AstroTalk: Behind the news headlines; December 2024

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Elusive dark matter signatures: Axions to the rescue?

The search for the Universe's dark matter could end tomorrow—given a nearby supernova and a little luck. Many different pieces of evidence suggest that approximately 85% of the matter content in the Universe is 'dark,' which means that it is not made up of any type of matter that we know of and can currently observe with regular telescopes.

Instead, the existence of dark matter is only inferred indirectly through the gravitational influence it exerts on visible matter. Fortunately, this does not automatically mean that dark matter has no other interactions with visible matter at all, but if such interactions exist, their strength is necessarily very weak. As the name suggests, any viable dark matter candidate will thus be incredibly difficult to observe directly.

Putting one and one together, physicists have realised that the axion may be exactly what they are looking for to solve the 'dark matter problem'. Astrophysicists at the University of California (UC) at Berkeley (USA) now argue that the axion could be discovered within seconds of the detection of gamma rays from a nearby supernova explosion. Axions, if they exist, would be produced in enormous quantities during the first 10 seconds after the eventual core collapse of a massive star into a neutron star, and those axions would escape and be transformed into high-energy gamma rays.

Such a detection is possible today only if the lone gamma-ray telescope in orbit, the *Fermi Gamma-ray Space Telescope*, is pointing in the direction of the supernova at the time it explodes. Given the telescope's field of view, that chance is about one in 10.

Yet, a single detection of gamma rays would narrow down the mass of the axion, particularly the so-called 'QCD axion', over a huge range of theoretical masses, including mass ranges now being checked in experiments on Earth. The lack of a detection, however, would eliminate a large range of potential masses for the axion, and make most current dark matter searches irrelevant. Either way, these results will have far-reaching consequences for our understanding of the Universe on the largest scales.

The problem is that, for the gamma rays to be bright enough to detect, the supernova must be nearby—within our Milky Way or one of its satellite galaxies—and nearby stars explode only once every few decades, on average. The most recent nearby supernova occurred in 1987, in the Large Magellanic Cloud. At the time, a now defunct gamma-ray telescope, the *Solar Maximum Mission*, happened to be pointing in the supernova's direction, but it wasn't sensitive enough to be able to detect the predicted intensity of gamma rays.

> "*If we were to see a supernova, like supernova 1987A, with a modern gamma-ray telescope, we would be able to detect or rule out this QCD axion, this most*

> *interesting axion, across much of its parameter space—essentially the entire parameter space that cannot be probed in the laboratory, and much of the parameter space that can be probed in the laboratory, too*," said UC Berkeley's Benjamin Safdi. "*And it would all happen within 10 seconds*."

The researchers are anxious, however, that when the long-overdue supernova pops off in the nearby Universe, we won't be ready to see the gamma rays produced by axions.

> "*I think all of us … are stressed about there being a next supernova before we have the right instrumentation*," Safdi said. "*It would be a real shame if a supernova went off tomorrow and we missed an opportunity to detect the axion—it might not come back for another 50 years*."

QCD axions

The axion is a particle that fits nicely within the 'standard model' of physics and solves several other outstanding puzzles in particle physics.

Named after a brand of soap, its existence was first postulated in the 1970s, to clean up a problem—hence the soap reference—in our understanding of a type of particle we can observe very well: the neutron. However, while theoretically very nice, if these axions existed, they would be extremely light, making them very hard to detect in experiments or observations.

Axions also fall neatly out of string theory, a hypothesis about the underlying geometry of the Universe, and they might be able to unify gravity—which explains interactions on cosmic scales—with the theory of quantum mechanics, which describes the infinitesimal. That's a lot to take in!

> "*It seems almost impossible to have a consistent theory of gravity combined with quantum mechanics that does not have particles like the axion*," Safdi said.

The strongest axion candidate, the QCD axion—named after the reigning theory of the strong force, 'quantum chromodynamics'—theoretically interacts with all matter, although weakly, through the four forces of nature: gravity, electromagnetism, the strong force (which holds atoms together) and the weak force, which explains the breakup of atoms.

One consequence is that, in a strong magnetic field, an axion should occasionally turn into an electromagnetic wave, or photon. The axion is distinctly different from another lightweight, weakly-interacting particle, the neutrino, which only interacts through gravity and the weak force and totally ignores the electromagnetic force.

Lab-bench experiments employ compact cavities that, like a tuning fork, resonate with and amplify the faint electromagnetic field or photon produced when a low-mass axion transforms in the presence of a strong magnetic field.

Alternatively, astrophysicists have proposed looking for axions produced inside neutron stars immediately after a core-collapse supernova, like 1987A. Until now,

however, they've focused primarily on detecting gamma rays from these axions' slow transformation into photons in the magnetic fields of galaxies. Safdi and his colleagues realised that that process is not very efficient at producing gamma rays, or at least not enough to detect from Earth.

Instead, they explored the production of gamma rays by axions in the strong magnetic fields around the very star that generated the axions. That process, supercomputer simulations showed, very efficiently creates a burst of gamma rays that is dependent on the mass of the axion, and the burst should occur simultaneously with a burst of neutrinos from inside the hot neutron star. That burst of axions, however, lasts a mere 10 seconds after the neutron star forms—after that, the production rate drops dramatically—hours before the outer layers of the star explode.

> "*This has really led us to thinking about neutron stars as optimal targets for searching for axions as axion laboratories*," Safdi said. "*Neutron stars have a lot of things going for them. They are extremely hot objects. They also host very strong magnetic fields. The strongest magnetic fields in our universe are found around neutron stars, such as magnetars, which have magnetic fields tens of billions of times stronger than anything we can build in the laboratory. That helps convert these axions into observable signals*."

Two years ago, Safdi and his colleagues put the best upper limit on the mass of the QCD axion—at about 16 million electron volts, or about 32 times less than the mass of the electron. This was based on the cooling rate of neutron stars, which would cool faster if axions were produced along with neutrinos inside these hot, compact bodies.

In their current work, the UC Berkeley team not only determines the production of gamma rays following stellar core collapse to a neutron star, but they also use the non-detection of gamma rays from the 1987A supernova to put the best constraints yet on the mass of axion-like particles (which differ from QCD axions in that they do not interact via the strong force).

They predict that a gamma-ray detection would allow them to identify the QCD axion mass if it is above 50 microelectron volts, or about one 10-billionth the mass of the electron. A single detection could refocus existing experiments to confirm the mass of the axion. While a fleet of dedicated gamma-ray telescopes is the best option for detecting gamma rays from a nearby supernova, a lucky break with *Fermi* would be even better.

> "*The best-case scenario for axions is* Fermi *catches a supernova. It's just that the chance of that is small*," Safdi said. "*But if* Fermi *saw it, we'd be able to measure its mass. We'd be able to measure its interaction strength. We'd be able to determine everything we need to know about the axion, and we'd be incredibly confident in the signal because there's no ordinary matter which could create such an event*."

Given these latests calculations by the UC Berkeley scientists, results obtained by an international team of physicists from the universities of Amsterdam (Netherlands), Princeton (USA) and Oxford (UK) just a few months ago have gained new importance:

this latter team showed that axions may occur in large clouds swirling around neutron stars. The team even suggested that such axions might not be too difficult to observe.

In their previous work the scientists investigated the axions that escape the neutron star; in their new work the researchers focus on the ones that are left behind—the axions that get captured by the star's gravity. As time goes by, these particles should gradually form a hazy cloud around the neutron star, and it turns out that such axion clouds may well be observable with our current telescopes.

Neutron stars as magnifying glasses

The idea of the axion as a dark matter particle is nice, but in physics an idea is only truly nice if it has observable consequences. Would there be a way to observe axions after all, fifty years after their possible existence was first proposed?

Light is something we know how to observe, but as the corresponding interaction strength should be very small, so is the amount of light that axions generally produce. That is, unless one considers an environment containing a truly massive amount of axions, ideally in very strong electromagnetic fields. That is, unless one considers an environment containing a truly massive amount of axions, ideally in very strong electromagnetic fields.

This led the researchers to consider neutron stars, the densest known stars in the Universe. These objects have Sun-like masses compressed into stars of 12 to 15 kilometres in size.

Such extreme densities create an equally extreme environment that also contains enormous magnetic fields, billions of times stronger than any on Earth. Recent research has shown that if axions exist, these magnetic fields allow for neutron stars to mass-produce these particles near their surface.

The ones that stay behind

The international team of physicists considered the axions that do not manage to escape from neutron stars—that is, the ones that, despite their tiny mass, get caught by the neutron star's immense gravity.

Due to the axions' very feeble interactions, these particles will stay around, and on timescales of up to millions of years, they will accumulate around their host neutron star. This can result in the formation of very dense clouds of axions around neutron stars, which provide some incredible new opportunities for axion research.

The scientists argue that if axions exist, axion clouds should be generic (for a wide range of axion properties they should form around most, perhaps even all, neutron stars), they should in general be very dense (forming a density possibly twenty orders of magnitude larger than local dark matter densities), and because of this they should reveal powerful observational signatures.

The latter potentially come in many types, such as a continuous signal emitted during large parts of a neutron star's lifetime or a one-time burst of light at the end of a neutron star's life, when it stops producing its electromagnetic radiation. Both signatures could be observed and used to probe the interaction between axions and photons beyond current limits, even using existing radio telescopes.

The present work is an important step in a new and exciting research direction. A full understanding of axion clouds will require complementary efforts from multiple branches of science, including particle (astro)physics, plasma physics and observational radio astronomy. These exciting developments are at the basis of a new, cross-disciplinary field with lots of opportunities for future research.

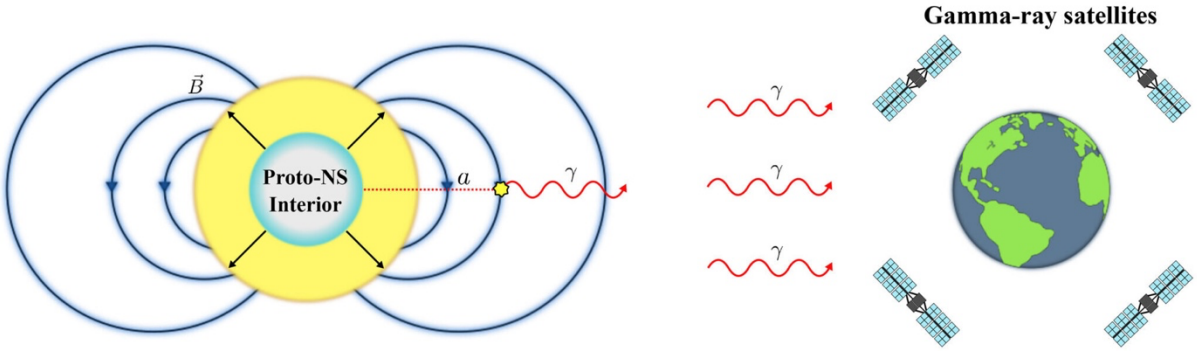


Fig. 1: After a hot, compact neutron star forms from the collapsed iron core of a massive star, axions should be produced in immense quantities for about 10 seconds. Some of these axions (left; red dotted line) will be converted into gamma rays in the intense magnetic field of the star. A fleet of gamma-ray telescopes around the Earth could detect these gamma rays, confirming the existence of axions and constraining the mass. (Credit: Benjamin Safdi, UC Berkeley)

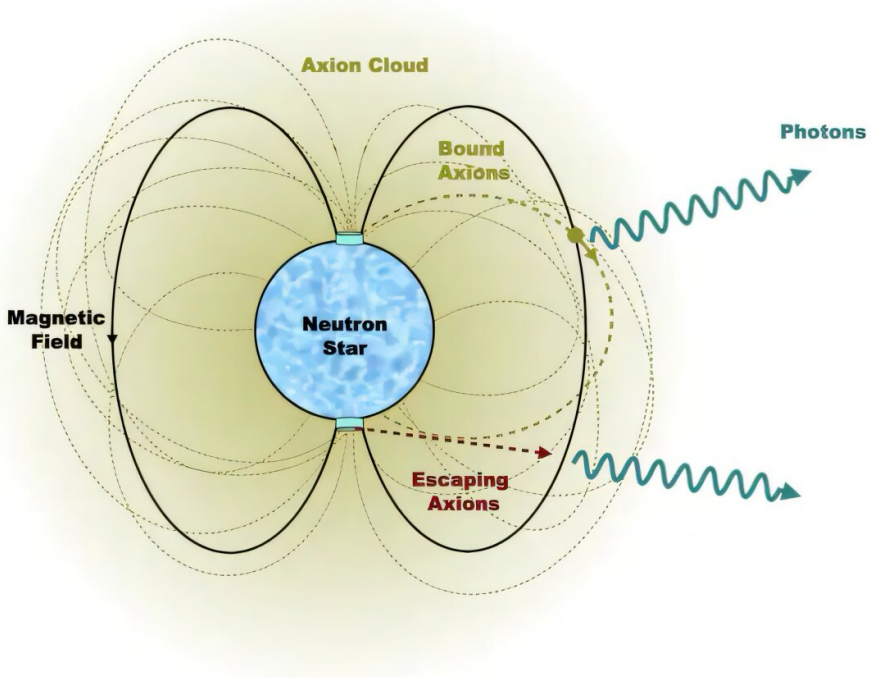


Fig. 2: An axion cloud around a neutron star. While some axions escape the star's gravitational pull, many remain bound to the star and over a long period of time form a cloud surrounding it. The interaction with the neutron star's strong magnetic field causes some axions to convert into photons – light that we can eventually detect with our telescopes on Earth. (Credit: University of Amsterdam)

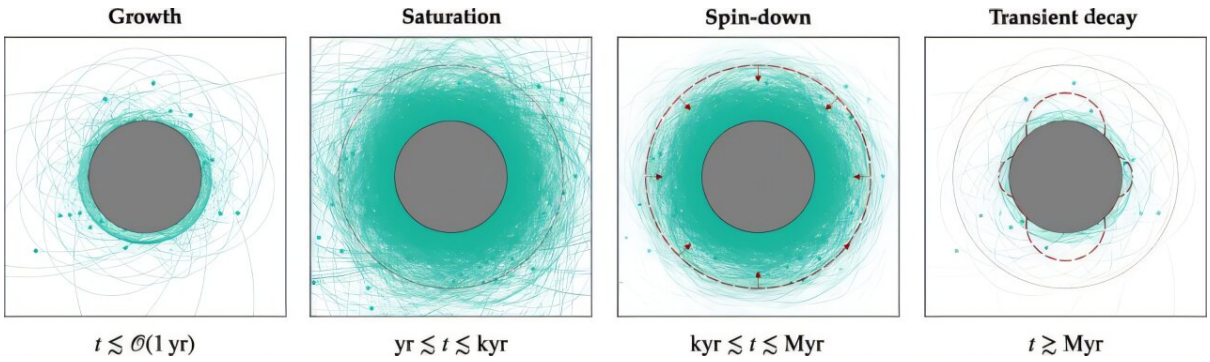


Fig. 3: Overview of the four stages characterizing the formation and evolution of axion clouds around neutron stars. (Credit: *Physical Review X* (2024). DOI: 10.1103/PhysRevX.14.041015)

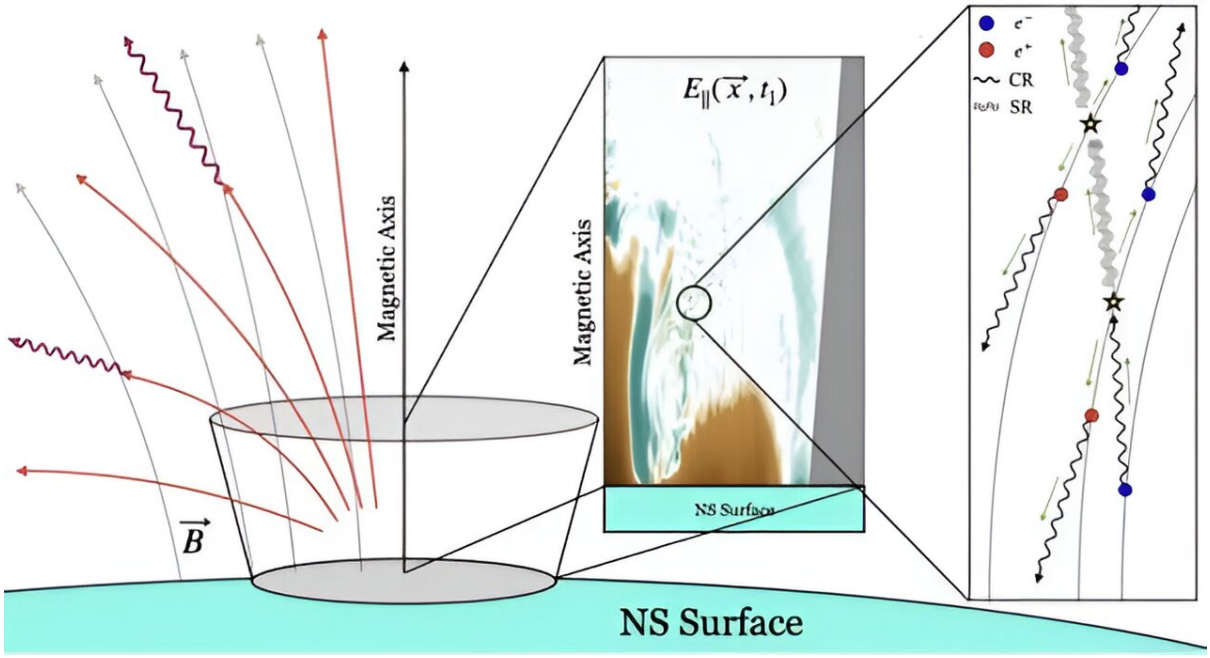


Fig. 4: How neutron stars might produce axions. (Credit: Noordhuis et al.)



Fig. 5: The CAST experiment at CERN, used for axion searches. (Credit: CERN)



Fig. 6: The Axion Dark Matter eXperiment, ADMX (Credit: Braine et al.)