Intermediate-mass Black Holes and Dark Matter at the Galactic Center

Thomas Lacroix 1 and Joseph Silk 2,3,4

1 Laboratoire Univers & Particules de Montpellier (LUPM), CNRS & Université de Montpellier (UMR-5299), Place Eugène Bataillon, F-34095 Montpellier Cedex 05, France
2 Institut d' Astrophysique de Paris, UMR 7095, CNRS & UPMC, Sorbonne Universités, 98 bis bd Arago, F-75014 Paris, France
3 Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA
4 Beecroft Institute of Particle Astrophysics and Cosmology, Department of Physics, University of Oxford, Oxford OX1 3RH, UK

Received 2017 December 11; revised 2018 January 11; accepted 2018 January 12; published 2018 January 24

Abstract

Could there be a large population of intermediate-mass black holes (IMBHs) formed in the early universe? Whether primordial or formed in Population III, these are likely to be very subdominant compared to the dark matter density, but could seed early dwarf galaxy/globular cluster and supermassive black hole formation. Via survival of dark matter density spikes, we show here that a centrally concentrated relic population of IMBHs, along with ambient dark matter, could account for the Fermi gamma-ray “excess” in the Galactic center because of dark matter particle annihilations.

Key words: dark matter – Galaxy: center – stars: black holes

1. Introduction

The diffuse Fermi-LAT “excess” (e.g., Goodenough & Hooper 2009; Ajello et al. 2016) or residual emission from the Galactic center (GC) remains the strongest evidence for dark matter (DM) that consists of weakly interacting massive particles (WIMPs). The hypothesis of weakly annihilating supersymmetry-motivated WIMPs is well supported by particle physics arguments, despite the lack of success in finding any evidence for supersymmetry. The morphology, density profile, and spectrum of the Fermi excess collectively support a DM interpretation.

However, recent analyses of the γ-ray statistical fluctuations demonstrate that any diffuse DM contribution must be subdominant. One needs to include a discrete source component of ∼1000 subthreshold sources to account for the results of a fluctuation analysis (Bartels et al. 2016; Lee et al. 2016). The leading candidate for such a component is an old population of millisecond pulsars (MSPs), as detected in massive globular clusters. If such a component can account not only for the fluctuations but the other observed characteristics of the diffuse excess, notably morphology, density profile, and spectrum, then the motivation for any DM component is largely removed.

Any such interpretation may be premature, if only because the population of weak MSPs is not well known. However, it is difficult for a DM self-annihilation model to be sufficiently clumpy. One such attempt involves strongly interacting DM that can in principle form a population of dark compact objects (Agrawal & Randall 2017).

Here, we propose an arguably more compelling clumpy DM model, in which we combine a population of IMBHs, originating either as Population III (Pop III) or primordial black holes (PBHs), with the standard WIMP DM model. The latter features the usual weakly interacting self-annihilating DM particles that have successfully reproduced the spectrum, profile, and morphology of the Fermi GC excess, but at the same time are challenging direct detection experiments (e.g., Aprile et al. 2017) and indirect detection of γ-rays from nearby dwarfs (Ackermann et al. 2015).

Our motivation is that DM WIMPs are plausible from the perspective of particle physics, and a highly subdominant population of IMBHs is equally plausible from astrophysics. Single field inflation models provide a strong case for PBH formation, when at the end of slow roll, there is a generic phase prior to reheating when small scale but high amplitude fluctuations are generated. These plausibly form rare PBHs (Carr & Hawking 1974). The predicted mass spectrum extends from the Hawking evaporation limit, about 10^10 g to 10^4 M_☉ or larger. PBHs as a DM contributor are compelling from astrophysical arguments, as one just needs Einstein gravity and essentially standard cosmology, without need for new particle physics. The primordial fluctuation mass range generating PBHs as a subdominant DM contributor is unconstrained by cosmic microwave background (CMB) or large-scale structure observations, which only constrain galactic scales or larger. Constraints on relevant scales are eventually possible from limits on CMB spectral distortions and stochastic gravity wave backgrounds.

The astrophysical motivation for an early universe population of IMBHs formed during the Pop III epoch is equally compelling. Recent observations favor a significant, although highly subdominant, population of massive central BHs in dwarf galaxies. These are observed as active galactic nuclei (AGNs), with X-ray, optical, and infrared signatures, and an occupation number of order 1% (Baldassare et al. 2017). Hence, the IMBH occupation number, allowing for a duty cycle, must be significantly higher, by at least an order of magnitude. Simulations of formation of SMBH by mergers of IMBHs suggest that Ω IMBH ∼ 10^{-3} Ω baryon (Islam et al. 2004; Rashkov & Madau 2014).

The IMBHs may be PBHs. This is an interesting, although not obligatory, option. Dwarf galaxy IMBHs need not be PBHs, although it is difficult to populate dwarfs, other than first-generation systems, with central massive BHs. Formation of massive IMBHs by merging of smaller BHs generates recoils. Either way, we are likely to have a highly subdominant population of IMBHs in massive galaxies. For a Pop III origin, a simple estimate of the mass fraction of first-generation dwarfs is of order 0.001, based on the Pop III metallicity threshold. If a
significant fraction of these undergo direct collapse (options are suppression of key coolant H$_2$ by UV from neighboring Pop III embryonic dwarfs, Regan et al. 2017, or supercritical Pop III BH accretion; Lupi et al. 2016; Begelman & Volonteri 2017), one coincidentally would arrive at the IMBH mass fraction required to account for the dwarf galaxy IMBHs as observed.

The idea that PBHs could be 1% or more of DM has been revived by the aLIGO detection of four confirmed binary merging BHs of mass 10–30 $M_\odot$, although the predicted mass fraction of PBHs required is model-dependent, ranging from $\sim$100% (Bird & Cholis 2016) to $\sim$1% (Sasaki et al. 2016; Ali-Haïmoud et al. 2017). Observations, most notably from gravitational microlensing (Alcock et al. 2001), dwarf galaxy heating (Brandt 2016), and CMB distortions (Ali-Haïmoud & Kamionkowski 2017), favor the lower range. Future aLIGO observations, combined with Virgo and other detectors, should be able to distinguish PBHs from the more conventional astrophysical explanation via the observed BH mass distribution. However, for the purposes of this Letter, a mass fraction of only 0.1% in intermediate-mass PBHs would be required, if indeed we have greatly overestimated the Pop III contribution.

More generally, a case can be made for massive BHs in all dwarfs that subsequently merge hierarchically as in the usual cold dark matter (CDM) model to form more massive galaxies. First, mergers of IMBHs form a natural, but admittedly inefficient, path to forming supermassive black holes (SMBHs), given the ubiquity of mergers in structure formation. Second, the most massive SMBHs, if formed by accretion at or below the Eddington limit, require seed IMBHs (Habouzit et al. 2016). Third, many, if not all, of the problems in dwarf galaxy formation scenarios, including abundance, cuspy/core controversy, too-big-to-fail, and baryon fraction, can potentially be resolved by the additional degrees of freedom provided by AGN feedback (Silk 2017), without recourse to exotic DM models.

Recent observations point to IMBHs in massive globular clusters (Kiziltan et al. 2017), which could provide additional indicators of their presence in low-mass systems. If indeed all merging substructures, to be envisaged for example as protoglobular clusters in typical bulge formation models or more generally, protodwarf galaxies, contain IMBHs, then not only does this provide a natural pathway for forming the central nuclear star cluster (NSC) and SMBH along with the bulge and stellar halo in the Milky Way Galaxy (MWG; Antonini et al. 2015), but also a robust prediction: there should be a large population of massive BHs that failed to merge (Islam et al. 2004; Rashkov & Madau 2014).

For IMBHs formed in the early universe, whatever their origin, DM density spikes are inevitable, with a profile $\rho(r) \propto r^{-\gamma_{sp}}$ within the BH influence radius, where $\gamma_{sp} > 3/2$. The limiting value is $\gamma_{sp} = 9/4$ for an isothermal DM core, up to a plateau determined by the annihilation rate (Gondolo & Silk 1999), but spikes around primordial IMBHs can be even steeper (Eroshenko 2016). Correction for the effect of mergers on the density profile (Merritt et al. 2002) remains an uncertainty, although spikes can regenerate via accretion. Moreover, flattening within the BH influence radius occurs to $\gamma_{sp} \approx 3/2$ due to stellar heating (Gnedin & Primack 2004) in the case of the SMBH at the GC, but it is not clear how this affects IMBHs or, in particular, the near-horizon density. One may wonder about the impact of a putative spike around the SMBH at the GC on the $\gamma$-ray emission. In this model, the SMBH formed by mergers. The IMBHs are the merged relics. Hence, the SMBH spike would have been destroyed or softened via dynamical heating from the mergers (like in Merritt et al. 2002). The central spike may also have been dynamically heated in the NSC (Gnedin & Primack 2004). Finally, the radial extension of the SMBH spike may also be sufficiently small for the associated $\gamma$-ray emission to be subdominant. In the end, we may have a significant contribution to the $\gamma$-ray emission from the mini-spikes and a subdominant one from the central SMBH spike.

The beauty of self-annihilating DM density spikes is that one can probe very low cross-sections, leading to unique constraints, as found for the case of M87 (Lacroix et al. 2015). Our model is largely motivated by dwarf galaxy observations that show a possibly high occupation number of massive BHs in dwarfs. One attractive feature of IMBHs is that, being in place before MWG-like galaxies, they can act, especially if PBHs, as seeds of dwarfs as well as of SMBHs and even of more massive systems (Clesse & García-Bellido 2015). PBHs may form via primordial non-Gaussian features in the initial fluctuation spectrum (Young et al. 2016), with possible implications for the stochastic gravitational-wave background (Nakama et al. 2017). Early formation of dwarfs has previously been invoked to address issues of reionization of the universe via primordial non-Gaussianities (Habouzit et al. 2014), and the relative roles of AGNs and massive stars in reionization are in principle distinguishable (Cohen et al. 2016). Such dwarfs most likely contain IMBHs if we accept the growing body of astrophysical evidence on nearby dwarfs.

Merging dwarf galaxies would generate a massive BH distribution that is steeper than that of the initial CDM-like profile, due to dynamical friction, and might plausibly approximate that of the stellar bulge, whose radial profile is $\propto r^{-2}$, which turns out to be possibly more consistent with the profile of the residual $\gamma$-ray emission. An unavoidable consequence would also be the formation of an NSC by the SMBH along with the bulge and stellar halo (Merritt et al. 2002), but spikes around primordial IMBHs may contribute of the order of the residual $\gamma$-ray emission. The integrated photon flux for a spike around an individual IMBH—referred to as a mini-spike in the following—between $E_{\gamma,\text{min}} = 1.893$ GeV and $E_{\gamma,\text{max}} = 11.943$ GeV (Lee et al. 2016) is given as usual by

$$\Phi_{\gamma} = \frac{\langle \sigma v \rangle_{\gamma}}{2m_{\text{DM}}^2d^2} \int_{E_{\gamma,\text{min}}}^{E_{\gamma,\text{max}}} dE_{\gamma} \int_0^{R_{\gamma}} r^2 \rho^2(r) \, dr \right|,$$

where $\langle \sigma v \rangle_{\gamma}$ is the velocity-averaged annihilation cross-section, $m_{\text{DM}}$ the mass of the DM candidate, $dN/dE_{\gamma}$ the $\gamma$-ray spectrum per annihilation—taken from Cirelli et al. (2011), and $d \approx 8.32$ kpc (Gillessen et al. 2017), the distance between Earth and the IMBH. Our benchmark scenario is a DM

2. Gamma-Rays from DM Spikes around IMBHs

We give simple numerical estimates that illustrate how the IMBH-spike scenario can readily account for the Fermi “excess” for very small annihilation cross-sections. Following Agrawal & Randall (2017), we estimate the DM parameters that can reproduce the flux of one point source from the analysis of Lee et al. (2016). About $10^5$ such point sources are then needed to contribute of the order of the residual $\gamma$-ray emission. The integrated photon flux for a spike around an individual IMBH— referred to as a mini-spike in the following—between $E_{\gamma,\text{min}} = 1.893$ GeV and $E_{\gamma,\text{max}} = 11.943$ GeV (Lee et al. 2016) is given as usual by

$$\Phi_{\gamma} = \frac{\langle \sigma v \rangle_{\gamma}}{2m_{\text{DM}}^2d^2} \int_{E_{\gamma,\text{min}}}^{E_{\gamma,\text{max}}} dE_{\gamma} \int_0^{R_{\gamma}} r^2 \rho^2(r) \, dr \right|,$$

where $\langle \sigma v \rangle_{\gamma}$ is the velocity-averaged annihilation cross-section, $m_{\text{DM}}$ the mass of the DM candidate, $dN/dE_{\gamma}$ the $\gamma$-ray spectrum per annihilation—taken from Cirelli et al. (2011), and $d \approx 8.32$ kpc (Gillessen et al. 2017), the distance between Earth and the IMBH. Our benchmark scenario is a DM
candidate with $m_{\text{DM}} = 30$ GeV annihilating into $b\bar{b}$, compatible with the spectral properties of the GC residual $\gamma$-ray emission. The DM profile in the mini-spike is defined as follows:5
\[
\rho(r) = \begin{cases} 
0 & r \leq 2R_s \\
\rho_{\text{sat}} & 2R_s < r \leq R_{\text{sat}} \\
\rho_0 \left( \frac{r}{R_{sp}} \right)^{-\gamma_{sp}} & R_{\text{sat}} < r \leq R_{sp}
\end{cases},
\]
where the saturation density is given by $\rho_{\text{sat}} = m_{\text{DM}}/\langle \langle \sigma v \rangle \rangle t_{\text{BH}}$ with $t_{\text{BH}}$ the BH age, and $R_{\text{sat}} = R_{sp}(\rho_{\text{sat}}/\rho_0)^{-1/\gamma_{sp}}$ by continuity. The radial extension of the spike $R_{sp}$ is of the order of the BH influence radius, $GM_{\text{BH}}/c_\text{s}^2$ (Peebles 1972). The extended $M_{\text{BH}}-\sigma_*$ relation for IMBHs (Tremaine et al. 2002) gives an estimated value of $\sigma_*$ $\approx 10$ km s$^{-1}$, and $R_{sp} \approx 0.043$ pc. Then, $\rho_0 \approx (3 - \gamma_{sp})M_{\odot}/(4\pi R_{sp}^2)\eta_s^2$ by requiring the mass inside the spike $M_{sp}$ be of the order of the BH mass, with $M_{sp} \approx M_{\text{BH}} \approx 10^{7-10} M_{\odot}$ for $\gamma_{sp} > 3/2$, the integrated flux for a single mini-spike reads6
\[
\Phi_{sp} = \frac{\gamma_{sp}}{3(2\gamma_{sp} - 3)} \left( \frac{3 - \gamma_{sp}}{4\pi} \right) \frac{1}{d^2} M_{\text{BH}}^{\gamma_{sp}} \\
\times \left( \frac{R_{sp}}{0.043 \text{ pc}} \right)^{-1} \left( \frac{m_{\text{DM}}}{30 \text{ GeV}} \right)^{-4/3} \\
\times \left( \frac{\langle \sigma v \rangle}{2 \times 10^{-40} \text{ cm}^3 \text{s}^{-1}} \right)^{1/3} \left( \frac{t_{\text{BH}}}{10^{10} \text{ yr}} \right)^{-2/3} N_{\text{tot}}^{(tot)} \\
\times \left( \frac{\langle \sigma v \rangle}{8.32 \text{ kpc}} \right)^{-2} \left( \frac{M_{\odot}}{36 \text{ cm}^3 \text{s}^{-1}} \right)^{1/3} N_{\text{tot}}^{(tot)}. \tag{3}
\]

The upper limit on $\langle \sigma v \rangle$ is extremely small ($\sim 10^{-40} \text{ cm}^3 \text{s}^{-1}$) for a steep mini-spike with $\gamma_{sp} = 9/4$ and $M_{\text{BH}} = 10^{3} M_{\odot}$. This is related to the very weak dependence of $\Phi_{sp}$ on the cross-section. For a relaxed spike with $\gamma_{sp} = 3/2$, the upper limit on the cross-section is of the order of $10^{-31} \text{ cm}^2 \text{s}^{-1}$ for a population of $10^{3} M_{\odot}$ IMBHs. For $M_{\text{BH}} = 10^{2} M_{\odot}$, the best-fit cross-sections become $2 \times 10^{-36} \text{ cm}^2 \text{s}^{-1}$ for $\gamma_{sp} = 9/4$ and $3 \times 10^{-29} \text{ cm}^2 \text{s}^{-1}$ for $\gamma_{sp} = 3/2$.

### 3. Global Signal and Spatial Morphology

We now consider a distribution of IMBHs that collect in the inner galaxy. Most of them are failed mergers, as mentioned above, with a total mass amounting to of the order of the mass of the central SMBH, $4 \times 10^6 M_{\odot}$. First, we note that to compute the radial profile of $\gamma$-rays, we need to convolve the radial distribution of the IMBHs with the radial dependence of the mini-spike flux.

The DM interpretation of the Fermi excess works for the morphology because it naturally gives the $\gamma$-ray profile as roughly the square of the NFW profile, or $r^{-2}$. The present model needs to address this point. However, the case for the DM interpretation may not be that strong. First, the MWG may have a DM core (Portail et al. 2017). Second, the Fermi excess can be fit, according to a reanalysis, by a stellar mass (bulge)-related profile (Bartels et al. 2017).

The point sources (IMBHs) have a $r^{-3/2}$ density profile toward the GC. This is a dynamically relaxed profile that follows the Bahcall–Wolf solution for a stellar cusp (Bahcall & Wolf 1976). This might not match the observed profile if the mini-spike masses and luminosities are independent of radius. In fact, there will be mass segregation, the more massive IMBHs falling in closer to the GC but still accreting at/near the final parsec. IMBHs are point masses, and too dense to be tidally disrupted. Let us estimate the radial dependence of the mini-spike luminosity. The radial flux profile for a set of mini-spikes around BHs is $\Phi_{r} \propto \Phi_{sp} r^{-3/2}$. From Equation (3), the flux for an individual mini-spike is $\Phi_{sp} \propto M_{\text{BH}}^{3/2} \gamma_{sp}$. Hence, we assume $M_{\text{BH}} = M_{\text{BH}}$ and $R_{sp} = GM_{\text{BH}}/\sigma_{s}^2$, with $\sigma_{s} \propto M_{\text{BH}}^{1/4}$ (Tremaine et al. 2002) so that $R_{sp} \propto M_{\text{BH}}^{3/2}$. Hence, $\Phi_{sp} \propto M_{\text{BH}}^{3/2}$. In addition, $M_{\text{BH}}$ increases as $r$ decreases because of mass segregation by settling. The two-body relaxation timescale is $\propto \chi_{t} \propto 1/M_{\text{BH}}$, as is the dynamical friction time that is $\sim M_{\text{MBH}}/M_{\text{BH}}$ orbital times. One needs a simple diffusion model to go further, but a rough guess using adiabatic invariants might be $r v M_{\text{BH}} = \text{const}$ (conservation of angular momentum), so that $M_{\text{BH}} \propto r^{-1/2}$. Hence, the radial flux profile is $\Phi_{r} \propto r^{-3/2}$. Generally, $\gamma_{sp} = (9 - 2\gamma)/(4 - \gamma)$, so that for a core, $\gamma = 0$ and $\gamma_{sp} = 9/4$, while for $\gamma = 1$, $\gamma_{sp} = 7/3$ and for $\gamma = 3/2$, $\gamma_{sp} = 12/5$. Hence, for adiabatic mini-spirals, the radial profile is $\Phi_{r}^{(sp)} = \propto r^{-3/2}$, $\Phi_{r}^{(sp)} = \propto r^{-1/2}$, and $\Phi_{r}^{(sp)} = \propto r^{-3/2}$. Therefore, $\Phi_{r} \propto r^{-2}$ for IMBH mini-spires, always approximating the observed $\gamma$-ray profile independently of the DM halo profile.

These predictions are illustrated in Figure 1, which shows the angular profile of the total GC $\gamma$-ray data at 2 GeV with bright point sources masked (Ackermann et al. 2017), along with the profiles of various components of the $\gamma$-ray emission.
Our model typically gives an angular profile that is consistent with expectations from bulge sources like MSPs.

The situation is complicated by the fact that the DM spikes may be heated—for relaxed mini-spires $\Phi_r \propto r^{-1.75}$—and partially stripped as the IMBHs fall into the GC region, although tidal disruption of PBH clusters and dynamical friction may in turn steepen the IMBH profile, as discussed in Fragione et al. (2017) for MSPs. Regardless, it seems plausible, pending detailed simulations, that our model gives a good approximation to the Fermi $\gamma$-ray excess profile.

4. Discussion

One attractive model for the LIGO events argues that hard massive BH binaries form in dense stellar clusters. This scenario has one advantage over rivals: it was proposed before the aLIGO detection (Bae et al. 2014) to give acceptable rates and masses. Protoglobular clusters are likely pregalactic sites and are dispersed as substructure disrupts when the bulge formed. Stellar cluster-enhanced formation of massive BH binaries quantitatively accounts for the observed LIGO rates, when integrated out to several hundred Mpc (Park et al. 2017). Such massive BHs may have formed prolifically at high redshift, when there was most likely a top-heavy initial mass function, providing a possible pathway to forming IMBHs. In the PBH case, one appeals to BH binary formation by early capture in the first bound DM substructures at the onset of matter domination (Sasaki et al. 2016). Some subsets of these (one needs the order of $10\%$) might have merged to form IMBHs.

We expect that massive binaries should be enhanced in number near the GC where the most massive protoglobulars dispersed to form the central NSC. These would generate MSPs as well as BH binaries. Hence, these two populations should track each other. Neither would have a significant disk component. Another consequence would be an enhanced rate of BH mergers in galactic nuclei that might be detectable by LIGO (Nishikawa et al. 2017). These LIGO events occur within the IMBH sphere of influence. This could lead to enhanced drag and affect the gravitational-wave signal phase evolution. This could potentially be seen as a cumulative phase shift by LISA over many cycles (Yue & Han 2017).

We showed that mini-spikes around a population of hundreds or thousands IMBHs can significantly contribute to the GC emission and can readily account for both the normalization and spatial morphology of the $\gamma$-ray excess for very small annihilation cross-sections. The expected morphology of the predicted excess does not necessarily follow the standard DM halo profile, for instance, it can effectively trace the Galactic bulge due to mass segregation and the dependence of mini-spike luminosities on BH mass. This circumvents the issue raised by the observation of an excess of $\gamma$-rays in control regions in the disk where no significant contribution from DM is expected (Ackermann et al. 2017). IMBHs would appear naturally in central regions due to three-body encounters and ejections. This distinctive morphology also allows the model to evade the constraints of Clark et al. (2016) that ruled out a DM interpretation of the excess in terms of ultra-compact mini-halos. We note that the constraints of Clark et al. (2016) do not account for more recent studies of the GC emission that revealed a more complex spatial morphology (Ackermann et al. 2017; Bartels et al. 2017). Finally, we expect the central massive BHs seen in nearby GCs, if indeed formed in the early universe, to have DM spikes, and hence to be Fermi $\gamma$-ray sources. 47 Tuc is a possible example (Abdo et al. 2009), although one cannot easily distinguish a possible $\gamma$-ray point source from the expected population of MSPs. Future observations may help us elucidate this point.

T.L. receives financial support from CNRS-IN2P3. T.L. also acknowledges support from the European Unions Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement Nos. 690575 and 674896; besides recurrent institutional funding by CNRS-IN2P3 and the University of Montpellier. The work of J.S. has been supported in part by European Research Council (ERC) Project No. 267117 (DARK) hosted by Université Pierre & Marie Curie—Paris VI, Sorbonne Universités.

References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, Sci, 325, 845
Ackermann, M., Ajello, M., Albert, A., et al. 2017, ApJ, 840, 43
Ackermann, M., Albert, A., Anderson, B., et al. 2015, PhRvL, 115, 231301
Agrawal, P., & Randall, L. 2017, ICAP, 12, 019
Ajello, M., Albert, A., Atwood, W. B., et al. 2016, ApJ, 819, 44
Alcock, C., Allsman, R. A., Alves, D. R., et al., 2001, ApJ, 550, L169
Ali-Haimoud, Y., & Kamionkowski, M. 2017, PhRvD, 95, 043534
Ali-Haimoud, Y., Kovetz, E. D., & Kamionkowski, M. 2017, PhRvD, 96, 123523
Antonini, F., Barausse, E., & Silk, J. 2015, ApJ, 812, 72
Aprile, E., Aalbers, J., Agostini, F., et al. 2017, PhRvL, 119, 181301
Bae, Y.-B., Kim, C., & Lee, H. M. 2014, MNRAS, 440, 2714
Bahcall, J. N., & Wolf, R. A. 1976, ApJ, 209, 214
Baldassare, V. F., Reines, A. E., Gallo, E., & Greene, J. E. 2017, ApJ, 836, 20
Bartels, R., Krishnamurthy, S., & Weniger, C. 2016, PhRvL, 116, 051102
Bartels, R., Storm, E., Weniger, C., & Calore, F. 2017, arXiv:1711.04778
Begelman, M. C., & Volonteri, M. 2017, MNRAS, 464, 1102

Figure 1. Angular profiles for the total $\gamma$-ray emission at 2 GeV with bright point sources masked (black solid line; Ackermann et al. 2017) and for various components of the $\gamma$-ray emission. Green squares: MSP-like component extracted from the data (Ackermann et al. 2017). Red dashed line: GeV excess in the sample model from Ackermann et al. (2017) corresponding to a generalized NFW profile template with slope $\gamma = 1.25$. Magenta dotted–dashed line: GeV excess in the sample model but for a regular NFW profile ($\gamma = 1$). Yellow line: prediction for MSPs in the bulge of the Milky Way from disrupted globular clusters (Brandt & Kocsis 2015). Our IMBH–mini-spike model is depicted by the blue shaded area for benchmark slopes discussed in the text. Here, we are mostly interested in illustrating the spatial morphology of the signal in our model, so we arbitrarily rescaled the angular IMBH–mini-spike profile at the level of the first MSP-like point.
Bird, S., Cholis, I., Muñoz, J. B., et al. 2016, PhRvL, 116, 201301
Brandt, T. D. 2016, ApJL, 824, L31
Brandt, T. D., & Kocsis, B. 2015, ApJ, 812, 15
Carr, B. I., & Hawking, S. W. 1974, MNRAS, 168, 399
Cirelli, M., Corella, G., Hektor, A., et al. 2011, JCAP, 3, 051
Clark, H. A., Scott, P., Trott, R., & Lewis, G. F. 2016, arXiv:1612.01539
Clesse, S., & García-Bellido, J. 2015, PRD, 92, 023524
Cohen, A., Fialkov, A., Barkana, R., & Lotem, M. 2016, MNRAS, 472, 1915
Eroshenko, Y. N. 2016, AstL, 42, 347
Fragione, G., Antonini, F., & Gnedin, O. Y. 2017, MNRAS, submitted (arXiv:1709.03534)
Gillessen, S., Plewa, P. M., Eisenhauer, F., et al. 2017, ApJ, 837, 30
Gnedin, O. Y., & Silk, J. 2004, PhRvL, 93, 061302
Gondolo, P., & Silk, J. 1999, PhRvL, 83, 1719
Goodenough, L., & Hooper, D. 2009, arXiv:0910.2998
Habouzit, M., Nishimichi, T., Peirani, S., et al. 2014, MNRAS, 445, L129
Habouzit, M., Volonteri, M., Latif, M., Dubois, Y., & Peirani, S. 2016, MNRAS, 463, 529
Islam, R. R., Taylor, J. E., & Silk, J. 2004, MNRAS, 354, 427
Kızıltan, B., Baumgardt, H., & Loeb, A. 2017, Natur, 542, 203
Lacroix, T., Boehm, C., & Silk, J. 2015, PhRvD, 92, 043510
Lee, S. K., Lisanti, M., Safdi, B. R., Slatyer, T. R., & Xue, W. 2016, PhRvL, 116, 051103
Lupi, A., Haardt, F., Dotti, M., et al. 2016, MNRAS, 456, 2993
Merritt, D., Milosavljević, M., Verde, L., & Jimenez, R. 2002, PhRvL, 88, 191301
Nakama, T., Silk, J., & Kamionkowski, M. 2017, PRD, 95, 043511
Nishikawa, H., Kovetz, E. D., Kamionkowski, M., & Silk, J. 2017, arXiv:1708.08449
Park, D., Kim, C., Lee, H. M., Bae, Y.-B., & Belczynski, K. 2017, MNRAS, 469, 4665
Peebles, P. J. E. 1972, ApJ, 178, 371
Portail, M., Gerhard, O., Wegg, C., & Ness, M. 2017, MNRAS, 465, 1621
Rashkov, V., & Madau, P. 2014, ApJ, 780, 187
Regan, J. A., Visbal, E., Wise, J. H., et al. 2017, NatAs, 1, 0075
Sadeghian, L., Ferrer, E., & Will, C. M. 2013, PhRvD, 88, 063522
Sasaki, M., Suyama, T., Tanaka, T., & Yokoyama, S. 2016, PhRvL, 117, 061101
Silk, J. 2017, ApJL, 839, L13
Tremaine, S., Gebhardt, K., Bender, R., et al. 2002, ApJ, 574, 740
Young, S., Regan, D., & Byrnes, C. T. 2016, JCAP, 2, 029
Yue, X., & Han, W. 2017, arXiv:1711.09706