UCRL-JC- 129345
PREPRINT

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This paper was prepared for submittal to the
proceedings of the conference "Dark Matter in the Universe and its Direct Detection"
Tokyo, Japan
November 26-28, 1996

January 1, 1998

AXION OVERVIEW AND THE U.S. RF CAVITY AXION SEARCH

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abstract

The axion, a hypothetical elementary particle, originally emerged from a solution to the strong CP problem in QCD. Later, axions were recognized as good dark matter candidates. Dark matter axions have only feeble couplings to matter and radiation, so their detection offers considerable challenges. Nonetheless, a new generation of exquisitely sensitive searches is underway. One such effort, in the United States, has already achieved sensitivity to plausible halo dark matter axion to photon couplings.

1. Overview

Confounding expectations, the strong interactions appear to conserve the product CP of charge conjugation and parity. This "strong CP problem" in QCD is resolved in an elegant way by invoking a new symmetry of nature, Peccei-Quinn (PQ) symmetry. When PQ symmetry is spontaneously broken, a new elementary particle—the axion—is born.[1]

There is abundant evidence for the existence of large halos of nonluminous matter—dark matter—surrounding galaxies. The density of dark matter near Earth is not very well determined; it is usually given as 0.3 GeV/cm^3 or less. The nature of halo dark matter remains a mystery, and unraveling this mystery is a key challenge of science today. It seems likely from the success of models of nucleosynthesis in explaining the abundance of light isotopes, and of inflation in explaining the near flatness of the universe, that the baryonic mass density can be no more than 10-20% of critical density and the universe is exactly flat, therefore requiring a substantial amount of dark matter. Some of the non-baryonic dark matter candidates, accounting for the remaining 80-90% of the mass density, are exotic objects like finite-mass neutrinos, weakly interacting massive particles (such as the lightest supersymmetric particle), primordial black holes, and axions. Axions are an example of "cold dark matter" whereas light finite-mass neutrinos are "hot dark matter", the hot and cold modifiers referring to their greater- or less-than thermal velocity dispersion at their birth in the early universe.

Axions are then doubly well motivated: they find important roles in resolving the strong CP problem and as a candidate for dark matter. Current laboratory, astrophysical and cosmological considerations constrain the axion mass to the three decade window 1-1000μeV, with laboratory experiments now underway to probe the first and perhaps most promising decade of mass. One such experiment, sited at Lawrence Livermore Laboratory in the United States, is already taking data at cosmological sensitivity in this first mass decade.

2. The Axion and QCD

QCD, the theory of the strong interactions, has amassed an impressive string of successes. Its non-Abelian nature is experimentally established. Decay rates and quantum statistics support the notion of color. Cross sections and branching ratios are in accord with perturbative predictions. There is, however, one annoying loose end, the strong CP problem. The non-Abelian nature of QCD, now seen in experiments, should introduce T, P and CP violating effects and, in particular, there should be a substantial CP violating neutron electric dipole moment. However, sensitive experiments see no such moment, and its lack is a genuine mystery. It seems surprising at first, for QCD to have CP violating interactions. The source of such interactions is traced to the complexity of the QCD vacuum. The QCD vacuum has gluon fields in their lowest energy configuration, and in QCD there are many degenerate vacuua. The various vacuua can be classified by winding number n—the non-Abelian nature allows non-zero n—and gauge transformations can change one winding number vacuum into another. In order to preserve gauge invariance, we construct a gauge invariant vacuum by a Bloch-wave-like superposition of vacuua, like so:

$$|\Theta\rangle = \sum_n e^{-in\Theta}|n\rangle \quad . \tag{1}$$

Such a vacuum, the Θ vacuum, is gauge invariant and is the physical vacuum of QCD. Effects of the Θ vacuum on vacuum transition amplitudes can be subsumed in a new effective non-perturbative term in the QCD Lagrangian proportional to

$\bar{\Theta}G\tilde{G}$, with G and $\tilde{G}$ the gluon field strength tensor and its dual, and (with M the quark mass matrix) $\bar{\Theta} = \Theta + \arg\det M$. The parameter $\bar{\Theta}$ takes contributions from the QCD vacuum Θ and phases from the quark mass matrix. The $G\tilde{G}$ term in the Lagrangian is a total derivative and does not contribute to classical equations of motion or perturbative effects. However, the term is explicitly CP violating and can induce non-perturbative effects. With a $\bar{\Theta}$ of order 1, the neutron can be shown[2] to have an electric dipole moment of order 10^{-15}e-cm. Current limits are pushing 10^{-25}e-cm,[3] and these limits in the context of the Θ vacuum restricts the magnitude of $\bar{\Theta}$ to less than 10^{-10}.

This immeasurably small value of $\bar{\Theta}$ is the strong CP problem. Of course, a parameter equal to zero is no cause for alarm. After all, the photon mass may very well be zero, and a zero mass neutrino would not be too surprising. However, the immeasurably small $\bar{\Theta}$ is of greater concern. Recall that $\bar{\Theta}$ has contributions from QCD (through the Θ vacuum) and weak interactions (through the quark mass matrix). Likely the weak contribution is non-zero, so, then, is the Θ vacuum contribution. Since the two contributions are independent, the zero in the strong CP problem is therefore more than just a zero, it is the near perfect cancellation of two independent but finite effects. Among the ideas for evading this problem,[4] We find most compelling the one invoking the axion.

It seems inescapable that the QCD vacuum is complicated and gives rise to interesting physical effects. However, in taking the vacuum seriously, we are left with the strong CP problem. The solution involving the axion developed from an idea proposed by Peccei and Quinn.[5] They showed that a slight extension of the Higgs sector endows the standard model with a global U(1) symmetry, the Peccei-Quinn (PQ) symmetry. Weinberg and Wilczek then noticed that since the symmetry is broken at some scale f_{PQ}, there must also be a Goldstone boson—the axion.[6] Although the axion starts out as a massless Goldstone boson, it eventually acquires an effective mass (as does, e.g., the η) through intermediate states coupled to its color axial anomaly. Besides mass, other effects of the axial anomaly can be considered as arising from a new effective term in the Lagrangian proportional to $(a/f_{PQ})\bar{\Theta}G\tilde{G}$, with a the axion field, and constant of proportionality dependent on the value of the axion color anomaly. The sum of Θ and anomaly terms, taken as a classical potential, is minimized at some axion vacuum expectation value proportional to $\bar{\Theta}f_{PQ}$. At this value of the axion field, the CP violating $G\tilde{G}$ terms, including those giving rise to a neutron electric dipole moment, vanish.

3. Interactions of the Axion with Matter and Radiation

For experiments, a crucial consideration is the interaction of axions with ordinary matter and radiation. The axion mass and the PQ symmetry breaking scale f_{PQ} are related through

$$m_a = \frac{\sqrt{z}}{1+z} \frac{f_\pi m_\pi}{f_{PQ}/N} \quad , \tag{2}$$

with z is the ratio of u- and d-quark masses (a ratio presumed near 0.5), and N the axion color anomaly. The model dependence—that is, the particular scheme for introducing the PQ symmetry—enters axion interactions through N (and the axion electromagnetic anomaly, as well). We avoid detailing the various schemes for establishing PQ symmetry and We give greater weight to the PQ symmetry itself. After all, there must be a solution to the strong CP problem, and PQ symmetry could very well be it, even when the symmetry's origin is unknown.

The strength of the axion's couplings to normal matter and radiation are given by effective coupling constants $g_{a\gamma\gamma}$, g_{aee}, g_{app}, etc., for the axion coupling to photons, electrons and protons. Since the elementary axion couplings are model dependent, these effective couplings are model dependent as well. For instance, the effective two photon coupling constant is

$$g_{a\gamma\gamma} = \frac{\alpha/2\pi}{f_{PQ}/N}(E/N - 2(4+z)/3(1+z) \quad , \tag{3}$$

where E is the electromagnetic anomaly, and the factor $2(4+z)/3(1+z)$ containing ratios of light quark masses is approximately 2. The tree level coupling of axions to color is fundamental to the axion's role in solving the strong CP problem. The tree level coupling of the axions to charged leptons is optional; here, different theories allow different couplings. Extremes of lepton couplings are cases with no tree level axion coupling to electrons (dubbed hadronic axions[7]), and axions where tree level quark and electron couplings are of the same strength (an example is axions layered on a simple GUTs scenario, dubbed DFSZ axions[8]). All the effective coupling constants of axions with normal matter and radiation depend on the inverse of the symmetry breaking scale f_{PQ}, with heavier axions have stronger couplings. With the axion very light, the couplings are very weak and the axion is hard to detect. Such axions are termed invisible axions. The current round of axion searches looks for these invisible axions through their coupling with two photons. There is nothing to forbid the anomaly ratio E/N from having the unfortunate value where the axion has effectively no photon coupling. However, in one example, E/N in the simple DFSZ GUTs model has value 8/3, and there is no reason to think E/N in other models would have the special zero coupling value.

4. Production of Relic Axions

The laboratory and astrophysics upper bounds on the axion mass depend on creation and detection of new axions. If axions are dark matter, they are a relic of the early universe. We know of several scenarios by which a substantial amount of relic axions can be created. A particular scenario coupled with the requirement that the axion mass density not severely overclose the universe results in a lower bound to the axion mass.

4.1. Relic Axions: Misalignment Production

In our Θ vacuum picture of QCD, CP conservation is a consequence of the classical $\bar{\Theta}$ parameter driven to zero as a consequence of the axion acquiring mass. Recall, however, that the axion did not start out with mass—it acquired mass at the temperature Λ_{QCD}—and the CP violating $\bar{\Theta}$ parameter has arbitrary value in early times. We say the initial value of $\bar{\Theta}$ is misaligned with its present near-zero value. Pierre Sikivie noticed an analogy with the simple pendulum: Without gravity, there is no special pendulum angle. Turn on gravity though, and the average pendulum angle is driven to zero. Although the pendulum average angle is zero, the pendulum oscillates with a non-zero RMS angle. There is energy stored in oscillations, and, returning from the pendulum analogy, quanta of these oscillations are axions. This is the mechanism of misalignment production.[9] You can carry this analogy too far—in particular, this simple pendulum does not include Hubble expansion damping—but as for the pendulum case, the quanta form a Bose condensate with minuscule velocity dispersion. Misalignment axions are cold dark matter. The present density of misalignment axions is[10]

$$\Omega_a = 0.85 \times 10^{\pm 0.4}(\Lambda_{QCD}/200\text{MeV})^{-0.7}(m_a/10^{-5}\text{eV})^{-1.18}/h^2 \quad , \qquad (4)$$

where the Hubble factor h enters through expansion driven damping, and the QCD scale enters as the temperature where mass appears. This prediction for the present axion energy density assumes an initial misalignment angle of $\pi\sqrt{3}$—the RMS of the interval $-\pi$ to π. This is a reasonable value as, without inflation, the initial misalignment angle is a composite of independent misalignment angles from a great number of causally disconnected volumes. With these assumptions and typical values for the Hubble and QCD scales, axions with mass near 10^{-5}eV form closure density and much lower axion masses would severely overclose the universe. This misalignment mechanism therefore provides a lower limit to the axion mass. Should inflation have occurred after axions appear, there is just the one initial misalignment angle corresponding to the angle in our particular pre-inflation volume. Here, the statistics of many causally disconnected volumes cannot be invoked, and the argument is the somewhat weaker one that a misalignment angle very near zero is highly improbable.

4.2. *Relic Axions: Phase Space Structure*

Axions are subject to gravitational forces, and in what is an overly-simplistic picture, relax with normal matter into something resembling an isothermal halo around our galaxy. As for normal matter, the peculiar velocity of isothermal halo axions is of order 10^{-3}c. In addition, halo axions exhibit large deviations from a thermal distribution, most notably in that the highest energy particles have discrete values of velocity. The phase space structure of radial infall halo axions is shown in upper figure 1.[11] Here the radial coordinate is distance from the center of the galaxy. The velocity spectrum of axions at our radius from the center of the galaxy is shown in lower figure 1. The isothermal peak is to the left, and the newer infall peaks are to the right. Perhaps 10% of the axions are in the first infall peak, a narrow structure with fractional width less than 10^{-19}.

5. Detection of Relic Axions

Besides the 1-1000μeV window, the combined stellar evolution and cosmological bounds allow a small window of axion mass near 2eV. These axions live long enough so that there are still significant numbers of them in halos, yet decay frequently enough into photons to be detected as a narrow optical line on the overall sky glow.[12] These decays are not seen, leaving the range 10^{-6} to 10^{-3}eV as the sole axion mass window.

5.1. *Detection of Relic Axions: Sikivie-Type Axion Detectors*

Halo axions in this mass window can be seen through their resonant conversion into photons in a high Q cavity threaded by a magnetic field. In practice, a tunable helium-cooled high Q cavity is placed in the bore of a superconducting solenoid, and the resonant frequency of its lowest TM mode is slowly changed while cavity output is monitored for excess power from resonant axion conversions.[13] The excess power is

$$P = 4 \cdot 10^{-26}\text{Watt}\left(\frac{V}{0.22\text{m}^3}\right)\left(\frac{B_0}{10\text{Tesla}}\right)^2$$
$$\times C_{nl}\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.5\cdot 10^{24}\text{g/cm}^3}\right)\left(\frac{m_a}{2\pi\text{GHz}}\right)\min(Q_L, Q_a)$$

with V the volume of the cavity, B_0 the magnetic field strength, C a mode-dependent form factor of order unity, ρ_a the density of galactic halo axions at the Earth, m_a the axion mass, Q_L the loaded Q of the cavity and $Q_a \sim 10^6$ the "quality factor" of the galactic halo axions (the ratio of their energy to their energy spread near Earth). Finally, g_γ is the coupling of axions to two photons. A value $g_\gamma \sim 0.36$ is predicted for DFSZ axions, and 0.97 for a model of hadronic axions. This is a tiny amount of power; consider that with the nominal value of constants in the above expression, the black body power in the Q_a bandwidth from a 1K cavity is ten times larger than the power from axion conversions.

Unfortunately, the axion mass is unknown, as is the corresponding resonant frequency $f = m_a c^2/h$. It is known, however, that misalignment axions with mass near 4μeV are near critical density. This is what makes the first decade of the axion search window so promising. The search rate for a constant signal to noise ratio (s/n) is

$$\frac{df}{dt} = \frac{72\text{GHz}}{\text{year}} \left(\frac{4}{\text{s/n}}\right)^2 \left(\frac{V}{0.22\text{m}^3}\right)^2 \left(\frac{B_0}{10\text{Tesla}}\right)^4$$

$$\times C^2 \left(\frac{g_\gamma}{0.97}\right)^4 \frac{\rho_a}{0.5 \cdot 10^{-24}\text{g/cm}^3} \left(\frac{5K}{T_n}\right)^2 \times \left(\frac{f}{1\text{GHz}}\right)^2 \left(\frac{Q_W}{Q_a}\right)$$

with T_n the total noise (the linear sum of cavity black body plus electronic noise) of the microwave detector.

Pilot experiments (also called first generation experiments) have been carried out using relatively small volume magnets and—by current standards—somewhat noisy amplifiers, at Brookhaven National Laboratory (BNL) and at the University of Florida (UF). These experiments had $B_0^2 V$ values of 0.36 and 0.45 $T^2 m^3$, respectively. The regions in the coupling-squared versus axion mass plane eliminated by these searches, assuming axions saturate the halo, compared with predictions from DFSZ and a range of axion models are shown in figure 3. The pilot experiments have demonstrated the principle of cosmic axion detection over a wide range of frequencies, but they lacked by factors of 100-1000 the needed sensitivity to detect plausible couplings of halo dark matter axions.

6. The U.S. RF Cavity Axion Search

A second-generation axion search, operated at the Lawrence Livermore National Laboratory in the United States, is now taking data. The spokespersons are Leslie J Rosenberg (MIT) and Karl van Bibber (LLNL). The capability of this experiment to either detect axions (with s/n of 4) or exclude them (at the 97.7% C.L.) is shown as the region extending into hadronic axion couplings in figure 3. The key goals of the experiment are (1) to attain a power sensitivity which is conservatively a factor of 40 improvement (and probably closer to a factor of

100) over the pilot experiments—achieved by increasing the magnet volume and incorporating recent advances in low noise microwave amplification, and (2) to search the entire mass range $1.5\mu eV < m_a < 12.6\mu eV$—achieved through filling the magnet volume with multiple higher frequency cavities.

The key parts of the U.S. experiment are sketched in figure 4. The experiment features a superconducting magnet with a central field near 8.0T. The experimental volume has inner diameter 50 cm and length 100 cm. Hence, $B_0^2 V = 12 T^2 m^3$, about a factor of 25 better than the pilot experiments. The experimental volume is separated from the magnet cryostat by a cold-vacuum wall. The vacuum wall allows exchanging cavity arrays and electronics while the magnet is energized and cooling the cavity arrays to below the magnet temperature of 4.2K. The cavity is operated at about 1.3K, a physical temperature somewhat lower than the noise temperatures of the best amplifiers available today in the UHF through S-bands (0.5 through 3GHz). The total noise temperature near 4K (physical plus electronic) yields another factor 1.6 in improved sensitivity over the pilot experiments.

The U.S. experiment features arrays of multiple cavities to extend the mass search range. Each cavity is separately tuned by moving dielectric or metallic rods within the cavity, and in this way the experiment will search the range $1.5\mu eV < m_a < 12.6\mu eV$. Additionally, the U.S. experiment looks for narrow peaks in the halo axion velocity spectrum. This has the potential to greatly increase sensitivity as the signal to noise power ratio improves with decreasing bandwidth. In the U.S. experiment, there are separate processing paths for the isothermal and narrow peak searches. Data taking started after a shake-down run in January 1995 and has been in continuous operation with over 90% duty factor.

7. Conclusions

The axion, still a likely solution to the strong CP problem, is also a likely candidate for dark matter. The primordial nucleosynthesis upper bound to the baryon density of 0.2 critical density has survived years of scrutiny and the bound is unlikely to topple soon. Since the mass density of the universe is within a factor of 10 or so of critical density, and since the mass density of the universe in a standard big bang cosmology evolves rapidly away from flatness, it is likely the universe is exactly flat. A critical density universe plus the nucleosynthesis bound implies substantial amounts of dark matter. The amount of visible mass is substantially less than 0.2, allowing room for some baryonic dark matter. Observationally, it is unlikely MACHOs are the dominant dark matter in our halo. Also, the Hubble telescope did not find substantial mass in the form of low mass stars. These two recent results considerably weaken the case for baryons as the principal dark matter. Measurements of the microwave background quadrupole anisotropy suggest that while pure cold dark matter—for example, axions—is not an ideal dark matter candidate, pure hot dark matter is a horrific candidate. The following is contentious, but we believe the anisotropy data tells us that dark matter—like axions—is substantially cold. The present window of allowed axion mass—10^{-6} to 10^{-3}eV—has likewise been under intense scrutiny and remains for now substantially unchanged, though reasoned voices sound for both shrinking and enlarging the window. It is intriguing that misalignment axions in the first decade of the mass window have just the mass needed to close the universe. Sikivie-type RF cavity experiments are underway to probe this window with reasonable sensitivity, and other ideas for experiments are in lesser stages of development. It looks promising for the axion: (1) they are on firm theoretical ground; (2) the data calls for substantial amounts of non-baryonic halo dark matter; (3) the data hints a substantial component of dark matter is cold, say, as axions; (4) the U.S. experiment is taking high quality production data and is already sensitive to these halo axions.

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Work performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

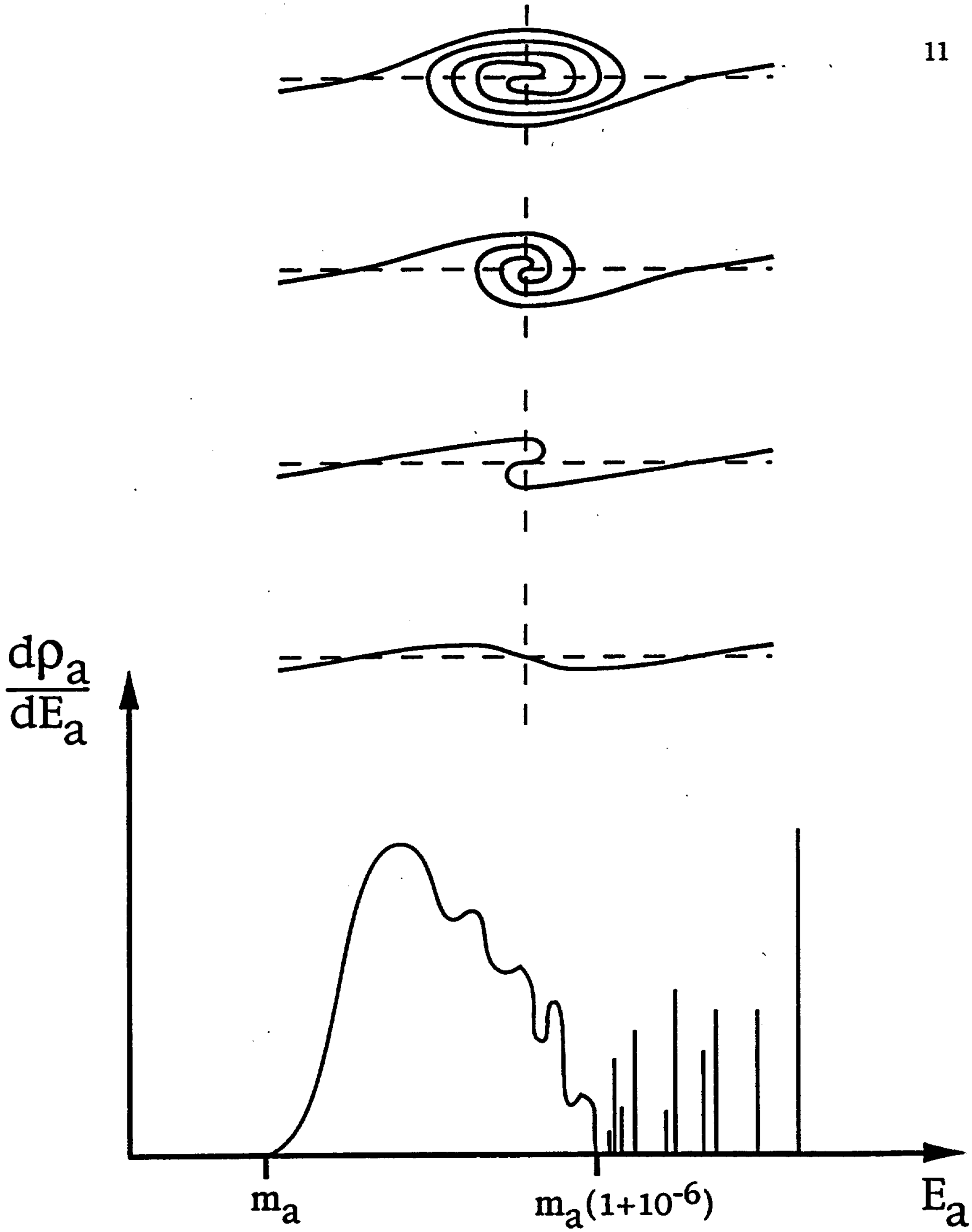

Fig. 1. (upper) Phase space of halo axions at various stages of galaxy formation. The origin of the distance coordinate is the galactic center. (lower) Velocity spectrum of axions near Earth.

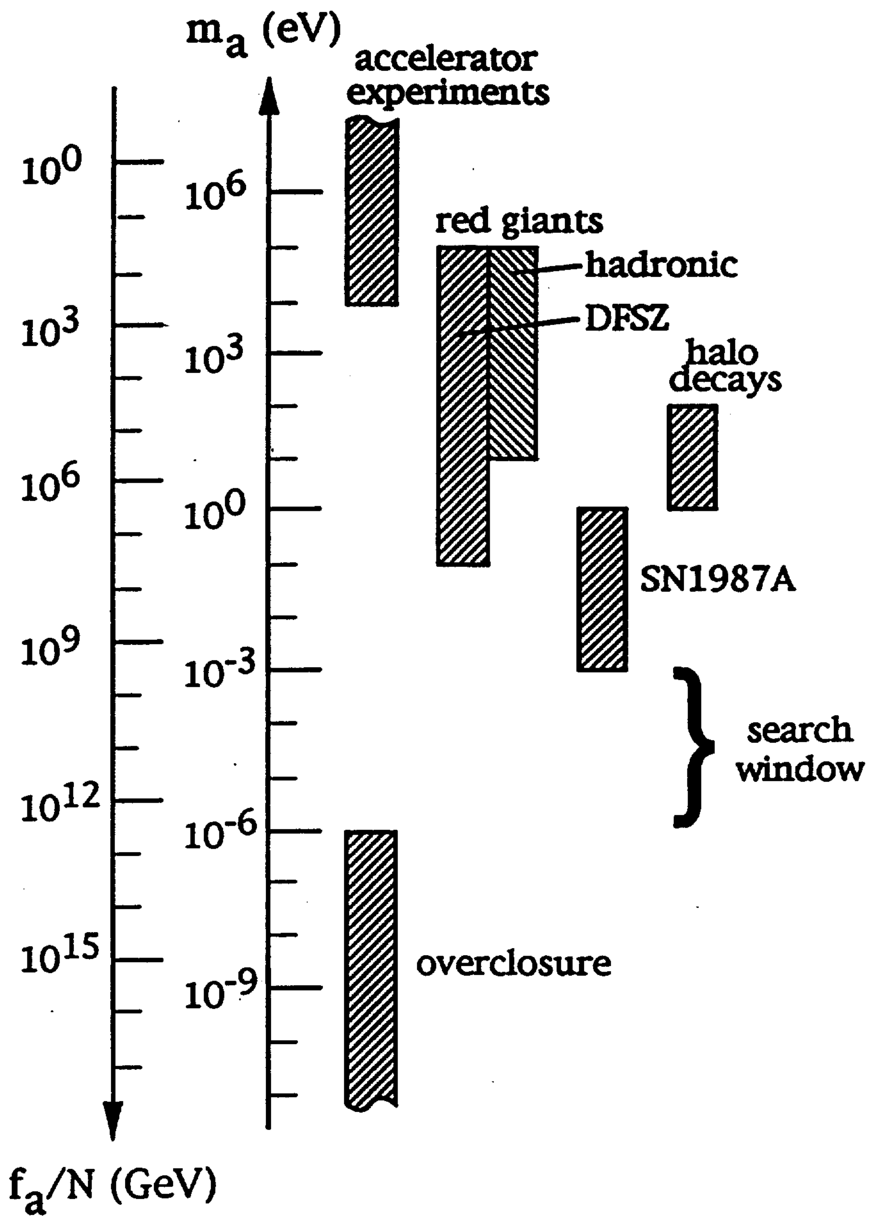

Fig. 2. Summary of laboratory, astrophysical and cosmological constraints on the axion mass.

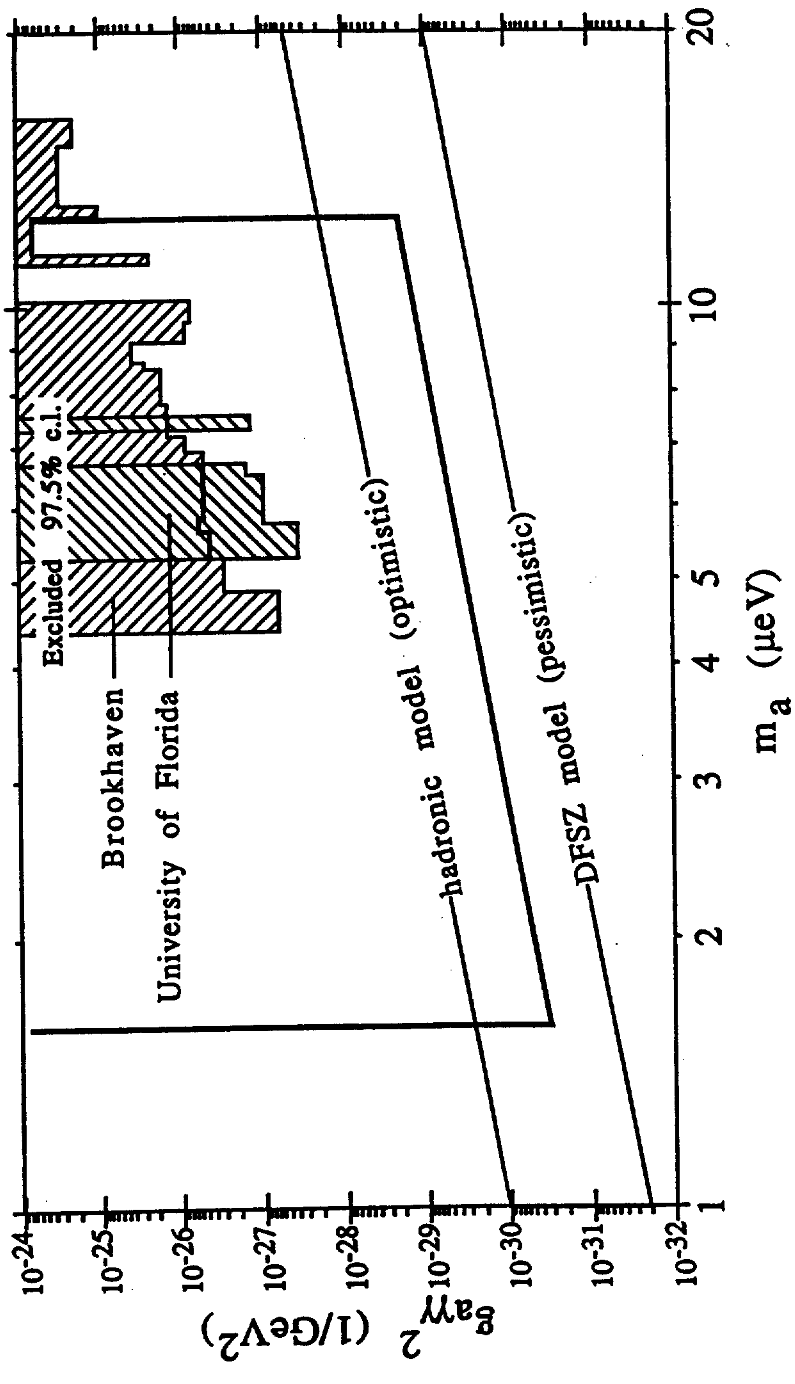

Fig. 3. Regions in the axion mass versus two photon coupling constant plane excluded by the pilot cavity experiments. Also shown are coupling constants expected in a range (DFSZ and hadronic) of axion models. The area extending into the hadronic axion region is the expected sensitivity of the U.S. experiment.

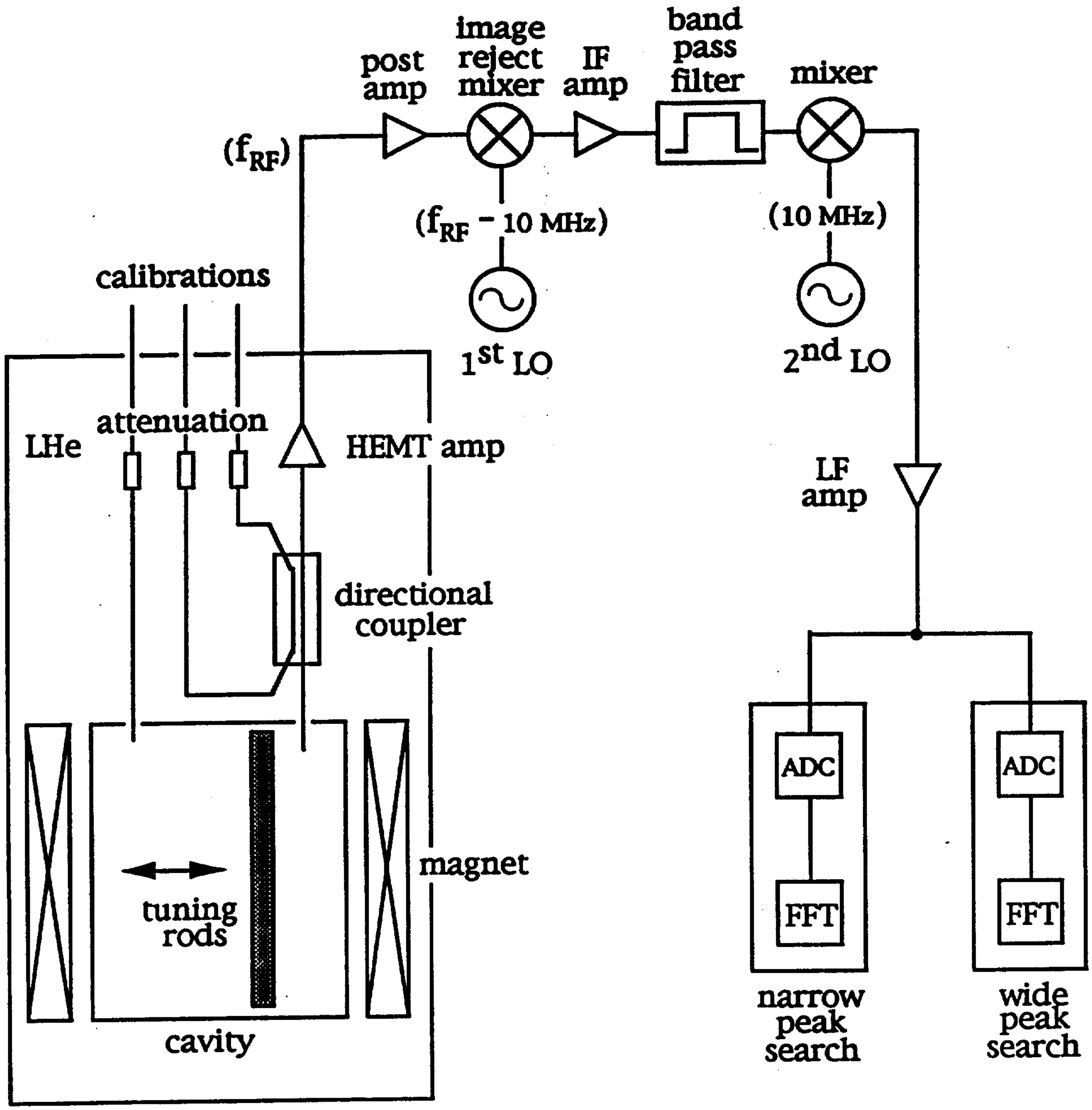

Fig. 4. Sketch of the major components of the U.S. axion search experiment.

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