Mon. Not. R. Astron. Soc. **000**, 1–4 (2014) Printed 5 April 2019 (MN LaTeX style file v2.2)

Annihilating dark matter or noise?: A statistical examination of the *Fermi* GeV excess around the Galactic Centre

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ABSTRACT

Excess *Fermi* GeV emission around the Galactic Centre has been interpreted as a possible signature of annihilating dark matter. Here we analyse three aspects of this claim: its spectral cutoff, the correlation between the spectral shape of the purported signal and known noise components, and its brightness profile. Experimentally, the correlations that exist between the GeV excess and known sources of noise make it difficult to conclude that a dark matter signal claim can be made without independent direct detection confirmation. As a possible way forward, we introduce three criteria that could potentially help to validate a dark matter annihilation signal in gamma rays.

Key words: (cosmology:) dark matter – gamma-rays: observations – (stars:) pulsars: general

1 INTRODUCTION

Distinguishing signal from noise is an everyday problem for experimental scientists. Examples of noise mimicking a potential signal will be familiar to everyone working in astrophysics. The Bicep2 finding of a B-mode polarization pattern is just the latest public example where residual foregrounds confused the sought signal (Ade et al. 2014). In retrospect, the early Bicep2 claim resembled a dust polarization signature but it was difficult to ascertain at the time of the original claim (Flauger, Hill & Spergel 2014).

Noise subtraction can be especially daunting in situations when the signal has to be extracted simultaneously from the same region of the sky and without a well-characterised noise model from neighbouring frequencies. Such is the case when attempting a detection of annihilating dark matter at the Galactic Centre. Over the past few years, a number of groups have found possible excess *Fermi* GeV emission around the Galactic Centre (Goodenough & Hooper 2009; Hooper & Linden 2011; Boyarsky, Malyshev & Ruchayskiy 2011; Abazajian & Kaplinghat 2012; Daylan et al. 2014). This result has opened the door to an avalanche of publications about dark matter models and interpretations. While it is wonderful to see practical applications of theoretical dark matter models and a possible solution to one of the hardest problems in science today, we might be over-interpreting the evidence.

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Rather than trying to delve into another discussion about the origin of the GeV excess, we will try to reduce our work to a more basic proposition: does the GeV excess constitute sufficient evidence of a dark matter signal or reflects the limitations of the current noise model?. Or more specifically, are the GeV excess and known sources of noise at the Galactic Centre uncorrelated?. We assume the perspective of an experimentalist perched on a laboratory stool pondering recent findings.

For practical purposes, we consider a situation in which dark matter annihilation represents the sought signal. Every other non-related gamma-ray contribution in the region of interest represents noise. We thus interpret noise in its broadest sense with four principal known noise components: π^0 decay (Ackermann et al. 2012), inverse Compton (Ackermann et al. 2012), bremsstrahlung (Ackermann et al. 2012), and unresolved point sources *e.g.,* millisecond pulsars (MSPs) (Abazajian & Kaplinghat 2012; Mirabal 2014; Yuan & Zhang 2014; Calore, Di Mauro & Donato 2014). For a more complete picture, one should also account for all the uncertainties/unknowns that can potentially contribute to the noise model. Figure 1 shows a schematic view of the noise components considered here.

In this brief note, the goal is to conduct a statistical assessment of the GeV excess. For this purpose we consider three specific aspects of the GeV excess: its spectral cutoff (Section 2), the correlation between the spectral shape of the purported signal and the noise components (Section 3), and its brightness profile (Section 4). Finally, some conclusions and selection criteria are presented in Section 5.

2 SPECTRAL CUTOFF

One of the most surprising facts about the GeV excess is that it displays a spectral cutoff that is aligned with the cutoff observed in the spectrum of *Fermi* MSPs (Hooper & Linden 2011; Abazajian & Kaplinghat 2012). A few years ago Baltz, Taylor & Wai (2007) anticipated that the spectral similarities between annihilating weakly interacting massive particles (WIMPs) and gamma-ray pulsars would be the most problematic obstacle to proving a dark mater astrophysical signal. Their reasoning was rather straightforward: pulsar emission and dark matter annihilation are predicted to share similar spectral signatures with sharp cutoffs. However, the idea was introduced in the context of dark matter subhalos and preceded all the extraordinary *Fermi* discoveries (Abdo et al. 2013). The intricacies of the Galactic Centre did not even enter into the discussion. A placement of the GeV excess in the Galactic Centre adds an extra layer of complexity.

Figure 1 clearly illustrates the remarkable match between the GeV excess and the unresolved MSP noise component. Shown are the GeV excess data set and a dark matter template from the analysis performed by Daylan et al. (2014). For comparison, we also plot the average contribution from unresolved MSPs in the Galactic Centre derived by Calore, Di Mauro & Donato (2014), scaled in flux. It is easy to see the conspicuous alignment of the cutoff at energies greater than 2 GeV.

The 100 MeV-1 TeV energy range covered by *Fermi*-LAT is the preferred scale for a myriad of viable dark matter particle models in the literature. Sticking with some of the most popular, models stretch from the WIMPless in the MeV range (Feng & Kumar 2008; Albert et al. 2014) to WIMPs in the GeV to TeV range (Jungman, Kamionkowski & Griest 1996). Our first question is obvious: what is the probability that out of all well-motivated dark matter candidates the one found shares the same spectral cutoff with a known noise component, namely unresolved MSPs?.

The problem would be very difficult to solve if MSP spectral cutoffs were distributed over a very wide energy range. However, the observed MSP spectral cutoffs actually cluster in a fairly narrow energy band 0.84 GeV $\lesssim E_{\rm cut} \lesssim$ 5.4 GeV (Abdo et al. 2013). To estimate the probability of a chance alignment between dark matter annihilation and a noise component, one can solve a version of the classical birthday problem (Von Mises 1932). The dark matter candidate must match the MSP cutoff within a very narrow energy bin width $\Delta E \sim 5$ GeV. Accordingly, there are 200 possible energy bins between 100 MeV and 1 TeV where this might have happened. Then the probability of having the same energy cutoff $P(same)$ by chance is rather small

$$P(same) = 1 - P(different) = 1 - \frac{199}{200} = 5 \times 10^{-3}. \quad (1)$$

A chance alignment is even less likely if one chooses to include sterile neutrinos and axions as possible dark matter candidates over a much wider energy range.

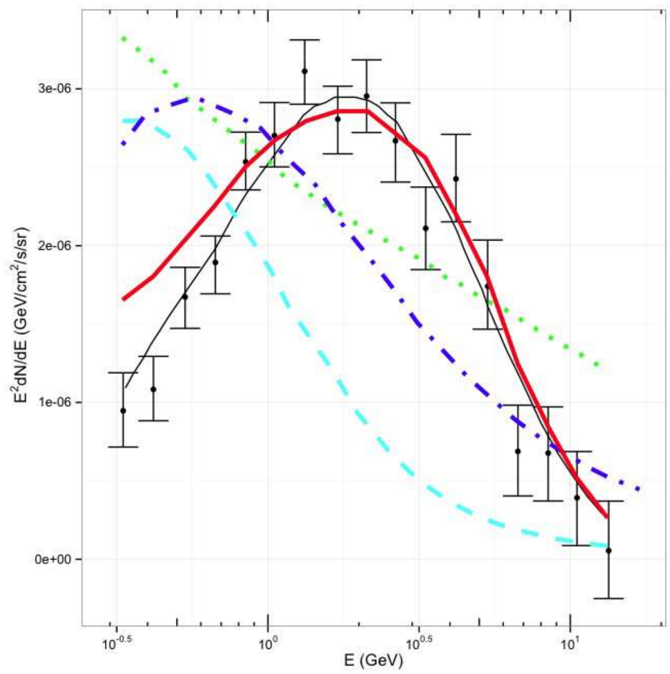

Figure 1. The spectrum of the GeV excess for an NFW profile with $\gamma = 1.26$ from the analysis by Daylan et al. (2014). Shown in the black solid line is the spectrum for a 35 GeV dark matter particle annihilating to $b\bar{b}$ with a cross section $\sigma v = 1.7 \times 10^{-26}$ cm^3 s^{-1} (Daylan et al. 2014). The noise is split into four components: π^0 decay (blue, dash-dotted), inverse Compton (green, dotted), bremsstrahlung (cyan,dashed) all taken from Ackermann et al. (2012), and the average unresolved MSP spectrum (thick solid red) from Calore, Di Mauro & Donato (2014). All components have been scaled in flux for clarity.

3 CORRELATION BETWEEN NOISE AND SIGNAL

Next, we extend our analysis by considering the GeV excess over the entire *Fermi* range. Abazajian & Kaplinghat (2012) noticed that the MSP noise component tends to be softer than the GeV excess below 0.8 GeV (see Figure 1). One could suppose that over-subtraction at energies below 1 GeV of any of the noise components rendered in Figure 1 is the cause for the slight mismatch. But let us rather pose the following question: is there a correlation between the spectral shape of the GeV excess and the spectral shape of individual noise components?.

For this exercise, we take the 17 spectral points from Daylan et al. (2014) and find their corresponding E^2 dN/dE intercepts in the Ackermann et al. (2012) and Calore, Di Mauro & Donato (2014) curves. We then perform a Spearman correlation analysis and find the highest Spearman's rank correlation coefficient $\rho = 0.973$ with a p-value of $p_{\rm s} = 5.8 \times 10^{-11}$ for unresolved MSPs, which suggests that a real correlation exists between the purported signal and a known source of noise.

Despite a near perfect spectral match, it has been argued that the predicted flux level of the MSP noise component is considerable lower than the observed GeV excess (Cholis, Hooper, & Linden 2014). In order to study the influence of the flux normalization, we run a Kolmogorov-

Smirnov (KS) test between the Daylan et al. (2014) points and the Calore, Di Mauro & Donato (2014) values scaled in flux (15×), which finds consistency with the samples having been drawn from the same parent distribution ($P = 0.98$).

Taken together, these significant correlations between the spectral shape of the GeV excess and the spectral shape of a known background could instead be a symptom of problems with the normalization term in a very complex noise subtraction exercise (Strong & Mattox 1996; Porter et al. 2008; Casandjian & Grenier 2008; Ackermann et al. 2012).

4 BRIGHTNESS PROFILE

Finally, the third aspect of the GeV excess we would like to discuss is its spatial extension. A canonical Navarro-Frenk-White (NFW) density profile with $\gamma = 1.4$ fits the brightness profile out to $\sim 12°$ (Daylan et al. 2014). Figure 2 shows the brightness profile from Daylan et al. (2014) and the corresponding NFW profile. An NFW density profile is quite majestic (Navarro, Frenk & White 1996), but in reality an observer can only measure a projected brightness profile. For Over small radial ranges, a generalized NFW profile asymptotes to a rather generic brightness fall that follows a single power-law index. As an illustration, we show an inverse-square law in Figure 2 where one can see that the NFW fit from Daylan et al. (2014) and the ψ^{-2} power law with no prior assumption about dark matter are nearly indistinguishable.

Our third question takes form: are these radial trends unique to annihilating dark matter?. Given the complexities of our own Galactic Centre and the extent of the GeV excess, we look for guidance in our nearest neighbour, M31. Andromeda is the nearest spiral galaxy similar to our own Milky Way and offers a unique line of sight encompassing both its bulge and galactic centre. Similar to the properties of the Milky Way, M31's stellar halo follows a power-law component with index -2.2 ± 0.2 (Gilbert et al. 2012). Further, Abazajian & Kaplinghat (2012) first noted that the low-mass X-ray binaries (LMXBs) population in M31 follows a power-law index of -1.5 ± 0.2 (see Figure 2). If LMXBs are the progenitors of MSPs (Grindlay & Bailyn 1988; Kulkarni & Narayan 1988), it is reasonable to expect that the unresolved MSP contribution will follow a similar spatial distribution.

Even if one dismisses known point sources as the perpetrators, M31 shows unresolved diffuse X-ray emission that extends to $8'$ from its galactic centre (Li & Wang 2007; Bogdán & Gilfanov 2010), which at the distance of our own Galactic Centre would fill its surrounding $\sim 13°$. This extension approximately matches the observed width of the GeV excess. There are related hints of unresolved diffuse X-ray emission in our own Galactic Centre that might indicate a population of uncharted high-energy sources or serious shortcomings in our understanding of the interstellar gas (Yusef-Zadeh et al. 2013).

Although not causally connected, these are spatial noise templates that could account for both the extent and profile of the GeV excess without direct dark matter involvement.

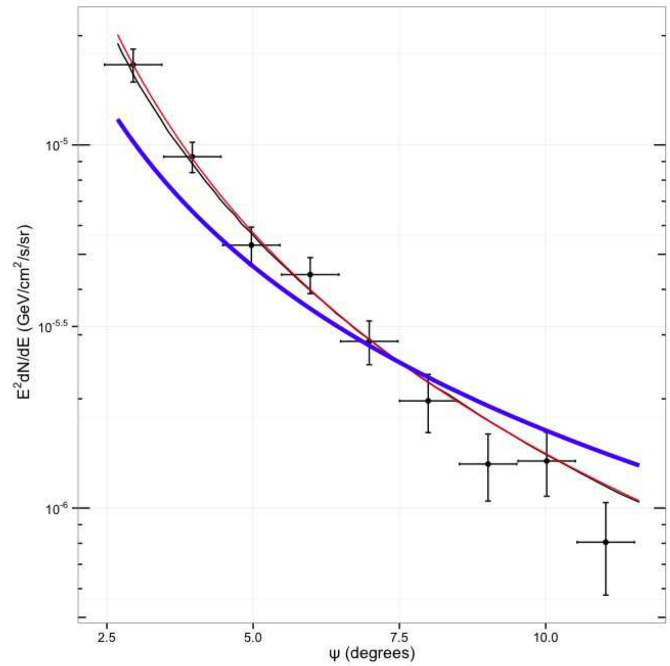

Figure 2. Flux points from the concentric ring analysis carried out by Daylan et al. (2014). The dark line shows the prediction for a generalized NFW profile with $\gamma = 1.4$. In red (nearly indistinguishable) we show an ψ^{-2} fit with no prior assumption about dark matter. The thick blue line shows the $\psi^{-1.5}$ radial distribution of LMXBs in M31 (Abazajian & Kaplinghat 2012).

5 CONCLUSION AND FUTURE WORK

We have considered three aspects of the GeV excess at the Centre of our Galaxy. As an experimentalist, the correlation that exists between individual noise components and the purported GeV excess cannot convincingly establish that it is an actual signal under the broad noise definition introduced here. Therefore, we conclude that the discovery criteria required to make a dark matter claim has not yet been met.

Using anomalies in the Galactic Centre to help pinpoint similar signatures in other sections of the Galaxy including dwarf galaxies and dark matter subhalos appears to be a sensible approach, but it might not be the most efficient route to take in every instance. A large variety of alternative searches that are conducted routinely by the *Fermi* collaboration and other groups can be used in lieu of the Galactic Centre approach (Ackermann et al. 2013, 2014).

Regardless of the final verdict on the GeV excess, it is clear that a more comprehensive discussion about what constitutes evidence for an annihilating dark matter signal in our Galaxy is needed, as other claims might appear again in the future. For an opening proposal, we suggest imposing the following three criteria before making any claim:

(i) There should not be a near perfect energy alignment between the dark matter spectral break and the cutoffs of any well-known noise components.

(ii) There should not be a correlation between the spectral shape of the dark matter signal and the spectral shape of known sources of noise.

(iii) There should be a spatially extended brightness profile. If the generic power-law index corresponds to $m = 2.0 \pm 0.2$, then we can borrow the traditional criterion for discovery in particle physics by requiring that an annihilating dark matter brightness profile be at least 5σ away and falls off as ψ^{-m}, with *i.e.,* $m \lesssim 1$ or $m \gtrsim 3$ for a distinct signature.

In our humble opinion, any dark matter signal worth pursuing in earnest should meet at least two out of the three criteria. Otherwise, direct detection is required to confirm any claim. With such tentative results, it might be more practical to devote theoretical efforts to other unsolved problems in astrophysics until a signal from direct detection experiments is found and then and only then return to the *Fermi* archives for final astrophysical confirmation.

Meanwhile, the appearance of tensions with other observations should be used discard claims that do not meet the 2/3 standard. In the case of the GeV excess, we are starting to reach the limits needed to evaluate possible tensions with dwarf galaxies observations (Geringer-Sameth, Koushiappas & Walker 2014; Anderson 2014).

As it stands now, one might invoke a vast cosmic conspiracy at work in the GeV excess (it is plausible) that makes dark matter annihilation nearly indistinguishable from known sources of noise. Or maybe one should pursue a possibly more banal explanation. To be fair, it is important to once again remark that the proposed criteria discussed here do not rule out a dark matter origin for the GeV excess (only direct detection limits can do that). In closing, we leave it to the adopters of these criteria (if any) to reach their own conclusions and expand the list.

ACKNOWLEDGEMENTS

I acknowledge support from the Spanish taxpayers through a Ramón y Cajal fellowship during the early stages of this work. I thank José Luis Contreras for helpful comments. I would like to acknowledge all the cooks at the ramen shop inside the Kanayama Station in Nagoya, where the bulk of the calculations were completed during the Fifth International *Fermi* Symposium. This research was supported by a senior appointment to the NASA Postdoctoral Program at the Goddard Space Flight Center, administered by Oak Ridge Associated Universities through a contract with NASA.

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