“Walking the Milky Way”

Robust identification of the Fermi GeV excess at higher latitudes

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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)]
Diffuse Galactic backgrounds

The diffuse gamma-ray emission from our Galaxy is produced by interaction of high energetic charged particles (electrons, protons, ...) with the interstellar medium (mostly Hydrogen and Helium) and interstellar radiation field (Cosmic Microwave background, starlight, dust radiation).

Proton-proton collisions & subsequent pion-decay:

- high energy proton
- p
- proton at rest
- p

Inverse Compton scattering:

- high energy electron
- $e^\pm$
- $\gamma$
- $e^\pm$
- low energy photon
- cosmic microwave background
- starlight

(at lower energies: also Bremsstrahlung)
The Fermi GeV excess

At the Galactic center (roughly 7deg x 7deg)

- Goodenough & Hooper 2009
- Hooper & Goodenough 2011
- Hooper & Linden 2011
- Boyarsky+ 2011
- Abazajian & Kaplinghat 2012
- Gordon & Macias 2013
- Macias & Gordon 2014
- Abazajian+ 2014
- Daylan+2014

In the inner Galaxy (roughly |b|>1 deg to tens of deg)

- Hooper & Slatyer 2013
- Huang+ 2013
- Zhou+ 2014
- Daylan+ 2014

[Daylan+ 2014]

[Hooper & Slatyer 2013]
**Astrophysical 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 electrons/protons at Galactic center
- Diffusion → approx. spherical profile
- Spectra will depend on latitude

Other possible interpretations fail to explain the high-latitude component.
Some problem with previous analyses

Results of previous analyses are largely based on one single (outdated & problematic) GDE model.

Hooper & Slatyer 2013
Huang+ 2013
Daylan et al. 2014

Hard ICS in BG model causes oversubtraction.

No GDE model gives a “good” fit. Typical p-values:

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

Beware of claims of excesses without study of systematics! There are excesses everywhere.

No clear statistical meaning of statements about
- extension & morphology
- spectrum
Biased or overly constrained?
Central questions & goals

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

• Characterize the impact of background uncertainties
• Give clear statistical meaning to all statements
Strategy

A. Use Galactic diffuse emission models
   • from literature [Ackermann+ 2012; 1202.4039]
   • extreme models [Galprop v54]
   to perform template fits

B. Characterize residuals

C. Fold residuals back into GC analysis

"Theoretical model systematics"

"Empirical model systematics"
Galactic Diffuse Emission (GDE) models
Relevant parameters

Cosmic ray propagation
- Diffusion zone height: 4-10 kpc
- Diffusion constant: $2-60 \times 10^{28}$ cm$^2$/s
- Reacceleration: 0-100 km/s
- Convective winds: 0-500 km/s/kpc

Cosmic ray sources
- Distributed like SNR, pulsars, OB stars
- Electron/proton injection spectra

Cosmic-ray interaction
- ISRF: 50% variations
- Magnetic field: 5.8-117 μG @ GC
- Spin temperature: 150 K, optical thin
- Dust correction parameters

Diffusion equation:
\[
\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \left( \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[ p \psi - \frac{p}{3} \left( \vec{\nabla} \cdot \vec{V} \right) \psi \right] \right) - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi
\]
Deliberate limitations of our analysis

- assumption of homogeneity and isotropy of CR diffusion
- assumption of homogeneity of CR re-acceleration, described through a scalar quantity,
- 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.
- no constraints from local CRs (although some models fit local CRs well)

→ 60 representative GDE models
**GDE models: Morphology**

**Model A:**

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

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**Model-to-model variations at 10% level (typically). Model A vs Model F:**

\[ \pi^0 + \text{Bremsstrahlung}, 1 \text{ GeV}, (\text{ModA} - N\cdot\text{ModB})/\text{ModA} \]

\[ \text{ICS}, 1 \text{ GeV}, (\text{ModA} - N\cdot\text{ModC})/\text{ModA} \]

\[ \text{ICS}, 1 \text{ GeV}, (\text{ModA} - N\cdot\text{ModD})/\text{ModA} \]
GDE models: Spectra

Models A to E:

- Energy spectra are vastly different from model to model
- But: we **refit** the normalization of each component **bin-by-bin**
  - GDE models act as templates for morphology
  - Allows to check whether reconstructed spectra are reasonable
Theoretical model systematics
## Technical details

### ROI:
- “**Inner Galaxy**”: $2^\circ \leq |b| \leq 20^\circ$ and $|\ell| \leq 20^\circ$
- We mask all **point sources** from the second Fermi source catalog

### Components:

<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 bubbles</em></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>
</tbody>
</table>

**Galactic Center Excess**

- Ackermann+ GDE models ($\times 13$)
- Additional GDE models ($\times 47$)

### Likelihood fctn:

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

$i$th energy bin

$i$th pixel

- **PSC mask**
- **Model components**
- **External constraints**

\[
 w_{i,j} = \frac{1}{\left( \frac{\mu_{i,j}^{\text{PSC}}}{f_{\text{PSC}} \mu_{i,j}^{\text{BG}}} \right)^{\alpha_{\text{PSC}}} + 1} \\
 \mu_{i,j} = \sum_k \theta_{i,k} \mu_{i,j}^{(k)} \\
 \chi^2_{\text{ext}} = \sum_{i,k} \left( \frac{\phi_{i,k} - \bar{\phi}_{i,k}}{\Delta \phi_{i,k}} \right)^2
\]
Typical residuals

Model A, 2.1-3.3 GeV

Longitude profile:

- GCE
- PSCs
- \(\pi^0 +\text{Bremss}\)
- ICS
- Isotropic
- Bubbles
- Sum

Residuals, GCE templ. readded
Component spectra

Solid lines: model prediction (model A)
Yellow: spectra extracted in case of all 60 GDE models!

Clear peak at 1-3 GeV

No cutoff at >10 GeV energies as observed previously.

Although we allow extreme variations in the GDE models, the reconstructed spectra are remarkably similar.
Empirical model systematics
Walking the Milky Way: Use Galactic disk as test region!

Previous examples:

GeV excess at Galactic center (but treated as uncorrelated)

Gordon & Macias 2013

Gamma-ray line searches

CW 2012
Finkbeiner, Su & CW 2013
Albert et al. 2014

High-latitude GDE is mostly local:
Estimating residuals

Analyze residuals along Galactic disk:

The “GeV excess”

Other excesses

Colored dots: Best-fit GDE model

Gray dots: All other models
Covariance matrix of residual spectra

Fluctuations define an empirical covariance matrix:

\[ \Sigma_{ij, \text{mod}} = \left\langle \frac{dN}{dE_i} \frac{dN}{dE_j} \right\rangle - \left( \left\langle \frac{dN}{dE_i} \right\rangle \right) \left( \left\langle \frac{dN}{dE_j} \right\rangle \right) \]
Principal component analysis

Decomposition of covariance matrix:

$$\Sigma = U \begin{pmatrix} \lambda_1 & 0 & \cdots \\ 0 & \lambda_2 & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix} U^{-1}$$

$$\lambda_1 > \lambda_2 > \lambda_3 > \lambda_4 > \cdots > \lambda_{24}$$

Main components

Mostly stat. noise

Flux per energy bin

$$U = \begin{pmatrix} w_{11} & w_{12} & \cdots \\ w_{21} & w_{22} & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix}$$

Solid lines: measured
Principal component analysis

This can be understood in terms of small variations in the ICS and π0 backgrounds.

Variations in true ICS, π0 flux:

\[
\frac{dN}{dE} \rightarrow \frac{dN}{dE} (1 + \delta \alpha) E^{-\delta \gamma}
\]

Corresponding over/undersubtraction is partially absorbed by GCE template

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

Normalization error <3% (from fit)
Spectral slope error <0.01 (from fit)

Solid lines: measured
Dashed lines: model
Empirical model uncertainties (yellow) and theoretical model uncertainties (blue lines) are significantly larger than the statistical error over the entire energy range.

Have to take into account systematics to get meaningful results in spectral fits.
### Fits with DM and astro spectra

![Graph showing energy distribution](image)

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Parameters</th>
<th>$\chi^2$/dof</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>broken PL</td>
<td>$\alpha_1 = 1.42^{+0.22}<em>{-0.31}, \alpha_2 = 2.63^{+0.13}</em>{-0.095}, E_{\text{break}} = 2.06^{+0.23}_{-0.17}$ GeV</td>
<td>1.06</td>
<td>0.47</td>
</tr>
<tr>
<td>DM $\chi\chi \rightarrow \bar{b}b$</td>
<td>$\langle \sigma v \rangle = 1.76^{+0.28}<em>{-0.27} \times 10^{-26}$ cm$^3$ s$^{-1}, m</em>\chi = 49^{+6.4}_{-5.4}$ GeV</td>
<td>1.08</td>
<td>0.43</td>
</tr>
<tr>
<td>DM $\chi\chi \rightarrow \bar{c}c$</td>
<td>$\langle \sigma v \rangle = 1.25^{+0.2}<em>{-0.18} \times 10^{-26}$ cm$^3$ s$^{-1}, m</em>\chi = 38.2^{+4.6}_{-3.9}$ GeV</td>
<td>1.07</td>
<td>0.44</td>
</tr>
<tr>
<td>PL with exp. cutoff</td>
<td>$E_{\text{cut}} = 2.53^{+1.1}<em>{-0.77}$ GeV, $\alpha = 0.945^{+0.36}</em>{-0.5}$</td>
<td>1.37</td>
<td>0.16</td>
</tr>
<tr>
<td>DM $\chi\chi \rightarrow \tau^+\tau^-$</td>
<td>$\langle \sigma v \rangle = 0.337^{+0.047}<em>{-0.048} \times 10^{-26}$ cm$^3$ s$^{-1}, m</em>\chi = 9.96^{+1.1}_{-0.91}$ GeV</td>
<td>1.52</td>
<td>0.065</td>
</tr>
</tbody>
</table>
Same procedure, but for ten GCE segments
Is the spectrum everywhere the same?

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

- North/south symmetric
- East/west symmetric

Results are consistent with hypothesis of one single spectrum at 95% CL!
How far does the excess extend from the GC?

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).

\[ \psi > 10.0^\circ \quad 95\% \text{ CL} \]
Leptonic burst event?

Injection of electrons at GC
- “Point like”, 1 Myr ago
- Spectral index 2.2

[benchmark from Petrovic+ 2014]

Results
- Cannot reproduce spectrum at low energies
- Gaussian morphology (underpredicts at few deg and >15 deg away from GC)

[Calore, Evoli, CW+ soon]
## Check list

<table>
<thead>
<tr>
<th></th>
<th>Spectrum</th>
<th>Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problems in the subtraction of Galactic foreground / Bubbles</td>
<td>✗</td>
<td>?</td>
</tr>
<tr>
<td>Recent burst-like events (protons)</td>
<td>?</td>
<td>✗</td>
</tr>
<tr>
<td>Recent burst-like events (electrons)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Unresolved PSCs (e.g. MSPs)</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Dark matter annihilation</td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>
Conclusions

- We performed first comprehensive analysis of BG systematics for the Fermi GeV excess in the inner Galaxy
  - Theoretical model systematics: From 60 GDE models
  - Empirical model systematics: From PCA of residuals
- We defined robust statistical tools to describe spectral and morphological properties of the excess emission

Results

- We robustly confirm the existence of the Fermi GeV excess in the inner Galaxy
- The spectrum features a peak at 1-3 GeV and is best fit with a broken power law. Excellent fits also with DM spectra possible.
- GeV excess extends to at least 10 degree away from GC at 95% CL
- Compatible with uniform spectrum and spherical symmetry within 95% CL
- This suggests: DM annihilation, unresolved point sources, maybe leptonic burst event, ...
- Outlook: Multi-wavelength, multi-messenger, ...
Thank you