COLLOQUIUM PAPER

Dark-matter QCD-axion searches

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In the late 20th century, cosmology became a precision science. Now, at the beginning of the next century, the parameters describing how our universe evolved from the Big Bang are generally known to a few percent. One key parameter is the total mass density of the universe. Normal matter constitutes only a small fraction of the total mass density. Observations suggest this additional mass, the dark matter, is cold (that is, moving nonrelativistically in the early universe) and interacts feebly if at all with normal matter and radiation. There's no known such elementary particle, so the strong presumption is the dark matter consists of particle relics of a new kind left over from the Big Bang. One of the most important questions in science is the nature of this dark matter. One attractive particle dark-matter candidate is the axion. The axion is a hypothetical elementary particle arising in a simple and elegant extension to the standard model of particle physics that nulls otherwise observable CP-violating effects (where CP is the product of charge reversal C and parity inversion P) in quantum chromo dynamics (QCD). A light axion of mass $10^{-(6-3)}$ eV (the invisible axion) would couple extraordinarily weakly to normal matter and radiation and would therefore be extremely difficult to detect in the laboratory. However, such an axion is a compelling dark-matter candidate and is therefore a target of a number of searches. Compared with other particle dark-matter candidates, the plausible range of axion dark-matter couplings and masses is narrowly constrained. This focused search range allows for definitive searches, where a nonobservation would seriously impugn the dark-matter QCD-axion hypothesis. Axion searches use a wide range of technologies, and the experiment sensitivities are now reaching likely dark-matter axion couplings and masses. This article is a selective overview of the current generation of sensitive axion searches. Not all techniques and experiments are discussed, but I hope to give a sense of the current experimental landscape of the search for dark-matter axions.

axions | dark matter | strong CP problem

What Makes Up the Dark Matter?

One of the great discoveries of the last century is that the vast majority of all matter in the universe is made of something other than dust, planets, gas, etc., which is the ordinary matter we see around us. From observations, we now have an accurate accounting of the dark-matter fraction of the universe at around one-quarter of its total energy density, with almost all of the remaining mass and energy density of the universe being the mysterious "dark energy." From Milky Way galactic observations, our nearby dark-matter density is around one-half of proton mass per cubic centimeter.

Observational constraints imposed by structure formation in the Universe plus the remnant light-isotope abundance from primordial nucleosynthesis suggest the dark matter is a new exotic particle relic left over from the Big Bang. Interestingly, light axions, with masses much less than that of the electron, have dark matter-like properties and would have frozen out in the early universe with the density to be dark matter.

What Is the Axion?

Quantum chromo dynamics (QCD) was firmly established in the early 1970s as the quantum field theory of nuclear interactions. It is remarkably successful, predicting, for example, the structure of hadronic jets and the "running" of the strong coupling constant. However, by the mid-1970s, it was realized that this theory predicts large violations of CP, the product of charge-reversal (C) and parity inversion (P), due to "instanton" (multiple degenerate QCD vacua) effects. It would be uncomfortable to have QCD without instanton-mediated CP violation, as degenerate vacua neatly explain hadron masses. One such CP-violating effect is a permanent electric dipole moment for a spinning nondegenerate object bound by strong interactions (e.g., the neutron).

In a pleasing series of measurements, the neutron is constrained to have a vanishingly small upper bound to its permanent electric dipole moment. This vanishingly small electric dipole moment strongly suggests QCD, despite its successes, is not the whole story of the strong interactions (1). In 1977, Roberto Peccei and Helen Quinn proposed an additional hidden U(1) axial symmetry of the quarks that had the effect of canceling unphysical CP-violating observables. This new symmetry leads to the "Peccei-Quinn (PQ) mechanism." Steven Weinberg and Frank Wilczek shortly thereafter realized that a PQ-symmetry, unseen in nature and therefore manifestly broken, implies the existence of a new pseudoscalar Goldstone-boson—the axion (2).

The properties of a light (micro eV mass range) axion make for an ideal dark-matter candidate. You can imagine why this is: take a neutral pion (the prototypical pseudoscalar) and run its mass to the micro eV scale. With pion lifetime scaling as mass to the fifth power, this light pion then becomes very long lived and incredibly weakly coupled; that is, it is a good dark matter candidate. For fundamental reasons, you can consider the axion as an extremely light neutral pion. In the early universe, axions appeared as a zero-temperature Bose condensate and remained at near-zero temperature thereafter. The axion lifetime is vastly longer than the age of the universe, and sufficiently light axions would have density to be the dark matter. Much lighter (<<micro eV), and axions would have severely overclosed the universe. Much heavier (>milli eV), and axions produced in supernova sn1987a would have efficiently transported energy out of the supernova explosion, thereby observably shortening the neutrino arrival pulse length recorded on Earth. These bounds leave an allowed axion mass window of $10^{-(6-3)}$ eV. Such light axions, although comprising the dominant matter in the universe, have interactions so feeble as to render them nearly invisible to normal matter and radiation (3).

Overview: Present Limits on Dark-Matter Axions

Recall that the axion arises from a new U(1) axial symmetry with its new axial charges. These charges are a priori unknown, so the model space of axion couplings is large. However, there is a great

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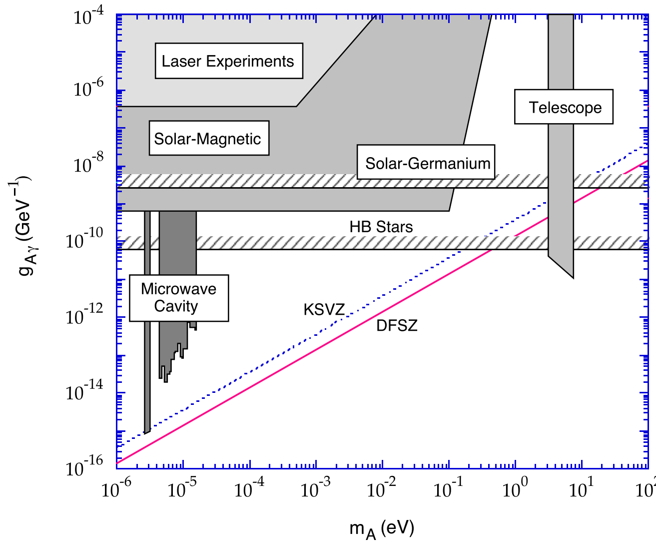

Fig. 1. Selected limits on axion masses and couplings. The horizontal axis is the putative axion mass. The vertical axis is the effective coupling of the axion to two photons. KSVZ and DSVZ refer to two classes of axion models commonly targeted by searches. Dark-matter axions lie between the KSVZ and DFSZ models in the mass range 1–100 μeV. Not shown is the very restrictive upper bound to the coupling from sn1987a, which is a horizontal line around a coupling of 10^{-13}/GeV.

simplification for the two-photon axion decay $a\rightarrow\gamma\gamma$. This decay, characterized by an effective coupling constant $g_{a\gamma\gamma}$, contains the ratio of color and electromagnetic anomalies of the new U(1) symmetry. Hence, this rate does not depend explicitly on the value of the uncertain U(1) couplings as they cancel in the ratio.

Fig. 1 shows historical selected limits on axion couplings and masses from a variety of techniques. The horizontal axis is the putative axion mass. The vertical axis is the effective coupling of the axion into two photons. KSVZ and DSVZ refer to two benchmark classes of axion models commonly targeted by searches (4–7); in a sense, they represent the extremes of allowing axions to couple with optional full or zero QCD strength to leptons. Dark-matter axions have properties that lie somewhere between the KSVZ and DFSZ couplings and in the mass range of 1–100 μeV. Not shown in Fig. 1 is the very restrictive upper bound to the coupling from sn1987a, which is a horizontal line around a coupling strength of 10^{-13}/GeV. Notice the wide variety of measurements. At the upper left, terrestrial measurements look for effects of interactions of photons with virtual axions in the propagation of light. Just below that, axions can affect the properties of the Sun in several ways, including its seismic signature and energy output. As well, those same solar axions could scatter off a terrestrial germanium crystal at the appropriate Bragg angle and convert into X-rays. To the right, axions in halos of astrophysical objects could spontaneously decay into pairs of optical photons and then be detected in telescopes. None of these methods are sensitive enough to dark-matter QCD axions of the expected couplings and masses. In the dark-matter band, next in sensitivity are astrophysical bounds. Here, axion emission from astrophysical objects would observably affect the evolution of those objects. Such objects include stars along the red giant horizontal branch and white dwarfs. More recently, the CERN Axion Solar Telescope, aiming to detect axions emitted from the Sun, achieved sensitivities bettering the usual astrophysical bounds. One important bound is that from axion emission in supernovae. As mentioned, such emission would have shortened the neutrino burst duration detected on Earth seen from sn1987a. This supernova bound by far provides the strongest astrophysical coupling constraint of around 10^{-13}/GeV. However, even here, the sn1987a bounds lack adequate sensitivity to dark matter axions in the mass range of interest. The current favored technique for detecting dark-matter axions is to convert nearby Milky Way halo axions into microwave photons ("microwave cavity" in Fig. 1).

Fig. 1 shows only a sampling of the limits and technologies. Much more information on axions and limits is contained in the summary (3) and references therein. However, because the topic here is axion dark matter, a simplification results because most technologies are by far too insensitive. Although those searches may be sensitive to unusual axion variants, they do not test the well-motivated QCD dark-matter axion hypothesis. I therefore focus the remaining discussion on the astrophysical bounds and the radio frequency (RF) cavity technique, picking one experiment from each as an example.

Example Search: The Axion Dark-Matter Experiment

The RF cavity apparatus consists of a high-Q microwave cavity threaded by a large static magnetic field. Nearby Milky Way halo axions interact with the magnetic field and thereby convert into microwave photons within the cavity (8). The outgoing photon energy is that of the total energy of the incident axion. The microwave photons are detected in what is in essence an ultralow noise double-heterodyne radio receiver. The resonant frequency of the cavity is tunable across a search bandwidth determined by the cavity geometry. At each tuning setting, the cavity power is averaged until the putative signal-to-noise ratio exceeds a confident detection threshold for realistic axions, and the power spectrum is examined for excess power of the appropriate line

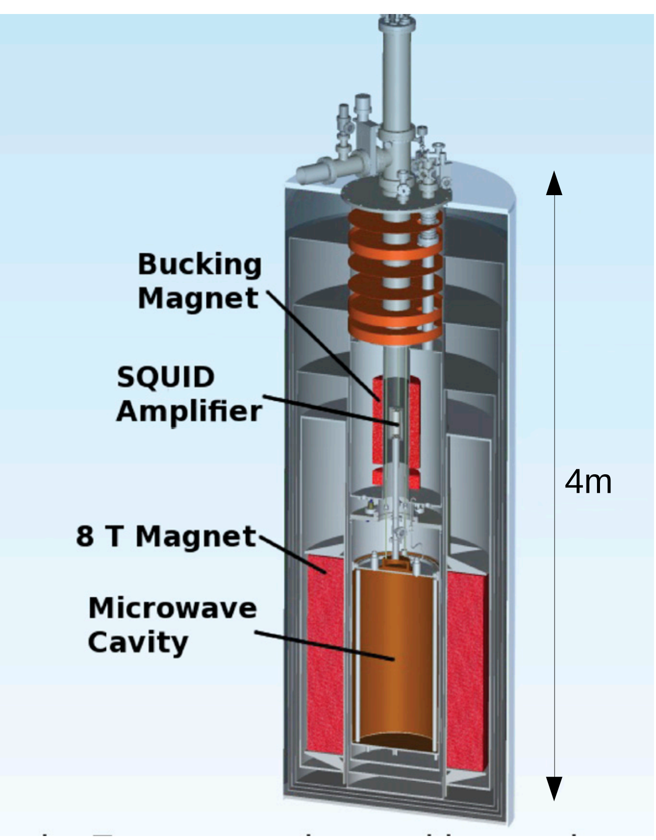

Fig. 2. Schematic of the ADMX axion detector. The RF cavity, 0.5 m diameter × 1.0 m long, is in the bore of an 8.5-T solenoid magnet. Microwave power is amplified by a low-noise cryogenic amplifier and mixed-down to near audio. The result is digitized and processed with FFT electronics and the power spectrum is searched for axion signals.

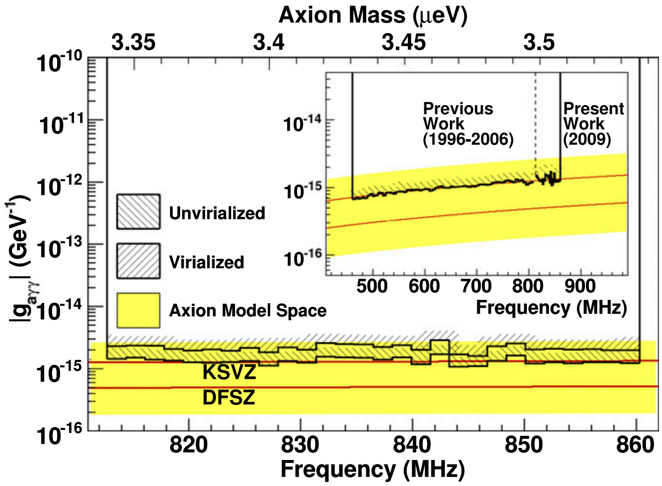

Fig. 3. Recent results from ADMX SQUID operation without a dilution refrigerator. The ADMX experiment is sensitive to plausible axion couplings in the dark-matter axion window.

width. The cavity is then retuned and the search is repeated until the cavity tuning range is exhausted. A schematic of the axion dark-matter experiment (ADMX) realization of this (9) is shown in Fig. 2. The sensitivity of the technique is very good because the exquisitely small axion-to-two photon coupling appears only once in the process, at the axion-to-photon conversion within the cavity. Other techniques, not relying on preexisting axions, must in addition produce axions, which necessitates another factor of the very small axion coupling. The main challenge of the RF cavity technique is that the expected microwave signal is very small: around 10^{-22} W or less. Detecting such feeble electromagnetic RF power levels requires liquid helium temperatures to reduce the cavity blackbody photon backgrounds and electronic noise.

Low-noise microwave amplification is a key technology of this search. The recent phase of this experiment replaces transistor amplifiers with dc superconducting quantum interference device (SQUID) microwave amplifiers. These devices, when cooled with a dilution refrigerator, have noise temperatures near the quantum limit: ~50 mK of noise at signal frequencies near 1 GHz. The averaging time to achieve a fixed signal-to-noise ratio scales as the square of the noise power. Hence, reducing the noise from 2 K to 50 mK in replacing transistor amplifiers by SQUIDs yields a search speed-up of more than 1,000, a very powerful improvement. In practice, some of this improvement will be used to increase sensitivity rather than simply speed up the search. Fig. 3 shows initial ADMX results with SQUID amplifiers but not at dilution refrigerator temperatures (10). In more detail, Fig. 4 shows the projected sensitivity of ADMX over the next 3 y. At present, this is the only technique with sensitivity to realistic dark matter axion masses and couplings. The first decade of allowed dark-matter axions will be sensitively explored in the next few years by ADMX. Technology is already developed to explore the following decade. For axions in the mass range $10^{-(4\text{–}3)}$ eV, an RF cavity search would need new developments in suitable RF structures and terahertz receivers.

Example Search: Shining Light Through Walls and Other Laser Techniques

Axions are pseudoscalar particles. An electric field crossed with a magnetic field is likewise pseudoscalar. Hence, photons of an appropriate polarization traveling through a transverse magnetic field can convert into axions. These axions may then leave the beam, thereby depleting one polarization component, or they may reconvert into photons in a magnetic field. Should axions reconvert into photons within the original magnet, the process introduces a birefringence to the vacuum. Alternatively, in the "shining light through walls" technique, polarized laser light is directed down the bore of a transverse dipole magnet, and the light is then blocked by an opaque wall. Some of the photons convert into axions, and these axions pass through the wall and reconvert to photons in a second dipole magnet, producing a light pulse. The photon-axion-photon conversion rate is very small, because the couplings are so tiny, and the entire photon-axion-photon process has the product of two such tiny couplings. These experiments are unlikely to be sensitive to PQ-type dark-matter axions and are less sensitive than the SN1987a bound.

More recently, experiments are under construction that increase the conversion rate by placing a pair of locked Fabry-Perot optical resonators on either side of the opaque wall. The conversion rate is enhanced by approximately the product of the cavity finesses, with the sensitivity improving as the square root of this product. A finesse of 10^4 is routine, and 10^6 is possible. A large experiment based on optical cavities is GammeV Resonantly Enhanced Photon Regeneration (REAPR), proposed for US funding (11). A second large experiment, Any Light Particle Search II (ALPS II), has started construction at Deutsches Elektronen-Synchrotron (DESY). These experiments will likely have improved sensitivity but are unlikely to reach sensitivity to PQ dark-matter axions (12).

As mentioned, photons in light entering a transverse magnetic field may convert into axions, depleting photons depleting polarization transverse to the magnetic field direction, thereby inducing vacuum dichroism. These axions may then reconvert into photons within the same magnet. This special direction of polarization for the conversion and reconversion alters the propagation velocity of one beam polarization, thereby introducing vacuum birefringence. Both effects lead to conversion of linearly polarized into elliptical polarization, and this may be detected by sensitive optical ellipsometers. This method was briefly in the spotlight in 2005 when the Polarizzazione del Vuoto con Laser (PVLAS) experiment reported detecting vacuum dichroism that could be interpreted as the effect of an axion, but was later retracted.

Example Search: CERN Solar Axion Telescope and Other Astrophysical Axions

Axion emission can affect the evolution of or energy transport out of astrophysical objects. These astrophysical bounds, especially the neutrino signal from SN1987a and the luminosity function of

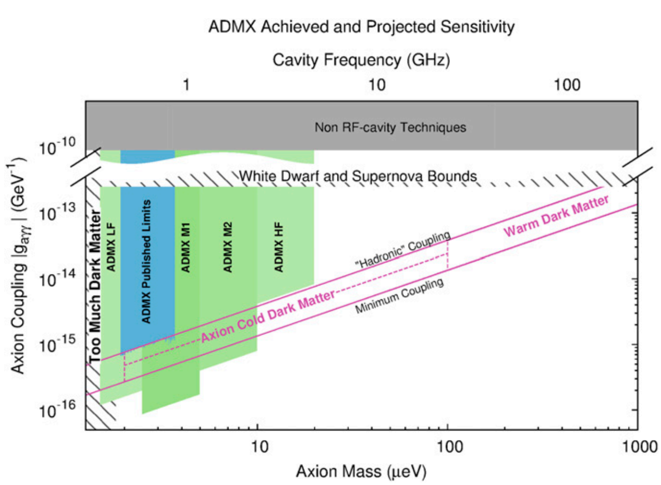

Fig. 4. Sensitivity reach of ADMX over the next several years. This experiment will have the sensitivity to detect the dark-matter QCD axion or reject the hypothesis at high confidence.

white dwarfs, are now the main observational constraint on PQ dark-matter axions across a broad mass range: they require such axions to have masses below about 1 meV, which puts these dark-matter axions out of reach of all but the RF cavity experiments.

Axions would be produced predominantly in the core of the Sun by photon-to-axion conversion in scatters off of solar nucleii. Because the core of the Sun is hot, the axion energy spectrum peaks in the X-ray. These axions may then be detected through their conversion into X-rays inside a terrestrial dipole magnet. Alternatively, the energy transport of axions from the Sun, combined with the constraint on the solar luminosity and the neutrino fluxes from the Sudbury Neutrino Observatory (SNO), provides limits to the axion coupling. The axion emission may also alter the solar temperature and thereby the solar density and the solar seismic modes. Approximately, these bounds are considerably less sensitive to PQ dark-matter axions than the bound from SN1987a.

The most restrictive experimental bound on PQ dark-matter axions comes from the width of the arrival time burst of neutrinos from SN1987a. The hot interiors of supernovae can release appreciable energy in axions and other light weakly interacting particles. This energy emission rate predicted with reasonable precision. Axions with too strong a coupling are trapped and have unobservable effects, whereas axions with too weak a coupling are rarely produced and likewise have little effect. Axions with interaction length on an order of the size of the supernovae core release the most energy. The signature of this energy release is a modification of the neutrino arrival time burst from SN1987a. Recall, ∼20 neutrinos were detected over the ∼10-s burst. Although perhaps in detail the arrival time distribution deviates from the predicted arrival time distribution, the overall number of neutrinos and the overall burst duration closely match expectations. The luminosity in axion emission is thereby constrained, as are the axion couplings. This SN1987a bound neatly fills the range between the upper end of the allowed mass window and other experimental bounds. This supernova bound is very constraining. It rules out conventional PQ axions with masses above about 1 meV. Further, below this mass, the SN1987a bound is much more sensitive than other astrophysical bounds and terrestrial experiments (with the exception of RF cavity experiments) (13).

As mentioned, axions may be produced in the Sun. These axions propagate to Earth and, when reconverted to photons in a detector, appear as an X-rays excess in the direction of the Sun. A terrestrial detector, a helioscope, consists of a dipole magnet with a bore steered in the direction of the Sun, plus X-ray detectors at the end of the bore. These detectors have evolved through several generations and are now highly developed. The most sensitive helioscope is the CERN Axion Solar Telescope (CAST). CAST consists of a large hadron collider (LHC) mainring dipole magnet on a steerable mount. The X-ray detection hardware include grazing incidence X-ray optics and "micromegas" X-ray detection. To optimize the axion-to-photon rate for different axion masses, the magnet bore can be filled with dilute gasses at various pressures. In general, CAST limits are at or are slightly better than non-SN1987a astrophysical bounds (14). A larger and more sensitive helioscope, the International Axion Observatory, is in the conceptualization stage. This sensitivity improvement is mainly achieved with a magnet having a much larger bore cross section (15).

Summary and Outlook

This overview only barely touched on dark-matter axion detection. Although the focus of this paper is QCD-axion dark matter, it may be that the relation between axion mass and couplings is loosened. In such a case, there could well be surprises. The potential for this surprise is what drives searches for higher- and lower-mass axions and axions with unexpectedly large couplings. Finally, in this short paper, I had to omit mention of many important searches and developments, for which I apologize. Perhaps the main message is that sensitivity to dark-matter QCD axions has at last been achieved with the RF cavity technique, and we may know soon whether the dark matter is made of axions.

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