Dark Matter
Indirect Detection:
anti-p, anti-D, anti-He

Marco Cirelli
(CNRS LPTHE Jussieu)
Dark Matter
Indirect Detection:
anti-p, anti-D, anti-He

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(CNRS LPTHE Jussieu)
Introduction
DM exists
DM exists

galactic rotation curves

weak lensing (e.g. in clusters)

‘precision cosmology’ (CMB, LSS)
Introduction

DM **exists**

- galactic rotation curves
- weak lensing (e.g. in clusters)
- ‘precision cosmology’ (CMB, LSS)

**DM is a neutral, very long lived, feebly-interacting corpuscle.**
DM exists

galactic rotation curves

weak lensing (e.g. in clusters)

‘precision cosmology’ (CMB, LSS)

DM is a neutral, very long lived, weakly interacting particle.

Some of us believe in the WIMP miracle.

- weak-scale mass (10 GeV - 1 TeV)
- weak interactions \( \sigma v = 3 \cdot 10^{-26} \text{ cm}^3/\text{sec} \)
- give automatically correct abundance
DM detection

Direct detection
Xenon, CDMS, Edelweiss, LUX,... (CoGeNT, Dama/Libra...)

Production at colliders
LHC

Indirect

\( \gamma \) from annihil in galactic center or halo and from secondary emission
Fermi, ICT, radio telescopes...

\( e^+ \) from annihil in galactic halo or center
PAMELA, Fermi, HESS, AMS, balloons...

\( \bar{p} \) from annihil in galactic halo or center

\( \bar{d} \) from annihil in galactic halo or center
GAPS, AMS

\( \nu, \bar{\nu} \) from annihil in massive bodies
SK, Icecube, Km3Net
DM detection

direct detection

production at colliders

indirect

\( \gamma \) from annihil in galactic center or halo and from secondary emission

\( e^+ \) from annihil in galactic halo or center

\( p^- \) from annihil in galactic halo or center

\( \bar{p} \) from annihil in galactic halo or center

\( d, \bar{d} \) from annihil in massive bodies

\( \nu, \bar{\nu} \) from annihil in massive bodies

Fermi, ICT, radio telescopes...
PAMELA, Fermi, HESS, AMS, balloons...
GAPS, AMS
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DM detection

direct detection

production at colliders

indirect

\[ \gamma \text{ from annihil in galactic center or halo}
\quad \text{and from secondary emission} \]
\[ e^+ \text{ from annihil in galactic halo or center} \]
\[ \bar{p} \text{ from annihil in galactic halo or center} \]
\[ \bar{d} \text{ from annihil in galactic halo or center} \]
\[ \nu, \bar{\nu} \text{ from annihil in massive bodies} \]

Fermi, ICT, radio telescopes
PAMELA, Fermi, HESS, AMS, balloons
GAPS, AMS
SK, Icecube, Km3Net
Predicting antiprotons from DM
Indirect Detection: charged CRs

$\bar{p}$ and $e^+$ from DM annihilations in halo

8 kpc
Indirect Detection: charged CRs
\( \bar{p} \) and \( e^+ \) from DM annihilations in halo
Indirect Detection: charged CRs

$\bar{p}$ and $e^+$ from DM annihilations in halo
Indirect Detection: basics

$W^-, Z, b, \tau^-, t, h \ldots \sim e^\pm, (\_\_\_), (\_\_\_), \mathcal{P}, D \ldots$

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \sim e^\pm, (\_\_\_), (\_\_\_), \mathcal{P}, D \ldots$
Indirect Detection: basics

$W^-, Z, b, \tau^-, t, h \ldots \Rightarrow e^+, p, D \ldots$

**primary channels**

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \Rightarrow e^-, p, D \ldots$
Indirect Detection: basics

DM → \( W^{-}, Z, b, \tau^{-}, t, h \ldots \) → \( e^{\mp}, p, D \ldots \)

primary channels

DM → \( W^{+}, Z, b, \tau^{+}, t, h \ldots \) → \( e^{\pm}, p, D \ldots \)
Indirect Detection: basics

$DM, W^-, Z, b, \tau^-, t, h \ldots$ $\rightarrow$ $e^\pm, p, D \ldots$

primary channels

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$ $\rightarrow$ $e^\pm, p, D \ldots$

decay

$e^+$ primary spectra

$\bar{p}$ primary spectra

$M_{DM} = 1000$ GeV

$\frac{dN}{d\log x}$

$x = K/M_{DM}$
Indirect Detection: basics

$DM \rightarrow W^-, Z, b, \tau^-, t, h \ldots \rightarrow e^\pm, p, D \ldots$

primary channels

$DM \rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightarrow e^\pm, p, D \ldots$

decay

primary spectra

$M_{DM} = 1000 \text{ GeV}$

$e^+$ primary spectra

$\bar{p}$ primary spectra

So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
Indirect Detection: basics

$DM \rightarrow W^-, Z, b, \tau^-, t, h \ldots \rightarrow e^\mp, \bar{p}, D \ldots$

primary channels

$DM \rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightarrow e^\pm, \bar{p}, D \ldots$

final products

ElectroWeak corrections!

Sala et al., 1009.0224
Cirelli, Panci, Sala et al., 1012.4515
Fluxes at production

Electroweak corrections are important!
Fluxes at production

Electroweak corrections are important!
Fluxes at production

ElectroWeak corrections are important!

\[ DM \rightarrow e^+ e^- Z \]
Fluxes at production

ElectroWeak corrections are important!
Fluxes at production

Electroweak corrections are important!

\[ DM \rightarrow e^+ + e^- \rightarrow q\bar{q} + \nu\bar{\nu} \rightarrow \pi^0 \rightarrow \gamma\gamma \]
Fluxes at production

Electroweak corrections are important!

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.
Fluxes at production

Electroweak corrections are important!

\[
\frac{\Delta \sigma}{\sigma} \propto \alpha_{\text{weak}} \ln^2 \left( \frac{M_{DM}^2}{M_Z^2} \right)
\]

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.
Fluxes at production

**ElectroWeak corrections are important!**

\[ \frac{\Delta \sigma}{\sigma} \propto \alpha_{\text{weak}} \ln^2 \left( \frac{M_{DM}^2}{M_Z^2} \right) \]

\[ \sim 0.03 \]

\[ \sim 25 \]

\[ \sim \text{TeV} \]

---

Ciafaloni et al., JCAP 1103 (2011)

See also: Serpico et al., Bell et al.
Fluxes at production

ElectroWeak corrections are important!

\[ \Delta \sigma \over \sigma \propto \alpha_{\text{weak}} \ln^2 \left( \frac{M_{DM}^2}{M_Z^2} \right) \]

\[ \sim 0.03 \quad \sim 25 \quad \sim 75\% \]

(NB the finite mass of Z, W regulates the divergencies, only log terms left)

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.
Fluxes at production

ElectroWeak corrections are important!

- unexpected species
- different spectra
  (especially at low energy, but not only)

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.
Fluxes at production

Electroweak corrections are important!

- unexpected species
- different spectra

(especially at low energy, but not only)

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.
Indirect Detection: charged CRs

$\bar{p}$ and $e^+$ from DM annihilations in halo
Indirect Detection: charged CRs

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Indirect Detection: charged CRs

$\bar{p}$ and $e^+$ from DM annihilations in halo
Indirect Detection: charged CRs
$
\bar{p}
$ and $e^+$ from DM annihilations in halo
Indirect Detection: charged CRs

\[ \bar{p} \text{ and } e^+ \text{ from DM annihilations in halo} \]

\[ \frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E} (b(E)f) + \frac{\partial}{\partial z} (V_c f) = Q_{\text{inj}} - 2h \delta(z) \Gamma_{\text{spall}} f \]
Indirect Detection: charged CRs

$\bar{p}$ and $e^+$ from DM annihilations in halo

<table>
<thead>
<tr>
<th>$L$ [kpc]</th>
<th>$D_0$ [$10^{28}$ cm$^2$ s$^{-1}$]</th>
<th>$\delta$</th>
<th>$\eta$</th>
<th>$v_A$ [km s$^{-1}$]</th>
<th>$\gamma$</th>
<th>$d\nu_c/dz$ [km s$^{-1}$ kpc$^{-1}$]</th>
<th>$\phi_F$ [GV]</th>
<th>$\chi^2_{\text{min}}$/dof ($p$ in [25])</th>
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</thead>
<tbody>
<tr>
<td>KRA</td>
<td>4</td>
<td>2.64</td>
<td>-0.39</td>
<td>14.2</td>
<td>2.35</td>
<td>0</td>
<td>0.650</td>
<td>0.462</td>
</tr>
<tr>
<td>KOL</td>
<td>4</td>
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<td>0.33</td>
<td>36</td>
<td>1.78/2.45</td>
<td>0</td>
<td>0.335</td>
<td>0.761</td>
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<tr>
<td>CON</td>
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<td>0.6</td>
<td>38.1</td>
<td>1.62/2.35</td>
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<td>1.602</td>
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<td>THK</td>
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<td>0.6</td>
<td>14.1</td>
<td>14.1</td>
<td>0</td>
<td>0.687</td>
<td>0.516</td>
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<tr>
<td>THN</td>
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<td>0.31</td>
<td>0.6</td>
<td>11.6</td>
<td>11.6</td>
<td>0</td>
<td>0.704</td>
<td>0.639</td>
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<tr>
<td>THN2</td>
<td>2</td>
<td>1.35</td>
<td>-0.15</td>
<td>11.6</td>
<td>11.6</td>
<td>0</td>
<td>0.626</td>
<td>0.343</td>
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<tr>
<td>THN3</td>
<td>3</td>
<td>1.98</td>
<td>-0.27</td>
<td>11.6</td>
<td>11.6</td>
<td>0</td>
<td>0.623</td>
<td>0.339</td>
</tr>
</tbody>
</table>

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173
cfr. Evoli, Cholis, Grasso, Maccione, Ullio, 1108.0664

<table>
<thead>
<tr>
<th>Model</th>
<th>Electrons or positrons</th>
<th>Antiprotons (and antideuterons)</th>
<th>$L$ [kpc]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta$ $K_0$ [kpc$^2$/Myr]</td>
<td>$\delta$ $K_0$ [kpc$^2$/Myr] $V_{\text{conv}}$ [km/s]</td>
<td></td>
</tr>
<tr>
<td>MIN</td>
<td>0.55 0.00595</td>
<td>0.85 0.0016 13.5</td>
<td>1</td>
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<tr>
<td>MED</td>
<td>0.70 0.01112</td>
<td>0.70 0.0112 12</td>
<td>4</td>
</tr>
<tr>
<td>MAX</td>
<td>0.46 0.07665</td>
<td>0.46 0.0765 5</td>
<td>15</td>
</tr>
</tbody>
</table>

Donato et al., 2003+
Indirect Detection: charged CRs

Solar wind Modulation of cosmic rays:

\[
\frac{d\Phi_{\vec{p}\oplus}}{dT_{\oplus}} = \frac{p_{\oplus}^2}{p^2} \frac{d\Phi_{\vec{p}}}{dT} , \quad T = T_{\oplus} + |Ze|\phi_F
\]

- Spectrum at Earth
- Spectrum far from Earth
- Potential \( \phi_F \approx 500 \text{ MV} \)

(11 yr) Solar Cycle Variations

- AMS-01
- Caprice
- PAMELA
Indirect Detection: charged CRs

Solar wind Modulation of cosmic rays:

\[
\frac{d\Phi_{\bar{p}\oplus}}{dT\oplus} = \frac{p^2_{\oplus}}{p^2} \frac{d\Phi_{\bar{p}}}{dT},
\]

spectrum at Earth

\[
T = T\oplus + |Ze|\phi_F
\]

spectrum far from Earth

Fisk potential \( \phi_F \approx 500 \text{ MV} \)

E.g.

![Graph showing antiproton flux vs energy with various models and parameters.](image)

Einasto MED

\( \chi\chi \to hh \)

\( m_\chi = 20 \text{ GeV} \)

\( \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3/\text{s} \)

- No TDR, No SMod
- No TDR, With SMod
- With TDR, No SMod
- With TDR, With SMod
- PPPC4DMID previous release

Boudaud, Cirelli, Giesen, Salati, 1412.5696
Indirect Detection: charged CRs

$\bar{p}$ and $e^+$ from DM annihilations in halo

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

spectrum from DM annihilations in halo

\[
\frac{df}{dt} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E} \left( b(E) f \right) + \frac{\partial}{\partial z} \left( V_c f \right) = Q_{\text{inj}} + 2h\delta(z)\Gamma_{\text{spall}} f
\]

diffusion energy loss convective wind source spallations

[uncert]
DM halo profiles

From N-body numerical simulations:

\[ \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r} \left( 1 + \frac{r}{r_s} \right)^{-2} \]

\[ \rho_{\text{Einasto}}(r) = \rho_s \exp \left\{ -2 \frac{\alpha}{\alpha} \left( \frac{r}{r_s} \right)^{\alpha} - 1 \right\} \]

\[ \rho_{\text{Isothermal}}(r) = \frac{\rho_s}{1 + (r/r_s)^2} \]

\[ \rho_{\text{Burkert}}(r) = \frac{\rho_s}{(1 + r/r_s)(1 + (r/r_s)^2)} \]

\[ \rho_{\text{Moore}}(r) = \rho_s \left( \frac{r_s}{r} \right)^{1.16} \left( 1 + \frac{r}{r_s} \right)^{-1.84} \]

At small \( r \): \( \rho(r) \propto 1/r^\gamma \)

6 profiles:

- cuspy: NFW, Moore
- mild: Einasto
- smooth: isothermal, Burkert

EinastoB = steepened Einasto (effect of baryons?)

<table>
<thead>
<tr>
<th>DM halo</th>
<th>( \alpha )</th>
<th>( r_s ) [kpc]</th>
<th>( \rho_s ) [GeV/cm(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFW</td>
<td>–</td>
<td>24.42</td>
<td>0.184</td>
</tr>
<tr>
<td>Einasto</td>
<td>0.17</td>
<td>28.44</td>
<td>0.033</td>
</tr>
<tr>
<td>EinastoB</td>
<td>0.11</td>
<td>35.24</td>
<td>0.021</td>
</tr>
<tr>
<td>Isothermal</td>
<td>–</td>
<td>4.38</td>
<td>1.387</td>
</tr>
<tr>
<td>Burkert</td>
<td>–</td>
<td>12.67</td>
<td>0.712</td>
</tr>
<tr>
<td>Moore</td>
<td>–</td>
<td>30.28</td>
<td>0.105</td>
</tr>
</tbody>
</table>

Angle from the GC [degrees]

Cirelli et al., 1012.4515

\[ \rho_{\text{DM}} \text{ [GeV/cm}^3\text{]} \]

\[ r \text{ [kpc]} \]
Antiprotons

Bottom line: Antiprotons are quite affected by propagation, but spectral shape somewhat preserved.
Predicting antiprotons from astrophysics
Antiprotons

Background computations for antiprotons:
Background computations for antiprotons:

Main ingredients:
- primary p (and He)
- spallation cross-sections $\sigma_{pH\rightarrow pX}$, $\sigma_{pHe\rightarrow pX}$, $\sigma_{HeH\rightarrow pX}$, $\sigma_{HeHe\rightarrow pX}$
- propagation
- solar modulation
Antiprotons

Background computations for antiprotons:

Main ingredients:
• primary p (and He)
• spallation cross-sections
• propagation
• solar modulation

New!
AMS-02 2015/16

\begin{align*}
\sigma_{p\rightarrow pX}, \sigma_{pHe\rightarrow pX}, \sigma_{HeH\rightarrow pX}, \sigma_{HeHe\rightarrow pX}
\end{align*}

NA49, BRAHMS
DiMauro, Donato, Goudelis, Serpico 1408.0288
+ Winkler 1701.04866
Antiprotons

Background computations for antiprotons:

Uncertainties:

- Primary slopes uncertainty:
- Cross-sections uncertainty:
- Propagation uncertainty:
- Solar Modulation uncertainty:

Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276
Antiprotons
Background computations for antiprotons:
Data
Data: antiprotons

AMS-02

Theoretical prediction based on pre-AMS knowledge of cosmic ray collisions

S. Ting - AMS days @ CERN apr 2015
A. Kounine - AMS days @ CERN apr 2015
Antiprotons

Antiproton data vis-à-vis the secondaries:

![Graph showing antiproton data](image-url)
Antiprotons

Antiproton data vis-à-vis the secondaries:

---

**Antiproton data vis-à-vis the secondaries**:

- PAMELA 2012
- AMS-02 2015
Antiprotons

Antiproton data vis-à-vis the secondaries:

![Graph showing Antiproton data with kinetic energy on the x-axis and flux ratio on the y-axis. The graph includes data from PAMELA 2012 and AMS-02 2015.](image)
Antiprotons

Antiproton data vis-à-vis the secondaries:

No evident excess
Antiprotons

Antiproton data vis-à-vis the secondaries:

No evident excess

Some preference for flatness

Giesen, Boudaud, Génolini, Poulin, Cirelli, Salati, Serpico 1504.04276
Antiprotons

Antiproton data vis-à-vis the secondaries:

Consistent results
Constraints
Model independent bounds
Based on AMS-02 $\bar{p}/p$ data (April 2015)
Model independent bounds
Based on AMS-02 $\bar{p}/p$ data (April 2015)

Annihilation constraints from $\bar{p}/p$

- EXCLUDED
- ALLOWED

NB: direct comparison with former PAMELA-based bounds (Boudaud et al., 1412.5695) is tricky because secondaries are reevaluated in between, but these are similar or very marginally stronger.
Model independent bounds
Based on AMS-02 $\bar{p}/p$ data (April 2015)

Annihilation constraints from $\bar{p}/p$

$\sigma v$ [cm$^3$/sec]

DM mass $m_{DM}$ [GeV]

$m_{DM} > 150$ GeV
(bb Ein MED)

bounds on leptonic channels

NB: direct comparison with former PAMELA-based bounds (Boudaud et al., 1412.5695) is tricky because secondaries are reevaluated in between, but these are similar or very marginally stronger
Model independent bounds
Based on AMS-02 $\bar{p}/p$ data (April 2015)

Astrophysical uncertainties on the constraints

Cross section $\langle \sigma v \rangle$ [cm$^3$/sec]

DM mass $m_{\text{DM}}$ [GeV]

EXCLUDED
ALLOWED

Note: direct comparison with former PAMELA-based bounds (Boudaud et al., 1412.5695) is tricky because secondaries are reevaluated in between, but these are similar or very marginally stronger.
Antiprotons

Recent developments

finds a possible excess

\[ m_{\text{DM}} = 80 \text{ GeV}, \text{ bb}, \]

thermal cross-section

similarly:

Cui, Yuan, Tsai, Fang 1610.03840
Huang, Wei, Wu, Zhang, Zhou 1611.01983
(light mediators)
Feng, Zhang 1701.02263
Antiprotons

Recent developments

Cuoco, Krämer, Korsmeier 1610.03071

finds a possible excess

\( m_{DM} = 80 \text{ GeV}, \ bb, \) thermal cross-section

similarly:
Cui, Yuan, Tsai, Pang 1610.03840
Huang, Wei, Wu, Zhang, Zhou 1611.01983
(light mediators)
Feng, Zhang 1701.02263

propagation parameters determined with \( p, \ He \) data only, w/o B/C

excess evaporates including low energies
Compared to other bounds

All ID constraints

status post 34th ICRC (winter 2016)

DM mass [GeV]

Annihilation cross section $\langle \sigma v \rangle$ [cm$^3$/s]

$\gamma$-rays, $\bar{p}$, CMB, $\nu$

$\mu\mu$, $bb$, WW

thermal cross section

FERMI dwarfs 6yr

ICECUBE

MAGIC Segue1

HESS GC

ANTARES
Model independent bounds

Based on AMS-02 $\bar{p}/p$ data (April 2015)

Decay constraints from $\bar{p} / p$

Einasto MED

- $\chi \rightarrow b\bar{b}$
- $\chi \rightarrow W^+ W^-$
- $\chi \rightarrow \gamma\gamma$
- $\chi \rightarrow \mu^+ \mu^-$

Life time $\tau$ [s] vs. DM mass $m_{DM}$ [GeV]

EXCLUDED

ALLOWED

NB: direct comparison with former PAMELA-based bounds (Boudaud et al., 1412.5695) is tricky because secondaries are reevaluated in between, but these are similar or very marginally stronger

Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico

1504.04276
Model independent bounds
Based on AMS-02 $\bar{p}/p$ data (April 2015)

Astrophysical uncertainties on the constraints

- Allowed
- Excluded

$\chi \rightarrow b\bar{b}$

- Einasto MED
- Varying halo profiles
- Varying propagation parameters

DM mass $m_{DM}$ [GeV]

10^23 10^25 10^27 10^29

Life time $\tau$ [s]

10 100 1000 10000

NB: Direct comparison with former PAMELA-based bounds (Boudaud et al., 1412.5695) is tricky because secondaries are reevaluated in between, but these are similar or very marginally stronger.
DM detection

**Direct detection**

**Production at colliders**

**Indirect**

- $e^+$
- $\bar{p}$
- $\bar{d}$
- $\gamma$
- $\nu, \bar{\nu}$

- from annihilations in galactic halo or center
- and from secondary emission

- Fermi, ICT, radio telescopes...
- PAMELA, Fermi, HESS, AMS, balloons...
- GAPS, AMS
- SK, Icecube, Km3Net
Indirect Detection $\bar{d}$ from DM annihilations in halo
Indirect Detection

$\bar{d}$ from DM annihilations in halo
Indirect Detection

$\bar{d}$ from DM annihilations in halo

$\bar{d}$-density in momentum space

probability to find $\bar{n}$ within a sphere of radius $p_0$ around $\vec{k}_p$ in momentum space

coalescence momentum

$p_0 \approx |\vec{k}_\bar{p} - \vec{k}_\bar{n}| \approx 80 \rightarrow 200$ MeV

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Bräuninger, Cirelli 2009
Kadastik, Raidal, Strumia, 2009
...
Vittino, Fornengo, Maccione 2013
Aramaki et al., 2015
**Indirect Detection**

\[ \bar{d} \text{ from DM annihilations in halo} \]

\[ \bar{n} \rightarrow \bar{d} \text{ 'coalescence'} \]

\[ \gamma \frac{d^3N_{\bar{d}}}{dk_{\bar{d}}^3} = \frac{4\pi}{3} p_0^3 \gamma \frac{d^3N_{\bar{n}}}{dk_{\bar{n}}^3} \]

\[ \text{probability to find } \bar{n} \text{ within a sphere of radius } p_0 \text{ around } \vec{k}_{\bar{p}} \text{ in momentum space} \]

\[ \vec{p} \text{-density in momentum space} \]

\[ \text{coalescence momentum} \]

\[ p_0 \approx |\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}| \approx 80 \rightarrow 200 \text{ MeV} \]

---

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Bräuninger, Cirelli 2009
Kadastik, Raidal, Strumia, 2009

... Vittino, Fornengo, Maccione 2013
Aramaki et al., 2015
Indirect Detection

from DM annihilations in halo

\begin{align*}
\bar{d} & \rightarrow \bar{n} \bar{p} \\
\bar{n} & \rightarrow e^+ e^- \rightarrow \text{anti-}d \\
\text{coalescence momentum} & \Rightarrow p_0 \approx |\vec{k}_\bar{p} - \vec{k}_\bar{n}| \approx 80 \rightarrow 200 \text{ MeV}
\end{align*}

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Bräuninger, Cirelli 2009
Kadastik, Raidal, Strumia, 2009
Vittino, Fornengo, Maccione 2013
Aramaki et al., 2015

NB naïve guess would be $p_0 = \sqrt{E_b m_p} = 47 \text{ MeV}$ (with $E_b$ the $d$ binding energy): not too far...
Indirect Detection
\( \bar{d} \) from DM annihilations in halo

GAPS detection principle

\( \bar{d} \) is slowed down, captured (exotic atom), annihilates with distinctive emissions

DM signal in the reach of GAPS and AMS-02

P. von Doetinchem et al., 2015
DM detection

**Direct detection**

**Production at colliders**

**Indirect**

- \( \gamma \) from annihil in galactic center or halo and from secondary emission
- \( e^+ \) from annihil in galactic halo or center
- \( \bar{p} \) from annihil in galactic halo or center
- \( \bar{d} \) from annihil in galactic halo or center
- \( \nu, \bar{\nu} \) from annihil in massive bodies
- \( He \) from annihil in galactic halo or center

Instruments:
- Fermi, ICT, radio telescopes...
- PAMELA, Fermi, HESS, AMS, balloons...
- GAPS, AMS
- SK, Icecube, Km3Net
- AMS?
Indirect Detection

$^4He$ from DM annihilations in halo

$\bar{p} \bar{n} \rightarrow 'coalescence'$

$\bar{n} + 3H \rightarrow 3He$

Cirelli, Fornengo, Vittino, Taoso 2014
Carlson, Linden, Ibarra, Profumo, Wild 2014

Galactic Bulge
Norma Arm
Scutum Arm
Outer Arm
Perseus Arm
Sagittarius

Norma Arm
Crux Arm
Carina Arm

|\vec{k}_1 - \vec{k}_2| \leq p_0
|\vec{k}_1 - \vec{k}_3| \leq p_0
|\vec{k}_2 - \vec{k}_3| \leq p_0

coalescence momentum $p_0 = 195$ MeV

event-by-event with Pythia

a bit arbitrary...
Indirect Detection

$\bar{H}e$ from DM annihilations in halo

Cirelli, Fornengo, Vittino, Taoso 2014
Carlson, Linden, Ibarra, Profumo, Wild 2014

Coulomb suppressed

‘coalescence’
Indirect Detection

$^{4}\text{He}$ from DM annihilations in halo

He statistically suppressed

Cirelli, Fornengo, Vittino, Taoso 2014
Carlson, Linden, Ibarra, Profumo, Wild 2014

'coalescence'
Indirect Detection

$^{3}\text{He}$ from DM annihilations in halo

$\text{DM DM} \rightarrow \bar{u}u$ $\quad m_{\text{DM}} = 20 \text{ GeV} \quad p_{\text{coal}} = 195 \text{ MeV}$

$\phi \left[ \text{m}^2 \text{s} \text{sr (GeV/n)}^{-1} \right]$ vs $T [\text{GeV/n}]$

$<\sigma v> = 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$

EIN profile

AMS-01 excluded
PAMELA excluded
BESS excluded
AMS-02 reach

MAX
MED
MIN

bkg

all

consistent with antiproton bounds

some tension $^{3}\text{He}/p$
Indirect Detection

\[ \text{He} \] from DM annihilations in halo

\[ \text{DM DM} \rightarrow u\bar{u} \quad m_{\text{DM}} = 20 \text{ GeV} \quad p_{\text{coal}} = 195 \text{ MeV} \]

\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} \]

EIN profile

\[ \phi \left[ \text{m}^2 \text{s sr (GeV/n)}^{-1} \right] \]

\[ 10^{-6} \quad 10^{-8} \quad 10^{-10} \quad 10^{-12} \quad 10^{-14} \quad 10^{-16} \]

\[ T \ [\text{GeV/n}] \]

AMS-01 excluded
PAMELA excluded
BESS excluded
AMS-02 reach

MAX
MED
MIN

bkg
Indirect Detection of Dark Matter (DM) annihilations in halo. Plotted are the fluxes for different DM annihilation modes and masses, with exclusion limits from experiments such as AMS-02, PAMELA, and BESS. The figure shows the flux in units of $\frac{m^2 \text{s sr (GeV/n)}}{1}$ as a function of the c.m. energy $T$ for annihilation processes $\text{DM DM} \rightarrow \ell \ell$, $\text{DM DM} \rightarrow b\bar{b}$, and $\text{DM DM} \rightarrow W^+W^-$. The excluded regions are indicated by shaded areas, with the central values of $\langle \sigma v \rangle$ given in $10^{-26} \text{cm}^3 \text{s}^{-1}$.
Indirect Detection $He$ from DM annihilations in halo
In five years, AMS has collected 3.7 billion helium events (charge \( Z = +2 \)). To date we have observed a few \( Z = -2 \) events with mass around \(^3\)He. An event is displayed in Figure 14.

S.Ting - AMS-02 press release - december 2016
Conclusions

DM not seen yet. *(Damn!...)*

Constraints are stronger and stronger.

**Antiproton** constraints are interesting and **competitive** with (e.g.) gamma ray ones. But they have important **uncertainties**.

**Antideuterons** are **challenging** but potentially very **rewarding**.

**Antihelium** is probably hopeless.
Back up slides
Propagation for antiprotons:

\[
\frac{\partial f}{\partial t} - K(T) \cdot \nabla^2 f + \frac{\partial}{\partial z} \left( \text{sign}(z) f V_{\text{conv}} \right) = Q - 2h \delta(z) \Gamma_{\text{ann}} f
\]

Diffusion

\[K(T) = K_0 \beta \left( p/\text{GeV} \right)^{\delta}\]

Convective wind

\[T \text{ kinetic energy}\]

Spallations
Propagation

Propagation for antiprotons:

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- **diffusion**
  \[ K(T) = K_0 \beta (p/\text{GeV})^\delta \]
  - \( T \) kinetic energy

- **convective wind**
  \[ V_{\text{conv}} \]

- **spallations**

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<tr>
<th>Model</th>
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Propagation

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- diffusion
- convective wind
- spallations

\[K(T) = K_0 \beta \left( p / \text{GeV} \right)^\delta\]

\[T\] kinetic energy

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Solution:

\[
\Phi_{\bar{p}}(T, \vec{r}_\odot) = B \frac{v_{\bar{p}}}{4\pi} \left( \frac{\rho_\odot}{M_{\text{DM}}} \right)^2 R(T) \sum_k \frac{1}{2} \langle \sigma v \rangle_k \frac{dN^k_{\bar{p}}}{dT}
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- diffusion
- convective wind
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\(T\) kinetic energy

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GC GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse $\gamma$ data from the GC?

Best fit: $\sim 35$ GeV, quarks, $\sim$thermal $\sigma v$

A compelling case for annihilating DM

Daylan, Finkbeiner, Hooper, Linden, Portillo, Redd, Slatyer: 1402.6703

Using events with accurate directional reconstruction

As found in previous studies [8, 9], the inclusion of the dark matter template dramatically improves the quality of the fit to the *Fermi* data. For the best-fit spectrum and halo profile, we find that the inclusion of the dark matter template improves the formal fit by $\Delta \chi^2 \sim 1672$, corresponding to a statistical preference greater than 40$\sigma$. 
GC GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse $\gamma$ data from the GC?

Antiproton constraints may be very relevant! But not robust.

**Assumption:** fixed solar modulation

**Result:** hooperon excluded
(except unrealistic THN)

Fermi-LAT excess
What if a signal of DM is already hidden in Fermi diffuse $\gamma$ data from the GC?

Antiproton constraints may be very relevant! But not robust.

Assumption: flexible solar modulation
Result: hooperon may be excluded or not
What if a signal of DM is \textit{already} hidden in Fermi diffuse $\gamma$ data from the GC?

\begin{itemize}
  \item \textbf{Antiproton constraints} may be very relevant! But \textbf{not} robust.
  \item Assumption: \textbf{conservative} solar modulation
  \item Result: hooperon probably \textbf{reallowed} (except THK models)
\end{itemize}
What if a signal of DM is *already* hidden in Fermi diffuse $\gamma$ data from the GC?

Antiproton constraints may be very relevant! But not robust.

Assumption: conservative solar modulation
Result: hooperon probably reallocated (except THK models)

NB Conclusion differs from Bringmann, Vollmann, Weniger 1406.6027 which finds exclusion / strong tension
GC GeV gamma excess?

Antiproton constraints compared:

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Benchmark propagation models

Bringmann, Vollmann, Weniger 1406.6027

Hooper, Linden, Mertsch 1410.1527

May be very relevant!
But not robust.

‘Rule out’ or ‘considerable tension’.

‘Significantly less stringent’.

How come?!?
GC GeV gamma excess?

Antiproton constraints compared:

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

May be very relevant!
But not robust.

Bringmann, Vollmann, Weniger 1406.6027

‘Rule out’ or
‘considerable tension’.

Hooper, Linden, Mertsch 1410.1527

‘Significantly less stringent’.

How come?!? The devil is in the (CR propagation) details:
solar modulation, convection, primary injection spectrum, tertiaries...