17th Patras Workshop on Axions, WIMPs and WISPs

CAPP
Center for
Axion and Precision
Physics Research

Preliminary results for DFSZ axion definitive searches at IBS-CAPP

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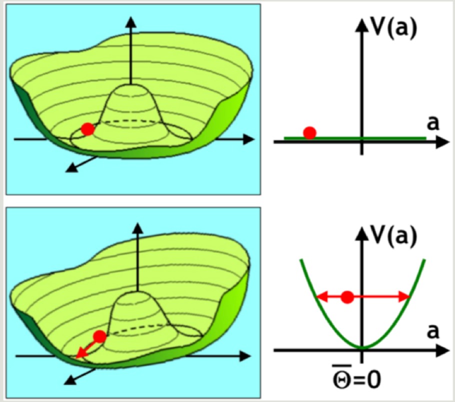
The Axion

The Strong CP Problem

The QCD Lagrangian has a CP-violating term $\mathcal{L}_{\bar{\theta}} = \frac{g^2}{32\pi^2}\bar{\theta}G_a^{\mu\nu}\tilde{G}_{a\mu\nu}$

Neutron EDM is not observed: $d_N \sim \bar{\theta}\frac{e}{m_N^2}\frac{m_u m_d}{m_u+m_d} \sim 10^{-16} \cdot \bar{\theta} e\ \mathrm{cm}$

Current limit: $|d_N| = \left(0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}\right) \times 10^{-26} e\ \mathrm{cm}\ (\bar{\theta} \lesssim 10^{-10})$



The axion is the result of the explicit determination of $\bar{\theta}$

Peccei-Quinn theory: Implements new $U(1)$ symmetry

A $U(1)_{PQ}$ symmetry is introduced to dynamically eliminate all effects of CP-violation for all orders

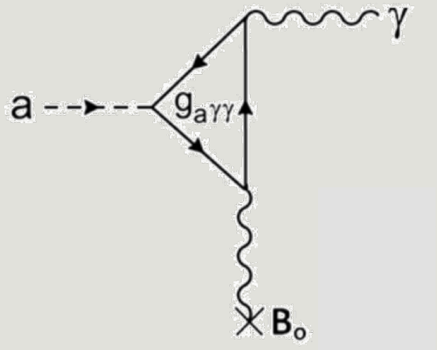
Implies existence of pseudo-Goldstone boson, the **axion**

Axions and Dark Matter

Axion Properties

Axion mass $m_a \approx 5.691(51)\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)$ meV (f_a: axion decay constant)

$$\mathcal{L}_{a\gamma\gamma} = \left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$



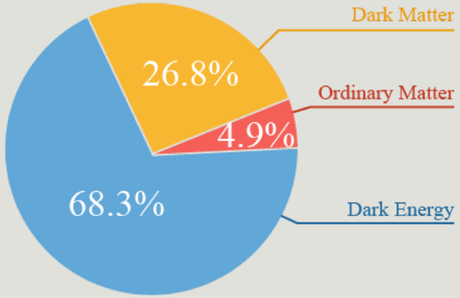
A strong magnetic field converts the axion into a photon which can be detected as a signal cavity experiments

Dark Matter

Evidence from galaxy rotation curves, etc.

Now accepted as part of ΛCDM model, constitutes 26.8% of energy budget

Candidates: WIMPs, **axions**, neutrinos, etc.



Energy budget of the universe

Axion Detection Using Microwave Cavity

The **axion haloscope** is a resonant axion search using microwave cavities

The axion frequency is unknown – the resonant cavity must be tunable for a range of frequencies

① **Cavity** has various resonant modes which enhances the signal power of converted photon

② **Tuning rods** are required to change the resonant frequency of cavity, usually copper or dielectric

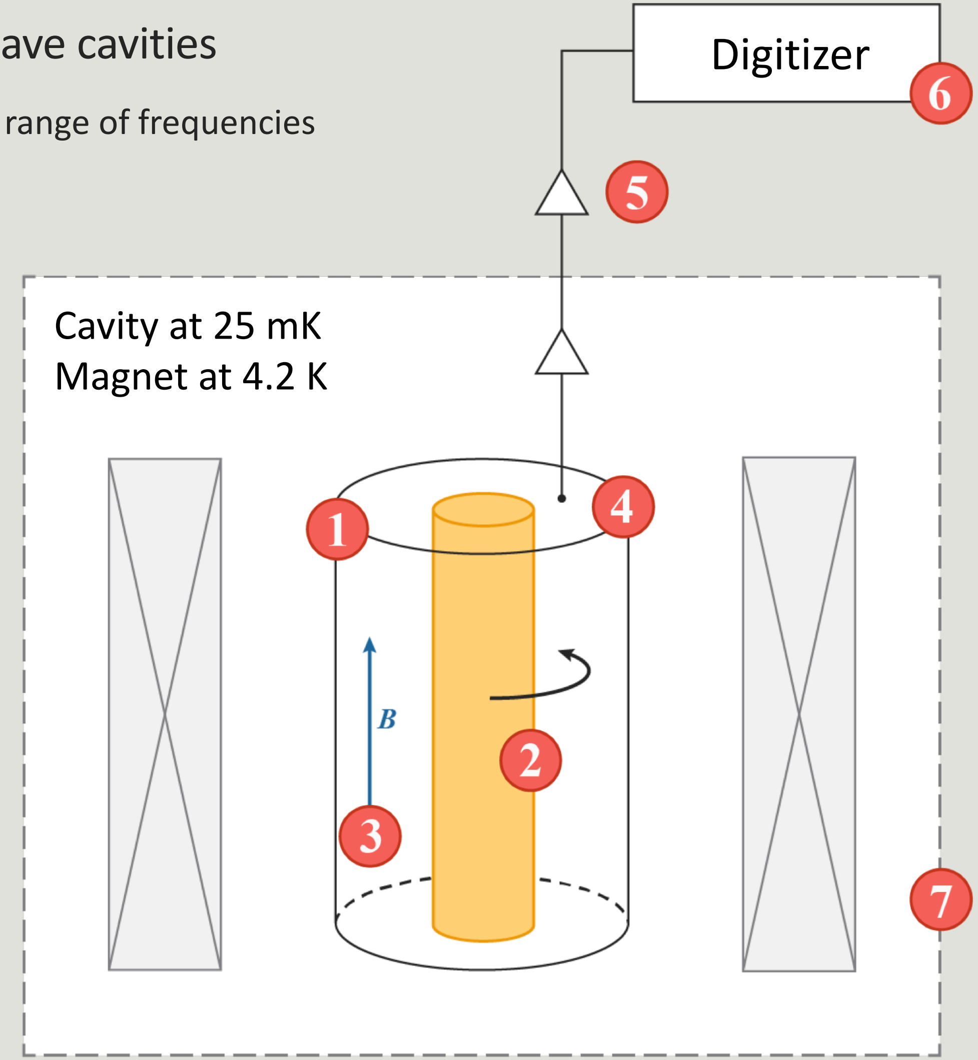
③ External static **magnetic field** allows axion to photon conversion

④ **Antenna** used to receive signal (Signal power depends on coupling)

⑤ **JPA** and other amplifiers in and outside cryostat amplify the signal

⑥ Signal is studied using a **digitizer** in the frequency domain

⑦ Experiments are conducted inside a cryostat and dilution fridge at **low temperatures** to reduce noise power



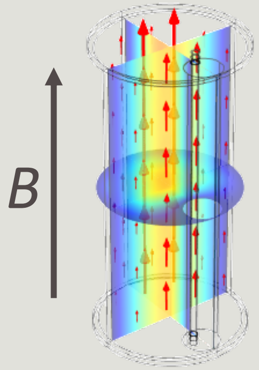
Axion Resonant Cavity and Signal Power

The CAPP-12TB experiment uses the TM_{010}-like mode to maximize the signal power

$\boldsymbol{C}$: Form factor, depends on internal electric field of mode and external magnetic field

Other factors: magnetic field (B_{avg}), volume (V), loaded quality factor (Q_L), frequency (ν), antenna coupling (β)

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



Ordinary
TM_{010}–like mode
Form factor: 0.6

$$P_{\mathrm{signal}} = 22.51\ \mathrm{yW}\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{B_{\mathrm{avg}}}{10.31\ \mathrm{T}}\right)^2\left(\frac{V}{36.85\ \mathrm{L}}\right)\left(\frac{C}{0.6}\right)\left(\frac{Q_L}{35000}\right)\left(\frac{\nu}{1.1\ \mathrm{GHz}}\right)\left(\frac{\rho_a}{0.45\ \mathrm{GeV/cc}}\right)$$

(when $\beta = 2$)

$\boldsymbol{g_\gamma}$: 0.36 (-0.97) for DFSZ (KSVZ) axions $\boldsymbol{\rho_a}$: Axion density in galaxy halos

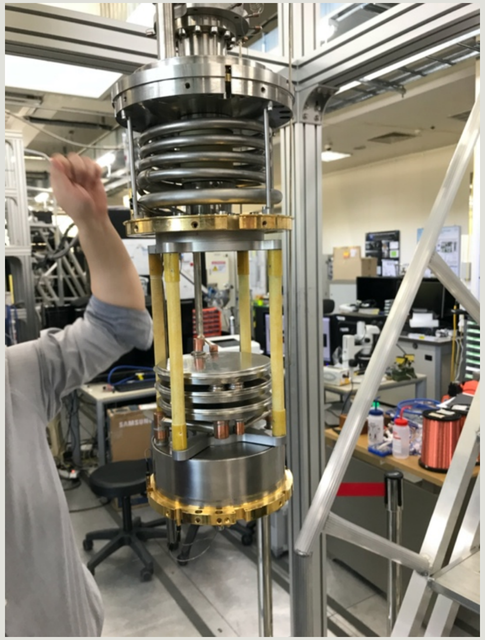
The experiment also needs to consider scan rate

Scan Rate $\propto g_\gamma^4 B_0^4 V^2 C^2 Q_L T_S^{-2}\mathrm{SNR}^{-2}$

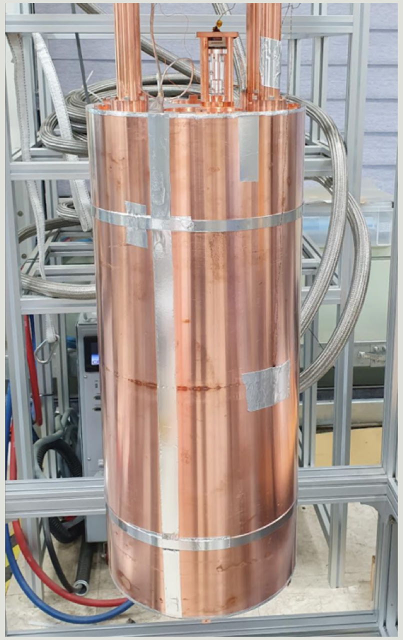
$\boldsymbol{T_S}$: Total system noise temperature **SNR**: Target signal-to-noise ratio

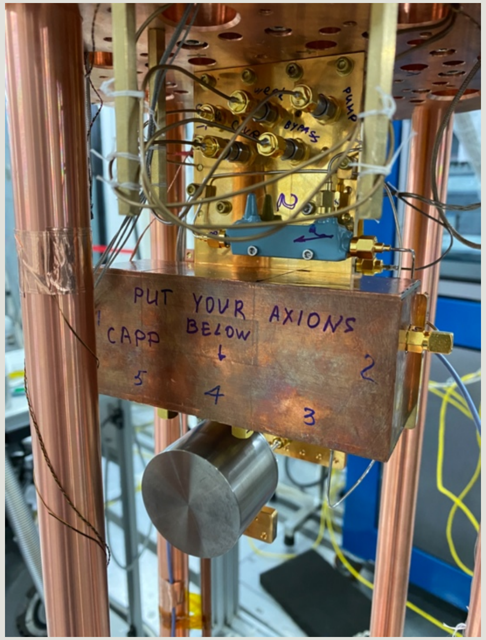
CAPP-12TB Experiment Overview

The CAPP-12TB experiment is a **DFSZ-sensitive** axion haloscope search for the mass range 3.3 – 16.5 μeV (0.8 – 4.0 GHz)


Dilution Refrigerator
1.3 mW cooling power @ 100 mK
Reaches **25 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 272 mm, **Q_0 ~ 100,000**

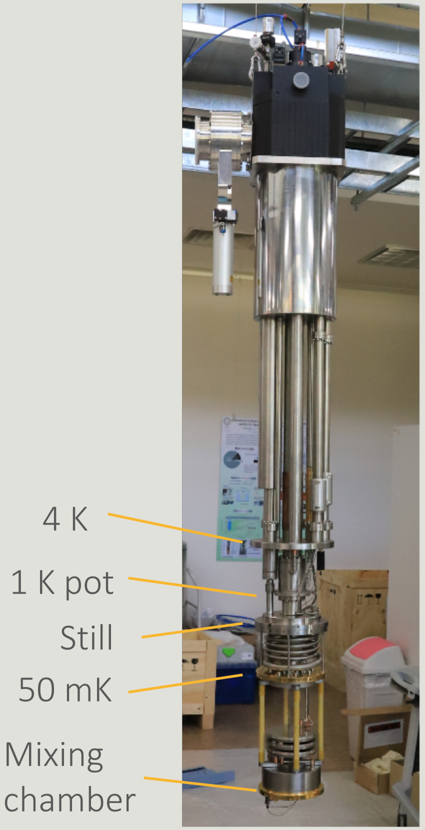


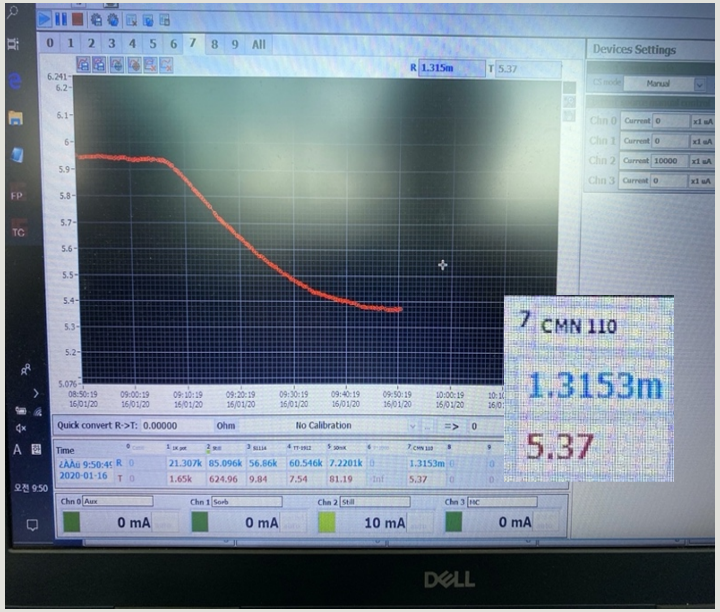
Josephson Parametric Amplifier
Several JPAs within tuning range
Noise temperature **100 – 200 mK**

Dilution Refrigerator

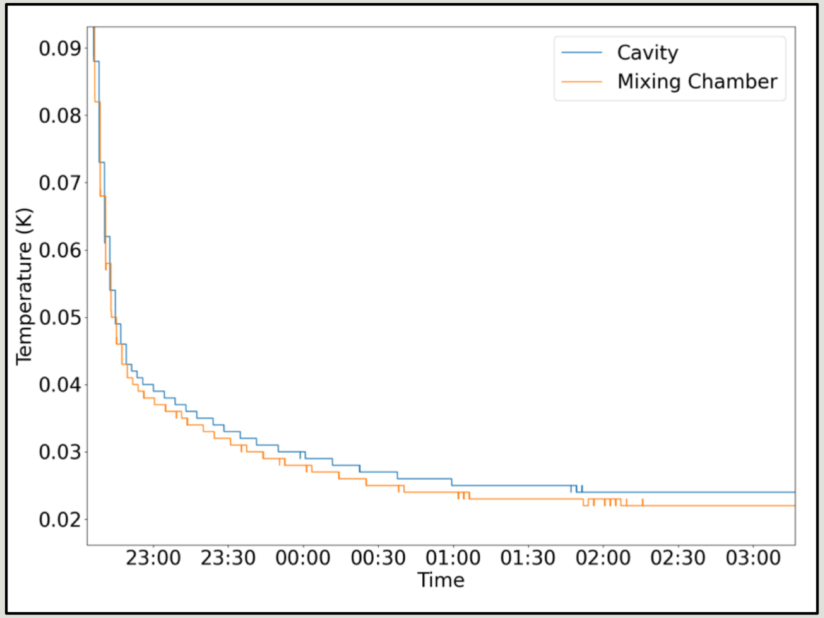
Wet type dilution fridge from Leiden Cryogenics (First arrived in July 2019)

The base temperature reached **5.4 mK** without any load, and **22 mK** when mounted





Without load (Mixing plate)



With load (Mixing plate)

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 and support structure

Field (T) 12.00001

Magnet (T) 12.00001

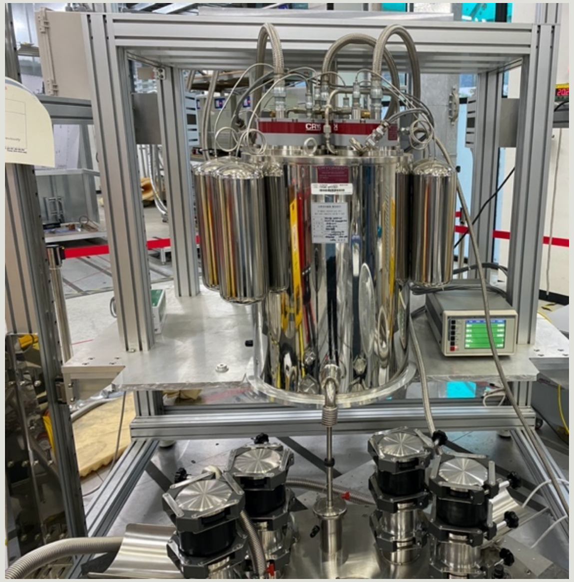
Voltage (V) 2.1458

Field (T) -0.00000

Magnet (T) 12.00001

Voltage (V) 0.0000

12 T shown in **Magnet (T)** for both driven (top) and persistent (bottom) mode

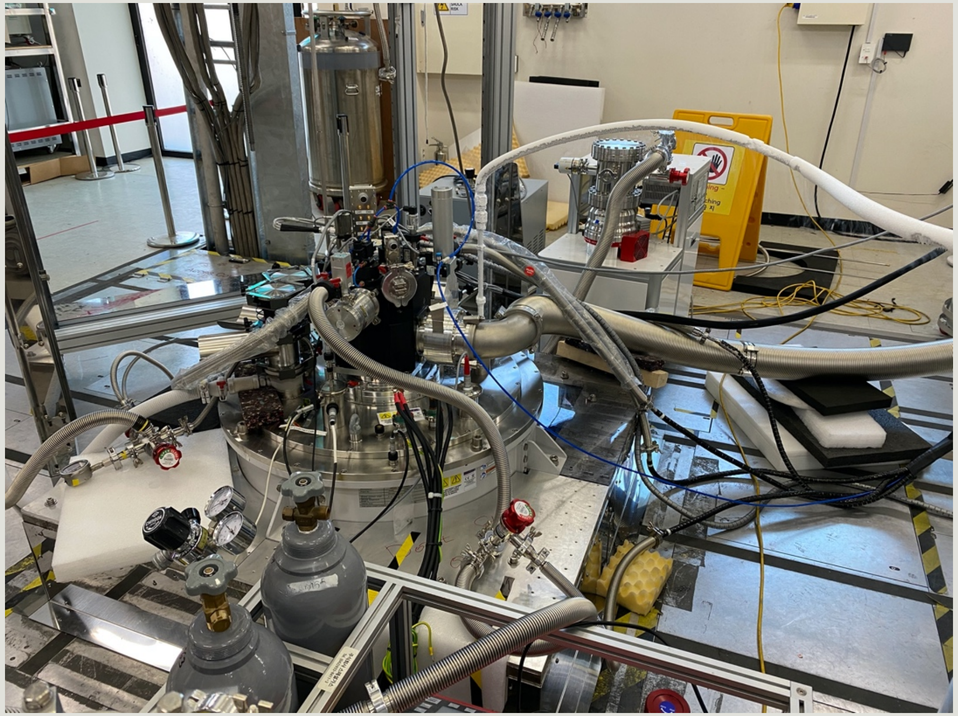


Reliquefier in operation (liquefaction rate is 80 L/day)

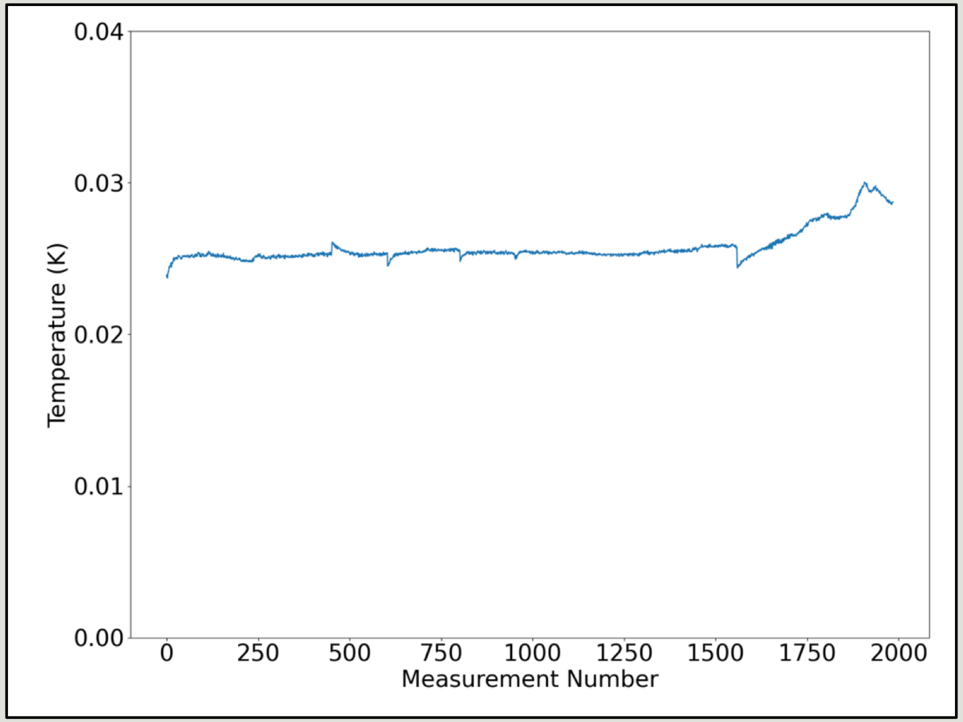
Superconducting Magnet

The dilution fridge was tested under the maximum magnetic field of 12 T in 2021

The cavity cools down to **25 mK at 12 T**: data acquisition began in March 2022

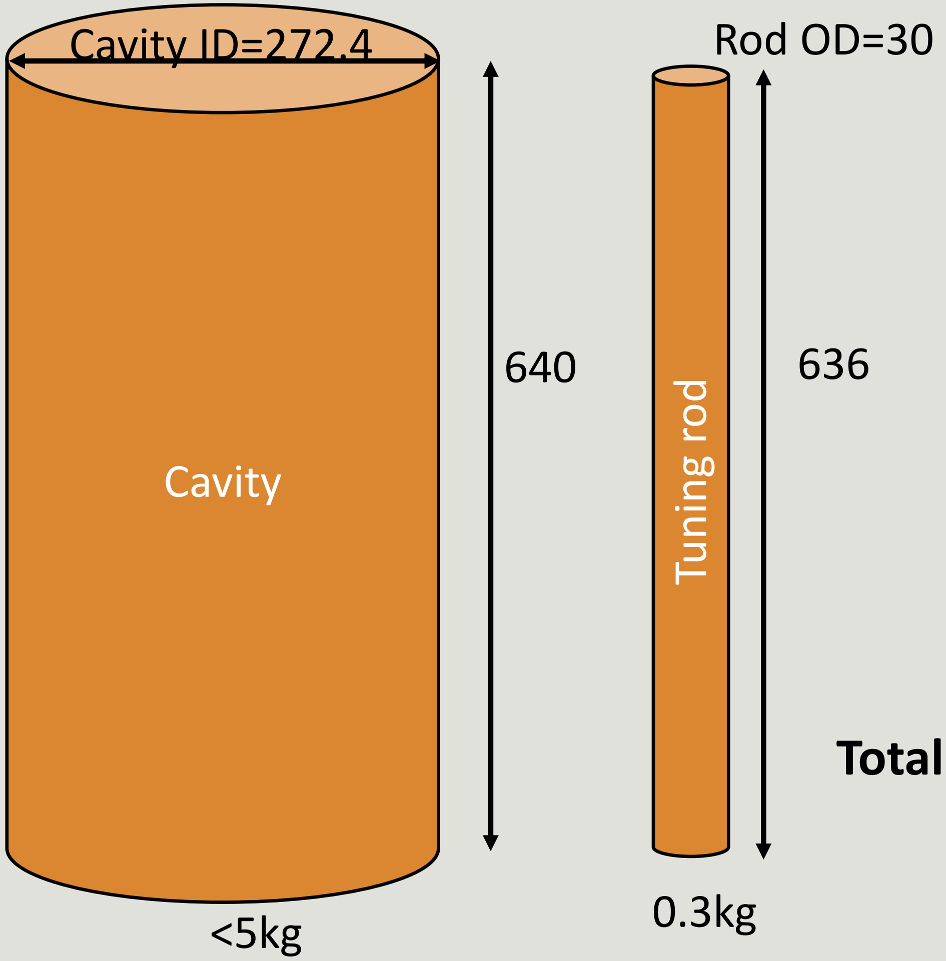


Magnet and fridge tested together

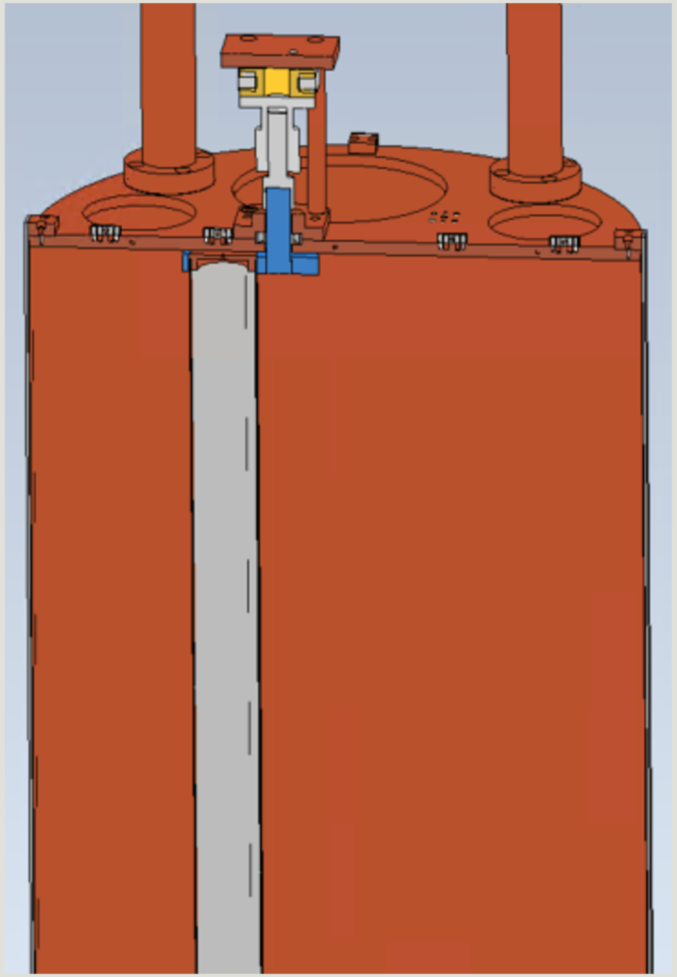


Cavity temperature at 12 T

CAPP-12TB Cavity – Ultra Light Cavity



Total < 6kg

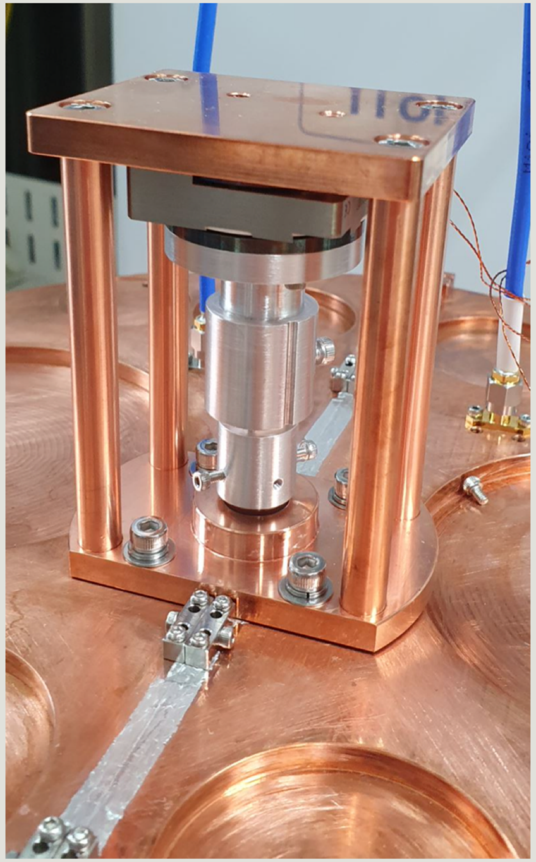


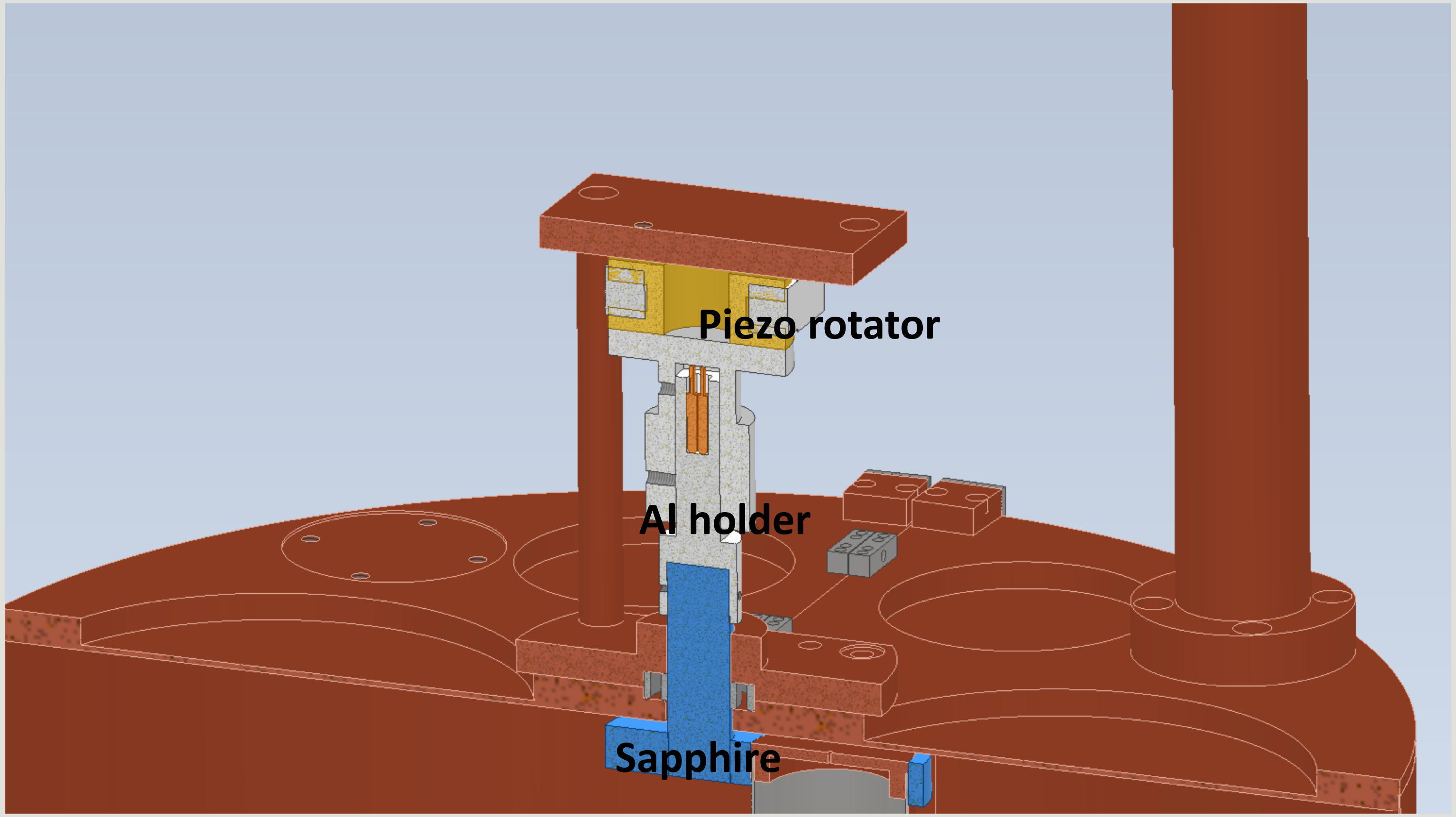
36.85 L

The cavity reduces the thickness and increases height to maximize volume

CAPP-12TB Cavity – Ultra Light Cavity

The tuning mechanism uses a piezo that connects the tuning rod with a sapphire axle





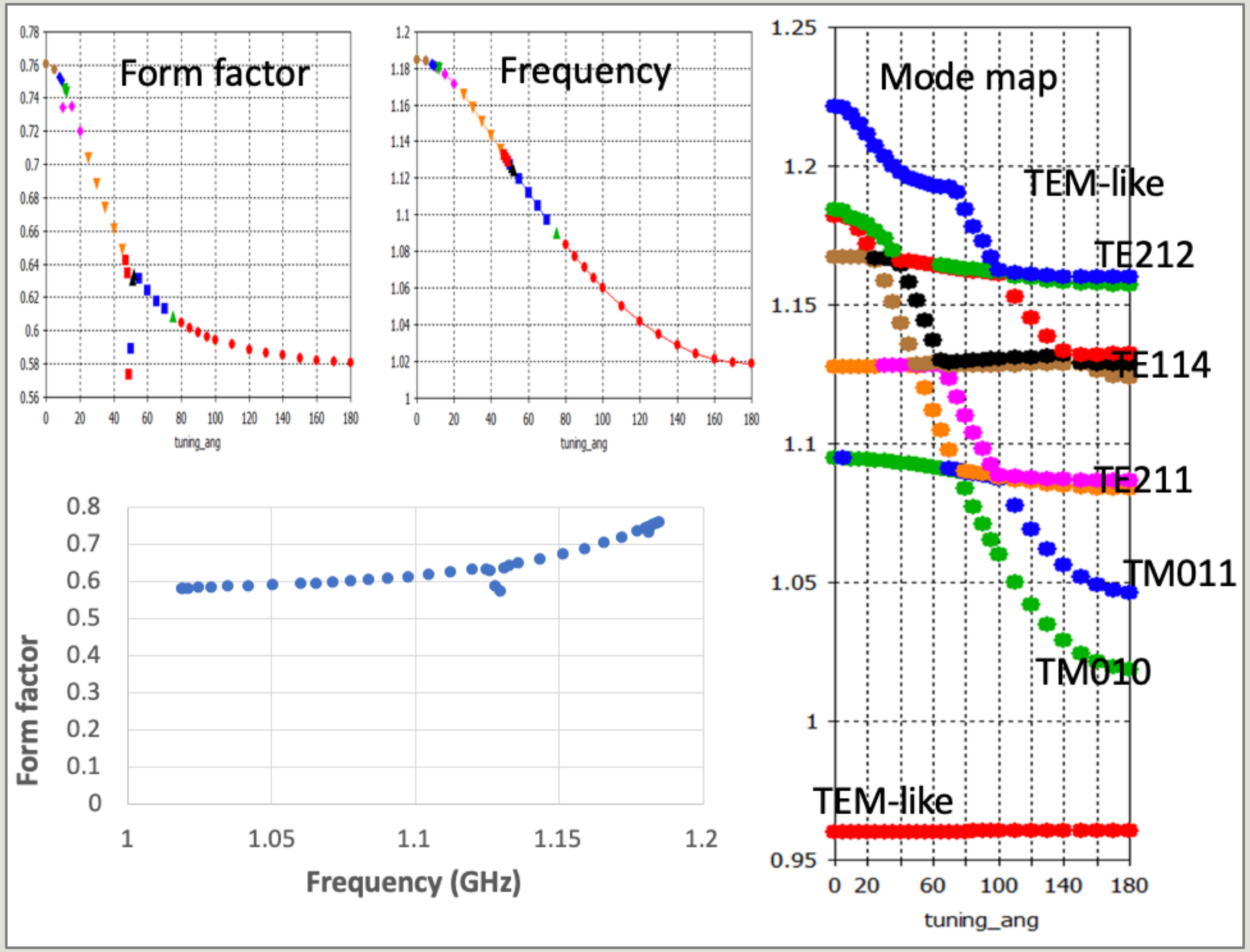
CAPP-12TB Cavity – Ultra Light Cavity

Ultra Light Cavity Simulations

Frequency range: 1.02 – 1.185 GHz

Form factor: ~0.6

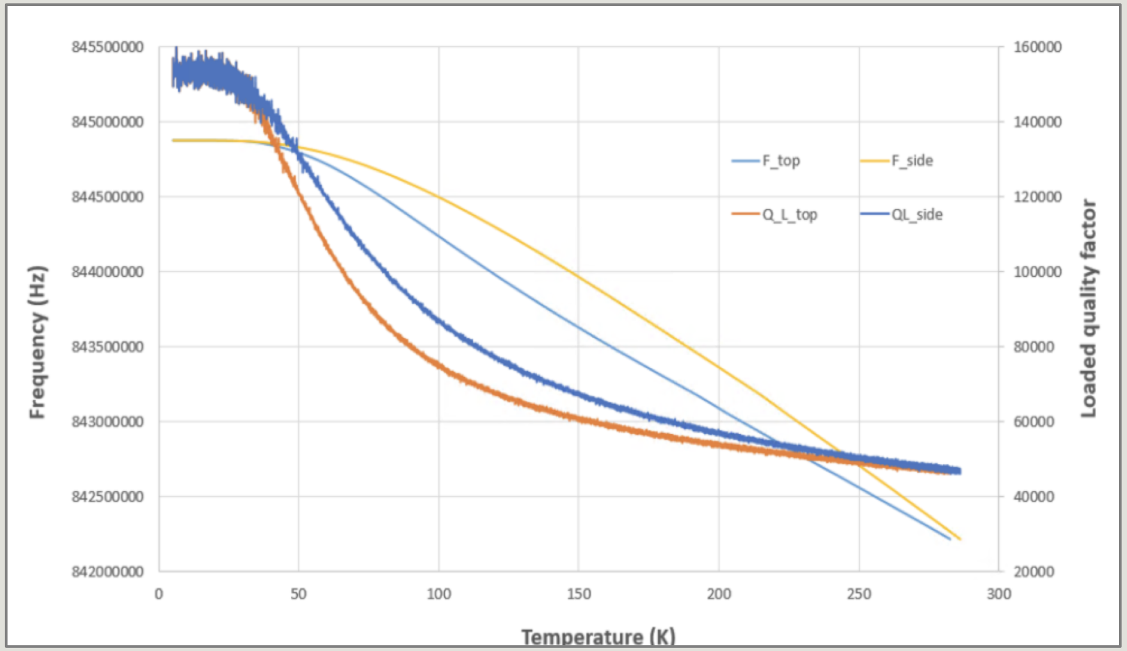
There are a few mode-crossing regions at the higher frequencies



CAPP-12TB Cavity – Ultra Light Cavity

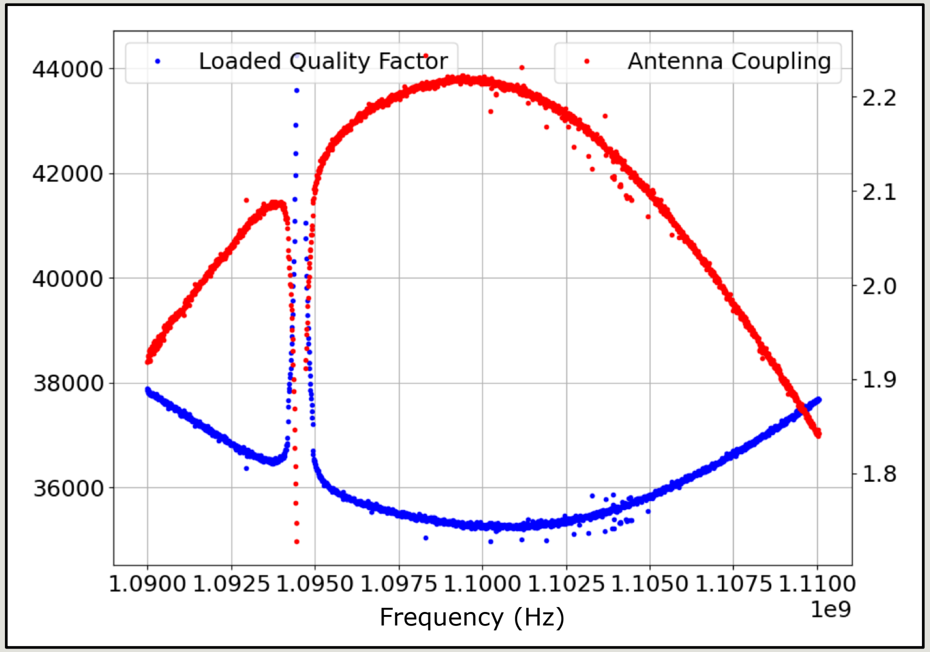
Without tuning rod

Q_L ~ 155,000, Q_0 >~ 170,000 estimated



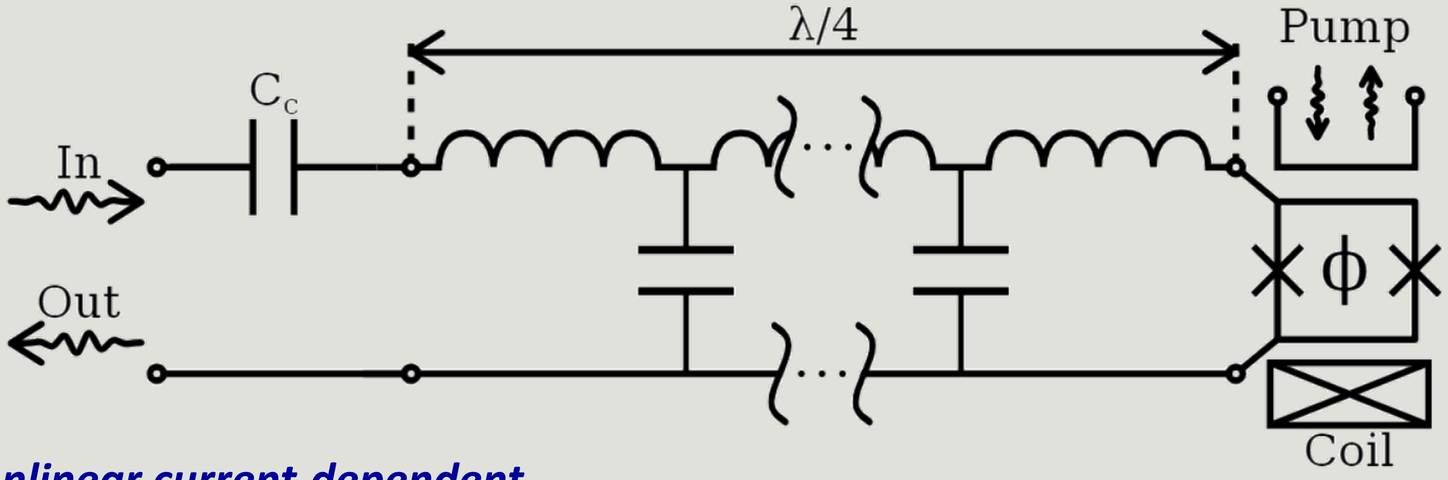
With tuning rod (at 1.09 – 1.11 GHz)

Q_0 >~ 100,000 estimated



Flux-driven Josephson Parametric Amplifiers

Josephson Parametric Amplifiers (JPAs) are used to amplify the raw power signal with low noise



The nonlinear current-dependent inductance of a Josephson junction L(I) ***- amplification***

$$L(I) = L_0\left[1+\frac{1}{2}\frac{I^2}{I_c^2}\right],\ L_0 = \frac{\Phi_0}{2\pi I_c}$$

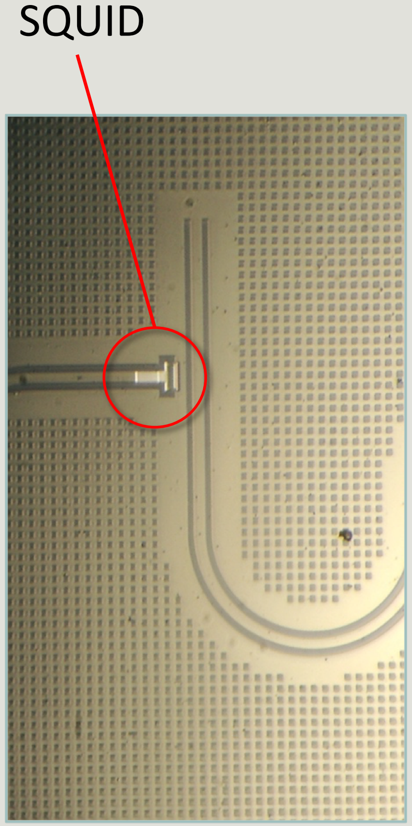
Ic –critical current of the SQUID
Φ_0 – flux quantum, $2.069\cdot10^{-15}$ Wb
I – DC persistent current, created by DC flux

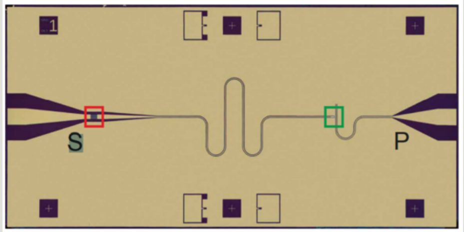
Inductance of a SQUID depends from flux bias Φ ***- frequency adjustment***

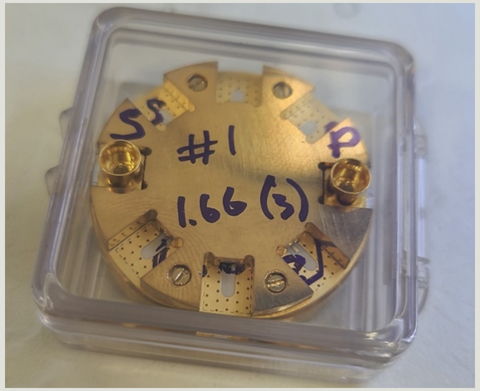
$$I_C = IC_0\cos(\pi\Phi/\Phi_0)$$

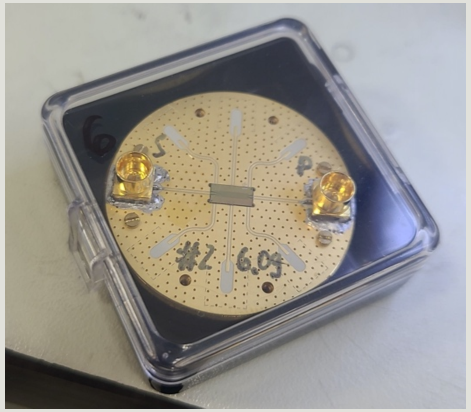
Flux-driven Josephson Parametric Amplifiers

Collaboration with University of Tokyo and RIKEN









With the help of
IBS/CAPP QLNA Team
Çağlar Kutlu, Jinmyeong Kim, Boris Ivanov, Sergey Uchaikin, Seonjeong Oh, Andrei Matlashov

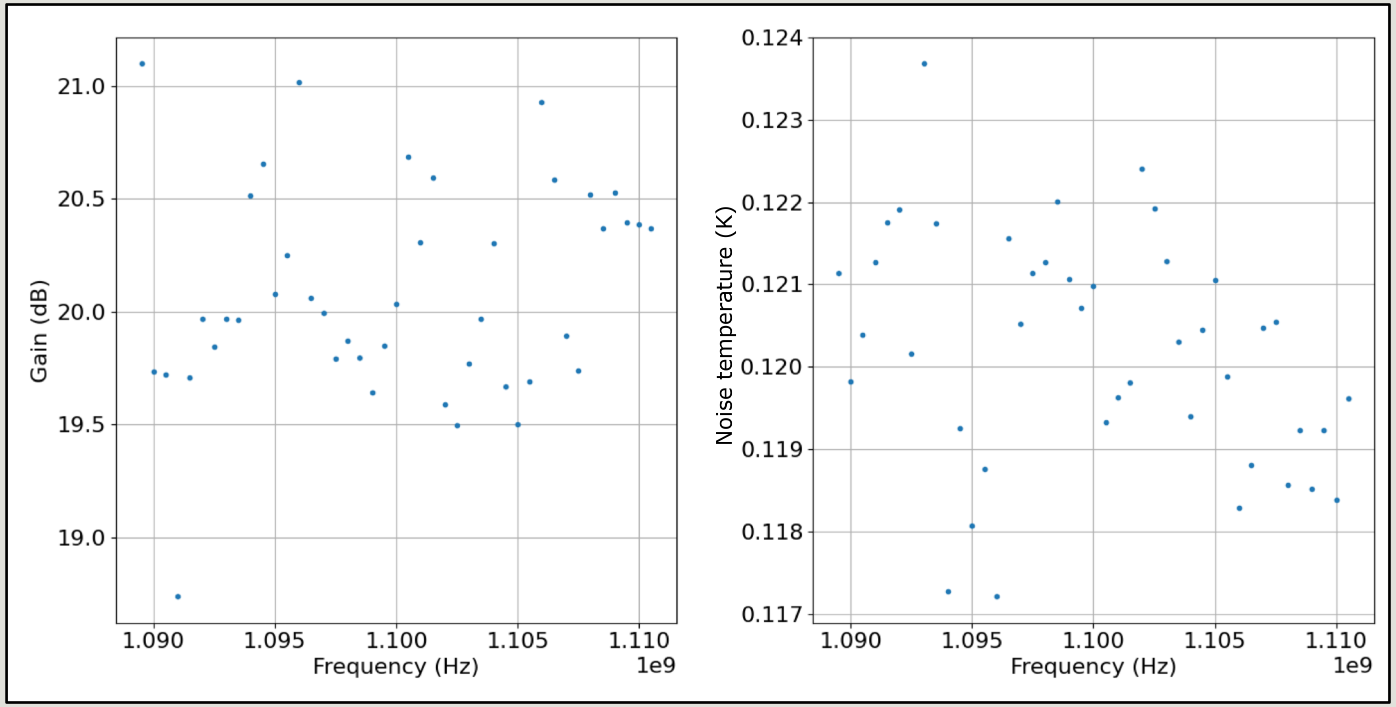
University of Tokyo and RIKEN
Arjan van Loo, Prof. Y. Nakamura

RF Chain and JPA operation

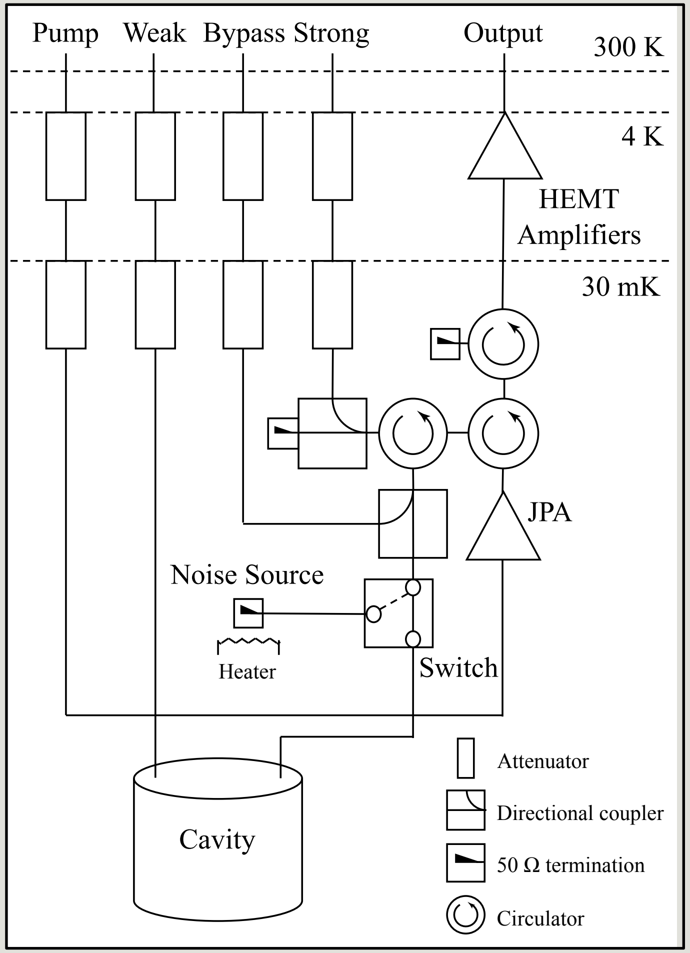
RF chain has been fully implemented in system

Multiple JPAs will be used to cover the full range (1.02 – 1.19 GHz)

A JPA with the working range 1.09 – 1.11 GHz is currently installed



Noise temperature (T_n) of full chain with current JPA (measured at 28 mK)



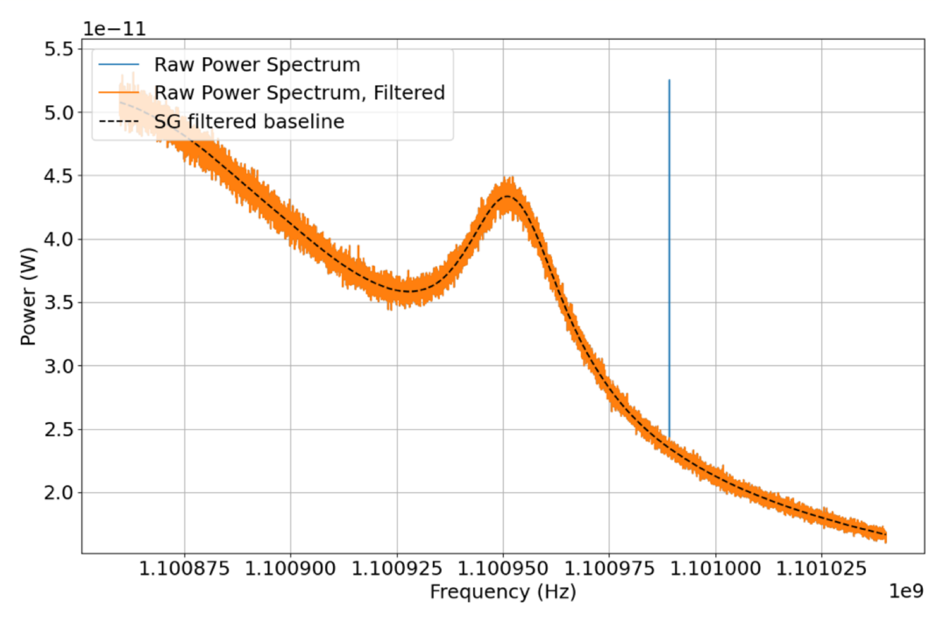
RF Chain schematic

Data Acquisition Process

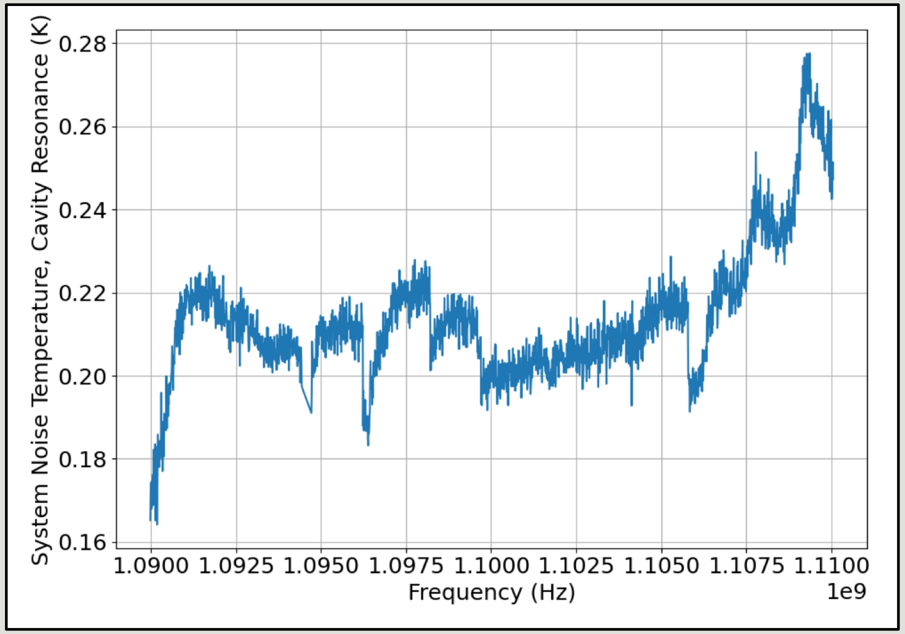
The CAPP-12TB experiment has currently scanned 20 MHz for its first run

Data acquired from March 1st to March 18th, 2022 (10 kHz tuning frequency steps x 1981 runs)

Data taken with a digitizer, including auxiliary data (transmission, gain, temperature data, etc.)



5000 power spectra taken and averaged
Baseline fit via Savitsky–Golay (SG) filter



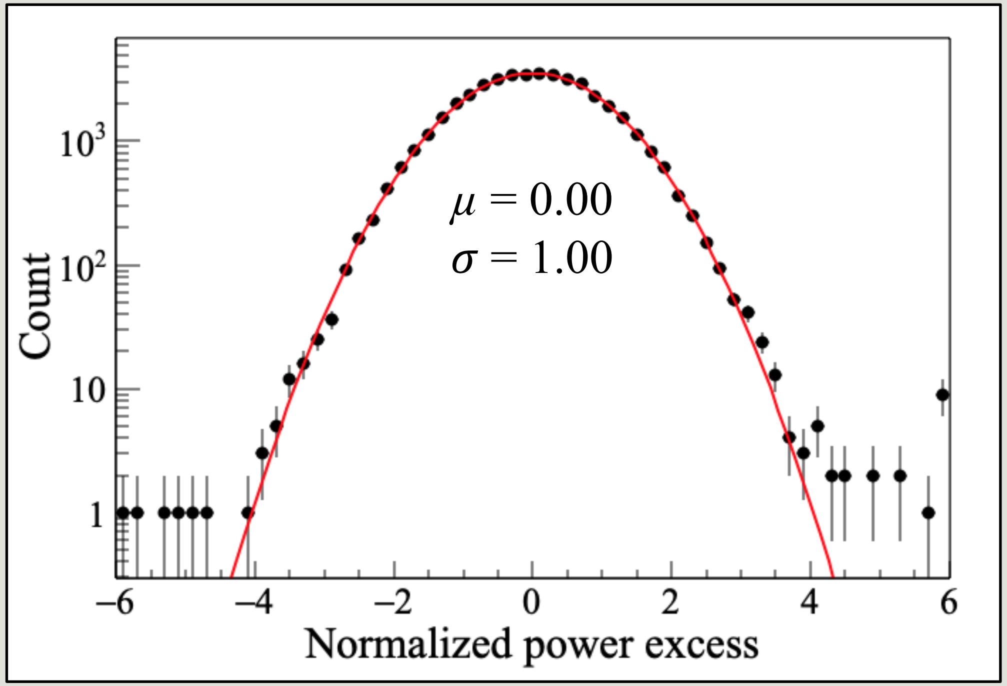
Noise temperature at cavity resonance
From noise power after total gain removal

Data Analysis

Pull distribution data from the grand spectrum (normalized power excess) of the physics run

The SG filter reduces the width (sigma) of the gaussian distribution to ~0.8 due to correlations

After correcting for correlations the statistics follow a standard normal gaussian distribution

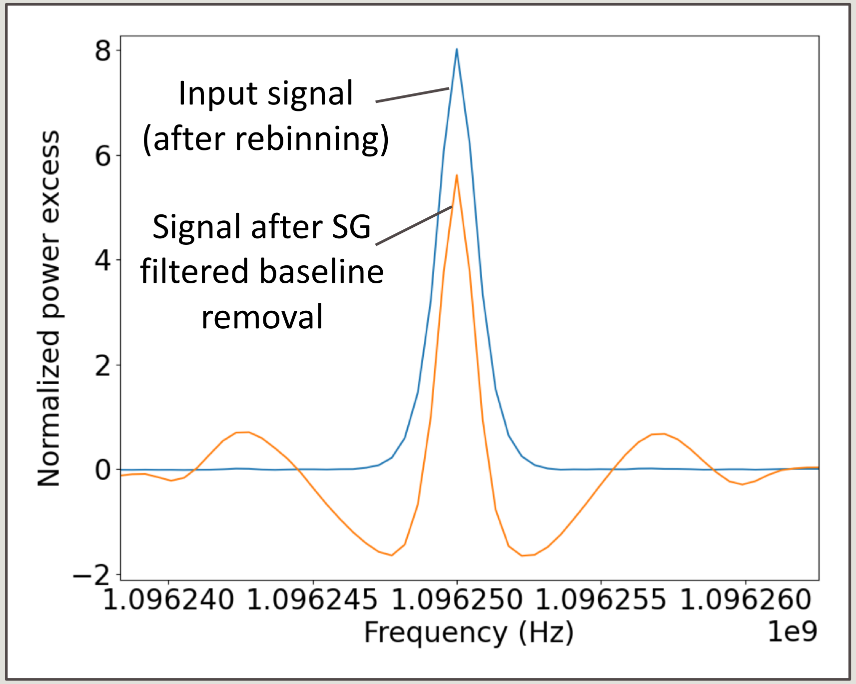


Data Analysis - Simulation

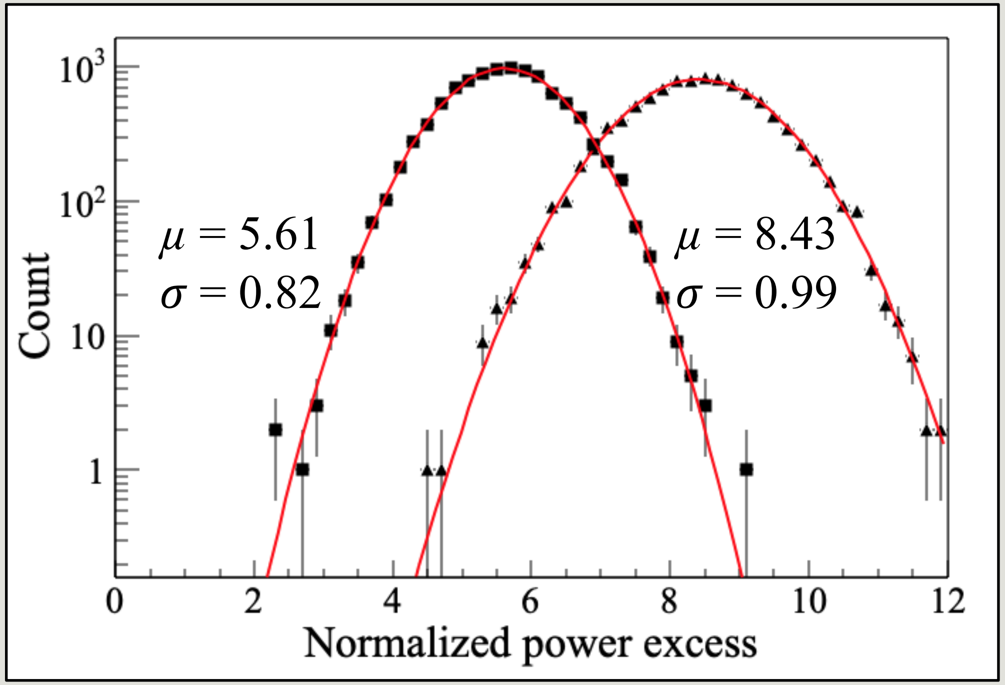
Monte Carlo Simulation for the CAPP-12TB background was performed (10000 iterations)

An axion signal is input via software to measure loss in SNR with current data analysis methods

Simulation: The SNR efficiency of the SG filter and effects of rebinning combined ~ 80%



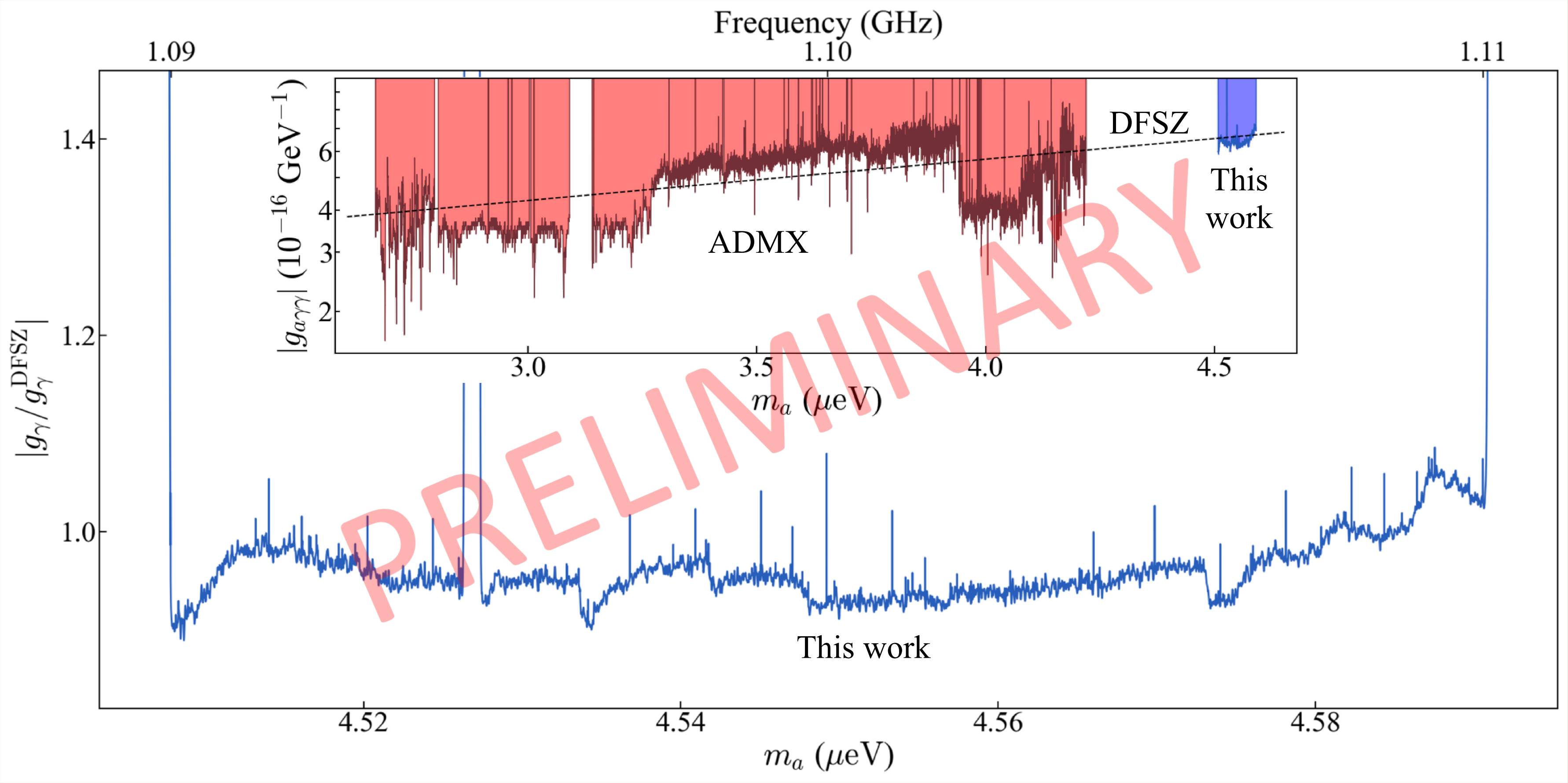
Comparison of signal in the grand spectrum



SG filter degrades SNR and reduces width of the signal

Data Analysis

After data analysis the current run excludes about 20 MHz for DFSZ axions



Summary & Future plans

All components of the experiment have progress and are currently integrated together

The CAPP-12TB cavity currently is configured to scan the 1.02 – 1.19 GHz with a 6 kg cavity

The superconducting magnet has a maximum magnetic field of 12 T and the dilution refrigerator load (cavity) reaches 25 mK in these conditions

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 has taken 20 MHz (1.09 – 1.11 GHz) of data in its first results of the first phase, targeting DFSZ sensitivity

After the first phase (1.02 – 1.19 GHz), the CAPP-12TB experiment will increase its frequency range up to 4 GHz

The CAPP-12TB team: Andrew Kunwoo Yi, Saebyeok Ahn, ByeongRok Ko, Boris Ivanov, HeeSu Byun, Sergey Uchaikin, Ohjoon Kwon, Yannis K. Semertzidis