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Ultralight Boson Dark Matter and Event Horizon Telescope Observations of M87*

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The initial data from the Event Horizon Telescope (EHT) on M87*, the supermassive black hole at the center of the M87 Galaxy, provide direct observational information on its mass, spin, and accretion disk properties. A combination of the EHT data and other constraints provides evidence that M87* has a mass $\sim 6.5 \times 10^9\ M_\odot$. EHT also inferred the dimensionless spin parameter $|a^*| \gtrsim 0.5$ from jet properties; a separate recent analysis using only the light from near M87* as measured by the EHT Collaboration found $|a^*| = 0.9 \pm 0.1$. These determinations disfavor ultralight bosons of mass $\mu_b \in (0.85, 4.6) \times 10^{-21}$ eV for spin-one bosons and $\mu_b \in (2.9, 4.6) \times 10^{-21}$ eV for spin-zero bosons, within the range considered for fuzzy dark matter, invoked to explain dark matter distribution on approximately kiloparsec scales. Future observations of M87* could be expected to strengthen our conclusions.

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Introduction.—Black holes (BHs) are at the same time simple and mysterious. They are characterized by only a few parameters—mass, spin, and charge—and are considered purely gravitational objects. Yet their essential character is quite enigmatic: they represent a one-way exit (up to quantum effects [1]) from the causally connected Universe, and their internal properties are masked by an event horizon that is the point of no return. The most direct evidence for their existence has until very recently been provided by the observation of gravitational waves from binary mergers ascribed to black holes [2]. This situation changed upon the release of a first ever image of the M87* supermassive black hole (SMBH) at the center of the Messier 87 (M87) Galaxy, by the Event Horizon Telescope (EHT) [3]. In some sense, this is the most direct evidence for BHs, as it manifests their defining characteristic: a region of space from which no matter and light can escape.

The EHT imaging of M87* through a worldwide network of radio telescopes is a historic scientific accomplishment. Future observations of this and other SMBHs will usher in a new age of radio astronomy where direct data on their event horizons and associated accretion dynamics become available and will get increasingly more precise. There are numerous astronomical questions that could be addressed with such observations and we can expect new and intriguing questions to arise as well. However, it is also interesting to inquire whether the impressive new EHT data on M87* could be used to shed light on fundamental questions of particle physics and cosmology.

In this Letter, we use the results of the EHT Collaboration on the parameters of M87* in the context of particle physics, and, in particular, ultralight bosons. These states could potentially provide motivated candidates for dark matter (DM), one of the most important open fundamental questions of physics. Dark matter constitutes the dominant form of matter in the Universe, making up ∼25% of its energy density [4], with at best feeble couplings to the visible world. It is generally assumed that DM has nongravitational interactions that led to its production in the early Universe. These interactions could then result in its detection in a variety of laboratory experiments. Nonetheless, DM has only been observed through its gravitational effects in astrophysics and cosmology. Therefore, purely gravitational probes of DM provide the most model-independent approach to constraining its properties.

It turns out that BHs, themselves purely gravitational, can provide a unique probe of ultralight DM states through the mechanism of superradiance [5–14]. That is, roughly speaking, a spinning BH will lose its angular momentum very efficiently if a boson with a particular mass exists in the spectrum of physical states. This is only a condition on the mass of the boson and does not depend on whether the boson has any nongravitational interactions. In fact, the boson does not even need to have any ambient number density, since quantum fluctuations suffice to populate a boson cloud around the BH by depleting its spin.

The superradiance mechanism can then provide an interesting probe of DM states that would be otherwise practically inaccessible to experiments. These states include ultralight axions [15–17] and vector bosons [18] that can appear in various high energy frameworks, such as string theory. For extremely small masses, $\mu_b \sim 10^{-(21-22)}$ eV, such states can also address certain observational features of the DM distribution on scales of approximately kiloparsec; this class of bosons is often referred to as fuzzy DM [19–21] (for a fuzzy DM model based on infrared dynamics, see Ref. [22]). We will show that the results of the EHT Collaboration on the M87* SMBH [23] can probe and constrain this interesting regime of ultralight DM masses. Possible implications of the EHT data on M87* for GeV scale DM have been discussed in Ref. [24].

Superradiance overview.—Black hole superradiance leads to the growth of the boson population once its energy ω_b satisfies the condition (see, e.g., Refs. [15,16])

$$\frac{\omega_b}{m} < \Omega_H, \tag{1}$$

where m is the magnetic quantum number of the boson, associated with its angular momentum. Here, Ω_H is the angular velocity of the BH event horizon related to the dimensionless spin parameter $a^* \equiv J_{\mathrm{BH}}/(G_N M_{\mathrm{BH}}^2) \in [0,1)$ by

$$\Omega_H = \frac{1}{2r_g}\frac{a^*}{1+\sqrt{1-a^{*2}}}, \tag{2}$$

where $r_g \equiv G_N M_{\mathrm{BH}}$, G_N is Newton's constant, and M_{BH} is the BH mass. In the above expression J_{BH} is the BH angular momentum.

In addition to the condition in Eq. (1), there is another condition that must be met for superradiance to deplete the spin of a BH,

$$\Gamma_b \tau_{\mathrm{BH}} \geq \ln N_m, \tag{3}$$

where τ_{BH} is the characteristic timescale of the BH, N_m is the final occupation number of the cloud after the BH spins down by Δa^*,

$$N_m \simeq \frac{G_N M_{\mathrm{BH}}^2 \Delta a^*}{m}, \tag{4}$$

and Γ_b is the growth rate of the field for $b \in \{S, V\}$ (scalar or vector). Note that superradiance applies to both parity even and parity odd particles, so the scalar case also applies to pseudoscalars such as axions. The leading contribution for Γ_b is different for scalars and vectors and, up to a factor of ~2, we have

$$\Gamma_S = \frac{1}{24} a^* r_g^8 \mu_S^9, \tag{5}$$

$$\Gamma_V = 4a^* r_g^6 \mu_V^7. \tag{6}$$

For an observation of a BH mass and spin, an upper and lower limit on μ_b can be placed (that is, demanding that superradiance has not depleted the spin of the BH by Δa^*) by

$$\mu_b > \Omega_H \tag{7}$$

or

$$\mu_S < \left(\frac{24 \ln N_m}{a^* r_g^8 \tau_{\mathrm{BH}}}\right)^{1/9}, \tag{8}$$

$$\mu_V < \left(\frac{\ln N_m}{4a^* r_g^6 \tau_{\mathrm{BH}}}\right)^{1/7}, \tag{9}$$

where we have used the fact that for the dominant mode one has $m = 1$ for both scalars and vectors. That is, if the constraint in Eq. (7) applies to a larger mass than the constraint in Eq. (8) or (9), the mass range of ultralight bosons in between is ruled out.

EHT observations of M87*.—The EHT has provided the first direct measurement of the environment immediately around M87*, leading to a mass estimate of $(6.5 \pm 0.7) \times 10^9\ M_\odot$ [23]. This is fairly consistent with previous estimates that are in the $[3.5, 7.2] \times 10^9\ M_\odot$ range [25–27].

The shortest timescale that could be relevant for a SMBH is the Salpeter time $\tau_{\mathrm{Salpeter}} \sim 4.5 \times 10^7$ yr [28], which is the case for when material is accreting on to the object at the Eddington limit. In Ref. [18] they conservatively take $\tau_{\mathrm{BH}} \sim \tau_{\mathrm{Salpeter}}/10$ to account for the possibility of super-Eddington accretion. Observations of M87*, however, show that $\dot{M}/\dot{M}_{\mathrm{Edd}} \sim 2.0 \times 10^{-5}$ [23], consistent with previous measurements [29], which suggests that the relevant timescale is much longer [30]. We conservatively take $\tau_{\mathrm{BH}} = 10^9$ yr as our fiducial value since both the accretion and the spin-down timescales [23] are much longer. In addition, in the last billion years there was likely only one merger event which involved a much smaller galaxy and was unlikely to significantly affect the spin of M87* [32]. We also note that the dependence of the ultralight boson limits on τ_{BH} is at most $\tau_{\mathrm{BH}}^{-1/7}$.

The final parameter that remains to be observationally constrained, and perhaps the most important in this context, is the spin. The EHT Collaboration checked if various spin configurations are consistent with their data and jet power measurements. They found that $a^* = 0$ is inconsistent with the data, while spins $|a^*| \geq 0.5$ up to $|a^*| = 0.94$ (as high as their analysis goes) are consistent with the data, although there was no analysis made of any spins $0 < |a^*| < 0.5$ [23]. This leads to an approximate estimate of $|a^*| > 0.5$, which relies strongly on the observed jet power to rule out the smaller spins. The EHT Collaboration takes a very conservative estimate of the jet power [23]. A separate detailed analysis was performed which finds $a^* = 0.9 \pm 0.1$ using only properties of the light around M87* as measured by the EHT Collaboration [33], which we take as our fiducial value and uncertainty.

Results.—Using Eqs. (7)–(9), it is possible to constrain light bosons across a range of masses. We assume that the largest value of Δa^* is $1 - a^*$, where a^* is the spin today. We report the 1σ results accounting for the uncertainties in the mass and spin as described in the previous section, as well as a factor of 2 in the uncertainty in the theoretical calculation of Γ_b. Then we find that M87* rules out light bosons in the following ranges,

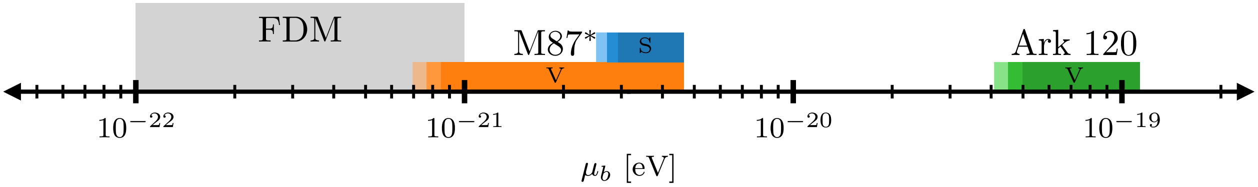

FIG. 1. Regions of parameter space constrained by observations of SMBHs. The orange (blue) region is ruled out for vector (scalar) bosons by M87*. Note that the constraints apply to both parity even and parity odd particles. Each constraint is derived using the 1σ conservative values for the mass and spin, and the shaded band on the left of each region represents the size of the theoretical uncertainty. The green region is the constraint on vector bosons from Ark 120 [18], which cannot constrain scalars. The region preferred by fuzzy DM (FDM) is shown in gray.

$$2.9 \times 10^{-21} < \mu_S < 4.6 \times 10^{-21}\ \text{eV}, \tag{10}$$

$$8.5 \times 10^{-22} < \mu_V < 4.6 \times 10^{-21}\ \text{eV}, \tag{11}$$

as shown in Fig. 1, which also includes the constraint from the lighter Ark 120 with $M_{\rm BH} = (0.150 \pm 0.019) \times 10^9\ M_\odot$ and $a^* = 0.64^{+0.19}_{-0.11}$ [18,34–36]. For the timescale of Ark 120 we have conservatively taken $\tau_{\rm BH} = \tau_{\rm Salpeter}/10 = 4.5 \times 10^6$ yr, as in Ref. [18]. The mass measurement of Ark 120 comes from reverberation methods [36] and the spin determination comes from x-ray data [34]. For larger boson masses, there is fairly continuous coverage from $\mathcal{O}(\text{few}) \times 10^{-20}$ eV to $\mathcal{O}(\text{few}) \times 10^{-17}$ eV from SMBH observations with just a small gap at $\mathcal{O}(\text{few}) \times 10^{-19}$ eV. Then there is large gap up to $\mathcal{O}(\text{few}) \times 10^{-14}$ eV at which point stellar mass BHs provide constraints up to $\sim 10^{-11}$ eV. It is interesting to note that this is the largest black hole for which we have a spin measurement [34,37,38], which means that M87* has the most angular momentum of any measured single object.

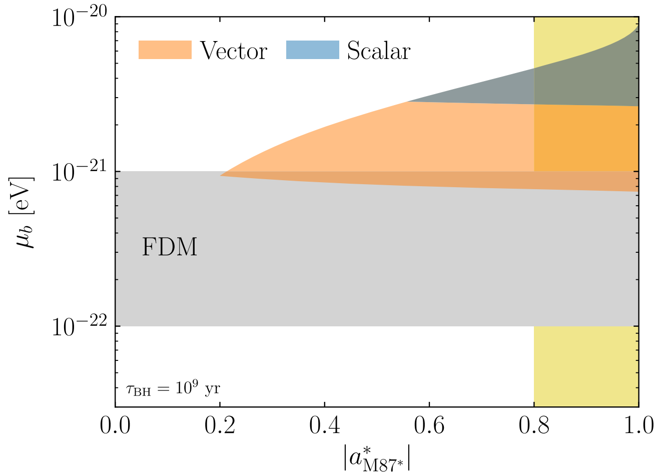

FIG. 2. The constraints on light bosons as a function of the spin of M87*. The region constrained for scalar bosons (blue) is also constrained for vector bosons (orange). The characteristic fuzzy DM range is shown in gray, and the 1σ inference region of the spin is shown in khaki [33].

We also explored the effect of the spin measurement of M87* on the constraint, as shown in Fig. 2. A constraint on vector bosons exists for any $|a^*| > 0.2$ which overlaps with the fuzzy DM range. A constraint on scalar bosons only exists for $|a^*| > 0.55$, none of which probes the fuzzy DM range.

Outlook.—With additional analyses and observations, the spin of M87* will become more precisely determined. If the spin is determined to be larger than assumed here, the constraints on ultralight bosons will become stronger.

The largest SMBHs are more than an order of magnitude more massive than M87*, but are significantly farther away, making them difficult targets for the EHT or other probes that could provide good spin measurements [39]. Still, this means that it is, in principle, possible to probe the entire fuzzy DM parameter spin using this technique, depending on the spins of the largest SMBHs.

Lyman-α forest measurements and observations of the heating of the core of star clusters provide separate constraints on fuzzy DM that disfavor most of the parameter space, leaving a possible opening around $\gtrsim 10^{-21}$ eV [40–42]. We note that this region is now constrained by M87*.

Conclusions.—The Event Horizon Telescope has provided the first direct image of a BH. We have shown that the information gained from this observation can be used to place constraints on particle physics, specifically ultralight bosons via the mechanism of superradiance. Superradiance leads to a large extraction of energy from a rotating BH and any determination of a BH's spin could place a constraint on the presence of ultralight bosons. The measurement of M87* provides constraints on both vector and scalar bosons (as well as axial-vector and psuedoscalars such as axions), and in the vector case constrains some of the fuzzy dark matter parameter space. Future observations of M87*'s spin can pin down the exact constraint and, in principle, future spin measurements of SMBHs could possibly cover the entire fuzzy dark matter parameter space.

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[1] S. W. Hawking, Commun. Math. Phys. **43**, 199 (1975).
[2] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **116**, 061102 (2016).
[3] K. Akiyama *et al.* (Event Horizon Telescope Collaboration), Astrophys. J. **875**, L1 (2019).
[4] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).
[5] R. Penrose, Riv. Nuovo Cimento **1**, 252 (1969); Gen. Relativ. Gravit. **34**, 1141 (2002).
[6] Y. B. Zel'Dovich, Sov. J. Exp. Theor. Phys. Lett. **14**, 180 (1971).
[7] C. W. Misner, Phys. Rev. Lett. **28**, 994 (1972).
[8] W. H. Press and S. A. Teukolsky, Nature (London) **238**, 211 (1972).
[9] W. H. Press and S. A. Teukolsky, Astrophys. J. **185**, 649 (1973).
[10] A. A. Starobinsky, Zh. Eksp. Teor. Fiz. **64**, 48 (1973) [Sov. Phys. JETP **37**, 28 (1973)].
[11] T. J. M. Zouros and D. M. Eardley, Ann. Phys. (N.Y.) **118**, 139 (1979).
[12] S. L. Detweiler, Phys. Rev. D **22**, 2323 (1980).
[13] R. Brito, V. Cardoso, and P. Pani, Lect. Notes Phys. **906**, 1 (2015).
[14] D. Gates, D. Kapec, A. Lupsasca, Y. Shi, and A. Strominger, arXiv:1809.09092.
[15] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, Phys. Rev. D **81**, 123530 (2010).
[16] A. Arvanitaki, M. Baryakhtar, and X. Huang, Phys. Rev. D **91**, 084011 (2015).
[17] A. Arvanitaki, M. Baryakhtar, S. Dimopoulos, S. Dubovsky, and R. Lasenby, Phys. Rev. D **95**, 043001 (2017).
[18] M. Baryakhtar, R. Lasenby, and M. Teo, Phys. Rev. D **96**, 035019 (2017).
[19] W. Hu, R. Barkana, and A. Gruzinov, Phys. Rev. Lett. **85**, 1158 (2000).
[20] D. J. E. Marsh, Phys. Rep. **643**, 1 (2016).
[21] L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, Phys. Rev. D **95**, 043541 (2017).
[22] H. Davoudiasl and C. W. Murphy, Phys. Rev. Lett. **118**, 141801 (2017).
[23] K. Akiyama *et al.* (Event Horizon Telescope Collaboration), Astrophys. J. **875**, L5 (2019).
[24] T. Lacroix, M. Karami, A. E. Broderick, J. Silk, and C. Bohm, Phys. Rev. D **96**, 063008 (2017).
[25] K. Gebhardt, J. Adams, D. Richstone, T. R. Lauer, S. M. Faber, K. Gultekin, J. Murphy, and S. Tremaine, Astrophys. J. **729**, 119 (2011).
[26] J. L. Walsh, A. J. Barth, L. C. Ho, and M. Sarzi, Astrophys. J. **770**, 86 (2013).
[27] L. J. Oldham and M. W. Auger, Mon. Not. R. Astron. Soc. **457**, 421 (2016).
[28] F. Shankar, D. H. Weinberg, and J. Miralda-Escude, Astrophys. J. **690**, 20 (2009).
[29] C. Y. Kuo *et al.*, Astrophys. J. **783**, L33 (2014).
[30] It is possible that the accretion rate of M87* is currently lower than it was in the past. Observations suggest that M87* is variable on scales of at most 2–3 orders of magnitude, although it may be even less since we now know M87* has large spin [31]. An increase in the accretion rate less than about 3–4 orders of magnitude would not be enough to decrease the timescale below 10^9 years from accretion.
[31] M. A. Prieto, J. A. Fernandez-Ontiveros, S. Markoff, D. Espada, and O. Gonzalez-Martin, Mon. Not. R. Astron. Soc. **457**, 3801 (2016).
[32] A. Longobardi, M. Arnaboldi, O. Gerhard, and J. C. Mihos, Astron. Astrophys. **579**, L3 (2015).
[33] F. Tamburini, B. Thidé, and M. Della Valle, arXiv:1904.07923.
[34] C. S. Reynolds, Space Sci. Rev. **183**, 277 (2014).
[35] D. J. Walton, E. Nardini, A. C. Fabian, L. C. Gallo, and R. C. Reis, Mon. Not. R. Astron. Soc. **428**, 2901 (2013).
[36] B. M. Peterson *et al.*, Astrophys. J. **613**, 682 (2004).
[37] M. J. Stott and D. J. E. Marsh, Phys. Rev. D **98**, 083006 (2018).
[38] C. S. Reynolds, Classical Quantum Gravity **30**, 244004 (2013).
[39] O. Shemmer, H. Netzer, R. Maiolino, E. Oliva, S. Croom, E. Corbett, and L. di Fabrizio, Astrophys. J. **614**, 547 (2004).
[40] M. Viel, G. D. Becker, J. S. Bolton, and M. G. Haehnelt, Phys. Rev. D **88**, 043502 (2013).
[41] V. Iršič, M. Viel, M. G. Haehnelt, J. S. Bolton, and G. D. Becker, Phys. Rev. Lett. **119**, 031302 (2017).
[42] D. J. E. Marsh and J. C. Niemeyer, arXiv:1810.08543.