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A tale of tails: Dark matter interpretations of the Fermi GeV excess in light of background model systematics

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Several groups have identified an extended excess of gamma rays over the modeled foreground and background emissions towards the Galactic center (GC) based on observations with the Fermi Large Area Telescope. This excess emission is compatible in morphology and spectrum with a telltale sign from dark matter (DM) annihilation. Here, we present a critical reassessment of DM interpretations of the GC signal in light of the foreground and background uncertainties that some of us recently outlined in Calore et al. (2014). We find that a much larger number of DM models fits the gamma-ray data than previously noted. In particular: (1) In the case of DM annihilation into $b\bar{b}$, we find that even large DM masses up to $m_{\chi} = 74$ GeV are allowed at $p$-value $>0.05$. (2) Surprisingly, annihilation into nonrelativistic $h\bar{h}$ gives a good fit to the data. (3) The inverse Compton emission from $\mu^+\mu^-$ with $m_{\mu} \sim 60-70$ GeV can also account for the excess at higher latitudes, $|b| > 2^\circ$, both in its spectrum and morphology. We also present novel constraints on a large number of mixed annihilation channels, including cascade annihilation involving hidden sector mediators. Finally, we show that the current limits from dwarf spheroidal observations are not in tension with a DM interpretation when uncertainties on the DM halo profile are accounted for.

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I. INTRODUCTION

Shedding light onto the origin of Dark Matter (DM) is one of the biggest challenges of current particle physics and cosmology. The most appealing particle DM candidates are the so-called weakly interacting massive particles (WIMPs) [1–3]. Among the different indirect messengers, gamma rays play a dominant role and they have often been defined as the golden channel for DM indirect detection (see Ref. [4] for an extensive review). The main challenge is to disentangle putative DM signals from the large astrophysical foregrounds and backgrounds that are generally expected to dominate the measured fluxes. The best example of a challenging target is the Galactic center (GC), where on the one hand the DM signal is expected to be brighter than anywhere else on the sky [5,6], but—given our poor knowledge of the conditions in the inner Galaxy—the astrophysical foreground and background (either from Galactic point sources or from diffuse emissions) is subject to very large uncertainties.

In this respect, it is not surprising for unmodeled gammaray contributions to be found towards the inner part of the Galaxy, above or below the expected standard astrophysical emission. Indeed, an extended excess in gamma rays at the GC was reported by different independent groups [7–16], using data from the Fermi Large Area Telescope (LAT), and dubbed “Fermi GeV excess” as it appears to peak at energies around 1–3 GeV. Intriguingly, the excess emission shows spectral and morphological properties consistent with signals expected from DM particles annihilating in the halo of the Milky Way. Recently, the existence of a GeV excess emission towards the GC above the modeled astrophysical foreground/background was also confirmed by the Fermi-LAT Collaboration [17]. This revitalizes the importance of understanding the origin of this excess.

Given that the Galactic diffuse emission is maximal along the Galactic disk and that a DM signal is expected to be approximately spherical, the preferable region to search for a DM annihilation signal in Fermi-LAT data is actually a region that, depending on the DM profile, extends between a few degrees and a few tens of degrees away from the GC, above and below the disk [18–23]. Indeed, different groups [15,24,25] extracted an excess with spectral properties similar to the GeV excess at the GC from the gamma-ray data at higher Galactic latitudes, up to about $|b| \sim 20^\circ$. The extension to higher latitudes is a critical test that the DM interpretation had to pass, and apparently has passed.

However, when talking about excesses, a rather central question is An excess above what? The excess emission is defined above the astrophysical foregrounds and backgrounds, i.e. the Galactic diffuse emission, point sources and extended sources, modeled in the data analysis. Most previous studies of the Fermi GeV excess are based on a small number of fixed models for the Galactic diffuse emission. These models were built for the sole purpose of point source analyses and hence introduce uncontrollable
systematics in the analysis of extended diffuse sources. In addition, since they are the result of fits to the data, they may falsely absorb part of the putative excess emission in some of their free components. This may in turn, lead to biased or overly constraining statements about the spectrum and morphology of the Fermi GeV excess emission.

To remedy this situation, in Ref. [26] some of the present authors reassessed the spectral and morphological properties of the putative GeV excess emission from the inner Galaxy. Relevant systematic uncertainties came from the modeling of the Galactic diffuse emission, Fermi-LAT detected point sources and the Fermi bubbles. The emission associated with the inner Galaxy was found to be larger than expected from standard Galactic diffuse emission models [where the distribution of the cosmic-ray (CR) sources peaks at kpc distances from the GC [27]]. This “excess” is—by definition—an excess above Galactic diffuse emission models that lead to subdominant contribution from the inner kpc around the GC. It hence should be understood as a characterization of the dominant part of the emission from these central spatial regions, which is robust with respect to uncertainties in the emission from other parts along the line of sight. This emission features a spectrum that rises at energies below 1 GeV with a spectral index harder than two, peaks at 1–3 GeV, and has a high-energy tail that continues up to 100 GeV. The large uncertainties in the spectrum were estimated from a study of residuals along the Galactic disk. The observed emission was found to be consistent with the hypothesis of a uniform gamma-ray energy spectrum at 95% C.L., with spherical symmetry around the GC and a radial extension of at least 1.5 kpc.

The proper treatment of systematic uncertainties has important consequences for the interpretation of the Fermi GeV excess: Although all studies find that the emission peaks around 1–3 GeV, the low- and high-energy tails of the spectrum are much more uncertain. As we will see below, this allows significant—previously ignored—freedom for DM models fitting the excess.

In what follows, we focus on the DM interpretations of the excess emission. We will therefore not further discuss potential astrophysical explanations, like the emission from an unresolved population of pointlike sources concentrated in the very center of the Galaxy (see [28–31] for relevant discussions) or the injection of leptons and/or protons during a burst event at the GC some kilo-/mega-years ago [32,33]. In particular, we will here entertain the possibility that all of the excess emission is coming from a single diffuse source. This obviously does not have to be the case, but it is a suggestive (and from the perspective of a particle

1With inner Galaxy we refer to the region contained in few tens of degrees away from the GC and avoiding the very inner few degrees in latitude. In particular, in Ref. [26] the region considered is $|l| < 20'$ and $2' < |b| < 20'$.
We show the differential intensity at a reference energy of 2 GeV. At this energy the putative excess emission is compared to other foreground/backgrounds—strongest, so the uncertainties due to foreground/background subtraction systematics are expected to be the smallest.

The intensities were derived by a careful rescaling of results in the literature that fully takes into account the assumed excess profiles. In most works, intensities are quoted as averaged over a given region of interest (ROI). Instead of showing these averaged values, which depend on the details of the adopted ROI, we use the excess profiles to calculate the differential intensity at a fixed angular distance from the GC. These excess profiles usually follow the predictions similar to those of a DM annihilation profile from a generalized Navarro-Frenk-White (NFW) density distribution, which is given by

$$\rho(r) = \rho_s \frac{r_s^3}{r^3 (r + r_s)^{3-\gamma}}. \tag{1}$$

Here, $r_s$ denotes the scale radius, $\gamma$ the slope of the inner part of the profile, and $\rho_s$ the scale density. As reference values we will—if not stated otherwise—adopt $r_s = 20$ kpc and $\gamma = 1.26$, and $\rho_s$ is fixed by the requirement that the local DM density at $r_\odot = 8.5$ kpc is $\rho_\odot = 0.4$ GeV cm$^{-3}$ [95,96].

We note that the intensities that we quote from Ref. [26] refer already to a $\bar{b}b$ spectrum and take into account correlated foreground systematics as discussed below. In Ref. [26] a broken power law was found to give a fit as good as the DM $\bar{b}b$ spectrum. Assuming a broken power law, the intensities in Fig. 1 would be somewhat larger.

We find that all previous and current results (with the exception of Ref. [7], which we do not show in Fig. 1) agree within a factor of about 2 with a signal morphology that is compatible with a contracted NFW profile with slope $\gamma = 1.26$, as it was noted previously [15,26]. As mentioned in our Introduction, the indications for a higher-latitude tail of the GeV excess profile is a rather nontrivial test for the DM interpretation and provides a serious benchmark for any astrophysical explanation of the excess emission. However, we have to caution that most of the previous analyses make use of the same model for Galactic diffuse emission (P6V11). An agreement between the various results is hence not too surprising. Instead in the work of Ref. [26], the $\pi^0$, bremsstrahlung and ICS emission maps, where calculated as independent components, with their exact morphologies and spectra as predicted from a wide variety of foreground/background models. As it was shown in Ref. [26], the exact assumptions on the CR propagation and the Galactic properties along the line of sight can impact both the spectrum and the morphology (which also vary with energy) of the individual gamma-ray emission maps. To probe the associated uncertainties on those diffuse emissions, the authors of Ref. [26] built different models allowing for extreme assumptions on the
gamma-ray energies. The first two contributions trace with
good accuracy the Galactic gas distribution and, as a
consequence, they are filamentary in their morphology.
The ICS component, instead, is much more diffuse and
could potentially contaminate or even mimic diffuse signals
from DM annihilation.

In most of the previous studies on the GeV excess
[11,12,14,15,24] the contribution from the Galactic diffuse
emission has been modeled by using the P6V11 model
provided by the Fermi-LAT Collaboration. This
model was originally developed to subtract the diffuse gamma-ray
background for pointlike source emission studies, and its
authors explicitly warn against using it for the study of
extended diffuse contributions. Reference [26] showed that
the P6V11 model has an unusually hard ICS component at
energies above 10 GeV (this is not apparent on first sight,
since ICS, $\pi^0$ and bremsstrahlung components are not
separate in this model). In template regression analyses,
this is likely to lead to over subtracting the emission above
10 GeV, leading to artificial cutoffs in the GeV excess
template at these energies.

In Fig. 2, we show the energy spectrum of the Fermi
GeV excess as derived in Ref. [26], including systematic
and statistical errors, compared to various DM annihilation
spectra that we will discuss further below. In contrast to
previous analyses, we find a clear power-law-like tail at
energies above 10 GeV. However, foreground/background
model uncertainties introduce large uncertainties that are
correlated between the energy bins. Their effect on the
fitted spectrum is rather simple to understand and illustrated
in the various panels of Fig. 2. The main foreground/
background components are ICS, $\pi^0$ and bremsstrahlung.
At first order, the modeling of these components can be off
in their normalization or their slope, leading to residuals in
the fit to the data that are partially absorbed by the Fermi
GeV excess template. Reference [26] estimated the size of
this effect from a study of residuals along the Galactic disk,
and showed that it can lead to a broadening or narrowing
of the Fermi GeV excess spectrum, as shown in Fig. 2.
An immediate implication is that, in light of these uncer-
tainties, the Fermi GeV excess spectrum can be fit
reasonably well with a broken power law and different
spectra from DM annihilation models.4

The impact of foreground/background model uncertain-
ties on the Fermi GeV excess spectrum can be parametrized
in terms of the covariance matrix of the flux uncertainties.
The principal components of the covariance matrix reflect the
above background variations, which we found to be at

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2Although the intensity of the Fermi GeV excess that was
found in Ref. [17] agrees at 2 GeV with previous findings, one
has to be careful with using the preliminary energy spectra
presented in that work for spectral studies. In particular for two of
the presented background models, the spectral slopes of the
background components were explicitly not tuned to match the
observations. This may bias the residual gamma-ray excess
towards higher energies, which could lead to biased results when
fitting the excess spectrum.


4Ref. [26] also estimated the uncertainties of the low-energy
(sub-GeV) tail of the spectrum. These uncertainties are mostly
coming from the masking of point sources. The corresponding
increase of the errors is shown in Fig. 2. At the lowest energies,
only upper limits on the flux can be derived.
the few percent level [26]. Fits to the *Fermi* GeV excess spectrum are then performed using this simple $\chi^2$ function,

$$\chi^2 = \sum_{ij} (\mu_i - f_i)\Sigma^{-1}_{ij} (\mu_j - f_j),$$

where $\mu_i$ and $f_i$ are the modeled and the measured flux in the $i$th energy bin, and $\Sigma$ is the covariance matrix.

Best-fit parameters and their uncertainties are then as usual derived by minimizing the $\chi^2$ function with respect to all model parameters, and determining the $\Delta\chi^2$ contours while profiling over the other parameters to infer confidence regions.

### IV. IMPLICATIONS FOR MODELS OF ANNIHILATING DARK MATTER

In typical DM scenarios, gamma rays are produced via a variety of mechanisms. As DM particles annihilate, they produce Standard Model (SM) particles such as quarks, gluons, gauge bosons and leptons. These SM particles then hadronize and/or decay producing lighter mesons that give rise to a continuous spectrum of gamma rays. Moreover, $O(\alpha_{EM})$ corrections to the two-body final state annihilation process generate gamma rays when an additional photon or an SU(2) gauge boson is emitted. Finally, at the loop level, gamma-ray lines are expected from generic WIMP models. In particular, gamma rays from loop processes or emitted via electromagnetic virtual internal bremsstrahlung and final state radiation (FSR) give hard spectra with evident cutoffs at the mass threshold, although suppressed in intensity. Both, higher order correction photons and the continuous spectrum, are emitted where the annihilation takes place and thus probe directly the annihilation rate profile. Typically, all these components are referred to as prompt emission.

The gamma-ray differential intensity (with units GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$) from the annihilation of self-conjugate DM $\chi$ is

$$\frac{dN}{dE} = \frac{\langle \sigma v \rangle_f dN_f^f}{8\pi m_\chi^2} \int_{0.8} ds p^2(r(s, \psi)),\quad (3)$$

where the sum extends over all possible annihilation channels with final state $f$, $\langle \sigma v \rangle_f$ is the annihilation cross section and $dN_f^f/dE$ is the DM prompt gamma-ray spectrum per annihilation to final state $f$. In this work, the DM prompt emission spectra for all channels except $u, d$ and $s$ quarks (generically $\bar{q}q$) and $hh$ are computed from the tabulated spectra provided by DarkSUSY [97], which, in turn, derives the $dN_f^f/dE$ from PYTHIA 6.4 [98]. We use the $\bar{q}q$ and $hh$ spectra from PPC4DMID [99] (as are not included in the DarkSUSY tables), which makes use of PYTHIA 8.135 [100]. For annihilation to bosons ($W, Z$ and $h$) and $t$ quarks, we
checked that the interpolation at mass threshold agrees with our own results from PYTHIA 8.186.

In addition to gamma rays, CR electrons and positrons are produced as final (stable) products of DM annihilations. These CR electrons/positrons, like all other electrons/positrons propagate in the Galaxy and produce ICS and bremsstrahlung emission.\footnote{CR \( p \) and \( \bar{p} \) from DM annihilations can also give their own \( \pi^0 \) emission of DM origin, but are suppressed from the \( p/\bar{p} \) measurements already by at least 5 orders of magnitude compared to the conventional Galactic diffuse \( \pi^0 \) emission.} Generally, the ICS emission is expected to be more important for DM models with significant branching ratios to (light) leptons. Therefore we separate our discussion to first address the cases when ICS emission can be safely ignored, before discussing in detail ICS emission for annihilation to leptons.

A. Single annihilation channels without ICS

We first discuss annihilation to pure two-body annihilation states for the cases when ICS emission can be safely ignored. This turns out to be all cases except annihilation to electrons and muons. In Fig. 3 we show the best-fit annihilation cross section and DM mass for all other two-body annihilation states involving SM fermions and bosons. The results are also summarized in Table I, where we furthermore give the \( p \)-value of the fit as a proxy for the goodness of fit. As with previous analyses, we find that annihilation to gluons and quark final states \( \bar{q}q \), \( cc \) and \( bb \), provides a good fit. In the case of the canonical \( bb \) final states, we find slightly higher masses are preferred compared to previous analyses, see e.g. Refs. [12,14,15]. This is because of the additional uncertainty in the high-energy tail of the energy spectrum that is allowed for in this analysis. The highest mass to \( bb \) final states that still gives a good fit (with a \( p \)-value > 0.05) is 73.9 GeV.

As the tail of the spectrum extends to higher energy, we also consider annihilation to on-shell \( tt \) and SM bosons. For \( tt \), we find that the fit is poor because the DM spectrum peaks at too high an energy (\( \sim 4.5 \) GeV rather than the observed peak at 1–3 GeV). As the \( p \)-value is very low for this channel, we do not consider it further. Pure annihilation to pairs of \( W \) and \( Z \) gauge bosons are also excluded at a little over 95% C.L. significance. However, perhaps surprisingly, annihilation to pairs of on-shell Higgs bosons (colloquially referred to as “Higgs in space” [102]) produce a rather good fit, so long as \( h \) is produced close to rest. This is analogous to the scenario studied in Ref. [103] in a different context. One interesting feature of this channel is the gamma-ray line at \( m_\gamma/2 \sim 63 \) GeV from \( h \) decay to two photons. This is clearly visible in the central panel of Fig. 2. The branching ratio for \( h \to \gamma \gamma \) is \( 2.3 \times 10^{-3} \). Following Table I, this implies a partial annihilation cross section into four photons with \( m_\gamma/2 \) energy of \( \langle \sigma v \rangle_{\gamma\gamma\gamma\gamma} = 1.2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \). Relevant limits from gamma-ray line searches can be found for example in Ref. [104] (see also Ref. [21]). For a contracted NFW profile (rescaled to \( r = 1.26 \), the limit for 125.7/2 GeV mass DM particles...
annihilating into two photons with energy 125.7/2 GeV is \( (\sigma v)_{\gamma\gamma} \lesssim 4.2 \times 10^{-29} \text{ cm}^3 \text{ s}^{-1} \) (at 95% C.L.). The relevant limit in our case is that \( (\sigma v)_{\gamma\gamma} \lesssim 8.4 \times 10^{-29} \text{ cm}^3 \text{ s}^{-1} \); there is a factor 2 because there are four \( \gamma \) in each annihilation instead of two, but this is compensated by a factor 1/4 from the reduction in the DM number density because, to produce photons with the same energy, the DM must be twice as heavy in \( XX \rightarrow \gamma\gamma\gamma\gamma \) compared to \( XX \rightarrow \gamma\gamma \). We find that \( (\sigma v)_{\gamma\gamma} \) is therefore just below current limits. It should be remembered that if the Higgs particles are not produced exactly at rest, the lines are somewhat broadened, which reduces the sensitivity of line searches \[105\].

We next turn to consider annihilation to leptons. Owing to the larger foreground uncertainties in this analysis, we find that there is a small mass window where \( e^+ e^- \) final state has a \( p \)-value larger than 0.05 (from about 9.4 GeV up to 10.5 GeV).

For completeness, we also list in Table I the result of our spectral fit to \( \mu^+ \mu^- \) final states without accounting for ICS emission.

Finally, we remind the reader that the quoted cross sections assume the Milky Way halo parameters detailed in Sec. II. These halo parameters are not well known and as we will discuss below in Sec. V, dynamical and micro-lensing constraints on the halo parameters (from \[106\]) translate to about a factor 5 uncertainty in the cross section in both directions.

### B. Single annihilation channels with ICS

ICS emission is expected to be important for DM models with significant branching ratios to (light) leptons (see for instance Ref. \[107\] for a discussion in the context of the GeV excess at the GC). Yet, any DM model that has a large branching ratio to monochromatic \( e^+ e^- \) is severely constrained by the positron fraction data from the AMS experiment \[82\]. Moreover, for any DM mass the annihilation channel to monochromatic \( e^+ e^- \) would lead to an ICS gamma-ray spectrum with a hard cutoff at the mass threshold. This though is in tension with the fact that the *Fermi* GeV excess spectrum has a very broad peak at \( \approx 2 \text{ GeV} \), making such a model an improbable one in the context of the *Fermi* GeV excess. Therefore, DM models annihilating into \( e^+ e^- \) will not be studied in this work. We concentrate instead on the ICS signatures from DM annihilations to \( \mu^+ \mu^- \).

For the calculation of the ICS spectrum of DM origin we use the GALPROP v54.1.984\[6\] \[108,109\]. The ICS signal depends on the assumptions with regards to the photon targets of the interstellar radiation field and those on the energy losses and diffusion time scales of the electrons/positrons. We use in this work four different Galactic diffuse emission (Galactic CR propagation) models that account for the relevant uncertainties. These four models are models A, C, D and F of Ref. \[26\]. As can be seen in Fig. 4, these four models give significantly different predictions (by almost an order of magnitude) for the averaged (over our ROI) ICS DM signal. Finally, bremsstrahlung of DM origin is insignificant in all these cases and thus can be ignored.\[7\]

As for annihilation into two-body final states, the ICS emission plays an important role for the \( \mu^+ \mu^- \) channel. Annihilation into \( \mu^+ \mu^- \) is excluded with high confidence level (\( p \)-value of 0.0036) when only the prompt emission is considered, as can be see in Table I. Instead, the inclusion of the ICS component significantly improves the fit. Table II quotes the best-fit parameter values and \( p \)-values for annihilation into \( \mu^+ \mu^- \) when the ICS emission is modeled according to the four different propagation models introduced above. The effect of ICS inclusion is twofold: First, the best-fit mass range is shifted towards higher masses (\( \sim 60–70 \text{ GeV} \)), while the best-fit cross-section value can vary by about a factor of 10 depending on the model. Second, it is possible to find models for which the goodness of fit is improved and can become competitive with annihilation to \( b\bar{b}, c\bar{c}, \) light quarks and gluons (compare models D and F for the \( \mu^+ \mu^- \) channel from Table II to the relevant channels of Table I). The reason why such a possibility opens is that, as shown in the lower panel of Fig. 2 and Fig. 4, the combined ICS and prompt gamma-ray spectrum can be significantly altered with the ICS emission.

\[6\]http://galprop.stanford.edu/

\[7\]We find the ratio of ICS/bremsstrahlung flux to be between 10 and 100, for all the relevant DM annihilation modes and for gamma-ray energies < 10 GeV that affect the spectral fits.
smooth bump dominating in the fit over the FSR hard spectral feature. This is the case for certain Galactic diffuse emission model assumptions; the model must allow for the injected electrons/positrons from DM annihilation to lose most of their energy via ICS emission. If CR electrons and positrons instead have large diffusion time scales (slow diffusion) and/or lose most of their energy via the competing synchrotron losses, the ICS at higher latitudes will be strongly suppressed.

For channels that have significant ICS emission, it is not enough to fit the spectral energy distribution, but also the morphology of the signal has to be checked. Indeed, as mentioned above, the ICS emission is strictly correlated with the distribution of the ambient photons. Thus, the morphology of the emission associated with ICS emission could in principle be different with the morphology of the GeV excess.\(^8\) For this reason, in Fig. 5 we show the results of the fits in the ten ROIs used in Ref. [26] to characterize the morphology of the GeV excess. The definition of the ten ROIs allowed us to study the symmetry properties of the excess and its extension in latitude. For the sake of completeness, we quote in Table III the definition of the ten ROIs as in Ref. [26]. In each subregion we display the GeV excess data together with the ICS emission from \(\mu^+\mu^-\) annihilation for the four Galactic diffuse emission models A, C, D and F, and for the DM masses and cross sections quoted in Table II. Models D and F are able to reproduce the correct morphology of the excess, while models A and C fail in this respect. The plot is illustrative of the fact that it is possible to find propagation models for which the morphological properties of the GeV excess are recovered. Thus, it is not possible to exclude ICS emission from muons only on the basis of gamma-ray data.

Other important constraints on DM annihilating to muons come from the CR positron fraction measured by AMS-02 [82]. For model F the combination of best-fit cross section and mass in Table II is still allowed at 95% C.L., once uncertainties on the local DM density and local CR electrons energy losses are taken into account. Instead, models A and C are already in strong tension. An appealing feature of this channel is that antiproton constraints [84–88,90] do not apply. Before drawing any final conclusion about the possibility of having annihilation into muons it is also important to test synchrotron radiation. This is beyond the scope of the present paper and will be addressed in a dedicated work.\(^9\)

We briefly mention why ICS emission is not important for annihilation into light quarks or \(\tau^+\tau^-\). For annihilations into light quarks and gluons, only a fraction of the available energy per annihilation goes to \(e^+e^-\) after all the hadronization and decay processes have occurred. Moreover, the spectra of these \(e^+e^-\) tend to be soft at injection, resulting in an ICS signal that is subdominant compared to the gamma-ray prompt emission signal around the energies of the \textit{Fermi} GeV excess. For direct annihilation to \(\tau^+\tau^-\), while a significant portion of the annihilation power does go into \(e^+e^-\), the prompt gamma-ray emission has a very prominent spectral bump, that cannot be “smoothed out” significantly by including the ICS contribution. In these cases, we have checked that including the ICS emission impacts the best-fit mass and cross section in Table I and their respective 1, 2 or 3σ ranges in Fig. 3 by no more than 5%.

Finally we notice that for a pointlike source of high-energy electrons located at the GC, either at a steady rate or for a sequence of burstlike events with a time-scale separation between the events of \(\sim\mathcal{O}(100)\) kyr or less, the simultaneous explanation of the spectrum in the entire ROI of Ref. [26] (\(|l| < 20°, 2° < |b| < 20°\)) and its ten subregions is going to be challenging. We expect for the ICS signature, even if it fits the entire ROI, it will overshoot the data in the inner subregions (mainly regions I and II) and undershoot the outer subregions data, much like in Galactic diffuse emission model A of Fig. 5.

C. Mixed annihilation channels

The discussion so far has focused on annihilation into a single channel of final states. In a realistic model, DM will likely annihilate into a variety of channels with different branching ratios, defined as \(BR(\bar{f}f) = \langle \sigma v \rangle_f / \sum_f \langle \sigma v \rangle_f\) where the sum extends over all available channels. For instance, all but two of the models in Refs. [34–77] annihilate into multiple final states (the exception being flavored DM models [49,50], where annihilation into only \(\bar{b}b\) is possible).

Previous multichannel fits to the GeV excess have generally focused on the cases where \(\langle \sigma v \rangle_f \propto \{m_f^2, e_f^2, \gamma\}\),

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\(^8\)The prompt-only component does not have such a drawback as a consequence of the fact that the prompt photons directly trace the DM distribution in the Galaxy.

\(^9\)It may also be interesting to include the bremsstrahlung emission in some cases [110].
where $m_f$ is the final state mass, $e_f$ the final state electric charge and $\perp$ denotes universal couplings. These scenarios can be motivated by considering models where the particle mediating the annihilation mixes with the SM Higgs (in variations of two-Higgs doublet (2HDM) or Higgs portal models [111]) or from minimal flavor violation [112] (in the case $\langle \sigma v \rangle_f \propto m_f^2$), where a vector mediator kinetically mixes with electromagnetism (when $\langle \sigma v \rangle_f \propto e_f^2$) or where the
coUplings are assumed universal as a simplifying assumption (when $h \propto 1$). Here however, we remain more agnostic to the allowed final states. We do this for two reasons: Firstly, models often predict deviations from the exact relations $h \propto f_m^2 f_e^2$; Secondly, not all models have been explored so we do not want to over restrict ourselves. We therefore show in Figs. 6 and 7 triangle plots with fits to three final state channels. The plots are such that the branching ratios (BR) sum to one (as required) and we have marginalized over the DM mass and the total annihilation cross section. Owing to the large uncertainty on the total cross section from the Milky Way halo

<table>
<thead>
<tr>
<th>ROI</th>
<th>Definition</th>
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<tr>
<td>I, II</td>
<td>$\sqrt{\ell^2 + b^2} &lt; 5', \pm b &gt; 2'$</td>
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<tr>
<td>III, IV</td>
<td>$5' &lt; \sqrt{\ell^2 + b^2} &lt; 10', \pm b &gt;</td>
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<tr>
<td>V, VI</td>
<td>$10' &lt; \sqrt{\ell^2 + b^2} &lt; 15', \pm b &gt;</td>
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<tr>
<td>VII, VIII</td>
<td>$5' &lt; \sqrt{\ell^2 + b^2} &lt; 15', \pm b &gt;</td>
</tr>
<tr>
<td>IX</td>
<td>$15' &lt; \sqrt{\ell^2 + b^2} &lt; 20'$</td>
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<tr>
<td>X</td>
<td>$20' &lt; \sqrt{\ell^2 + b^2},</td>
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</tbody>
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FIG. 6 (color online). Constraints on the BR to mixed final states that include quarks and leptons. We marginalize over the DM mass and the total annihilation cross section. The angles of each triangle represent annihilations to a pure channel, with the mass and cross section being the best-fit values given in Tables I and II (model F). The black dot in each plot corresponds to the best-fit point (we give the $p$-value here), the solid, dashed and dot-dashed black lines show the 1, 2, and 3σ contours about the best-fit point, and the solid, dashed and dot-dashed red lines indicate $p$-value contours of 0.32, 0.05 and 0.01 respectively. Any combination of light quarks always results in a good fit. The BR to $\tau^+ \tau^-$ can be substantial, with values over ~50% allowed at 2σ. Owing to the inclusion of ICS emission, any value of BR ($\mu^+ \mu^-$) results in a good fit (cf. bottom panels) when some fraction of $\bar{q} q$, $b \bar{b}$ or $\tau^+ \tau^-$ is also included. In each panel the background coloring refers to the best-mass range as indicated by the color bar. Masses in the range 35–60 GeV lie inside the best-fit regions for all the shown combinations.
parameters (about a factor 5 as we anticipated in Fig. 3 and discussed in Sec. V), we choose to show the DM mass that minimizes the $\chi^2$ at each point by means of the background coloring.

Figure 6 focuses on the case of annihilation to quark and lepton channels. The top-left triangle is for quark-only final states (we don’t consider $gg$ as it is loop suppressed so its branching ratio is naturally smaller). As each channel individually gives a good fit, it is no surprise that any combination of $\bar{q}q, \bar{c}c$ and $\bar{b}b$ also gives a good fit with DM in the mass range between 25 and 60 GeV. The top-right triangle is for heavy quark and $\tau$ final states, as would be expected for 2HDM and Higgs-portal models with $m_\tau < m_\tau$. The best-fit point lies close to the ratios predicted in these models $\bar{b}b: \bar{c}c: \tau^+\tau^- = 0.87: 0.08: 0.05$. We also find that $\text{BR}(\tau^+\tau^-)$ can be substantial (up to around 75%) while still providing a good spectral fit ($p$-value > 0.05). The bottom two triangles consider annihilation channels involving quarks, where we include ICS emission assuming propagation model F. Considering first the case of annihilation into $\mu^+\mu^−$ and $\tau^+\tau^−$ only [along the axis $\text{BR}(\bar{q}q) = 0$], we see that a good fit can always be obtained when $\text{BR}(\mu^+\mu^-) \gtrsim 0.6$ and $m_\tau \sim 50$ GeV. Constructing models giving only $\mu^+\mu^−$ and $\tau^+\tau^−$ final states may be challenging but see Ref. [41] for a prototype. When allowing for additional annihilation into $\bar{q}q$ or $\bar{b}b$, we find that all values of $\text{BR}(\mu^+\mu^-)$ result in a good fit.

In Fig. 7 we consider final states which contain at least one heavy boson. The single channel annihilation to $W^+W^-$ or $ZZ$ is just excluded at 95% C.L., therefore in the upper triangle we investigate whether a combination of $\bar{b}b$ in addition to $W^+W^-$ and $ZZ$ improves the fit. Unfortunately we find that this is not the case: The best-fit point remains pure annihilation to $ZZ$. We find the same conclusion for annihilation to other light quark and lepton pairs (not shown). This is expected because of the constraints imposed on the DM mass, $m_\chi > m_\tau$ (due to the requirement of producing the heavy bosons on shell).

In Sec. IVA, we found that single channel annihilation to $hh$ gives a fit that is compatible with the observed energy spectrum. In the middle and lower triangles we investigate if the inclusion of additional quark and lepton final states, and additional $W^+W^−$ and $ZZ$ final states improves the pure $hh$ fit. A small fraction with $\bar{b}b$ provides a marginally better fit but generally—when adding both quark and leptons or heavy gauge bosons—we find that a good fit is obtained only when $\text{BR}(hh) \gtrsim 0.8$ and when the DM mass is close to $m_b$ (recall that also in this case the production of on-shell Higgs imposes $m_\chi > m_b$). This implies that simple models such as singlet scalar DM [113–116], which predicts sizable branching ratios to $W^+W^-$, $ZZ$ and $hh$, are excluded since there $\text{BR}(W^+W^-)$ is largest. Building realistic models that annihilation dominantly to $hh$ may prove challenging, but opens to new, unexplored, possibilities.

FIG. 7 (color online). Same as Fig. 6, but for a selection of mixed final states that include SU(2) gauge bosons and the Higgs channel on shell. Upper panel: We show the combination of heavy gauge bosons, $W$ and $Z$, together with the possibility to annihilate into $b$ quark final states. Given the imposed constraint $m_\chi > m_Z$, the best-fit region is forced to be close to the pure annihilation to $ZZ$. Central panel: We show a combination of $b$ quarks, $\tau$-leptons and $hh$. As above the constraint from the Higgs channel on the DM mass, $m_\chi > m_h$, causes the best-fit region to be close to the pure annihilation to $hh$. We notice that, when a substantial fraction of $\tau^+\tau^−$ is allowed, together with the mass constraint, the fit is very bad. Lower panel: We show the combination of $W^+W^-$, $ZZ$ and $hh$ annihilation states.
TABLE IV. As in Table I, results of spectral fits to the Fermi GeV excess emission, for DM models annihilating into light bosons \( \phi \). The corresponding \( p \)-value is \( \geq 0.05 \) in all cases. A slightly better fit is provided by \( \phi \rightarrow e^+e^- \). For the ICS emission we considered the diffuse emission model F.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \langle \sigma v \rangle ) (10^{-26} \text{ cm}^3 \text{ s}^{-1})</th>
<th>( m_\chi ) (GeV)</th>
<th>( \chi^2_{\text{min}} )</th>
<th>( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi \rightarrow e^+e^- )</td>
<td>( 0.384^{+0.052}_{-0.051} )</td>
<td>( 45.7^{+3.4}_{-3.3} )</td>
<td>31.35</td>
<td>0.09</td>
</tr>
<tr>
<td>( \phi \rightarrow \mu^+\mu^- )</td>
<td>( 2.90^{+0.43}_{-0.43} )</td>
<td>( 91.7^{+9.9}_{-9.7} )</td>
<td>33.6</td>
<td>0.05</td>
</tr>
<tr>
<td>( \phi \rightarrow \pi^+\pi^- )</td>
<td>( 5.11^{+0.71}_{-0.71} )</td>
<td>( 124.5^{+11.2}_{-10.8} )</td>
<td>33.3</td>
<td>0.06</td>
</tr>
</tbody>
</table>

D. Annihilation to hidden sector mediators

Up to this point we have only considered scenarios where the DM particles annihilate directly to SM particles. However it is also plausible that the DM first annihilates to intermediate hidden sector mediators \( \phi \) that subsequently decay to SM particles. The mediator \( \phi \) can mix with the SM Higgs or with hypercharge/electromagnetism, allowing for a variety of possible SM states from their decays.

These “cascade” annihilations produce boosted SM final states, which, depending on the \( \phi \) mass, allow for heavier DM particles than in the more conventional scenarios discussed previously. The case in which a general mediator \( \phi \) decays primarily to \( b \) quarks has already been discussed extensively in the literature [53–55,57,59,60,70]. In fact the single channel annihilation to \( hh \) can be considered in this class since, after the \( h \) is produced, it decays dominantly to \( bb \) with each \( b \) having energy \( m_\phi/2 \). This is why a DM interpretation for this channel results in a good fit even though the DM mass is over twice as heavy compared with the values for other channels.

Here we consider eXciting dark matter models (XDM) [117,118]. For an earlier discussion of XDM models in the context of the Fermi GeV excess see [119]. If the gauge bosons \( \phi \) are lighter than 2 GeV, the kinematically allowed final states are \( e^+e^- \), \( \mu^+\mu^- \) and \( \pi^+\pi^- \) or \( \pi^0 \)s, while no antiprotons are produced, thus evading the current constraints [120]. Such channels will produce, after all the subsequent cascades, boosted electrons and positrons and a subdominant contribution to FSR [121].

The \( \pi^0 \) channel can be evaded if the \( \phi \) mixes with electromagnetism, thus coupling to charge [118]. We will therefore concentrate here on the annihilation channel \( \chi\chi \rightarrow \phi\phi \), with subsequent \( \phi \) decays as \( \phi \rightarrow e^+e^- \), \( \phi \rightarrow \mu^+\mu^- \) or \( \phi \rightarrow \pi^+\pi^- \).[10]

As the final states contain light leptons, it is again crucial to include ICS emission. We do this as before using the Galactic diffuse emission model F. We show the results from our spectral fits in Table IV for single channel decay to each of the three possible \( \phi \) decay modes: \( e^+e^- \), \( \mu^+\mu^- \) or \( \pi^+\pi^- \). We find that the best-fit case, \( \phi \rightarrow e^+e^- \), suggests a mass and a cross section that is still allowed from AMS positron fraction limits, within their uncertainties, similarly to the case of direct DM annihilation to \( \mu^+\mu^- \) discussed in Sec. IV B. Figure 8 shows the resulting triangle plot for floating BRs between the three \( \phi \) decay modes, after marginalizing over the DM mass and the annihilation cross section to produce \( \phi\phi \). Again the AMS positron fraction limits constrain (but not severely) these possibilities. For reference in these calculations we have chosen \( \phi \) to be a vector with a mass of \( \approx 0.6 \) GeV. Our spectral fit results do not depend on the exact value of the \( \phi \) mass, as long as it remains within 0.3–1 GeV, and on whether \( \phi \) is a vector or a scalar, given the similarity of the injected electron/positron spectra into the interstellar medium from these options. Yet, on the model building side these can be important assumptions [118,123].

V. CURRENT AND FUTURE CONSTRAINTS FROM DWARF SPHEROIDALS

The arguably most promising channel for a confirmation of the DM interpretation of the Fermi GeV excess are searches for corresponding signals in dwarf spheroidal galaxies of the Milky Way. These observations probe already— for typical assumptions on the Milky Way DM halo—DM scenarios that could explain the Fermi GeV excess [91–94]. The currently strongest (though still preliminary) limit on the annihilation cross section was presented in Ref. [124]. For annihilation into \( bb \) final states and a DM mass of 49 GeV, they read \( \langle \sigma v \rangle < 1.5 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \) at 95% C.L., which is at face value in mild tension with the values of the cross section that we derived above (see Sec. IV). However, the link between the GC and
the dwarf signals is subject to uncertainties in the DM distribution in the Milky Way and the DM distribution in dSphs (note that the latter have been marginalized over in the analysis of Ref. [124]). Concerning the Milky Way halo, a decrease of the scale radius $r_s$, an increased slope $\gamma$ of the inner part of the profile, or an increased local density $\rho_\odot$ enhance the expected GC signal relative to the signal in dwarf spheroidals. Also more cored profiles for dSphs can reduce further their constraining power. It is important to investigate to what extent uncertainties in these parameters can mitigate potential tensions between GC and dSph observations [125].

In Fig. 9 we show the expected signal flux for DM annihilation into $\bar{b}b$ final states and with $m_\chi = 48.7$ GeV. As DM profile we adopt here the reference generalized NFW profile as above and the cross section is set to $\langle \sigma v \rangle = 1.75 \times 10^{-26}$ cm$^3$ s$^{-1}$. This leads to a signal intensity that is consistent with the results found in Ref. [26] at $\psi \approx 5^\circ$. Note that $\psi = 5^\circ$ was found to be a good pivot point for the intensity measurement in Ref. [26], as the flux there is relatively independent of the adopted profile slope. We also show the preliminary GC results by the Fermi-LAT Collaboration, cf. Fig. 1.

To explore the validity of measured signal profile, we generate a large set of Milky Way DM halo models that are compatible with the microlensing and dynamical constraints from Ref. [106] at 95% C.L. This set includes DM halo models that follow a generalized NFW profile with scale radii in the range $r_s = 10$ to 30 kpc, and arbitrary normalization $\rho_s$ and inner slope $\gamma$ (note that for illustrative purposes we allow also values of $\gamma$ that would be incompatible with the Fermi GeV excess measurements at the GC). To this end, we adopt the following method: We derive the envelope of all density profiles that are compatible with the left panel of Fig. 5 of Ref. [106] (which shows results for $r_s = 20$ kpc only) in the radial range $r = 2.5$ to 10 kpc. A model with scale radius $r_s \neq 20$ kpc is considered to be compatible with the observations when its profile lies within the derived envelope.

From the set of all observationally allowed halo models we select those that lead to a signal intensity that is consistent with the measurements at $\psi = 5^\circ$, assuming a reference cross section $\langle \sigma v \rangle = 1.5 \times 10^{-26}$ cm$^3$ s$^{-1}$ (the current dSph limit at 95% C.L.) and the above annihilation channel and DM mass. The envelope of the corresponding allowed signal profiles is shown by the red band in Fig. 9. The band contains both the signal morphology as derived for the reference generalized NFW profile with $\gamma = 1.26$, as well as with the preliminary GC results by the Fermi-LAT Collaboration. We hence find that current dSph limits on the annihilation cross-section are well consistent with a DM interpretation of the Fermi GeV excess when uncertainties in the DM distribution in the Milky Way are accounted for.\textsuperscript{11}

The situation changes drastically however if current limits would increase by only a factor of 3. This is demonstrated by the blue band in Fig. 9, which shows the corresponding signal profiles assuming that $\langle \sigma v \rangle = 0.5 \times 10^{-26}$ cm$^3$ s$^{-1}$. The allowed signal slope becomes much steeper since smaller cross sections require larger DM densities towards the GC. We find that there would be significant tension between measured and observationally allowed signal morphologies, both towards the Galactic center ($\psi \lesssim 5^\circ$), but even more importantly in the higher-latitude tail (above $\psi \gtrsim 5^\circ$).

To enforce consistency between the measured and gravitationally allowed signal morphologies even when dSph limits further strengthen in the future, one would have to resort to more drastic assumptions, such as a DM profile that considerably flattens within the inner 1 kpc or so, or substructure enhancement at larger distances from the GC (which however already seems unlikely to be relevant since due to tidal disruption this effect is expected to be small at $\psi \lesssim 25^\circ$ [126]), or more complex theories of particle

\textsuperscript{11}Note that this statement does not depend on the annihilation channel or the DM mass, since we are comparing predicted and measured intensities at the peak of the GeV excess at 2 GeV, which have to be very similar for any DM interpretation of the Fermi GeV excess.
DM [127]. We leave the exploration of these scenarios to future work.

Finally, we will estimate the general uncertainty of the annihilation cross section that is quoted in Table I. To this end, we again make use of the above set of valid DM halo models, compatible with the constraints discussed in Ref. [106] at 95% C.L. Using all these models, with the additional constraint that \( \gamma \geq 1.1 \), we find that the line-of-sight integral over the DM density in direction \( \psi = 5^\circ \) can vary by a factor 5.9 up and by a factor 0.19 down with respect to the value that is obtained for our reference profile (\( \gamma = 1.26, r_s = 20 \) kpc, \( \rho_0 = 0.4 \) GeV cm\(^{-3} \)). Hence, we attribute a generous astrophysical uncertainty to our best-fit annihilation cross sections that is multiplicative and in the range \( \mathcal{A} = [0.17, 5.3] \). Note that some of the halo models would at face value be too steep in the inner kpc to be compatible with the Fermi GeV excess morphology; in these cases we assume that the profile flattens out towards the center.

VI. CONCLUSIONS

In this paper, we presented a critical reassessment of DM interpretations of the Fermi GeV excess in light of the foreground/background uncertainties. To this end, we made use of the results from Ref. [26], where the emission from the inner \( \sim 1 \) kpc around the GC as seen at higher latitudes (\(|b| > 2^\circ \)) was robustly characterized with respect to foreground/background uncertainties. In Sec. II, we showed that at the peak energy of 2 GeV, all previous studies of the Fermi GeV excess (including the preliminary results from the Fermi-LAT team [17]) suggest a signal morphology that is consistent with a contracted DM profile. We entertained here the exciting and suggestive possibility that all of this emission is due to a signal from DM annihilation. Given the complexity of the Galactic foregrounds/backgrounds, we found that a much larger number of DM models fits the gamma-ray data than was previously noted, which should be taken into account in future DM searches. In particular the low and high tails of the excess energy spectrum, which are highly relevant to constrain different DM scenarios, are subject to large uncertainties.

Our main findings are as follows.

(i) We confirmed previous findings that annihilation to gluons, and quark final states \( \bar{q}q, \bar{c}c \) and \( \bar{b}b \), provide a good fit. However, we found that somewhat higher masses are preferred compared to previous analyses, which is due to the additional uncertainty in the high-energy tail of the energy spectrum. In the case of DM annihilation into \( \bar{b}b \), we found that DM masses up to \( \chi \approx 74 \) GeV are allowed (giving a \( p \)-value above 0.05).

(ii) Pure annihilation to pairs of \( W \) and \( Z \) gauge bosons are excluded at a little over 95% C.L. However—and perhaps surprisingly—annihilation to pairs of on-shell Higgs bosons produce a rather good fit. Associated gamma-ray lines from \( h \rightarrow \gamma \gamma \) are close to the sensitivity of current instruments.

(iii) For annihilation into \( \mu^+\mu^- \), the ICS emission plays an important role. We showed that it is possible to find CR propagation models for which fits with the ICS emission from \( \mu^+\mu^- \) final states and \( m_\chi \approx 60-70 \) GeV can become competitive with those of annihilation to \( \bar{b}b \). Furthermore, we demonstrated that for some models the morphological properties of the GeV excess are well reproduced, and thus that it is not possible to exclude ICS emission from muons only on the basis of gamma-ray data at \(|b| > 2^\circ \).

(iv) In a realistic model, DM will likely annihilate into a variety of channels with different branching ratios. We remained agnostic to the composition of allowed final states and derived constraints on different final state triples. In the case of \( \bar{b}b, \bar{c}c \) and \( \tau^+\tau^- \) final states, we found that the best-fit point lies close to the ratios predicted for 2HDM, \( \bar{b}b; \bar{c}c; \tau^+\tau^- = 0.87:0.08:0.05 \). We also found that BR(\( \tau^+\tau^- \)) can be substantial (up to around 75%) while still providing a good spectral fit. In the case of annihilation into \( \mu^+\mu^- \) and \( \tau^+\tau^- \), we saw that a good fit can always be obtained when BR(\( \mu^+\mu^- \)) \( \gtrsim 0.6 \) and \( m_\chi \approx 50 \) GeV. When allowing for additional annihilation into \( \bar{q}q \) or \( \bar{b}b \), we found that all values of BR(\( \mu^+\mu^- \)) result in a good fit. Lastly, for the annihilation into \( hh \), we found that a good fit is obtained only when BR(\( hh \)) \( \gtrsim 0.8 \) and when the DM mass is close to \( m_h \).

(v) For hidden sector models with a light mediator \( \phi \) that subsequently decays into combinations of \( e^+e^- \), \( \mu^+\mu^- \) and \( \pi^+\pi^- \)—much like in the case of direct annihilation to \( \mu^+\mu^- \)—the ICS emission dominates. We found that the allowed DM particle mass range is between 45 and 125 GeV, with cross sections that are constrained (but not severely) by the AMS positron fraction data.

(vi) We showed that, given dynamical and microleptonic constraints on the DM halo, current limits from dwarf Spheroidal galaxies are not yet in tension with the DM interpretation of the Fermi GeV excess. However, we also demonstrated that if these limits further strengthen by a factor of 3, there would be significant tension between measured and observationally allowed morphologies of the GC signal. We furthermore showed that given current constraints, the annihilation cross section is uncertain by a factor of about 5 up and down (at 95% C.L.).

The covariance matrix as well as the flux of the Fermi GeV excess emission that are used for the spectral analysis are available online.\(^{12}\)

\(^{12}\)https://staff.fnwi.uva.nl/c.weniger/pages/material/
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Note added.—While finalizing this work, a preprint appeared [128] that also considers quarks and massive gauge boson final states in light of the background model systematics from Ref. [26]. For the cases where our analyses overlap we find agreeing results.

[27] M. Ackermann et al. (Fermi-LAT Collaboration), Fermi-LAT observations of the diffuse gamma-ray emission:


[110] C. Boehm et al. (to be published).


