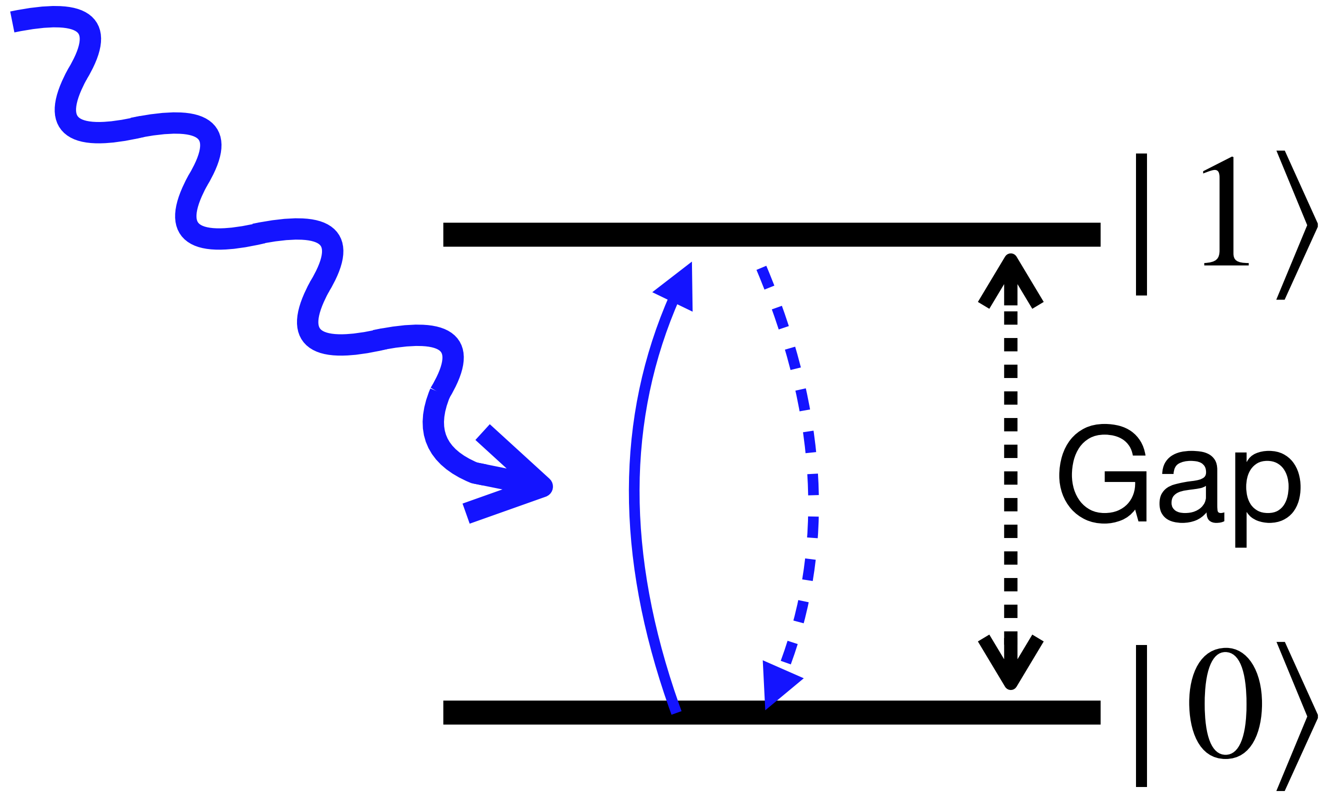
Quantum circuit for DM enhanced signal detection: DM wind probe

Ongoing work: Hajime Fukuda (UTokyo), Yuichiro Matsuzaki (Chuo U), TS

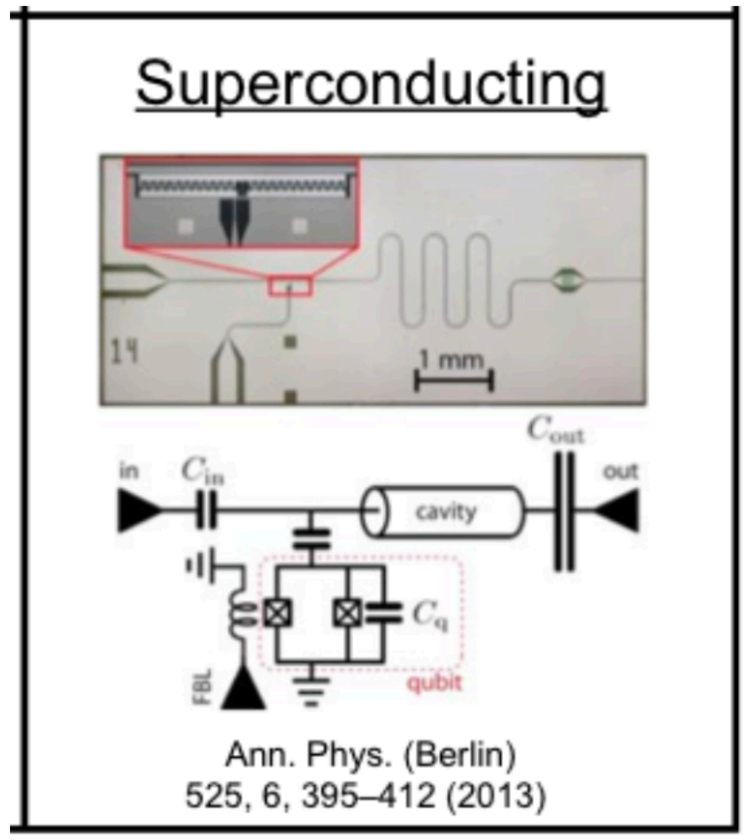
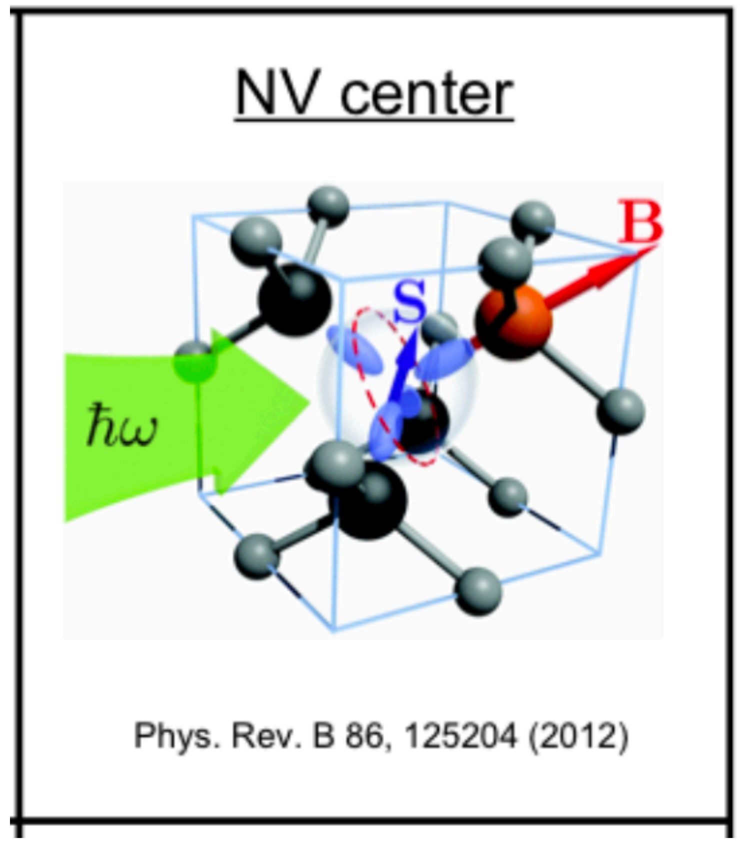
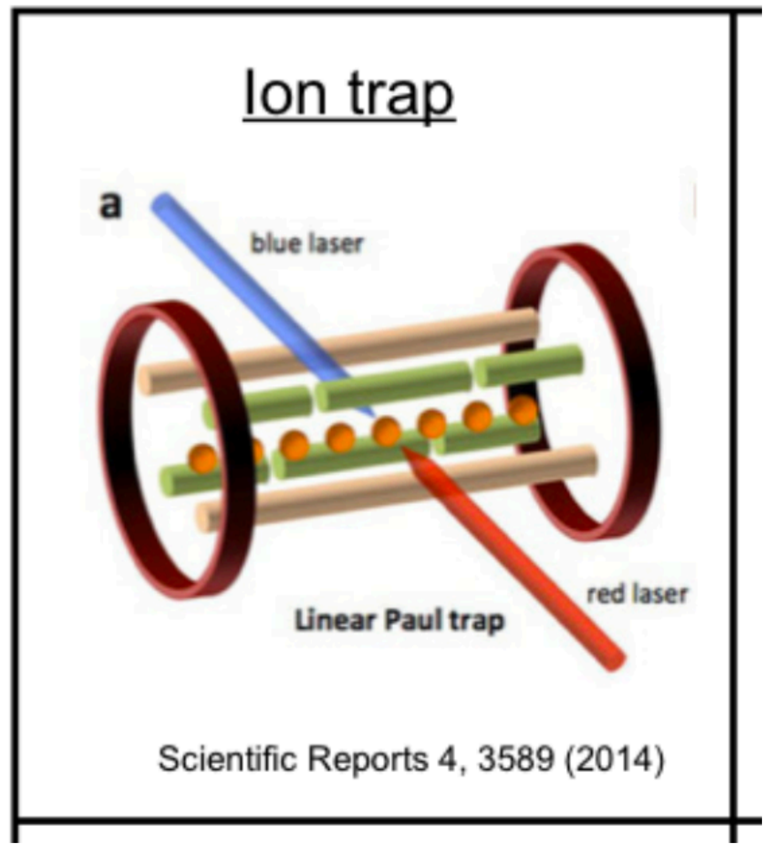
Thanaporn Sichanugrist, UTokyo, The Frontier of Particle Physics 2025

Qubit can be good DM quantum sensor

Wave-like dark matter



State change due to DM

Nitta-san's Talk	Chigusa-san's Talk	Ito-san's Talk
		
Chen et al., PRL 131 (2023) 21, 211001	Chigusa, *JHEP* 03 (2025) 083	Ito et al, *JHEP 02 (2024) 124*

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

Quantum circuit can help enhance sensitivity

Using quantum circuit, one can enhance and obtain:

- **DM Coupling** (improve scaling with same-order of noises)

  S. Chen, H. Fukuda, T. Inada, T. Moroi, T. Nitta, TS, *PRL 133 (2024) 2, 021801*
  A. Ito, R. Kitano, W. Nakano, R. Takai, *JHEP 02 (2024) 124*

- **DM Velocity** (outperform classical correlation meas.)

  ongoing work with Hajime Fukuda and Yuichiro Matsuzaki

Quantum circuit can help enhance sensitivity

Using quantum circuit, one can enhance and obtain:

- **DM Coupling** (improve scaling with same-order of noises)

  S. Chen, H. Fukuda, T. Inada, T. Moroi, T. Nitta, TS, *PRL 133 (2024) 2, 021801*
  A. Ito, R. Kitano, W. Nakano, R. Takai, *JHEP 02 (2024) 124*

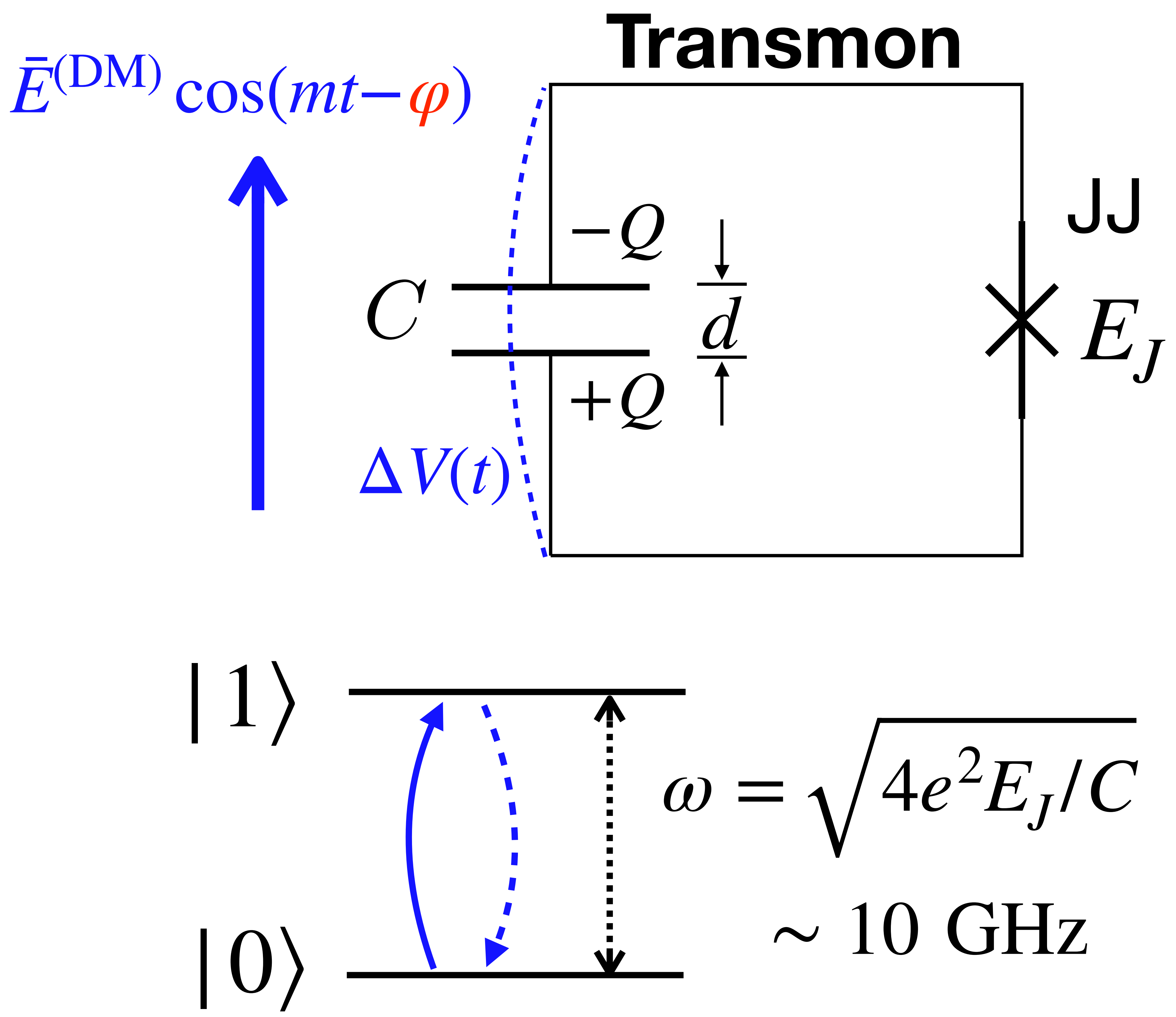
I will talk about this today!!

- **DM Velocity** (outperform classical correlation meas.)

  ongoing work with Hajime Fukuda and Yuichiro Matsuzaki

As an example, transmon qubit as DM sensor

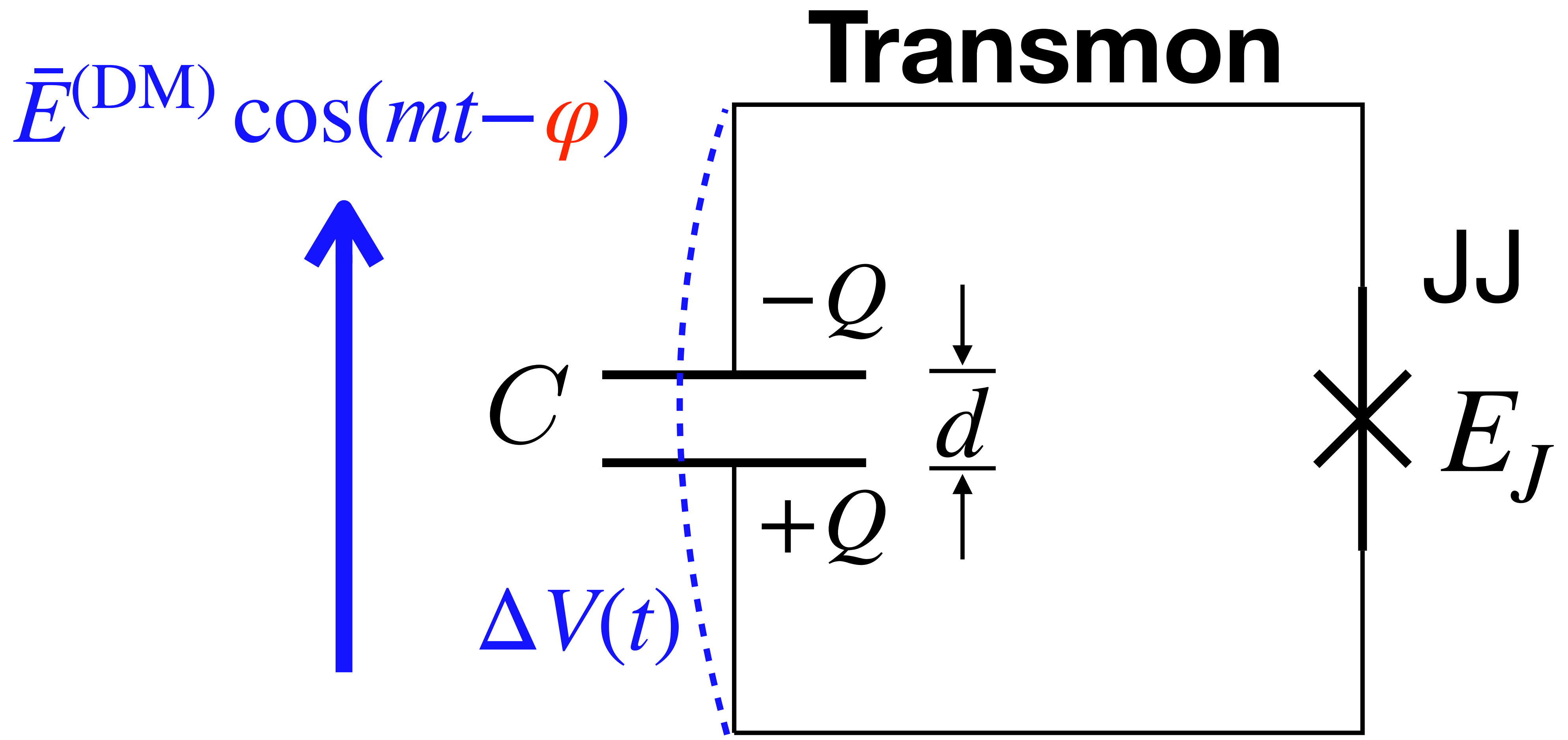
S. Chen, H. Fukuda, T. Inada, T. Moroi, T. Nitta, TS, *PRL 131 (2023) 21, 211001*

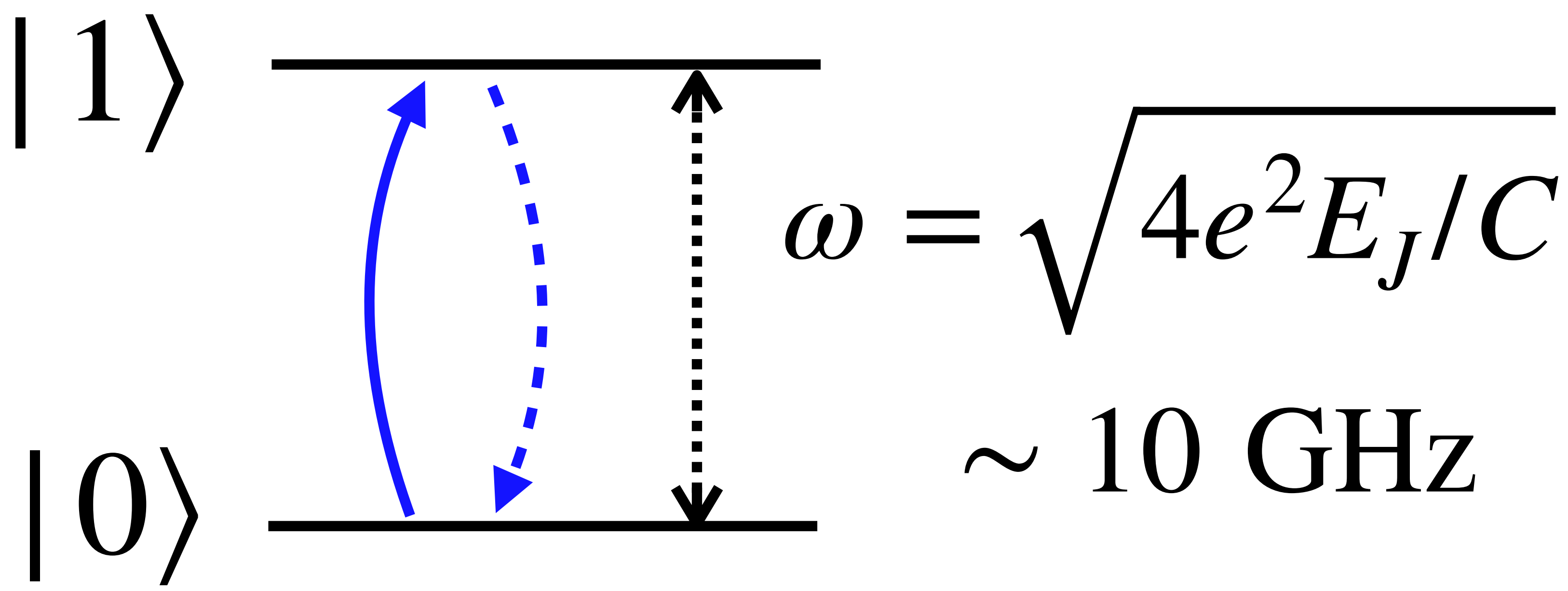


Direct excitation due to DM

As an example, transmon qubit as DM sensor

S. Chen, H. Fukuda, T. Inada, T. Moroi, T. Nitta, TS, *PRL 131 (2023) 21, 211001*





Direct excitation due to DM

$$H = \omega|1\rangle\langle 1|$$
$$-2\epsilon\cos(m_{\mathrm{DM}}t-\varphi)(|0\rangle\langle 1| + |1\rangle\langle 0|)$$

with $\epsilon \equiv \sqrt{\omega C}d\bar{E}^{(\mathrm{DM})}/2\sqrt{2}$

For resonant condition $m_{\mathrm{DM}} = \omega$

$$\frac{d}{dt}\begin{pmatrix}\psi_0(t)\\ \psi_1(t)\end{pmatrix} \simeq \begin{pmatrix}0 & ie^{-i\varphi}\epsilon\\ ie^{i\varphi}\epsilon & 0\end{pmatrix}\begin{pmatrix}\psi_0(0)\\ \psi_1(0)\end{pmatrix}$$

Measurement with qubits *Phys. Rev. Lett. 131 (2023) 21, 211001*

Evolution from zero state

Strength　Time　DM Phase

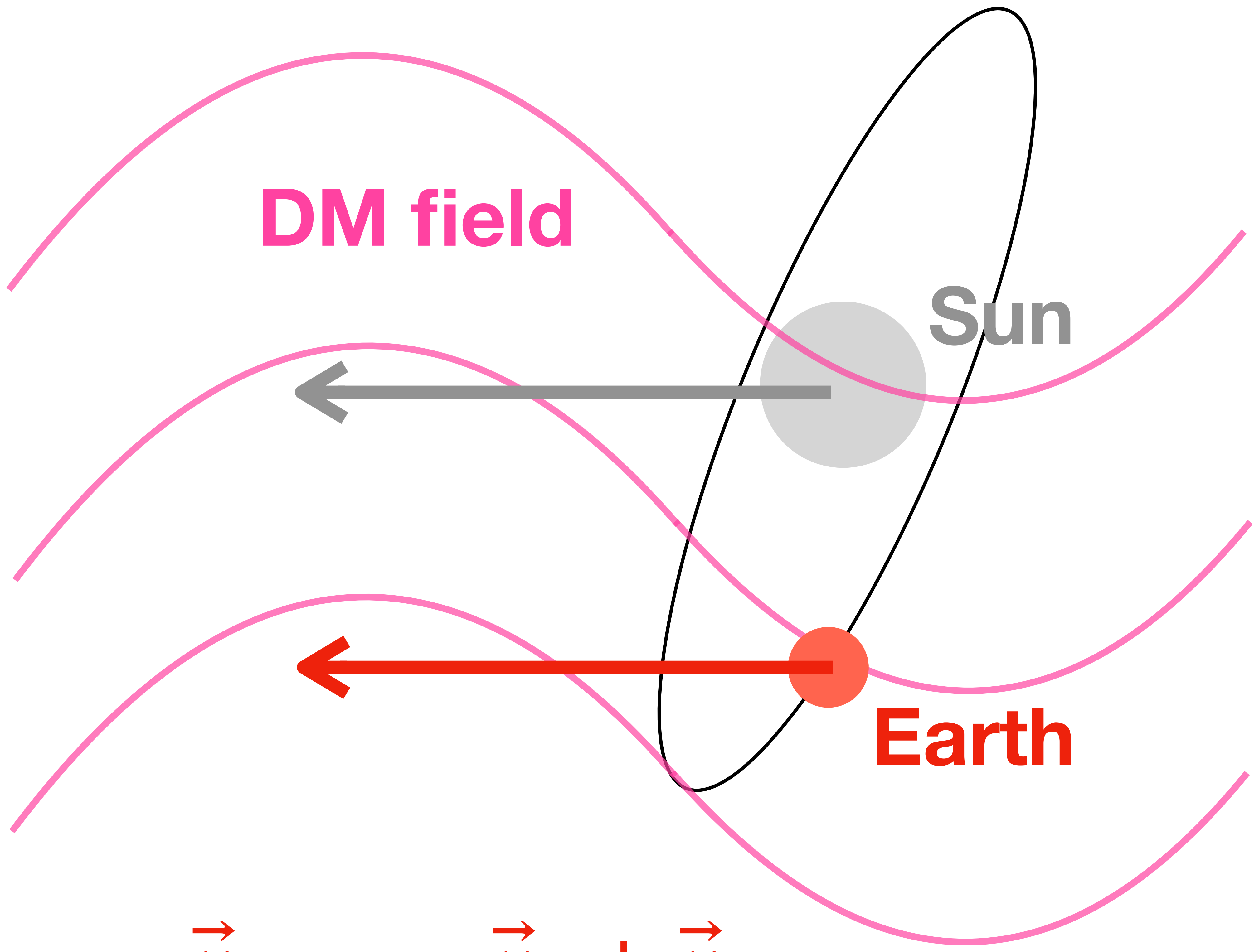
$$|0\rangle \longrightarrow |0\rangle + \epsilon\tau e^{i\varphi}|1\rangle$$

Propbability to be excited, e.g., transmon case:

$$p_1 = |\langle 1|\psi\rangle|^2 = (\epsilon\tau)^2 \simeq 0.12 \times \left(\frac{\text{kinetic mixing}}{10^{-11}}\right)^2 \left(\frac{\tau}{100\ \mu s}\right)^2 \left(\frac{C}{0.1\ \text{pF}}\right)$$

Probing DM wind

Earth pass through DM flux

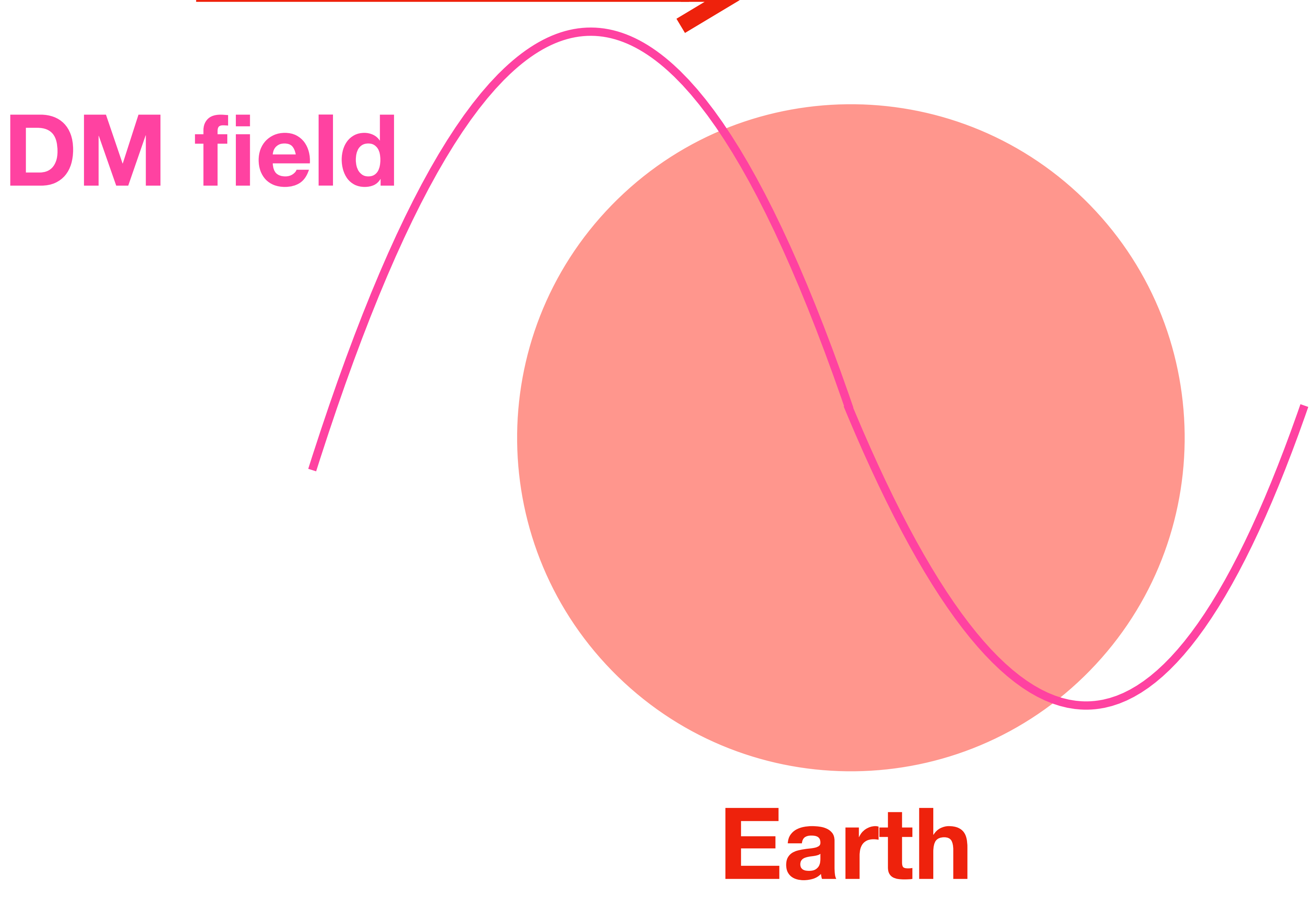


$\vec{v}_{\rm wind} = \vec{v}_0 + \vec{v}_{\rm Earth}$

Solar system velocity

Earth rest frame

$\vec{v}_{\rm wind} \simeq 230~{\rm km/s}$



Information of $\vec{v}_{\rm wind}$ embeded in qubit phase and can be probed

Probing DM wind with 2 qubits

$$\Phi_{DM}(x, t) \propto \cos(mt - m\vec{v}_{wind} \cdot \vec{x} + \varphi)$$

$\vec{v}_{wind} = \vec{v}_0 + \vec{v}_{Earth}$

Dispersion v_0

Qubit 1: position $\vec{x}_1$

$$|0\rangle \rightarrow |0\rangle + \epsilon\tau e^{i\varphi}|1\rangle$$

Qubit 2: position $\vec{x}_1 + \overrightarrow{\Delta r}$

$$|0\rangle \rightarrow |0\rangle + \epsilon\tau e^{i\varphi + \underline{im\vec{v}_{wind}\cdot\overrightarrow{\Delta r}}}|1\rangle$$

Visible for $mv_0\Delta r \sim 1$

suppressed for $mv_0\Delta r \gg 1$

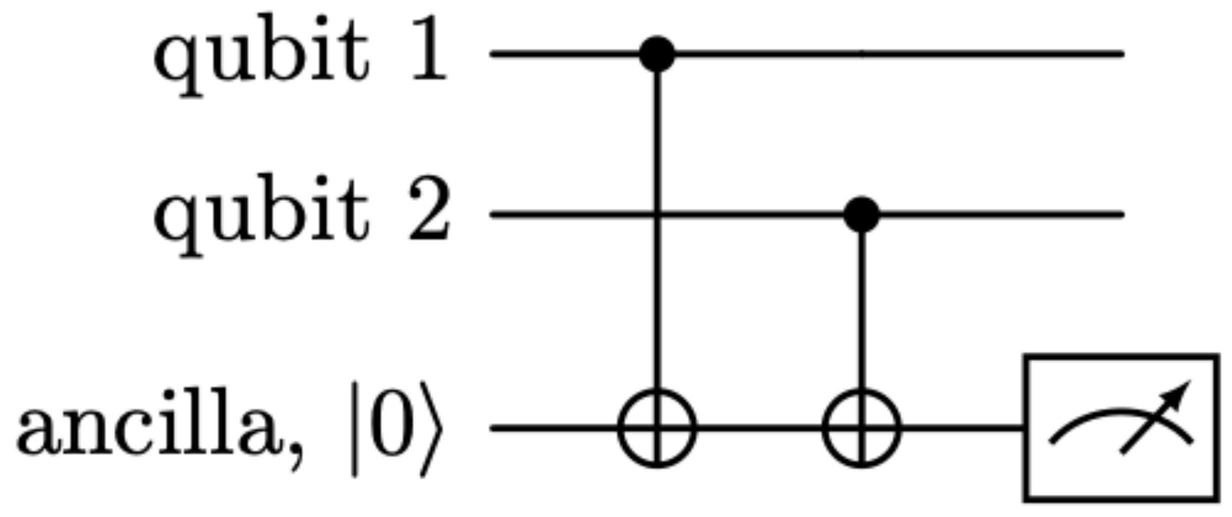
Extraction of the DM wind

(1) Teleport state: distant quantum states -> nearby position for data processing

Length 1-10 km is now already possible with high fidelity 80%

- Entangling NV centers at **1 km** [Hensen, B. J. et al. , Nature 526, 682–686 (2015).]
- Entangling single atoms over **33 km** [van Leent et al., Nature 609, 69 (2022)]

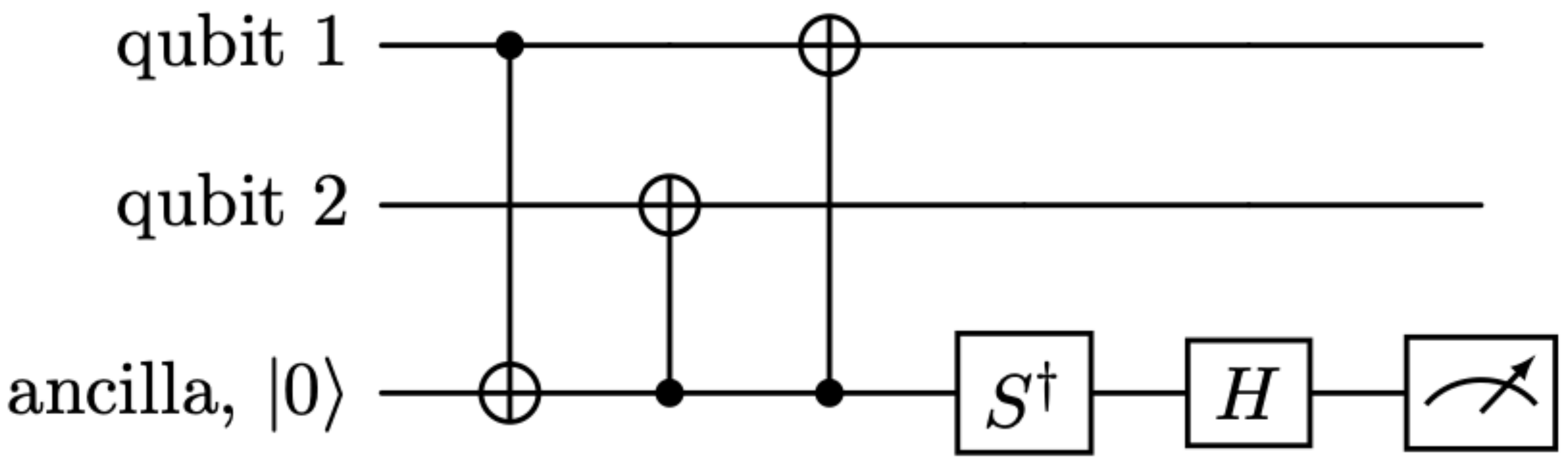
(2) Post-selection



$$P_1 = |10\rangle\langle 10| + |01\rangle\langle 01|$$

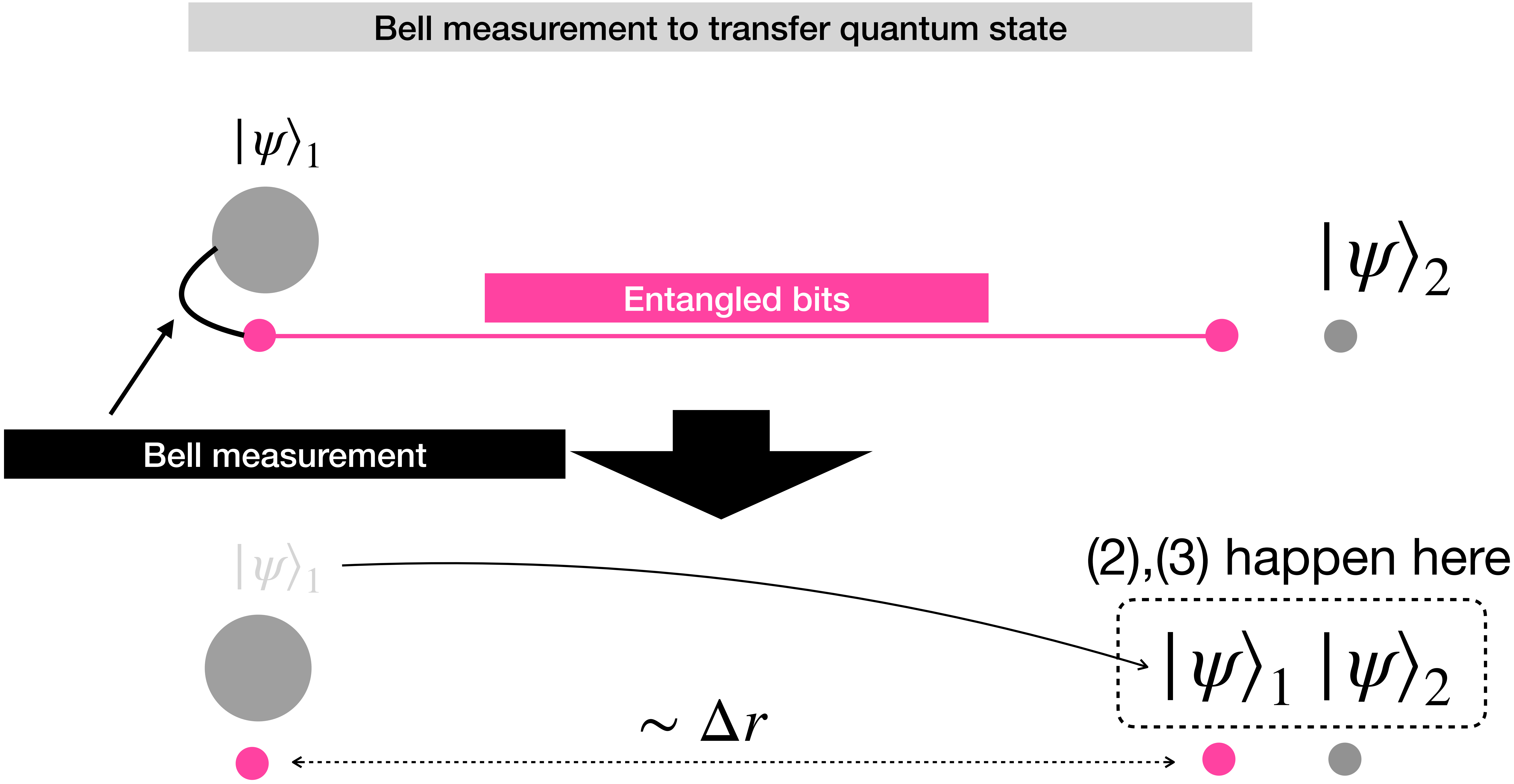
First qubit excited   second qubit excited

(3) Phase extraction circuit



$$M = -i|01\rangle\langle 10| + i|10\rangle\langle 01|$$

(1) Quantum teleportation



(2), (3) data processing

Phase shift due to spatial separation

Intital state: $|\psi\rangle = (|0\rangle + \epsilon\tau e^{i\varphi}|1\rangle) \otimes (|0\rangle + \epsilon\tau e^{i\varphi + im\vec{v}\cdot\overrightarrow{\Delta r}}|1\rangle)$

(2) **Select events where one qubit is excited** $P_1 = |01\rangle\langle 01| + |10\rangle\langle 10|$

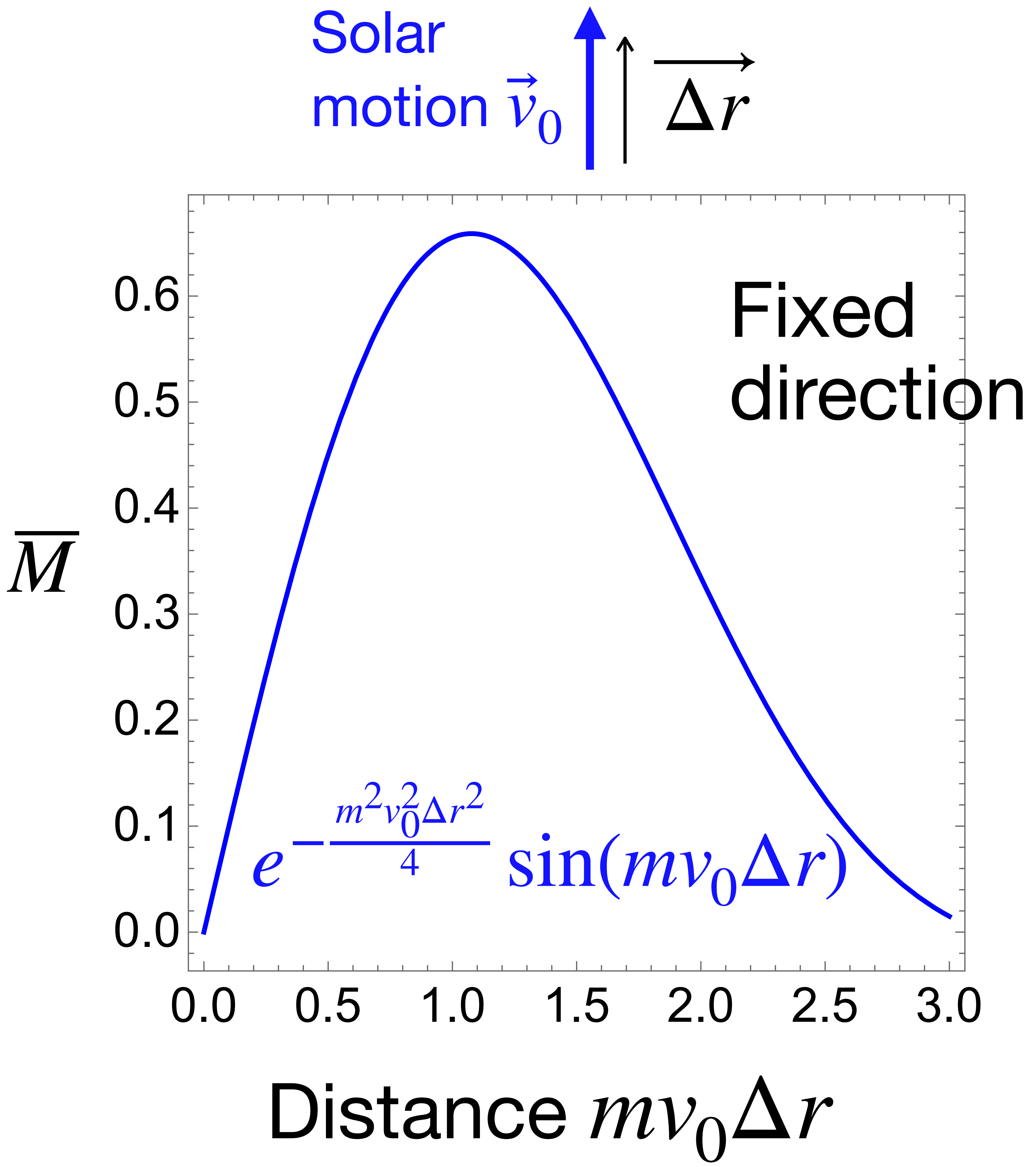
Probability $p_1 = 2(\epsilon\tau)^2 : |\psi\rangle \to |10\rangle + e^{im\vec{v}\cdot\overrightarrow{\Delta r}}|01\rangle$

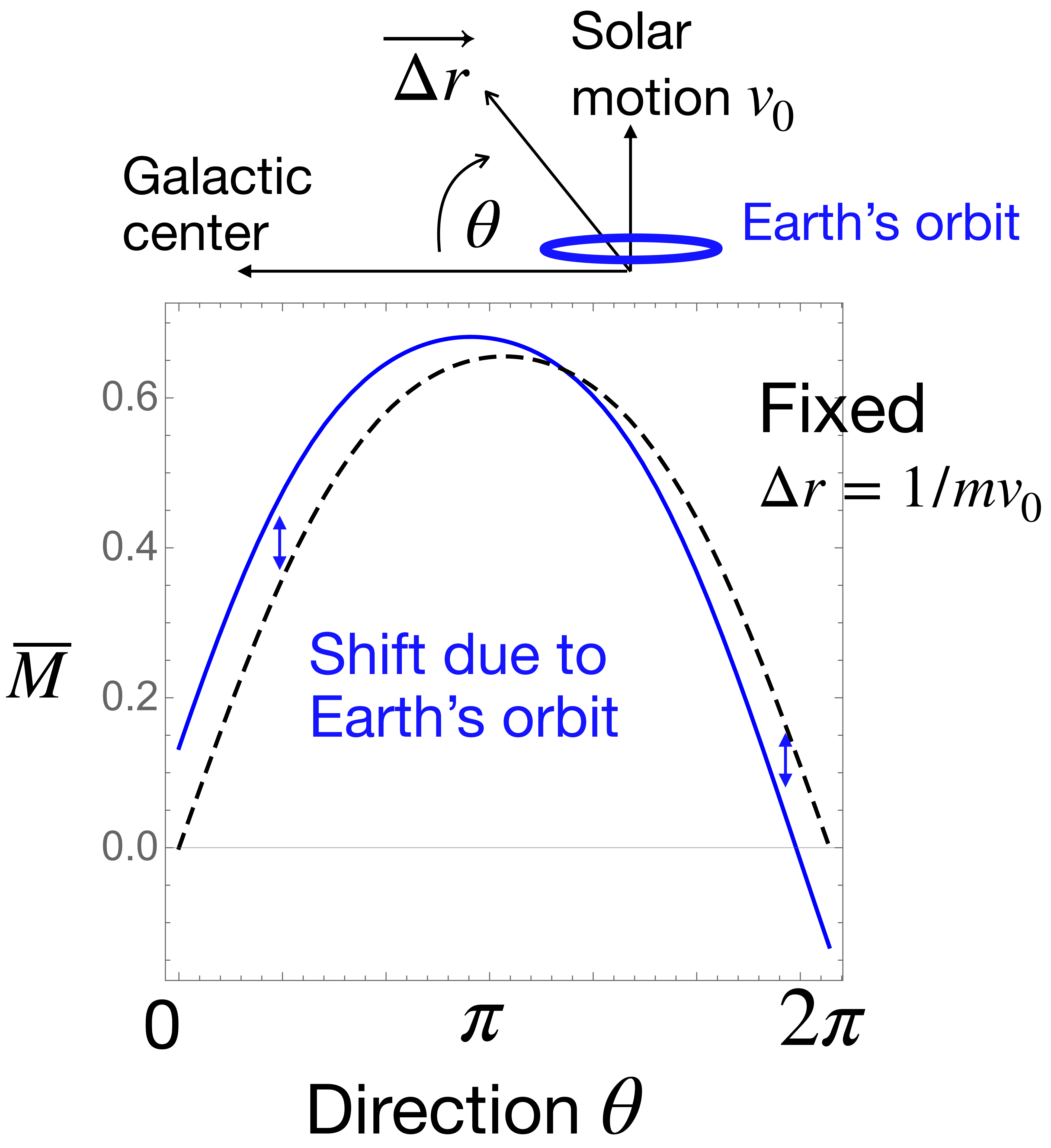
(3) **Expectation value of** $M = -i|01\rangle\langle 10| + i|10\rangle\langle 01|$

$$\overline{M} = \int d^3v\, f(\vec{v})\sin(m\vec{v}\cdot\overrightarrow{\Delta r}) \simeq e^{-\frac{m^2 v_0^2 \Delta r^2}{4}} \sin(m\vec{v}_{\rm wind}\cdot\overrightarrow{\Delta r})$$

Taking into account velocity dispersion

Shape of phase shift





Relation between δM and $\delta v_{\rm wind,i}$

Uncertainty of M

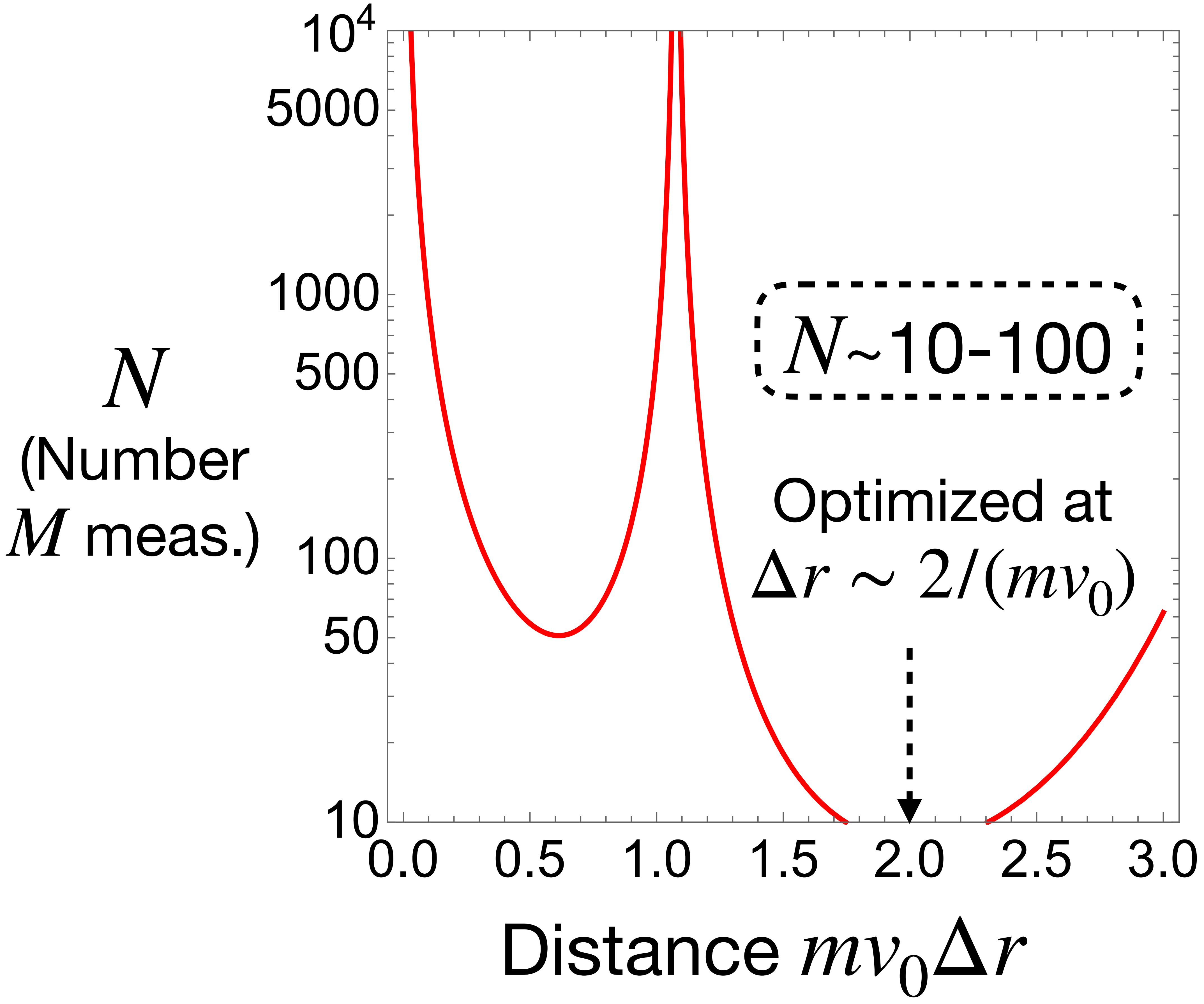
Velocity resolution $\delta v_i \equiv \frac{1}{\sqrt{N}} \frac{\delta M}{|dM/dv_i|}$ with $\delta M \equiv \sqrt{\langle M^2 \rangle - \langle M \rangle^2}$

Number of measurements

How sensitive of M to v_i

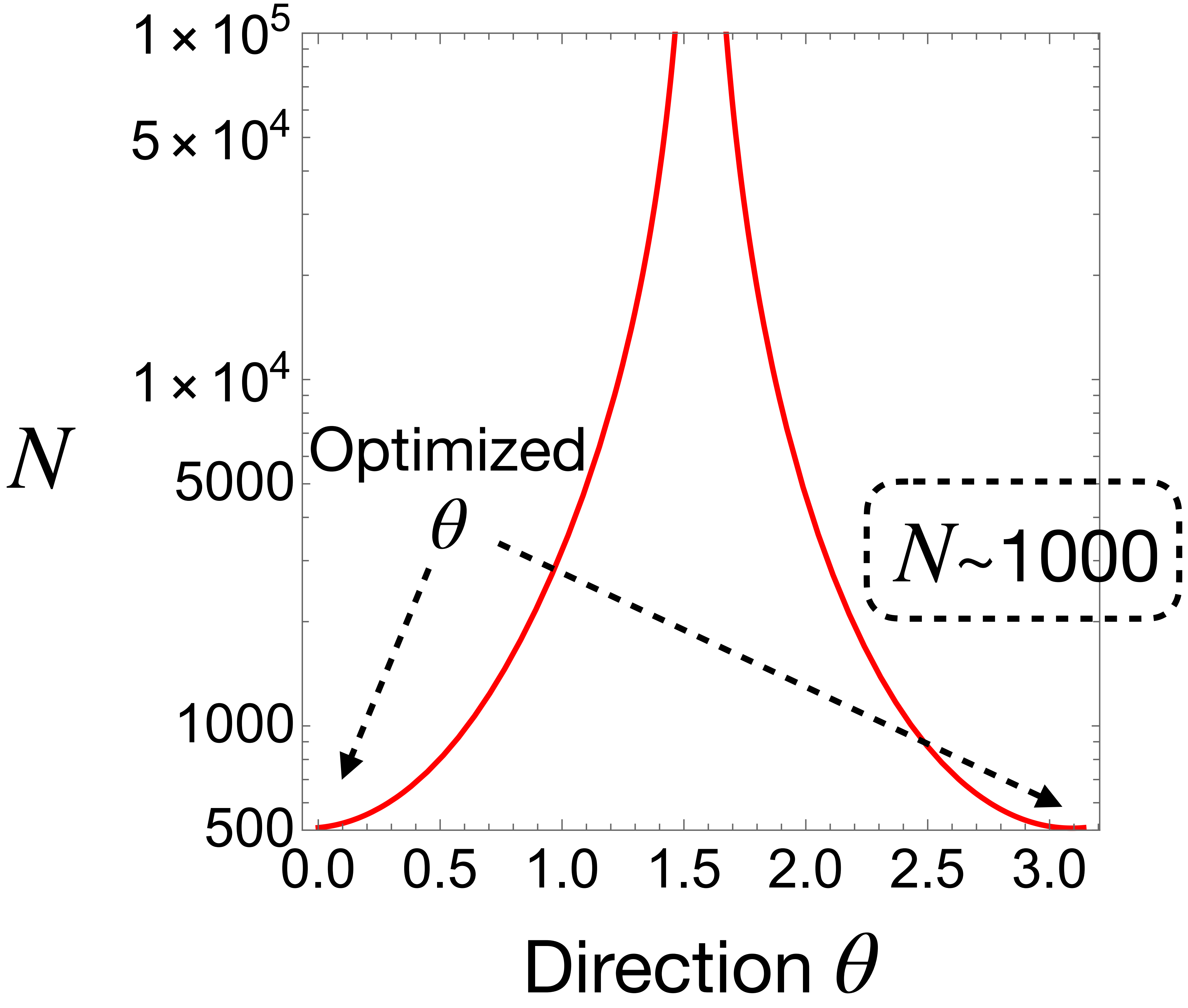
Probe solar velocity v_0 ($\overrightarrow{\Delta r} \parallel \overrightarrow{v_0}$)

SNR= $v_0/\delta v_0$=3

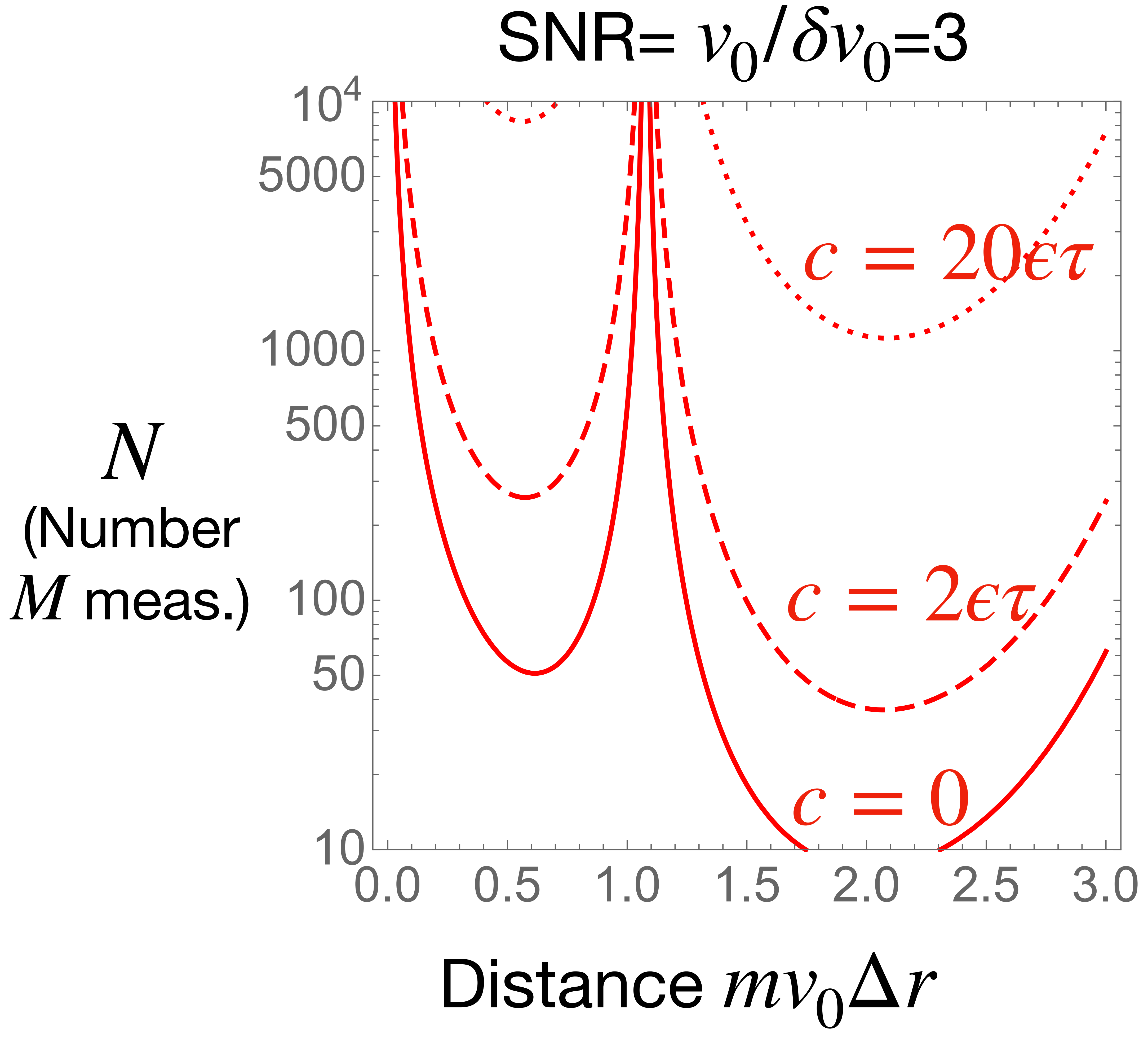


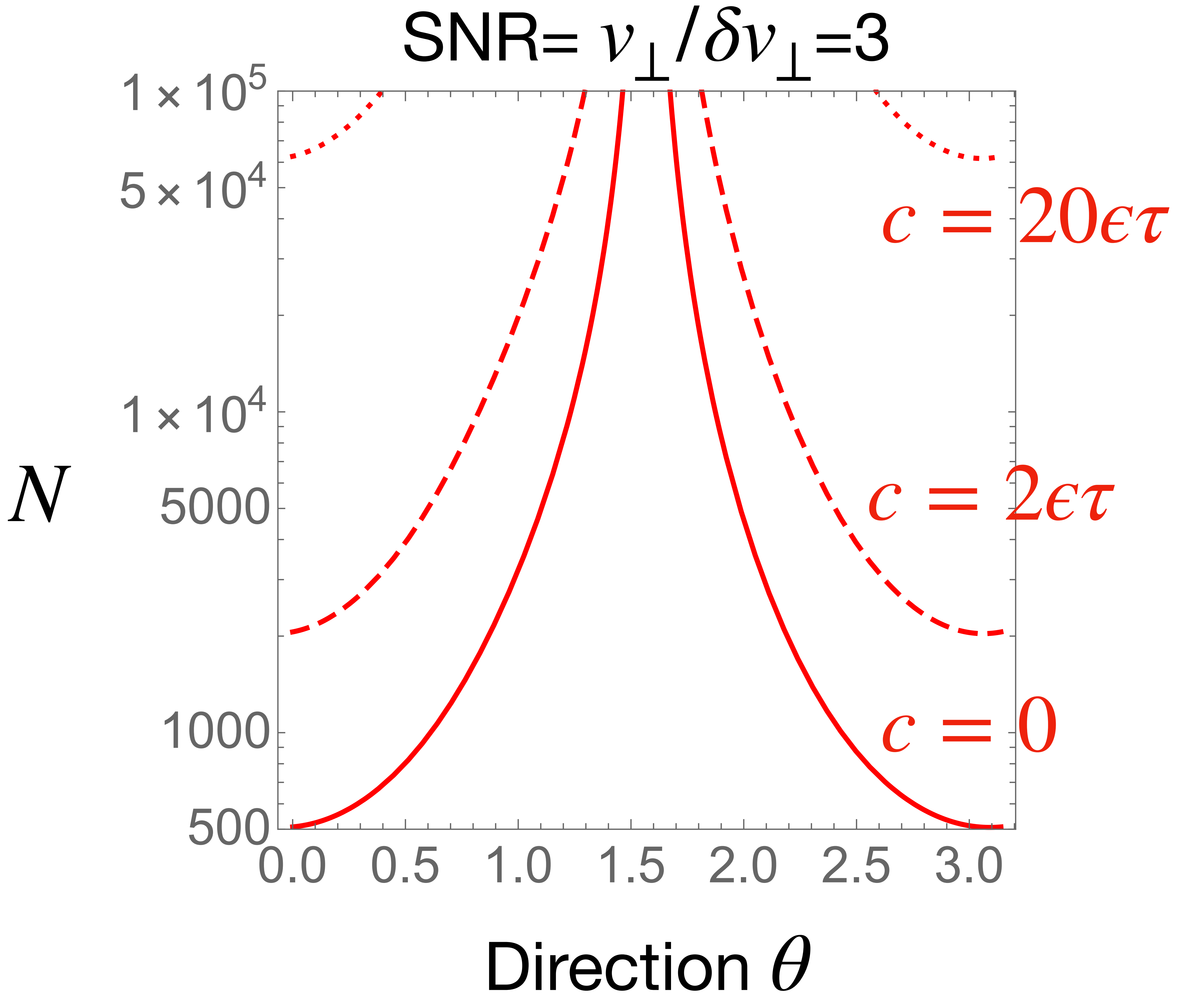
Probe Earth velocity $v_\perp$

SNR= $v_\perp/\delta v_\perp$=3

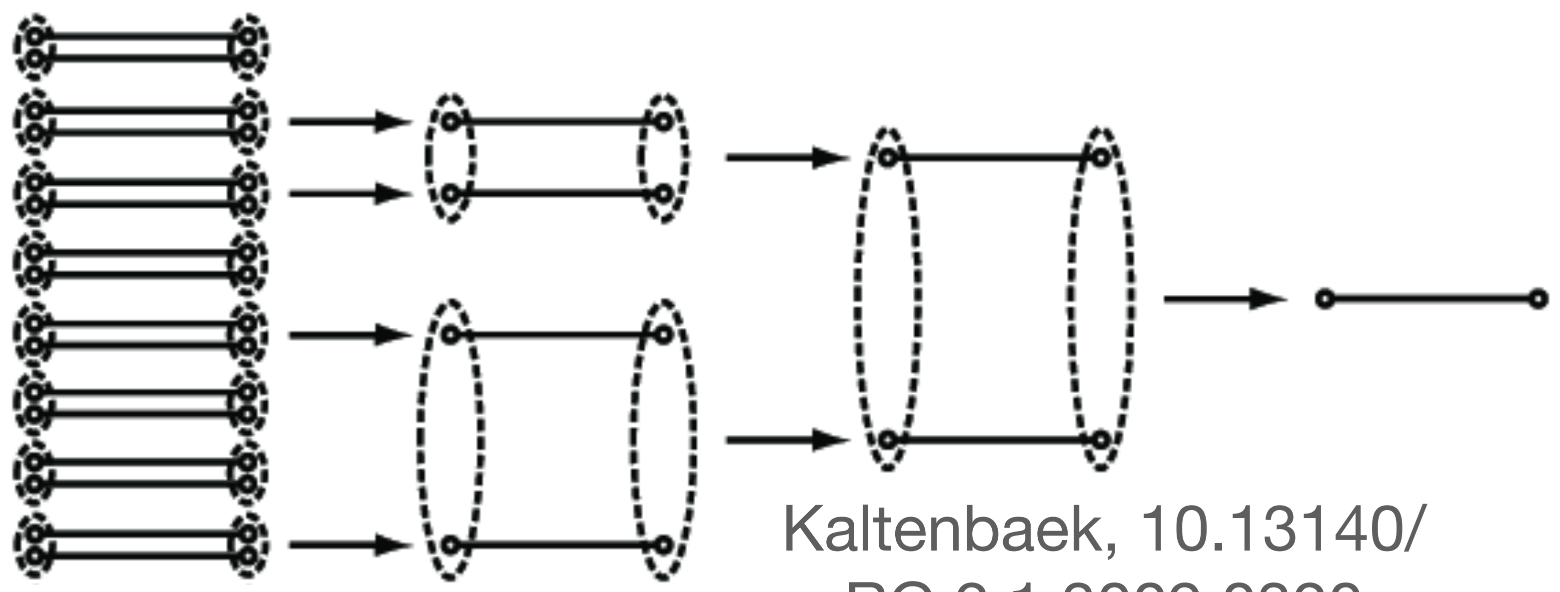


Add depolarizing noise with rate c during state trasnfer





Noise in processes



Kaltenbaek, 10.13140/
RG.2.1.3009.0320

1. State transfer:

Depolarizing noise, but in principle could solved by entangle purification (overhead clean EPR pair preparation)

R. Reichle et al., Nature 443, 838–841 (2006)
Azuma et al., Rev. Mod. Phys. 95, 045006 (2023)

2. P_1 excitation projection:

Readout error & gate error -> same order as usual coupling measurement

3. M phase measurement

Quantum uncertainty dominates and already taken into accounted

Note that *P1* and *M* are very short circuit

Theoretical comparison to field correlation (assume only quantum noise and $|\psi_{\rm ini}\rangle = (|0\rangle + \epsilon\tau e^{i\varphi}|1\rangle) \otimes (|0\rangle + \epsilon\tau e^{i\varphi + im\vec{v}\cdot\overrightarrow{\Delta r}}|1\rangle)$ without *P1 for convenience*)

Our method measure entangle operator M directly

giving $\delta M = \sqrt{\langle M^2\rangle - \langle M\rangle^2} \simeq (\epsilon\tau)^2 \ll 1$

Operator $\langle M\rangle = (\langle \sigma_Y^1 \otimes \sigma_X^2\rangle - \langle \sigma_X^1 \otimes \sigma_Y^2\rangle)/2 = (\epsilon\tau)^2 \sin(mv\Delta r)$

Local meas.

Field correlation $\langle \sigma_{X,Y}^1\rangle \otimes \langle \sigma_{Y,X}^2\rangle \propto \Phi_{\rm DM}(x_1)\Phi_{\rm DM}(x_2)$

A. Derevianko, Phys. Rev. A 97, 042506 (2018)

giving larger uncertainty $\delta(\sigma_X \otimes \sigma_Y) \simeq 1$

Quantum method outperforms: $\dfrac{N^{\rm (classic\ correlation)}}{N^{\rm (entangle\ measure)}} \simeq \dfrac{1}{(\epsilon\tau)^2} \gg 1$

Summary

- Entangle measurements with 2 qubits -> in addition to coupling strength, one can extract DM wind.

- The sensitivty is better than classical correlation

- The protocol is general for sensors given that the information can be taken quantum mechanically and quantum communication is provided

Backup

Wavelike dark matter as target

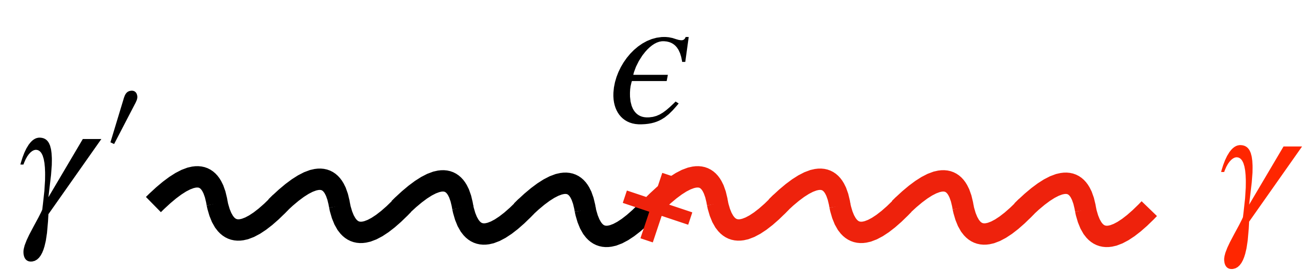
- For a small mass below 1 eV, the number of particles is enormous, it is described approximately by a classical wave

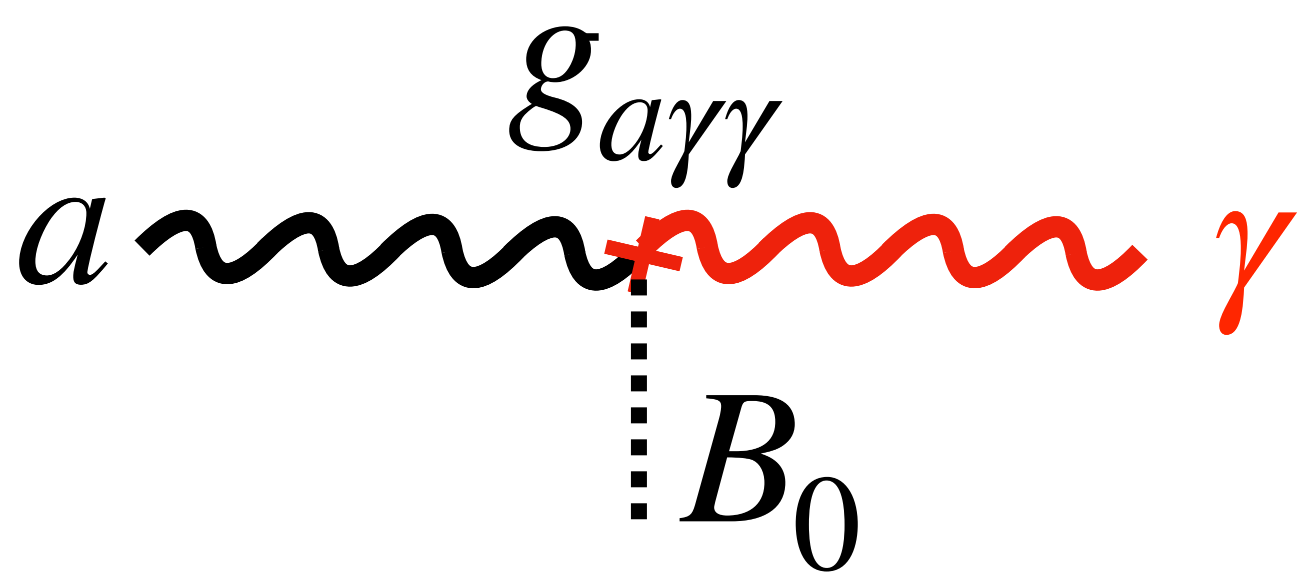
https://arxiv.org/abs/1711.10489

- Candidates: dark photon DM, axion DM

Hidden photon $\mathscr{L}_{\mathrm{int}} = \epsilon E E'$

Axion $\mathscr{L}_{\mathrm{int}} = g_{a\gamma\gamma} a E B$



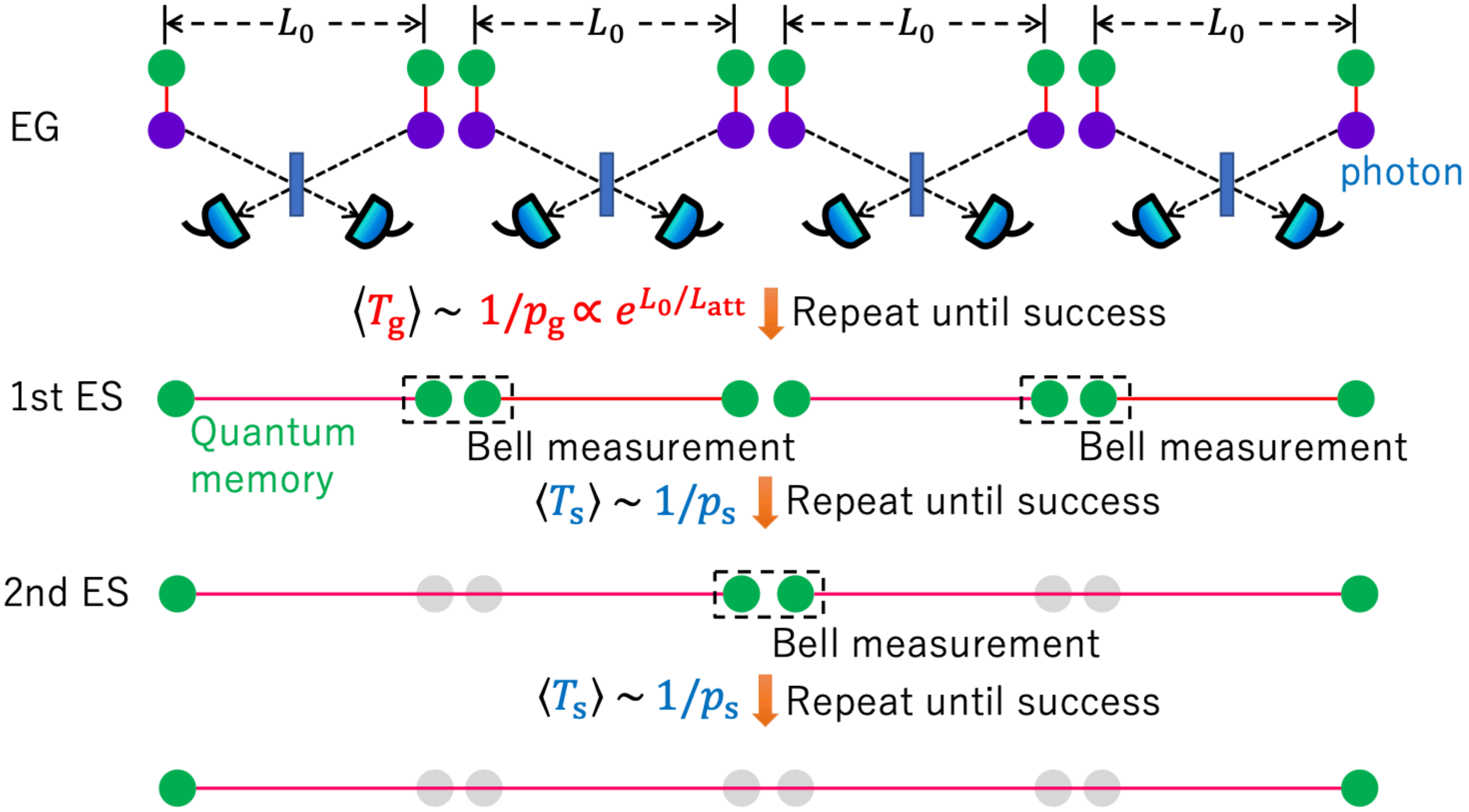


Induced electric field -> measurable by superconducting qubits

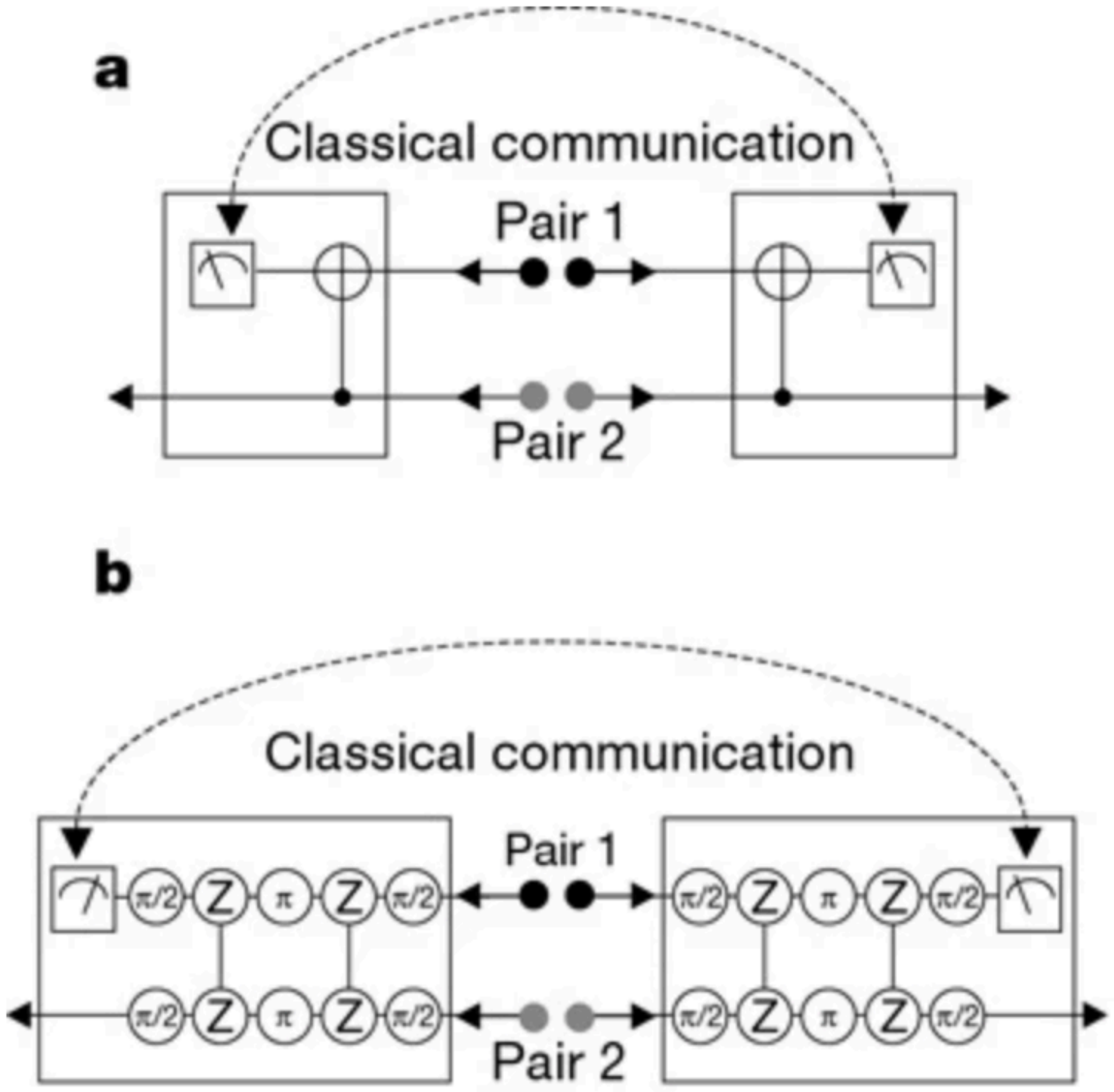
Other strategies for probing DM wind

- **Spin systems:** unknown coupling is sticked to the velocity -> could check the existence but not for the measurement of the value of the velocity
- **Large size cavity:** Practically challenging for very ligt DM
- **Field Correlation:** Larger quantum uncertaity

Entanglement swapping



Entanglement purification



Azuma et al., Rev. Mod. Phys. 95, 045006 (2023)

R. Reichle, et al., Nature 443, 838–841 (2006)

Constraints

Phys. Rev. Lett. 131 (2023) 21, 211001

Evolution from zero state

Strength Time DM Phase

$$|0\rangle \longrightarrow |0\rangle + \epsilon\tau e^{i\varphi}|1\rangle$$

Propbability to be excited, e.g., transmon case:

$$p_1 = |\langle 1|\psi\rangle|^2 = (\epsilon\tau)^2 \simeq 0.12 \times \left(\frac{\text{kinetic mixing}}{10^{-11}}\right)^2 \left(\frac{\tau}{100\ \mu s}\right)^2 \left(\frac{C}{0.1\ \text{pF}}\right)$$

SNR $= \frac{\epsilon^2\tau^2}{\sqrt{p_{\text{error}}}}\sqrt{N_{\text{measure}}} \rightarrow$ **Constraint** $\epsilon \propto \frac{p_{\text{error}}^{1/4}}{\tau^{1/2} n_{\text{qubit}}^{1/4} T_{\text{total}}^{1/4}}$ for fixed scan range and time T_{total}