Dark Matter direct detection using Qubits

(1) *Phys. Rev. Lett.* 131 (2023) 21, 211001
(2) *arXiv: 2311.10413*

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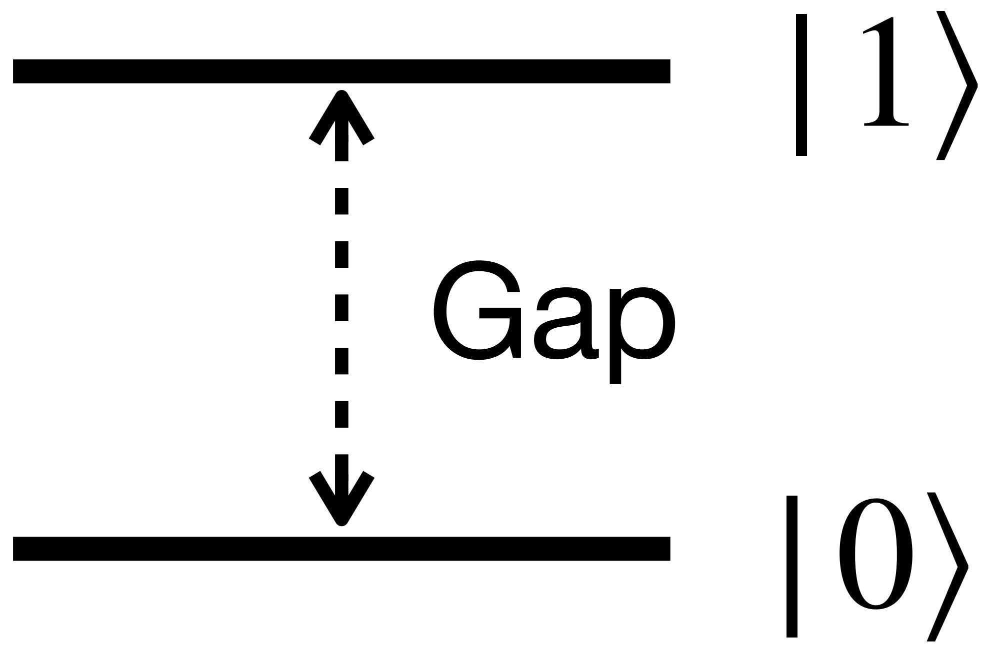
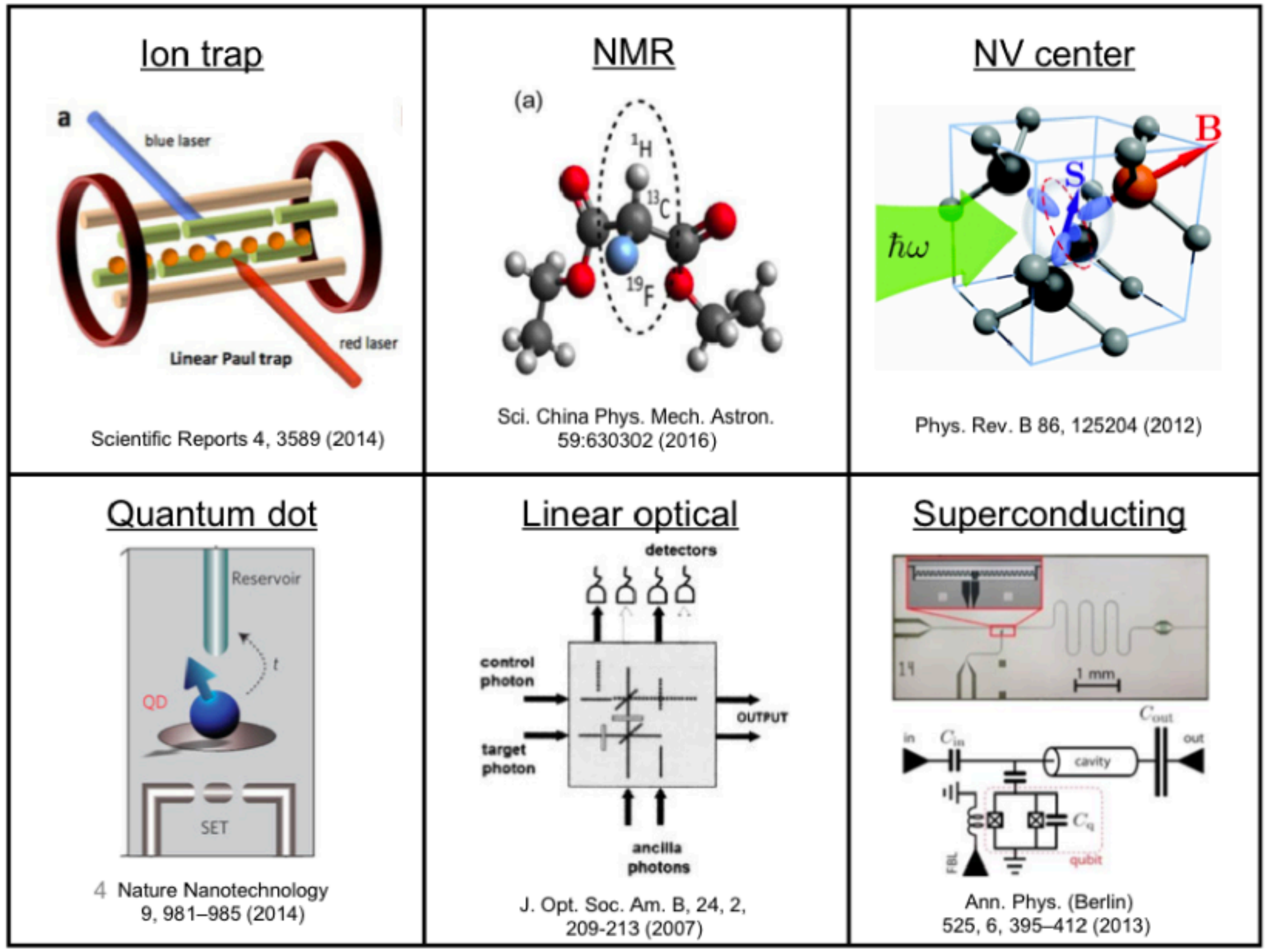
Background and Motivation

Qubit is two-level system developed for computation



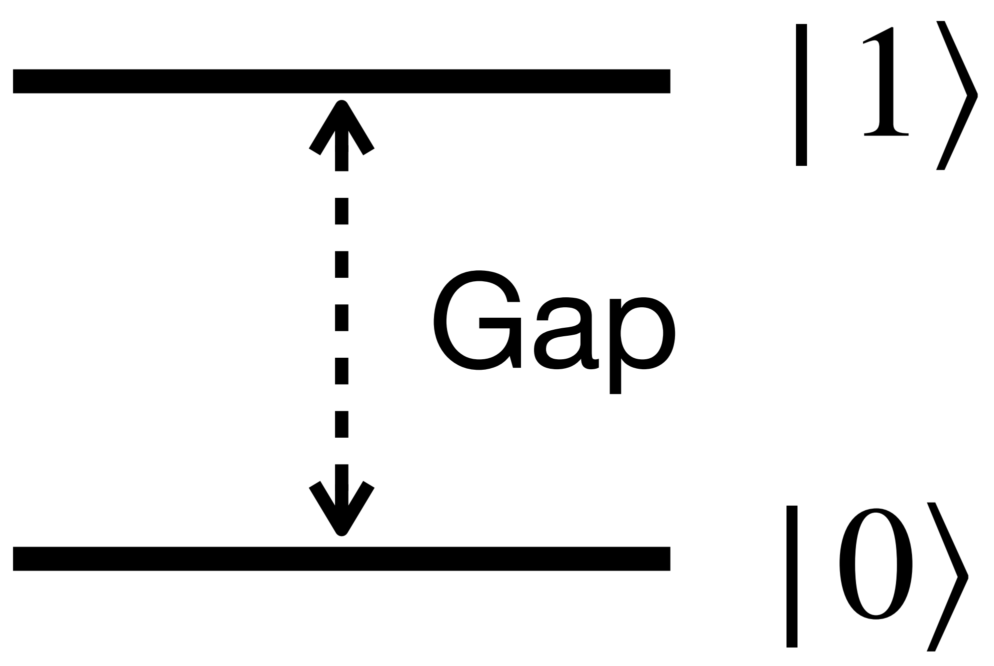


James Amundson, Elizabeth Sexton-Kennedy, EPJ Web of Conferences 214, 09010 (2019)

Background and Motivation

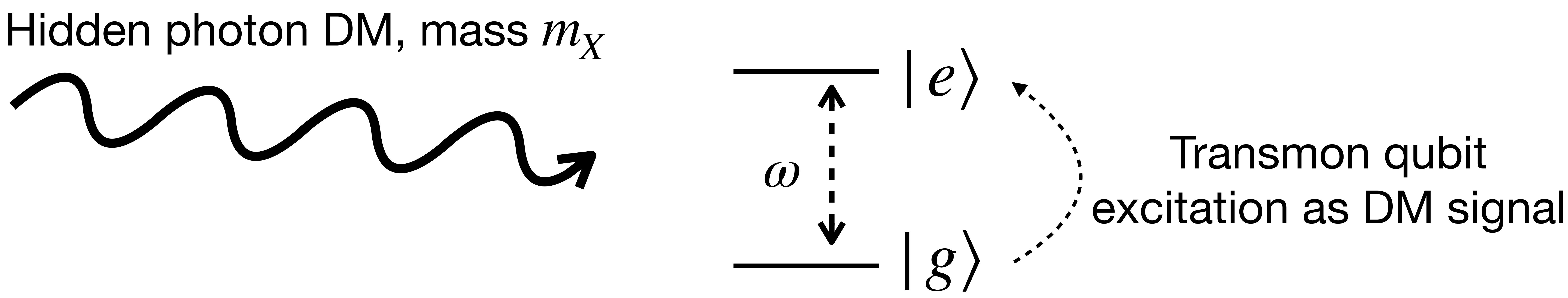
Qubit is two-level system developed for computation

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



- precise readout
- state controllability
- tunable energy gaps

Dark matter search using qubit



Outline

- (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, *arXiv: 2311.10413*]

Dark matter detection using transmon qubit excitation

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

Hidden photon DM

In kinetic-mixing basis,

$$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} \underbrace{-\frac{\epsilon}{2}F^{\mu\nu}X_{\mu\nu}}_{\text{Kinetic mixing}} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu + e\bar{\Psi}_e\gamma^\mu A_\mu \Psi_e$$

In mass-eigenstate basis ($A_\mu \to A_\mu + \epsilon X_\mu$),

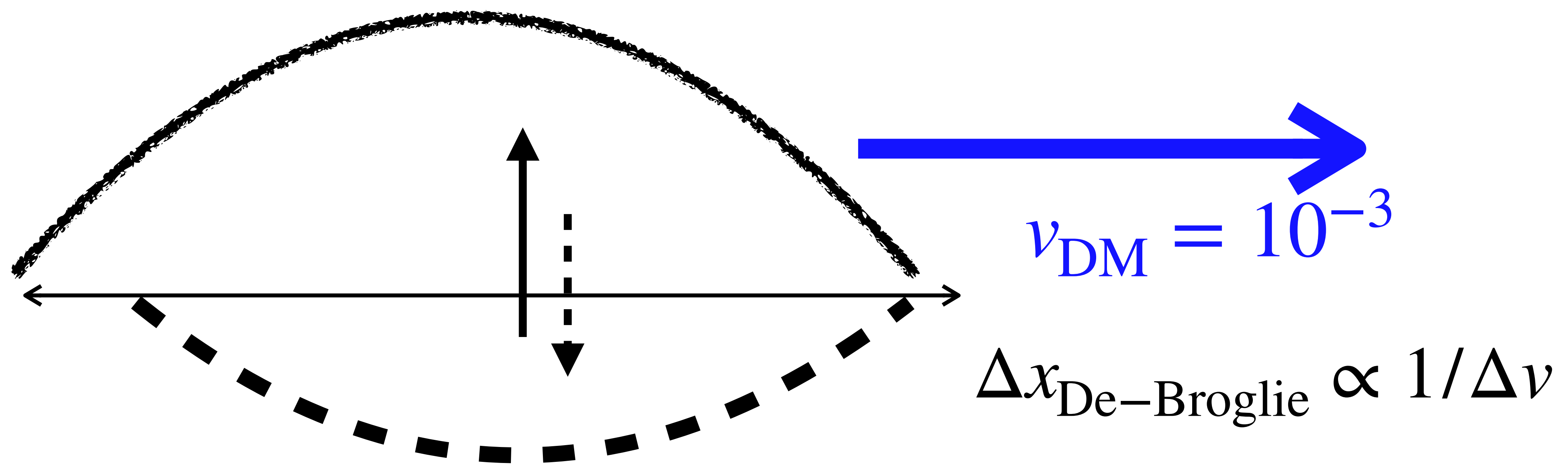
$$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu + \underbrace{e\bar{\Psi}_e\gamma^\mu(A_\mu + \epsilon X_\mu)\Psi_e}_{\text{Direct interaction between DM and matters}}$$

Hidden photon DM as effective E-field

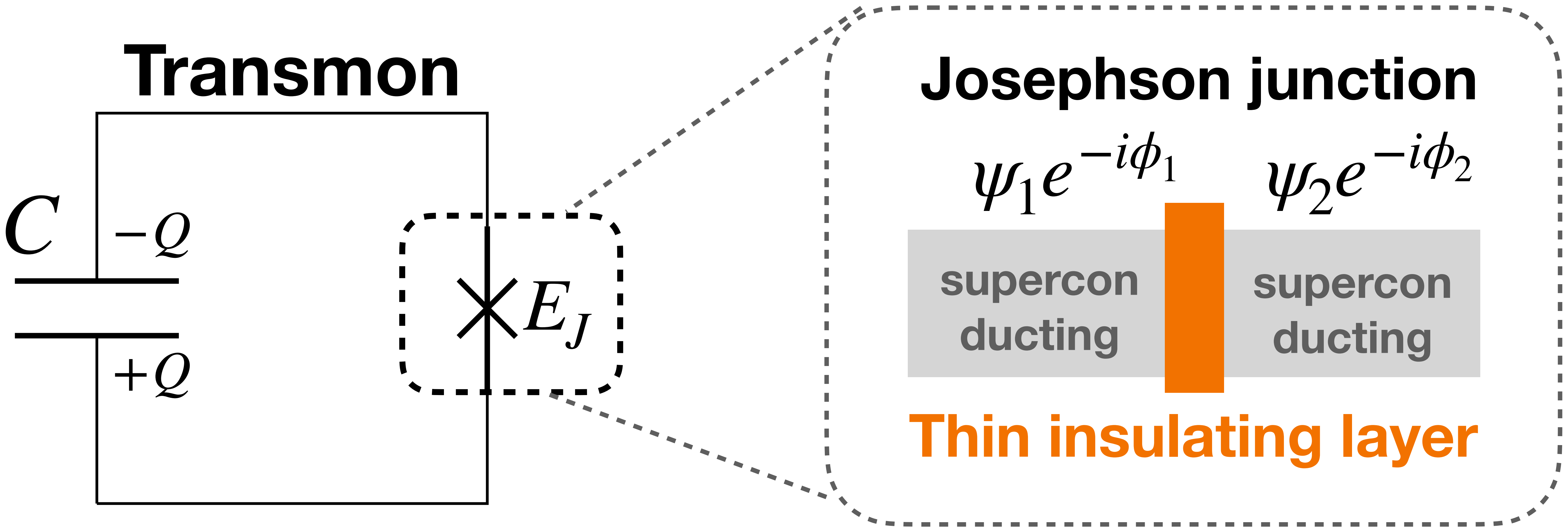
https://arxiv.org/abs/1711.10489

- Mass $m_X \ll 1\ \mathrm{eV} \Rightarrow$ [# particles within De-Broglie volume] $\gg 1$
- Hidden photon field $\vec{X} = \bar{X}\vec{n}_X \sin(m_X t + \alpha)$
- DM density $\rho_{\mathrm{DM}} = \frac{1}{2} m_X^2 \bar{X}^2$ (local $\rho_{\mathrm{DM}} \sim 0.45\ \mathrm{GeV/cm^3}$)
- Effective E-field $\vec{E}^{(X)} := -\epsilon \partial_t \vec{X} = \bar{E}^{(X)}\vec{n}_X \cos(m_X t + \alpha)$; $\bar{E}^X = \epsilon\sqrt{2\rho_{\mathrm{DM}}}$

Coherent packet of hidden photons



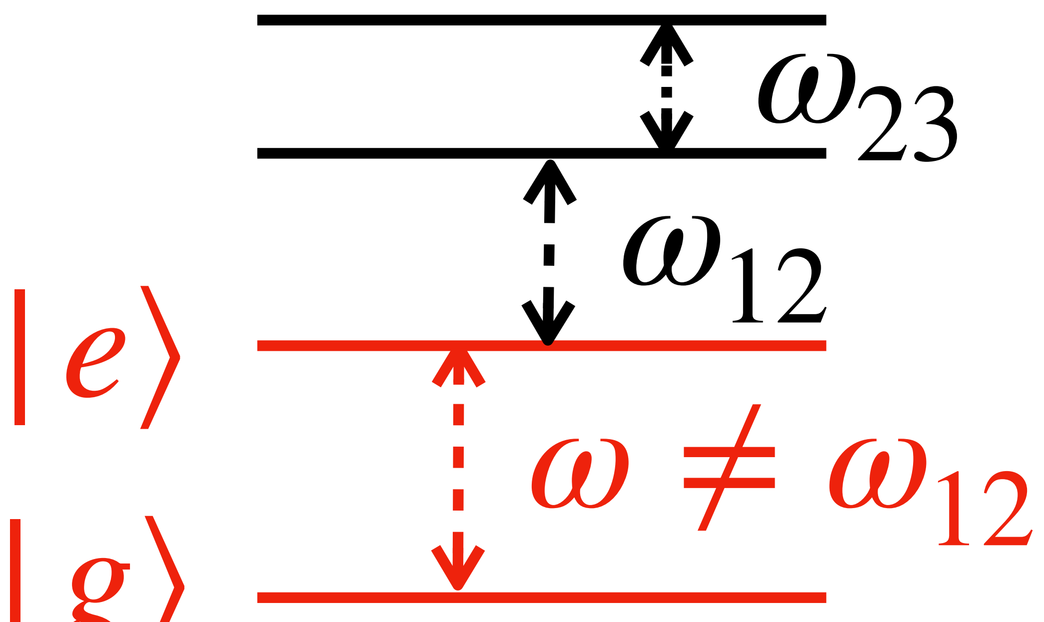
Transmon qubit as DM sensor



Hamiltonian

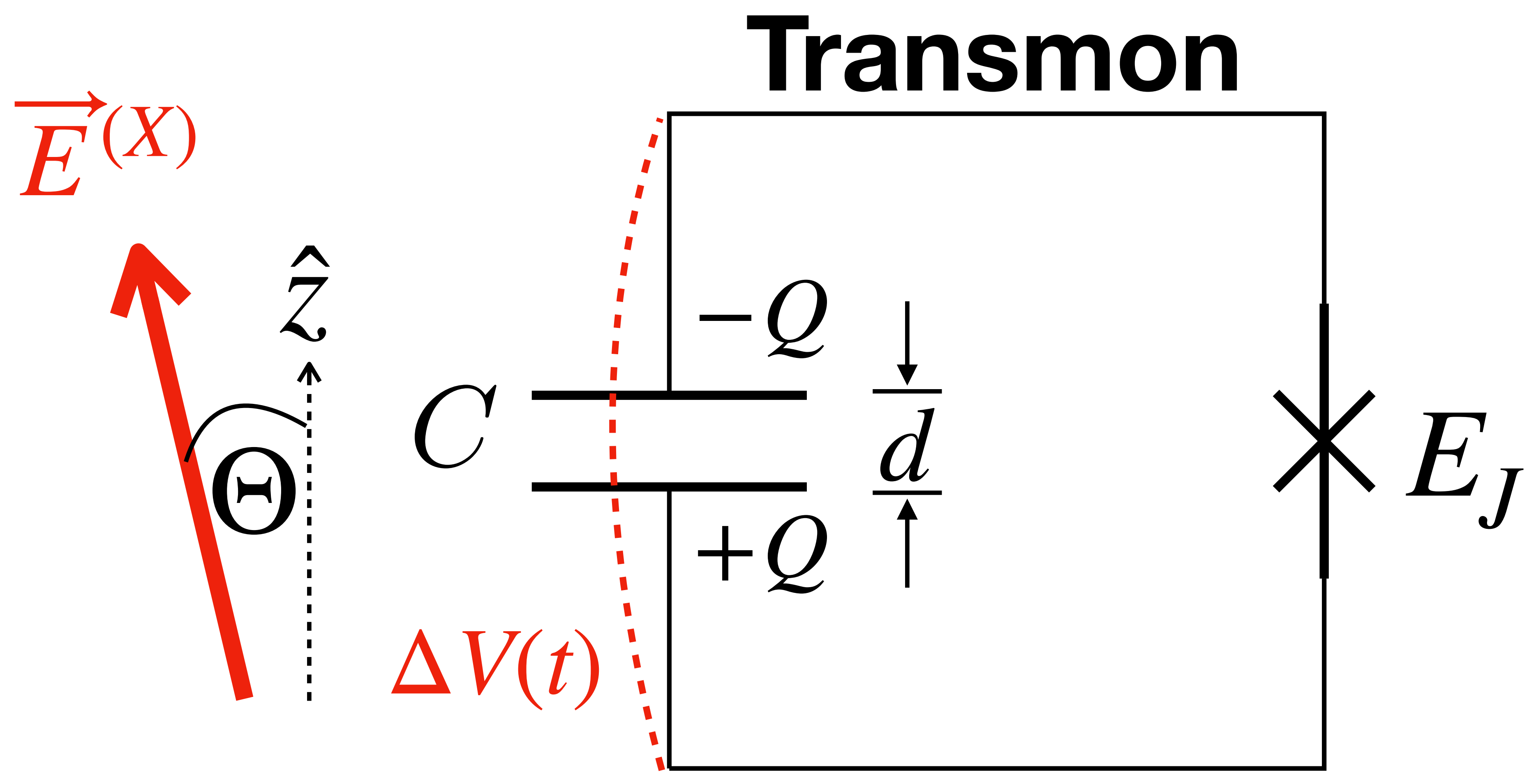
$$H_0 = Q^2/2C - E_J \cos\theta \,;\, \theta \equiv \phi_1 - \phi_2$$

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



Gap not the same

Transmon qubit as hidden photon DM sensor



Induced voltage on capacitor:

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

Interaction hamiltonian:

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

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

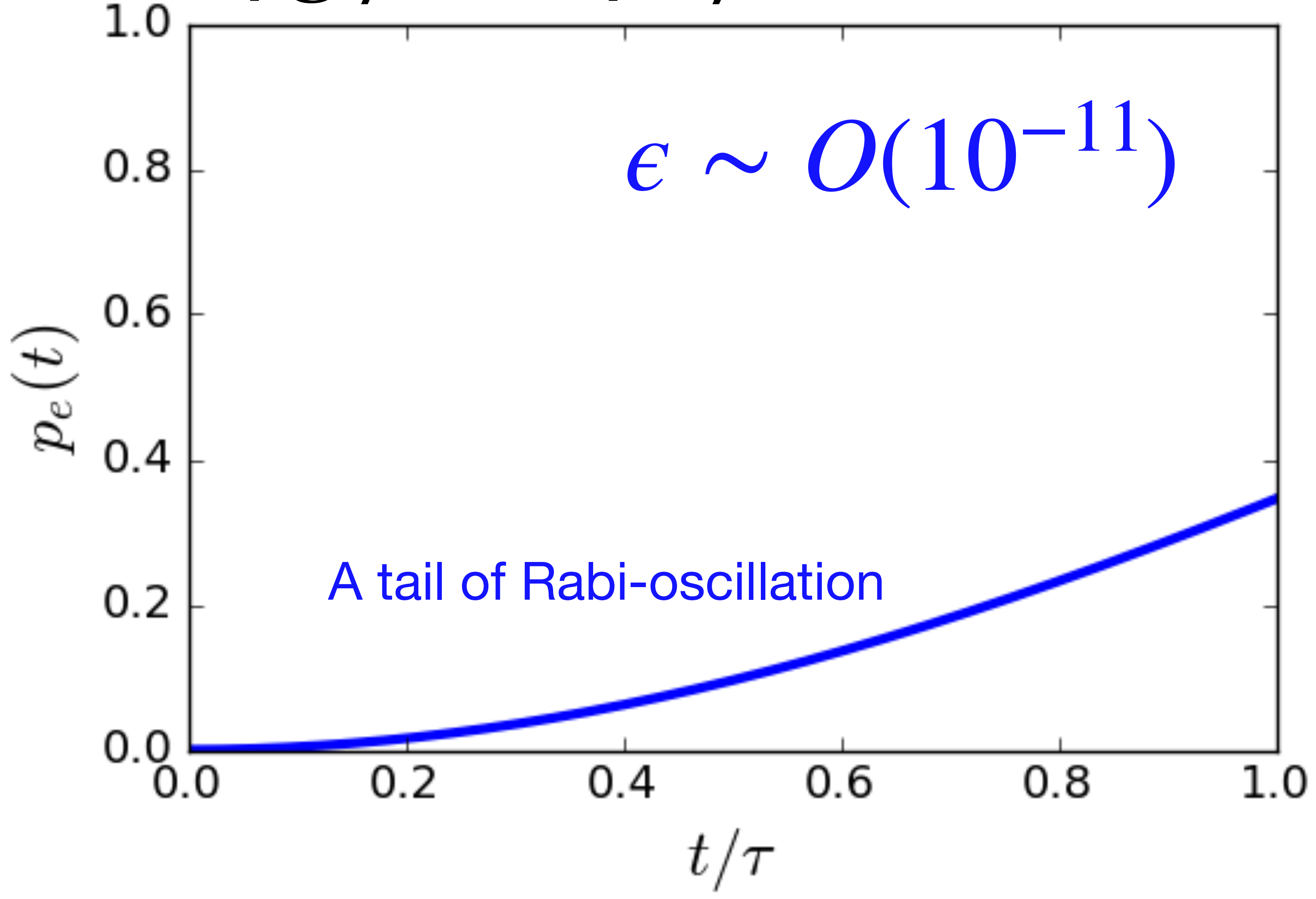
For $m_X = \omega$, the Schrödinger Eq. is

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

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

Qubit direct excitation due to external field

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



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

Gradual growth of probability

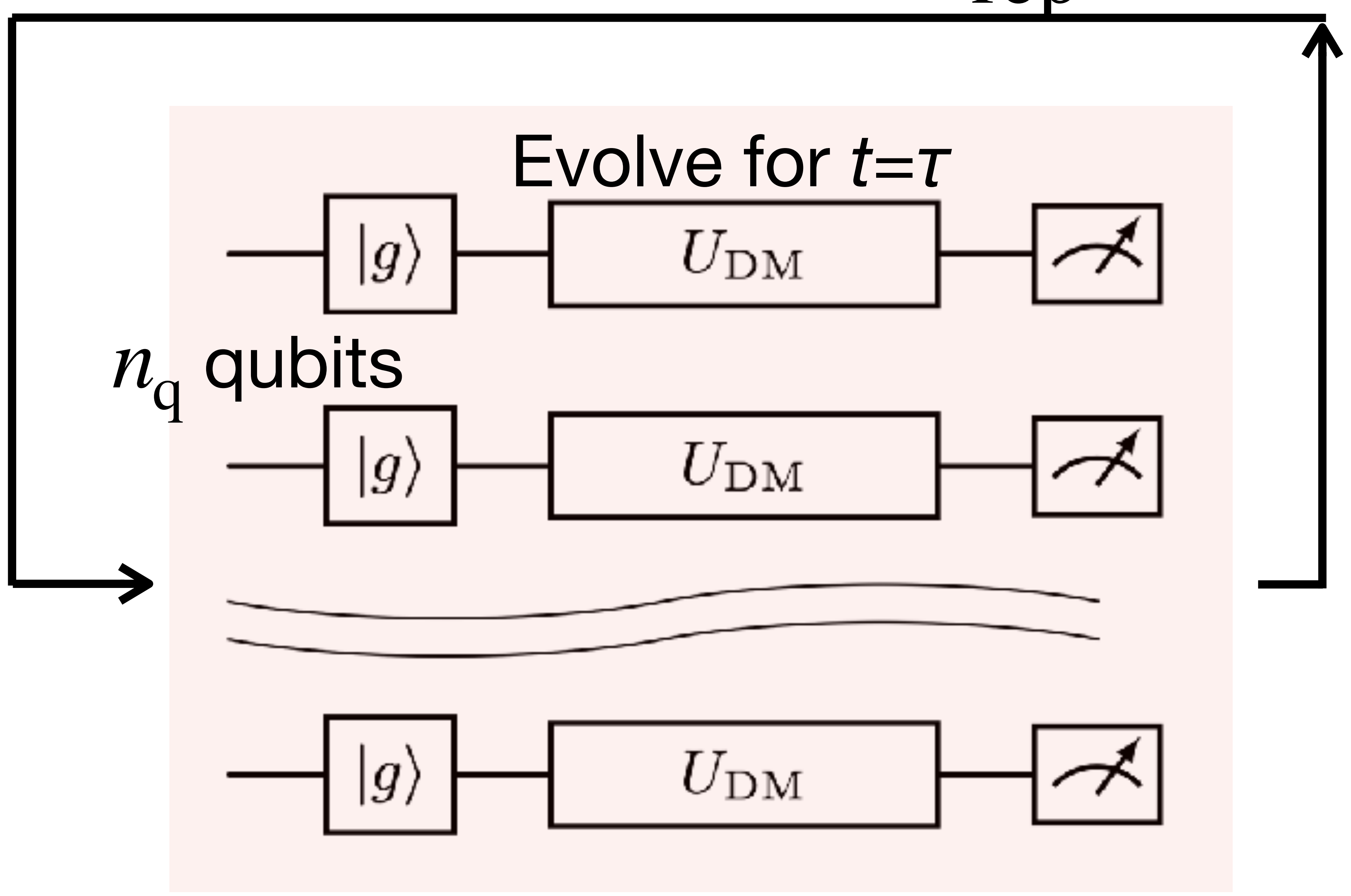
$$;\, \tau = \min\{\tau_{\rm DM}, \tau_{\rm qubit}\} \sim 100\ \mu s$$

$$p_e(\tau) \simeq 0.12 \times \cos^2\Theta \left(\frac{\epsilon}{10^{-11}}\right)^2 \left(\frac{f}{1\ \mathrm{GHz}}\right) \times \left(\frac{\tau}{100\ \mu\mathrm{s}}\right)^2 \left(\frac{C}{0.1\ \mathrm{pF}}\right) \left(\frac{d}{100\ \mu\mathrm{m}}\right)^2 \left(\frac{\rho_{\rm DM}}{0.45\ \mathrm{GeV/cm^3}}\right)$$

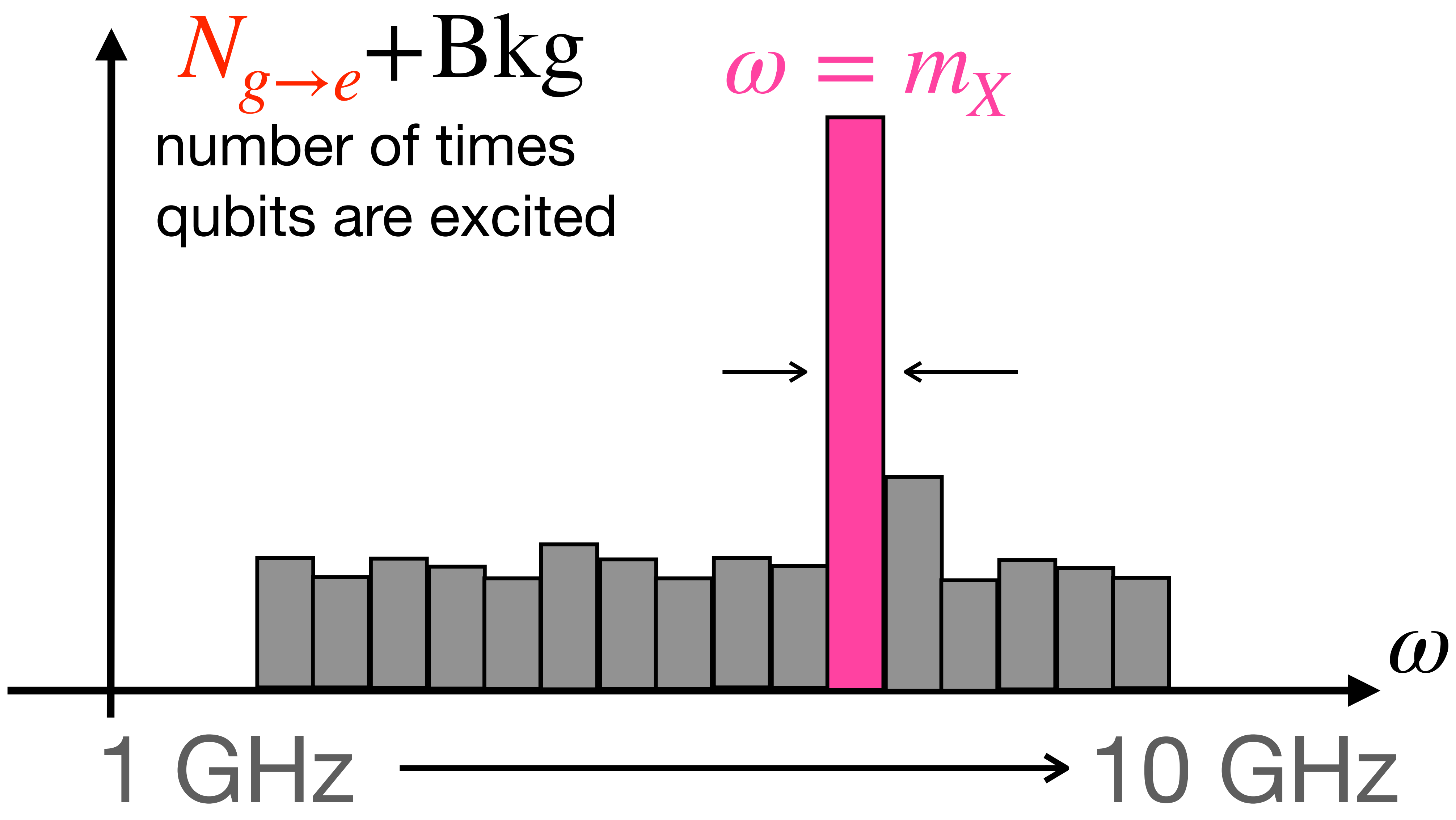
Process of measurement

For each frequency bin

Repetitions N_{rep}



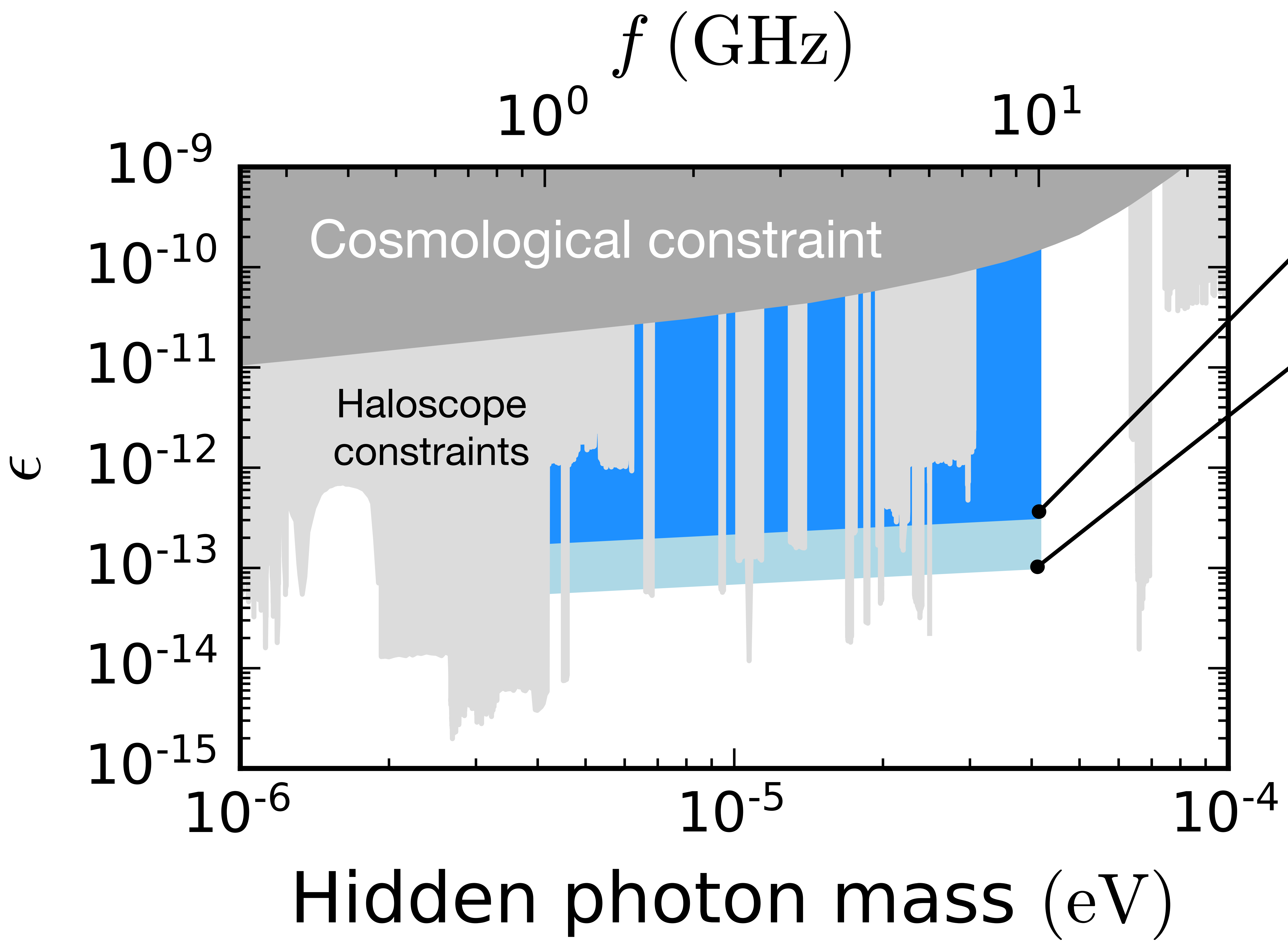
$$N_{g\to e} \simeq N_{\mathrm{rep}} n_{\mathrm{q}} \delta^2 \propto n_{\mathrm{q}}$$



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

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

Sensitivity plot



readout error 0.1%

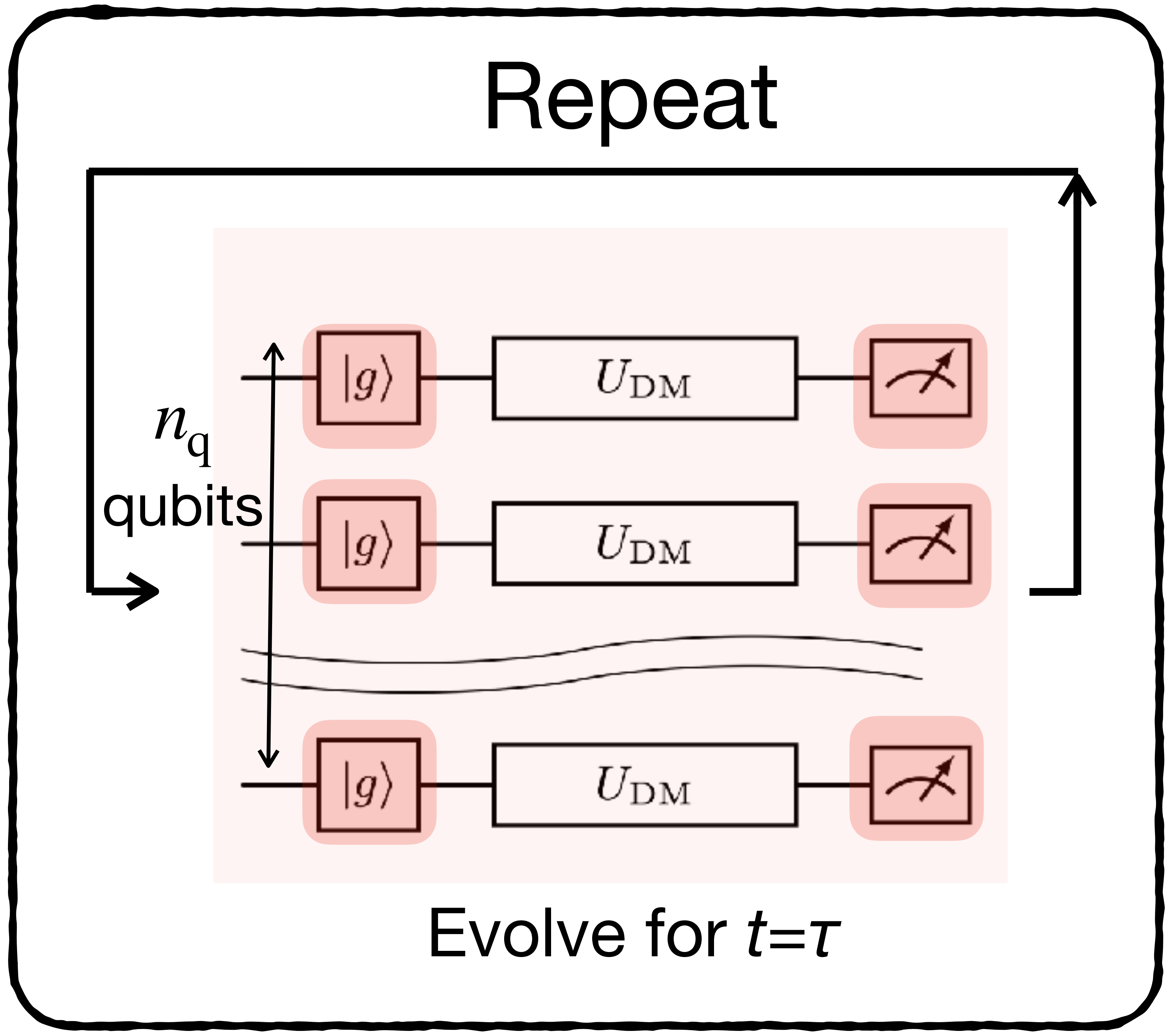
- 10^6 bins
- Each m_X take time ~ 15 sec
- Total measurement time ~ 1 year

Enhancement using quantum computation

[Chen, Fukuda, Inada, Moroi, Nitta, TS, *arXiv: 2311.10413*]

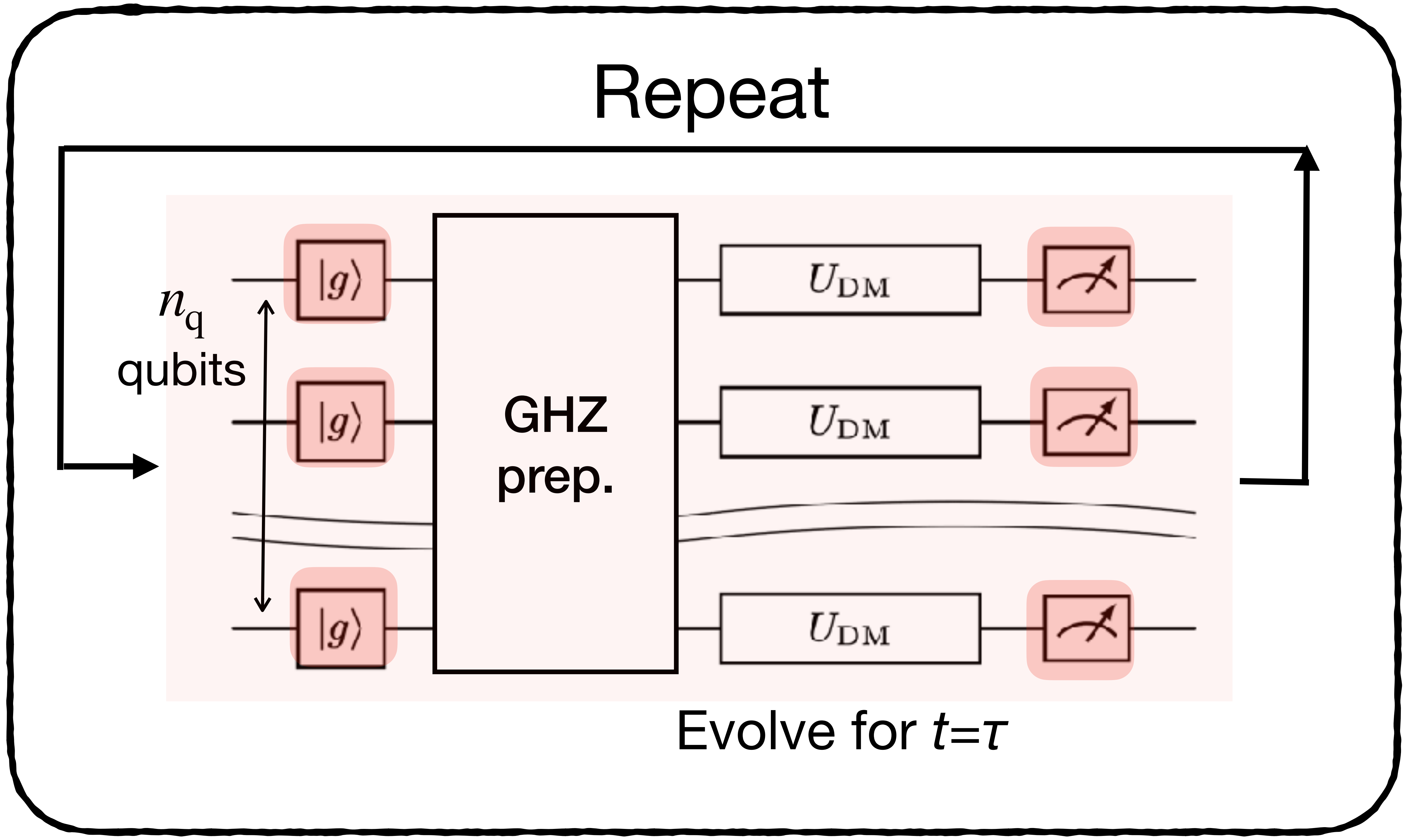
Quantum enhancement by quantum circuits

Individual measurement



(2) arXiv: 2311.10413

Using quantum circuit



The number that qubits are excited

$$N_{\text{signal}} \propto n_{\text{q}}$$

The number of DM signal*

$$N_{\text{signal}} \propto n_{\text{q}}^2$$

Accumulated phase with the effect of DM

For $m_X = \omega$, the resonant evolution is

$$\frac{d}{dt}\begin{pmatrix}\psi_g \\ \psi_e\end{pmatrix} = \begin{pmatrix} 0 & ie^{-i\alpha}\eta \\ ie^{i\alpha}\eta & 0 \end{pmatrix}\begin{pmatrix}\psi_g \\ \psi_e\end{pmatrix} \Rightarrow \; U_{\rm DM} \simeq \begin{pmatrix} 1 & ie^{-i\alpha}\eta t \\ ie^{i\alpha}\eta t & 1 \end{pmatrix}$$

For $\alpha = 0$: eigenstate $U_{\rm DM}|\pm\rangle = e^{\pm i\delta}|\pm\rangle$ with $\delta \equiv \eta\tau$,

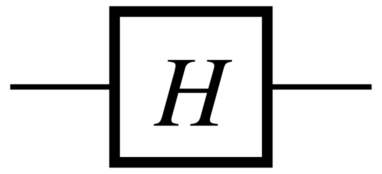
For $n_{\rm q}$ qubit state

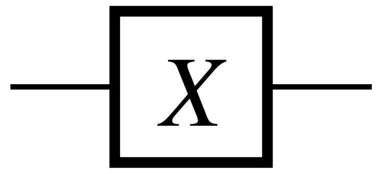
Phase accumulated coherently !

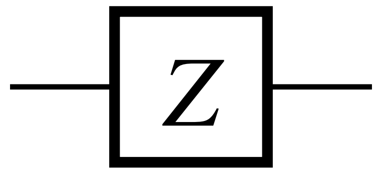
$$U_{\rm DM}^{\alpha=0}|\pm\rangle^{\otimes n_{\rm q}} = e^{\pm i n_q \delta}|\pm\rangle^{\otimes n_{\rm q}}$$

$;|\pm\rangle \equiv (|g\rangle \pm |e\rangle)/\sqrt{2}.$

Quantum computation basics

- Hadamard: 

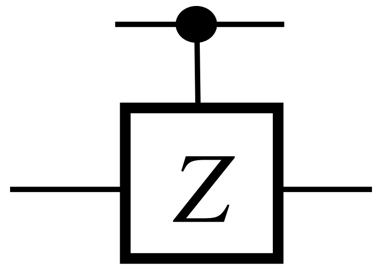
$\Rightarrow H|g\rangle = |+\rangle, H|e\rangle = |-\rangle\,;\ |\pm\rangle \equiv (|g\rangle \pm |e\rangle)/\sqrt{2}.$
- X gate: 

$\Rightarrow \quad X = |g\rangle\langle e| + |e\rangle\langle g|$
- Z gate: 

$\Rightarrow \quad Z = |g\rangle\langle g| - |e\rangle\langle e| = |+\rangle\langle -| + |-\rangle\langle +|$
- Controlled NOT:

$$\Rightarrow \quad |g\rangle\langle g| \otimes I + |e\rangle\langle e| \otimes X$$

- Controlled Z:



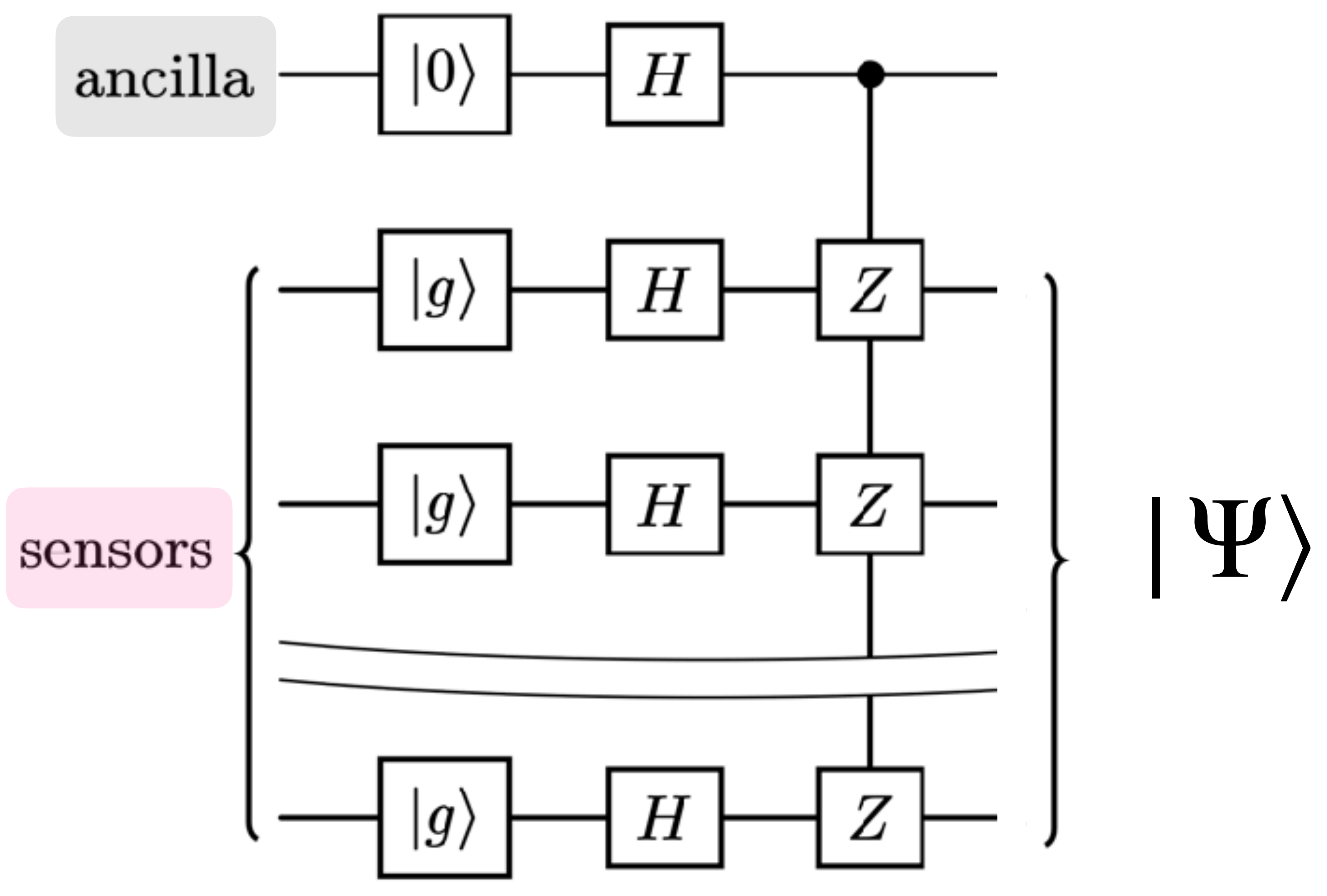
$$\Rightarrow \quad |g\rangle\langle g| \otimes I + |e\rangle\langle e| \otimes Z$$

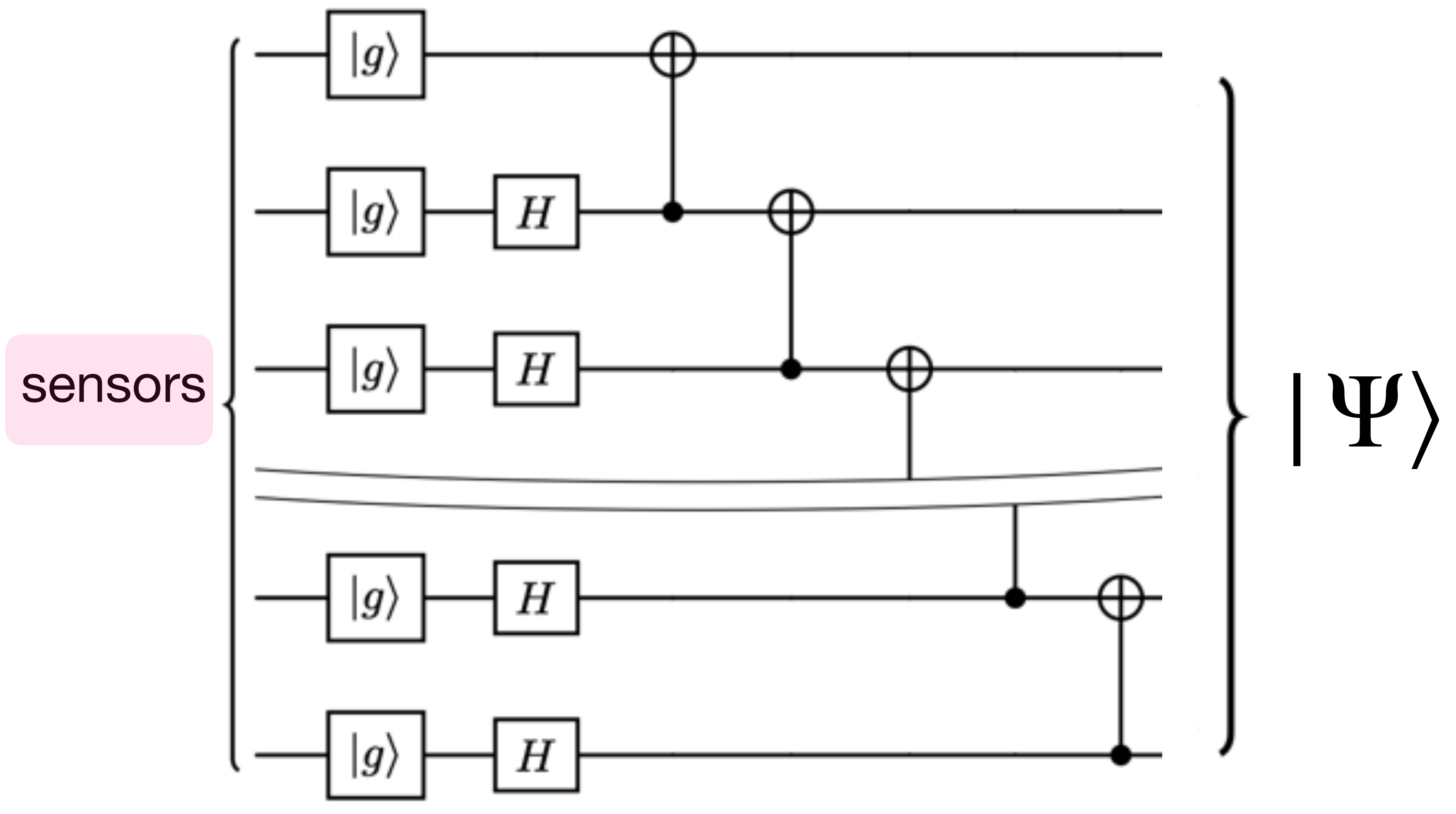
GHZ state

GHZ state in Hadamard basis (highly entangled state)

$$|\Psi\rangle = |+\rangle^{\otimes n_\mathrm{q}} + |-\rangle^{\otimes n_\mathrm{q}} \quad \Rightarrow \quad U_\mathrm{DM}^{\alpha=0}|\Psi\rangle = e^{in_\mathrm{q}\delta}|+\rangle^{\otimes n_\mathrm{q}} + e^{-in_\mathrm{q}\delta}|-\rangle^{\otimes n_\mathrm{q}}$$

Example circuit to prepare the GHZ state in Hadamard basis





DM signal = Observing odd excitations

Prep. $|\Psi\rangle = |+\rangle^{\otimes n_q} + |-\rangle^{\otimes n_q}$

$$U_{\rm DM}^{\alpha=0}|\Psi\rangle = e^{in_q\delta}|+\rangle^{\otimes n_q} + e^{-in_q\delta}|-\rangle^{\otimes n_q}$$

Induced by effect of DM

$$= \cos(n_q\delta)(|+\rangle^{\otimes n_q} + |-\rangle^{\otimes n_q}) + i\sin(n_q\delta)(|+\rangle^{\otimes n_q} - |-\rangle^{\otimes n_q})$$

Contain only even $|e\rangle$ states

$Z_1Z_2\ldots Z_n = +1$

Contain only odd $|e\rangle$ states

$Z_1Z_2\ldots Z_n = -1$

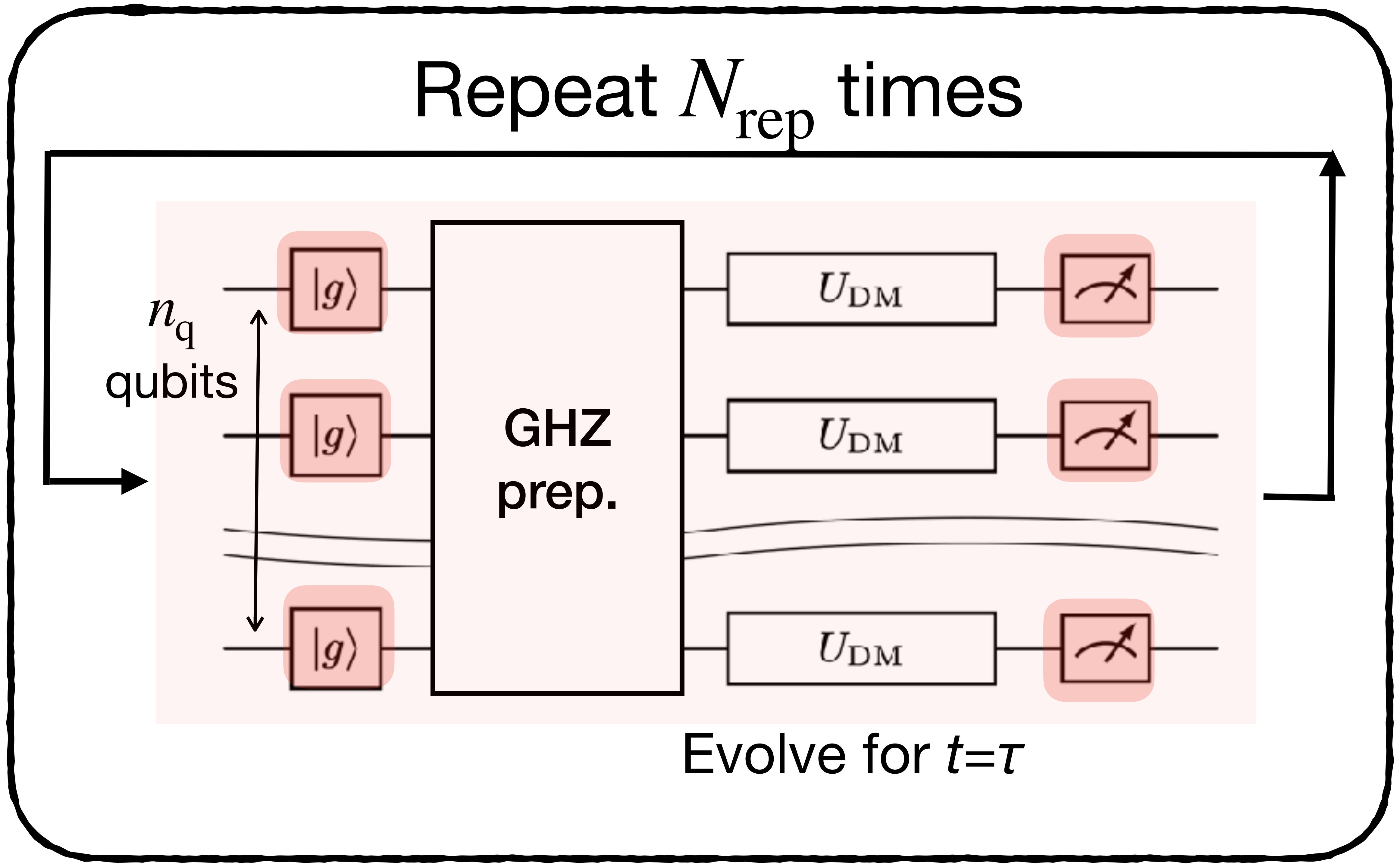
DM signal = observing odd qubits excited; Prob. $p_{\rm odd} = \sin^2(n_q\delta) \simeq (n_q\delta)^2$

For general α: $p_{\rm odd} \simeq (n_q\delta)^2\cos^2\alpha$

Quantum enhancement by quantum circuits

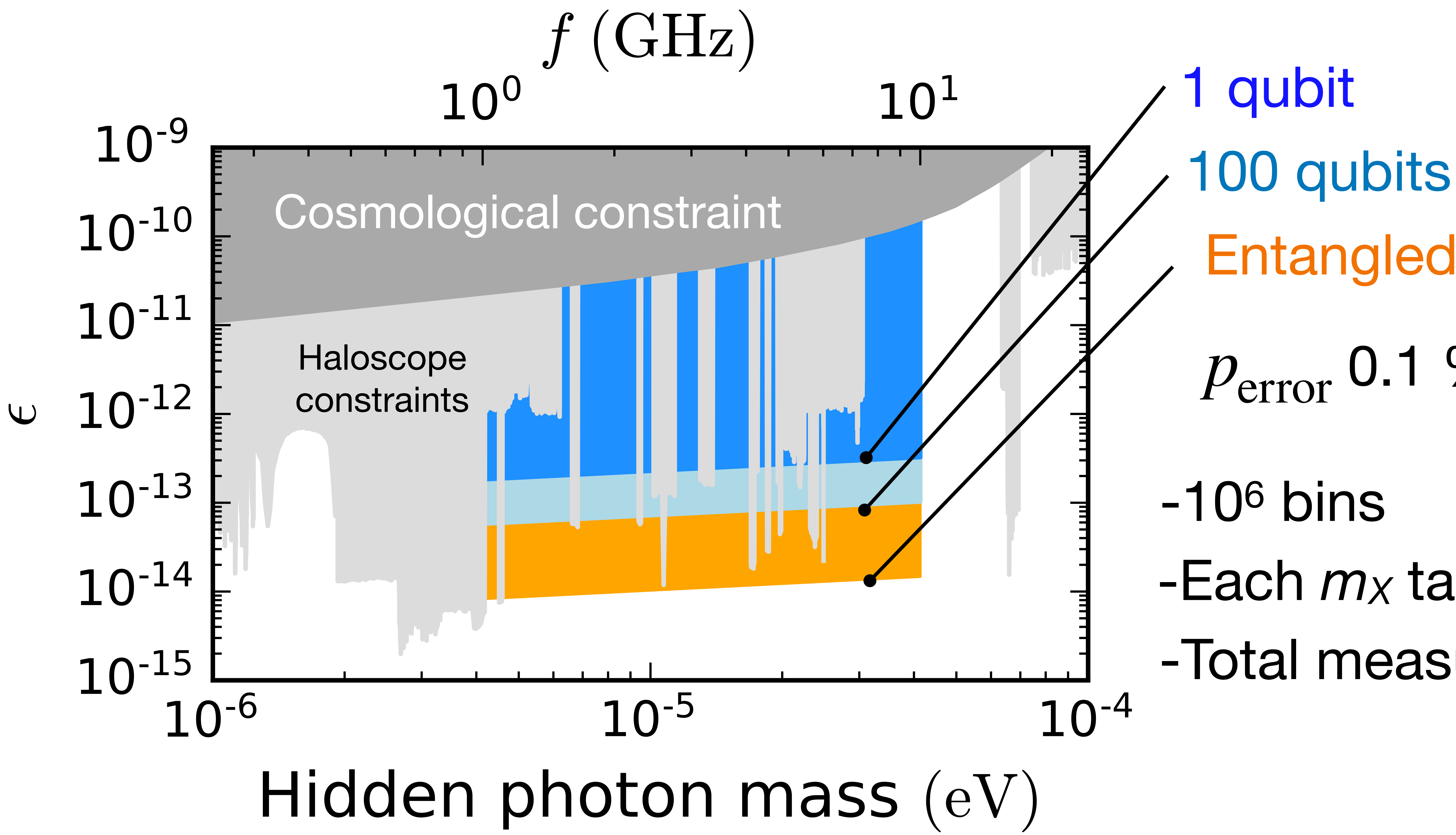
(2) arXiv: 2311.10413

Using quantum circuit



- Signal with $N_{\rm rep}$ repetition of experiment
  - $N_{\rm signal} = \frac{1}{2} n_{\rm q}^2 \delta^2 N_{\rm rep} \propto n_{\rm q}^2$
- Noise with $N_{\rm rep}$ repetition of experiment
  - $\mathrm{Bkg} = p_{\rm noise} n_{\rm q} N_{\rm rep}$
- Significance $\sigma = N_{\rm signal}/\sqrt{\mathrm{Bkg}}$ for claiming detection

Sensitivity plot (Hidden photon)



p_{error} 0.1 %

-10^6 bins

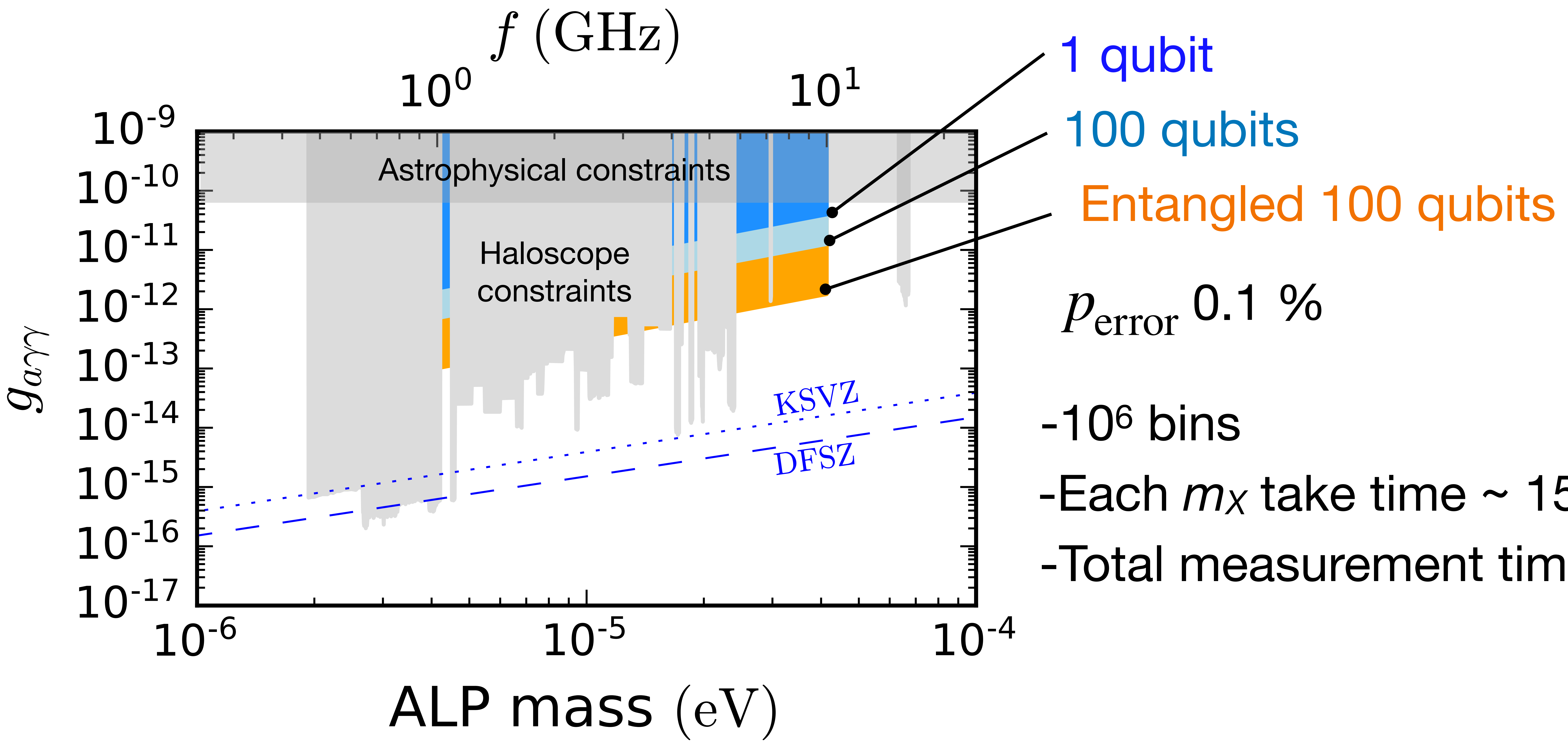
-Each m_X take time ~ 15 sec

-Total measurement time ~ 1 year

Summary

- Coherent wave-like dark matter can excite qubits, resulting in detectable signal
- Transmon has good sensitivity, reaching unexplored parameter regions of hidden photon dark matter
- Enhancement with the quantum circuit is possible
- Extension to axion detection

Sensitivity plot (Axions)



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