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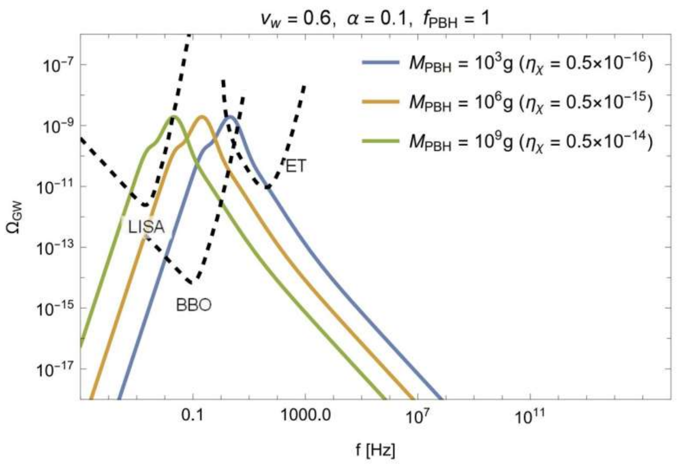
DIALOG

Gravitational waves may prove black holes' quantum effect and resolve the dark matter problem

by Ngo Phuc Duc Loc



GW spectrum from a first-order phase transition for different PBH masses. The black dashed contours represent sensitivity regions from different experiments. Credit: *Phys. Rev. D* 111, 023509 (2025). DOI: 10.1103/PhysRevD.111.023509

Black hole quantum effects are usually thought to be too small to have any observable signatures. This is indeed the case for heavy black holes, such as the ones detected via gravitational waves by LIGO in 2015. These black holes have mass of a few tens of solar mass and, consequently, their Hawking radiation is negligible.

But what is Hawking radiation, anyway? In quantum mechanics, quantum fluctuation could produce virtual pairs of particles out of vacuum. At the vicinity of a black hole's event horizon, one particle will fall into the black hole (and apparently cannot escape), while the other one outside the hole can escape to infinity and become "real." The outgoing quanta is called Hawking radiation.

Because of energy conservation, the infalling quanta must carry negative energy, which implies that the mass (and hence size) of the black hole must reduce when it evaporates. It turns out that the strength of this quantum effect depends on the mass of black holes: small-mass black holes would produce Hawking radiation more efficiently and are more unstable.

However, the recently discovered quantum memory burden effect could be a game changer. The quantum memory burden effect states that the evaporation of a black hole after the half-decay time, which is the time a black hole has lost half of its initial mass, would be halted, and therefore, the black hole becomes stabilized.

The physical origin of this effect is that the information pattern inside the black hole written in memory modes is more energy favorable than the highly gapped modes outside, so that the black hole tends to become stable. This novel quantum effect has important observable consequences for primordial black holes and the nature of dark matter, which we will now discuss.

Types of black holes

As of now, we know that there are two types of black holes that exist in nature: stellar-mass black holes and supermassive black holes. Stellar-mass black holes, with mass of order 10 to 100 solar masses, could have been formed due to the collapse of massive stars at the end of their lifetime. Supermassive black holes have mass greater than 100,000 solar mass and are typically located at the center of galaxies; their origins remain a debate.

There is also a hypothetical kind of black hole known as a primordial black hole (PBH). PBHs were not formed from the collapse of massive dead stars, but were instead formed in the very early universe due to, for example, the collapse of sufficiently large cosmological perturbations or the collapse of Fermi balls in a strong first-order phase transition. These PBHs could have a very wide mass range, from microscopic black holes with mass of order 1g to supermassive black holes with mass of order 100,000 solar mass.

Dark matter

We have strong astrophysical evidence from both the early and the late universe that there must be something called dark matter (DM). This mysterious stuff dominates the matter content of the universe today and is crucial for structure formation that made human existence possible. Nevertheless, we have not seen any experimental evidence of this elusive matter here on Earth. This raises serious questions about the nature of DM.

If DM consists of particles, the same observed DM abundance would imply that there must be many of these particles wandering across the universe, so the probability for these particles to hit our detectors on Earth is very high. But because we have not been able to detect DM on Earth, we can imagine that maybe DM is in the form of some compact object with a very high energy density.

This implies that for the same observed DM abundance, DM is concentrated in these compact objects, and therefore, the probability for these objects to hit the Earth is very low because there are not so many of them.

Putting all the pieces together

Here is the proposal: What if DM consists of PBHs? This is a very natural and compelling possibility, because PBHs behave similarly to DM: They both move slowly and only have gravitational interaction. Because DM is highly concentrated inside PBHs, this justifies the null results of Earth-based DM experiments mentioned earlier.

Researchers have studied this scenario intensively in recent decades. It turns out that in the standard semiclassical calculation of Hawking radiation, only PBHs in the mass range from 10^{17}g to 10^{22}g can be the entire DM. PBHs lighter than the lower bound would have evaporated by now, and therefore cannot be DM because we do see DM today.

However, the novel quantum memory burden effect discussed earlier would halt the evaporation of PBHs after the half-decay time. This quantum effect opens up a new mass window below 10^{10}g where PBHs could still exist today and be the totality of DM.

The question, then, is how to confirm this scenario. The answer is using gravitational waves (GWs). GWs are ripples of spacetime predicted by Einstein's general theory of relativity. The formation of PBHs in the early universe would require violent displacement of matter or energy, which would in turn induce the corresponding GW signals.

My paper published in *Physical Review D* shows that the GW signals associated with the formation of memory-burdened PBHs could be detected in future experiments. In particular, I considered PBHs formed from inflationary perturbation and PBHs formed from a strong first-order phase transition.

Although GWs produced in the former case peak at a high frequency that is somewhat beyond the observational targets of detectors, GWs produced in the latter case are perfectly detectable. As can be seen in the figure above, the GW spectrum peaks at around 0.01–1 Hz with the maximum amplitude of order 10^{-9}, which should be easily detected by upcoming experiments such as LISA, BBO, or ET.

If my predicted GW spectrum is detected in the future, it will be strong evidence that the quantum memory burden effect of holes is correct and supports the idea that PBHs are DM.

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Ngo Phuc Duc Loc is a passionate theoretical physicist and cosmologist at the University of New Mexico, U.S., who is interested in diverse research areas such as inflation, cosmological phase transition, primordial black holes, gravitational waves, dark matter, extra dimension, and foundations of physics.

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