Black hole superradiance to search for new particles

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Rotational superradiance generates the amplification of incoming waves of sufficiently low frequency when scattered with a rotating absorbing body. This may be used to discover new bosonic particles of mass $m_b$ if the rotating body has a sufficiently strong gravitational field, that may confine the massive particle and turn amplification into exponential growth. As a result, the initial seed may be amplified until generating a large cloud around the body, which may have a number of phenomenological consequences. Rotating black holes are perfect candidates to source this effect, not only from their absorbing and gravitational properties (and hence confining mechanism), but also because for black holes of mass $M_{BH}$, rotational superradiance is efficient for $m_b \sim 10^{-10} \left(\frac{M_{BH}}{M_\odot}\right)$ eV. The wide range of astrophysical black hole masses brings about new opportunities to probe particles of low masses in a large span very hard to detect by any other known method. In this brief contribution I will comment on some of these opportunities.

1 Introduction to (black hole) rotational superradiance

Before introducing rotational superradiance, I want to make clear that this short contribution is by no means a review on this very interesting phenomenon. For this, I strongly recommend\(^1,2\) together with the original references\(^3,4\). Furthermore, the constraints that apply to these proceedings also mean that I can not fairly represent all the interesting works in this field of research in recent years. My hope is to trigger the curiosity of the reader to explore more by herself/himself\(^b\). The Planck mass is set to 1 in this note. Also $\hbar = c = 1$.

After this preamble, we can follow\(^3\) and introduce rotational superradiance (superradiance from now on\(^c\)): given a wave propagating radially and with azimuthal number $m$,

$$\Phi \sim A_i e^{-i\omega(t+r)} e^{im\phi} S(\theta),$$

when scattered from an absorbing rotating body of rotational frequency $\Omega$ satisfying

$$\omega < m\Omega,$$
the wave is amplified (technically, the reflection coefficient is larger than one). The energy for this amplification is extracted from the rotation of the absorbing body.

Three extra ingredients are necessary to make this process more interesting for fundamental physics: i) adding a mass \( m_b \) to the incoming wave (this, together with point iii) will confine the wave to the gravitational object and generate an exponential growth) ii) making it correspond to a bosonic degree of freedom (to allow for large occupation numbers) and iii) considering a rotating body with strong dissipation and gravitational field. In this case, superradiance can be tremendously amplified by generating what is known as a cloud of the incoming field with huge occupation numbers. Point iii) is satisfied automatically by rotating black holes (BHs), which is one of the reasons why I will only discuss ‘black hole superradiance’ (see e.g. 7,8 for a related phenomenon in stars). Several details about this process and the final configuration can be found in the review. Here I will only give some simple estimates for concrete situations.

One of the most important aspects of black hole superradiance in what respects the growth of a cloud, is that it is efficient when

\[
m_b M_{\text{BH}} \sim \frac{m_b}{10^{-10}\text{eV}} \frac{M_{\text{BH}}}{M_\odot} \sim O(1),
\]

where \( M_{\text{BH}} \) is the mass of the BH. This is a manifestation of the process being related to the appearance of a bound state for particles of mass \( m_b \) in the gravitational potential of the black hole. For instance, the time of generation of the cloud for \( m_b M_{\text{BH}} \ll 1 \) in the case of a scalar has been found to be \( \tau \approx 30 \text{ days} \left( \frac{M_{\text{BH}}}{10 M_\odot} \right) \left( \frac{0.1}{M_{m_b}} \right) \left( \frac{0.9}{\chi_i} \right) \), where \( \chi_i \) refers to the initial spin of the black hole, see e.g. 9. The parametric form of this equation is not important for the present discussion, just the fact that it is very short in astrophysical timescales only if the condition (3) is not badly broken. The rest of the estimates in this section will be performed in the limit where \( m_b M_{\text{BH}} \ll 1 \) (though not extremely small, since otherwise \( \tau \) becomes too large). The radius of the cloud in this case is given by \( r \sim 1/(M_{\text{BH}} m_b^2) \) (another manifestation of this being a non-relativistic bound state). Also, a significant fraction of the total energy of the black hole may be converted into the cloud, as much as \( 0.1 M_{\text{BH}} \). The previous two points imply the large energy density,

\[
\rho_b \sim 0.1 M_{\text{BH}}/r \sim 10^{48} \frac{M_{\text{BH}}}{M_\odot} \left( \frac{m_b}{10^{-10}\text{eV}} \right)^3 \text{eV}/\text{cm}^3.
\]

The cloud has orbital quantum numbers \( l \geq 1 \), with \( l = 1 \) typically dominant. These two last aspects are important for the emission of gravitational waves. In the following sections, I will focus on some possible ways to detect the cloud (see also 10 for early ideas in this direction).

2 Phenomenological consequences of superradiance

From the previous section, since the cloud of bosons may be as massive as \( 0.1 M_{\text{BH}} \), its influence in the dynamics of black holes of mass \( M_{\text{BH}} \) may be significant. As a consequence, the rotation of the latter may be affected. Furthermore, any orbital motion around the black hole should also be modified by the existence of this very asymmetric cloud. Finally, the dynamics of the cloud is also very interesting: as it rotates, it generates a large time-dependent quadrupole sourcing gravitational waves; it can also decay among different modes either emitting gravitational waves or other particles that may be coupled to the new boson.

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4For the description of superradiance for fermions and its connection to the Klein paradox see 2. 
5Technically, the presence of an ergoregion plays an important role for BH superradiance6. 
6One can also consider new massive particles of spin-1 or spin-2. The spin degree of freedom changes parametrically the predictions, though the main picture remains universal. 
7This has lead to the claim that any small amount of the massive field (even a quantum fluctuation) would easily generate the cloud.
For this fantastic phenomenology to be possible with astrophysical black holes (in particular with masses $10^9 \, M_\odot > M_{\text{BH}} > M_\odot$), one sees from (3) that the new bosons should be of very low mass. If this corresponds to the fundamental mass, then one necessarily has to consider particles beyond the standard model. This is hardly a problem, since there are very well motivated ultralight particles appearing in physics beyond the standard model (see e.g. 12), which are very hard to detect by any other methods. Furthermore, an “effective” mass (a gap in the dispersion relation) can also be generated by the propagation of the boson in a medium (recall that the purpose of the mass is to make the wave ‘fall back’ into the black hole and generate bound states). As I will discuss briefly, the mass of low frequency photons in the intergalactic medium has a bulk value at cosmological times within the range to generate superradiant clouds around astrophysical BHs. Let me discuss these two cases a bit more in detail.

2.1 Looking for superradiance of fundamental fields: gravitational effects

The first searches I want to discuss are those related to the Regge plane, namely the distribution of spins for black holes of different masses. The logic is relatively straightforward: when a cloud is formed, it reduces the angular momentum of the back hole until the condition (2) is no longer satisfied. As a consequence, given a new particle with mass $m_b$, the black holes satisfying (3) should not be spinning very fast. This is true unless another mechanism (for instance, accretion) spins them up, which complicates the analysis. Still, the time scales of the spin-down related to superradiance are so short that the observation of any highly spinning black hole should be a rather convincing evidence to exclude certain masses. As a result, once the Regge plane is populated by observations of spins of astrophysical black holes (in particular from the observations of gravitational waves), one may be able to constrain the presence of new bosons of masses in the range $(10^{-12} \, \text{eV}, 10^{-19} \, \text{eV})$. A precise analysis in this direction from LIGO-Virgo GWTC-2 data can be found in 14 (as the reader may have guessed, it corresponds to masses around $10^{-13} \, \text{eV}$).

Another rather direct consequence of the existence of the superradiant cloud is the emission of gravitational waves through different channels. The most straightforward and universal signal comes from the time dependent quadrupole of the cloud itself. The emitted gravitational waves have characteristic frequency $\omega_{gw} = 2m_b$, with characteristic decay time (for the case of scalar bosons)

$$\tau_{GW}^S \approx 10^5 \, \text{yr} \left( \frac{M_{\text{BH}}}{10M_\odot} \right) \left( \frac{0.1}{M_{\text{BH}}m_b} \right)^{15} \left( \frac{0.5}{\chi_i - \chi_f} \right),$$

where $\chi_i/f$ refers to the initial/final spin of the black hole. These estimates are discussed in detail in e.g. 16. A big challenge in modelling this signal comes from the need to understand the population of BHs of given masses. This has large astrophysical uncertainties. Still, quite remarkably, future interferometers may detect these signals if new bosons with masses in the appropriate range do exist (see also 17 for analysis of the stochastic signal expected for scalar fields). Another possible signal from the clouds arises from energy emitted from the transitions between excited levels of the cloud itself. Their possible detection has also triggered growing interest in the community, and may offer a unique handle in the existence of new particles of masses $10^{-17} - 10^{-12} \, \text{eV}$. Finally, one may wonder about what happens if the BH is not isolated, but is part of a binary system. In this case, the phenomenology is even richer.

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1One can also consider the consequences for e.g. pions or even the Higgs particle if very small black holes are somehow generated in the early Universe, but I won’t discuss this possibility here. See, e.g. 11.

2For instance, these particles naturally appear with very small couplings to the standard model, and as dark matter candidates carry very small momentum.

3Another interesting signal of GWs created by superradiance is related to the (very strong) emission of GWs by black hole mimickers 15.
with possible new transitions, the possible depletion of the cloud, the modification of the binary
dynamics from the existence of the cloud and other new phenomena, see eg. 20,21,22.

Altogether, there are realistic chances of detecting the superradiant clouds associated to
the existing of new particles or forbidding the existence of these particles in a wide range of
masses. Thinking that we can comprehensibly explore the presence of new particles in this way
is mind-blowing. These prospects have generated a significant amount of activity in the field
summarized in the references before (see also 23 and a battery of references in my slides in
https://indico.cern.ch/event/1133536/contributions/4834373/).

2.2 Looking for superradiance of fundamental fields: other astrophysical effects

The universality of gravitation means that the conclusions of the previous section are very
generic. Furthermore, when a new particle is motivated for some reason (e.g as a candidate of
dark matter, related to the strong CP problem, origin of neutrino masses, etc) it is expected
that it will also interact with fields of the standard model (photons, gluons, quarks, leptons...)
or itself. This opens new directions to use superradiance for fundamental physics. The self-
interactions of the boson may generate extra decays of the cloud, or even explosive (bose-nova)
events\(^10\). In this section I will only discuss the situation where the new boson \(a\) is a pseudo-scalar
particle, and a coupling with electromagnetism of the form

\[
 g_a a \tilde{F}_{\mu\nu} F^{\mu\nu},
\]

is expected. In this situation, it has been shown that for a large range of values of \(g_a\) (basically for
\(g_a > 10^{-19} \sqrt{\frac{m_a}{M_{BH}}} \frac{1}{(m_a M_{BH})^2} \text{GeV}^{-1}\), \(M_a\) being the mass of the cloud), the cloud may explosively
decay into pairs of photons\(^24,25\). The fate of these photons was studied in \(^26\). The picture is
the following: if the medium surrounding the BH contains free charged particles, these very low
frequency photons will be absorbed almost instantaneously by inverse Brehmstrahlung. This
absorption will inject the tremendous energy

\[
 \frac{dE}{dt} \sim 10^{66} \left( \frac{M_a}{M_{BH}} \right) \text{eV/s},
\]

into the surrounding plasma, heating it, and generating a burst of ultra-hot baryons/electrons.

As discussed in \(^26\), for this to happen one requires the mean free path to be short enough, and
the mass of the axion to be above the plasma mass. For the astrophysical phenomenology of
interest, this reduces the range of masses of interest to \(m_a \sim (10^{-13} - 10^{-10})\) eV. Our estimates
show that this burst generates a bubble of up to Mpc size at redshifts before or after reionization.
As a result, this bubble may not only emit high energy radiation, but will also contribute to the
reionization of the Universe, and generate spectral distortions in the CMB. Our conclusion of\(^26\)
is that a single bubble may have visible consequence for the next generation of CMB observations,
and, even better, if several bubbles are produced their detection is almost guaranteed. Still, the
difficulty lays in understanding the population of BHs at high redshift, something we would like
to include in a future analysis.

Before moving to the next section, I would like to mention the less known fact that black
hole superradiance may also impact the searches for dark photons through their interaction with
light, see \(^27\).

2.3 Superradiance of photons?

The superradiance phenomenon, in particular the ‘bomb’ effect of massive fields in the gravita-
tional field of a black hole, requires the wave to correspond to a field that can be bounded to
the gravitational source. This is not possible for massless fields, unless the dispersion relation
is modified by the medium. As it is well known, the simplest case where a photon may be considered massive is when it propagates in a ionized medium with frequencies above the plasma mass. Quite remarkably (almost ‘miraculously’), when one considers the plasma mass induced by the intergalactic medium, its value

\[ m_\gamma \simeq m_p \sqrt{\frac{4\pi \alpha n_e}{m_e}} \sim 10^{-10} \sqrt{n_e} \text{cm}^3 \text{eV}, \]  

for the expected average number density of free electrons \( n_e(z) \) from \( z \approx 10^4 \) to \( z \approx 0 \), corresponds to BHs of astrophysical mass after using (3), (29), (30), (31). One can then dream of the possibility that astrophysical black holes could be used as probes of the intergalactic medium, or that this phenomenon could be a way to understand the population of astrophysical black holes!

Unfortunately, this possibility does not seem to be realized in nature. Some early criticism was related to the fact that the effective mass in an accreting situation would not be homogeneous, though the work showed that this was not necessarily a problem. More relevant is the fact that several mechanisms are at play when a very dense cloud of photons (cf. (4)) is generated, which eventually quenches superradiance. This was first realized in, where they considered the dissipation of the cloud through pair creation, and latter in, where it was shown that non-linear effects and other electrodynamical effects (e.g the acceleration of the surrounding electrons) quench the cloud at times many orders of magnitude faster than the typical time scale required for the cloud to be generated.

3 Conclusions

Rotational superradiance offers an extraordinary handle into physics beyond the standard model. It complements other searches of new particles by accessing the (otherwise very hard to constrain) mass range of ultralight particles with masses \( m_b \in 10^{-18} - 10^{-12} \text{eV} \). Furthermore, the phenomenon is extraordinary in its almost independence of the initial density of the new field. As a result, one can not only explore dark matter models (where the energy density of the field is already present), but any candidate with the correct mass.

The phenomenology is extremely rich, and one expects a collection of disparate signals, as coherent radiation, stochastic gravitational wave backgrounds, modifications of the Regge plane, large explosions able to heat up bubbles of Mpc size (a manifestation of the large amount of energy in the cloud)... In my opinion, there are still many new possibilities to explore, in particular if the new boson interacts with the fields of the standard model. Still, the most spectacular progress will come once LISA flies and the next generation of Earth-based gravitational wave observatories start to work. This is because despite the uncertainties in the populations of BHs at different cosmological times, most models predict that future data will be sensitive to some of the implications of superradiant clouds.

Several puzzling aspects of our universe (dark matter, strong CP-problem, string theory landscape...) points towards the existence of new ultralight fields. Superradiance will play a unique role in the search for these new building-blocks of Nature, and it is even possible that it will be the channel to discover them.

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4In principle, more complex dispersion relations may also generate a cloud, something which to my knowledge has not been systematically explored. I also want to remark that there has been some work showing that the plasma mass is not completely equivalent to a Proca mass term, which may have some implications for superradiance.28.
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