A global fit of the gamma-ray galactic center excess within the scalar Higgs portal model

[A. Cuoco, B. Eiteneuer, JH, M. Krämer; JCAP 1606 (2016) 050, 1603.08228]

Jan Heisig (RWTH Aachen)

TeVPA2016
CERN, September 15
Fermi GeV Galactic Center Excess

- Fermi gamma-ray sky
- Pion decay/Bremsstr.
- Inverse Compton
- Point sources
- Fermi bubbles
- Excess

[Calore, Cholis, Weniger '14]

[Goodenough, Hooper '09, '10; Vitale, Morselli '09; Hooper, Linden '11; Abazajian, Kaplinghat '12; Hooper, Slatyer '13; Macias, Gordan '13; Huang et al. '13; Abazajian et al. '14; Daylan et al. '14; Zhou et al. '14; Calore et al. '14; Gaggero et al. '15; Cholis et al. '15; Bartels et al. '15; Lee et al. '15; Ajello et al. (Fermi-LAT) '15; ...]

⇒ Excess over the known foregrounds in Fermi-LAT data

Jan Heisig (Aachen University)
Fermi GeV Galactic Center Excess

DM searches in the inner Galactic region with Fermi LAT

[Calore, Cholis, Weniger '14]

[Goodenough, Hooper '09, '10; Vitale, Morselli '09; Hooper, Linden '11; Abazajian, Kaplinghat '12; Hooper, Slatyer '13; Macias, Gordan '13; Huang et al. '13; Abazajian et al. '14; Daylan et al. '14; Zhou et al. '14; Calore et al. '14; Ajello et al. '15; Ajello et al. (Fermi-LAT) '15; ...]

Origine controversially discussed

⇒ Excess over the known foregrounds in Fermi-LAT data

Jan Heisig (Aachen University)
Fermi GC Excess $\rightarrow$ Galactic bulge emission

“Say Fermi GeV excess one more time... I dare you!
I double dare you!”

[Christoph's talk]
Fermi GeV Galactic Center Excess

Astrophysical sources

⇒ Excess over the known foregrounds in Fermi-LAT data
Fermi GeV Galactic Center Excess

Astrophysical sources

WIMP Dark Matter

⇒ Excess over the known foregrounds in *Fermi*-LAT data

Jan Heisig (Aachen University)
In the previous section, we found that theoretical and empirical model uncertainties in the way we discussed them here are due to various sources of systematic errors. The shown systematic errors are not negligible.

\[ \sigma_{\text{stat. and corr. syst. errors}} \]

\[ \Delta \]

On the other hand, the empirical model uncertainties are simpler. We emphasize that this is due to the nature of the data and the modeling approach.

In We show fits to the GCE with various spectral models. We emphasize that the empirical model uncertainties are simple. We show fits to the GCE with various spectral models.

\[ \chi^2 \]

On the other hand, the empirical model uncertainties are simple. We show fits to the GCE with various spectral models.

\[ \text{We show fits to the GCE with various spectral models. We emphasize that the empirical model uncertainties are simple. We show fits to the GCE with various spectral models.} \]

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\[ \sigma \]

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Fermi GeV Galactic Center Excess

\[ \sigma v \approx 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

~ Cross section necessary for thermal relic!

[Image: Eiteneuer '16]

\[ E^2 dN/dE \text{ [GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}] \]

- broken PL
- PL with exp. cutoff
- DM \( \tau^+ \tau^- \)
- GC excess spectrum with stat. and corr. syst. errors

[Image: Calore, Cholis, Weniger '14]

\[ E \text{ [GeV]} \]

\( \Rightarrow \) Excess over the known foregrounds in Fermi-LAT data

Jan Heisig (Aachen University)
This work:

- Very simple Dark Matter model (singlet scalar Higgs portal)
- Detailed numerical fit involving further constraints (invisible Higgs width, LUX, relic density,...)
- Allow for additional non-WIMP DM component (PBHs, axions,...)

→ Interesting implications
Scalar Singlet Higgs Portal Model

[Silveira, Zee '85; McDonald '94; Burgess, Pospelov, Veldhuis: '01; ...]

- Higgs bilinear $H^+ H$ unique (renormalizable) way to directly couple DM to the SM
- Add Singlet Scalar $S$ with $Z_2$-symmetry:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_{S,0}^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{2} \lambda_{HS} S^2 H^+ H$$

(before EWSB)
Scalar Singlet Higgs Portal Model

[Silveira, Zee '85; McDonald '94; Burgess, Pospelov, Veldhuis: '01; ...]

- Higgs bilinear $H^\dagger H$ unique (renormalizable) way to directly couple DM to the SM
- Add Singlet Scalar $S$ with $Z_2$-symmetry:

\[
\mathcal{L} \supset -\frac{1}{2} m_S^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{4} \lambda_{HS} h^2 S^2 - \frac{1}{2} \lambda_{HS} v h S^2 ,
\]

where $m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2 / 2$. (after EWSB)
Scalar Singlet Higgs Portal Model

[Higgs bilinear \( H^\dagger H \) unique (renormalizable) way to directly couple DM to the SM]

- Add Singlet Scalar \( S \) with \( Z_2 \)-symmetry:

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\mathcal{L} \supset -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HS} h^2 S^2 - \frac{1}{2}\lambda_{HS} v h S^2 ,
\]

where \( m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2 / 2 \).

Important for this work

⇒ Only two parameters: \( m_S, \lambda_{HS} \)
Dark Matter annihilation

- **Annihilation processes:**

  a) $S \rightarrow h$  
  $\propto v\lambda_{HS}$  
  b) $S \rightarrow h$  
  $\propto (v\lambda_{HS})^2$  
  c) $S \rightarrow h$  
  $\propto \lambda_{HS}$

SM = $t, h, Z, W, b, \tau, c, g, \gamma$

[see also e.g. Cline, Scott, Kainulainen, Weniger '13; Duerr, Pérez, Smirnov '15; Beniwal et al. '15]

Only present above Higgs threshold
Dark Matter annihilation

- Annihilation processes:

\[
\begin{align*}
\text{a) } S & \rightarrow h & \text{SM} & \propto v \lambda_{HS} \\
\text{b) } S & \rightarrow S & \text{SM} & \propto (v \lambda_{HS})^2 \\
\text{c) } S & \rightarrow h & \text{SM} & \propto \lambda_{HS}
\end{align*}
\]

SM =ER]

\[
\begin{align*}
\text{SM} = t, h, Z, W, b, \tau, c, g, \gamma
\end{align*}
\]

[see also e.g. Cline, Scott, Kainulainen, Weniger '13; Duerr, Pérez, Smirnov '15; Beniwal et al. '15]
Gamma-ray spectrum

- Continuous photon spectrum
- Slow in fit
  ⇒ Precompute spectra for all channels with MadGraph/Pythia 8
- During fit: Combine spectra according to contribution

Photon spectra for several masses/couplings:
\(\chi^2\)-computation for the GCE

- Take measured spectrum \(d_i\) and covariance matrix \(\Sigma_{ij}\) from [Calore, Cholis, Weniger: 1409.0042]
- Additional uncertainty on the theoretical prediction of the spectrum \(\Sigma_{ij} \rightarrow \Sigma_{ij} + \Sigma_{ij} \delta_{ij} t_i^2 \sigma_t^2, \ \sigma_t = 10\%\) [Achterberg et al. 1502.05703]
- Large theoretical uncertainties on DM distribution in galaxy:
  - Take NFWc profile
  - Vary around best fit parameters with MC [from Calore, Cholis, Weniger: 1409.0042]
    - Distribution for \(J\)-factor
    - Determine \(\sigma_\xi\) for \(\xi = \ln(\bar{J}/\bar{J}_{\text{nom}})\)
  - Compute \(\chi^2\):
    \[
    \chi^2 = \sum_{i,j} (d_i - e^\xi t_i)(\Sigma_{ij})^{-1}(d_j - e^\xi t_j) + \frac{\xi^2}{(\sigma_\xi)^2}
    \]
Constraints on the parameter space
Constraints on the parameter space

(i) Collider constraints:
   Higgs invisible BR

(ii) Direct detection constraints: LUX '13
    log-likelihood from
    LUXCalc \cite{Savage1502.02667}

(iii) Dwarf Spheroidal Galaxies
    \cite{Fermi-LAT:1503.02641}
Constraints on the parameter space

(iv) Gamma-lines:
[Fermi-LAT: 1506.00013]
$J$-factor different from GCE
almost 100% correlation

(v) Relic density constraint
[Planck: 2013]
Apply 10% theoretical uncertainty
[computed with micrOMEGAs]
Fit parameters and tools

- Allow for additional unspecified DM component
  \[ R = \frac{\rho_{\text{WIMP}}}{\rho_{\text{DM, total}}} \]
- 4 scan parameters:
  \[ m_S: \quad 5 \ldots 220 \text{ GeV} \]
  \[ \lambda_{HS}: \quad 3 \times 10^{-5} \ldots 4\pi \]
  \[ \ln(\bar{J}/\bar{J}_{\text{nom}}): \quad -4\sigma_\xi \ldots 4\sigma_\xi \]
  \[ R: \quad 10^{-3} \ldots 1 \]

- Use MultiNest (nested sampling algorithm) [Feroz et al. '13]
- Annihilation cross sections and BRs: micrOMEGAs [Bélanger et al. '14]
- Frequentist interpretation
Results
GCE only

$$\chi^2_{\text{GCE}} = 19.3$$
GCE+BR_{inv}

$$\chi^2_{\text{GCE}} = 25.3$$
GCE+$BR_{inv}$+LUX

$\chi^2_{GCE} = 25.6$

After LUX: only Higgs-resonant region, $m_S \approx m_h/2$, remains
GCE+BR_{inv}+LUX+dwarfs+γ-lines

χ^2_{GCE} = 26.0

Limits from dwarf spheroidal galaxies and gamma lines tighten range for \( \ln(\bar{J}/\bar{J}_{\text{nom}}) \)
GCE+\text{BR}_{\text{inv}}+\text{LUX}+\text{dwarfs}+\gamma\text{-lines}+\text{relic density}

\[\chi^2_{\text{GCE}} = 26.8\]

Interesting structure in \( R \)
Two distinct regions

\[ R = \frac{\rho_{\text{WIMP}}}{\rho_{\text{total}}} \]
Table 2: Best fit points and corresponding $\sigma$-values represent the confidence level at which the best fit is compatible with the constraints coming from each extra-observable we include in the fit (see text).

$\lambda_{HS}$

$R = \rho_{WIMP}/\rho_{total}$

$\chi^2_{GCE} = 26.8$

Interesting structure in $R$

Two distinct regions
GCE+BR_{inv}+LUX+dwarfs+γ-lines+relic density

- Large velocity dependence around Higgs resonance
  \[ \sigma v \propto \frac{1}{(m_h^2 - s)^2 + m_h^2 \Gamma_h^2} \approx \frac{1/m_h^2}{(\delta^2 - v_{rel}^2)^2 + \Gamma_h^2}, \quad \delta^2 \equiv \frac{m_h^2 - 4m_S^2}{m_h^2} \]

- Annihilation today: \( v_{rel} \lesssim 10^{-3} \), freeze-out: \( v_{rel} \lesssim 0.3 \)
- Large velocity dependence around Higgs resonance
  - \( \sigma v \propto \frac{1}{(m_h^2 - s)^2 + m_h^2 \Gamma_h^2} \approx \frac{1/m_h^2}{(\delta^2 - v_{\text{rel}}^2)^2 + \Gamma_h^2} \), \( \delta^2 \equiv \frac{m_h^2 - 4m_S^2}{m_h^2} \)
- Annihilation today: \( v_{\text{rel}} \approx 10^{-3} \), freeze-out: \( v_{\text{rel}} \lesssim 0.3 \)
GCE+BR_{inv}+LUX+dwarfs+\gamma\text{-lines}+relic density

- Large velocity dependence around Higgs resonance
  \[ \sigma v \propto \frac{1}{(m_h^2 - s)^2 + m_h^2 \Gamma_h^2} \sim \frac{1/m_h^2}{(\delta^2 - v_{rel}^2)^2 + \Gamma_h^2}, \quad \delta^2 = \frac{m_h^2 - 4m_S^2}{m_h^2} \]
- Annihilation today: \( v_{rel} \lesssim 10^{-3} \), freeze-out: \( v_{rel} \lesssim 0.3 \)
For $R < 1$:

- Relic density: $\Omega_{DM,\text{total}} = \frac{\Omega_{\text{WIMP}}}{R} \propto \frac{1}{R \langle \sigma v \rangle_{\text{f.o.}}}$
- GCE flux: $\phi \propto R^2 \langle \sigma v \rangle_{\text{today}}$

\[ R = 1 \]
For $R < 1$:

- **Relic density:** $\Omega_{\text{DM, total}} = \frac{\Omega_{\text{WIMP}}}{R} \propto \frac{1}{R \langle \sigma v \rangle_{\text{f.o.}}}$
- **GCE flux:** $\phi \propto R^2 \langle \sigma v \rangle_{\text{today}}$

$R = 0.5$
- For $R < 1$:
  - Relic density: $\Omega_{DM, \text{total}} = \frac{\Omega_{\text{WIMP}}}{R} \propto \frac{1}{R \langle \sigma v \rangle_{\text{f.o.}}}$
  - GCE flux: $\phi \propto R^2 \langle \sigma v \rangle_{\text{today}}$

\[ R = 0.3 \]
GCE + BR_{inv} + LUX + dwarfs + \gamma - lines + relic density

- For $R < 1$:
  - Relic density: $\Omega_{DM, total} = \frac{\Omega_{WIMP}}{R} \propto \frac{1}{R \langle \sigma v \rangle_{f.o.}}$
  - GCE flux: $\phi \propto R^2 \langle \sigma v \rangle_{today}$

$R = 0.1$

\[ m_S \text{ [GeV]} \]

\[ \lambda_{HS} \]

\[ R = \frac{\rho_{WIMP}}{\rho_{total}} \]
GCE+BR_{inv}+LUX+dwarfs+γ-lines+relic density

- For $R < 1$:
  
  → Relic density: $\Omega_{DM, \text{total}} = \frac{\Omega_{WIMP}}{R} \propto \frac{1}{R \langle \sigma v \rangle_{\text{f.o.}}}$
  
  → GCE flux: $\phi \propto R^2 \langle \sigma v \rangle_{\text{today}}$

$R = 0.01$
GCE+BR\textsubscript{inv}+LUX+dwarfs+\gamma lines+relic density

- For $R < 1$:
  - Relic density: $\Omega_{DM, \text{total}} = \frac{\Omega_{WIMP}}{R} \propto \frac{1}{R \langle \sigma v \rangle_{\text{f.o.}}}$
  - GCE flux: $\phi \propto R^2 \langle \sigma v \rangle_{\text{today}}$

- $R=1$: only one spot
- $R < 1$: two regions remain
  - Consistent fit with per mille WIMP fraction!
Summary

- GCE: Astrophysics of WIMPs?
- Higgs Portal: Unique coupling to minimal DM
- Singlet Scalar Model: Good fit!
- After constraints: Only Higgs-resonance remains
- Allow for additional non-WIMP DM component
- Non-trivial implications for WIMP fraction near resonance (large velocity dependence)
Back-up I: Future experimental prospects

- Collider constraints: virtually unchallenged
- Constraints from dwarfs: General challenge for GCE
- Direct detection projections:

![Plot](image)

LUX

10 x LUX sens.

50 x LUX sens.
Back-up II: Photon spectra for best-fit points

GCE only (blue) and after all constraints (red):

- $m_S = 62.7$ GeV
- $m_S = 45.5$ GeV

Fermi LAT
Diag. err $+10\%$ flux

Figure 1: The correlation between the annihilation cross section as of today and the input parameters of the fit $m_S$, $\lambda$, $R$, and $\log p J_{40}^\circ / J_{40}^\circ$, nom for the case of the GCE-only fit a and taking into account all the constraints including the relic density constraint. The white dot denotes the best-fit point. The dark red, orange, and yellow points lie within the 1, 2, 3, and 4 $\sigma$ region around the best-fit point, respectively.

In Fig. 1 we show the errors for the GCE-only fit although the difference to the fit including all constraints would be barely noticeable in the figure.

In Table 2 we have collected the best fit values for the scalar Higgs portal model parameters $m_S$, $\lambda$, $R = \rho_{WIMP}/\rho_{total}$, and $J_{40}^\circ$. We show results for the various global fits, including the GCE signal only, and for the GCE signal with the different constraints added successively. As discussed above, the scalar Higgs portal model can describe the GCE signal for dark matter masses near $m_S = m_h/2$, and for perturbative values of the...
## Back-up III: Table with best-fit points

<table>
<thead>
<tr>
<th>log $L$ contribution</th>
<th>GCE</th>
<th>+BR$_{\text{inv}}$</th>
<th>+LUX</th>
<th>+dwarfs</th>
<th>+lines</th>
<th>+relic den.</th>
<th>2nd region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_S$ [GeV]</td>
<td>45.50$^{+5.98}_{-5.36}$</td>
<td>61.07$^{+2.65}_{-1.98}$</td>
<td>61.55$^{+1.78}_{-0.85}$</td>
<td>61.35$^{+1.90}_{-0.79}$</td>
<td>61.46$^{+1.87}_{-0.85}$</td>
<td>62.70$^{+0.57}_{-0.18}$</td>
<td>62.52$^{+0.02}_{-0.01}$</td>
</tr>
<tr>
<td>$\lambda_{HS}$</td>
<td>0.17$^{+11.67}_{-0.09}$</td>
<td>0.0125$^{+7.31}_{-0.0125}$</td>
<td>0.0082$^{+0.317}_{-0.0082}$</td>
<td>0.0087$^{+0.312}_{-0.0087}$</td>
<td>0.0082$^{+0.315}_{-0.0082}$</td>
<td>0.022$^{+0.015}_{-0.013}$</td>
<td>0.00029$^{+0.0078}_{-0.00010}$</td>
</tr>
<tr>
<td>$R$</td>
<td>0.68$^{+0.32}_{-0.65}$</td>
<td>1.0$^{+0.0}_{-1.0}$</td>
<td>0.99$^{+0.01}_{-0.99}$</td>
<td>1.0$^{+0.0}_{-1.0}$</td>
<td>1.0$^{+0.0}_{-1.0}$</td>
<td>1.0$^{+0.0}_{-1.0}$</td>
<td>1.0$^{+0.0}_{-1.0}$</td>
</tr>
<tr>
<td>log $J/J_{\text{nom}}$</td>
<td>0.0$^{+0.44}_{-0.44}$</td>
<td>0.05$^{+0.48}_{-0.36}$</td>
<td>0.02$^{+0.42}_{-0.43}$</td>
<td>0.22$^{+0.36}_{-0.35}$</td>
<td>0.12$^{+0.31}_{-0.29}$</td>
<td>0.13$^{+0.30}_{-0.32}$</td>
<td>0.13$^{+0.32}_{-0.31}$</td>
</tr>
<tr>
<td>$\sigma v$ [10$^{-26}$ cm$^3$/s]</td>
<td>1.97$^{+1034}_{-1.38}$</td>
<td>1.28$^{+4.1e6}_{-0.61}$</td>
<td>1.23$^{+1.7e6}_{-0.55}$</td>
<td>0.96$^{+1.3e6}_{-0.37}$</td>
<td>1.04$^{+1.3e6}_{-0.42}$</td>
<td>359$^{+9.7e5}_{-327}$</td>
<td>4.3$^{+1.6e5}_{-0.9}$</td>
</tr>
<tr>
<td>$\sigma v R^2$ [10$^{-26}$ cm$^3$/s]</td>
<td>0.91$^{+0.53}_{-0.35}$</td>
<td>1.28$^{+2.02}_{-0.53}$</td>
<td>1.21$^{+0.68}_{-0.45}$</td>
<td>0.96$^{+0.43}_{-0.31}$</td>
<td>1.04$^{+0.39}_{-0.32}$</td>
<td>1.06$^{+0.42}_{-0.32}$</td>
<td>1.06$^{+0.43}_{-0.31}$</td>
</tr>
<tr>
<td>$\chi^2_{\text{GCE}}$</td>
<td>19.3</td>
<td>25.3</td>
<td>25.6</td>
<td>26.0</td>
<td>26.0</td>
<td>26.8</td>
<td>26.7</td>
</tr>
<tr>
<td>$p(\chi^2_{\text{GCE}})$</td>
<td>0.57</td>
<td>0.20</td>
<td>0.24</td>
<td>0.22</td>
<td>0.21</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>$p(\text{BR}_{\text{inv}})$</td>
<td>0.0</td>
<td>0.90</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>$p(\text{LUX})$</td>
<td>0.0</td>
<td>0.32</td>
<td>0.62</td>
<td>0.58</td>
<td>0.62</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>$p(\text{dwarfs})$</td>
<td>0.18</td>
<td>0.16</td>
<td>0.18</td>
<td>0.24</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>$p(\text{lines R3})$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$p(\text{relic den.})$</td>
<td>0.03</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.99</td>
<td>1.0</td>
</tr>
</tbody>
</table>