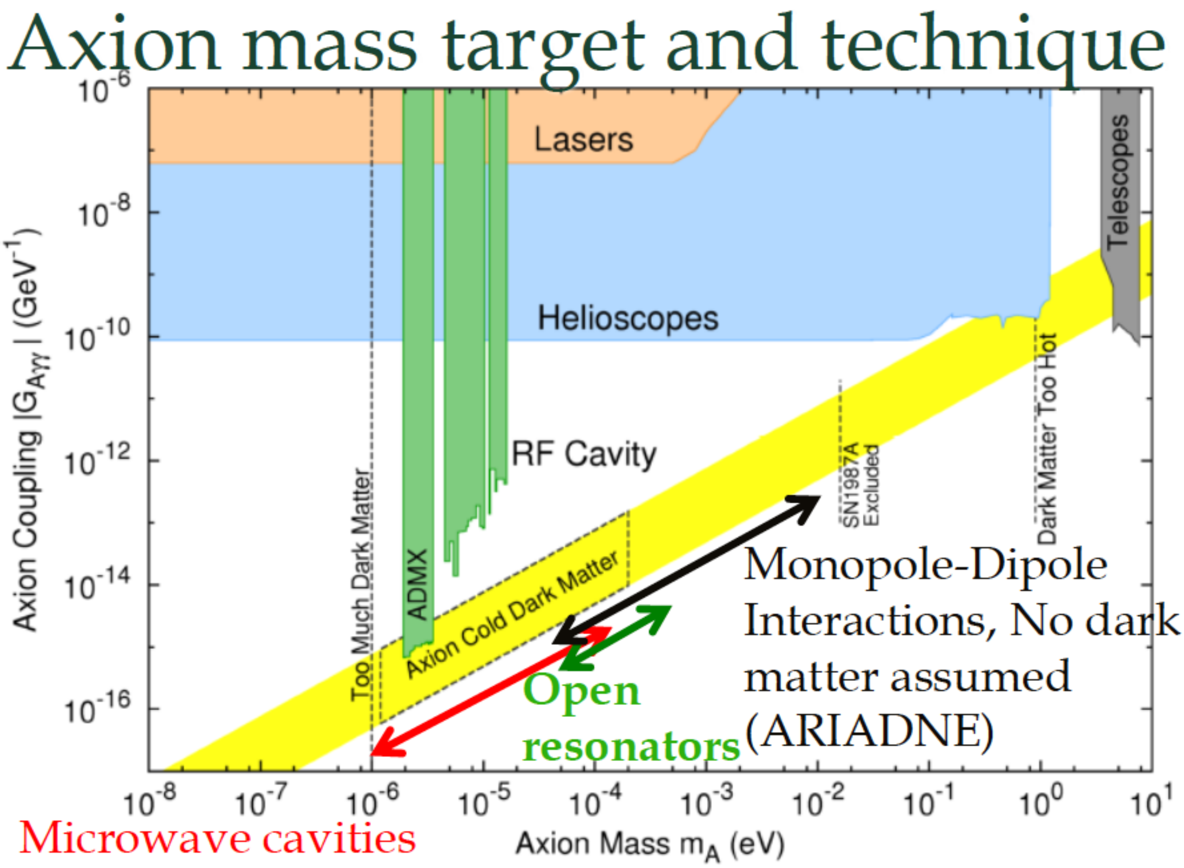
The IBS/CAPP research plan

YkS, March 2018

The axion is a consequence of the most elegant solution, suggested by Alberto Peccei and Helen Quinn in the 1970's, to the strong CP problem, i.e., why the experimental limit of the electric dipole moment of the neutron is at least ten orders of magnitude below its natural level dictated by the theory of QCD. The original axion, predicted by Steve Weinberg and Frank Wilczek, was heavy and its existence was experimentally excluded almost immediately after its prediction. Soon after, Jihn E. Kim proposed a new model, the so-called invisible axion, with very light mass and very weak coupling, which also turned out to be an excellent cold dark matter candidate if its mass is below ~1meV. Pierre Sikivie suggested using the inverse Primakof effect in the presence of a strong magnetic field and high quality microwave resonator to make it visible. Most of our current experimental efforts are based on this method, but we are also engaged in alternate methods depending on the specific axion mass range probed. The range and depth of the axion searches demonstrates the power of synergy and diversity in our approaches.



The axion coupling constant as a function of the axion mass. The yellow band indicates the axion models that also solve the strong CP-problem. The technique used to search for axions depends on the axion mass range: The red arrow shows the range where microwave resonators can be used, in green the open resonators, and in black the axion mass sensitivity of the monopole-dipole interactions based experiment (ARIADNE).

The axion to photon conversion power is given by

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L$$

$$= \; 2 \cdot 10^{-22} \text{ Watt} \left(\frac{V}{500 \text{ liter}}\right)\left(\frac{B_0}{7 \text{ Tesla}}\right)^2 \left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho_a}{5 \cdot 10^{-25} \text{ gr/cm}^3}\right)\left(\frac{m_a c^2}{h \text{ GHz}}\right)\left(\frac{Q_L}{10^5}\right)$$

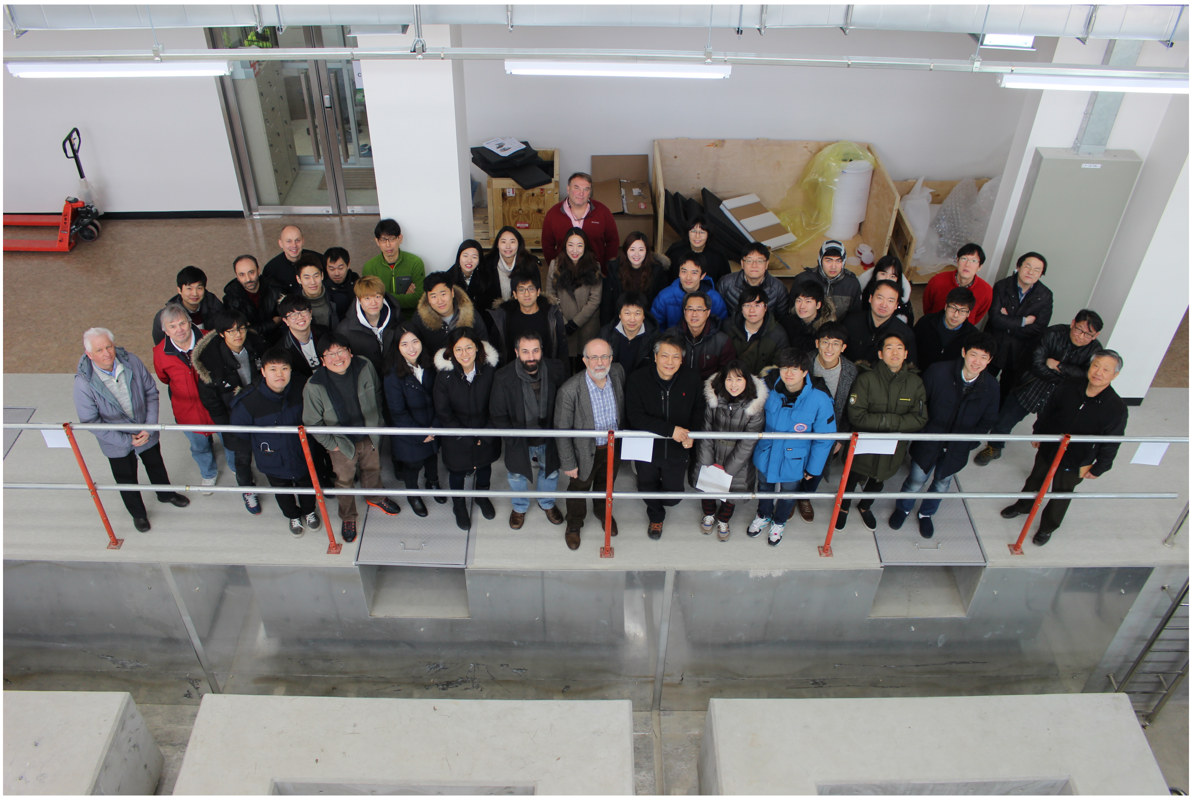
indicating a very small power output. Since we don't know the axion mass, it is more relevant to look at the axion mass scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1 \text{ GHz}}{year}\left(g_{a\gamma\gamma} 10^{15} \text{GeV}\right)^4 \left(\frac{5 \text{ GHz}}{f}\right)^2 \left(\frac{4}{SNR}\right)^2 \left(\frac{0.25 \text{ K}}{T}\right)^2$$
$$\times \left(\frac{B}{25T}\right)^4 \left(\frac{c}{0.6}\right)^2 \left(\frac{V}{5l}\right)^2 \left(\frac{Q}{10^5}\right)$$

where it is clear that large volume (V), large magnetic fields (B), large quality factors (Q), and large geometrical coefficients (c) are very critical, as well as low temperature (T) referring to the sum of the physical plus amplifier equivalent electronic noise. We are developing in-house expertise on SQUID-based, quantum noise limited amplifiers and an infra-structure that can support sub 0.1K physical temperatures for the microwave resonators.

1. Axion Searches

The IBS/CAPP infrastructure in the axion dark matter field is the best in the world. We are currently capable of running seven, high-sensitivity axion dark matter experiments in parallel.

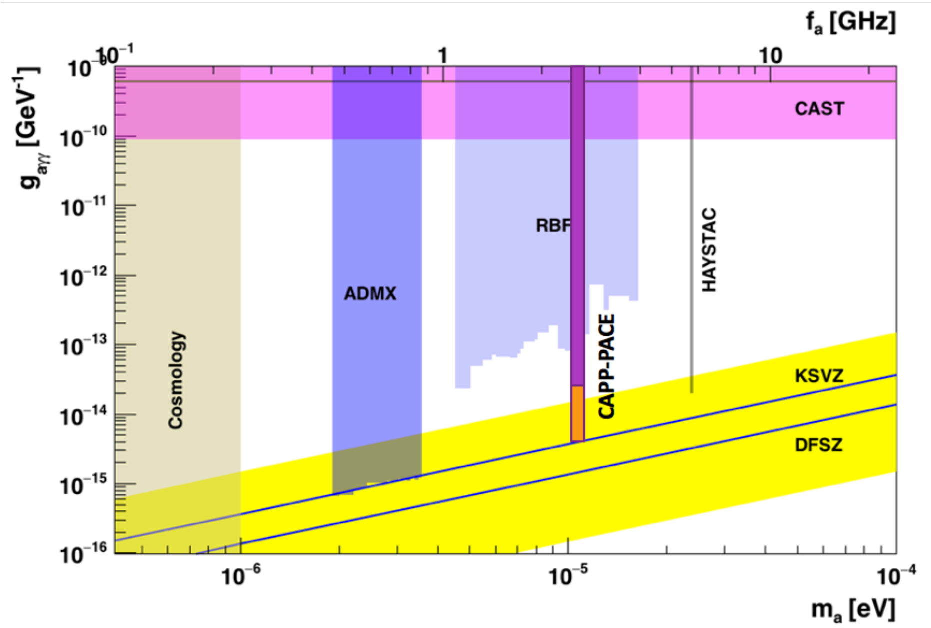


The IBS/CAPP members and associates at the low vibration pads of our KAIST Munji Campus lab, in January 2017.

The experimental area showing the area of three on-going experimental efforts on axion dark matter searches. A fourth on-going experimental effort is on the other side of the LVP hall (not shown in the picture).

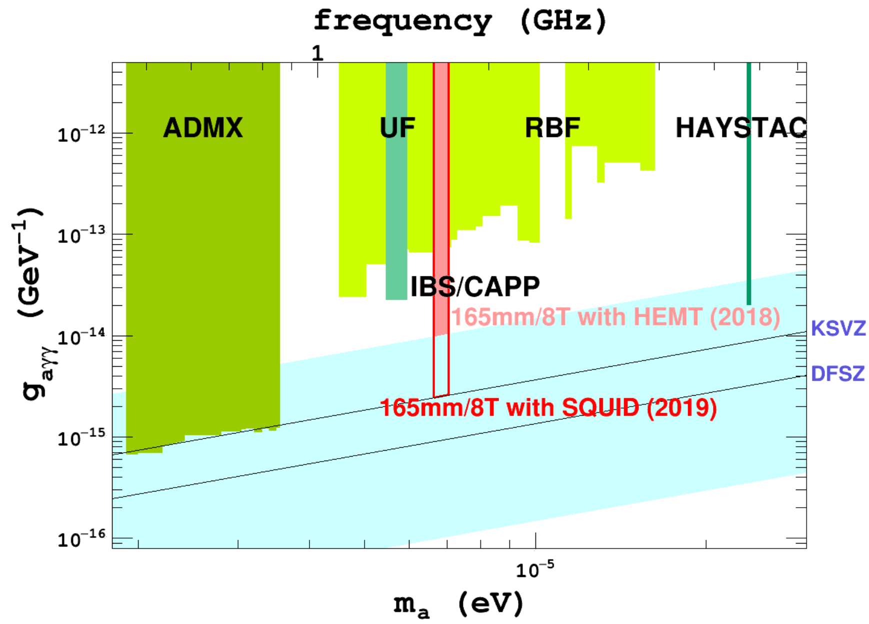
Currently, our projects are either taking data or preparing to take high sensitivity data in the near future. Our axion dark matter projects in Korea are under the project name: CAPP Ultra Low Temperature Axion Search in Korea (CULTASK). They consist of the following independent/parallel efforts:

1.1 CAPP-PACE (pilot axion cavity experiment), using an 8T SC magnet, high quality factor microwave cavity at <0.1K physical temperature, using a dilution refrigerator (as are most of the CULTASK projects) and low noise HEMT amplifier. This project is already taking data. We are in the process of replacing the HEMT amplifier with a quantum noise limited SQUID amplifier to increase the sensitivity of the experiment, eventually reaching the KSVZ line. The axion frequency range is 10.1 – 11.37 μeV (2.45 – 2.75 GHz) using a single cavity.



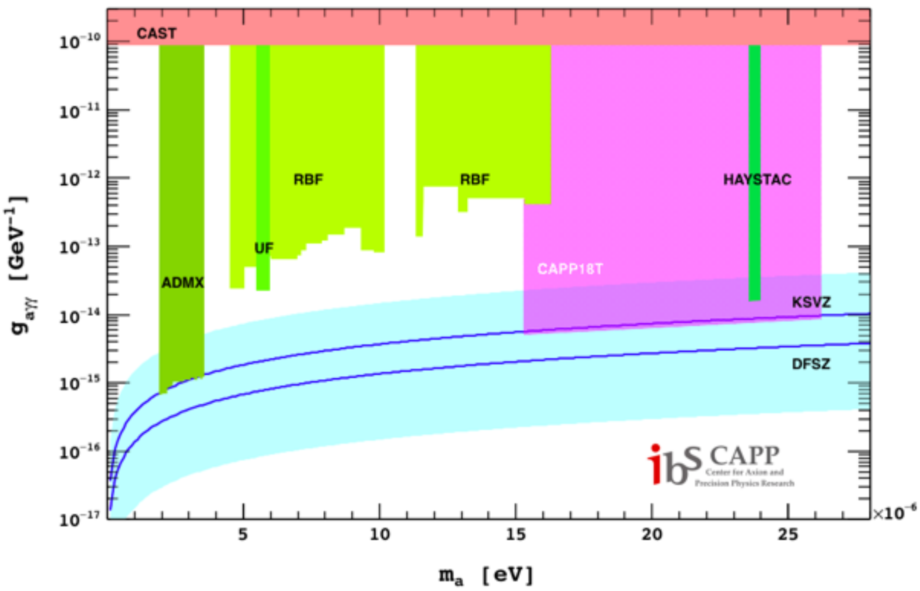
The projected sensitivity of the CAPP-PACE experiment with a HEMT and SQUID amplifier at 10^{-5} eV.

1.2 CAPP-8TB, utilizing a large aperture 8T magnet and using different approaches in tuning the microwave cavity. The plan is to reach the hadronic axion band. The axion mass range is 6.62 – 7.04 μeV (1.6 – 1.7 GHz).



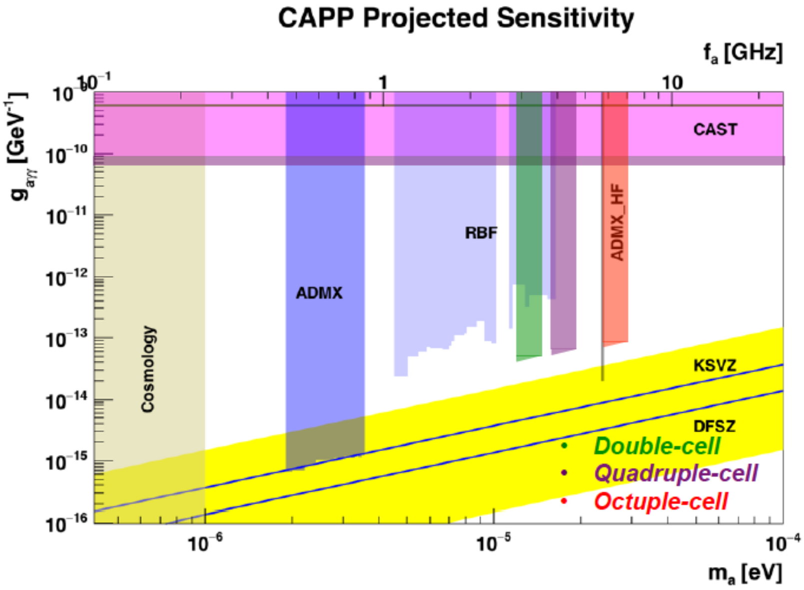
The CAPP-8TB projected limits with HEMT and SQUID amplifiers, using a single cavity.

1.3 CAPP-18T, utilizing the first high Tc magnet in axion searches (Axion group project with significant support from the rest of IBS/CAPP). The magnet is made by SuNAM and it is a demonstration of pioneering technology. We expect to reach the KSVZ axion sensitivity in the axion mass range of 15.30 – 26.22 μeV (3.7 – 6.5 GHz) after several years of development and running.



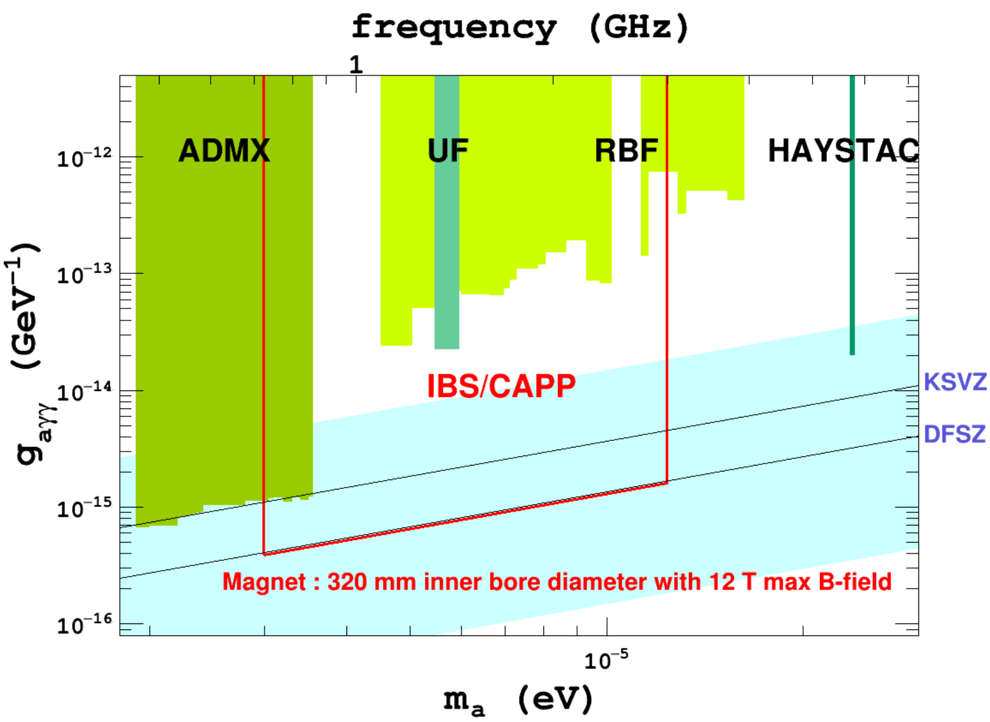
The projected (nominal) sensitivity of CAPP-18T using an 18T, 7cm inner diameter, HTS magnet, and a single cavity with a quantum-noise limited amplifier and several years of development and running. Note the linear scale horizontally.

1.4 CAPP-MC (multiple cell), utilizing the "pizza-cylinder" cavity phase matching method invented at IBS/CAPP (YS project). The sensitivity is above the hadronic axion band, and the mass range is 10–30 μeV (2.4 – 7.2 GHz).



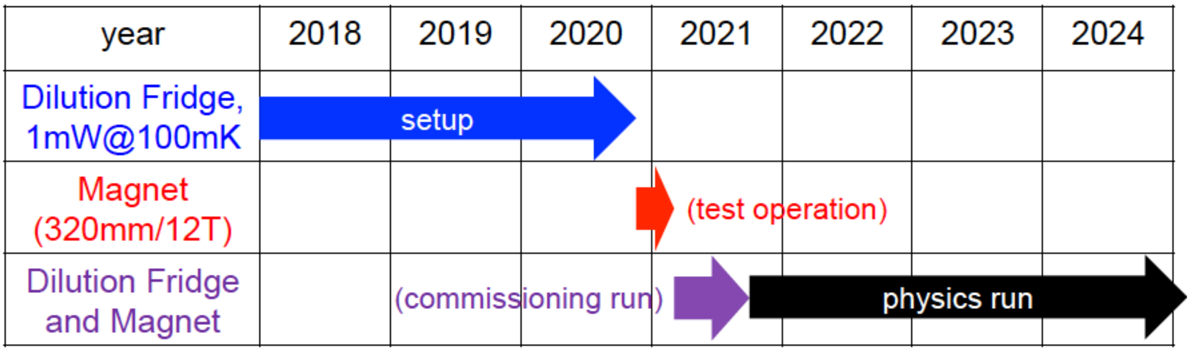
The projected sensitivity of CAPP-MC using a double, quadruple, and octuple cell cavity and a physical cavity temperature of 2K. The sensitivity is about 10 times the KSVZ line in about total running time of one year.

1.5 CAPP-12TB, utilizing a 12T magnet under construction by Oxford company using Nb_3Sn low temperature superconductor with a delivery in 2020. The magnet aperture is very large, 320 mm and it is expected to reach all the way down to the DFSZ limit for an axion mass range 3.0 – 12.4 μeV (0.72 – 3 GHz) using a single cavity.

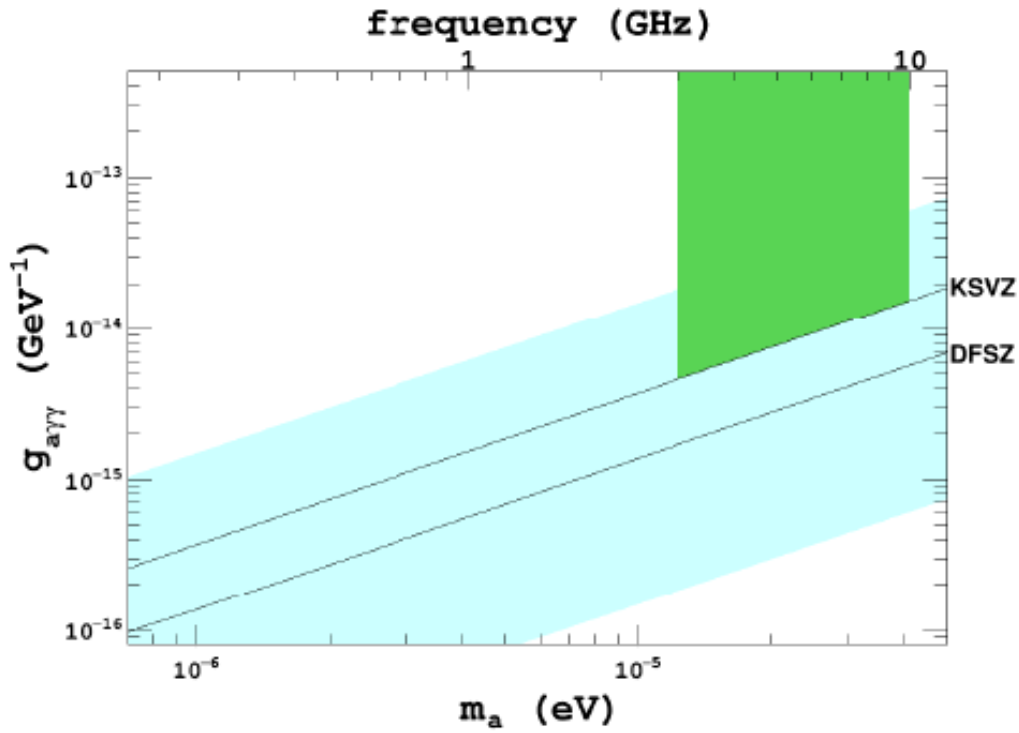


The CAPP-12TB projected limits with SQUID amplifiers and a single cavity. This project is expected to reach sensitivity beyond the DFSZ level for a wide axion mass range.

Timeline of axion haloscope searches with the 320mm/12T magnet

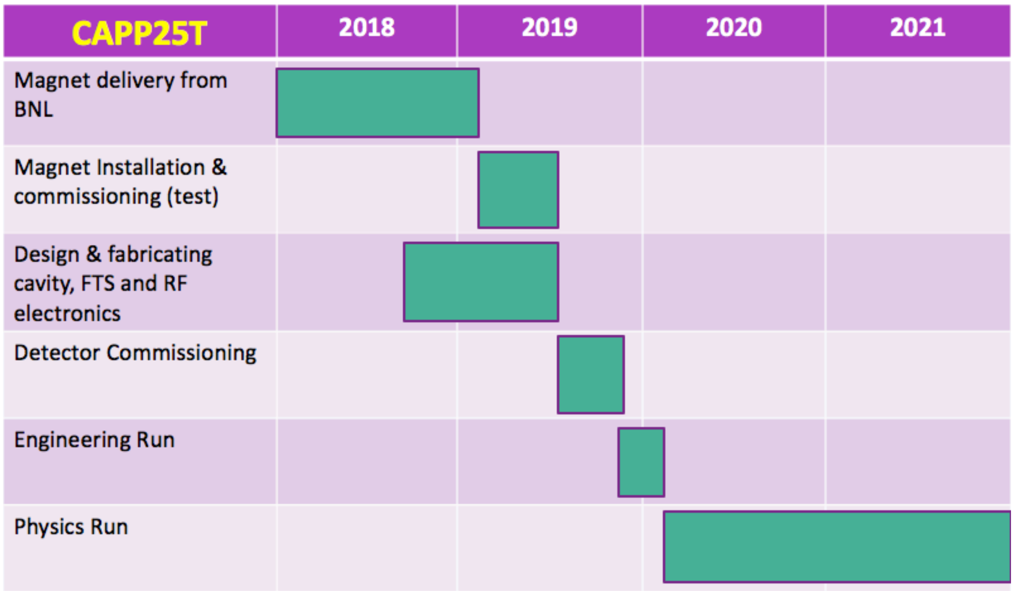


1.6 CAPP-25T, utilizing a high T_c superconductor, with a magnet aperture of 100 mm being under construction by Brookhaven National laboratory with an expected delivery in 2019 (technically driven schedule). The sensitivity is the KSVZ hadronic axion model and the axion mass range is 12.4 – 41.4 μeV (3 – 10 GHz) using a single cavity.

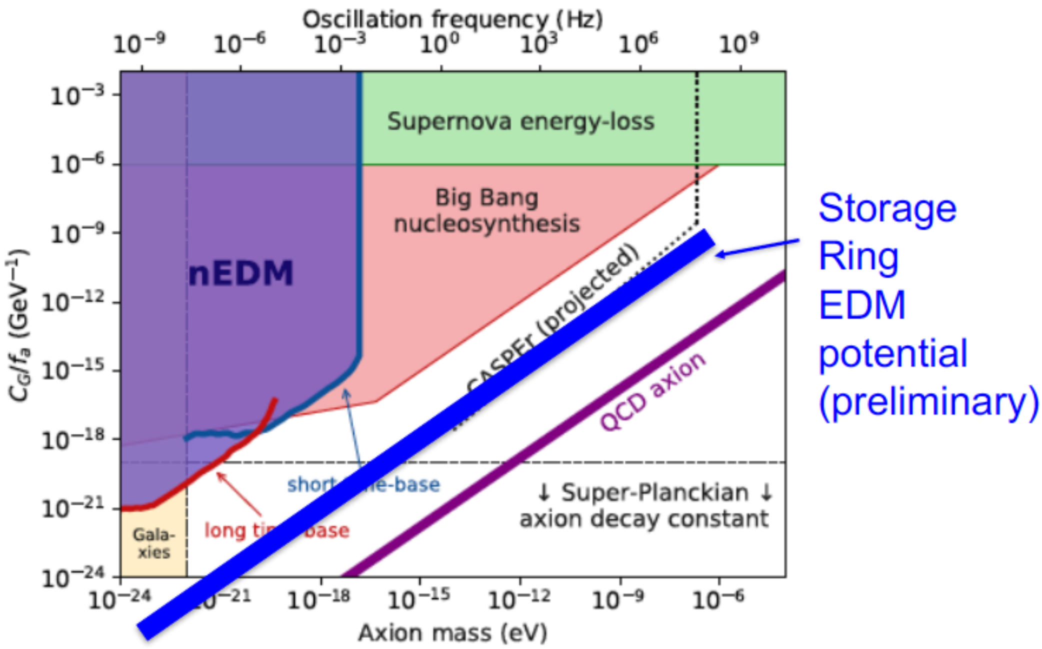


The sensitivity of the CAPP-25T experiment reaches the KSVZ line in the frequency range of 3-10 GHz using a single cavity. With multi-cavity configuration the frequency reach is up to 20 GHz with similar sensitivity.

The technically driven schedule of the 25T, 10cm inner diameter magnet and its operation.



1.7. CAPP-srEDM. Finally, for low frequency axions below 100MHz, we have recently proposed a new method based on the combination of the storage ring EDM method and the g-2 method. The axion mass sensitivity is going to be the best of any experiment currently under construction for an axion mass range of 4×10^{-24}eV – 0.4 μeV (1 nHz – 100 MHz).



arXiv:1708.06367v1

PhysRevX.7.041034

The storage ring EDM method and the g-2 method can be combined to a powerful new method, sensitive to an oscillating nuclear EDM driven by the dark matter axion field oscillations.

GNOME and ARIADNE and Dipole geometry magnets

In parallel, we have finished the first phase of construction for GNOME (sensitive to axion stars with low mass axions) based on sensitive optical magnetometers. A more generic axion experiment based on monopole-dipole interactions is under construction with an international collaboration (ARIADNE) with a mass range sensitivity of 0.1 – 10 meV (25 GHz – 2.5 THz). ARIADNE doesn't need the existence of axion dark matter, however it requires the realization of the axion mechanism plus the existence of CP-violation beyond the standard model (SM). Combining the physics results of ARIADNE and that of the proton EDM can shed light into the existence of the axion physics in the related axion mass range.

In addition, we are planning to complete (2018) our hardware installation in the CAST-CAPP experiment at CERN, successfully developing a new geometry for sensitive, higher frequency (6 - 7 GHz) axion dark matter search, taking advantage of existing, high-field dipole magnets. The method utilizes a prototype LHC magnet, delivering 9T in a large volume, becoming very competitive due to its B^2V parameter strength.

Short-range future plans in axion search projects

1. Combining the 12T and the 25T magnets we may be able to achieve a field of 37T with an inner bore aperture of 10cm, enhancing the sensitivity in the axion to two photons coupling constant.
2. Due to lack of funding we are freezing the development of the toroidal geometry magnets, which would give us access to axion masses below 0.4 μeV with high sensitivity. Instead, we have initiated a collaboration with the high field lab at Grenoble/France to use the high-field, large aperture magnets under construction at Grenoble to launch a powerful axion dark matter search in the lower axion mass range.
3. In addition, we are in the process of forming a collaboration with ADMX and the Physics dept. faculty of KAIST to develop an axion dark matter search using the open resonator technique. This method expected to reach high sensitivity in the axion frequency range favored by recent theoretical work, upwards of 25 GHz.

2. Precision Physics

We are continuing the R&D on the proton EDM experiment, which can help answer one of the most fundamental questions in physics today regarding the matter-antimatter asymmetry of our universe. CERN is seriously considering to host this experiment and we developing it as part of the physics beyond colliders (PBC) effort at CERN. The intermediate goal is to produce a conceptual design report and its conclusions to be reported at the European Strategy meeting in Venice, June 2019. Our institution (IBS/CAPP) is playing a leading role in the experiment.

We are involved in the Muon g-2 experiments, where our students and post-docs are making significant contributions to the success of those experiments and they are trained to acquire skills for the proton EDM experiment. We are also involved in the muon to electron conversion experiment COMET at J-PARC, where we play a small, but significant role related to high-tech trigger electronics.