  

GAPS, low-energy antimatter for indirect dark-matter search

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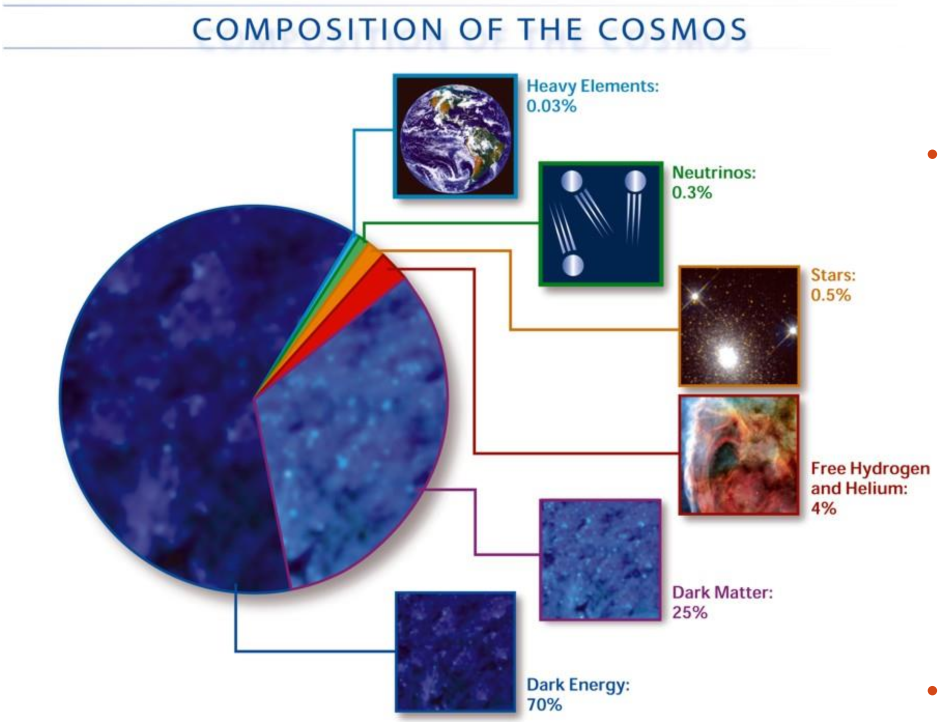
On behalf of the GAPS collaboration

Istituto Nazionale di Fisica Nucleare

Dark Matter (DM)



- ~1/4 of our Universe is composed of DM:
  - Weakly coupled to SM particles
  - Dynamically cold
  - No direct indication on the mass scale

    (but **GeV-TeV** well motivated range,

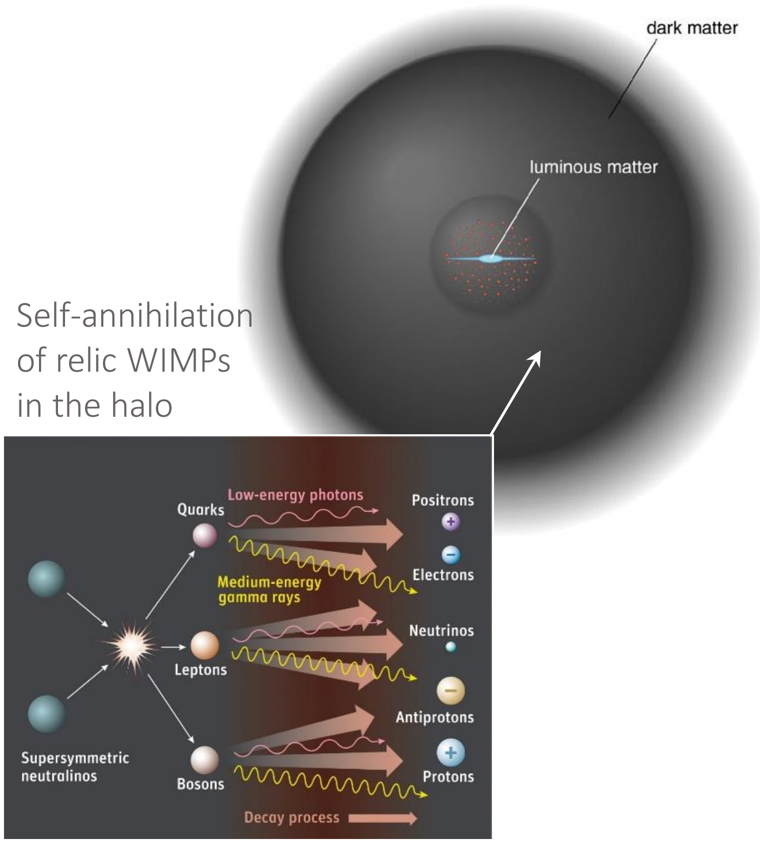
    → Weakely Interacting Massive Particle (**WIMP**))
- Evidence of DM is purely of gravitational origin

Non-gravitational signal is needed to understand its particle-physics nature

Astrophysical messengers of DM

(Fornengo. XXV ECRS 2016)

Self-annihilation
of relic WIMPs
in the halo



Halo signals

- Charged lepton CRs: $e^{\pm}$
- Charged baryionic CRs: $\bar{p}, \overline{D}, \overline{He}$
- Photons
  - Gamma rays
    Prompt production
    IC from $e^{\pm}$ on ISRF and CMB
  - X-rays
    IC from $e^{\pm}$ on ISRF and CMB
  - Radio
    Synch. from $e^{\pm}$ on B fields
- Neutrinos

Local signals

- Neutrinos from Earth and Sun
- Direct detection

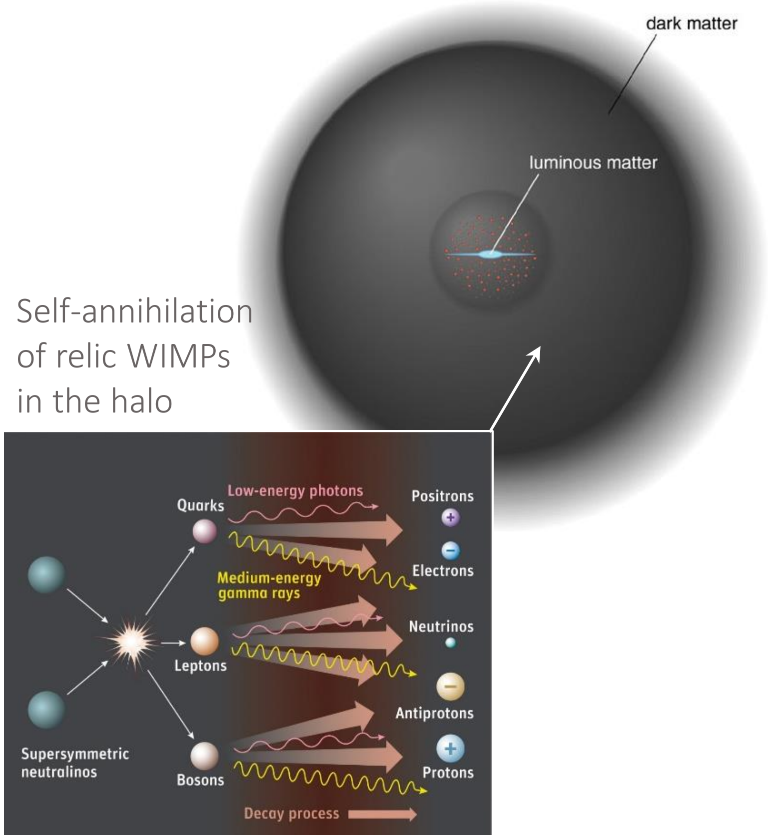
} Indirect detection

Multi-messenger, multi-wavelength approach to DM search
(available channels depend on DM mass and astrophysical background)

Astrophysical messengers of DM

(Fornengo. XXV ECRS 2016)

Self-annihilation of relic WIMPs in the halo

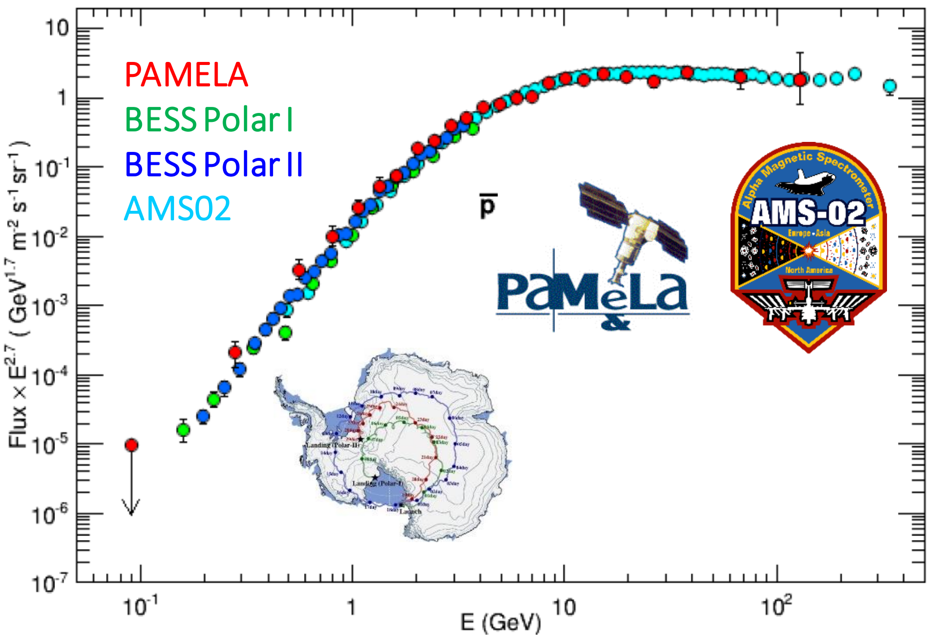


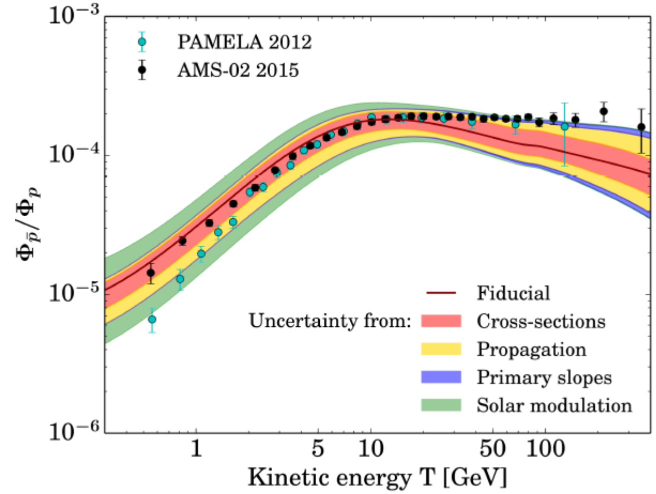
- Charged baryionic CRs: $\bar{p}, \overline{D}, \overline{He}$

General Antiparticle Spectrometer (GAPS) science

Multi-messenger, multi-wavelength approach to DM search
(available channels depend on DM mass and astrophysical background)

Cosmic $\bar{p}$





Giesen et al. 2015

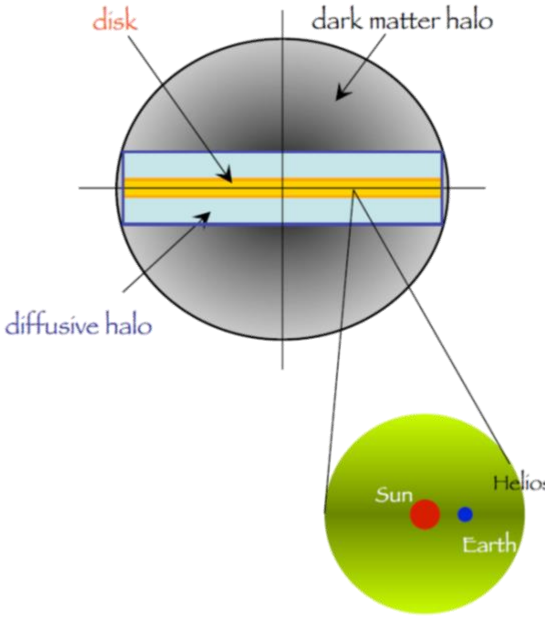
- Most abundant baryonic antiparticle component in CRs
- Extensively measured with **magnetic spectrometers** from **200 MeV up to 450 GeV**
- Consistent, within uncertainties, with secondary background
  - → Upper bound to WIMP mass (eg ~40 GeV from PAMELA data)

Low-energy $\bar{p}$ …

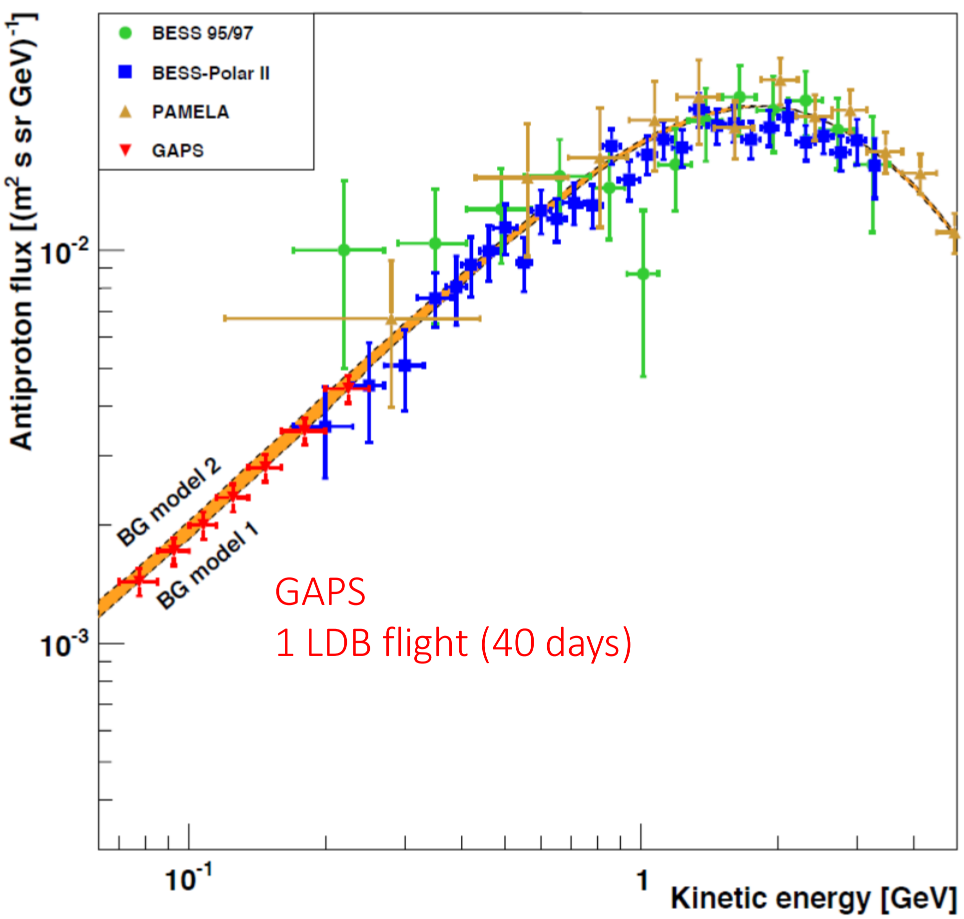
Secondaries (background)

$$p_{CR} + p_{ISM} \rightarrow \bar{p} + ppp$$

- Produced in the disk (kin. threshold)
- Propagate in the diffusive halo



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



Low-energy p̄ probe light-DM…

Secondaries (background)

$p_{CR} + p_{ISM} \rightarrow \bar{p} + ppp$

- Produced in the disk (kin. threshold)
- Propagate in the diffusive halo

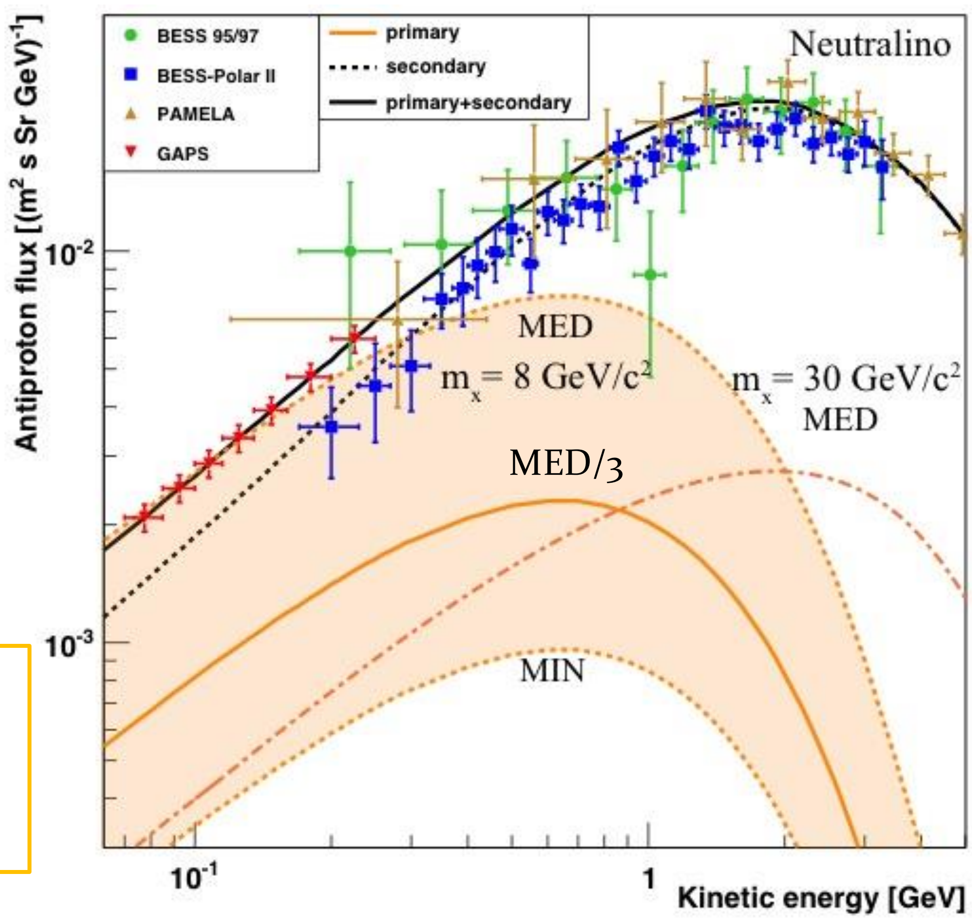
DM signal

$\chi\chi \rightarrow (\dots) \rightarrow \bar{p} + p$

- Produced in the DM halo
- Propagate in the diffusive halo

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

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



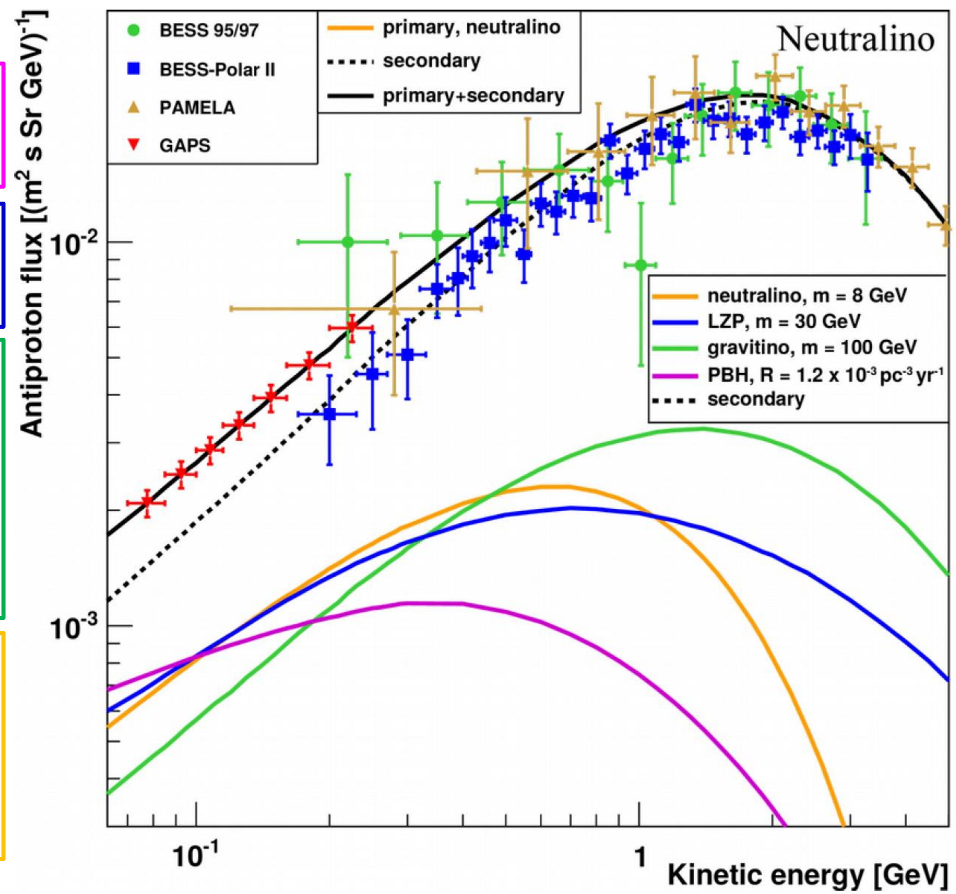
...and other DM models

Evaporating primordial BHs
(Abe et al, 2012)

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

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

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



Cosmic $\bar{D}$

Donato, Fornengo, Salati PRD 62 (2000) 043003
Aramaki et al – Phys.Rep. 618 (2016) 1

Secondaries (background)

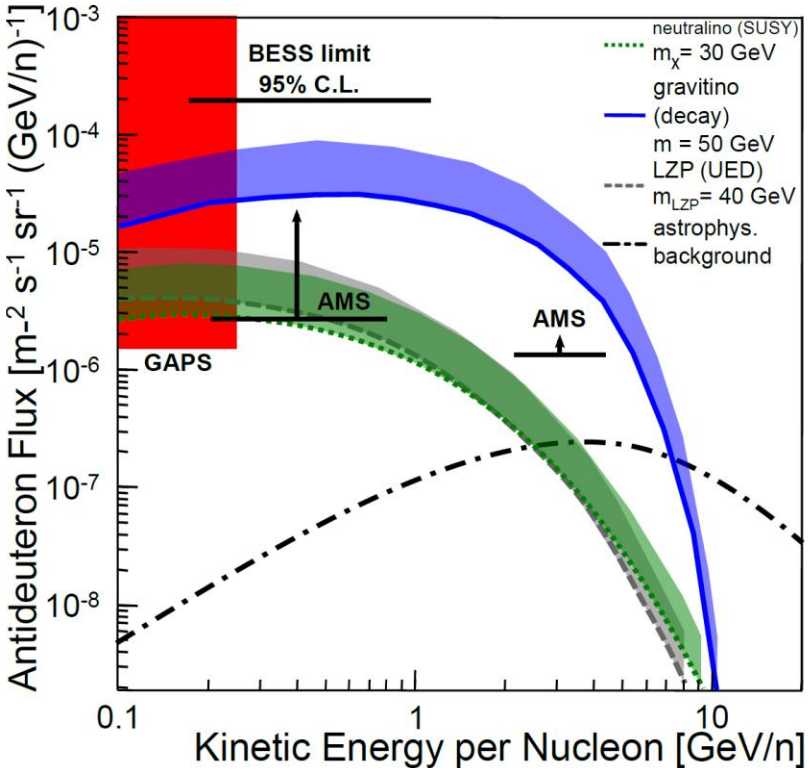
$$p_{CR} + p_{ISM} \rightarrow \underbrace{\bar{p}\bar{n}}_{coalescence} + pn + pp$$

- Produced in the disk
  kin. threshold
  → strongly suppressed
- Propagate in the diffusive halo

DM signal

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

- Produced in the DM halo
- Propagate in the diffusive halo



→ Favourable signal-to-background ratio al low energy

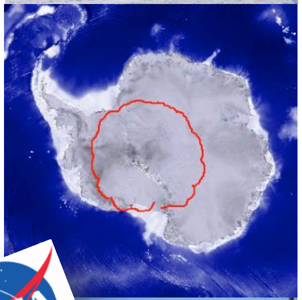
The GAPS experiment

General Anti-Particle Spectrometer

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

- Science summary:
  - **Search for antideuterons** 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**
    ~1500 $\bar{p}$ (vs ~30 $\bar{p}$ BESS ~7 $\bar{p}$ PAMELA E < 250 MeV)
  - 2 LDB flights (~ 70 days) -> **improved antideuteron statistics**
    sensitivity: ~ 3.0×10^{-6} $m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}$
  - 3 LDB flights (~ 105 days) ->
    sensitivity: ~ 2.0×10^{-6} $m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}$

→ First flight approved by NASA for antarctic summer 2020/2021

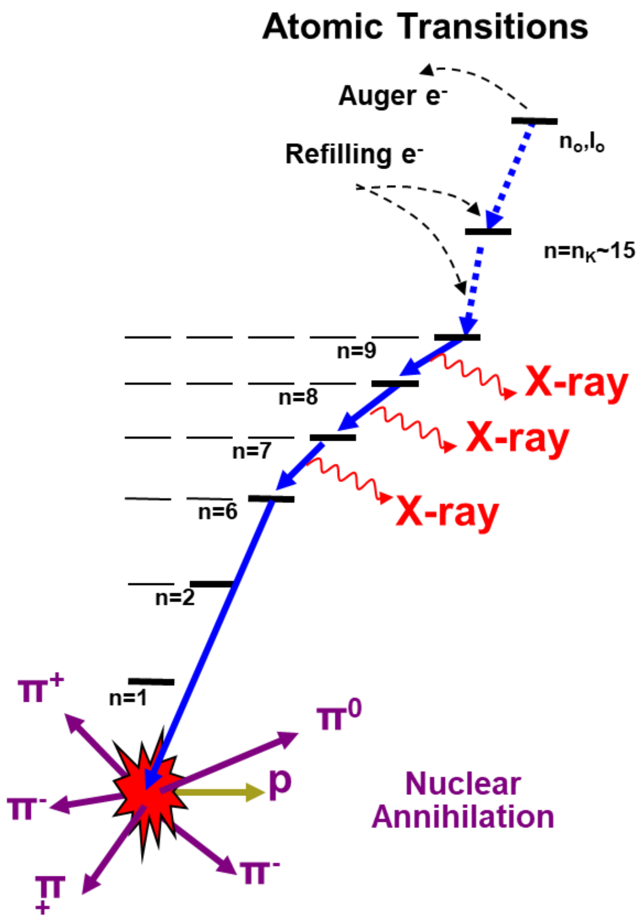

The GAPS collaboration

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
INFN

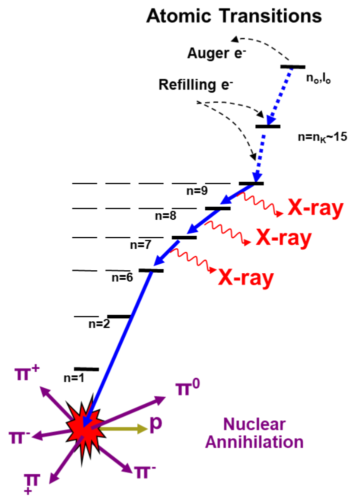
GAPS detection method

Based on the antiparticle annihilation process inside a medium

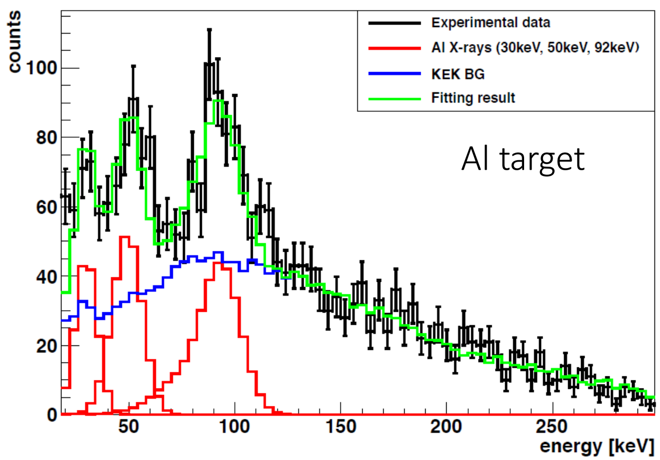
1. Low-energy antiparticles ($\bar{p}$, $\bar{D}$) slow-down traversing the medium
2. They stop, forming an **exotic atom** in an **excited** state, which de-excites through radiative transitions, emitting detectable **X-rays**
3. They are captured by atomic nuclei and undergoes **nuclear annihilation**, emitting **pions** and **protons**



X-ray emission by exotic atom



Aramaki et al. Astro.Ph. 49 (2013) 52



$\bar{p}$-Si	Cascade Mode
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%

- X-ray yield for **antiprotonic exotic atoms** formed with Al and S target measured @KEK (Japan) in 2004/2005
- Development of a comprehensive atomic cascade model tuned on KEK data
  - benchmarked against other anti-protonic and muonic exotic atoms
  - extended to any other exotic atom → **prediction for $\overline{D}$ in Si**

The GAPS apparatus

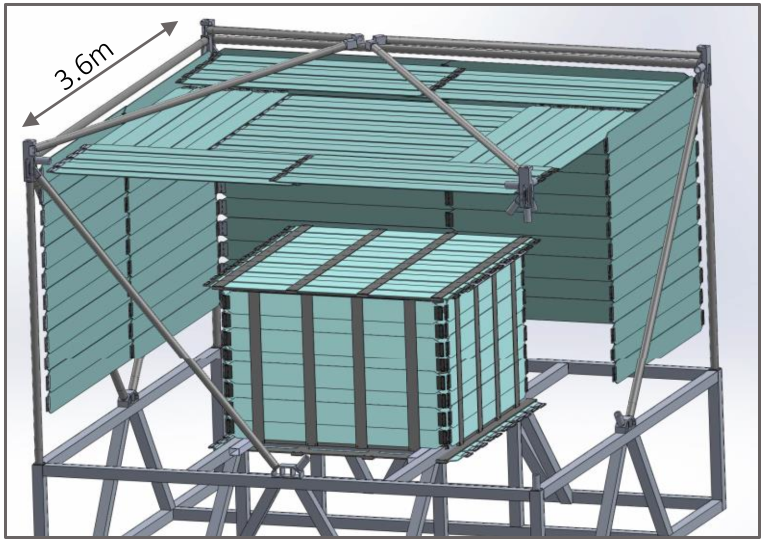
Time-of-Flight system

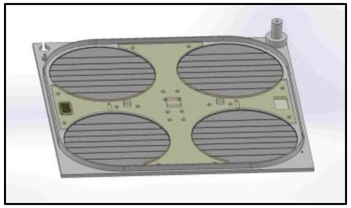
- 1 outer + 1 inner layers
  - Plastic scintillator, readout on each end by SiPMs
  - 1 m b/w outer and inner layers
  - < 500 ps resolution

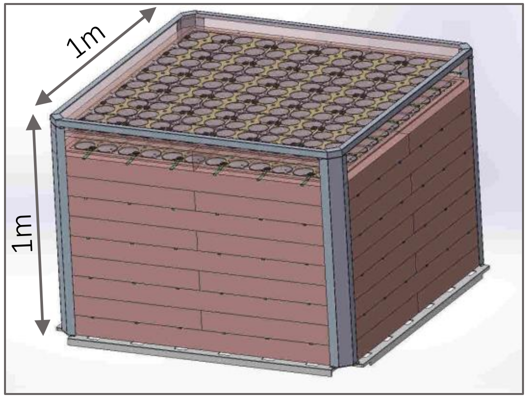
Tracking system

- 12×12 Si(Li) wafers
  - -48°C operation temperature
  - 10 cm ∅ × 2.5mm thickness
  - segmented into 8 strips
- 10 layers with 10 cm spacing
  → 3D particle tracking
- dual channel electronics
  - X-ray (20 - 80 keV)
  - charged particles (up to 50 MeV)
- 4 keV energy resolution

Oscillating Heat Pipe (OHP) passive cooling system

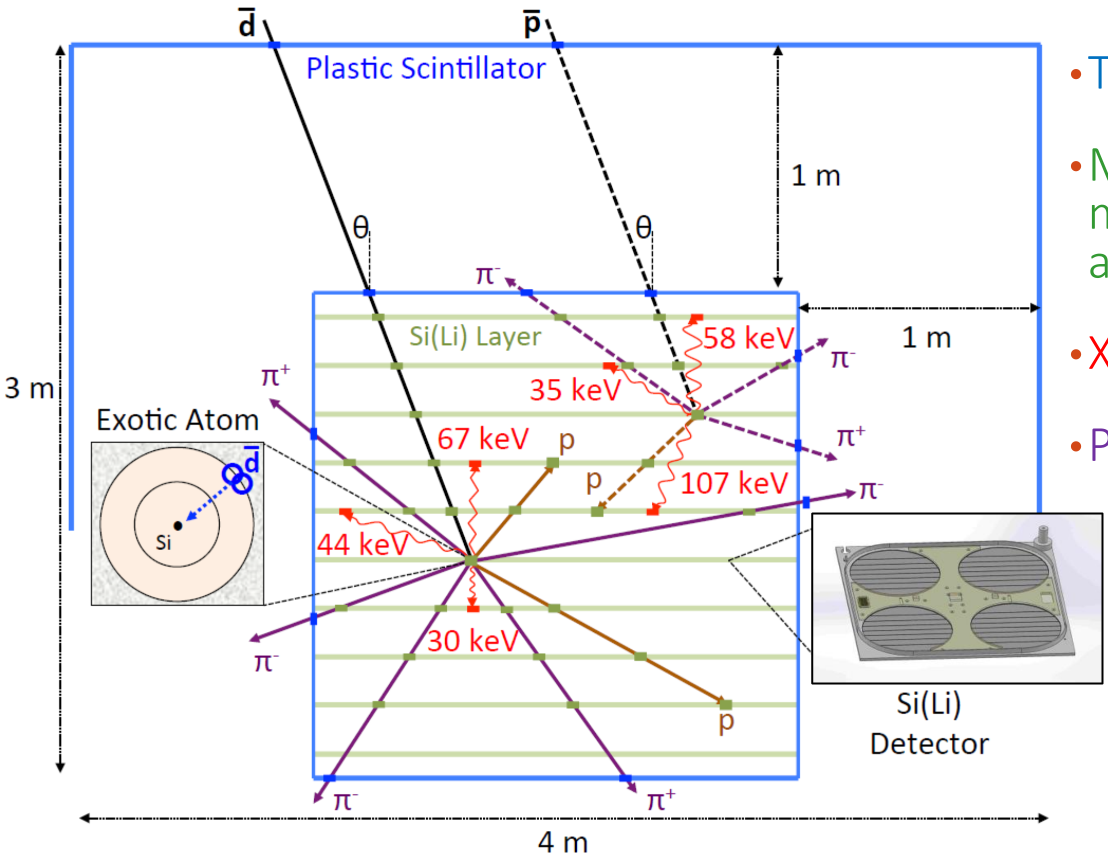






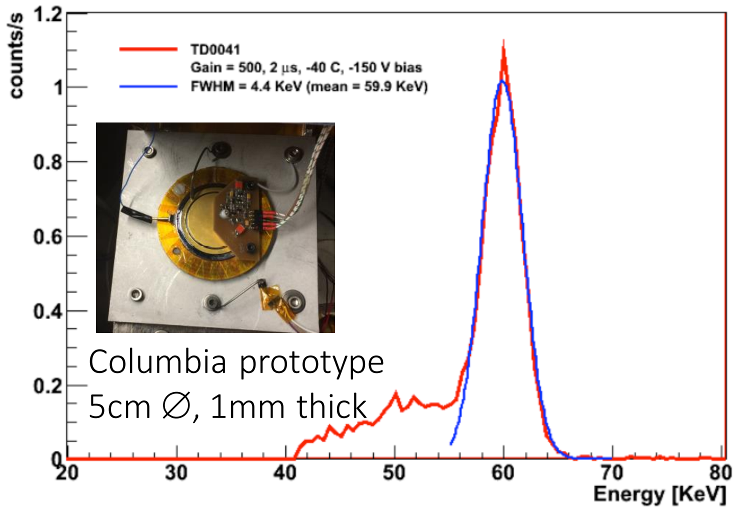
weight: 1700kg
power: 1.4kW

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



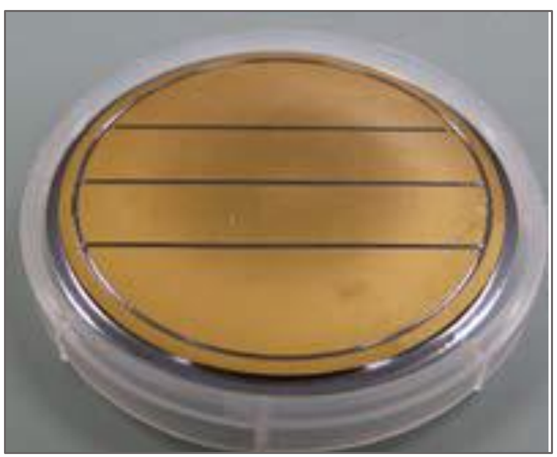
- Time-of-light
- Multiple dE/dx measurements along antiparticle trajectory
- X-ray energies
- Pion/proton multiplicity

Si(Li) detectors

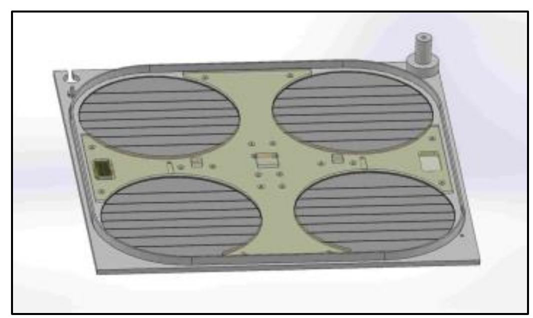


Perez et al – IEEE (2013)

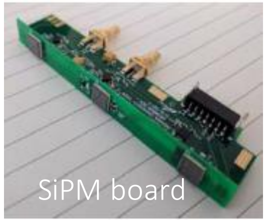
- 1440 Si(Li) needed
  - 10cm ∅, 2.5mm thick, 8-strip design
  - 4 keV energy resolution
- Fabrication facility set up @ Columbia University
  - 4.4 keV FWHM resolution with ^{241}Am X-rays @-40°C achieved
- Mass production by Shimazu (Japan)
  - Achieved leakage current <10 nA @-35°C
  - Final design 8 strips, operated @ -48°C

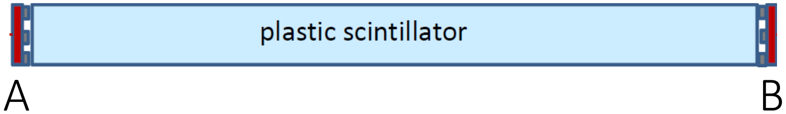


Shimazu prototype
10 cm wafer ∅,
2.5 mm thick
4-strip design



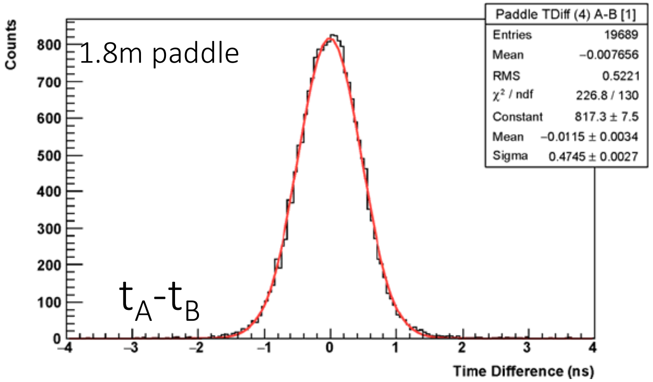
TOF detectors



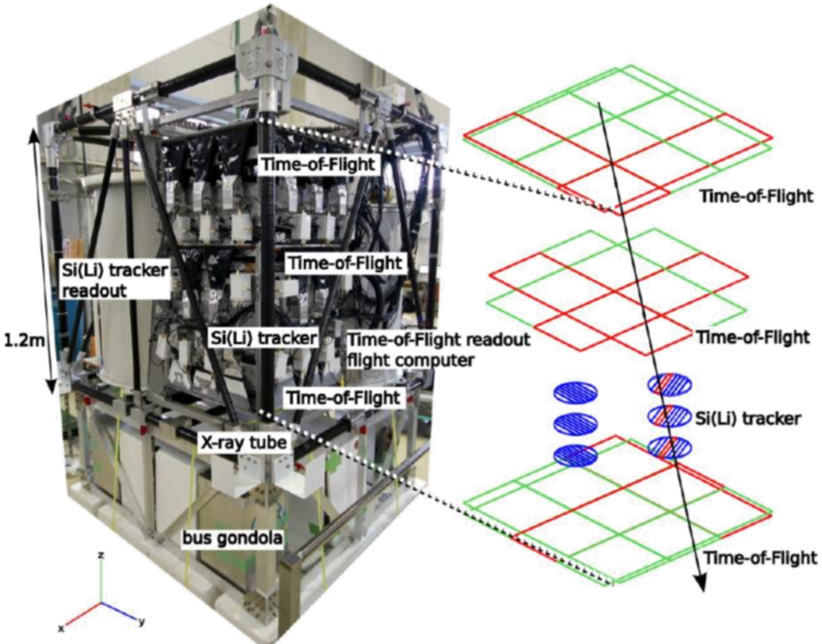


- 240 scintillators
  - 160×18 cm^2 (inner)
  - 180×18 cm^2 (outer)
  - 5mm thick EJ-200 (Eljen Tech.)
- SiPM readout
  - 3+3 MPPC S13360-6050VE (Hamamatsu)
- Achieved timing resolution @ paddle center 485ps

  → Time-of-flight resolution 343 ps

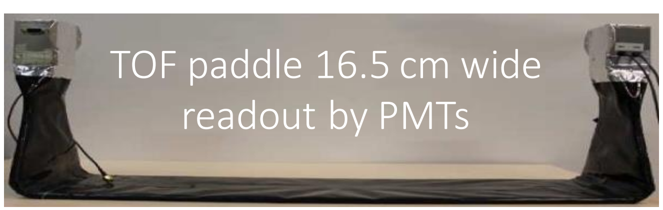


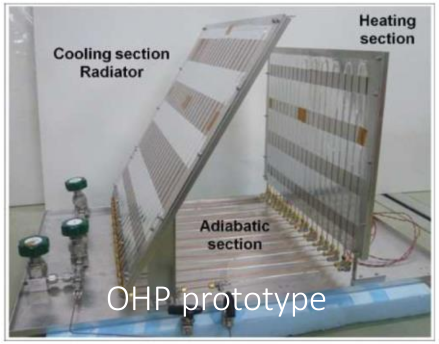
pGAPS



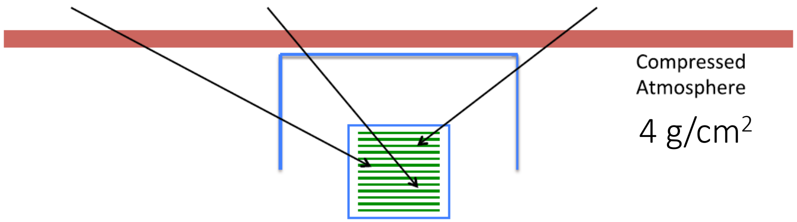
- Successful flight of GAPS prototype in June 2012 from Taiki (Japan)
  - First balloon experiment with Si(Li) detectors
    - Stable response to X-rays (calibration sources) and MIPs
  - X-ray background measured
  - Standalone OHP cooling system demonstrated

Mognet et al – NIM 735 (2014) 24
Von Doetinchem et al – Astro.Ph. 54 (2014) 93





GAPS $\bar{D}$ sensitivity



> 3 m² sr effective grasp for anti-particles annihilating within the detector

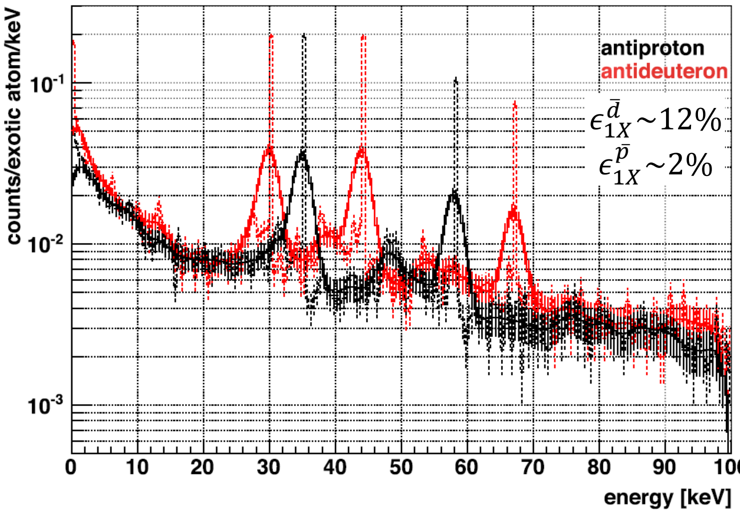
Monte Carlo simulation:

- **X-ray** yield from atomic cascade model
- **π and p** multiplicity from Intra-Nuclear Cascade (INC) model
- All particles propagated with Geant4 (v10.01)

- $\bar{D}$ Selection
  - Stopping depth + (X, π, p)

→ **Sensitivity (105 days, 99% CL)**

~ 2.0 × 10^{-6} m^{-2} s^{-1} sr^{-1} (GeV/n)$^{-1}$



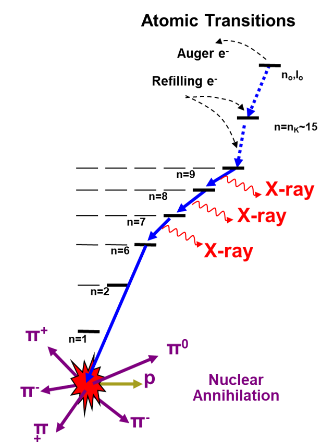
$\langle M_{\pi^\pm} \rangle$	$\epsilon^{\bar{p}}_{\pi}$	$\epsilon^{\bar{d}}_{\pi}$
≥3	0.53	0.93
≥4	0.25	0.80
≥5	0.070	0.62
≥6	0.093	0.41
≥7	0.00067	0.23
≥8	0.000026	0.11

$\langle M^{60}_{p} \rangle$	$\epsilon^{\bar{p}}_{p}$	$\epsilon^{\bar{d}}_{p}$
≥1	0.31	0.87
≥2	0.054	0.60
≥3	0.0064	0.34
≥4	0.00058	0.16

Aramaki et al. Astro.Ph. 74 (2016) 6

Conclusions

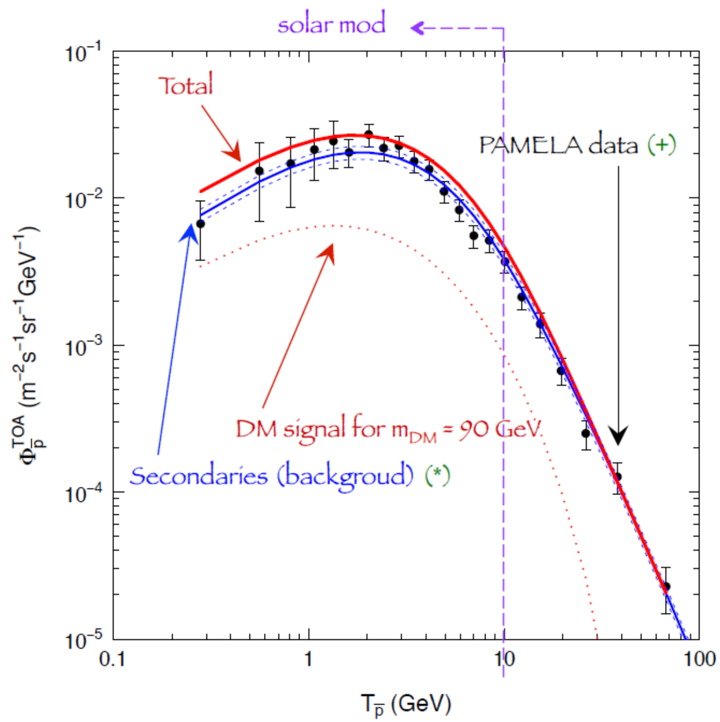
- Measurement of cosmic $\overline{D}$ and $\overline{p}$ is a promising way of indirect DM search
- The General Anti-Particle Spectrometer (GAPS) is specifically designed for low-energy $\overline{D}$ search and $\overline{p}$ flux measurement (< 250 MeV)
  - Novel detection technique based on detection and reconstruction of annihilation events
    - Exotic-atom radiative de-excitation + star-like annihilation products
    - → Complementary to spectrometer-based $\overline{D}$ searches
  - First LDB flight approved by NASA in Antarctic summer 2020/2021
    - → 100× statistics of $\overline{p}$ below 250 MeV
  - Full $\overline{D}$ sensitivity after ~100 hours (~3 LDB) flight
- Status of the experiment
  - Detection concept and detector in-flight operation demonstrated
  - Design finalized
  - Si(Li) detector production ready to start

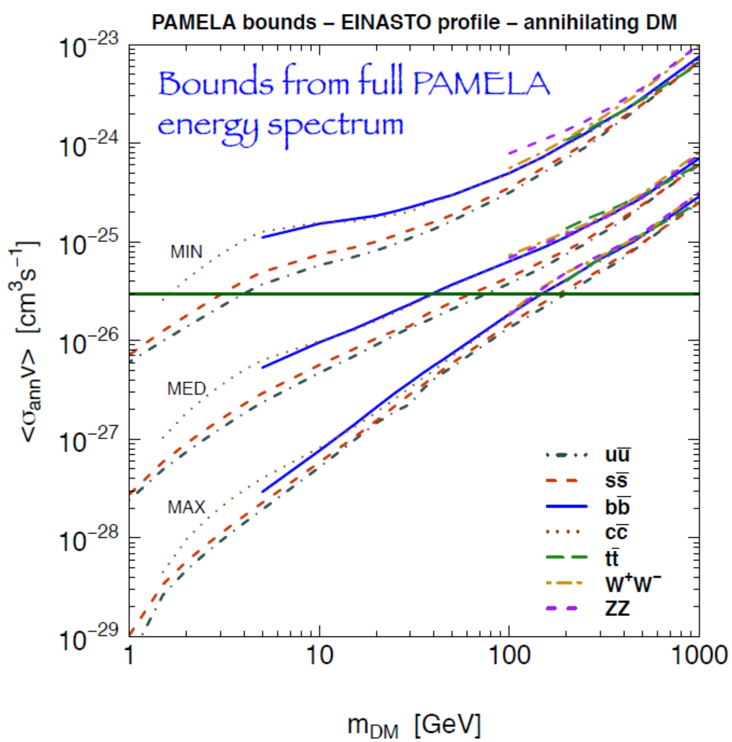


Thank you for the attention!

(… and cross the finger for a $\overline{D}$ detection !!!)

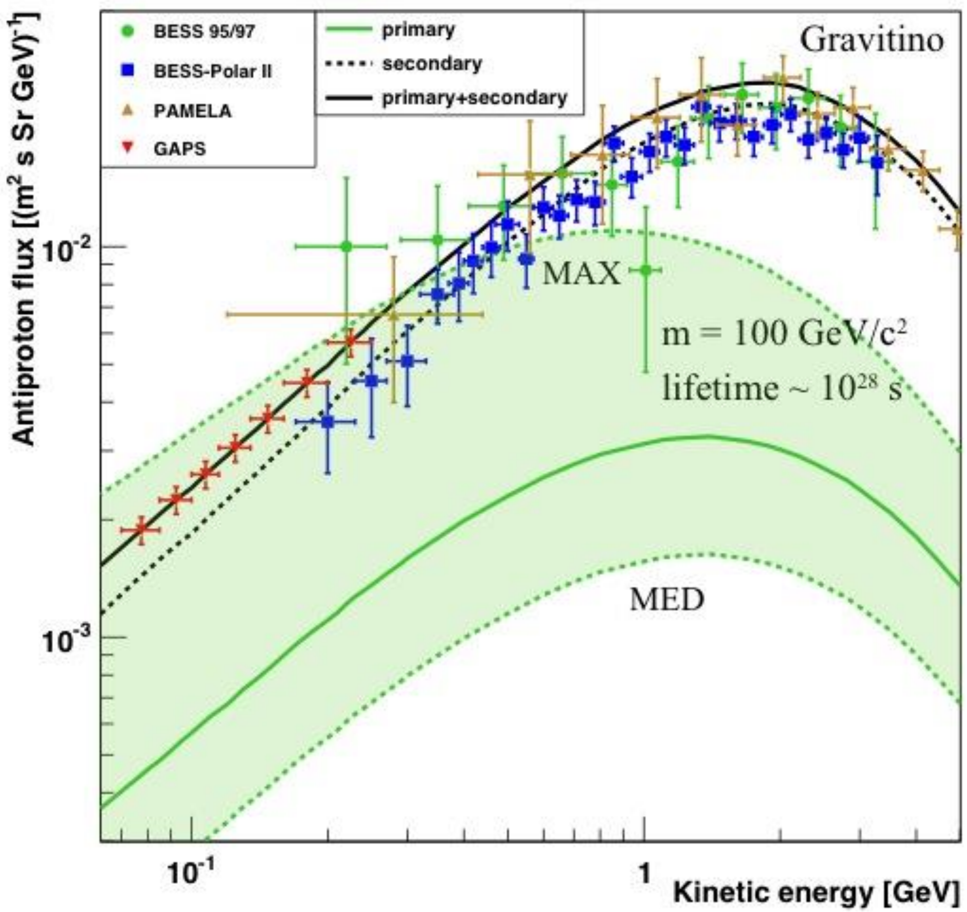
Spares

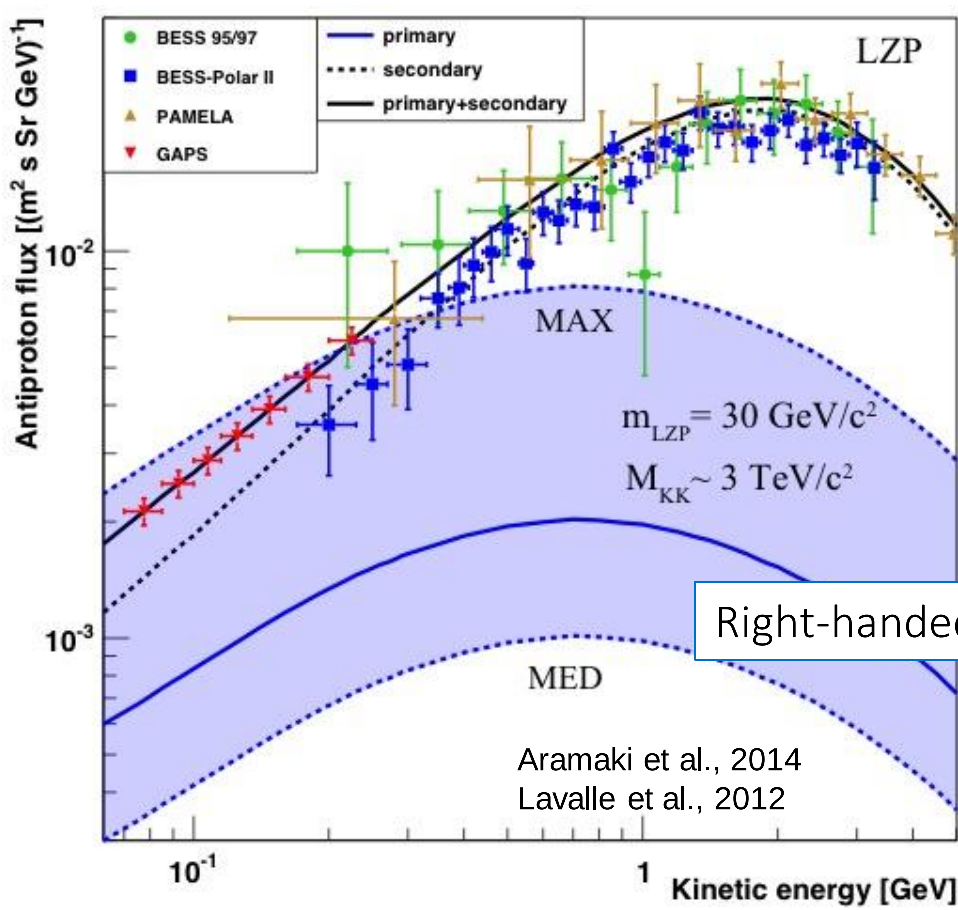




Fornengo, Maccione, Vittino – JCAP 9 (2013) 031

Low-energy p̄ probe SUSY DM, ...

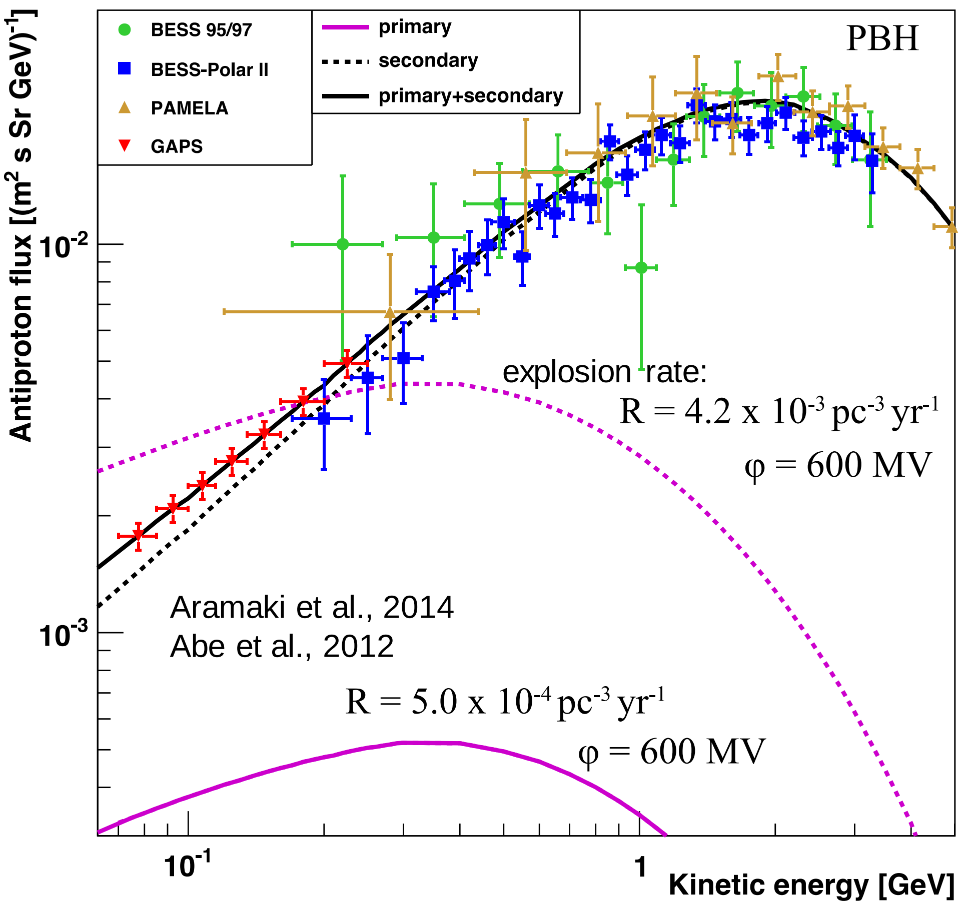




Right-handed neutrino

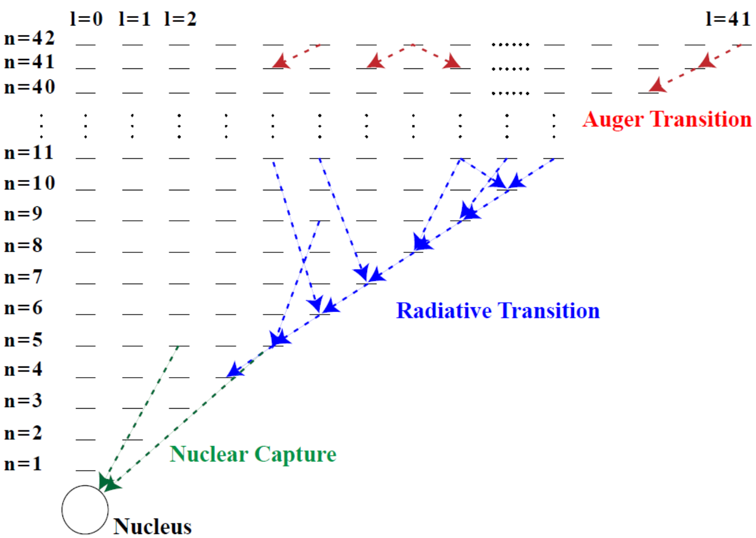
Aramaki et al., 2014
Lavalle et al., 2012

Low-energy p̄ probe SUSY DM, KK-DM and PBHs



Atomic cascade model

Aramaki et al. Astro.Ph. 49 (2013) 52

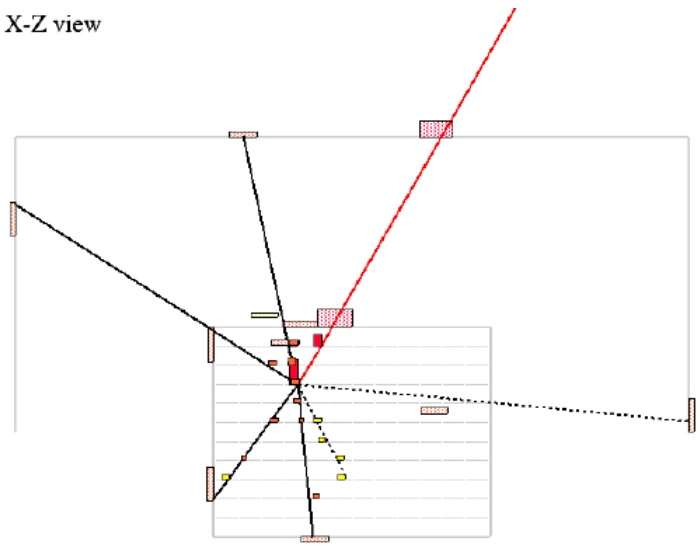


- Focusing on low-n state transition (E>10keV)
- Antiparticle captured at the radius of the outermost e-
- Hydrogen-like exotic atom
- Three de-excitation transitions:
  - Auger
  - Radiative
  - Nuclear capture

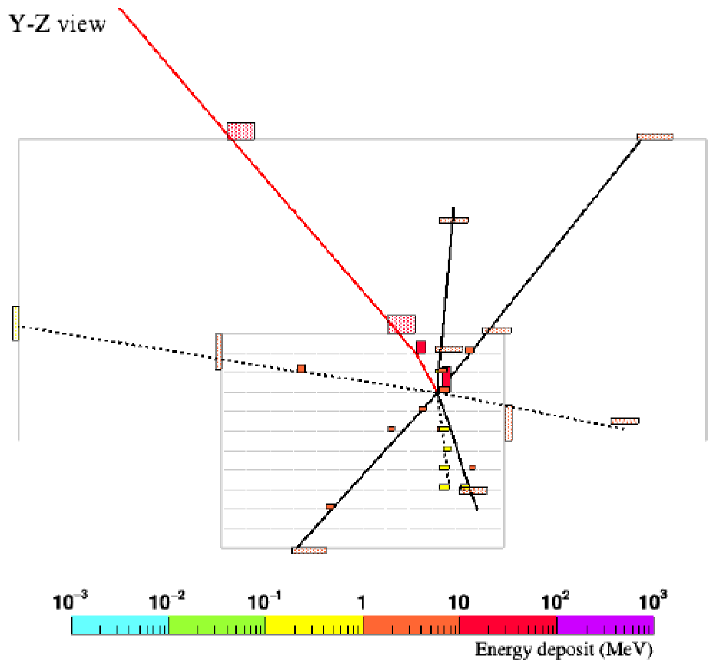
$\bar{p}$-Si	Cascade Mode
106 keV ($5 \rightarrow 4$)	70%
58 keV ($6 \rightarrow 5$)	84%
35 keV ($7 \rightarrow 6$)	73%

$\bar{d}$-Si	W = 10 MeV	W = 20 MeV
112 keV ($6 \rightarrow 5$)	28%	17%
67 keV ($7 \rightarrow 6$)	96%	94%
44 keV ($8 \rightarrow 7$)	92%	93%
30 keV ($9 \rightarrow 8$)	80%	80%

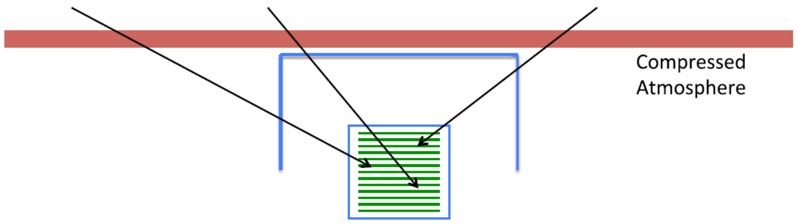
$$W_{\bar{d}} \sim 2W_{\bar{p}} = 10 \text{ MeV},$$

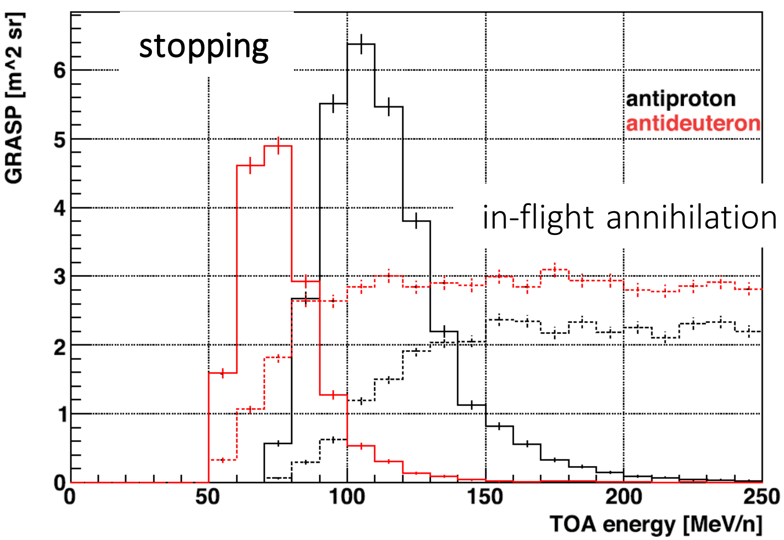


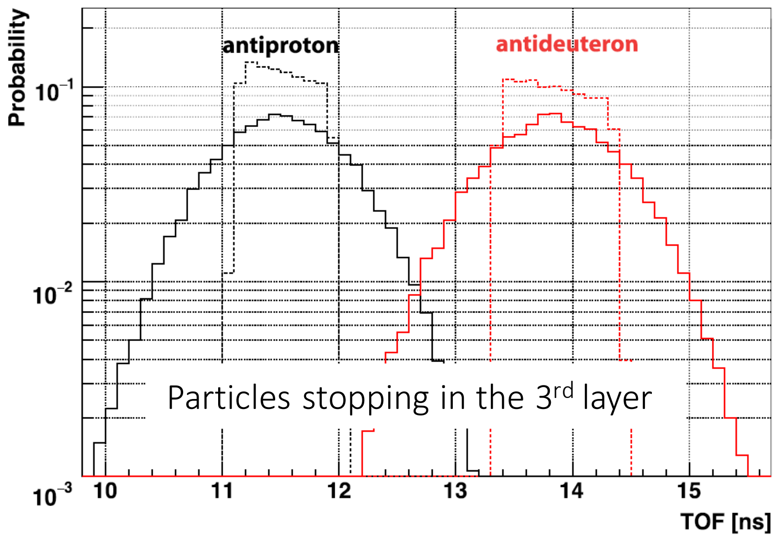
Antideuteron	Photon	Primary Energy 90.3 MeV	Tracker hits 19
Pion	Muon	Primary Beta 0.30	
Proton	Neutron	N. secondaries 39	ToF hits 12
Electron	ν (e,μ,τ)	Tot energy release 115 MeV	



GAPS $\bar{D}$ sensitivity (bis)





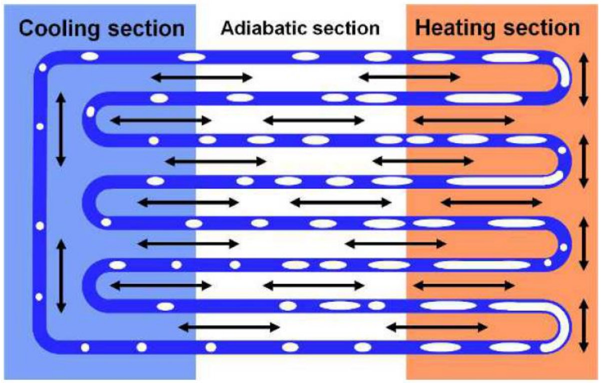


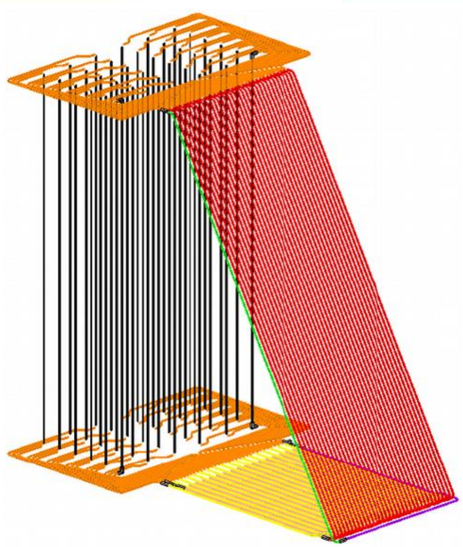
GAPS $\bar{D}$ sensitivity (tris)

$\langle M_{\pi^\pm} \rangle$	Aannihilation at rest		In-flight	
	$\epsilon_\pi^{\bar{p}}$	$\epsilon_\pi^{\bar{d}}$	$\epsilon_\pi^{\bar{p}}$	$\epsilon_\pi^{\bar{d}}$
≥3	0.53	0.93	0.57	0.93
≥4	0.25	0.80	0.58	0.82
≥5	0.070	0.62	0.092	0.64
≥6	0.093	0.41	0.019	0.44
≥7	0.00067	0.23	0.0024	0.26
≥8	0.000026	0.11	0.00016	0.13

$\langle M_p^{60} \rangle$	Annihilation at rest		In-flight	
	$\epsilon_p^{\bar{p}}$	$\epsilon_p^{\bar{d}}$	$\epsilon_p^{\bar{p}}$	$\epsilon_p^{\bar{d}}$
≥1	0.31	0.87	0.32	0.88
≥2	0.054	0.60	0.057	0.62
≥3	0.0064	0.34	0.0070	0.36
≥4	0.00058	0.16	0.00066	0.0.16

OHP cooling system





Okazaki et al – J.Astr. 3 (2014)

- Oscillating Heat Pipe
  - 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