Search for the axion dark matter in the mass range of 6.62–6.82 μeV

Saebyeok Ahn, Jihoon Choi, ByeongRok Ko, Soohyung Lee and Yannis Semertzidis

Korea Advanced Institute of Science and Technology (KAIST)

Institute for Basic Science(IBS)/Center for Axion and Precision Physics Research (CAPP)

CAPP

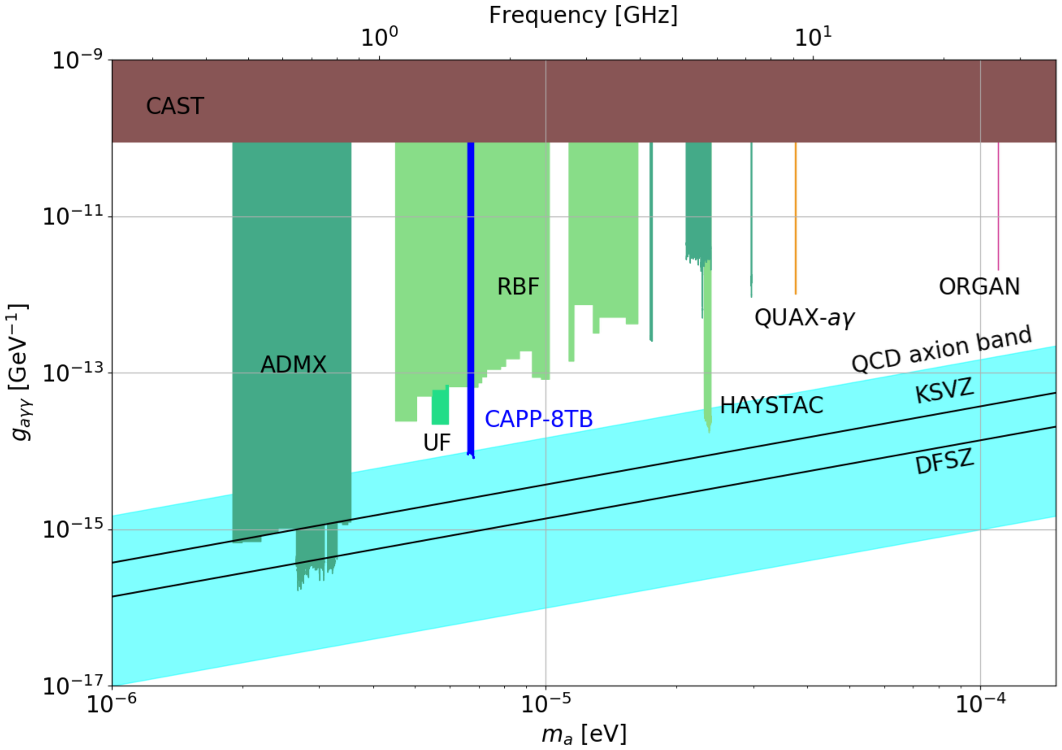
Center for
Axion and Precision
Physics Research

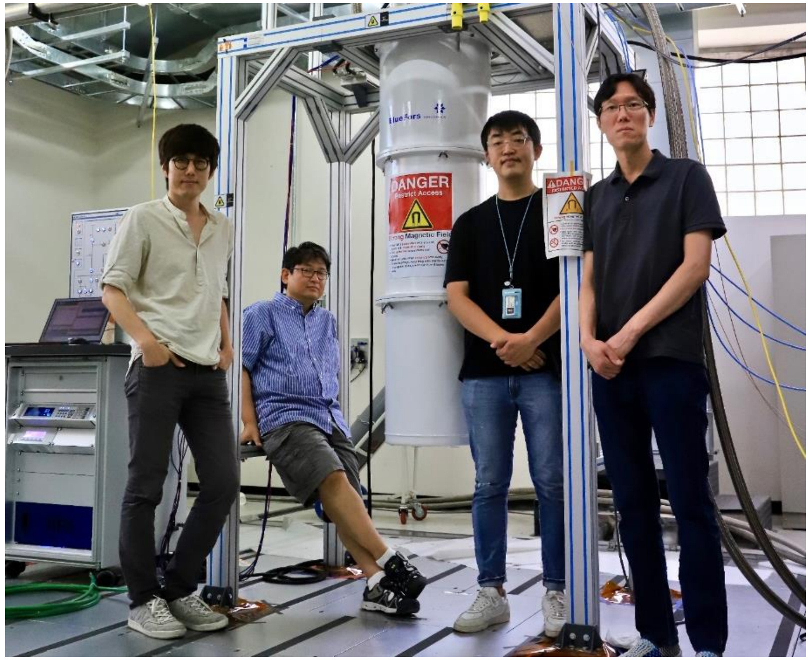
Axion dark matter search in IBS/CAPP

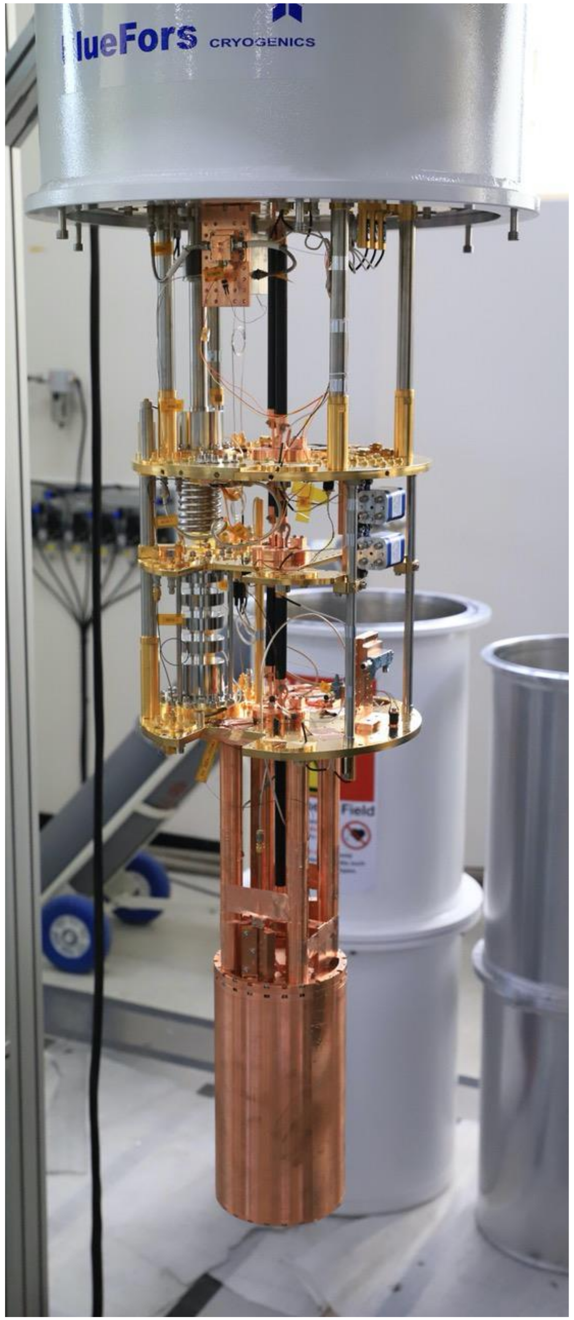
CAPP : **C**enter for **A**xion and **P**recision **P**hysics at **I**nstitute for **B**asic **S**cience (IBS) in Daejeon, South Korea

Four axion search experiments running in a variety of mass range

CAPP-8TB axion haloscope







CAPP-8TB : Axion dark matter search in IBS/CAPP

- Phys. Rev. Lett. 124, 101802 (2020) : $6.62 < m_a < 6.82$ μeV (1.6 – 1.65 GHz)

8TB stands for **8 T** magnetic field, relatively **B**ig magnet bore size

Axion

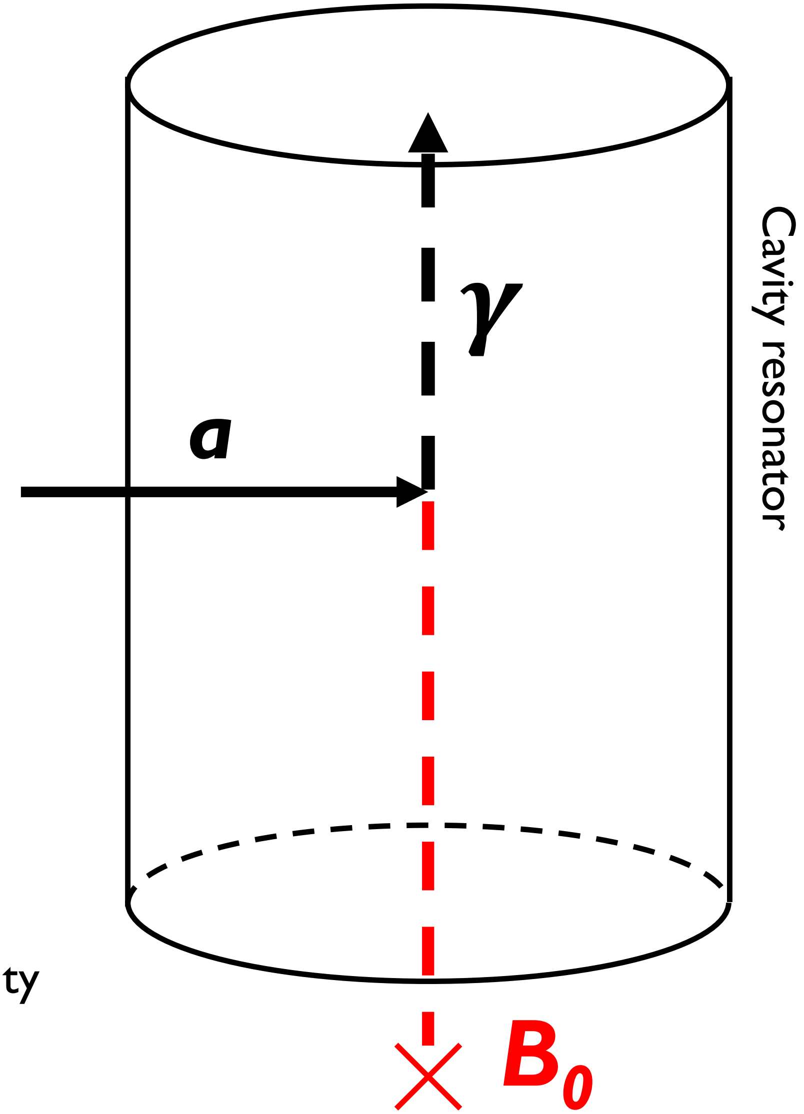
[1] Phys. Rev. Lett, 124, 081803 (2020)
[2] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)
[3] P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983); Phys. Rev. D 32, 2988 (1985).

Strong CP problem

- CP violation in QCD by introducing $\theta - \text{vacuum}$
- Neutron EDM in QCD and θ
  - $|d_n| < 1.8 \times 10^{-26}$ e.cm [1] from the recent measurement
  - Corresponding to $\theta < O(10^{-9})$ *why should it be so small?*
- Resolution of the strong CP problem
  - A global chiral $U(1)$ symmetry, or $U(1)_{PQ}$ *symmetry* [2]

Axion

  - Result of spontaneous breaking of $U(1)_{PQ}$ *symmetry*
- Invisible axion
  - KSVZ and DFSZ model
  - Long life-time, very light and long-lived
  - ***A promising candidate for cold dark matter*** (*1 μeV to 3 meV*)
- *Sikivie* effect [3]
  - Resonant conversion of axion (a) to photon (γ) in a microwave cavity in a static magnetic field (B_0)



Axion haloscope

Axion to photon conversion power P_a picked up by the receiver

$$P_a^{a\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a \hbar^2}{m_a^2 c} \omega(2U_M) C Q_L \frac{\beta}{\beta + 1}$$

$g_{a\gamma\gamma}$: *Axion-photon coupling strength*

ρ_a : *Local dark matter density*

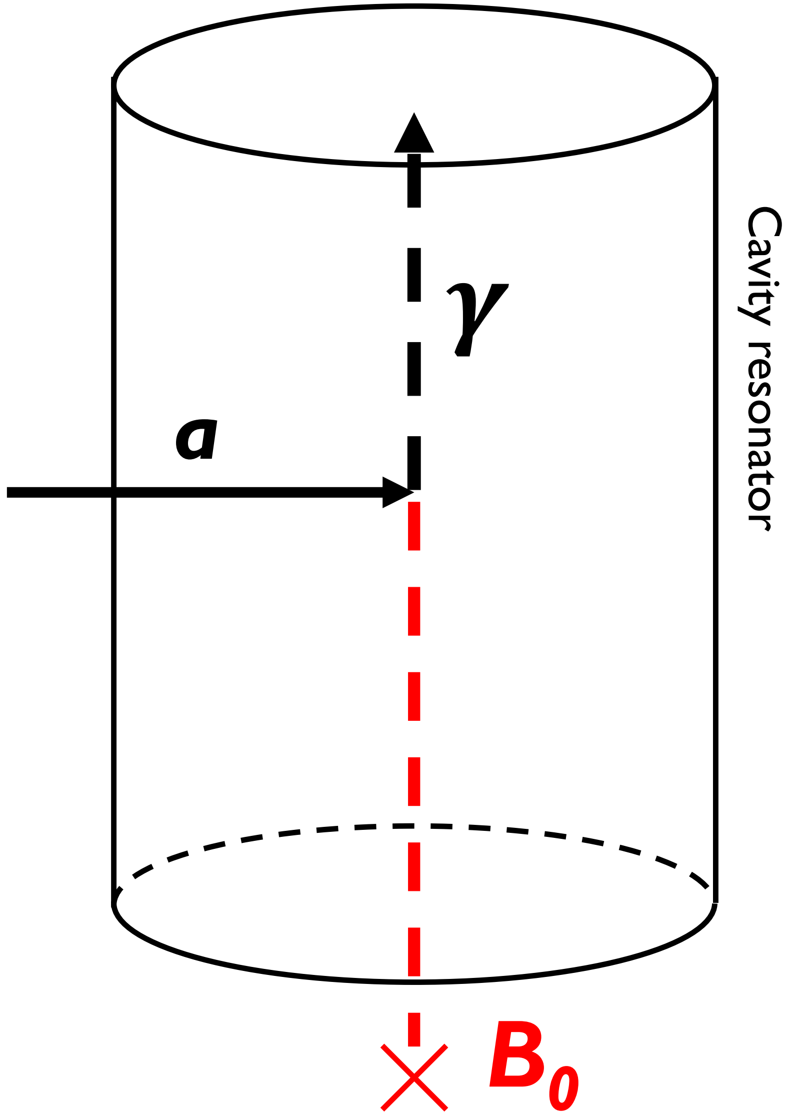
$U_M = \frac{1}{2\mu_0}\int dV\left|\vec{B}\right|^2 = B_{avg}^2 V$: *Magnetic field energy in the resonator*

($\vec{B}$: *Static magnetic field,* V : *resonator volume)*

C : *Form factor*

Q_L : *Loaded Quality factor of the resonator*

β : *Resonator mode coupling to the load (antenna)*



Axion haloscope

System noise

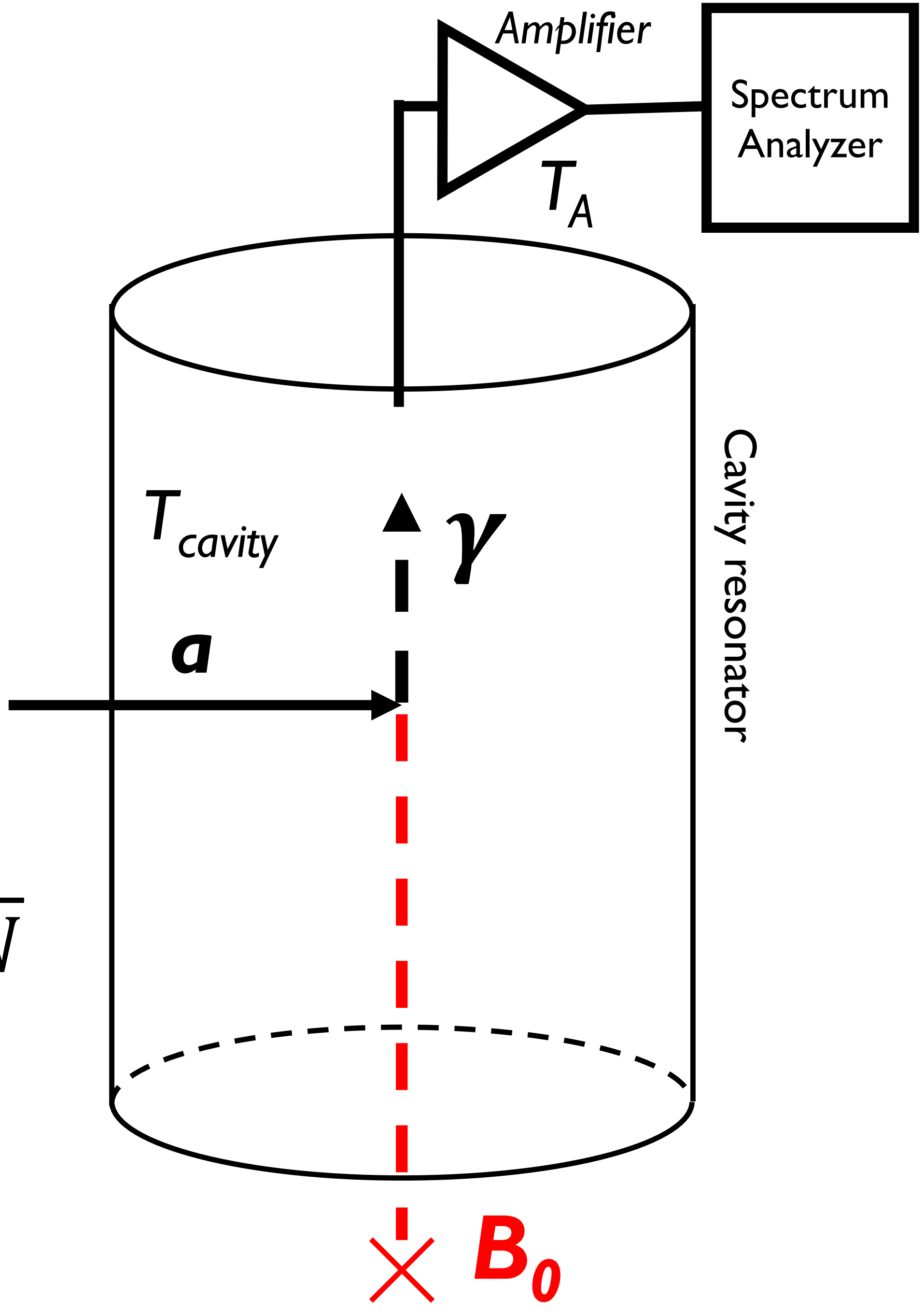
$$T_n = T_A + T_{cavity}$$

T_n : *System noise temperature*
T_A : *Equivalent noise temperature of the amplifier*
T_{cavity} :*Thermal noise from the resonator*

Signal-to-noise ratio (SNR)

$$SNR \equiv \frac{P_a^{a\gamma\gamma}}{\sigma_{P_n}} = \frac{P_a^{a\gamma\gamma}}{P_n}\sqrt{N} = \frac{P_a^{a\gamma\gamma}}{k_B \Delta\nu_a T_n}\sqrt{N}$$

P_n , σ_{P_n} : *noise powe, fluctuations of noise power*
k_B : *Boltzmann's constant*
$\Delta\nu_a$:*Axion signal window*
N : number of spectra averaged

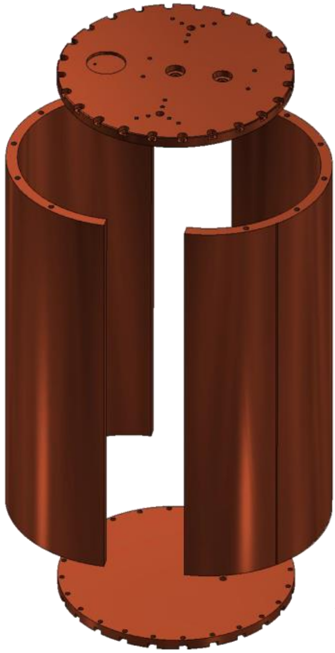


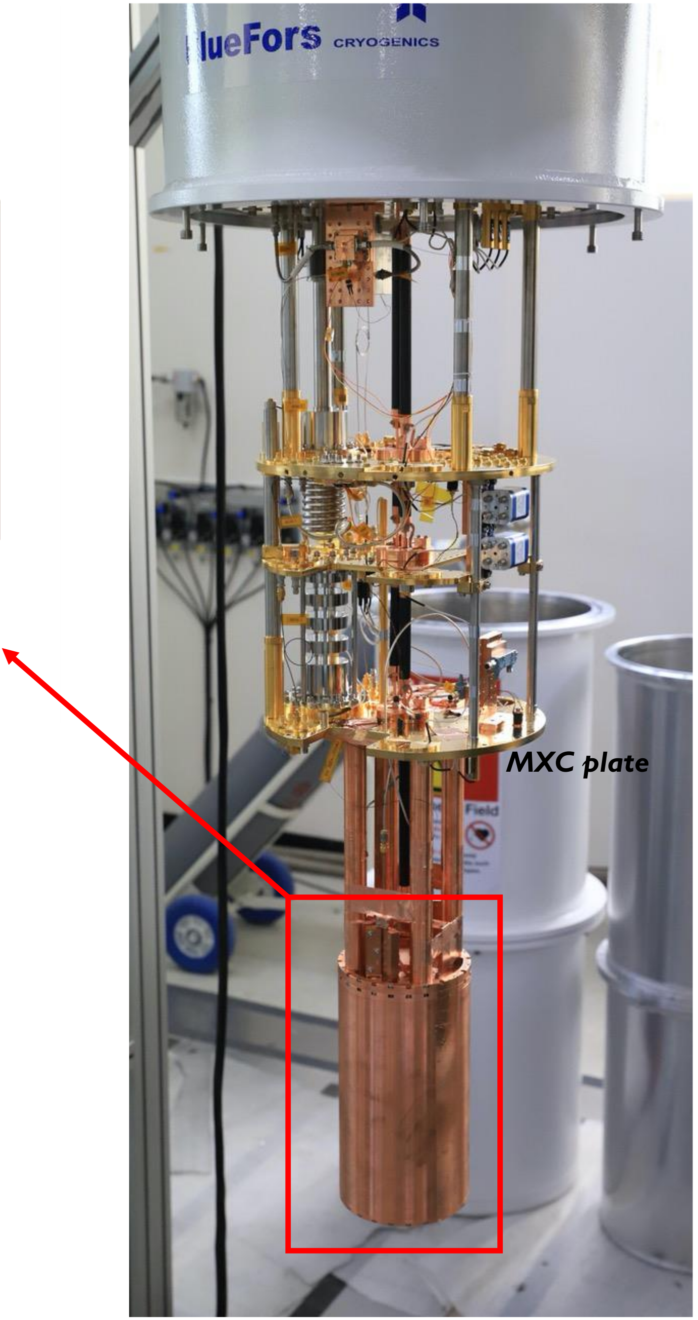
Microwave cavity resonator

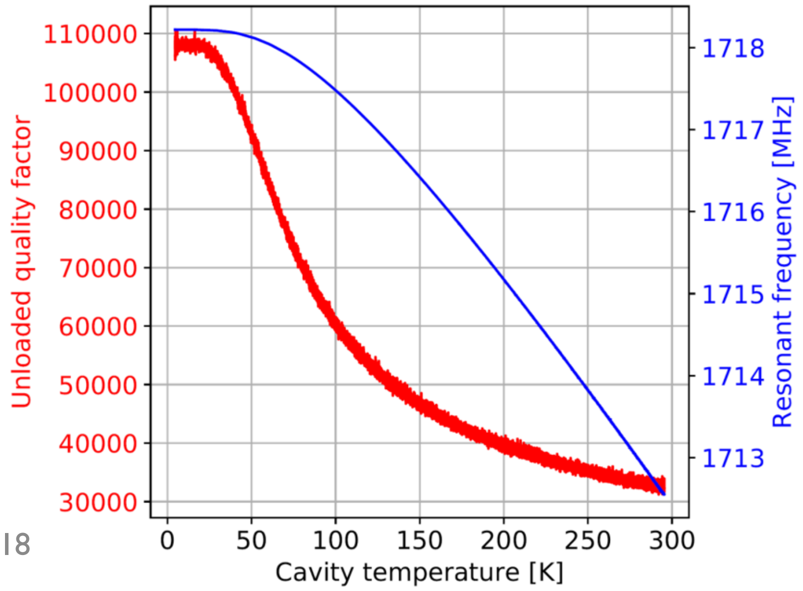
- Cavity : OFHC copper,134 mm diameter, 246 mm height
    - *V = 3.47 Liters*
- TM_{010} mode: maximum C factor among the cavity modes

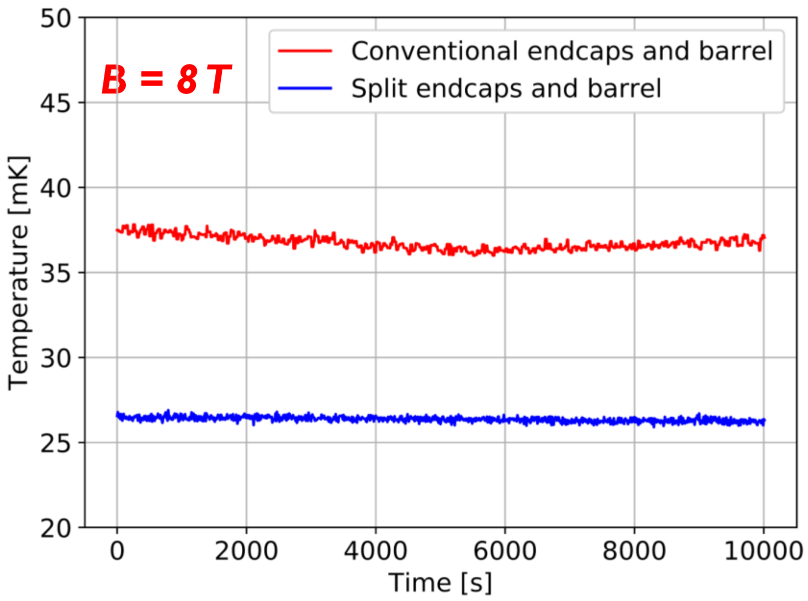
$$f_{010} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}}\frac{X_{01}}{R} \sim \frac{0.1147}{R}\ [\mathrm{GHz}] = 1.712\ [\mathrm{GHz}]$$

- Q factor at low temperature ~ 110,000
- Split design : minimizing the heat from the eddy current



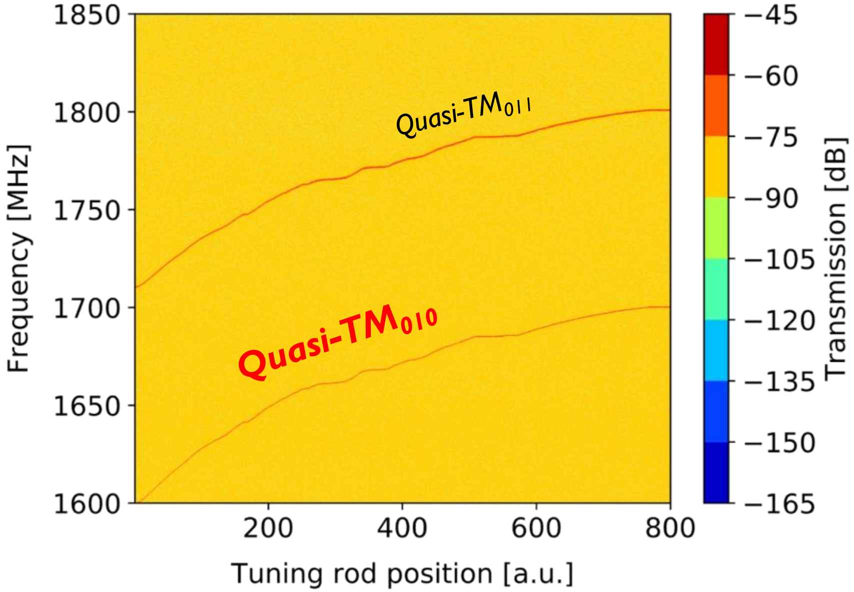


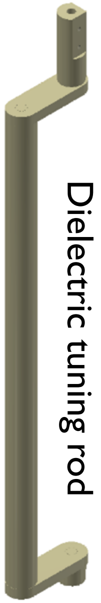


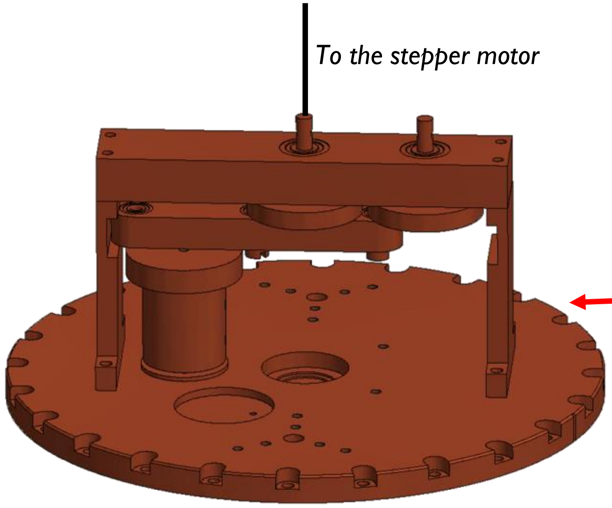


Frequency tuning

- Dielectric tuning rod (Al_2O_3)
- Frequency range of Quasi-TM_{010} mode = 1.43 – 1.7 GHz
- **No mode crossing** throughout the range
- Stepper motor at room temperature
- **CFRP (carbon fiber) tube**
  - All the way from the motor to the cavity
- Frequency tuning tolerance = ± 500 Hz







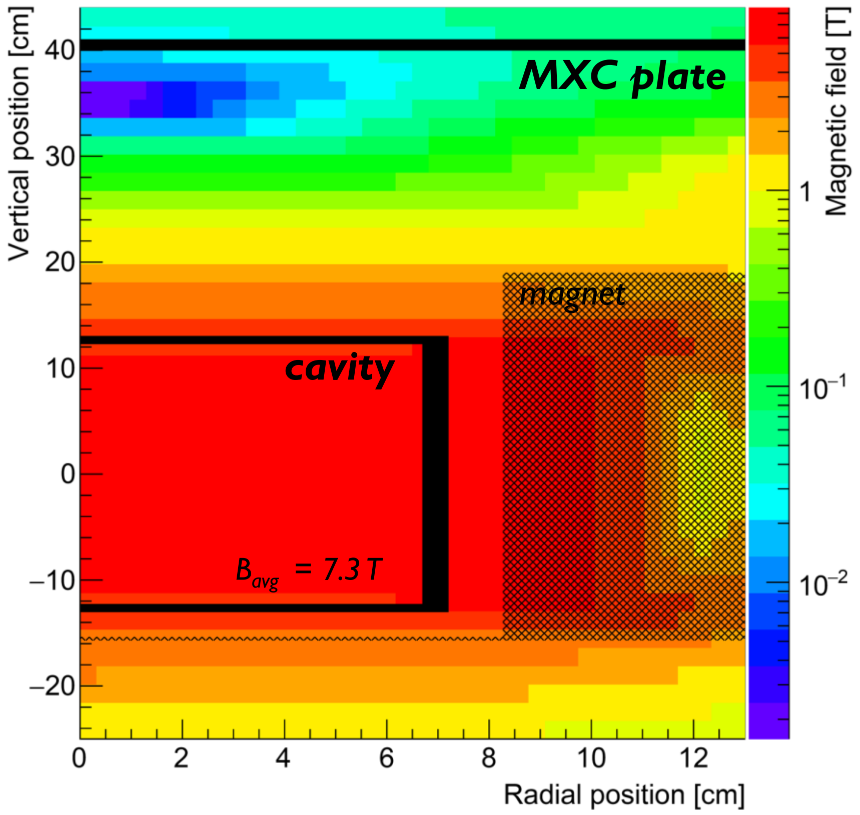
Locomotive shaft

Magnetic field & form factor

- Solenoid magnet : superconducting (NbTi) wire
  - With compensation coil : few hundred Gauss near MXC plate
- Maximum B field = 8 T
- Volume average in cavity = 7.3 T

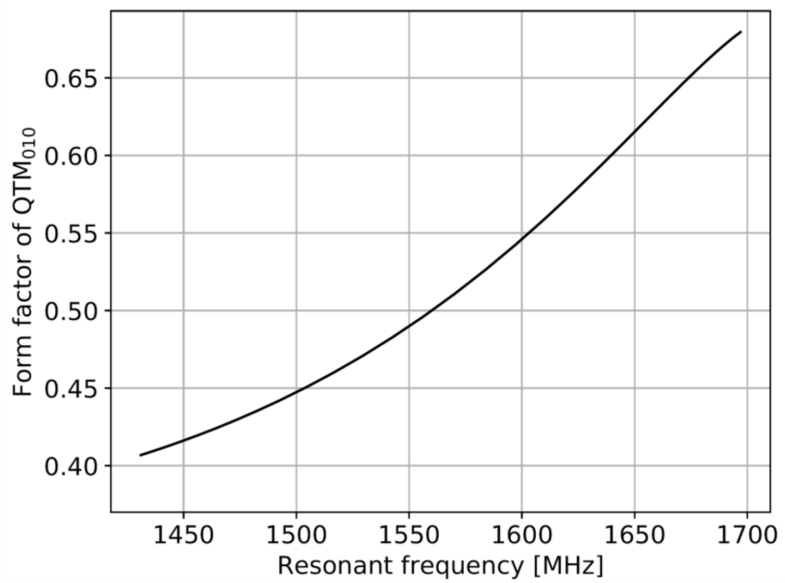
$$C_{lmn} = \frac{\left| \int_V dV \vec{E}_{lmn} \cdot \vec{B}_{ext} \right|^2}{B_{avg}^2 V \int_V dV \, \epsilon \left| \vec{E}_{lmn} \right|^2}$$

$\vec{E}$: Electric field of the cavity mode
$\vec{B}_{ext}$: External static magnetic field
l, m, n : cavity mode number
B_{avg} : Volume average of external B field
V : cavity volume
ϵ : relative dielectric constant



- Form factor : alignment between mode E field and external B field
  - Calculated with E field profile from EM wave simulation (COMSOL)

- TM_{010} mode, uniform B field with perfect alignment = 0.69
- C factor of QTM_{010} modes : frequency dependent < 0.69
  - Asymmetry in electric field due to dielectric tuning rod
  - Uniformity of B field



Q factor & antenna coupling

$$Q = \frac{\nu_c}{\Delta\nu_c}, \qquad \beta \equiv \frac{Q_0}{Q_{ext}}, \qquad Q_L = \frac{Q_0}{\beta + 1}$$

ν_c : *resonance frequency*
$\Delta\nu_c$: *FWHM of cavity transmission signal*
β : *antenna coupling*
Q_0, Q_L : *Unloaded and loaded Q factor*
Q_{ext} : *antenna Q factor*

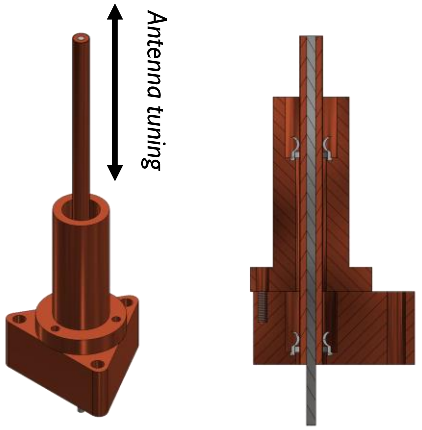
- Antenna coupling measurement from smith chart*

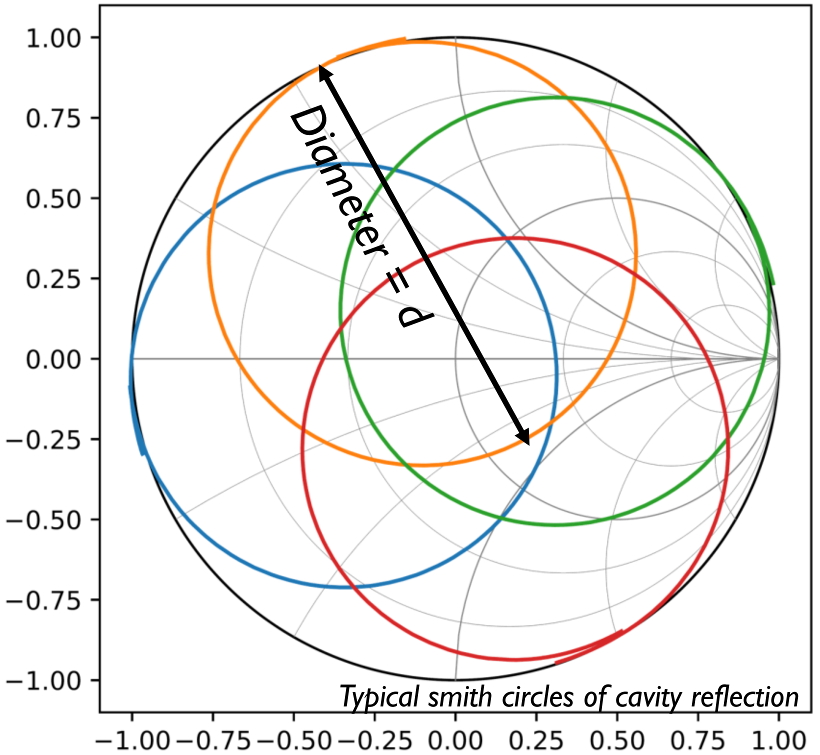
$$\beta = \frac{d}{2 - d}$$ *(d = diameter of smith circle)*

- Scan rate = $\Delta\nu_c$ / τ
  - $\Delta\nu_c$ = loaded cavity bandwidth, τ = integration time
  - $\beta = 2$ is optimum for the scan rate

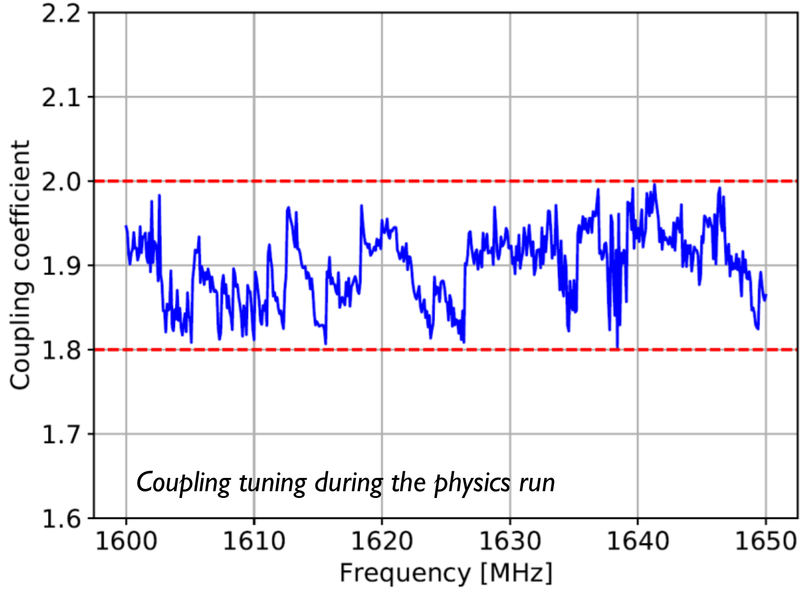
- Tuning the antenna coupling
  - Linear stepper motor
  - Increase/decrease the depth of antenna in cavity

- Tuning tolerance : $\beta = [1.8,\ 2.0]$





Typical smith circles of cavity reflection



Coupling tuning during the physics run

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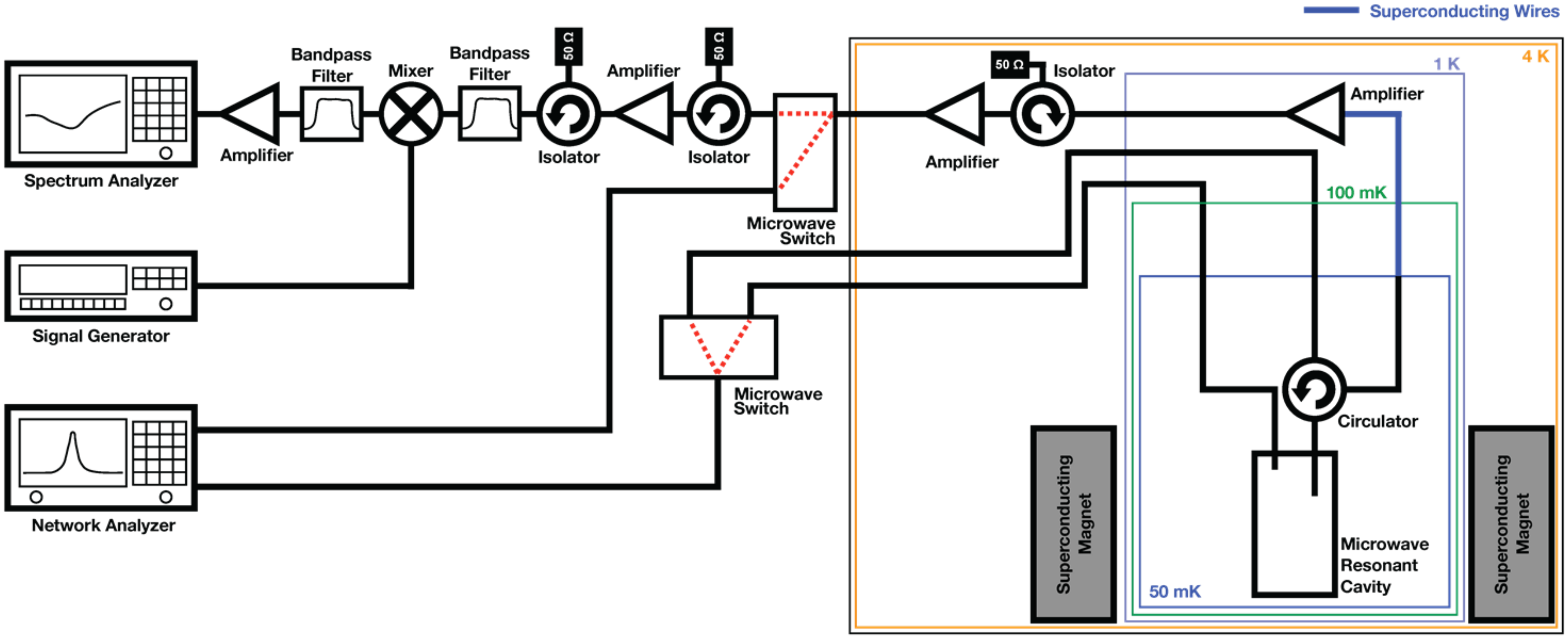
* *D. Kajfez and E. J. Hwan,, IEEE Trans. Microw. Theory Tech. MTT-32 (1984) 666.*

Receiver chain



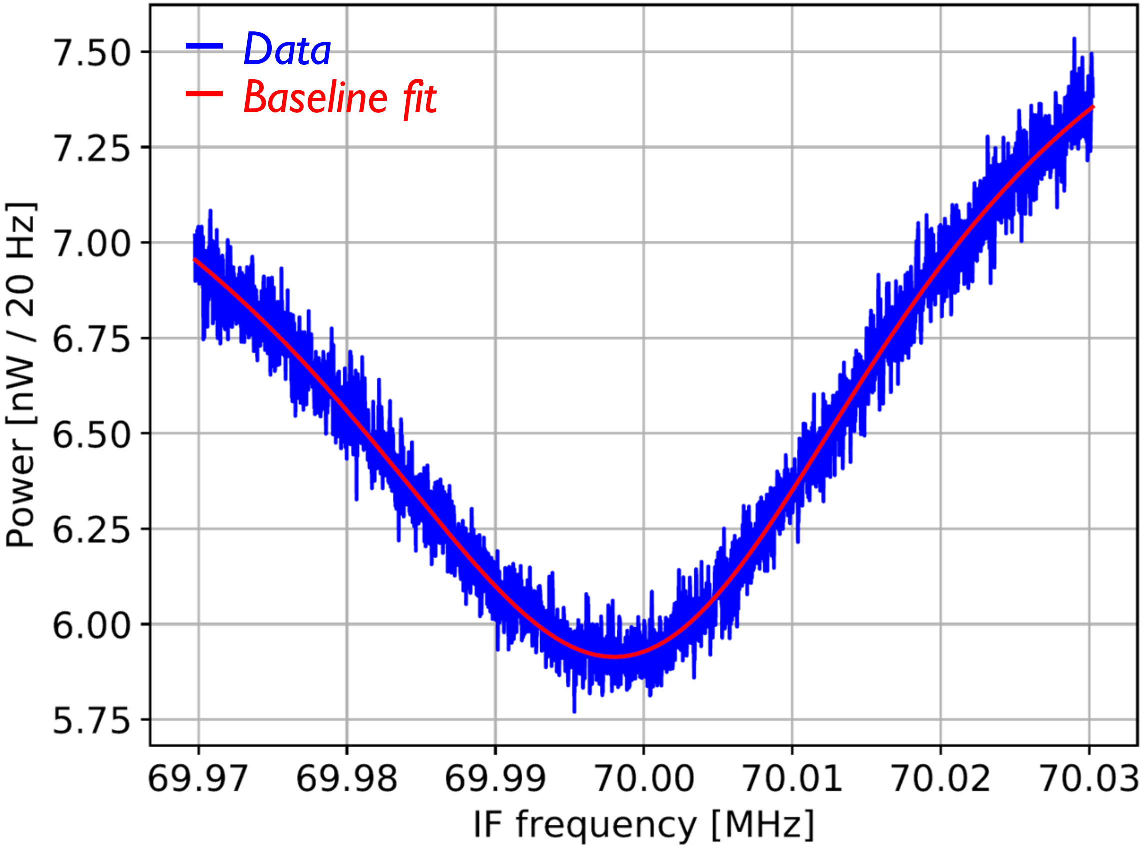
- First and second amplifier : HEMT at 1 K, 4 K stage
- Typical effective noise temperature of the first amplfier < 1 K
- Total system gain ~ 132 dB

Noise power spectrum

- Noise analysis from the equivalent circuit*

$$P(\Delta) = k_B \Delta\nu_b G \frac{\mathrm{a}_1 + 8a_3\left(\frac{\Delta - a_5}{a_2}\right)^2 + 4a_4\left(\frac{\Delta - a_5}{a_2}\right)}{1 + 4\left(\frac{\Delta - a_5}{a_2}\right)^2}$$

k_B : *Boltzmann's constant*
$\Delta\nu_b$: *Resolution bandwidth*
G :*Total system gain*
Δ : *Frequency offset from the spectrum center*
$a_1 \sim a_5$: *Fit parameters*



*S. Asztalos et al., *Large-scale microwave cavity search for dark-matter axions, Phys. Rev. D 64 (2001) 092003*

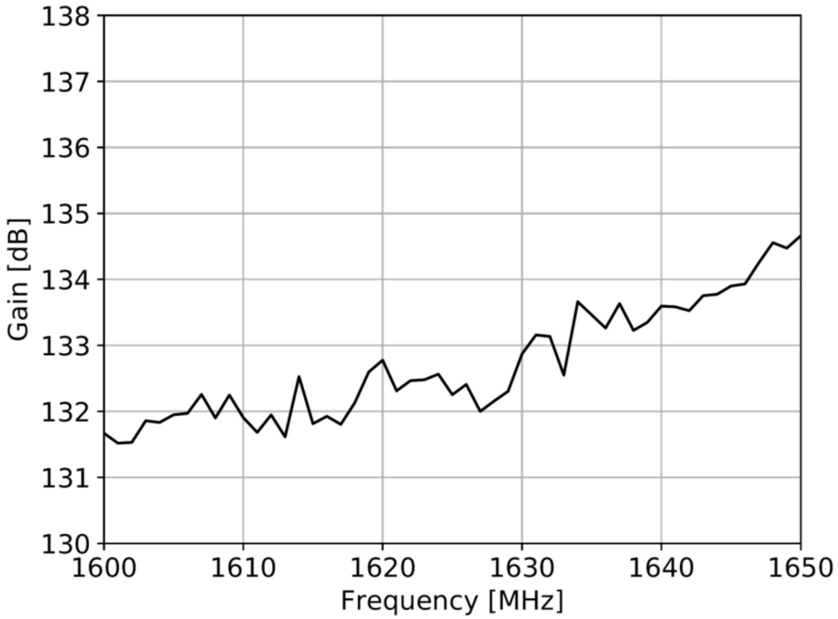
Noise & gain measurements

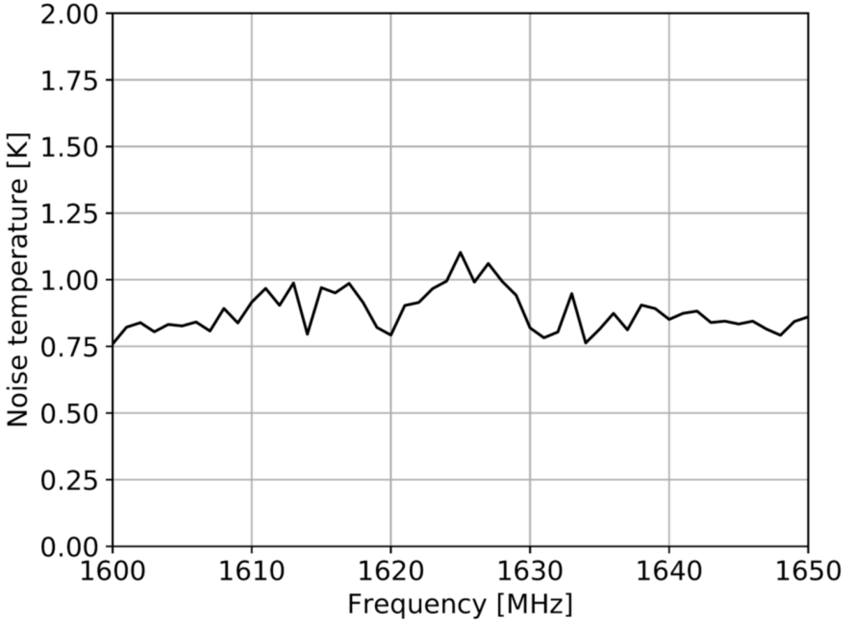
- Cavity as a noise source
- Noise power measurements at different cavity temperatures (50 mK, 200 mK)

$$G = \frac{P_h - P_c}{k_B \Delta\nu_b (T_h - T_c)}$$

P_c, P_h *: on-resonance power measured at cold/hot temperatures*
T_c, T_h *: hot/cold cavity temperature*

- Total system gain = 132 ~ 135 dB
- Noise from obtained system gain = 0.75 ~ 1.2 K



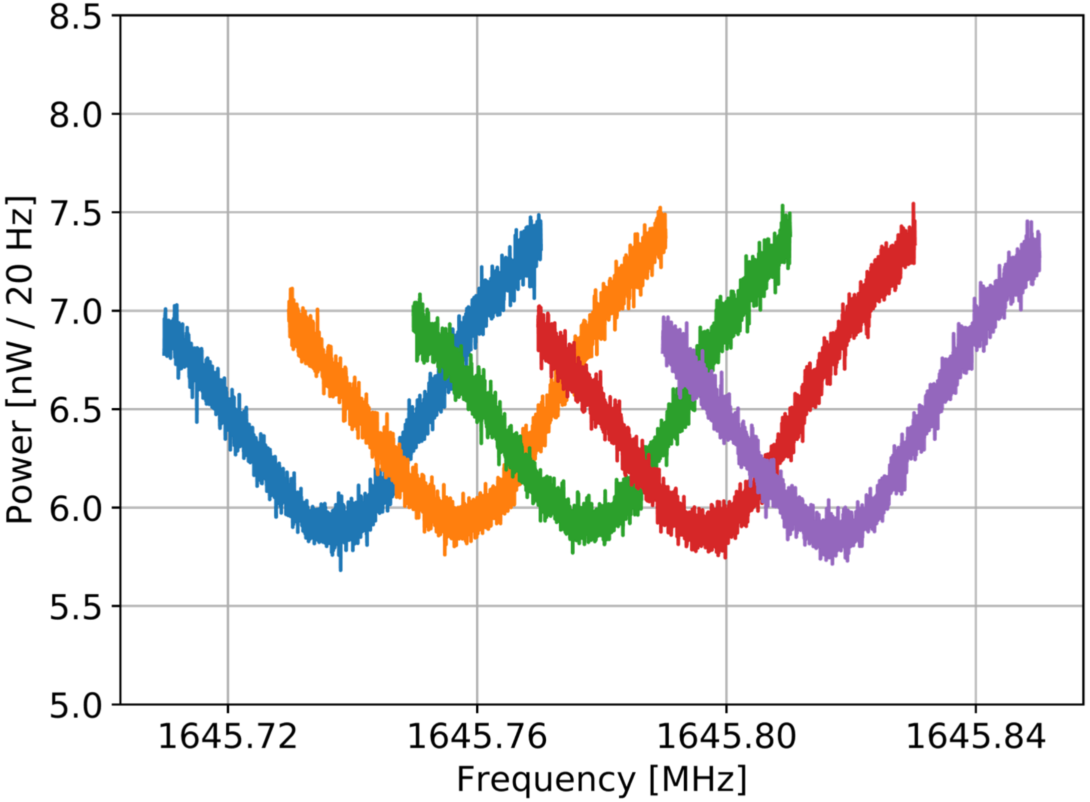


Scan parameter

- Target sensitivity = $4 \times g_{a\gamma\gamma}^{KSVZ}$ (~ QCD upper band)
  - Target SNR = 5
- RBW = 20 Hz
  - Optimized for DAQ efficiency (~ 46 %)
- Span = 60.48 kHz, 3025 points per spectrum
  - Bin merged to RBW = 500 Hz in analysis
  - Resultantly 60 kHz span, 121 points

- Frequency tuning step = 20 kHz
  - Number of spectra to overlap = 3 (optimized for SNR)

- Number of spectra for a step = 12,000
  - 400 average X 30



Analysis

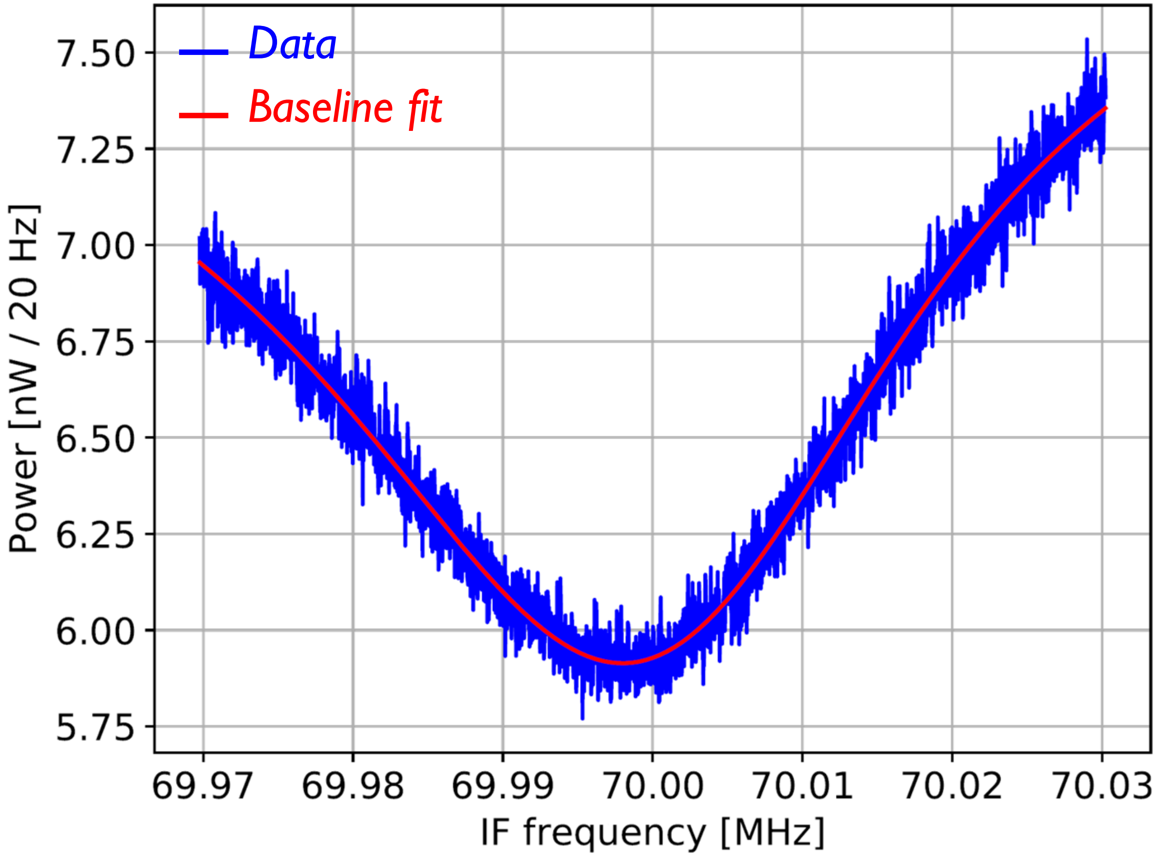
Removing baseline

- Merging 5 bins, RBW = 20 Hz → 100 Hz
- 5-parameters fit
- Filtering spurious peaks (> 4.5 σ)

- Merging 5 bins again, RBW = 100 Hz → 500 Hz

- Pull distribution

$$Pull = \frac{DATA\ - MODEL}{UNCERTAINTY}$$

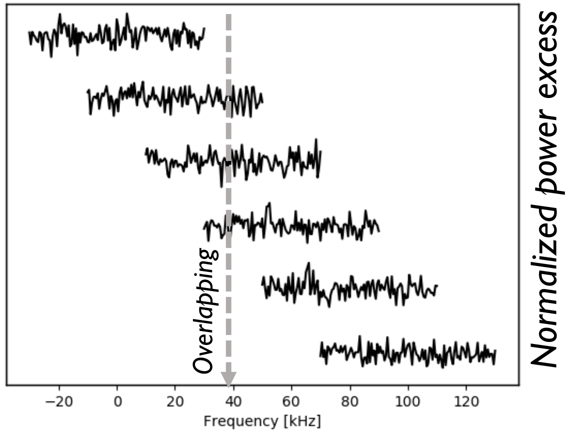


(Down converted)

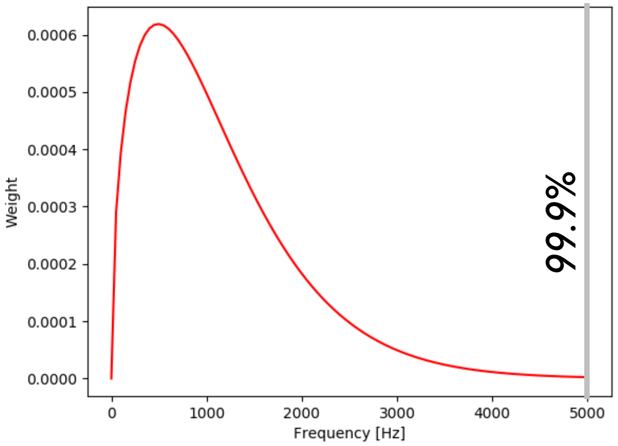
- Heavily averaged (12,000) spectra : Gaussian statistics
- In each frequency bins,
  - Mean = $k_B \Delta\nu_b T$, Standard deviation = $k_B \Delta\nu_b T\ /\ \sqrt{N}$

    (T : effective noise temperature, N = number of averaged spectra)
- Pull becomes the standard normal distribution (mean = 0, width = unity)

Analysis



Axion signal shape



Vertical average (overlapping)

- 3 overlapped bins (span = 60 kHz, step = 20 kHz)
- Average with inverse variance weighting (maximum likelihood estimate)

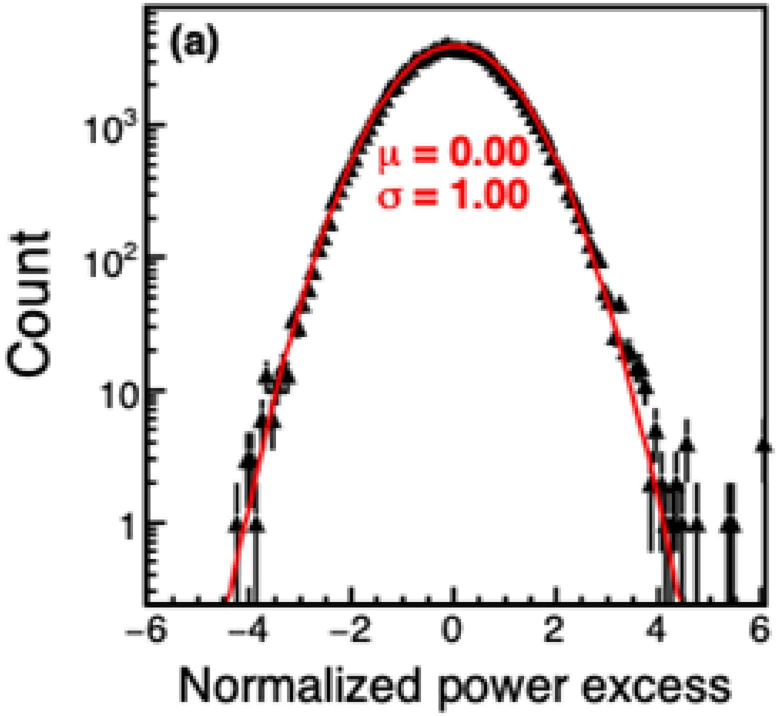
*Horizontal co-adding**

- Weighted sum of neighboring bins, weighting factor = axion signal shape
- 10 neighboring bins (500 Hz X 10 = 5000 Hz)
    - Containing 99.9 % axion signal power (1.6 – 1.65 GHz mass of axion)
- Grand spectrum : Gaussian statistics
    - Correlation correction (due to baseline fit)

Rescan

- 3.718 σ threshold corresponding to 90 % upper exclusion limit of axion to photon conversion sensitivity
- 36 candidates
    - rescan with larger number of average

Histogram of normalized grand power spectra



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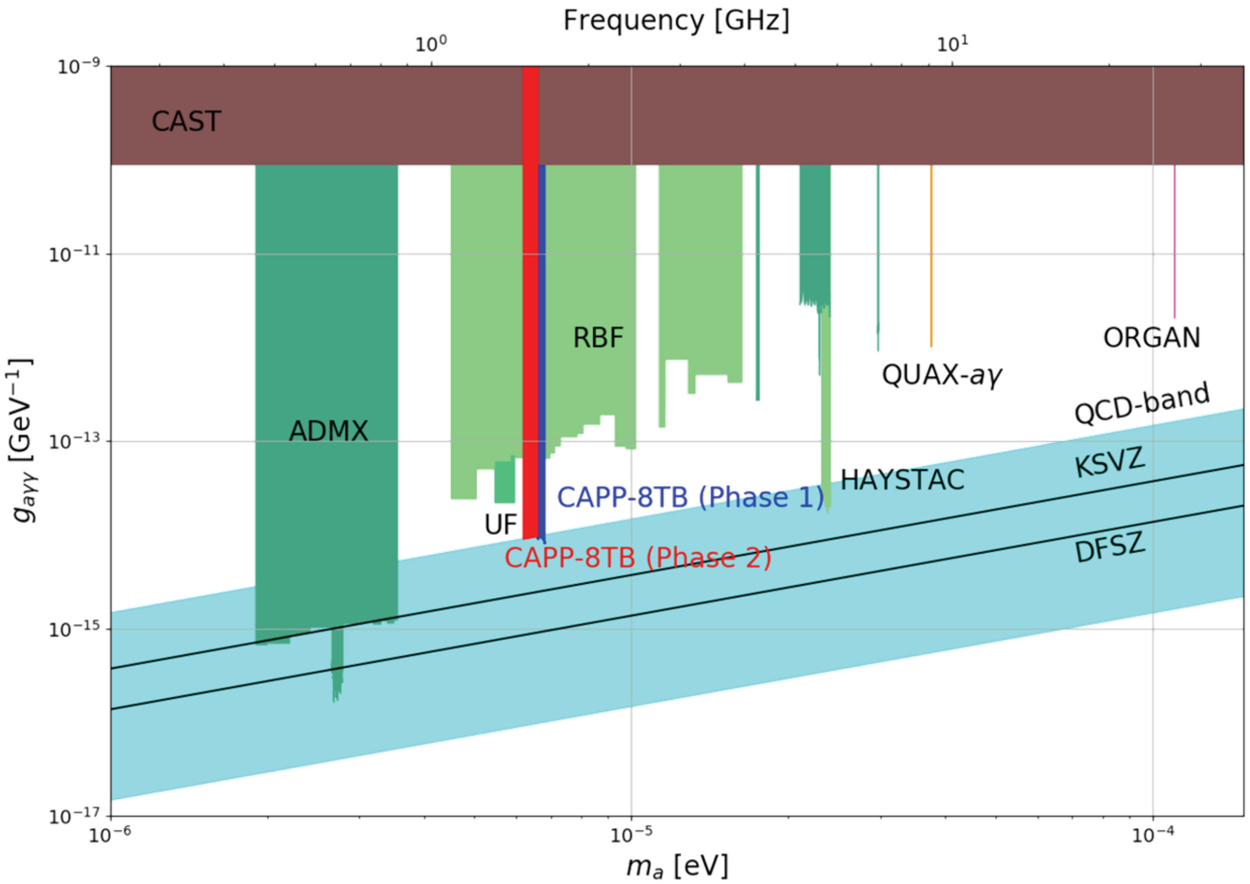
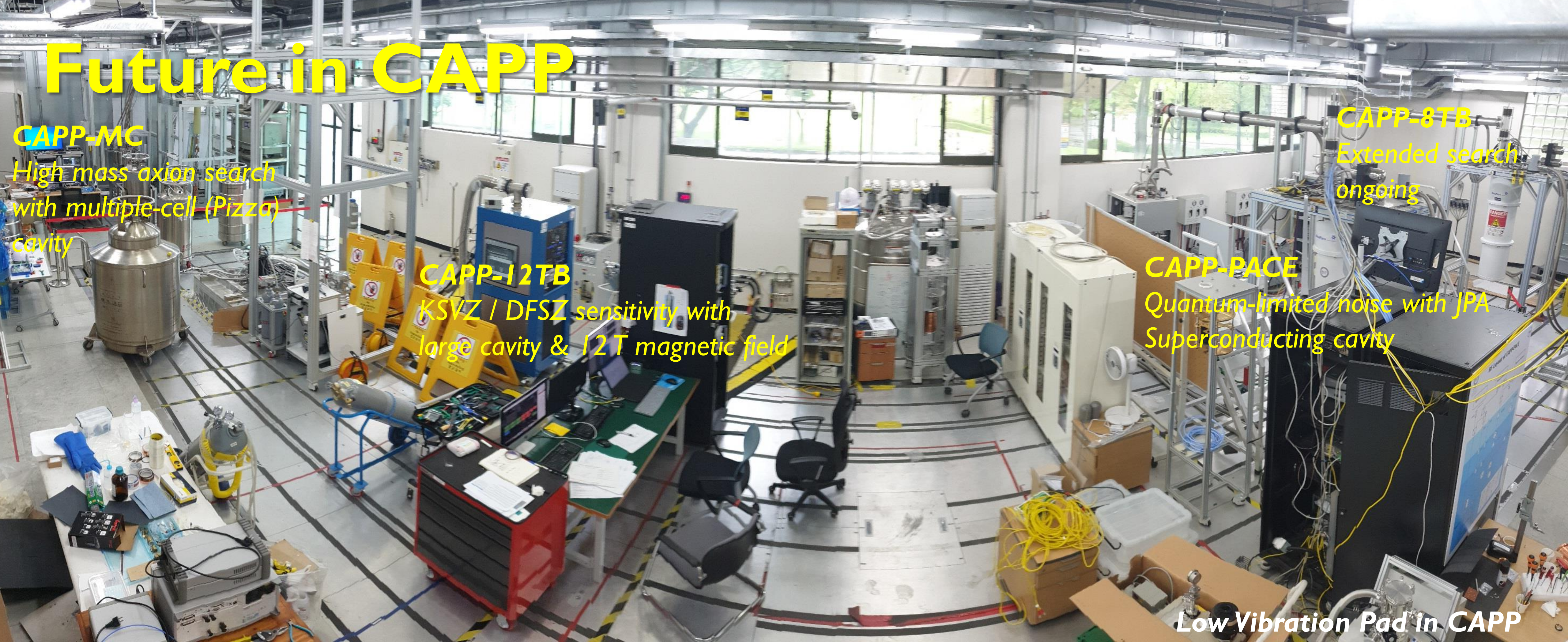
* *B. M. Brubaker, L. Zhong, S. K. Lamoreaux, K.W. Lehnert, and K.A. van Bibber, Phys. Rev. D 96, 123008 (2017).*

Result & future plan



- Setting upper limit on $g_{a\gamma\gamma}$ at 90 % C.L.
- Reached sensitivity down to QCD axion band in $6.62 < m_a < 6.82$ μeV
  - Most sensitive at this particular mass range to date
- Scan 6.20 – 6.62 μeV (1.5 – 1.6 GHz) for CAPP-8TB phase 2 is under preparation

Future in CAPP



STAY TUNED!

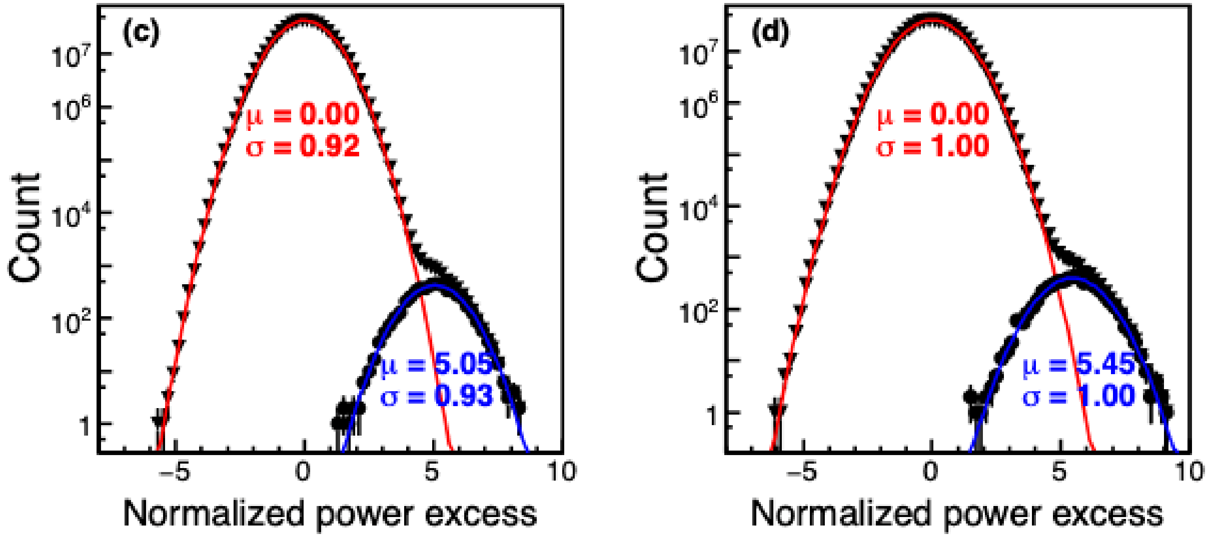
Correlation correction

- Standard deviation of Grand spectrum
  - σ = 0.93 < 1
  - Fitting induced negative correlations between co-adding bins
  - Signal power degradation ~ 84 %

- 5,000 (X 2501 steps) simulated experiment using the baseline fit result

- Incorporating the correlation
  - Width = unity
  - Signal power efficiency 84 % → 90 %

Correlation correction



Simulation