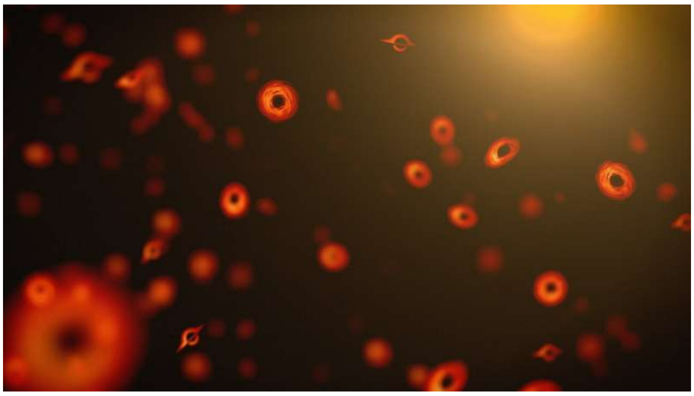
PHYS.ORG

MAY 23, 2025
FEATURE

Detecting the primordial black holes that could be today's dark matter

by David Appell, Phys.org

edited by Sadie Harley, reviewed by Robert Egan



A conception of primordial black holes in the very early universe. The accretion disks are to make the black holes visible; they would likely not form in the actual baby universe. Credit: NASA's Goddard Space Flight Center Via https://svs.gsfc.nasa.gov/14524#media_group_37…

Besides particles like sterile neutrinos, axions and weakly interacting massive particles (WIMPs), a leading candidate for the cold dark matter of the universe are primordial black holes—black holes created from extremely dense conglomerations of subatomic particles in the first seconds after the Big Bang.

Primordial black holes (PBHs) are classically stable, but as shown by Stephen Hawking in 1975, they can evaporate via quantum effects, radiating nearly like a blackbody. Thus, they have a lifetime; it's proportional to the cube of their initial mass. As it's been 13.8 billion years since the Big Bang, only PBHs with an initial mass of a trillion kilograms or more should have survived to today.

However, it has been suggested that the lifetime of a black hole might be considerably longer than Hawking's prediction due to the memory burden effect, where the load of information carried by a black hole stabilizes it against evaporation.

Thus, PBHs previously thought to have evaporated by now could still be present as cold, dark matter, lighter than about 10 million kilograms.

A research team from Japan has now proposed detecting the hypothetical PBH dark matter by studying the gravitational waves induced by the primordial curvature perturbations that produced the PBHs. Their work is published in *Physical Review D*.

"This research is the first in the world to propose that evidence of PBHs being dark matter will be confirmed by future gravitational wave observations," said Kazunori Kohri of the National Astronomical Observatory of Japan in Tokyo and affiliated with several other physics research organizations in the country.

Despite a large number (by now) of experimental searches, physicists have yet to see signs of dark matter in particle accelerators, in underground and under ice detectors and via exploring space, directly or indirectly.

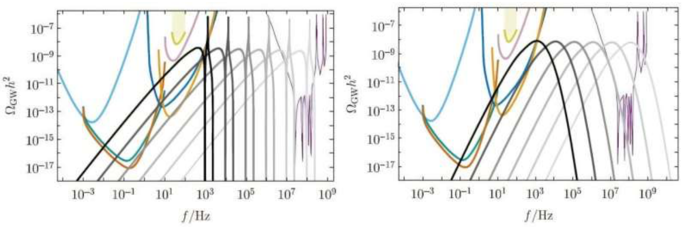
"If this situation continues, the nightmare scenario of dark matter, namely the scenario with only gravitationally interacting dark matter, will become important," write Kohri and his co-authors. Macroscopic dark matter might be the answer, such as the PBH scenario if the PBHs have survived to today.

Hawking's conclusion that black holes radiate means they will eventually evaporate completely and cease to exist. But Hawking's calculation assumed a semiclassical black hole during its entire lifetime, ignoring the quantum back reaction of the created particles on the evaporating black hole.

The full treatment reveals a memory burden effect, discovered by Georgian theoretical physicist Gia Dvali in 2018.

Viewing a black hole as a condensate of gravitons, the presumed carriers of the gravitational force, micro quantum states are responsible for the entropy of the black hole.

"Memory" refers to the information stored in the black hole; this stored information stabilizes the black hole, making it more resistant to decay. A state of the black hole becomes stabilized by the burden of its own memory. The effect becomes important when a black hole has lost about half its initial mass.



The induced gravitational wave strength (vertical axis) versus the spectra frequency (horizontal axes), for various PBH initial masses from 1 gram to 10 billion grams. The left versus right figures relate to two different choices for the dimensionless power spectra of the primordial curvature perturbations. Credit: American Physical Society

"If we believe in the Memory Burden Effect, which is a hot topic in the field of quantum gravity," said Kohri, "we can build a theory with extremely little uncertainty."

It's not yet completely clear what happens to a black hole when the memory burden becomes significant—possibly the Hawking evaporation is suppressed, or perhaps the black hole decays into some lumps and gravitational waves.

Kohri and his co-authors focused on the first possibility. Dvali and his collaborators argued that the Hawking emission rate is suppressed by some integer power of the black hole's entropy.

Black holes have a huge amount of entropy; a Schwarzschild black hole with a mass of the sun has an entropy of 10^{77} in units of Boltzmann's constant. By comparison, the sun's entropy is 10^{58}.

So the lifetime of a black hole is greatly extended. Cosmological constraints put lower and upper limits on the PBHs at play: Kohri and colleagues thus focus on PBHs with an initial mass greater than 100 kg up to 10 million kg.

One popular PBH production mechanism is the gravitational collapse of early cosmological patches with extremely enhanced spacetime curvature perturbations. Significant amounts of gravitational waves are also induced in this radiation-dominated era of the universe, with a typical frequency in a one-to-one correspondence with the PBH's initial mass.

Studying the observational properties of these gravitational waves in the present universe, extensive calculations resulted in the spectra of gravitational waves as would exist today as a function of frequency, and also the expected signal-to-noise ratio for one-year of observations with proposed future gravitational wave observatories.

Their calculations of the expected induced gravitational wave spectra reveal that sufficiently heavy memory-burdened PBH dark matter could be observable today because they induce relatively low-frequency gravitational waves.

Future observatories are being designed with this goal in mind, such as the space-based LISA (Laser Interferometer Space Antenna), DECIGO (Deci-hertz Interferometer Gravitational wave Observatory) in Japan, the Big Bang Observatory (BBO) proposed by the European Space Agency (ESA) to replace LISA when it's run its course, and others.

Kohri and his colleagues produced graphs of the expected spectra in terms of the waves' frequency and extend their equations to predict the signal-to-noise ratios that would be seen in the actual observations.

The researchers also present criteria by which gravitational wave astronomers could confirm or exclude the scenario of the memory-burdened PBH dark matter. Still, nonlinear dynamics of the memory-burdened PBH dark matter will determine the detailed form of the gravitational waves.

The peak frequency of the induced waves can be as high as 30 megahertz, 3,000 times higher than the 10 kilohertz peak the two LIGOs in the US can detect. However, the calculations show there is an infrared trail in the spectra that implies lower peak frequencies.

These could be detected by the proposed Cosmic Explorer, a third-generation ground-based gravitational wave observatory that would have the same L-shaped design as LIGO but with interferometer arms that are 40 km long instead of LIGO's 4 km.

More information: Kazunori Kohri et al, Induced gravitational waves probing primordial black hole dark matter with the memory burden effect, *Physical Review D* (2025). DOI: 10.1103/PhysRevD.111.063543. On *arXiv*: DOI: 10.48550/arxiv.2409.06365

Journal information: arXiv , Physical Review D

© 2025 Science X Network

Citation: Detecting the primordial black holes that could be today's dark matter (2025, May 23) retrieved 31 May 2025 from https://phys.org/news/2025-05-primordial-black-holes-today-dark.html

This document is subject to copyright. Apart from any fair dealing for the purpose of private study or research, no part may be reproduced without the written permission. The content is provided for information purposes only.