The search for antideuterons with GAPS

UCLA Dark Matter
February 2012

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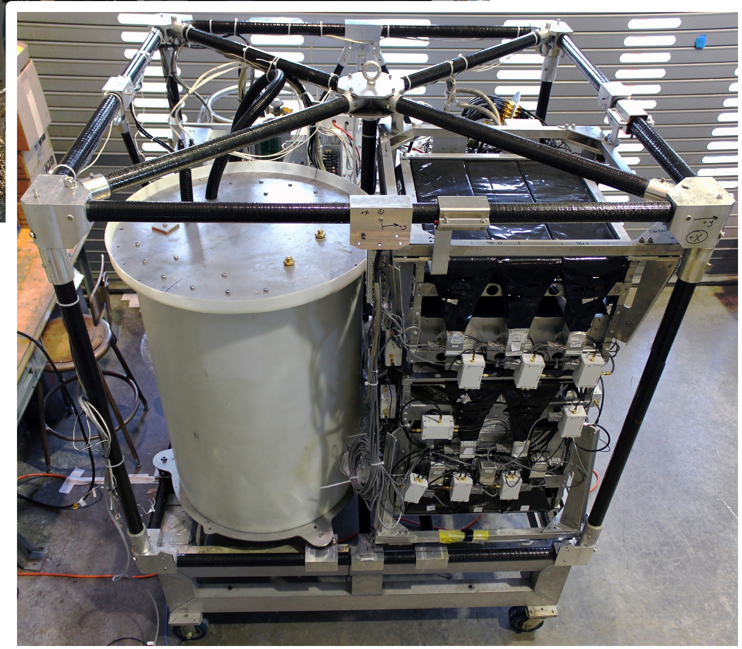

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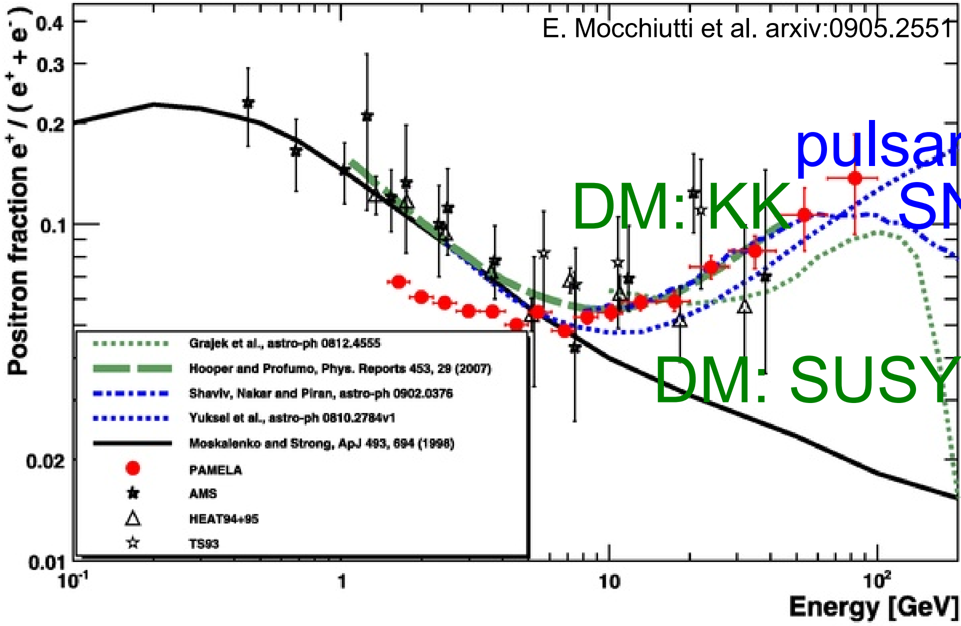
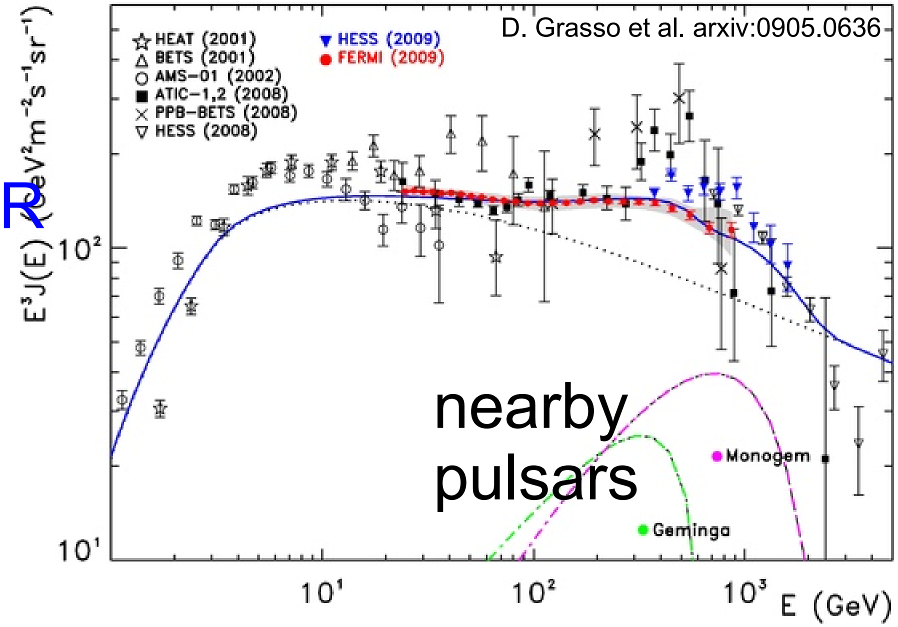
Positron fraction & electron flux





- unexplained features in positron and electron spectra
- proposed theories:
  - γ-ray pulsars can produce electron and positrons via pair production in the magnetosphere
  - positrons and electrons can also be accelerated in PWN or SNR shocks
  - dark matter self-annihilation

Drawbacks...

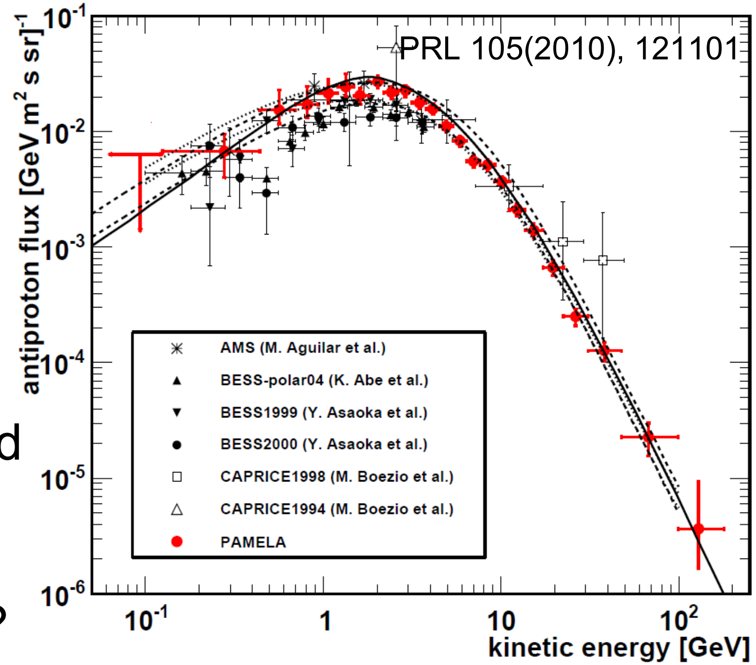
Drawbacks exist for astronomical interpretations:

Are pulsars really able to produce enough electrons and positrons?

Drawbacks exist also for dark matter interpretations:

- observed deviations are relatively small
- boosting mechanisms are needed

Hard to disentangle the different contributions!

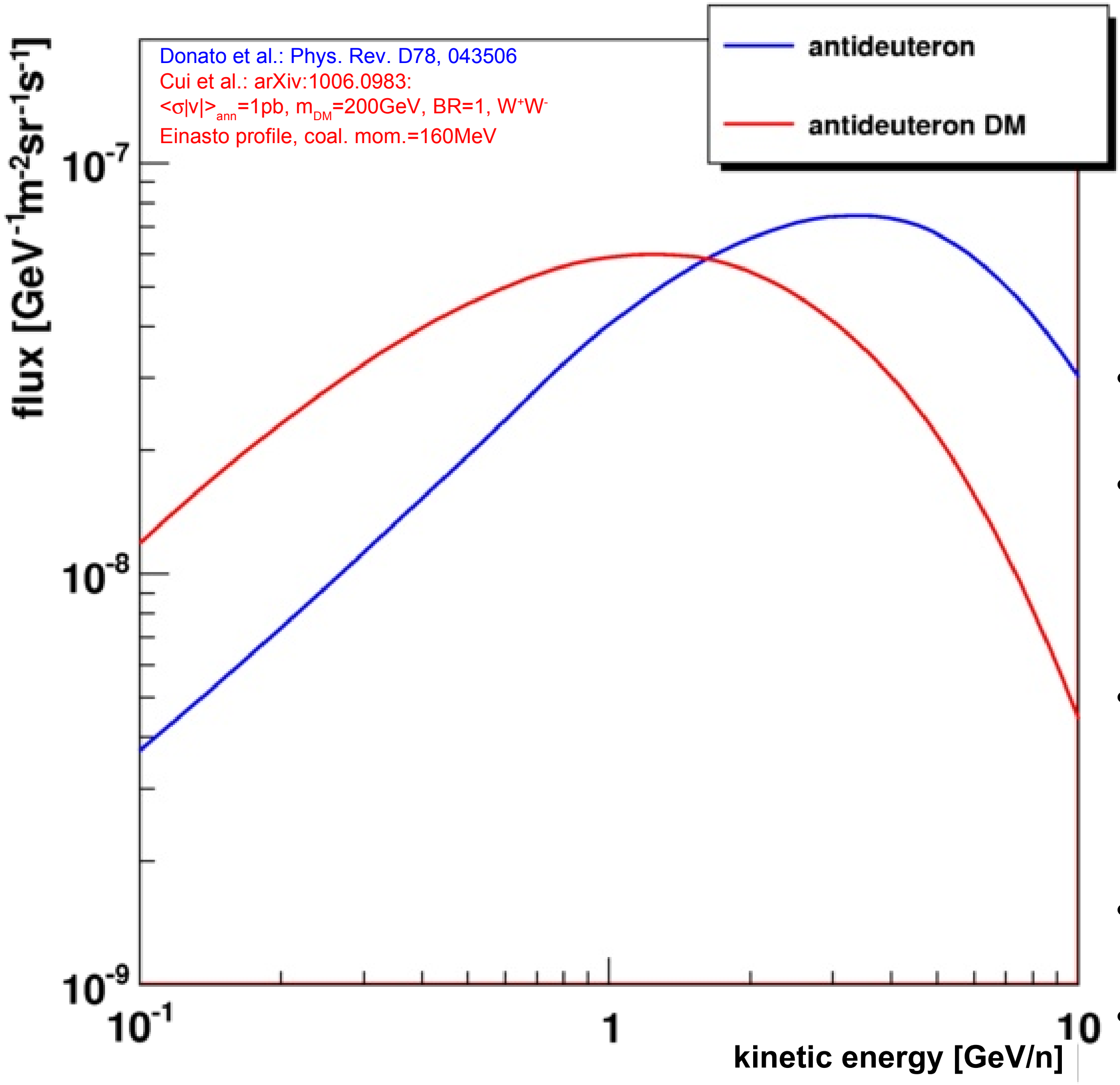


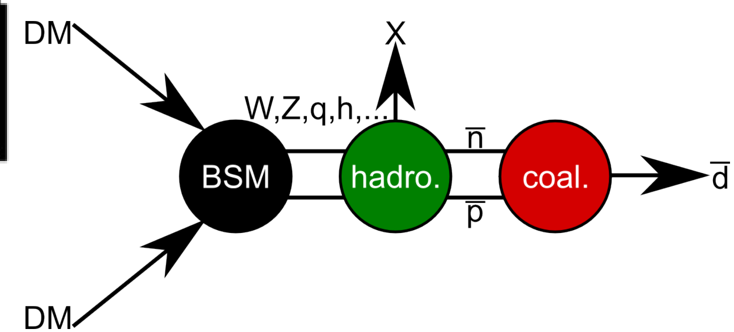
Further questions:

- Are the experimental data well understood (large rejections are needed)?
- Why do antiprotons show no deviation?
- Are propagation models well understood?

Existing data are inconclusive!
Additional contribution to the astrophysical cosmic-ray flux must be as large as possible to study new effects!

Antideuterons and dark matter



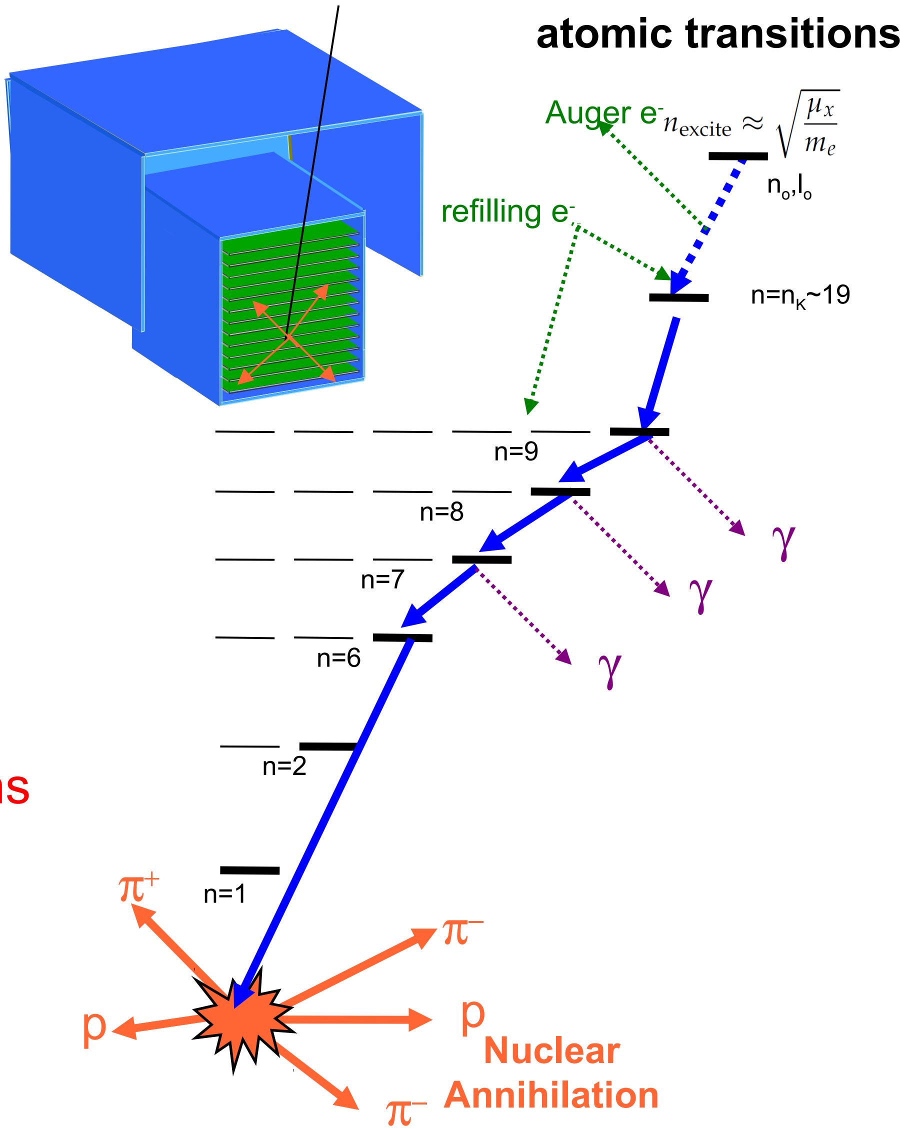


- antideuterons have high production threshold for p-ISM
- generic model with dark matter self-annihilation shows different shape (consistent with antiproton flux!)
- predicts large signal over background for low-energy antideuteron signals

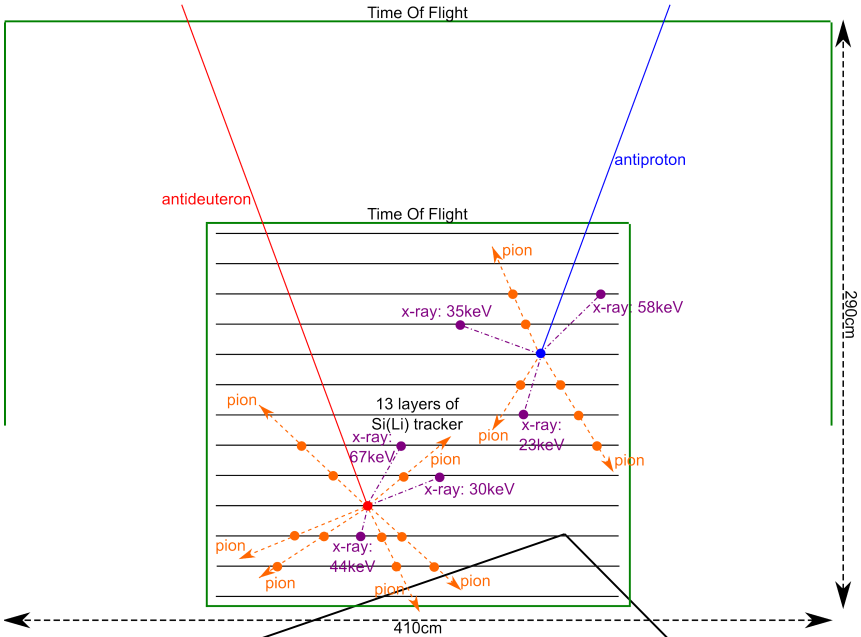
- identification needs very high background rejection
- nuclear and propagation uncertainties exist

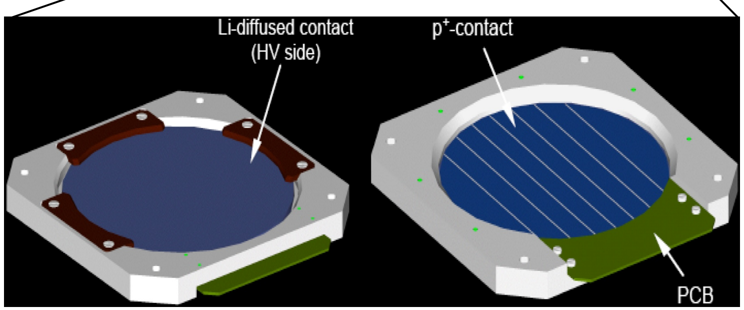
Antideuteron identification

- antideuteron slows down and stops in material
- large chance for creation of an excited exotic atom ($E_{kin} \sim E_I$)
- deexcitation:
  - fast ionisation of bound electrons (Auger)
    → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic x-ray transitions
- nucleus-antideuteron annihilation: pions and protons
- exotic atomic physics quite well understood (tested in KEK 2004/5 testbeam)



GAPS concept





GAPS consists of two detectors (acceptance: ~1.8m^{2}sr)

Si(Li) tracker:

- 13 layers composed of Si(Li) wafers (total: ~3500)
- relatively low Z material → target and detector
- dual channel electronics
- 5-200keV: X-rays (resolution:~2 keV)
- 0.1-200MeV: charged particle

Time of flight and anticoincidence shield:

- plastic scintillator with PMTs surrounds tracker

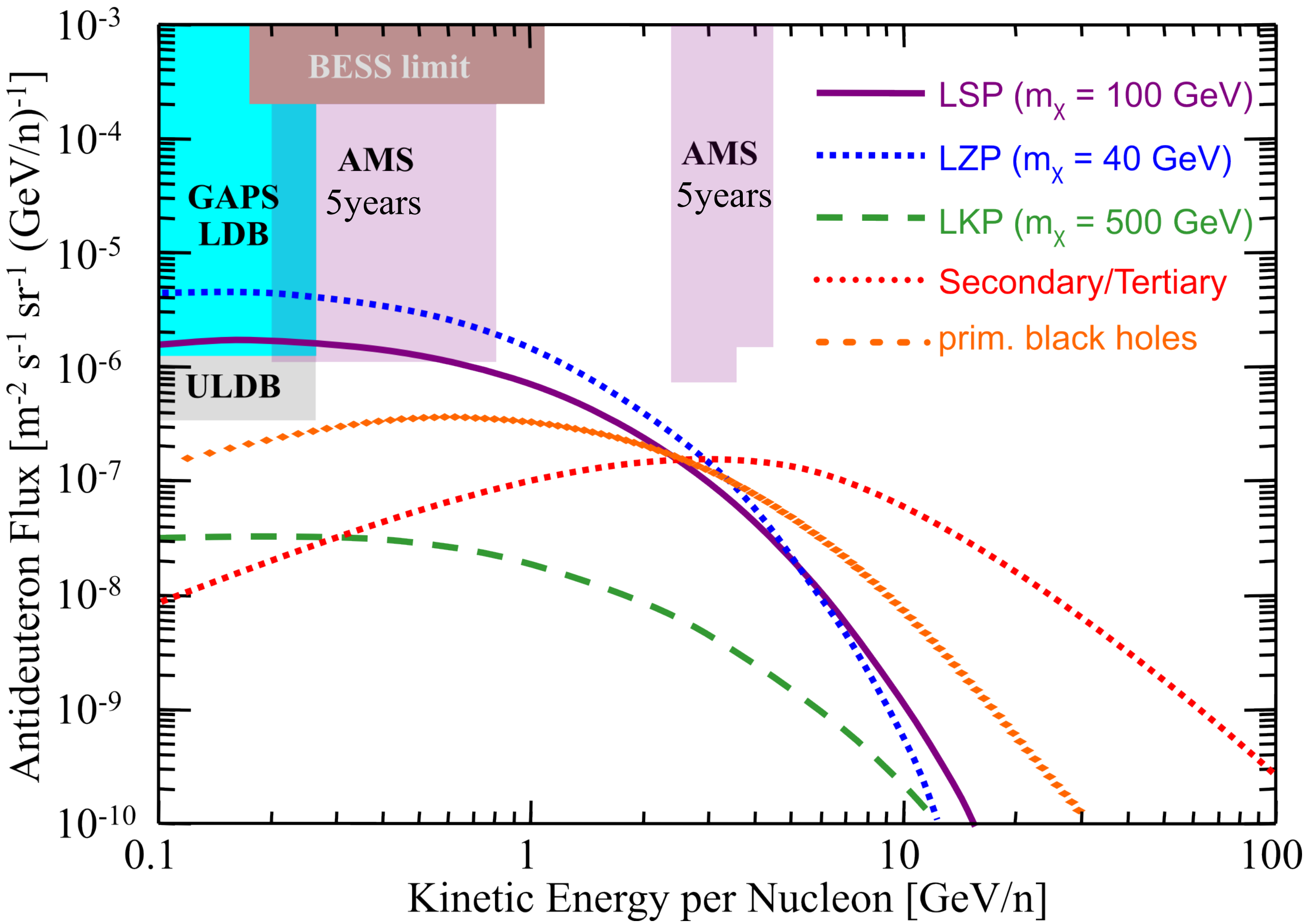
GAPS needs a very reliable particle identification:

- TOF velocity and tracks
- charge |Z|
- depth in tracker
- x-rays from deexcitation
- pions and protons from annihilation

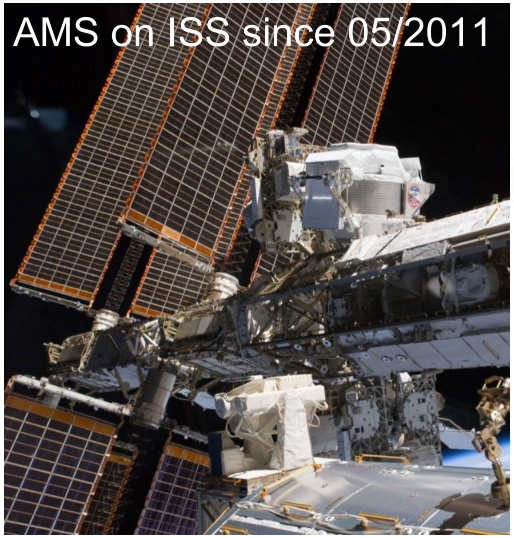
Scientific balloon flights (bGAPS) planned from Antarctica in 2016

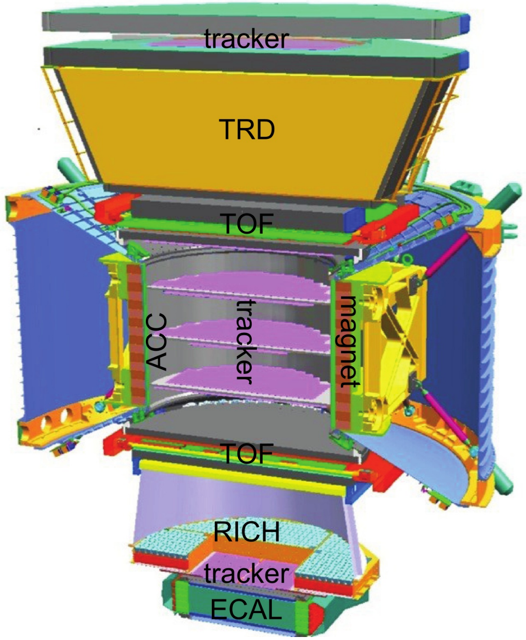
GAPS antideuteron sensitivity

- low-energy antideuteron search needs small geomagnetic cut-off → therefore (ultra) long duration balloon flights from South Pole are planned: 60 (300) days
- different scenarios give reasonable antideuteron fluxes within sensitivity: Supersymmetry, warped extra dimensions, primordial black holes, gravitino, Kaluza-Klein UED
- synergy with direct searches and neutrino telescopes: GAPS probes complementary dark matter regions!

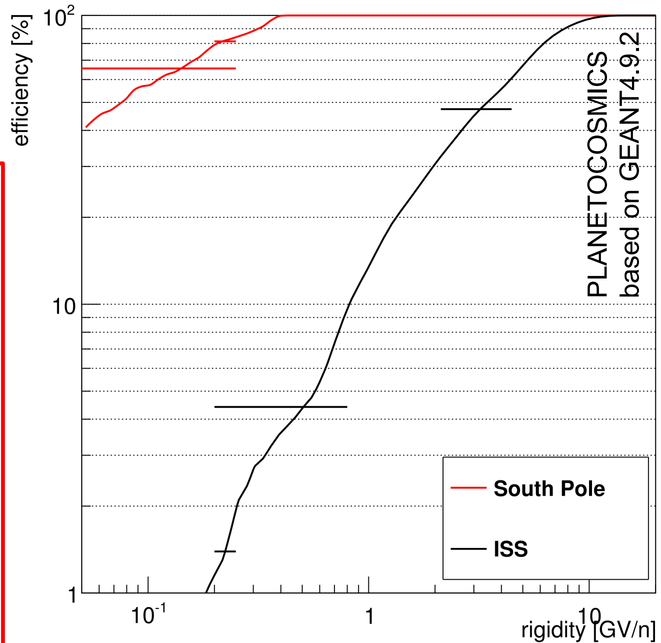


AMS comparison





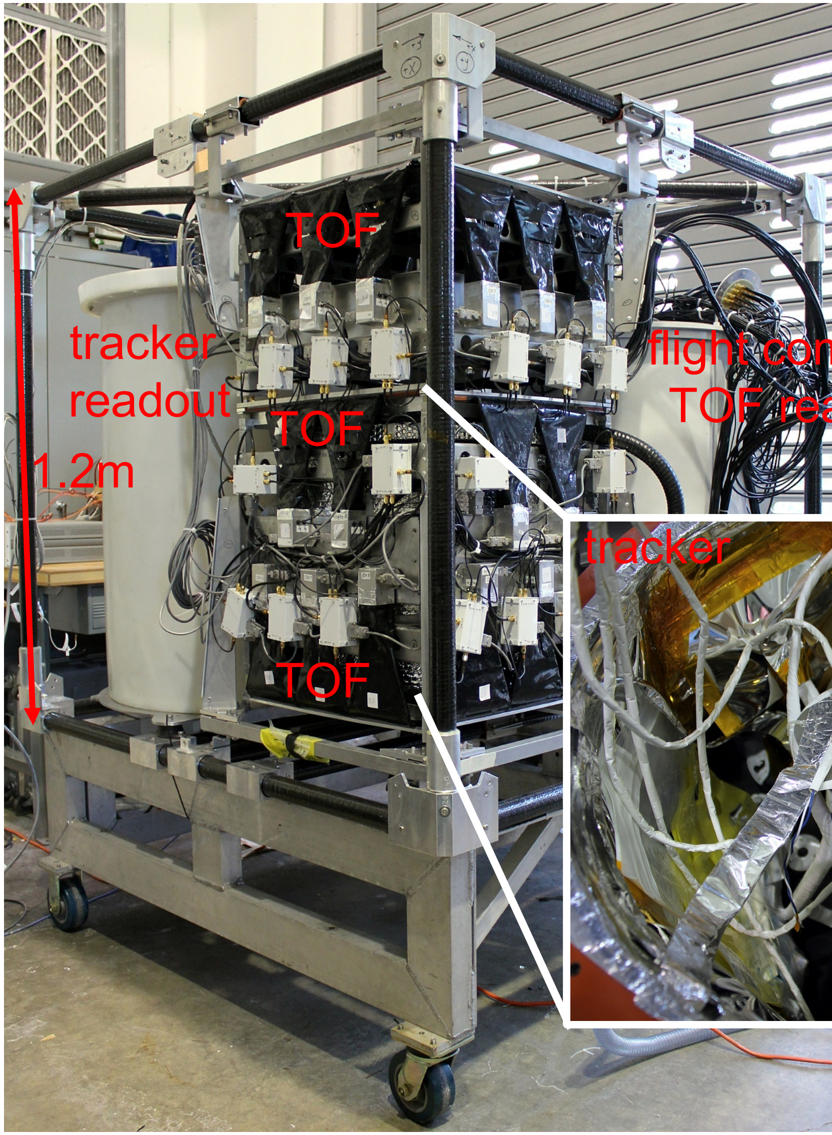
- BESS and AMS-02 use magnetic spectrometer for the antideuteron measurements
- protons are a huge source of background and require large rejections
- AMS setup (permanent magnet, tracker configuration) changed in 2010
- ISS lifetime was extended to at least 2020
- AMS recalculation for longer time and more detailed geomagnetic cutoff model, but same detector setup using the PhD thesis of F. Giovacchini (2007) (http://amsdottorato.cib.unibo.it/335/1/TESI_DOT.PDF)

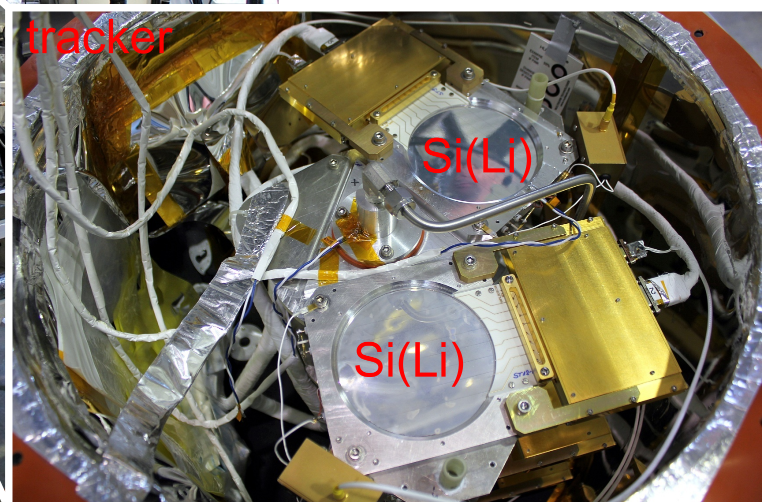


- ISS orbit is not ideal for low-energy cosmic rays, geomagnetic correction for GAPS is 15× smaller
- GAPS and AMS use different detection techniques: mandatory for a reliable confirmation of results to reduce systematic effects
- GAPS (LDB) and AMS (5yrs) deliver similar sensitivities in the signal region
- GAPS (ULDB) reaches ~3-4× lower fluxes than AMS (5yrs)


prototype GAPS integration

Prototype experiment



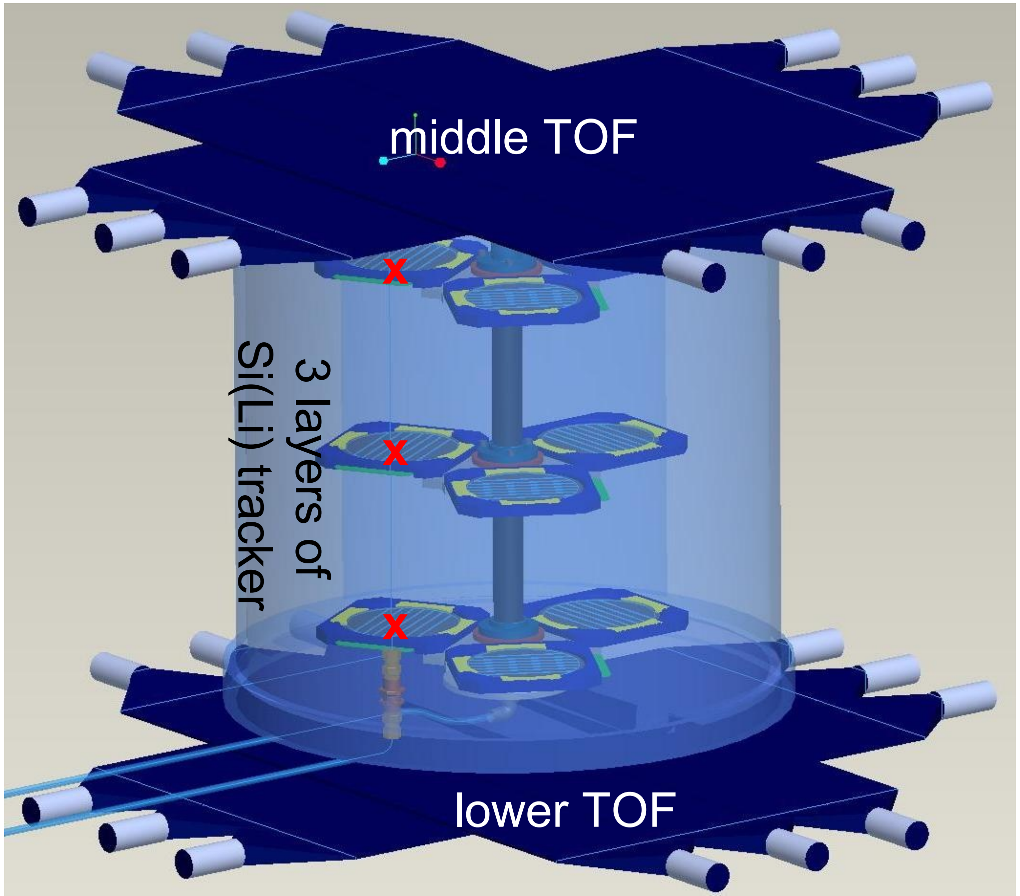


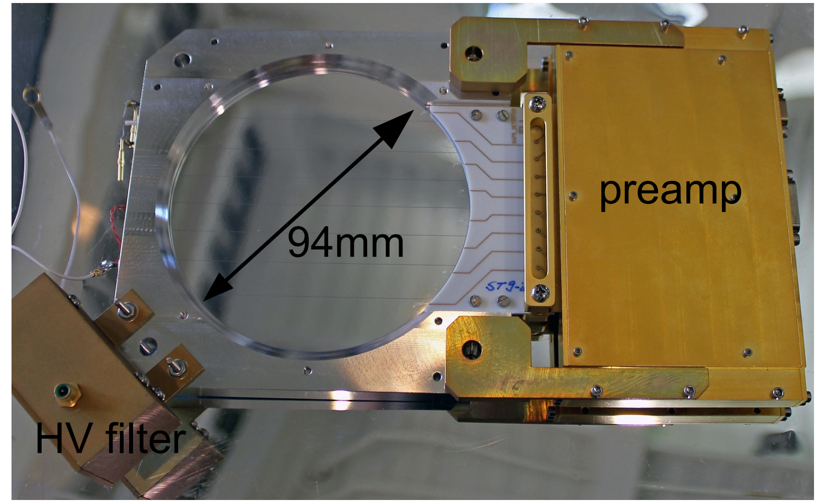
Prototype GAPS (pGAPS) goals:

- demonstrate stable, low noise operation of the detector components at float altitude and ambient pressure.
- demonstrate the Si(Li) cooling approach and verify thermal model
- measure incoherent background level in a flight like configuration.

May 2012 flight
from Taiki, Japan

Si(Li) tracker

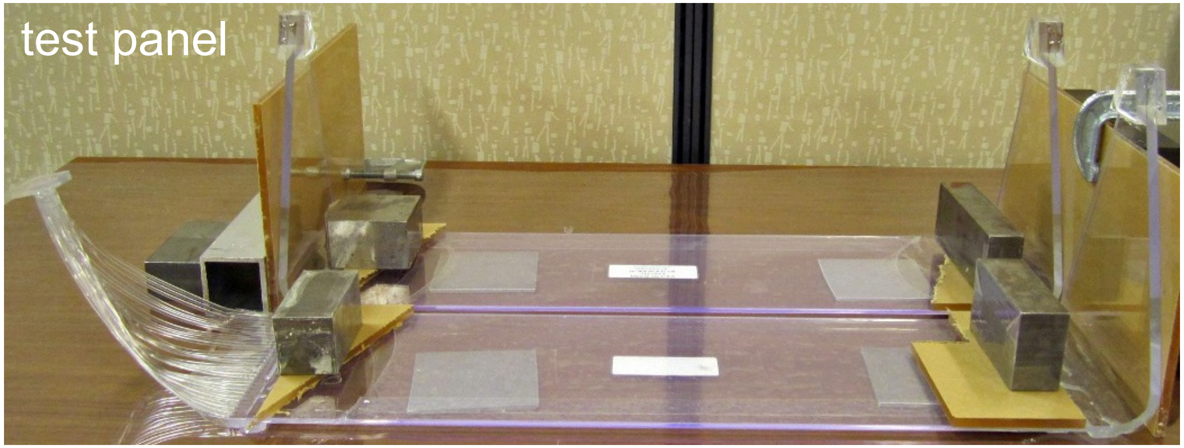


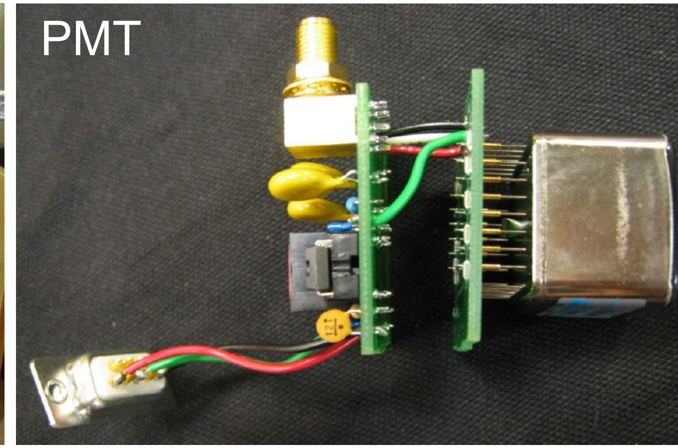


- 6 commercial Semikon detectors
- 94mm diameter and 4mm/2.5mm thick, 8 strips
- operation at ambient pressure during flight (8mbar) and in N_2 atmosphere on ground
- cooling system has to deliver ~-35°C
- N+: Lithium contact
- P+: Boron implanted (strips)

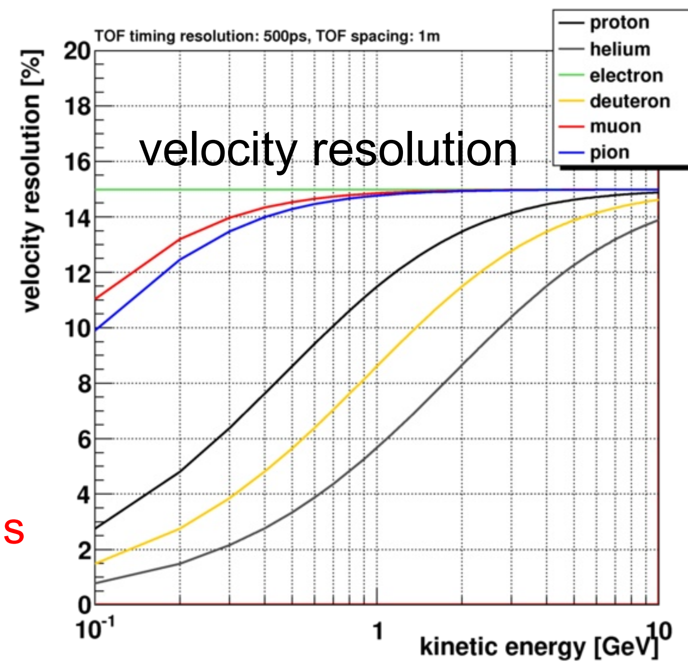
- closed-loop fluid pumping system (Fluorinert)
- space radiator

Time of flight system

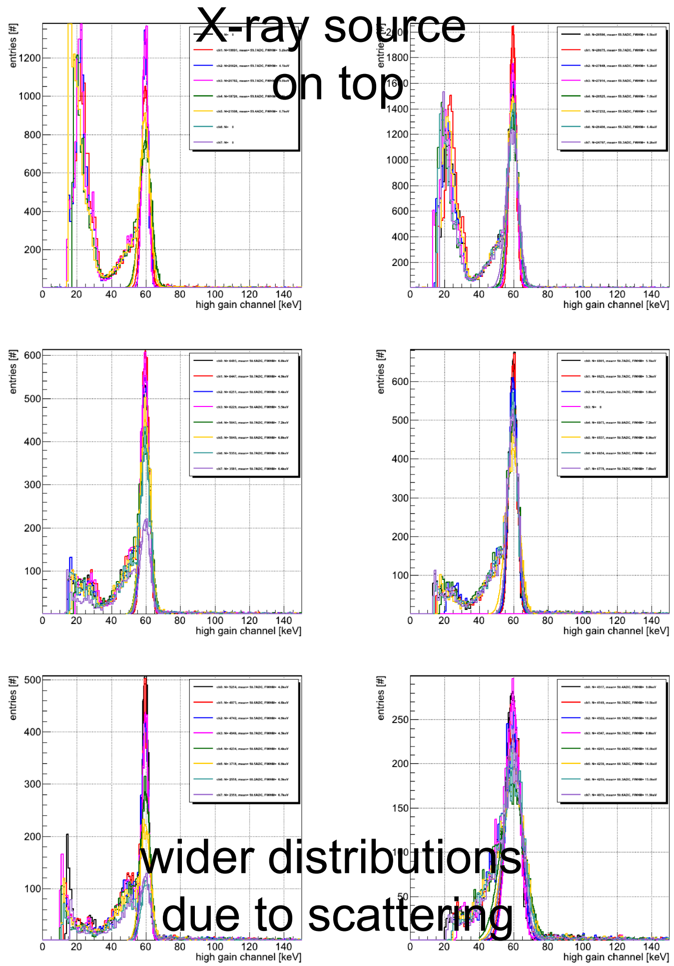




- 3 planes of TOF
  2 plane consists of 3×3
  middle plane 2×2, crossed panels
  1 panel has 2 PMTs
  = 16 panels and 32 PMTs
- 3mm scintillator from Bicron (BC-408)
- Hamamatsu R-7600 PMT
- timing resolution: 500ps
- charge resolution: 0.35e
- MIP value: ~15 photo electrons
- angular resolution: 8°

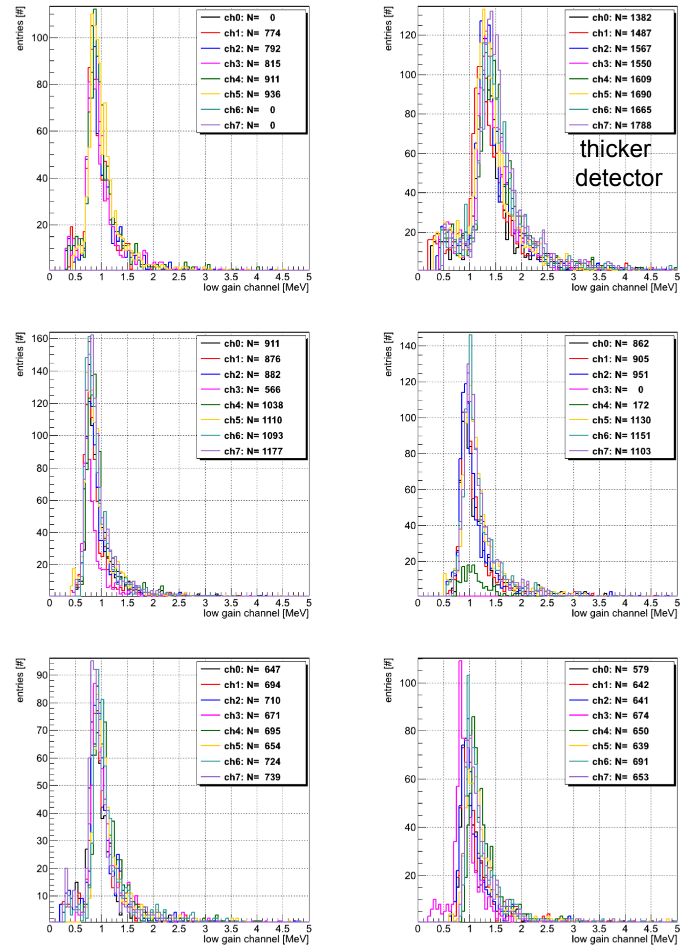


First tracker results



Am241 calibration:

- FWHM of 59.5keV line: (5.6±1.4)keV
- minimum energy: ~15keV

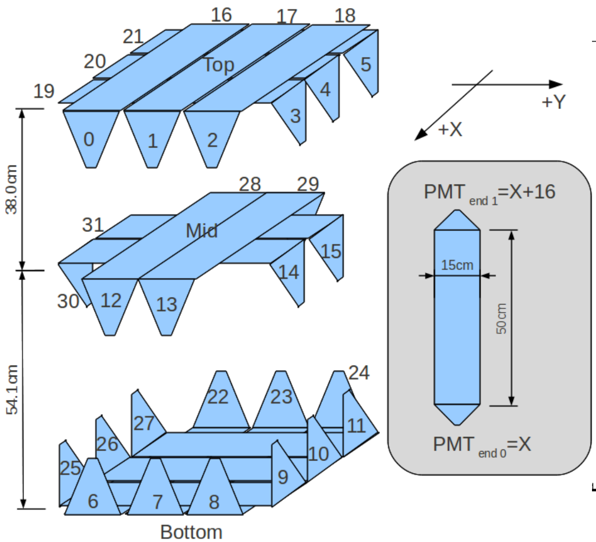


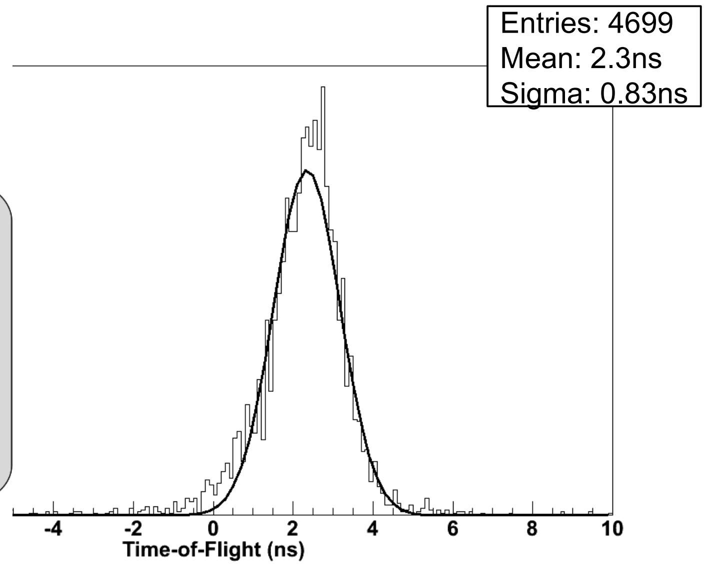
Atmospheric muons:

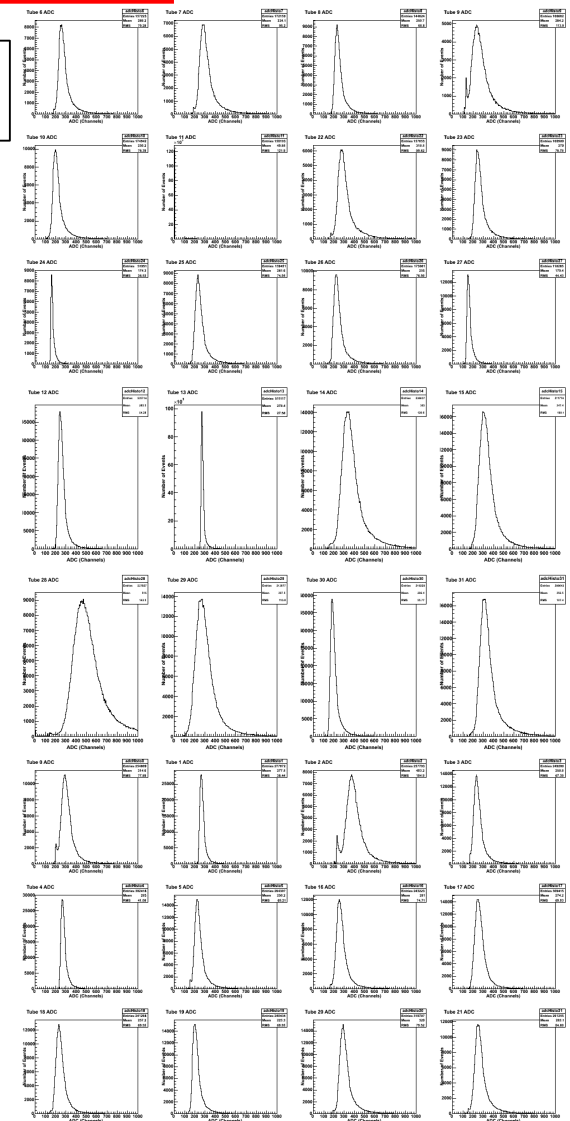
- Landau shape distribution
- MOP value at ~1MeV

TOF testing

PGAPS TOF Paddle Numbering (flight config.)

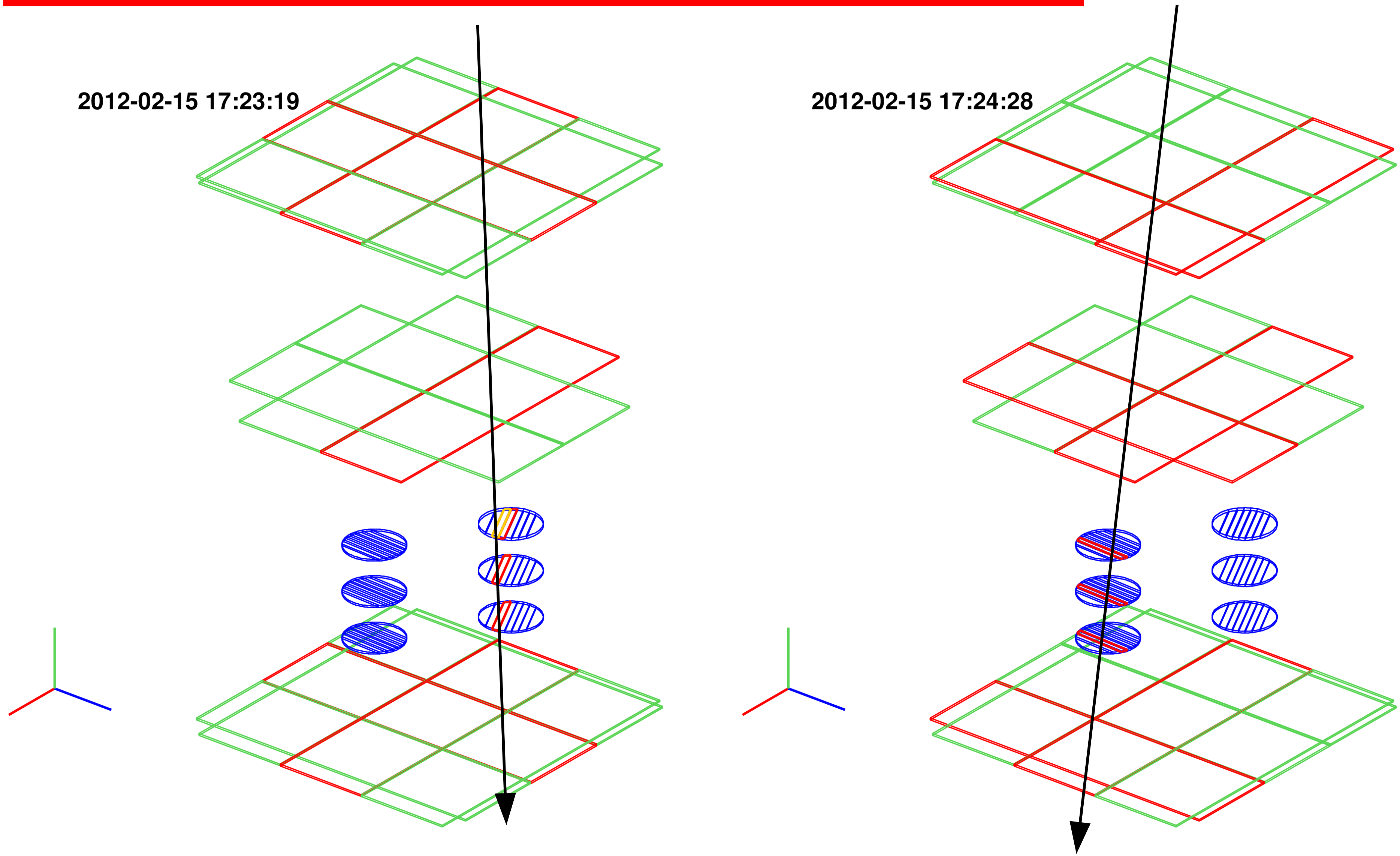




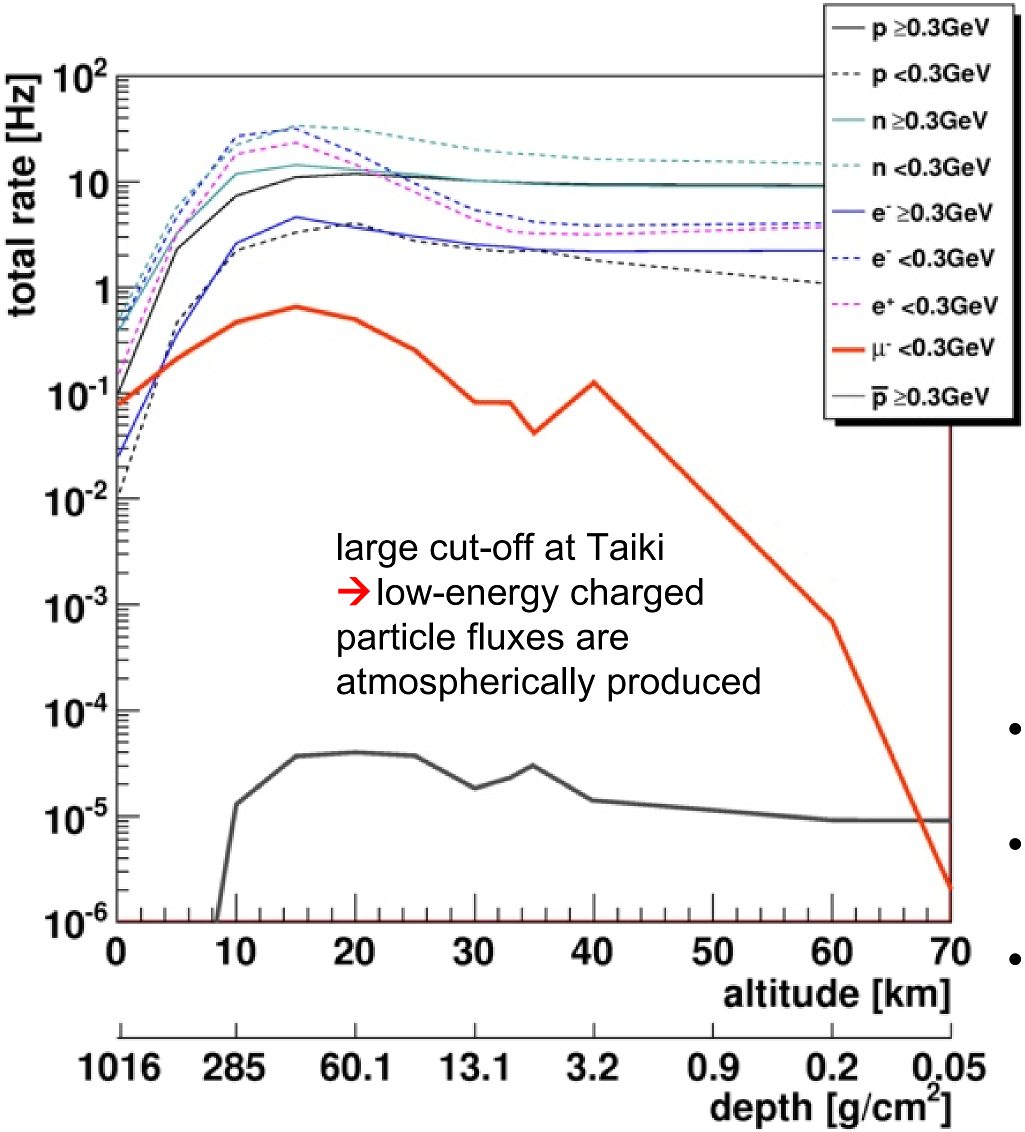


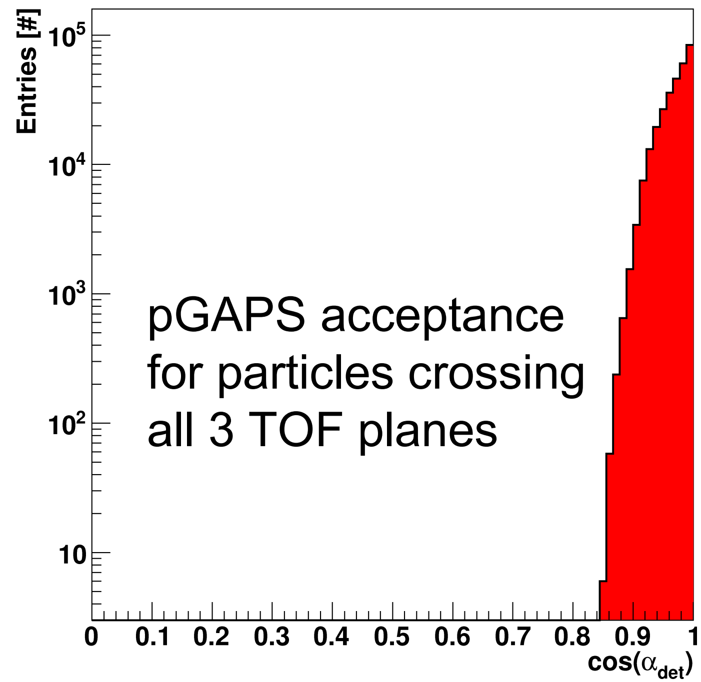
- TOF shows good distributions the energy depositions for each of the 32 tubes
- timing resolution is 590ps per paddle
- tracking resolution of the TOF is of order several cm

Tracks in pGAPS



Particle rates for pGAPS

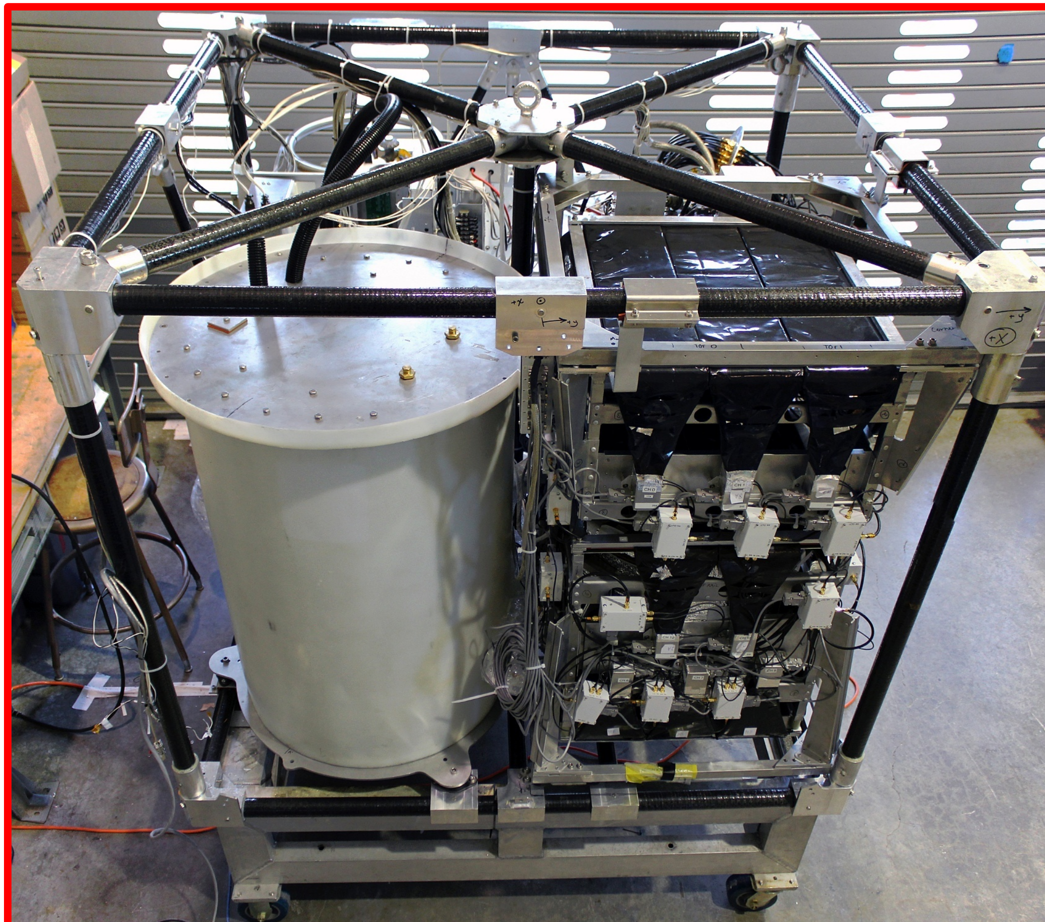




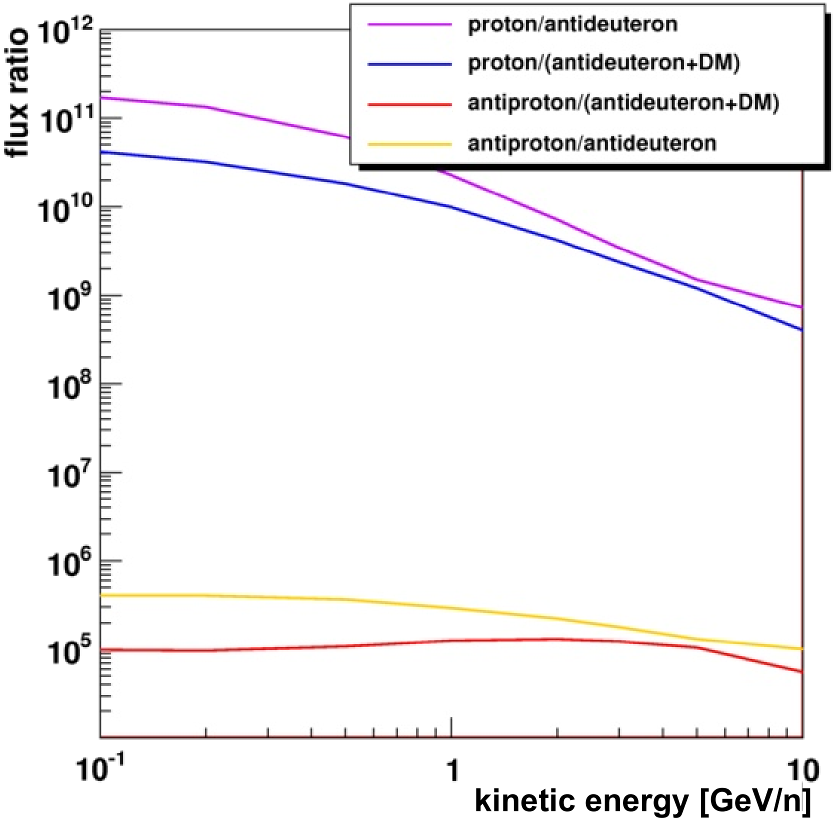
- particle rate at 33km at Taiki: total ~30Hz (accep.: 0.054m^2sr)
- strongest backgrounds by neutrons, protons, electrons, positrons
- no antiprotons will be measured, but muons might be used to create muonic atoms to study exotic physics at flight

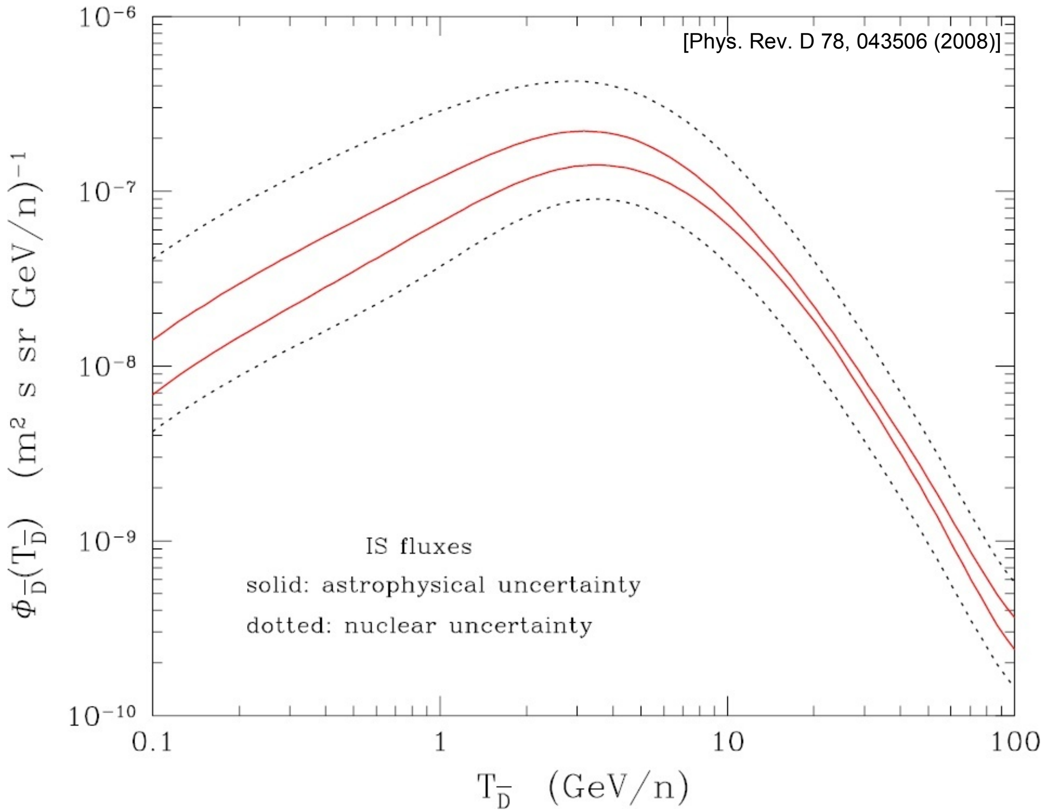
Conclusion and outlook

- measurement of low-energetic antideuteron flux is a promising way for indirect dark matter search
- GAPS is specifically designed for low-energetic antideuterons with a unique detection technique using the creation of exotic atoms
- GAPS is planned to have (U)LDB flights from South Pole starting from 2016
- LDB flights are compatible with AMS and ULDB flights will exceed the AMS capabilities
- prototype experiment is ready, currently under test, and will fly from Taiki, Japan in May 2012



Antideuteron detection



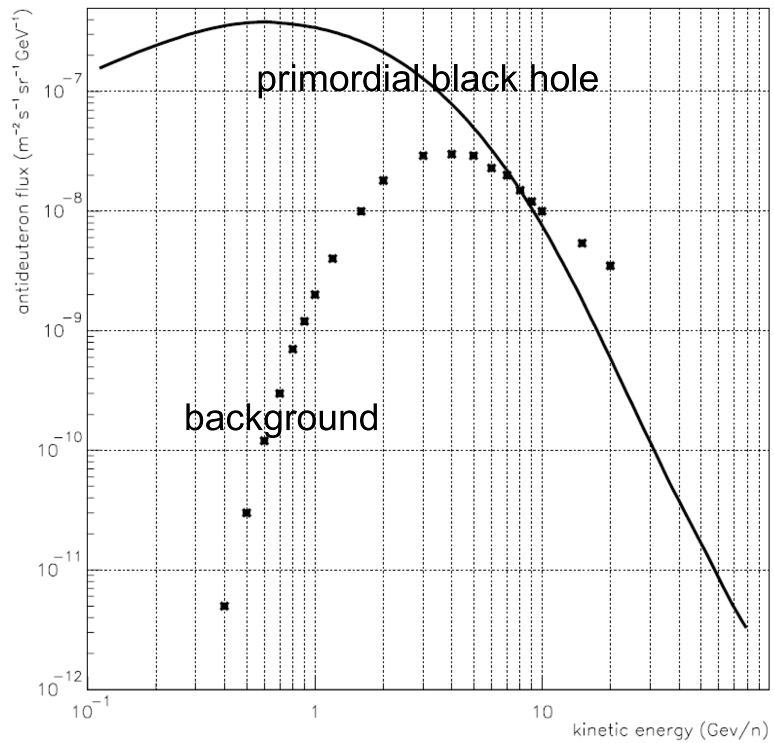


- good background suppression
- long flight time and large acceptance
- small sources of background (high altitudes with balloons in the atmosphere or Space)

- nuclear uncertainties: production cross-section and coalescence momentum
- propagation uncertainties: fit of all propagation parameters shows degeneracy, such that the average uncertainty is about 50%

Antideuterons and primordial black holes

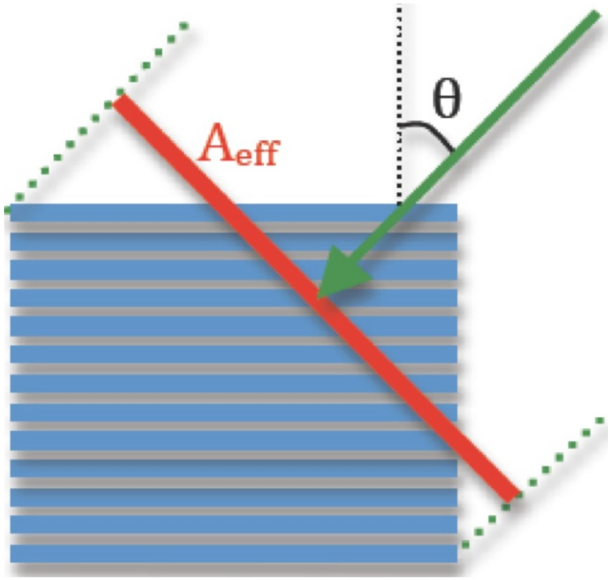
- very small black holes could have formed in the early Universe due to a variety of mechanisms:
  - initial density inhomogeneities
  - phase transitions
  - double inflation
- Hawking black hole evaporation can be understood as quantum creation of particles from the vacuum by an external field
- if the black hole temperature is greater than the QCD confinement scale, quark and gluon jets are emitted instead of hadrons and can form antideuterons

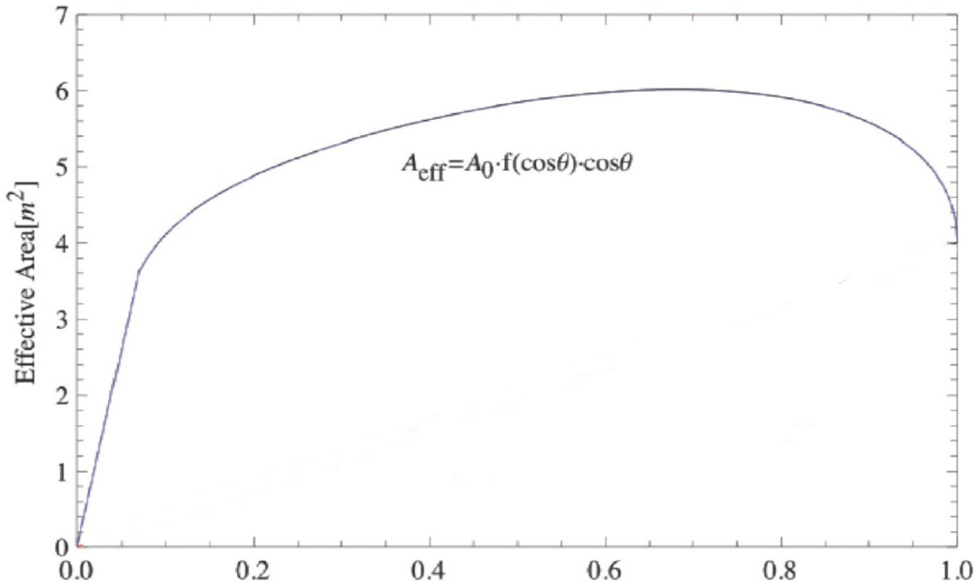


Antideuterons are maybe the only chance to detect PBHs!

[A&A 398, 403–410 (2003)]

Sensitivity calculation





$$\Gamma_{\text{GAPS}} = \frac{N_{stop}}{N_{\text{total}}} \cdot \Gamma_{\text{OA}}$$

$$\frac{\Gamma_{\bar{d}}}{\Gamma_d} = \frac{\Gamma_{\bar{p}}}{\Gamma_p}$$

$$\sigma_{\bar{d}}^{\text{annih}} = \sigma_{\bar{p}}^{\text{annih}} \cdot 2^{\frac{2}{3}}$$

- no ready to use tools for antideuteron simulation available!
- stopping power and annihilation probability calculation uses antiproton comparison

Sensitivity calculation

- once an antiparticle is stopped, the exotic atom formation probability is 100%
- x-rays are dropped into the simulation with a 50% detection efficiencies (isotropic)

$$\Delta E = 13.6\,eV \cdot (z_x Z_N)^2 \cdot \frac{\mu_x}{\mu_H} \cdot \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

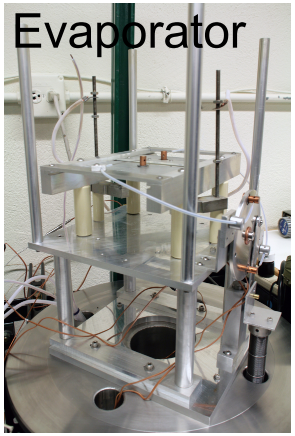
$$\mu_x = \frac{m_x \cdot m_N}{m_x + m_N} \quad \wedge \quad \mu_e = \frac{m_e \cdot m_N}{m_e + m_N}$$

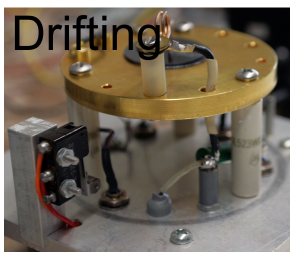
- hadron models for annihilation for antiprotons (fireball, INC):
  pions: ~5.1 (3.1 charged)
  proton: ~1
- antideuteron (no data): models estimate roughly double hadron yield

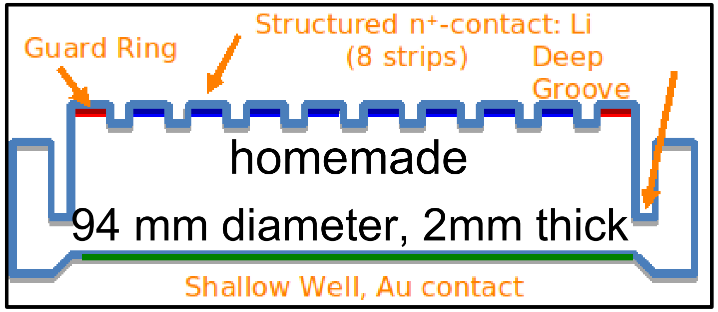
Expected background for a 300 day flight

Type of Background	Expected Events	Basis for estimate
Temporally incoherent X-rays	< 0.003	Scaling from γ-ray telescopes
Temporally coherent X-rays	0.001	Measured at GAPS-KEK experiment
Elastic neutrons	0.002	Monte-Carlo of evaporative & cascade model, KEK limits
Secondary-tertiary-atmospheric antideuterons	0.006	Propagate calculated spectra through atmosphere to instrument
Nuclear γ-rays, π^o shower photons, internal bremastrahlung	negligible	Data on energy & branching ratio of all possible lines; analytic calc.; GEANT4 sim.

Si(Li) fabrication for bGAPS







N+: Lithium contact (strips)
Au contact with shallow well

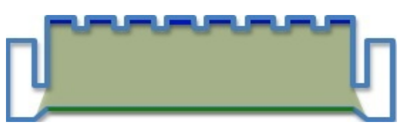
1. Cut from the ingot

2. Evaporate Lithium

3. Produce the deep groove and mesa (optional)

4. Drift the Li into the silicon

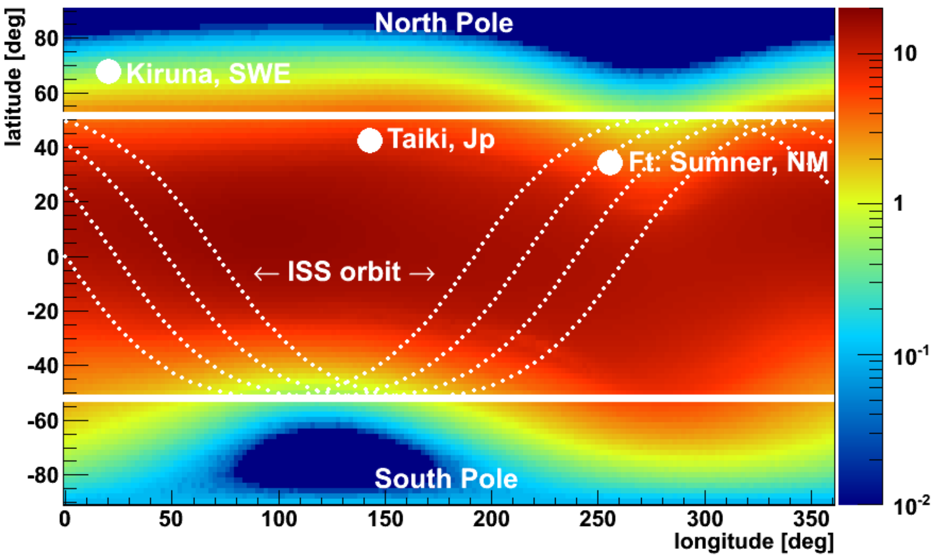
5. Make strips and guard ring

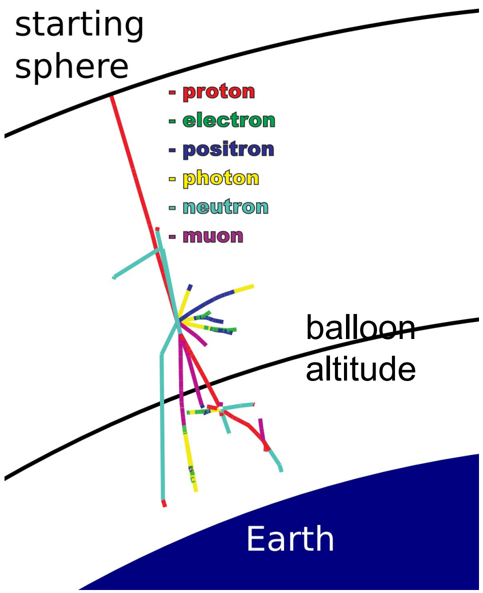


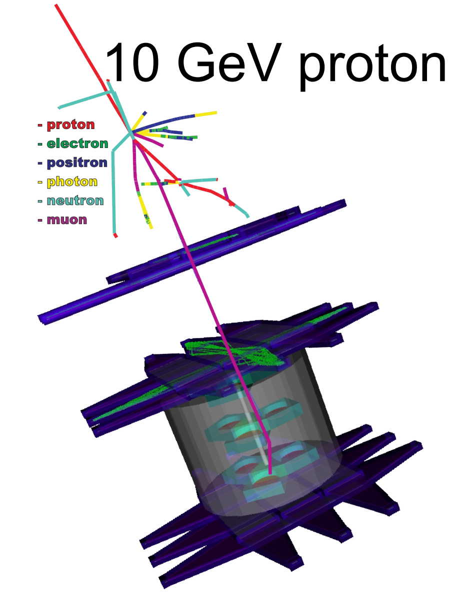
6. Etch the back (shallow well) and evaporate Au

GAPS simulations

cosmic antideuterons	atmospheric simulation	detector simulation	exotic atomic physics

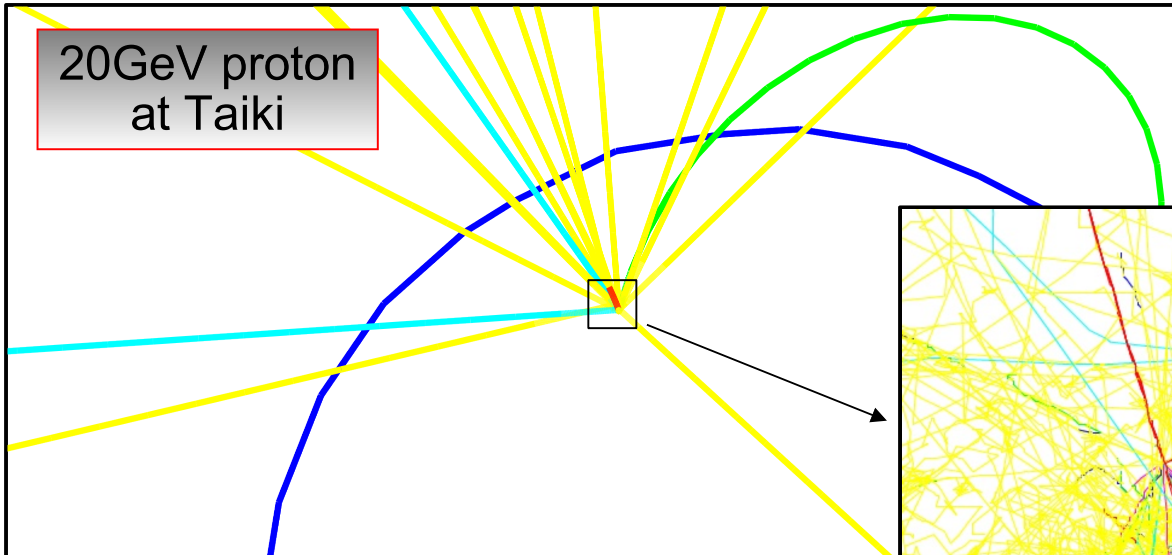


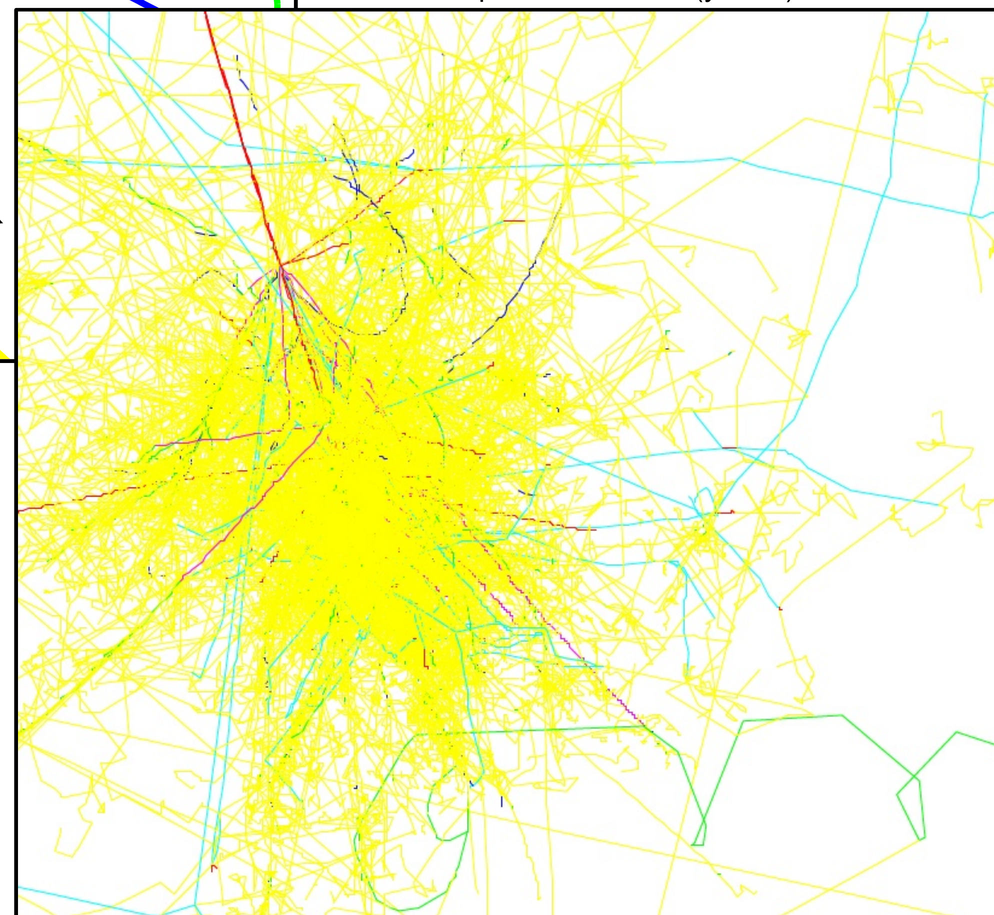




- Atmospheric and geomagnetic simulations with PLANETOCOSMICS based on GEANT4
- Instrument simulation with GEANT, ROOT output format:
  - electromagnetic, hadronic, optical physics are running
  - basic components are implemented, frames and structures must be added
  - ion and exotic physics are under development

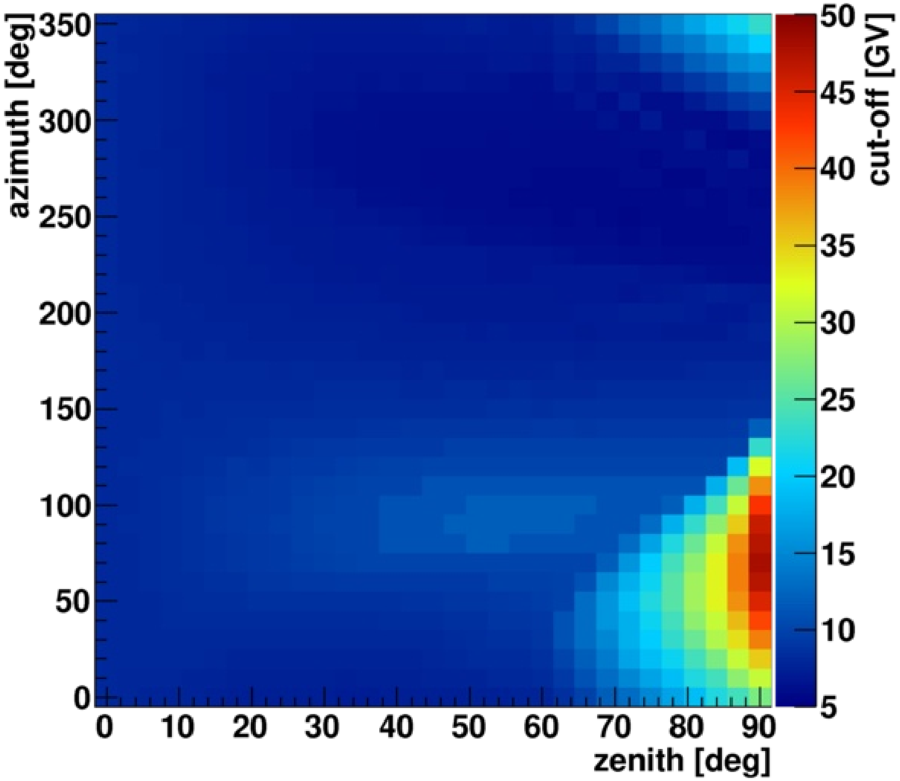
Air shower & geomagnetic field

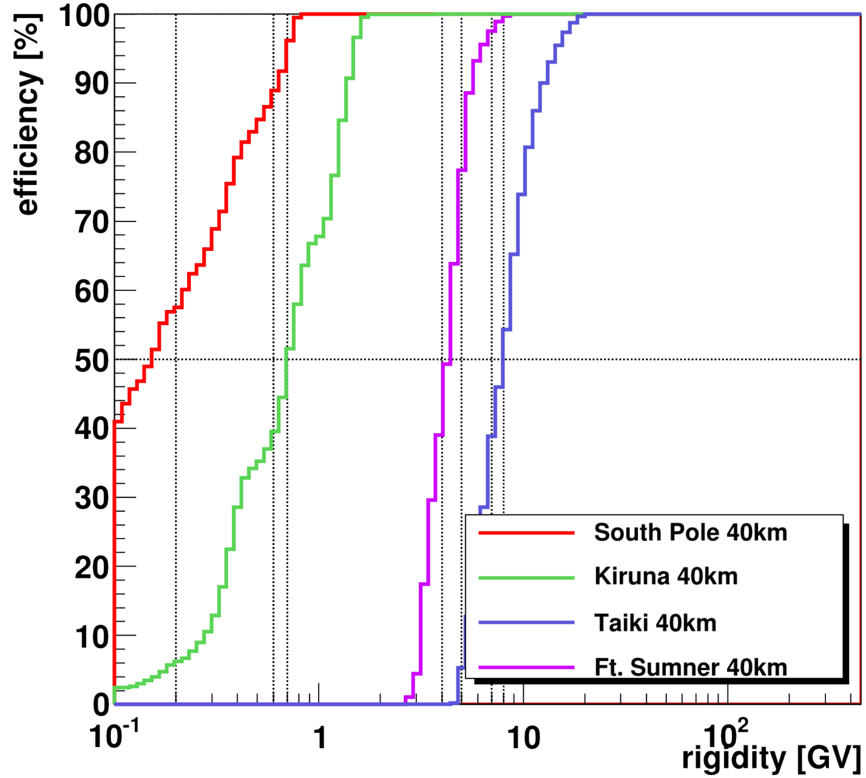




- use of NRLMSISE-00 atmospheric model: models the temperatures and densities of the atmosphere's components.
- grammage of matter in front of 33km: ~8.4g/cm^2 (Space: 6-10g/cm^2)
- on average ~20% of a radiation length (nuclear mean free pathlength ~10%) before 33km: Atmospheric background has to be calculated!

Cut-off and particle direction

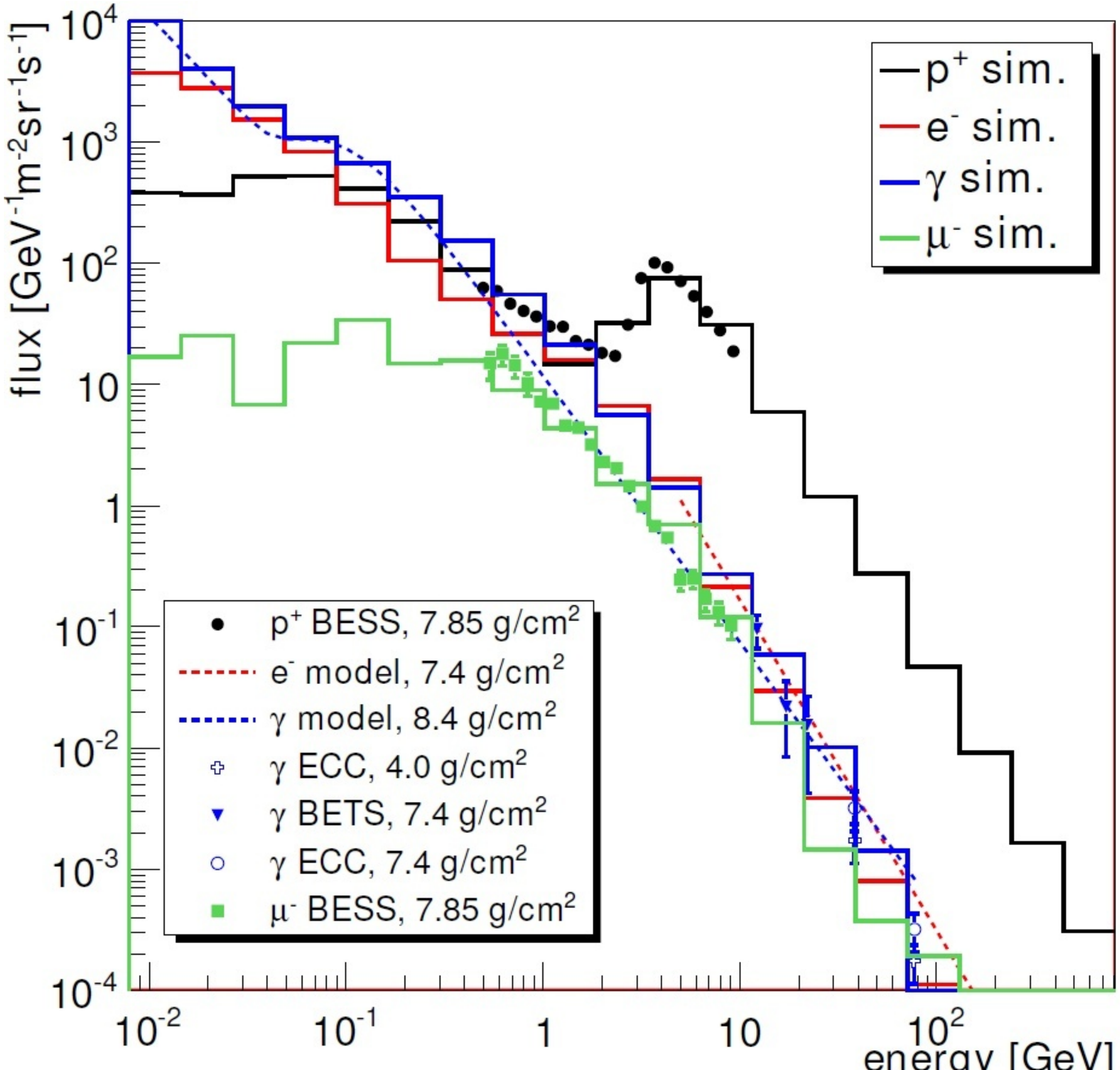


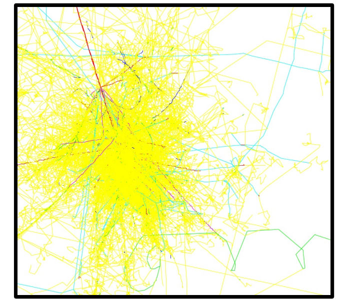


cut-off in Taiki as function of direction

cut-off averaged over isotropic distribution at different positions:
50% of cosmic rays with ~8GV get through to balloon altitude in Taiki

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