

# Superradiance Properties of Light Black Holes & $10^{-12} - 10^{21}$ eV Bosons

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We derive the minimum spin value for the light black holes,  $10^{-33} - 1 M_\odot$  ( $\sim 1 - 10^{33}$  gr), to experience superradiance via scalar, vector and tensor perturbations, corresponding to boson mass range  $10^{-12} - 10^{21}$  eV. We find that superradiance instability can happen even for very low spin values,  $\tilde{a} \sim 10^{-5} - 10^{-2}$ . Since light black holes (BHs) are very unstable to these perturbations and sensitive probes of bosonic particles, a single moderately spinning BH can probe/cover 2-5 orders of magnitude scalar (axion), vector (dark photon and/or photon with effective mass) and spin-2 mass. If superradiance exists, this drives the spin of the BH to almost zero immediately, independent of the BH formation mechanism. In the case that superradiance is not observed due to self-interactions, we find limits on the axion decay constant and energy density. We finally discuss briefly the implications on the Standard Model bosons and Higgs self-interaction.

**Introduction.** Black holes (BHs) formed via stellar collapse have mass over  $2.5 M_\odot$ , but BHs can also come from cosmological primordial/early universe processes, including enhanced inflationary curvature perturbations, phase transitions and cosmic strings, called as primordial black holes [1–3]<sup>1</sup>. Parameter space for those BHs is still open in such a way that they can make up nearly all dark matter in the mass range  $10^{-15} - 10^{-11} M_\odot$  [4–9], and more than percent of dark matter in the range  $10^{-11} - 1 M_\odot$  [10–12]<sup>2</sup>. Hence, light BHs can make up part of dark content. Even if they form a small fraction of the energy density of our universe, they might have important implications on inflationary stage, field content, primordial universe, and the evolution of our universe.

Light BHs formed via primordial processes have the same properties as astrophysical origin ones except their formation time and mechanism. Therefore, these light Kerr BHs also exhibit superradiace instability in the presence of bosonic degrees of freedom whose Compton wavelength is about the horizon size. Superradiance has been worked out for the stellar mass BHs ( $1 - 10^2 M_\odot$ ) [14–17] and supermassive BHs ( $10^6 - 10^{10} M_\odot$ ) [14–21]. In this work, we focus on BHs lighter than solar mass, ( $10^{-33} - 1 M_\odot$ ) we derive the minimum BH spin required to have superradiance for scalar, vector and tensor perturbations as a function of BH mass. We find that superradiance can happen even for very low spin values,  $\tilde{a} \sim 10^{-5} - 10^{-2}$ . Therefore if perturbed by bosons, for example axions [14, 15], dark photons and photons with effective mass from plasma interactions [22–27], rotating light black holes deplete their spin rapidly indepen-

dent of their initial spin which depends on the formation mechanism [31]. Small spin is expected with horizon size collapse in radiation domination [32, 33], or large spin in matter era [34]. BH spin can reach moderate values  $\tilde{a} \sim 0.7$  via mergers, and for light BHs, accretion has usually negligible effect [35].

Particles beyond the Standard Model are interest of any community. Light black holes, ( $10^{-33} - 1 M_\odot$ ), are very sensitive to such particles, they can interact with and probe them. They can enter superradiance and produce abundantly beyond Standard Model particles that are highly motivated such as axions, dark photon, extra spin-2 in the interesting mass range  $10^{-12} - 10^{21}$  eV. Due to the fact that very small spin values are enough for instability, moderately spinning single BH can probe/constrain 2-5 decades of mass range for bosons, which implies that just 9-10 spinning light BHs with distinct masses can cover 33 orders of magnitude boson parameter space. Detection of superradiance would be revolutionary, but still if we detect spinning BHs and no superradiance, then it can be prevented via self/external interactions [36, 37]. If superradiance is quenched by self-interactions, then we derive bounds on axion decay constant and find that the corresponding mass bosons can not contribute more than  $10^{-24} - 10^{-6}$  of dark matter.

**Basics of Superradiance.** Spinning BHs can deplete their rotational energy into bosonic particles via superradiance [38–44]. The instability rate of black hole is different for distinct types of perturbations. When the Compton wavelength of the bosonic fields, become comparable to the horizon size, they couple to the BH and can extract energy and angular momentum from it. First condition for that is BH angular velocity is larger than field's angular velocity, expressed as

$$\mu_b < m \Omega_H , \quad (1)$$

$m$  being the azimuthal number and  $\Omega_H(w_H)$  the angular speed (dimensionless angular speed), defined as

$$\Omega_H \equiv \frac{a}{2r_g (1 + \sqrt{1 - a^2})} = \frac{1}{2r_g} w_H , \quad (2)$$

<sup>1</sup> Although end result is a black hole, there exists a stochastic GW background resulting from density perturbations which form these BHs with early universe collapse. This stochastic background related to the formation of the primordial black holes is different than the stochastic GW background due to primordial black hole binary mergers [28], hence both GW spectrums have different features. See [29, 30] for GW signatures of light BHs.

<sup>2</sup> Recent lensing data can be related to  $10^{-6} - 10^{-3} M_\odot$  BHs [13].

$r_g = G M_{BH}$  is the gravitational radius. We will suppress the subscript BH for the rest of the paper.

Besides (1), one also requires instability rate is faster than accretion time rate, or equivalently the characteristic time scale for BH accretion is longer than the instability time scale [14–16]

$$\tau_{BH} > \tau_{SR} \quad (3)$$

Accreting black holes build up mass and spin (this usually depends on how chaotic accretion is). When BH has twice its mass via thin disk and smooth accretion, the spin reaches nearly maximum value [45]. Typical BH growth time scale is given by

$$\tau_{BH} \simeq \frac{\mathcal{E}}{1-\mathcal{E}} \frac{5 \times 10^8}{f_{edd}} \text{ years.} \quad (4)$$

where  $\mathcal{E}$  is the radiative efficiency,  $f_{edd} = L_{bol}/L_{edd}$ , and  $t_{edd} = M_{BH}/L_{edd}$ , given by

$$\mathcal{E} = 1 - \frac{\tilde{r}^{3/2} - 2\tilde{r}^{1/2} \pm \tilde{a}}{\tilde{r}^{3/4} (\tilde{r}^{3/2} - 3\tilde{r}^{1/2} \pm 2\tilde{a})^{1/2}} \Big|_{\tilde{r}=\tilde{r}_{ISCO}} \quad (5)$$

where  $\tilde{r} = r/GM$ , and  $\mathcal{E}(\tilde{a}=0) \simeq 0.057$  and  $\mathcal{E}(\tilde{a}=1) \simeq 0.423$ , and the Eddington Luminosity is  $L_{edd} = 10^{38} \left( \frac{M}{M_\odot} \right)$  erg/s. In order to keep our analysis conservative, we set  $\tau_{BH} = 10^8$  years, although accretion rate is usually negligible for light BHs <sup>3</sup>.

The instability time scale,  $\tau_{SR}$ , is expressed as <sup>4</sup>

$$\tau_{SR} = \frac{\log(N_m)}{\Gamma_b}, \quad (6)$$

where  $N_m$  is the occupation number for the corresponding state expressed as

$$N_m \equiv \frac{GM^2 \Delta a}{m}, \quad (7)$$

$\Delta a$  is the spin depleted by instability, and  $\Gamma_b$  is the growth rate of the bosonic field that has different mass dependencies for different spins. The field growth for scalar, vector and tensor fields [16] is given by

$$\begin{aligned} \Gamma_{s=0} &\simeq \frac{1}{12} w_H (r_g \mu)^8 \mu \\ \Gamma_{s=1} &\simeq 8 w_H (r_g \mu)^6 \mu \\ \Gamma_{s=2} &\simeq 8 w_H (r_g \mu)^8 \mu \end{aligned} \quad (8)$$

<sup>3</sup> BH time scale,  $\tau_{BH}$ , is a dynamical quantity set by the accretion rate and efficiency, and this time-scale grows with increasing radiation efficiency and decreasing accretion rate. As radiation efficiency increases, inflating matter loses larger fraction of its energy in form of radiation, and as accretion rate drops obviously BH eats less. Typical accretion rate varies depending on the mass and accretion phase of the BH. Rate can reach Eddington rate or could be many orders of magnitude smaller in both stellar mass BHs and supermassive ones. There is a lower ( $\gtrsim 0.057$ ) and upper bound ( $\lesssim 0.42$ ) on accretion efficiency.

<sup>4</sup> Evolution of spin for different accretion rates in [47].

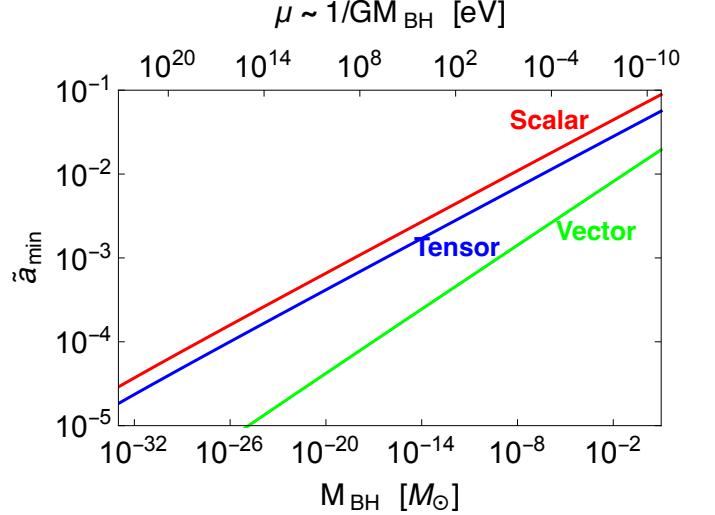


FIG. 1. The minimum spin required for the black holes in the  $10^{-33} - 1 M_\odot$  mass range to experience superradiance

There is a minimum spin value (and corresponding minimum mass for the boson) for the superradiance to happen for a given BH mass, given by

$$\Omega \geq \mu \geq \Omega_{min} = \mu_{min} \Big|_{\tau_{BH} = \tau_{SR}} \quad (9)$$

If the spin of the BH is larger than this minimum value, then it probes/constrains a range of bosonic particle masses. Hence, more rapidly rotating BHs probe a larger mass range. In Figure 1, we obtain the minimum spin value for a given BH mass using (9) by setting  $\tau_{BH} = 10^8$  years. The strength of instabilities are highest for vectors, then for spin-2 and weakest for scalars, however in all cases even tiny spin values are enough to experience superradiance for light black holes (see also discussions in [14–18, 48, 49]).

**Light Black Holes as Boson Probes.** Black holes can interact with scalar (axionlike), vector (dark photon and/or photon with effective mass via interactions with plasma) and spin-2 particles, and the interaction strength is set by the instability rate. For larger rates even small spin values are enough for BH to enter superradiance. This minimum spin value also defines a minimum boson mass the BH can interact, hence for high instability rate smaller mass bosons could interact with BH. The upper mass limit is set by the maximum allowed spin value which is  $\tilde{a} = 1$  corresponding to speed of light. Therefore, BH probes a range of boson mass starting from the minimum boson mass corresponding to minimum superradiance spin until maximum boson mass corresponding to the spin value of the BH, which is larger than minimum spin value. If the spin value is large, this allows probing large range of boson masses.

For a given BH mass and spin, there is a corresponding

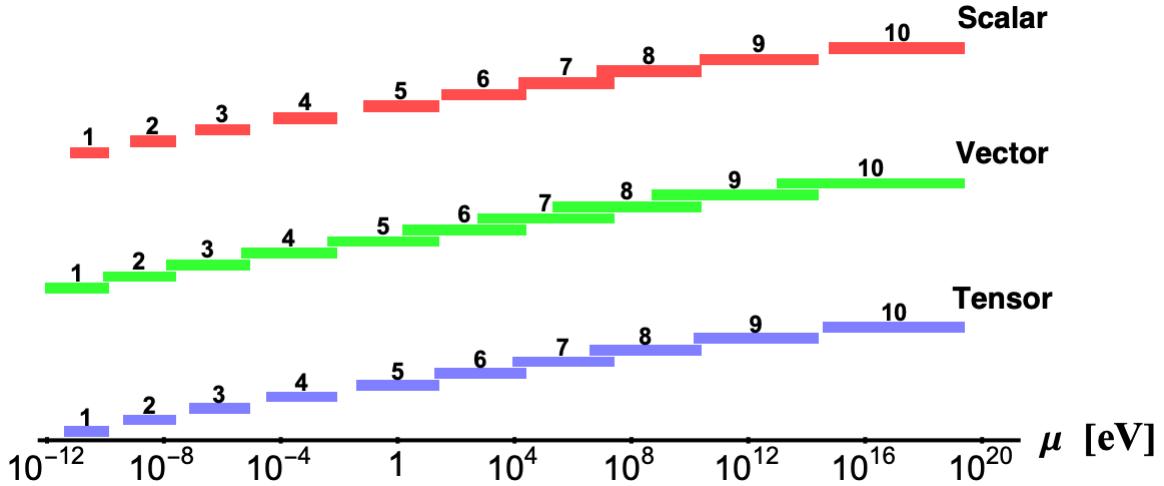


FIG. 2. Scalar, Vector and Spin-2 particles probed by light mass BHs

mass range that can be probed for scalar, vector and tensor (spin-2) particles. We assume hypothetical detection of spinning ( $\tilde{a} \sim 0.7$ ) black holes,  $BH_{1-10}$ , with masses

$$M_{BH}/M_\odot = \{0.2, 10^{-3}, 10^{-5.5}, 10^{-8.5}, 10^{-12}, 10^{-15}, 10^{-18}, 10^{-21}, 10^{-25}, 10^{-30}\}$$

We show in Figure 2 that each spinning BH will allow us to probe a mass range of nearly 2-5 decades and in total around 33 decades,  $10^{-12} - 10^{21}$  eV, an example model for wide range of PBHs is given in Ref. [50].

**Bounds on Self-Interactions of Scalar Fields.** We start with the sinusoidal axion potential, neglecting higher harmonics,  $V = \Lambda^4(1 - \cos \frac{\phi}{f_a})$ , where  $\phi$  is the axion, and  $f_a$  is the axion decay constant. The mass is given by  $\mu = \Lambda^2/f_a$ , and self-interaction by  $\lambda = \frac{\Lambda^4}{f_a^2}$ . In the case of strong external and self-interaction, superradiance can be prevented [51–53].

In the presence of self-interaction, superradiance condition can be expressed as [14–16, 54] (see also [55–57])

$$\Gamma_{SR} \tau_{BH} (N_{BOSE}/N_m) > \log N_{BOSE}, \quad (10)$$

where  $N_m$  being the occupation number

$$N_{BOSE} \simeq 5 \cdot 10^{44} \frac{n^4}{(r_g \mu)^3} \left( \frac{M}{10^{-8} M_\odot} \right)^2 \left( \frac{f_a}{10^{10} \text{GeV}} \right)^2 \quad (11)$$

where the prefactor is obtained via numerical analysis,  $\sim 5$ , in Ref. [54].

If BH is spinning fast and superradiance is not observed, then one option is that there is no such particle in the corresponding mass range. The other option for the non-observation of the superradiance could be self (and/or external) interactions. The growing self-interactions with decreasing decay constant  $f_a$ , could prevent the BH from superradiance. In such a case, one can derive limits on the decay

constant of the axion as in Figure 3. A more in depth study is performed in [36] that the bounds on the self-interaction can be derived via interactions of different energy levels. The signatures of axion clouds are interesting direction to explore [58, 59]. For even smaller mass PBHs and large mass axions interplay see Ref. [60].

**The Fraction of Dark Matter in Scalar Fields.** Dark matter can have scalar, vector and spin-2 components [61–64]. We focus on the contribution of scalar particles to the energy density. In order to derive its current energy density we focus on two times:

i) Start of rolling time:  $H \sim \mu$ . At early times, when the Hubble parameter is larger than its mass, scalar field does not roll, so rolling time is

$$\rho = 3H_{roll}^2 M_p^2 \sim T_{roll}^4 \Rightarrow H_{roll} \sim \mu \sim T_{roll}^2/M_p \quad (12)$$

ii) Matter-radiation equality : When  $\mu > H$ , field oscillates and behaves like non-relativistic dust. Around matter-radiation equality,  $S$  being scale factor, the fraction of dark matter in terms of axion is given as

$$\begin{aligned} \mathcal{R} \equiv \frac{\Omega_{scalar}}{\Omega_{DM}} &= \left. \frac{\rho_{axion}}{\rho_{radiation}} \right|_{t_{eq}} \sim \frac{\Lambda^4}{T_{roll}^4} \frac{S_{eq}}{S_{roll}} \sim \frac{\mu^2 f_a^2}{T_{roll}^3 T_{eq}} \\ &\Rightarrow \mu^2 f_a^2 \sim \mathcal{R} (\mu M_p)^{3/2} T_{eq} \end{aligned} \quad (13)$$

They result in

$$\mathcal{R} \equiv \frac{\Omega_{scalar}}{\Omega_{DM}} \sim \left( \frac{\mu}{10^{-9} \text{eV}} \right)^{1/2} \left( \frac{f_a}{10^{14} \text{GeV}} \right)^2. \quad (14)$$

If spinning BHs are detected, then using the upper bounds on the decay constant, we can derive upper limits on the energy density as a function of particle mass via (14). In Figure 4, we show the bounds on the ratio of energy density in scalars to total dark matter energy density as a function of particle mass. We note that our analysis is conservative since focuses only for

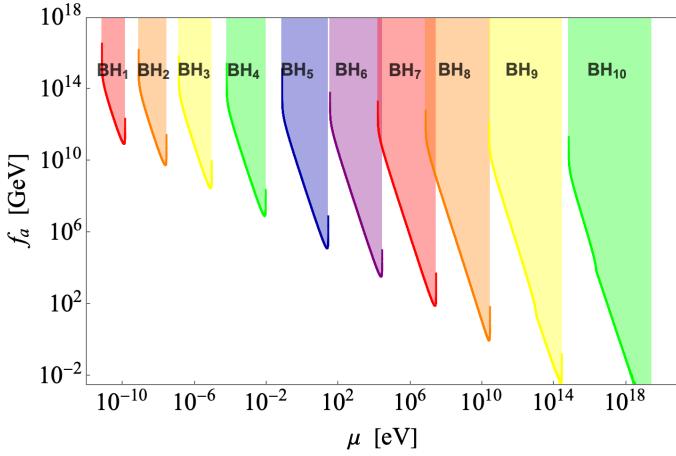


FIG. 3. Bounds on  $f_a$  in the presence of spinning light BHs as a function of scalar/axion mass

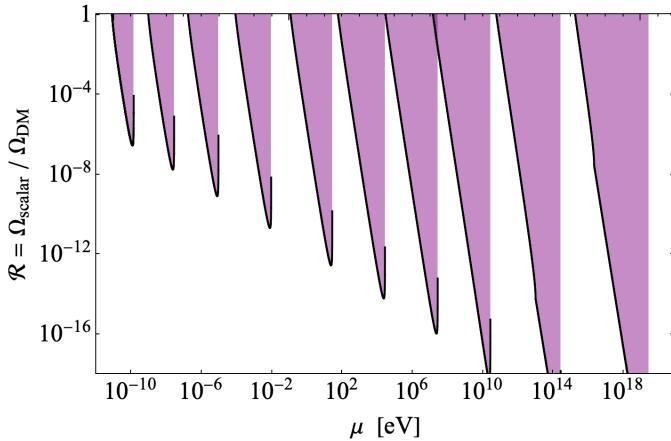


FIG. 4. Bounds on the energy density as a function of scalar/axion mass

the most unstable superradiance state, and it is possible to probe/constrain higher mass particles (with higher azimuthal number) but with less constraint, for a given BH mass and spin. In our conservative analysis, we find that if highly spinning light BHs exist, and quenching of superradiance is due to self-interactions, then scalar particles in the corresponding boson mass range can constitute at most  $\Omega / \Omega_{DM} < 10^{-24} - 10^{-6}$  of dark matter. Similar results are also expected for vector and tensor particles. These conclusions are independent from whether light (primordial) BHs are the main component of the dark matter or not.

**BH Evaporation, Standard Model Bosons & Higgs Self-Coupling.** As the mass of the BH decreases, its horizon size decreases then mass of the corresponding boson masses increase. BHs less than  $10^{15}$  grams =  $10^{-18} M_\odot$ , corresponding to  $10^5 - 10^8$  eV bosons and can probe pions [65], experience Hawk-

ing evaporation<sup>5</sup> unless they accrete or merge and increase their mass. Furthermore, if there exists BHs  $10^{12}$  grams =  $10^{-21} M_\odot$  or lighter BHs, corresponding to  $10^8 - 10^{11}$  eV, they can probe Higgs field. However, due to external interactions, deriving bounds on the self-coupling is not immediate since in such a case one expects a complicated field evolution, which requires trusted numerical evolution.

**Conclusions.** Superradiance instability is stronger for light black holes ( $10^{-33} - 1 M_\odot$ ). We derive the minimum spin value required for this phenomenon for scalar, vector and tensor perturbations. We find that superradiance starts from tiny spin values as low as  $10^{-5} - 10^{-2}$ . Since light BHs are unstable for such perturbations and sensitive probes of bosons, we show that a single BH can probe 2-5 decades of mass range for corresponding bosons. If mass function of light BHs are wide, then moderately spinning 9 or 10 light BHs with distinct masses is enough to probe/cover 33 orders of magnitude boson mass range, ( $10^{-12} - 10^{21}$ ) eV.

Detection of superradiance can imply existence of such particles, but if there are spinning light BHs implying the non-existence of superradiance, this can also lead to potentially two conclusions: i) The scalar, vector, tensor particles do not exist in that relevant mass range and ruled out (see Figure 2), ii) Such particles have strong self-interactions which prevent them from experiencing superradiance. In such a case, strong self-interactions requires upper bounds on axion decay constant (Figure 3) and the energy density (Figure 4), and the corresponding mass bosons can not contribute more than  $10^{-24} - 10^{-6}$  fraction of the dark matter.

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<sup>5</sup> [66–70] explore dark sector via BH evaporation and superradiance.

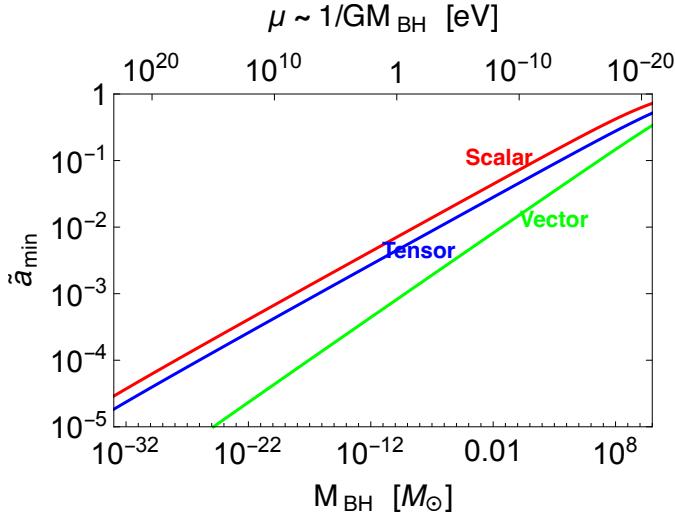


FIG. 5. The minimum spin required for the black holes in the  $10^{-33} - 10^{11} M_\odot$  mass range to experience superradiance

**Supplementary Material** Here for completeness, we give minimum spin required for superradiance for scalar, vector and tensor perturbations all the mass range of BHs,  $10^{-33} - 10^{11} M_\odot$ .

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