A null result full of insights

A laboratory-based search for axion dark matter ended, not unexpectedly, without a discovery. It provides, however, valuable constraints for the properties that these hypothetical particles can have — and thus a guide to where to look next.

Among Paul Scherrer's doctoral students, Fritz Zwicky (1898–1974) was one who stood out. A man of many interests, Zwicky worked under Scherrer and Peter Debye at ETH Zurich on the theory of ionic crystals, moved then to the US to make at Caltech major contributions to numerous areas of astronomy, and developed later 'morphological analysis', a general heuristic approach to solving complex problems. But one unsolved problem that the Swiss astronomer left behind keeps puzzling scientists to this day: In 1933 he published a paper discussing orbital velocities of objects in the Coma cluster of galaxies, and he concluded that to make sense of the astrophysical observations, the mass density in the cluster had to be many times higher than the 'visible' matter detected from in this system could account for. In other words, mass was missing. Today we know that only some 15% of the matter in the Universe consists of ordinary, visible matter, whereas the much larger remainder is invisible 'dark' matter. What these missing components — which also include dark energy — are made of remains one of the great mysteries of modern science. But while the nature of dark matter is unknown, there exist a number of limits, putting constraints on the energy and coupling ranges of dark-matter particles. New results of a PSI-based international collaboration, published today in *Physical Review X*, now add further such constraints — notably in an energy range that has so far been unexplored in laboratory experiments.

Searching in the dark

While the nature of dark matter is still wide open, its telltale gravitational effects are well documented. In particular, the spatial distribution of dark matter is known to ever-greater detail, thanks to observational efforts such as the ongoing Dark Energy Survey (DES). Astronomical observations also place a number of restrictions on the properties that dark-matter particles can have. In addition to exerting gravitational forces, dark-matter particles might also directly interact with ordinary matter, opening up a window to laboratory-based experiments. As it is not clear which form non-gravitational interactions take, these experiments are guided by theoretical models.

Most searches up to now have been focused on so-called weakly interacting massive particles (or, WIMPs). Searching for WIMPs typically involves the detection of either scattering or annihilation events (or, alternatively, the creation of WIMPs in high-energy collisions). Experiments along these lines have so far come out empty-handed. And so have searches for another class of candidate particles, the so-called axion.

The axions were originally introduced as a solution to the strong-CP problem in quantum chromodynamics (QCD), but these particles would also explain dark matter in a rather natural manner. But nobody has yet detected axions or axion-like particles (which are axions with parameters different to those for the ‘QCD axion’). The only systematic searches to date for axions have looked for the conversion of axions to photons, typically in the microwave range (that is, at GHz frequencies). However, in recent theoretical work it has been predicted that axions, should they then exist, could also couple to nucleons and the gluons therein. This motivated the nEDM collaboration — bringing together scientists from seven countries, including Prof. Klaus Kirch and his team at PSI and ETH Zurich — to search for axions in the nano- to milli-hertz range, corresponding to considerably lower masses than those covered in previous efforts.

A new spin on dark-matter searches

The approach of the international team was not to look for rare single events (such as scatting, annihilation or conversion), but for a constantly oscillating axion-like background field that is predicted to interact with ordinary matter. More specifically, axion-like fields should induce harmonic oscillations in the electric dipole moment (EDM) and energy levels of the neutron and of atoms. But as the effect would be extremely small, and exquisitely sensitive experiments are needed to measure it.

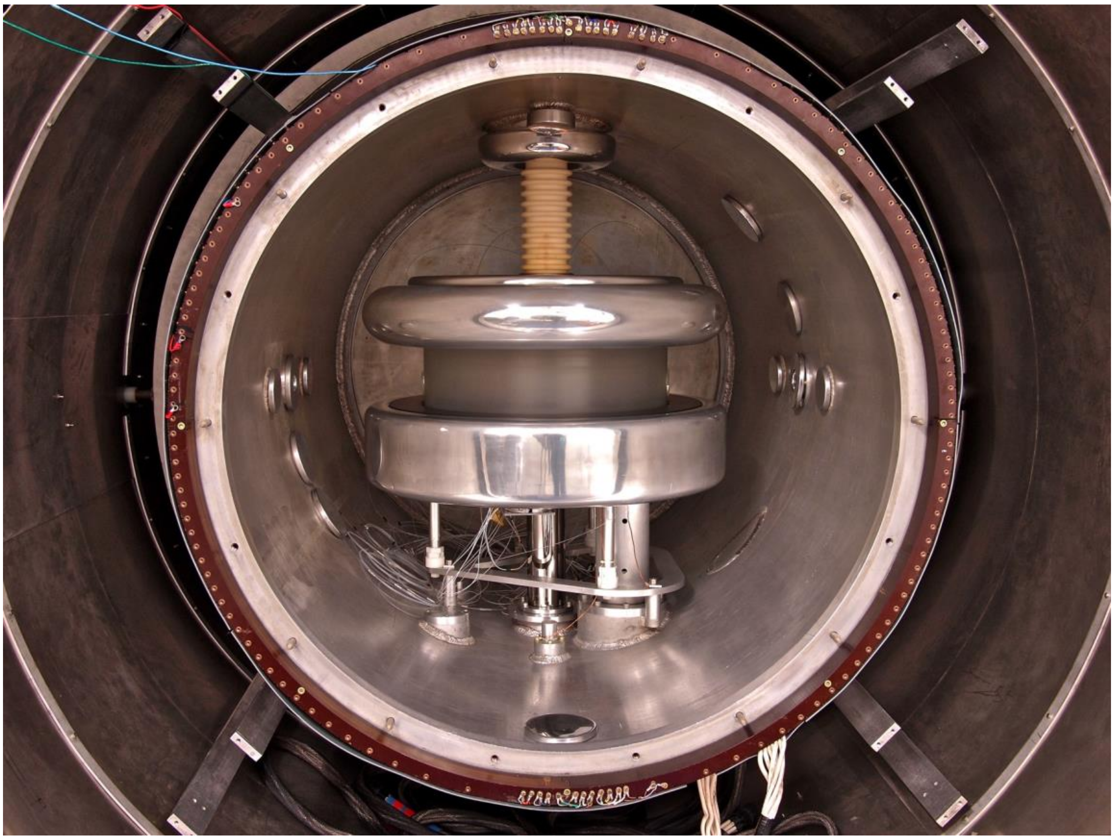
The nEDM collaboration has such high-precision data for the EDM of the neutron (hence the name of the collaboration). Their apparatus acquired the currently most precise published data set on the neutron EDM between 1998 and 2002 at the Institut Laue–Langevin (ILL) in Grenoble. The experimental setup used there was subsequently dismantled and reassembled in the Laboratory for Particle Physics at PSI, where it has been improved and further, more sensitive data have been taken in recent years. These experiments essentially measure the nuclear magnetic resonance (NMR) frequency of neutrons and mercury atoms, and test whether that frequency is affected when the spins are exposed to not only a magnetic, but also an electric field. (So far, these measurements have produced results that are consistent with a zero EDM.)

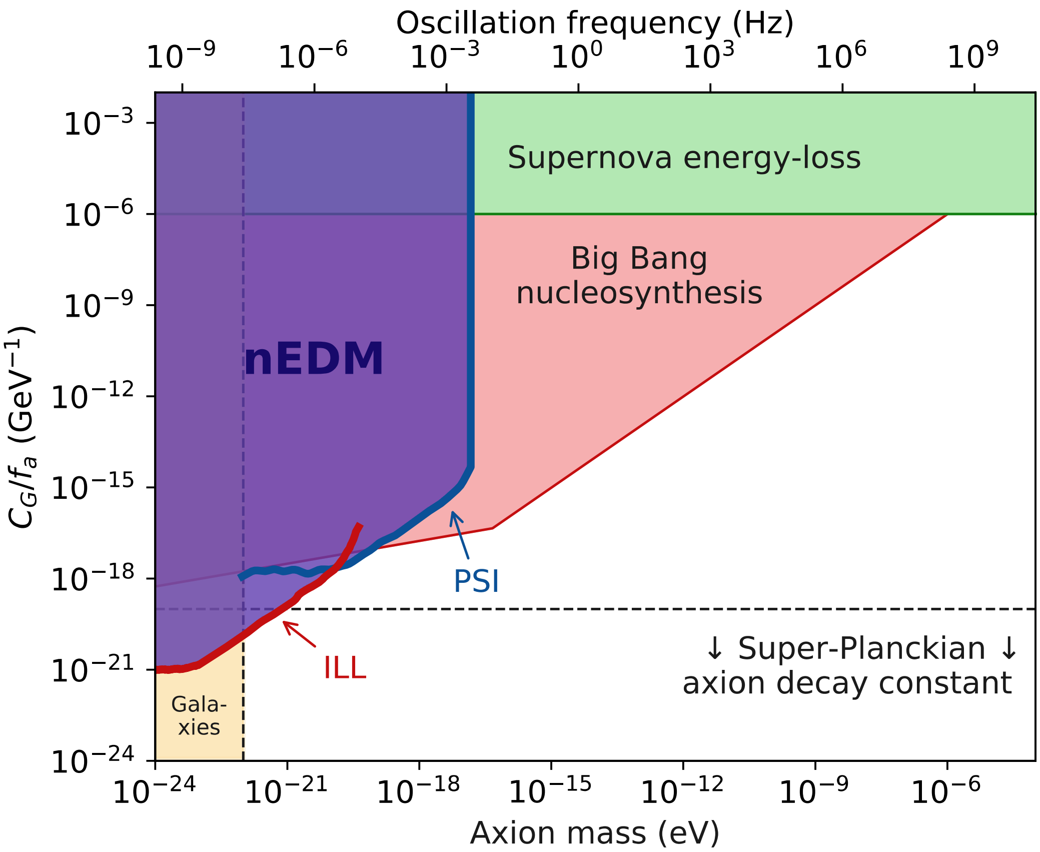
Recycle your data

The collaborations involved in these two experiments at ILL and PSI have now meticulously combed through their neutron-EDM data, to search for time variations that might have been caused by axion-like dark matter. Owing to the way that the data were collected, the analysis of the ILL data covered oscillation periods on the order of days and longer, whereas the analysis of the PSI data provided information for oscillation periods down to minutes. For both frequency ranges the search ended with a null result — no signal consistent with the presence of axions was spotted. However, in this way the team has obtained the first laboratory constraints on the coupling of axion-like dark matter to gluons. In doing so, they have improved on astrophysical limits by up to three orders of magnitude. Moreover, the results obtained tighten previous laboratory limits on the coupling between axions and nucleons by a factor of up to 40. Taken together, these results significantly constrain the strengths of interactions in an axion-mass range where information has been sparse so far.

With these new constraints for ultra-low-mass axion-like dark matter, the new analysis should help to guide both future searches and model refinement. Moreover, the approach of looking for signatures of oscillating signals in existing high-precision data is currently being pursued within other experiments worldwide, and dedicated new experiments are being constructed to hunt for axion-like particles. These efforts might bring us step by step closer to solving that long-standing mystery that puzzled Zwicky, and so many after him.

Andreas Trabesinger





Oscillation frequency (Hz)
10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9}
Supernova energy-loss
Big Bang nucleosynthesis
nEDM
PSI
ILL
↓ Super-Planckian ↓ axion decay constant
Gala-xies
C_G/f_a (GeV^{-1})
10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21} 10^{-24}
10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6}
Axion mass (eV)