Indirect searches of TeV Dark Matter at the Galactic Center

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Trieste (Italy)

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Outline

- Dark Matter (DM) gravitational evidences and indirect searches.
- Gamma rays from the Galactic Center (GC): the TeVDM hypothesis.
- Astrophysical factor: density enhancement, spatial tail and background model.
- Conclusions.
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• Dark Matter (DM) gravitational evidences and indirect searches.
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DM gravitational evidences

The observations of the almost **flat rotation curve** in several spiral galaxy was one of the first motivation to hypothesize the existence of DM later confirmed by gravitational lensing and cosmological observation.
**Indirect Searches**

DM is usually assumed to be a Weakly Interactive Massive Particle (WIMP):

\[
\frac{d\Phi_{\text{cr-DM}}}{dE} = \eta_{\text{cr}} \cdot \sum_{a=1}^{2} \sum_{i} \zeta_{i}^{(a)} \frac{dN_{i}^{(\text{cr})}}{dE} \cdot \kappa_{\text{cr}}^{(a)} \cdot 4\pi m_{\text{DM}}^{a}
\]
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Gamma rays from the Galactic Center

H.E.S.S. - The High Energy Stereoscopic System

$\Theta < 0.1^\circ$  270 GeV-70 TeV

Previous works discarded the possibility to fit the HESS data with a supersymmetric or Kaluza-Klein DM particle of mass < 10 TeV

Our work: \( \frac{d\Phi_{\gamma-Tot}}{dE} = \frac{d\Phi_{\gamma-Bg}}{dE} + \frac{d\Phi_{\gamma-DM}}{dE} \)

Background component: \( \frac{d\Phi_{\gamma-Bg}}{dE} = B(\gamma)^2 \cdot \left( \frac{E}{\text{GeV}} \right)^{-\Gamma} \)

4 free parameters: \( B, \Gamma, A, m_{DM} \)
Gamma rays from the Galactic Center

\[ m_{\text{DM}} = 12.4 \text{ TeV} \quad \tau^+ \tau^- \quad \chi^2 / \text{dof} = 1.59 \]

\[ m_{\text{DM}} = 27.9 \text{ TeV} \quad \bar{u} \bar{u} \quad \chi^2 / \text{dof} = 0.78 \]

\[ m_{\text{DM}} = 48.8 \text{ TeV} \quad W^+ W^- \quad \chi^2 / \text{dof} = 0.84 \]

\[ m_{\text{DM}} = 82.0 \text{ TeV} \quad b \bar{b} \quad \chi^2 / \text{dof} = 1.32 \]

Gamma rays from the Galactic Center

\[ \frac{d\Phi_{\gamma-Tot}}{dE} = \frac{d\Phi_{\gamma-Bg}}{dE} + \frac{d\Phi_{\gamma-DM}}{dE} \quad \frac{d\Phi_{\gamma-Bg}}{dE} = B(\gamma)^2 \cdot \left( \frac{E}{\text{GeV}} \right)^{-\Gamma} \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>( m_{\text{DM}} ) (TeV)</th>
<th>( A(\gamma) \times 10^{-7}\text{cm}^{-1}\text{s}^{-1/2} )</th>
<th>( B(\gamma) \times 10^{-4}\text{GeV}^{-1/2}\text{cm}^{-1}\text{s}^{-1/2} )</th>
<th>( \Gamma )</th>
<th>( \chi^2 / \text{dof} )</th>
<th>( \Delta \chi^2 )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^+e^- )</td>
<td>7.51 ± 0.11</td>
<td>8.12 ± 0.73</td>
<td>2.78 ± 0.79</td>
<td>2.55 ± 0.06</td>
<td>2.09</td>
<td>32.6</td>
<td>111 ± 20</td>
</tr>
<tr>
<td>( \mu^+\mu^- )</td>
<td>7.89 ± 0.21</td>
<td>21.2 ± 1.92</td>
<td>2.81 ± 0.53</td>
<td>2.55 ± 0.06</td>
<td>2.04</td>
<td>31.4</td>
<td>837 ± 158</td>
</tr>
<tr>
<td>( \tau^+\tau^- )</td>
<td>12.4 ± 1.3</td>
<td>7.78 ± 0.69</td>
<td>3.17 ± 0.62</td>
<td>2.59 ± 0.06</td>
<td>1.59</td>
<td>20.6</td>
<td>278 ± 76</td>
</tr>
<tr>
<td>( uu )</td>
<td>27.9 ± 1.8</td>
<td>6.51 ± 0.46</td>
<td>9.52 ± 9.47</td>
<td>3.08 ± 0.35</td>
<td>0.78</td>
<td>1.2</td>
<td>987 ± 189</td>
</tr>
<tr>
<td>( dd )</td>
<td>42.0 ± 4.4</td>
<td>4.88 ± 0.48</td>
<td>8.26 ± 7.86</td>
<td>3.03 ± 0.34</td>
<td>0.73</td>
<td>0.0</td>
<td>1257 ± 361</td>
</tr>
<tr>
<td>( ss )</td>
<td>53.9 ± 6.2</td>
<td>4.85 ± 0.57</td>
<td>6.59 ± 5.43</td>
<td>2.92 ± 0.29</td>
<td>0.90</td>
<td>4.1</td>
<td>2045 ± 672</td>
</tr>
<tr>
<td>( cc )</td>
<td>31.4 ± 6.0</td>
<td>6.90 ± 1.06</td>
<td>53.0 ± 157</td>
<td>3.70 ± 1.07</td>
<td>1.78</td>
<td>25.0</td>
<td>1404 ± 689</td>
</tr>
<tr>
<td>( bb )</td>
<td>82.0 ± 12.8</td>
<td>3.69 ± 0.61</td>
<td>6.27 ± 6.07</td>
<td>2.88 ± 0.35</td>
<td>1.32</td>
<td>14.2</td>
<td>2739 ± 1246</td>
</tr>
<tr>
<td>( tt )</td>
<td>87.7 ± 8.2</td>
<td>3.68 ± 0.34</td>
<td>6.07 ± 3.34</td>
<td>2.86 ± 0.19</td>
<td>0.88</td>
<td>3.6</td>
<td>3116 ± 820</td>
</tr>
<tr>
<td>( W^+W^- )</td>
<td>48.8 ± 4.3</td>
<td>4.98 ± 0.40</td>
<td>5.18 ± 2.23</td>
<td>2.80 ± 0.15</td>
<td>0.84</td>
<td>2.6</td>
<td>1767 ± 419</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>54.5 ± 4.9</td>
<td>4.73 ± 0.40</td>
<td>5.38 ± 2.45</td>
<td>2.81 ± 0.16</td>
<td>0.85</td>
<td>2.9</td>
<td>1988 ± 491</td>
</tr>
</tbody>
</table>

\[
A_i(\gamma)^2 = \frac{\langle \sigma_i v \rangle \Delta \Omega \langle J(2) \rangle \Delta \Omega}{8\pi m_{\text{DM}}^2} \quad \langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3\text{s}^{-1} \quad \Delta \Omega \simeq 10^{-5}
\]

\[
b \equiv \frac{\langle J(2) \rangle}{\langle J_{\text{NFW}}(2) \rangle} \quad \langle J_{\text{NFW}}(2) \rangle \simeq 280 \times 10^{23} \text{GeV}^2\text{cm}^{-5}
\]

Gamma rays from the Galactic Center

By Fermi-LAT:

100 MeV-300 GeV

$\Theta = 0.5^\circ$

$E > E_{br} \simeq 2 \text{ GeV}$

$\chi^2/\text{d.o.f.} = 0.81$

$\Gamma = 2.68 \pm 0.05$

Gamma rays from the Galactic Center

\[ m_{DM} > 10 \text{ TeV} \]

Boost factor \( b = \langle J \rangle / \langle J \rangle_{NFW} \approx 10^3 \)

Bg compatible with Fermi-LAT

<table>
<thead>
<tr>
<th>(FERMI-LAT Data)</th>
<th>( W^+W^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{DM} )</td>
<td>51.7 \pm 5.2</td>
</tr>
<tr>
<td>( A(\gamma) )</td>
<td>4.44 \pm 0.34</td>
</tr>
<tr>
<td>( B(\gamma) )</td>
<td>3.29 \pm 1.03</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>2.63 \pm 0.02</td>
</tr>
<tr>
<td>( \chi^2 / \text{dof} )</td>
<td>0.75</td>
</tr>
</tbody>
</table>

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Keeping the hypothesis of thermal TeVDM candidate, the boost may be explained by a local enhancement in the DM distribution at the GC with respect to the NFW density distribution.

\[
\frac{d\Phi_{\text{cr-DM}}}{dE} = \eta_{\text{cr}} \cdot \sum_{a=1}^{2} \sum_{i} \frac{\zeta^{(a)}_i}{a} \frac{dN^{(\text{cr})}_i}{dE} \cdot \frac{\kappa^{(a)}_{\text{cr}}}{4\pi m_{\text{DM}}^a}
\]

Astrophysical factor for gamma rays:

\[
\kappa_{\gamma,\nu} \equiv \langle J^{(a)} \rangle_{\Delta \Omega} = \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega \int_{l_{\text{min}}(\hat{\theta})}^{l_{\text{max}}(\hat{\theta})} \rho^a[r(l, \hat{\theta})] dl(\hat{\theta})
\]

DM density distribution:

\[
\rho_h(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma} \left(1 + \left(\frac{r}{r_s}\right)^{\alpha}\right)^{\frac{\beta-\gamma}{\alpha}}}
\]
DM density enhancement

**DM density distribution:**

\[ \rho_h (r) = \frac{\rho_s}{\left( \frac{r}{r_s} \right)^\gamma \left( 1 + \left( \frac{r}{r_s} \right)^\alpha \right)^{\frac{\beta - \gamma}{\alpha}}} \]

**Only-DM N-body simulations (NFW):**

\( (\alpha, \beta, \gamma) = (1, 3, 1) \)

**EVANS:**

\[ \langle J_{(2)}^{\text{NFW}} \rangle \approx 280 \cdot 10^{23} \text{ GeV}^2 \text{cm}^{-5} \]

**N-body + Hydrodynamics:**

<table>
<thead>
<tr>
<th>Profile</th>
<th>( \rho_s ) ( \text{(M}_\odot/\text{Kpc}^{-3}) )</th>
<th>( r_s ) (Kpc)</th>
<th>( r_{\text{vir}} ) (kpc)</th>
<th>( \gamma )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \rho_{\odot} ) ( \text{(GeVcm}^{-3}) )</th>
<th>( R_{\text{sp}} ) (pc)</th>
<th>( \theta_{\text{sp}}^\circ ) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVANS</td>
<td>5.38 \times 10^6</td>
<td>21.5</td>
<td>215</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0.27</td>
<td>24</td>
<td>0.16</td>
</tr>
<tr>
<td>GARR-I</td>
<td>4.97 \times 10^8</td>
<td>2.3</td>
<td>230</td>
<td>0.59</td>
<td>1</td>
<td>2.70</td>
<td>0.33</td>
<td>16</td>
<td>0.11</td>
</tr>
<tr>
<td>GARR-I300</td>
<td>1.01 \times 10^8</td>
<td>4.6</td>
<td>230</td>
<td>1.05</td>
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<td>ERIS</td>
<td>2.25 \times 10^7</td>
<td>10.9</td>
<td>239</td>
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DM density enhancement

DM density enhancement

DM-spike induced by the Black Hole:

\[ \rho_s(r) = \frac{\rho_{\text{ann}}\rho(r)_{\text{BH}}}{\rho_{\text{ann}} + \rho(r)_{\text{BH}}} \]

\[ \rho_{\text{BH}} = \rho_R g_{\gamma}(r) \left( \frac{R_{sp}}{r} \right)^{\gamma_{sp}} \]

\[ \rho_{\text{ann}} = \frac{m_{\text{DM}}}{\langle \sigma v \rangle t_{\text{BH}}} \]

\[ \rho_R = \rho_s (R_{sp}/r_s)^{-\gamma} \]

\[ \gamma_{sp} = \frac{9 - 2\gamma}{4 - \gamma} \]

\[ R_{sp} = \alpha_s (r_s (M_{\text{BH}}/\rho_s r_s^3))^{1/(3-\gamma)} \]


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DM density enhancement

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Spatial tail

\begin{align*}
\langle J^{(a)} \rangle_{\Delta \Omega} &= \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d \Omega \int_{l_{\text{min}}(\hat{\theta})}^{l_{\text{max}}(\hat{\theta})} \rho^a [r(l, \hat{\theta})] dl(\hat{\theta}) \\
&= 0 \\
&= D_\odot \cos \hat{\theta} + \sqrt{r^2 - D_\odot^2 \sin \hat{\theta}}.
\end{align*}
Spacial tail

Spatial tail

HESS II collaboration confirms an excess source at the position of the Black Hole Sgr A* at a significance of 40σ in the 0.015 deg² (0.12º) and a spatial tail to 0.3 deg² (0.54º)

R.D. Parsons et al. for the HESS II Collaboration, [arXiv:1509.03425v1], ICRC 2015 Proceedings
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Background model

The HESS II data were taken in wobble mode (the pointing direction is chosen at alternating offsets from the target position) in a range from 0-1.5°, with the majority of offsets lying in the 0.4-0.9° range and the reflected region background model.
Background model

We analyze the possibility that some relation exits between the spatial tail and the gamma-ray emission of the inner 10 pc and:

1. the cusp in the DM halo profile
2. the BH-induced DM-spike

Phenomenological $N_{ON}/N_{OFF}$ and background model:

Assumption: the gamma ray astrophysical background in the outer 10 pc region is comparable to (or bigger than) the secondary gamma rays produced by DM annihilation events without any boost.

The analysis is independent from the nature of the DM particle:

$$\frac{1}{N_{OFF}} \frac{dN(\theta)_{ON}}{d\theta} \propto \frac{d\Phi_{DM-spike}(\theta)}{d\Phi_{DM-halo}(\theta)} = \frac{\int_{0}^{l_{max}(\hat{\theta})} \rho^2[l(r(l)] dl(\theta)}{\int_{0}^{l_{max}(\hat{\theta})} \rho_h^2[l(r(l)] dl(\theta)}$$
Spatial tail vs Bg model

Spatial tail vs Bg model

(a, 1) $N_{ON} = DM$ increases as the Bg -> no signal
(a, 2) $N_{ON} = BH$-induced DM-spike ->
the tail may be explained as the DM-spike
associated to EAGLE, GARRI and GARRI300
Milky Way-like DM profiles
(a, 3) $N_{ON} = BH$-induced DM-spike + stars ->
slight difference with panel (a, 2)

$$\frac{1}{N_{OFF}} \frac{dN(\theta)}{d\theta}$$

$N_{OFF}$ increases as the extrapolated DM-halo
(with different power laws through the GC)
Spatial tail vs Bg model

\[ \frac{1}{N_{\text{OFF}}} \int_{0}^{\theta} dN(\theta) \] is the integrated constant value of DM-halo at 0.54°

(b, 1) \(N_{\text{ON}}\) = extrapolated DM-halo -> mildly cusped profiles as \text{GARRI} may produce the tail (without BH-induced DM-spike)

(b, 2) \(N_{\text{ON}}\) = BH-induced DM-spike -> mildly cusped profiles \text{(GARRII300)} may produce the spatial tail

(b, 3) \(N_{\text{ON}}\) = BH-induced DM-spike + stars -> slight difference with panel (b, 2)
Spatial tail vs Bg model

\[
\frac{1}{N_{OFF}} \frac{dN(\theta)}{d\theta}_{ON} = N_{ON, integrated constant value of DM-halo at 0.13^{\circ}}
\]

(c, 1) \( N_{ON} = \) extrapolated DM-halo -> EVANS, ERIS, GARRII300 could roughly explain the tail extent

(c, 2) \( N_{ON} = \) BH-induced DM-spike -> the tail may be explained by mildly cored profiles such as GARRII300

(c, 3) \( N_{ON} = \) BH-induced DM-spike + stars -> slight difference with panel (c, 2)
• The spectral feature of the gamma-ray HESS data of the J1745-290 point-like source in the GC are well fitted as TeVDM in combination with a power-law background component. The latter is compatible with the Fermi-LAT gamma-ray observation of the same region.
• The $10^3$ enhancement required in the DM flux may be partially explained as the DM-spike induced by the black hole Sgr A*, depending on the underlying DM-halo model.
• The spatial tail in the gamma-ray signal recently observed by HESS II may be explained as the extend of the BH-induced DM-spike. However, the analysis shows very strong dependence on the background normalization model.
• The current generation of neutrino and antiproton data are compatible with such DM hypothesis mainly due to low value for the detector angular resolution and effective area. The next generation of neutrino telescope could verify such a TeVDM hypothesis.
• The TeV DM remains unconstrained by direct searches and collider experiments.
Thank you for your attention!