Search for Dark Matter using Low-energy Antimatter with the GAPS experiment

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• ~1/4 of our Universe is composed of Dark Matter:
  - Weakly coupled to SM particles
  - Dynamically cold
  - No direct indication on the mass scale (but GeV-TeV well motivated range)
  - Weakly Interacting Massive Particle or WIMP

• Evidence of DM is purely of gravitational origin

• Non-gravitational signal is needed to understand its particle-physics nature
Halo signals
- Charged leptonic CRs: $e^\pm$
- Charged baryonic CRs: $\bar{\rho}, \bar{d}, \overline{He}$
- Photons
  - $\gamma$ rays
    - Prompt production
    - IC from $e^\pm$ on ISRF and CMB
- Neutrinos

Local signals
- Neutrinos from Earth and Sun
Astrophysical messengers of DM

- Charged baryonic CRs: \( \bar{p}, \bar{d}, \bar{He} \)

GENERAL ANTIPARTICLE SPECTROMETER (GAPS)
Cosmic anti-protons ($\bar{p}$)

- Most abundant baryonic antiparticle component in CRs
- Extensively measured with magnetic spectrometers from 200 MeV up to \(~400\) GeV


Upper bound to WIMP mass (eg >40 GeV from PAMELA data) \(\rightarrow\) Hooper, D. et al JCAP 03 (2015) 021
Various DM predictions for $\bar{\rho}$

**KK Right-ended neutrino (LZP)**
(Lavalle et al, 2012)

Decaying gravitino
SUSY with small R-parity violation
Lifetime $10^{28}$ s $\gg$ age of the Universe
(Grefe et al, 2012)

Annihilating neutralino
Lighter SUSY particle
$\sigma v = 3 \times 10^{-26} \text{cm}^3/\text{s}$
(Kappl et al 2012)

EXTRA: Evaporating primordial BHs
(Abe et al, 2012)

Aramaki et al. – Astro.Ph. 59 (2014) 12
Cosmic anti-deuterons ($\bar{d}$)


**Secondary (background)**

$$p_{CR} + p_{ISM} \rightarrow \bar{p}n + pn + pp$$

- Produced in the disk
- Propagated in kinetic threshold
- Strongly suppressed @ LE
- Propagated in the diffusive halo

**DM signal**

$$\chi \chi \rightarrow (...) \rightarrow \bar{p}n + pn$$

- Produced in the DM halo
- Propagated in the diffusive halo
- Much higher flux than bckg wr to e$^+$ and $\gamma$

Favourable signal-to-background ratio at low energy
General Anti-Particle Spectrometer

- Balloon-based experiment optimized for the detection of low-energy baryonic antiparticles ($E < 250$ MeV)

Science summary:
- Search for anti-deuterons as DM signatures
- No astrophysical background
- Precise measurement of antiproton flux
- Possible spectral signatures of DM and evaporating PBH
- Flight plan:
  - 1 LDB flight (>35 days) → high-statistic antiproton measurement
  - 2 LDB flights (>70 days) → improved anti-deuteron statistics
  - 3 LDB flights (>105 days)

- First flight approved by NASA for austral summer 2020/2021
The GAPS Collaboration

Meeting @ UCSD November 2017

University of Columbia, MIT, UC Berkley, UC Los Angeles, UC San Diego, University of Hawaii at Manoa, Penn State University, Oak Ridge Laboratory, ISAS-JAXA
GAPS detection technique

- Based on the antiparticle annihilation process inside a medium
  - Low-energy antiparticles ($\bar{p}, \bar{d}$) slow-down traversing the medium
  - They stop, forming an exotic atom (capture) in an excited state, which de-excites through radiative transitions, emitting detectable $X$-rays
  - Nuclear annihilation $\rightarrow$ pions and protons

Intra-Nuclear Cascade model (INC)
**GAPS apparatus**

**Time-of-Flight system**
- 1 outer + 1 inner layers
  - Plastic scintillator, readout on each end by SiPMs or PMT
  - 1 m b/w outer and inner layers
  - < 500 ps resolution
  - $\beta +$ particle charge + trigger

**Tracking system**
- 12x12 Si(Li) wafers
  - -48°C operation temperature
  - 10 cm, 2.5 mm thickness
  - segmented into 8 strips
  - 10 layers with 10 cm spacing $\rightarrow$ trajectory + incoming/outgoing particle energy loss + number of secondaries + X-rays
- non-linear ADC
- X-ray (20 -100 keV)
- charged particles (max res. 50 MeV)
- 3/4 keV energy resolution

**Oscillating Heat Pipe (OHP) passive cooling system**
\( \bar{d} \) vs \( \bar{p} \) identification

- Simulation checked against data measured @KEK in 2004

\[
\begin{array}{|c|c|}
\hline
\bar{p}\text{-Si} & \text{Cascade Model} \\
\hline
106 \text{ keV (5 } \rightarrow \text{ 4)} & 70\% \\
58 \text{ keV (6 } \rightarrow \text{ 5)} & 84\% \\
35 \text{ keV (7 } \rightarrow \text{ 6)} & 73\% \\
\hline
\end{array}
\]

- \( \bar{d}\text{-Si} \)

\[
\begin{array}{|c|c|}
\hline
\text{Energy} & \text{Probability} \\
\hline
112 \text{ keV (6 } \rightarrow \text{ 5)} & 28\% \\
67 \text{ keV (7 } \rightarrow \text{ 6)} & 96\% \\
44 \text{ keV (8 } \rightarrow \text{ 7)} & 92\% \\
30 \text{ keV (9 } \rightarrow \text{ 8)} & 80\% \\
\hline
\end{array}
\]

- Time-of-flight
- Multiple \( dE/dx \) measurements along antiparticle trajectory
- X-ray energies
- Pion/proton multiplicity

Exotic Atom

\[ \begin{aligned}
\text{Si(Li) Layer} & \quad 58 \text{ keV} \\
35 \text{ keV} & \quad \pi^+ \quad \pi^- \\
67 \text{ keV} & \quad p \\
107 \text{ keV} & \quad \pi^+ \\
30 \text{ keV} & \end{aligned} \]
GAPS Si(Li) detector

- Process developed at Columbia and MIT!
- Readout ASIC designed by INFN

- Low-cost fabrication scheme developed in partnership with Shimadzu Corp.
- Demonstrates required ~4 keV energy resolution at relatively high temp of -35° to -45° C
- Readout via custom ASIC: integrated low-noise preamplifier, dynamic range compression 20 keV to 50 MeV
GAPS ToF system

- 206 scintillators
  - 160x18 cm² (inner)
  - 180x18 cm² (outer)
  - 6.35 mm thick EJ-200 (Eljen Tech.)
- SiPM readout
  - 6+6 MPPC S14160-6050HS (Hamamatsu)
- Achieved timing resolution @ paddle center 485 ps
- Time-of-flight resolution 343 ps
OHP cooling system

- Small capillary tubes filled with phase-changing refrigerant liquid
- Thermo-hydrodynamic waves set by expansion and collapse of vapor bubbles
- Fluid oscillation between cooling and heating sections
- No active-pump required
- Developed by JAXA/ISAS
Conclusions

- Measurement of cosmic $\bar{d}$ and $\bar{p}$ is a promising way of indirect DM search
- The General Anti-Particle Spectrometer (GAPS) is specifically designed for low-energy $\bar{p}$ search and $\bar{d}$ flux measurement ($< 250$ MeV)
  - Novel detection technique based on detection and reconstruction of annihilation events
  - Exotic-atom radiative de-excitation + star-like annihilation products $\rightarrow$ Complementary to spectrometer-based $\bar{d}$ searches
- First LDB flight approved by NASA in austral summer 2020/2021 $\rightarrow$ statistics of $\bar{p}$ below 250 MeV
- Full $\bar{d}$ sensitivity after $\sim$100 hours (3 LDB) flight
- Highest statistics of every experiment for low-energy $\bar{p}$ $\rightarrow$ exceeds by orders of magnitude

- Status of the experiment
  - Detection concept and detector in-flight operation demonstrated
  - Design finalized
  - Si(Li) detector production ready to start
  - rapid development/production/integration/deployment schedule