Directional Searching for Ultralight Dark Matter

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Based on Phys.Rev.Lett. 135 (2025) 24, 241802 (arXiv: 2506.19614)

with Y. Matsuzaki and T. Sichanugrist

Self Introduction

Name: Hajime Fukuda

Research Interest: Elementary Particle Physics (theory)

In these days, I'm curious about application of quantum sensing to high-energy physics.

Today's Focus:
Quantum Sensing meets Dark Matter Detection.

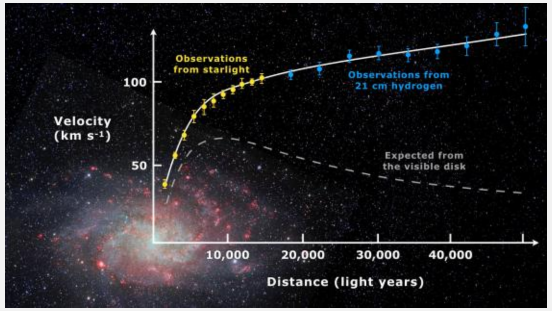
I'd love to discover new quantum sensing applications together as a member of A02 group!

Me ↓

Quantum sensing →

Cosmic Dark Matter

Plenty of evidences exist for the dark matter (DM)



From Wikimedia Commons

Bullet cluster, From ESA

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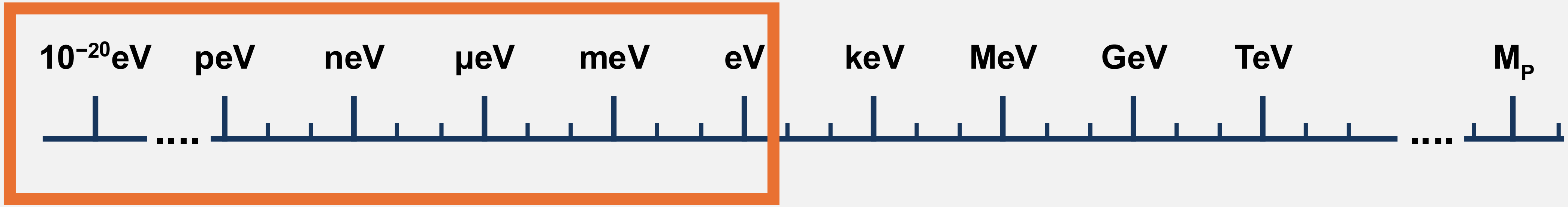
The true identity of Dark Matter remains a mystery.

➔ We need Direct Detection of DM!

Wave-like DM

What is the mass of DM?

A Huge Range of Possible Masses!



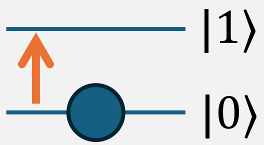
Focusing on the Ultralight Regime
High occupation number ➔ **DM behaves like a wave** (just like classical light).

From Wikimedia Commons

Quantum Sensors

Detecting weak waves ➔ **Quantum Sensors**

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



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

Quantum Sensing: Use of Entanglement

As long as I know, there could be two possible advantages:

1. **Quantum Version of Signal Processing**

Case Study:
Directional Detection of Dark Matter

HF et al., 2506.19614
Shu et al., 24; HF et al., 2511.03253, 2510.01816; Freiman et al., 25

2. **Enhancing Signals**

Ito et al. 23; Sichanugrist, HF, et al., 23; Zheng et al., 25; He et al., 25

Note: These are strictly theoretical examples. (Not ready for experiment now)

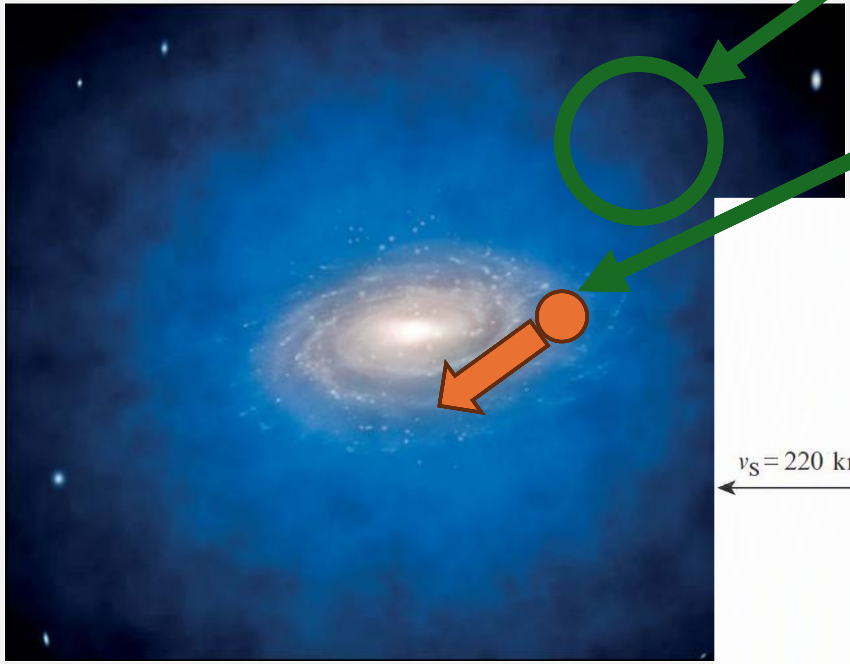
<u>We hope to collaborate with you through this Research Area to discuss:</u>

- Implementation methods
- Yet another way to utilize entanglement

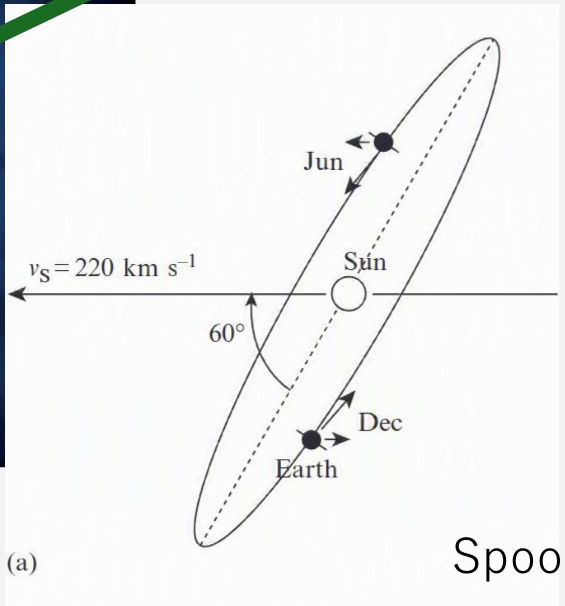
DM Direction and Velocity

DM distribution $f(\vec{v}) \sim \exp -\frac{v^2}{v_0^2}$

From CERN



Our solar system



Spooner 2010

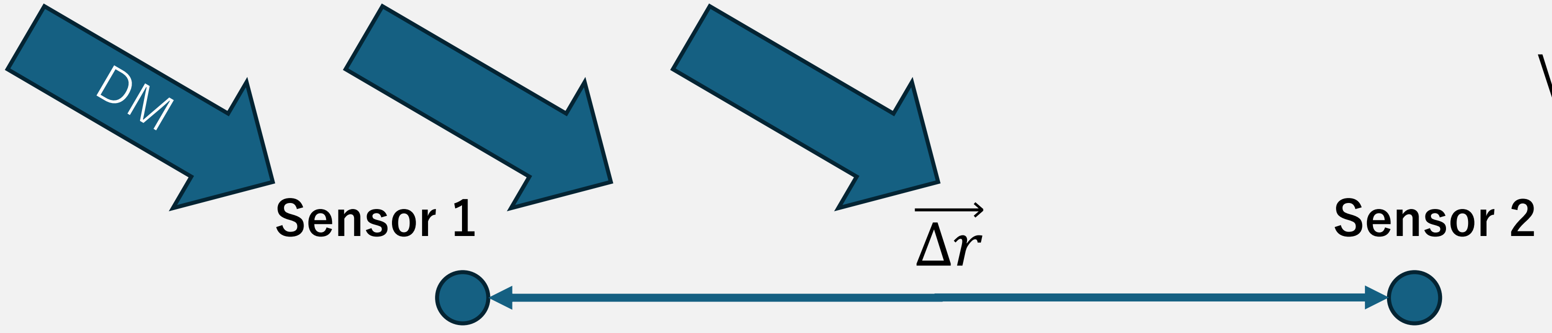
Detectors on Earth feel a **"DM Wind"**. This wind is the **smoking gun** for DM signals!

Sensors' Phases and DM Velocity

DM Wind Information: Encoded in the sensors' **phases**.

Note: Absolute phase has no physical meaning.

➔ Only the **phase difference** between sensors is physical.



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

Velocity is encoded in α:

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

Classical Protocol

"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

Two measurements of a weak signal needed ➔ **Loss of Sensitivity**

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: $P|\psi_1 \otimes \psi_2\rangle \sim |10\rangle + e^{-ik_{\mathrm{DM}}\Delta r}|01\rangle \equiv |\Psi\rangle$

The outcome is suppressed by only (very small rate)[1] !

Step 2: Information Readout

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

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

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
- This study is just one illustrative example. **Let's discuss new applications of quantum sensors together through this project!**