“Walking the Milky Way”

Background systematics for dark matter searches with gamma rays

arXiv:1409.0042, with F. Calore and I. Cholis

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Searches for non-gravitational signatures of DM

Indirect searches for DM annihilation or decay products in cosmic rays.

Candidates
- **WIMPs** (weakly interacting massive particles) 'Freeze-out mechanism'
- **Sterile neutrinos** 'Dodelson-Widrow' mechanism”
- **Gravitino DM** 'Freeze-in mechanism'

Different probes
- Atomic recoil
- Missing energy
- Small scale structure
- Displaced vertices

\[ \chi \chi \rightarrow \bar{X} X \]
\[ \chi \rightarrow \gamma \nu \]
Potential targets for searches with photons

Signal is approx. proportional to column square density of DM:

\[ \propto \int_{1.o.s.} ds \, \rho_{DM}^2 \]

Extended or diffuse:
(for observations with gamma rays)

Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Extragalactic
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

Point-like:
(for observations with gamma rays)

Galactic center (~8.5 kpc)
- brightest DM source in sky
- but: bright backgrounds

DM clumps
- w/o baryons
- bright enough?
- boost overall signal

Dwarf Spheroidal Galaxies
- harbour small number of stars
- otherwise dark (no gamma-ray emission)

[review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)]
The photon energy spectrum

Continuum emission aka secondary photons
(from hadronic channels, as discussed above)

Internal Bremsstrahlung (IB)

\[ \chi\chi \rightarrow \bar{f}f\gamma \]

Gamma-ray lines
\[ \chi\chi \rightarrow \gamma\gamma \]

Cascade decays
\[ \chi\chi \rightarrow \phi\phi \rightarrow \gamma\gamma\gamma\gamma \]
Overview

A. Gamma-ray lines*

B. Fermi GeV excess

C. Conclusions

*Not the 130 GeV line.
Gamma-ray lines
Smoking-gun signatures for DM annihilation

**Gamma-ray lines**

- Generically small branching ratio:
  \[ \text{BR}(\chi\chi \rightarrow \gamma\gamma) \sim \alpha^2 \sim 10^{-4} \]
- Multiple lines
  \[ \chi\chi \rightarrow \gamma\gamma, \gamma Z^0, \gamma h^0 \]
- Line energy is direct measure of DM mass

Examples with stronger line-like features:

- **Loop enhancement**
  - e.g. Jackson+ 2010

- **Internal Bremsstrahlung (IB)**
  - Bringmann+ 2008

- **DM decay (gravitinos)**
  - e.g. Ibarra & Tran 2008
Gamma-ray line searches below 10 GeV

ROI for DM annihilation.

ROI for DM decay.

PL + line model fit to data

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

This is formally a $\sim$9 sigma line.

[A. Albert, CW, Fermi coll+ 2013]
Background systematics from the Galactic disk

Galactic disk can be used as control region.

Distribution of residuals

327 MeV line

Estimate fake signal events:

\[ n_{\text{syst}} = \frac{n_{\text{res,control}}}{b_{\text{eff,control}}} b_{\text{eff,signal}} \]

Fractional deviation

Total likelihood:

\[ \mathcal{L}(\alpha, \Gamma, n_{\text{sig}}, n_{\text{syst}}) = P_F(n_{\text{syst}}, b_{\text{eff}}) \prod_i P(c_i | \mu_i(\alpha, \Gamma, n_{\text{sig}} + n_{\text{syst}})) \]

[A. Albert, CW, Fermi coll+ 2013]
Lower limits on gravitino lifetime

Our result when main systematics are taken into account.

- First study that consistently takes into account systematics
- We slightly improve over previous limits from EGRET

Purely statistical

[A. Albert, CW, Fermi coll+ 2013]
The 'Fermi GeV excess'
The Galactic halo
Foreground subtraction

Fermi LAT data

Subtract
- Diffuse foregrounds
- Point sources

Residual: Dark matter?

Pion decay
Traces ISM*CR protons

Inverse Compton
Traces ISRF*CR electrons

Bremsstrahlung
Traces ISM*CR electrons

Fermi bubbles
Effective template
Cause uncertain
The Fermi GeV excess

Claims for an extended emission of gamma-rays at the Galactic center

- point sources – “diffuse emission”

Extracted spectrum:

Dark matter interpretation:
- annihilation into e.g. tau+ tau-
- ~10 GeV DM mass
- contracted NFW profile

See also Hooper & Goodenough 2011; Boyarsky+ 2011; Abazajian & Kaplinghat 2012, Gordon & Macias 2013, Macias & Gordon 2014; Abazajian+ 2014; Daylan+ 2014
The Fermi GeV excess at high latitudes

Claims for the emission being extended up to high latitudes:

\[ \chi\chi \rightarrow \tau^+ \tau^- \]

Hooper & Slatyer 2013
Non-DM Interpretations

Milli-second pulsars:

- Spectrum of known MSPs agrees reasonably well with claimed GCE spectrum (except at sub-GeV energies)
- Observed luminosity function is claimed to be incompatible with GCE (we don't see resolved MSPs at GC) Hooper+, Calore+, Cholis+ 2013
- Compatible with distribution of low-mass X-ray binaries (possible MSP progenitors)

Recent active past of GC:
Petrovic+ 2014; Carlson+ 2014

- Recent injection of CR in Galactic center
- Diffuse out → approx. spherical profile
- Plausible possibility
- Spectra will depend on latitude

Other possible interpretations fail to explain the high-latitude component.
Problem I: Most analyses adopt the P6V11 BG model

Decomposition of P6V11 in Inverse Compton and pi0+Bremss. components:

ICS component very hard at >10 GeV energies
→ oversubtraction guaranteed
Problem II: **All** GDE models give a bad fit to data

None of the existing GDE models gives a “good” fit to the data in the statistical sense.

Typical values are

\[ \chi^2_{\text{red}} \sim 1.1 \]

which corresponds to ridiculously small p-values:

\[ p \leq 10^{-300} \]

→ Check background model systematics before make statistics based claims.
Central Questions

- What is the energy spectrum of the excess?
- How far does the excess extend to high latitudes?
- Is the energy spectrum the same everywhere?
- Is the excess spherically symmetric?

To this end, we estimated...

...theoretical model systematics
- What is the impact of extreme variations – within certain boundaries – of the Galactic diffuse emission (GDE) model on the GeV excess?

...empirical model systematics
- How well do GDE models describe the data?
- What are the characteristics of residuals?
Theoretical model uncertainties
60 Galactic Diffuse Emission (GDE) models

Our region of interest:

\[ |\ell| < 20^\circ \quad \& \quad 2^\circ < |b| < 20^\circ \]

**Galactic Center Excess (GCE) template derived from generalized NFW profile:**

\[
\rho(r) = \rho_0 \frac{r_s^3}{r^{\gamma}(r_s + r)^{3-\gamma}}
\]

In the fits, background model spectra will be neglected!
What we varied and what we kept fixed

Variations:
- geometry of the diffusion zone: \(4 \leq z_D \leq 10 \text{ kpc}\) and \(r_D = 20\) or \(30\) kpc;
- source distributions: SNR, pulsars, OB stars;
- diffusion coefficient at 4 GV: \(D_0 = 2 - 60 \times 10^{28} \text{ cm}^2\text{s}^{-1}\);
- Alfvén speed: \(v_A = 0 - 100 \text{ km s}^{-1}\);
- gradient of convection velocity: \(dv/dz = 0 - 500 \text{ km s}^{-1}\text{kpc}^{-1}\);
- ISRF model factors (for optical and infrared emission): \(0.5 - 1.5\);
- \(B\)-field parameters: \(5 \leq r_c \leq 10 \text{ kpc}, 1 \leq z_c \leq 2 \text{ kpc},\) and \(5.8 \leq B(r = 0, z = 0) \leq 117 \mu\text{G}\

Limitations:
- assumption of homogeneity and isotropy of CR diffusion, eq. (3.1);
- assumption of homogeneity of CR re-acceleration, described through a scalar quantity, eq. (3.2);
- lack of radial dependence of CR convection;
- assumption of radial symmetry of CR source distribution in the Galactic disk, not fully accounting for the spiral arms;
- assuming a steady state solution for the CRs, excluding transient phenomena;
- same spatial distribution of hadronic and leptonic CR sources;
- lack of a physical model for the Fermi bubbles.
**Results: Typical residuals for one FG model**

- Point source mask clearly visible
- Residuals at the level of <20% are observed
- Co-adding the DM template clearly shows an extended excess around the GC
Component spectra

Solid lines: model prediction (for model A)
GeV excess spectra

Yellow: spectra extracted in case of all 60 GDE models!

Peak at 1-3 GeV

Steep rise

No cutoff at >10 GeV energies as observed previously.

Why should one trust this result?
Empirical model uncertainties
Estimating residuals: “Walking the Milky Way”

Analyze residuals along Galactic disk:

The Galactic center excess.

Other excess

Colored dots: Best-fit GDE model

Gray dots: All other models
Line-of-sight emissivity

GDE is mostly local
Covariance matrix of residual spectra

Fluctuations define an empirical covariance matrix:

$$\Sigma_{ij, \text{mod}} = \left\langle \frac{dN}{dE_i} \frac{dN}{dE_j} \right\rangle - \left\langle \frac{dN}{dE_i} \right\rangle \left\langle \frac{dN}{dE_j} \right\rangle$$
Principal component analysis of covariance matrix

First three principal components of the covariance matrix.

This can be understood in terms of small variations in the ICS and pi0 backgrounds.

\[ \Sigma_{ij, \text{mod}} \simeq \sum_k \left( \Delta \alpha_k^2 + \Delta \gamma_k^2 \ln \frac{E_i}{E_{\text{ref}}} \ln \frac{E_j}{E_{\text{ref}}} \right) \frac{dN_k}{dE_i} \frac{dN_k}{dE_j} \]

Normalization error <3\% (from fit)

Spectral slope error <0.01 (from fit)

ICS and pi0 spectra
Empirical model uncertainties (yellow) and theoretical model uncertainties (blue lines) are significantly larger than the statistical error over the entire energy range.
Results
Fits with DM and astro spectra

Relevant chi2:

$$\chi^2 = \sum_{ij} \left( \frac{d\tilde{N}}{dE_i}(\theta) - \frac{dN}{dE_i} \right) \sum_{ij} \left( \frac{d\tilde{N}}{dE_j}(\theta) - \frac{dN}{dE_j} \right)$$

Good fits to data with:
- Simple broken power-law
- DM annihilation into bb

Both scenarios have comparable p-values
The GCE in ten different sky segments
Spectra in different segments are mutually compatible

A fit of DM bb spectra in each of the ten segments

Results are consistent with hypothesis of **one single spectrum at 95% CL!**
How far does the excess reach in the sky?

To explore the **extension of the excess to high latitudes**, we consider a hypothetical source with volume emissivity profile

\[ q \propto r^{-\Gamma} e^{-r/R_{\text{cut}}} \]

We find a lower limit on the extension of at least 1.48 kpc (corresponding to more than 10 degrees).

\[ \psi > 10.0^\circ \quad 95\% \text{CL} \]
Fits with DM spectra

Previous results
Fit with PL with exponential cutoff

\[ \frac{dN}{dE} \propto E^{-\alpha} e^{-E/E_{cut}} \]

Average MSP spectrum [from Cholis+ 2014]
Conclusions

• The Galactic disk is an excellent test region for indirect dark matter searches → Use It!

• After including systematics, no gamma-ray line emission from DM decay/annihilation was found at 300 MeV to 10 GeV energies → Most robust lower limits on gravitino DM lifetime

• Previously adopted BG subtraction for “Fermi GeV excess” was deficient and overly constraining

• We estimate theoretical model systematics with 60 GDE models

• We estimate empirical model systematics (and quality of GDE models) from scan along the Galactic disk

• Results for GCE:
  • can be fit with broken PL and with DM spectra
  • is compatible with spherical symmetry and uniform spectrum
  • robustly extends far from the GC (10 deg and more)

Outlook: Multi-wavelength, one-point fluctuations and point sources, dynamical leptonic models, cross-correlations with 2MASS...
Backup
No signal photons since Summer 2012

Using Fermi LAT data alone, the signal hypothesis can be excluded at more than 3 sigma.

P-value (assuming P7rep best-fit; 21.5\pm11.2 expected, -9.0 observed):

\[ p \lesssim 0.001 \]
# GDE: Ingredients

<table>
<thead>
<tr>
<th>Name</th>
<th>$z_D$</th>
<th>$D_0$</th>
<th>$v_A$</th>
<th>$dv/dz$</th>
<th>Source</th>
<th>$\alpha_e(\alpha_p)$</th>
<th>$N_e(N_p)$</th>
<th>$B$-field</th>
<th>ISRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4</td>
<td>5.0</td>
<td>32.7</td>
<td>50</td>
<td>SNR</td>
<td>2.43(2.47)</td>
<td>2.03(5.8)</td>
<td>090050020</td>
<td>1.36,1.36,1.0</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>28.0</td>
<td>31.0</td>
<td>0</td>
<td>SNR</td>
<td>2.43(2.39)</td>
<td>1.00(4.9)</td>
<td>105050015</td>
<td>1.4,1.4,1.0</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>5.0</td>
<td>32.7</td>
<td>0</td>
<td>SNR</td>
<td>2.43(2.39)</td>
<td>0.40(4.9)</td>
<td>250100020</td>
<td>1.0,1.0,1.0</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>5.2</td>
<td>32.7</td>
<td>0</td>
<td>SNR</td>
<td>2.43(2.39)</td>
<td>0.40(4.9)</td>
<td>050100020</td>
<td>0.5,0.5,1.0</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>2.0</td>
<td>32.7</td>
<td>0</td>
<td>SNR</td>
<td>2.43(2.39)</td>
<td>0.40(4.9)</td>
<td>050100020</td>
<td>1.0,1.0,1.0</td>
</tr>
</tbody>
</table>

Table 2. The properties of GDE models A–E. Here, $z_D$ is in kpc, while $r_D$ is taken to be 20 kpc. $D_0$ is in units of $10^{28}$ cm$^2$ s$^{-1}$, $v_A$ is in km s$^{-1}$ and $dv/dz$ in km s$^{-1}$ kpc$^{-1}$. The CR electron and proton normalizations are $N_e(N_p)$ in units $10^{-9}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ MeV$^{-1}$ and refer to the differential flux at $E_{\text{kin}}$ of 34.5 and 100 GeV. $\alpha_e$ and $\alpha_p$ are the electron and proton injection indices above rigidities of 2.18 and 11.3 GV, respectively (and are respectively equal to 1.6 and 1.89 below these rigidities). For the gas assumptions we take, $T_S = 150$ K and an E(B-V) magnitude cut of 5 (see discussion in section 3.2). For model A the magnetic field “090050020” denotes in eq. (3.3) $B_0 = 9.0$ $\mu$G, $r_e = 5$ kpc and $z_e = 2$ kpc (similarly for the other models). Finally, the three numbers in the “ISRF” column refer to the multiplication factors of the “optical”, “IR” and CMB components of the ISRF model used in Galprop v54 webrun.
Typical residuals and morphological fits

The GeV excess template
Likelihood function

<table>
<thead>
<tr>
<th>Name</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSC</td>
<td>Spectra fixed to 2FGL</td>
</tr>
<tr>
<td><em>Fermi</em> bubbles</td>
<td>Flat emission — Spectrum constrained</td>
</tr>
<tr>
<td>IGRB</td>
<td>Constant emission — Spectrum constrained</td>
</tr>
<tr>
<td>GCE</td>
<td>Generalized NFW profile with inner slope $\gamma$</td>
</tr>
<tr>
<td>Ackermann+ GDE models</td>
<td>$(\pi^0 + \text{Bremss}) + \text{ICS}$</td>
</tr>
<tr>
<td>Additional GDE models</td>
<td>$(\pi^0 + \text{Bremss}) + \text{ICS}$</td>
</tr>
</tbody>
</table>

\[-2 \ln \mathcal{L} = 2 \sum_{i,j} w_{i,j} (\mu_{i,j} - k_{i,j} \ln \mu_{i,j}) + \chi^2_{\text{ext}}\]

\[w_{i,j} = \frac{1}{\left( \frac{f_{PSC}}{f_{PSC_{\mu_{i,j}^{BG}}}} \right)^{\alpha_{PSC}} + 1}\]

\[\mu_{i,j} = \sum_k \theta_{i,k} \mu_{i,j}^{(k)}\]

\[\chi^2_{\text{ext}} = \sum_{i,k} \left( \frac{\phi_{i,k} - \bar{\phi}_{i,k}}{\Delta \phi_{i,k}} \right)^2\]

We refit in every energy bin → throw away spectral information!