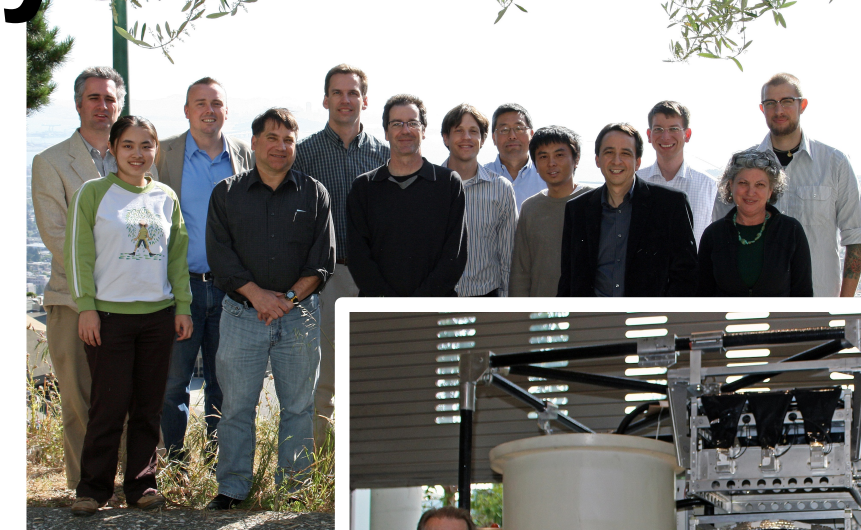
The General Antiparticle Spectrometer (GAPS) - Dark matter search using cosmic-ray antideuterons



Space Sciences Lab, UC Berkeley
October 2011

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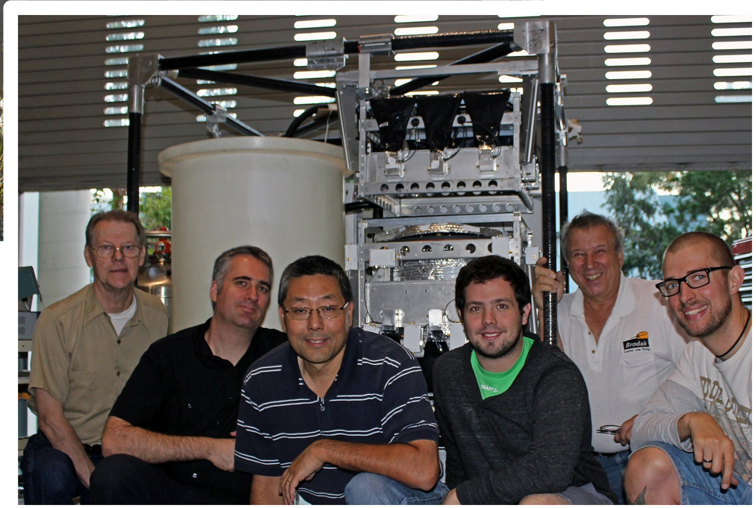

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Outline

Why are antideuterons interesting?

How to measure them?

cosmic rays

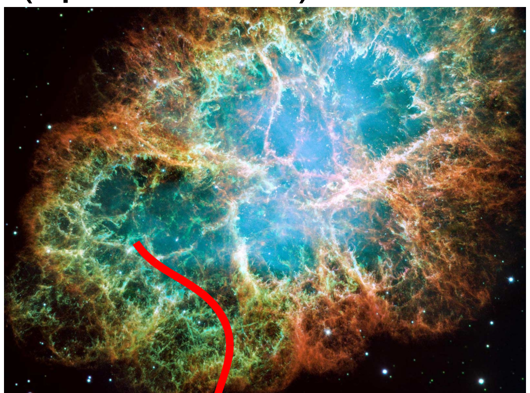
antideuteron physics

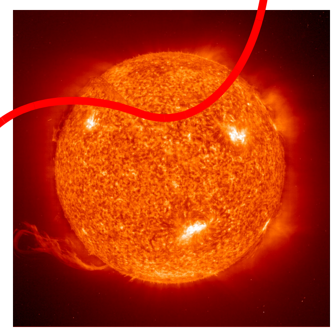
GAPS concept

GAPS prototype instrument

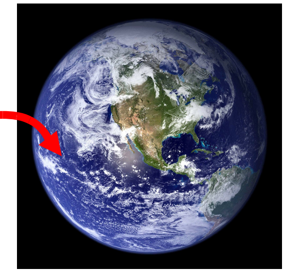
Cosmic rays as messengers

sources and acceleration:
supernovae shocks
(up to 10^{18} eV)

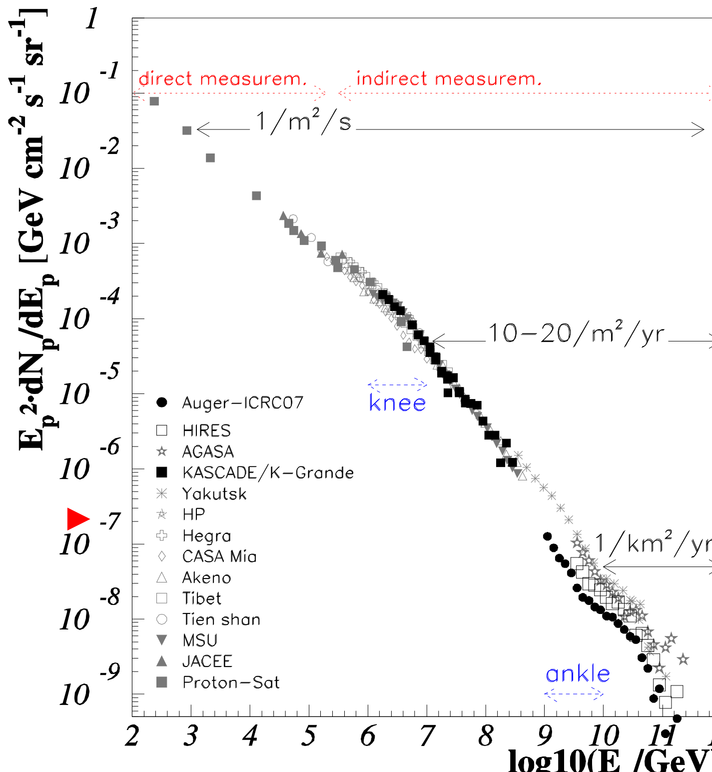




modulation
by solar wind



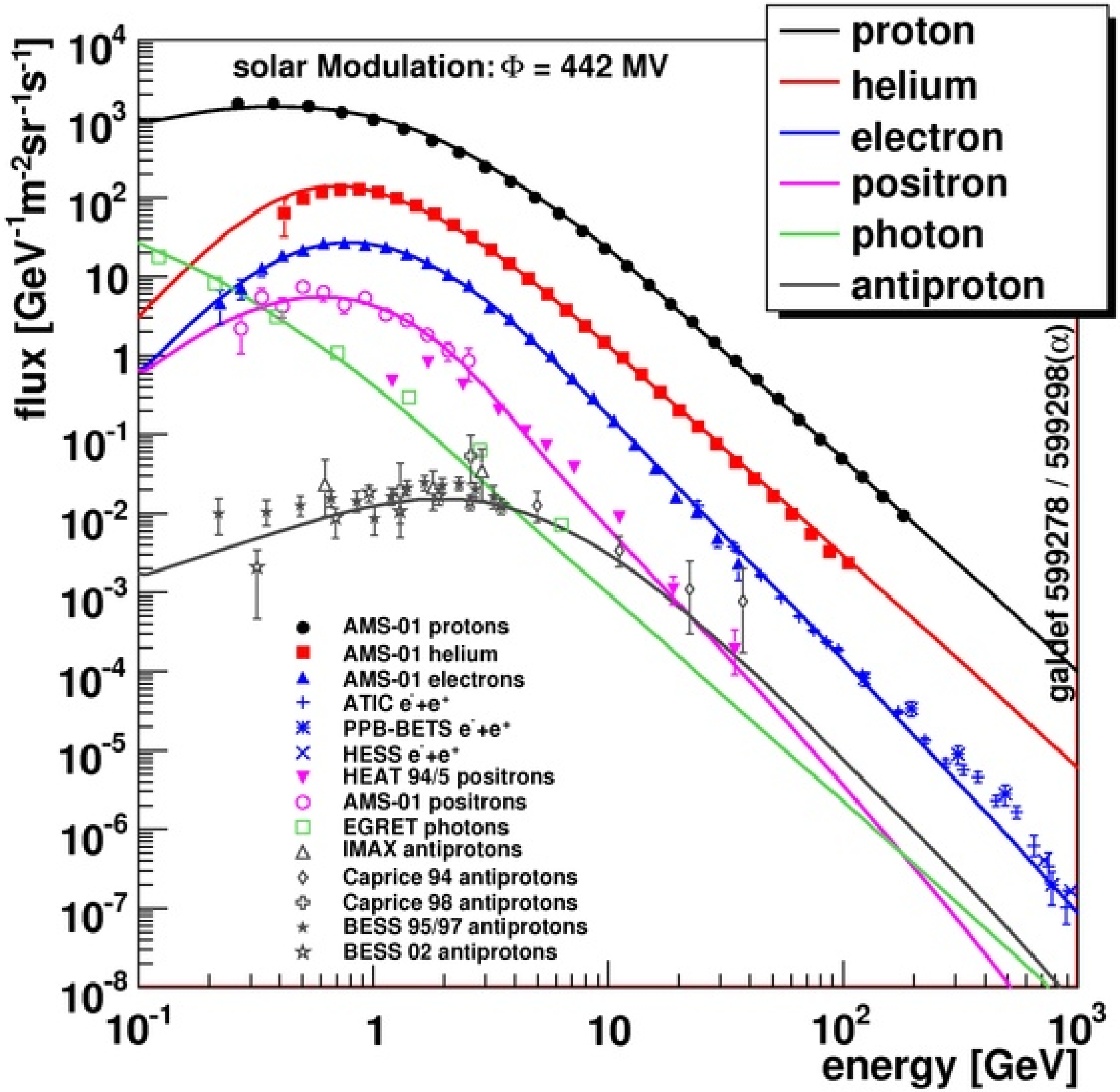
deflection in Earth's
magnetic field
interactions with the
atmosphere



all particle cosmic-ray spectrum

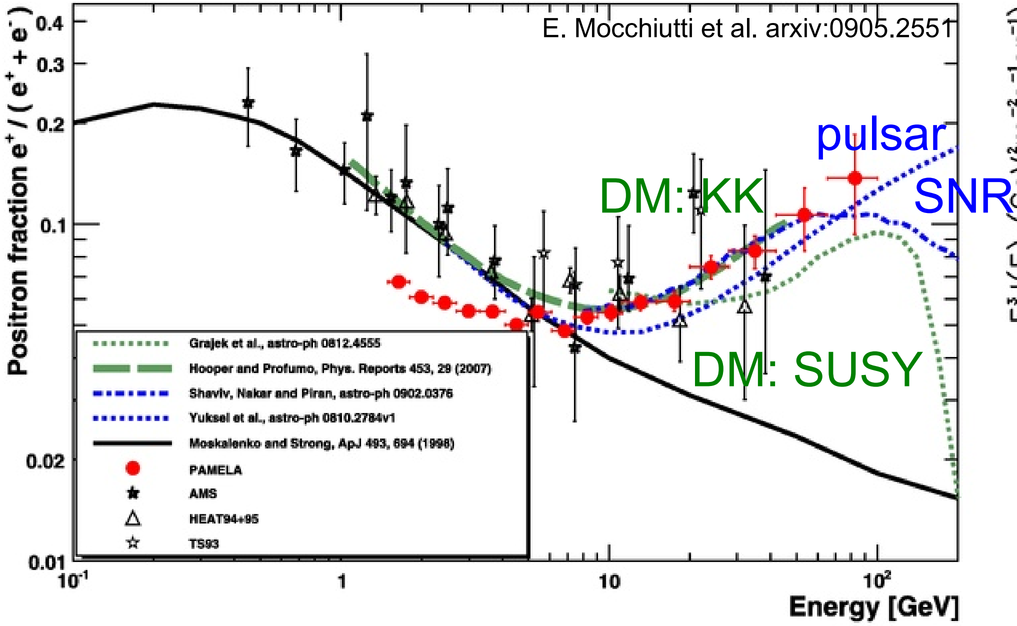
scattering in magnetic fields,
interaction with interstellar
medium (γ, $e^{-/+}$, $\bar{p}$, ν, $\bar{D}$ production),
decay, diffusion, reacceleration

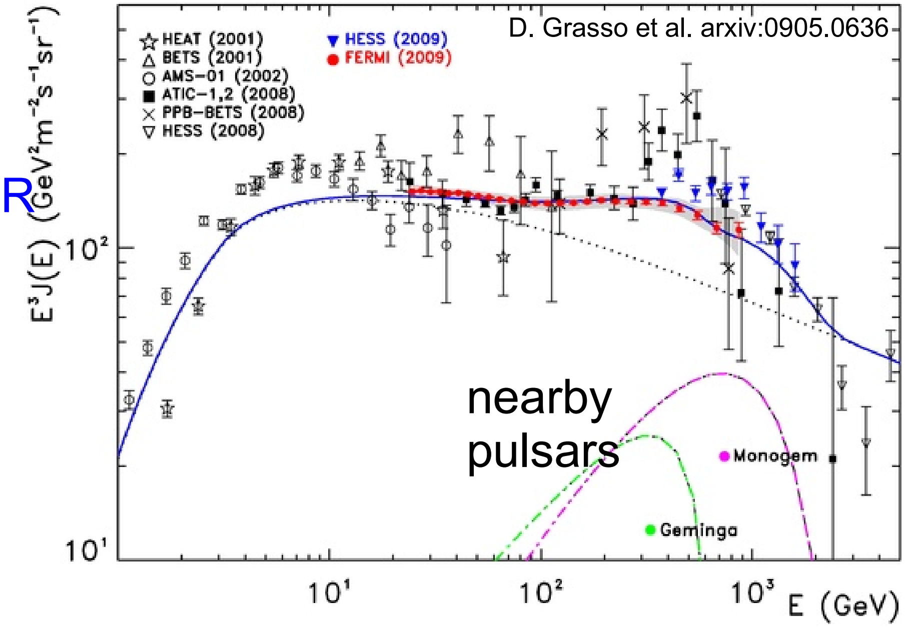
Cosmic rays in the GeV to TeV range



- in general good agreement of models and data
- what we already learned:
  - particle physics
  - interstellar medium
  - astronomical objects
  - …
- small fluxes with no primary astronomical source are especially sensitive to new effects

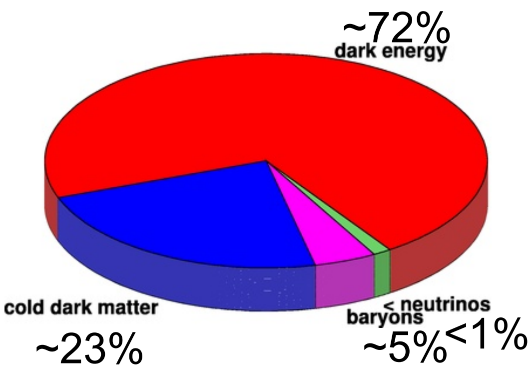
Positron fraction & electron flux



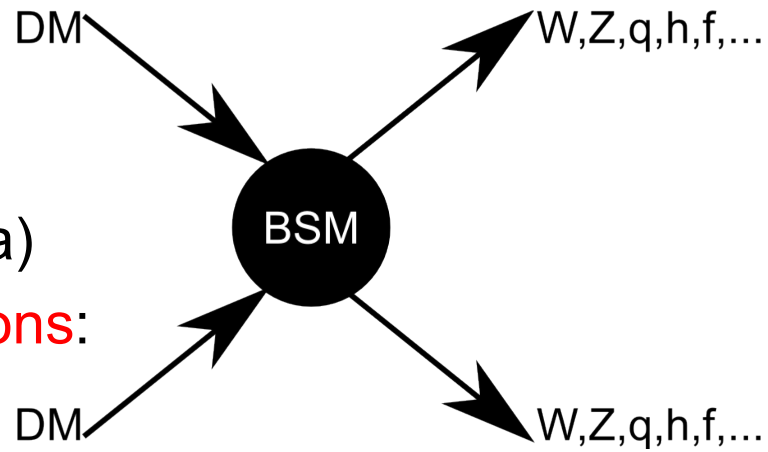


- unexplained features in positron and electron spectra
- proposed theories:
  - γ-ray pulsars can produce electron and positrons via pair production in the magnetosphere
  - positrons and electrons can also be accelerated in PWN or SNR shocks
  - dark matter self-annihilation

Dark matter



- evidence for dark matter exists in many different fields
- BUT we do not know its nature
- different search approaches: direct and indirect: here cosmic rays



dark matter annihilation

- different popular scenarios:
  - Supersymmetry: neutralino (majorana)
  - Kaluza-Klein universal extra dimensions: 1st excitation of photon (boson)
- requires boost factors to explain $e^{+/-}$ fluxes
- indirect dark matter searches are especially sensitive to extra contributions in the antiparticle spectra

Drawbacks...

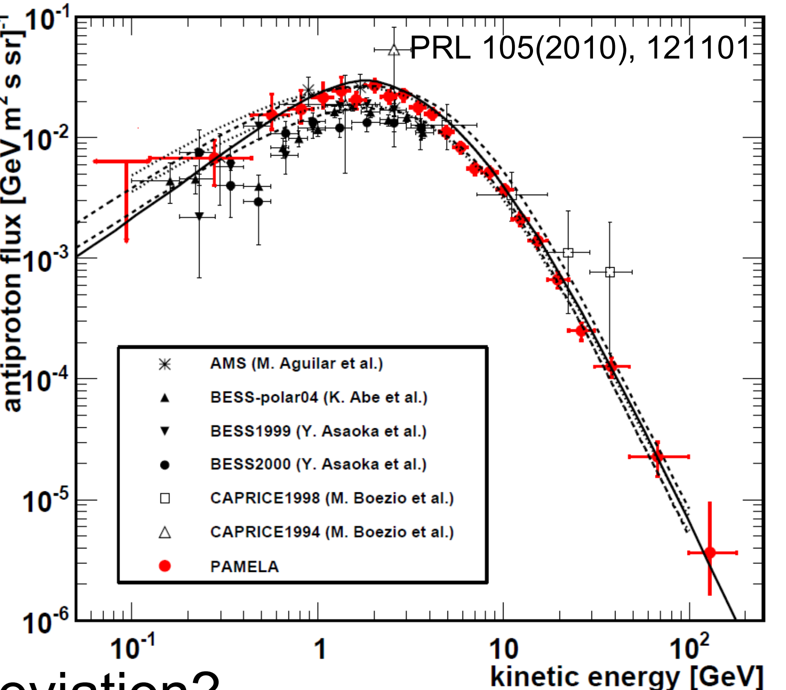
Drawbacks exist for astronomical interpretations:

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:

- Is the experimental data well understood (large rejections are needed)?
- Why do antiprotons do not show a deviation?
- Are propagation models well understood?

Cosmic-ray models

Diffusion equation must take into account the following processes:

- diffusion (coefficient, anisotropic, inhomogeneous?)
- escape (boundary conditions, geometry of diffusion volume)
- spallations
- sources
- energy losses
- diffusive reacceleration
- galactic wind (convection)
- inelastic non annihilating reactions

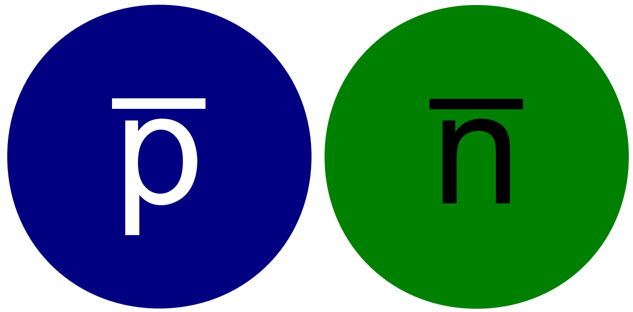
Astrophysical uncertainties (assuming the model is correct):

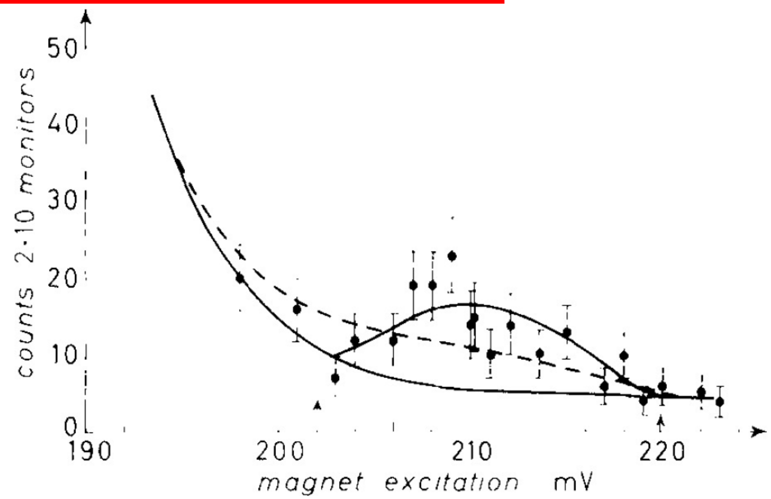
- distribution of sources
- distribution of interstellar matter
- energy losses
- nuclear cross-sections

Many unknown parameters: maybe the propagation models are not as "standard" as some people believe...?

Conclusion: Additionial contribution to the astrophysical cosmic-ray flux must be as large as possible to study new effects!

Antideuterons





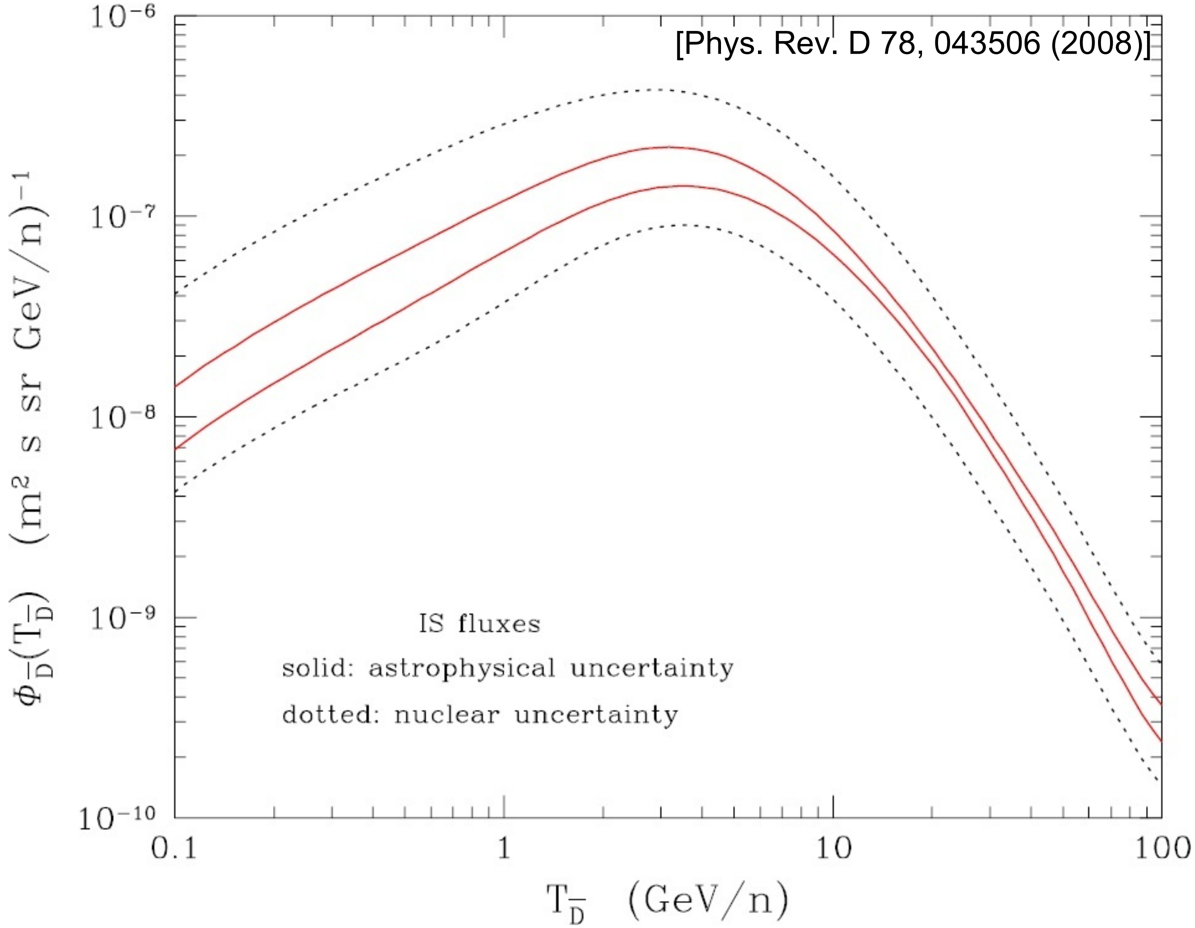
- deuterons are the nuclei of heavy water and antideuterons are the corresponding antimatter (q=-1,m=1876MeV, s=1)
- antideuterons were discovered in 1965 at CERN and Brookhaven and were the first real antimatter ever discovered

Cosmic rays

- antideuterons have never been detected in cosmic rays
- antideuteron production is understood and it should form in the galactic disk from the collisions of protons, alphas and antiprotons with Hydrogen and Helium IS gas
- if the antiproton and antineutron coalescence momentum is below 160MeV (ALEPH)
- understanding of jet structure is important for precise predictions

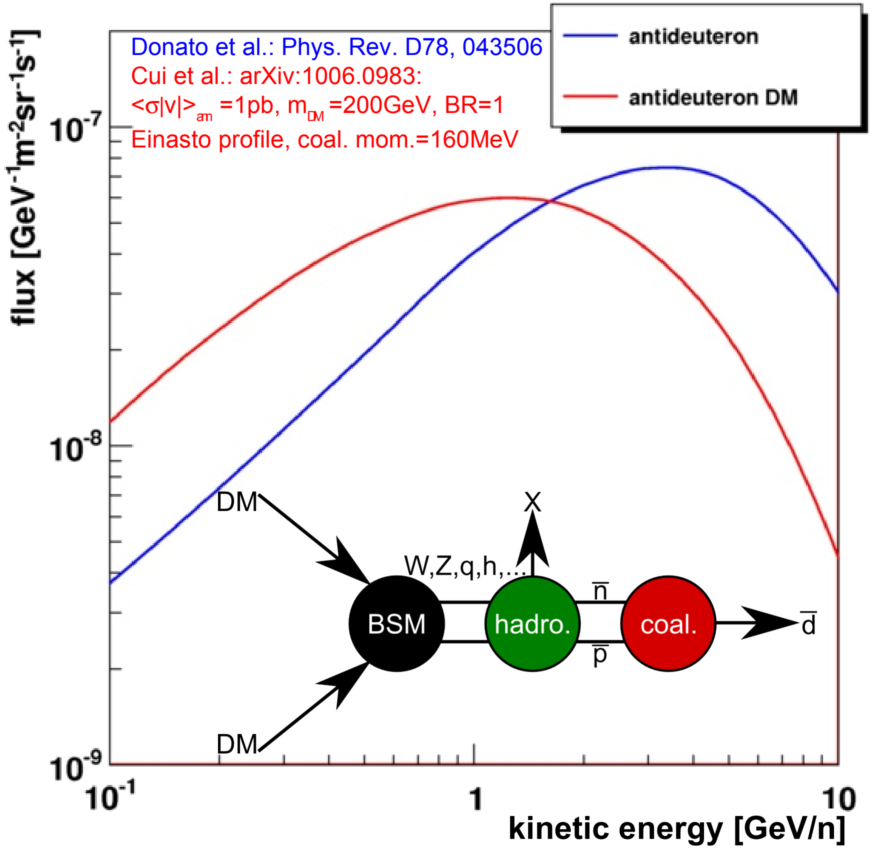
[arXiv:0803.264, arXiv:0908.1578]

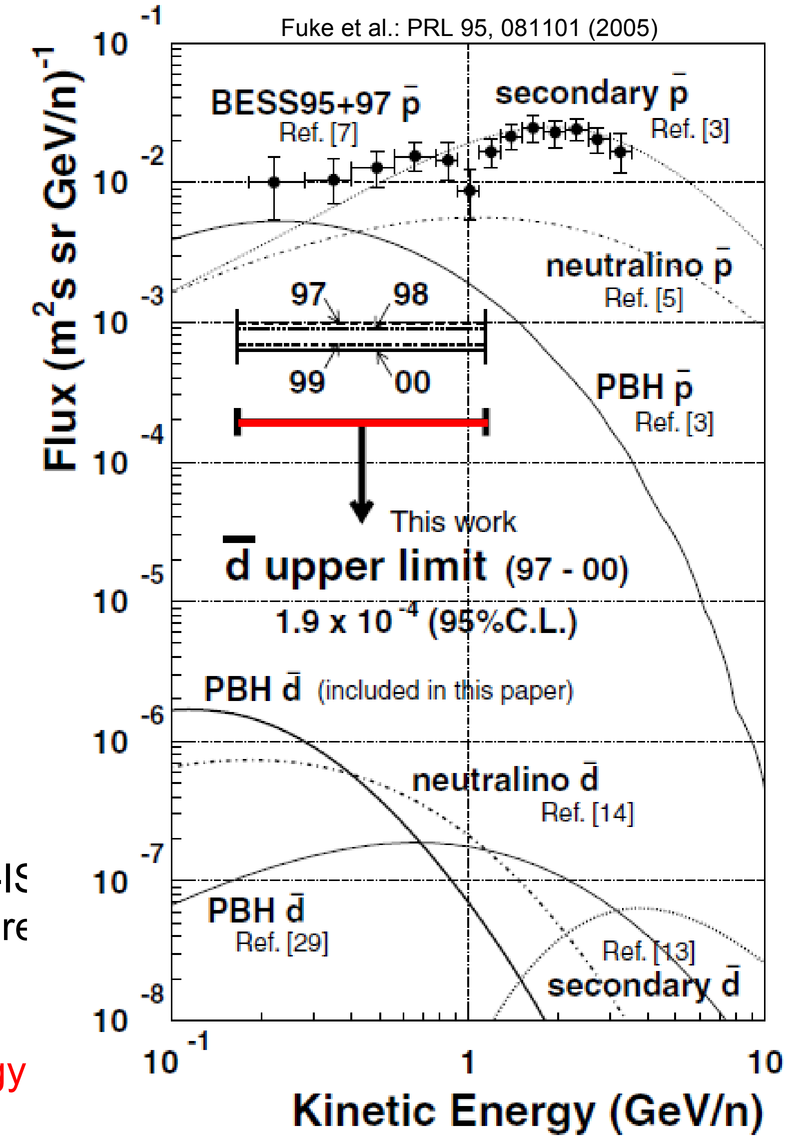
Antideuteron uncertainties



- **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%
- in the following: plotted background flux is the mean of these uncertainties

Antideuterons and dark matter

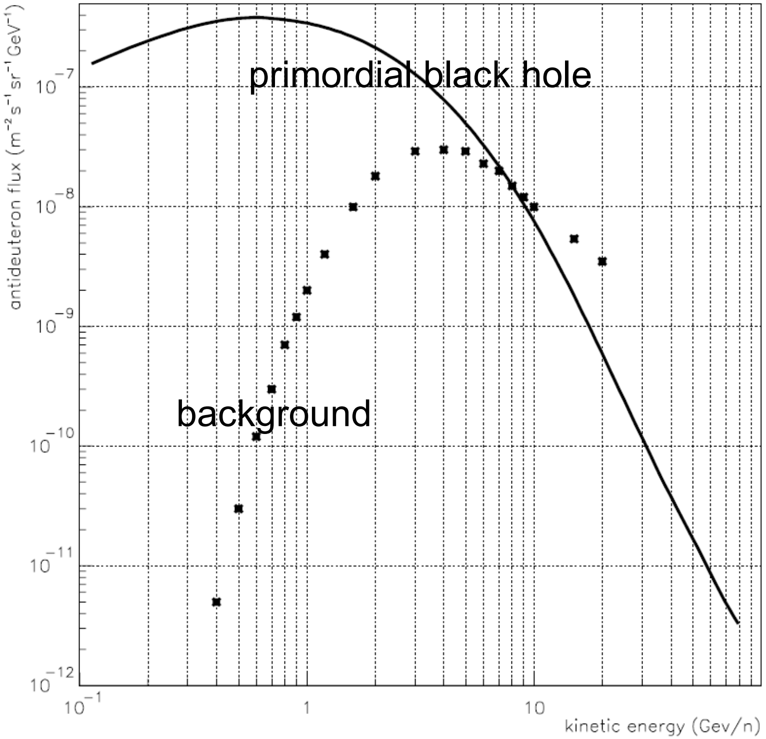




- antideuterons have high production threshold for p-IS
- generic model with dark matter self-annihilation (here via W^+W^-) show different shape (consistent with antiproton flux!)
- predicts large signal over background for low-energy antideuteron signals

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



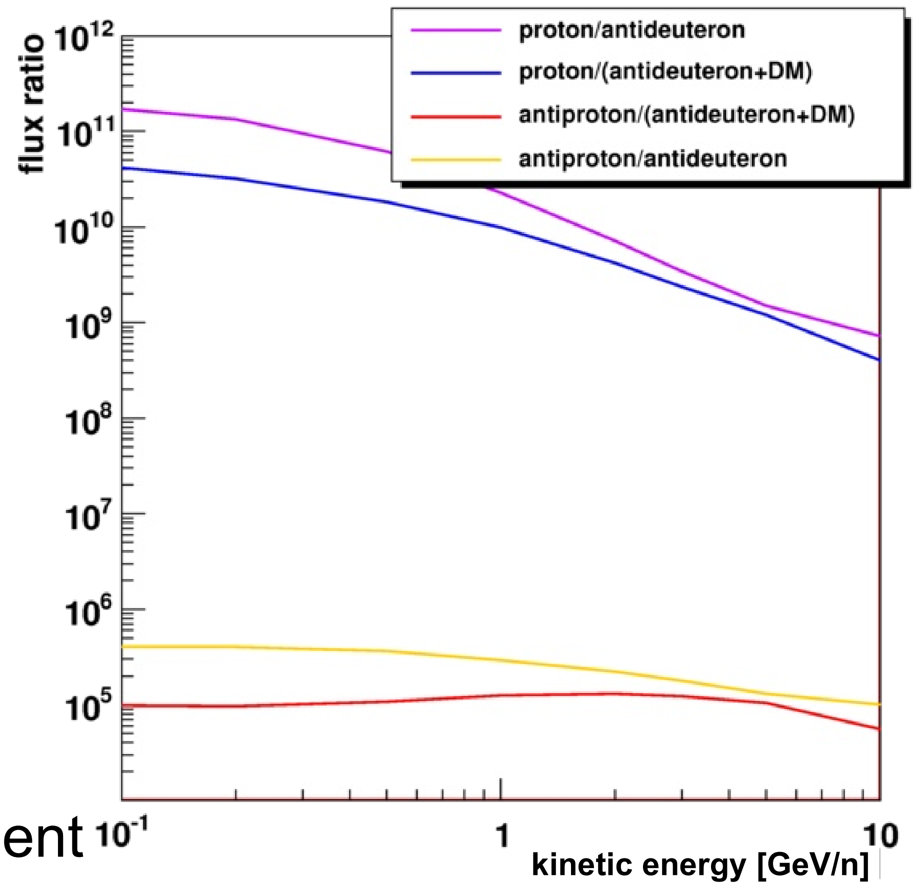
Antideuterons are maybe the only chance to detect PBHs!

[A&A 398, 403–410 (2003)]

Detection of antideuterons

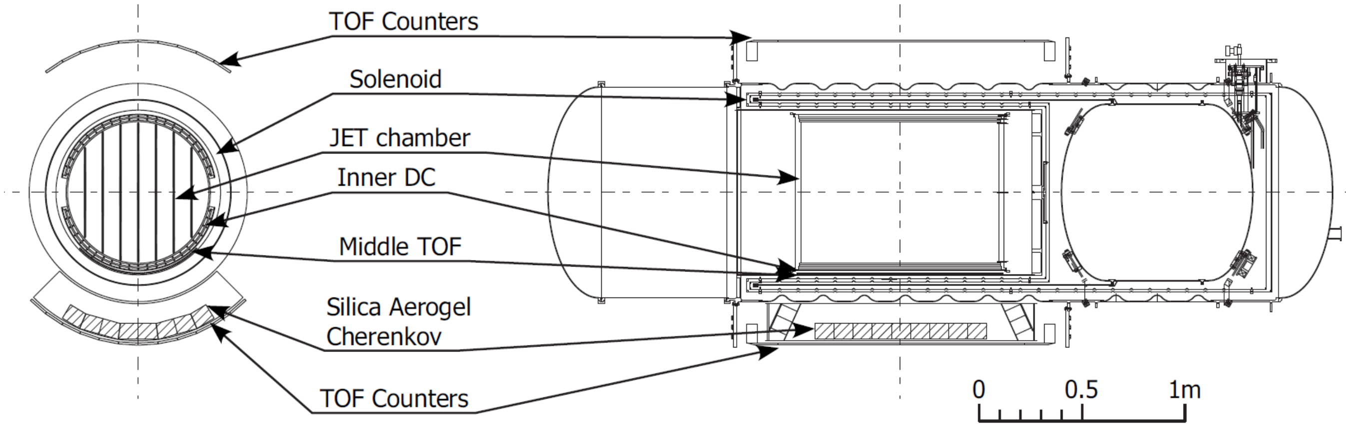
general requirements for direct measurements of cosmic-ray antiparticles with balloon and Space experiments:

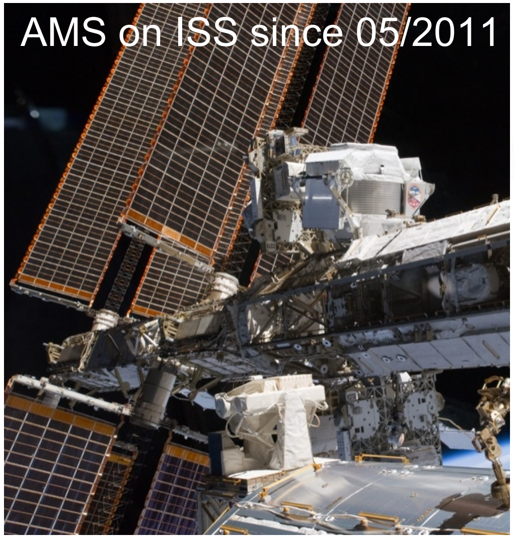
- good background suppression
- long flight time and large acceptance
- small sources of background (high altitudes with balloons in the atmosphere or Space)
- very robust behavior (shocks up to 10g possible), harsh environment

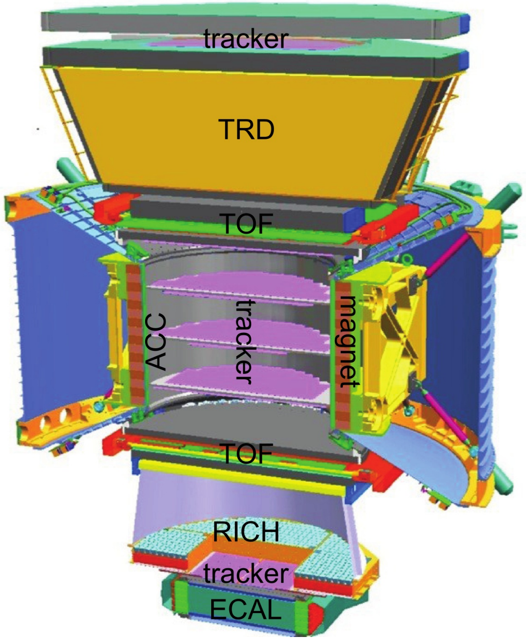


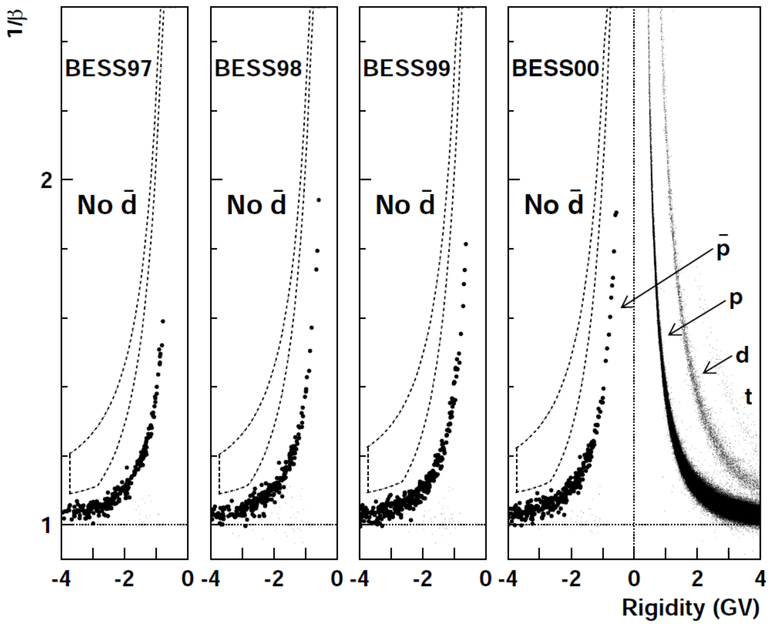
BESS & AMS-02 antideuterons

- BESS and AMS-02 use magnetometers for the antideuteron measurements
- protons are a huge source of background taking the momentum resolution of the tracker into account

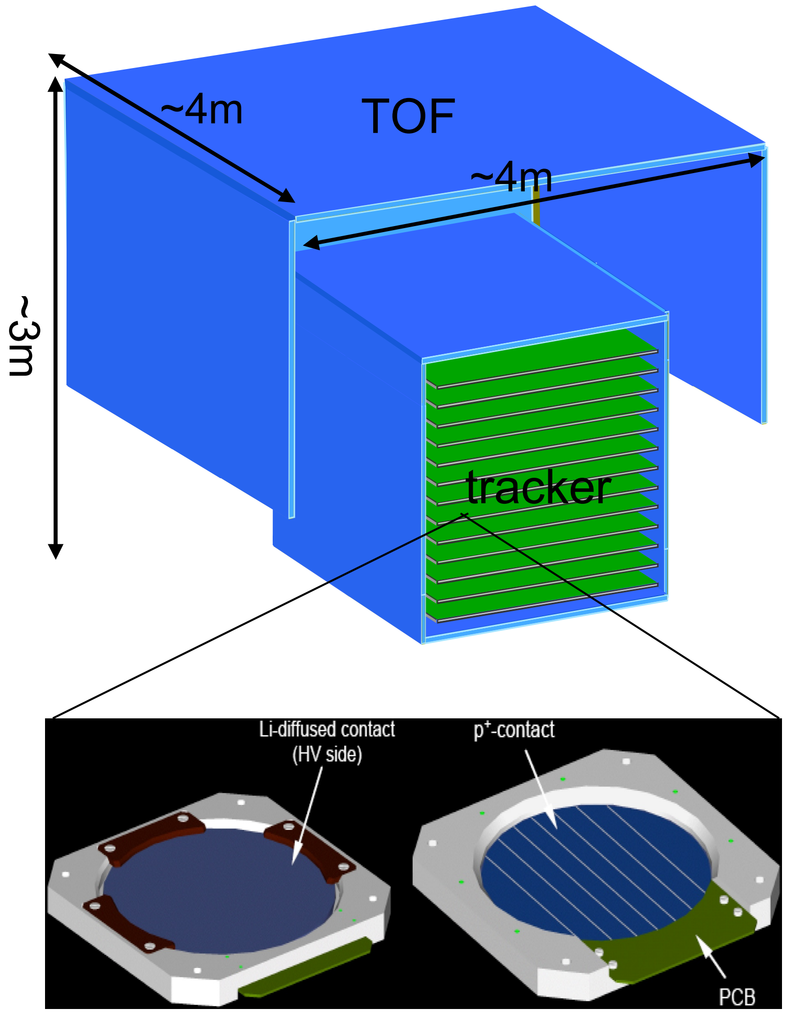








GAPS concept



GAPS consists of two detectors (accep.: ~2.7m²sr):

Si(Li) tracker:

- Si(Li) tracker:13 layers composed of Si(Li) wafers
- relatively low Z material (2/3mm,escape fraction ~20keV)
  → target and detector
- Lithium doped Silicon detectors for a good x-ray resolution
- circular modules segmented into 8 strips, ~8cm² each
  → 3D particle tracking
- 270 per layer (total: ~3500)
- timing: ~50ns
- dual channel electronics
  5-200keV: X-rays (resolution:~2 keV)
  0.1-200MeV: charged particle

Time of flight and anticoincidence shield:

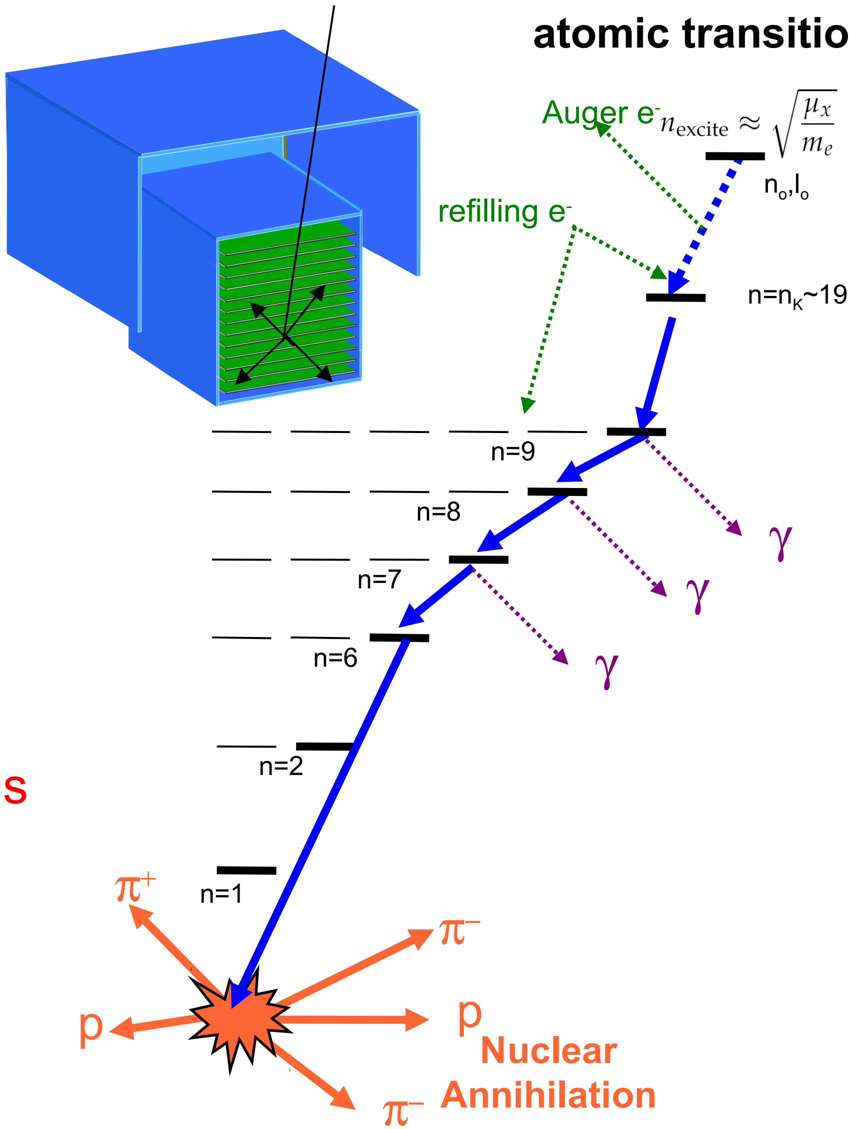
- plastic scintillator with PMTs surrounds tracker
- track charged particles
- velocity and charge measurement

Scientific balloon flights (bGAPS) planned from Antarctica in 2016

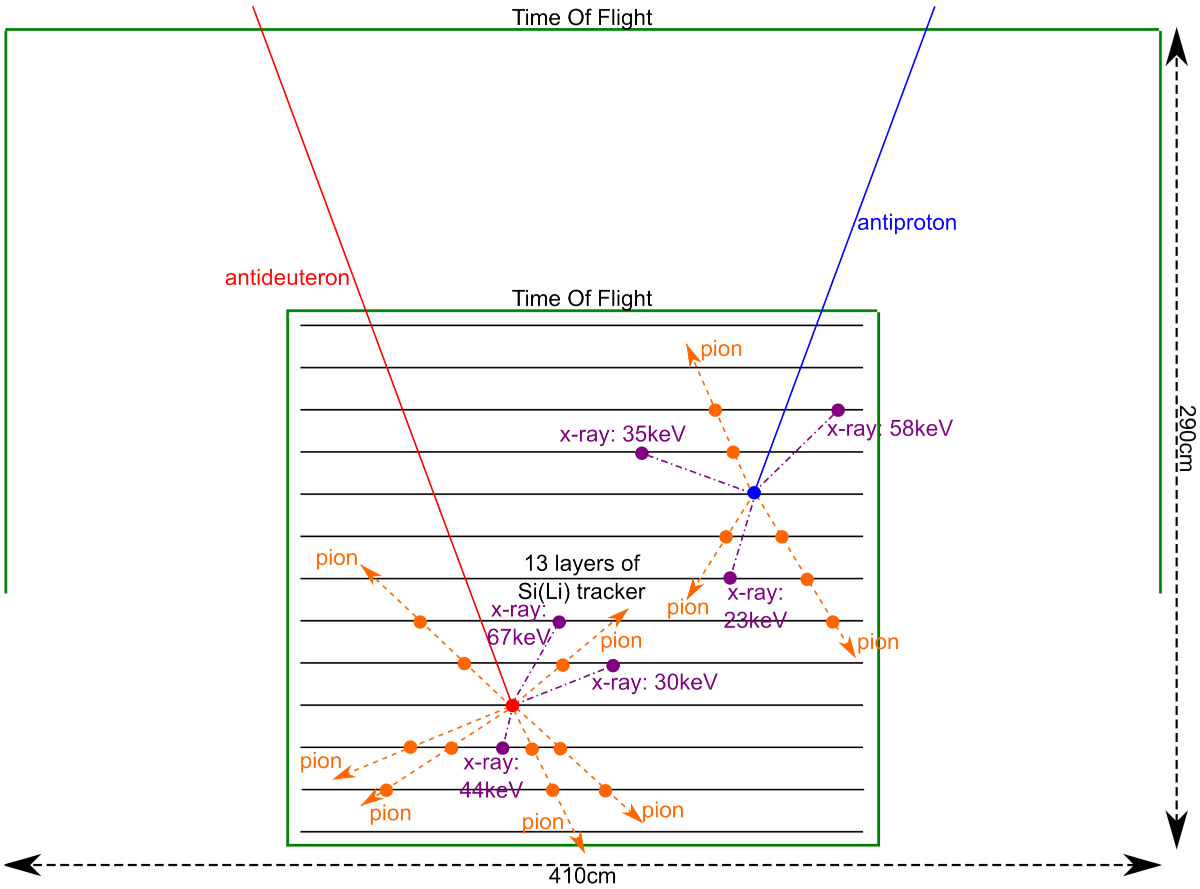
Antideuteron identification

- 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)

atomic transitions



Backgrounds

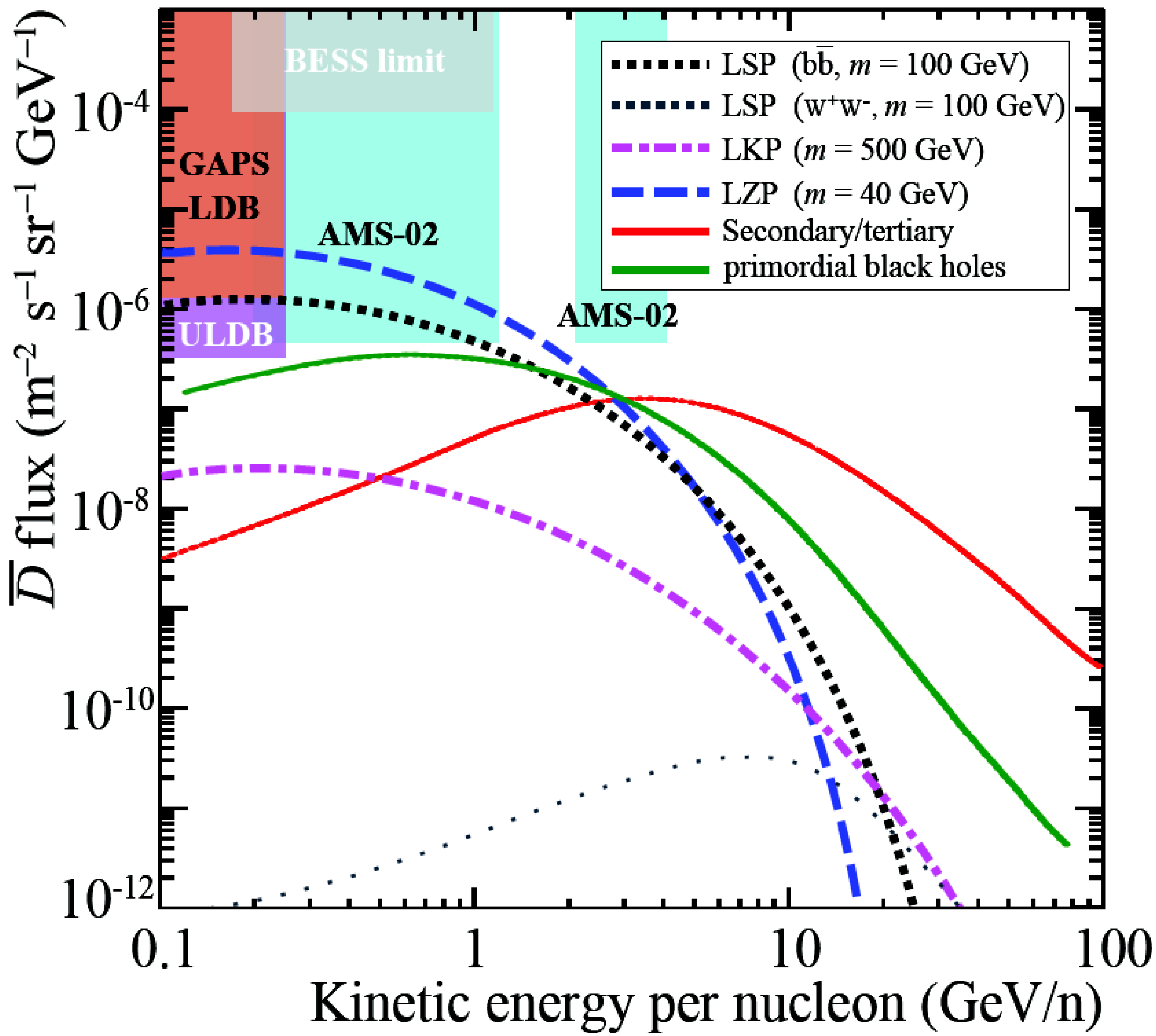


GAPS needs a very reliable particle identification:

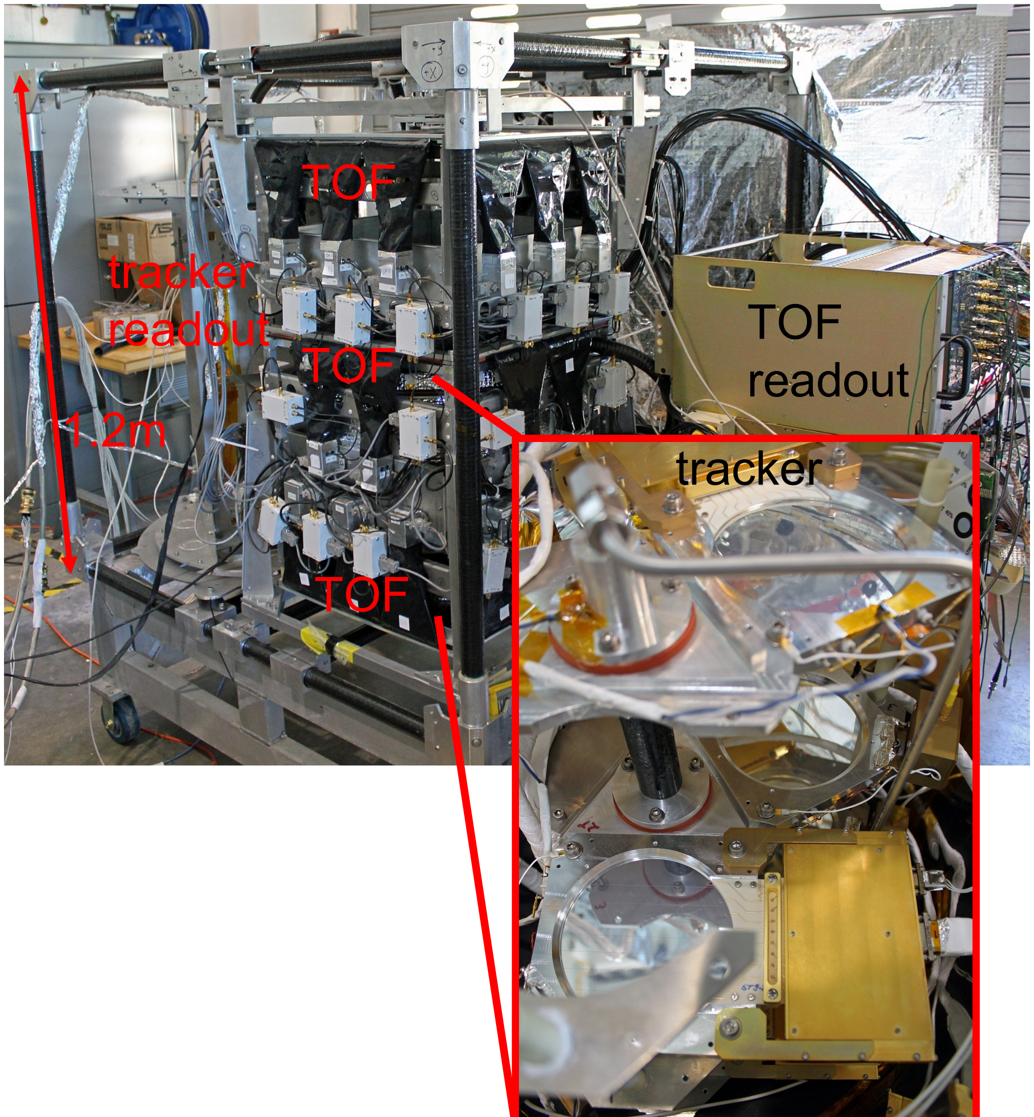
- identification uses:
  - TOF velocity and tracks
  - charge |Z|
  - depth in tracker
  - x-rays from deexcitation
  - pions and protons from annihilation
- important background sources for antideuteron events:
  - antiprotons
  - primary cosmic rays in coincidence with cosmic x-rays
  - atmospheric production of antideuterons
  - etc...needs to studied in great detail

GAPS antideuteron sensitivity

- GAPS need 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
  - Kaluza-Klein UED
  - Warped extra dimensions
  - primordial black holes
- synergy with direct searches and neutrino telescopes: **GAPS probes complementary dark matter regions!**



Prototype experiment

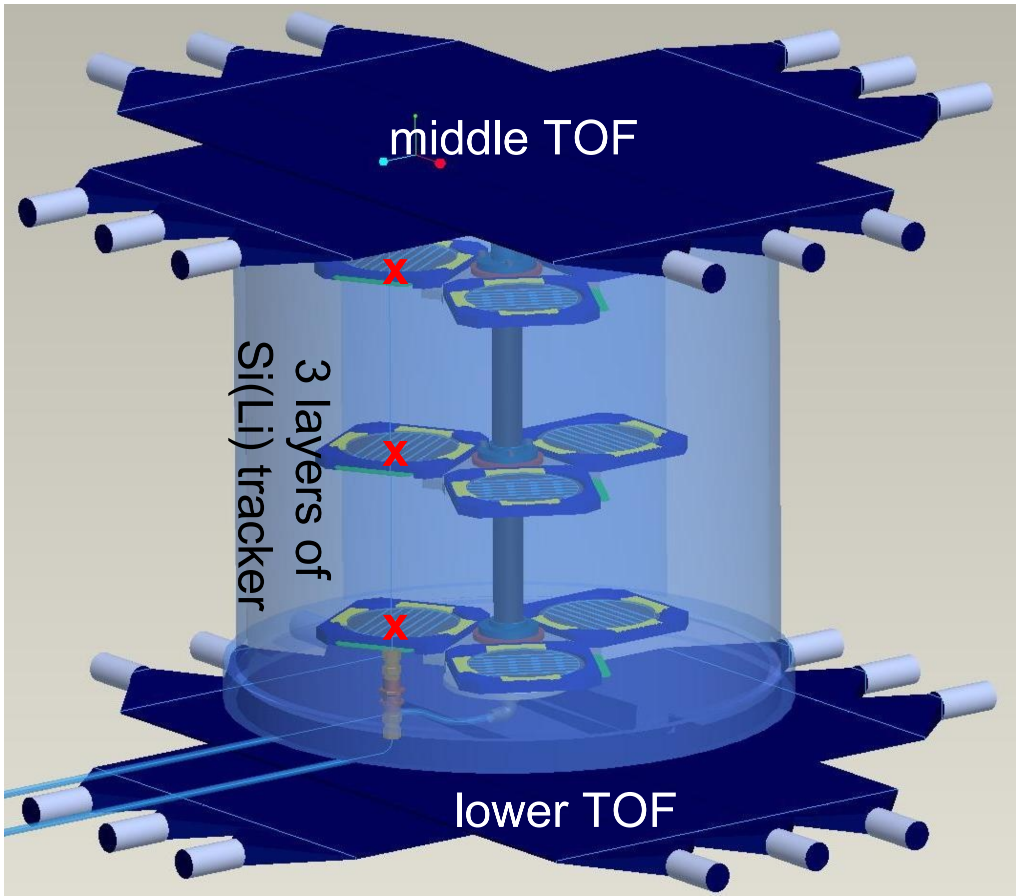


Prototype GAPS (pGAPS) goals:

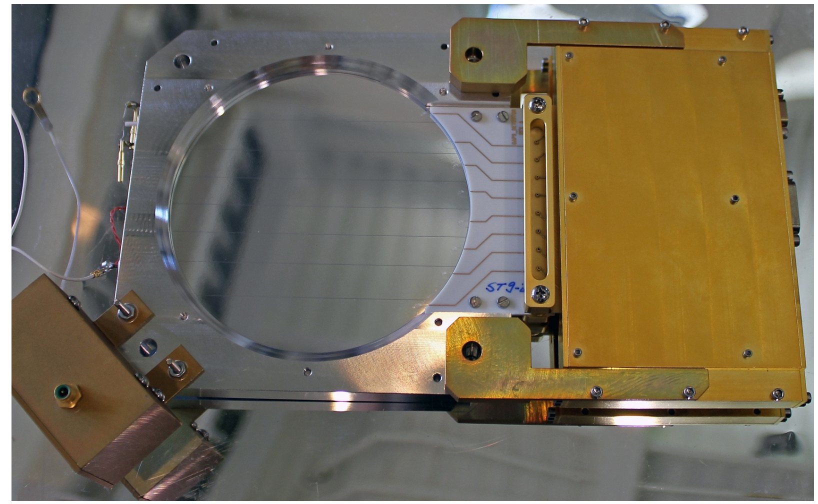
- demonstrate stable, low noise operation of the detector components at float altitude and ambient pressure.
- demonstrate the Si(Li) cooling approach and verify thermal model
- measure incoherent background level in a flight like configuration.

2012 flight from Taiki, Japan

Si(Li) tracker

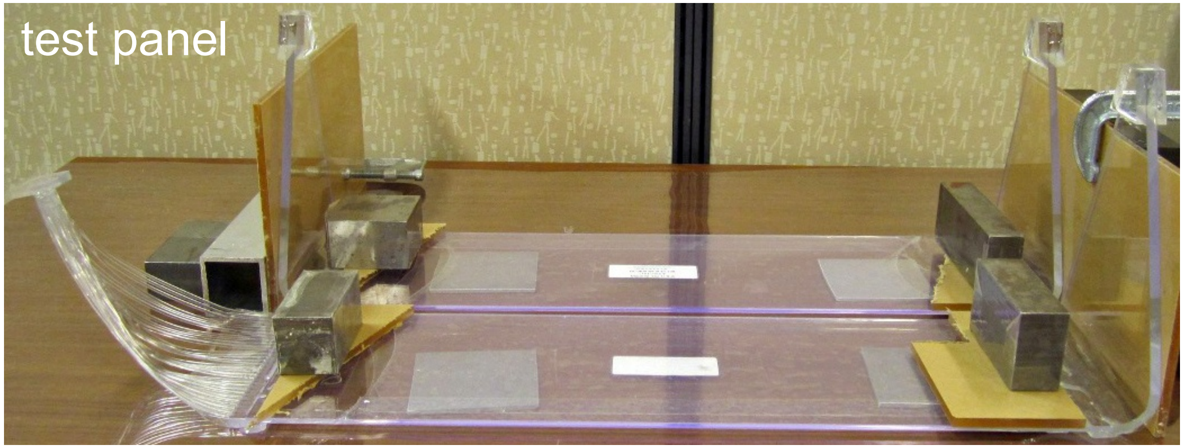


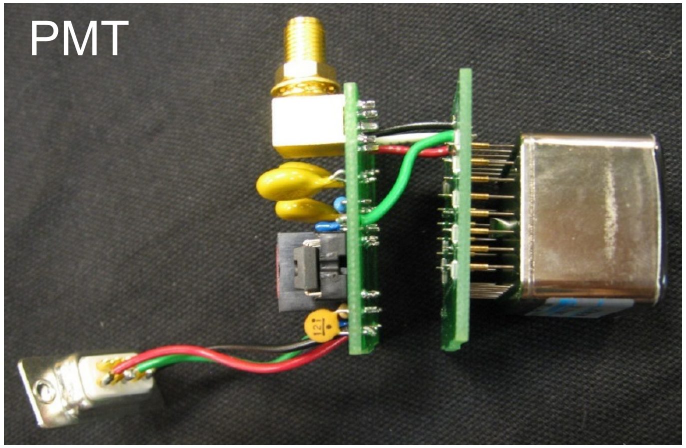
- closed-loop fluid pumping system (Fluorinert)
- space radiator



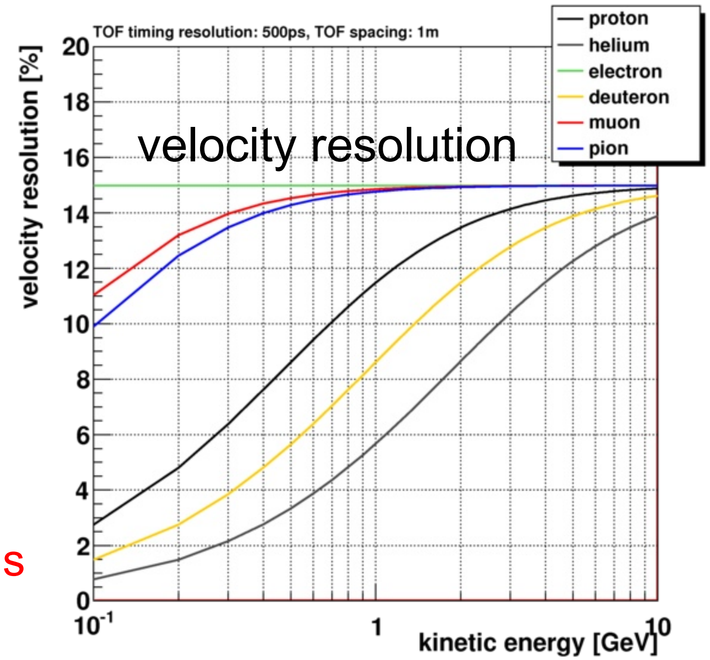
- 6 commercial Semikon detectors (5 currently installed)
- 94mm diameter and 4mm/2.5mm thick, 8 strips
- operation at ambient pressure during flight (8mbar) and in N_2 atmosphere on ground
- cooling system has to deliver ~-35°C
- N+: Lithium contact
- P+: Boron implanted (strips)

Time of flight system

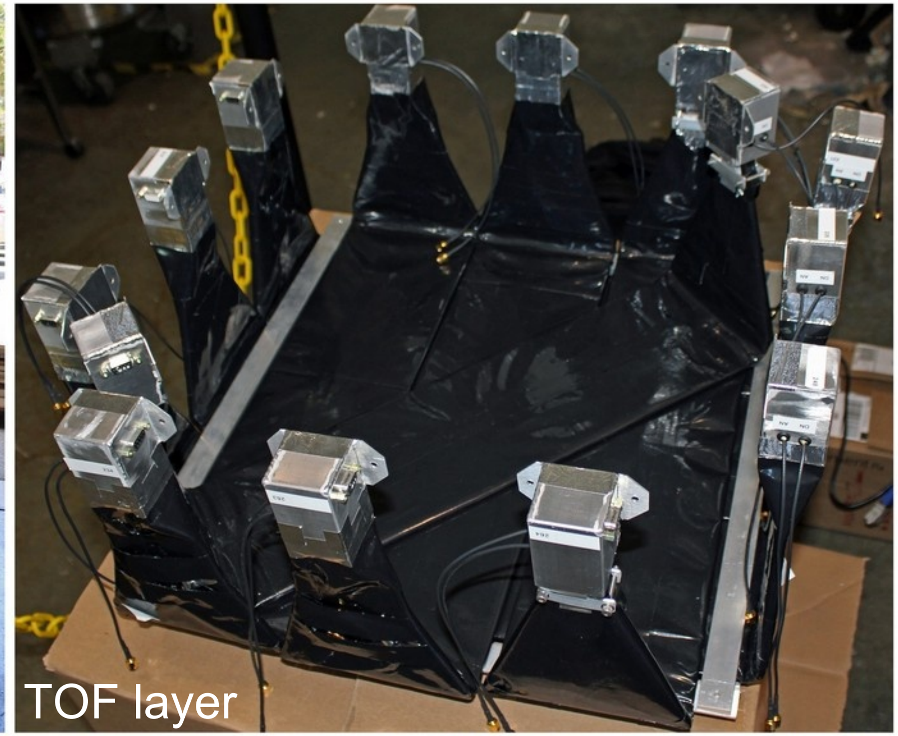




- 3 planes of TOF
  1 plane consists of 3×3
  (2×2 in the middle) crossed panels
  1 panel has 2 PMTs
  = 16 panels and 32 PMTs
- 3mm scintillator from Bicron (BC-408)
- Hamamatsu R-7600 PMT
- timing resolution: 500ps
- charge resolution: 0.35e
- MOP value: ~15 photo electrons
- angular resolution: 8°



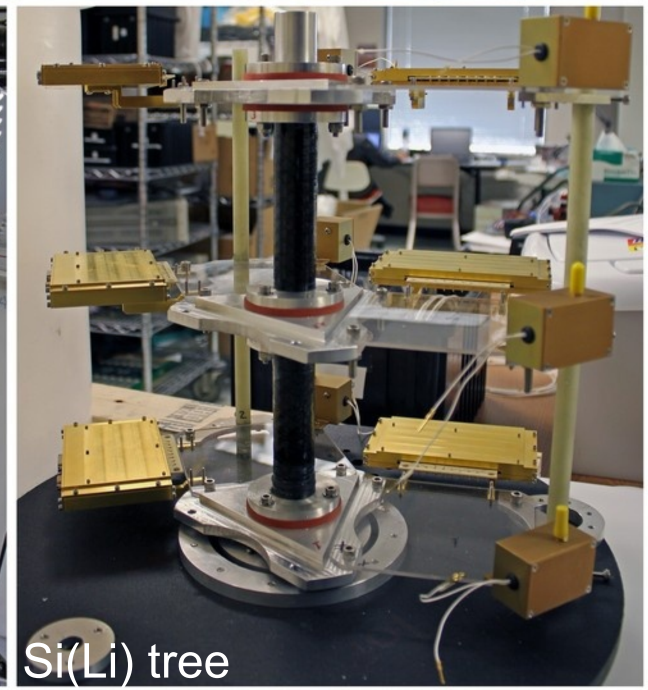
putting the gondola together



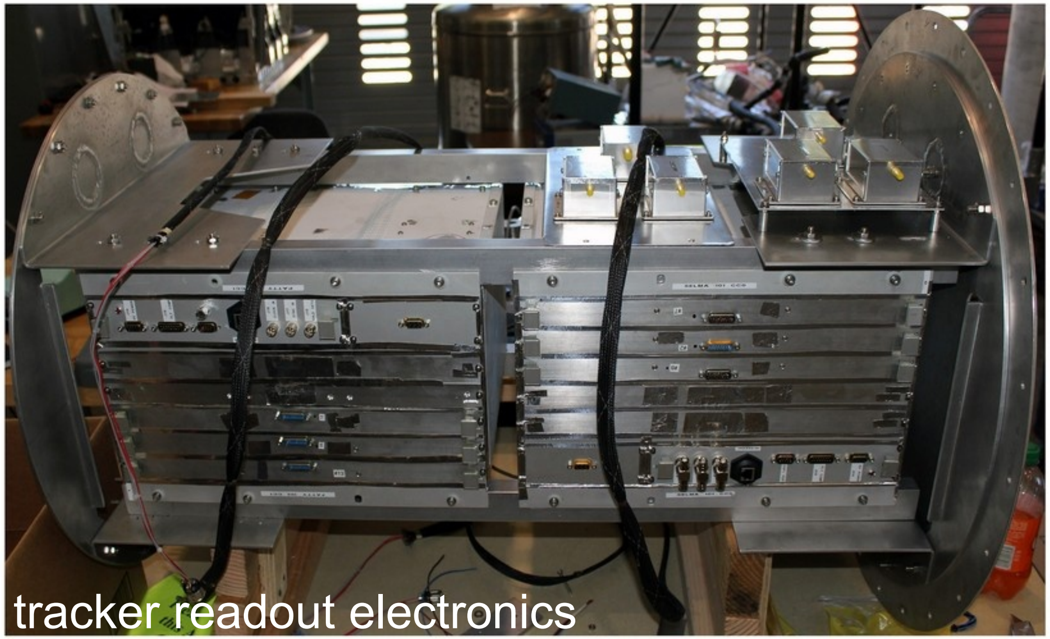
TOF layer

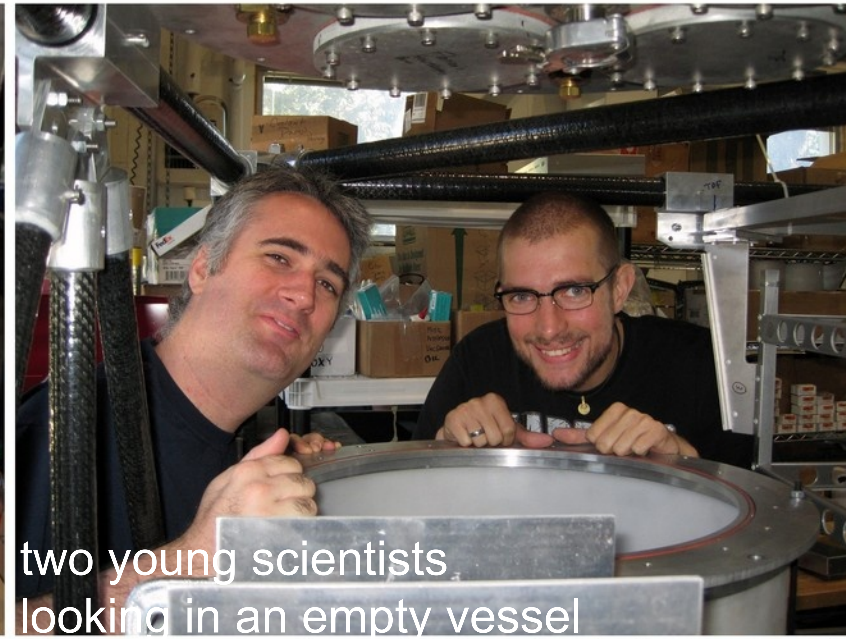
mockup boxes and pressure vessel

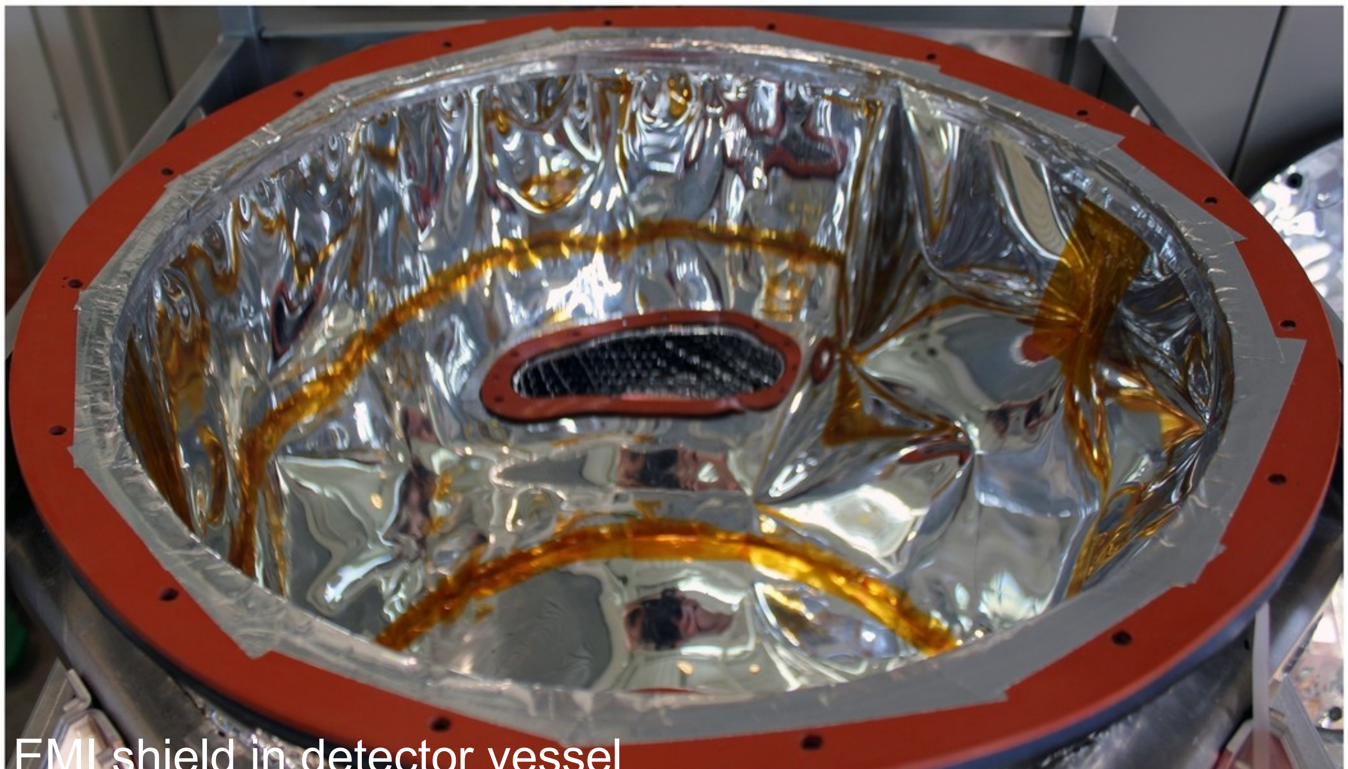
detector structure



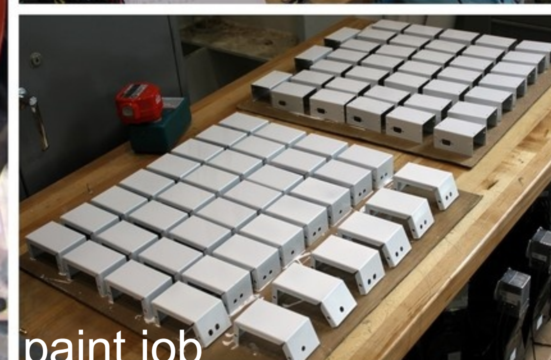
Si(Li) tree

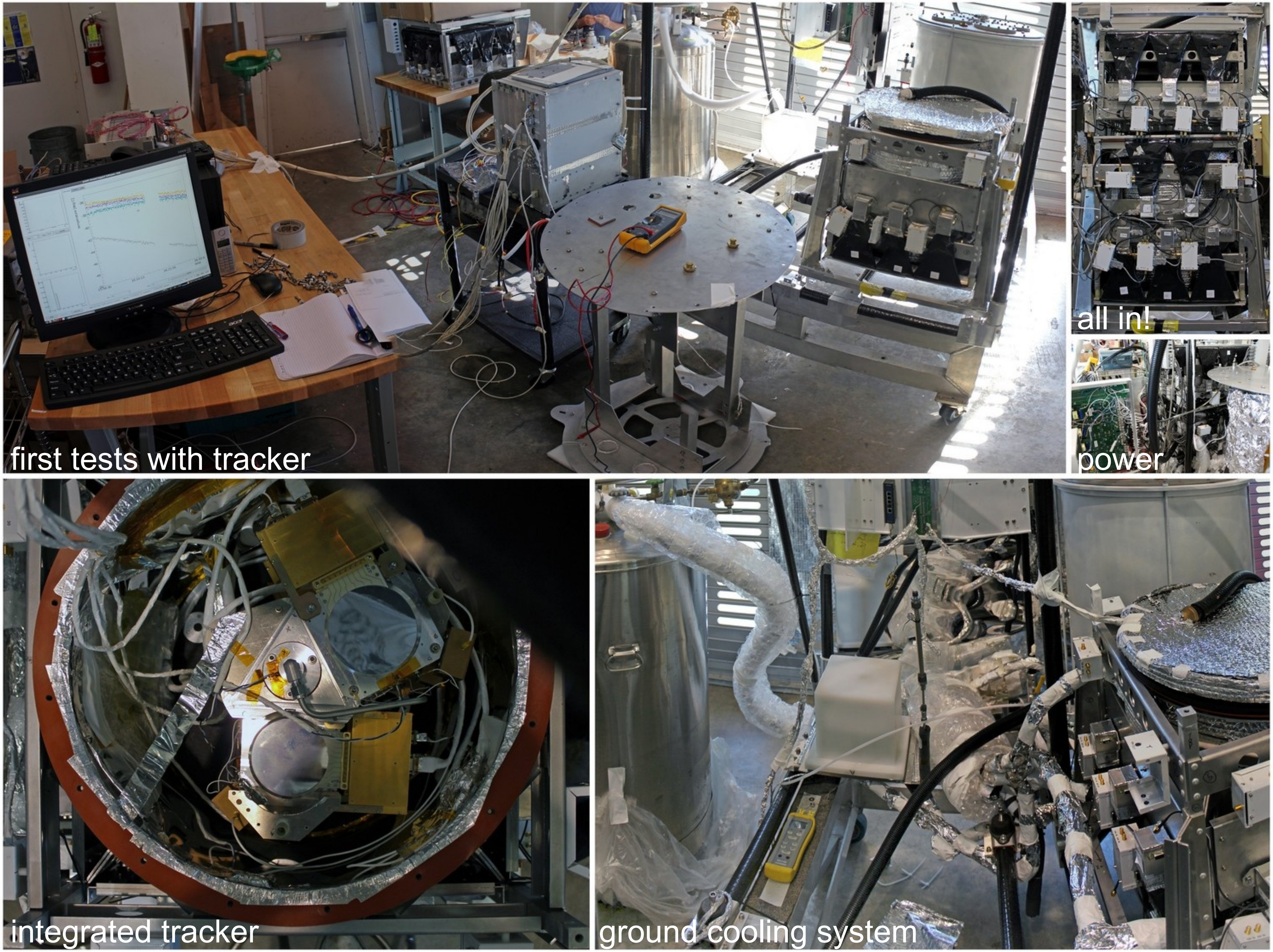

tracker readout electronics


two young scientists
looking in an empty vessel

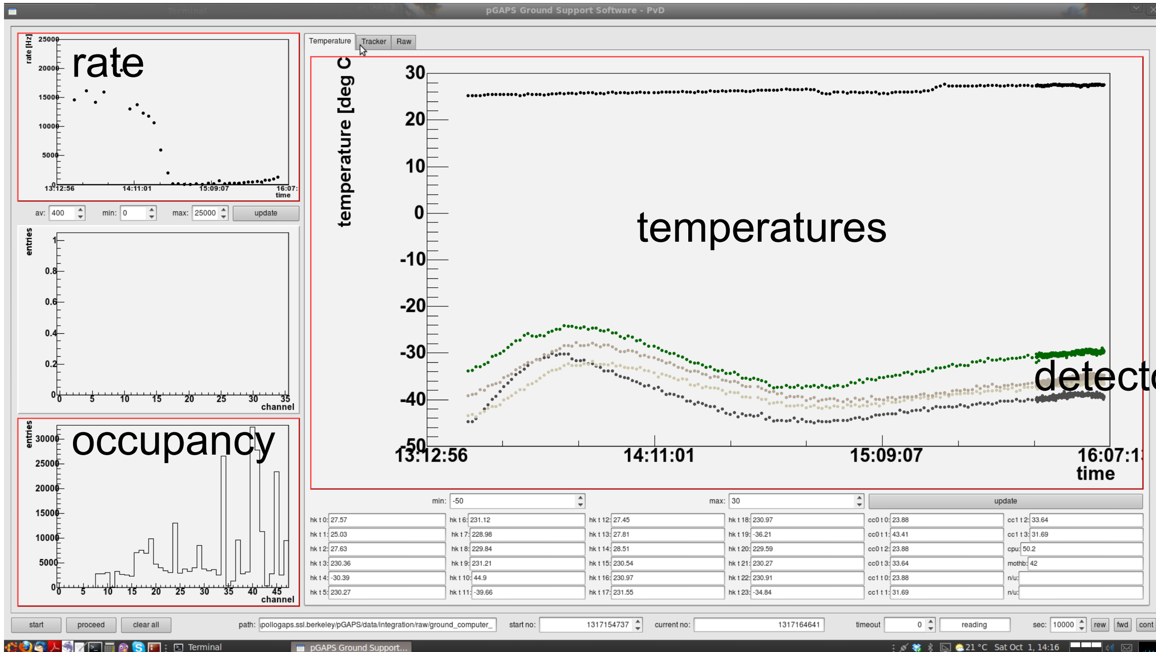

EMI shield in detector vessel

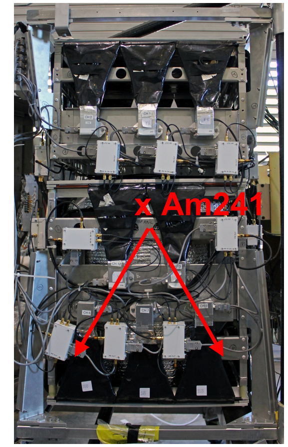

soldering job


paint job

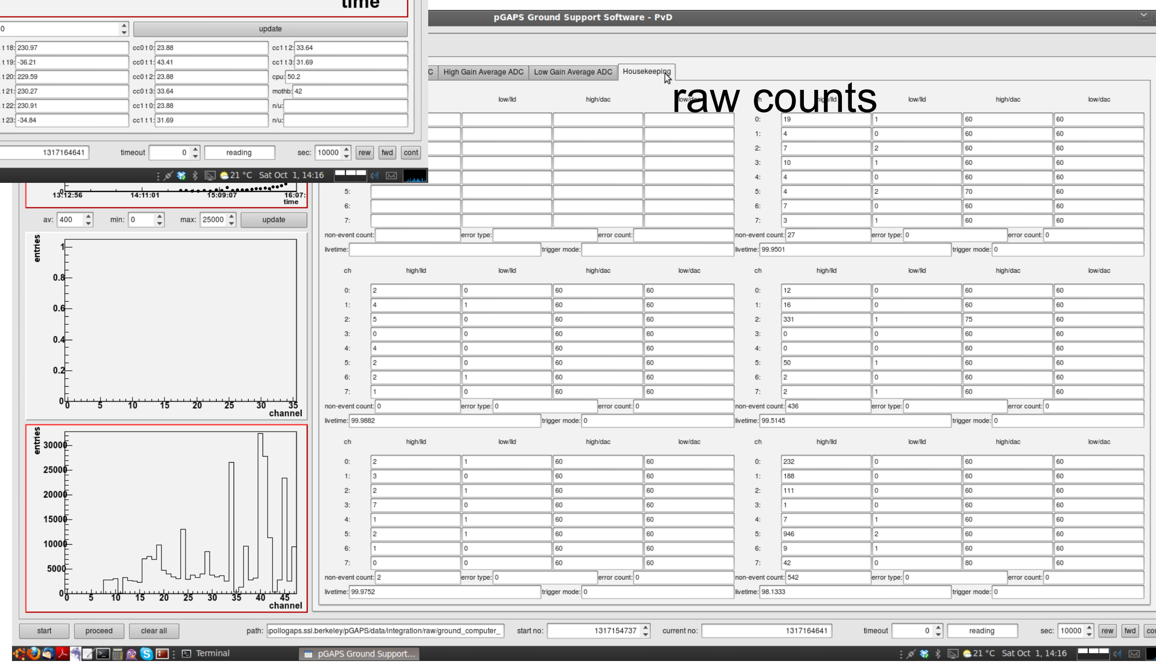

first tests with tracker
all in!
power
integrated tracker
ground cooling system

Tracker testing





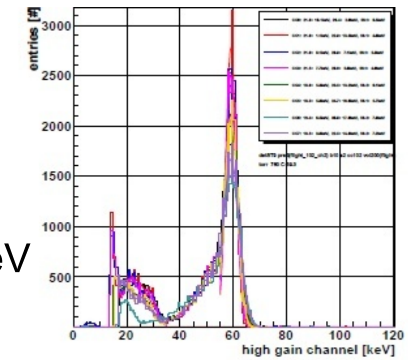
- ground cooling is getting the detector vessel down to -40C in about 1-2h
- high gain tracker channel is tested with X-ray source AM241 (prominent line at 59.5keV)
- low gain channel with atmospheric muons

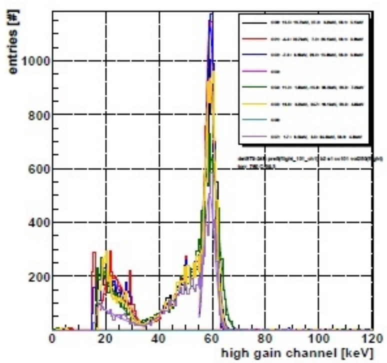


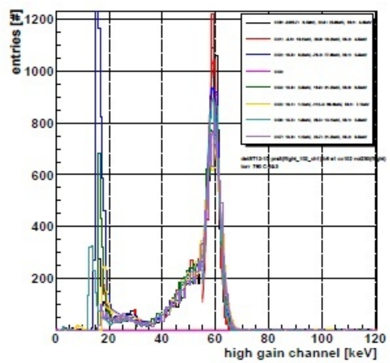
First tracker results

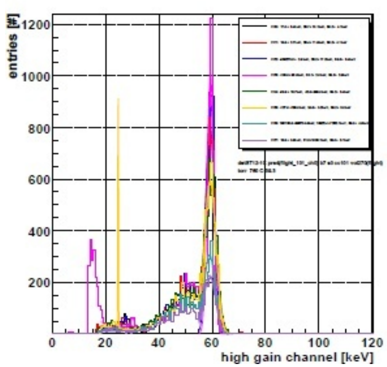
Am241:

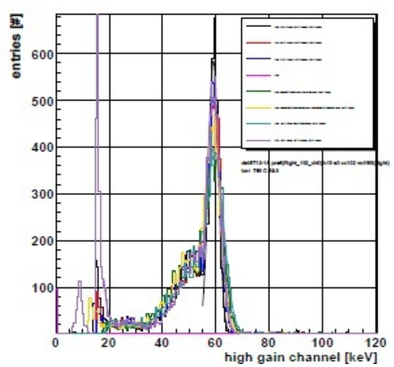
- FWHM of 59.5keV line: (5.6±1.4)keV
- minimum energy: ~15keV





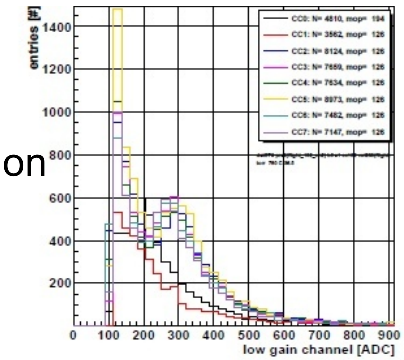


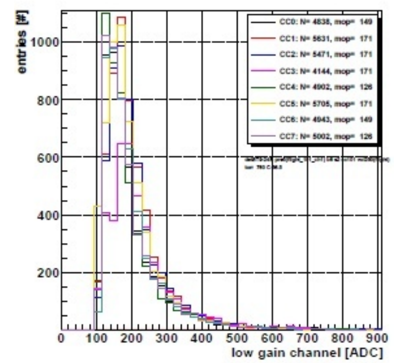


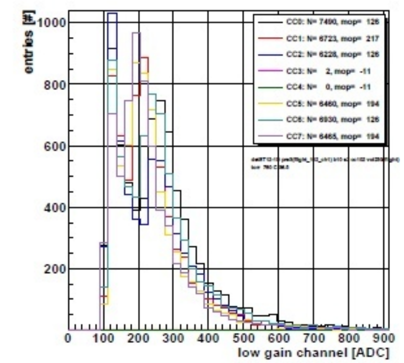


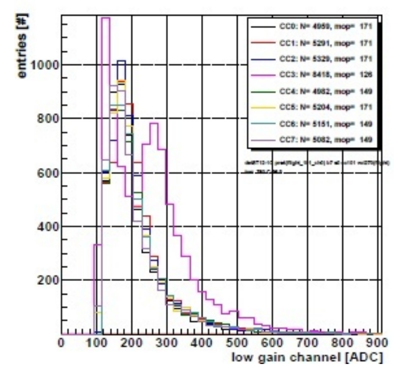
Atmospheric muons:

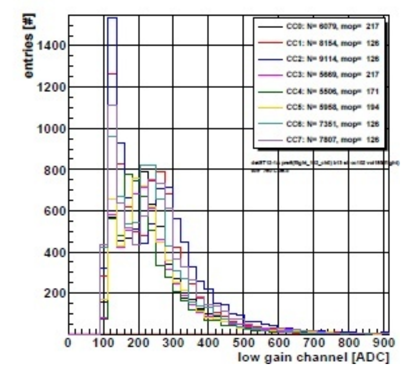
- Landau shape distribution
- MOP value at ~1MeV



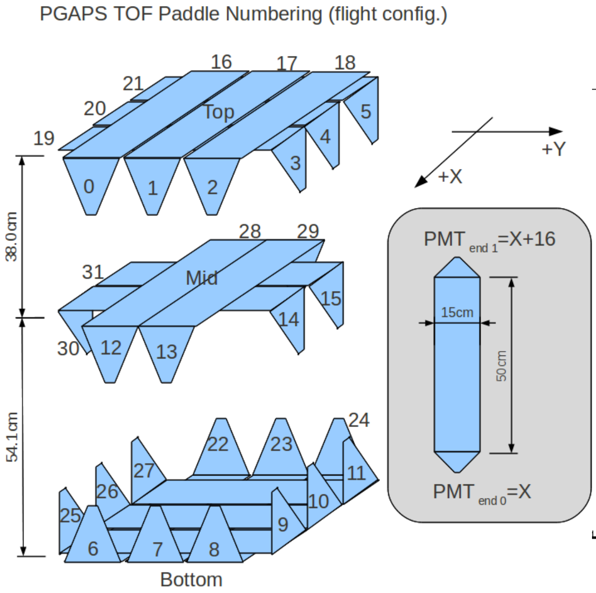


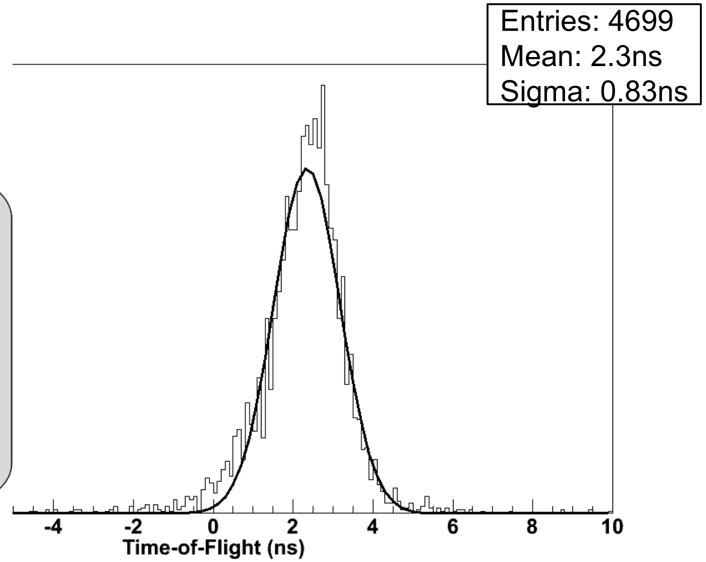


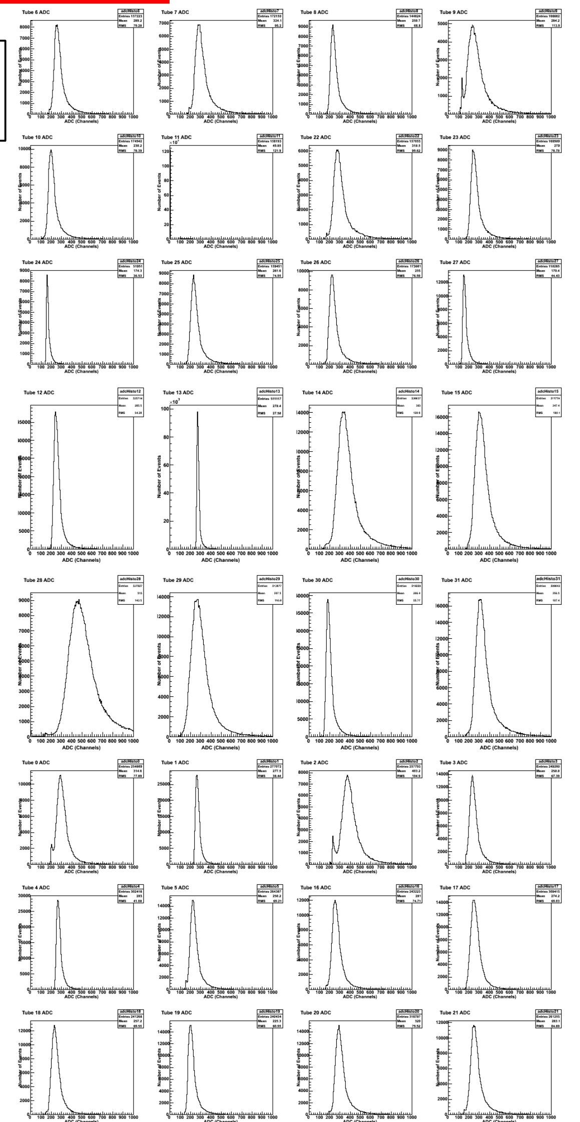




TOF testing



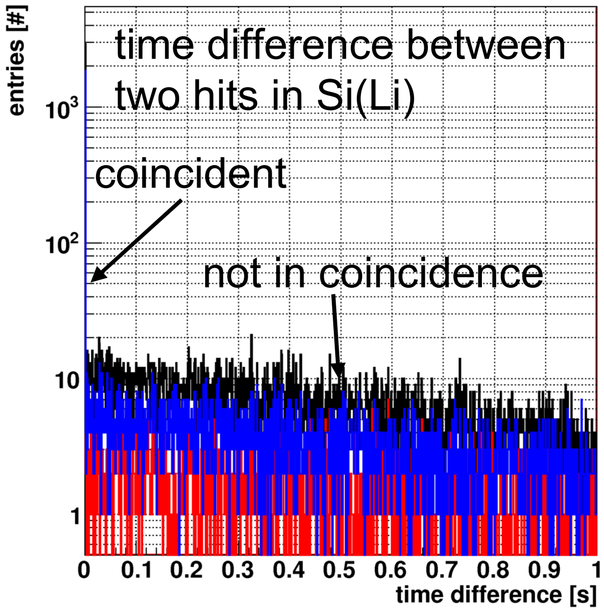


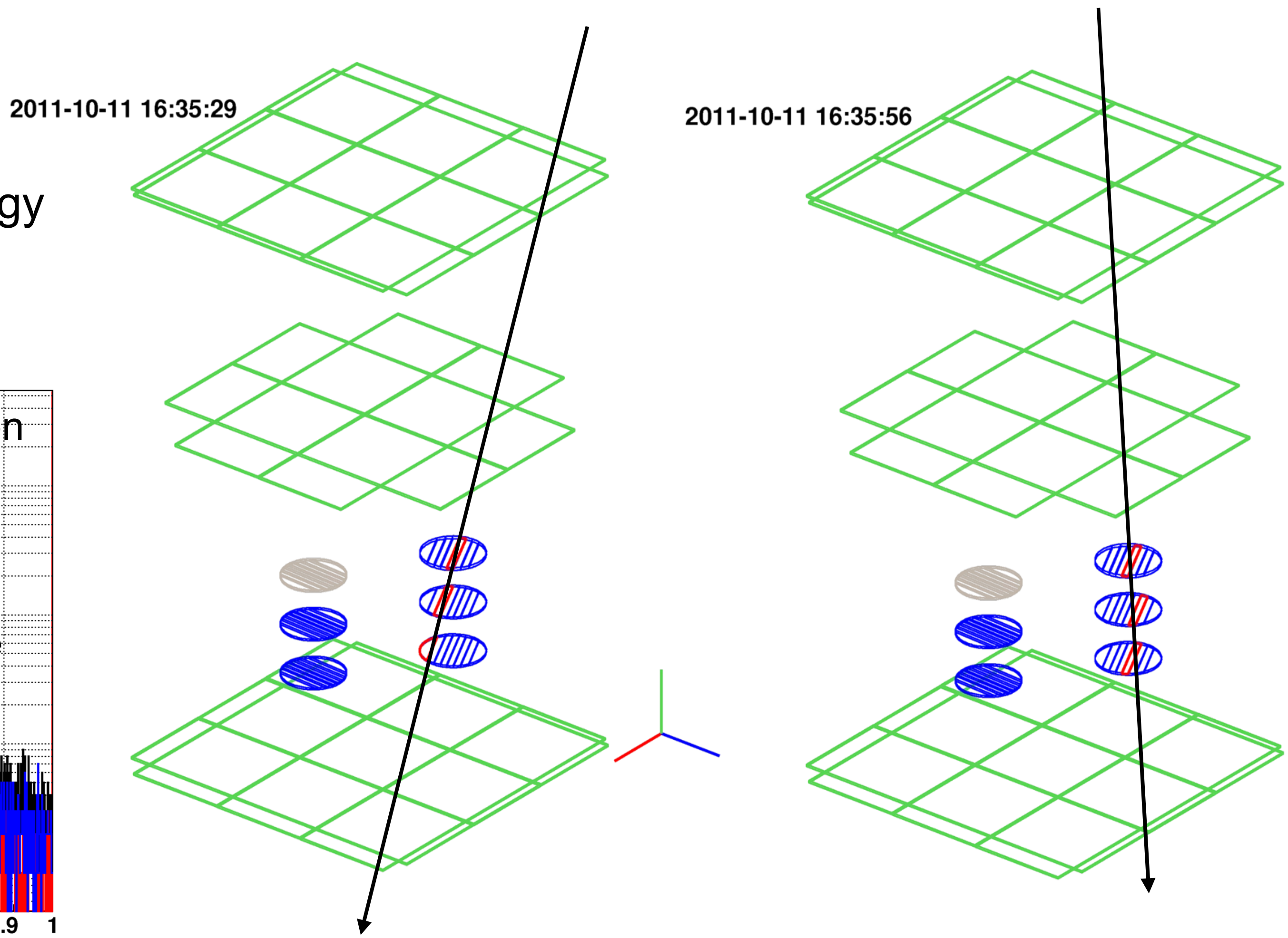


- TOF shows good distributions the energy depositions for each of the 32 tubes
- timing resolution is 590ps per paddle
- tracking resolution of the TOF is of order several cm

First tracks

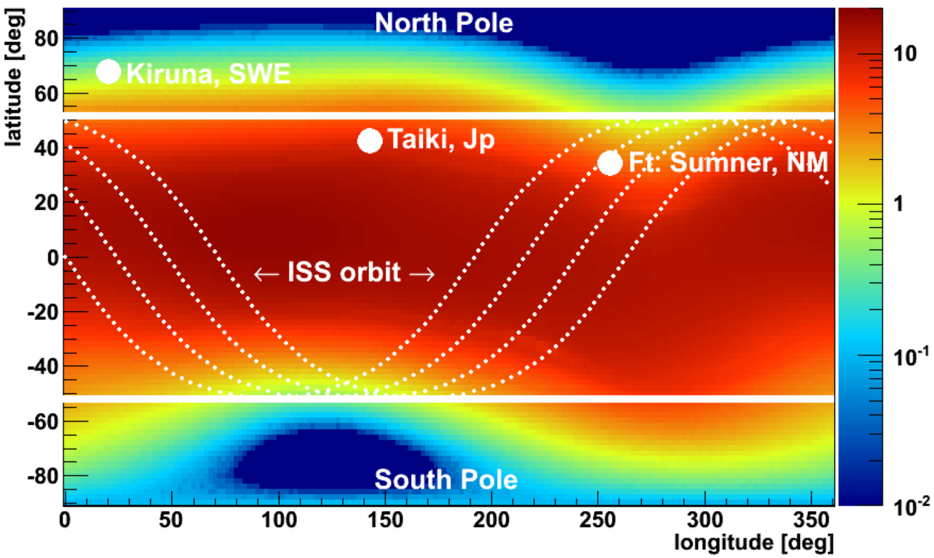
- TOF triggered with (T&&M) | (M&&B) the tracker readout
- nicely coincident energy depositons in Si(Li)

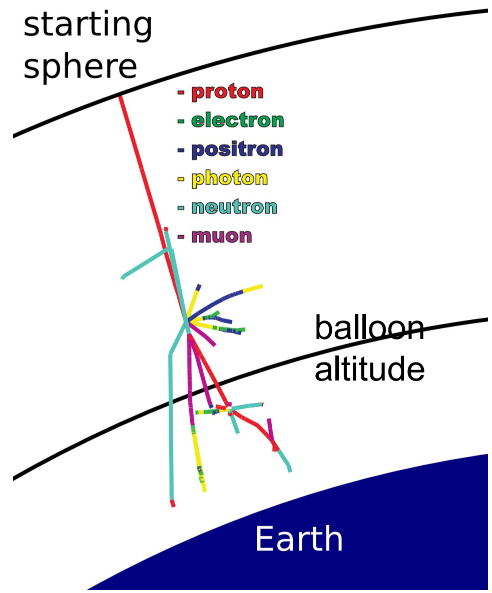


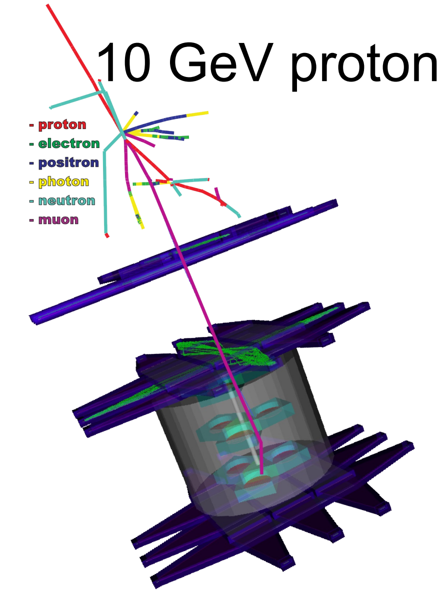


GAPS simulations

cosmic antideuterons	atmospheric simulation	detector simulation	exotic atomic physics

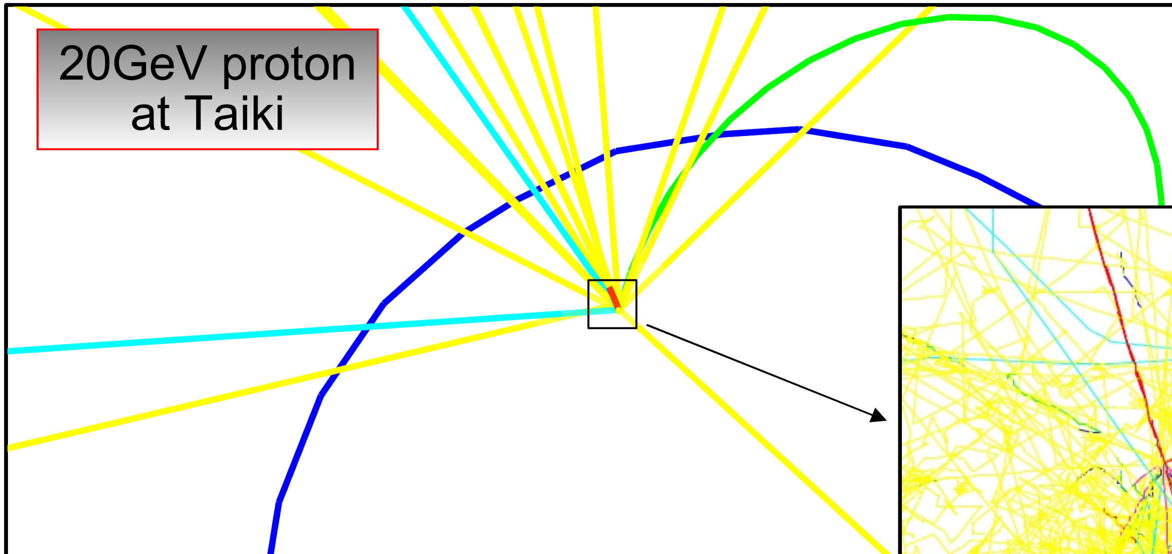




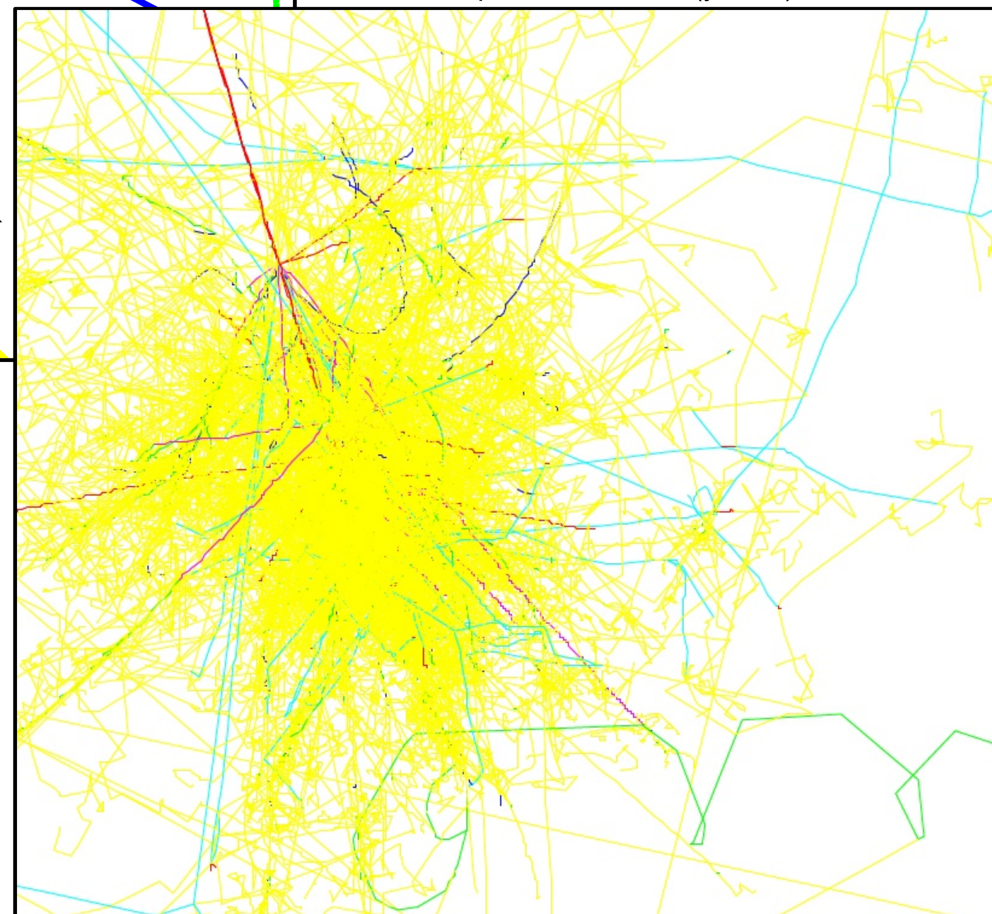


- Atmospheric and geomagnetic simulations with PLANETOCOSMICS based on GEANT4
- Instrument simulation with GEANT, ROOT output format:
  - electromagnetic, hadronic, optical physics are running
  - basic components are implemented, frames and structures must be added
  - ion and exotic physics are under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

Air shower & geomagnetic field

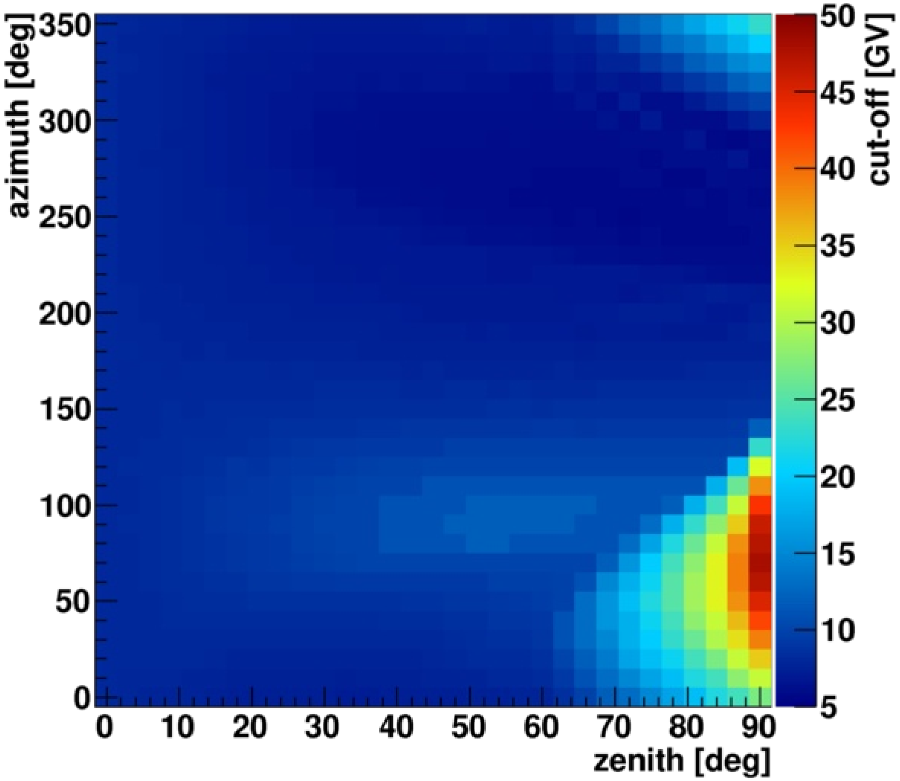


proton > 10MeV (red)
electron > 10MeV (green)
positron > 10MeV (blue)
neutron > 10MeV (turquoise)
muon > 10MeV (purple)
photon > 10keV (yellow)

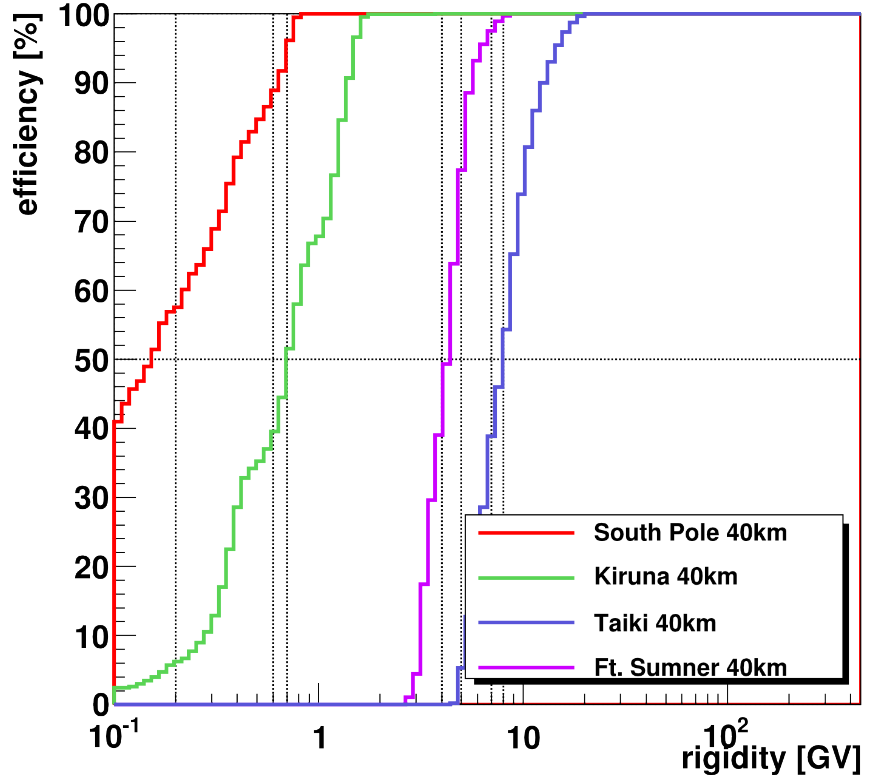


- use of NRLMSISE-00 atmospheric model: models the temperatures and densities of the atmosphere's components.
- grammage of matter in front of 33km: ~8.4g/cm² (Space: 6-10g/cm²)
- on average ~20% of a radiation length (nuclear mean free pathlength ~10%) before 33km: **Atmospheric background has to be calculated!**

Cut-off and particle direction

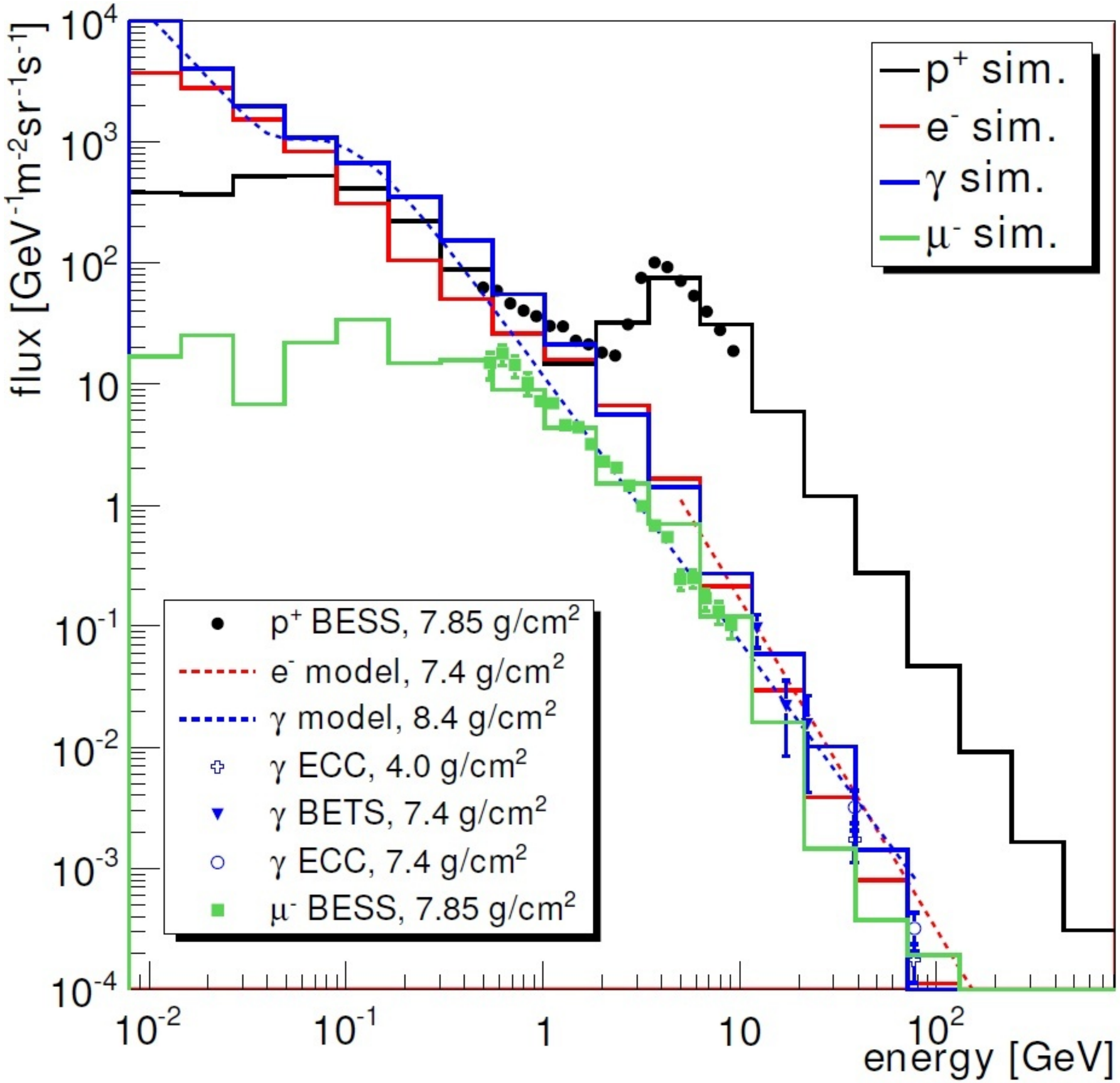


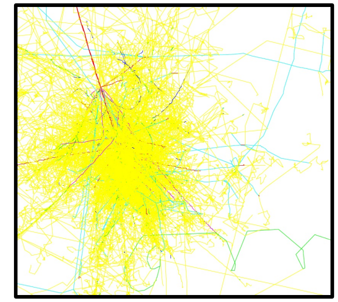
cut-off in Taiki as function of direction



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

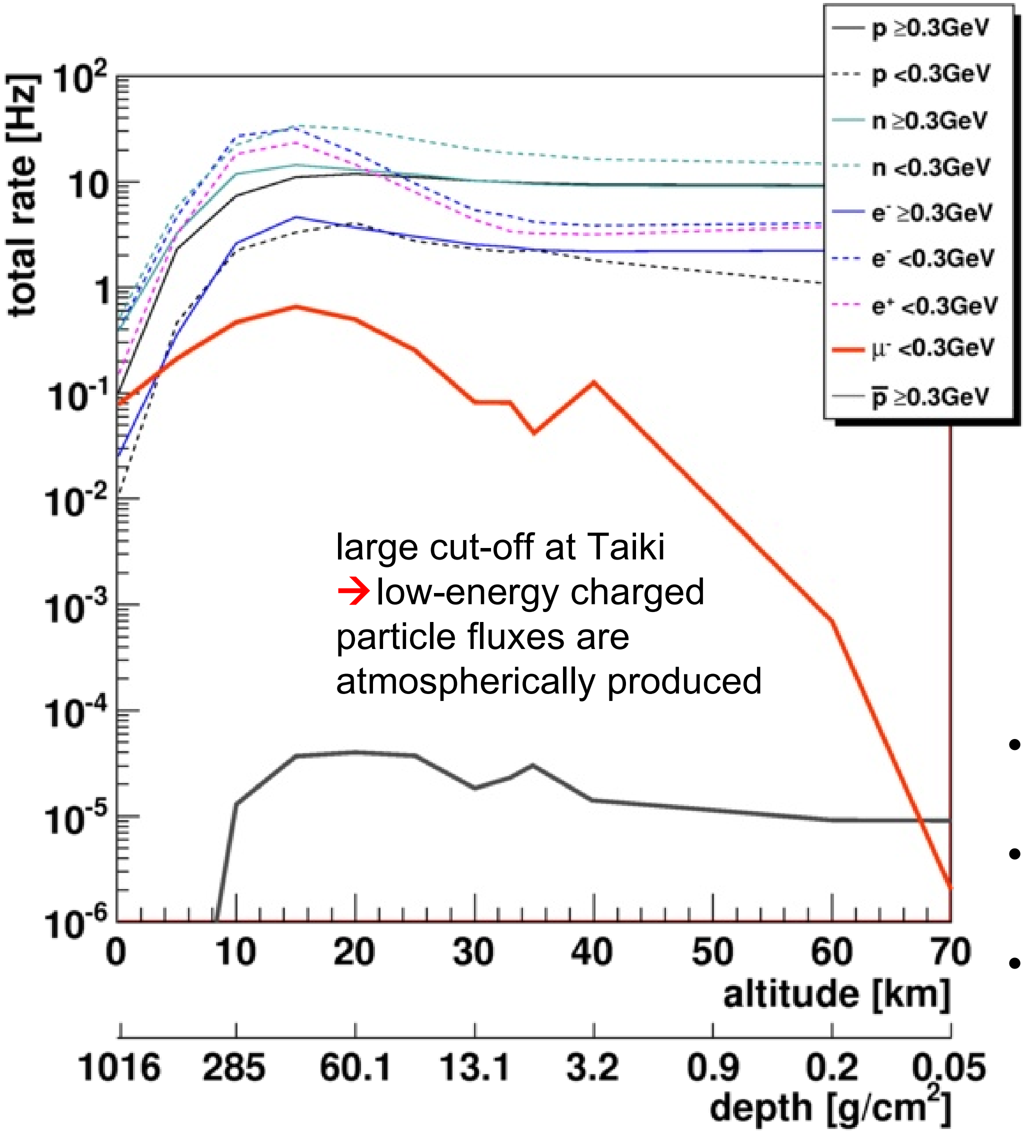
Validation of air shower simulations

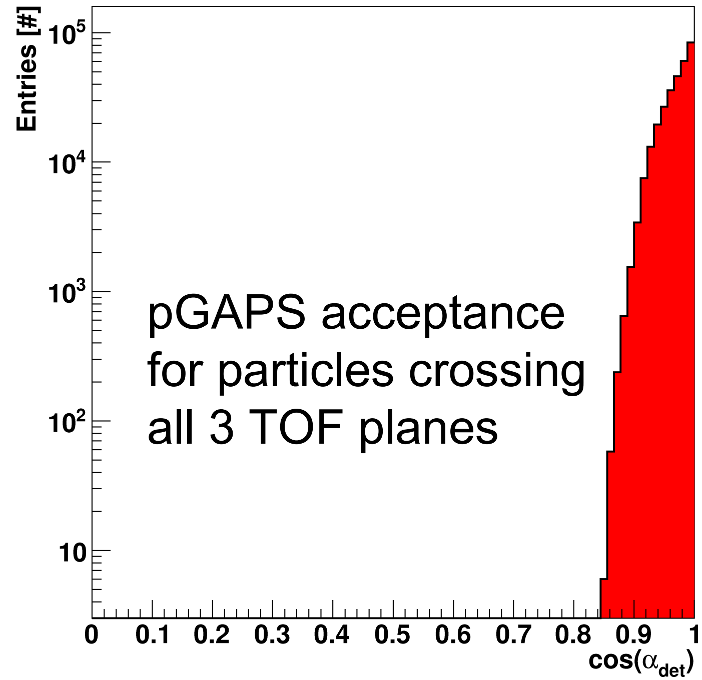




- particle fluxes (ATM+CR) for certain particle types at different altitudes
- comparison of atmospheric simulations shows **good agreement** with BESS, ECC, BETS, PPB-BETS, CAPRICE measurements and models

Particle rates for pGAPS



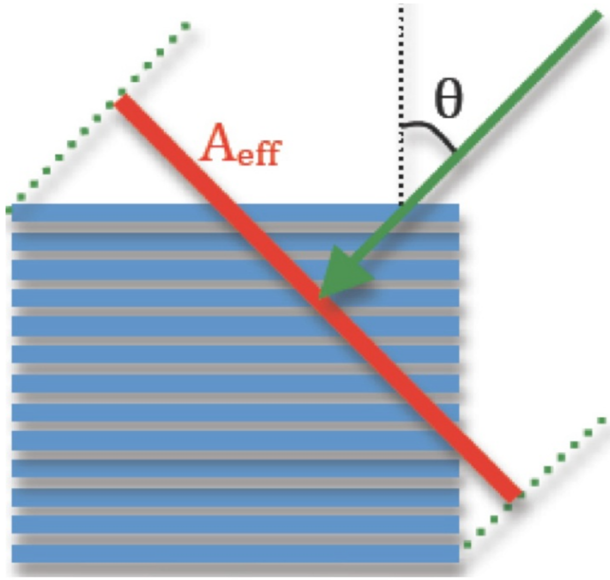


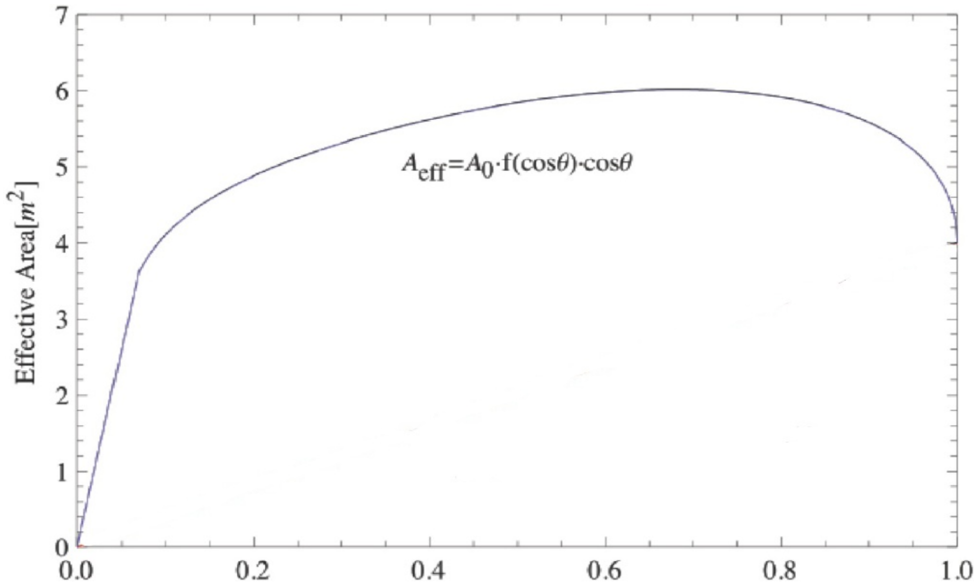
- particle rate at 33km at Taiki: **total ~30Hz** (accep.: $0.054 m^2 sr$)
- strongest backgrounds by neutrons, protons, electrons, positrons
- no antiprotons will be measured, but muons might be used to create muonic atoms to study exotic physics at flight

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
- prototype experiment is currently under test and a flight is planned for spring 2012 from Taiki, Japan

Sensitivity calculation





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

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

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

- 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)

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

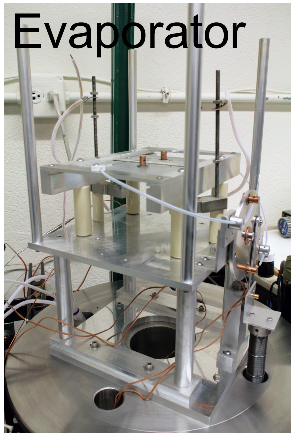
$$\mu_x = \frac{m_x \cdot m_N}{m_x + m_N} \quad \wedge \quad \mu_e = \frac{m_e \cdot m_N}{m_e + m_N}$$

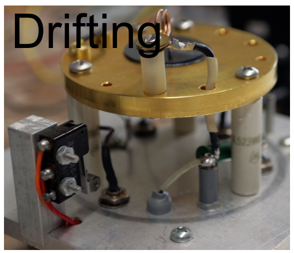
- hadron models for annihilation for antiprotons (fireball, INC):
  pions: ~5.1 (3.1 charged)
  proton: ~1
- antideuteron (no data): models estimate roughly double hadron yield

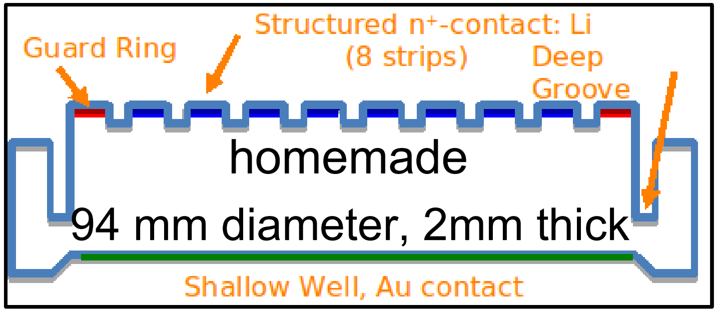
Expected background for a 300 day flight

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







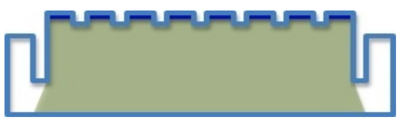
N+: Lithium contact (strips)
Au contact with shallow well

1. Cut from the ingot

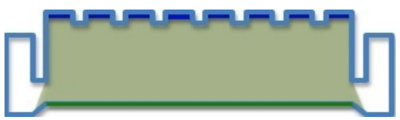
2. Evaporate Lithium

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