

Illuminating Black Hole Shadows with Dark Matter Annihilation

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 (Received 8 October 2024; revised 26 May 2025; accepted 29 July 2025; published 16 September 2025)

The Event Horizon Telescope (EHT) has significantly advanced our ability to study black holes, achieving unprecedented spatial resolution and revealing horizon-scale structures. Notably, these observations feature a distinctive dark shadow—primarily arising from faint jet emissions—surrounded by a bright photon ring. Anticipated upgrades of the EHT promise substantial improvements in dynamic range, enabling deeper exploration of low-background regions, particularly the inner shadow defined by the lensed equatorial horizon. Our analysis shows that observations of these regions transform supermassive black holes into powerful probes for annihilating dark matter, which is expected to accumulate densely in their vicinity. By analyzing the black hole image morphology and performing electron-positron propagation calculations in realistic plasma backgrounds derived from general relativistic magneto-hydrodynamic simulations, we set stringent constraints on dark matter annihilation, requiring contributions below the astrophysical emission. These constraints, derived from both current EHT observations and projections for future upgraded arrays, exclude a substantial region of previously unexplored parameter space and remain robust against astrophysical uncertainties, including black hole spin and plasma temperature variations.

DOI: [10.1103/physrevlett.135.121001](https://doi.org/10.1103/physrevlett.135.121001)

Introduction—The rapid development of the very long baseline interferometry (VLBI) technique has enabled extraordinarily high angular resolution in radio astronomy. A notable illustration of this progress is the recent imaging of supermassive black holes (SMBHs) achieved by the Event Horizon Telescope (EHT) [1,2], which unveiled detailed astrophysical information in the strong gravity

regions. Anticipated future upgrades of the EHT, including possible ground-based expansions and the proposed space-based Black Hole Explorer (BHEX), promise further enhancements in angular resolution, dynamic range, and baseline coverage [3,4]. These advancements are pivotal not only for astrophysical insights but also for exploring fundamental physics, including testing general relativity, examining black hole (BH) properties, and investigating new fundamental fields [5].

One class of potential new particles, often considered as dark matter (DM) candidates, is found around the GeV mass scale. These candidates include weakly interacting massive particles (WIMPs) [6] and sub-GeV DM [7]. In regions dominated by SMBHs' gravitational potential, the distribution of particlelike DM can steeply concentrate toward the BH, resulting in densities significantly higher than those near Earth [8]. Thus, SMBHs could serve as effective detectors for DM particles.

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A promising approach for observing the DM spike is through indirect detection methods, like observing photons or cosmic rays resulting from potential DM annihilation [8]. These methods leverage the principle that the annihilation rate, directly proportional to the square of the density, increases significantly in regions of high density, thereby enhancing the production of particles. At the EHT's millimeter radio band, photons are typically produced via synchrotron radiation, where electrons spiral around magnetic field lines [9]. Understanding the magnetic field structure near the horizon is essential for predicting radio fluxes from DM annihilation. In this Letter, we employ the best-fit general relativistic magnetohydrodynamic (GRMHD) simulation, which aligns with EHT's observations of SMBH M87* [10,11], specifically the magnetically arrested disk (MAD) model [12], to calculate the spectrum of DM annihilated electron-positron pairs near the SMBH and their resulting synchrotron radiation. Our results indicate that the density distribution of these pairs is similar in both equatorial and polar regions, contrasting with the MAD model prediction where electrons predominantly inhabit the disk, with lower densities in the jet region. Therefore, we utilize the morphology of BH images to impose constraints on DM annihilation, analyzing both current observations of the dark region resulting from faint jet emissions and future observations of the inner shadow—a region delineated by the lensed image of the equatorial horizon [13]. These constraints, based on the morphology, prove significantly more stringent than those derived from the total intensity of the image [14,15].

Electron-positron spectrum from dark matter annihilations near supermassive black holes—The density of DM within a galaxy is typically highest at its center, and the presence of an SMBH can further sharpen this distribution, leading to an increased density toward the center. When considering an initial DM distribution profile where the mass of the central SMBH is sufficiently low to influence the distribution, the slow accretion of ordinary matter onto the SMBH can lead to an adiabatic distortion of DM phase space by the SMBH's gravitational potential [8]. For instance, in a standard Navarro-Frenk-White (NFW) profile derived from N-body simulations, which neglect the SMBH, the energy density $\rho(r) \propto r^{-1}$ in the central region, where r represents the distance from the galaxy's center [16]. The presence of an SMBH, assuming its adiabatic growth, leads to the formation of a DM spike, with its density scaling as $\propto r^{-7/3}$ at the center and transitioning back to the NFW profile in the outer regions. However, this adiabatic formation of a spike can be mitigated by factors such as stellar interactions [17]. Furthermore, DM annihilation introduces an upper limit on the density, inversely proportional to $\langle\sigma v\rangle$, the thermally averaged cross section times the relative velocity of DM particles, which effectively regulates the central spike into a flat core [8].

Depending on their mass and interaction channels with standard model particles, DM can annihilate into a

spectrum of final-state particles, notably electrons and positrons in this Letter, which emit synchrotron radiation in magnetic fields [18]. These particles, after being produced near an SMBH, move under the influence of both gravitational and magnetic fields. We have developed a comprehensive framework, detailed in Supplemental Material [19], to calculate the steady-state electron-positron spectrum after propagation in the complex magnetic field environment surrounding an SMBH. We also include a discussion of the approximations employed, such as the omission of certain general relativistic effects, which have only a minor impact on our results. This framework represents an advancement over prior spherical models of DM propagation [14,15,49,50], aiming for a more astrophysically precise description.

The background magnetic field utilized for calculating the propagation of electrons and positrons is derived from MAD-type models [12], which is supported by observations of the SMBH M87* by the EHT [10,11]. In Fig. 1, we show an example of the azimuthally and time-averaged electron-positron density distribution, n_e , for a BH spin of $a_J = 0.9375$. The z axis is aligned with the BH's spin. The density is primarily concentrated in the disk region, with significantly lower values in the jet region. We utilize an axisymmetric ansatz to fit the magnetic field configurations in both the disk and jet regions, based on GRMHD simulations for the MAD. We assume that the bulk velocities of the electron-positron plasma resulting from DM annihilation align with the magnetic field lines. In the disk region, their radial components are directed toward the BH, with a magnitude scaling as $(2r_g/r)^{1/2}$, where r_g is the gravitational radius of the BH. In the jet region,

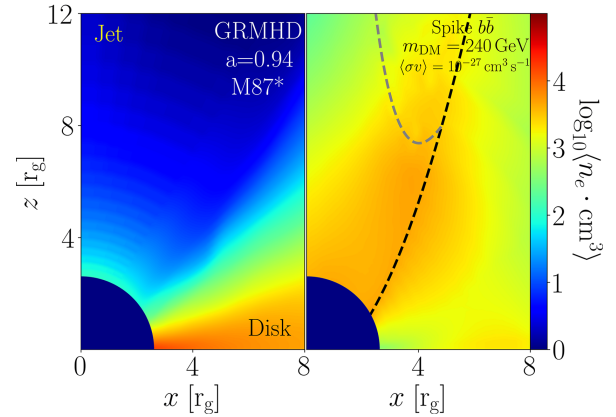


FIG. 1. Electron-positron number density n_e from an azimuthally averaged MAD model based on GRMHD (left) versus from DM annihilation (right). The z axis is aligned with the BH spin, adopting a BH spin of $a_J = 0.9375$ in the GRMHD simulation. The DM profile assumes a standard spike originating from an initial NFW profile, with a DM mass of $m_{\text{DM}} = 240$ GeV, annihilation via the $b\bar{b}$ channel, and a cross section of $\langle\sigma v\rangle = 10^{-27} \text{ cm}^3 \text{ s}^{-1}$. The black dashed line marks the jet boundary, while the gray dashed line indicates the stagnation surface.

we account for the rotation of the magnetic field by incorporating both the inertial centrifugal potential in the corotating frame and the gravitational potential, leading to the identification of a zero-velocity surface known as the stagnation surface [51–53]. The initial spectra of DM annihilated electron-positron pairs are calculated using the PPPC [18] and MadDM [54] packages.

The right panel of Fig. 1 presents an example of the resulting electron and positron density, excluding electrons from the GRMHD MAD model, where the DM mass is $m_{\text{DM}} = 240$ GeV, with the annihilation channel being $b\bar{b}$ and $\langle\sigma v\rangle = 10^{-27} \text{ cm}^3 \text{ s}^{-1}$. The black dashed line marks the jet boundary, while the gray dashed line indicates the stagnation surface. The densities in the jet and disk regions prove to be comparable, differing markedly from the GRMHD MAD case. This discrepancy arises because the distribution of electrons and positrons is expelled by the jet in the GRMHD scenario, whereas DM annihilation continuously supplies them within the jet cone.

Constraints from the EHT and future EHT upgrades— Constraints on DM annihilation require that radiation from

this process remains below the astrophysical background, positioning astrophysical radiation as a pivotal factor in determining the exclusion parameter space. We focus on the synchrotron radiation from the MAD model at 230 GHz radio frequency band. Our analysis concentrates on the synchrotron radiation emanating from the MAD model within the 230 GHz radio frequency band. By employing the RAPTOR covariant radiative transfer package [55], we generate a horizon-scale intensity (I) map for MAD outside an SMBH with an inclination angle of $\theta_o = 163^\circ$, consistent with observations of M87*, depicted in the top left panel of Fig. 2. Subsequent application of Gaussian smearing with an approximately $2r_g$ kernel to simulate the current EHT’s angular resolution yields an image that closely matches the observed data [10], with a total flux of approximately 0.6 Jy.

The BH image, presented on a logarithmic scale, reveals fascinating morphological features that reflect the interplay between Kerr spacetime and the sources of emission. The dashed line in Fig. 2 delineates the critical curve, beyond which null geodesics are captured into bound orbits around

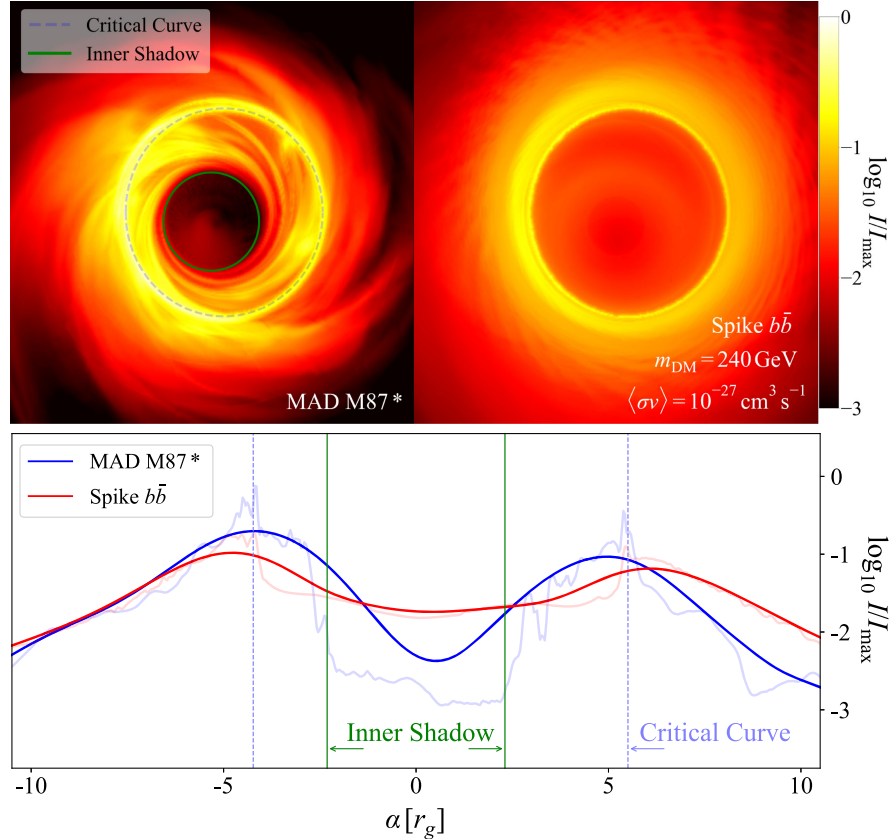


FIG. 2. Top: normalized intensity map (I/I_{max}) in logarithmic scale comparing the MAD model from GRMHD (left) to DM annihilation (right), for the SMBH M87* with $a_J = 0.9375$ at an inclination angle of $\theta_o = 163^\circ$. Normalization is against the maximum intensity in the MAD model, I_{max} . The critical curve and the inner shadow’s boundary are denoted by dashed and green lines, respectively. Both maps exhibit a total intensity of 0.6 Jy. Bottom: one-dimensional normalized intensity profile along the axis (α), centered on the BH and perpendicular to the spin projection, showcasing contrasts between GRMHD MAD (blue) and DM annihilation (red) scenarios. Dark and light shades indicate the original image and its Gaussian-smoothed counterpart with an $1r_g$ kernel, respectively.

the BH, creating a photon ring from light circling multiple times [56–58]. Consequently, the intensity observed in the adjacent region results from the cumulative effect of photons undergoing multiple loops, achieving their peak in the map [59]. Within the critical curve, backward geodesics terminate at the BH horizon, known as the BH “shadow” [9]. Nonetheless, this area is not completely devoid of light, as emission, proportional to electron density n_e and magnetic field strength B , reaches up to the horizon. As shown in Fig. 1 and Supplemental Material [19], the distribution of B slightly changes with the polar angle, whereas n_e is predominantly found in the accretion disk, with much lower concentrations in the jet region. This distribution creates a geometrically thin emission profile mainly in the equatorial disk, leading to sharp intensity depression in the central area, identified as the “inner shadow” [13]. The boundary of this inner shadow, marked in green in Fig. 2, outlines the lensed contour of the BH’s equatorial horizon.

The current EHT’s capability to detect the inner shadow is hindered by its limited dynamic range (~ 10) and angular resolution on the intensity dip. In contrast, future EHT upgrades are anticipated to achieve a substantial enhancement in both dynamic range (~ 1000) and angular resolution, equivalent to a Gaussian kernel of approximately $1r_g$. This improvement holds the promise of capturing this fascinating feature and delving into the BH horizon [13]. The bottom panel of Fig. 2 displays the one-dimensional intensity distribution along an axis that crosses the BH center and is perpendicular to the projection of its spin. The use of dark and light shades serves to distinguish between the original image and the image after applying Gaussian smearing. Notably, within the inner shadow, the foreground emission from the jet region is significantly suppressed—by roughly 2 orders of magnitude compared to the peak intensity—and, thus, well within the detection capabilities of the proposed EHT upgrades [13].

The pronounced dimming within the shadow region establishes a solid framework for testing DM annihilation. As shown in Fig. 1, the electron-positron density n_e , induced by DM annihilation, attains comparable levels in both the jet and disk regions, akin to the results observed in spherical emission models [60]. This morphology allows the DM-induced density to exceed the jet’s emission in the shadow area. The intensity map, derived solely from DM annihilation and presented in the top right panel of Fig. 2 with the benchmark parameters from Fig. 1, reveals a total intensity nearly matching the astrophysical emission of 0.6 Jy. In contrast, the inner shadow is significantly illuminated, lacking the expected intensity reduction. This discrepancy becomes even more evident in the bottom panel of Fig. 2, where the red line for DM annihilation markedly exceeds the expected intensity levels within the inner shadow, deviating from the astrophysical emission patterns.

In Fig. 3, we illustrate the exclusion regions derived from analyses using both the current EHT observations and the

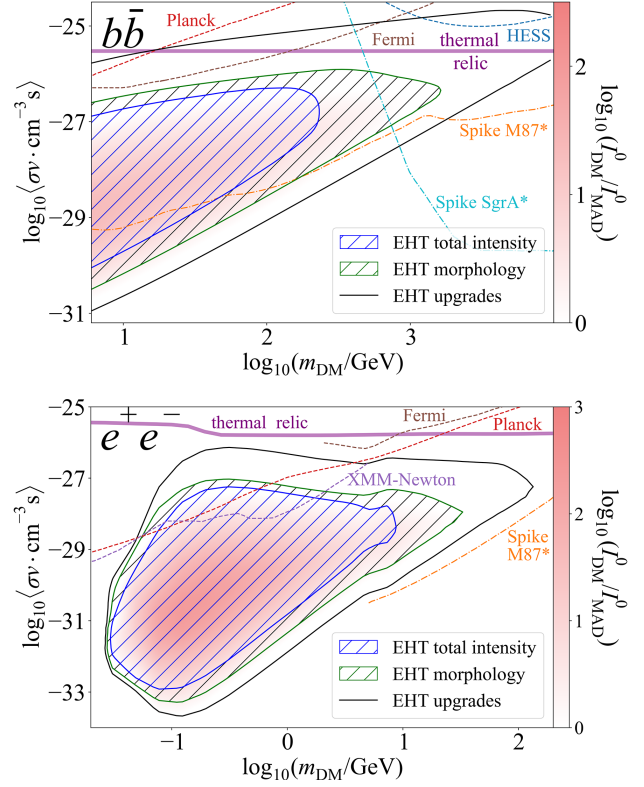


FIG. 3. Constraints on DM annihilation channels $b\bar{b}$ (top) and e^+e^- (bottom), derived from current EHT observations (diagonal stripes), which include criteria based on total intensity (blue) and BH image morphology (green), as well as projections for the EHT upgrades (black). The pink shades illustrate the ratio of local intensity between DM annihilation and astrophysical emissions from the MAD model in the inner shadow. The thermal relic annihilation cross section [61] is depicted by the purple line. Previous constraints from various sources, including Planck CMB observations [62], Fermi-LAT [63], H. E. S. S. [64], AMS [65], and XMM-Newton [66,67], as well as spike-based constraints [68,69], are shown for comparative analysis in dashed and dot-dashed lines, respectively.

future prospects, targeting DM annihilation channels $b\bar{b}$ and e^+e^- , associated with a DM spike around M87*. The regions with diagonal stripes represent constraints from current EHT observations. The regions enclosed by the blue lines represent exclusion constraints, ensuring that the total intensity from DM annihilation does not exceed the overall astrophysical emission within the EHT field of view, which extends to approximately $16r_g$ from the BH. The morphological constraints, shown within the green lines, impose a stricter criterion by demanding that the local intensity from DM annihilation, after Gaussian smearing with a $2r_g$ kernel, consistently remains below the astrophysical emission within $10r_g$ and exceeds the dynamic range threshold of $1/10$. The prospective morphological constraints from the EHT upgrades, depicted in black, significantly expand beyond that established by the current EHT, underscoring the increased sensitivity to the BH image’s morphology.

The density within the exclusion zone represents the ratio of local intensity between DM annihilation and MAD-induced emissions in the inner shadow region. The EHT upgrades' exclusion region primarily arises from the enhanced dynamic range of approximately 1000. In the $b\bar{b}$ channel, the exclusion region closely aligns with areas exhibiting the highest electron-positron densities as shown in Supplemental Material [19]. In contrast, the exclusion contour for the e^+e^- channel exhibits a notable turnover near 0.1 GeV, due to the reduced efficiency of synchrotron radiation at 230 GHz for m_{DM} below this threshold.

Several astrophysical uncertainties can influence our results, even within the MAD model class favored by multiple EHT observations of M87* [70–72]. One such parameter is the BH spin a_J , which is currently favored to be high [70], but has only a lower bound of $a_J \geq 0.5$ [73]. While the main text presents results using $a_J = 0.9375$, we also perform a full analysis for $a_J = 0.5$. The resulting constraints, shown in Supplemental Material [19], vary only slightly from the fiducial case, demonstrating the robustness of our conclusions. We additionally explore variations in plasma-related parameters such as R_{high} and R_{low} , which characterize the proton-to-electron temperature ratio in regions of weak and strong magnetization, respectively [55,74]. These variations likewise show minimal impact on our exclusion limits.

The purple line in Fig. 3 denotes the theoretically well-motivated thermal relic annihilation cross section [61], which the EHT upgrades could potentially probe for DM masses up to approximately 10 TeV. For context, the figure also presents previous constraints obtained from the Planck observation of the cosmic microwave background (CMB) [62], as well as constraints from the Fermi Large Area Telescope (Fermi-LAT) [63], the High Energy Stereoscopic System (H. E. S. S.) [64], the Alpha Magnetic Spectrometer Experiment (AMS) [65], and the X-ray Multi-Mirror Mission (XMM-Newton) [66,67], depicted with dashed lines. Additionally, dot-dashed lines highlight previous constraints that are specific to a DM spike profile [68,69]. Notably, some previous constraints derived from synchrotron radiation may lead to an overestimation of the exclusion region, attributed to the adoption of a simplified magnetic field profile [68]. Our constraints improve upon these existing bounds primarily due to the EHT's superior angular resolution and dynamic range, which enable probing DM annihilation in a compact region with minimal astrophysical foreground contamination.

Discussion—The exceptional angular resolution offered by the EHT and its future upgrades not only enriches our understanding of astrophysical phenomena but also provides robust constraints on fundamental particle physics [5,75–79]. This Letter illustrates how the detailed morphology of BH images, particularly the shadow regions, can inform constraints on DM annihilation. We capitalize on the heightened DM density near SMBHs and the unique

characteristics of BH images—most notably, the diminished intensity in the inner shadow area, a result of the jet's sparse electron density. To ensure the reliability of our constraints, we have developed an advanced framework for simulating the propagation of electrons and positrons within a background fit derived from a realistic GRMHD profile. This profile is consistent with the latest intensity and polarimetric observations and represents an advancement beyond previously assumed simpler spherical accretion models [14,15,49,50]. While our analysis uses M87* as a primary example, our discussions and constraints are equally applicable to another EHT focus, Sgr A*, within the Milky Way—given that observations similarly support a MAD profile around it and an almost direct line of sight [2,80]. Note that the DM considered here contributes solely to intensity enhancement, with negligible effects on geodesics due to its minimal mass distribution near the horizon. This distinguishes it from other dark sector phenomena, such as superradiant clouds [79,81], which can reach up to 10% of the BH's mass, or BH alternatives [82,83].

Looking ahead, this research aims to extensively explore DM characteristics, including an expanded range of annihilation channels, a wider spectrum of mass scales, and exploring phenomena such as p -wave annihilation [84] and forbidden DM [85], both of which are expected to be significantly amplified in the vicinity of SMBHs. Furthermore, our analysis of the horizon-scale intensity map could be broadened to assess morphological changes at larger scales, encompassing extended jet structures and the accretion flow at greater distances from the BH. In these areas, the electron density from DM annihilation with a large cross section decreases more slowly than the astrophysical background.

From an observational standpoint, the incorporation of linear and circular polarization intensity measurements could unveil new perspectives in differentiating between electrons and positrons [86–89]. This differentiation is crucial since astrophysical plasmas typically exhibit a significant deficit in positron populations, potentially facilitating the imposition of tighter constraints. The advent of forthcoming multifrequency observations [90] is expected to further improve detection capabilities.

Acknowledgments—We are grateful to Richard Anantua, Marco Cirelli, Razieh Emami, Jordan Koechler, George Wong, Xiao Xue, Daixu Yang, and Yue Zhao for useful discussions. The Center of Gravity is a Center of Excellence funded by the Danish National Research Foundation under Grant No. 184. Y.C. acknowledges support by VILLUM Foundation (Grant No. VIL37766) and the DNRF Chair program (Grant No. DNRF162) by the Danish National Research Foundation, the European Union's H2020 ERC Advanced Grant “Black holes: gravitational engines of discovery” Grant Agreement No. Gravitas–101052587, the Rosenfeld foundation in

the form of an Exchange Travel Grant, and the COST Action COSMIC WISPerS CA21106, supported by COST (European Cooperation in Science and Technology). This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie Grant Agreement No. 101007855 and Grant Agreement No. 101131233. R. D. is supported in part by the National Key R&D Program of China (No. 2021YFC2203100). Y.M. is supported by the National Natural Science Foundation of China (Grant No. 12273022), the Shanghai Municipality orientation program of Basic Research for International Scientists (Grant No. 22JC1410600), and the National Key R&D Program of China (No. 2023YFE0101200). J. S. is supported by the National Key Research and Development Program of China under Grants No. 2020YFC2201501 and No. 2021YFC2203004, Peking University under startup Grant No. 7101302974, and the NSFC under Grants No. 12025507, No. 12150015, and No. 12450006.

Views and opinions expressed are, however, those of the author only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

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