Dark Matter Searches with the Fermi Large Area Telescope

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On behalf of the Fermi-LAT Collaboration

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Beyond standard model physics needed!

WIMPs a ‘popular’ DM scenario that give gamma-ray signals:

**Weakly Interacting Massive Particle (WIMP)**

DM particles with **EW couplings**. Typical mass ~ 1 GeV to 10 TeV and the DM relic density thermally produced when annihilation x-section:

\[ \langle \sigma v \rangle_{\text{thermal}} \sim 3 \times 10^{-26} \text{cm}^3/\text{s} \]
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  \[
  \langle \sigma v \rangle_{\text{thermal}} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}
  \]

Monochromatic gamma-rays

\[
\langle \sigma v \rangle_{\gamma\gamma} \simeq \alpha^2 \langle \sigma v \rangle \simeq 10^{-30} \text{ cm}^3/\text{s}
\]
Gamma-rays from WIMPs

Flux from annihilating DM particles

What we observe

\[ \Phi_\chi (E, \psi) = \frac{\langle \sigma_\chi v \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2} \]
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Photon Flux (events/area/time/energy)

Energy spectrum

Region of Interest (ROI)
(dwarf galaxy, the whole sky, etc)
Gamma-rays from WIMPs

Flux from annihilating DM particles

\[ \Phi_X(E, \psi) = \frac{\langle \sigma_X v \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{\text{LOS}} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_X^2} \]

DM Annihilation Cross Section
averaged cross-section \( \times \) velocity,
@ freeze-out \( \approx 3 \times 10^{-26} \text{ cm}^3/\text{s} \)

What we observe

Intrinsic Particle Properties

Predicted Energy Spectra
\( dN_f/dE \) from various annihilation channels \( f \)

Continuum
Monochromatic lines

Gustafsson et al. PRL 99.041301
Gamma-rays from WIMPs

Flux from annihilating DM particles

\[ \Phi_\chi(E, \psi) = \frac{\langle \sigma \chi v \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LO(S)} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2} \]

What we observe

Intrinsic Particle Properties

Astrophysics (J-factor)

WIMP number density squared

Dark matter annihilations

Galactic Centre

Line of sight

Direction of Galactic Anti-centre

The Sun

Direction of South Galactic Pole
Gamma-rays from WIMPs

Flux from annihilating DM particles

\[ \Phi_{\chi}(E, \psi) = \frac{\langle \sigma_{\chi} \nu \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_{\chi}^2} \]

What we observe

Intrinsic Particle Properties

Astrophysics (J-factor)

Extended DM halo

WIMP number density squared

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Dark matter distributions (from sim. and obs.)

- Moore
- NFW
- Einasto, \( \alpha = 0.17 \)
- IR-GC
- radio-GC
- \( \gamma \)-Galactic Center
- \( \gamma \)-Galactic Ridge
- Earth

\( \rho \) in pc GeV/cm\(^3\)

\( r \) in pc

Bertone et al. 2009
Gamma-rays from WIMPs

Flux from annihilating DM particles

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Galactic center

Signal morphology (in Galactic coordinates)

Sub structures (e.g. dwarf galaxies)
Fermi Large Area Telescope (LAT)
On board the Fermi Gamma-ray Space Telescope
– Launched June 2008, mission to at least 2016
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- **Pair conversion detector**
  - Silicon strip tracker
    (with tungsten converter foils)
  - Electromagnetic CsI calorimeter
  - Anti-coincidence shield
    (plastic scintillators to veto charge particles, eff. >99.97%)
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- **Key features for DM searches**
  - Effective area ~0.8 m²
  - Energy range: 20 MeV to >300 GeV
    resolution: $\sigma_E < 10\%$ (for $E > 10$ GeV)
  - Angular resolution: <0.2° (for $E > 10$ GeV)
  - Full-sky coverage (~2.4sr)
    • All sky in 2 orbits (3 hrs)

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

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**QED Process**
- Pair conversion detector
  - Measured Track co-ordinates
  - Plastic scintillation counters to veto entering charged particles
  - Calorimeter to measure gamma-ray energy
  - Tungsten Conversion Foils
  - Position - measuring detectors
  - Z=74 Tungsten
The Gamma-ray Universe as seen by Fermi-LAT

Aitoff projection of the Sky in Galactic Coordinates

Galactic plane

Galactic centre

(Energy > 1 GeV, 4 Years)

Aitoff projection of the Sky in Galactic Coordinates
Are there any hiding DM signals?

Aitoff projection of the Sky in Galactic Coordinates

Galactic plane

Galactic centre

(Energy > 1 GeV, 4 Years)

Aitoff projection of the Sky in Galactic Coordinates
Are there any hiding DM signals?

Dark matter N-body simulation: $\log(J{-}\text{factor})$

Colors span 4 orders of magnitude for the l.o.s. intensity

$$J{-}\text{factor} \propto \int_{\text{LOS}} dl(\psi) \frac{\rho(l)^2}{m_X^2}$$
Are there any hiding DM signals?

Dark matter N-body simulation: \( \log(\text{J-factor}) \)
Colors span 4 orders of magnitude for the l.o.s. intensity

\[
J - \text{factor} \propto \int_{\text{LOS}} \frac{d\ell(\psi)}{d\ell} \frac{\rho(l)^2}{m_{\chi}^2}
\]
Are there any hiding DM signals?

Dark matter N-body simulation: \( \log(\text{J-factor}) \)
Colors span 4 orders of magnitude for the l.o.s. intensity

\[
J \propto \int_{LOS} d\ell(\psi) \frac{\rho(l)^2}{m^2_\chi}
\]
Are there any hiding DM signals?

Dark matter N-body simulation: log(J-factor)
Colors span 4 orders of magnitude for the l.o.s. intensity

\[ J - \text{factor} \propto \int_{LOS} dl(\psi) \frac{\rho(l)^2}{m^2_\chi} \]
Search for a DM signal from dwarf galaxies
Numerical simulations predict that the DM halos hosting galaxies should be surrounded by many smaller DM halo structures.

N-body simulation of galactic size Dark Matter halo.

Via Lactea II (Diemand et al. 2008)
Search for a DM signal from dwarf galaxies

✓ Optically observed Dwarf Spheroidal (dSphs) galaxies the most attractive DM subhalo candidates

✓ Relatively nearby, known positions
✓ Low gamma-ray backgrounds
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✓ DM density measured (from stellar velocity dispersion)
Search for a DM signal from dwarf galaxies

✓ Optically observed **Dwarf Spheroidal (dSphs) galaxies** the most attractive DM subhalo candidates

✓ Relatively nearby, known positions
✓ Low gamma-ray backgrounds
✓ DM density measured (from stellar velocity dispersion)
✓ Mass–to-Light ratio indicate DM dominated \((M/L > 100 \ M_{\text{sun}}/L_{\text{sun}})\)

[Graph showing M/L ratio (Gilmore+ '06)]

[Histogram showing uncertainty on J-factor]

\(1 \times M_{\text{sun}}/L_{\text{sun}}\)
Dwarf Spheroidal Galaxies (dSphs)
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No gamma-ray signals from any individual dSph.
Dwarf Spheroidal Galaxies (dSphs)

To set upper bounds on DM annihilations.

No gamma-ray signals from any individual dSph.

Select the 10 “best” high latitude dShps and do a joined Likelihood analysis ⇒ To set upper bounds on DM annihilations
Upper bounds on DM annihilations $\langle \sigma v \rangle$

Limits on DM+DM

- $\rightarrow$ b-quarks
- $\rightarrow$ taus
- $\rightarrow$ muons
- $\rightarrow$ W bosons

Exclude WIMPs of mass $\lesssim 10$ GeV, with annihilations into $b\bar{b}, \tau^+\tau^-$. 

Similar results already by Fermi 2yrs, Ackermann et al. PRL 107, 241302 (2011)
Upper bounds on DM annihilations $\langle \sigma v \rangle$
[2]

Milky Way Dark Matter Halo
Milky Way Dark Matter Halo

Search for emission from annihilating or decaying DM in an extended region of the Milky Way DM halo

- Analyze two 10x80 degree bands 5 degrees off the plane
  - to decrease astrophysical background
  - to mitigate uncertainties from inner DM density profile

- Two approaches to set limits:
  I. more conservative — Assume emission only from DM
  II. more accurate — Fit the DM and astrophysical emission simultaneously

Method I

Compare expected counts from DM \( (n_{DM}) \) to observed counts \( (n_{obs}) \) to set 3σ upper limit by

\[
n_{DM} - 3\sqrt{n_{DM}} \leq n_{data}
\]

Method II

Find the maximal possible contribution from DM, while astrophysical background models are allowed to vary within certain ranges.

Allows to disentangle DM signal by utilizing both spatial and spectral shape (good astrophysical model important)
Constraints from Milky Way Halo

- Including modeling of the astrophysical emission improves the DM constraints by a factor of \(~5\)

DM annihilation x-section
to b-quarks limits

DM lifetime limits for
decay into tau-leptons

- with inclusion of astrophysical backgrounds, a canonical thermal cross section into b-quarks limits the WIMP mass to \(\geq 20\) GeV (comparable to the dSphs limits)

Method I, II

Pamela (~AMS02) preferred region
Gamma-ray Line Searches
[3]

Gamma-ray Line Searches
Evidence for 130 GeV gamma-ray line?
Gamma-ray line — a ‘smoking gun’ for DM

Continuum emission/secondary photons
Difficult to distinguish from astrophysical backgrounds

\[ \chi \chi \rightarrow \bar{q}q \rightarrow \pi^0 \ldots \]
\[ \pi^0 \rightarrow \gamma \gamma \]

Direct annihilation into photons. Forbidden at tree-level.
Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV and near the Galactic centre:

- Signal is particularly strong in 2 out of their 5 test sky regions, shown above.
- 4–5 $\sigma$ (local), with S/N $\approx$30–60% in optimized regions of interest (ROI).
Su & Finkbeiner showed that the spectral feature was close to, but slightly (~1.5 deg) offset from, the Galactic centre [arXiv:1206.1616].

- Their likelihood analysis included a spatial morphology of signal, and data-driven model of Galactic astrophysical backgrounds.
- Claimed $6\sigma$ statistical significance, after a trials factor of $\sim6000$, but acknowledge uncertainties of modeling the Galactic astrophysical backgrounds.
Fermi-LAT line search
Latest Fermi publication put upper limits on gamma-lines (before claims of a 130 GeV $\gamma$-line)
Methodology improvements:

1. Region Of Interest (ROI)
   - Optimize: signal/sqrt(Bkg)
     for a given DM profile against template model of the diffuse gamma-ray bkg.

2. Spectral analysis (5-300 GeV)
   - Unbinned maximum likelihood
   - Model bkg as single powerlaw
   - bkg $n_{bkg}$ and signal $n_{sig}$ free
   - Use sliding $\pm 6\sigma_E$ windows
   - Fit for energies in 0.5 $\sigma_E$ steps

Search in 5 ROIs:
- 3° circle (R3)
- Einasto Optimized (R16)
- NFW Optimized (R41)
- Isothermal Optimized (R90)
- 2 year Analysis ROI (R180)
Further improvements

- **Data reprocessed** (Pass7 clean rep.)
  - ✓ Updated calorimeter response
  - ➡ Affects energy reconstruction: up to 5% shift in energy scale
  - ➡ Improves PSF at high energies (80%+ overlap in events after reprocessing)

- **Improved line shape**
  - ✓ Line shape determined event by event w/ “2D pdf” – function of both $E$ and $P_\text{E}$ ($P_\text{E}$ is an assigned probability that measured energy is close to true energy).
  - ➡ Incl. $P_\text{E}$ gives ~15% improvement to signal sensitivity (when there is signal) and upper limits (when there is no signal)
Results
Spectral line 95% CL Flux upper limit

- Spectral line 95% CL Flux upper limit
- S/N < 4%
- Einasto optimized ROI
- Expectations bands include statistical uncertainties only

Flux 95% CL Limit (cm^{-2}s^{-1})

- Preliminary
- 4 year R16
- Expected Limit
- Observed Limit
- Expected 68% Containment
- Expected 95% Containment

130 GeV
95% CL $\langle \sigma v \rangle_{\gamma\gamma}$ upper limits (Einasto)

$\rho(r) = \rho_s \exp\left\{-\frac{2}{\alpha}[(r/r_s)^\alpha - 1]\right\}$

with $r_s = 20$ kpc and $\alpha = 0.17$

$\rho(r_\odot) = 0.4$ GeV cm$^{-3}$
Fermi-LAT feature near 130 GeV

- Preliminary

• $4.01\sigma$ (local) 1D fit at 130 GeV with 4 year unreprocessed data
• Look in $4^\circ\times4^\circ$ GC ROI, Use 1D PDF (no use of $P_E$)

Note: Fit in $4^\circ\times4^\circ$ GC ROI
Not one of our a priori ROIs
Fermi-LAT feature near 130 GeV

- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4° GC ROI, Use 1D PDF (no use of $P_E$)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI, Use 1D PDF (no use of $P_E$)

Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

Peak shifts from 130 to ~135 GeV
Fermi-LAT feature near 130 GeV

- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4° GC ROI, Use 1D PDF (no use of $P_E$)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI, Use 1D PDF (no use of $P_E$)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI, Use 2D PDF ($P_E$ in data)
  - <2σ global significance after trials factor

Peak shifts from 130 to ~135 GeV

Peak 'too' narrow

Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs
Control Regions (No DM signal regions)

The **Earth Limb**: bright, and expected to be a smooth power-law

The **Galactic Disk**: bright, and astrophysical source dominated
Control Regions (No DM signal regions)

The **Earth Limb**: bright, and expected to be a smooth power-law

**Line-like feature** in limb near 130 GeV

2.2σ, S/N ≈ 15% (GC: 3.4σ, S/N≈70%)

The **Galactic Disk**: bright, and astrophysical source dominated
Control Regions (No DM signal regions)

The Earth Limb: bright, and expected to be a smooth power-law

Line-like feature in limb near 130 GeV

$2.2\sigma$, $S/N \approx 15\%$ (GC: $3.4\sigma$, $S/N \approx 70\%$)

The Galactic Disk: bright, and astrophysical source dominated

No feature near 130 GeV
Summary
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The Fermi LAT team looks for indirect DM signals in a wide variety of methods
✓ So far no unambiguous DM like signal detected.
✓ Strong constraints have been set.
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✓ So far no unambiguous DM like signal detected.
✓ Strong constraints have been set.

Still too soon for definite statements about claimed evidence of a line:

Pros & Cons for \( \sim 130 \text{ GeV line} \)

**Pros**
- Tantalizing signal (>3\( \sigma \))
- Signal from the GC region
- No signal in Galactic plane
- Signal (roughly) consistent with expected DM profiles

**Cons**
- Similar signal in limb data (not as strong)
- Similar features at other energies
- Decreased in significance w/ more data and analysis improvements (‘too’ narrow line)
- Global significance (incl. trial factors) \( \sim 2\sigma \) with Fermi energy scan and ROI:s
- Requires large \( \gamma\gamma \) BR. Displaced from GC

More Fermi-LAT data + Pass 8 processed data will give more information. Cherenkov telescopes (HESS II), future CTA, Gamma400...
BACKUP SLIDES
Constraints from Milky Way Halo

- Including modeling of the astrophysical emission improves the DM constraints by a factor of $\sim 5$

- with inclusion of astrophysical backgrounds, a canonical thermal cross section into $b$-quarks limits the WIMP mass to $\gtrsim 20$ GeV (comparable to the dSphs limits)
Isotropic Extra Galactic DM Signal
μ⁺μ⁻ final state

Not exceed the isotropic background

Not above power-law background

\[ \langle \sigma v \rangle_{\mu^+\mu^-} \cdot \text{cm}^3 \cdot \text{s}^{-1} \]

- Conservative limits
  - MSII-Res
  - MSII-Sub1
  - MSII-Sub2

- Stringent limits
  - PAMELA fit
  - Fermi fit

WIMP mass [GeV]
Different data selections for different science cases
Data selection for line search

**TABLE I.** Summary table of data selections.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Galactic data</th>
<th>Limb data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Elapsed Time (s)</td>
<td>[239557447, 356434906]</td>
<td>[239557447, 371176784]</td>
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<tr>
<td>Energy range (GeV)</td>
<td>[2.6, 541]</td>
<td>[2.6, 541]</td>
</tr>
<tr>
<td>Zenith cut (°)</td>
<td>$\theta_z &lt; 100$</td>
<td>$111 &lt; \theta_z &lt; 113$</td>
</tr>
<tr>
<td>Rocking angle cut (°) $^a$</td>
<td>$</td>
<td>\theta_r</td>
</tr>
<tr>
<td>Data quality cut $^b$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Source masking (see text)</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
Earth Limb residuals as a function of energy

Fits to Earth Limb data at ~1.5% energy steps

- Below 100 GeV the residuals in the limb are small ($\delta f < 0.02$).
- At higher energies make it difficult to exclude large fractional residuals. At 130 GeV we see S/N~18% and 3.0 $\sigma$ significance residuals.
The efficiency at ~115GeV is $0.57/0.75 = 75\%$ of the MC prediction. This would cause something < 30% boost in signal at 130 GeV relative to the prediction from nearby energy bins.
Spatial Morphology of Features in Galactic Plane

- Fit in 4°x4° ROIs along the Galactic plane in 1° steps
  - Fit with “1D PDF”
    - To find where the counts are coming from
    - Allowed for negative fluctuations
- Find excess near ~135 GeV near GC
  - But find similar features at other energies along the GP
- Excess near 135 GeV is one of the largest and near GC, but is not otherwise unique
Dedicated Galactic-Center Observation
(For Line Searches)

- Galactic-Center data so far has come from Survey Mode Observations
- Pointing directly at or close to GC increases rate by up to \( \sim 3X \)
- Energy resolution on-axis at 130 GeV \( \sim < 10\% \)
- Energy resolution 45\(^\circ\) off axis \( \sim 5\% \)
- Lots of other science from GC region!
- How to optimize GC Pointed Mode with other science under study.

Toy MC simulations for a range of signal-to-noise ratios favor energy resolution over \( A_{\text{eff}} \) slightly less than naïve scaling predictions.

Out to about \( \theta=50\% \), the improving energy resolution balances out the decreasing \( A_{\text{eff}} \). Less sensitivity past \( \theta=60\% \).
Pass8

Better event selection (higher signal efficiency at the same bkg level)
- Expect a ~25% increase in high-energy effective area in the “standard” photon classes

Include calorimeter-only events (substantial effective area increase above 40 GeV)

Dedicated GC observations:
- Pointing to GC increase rate by ~3X
- Energy resolution at 45° off-axis is ~5%, while on-axis ~10%
- At about 50° the improving energy resolution balances out the decreasing effective areas.
Cosmic-ray Positron fraction

Fermi measurement of $e^+$ fraction

“Unfortunately” Fermi-LAT doesn’t carry a magnet

**IDEA:** *Use the Earth Magnetic Field to Distinguish $e^+$ from $e^-$*

- pure $e^+$ region in the West and pure $e^-$ region in the East
- the regions vary with particle energy and the LAT geomagnetic coordinates
- to locate these regions, we use a code written by Smart and Shea, which numerically calculates a particle’s trajectory in the Earth geomagnetic field
MSSM neutralinos remain unconstrained

[Bergström et al., 1998]
Other models (soon) probed

The Inert Doublet Model