Dark Matter
Indirect Detection:
charged particles

Marco Cirelli
(CNRS LPTHE Jussieu)
Dark Matter
Indirect Detection:
charged particles

Marco Cirelli
(CNRS LPTHE Jussieu)
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

$\nu, \bar{\nu}$ 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

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

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

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

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

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

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

$W^-, Z, b, \tau^-, t, h \ldots \leadsto e^\mp, p, D \ldots$

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

$\begin{align*}
W^-, Z, b, \tau^-, t, h \ldots &\rightsquigarrow e^\mp, (\vec{p}), (\vec{D}) \ldots \\
W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots &\rightsquigarrow e^\pm, (\vec{p}), (\vec{D}) \ldots
\end{align*}$

primary channels
Indirect Detection: basics

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

primary channels

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

$DM \to W^-, Z, b, \tau^-, t, h \ldots \to e^\pm, \vec{p}, D \ldots$

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

$e^+$ primary spectra

$\bar{p}$ primary spectra

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

$x = K/M_{DM}$
Fluxes at production

So what are the particle physics parameters?
Fluxes at production

Flux

energy

So what are the particle physics parameters?

1. Dark Matter mass
So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section
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

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Indirect Detection: charged CRs

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Indirect Detection: charged CRs

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

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

spectrum

diffusion energy loss convective wind source spallations

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maur Brun... ‘90s, ’00s
Indirect Detection: charged CRs

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

<table>
<thead>
<tr>
<th>thickness</th>
<th>diffusion</th>
<th>diff. reacc.</th>
<th>$p$ index</th>
<th>convection</th>
<th>solar mod.</th>
</tr>
</thead>
</table>

<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>$dv_c/dz$ [km s$^{-1}$ kpc$^{-1}$]</th>
<th>$\phi_F$ [GV]</th>
<th>$\chi^2_{\text{min}}$/dof ($p$ in [25])</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.64</td>
<td>0.50</td>
<td>-0.39</td>
<td>14.2</td>
<td>2.35</td>
<td>0</td>
<td>0.650</td>
<td>0.462</td>
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<tr>
<td>4</td>
<td>4.46</td>
<td>0.33</td>
<td>1</td>
<td>36</td>
<td>1.78/2.45</td>
<td>0</td>
<td>0.335</td>
<td>0.761</td>
</tr>
<tr>
<td>4</td>
<td>0.97</td>
<td>0.6</td>
<td>1</td>
<td>38.1</td>
<td>1.62/2.35</td>
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<td>0.282</td>
<td>1.602</td>
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<tr>
<td>10</td>
<td>4.75</td>
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<td>-0.15</td>
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<td>0</td>
<td>0.704</td>
<td>0.639</td>
</tr>
<tr>
<td>2</td>
<td>1.35</td>
<td>0.50</td>
<td>-0.27</td>
<td>11.6</td>
<td>2.35</td>
<td>0</td>
<td>0.626</td>
<td>0.343</td>
</tr>
<tr>
<td>3</td>
<td>1.98</td>
<td>0.50</td>
<td>-0.27</td>
<td>11.6</td>
<td>2.35</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>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta$</td>
<td>$K_0$ [kpc$^2$/Myr]</td>
</tr>
<tr>
<td>MIN</td>
<td>0.55</td>
<td>0.00595</td>
</tr>
<tr>
<td>MED</td>
<td>0.70</td>
<td>0.0112</td>
</tr>
<tr>
<td>MAX</td>
<td>0.46</td>
<td>0.0765</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KRA</th>
<th>KOL</th>
<th>CON</th>
<th>THK</th>
<th>THN</th>
<th>THN2</th>
<th>THN3</th>
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<tbody>
<tr>
<td>$L$ [kpc]</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>10</td>
<td>0.5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$D_0$ [$10^{28}$ cm$^2$ s$^{-1}$]</td>
<td>2.64</td>
<td>4.46</td>
<td>0.97</td>
<td>4.75</td>
<td>0.31</td>
<td>1.35</td>
<td>1.98</td>
</tr>
<tr>
<td>$\delta$</td>
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<td>0.33</td>
<td>0.6</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>$\eta$</td>
<td>-0.39</td>
<td>1</td>
<td>1</td>
<td>-0.15</td>
<td>-0.27</td>
<td>-0.27</td>
<td>-0.27</td>
</tr>
<tr>
<td>$v_A$ [km s$^{-1}$]</td>
<td>14.2</td>
<td>36</td>
<td>38.1</td>
<td>14.1</td>
<td>11.6</td>
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</tr>
<tr>
<td>$\gamma$</td>
<td>2.35</td>
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<td>1.62/2.35</td>
<td>2.35</td>
<td>2.35</td>
<td>2.35</td>
<td>2.35</td>
</tr>
<tr>
<td>$dv_e/dz$ [km s$^{-1}$ kpc$^{-1}$]</td>
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<td>0</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\phi_F$ [GV]</td>
<td>0.650</td>
<td>0.335</td>
<td>0.626</td>
<td>0.623</td>
<td>0.639</td>
<td>0.809</td>
<td></td>
</tr>
<tr>
<td>$\chi^2_{\text{min}}$/dof ($p$ in [25])</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
</tr>
</tbody>
</table>

### Modeling Parameters

- **Electrons or positrons**
- **Annihilation rate**
- **$K_0$ [kpc$^2$/Myr]**
- **$\delta$**

<table>
<thead>
<tr>
<th>Model</th>
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<th>$K_0$ [kpc$^2$/Myr]</th>
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<th>$\gamma$</th>
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<th>$L$ [kpc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIN</td>
<td>0.55</td>
<td>13.5</td>
<td>0.00595</td>
<td>0.85</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MED</td>
<td>0.70</td>
<td>12</td>
<td>0.0112</td>
<td>0.70</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MAX</td>
<td>0.46</td>
<td>5</td>
<td>0.0765</td>
<td>0.46</td>
<td>3</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

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**Notes:**
- Donato et al., 2003+
- Carmelo Evoli’s talk
- Yoann Génolini’s talk
Indirect Detection: charged CRs

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

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

Spectrum, diffusion, energy loss, convective wind, source, spallations [uncert]

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

Spectrum from DM annihilations in halo
DM halo profiles

From N-body numerical simulations:

- NFW: \( \rho_{\text{NFW}}(r) = \frac{\rho_s r_s}{r} \left( 1 + \frac{r}{r_s} \right)^{-2} \)
- Einasto: \( \rho_{\text{Ein}}(r) = \rho_s \exp \left\{ -\frac{2}{\alpha} \left[ \left( \frac{r}{r_s} \right)^\alpha - 1 \right] \right\} \)
- Isothermal: \( \rho_{\text{Iso}}(r) = \frac{\rho_s}{1 + (r/r_s)^2} \)
- Burkert: \( \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1 + r/r_s)(1 + (r/r_s)^2)} \)
- Moore: \( \rho_{\text{Moo}}(r) = \rho_s \left( \frac{r_s}{r} \right)^{1.16} \left( 1 + \frac{r}{r_s} \right)^{-1.84} \)

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]
Fluxes at detection

So what are the astrophysics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

Flux

$\sigma_{\nu}$

$M_{DM}$

energy

background?
Fluxes at detection

So what are the astrophysics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

1. DM abundance/profile
Fluxes at detection

So what are the astrophysics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

1. DM abundance/profile
2. propagation

Flux

energy

CR prop

profile

background?

σν

MDM

MDM
Fluxes at detection

So what are the astrophysics parameters?

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Fluxes at detection

So what are the astrophysics parameters?
1. Dark Matter mass
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3. cross section

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3. background
Data
Data: leptons

\[ e^+/e^+e^- \]

\[ e^+e^- \]

\( E^+ (e^- + e^+) \text{ GeV} \cdot \text{cm}^2 \cdot \text{sec} \cdot \text{sr} \)

\( E^+ (e^- + e^+) \text{ GeV} \cdot \text{cm}^2 \cdot \text{sec} \cdot \text{sr} \)
Data: leptons

Energy scale is determined by absolute calibration using cutoff rigidity (difference from MIP calibration is $\pm 3.5\%$).

CALET Preliminary

D. Kerszberg, HESS coll., ICRC 2017

M. Cirelli - compilation ICRC 2015

+ DAMPE coll. $\rightarrow$ soon
Data: leptons

CALET coll., ICRC 2017

Energy scale is determined by absolute calibration using cutoff rigidity (difference from MIP calibration is ±3.5%).

CALET Preliminary

Energy [GeV] vs. $E^{\mu}$ s$^{-1}$ [GeV$^{-2}$ cm$^{-2}$ sr$^{-1}$]

e$^+$ + e$^-$

HESS Preliminary

Flux $E^{\nu}d\sigma/dE$ (GeV$^{-2}$ cm$^{-2}$ s$^{-1}$)

Preliminary

D. Kerszberg, HESS coll., ICRC 2017

IRIS GEBAUER’S TALK

M. Cirelli - compilation ICRC 2015

FERMI 2017 LE
FERMI 2017 HE
VERITAS 2015
AMS-02 2014
MAGIC 2011
HESS 2009
HESS 2008

+ DAMPE coll. —> soon
Dark Matter interpretation

- leptophilic

- $m_{DM} > \text{few } 100 \text{ GeV}$

- huge annihilation cross section
Dark Matter interpretation

- leptophilic

- $m_{DM} \sim 1$ TeV

- huge annihilation cross section

![Graph showing $\sigma v$ vs. $M_{DM}$ with PAMELA e$^+$ and AMS2013 e$^+$ data points.](image)
- leptophilic
- $m_{DM} \lesssim 1 \text{ TeV}$
- huge annihilation cross section
Dark Matter interpretation

- leptophilic
- $m_{\text{DM}} \sim 1 \text{ TeV}$
- huge annihilation cross section

![Graph showing the DM DM → $\mu\mu$, NFW profile with data points from FERMI e$^\pm$ + HESS e$^\pm$ 2015 and PAMELA e$^+$ + AMS2014 e$^+$]
Dark Matter interpretation

- leptophilic
- \( m_{\text{DM}} \sim 1 \text{ TeV} \)
- huge annihilation cross section
Dark Matter interpretation

However:
However:

- **increased precision brings increased tension**

  "The improved accuracy of AMS-02 on the lepton flux now excludes channels previously allowed."
However:

- **increased precision brings increased tension**
  
  “The improved accuracy of AMS-02 on the lepton flux now excludes channels previously allowed.”

- **combination** of annihilation channels are possible
However:

- **increased precision brings increased tension**
  “The improved accuracy of AMS-02 on the lepton flux now excludes channels previously allowed.”

- **combination** of annihilation channels are possible

- **constraints**: gamma rays, neutrinos, CMB...

---

**Graphs:**
- **Graph 1:** Shows the relation between DM mass (GeV) and $<\sigma v>$ (cm$^3$/s) with different annihilation channels.
- **Graph 2:** Illustrates $f_{\text{eff}} <\sigma v>$ (cm$^3$/s) against $m_x$ (GeV) with constraints from Planck TT, TE, EE, lowTEB, WMAP9, CVL, and possible interpretations for AMS-02, Fermi/Pamela, and Fermi GC.
Astro interpretation

- far SNR
- near SNR
- secondaries

M. Di Mauro et al.
1507.07001
Astro interpretation

Mathieu Boudaud's talk
Data: antiprotons

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

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

AMS-02

S. Ting - AMS days @ CERN apr 2015
A. Kounine - AMS days @ CERN apr 2015
Data: antiprotons

AMS-02

AMS coll., PRL 117, 091103 (2016)
Antiprotons
Antiproton data vis-à-vis the secondaries:

![Graph showing antiproton data vis-à-vis the secondaries.](image)
Antiprotons

Antiproton data vis-à-vis the secondaries:

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

Kinetic energy \( T \) [GeV]

- PAMELA 2012
- AMS-02 2015
Antiprotons

Antiproton data vis-à-vis the secondaries:

![Graph showing antiproton data and uncertainties](image-url)
Indirect Detection

Background computations for antiprotons:
Indirect Detection

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
Indirect Detection

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

Antiproton data vis-à-vis the secondaries:

No evident excess

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

Antiproton data vis-à-vis the secondaries:

No evident excess

Some preference for flatness
Antiprotons

Antiproton data vis-à-vis the secondaries:

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

Using p, He, B/C by AMS-02, B/C by PAMELA.


Using p, He, B/C by AMS-02.


With AMS-02 preliminary B/C data.

Using p, He by AMS-02 and CREAM, B/C by AMS-02, heavier nuclei by compilation.
Dark Matter interpretation

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

Astrophysical uncertainties on the constraints

Excluded

Allowed

$\sigma v \rightarrow b\bar{b}$

DM mass $m_{DM}$ [GeV]
Antiprotons

Recent developments

Cusco, Krämer, Korsmeier 1610.03071

finds a possible excess
(formally ~4.5σ)

\( m_{\text{DM}} = 80 \text{ GeV, } bb, \) 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

finds a possible excess

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

excess evaporates
including low energies
Antiprotons

Recent developments

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finds a possible excess

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

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propagation parameters determined with \( p, \text{He} \) data only, w/o B/C excess evaporates including low energies

MARTIN WINKLER’S TALK
Compared to other bounds

All ID constraints

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

DM mass [GeV]

\(\gamma\)-rays \(\bar{p}\) CMB \(\nu\)

\(\mu\mu\)

\(bb\)

\(WW\)

status at 35\(^{th}\) ICRC (summer 2017)

SuperKamiokande

ANTARES

FERMI dwarfs 6yr

HESS GC

updated from M. Cirelli 1511.02031; M. Cirelli, A. Strumia, J. Zupan to appear
DM detection

direct detection

production at colliders

indirect

\[ \gamma \text{ from annihil in galactic center or halo and from secondary emission} \]

\[ e^+ \text{ from annihil in galactic halo or center} \]

\[ p, \bar{p} \text{ from annihil in galactic halo or center} \]

\[ d, \bar{d} \text{ from annihil in galactic halo or center} \]

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GAPS, AMS

Fermi, ICT, radio telescopes...

PAMELA, Fermi, HESS, AMS, balloons...

SK, Icecube, Km3Net
Indirect Detection

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

$\bar{d}$
Indirect Detection

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

$\gamma_{\bar{d}} \frac{d^3 N_{\bar{d}}}{dk^3_{\bar{d}}}$

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

$\gamma_{\bar{n}} \frac{d^3 N_{\bar{n}}}{dk^3_{\bar{n}}}$

probability to find $\bar{n}$ within a sphere of radius $p_0$ around $\vec{k}_{\bar{p}}$

$\gamma_{\bar{p}} \frac{d^3 N_{\bar{p}}}{dk^3_{\bar{p}}}$

$\bar{p}$-density 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

\( \bar{d} \) from DM annihilations in halo

\[ \bar{d} - \text{density in momentum space} = 4 \| \vec{p} \|^3 \frac{d^3 N_{\bar{d}}}{d\vec{k}^3_{\bar{d}}} \]

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

\[ \frac{d^3 N_{\bar{n}}}{d\vec{k}^3_{\bar{n}}} \]

\[ \gamma_{\bar{n}} \]

\[ \frac{d^3 N_{\bar{p}}}{d\vec{k}^3_{\bar{p}}} \]

event-by-event with Pythia

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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...

coalesscence momentum

$p_0 \simeq |\vec{k}_p - \vec{k}_\bar{n}| \approx 80 \rightarrow 200 \text{ MeV}$
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
Indirect Detection
\[ \bar{d} \] from DM annihilations in halo

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DM signal in the reach of GAPS and AMS-02
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

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

Fermi, ICT, radio telescopes...
PAMELA, Fermi, HESS, AMS, balloons...
GAPS, AMS
SK, Icecube, Km3Net
AMS?
Indirect Detection $^{4}\text{He}$ from DM annihilations in halo

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

event-by-event with Pythia

coalessence momentum $p_0 = 195 \text{ MeV}$
Indirect Detection

\( \overline{He} \) from DM annihilations in halo

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

Coulomb suppressed

\( \overline{p} \) ‘coalescence’
Indirect Detection
$^{4}\text{He}$ from DM annihilations in halo

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

statistically suppressed
Indirect Detection
$^4He$ from DM annihilations in halo

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

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

EIN profile

AMS-01 excluded
PAMELA excluded
BESS excluded

AMS-02 reach

MAX
MED
MIN

all
consistent with antiproton bounds
Indirect Detection of $H^e$ from DM annihilations in halo

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

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

EIN profile

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

$10^{-2}$

$10^{-4}$

$10^{-6}$

$10^{-8}$

$10^{-10}$

$10^{-12}$

$10^{-14}$

$10^{-16}$

$0.1$ $1$ $10$ $100$

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

$\langle \sigma v \rangle$ is constrained by various experiments, including

- AMS-01
- PAMELA
- BESS

AMS-02 reach

MIN, MED, MAX

bkg
Indirect Detection

$He$ from DM annihilations in halo
Indirect Detection

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

![Graphs showing indirect detection of dark matter annihilations into different channels and mass ranges.](image)
Indirect Detection $^4\text{He}$ 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 $^3\text{He}$. An event is displayed in Figure 14.

S. Ting - AMS-02 press release - December 2016
Indirect Detection of $^4He$ from DM annihilations in halo

update: Blum, Ng et al (1704.05431)
find very high bkg calibrating on ALICE data
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Conclusions
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DM not seen yet \(\text{Damn!...}\)
Conclusions

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Charged cosmic rays are in principle a very powerful tool
Conclusions

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in $e^+$: long standing ‘excesses’
in $p$: still large uncertainties
in $d$: challenging flux
in $He$: hopeless? who knows
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Conclusions

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Back up slides
Introduction
Introduction

DM exists
DM exists

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

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

Some of us believe in the WIMP miracle.

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

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

DM need not be absolutely stable, just \( \tau_{\text{DM}} \gtrsim \tau_{\text{universe}} \approx 4.3 \times 10^{17} \text{ sec} \).
What sets the overall expected flux?

\[ \text{flux} \propto n^2 \sigma_{\text{annihilation}} \]
Indirect Detection: charged CRs

 indicate DM annihilations in halo

What sets the overall expected flux?

$$flux \propto n^2 \sigma_{\text{annihilation}}$$

astro&cosmo

particle
Indirect Detection: charged CRs

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

What sets the overall expected flux?

$$\text{flux} \propto n^2 \sigma_{\text{annihilation particle}}$$

reference cross section:

$$\sigma v = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$$
DM halo profiles

From N-body numerical simulations:

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

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

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

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

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

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>
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</table>

Figure 1 at the Galactic Center is a traditional benchmark choice motivated by N-body simulations.

The density of Dark Matter at the location of the Sun is \( 10^4 \) GeV/cm\(^3\).

The planned GAIA space mission will most probably change the situation and give good constraints on the Dark Matter distribution in the Galaxy.

Whenever possible we use a comprehensive set of results for DM indirect detection, as opposed to the generating code. We make an effort to provide a useful to have at disposal the whole range of possible choices when computing Dark Matter signals in the Milky Way.

As long as a convergent determination of the actual DM profile is not reached, it is still subject to debate.

Notice that we here provide 2 (3) decimal significant digits for the value of \( \rho(r) \).

The parameters that we adopt and the profiles are thus given explicitly in Fig. 1.

This number is based on recent computations that have found such a trend, ref. simulating the haloes.

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

At the edge of the reader with ready-to-use final product, as opposed to the generating code.
Local **clumps** in the DM halo enhance the density.

For illustration:
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

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

convective wind

\[\Gamma_{\text{ann}} f\]

spallations

\[T \ \text{kinetic energy}\]
## Propagation

### Propagation for antiprotons:

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\frac{\partial f}{\partial t} - K(T) \cdot \nabla^2 f + \frac{\partial}{\partial z} (\text{sign}(z) f V_{\text{conv}}) = Q - 2h \delta(z) \Gamma_{\text{ann}} f
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- **diffusion**
- **convective wind**
- **spallations**

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

**T** kinetic energy

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<tr>
<th>Model</th>
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<th>( L ) in kpc</th>
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<tr>
<td>min</td>
<td>0.85</td>
<td>0.0016</td>
<td>1</td>
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Solution:

\[
\Phi_p(T, \vec{r}_\odot) = B \frac{v_p}{4\pi} \left( \frac{\rho_\odot}{M_{\text{DM}}} \right)^2 R(T) \sum \frac{1}{2} \langle \sigma v \rangle_k \frac{dN^k_{\vec{p}}}{dT}
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Propagation

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