Use of Entanglement of Quantum Sensors for Detecting Dark Matter

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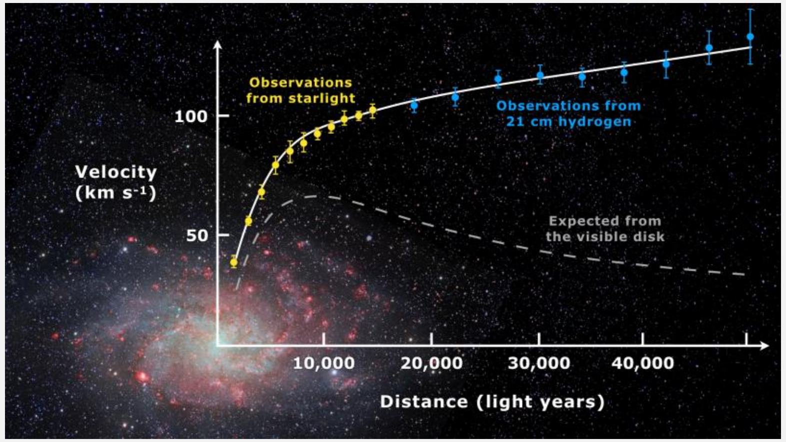
Introduction and Motivation

Cosmic Dark Matter

Plenty of evidences exist for the dark matter (DM)



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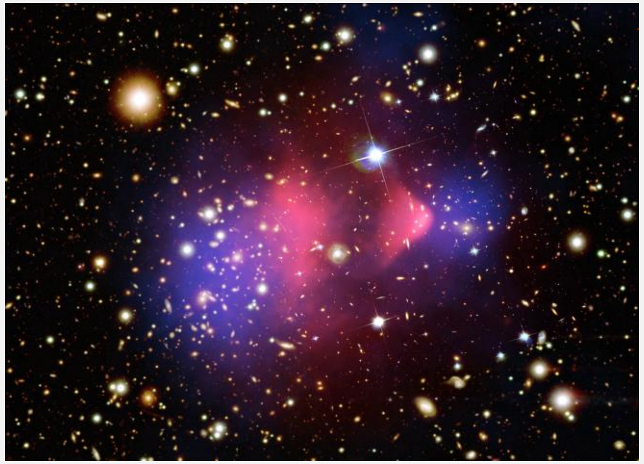


Bullet cluster, From ESA

…

For light DM ($m \ll \mathrm{eV}$), DM behaves like a classical wave

- We want to detect this weak wave directly by some detector
- Quantum sensors are getting more attention for that

Quantum Sensors

Photo credit: Chen, Inada and Nitta
See also Chen's talk

Artificial two-level system with some energy gap

- e.g. superconducting qubit, NV center, ion trap, ⋯

$|1\rangle$

$|0\rangle$

Why do we use quantum sensors?

- Very small energy gaps ($\mathrm{GHz} \sim \mu\mathrm{eV}$ for superconducting qubit)
- Can be insensitive to the unknown DM phase
- We may manipulate the sensor states: **use of entanglement**

I'm going to talk about how we may exploit the sensor entanglement

Note: Our proposals are *theoretical*. I admit our proposals may be experimentally difficult now, but I hope they will be possible in 5-10 years.

A Simplified Model: Signal-Sensor Interaction

Core setup for our quantum sensing protocols

(Details vary, but the essential physics is often similar)

Sensor: A Quantum Two-Level System

- E.g., qubits
- Two states: Ground $|0\rangle$ and Excited $|1\rangle$
- Can be a physical qubit, a cavity mode ($|n=0\rangle$, $|n=1\rangle$), etc.

Signal: A Weak Classical DM Field

- Drive transitions from $|0\rangle$ to $|1\rangle$
- Interaction Hamiltonian: $H_I = \varepsilon(\sigma_X \cos\alpha + \sigma_Y \sin\alpha)$,

  $\boldsymbol{\varepsilon}$: Signal strength (the quantity to be estimated)

  $\boldsymbol{\alpha}$: Signal phase (often stochastic/random)

The Goal: Estimate the signal strength $\boldsymbol{\varepsilon}$

1. **Evolve:** System evolves from $|0\rangle$ under H_I. For a weak signal $\varepsilon t \ll 1$, $|\psi(t)\rangle \simeq |0\rangle - ie^{i\alpha}\varepsilon t|1\rangle$
2. **Measure:** Project onto $|0\rangle$ and $|1\rangle$. Probability of finding $|1\rangle$: $p_1 = |\langle 1|\psi(t)\rangle|^2 = \varepsilon^2 t^2$

Avenues for Quantum-Enhanced Sensing

In my opinion, there could be two possible direction:

1. **Quantum Analogs of Classical Signal Processing**

   HF, Matsuzaki, Sichanugrist, 25, HF, Moroi, Sichanugrist 25

   Chen, HF, Sichanugrist et al., 25

   He's a PhD student applying to postdoc this year!

2. **Enhancing Signals**

   Using entanglement to enhance signals (e.g., the GHZ state)

   Chen, HF, Sichanugrist et al., 23, Sichanugrist, HF, Moroi, Matsuzaki et al., 25

I'll focus on the former in my talk.

Use of Entanglement: Signal Processing

Quantum Analogs of Classical Signal Processing

Core Idea: Move signal processing from the classical to the quantum domain.

- Instead of processing measurement results, we propose to directly manipulate and interfere the quantum states of the sensors.
- We'll see it has an advantage for weak signals

Topics I'm going to mention:

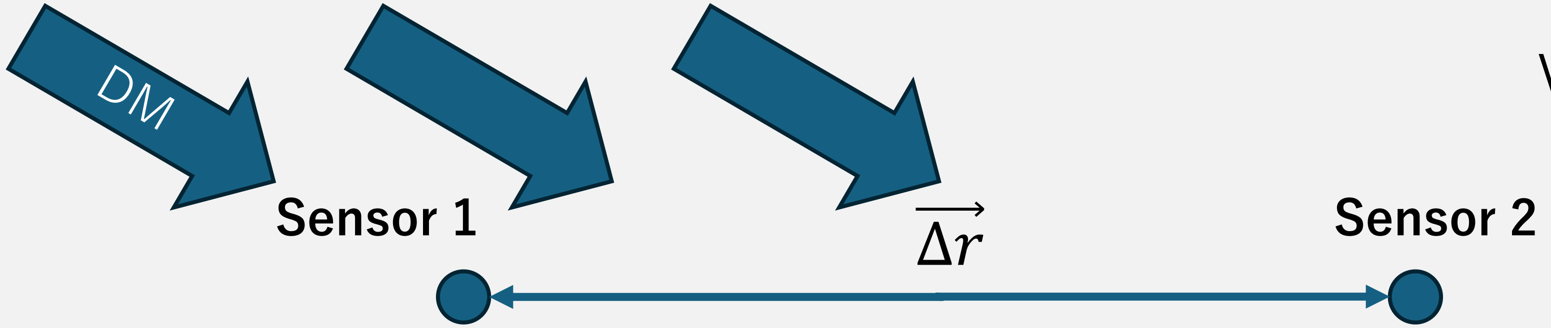
- Directional Sensing
- Noise Suppression

Case Study 1: Measuring Dark Matter Direction

The direction of the DM is a smoking-gun signature

"Classical" Protocol [Derevianko '18]

1. **Interaction:** The DM signal field interacts with two sensors
2. **Measurement:** Measure an observable σ_X, for each sensor independently: $\langle \sigma_X \rangle = 2\varepsilon\tau \sin\alpha$
3. **Correlation:** Take the correlation of the result



Velocity is encoded in α:

$$\alpha' = \alpha - \vec{k}_{\mathrm{DM}} \cdot \overrightarrow{\Delta r}$$

$$|\psi_1\rangle = |0\rangle - i e^{i\alpha} \varepsilon\tau |1\rangle \qquad |\psi_2\rangle = |0\rangle - i e^{i\alpha'} \varepsilon\tau |1\rangle$$

The Challenge of Weak Signals

Only the difference is meaningful
$\alpha' - \alpha = -\vec{k}_{\mathrm{DM}} \cdot \overrightarrow{\Delta r}$

What limits the Classical Protocol?

- Zero-point fluctuation of σ_X is $\mathcal{O}(1)$: $\langle \sigma_X^2 \rangle - \langle \sigma_X \rangle^2 = \mathcal{O}(1)$
- The information of $\alpha' - \alpha$ is suppressed by $\varepsilon\tau \cdot \varepsilon\tau = \varepsilon^2\tau^2$

More quantitatively, the classical Fisher information is $\mathcal{O}(\varepsilon^4\tau^4)$

Our Quantum Approach: A Disclaimer

- Our proposed method requires creating quantum correlations between **distant** sensors (from meters to kilometers).
- The Fisher information is $\mathcal{O}(\varepsilon^2\tau^2)$: **sensitivity improved by $\boldsymbol{\varepsilon\tau}$!**
- **Assumption:** We assume it's possible to transfer quantum states b/w two sites
  - This is a key quantum technology and being developed seriously

Quantum Protocol: Interference of Distributed Sensors

HF, Matsuzaki, Sichanugrist, 2506.19614 Phys. Rev. Lett. **135**, 241802

Step 1: Entangling Measurement (Projection)

- Two-sensor state: $|\psi_1 \otimes \psi_2\rangle = \left(|0\rangle - ie^{i\alpha}\varepsilon\tau|1\rangle\right) \otimes \left[|0\rangle - ie^{i(\alpha - \vec{k}_{\mathrm{DM}} \cdot \overrightarrow{\Delta r})}\varepsilon\tau|1\rangle\right]$
- Measure $P = |10\rangle\langle 10| + |01\rangle\langle 01|$, which succeeds with probability $\langle P\rangle = 2\varepsilon^2\tau^2$
- State after measurement: $P|\psi_1 \otimes \psi_2\rangle \sim |10\rangle + e^{-ik_{\mathrm{DM}}\Delta r}|01\rangle \equiv |\Psi\rangle$

Step 2: Information Readout

$\delta P^2 = \langle P^2\rangle - \langle P\rangle^2 = \mathcal{O}(\varepsilon^2\tau^2)$

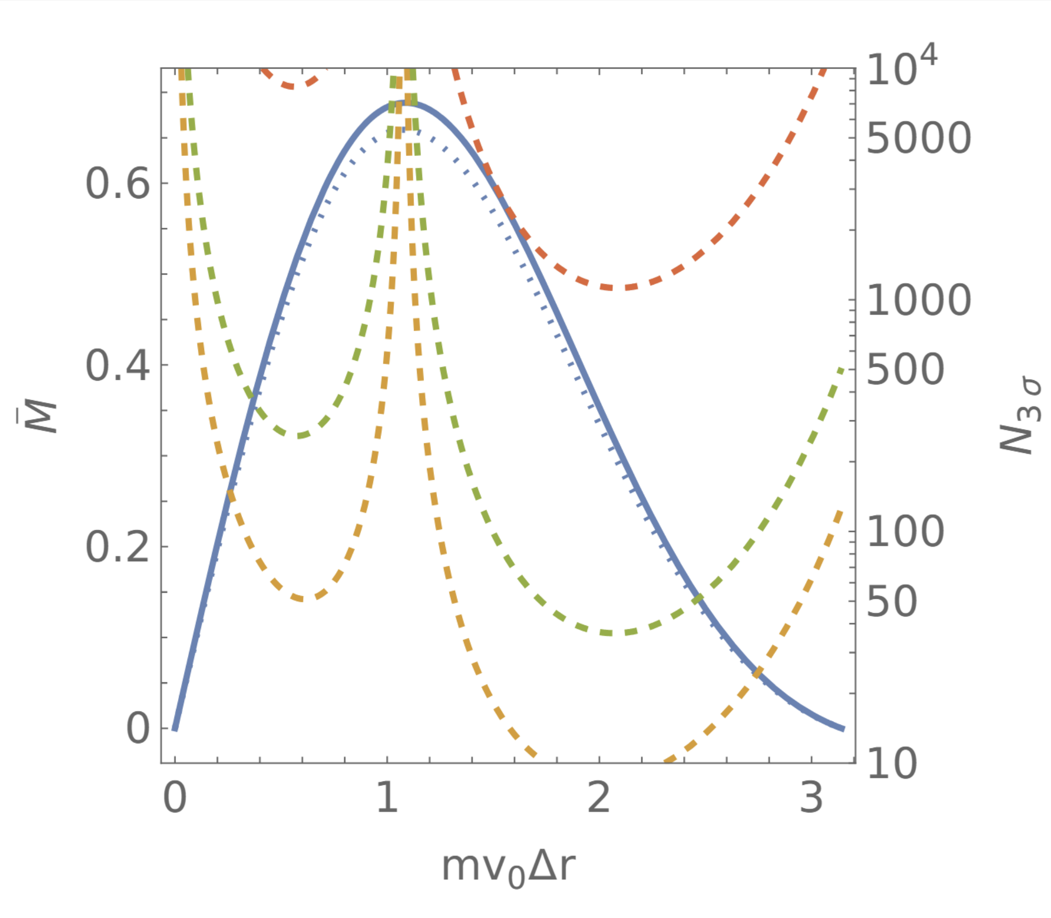
- Measure $M = -i|01\rangle\langle 10| + i|10\rangle\langle 01|$
- $\langle M\rangle = -\sin k_{\mathrm{DM}}\Delta r$

- We can rigorously prove our method is optimal
  - Our method saturates the quantum Cramér-Rao bound

Result

$$\delta \bar{M}_{3\sigma} = \frac{\sqrt{\langle \bar{M}^2 \rangle - \langle \bar{M} \rangle^2}}{\sqrt{N_{3\sigma}}}, \frac{\bar{M}}{\delta \bar{M}_{3\sigma}} = 3$$

- We check the effect of the local standard of rest velocity
- Blue: $\langle M \rangle$ (analytic for dotted)
- Dashed lines: Number of post-measurements needed to measure $\langle M \rangle$
  - Yellow: no error
  - Green: same noise rate as the signal
  - Red: 10x more noise than the signal



Case Study 2: Noise Reduction in a Sensor Array

Setup: An array of N identical sensors.

The Signal vs. The Noise

- **Signal:** Acts **globally** across the entire array.
- **Noise:** Acts **locally** on each sensor.

Classical Approach:

- Take the correlation of each sensor.
- As we've seen, it’s difficult for weak signals.

Use of W-state

Shu, Xu, Xu, 24;
Chen, HF et al., 2510.01816
Freiman et al, 25
See B. Xu and J. Shu's talks

Our task (in QM language): To distinguish

$$\rho_s = \left(\sum_i \sigma_X^i \,|0\rangle^{\otimes N}\right)\left(\sum_i \langle 0|^{\otimes N}\sigma_X^i\right) \qquad \rho_n = \sum_i \left(\sigma_X^i|0\rangle^{\otimes N}\langle 0|^{\otimes N}\sigma_X^i\right)$$

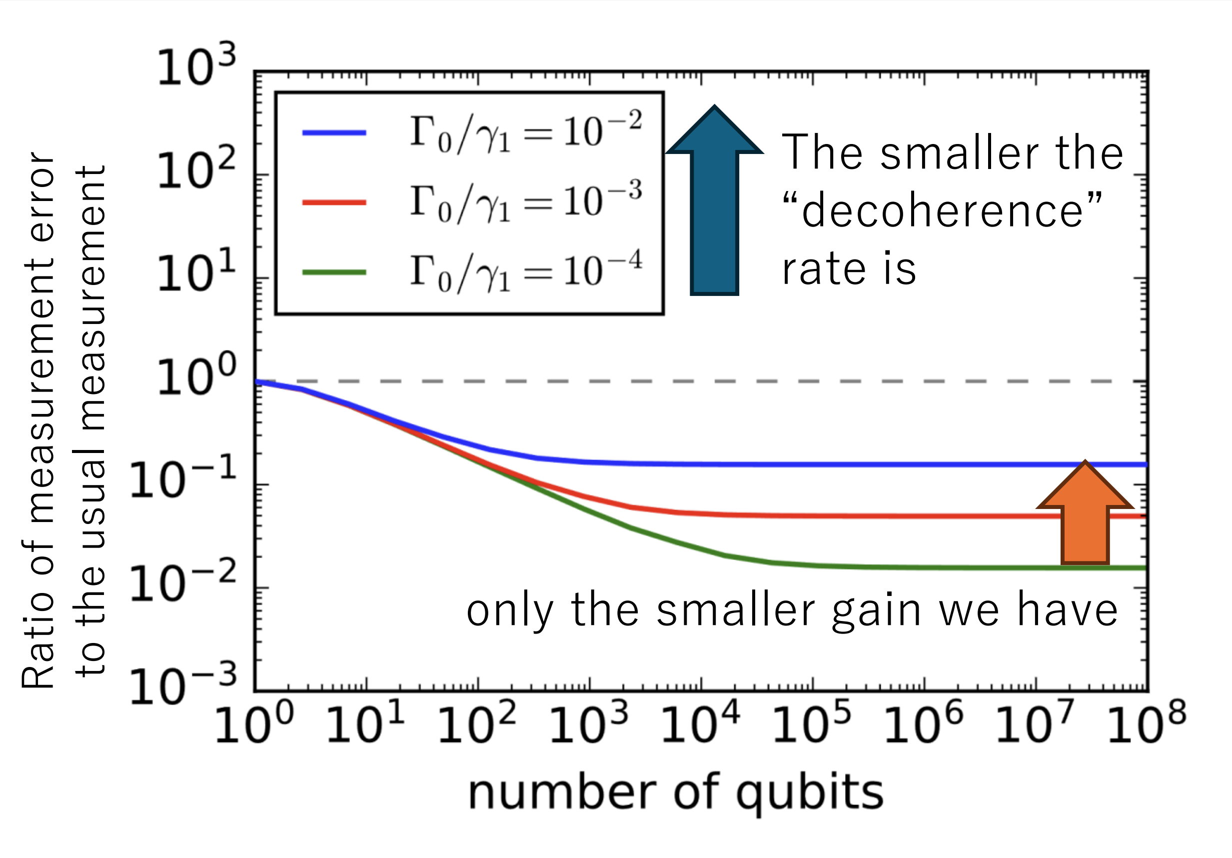
Signal: operators act on **all** qubits

Noise: operators act on a **single** qubit

- Use $|W\rangle \equiv \frac{1}{\sqrt{N}}(|10\ldots0\rangle + |01\ldots0\rangle + \cdots |00\ldots1\rangle)$:
  - $\langle W|\rho_s|W\rangle = \mathcal{O}(N)$, whereas $\langle W|\rho_n|W\rangle = \mathcal{O}(1)$
  - Noise is suppressed!

Result

- We let N sensors evolve independently and measure them by the W-state
- We consider a system with thermal noises
  - "Decoherence" $(\sim \gamma_1)$
  - Excitation (Γ_0)
- For $\gamma_1 \lesssim \Gamma_0$, no gain is expected. Why?



Noise Reduction by Quantum Error Correction

$$|W\rangle \equiv \frac{1}{\sqrt{N}}(|10\cdots 0\rangle + |01\cdots 0\rangle + \cdots + |00\cdots 1\rangle)$$

The noise not only mimics signals but also **reduces** signals:

noise on the 1st qubit $|0\rangle - i\varepsilon t|W\rangle \rightarrow |10\cdots 0\rangle - i\varepsilon t|1\rangle \otimes |W\rangle_{N-1} + \cdots$

N qubit W states cannot measure ε anymore!

Instead of measuring by W, we may perform the **quantum error correction** (QEC) like procedure to putting back

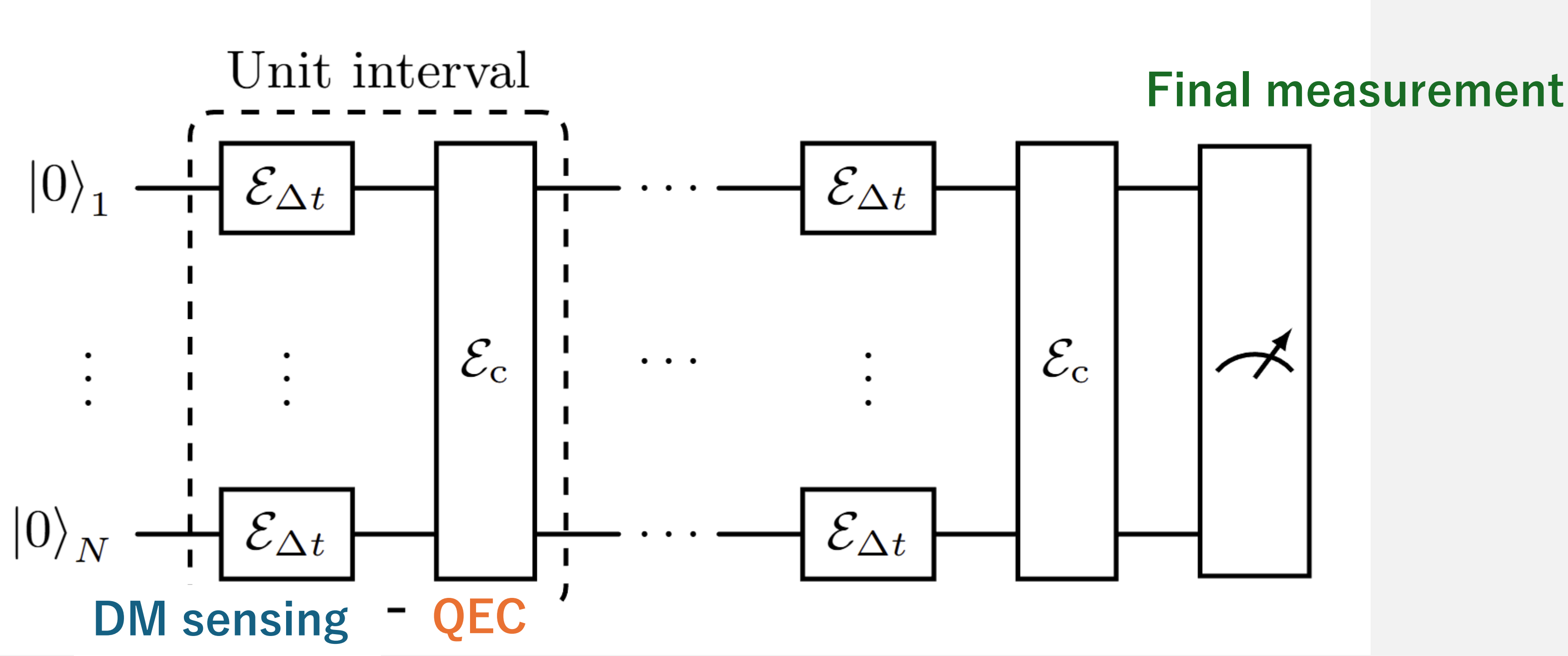
- $|10\cdots 0\rangle$ to $|0\rangle$ and $|1\rangle \otimes |W\rangle_{N-1}$ to $|W\rangle$,
- $\cdots$ and so on for other errors

HF Moroi Sichanugrist 2511.03253

QEC-Sensing Protocol

Kessler et al 14, Dür et al 14, Arrad et al 14
Sekatski et al 17, Demkowicz-Dobrzański et al 17, Zhou et al 17
HF Moroi Sichanugrist 2511.03253

Repeating “correction and sense” many times



Result

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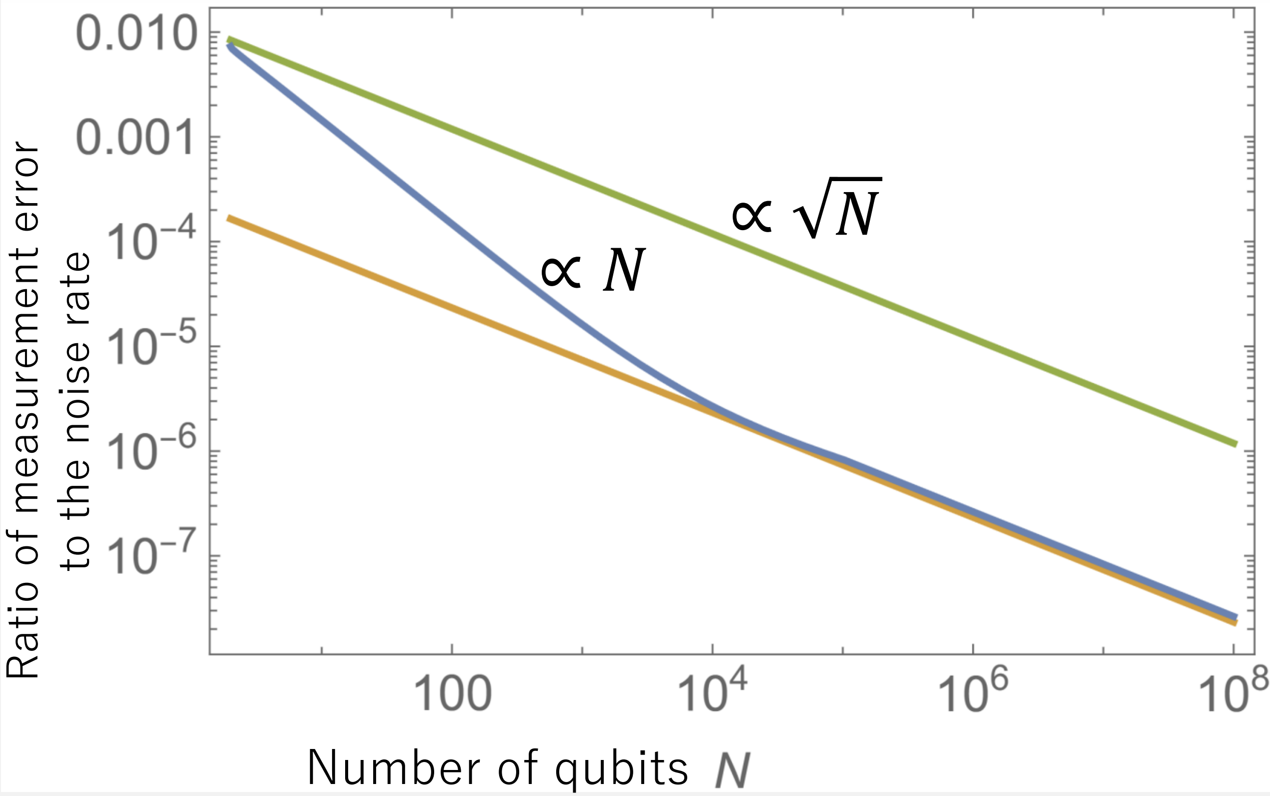
We consider only the ex. noise.

Green: without QEC

Blue: with QEC

Orange: Quantum Cramér–Rao bd.

- Our protocol approaches to the QCRB
  - The QCRB cannot be achieved for DM measurement due to its unknown phase!



Summary

Summary

- Quantum sensing is a powerful tool for searching for extremely weak signals, such as those from dark matter.
- Using entanglement between sensors, we can achieve better sensitivity than classical counterparts
  - Directional detection
  - Noise reduction
  - …