

The GAPS Project: Antarctic Balloon Flight for Antinuclei-Based Indirect Dark Matter Searches



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Outline

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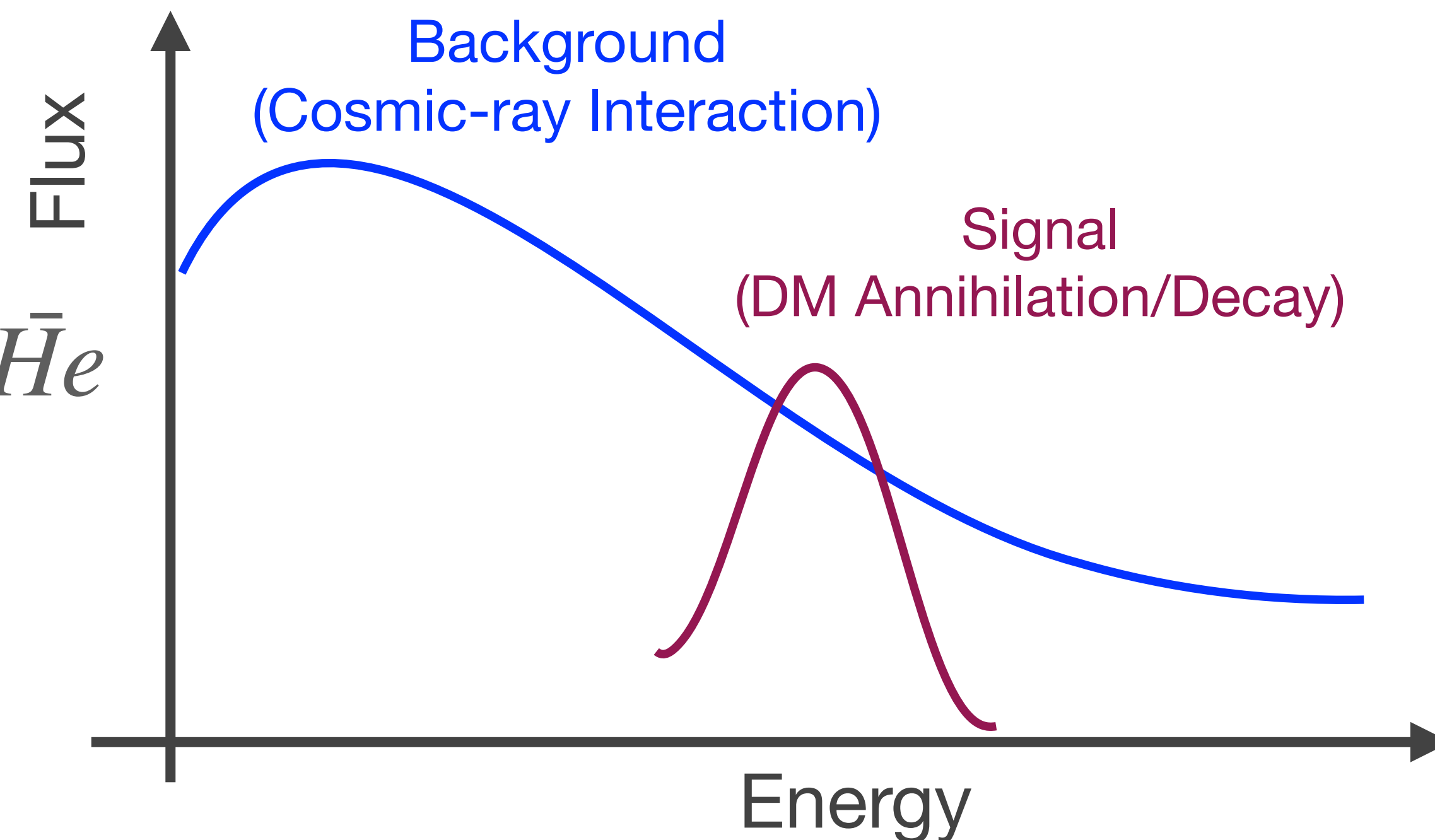
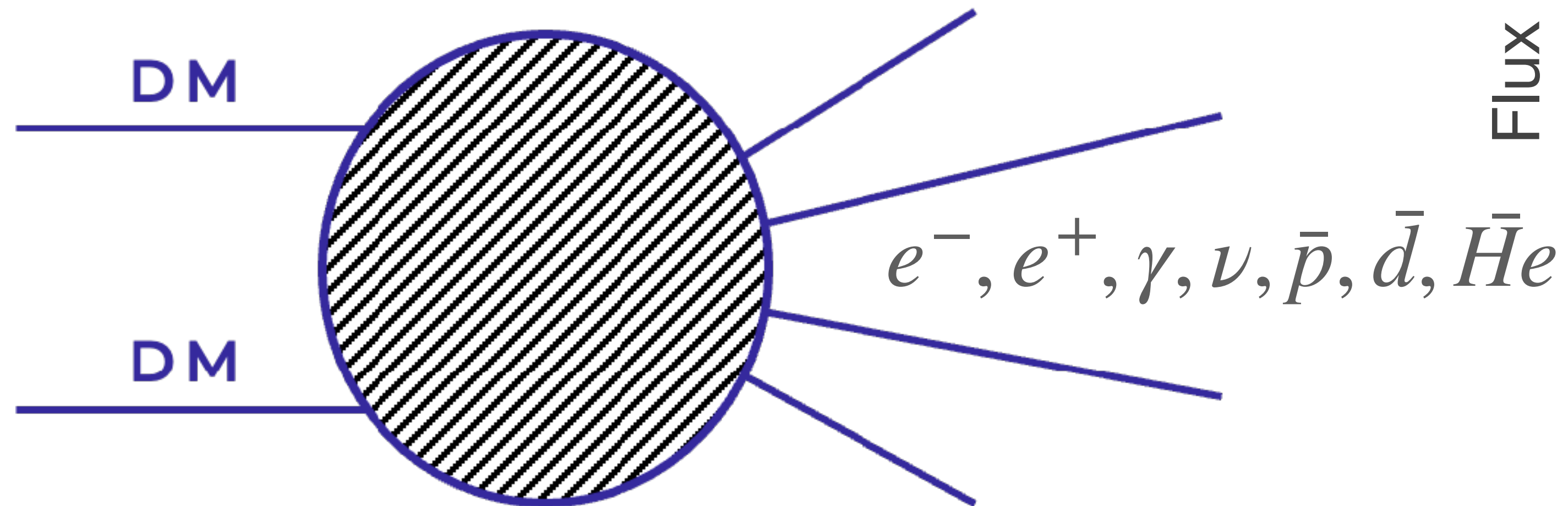
- Indirect DM searches
- GAPS mission
 - Detector design
 - Detection method/particle identification techniques
 - Current status
- Summary



Indirect Dark Matter Searches

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Measure DM annihilation/decay products



- Positron: AMS-02, PAMELA, Fermi-LAT ...
- Gamma-ray: Fermi-LAT, CTA, GRAMS...
- Neutrino: IceCube, ANTARES...

- Antiproton: AMS-02, **GAPS**, GRAMS
- Antideuteron : AMS-02, **GAPS**, GRAMS
- Antihelium: AMS-02, **GAPS**, GRAMS

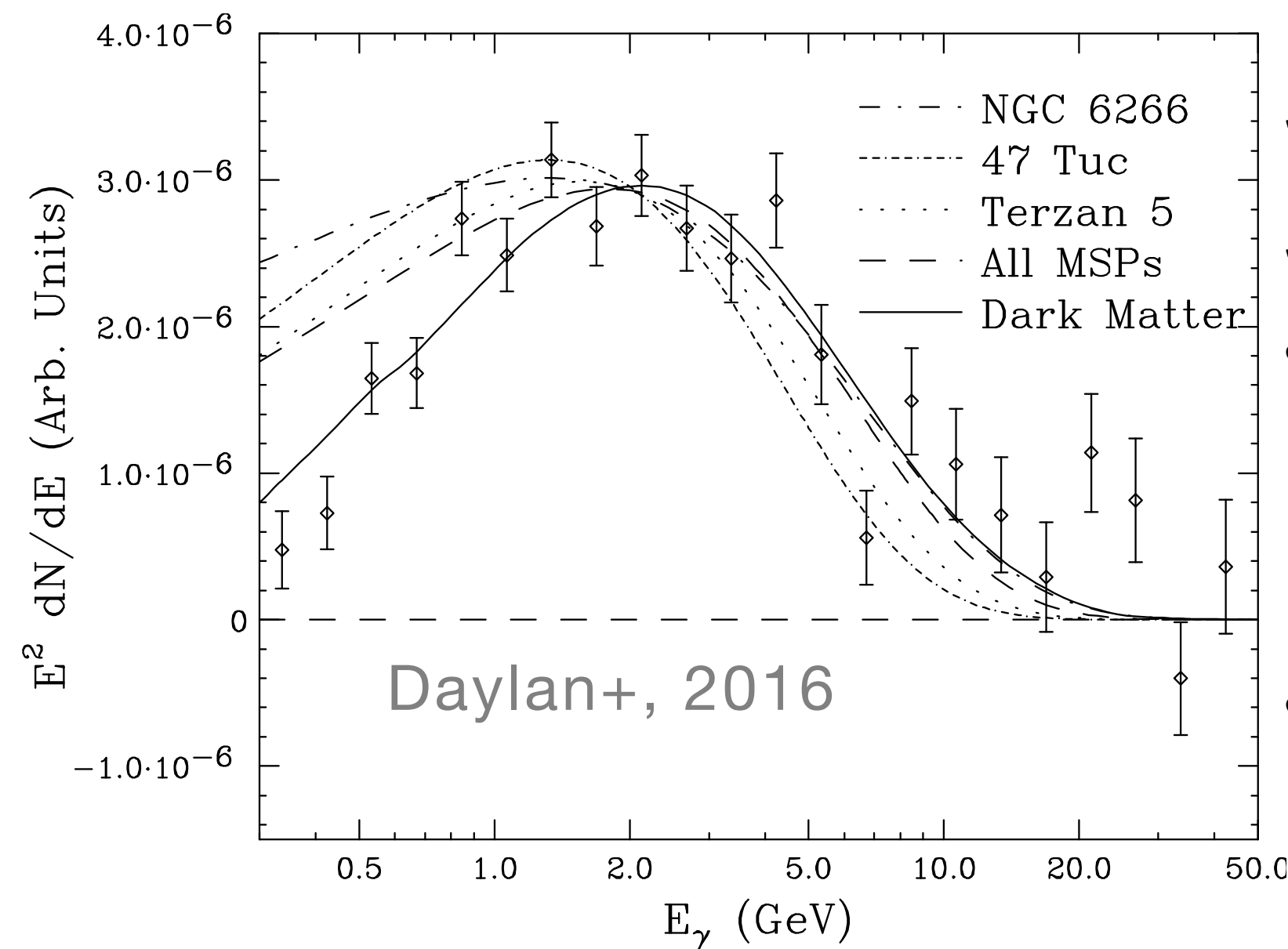


Indirect Dark Matter Searches: Recent Results

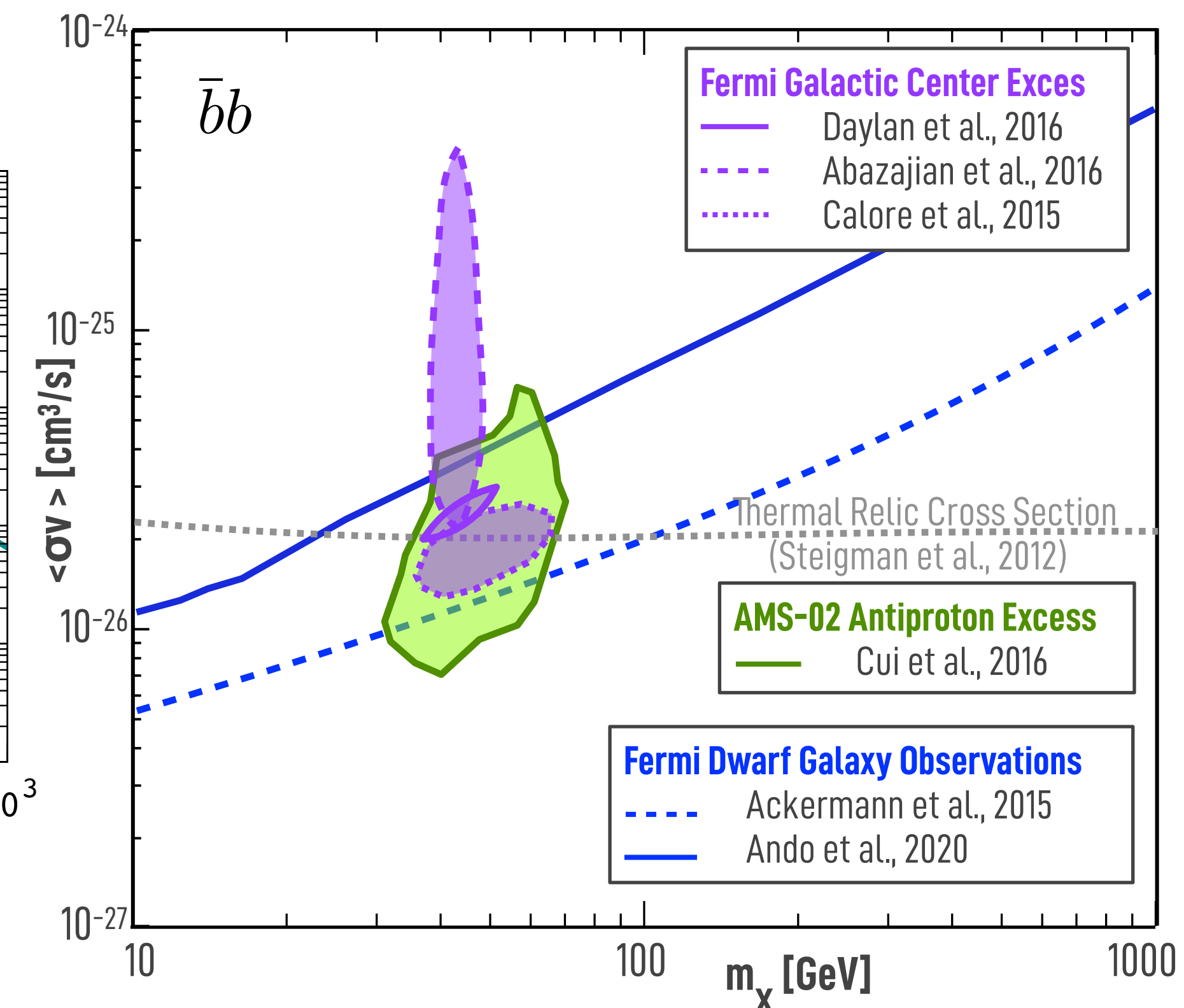
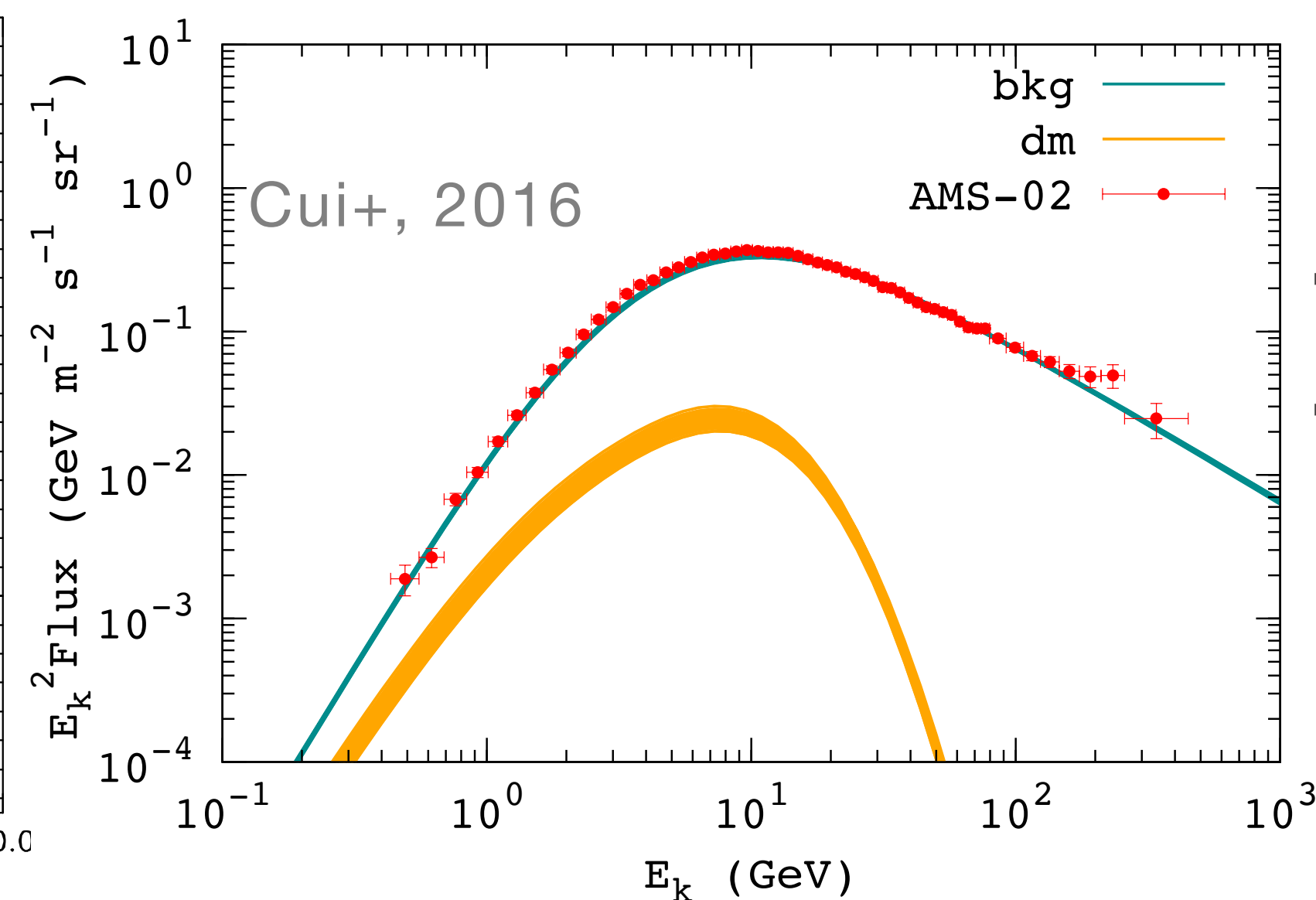
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- Potential DM signatures in Fermi/AMS-02 measurements
- Detection of antideuteron/antihelium-like events in AMS-02

Fermi gamma-ray excess



AMS-02 antiproton excess



How do we validate these results?



GAPS Mission

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GAPS = General AntiParticle Spectrometer

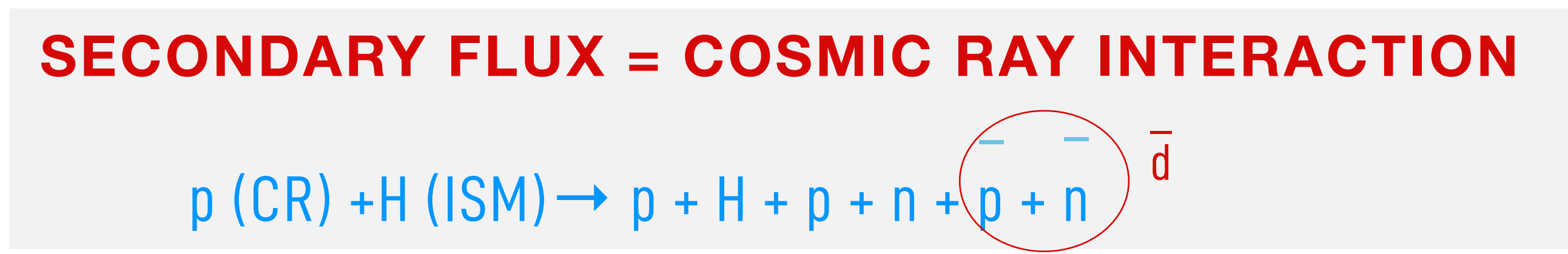
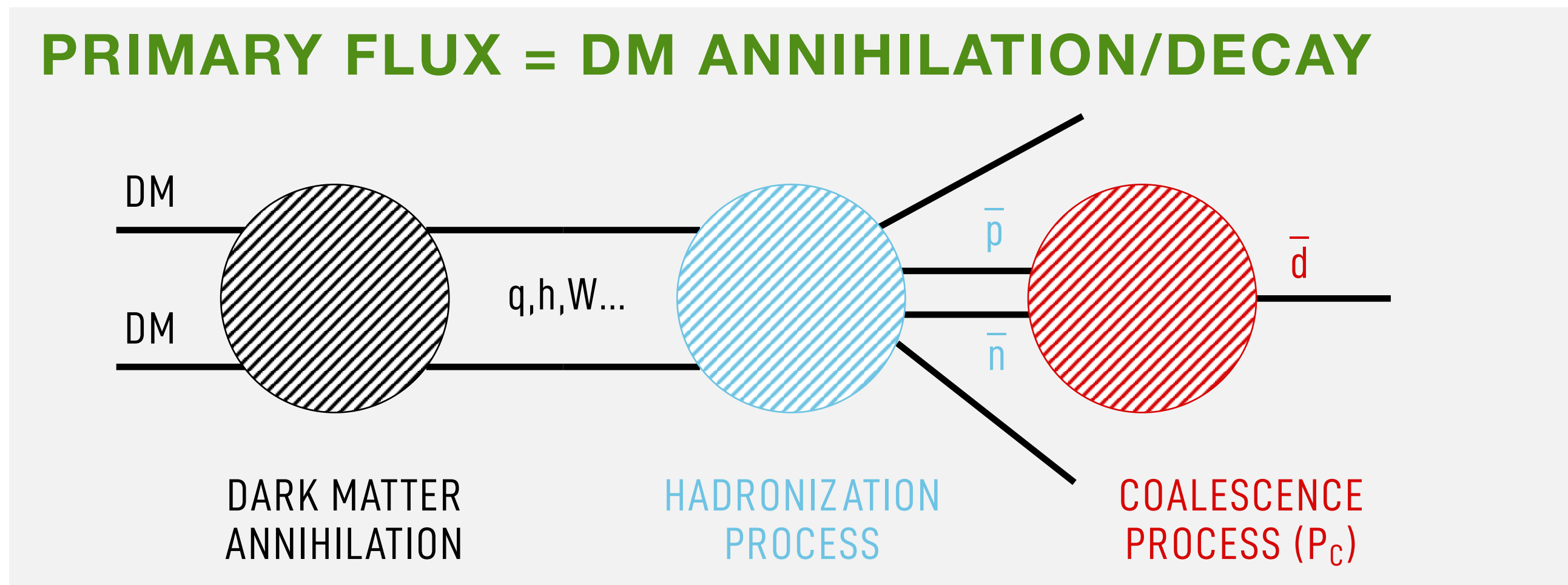
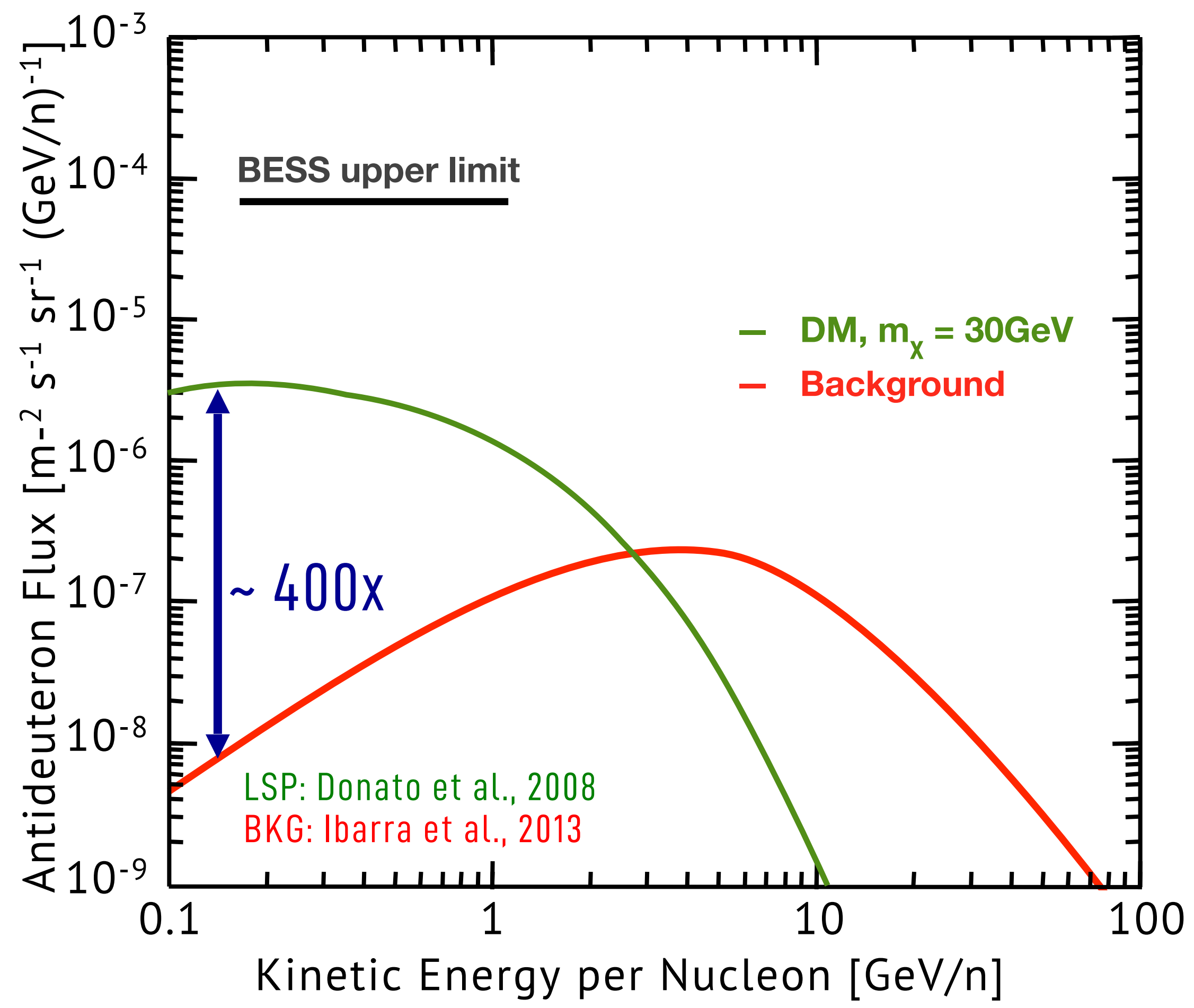
- First experiment optimized for low-energy antinuclei measurements
 - Background-free dark matter searches with antideuteron
 - High-statistics antiproton measurements at low energy
 - Uniquely approach and potential detection of antihelium
- First science balloon flight is scheduled from the Antarctic in 2024



Why Antideuteron?

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Background-free dark matter searches at low energy

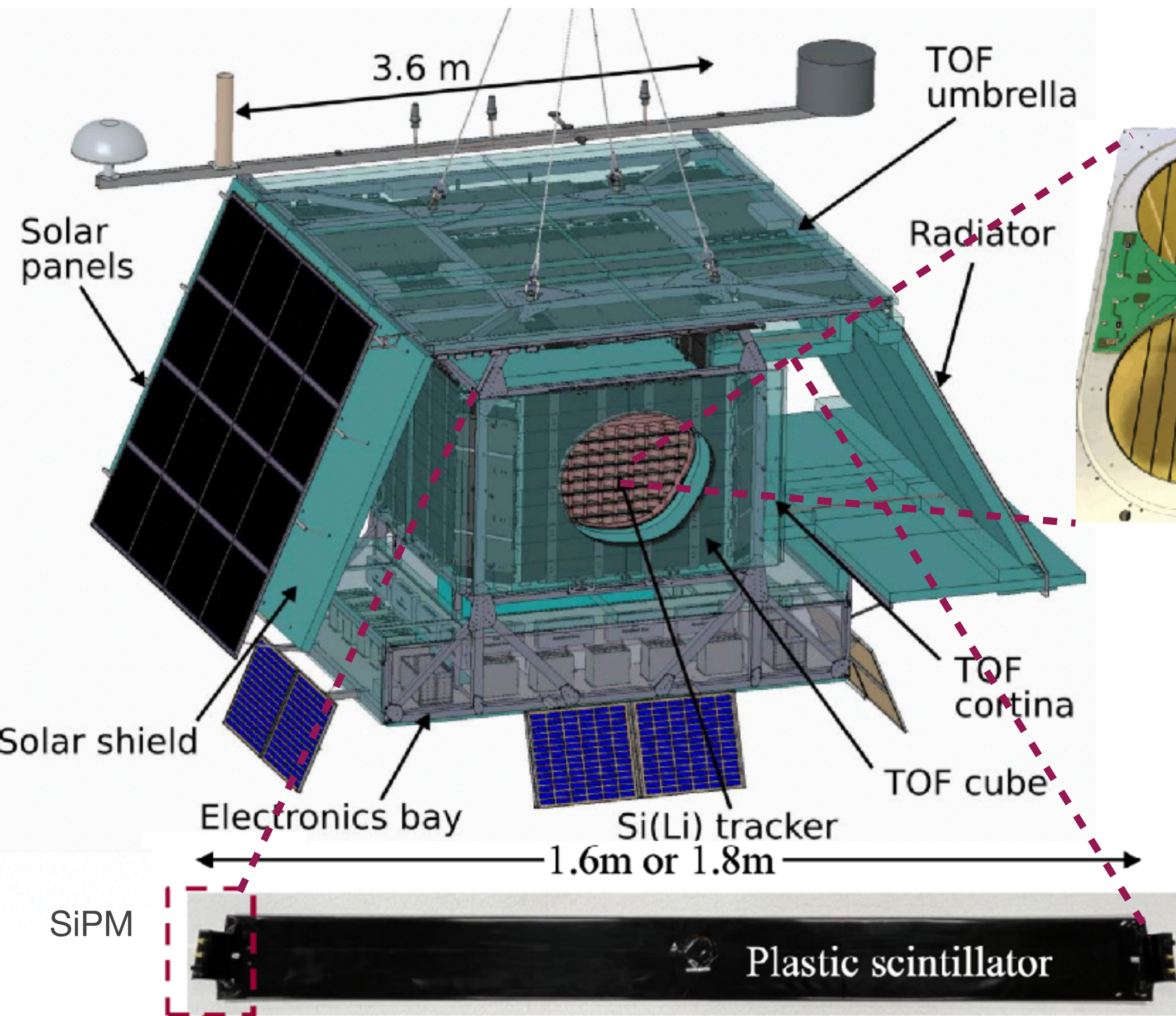




GAPS Detector Design

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Si(Li) tracker surrounded by plastic scintillators



Total Power: ~1.3 kW, Mass: ~2,500 kg

Si(Li) Tracker

- X-ray/charged particle measurements
- 10 layers of Si(Li) detectors
 - 4-inch diameter, 2.5 mm thick
 - 8 strips -> 3D particle tracking
- Operation at ~-35C
 - OHP cooling system

Time of Flight (TOF) System

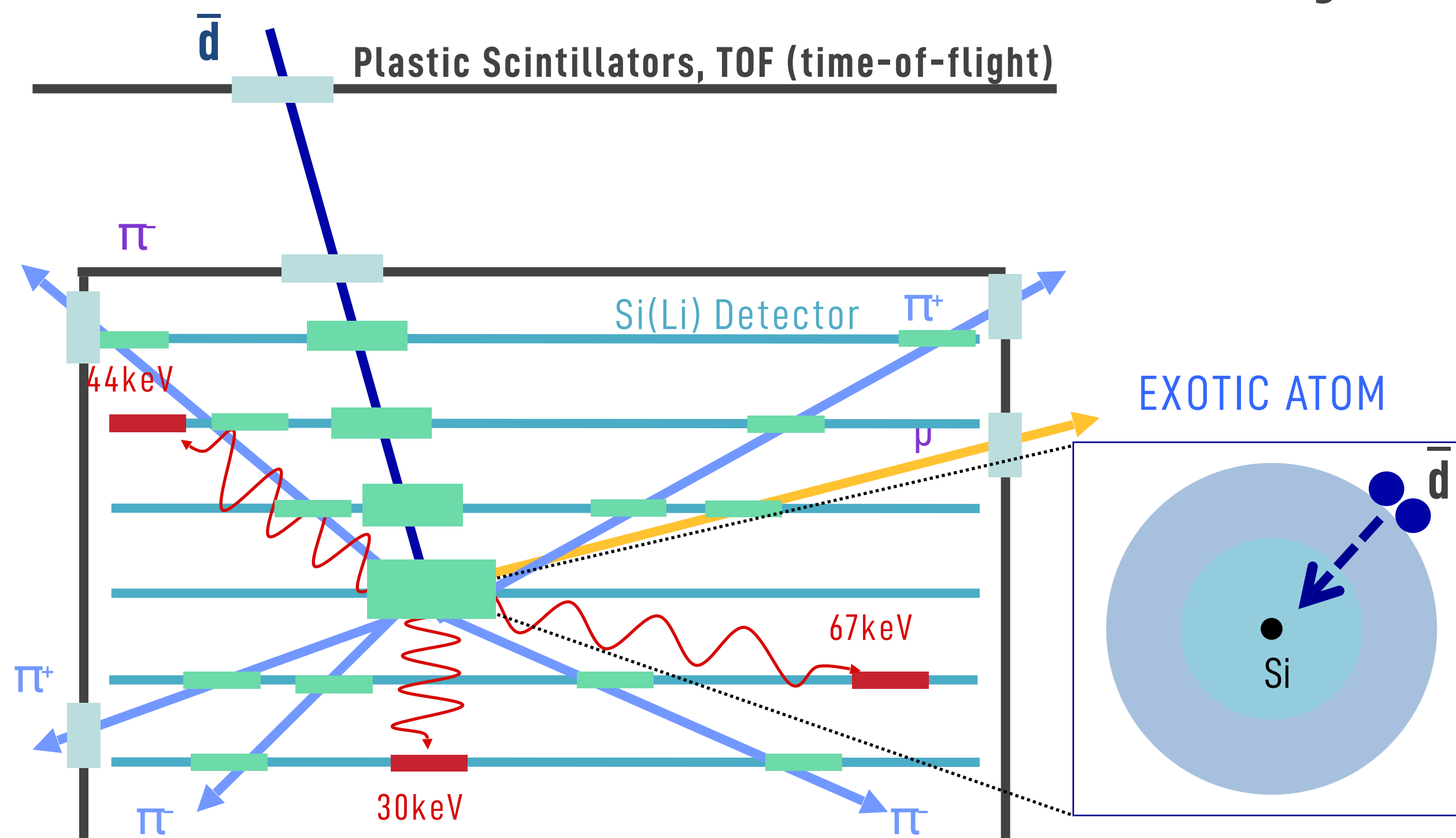
- Particle tracking, velocity and dE/dx measurements, and high-speed trigger
- Inner and outer TOF layers
 - ~6mm thick plastic scintillators
 - 6 SiPMs on each end



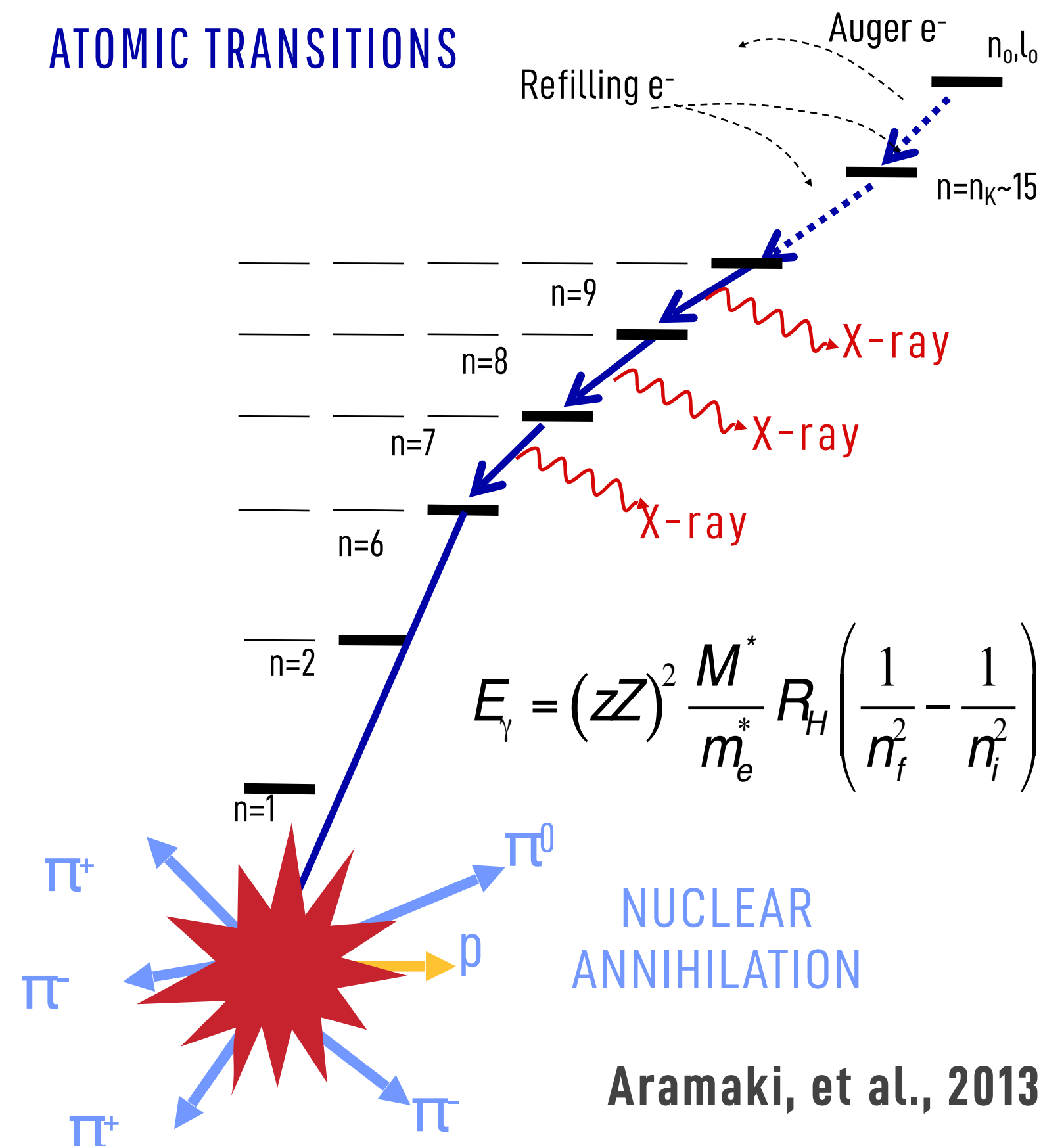
GAPS Detection Concept

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Measure atomic X-rays and annihilation products



ATOMIC TRANSITIONS



Aramaki, et al., 2013

- TOF system tags candidate events and records velocity
- The antiparticle slows down & stops, forming an excited exotic atom
- De-excitation X-rays provide signature
- Annihilation products provide additional background suppression

- Concept proven with accelerator beam test
- Cascade model developed for X-ray yields



GAPS Antideuteron Identification Techniques

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CR p , $e^\pm$ rejection = antiproton and antideuteron selection

- Select **slow particles** with TOF
- Simultaneous detection of secondary/annihilation products (pions/protons)
 - Slow CR p and $e^\pm$ may not be able to produce secondary particles

Antideuteron identification techniques

atomic X-rays from exotic atom

- different energy

pion/proton multiplicity

- different energy more for antideuteron

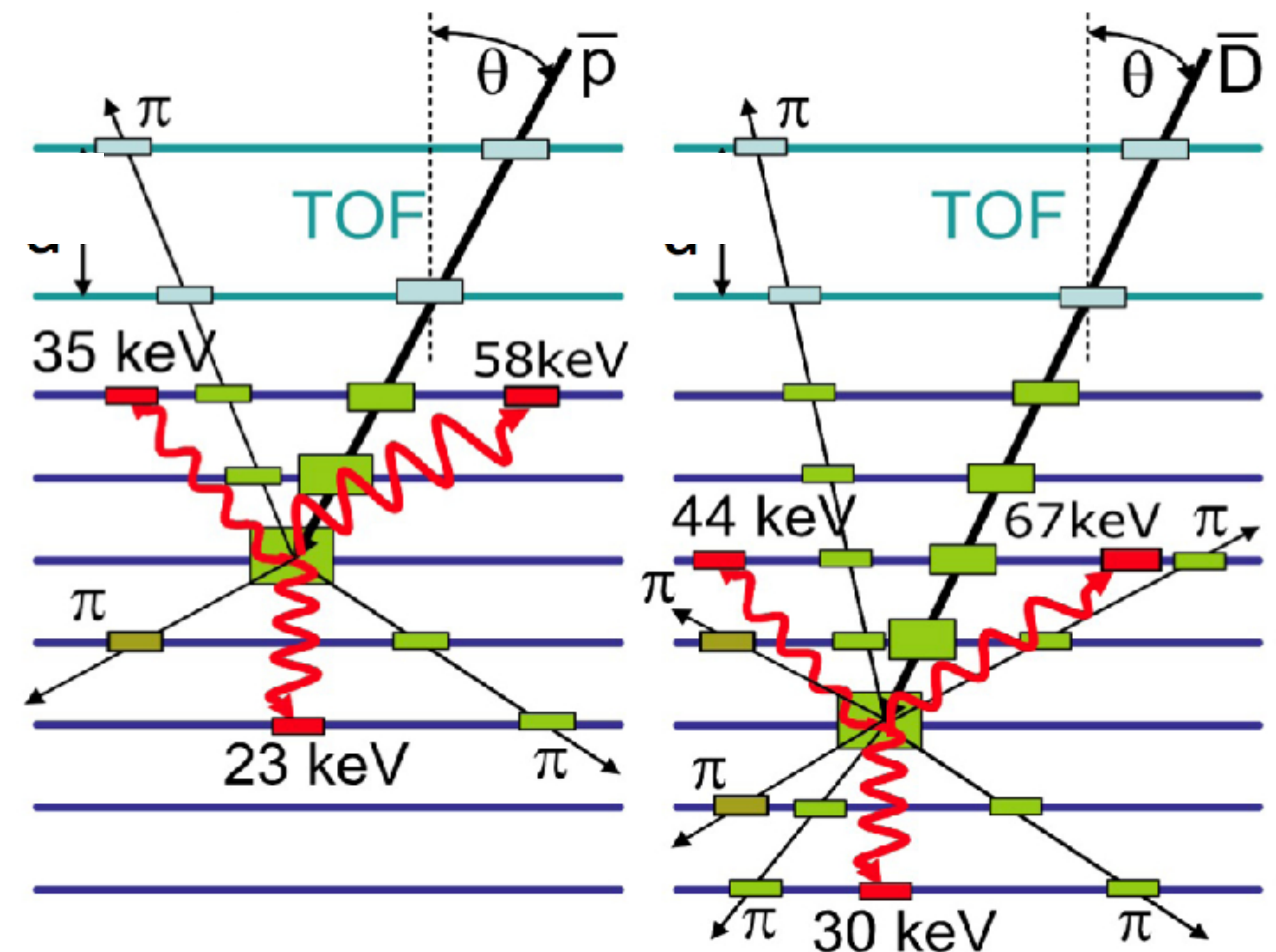
stopping range (depth sensing)

- antideuteron go deeper

dE/dX energy deposit in layers

- more for antideuteron

Expected background: ~ 0.01 events

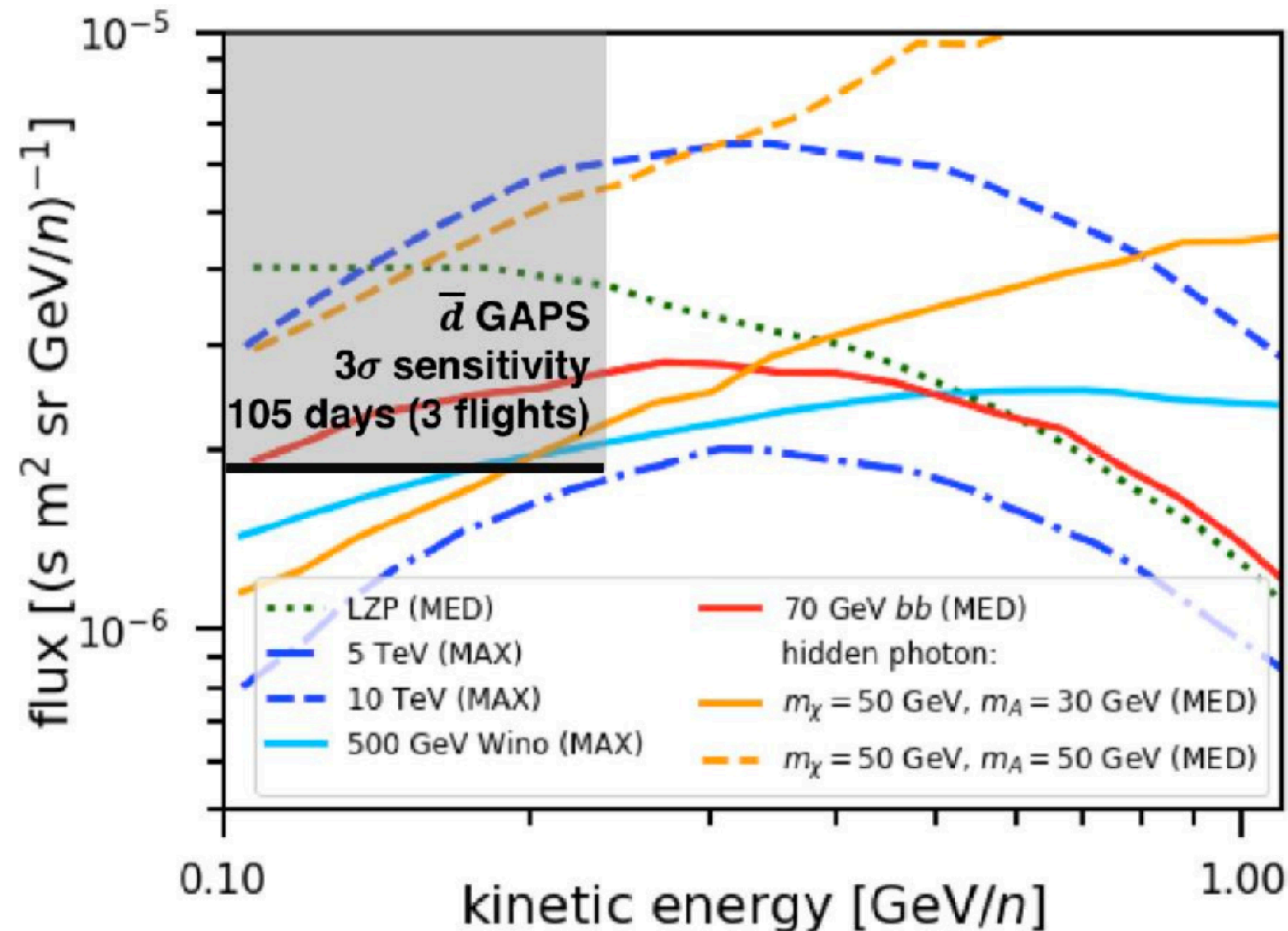




Sensitivities to Antideuteron

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Sensitive to a wide range of dark matter models



- Generic 70-GeV WIMP annihilation
 - Could explain Fermi/AMS results
- Gravitino dark matter decay
- Extra dimensions theory
- Dark photons
- Heavy DM models
 - Sommerfeld enhancement

Korsmeier+ 2018, Dal+ 2014, Baer+ 2005, Randall+ 2020, Braeuninger+ 2009, Hryczuka+ 2014

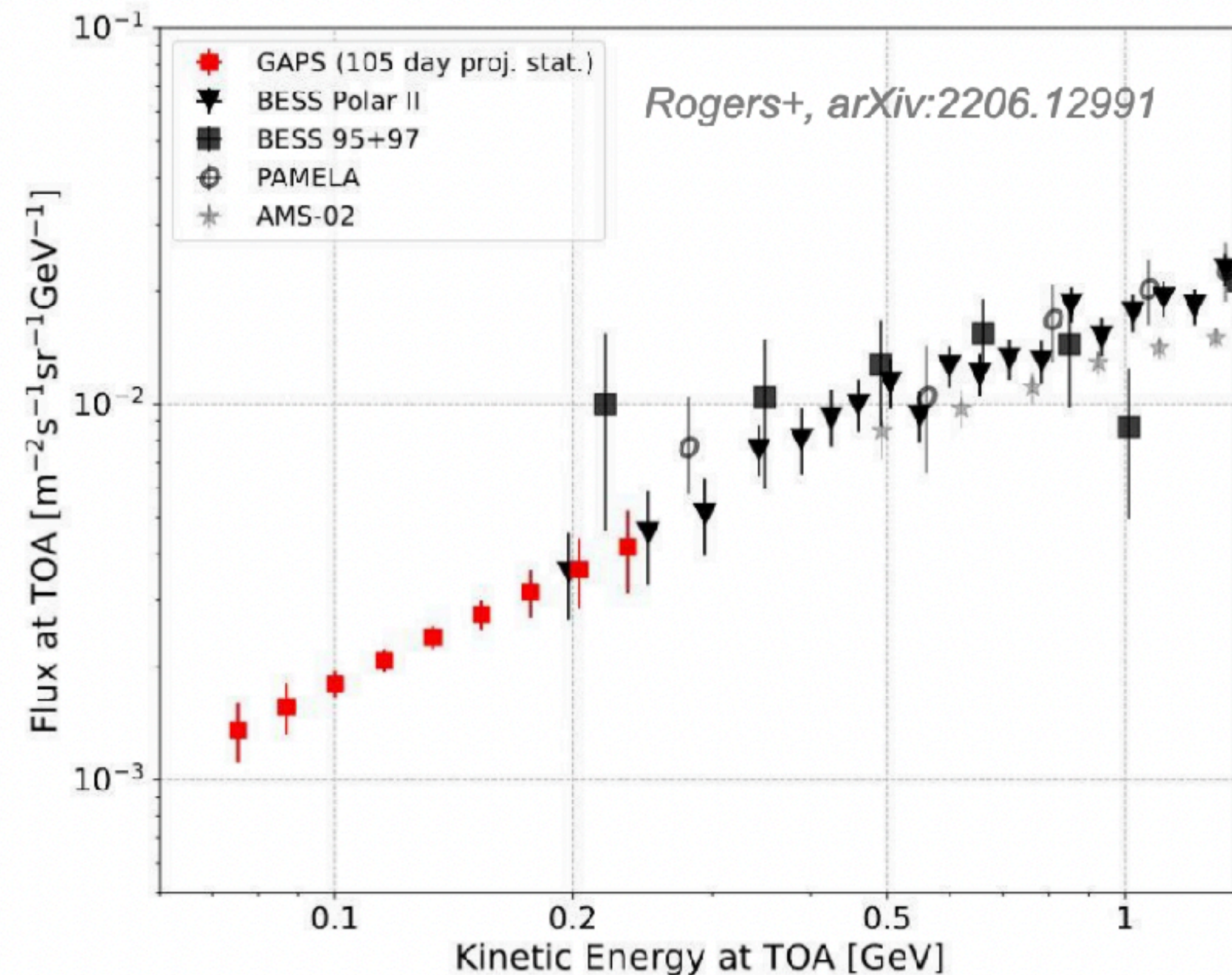


Sensitivities to Antiprotons and Antiheliums

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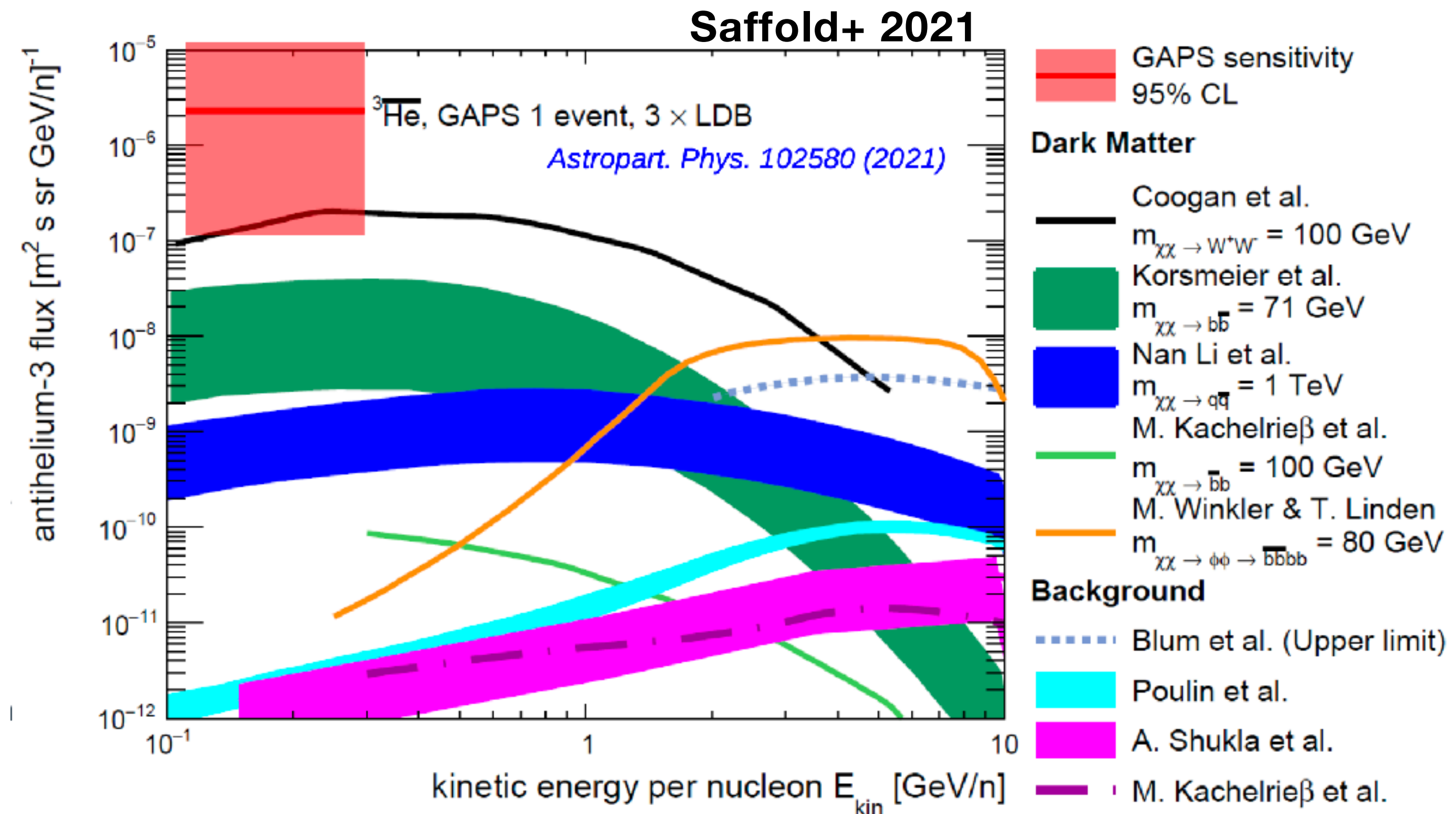
Antiprotons

- Precision measurements ($\sim 20\times$ statistics)
- Low-mass DM search
- Propagation model, solar modulation studies
- Verification of antiparticle detection



Antiheliums

- Complementary to AMS-02
- Potentially explore some DM models



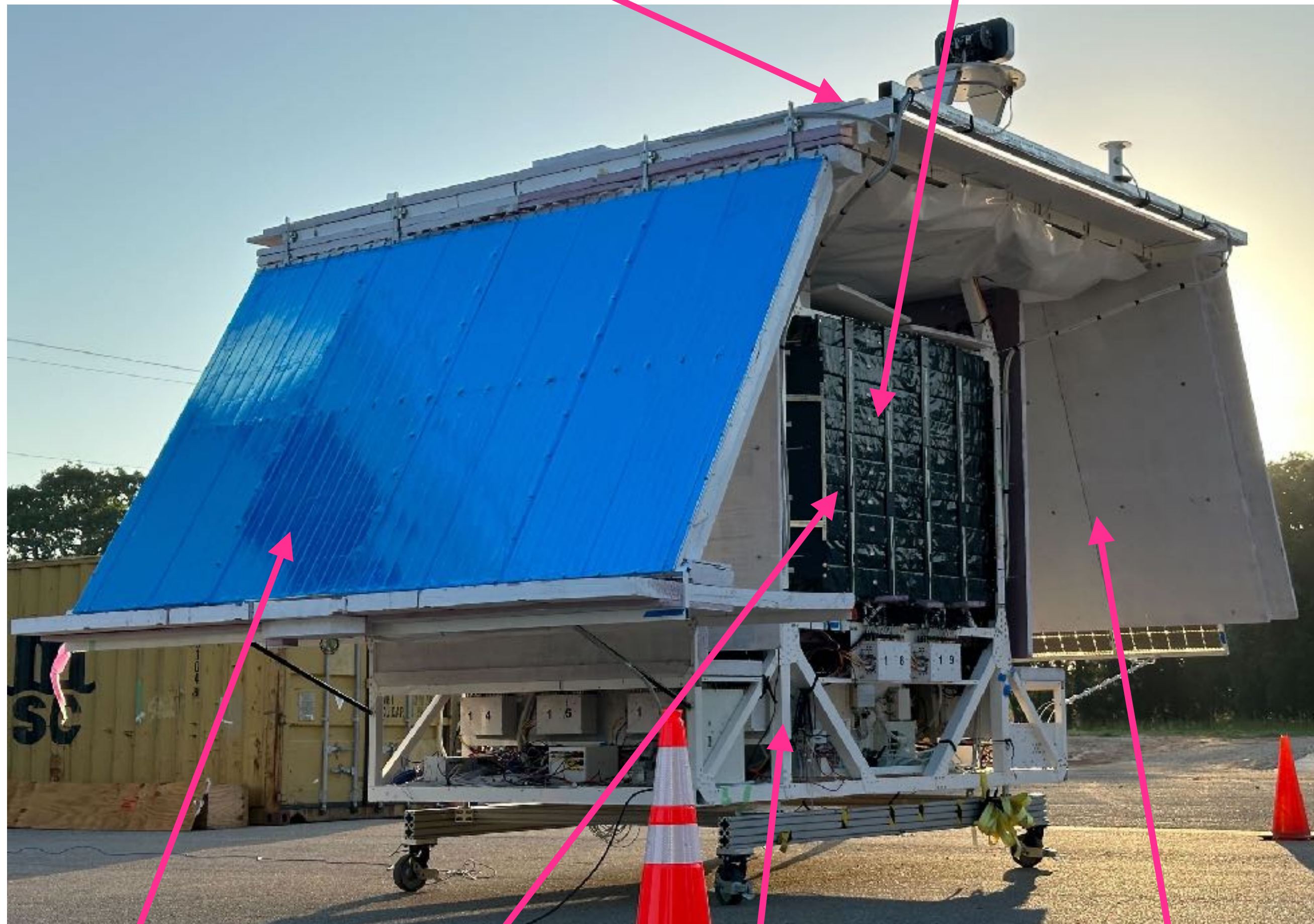


Current Status: Time-Of-Flight (TOF) System

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TOF umbrella TOF Cortina and Cube (inside)

Mengjiao's talk in PSB.1 (Tue)

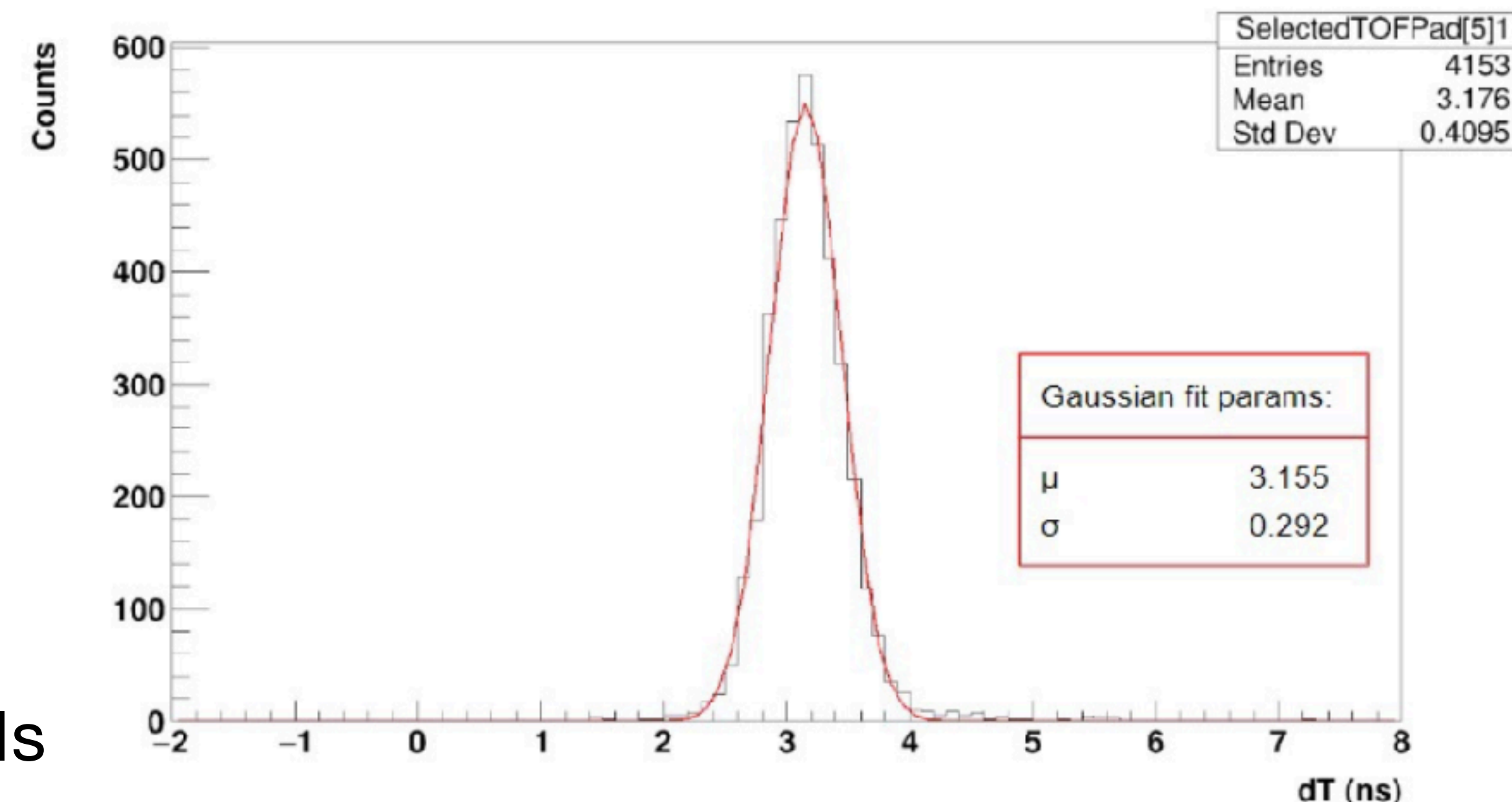


Radiator Tracker Electornics Bay Solar Panels

Total area: $\sim 25 \text{ m}^2$ with 21 panels

- 160 scintillation paddles
- TOF Umbrella - Cube top: $\sim 90 \text{ cm}$
- TOF Cortina - Cube side: $\sim 30 \text{ cm}$

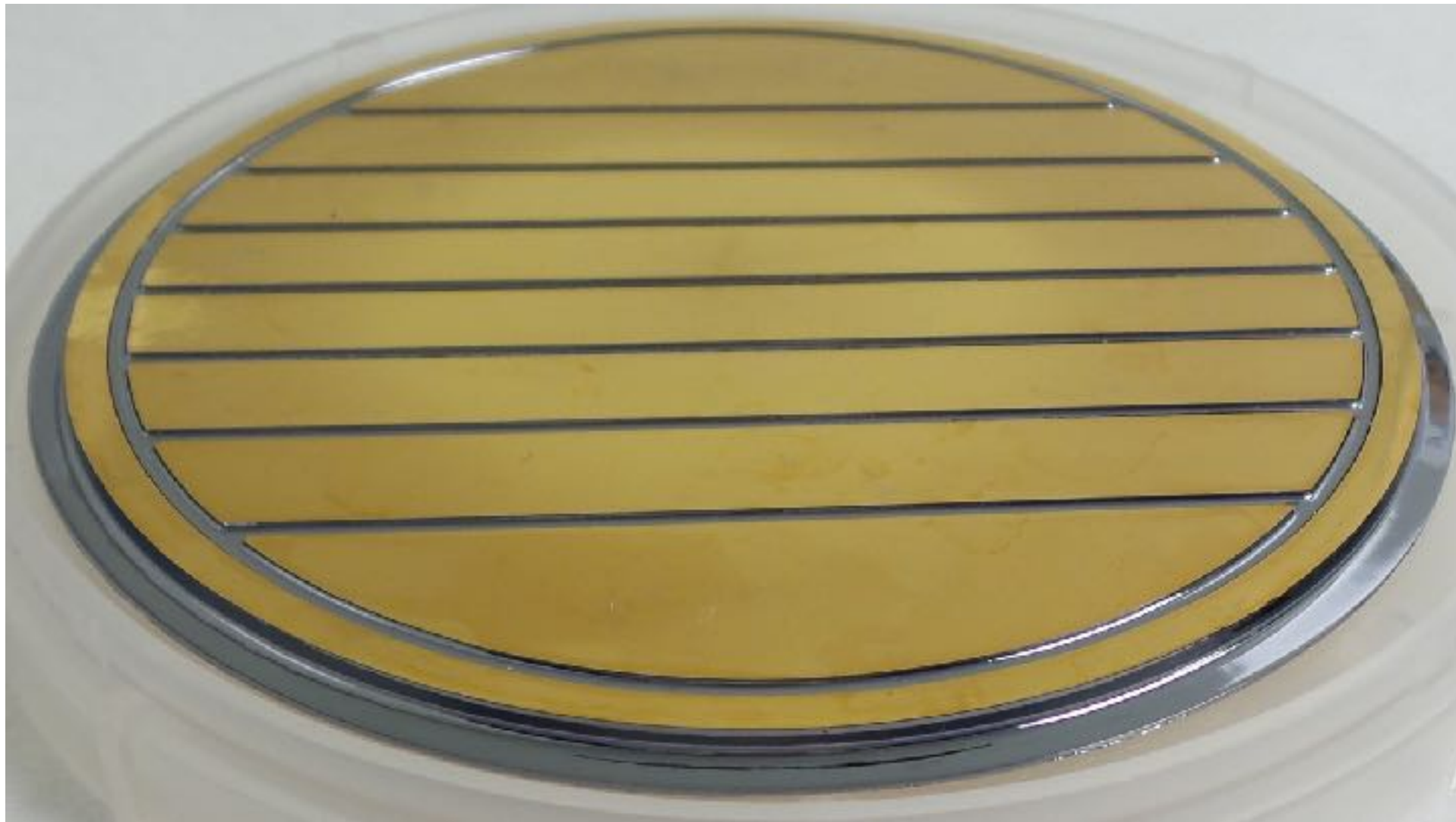
Timing resolution: $\sigma < 400 \text{ ps}$





Current Status: Si(Li) Detector

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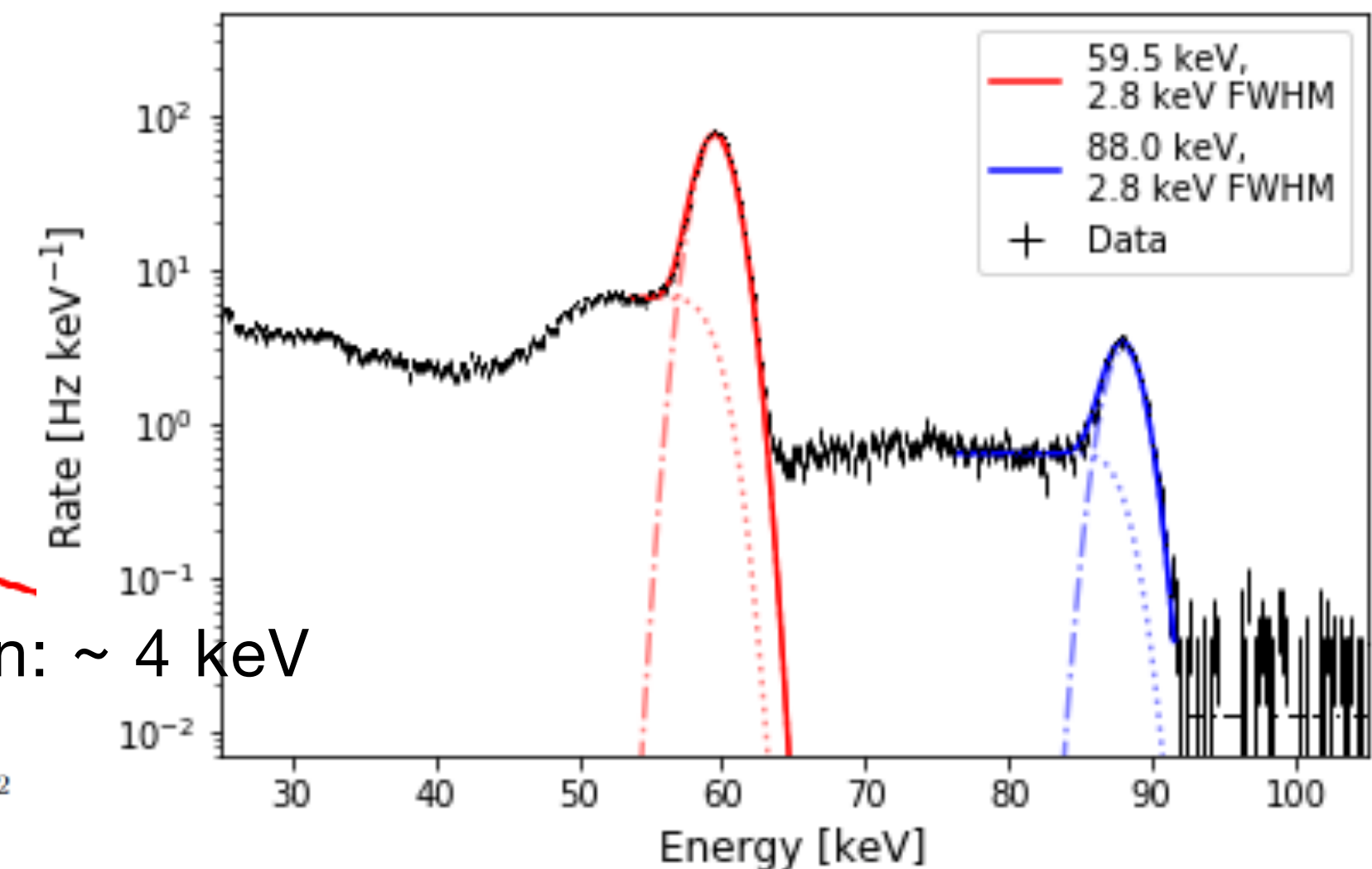
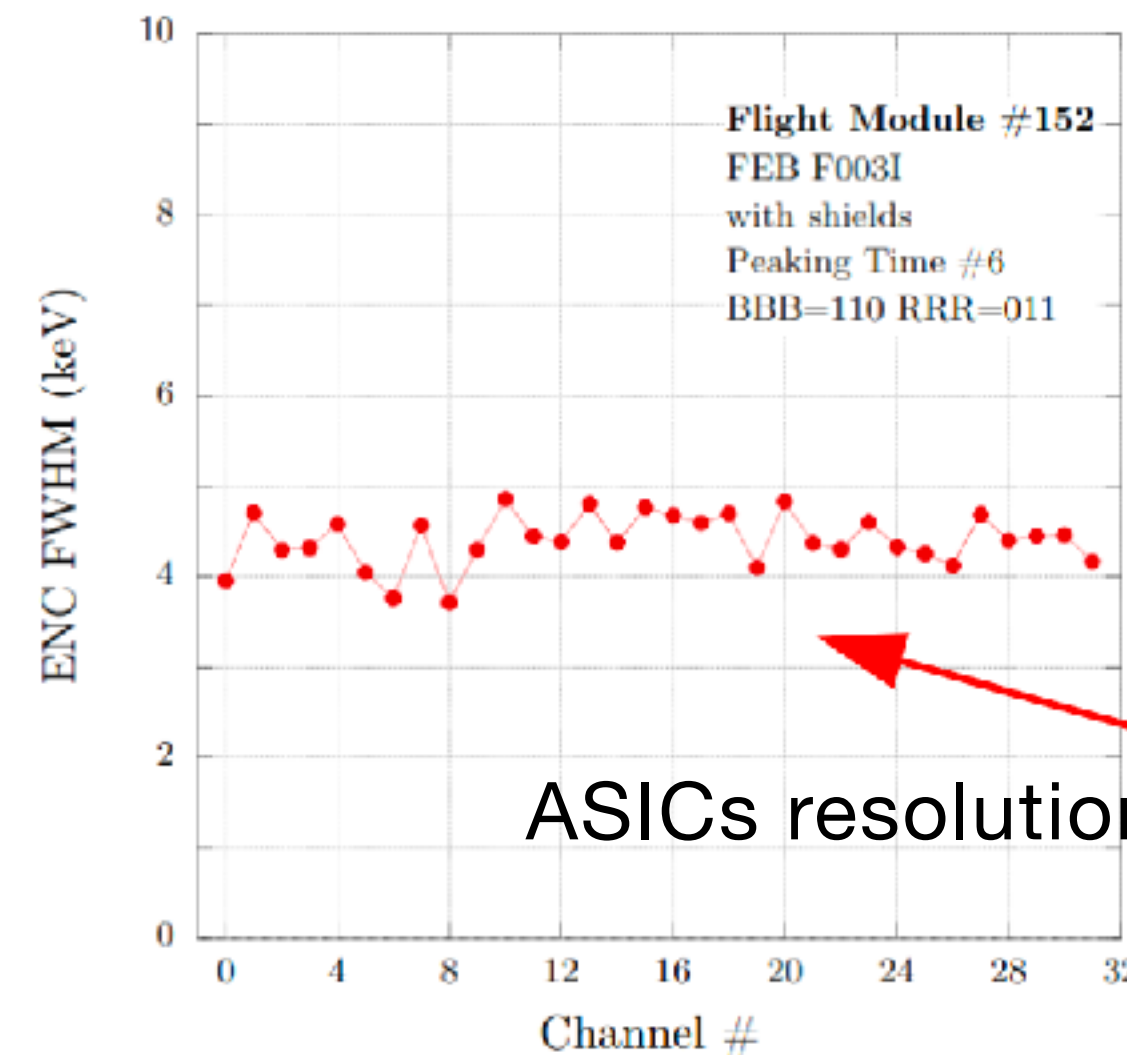
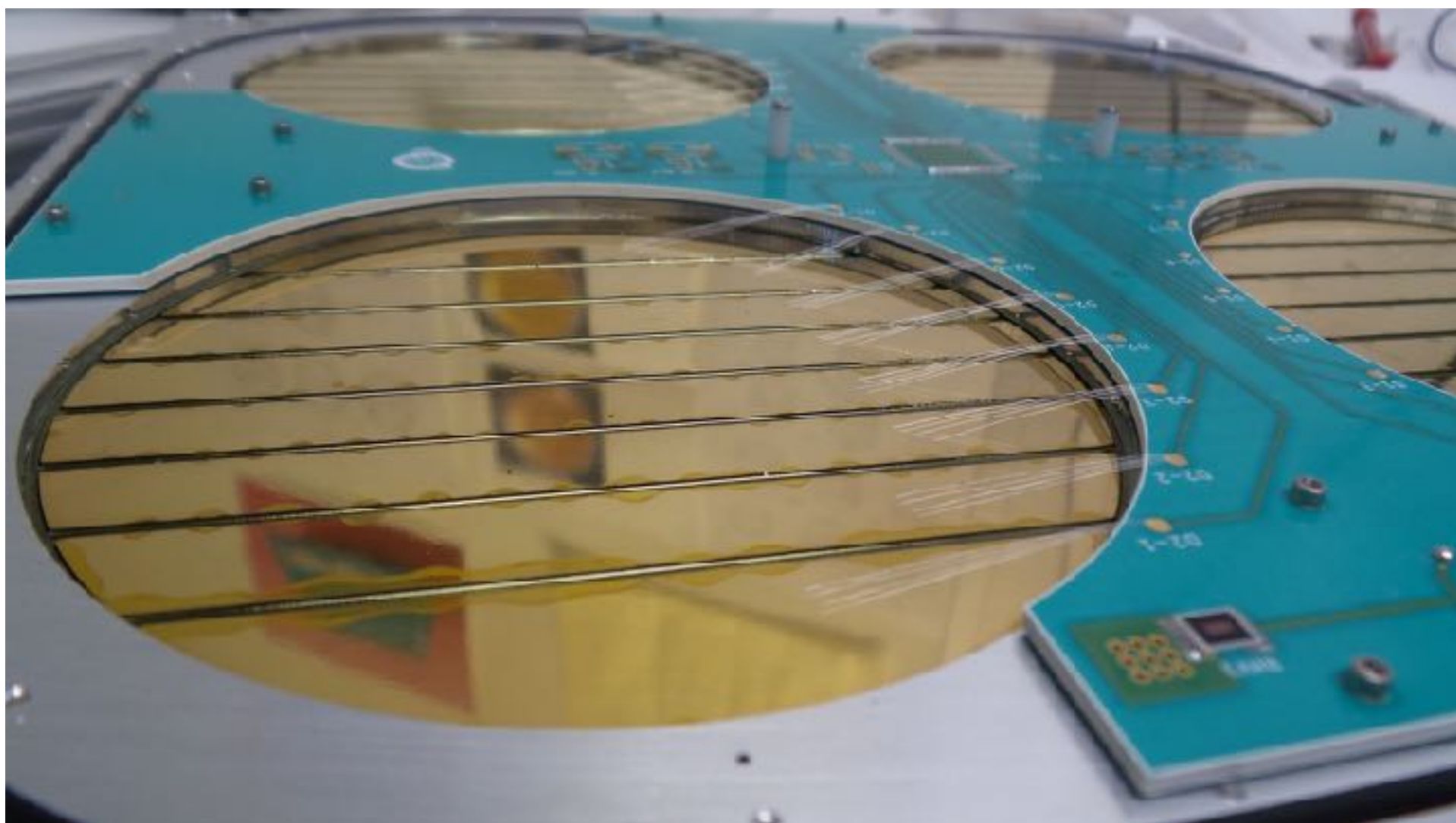


10 cm diameter, 2.5 mm thick Si(Li) sensors

- 10 layers, ~1000 Si(Li) sensors in total
- Qualification test completed in 2022

Custom-made ASICs (SLIDER-32)

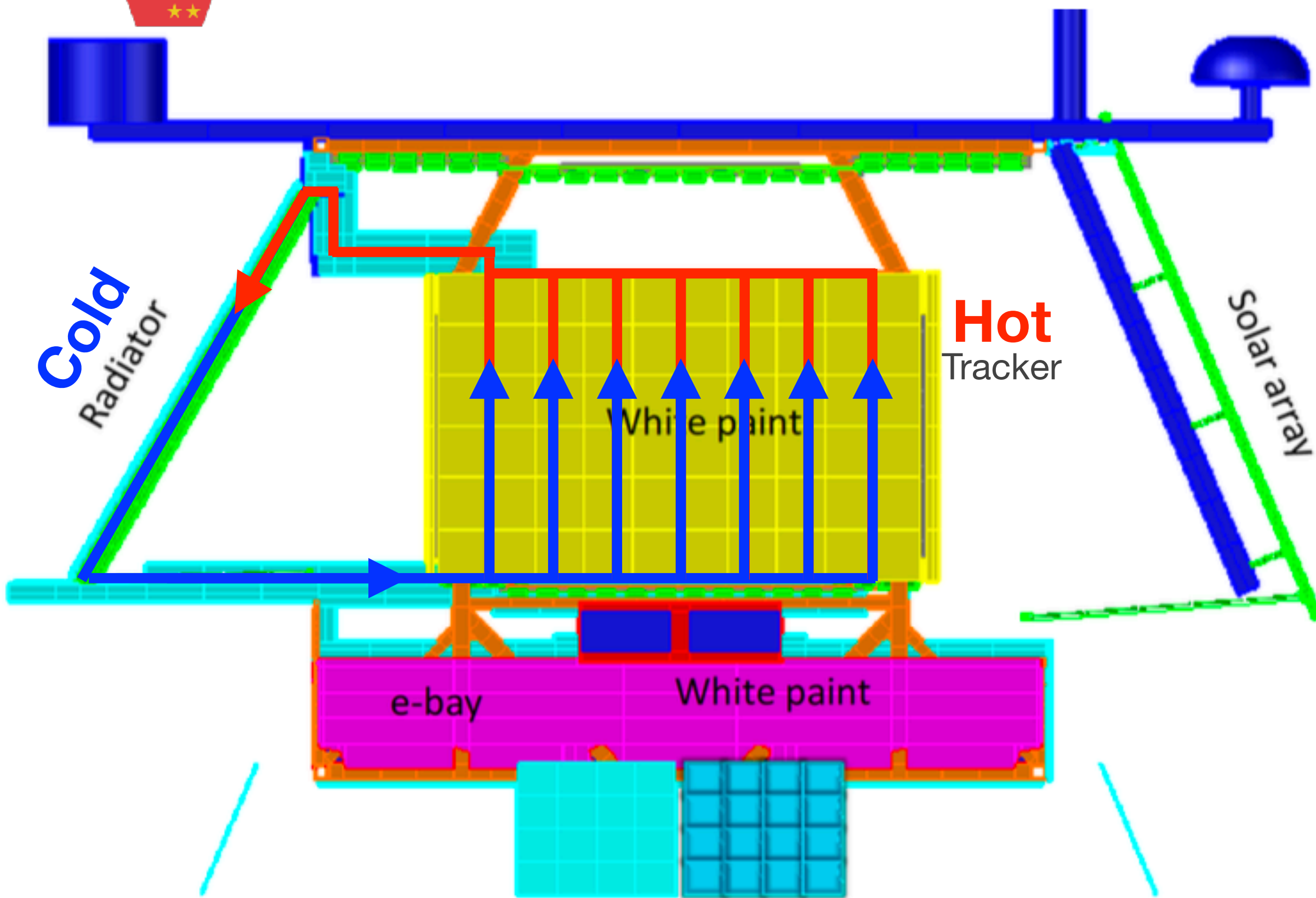
- 32 channels, 11-bit ADC
- Low power consumption (<10 mW/channel)
- X-ray resolution ~ 4 keV
- < 10% resolution up to 100 MeV





Current Status: OHP Cooling System

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- Developed at JAXA/ISAS (10+ years), but first time for the large-scale balloon mission
- Low-power, low-mass cooling system without an active pump
- Capillary tubes with a two-phase fluid self-oscillating/circulating

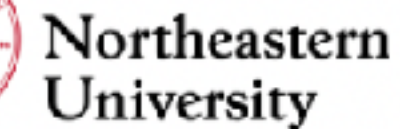
- Thermal model developed and confirmed in two piggyback balloon flights at Ft. Sumner.
- Thermal performance validated in Functional Prototype, integration, and thermal vacuum test





Timeline and Collaboration

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2002: GAPS concept paper published

2004/2005: Beam test at KEK

2012: Prototype/engineering flight

2016: NASA APRA program selected

2021: GAPS Functional Prototype testing started

2022: Integration and Testing started

2023.5: Thermal vacuum test at NTS

2024.7: Compatibility/hang tests at NASA CSBF

2024.12: First balloon flight from the Antarctic





Summary

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- GAPS is the first experiment optimized for low-energy (< 250 MeV/n) **antinuclei** measurements
 - Antideuteron measurements are essentially **background-free** DM searches
 - **Precision antiproton measurements** could allow us to investigate low-mass DM models and propagation model/solar modulation
 - GAPS could detect low-energy **antiheliums**
 - GAPS antinuclei measurements are **complementary** to AMS-02
- Small-scale functional prototype testing, thermal vacuum testing, full payload integration and testing, and telemetry compatibility/hung tests are all completed.
- We are **ready** for the first balloon flight from the **Antarctic** in late 2024