GAPS: a new cosmic ray antimatter experiment

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Dark Matter: historical/contemporary evidence

- Canonical calculation of virialized cluster, Newtonian gravity (a la Zwicky)
- Flat rotation curves (Rubin & Kent 1970)
- X-ray halos and mis-aligned mass density contours: Bullet cluster
- BAO $\Omega_\chi h^2 = 0.1198 \pm 0.0015$ from Planck
- Simple GR+stat mech+particle physics (BBN) gives: $\Omega_b h^2 = 0.0205 \pm 0.0018$ (O’Meara et al. 2001), agrees with Planck
- Baryon density only about 5% of overall critical density
- Strong limits set by Planck on neutrino contribution to matter density, no more than 2%
Proposed explanations

DM phenomenon

- Modified gravity
  - MOND, TeVeS, $R^2$, F(R), Emergent gravity, Massive gravity, ...

- Non/weakly-emitting SM matter
  - MACHOS, ...

- Non-SM matter
  - WIMPs, axions, MACROs, SIMPs, ELDERs, SuperWIMP, Hidden DM, Sterile neutrinos, ...
Proposed explanations

NS-NS merger limits
ms pulsar stellar triple systems
double pulsar systems

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LUX null result
PandaX-II null result
No new physics at LHC
dwarf spheroidals
ultra faint dwarves
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LUX null result PandaX-II null result
- No new physics at LHC dwarf spheroidals

Ultra faint dwarves
Testing the (WIMP) theories: *indirect* detection

- Look at standard model fragments from pair annihilation or decay
- Produced for free in the galaxy
- Kinematics of primaries arriving in upper atmosphere, low earth orbit

http://pamela.roma2.infn.it/index.php

https://asd.gsfc.nasa.gov/bess/BESS.html
Cosmic-rays from DM: anti-deuteron fluxes

- Annihilation/decay
- Source term:
  - Fusion from simple coalescence as before
  - Propagation to Earth using standard methods. Variety of models possible: MIN, MED, MAX
  - Difference due mostly to variations in galactic scale height
  - Tension between MIN and variety of measurements see e.g. Giesen et al. 2015

\[ q_{d}^{\text{prim}}(r, z, E) = \eta \xi^{2} \langle \sigma_{\text{ann}} v \rangle_{0} \frac{dN_{\tilde{d}}}{dE_{\tilde{d}}} \left( \frac{\rho_{\text{DM}}(r, z)}{m_{\chi}} \right)^{2} \]

\( \frac{1}{2} \) or \( \frac{1}{4} \) type of fermion

2.3x10^{-26} cm^3 s^{-1}

Source spectrum

Halo profile

Cosmic ray anti-matter: astrophysical background

- Typical spallation process:
  - Turns on \(~7\) GeV
  - "natural" \(\bar{p}/p\) peak KE separated from DM KE peak due to annihilation, decay, ..

- Astrophysical vs DM peak for \(\bar{d}/d\) has better separation!
  - Turns on \(~17\) GeV
  - Astrophysical population: no additional scattering/energy loss. Simply break up!

\[
p + p \rightarrow p + p + \bar{p} + p + n + n
\]

\[
p + p \rightarrow p + p + \bar{p} + p + \bar{n} + n
\]

\(\bar{d}\) from fusion
Coalescence described in
10.1103/PhysRevD.71.08301
DM Anti-deuteron fluxes, top of atmosphere

F. Donato, N. Fornengo, and D. Maurin. Phys. Rev. D 78, 043506
GAPS sensitivity: $\bar{d}$

- Low mass WIMPs (MED prop.)
- Lightest Kaluza-Klein particle universal extra-dimensions
- SuperWIMP gravitinos
- Given the secondary flux estimate, a detection of a handful of anti-deuterons is significant
GAPS sensitivity: $\bar{\rho}$

- Overlap with complementary searches
- Extends spectrum to lower energies
- SuperWIMP
- Sensitive to other models, see T. Aramaki’s paper for more details

T. Aramaki et al., Astroparticle Physics, Volume 59, 2014, Pages 12-17
Detection technique

- TOF using plastic scintillator: $\beta$, $dE/dx$
- Exotic atom formation
- De-excitation produces characteristic x-rays
- Si(Li) tracker concept provides powerful x-ray discrimination
- Annihilation event produces pions, protons
- Combination of TOF and Si(Li) should provide excellent reconstruction capability

\[ E_x = \left( zZ \right)^2 \frac{\bar{M}}{m_e} R_H \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \]

T. Aramaki et al., Astroparticle Physics, Volume 74, 2016, Pages 6-13
Example simulated events

**ANTI-PROTON**

*Primary:* $\beta = 0.388, KE = 79.9$ MeV

Energy deposited: 1, 10, 100 MeV

TOF HIT = 10, Si(Li) HIT = 6

**ANTI-DEUTERON**

*Primary:* $\beta = 0.334, KE = 114.4$ MeV

Energy deposited: 1, 10, 100 MeV

TOF HIT = 14, Si(Li) HIT = 11
Instrument design: time of flight

- 202 PVT paddles: umbrella with hermetic cube
- State of the art carbon fiber mechanical support structure
- Detailed study of PMT vs. SiPM.
- SiPM low-light detectors: low mass, low HV, no B-field issues
- Resistively loaded voltage pre-amp
- Read out using low power, fast and channel dense DRS4 chip
- Data management using custom SPI bus
Instrument design: time of flight

- TOF requirement: ~500 ps resolution
- ~350 ps achieved with DRS4 eval board in lab
- 0.4-36 MIP dynamic range (0-2200 p.e.)

Timing RMS (end-end) / √2

Prelim. single p.e.

V3 preamp upgraded to 6 SiPMs!
Instrument design: time of flight

- 8 paddles per read out board
- 16 input channels
- Up to 2 digital input triggers
- SPI bus for fast communications and data throughput
- 27 read out boards for TOF system (umbrella + cube)
- v1.0.0-beta assembled, testing + debugging underway
Instrument design: silicon tracker

- Lithium drifted silicon Si(Li)
- 4 keV energy resolution and 100 ns timing requirements
- 10 layers, 4” dia. & 2.5mm thick wafer
- Original fabrication technique pioneered at Columbia U. Tech transfer to private company
- Several commercially produced (Shimadzu corp.) detectors delivered. Measurements ongoing at MIT
Instrument design: silicon tracker

- Integral pre-amp
- 16 channel ASICs
- 11,520 total channels for 10 layers
- Bias: ~300V
- -40 C operating temp
- SPI communications for speed
- FPGA based digital back-end

Image credit: L. Fabris
Instrument design: silicon tracker

- Cooled using oscillating heat pipe (OHP) system
- Phase change in capillary tube
- Easy to design and build, low cost
- Does not require active pumping
Long duration (35 d) balloon flight

- Early 2021 launch (solar minimum)
- ~1700kg payload
- ~1400W power budget
- 36km altitude, 5 gm cm$^{-2}$ overburden
The GAPS collaboration

Funding agencies (started 2017)
Summary + Time-line

- Anti-deuteron cosmic rays interesting for astrophysics, in addition to DM probe
- GAPS designed for anti-protons and anti-deuterons
- Independent detection technique that can complement AMS02, BESS, PAMELA
- Extend anti-proton energy spectrum to unexplored regime
- Viability of design demonstrated in successful pGAPS flight
- TOF and Si(Li) development nearing completion, measurements and testing recently started
Backup: Exotic atom

- Energy of atomic X-ray unique to the exotic atom, allows discrimination of dbar vs. pbar
- Predicted in 1940s, cascade models developed since then
- Generalized, extend-able cascade model developed for GAPS
- Free parameters optimized with beam tests using Al, S, Cl, Br targets at KEK in 2005
- For comprehensive description see: Aramaki et al. 2013

Image credit: Aramaki et al. 2013
Backup: KEK beam tests

- GAPS cascade model validated with data
- Extrapolate X-ray yield of pbar or dbar exotic atom formed by any material (active or structural) of GAPS detector
- dbar/pbar yield for Si target estimated at ~80%
- See Aramaki et al. 2013 for more details

<table>
<thead>
<tr>
<th>Table 10</th>
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</thead>
<tbody>
<tr>
<td>The experimental data and the cascade model for X-ray yields of antiprotonic exotic atom with the Al target ($a = 0.16$, $W = 5$ MeV and $\Gamma_{ref} = 10^{14}$ s$^{-1}$).</td>
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<tr>
<th>p-Al</th>
<th>Experiment</th>
<th>Cascade model</th>
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</thead>
<tbody>
<tr>
<td>92 keV ($5 \rightarrow 4$)</td>
<td>90% ± 13%</td>
<td>78%</td>
</tr>
<tr>
<td>50 keV ($6 \rightarrow 5$)</td>
<td>76% ± 10%</td>
<td>84%</td>
</tr>
<tr>
<td>30 keV ($7 \rightarrow 6$)</td>
<td>84% ± 13%</td>
<td>71%</td>
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<tr>
<td>The experimental data and the cascade model for X-ray yields of antiprotonic exotic atom with the S target ($a = 0.16$, $W = 5$ MeV and $\Gamma_{ref} = 10^{14}$ s$^{-1}$).</td>
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<tr>
<th>p-S</th>
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<tbody>
<tr>
<td>139 keV ($5 \rightarrow 4$)</td>
<td>59% ± 20%</td>
<td>50%</td>
</tr>
<tr>
<td>76 keV ($6 \rightarrow 5$)</td>
<td>72% ± 18%</td>
<td>83%</td>
</tr>
<tr>
<td>46 keV ($7 \rightarrow 6$)</td>
<td>72% ± 18%</td>
<td>78%</td>
</tr>
<tr>
<td>30 keV ($8 \rightarrow 7$)</td>
<td>72% ± 18%</td>
<td>60%</td>
</tr>
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Image credits: Aramaki et al. 2013
Backup: pGAPS

- Prototype successfully flow in June 2012
- Si(Li) modules and TOF worked reliably, thermal model verified
- X-ray fluxes measured
- For comprehensive description see: von Doetinchem et al. 2014
Backup: Coalescence process

- (Anti)Nucleons close in phase space can form (anti)nuclei
- Coalescence momentum of 79 MeV
- Detailed description available in Donato et al. 2008

\[ B_2 \equiv \sigma_{\text{inel}}^R \cdot E_d \frac{d^3 \sigma^R_d}{dk_d} \cdot \left( \frac{d\sigma^R_p}{dk_p} \right)^{-2} \]

\[ p_0 = \left( \frac{1}{B_2} \cdot \frac{m_d}{m_p^2} \cdot \frac{4\pi}{3} \right)^{-1/3} \]

Equations 8, 9 from Donato et al. 2008