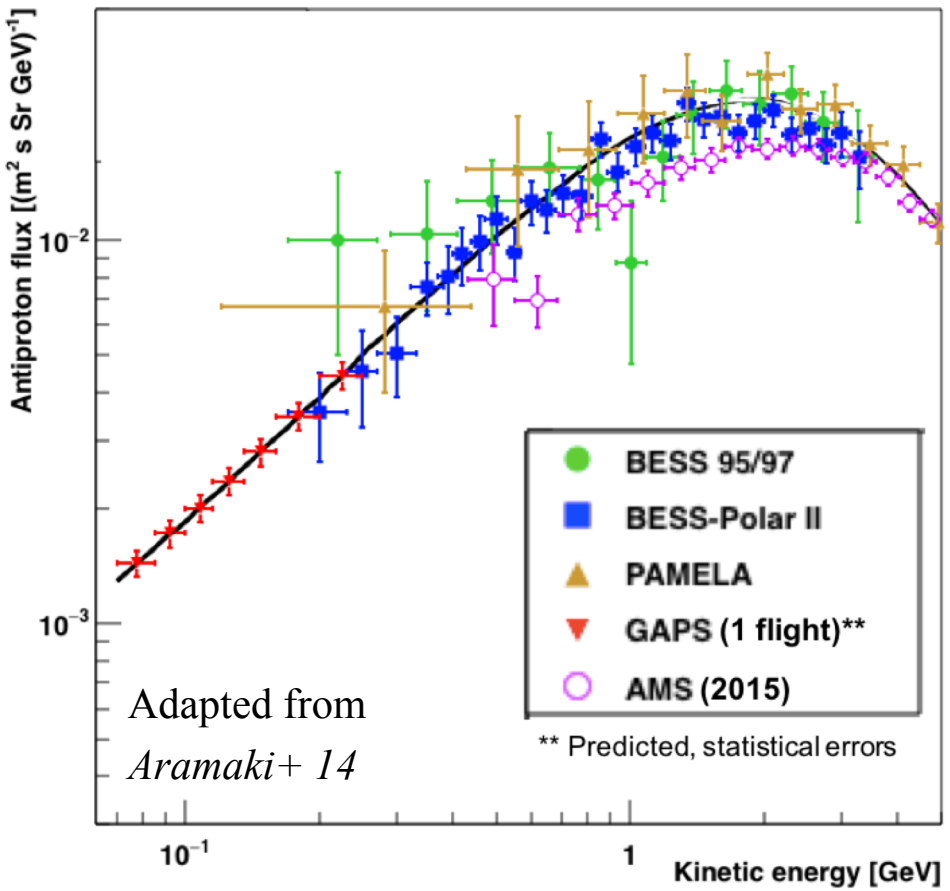
Antideuteron, β = 0.54



See Poster By R. Munini for more details on the event reconstruction.

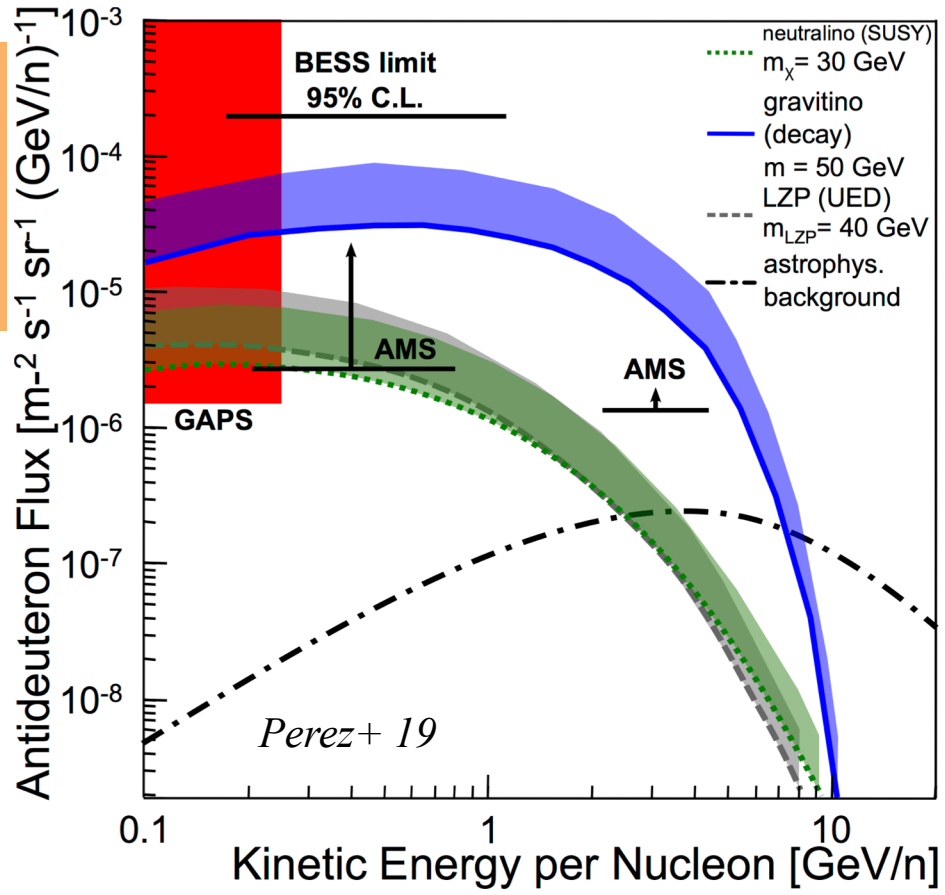
Sensitivity

One flight – The best measurement of low energy antiprotons.



GAPS will also be sensitive to antihelium. Sensitivity calculations in progress!

Three flights – The most sensitive low energy antideuteron search.



Antinuclei provide a complementary channel for indirect dark matter searches

GAPS will search for low energy antinuclei and provide the best low energy measurement of antiprotons to date

Using the exotic atomic technique, it will provide a sensitive, complementary search to existing rigidity measurements

Significant progress has been made since funding started in 2017, including a successful CDR in January 2019

GAPS is on course for a first flight in the austral summer of 2021-22

FIRST FLIGHT

2012	2013	2014-6	2017	2018	2019	2020	2021	2022	2023
pGAPS flight	Data Analysis		Funding Starts		CDR	Functional Prototype	Integration	Data Analysis	

NASA