Highlights on Indirect Dark Matter Detection

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MPIK

“An experiment is a question which science poses to Nature, and a measurement is the recording of Nature’s answer”. Max Planck (1858-1947)
1. Introduction to the WIMP Paradigm

2. Brief review on Indirect Dark Matter Detection

3. GeV gamma-ray excess in the Galactic Center

4. 3.5 KeV line emission – Galaxy Cluster and Galactic Center

5. Search for line emissions from dark matter annihilations
Please Remember

1) The Dark Matter Interpretation of the Galactic Center Excess is still viable and will remain viable for several years

2) We can search for neutrinos from dark matter annihilation using gamma-ray telescopes with the potential to distinguish neutrino flavors
Evidences for Dark Matter

Galaxy Rotation Curves

Structure Formation

Gravitational Lenses

Cluster Collisions

Cosmic Microwave Background Radiation

Without Dark Matter

With Dark Matter

access Planck website, it's really cool
Effectively Neutral
Abundance of 27%
Cosmologically Stable
Not strongly Interacting?
Cold/warm

WIMPs

What do we know about DM?
### Basic Concepts

**A.** Dark matter particles could interact with standard model particles and reach thermal equilibrium. Non-thermal processes are also OK.

**B.** After the universe cooled down and expanded, eventually the expansion rate equaled the interaction rate → freeze-out.

**C.** After the freeze-out the dark matter particles clustered forming the structures we observe today.

**D.** In the WIMP paradigm the abundance is connected to the annihilation cross section at freeze-out.

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### Dark Matter Abundance (WIMP)

Right relic abundance → Annihilation cross section at the weak scale

![Diagram showing the relationship between temperature, number density, and time](image)

- $m_X = 100$ GeV
- Increasing Cross section

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**Number density $\rho$**

- $10^{-4}$
- $10^{-6}$
- $10^{-8}$
- $10^{-10}$
- $10^{-12}$
- $10^{-14}$
- $10^{-16}$

**Temperature $T$ (GeV)**

- $10^0$
- $10^1$
- $10^2$
- $10^3$

**Time $t$ (ns)**

- $10^0$
- $10^1$
- $10^2$
- $10^3$

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**Farinaldo Queiroz - MPIK**
Mediators

- Higgs portal (Westhoff+ 1506.04149, Duerr+ 1508.04418)
- Dark Photon (Pospelov+ 1603.01256)
- Z' portal (Berlin+ 1402.6287, Ohmer+ 1506.00954, Fairbairn+ 1605.07940)
- Co-annihilation (Baker+, 1510.03434)
- Freeze-in (Klasen+ 1309.277)

WIMP

Standard Model

Lindner group
I will not care about what happens in the black box
Gamma-ray searches for dark matter annihilation are based on measuring the differential gamma-ray flux.

\[ \text{# of Photons} \sim \text{Anni. cross section} \times \text{Number density squared} \times \text{Volume of the sky} \]
The number of photons detected is proportional to the annihilation cross section, the number density squared, and the volume of the sky, expressed as:

\[
\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\text{rel}} \rangle}{8\pi m^2_\chi} \frac{dN_\gamma}{dE} \times \int_{1\text{o.s.}} ds \rho(r[s, \Omega])^2
\]
# of Photons \sim \text{ Anni. cross section} \times \text{ Number density squared} \times \text{ Volume of the sky}

\[
\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\text{rel}} \rangle}{8\pi m^2_\chi} \frac{dN_\gamma}{dE} \times \int_{\text{l.o.s.}} d\mathbf{s} \rho(\mathbf{r}[s, \Omega])^2
\]
Basic Concepts

A. The dark matter particles might still be able to interact with standard model particles and produce an observable signal.

B. We know how to account for hadronization and final state radiation well up to the dark matter mass, which can be very heavy.

\[
\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\text{rel}} \rangle}{8\pi m_{\chi}^2} \frac{dN_{\gamma}}{dE} \times \int_{\text{l.o.s.}} \rho(\vec{r}[s, \Omega])^2 \]
Dark Matter Annihilation: Gamma-ray Excess at the Galactic Center

First observation (2009)

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough¹ and Dan Hooper².³

¹Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003
²Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510
³Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of \( \sim 9 \times 10^{-26} \text{ cm}^3/\text{s} \), and that are distributed with a cusped halo profile, \( \rho(r) \propto r^{-1.1} \), within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astro-

First Fermi-LAT team members – report (2009)

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration

Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy

Crucially, it is reported. The unobserved gamma-ray background and detected sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models.

An improved model of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.
Fermi–LAT OBSERVATIONS OF HIGH-ENERGY $\gamma$-RAY EMISSION TOWARD THE GALACTIC CENTRE

M. Ajello$^1$, A. Albert$^2$, W. B. Atwood$^3$, G. Barbiellini$^{4,5}$, D. Bastieri$^{6,7}$, K. Bechtol$^8$, R. Bellazzini$^9$, E. Bissaldi$^{10}$, R. D. Blandford$^2$, E. D. Bloom$^2$, R. Bonino$^{11,12}$, E. Bottacini$^2$, T. J. Brandt$^{13}$, J. Bregong$^{14}$, P. Bruel$^{15}$, R. Buehler$^{16}$, S. Buson$^{6,7}$, G. A. Caliandro$^{17}$, R. A. Cameron$^2$, R. Caputo$^3$, M. Caragiulo$^{10}$, P. A. Caraveo$^{18}$, C. Cecchi$^{19,20}$, A. Chekhtman$^{21}$, J. Chiang$^2$, G. Chiaro$^7$, S. Ciprini$^{22,19,23}$, J. Cohen-Tanugi$^{14}$, L. R. Cominsky$^{24}$, J. Conrad$^{25,26,27}$, S. Cutini$^{22,23,19}$, F. D’Ammando$^{28,29}$, A. De Angelis$^{30}$, F. De Palma$^{10,31}$, R. Desiante$^{32,11}$, L. Di Venere$^{33}$, P. S. Drell$^2$, C. Favuzzi$^{33,10}$, E. C. Ferrara$^{13}$, P. Fusco$^{33,10}$, F. Gargano$^{10}$, D. Gasparrini$^{22,23,19}$, N. Giglietto$^{33,10}$, P. Giommi$^{22}$, F. Giordano$^{33,10}$, M. Giroletti$^{28}$, T. Glanzman$^2$, G. Godfrey$^2$, G. A. Gomez-Vargas$^{34,35}$, I. A. Grenier$^{36}$, S. Guiriec$^{13,37}$, M. Gustafsson$^{38}$, A. K. Harding$^{13}$, J. W. Hewitt$^{39}$, A. B. Hill$^{40,2}$, D. Horan$^{15}$, T. Jogler$^2$, G. Jóhannesson$^{41}$, A. S. Johnson$^2$, T. Kamae$^{42}$, C. Karwin$^{43}$, J. Knödlseder$^{44,45}$, M. Kuss$^9$, S. Larsson$^{46,26}$, L. Latronico$^{11}$, J. Li$^{17}$, L. Li$^{46,26}$, F. Longo$^{4,5}$, F. Loparco$^{33,10}$, M. N. Lovellette$^{48}$, P. Lubrano$^{19,20}$, J. Magill$^{49}$, S. Maldera$^{11}$, D. Malyshev$^2$, A. Manfreda$^9$, M. Mayer$^{16}$, M. N. Mazziotta$^{10}$, P. F. Michelson$^2$, W. Mitthumsiri$^{50}$, T. Mizuno$^{51}$, A. A. Moiseev$^{52,49}$, M. E. Monzani$^2$, A. Morselli$^{34}$, I. V. Moskalenko$^2$, S. Murgia$^{43,4}$, E. Nuss$^{14}$, M. Ohno$^{54}$, T. Ohsugi$^{51}$, N. Omodei$^2$, E. Orlando$^2$, J. F. Ormes$^{55}$, D. Paneque$^{56,2}$, M. Pesce-Rollins$^{9,2}$, F. Piron$^{14}$, G. Pivato$^9$, T. A. Porter$^{2,2}$, S. Rainò$^{33,10}$, R. Rando$^{6,7}$, M. Razzano$^{9,58}$, A. Reimer$^{59,2}$, O. Reimer$^{59,2}$, S. Ritz$^3$, M. Sánchez-Conde$^{26,25}$, P. M. Saz Parkinson$^{3,60}$, C. Sgrò$^9$, E. J. Siskind$^{61}$, D. A. Smith$^{62}$, F. Spada$^9$, G. Spano$^{9}$, P. Spinelli$^{33,10}$, D. J. Susan$^{63}$, H. Tajima$^{64,2}$, H. Takahashi$^{54}$, J. B. Thayer$^2$, D. F. Torres$^{47,65}$, G. Tosti$^{19,20}$, E. Troja$^{13,49}$, Y. Uchiyama$^{66}$, G. Vianello$^2$, B. L. Winer$^{67}$, K. S. Wood$^{48}$, G. Zaharijas$^{68,69}$, S. Zimmer$^{25,26}$

Draft version November 11, 2015

ABSTRACT

Fermi-LAT collab. has confirmed the excess

$\sim 1$ kpc derived for the IEMs used in this paper, and comparable to the integrated brightness of the point sources in the region for energies $\gtrsim 3$ GeV. If spatial templates that peak toward the GC are used to model the positive residual and included in the total model for the $15^\circ \times 15^\circ$ region, the agreement with the data improves, but they do not account for all the residual structure. The spectrum of the positive residual modelled with these templates has a strong dependence on the choice of IEM.
Gamma-ray Excess in the Galactic Center

Many dark matter models fit the Galactic excess easily, but only some are consistent with direct detection and collider bounds.

1. Young Pulsars
   - K. N. Abazajian+, 1402.4090.
   - R. Bartels+, 1506.05104;
   - S. Lee+, 1506.05124;

2. Collisions between gas with protons accelerated by a black holes.
   - T. Linden+, 1203.3539;
   - O. Macias+, 1410.1678

3. Collisions between gas with cosmic-rays (e.g. non-thermal bremsstrahlung from a population of electrons scattering off neutral molecular clouds)
   - F. Yusef-Zadeh+, 1206.6882

4. Series of Burst-like events during an active past of our galaxy
   - E. Carlson+, 1405.7685
   - J. Petrovic+, 1405.7928

5. Different distributions of distribution cosmic-ray sources
   - E. Carlson+, 1510.04698
   - D. Gaggero+, 1507.06129
From the right panel, one could conclude that the dark matter interpretation of the galactic center excess will be decisively confirmed or ruled in the near future.

Isn't that a bit optimistic?
Conservative

Status of the Gamma-ray Excess in the Galactic Center

Work in progress..
Farinaldo Queiroz, Carlos Yaguna, Christoph Weniger

Preliminary

Graph showing the status of the gamma-ray excess in the Galactic Center, with data from various sources including dphs Pass 8, Low J, High J, Fermi-LAT Pass 8, Gordon+, Dylan+, and Calore+.
Dark Matter Decay: KeV Excess at the Galactic Center and Galaxy Clusters

Detection of an unidentified emission line in the stacked x-ray spectrum of 73 galaxy clusters using XMM-Newton instrument

“we argue that there should be no atomic transitions in thermal plasma at this energy”

A. Boyarsky+, 1402.4119 and 1408.2503
E. Bulbul+, 1402.2301

KeV Sterile Neutrino as dark matter

\[ \Gamma_\gamma(m_s, \theta) = 1.38 \times 10^{-29} \text{ s}^{-1} \left( \frac{\sin^2 2\theta}{10^{-7}} \right) \left( \frac{m_s}{1 \text{ keV}} \right)^5 \]

Dodelson&Widrow hep-ph9303287
**Dark Matter Decay:** KeV Excess at the Galactic Center and Galaxy Clusters

**Follow-up observations**

- Observations of Draco is in tension with other observations at 95-99% C.L.
  - Ruchayskiy, Boyarsky+, 1512.07217
- Stacked Analysis of Dwarf Galaxies is in strong tension with the 3.5KeV line emission
  - Queiroz+, work in progress...

1. They focused on the 3-4KeV energy range, differently from previous papers

2. They a public version of the tool used to compute the line emissions, differently from previous papers

3. They found no evidence for a 3.5KeV line emission.

4. Updated limits on decaying DM are closing in
   - Mambrini, Profumo, Queiroz, 1508.06635

One needs to either stack dwarf galaxies or to gather much more data to clarify the origin of the KeV line emission
Thinking about neutrino lines...

Which detector would you use to search for this dark matter particle?

Icecube/Antares/Super-K?
Gamma-ray Limits on Neutrino Lines

Queiroz, Yaguna, Weniger – JCAP 1605 (2016) no.05, 050- arxiv:1602.05966

Several searches for neutrinos flavors from dark matter annihilations have been conducted by Super-K, IceCube and ANTARES collaborations.

Electroweak corrections are important and a neutrino final state also gives rise to a gamma-ray emission which can be probed by Fermi-LAT/H.E.S.S. instruments.

Notice that all three annihilation modes produce sizable continuous gamma-ray emission.
The best limits from Icecube are \(~3\) orders of magnitude weaker than best limits from Fermi-LAT....

First works: Kachelriess, Serpico, 0707.0209
Bell, Dent, Jacques, Weiler, 0805.3423

**Gamma-ray Limits on Neutrino Lines**

Queiroz, Yaguna, Weniger – JCAP 1605 (2016) no.05, 050- arxiv:1602.05966
Search for line emissions from DM

**Gamma-ray Limits on Neutrino Lines**

Queiroz, Yaguna, Weniger – JCAP 1605 (2016) no.05, 050- arxiv:1602.05966

Super-K/Antares/Icecube for $\nu\nu$

Fermi-LAT for $\nu\nu$

Dark Matter Mass

$M_{DM} = 3$ TeV

Cirelli+, 1012.4515
Concerning the spectrum

\[ x = \frac{E}{m} \quad I = \log \left[ \frac{s}{m} \right] \]

<table>
<thead>
<tr>
<th>Splitting 1 → ( x + x' )</th>
<th>Splitting function: real and virtual</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{0,M} \rightarrow F_{0,M} + V_M )</td>
<td>( P_{F\rightarrow F} = \frac{1 + x^2}{1 - x} L(1 - x) )</td>
</tr>
<tr>
<td>( F_{0,M} \rightarrow V_M + F_{0,M} )</td>
<td>( P^{\text{vir}}_{F\rightarrow F} = 3\ell - \frac{\ell^2}{2} )</td>
</tr>
<tr>
<td>( V \rightarrow F + \bar{F} )</td>
<td>( P_{V\rightarrow F} = [x^2 + (1 - x)^2]\ell )</td>
</tr>
<tr>
<td>( S_M \rightarrow S_M + V_M )</td>
<td>( P^{\text{vir}}_{V\rightarrow F} = -\frac{2\ell}{3} )</td>
</tr>
<tr>
<td>( S_M \rightarrow V_M + S_M )</td>
<td>( P_{S\rightarrow S} = \frac{2x}{1 - x} L(1 - x) )</td>
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</tr>
<tr>
<td>( V \rightarrow S + S' )</td>
<td>( P_{V\rightarrow S} = x(1 - x)\ell )</td>
</tr>
<tr>
<td>( V_M \rightarrow V_M + V_M )</td>
<td>( P^{\text{vir}}_{V\rightarrow S} = -\frac{\ell}{6} )</td>
</tr>
<tr>
<td>( V_M \rightarrow V_M + V_0 )</td>
<td>( P_{V\rightarrow V} = 2\left[ \frac{x}{1 - x} L(1 - x) + \frac{1 - x}{x} L(x) + x(1 - x)\ell \right] )</td>
</tr>
<tr>
<td>( V_M \rightarrow V_0 + V_M )</td>
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As for dark matter decays, gamma-ray telescopes are not very sensitive.
Several searches for neutrinos flavors from dark matter annihilations have been conducted by Super-K, IceCube and ANTARES collaborations.

Electroweak corrections are important and a neutrino final state also gives rise to a gamma-ray emission which can be probed by Fermi-LAT/H.E.S.S. instruments.

As for dark matter decays, gamma-ray telescopes are not very sensitive.
Another promising dark matter signal would be the detection of gamma-ray lines.

Fermi-LAT and H.E.S.S. Telescopes have placed stringent limits on the annihilation cross section into photon pairs.

**Fermi-LAT - 2015**

- ~ 6 years of data – PASS 8
- Energy: 200 MeV - 500 GeV
- CLEAN event selection
- Target: Milky Way Halo

**H.E.S.S. - 2013**

- 112 h (live time)
- Energy: 500 GeV – 25 TeV
- Target: Milky Way Halo

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Phys.Rev. D91 (2015) no.12, 122002

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Can we extend their limits to heavier DM masses? YES.
How? Using the continuum gamma-ray emission data.

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**Break at 500 GeV**

**Break at 25 TeV**

Phys.Rev. D91 (2015) no.12, 122002

Can we extend their limits to heavier DM masses? YES.
How? Using the continuum gamma-ray emission data.

Four steps

I) Assume a 2 TeV DM particle annihilating into gamma-gamma or gamma-Z or gamma-h.

II) The process above is subject to electroweak corrections

III) The gamma-rays resulted from such processes appear at lower energies within Fermi-LAT sensitivity

IV) The same idea can be applied for a 50 TeV particle, in reference to H.E.S.S. telescope.

Using the gamma-ray continuum emission one can extend Fermi-LAT and H.E.S.S. limits to heavier dark matter masses.
Extending Fermi-LAT and H.E.S.S. Limits on Gamma-ray Lines from Dark Matter Annihilation

Profumo, Queiroz, Yaguna, Submitted to MNRAS – arxiv:1602.08501

First limits above 25 TeV
1) The Dark Matter Interpretation of the Galactic Center Excess is still viable and will remain viable for several years.

2) We can search for neutrinos from dark matter annihilation using gamma-ray telescopes with the potential to distinguish neutrino flavors.