Search for Dark Matter in the sky

Aldo Morselli
INFN, Sezione di Roma Tor Vergata

Rencontres de Moriond, XLIVth Rencontres de Moriond La Thuile, Italy, February 1-8, 2009
Search for exotic process with space experiments

Aldo Morselli

INFN, Sezione di Roma 2 & Università di Roma Tor Vergata

Rencontres de Moriond, Very High Energy Phenomena in the Universe

Dark Matter in the era of precision cosmology

\[ \Omega_{\text{CDM}} \sim 5 \Omega_b \]
So, what is Dark Matter?
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
Dark Matter Candidates

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Neutralino WIMPs

Assume $\chi$ present in the galactic halo

- $\chi$ is its own antiparticle $\Rightarrow$ can annihilate in galactic halo producing gamma-rays, antiprotons, positrons….
- Antimatter not produced in large quantities through standard processes (secondary production through $p + p \rightarrow p + X$)
- So, any extra contribution from exotic sources ($\chi \chi$ annihilation) is an interesting signature
- ie: $\chi \chi \rightarrow \bar{p} + X$
- Produced from (e.g.) $\chi \chi \rightarrow q / g / gauge \ boson / Higgs \ boson$ and subsequent decay and/or hadronisation.
Pamela
Separating p from e⁻
PAMELA: Cosmic-Ray Antiparticle Measurements: Antiprotons

an example in mSUGRA 5 years simulation

\( f_d \): Clumpiness factors needed to disentangle a neutralino induced component in the antiproton flux

\( f = \) the dark matter fraction concentrated in clumps
\( d = \) the overdensity due to a clump with respect to the local halo density

A.Lionetto, A.Morselli, V.Zdravkovic
Supersymmetry introduces free parameters:

In the MSSM, with Grand Unification assumptions, the masses and couplings of the SUSY particles as well as their production cross sections, are entirely described once 5 parameters are fixed:

• $M_{1/2}$ the mass parameter of supersymmetric partners of gauge fields (gauginos)

• $\mu$ the higgs mixing parameters that appears in the neutralino and chargino mass matrices

• $m_0$ the common mass for scalar fermions at the GUT scale

• $A$ the trilinear coupling in the Higgs sector

• $\tanh \beta = v_2 / v_1 = <H_2> / <H_1>$ the ratio between the two vacuum expectation values of the Higgs fields
Signal and Background are separated?

\[ \tan(\beta) = 55, \text{ sign}(\mu) = +1 \]

Signal and Background are separated?
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Antiproton-Proton Ratio

- PAMELA data  arxiv:0810.4994
Antiproton-Proton Ratio

antiproton / proton

Diffuse and Convention
Propagation Model
Upper and lower bounds
A.Lionetto, A.Morselli, V.Zdravkovic

• PAMELA data arxiv:0810.4994
**PAMELA WIMP Detection Sensitivity**

- **PAMELA allowed region** for a boost factor 10
- **PAMELA excluded region** for a boost factor 10
- **no electroweak symmetry breaking**

**Equation:**
\[ \tan(\beta) = 55, \ \text{sign}(\mu) = +1 \]
Fermi PAMELA and LHC WIMP Detection Sensitivity

Fermi sensitivity in five years for a Navarro Frank and White (NFW) halo profile

Region that Fermi will probe for boost factor 1
larger values of $tg(B)$ gives larger signals both in antiprotons and gammas.
Positron ratio

PAMELA data: arXiv: 0810.4995

Secondary production
Positron ratio

PAMELA data: arXiv: 0810.4995

electron + positron flux excess at about 300-600 GeV by ATIC and PPB-BETS

electron + positron flux

excess at about 300-600 GeV by ATIC and PPB-BETS and HESS results


H.E.S.S. Coll. arXiv:0811.3894
some articles about the positron excess

**arXiv:0902.0071** PAMELA/ATIC anomaly from the meta-stable extra dark matter component and the leptophilic Yukawa interaction [Bumseok Kyae](http://example.com)

1. **arXiv:0901.3474** Cosmic Ray Positrons from Cosmic Strings [Robert Brandenberger](http://example.com), [Yi-Fu Cai](http://example.com), [Wei Xue](http://example.com), [Xinmin Zhang](http://example.com)

2. **arXiv:0901.2556** Positrons and antiprotons from inert doublet model dark matter [Emmanuel Nezri](http://example.com), [Michel H.G. Tytgat](http://example.com), [Gilles Vertongen](http://example.com)

3. **arXiv:0901.1520** On the cosmic electron/positron excesses and the knee of the cosmic rays - a key to the 50 years' puzzle? [Hong-Bo Hu](http://example.com), [Qiang Yuan](http://example.com), [Bo Wang](http://example.com), [Chao Fan](http://example.com), [Jian-Li Zhang](http://example.com), [Xiao-Jun Bi](http://example.com)


5. **arXiv:0812.4555** Is the PAMELA Positron Excess Winos? [Phill Grajek](http://example.com), [Gordon Kane](http://example.com), [Dan Phalen](http://example.com), [Aaron Pierce](http://example.com), [Scott Watson](http://example.com)

6. **arXiv:0812.4457** Dissecting Pamela (and ATIC) with Occam's Razor: existing, well-known Pulsars naturally account for the "anomalous" Cosmic-Ray Electron and Positron Data [Stefano Profumo](http://example.com)

7. **arXiv:0812.4272** Study of positrons from cosmic rays interactions and cold dark matter annihilations in the galactic environment [Roberto A. Lineros](http://example.com) thesis

8. **arXiv:0812.3895** Gamma-ray and Radio Constraints of High Positron Rate Dark Matter Models Annihilating into New Light Particles [Lars Bergstrom](http://example.com), [Gianfranco Bertone](http://example.com), [Torsten Bringmann](http://example.com), [Joakim Edsjo](http://example.com), [Marco Taoso](http://example.com)

9. **arXiv:0812.0219** Neutrino Signals from Annihilating/Decaying Dark Matter in the Light of Recent Measurements of Cosmic Ray Electron/Positron Fluxes [Junji Hisano](http://example.com), [Masahiro Kawasaki](http://example.com), [Kazunori Kohri](http://example.com), [Kazunori Nakayama](http://example.com)

10. **arXiv:0811.0477** High-energy Cosmic-Ray Positrons from Hidden-Gauge-Boson Dark Matter [Chuan-Ren Chen](http://example.com), [Fuminobu Takahashi](http://example.com), [T. T. Yanagida](http://example.com)

11. **arXiv:0811.3526** Status of indirect searches in the PAMELA and Fermi era [Aldo Morselli](http://example.com), [Igor Moskalenko](http://example.com)
14. arXiv:0810.4846  Possible causes of a rise with energy of the cosmic ray positron fraction [Pasquale Dario Serpico]
17. arXiv:0810.1527  Pulsars as the Sources of High Energy Cosmic Ray Positrons [Dan Hooper, Pasquale Blasi, Pasquale Dario Serpico]
19. arXiv:0809.2601  Two dark matter components in $N_{\text{DM}}$MSSM and dark matter extension of the minimal supersymmetric standard model and the high energy positron spectrum in PAMELA/HEAT data [Ji-Haeng Huh, Jihn E. Kim, Bumseok Kyae]
24. arXiv:0811.3744  Gamma-ray and radio tests of the e+e- excess from DM annihilations [Gianfranco Bertone, Marco Cirelli, Alessandro Strumia, Marco Taoso]
Positron ratio

Aharonian et al A&A 294 L41 1995 (translated)

pulsars contribution ?

cut off : 2 TeV electrons from 300 pc
Pre-Fermi era :
Vela 500 pc (287 pc now) t=2 \times 10^4 yr (now 1.1 \times 10^4 yr) require a very big diffusion coefficient \( D_{10}= 2 \times 10^{30} \text{ cm}^2/\text{s} \)
and energy \( W=2 \times 10^{50} \text{ erg in e}^+\text{e}^- \) (difficult)
Geminga 100 pc (160 now) t=3 \times 10^5 yr \( D_{10}= 5.5 \times 10^{26} \text{ cm}^2/\text{s} \) \( W=2 \times 10^{47} \text{ erg} \) (may be ?)
CTA 1 1.4 k pc (no) B0656+14 ? 200-600 pc (may be)

see also Profumo

arXiv:0812.4457
Millisecond pulsars detected by Fermi

<table>
<thead>
<tr>
<th>PULSAR</th>
<th>PERIOD</th>
<th>PERIOD DERIV.</th>
<th>D</th>
<th>Edot</th>
<th># PHOTONS</th>
<th>H-TEST TS</th>
<th>CHANCE PROB</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0030+0451</td>
<td>4.86 ms</td>
<td>$10^{-20}$ s/s</td>
<td>0.317</td>
<td>3.44E+33</td>
<td>361</td>
<td>306.8</td>
<td>&lt; 4e-08</td>
</tr>
<tr>
<td>J0218+4232</td>
<td>2.32 ms</td>
<td>7.74</td>
<td>3.2</td>
<td>2.44E+35</td>
<td>455</td>
<td>12</td>
<td>0.0084</td>
</tr>
<tr>
<td>J0437-4715</td>
<td>5.76 ms</td>
<td>5.73</td>
<td>0.15</td>
<td>1.18E+34</td>
<td>166</td>
<td>89.1</td>
<td>&lt; 4e-08</td>
</tr>
<tr>
<td>J0613-0200</td>
<td>3.06 ms</td>
<td>0.96</td>
<td>0.48</td>
<td>1.32E+34</td>
<td>549</td>
<td>60</td>
<td>&lt; 4e-08</td>
</tr>
<tr>
<td>J1024-0719</td>
<td>5.16 ms</td>
<td>1.85</td>
<td>0.53</td>
<td>5.31E+33</td>
<td>135</td>
<td>14</td>
<td>0.0038</td>
</tr>
<tr>
<td>J1744-1134</td>
<td>4.07 ms</td>
<td>0.89</td>
<td>0.48</td>
<td>5.21E+33</td>
<td>1014</td>
<td>25.1</td>
<td>5.04E-05</td>
</tr>
<tr>
<td>J2124-3358</td>
<td>4.93 ms</td>
<td>2.1</td>
<td>0.25</td>
<td>6.91E+33</td>
<td>277</td>
<td>577</td>
<td>&lt; 4e-08</td>
</tr>
</tbody>
</table>

- Search for pulsations at radio period in first 4 months of Fermi LAT data using radio ephemerides
- Detection of pulsations from 7 millisecond pulsars - 5 with high significance
- Confirmation of pulsations from PSR J0218+4232 but with lower significance
Fermi has found 12 previously unknown pulsars (orange).

Fermi detected gamma-ray emissions from known radio pulsars (magenta, cyan) and from known or suspected gamma-ray pulsars identified by EGRET (green). (known pulsars ~ 1800)
ms γ-ray pulsars

- Very different characteristics from the normal γ-ray pulsars:
  - Spinning 100 times faster
  - Magnetic fields ~10,000 times lower
  - ~10,000 times older
- "Recycled" pulsars spun-up by binary companion stars (movie)
  - Old recycled pulsars can accelerate particles to very high (TeV) energies
  - Fermi is seeing so far the nearby ms pulsar population
  - This may be the tip-of-the-iceberg with many more to be discovered
New Data is Forthcoming

Electron Spectrum:

- **PAMELA & FERMI (GLAST)** (taking data in space);
- **ATIC-4** (had successful balloon flight, under analysis);
- **CREST** (new balloon payload under development);
- **AMS-02** (launch date TBD);
- **CALET** (proposed for ISS);
- **ECAL** (proposed balloon experiment).

### Comparison of High-Energy Electron Missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>Upper Energy (TeV)</th>
<th>Collecting Power (m$^2$sr)</th>
<th>Calorimeter Thickness ($X_0$)</th>
<th>Energy Resolution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALET</td>
<td>20</td>
<td>0.75</td>
<td>30.8</td>
<td>&lt; 3 (over 100 GeV)</td>
</tr>
<tr>
<td>PAMELA</td>
<td>0.25 (spectrometer)</td>
<td>0.0022</td>
<td>16.3</td>
<td>5.5 (300 GeV)</td>
</tr>
<tr>
<td></td>
<td>2 (calorimeter)</td>
<td>0.04</td>
<td></td>
<td>12 (300 GeV)</td>
</tr>
<tr>
<td>GLAST</td>
<td>0.7</td>
<td>2.1 (100 GeV) 0.7 (700 GeV)</td>
<td>8.3</td>
<td>6 (100 GeV)</td>
</tr>
<tr>
<td>AMS-02</td>
<td>0.66 (spectrometer)</td>
<td>0.5</td>
<td>16.0</td>
<td>&lt; 3 (over 100 GeV)</td>
</tr>
<tr>
<td></td>
<td>1 (calorimeter)</td>
<td>0.06 (100 GeV) &lt; 0.04 (1 TeV)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Positron / Electron Separation:** **PAMELA & AMS-02**
5 years of GLAST LAT observation, clump at 100 pc, $D_0 = 10^{28}$ cm$^2$/s


Fermi measurements of the total lepton flux with large statistics will be able to distinguish a gradual change in slope with a sharp cutoff with high confidence for a NFW DM distribution with boost factor of 5 and $\rho_{\text{local}} = 0.4$ GeV cm$^{-3}$
• The key to understanding the origin of the excess in the ratio is the accurate measurement of positron and electron fluxes separately.

• To confirm the DM signature, we should look into the signal in HE pbars (PAMELA) and gamma-rays and electron total flux (Fermi (GLAST)).

• If this is an astrophysical source of positrons, it should be quite close and we should probably be able to see it with Fermi.
Fermi
Gamma-ray Space Telescope
At Six Months
Crosses mark source locations, in Galactic coordinates.

presented at this conference by Jean Ballet
EGRET on the Compton Observatory found fewer than 30 sources above 10 $\sigma$ in its lifetime.

Typical 95% error radius is less than 10 arcmin. For the brightest sources, it is less than 3 arcmin. Improvements are expected.

About 1/3 of the sources show definite evidence of variability.

More than 30 pulsars are identified by gamma-ray pulsations.

Over half the sources are associated positionally with blazars. Some of these are firmly identified as blazars by correlated multiwavelength variability.

Over 40 sources have no obvious associations with known gamma-ray emitting types of astrophysical objects.

Additional results on many of these sources in 213th AAS Meeting — Long Beach, CA.
A galactic dark matter halo

Springel, Wang, Volgensberger, Ludlow, Jenkins, Helmi, Navarro, Frenk & White '08

$z = 0.1$

1.1 billion particles inside $r_{\text{vir}}$

$2400^3$ run
Mare Nostrum simulation (with baryons)

- MareNostrum Supercomputer
  - 5th biggest supercomputer of the world (Top500 November 2006. (Now is 23rd)
  - 1st supercomputer in Europe. (until last year, now 2nd)
  - 10,240 PPC processors and 20 TeraBytes Memory
  - 280+90 Tbytes disk space.
  - More than 6,000,000 CPU hours (680 years) used for this project since 2005.

The Marenostrum Numerical Cosmology Project
Mare Nostrum simulation (without baryons)
Mare Nostrum simulation (with baryons)

preliminary
Where should we look for WIMPs with FERMI?

- Galactic center
- Galactic satellites
- Galactic halo
- Extra-galactic
### How the GLAST-LAT* telescope could help to disentangle the Dark Matter puzzle?

<table>
<thead>
<tr>
<th>Search Technique</th>
<th>advantages</th>
<th>challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic center</td>
<td>Good Statistics</td>
<td>Source confusion/Diffuse background</td>
</tr>
<tr>
<td>Satellites, Subhalos, Point Sources</td>
<td>Low background, Good source id</td>
<td>Low statistics</td>
</tr>
<tr>
<td>Milky Way halo</td>
<td>Large statistics</td>
<td>Galactic diffuse background</td>
</tr>
<tr>
<td>Extra-galactic</td>
<td>Large Statistics</td>
<td>Astrophysics, galactic diffuse background</td>
</tr>
<tr>
<td>Spectral lines</td>
<td>No astrophysical uncertainties, good source id</td>
<td>Low statistics</td>
</tr>
</tbody>
</table>
EGRET data & Susy models

Annihilation channel $W^+W^-$
$M_\chi = 80.3$ GeV

Typical $N_\chi$ values:
- NFW: $N_\chi = 10^4$
- Moore: $N_\chi = 9 \times 10^6$
- Isotermal: $N_\chi = 3 \times 10^1$

$N_b = 1.82 \times 10^{21}$
$N_\chi = 8.51 \times 10^4$

A. Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, astro-ph/0211327
~2 degrees around the galactic center, 2 years data

Annihilation channel $W^+W^-$  
$M_\chi = 80$ GeV

$N_b = 1.82 \times 10^{21}$  
$N_\chi = 8.51 \times 10^4$

Typical $N_\chi$ values:  
NFW: $N_\chi = 10^4$  
Moore: $N_\chi = 9 \times 10^6$  
Isotermal: $N_\chi = 3 \times 10^1$
Model independent results for the GC

5 years of operations, truncated NFW

\begin{align*}
\langle \sigma v \rangle &= (10^{-26} \text{ cm}^3 \text{ s}^{-1}) \\
\text{above 3 } \sigma \text{ EGRET observation} \\
\text{detectable by GLAST (conventional and optimized GALPROP models assumptions)} \\
\text{detectable by GLAST (only for the conventional GALPROP model assumption)} \\
\text{Not detectable by GLAST} \\
a) \text{ channel } b\bar{b} \text{ at 3 } \sigma \\
\end{align*}

Model independent results for the Sagittarius

Fermi and LHC WIMP Detection Sensitivity

Fermi sensitivity in five years for a Navarro Frank and White (NFW) halo profile

arXiv:0811.3526
Fermi sensitivity in five years for a Navarro Frank and White (NFW) halo profile.
Optimized diffuse background and a $5\sigma$ line signal at 200 GeV

Energy (GeV)

Events/Bin
5σ sensitivity contours to line signal (5 years)

con: conventional Galactic background model
opt: Optimized Galactic background model

arXiv:0806.2911
Conclusion:

- Astrophysics of cosmic rays and related topics is a very dynamic field: expect many breakthroughs and discoveries soon!
- Intermediate latitude $\gamma$-ray spectra can be explained by cosmic-ray propagation models based on local cosmic-ray nuclei and electron spectra. The EGRET GeV excess is not seen in this region of the sky with the Fermi LAT.
- Work to analyse and understand diffuse emission over the entire sky is in progress.
- Fermi has started to probe interesting regions of the supersymmetric parameter space. More statistics and the high energy all-electron spectra will expand these regions.
you are all invited

more results from PAMELA and FERMI will be presented

thank you!