Dark Matter and the PAMELA/ATIC data

Marco Cirelli
(CNRS, IPhT-CEA/Saclay)

Thanks to:

UniverseNet
The origin of our universe:
Seeking links between fundamental physics and cosmology
1. Are we seeing Dark Matter in cosmic rays?
1. Are we seeing Dark Matter in cosmic rays?

2. Why there is new theory of DM on the arXiv every day?
Indirect Detection
$p$ and $e^+$ from DM annihilations in halo

Galactic Bulge
Norma Arm
Scutum Arm
Outer Arm
Perseus Arm
Sagittarius Arm
Sun
Local Arm
Crux Arm
Carina Arm
8 kpc
Indirect Detection

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

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

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

- diffusion
- energy loss
- convective wind source
- spallations

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s
Indirect Detection
$
\bar{p} \text{ and } e^+ \text{ from DM annihilations in halo}
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What sets the overall expected flux?

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

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

What sets the overall expected flux?

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

astro & cosmo
Indirect Detection

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

What sets the overall expected flux?

\[
\text{flux} \propto n^2 \frac{\sigma_{\text{annihilation particle}}}{\sigma_{\text{particle reference}}} \]

reference cross section:
\[
\sigma = 3 \cdot 10^{-26} \text{ cm}^3/\text{sec}
\]
DM halo profiles

From N-body numerical simulations:

\[ \rho(r) = \rho_\odot \left[ \frac{r_\odot}{r} \right]^\gamma \left[ \frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha} \right]^{(\beta-\gamma)/\alpha} \]

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

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

<table>
<thead>
<tr>
<th>Halo model</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>( r_s ) in kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cored isothermal</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Navarro, Frenk, White</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Moore</td>
<td>1</td>
<td>3</td>
<td>1.16</td>
<td>30</td>
</tr>
</tbody>
</table>

Einasto | \( \alpha = 0.17 \) | \( r_s = 20 \text{ kpc} \) | \( \rho_s = 0.06 \text{ GeV/cm}^3 \)

cuspy: NFW, Moore
mild: Einasto
smooth: isothermal
Indirect Detection

**Boost Factor:** local clumps in the DM halo enhance the density, boost the flux from annihilations. Typically: $B \sim 1 \rightarrow 20 \ (10^4)$

For illustration:
Computing the theory predictions
Spectra at production

\[ W^{-}, Z, b, \tau^{-}, t, h \ldots \leadsto e^{\mp}, p, D \ldots \]

\[ W^{+}, Z, b, \tau^{+}, t, h \ldots \leadsto e^{\pm}, p, D \ldots \]
Spectra at production

\[ \sum W^-, Z, b, \tau^-, t, h \ldots \rightarrow e^\mp, \frac{(\cdot)}{p}, \frac{(\cdot)}{D} \ldots \]

primary channels

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Spectra at production

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

primary channels

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Spectra at production

primary channels

final products

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

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

Primary channels leading to final products through decay.
Spectra at production

\[ W^-, Z, b, \tau^-, t, h \ldots \rightarrow e^+, p, D \ldots \]

primary channels

\[ W^+, Z, \overline{b}, \tau^+, \overline{t}, h \ldots \rightarrow e^\pm, \overline{p}, D \ldots \]

final products

So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
Comparing with data
Positrons from PAMELA:

- steep $e^+$ excess above 10 GeV!
- very large flux!

Positron fraction: $\frac{e^+}{e^+ + e^-}$

(9430 $e^+$ collected)

(errors statistical only, that's why larger at high energy)

PAMELA might be a real breakthrough!
Data sets

Antiprotons from PAMELA:

- consistent with the background

(about 1000 $p$ collected)
Results

Which DM spectra can fit the data?
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E.g. a DM with: -mass $M_{DM} = 150$ GeV
-annihilation $DM \, DM \rightarrow W^+ W^-$
(a possible SuperSymmetric candidate: wino)

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Positrons:

Anti-protons:

[insisting on Winos]
Results

Which DM spectra can fit the data?

E.g. a DM with: - mass $M_{DM} = 10$ TeV
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Which DM spectra can fit the data?

E.g. a DM with:
- mass $M_{DM} = 10$ TeV
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but...:
- cross sec $\sigma_{ann} \nu = 6 \cdot 10^{-22} \text{cm}^3/\text{sec}$

Positrons:

Anti-protons:
Results
Which DM spectra can fit the data?

E.g. Minimal DM: -mass $M_{\text{DM}} = 9.7 \text{ TeV}$
-annihilation $\text{DM} \text{ DM} \rightarrow W^+W^-$
-boost $B \approx 30$ Yes!

Positrons: [Cirelli, Strumia et al. 2006]

Anti-protons: [thanks to Sommerfeld enhancement]

**Results**

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Results
Which DM spectra can fit the data?

Model-independent results:
fit to PAMELA positrons only
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(1) annihilate into leptons (e.g. $\mu^+ \mu^-$)
Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons + anti-protons

(1) annihilate into leptons (e.g. $\mu^+\mu^-$) or
(2) annihilate into $W^+W^-$ with mass $\gtrsim$ 10 TeV
Results
Which DM spectra can fit the data?

Model-independent results:
Boost required by PAMELA
Data sets

Electrons + positrons from ATIC, PPB-BETS and HESS!:
- an $e^+ + e^-$ excess at $\sim 700$ GeV??

**Data sets**

**Electrons + positrons from ATIC, PPB-BETS and HESS!:**
- an $e^+ + e^-$ excess at $\sim 700$ GeV??

**HESS:**
very interesting (independent!)
but difficult analysis
(particle ID: contamination from gamma & hadronic showers):
are these upper limits?

[future data from GLAST]
Results

Which DM spectra can fit the data?

A DM with:
- mass $M_{DM} = 1$ TeV
- annihilation $DM \, DM \rightarrow \mu^+ \mu^-$
Results

Which DM spectra can fit the data?

A DM with:
- mass $M_{DM} = 1$ TeV
- annihilation $DM \rightarrow \mu^+\mu^-$

Positrons: Yes!

Anti-protons: Yes!

Electrons + Positrons: Yes!
Results
Which DM spectra can fit the data?

A DM with:
- mass $M_{\text{DM}} = 1 \text{ TeV}$
- annihilation $\text{DM} \rightarrow \mu^+ \mu^-$

Positrons: Yes!
Anti-protons: Yes!
Electrons + Positrons: Yes!

Have we identified the DM for the first time???
Arkani-Hamed, Weiner et al. 0810: Yes!
+ a ton of others
Results

Which DM spectra can fit the data?

Model-independent results:

fit to PAMELA positrons* + balloon experiments

*adding anti-protons does not change much, non-leptonic channels give too smooth spectrum for balloons
Results

Which DM can fit the data?

Two important remarks

A. Maybe it’s just a pulsar, or other astrophysics

diffuse mature &
neighboring young
pulsars
Two important remarks

A. Maybe it’s just a pulsar, or other astrophysics

B. Associated gamma ray and radio constraints from the GC and dwarf galaxies are severe
1. Are we seeing Dark Matter in cosmic rays?

2. Why there is new theory of DM on the arXiv every day?
1. Are we seeing Dark Matter in cosmic rays?

*I don't know, I fear it's unlikely, but maybe... Maybe it's a pulsar.*

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Because the signals point to a “weird” DM so theorists try to reinvent the field:
- DM is heavy-ish
- annihilates into leptons and not anti-protons
- huge cross section (boost? Sommerfeld?)
- must not produce too many gammas
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Upcoming data: Fermi, ATIC-4, Pamela...
Back up slides
Indirect Detection

**Boost Factor:** local clumps in the DM halo enhance the density, boost the flux from annihilations. Typically: \( B \approx 1 \rightarrow 20 \ (10^4) \)

In principle, \( B \) is different for \( e^+ \), anti-\( p \) and gammas, energy dependent, dependent on many astro assumptions (inner density profile of clump, tidal disruptions and smoothing...), with an energy dependent variance, at high energy for \( e^+ \), at low energy for anti-\( p \).

**positrons**

**antiprotons**
Astrophysical explanation?
Or perhaps it’s just a young, nearby pulsar...

'Mechanism': the spinning $\vec{B}$ of the pulsar strips $e^-$ that emit $\gamma$ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \rightarrow 10^5$ yr (typical total energy output: $10^{46}$ erg).

Must be young ($T < 10^5$ yr) and nearby (< 1 kpc); if not: too much diffusion, low energy, too low flux.

Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

(1.4 < p < 2.4, Profumo 2008)

Not a new idea:

A.Boulares, APJ 342 (1989)

A. Atoyan, Aharonian, Volk (1995)
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Try the fit with known nearby pulsars:

---

**TABLE 1**

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<tbody>
<tr>
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Must be young ($T < 10^5$ yr) and nearby ($< 1$ kpc); if not: too much diffusion, low energy, too low flux.

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Try the fit with known nearby pulsars and diffuse mature pulsars:

diffuse mature & nearby young pulsars

Geminga pulsar
Or perhaps it’s just a **young, nearby pulsar**...

‘Mechanism’: the spinning \( \vec{B} \) of the pulsar strips \( e^- \) that emit \( \gamma \) that make production of \( e^\pm \) pairs that are trapped in the cloud, further accelerated and later released at \( \tau \sim 0 \rightarrow 10^5 \) yr.

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Predicted flux: \( \Phi_{e^\pm} \approx E^{-p} \exp(E/E_c) \) with \( p \approx 2 \) and \( E_c \sim \) many TeV

But ATIC needs a different (and very powerful) source:
Or perhaps it’s just a **young, nearby pulsar**...

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---

**Open issue.**

(look for anisotropies, (both for single source and collection in disk) **antiprotons, gammas**... (Fermi is discovering a pulsar a week) or shape of the spectrum...)

---

*e.g. Yuksel, Kistler, Stanev 0810.2784 Hall, Hooper 0811.3362*
DM detection

**Direct detection**

**Production at colliders**

**Indirect**

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

**Detection:**

- HESS, radio telescopes
- PAMELA, AMS02, balloons
Indirect Detection

$\gamma$ from DM annihilations in galactic center

$W^{-}, Z, b, \tau^{-}, t, h \ldots \rightarrow e^{\pm}, p, D \ldots$ and $\gamma$

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

\( \gamma \) from DM annihilations in galactic center

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Indirect Detection

$\gamma$ from DM annihilations in galactic center

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

typically sub-TeV energies
Indirect Detection

\[ \gamma \] from DM annihilations in \textit{Sagittarius Dwarf}
Indirect Detection

radio-waves from synchrotron radiation of $e^\pm$ in GC
Indirect Detection

Radio-waves from synchrotron radiation of $e^\pm$ in GC

- compute the population of $e^\pm$
- from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

(assuming ‘scrambled’ B; in principle, directionality could focus emission, lift bounds by O(some))
Comparing with data
Gamma constraints

**HESS** has detected $\gamma$-ray emission from Gal Center and Gal Ridge. The DM signal must not exceed that.
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**Gamma constraints**

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\[ \sigma v_{\text{ann}} = 10^{-23} \text{cm}^3/\text{sec} \]

**a)** $M = 10$ TeV into $W^+ W^-$, Galactic Center

\[ E^2 \frac{dN_\gamma}{dE} \text{ in TeV/cm}^2\text{sec} \]

\[ 10^{-13}, 10^{-12}, 10^{-11} \text{ in TeV/cm}^2\text{sec} \]

\[ \gamma \text{ energy in TeV} \]

**Ok**
Gamma constraints

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Data: HESS coll., astro-ph/0603021

$\sigma_{v_{\text{ann}}} = 10^{-23}\text{ cm}^3/\text{sec}$
**Gamma constraints**

**HESS** has detected $\gamma$-ray emission from Gal Center and Gal Ridge. The DM signal must not exceed that.

Moreover: no detection from Sgr dSph => upper bound.

**Data:** HESS coll., astro-ph/0408145 and astro-ph/0603021

\[ \sigma v_{\text{ann}} = 10^{-23} \text{cm}^3/\text{sec} \]
Gamma constraints

Several observations detected radio to IR emission from the Gal Center. The DM signal must not exceed that.
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Davies 1978 upper bound at 408 MHz.
Gamma constraints

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Davies 1978 upper bound at 408 MHz.

VLT 2003 emission at $10^{14}$ Hz.

integrate emission over a small angle corresponding to angular resolution of instrument
Gamma constraints

The PAMELA and ATIC regions are in conflict with gamma constraints, unless...
Gamma constraints

Bertone, Cirelli, Strumia, Taoso 0811.3744
Gamma constraints

...not-too-steep profile needed.
Gamma constraints

...not-too-steep profile needed.

Or: take different boosts here (at Earth, for $e^+$) than there (at GC for gammas).
Or: take ad hoc DM profiles (truncated at 100 pc, with central void..., after all we don’t know).