Antiproton and Electron Measurements and Dark Matter Indirect Searches

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Astrophysics and Cosmology compelling Issues

- Apparent absence of cosmological Antimatter

- Nature of the Dark Matter that pervades the Universe
The Big Bang origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning.
THE UNIVERSE ENERGY BUDGET

- Stars and galaxies are only \( \sim 0.5\% \)
- Neutrinos are \( \sim 0.1-1.5\% \)
- Rest of ordinary matter
  
  \((\text{electrons, protons \& neutrons})\) are \(4.4\%\)
- Dark Matter 23\%
- Dark Energy 73\%
- Anti-Matter 0\%
- Higgs Bose-Einstein condensate
  
  \(\sim 10^{62}\%??\)
The first historical measurements on galactic antiprotons

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

- Golden 1979
- Bogomolov 1979
- Buffington 1981

Expected ratio from secondary production

\[ p + p \rightarrow \bar{p} + \text{anything} \]
Balloon data: Positron fraction before 1990

Charge ratio \( \left( \frac{e^+}{e^+ + e^-} \right) \)

-漏气箱 (leaky box)
-动态的晕 (dynamic halo)

\[ m_\chi = 20 \text{GeV} \]

Tilka 89

能量 (GeV)

- Golden et al. 1987
- Muller & Tang 1987
- Buffington 1975
- Daugherty 1975
- Fanselow 1969
ANTIMATTER

Collision of High Energy Cosmic Rays with the Interstellar Gas

Annihilation of Exotic Particles

Evaporation of Primordial Black Holes

Pulsar’s magnetospheres

Cosmic Rays Leaking Out of Antimatter Galaxies

Antimatter Lumps In the Milky Way

He

e+

p

p

p

e+

e+

e−

e−
Antimatter Direct research

Observation of cosmic radiation hold out the possibility of directly observing a particle of antimatter which has escaped as a cosmic ray from a distant antigalaxy, traversed intergalactic space filled by turbulent magnetic field, entered the Milky Way against the galactic wind and found its way to the Earth.

Streitmatter, R. E., 24th ICRC, Rome, Italy, 1995

High energy particle or antinuclei
Dark Matter Candidates

- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworld DM
- Heavy neutrino
- NEUTRALINO
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

L. Roszkowski
# The SUSY Particle Spectrum

## Standard Model

<table>
<thead>
<tr>
<th>Particles</th>
<th>Symbol</th>
<th>Spin</th>
<th>Sparticles</th>
<th>Symbol</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>leptons</td>
<td>$l, \nu$</td>
<td>1/2</td>
<td>sleptons</td>
<td>$\tilde{l}_R, \tilde{l}_L, \nu_L$</td>
<td>0</td>
</tr>
<tr>
<td>quarks</td>
<td>$q_{L,R}$</td>
<td>1/2</td>
<td>squarks</td>
<td>$\tilde{q}_{L,R}$</td>
<td>0</td>
</tr>
<tr>
<td>photon</td>
<td>$\gamma$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z boson</td>
<td>$Z$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>light Higgs</td>
<td>$h$</td>
<td>0</td>
<td>neutralinos</td>
<td>$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$</td>
<td>1/2</td>
</tr>
<tr>
<td>heavy Higgs</td>
<td>$H$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pseudoscalar Higgs</td>
<td>$A$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W boson</td>
<td>$W^\pm$</td>
<td>1</td>
<td>charginos</td>
<td>$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$</td>
<td>1/2</td>
</tr>
<tr>
<td>charged Higgs</td>
<td>$H^\pm$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gluon</td>
<td>$g$</td>
<td>1</td>
<td>gluino</td>
<td>$\tilde{g}$</td>
<td>1/2</td>
</tr>
<tr>
<td>graviton</td>
<td>$G$</td>
<td>2</td>
<td>gravitino</td>
<td>$\tilde{G}$</td>
<td>3/2</td>
</tr>
</tbody>
</table>

\[
\chi = N_1 \gamma + N_2 \tilde{Z}^0 + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0; \quad \sum_{i=1}^{4} |N_i|^2 = 1
\]

Astroparticle Physics [5A1312]
Another possible scenario: **KK Dark Matter**

Lightest Kaluza-Klein Particle (LKP): $B^{(1)}$

**Bosonic Dark Matter:**
- fermionic final states no longer helicity suppressed.
- $e^+e^-$ final states directly produced.

As in the neutralino case there are 1-loop processes that produces monoenergetic $\gamma\gamma$ in the final state.
DM annihilations

DM particles are stable. They can annihilate in pairs.

\[ \chi \quad \chi \]

Primary annihilation channels:

- $W^-, Z^0, b, \tau^-, t, h^0, \ldots$
- $W^+, Z^0, \bar{b}, \tau^+, \bar{t}, h^0, \ldots$

Decay:

- $e^\mp, p^{(-)}, D^{(-)}, \ldots$

Final states:

- $e^\pm, p^{(-)}, D^{(-)}, \ldots$

\[ \sigma_a = \langle \sigma \nu \rangle \]
Where do positrons come from?

Mostly locally within 1 Kpc, due to the energy losses by Synchrotron Radiation and Inverse Compton scattering.

Typical lifetime:

$$\tau \simeq 5 \cdot 10^5 \text{yr} \left( \frac{1 \text{ TeV}}{E} \right)$$

Antiprotons within 10 Kpc
Decay Channels

Positron fraction from decaying dark matter: model independent analysis

Possible decay channels

fermionic DM

$\psi \rightarrow Z^0 \nu$

$\psi \rightarrow W^\pm \ell^\mp$

$\psi \rightarrow \ell^+ \ell^- \nu$

scalar DM

$\phi \rightarrow Z^0 Z^0$

$\phi \rightarrow W^+ W^-$

$\phi \rightarrow \ell^+ \ell^-$
Antimatter Search

Wizard Collaboration

- MASS - 1,2 (89,91)
- TrampSI (93)
- CAPRICE (94, 97, 98)
- BESS (93, 95, 97, 98, 2000)
- Heat (94, 95, 2000)
- IMAX (96)
- BESS LDF (2004, 2007)
- AMS-01 (1998)
Cosmic Ray Antimatter
Pre-PAMELA-Fermi status

- Antiprotons
  - CR + ISM → π⁻ + x → μ⁻ + x → e⁻ + x
  - CR + ISM → π⁺ + x → μ⁺ + x → e⁺ + x
  - CR + ISM → p-bar + …
  - Kinematic threshold: 5.6 GeV for the reaction PP → PPPP

- Positrons
  - Moskalenko & Strong 1998
  - Positron excess?

Charge-dependent solar modulation
Asaoka Y. et al. 2002

1999/2000

Pre-PAMELA-Fermi status
What did we need?

- Measurements at higher energies
- Better knowledge of background
- High statistics
- Continuous monitoring of solar modulation

Long Duration Flights
Dark Matter
Space Missions

PAMELA
15-06-2006

ATIC
2002 - 2007

BESS
12-2007

AMS-02
2010

GLAST/Fermi
11-6-2008
PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics
- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

- Permanent magnet, 0.43 T
- 21.5 cm² sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view \( \rightarrow \) MDR
  ~800 GV (6 plane) ~500 GV (5 plane)

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm² sr

- 36 \(^3\)He counters
- \(^3\)He(n,p)T; \( E_p = 780 \) keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

\[ \text{~470 Kg / ~360 W} \]
PAMELA

Launch
15/06/06

16 Gigabytes transmitted daily to Ground
NTsOMZ Moscow
• Low-earth elliptical orbit
• 350 – 610 km
• Quasi-polar (70° inclination)
• SAA crossed
Antiprotons
Antiproton flux

The graph shows the antiproton flux in GeV m$^{-2}$ s$^{-1}$ sr$^{-1}$ as a function of kinetic energy in GeV. The data points are from various experiments:

- AMS (M. Aguilar et al.)
- BESS-polar04 (K. Abe et al.)
- BESS1999 (Y. Asaoka et al.)
- BESS2000 (Y. Asaoka et al.)
- CAPRICE1998 (M. Boezio et al.)
- CAPRICE1994 (M. Boezio et al.)
- PAMELA
Antiproton to proton ratio

\[ \frac{\bar{p}}{p} \]

- **PAMELA**

![Graph showing antiproton to proton ratio vs. kinetic energy.](image)

- BESS 2000 (Y. Asaoka et al.)
- BESS 1993 (A. S. Brauch et al.)
- BESS 1999 (Y. Asaoka et al.)
- BESS-polar 2004 (K. Abo et al.)
- CAPRICE 1994 (M. Boezio et al.)
- CAPRICE 1998 (M. Boezio et al.)
- HEAT-pbar 2000 (Y. Asaoka et al.)
- PAMELA
The antiproton/proton ratio

Trapped pbar

- PAMELA

GCR

- PAMELA

SAA
Positrons
Positron to all electron ratio

Nature 458, 697, 2009

\[ R(E) = \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} \]

Secondary production
Moskalenko & Strong 98

PAMELA
Positron Fraction

![Graph showing positron fraction vs. energy (GeV)](image-url)
Positron Fraction

Secondary production
Moskalenko & Strong 98

Pulsar Component
Atoyan et al. 95

Pulsar Component
Yüksel et al. 08

KKDM (mass 300 GeV)
Hooper & Profumo 07

Pulsar Component
Zhang & Cheng 01

Secondary production
Moskalenko & Strong 98
A Challenging Puzzle for Dark Matter
Data fitting

Which DM spectra can fit the data?

DM with $m_\chi \approx 150 \text{ GeV}$ and $W^+W^-$ dominant annihilation channel (possible candidate: Wino)

![Graph showing positron fraction vs. positron energy in GeV](image1)
- Yes!

![Graph showing antiproton fraction vs. antiproton kinetic energy in GeV](image2)
- No!
Data fitting

DM with $m_\chi \simeq 1\,\text{TeV}$ and $\mu^+\mu^-$ dominant annihilation channel
Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by $>10^3$. 

Kaluza-Klein dark matter
Enhancement

How to reconcile $\sigma = 3 \cdot 10^{-26}\text{cm}^3/\text{sec}$ with $\sigma \sim 10^{-23}\text{cm}^3/\text{sec}$?

- DM is produced non-thermally: the annihilation cross section today is unrelated to the production process

- astrophysical boost

- resonance effect

- Sommerfeld effect + (Wimponium)

at freeze-out

no clumps
today

clumps

off-resonance

$v/c \sim 0.1$
on-resonance

$v/c \sim 10^{-3}$
Electrons
PAMELA Electron ($e^-$) Spectrum

$\gamma = 3.213 \pm 0.017$
PAMELA Electron (e\textsuperscript{-}) Spectrum

\[ \gamma = 3.226 \pm 0.02 \]

\[ \gamma = 2.982 \pm 0.197 \]
All electrons

\[ e^+ + e^- \]
**Detector concepts**

- Imaging calorimeters (energy measurement and background rejection).
- Many different implementations explored.

Courtesy Luca Baldini
**All electron inclusive spectrum**

**ATIC (Advanced Thin Ionization Calorimeter)**
- Si matrix + C target + BGO calorimeter.
- Primary goal: CR hadronic component.

**H.E.S.S. (High Energy Stereoscopic System)**
- Array of Čerenkov telescopes.
- Primary goal: study of VHE $\gamma$-ray sources.

**Fermi LAT (Large Area Telescope)**
- Pair conversion telescope (Si tracker + CsI calorimeter + ACD).
- Primary goal: survey of the HE $\gamma$-ray sky.

- All electrons inclusive spectra published by the three experiments in 2008–09.
- None of the experiments specifically designed to detect electrons.
All three ATIC flights are consistent

“Source on/source off” significance of bump for ATIC1+2 is about 3.8 sigma


ATIC-4 with 10 BGO layers has improved e, p separation. (~4x lower background)

“Bump” is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma
• Propose a new light boson \( m_\Phi \leq \text{GeV} \), such that \( \chi\chi \rightarrow \Phi\Phi; \Phi \rightarrow e^+e^-\), \( \mu^+\mu^-\), ...
• Light boson, so decays to antiprotons are kinematically suppressed
Fermi ($e^+ + e^-$)
Electrons measured with H.E.S.S.

Results: Low-Energy Spectrum

- Cuts:
  - impact distance < 100 m
  - image size in each camera > 80 photo electrons
  - Data set of 2004/2005

- Syst. uncertainty: atmospheric variations + model dependence of proton simulations (SIBYLL vs. QGSJET-II)

- Spectral index:
  \[ \Gamma_1 = 3.0 \pm 0.1 \text{(stat)} \pm 0.3 \text{(syst.)} \]
  \[ \Gamma_2 = 3.9 \pm 0.1 \text{(stat)} \pm 0.3 \text{(syst.)} \]
Fermi (e^+\, e^-) and PAMELA ratio
Bergstrom et al. astro-ph 0905.0333v1
Fermi \((e^+ + e^-)\)

astro-ph 0912.3887
Fermi ($e^++ e^-$)

$\gamma_0 = -2.7$
PAMELA all electrons

Preliminary
Gamma Constraints

- $\gamma$ from DM annihilation

- $\gamma$ from Inverse Compton on $e^\pm$ in halo
  - upscatter of CMB, infrared and starlight photons on energetic $e^\pm$

(Constraints on cosmological dark matter annihilation from the Fermi-LAT isotropic diffuse gamma-ray measurement)
astro-ph. 1002.4415v1

(Constraints on Dark Matter Annihilation in Clusters of Galaxies with the Fermi Large Area Telescope)
astro-ph.1002.2239v1

- radio-waves from synchrotron radiation of $e^\pm$
Astrophysical Explanation

Pulsars

S. Profumo Astro-ph 0812-4457

- Mechanism: the spinning $B$ of the pulsar strips $e^-$ that accelerated at the polar cap or at the outer gap emit $\gamma$ that make production of $e^\pm$ that are trapped in the cloud, further accelerated and later released at $\tau \sim 10^5$ years. $E_{tot} \sim 10^{46}$ erg

- Young ($T \sim 10^5$ years) and nearby ($< 1$ kpc)
- If not: too much diffusion, low energy, too low flux.

- Geminga: 157 parsecs from Earth and 370,000 years old
- B0656+14: 290 parsecs from Earth and 110,000 years old
- Many others after Fermi/GLAST

- Diffuse mature pulsars
Example: pulsars

H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar

diffuse mature & nearby young pulsars
Hooper, Blasi, and Serpico
arXiv:0810.1527
Pulsars: Most significant contribution to high-energy CRE: Nearby \((d < 1 \text{ kpc})\) and Mature \((10^4 < T/\text{yr} < 10^6)\) Pulsars

D. Grasso et al.

- Example of fit to both Fermi and Pamela data with known (ATNF catalogue) nearby, mature pulsars and with a single, nominal choice for the \(e^+/e^-\) injection parameters
Fermi is performing a detailed study of dipole anisotropy and it is setting an upper limit.
How reliable is the background calculation?

Secondary production
Moskalenko & Strong 98
Cosmic Rays Propagation in the Galaxy

\[
\frac{\partial N_i(E, z, t)}{\partial t} = D(E) \cdot \frac{\partial^2}{\partial z^2} N_i(E, z, t) - N_i(E, z, t) \left\{ \frac{1}{\tau_{\text{int}}^i(E, z)} + \frac{1}{\gamma(E)\tau_{\text{dec}}^i} \right\} + \sum_{k>i} \frac{N_k(E, z, t)}{\tau_{\text{int}}^{k\rightarrow i}(E, z)} + Q_i(E, z)
\]

- diffusion
- interaction and decay

- secondary production
- primary sources

- energy changing processes (ionisation, reacceleration)
Antiproton to proton ratio

![Graph showing the antiproton to proton ratio as a function of kinetic energy in GeV. The graph includes data points from PAMELA with error bars, and theoretical curves.](image)
Proton and Helium fluxes

Flux $\times E^{2.7} \ (m^2 s sr GeV)^{-1}$ vs. Kinetic energy (GeV/n)
Proton to Helium ratio

\[ \Delta \gamma = -0.092 \pm 0.001 \]
CREAM

\[ \delta = 0.33 \text{ top} \]
\[ 0.6 \text{ med.} \]
\[ 0.7 \text{ bot.} \]
Preliminary Analysis
- 70% Aperture
- Conservative cuts

Energy bin (10-300 GeV/amu) from analysis of DEDX detector only.

- Boron 8,000 events
- Carbon 55,000 events

Increased statistics over CRN

Expect several energy bins after energy deconvolution analysis

Analysis of events with transition radiation signal underway (ie > 400 GeV/amu)
B/C ratio vs. Kinetic energy, GeV/n (Preliminary data)

- ATIC, Panov et al., ICRC07
- CREAM, Ahn et al., Astro-ph 0808.1718
- HEAO3, Engelmann et al., A&A 223 (1990) 96E
- PAMELA (2009)
PAMELA preliminary results

Li/C

Be/C

Kinetic energy, GeV/n
Positron Fraction

![Graph showing positron fraction vs energy in GeV]

- PAMELA data
- Moskalenko and Strong (1998)
- $A>0$ [Clem et al. (2004)]
- $A<0$ [Clem et al. (2004)]
- Grimani (ICRC09)
Solar Modulation of galactic cosmic rays

- Study of charge sign dependent effects
  Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101,
  J. Clem et al. 30th ICRC 2007
Solar modulation

Interstellar spectrum

July 2006
August 2007
February 2008

Decreasing solar activity
Increasing GCR flux

Ground neutron monitor
PAMELA

Cosmic rays variations (%)

Preliminary

kinetic energy (GeV)

sun-spot number

Cycle 22
Cycle 23
Charge dependent solar modulation

- Positive particles: $A > 0$
- Negative particles: $A < 0$

Pamela 2006
(Preliminary!)
BESS-Polar II Launch - December 22, 2007
BESS Detector

- Rigidity measurement
- SC Solenoid (L=1m, B=1T)
- Min. material (4.7g/cm²)
- Uniform field
- Large acceptance
- Central tracker
  - (Drift chamber
  - $\delta \sim 200\mu m$
- Z, m measurement
  - $R, \beta \rightarrow m = Z e R^\sqrt{1/\beta^2 - 1}$
  - $dE/dx \rightarrow Z$
BESS Polar II Observations/Expectations

- Event rate ~2.5 kHz; Total events ~4.7 x 10^9
- Total data volume 13.5 TB (3.07 kB/event)
- Expected antiprotons ~10,000 10-20 times previous Solar minimum dataset
AMS-02 on ISS
In Orbit 2010
The Completed AMS Detector on ISS

- Transition Radiation Detector (TRD)
- Silicon Tracker
- Electromagnetic Calorimeter (ECAL)
- Magnet
- Ring Image Cerenkov Counter (RICH)
- Time of Flight Detector (TOF)

Size: 3m x 3m x 3m
Weight: 7 tons
AMS-02 goals and capabilities

Cosmic rays spectra and chemical composition up to 1 TeV

Search for Antimatter in Space

Search for Dark Matter

Gamma Rays

AMS will identify and measure the fluxes for:
- \( p \) for \( E < 1 \) TeV with unprecedented precision
- \( e^+ \) for \( E < 300 \) GeV and \( e^- \) for \( E < 1 \) TeV (unprecedented precision)
- Light Isotopes for \( E < 10 \) GeV/n
- Individual elements up to \( Z = 26 \) for \( E < 1 \) TeV/n

Absolute fluxes and spectrum shapes of protons and helium are important for calculation of atmospheric neutrino fluxes
Composition and spectra are important to constraint propagation, confinement, ISM density
Sensitivity of AMS: If no antimatter is found => there is no antimatter to the edge of the observable universe (~ 1000 Mpc).

Direct search for antimatter: AMS on ISS

Collect 2 billion nuclei with energies up to 2 trillion eV

Atomic Number

Number of events
Combining searches in different channels could give (much) higher sensitivity to SUSY DM signals. Unique Feature of AMS.
The Next Future

**PEBS (Positron Electron Balloon Spectrometer)**
- Positron fraction (and all electrons) up to 2 TeV.
- Scintillating fiber tracker with SiPM readout and superconducting magnet; ToF, TRD and ECAL for background rejection.
- PEBS-1 (with a permanent magnet, $e^+$ fraction up to 20 GeV) planned from 2012.

**CALET (CALorimetric Electron Telescope)**
- Three years on the ISS, starting in $\approx$ 2013.
- All electrons up to 20 TeV.
- ACD, double layer Si array, IMaging Calorimeter (IMC), Total Absorption Calorimeter (TASC).
- CALET-Polar to be flown on a LDBF in $\approx$ 2010 (3 technical flights before that).
Perspectives

ECAL (Electron CALorimeter)

- Two Long Duration Balloon Flights from Antarctica.
- All electrons up to a few TeV.
- Double-layer Si matrix, Scintillating Optical Fiber Track Imager (SOFTI), BGO calorimeter, neutron detector.
- Based on the ATIC heritage.

3D-symmetric detector
AC - anomalous coldness detector
Central system
- C1-C6 - 6 x 0.145 x 1.6 MEGW
- CD1-CD6 - 6 x 5 (x, y) strip coordinate detectors (pitch 0.5 mm)
- CD7-CD8 - Si (x, y) strip coordinate detector (pitch 0.5 mm)
- S1, S2 - TOF modules
- E1D - transition radiation detectors
- CCI - coordinate calibrator
  - C1 (x, 0.25 x)
  - 20 layers (14 x 56) + Si (x, y) strip coordinate detectors (pitch 1 mm)
- C12 - BGO coordinate calibrator
  - along 3 axes: 21.350, 1.1 A
  - along X axes: 71.500, 3.4 A
- S3, S4 - scintillators
- LS1, LS2 - lateral modules
- SCD - side Si (x, y) strip coordinate detectors (pitch 1 mm)
- ND - neutron detector

GAMMA-400

- Coordinates: 0000 - 1500 - 1200 - 0000
- S1(ToF), S2 (ToF), S3(ToF)
- TGD, 1200 - 1500
- S3, S4: 0000 - 1500
- SCD: 0000 - 1500
- ND: 0000 - 1500

- 800 - 800
Perspectives

**CREST (Cosmic Ray Electron Synchrotron Telescope)**
- Large proton rejection
- Large acceptance

- Two Antarctic LDBFs planned for 2010-2012.
- All electrons from 2 TeV to 50 TeV.
- Detect synchrotron radiation of primary electron as it passes through Earth’s magnetic field: 1024 BaF2 crystal with hermetic ACD.
- Signal: line of photons arriving nearly simultaneously (mean energy 10 keV–5 MeV, related to the primary electron energy).

**CTA, AGIS**
- Planning for the next-generation ground-based gamma-ray observatories started.
- Efforts currently ongoing in the U.S., Europe, and Japan may unify into a world-wide collaboration.
- Sensitivity improved by one order of magnitude.
- All electrons up to $\approx 10$ TeV.
Thanks!

http://pamela.roma2.infn.it