Search for Gamma-ray Emission from p-wave Dark matter Annihilation in the Galactic Center

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• Standard WIMP picture
  – Relic density set by thermal decoupling
    • predictive: dwarfs, GC... etc
    • complementarity! (Direct detection/Collider)
  – Assumption: s-channel annihilation i.e.: velocity independent $\langle \sigma v \rangle$
    • Solve Boltzmann equation...
    • $\langle \sigma v \rangle \rightarrow a + bv^2 +...$

• Step Beyond Standard WIMP picture
  – DM doesn’t have to thermally decouple
    • Thermally produced (freeze-out via BSM mediator)
    • Non-thermally produced (asymmetric DM)
  – s-channel annihilation suppressed or non existent
    • BSM Mediators! New search strategy, lower bound on couplings
• DM freeze-out independent of Standard Model until mediator decays
  – however... DM Couplings to SM can be very small
    (Nightmare DM Scenario)
  – Leading order term (s-wave component) gone!
    • Fermionic DM → dark scaler bosons (DSB)
  – Orders of magnitude less sensitive
    • Complementarity can be doomed
    • Need high densities of DM

• Indirect detection implications
  – Low couplings need high density and high velocity
    • Overcome low DM annihilation couplings: SMBH (AGN or GC)

• SMBH offer a unique possibility to test these signals
Models where velocity dependent term is dominant:

Hidden Sector Higgs Portal \((s)\)

Hidden Sector Axion Portal \((a)\)

To SM via \(\epsilon\) coupling

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arXiv:1506.04143
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Hidden Sector Axion Portal:
Majorana DM annihilates to $\phi$, which then decays into SM particles

Coupling needed to get correct relic abundance
Search Strategy

Box-like spectrum: consequence of the mediator $a \rightarrow \gamma \gamma$ boosted in the Galactic reference frame.

Box width depends on mediator mass.

\[
\frac{m_\chi}{2} \left( 1 \pm \sqrt{1 - \frac{m_{s/a}^2}{m_\chi^2}} \right)
\]
Box-like spectrum: consequence of the mediator ($a \rightarrow \gamma \gamma$) boosted in the Galactic reference frame.

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Spikes well motivated (Silk & Gondolo 1999)

Total reconstructed spectrum
Reconstructed box signal
Data
Box folded w/IRFs
Closest SMBH: Center of Milky Way

• DM density profile Steep PL

• Input Parameters
  – $M_{\text{BH}} = 4 \times 10^6 \, M_{\odot}$
    • note: fairly known from stellar orbits
  – $v_0 = 105 \pm 20 \, \text{km/s}$
    • note: not quite as well known from stellar population
  – $R_{\text{sun}} = 8.46^{+0.42}_{-0.38} \, \text{kpc}$
  – $\rho_{\text{sun}} = 0.3 \pm 0.1 \, \text{GeV/cm}^3$
  – $t_{\text{ann}} = 10^{10} \, \text{y}$
  – typical $r_{\text{in}}: 10^{-3}-10^{-5} \, \text{pc}$

• Free parameters:
  – Inner/Spike NFW index: $\gamma_{c}/\gamma_{sp}$

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• 4 regions of the spike
  • Inner Halo (gNFW)
    – $\rho(r) = \rho(r_0)(r_0/r)^{\gamma_c}$
  • DM spike region ($r_b \approx 0.2 \, r_h$)
    – $\rho(r) = \rho(r_b)(r_b/r)^{\gamma_{\text{sp}}}$
  • Annihilation plateau
    – $\rho_{\text{ann}}(r) = m_\chi/\langle \sigma v \rangle t \quad @ \ r \equiv r_{\text{in}},$
      $t \sim \text{age of SMBH}$
  • Inner Spike
    – $\rho_{\text{in}}(r) = \rho_{\text{ann}}(r_{\text{in}}/r)^{1/2}$
    – search still sensitive if no adiabatic spike
Closest SMBH: Center of Milky Way

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yields: $r_h = 1.7 \, \text{pc} \ (0.012^\circ)$

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Milky Way’s Spike

\[ \rho(r) = \rho(\text{GeV/cm}^3) \]

- **inner spike:** \( \rho \propto r^{-1/2} \)

- **spike:** \( \rho \propto r^{-\gamma_{sp}} \)

\[ \gamma_{sp} = 2 + \frac{1}{4 - \gamma_c} \]

- **annihilation density:** \( \rho(\text{ann}) = \frac{m}{\langle \sigma v \rangle \tau} \)

- **black hole zone of influence**

- **inner halo:** \( \rho \propto r^{-\gamma_c} \)

\[ r_b = 0.2 \, r_h \quad r_h = \frac{M_{BH}}{M_{Pl}^2 \, v_0^2} \]
Milky Way’s Spike

inner spike:
\[ \rho \propto r^{-1/2} \]

annihilation density:
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black hole zone of influence

\[ r_b = 0.2 \, r_h \]
\[ r_h = \frac{M_{BH}}{M_{Pl}^2 v_0^2} \]

~0.01°

inner halo:
\[ \rho \propto r^{-\gamma_c} \]
## The Analysis

### Selection Criteria

| Selection                  | Criteria                          |
|----------------------------|-----------------------------------|
| Mission Elapsed Time       | 9 years                           |
| Instrument Response Functions | P8R2_SOURCE_V6                    |
| Energy Range (GeV)         | 6-800 GeV                         |
| Fit Region                 | 2°x2°, centered on (RA, DEC)=(266.4°, -29.0°) |
| Zenith Range               | θ_z < 100°                        |
| Data Quality Cuts          | Yes                               |
The Galactic Center

Data (> 6 GeV)

Preliminary

3FHL Source | Location (RA, DEC)
--- | ---
Galactic Diffuse | N/A
J1745.6-2900 | (266.42, -29.01)
J1746.2-2852 | (266.56, -28.88)
J1747.2-2959 | (266.80, -30.00)
J1747.2-2822 | (266.82, -28.37)
J1748.1-2903 | (267.04, -29.06)
J1748.6-2816 | (267.16, -28.28)

Pixel size: 0.04° Gaussian smoothing
The Galactic Center

Residuals (＞6 GeV)

Galactic Longitude

Galactic Latitude

Preliminary

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Pixel size: 0.04° Gaussian smoothing
Fitting the models

Hidden Sector Axion Portal:
Majorana DM annihilates to $\phi$, which then decays into SM particles

\[(m_\phi/m_\chi)^2 = 0.999\]  
\[(m_\phi/m_\chi)^2 = 0.44\]
Correlation with The Galactic Center Source

Upper edge of DM Signal Box: the GC source

Sources are spatially coincident

Negligible at high energies

Preliminary

Correlation Coefficient

Box Upper Edge [MeV]

$\zeta = 0.44$
$\zeta = 0.9999$
Results

Narrow Box

\[(m_\phi/m_\chi)^2 = 0.999\]

Wide Box

\[(m_\phi/m_\chi)^2 = 0.44\]
Interpretation

Fixed $m_\chi = 20$ GeV, 110 GeV, $\zeta = 0.99$

Fixed $m_\chi = 20$ GeV, 110 GeV, $\zeta = 0.44$

Preliminary
**Interpretation**

For different values of $\zeta$:
- $\zeta = 0.9999$
  - $\gamma_c = 1.0$, Adiabatic
  - $\gamma_c = 1.0$, $\gamma_{sp} = 1.8$
  - $\gamma_c = 1.1$, $\gamma_{sp} = 1.8$

For $\zeta = 0.44$:
- $\gamma_c = 1.0$, Adiabatic
- $\gamma_c = 1.0$, $\gamma_{sp} = 1.8$
- $\gamma_c = 1.1$, $\gamma_{sp} = 1.8$

**Preliminary**
Summary and Conclusions

- Considered a dark matter paradigm where the standard assumption about the annihilation cross section is suppressed.

- Found no evidence of a dark matter signal and placed an upper limit on the total $\gamma$-ray flux from p-wave annihilation.

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\[ \chi \quad s/a \quad \chi \quad s/a \]

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Bonus Slides!
Injecting a Dark Matter Signal

Upper edge 100 GeV flux: $1.5 \times 10^{-11}$ ph/cm$^2$/s

Preliminary

Counts

Upper Edge Energy [MeV]
Injecting a Dark Matter Signal

Upper edge 100 GeV flux: \(1.5 \times 10^{-11}\) ph/cm\(^2\)/s

Preliminary

Counts

Upper Edge Energy [MeV]

Flux Upper Limit

Injected Signal

95% Containment

68% Containment

Flux Upper Limit [ph s\(^{-1}\) cm\(^{-2}\)]
Preliminary