Results of the HAYSTAC Phase II search for dark matter axions

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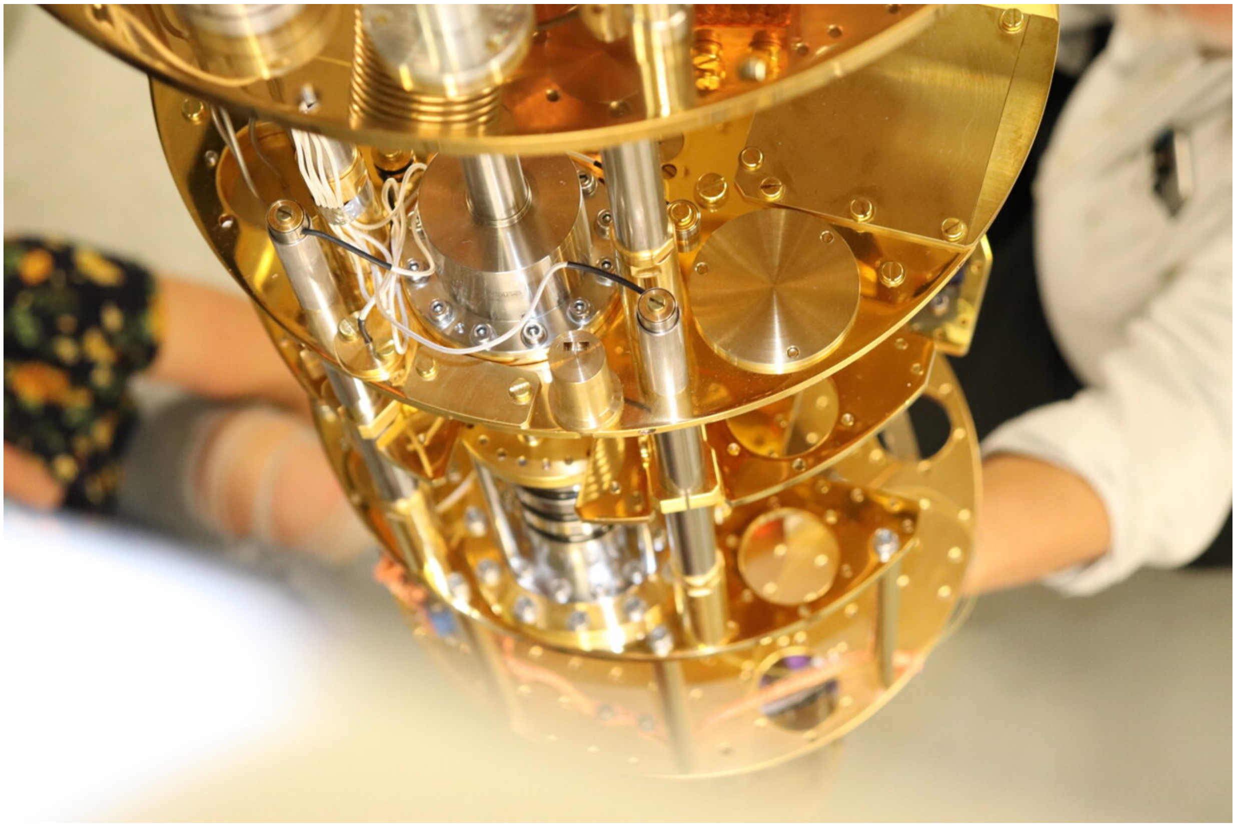


Image showing the top of the experiment in greater detail. Credit: HAYSTAC Collaboration.

Axions, hypothetical subatomic particles that were first proposed by theoretical physicists in the late 1970s, remain among the most promising dark matter candidates. Physics theories suggest that the interactions between these particles and regular matter are extremely weak, which makes them very difficult to detect using conventional experimental set-ups.

The HAYSTAC (Haloscope at Yale Sensitive to Axion Cold Dark Matter) experiment is a research collaboration between Yale, Berkeley and Johns Hopkins, aimed at detecting axions by searching for the small electromagnetic signals that they could produce within a strong magnetic field.

In a recent paper published in *Physical Review Letters*, the HAYSTAC collaboration has reported the results of the broadest search for axions performed to date, utilizing a technique known as quantum squeezing, which is designed to reduce quantum noise (i.e., random fluctuations that adversely affect their haloscope's measurements).

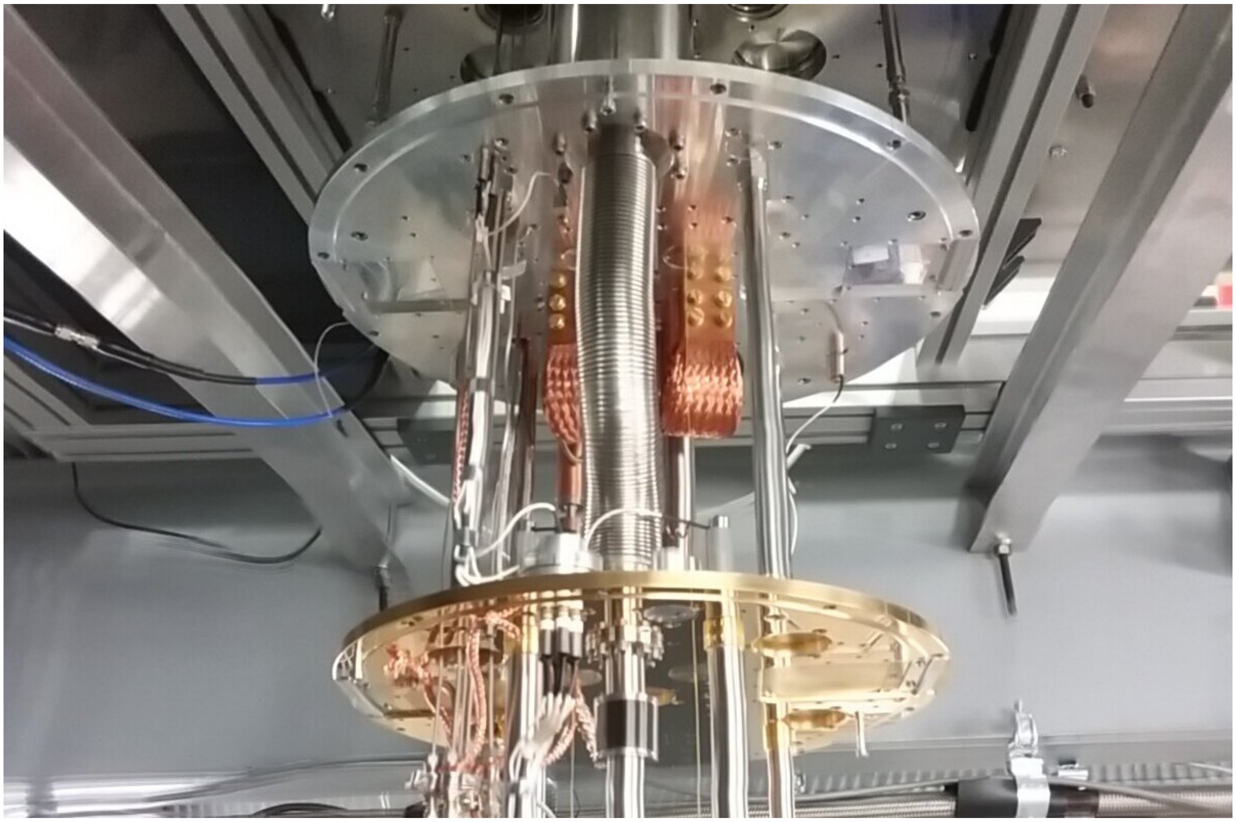
"The axion was introduced to explain the lack of charge conjugation and parity (CP) asymmetry in the strong force, and the original idea for how to search for axions came from Sikivie," Reina Maruyama, co-author of the paper, told Phys.org. "Steve Lamoreaux has long worked on the strong CP problem, starting from his work on looking for the permanent electric dipole moment in mercury atoms and in neutrons."

Originally, axions were introduced by theorists Frank Wilczek and Steven Weinberg to explain time-reversal symmetry in strong nuclear forces. Eventually, however, they also became a possible candidate for dark matter, the elusive type of matter that only weakly interacts with electromagnetic radiation and yet is believed to account for most of the universe's mass.

"Theoretically, there is a pure-number parameter (theta, the Greek letter) that sets the level of time reversal asymmetry, and it can in principle be just about anything, but its value is below 0.0000000001 (10^{-10}) as limited primarily by the neutron electric dipole moment," said Steve Lamoreaux, co-author of the paper.

"Time-reversal asymmetry is, however, observed in the decay of 'strange' mesons, so why it should be so small in the nuclear force is a mystery that is solved by the axion (in the collective sense). Pierre Sikivie appears to be the first to appreciate that the axion could serve as a dark matter candidate particle, because it interacts only very feebly with matter or electromagnetic fields."

The realization that light axions could saturate the matter density of the universe was almost simultaneously reported by three distinct research groups. The first was led by Sikivie and Lou Abbott, the second by Michael Dine and Willy Fischler, and the third by John Preskill, Mark Wise and Frank Wilczek.



The inside of the experiment, with the resonator cavity at the bottom. Credit: HAYSTAC Collaboration

Shortly after introducing the idea that axions could be a dark matter candidate, however, Sikivie also outlined the concept of a "haloscope" galactic halo dark matter axion detector, an instrument that relies on a microwave cavity placed in a very strong magnetic field. This magnetic field should prompt the conversion of axions into photons at radio or microwave frequencies, which would in turn enable their direct detection, despite associated signals being very small.

"Fifteen years ago, it seemed to us that while the Sikivie-type microwave cavity experiments were making good progress, improving in sensitivity in the gigahertz range, what was needed was a vanguard effort to open the higher mass range towards the post-inflation axion," said Karl van Bibber, co-author of the paper. "The HAYSTAC experiment was conceived as a pathfinder and an innovation testbed for new amplifier and resonator concepts at ever-higher frequencies. This would require that we remain a small, agile experiment."

As frequencies increased, so did the challenges encountered when trying to detect axions with haloscopes. For instance, higher frequencies also entail a reduction in the conversion cavity's volume and a lower density of axions for a given halo mass per unit volume.

In Phase II of their experiment, the researchers employed quantum measurement technologies and used quantum squeezing to enhance their sensitivity. So far, HAYSTAC is one of the two experiments worldwide, along with the larger research effort Advanced LIGO, which relied on quantum squeezing to boost the sensitivity of measurement tools.

The HAYSTAC collaboration also integrated external cryogen-free dilution refrigerators into their setup, which were not employed during earlier axion searches. Both quantum squeezing and the dilution refrigerators allowed them to lower the financial costs associated with building their haloscope and operating it.

While they did not detect any signals that could be linked to axions, the team was able to search a larger parameter space. In the future, they plan to continue improving the HAYSTAC equipment and continue their search for axion dark matter, while also working on other dark matter searches using haloscopes and equipment at Yale.

"We have several ideas on pushing the experiment to search for axions with higher masses, and we are working on several quantum technology-inspired ideas to improve the detection techniques," said Danielle Speller, co-author of the paper.

"The ALPHA experiment is a natural extension, as are single photon detection with Rydberg atoms, and detection enhancement, which we call CEASEFIRE, described in this paper. CEASEFIRE is a powerful quantum enhancement scheme, using two-cavity entanglement with state exchange to accelerate the search by an order of magnitude. The search above 10 GHz also brings cavities into the world of photonic structures and ultimately superconducting metamaterial-based resonators, which we're working on."

The ALPHA experiment is a larger research collaboration aimed at detecting axions with significantly greater masses, specifically in the post-inflation axion mass regime. This experiment will rely on a different instrument known as a plasma haloscope, which is currently being built at Yale.

More information: Xiran Bai et al, Dark Matter Axion Search with HAYSTAC Phase II, *Physical Review Letters* (2025). DOI: 10.1103/PhysRevLett.134.151006

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