Stringent constraints on the light boson model with supermassive black hole spin measurements

Lei Zu\textsuperscript{1,2}, Lei Feng\textsuperscript{1,3*}, Qiang Yuan\textsuperscript{1,2,4†}, Yi-Zhong Fan\textsuperscript{1,2‡}

\textsuperscript{1}Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210033, China
\textsuperscript{2}School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui 230026, China
\textsuperscript{3}Joint Center for Particle, Nuclear Physics and Cosmology, Nanjing University – Purple Mountain Observatory, Nanjing 210093, China
\textsuperscript{4}Center for High Energy Physics, Peking University, Beijing 100871, China

Massive bosons, such as light scalars and vector bosons, can lead to instabilities of rotating black holes by the superradiance effect, which extracts energy and angular momentum from rapidly-rotating black holes effectively. This process results in spinning-down of black holes and the formation of boson clouds around them. In this work, we used the masses and spins of supermassive black holes measured from the ultraviolet/optical or X-ray observations to constrain the model parameters of the light bosons. We find that the mass range of light bosons from $10^{-22}$ eV to $10^{-17}$ eV can be largely excluded by a set of supermassive black holes (including also the extremely massive ones OJ 287, Ton 618 and SDSS J140821.67+025733.2), particularly for the vector boson scenario, which eliminates a good fraction of the so-called fuzzy dark matter parameter regions. For the scalar bosons with self-interaction, most part of the mass range from $\sim 3 \times 10^{-19}$ eV to $10^{-17}$ eV with a decay constant $f_\alpha > 10^{15}$ GeV can be excluded, which convincingly eliminate the QCD axions at these masses.

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\textbf{I. INTRODUCTION}

The scattering between a rotating black hole (BH) and light bosons can extract energy and angular momentum of the BH, which is the so-called superradiance effect \cite{1,12}. This phenomenon takes place when the superradiance condition is satisfied, i.e.,

\begin{equation}
0 < \omega < mw_+,
\end{equation}

where $\omega$ is the frequency corresponding to the light boson, $m$ is the magnetic quantum number, and $w_+$ is the angular velocity of the BH horizon which reads

\begin{equation}
w_+ = \frac{1}{r_g} \frac{a_*}{1 + \sqrt{1 - a_*^2}},
\end{equation}

where $a_* = a/r_g$ is the dimensionless spin parameter of the BH with $a = J/M_{bh}$ being the spin-to-mass ratio and $r_g = G M_{bh}$ being the gravitational radius.

When the wavelength of the light boson is comparable to the size of the BH, the number of bosons surrounding the BH grows exponentially to form a boson cloud. The self-interaction of the bosons would lead to the collapse of the cloud when reaching a critical size, which is known as “bosonova” \cite{10,13}. The superradiance process extracts energy and angular momentum from the BH, which enables us to constrain the parameters of the light boson if the masses and spins of BHs have been reasonably measured \cite{10,14,16}.

Supermassive black holes (SMBH) at the centers of galaxies have been found with masses $\sim 10^6 - 10^{11}$ $M_\odot$. To measure the spin of the SMBHs is somehow challenging. By means of the first direct imaging of the SMBH in the center of M 87 with the Event Horizon Telescope (EHT), the mass of the SMBH was determined to be $\sim 6.5 \times 10^9$ $M_\odot$ \cite{17,18}, and it was inferred to be likely highly spinning \cite{19,20}. The EHT measurement was then applied to exclude the ultralight bosons with mass between $8.5 \times 10^{-22}$ eV and $4.6 \times 10^{-21}$ eV for a given BH time scale $\tau_{bh} \sim 10^9$ years \cite{14}. For most of SMBHs, there are lack of direct imaging of the shadows, and the spin parameters are instead estimated through fitting the X-ray and/or UV-optical spectral energy distributions \cite{21,23}.

In this work we employ the currently available sample of high-spin SMBHs based on the UV-optical/X-ray spectroscopy method \cite{22,24}, to constrain the ultralight boson model. The sample of SMBHs with different masses can cover a wide mass range of the light bosons. Moreover, with a few extremely massive BHs, we probe the fuzzy dark matter (FDM) scenario with boson mass of $(1 \sim 10) \times 10^{-22}$ eV \cite{25,27} which is almost out of reach via only the EHT observations of M 87 \cite{14}.

\textbf{II. SUPERRADIANCE}

Superradiance is a kind of Penrose process related to waves. A massive boson field in the Kerr background may cause an unstable solution with an imaginary part of the frequency \cite{10,28,29}. It leads to an exponential growth of the number of bosons, forming a “gravitational atom” with energy levels $\epsilon = \hbar \mu (1 - \frac{\alpha^2}{2\tilde{n}})$, \hspace{1cm} (3)

where $\mu$ is the mass of the boson, $\alpha = r_g \mu$, and $\tilde{n} = n + l + 1$ with $n$ and $l$ being the principal and orbital quantum numbers, respectively \cite{10,29}.
The leading contribution of the imaginary part of frequency is (i.e., the fastest-superradiating mode of the small-\(\alpha\) analytical approximation) \[6, 30\]

\[
\Gamma_i = \frac{1}{24} a_i \varepsilon^8 \mu^9 \tag{4}
\]

\[
\Gamma_v = 4a_i \varepsilon^6 \mu^7 \tag{5}
\]

where \(\Gamma_i\) and \(\Gamma_v\) are the superradiance rates related to scalar and vector bosons. In this work, we use the leading term of the analytical solution, which is consistent with the numerical results \[29, 30\], to constrain the masses of the bosons.

Without taking into account self-interactions, the number evolution is simply

\[
\frac{dN}{dt} = \Gamma N. \tag{6}
\]

For a BH with given spin, the maximally allowed size of the boson cloud is

\[
N_{\text{max}} \approx \frac{GM_{\text{bh}}^3}{\mu} \Delta a_s, \tag{7}
\]

where \(\Delta a_s\) is the difference between the initial and final spins of the BH. The corresponding boson parameter space is simply ruled out if the superradiance process is efficient enough that the BH lose too much angular momentum within its lifetime \(\tau_{\text{bh}}\), i.e.,

\[
\Gamma \tau_{\text{bh}} > \ln N_{\text{max}}, \tag{8}
\]

which in turn sets a bound on the boson parameters.

As the size of the cloud keeps growing, the self-interaction effect becomes important. When it grows up to a critical size, \(N_{\text{bosenova}}\), the cloud collapses which is known as “bosenova”.

For scalar particles we have

\[
N_{\text{bosenova}} \approx 10^{78} c_0^4 \alpha^{-3} \left( \frac{M_{\text{bh}}}{M_\odot} \right)^2 \left( \frac{f_a}{M_\odot} \right)^2, \tag{9}
\]

where \(f_a\) is the decay constant for the scalar bosons, \(M_\odot = 2 \times 10^{33} \text{ GeV}\) is the Planck energy, and \(c_0 \approx 5\) is determined by numerical simulations \[8, 31\].

If the self-interaction is strong enough (i.e., \(N_{\text{bosenova}} < N_{\text{max}}\)), the cloud collapse happens when its size reaches \(N_{\text{bosenova}}\). Thus this process would repeat \(N_{\text{max}}/N_{\text{bosenova}}\) times at most and the maximally allowed size of the boson cloud would be replaced by \(N_{\text{bosenova}}\). Therefore the exclusion condition Eq. (8) can be revised as \[8\]

\[
\Gamma \tau_{\text{bh}} (N_{\text{bosenova}}/N_{\text{max}}) > \ln N_{\text{bosenova}}. \tag{10}
\]

### III. THE SMBH SAMPLE AND CONSTRAINTS

A widely adopted way to estimate the spin of an SMBH is to fit the radiation spectrum in UV-optical or X-ray bands (i.e., to model the AGN continuum emission or relativistic X-ray reflection). We summarize some SMBHs with inferred high spins with this method in Table 1. There are some even more massive black holes. OJ 287 has the dynamically measured mass \(M_{\text{bh}} = (1.8348 \pm 0.0008) \times 10^{10} M_\odot\) and spin \(a_\text{\ast} = 0.381 \pm 0.004\) \[32\]. The masses of Ton 618 and SDSS J140821.67+025733.2 are estimated to be \(6.6 \times 10^{10} M_\odot\) \[33\] and \(1.96 \times 10^{11} M_\odot\) \[34\], respectively. The allowed parameter space of the BH mass and spin within the thin disc accretion model has been examined in Ref. \[35\], giving lower limits of the spin of about 0.6 for Ton 618 and 0.97 for SDSS J140821.67+025733.2. These SMBHs will also be included in this study. Note that for the spins with only lower limits available, we adopt the lower limits in the calculation. For the timescales that the SMBH maintains such a high spin, we take the Salpeter time \(\tau_{\text{salpeter}} \sim 4.5 \times 10^5\) years \[36\], which is the Eddington limit for the accreting material.

We firstly ignore the self-interaction of light bosons \[13, 16, 30\]. In this case the constraints can be obtained through the combination of Eq. (1) and Eq. (9). We further restrict our discussion in the \(m = 1\) mode of the boson cloud, which is the dominant mode with the largest field strength. The exclusion mass ranges for different sources are shown in Fig. 1. The green (red) bands correspond to the exclusion regions for the scalar (vector) bosons by the SMBHs summarized in Table 1. The orange (blue) bands are those for the most massive SMBHs OJ 287, Ton 618, and SDSS J140821.67+025733.2. Our results extend remarkably the constraints compared with earlier approaches \[8, 14, 30\]. Panel (b) of Fig. 1 summarizes the combined exclusion mass regions for all the SMBHs used in this work. We can see that the mass range of \(10^{-22} \sim 10^{-17}\) eV can be effectively constrained by these sources, particularly for the vector boson scenario due to its faster superradiance rate compared with the scalar scenario (see Eq. (4) and Eq. (5)). There is a lack of constraints for \(\mu \sim 10^{-19}\) eV. We expect that additional SMBHs with masses around \(10^8 M_\odot\) will be helpful to close the mass window around \(10^{-19}\) eV. Fig. 2 shows the exclusion capabilities of SDSS J140821.67+025733.2 and Ton 618 for a wide range of spin. Even for \(a_\ast \sim 0.4\), the constraints are still effective.

It is interesting to note that the most massive SMBHs OJ 287, SDSS J140821.67+025733.2, and Ton 618 can exclude a good fraction of the region of the so-called FDM model (with boson mass of \(10^{-22} \sim 10^{-21}\) eV \[27\]) if it consists of vector bosons. For the scalar case, the constraint is less stringent.

The exclusion regions also depend on the value of the BH lifetime \(\tau_{\text{bh}}\). Longer lifetime would give wider exclusion regions. In Fig. 1 we also show the constraints from M 87, with \(M_{\text{bh}} = (6.5 \pm 0.7) \times 10^9 M_\odot\) and \(a_\ast = 0.9 \pm 0.1\). Here we take \(\tau_{\text{bh}} \sim 4.5 \times 10^7\) years rather than \(\sim 10^9\) years as in Ref. \[14\]. This is why our constraint is not as strong as that in Ref. \[14\] for this specific object. Anyhow, our enlarged SMBH sample with diverse masses and spins are clearly more powerful in constraining the light boson model.

If the self-interaction is strong enough (\(N_{\text{bosenova}} < N_{\text{max}}\)), the boson cloud collapses when growing up to the critical size \(N_{\text{bosenova}}\), after which the superradiance process restarts and the cycle repeats. The exclusion condition is now Eq. (1) and Eq. (10). Generally speaking, including the self-interaction of


We use the numerical solution to the superradiance rate $\Gamma_{\text{tr}}$ and discuss the scalar case in this work. The bosenova process for vector bosons with self-interactions is more complicated, and may need more dedicated studies in future. Here we use the numerical solution to the superradiance rate $\Gamma$ for scalars such as axions in Ref. [29]. The excluded parameter space in the mass-coupling plane of the scalars is shown by the shaded regions in Fig. 3, assuming $\tau_{\text{bh}} = 4.5 \times 10^7$ years. The mass range from $3 \times 10^{-19}$ eV to $10^{-17}$ eV with a decay constant $f_a > 10^{15}$ GeV can be excluded. It is very interesting to see that the theoretical prediction of the mass-coupling relation for QCD axions [8] has been excluded in a wide mass range with our sample. Note also that the spin method constrains the axion parameters with large $f_a$, which is complementary to the polarization method [49].

| Object       | $M_{\text{bh}}$ (10^3$M_\odot$) | Spin     | Refs. |
|--------------|----------------------------------|----------|-------|
| 3C 120       | $0.5^{+0.31}_{-0.23}$           | > 0.95   | [37, 38] |
| MCG 6-30-15  | $0.029^{+0.018}_{-0.016}$       | > 0.98   | [39, 40] |
| Mrk 110      | $0.25^{+0.061}_{-0.061}$        | $0.96^{+0.03}_{-0.07}$ | [37, 41] |
| Mrk 335      | $0.14^{+0.037}_{-0.037}$        | > 0.91   | [37, 42] |
| NGC 3783     | $0.298^{+0.054}_{-0.054}$       | > 0.98   | [37, 43] |
| NGC 4001     | $0.019^{+0.008}_{-0.008}$       | > 0.99   | [37, 44] |
| NGC 4151     | $0.45^{+0.057}_{-0.042}$        | > 0.90   | [45, 46] |
| NGC 5506     | $0.051^{+0.022}_{-0.022}$       | $0.93^{+0.04}_{-0.04}$ | [47, 48] |
| J1152 + 0702 | $32.3^{+2.2}_{-1.2}$           | 0.998$^{+0.000}_{-0.032}$ | [22] |
| J1158 – 0322 | $31.6^{+2.4}_{-2.4}$           | 0.898$^{+0.036}_{-0.035}$ | [22] |
| J0941 + 0443 | $44.7^{+2.4}_{-2.4}$           | 0.998$^{+0.000}_{-0.032}$ | [22] |
| J0303 + 0027 | $63.1^{+2.7}_{-2.9}$           | 0.998$^{+0.000}_{-0.032}$ | [22] |
| J0927 + 0004 | $15.8^{+1.9}_{-1.9}$           | 0.998$^{+0.000}_{-0.036}$ | [22] |
| OJ 287       | $183.48 \pm 0.08$              | $0.381 \pm 0.004$ | [32] |
| Ton 618      | 660                              | > 0.60   | [33] |
| Most          |                                  |          |       |
| massive      |                                  |          |       |
| SDSS J140821.67 +025733.2 | 1960       | > 0.97 | [44] |

Table I: SMBHs with masses and spins measured with various method.

IV. SUMMARY AND DISCUSSION

Superradiance leads to an effective extraction of angular momentum from a rapidly-rotating BH. Therefore the SMBHs with measured masses and spins serve as powerful probes of the presence of light bosons around rotating BHs. Using a sample of high-spin SMBHs, inferred from the UV-optical or X-ray spectroscopy, we constrain the model parameters of light bosons in this work. The boson mass in the range of $10^{-22} \sim 10^{-17}$ eV are effectively constrained. The most massive BHs OJ 287, SDSS J140821.67+025733.2, and Ton 618 can effectively extend the constraints to the FDM mass range. We also consider to include the self-interactions for scalar bosons, and exclude a large part of the parameter space for $3 \times 10^{-19} < \mu/eV < 10^{-17}$ and $f_a > 10^{15}$ GeV.

We are aware that there are several uncertainties of the results, such as the systematical uncertainties of the parameter estimates of the BH masses and spins, and the calculation of the superradiance rate of bosons. Furthermore, the inclusion of other modes of the boson cloud would also change somehow the quantitative results derived in this work. We leave such improvements/refinements in future works. We expect that more precise determinations of the masses and spins of SMBHs in future will provide significantly improved and robust constraints on the light bosons in a wide mass region.

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FIG. 1: The light boson mass regions excluded by the SMBH samples summarized in Table I (a) together with those from M 87. The green and red regions are for the cases of scalar and vector bosons, respectively. For the most massive SMBHs, the corresponding bands are shown in orange and blue. Here we assume $\tau_{\text{in}} = 4.5 \times 10^7$ years.

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FIG. 2: Constraints on the light boson mass as a function of the spin of the BH, for SDSS J140821.67+025733.2 (a) and Ton 618 (b). The gray regions show the allowed spins based on the accretion model of Ref. [35]. The orange (blue) regions are those for scalar (vector) bosons. Again we assume τ_{bh} = 4.5 \times 10^7 years.

FIG. 3: Constraints on the mass and coupling of axions from quickly rotating SMBHs (at 1σ confidence level). The blue line is the theoretical prediction for QCD axions [8].