Haloscope Searches for DM Axions at the Center for Axion and Precision Physics Research

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CAPP
Center for Axion and Precision Physics Research

ICNFP2016, Kolymbari, Crete

STRONG CP PROBLEM AND AXIONS

THE STRONG CP PROBLEM

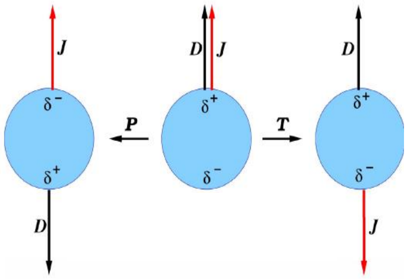
- The QCD lagrangian contains an “absent” term:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \sum_{j=1}^{n}[\bar{q}_j\gamma^\mu iD_\mu q_j - (m_j q^\dagger_{Lj} q_{Rj} + \text{H.c.})] + \frac{\theta g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}.$$

- Dependence on the theta-term must exist for correct QCD predictions.
- However, it results in CP- and P-violation, unless the *quarks mass matrix* is finely tuned!

At the same time,

- The electric dipole moment of hadrons will imply CP- and P-violation in QCD.
- However, neutron EDM < 3.0 x 10^{-26} e·cm and proton EDM < 7.9 x 10^{-25} e·cm.



- These experimental limits mean that the “theta phase” in the lagrangian is ~10 orders lower than expected.
- (More accurately, <10^{-9} while expecting ~1. A fine-tuning non-anthropic issue.)

Why is the CP symmetry conserved by QCD? "Strong CP Problem"

ENTER THE AXION

Why is the CP symmetry conserved by QCD? "Strong CP Problem"

Peccei & Quinn ('77):

- The Strong CP Problem conceals a new symmetry.
- The global “ $U_{PQ}(1)$ “ quasisymmetry.
- The potential of theta is modified.
- Theta is a dynamical variable, with perturbative effects "pulling" it towards zero.

- Axion: the quantum of oscillation of the QCD θ parameter. (Weinberg, Wilczek '78)

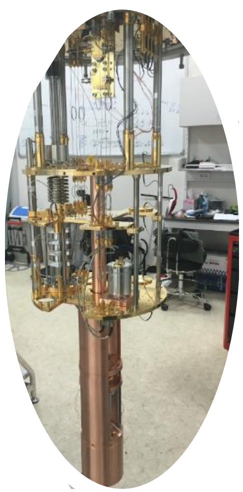
Searches at CAPP: Two sides of the same coin

The axion was invented to solve
the "Strong CP Problem":
Why is the neutron EDM ~10 orders of magnitude
smaller than its expected value?

Microwave cavities

DIRECT AXION DETECTION

Today's talk



Accelerator experiments

HADRONIC ELECTRIC DIPOLE MOMENT MEASUREMENTS

AXION "EVOLUTION"

Initially the vev was thought to be of the order of EW scale.

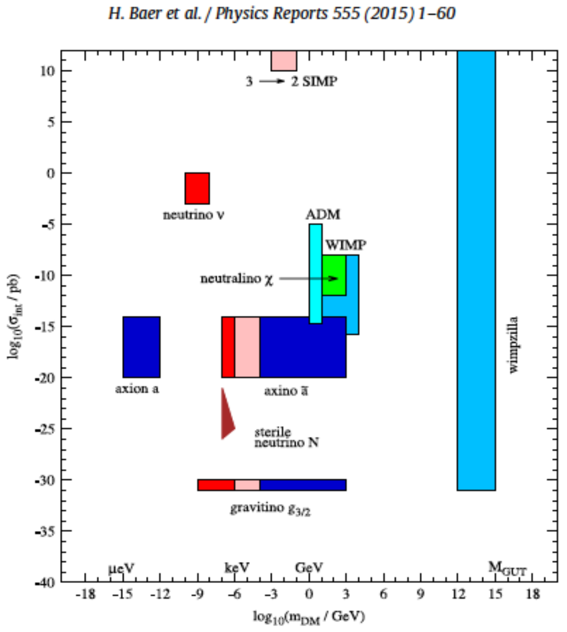
Axion mass -> ~100 keV.

Then a success of the model occured: It was heavily constrained by indirect lab searches and cosmology ^^

Axion mass -> less than 10^{-3} eV.

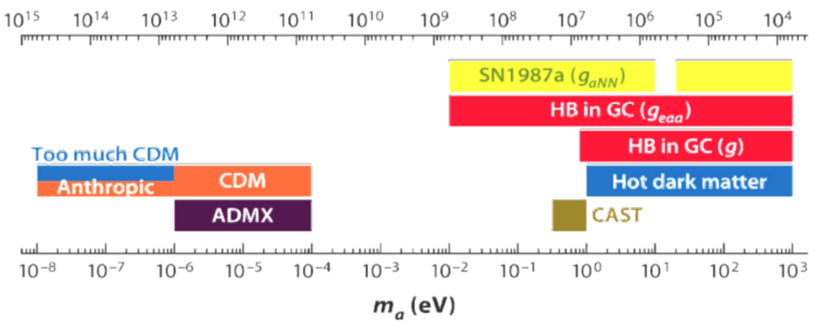
Today, more elaborate models give naturally rise to light axions.

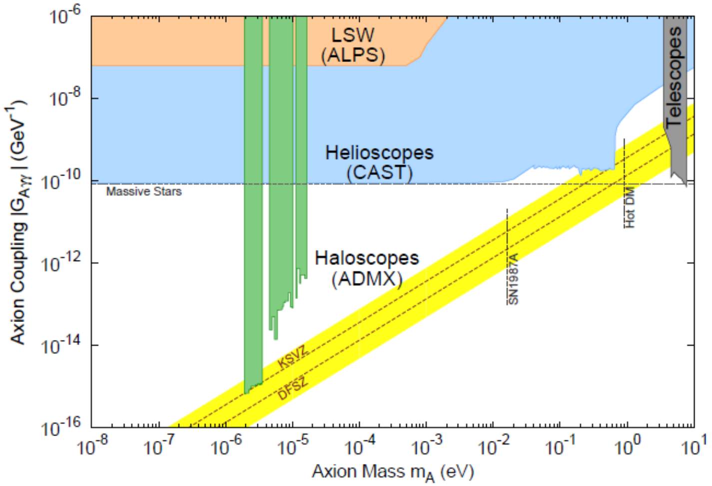
Initially dubbed "invisible axions" for their impossible detection ... until 1983 (see sl.9).



Main invisible axion models:
KSVZ (Kim-Shifman-Vainshtein-Zakharov)
DFSZ (Dine-Fischler-Srednicki-Zhitnitskii)

COSMOLOGICAL AXIONS





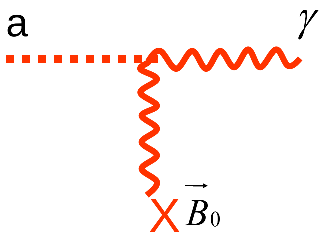
- Good dark matter candidate if mass m_a is between 1 and 300μeV.
- Kinetic energy ~10^{-6} m_a (cold dark matter).
- Coherent field.
- Cosmological and astrophysical constraints. E.g.:
  - Stellar evolution: Axions emitted in stellar processes would dissipate more energy and stellar evolution would be accelerated.
  - SN1987a: If the collapsing core is also cooled by axion emission, the duration of the neutrino signal will be shorter.

DIRECT AXION DETECTION / HALOSCOPES

DIRECT AXION DETECTION

Detection scheme by P. Sikivie (PRL 51:1415 1983)

- Axions will convert to photons in a strong magnetic field. ("reverse Primakoff effect")



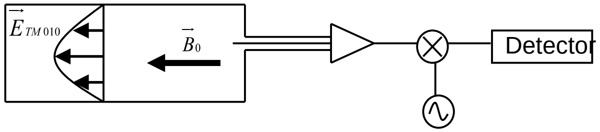
$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

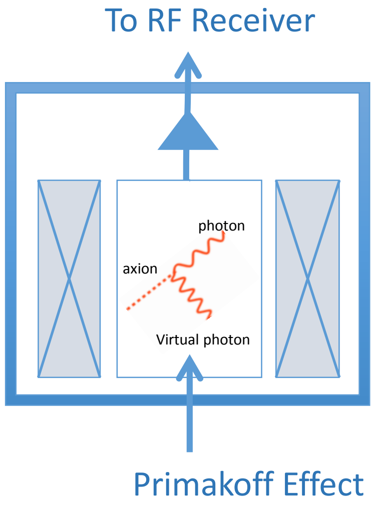
- Process proceeding through loop; both regular SM and new U(1) couplings of axion to fermions.

- Powerful magnets.

- Very weak signal (~10^{-21} W)
  - $\Rightarrow$ Cryogenic temperatures.
  - $\Rightarrow$ Resonant radiofrequency (RF) cavities for enhancement.
  - $\Rightarrow$ Tunable over a good frequency range.

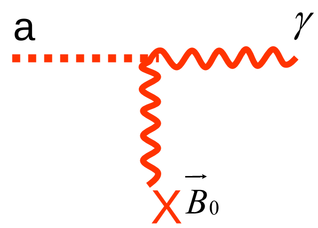
At the cavity's resonant frequencies the microwaves reinforce to form standing waves in the cavity. Therefore, the cavity functions similarly to an organ pipe or sound box in a musical instrument, oscillating preferentially at a series of frequencies, its resonant frequencies.





HALOSCOPES AND HELIOSCOPES

Axions will convert to photons in a strong magnetic field. ("reverse Primakoff effect")



Helioscopes

Pointing to the Sun for axions produced by photons.

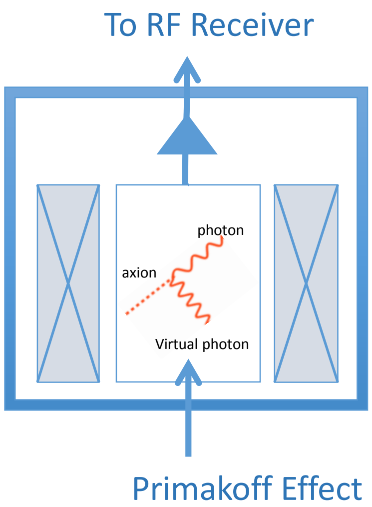
Haloscopes

Looking for ambient axions from the Milky Way's DM halo (~10^{14} cm^{-3}).

HALOSCOPE PROGRAMME IN CAPP

Axion Conversion Power: $P = 1.5\times10^{-24}\,\mathrm{W}\left(\frac{g_{a\gamma\gamma}}{10^{15}\,\mathrm{GeV}}\right)^2\left(\frac{C}{0.69}\right)\left(\frac{B}{8\mathrm{T}}\right)^2\left(\frac{V}{5l}\right)\left(\frac{\rho_a}{300\ \mathrm{MeV/cm^3}}\right)\left(\frac{20\mu\mathrm{eV}}{m_a}\right)\left(\frac{Q}{50\times10^3}\right)$

Signal to Noise Ratio: $\mathrm{SNR} = (P_a/P_N)\sqrt{bt} = (P_a/k_B T_S)\sqrt{t/b}.$



What can be improved?

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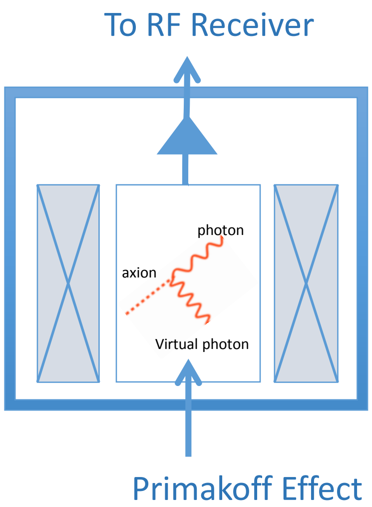

What can be improved?

TECHNOLOGIES FOR ADVANCING HALOSCOPES

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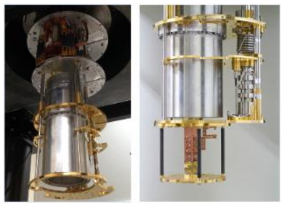
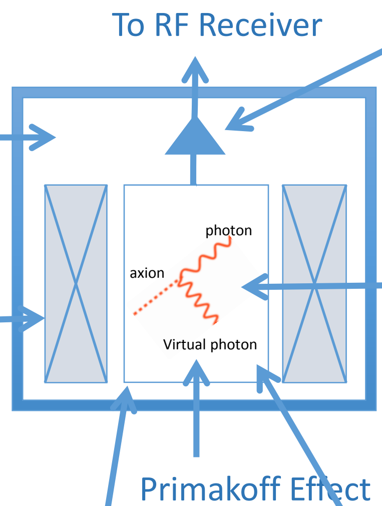


Cryogenics

< 100mK

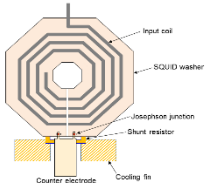
with KAIST (Korea Advanced Institute of Science and Technology)



SQUID Amplifier

quantum limit for noise [50mK·f(GHz)]

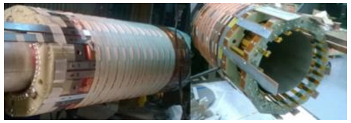
with KRISS (Korea Research Institute of Standards and Science)



High Field SC Magnet

12T -> 25T -> 35T / 40T

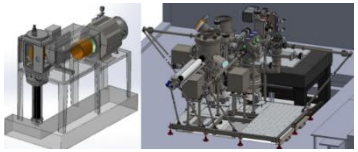
with Korean company / BNL



Superconducting Cavity

superconducting coating, high Q-factor

with KAIST (Korea Advanced Institute of Science and Technology)

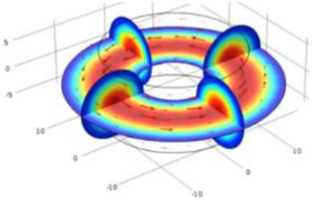


Multiple cavities readout

increased volume in high frequencies

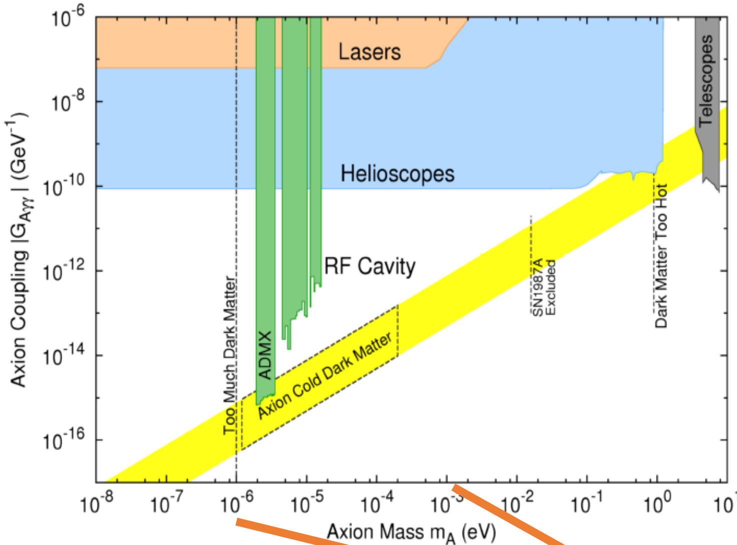
Giant toroidal cavity

gain 10-20x



CAPP ROADMAP

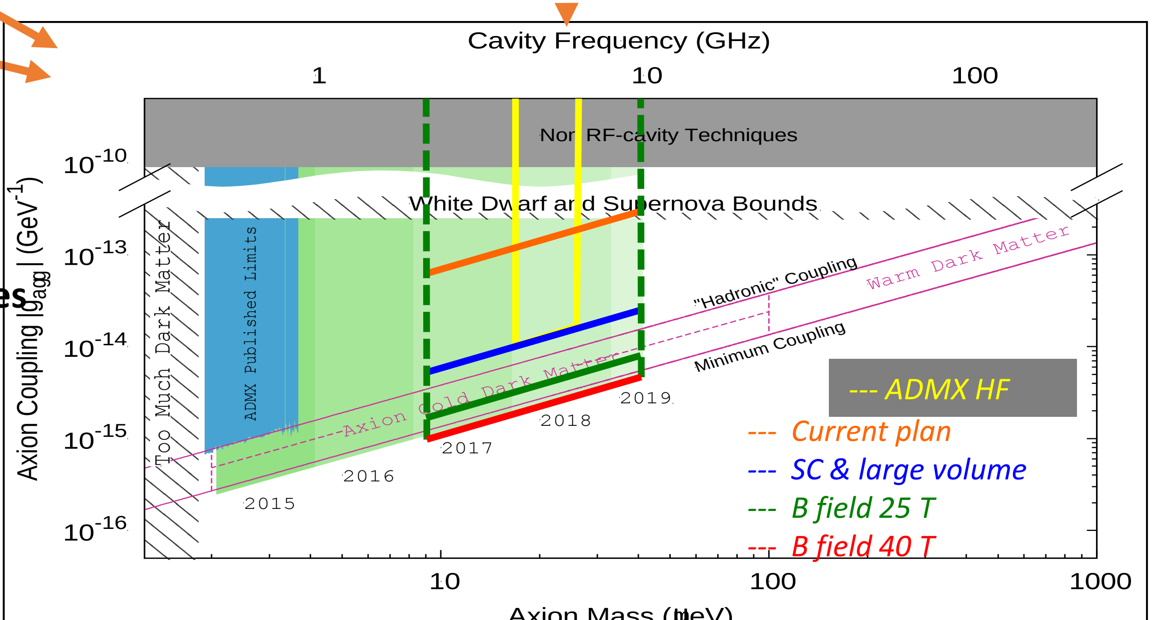
Expected coverage:



Major improvements in haloscopes expected within 5 years

CAPP Projected Sensitivity

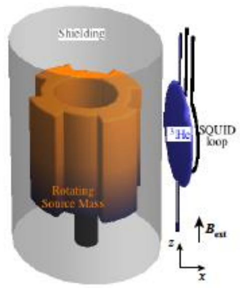
e.g. 25μeV: 5.8GHz



- **2-3 years development**
- **2018: Main axion experiment**
- **R&D for higher and lower frequencies**

by WooHyun Chung

BEYOND DIRECT DETECTION: ARIADNE EXPERIMENT



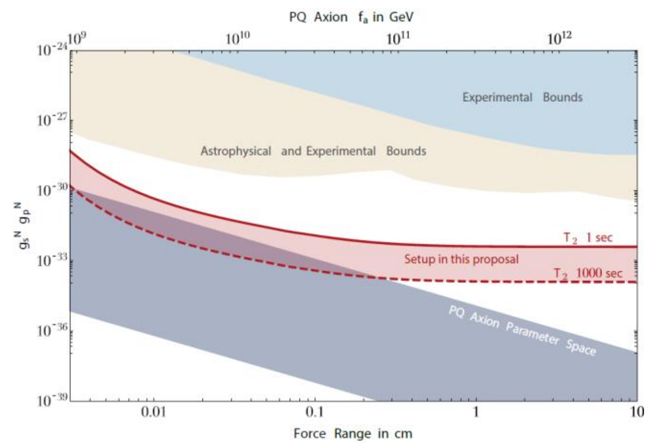
by YunChang Shin

ARIADNE:

Axion Resonant InterAction DetectioN Experiment

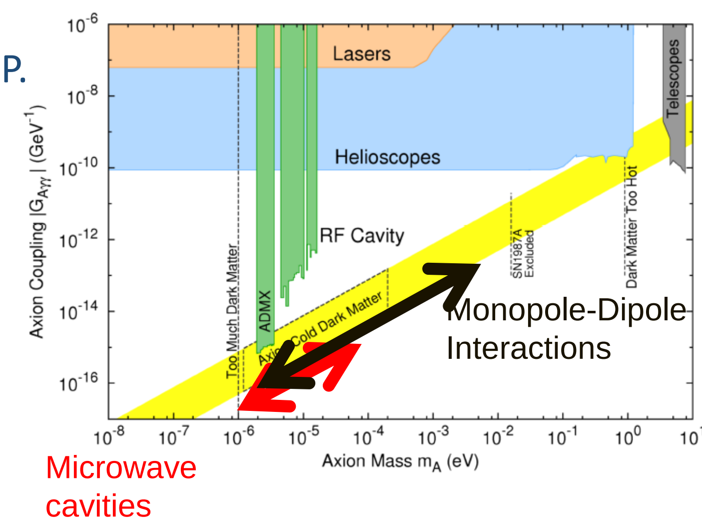
A rotating mass will induce spin precession and magnetization detectable by SQUIDS. Explores monopole-dipole interactions in the axion lagrangian.
(No dark matter assumed.)

A. Arvanitaki, A. A. Geraci, arXiv:1403:1290

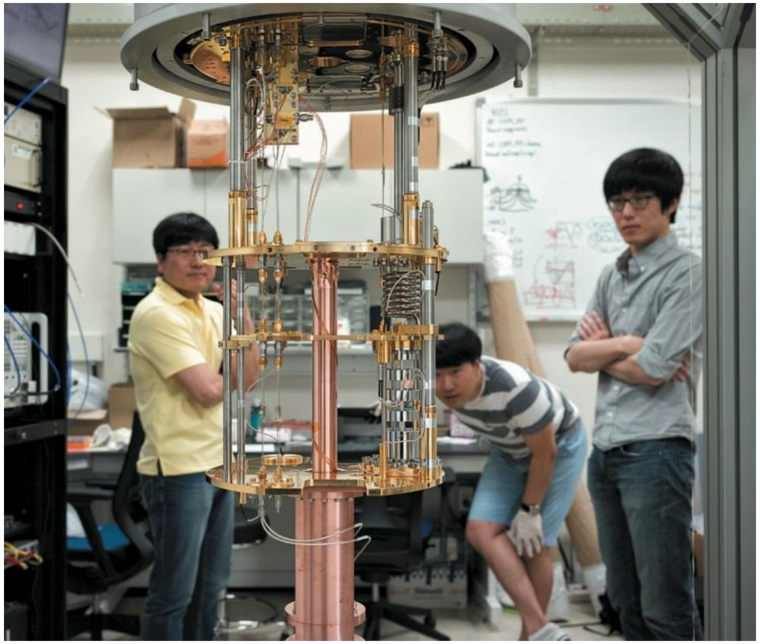


Projected reach for monopole-dipole axion mediated interaction

- Collaboration: Indiana, Nevada, Stanford Universities, CAPP.
- R&D in progress.
- Data taking in 2019.
- [Poster at Patras2016]

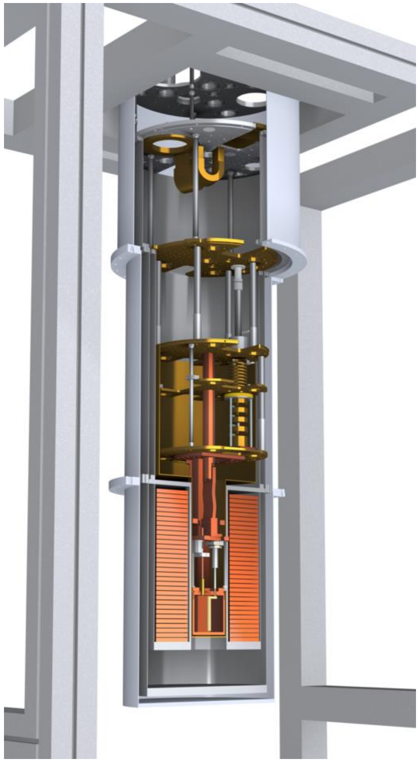


HALOSCOPE PROGRAMME IN CAPP: STATUS

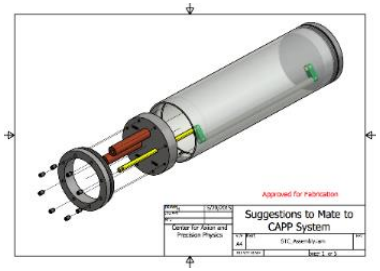


CULTASK: CAPP ULTRA-LOW TEMPERATURE AXION SEARCH IN KOREA

- New lab space - February -> June 2016
- Two Bluefors dilution refrigerators LD400
- Nominal temperature 10mK (~50mK with load)
- 8T magnet
- Cu cavity. 9cm ø -> ~2GHz -> ~10μeV axion mass
- Sapphire tuning rod



by WooHyun Chung



Talk at Patras2016

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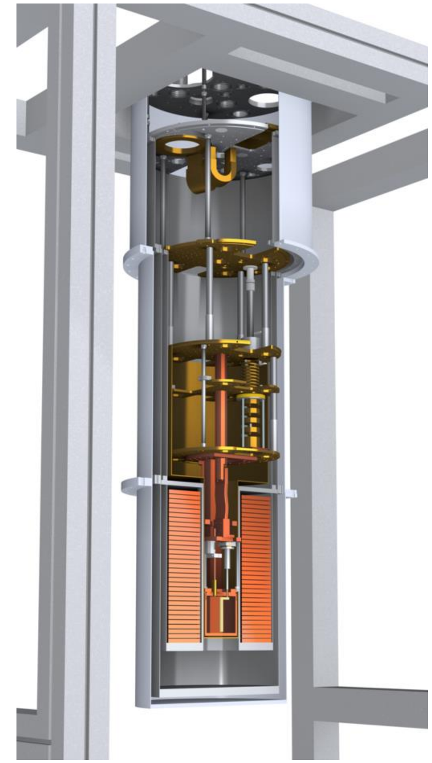

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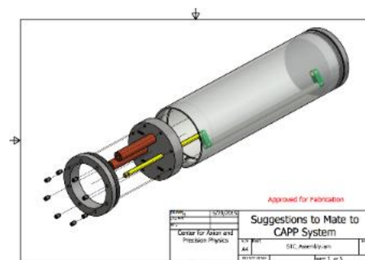
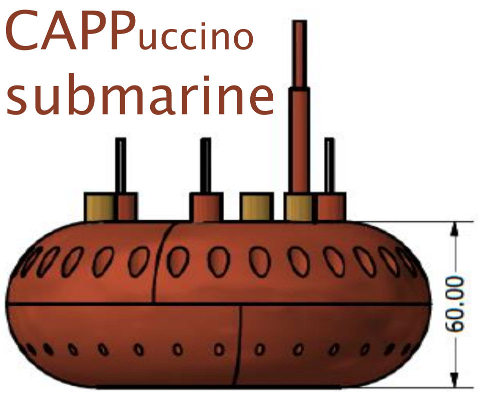


- Installations ✓
- Engineering runs ✓
- RF chain, DAQ commissioning ✓
- Cavity R&D ✓
- Reasonable sensitivity data expected in 2016.

Talk at Patras2016

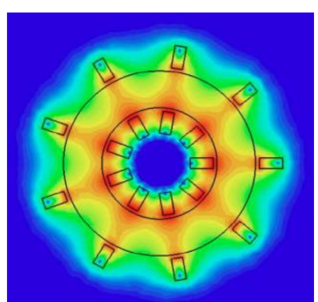
CAPPuccino SUBMARINE

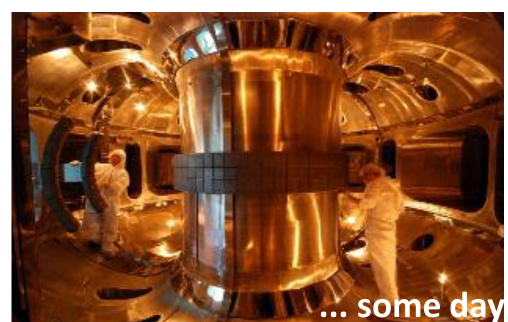


- Very small toroid for R&D
  - Major radius 1.4cm, minor radius 0.2cm.
- Precursor to small toroid
  - Magnetic field 12T. Major radius 50cm, minor radius 10cm, volume ~80 liters.
  - 1.3-1.8 GHz.
- Precursor to giant toroidal cavity
  - Magnetic field 5T. Major radius 2m, minor radius 0.5m, volume ~10,000 liters.
  - Less than 1GHz (axion mass ~4μeV).

- **Why toroid:**
  - **Better form factor (EM field coverage)**
  - **Less fringe magnetic field**
  - **No losses from mode crossing (between different EM modes)**

Talk at Patras2016

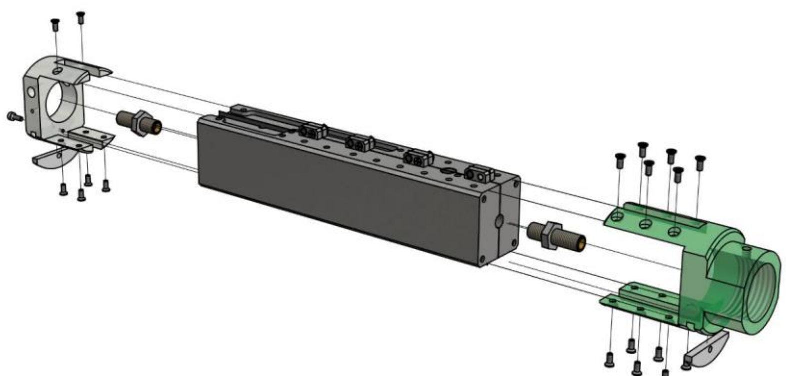




CAPP-CAST EXPERIMENT

- Collaboration with the CAST experiment at CERN.

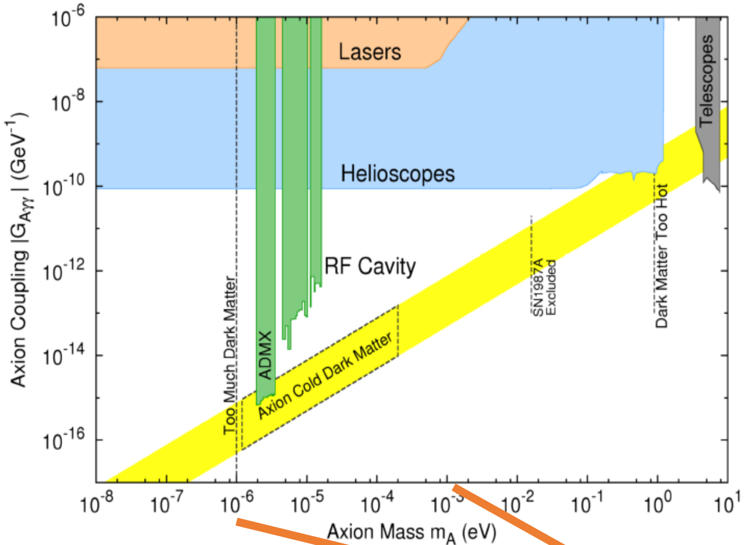
- Rectangular cavity inside the dipole magnet bore.
- Frequency 5-6 GHz. Axion mass 20-24 μeV.
- Cavity installed in June '16. ✓



[Talk at Patras2016]

SUMMARY (ROADMAP, AGAIN)

Expected coverage:



Major improvements in haloscopes expected within 5 years

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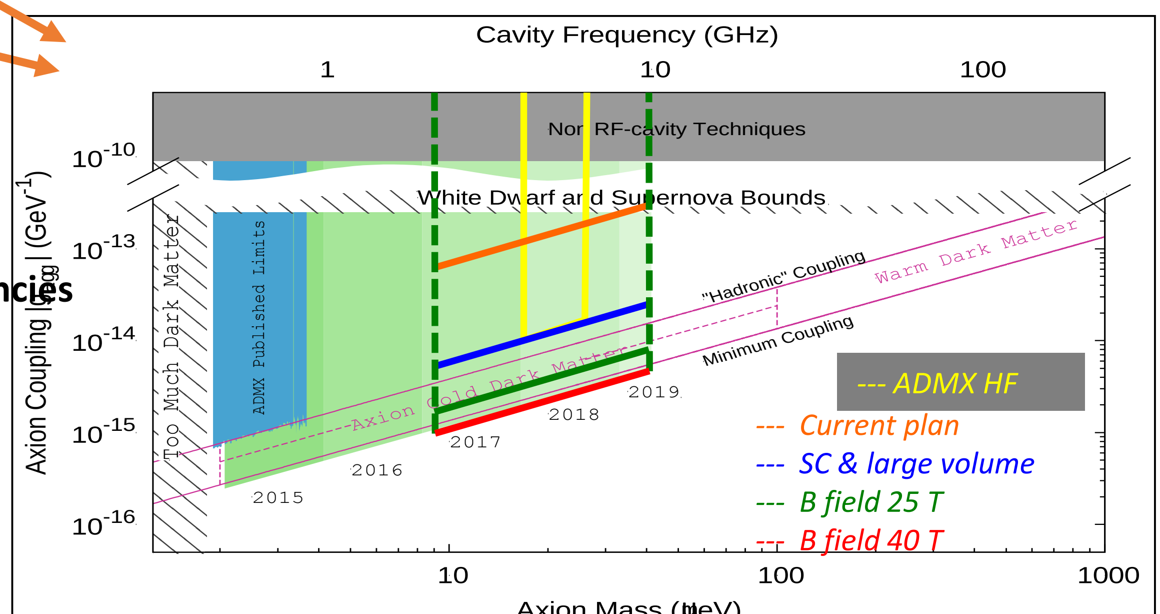

CAPP/IBS

CAPP
Center for Axion and Precision Physics Research

The IBS Center for Axion and Precision Physics Research (KAIST campus, Daejeon)

- Institute for Basic Science (IBS):
  - Founded in November 2011.
  - Currently 26 Centers.
  - https://www.ibs.re.kr/
- CAPP: Founded in October 2013:
  - http://capp.ibs.re.kr/
- Director: Prof. Yannis K. Semertzidis
- Currently:

~15 research fellows + visitor program,

~10 students, ~5 administrators.

CAPP
Center for Axion and Precision Physics Research

The IBS Center for Axion and Precision Physics Research (KAIST campus, Daejeon)

Patras 2016

KUSP

- Green-field center. Motivation to play leading role in axion searches.
- Cutting edge research (cryogenics, SC, quantum electronics, precision accelerator physics and more).
- Next generation of direct axion detection with RF cavities.
- Closing in on theoretical limit of hadronic EDMs.
- Scientific potential, education & outreach.

} The two sides of axionic CP-violation and DM searches.

Thank you

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