Indirect Dark Matter Search with Antideuterons: Progress and Future Prospects for General Antiparticle Spectrometer (GAPS)

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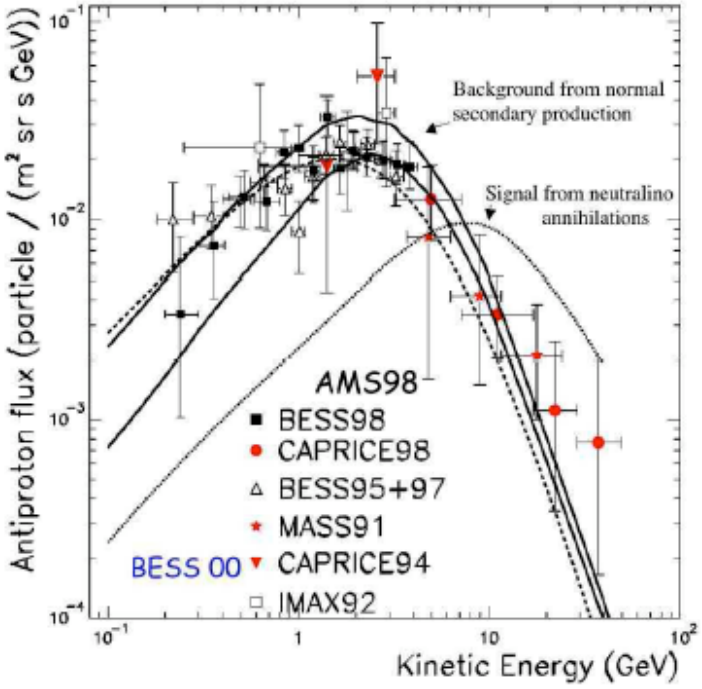
Why an antideuteron search for supersymmetric dark matter?

- **Growing number of papers in past 3 years suggesting antideuterons can probe very significant volume of parameter space in many SUSY models (eg. Recent review of mSUGRA concludes direct detection and antideuterons are the best means to find the neutralino and constrain mSUGRA (Edsjo, Schelke and Ullio 2004)**
- **Important complementarity with other approaches such as direct searches, gamma-rays and antiprotons**
- **Avoids well-known limitations of antiproton searches**
- **There are lots of direct searches and no antideuteron searches!**

Antiprotons are produced in neutralino-neutralino annihilation but are hard distinguish from cosmic-ray produced antiprotons



Picozza & Morselli 2002

- **Primaries:**

  $\chi + \chi \rightarrow p + \bar{p}$

- **Secondaries:**

  $p + p \rightarrow p+p+p+\bar{p}$

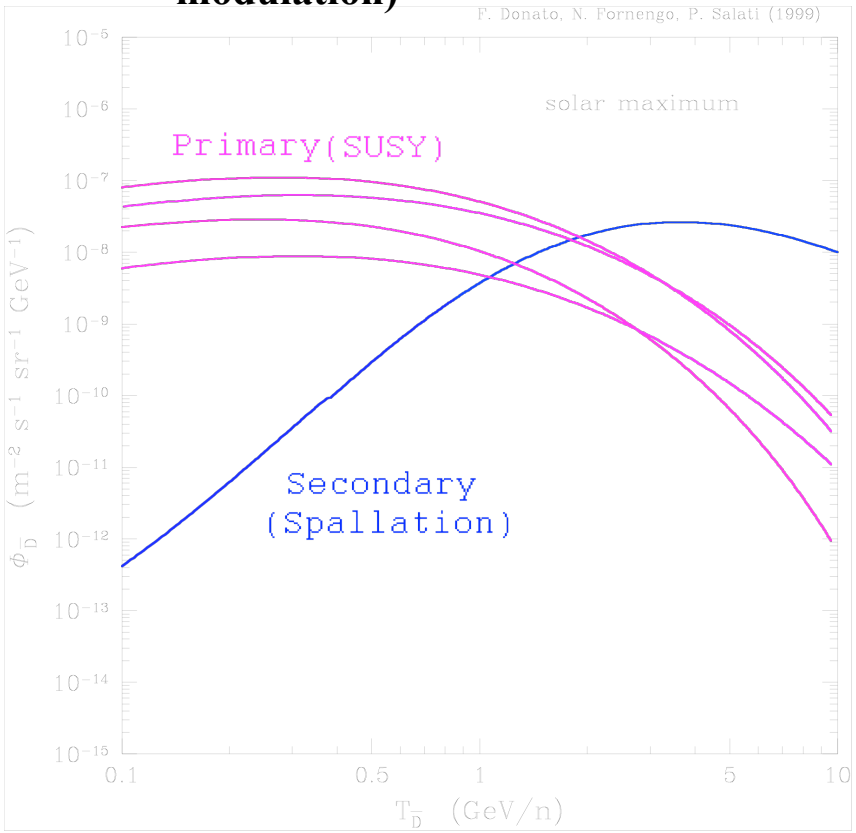
  $p + He \rightarrow p + He + p + \bar{p}$

- **Tertiaries:**

  $\bar{p}$ **with diffusive energy loss to low energies**

Low energy, neutralino-neutralino produced antideuterons are near background free

Antideuteron flux at the earth (w/propagation and solar modulation)



primary component: neutralino annihilation

$$\chi+\chi \rightarrow \gamma,\ \bar{p},\ \bar{D}$$

Secondary component: spallation

$$p + H \rightarrow p + H + X + \bar{X}$$

$$p + He \rightarrow p + He + X + \bar{X}$$

Cleaner signature than antiprotons (but see Barrau 2004) but sensitivity demand is daunting

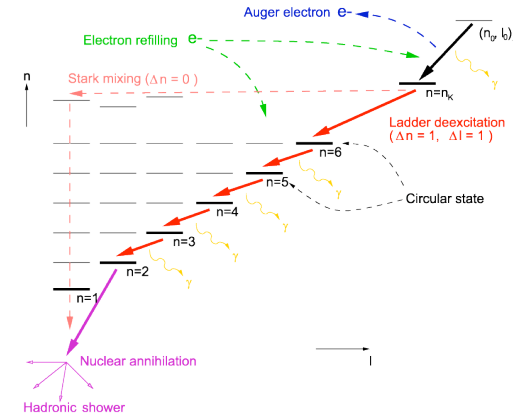
Sensitivity needs of antideuteron searches for DM will require next generation experiments

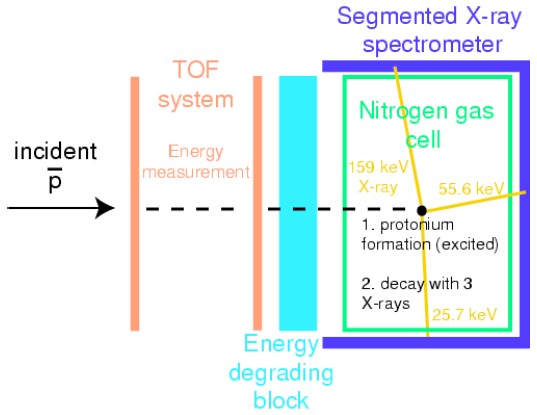
- **Current premier techniques utilize magnetic spectrometers from balloons (BESS/BESS-Polar) and space station (AMS) with grasp ~ 0.2 m^2-sr; these have reached practical limits of mass/grasp**
- **Optimal antideuteron search requires ~2-20 m^2-sr in package of ~ 1-2 metric tons with proton discrimination of ~ 1 part in 10^{12}**
- **AMS will just begin to obtain interesting sensitivity at higher antideuteron energies (>~ 1 GeV/n)**
- **First upper limit for antideuteron search recently reported by BESS (Fuke et.al. 2003)!**

GAPS is based on radiative emission of antiparticles captured into exotic atoms

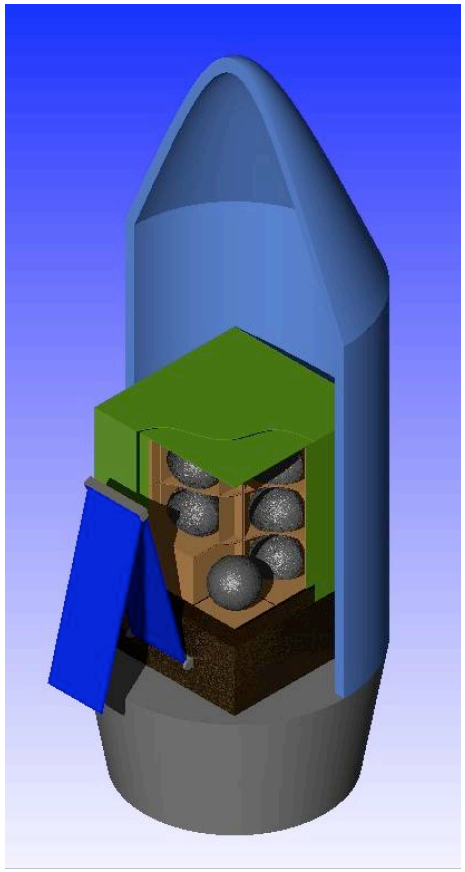
- **Slow down antiparticle in degrader (can be atmosphere)**
- **Capture into target atom**
- **Cascade of deexcitation X-rays of precisely known energy emitted in <~ 10ns**
- **Nuclear annihilation followed by pion star**
- **Nuclear deexcitation gamma-rays**

>> very precise signature of antimatter detection



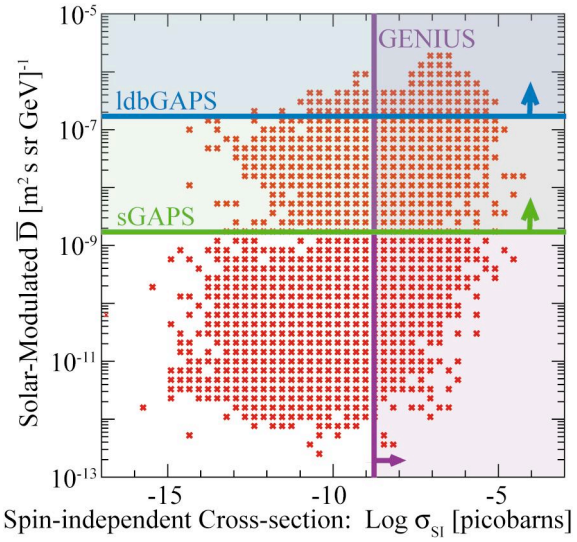


GAPS optimization principles have been discussed and experiments designed for both long duration balloon and Explorer missions



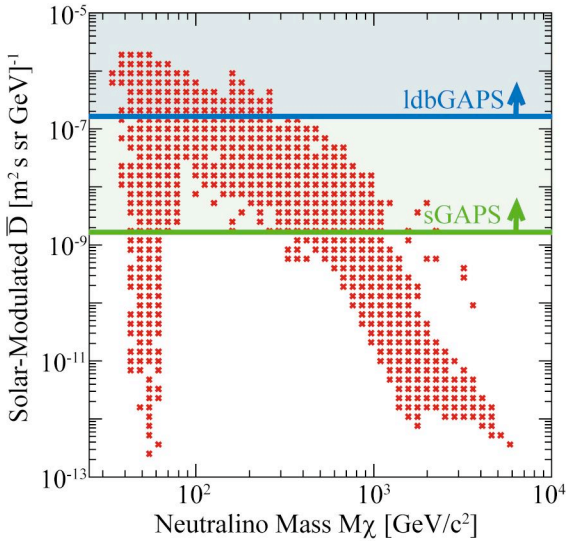
- Mori et.al. 2002 Astrophys. J. 566, 604
- Hailey et.al. 2004 Nucl. Instr.Meth B, 214, 122.

Antideuteron searches are complementary to direct dark matter searches



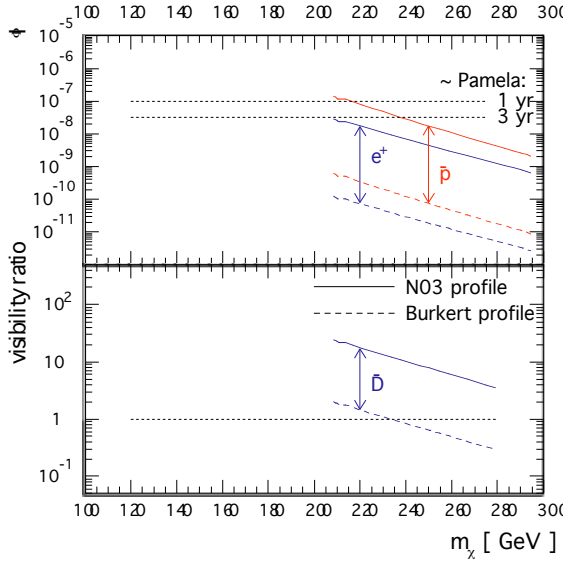
- CMSSM models collapsed down to one-dimensional parameter space (T.Baltz 2003)
- Balloon and satellite implementations of GAPS shown
- GENIUS shown as typical 3rd generation direct experiment
- Second quadrant is probed uniquely by antideuterons

Antideuterons provide a powerful means to probe CMSSM even at very high neutralino mass



- Experiment sensitivity is independent of neutralino mass
- Even a modest balloon experiment can probe SUSY parameter space
- Satellite experiment can bottom out a good fraction of parameter space
- Great low energy antiproton physics too

Antideuterons often represent either the best neutralino probe or a unique probe

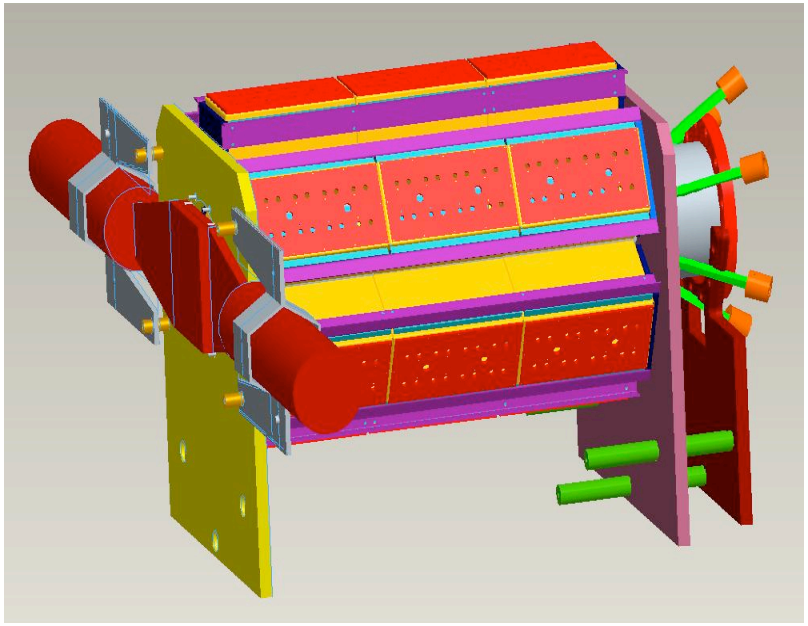


- **(left) stop coannihilation region of a mSUGRA model (direct detection cross-section too low for even 3rd generation expts.) (Edsjo et.al. 2004)**
- **For 3 benchmarks of Profumo and Ullio (2004) (mSUGRA funnel, non-universal gaugino (NUGM) and minimal anomaly mediated SUSY breaking (AMSB), GAPS can detect neutralino – even balloon based experiment can do this**

The atomic physics of exotic atoms is understood but accelerator testing was mandated by NASA peer review: much useful info was learned

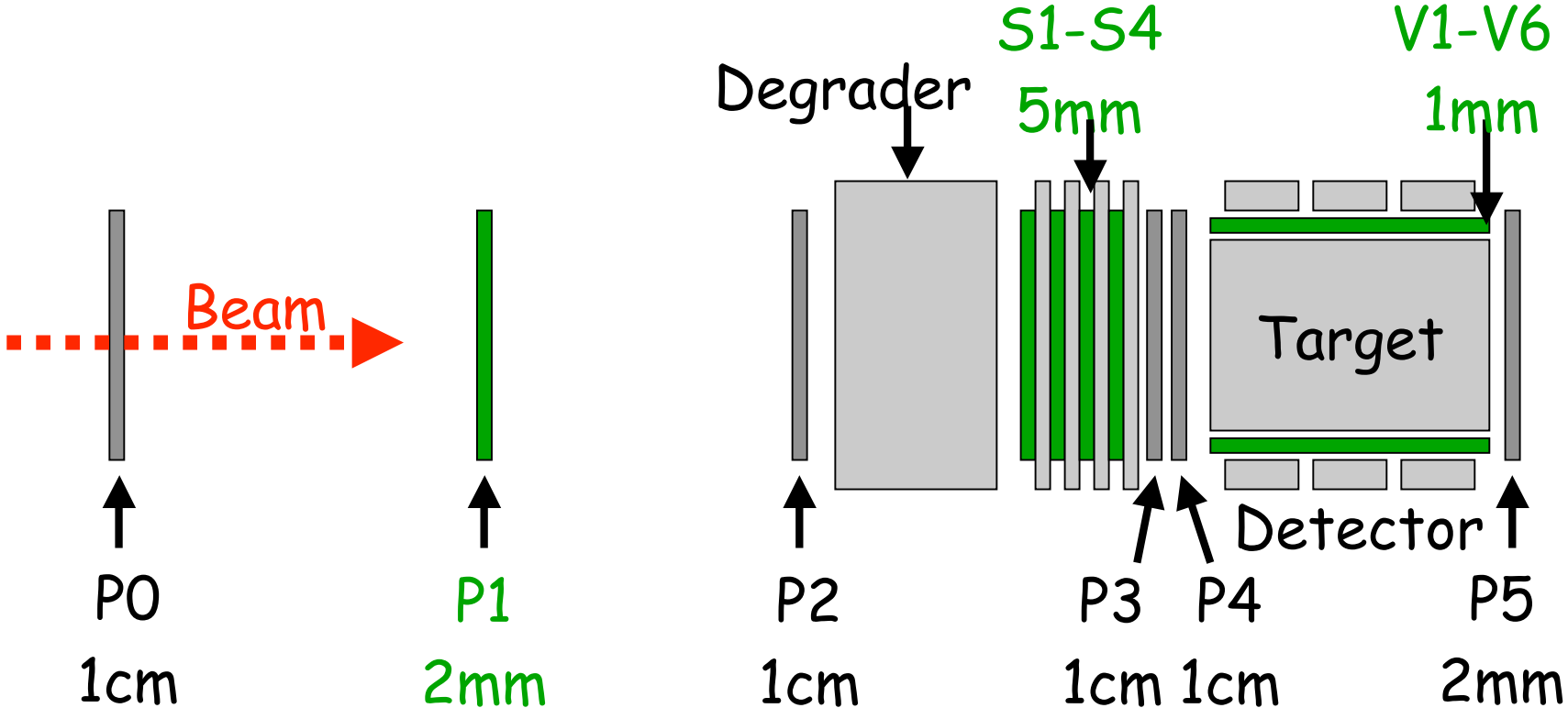
- What is the detection efficiency? (measure yield of X-rays per capture)
- Investigate flight representative data acquisition electronics and detector approaches
- Investigate signatures generated by particle backgrounds (protons, pions, electrons etc.)
- Investigate specific target materials
- Investigate processes not well charaterized by previous experiments (higher energy X-ray transitions, nuclear gamma-rays)
- Investigate solid targets (original concept used gas…)

Detector approach was dictated by trade between performance and shoe string budget



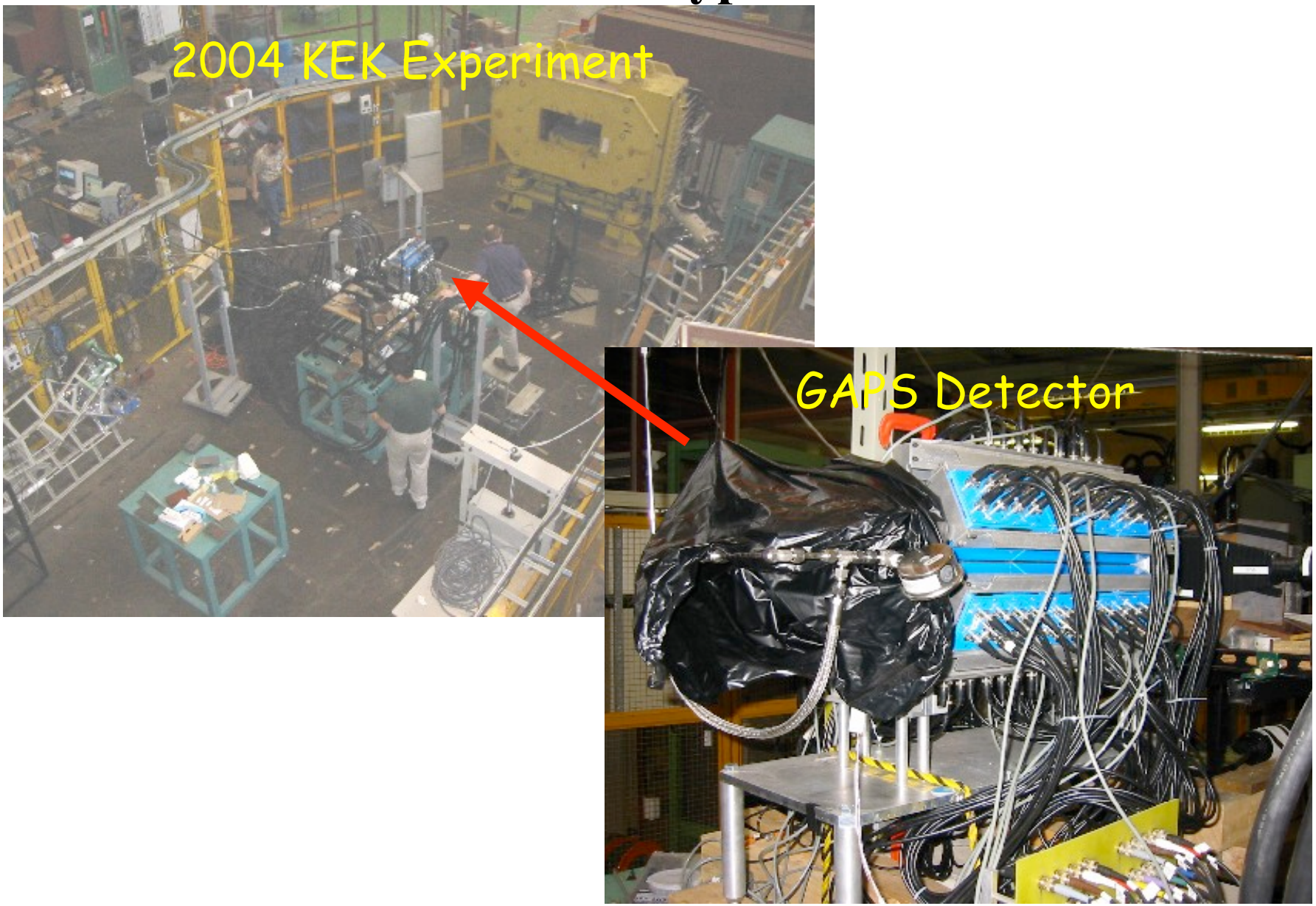
- 16 modules of 5mm NaI(Tl) arranged to cover 40cm target cell
- Each modular 4x2 arrays of 25mm crystals
- Solid angle coverage ~ 0.3

KEK Accelerator tests were designed to obtain data on X-ray performance in well-characterized particle beams



- P0-P5: XP2020 (Beam Counters)
- S1-S4: XP2072/XP2042 (Shower counters)
- V1-V6: 1924A (Charged particle veto counters)

GAPS Prototype Detector

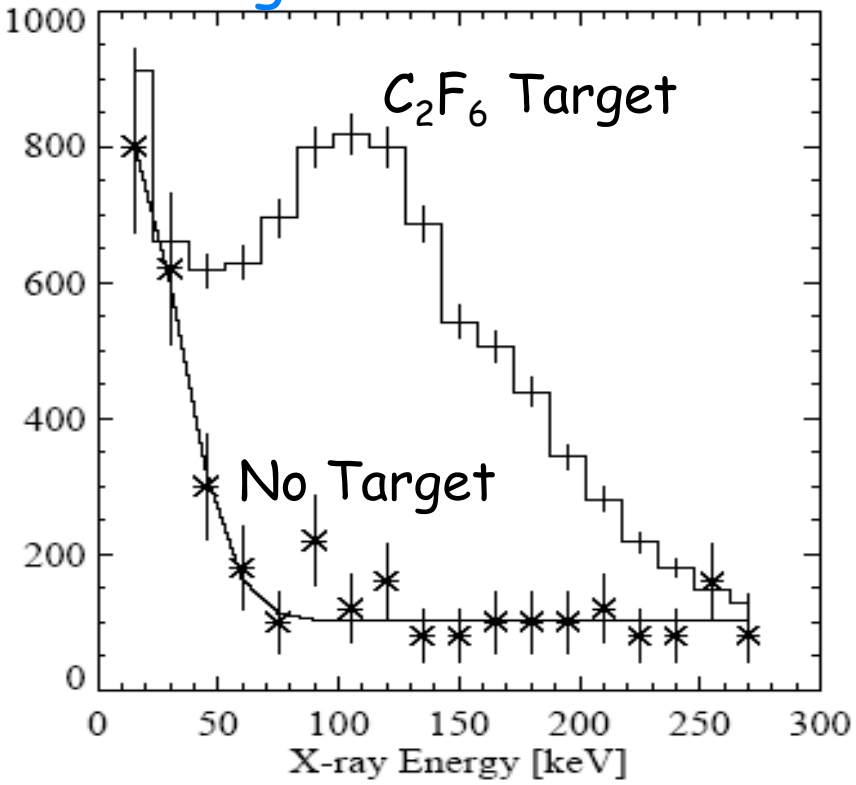


Run Summary KEK 2004 and 2005

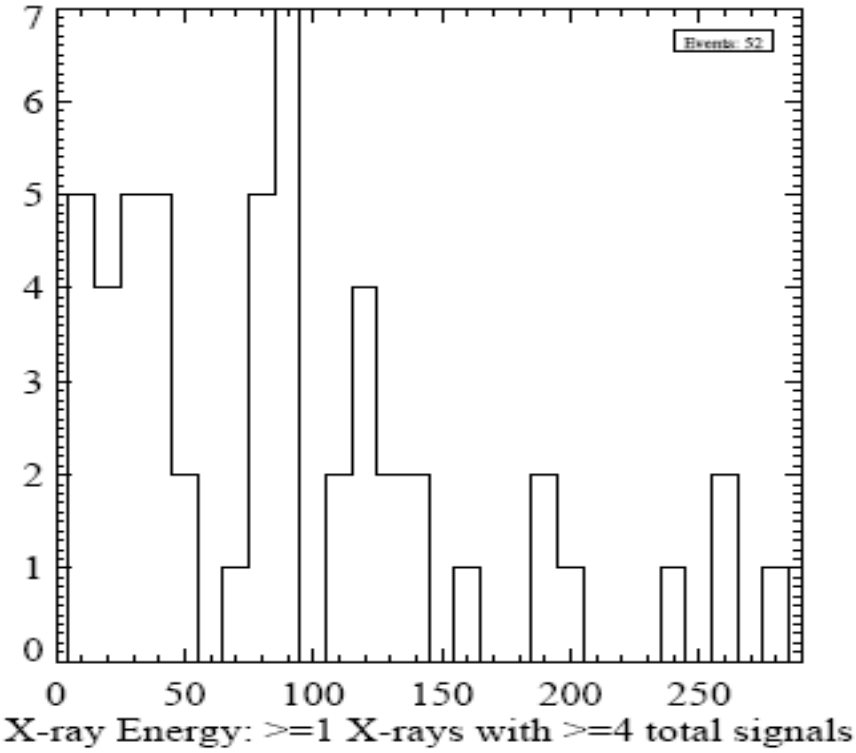
- **Targets of C_2F_6 (gas), C(Aerogel), Al, S, CCl_4 and CBr_4 were utilized motivated by known high kaonic X-ray yields and favorable X-ray energies**
- **Targets were also studied with protons and pions of energies between 0.2-1.2 GeV, a primary background source in space-based experiments**
- **Al and Fe targets were also tested with muons**
- **Measurements were made with and without target in detector and without degrader**
- **Successfully identified antiprotons in environment with S/B ~ 10^{-5} without use of external triggers**

2004 KEK GAPS Results

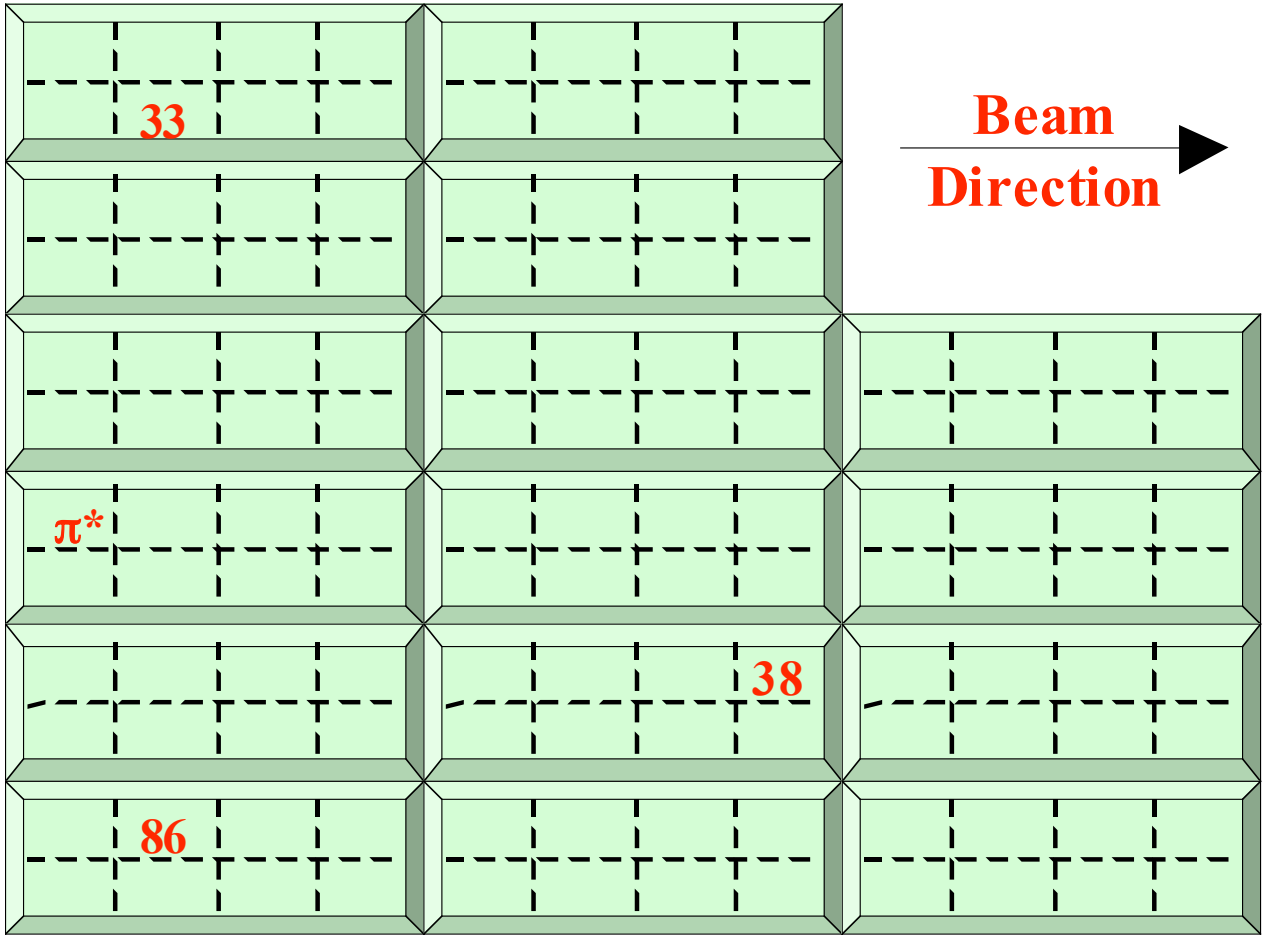
We clearly get X-rays when we dump Pbars into our target



More importantly, we see exotic X-ray transitions!!!

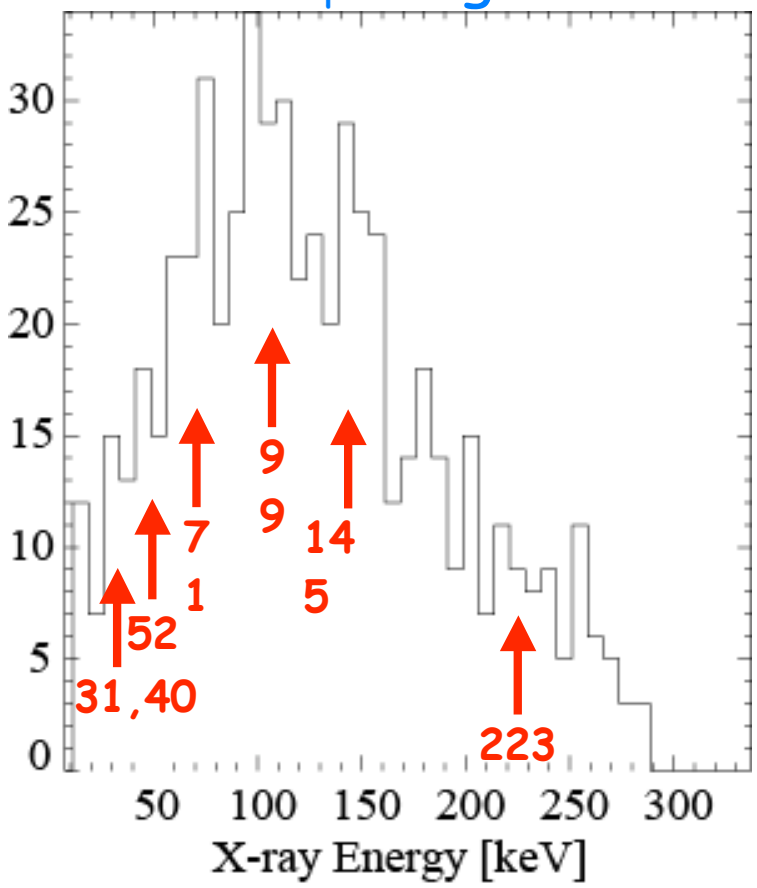


GAPS C_2F_6 Event (2004): 3 X-ray Transitions + 1 Pion

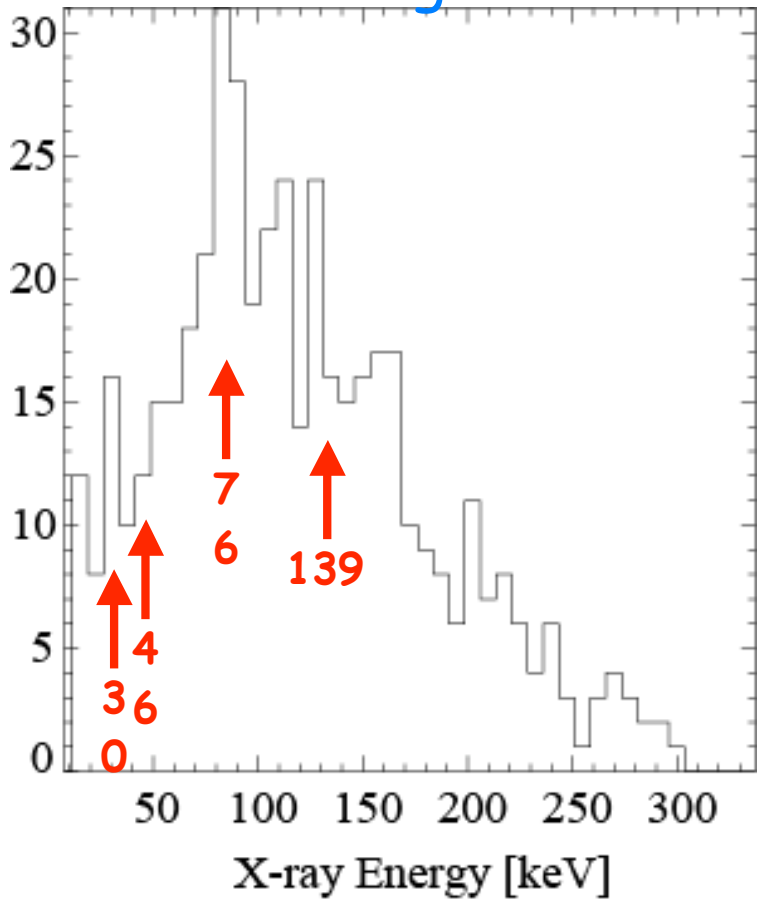


KEK 2005 integrated antiproton spectra

CBr_4 Target:

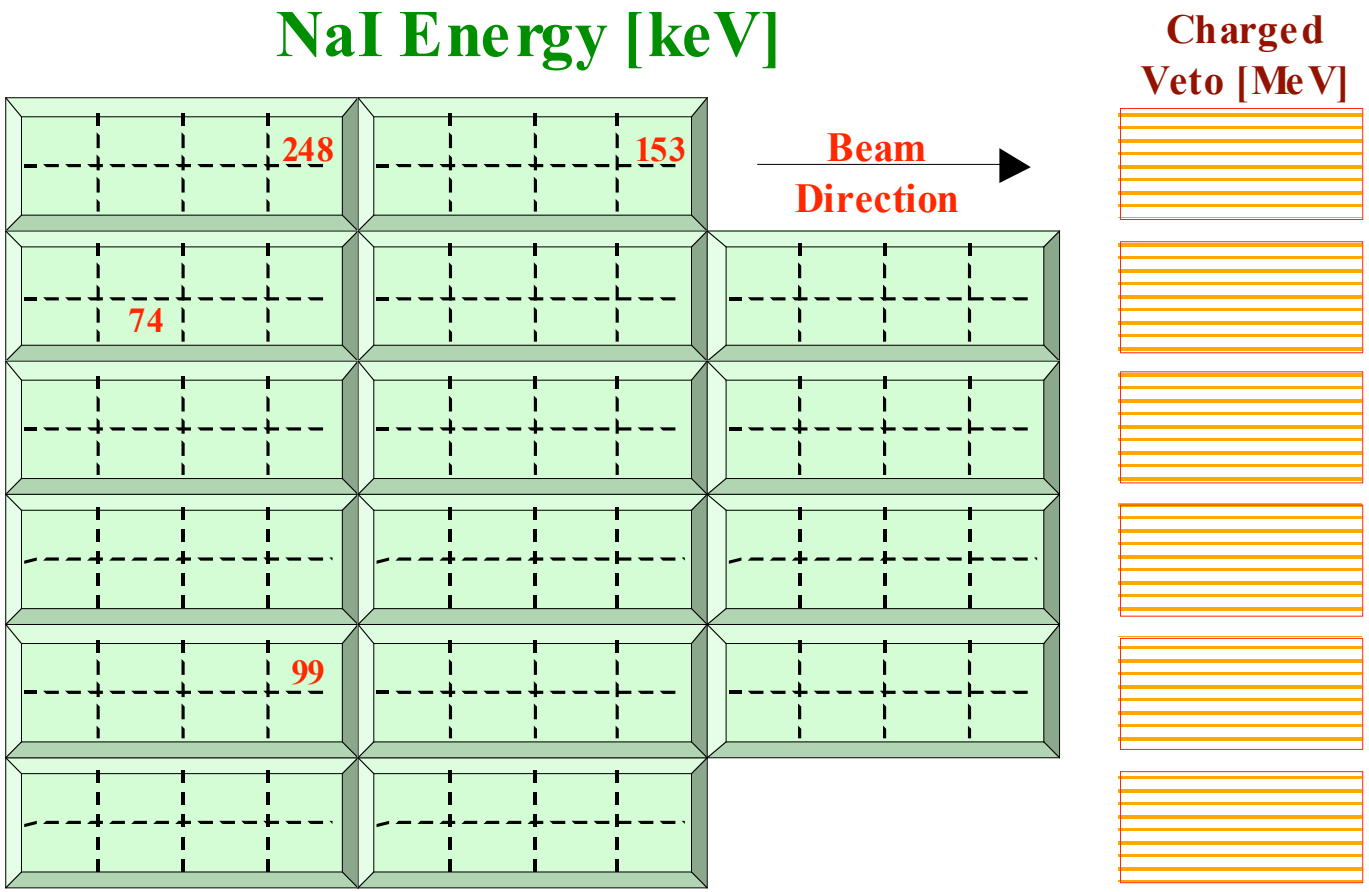


S Target:

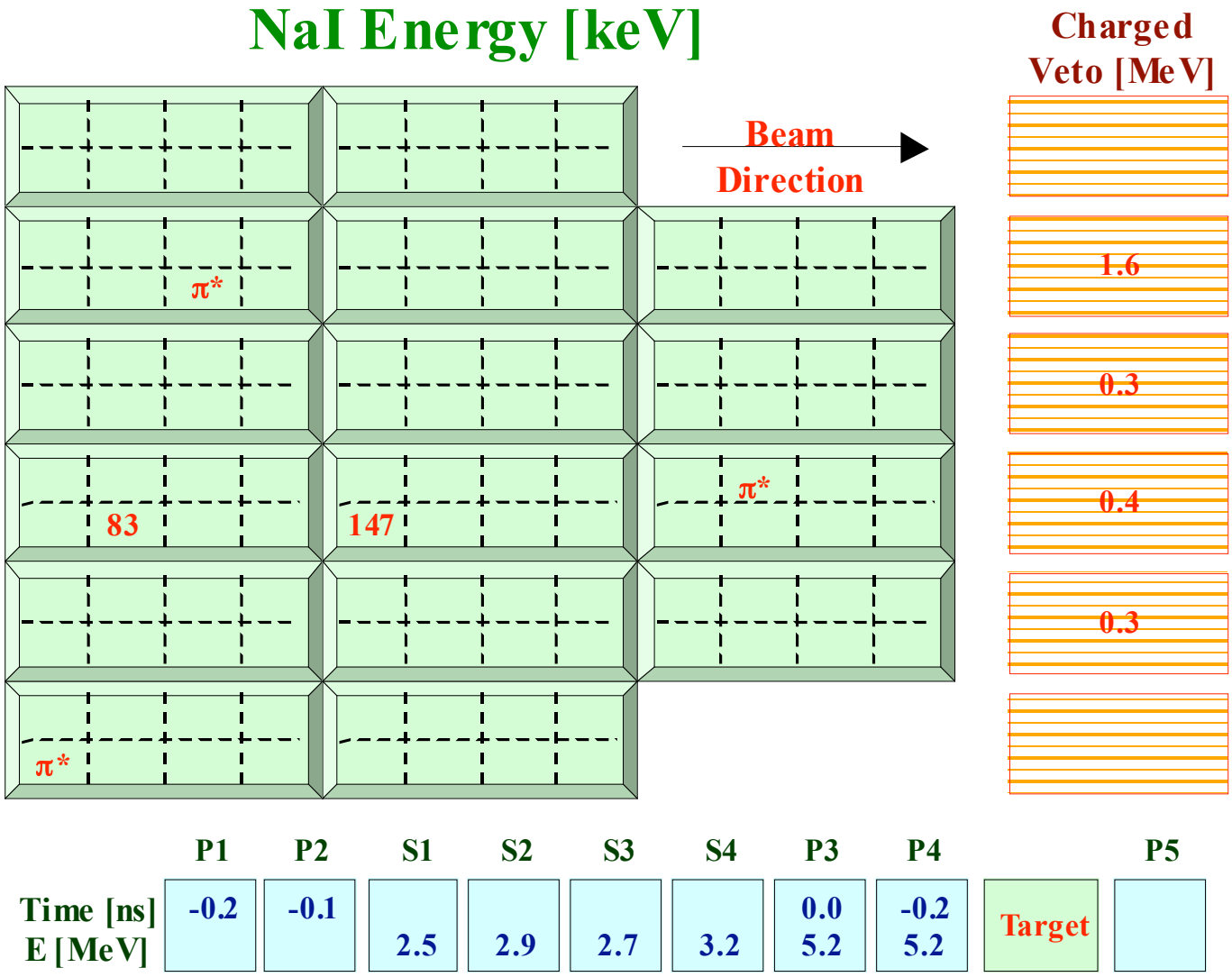


Cuts: ≥ 2 X-ray & ≥ 4 total signals

CBr_4 Event KEK 2005: 4 X-ray Transitions



S Event KEK (2005):
2 X-ray + 3 Pi* Transitions



Preliminary results from KEK experiments and implications for Antideuteron searches

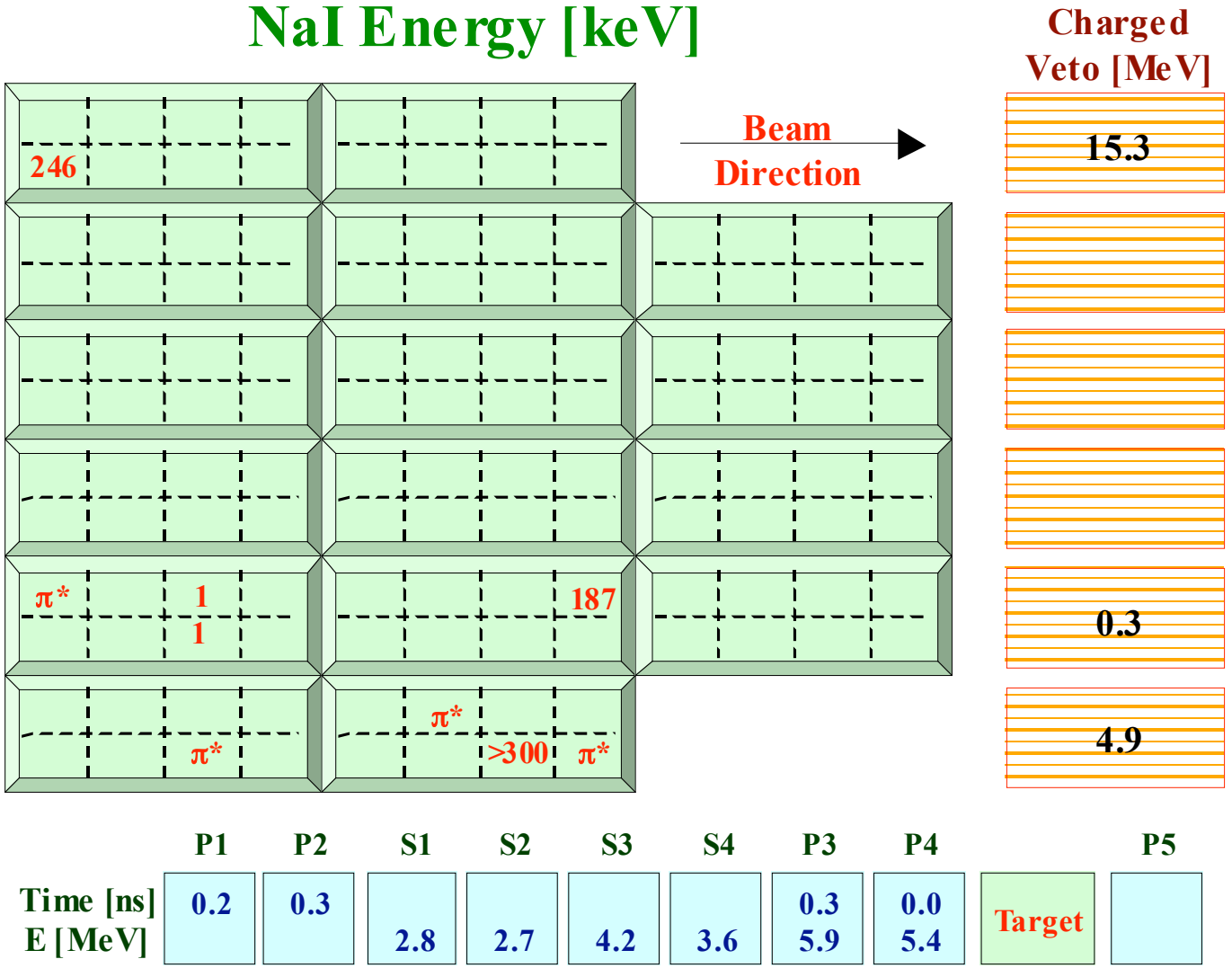
- **Solid targets have been successfully utilized: simplification over initial concept is enormous (reduced mass and complexity, higher efficiencies for detection due to reduction of dead mass)**
- **Solid targets provide more design options, enabling >=4 X-ray captures, increasing background rejection capability over original 3 X-ray concept**
- **Pion stars provide substantial additional antiparticle identification capability (ignored in initial concept sensitivity calculations)**
- **Nuclear X-rays are added confirmation of antiparticle capture also ignored in original sensitivity calculations**
- **Preliminary results on X-ray yields per capture are consistent with those used in original sensitivity calculations**
- **Non-antiparticle background is cleanly identified and rejected**

Conclusion: GAPS is probably more promising than originally anticipated

Goal is to conduct balloon-based GAPS antideuteron search by 2011 (or sooner)

- **Investigation of flight detectors (eg. CZT, LaCl, NaI) and readout geometries (PMT, APD, fiber-coupled scintillator bars) and low cost electronics. Baseline is NaI bars with very small PMTs on both ends in TO-5 electronics cans from Hamamatsu 2006-2008**
- **Detailed design and simulation of flight geomtry, extending on original work 2006-2008**
- **Design and construction of gondola 2008-2009**
- **Flight test of prototype GAPS from Lynn Lake, Canada to evaluate in-flight background, 2009**
- **LDB flight from Antarctica or ULDB flight from Australia (if available) 2011**

CBr_4 Event (2005): Pbar Track Through Detector



S Event KEK (2005):
Pbar Track Through Detector