Wavelike dark matter detection using qubits

(1) *Phys. Rev. Lett. 131 (2023) 21, 211001*
(2) *Phys. Rev. Lett. 133 (2024) 2, 021801*

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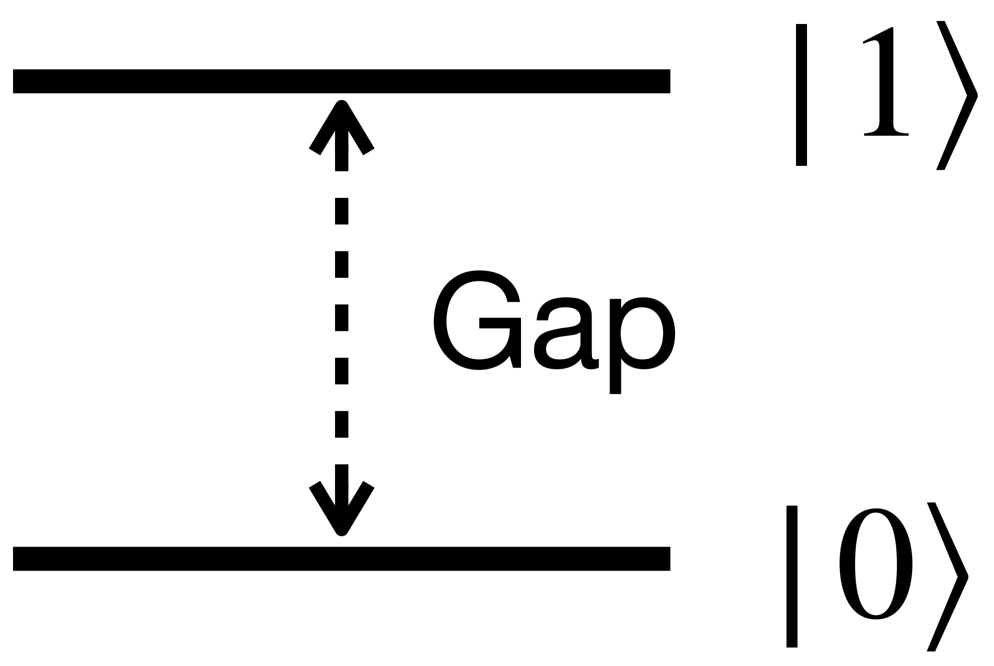
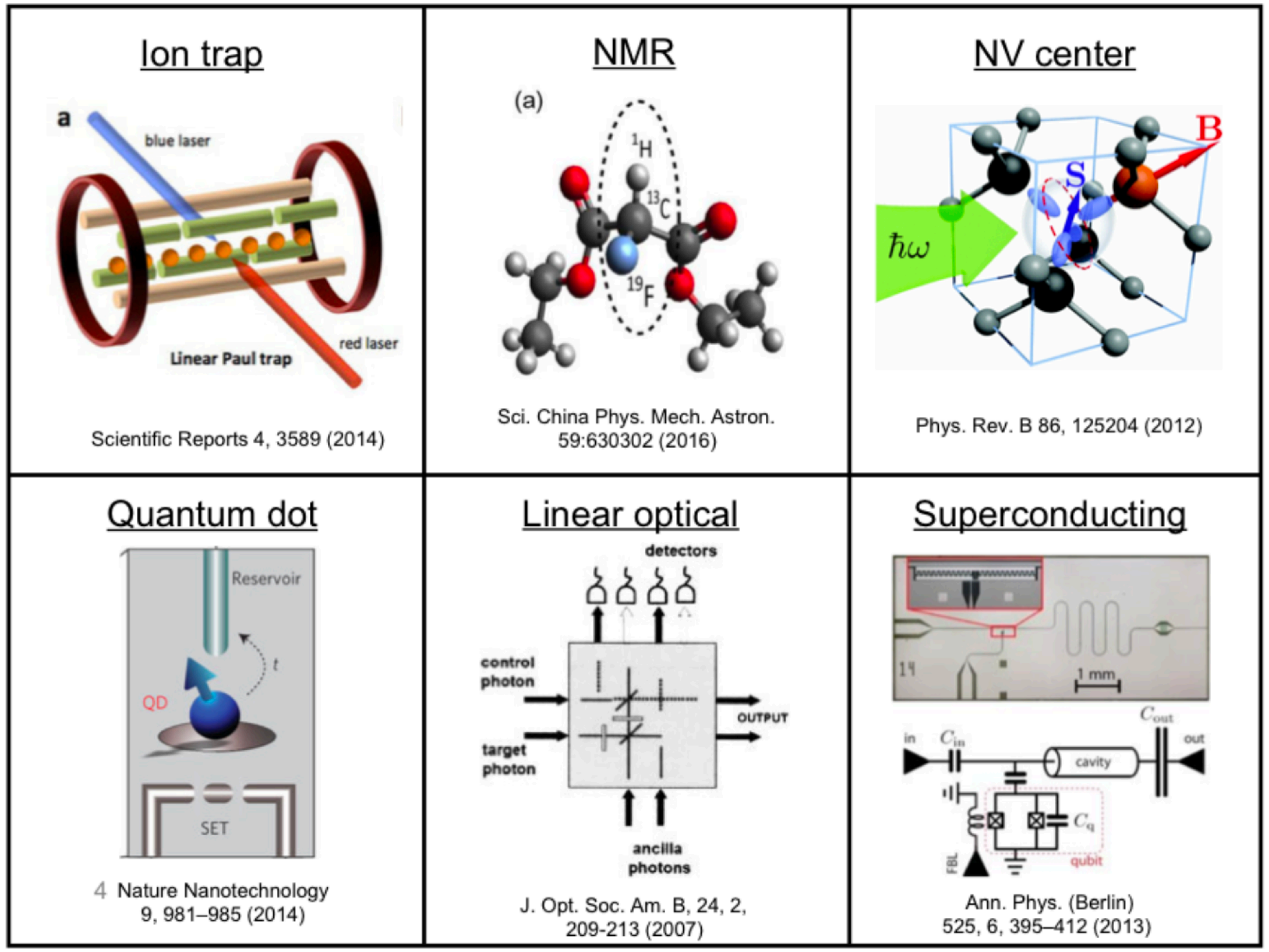
Background and Motivation

Qubit is two-level system developed for computation



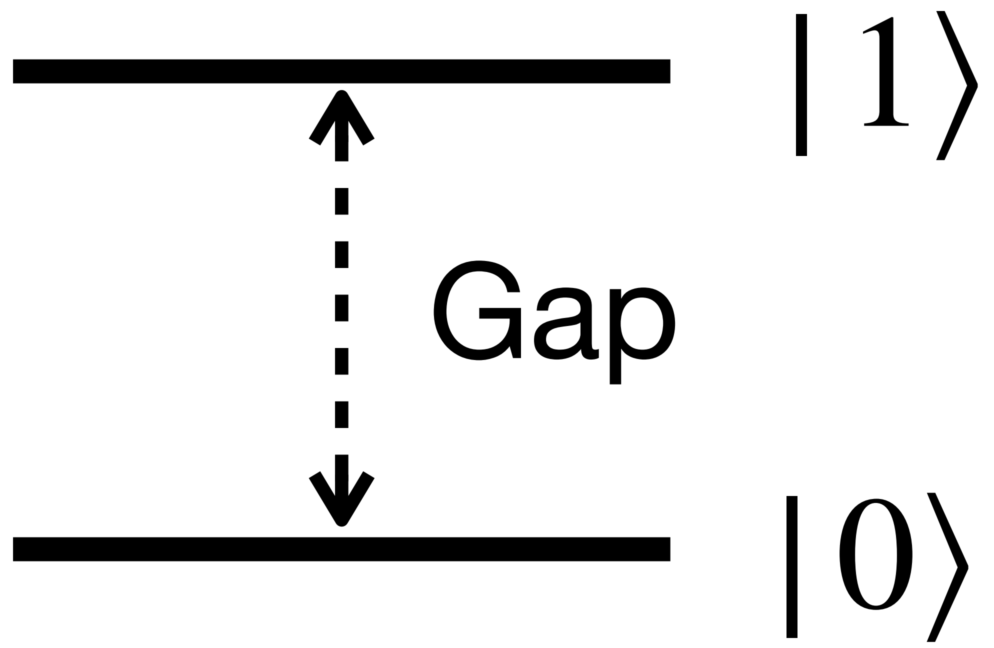


James Amundson, Elizabeth Sexton-Kennedy, EPJ Web of Conferences 214, 09010 (2019)

Background and Motivation

Qubit is two-level system developed for computation

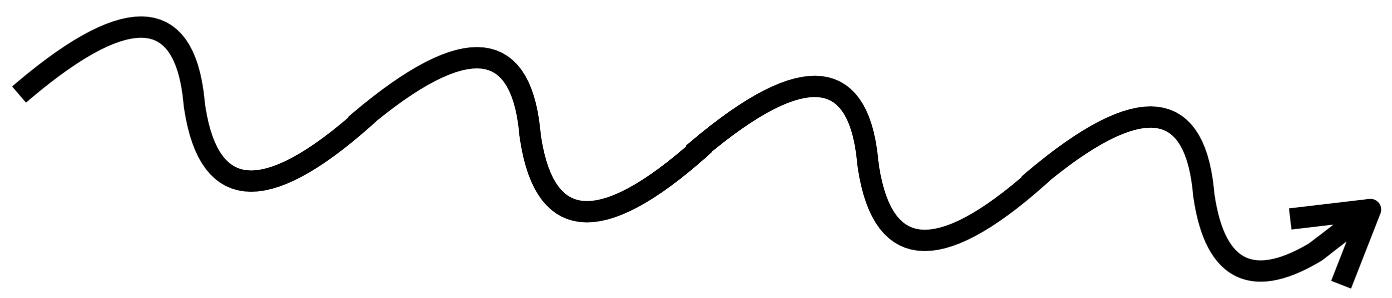
In the same time, it could be a good quantum sensor

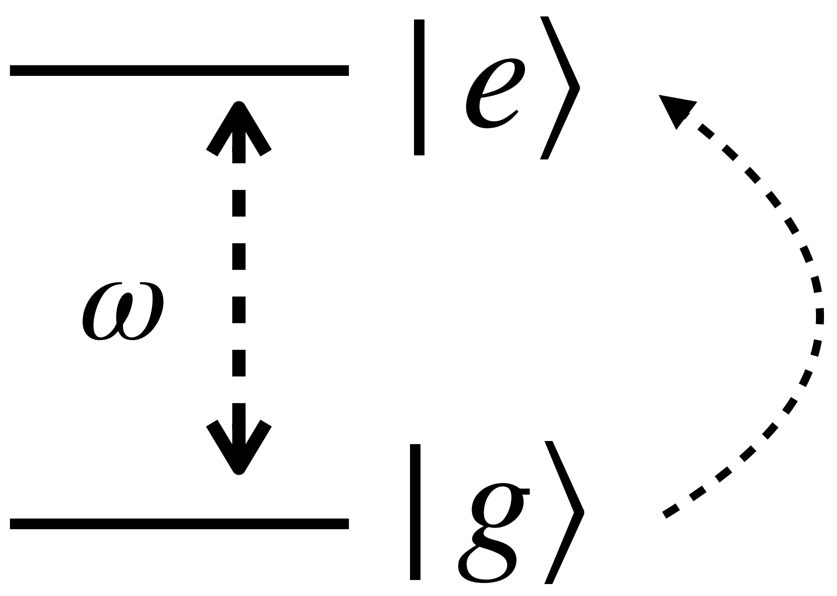


- precise readout
- state controllability
- tunable energy gaps
- Quantum enhancement

Dark matter search using qubit

Axion dark matter, mass m_a





Transmon qubit
excitation as DM signal

Based on

- (1) Hidden photon DM search with transmon qubits

  [Chen, Fukuda, Inada, Moroi, Nitta, TS, *Phys. Rev. Lett. 131 (2023) 21, 211001*]

- (2) Quantum computation to enhance detection

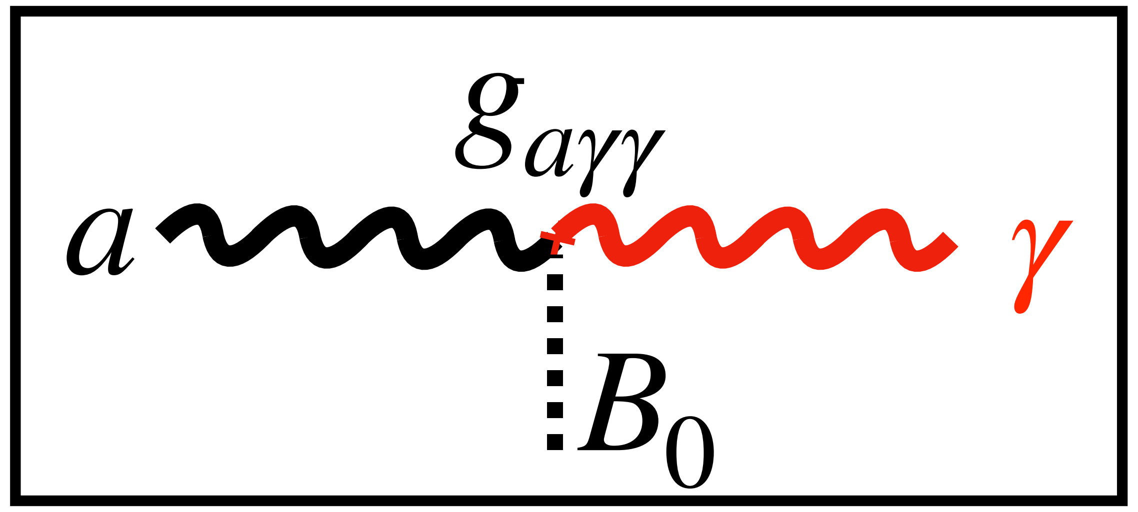
  [Chen, Fukuda, Inada, Moroi, Nitta, TS, *Phys. Rev. Lett. 133 (2024) 2, 021801]*

Axion dark matter

Axion Lagrangian

Axion-photon coupling

$$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 - g_{a\gamma\gamma} a \vec{E}\cdot\vec{B}$$

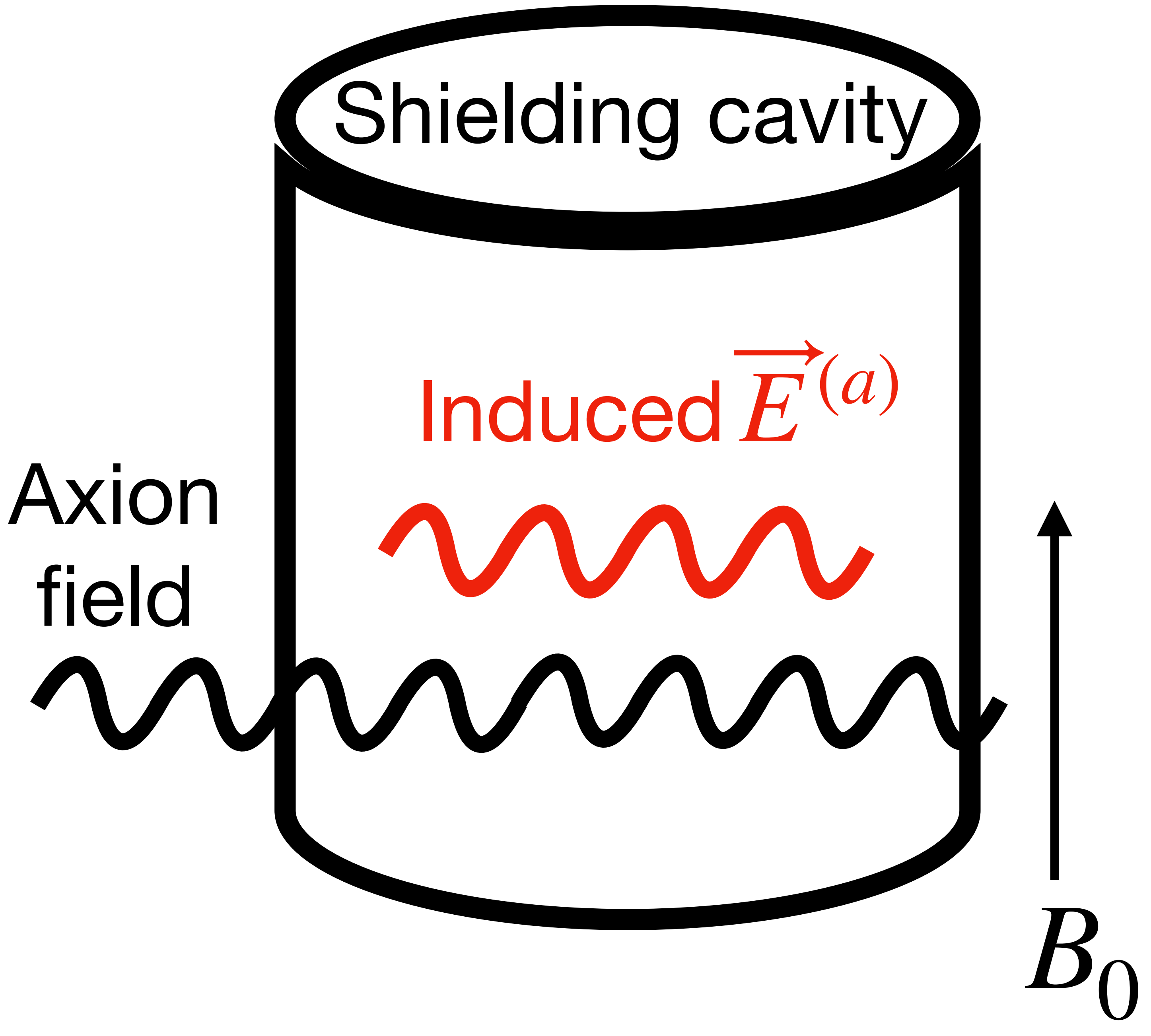


Axion dark matter

- Mass $m_a \ll 1\ \mathrm{eV} \Rightarrow$ [# particles within De-Broglie volume] $\gg 1$
- Axion field $a(t) = a_0 \cos(m_a t - \alpha)$
- DM density $\rho_{\mathrm{DM}} = \frac{1}{2}m_a^2 a_0^2$ (local $\rho_{\mathrm{DM}} \sim 0.45\ \mathrm{GeV/cm^3}$)

Axion induced electric field

Axions induce electric field $\vec{E}$ under the presence of magnetic field B_0 applied



Equation of motion

$$(\nabla^2 - \partial_t^2)\vec{E} = -g_{a\gamma\gamma}a_0\cos(m_a t - \alpha)\vec{B}_0$$

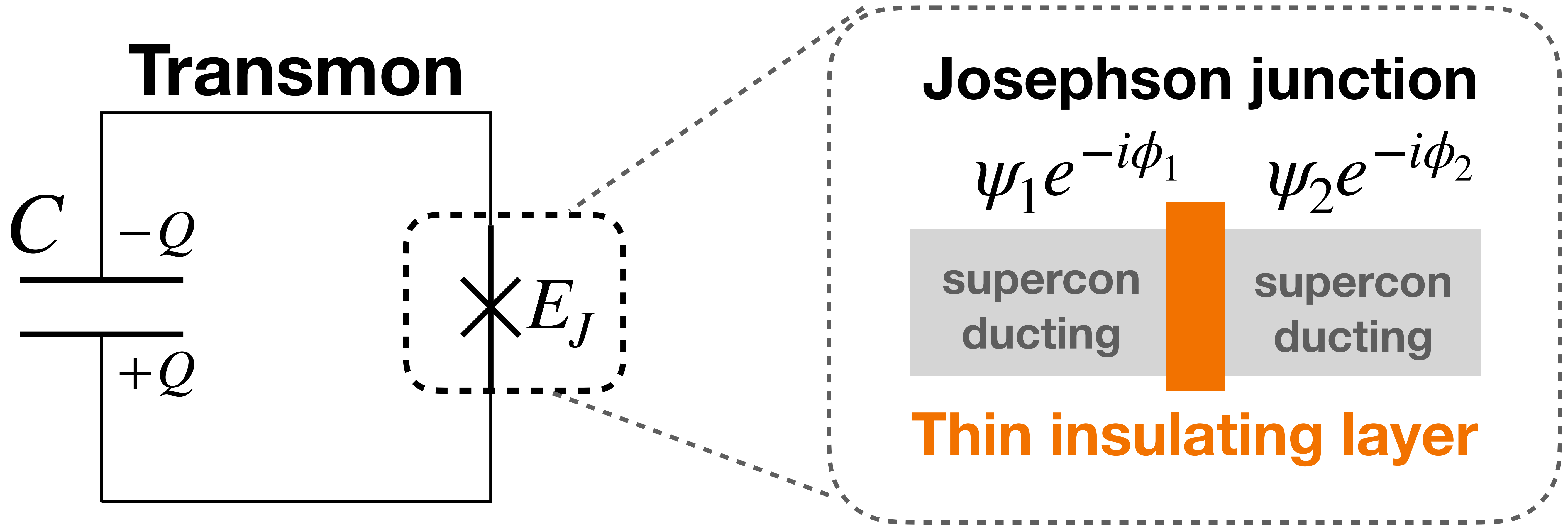
with boundary condition $E_{\|} = 0$

Solution

$$\vec{E}^{(a)} = \bar{E}^{(a)}\cos(m_a t - \alpha)\,;\, \bar{E}^{(a)} = g_{a\gamma\gamma}a_0B_0\kappa$$

With κ expresses the cavity effect
and κ can be larger than 1

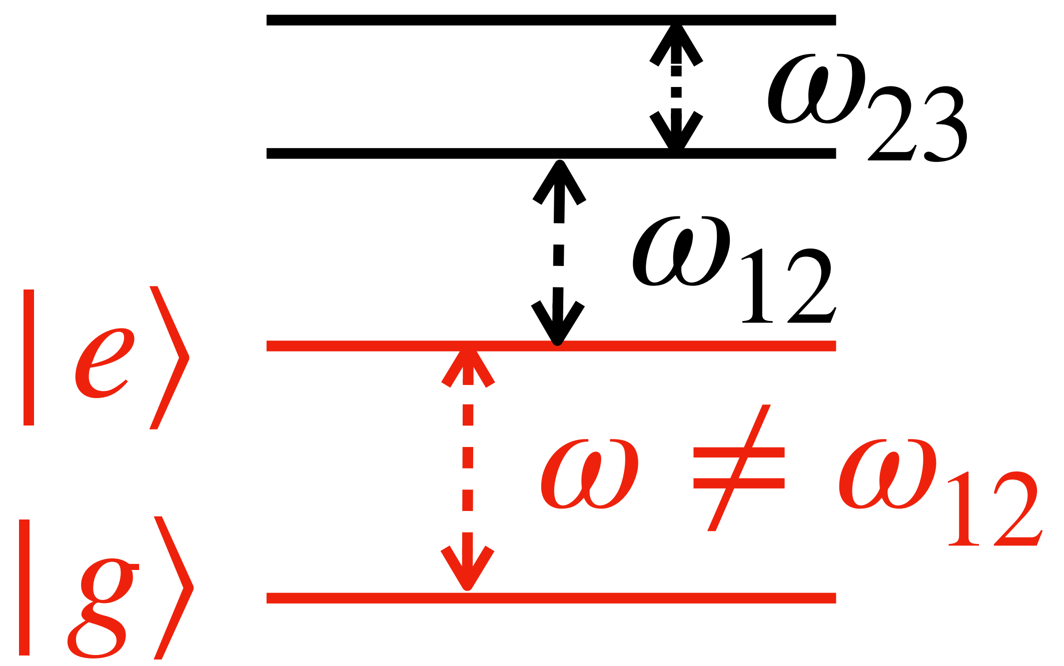
Transmon qubit as DM sensor



Hamiltonian

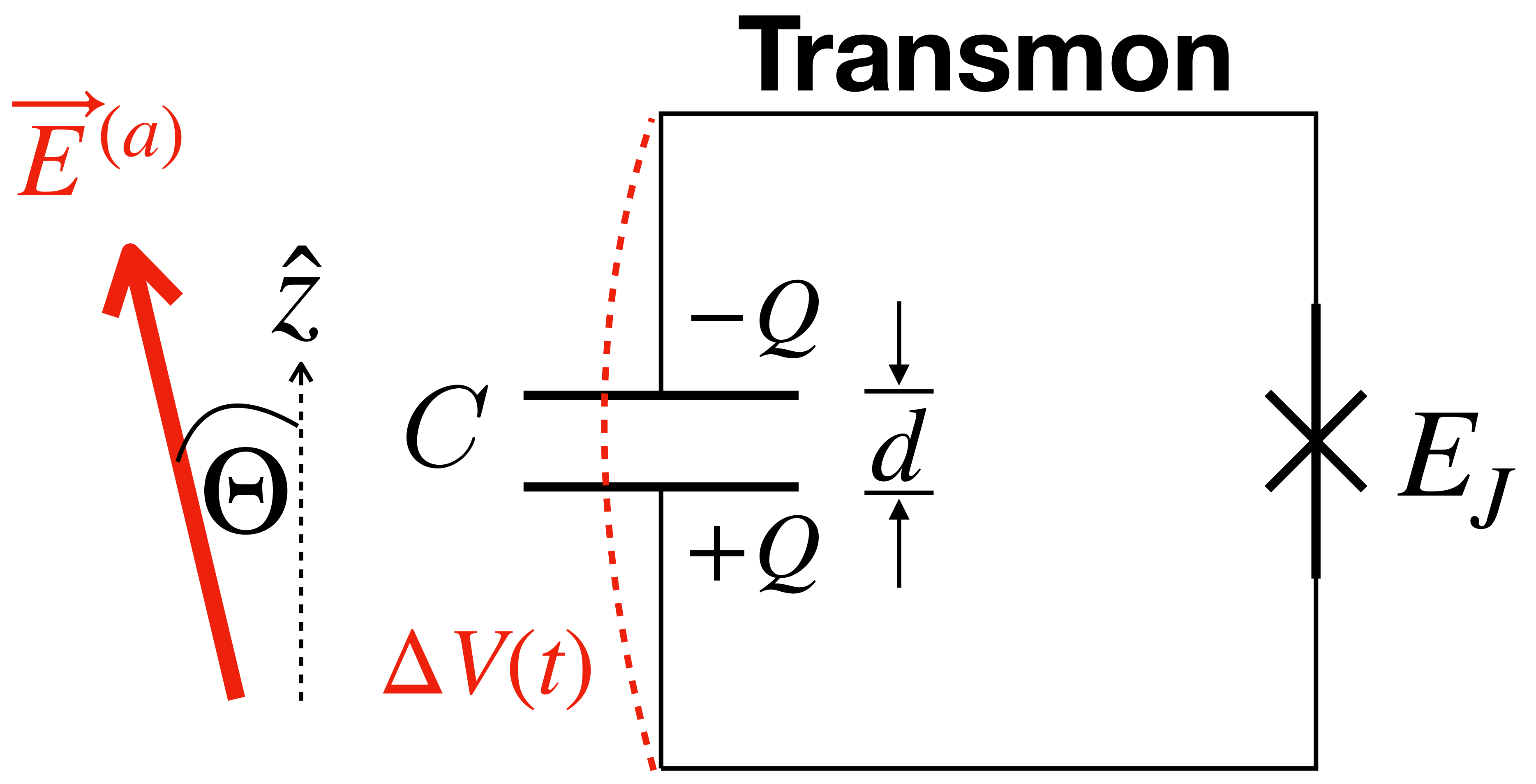
$$H_0 = Q^2/2C - E_J \cos\theta \, ; \theta \equiv \phi_1 - \phi_2$$

$$H_0 \simeq \omega |e\rangle\langle e| \text{ with } \omega = \sqrt{4e^2 E_J / C}$$



Gap not the same

Transmon qubit as axion DM sensor



Induced voltage on capacitor:

$$\Delta V(t) = d\vec{E}^{(a)}(t) \cdot \hat{z}$$

Interaction hamiltonian:

$$H_{\text{int}} = Q\Delta V$$

$$H = \omega |e\rangle\langle e|$$
$$-2\eta \cos(m_a t - \alpha)(|g\rangle\langle e| + |e\rangle\langle g|)$$

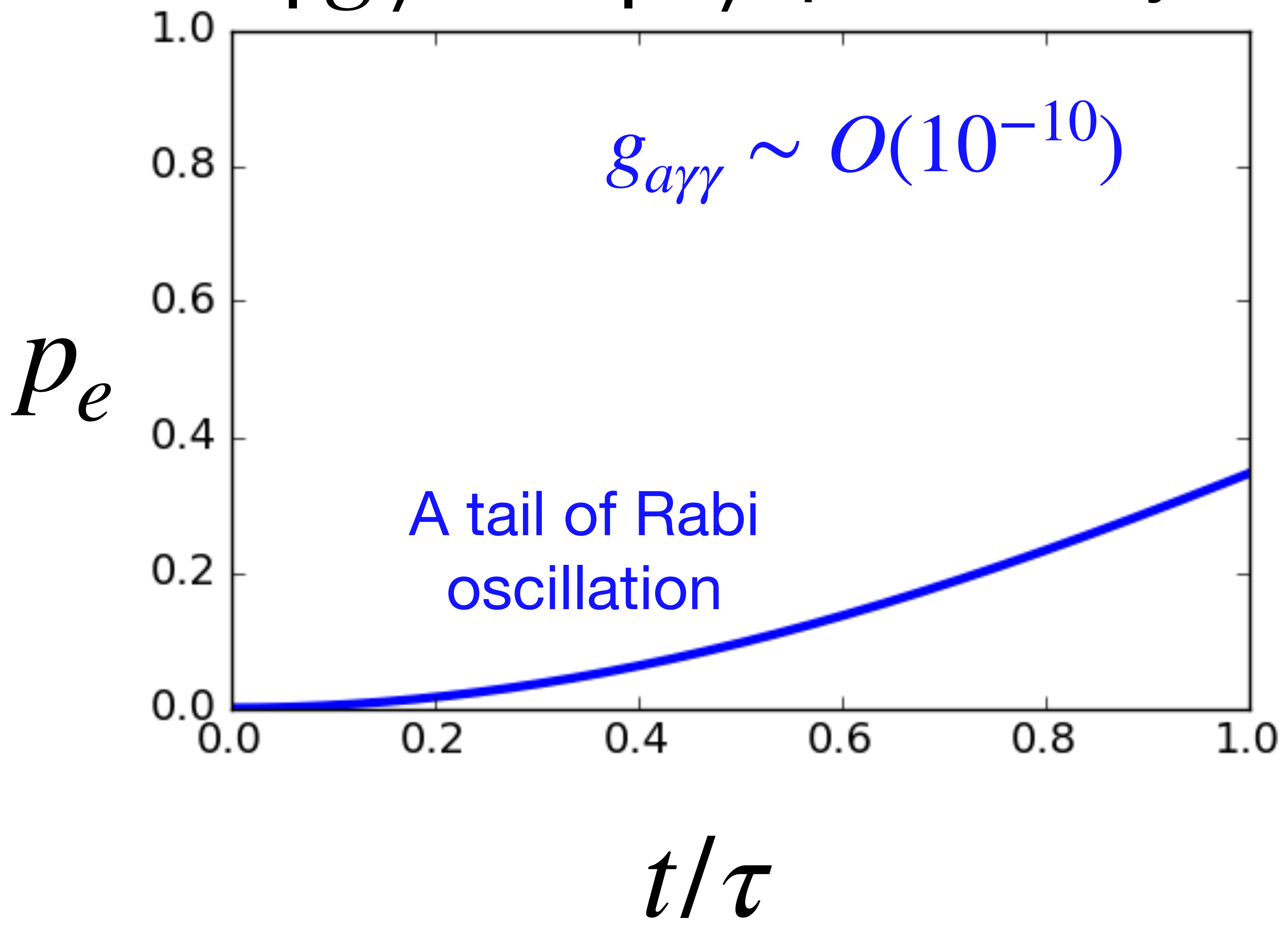
For $m_a = \omega$, the Schrödinger Eq. is

$$\frac{d}{dt}\begin{pmatrix}\psi_g \\ \psi_e\end{pmatrix} = \begin{pmatrix} 0 & ie^{-i\alpha}\eta \\ ie^{i\alpha}\eta & 0 \end{pmatrix}\begin{pmatrix}\psi_g \\ \psi_e\end{pmatrix}$$

$$;\ \eta \equiv \sqrt{\omega C} d\bar{E}^{(a)} \cos\Theta / 2\sqrt{2}$$

Qubit direct excitation due to external field

$|g\rangle \to |e\rangle$ probability



$$p_e(\tau) \equiv |\langle g|e\rangle|^2 \simeq \eta^2\tau^2$$

Gradual growth of probability

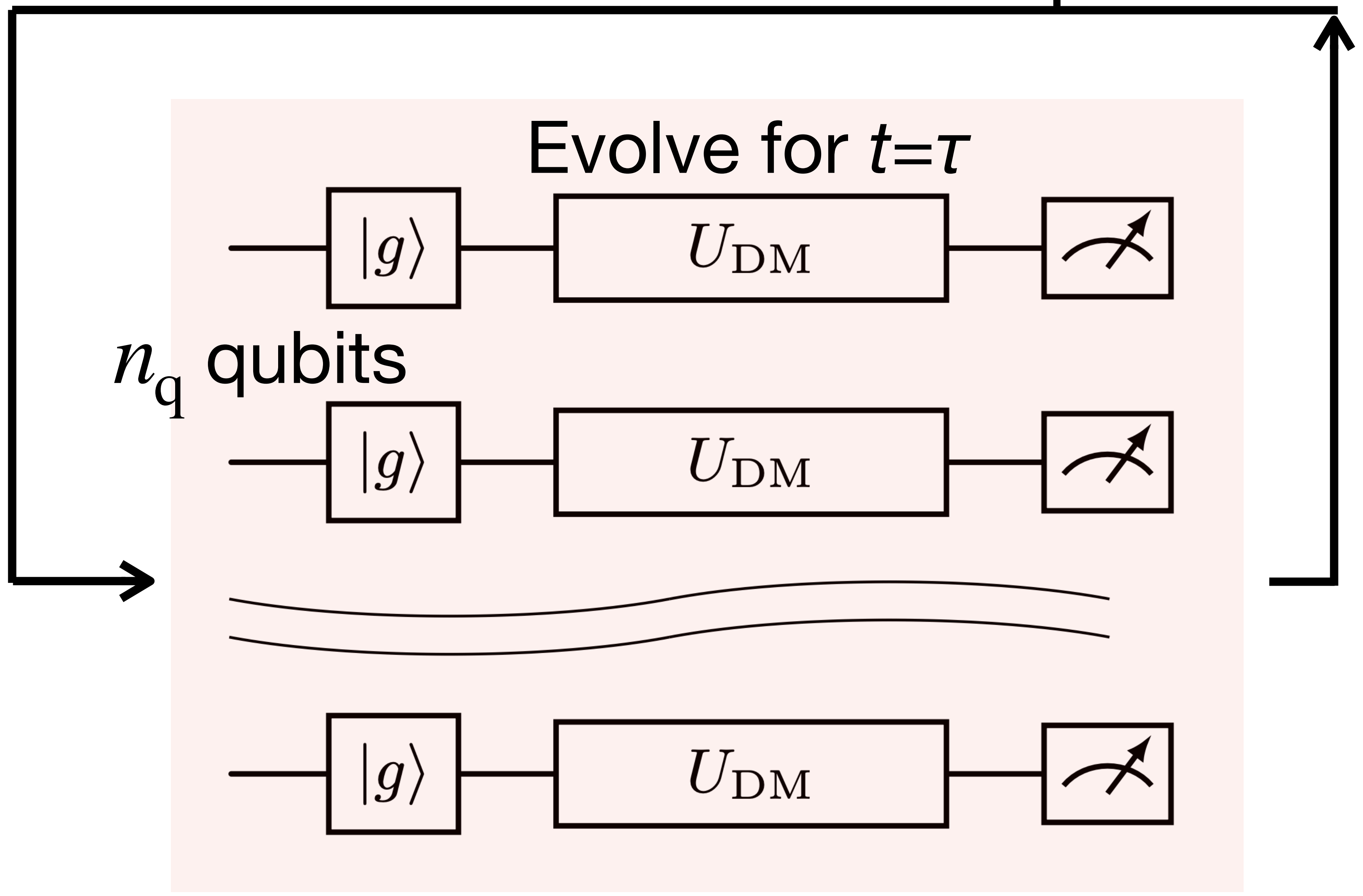
; $\tau = \min\{\tau_{\rm DM}, \tau_{\rm qubit}\} \sim 100\ \mu s$

$$p_e(\tau) \simeq 0.11 \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ {\rm GeV}^{-1}}\right)^2 \left(\frac{m_a}{1\ \mu{\rm eV}}\right)^{-1} \left(\frac{B}{1\ {\rm T}}\right) \left(\frac{\kappa}{1}\right)^2 \times \left(\frac{\tau}{100\ \mu{\rm s}}\right)^2 \left(\frac{C}{0.1\ {\rm pF}}\right) \left(\frac{d}{100\ \mu{\rm m}}\right)^2 \left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeV/cm^3}}\right)$$

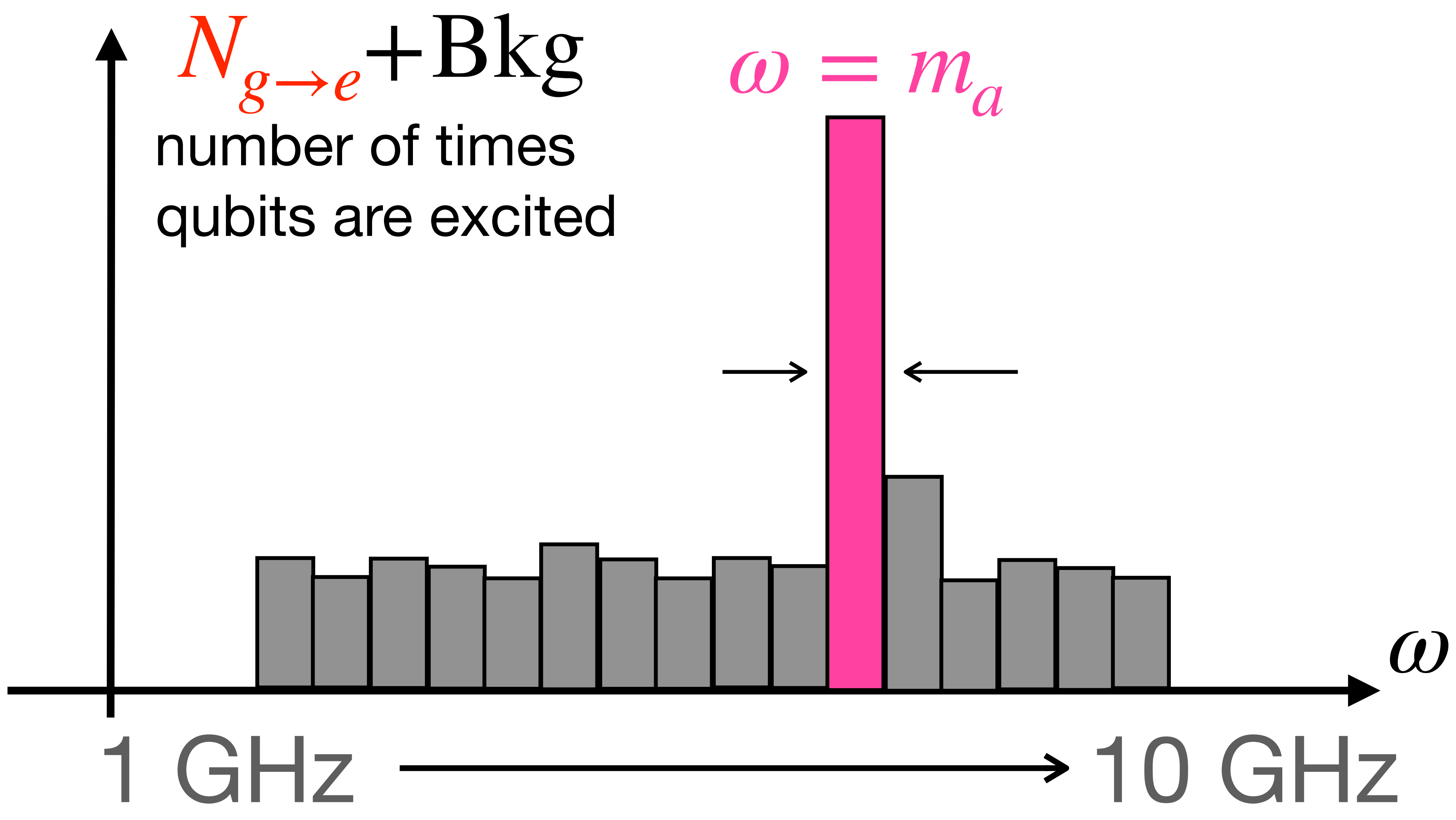
Process of measurement

For each frequency bin

Repetitions N_{rep}



$$N_{g\to e} \simeq N_{\mathrm{rep}} n_{\mathrm{q}} \eta^2 \tau^2$$



Significance $\sigma = N_{g\to e}/\sqrt{\mathrm{Bkg}}$

$; \mathrm{Bkg} = p_{\mathrm{noise}} n_{\mathrm{q}} N_{\mathrm{rep}}$

Quantum enhancement by quantum circuits

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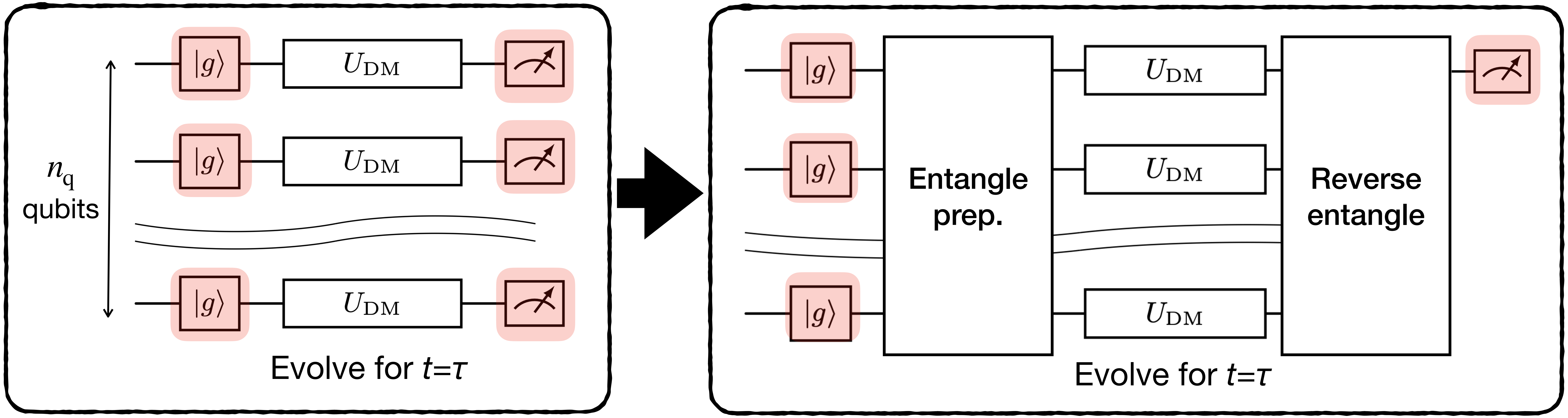
Individual measurement / **Using quantum circuit**



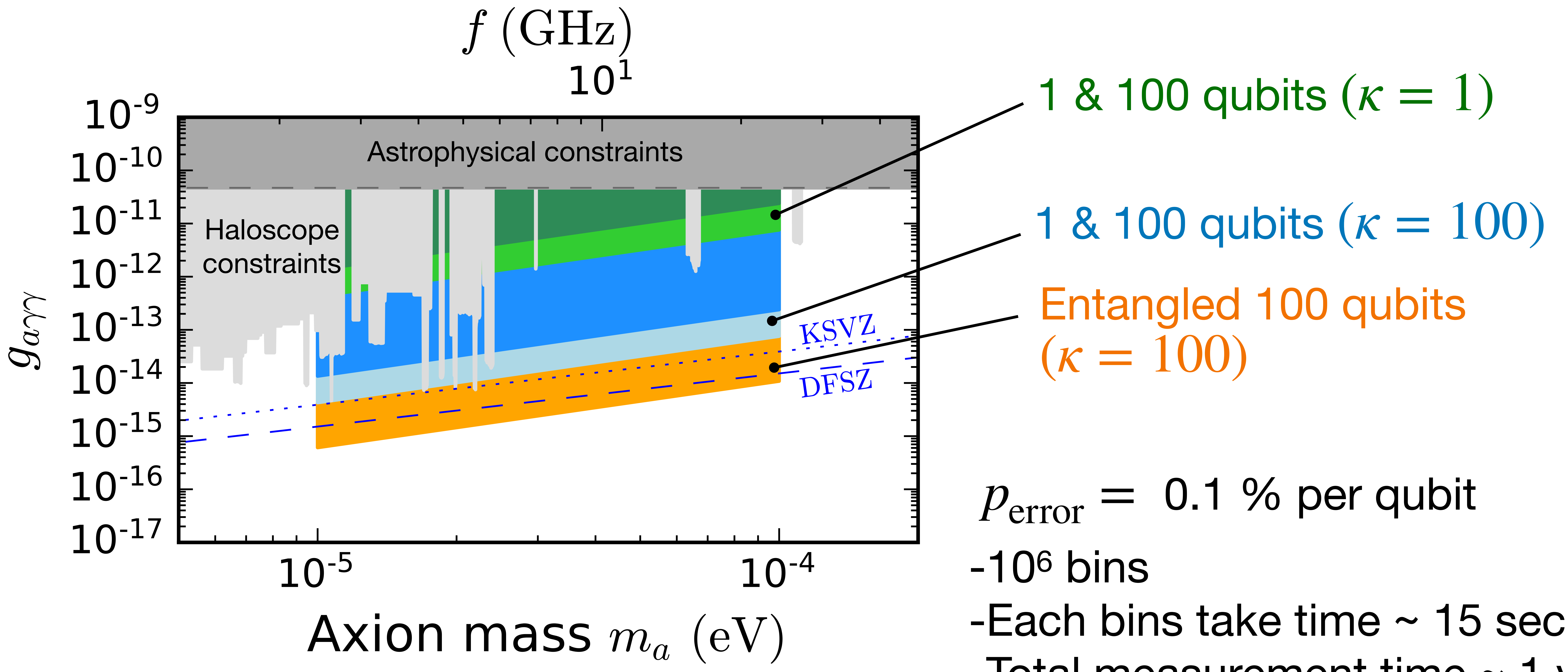
Prob. that a qubit is excited

$$p_e \propto n_{\rm q}$$

Prob. that a qubit is excited

$$p_e \propto n_{\rm q}^2$$

Sensitivity plot (Axions)



$p_{\text{error}} =$ 0.1 % per qubit

- 10^6 bins
- Each bins take time ~ 15 sec
- Total measurement time ~ 1 year

Summary

- Coherent wave-like dark matter (axion DM or hidden photon DM) can excite qubits, resulting in detectable signal

- Transmon has good sensitivity, reaching unexplored parameter regions of axion DM

- Enhancement with cavity effect and the quantum circuit is possible, even reaching QCD axions

Backup kappa factor

κ factor from cavity effect

- In general, we can write,

$$\kappa = \sum_m \vec{E}_m(r) \cdot \hat{z} \left[\int d^3x \frac{m_a^2}{m_a^2 - \omega_m^2} \vec{E}_m \cdot \hat{B}_0 \right]$$

With cylinder shielding cavity, we have mode functino $E_m = \frac{1}{\sqrt{V}} \frac{J_0(\omega_m r)}{J_1(\omega_m R)}$

$\kappa = 1 - \frac{J_0(m_a r)}{J_0(m_a R)}$ which can be larger than 1 and scale $\sqrt{m_a R}$ at large R

Example of cavity effect with $m_a R = 10$

$E^{(a)} = \bar{E}^{(a)} \cos(m_a t)\hat{z}$ with $\bar{E}^{(a)} = g_{a\gamma\gamma} a_0 B_0 \kappa$ due to axion DM field

E Field inside cylindrical cavity