History of ADMX

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Strong CP problem

QCD Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_{j=1}^{n} \bar{q}_j \left(i\gamma^\mu D_\mu - m_j \right) q_j + \underbrace{\frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}}_{\text{Theta term}}$$

Gluon field

Quark field

Theta term

Upper limit on the neutron electric dipole moment

$$\theta \leq 5 \times 10^{-11}$$

C. Abel *et al.*, Phys. Rev. Lett. **124**, 081803 (2020).

$\Big\downarrow$ θ is so small

In quantum chromodynamics (QCD), CP symmetry should be broken, but not!

C (Charge conjugation): Symmetry that transforms a particle into its antiparticle

P (Parity transformation): Symmetry of spatial inversion

QCD axion

- Peccei and Quinn proposed QCD axion to solve the strong CP problem
- QCD axion produce its effective potential $V(\bar{\theta})$ whose minimum is at $\bar{\theta} = 0$
- $\bar{\theta}$ is dynamically allowed to relax to zero and the strong CP problem is solved

$$\bar{\theta} = \theta - \arg(m_1, m_2, ..., m_n)$$

Argument of the quark mass matrix

$$\Big\downarrow$$

$$\bar{\theta} = \theta - \arg(m_1, m_2, ..., m_n) - \frac{a(x)}{f_a}$$

Axion field

Axion decay constant

KSVZ and DFSZ model

Axion-photon coupling

Model-dependent axion-photon coupling

$$g_{a\gamma\gamma} = \frac{g_\gamma \alpha}{\pi f_a}$$

$$g_\gamma = \frac{1}{2}\left(\frac{N_e}{N} - \frac{5}{3} - \frac{m_d - m_u}{m_d + m_u}\right)$$

Fine structure constant

Up quark mass

Down quark mass

Axion decay constant

$N_e = 0$ ➡ Kim-Shifman-Vainshtein-Zakharov (KSVZ) model

$N_e = \frac{8}{3}N$ ➡ Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) model

Axion mass
$$m_a = \frac{f_\pi m_\pi}{f_a}\frac{\sqrt{m_d m_u}}{m_d + m_u} \simeq 6\ \mu\text{eV}\left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$$

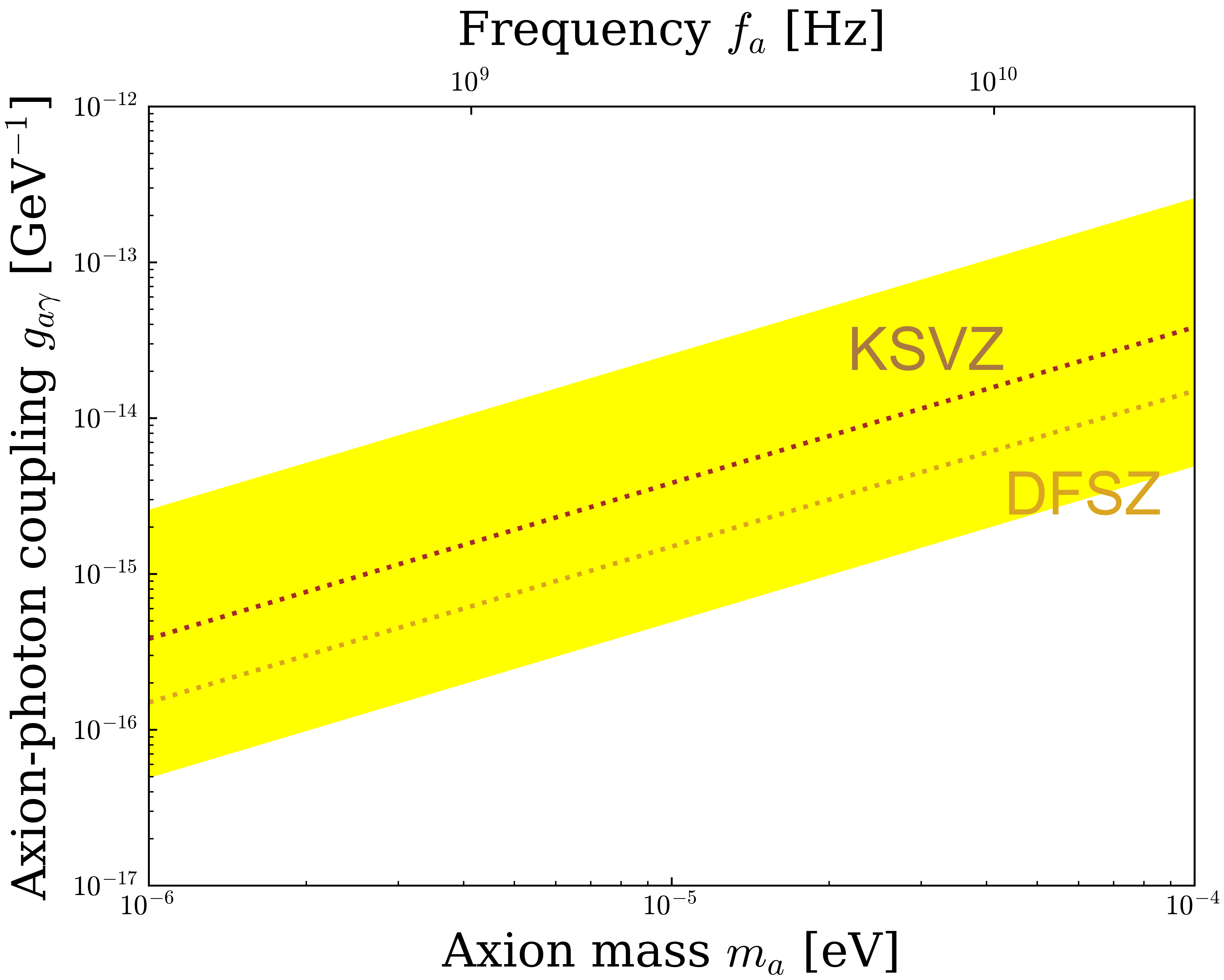
Pion decay constant

Pion mass

C. Hagmann *et al*., Phys. Rev. D **42**, 1297 (1990).

Axion Dark Matter eXperiment (ADMX)

ADMX aims to detect QCD axion (particularly KSVZ and DFSZ model)

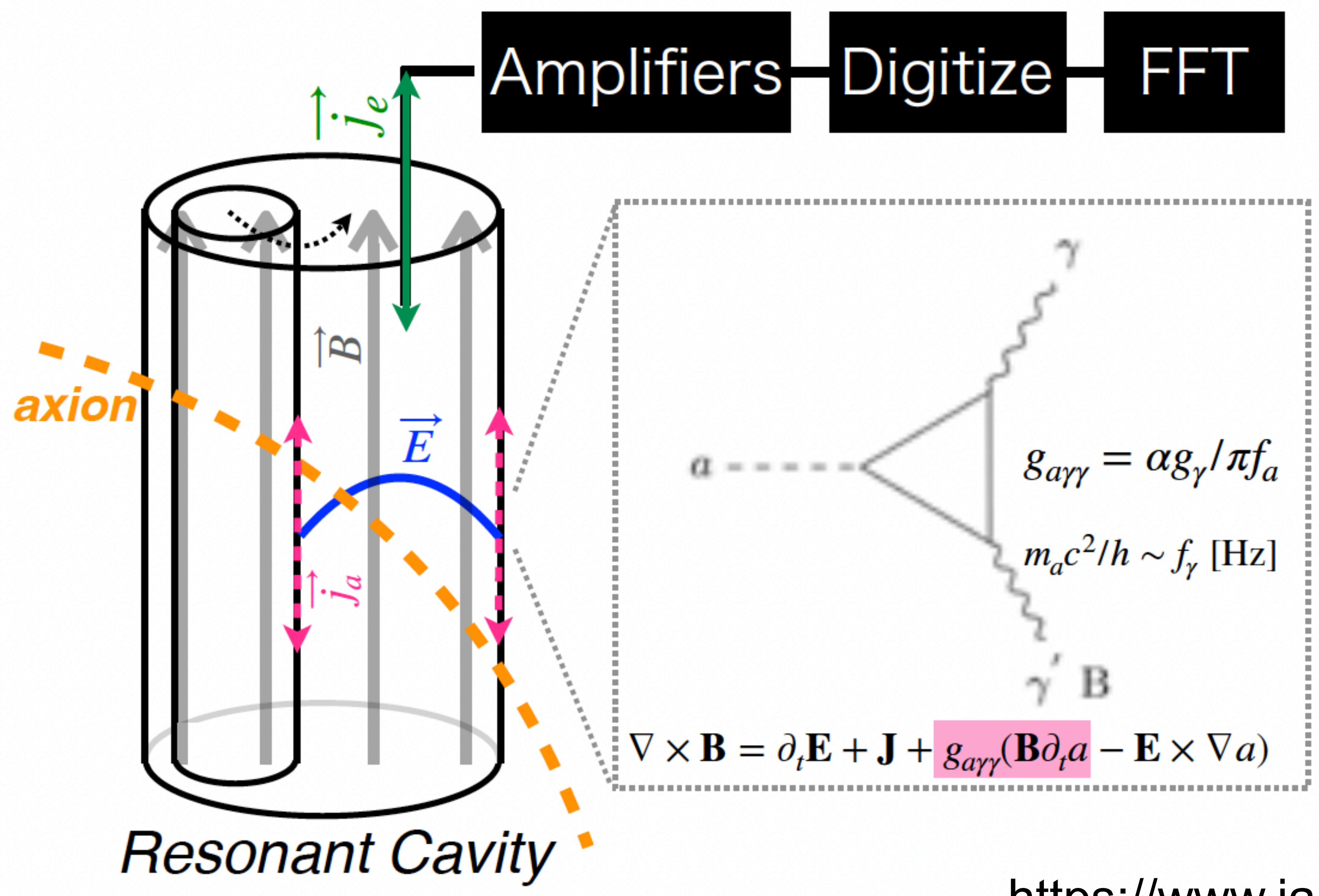


Principle of ADMX

Detection method

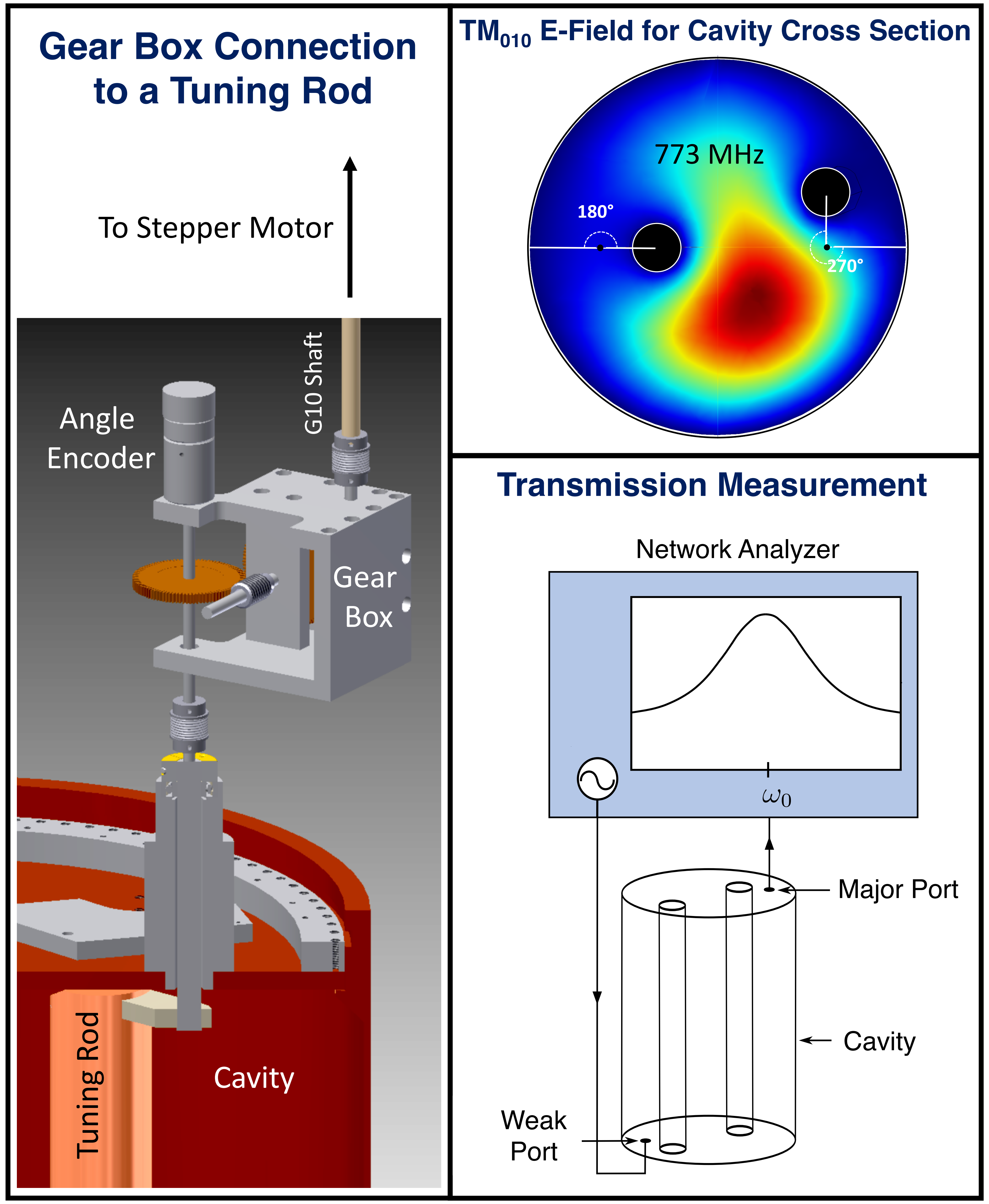
① Axions interact with a parallel magnetic field and are converted into photons, generating an effective current

② The resonant mode excited by this effective current moves the electrons in the antenna, which is then read out as a detectable RF signal



https://www.jahep.org/hepnews/2021/40-4-2-ADMX.pdf

Principle of ADMX



R. Khatiwada *et al*., Rev. Sci. Instrum. **92**, 124502 (2021).

Empty cylindrical cavity with the identical TM_{010} frequency

First root of the Bessel function J_0

$$f_0 = \frac{x_{01} c}{2\pi R_0} = 0.115\ \mathrm{GHz} \left(\frac{1\ \mathrm{m}}{R_0} \right)$$

Radius of the cavity

- Tuning resonant frequency of the microwave cavity with tuning rods inside the cavity
- The rods swing around a fixed axis of rotation, moving while changing the distance from the center of the cavity

Principle of ADMX

Volume of the cavity

Axion dark matter density

Frequency of the photon

Quality factor

$$P_{\mathrm{axion}} = 2.2 \times 10^{-23}\ \mathrm{W} \left(\frac{V}{136\ \mathrm{L}}\right) \left(\frac{B}{7.6\ \mathrm{T}}\right)^2 \left(\frac{C}{0.4}\right) \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho_a}{0.45\ \mathrm{GeV\,cm^{-3}}}\right) \left(\frac{f}{740\ \mathrm{MHz}}\right) \left(\frac{Q}{30000}\right)$$

Magnetic field

Form factor

P. Sikivie, Phys. Rev. D **32**, 2988 (1985).

* Form factor: Ratio between electric field of the cavity mode and external magnetic field ($\mathrm{TM}_{010} = 0.69$ is largest value)

Integration time

Detection bandwidth

Signal-to-noise ratio

$$\mathrm{SNR} = \frac{P_{\mathrm{axion}}}{k_{\mathrm{B}} T_{\mathrm{sys}}} \sqrt{\frac{t}{b}}$$

R. H. Dicke, Phys. Sci. Instrum. **17**, 268 (1946).

Boltzmann constant

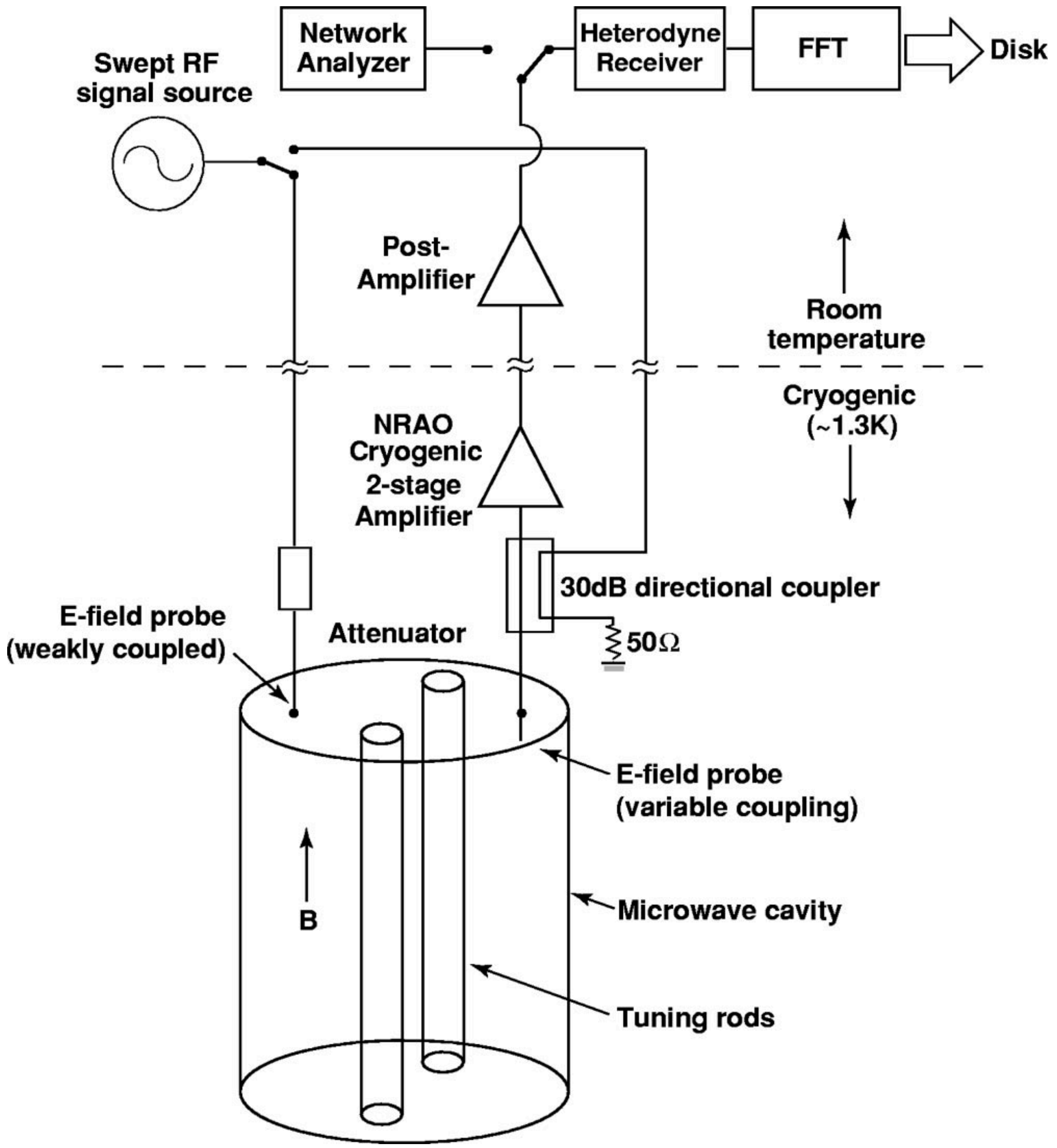
System noise temperature

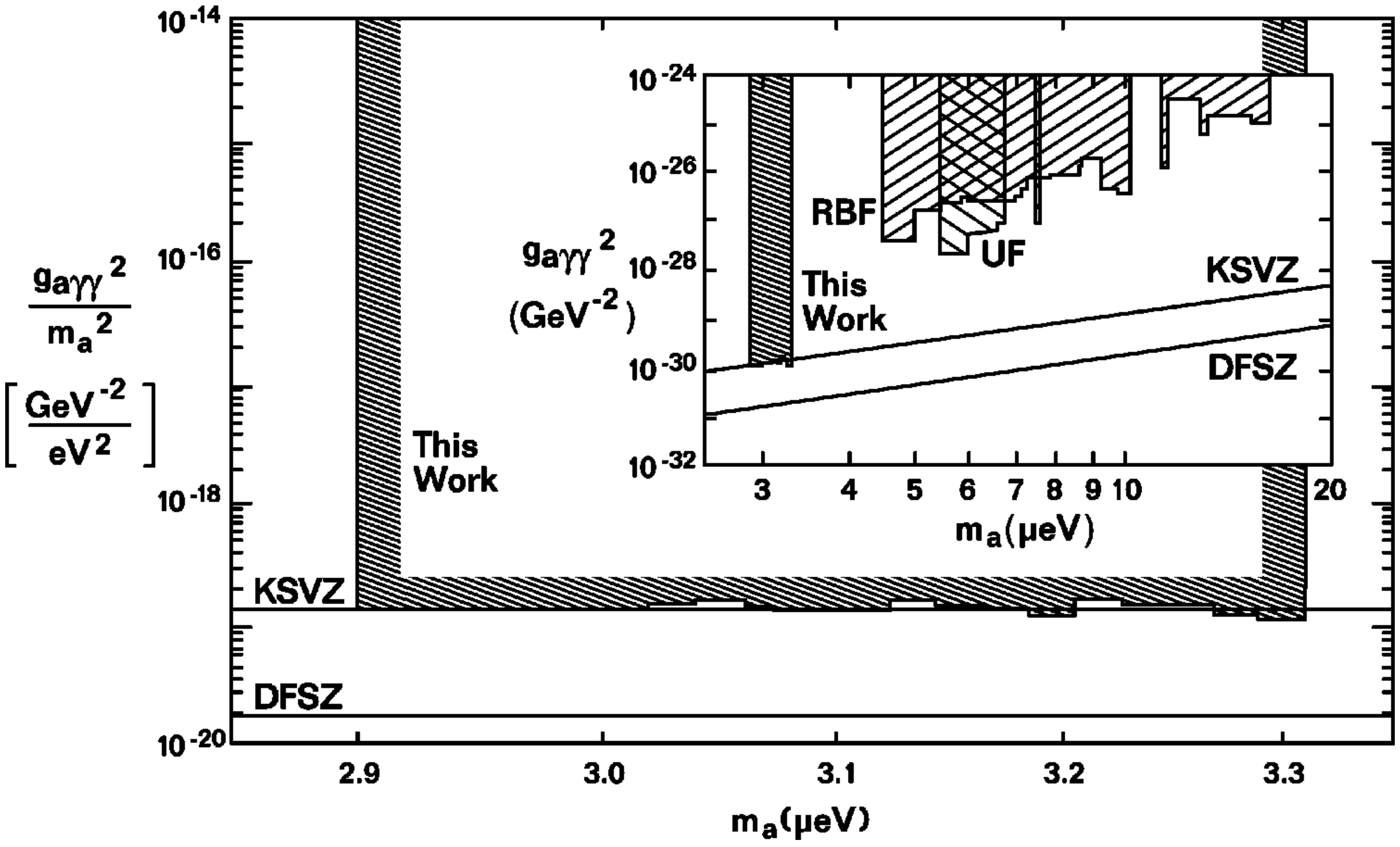
- Physical temperature of the cavity
- Noise temperature of the receiver chain in the Rayleigh-Jeans limit of the blackbody distribution

2001

First result of ADMX

→ Reached KSVZ model sensitivity for the first time





S. Asztalos *et al.*, Phys. Rev. D **64**, 092003 (2001).

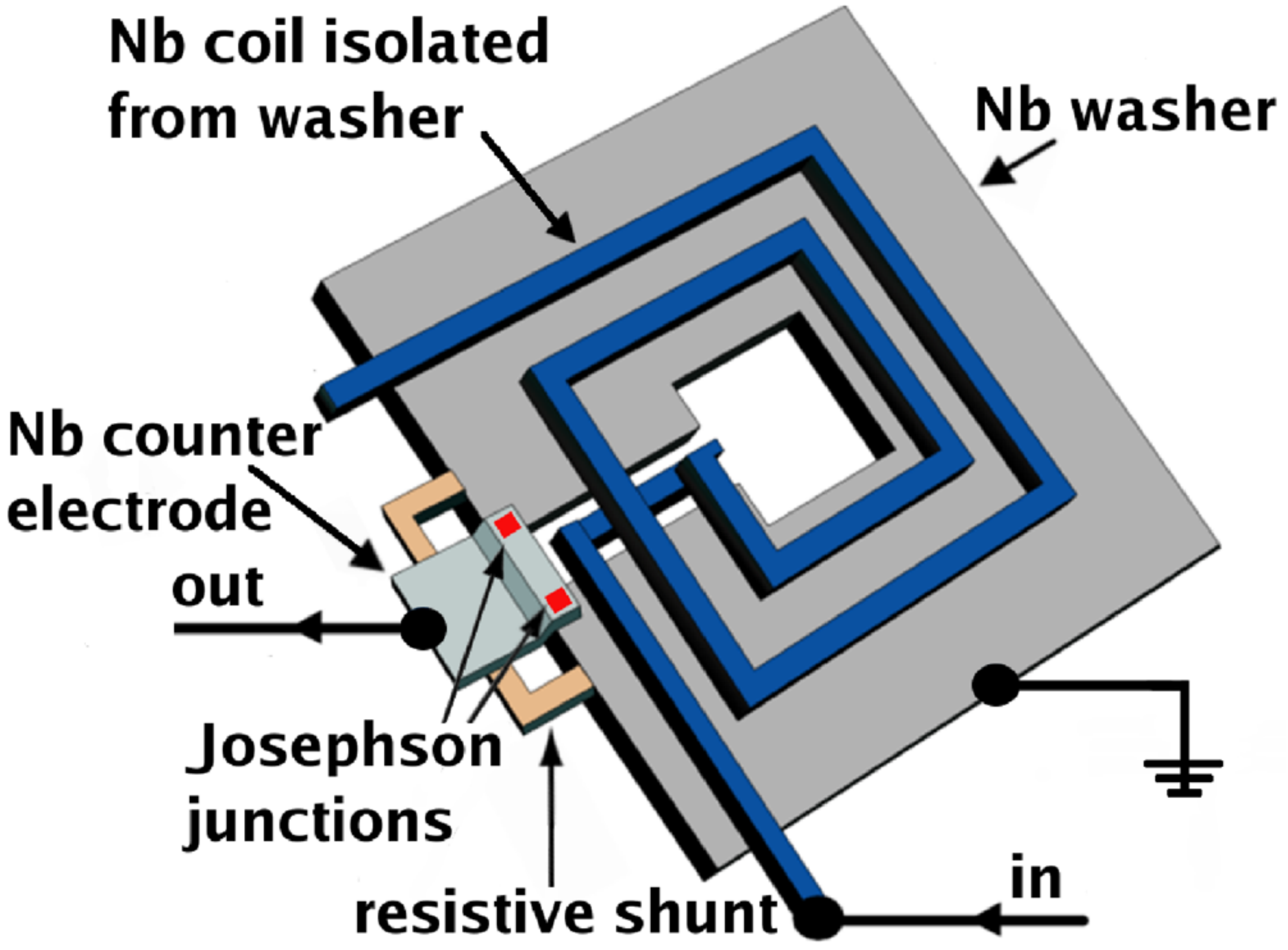
2010

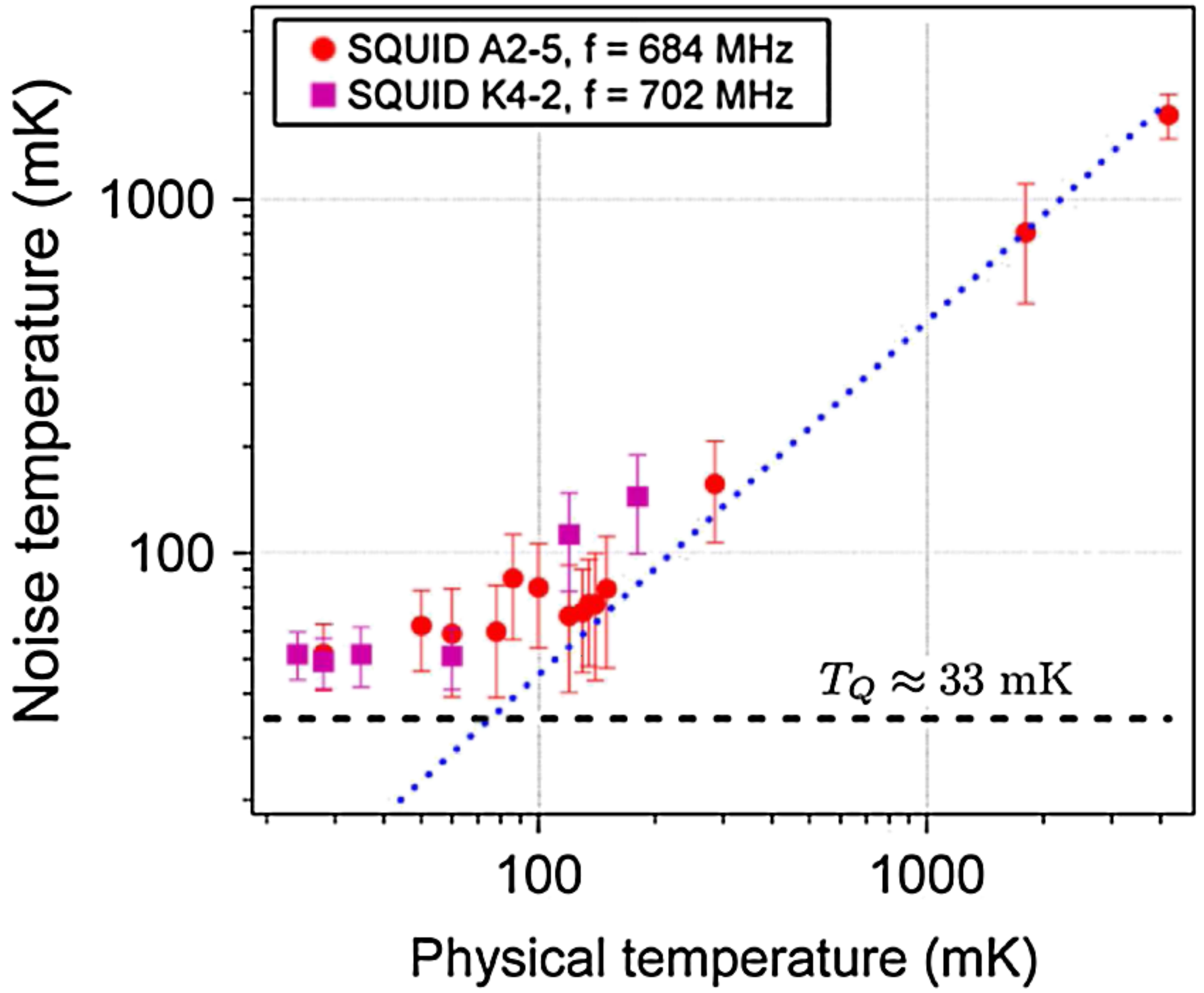
Superconducting Quantum Interference Device (SQUID)

- Resonant microstrip input coil to avoid gain role-off at microwave frequencies
- Extraordinary magnetic flux sensitivity

→ Use magnetic shield to prevent strong magnetic field injected into the cavity

- Noise temperature continues to drop with decreasing physical temperature

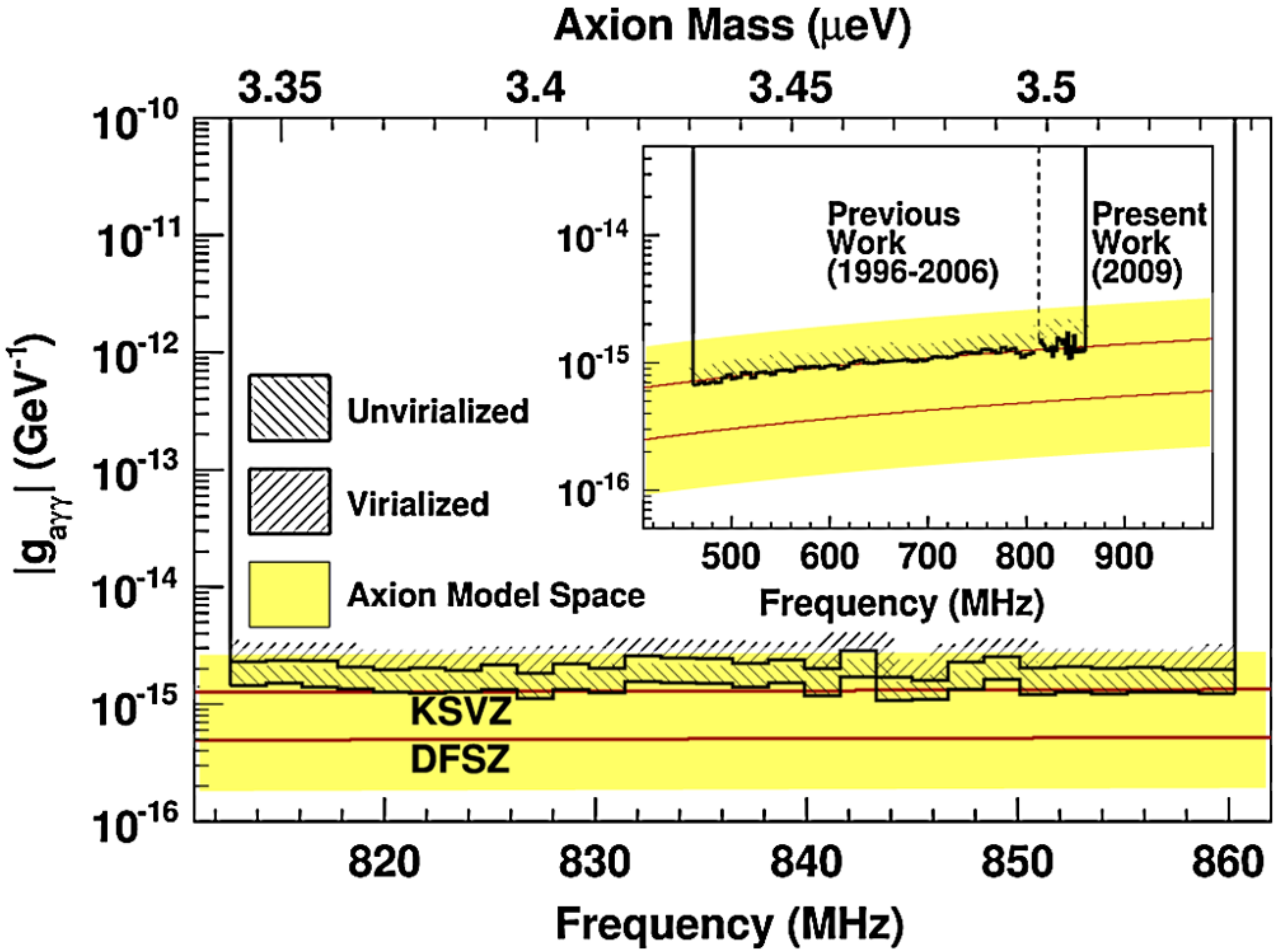




S. J. Asztalos *et al.*, Phys. Rev. Lett. **104**, 041301 (2010).

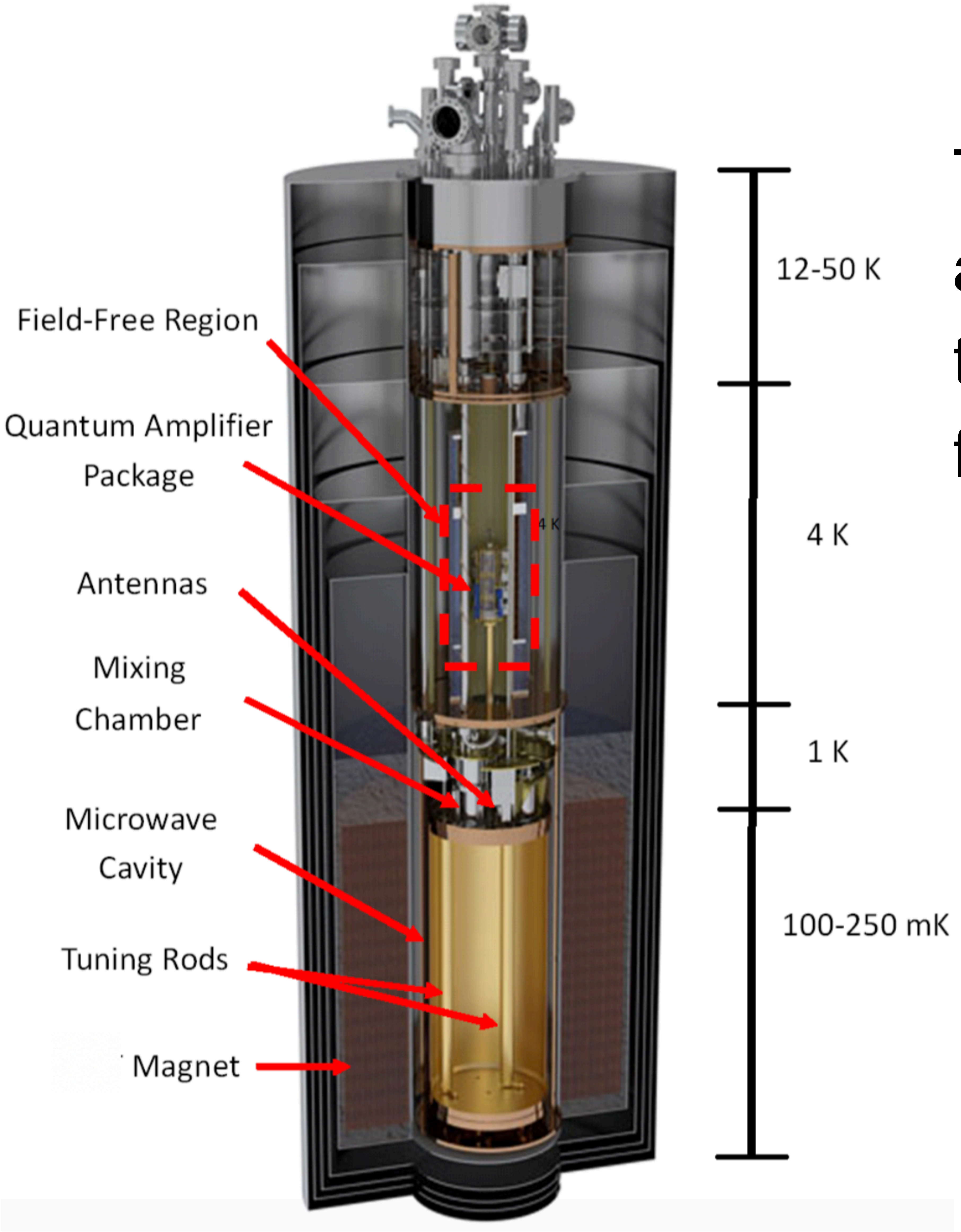
2010

Demonstration of the first application of a SQUID with a noise temperature comparable to previous runs with the Heterostructure Field Effect Transistor (HFET) amplifier



S. J. Asztalos *et al.*, Phys. Rev. Lett. **104**, 041301 (2010).

2018



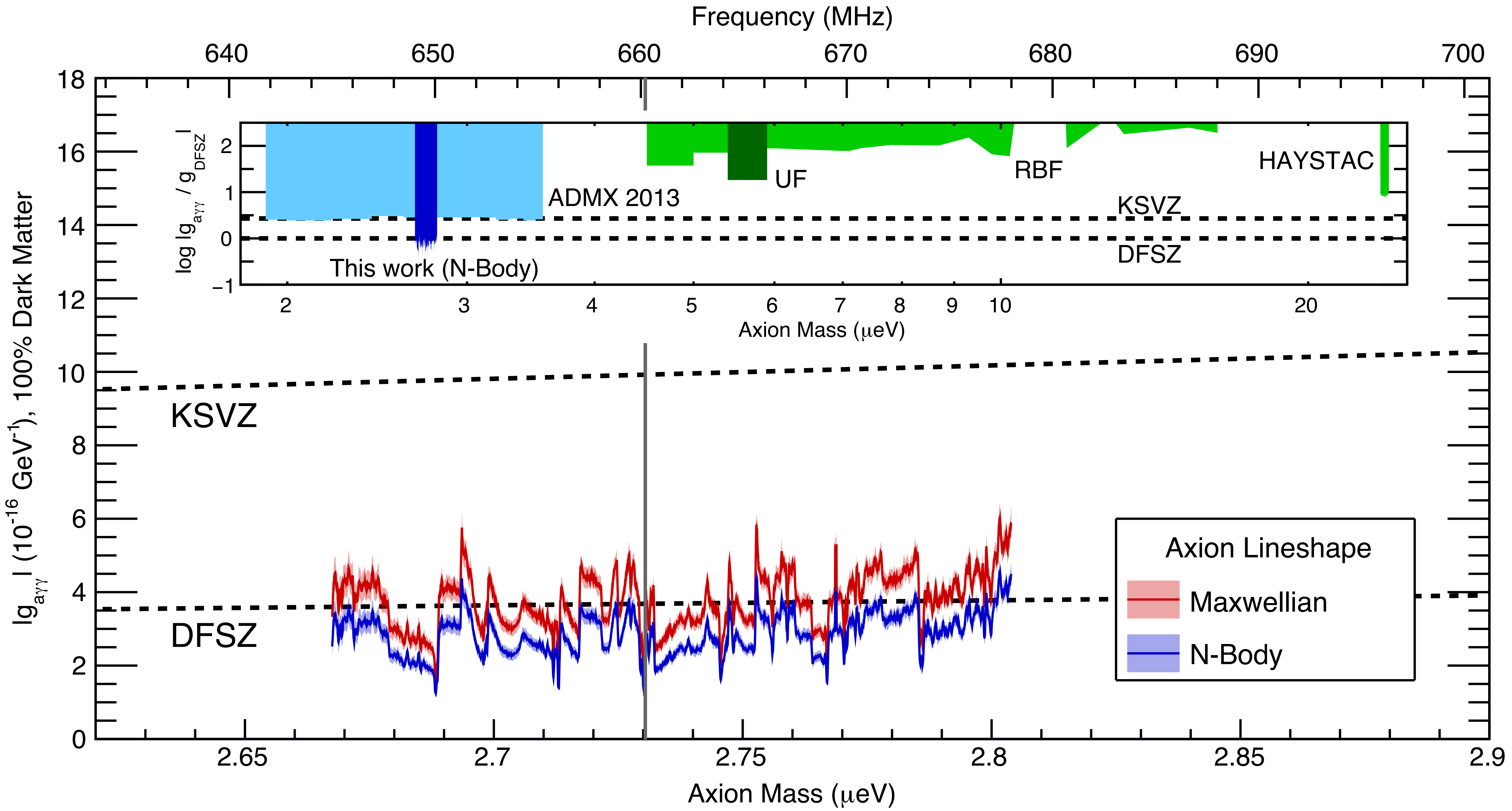
The cavity and Microstrip SQUID Amplifier (MSA) are cooled by a dilution refrigerator to minimize thermal background and excess thermal noise from the amplifier

R. Khatiwada *et al.*, Rev. Sci. Instrum. **92**, 124502 (2021).

2018

Operating at subkelvin temperatures, reducing thermal noise as well as the excess noise from the SQUID

→ Reached DFSZ model sensitivity for the first time

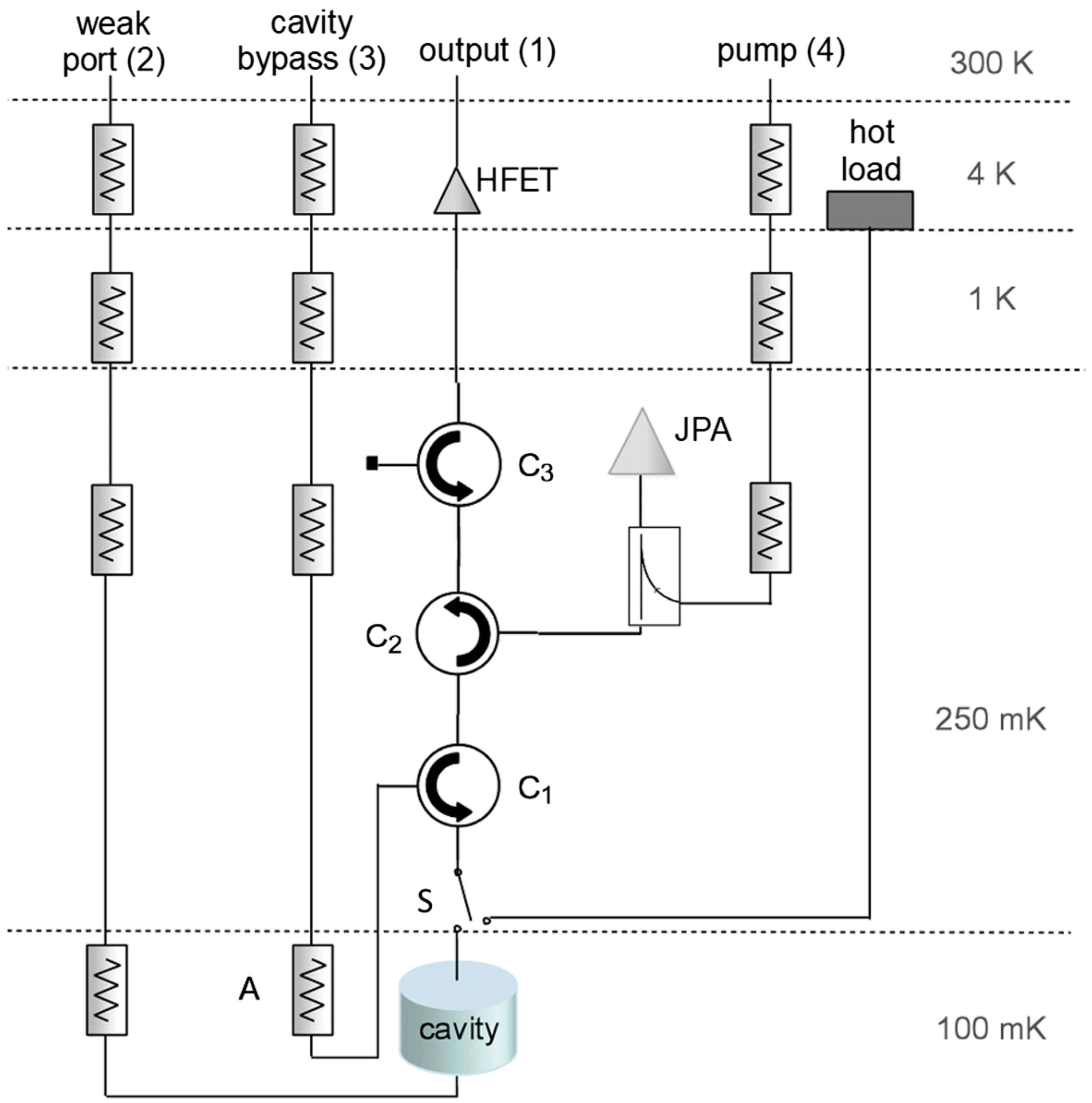


N. Du *et al*., Phys. Rev. Lett. **120**, 151301 (2018).

2020

Josephson Parametric Amplifier (JPA)

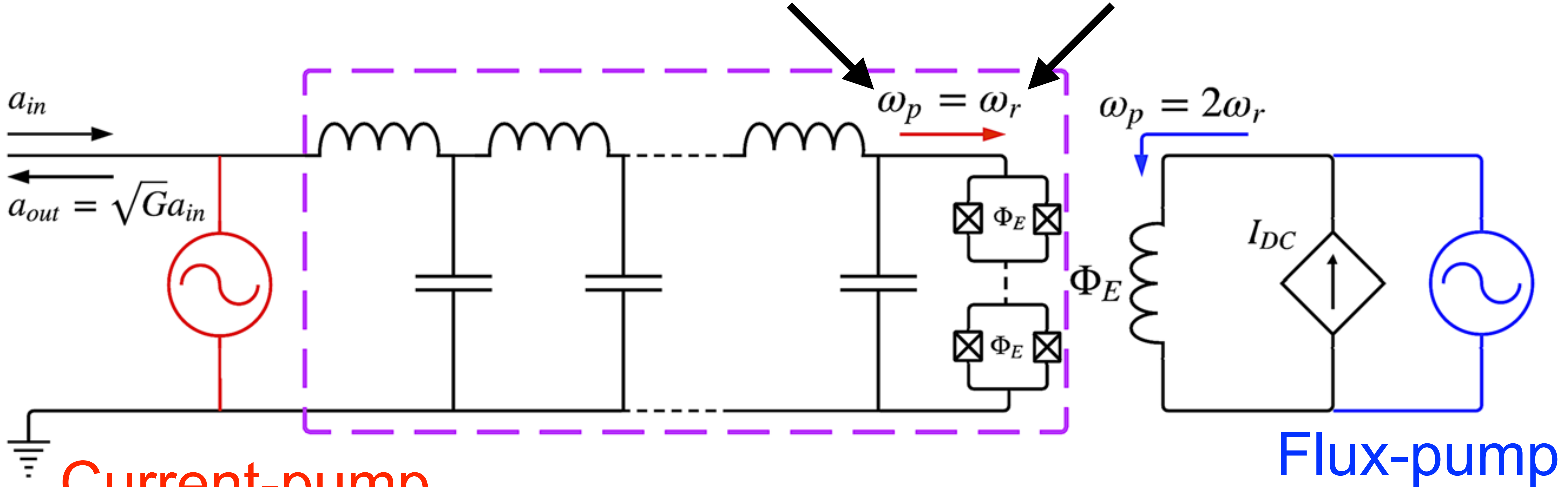
- Non-linear oscillator that consists of an array of SQUIDs in series
- Pump energy transfers to signal (Current-pump was used)



T. Braine *et al.*, Phys. Rev. Lett. **124**, 101303 (2020).

Pumping frequency

Resonant frequency of a JPA



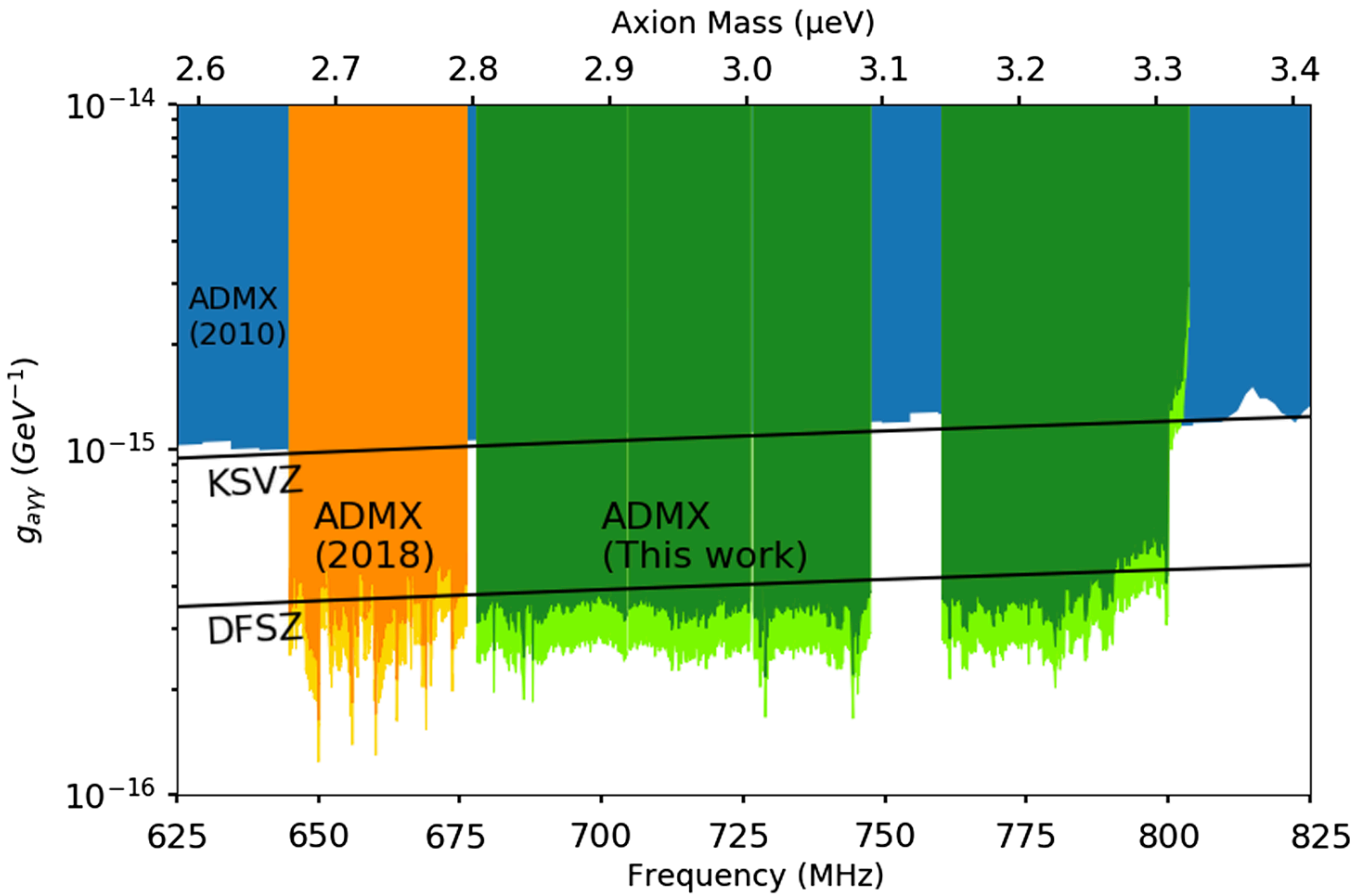
Current-pump

Flux-pump

R. Khatiwada *et al.*, Rev. Sci. Instrum. **92**, 124502 (2021).

2020

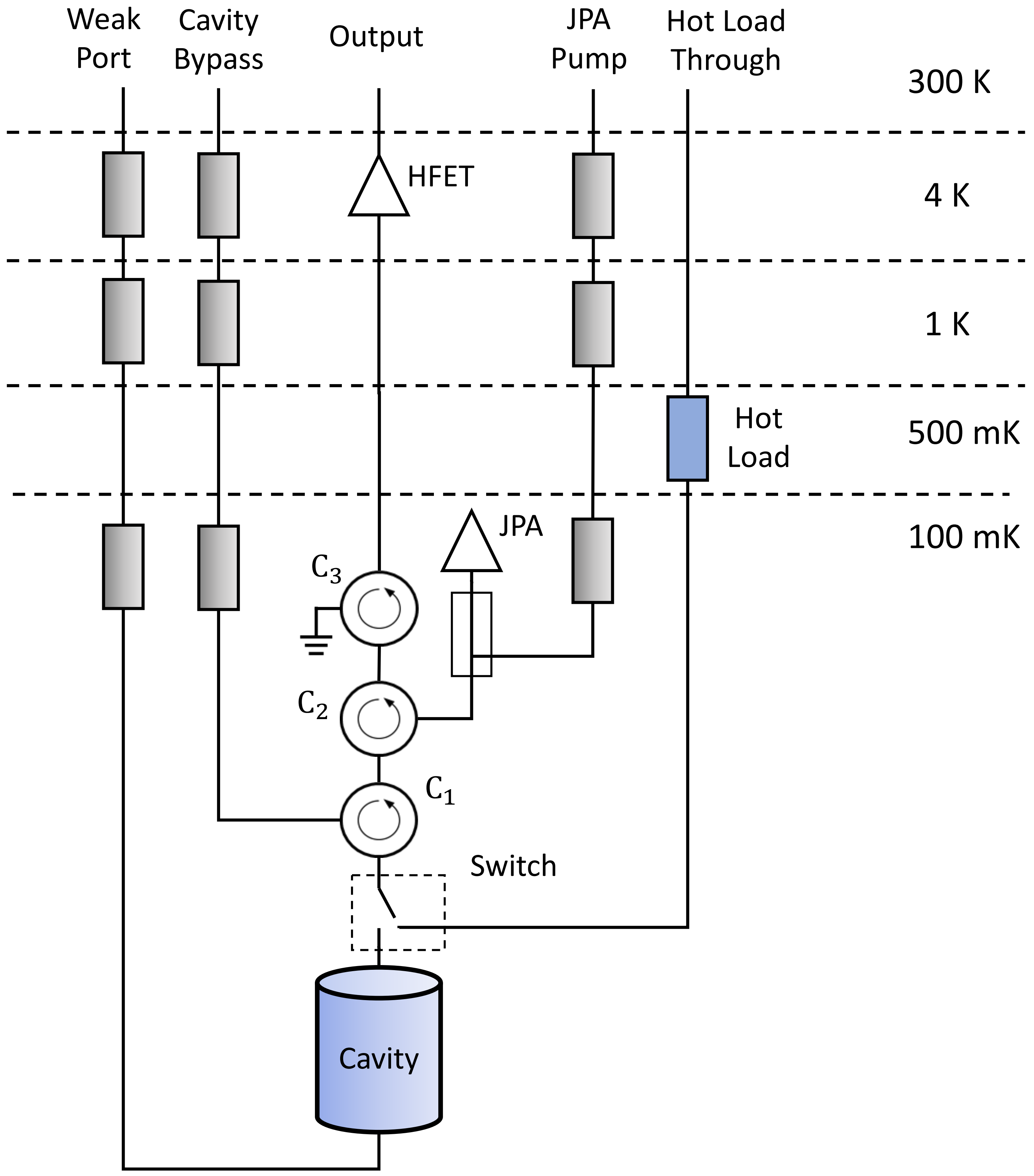
Extended region using JPA and a large microwave cavity

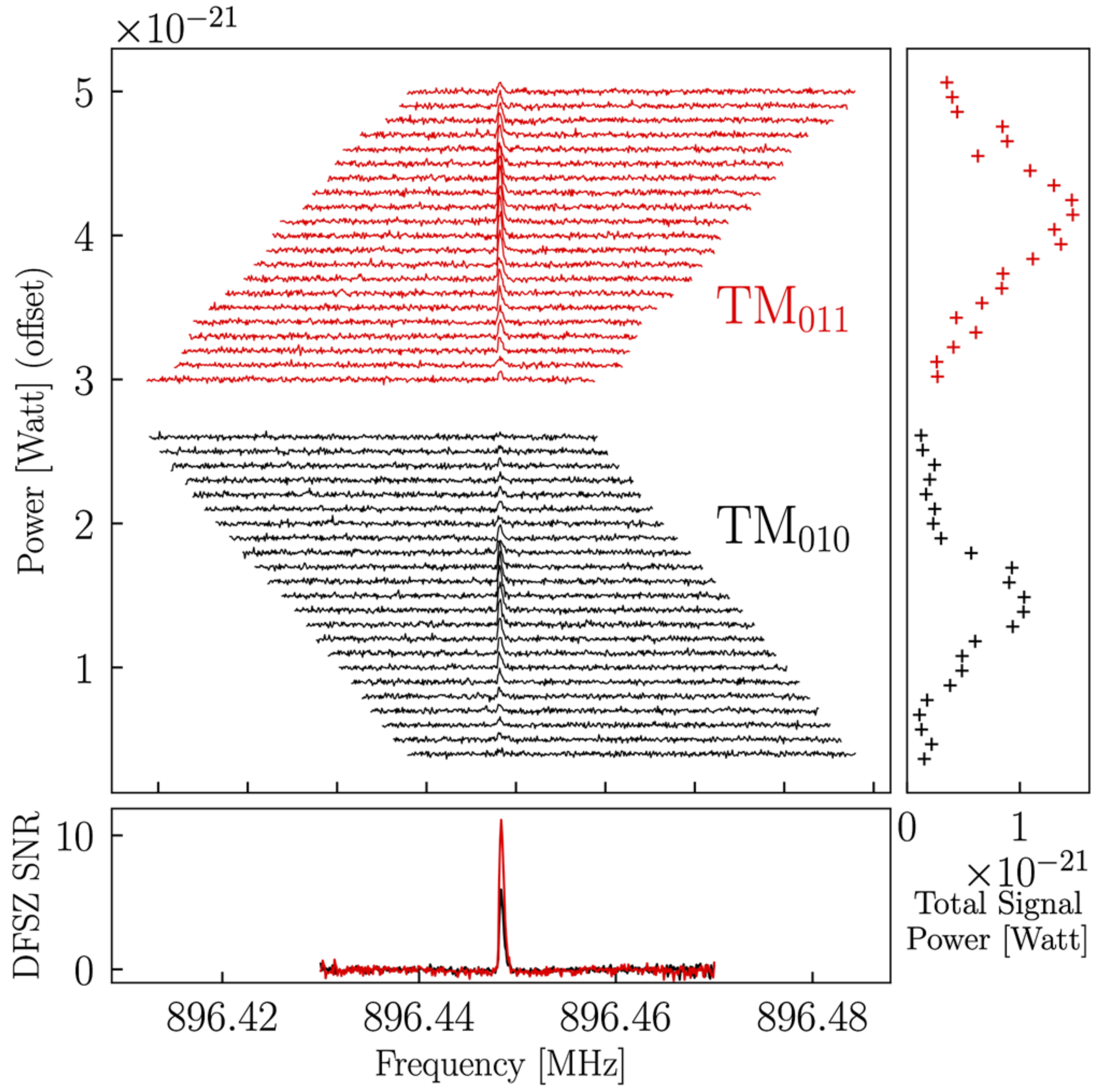


T. Braine *et al.*, Phys. Rev. Lett. **124**, 101303 (2020).

2021

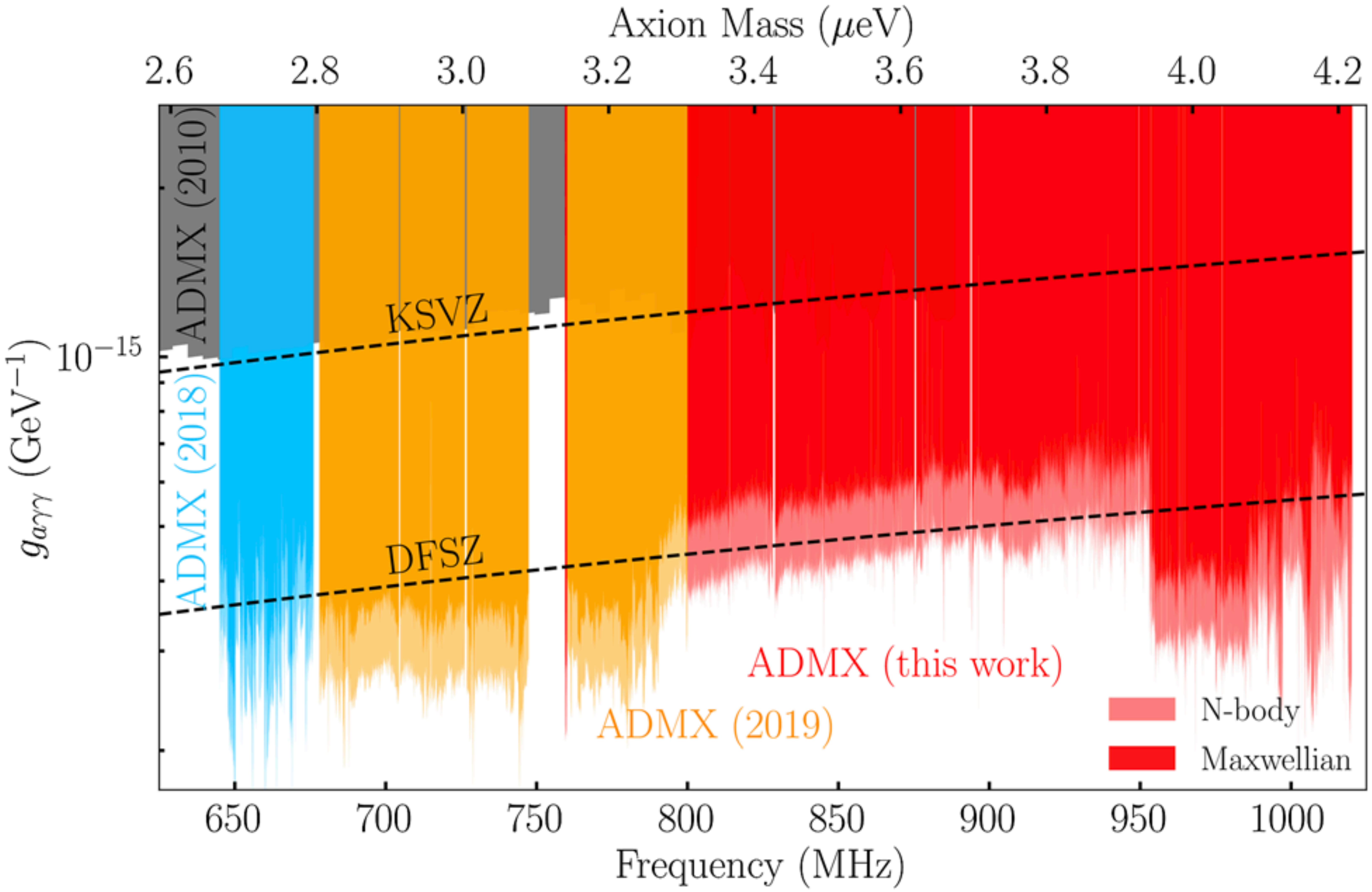
Synthetic Axion Generator (SAG) were injected into the cavity via its weak port to ensure the robustness of the experiment





C. Bartram *et al.*, Phys. Rev. Lett. **127**, 261803 (2021).

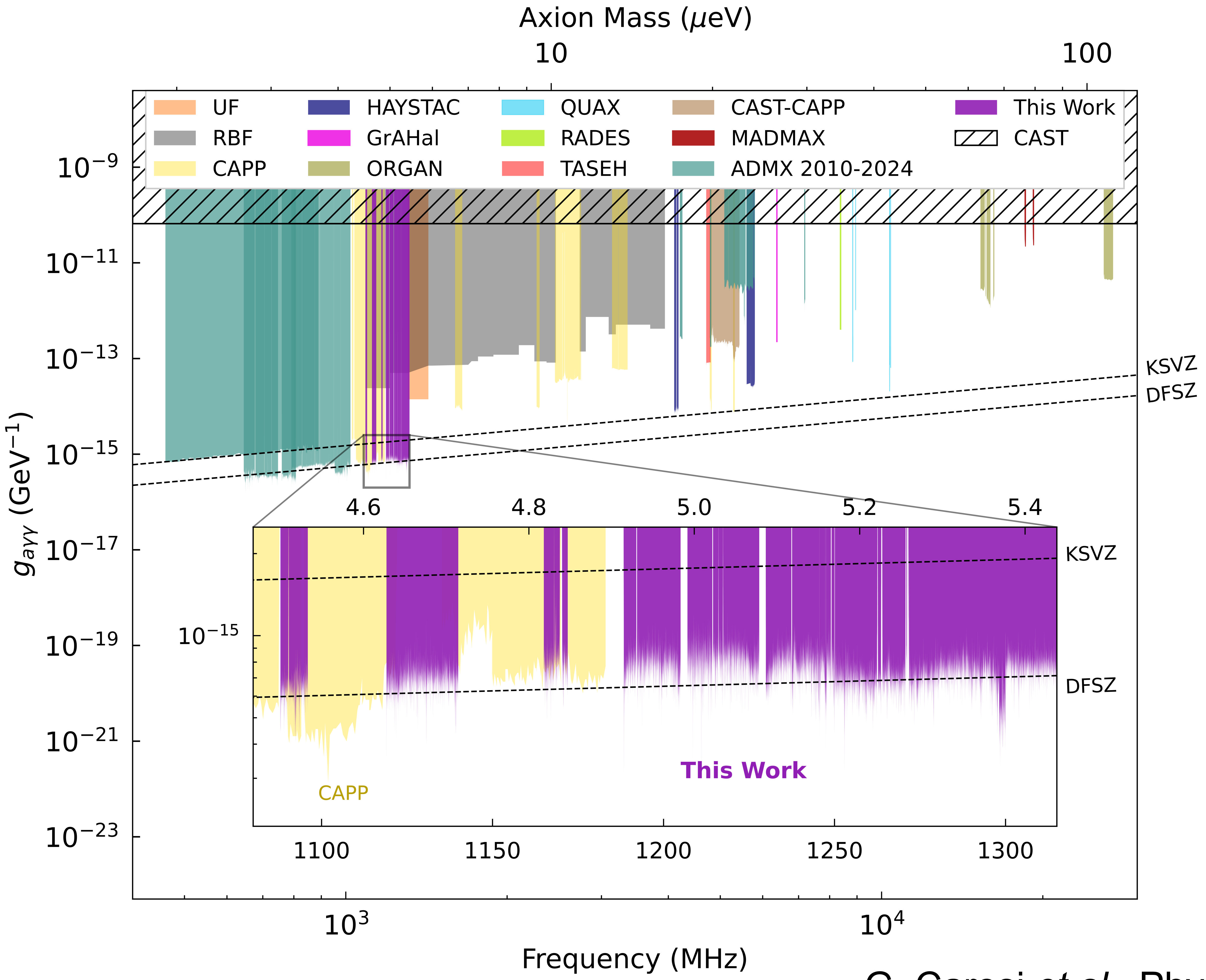
2021



C. Bartram *et al*., Phys. Rev. Lett. **127**, 261803 (2021).

2025

- Resonant frequency was tuned by a single 20.3 cm copper tuning rod
- The coupling of the antenna was improved by adjusting the insertion depth



G. Carosi *et al*., Phys. Rev. Lett. **135**, 191001 (2025).

Summary

Axion Dark Matter eXperiment (ADMX)

- Aim to detect QCD axion using a microwave cavity
- SQUID, JPA, and dilution refrigerator for reducing noise temperature
- SAG system for robustness of the experiment
- No axionlike excess was observed yet
- Many upgrades are needed for expanding the parameter space