Overview of present and future cosmic-ray experiments
(for indirect searches of Dark Matter)

Mirko Boezio
INFN Trieste, Italy

UCLA Dark Matter 2016
February 17th 2016
Galactic DM signals

**Halo signals**
- Charged Leptonic CR: $e^\pm$
- Charged Baryonic CR: antiP, antiD, antiHe

**Photons**
- Gamma-rays
  - Prompt production
  - IC from $e^\pm$ on ISRF and CMB
- X-rays
  - IC from $e^\pm$ on ISRF and CMB
- Radio
  - Synchro from $e^\pm$ on mag. field

**Neutrinos**

**Local signals**
- Direct detection
- Neutrinos from Earth and Sun

Courtesy of N. Fornengo
Cosmic Rays and Anti-Particles

p, He, C, N, O

CR secondary production (pp → X)

ISM gas

Bremsstrahlung, Synchrotron, Inverse Compton

Solar Modulation, lower interstellar cosmic ray spectra

e-, γs

p, He, C, N, O, Li, Be, B, ...

p, He, C, N, O, Li, Be, B, ...

π+, π-

decay

π0

decay

γ

Mirko Boezio, UCLA Dark Matter 2016, 02/17/16
The first historical measurements on galactic antiprotons

\[ CR + ISM \rightarrow p-bar + \ldots \]

kinematic threshold:
5.6 GeV for the reaction

expected ratio from secondary production
BESS-Polar Program

Status of the BESS-Polar I Flight

Observation Time: 8.5 days
Float Time: 8.5 days (12/13/2004-12/21/2004)
Events recorded: \( > 0.9 \times 10^9 \)
Data volume: \( \sim 2.1 \) terabytes
Data recovery: **completed** 2004
Payload recovery: **completed** 2004

Status of the BESS-Polar II Flight

Observation Time: 24.5 days
Float Time: 29.5 days (12/23/2007-01/21/2008)
Events recorded: \( > 4.7 \times 10^9 \)
Data volume: \( \sim 13.5 \) terabytes
Data recovery: **completed** Feb 3, 2008
Payload recovery: **completed** Jan 16, 2010

Makoto Sasaki, Antideuteron 2014, UCLA
BESS-Polar II: Lower Energy, High Statistics
Antiproton Measurement

BESS–Polar II Z=1 Particle Id

7886 Antiprotons

* MDR 240 GV, TOF 120 ps, ACC rejection 6100
* 7886 Antiprotons ~10-20 times previous Solar minimum dataset

Antiproton Spectrum

- BESS–Polar II and PAMELA spectra agree in shape but differ ~14% in absolute flux
- Both agree in shape with secondary

Makoto Sasaki, Antideuteron 2014, UCLA
PAMELA detectors

Main requirements → high-sensitivity antiparticle identification and precise momentum measure

GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- Magnetic rigidity → \( R = \frac{p}{Ze} \)
- Charge sign
- Charge value from \( \frac{dE}{dx} \)

Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from \( \frac{dE}{dx} \).

Electromagnetic calorimeter
W/Si sampling (16.3 X₀, 0.6 \( \lambda_I \))
- Discrimination e⁺ / p, anti-p / e⁻ (shower topology)
- Direct E measurement for e⁻

Neutron detector
3He tubes + polyethylene moderator:
- High-energy e/h discrimination

Launched on 15th June 2006 PAMELA in nearly continuous data-taking mode since then. Recently celebrated 9 years!
PAMELA Antiparticle Results: Antiprotons


Secondary production calculations
The Alpha Magnetic Spectrometer (AMS) on the International Space Station
AMS: A worldwide Collaboration

17 years, 16 Countries, 60 Institutes and 600 Physicists
AMS: A TeV precision, multipurpose spectrometer

Particles are defined by their charge ($Z$) and energy ($E$) or momentum ($P$).

The Charge and Energy (momentum) are measured independently by many detectors.
Cosmic-Ray Antiprotons and DM limits

PAMELA and preliminary AMS-02 antiproton data constrains on various dark matter models and astrophysical uncertainties.


Fornengo, Maccione, Vittino, JCAP 1404 (2014) 04, 003
Cosmic-Ray Antiprotons and DM limits

PAMELA and preliminary AMS-02 antiproton data constrains on various dark matter models and astrophysical uncertainties.

The Beam: Absolute fluxes of primary GCRs

Protons, helium nuclei, light nuclei, electrons
Proton (Hydrogen) Spectrum

Solar modulation

Flux $\times E^{2.7}$ (m$^2$ s sr GeV$^{-1}$) $\times$ GeV$^{-2.7}$

$E$ (GeV)

$10^3$ $10^4$ $10^5$ $10^6$

10 100 1000 10000 100000

PAMELA, CAPRICE94, AMS-01, BESS, JACEE (1994), Ryan et al. (1972), RICH2, GRAPES-3 (QGSJet), Kascale (QGSJet), Kascale (SH), IMAX, CAPRICE98, ATIC-2, CREAM, CREAM, CREAM, CREAM, CREAM, EASTOP, EASTOP, EASTOP, EASTOP, EASTOP, EASTOP, EASTOP, EASTOP, EASTOP.
PAMELA Proton and Helium Nuclei Spectra & H/He ratio

- First high-statistics and high-precision measurement over three decades in energy
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV $\Delta \gamma \sim 0.2 \div 0.3$
  SPL is rejected at 98% CL

Origin of the hardening?
(e.g. see P. Blasi, Braz.J.Phys. 44 (2014) 426)
- At the sources: multi-populations, etc.?
- Propagation effects?

Clear evidence of different H and He slopes above ~ 10 GV

O. Adriani et al., Science 332 (2011) 6025
AMS-02 Proton and Helium Nuclei Spectra

AMS-02 H flux measurement:
300 million events

AMS-02 He flux measurement:
50 million events

M. Aguilar et al., PRL 114 (2015) 171103
M. Aguilar et al., PRL 115 (2015) 211101
Propagation: Secondary cosmic rays

Secondaries from homogeneously distributed interstellar matter (light nuclei)
AMS-02 and others: B/C and Boron and carbon fluxes

B. Bertucci, CRIS 2015, Gallipoli, Italy
4 layer Silicon Charge Detector
- Precise charge measurements
- 380-µm thick 2.12 cm² pixels
- 79 cm x 79 cm active detector area

Top & Bottom Counting Detectors
- Each with 20 x 20 photodiodes and a plastic scintillator for e/p separation
- Independent Trigger

Carbon Targets (0.5 $\lambda_{\text{int}}$) induces hadronic interactions

Calorimeter (20 layers W + Scn Fibers)
- Determine Energy
- Provide tracking
- Provide Trigger

Boronated Scintillator Detector
- Additional e/p separation
- Neutron signals

Launch 2017
PAMELA Positron to Electron Fraction

O. Adriani et al., Astropart. Phys. 34 (2010) 1
O. Adriani et al., PRL 111 (2013) 081102
AMS-02 positron fraction: significant increase in statistics allows a detailed study of the positron fraction behavior with energy.

10.9 million e+ and e- events

AMS-02 positron fraction: significant increase in statistics allows a detailed study of the positron fraction behavior with energy

L. Accardo et al., PRL 113 (2014) 121101
AMS-02 $e^-$ and $e^+$ energy spectra

For the first time a detailed study of the spectral index variation with energy:

$$\gamma_{e^\pm} = \frac{d[\log(\Phi_{e^\pm})]}{d[\log(E)]}$$

Hardening of the positron spectrum is at the origin of the positron fraction increase...

M. Aguilar et al., PRL 113 (2014) 121102
Implications

A rising positron fraction requires:

1. An additional component of positrons with spectrum flatter than CR primary electrons

2. A diffusion coefficient with a weird energy dependence (BUT this should reflect in the CR spectrum as well)

3. Subtleties of Propagation

Courtesy by P. Blasi
Dark Matter Explanation


SNR Explanation

Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.

But also other secondaries are produced: significant increase expected in the p/p and secondary nuclei ratios.


Pulsar Explanation

Contribution from diffuse mature & nearby young pulsars.

Contributions of e⁻ & e⁺ from Geminga assuming different distance, age and energetic of the pulsar.

P. Blasi & E. Amato, arXiv:1007.4745
Contribution from pulsars varying the injection index and location of the sources.
Electrons can tell us about local GCR sources

- High energy electrons have a high energy loss rate $\propto E^2$
  - Lifetime of $\sim 10^5$ years for $>1$ TeV electrons
- Transport of GCR through interstellar space is a diffusive process
  - Implies that source of high energy electrons are $< 1$ kpc away

Only a handful of SNR meet the lifetime & distance criteria


J. P. Wefel, TeVPA 2011, Stockholm
AMS-02, Fermi & PAMELA
\((e^- + e^+)\) Spectrum

\[ \gamma_{e^\pm} = d[\log(\Phi_{e^\pm})]/d[\log(E)] \]

M. Aguilar et al., PRL 113 (2014) 221102
Electron \((e^- + e^+)\) Spectrum

\[
E^3 \times J(E) \text{ [GeV}^{-1} \text{s}^{-1} \text{m}^{-2} \text{sr}^{-1}]
\]

- **Fermi (2010)**
- **AMS-02 preliminary**
- **H.E.S.S. (2010)**
- **Fermi (2012)**
- **Fermi Pass 8 PRELIMINARY**

Energy \([\text{GeV}]\) vs. \(E^3 \times J(E)\) for different datasets.
The beam!
(charged particles)

PAMELA
CREAM
ATIC
FERMI
AMS-02

CALET
DAMPE
ISS-CREAM
GAMMA-400
HERD

Energies and rates of the cosmic-ray particles

$E^2 dN/dE$ (GeV m$^{-2}$ sr$^{-1}$ s$^{-1}$)

$E_{kin}$ (GeV/particle)
CALorimetric Electron Telescope

A Dedicated Detector for Electron Observation in 1GeV - 10,000 GeV
CALET Collaboration Team


1) Aoyama Gakuin University, Japan
2) Hirosaki University, Japan
3) ICRRR, University of Tokyo, Japan
4) JAXA/SEUC, Japan
5) JAXA/ISAS, Japan
6) Kanagawa University of Human Services, Japan
7) Kanagawa University, Japan
8) KEK, Japan
9) Louisiana State University, USA
10) NASA/GSFC, USA
11) National Inst. of Radiological Sciences, Japan
12) Nihon University, Japan
13) Ritsumeikan University, Japan
14) Saitama University, Japan
15) Shibaura Institute of Technology, Japan
16) Shinshu University, Japan
17) Tokyo Technology Institute, Japan
18) University of Denver, USA
19) University of Florence, IFAC (CNR) and INFN, Italy
20) University of Pisa and INFN, Italy
21) University of Rome Tor Vergata and INFN, Italy
22) University of Siena and INFN, Italy
23) Waseda University, Japan
24) Washington University-St. Louis, USA
25) Yokohama National University, Japan
26) University of Padova and INFN, Italy
27) Ibaraki University, Japan
28) Tokiwa University, Japan
Main Telescope: CAL (Calorimeter)

Expected Performance (from Simulations and/or Beam Tests)
- $S\Omega$:
  - 1200 cm$^2$sr for electrons, light nuclei
  - 1000 cm$^2$sr for gamma-rays
  - 4000 cm$^2$sr for ultra-heavy nuclei*
    * for $E > 600$ MeV/nucleon
- $\Delta E/E$:
  - $\sim 2\% (>10$ GeV) for $e'$s, $\gamma'$s
  - $\sim 30\%$ for protons
- $e/p$ separation: $10^{-5}$
- Charge resolution: 0.15-0.3 e
- Angular resolution: $\sim 0.1^\circ$ $e'$s, $\gamma'$s

<table>
<thead>
<tr>
<th>CHD (Charge Detector)</th>
<th>IMC (Imaging Calorimeter)</th>
<th>TASC (Total Absorption Calorimeter)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
<td><strong>Arrival Direction, Particle ID</strong></td>
<td><strong>Energy Measurement, Particle ID</strong></td>
</tr>
</tbody>
</table>
| Sensor (+ Absorber)    | Plastic Scintillator: $14 \times 1$ layer ($x,y$)  
    Unit Size: 32mm x 10mm x 450mm | SciFi: $448 \times 8$ layers ($x,y$) = 7168  
    Unit size: $1mm^2 \times 448$ mm  
    Total thickness of Tungsten: $3 X_0$ | PWO log: $16 \times 6$ layers ($x,y$)= 192  
    Unit size: $19mm \times 20mm \times 326mm$  
    Total Thickness of PWO: $27 X_0$ |
| Readout                | PMT+CSA                   | 64 -anode PMT+ ASIC                | APD/PD+CSA  
                          |                           | PMT+CSA (for Trigger)    |
CALET is now on the ISS!

① August 19th: After a successful launch of the Japanese H2-B rocket by the Japan Aerospace Exploration Agency (JAXA) at 20:50:49 (local time), CALET started its journey from Tanegashima Space Center to the ISS.

② August 24th:
The HTV-5 Transfer Vehicle (HTV-5) is grabbed by the ISS robotic arm.

③ August 24th:
The HTV-5 docks to the ISS at 19:28 (JSTT).

④ August 25th:
CALET is emplaced on port #9 of the JEM-EF and data communication with the payload is established.
CALET Capability for Electron (+ Positron) Observation: Nearby Sources

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Primary $e^-$</th>
<th>$e^-$ from Vela</th>
</tr>
</thead>
<tbody>
<tr>
<td>500-600</td>
<td>1188</td>
<td>154</td>
</tr>
<tr>
<td>600-800</td>
<td>1235</td>
<td>239</td>
</tr>
<tr>
<td>800-1000</td>
<td>601</td>
<td>163</td>
</tr>
<tr>
<td>1000-1500</td>
<td>546</td>
<td>279</td>
</tr>
<tr>
<td>1500-2000</td>
<td>146</td>
<td>134</td>
</tr>
<tr>
<td>2000-3000</td>
<td>99</td>
<td>134</td>
</tr>
<tr>
<td>3000-4000</td>
<td>23</td>
<td>51</td>
</tr>
<tr>
<td>4000-5000</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>5000-7000</td>
<td>5</td>
<td>22</td>
</tr>
<tr>
<td>7000-9000</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>&gt;9000</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>827</td>
<td>644</td>
</tr>
</tbody>
</table>

Conditions applied:
- Electromagnetic efficiency = 70%
- Proton rejection factor = $10^5$
- Geometrical factor = 0.12 m$^2$sr
- Exposure time = 5 years

Primary electron spectrum from Fermi data with Hess cutoff:
- $J(E) = 183^a (E/1 \text{ GeV})^{-3.645} \cdot e^{-E/3.4 \text{ TeV}} \text{ GeV}^{-1} \text{ m}^2 \text{ s}^{-1} \text{ sr}^{-2}$

Vela spectrum from Astro-ph/0308470v1, Kobayashi et al., Figure 4 Top

Expected Flux

$E_c=\infty$, $\tau=0$yr
$D_0=4 \times 10^{29} (\text{cm}^2 \text{s}^{-1})$

$\sim 10\%$ @1TeV

Expected Anisotropy from Vela SNR

$E_c=\infty$, $\tau=0$yr
$D_0=4 \times 10^{29} (\text{cm}^2 \text{s}^{-1})$

S. Torii, TeVPA 2013, Irvine, USA
The DAMPE Collaboration

- China
  - Purple Mountain Observatory, CAS, Nanjing
    - Chief Scientist: Prof. Jin Chang
  - Institute of High Energy Physics, CAS, Beijing
  - National Space Science Center, CAS, Beijing
  - University of Science and Technology of China, Hefei
  - Institute of Modern Physics, CAS, Lanzhou

- Switzerland
  - University of Geneva

- Italy
  - INFN and University of Perugia
  - INFN and University of Bari
  - INFN and University of Lecce
The DAMPE Detector

- Plastic Scintillator Detector
- Silicon-Tungsten Tracker
- BGO Calorimeter
- Neutron Detector

W converter + thick calorimeter (total 33 $X_0$) + precise tracking + charge measurement ➔ high energy $\gamma$-ray, electron and CR telescope
**Dark Matter Particle Explorer Satellite**

- One of the 5 satellite missions of the Chinese Strategic Priority Research Program in Space Science of CAS
  - Approved for construction (phase C/D) in Dec. 2011
  - Launched on 17 December 2015 from Jiuquan Satellite Launch Center

- Satellite ≈ 1900 kg, payload ≈ 1300kg
- Power consumption ≈ 640W
- Lifetime > 3 years
- Launched by CZ-2D rockets

- Altitude 500 km
- Inclination 97.4°
- Period 95 minutes
- Sun-synchronous orbit
Electrons: Dark Matter vs Nearby Sources
**Nuclei: CR Spectra & Composition toward the knee(s)**

- Proton spectrum to $\approx 900$ TeV
- He spectrum to $\approx 400$ TeV/n
- Spectra of C, O, Ne, Mg, Si to $\approx 20$ TeV/n
- B/C ratio to $\approx 4-6$ TeV/n
- Fe spectrum to $\approx 10$ TeV/n

(Depending on the assumed single primary spectra)
OBSERVATION MODES AND THE GAMMA-400 ORBIT EVOLUTION

Observation modes:
- continuous long-duration (~100 days) observation of some regions of celestial sphere, including point and extended gamma-ray sources;
- monitoring of the celestial sphere.

Initial orbit parameters:
- apogee: 300,000 km;
- perigee: 500 km;
- inclination: 51.4°

After ~5 months the orbit will transform to nearly circular with a radius of ~150,000 km.

Mirko Boezio, UCLA Dark Matter 2016, 02/17/16
AC – anticoincidence detectors

C – Conveter-Tracker

S1, S2 – ToF detectors

S3, S4 calorimeter scintillator detectors

CC1 – imaging calorimeter (2 $X_0$)
2 layers: CsI(Ti) 1 $X_0$ + Si(x,y) (pitch 0.1 mm)

CC2 - electromagnetic calorimeter
CsI(TI) 20 $X_0$ 3.6x3.6x3.6 cm$^3$ – 22x22x10 = 4840
HERD Design: 3D Calo & 5-Side Sensitive

About a factor 10 increase in statistics respect to existing experiments with a weight 2.3 T ~1/3 AMS

STK(W+SSD)
Charge
gamma-ray direction
CR back scatter

STK(W+SSD)
3D CALO
e/G/CR energy
e/p discrimination

Shuang-Nan Zhang, 3rd HERD Workshop, XiAn, Jan 2016
<table>
<thead>
<tr>
<th>type</th>
<th>size</th>
<th>$X_0,\lambda$</th>
<th>unit</th>
<th>main functions</th>
</tr>
</thead>
</table>
| tracker (top)    | Si strips      | 70 cm $\times$ 70 cm | 2 $X_0$          | Charge
|                  |                |               | 7 x-y (W foils)     | Early shower Tracks     |
| tracker 4 sides  | Si strips      | 65 cm $\times$ 50 cm | 2 $X_0$          | Charge
|                  |                |               | 7 x-y (W foils)     | Early shower Tracks     |
| CALO             | $\sim$10K LYSO cubes | 63 cm $\times$ 63 cm $\times$ 63 cm | 55 $X_0$
|                  |                |               | 3 cm $\times$ 3 cm $\times$ 3 cm | e/$\gamma$ energy
|                  |                |               |                  | nucleon energy          |
|                  |                |               |                  | e/p separation          |

Detection prospects

DM configurations allowed by antiproton bounds

Relevant detection prospects for Dbar energies below few GeV/n, where dependence on solar modulation modeling can have an impact on the DM signal up to a factor of 2

Experimental expected sensitivities: 3σ C.L.

- GAPS LDB+: 1 detected event
- AMS: 2 detected events

Fornengo, Maccione, Vittino, JCAP 1309 (2013) 031

See talk by Philip von Doetinchem tomorrow
Conclusions

The first historical measurements on galactic antiprotons

\[
\bar{p}/p \text{ Ratio}
\]

\[
p + p_{\text{CR}} \rightarrow \bar{p} + \text{anything}
\]

- Golden 1979
- Bogomolov 1979
- Buffington 1981

expected ratio from secondary production
Conclusions
Thanks!
SPARE SLIDES
PAMELA vs AMS02

PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013

(rescaled, according to solar-modulation analysis)

M. Aguilar et al., PRL 114 (2015) 171103

Mirko Boezio, UCLA Dark Matter 2016, 02/17/16
PAMELA vs AMS02

PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013

O. Adriani et al. - Science 332 (2011) 6025
M. Aguilar et al., PRL 115 (2015) 211101

Mirko Boezio, UCLA Dark Matter 2016, 02/17/16
Two power laws $R^\gamma, R^{\gamma+1}$ with a characteristic transition rigidity $R_0$ and a smoothness parameter $s$ well describe H, He measured spectra:

$$\Phi = C \left( \frac{R}{45\text{GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta\gamma/s} \right]^s$$
Boron and carbon fluxes and B/C

- Tracking performance:
  - $\sigma_x = 14\,\mu m$, $\sigma_y = 19\,\mu m$
  - MDR = 250 GV

- Modelization of cosmic-ray propagation in the Galaxy
AMS-02 positron fraction

- No sharp structures
- Steady increase of the positron content up to $\approx 275$ GeV
- Well described by an empirical model with a common source term for $e^+/e^-$
SECONDARY POSITRONS (1)

PRIMARY COSMIC RAY SPECTRUM AT EARTH

\[ n_{CR}(E) = \frac{N(E)R}{2\pi R_d^2} \frac{H}{D(E)} = \frac{N(E)R}{2H\pi R_d^2} \frac{H^2}{D(E)} \propto E^{-\gamma-\delta} \]

SPECTRUM OF PRIMARY ELECTRONS AT EARTH

\[ n_e(E) \approx \frac{N(E)R \tau_{loss}(E)}{\sqrt{D(E)\tau_{loss}(E)}} \propto E^{-\gamma-1/2-\delta/2} \]

IF ENERGY LOSSES ARE DOMINANT UPON DIFFUSION (TYPICALLY E>10 GeV)

Courtesy by P. Blasi
**Secondary positrons (2)**

**INJECTION RATE OF SECONDARY POSITRONS**

\[ q_{e^+}(E')dE' = n_{CR}(E)dE \ n_H \ \sigma_{pp} \ c \propto E^{-\gamma-\delta} \]

**EQUILIBRIUM SPECTRUM OF SECONDARY POSITRONS (AND ELECTRONS) AT EARTH**

\[ n_{e^+}(E) \approx \frac{q_{e^+}(E)\tau_{loss}(E)}{\sqrt{D(E)\tau_{loss}(E)}} \propto E^{-(\gamma-1/2)-3\delta/2} \]

**POSITRON FRACTION**

\[ \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} \approx \frac{\Phi_{e^+}}{\Phi_{e^-}} \propto E^{-\delta} \]

**MONOTONICALLY DECREASING FUNCTION OF ENERGY**

*Courtesy by P. Blasi*
3. Results of the on orbit checkout

3.1 Progress from the launch to the initial operation (2)

- **9/22** L+34: CGBM High Voltage checkout
- **9/24** L+36: Reached required vacuum for Calorimeter
- **10/5** L+47: Confirmed 72 hours continuous operation
- **10/8** L+50: Completed functional checkout
- **10/20** L+62: Measurement of the calorimeter calibration data
- **11/17** L+90: End of the initial operation

**Calorimeter**
Electron event around the TeV region (candidate)

**CGBM first observed GRB event**
Light Curve (GRB 151006A)
Detection of High Energy Gamma-rays

Performance for Gamma-ray Detection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>4 GeV-10 TeV</td>
</tr>
<tr>
<td>Effective Area</td>
<td>600 cm² (10 GeV)</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>2 sr</td>
</tr>
<tr>
<td>Geometrical Factor</td>
<td>1100 cm²sr</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>3% (10 GeV)</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>0.35° (10 GeV)</td>
</tr>
<tr>
<td>Pointing Accuracy</td>
<td>6'</td>
</tr>
<tr>
<td>Point Source Sensitivity</td>
<td>$8 \times 10^{-9}$ cm²s⁻¹</td>
</tr>
<tr>
<td>Observation Period (planned)</td>
<td>2014-2019 (5 years)</td>
</tr>
</tbody>
</table>

Simulation of Galactic Diffuse Radiation

~25,000 photons are expected per one year

*) ~7,000 photons from extragalactic y-background (EGB) each year

Simulation of point source observations in one year

Vela: ~ 300 photons above 5 GeV  
Geminga: ~150 photons above 5 GeV  
Crab: ~ 100 photons above 5 GeV

S. Torii, TeVPA 2013, Irvine, USA
Monochromatic gamma-ray signals from WIMP dark matter annihilation would provide a distinctive signature of dark matter, if detected. Since gamma-ray line signatures are expected in the sub-TeV to TeV region, due to annihilation or decay of dark matter particles, CALET, with an excellent energy resolution of 1 - 3 % above 100 GeV, is a suitable instrument to detect these signatures.

- Simulated 1.4 TeV gamma-ray line from dark matter toward the Galactic center (300° < |l| < 60°, |b| < 10°) including the Galactic diffuse background for CALET 5 year observations.

- The annihilation cross-section is taken as $\langle \sigma v \rangle_{W} = 1 \times 10^{-25}$ cm$^3$s$^{-1}$ with a NFW halo profile. The distinctive line signature is clearly seen in the gamma-ray spectrum.
Dec. 24 2015 First Light of DAMPE

328 GeV electron

G. Ambrosi, CSN2, 09/02/2016, Rome
The GAMMA-400 spacecraft and Navigator service module are designed by Lavochkin.
Increasing the energy resolution

The $\gamma$-ray differential energy results for a 135 GeV right-handed neutrino dark matter candidate.

### Expected performance of HERD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ/e energy range (CALO)</td>
<td>tens of GeV-10TeV</td>
</tr>
<tr>
<td>Nucleon energy range (CALO)</td>
<td>up to PeV</td>
</tr>
<tr>
<td>γ/e angular resol.</td>
<td>0.1°</td>
</tr>
<tr>
<td>Nucleon charge resol.</td>
<td>0.1-0.15 c.u</td>
</tr>
<tr>
<td>γ/e energy resolution (CALO)</td>
<td>&lt;1%@200GeV</td>
</tr>
<tr>
<td>Proton energy resolution (CALO)</td>
<td>20%</td>
</tr>
<tr>
<td>e/p separation power (CALO)</td>
<td>&lt;10⁻⁵</td>
</tr>
<tr>
<td>Electron eff. geometrical factor (CALO)</td>
<td>3.7 m²sr@600 GeV</td>
</tr>
<tr>
<td>Proton eff. geometrical factor (CALO)</td>
<td>2.6 m²sr@400 TeV</td>
</tr>
</tbody>
</table>

Expected HERD Proton and He Spectra

Horandel model as HERD input
Only statistical error

**Protons**

**He**

Comparison of DM sensitivity

![Graph showing comparison of DM sensitivity]
95% upper limits on decay lifetime of DM

Comparison with DM models
Light antinuclei can form excited exotic atom states with normal matter.

GAPS: The General Antiparticle Spectrometer

Atomic transition x-rays, charged pion multiplicity, and other products provide distinct signature for antinuclei.
GAPS instrument summary

**TOF plastic scintillators**
- outer TOF: 3.6m x 3.6m, 2m height
- inner TOF: 1.6m x 1.6m, 2m height
  - 1m b/w outer and inner TOFs
- 500 ps timing resolution
- 16.5 cm wide plastic paddles
- PMT on each end

**Si(Li) detectors**
- 10 layers, 1.6m x 1.6m
- layer space: 20 cm
- Si(Li) wafer (~1500 wafers)
  - 4 inch diameter
  - 2.5mm thick wafer
  - 12 x 12 rectangular
- segmented into 4 strips
  - 3D particle tracking
- timing resolution: ~ 100 ns
- energy resolution: 3 keV
- operation temperature: -35 C
- dual channel electronics
  - X-ray: 20 - 80 keV
  - charged particles: 0.1 - 100 MeV

**Cooling system**
- oscillating heat pipe (OHP)
- demonstrated in pGAPS

Science weight: ~1700 kg, 34H balloon

M. Hailey, Dark Matter 2014, UCLA