



Black holes as laboratories: searching for ultralight fields

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Abstract

The interaction of black holes with classical fields can lead to many interesting phenomena such as black-hole superradiance and the superradiant instability. The existence of these effects has been shown to have implications for beyond Standard Model particles that could explain dark matter, namely ultralight bosonic fields. In this note I give a historical account of this topic and briefly go through some recent developments. I conclude with some personal reflections on the importance of constraining simple dark matter models, even if such models may ultimately be the incorrect description of nature.

Keywords Black holes · Superradiance · Ultralight fields · Dark matter

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1 Black holes and classical fields

The study of how classical fields interact with black hole (BH) spacetimes has a long story that can be traced back to the early studies regarding the mathematical properties of the Kerr metric that followed its discovery in 1963 [1]. Not long after Roy Kerr first wrote down the metric that bears its name, it was quickly understood that the Kerr family of solutions features a number of important mathematical properties that make many calculations tractable¹ (to this day the best and most remarkable review

¹ As Subrahmanyan Chandrasekhar noted in his 1983 Nobel Lecture “contrary to every prior expectation, all the standard equations of mathematical physics can be solved exactly in the Kerr space-time” [2].

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on the topic continues to be Chandrasekhar's influential book [3]). Most notably, as first noted by Carter in 1968, the Hamilton-Jacobi and the scalar wave equation are separable in the Kerr metric [4, 5] (see also Ref. [6] where the details of this separability for the Klein-Gordon equation were first given explicitly). A no less remarkable result is the fact that scalar, neutrino, electromagnetic, and gravitational perturbations of the Kerr metric can all be described by a single *separable* master equation, as was first shown by Teukolsky in 1972 and 1973 [7, 8]. These results were fundamental to explicitly show that by scattering massless bosonic waves (i.e. scalar, electromagnetic and gravitational waves) off a Kerr BH, one can extract energy and angular momentum from a BH through a process now known as *superradiance* [9–12], a wave analogue to the Penrose process [13] that had been first predicted by Zel'Dovich in 1971 [14]. The existence of superradiance was used to devise a *gedankenexperiment* in which one can make a Kerr BH unstable by placing a mirror around it that reflects radiation back towards the hole multiple times, the “*black-hole bomb*” [9] idea (this effect was latter studied in more detail in Ref. [15]). This was followed by works showing that a *massive* scalar field can become unstable in a Kerr BH [16–19] (the existence of this instability has also been rigorously demonstrated in Ref. [20]). The physical mechanism behind this instability can be traced back to superradiance: massive fields admit quasi-bound state modes in BH spacetimes which can be superradiantly amplified multiple times inside the ergoregion, leading to an instability in analogy with the BH bomb effect.

These early studies regarding classical fields in BH spacetimes were mostly concerned about understanding the properties of Kerr BHs, such as their stability under small perturbations. This was crucial to establish the astrophysical relevance of the Kerr solution, given that the superradiant instability, the only known (classical) instability for (sub-extremal) Kerr BHs, seemed to be irrelevant for astrophysical purposes.² Specifically, the superradiant instability was shown to be maximized when the Compton wavelength λ_c of the massive field is comparable to the BH's horizon radius r_H .³ On the other hand, if $r_H/\lambda_c \gg 1$, the instability growth rate Γ is exponentially suppressed $\Gamma \propto e^{-r_H/\lambda_c}$ [18]. This then means that for a BH of mass M , the instability is maximized for bosons with mass

$$m_b \sim 5.6 \times 10^{-11} \left(\frac{M_\odot}{M} \right) \text{ eV}. \quad (1)$$

The conclusion was then that no particles known within the Standard Model can turn astrophysical BHs unstable on a relevant timescale. For example, a simple calculation shows that for a pion field (which can be described as a massive scalar field) around a

² I am not including mass inflation as a relevant instability here since in principle it should not affect the spacetime outside the event horizon. Also note that the full nonlinear stability of the (sub-extremal) Kerr metric under gravitational perturbations has not yet been formally established. However, the sub-extremal Kerr metric has been shown to be linearly mode stable [21] against massless perturbations, whereas significant steps towards proving the full linear stability of the sub-extremal Kerr metric under massless perturbations were recently made in Refs. [22, 23].

³ Early works on the subject computed the superradiant instability rates only in the limits $r_H/\lambda_c \gg 1$ [18] and $r_H/\lambda_c \ll 1$ [19]. As far as I am aware, the first studies looking at the most interesting regime $r_H/\lambda_c \sim 1$ were actually only done in the 2000s through time-domain [24] and frequency-domain computations [25–27].

solar-mass BH one has $r_H/\lambda_c \sim 10^{18}$ and the instability is extremely suppressed. In order to have $r_H/\lambda_c \sim 1$ for pions one would need to have BHs with masses $M \sim 10^{12}$ kg, i.e., if one only considers Standard Model particles, such instability is only relevant for primordial BHs (if at all relevant, given that the maximum instability growth rate for the specific case of the pion field is of the same order of magnitude as its lifetime [19, 27]).

2 Black holes as particle detectors for ultralight fields

Although many applications of the superradiant instability were found through the years (for extensive reviews on superradiance and its applications see Refs. [28, 29]), its relevance for searches of physics beyond the Standard Model seems to have remained mostly under the radar at least until 2009, when Ref. [30] proposed the *string axiverse* scenario. In particular they argued that “string theory suggests the simultaneous presence of many ultralight axion-like particles, possibly populating each decade of mass down to the Hubble scale 10^{-33} eV” [30]. They then realized that axion-like particles⁴ in the mass range $\sim 10^{-21} - 10^{-10}$ eV [see Eq. (1)], as the ones possibly arising from the string axiverse scenario, could significantly affect the dynamics of rapidly rotating astrophysical BHs⁵ precisely due to the superradiant instability of massive scalar fields that had been discovered back in the 1970s.

The realization that BH superradiance has implications for a well motivated beyond Standard Model scenario, as well as the fact that ultralight bosons are known to be possible candidates for cold dark matter (see Ref. [35] for an extensive review on ultralight dark matter) have been one of the main motivations behind the flurry of developments that have occurred since 2010. For example, it was only in the last ~ 10 years that it was shown for the first time that massive vector fields [36–43], as well as massive tensor fields [44–46] are also prone to the superradiant instability.⁶ This was somehow expected given that superradiance occurs for any bosonic field, however the more complex structure of the field equations (as well as perhaps a lack of motivation to study this problem before 2010) meant that it took nearly 40 years to go from the first works showing that massive scalar fields were superradiantly unstable to similar works for higher-spin fields.

The newly-found motivation to study the superradiant instability also prompted the need to understand in more detail how the instability evolves over time and what

⁴ Axion-like particles are pseudo-scalar particles with properties similar to the QCD axion [31–34], hence their name.

⁵ I should note however that Ref. [18] did notice that the superradiant instability would be relevant for a BH with mass $M \sim M_\odot$ if fields with masses around $m_b \sim 10^{-10}$ eV existed, noticing also that the observations of a rapidly rotating black hole could rule out the existence of these fields. Similarly Ref. [27] noted that “the instability is insignificant for astrophysical black holes, unless there exists an unknown particle with a tiny but non-zero rest mass”. However, apart from these short remarks, Ref. [30] seems to have been the first paper noticing that the BH superradiant instability could have implications for physics beyond the Standard Model in a well-motivated model.

⁶ The relevance of the superradiant instability for massive tensor fields is still not fully clear though, since massive tensors are also prone to an axisymmetric instability around Kerr BHs [44, 47, 48] that is unrelated to superradiance and that dominates over the superradiant instability in much of the parameter space.

its astrophysical consequences are. Studies of the evolution of the instability have been done using both quasi-adiabatic approximations [49–51] and through numerical relativity simulations [52, 53] (this later case only for massive vector fields) and have explicitly shown that the instability leads to an exponentially growing bosonic field around the BH, while the BH spins down in the process. This process continues until the BH and the bosonic environment synchronize their rotation, a process that is analogous to tidal locking in binary systems [54]. This scenario provides a natural mechanism to form long-lived *boson clouds* around BHs, also known as *gravitational atoms* due to the similarity of these configurations with the hydrogen atom (see e.g. [19, 27, 30, 55]). The long term evolution of these clouds depends in general on whether the field is complex (i.e. the field admits a global $U(1)$ symmetry) or real. For complex fields, the stress-energy tensor of the cloud can be stationary and axisymmetric (even though the bosonic field itself might not be) and therefore the instability can evolve towards truly stationary and axisymmetric BH solutions known as “Kerr BHs with bosonic hair” [56–58].⁷ On the other hand, for real fields, the bosonic cloud will necessarily dissipate through the emission of nearly monochromatic gravitational-waves (GWs) over long timescales [39, 60–64].

A large number of observational consequences of the superradiant instability have also been uncovered in the last fifteen years. In particular, purely gravitational signatures that have been studied over the years include: the prediction that the existence of ultralight bosons in nature would imply a lack of highly spinning BHs in certain mass ranges, with the specific range being dependent on the putative boson mass [30, 39, 41, 60, 63, 65–70]; the possibility to detect long-lived nearly monochromatic GWs emitted by boson clouds [30, 39, 60–64, 71] either through all-sky [62, 63, 72–74], targeted [65, 75–78] or stochastic background searches [79–83]; the prediction that the dynamics of binary BH systems can be strongly affected by boson clouds if one or both BHs is surrounded by a cloud [84–96]; or even signatures in the motion of S-stars orbiting around Sgr A* which could be perturbed by the presence of a cloud if it exists around the BH at the center of our galaxy [84, 97–99]. Some of these observables have in fact already been used to impose constraints on ultralight bosons in parts of the parameter space (I refer the reader to Ref. [29] for a review of these constraints).

One of the most important caveats of the works I mentioned so far, is the fact that, in general, they assume ultralight fields described by a simple massive bosonic field that only interacts with other particles through gravity. As such, especially in the last five years, several studies have started to explore in more detail how self-interactions or couplings of the bosonic field with Standard Model particles affect the superradiant instability and its observables (see e.g. [100–109]). From these studies it is now clear that non-gravitational interactions can significantly affect the evolution of the superradiant instability, mainly by limiting the growth of the cloud and slowing down the rate at which the BH spins down during the instability phase, which can then affect the purely gravitational-wave observables I mentioned before. Moreover, perhaps not surprisingly, novel signatures that do not occur in the free field case, have also been

⁷ Kerr BHs with bosonic hair are themselves unstable against the superradiant instability of higher-order modes [59], and therefore they are only metastable configurations with a lifetime that depends on the specific parameters of the system. However, since the instability rates are smaller for higher-order modes, effectively only a couple of modes will be relevant over the lifetime of a given BH.

uncovered. To give some recent examples: in clouds formed by self-interacting scalar fields, GW signals due to level transitions in the cloud can be more common and longer-lived than in the absence of self-interactions [102, 110, 111]; binary tidal interactions can facilitate the “bosonova” collapse of the cloud if self-interactions are sufficiently strong [109] (see also [112] where a similar effect was seen in numerical simulations of binary BHs surrounded by self-interacting scalar dark matter); couplings of the bosons in the cloud with photons could lead to electromagnetic signatures [106, 107] or birefringence effects that can be measured through polarimetric measurements of the radiation emitted near supermassive BHs [113, 114].

The (incomplete) overview I gave above highlights the fact that most of what has been learned regarding the implications of BH superradiance for beyond Standard Model physics, happened just in the last fifteen years. I will not try to speculate where this line of research will be in fifteen years from now, but I believe there is still plenty of work to be done. A specific example regards the modelling of BH binaries moving inside ultralight bosonic environments (such as boson clouds). While I would say that the general picture of how a bosonic environment can affect the dynamics of BH binaries is now understood (see e.g. [84–96, 112, 115–118]), there is still a lot of work to be done in order to eventually produce *generic* and *accurate* gravitational waveforms from binary BH systems moving in such environments, both in the comparable-mass-ratio regime and in the extreme-mass-ratio regime. This problem is especially interesting given that future GW detectors will most likely have the capability to detect the impact of astrophysical environments, such as accretion disks, dark matter spikes or boson clouds, on the evolution of binary BH systems (see e.g. [119–122]). Within this context, attempting at modeling BH binaries in ultralight bosonic environments offers a perfect playground, much simpler to model than other astrophysical environments. Therefore I am certain there is a lot to be learned from this exercise.

3 Concluding remarks

Particles such as the QCD axion, axion-like particles or dark photons remain elusive so far, with laboratory and astrophysical data constraining them to have a mass below the eV scale and to couple “weakly” enough with Standard Model particles. A very interesting aspect of BH superradiance is the fact that it is a pure gravitational effect. Therefore the phenomenology associated with this effect is particularly suited to constrain ultralight bosons in regions that are difficult to constrain through usual laboratory searches, in which some type of non-gravitational interaction of the bosons with Standard Model particles is assumed (see e.g. [123] for the latest limits on the mass and couplings of axion-like particles and dark photons). Therefore, constraints coming from BH superradiance are in general highly complementary to other type of searches, making this a particularly interesting topic to explore.

In the most pessimistic (or optimistic, depending on the point-of-view) scenario one can envision that in the not so far future the joint constraints coming from BH superradiance (and associated phenomenology) and other types of searches will exclude most of the parameter space for ultralight bosons in the mass range $\sim [10^{-21}, 10^{-10}]$ eV. Perhaps a more exciting possibility would be to actually detect some signatures

signaling the existence of bosons with such masses. The main difficulty then, will be to convince ourselves that what we are observing are in fact ultralight bosons. In that respect, another particularly interesting aspect of BH superradiance, is that it predicts a wide array of possible observables. Therefore, a convincing way to pinpoint the existence of an ultralight boson would be to find convincing evidence for the same type of boson through more than one observational channel (for example through both continuous GW searches and BH spin measurements).

3.1 Constraining dark matter models: an endless game?

One of the motivations for the line of research discussed in this document is the fact that ultralight bosons provide a possible solution to the dark matter problem [35]. This is in fact one of the simplest solutions to the problem given that it only requires the existence of an ultralight scalar field. As with other dark matter candidates, such as WIMPs or primordial BHs, one can also motivate the model from the fact that such particles arise naturally in some well-motivated theoretical scenarios (in this particular case, from the string axiverse scenario for example [30]). However, theoretical motivations alone are not really enough to constrain the nature of dark matter. The main difficulty in devising dark matter searches is precisely the fact that based on what we know currently from observations of dark matter, a wide range of theoretical scenarios provide viable dark matter candidates (see e.g. [124]). Therefore, one of the standard paradigms in dark matter searches has been to remain as agnostic as possible, considering simple dark matter candidates that can be parameterized by very few parameters (for example the mass of the particles, their interaction to photons, etc...), and ultimately to come up with methods to constrain the parameter space of these candidates as much as possible. Some of the research discussed in this document falls precisely within this line of reasoning.

There is of course a possibility that this might become an endless game of putting stronger and stronger constraints without ever actually detecting new particles that could explain dark matter. The solution to the dark matter problem may require more complex models than just hypothesizing a new particle and could even require a dramatic paradigm shift in physics. However, even with this possibility in mind, I do not think that playing the game of constraining simple models is a worthless effort (although perhaps discouraging at times). In fact, I would say it is almost an obligation. On the one hand, if dark matter can be explained within the simplest models we currently know, then attempting at constraining them as best as we can might eventually result in a positive detection. On the other hand, in a scenario where explaining dark matter might require a more complex solution, then such solution will only be accepted once all the simplest explanations have been excluded. Therefore I see the current paradigm of trying to constrain simple dark matter models as being part of a long journey that might take decades or even centuries to reach its conclusion. Whether at the end of this (most likely very long) journey some future humans will find a proper solution to the dark matter problem I do not know, but I am confident that by attempting at constraining all the simplest explanations we can think of, we will eventually either

find positive evidence for a dark matter candidate or reach the conclusion that a drastic paradigm shift might actually be needed.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The author declares that there is no competing interests.

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