Cosmic-ray antiproton constraints on light dark matter candidates

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Lavalle 10, arXiv:1007.5253

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Credit to original ideas: back to the 80's

Rudaz & Stecker (1988)

Status by the end of the 80's:

- CR antimatter signals => low background
- A few data on the CR antiproton flux (eg. Buffington+81, Bogomolov+81, Golden+84)
- Secondary predictions (eg. Protheroe 81) too low
- Primary source required: dark matter may fit.
Secondary antiprotons

Bottino+98 (no tertiaries)

Cosmic rays + interstellar gas → antiprotons

Bergström+99 (tertiaries incl.)

Moskalenko+02 (Galprop)

CONSISTENT WITH CURRENT DATA, eg BESS, PAMELA (AMS awaited)

Donato+01, Bringmann & Salati 07
The case for light WIMPs

CoGeNT (Collar+10-11)

XENON-10-100 (Aprile+10-11)

Motivations are above:
CoGeNT (Collar+10-11), DAMA (Bernabei+00-11), CRESST (Angloher+11)
Predictions in the plot by Bottino+10 (non-unified gaugino masses models)
Favored mass range: ~ 10 GeV

But see also: CDMSII (Ahmed+10), XENON-10-100 (Aprile+10-11), SIMPLE (Felizardo+11)
Light WIMPs: direct annihilation into quarks

Lavalle 10
(see also Bottino+05)

6 GeV < mass < 15 GeV
→ big trouble with data
<\sigma v> < 10^{-26} \text{ cm}^3/s

Ingredients:
• NFW halo
  (Catena & Ullio 10)
• Diff halo size:
  L=3-4 kpc
  (eg. Putze, Maurin+10-11)
Uncertainties in the diffusion halo size?

Quick digression towards positrons

Secondary positrons
(eg. Delahaye+09, Lavalle 11)

\[ \phi_e^+ \propto 1/\sqrt{K_0} \]

\[ \frac{K_0}{L} \approx C_{st} \]

Small halo models in serious trouble with positron data

++ Positron fraction => primary source required

L > 1 kpc => Very conservative statement!

Perspectives:

- PAMELA data to come (low solar activity period)
- Pheno/theory: Improve models!
  [L-models not consistent for DM, L>3 kpc OK when K(E,z) is used instead]
Singlet extensions of the MSSM: make all of them light

Add a singlet superfield coupled to the Higgs superfields

\[ \phi_k \]

\[ \chi \]

\[ \lambda_{ijk} \]

\[ \phi_j \]

\[ \chi' \]

\[ \phi_i \]

\[ \chi' \]

\[ \phi_k \]

\[ \phi_j \]

\[ \phi_i \]

\[ \chi' \]

\[ \phi_k \]

\[ \phi_j \]

Sets indirect detection signals

Set relic density

See also: Belikov+10, Draper+10 (NMSSM), Albornoz-Vasquez+11

Light dark matter in the singlet-extended MSSM

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Direct detection: CP-even exchange

Effective low energy interacting Lagrangian:

\[ \mathcal{L}_{\text{eff}} = -\frac{1}{2} \sum_i \bar{\chi} C_{X_i} \chi \phi_i - \sum_{i,j,k} \lambda_{ijk} \frac{1}{\eta_{ijk}} \phi_i \phi_j \phi_k + \text{h.c.,} \]
**Direct detection of singlino-like WIMP**

**Setup:**
- Singlino-like WIMP
- Realistic Higgs sector with mixing angles: additional singlet-like CP-even \( (h) \) and CP-odd \( (a) \) light Higgs bosons

**Constraints:**
- Some collider constraints (\( \Rightarrow \) large singlet fraction)
- Direct detection signal dominated by \( h \) exchange (MSSM Higgs decoupled)
- DD signal region encompasses CoGeNT
- \( 2 \, m_{\chi} > m_a + m_h \)

**Free parameters:**
- Masses
- Couplings
- \( \tan \beta \)
Setting the antiproton constraints

Cerdeno, Delahaye & JL 11

The data:
PAMELA only
[low solar activity
++ competitive errors]

Propagation and secondaries:
Maurin+01 best fit (med)
Donato+01 secondary flux
Conservative sol. mod.: 600 MV

Primary spectra:
$\alpha, h$ will decay to quarks
=> fragmentation with Pythia
++ Lorentz boost ($\alpha, h$ not produced at rest)
Understanding the results: 

$S$-to-$P$ wave ratio and mass range

Indirect detection signal $\Rightarrow$ pure $S$-wave required

Light Higgs bosons masses

$$\langle \sigma v \rangle \approx a + b / \{ x \equiv m_\chi / T \}$$

$m < 2 \text{ mp}$ or $m \sim 2 \text{ mb} \sim 10 \text{ GeV}$

do not produce antiprotons
In terms of annihilation cross section

Select S-wave dominated annihilation
++ light Higgs bosons' mass range

\[ \langle \sigma v \rangle_0 \lesssim 1.5 \times 10^{-26} \text{ cm}^3/\text{s} \]
Can we do better?

Typical signature = low energy spectral break

PAMELA, AMS: achieve 5% error @ 100 MeV
Theory: improve solar modulation treatment!
Conclusions

- Cosmic-ray antiprotons may provide strong constraints to light WIMP candidates with ~10 GeV masses (no boost required from eg. DM substructures)

- This requires an S-wave dominated annihilation at freeze out + quarks among final states
  => P-wave dominated models do escape the antiproton constraints

- Direct annihilation into quarks more strongly constrained:
  \( <\sigma v> < 8 \times 10^{-27} \text{ cm}^3/\text{s}, \text{ typically (100\% into quark pairs)} \)

- Singlino-like WIMP candidates also strongly constrained in some cases
  [annihilation into CP-even + CP-odd <= 2 mchi > ma + mh]

- Limits could be significantly improved if PAMELA/AMS achieve 5\% error @ 100 MeV
  => look for low energy spectral break
  => complementary discovery channel ?

- Complementarity with gamma-rays + radio in prep. !
Backup slides
**Propagation of Galactic cosmic rays:**

*The standard picture*

e.g. Berezinsky et al 90, Ptuskin's talk, Putze's talk

\[
\frac{\partial_t N}{\text{time evolution}} = Q(\vec{x}, E, t) + \nabla \left\{ \left( K_{xx}(E) \nabla - \vec{V}_c \right) N \right\} - \partial_p \left\{ \left( \frac{\vec{p}}{3} \nabla \cdot \vec{V}_c - p^2 K_{pp}(E) \partial_p \frac{1}{p^2} \right) N \right\} - \frac{\tau_s + \tau_r}{\tau_s \tau_r} N
\]

- **time evolution**
- **source**
- **spatial current** $\mathcal{J}_{xx}$
- **momentum current** $\mathcal{J}_{pp}$
- **spallation, decay**

**Galactic Disk:**

- Astrophysical CR sources + Interstellar gas + Interstellar radiation field + Magnetic field

**Convection from winds**

**Diffusion on magnetic turbulences**

(confinement)

408 MHz synchrotron, Haslam et al (1982)

**In the GeV-TeV energy range, electrons lose energy quickly as they propagate, protons do not**

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Light Higgs bosons' couplings to SM fermions

\[ h = s_\varphi \left[ s_\theta \text{Re}(H_d) - c_\theta \text{Re}(H_u) \right] + c_\varphi \text{Re}(S) \]

\[ a = s_\varphi a \left[ s_\theta a \text{Im}(H_d) - c_\theta a \text{Im}(H_u) \right] + c_\varphi a \text{Im}(S) \]

\[ = s_\varphi a \left[ A_{\text{MSSM}} \right] + c_\varphi a \text{Im}(S) \]

\[ C_{\phi_{\text{up,up}}} = - \frac{g m_u}{2 M_W s_\beta} \left\{ s_\varphi c_\theta - i \gamma_5 s_\varphi a c_\theta a \right\} \]

\[ C_{\phi_{\text{down,down}}} = - \frac{g m_d}{2 M_W c_\beta} \left\{ s_\varphi s_\theta - i \gamma_5 s_\varphi a s_\theta a \right\} \]
Relic density: theoretical uncertainties
Considering dark matter subhalos

JL, Yuan, Maurin & Bi (08)

Pieri, JL, Bertone & Branchini 10