General AntiParticle Spectrometer (GAPS)

Hunt for dark matter using low energy antideuterons

Identification of Dark Matter, July 2012

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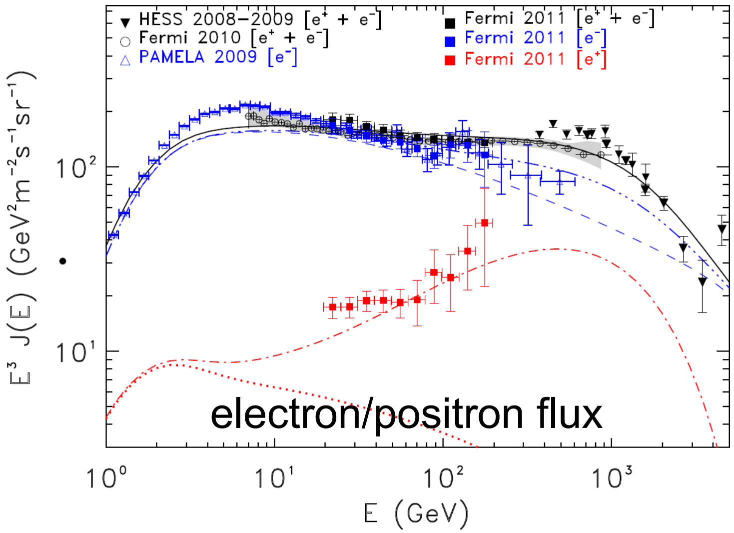
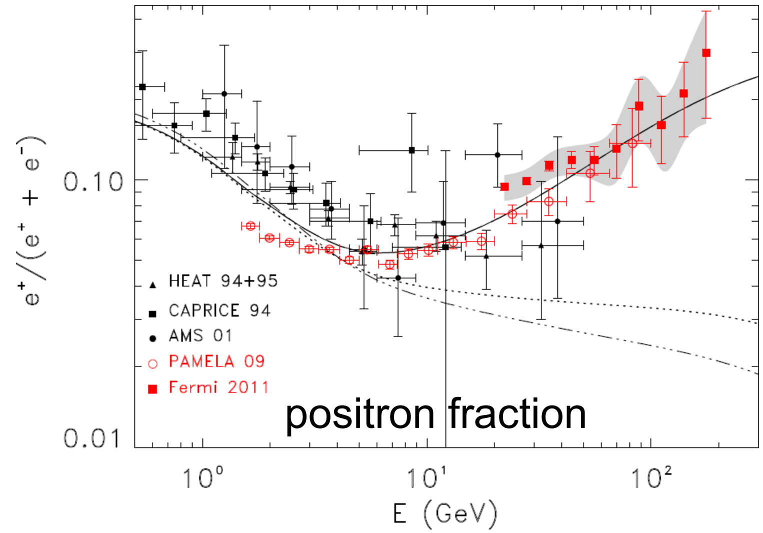
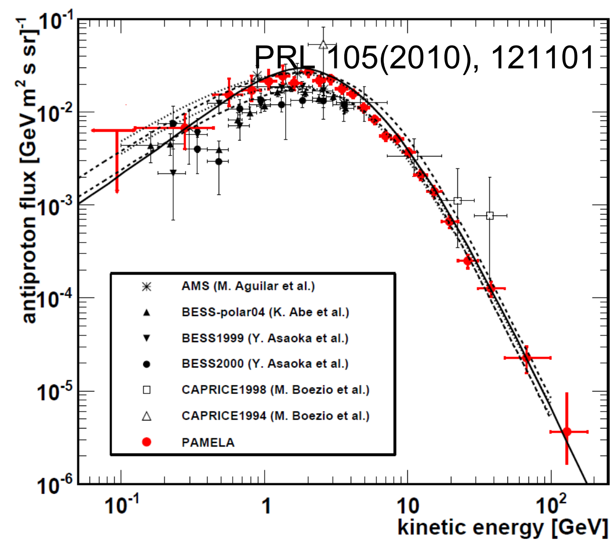
Indirect dark matter search





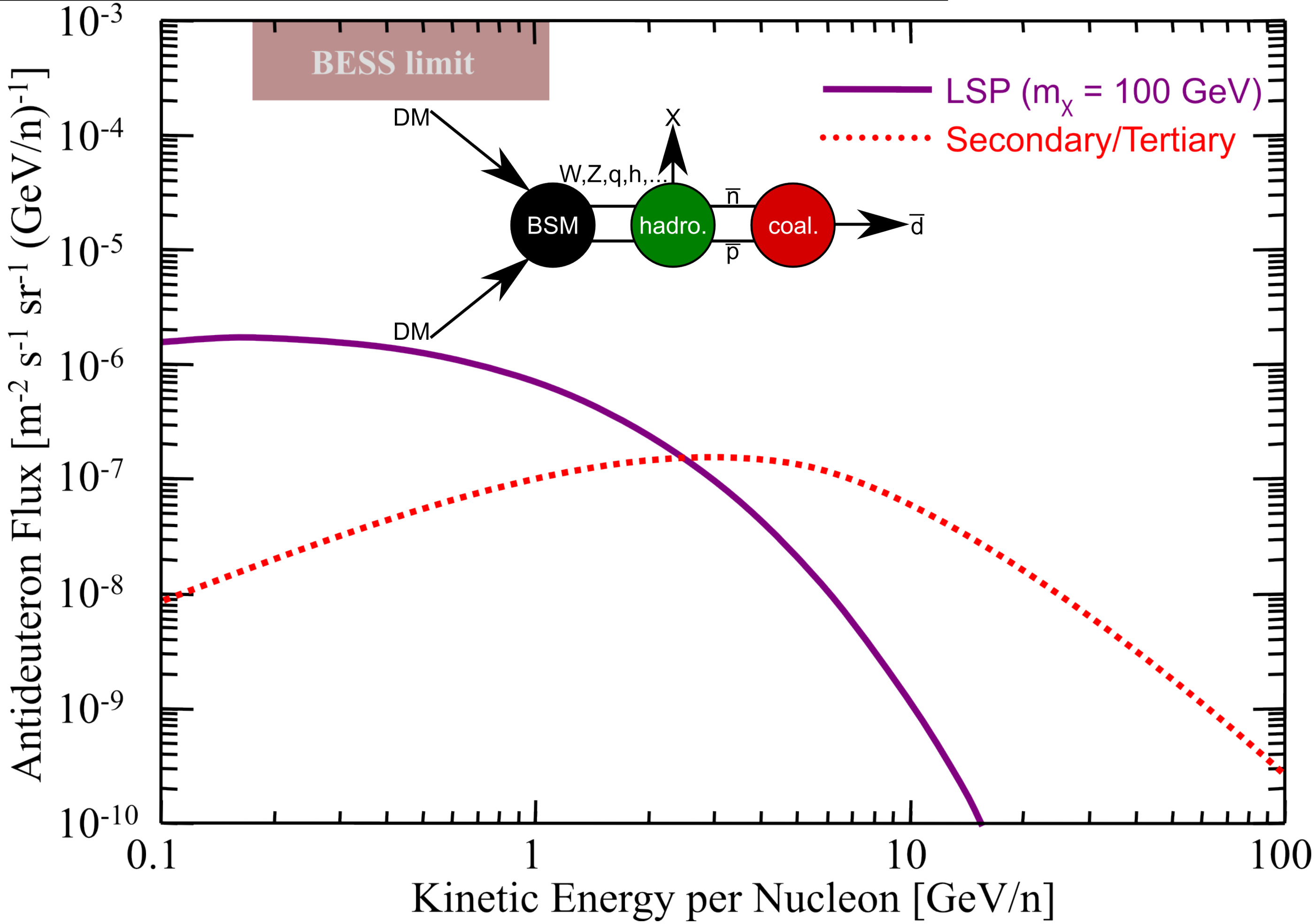
arXiv:1110.6626

- **unexplained features** in positron and electron spectra, but not in antiprotons
- **proposed theories**: γ-ray pulsars, **dark matter self-annihilation**, ...
- **open questions:**
  - –Are pulsars able to produce enough electrons and positrons?
  - –observed deviations are small/boosting mechanisms are needed
  - –Are the experimental data well understood (large rejections)?
  - –Why do antiprotons show no deviation?



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

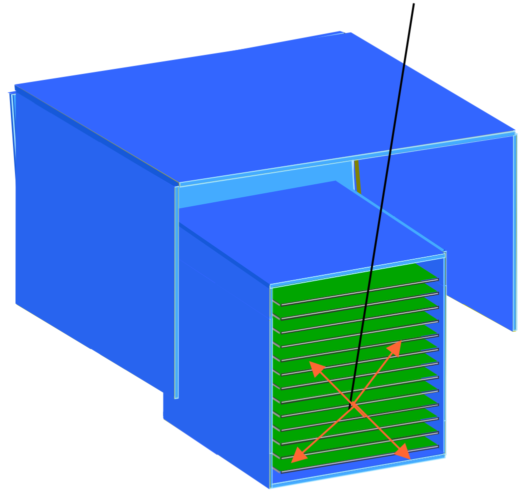
Antideuterons and dark matter



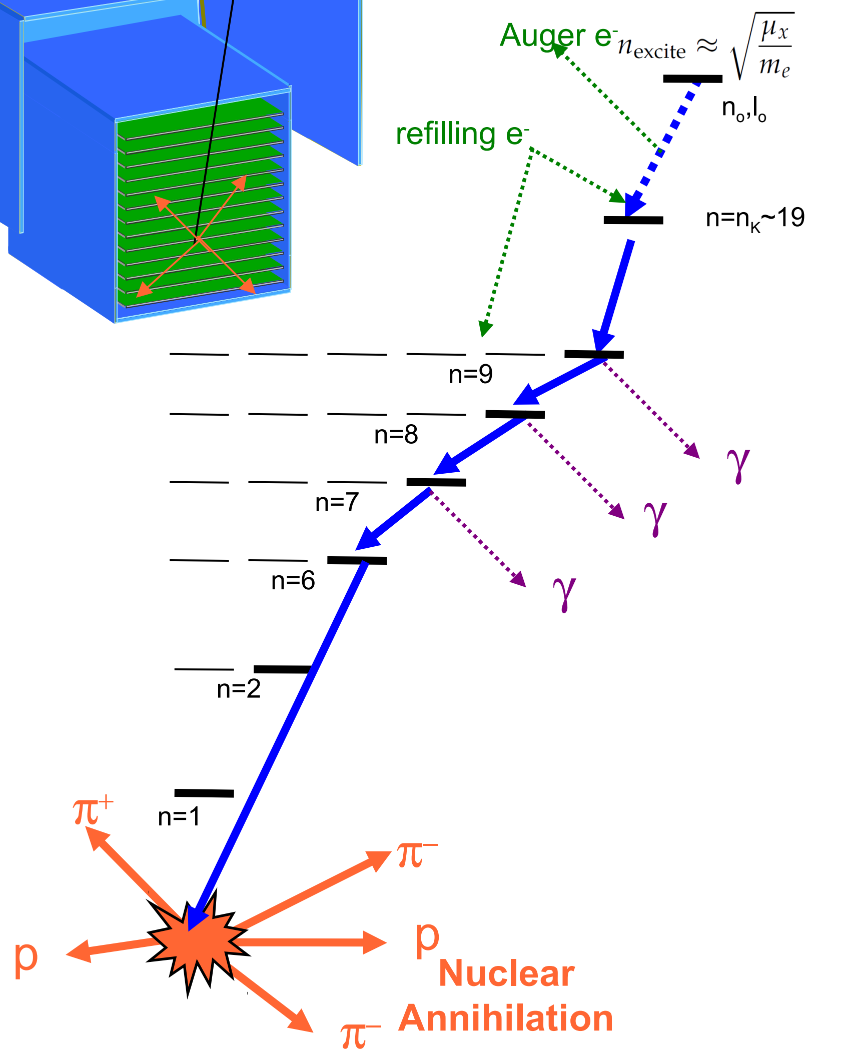
- antideuterons have high production threshold for p-ISM
- **large signal over background for low-energy antideuterons predicted**

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

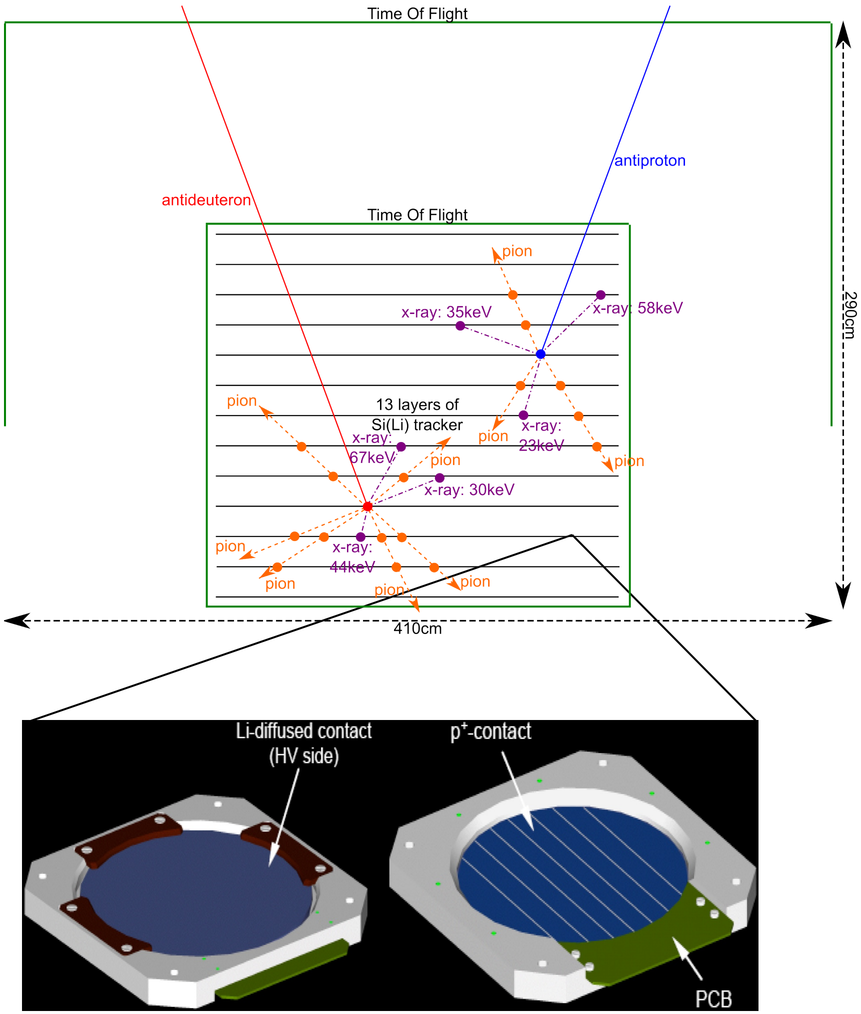
Antideuteron identification



- antideuteron slows down and stops in material
- large chance for creation of an excited exotic atom (E_{kin}~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)



The GAPS experiment



GAPS consists of two sub-detectors (acceptance: ~1.8m²sr)

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:

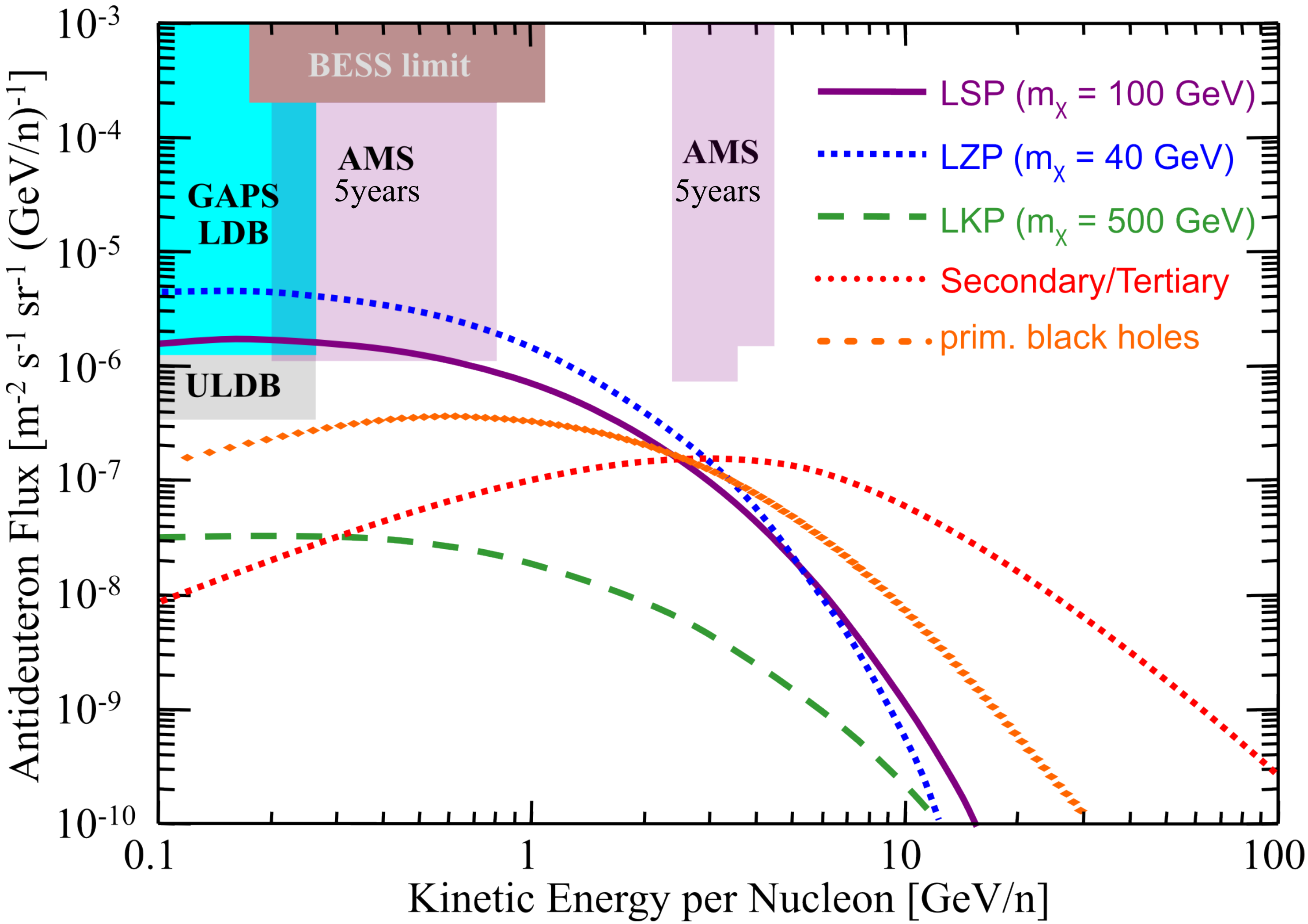
- plastic scintillator with PMTs surrounds tracker

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

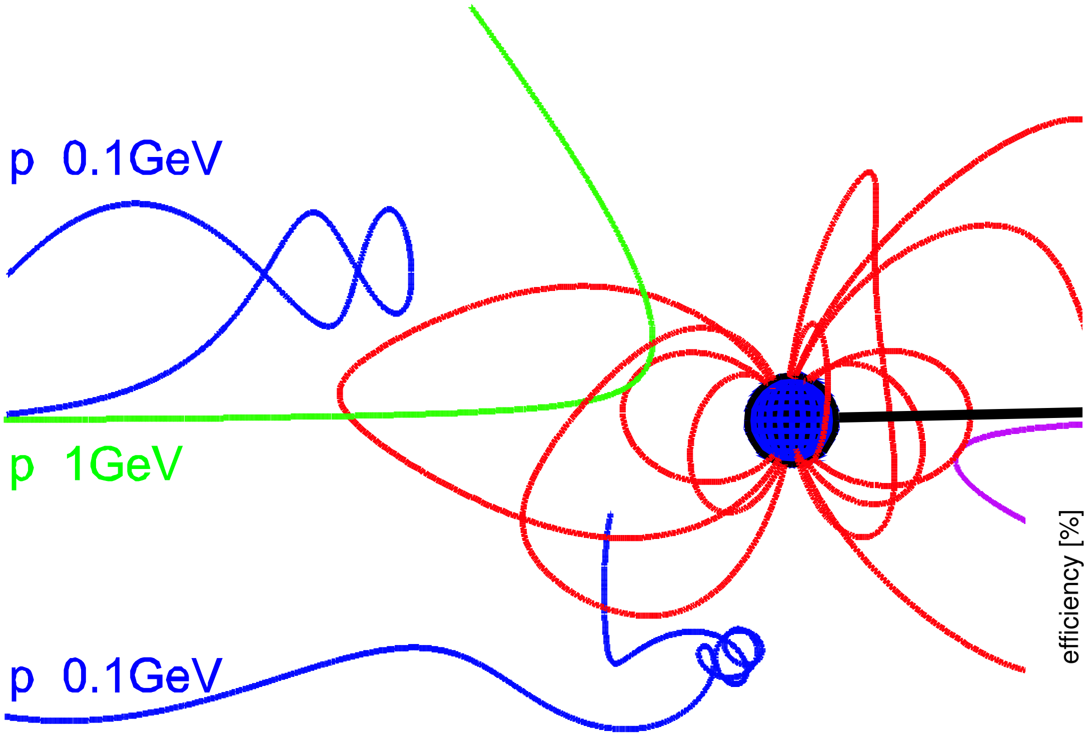
Scientific balloon flights (bGAPS) planned from Antarctica in 2016

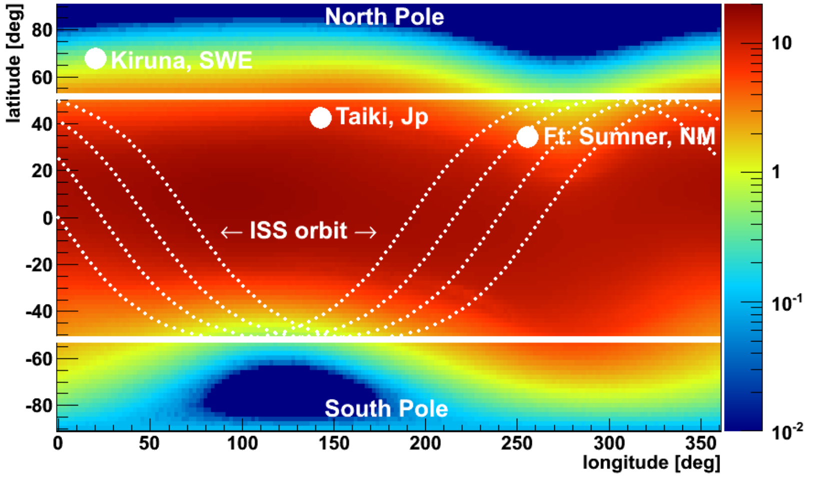
Antideuteron sensitivity

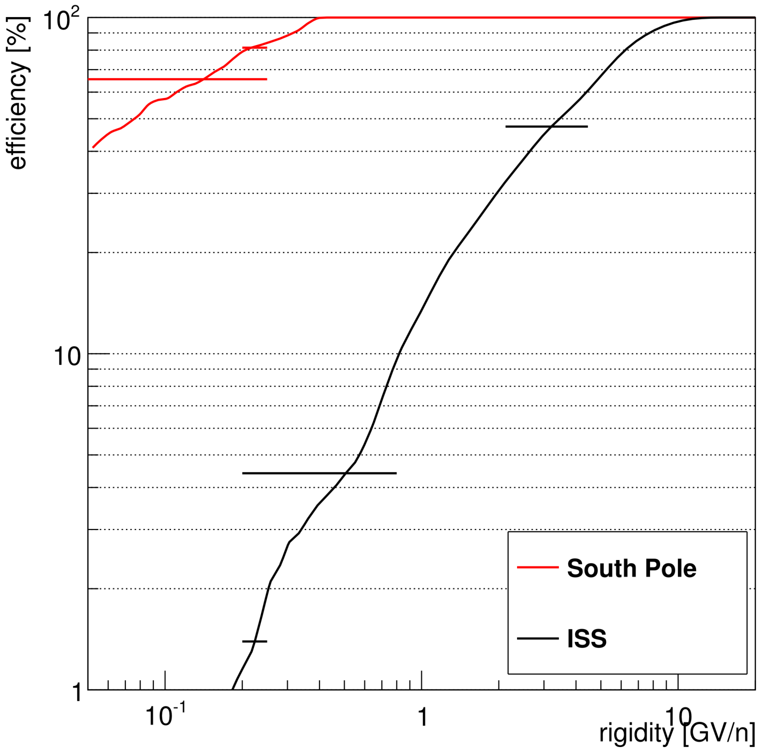


- different scenarios give reasonable antideuteron fluxes within sensitivity:
  Supersymmetry, extra dimensions, primordial black holes, gravitino
- synergy with direct searches and neutrino telescopes (scattering cross-section):
  GAPS probes complementary dark matter regions (annihilation cross-section)

Geomagnetic shielding

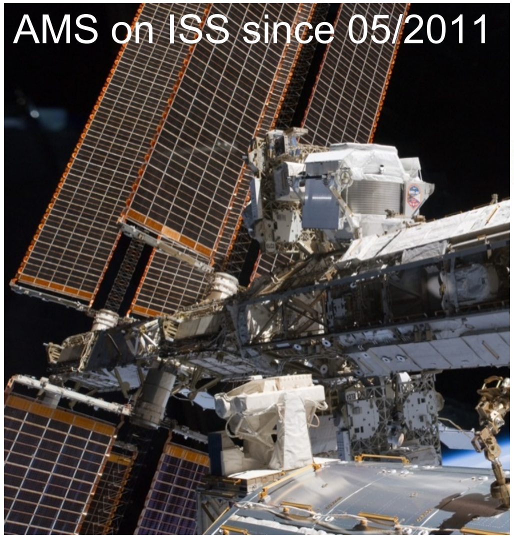


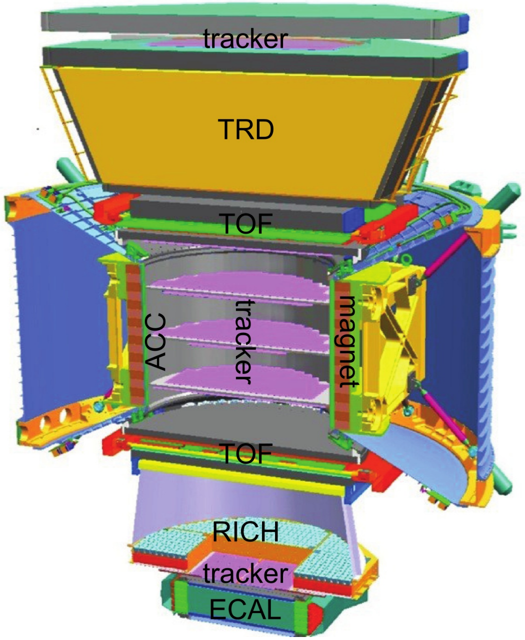




- geomagnetic field shields especially low-energy charged particles
- effect depends on the position
- systematic corrections are smaller the closer you got the poles

AMS comparison





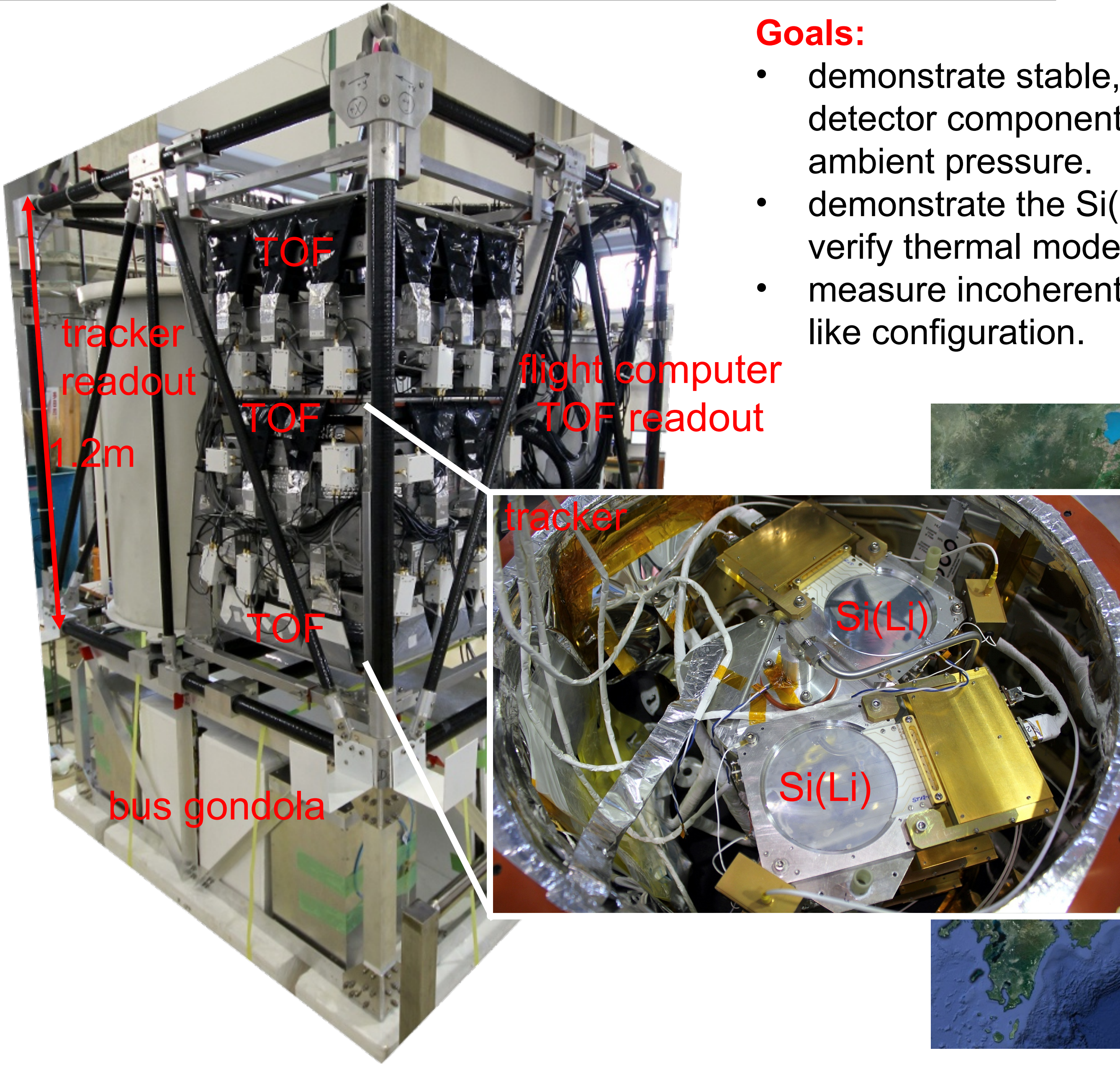
- BESS and AMS-02 use magnetic spectrometer for the antideuteron measurements
- (anti)protons are a huge source of background and require large rejections
- AMS setup (permanent magnet, tracker configuration) changed in 2010
- ISS lifetime was extended to at least 2020
- AMS recalculation for longer 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

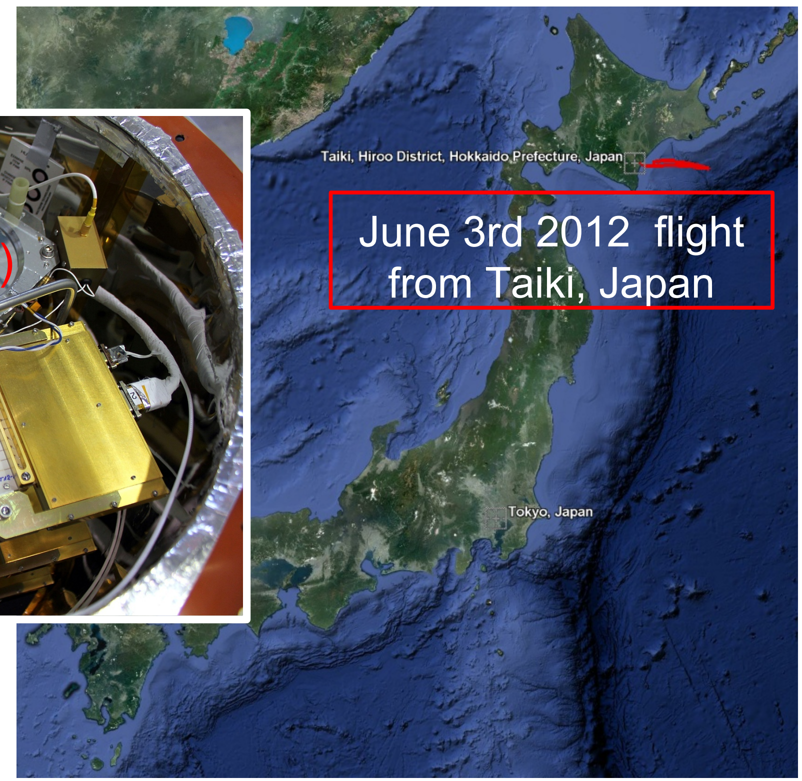
- ISS orbit is not ideal for low-energy cosmic rays, geomagnetic correction for GAPS is 15× smaller
- lower magnetic field increases multiple scattering, which decreases the mass resolution (antiproton background)
- GAPS and AMS use different detection techniques: mandatory for a reliable confirmation 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

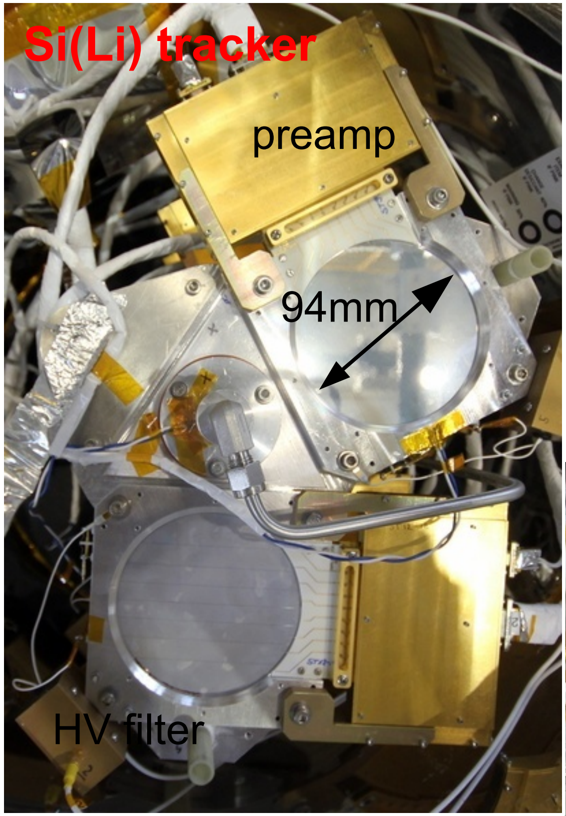
Goals:

- 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.

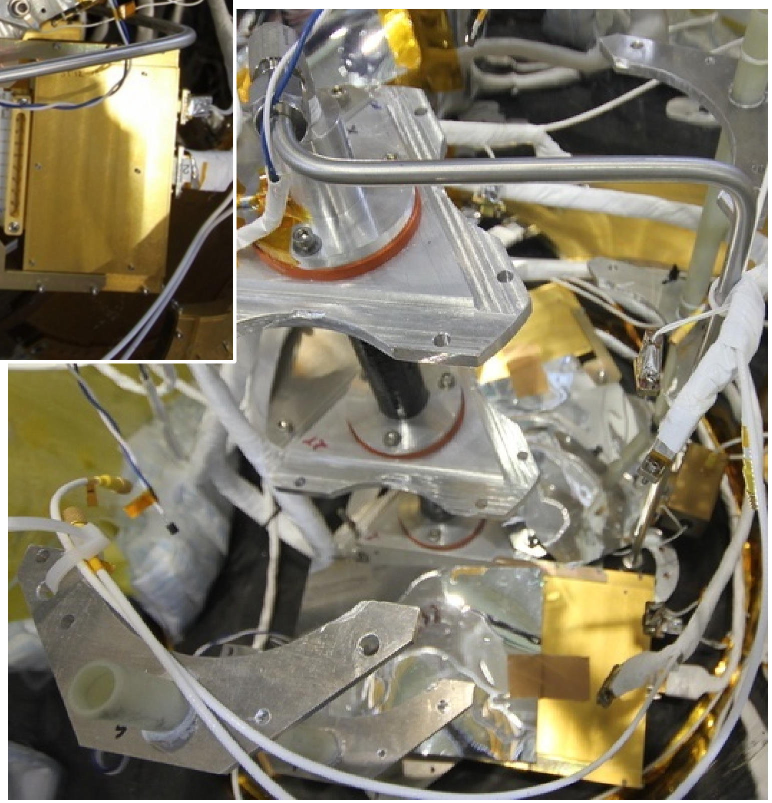




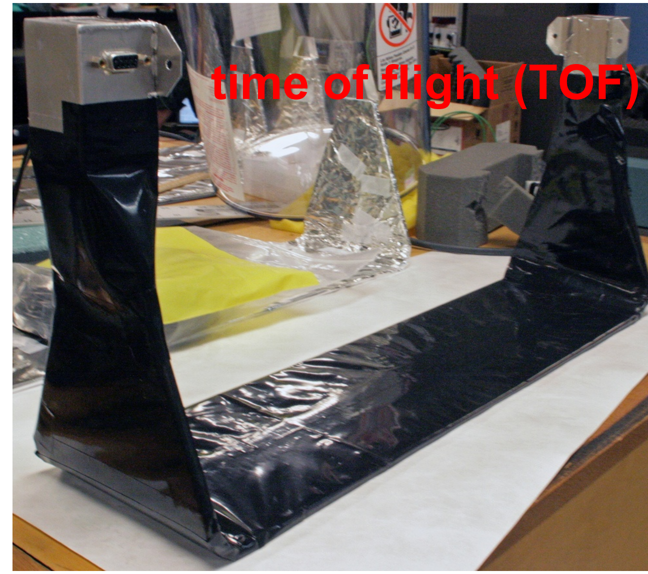
Si(Li) tracker & time of flight



- 6 commercial Semikon detectors
- 4mm/2.5mm thick, 8 strips
- operation at ambient pressure during flight (8mbar)
- closed-loop fluid pumping system (Fluorinert)
- N+: Lithium contact
  P+: Boron implanted (strips)



2 stacks with 3 layers of Si(Li) detectors



- 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 Saint-Gobain (BC-408)
- Hamamatsu R-7600 PMT
- timing resolution: 500ps
- charge resolution: 0.35e
- MIP value: ~15 photo electrons
- angular resolution: 8°

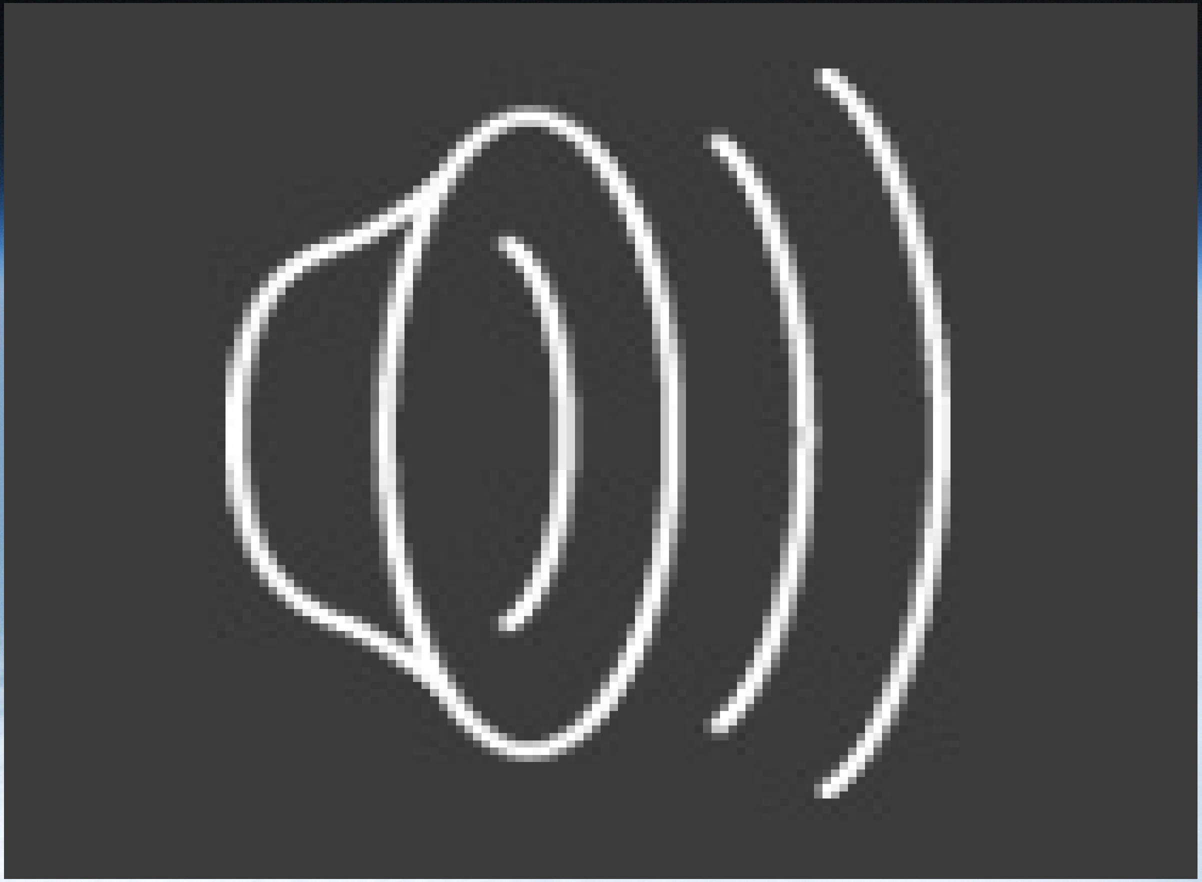
pGAPS flight – June 3rd 2012

preparations
4:36am

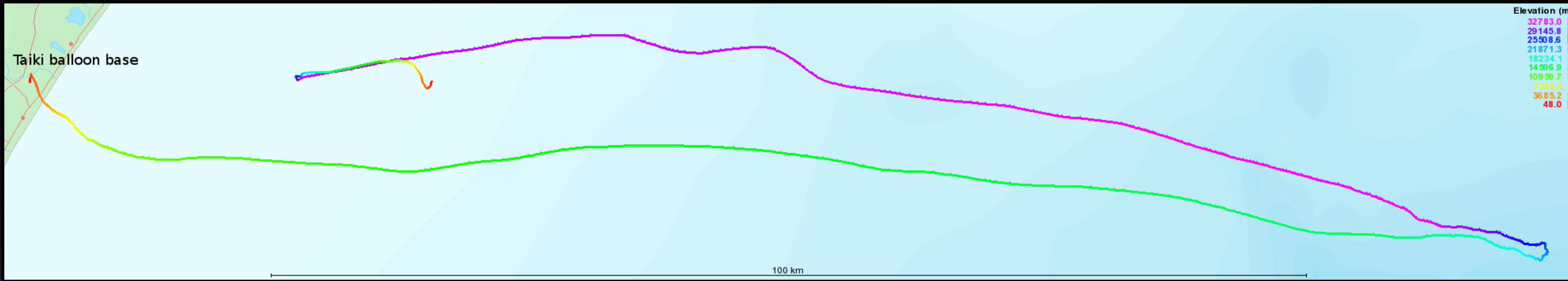
4:55am

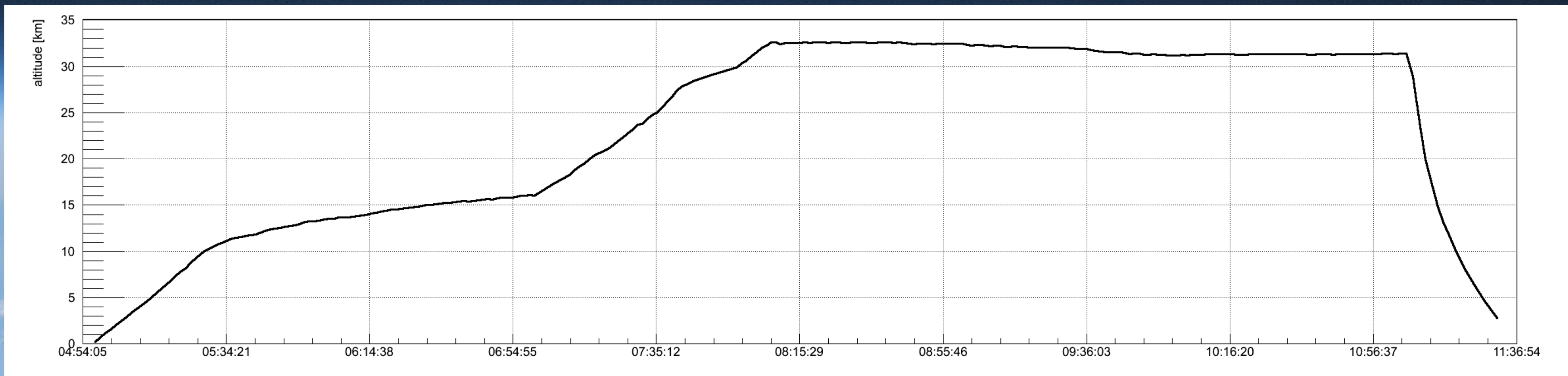
take off

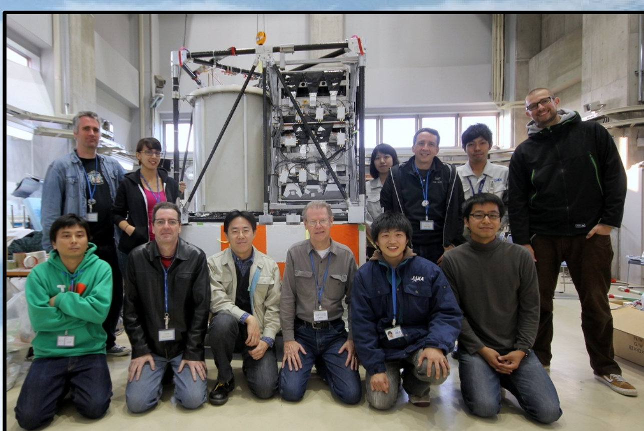
return to the harbor 1:05pm



pGAPS flight – June 3rd 2012

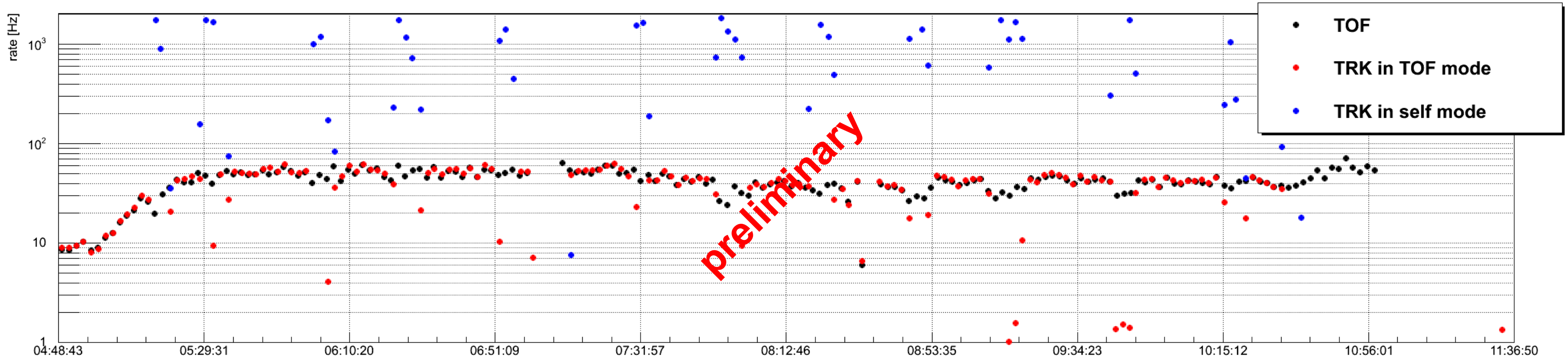


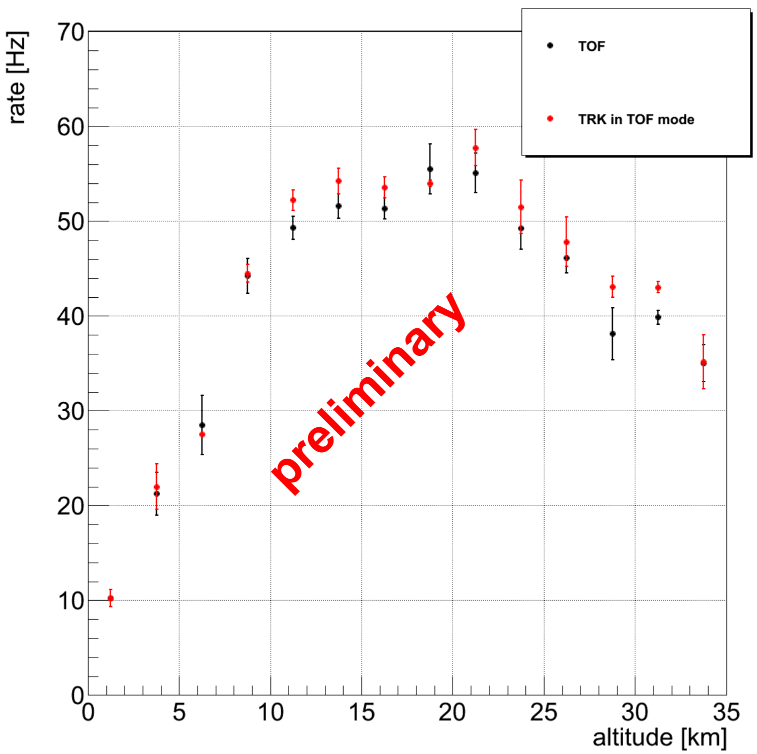




Successful prototype flight from Taiki!

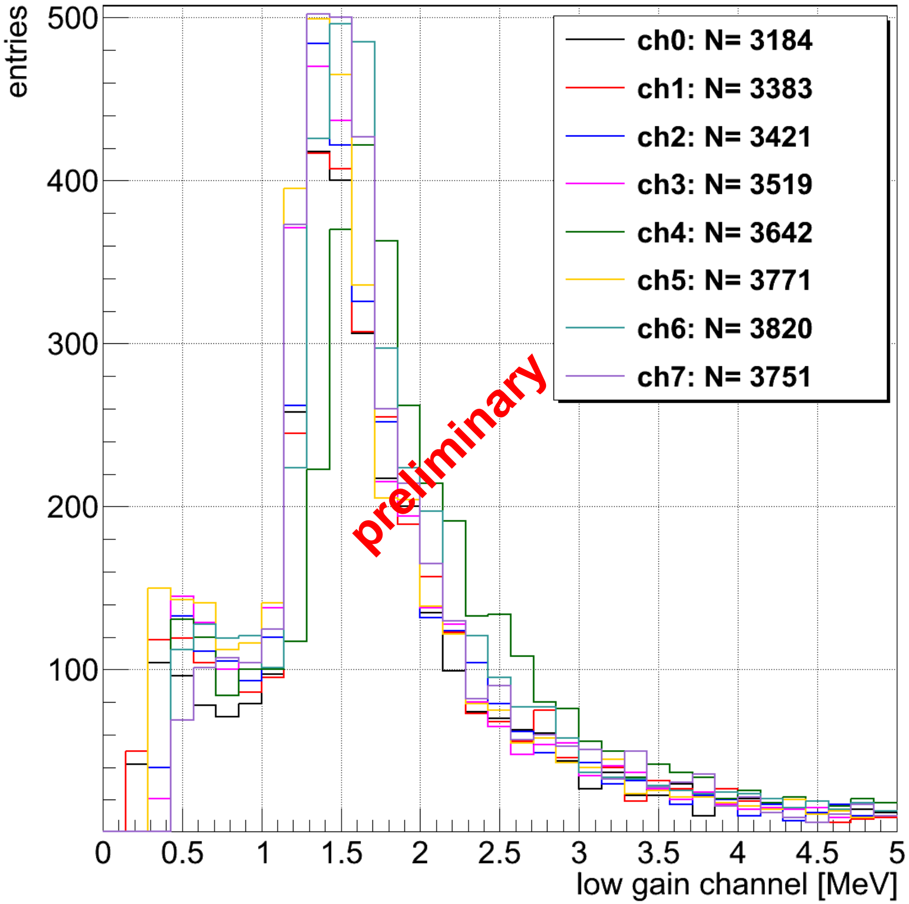
Trigger rates

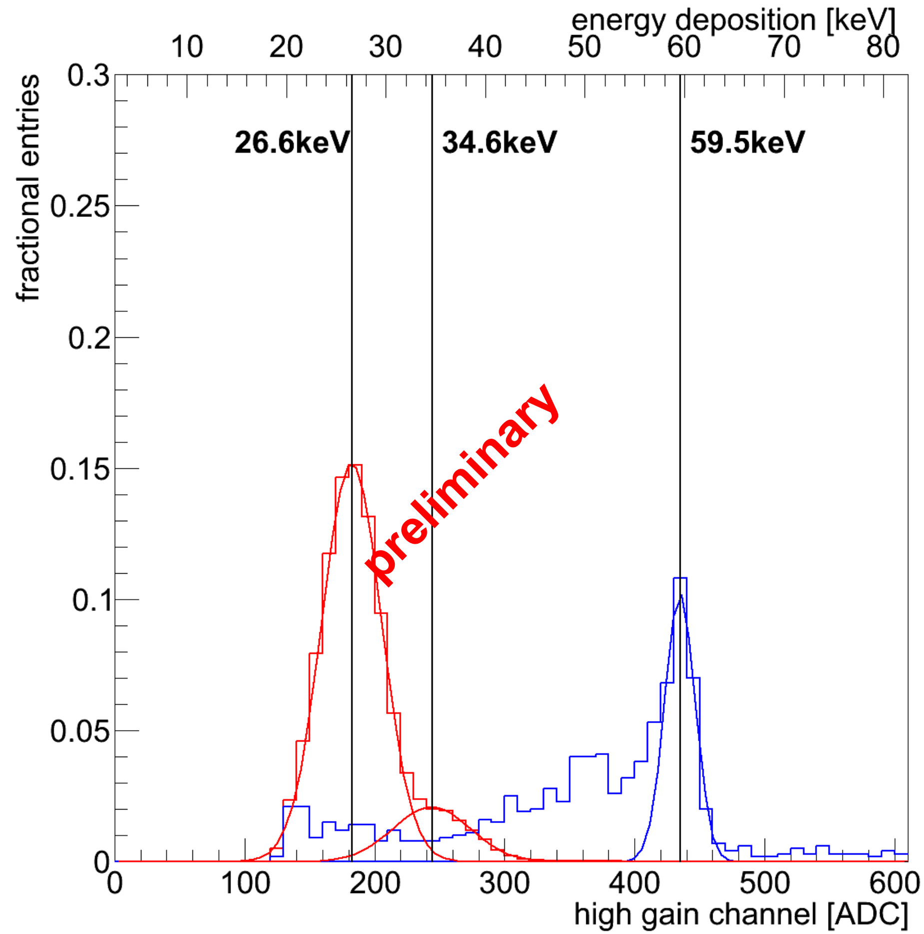




- operation in different data taking modes:
  - **~1Million TOF triggers**
  - X-ray tube in-flight calibration
- stable trigger rate vs time
- raw TOF trigger rate as function of altitude changes roughly as expected (more analysis to be done for precise comparison)

Si(Li) tracker distributions

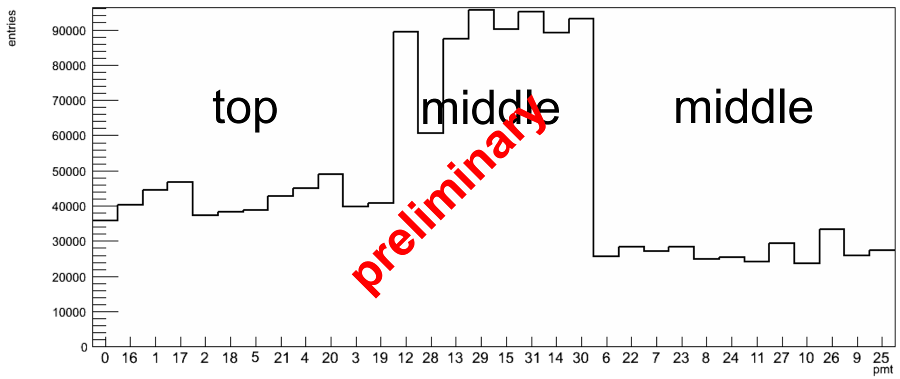




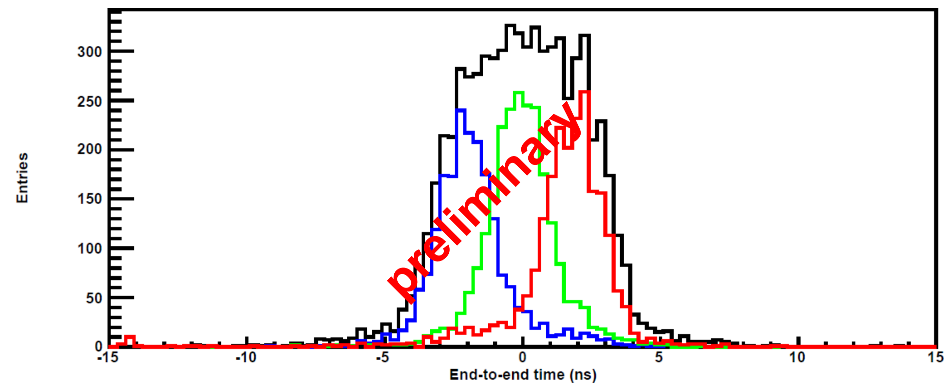
- low gain channel in TOF trigger mode
  calibrated energy depositions close to the end of the flight

- high gain channel in TRK trigger mode
  energy calibration
  blue: Am241 calibration on ground
  red: X-ray tube with Ag/Au filters close to the end of the flight

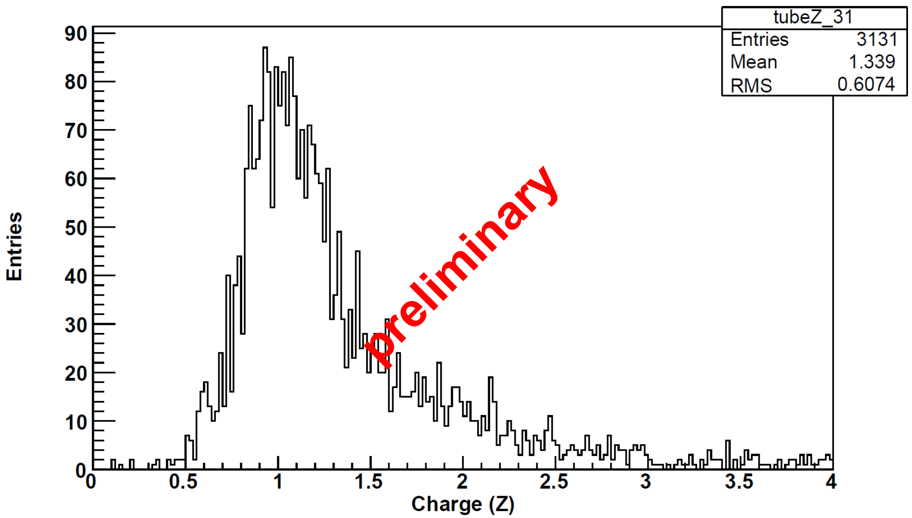
Time of flight



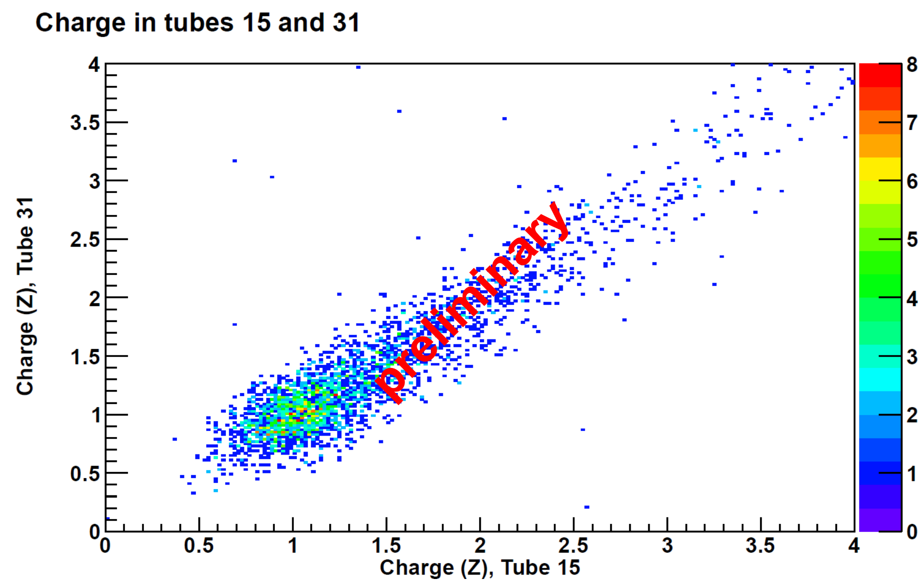
TOF occupancy



TOF paddle: end-to-end time from TDC

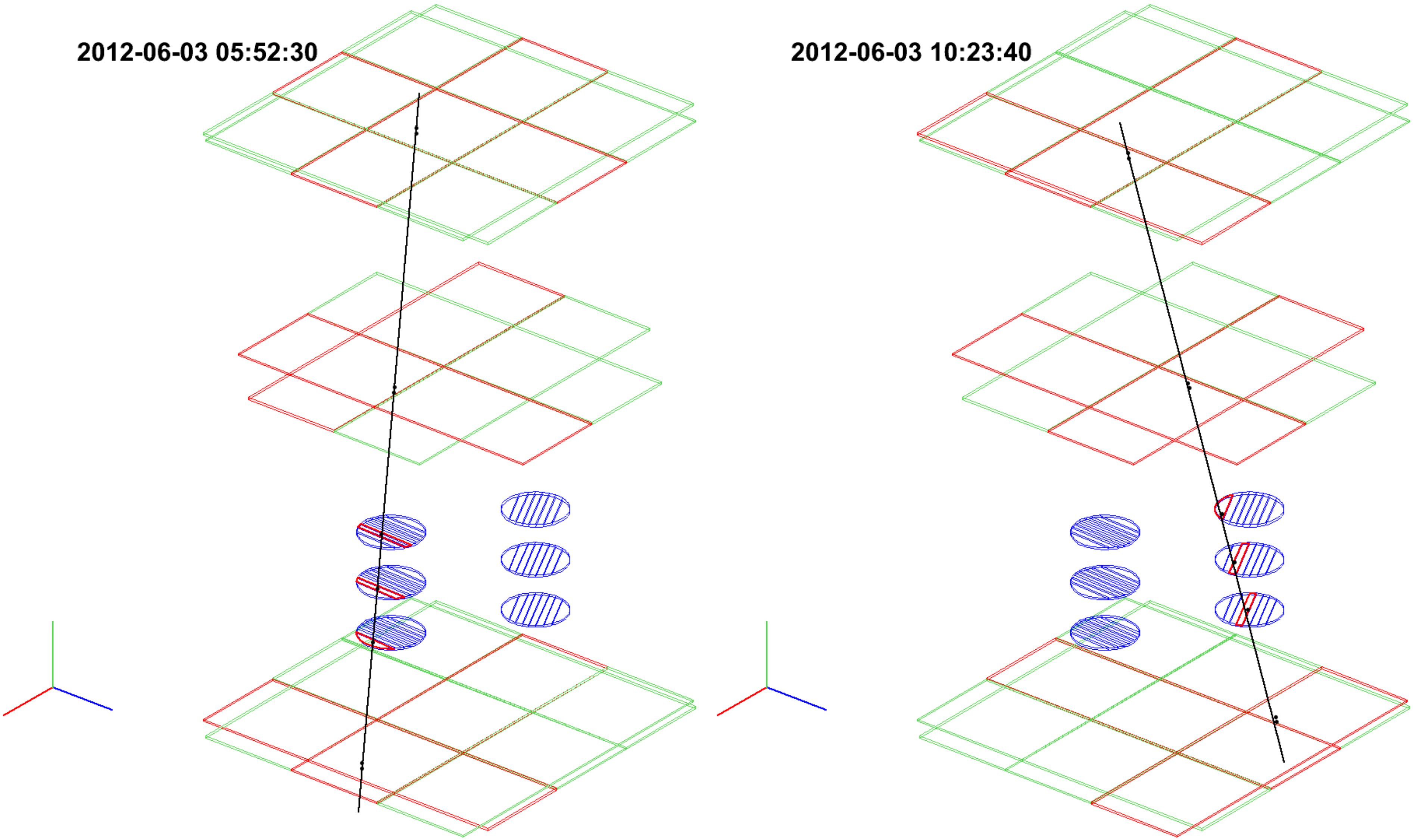


charge distribution for an individual tube

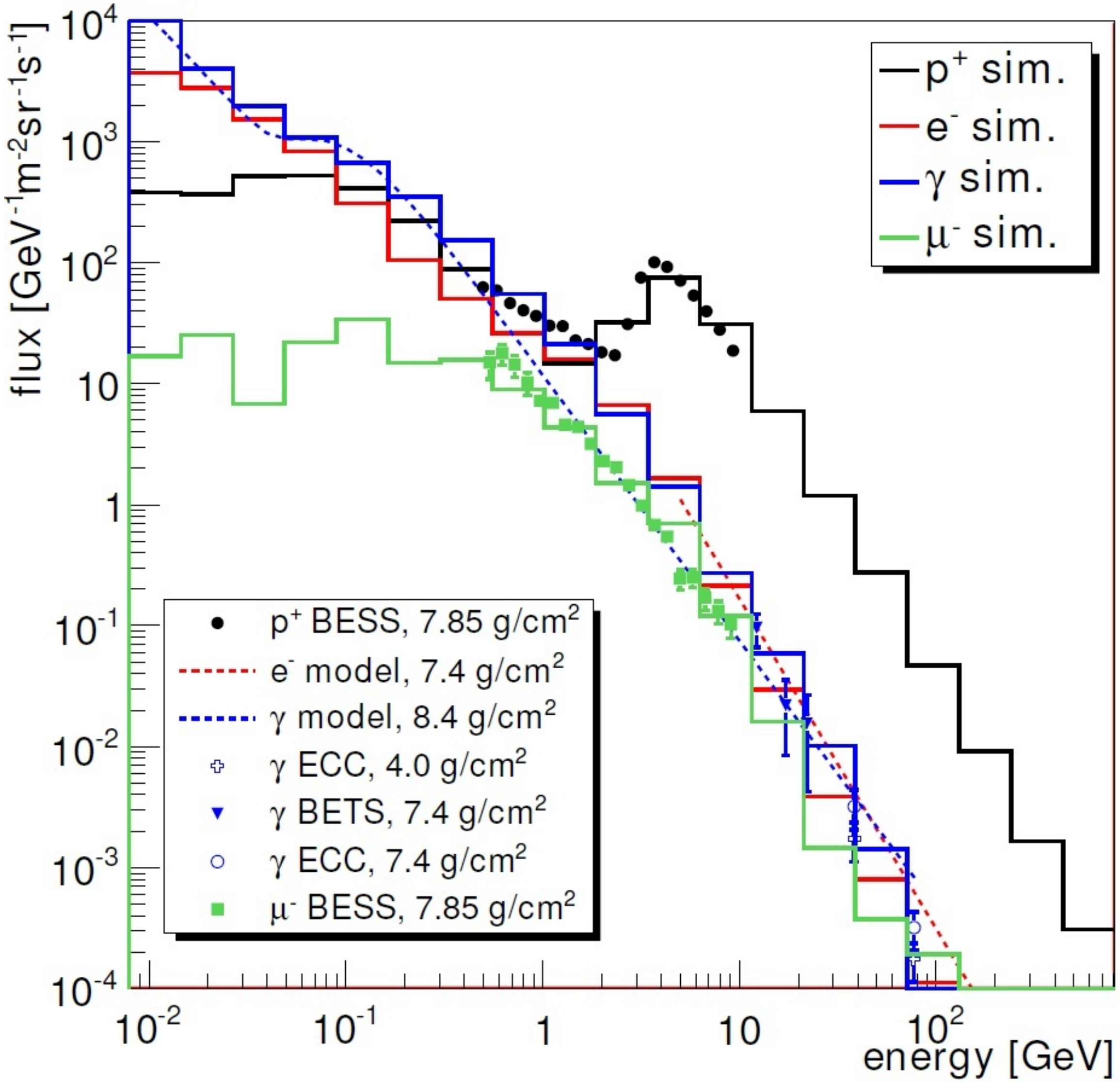


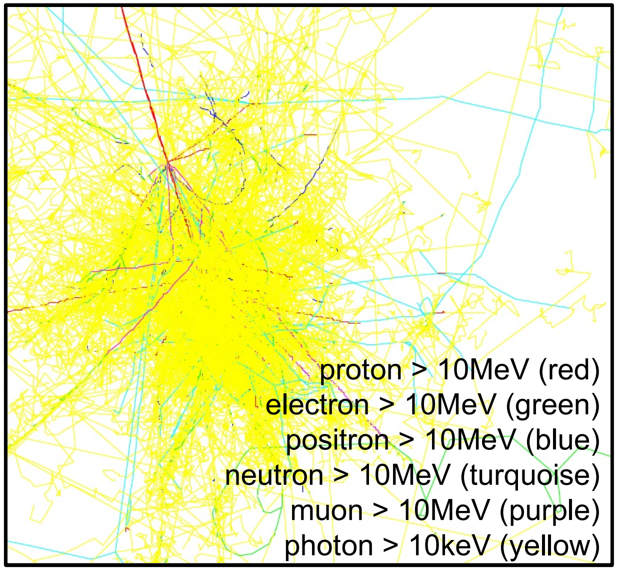
charge correlation between tubes on one paddle

Tracks in pGAPS



Goal: Compare to atmospheric simulations





- GEANT4 simulation of air showers using Planetocosmics
- grammage of matter in front of 33km: ~8.4g/cm^2 (Space: 6-10g/cm^2)
- **compare simulations to pGAPS measurements**

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 (5yr) and ULDB flights will exceed the AMS (5yr) capabilities
- **all goals for prototype GAPS flight were met**
  - flight from Taiki, Japan on June 3rd, 2012
  - stable low-noise operation of Si(Li) detectors
  - functionality and operation of TOF system
  - Si(Li) cooling approach
  - measure background in flight-like configuration
- more pGAPS data analysis ongoing

- We thank the Scientific Balloon Office of ISAS/JAXA for the professional support of the pGAPS flight.

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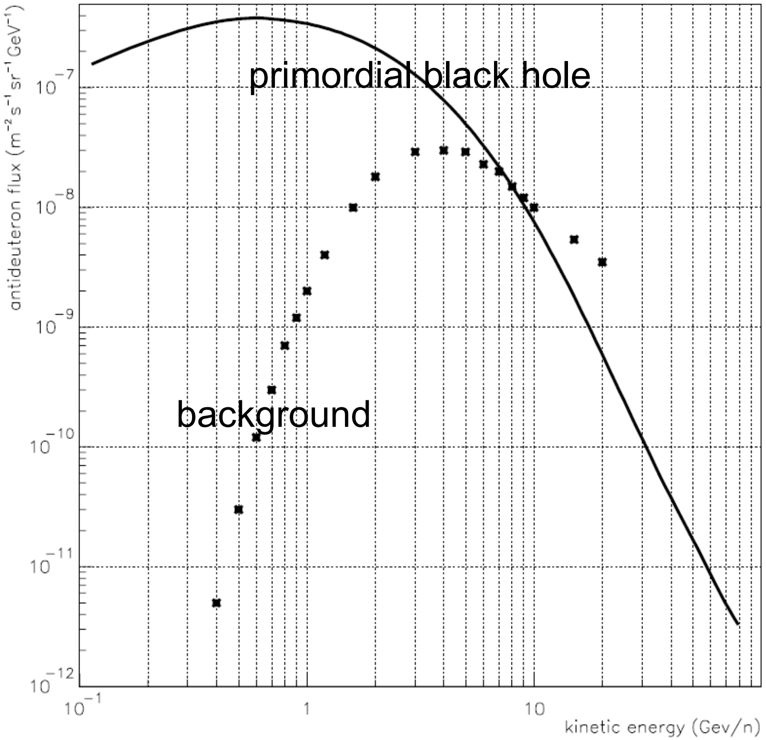
Antideuterons and primordial black holes

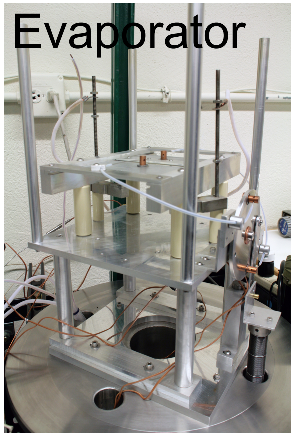
- very small black holes could have formed in the early Universe due to a variety of mechanisms:
  - initial density inhomogeneities
  - phase transitions
  - double inflation
- Hawking black hole evaporation can be understood as quantum creation of particles from the vacuum by an external field
- if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

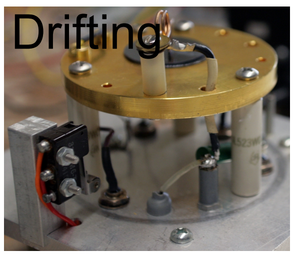


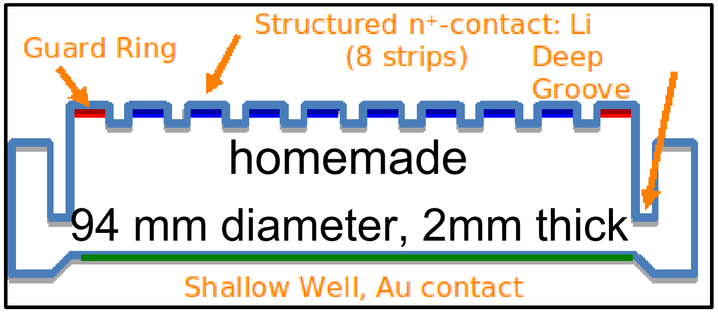
Antideuterons are maybe the only chance to detect PBHs!

[A&A 398, 403–410 (2003)]

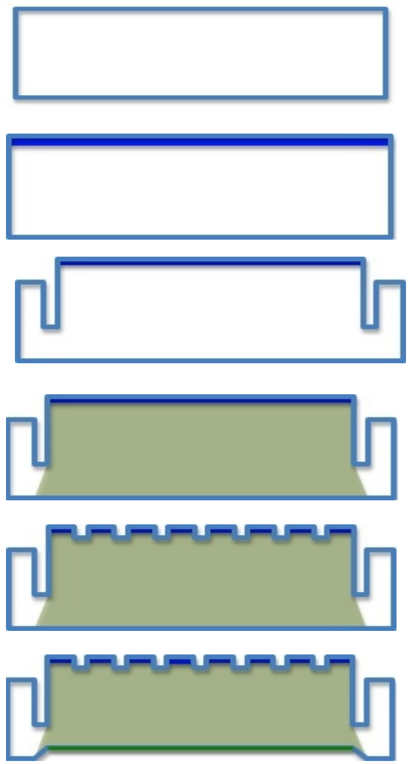
Si(Li) fabrication for bGAPS





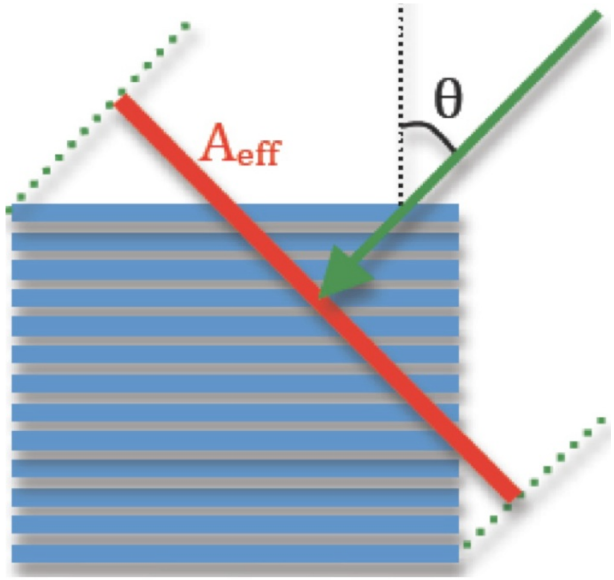


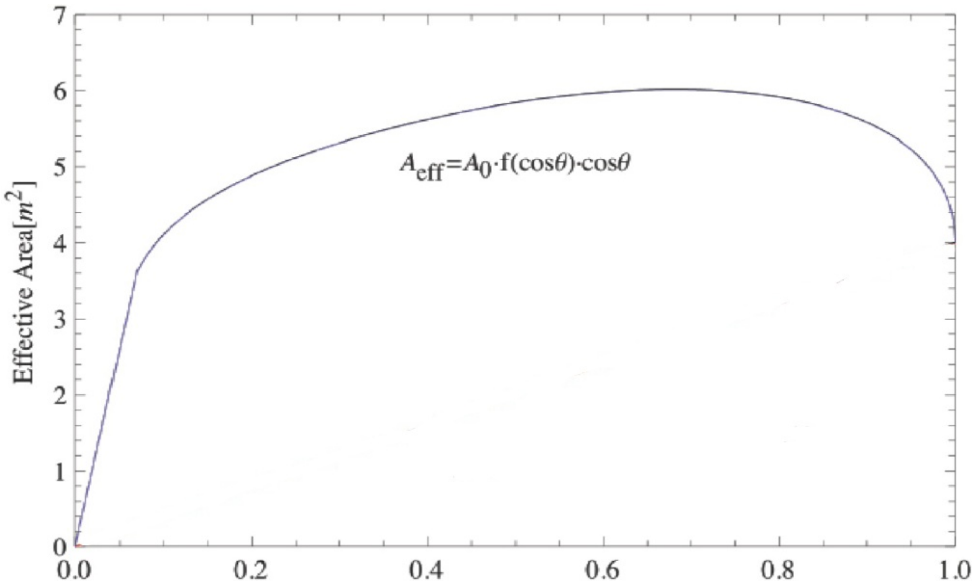
N+: Lithium contact (strips)
Au contact with shallow well



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

Sensitivity calculation





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

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

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

- 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)

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

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

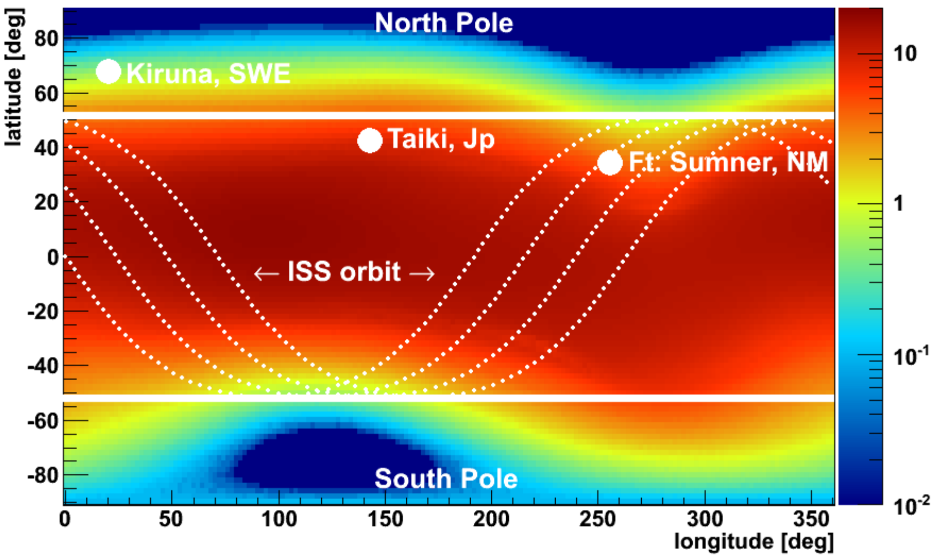
- hadron models for annihilation for antiprotons (fireball, INC): pions: ~5.1 (3.1 charged) proton: ~1
- antideuteron (no data): models estimate roughly double hadron yield

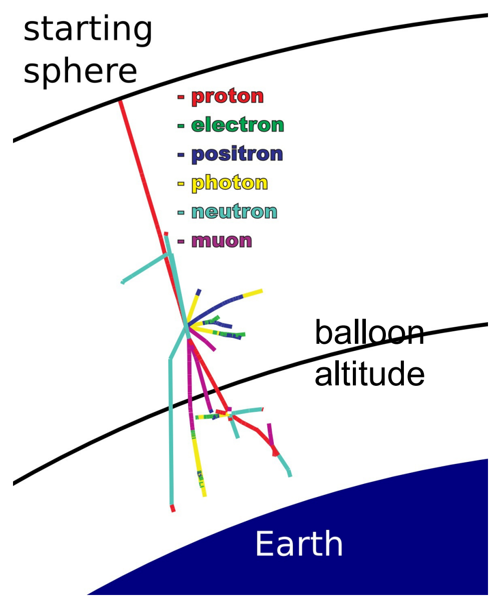
Expected background for a 300 day flight

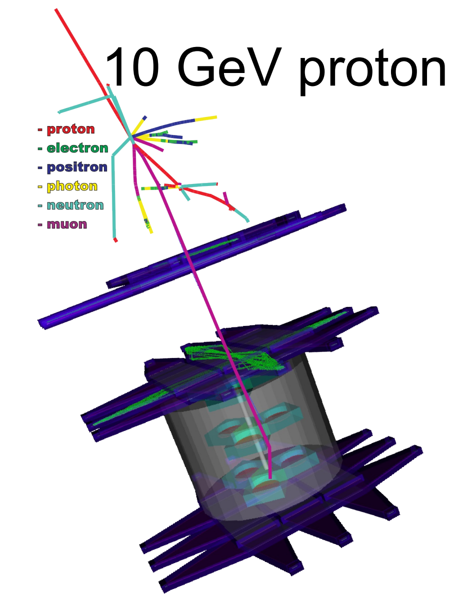
Type of Background	Expected Events	Basis for estimate
Temporally incoherent X-rays	< 0.003	Scaling from γ-ray telescopes
Temporally coherent X-rays	0.001	Measured at GAPS-KEK experiment
Elastic neutrons	0.002	Monte-Carlo of evaporative & cascade model, KEK limits
Secondary-tertiary-atmospheric antideuterons	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.

GAPS simulations

cosmic antideuterons	atmospheric simulation	detector simulation	exotic atomic physics

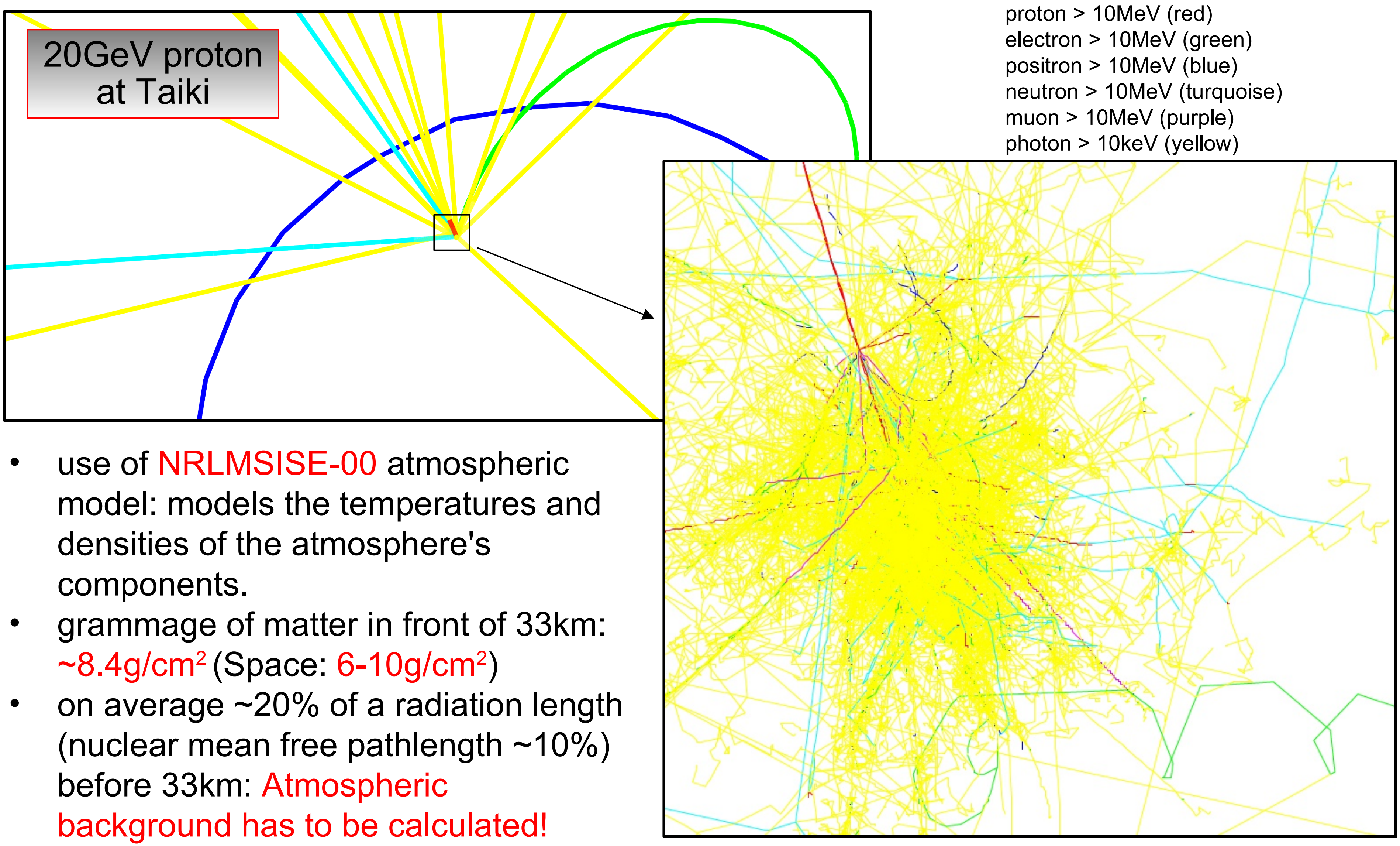






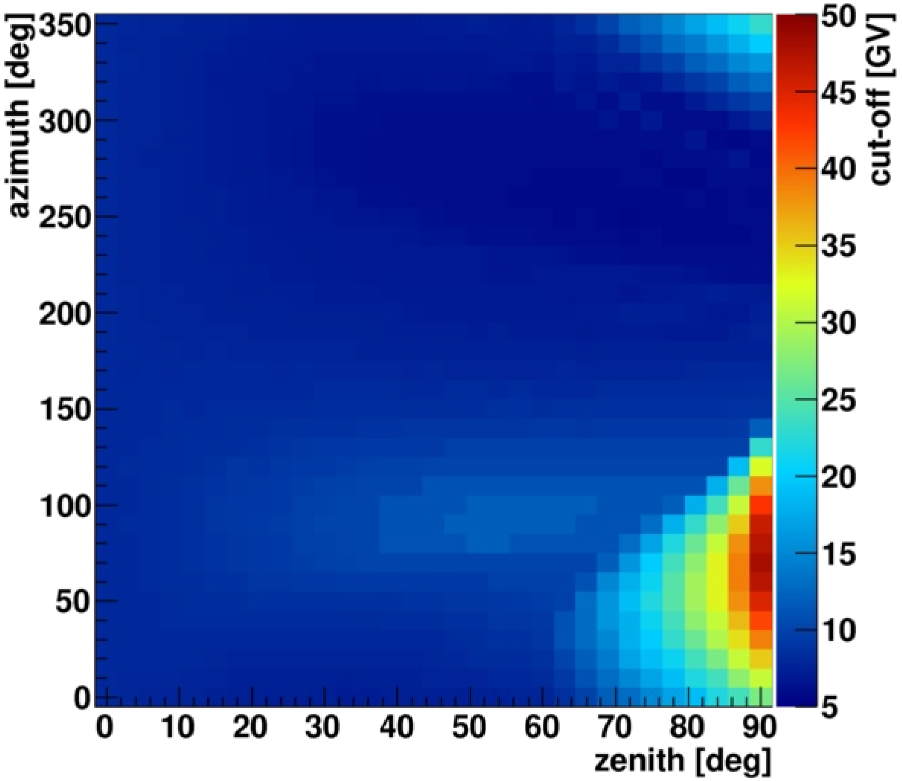
- Atmospheric and geomagnetic simulations with PLANETOCOSMICS based on GEANT4
- Instrument simulation with GEANT, ROOT output format:
  - electromagnetic, hadronic, optical physics are running
  - basic components are implemented, frames and structures must be added
  - ion and exotic physics are under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

Air shower & geomagnetic field

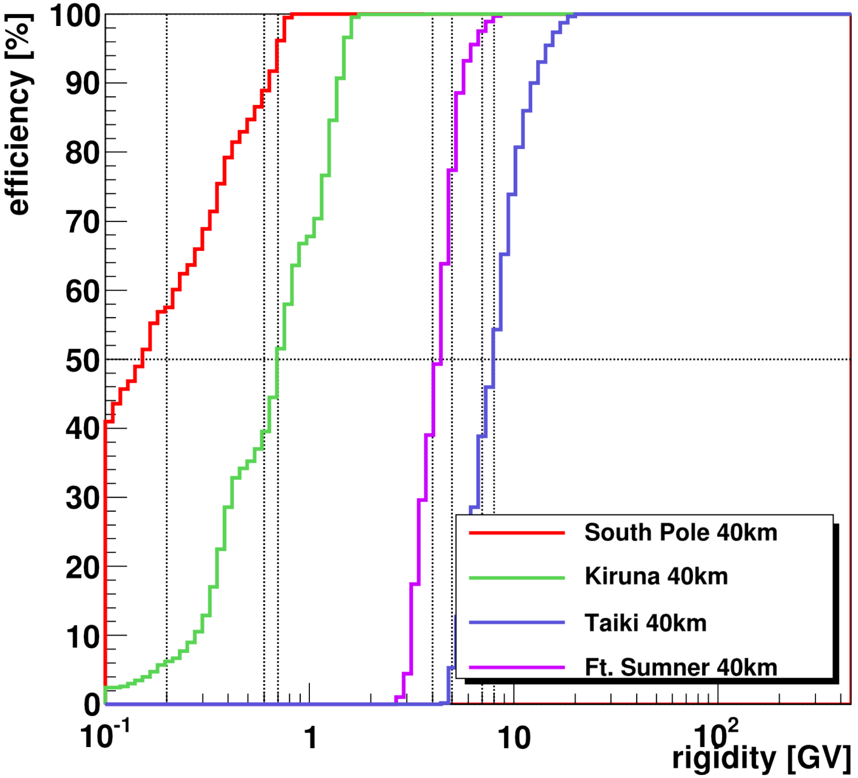


- use of NRLMSISE-00 atmospheric model: models the temperatures and densities of the atmosphere's components.
- grammage of matter in front of 33km: ~8.4g/cm^2 (Space: 6-10g/cm^2)
- on average ~20% of a radiation length (nuclear mean free pathlength ~10%) before 33km: Atmospheric background has to be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