# Searching for dark matter with superconductor circuits

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# Outline

Background

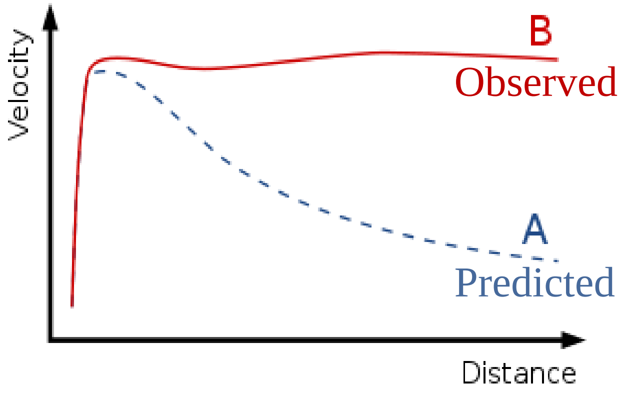
Dark photon searching base on
superconducting cavities and Josephson parametric amplifiers

Dark photon searching base on
scalable superconducting qubit architectures

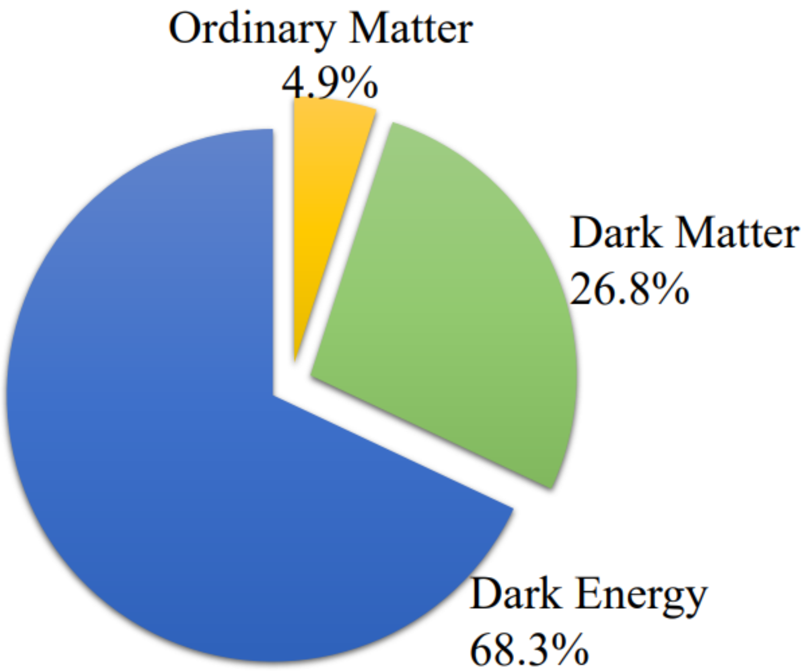
Summary

# Dark matter

Evidences of dark matter




Composition of our universe




D. Clowe, et al., ApJL 604, 596 (2004)

# New $U(1)$: Dark photon (DP)

The extra $U(1)$ symmetry gives rise to DP– a well motivated dark matter candidate

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{m_X^2}{2}V^\mu V_\mu - \frac{\chi}{2}V_{\mu\nu}F^{\mu\nu}.$$

Photon Dark photon Kinetic mixing

The DP-induced electric field

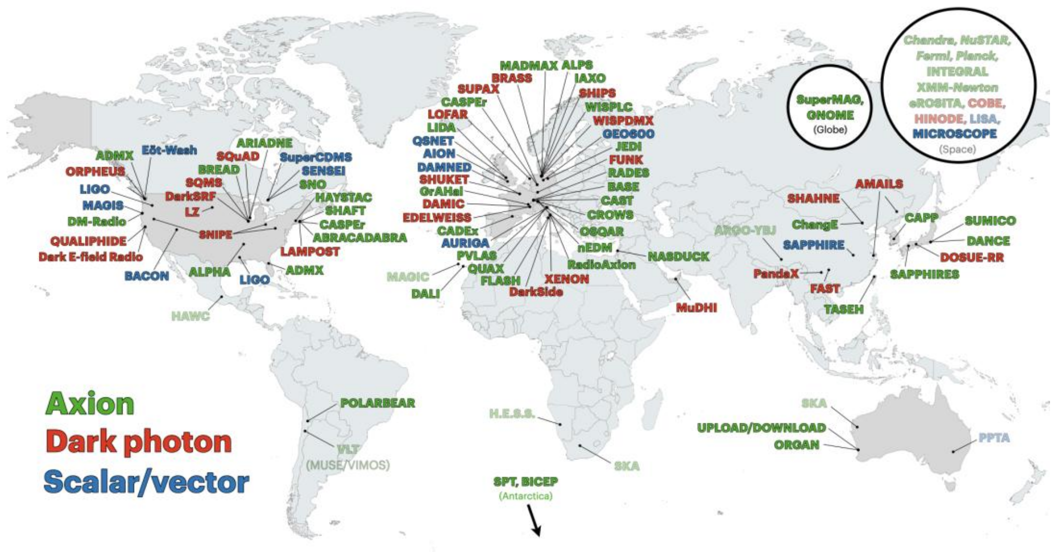
$$E_X = \chi\sqrt{2\rho_{DM}/\epsilon_0}\cos m_X t$$

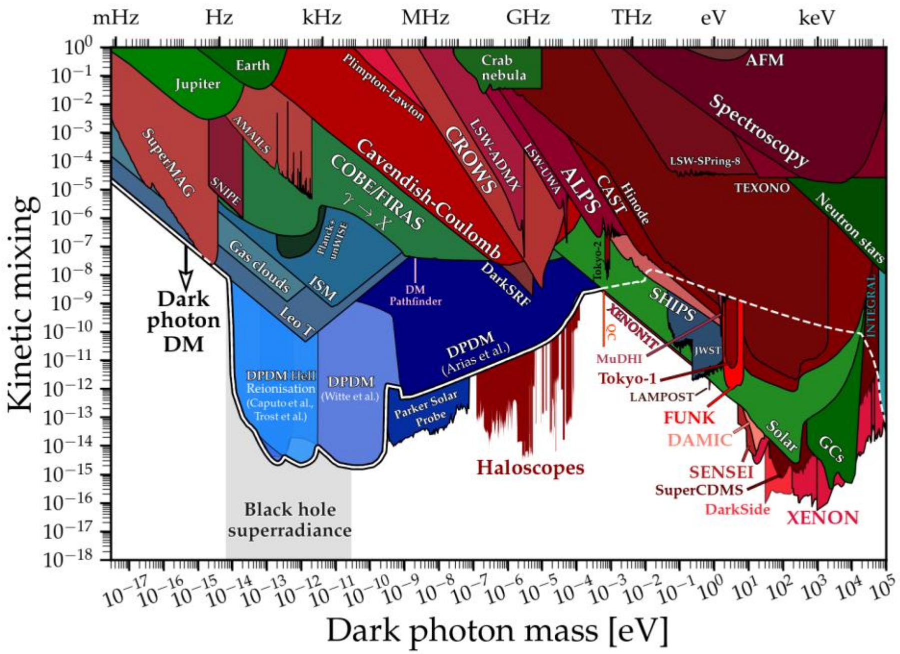


A. Caputo, et al., Phys. Rev. D **104**, 095029 (2021)

# Efforts to search for DP

Many groups around the world are trying to search for dark photons, and have set constraints on the kinetic mixing at various possible DP masses.



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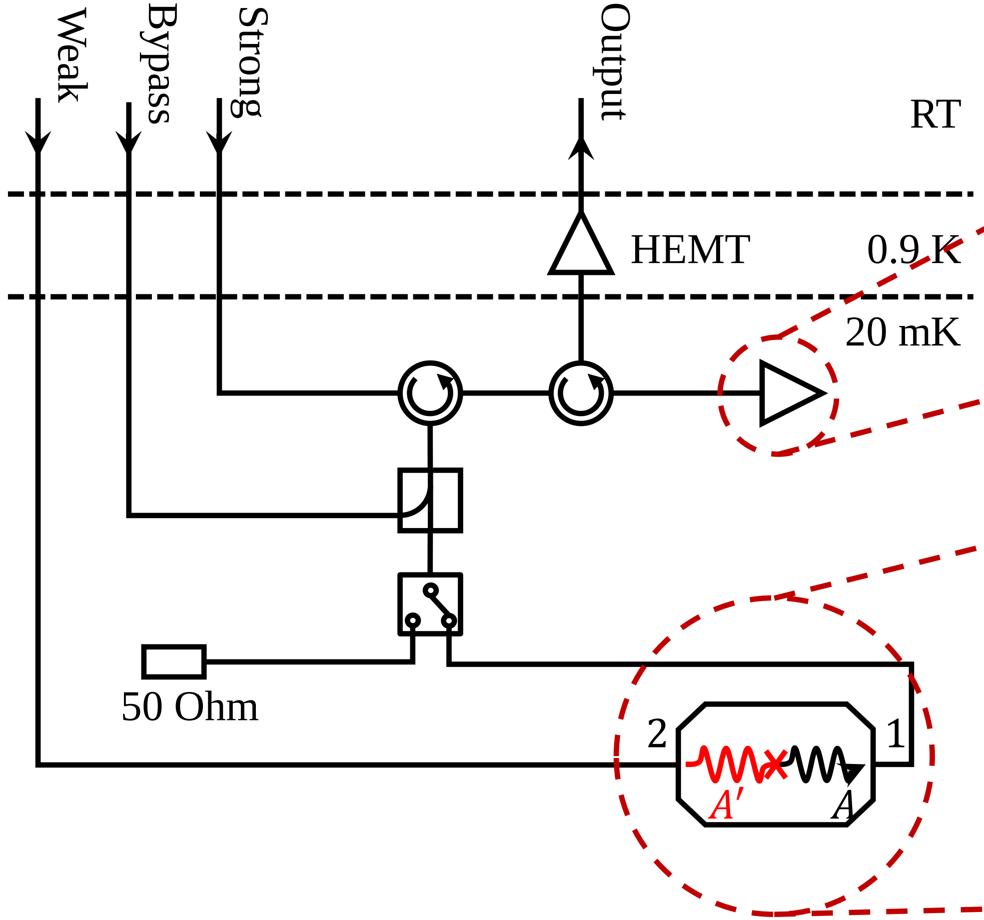
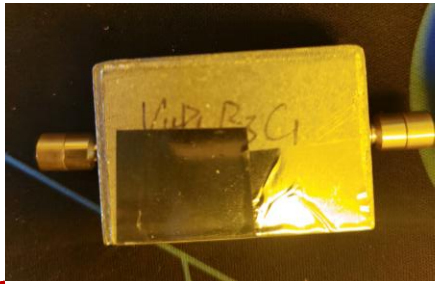
# Setup

First completely superconducting DP haloscope in China.



JPA: Noise temperature = 300 mK (SQL)

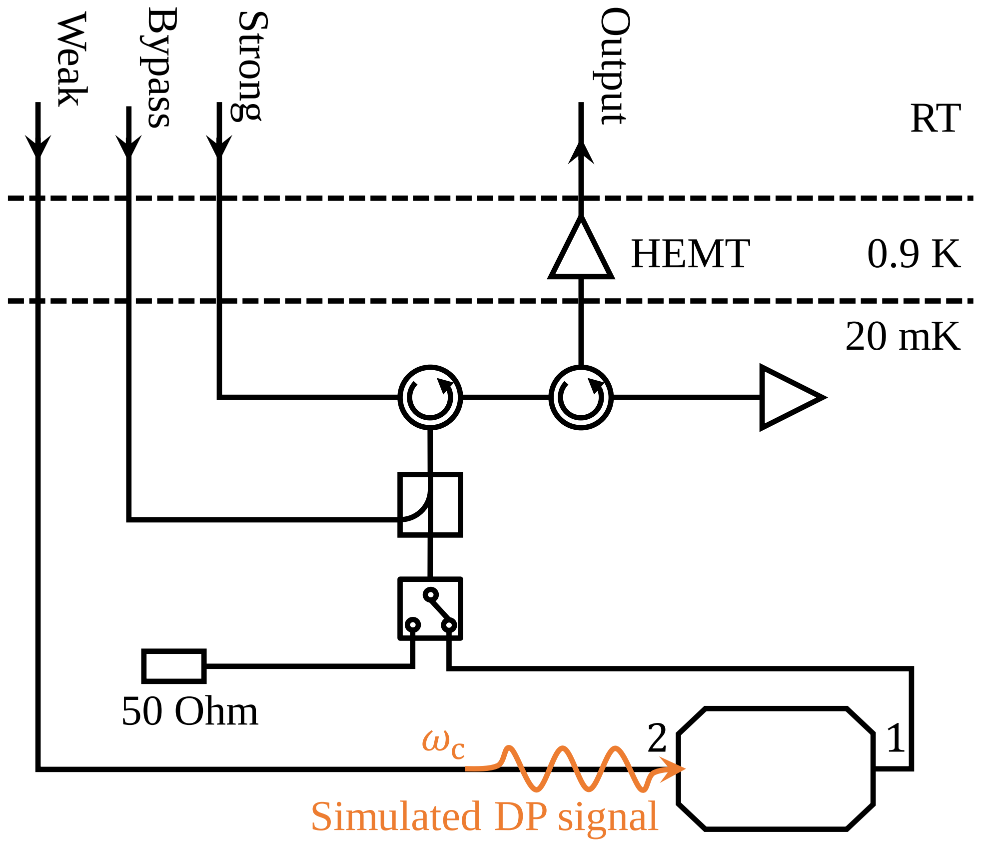
Superconducting cavity:

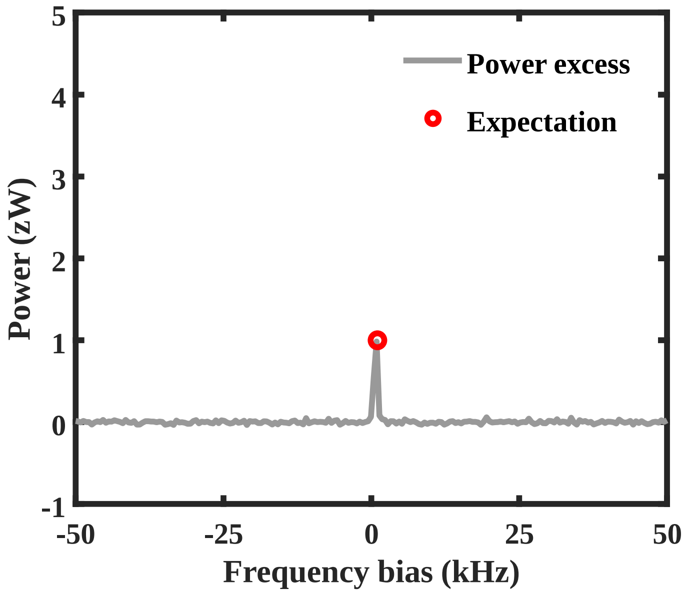
$Q_L = 600{,}000$

$f_c = 6.52014$ GHz

# Verification

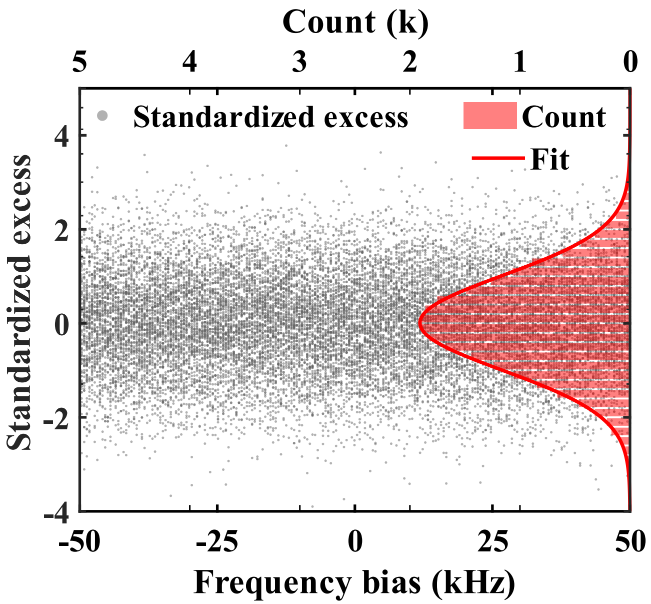
The detection ability of our system was verified by injecting a pure-tone microwave of -43 dBm which is equivalent to a dark photon signal with $\chi = 6 \times 10^{-15}$.

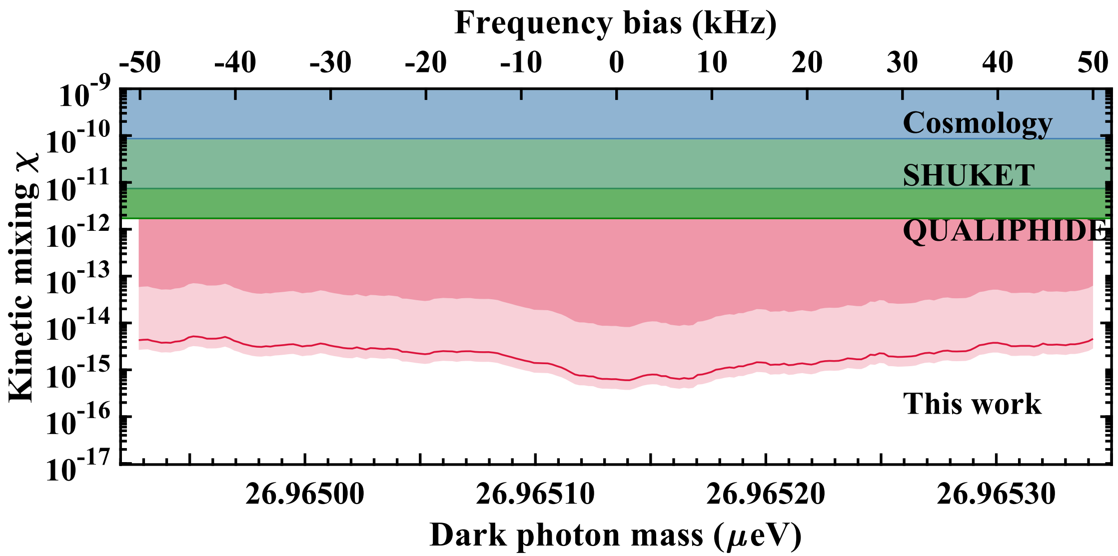


# Constraints

After 6-hour integration, we set the most stringent constraints in a 100 kHz range around 6.520140 GHz.






R. Kang, et al., Phys. Rev. D **109**, 095037 (2024)

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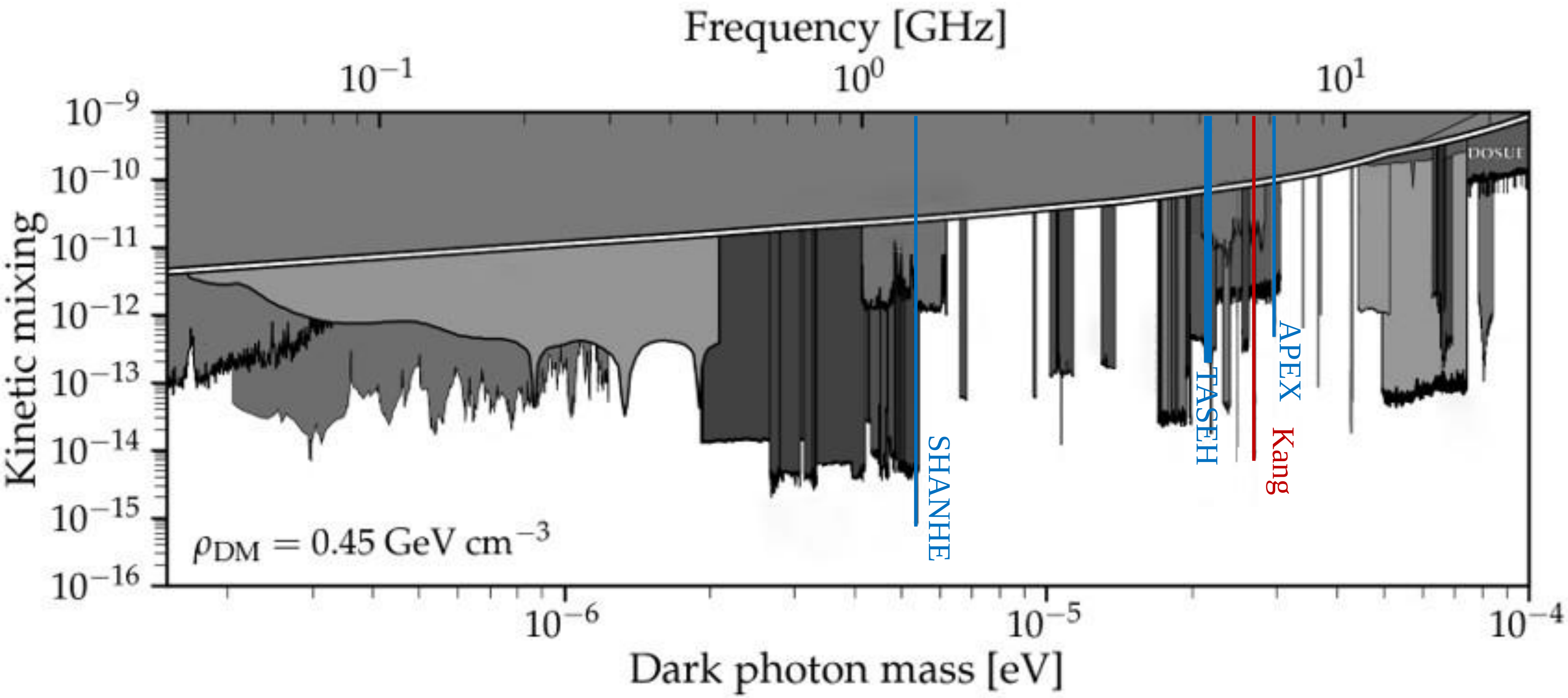




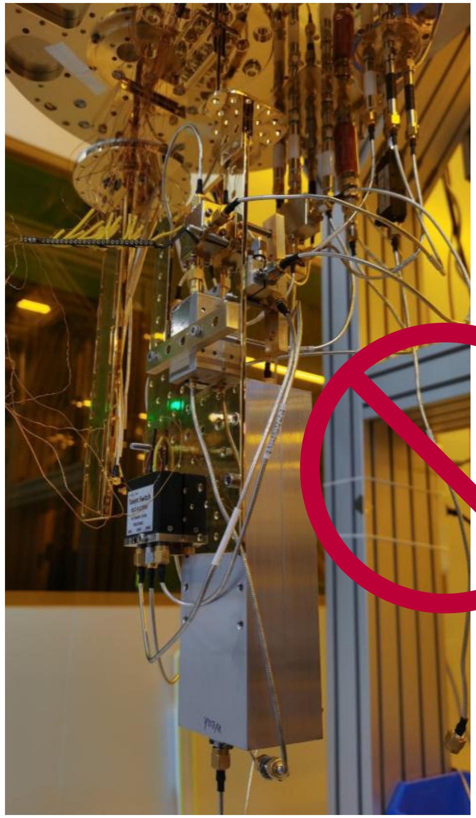
H. Chang, et al., Phys. Rev. Lett **129**, 111802 (2022)

Z. Tang, et al., Phys. Rev. Lett **133**, 021005 (2024)

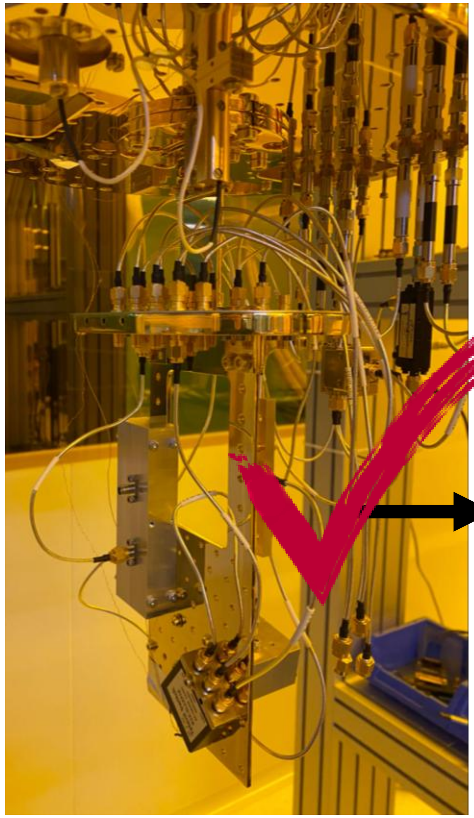
D. He, et al., Phys. Rev. D **110**, L021101 (2024)

# Challenge – scalable searching

A scalable searching scheme would greatly boost the searching for DP,  but impractical for existing haloscopes due to their large volume.



$\times N$



$N$ small detection units

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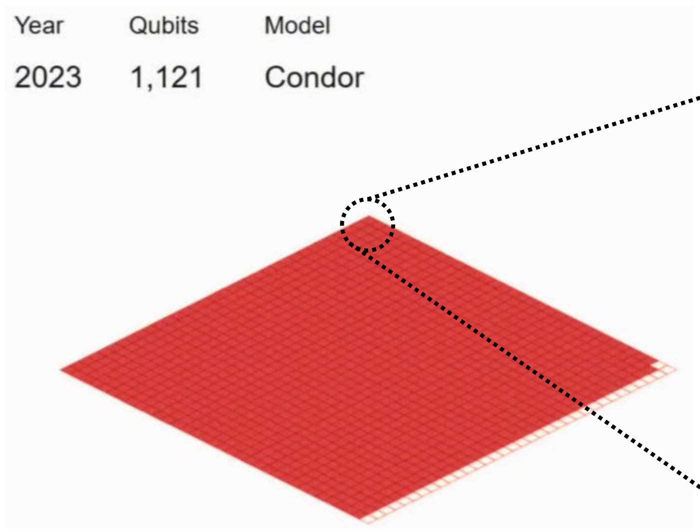
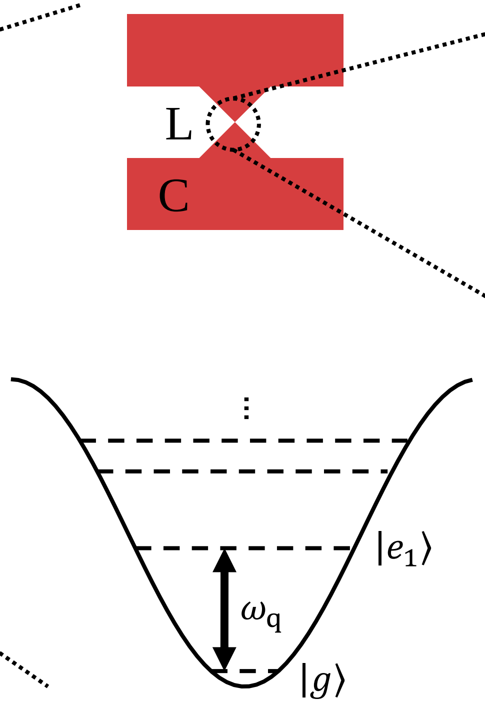
# Superconducting qubit (SQ)

Transmon: a type of SQ with high sensitivity of electric field and remarkable scalability

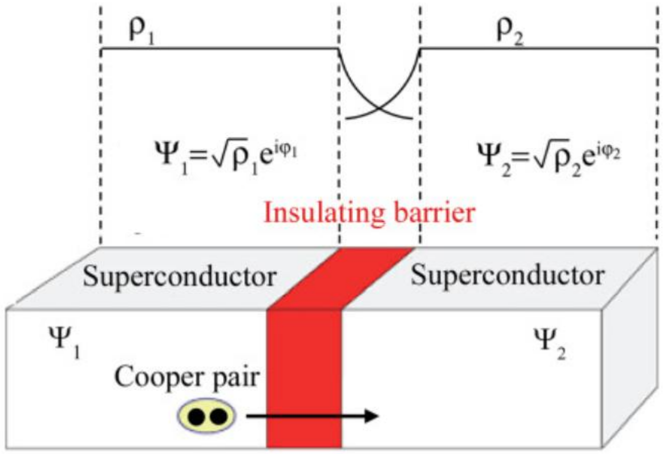
IBM scalable transmon architecture




Transmon




Josephson junction



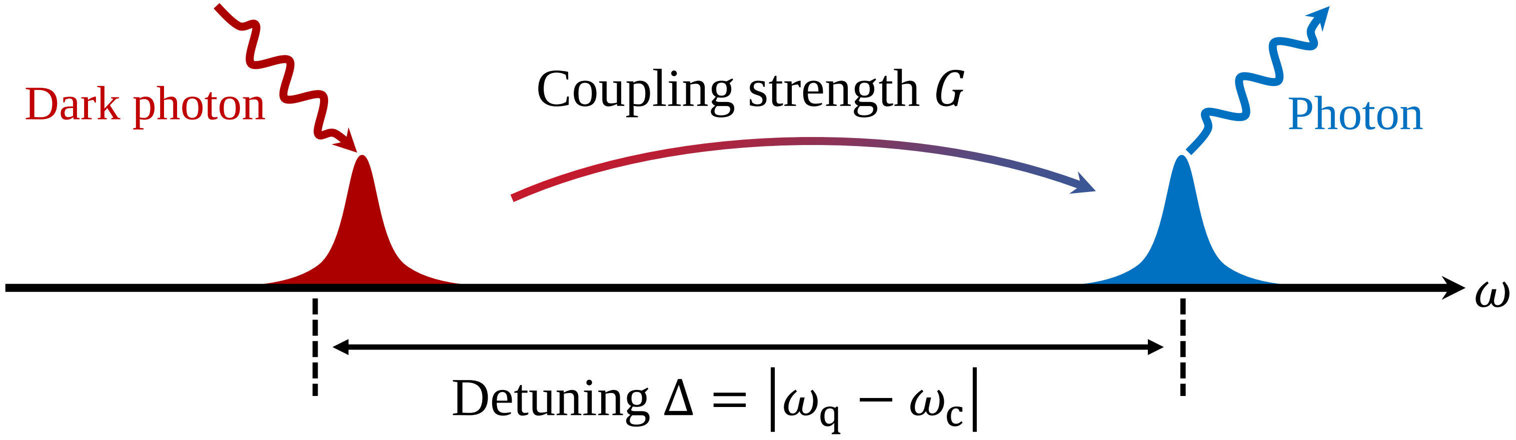



D. Castelvecchi, Nature. **624**, 238 (2023)

# Dispersive coupling (single-SQ)

Change of $\hat{\sigma}_z$ of the qubit will be transduced into a frequency bias of the readout cavity.

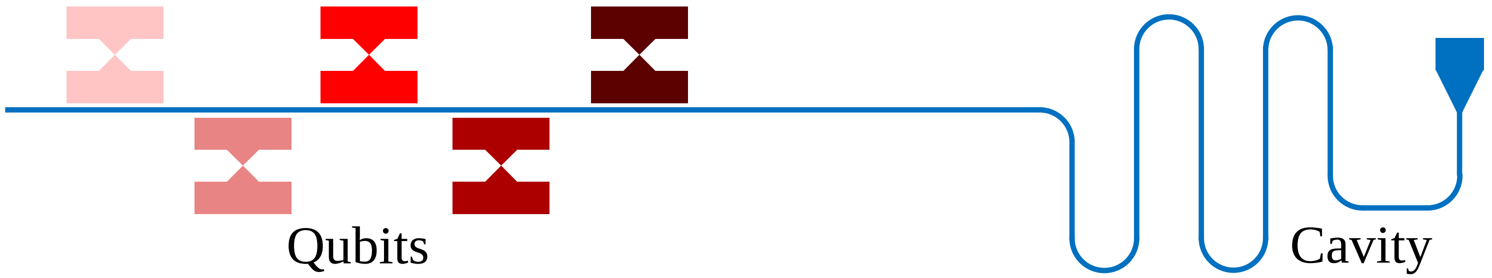

$$H_{\mathrm{int}} = \hbar \frac{G^2}{\Delta} \hat{\sigma}_z \hat{a}^\dagger \hat{a}$$



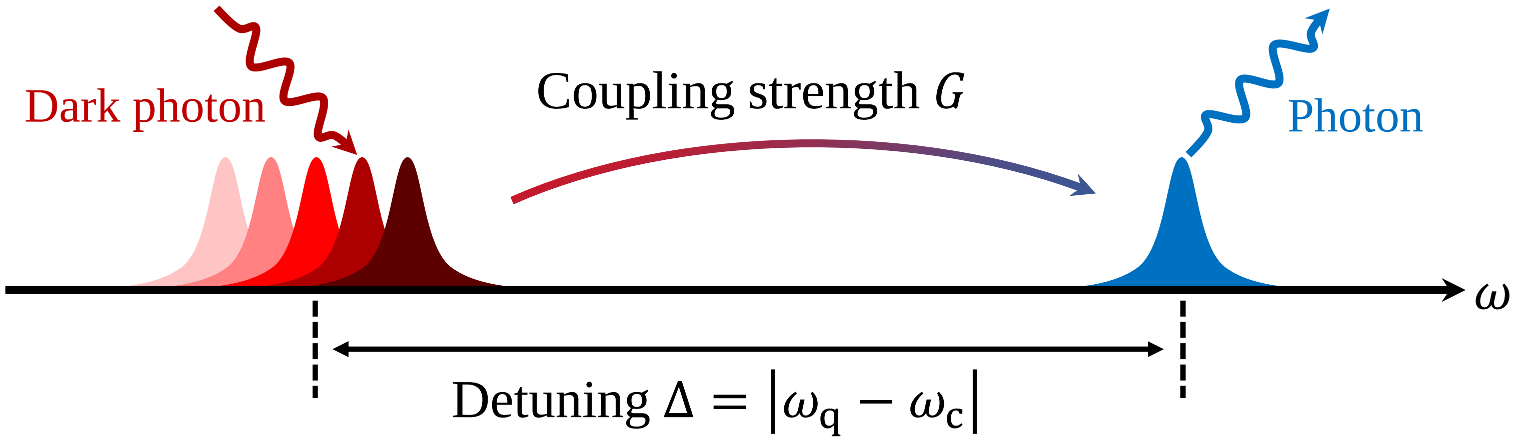

$$H_{\mathrm{cavity}}^{\mathrm{eff}} = \hbar \left( \omega_c + \frac{G^2}{\Delta} \hat{\sigma}_z \right) \hat{a}^\dagger \hat{a}$$

# Dispersive coupling (multi-SQ)

Change of $\hat{\sigma}_z$ of any qubit will be transduced into a frequency bias of the readout cavity.

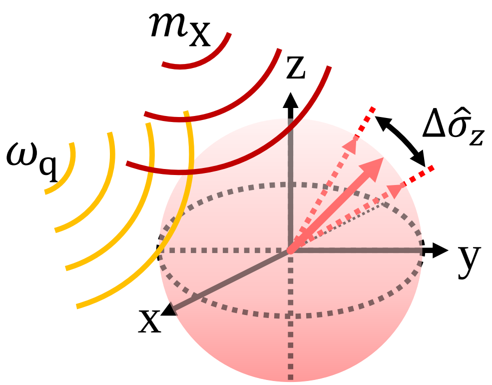


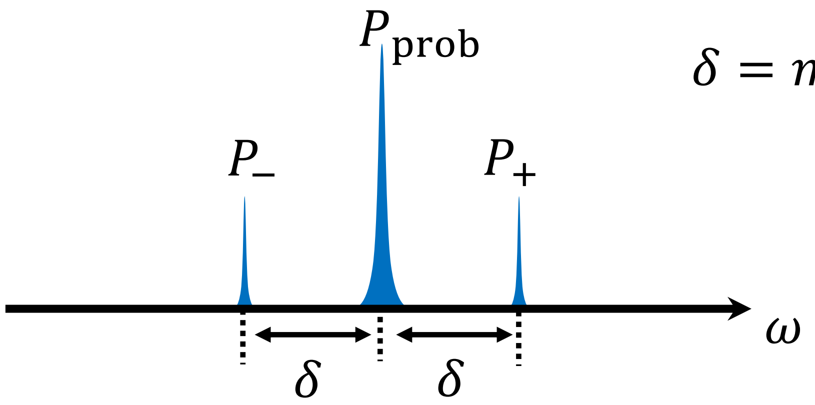

$$H_{\mathrm{int}} = \sum_{\mathrm{k}} \hbar \frac{G^2}{\Delta} \hat{\sigma}_{\mathrm{z}}^{\mathrm{k}} \hat{a}^\dagger \hat{a}$$



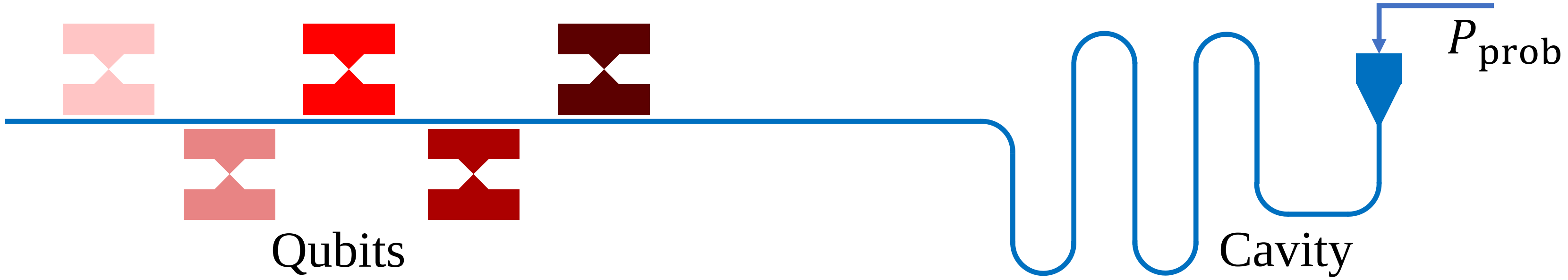

$$H_{\mathrm{cavity}}^{\mathrm{eff}} = \hbar \left( \omega_{\mathrm{c}} + \sum_{\mathrm{k}} \frac{G^2}{\Delta} \hat{\sigma}_{\mathrm{z}}^{\mathrm{k}} \right) \hat{a}^\dagger \hat{a}$$

# Heterodyne detection

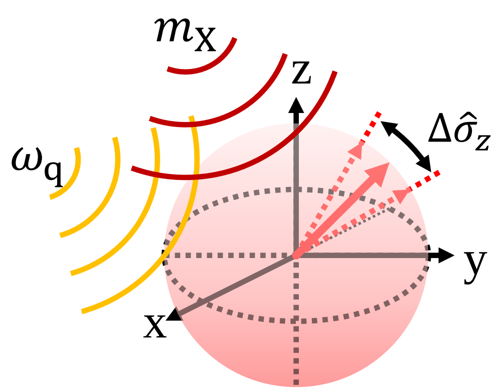


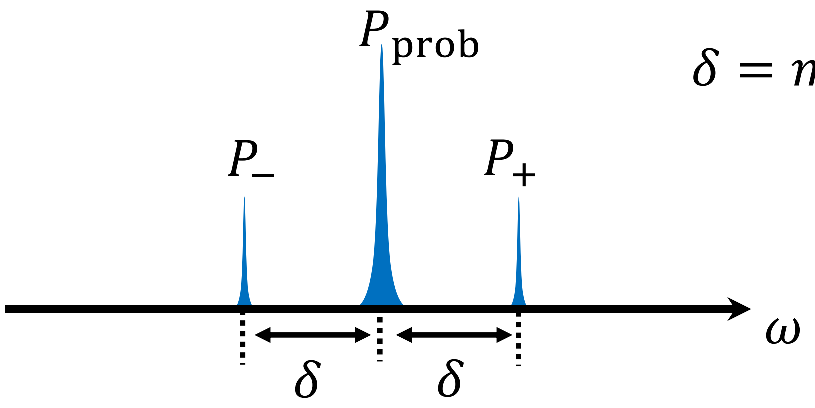




$$\delta = m_X - \omega_q$$



# DP signal




$\delta = m_X - \omega_q$

$$H = \underbrace{\hbar\omega_q\hat{\sigma}_z}_{\text{Qubit}} + \underbrace{\hbar\nu\left(\hat{\sigma}_+ e^{-i\omega_d t} + \hat{\sigma}_- e^{+i\omega_d t}\right)}_{\text{Drive}} + \underbrace{\hbar\eta\left(\hat{\sigma}_+ e^{-i(m_X t+\phi)} + \hat{\sigma}_- e^{+i(m_X t+\phi)}\right)}_{\text{Dark photon}}$$

$$\Delta\hat{\sigma}_z \propto \chi d\sqrt{T_1 T_2^* C m_X}$$

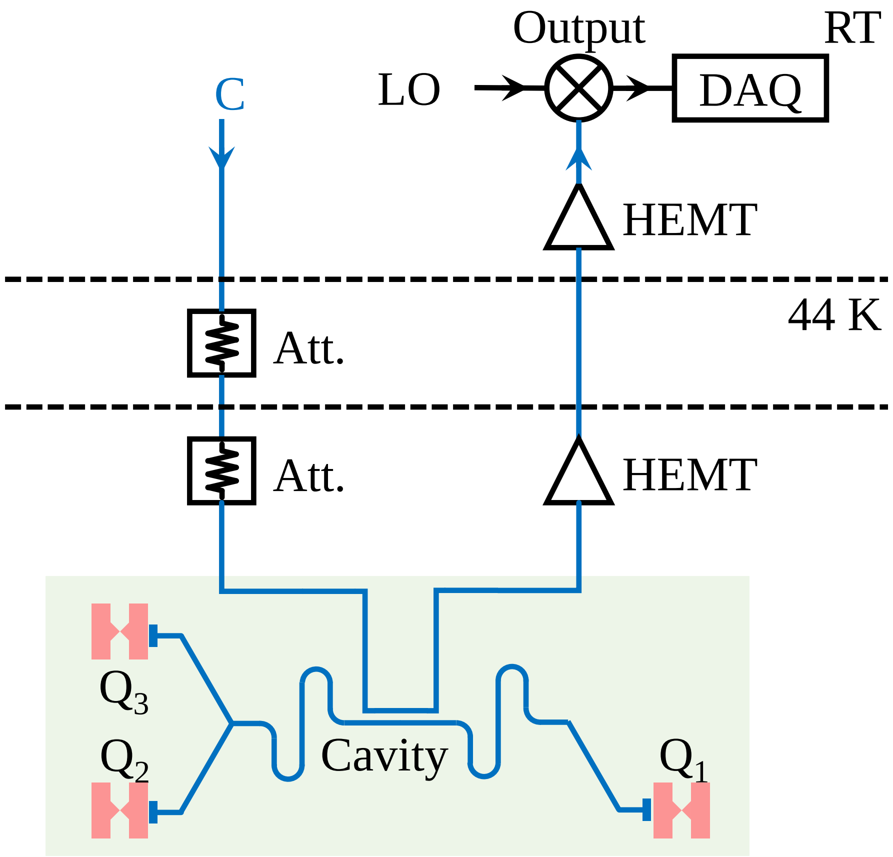
$$P_\pm \propto |\Delta\hat{\sigma}_z|^2 P_{\rm prob}$$

# Noise analysis

Noise sources

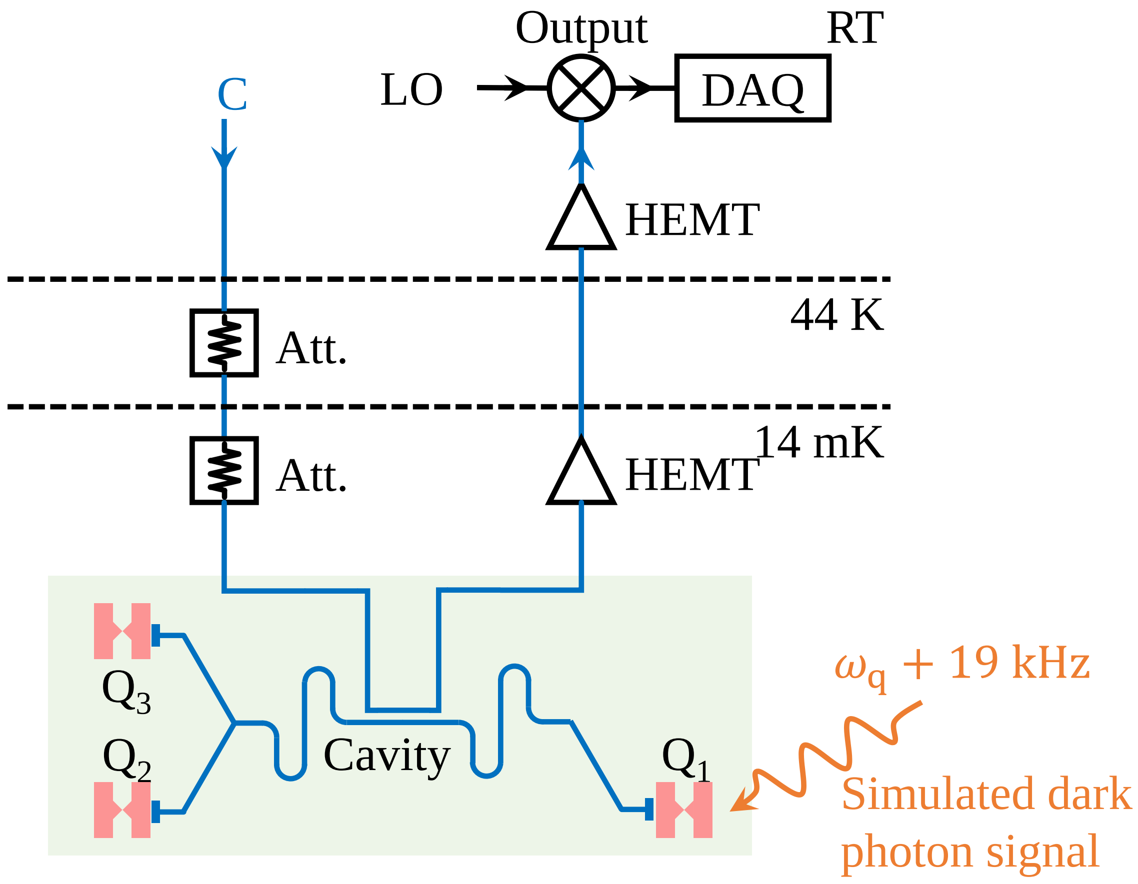
1. Readout noise: $P_r(\omega) = \hbar\omega_c\left[\frac{1}{e^{\hbar\omega_{\mathrm{c}}/k_B T}-1} + \frac{1}{2} + N_{\mathrm{r}}\right]\Delta\omega_{\mathrm{X}}$
2. Projection noise: $\Delta\sigma_z(\omega) = \sqrt{p_\uparrow p_\downarrow}\, L(\omega, 0, T_2^*)\Delta\omega_{\mathrm{X}} \approx \sqrt{0.25 \times 0.75}\, L(\omega, 0, T_2^*)\Delta\omega_{\mathrm{X}}$
3. Black body radiation: $u(\omega, T)d\omega = \hbar\omega\frac{\omega^2\Delta\omega_{\mathrm{X}}}{\pi^2 c^3} \times \frac{1}{e^{\hbar\omega/k_B T}-1}$
4. Vacuum fluctuation: $u(\omega, T)d\omega = \hbar\omega\frac{\omega^2\Delta\omega_{\mathrm{X}}}{\pi^2 c^3} \times \frac{1}{2}$

# Experimental setup

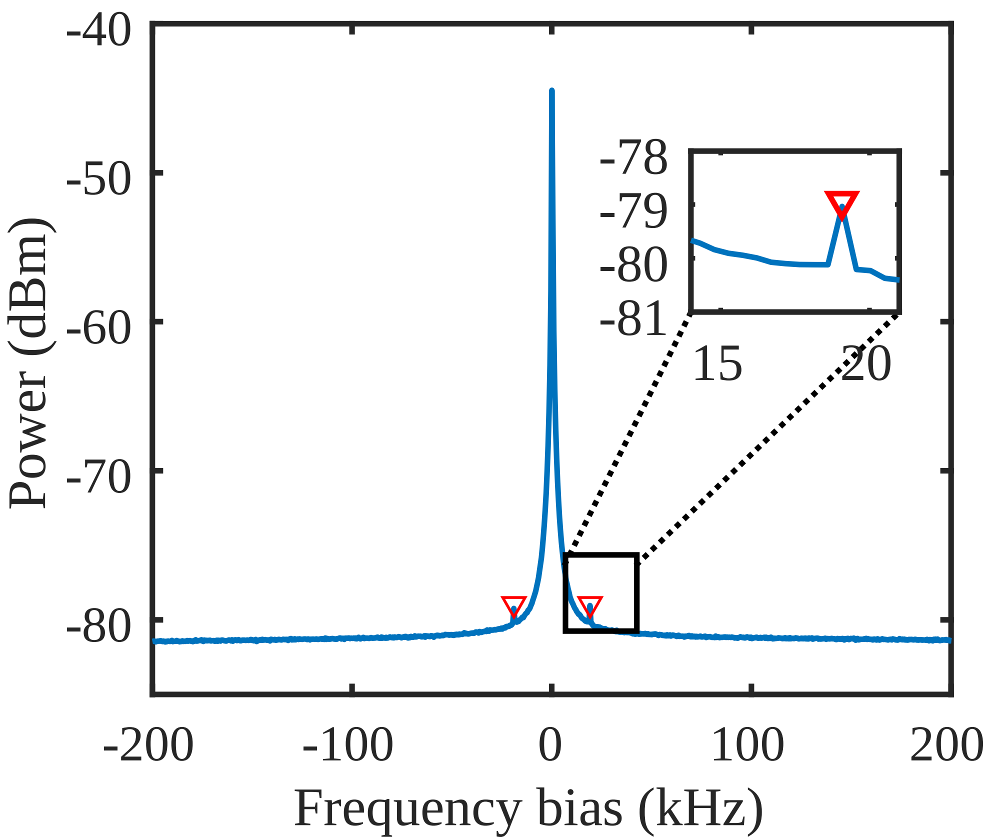



| Item | $Q_1$ | $Q_2$ | $Q_3$ |
|---|---|---|---|
| $\omega_q/2\pi$ | 3781 MHz | 3831 MHz | 3982 MHz |
| $T_2^*$ | 2.0 μs | 1.1 μs | 1.7 μs |
| $T_1$ | 2.3 μs | 3.7 μs | 5.5 μs |
| Coupling $G$ | 55 MHz | 68 MHz | 49 MHz |

# Verification

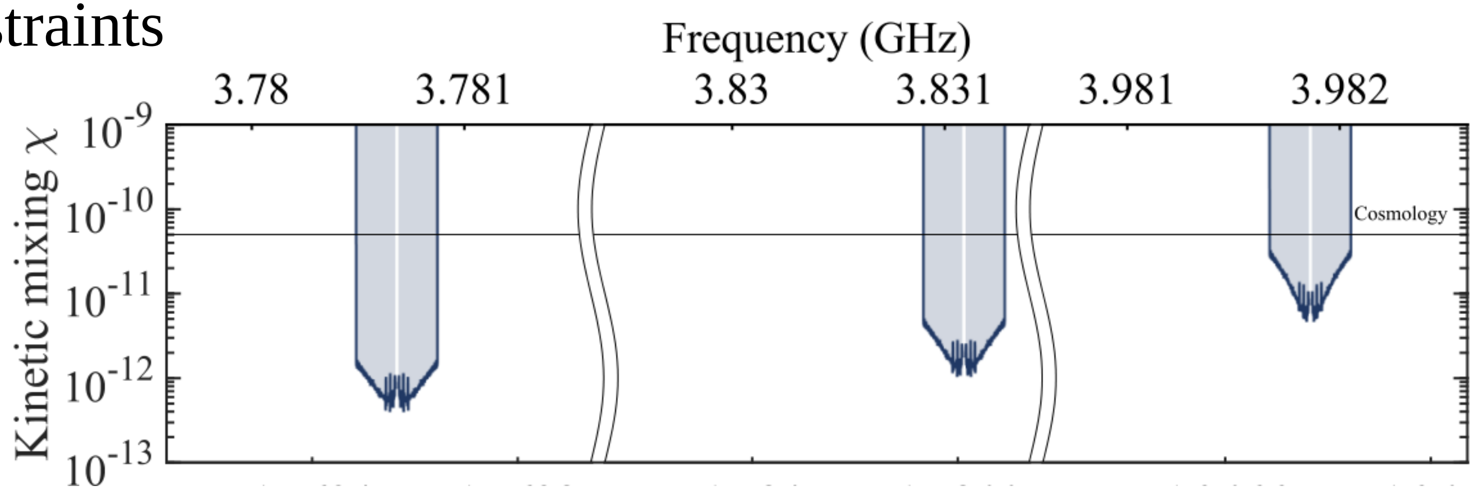



Output spectrum of the readout cavity

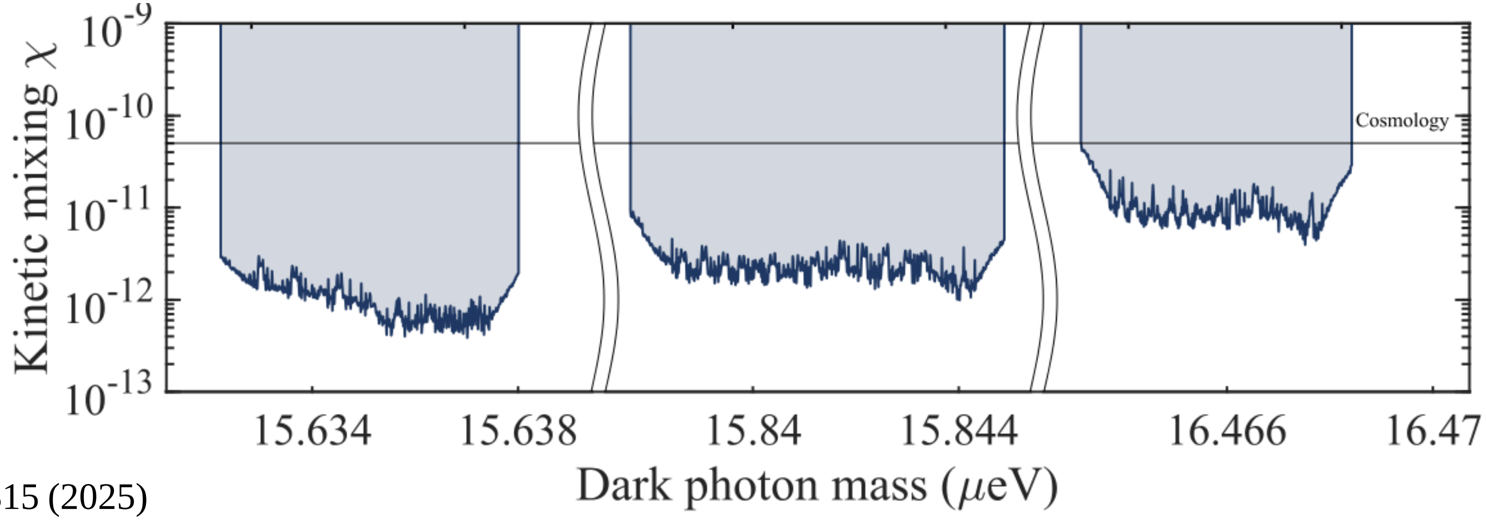


# Constraints

9-hour constraints




17×9-hour constraints



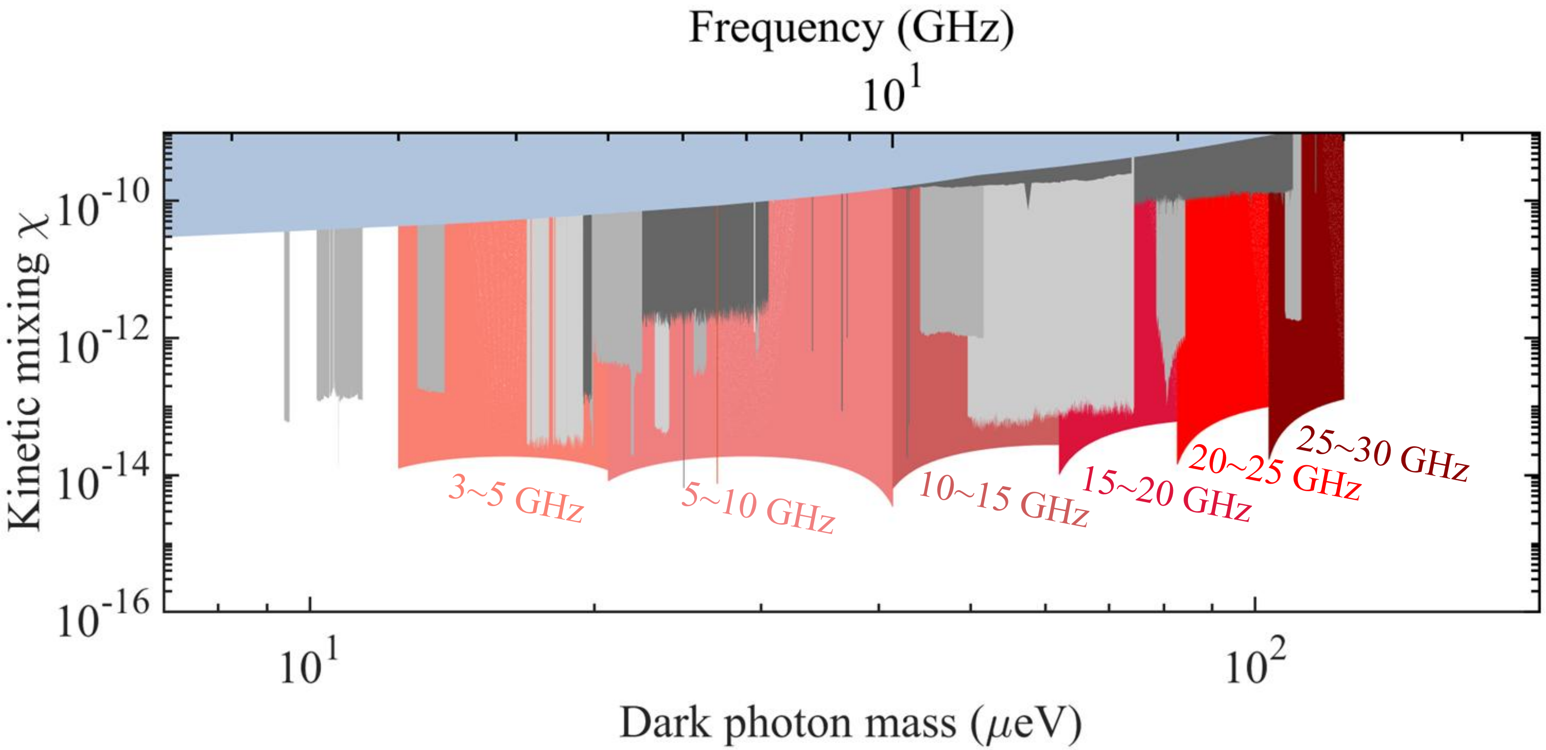



R. Kang, et al., arXiv: 2503.18315 (2025)

# Expected constraints

The red regions refer to the parameter space expected to be excluded with 1000 qubits. Each qubit covers a band of 0.25 MHz and is 5 MHz away from its neighbors. The integration time is assumed to be 20 day.

| Parameter | Value |
|---|---|
| $n_{\mathrm{q}}$ | 1000 |
| $C$ | 0.1 pF |
| $d$ | 300 μm |
| $T_1, T_2^*$ | $50\ \mu s, 100\ \mu s$ |
| $G$ | 100 MHz |
| $Q_{\mathrm{cavity}}$ | $2 \times 10^4$ |
| $T_{\mathrm{phy}}$ | 10 mK |

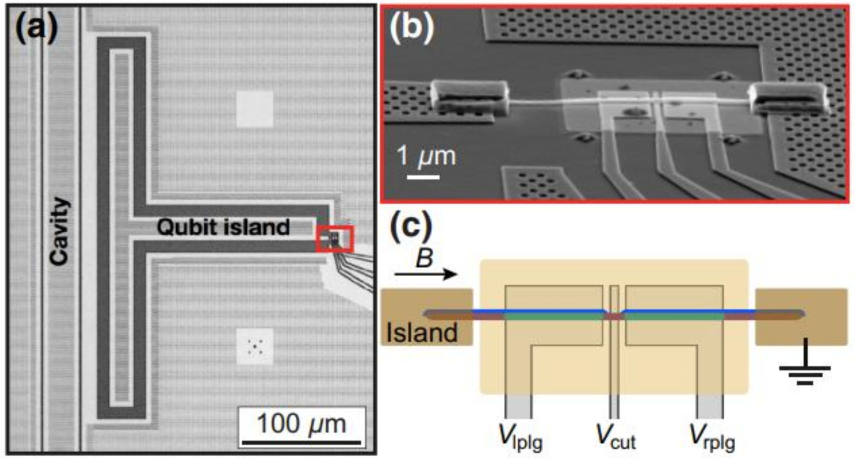




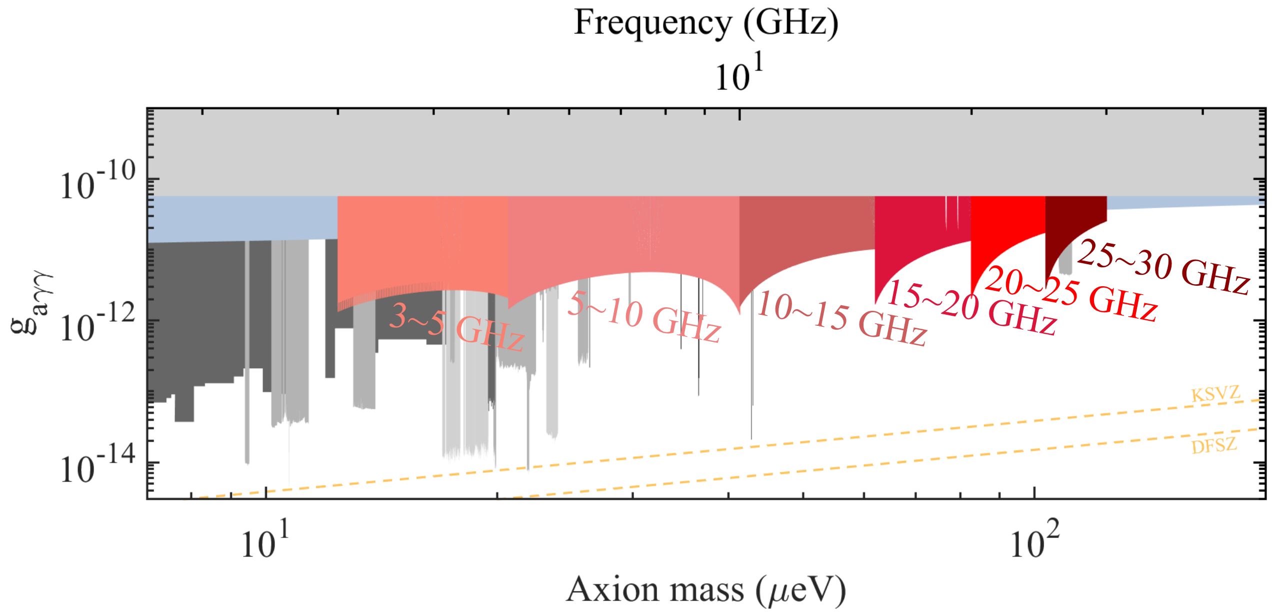

R. Kang, et al., arXiv: 2503.18315 (2025)

# Expected constraints

Magnetic-field-compatible qubit




Expected constraints on axion-photon coupling (100 day)






A. Kringhoj, et al., Phys. Rev. Lett. **15**, 054001 (2021)

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- Performed China's first DP searching based on all-superconducting haloscope

- Proposed the scalable dark matter searching scheme based on superconducting qubits

- Experimentally demonstrated the scheme using a three qubit sample and set the most strigent constraints on dark photons in the mass range of 15.632~15.638 μeV, 15.838~15.844 μeV, 16.464~16.468 μeV

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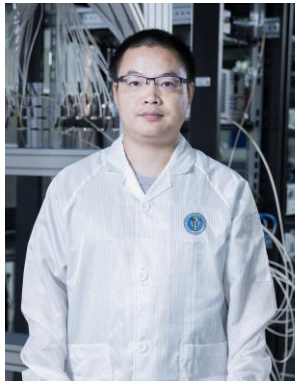
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Yi-Fu Cai


Man Jiao


Yu Tong


Qingqin Hu

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