CAPP

Center for Axion and Precision Physics Research

Revisiting the Detection Rate for Axion Haloscope

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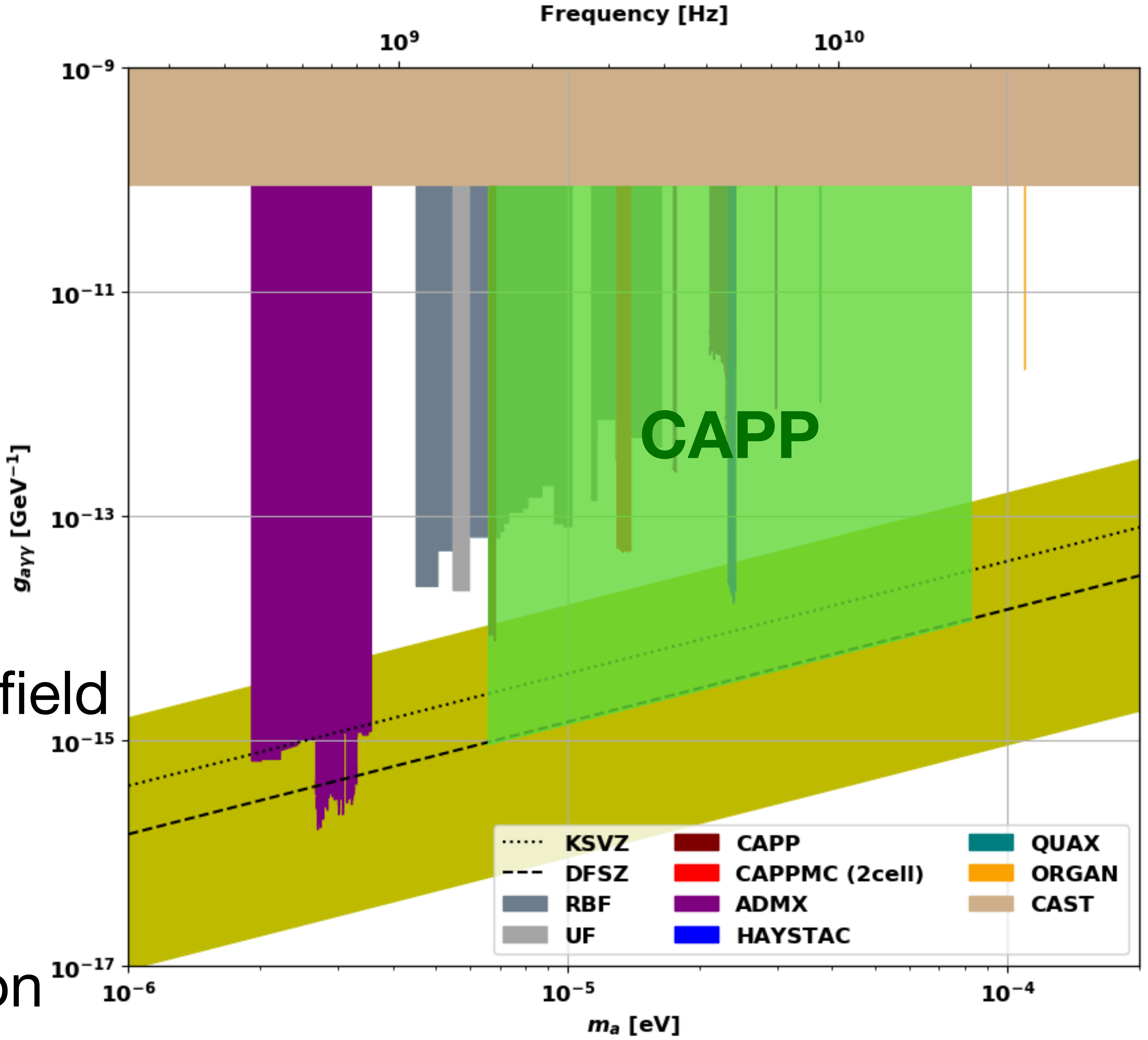
Overview

- Motivation and Introduction
- Axion Conversion Power
- Noise Powers of the Detection Scheme
- Scanning Rate of the Cavity Experiment for Axion Haloscope Searches
- Summary and Conclusion

Motivation

- Axion searches before CAPP
  - No path for frequency > 5 GHz
- Now we have a path
  - High-frequency cavity design
  - Superconducting cavities with large B-field
  - Single-photon detector work
  - Revisiting detection rate for optimization



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[J. Jeong PLB (2018)]

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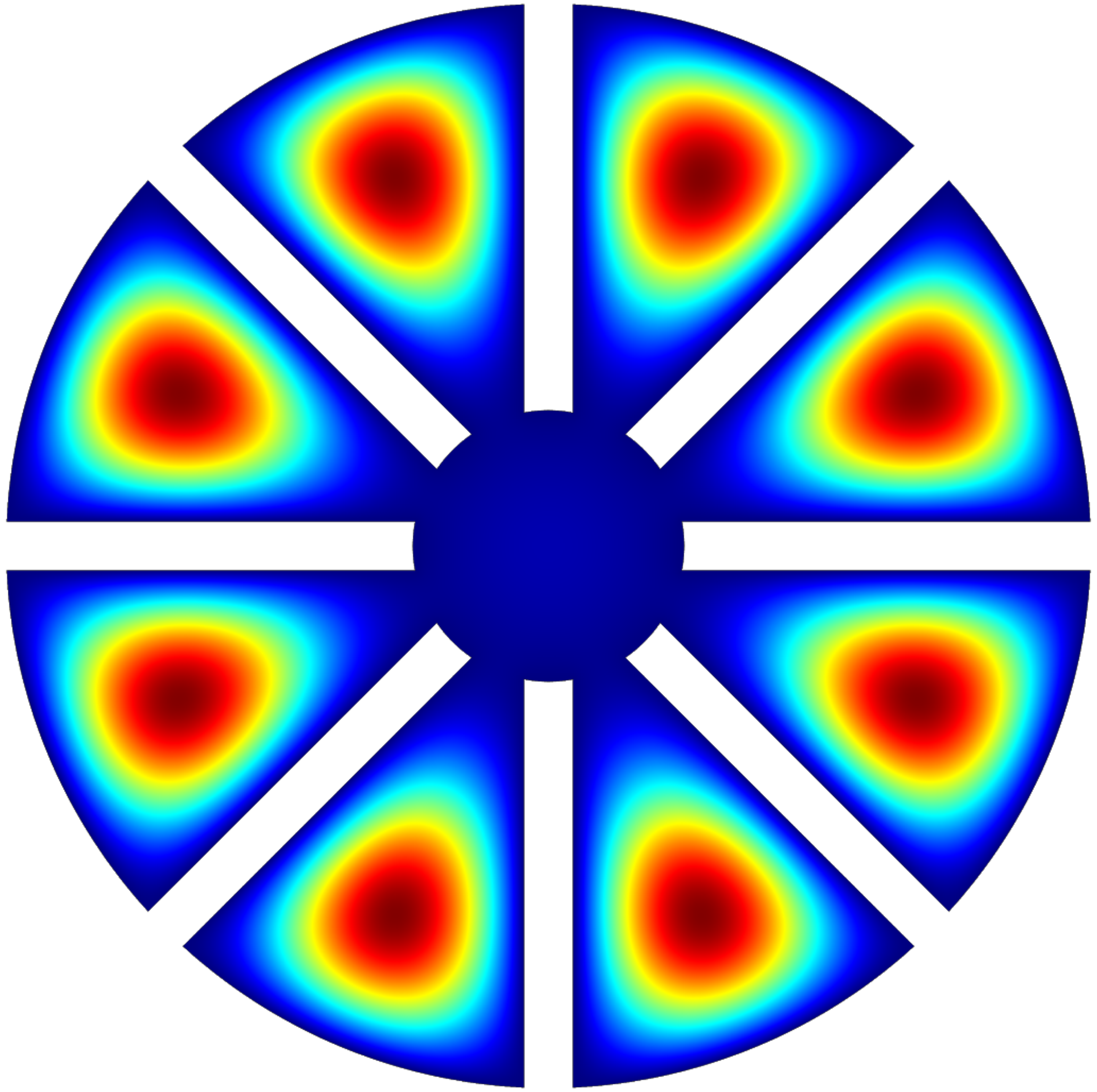

$$f_{\text{target}} \longrightarrow 3f_{\text{target}}$$

Motivation

[D. Ahn 2002:08769]

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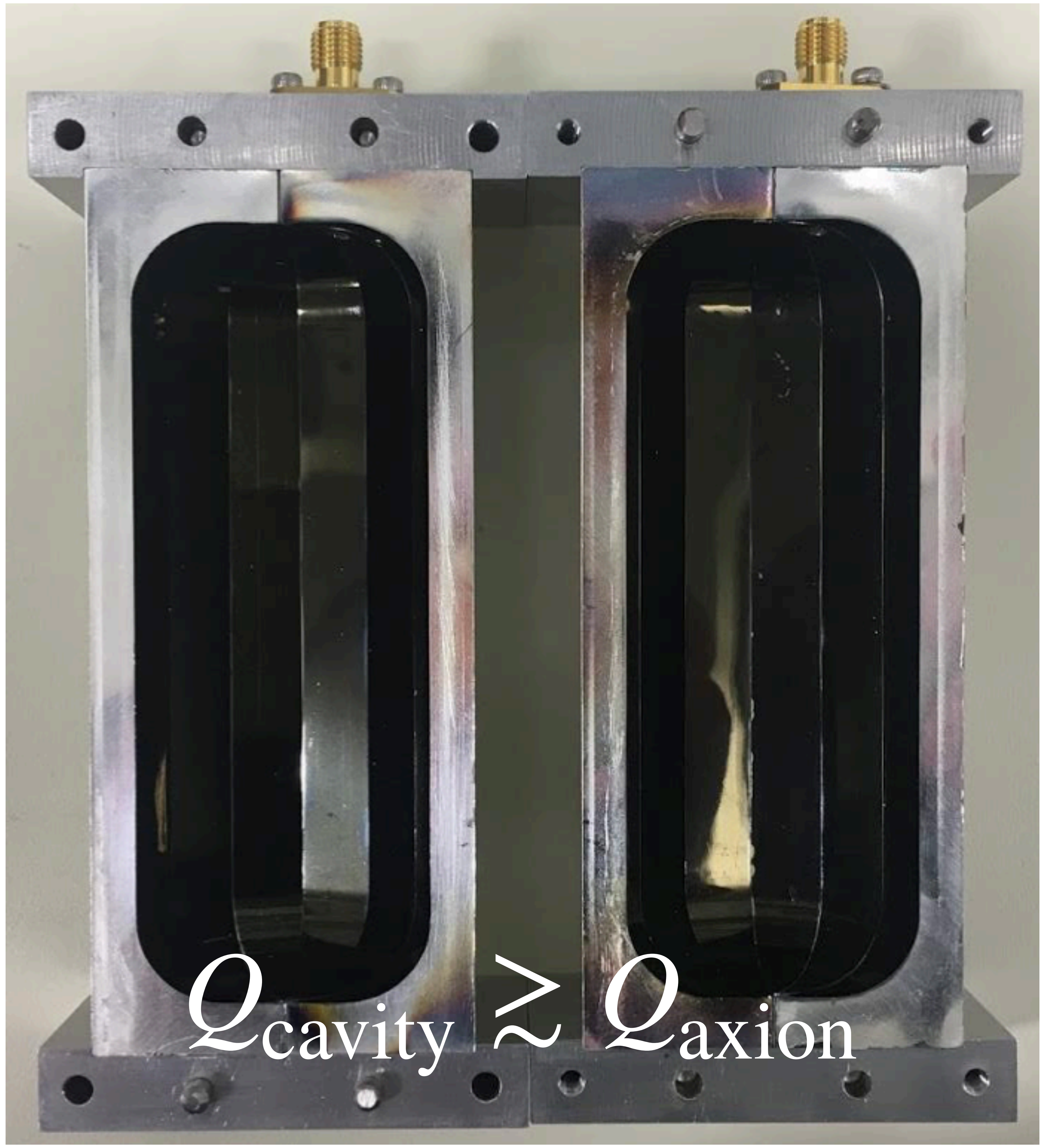

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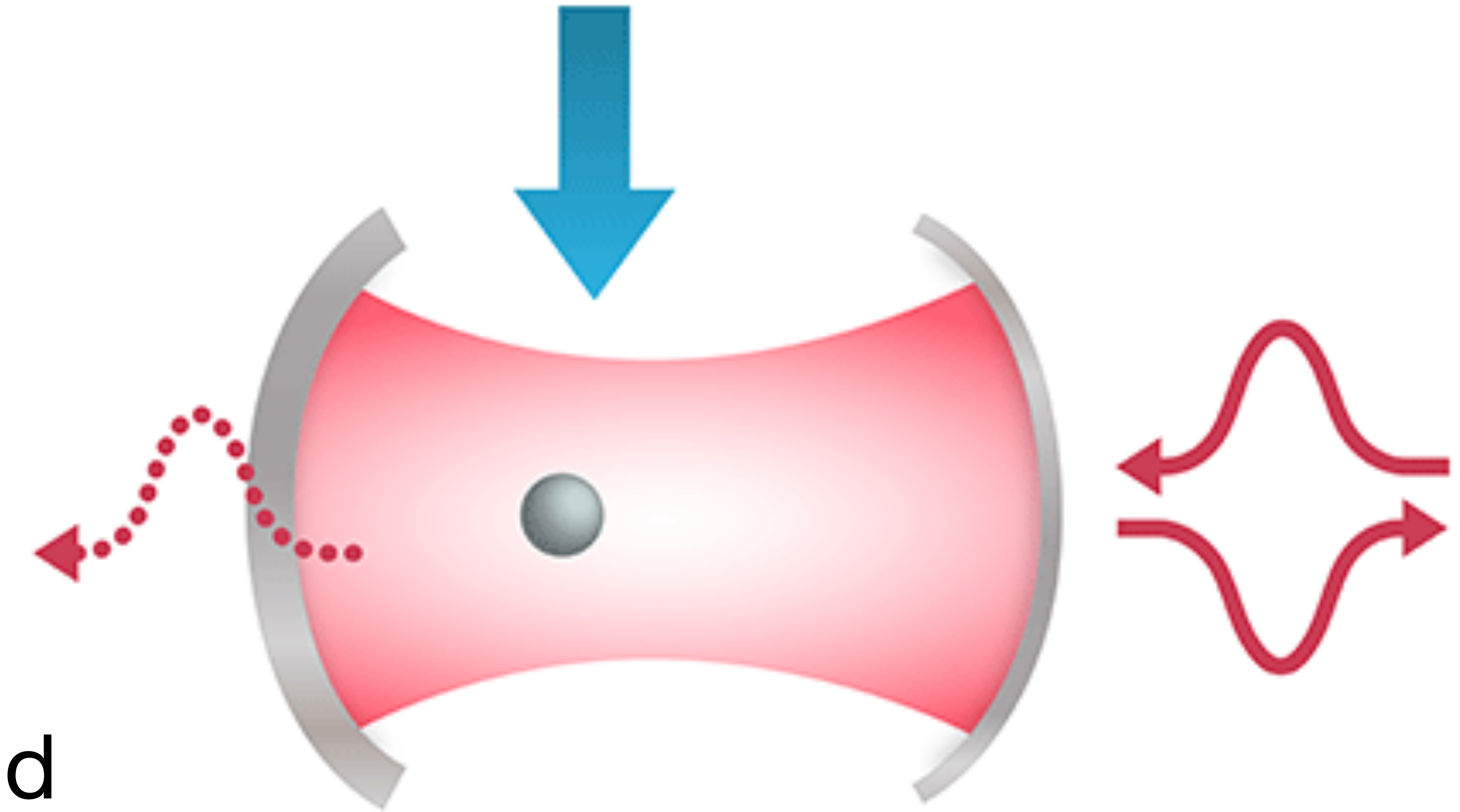

Adapted from O. Morin *et al.*, Phys. Rev. Lett. (2019) by APS/Ashley Mumford

Substantial improvement for
high frequency & low temperature

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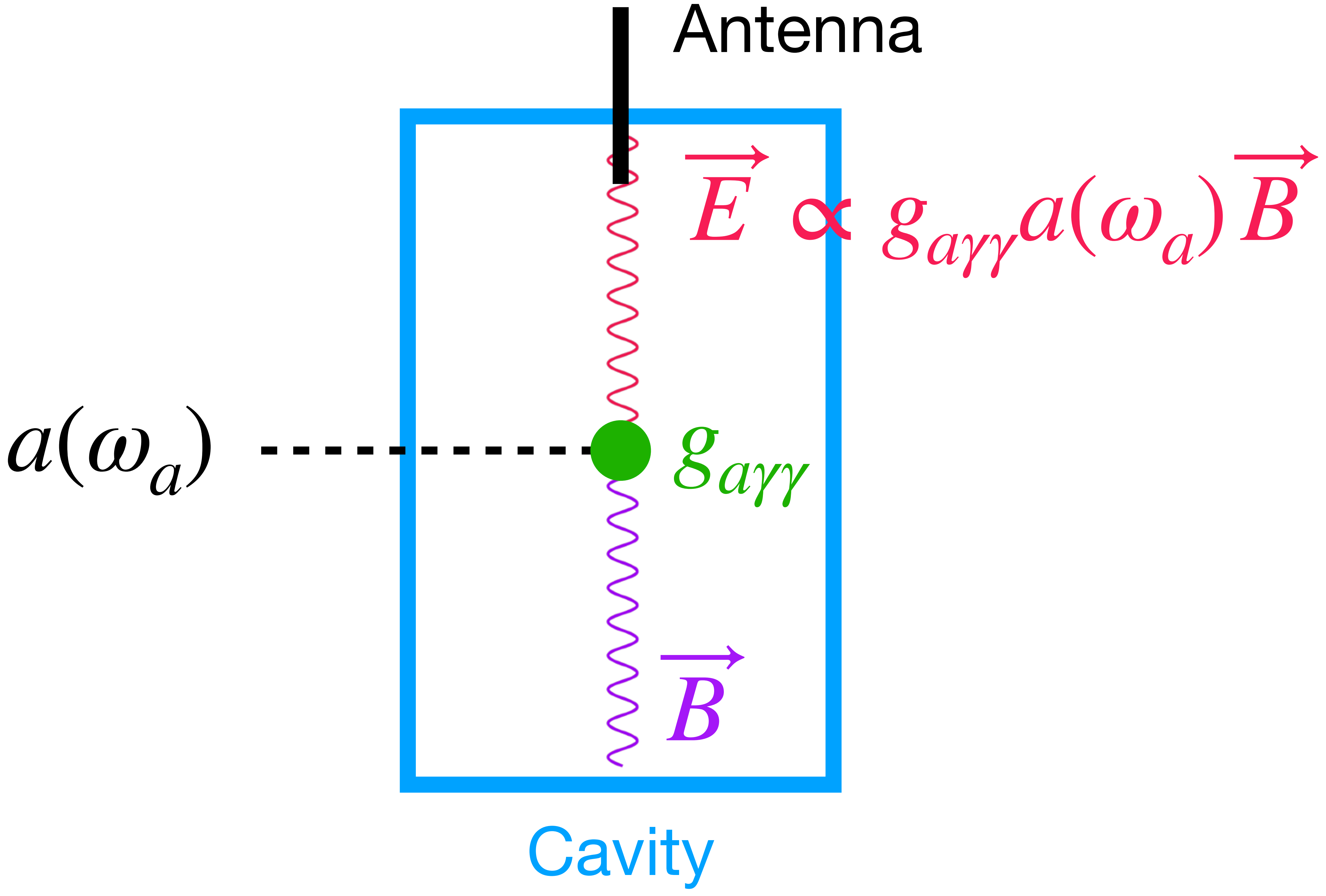
Introduction

- For detecting resonantly converted photon from dark matter axion under a strong magnetic field based on the scheme: [Sikivie PRL (1983), Sikivie PRD (1985)]



Axion signal power:

$$P_{\rm sig} = \frac{\beta}{1+\beta} g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \min(Q_l, Q_a)$$

Noise fluctuation:

$$\delta P_{\rm noise} = k_B T_{\rm sys} \sqrt{\frac{\Delta\nu}{\Delta t}}$$

Scanning rate:

$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2} g_{a\gamma\gamma}^4 \frac{\rho_a^2}{m_a^2} \frac{B_0^4 V^2 C^2}{k_B^2 T_{\rm sys}^2} \frac{\beta^2}{(1+\beta)^2} Q_a \min(Q_l, Q_a)$$

Introduction

- Development of a high-Q factor SC cavity: [D. Ahn 1902:04551, 2002:08769]

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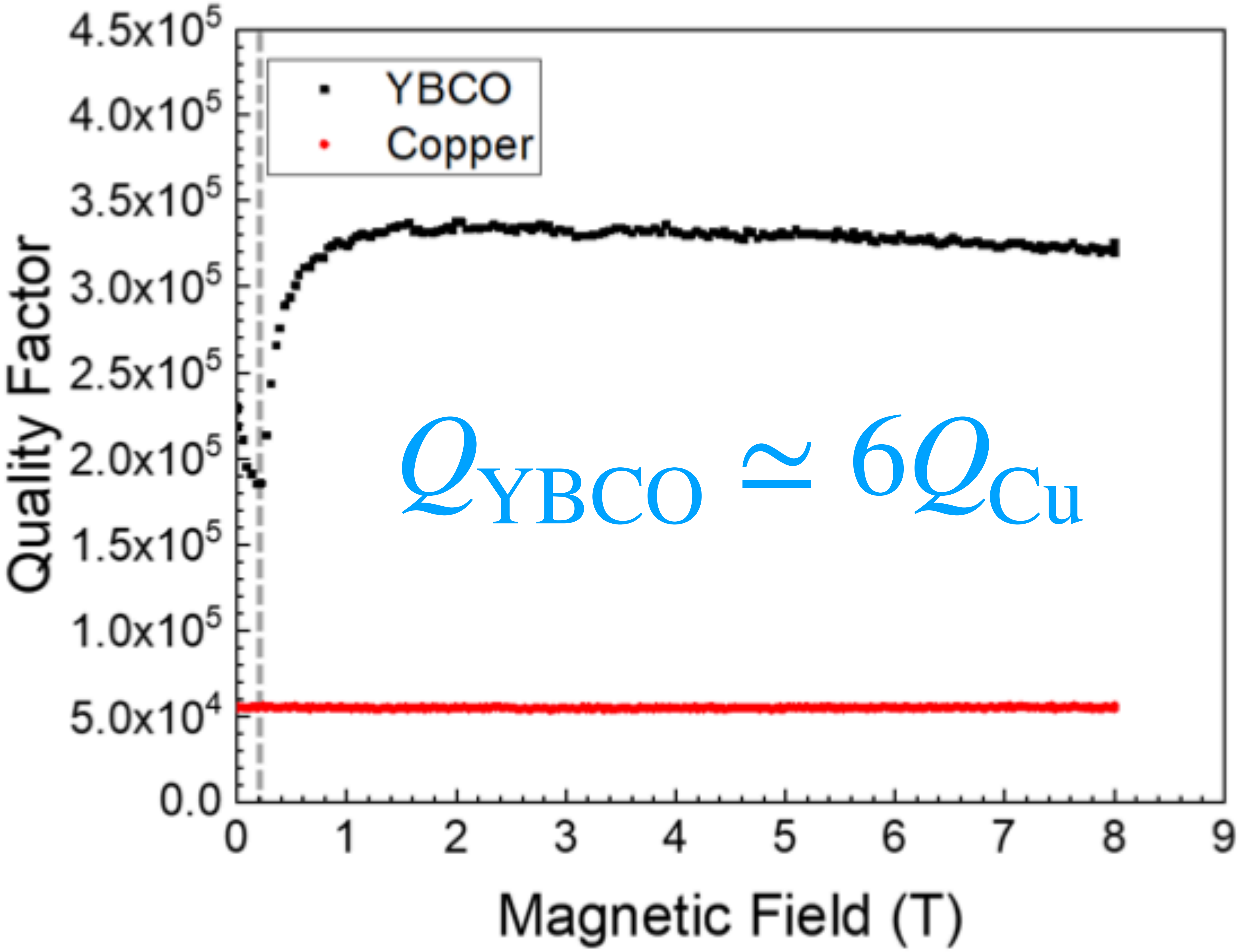
$$Q_c = (1+\beta) Q_l \simeq Q_a \approx 10^6$$



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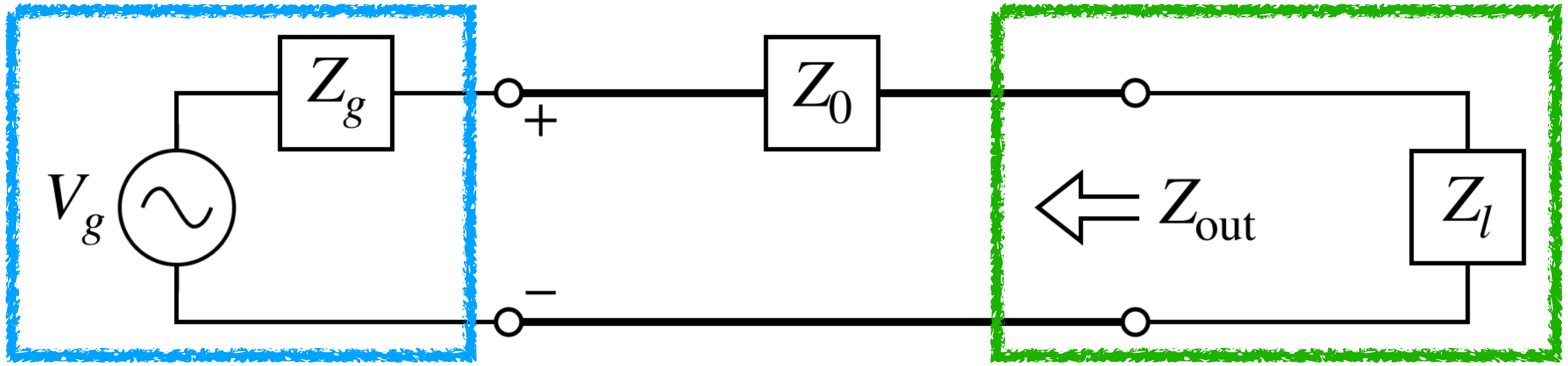
$$Q_c = (1+\beta) Q_l \simeq Q_a \approx 10^6$$

- Isolator is placed between the cavity and RF chain to match impedance independent of the coupling. Impedance is not matched in general.

Noise source (cavity)



Noise seen by detector (RF chain)

Axion Conversion Power

- Non-smooth part of the traditional formula

$$P_{\mathrm{conv}} = g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \min(Q_c, Q_a)$$

- This remedy works only for two extrema: $Q_c \ll Q_a,\ Q_c \gg Q_a$

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- Axion electrodynamics for cavity haloscope: [Y. Kim, Phys. Dark Univ. (2019)]

$$\nabla \cdot \vec{E}_r = 0$$
$$\nabla \cdot \vec{B}_r = 0$$
$$\nabla \times \vec{E}_r = -\frac{\partial}{\partial t}\vec{B}_r$$
$$\nabla \times \vec{B}_r = \frac{1}{c^2}\frac{\partial}{\partial t}\vec{E}_r - g_A \vec{B}_0 \frac{1}{c}\frac{\partial \theta}{\partial t}$$

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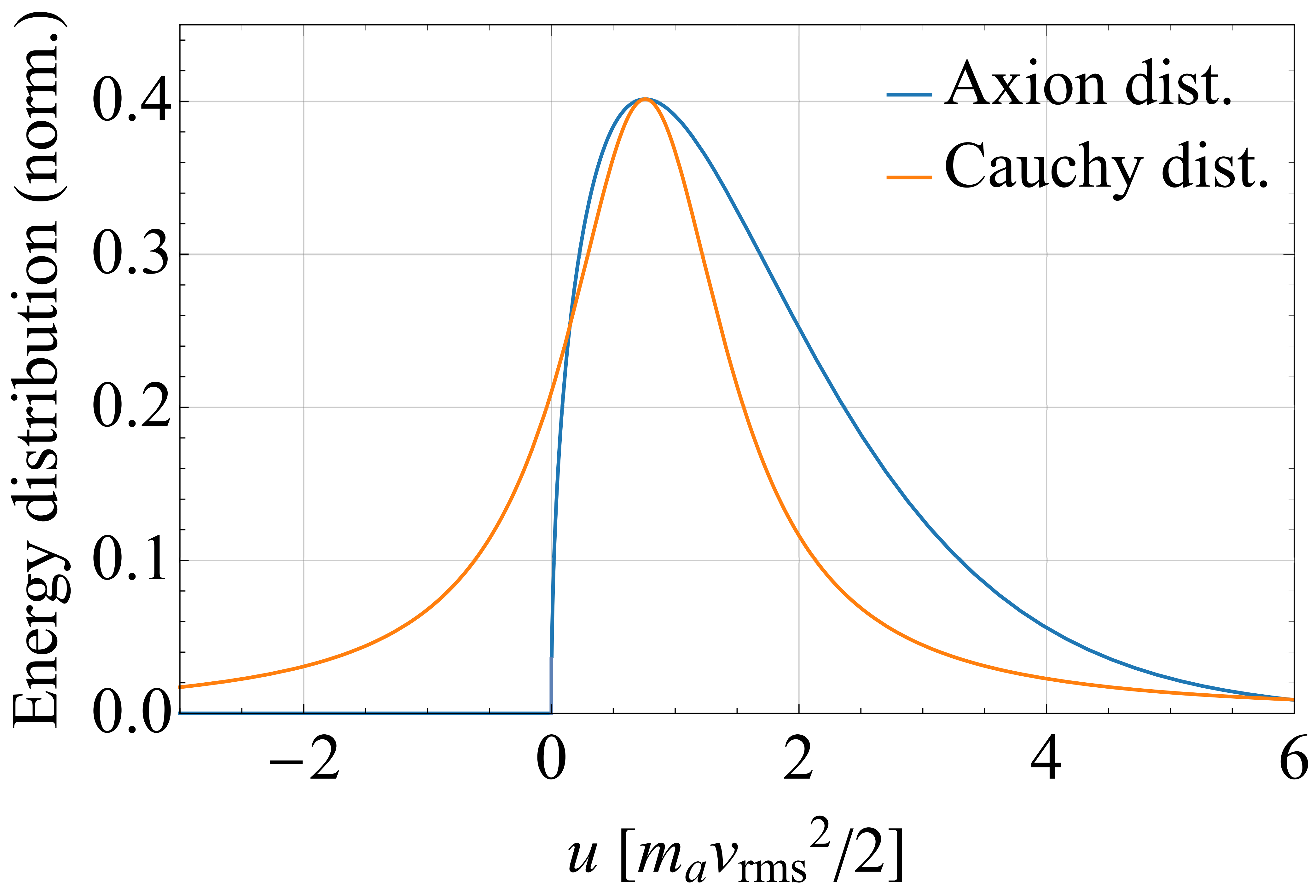
$$P_{\rm conv} = g_{a\gamma\gamma}^2 B_0^2 V C \omega_c Q_c \int \frac{d\omega}{2\pi} \left| \mathcal{F}(\omega, \omega_c) \right|^2 \left| \mathcal{A}(\omega, \omega_a) \right|^2$$

$$\mathcal{F}(\omega, \omega_c) = \frac{1}{(\omega - \omega_c) + i\omega_c/2Q_c}$$

$$\left\langle a^2(t) \right\rangle = \int \frac{d\omega}{2\pi} \left| \mathcal{A}(\omega, \omega_a) \right|^2$$

Cauchy Approximation

- Axion velocity distribution is assumed to follow the Maxwell-Boltzmann in the haloscope.
- Approximation of the axion power distribution as the Cauchy distribution allows for analytical calculation.



$$P_{\rm conv} = g_{a\gamma\gamma}^2 B_0^2 V C \omega_c Q_c \int \frac{d\omega}{2\pi} \left|\mathscr{F}(\omega,\omega_c)\right|^2 \left|\mathscr{A}(\omega,\omega_a)\right|^2$$

$$\mathscr{F}(\omega,\omega_c) = \frac{1}{(\omega-\omega_c) + i\omega_c/2Q_c}$$

Cavity response

$$\langle a^2(t)\rangle = \int \frac{d\omega}{2\pi} \left|\mathscr{A}(\omega,\omega_a)\right|^2 = \int \frac{d\omega}{2\pi} \frac{4\rho_a Q_a}{\omega_a m_a^2} \left(\frac{1}{1+\left(\frac{\omega-\omega_a}{\omega_a/2Q_a}\right)^2} \right)$$

Axion dispersion

Axion Conversion Power

- Then the corresponding axion conversion power becomes

$$P_{\text{conv}} = g_{a\gamma\gamma}^2 B_0^2 V C \omega_c Q_c \int \frac{d\omega}{2\pi} \left|\mathcal{F}(\omega, \omega_c)\right|^2 \left|\mathcal{A}(\omega, \omega_a)\right|^2 \propto \int \frac{d\omega}{2\pi} \left[\frac{1}{1 + \left(\frac{\omega - \omega_c}{\omega_c/2Q_c}\right)^2} \right] \left[\frac{1}{1 + \left(\frac{\omega - \omega_a}{\omega_a/2Q_a}\right)^2} \right]$$

- The integration becomes straightforward when the cavity frequency (ω_c) matches the axion frequency (ω_a) as $\omega_c = \omega_a = \omega_0$.

$$P_{\text{conv}} = g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \frac{Q_c Q_a}{Q_c + Q_a}$$

Axion Signal Power

- The axion conversion power is revised to

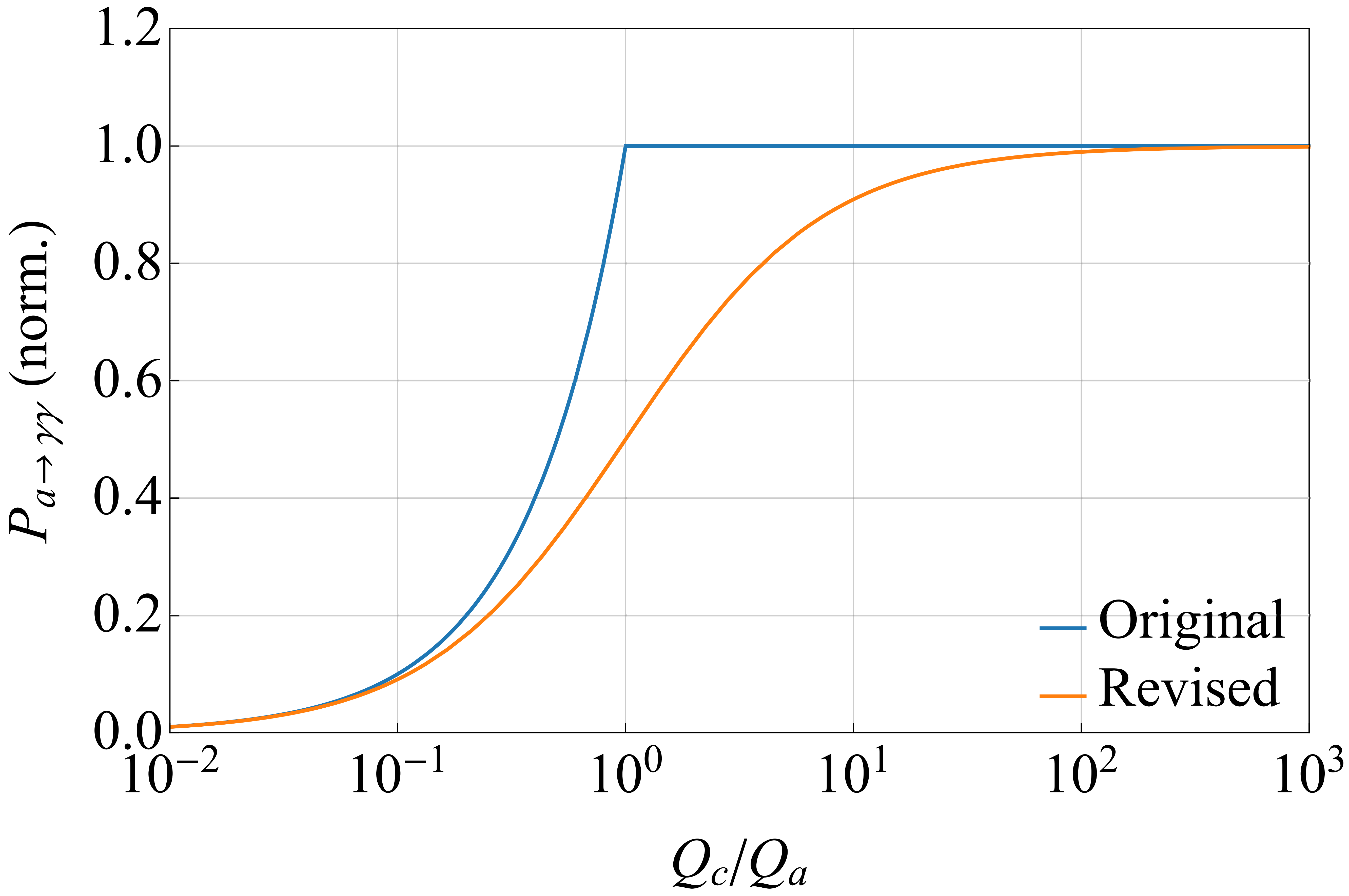
$$P_{\rm conv} = g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \frac{Q_c Q_a}{Q_c + Q_a}$$

reduced Q factor is naturally appeard

$$\frac{1}{Q_\mu} \equiv \frac{1}{Q_c} + \frac{1}{Q_a}$$

original formular

$$P_{\rm conv} = g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \min(Q_c, Q_a)$$



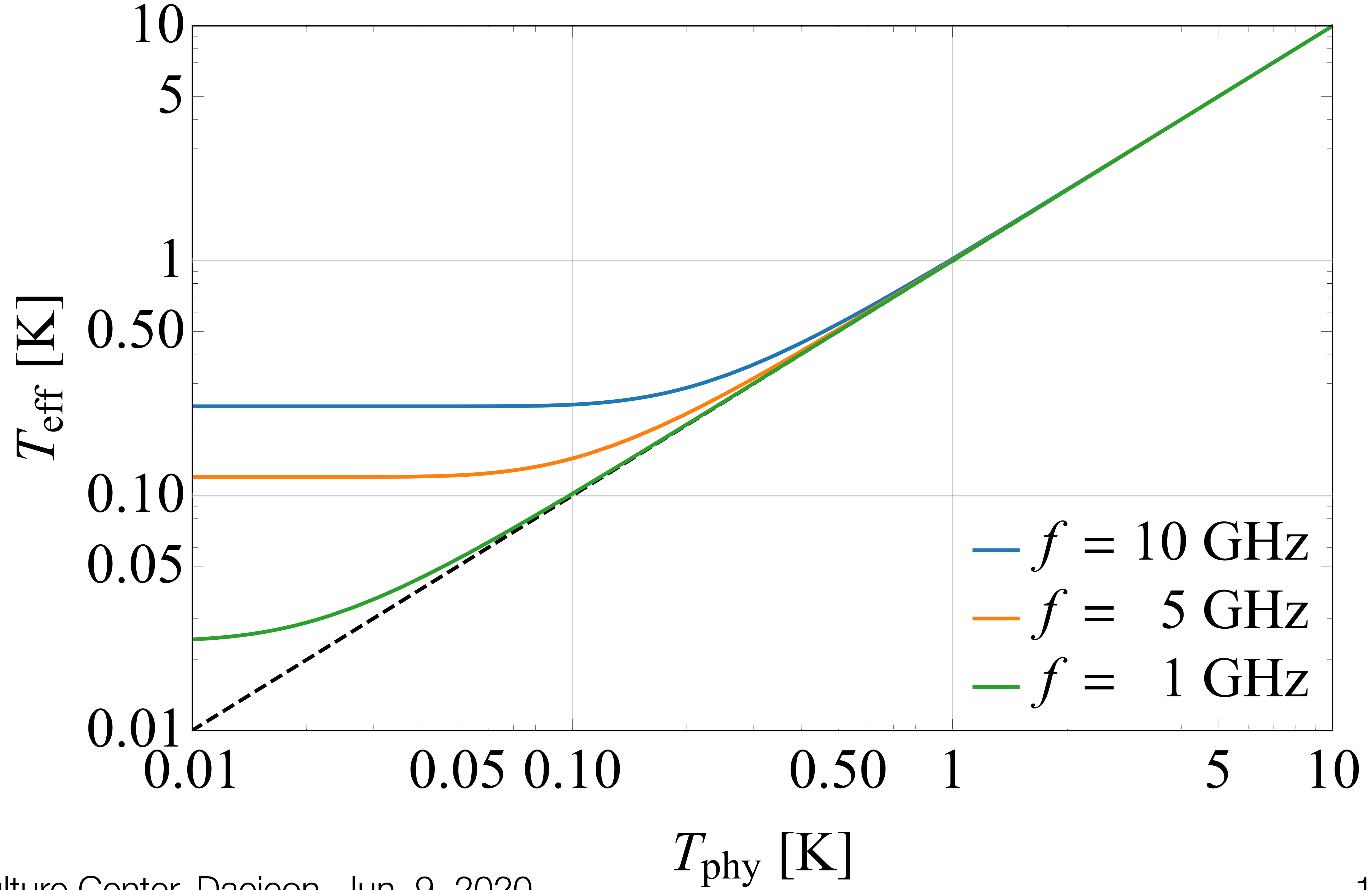
Noise Powers

- Two noise sources are major in the cavity haloscope.

  - Johnson-Nyquist thermal noise: [Johnson, Phys. Rev. (1928), Nyquist, Phys. Rev. (1928)]

$$P_{\rm JN} = k_B T_{\rm eff} \Delta\nu \frac{4\beta}{(1+\beta)^2}$$

$$T_{\rm eff} = T_{\rm phys}\eta(\omega) = \frac{\hbar\omega}{k_B}\left(\frac{1}{e^{\hbar\omega/k_B T_{\rm phys}} - 1} + \frac{1}{2}\right)$$



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$$P_{\mathrm{JN}} = k_B T_{\mathrm{eff}} \Delta\nu \frac{4\beta}{(1+\beta)^2}$$

  - Added noise (equivalent noise temperature) by the RF readout chain:

$$P_{\mathrm{add}} = k_B T_{\mathrm{add}} \Delta\nu$$

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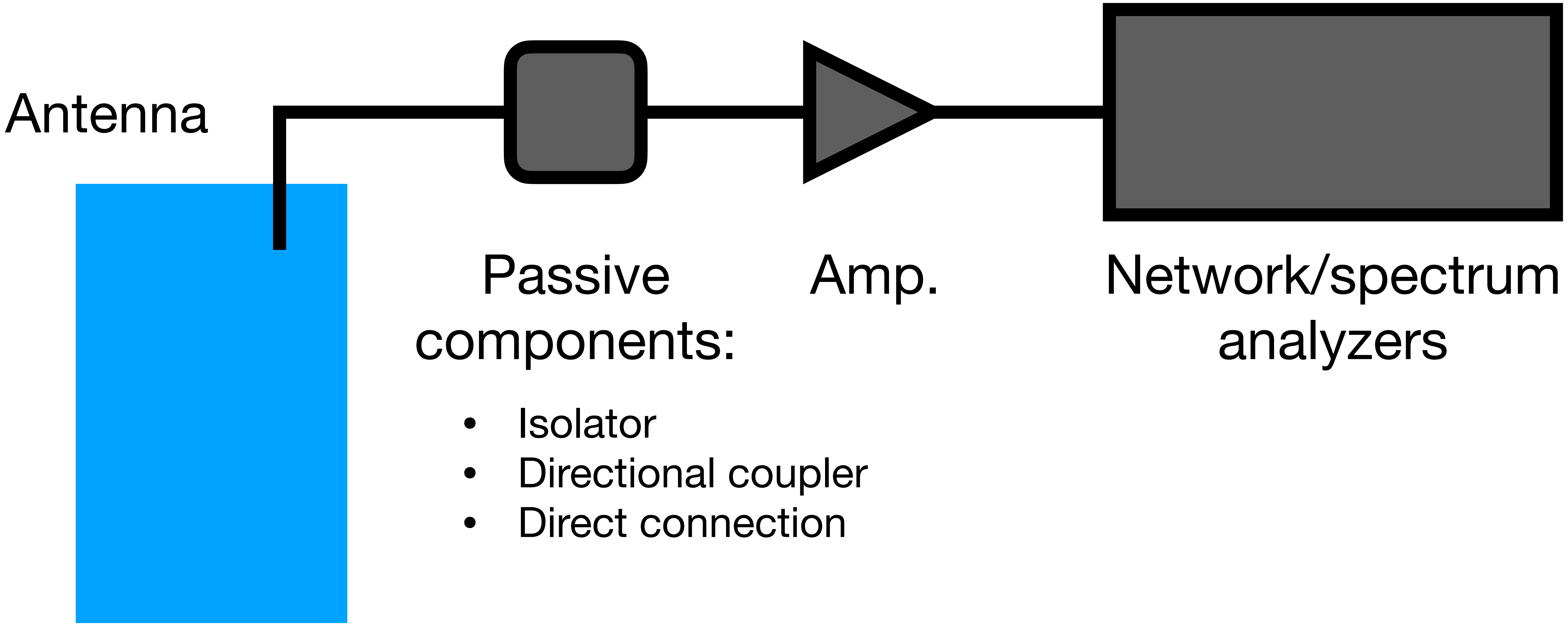
- Total noise: $P_{\rm noise} = P_{\rm JN} + P_{\rm add} = k_B T_{\rm eff} \Delta\nu \left(\frac{4\beta}{(1+\beta)^2} + \lambda \right)$ $\qquad \lambda \equiv \frac{T_{\rm add}}{T_{\rm eff}}$

Experimental Demonstration

- We conducted an experiment to demonstrate the acquired noise power from the cavity through the amplifier at room temperature.

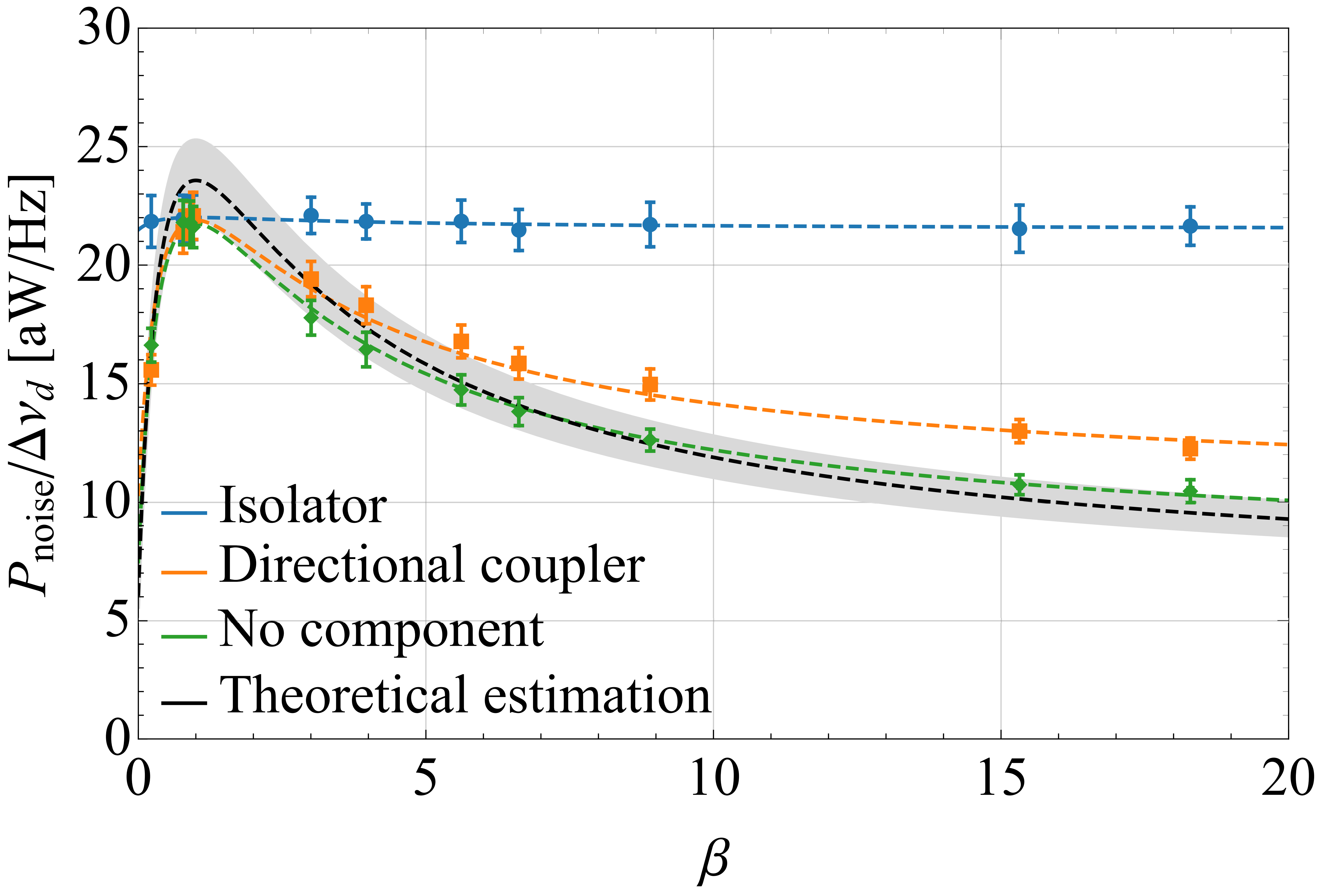


Cavity ($\omega_0/2\pi \approx 5.9$ GHz)

Noise Power

- Measured noise powers with respect to the antenna couplings agreed with expectation.

$$P_{\rm noise} = k_B T_{\rm eff} \Delta\nu \left(\frac{4\beta}{(1+\beta)^2} + \lambda \right)$$



Scanning Rate

- Based on the revised forms of **axion signal power** and **noise power**, the scanning rate is newly derived.

$$P_{\rm sig} = \frac{\beta}{1+\beta} g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \min(Q_l, Q_a)$$

$$\delta P_{\rm noise} = k_B T_{\rm sys} \sqrt{\frac{\Delta\nu}{\Delta t}}$$

$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2} g_{a\gamma\gamma}^4 \frac{\rho_a^2}{m_a^2} \frac{B_0^4 V^2 C^2}{k_B^2 T_{\rm sys}^2} \frac{\beta^2}{(1+\beta)^2} Q_a \min(Q_l, Q_a)$$

→

$$P_{\rm sig} = \frac{\beta}{1+\beta} g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \frac{Q_l Q_a}{Q_l + Q_a}$$

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Original relations

$$P_{\rm sig} = \frac{\beta}{1+\beta} g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \frac{Q_l Q_a}{Q_l + Q_a}$$

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Revised relations

Scanning Rate Optimization

- Both original and revised forms of the scanning rate can be optimized with respect to the antenna coupling β.

$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2} g_{a\gamma\gamma}^4 \frac{\rho_a^2}{m_a^2} \frac{B_0^4 V^2 C^2}{k_B^2 T_{\mathrm{sys}}^2} \frac{\beta^2}{(1+\beta)^2} Q_a \min(Q_l, Q_a)$$

$$\beta_{\mathrm{opt}} = 2$$

$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2} g_{a\gamma\gamma}^4 \frac{\rho_a^2}{m_a^2} \frac{B_0^4 V^2 C^2}{k_B^2 T_{\mathrm{eff}}^2} \left(\frac{\beta/(1+\beta)}{4\beta/(1+\beta)^2 + \lambda} \right)^2 Q_a \frac{Q_l Q_a}{Q_l + Q_a}$$

Q_c and λ dependence

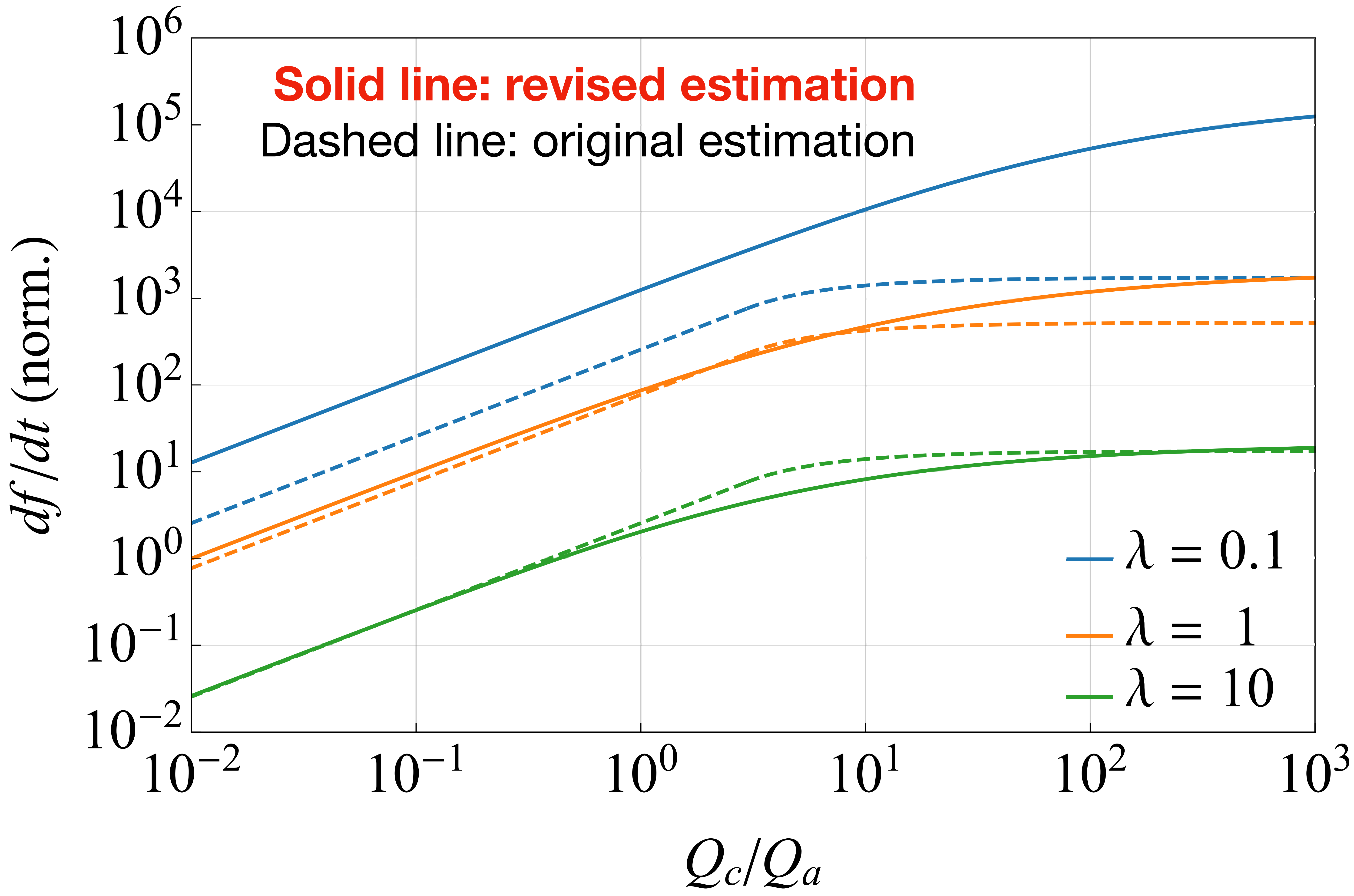
$\beta_{\mathrm{opt}} =$

Qc/Qa	λ = 10	λ = 1	λ = 0.1
0.01	2.2	4.7	40
0.1	2.3	4.8	40
1	2.9	6.1	42
10	6.9	12.1	55
100	17.2	33.5	112

Optimized Scanning Rate

Qc/Qa	λ = 10	λ = 1	λ = 0.1
0.01	< 0.1	1	12
0.1	0.3	10	127
1	2.0	87	1245
10	8.2	470	10565
100	15.2	1185	52898

Optimized scanning rate
for revised case
(solid line, normalized)



Original formula is compared for each case
(dashed line, normalized)

Summary

- The traditional approach to the cavity haloscope for axion search is revisited to reflect development of technologies in superconducting and quantum science

- Revised axion signal power and scanning rate are

$$P_{\rm sig} = \frac{\beta}{1+\beta} g_{a\gamma\gamma}^2 B_0^2 V C \frac{\rho_a}{m_a} \frac{Q_l Q_a}{Q_l + Q_a} \qquad \frac{df}{dt} = \frac{1}{\mathrm{SNR}^2} g_{a\gamma\gamma}^4 \frac{\rho_a^2}{m_a^2} \frac{B_0^4 V^2 C^2}{k_B^2 T_{\rm eff}^2} \left(\frac{\beta/(1+\beta)}{4\beta/(1+\beta)^2 + \lambda} \right)^2 Q_a \frac{Q_l Q_a}{Q_l + Q_a}$$

- Further enhancement of the scanning rate is expected with high Q factor cavities and low noise amplifiers.

- This work was published [D. Kim, JCAP (2020)].

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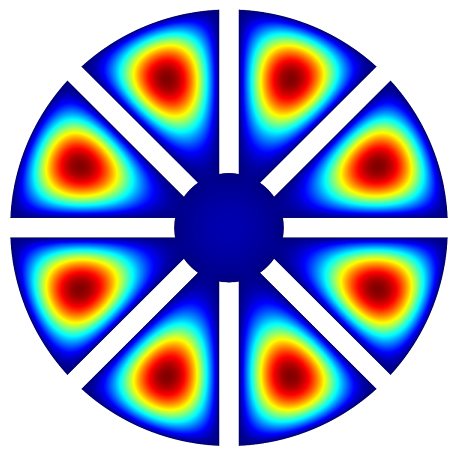
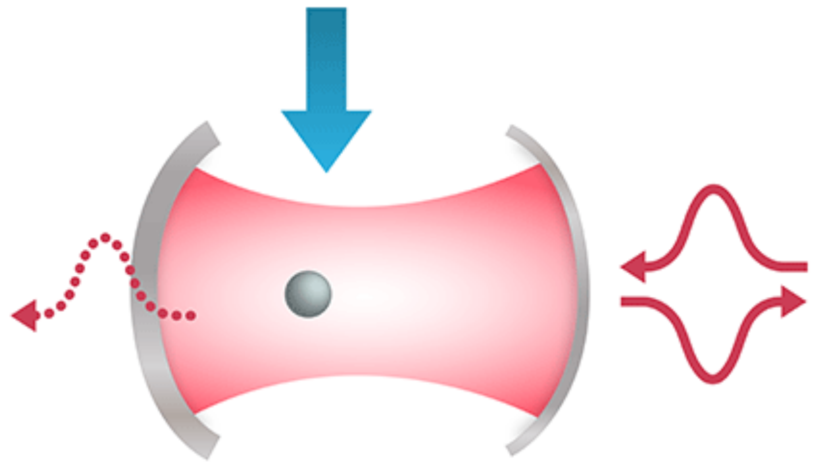
Conclusion

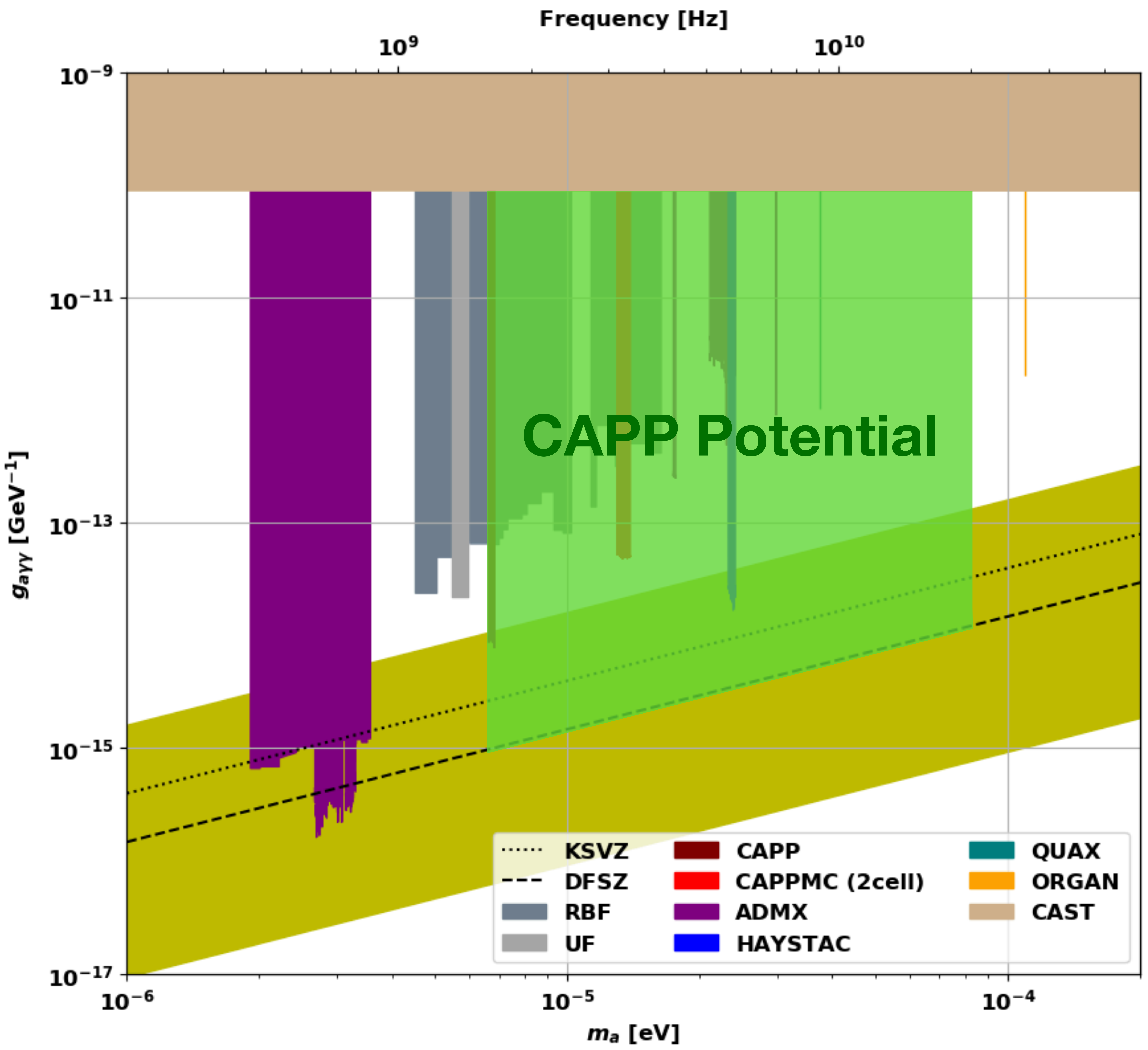
- Innovative breakthroughs for high-frequency axion dark matter searches at IBS/CAPP
  - High-frequency detector design
  - High-Q SC cavity
  - Single-photon detector (initiating)





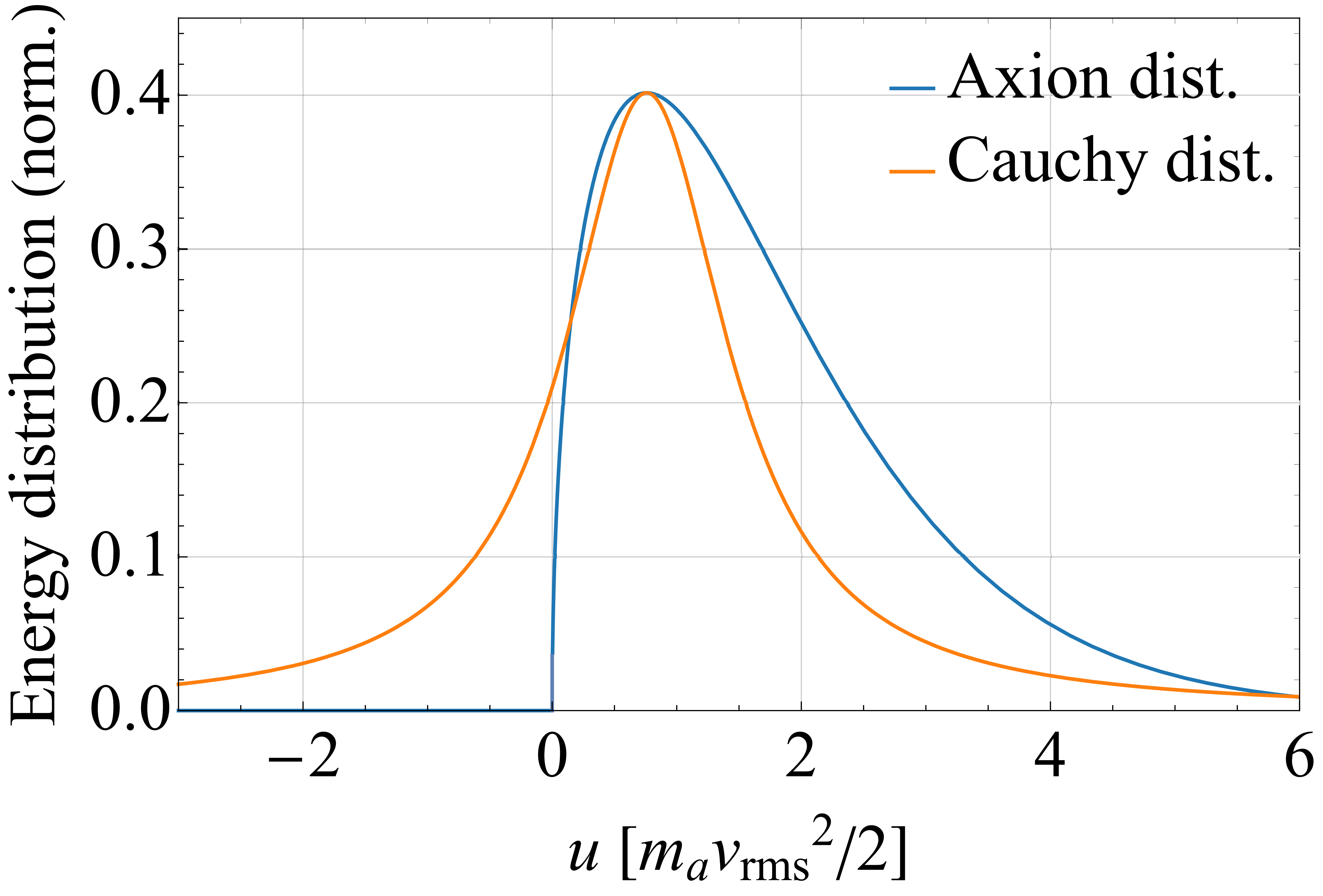
- Reformulation of the detection rate => non-trivial impacts on axion society
- IBS/CAPP makes significant contributions to axion search business in all experimental aspects!

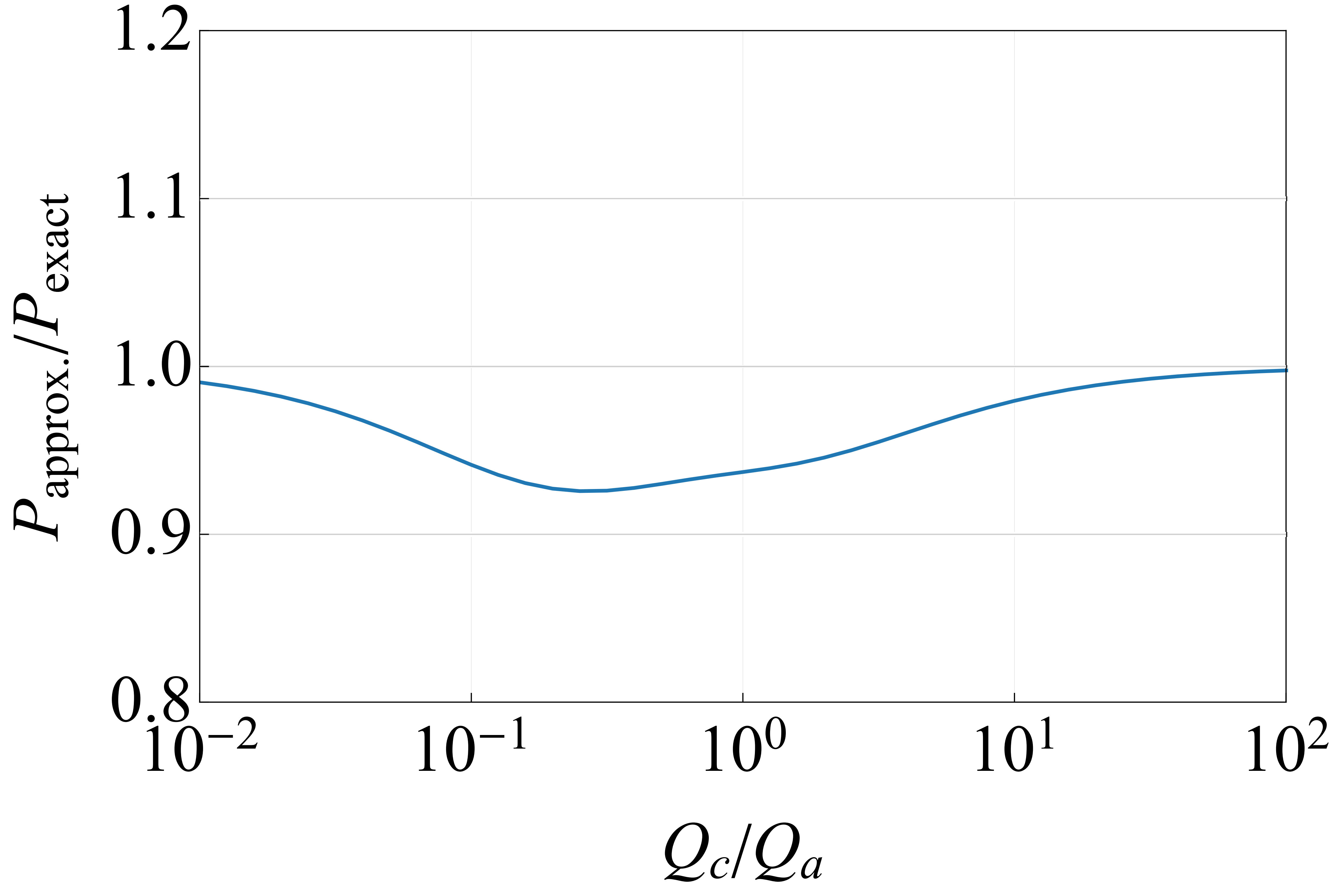
Thank you !


Frequency [Hz]
10^9
10^{10}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
$g_{a\gamma\gamma}$ [GeV^{-1}]
CAPP Potential
KSVZ
DFSZ
RBF
UF
CAPP
CAPPMC (2cell)
ADMX
HAYSTAC
QUAX
ORGAN
CAST
10^{-6}
10^{-5}
10^{-4}
m_a [eV]

Cauchy Approximation

- The correction error will be less than 10% in this approximation





Theoretical Estimation

- Based on the noise formula $P_{\text{noise}}/\Delta\nu = k_B T_{\text{eff}} G \left(\frac{4\beta}{(1+\beta)^2} + \lambda \right)$
  - We considered the noise parameter effect that may come the amplifier input end.
  - The amplifier gain (G) and temperature (λ) are measured and considered as a statistical error.
  - The amplifier excess noise ratio (ENR) uncertainty is considered as a systematical error as well.