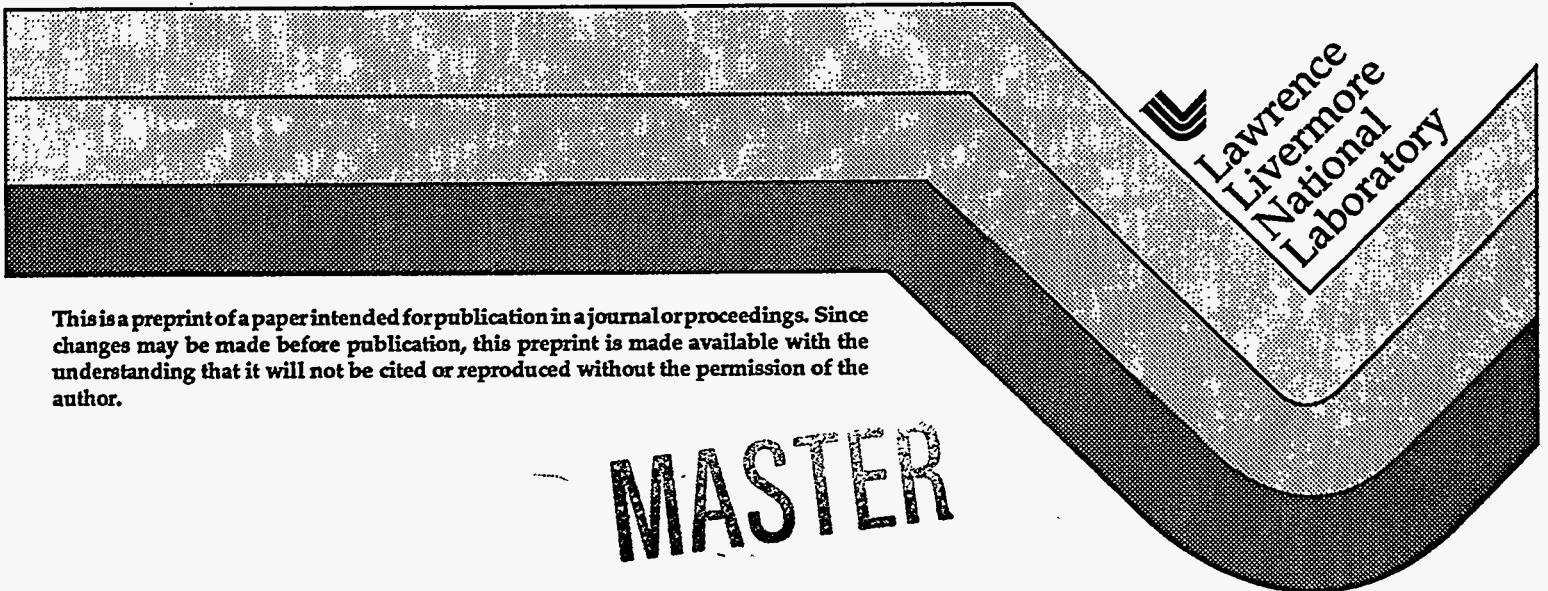


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## STATUS OF THE LARGE-SCALE DARK-MATTER AXION SEARCH

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### ABSTRACT

If axions constitute the dark matter of our galactic halo they can be detected by their conversion into monochromatic microwave photons in a high-Q microwave cavity permeated by a strong magnetic field. A large-scale experiment is under construction at LLNL to search for halo axions in the mass range 1.3 - 13  $\mu\text{eV}$ , where axions may constitute closure density of the universe. The search builds upon two pilot efforts at BNL and the University of Florida in the late 1980's, and represents a large improvement in power sensitivity ( $\sim 50$ ) both due to the increase in magnetic volume ( $B^2V = 14 \text{ T}^2\text{m}^3$ ), and anticipated total noise temperature ( $T_n \sim 3\text{K}$ ). This search will also mark the first use of multiple power-combined cavities to extend the mass range accessible by this technique. Data will be analyzed in two parallel streams. In the first, the resolution of the power spectrum will be sufficient to resolve the expected width of the overall axion line,  $\sim O(1\text{kHz})$ . In the second, the resolution will be  $O(0.01-1 \text{ Hz})$  to look for extremely narrow substructure reflecting the primordial phase-space of the axions during infall. This experiment will be the first to have the required sensitivity to detect axions, for plausible axion models.

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## 1. Introduction

### 1.1. Generic Features of the Axion

The axion is a consequence of the most minimal and elegant solution to the strong-CP problem<sup>1,2</sup>. Its mass is inversely proportional to an unknown but large energy scale  $f_a$  where the Peccei-Quinn symmetry is broken:

$$m_a = 0.6 eV \cdot \left( \frac{10^7 \text{ GeV}}{f_a} \right). \quad (1)$$

All its couplings to matter and radiation are likewise inversely proportional to  $f_a$ . The axion couples to two photons with a strength  $g_{a\gamma\gamma}$ :

$$g_{a\gamma\gamma} \equiv g_\gamma \left( \frac{\alpha}{\pi f_a} \right). \quad (2)$$

The parameter  $g_\gamma$  in Eq. (2) is model dependent, and is  $\sim 0.36$  in all grand-unified models such as that of Dine-Fischler-Srednicki-Zhitnitskii (DFSZ)<sup>3</sup>, but is  $\sim -0.97$  in the Kim-Shifman-Vainshtein-Zakharov (KSVZ)<sup>4</sup> model. Equally well-motivated variants of KSVZ could result in much stronger coupling still. The two-photon coupling permits the axion to convert, via the Primakoff effect, into a single real photon carrying the entire axion energy in the presence of an external static electromagnetic field. This is the basis of the present experiment.

### 1.2. Limits on the Axion Mass

When the axion was first proposed, it was thought that the Peccei-Quinn (PQ) symmetry breaking scale was on the order of  $f_a \sim 250$  GeV. The corresponding axion was searched for in various laboratory experiments (e.g., nuclear decays, accelerator- and reactor-based experiments), but was not found. Subsequently, there were proposed the "invisible axion" models, with arbitrarily large values of  $f_a$ . These models were so named because for  $f_a \gg 250$  GeV, all axion couplings would be so hopelessly weak as to render the axion undetectable in conventional experiments.

The upper limit on the mass of the axion is constrained as a consequence of thermal production of axions on stellar cooling. The basic idea is that, although created only rarely in a star's interior, once made they stream out freely due to their extreme weakness of coupling. Thus they would provide an efficient means of energy transport out of the star and would compete with radiation from the photosphere leading to discrepancies between observational and model life histories. This method has been applied to a

variety of astrophysical objects such as white dwarfs, red giants, and SN1987A. The most stringent upper bound comes from the latter, ruling out axions  $10^{-3} < m_a < 3$  eV.<sup>5</sup> This plus other astrophysical limits provide a complete overlapping set of excluded ranges up to that already ruled out by laboratory experiments.

Cosmology provides the lower limit on the axion's mass, which follows from the requirement that the universe not be "overclosed" by axions. For the vacuum realignment production of axions, the energy density in axions at present is given approximately by<sup>6</sup>

$$\Omega_a^{\text{vac}} \cong 10^{\pm 0.4} \left( \frac{0.8 \cdot 10^{-5} \text{ eV}}{m_a} \right)^{1.18} \left( \frac{200 \text{ MeV}}{\Lambda_{\text{QCD}}} \right)^{0.7} \left( \frac{\theta}{\pi / \sqrt{3}} \right)^2 \left( \frac{75}{H_0} \right)^2 \quad (3)$$

where  $\theta$  is the misalignment angle,  $H_0$  is the present value of the Hubble constant in (km/sec/Mpc), and  $\Lambda_{\text{QCD}}$  is the QCD scale factor. The factor  $10^{\pm 0.4}$  represents known theoretical uncertainties. If the PQ-symmetry breaking takes place after inflation, then axion production by radiation from axion strings must be considered. How this changes the lower bound on the axion mass is controversial. Some have found that the mass limit does not change at all<sup>7</sup>; others concluded that the mass limit would be revised upwards to  $10^{-3}$  eV, perhaps closing the window on the axion.<sup>8</sup> However, more recent work mitigates the change of the upper limit to  $5 \cdot 10^{-5}$  eV.<sup>9</sup> Again, it is to be kept in mind that any modifications due to the string scenario pertains to a specific assumption about the relative ordering of events in the early universe, of which we have no sure knowledge.

Further uncertainties in the lower mass bound for the axion derive from possible entropy production shortly after the QCD phase transition<sup>10</sup>, and if the universe inflates,  $\theta$  could take on any value from 0 to  $\pi$ .<sup>11</sup> Keeping in mind all of the above qualifications, we take the nominal open window for the axion to be  $10^{-6} < m_a < 10^{-3}$  eV.

### 1.3. The Axion as a Dark-Matter Candidate

Cosmic axions are "cold dark matter" as they never were in thermal equilibrium with the rest of the universe, and were non-relativistic from the moment they acquired mass during the QCD phase transition. If they do constitute the dark matter of our galactic halo, whose local density is  $\rho_{\text{halo}} \sim 5 \cdot 10^{-25} \text{ g/cm}^3 = 300 \text{ MeV/cm}^3$  (to within 50%), then they would have only the virial velocity of the galaxy  $\sim 270 \text{ km/sec}$  ( $\sim 10^{-3}c$ ). Thus a light axion of 10  $\mu\text{eV}$  mass would have an enormous de Broglie wavelength, on the order of 100 m, as well as a prodigious number density,  $\sim 10^{13} \text{ cm}^{-3}$ .

## 2. The Cavity Microwave Experiment

### 2.1. The Detector Principle

It was ironic that a very light axion might be the most abundant form of matter in the universe, and yet couple so extraordinarily weakly to anything as to be undetectable. This conundrum was solved in 1983 by P. Sikivie,<sup>12</sup> who showed that such light axions constituting our galactic halo could be detected in an experiment feasible with existing technology. In this technique, a tunable high- $Q$  microwave cavity is permeated by a strong magnetic field, and an ultra-low noise receiver measures the power spectrum emitted by the cavity. The cavity is tuned, and when the frequency of a particular mode equals the mass of the axion,  $h\nu = m_a c^2$ , axions convert into single monochromatic microwave photons via the Primakoff effect. The signal shows up as a narrow line on the noise spectrum. The energy of the axion is given by  $E_a = m_a + m_a \beta^2 / 2$ , and since the virial velocity of the axions is  $\beta \sim O(10^{-3})$ , the line is monochromatic to about  $\Delta\nu/\nu \sim O(10^{-6})$ . A frequency of 1 GHz corresponds to an axion of mass 4.135  $\mu\text{eV}$ .

In a practical realization of the experiment, the magnet is a large, high-field superconducting solenoid, with volume ideally on the order of  $\sim 1 \text{ m}^3$ , and field  $\sim 10 \text{ T}$ . The cavities are right circular cylinders of very pure copper, with  $Q \sim$  several  $10^5$  in the GHz range, at 4K. As will be seen later, both the conversion power and search rate are proportional to the cavity  $Q$ , up to the monochromaticity of the axion line, expected to be  $Q_a \sim 10^6$ . Unfortunately, there is no possibility at present of improving  $Q$  by making a superconducting cavity on account of the large magnetic field. The amplifier is typically a high-electron mobility transistor (HEMT) device, whose noise temperatures today can be as low as  $T_{\text{elec}} \sim (\nu/1 \text{ GHz}) \cdot 1\text{K}$  for frequencies of 1 GHz and higher, but worse at lower frequencies due to  $1/f$  noise. As the search rate will depend on  $(T_{\text{noise}})^{-2}$ , where  $T_{\text{noise}} = T_{\text{phys}} + T_{\text{elec}}$ , one wants to cool the cavity and amplifier at least to a physical temperature  $T_{\text{phys}} < T_{\text{elec}}$ . The bandpass of the cavity ( $\sim 20 \text{ KHz}$ ) is mixed down to the audio range in a double superheterodyne receiver, and a Fast-Fourier Transform is performed to generate the power spectrum within the bandpass. A desktop computer is adequate to do the data acquisition and experiment control.

The interaction which describes the conversion of axions into photons is  $\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$ . Consequently only those modes which have a non-vanishing integral of the cavity mode electric field with the external magnetic field are relevant. For a uniform magnetic field only the  $\text{TM}_{n10}$  modes have a non-zero 'form factor'  $C_{nl}$  representing the normalized overlap integral and by far the largest (0.69) is that of the  $\text{TM}_{010}$ . This is the only feasible mode with which to perform the experiment and we will restrict our discussion to it hereafter. For a right circular cylindrical cavity,  $\nu = (0.115 \text{ GHz}/R[\text{m}])$ , where  $R$  is the cavity radius.

The axion-to-photon conversion power on resonance is given by:

$$P_{nl} = \left( \frac{\alpha g_\gamma}{\pi f_a} \right)^2 \cdot V B_0^2 \rho_a C_{nl} \cdot \frac{1}{m_a} \cdot \text{Min}(Q_L, Q_a) \quad (4a)$$

$$P_{nl} = 4 \cdot 10^{-26} \text{ Watt} \left( \frac{V}{0.22 \text{ m}^3} \right) \left( \frac{B_0}{8.5 \text{ T}} \right)^2 C_{nl} \left( \frac{g_\gamma}{0.97} \right)^2 \cdot \left( \frac{\rho_a}{0.5 \cdot 10^{-24} \text{ g/cm}^3} \right) \left( \frac{m_a}{2\pi(1\text{GHz})} \right) \text{Min}(Q_L, Q_a) \quad (4b)$$

The search rate to achieve a prescribed signal-to-noise ratio  $s/n$  not only depends upon the conversion power, but also upon the total noise temperature  $T_{\text{noise}}$ , where  $T_{\text{noise}} = T_{\text{phys}} + T_{\text{elec}}$ . The search rate for this experiment is given by

$$\frac{dv}{dt} = 94 \text{ GHz/yr} \cdot \left( \frac{4}{s/n} \right)^2 \left( \frac{V}{0.22 \text{ m}^3} \right)^2 \left( \frac{B_0}{8.5 \text{ T}} \right)^4 C_{nl}^2 \cdot \left( \frac{g_\gamma}{0.97} \right)^2 \left( \frac{\rho_a}{0.5 \cdot 10^{-24} \text{ g/cm}^3} \right)^2 \left( \frac{3 \text{ K}}{T_{\text{noise}}} \right)^2 \left( \frac{v}{1 \text{ GHz}} \right)^2 \frac{Q_w}{Q_a} \quad (5)$$

where  $Q_w$  is the unloaded, or 'wall'  $Q$  of the cavity, and the loaded  $Q$ ; denoted above by  $Q_L$  is adjusted to maximize the search rate,  $Q_L = Q_w / 3$ . The loaded quality factor  $Q_L^{-1} = Q_w^{-1} + Q_h^{-1}$ , where  $Q_h^{-1}$  represents the contribution from the output coupler ('h' = 'hole').

## 2.2. Previous Experiments

At the present time, two groups have conducted axion searches using cavity detectors. During 1986-1989 a collaboration between the University of Rochester, BNL and FNAL (RBF) carried out a search in the energy range 4.5 - 18  $\mu\text{eV}$ <sup>13</sup>, and in 1989-1990 a group at the University of Florida (UF) scanned 5.5 - 7  $\mu\text{eV}$  with about a factor of 10 better power sensitivity<sup>14</sup>. These experiments focussed on establishing the feasibility of the technique. They utilized small single cavities ( $10^{-2-3}$   $\text{m}^3$ ) in magnetic fields of 5.8 - 8.5 T with either GaAs FETs of  $T_{\text{elec}} \sim 10$  K (RBF) or HEMTs ( $T_{\text{elec}} \sim 4$  K). For part of their running, the Florida group operated their experiment at the lambda point, 2.2 K, both to increase the magnetic field and to reduce  $T_{\text{phys}}$ . Two power spectra from the UF experiment are shown in Figure 1. One spectrum is typical, showing no peaks outside of  $2\sigma$ ; the other shows a peak which



persisted after five automatic remeasurements. It remained even with the magnetic field off, and therefore was spurious. (It was found to be a harmonic of the clock frequency of the computer.) Also shown are the exclusion regions of both their experiment and that of RBF, assuming that axions saturate the halo, i.e.  $\rho_a = \rho_{\text{halo}} = 5 \cdot 10^{-25} \text{ g/cm}^3$ .

No candidate peaks survived from either experiment. However, their power sensitivities were  $10^2 - 10^3$  too high to detect axions with  $g_{\gamma} \sim O(1)$ .

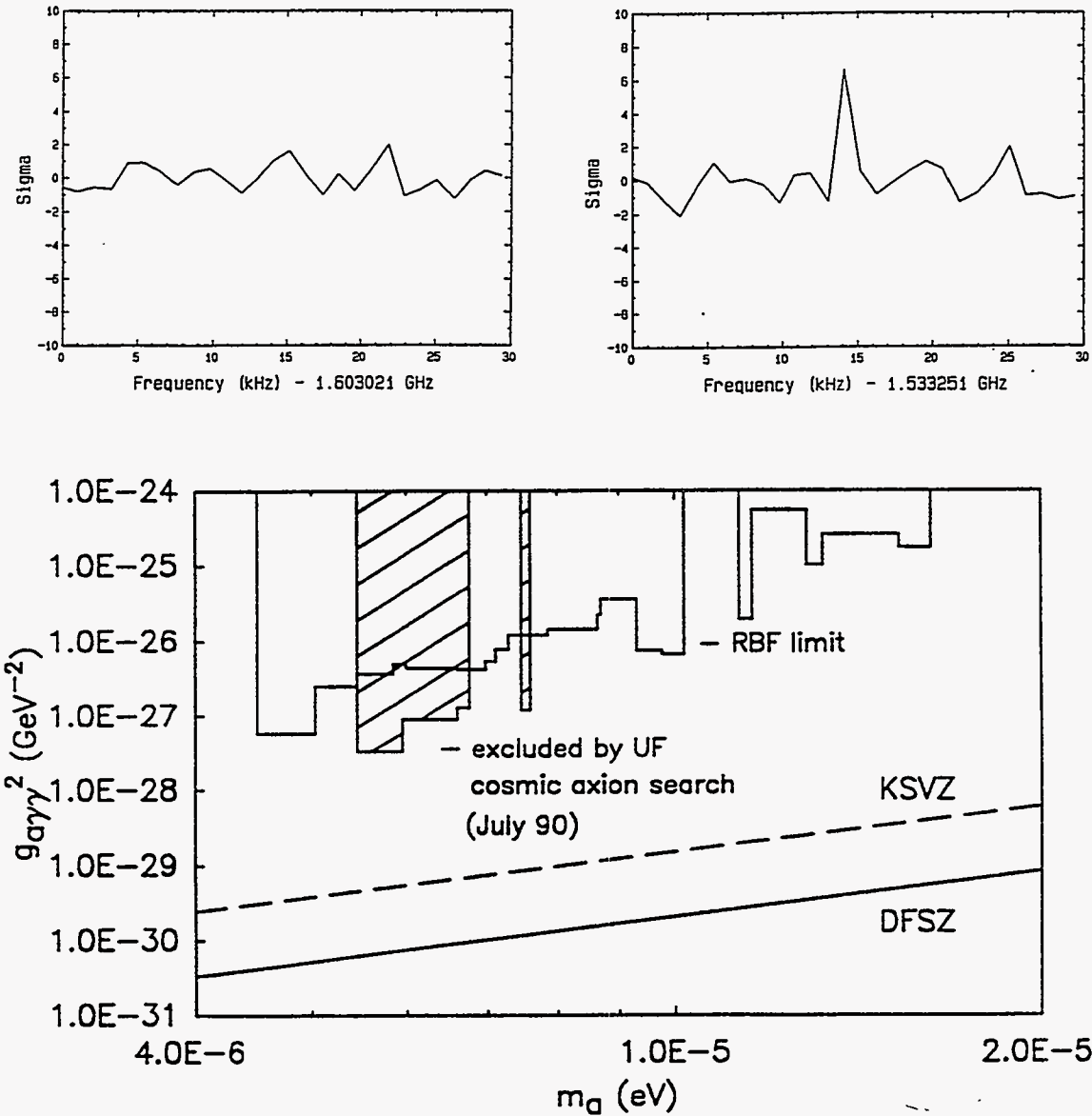


Figure 1. Data from the UF pilot axion experiment<sup>15</sup>. *Upper left:* Typical power spectrum. *Upper right:* Spectrum with spurious candidate peak which persisted after five automatic rescans. *Lower:* Exclusion region for the UF and RBF experiments.

### 3. The Large-Scale Experiment

The present experiment under construction represents a significant scaleup from the RBF and UF experiments, and will also benefit from progress made in reducing the noise temperatures of HEMTs in recent years.

#### 3.1. Magnet

The magnet for this experiment is a superconducting coil and cryostat under construction at Wang NMR Inc. of Livermore, California. The mandrel for the coil has a clear-bore diameter of 60 cm, and a length of 100 cm. The coil is mounted near the bottom of the cryostat, which is 3.5 m high and 1.3 m in diameter. The total weight of the magnet and cryostat is 11 tons.

The coil consists of 52 layers of NbTi conductor in a copper stabilizer. The magnet will operate at 4.2 K in persistent mode, with a central field of 8.5 T. The coil has been wound, and all persistent joints have been made (see Figure 2). The total voltage drop across for all joints in the circuit has been measured to be 7000 nV at the operating current of 250 A and at the ambient B-field seen by the joints. With the total coil inductance of  $L = 540$  H the  $1/e$  time for the current will be approximately  $\tau \sim 2 \cdot 10^{10}$  sec.

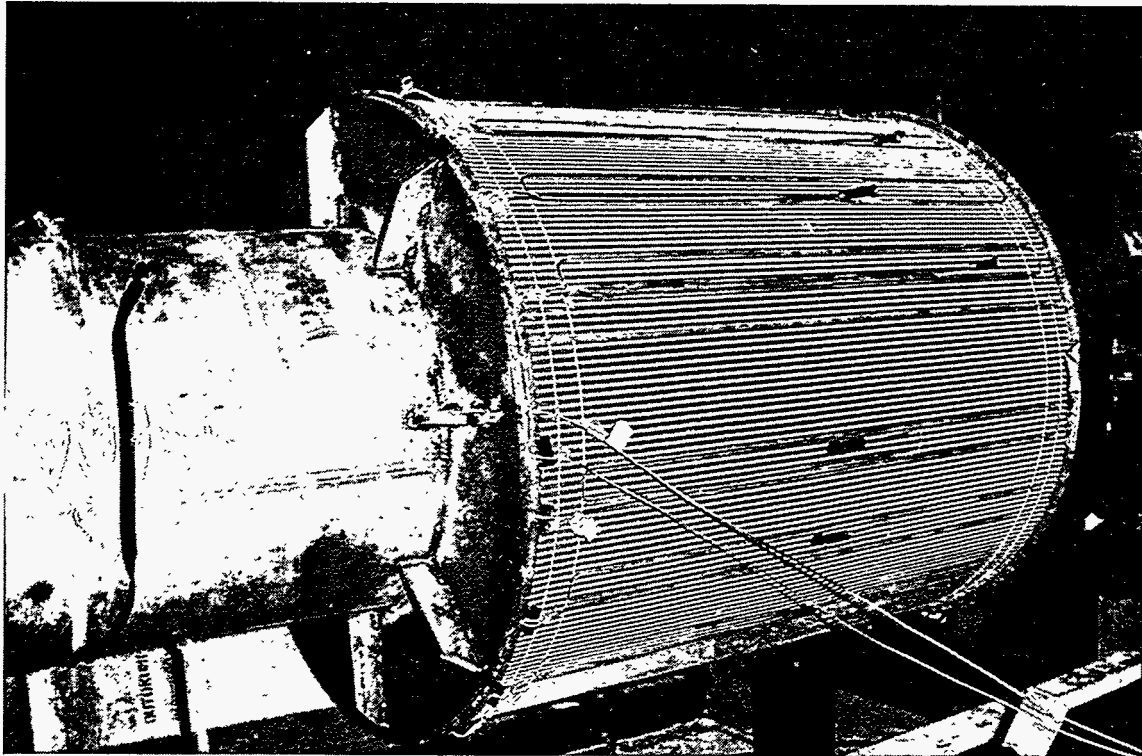


Figure 2. Photograph of the coil for the axion experiment. The copper slugs containing the persistent joints, made every two layers, are mounted outside the coil on its midplane where the ambient magnetic field is lowest. The total coil weight is 6 tons.

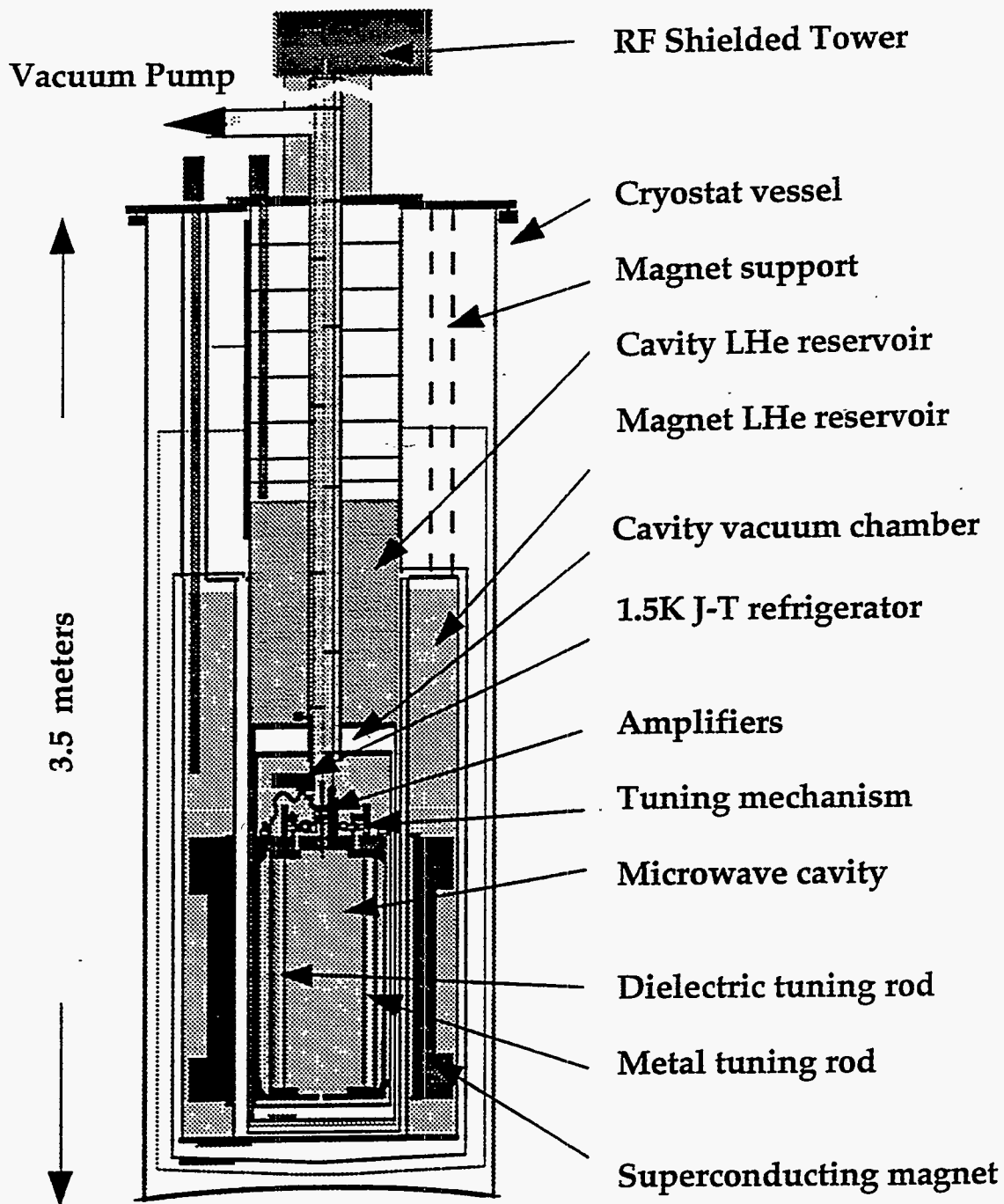


Figure 3. Schematic of the magnet and cryostat, with the physics package inserted.

The magnet cryostat has a vertical clear bore which will permit the physics package consisting of the cavity, amplifiers, cryogenics, etc. to be inserted and removed without de-energizing or warming up the magnet (see Figure 3).

### 3.2. Microwave Cavity Arrays

To cover the one decade frequency range proposed, three cavity arrays are planned (Figure 4). The first will be a single cylindrical cavity of copper-plated stainless steel, with an inner diameter of 50 cm and length 100 cm. The second will consist of four quarter-circular cylindrical cavities, of length 100 cm. The unperturbed frequency of the  $TM_{010}$  mode of a quarter-circular cavity is  $f_2 = 2.1f_1$ , where  $f_1$  is the frequency of the full circular cavity. The third is a group of 32 cavities, 16 in a transverse section, but longitudinally divided into two independent cavities of length 50 cm. (Mode crowding and mode localization become problematic for cavities of too great an aspect ratio; see Ref. 16 for a complete discussion.) Each individual cavity in this array has an unperturbed frequency  $f_3 \sim 4.4f_1$ .

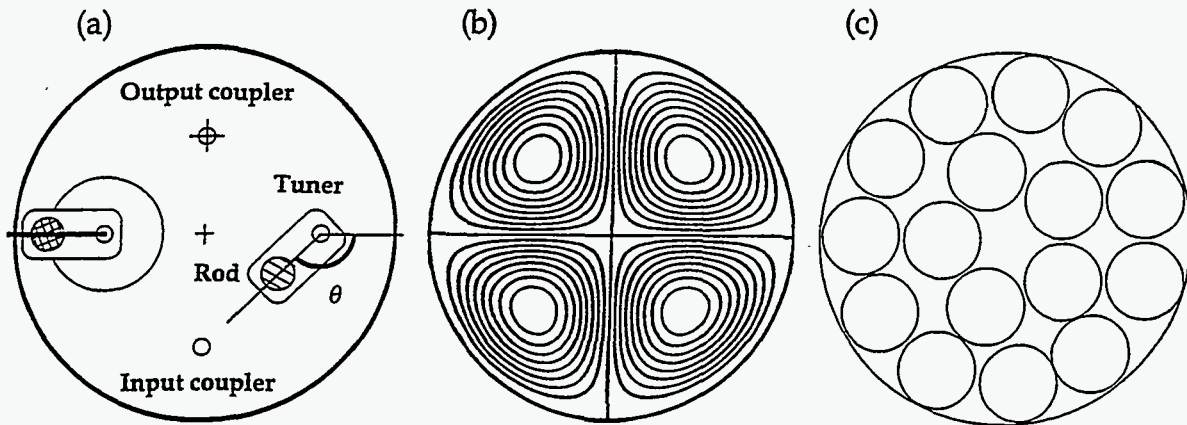


Figure 4. Cavity arrays consisting of (a) a single circular cylindrical cavity, (b) four quarter-circular cylindrical cavities, and (c) 16 x 2 cylindrical cavities. The two rotating tuner mechanisms are shown in (a). In (b) the contours of equal  $E_z$  for the  $TM_{010}$  mode are shown.

Tuning is accomplished by radial displacement of either copper or alumina rods within each cavity. Moving a dielectric rod from the wall towards the center shifts the frequency down; moving a metal post inwards shifts the frequency up (see Figure 5). A continuous tuning range of -30% to +50% can be effected without undue sacrifice of  $C^2Q$ . In this way, the entire decade of mass range can be covered with three cavity arrays. The outputs of the multiple cavities (chosen to be  $2^n$ ) are fed into a Wilkinson power combiner. If the inputs are kept equal in amplitude and phase, the output power of the power combiner will correspond to the total active volume of all the cavities. Note that the device does not couple cavities together (which would result in symmetric and antisymmetric linear combinations with consequent splitting of the resonance), but instead isolates them and

combines their power output in phase. The technique has been demonstrated exactly for this application in the case of two independently tunable cavities at 300K (Ref. 15).

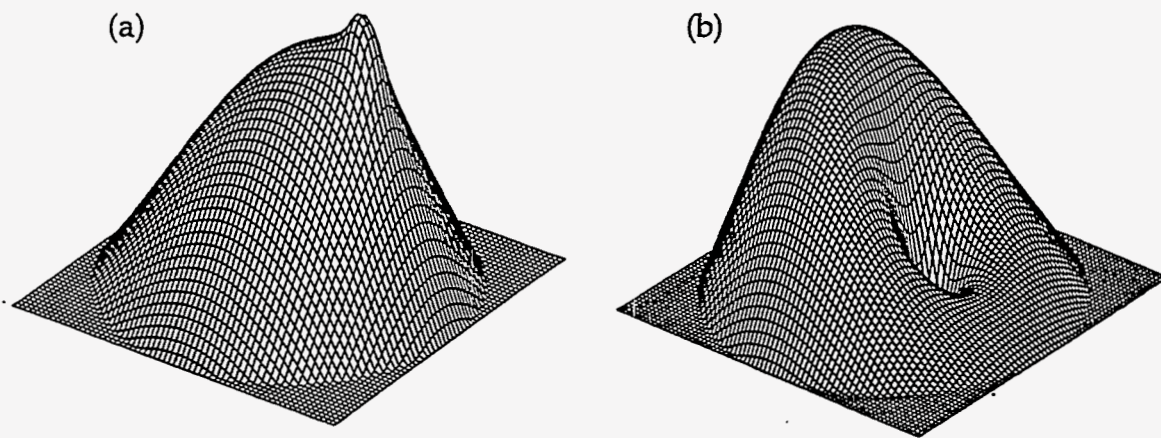


Figure 5. The calculated electric field profile,  $E_z$ , for the  $TM_{010}$  mode in a cylindrical cavity perturbed by a tuning rod of the full length of the cavity. (a) A dielectric rod ( $\epsilon = 9.5$ ); (b) a metal rod. In both cases the rod diameter is  $\sim 0.1$  of the cavity diameter, and partway between the center and wall.

### 3.3. Microwave electronics

The microwave amplifiers to be used in this experiment, at least initially, will be HEMTs. HEMTs achieve their lowest noise temperature around a frequency of 1 GHz, with  $T_{elec} \sim 1K$  and increasing  $\sim 1K/GHz$  at higher frequencies. The experiment will begin taking data in the 300-700 MHz range

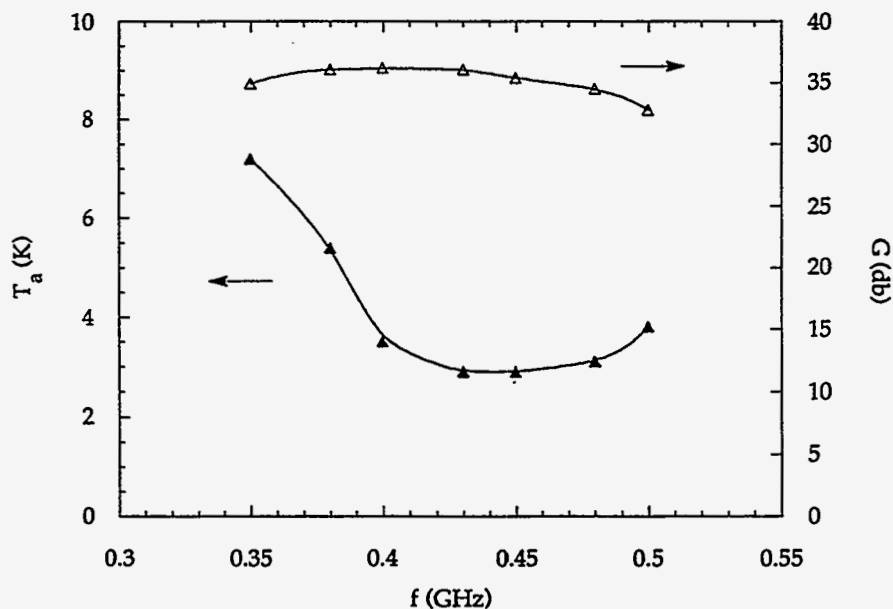


Figure 6. Noise and gain for a prototype two-stage HEMT amplifier<sup>17</sup>.

range first, where the noise will be higher. Figure 6 shows the noise and gain for an early prototype which achieves  $T_{\text{elec}} < 3\text{K}$  at  $T_{\text{phys}} = 12\text{K}$ , at least over a bandwidth of 50 MHz<sup>17</sup>. This is a two-stage amplifier with a total power consumption of under 50 mW, an important consideration for LHe consumption as the amplifier and cavity will be bathed in LHe at  $\sim 1.5\text{K}$ .

To maintain perspective however, it should be emphasized that even where HEMT devices are optimal, they are still far from the quantum limit ( $T = h\nu/k = 50\text{ mK}$  at 1 GHz). This experiment is designed to be sensitive to axions with couplings of the strength of the KSVZ model which fully saturate the halo, in a reasonable period of time (a decade of mass in three years). A quantum-limited detector would be sensitive to DFSZ axions comprising only 10% of the halo density with the same search rate. Reducing the noise temperature is clearly the most fruitful way to improve the experiment. Rydberg atom single-quantum detectors being developed for axion detection by Matsuki and collaborators are very important in this regard<sup>18</sup>.

The double superheterodyne receiver for the experiment (Figure 7) will be similar to that of both the UF and RBF experiments. The signal will be mixed down to 10 MHz by a very stable first local oscillator, and then mixed down to the audio range by the second local oscillator, where the power spectrum will be analyzed by a stand-alone Fast Fourier Transform unit. Data acquisition as

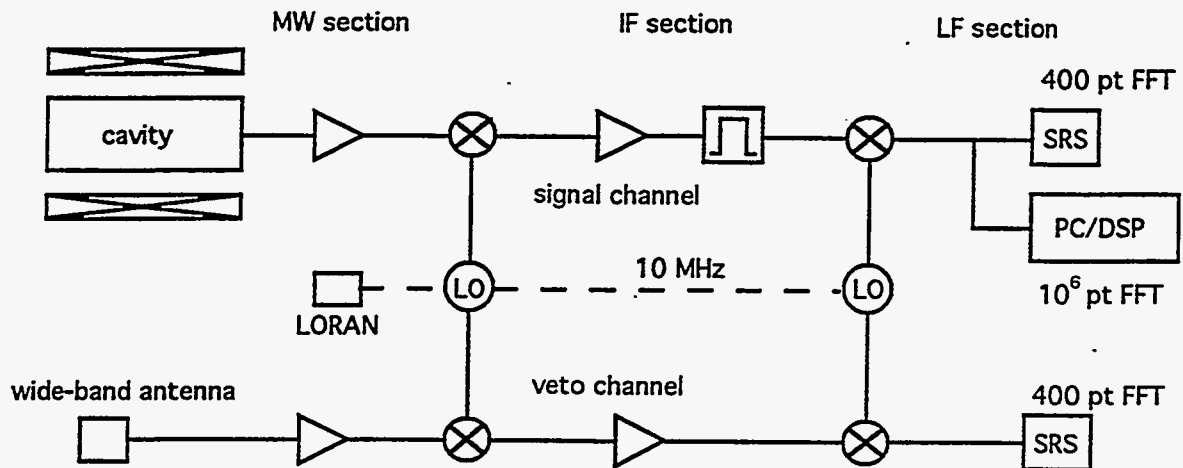


Figure 7. Block schematic for the axion detector.

well as overall experimental monitoring and control is performed by a Macintosh computer. This receiver will have two new features relative to the pilot experiments. The first is that there will be two parallel power spectra calculated and collected per run at each central frequency. The first will be a moderate-resolution spectrum, up to 400 points, whose channel width will be chosen to be somewhat better than the expected virial width of the axion line,  $\sim 10^{-(6-7)}$ . This power spectrum will be the average of individual spectra with short integration times (1-10 ms) repeated  $10^{(3-4)}$  times over 10-100 seconds. The second will be the average of (1-10) high-resolution spectra ( $\sim 10^6$  points) for this same period. In the scenario of Sikivie and Ipser, the original phase-space structure of the axions in our galaxy will likely have been preserved.<sup>19</sup> The manifestation of the memory of phase space would be that the axion spectrum seen with sufficient resolution would really consist of extremely narrow lines ( $\Delta\nu/\nu \sim 10^{-19}$ ) rather than a continuum. Only those axions that had made very many radial oscillations through the galaxy would approximate a true virialized Maxwellian. In particular, the highest energy lines representing the 'last infall' component might account for a few percent of the total population of axions in our halo. The entire high-resolution spectrum will not be archived, but rather a threshold of  $(4-5)\sigma$  will be applied to reduce the number of statistically false candidate peaks to a tractable number. Even with such a threshold, and only  $\sim 1\%$  of the axions in one or a few discrete peaks, an enhancement in the signal-to-noise of 3 or so might be possible.

The other innovation is a third data stream where the signal comes from an external antenna rather than the cavity. Otherwise, the signal will go through an identical superheterodyne receiver and FFT (moderate resolution). This will serve as a veto channel to identify spurious signals from environmental sources immediately, so time need not be spent on them later in a magnet on/magnet off examination of the final remaining candidate peaks.

#### 4. Anticipated Experimental Sensitivity

Commissioning and the beginning of the first run should occur in early 1995. With one year of running per cavity array, a decade of mass range should be covered at the KSVZ limit as shown in Figure 8. Other well-motivated choices of parameters within the framework of the KSVZ model are possible which could increase the conversion power by more than an order of magnitude.<sup>20</sup>

Nevertheless, this experiment is not a definitive search in either power sensitivity or mass range. Concerning power sensitivity, not only does one need to reckon with the more pessimistic axion-photon coupling of the DFSZ model, which is the more generic, but also with the possibility that MACHOs may account for some fraction of the local halo density, though it is unlikely

that this fraction is more than 50%.<sup>21</sup> The coupling of a large volume experiment such as this one with a Rydberg atom single-quantum detector as mentioned previously holds promise to provide the required sensitivity in a few years. The problem of extending the search upwards in mass (10-1000  $\mu\text{eV}$ ) is equally challenging. Combining large numbers of very small cavities with poor  $Q$  is not workable. Alternative ideas have been examined, including the use of solid-state based resonators where the plasma frequency may be varied by doping or optical excitation of the carriers<sup>22</sup>, as well as periodic magnetic fields in a confocal resonator<sup>23</sup>.

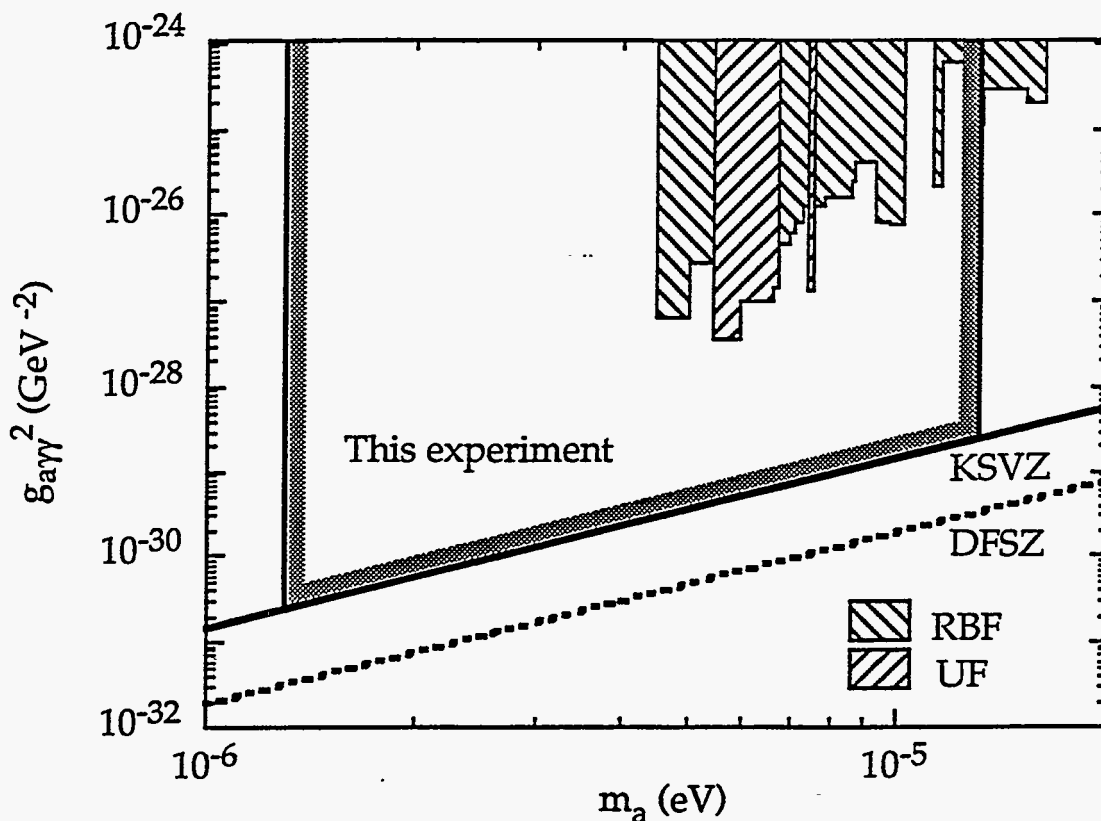


Figure 8. Region in mass - coupling constant plane where the axion would be detected with  $s/n = 4$ , or excluded at the 97.7% c.l. in this experiment.

## 5. Acknowledgments

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