A comment on the emission from the Galactic center as seen by the Fermi telescope

Alexey Boyarsky$^{1,2}$, Denys Malyshev$^3$, Oleg Ruchayskiy$^4$

$^1$Ecole Polytechnique Federale de Lausanne, FSB/IP/LLPC, BSp CH-1015, Lausanne, Switzerland
$^2$Bogolyubov Institute for Theoretical Physics, Metrologichna str., 14-b, Kiev 03680, Ukraine
$^3$Dublin Institute for Advanced Studies, Astronomy & Astrophysics Section, 31 Fitzwilliam Place, Dublin, 2 Ireland
$^4$CERN TH-Division, PH-TH, Case C01600, CERN, CH-1211 Geneva 23, Switzerland

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ABSTRACT
In the recent paper of Hooper & Goodenough (2010) it was reported that γ-ray emission from the Galactic Center region contains an excess compared to the contributions from the large-scale diffuse emission and known point sources. This excess was argued to be consistent with a signal from annihilation of Dark Matter with a power law density profile. We reanalyze the Fermi data and find instead that it is consistent with the “standard model” of diffuse emission and of known point sources. The main reason for the discrepancy with the interpretation of Hooper & Goodenough (2010) is different (as compared to the previous works) spectrum of the point source at the Galactic Center assumed by Hooper & Goodenough (2010). We discuss possible reasons for such an interpretation.

1 INTRODUCTION
The origin of the emission from the Galactic Center (GC) at keV–TeV energies has been extensively discussed in the literature over last few years. In their recent paper, Hooper & Goodenough (2010) claimed that the γ-ray emission from the Galactic Center region, measured with the Fermi LAT instrument (Atwood et al. 2009) cannot be described by a combination of spectra of known point sources, diffuse emission from the Galactic plane and diffuse spherically symmetric component (changing on the scales much larger than 1°). An additional spherically symmetric component was suggested to be needed in the central several degrees. This component was then interpreted as a dark matter annihilation signal with the dark matter distribution having power law density profile $\rho(r) \propto r^{-\alpha}$, $\alpha \approx 1.34$. The observed excess is at energies between $\sim 600$ MeV and $\sim 6$ GeV and the mass of the proposed DM particle was suggested to be in the GeV energy band.

In this work we analyze the Fermi data, used in Hooper & Goodenough (2010), utilizing the data analysis tool, provided by the Fermi team.

2 DATA
For our analysis we consider 2 years of Fermi data collected between August, 4th, 2008 and August 18th, 2010. The standard event selection for source analysis, resulting in the strongest background-rejection power (diffuse event class) was applied. In addition, photons coming from zenith angles larger than 105° were rejected to reduce the background from gamma rays produced in the atmosphere of the Earth.

The Fermi point-spread function (PSF) is non-Gaussian and strongly depends on energy (Abdo et al. 2009; Atwood et al. 2009). In order to properly take it into account and better constrain the contributions from Galactic and Extragalactic diffuse backgrounds we analyze a $10^5 \times 10^5$ region around the Galactic Center.

2.1 Model
To describe emission in the $10^5 \times 10^5$ region we use the model containing two components – point sources and diffuse backgrounds.

To model the contribution from the point sources we include 19 sources from 11 months Fermi catalog (Abdo et al. 2010a) falling into the selected region plus 4 additional sources described in Chernyakova et al. (2010). We fix the positions of the sources to coordinates given in the catalog. We model their spectra as power law (in agreement with Abdo et al. 2010a).

Thus we have 46 free parameters (power law index and norm for each of the sources) to describe the point-source component of the model.

To describe the diffuse component of emission, we use the models for the Galactic diffuse emission (gll_iem_v02.fit) and isotropic (isotropic_iem_v02.fit) backgrounds that were developed by the LAT team and recommended for the high-level analysis (Abdo et al. 2010b). These models describe contributions from galactic and extragalactic diffuse

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1 See e.g. http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools
2 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/likelihood_tutorial.html
Fig. 1. The map of significance of residuals for the region around the Galactic Center.

The data analysis was performed using the LAT Science Tools package with the P6_V3 post-launch instrument response function (Rando et al. 2009).

We find the best-fit values of all parameters of the model of Section 2.1 (using gtlike likelihood fitting tool) and determine resulting log-likelihood (Mattox et al. 1996) of the model. Best fit values for the obtained fluxes agree within statistical uncertainties with fluxes reported in Chernyakova et al. (2010) (e.g. for the central components). The discrepancy is then due to a different interpretation. They assume that there is no significant change in the spectrum of the central source at \( \sim 6 \times 10^{-8} \) cts/cm²/s above 1 GeV, compared to the \( \sim 5 \times 10^{-9} \) cts/cm²/s at the same energies in HG10. The change of the slope of the source spectrum below \( \sim 100 \) GeV, as compared with the HESS data is explained by Chernyakova et al. (2010) with the model of energy dependent diffusion of protons in the few central parsecs around the GC. Alternatively, the spectrum can be explained with the model developed in Aharanian & Neronzov (2005).

The low-energy (GeV) component of the spectra in this model is explained by synchrotron emission from accelerated electrons, while high-energy (TeV) one by inverse Compton radiation of the same particles. According to the analysis of Abdo et al. (2010a); Chernyakova et al. (2010) the central point source provides significant contribution to the flux in the 1.25° central region. HG10 suggest, apparently, a different interpretation. They assume that there is no significant change in the spectrum of the central source at \( \sim 100 \) GeV and the spectrum observed by HESS at high energies continues to lower energies. Then, large fraction of the flux between the energies \( \sim 600 \) MeV and \( \sim 6 \) GeV has to be attributed to the Galactic black hole Sgr A* which was taken in HG10 to be a featureless power-law starting from energies about 10 TeV (results of HESS measurements, blue points with error bars in Fig. 2 (Aharonian et al. 2004; van Eldik et al. 2008)) and continuing all the way down to \( \sim 1 \) GeV. The flux attributed in this way to the central point source is significantly weaker than in the previous works. For comparison, the (PSF corrected) spectrum of the GC point source reported in Chernyakova et al. (2010) is shown in Fig. 2 in green points. Its spectral characteristics are fully consistent with the results of 11-months Fermi catalog (Abdo et al. 2010a) and continuing all the way down to \( \sim 1 \) GeV.

The spectrum of the central point source (1FGL J1745.6-2900c, probably associated with the Galactic black hole Sgr A*) was taken in HG10 to be a featureless power-law starting from energies about 10 TeV (results of HESS measurements, blue points with error bars in Fig. 2 (Aharonian et al. 2004; van Eldik et al. 2008)) and continuing all the way down to \( \sim 1 \) GeV.

We then freeze the values of the free parameters of our model and simulate spatial distribution of photons at energies above 1 GeV (using gtmodel tool). The significance of residuals, (Observation - Model)/statistical error, is shown in Fig. 1. We see the absence of structures in the central 2° region. The average value of residuals is about 10% in the 2° region around the GC, compatible with estimated systematic errors (10-20%) of Fermi LAT at 1 GeV.

Thus we see that the adopted model (point sources plus galactic and extragalactic diffuse components) explains the emission from the GC region and no additional components is required.

3 DISCUSSION

We conclude that the signal within central 1°-2°, containing the “excess” found by Hooper & Goodenough (2010) (HG10 hereafter), can be well described by our model: (point sources plus Galactic and extragalactic diffuse background components). The discrepancy is then due to a different interpretation of the data.

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**Figure 2. Spectrum of the point source at the GC reported in Chernyakova et al. (2010) (green points) together with the HG10 total spectrum from 1.25° (black points), excess (blue squares) and GC point source flux from HG10 (red open circles). Continuation of the HESS data van Eldik et al. (2008); Aharonian et al. (2004) (blue points) data with a power law is shown with dashed black line.**
gies we collected “front converted” (FRONT) photons from the region of the width $5^\circ$ around the Galactic Plane (the “inner” region) and from the “outer” region as demonstrated on the left panel in Fig. 3. The count rate from each of these regions was divided by the constant effective area ($3500 \text{ cm}^2$) to obtain the flux. One sees that the total emission from both regions demonstrates the same spectral behavior as the excess of HG10, suggesting that this spectral shape is not related to the physics of the several central degrees. This drop of flux at low energies is mainly due to the decreasing effective area of the satellite. If we properly take into account the dependence of the effective area on energy, we obtain the spectrum that “flattens” at small energies and exceeds by a significant factor the flux from the central point source (as it should) (compare red and magenta points on the right panel in Fig. 3).

Another reason for the decrease of the HG10 spectrum is the increase of Fermi LAT PSF at low ($\lesssim 1 \text{ GeV}$) energies. This means that if one collects photons from a relatively small region, such that a contribution from its boundary (with the PSF width) is comparable to the flux from the whole region, the spectrum would artificially decline, due to increasing loss of photons at low energies. To disentangle properly what photons in the PSF region had originated from a localized source, and what are parts of the diffuse background, special modeling is needed. In the monotonic spectrum of the GC, obtained by Chernyakova et al. (2010a); Chernyakova et al. (2010), both these effects (effective area and PSF) were taken into account as it was obtained from $10^7 \times 10^8$ region, using the Fermi software.

To further check the nature of the emission from the central several degrees, we took a fiducial model, that contained the same galactic and extragalactic diffuse components plus all the same point sources, but excluding the point source in the center. We then fit our data to this new model. Such a fit attempts to attribute as many photons as possible from the region around the GC to the emission of diffuse components. The procedure leaves strong positive residuals within the central $1^\circ$–$2^\circ$. The spectrum of these residuals is consistent with the spectrum of the central point source of Chernyakova et al. (2010) (green points in Fig. 3). To demonstrate, that the spatial distribution of these residuals is fully consistent with the PSF of Fermi, we compare their radial distribution in various energy bins with the radial distribution around the Crab pulsar (as it was done e.g. in Neronov et al. (2010)). The pulsar wind nebula, associated with the Crab has an angular size $\sim 0.05^\circ$ (Hester 2008). Thus, for Fermi LAT Crab is a point source. The radial profile of residuals at all energies has the same shape as Crab, as Fig. 5 clearly demonstrates. As an additional check, we repeated the above test using only FRONT photons (as in this case the PSF is more narrow) and arrived to the same conclusion.

The above analysis demonstrates that the emission around the GC in excess of diffuse components (galactic and extragalactic) is fully consistent with being produced by the point source with the power-law spectrum, obtained in Abdo et al. (2010a); Chernyakova et al. (2010), and no additional component is required.

A different question however is whether such an additional component may be ruled out. To this end we have added to our model of Sec. 2.1 an additional spherically symmetric component, whose intensity is distributed around the center as $\rho^2(r)$ (where $\rho(r) \propto r^{-1.54}$, as found in HG10). We observe, that such a procedure does improve the fit (change in the log-likelihood is 25 with only one new parameter added). The resulting spectral component is shown in Fig. 5. Some of the photons from the galactic diffuse background were attributed by the fit procedure to the new component, concentrated in several central degrees (within the Galactic Plane). This phenomenon is probably related to the complicated and highly non-uniform

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**Figure 3.** Left: the “inner” ($5^\circ$ around the Galactic plane) and “outer” regions. Right: Effects of the energy dependence of the effective area for the spectra of the “inner” and “outer” regions.
Figure 4. Radial profile of residuals at different energies around the GC as compared to the radial profile of Crab emission (renormalized so that the total flux in each energy range coincide). In both cases only FRONT photons were used.

Figure 5. Spectrum of an additional spherically symmetric component, distributed around the GC as the HG10 excess.

We should also note that HG10 modeled diffuse background differently. They considered contributions from the Galactic disk and spherically symmetric emission in the region outside central 2° and then extrapolated the diffuse model into the innermost 1° – 2°, arguing that the contribution does not vary significantly in the range 2° – 10° off-center. The background model we used (see Abdo et al. 2010a; Abdo et al. 2010b for the detailed description) is different from that of HG10, especially in the central 1–2°, where the model flux is higher than the one extrapolated from larger galactic longitudes, as one can clearly see on the right panel of the Fig. 6.

Having the above considerations in mind, we think that the spectrum of the central region, changing monotonously with the energy, is well described by purely astrophysical model of the central point source and therefore present data do not require any additional physical ingredients, such as DM annihilation signal or additional contributions from millisecond pulsars. However, to firmly rule out the emission from DM annihilation in the GC, more detailed model of the galactic diffuse background is required. Additionally, with the future data, better statistics will reduce the error bars on the data point around ∼ 100 GeV which will be helpful to better understand the central point source physics.

See “Description and Caveats for the LAT Team Model of Diffuse Gamma-Ray Emission” by the Diffuse and Molecular Clouds Science Working Group, Fermi LAT Collaboration, http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ring_for_FSSC_final4.pdf

in the central region galactic diffuse background (cf. also the right panel of the Fig. 6).

7 See “Description and Caveats for the LAT Team Model of Diffuse Gamma-Ray Emission” by the Diffuse and Molecular Clouds Science Working Group, Fermi LAT Collaboration, http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ring_for_FSSC_final4.pdf.
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REFERENCES

Abazajian, K. N. 2010, ArXiv:1011.4275
Abdo, A. A. et al. 2009, Astroparticle Physics, 32, 193
Abdo, A. A., et al. 2010a, ApJS, 188, 405, ArXiv:1002.2280
Abdo, A. A., et al. 2010b, Phys. Rev. Lett., 104, 101101, ArXiv:1002.3603
Aharonian, F., & Neronov, A. 2005, ApJ, 619, 306, ArXiv:astro-ph/0408303
Aharonian, F., et al. 2004, Astron. Astrophys., 425, L13, ArXiv:astro-ph/0408145
Atwood, W. B., et al. 2009, Astrophys. J., 697, 1071, ArXiv:0902.1089
Chernyakova, M., Malyshev, D., Aharonian, F. A., Crocker, R. M., & Jones, D. I. 2010, ArXiv:1009.2630
Hester, J. J. 2008, ARA&A, 46, 127
Hooper, D., & Goodenough, L. 2010, ArXiv:1010.2752
Mattox, J. R. et al. 1996, ApJ, 461, 396
Neronov, A., Semikoz, D. V., Tinyakov, P. G., & Tkachev, I. I. 2010, A&A, ArXiv:1006.0164
Rando, R., et al. 2009, ArXiv:0907.0626
van Eldik, C., et al. 2008, J. Phys. Conf. Ser., 110, 062003, ArXiv:0709.3729