16th Patras Workshop on Axions, WIMPs and WISPs

DFSZ axion definitive searches at IBS/CAPP

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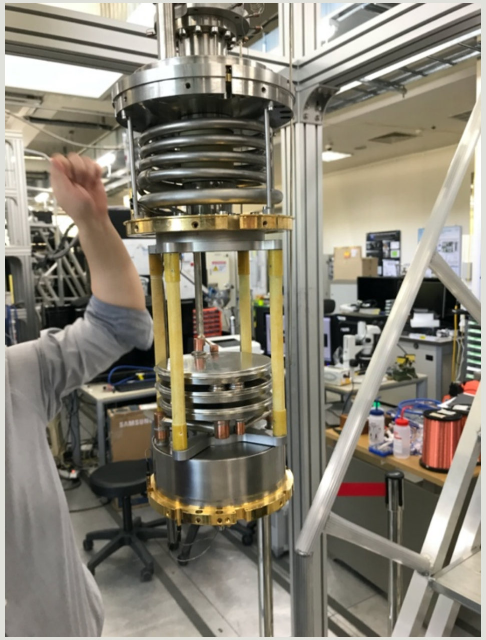
KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY AND IBS/CAPP

JUNE 17TH, 2021

CAPP-12TB Experiment Overview

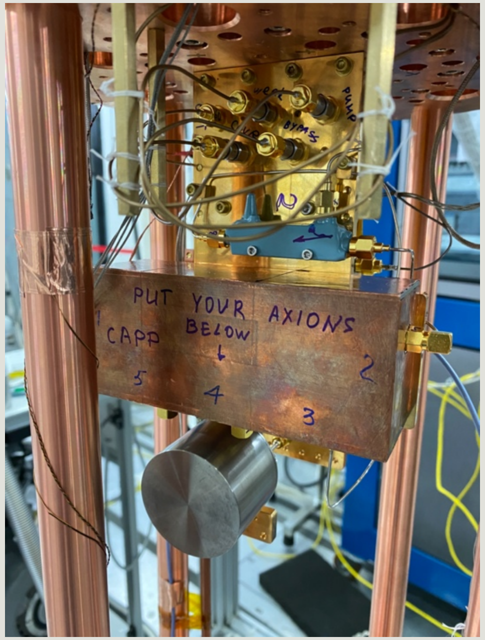
The CAPP-12TB experiment is a **DFSZ-sensitive** axion haloscope search for the mass range 3.3 – 12.4 μeV (0.8 – 3.0 GHz)



Dilution Refrigerator
1.3 mW cooling power @ 100 mK
Reaches **55 mK with load @ 12 T**

Superconducting magnet
Center field **12 T @ 4.2 K**
Bore diameter of 320 mm

Resonant Cavity
Copper tuning rod
ID 262 mm, **Q_0 ~ 100,000**

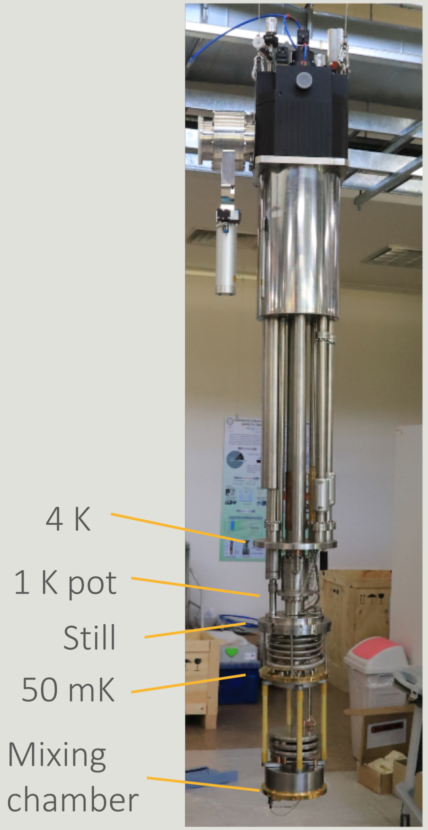


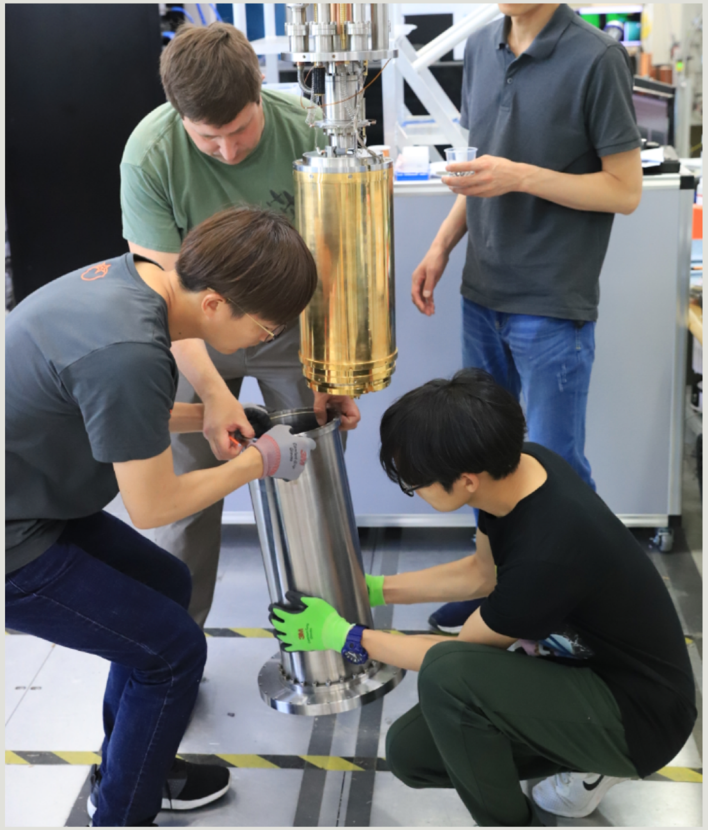
Josephson Parametric Amplifier
Several JPAs within tuning range
Noise temperature **100 – 200 mK**

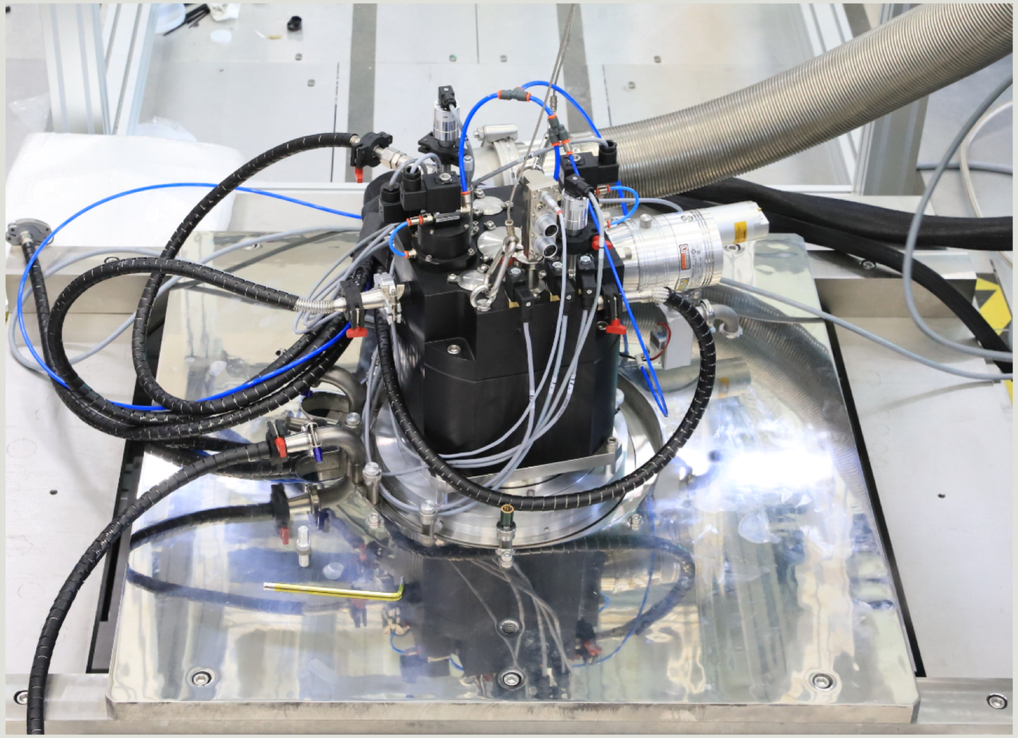
Dilution Refrigerator

Wet type dilution fridge from Leiden Cryogenics

First arrived in July 2019





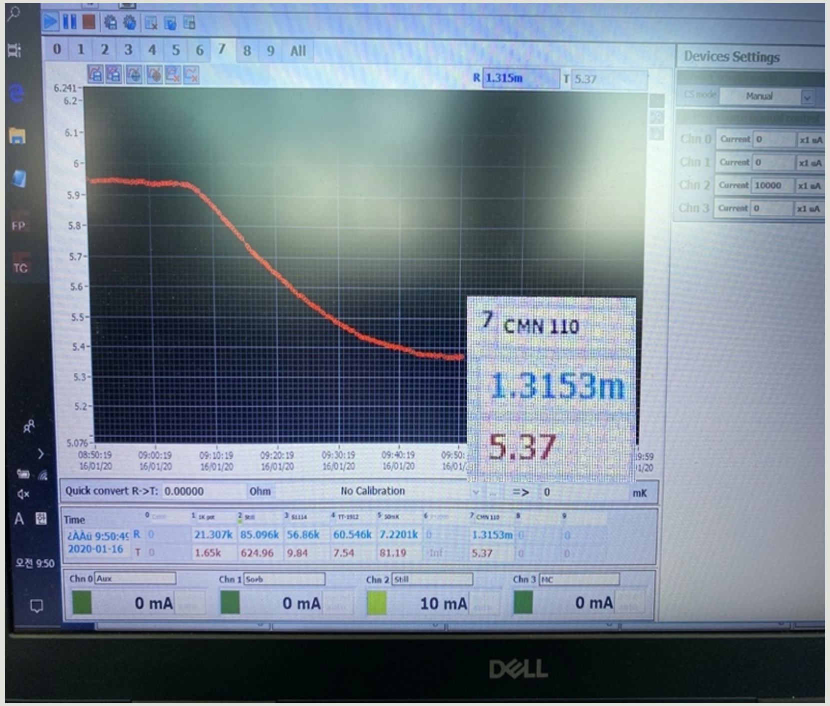


Fridge inserted at the LVP Hall of CAPP

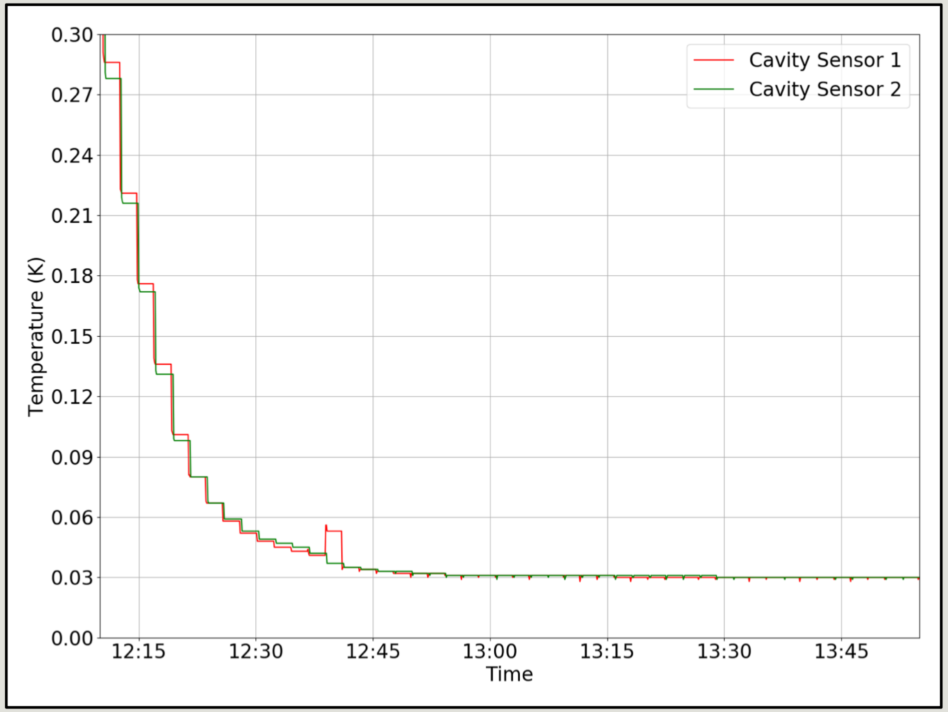
Dilution Refrigerator

The base temperature reached **5.4 mK** without any load

The cavity reaches **30 mK** when mounted without magnetic field



Without load (Mixing plate)



Cavity temperature when mounted

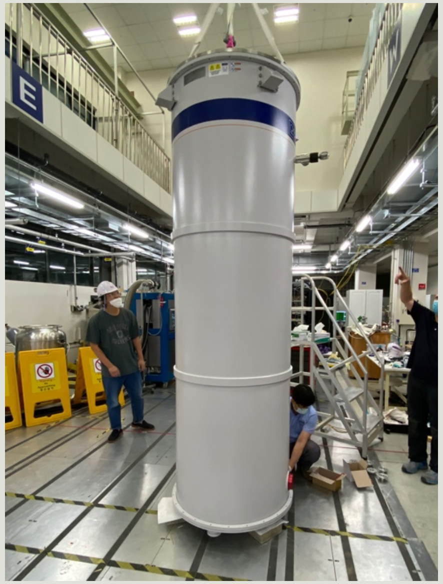
Superconducting Magnet

Magnet from Oxford Instruments

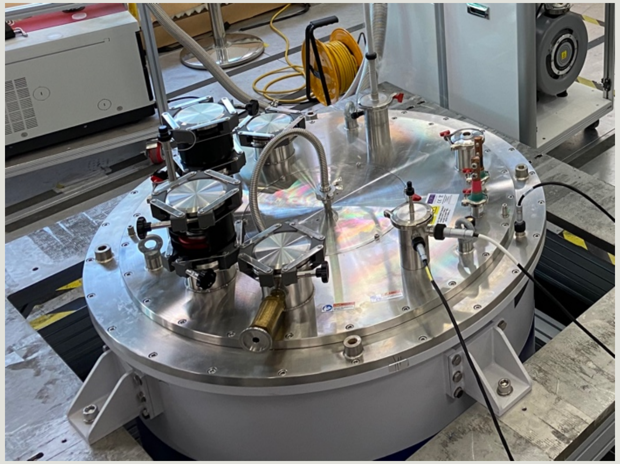
The magnet has a big bore with a diameter of 320 mm and stores approximately 5.6 MJ energy

First arrived in March 2020, assembled August 2020 (delayed due to COVID-19)

The magnet



Dewar (3 m tall!)



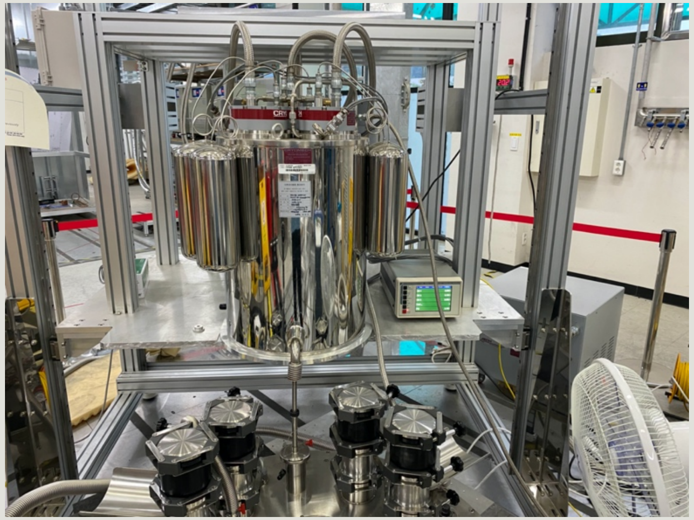
Magnet inserted in dewar at LVP Hall

Superconducting Magnet

The magnet successfully reached 12 T and operates in both driven and persistent modes

Reliquefier installed to save liquid helium (liquefaction rate is 80 L/day)

12 T shown in **Magnet (T)** for both driven (left) and persistent (right) mode

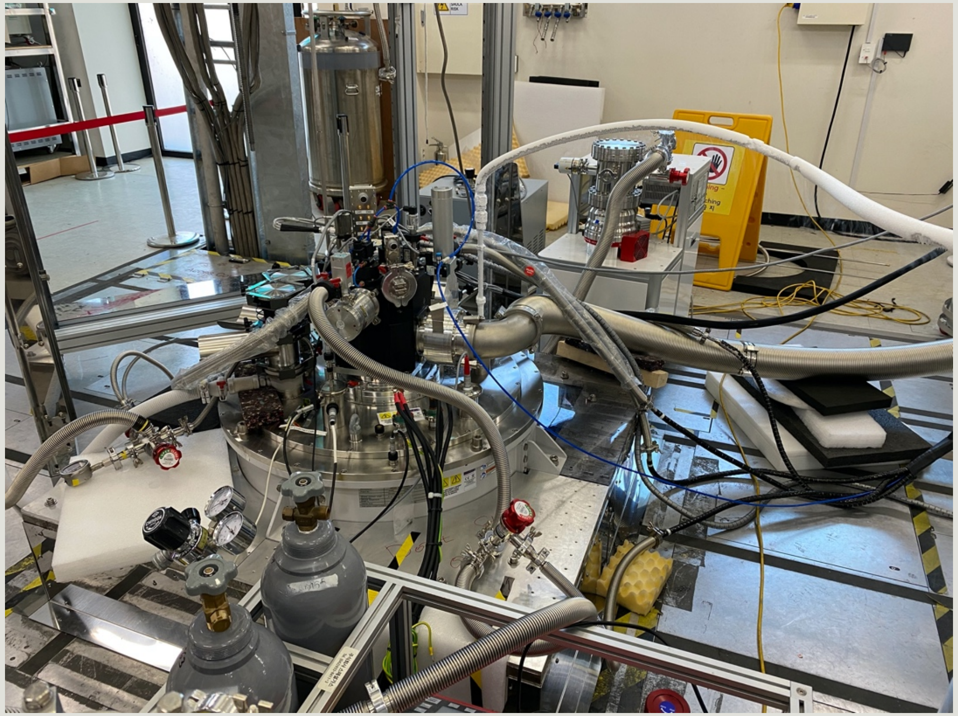


Reliquefier in operation

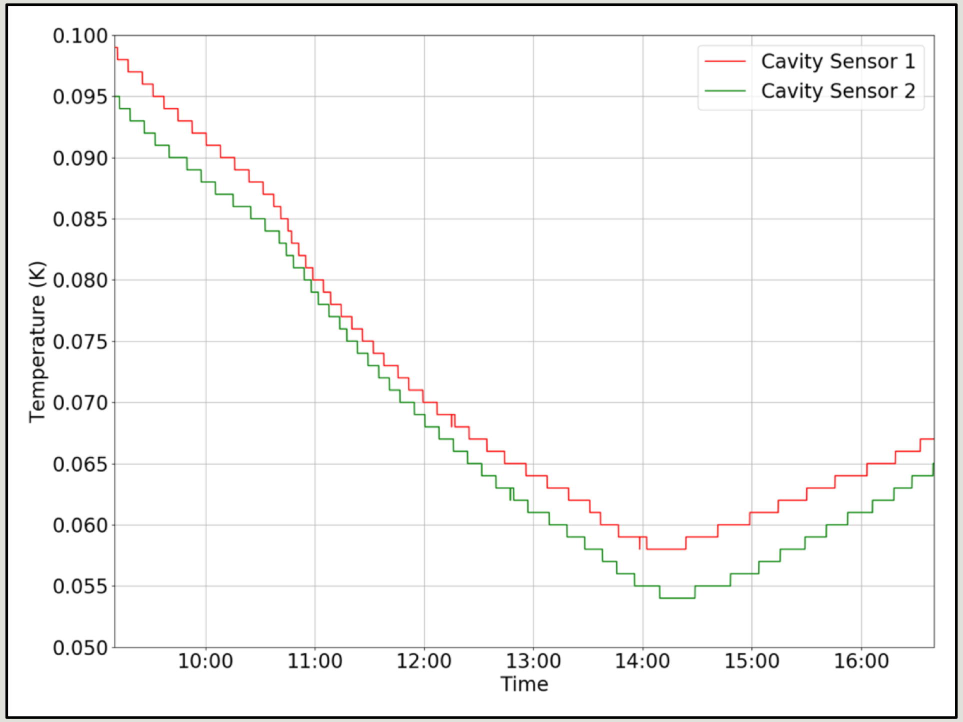
Superconducting Magnet

The dilution fridge has been tested under the maximum magnetic field of 12 T

The cavity cools down to **55 mK at 12 T**



Magnet and fridge tested together

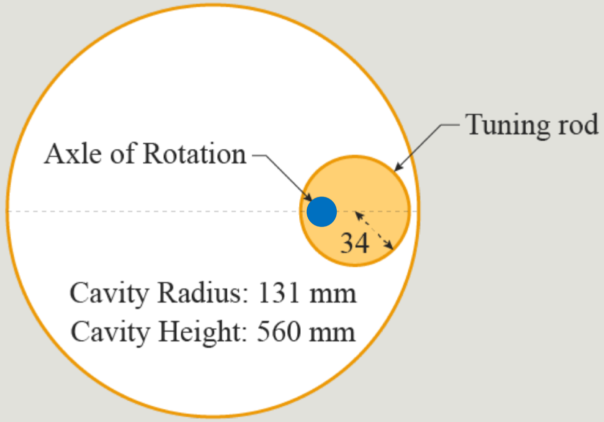


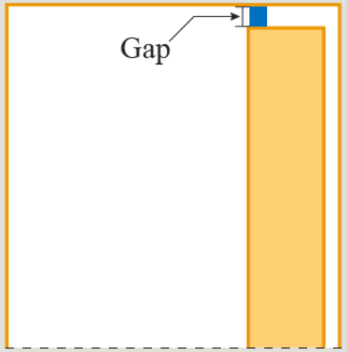
Cavity temperature at 12 T

CAPP-12TB Cavity

Copper cavity with a copper tuning rod (Volume: 30 L)

Frequency range: 0.99 – 1.19 GHz

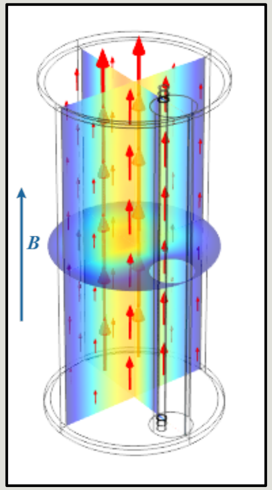




Tuning rod moves about the axle. **Frequency increases towards center**

Rotation angle defined to increase when rotating counterclockwise

Tuning rod has 0.5 mm **gap** to ensure movement (not to scale in figure)



TM_{010}–like modes are used for the experiment for their high C (form factor)

Closest to cavity walls

ν_c : 0.99 GHz

Q_L: 35700 (low T)

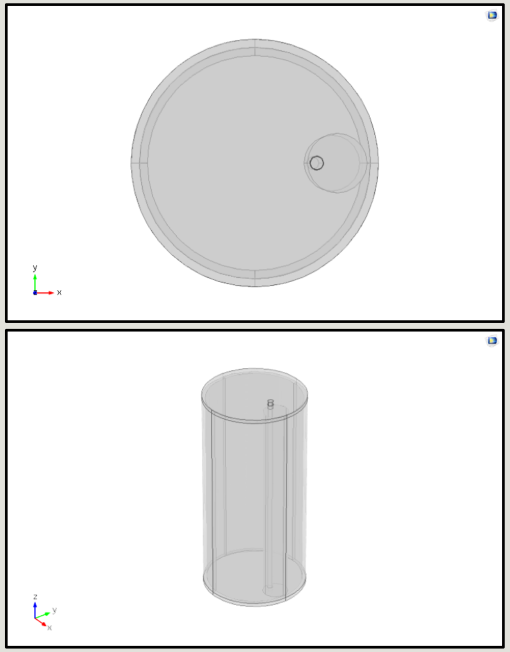
C: 0.57

$$C = \frac{\left|\int_V d^3x\ \vec{E}\cdot\vec{B}\right|^2}{B_0^2 V \int_V d^3x\ \varepsilon_r \left|\vec{E}\right|^2}$$

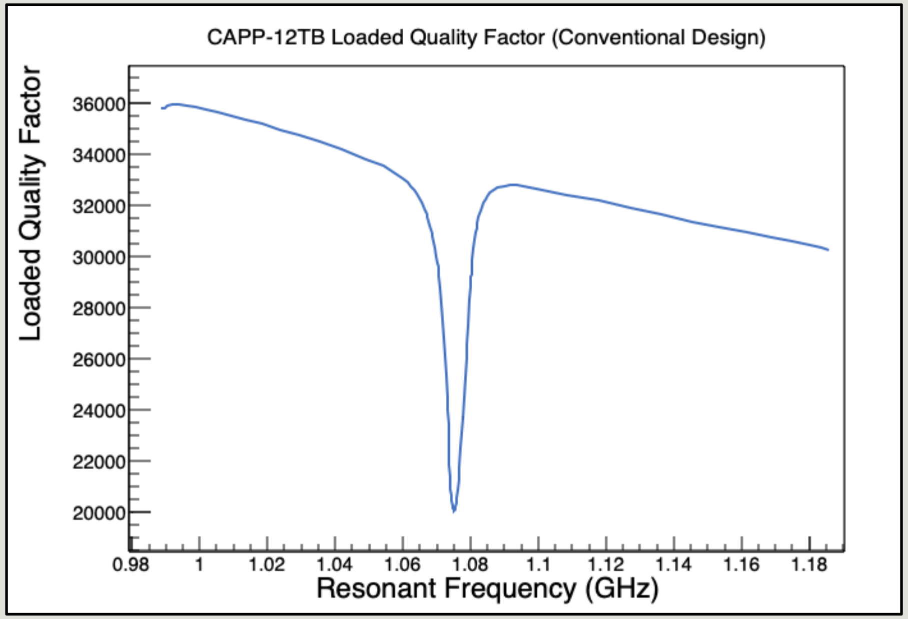
Cavity Design Using COMSOL Simulations

The cavity geometry is simulated using COMSOL eigenfrequency studies of the RF module

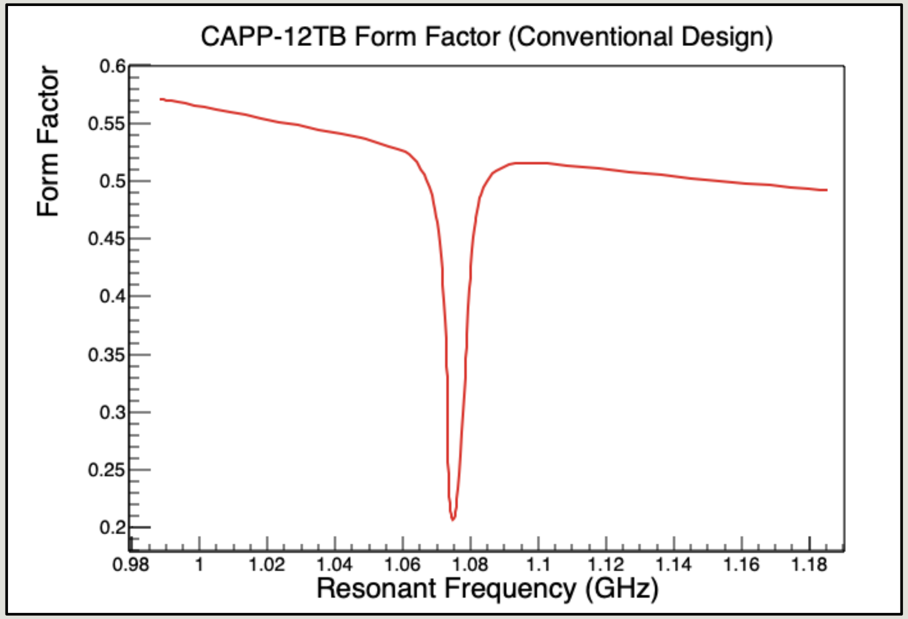
There is a drop in both the loaded quality factor (Q_L) and form factor (C) of the cavity mid-rotation (right), which greatly reduces the axion scan rate ($\propto C^2 Q_L$)



(Top view / side view)



Q_L@ 4 K assuming $\beta = 2$

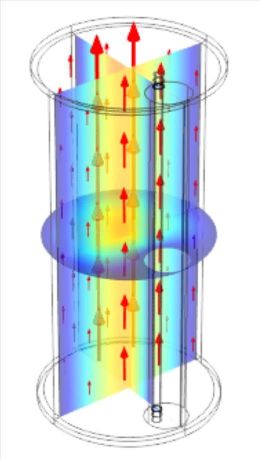


C with simulated electric field from COMSOL and simulated magnetic field of actual magnet

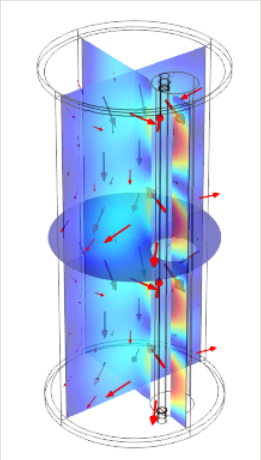
Mode mixings found in cavity simulations

"Mode mixings" occur due to capacitive effects in the gap between the copper tuning rod and cavity endcap

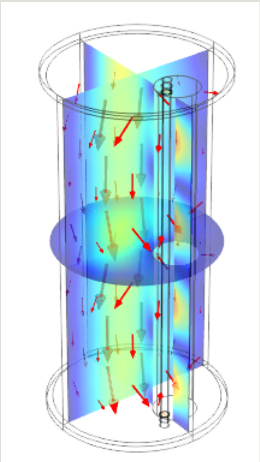
Orthogonal TE/TM modes are perturbed and both modes coexist at the same frequency



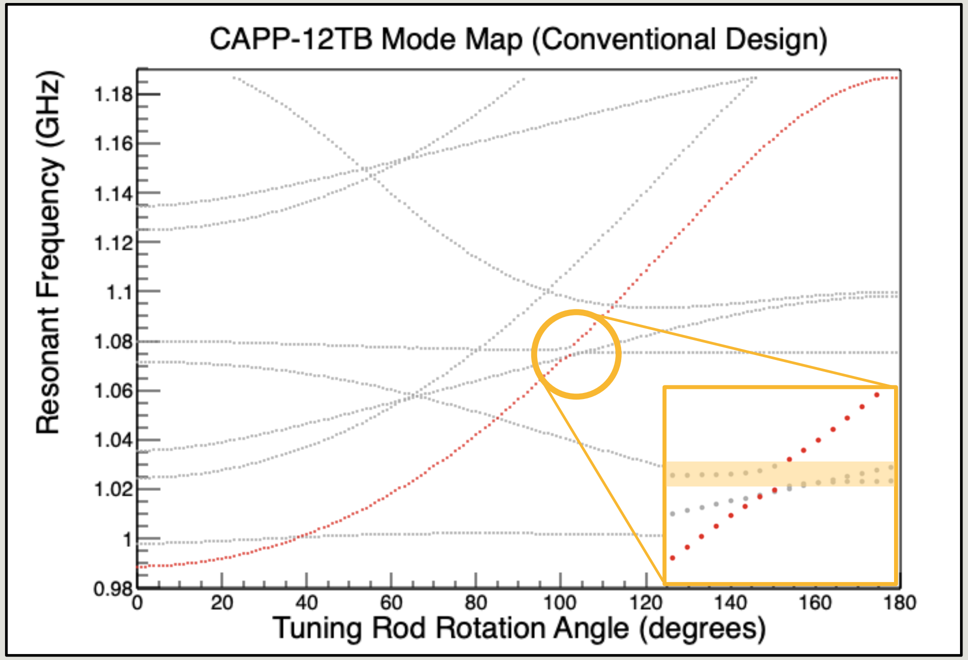
Ordinary
TM_{010}–like mode



Mode mixing I
ν_c: 1.073 GHz
Q_L: 24400
C: 0.36



Mode mixing II
ν_c: 1.077 GHz
Q_L: 18400
C: 0.14

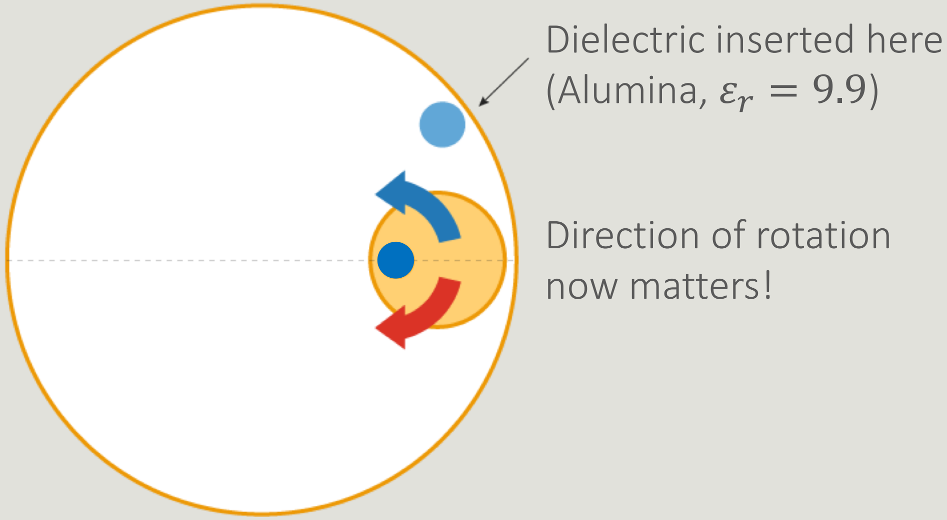


There is a gap of frequencies inaccessible when using TM_{010}–like modes (points in red)

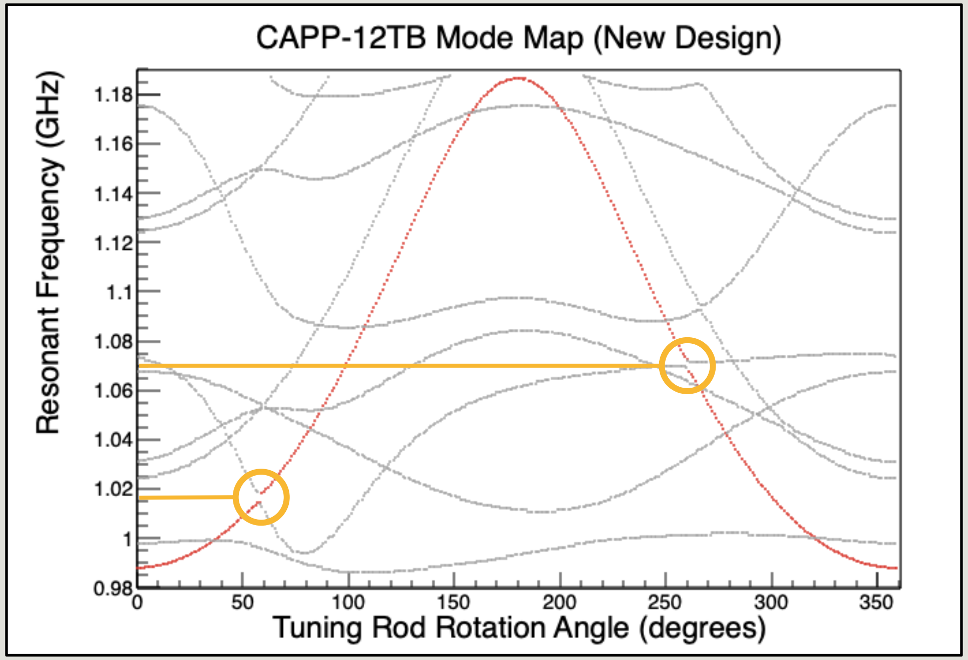
Resolving the mode mixing problem

Placing a dielectric insert in the cavity changes the mode mixing region

Previously unscannable frequencies are now available by rotating in the opposite direction



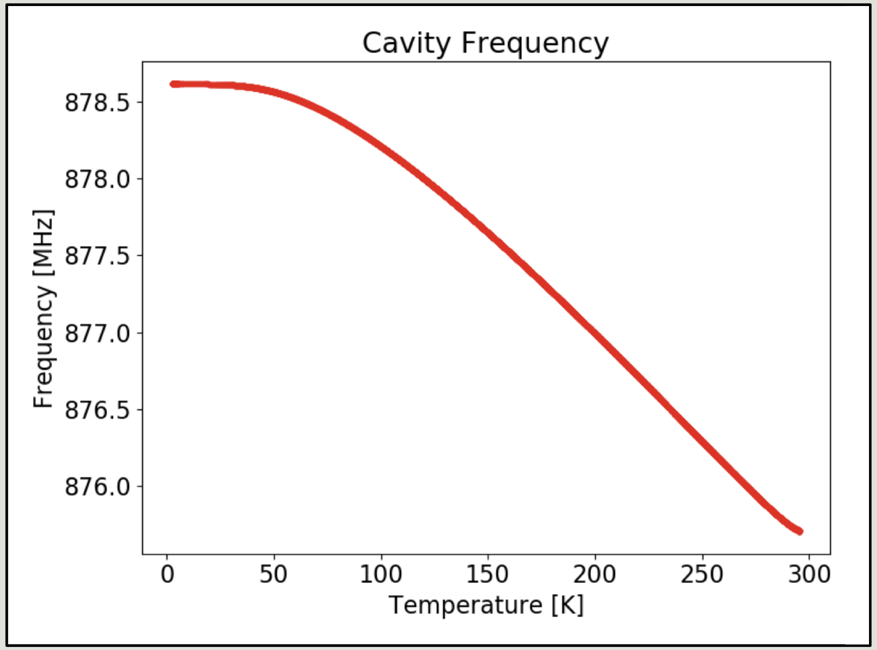
From APS 2019 Meeting Slides

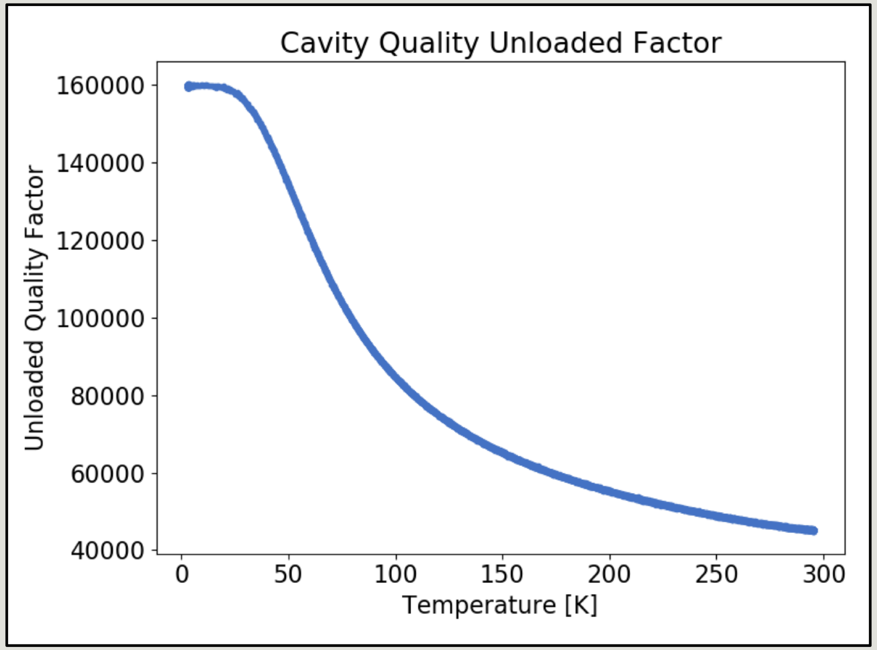


Mode mixings are now at different frequencies

Empty cavity measurements

The empty cavity has an unloaded quality factor (Q_0) of 160,000 at 4 K





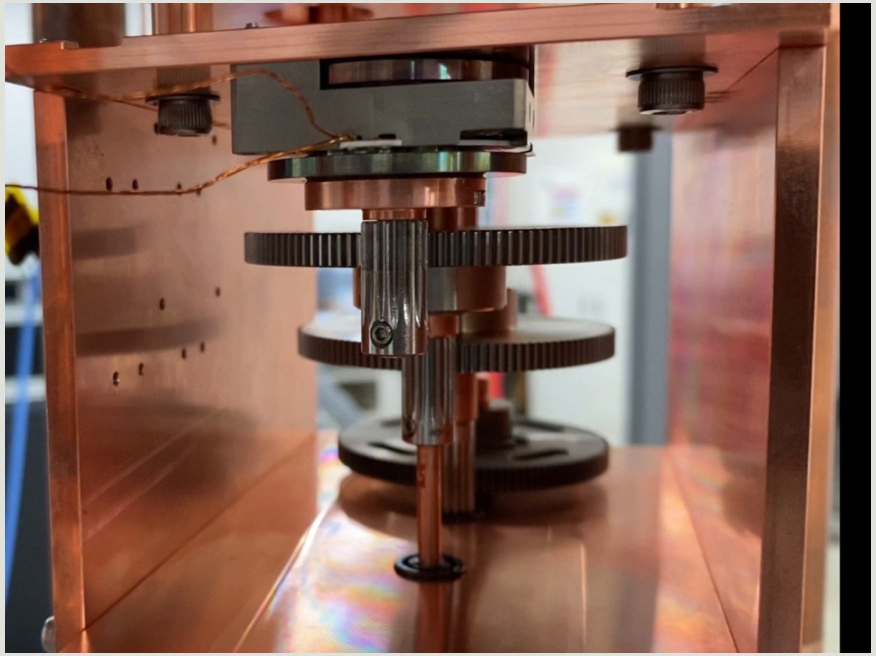
Resonant frequency / Quality factor of empty cavity down to 4 K

Tuning mechanism

The cavity is tuned using a series of gears connected to a piezo driven rotator

Gears multiply force from piezo to provide enough force to rotate the tuning rod

Various configurations under test to ensure a stable tunable mechanism at low temperatures

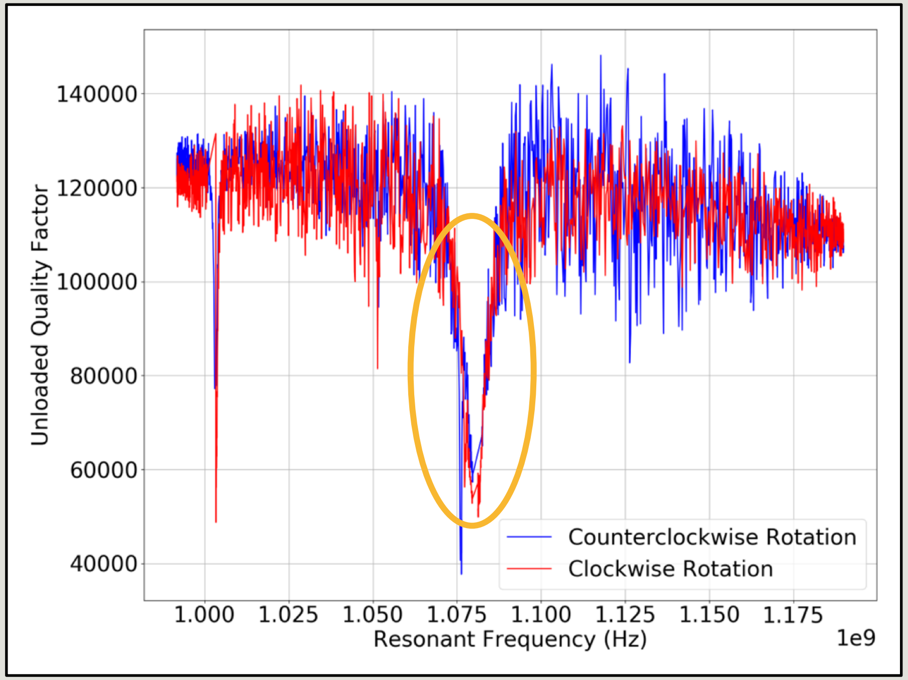


Cavity response over tuning

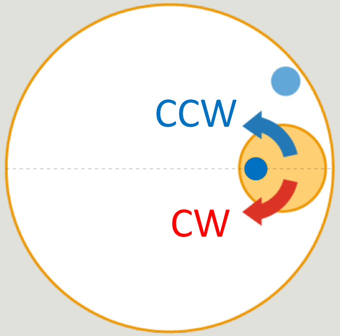
The unloaded quality factor of the cavity is over 100,000 outside of mode mixing regions at 4 K

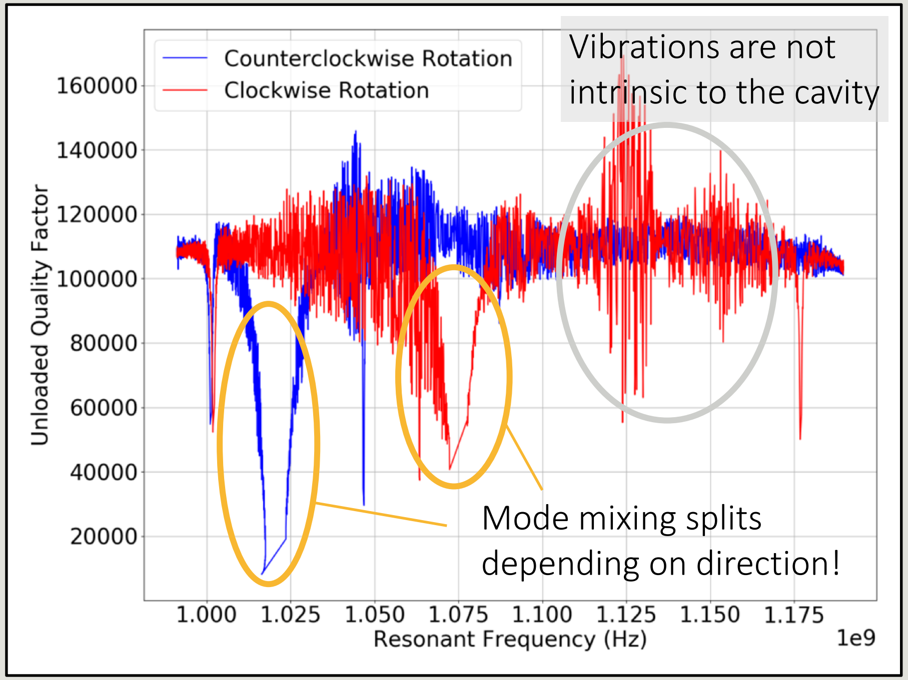
Cavity scans are done in a full, 360 degrees rotation

Instability in quality factor due to ambient vibrations



No dielectric insert





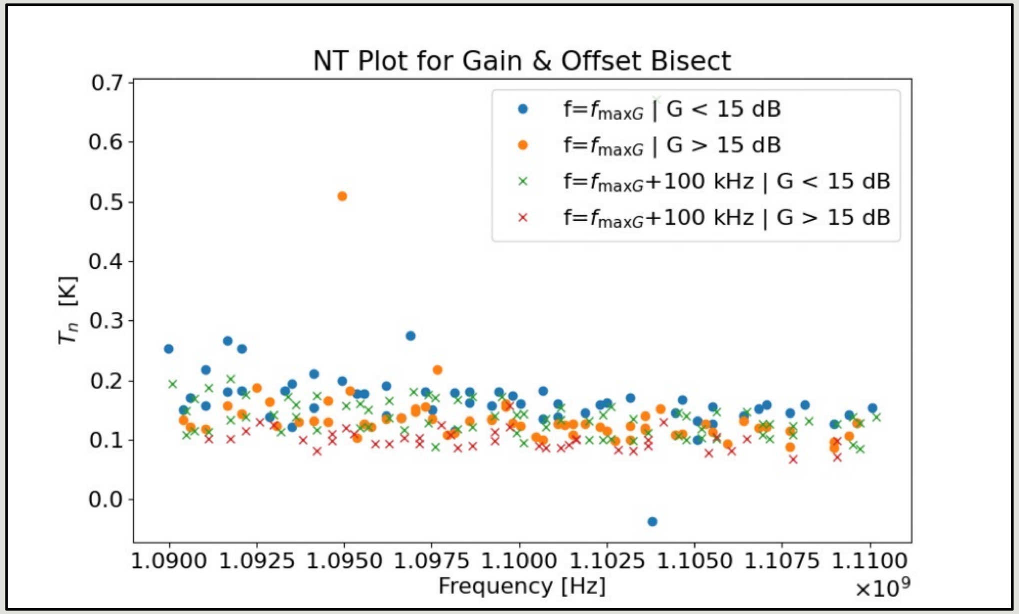
Dielectric insert - **changes mode mixing regions**

RF Chain and JPA operation

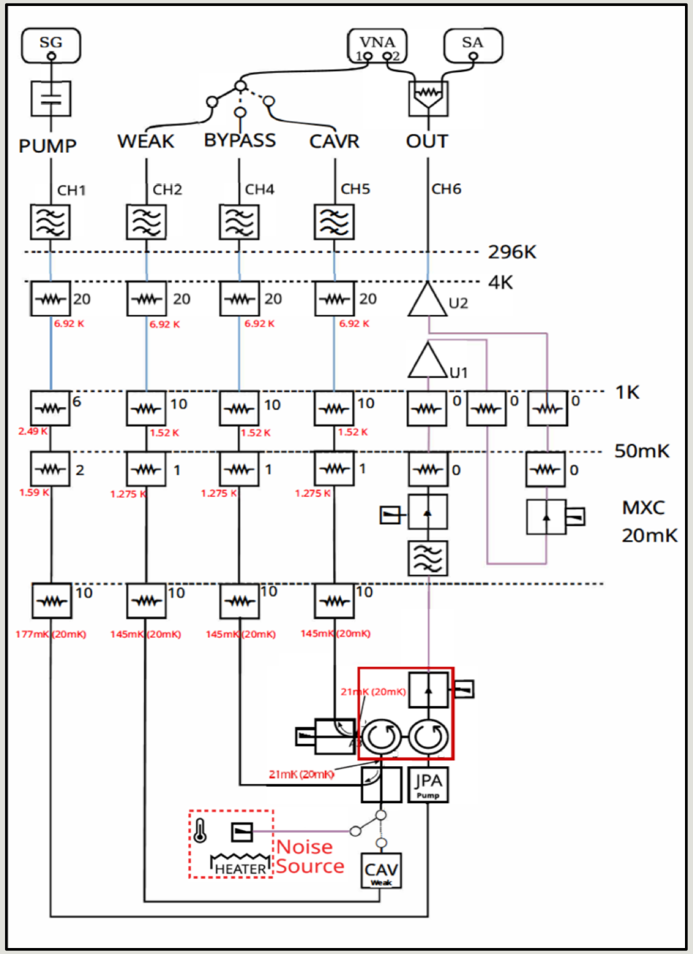
RF chain has been fully implemented in system

Multiple JPAs will be used to cover the full range (0.99 – 1.19 GHz)

A JPA with the working range 1.09 – 1.11 GHz is currently installed (T_n measured with Y-factor method in-situ using a noise source)

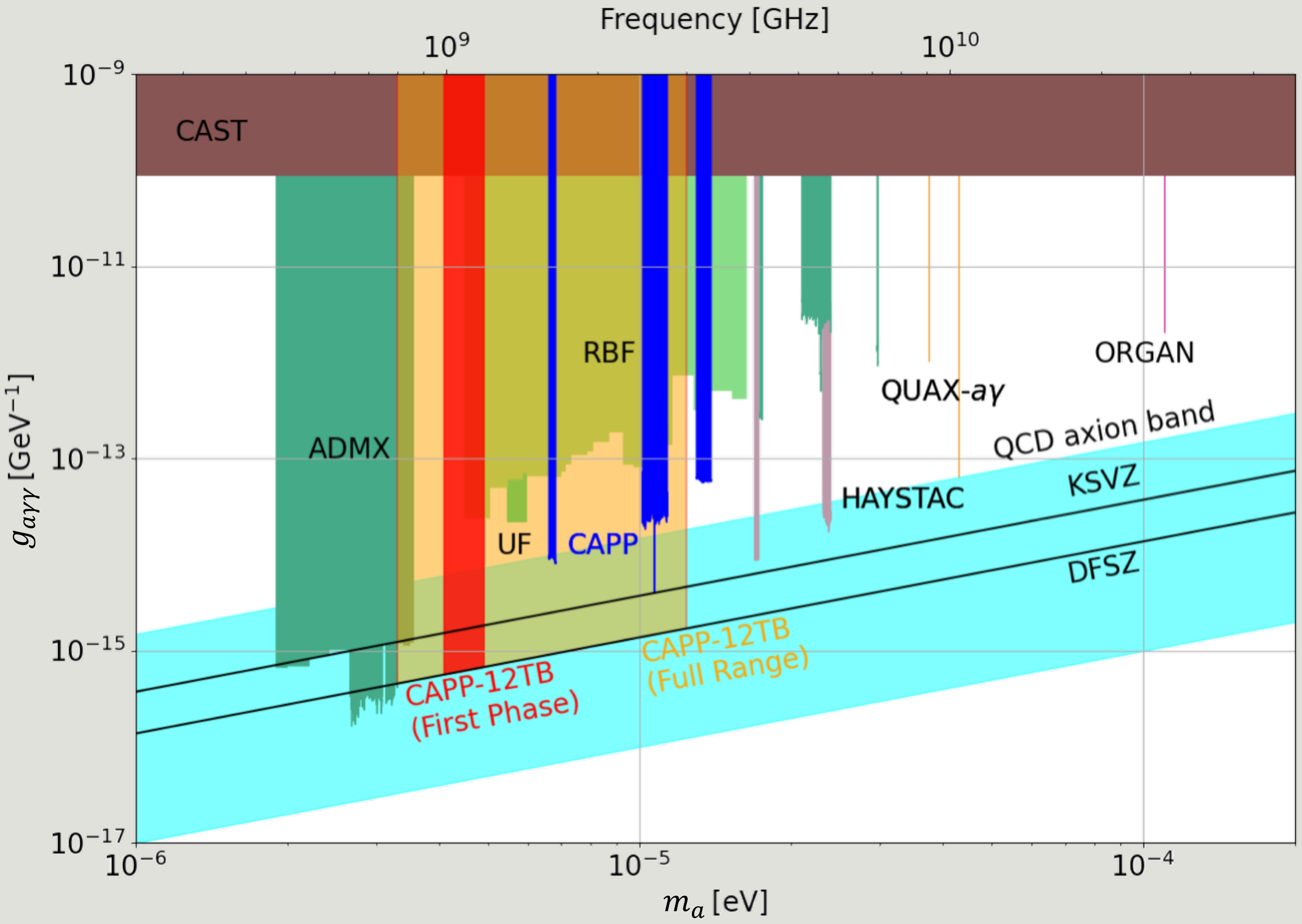


Noise temperature (T_n) of full chain for current JPA



RF Chain schematic

Outlook of the CAPP-12TB Experiment



Target frequency range (at **DFSZ sensitivity**)

First phase

0.99 – 1.19 GHz

(4.10 – 4.92 μeV)

Scan Rate: **410 MHz/yr** (SNR = 5)

Benchmark parameters below

B	V	C	Q_L	T_S
12 T	30 L	0.52	36000	250 mK

Full scan range

0.8 – 3.0 GHz

(3.3 – 12.4 μeV)

The CAPP-12TB experiment will start taking data for the first phase this year

Summary & Future plans

All components of the experiment have progress and are currently being worked on

The CAPP-12TB cavity currently is configured to scan the 0.99 – 1.19 GHz with an asymmetric design to avoid mode mixings

The dilution refrigerator can cool down the cavity to 55 mK with the superconducting magnet at 12 T

The cavity signal is amplified with an RF chain that includes nearly quantum-noise-limited JPAs that operate within the tuning range

The CAPP-12TB experiment is planning to take data within this year