The General AntiParticle Spectrometer

Hunt for dark matter using cosmic-ray antideuterons

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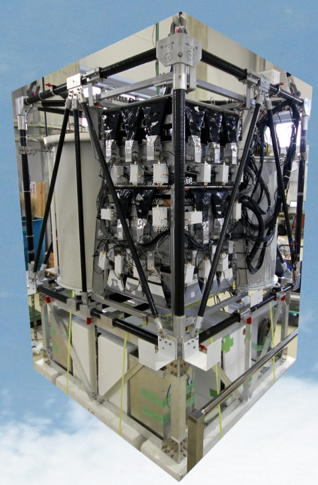
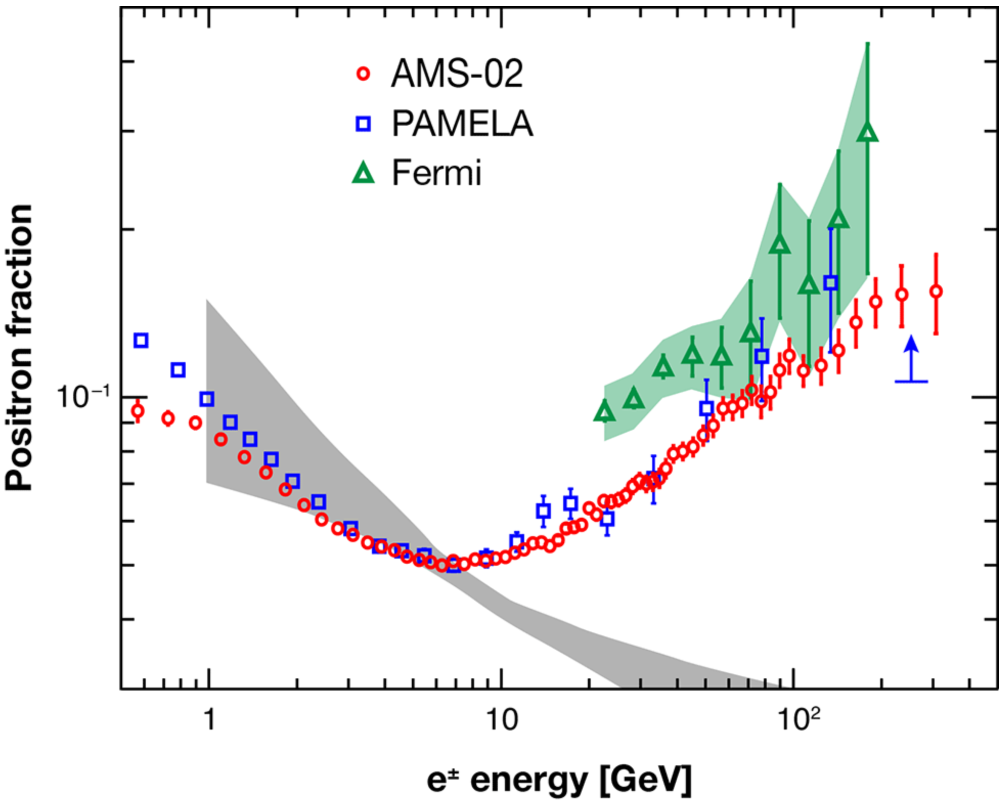
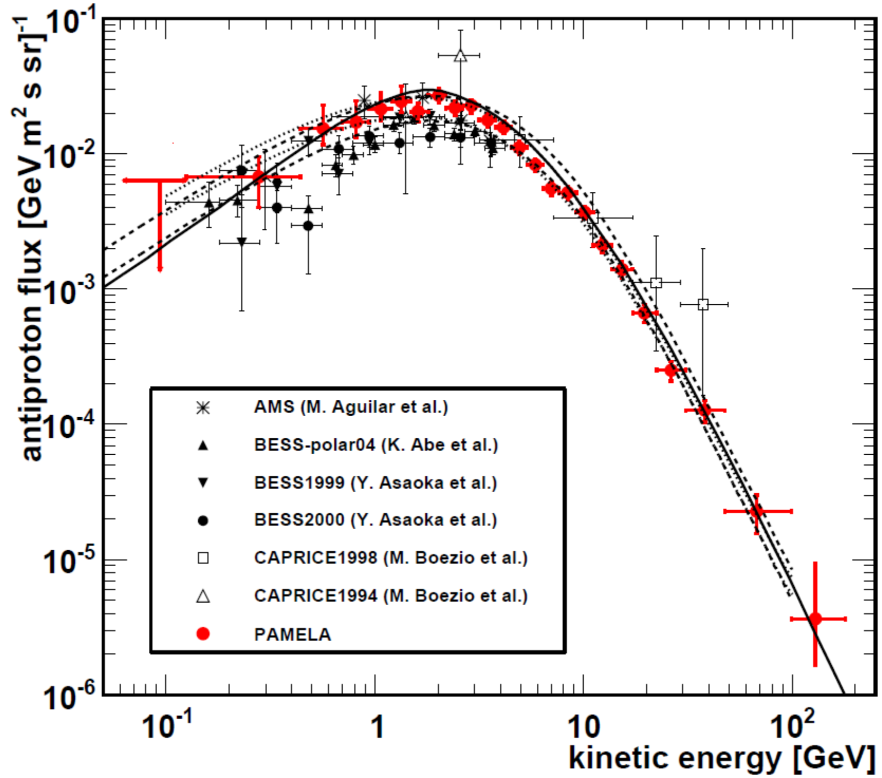


Indirect dark matter search with charged particles

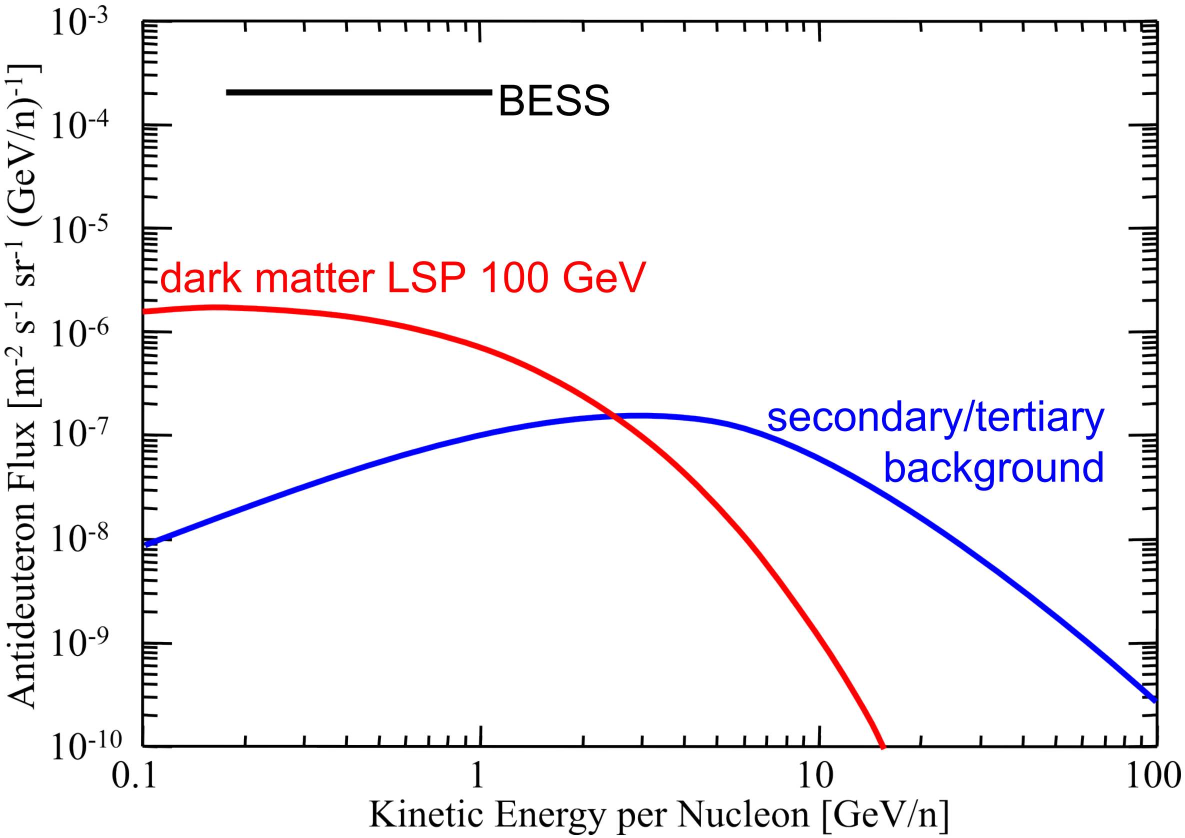


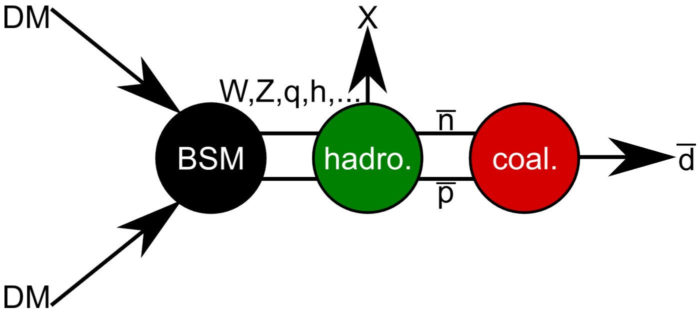


- unexplained features in positron and electron spectra
- proposed theories:
  - astrophysical origin
  - **dark matter self-annihilation**
- no feature visible in antiprotons

- we entered the era of discovery
- data analysis is starting to make claims, but so far inconclusive
- **strategy: use search channel where additional dark matter contribution is much larger than astrophysical flux!**

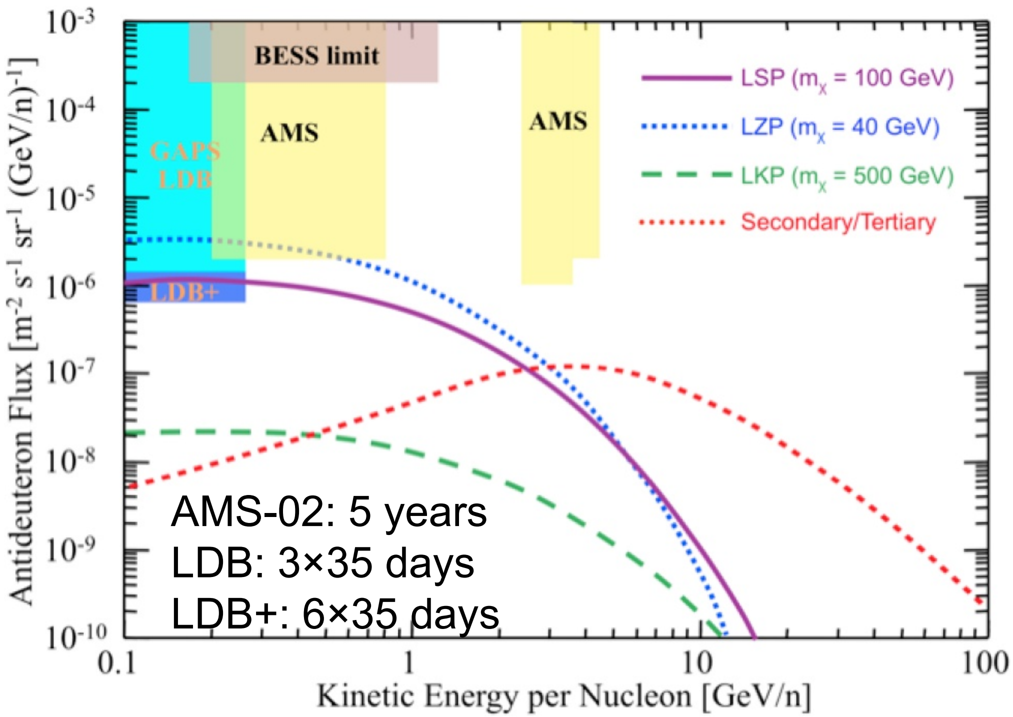
Antideuterons and dark matter

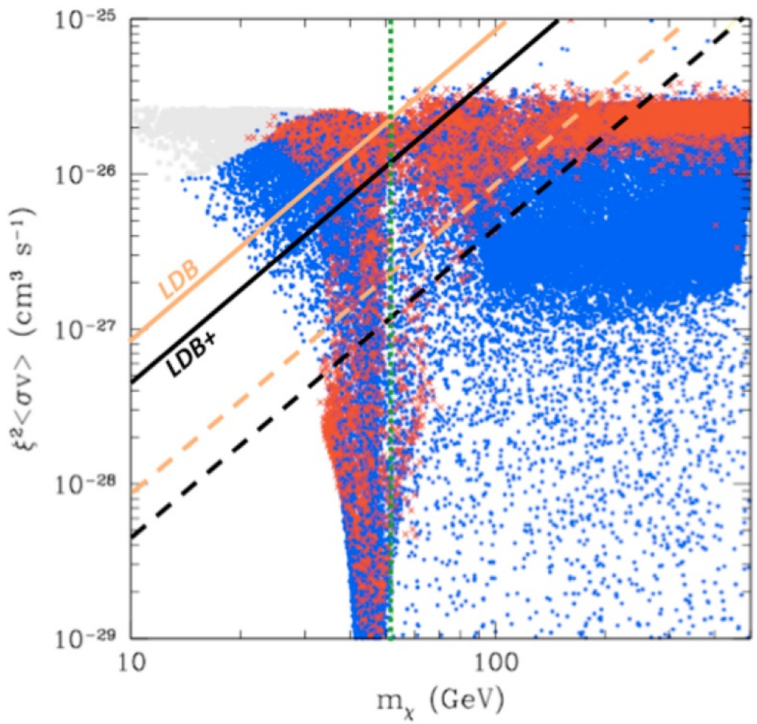




- **antideuterons are the most important unexplored indirect detection technique**
- **uncertainties:**
  - dark matter:
    - concentrated in halo, dominant uncertainty from propagation: factor ~10
    - antideuteron coalescence: factor ~2
    - boost factors
  - background: production in galactic disk dominant uncertainty from production cross-section

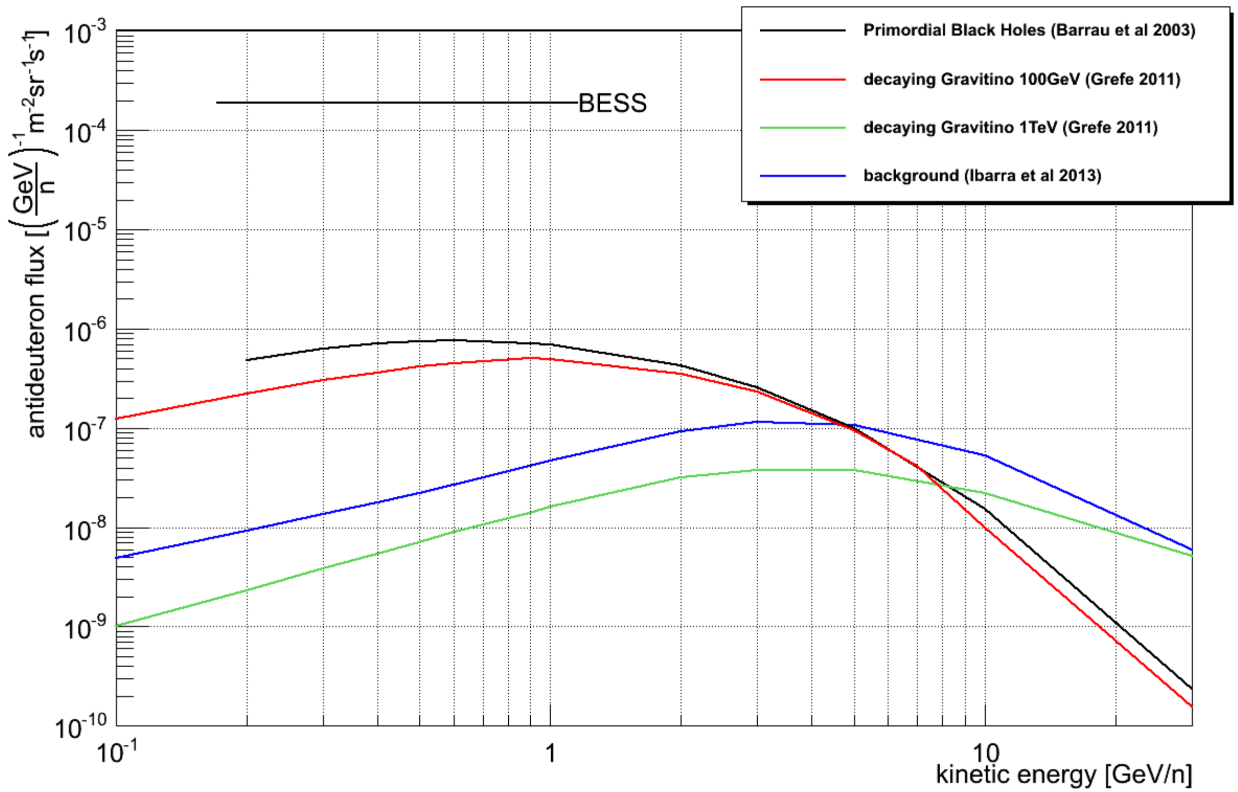
Antideuteron sensitivity





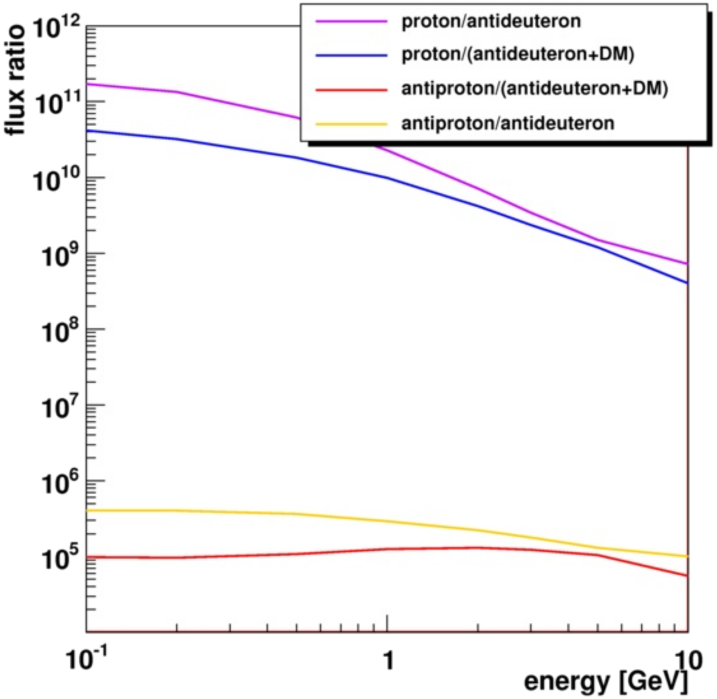
- different scenarios give antideuteron fluxes within sensitivity: Supersymmetry, extra dimensions
- GAPS is very effective to search for light WIMPS such as proposed to explain DAMA/LIBRA/CoGENT/CDMS results

Primordial black holes and gravitinos

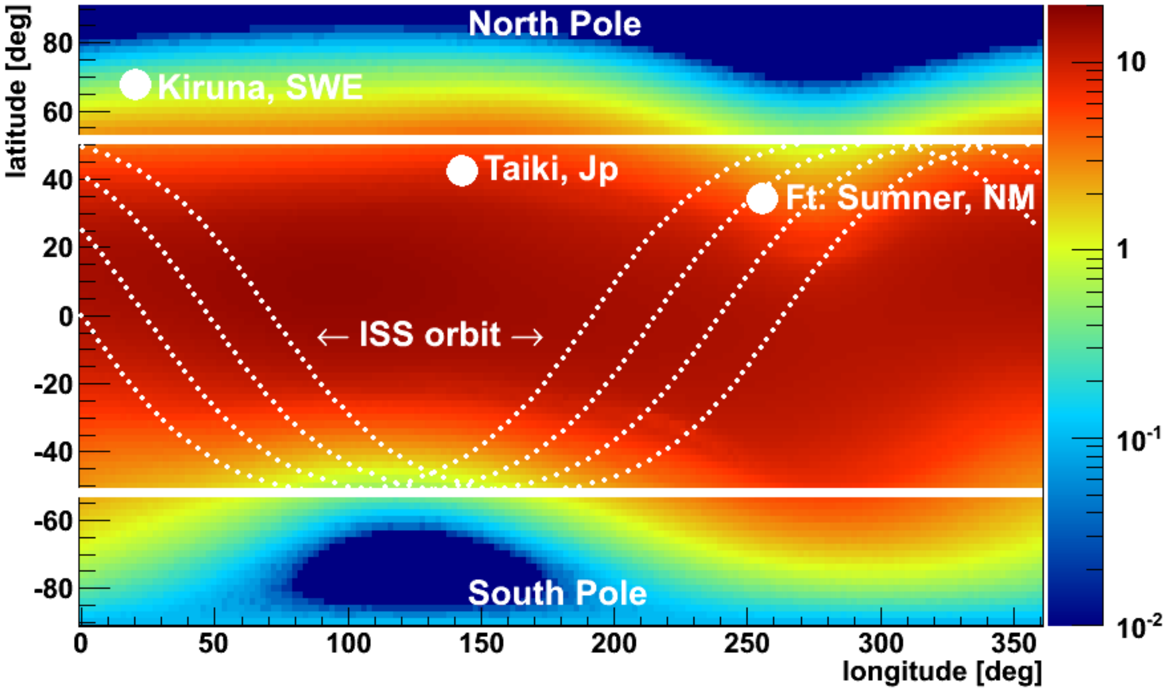


- **primary black holes:**
  - very small black holes could have formed in the early universe due to, e.g., initial density inhomogeneities
  - might evaporate antideuterons and **maybe the only chance to detect primordial black holes**
- **baryon asymmetry/cosmological gravitino problem:**
  - hypothetical mediator of gravity: graviton → superpartner gravitino
  - late decays of unstable gravitinos to standard particles would produce antideuterons

Observational challenges



flux ratios



geomagnetic cut-off

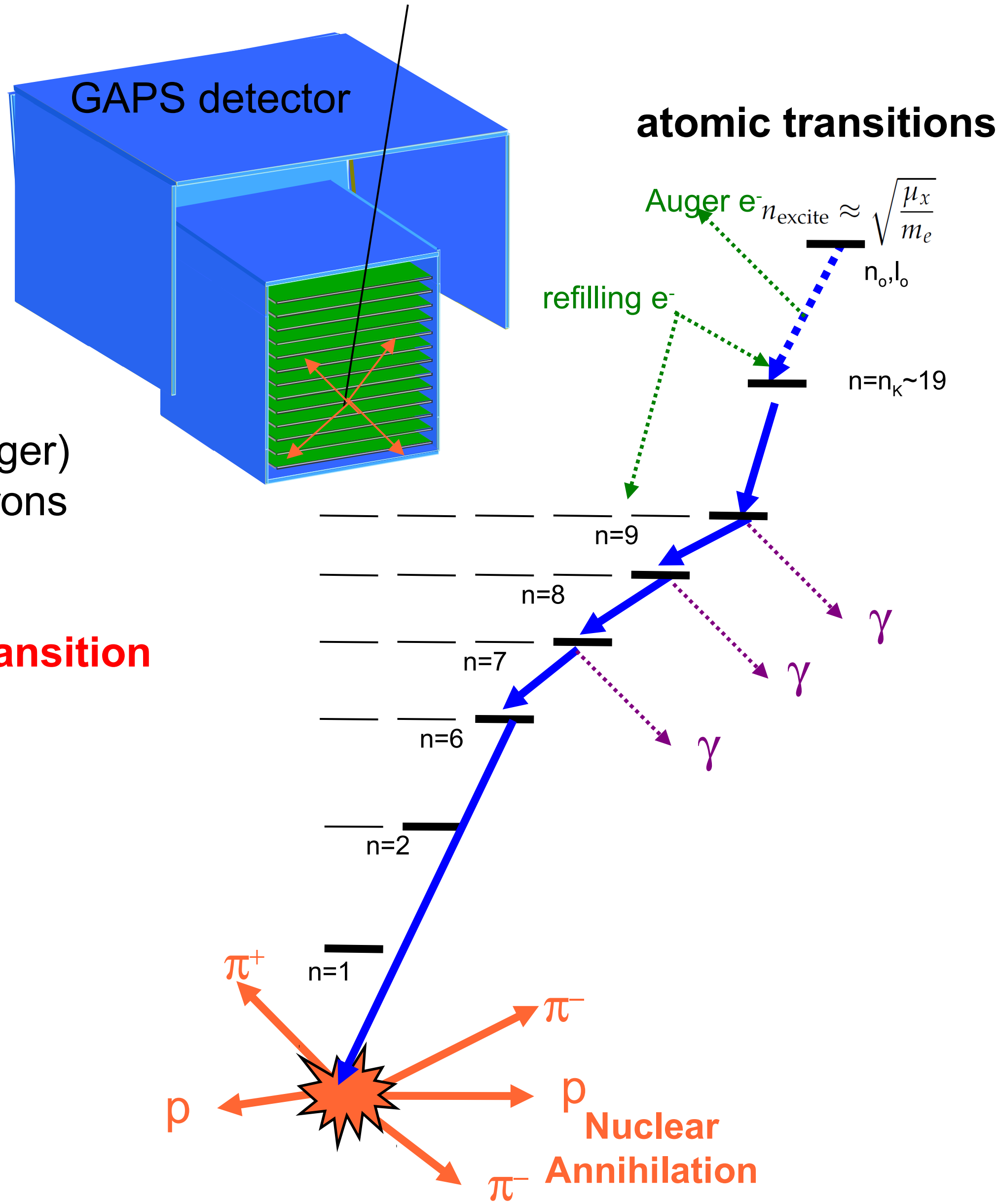
antideuteron measurement with balloon and space experiments requires:

- **strong background suppression**
- **long flight time and large acceptance**
- **geomagnetic location of experiment**

Novel approach for antideuteron identification

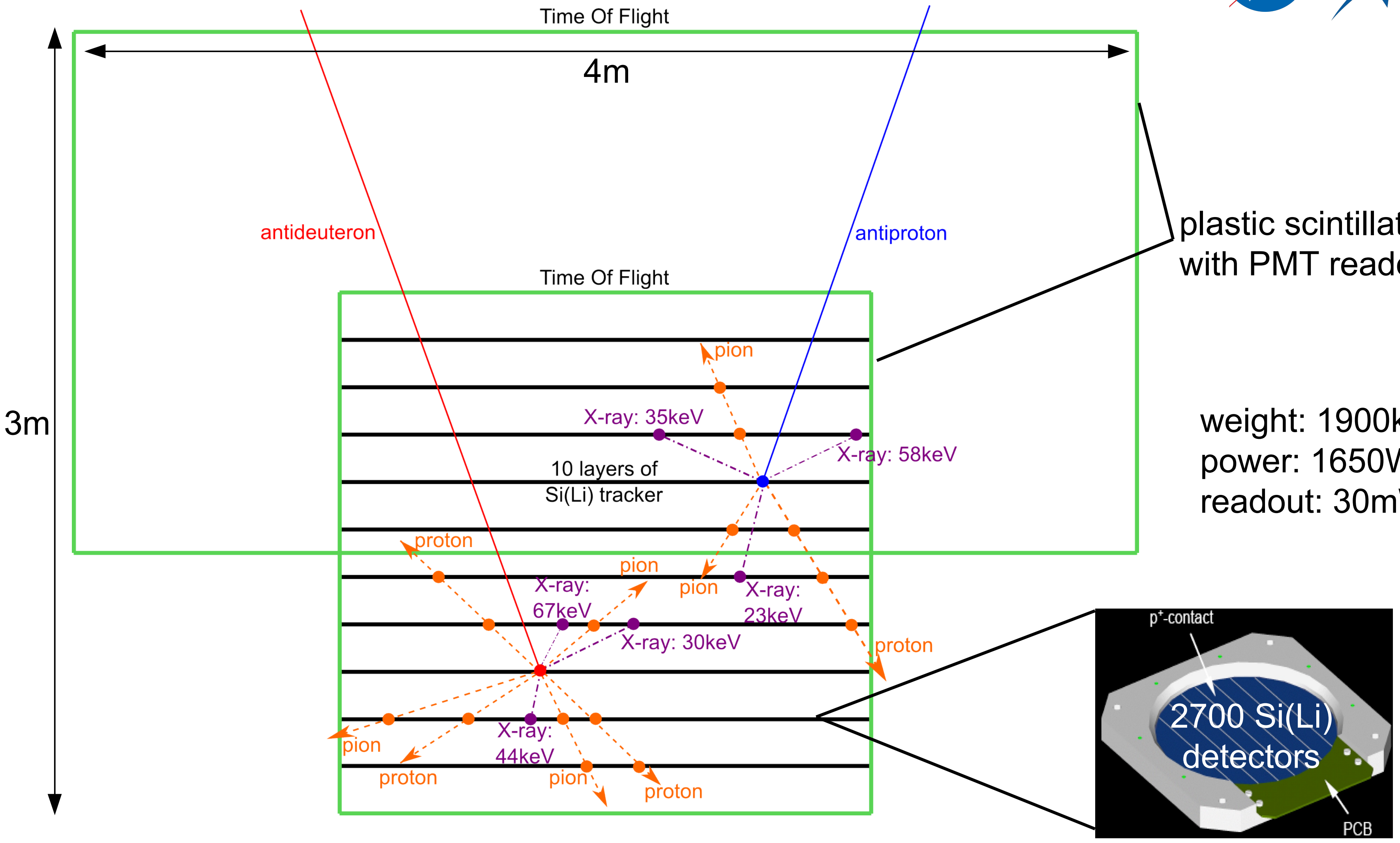
- antideuteron slows down and stops in material
- large chance for creation of an excited exotic atom (E_{kin}~E_l)
- Deexcitation [ns]:
  - fast ionisation of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via **characteristic X-ray transition**
- nucleus-antideuteron annihilation: **pions and protons**

- KEK testbeam measurements → exotic physics well understood [Astropart. Phys. 49, 52 (2013)]



The GAPS experiment

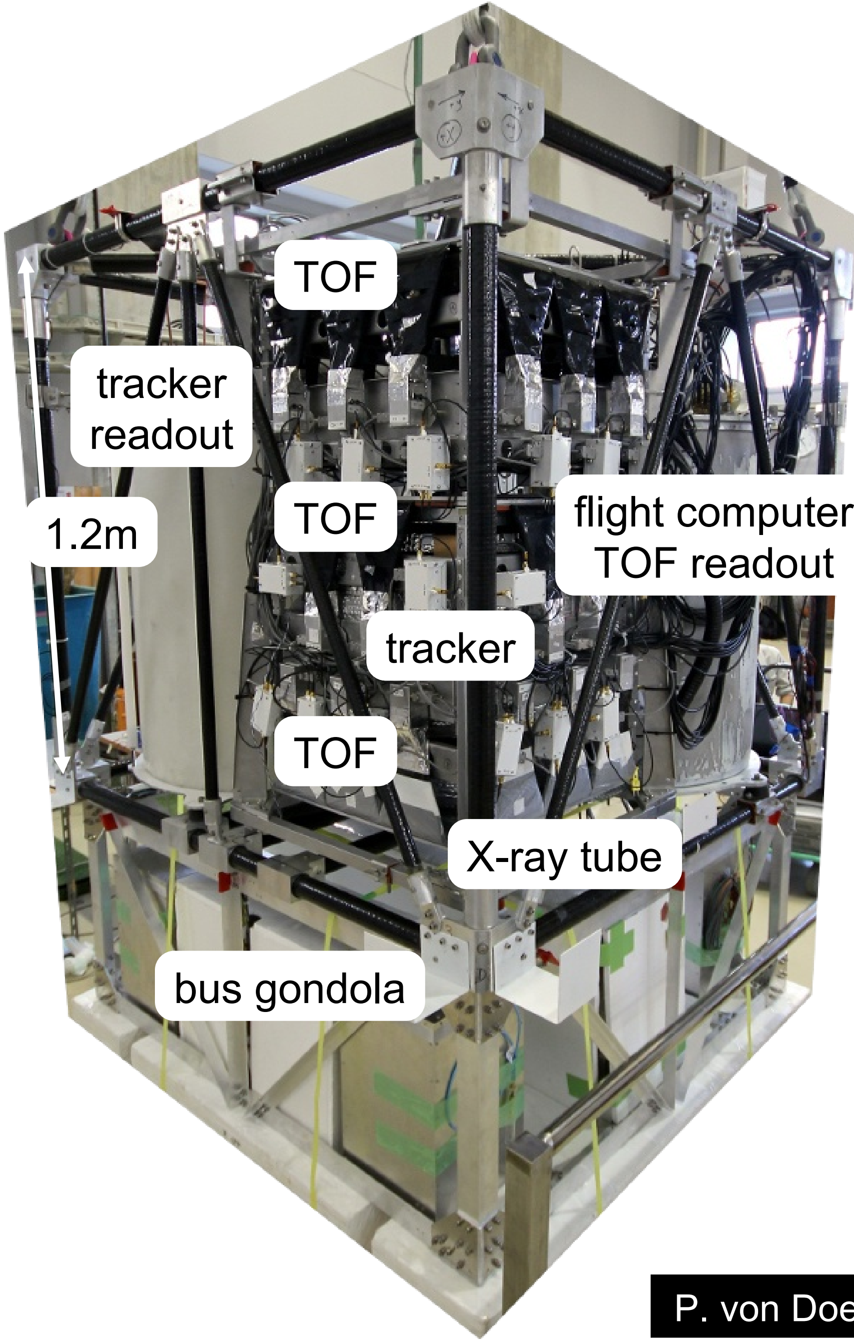
Columbia U, UC Berkeley
UCLA, U Hawaii



weight: 1900kg
power: 1650W
readout: 30mW/ch.

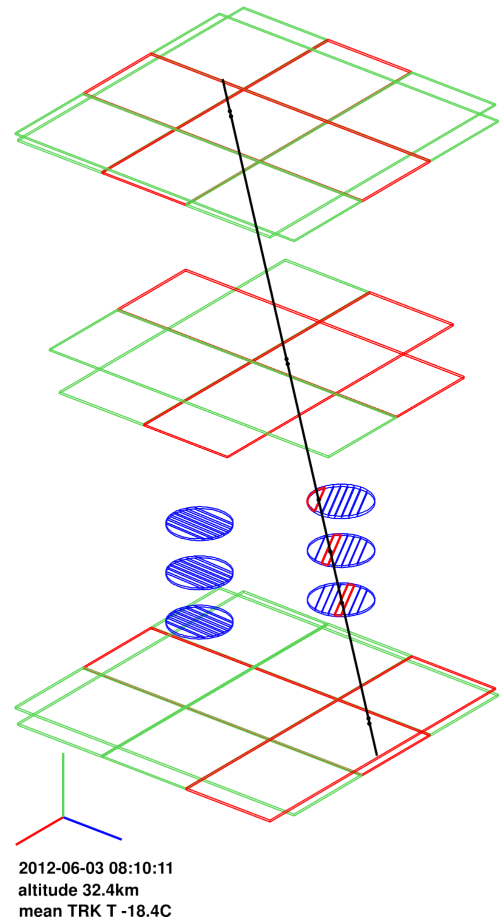
- the **G**eneral **A**nti**P**article **S**pectrometer is especially designed for **low-energy antideuterons**
- identification by stopping them in the tracker and creating an exotic atom
- long duration balloon flights from Antarctica starting in 4-5 years

Prototype GAPS

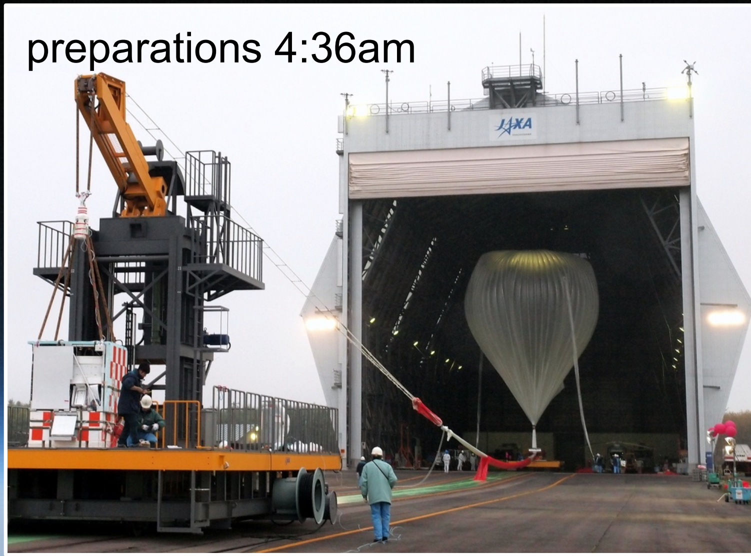


Goals:

- demonstrate stable operation of the detector components during flight
- study Si(Li) cooling approach for thermal model
- measure background levels



pGAPS flight: June 3rd 2012 from Taiki, Japan

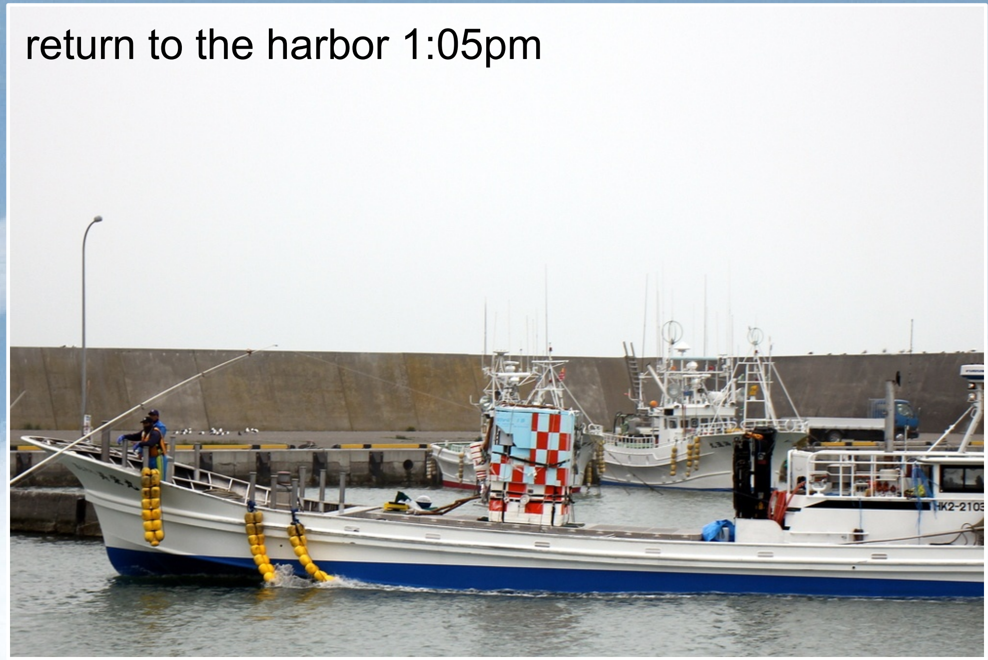


preparations 4:36am

release of balloon

4:55am

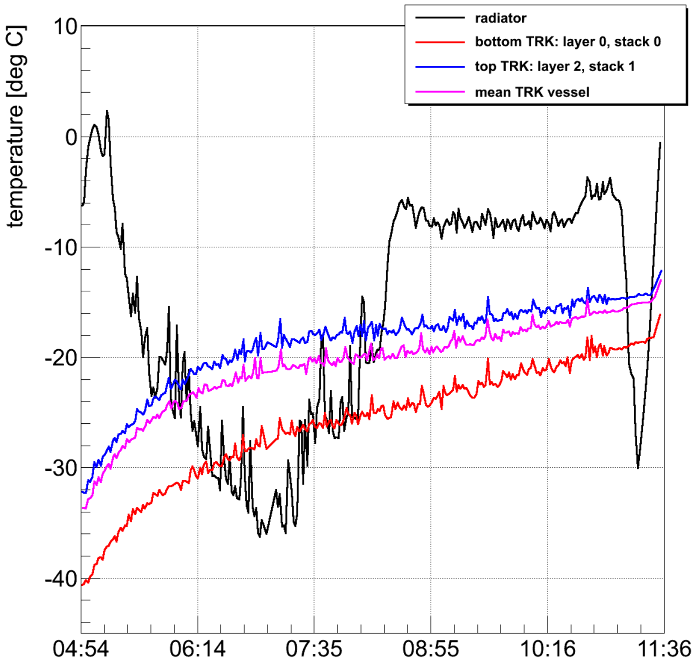
take off

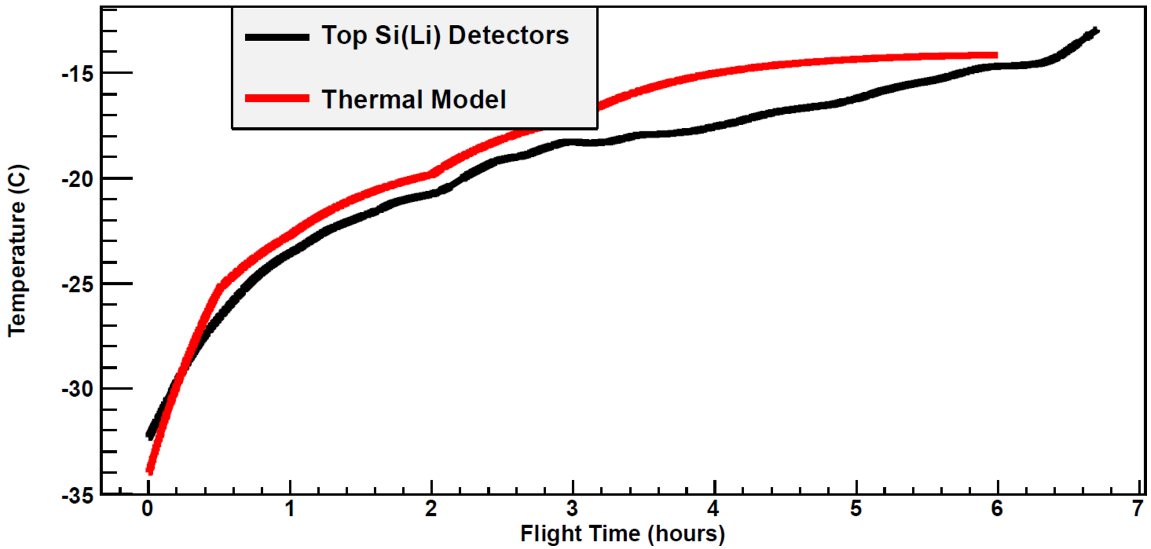


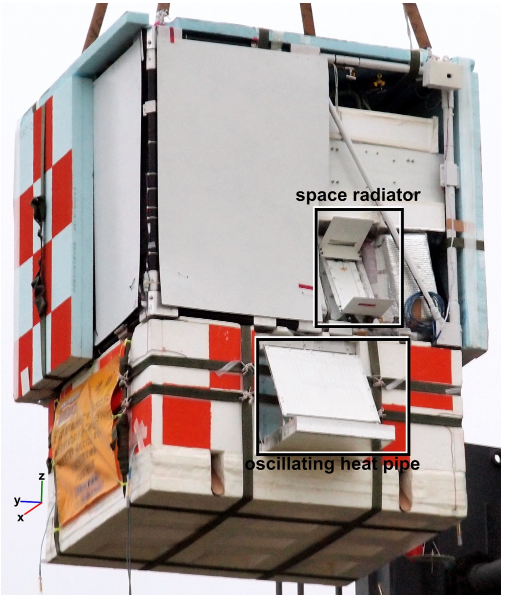
return to the harbor 1:05pm

- **well defined TOF trigger and tracker runs**
  - time: 245min
  - ~600,000 triggers
- **carry out in-flight calibration of Si(Li) detectors**
  - run X-ray tube
  - time: 50min
- **trigger on Si(Li) detectors to study incoherent X-ray background**
  - time: 29min

Thermal model







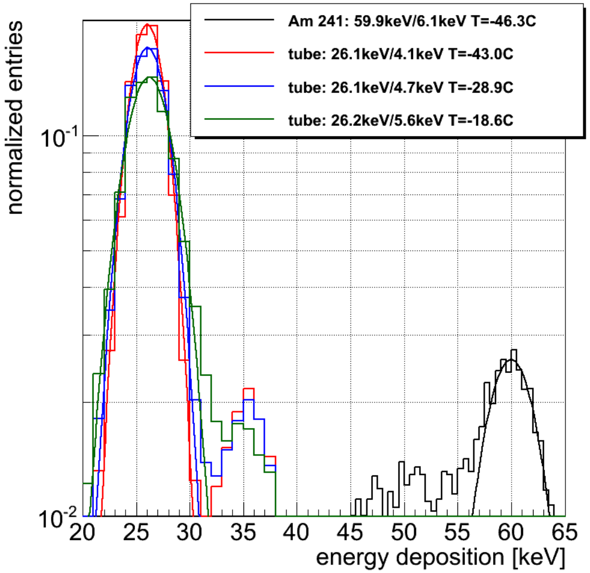
- Si(Li) detectors were cooled down to -46°C to ensure operation during flight
- in addition bGAPS flight representative radiator and cooling pipe system tested

- unfortunately: rotator failure → detectors warmed up (64% still depleted by the end of the flight)
- **BUT** all critical parts were equipped with temperature sensors and **thermal model was verified**

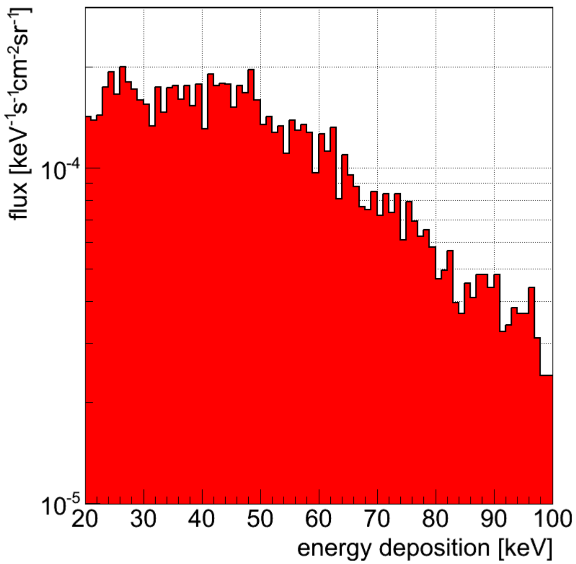
- **cooling approach would have worked with correct pointing**

Si(Li) tracker

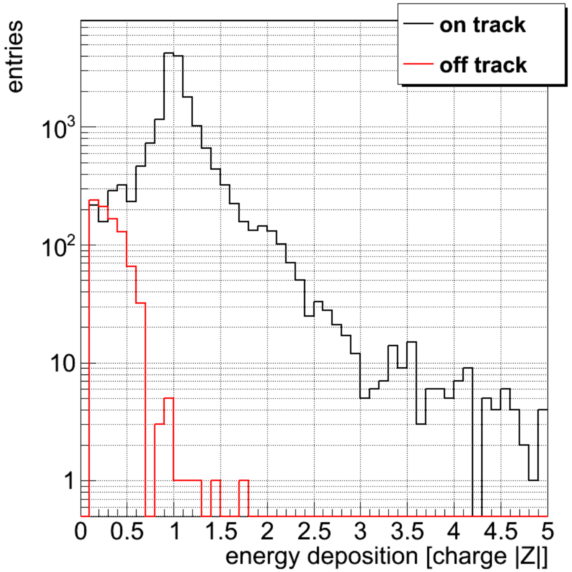
X-ray stability



X-ray flux at 33km



particle charge on/off track

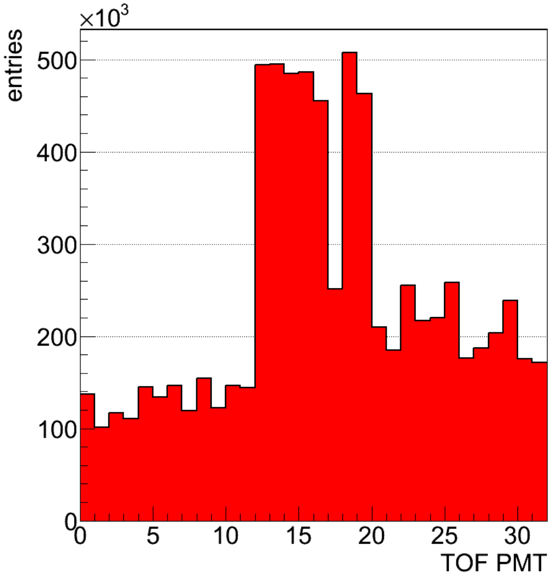


- both TRK electronics channels worked very well:
  - **high gain:** X-ray measurement stable over the course of the flight within the expected change due to the temperature increase
  - **low gain:** clear Landau distribution for energy depositions on track
- detectors work flawlessly after the flight in the lab

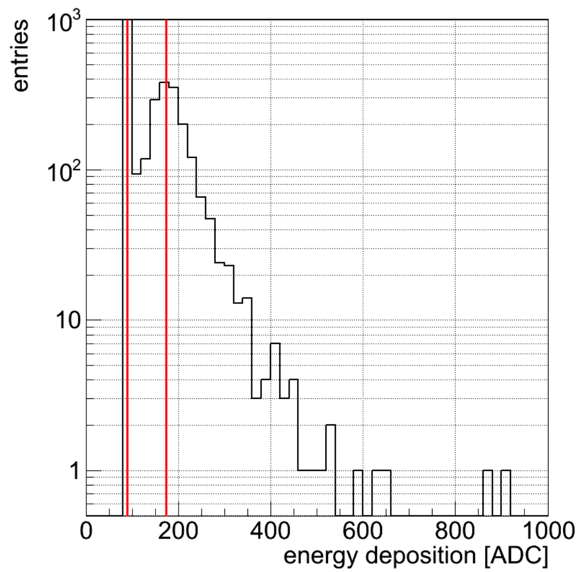
- flux of coincident charged particles and atmospheric and cosmic X-rays is very small
  → antideuteron analysis can easily reject this background type by requiring more than one coincident X-ray in the right range

Time-of-flight

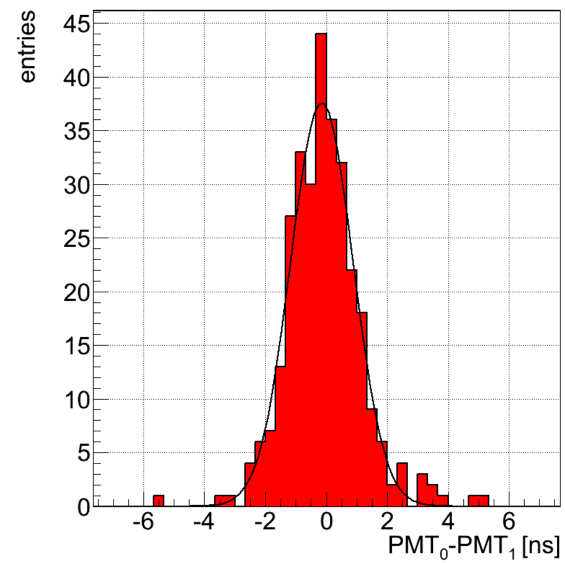
PMT occupancy



typical energy deposition



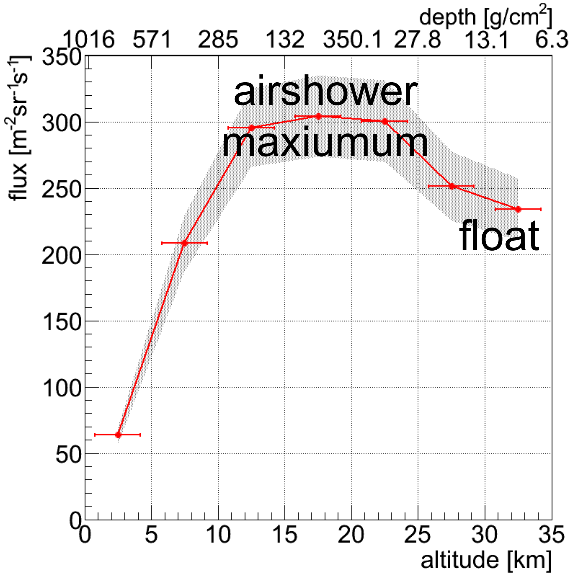
timing resolution



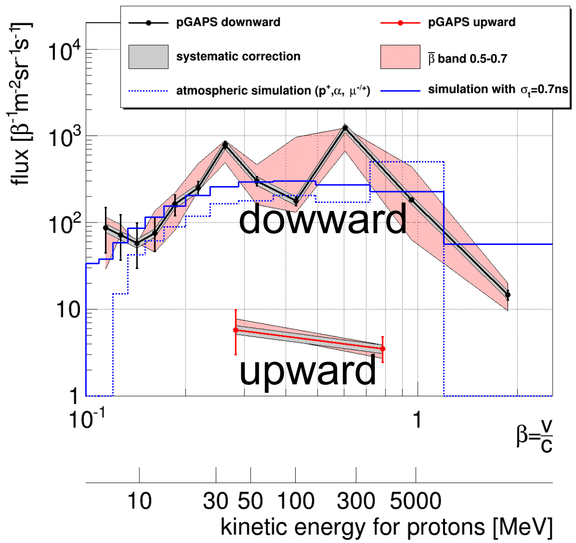
- only one tube failed → understood why → no problem in the future
- stable energy deposition measurement over time
- detectors work flawlessly after the flight in the lab (after careful cleaning of salt water)
- average of 640ps timing resolution per PMT
  → under further investigation for improvements in the future

pGAPS flux measurement

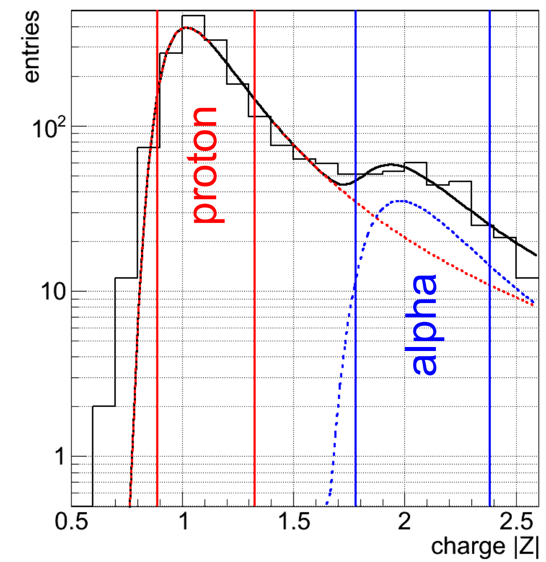
total flux vs. altitude



flux vs. β at 33km

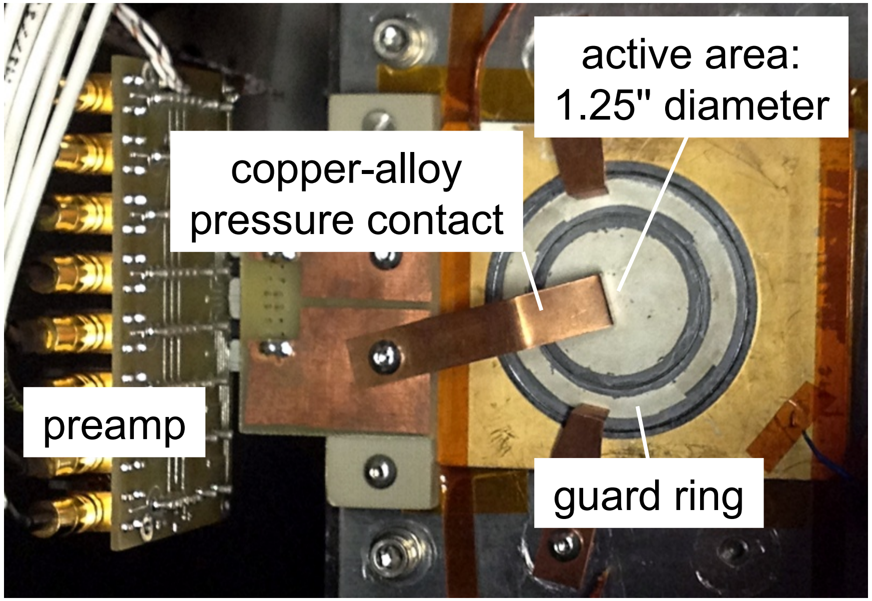


particle composition at 33km

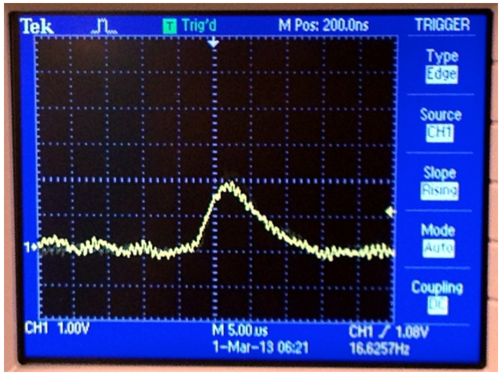


- flux at drift-out “boomerang” altitude (10-15km) is ~30% higher than at float (33km)
- flux as function of velocity compared to simulations with PLANETOCOSMICS
  - $\beta<0.2$ ($E_{kin,proton}$ ~20MeV) very good agreement
  - $\beta=0.3-0.5$ ($E_{kin,proton}$ ~50-150MeV) within systematic errors
  - $\beta>0.7$ ($E_{kin,proton}$ ~400MeV) good agreement
  - deviations at 0.3 and 0.6 visible → more simulation work at low energies in the future
- α particles constitute about ~10% of the flux at 33km (~9g/cm^2) → in good agreement with BESS data

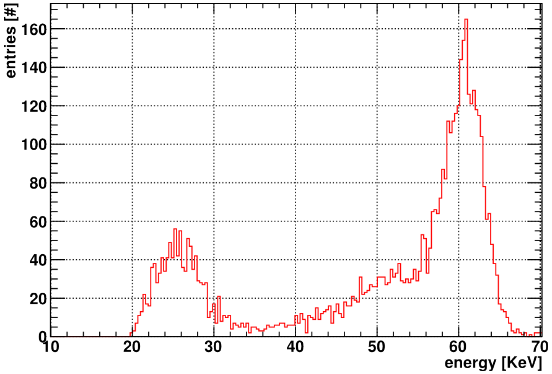
Si(Li) detector production



- GAPS will use 2875 4” Si(Li) detectors
- 2”-diameter detectors being produced at Columbia U. using simple fabrication scheme
- successfully drifted diameters from 1" to 2" with >90% yield, both 1 mm (prototype) and 2.5 mm thick
- leakage current ~1nA at -35 C
- confirmed performance with cosmic rays (MIPs) and Am-241 source (X-rays)
- FWHM at 59.5keV: 5keVeasy to improve with better mounting and preamp board
- 4” detector development underway!

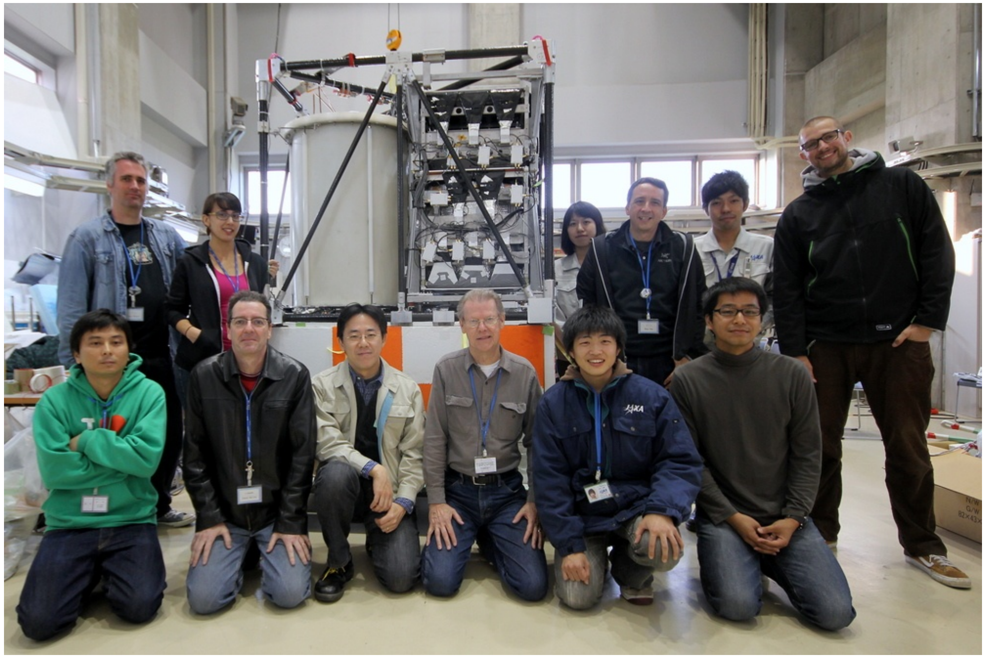


X-rays from Am-241



Timeline for GAPS

- **2000** first idea
- **2004/05** KEK beamtests with antiprotons
- **2006-08** design work
- **2008-12** technical validation
- **2009-12** prototype flight from Japan
- **2013-2017** detailed design and construction
- **2017** first science flight from Antarctica



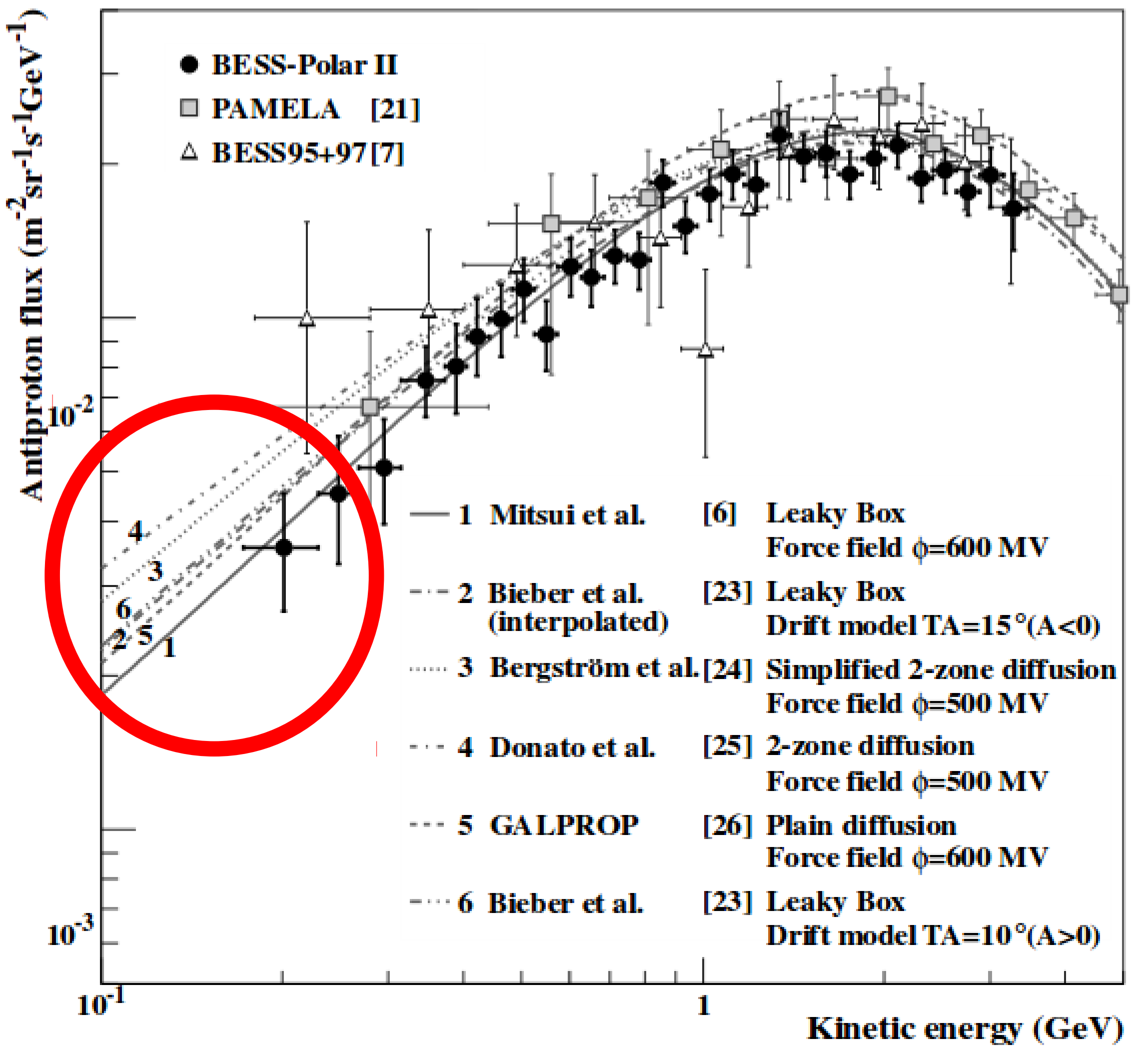
pGAPS team before launch

Columbia University, UC Berkeley, Lawrence Livermore National Laboratory
Japan Aerospace Exploration Agency, UC Los Angeles, U Hawaii

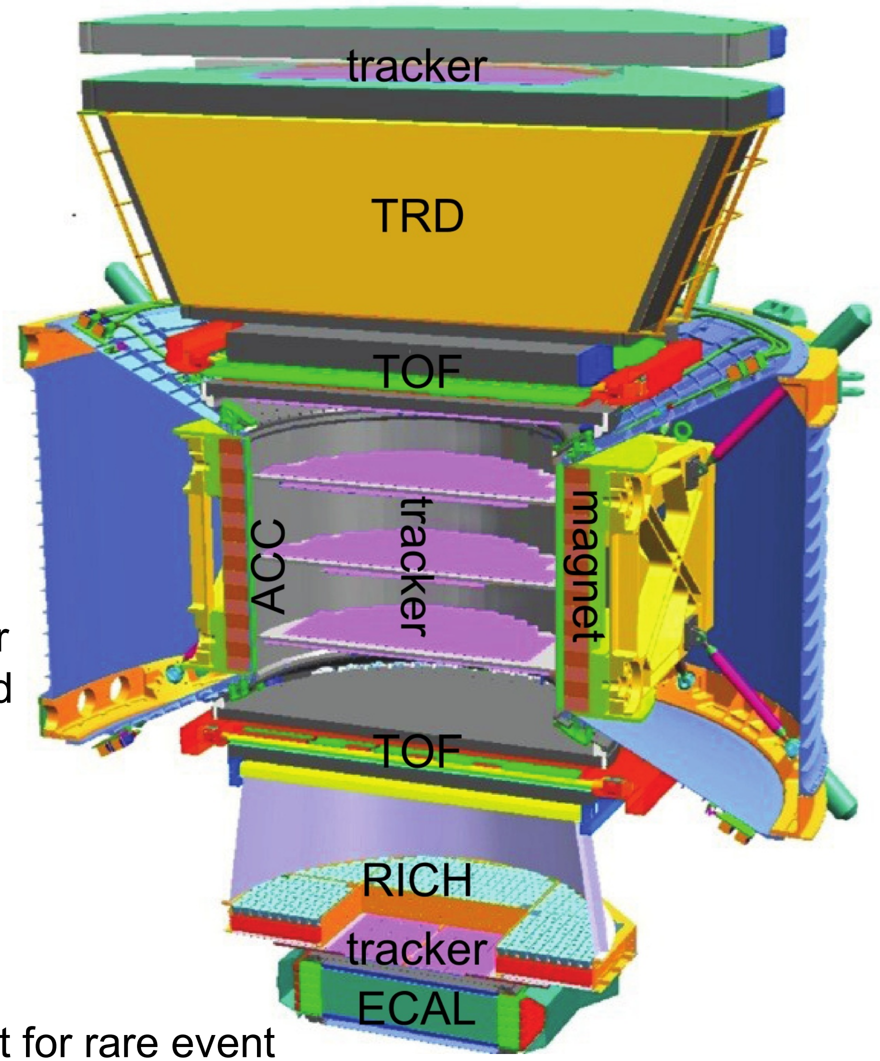
GAPS: Antiproton precision instrument?

GAPS should be able to detect ~10^4 low-energy antiprotons

→ currently under study



AMS comparison



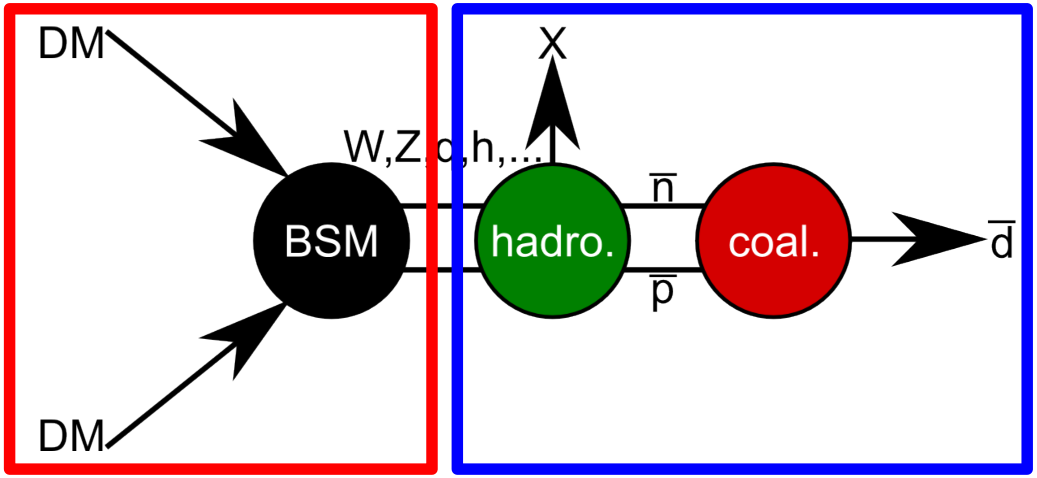
- AMS is a multi-purpose particle physics detector using subsequent detectors and a magnetic field
- AMS low-energy antideuteron challenges: geomagnetic cut-off, multiple scattering

- **if AMS detects $\bar{d}$: confirmation is needed**
  if no detection: GAPS goes deeper
- different detection techniques are very important for rare event search
- building GAPS right now is important for timely comparison

Conclusion

- measurement of antideuterons is a promising way for indirect dark matter search
- future GAPS is specifically designed for low-energetic antideuterons
- **all goals for prototype GAPS were met**
  - Nucl. Instr. Meth. A 735, 24 (2014)
  - arXiv:1307.3538
- **Si(Li) detector production understood**
- **it is the right time to start building GAPS to compare to AMS and direct searches**

Antideuteron formation



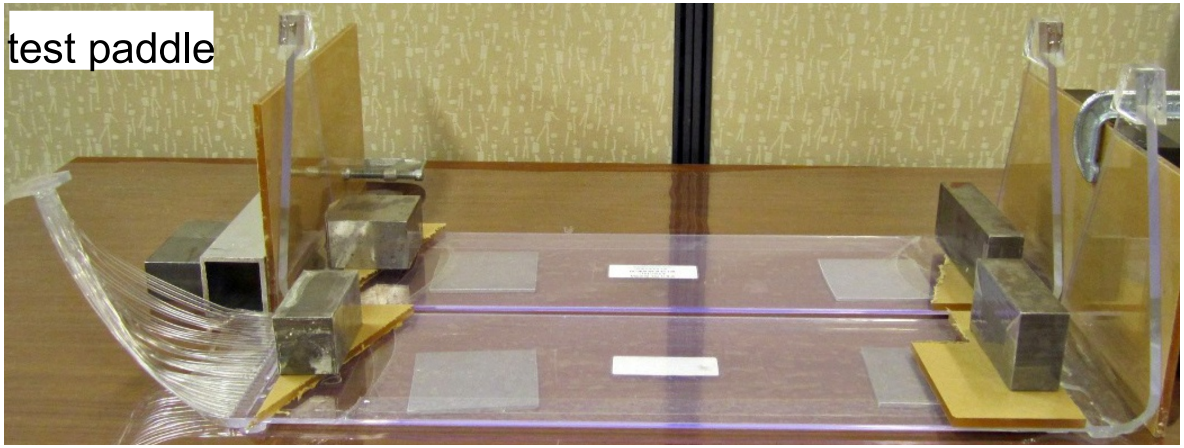
- antideuterons can be formed by an antiproton-antineutron pair if relative momentum is small (coalescence momentum p_0)

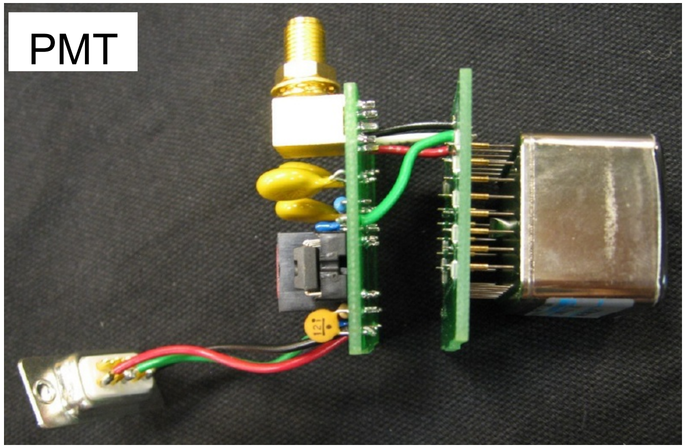
$$\gamma \frac{d^3 N_{\bar{d}}}{d\vec{p}^3_{\bar{d}}} = \frac{4\pi}{3} p_0^3 \left(\gamma \frac{d^3 N_p}{d\vec{p}^3_p} \right)^2 ; \qquad \frac{d^3 N_i}{d\vec{p}^3_i} = \frac{1}{\sigma_R} \frac{d^3 \sigma_i}{d\vec{p}^3_i} .$$

- major conventional production mechanisms of cosmic rays with ISM protons at rest:
  - $p+p \rightarrow \bar{d}+X$ (threshold 17GeV)
  - $\bar{p}+p \rightarrow \bar{d}+X$ (threshold 7GeV) → important even though antiproton flux is small

- coalescence momentum plays crucial role for cosmic-ray yield, but literature discusses p_0 from 80MeV to 240MeV depending on exact process

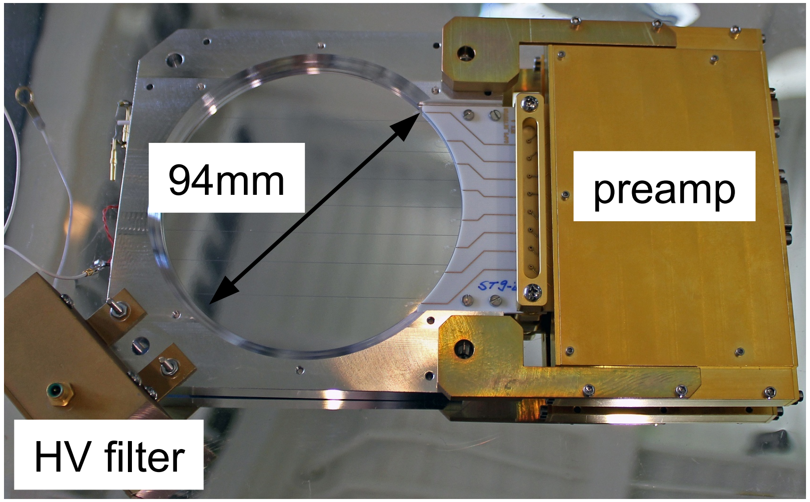
Time of flight



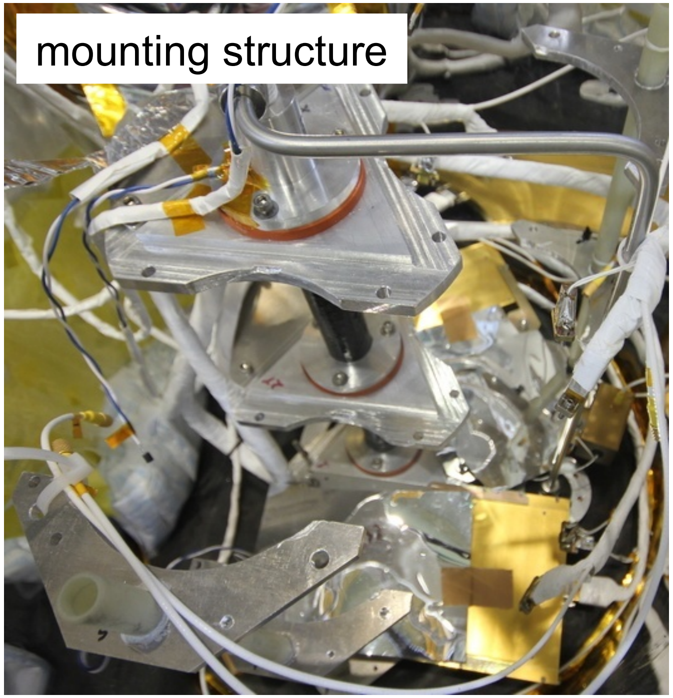


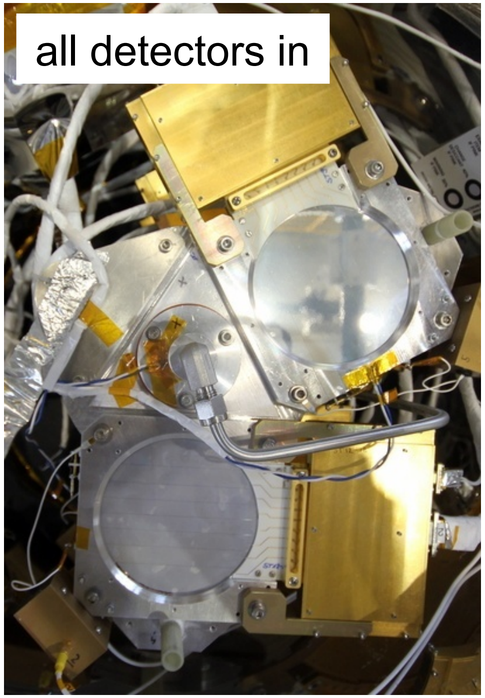
- **tasks:**
  - charged particle trigger
  - velocity measurement
  - tracking
- **design:**
  - 3 planes of TOF
    outer planes consists of 3×3, middle plane 2×2 crossed paddles
    1 paddle has 2 PMTs = **16 paddles and 32 PMTs**
  - 3mm scintillator from Saint-Gobain (BC-408)
  - Hamamatsu R-7600 PMT

Si(Li) tracker

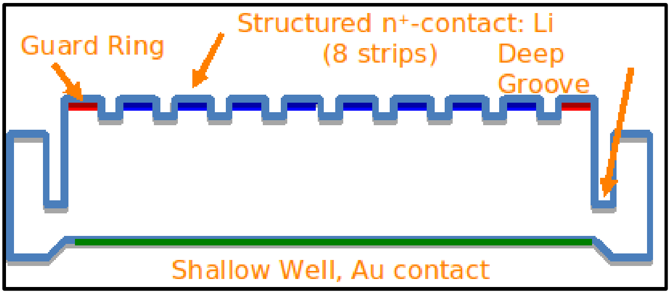


- 6 detectors
  2 stacks with 3 layers
- 4mm/2.5mm thick, 8 strips
- N+: Lithium contact
  P+: Boron implanted (strips)
- operation at ambient pressure during flight (8mbar)
- closed-loop coolant pumping system (Fluorinert)
- first time Si(Li) on a balloon payload





Si(Li) detector production

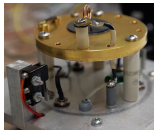


- GAPS needs ~3000 individual Si(Li) detector modules (4" diameter, 2mm thick)
- production technique well understood:
  - **2" diameter detector delivers good muon and X-ray resolution (close to the desired 3keV FWHM at 59.5keV)**
  - low leakage currents
- **ready to start building 4" detectors**

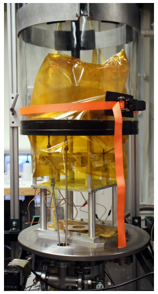
Production technique:

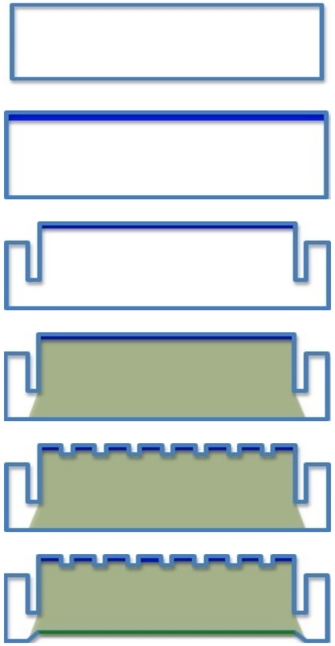
grinding

drifting



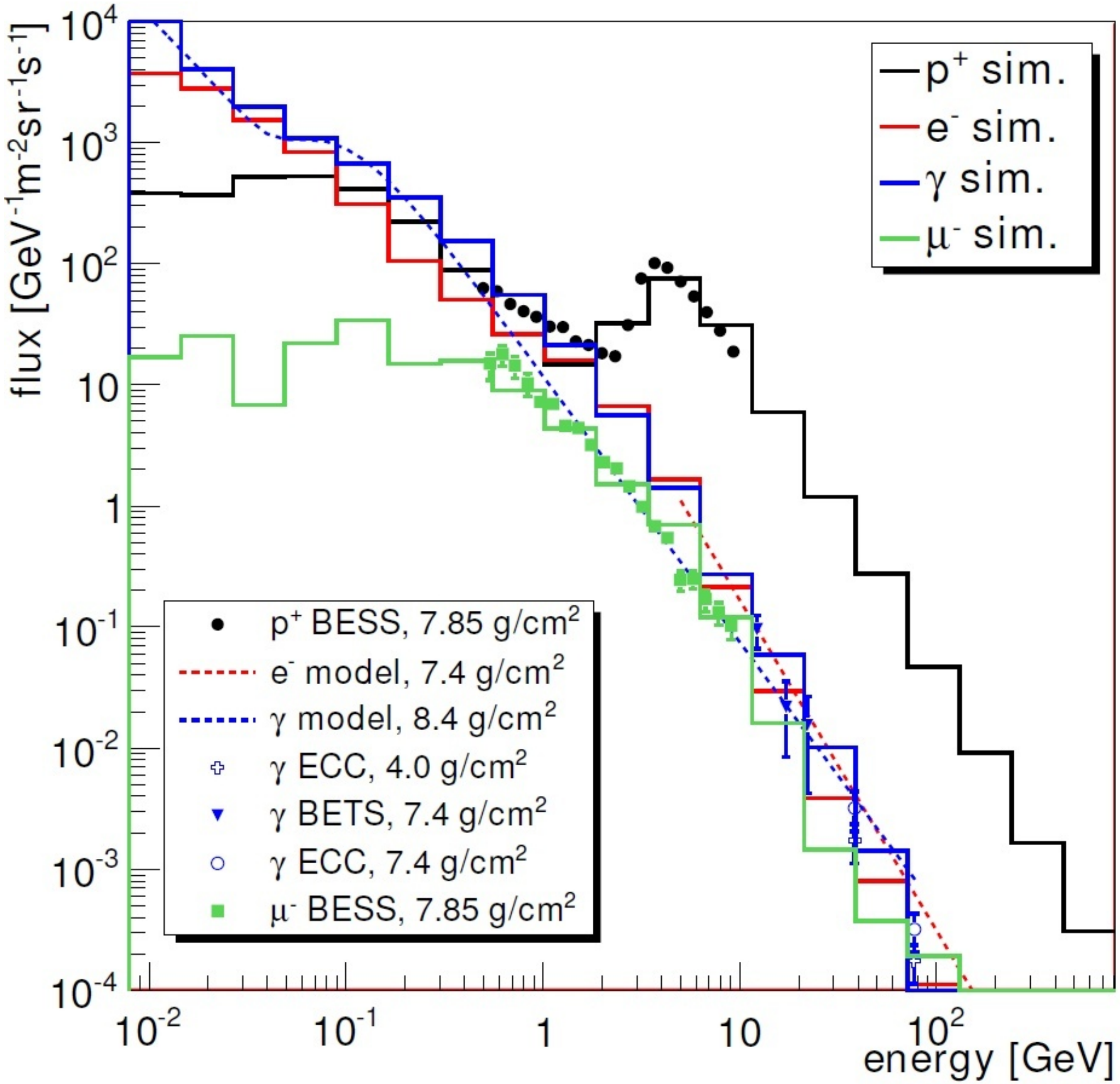
evaporator

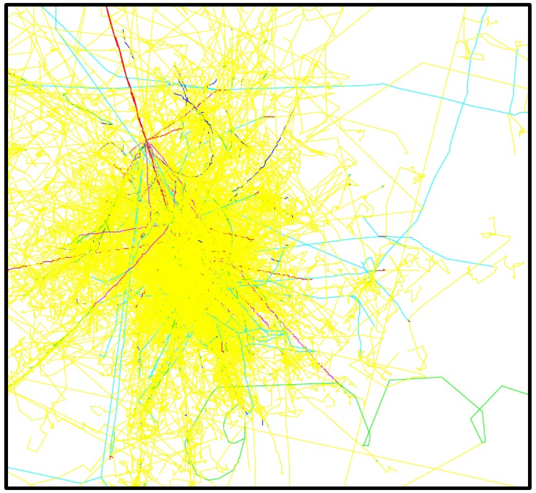




1) cut from the ingot
2) cut grove with ultrasonic grinder
3) evaporate Lithium on surface
4) drift the Li into the silicon
5) make strips and guard ring
6) etch the back (shallow well) and evaporate Au

Validation of air shower simulations





- particle fluxes (ATM+CR) for certain particle types at different altitudes
- comparison of atmospheric simulations shows good agreement with BESS, ECC, BETS, PPB-BETS, CAPRICE measurements and models