CLOSING IN ON MASS-DEGENERATE DARK MATTER SCENARIOS

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1. CONTEXT: THE QUEST FOR WIMPS

long-awaited data are being collected as we speak...

- **Direct detection**
  - DM scattering off nuclei underground

- **Indirect detection**
  - Yields of DM annihilation or decay

- **Collider searches**
  - DM production in the lab

**Complementarity is key for wimp identification**

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1. CONTEXT: THE QUEST FOR WIMPS

before:

... a data-starved field
experiments lagged far behind predictions
1. CONTEXT: THE QUEST FOR WIMPS

now:

... carving into theoretical models
“moment of truth for wimps” [Bertone ’10]
1. COMPLEMENTARITY IN WIMP SEARCHES

the idea

![Diagram showing collider and indirect searches with a mediator particle χ and a quark q.](image)
1. COMPLEMENTARITY IN WIMP SEARCHES

the idea

collider searches

q
(     )

indirect searches

direct searches

χ
χ
q
q

the complications

1. model-dependence
2. uncertainties
1. COMPLEMENTARITY IN WIMP SEARCHES

**our approach** [Garny+ '12, arXiv:1207.1431]

focus on mass-degenerate dark matter scenarios \( m_\eta \gtrsim m_\chi \)

.. enhanced direct and antiproton signals as \( m_\eta \rightarrow m_\chi \)

.. this is precisely the regime that escapes detection at colliders!

fold in all uncertainties

**direct searches** – **antiprotons** – **collider searches**
2. THE MODEL

**minimal extension of the standard model** [Garny+ ’12, arXiv:1207.1431]

extra: Majorana fermion $\chi$ (WIMP DM), scalar $\eta$

interaction: $\mathcal{L}_{\text{int}} = -f \bar{\chi} \Psi R \eta + \text{h.c.}$

coupling scheme: light quarks + fiducial $\chi\chi \rightarrow b\bar{b}$

$\Psi = (u, d, s, uds, b)$

**our parameter space**

DM mass $m_\chi$ – mass splitting $m_\eta/m_\chi$ – coupling $f$

**thermal freeze-out**

mass degeneracy $\rightarrow$ coannihilations ($\chi\eta \rightarrow qg$, $\eta\bar{\eta} \rightarrow gg$, $\eta\eta \rightarrow qq$)

use micromegas to compute $f_{\text{thermal}}$ corresponding to 7-yr WMAP $\Omega_{dm}$

$\sigma v(\eta\bar{\eta} \rightarrow gg) \propto g_s^4/m_\eta^2$, so sizable even for $f \sim 0$!

thermal WIMPs $\rightarrow m_\chi \gtrsim 200$ (1000) GeV for $m_\eta/m_\chi = 1.1$ (1.01)
3. ANTI PROTONS

\[ 0 = \frac{\partial f_{\bar{p}}}{\partial t} = \nabla \cdot (K(T, \vec{r}) \nabla f_{\bar{p}}) - \nabla \cdot (\vec{V}_c(\vec{r}) f_{\bar{p}}) - 2h \delta(z) \Gamma_{\text{ann}} f_{\bar{p}} + Q(T, \vec{r}) \]

\[ \Phi_{\bar{p}}^{\text{IS}}(T) = \frac{v}{4\pi} f_{\bar{p}}(T, r_\odot) \]

solar modulation \( \phi_F = 500 \text{ MV} \)
3. **ANTIPROTONS**

**on-site production**

lowest order: $\chi\chi \rightarrow q\bar{q}$

s-wave helicity-suppressed ($\propto m_q^2$)

p-wave velocity-suppressed ($v/c \sim 1/1000$)

2→3 processes: $\chi\chi \rightarrow q\bar{q}\gamma$  $\chi\chi \rightarrow q\bar{q}g$  $\chi\chi \rightarrow q\bar{q}Z$

strongly enhanced when $m_\eta \rightarrow m_\chi$

**formalism & uncertainties**

source term: NFW – Einasto – isothermal profiles

fix $\rho_0 = 0.4$ GeV/cm$^3$

propagation: semi-analytical two-zone diffusion model

$(L, \delta, K_0, V_c)$ MIN – MED – MAX
3. Antiprotons

On-site production

Lowest order: $\chi\chi \rightarrow q\bar{q}$

- s-wave helicity-suppressed ($\propto m_q^2$)
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Formalism & uncertainties

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$(L, \delta, K_0, V_c)$ MIN - MED - MAX

Experimental data

Draw 95% CL upper limit on $f$
(given $m_\chi$, $m_\eta/m_\chi$)
4. DIRECT DETECTION

**driving idea:** detect WIMP scattering off nuclei

\[
\frac{dR}{dE_R} = \frac{1}{m_N} \int_{v_{\text{min}}}^{\infty} d^3 \vec{v} \frac{\rho_0 \nu}{m_\chi} f(\vec{v} + \vec{v}_e) \frac{d\sigma_{\chi N}}{dE_R}
\]

**astrophysics**

**nuclear/particle physics**
4. DIRECT DETECTION

**driving idea:** detect WIMP scattering off nuclei

\[
\frac{dR}{dE_R} = \frac{1}{m_N} \int_{v_{\text{min}}}^{\infty} d^3 \tilde{v} \frac{\rho_0 v}{m_\chi} f(\tilde{v} + \tilde{v}_e) \frac{d\sigma_{\chi-N}}{dE_R}
\]

\[
\sigma_{\chi-N}^{SD} \propto (a_p \langle S_p^N \rangle + a_n \langle S_n^N \rangle)^2
\]

\[
\sigma_{\chi-N}^{SI} \propto (Z f_p + (A - Z) f_n)^2
\]
4. DIRECT DETECTION

in the framework of our minimal model...

\[ \text{[Garny+ '12, arXiv:1207.1431]} \]

spin-dependent

\[
a_p = \sum_{q=u,d,s} \frac{d_q}{\sqrt{2}G_F} \Delta q^{(p)}
\]

\[
d_q = \frac{1}{8} \frac{f^2}{m_{\eta}^2 - (m_\chi + m_q)^2}
\]

spin-independent

\[
\frac{f_p}{m_p} = -\frac{m_\chi}{2} \sum_{q=u,d,s} f_{T_q}^{(p)} g_q - \frac{8\pi}{9} b f_T^{(p)} - \frac{3}{2} m_\chi \sum_{q=u,d,s,b} g_q \left( q^{(p)}(2) + \bar{q}^{(p)}(2) \right)
\]

\[
g_q = -\frac{1}{8} \frac{f^2}{(m_{\eta}^2 - (m_\chi + m_q)^2)^2}
\]

\[
b = \left( B_S - \frac{m_\chi}{2} B_{2S} - \frac{m_\chi^2}{4} B_{1S} \right) \propto f^2
\]

mass degeneracy

\[ d_q, g_q \text{ resonate at } m_\eta = m_\chi + m_q \rightarrow \text{enhanced SD, SI signals [Hisano+ '11]}
\]

not too close to resonance: \[ m_\eta - m_\chi > 1 \text{ GeV, } (m_\eta - m_\chi) \geq 2m_q \]
4. DIRECT DETECTION

uncertainties

- **astrophysics**
  \[ \rho_0 = 0.4 \text{ GeV/cm}^3, \quad v_0 = 230 \pm 30 \text{ km/s} \quad v_{\text{esc}} = 544 \text{ km/s} \]

- **nuclear physics**
  \[ \Delta s^{(p)} = -0.09 \pm 0.03, \quad \Sigma_{\pi n} = 64 \pm 8 \text{ MeV} \quad \sigma_0 = 36 \pm 7 \text{ MeV} \quad q(2) \pm 15\% \]

\[
\frac{dR}{dE_R} = \frac{1}{m_N} \int_{v_{\text{min}}}^{\infty} d^3 \tilde{v} \frac{\rho_0 v}{m_\chi} f(\tilde{v} + \tilde{v}_e) \frac{d\sigma_{\chi-N}}{dE_R}
\]

\[
a_p = \sum_{q=u,d,s} \frac{d_q}{\sqrt{2} G_F} \Delta q^{(p)}
\]

\[
\frac{f_p}{m_p} = -\frac{m_\chi}{2} \sum_{q=u,d,s} f_{T_q}^{(p)} g_q - \frac{8\pi}{9} b f_{T_G}^{(p)} - \frac{3}{2} m_\chi \sum_{q=u,d,s,b} g_q (q^{(p)}(2) + \bar{q}^{(p)}(2))
\]
4. DIRECT DETECTION

uncertainties

- **astrophysics**
  \[ \rho_0 = 0.4 \text{ GeV/cm}^3, \quad v_0 = 230 \pm 30 \text{ km/s}, \quad v_{esc} = 544 \text{ km/s} \]

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**Experimental data**

Xenon100 - best published SI limit

- exposure of 1471 kg.day
- \( E_R = 8.4 - 44.6 \text{ keV} \)
- \( N_{obs} = 3, \quad N_{bkg} = 1.8 \)
- Feldman-Cousins 95%CL \( N_R \leq 6.45 \)
  
  (new limit 3.5 times better)
4. DIRECT DETECTION

uncertainties

- astrophysics
  \[ \rho_0 = 0.4 \text{ GeV/cm}^3, \nu_0 = 230 \pm 30 \text{ km/s}, \nu_{\text{esc}} = 544 \text{ km/s} \]

- nuclear physics
  \[ \Delta s^{(p)} = -0.09 \pm 0.03, \Sigma_{\pi n} = 64 \pm 8 \text{ MeV}, \sigma_0 = 36 \pm 7 \text{ MeV}, q(2) \pm 15\% \]

experimental data

**Xenon10** – best SD-n limit

- exposure of 136 kg.day
- \( E_R = 4.5 - 27 \text{ keV} \)
- \( N_{\text{obs}} = 10, N_{\text{bkg}} = 0 \)
- Feldman-Cousins 95%CL \( N_R \leq 17.82 \)
4. DIRECT DETECTION

uncertainties

- astrophysics

\[ \rho_0 = 0.4 \text{ GeV/cm}^3, \ v_0 = 230 \pm 30 \text{ km/s}, \ v_{esc} = 544 \text{ km/s} \]

- nuclear physics

\[ \Delta s^{(p)} = -0.09 \pm 0.03, \ \Sigma_{\pi n} = 64 \pm 8 \text{ MeV}, \ \sigma_0 = 36 \pm 7 \text{ MeV}, \ q(2) \pm 15\% \]

experimental data

**SIMPLE** - within best SD-p limits

phase II = stage 1 + stage 2
exposure of (13.47+6.71) kg.day
\[ E_R = 8 - 100 \text{ keV} \]
\[ N_{obs} = 14 + 1, \ N_{bkg} = 12.07 + 1.70 \]
Feldman-Cousins 95%CL \[ N_R \leq 10.54 \]
4. DIRECT DETECTION

uncertainties

- astrophysics
  \[ \rho_0 = 0.4 \text{ GeV/cm}^3, \; v_0 = 230 \pm 30 \text{ km/s}, \; v_{esc} = 544 \text{ km/s} \]

- nuclear physics
  \[ \Delta s^{(p)} = -0.09 \pm 0.03, \; \Sigma_{\pi n} = 64 \pm 8 \text{ MeV}, \; \sigma_0 = 36 \pm 7 \text{ MeV}, \; q(2) \pm 15\% \]

experimental data

**COUPP** – within best SD-p limits

- high-threshold run
- exposure of 394.0 kg.day (\( \times 79.1\% \))
- \( E_R = 15.5 - 100 \text{ keV} \)
- \( N_{obs} = 8, \; N_{bkg} = 0 \)
- Feldman-Cousins 95\% CL \( N_R \leq 15.29 \)
5. RESULTS: OUR METHODOLOGY

**our parameter space**

DM mass $m_\chi$ – mass splitting $m_\eta/m_\chi$ – coupling $f$

![Graph showing coupling $f$ vs. $m_\chi$ in GeV](image)

**loose notes**


signals go as $f^4$!

Xenon100 dominates direct detection limits (for our models)

taking bino couplings, exclusion at $m_\chi \lesssim 215$ GeV
5. RESULTS: OUR METHODOLOGY

our parameter space

DM mass $m_\chi$ – mass splitting $m_\eta/m_\chi$ – coupling $f$

![Graph showing the parameter space of DM mass, mass splitting, and coupling.]

loose notes

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our parameter space

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![Graph showing the parameter space for dark matter mass, mass splitting, and coupling.]

loose notes


signals go as $f^4$!

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5. RESULTS: OUR METHODOLOGY

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DM mass $m_{\chi}$ – mass splitting $m_{\eta}/m_{\chi}$ – coupling $f$

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Xenon100 dominates direct detection limits (for our models)
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5. RESULTS: MASS DEGENERACY

mass degeneracy $m_\chi \leftarrow m_\eta$

both direct detection and antiprotons enhanced as $m_\eta \rightarrow m_\chi$

but: enhancement much stronger in direct detection

direct detection takes the lead over antiprotons for $m_\chi \lesssim$ few TeV

(thermal relic cut-off due to $\sigma_\nu(\eta \bar{\eta} \rightarrow gg) \propto g_s^4/m_\eta^2$)
5. RESULTS: DOMINANT CONSTRAINT?


(note: not an exclusion plot!)

antiprotons constraints kick in only for \( f \gtrsim 10 \)
5. RESULTS: COUPLING SCHEMES

similar constraints for light quarks
weaker constraints for b-quark (through loop coupling to gluons)
but: still stronger than antiproton limits
5. RESULTS: USER-FRIENDLY PLOTS


\begin{itemize}
\item u-coupling
\item $m_{\eta}/m_{\chi} = 1.1$
\item thermal relic antiprotons
direct detection
\end{itemize}

\begin{itemize}
\item $10^{-2}$
\item $10^{-3}$
\item $10^{-4}$
\item $10^{-32}$
\item $10^{-31}$
\item $10^{-30}$
\item $10^{-29}$
\item $10^{-28}$
\item $10^{-27}$
\item $10^{-26}$
\item $10^{-25}$
\item $m_{\chi}$ [GeV]
\item $\langle x^2 \rangle$ [cm$^3$ s$^{-1}$]
\end{itemize}

note: translation *is* model-dependent
again, antiprotons kick in at high masses where $f \gtrsim 10$
5. RESULTS: USER-FRIENDLY PLOTS

\[ \text{Garny+ '12, arXiv:1207.1431} \]

Note: translation *is* model-dependent
again, antiprotons kick in at high masses where \( f \gtrsim 10 \)
5. RESULTS: COMPLEMENTARITY AT ITS BEST

\begin{center}
\begin{tikzpicture}
  \begin{loglogaxis}[
    width=\textwidth,
    height=\textwidth,
    xlabel={$m_\chi$ [GeV]},
    ylabel={mass splitting $\frac{m_\eta}{m_\chi} - 1$},
    xmin=10, xmax=10000,
    ymin=10^{-2}, ymax=10,
    xtick={10^2,10^3,10^4},
    ytick={10^{-2},10^{-1},1,10},
    legend pos=north east,
    grid=major,
    \addlegendentry{u-coupling $f = 1$}
  ]
  \end{loglogaxis}
\end{tikzpicture}
\end{center}

Direct searches exclude low splittings, colliders probe high splittings.

Two numbers, one disclaimer:

- Xe100 excludes splittings.
- 19 (2)% at $m_\chi = 300$ (1000) GeV ($f = 1$)

Xe1T shall exclude.
- 114 (10)% at $m_\chi = 300$ (1000) GeV ($f = 1$)

to be fair, collider searches don't depend on $f$.

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5. RESULTS: COMPLEMENTARITY AT ITS BEST

- **Excluded by antiprotons**
- **Allowed region**
- **95% CL exclusion**
- **Direct searches exclude low splittings, colliders probe high splittings**
- **Two numbers, one disclaimer**
- **Xe100 excludes splittings**
  \[ \frac{m_{\eta}}{m_\chi} - 1 \]
- **Xe1T shall exclude**
  \[ \frac{m_{\eta}}{m_\chi} - 1 \]
- **To be fair, collider searches don't depend on** f

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5. RESULTS: COMPLEMENTARITY AT ITS BEST

\[ m_{\eta}/m_{\chi} - 1 \]

Direct searches exclude low splittings, colliders probe high splittings.

Two numbers, one disclaimer.

Xe100 excludes splittings.

\[ 19 (2)\% \text{ at } m = 300 (1000) \text{ GeV (} f = 1) \]

Xe1T shall exclude.

\[ 114 (10)\% \text{ at } m = 300 (1000) \text{ GeV (} f = 1) \]

to be fair, collider searches don't depend on \( f \).

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5. RESULTS: COMPLEMENTARITY AT ITS BEST

- Complementarity at its best

- Excluded by direct detection
- Excluded by ATLAS
- Excluded by antiprotons
- Allowed region
- 95% CL exclusion
- ATLAS jets + MET

- Two numbers, one disclaimer

- Xe100 excludes splittings.
- 19 (2)% at $m = 300$ (1000) GeV ($f = 1$)

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- 114 (10)% at $m = 300$ (1000) GeV ($f = 1$)

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5. RESULTS: COMPLEMENTARITY AT ITS BEST

- **monophoton** searches excluded by antiprotons
- **monophoton** + MET excluded by direct detection
- **Belanger** + '12

\[ \frac{m_{\eta}}{m_\chi - 1} \]

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

\[ \text{mass splitting} \]

\[ \text{95\% CL exclusion} \]

\[ \text{allowed region} \]

\[ \text{excluded by ATLAS} \]

\[ f = 1 \]

\[ \text{excluded by direct detection} \]

\[ \text{excluded by monophoton searches} \]

\[ \text{ excluded by antiprotons} \]

\[ \text{Xe100 excludes splittings} \].
\[ 19 (2)\% \text{ at } m_\chi = 300 (1000) \text{ GeV (} f = 1) \]

\[ \text{Xe1T shall exclude} \].
\[ 114 (10)\% \text{ at } m_\chi = 300 (1000) \text{ GeV (} f = 1) \]

\[ \text{to be fair, collider searches don't depend on} \] f.

\[ \text{Miguel Pato (TU Munich) arxiv:1207.1431} \]
5. RESULTS: COMPLEMENTARITY AT ITS BEST

- Excluded by ATLAS
- Excluded by direct detection
- Excluded by monophoton searches
- Excluded by antiprotons

Direct searches exclude low splittings, colliders probe high splittings.

Direct-collider complementarity looking good!

Two numbers, one disclaimer.

- Xe100 excludes splittings at $m = 300 \pm 100$ GeV ($f = 1$).
- Xe1T shall exclude $114 \pm 10\%$ at $m = 300 \pm 1000$ GeV ($f = 1$).

To be fair, collider searches don't depend on $f$. Miguel Pato (TU Munich)
5. RESULTS: COMPLEMENTARITY AT ITS BEST

direct searches exclude low splittings, colliders probe high splittings
direct-collider complementarity looking good!
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  Xe100 excludes splittings $\lesssim 19 (2)\%$ at $m_\chi = 300 (1000) \text{ GeV}$ ($f = 1$)
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to be fair, collider searches don’t depend on $f$
6. CONCLUSION

.. mass degeneracy enhances direct and indirect signals
.. antiproton constraints lag behind direct searches
.. complementarity antiprotons-direct-collider looks promising
.. closing in on degenerate setups is feasible within next few years
5. RESULTS: USER-FRIENDLY PLOTS


Note: Translation *is* model-dependent.

Again, antiprotons kick in at high masses where $f \gtrsim 10$. 

$m_\chi [\text{GeV}]$ vs. $\langle \sigma v \rangle [\text{cm}^3 \text{s}^{-1}]$
5. RESULTS: USER-FRIENDLY PLOTS


note: translation *is* model-dependent
again, antiprotons kick in at high masses where $f \gtrsim 10$