

OBSERVATIONS CONSTRAINING BOSON CLOUDS AROUND SPINNING BLACK HOLES IN OUR GALAXY

The mysterious **dark matter** exists all around us and yet is invisible to us. Such dark matter could be composed of extremely light particles known as **bosons**, each having a mass of approximately 10^{-47} kg (that's a number with 46 zeros after the decimal point, followed by a single "one"). These particles are about 20 orders of magnitude lighter than an electron! If they exist, they could randomly pop into existence near rotating **black holes**, and could [scatter](#), i.e. bounce, off the black holes, extracting energy and momentum from them. Because these bosons have mass, and the black hole exerts a strong gravitational pull, they become bound to it, which allows for successive scatterings and for more energy and momentum to be extracted. There is no limit on the number of bosons that can have a particular energy value, which means it is possible for 10^{50} of them to exist around the black hole and all extract energy from it!

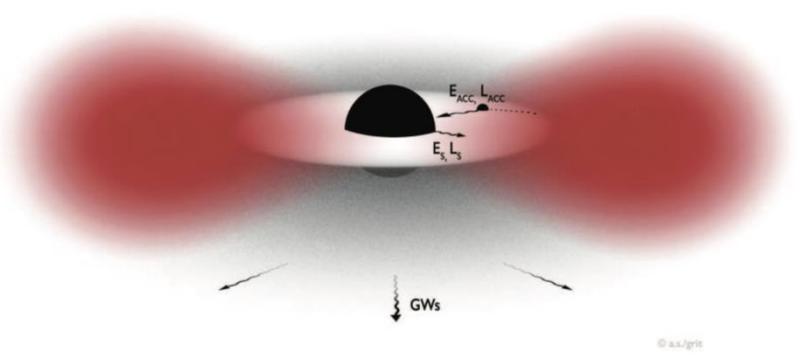


Figure 1: A schematic showing a rotating black hole surrounded by a boson cloud (in red). The macroscopic cloud takes on a dipolar shape because that is the lowest energy state for bosons to fill. Credit: Richard Brito, Vitor Cardoso, Paolo Pani, <https://arxiv.org/pdf/1501.06570.pdf>

The sheer number of particles leads to a macroscopic cloud of bosons forming around the black hole. At this stage, the bosons will [annihilate](#) over time, i.e. they will collide with each other, resulting in the emission of gravitational waves at an almost fixed frequency, almost a single tone. Very slowly over time, the cloud will get smaller and smaller as more and more bosons collide with each other, but it could take tens of thousands of years for it to disappear! The time it takes for the cloud to be created is much shorter than the time for the cloud to deplete through annihilation, ensuring that, in our lifetimes, these boson clouds will be emitting gravitational waves.

Using the most recent **LIGO** data, the **LIGO/Virgo/KAGRA** collaborations performed a search for gravitational-wave signals arising from depleting boson clouds that could come from anywhere in the sky. Such a search is very computationally intensive because we need to analyze each sky position separately at all frequencies, since we do not know the mass of each boson particle, nor where in the sky black holes have formed. Our method breaks the one-year dataset into small chunks of at most a few hours, looks for a monochromatic (i.e. with a single frequency) signal in these chunks, and combines them afterwards. Though we expect the signal to be monochromatic, we wish to also be robust towards uncertainties in the theories that govern gravitational-wave emission from depleting boson clouds. Therefore, we consider the possibility that the frequency of the gravitational-wave signal could wander randomly in time. In both cases, we do not find a significant signal at any boson mass or sky position, and so we set some of the most stringent **upper limits** on the existence of boson clouds around spinning black holes in our galaxy.

FIND OUT MORE:

Read a free preprint of the full scientific article [here](#) or on [arXiv.org](https://arxiv.org).

Visit our websites:

www.ligo.org
www.virgo-gw.eu
gwcenter.icrr.u-tokyo.ac.jp/en/



We interpret these limits in two ways. First, for a given distance, **spin** and age of a black hole, we compute the amplitude of the gravitational-wave signal that could have arisen from it for a variety of boson mass/black hole mass pairs. If this amplitude is larger than that derived in the analysis (which doesn't explicitly assume a depleting boson cloud model), we can exclude the presence of a cloud around a black hole at particular boson masses between 10^{-13} to 10^{-12} eV ($\sim 10^{-47}$ to 10^{-46} kg) and black hole masses between 5 and 100 solar masses, respectively. Second, we assume a model for the way that black hole masses are distributed, and for a fixed boson cloud age and random black hole spins, we calculate at what distance a cloud composed of bosons with a certain boson mass would have produced a strong enough signal to be detected. Our results imply that we would have been sensitive to, at best, black hole/boson cloud systems around 100 kpc (over 300,000 light years) away!

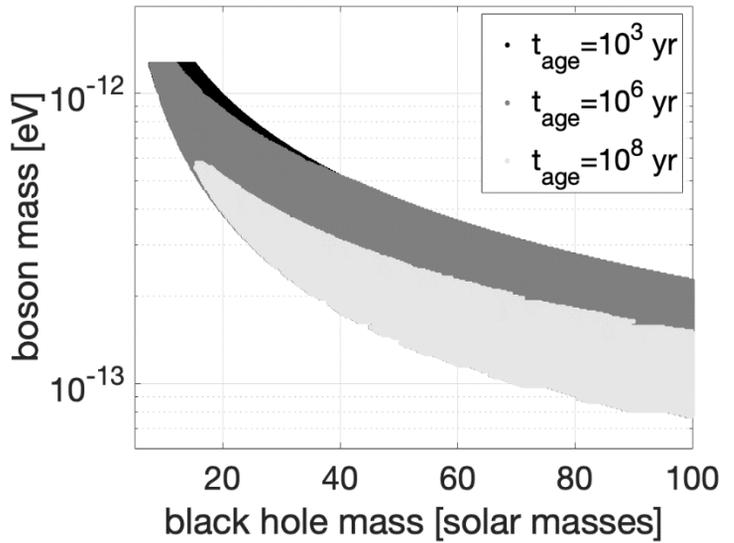


Figure 2: (Fig. 6 in the paper). Here, we assume that black holes with boson clouds could form at a distance of 1 kpc with a spin of 0.9 and could have one of three ages. We exclude the presence of a boson cloud around a black hole over particular mass ranges for the three possible ages given in the figure. Younger black holes emit stronger gravitational waves; hence, the solid black exclusion region given by $t_{\text{age}}=10^3$ years (one thousand years) also includes the entire parameter space excluded by systems with greater t_{age} , making it the most constraining of the three ages.

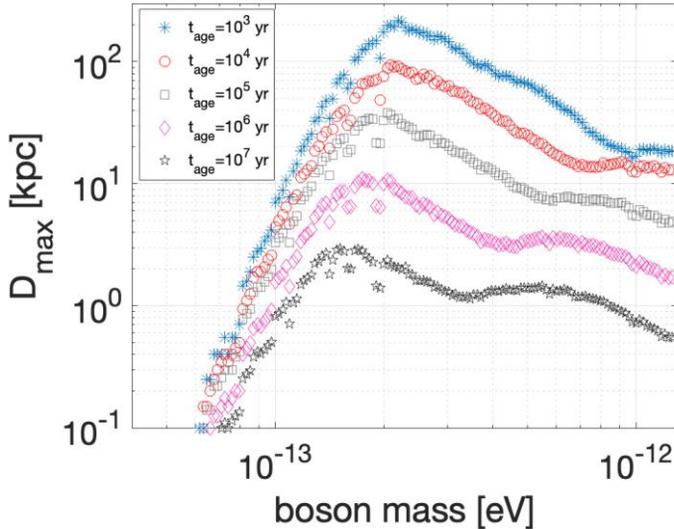


Figure 3: (Fig. 8 in the paper). Maximum distance reached as a function of boson mass, for fixed age of the cloud, for randomly chosen black hole spins and for black hole masses between 5-100 solar masses, chosen according to a particular mass distribution that favors light black hole masses. We can see that the youngest systems with $t_{\text{age}}=10^3$ years can be constrained at the farthest distance away from us. Furthermore, these results are dependent on the population of black holes that we assumed, and could change if we allow for masses, spins and ages to be distributed in a different way.

GLOSSARY

Dark matter: Invisible matter that accounts for 85% of the matter in the Universe. We cannot see it with our eyes, but it interacts gravitationally, so we can infer its effects on a variety of astrophysical objects, e.g. on the velocities of stars in our galaxy. See also [here](#).

Bosons: Class of elementary particles (the other ones are called fermions). Bosons carry an integer spin, while fermions have a half-odd integer spin. For example, the photon, the force carrier for electromagnetic waves, is a spin-1 boson. For more information, click [here](#).

Black hole: A region in spacetime that exerts such a strong gravitational pull that not even light can escape its grasp. A star that is massive enough will, at the end of its life, explode and leave behind a [black hole](#). Can span a wide range of masses, from one solar mass all the way up to 10^9 solar masses! Such "supermassive" black holes also exist at the center of galaxies.

Electronvolt (eV): A unit of energy commonly used in atomic and particle physics, e.g., to measure how much energy is needed to remove an electron from an atom. Because of the relation between energy and mass established by Einstein, $E=mc^2$, masses of particles can be given in units of energy divided by the square of the speed of light, i.e., eV/c^2 . ([Wikipedia](#))

Kiloparsec (kpc): A thousand parsecs. A [parsec](#) is an astronomical unit of length corresponding to roughly 3 light-years or 30 trillion kilometers.

LIGO: The Laser Interferometric Gravitational-Wave Observatory (LIGO) is a US-based pair of gravitational-wave detectors. One is situated near Livingston, Louisiana, and the other near Hanford, Washington. Both detectors are large-scale laser interferometers, with two perpendicular 4-km long arms, that attempt to measure any changes in the relative arm length caused by a passing gravitational wave.

Virgo: A gravitational-wave detector situated near Pisa, Italy. It is also a laser interferometer, but with 3-km long arms.

KAGRA: An underground gravitational-wave detector situated near Toyama, Japan. It is also a laser interferometer, but with 3-km long arms, and cryogenically cooled mirrors.

Spin: Angular momentum of a rotating black hole; one of the defining properties of black holes, along with mass and charge.

Upper limit: A statement about the maximum value some quantity can have while still being consistent with the data. Here, we use the concept to place constraints on the dark photon coupling strength at different frequencies. We use a 95% degree-of-belief limit, i.e. given the data there is a 95% probability that the quantity is below this limit.