Black Hole Window into p-Wave Dark Matter Annihilation

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We present a new method to measure or constrain p-wave-suppressed cross sections for dark matter (DM) annihilations inside the steep density spikes induced by supermassive black holes. We demonstrate that the high DM densities, together with the increased velocity dispersion, within such spikes combine to make thermal p-wave annihilation cross sections potentially visible in γ-ray observations of the Galactic center (GC). The resulting DM signal is a bright central point source with emission originating from DM annihilations in the absence of a detectable spatially extended signal from the halo. We define two simple reference theories of DM with a thermal p-wave annihilation cross section and establish new limits on the combined particle and astrophysical parameter space of these models, demonstrating that *Fermi Large Area Telescope* is currently sensitive to thermal p-wave DM over a wide range of possible scenarios for the DM distribution in the GC.

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Most astrophysical searches for dark matter (DM) annihilation look for velocity-independent, or s-wave, cross sections $\langle \sigma v \rangle$. Theories with p-wave cross sections, $\langle \sigma v \rangle \propto v^2$, have largely remained out of reach in standard searches for DM. The only previous limits on thermal p-wave DM annihilation come from cosmic microwave background and radio observations, which are sensitive to sub-GeV DM annihilating to e^+e^- [1], while at higher masses cosmic microwave background observations are orders of magnitude away from sensitivity to thermal p-wave annihilations [2].

Here, we show that thermal p-wave DM annihilation can be discovered via γ-ray emission within the density spikes that form around the supermassive black holes (SMBHs) at the centers of DM halos. The high DM densities within such a BH-induced spike, and the increased velocity dispersion required to support such densities, together boost a p-wave-suppressed DM annihilation rate to potentially observable values. Such spikes would appear as point sources to γ-ray telescopes, and would contain sharp spectral features strongly indicating a DM origin. As a concrete illustration we consider the Milky Way's SMBH Sgr A*, showing that the *Fermi* telescope's observations of the Galactic center (GC) already place new constraints on p-wave DM annihilation, and opening the door to the potential discovery of thermal p-wave DM.

Models of thermal p-wave DM.—A thermal p-wave annihilation cross section is a generic prediction of a broad class of well-motivated DM models. If DM is fermionic, then in a parity-conserving theory its annihilation to spin-0, P-even final states cannot receive any contribution from the s wave. Thus, for instance, the well-known model of fermionic Higgs portal DM [3,4] exhibits an annihilation cross section that receives its leading contribution in the p wave.

We consider here two simple reference models of thermal p-wave dark matter. First is a hidden sector Higgs portal (HSHP) model, where a Majorana DM particle χ annihilates to pairs of dark scalars s. We consider a minimal implementation of this model, described by the Lagrangian $\mathcal{L} = \mathcal{L}_{\text{kin}} - \frac{1}{2} y S(\chi\chi + \text{H.c.}) + (\mu_s^2/2)S^2 - (\lambda_s/4!)S^4 - (\epsilon/2)S^2|H|^2$, where a discrete symmetry $S \to -S$, $\chi \to i\chi$ forbids cubic and linear terms in $V(S)$ and a Majorana mass term for χ. After S obtains a vacuum expectation value, it mixes with the Higgs boson, allowing the mass eigenstate s to decay to standard model (SM) states. The four free parameters describing this model can be taken to be m_χ, m_s, and the dimensionless Yukawa and portal couplings y and ϵ. For $m_s < 2m_h$, the branching ratios of s are given by the branching ratios of the SM Higgs boson at the same mass, while for $m_s > 2m_h(2m_t)$ the decays $s \to hh(t\bar{t})$ must also be included.

Our second example is a hidden sector axion portal (HSAP) model, where Majorana DM annihilates to pairs of pseudoscalars a, which can be described by the simple Lagrangian $\mathcal{L} = \mathcal{L}_{\text{kin}} - (m_\chi/2)(\chi\chi + \text{H.c.}) - i\frac{1}{2} y a(\chi\chi - \text{H.c.}) - (m_a^2/2)a^2$; if an approximate symmetry is responsible for protecting m_a, then higher-order polynomial self-interactions of a are suppressed [5]. The pseudoscalar can decay via dimension-five couplings to SM gauge bosons. We will consider the case where its coupling to gluons is absent at leading order, which has the important consequence that $\text{Br}(a \to \gamma\gamma)$ is then $O(1)$. For simplicity, we will take $\text{Br}(a \to \gamma\gamma) = 1$, neglecting (for example) the generic but model-dependent $\text{Br}(a \to Z\gamma)$ that opens up for $m_a > m_Z$. With this assumption, there are again four free parameters describing this model, which can be taken to be m_χ, m_a, y, and $\epsilon \equiv m_a/\Lambda$, where $1/\Lambda$ is the dimensionful coupling of the pseudoscalar to pairs of photons.

The range of γ-ray signatures exhibited by these two theories provides a representative guide to the observability of a general model of thermal p-wave DM annihilating ultimately to visible SM particles. The thermally averaged annihilation cross section in our two reference theories may be written

$$\langle\sigma v\rangle = \frac{y^4 v^2}{\pi m_\chi^2}\sqrt{1-z}f(z) + \mathcal{O}(\sqrt{1-z}v^4), \quad (1)$$

where v is the relative velocity, $z \equiv m_{s,a}^2/m_\chi^2$, and $\sqrt{1-z}$ reflects final state phase space. The function $f(z)$ is

$$f_s(z) = \frac{72 - 160z + 165z^2 - 99z^3 + 37z^4 - \frac{33}{4}z^5 + \frac{27}{32}z^6}{32(4-z)^2(2-z)^4} \quad (2)$$

for the HSHP model, and

$$f_a(z) = \frac{(1-z)^2}{24(2-z)^4} \quad (3)$$

for the HSAP model [7]. We numerically solve the Boltzmann equation using the full thermally averaged expression for the cross section to determine the value of y yielding the observed relic abundance, leaving m_χ and z as the free parameters of each model (we assume for simplicity that the SM and the dark sector have the same temperature at freeze-out). This determines the thermal annihilation cross section $\sigma_{\rm thermal}$ as a function of m_χ and z. The coupling ϵ is irrelevant for astrophysical signatures provided that (i) $\epsilon \ll y$ and (ii) the mediator (a, s) decays before nucleosynthesis.

These models are both examples of secluded weakly interacting massive particles [8]; their direct detection and collider signals are $\propto \epsilon^2$ and can be parametrically small. The indirect detection signal, on the other hand, remains directly tied to the relic abundance, and thus for these models γ rays from DM annihilation in a black hole (BH) spike can easily be the most robust route to discovery.

The Milky Way's BH spike.—A DM density spike due to the presence of the central SMBH Sgr A* forms inside the radius of gravitational influence of the SMBH, $r_h = M/v_0^2$ $(G \equiv 1)$. Here, M is the mass of the SMBH and v_0 is the velocity dispersion of DM in the halo outside the spike. The precise form this spike takes depends on both the properties of DM and the formation history of the BH, making DM annihilation signals from such spikes potentially powerful probes of both the particle properties of DM and the evolution of the Milky Way.

A general DM spike $\rho(r)$ may be well approximated by a series of connected power-law profiles. The spike begins its growth from the inner halo, which in a generalized NFW halo follows a power law $\rho(r) = \rho(r_0)(r_0/r)^{\gamma_c}$. DM-only simulations yield typical values of $0.9 \lesssim \gamma_c \lesssim 1.2$ [9,10], while the dissipative collapse of baryons into the disk can adiabatically contract the central DM halo into a steeper power law [11–13], with values as high as $\gamma_c \sim 1.6$ being possible in the Milky Way [14].

The DM spike grows inside $r_b \approx 0.2 r_h$ [15], and is well described by $\rho_{\rm sp}(r) = \rho(r_b)(r_b/r)^{\gamma_{\rm sp}}$. The power-law index $\gamma_{\rm sp}$ depends on possible formation histories. The steepest spikes are formed by the response of a collisionless DM halo to the adiabatic growth of a central SMBH, in which case $\gamma_{\rm sp}(\gamma_c) = (9-2\gamma_c)/(4-\gamma_c)$, which for $0 < \gamma_c \leq 2$ yields $2.25 < \gamma_{\rm sp}(\gamma_c) < 2.5$ [15–18]. The heating of DM from gravitational scattering off of a sufficiently dense and cuspy stellar density within r_h could substantially soften the DM spike over the lifetime of the Milky Way [17,18]. The final equilibrium spike profile attained as a result of this stellar heating has $\gamma_{\rm sp} = 1.5$, while a spike that is in the process of being heated would have an intermediate value of $\gamma_{\rm sp}$, perhaps $\gamma_{\rm sp} \sim 1.8$. See Ref. [19] for a recent summary and discussion, including other possible spike and halo solutions, such as those arising from mergers, DM self-interactions, etc.

Once the DM spike attains the "annihilation plateau" density $\rho_{\rm ann} = m_\chi/\langle\sigma v\rangle t$ at $r \equiv r_{\rm in}$, DM annihilations become relevant over the lifetime t of the spike ($\approx$ the age of the SMBH). For $r < r_{\rm in}$, annihilations weaken the power law growth to $\rho_{\rm in}(r) = \rho_{\rm ann}(r_{\rm in}/r)^{1/2}$ [20]. In this innermost region only particles in eccentric orbits with apocenters outside $r_{\rm in}$ contribute significantly to the density inside $r_{\rm in}$. This weakened profile arises whenever the time scale for annihilation in the Galaxy lifetime decreases with decreasing r in a canonical spike, which is the case for p-wave as well as s-wave annihilations. Finally, the inner boundary of the spike is at $4M$ [21,22]. The resulting density profile thus may be written as [19]

$$\begin{aligned}
\rho(r) &= 0, r < 4M \quad \text{(capture region)},\\
&= \frac{\rho_{\rm sp}(r)\rho_{\rm in}(t,r)}{\rho_{\rm sp}(r)+\rho_{\rm in}(t,r)}, \qquad 4M < r < r_b \quad \text{(spike)},\\
&= \rho_b(r_b/r)^{\gamma_c}, \qquad r_b < r < R_H \quad \text{(cusp)},\\
&= \rho_H(R_H/r)^{\gamma_H}, \qquad R_H < r \quad \text{(outer halo)}. \quad (4)
\end{aligned}$$

The dominant contribution to any annihilation signal comes from the region where $r \sim r_{\rm in}$.

Critically, the velocity dispersion increases inside the spike to support the power-law increase in density. For the (isotropic) velocity dispersion profile, we match an approximate, piecewise continuous solution of the Jeans equation in the spike onto a constant dispersion in the inner halo [7],

$$\begin{aligned}
v^2(r) &= \frac{M}{r}\frac{1}{1+\gamma_{\rm in}}\left[1 + \frac{r}{r_{\rm in}}\left(\frac{\gamma_{\rm in}-\gamma_{\rm sp}}{1+\gamma_{\rm sp}}\right)\right],\\
&\qquad 4M \leq r < r_{\rm in} \quad \text{(inner spike)},\\
&= \frac{M}{r}\frac{1}{1+\gamma_{\rm sp}}, \qquad r_{\rm in} \leq r < \frac{r_h}{1+\gamma_{\rm sp}} \quad \text{(outer spike)},\\
&= v_0^2 = \text{const}, \qquad \frac{r_h}{1+\gamma_{\rm sp}} \leq r \quad \text{(cusp)}. \quad (5)
\end{aligned}$$

Following Ref. [19], we adopt the following parameter values for the Milky Way's DM halo and SMBH: $M = 4\times10^6 M_\odot$ [23,24], $\rho_\odot = 0.3 \pm 0.1\ \text{GeV cm}^{-3}$ [25], $v_0 = 105 \pm 20\ \text{km s}^{-1}$ [26], $R_\odot = 8.46^{+0.42}_{-0.38}$ kpc [27], and

$t_{\rm ann} = 10^{10}$ yr. With these parameters we find a spike radius of $r_h = 1.7$ pc, subtending 0.012°, well below the resolution of current and future γ-ray telescopes [28–36]. The remaining parameters of the spike solution are the exponents $\gamma_c, \gamma_{\rm sp}$; with no direct measurements of these quantities, we treat them as free parameters of our model. To bracket the range of possibilities, we consider $\gamma_{\rm sp}$ ranging between 1.5 (the limiting value obtained from either stellar heating or growth from an isothermal core) and the adiabatic value $\gamma_{\rm sp}(\gamma_c)$. Einasto haloes [12,37,38], which do not follow a power law as $r \to 0$, are expected to yield adiabatic spikes somewhere within this range. Typical values for $r_{\rm in}$ fall in the range 10^{-3}–10^{-5} pc, where the velocity dispersions are still nonrelativistic, $v(r_{\rm in}) \sim 10^{-2}$.

Observability of p-wave DM: continuum emission.—Our aim here is to demonstrate that there is a sizable range of possible spike and halo parameters for which emission from thermal HSHP DM annihilation in a BH spike at the GC is comparable or greater in brightness to detected γ-ray point sources in the same region. The *Fermi Telescope* Third Point Source Catalogue (3FGL) [39] contains several point sources near the GC. The *Fermi Large Area Telescope* (*LAT*) localization accuracy for a point source depends on its brightness and that of the surrounding diffuse emission, and is ∼9arcmin for the sources in question. The *Fermi-LAT* team has associated source 3FGL J1745.6-2859c with Sgr A*. This has an integrated flux of 2.18×10^{-8} photons/cm^2 s in the energy range 1–100 GeV. The source 3FGL J1745.3-2903c is slightly brighter, with an integrated flux $\Phi = 3.87 \times 10^{-8}$ photons/cm^2 s in the same energy range, but is 5.1 arcsec offset from Sgr A*, and so is a less likely association. Spectra of these two sources appear in Fig. 1, together with spectra from HSHP DM annihilating inside possible BH spikes. The remaining bright 3FGL source within 30 arcmin of Sgr A* is associated with a pulsar wind nebula and thus is not a BH spike candidate. *Fermi LAT*'s Second Point Source Catalogue [40] reported a single central point source 2FGL J1745.6-2858, previously identified as a BH spike candidate [19], and is shown for comparison.

In Figs. 2 and 3 we compare the flux from HSHP DM to the point source fluxes detected by *Fermi LAT*. For each of the three point sources, we find the minimum value of the cross section such that the primary photon flux from DM annihilations exceeds the observed flux in any energy bin at more than 95% C.L., treating each bin as an independent Poisson-distributed variable. We use PYTHIA 8 [41] to generate photon spectra. Scalar branching ratios in the range $m_s < 75$ GeV are calculated using HDECAY [42]; for $m_s > 75$ GeV, we use branching ratios from the LHC Higgs Cross-Section Working Group [43]. Our results are shown in the top panel of Fig. 2 for the representative choice of mass-squared ratio $z = 0.2$. The large differences between the maximum cross section allowed by the three different point sources arise because the flux from a BH spike is only weakly dependent on the annihilation cross section; for a

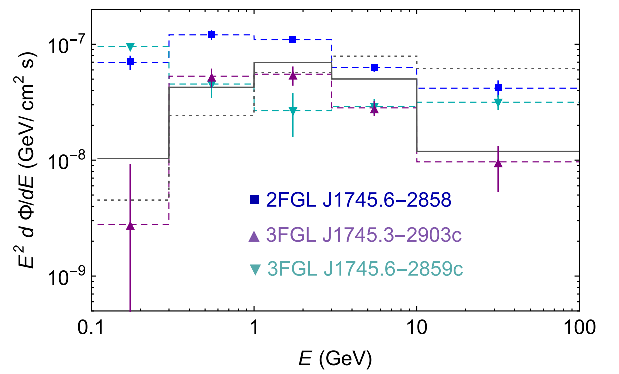

FIG. 1 (color online). Spectra of three possible candidates to contain emission from a BH-induced DM density spike [39,40]. In black are two example predictions of thermal HSHP DM with different particle masses (determining the shape) and spike and halo parameters (controlling the normalization). The solid line shows predictions for $m_\chi = 45$ GeV, $m_s = 10$ GeV, $\gamma_c = 1.3$, and $\gamma_{\rm sp} = 1.8$; the dashed line shows predictions for $m_\chi = 110$ GeV, $m_s = 50$ GeV, and an adiabatic spike in a halo with $\gamma_c = 1.1$.

p-wave spike, $\Phi \propto (\sigma/\sigma_{\rm thermal})^{(3-\gamma_{\rm sp})/(1+\gamma_{\rm sp})}$. This exponent is ∼1/5 for adiabatic spikes, and ∼1/2 for heated spikes. The BH spike would outshine detected point sources across a wide range of possible spike and halo scenarios, notably including adiabatic spikes for $\gamma_c \gtrsim 1$, as we show in Fig. 3.

Greater sensitivity could be obtained in a dedicated search using more sophisticated signal and background modeling. Signal will also include sizeable secondary

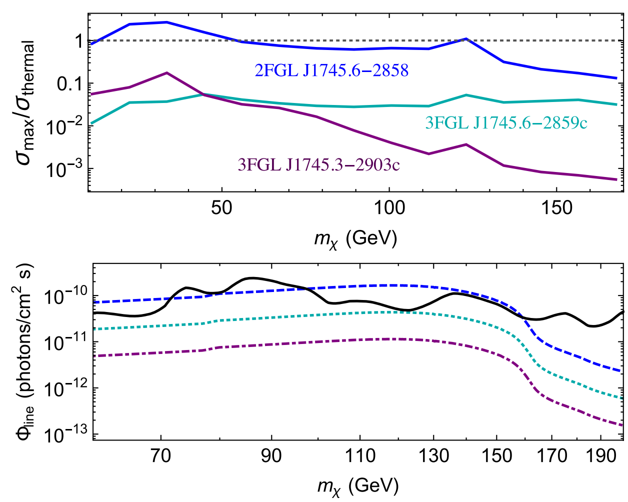

FIG. 2 (color online). Sensitivity to HSHP DM from the *Fermi* telescope's observations of the GC. Top: the minimum value of the DM annihilation cross section for which the primary photon emission exceeds observed point source spectra at 95% C.L. in at least one bin, as a function of DM mass, for adiabatic spikes with $\gamma_c = 1.1$ and $z = 0.2$. Bottom: the predicted flux in a box-shaped spectral feature from HSHP DM annihilating inside adiabatic spikes for $\gamma_c = 1.3$ (blue, dashed), 1.2 (cyan, dotted), 1.1 (purple, dash dotted). Results are shown for $z = 0.99$, where the box is sufficiently narrow to appear as a line, and compared to the *Fermi-LAT* limit [44] on line flux from the GC (black).

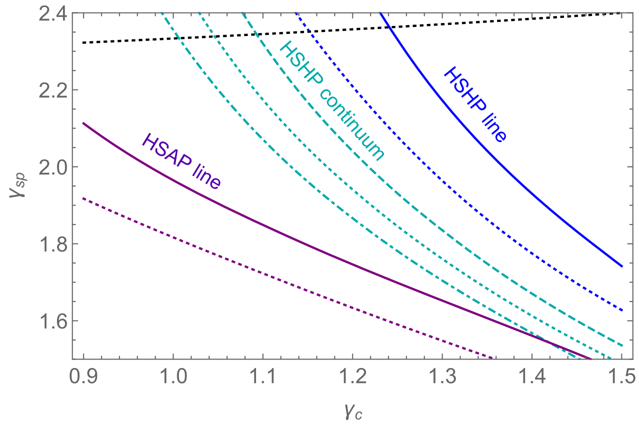

FIG. 3 (color online). The region of combined halo + spike parameter space where *Fermi LAT* observations constrain thermal p-wave annihilation cross sections for $m_\chi = 110$ GeV. In cyan are continuum constraints for HSHP DM ($z = 0.2$), from comparison with 2FGL J1745.6-2858, 3FGL J1745.6-2959c, and 3FGL J1745.3-2903.c in the dashed, dotted, and dot-dashed lines respectively; the blue solid line shows the line search limit of Ref. [44] on HSHP DM ($z = 0.99$); the purple solid line shows the line search limit on HSAP DM ($z = 0.99$). Dotted blue and purple lines show an estimate of the improved sensitivity to HSHP and HSAP DM, respectively, offered by a dedicated line search. Regions above the curves exceed observations. Adiabatic spikes are indicated by the dotted black line.

emission arising from the interaction of DM annihilation products with ambient dust, starlight, and magnetic fields. Meanwhile, a given BH spike candidate will generically contain astrophysical emission in addition to any DM signal. The 3FGL "variability index" for 3FGL J1745.6-2859c suggests that it may be time variable, which, if confirmed, would set a floor for the astrophysical contribution to the γ-ray flux from this source.

Limits on p-wave DM: box and line searches.—Given the large systematic uncertainties on DM halo and spike distributions, it is difficult to conclusively discover or exclude p-wave DM using a continuum signal alone. Even for DM with an s-wave annihilation cross section, where support for a DM interpretation of a potential γ-ray signal may be obtained from its extended spatial distribution, the subdominant but sharp γ-ray line at $E_\gamma = m_{\mathrm{DM}}$ remains a smoking gun for a DM origin, in contrast to the broad continuum signature that may more easily be mimicked by astrophysical processes [45,46]. The analog of a γ-ray line in our reference models is a γ-ray box, from the decay of a (boosted) mediator to a pair of photons [47]. The upper and lower end points of the box depend on the mass splitting between the DM and the mediator, and are given by $E_\gamma^\pm = (m_\chi/2)(1 \pm \sqrt{1-z})$. In the near-degenerate limit $z \approx 1$, the box becomes narrower than the *Fermi LAT* energy resolution, and limits from line searches may be directly applied. Sensitivity to the flux in wider boxes in less degenerate spectra is ~2–5 times weaker than the sensitivity to the flux in linelike features at the same value of m_χ [47,48].

The line search with the best sensitivity to p-wave DM is region R3 from [44], which considers the inner 3° around the GC and notably does not mask point sources. We reinterpret this search as a constraint on narrow boxes ($z = 0.99$) originating from a BH spike [49]. We show the resulting exclusions for HSHP DM annihilating in adiabatic spikes in the bottom panel of Fig. 2. In this model, $\mathrm{Br}(s \to \gamma\gamma) \lesssim 10^{-3}$, making the current line search less sensitive than the continuum constraints; this conclusion would also apply to line searches in fermionic Higgs portal models, and to HSAP models where the pseudoscalar dominantly decays to gluons. Thus a DM origin for a potential Milky Way signal in Higgs portal models would be established via the discovery of a sharp spectral feature within the emission of a previously discovered point source. For our HSAP model, however, the box is the leading signal, resulting in much greater sensitivity. Our limits on HSAP DM are shown in Fig. 3. In this model the nonoptimized line search of Ref. [44] is already sufficiently powerful to exclude adiabatic spikes given the Galactic parameters adopted here.

As a rough estimate of the potential improvement offered by a dedicated search for lines near Sgr A* we approximate the gain in significance as $\sqrt{B_3/B_{0.3}}$, where $B_{0.3}$ is the background flux in a search region of radius of order the angular resolution for high-energy photons, 0.3°, and B_3 is the background flux in the *Fermi LAT* search region R3. Examining SOURCE class photons with energies above 10 GeV gives an estimate for this ratio of $B_3/B_{0.3} \approx 10$. We show the resulting estimate of the potential sensitivity to thermal p-wave DM annihilation in the dotted lines in Fig. 3.

Summary and conclusions.—High densities in DM spikes around SMBHs, together with the enhanced velocity dispersions required to support them, allow p-wave-suppressed DM annihilation cross sections to yield visible signals in current γ-ray telescopes. Using the *Fermi* telescope's observations of the GC, we placed entirely novel constraints on thermal p-wave annihilation cross sections. More precisely, we constrained a sizeable range of combined particle and astrophysical models (in much the same spirit as Galactic searches for s-wave annihilation that depend on a halo model as well as the final state), and established a well-motivated range of particle and astrophysical parameter space where DM discovery may be uniquely possible via the detection of sharp spectral features in a central γ-ray point source.

Beyond the Milky Way, most bulge galaxies are expected to host SMBHs, which will in turn create DM density spikes of varying steepness. DM annihilation within these spikes yields γ-ray point sources with a common spectrum of primary photons, although the secondary emission will depend on the local environment of each SMBH. This conclusion is true for s-wave as well as p-wave DM; the novelty for p-wave DM is that the point sources may be observable even in the absence of a detectable halo signature. When the point sources are too dim to be resolved, BH spikes provide a novel mechanism for p-wave DM to contribute at potentially non-negligible levels to the extragalactic diffuse background.

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