Indirect Dark Matter Searches with Gamma RAYs

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Dark Matter Searches

**INDIRECT SEARCHES**
- Find its annihilation byproducts

**DIRECT SEARCHES**
- Detect energy it deposits

**COLLIDER SEARCHES**
- Produce it in the lab

- Fermi-LAT
- IceCube
- AMS-02
- CDMS
- XENON100

Standard Model
Dark Matter

Fermi-LAT
IceCube
AMS-02
Large Hadron Collider
CDMS
XENON100
Dark Matter Searches

INDIRECT SEARCHES

Fermi-LAT

AMS-02

IceCube

DIRECT SEARCHES

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COLLIDER SEARCHES

Large Hadron Collider

COLLIDER SEARCHES

Standard Model

Dark Matter

Direct Searches

Detect energy it deposits

Produce it in the lab
**Indirect Searches**

**Gamma Rays**

\[
\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{<\sigma_{\text{ann}}v_\text{rel}>}{2m^2_{\text{WIMP}}} \sum_f \frac{dN_f}{dE_\gamma} B_f
\]

\[
\times \int_{\Delta\Omega(\phi,\theta)} \int_{\text{los}} \rho^2(r(l, \phi')) dl(r, \phi')
\]

**DM distribution**

**J - factor**

Fermi-LAT

VERITAS

H.E.S.S.

MAGIC

HAWC

particle physics
**INDIRECT SEARCHES**

**Gamma Rays**

Slatyer, arXiv:1710.05137

X-RAY AND GAMMA-RAY TELESCOPES

ACTs: HESS, VERITAS, MAGIC etc

<table>
<thead>
<tr>
<th>1 MeV</th>
<th>1 GeV</th>
<th>1 TeV</th>
<th>10 TeV</th>
</tr>
</thead>
</table>

**Fermi-LAT**

**H.E.S.S.**

**MAGIC**

**VERITAS**

**HAWC**
Gamma rays from Dark Matter Annihilation:
The Milky Way & its satellites

Pieri et al, arXiv:0908.0195
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Dark matter substructures

Galactic center

Predicted signal from galactic center much larger than dark matter substructures (~10-1000x or more, depending on DM profile, region around GC)
The Fermi Sky

Fermi LAT data
The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field.
Galactic Gamma-Ray Interstellar Emission

The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field.

 Galactic center region: a dark matter signal is predicted to be largest here, where modeling of the interstellar emission (and sources) is problematic! CR intensities, density of radiation fields and gas are highest and most uncertain, long integration path over the entire Galactic disc, large density of sources.
Galactic Center Excess

An excess in the Fermi LAT GC data consistent with dark matter annihilation was first claimed by Goodenough and Hooper in 2009 (arXiv: 0910.2998.) Several analyses since then confirm the excess.

Different approaches in modeling the interstellar emission model:

**the characterization of the signal depends on this!**

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**SPECTRUM**

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Daylan et al, arXiv:1402.6703

**Calore et al, arXiv:1409.0042**

**Fermi LAT Collaboration, arXiv:1511.02938**
**Galactic Center Excess**

Excess extends out to $10^\circ$ from GC, approximately spherically symmetric NFW profile with slope $\gamma=1\text{--}1.3$ (but see also Linden et al arXiv:1604.01026, Horiuchi et al arXiv:1604.01402, Macias et al arXiv:1611.06644, Bartels et al arXiv:1711.04778)


**MORPHOLOGY**

Daylan et al, arXiv:1402.6703

Karwin et al, arXiv:1612.05687

The data favor a DM particle with mass in the range ~50 (200) GeV, annihilating mainly into bottom (top) quarks with an annihilation cross section consistent with predictions for a thermal relic, ~ $10^{-26}$ cm$^3$/s (see e.g. EFT interpretation by Karwin et al arXiv:1612.05687).

Pulsars

An unresolved population of millisecond pulsars can explain the excess
- Claimed excess is found consistent with $O(1000)$ millisecond pulsars within ~1 kpc of GC (Abazajian et al arXiv:1402.4090, but see also Hooper et al arXiv:1606.09250.) Very young pulsars might also contribute to the excess (O’Leary et al arXiv:1504.02477)

Analyses based on non-poissonian photon statistics templates and wavelet decomposition (Lee et al arXiv:1412.6099, 1506.05124; Bartels et al arXiv:1506.05104) find that the excess is consistent with a collection of discrete gamma-ray emitters

Abazajian et al, arXiv:1402.4090

Lines: GC excess spectrum
Data: spectra from collections of millisecond pulsars

Lee et al, arXiv:1412.6099
Caveats

- It is likely that some of the point sources are mis-identified structured gas emission.

Lee et al, arXiv:1412.6099
Caveats

These sources must be detected to confirm that the GC excess is generated by a collection of millisecond pulsars.

More $\gamma$-ray data will help, but even more crucial is the potential of radio surveys (MeerKAT, SKA) to uncover a large number of millisecond pulsars in the Galactic bulge that contribute to the GC excess (Calore et al arXiv:1512.06825).

(A recent claim by the Fermi LAT collaboration on the detection of the point sources generating the Galactic center excess has been retracted, see Fermi LAT Collaboration arXiv:1705.00009 and Bartels et al arXiv:1710.10266).
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More on GC excess tomorrow (talks by D. Hooper and W. de Boer).
There are limitations in all interstellar emission models employed so far (e.g., cylindrical symmetry, the gas distribution, as well as interplay between the interstellar emission and point sources). Work is underway to improve these models.
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**CR energy density at plane**

Porter et al, arXiv:1708.00816
The GC excess is a small fraction of the total observed emission (e.g. ~5-10% in a 15°x15° region)

Improvements in modeling the interstellar emission are crucial to determine/confirm the properties of the excess!

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Dwarf Spheroidal Galaxies

Optically observed dwarf spheroidal galaxies: largest clumps predicted by N-body simulations

Excellent targets for gamma-ray DM searches

- Very large M/L ratio: 10 to \(\sim 1000\) (M/L \(\sim 10\) for Milky Way)
- DM density inferred from the stellar data!
- Expected to be free from other gamma ray sources and have low dust/gas content, very few stars
Dwarf Spheroidal Galaxies

No significant emission in stacked analysis of dwarf spheroidal galaxies with Fermi LAT 6 yrs of data (Fermi LAT Collaboration arXiv 1503.02641, Albert et al arXiv:1611.03184)

Limits probe DM explanation of the GC excess
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Limits probe DM explanation of the GC excess

N.B.:
Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv:1411.2592, Karwin et al arXiv:1612.05687)


GC excess contours do not fully reflect uncertainties in the DM distribution (also see Abazajian et al, arXiv:1510.06424, Benito et al arXiv:1612.02010)
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Gamma rays from Dark Matter Annihilation: Beyond the Milky Way

Lisanti et al, arXiv1708.09385
**Andromeda (M31)**

- DM halo extends several degrees across the sky, with a gradient strongly dependent on DM distribution, substructures and profile.
- Disentangling a DM contribution from M31 is complicated by conventional astrophysics, including the foreground from the Milky Way.

![Observed Counts (saturated)](image)
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DM and/or millisecond pulsars are possible interpretations of the spherical $\gamma$-ray halo, also compatible with GC excess.

Search for $\gamma$-ray emission beyond the boundaries of the M31 galactic disk is complicated by Milky Way foreground (see poster by C. Karwin).
Beyond the Local Group

- A stacked analysis of ~500 galaxy groups ($z < 0.03$, $M \approx 10^{12} M_\odot$) from recent catalogs shows no evidence for a DM signal and set constraints comparable to the dwarf spheroidals.
- J-factors inferred by luminosity-based mass estimates and mass-to-concentration relations

Lisanti et al, arXiv1708.09385

Galaxy Group J-factors

Stacked Galaxy Groups

$Fermi$-LAT Pass 8 Data, bb

$\langle \sigma v \rangle$ vs. $m_\chi$ [GeV]

Thermal relic cross section

68/95% containment

$Fermi$ dwarfs (2016)

Galaxy groups (this work)

Galaxy groups, no boost
Summary

Indirect dark matter searches with Fermi LAT continue to set strong constraints on the nature of DM.

Although other plausible interpretations exist (notably millisecond pulsars), a DM interpretation of the excess from the Galactic center cannot be ruled out. Complementarity with other searches is crucial, e.g., a consistent signal from other DM targets/searches (e.g., dSph, direct and collider DM searches) would provide the most compelling confirmation of a DM origin.
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**Thank you!**