Space-based Detection of Antimatter with a Novel Detector Based on X-ray Deexcitation of Exotic Atoms and Applications to Dark Matter Searches

Contents:

- **Antideuterons for detection of dark matter**
- **Concept of the Gaseous Antiparticle Spectrometer (GAPS)**
- **Plans for laboratory testing**
- **Potential space applications**

- **C.J. Hailey, J. Koglin, K. Mori and H.T. Yu Columbia Univ.**
- **F.A. Harrison, CalTech**
- **J. Hong, Harvard Univ.**
- **W.W. Craig and K.P. Ziock, Univ. of California, Lawrence Livermore National Laboratory**

The observational evidence for dark matter is overwhelming

- **Observed mass to light ratios increase with cosmic length scale: Ω_m varies from ~.001 to ~0.3 from solar neighborhood to cluster of galaxy scale**
- **Galactic have flat rotation curves beyond their visible mass distributions → extended dark halos**
- **X-ray emitting gas in hot clusters: mass required to bind gas to clusters is much greater than radiatively emitting gas**
- **Galaxy formation theory: cannot explain the power spectrum of galaxies without invoking existence of dark matter**

The observed dark matter must be primarily non-baryonic and primarily “cold”

- **Observed deuterium abundance + big bang puts upper limit in baryons Ω_b ~ 0.04 << Ω_m (MAP Ω_b = .032)**
- **Cold (non-relativistic) dark matter (CDM) is required to obtain adequate growth of fluctuations at epoch of recombination so that CMB power spectrum and galaxy power spectrum agree**
- **Hot dark matter (such as light neutrinos) generate too little power on small scales to be significant DM source (also ruled out by WMAP: universe reionized too early for neutrinos as DM)**
- **Microlensing searches show massive compact halo objects (MACHO) eg. brown dwarf, white dwarf, black hole are a negligible contributor to dark matter in our galaxy in mass range ~10^{-7}- 10 M_{solar}**

Several cold dark matter candidates are well-motivated by theoretical considerations

Axion:

- **explains why P and PC are conserved in strong interactions but not weak interactions**
- **Current search uses microwave cavity – spans 1 of 3 decades of mass where axion can lie**

- **Supersymmetric (SUSY) dark matter candidates:**
- **Charginos: ruled out by accelerator and underground searches since color and charge would bind to normal matter making very heavy isotopes**
- **Gravitinos: difficult to rule out**
- **Neutralino**

The neutralino is a cold dark matter candidate particularly well-motivated by SUSY theory

- **SUSY solves the mass hierarchy problem between weak scale and Planck scale**

- **To avoid rapid proton decay assume R-parity conservation ($R = (-1)^{3B+L+2S}$) is unbroken → the lightest supersymmetric particle (LSP) must be stable**

- **Neutralino $X = a\,\tilde{B} + b\,\tilde{W}^3 + c\,\tilde{H}_1 + d\,\tilde{H}_2$**

- **Coefficients a, b, c, d depend on common gaugino mass, Higgs mass mixing parameter and ratio of Higgs VEV**

- **For a broad range of SUSY parameters can obtain cosmologically significant relic LSP density**

Direct searches for the neutralino are plentiful

Direct searches rely on neutralino-nucleon elastic scattering and search for a recoiling target nucleus

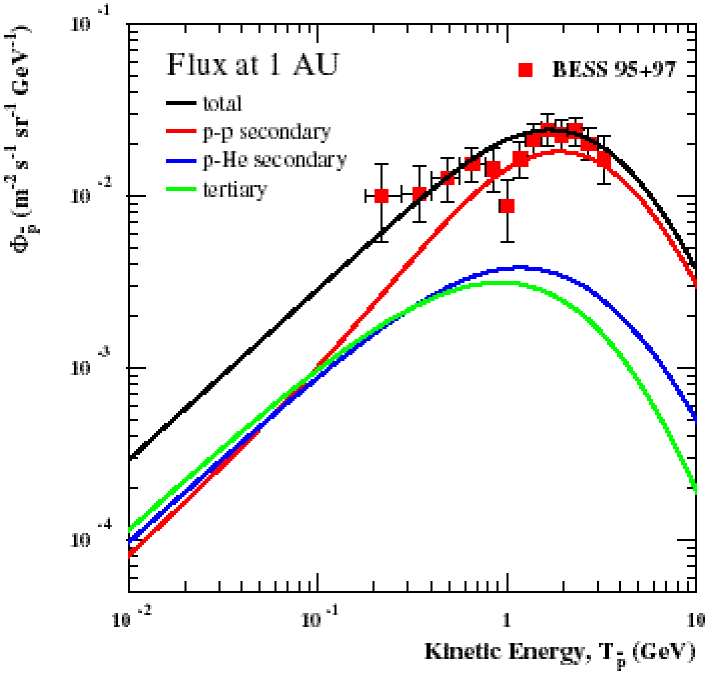
- **Working in Xenon: ZEPLIN I**
- **Planned in Xenon: ZEPLIN II/III; XENON; XMASS**
- **Working in Si/Ge: CDMS II, EDELWEISS**
- **Working in $CaW0_4$: CRESST I; CRESST II (planned)**
- **Low Z gas: DRIFT I (working), DRIFT II (planned)**
- **Germanium: GENIUS (planned)**
- **Argon (planned?)**

Must do these experiments deep underground to avoid contamination from tertiary muon produce neutrons and secondary atmospheric neutrons

Indirect searches can exploit neutralino annihilation, since the neutralino is a Majorana particle

- **Neutrinos**
- **Gamma-ray searches with Compton Gamma-ray Observatory (continuum) and GLAST (line emission) – not very sensitive**
- **Positron searches: HEAT reported a high energy bump ~ 1 GeV (Tarle 2002)**
- **Antiproton searches with BESS 95 and 97, BESS POLAR**
- **Antideuteron searches : GAPS ?**

The low energy antiproton spectrum is adequately fit by models without primary antiprotons



- **Primaries:**

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

- **Secondaries:**

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

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

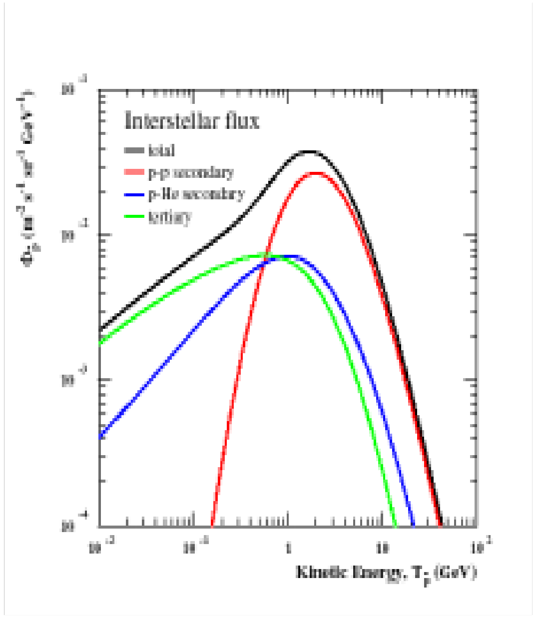
- **Tertiaries:**

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

To search for new physics requires ultra-low energy antiprotons and this is difficult

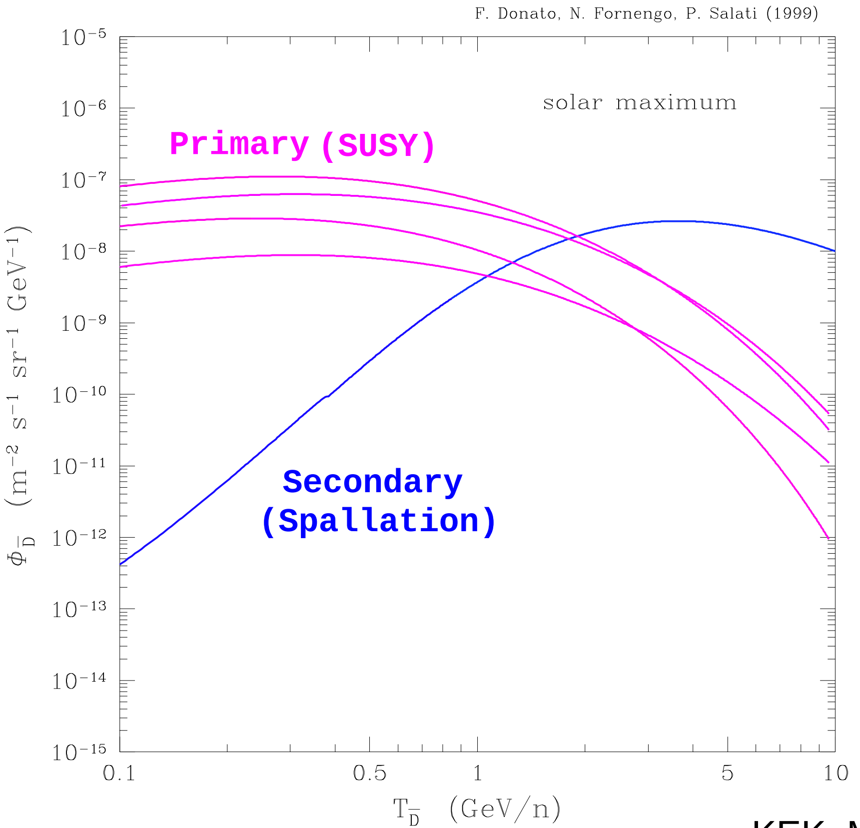
- To get new physics (dark matter, evaporating black holes) must get to low antiproton energies BUT
- Solar modulation effects in low earth orbit wash out low energy antiproton signal: must launch satellites out of the heliosphere
- Kinematic effects allow secondary antiproton signal to contaminate spectrum to very low energies

P. Ullio (2000)



Cosmic antideuterons are an indirect but clear sign of dark matter

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

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

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

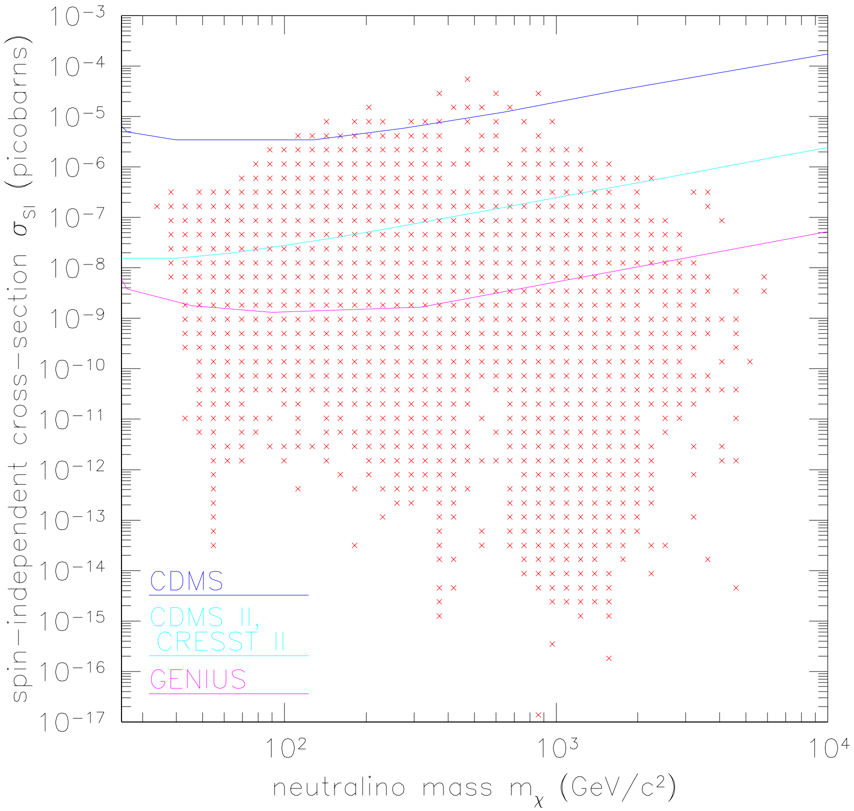
Cleaner signature than antiprotons

Antideuteron flux ~10^{-8} $m^{-2}s^{-1}sr^{-1}GeV^{-1}$

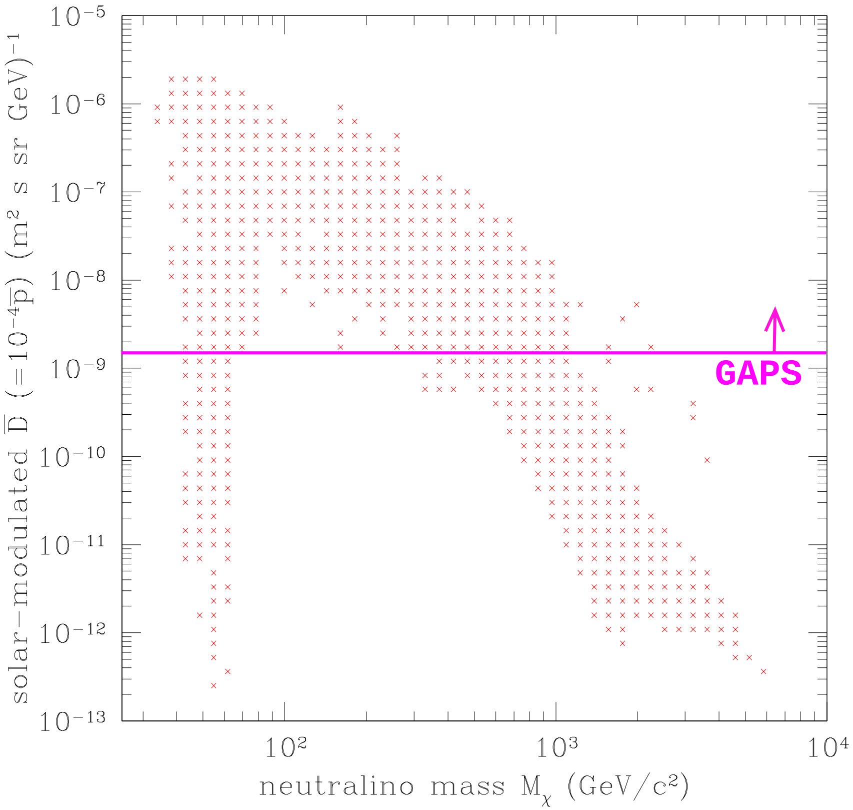
Large grasp AΩ [m^2 sr] required

GAPS measures low energy antideuterons produced by neutralino annihilation in the mass range M_χ ~80-350 GeV

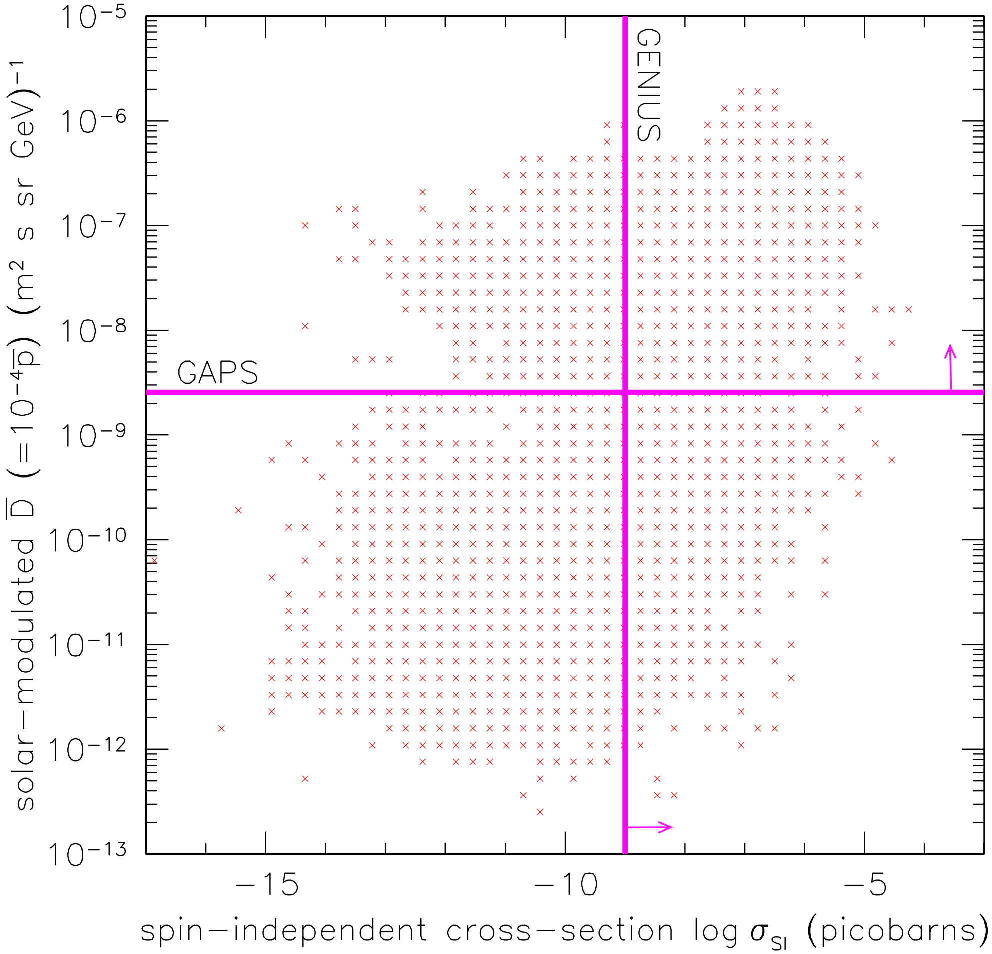
Direct Dark Matter Searches



GAPS (3 year Explorer Mission)



GAPS plays a complementary role to direct detection neutralino searches



Current antimatter detection methods exploit particle deflection or calorimetery

- **Magnetic Spectrometers**
  - **momentum (deflection angle in B-field + velocity (TOF)**
  - **AMS (2005?), PAMELA (2003), BESS (95, 97), BESS POLAR**
- **Calorimeters**
  - **deposited energy (calorimeter) + velocity (TOF)**

Problems:

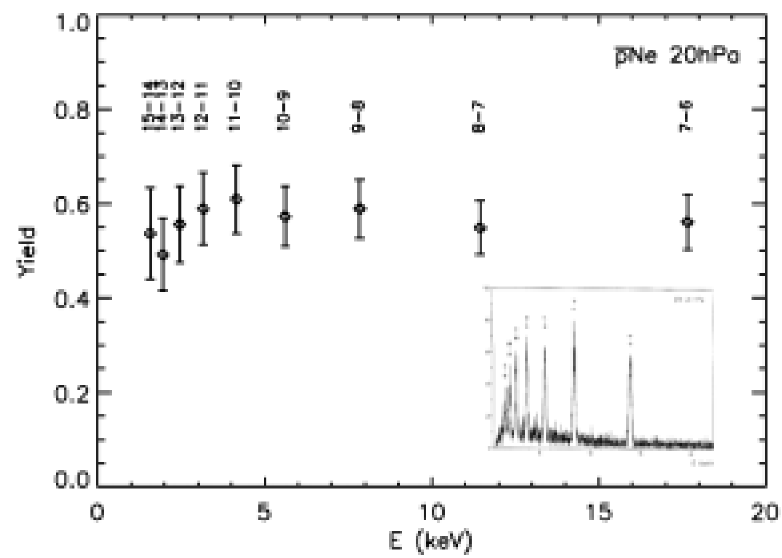
Heavy mass (magnetic spectrometers)

poor background rejection power (calorimeters)

limited field of view and small effective grasp (both)

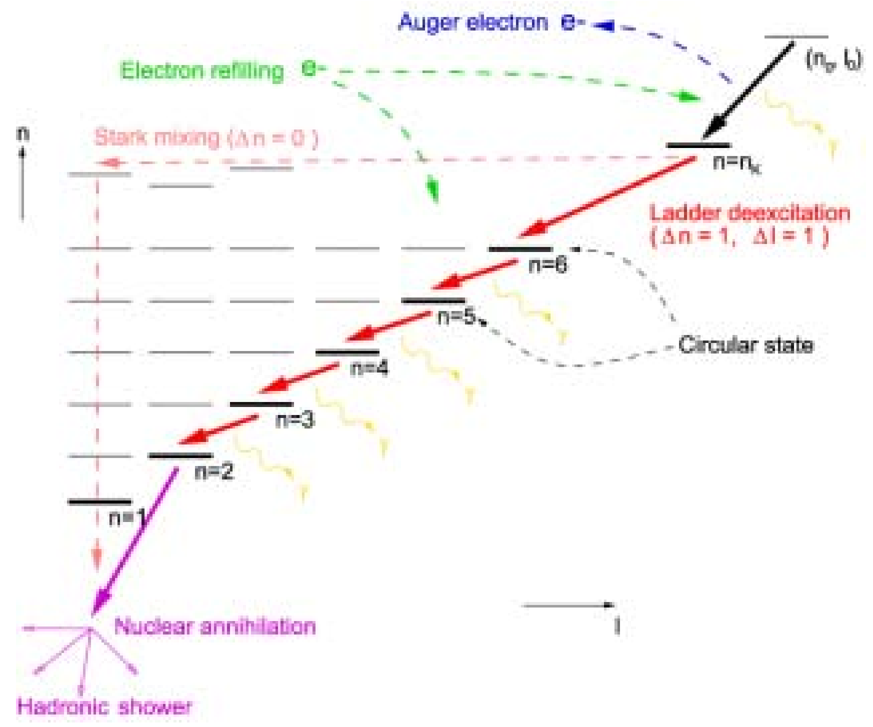
Gaseous Antiparticle Spectrometer (GAPS) operating principles

- **Particle identification and energy determination >> spectroscopy**
- **Velocity measurement by TOF + mass >> energy**
- **Deceleration of incident particle by dE/dx in degrader and gas**
- **Capture of antiparticle into exotic atom >> negative charge**
- **Detection of photons from radiative deexcitation by X-ray detectors**
- **Well-defined hard X-rays (~20-150 KeV) >>particle ID >>mass**



The atomic physics of GAPS is well understood

- Capture of antiparticle into highly-excited state
- Deexcitation via radiative or Auger transition (emitting electrons)
- Complete depletion of bound electrons
- Radiative ladder deexcitation >> X-rays
- Annihilation with nucleus emitting pionic shower



Atomic physics sets operating range for GAPS gas cell

- **All bound electrons are depleted via Auger ionization at n~ 19 for antideuteron**

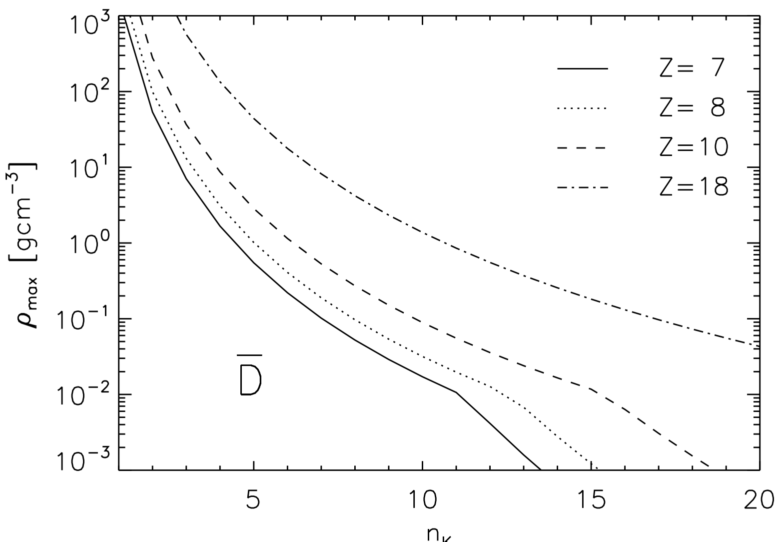
>> decays only via radiative deexcitation

Ladder Transitions for antideuteron in Nitrogen

Ladder transition	6 → 5	5 → 4	4 → 3
Photon energy (KeV)	26.2	48.2	104

Operating range for gas pressure is determined by:

- **Stark mixing (Δn=0 transitions)**
- **electron refilling**



Gas and pressure optimization is based on minimizing Stark mixing and gas opacity for X-rays

Electron refilling suppresses Stark mixing at high n

Radiative transition rate is higher than Stark mixing rate at low n

→ adjust pressure so that Stark mixing rate is lower than electron refilling rate UNTIL radiative rate of X-ray transitions is dominant

Require $\Gamma_{refill} > \Gamma_{stark}$ while n > n(lines) [this will suppress Stark effect]

Require $\Gamma_{ladder} > \Gamma_{stark}$ when $\Gamma_{ladder} > \Gamma_{refill}$ [radiative transitions dominate]

- **H, He Stark effect too big**
- **Xe, Kr photelectric absorption (~Z^4) too large**
- **Conclude N_2 ,O_2 , Ne, Ar ~ 5-50 atmospheres**

GAPS atomic physics is complex

- **Normal transition Γ(ladder)~ $(zZ)^4$ n^{-5}**
- **Complete Ionization due to Auger effect when E(ladder) = I_K = Z^2 Ry**
- **Stark splitting due to E-field of adjacent atoms leads to critical density $\acute{\omega}_{stark}(R) = \Gamma_{ladder}(n)$**
  $R(n) \sim (zZ)^{-5/2}\ n^{7/2}$
  require R = intermolecular distance > R(n)
- **gases $\Gamma_{stark}(n) = \langle N_a \pi R(n)^2\ v \rangle \sim n^7 \rho T^{1/2}\ (zZ)^{-5}$**
- **$\Gamma_{refill} = \langle n_e\ v\ \sigma_r \rangle \sim \rho\ \sigma_r\ T^{1/2}$: electron shell refill time**

Total antideuteron losses by nuclear processes are <~ 5 - 10%

Calculated probability of antideuteron loss by integrating the energy-dependent cross section of the following nuclear processes over the particle paths in the GAPS detector.

- **Direct annihilation**

  $\bar{D} + N \rightarrow C(Z+1, A+2)$

- **Coulomb disintegration**

  $\bar{D} + N \rightarrow \bar{p} + \bar{n} + N$

- **Oppenheimer – Phillips process**

  $\bar{D} + N \rightarrow C'(Z, A+1)$ or $C''(Z+1, A+1)$

Irrelevant because antiproton and antineutron are both attracted to the nucleus by Coulomb and strong force

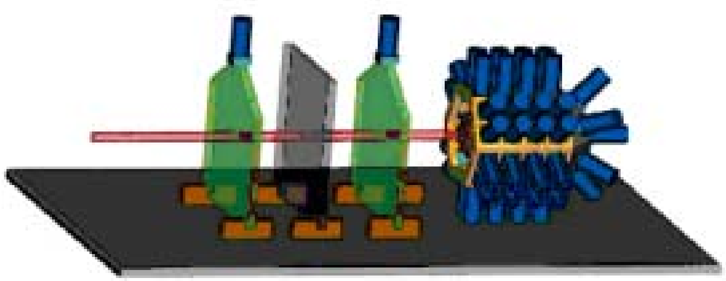
GAPS background is complicated

- High proton flux, ~10^9 proton per antideuteron
- Coincidence of proton + 3 photon background is primary problem
- spallation and activation produce beta-particles, neutrons (n,gamma),(n,n')
- gamma-ray from diffuse continuum

  Rejection power ~ $(\tau\ \Delta E)^n$ n = # ladder γ

Accelerator tests can address fundamental issues prior to flight testing

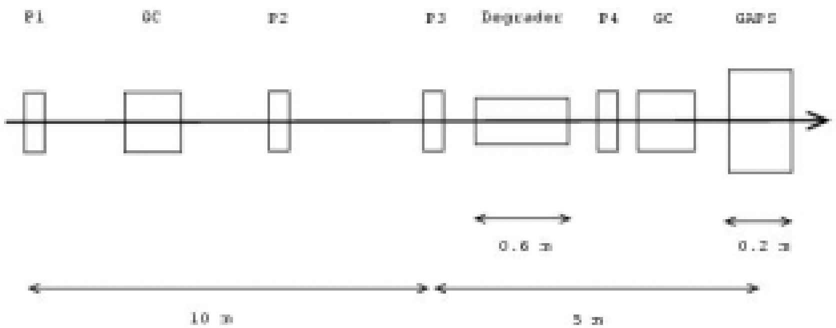
- 6 panels of 4 x 2 NaI(Tl) + PMTs
- NaI 5mm thick
- Carbon composite gas cell
- ~100 g/cm^2 degrader



Antiprotons address all key physics with simple scaling to antideuterons

- Yield of ladder transitions as a function of gas type and pressure (Stark mixing)?
- Fraction of captures with abrupt ladder termination?
- Statistical distribution of captures into high angular momentum states?
- Lifetime of antiparticle in exotic atom
- Triggers in presence of pionic shower and exploitation of higher energy X-rays in coincidence
- Overall detector performance

A proposal for accelerator testing has been submitted to KEK



Test matrix for GAPS in accelerator testing

- O_2, N_2, Ar, Ne
- 5, 10, 15, 20 atmosphere

Gas Cerenkov counters and plastic scintillators to provide particle discrimination

Good detection efficiency combined with high antiproton intensity allows rapid data taking

	O_2	N_2	Ar	Ne
5 atm	1/.02	1/.02	1/.02	1/.02
10 atm	1/.02	1/.02	1/.02	1/.02
15 atm	1/.02	1/.02	1/.02	1/.02
20 atm	1/.02	1/.02	1/.02	1/.02

- **Test matrix showing number of shifts required to get 6% and 3% statistics on the π2 and K2 beam lines respectively**
- **Higher count rate allows probing > 3 X-ray coincidences**

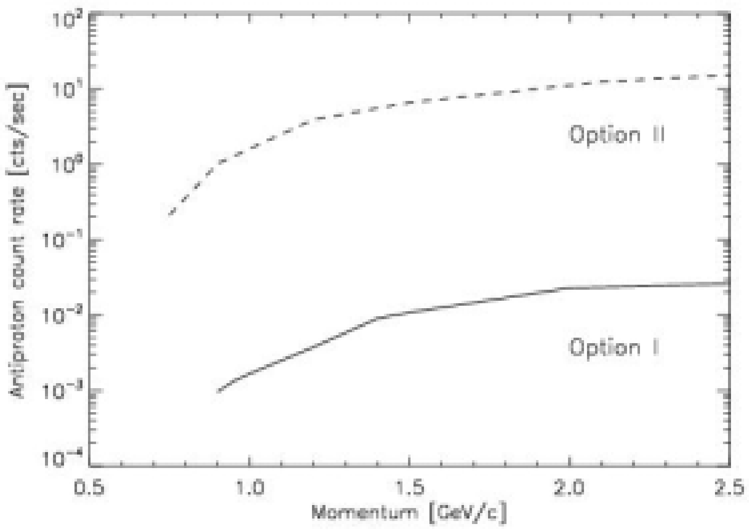
Background count rate is high at π2 beamline but produces little effect on GAPS

- ~10,000 counts/s in π^+, π^-, p respectively
- Kaons ~ few hundred counts/s
- π^- can produce exotic atom in gas but they have too much energy to stop in significant numbers; small number of interactions are uniquely identified by pionic X-rays
- π^+, kaons are too energetic to stop
- Protons stop, but do not produce exotic atoms
- dE/dx loss of particles in gas can produce delta electrons which produce bremstrahlung – this process is very rare and generally produces a single X-ray event.

We calculated this background using the known delta-electron spectrum

Calculation of antiprotonic X-ray signal in GAPS is straightforward

$R_{det} = (1 - \varepsilon_a(p))\ \Gamma \varepsilon_f\ \varepsilon_u\ \varepsilon_{pa}\ f_p\ R(p)$

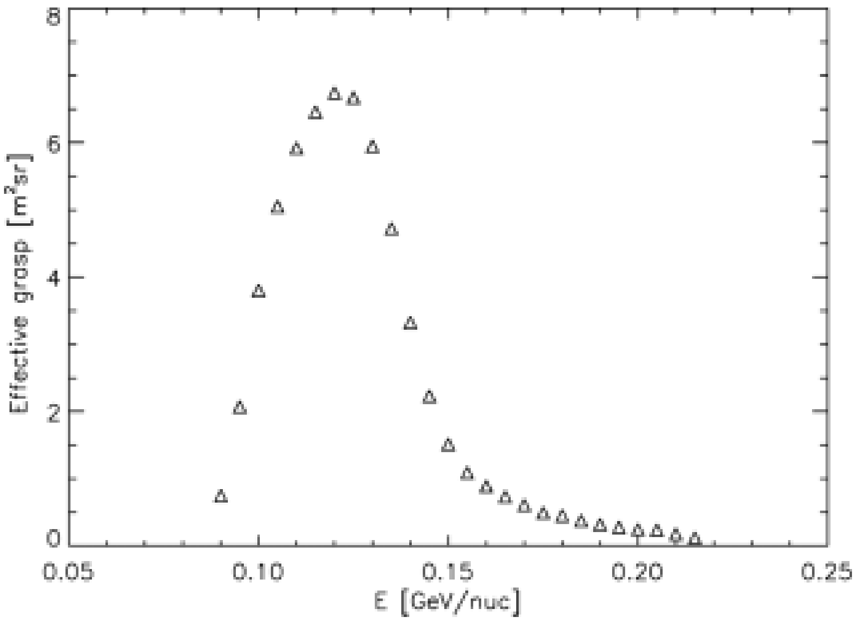


- $\varepsilon_a(p)$ = degrader absorption
- ε_f = fraction of captures with 3 X-rays hitting separate cells
- ε_x = fraction of captures with 3 ladder X-rays generated
- ε_{pa} = fraction of X-rays photoabsorbed in crystal
- R(p) = incident antiproton count rate as function of p
- Γ = beam straggling loss
- f_p = beam repetition rate
- ε_u = abs. downstream of degrader

GAPS sensitivity to new physics is obtained by maximizing grasp and sacrificing bandwidth

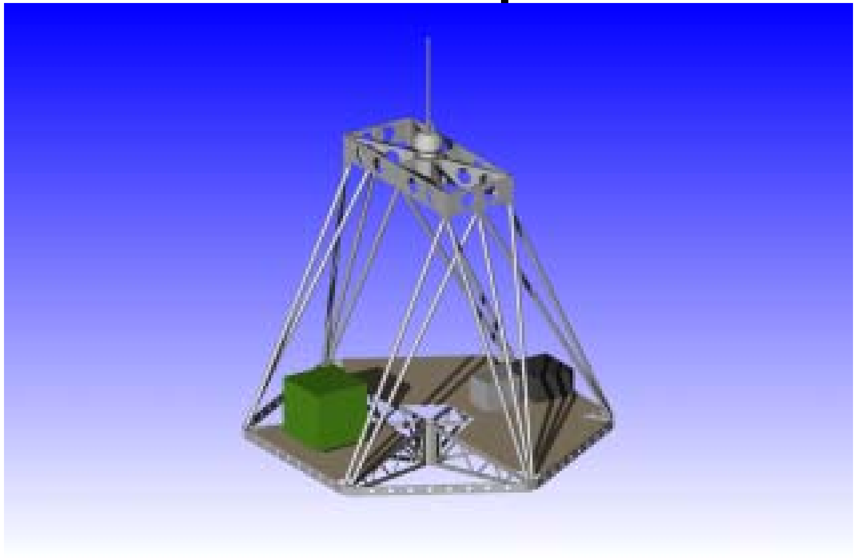
- GAPS degrader leads to narrow energy band in which antiparticles can be stopped
- Can use several degraders to obtain two color spectroscopy
- For broad bandwidth survey magnetic spectrometers are still the detector of choice

GAPS grasp in satellite experiment



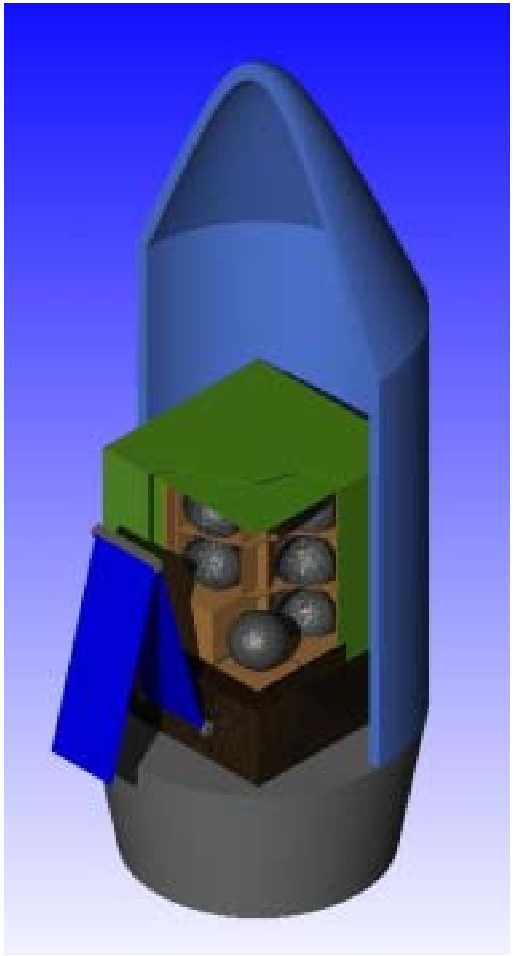
An ultralong balloon mission would cover about ½ of the searchable SUSY parameter space where the neutralino is likely to be

- **ubGAPS concept**



	ubGAPS
Energy band (GeV/n)	0.125-0.36 NaI
Pk. Eff. Grasp (m^2 sr)	0.88 NaI
Background rejection power	10^{12}
Mission life	200 days
Sensitivity (m^2 sr s GeV)$^{-1}$	9.7×10^{-8}

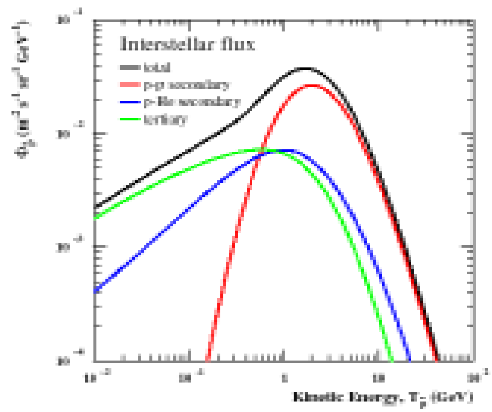
GAPS antideuteron search on Explorer class mission in low earth orbit



- Probe primary antideuterons at E < 0.2 GeV
- NASA Explorer mission (total cost = 199.6 M$)
- Delta II 2420-10 3m rocket
- High latitude orbit (L = 70^{o}N)
- 3 year mission
- Total size = 5 m
- Total weight = 2200 kg
- 27 CZT cells with Nitrogen gas
- Total column density = 5 g/cm^2
- Energy band 0.1-0.2 GeV/n
- Peak eff. Grasp 45 m^2 sr
- Background rejection 10^{12}
- I_{min} 2.6 x 10^{-9}m^{-2} s^{-1} sr^{-1} GeV^{-1}
  >> 20 times more sensitive than a magnetic spectrometer type mission

Antiproton search with GAPS in probe beyond the heliosphere can yield new physics too

Source	40-60 MeV	100-120 MeV
Secondary (no p-p)	20	30
Neutralino annihilation	60	100
Primordial black hole (Maki et.al. 1996)	280	400



- Grasp 65 cm^2 per channel
- Cube 6 cm per side
- Mass ~ few kilograms
- Argon gas cell