Tentative observation of a gamma-ray line at the Fermi Large Area Telescope

arXiv:1203.1312 with T. Bringmann, X. Huang, A. Ibarra, S. Vogl (accepted for JCAP),
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Outline

➢ Motivation for gamma-ray line searches
  ➢ Analysis of Fermi LAT data
    ➢ Discussion
  ➢ Conclusions
Indirect Dark Matter Searches

\[ \langle \sigma v \rangle_{\text{tot}} \simeq 3 \times 10^{-26} \text{cm}^3\text{s}^{-1} \]

Searching WIMPs

- "Weakly Interacting Massive Particles"
- Compatible with observed relic density due to self-annihilation in early Universe
- Still annihilate today → contribute to cosmic rays

H.E.S.S.
MAGIC
Fermi LAT
EGRET
Integral
WMAP
Planck
...

PAMELA
AMS-02
Fermi LAT
ATIC
...

IceCube
SuperK
...

B-field
The gamma-ray flux from dark matter annihilation at energy $E$ in direction $\Omega$:

$$\frac{dJ_{\text{ann.}}}{d\Omega dE} = \frac{\langle \sigma v \rangle}{8\pi m_{\text{dm}}^2} \frac{dN}{dE} \times \int_{\text{l.o.s.}} ds \, \rho(\vec{r}[s, \Omega])^2$$

Characteristic **Energy Spectrum**

Characteristic **Spatial Dependence**

"Particle Physics Factor"

"Astrophysics Factor"
On Signal/Background Discrimination

Measured Events: $(E_i, \Omega_i)$

\[ \int_{E_0}^{E_1} dE \]

\[ \int_{\Delta\Omega} d\Omega \]

Countmap:

Target region

Energy spectrum:

Spatial BG extrapolation ("Astrophysical Factor")
- Dwarf Galaxies
- Galaxy Clusters
- Angular power spectrum
- EGBG ...

Spectral BG extrapolation ("Particle Physics Factor")
- Gamma-ray lines
- Internal Bremsstrahlung

→ works everywhere in the sky

→ works for all signal spectra
Gamma-Ray Lines

- Are produced in two-body annihilation
  \[ \chi\chi \rightarrow \gamma\gamma, \gamma Z, \gamma h \]
- Trivial energy spectrum
  \[ \frac{dN}{dE} \propto \delta(E - E_\gamma) \text{ with } E_\gamma \leq m_\chi \]
- Process is one-loop suppressed
  \[ \text{BR}(\chi\chi \rightarrow \gamma\gamma) \sim \alpha_{\text{em}}^2 \sim 10^{-4} \]

Some models with enhanced lines:
- Singlet Dark Matter [Profumo et al. (2010)]
- Hidden U(1) dark matter [Mambrini (2009)]
- Effective DM scenarios [Goodman et al. (2010)]
- “Higgs in Space!” [Jackson et al. (2010)]
- Inert Higgs Dark Matter [Gustafsson et al. (2007)]
- Kaluza-Klein dark matter in UED scenarios [Bertone et al. (2009)]
  ...

→ “Smoking gun signature” / “Wishful thinking”
The Fermi Large Area Telescope (LAT)

Launch: June 2008

- Main Instrument on the Fermi Gamma-Ray Space Telescope
- Pair conversion instrument
- 30 MeV to >300 GeV energy range
- 2.4 sr field of view

Main components (in 16 towers)
- Plastic anticoincidence detector
- Tungsten conversion foils
- Silicon strip detectors
- Cesium Iodine Calorimeter

High-level data is publicly available
http://fermi.gsfc.nasa.gov
General strategy

I) Target region selection

- Target: Annihilation signal from Galactic center
- Aim: Maximize signal-to-noise ratio
- Problem: Specification of signal & background morphologies

II) Analysis of energy spectra

- Forget about spatial information (integral over $d\Omega$)
- Perform a “bump-search” in the integrated energy spectrum
I) Target Region Selection

Criteria for a good target region:

1) **Sufficient Exposure** (nearly uniform at Fermi LAT)
2) **Large signal-to-noise ratio** (minimize statistical errors) \( S/N \)

\[
S \propto \int_{\Delta \Omega} d\Omega \frac{dJ_{\text{signal}}}{d\Omega} \quad \quad \quad B \propto \int_{\Delta \Omega} d\Omega \frac{dJ_{\text{bg}}}{d\Omega} \quad \quad \quad N \propto \sqrt{S + B} \approx \sqrt{B}
\]

3) **Large Signal-to-background ratio** \( S/B \) (minimize systematical errors)
4) **Reliable modeling of backgrounds** (not much of a problem for lines)

**Previous Examples:**

**EGRET:**

[Pullen et al., 2007]

\[ |\ell|, |b| < 5^\circ \]

**Fermi LAT collaboration:**

[from 1205.2739]

\[ |b| > 10^\circ \quad \text{plus} \quad |\ell|, |b| < 10^\circ \]

Previously, not much effort was put into the details.
Adaptive target region selection

Fermi-LAT photons above 1 GeV are binned into 1x1 deg^2 pixels.

- **Background morphology estimated from data**
  We use events between 1 and 20 GeV for background estimation, and search for lines above 20 GeV.

- **Signal morphology** derived for a few reference dark matter profiles (centered at Galactic center)
  - Cored isothermal
  - NFW
  - Contracted profiles
  - Einasto

- **Pixel-by-pixel optimization of target region**
  Goal: Find subset of pixels T that maximizes S/N

\[
(S/N)_T = \frac{\sum_{i \in T} \mu_i}{\sqrt{\sum_{i \in T} c_i^{1\text{to}20\text{GeV}}}}
\]
Target regions for different dark matter profiles

- Steeper dark matter halo profiles $\rightarrow$ smaller target region
- Galactic center always included (except for cored isothermal profile)
- Slight north/south asymmetry as consequence of asymmetric diffuse fluxes at $\sim 1$ GeV
II) Spectral Analysis: Bump hunting

All spectral fits are performed within a small energy window around the gamma-ray line position

- Sliding energy window technique
- Secondary photons from DM signal can be neglected
- At 1\textsuperscript{st} order, all backgrounds can be approximated by power-law
- → Trading systematical for statistical errors
**Background fluxes vs window size**

Expected astrophysical fluxes:

- **PCSs**
- **ICS**
- **EGBG**
- **Bremss.**

Approximating background fluxes with a single power-law is a very reasonable 1st order approximation when looking for lines.

**Adopted energy window size:**

\[ E_{\gamma}^2 J_{\gamma}(E_{\gamma}) \text{ [MeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}] \]

\(-80^\circ \leq l \leq 80^\circ\)

\(-8^\circ \leq b \leq 8^\circ\)

\text{SSZ}_4^R \text{R}^T \text{I}_{150}^C \text{S}_{5} \)

[1202.4039, Fermi-LAT coll.]
Statistical analysis

We perform a **binned likelihood analysis**, using the likelihood function (we use many bins, practically in the **unbinned limit**)

\[ \mathcal{L} = \prod_i P(c_i | \mu_i) \]

with

- \( c_i \): observed events
- \( \mu_i \): expected events

\[ P(c | \mu) = \frac{\mu^c e^{-\mu}}{c!} \]

- **Power-law background + line model** (three free parameters)

\[ \frac{dJ}{dE} = S \, \delta(E - E_\gamma) + \beta E^{-\gamma} \]

- **Convolution** with energy dispersion and exposure yields expected event number

\[ \mu_i = \int_{\Delta E_i} dE \int dE' \, D(E, E') \mathcal{E}(E') \frac{dJ}{dE'} \]

\( D(E, E') \) : LAT energy dispersion
\( \mathcal{E}(E) \) : LAT exposure
Spectral Analysis - Likelihood analysis

- **Signal significance** for fixed $m_\chi$ follows from the TS value
  (maximum likelihood ratio test)

  \[ TS = -2 \ln \frac{\mathcal{L}_{\text{null}}}{\mathcal{L}_{\text{alt}}} \]

  - $\mathcal{L}_{\text{alt}}$: Best-fit model with DM, $S \geq 0$
  - $\mathcal{L}_{\text{null}}$: Best-fit model without DM, $S = 0$

  \[ \Rightarrow \mathcal{L}_{\text{alt}} \geq \mathcal{L}_{\text{null}} \]

  Significance **before trial correction**: $\sqrt{TS}$ [\sigma]

- **95% CL upperlimits** are derived using the **profile likelihood method**:
  increase $S$ until \( \Delta(-2 \ln \mathcal{L}) = 2.71 \), while profiling over other parameters
III) Results

Local significance: 4.6σ

Global significance (spatial and spectral trial correction): ~3.3σ

\[ E_\gamma = 129.8 \pm 2.4^{+7}_{-13} \text{GeV} \]

Assuming Einasto profile with 0.4 GeV/cm³ local density:

\[ \langle \sigma v \rangle_{\chi \chi \rightarrow \gamma \gamma} = 1.27 \pm 0.32^{+0.18}_{-0.28} \times 10^{-27} \text{cm}^3/\text{s} \]

Based on 43 month of P7V6 source class, similar for clean events.
Sensitivity vs observed limits

Expected and observed limits in Reg4 (SOURCE)

Green: 68% CL expected limit
Yellow: 95% CL expected limit
Black: actual limit

(Derived from null model mock data)
The signature is sharp

Signal width (RMS): <17% (95%CL)
The signature is sharp

Data vs. possible source fluxes; Reg4 (SOURCE)

- $E^{-1} e^{-E/20\text{GeV}}$
- $E^{-1} e^{-(E/18\text{GeV})^2}$
- ICS from $e^\pm$ line

Line: TS = 21.4

ICS from monoenergetic electrons: TS $\sim$ 12
At Galactic center only

Scan along the galactic disk:

- TS value of (line+PL) vs PL
- p-value of PL-background fit

Graphs showing TS and p-value distributions for regions along $b=0^\circ$, $l=-30^\circ$ to $30^\circ$.
Spatially extended

TS from outer parts of Reg4:

- Green: 1sigma band from data
- TS > 4 up to ~5 deg

Target region with variable size:

- Preliminary

Green: 1sigma band from data
Displaced from the Galactic Center

Photons responsible for high TS appear to be significantly displaced by O(100pc) (if GC is origin).

(Talk by Meng Su this afternoon!)

(Talk by Michael Kuhlen tomorrow!)
The Earth limb/albedo as test sample

Impact angle distribution of dataclean events:
- Blue: all z
- Green: z > 60°
- Red: z > 110°

Limb events

Survey Mode (rocking angle ~50deg)

Limb photons (z > 110)

Rocking angle

Target-of-opportunity observation (potentially large rocking angle)

Earth
A 130 GeV line in part of the limb data

- statistical (comes with a large trial factor)?
- systematic (why only there and at the GC)?
Conclusions

• The public LAT data contains an excellent candidate for a gamma-ray line from DM annihilation at ~130 GeV. The cause is unclear.

• Good astrophysical explanations are difficult to find. Different toy scenarios are disfavoured w.r.t. a line by the data.

• Maybe indication for instrumental effect in Earth limb. But: why strongest where one expects the DM signal? Why compatible with NFW/Einasto profile? Why just in low incident events?

• Statistical fluctuation: quite significant, but maybe the most likely explanation? You get what you optimized for.

Outlook:

• More data (including Pass 8)
• Study of instrumental effect (Earth albedo, Pass 8)
• Study of apparent displacement of signal center by 200 pc
• Any sign for continuum part of signal?
• HESS-II
• CTA, GAMMA-400
Thank you & stay tuned!
Backup Slides
Broken Power Laws?

Linden & Profumo [1204.6047]:

I) Target regions overlap with Fermi Bubbles
II) Bubble spectrum is possibly a broken power-law
→ „Spurious Line“

\[ \gamma_1 = 1.3 \]
\[ \gamma_2 = 4.9 \]
Broken Power Laws?

**Broken power-law signal + PL background ($\gamma_{bg} \simeq 2.6$)**

- TS$=9.6$
- $\gamma_1 = 1.3$
- $\gamma_2 = 4.9$

**Line signal + PL background ($\gamma_{bg} \simeq 2.6$)**

- TS$=21.1$
- bg only
- bg + signal

**Preliminary**
A toy example: ICS emission

Toy scenario:
1) Inject hard electron spectrum (spectral index 1 to 1.5) and cutoff at ~10 TeV into GC.
2) Let it cool down by **synchrotron losses** on the dominating magnetic field.
3) In the ideal case, electron pile up $\rightarrow$ Even more idealized, this gives an **electron line**.
4) **Inverse Compton Scattering** on the ISRF

But: even this scenario is disfavoured by the data (at ~3sigma)
Dependence on energy window size

**Gray bands:** Monte Carlo results for TS value, assuming best-fit signal

**Black line:** Observed TS value as function of window size

**Blue stars:** actually adopted energy window / quoted TS value

→ The TS value is stable w.r.t. to changes of the window size.

\[
E_0 = E_\gamma / \sqrt{\epsilon} \\
E_1 = \min(300 \text{ GeV}, E_\gamma \sqrt{\epsilon})
\]
Spatial dependence

Target region: circle with 10deg radius, moved along the galactic disc / along l=0.

schematically

Non-zero annihilation cross-sections at 3sigma are only preferred when target region intersects with galactic center.
Look Elsewhere Effect & Subsampling Analysis

- The signal does not appear in other sky regions. We checked this by
  - moving the target regions around (see above)
  - performing a bootstrap analysis of anti-galactic-center data (~40000 random test regions from $|l|>90\text{deg}$ data)

- Taking into account the look-elsewhere effect, the significance is about $3.3\sigma$
  (ten target regions times the scan from 20 to 300 GeV)
- Cosmic-ray contamination and artefacts in effective area would likely show up in large parts of the sky.
Consistent values are obtained for Einasto & NFW profiles
Isothermal or contracted profiles with $\alpha = 1.3$ favour inconsistent values
Upper Limits from presentations of the Fermi LAT coll. [Edmonds, thesis 2011]

Branching ratio for thermal relic is surprisingly large, but not impossible:

$$\text{BR}(\chi\chi \rightarrow \gamma\gamma) \sim 5\% \gg 10^{-4}$$