DM Indirect Detection: some anomalies and many constraints

Marco Cirelli
(CNRS IPhT Saclay)
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Introduction
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DM exists
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- Galactic rotation curves
- Weak lensing (e.g. in clusters)
- 'Precision cosmology' (CMB, LSS)
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.
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
Candidates
A matter of perspective: plausible mass ranges

thermal particles

$10^{10}$ $10^{20}$ eV

weak scale (1 TeV)
Candidates

A matter of perspective: plausible mass ranges

‘only’ 90 orders of magnitude!
Candidates
A matter of perspective: plausible mass ranges

‘only’ 90 orders of magnitude!
A matter of perspective: plausible mass ranges

‘only’ 90 orders of magnitude!
DM detection

**direct detection**  
Xenon, CDMS, Edelweiss... (CoGeNT, Dama/Libra...)

**production at colliders**  
LHC

**indirect**

- $\gamma$ from annihil in galactic center or halo and from synchrotron 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

$\bar{p}$, $\nu$
DM detection

- **direct detection**
- **production at colliders**

**indirect**

- $\gamma$ from annihilation in galactic center or halo and from synchrotron emission
  - Fermi, ICT, radio telescopes...
- $e^+$ from annihilation in galactic halo or center
  - PAMELA, Fermi, HESS, AMS, balloons...
- $\bar{p}$ from annihilation in galactic halo or center
- $\bar{d}$ from annihilation in galactic halo or center
- $\nu, \bar{\nu}$ from annihilation in massive bodies
  - GAPS
- $Km3Net$, Icecube, SK
DM detection

direct detection

production at colliders

indirect

\( \gamma \) from annihilations in galactic center or halo and from synchrotron emission

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

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

\( \bar{d} \) from annihilations in galactic halo or center

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

GAPS

Fermi, ICT, radio telescopes...

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

SK, Icecube, Km3Net
Charged CRs

1. the PAMELA/Fermi/HESS ‘excesses’
DM Candidates

A matter of perspective: plausible mass ranges

Credit: Jester, Résonances

'Bulbulon' 'Hooperon' 'Wenigon' 'Pamelon'

Ultra-light scalars, axion  \( T_{\text{now}} \)

\( v_s \)

thermal particles

Planck scale

weak scale

Planck scale

Primordial black hole

Solar mass

'only' 90 orders of magnitude!
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
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$\bar{p}$ 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

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

- spectrum
- diffusion
- energy loss
- convective wind
- source
- spallations

Salati, Chardonay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s
Indirect Detection: basics

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

What sets the overall expected flux?

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

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

What sets the overall expected flux?

\[
\text{flux} \propto n^2 \sigma_{\text{annihilation}}
\]
What sets the overall expected flux? 

\[ \text{flux} \propto n^2 \]

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

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

From N-body numerical simulations:

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

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>
Indirect Detection: hints

positron fraction

antiprotons

electrons + positrons
Are these signals of Dark Matter?
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**YES:** few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23} \text{ cm}^3/\text{sec}$
Are these signals of Dark Matter?

**YES:** few TeV, leptophilic DM

with huge $\langle \sigma v \rangle \approx 10^{-23}$ cm$^3$/sec

**NO:** a formidable ‘background’ for future searches
Positrons & Electrons
**PS: post AMS 2013**

**positron fraction**

**antiprotons**

**electrons + positrons**

**Are these signals of Dark Matter?**

**YES:** one TeV, **leptophilic** DM

with huge $\langle \sigma v \rangle \approx 10^{-23} \text{ cm}^3/\text{sec}$

‘tension’ between positron frac and $e^+ + e^-$

Indirect Detection: constraints

direct detection

production at colliders

indirect

$\gamma$ from annihil in galactic center or halo and from synchrotron 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

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

\[ \gamma \text{ from DM annihilations in galactic center} \]

\[ W^{-}, Z, b, \tau^{-}, t, h \ldots \sim e^{\pm}, p, D \ldots \text{ and } \gamma \]

\[ W^{+}, Z, b, \tau^{+}, \bar{t}, h \ldots \sim e^{\pm}, p, D \ldots \text{ and } \gamma \]
Indirect Detection: constraints

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

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

$\text{and } \gamma$

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

$\text{and } \gamma$
Indirect Detection: constraints

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

\[ W^-, Z, b, \tau^-, t, h \ldots \sim e^\pm, p, D \ldots \text{ and } \gamma \]

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Indirect Detection: constraints

(a) $\gamma$ 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 $\gamma$

typically sub-TeV energies
Indirect Detection: constraints

$\gamma$ from DM annihilations in Satellite Galaxies

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

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

- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$ in halo
- probes regions outside of Galactic Center
Indirect Detection: constraints

$\gamma$ from Inverse Compton on $e^\pm$ in halo

- upscatter of CMB, infrared and starlight photons on energetic $e^\pm$
- probes regions outside of Galactic Center
Indirect Detection: constraints

\( \gamma \) from Inverse Compton on \( e^\pm \) in halo

- upscatter of CMB, infrared and starlight photons on energetic \( e^\pm \)
- probes regions outside of Galactic Center
Gamma constraints

\( \gamma \) from Inverse Compton on \( e^{\pm} \) in halo

The PAMELA and FERMI regions are in conflict with these gamma constraints, and here...
Gamma constraints

\( \gamma \) from Inverse Compton on \( e^\pm \) in halo

DM DM \( \rightarrow \) ee, Einasto profile

DM DM \( \rightarrow \) \( \mu \mu \), Einasto profile

DM DM \( \rightarrow \) \( \tau \tau \), Einasto profile

DM DM \( \rightarrow \) ee, Iso profile

DM DM \( \rightarrow \) \( \mu \mu \), Iso profile

DM DM \( \rightarrow \) \( \tau \tau \), Iso profile
Gamma constraints
from Inverse Compton on $e^\pm$ in halo

Updated results from the FERMI coll. itself
Theorist’s reaction
Theorist’s reaction

1. the ‘PAMELA frenzy’
Challenges for the ‘conventional’ DM candidates

Needs:

- TeV or multi-TeV masses
- no hadronic channels
- very large flux

<table>
<thead>
<tr>
<th></th>
<th>SuSy DM</th>
<th>KK DM</th>
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<td>TeV or multi-TeV masses</td>
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<td>ok</td>
</tr>
<tr>
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<tr>
<td>very large flux</td>
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</table>

for any Majorana DM, s-wave annihilation cross section

\[
\sigma_{\text{ann}}(\text{DM D}\bar{\text{M}} \rightarrow f \bar{f}) \propto \left( \frac{m_f}{M_{\text{DM}}} \right)^2
\]
Gamma rays

2. the ‘130 GeV line’
DM Candidates

A matter of perspective: plausible mass ranges

‘only’ 90 orders of magnitude!
Prompt emission: line(s)

primary channels
Prompt emission: line(s)

\[ E_\gamma = m_{DM} \]

primary channels

\[ X^\pm \]

\[ DM \]

\[ DM \]

flux

\[ m_{DM} \]

\[ E_\gamma \]
Prompt emission: line(s)

\[ E_\gamma = m_{DM} \]

\[ E_\gamma = m_{DM} \left( 1 - \frac{m_Z^2}{4 m_{DM}^2} \right) \]

\( DM \)

\( X^\pm \)

\( \gamma \)

primary channels

\( Z, h \ldots \)

flux

\( E_\gamma \)

\( m_{DM} \)
Prompt emission: line(s)

So what are the particle physics parameters?

1. Dark Matter mass
2. Annihilation cross section $\sigma_{\text{ann}}$
Fermi 130 GeV line

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

Reg3
Einasto

Ch. Weniger, 1204.2797

4.6$\sigma$ (3.3$\sigma$ with LEE)

$\langle \sigma v \rangle_{\chi\chi \to \gamma\gamma} \simeq 1.3 \cdot 10^{-27}\text{cm}^3/\text{s}$ (large!)
What if a signal of DM is already hidden in Fermi diffuse $\gamma$ data?

Similar excesses found elsewhere (fluctuation?)

Fermi 130 GeV line

The excess is only in the GC (actually, a bit off-set)

And there might be 2 lines: 111 GeV, 129 GeV

Ch. Weniger, 1204.2797

4.6$\sigma$ (3.3$\sigma$ with LEE)

$\langle \sigma v \rangle_{\chi \chi \rightarrow \gamma \gamma} \simeq 1.3 \cdot 10^{-27}$ cm$^3$/s

(large!)
Fermi 130 GeV line

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

The Fermi coll’s cold shower. An instrumental effect?

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$\langle \sigma v \rangle_{\chi \chi \rightarrow \gamma \gamma} \approx 1.3 \cdot 10^{-27} \text{cm}^3/\text{s (large!)}$
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What if a signal of DM is \textit{already} hidden in Fermi diffuse $\gamma$ data?

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$\langle \sigma v \rangle_{XX\rightarrow\gamma\gamma} \approx 1.3 \cdot 10^{-27} \text{cm}^3/\text{s}$ (large!)
Theorist’s reaction

2. the ‘130 GeV line’ frenzy
Challenges

DM is neutral: need ‘something’ to couple to $\gamma$
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- a loop
- Chern-Simons
- axions
- magn dipole...
Challenges

DM is neutral: need ‘something’ to couple to $\gamma$

The ‘something’ implies usually a suppression.
Challenges

DM is neutral: need ‘something’ to couple to $\gamma$

The ‘something’ implies usually a suppression, but one needs a large $\gamma\gamma$ cross section ($\sim 10^{-27} \text{cm}^3/\text{s}$)
Challenges

DM is neutral: need ‘something’ to couple to $\gamma$

$$DM \rightarrow \gamma \gamma = 10^{-n} \times$$

The ‘something’ implies usually a suppression, but one needs a large $\gamma \gamma$ cross section ($o(10^{-27} \text{cm}^3/\text{s})$)

so the corresponding unsuppressed processes are too large:

- may overshoot other observations
- too large annihilation in the EU

[References: Buchmuller, Garny 1206.7056, Cohen et al. 1207.0800, Cholis, Tavakoli, Ullio 1207.1466, Huang et al. 1208.0267]
Challenges

DM is neutral: need ‘something’ to couple to \( \gamma \)

\[ DM \rightarrow \gamma \rightarrow DM = 10^{-n} \times \]

The ‘something’ implies usually a suppression, but one needs a large \( \gamma \gamma \) cross section (\( o(10^{-27} \text{ cm}^3/\text{s}) \))

so the corresponding unsuppressed processes are too large:

- may overshoot other observations
- too large annihilation in the EU
Challenges

DM is neutral: need ‘*something*’ to couple to $\gamma$

\[ DM \rightarrow \gamma \rightarrow DM \]

\[ = 10^{-n} \times \]

The ‘*something*’ implies usually a suppression, but one needs a large $\gamma\gamma$ cross section ($\sigma(10^{-27} \text{cm}^3/\text{s})$)

so the corresponding *unsuppressed* processes are too large:

- may overshoot other observations
- too large annihilation in the EU

But solutions exist
Model building

Ex. 1: ‘resonance, loop and forbidden channel’

(a) DM charged under \( U'(1) \)
(b) \( Z' \) is \( t_R \)-philic
(c) \( m_{DM} \lesssim m_{top} \)

\[ \begin{align*}
\text{line(s)} \\
\text{with large rate if on resonance (a)} \\
\text{(masses & couplings)} \\
\end{align*} \]

\[ \begin{align*}
\text{today:} \\
\text{kinematically forbidden (c)} \\
\text{little in other channels (b)} \\
\text{(only via } Z - Z' \text{ mixing)} \\
\end{align*} \]

\[ \begin{align*}
\text{Early Universe:} \\
\text{relief abundance} \\
\end{align*} \]

However:
- anomalies, need to UV complete (b)

Jackson, Servant, Shaughnessy, Tait, Taoso, ‘Higgs in space’, 0912.0004
Ex. 2: ‘resonance, tri-boson vertices, Chern-Simons’

(a) DM charged under $\mathcal{U}'(1)$
(b) anomaly cancellation $\rightarrow$ tri-boson CS terms

$$L_{CS} = \alpha \varepsilon^{\mu \nu \rho \sigma} Z'_\mu Z_\nu F'^Y_{\rho \sigma}$$

(c) $m_{Z'} < m_{DM}$

---

### Relic abundance

A different diagram wrt to line, open thanks to (c), works for large gauge coupling and small (loop?) CS coeff

---

Continuum? Under control
Ex. 3: ‘pseudo-scalar mediation, $p$- and $s$-waves’

(a) DM charged under $U(1)_{\text{PQ}}$

(b) anomalies $\rightarrow$ tri-boson terms

Continuum? Assume couplings to $W$ and $Z$ are suppressed

Exchange of s/h is $p$-wave, i.e. $\nu$ dependent.

Suppressed today, large in EU.

Relic abundance
Ex. 4: ‘magnetic moments and coannihilations’

(a) DM has a magnetic moment
\[ \mu \bar{\chi}_1 \sigma_{\mu \nu} \chi_2 F^{\mu \nu} \]

(b) DM sits in a multiplet with \( \sim 10 \) GeV splitting

- with large rate if \( \mu \) is large
- Continuum? Under control (it’s same order as \( \gamma \gamma \))

relief abundance

- is set by coannihilations, they would be too effective for large \( \mu \), but the splitting (b) suppresses.
- Continuum? Ultra suppressed by the splitting (b)
Ex. 5: ‘asymmetric DM’

(a) **DM-DM initial asymmetry**
(b) **DM-DM mixing** → late time oscillations, re-balance

relic abundance (a)

is produced via the asymmetry

is decoupled from the annihilation
Model building

Ex. 5: ‘asymmetric DM’

(a) DM-DM initial asymmetry
(b) DM-DM mixing $\rightarrow$ late time oscillations, re-balance

\begin{align*}
Y^+ & = \eta_0 = 1.02 \times 10^{-10} \\
Y^- & = \sigma_0 = 14 \text{ pb} \\
\Sigma & = m_{\text{DM}} = 9 \text{ GeV} \\
\Sigma \text{ no osc} & = \delta m = 10^{-12} \text{ eV}
\end{align*}

$\eta_0$

$\Omega_{\text{DM}}^0$

$y_{\eta_0=0}$

$x = m_{\text{DM}}/T$

relic abundance (a)
is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)
Model building

Ex. 5: ‘asymmetric DM’

(a) DM-DM initial asymmetry
(b) DM-DM mixing $\rightarrow$ late time oscillations, re-balance

$\Rightarrow$ relic abundance (a)
is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

Model building not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009
Ex. 5: ‘asymmetric DM’

(a) DM-DM initial asymmetry
(b) DM-DM mixing → late time oscillations, re-balance

Model building

Relic abundance (a)

is produced via the asymmetry

is decoupled from the annihilation

Annihilations resume (b)
Ex. 5: ‘asymmetric DM’

(a) DM-DM initial asymmetry
(b) DM-DM mixing $\rightarrow$ late time oscillations, re-balance

relic abundance (a)
is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)
(and the cross section needs to be large)
Ex. 5: ‘asymmetric DM’

(a) DM-DM initial asymmetry
(b) DM-DM mixing → late time oscillations, re-balance

→ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b) → line
(and the cross section needs to be large)
Ex. 5: ‘asymmetric DM’

(a) DM-DM initial asymmetry
(b) DM-DM mixing → late time oscillations, re-balance

⇒ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b) ⇒ line
(and the cross section needs to be large)

⇒ Continuum? Needs to be suppressed in some way today.

Model building not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009
Challenges

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so the corresponding unsuppressed processes are too large:

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But solutions exist
Model building
- may overshoot other observations
- too large annihilation in the EU

But solutions exist
Model building

- may overshoot other observations
- too large annihilation in the EU

But solutions exist

In summary:

- kinematically forbidden channel
- different diagrams
- s-wave vs p-wave
- coannihilations and splitting
- DM production is decoupled from annihilations
- ...

3. the ‘Hooperon’

Gamma rays
DM Candidates

A matter of perspective: plausible mass ranges

Credit: Jester, Résonances

‘only’ 90 orders of magnitude!
GeV gamma excess?

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

A diffuse GeV excess from around the GC

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

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

Objection: know your backgrounds!

A diffuse GeV excess from around the GC

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

Best fit: $8$ GeV, $\tau^+\tau^-$, $\sim$thermal $\sigma v$

A diffuse GeV excess from around the GC

Objection: know your backgrounds!

Still works...

No, too few (and we should have seen them elsewhere) and wrong spectra

Dan Hooper
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A diffuse GeV excess from around the GC

Objection: know your backgrounds!

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MSPs exist.

Still works...

Hooper, Goodenough 1010.2752

Boyarsky et al., 1012.5839

Abazajian 1011.4275

Hooper et al. 1305.0830

Hooper, Linden 1110.0006
GeV gamma excess?

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A diffuse GeV excess from around the GC

Best fit: 8 GeV, $\tau^+ \tau^-$, $\sim$thermal ov

Objection: know your backgrounds!

Still works...

No, too few (and we should have seen them elsewhere) and wrong spectra

No no, MSPs can do.

A diffuse GeV excess from around the GC

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Hooper, Goodenough 1010.2752

Boyarsky et al., 1012.5839

Still works...

No, too few (and we should have seen them elsewhere) and wrong spectra

Hooper et al. 1305.0830

No no, MSPs can do.

Yuan, Zhang 1404.2318

(LMXB (tracers of MSP?) seen in M31 with this distribution)
What if a signal of DM is already hidden in Fermi diffuse $\gamma$ data from the GC?
What if a signal of DM is already hidden in Fermi diffuse $\gamma$ data from the GC?
GeV gamma excess?

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

Here there’s no excess which cannot be explained in terms of ordinary ICS.
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Best fit: 
\sim 10 \text{ GeV}, \text{ leptons}, \sim \text{thermal } \nu \nu

Fermi gamma excess?

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

Essentially confirmed by: Huang, Urbano, Xue 1307.6862

Dan Hooper

Hooper, Slatyer 1302.6589
GeV gamma excess?

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

Here there’s no excess which cannot be explained in terms of ordinary ICS.

Best fit: 
$\sim 10$ GeV, leptons, $\sim$thermal $\sigma v$

Objection: nothing tells you that the input $e^\pm$ spectrum stays the same at high and low latitudes (the ISRF too, but one can better model that)

---

Fermi bubbles

Dan Hooper

Hooper, Slatyer 1302.6589
Essentially confirmed by: Huang, Urbano, Xue 1307.6862
Here there’s no excess which cannot be explained in terms of ordinary ICS.

Objection: nothing tells you that the input e± spectrum stays the same at high and low latitudes (the ISRF too, but one can better model that)

Response: even if you try, the input e± spectrum has to be weird (a δ fnct at 16 GeV?!?)

Best fit: 
~10 GeV, leptons, ~thermal ov

Fermi bubbles

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

Using events with accurate directional reconstruction

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

A compelling case for annihilating DM

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

Best fit: $\sim 10$ GeV, leptons, $\sim$thermal $\sigma v$

Including secondary emission changes the conclusions
But: propagation is approximate

**Fermi-LAT excess**
GeV gamma excess?

An excess with respect to what?

Extracting ‘data points’ is not trivial:

i. choose a ROI (shape, extension, masking...) and harvest Fermi-LAT data
ii. impose sensible cuts (Pass N, angles, CTBCORE...)
iii. in each energy bin, fit to a sum of spatial templates:
   1. Fermi Coll. diffuse
   2. isotropic
   3. unresolved point sources
   4. features (bubbles...)
   5. AOB (molecular gas...)
iv. repeat the same, adding a template for:
   6. Dark Matter, having chosen a certain profile!
v. if iii. → iv. improves $\chi^2$, there’s evidence for DM
vi. the component fitted by 6 is the residual excess to be explained

Note:
Adding 6 will in general change the recipe of 1...5 (you’ll need a bit more of x here, a bit less of y there...). Changing the profile of 6 too.
Astrophysical interpretation

Millisec pulsars

A transient phenomenon:

the GC spit $10^{52}$ ergs in $e^\pm$ 1 mln yrs ago and they do ICS on ambient light, ‘fits’ both spectrum and morphology

Non-trivial SgrA spectrum

a SN explosion spits protons 5000 yrs ago and they do spallations + bremsstrahlung as well as $e^\pm$ which do ICS... fits spectrum & morphology

but: can one really get everything right?

but: why correlation with gas density not seen?
Theorist’s reaction

3. the ‘Hooperon’
Theorist’s reaction

3. the ‘Hooperon’
X-rays

4. the ‘3.5 KeV line’
A matter of perspective: plausible mass ranges

DM Candidates

‘only’ 90 orders of magnitude!
Bulbul et al., 1402.2301
3.55 - 3.57 ± 0.03 KeV
73 clusters
z = 0.01 - 0.35

Boyarsky, Ruchayskiy, 1402.4119
3.5 KeV
Andromeda galaxy + Perseus cluster
z = 0 and 0.0179
Theorist’s reaction

4. the ‘3.5 KeV’ line
X-ray line

Sterile neutrino decay

\[ m_\nu = 7.1 \text{ KeV} \]
\[ \tau \approx 10^{29} \text{ sec} \]
\[ \sin^2 2\theta \sim \text{few } 10^{-11} \]
Sterile neutrino decay

\[ m_\nu = 7.1 \text{ KeV} \]
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Possible challenges:
- EU production?
- Perseus flux too large?
X-ray line

Sterile neutrino decay

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Possible challenges:
- EU production?
- Perseus flux too large?

Caveat:
- no line seen with Chandra in the Galactic Center

(But conclusion depends on how one models the local background)

Riemer-Sørensen, 1405.7943
**X-ray line**

Sterile neutrino decay

\[ m_\nu = 7.1 \text{ KeV} \]
\[ \tau \approx 10^{29} \text{ sec} \]
\[ \sin^2 2\theta \sim \text{few } 10^{-11} \]

**Possible challenges:**
- EU production?
- Perseus flux too large?

**Other possibilities:**
- axion (1402.7335), axino (1403.1536, 1403.1782, 1403.6621), modulus (1403.1733), ALP (1403.2370),
- gravitino (1403.6503), excited DM (1404.4795), the good the bad and the unlikely (1403.1570),
- sgoldstino (1404.1339), magnetic DM (1404.5446), majoron (1404.1400), annihilating effective DM (1404.1927), 7KeV scalar DM (1404.2220)...
Conclusions & Outlook

- Hints
- Constraints
- Hopes
Conclusions & Outlook

**Hints**
- $e^\pm$
- PAMELA
- FERMI
- HESS
- $\gamma$
- FERMI
- $X$
- XMM-Newton

**Constraints**

**Hopes**
Conclusions & Outlook

**Hints**
- $e^{\pm}$: PAMELA, FERMI, HESS
- $\gamma$: FERMI
- $X$: XMM-Newton

**Constraints**
- $\gamma$: FERMI, HESS, VERITAS etc
- $\vec{p}$: PAMELA
- $\nu$: SK, ICECUBE

**Hopes**
- Cosmology
Conclusions & Outlook

**Hints**
- $e^\pm$: PAMELA, FERMI, HESS
- $\gamma$: FERMI
- $X$: XMM-Newton

**Constraints**
- $\gamma$: FERMI, HESS, VERITAS etc
- $\bar{p}$: PAMELA
- $\nu$: SK, ICECUBE

**Hopes**
- $\bar{d}$: GAPS, AMS-02
- $\gamma$:ν
- $\bar{p}$: AMS-02
  - ‘enhancements’
  - new theory directions
Conclusions & Outlook

Hints

$e^{\pm}$ PAMELA
FERMI
HESS

$\gamma$ FERMI

$X$ XMM-Newton

Constraints

$\gamma$ FERMI, HESS, VERITAS etc

$\bar{p}$ PAMELA

$\nu$ SK, ICECUBE

Cosmology

Hopes

$\bar{d}$ GAPS, AMS-02

$\gamma$ $\nu$

AMS-02

- ‘enhancements’

- new theory directions

Old wise remarks:
Conclusions & Outlook

Hints
- $e^\pm$
  - PAMELA
  - FERMI
  - HESS
- $\gamma$
  - FERMI
- $X$
  - XMM-Newton

Constraints
- $\gamma$
  - FERMI, HESS, VERITAS etc
- $\bar{p}$
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Hopes
- $\bar{d}$
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directions

Old wise remarks:
- any convincing result must be multimessenger
Conclusions & Outlook

**Hints**
\[ e^{\pm} \]
- PAMELA
- FERMI
- HESS
\[ \gamma \]
- FERMI
\[ X \]
- XMM-Newton

**Constraints**
\[ \gamma \]
- FERMI, HESS, VERITAS etc
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**Hopes**
\[ \bar{d} \]
- GAPS, AMS-02
\[ \gamma \]
\[ \nu \]
\[ \bar{p} \]
- AMS-02
  - ‘enhancements’
  - new theory directions

**Old wise remarks:**
- any convincing result must be **multimessenger**
- beware of **uncertainties**, beware of **astrophysics**