# Antideuterons as an Indirect Dark Matter Signature: Si(Li) Detector Development and a GAPS Balloon Mission


Tsuguo Aramaki
Columbia Astrophysics Laboratory

C.J. Hailey (PI), T. Aramaki, J.E. Koglin, N. Madden, K. Mori, H.T. Yu
Columbia University

S.E. Boggs
University of California, Berkeley

W.W. Craig
Lawrence Livermore National Laboratory

H. Fuke, T. Yoshida
Institute of Space & Astronautical Science, Japan Aerospace Exploration Agency

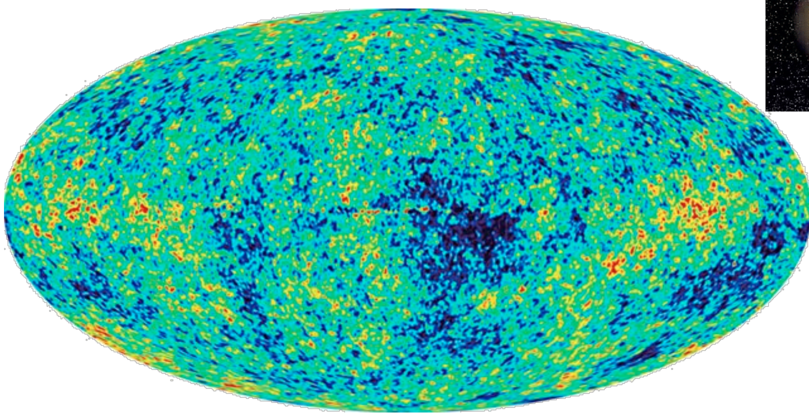
F. Gahbauer
University of Latvia

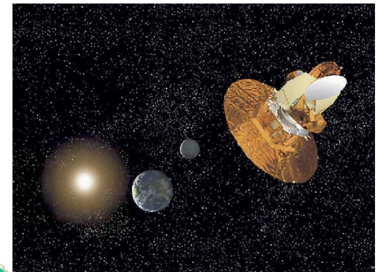
R.A. Ong, J. Zweerink
University of California, Los Angeles

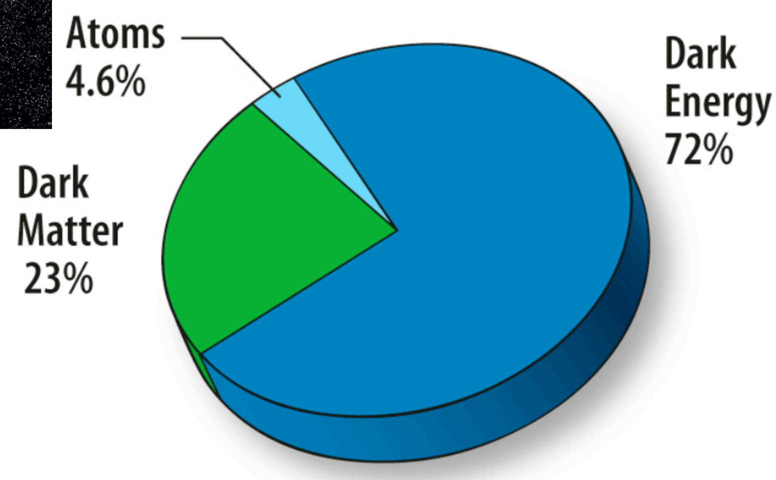
K.P. Ziock
Oak Ridge National Laboratory

# Our universe is dominated by Dark Matter and Dark Energy

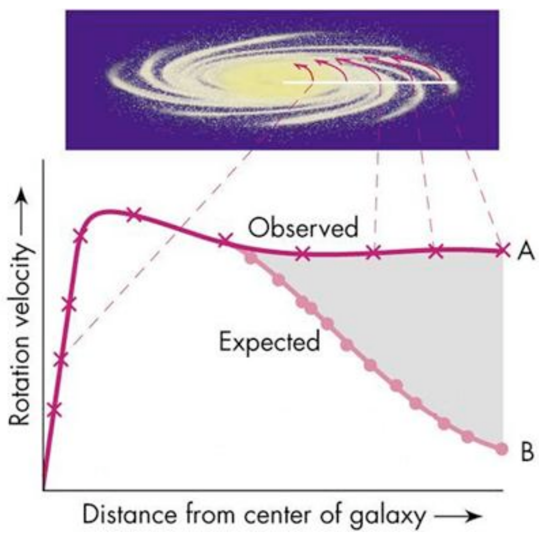
WMAP measured accurate cosmological information



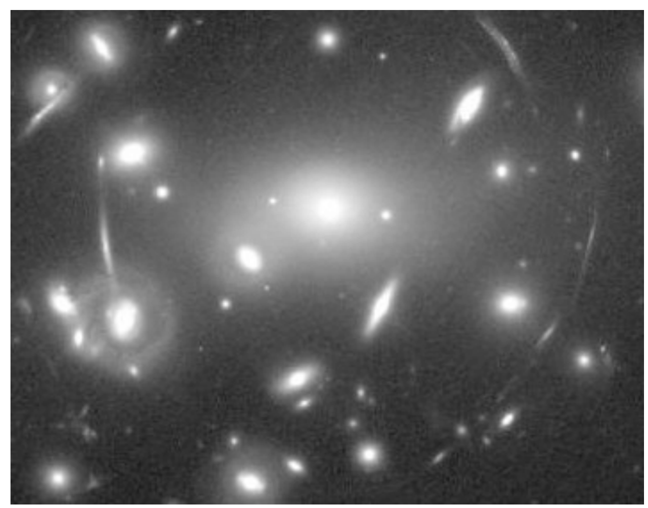





Galactic Rotation Curve




Gravitational Lens

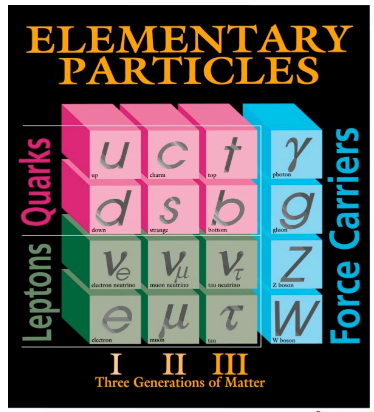


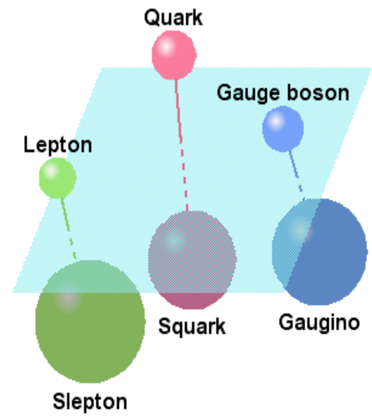
# What is Dark Matter?

Lots of theories!

- 4th generation heavy neutrino
- Axinos
- Bino
- Brane world DM
- CHAMPS
- Cryptons
- D-matter
- Gravitinos
- Kaluza-Klein
- Higgsino
- Light scalars
- Minimal DM
- Mirror particles
- Neutralinos
- New symmetry little Higgs
- Q-balls
- Photino
- Self-interacting DM
- Simpzillas
- SM neutrinos
- Sneutrinos
- Sterile neutrinos
- SWIMPS
- Theory space little Higgs
- Wimpzillas
- Wino

**Supersymmetry**



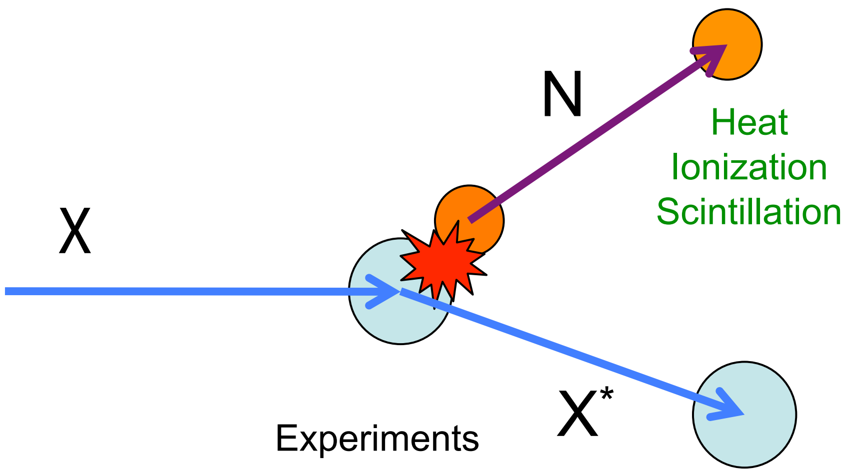

## Neutralino DM

- Lightest Supersymmetric Particle (LSP) in SUSY theory
  - Stable
- Interacts with matter very weakly like a heavy neutron
  - Underground experiments measure nuclear recoil
  - Underground experiments must be massive – 3rd generation experiments ~ 1 ton targets
- The neutralino is a Majorana particle
- It is its own antiparticle and will co-annihilate

# There are two different Dark Matter searches

## Direct Search

Underground detection of nuclear recoils



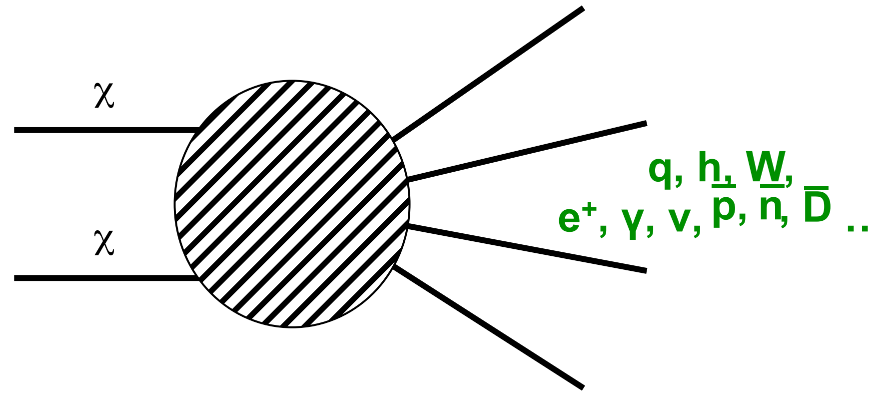

Experiments

| | | |
|---|---|---|
| ANAIS | ELEGANT V | LIBRA |
| ArDM | EDELWEISS | NAIAD |
| CDMSII | EURECA | PICASSO |
| CUORICINO | GEDEON | SIMPLE |
| COSME | GENIUS | SuperCDMS |
| CRESST | Genino | SuperK |
| DAMA | GERDA | WARP |
| DMRC | HDMS | XENON |
| DRIFT | IGEX | ZEPLIN |

**Large scale (~ton) detector is required**

## Indirect Search

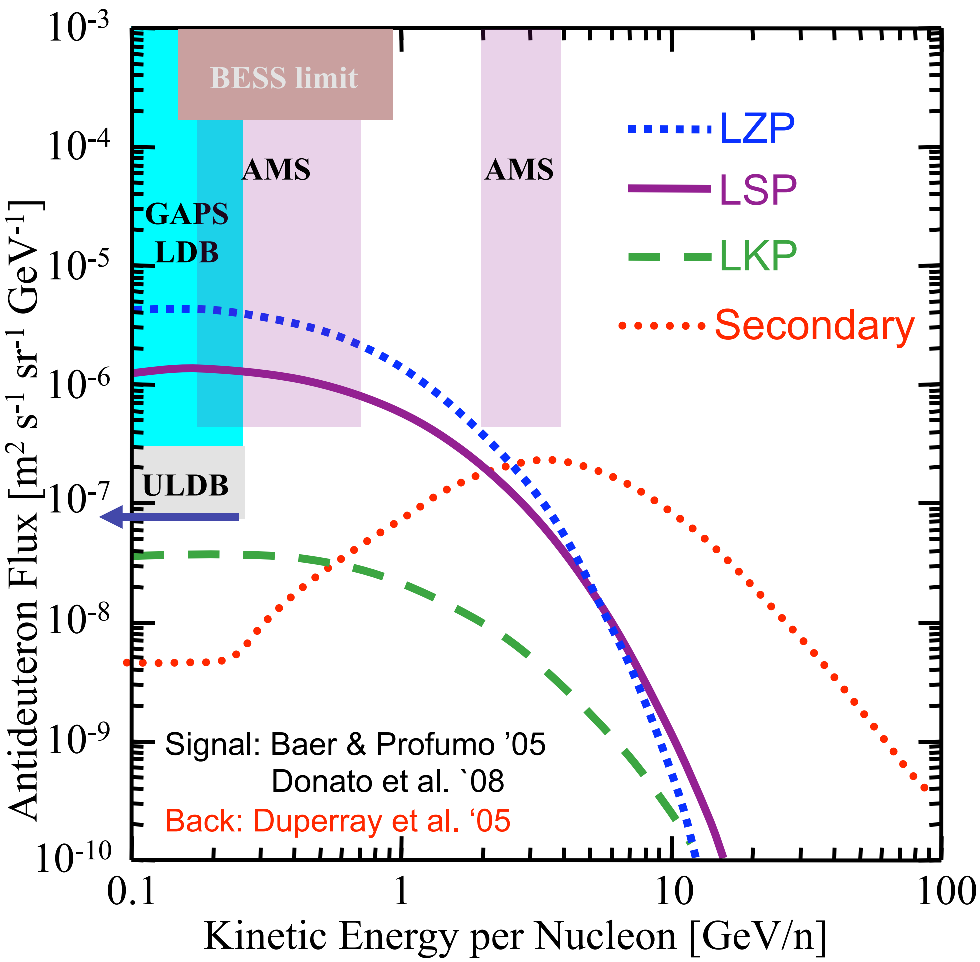
Detect annihilation products




- Positron ($e^+$): PAMELA, AMS…
  $\chi\chi \to W^+W^-$, $W^+ \to e^+\nu$
- Photon (γ): GLAST, HESS…
  $\chi\chi \to \gamma\gamma$, $\chi\chi \to \gamma Z$
- Neutrino (ν): AMANDA, IceCube…
  Annihilate in the sun, detect upward μ
- Antiproton ($\bar{p}$): BESS, AMS, PAMELA
- Antideuteron ($\bar{D}$): GAPS, AMS

# Why Antideuterons?

GAPS Band = 0.05-0.25 GeV/n




**Background free at low energy!**

Primary component:

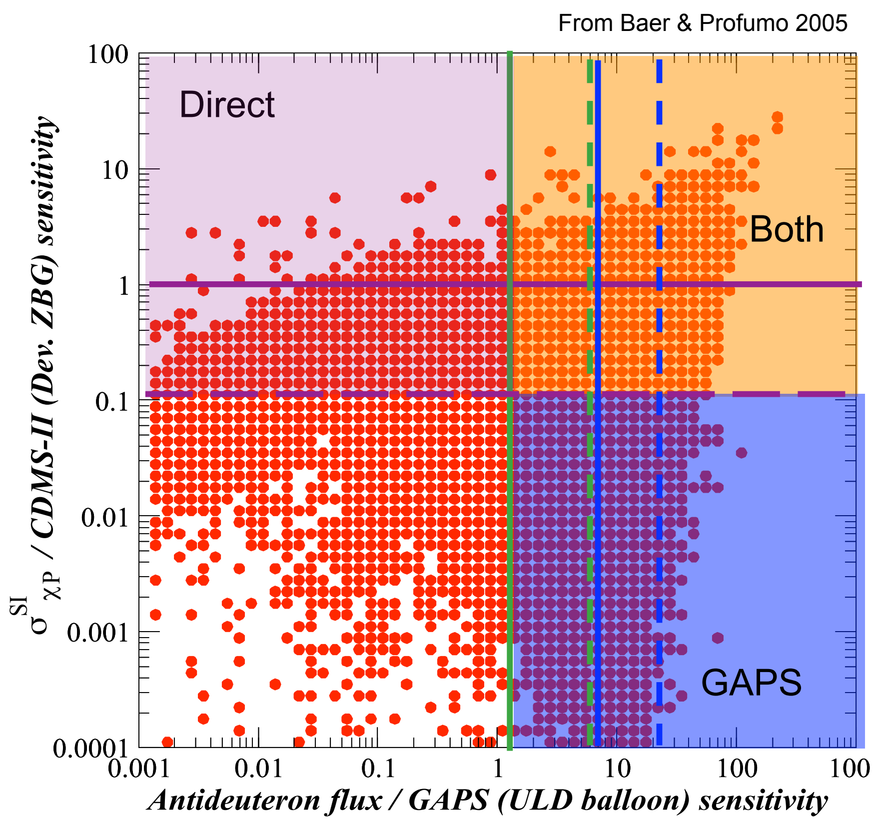
- Neutralino annihilation
- Other DM models
  - eg. Right-Handed Neutrino (LZP)
  - Kaluza-Klein Particle (LKP)

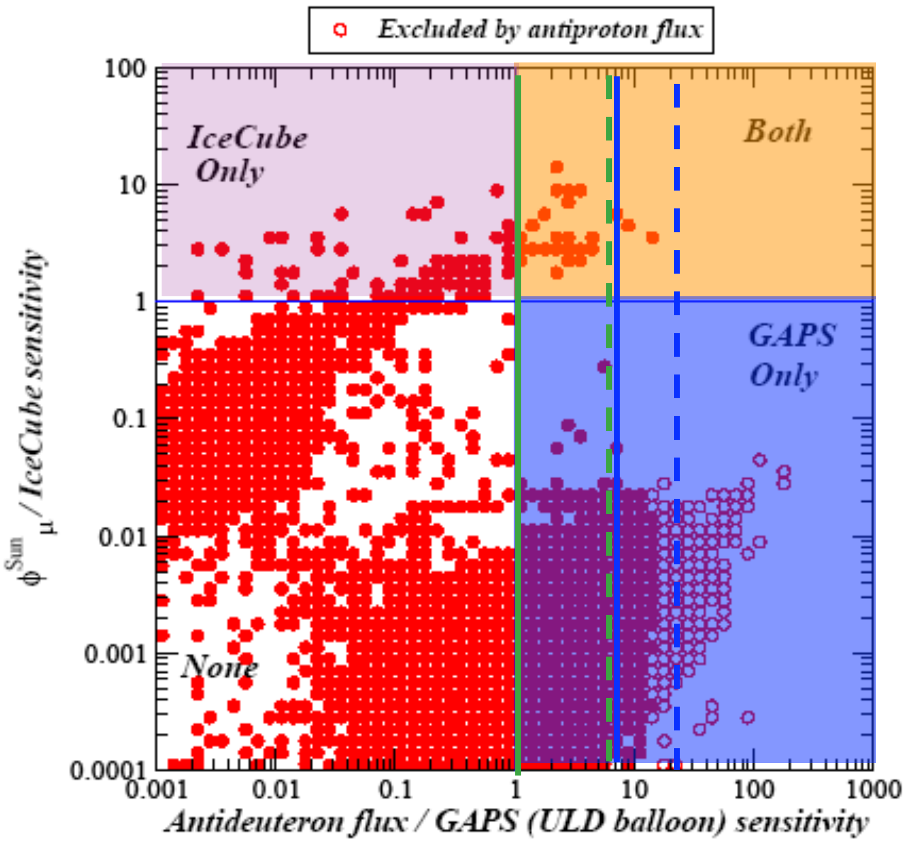
Secondary component (Background):

- Cosmic ray interactions
- $p/\bar{p}$ (CR) +H/He (IS)$\rightarrow \bar{D}$+…

- Flux is low, but primary/secondary is large
- High sensitivity with balloon
- Sensitive to other DM models

# GAPS searches unique parameter space complementary to other direct/indirect searches

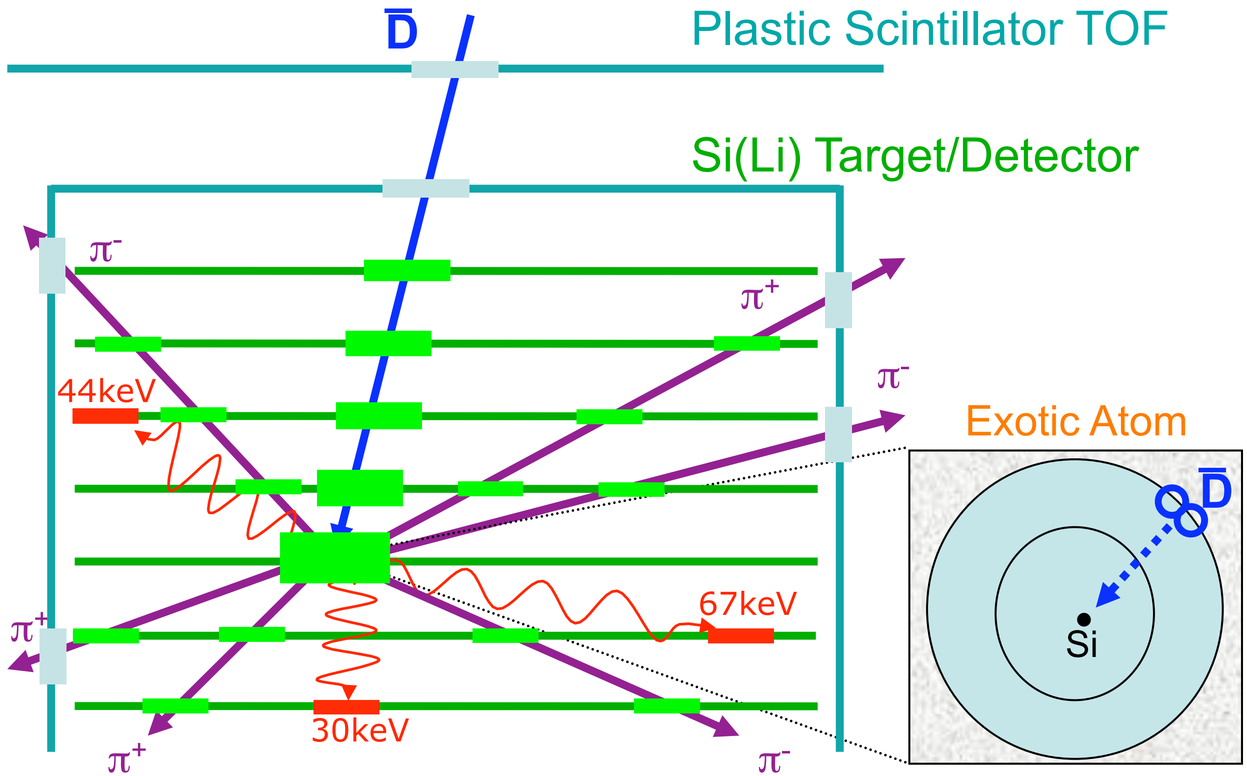


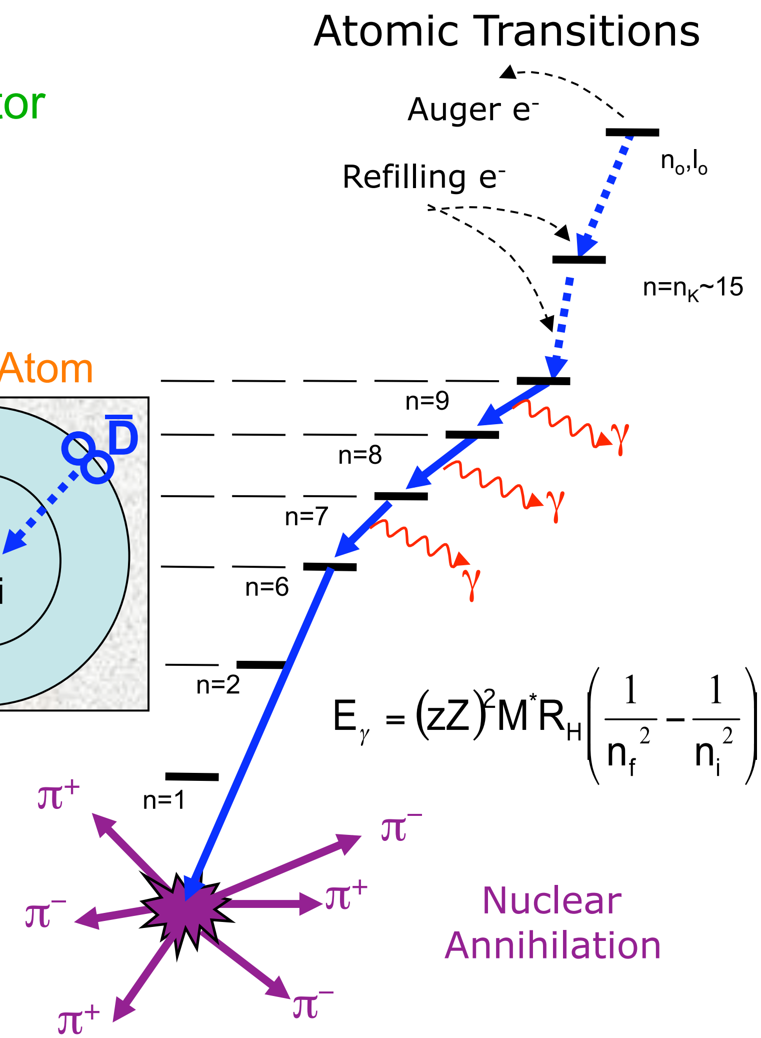




| | LDB (60days) | ULDB (300days) |
|---|---|---|
| Exploratory | | |
| Discovery | | |

Probe unique regions of parameter space

# Detection Concept: Atomic X-rays and Pions




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 with near unity probability

Deexcitation X-rays provide signature

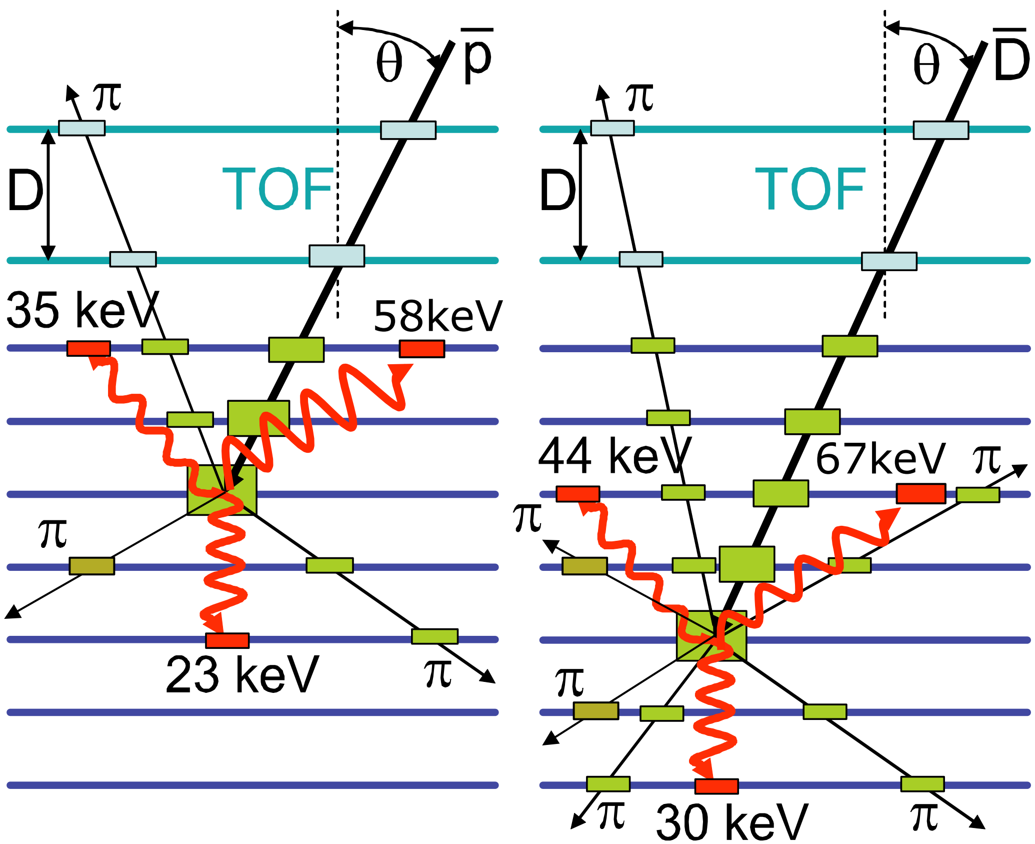
Pions from annihilation provide added background suppression

X-ray yields were shown to be high
→ <KEK test in 2004, 2005>

# GAPS employs three techniques to uniquely identify Antideuterons with enormous background suppression

1. TOF and Depth Sensing
2. Atomic X-rays
3. Charged Pion Multiplicity

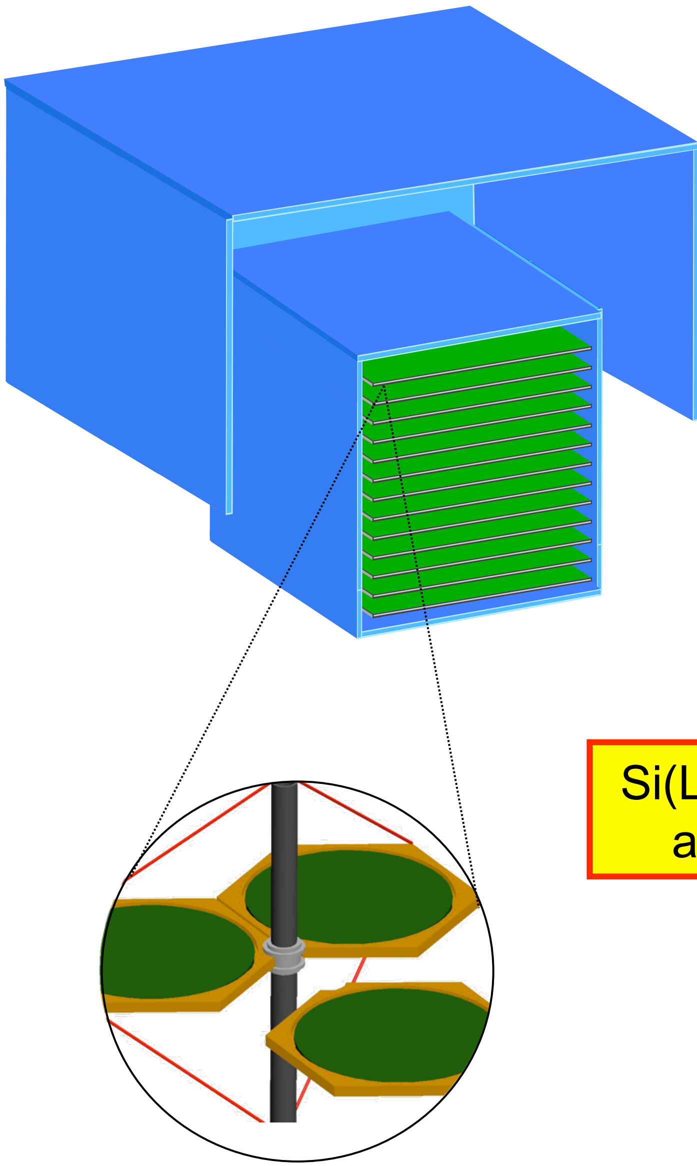
Antiproton/Antideuteron misidentification




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, $\pi^o$ shower photons, internal bremastrahlung | negligible | Data on energy & branching ratio of all possible lines; analytic calc.; GEANT4 sim. |

# GAPS Detector: Si(Li) & Plastic Scintilator



13 layers composed of Si(Li) wafers

- Relatively low Z material, 2mm thick
- Segmented into 8 strips, ~8cm$^2$ each

  → 3D particle tracking
- Timing: ~50 ns
- Energy resolution:~2 keV
- Proven technology dating from the 1960's
- Dual channel electronics

  5-200 keV: X-rays

  0.1-200 MeV: charged particle

**Si(Li) serves as a target for stopping antideuterons as well as an x-ray detector & particle Tracker**

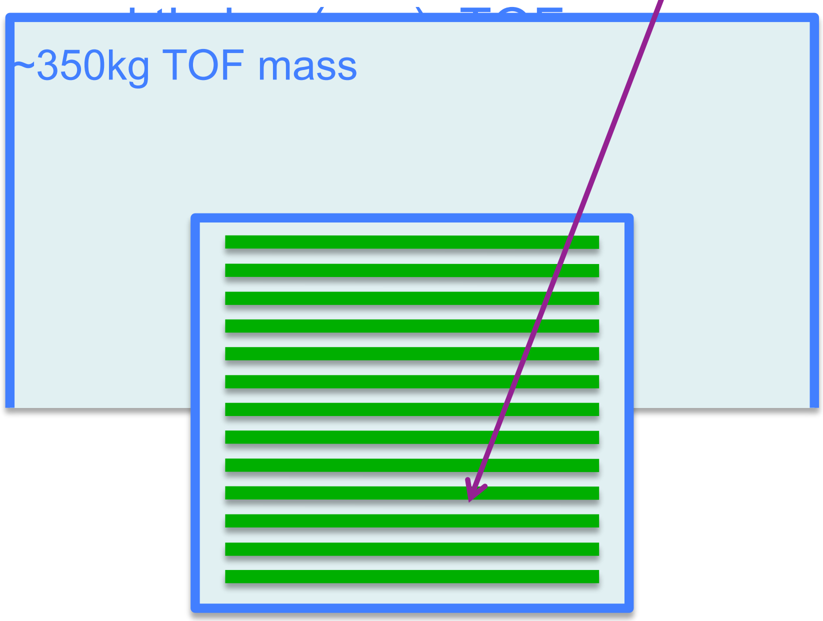
Surrounded by Plastic TOF

- Identify incoming charged particles

# Interesting Feature of GAPS Balloon Experiment

- Very large (~4m$^2$) Si(Li) detector, but simple fabrication dating to 1960's
- 1st balloon flight of cooled pixellated Si(Li) detector
- No pressure vessel

  (allows more mass for target)
- Very large plastic area (>10m$^2$) with




~200 kg Si(Li) mass

| Heat Dissipation & Power Load | [W] |
|---|---|
| Heat Dissipation per Si(Li) channel | 0.005 |
| Solar and other heat | 130 |
| **Total Heat Dissipation** | **400** |
| Power for Si(Li) Detector System | 1622 |
| Power for Plastic Detector System | 186 |
| Other power requirements | 200 |
| **Total Power** | **2008** |

| Mass Breakdown | [kg] |
|---|---|
| Si(Li) Detectors | 204 |
| Si(Li) Electronics, Cables, Support & Cooling | 315 |
| Plastic Scintillator | 151 |
| PMT, Light-guide, Cables, Electronics, Wrapping Support | 190 |
| Gondola, Computers, Telemetry Power, Radiator, | 376 |
| **Total** | **1237** |

Preliminary design estimates are compatible with doing good science on a balloon

# GAPS Detector Development involves commercial prototype evaluation and in-house flight production

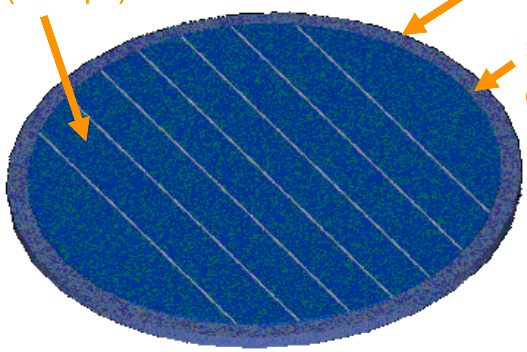
- Prototype flight consisting of ~ 10 commercial Si(Li) + TBD number of in-house fabricated Si(Li)
- Evaluate thick (4mm) SEMIKON Si(Li), Jan 2009
  - Energy resolution
  - Timing
  - Detection efficiency
  - Noise, capacitive cross talk, etc…
- Evaluate flight representative thin (2mm) SEMIKON Si(Li), spring 2009
- Parallel development of flight fabrication techniques & facility

# SEMIKON Si(Li) detector

Structured $P^+$-contact: Boron
(8 strips)

Ø = 102 mm

Ø = 94 mm
(4 mm Guard Ring)



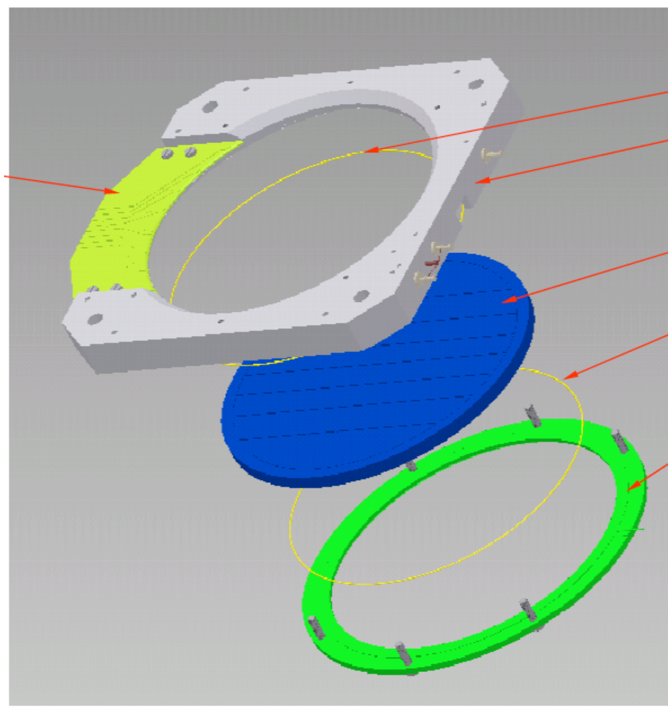
2mm thick

Active Area:  69.4 $cm^2$

4” diameter, 4mm/2mm thick

- N+ contact: Lithium
  - HV
- P+ contact: Boron
  - 8 strips
  - Guard Ring
  - Grounded

PC board



Indium ring

Detector holder

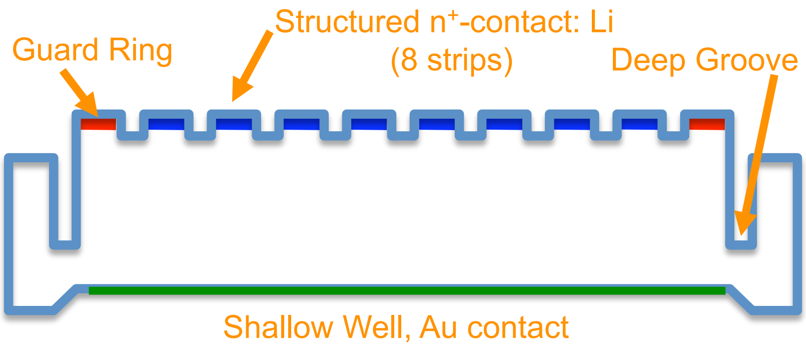
Si(Li) detector

Indium ring

POM ring

SEMIKON Detector GmbH

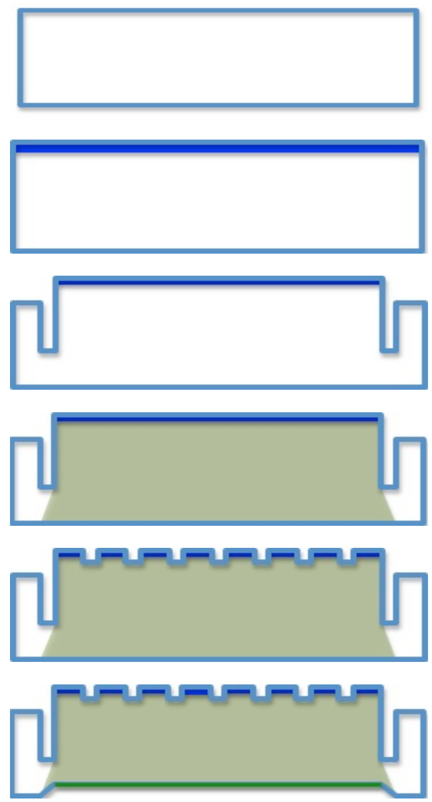
# Homemade Si(Li) Detector




4” diameter, 2mm thick

- N+ contact: Lithium (Al coating)
  - HV
  - 8 strips
  - Guard Ring
- P+ contact: Au
  - Shallow well
  - Grounded

**Proven, easy process**



Cut from the ingot

Evaporate Lithium

Produce the deep groove and mesa (optional)

Drift the Li into the silicon

Make strips and guard ring

Etch the back (shallow well) and evaporate Au

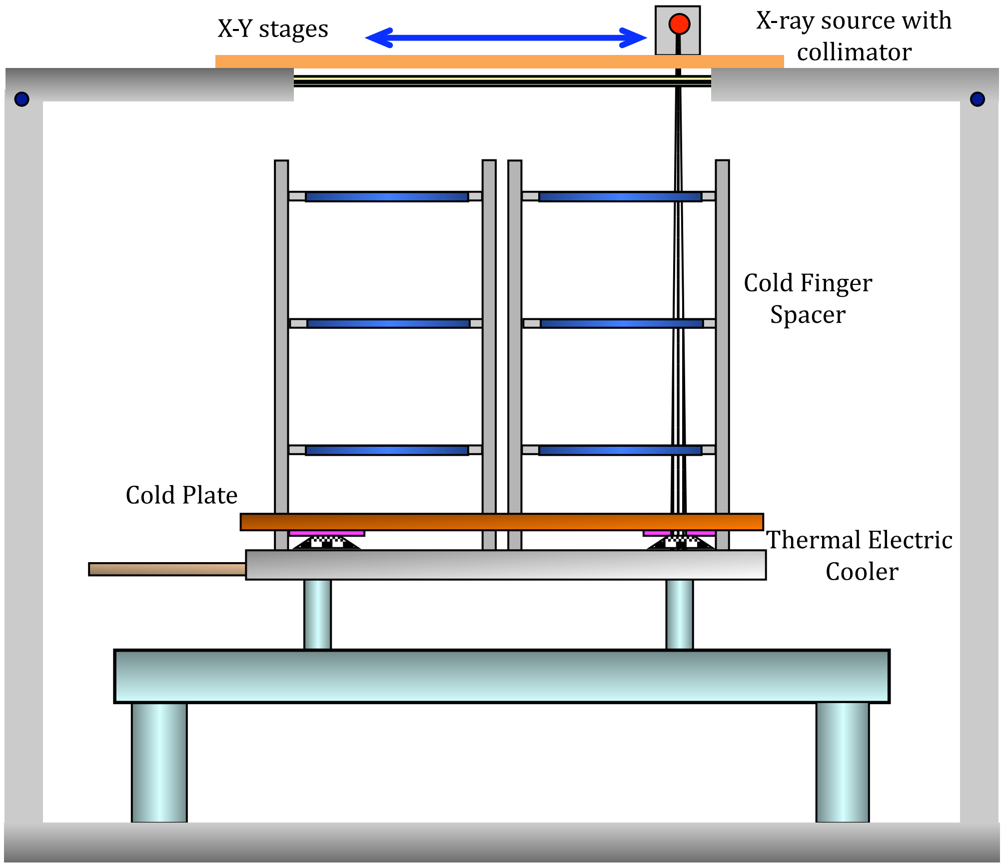
In-house facility at CU/DTU-NSC


Cutting

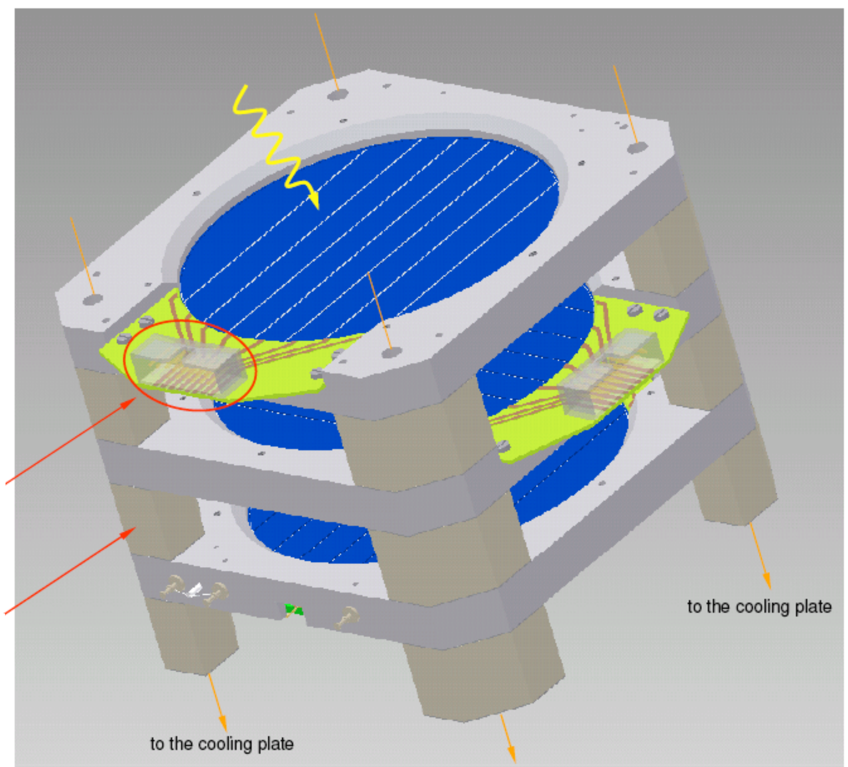
Drifting


Etching

# Si(Li) Characteristic Test

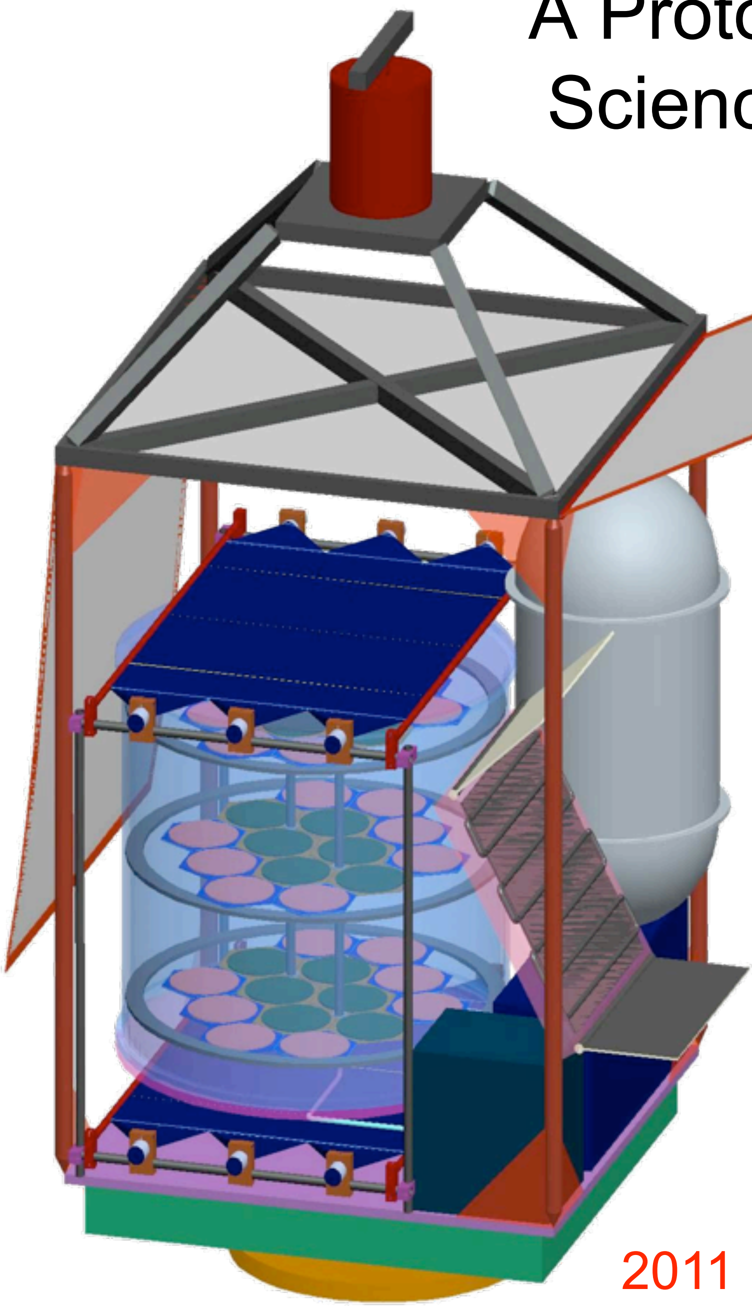



- Energy resolution
  - Dead layer
  - Dark current
- Timing
- Electronics test




- Pressure: $10^{-6}$torr – 1atm
- Temperature: –50°C
- Source:
  $^{22}$Na $^{55}$Fe, $^{109}$Cd, $^{133}$Ba, $^{241}$Am

# A Prototype Flight will provide a Crucial Science & Engineering Demonstration

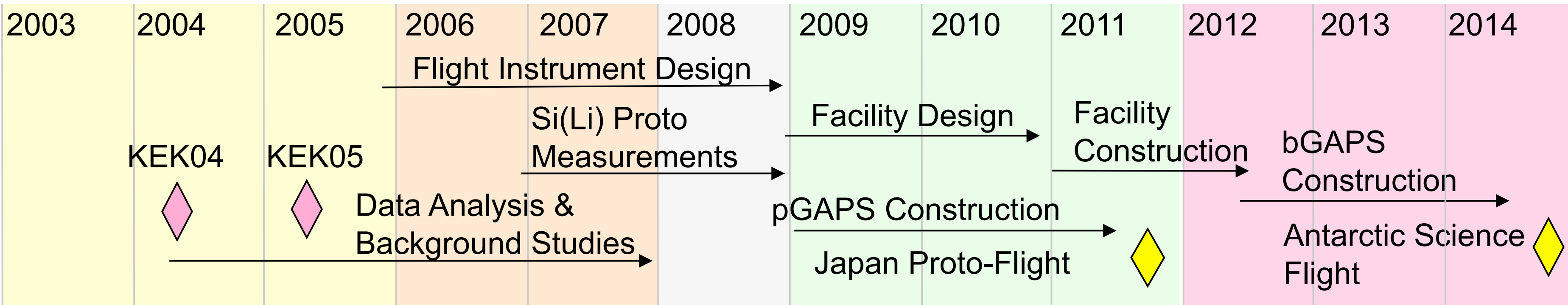


## Balloon Prototype Goals:

- Include ~10 commercial (SEMIKON) and a few of our in-house detectors.
- Demonstrate stable, low noise operation of the Si(Li) with its polymer coating at float altitude & ambient pressure.
- Demonstrate the basic functionality and operation of the TOF system.
- Demonstrate the Si(Li) cooling approach & deployable sun shades. Verify thermal model.
- Measure incoherent background level in a flight-like configuration.

2011 Prototype flight planned from Hokkaido, Japan

# GAPS Development Plan Culminates in a Long-Duration Balloon (LDB) Experiment




ORNL

C Hailey (PI), J Koglin, H Yu (PhD thesis '08), T Aramaki – Columbia
F Gahbauer – U. Latvia/Columbia - modeling
T Yoshida & H Fuke – JAXA/ISAS – Gondola systems (BESS Antartica)
S Boggs – UC Berkeley – Balloon electronics & background simulation
R Ong, J Zweerink – UCLA – TOF, Trigger system & instrument simulations
F Christensen – DNSC – Coatings Technology, Si(Li) fabrication
N Madden (Columbia), D Landis & Semikon GmBH (T Krings) – Si(Li) and detector electronics
K Ziock & L Fabris – ORNL – Electronics & ASIC design

# Source of Uncertainty