Istituto Nazionale di Fisica Nucleare

Università di Roma Tor Vergata

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

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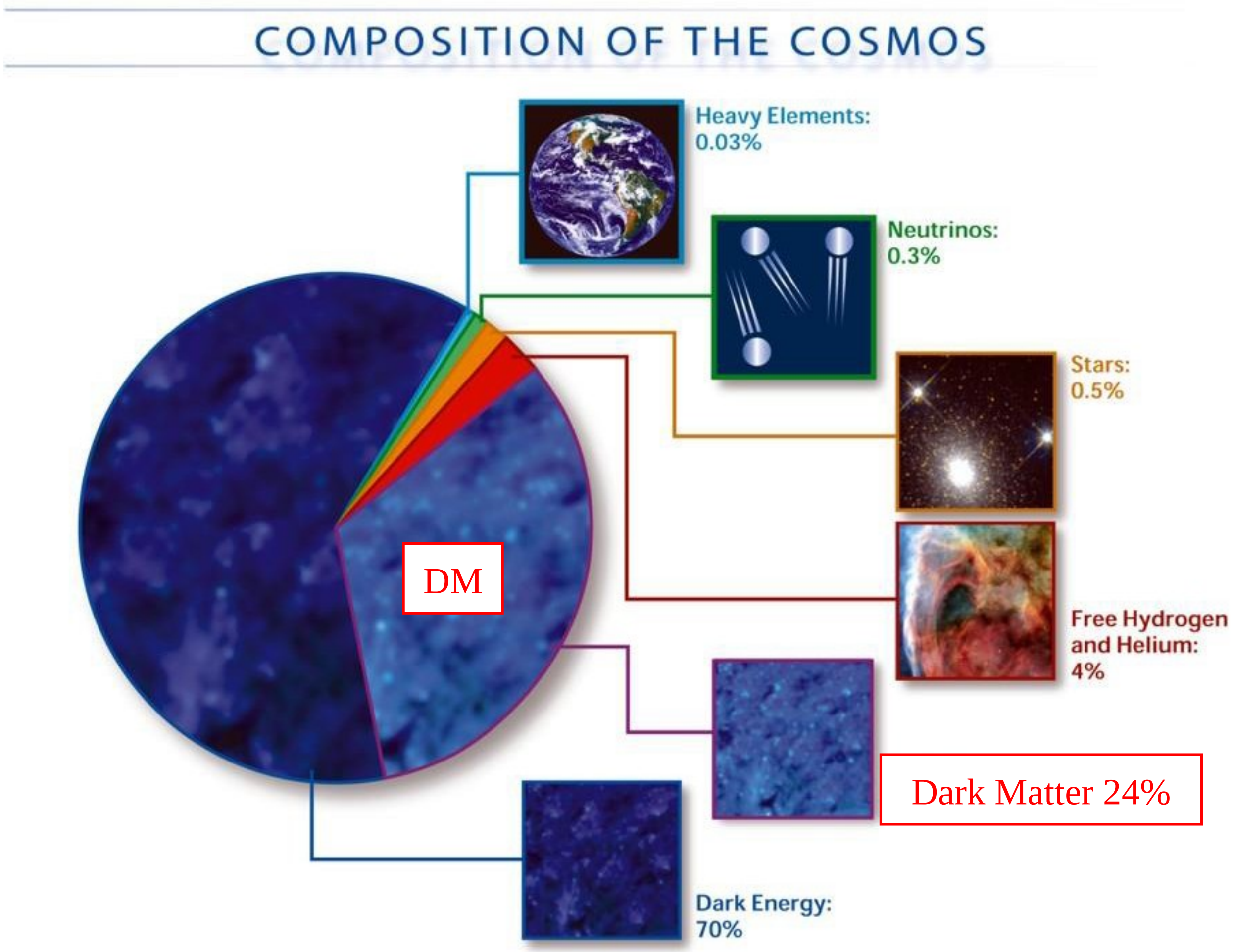
RICAP 18

7th Roma International Conference on AstroParticle Physics

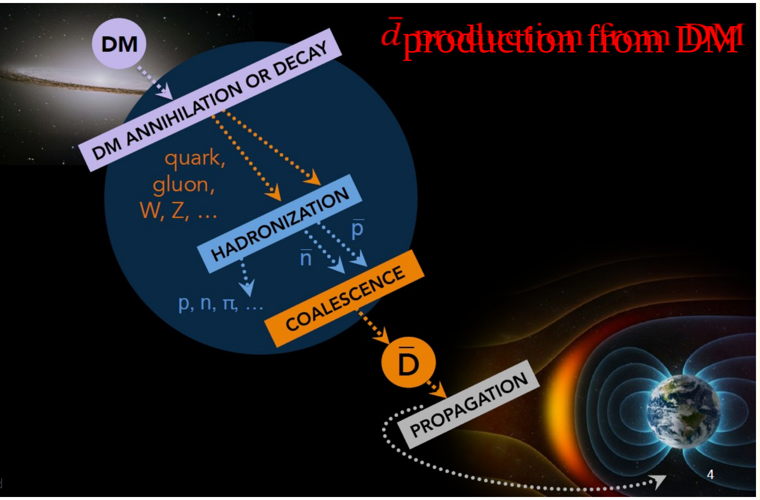
INFN Istituto Nazionale di Fisica Nucleare · Università degli Studi di Roma Tor Vergata · Sapienza Università di Roma · Roma Tre Università degli Studi Dipartimento di Fisica

Dark Matter (DM) in space



- ~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

Astrophysical messengers of DM



Halo signals

- Charged leptonic CRs: $e^{\pm}$
- Charged baryonic CRs: $\bar{p}$, $\bar{d}$, $\overline{He}$
- Photons
    - γ rays
    - Prompt production
    - IC from $e^{\pm}$ on ISRF and CMB
- Neutrinos

Local signals

- Neutrinos from Earth and Sun

INDIRECT SEARCHES

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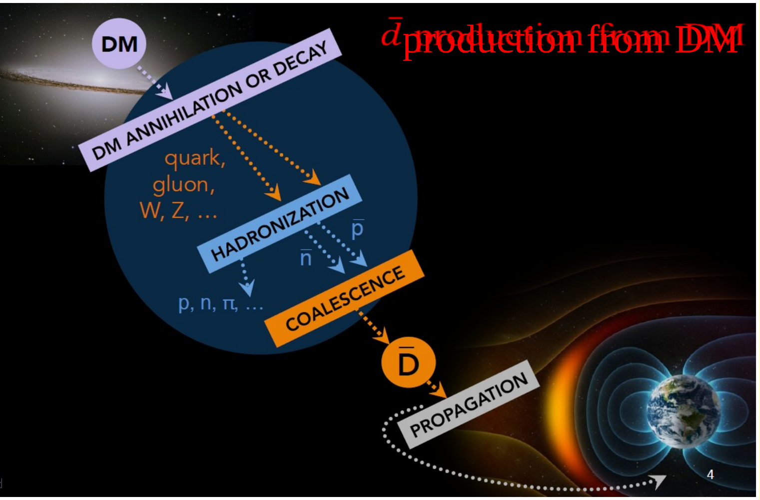
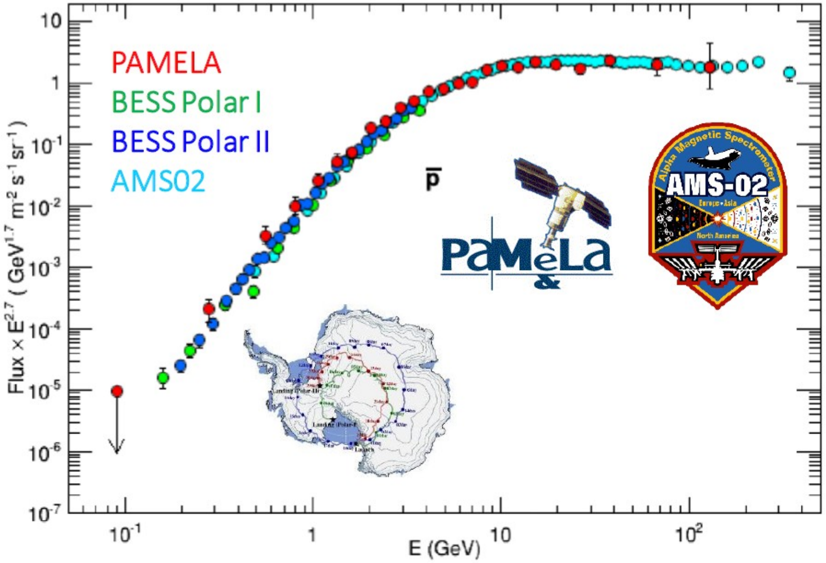
- **Charged baryonic CRs: $\bar{p}$, $\bar{d}$, $\overline{He}$**

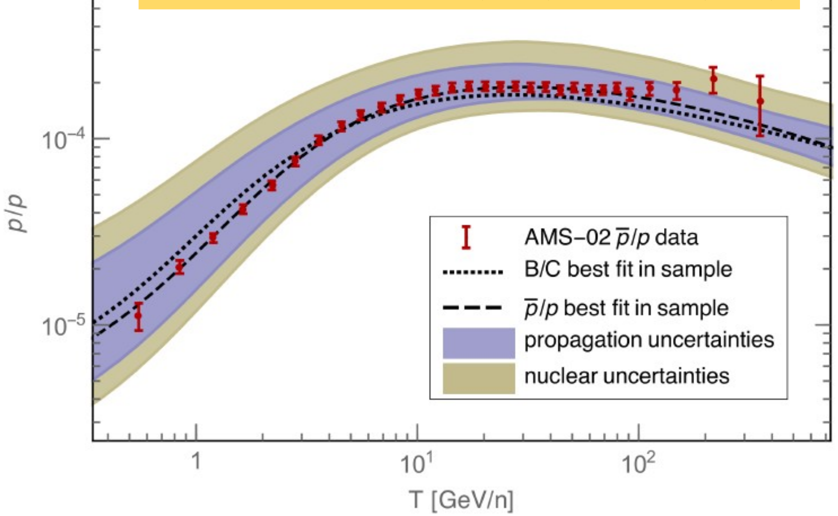


GENERAL ANTIPARTICLE SPECTROMETER (GAPS)

Cosmic anti-protons ($\bar{p}$)



Winkler *et al* - JCAP 09 (2014), JCAP 10 (2015)



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

Consistent, within uncertainties, with secondary background (AMS-02 data?) → Kappl 2015 arXiv:1506.04145 [astro-ph.HE] / Cui, M-Y arXiv:1610.03840 [astro-ph.HE]

Upper bound to WIMP mass (eg >40 GeV from PAMELA data) → Hooper, D. et al JCAP 03 (2015) 021

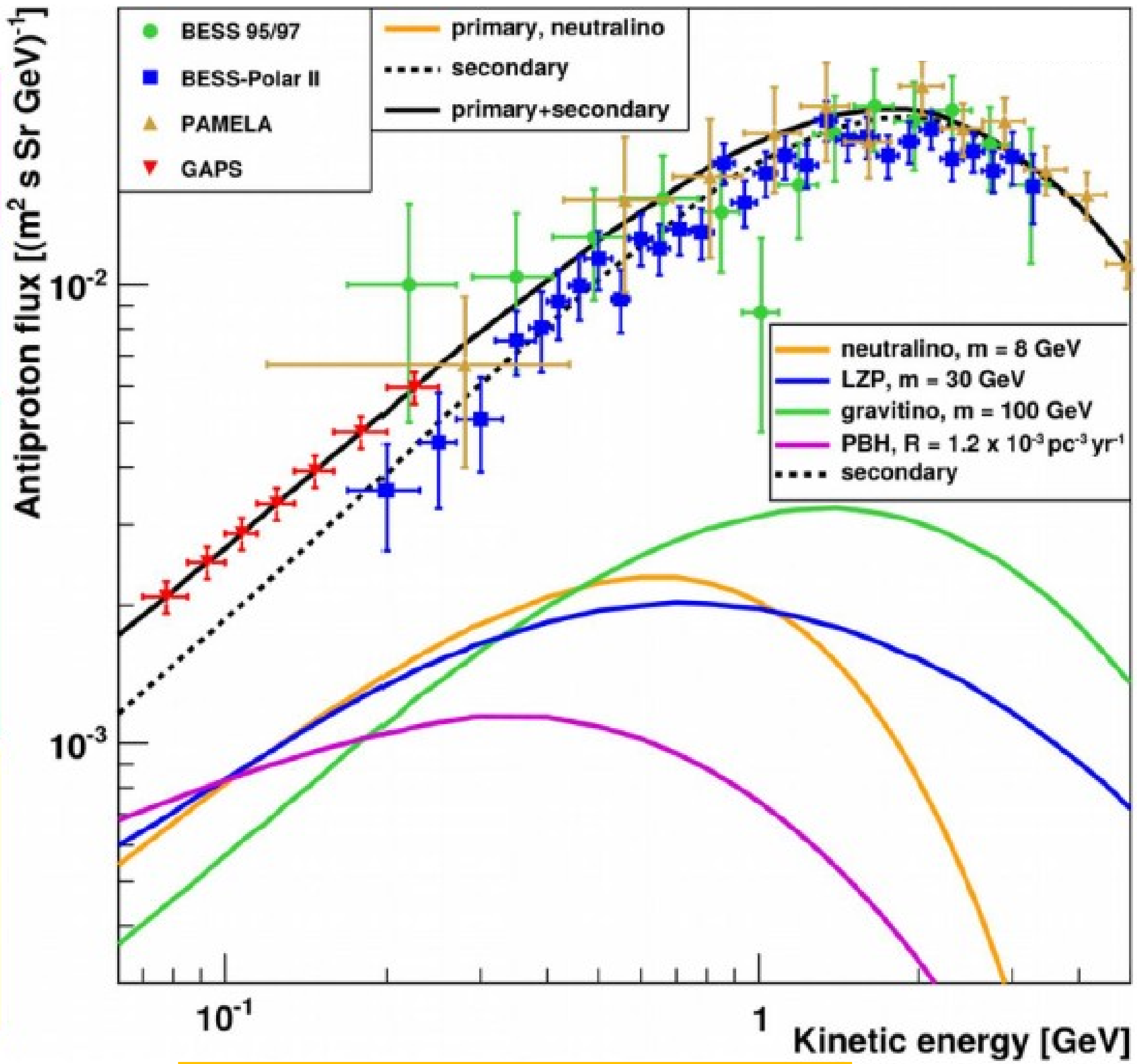
Various DM predictions for $\bar{p}$

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
$\sigma v = 3\ 10^{-26}\ cm^3/s$
(Kappl *et al* 2012)

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



Aramaki *et al.* – Astro.Ph. 59 (2014) 12

Cosmic anti-deuterons ($\bar{d}$)

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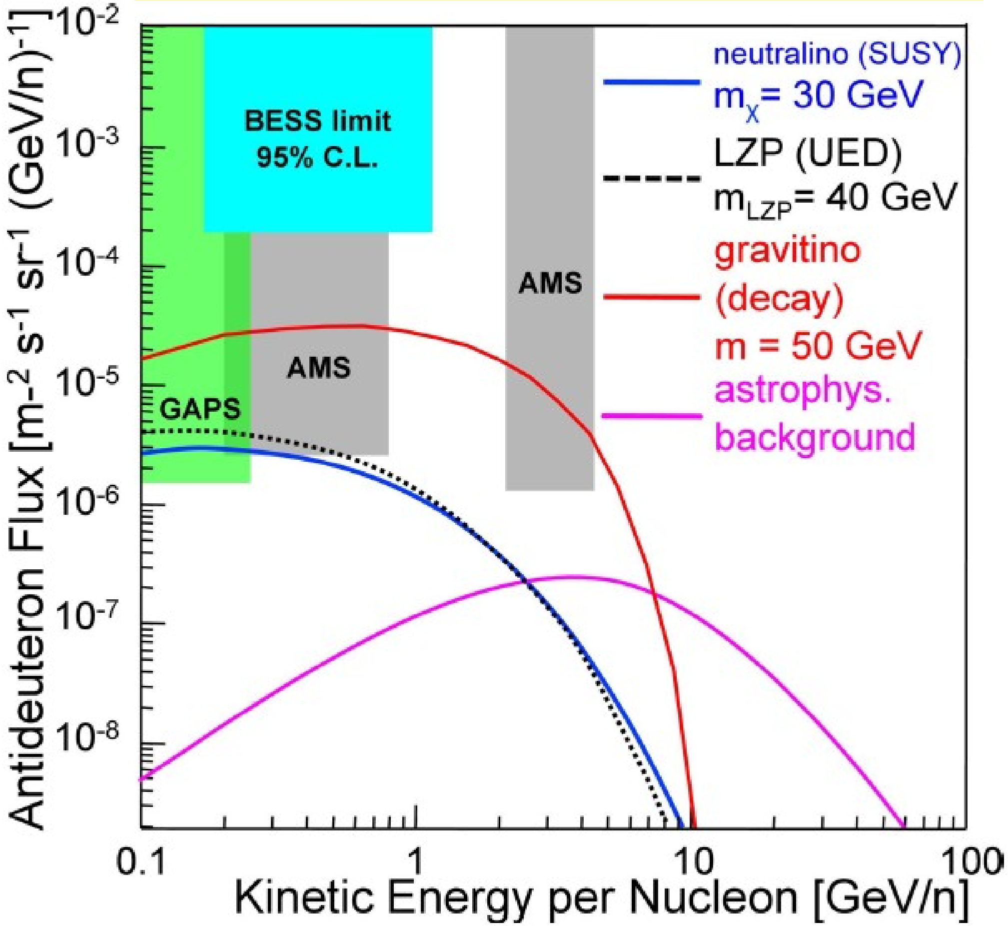
R.A. Ong *et al* - *https://arxiv.org/abs/1710.00452*



Favourable signal-to-background ratio al low energy

Secondaries (background)

$$p_{CR} + p_{ISM} \to \underbrace{\bar{p}\bar{n}}_{coalescence} + pn + pp$$

- Produced in the disk
  kin. threshold

 strongly suppressed @ LE

- Propagate in the diffusive halo

DM signal

$$\chi\chi \to (\ldots) \to \underbrace{\bar{p}\bar{n}}_{coalescence} + pn$$

- Produced in the DM halo
- Propagate in the diffusive halo
- Much higher flux than bckg wr to e^+ and γ

GAPS mission overview

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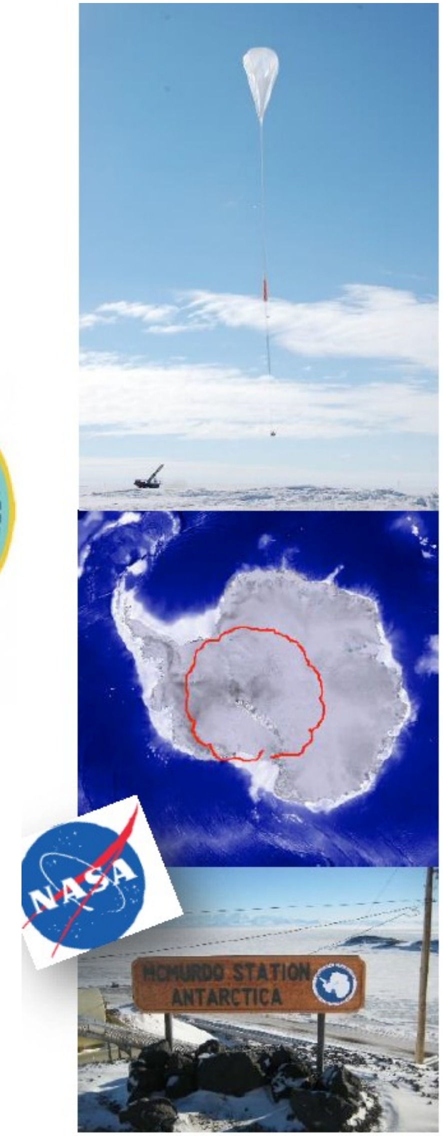
General Anti-Particle Spectrometer

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

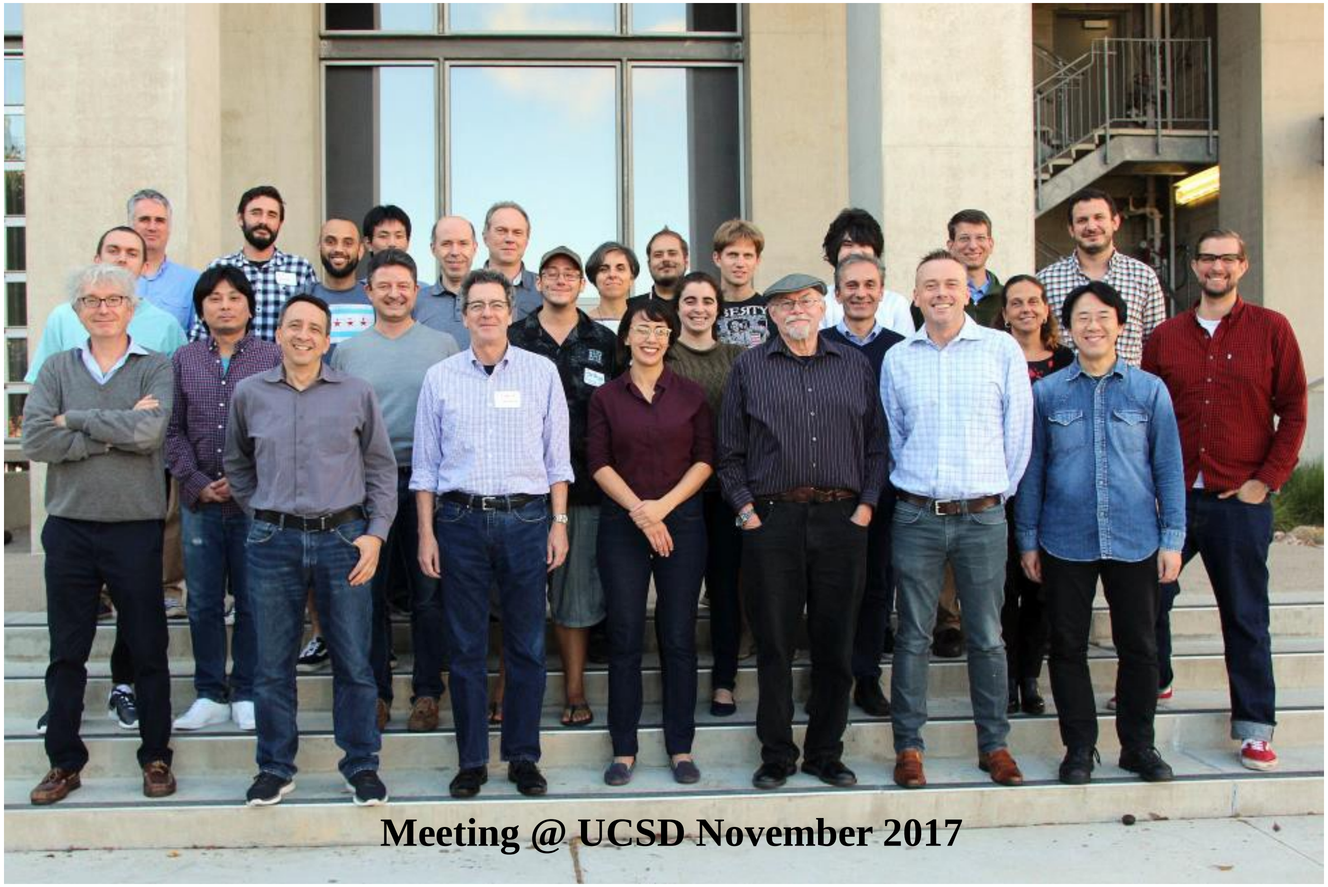
Science summary:

- 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

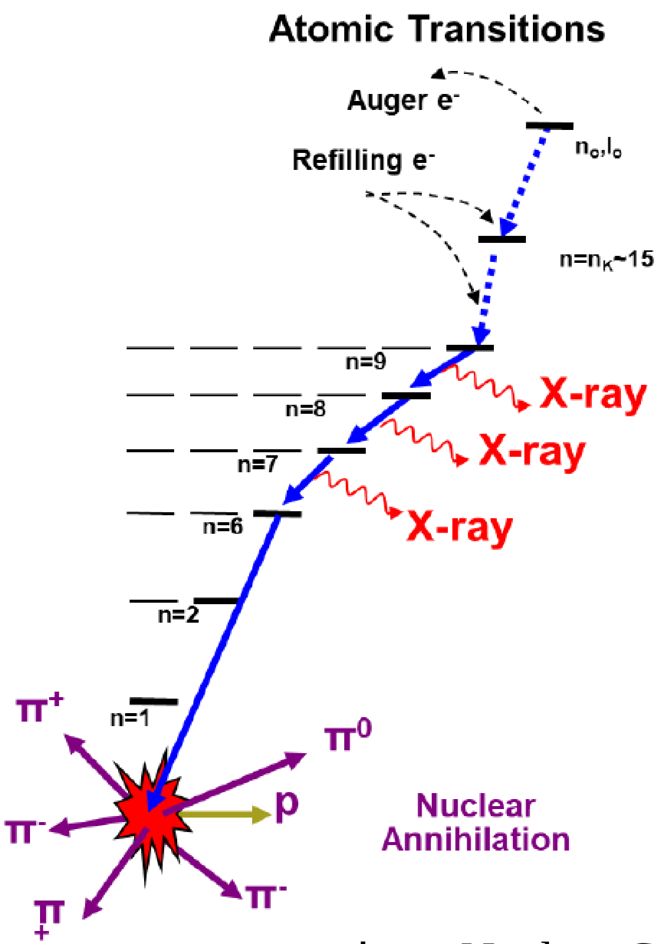


The GAPS Collaboration



Meeting @ UCSD November 2017

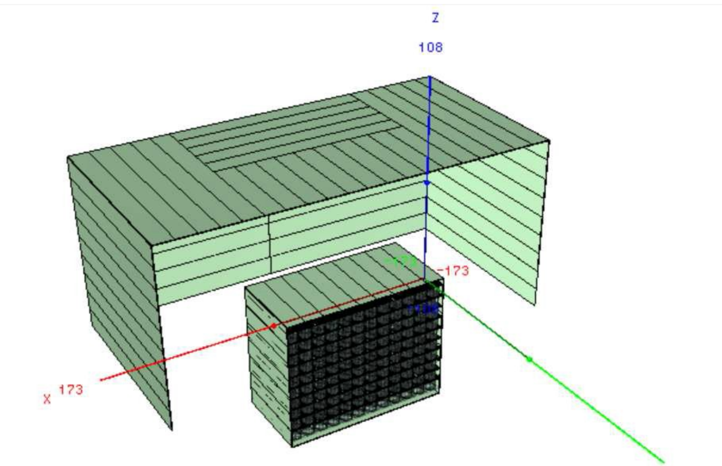
University of Columbia, MIT, UC Berkley, UC Los Angeles, UC San Diego, University of Hawaii at Manoa, Penn State University, Oak Ridge Laboratory, ISAS-JAXA

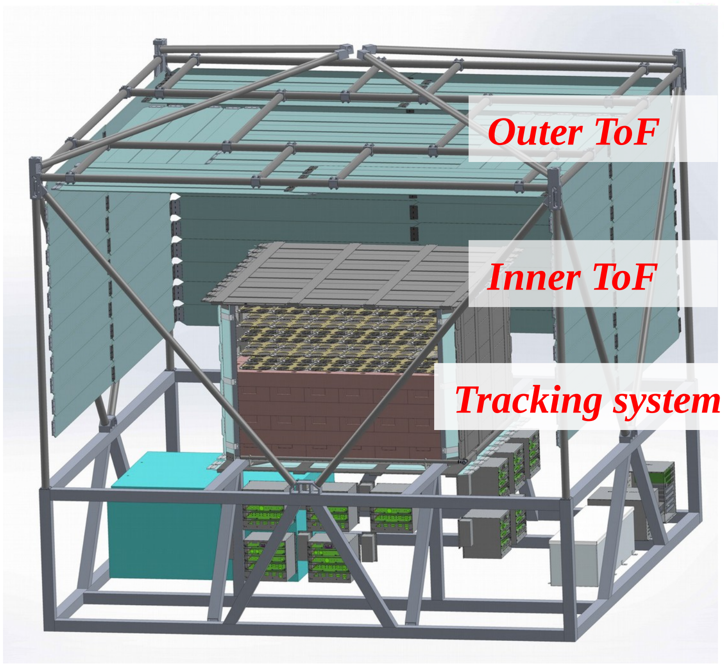


- Based on the antiparticle annihilation process inside a medium
  - Low-energy antiparticles ($\bar{p}, \bar{d}$) slow-down traversing the medium
  - They stop, forming an exotic atom (capture) in an excited state, which de-excites through radiative transitions, emitting detectable X-rays
  - Nuclear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

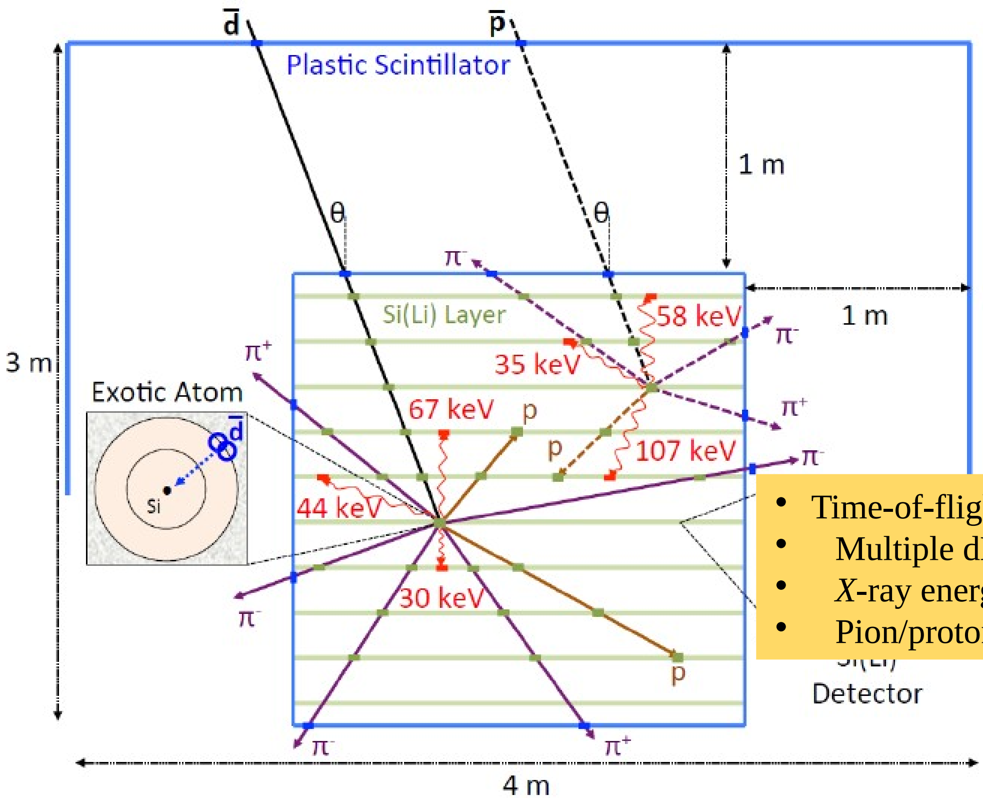
Oscillating Heat Pipe (OHP) passive cooling system

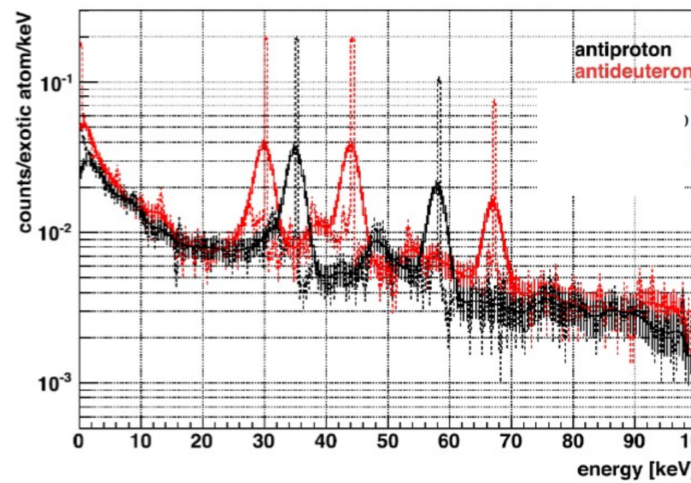
$\bar{d}$ vs $\bar{p}$ identification

$\bar{p}$-Si	Cascade Model
106 keV (5 → 4)	70%
58 keV (6 → 5)	84%
35 keV (7 → 6)	73%

$\bar{d}$-Si	
112 keV (6 → 5)	28%
67 keV (7 → 6)	96%
44 keV (8 → 7)	92%
30 keV (9 → 8)	80%

- Simulation checked against data measured @KEK in 2004

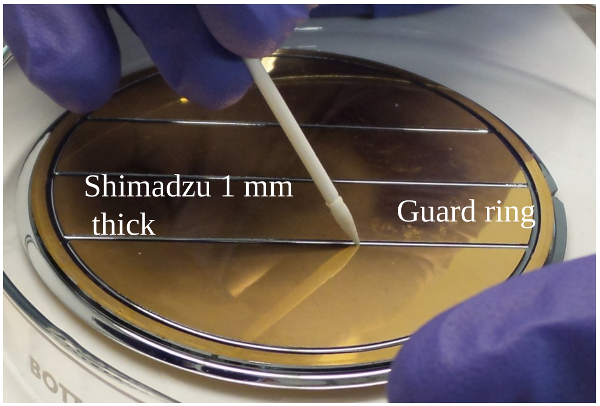


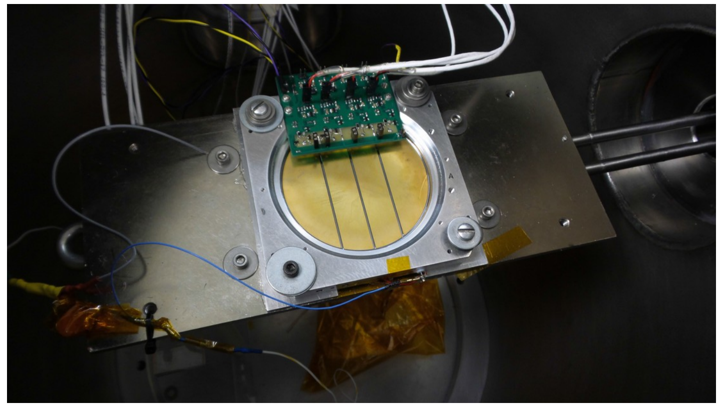


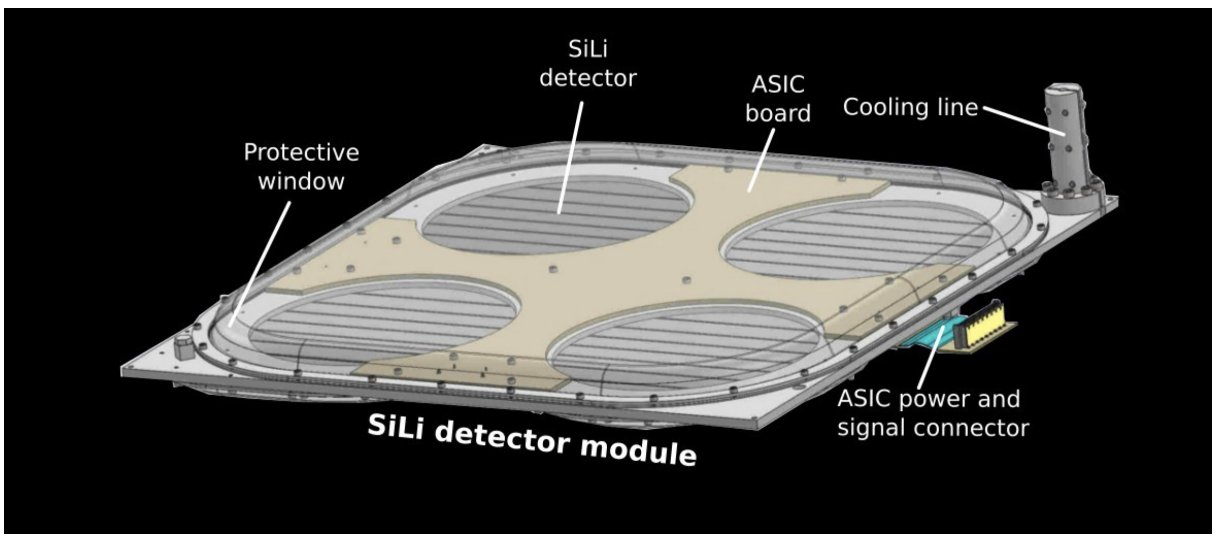
- Time-of-flight
- Multiple dE/dx measurements along antiparticle trajectory
- *X*-ray energies
- Pion/proton multiplicity

GAPS Si(Li) detector

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





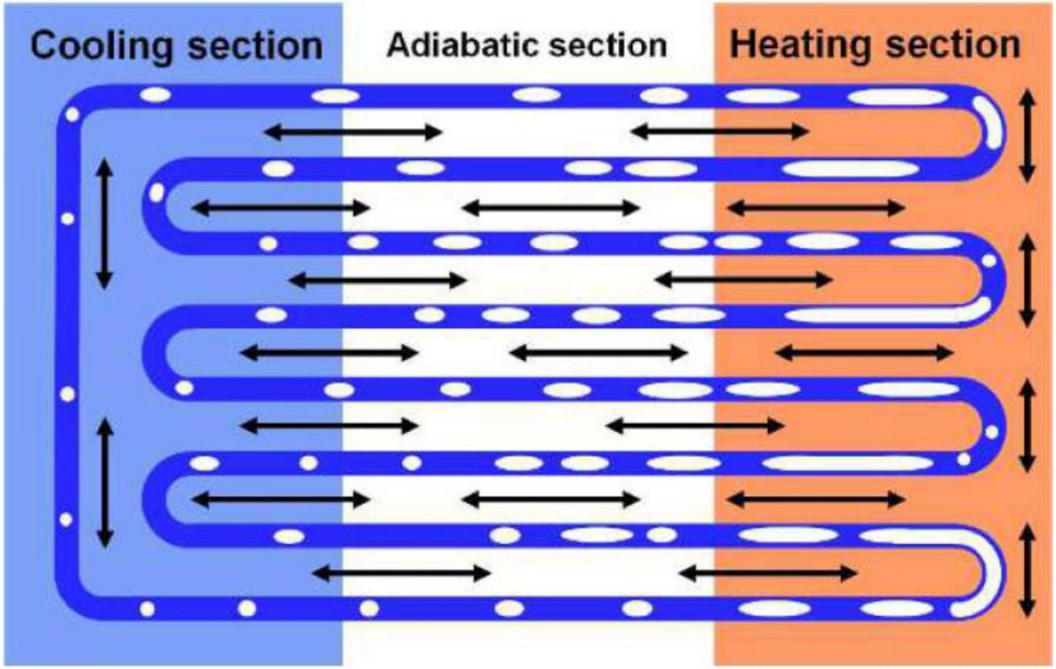


- Low-cost fabrication scheme developed in partnership with Shimadzu Corp.
- Demonstrates required ~4 keV energy resolution at relatively high temp of -35° to -45° C
- Readout via custom ASIC: integrated low-noise preamplifier, dynamic range compression 20 keV to 50 MeV

GAPS ToF system

- 206 scintillators
  - 160x18 cm^2 (inner)
  - 180x18 cm^2 (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 → Complementary to spectrometer-based $\bar{d}$ searches

  - First LDB flight approved by NASA in austral summer 2020/2021 → statistics of $\bar{p}$ below 250 MeV
  - Full $\bar{d}$ sensitivity after ~100 hours (3 LDB) flight
  - Highest statistics of every experiment for low-energy on $\bar{p}$ → 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