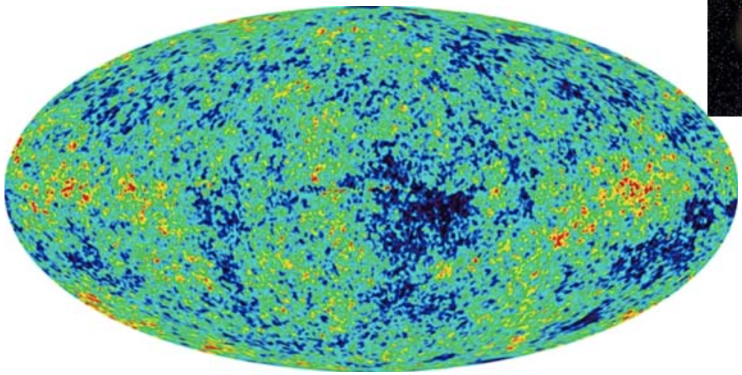
GAPS
General AntiParticle Spectrometer

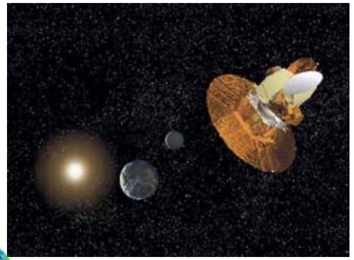
GAPS

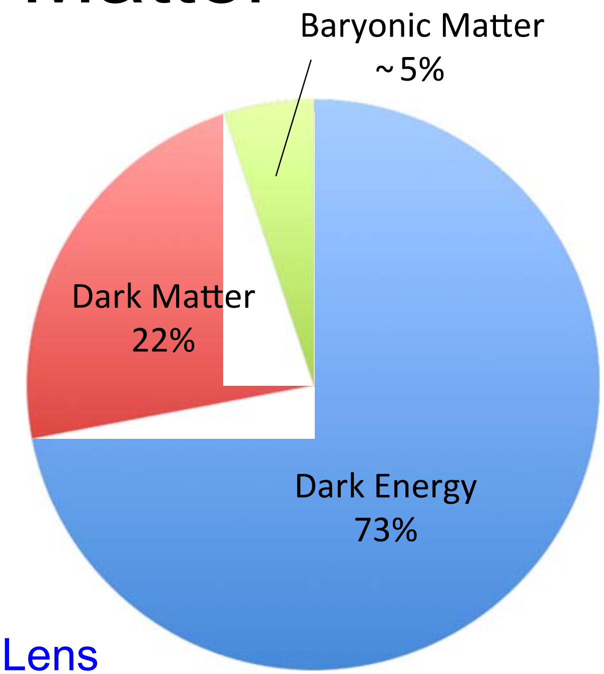
- The two towering problems of early 21st century physics are the nature of dark matter (DM) and dark energy.
- With regards to DM, balloon experiments under development will also have the potential to detect antideuterons, which may be produced in dark matter annihilations.
- Proposal to build GAPS, an experiment to detect antideuterons produced when DM particles annihilate in the Galactic halo.
- This antideuteron search experiment will culminate in a balloon flight from Antarctica

Evidence for Dark Matter

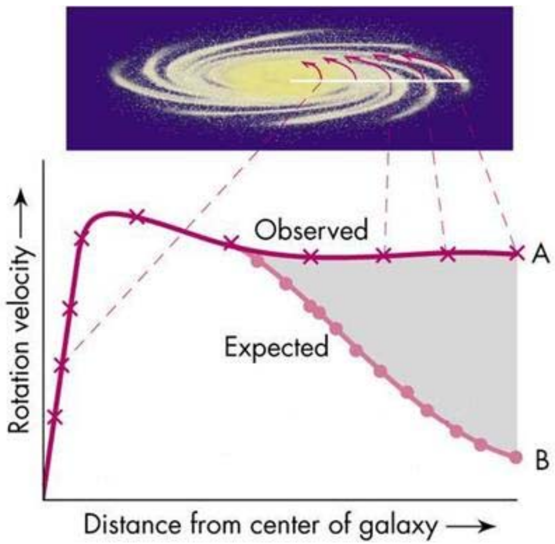
WMAP/Planck measured
accurate cosmological information



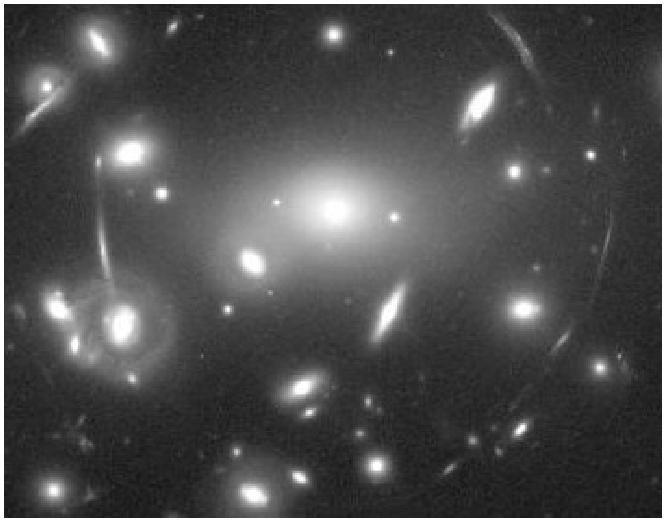




Galactic Rotation Curve



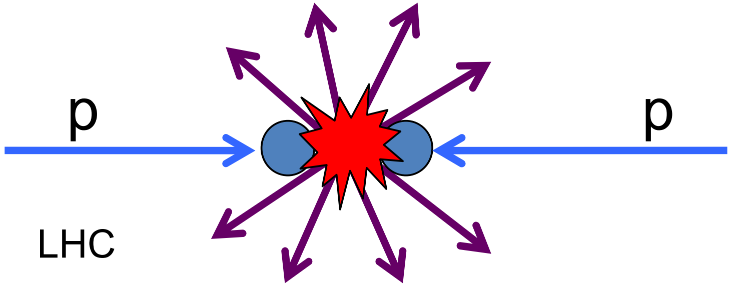
Gravitational Lens



Dark matter searches

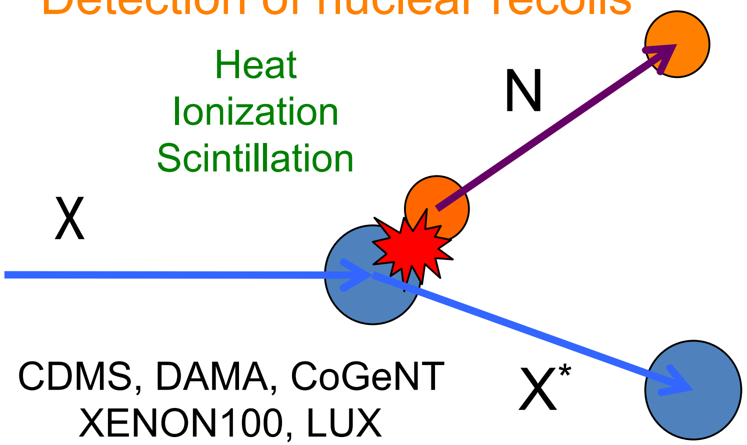
Collider Search

Missing energy and momentum for DM particle



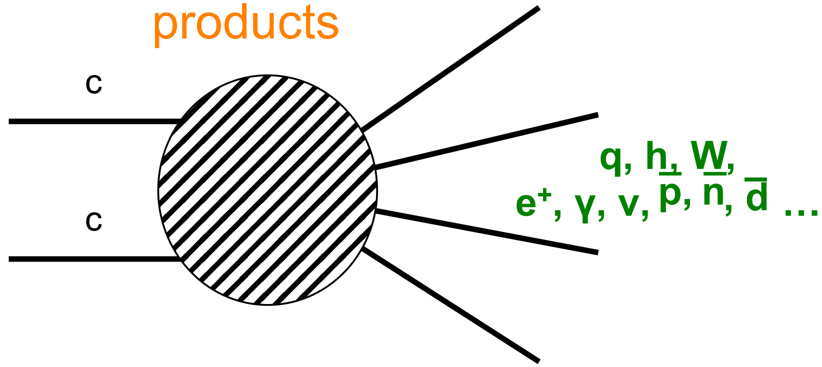
Direct Search

Detection of nuclear recoils



Indirect Search

Detect annihilation products



- Positron (e^+):
  PAMELA, Fermi-LAT, ATIC, AMS
- Photon (γ)
  Fermi-LAT, HESS…
- Neutrino (ν): AMANDA, IceCube…
- Antiproton ($\bar{p}$)
  BESS, AMS, PAMELA, GAPS
- Antideuteron ($\bar{d}$)
  GAPS, AMS

GAPS Antideuteron identification

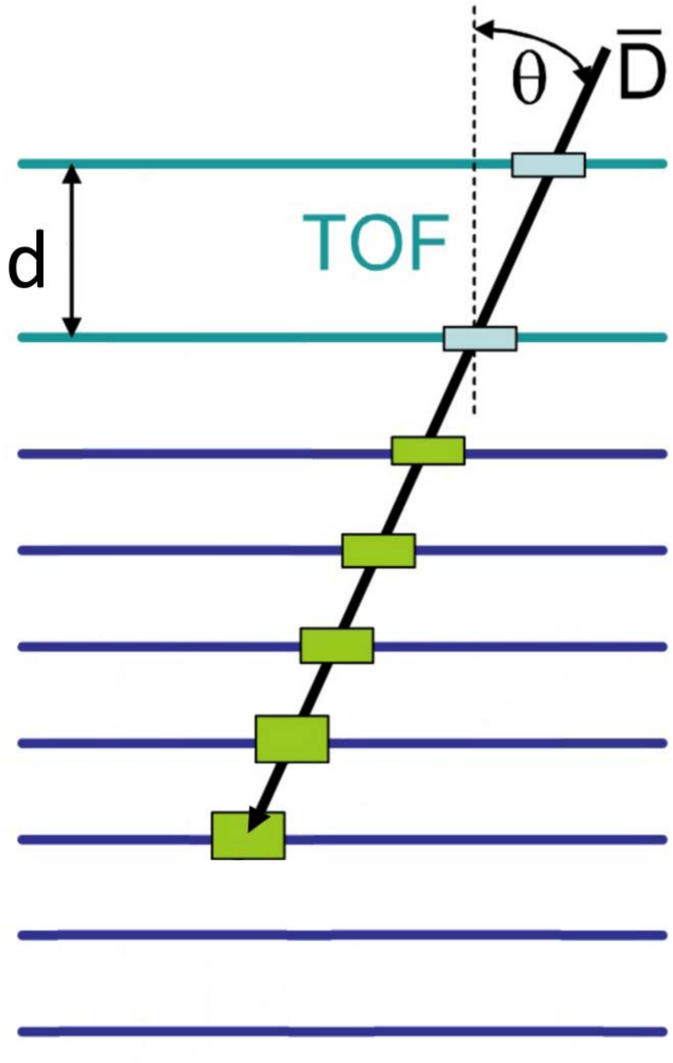
GAPS relies on three techniques to uniquely identify antideuterons:

- **time of flight (TOF), depth sensing and dE/dx loss** to distinguish heavier antideuterons from the lighter protons and antiprotons,

- **simultaneous detection of X-rays** emitted when a captured antiparticle makes atomic transitions from an excited state (the X-ray energies for the antiparticle are unique and provide a mass measurement), and

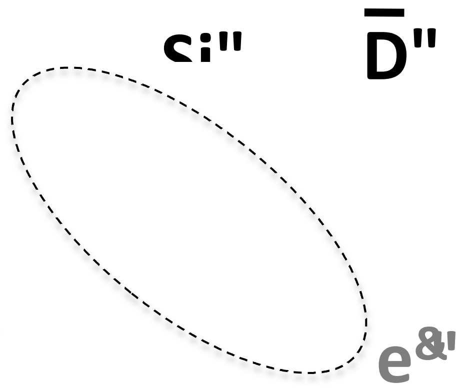
- **multiplicity of pions, protons and other particles emitted from the nuclear annihilation** (which we refer to as a ‘nuclear star’), which scales with the antiparticle mass.

GAPS Detection Concept



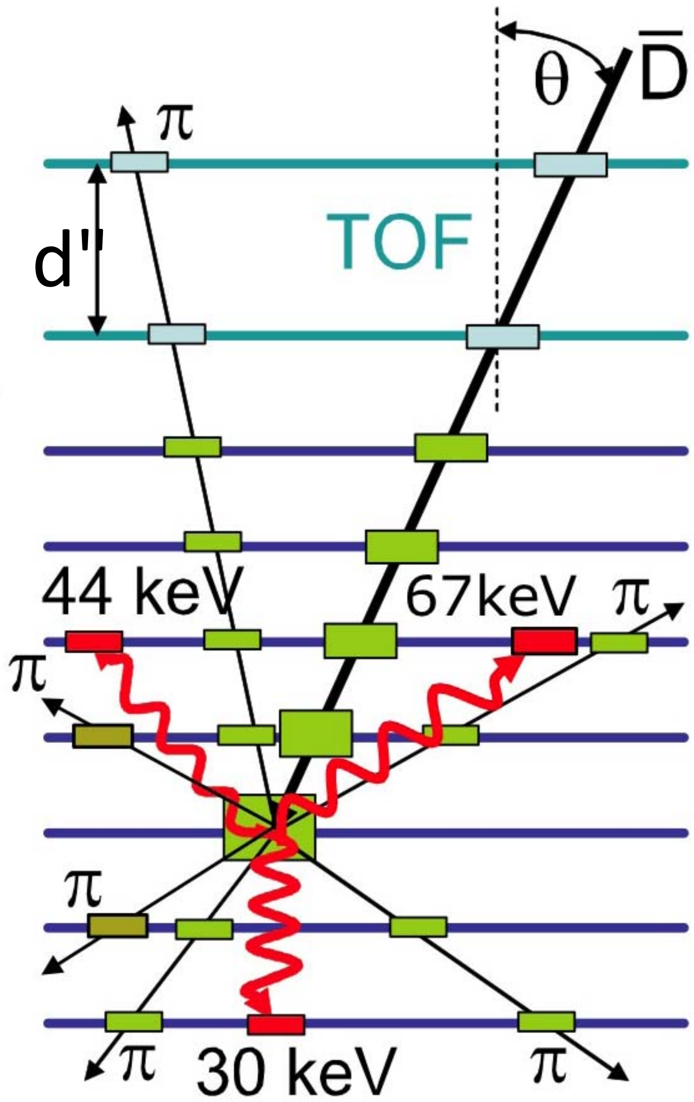
- **Time-of-flight** system measures velocity
- Loses energy in layers of semiconducting
  Silicon targets/detectors
- Stops, forming **exotic excited atom**

%



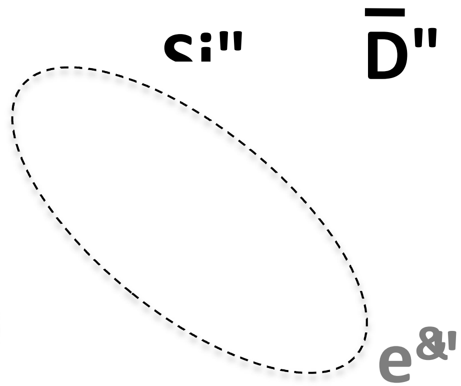
T. Aramaki et al. (2013) 1303.3871

GAPS Detection Concept



- **Time-of-flight** system measures velocity
- Loses energy in layers of semiconducting **Silicon targets/detectors**
- Stops, forming **exotic excited atom**
- Atom de-excites, emitting **x-rays**
- Remaining nucleus annihilates, emitting **pions and protons**

%



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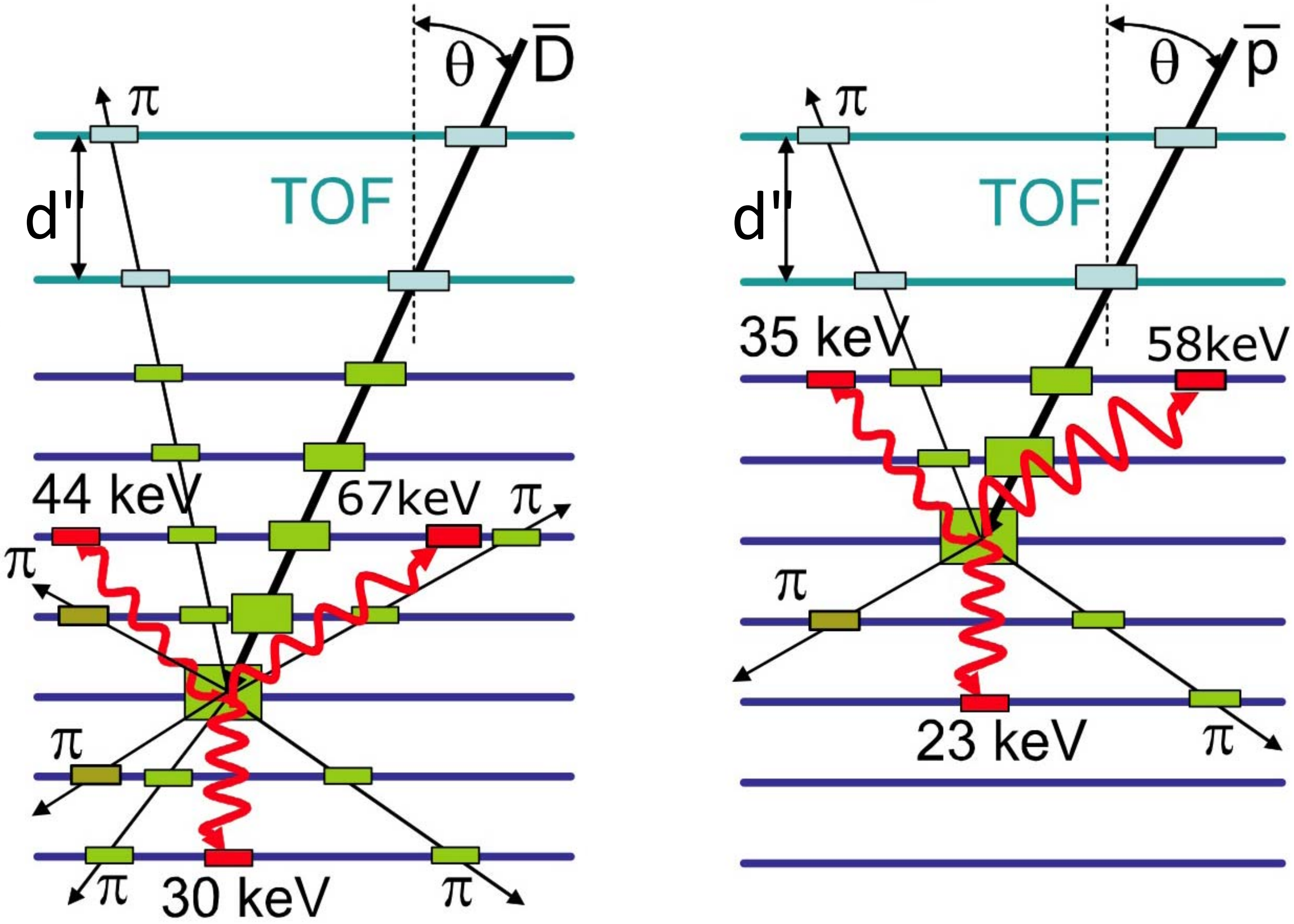
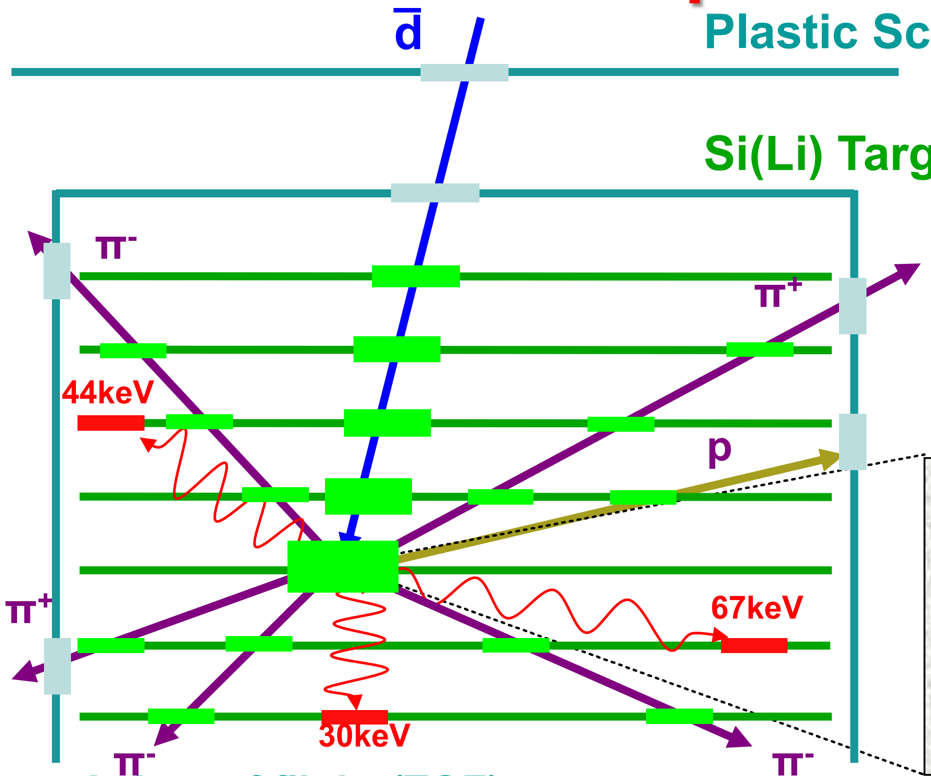
GAPS Background Rejection



Combination of time-of-flight + depth-sensing, X-ray, and π detection yield rejection > 10^6

GAPS etects tomic rays and annihilation products from exotic atoms

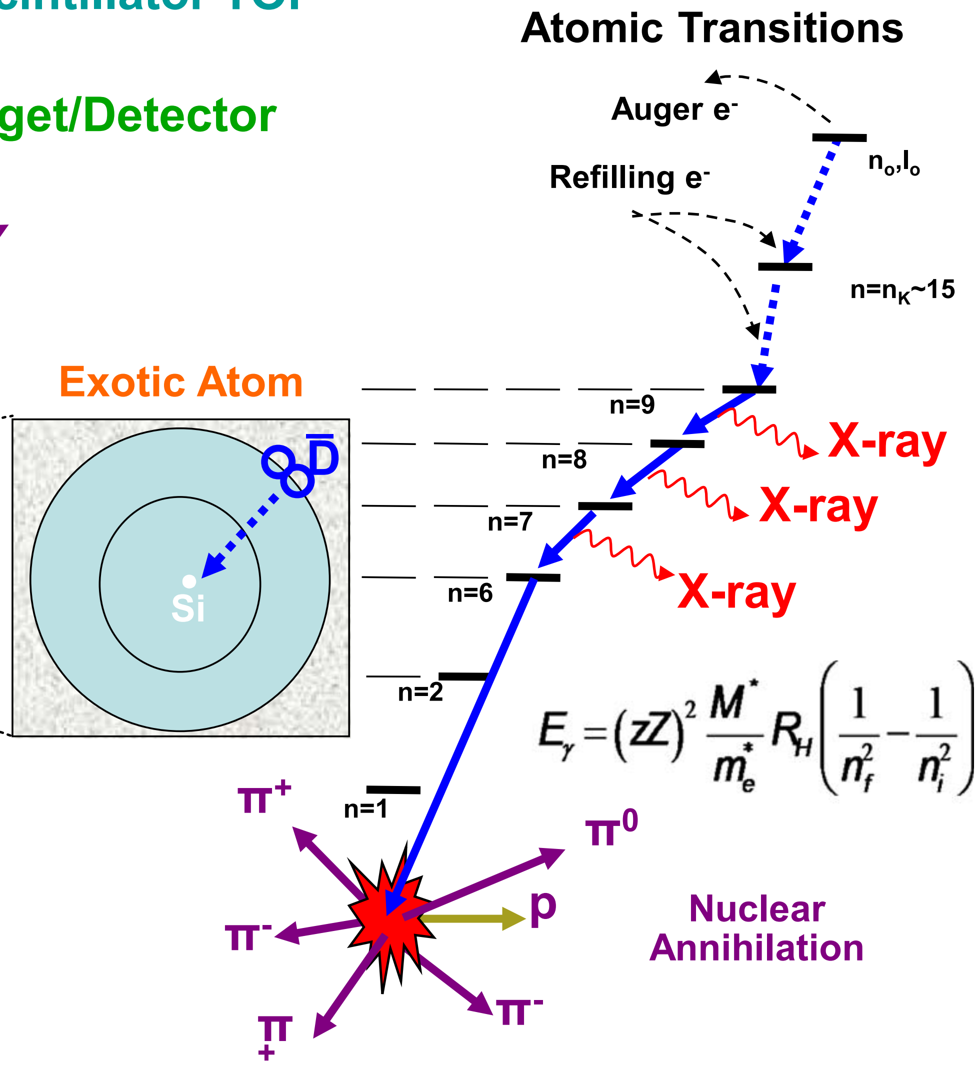


A time of flight (TOF) system tags candidate events and records velocity

The antiparticle slows down & stops in a target material, forming an excited exotic atom

Deexcitation X-rays provide signature

Annihilation products provide added background suppression

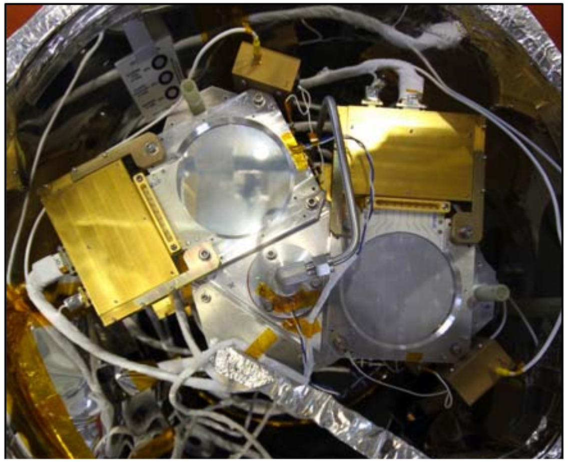


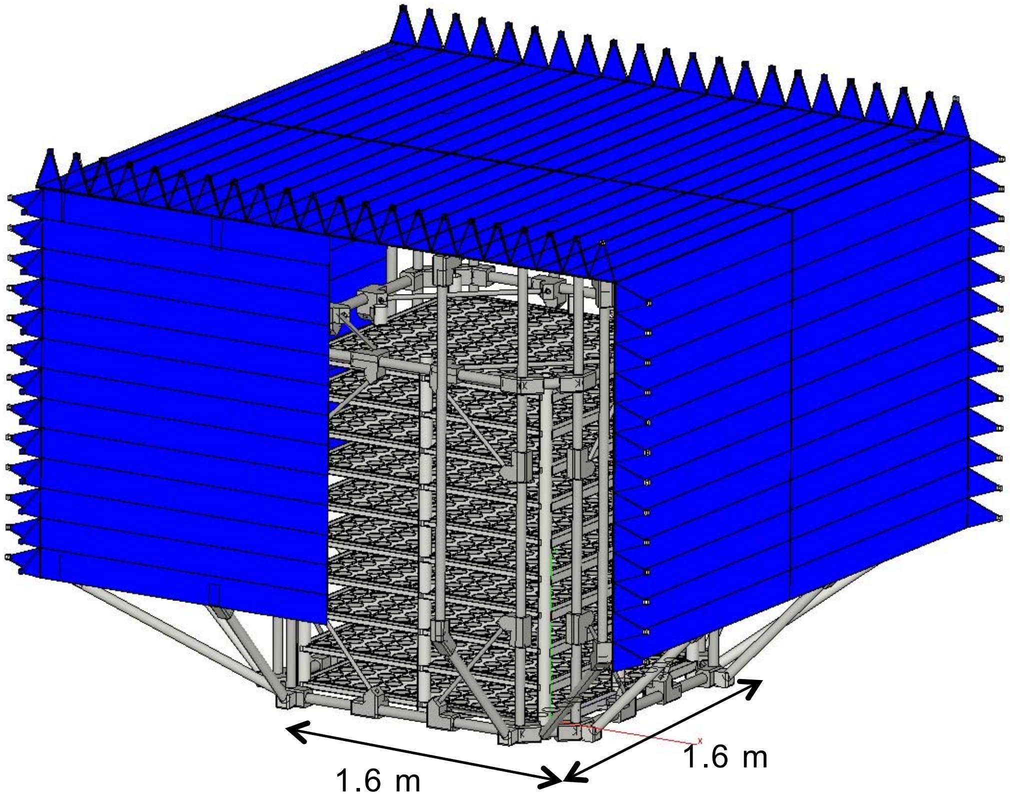
X-ray yields were measured at KEK in 2004 and 2005

GAPS Detector Design

Plastic scintillator TOF

- high-speed trigger and veto
- 160-180 cm long, 0.5 cm thick
- read out both ends
- ~500 ps timing resolution





Si(Li) targets/detectors

- X-ray identification, dE/dx, stopping depth, and shower particle multiplicity
- 2.5 mm thick, 4” (or 2”) diameter
- 4 keV resolution for X-rays

GAPS science summary

- *Antideuterons* **as DM signatures**
    - **no astrophysical background** at low energy
    - **complementary** to direct/indirect searches and collider experiments
    - search for: **light DM**, heavy DM, gravitino DM,
      LZP in extra-dimensions theories, (evaporating PBH)
- *Antiprotons* **as DM and PBH signatures**
    - precision flux measurement at ultra-low energy (E < 0.25 GeV)
    - **complimentary** to direct/indirect searches and collider experiments
    - **~ 10 times more statistics** @ 0.2 GeV, compared to BESS/PAMELA
    - search for: **light DM** gravitino DM,
      LZP in extra-dimensions theories, evaporating PBH
- *Expected to launch from Antarctica in 2020/2021*

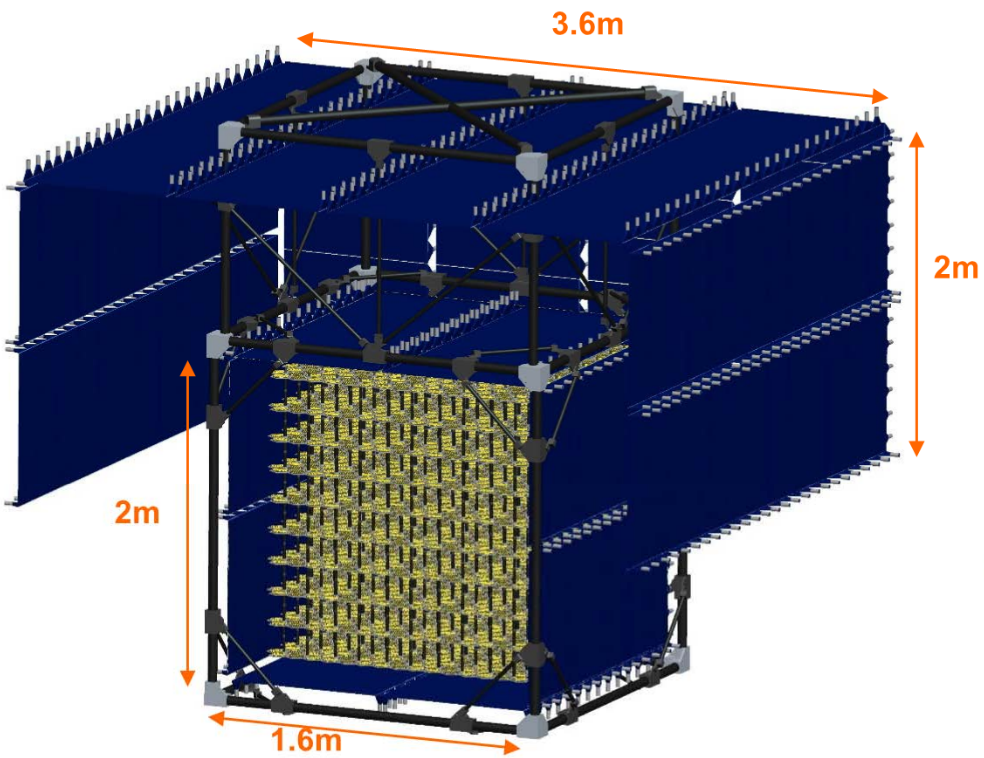
- **1 LDB flight (~35 days) -> precision antiproton flux measurement**
  ~1500 antiprotons in GAPS $E < 0.25$ GeV, while 30 for BESS, 7 for PAMELA at $E \sim 0.25$ GeV
- **2 LDB flights (~70 days) -> improved antideuteron statistics**
  Antideuteron sensitivity: ~3.0 x 10^{-6} [$m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}$] at $E < 0.25$ GeV
- **3 LDB flights (~105 days) -> Antideuteron sensitivity: ~2.0 x 10^{-6} [$m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}$] at $E < 0.25$ GeV**

M. Hailey, Dark Matter 2014, UCLA

GAPS instrument summary

TOF plastic scintillators

- outer TOF: 3.6m x 3.6m, 2m height
- inner TOF: 1.6m x 1.6m, 2m height
  - 1m b/w outer and inner TOFs
  - 500 ps timing resolution
  - 16.5 cm wide plastic paddles
  - PMT on each end



Science weight: ~1700 kg, 34H balloon

Si(Li) detectors

- 10 layers, 1.6m x 1.6m
- layer space: 20 cm
- Si(Li) wafer (~1500 wafers)
  - 4 inch diameter
  - 2.5mm thick wafer
  - 12 x 12 rectangular
- segmented into 4 strips
  - → 3D particle tracking
- timing resolution: ~ 100 ns
- energy resolution: 3 keV
- operation temperature: -35 C
- dual channel electronics
  - X-ray: 20 - 80 keV
  - charged particles: 0.1 - 100 MeV

Cooling system

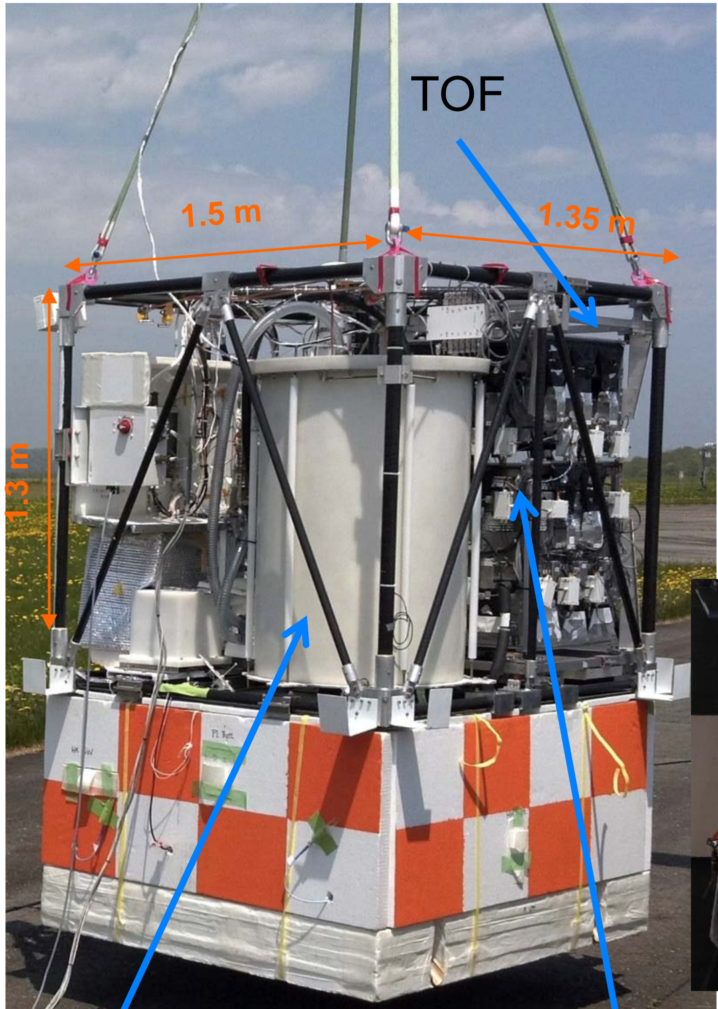
- oscillating heat pipe (OHP)
- demonstrated in pGAPS

M. Hailey, Dark Matter 2014, UCLA

Successful prototype (pGAPS) flight in 2002 @ Taiki, JAXA balloon facility in Japan

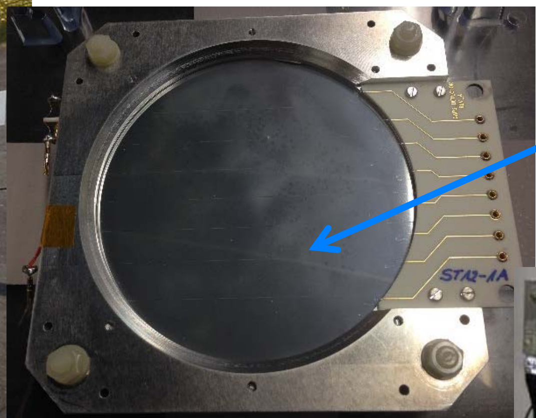
- ✓ First balloon experiment with Si(Li) detectors
- ✓ TOF performance test and measure cosmic-ray proton count rate
- ✓ Demonstrate cooling system

M. Hailey, Dark Matter 2014, UCLA



Vessel for DAQ

Si(Li) detector surrounded by TOF



Commercial SEMIKON Si(Li)
4 inch diameter, 2.5mm thick

The Flight

Instrument Paper

S. A. I. Mognet et al.
http://arxiv.org/abs/1303.1615

Flight Paper

P. von Doetinchem et al.
http://arxiv.org/abs/1307.3538v2

- Both TOF and Si(Li) systems worked very well.
- Rotator failed so no pointing (no active cooling available).
- Si(Li) operated for duration of flight from initial ground cooling (64% of strips still depleted at termination).
- OHP test very successful (first operation in a balloon flight).
- Thermal model fully validated (with pointing, active cooling would have worked).

The pGAPS flight was a great success!

Ready for Si(Li ı ass production

M. Hailey, Dark Matter 2014, UCLA

Ultrasonic Impact Grinder

Si(Li) fabrication

- requires 1500 Si(Li) detectors
- Li evaporator, UI grinder in the lab
- HF etching in clean room
- computer controlled Li drifting system

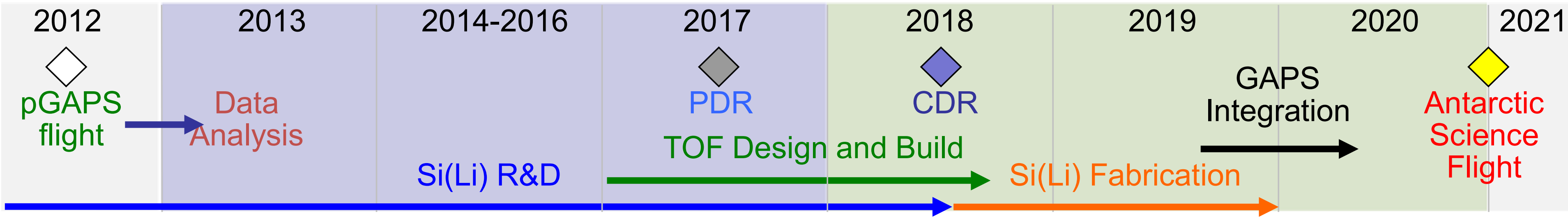
Fabrication facility has been set up at Columbia University

Li evaporator

Etching in cleanroom

Li drifting station

Development Plan



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Possibile Partecipazione INFN

- Collaborazione GAPS desidererebbe una partecipazione INFN in quanto ritiene che aumenti sia la credibilità scientifica (impatto internazionale dell'INFN ed il nostro successo con PAMELA) che finanziaria (nel loro budget manpower specializzato, come ingegneri elettronici, conta molto).
- L'INFN potrebbe contribuire alla realizzazione degli ASIC per il DAQ dei rivelatori al silicio. **A questa attività parteciperebbe INFN TS e Università Bergamo:**
  - **INFN Trieste: Valter Bonvicini (I Ric.); Benigno Gobbo (I Ric.); Gianluigi Zampa (Tecnologo) ed i laboratori di elettronica ed alte energie della sezione di Trieste (c'è l'approvazione del direttore di Sezione);**
  - **Università Bergamo (INFN Pavia): Valerio Re (PO); Massimo Manghisoni (Ric. Univ.), Elisa Riceputi (Dott.)**
- **Partecipazione allo sviluppo del software di simulazione e di analisi dei dati così pure all'interpretazione degli stessi: INFN TS e INFN FI, Università di Torino e di Tor Vergata:**
  - **INFN TS: Mirko Boezio (I. Ric.), post. Doc.;**
  - **INFN FI: Elena Vannuccini (Ric.);**
  - **Università Torino: Nicolao Fornengo (PA); Fiorenza Donato (PA);**
  - **Università Roma Tor Vergata: Roberta Sparvoli (PA).**

Si(Li) front-end electronics

The Si(Li) detector readout must perform:

1) **high-resolution spectroscopy of X-rays** (<4 keV 580 FWHM or <470 e rms for 75 pF capacitance and < 10 nA leakage current) over the energy range 10-100 keV

2) **coarse-resolution spectroscopy and tracking of the nuclear annihilation products** (~10% FWHM) over the energy range 1-50MeV.

This **dual-mode detection** has already been demonstrated in the prototype DAQ system on pGAPS. The readout must also provide coincidences of <1 µs between tracker and TOF.

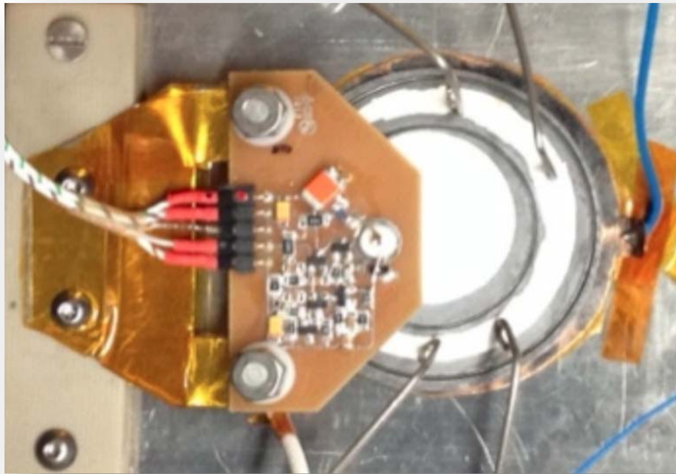
To achieve the required spectral resolution and dynamic range, while using a total of ~110 µW per full readout channel (for ~5,400 channels) and maintaining low passive mass near the tracker, **a custom ASIC is required**.

GAPS ASIC design

Objective read out 2.5 mm thick, 1” diameter Si(Li) detectors [$C_D \approx 75$ pF, I_{LEAK} = O(1 nA)]

Requirements

- dynamic range of 50 MeV, minimum signal ≈20 keV
- energy resolution of 4 keV FWHM at the lower end (goal of 3 keV FWHM)
- interface to already available discrete preamplifier



Available design choices and optimization opportunities

- Selection of the CMOS technology (at present all electronics is discrete)
- Investigate the possibility to integrate the preamplifier
- ASIC architecture (shaper, peak detector vs S/H, multiplexing, internal digitization?)

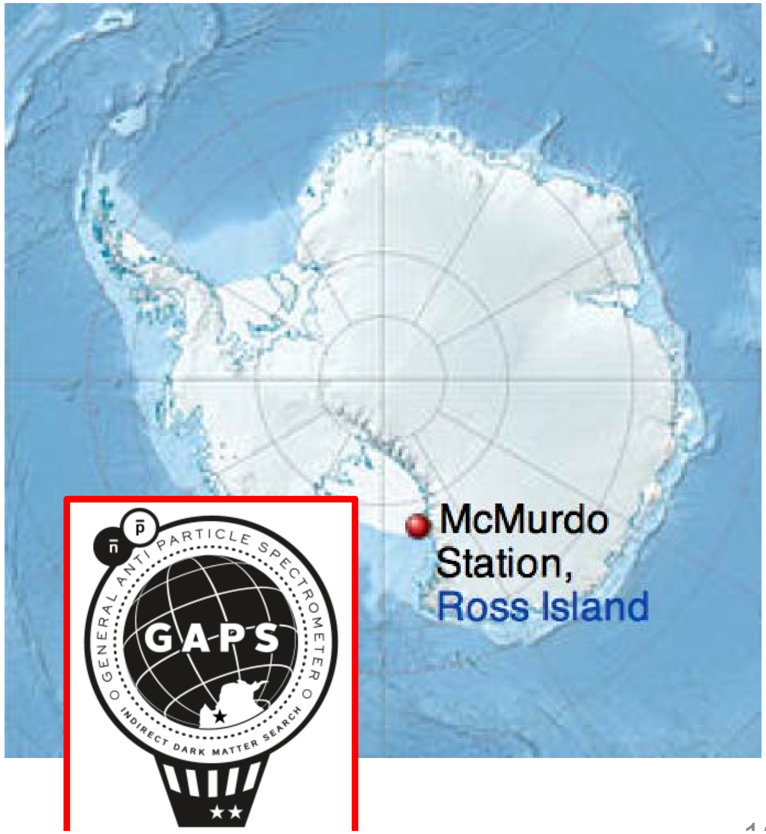
Sviluppo temporale

- Dead line per la sottomissione del proposal alla NASA è verso la metà marzo. Se partecipazione INFN, necessaria una lettera indicante il contributo italiano (se progetto approvato da NASA) entro fine febbraio.
- Verso inizio autunno 2016 vi sarà la risposta NASA.
- Se positiva avvio ufficiale attività gennaio-marzo 2017.
- Se approvato il progetto si svilupperà su un periodo di 5 anni nei quali si dovrà fare un volo in pallone e produrre i primi risultati scientifici.
- Volo previsto inverno 2020-2021. Si tratterà di un “long duration” da McMurdo (Antartide).
- È abbastanza probabile che la NASA supporti e finanzi voli successivi.

Onwards to GAPS Antarctic flight!

- **Exciting time for antideuteron searches!**
  - **Experimental sensitivities now approaching flux levels predicted from a range of DM models**
  - Rare event search, GAPS and AMS partners
- **GAPS development ongoing!**
  - 4” Si(Li) detector development between Columbia, Haverford, and Japanese collaborators
  - increase TOF paddle length and verify mechanical integrity, signal size, and timing performance
  - based on existing prototypes, develop ASICs for both Si(Li) and TOF systems and a custom pre-amplifier for Si(Li)

Building on experience from successful pGAPS and Si(Li) development, plan for an initial GAPS flight in winter 2019/2020



Richieste finanziarie

- Costi sviluppo e produzione prototipo ASIC: ~35 keuro.
- Se si volesse contribuire al run di produzione finale la stima costi è di 200 keuro, altrimenti inserita nelle richieste gruppi americani alla NASA.
- Trasferte (da perfezionare con resto collaborazione):
  - Italia: Trieste-Bergamo per sviluppo ASIC:
    - 2017: 5 keuro
    - 2018: 5 keuro
  - Italia: Riunioni componente italiana: 4 persone x 1 keuro per anno
  - USA: riunioni per sviluppo sottorivelatori:
    - 2017: 2 m.u.: 12 keuro
    - 2018: 2 m.u.: 12 keuro
  - USA: Integrazione
    - 2019: 3 m.u.: 18 keuro
    - 2020: 3 m.u.: 18 keuro
  - McMurdo: 1 o 2 persone per preparazione lancio ed operazioni di volo (Nov. 2020-Feb 2021). Costi permanenza base dovrebbero essere a carico NASA. Da verificare se questo vale anche per collaboratori stranieri. Se sì solo costi di viaggio: 5 keuro
  - Meeting collaborazione negli USA (2 all’anno): 4 persone x 4 keuro per anno

Previsione richieste complessive
(in keuro)

Anno	Costruzione+ Cons. & Inv.	Missioni	Totale
2017	30	37	67
2018	10	37	47
2019	10	38	48
2020	10	38	48
2021	5	25	30
2022	5	20	25
2017-2022	70	195	265