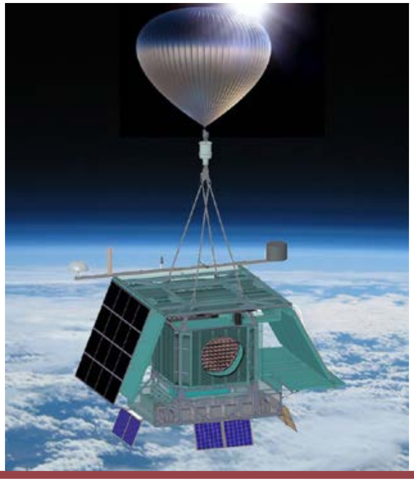

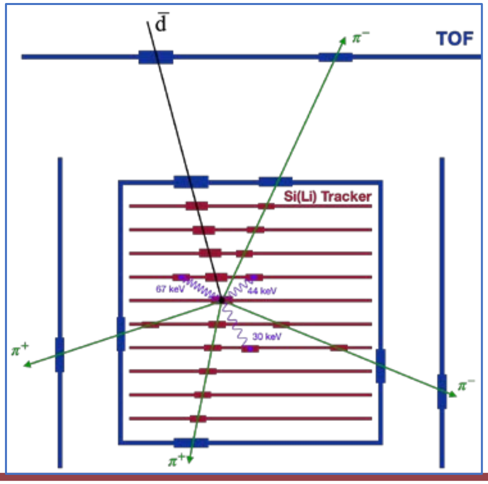

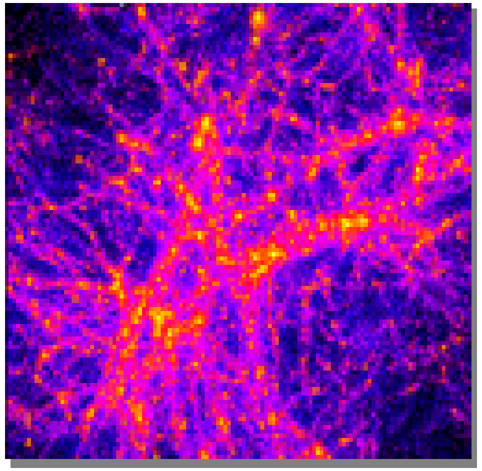

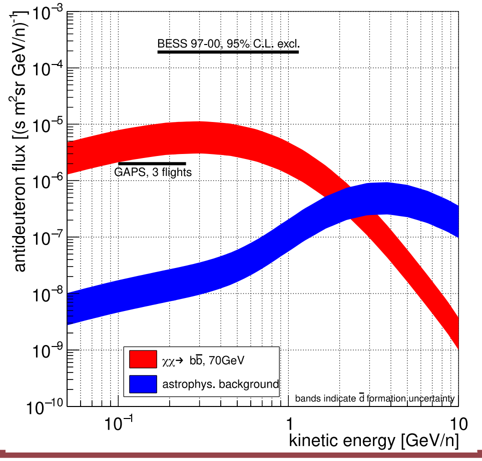

The Search for Primary Antimatter with GAPS

Univ. of Trieste

Nuclear & Particle Astrophysics Class

Rene A. Ong (UCLA, INFN)

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Outline

- The mystery of antimatter
- Antimatter as a signature for new physics – e.g. dark matter
- Cosmic ray antimatter status
  - Current experiments & latest results
  - Antideuterons – the pristine signature
- The GAPS experiment
  - Design and exotic atom technique
  - Si(Li) tracker, Time-of-Flight system, integration → **Flight**
- Summary

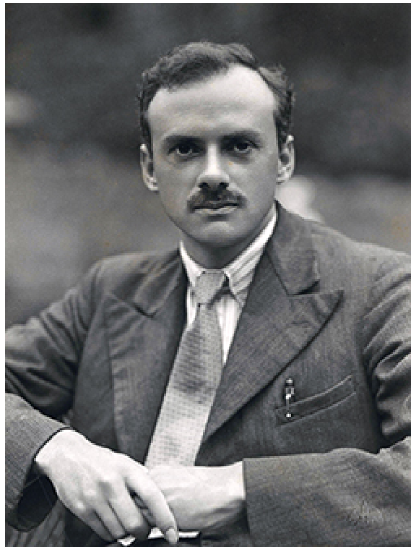
The Existence of Antimatter

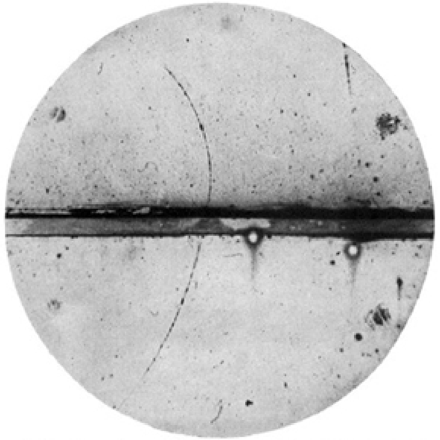
- **A. Schuster (1898):** Coined the term “antimatter in two letters to Nature; conceived of anti-atoms and anti-solar-systems.

- **P.A.M. Dirac (1928):** *“The Quantum Theory of the Electron”,* developed a quantum theory that included relativity → argued for the existence of a positively charged electron (e^+). Nobel Prize in 1933 (w. Schrödinger).

- **C. Anderson (1932): “***The Apparent Existence of Easily Deflected Positives”***,** first detection of an antiparticle (positron) by studying cosmic ray tracks in a cloud chamber. Nobel Prize in 1936. Antiproton (1955), antideuteron (1965), anti-H (1995).

- When we say “antimatter”, we generally mean “antiparticles”. Positrion (e^+) = anti-electron, Antiproton ($\bar{p}$) = anti-proton





The Essential Problem

“If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind.“

P.A.M. Dirac, Nobel Lecture, Dec. 12, 1933.

Theoretically, 30 years forward (1960's)

- **There is almost an exact symmetry between matter and antimatter.** CP violation, first observed in 1964 in K-meson decays (and now in B and D mesons), predicts only a small imbalance. There is no evidence for CP violation in the SI. Leptons?

- **Simple Big Bang model predicts equal (and very low) amounts of matter and antimatter.**
  - Early universe is a hot, expanding plasma of particles/antiparticles and photons in thermal equilibrium. For the baryons, the two way reaction is:

$$B + \bar{B} \leftrightarrow \gamma + \gamma$$

  - In the expanding universe, the density falls and the annihilation stops, effectively "freezing" the expected abundance:

$$B / \gamma = \bar{B} / \gamma \approx 10^{-18}$$

  - But the measured abundances are: $\frac{B}{\gamma} \approx 10^{-9}$ (CMB) $\frac{\bar{B}}{B} < 10^{-7}$ (cosmic rays)

(too much matter, not enough antimatter)

Experimental Facts

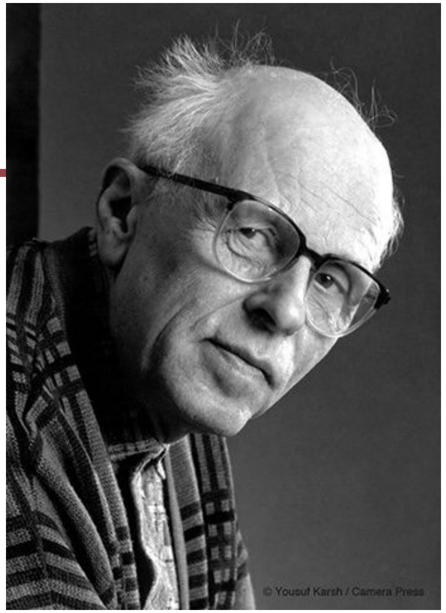
There is no evidence for significant amounts of antimatter in the universe.

- **The cosmic rays represent the largest known reservoir of antimatter.** However, the cosmic rays are completely dominated by nuclei and not anti-nuclei. The small amounts of CR antimatter appear to be (almost) completely accounted for by secondary production (e.g. CR + matter → $e^- + e^+$, $p + \bar{p}$). <u>No cosmic ray anti-nuclei have been definitively detected</u>.

- **There is no evidence for clouds or domains of antimatter distributed locally, in the Galaxy or outside the Galaxy**. Measurement of the diffuse X-ray / γ-ray backgrounds provide significant limits on the possibility of such clouds.

"A beautiful theory, killed by a nasty, ugly, little fact." (T. Huxley, 1908)

Sakharov Conditions (1967)



Inspired by the discoveries of CP violation and the CMB, A. Sakharov proposed 3 conditions, necessary to account for the predominance of matter over antimatter, and hence to allow **baryogenesis** to occur:

1. **Baryon # violation**
2. **C and CP violation**
3. **Interactions out of thermal equilibrium**

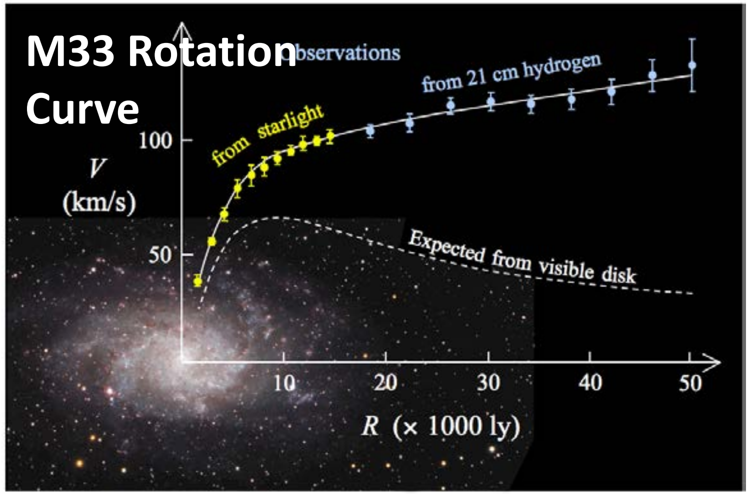
The processes responsible for baryon # violation are not understood and the observed level of CP violation is not sufficient → there is considerable theoretical speculation on possible extensions to the SM, e.g. GUT theories, leptogenesis, etc.

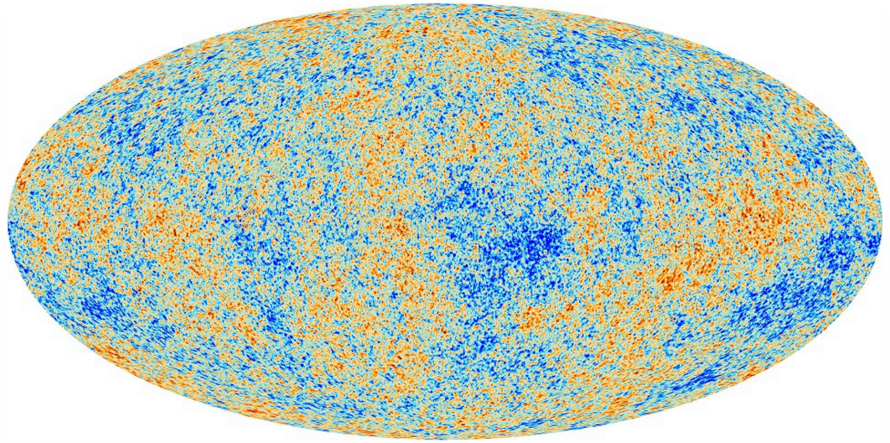
Conclusion: We do not understand the origin of the baryon asymmetry and experimental progress is needed. <u>Finding unexpected antimatter would have a profound impact</u>.

Antimatter as a Signature for New Physics

Dark Matter

- ❑ There is strong evidence for the existence of dark matter

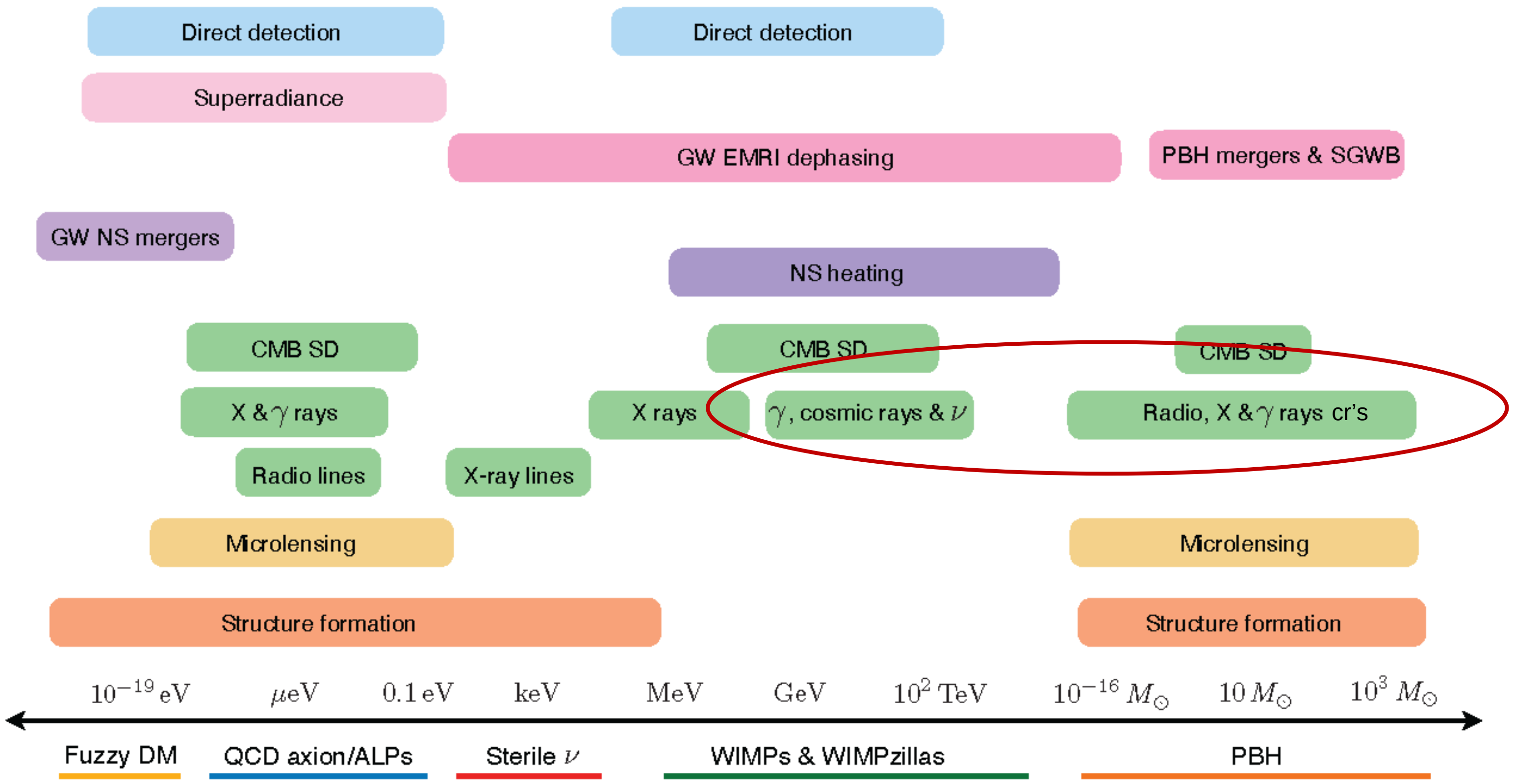




Structure formation - CMB (PLANCK)

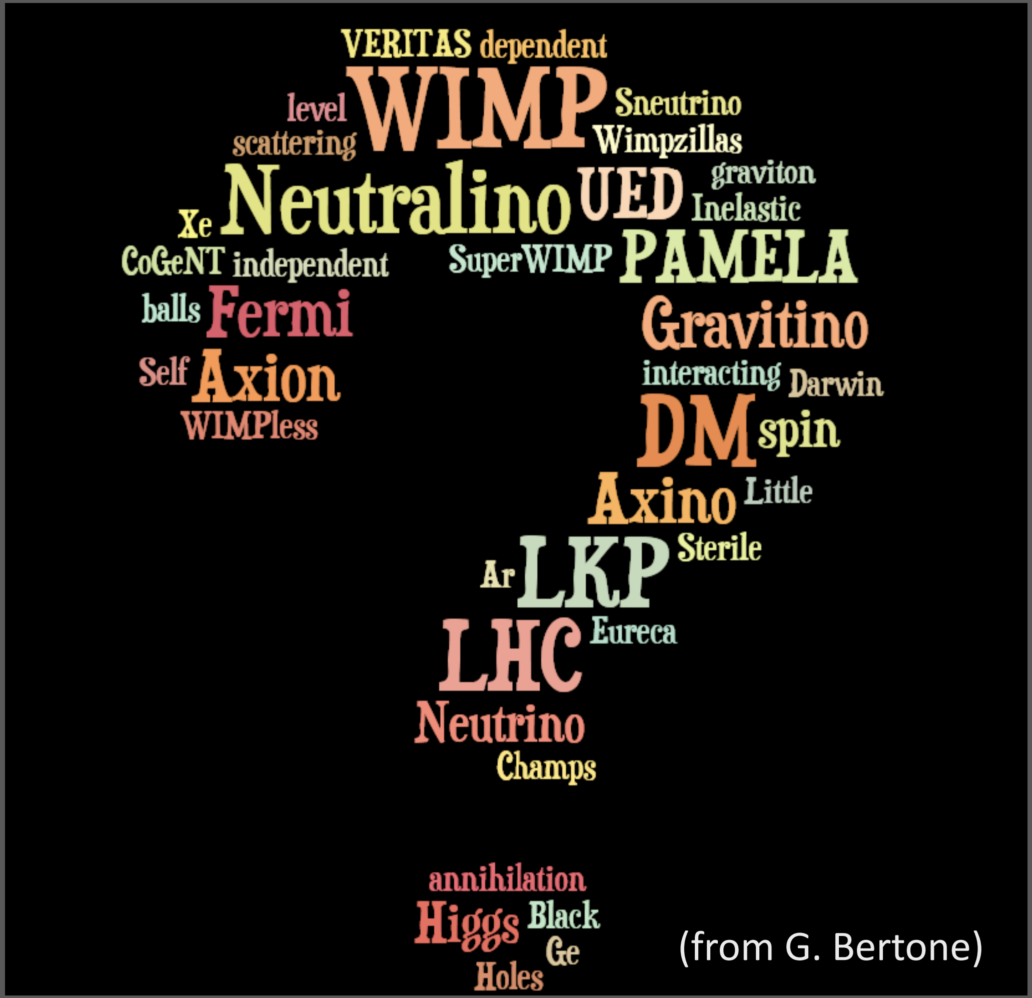
Dark Matter Candidates and Probes

EuCAPT White Paper
2110.10074



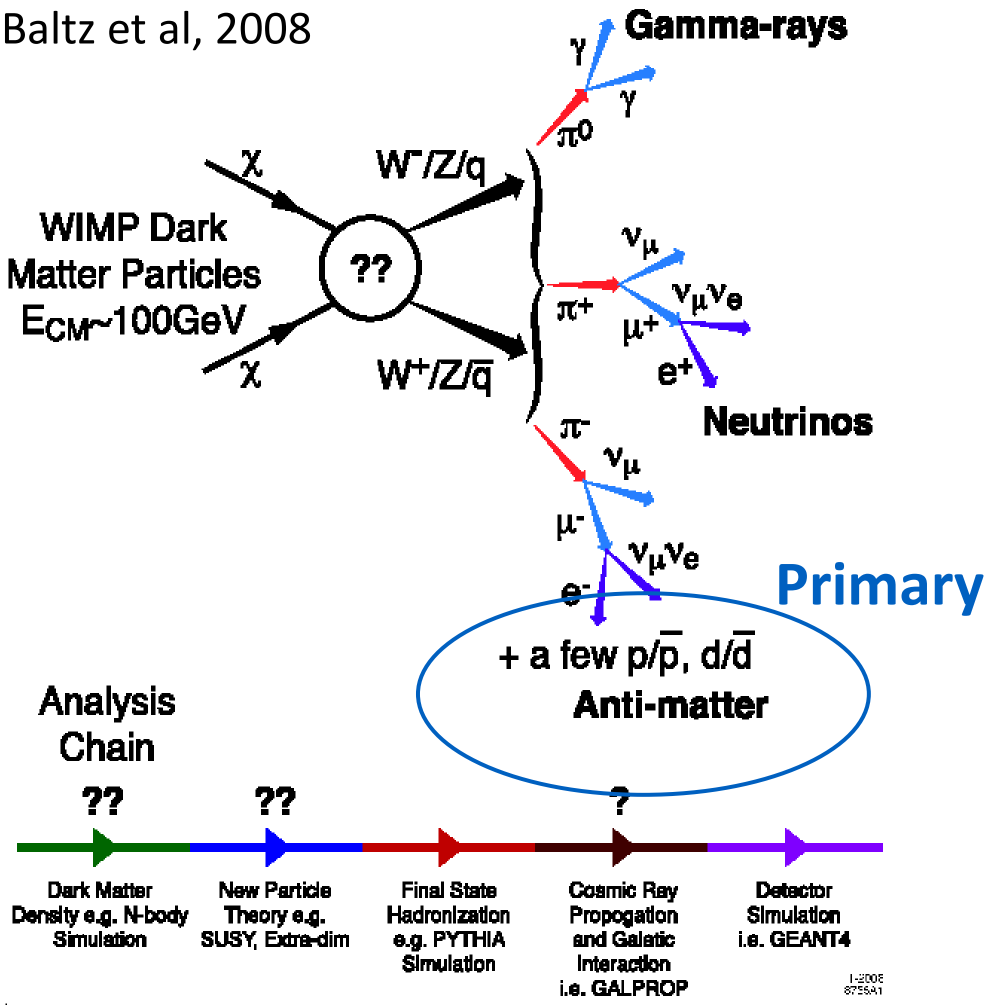
- WIMPs and PBHs are probed by cosmic ray antimatter.

... actually, we have no idea !



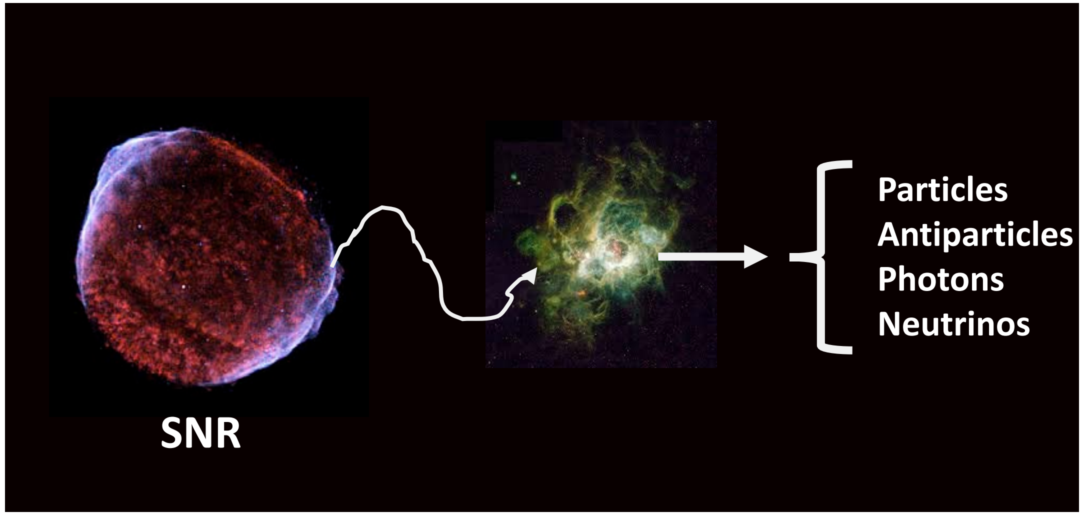
... and we need to search for DM particles using all well-motivated techniques.

Primary and Secondary Antimatter



Indirect detection channels

WIMP annihilation produces primary antimatter.



Cosmic rays (e.g. from SNRs) interact with Galactic material:

$$p + \text{ISM} \rightarrow p/\bar{p}\,,\, d/\bar{d}$$ **Secondary**

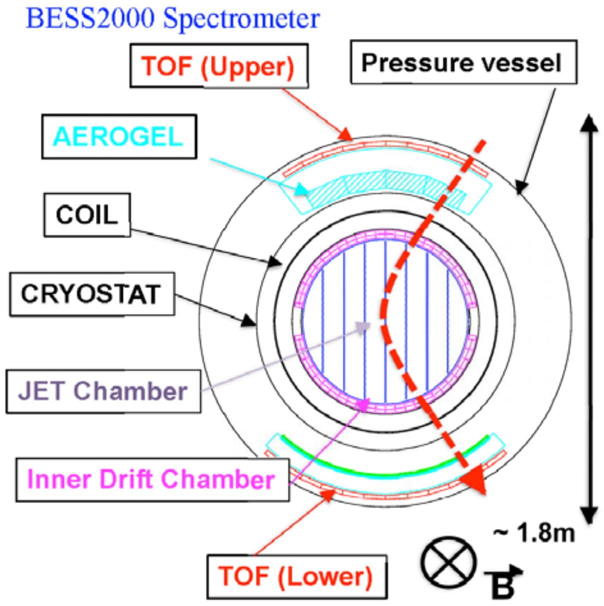
The secondary antimatter forms the background to any BSM signal.

(similar terminology to CR's on Earth).

Cosmic Ray Antimatter Detectors & Measurements

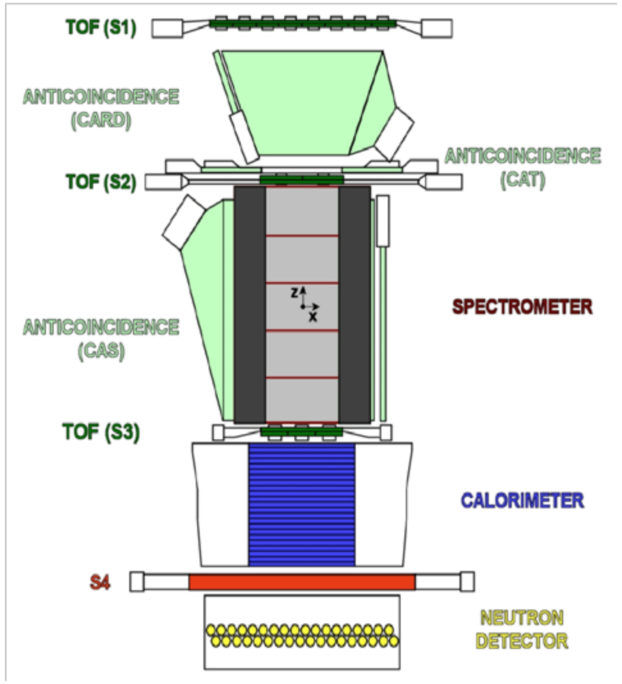
Recent Experiments

BESS



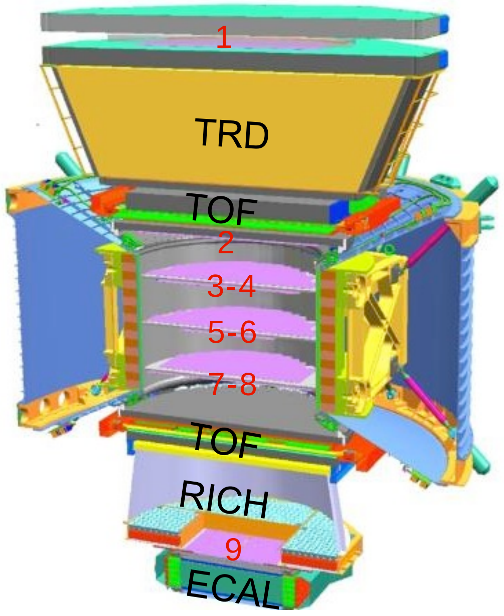
- Balloon expt: 11 flights between 1993 and 2004
- Magnetic spectrometer: SC magnet ~1T; JET drift chamber
- Particle ID: TOF, aerogel
- Acceptance: ~ 0.3 m^2-sr

PAMELA



- Satellite expt: 2006-2016, polar elliptical orbit
- Magnetic spectrometer: 0.43T, Si tracker
- TOF, Si-W calorimeter
- Acceptance: ~0.022 m^2-sr

AMS-02

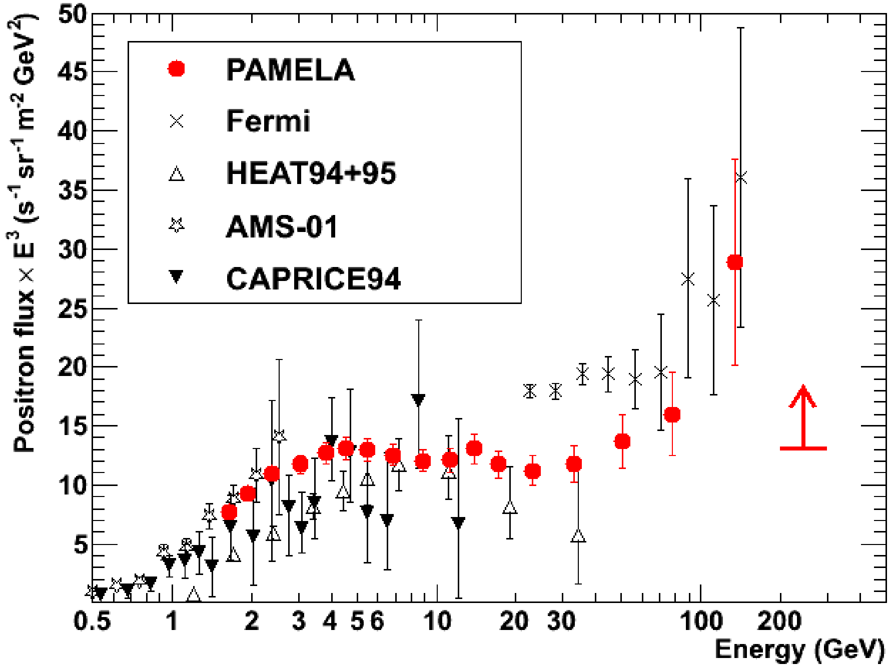


- ISS: 2011-present, mid-latitude orbit, Geomag. cutoff ~ 15 GeV
- Magnetic spectrometer: 0.14T, Si tracker (9 planes)
- Particle ID: TRD, TOF, RICH
- Pb-scint fiber calorimeter
- Acceptance: ~0.2 m^2-sr

Cosmic Ray Positrons

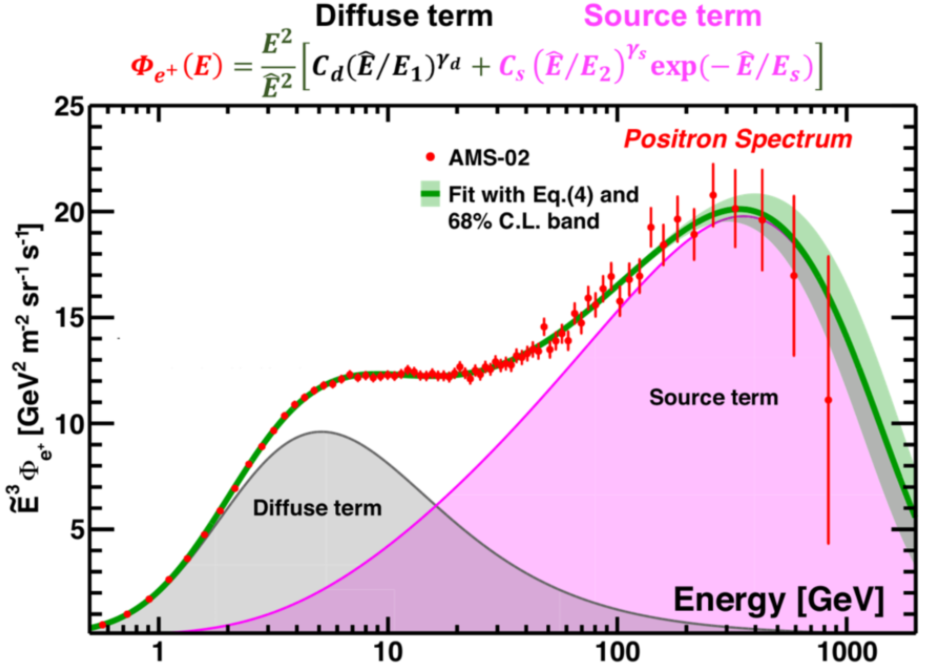
Flux x E^3

O. Adriani et al., (2013)



- 2013: Pamela (and Fermi) show clear and unexpected rise in e$^+$ flux above 20 GeV.

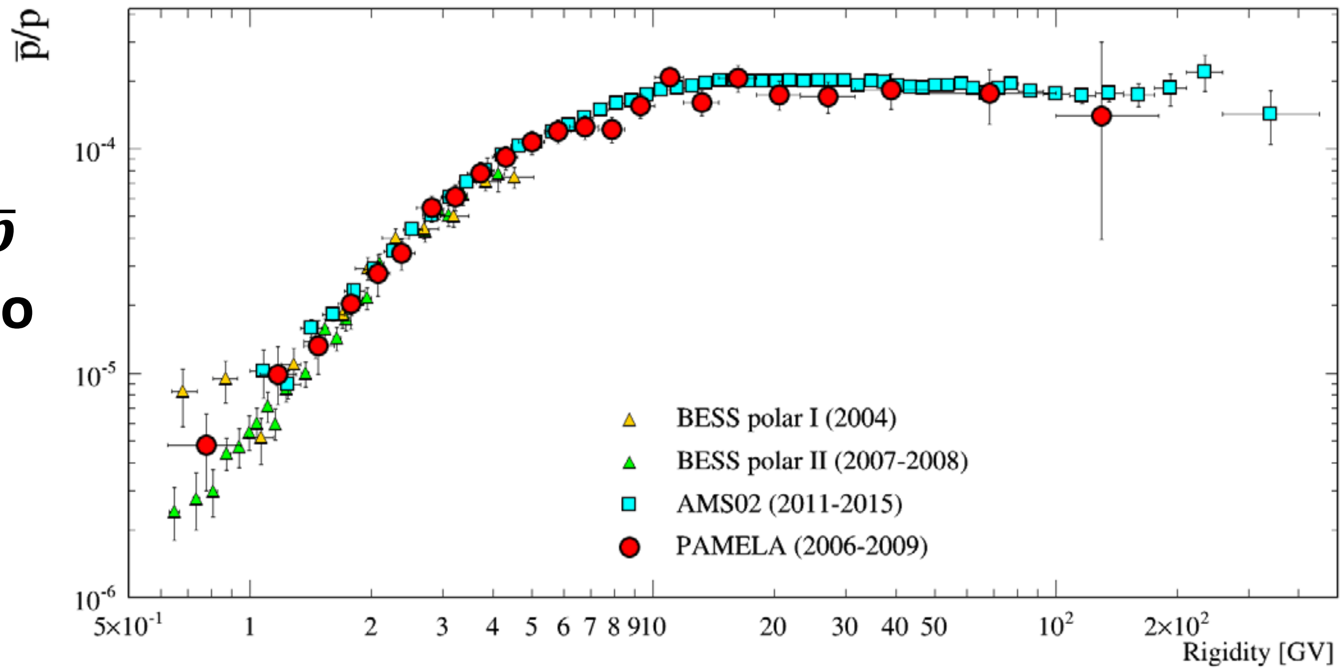
M. Aguilar et al., (2019)



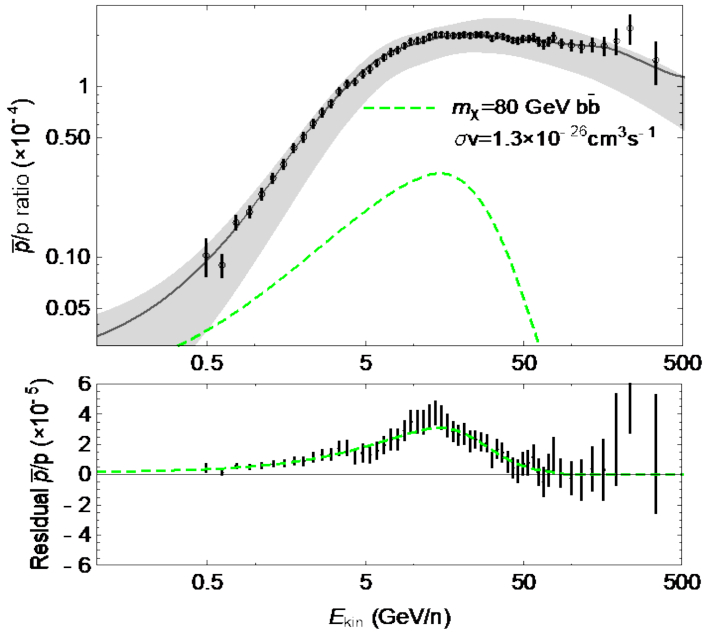
- 2014, 2019: AMS-02 extends the positron measurement to higher energies and estimates an exponential cutoff ~800 GeV.
- General consensus → <u>new source of positrons, but origin is not clear</u>. Interpretation is difficult because of relative ease in producing e$^+$ astrophysically. <u>But, most likely not due to dark matter.</u>

Cosmic Ray Antiprotons

$p/\overline{p}$
ratio



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



- DM fit to apparent $\bar{p}$ excess.

- Good agreement between BESS, PAMELA and AMS-02.
- Flux extends to ~500 GV and then falls down.
- Generally, good agreement with expectation from secondary production

- Some claims of excess – hard to prove because of large secondary flux.

Rigidity R ≡ pc / Ze

e⁺ and $\overline{p}$ all have significant backgrounds and/or astrophysical interpretations → need a cleaner signature.

Antideuterons – the pristine signature

- Antideuterons at low KE are an essentially background-free signature of new physics.

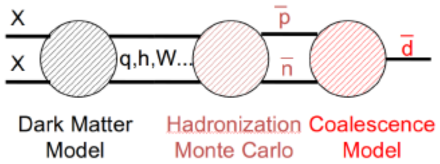
Background

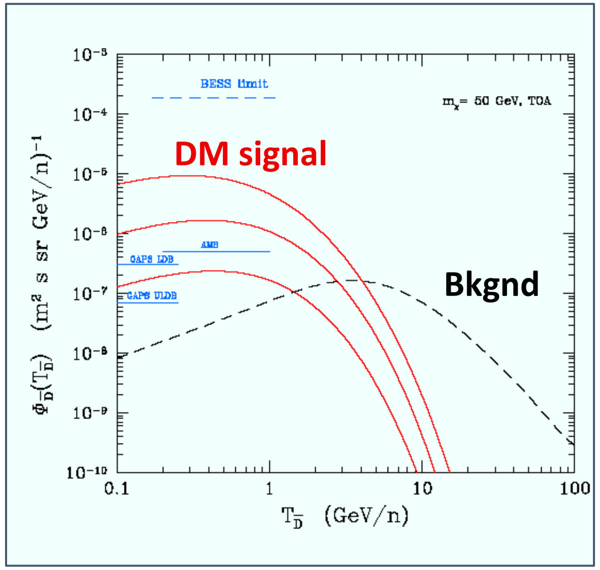
$$\underbrace{p_{CR}}\, + \overbrace{p_{ISM}}^{\text{at rest}} \longrightarrow \bar{p}\bar{n} + pn + pp$$

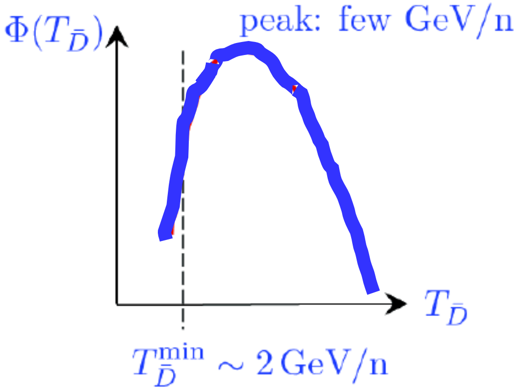
$E_{\text{th}} > 17\, m_p$

Signal

$$\underbrace{\chi}_{\text{at rest}} + \overbrace{\chi}^{\text{at rest}} \longrightarrow \bar{p}\bar{n} + pn$$







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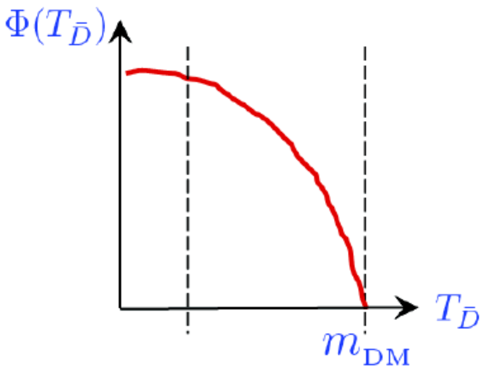
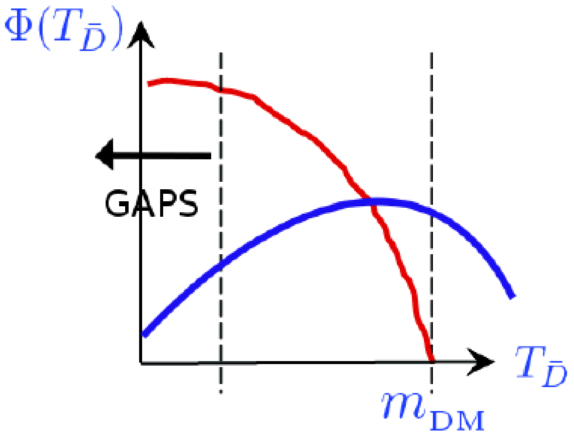




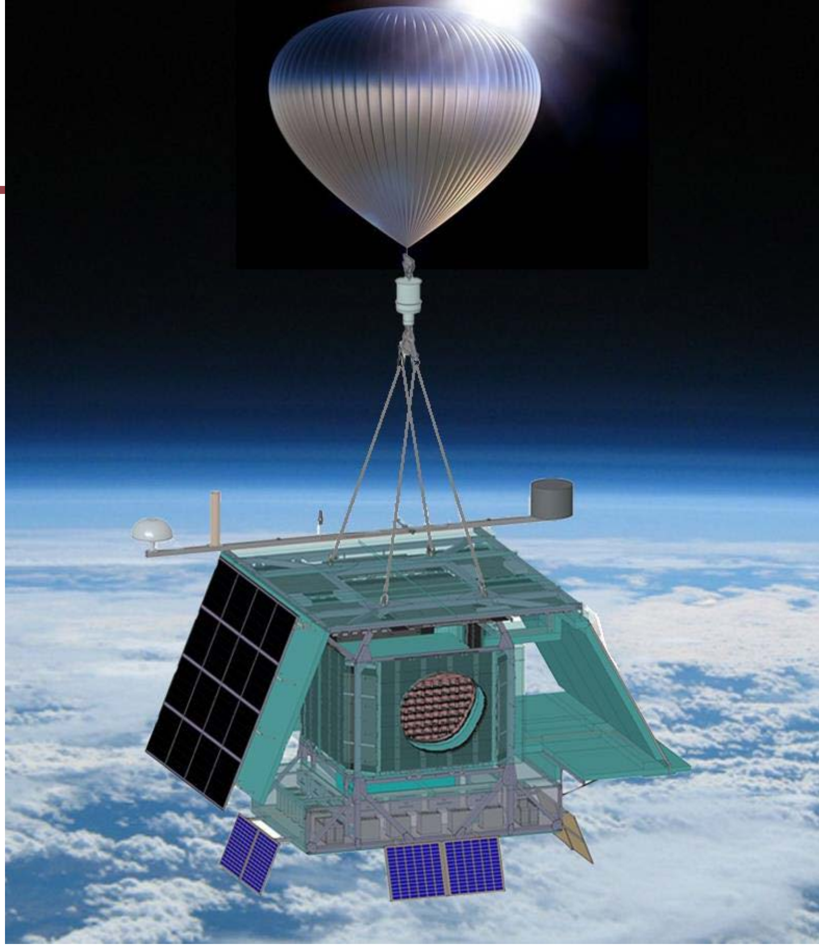
Physics and Experimental Summary

- Two of the deepest mysteries in physics are the baryon asymmetry and the nature of dark matter; antimatter searches can shed light on both of these topics.
- Cosmic ray positrons and antiprotons are now well measured by magnetic spectrometer experiments. The results are generally consistent with expectations from secondary production, but there are puzzles that are hard to interpret.
- Antideuterons offer a very promising approach; at low KE, the backgrounds are expected to be negligible and the detection of even a few events would be a strong indication of new physics → <u>a dedicated $\bar{d}$ experiment is needed</u>.

GAPS Summary

- **GAPS**: **G**eneral **A**nti-**P**article **S**pectrometer
  - Balloon-borne experiment
  - US (NASA), Japan (JAXA) and Italy (INFN, ASI)
  - Flight from Antarctica (McMurdo Station)
  - Instrument size: $\sim 3.5\ \mathrm{m} \times 3.5\ \mathrm{m} \times 3.2\ \mathrm{m}$ (big!)
- Search for low-energy ($\lesssim 500\ \mathrm{MeV/n}$) cosmic antinuclei as signature of new physics.
- Uses exotic atom technique: antinuclei are identified by a unique signature, including a single stopping track and the emission of uniquely characterized atomic X-rays and charged particles from the annihilation star.
- Leading sensitivity to cosmic antideuterons and anti-He.
- High statistics measurement of low-energy antiprotons.

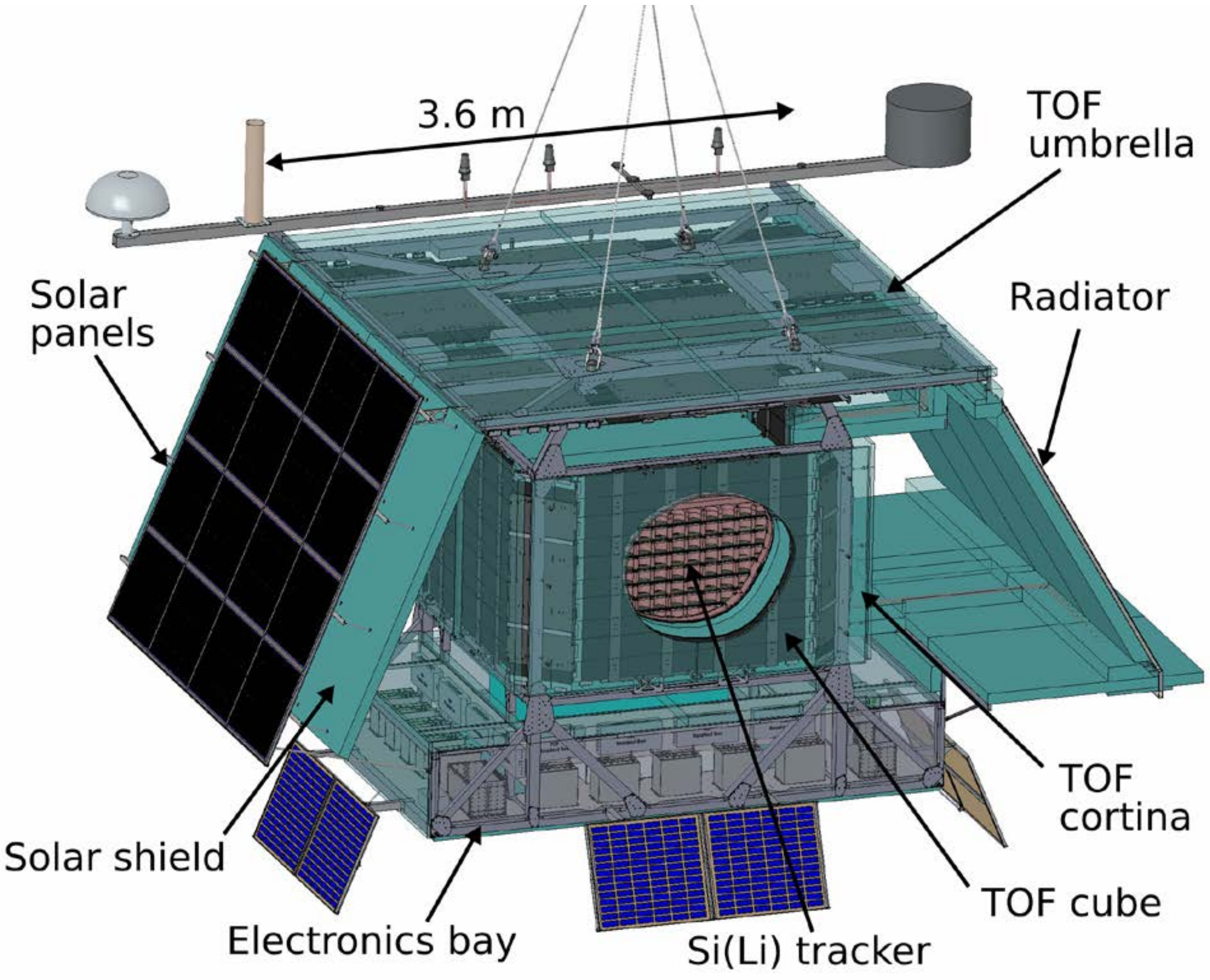
The first of a series of $\sim$30 days flights is planned for the austral summer of 2024-2025.



Summer 2023 Collaboration Meeting at Columbia University

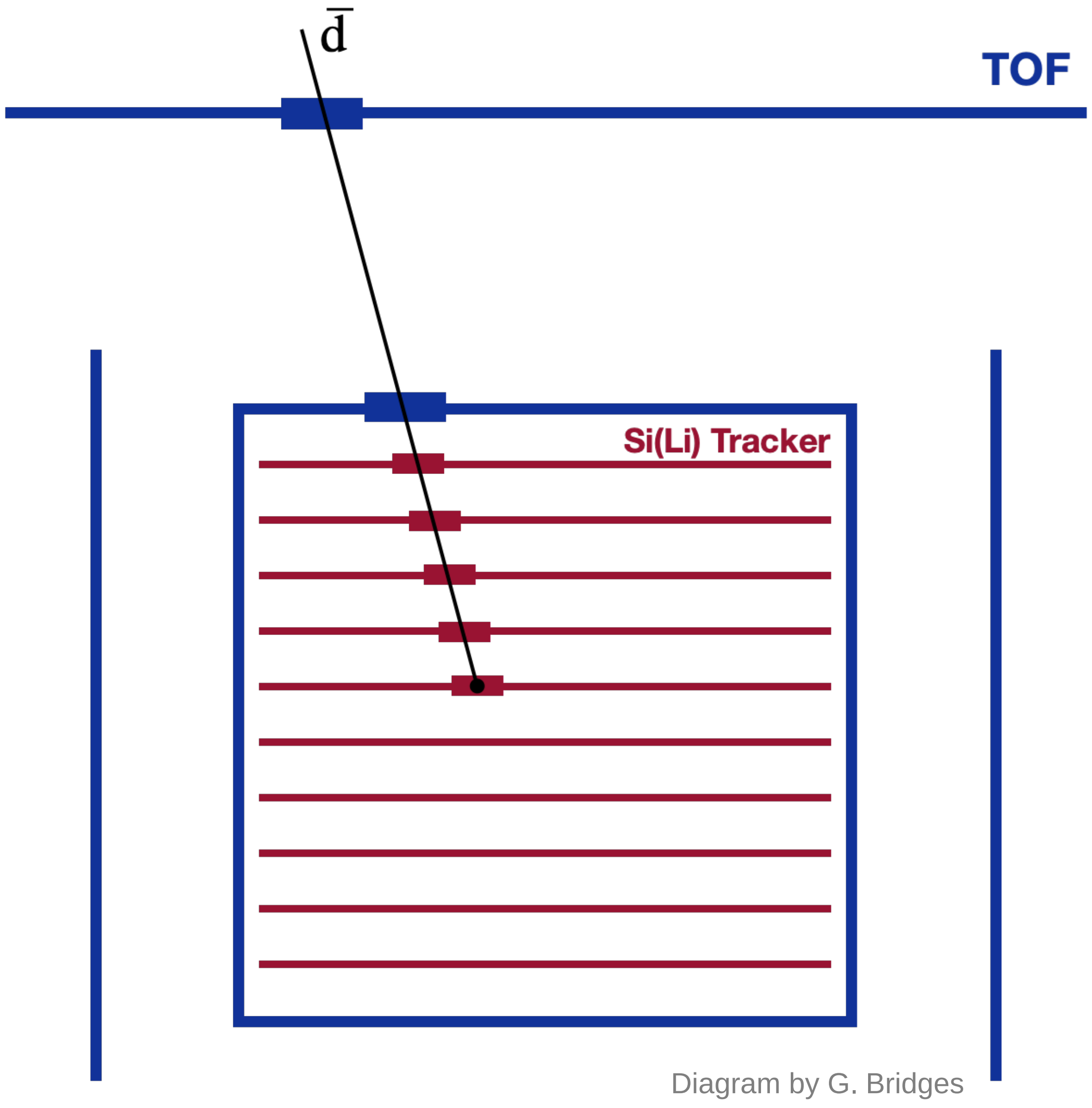
GAPS Design

- **Time of Flight (TOF):**
  - Velocity measurement $\beta = \frac{v}{c}$
  - dE/dx measurement
  - Tracking of incoming/outgoing particles
  - High-speed trigger and veto
- **Si(Li) Tracker:**
  - Stopping depth, dE/dx
  - Charged particle multiplicity
  - X-ray identification
  - Annihilation vertex reconstruction
- **Thermal system:**
  - Novel oscillating heat pump (OHP) design
  - Cools Si(Li) detectors to ~ -35° C



Total mass: ~ 2500 kg, **Power:** ~ 1.2 kW

Particle ID by Exotic Atom Technique



Interaction of antinucleus in GAPS:

- Tracked in the TOF, which measures **velocity** and **dE/dx loss**
- Slows to stop in the tracker, where it is captured by a target nucleus to form an exotic atom

Particle ID by Exotic Atom Technique

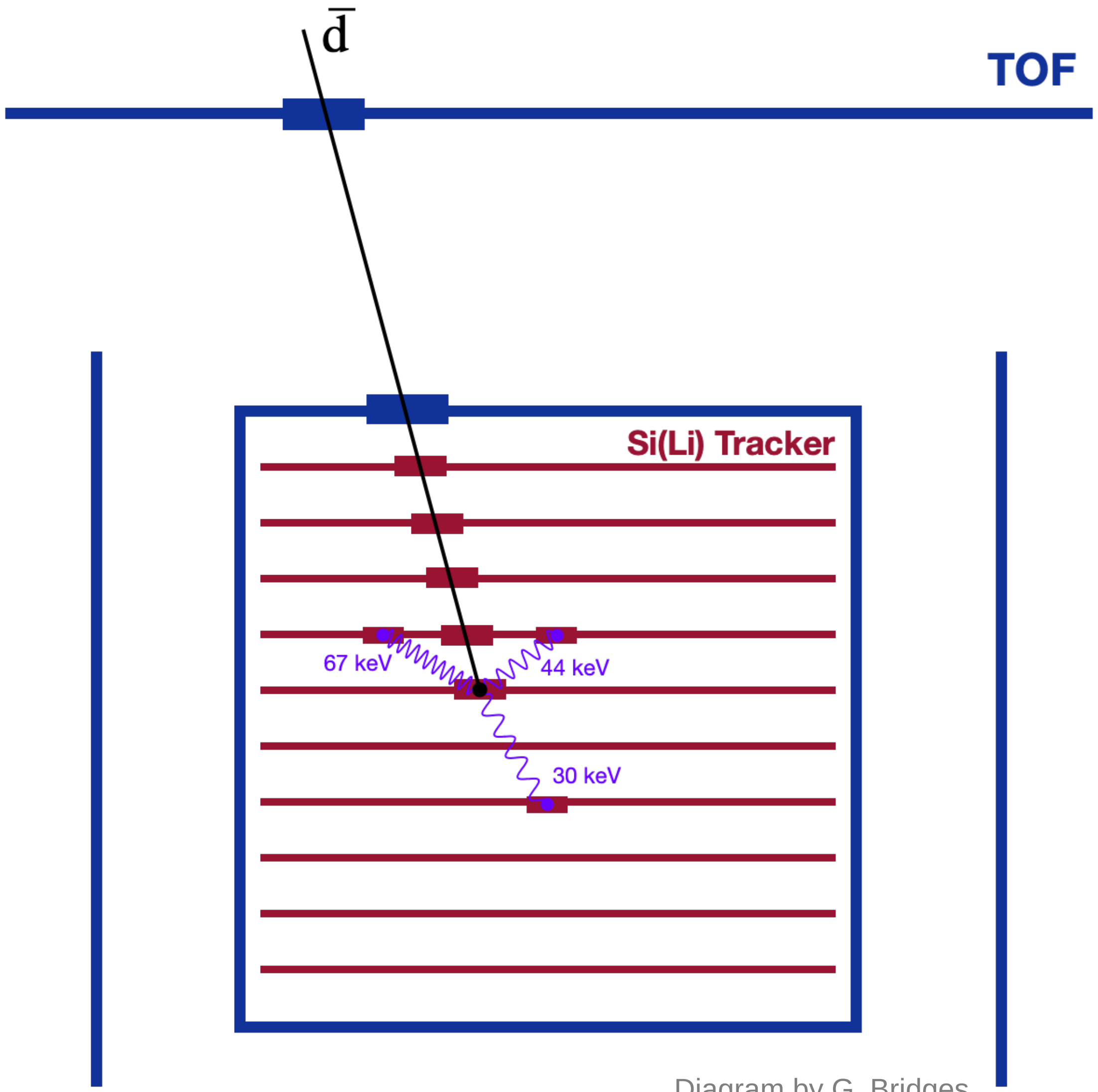
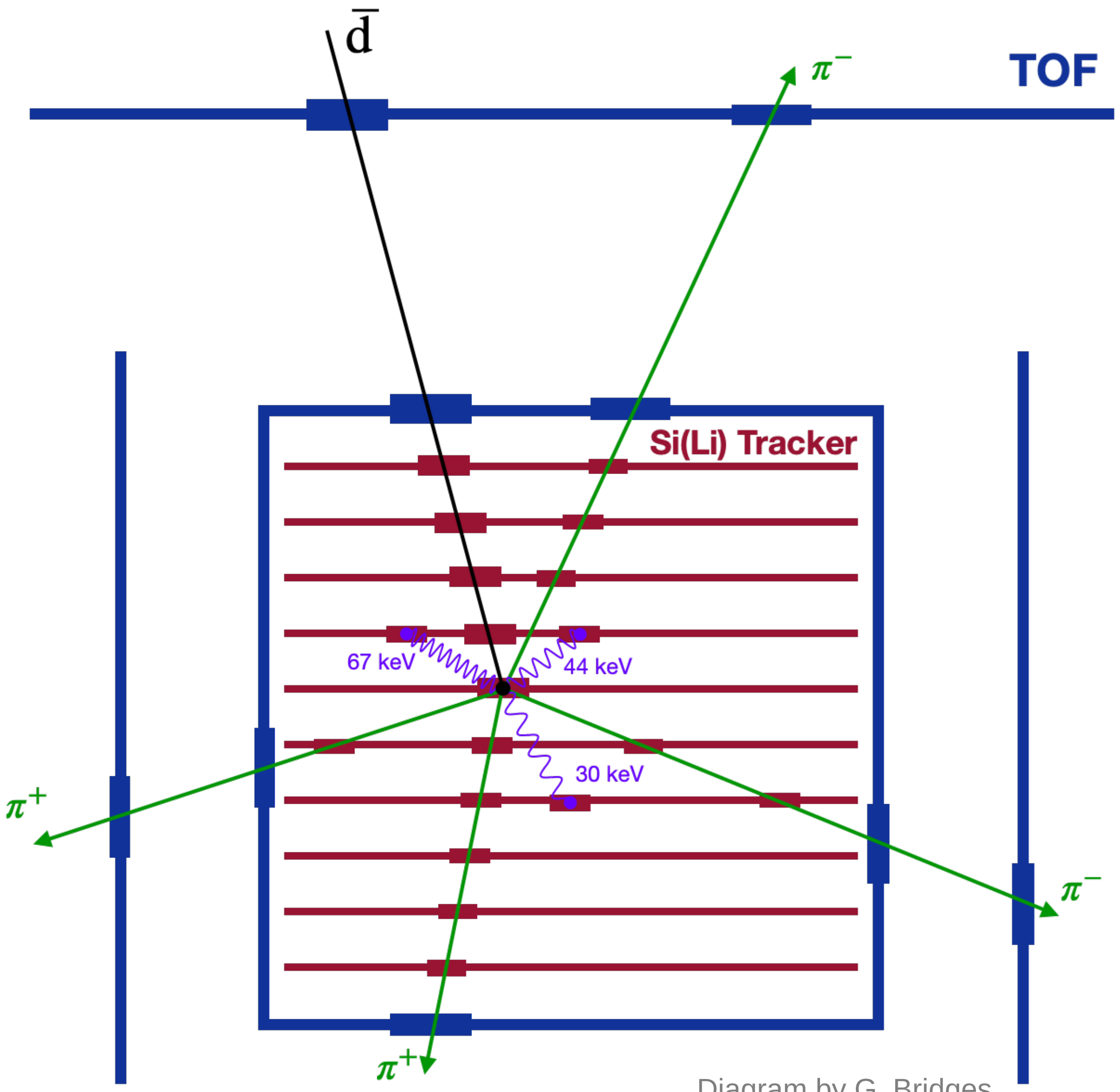


Diagram by G. Bridges

Interaction of antinucleus in GAPS:

- Tracked in the TOF, which measures **velocity** and **dE/dx loss**
- Slows to stop in the tracker, where it is captured by a target nucleus to form an exotic atom
- The exotic atom de-excites via **X-rays** (detected in the tracker)

Particle ID by Exotic Atom Technique



Interaction of antinucleus in GAPS:

- Tracked in the TOF, which measures **velocity** and **dE/dx loss**
- Slows to stop in the tracker, where it is captured by a target nucleus to form an exotic atom
- The exotic atom de-excites via **X-rays** (detected in the tracker)
- Then annihilates to secondary hadrons (tracked in the tracker and TOF)

Antinucleus discrimination based on:

- Stopping depth, dE/dx losses, β
- Multiplicity of secondary hadrons
- X-ray energies

Exotic atom technique verified:
Hailey+, JCAP 0601 (2006)
Aramaki+ Astropart.Phys. 49 (2013)

GAPS vs Conventional Techniques

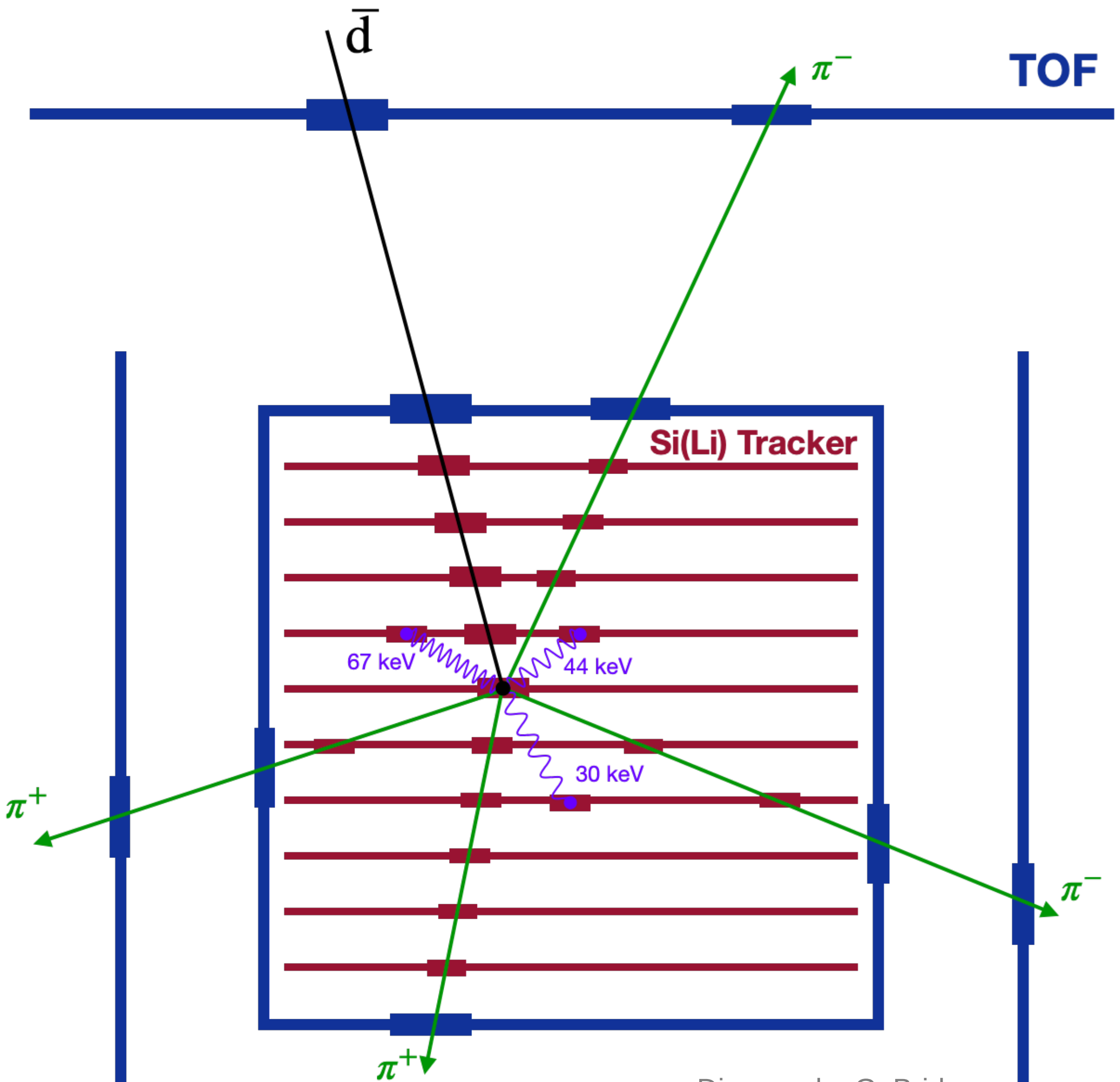


Diagram by G. Bridges

Compared to magnetic spectrometer, the exotic atom technique is:

- Specific to negative particles (form exotic atom)
- Specific to low energies (particles are stopped in the detector)
- Very large sensitive area (no magnet required and large aperture)

Unique features of Antarctic LDB flight:

- Very low geomagnetic cutoff
- Massive payload possible

GAPS Timeline

2000	GAPS concept
2004	KEK beam tests
2012	pGAPS flight (Hokkaido, Japan)
2017-18	Payload and subsystem design
2018-22	TOF and Si(Li) fabrication
Sep 21 – Feb 22	GAPS Functional Prototype (MIT Bates Lab)
Mar 22 – May 23	Pre-Integration (MIT Bates Lab, UCLA, Berkeley SSL)
June 2023	Thermal-vacuum test (NTS El Segundo, CA)
Aug 23 – May 24	Re-build, calibration, testing (Columbia Nevis Lab)
May, June 2024	Compatibility and hang test (CSBF Palestine, TX)
Dec 2024	**First Antarctic flight!**

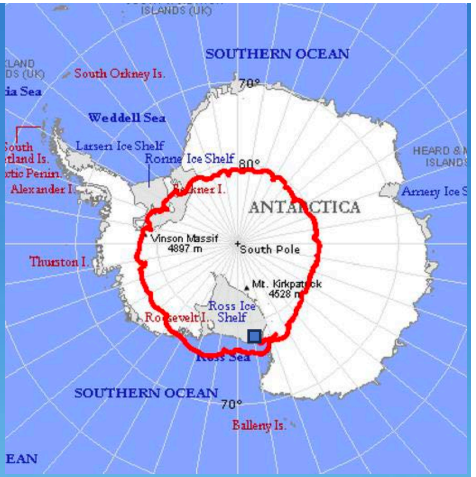
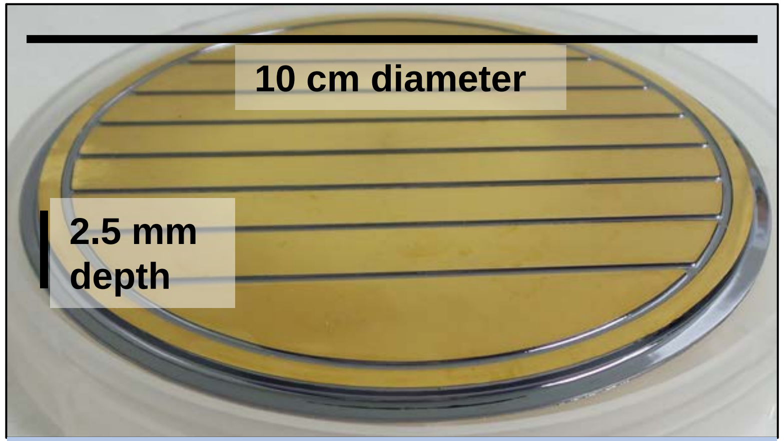


Image: NASA

Silicon Tracker

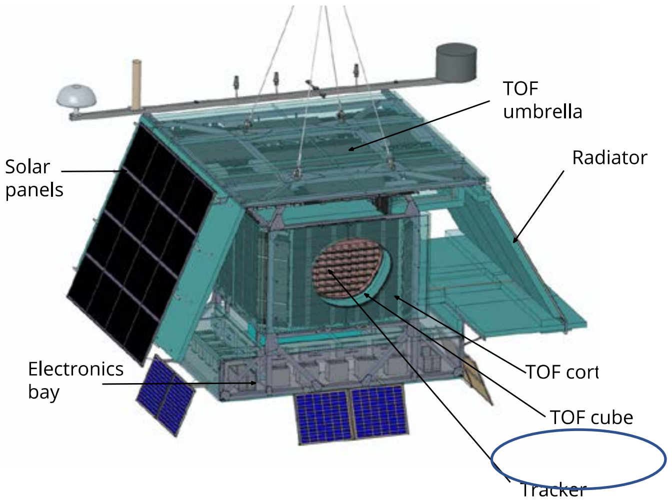
- ❑ Columbia, MIT, UCB, Hawaii, Trieste, Bergamo
- ❑ 2.5m^3 tracker volume
  - 1060 custom silicon sensors
  - 10 layers (7 with active sensors)
- ❑ Individually-calibrated modules of 4 sensors with readout electronics
  - X-ray energy resolution <4 keV (FWHM)
  - <10% energy resolution up to 100 MeV
- ❑ Operates around –35°C

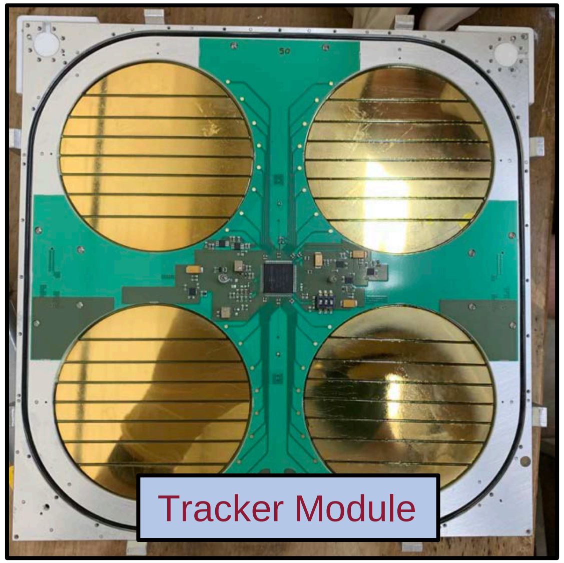


8-strip lithium-drifted silicon (Si(Li)) sensor

Si(Li):
Kozai et al., NIM A 1034 (2022)
Xiao et al., IEEE 70 (2023)

ASIC:
Manghisoni et al., IEEE 68 (2021)





Tracker Module

Tracker layer contains 36 modules, with integrated oscillating heat pipes

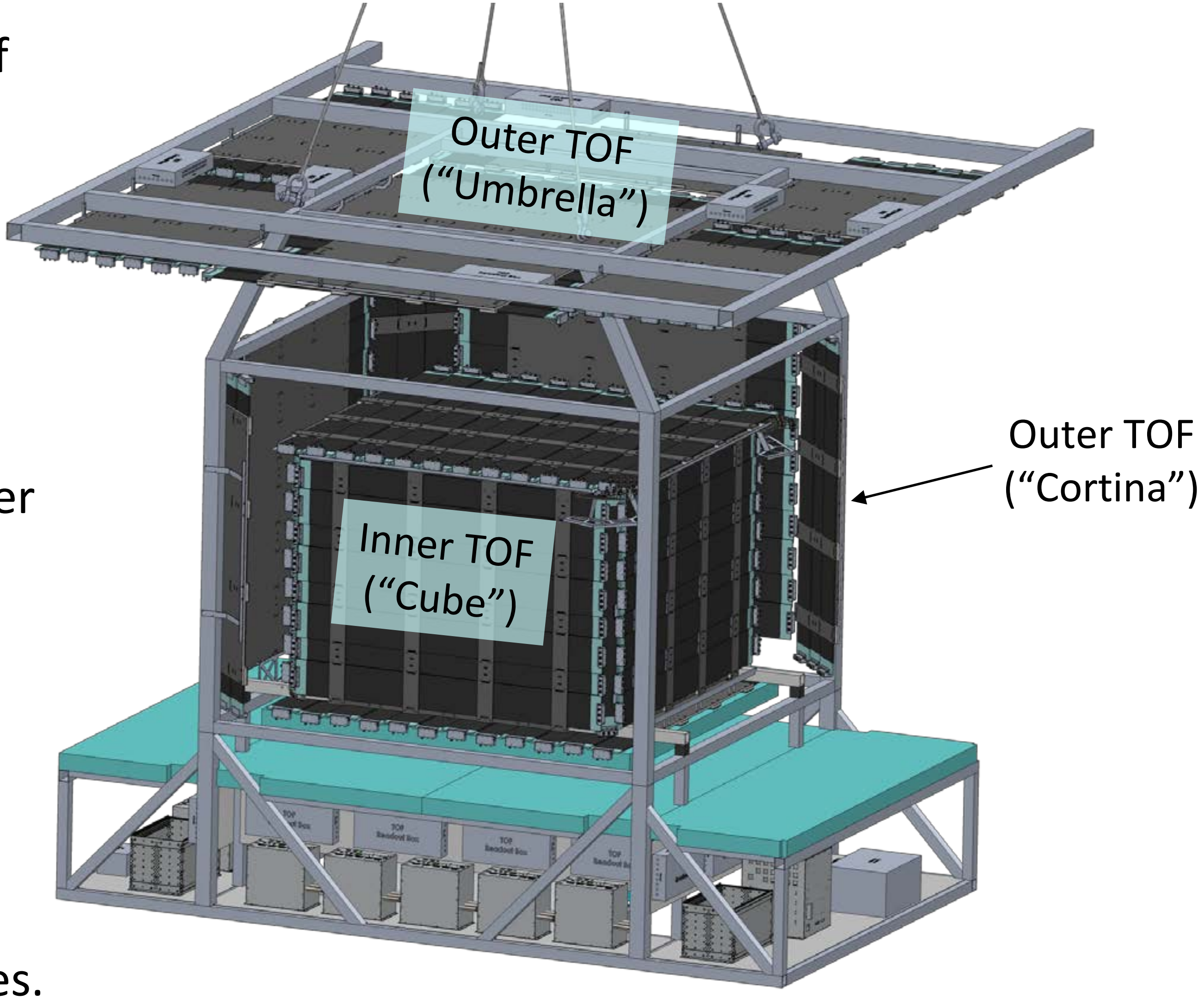
Time of Flight (TOF)

- UCLA
- The TOF measures β, dE/dx, and trajectory of incoming antimatter track.
- TOF provides the main trigger for GAPS.
- Required performance σ_t < 400ps over 1m.

Overall Design:

- Two layers of long, thin scintillator paddles, arranged in inner Cube surrounding the tracker and outer Umbrella and Cortina.
- 160 counters arranged into 21 lightweight, rigid carbon-fiber panels.
- Custom electronics for high-speed waveform readout, trigger, and LV power.

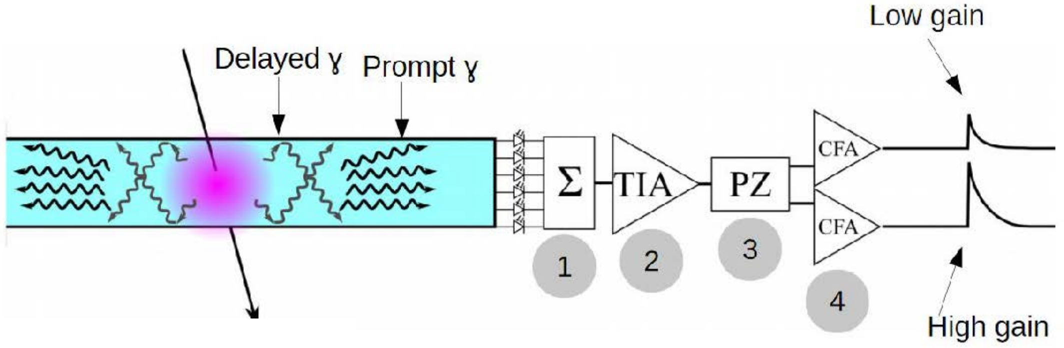
<u>The size of the TOF and the severe mass/power constraints posed significant technical challenges.</u>



TOF Paddles

Paddle Design:

- ❑ EJ-200 scintillator: (1.4m-1.8m) x 0.16m x 0.63cm, ~30 m^2 in total area.
- ❑ Read out on both ends by 6 SiPMs (S13360-6050CS), using custom pre-amp and housed in Al enclosure.
- ❑ Preamp incorporates TIA and PZ stages, with two outputs: high gain (timing) and low gain (trigger).
- ❑ Multi-step wrapping/sealing procedure; fabrication done in 2021-23 largely by UCLA students.

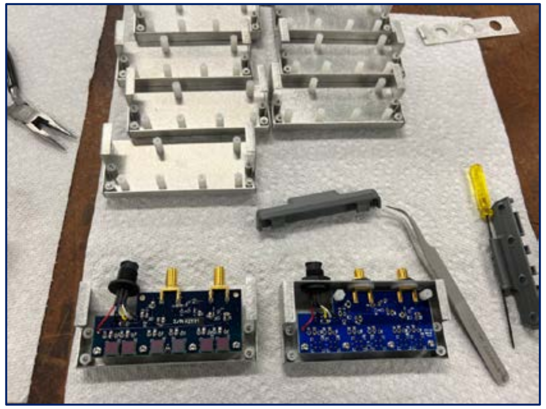


1. Analog sum stage
2. Transimpedance amplifier stage
3. Pole zero cancellation
4. Current feedback amplifier stage

TOF Paddle Fabrication

Wrapping

Prep enclosures

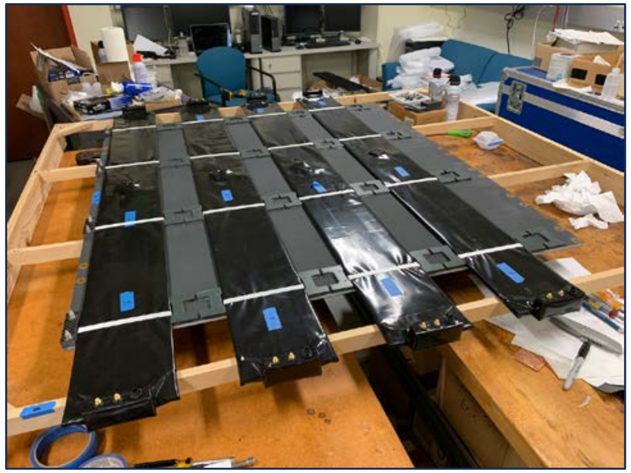


Awaiting final wrap

TOF Panel Fabrication

Foam board w. ribs

Cross members, paddle spacers



Strap first paddle layer

Final panel strapping

Finished 8pp (Cube side)

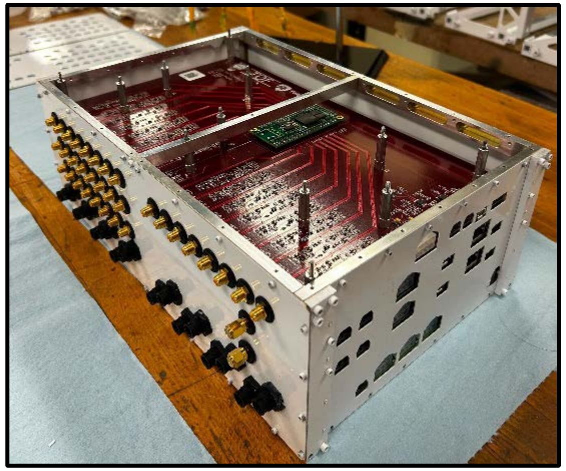
TOF Electronics

Five separate custom-boards designed and fabricated:

- ❑ SiPM **preamp**.
- ❑ Power board (**PB**).
- ❑ Local and master trigger boards (**LTB**, **MTB**).
- ❑ Readout board (**RB**): based on DRS-4 2 GS/s ASIC, onboard FPGA and SOC with Linux OS, Gbit ENET, etc.

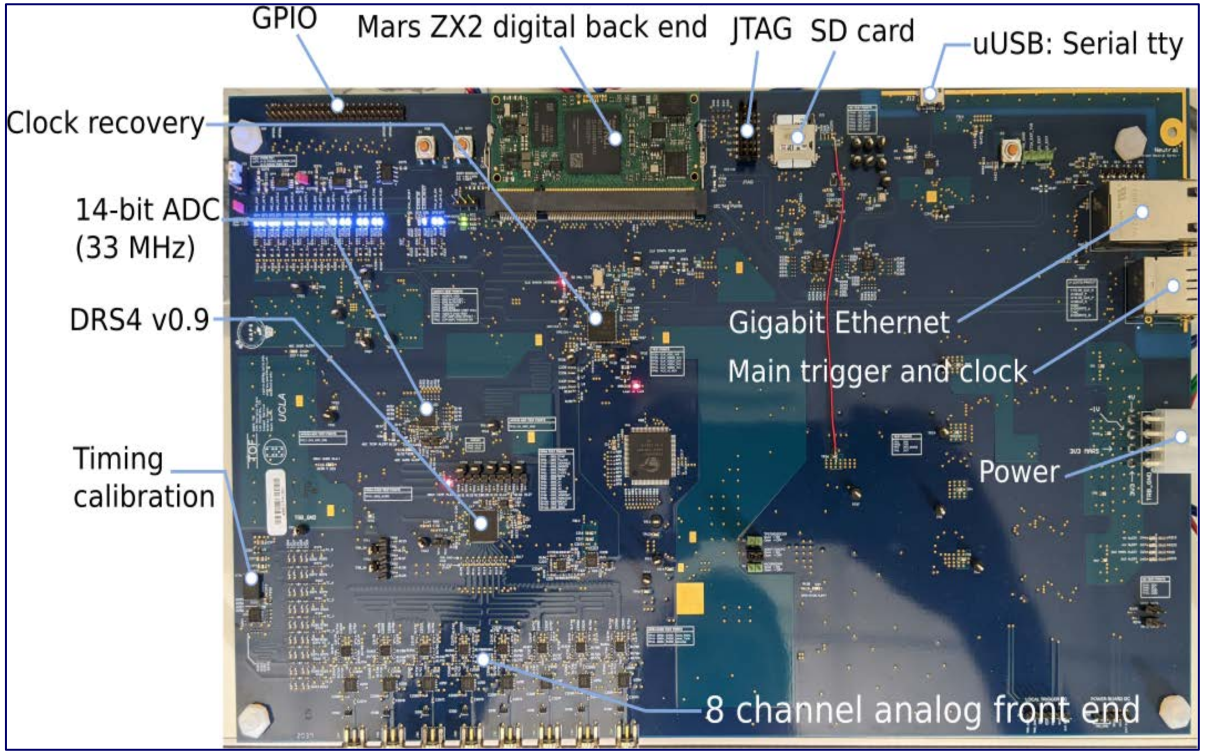
Electronics mounted in enclosures (RAT boxes).

Electronics stack
(1 PB, 1 LTB, 2 RBs)

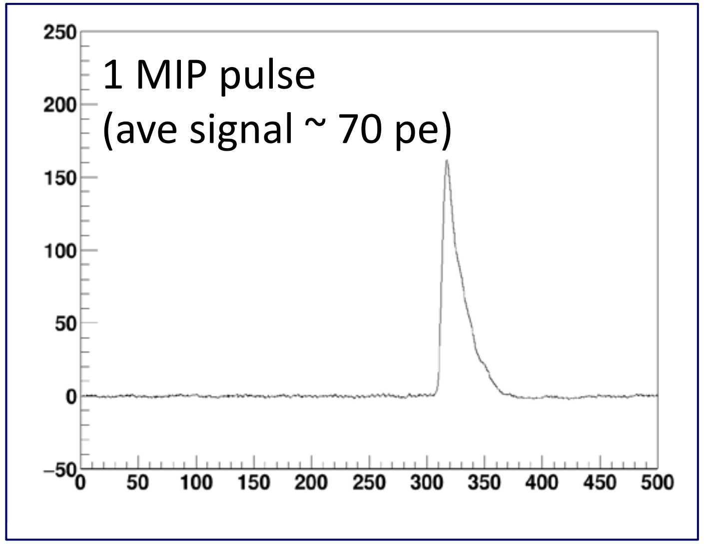


Assembly of a RAT box

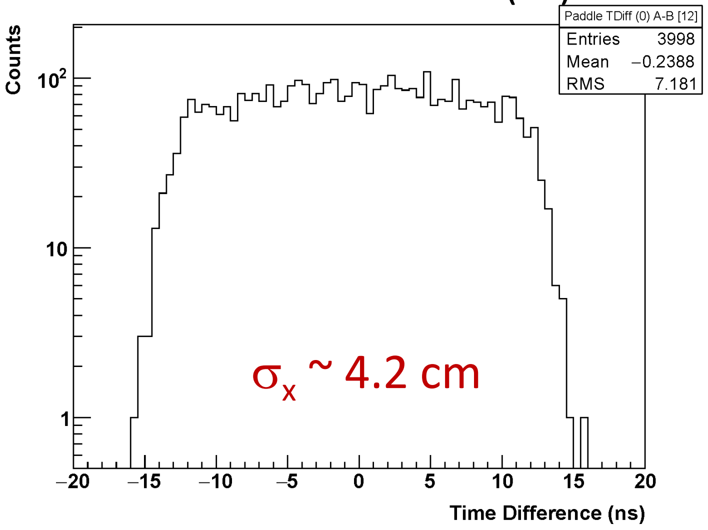
TOF READOUT BOARD



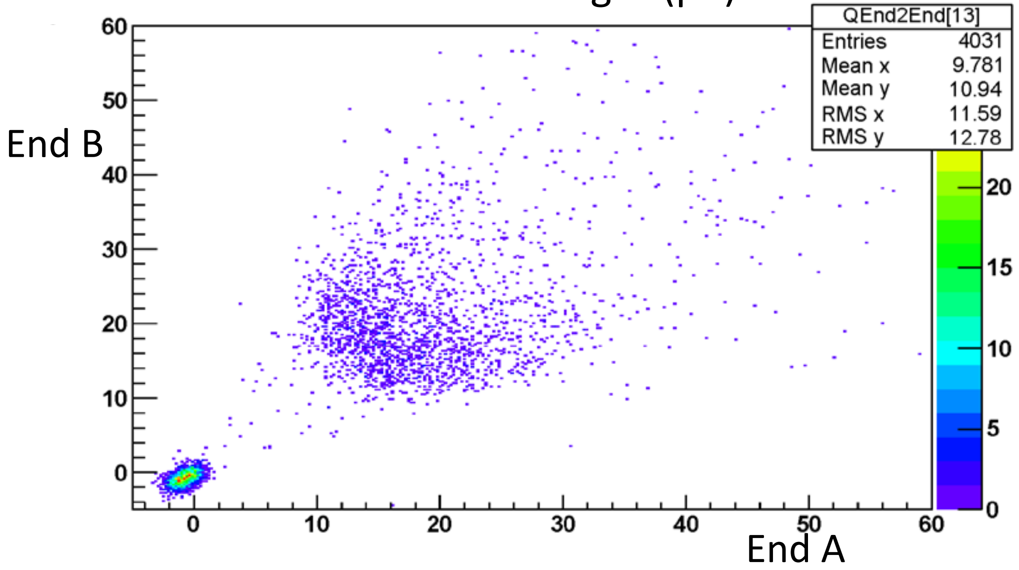
TOF Performance Plots



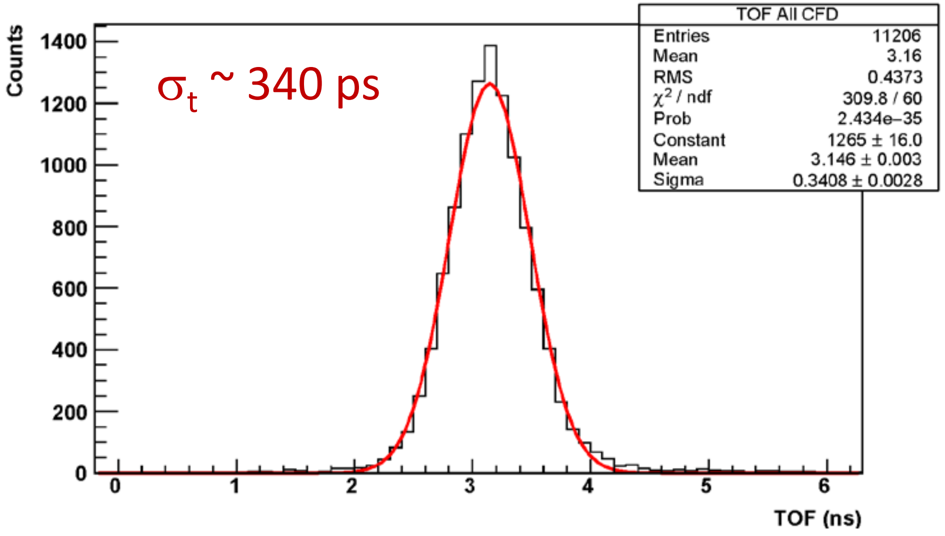
End-End time diff (ns)



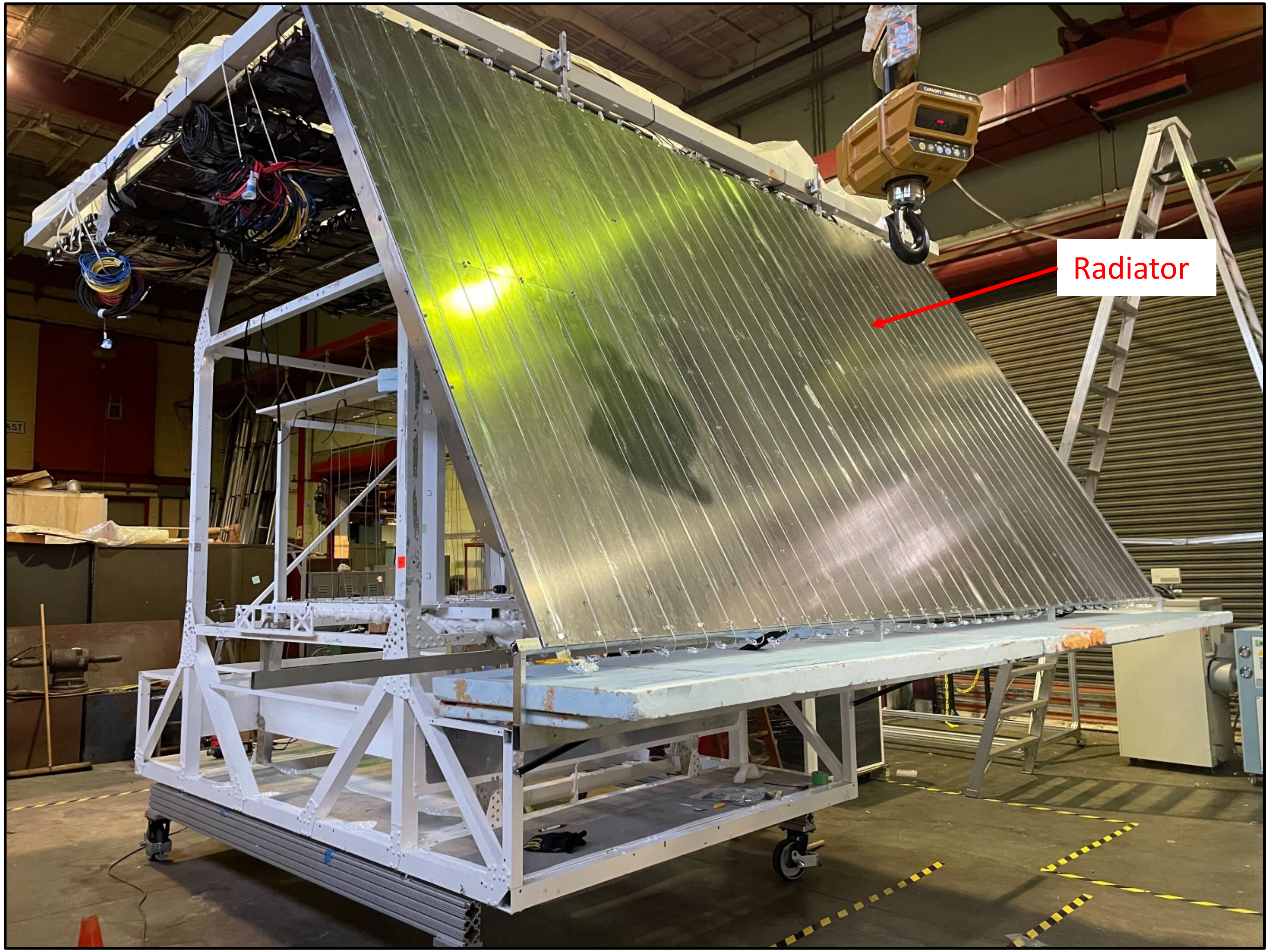
End-End charges (pC)



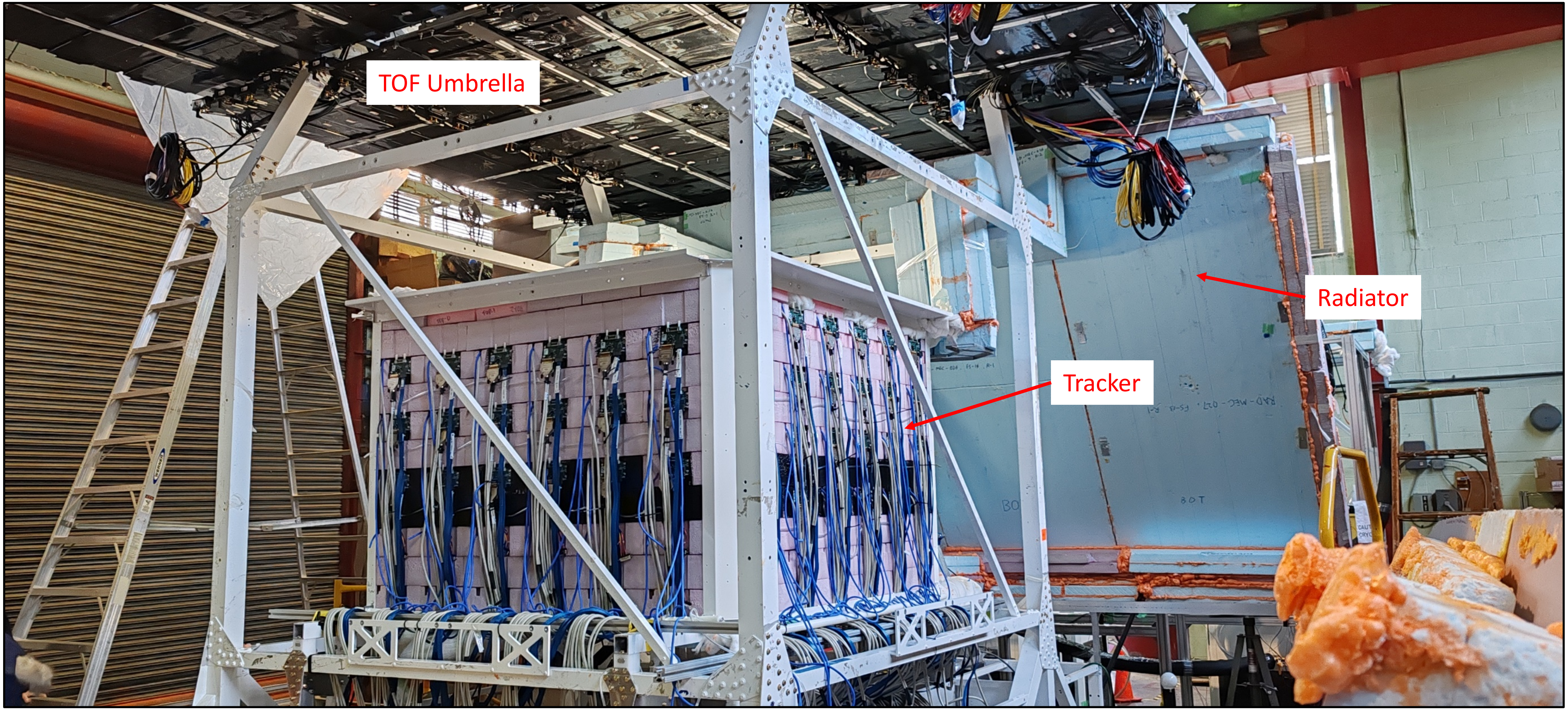
TOF over 0.95m distance



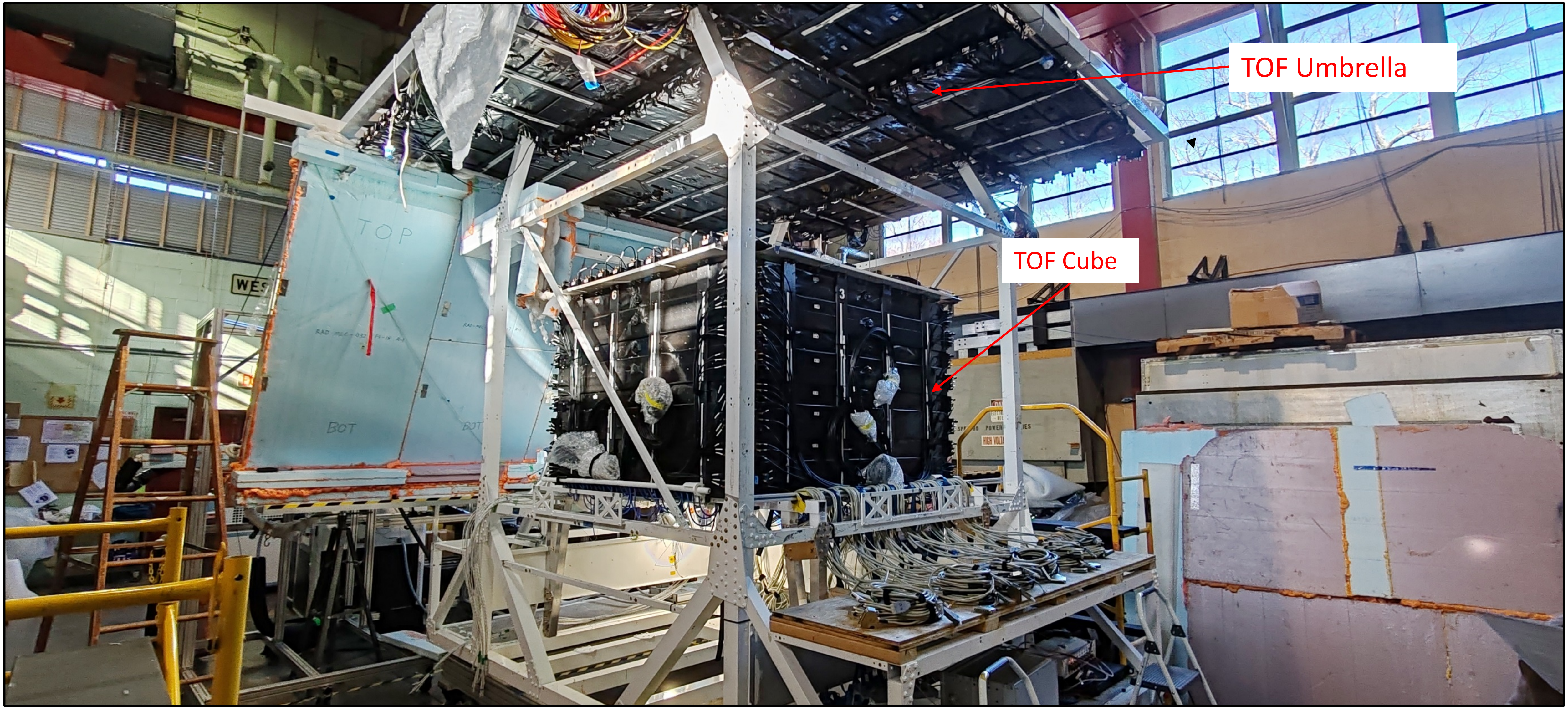
Integration @Nevis Labs (Oct 2023)



Integration @Nevis Labs (Dec 2023)

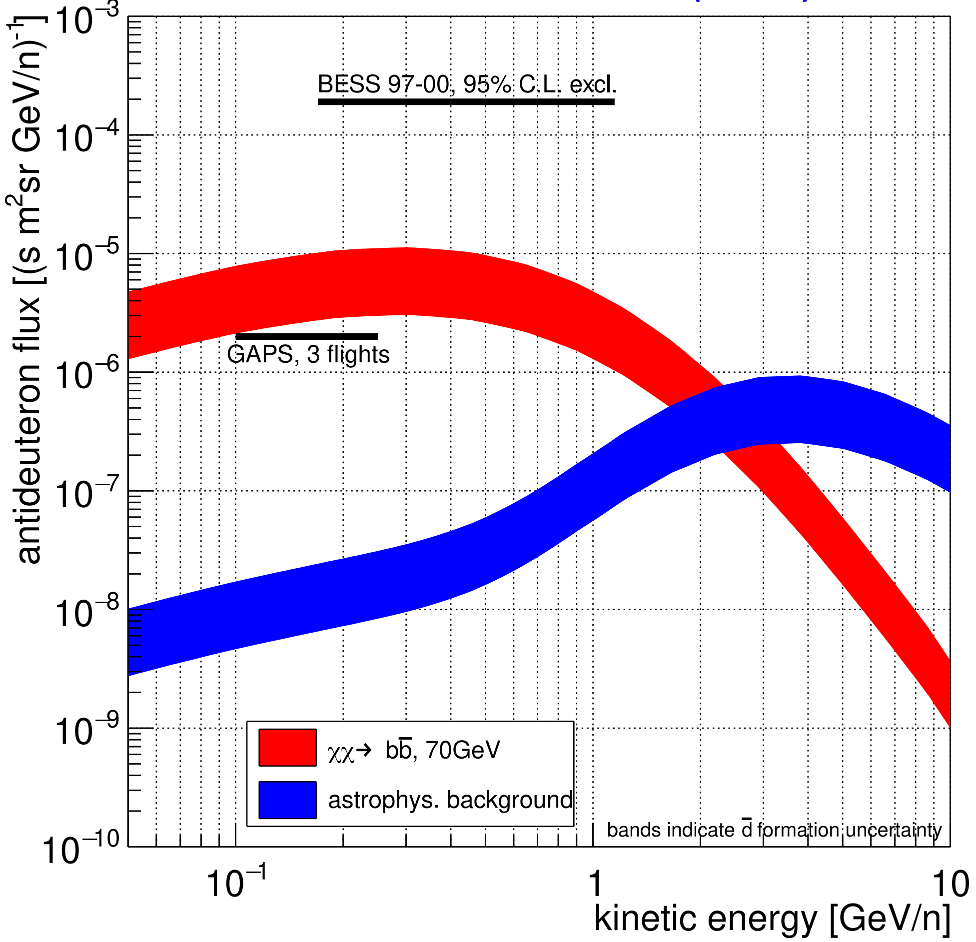


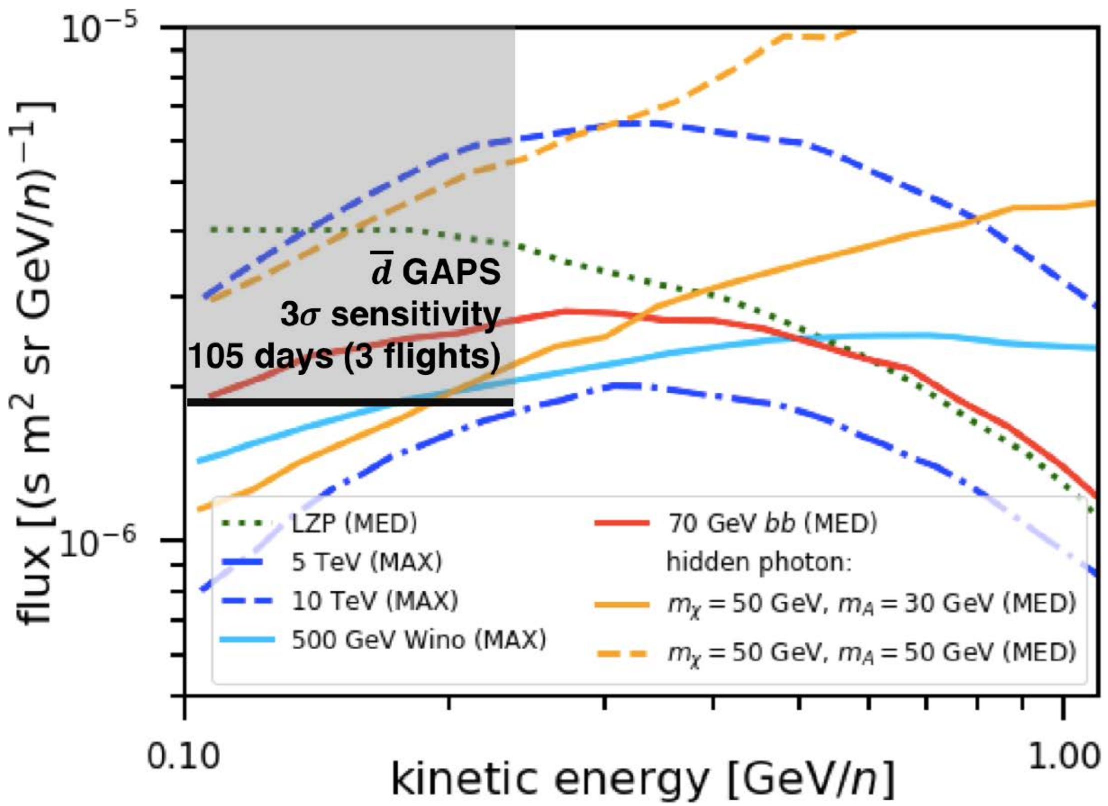
Integration @Nevis Labs (Jan 2024)



The Full Payload (Mar 2024)

Antideuteron Sensitivity





- ❑ Generic 70 GeV WIMP model that $\bar{p}$, γ evidence
- ❑ Gravitino decay, extra dimensions, dark photon models

- ❑ Detectable $\bar{d}$ flux from range of DM models, including many that evade direct detection/colliders.
- ❑ Astrophysical (secondary) flux is several orders of magnitude below DM signal.

Conclusions

- Cosmic ray antimatter provides a critical window into deep questions in physics. Current measurements of positrons and antiprotons are generally consistent with secondary production, leaving little room for new physics.
- Antideuterons (and anti-He) offer a background-free technique to search for primary sources of antimatter.

- **GAPS** is the first experiment dedicated to the observation of antiprotons, antideuterons and anti-He at KE ≤ 250 MeV/n. GAPS will use a novel technique that is complementary to all previous experiments.
- Main scientific goals of GAPS: 1) <u>first detection of cosmic antideuterons</u>, 2) precision measurements of the antiproton spectrum at low KE, and 3) detection of anti-He (if present) with a different technique than AMS-02.
- Hardware integration of GAPS is complete, with first flight scheduled for December 2024.