Title: Quantum Computing Enhanced Sensing (Plenary Talk)

Speakers: Soonwon Choi

Collection/Series: Year of Quantum Across Canada

Subject: Quantum Information

Date: October 08, 2025 - 1:00 PM

URL: https://pirsa.org/25100049

Abstract:

Quantum computing and sensing represent two distinct frontiers of quantum information science. Here, we harness quantum computing to solve a fundamental and practically important sensing problem: the detection of weak oscillating fields with unknown strength and frequency. We present a quantum computing enhanced sensing protocol, that we dub quantum search sensing, outperforming all existing approaches. Furthermore, we prove our approach is optimal by establishing the Grover-Heisenberg limit -- a fundamental lower bound on the minimum sensing time. The key idea is to robustly digitize the continuous, analog signal into a discrete operation, which is then integrated into a quantumalgorithm. Our metrological gain originates from quantum computation, distinguishing our protocol from conventional sensing approaches. Indeed, we prove that broad classes of protocols based on quantum Fisher information, finite-lifetime quantum memory, or classical signal processing are strictly less powerful. We propose and analyze a proof-of-principle experiment using nitrogen-vacancy centers, where meaningful improvements are achievable using current technology. This work establishes quantum computation as a powerful new resource for advancing sensing capabilities.

Quantum Computing Enhanced Sensing

arXiv:2501.07625

Soonwon Choi

MIT

Massachusetts Institute of Technology

@Year of Quantum, Toronto
October 8, 2025

Quantum Computing Enhanced Sensing

arXiv:2501.07625

Soonwon Choi

MIT

Richard Allen

Francisco Machado

Isaac Chuang

Robert Huang

Massachusetts Institute of Technology

@Year of Quantum, Toronto
October 8, 2025

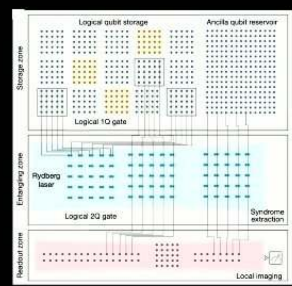
Exciting Time for Quantum Information Science

High fidelity operations

Quantinuum

✓ Quality

Logical qubits & circuits

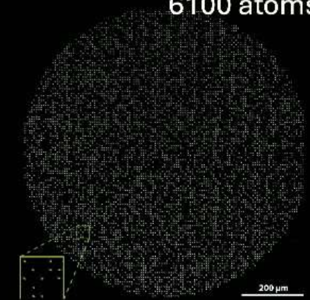


MIT & Harvard groups

✓ Control

Large qubit arrays

6100 atoms



Caltech group

✓ Size

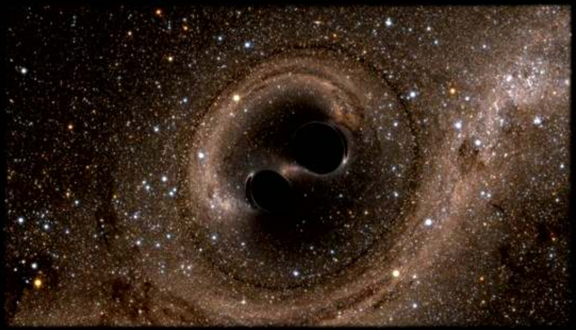
What should we do with quantum devices?

- Useful
- Useful for a long time
- Quantumness is used

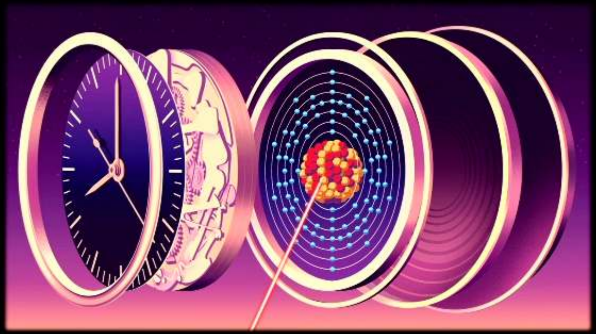
Quantum Sensing & Metrology

Driving force for new sciences and technologies

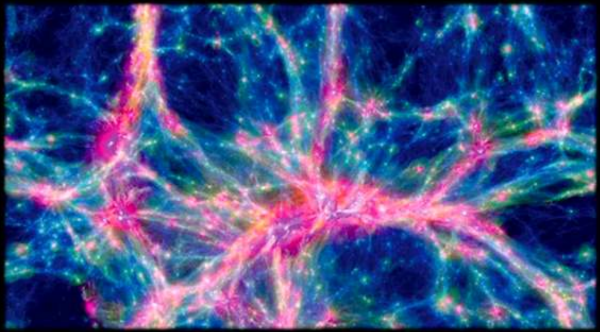
Gravitational Wave (2016)



Atomic Clock (2024)



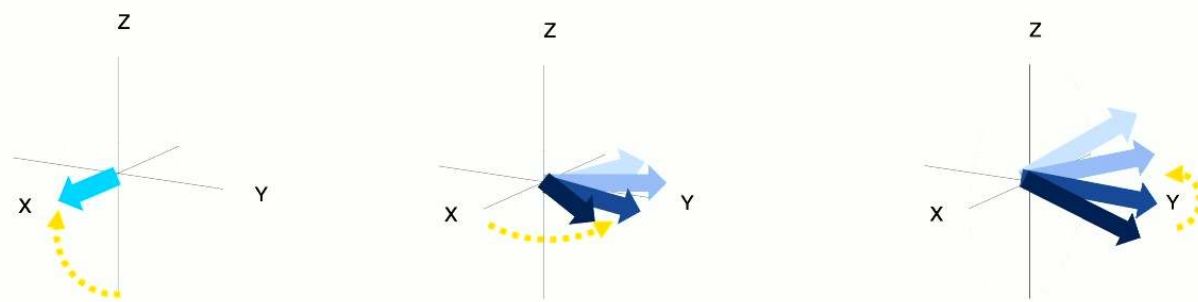
Dark Matter Search (?)



Images taken from LIGO, Quanta Magazine, and cerncourier.com.

Quantum Sensing

Ramsey spectroscopy $H = B\,S^z$



Initialization along x axis

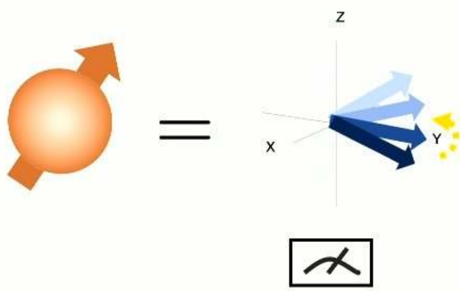
Evolve for time $t \sim T$
$\theta = BT$

Rotate and measure
 S^z

Sensitivity: $T\,B = O(1)$ $\Rightarrow$ $B_{\min} \sim \dfrac{1}{T}$

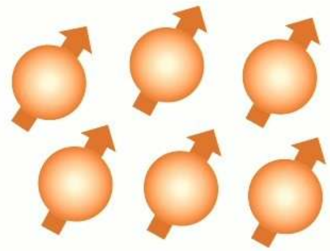
Sensitivity Limits in Quantum Sensing

One particle



$$B_{\min} \sim \frac{1}{T}$$

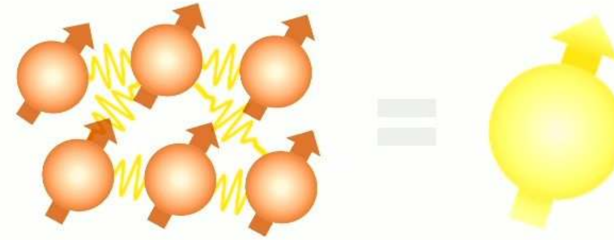
N particles



Standard Quantum Limit (SQL)

$$B_{\min} \sim \frac{1}{\sqrt{N}\, T}$$

N *entangled* particles



Heisenberg Limit (HL)

$$B_{\min} \sim \frac{1}{N\, T}$$

Efforts to achieve the Heisenberg Limit

Quantum Error Correction

ARTICLE OPEN

Spatial noise filtering through error correction for quantum sensing

David Layden[1] an

ARTICLE

DOI: 10.1038/s41467-017-02510-3 OPEN

Achieving the Heisenberg limit in quantum metrology using quantum error correction

Sisi Zhou[1,2], Mengzhen Zhang[1,2], John Preskill[3] & Liang Jiang[1,2]

Variational Optimization

Article

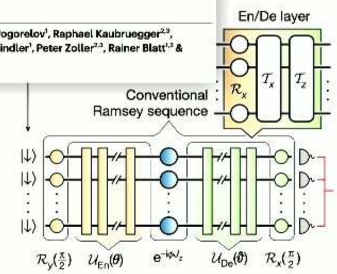
Optimal metrology with programmable quantum sensors

https://doi.org/10.1038/s41586-022-04435-4

Received: 20 July 2021

Accepted: 18 January 2022

Christian D. Marciniak[1,5], Thomas Feldker[1,5], Ivan Pogorelov[1], Raphael Kaubruegger[2,3], Denis V. Vasilyev[2,3], Rick van Bijnen[2,3], Philipp Schindler[1], Peter Zoller[2,3], Rainer Blatt[1,2] & Thomas Monz[1,4]



Scalable Approach

nature physics

Article

https://doi.org/10.1038/s41567-024-02562-5

Scalable spin squeezing from finite-temperature easy-plane magnetism

Received: 3 February 2024

Accepted: 23 May 2024

Published online: 29 July 2024

Maxwell Block[1,5], Bingtian Ye[1,5], Brenden Roberts[1], Sabrina Chern[1], Weijie Wu[2], Zilin Wang[2], Lode Pollet[3,4], Emily J. Davis[2], Bertrand I. Halperin[1] & Norman Y. Yao[1,2]

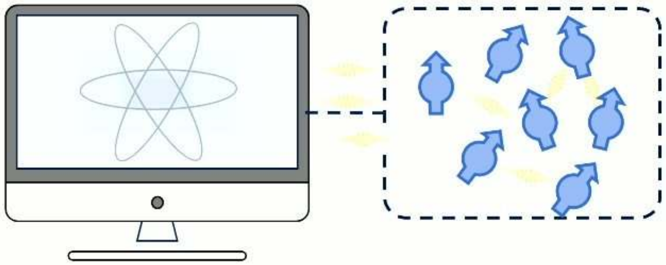
many more...

Efforts to achieve the Heisenberg Limit

Not in this talk

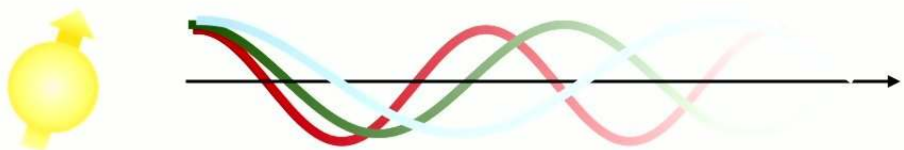
Qualitatively different sensing advantage?

Quantum computer × Quantum sensors



Task: **AC sensing**

Detect a **weak** oscillating field at an **unknown frequency** as quickly as possible



$$B(t) = B\cos(\omega t + \phi) \qquad H(t) = B(t)S^z$$

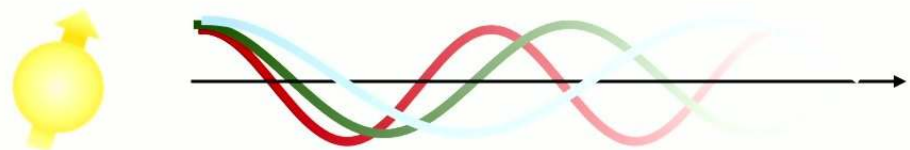
- Sensitivity B_{min}
- Bandwidth $\Delta\omega$

Minimize sensing time

$$\tau = \tau(B_{\text{min}}, \Delta\omega)$$

Task: **AC sensing**

Detect a **weak** oscillating field at an **unknown frequency** as quickly as possible



$$B(t) = B\cos(\omega t + \phi) \qquad H(t) = B(t)S^z$$

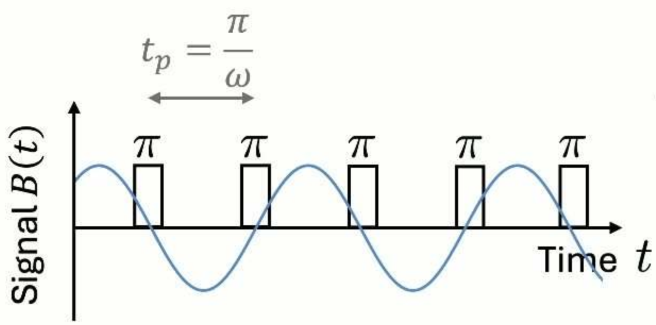
Real-world applications

Gravitational wave detection | Dark matter detection | NMR | Quantum clocks | ...

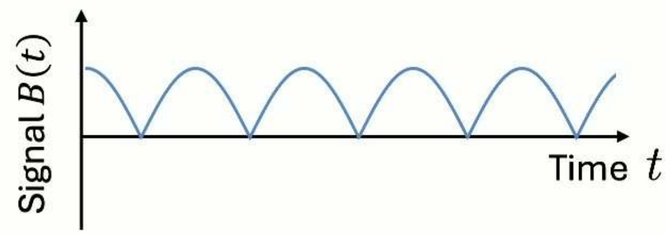
Foundational problems

- Simplest *time-dependent* Hamiltonian learning
- Formal hardness (complexity)?
- Optimal algorithms?
- How fast can we detect?

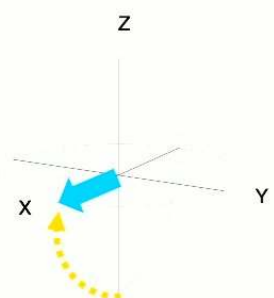
Conventional approach



Toggling frame

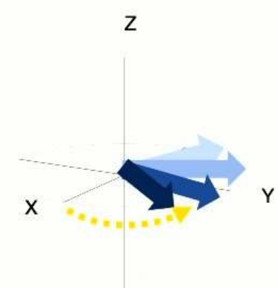


Initialize



$|\psi(0)\rangle = |+\rangle$

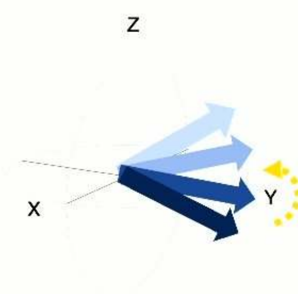
Evolve for time



$|\psi(t)\rangle \propto |0\rangle + e^{-i\theta}|1\rangle$

$\theta = \int f(t)B(t)dt \approx \alpha B\, T$

Rotate and measure



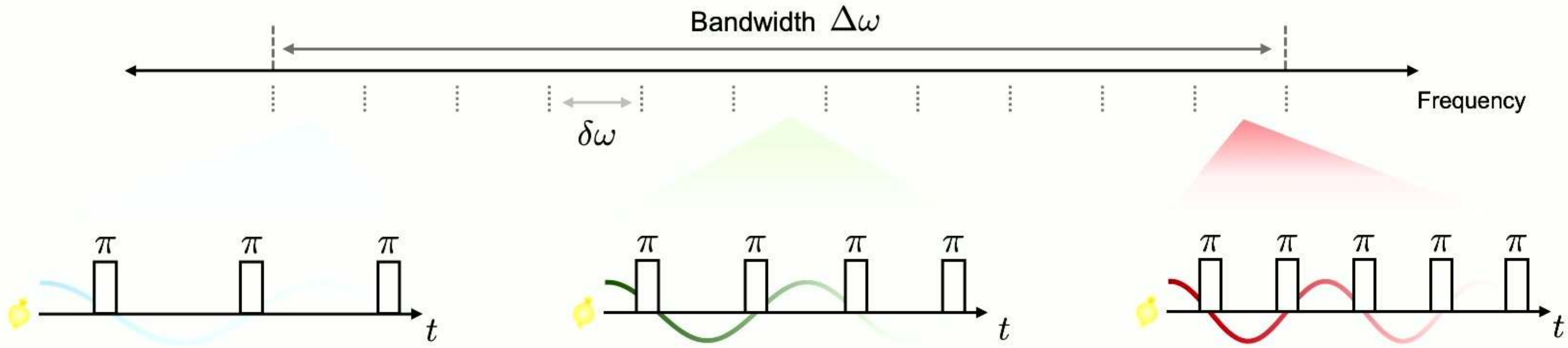
S^z

Optimal strategy
(if ω given)

Sensitivity: $B_{\min} = O\left(\frac{1}{T}\right)$

Bandwidth: $\delta\omega = O\left(\frac{1}{T}\right)$

Conventional approach

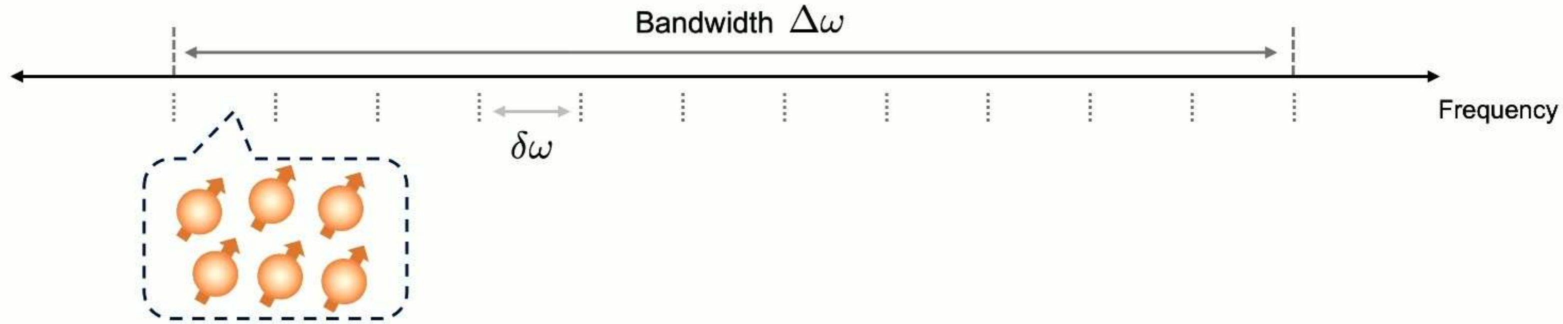


- Sensitivity: $B_{\min} = 1/T$
- Freq bin size: $\delta\omega = 1/T$
- # intervals: $M = \Delta\omega/\delta\omega$

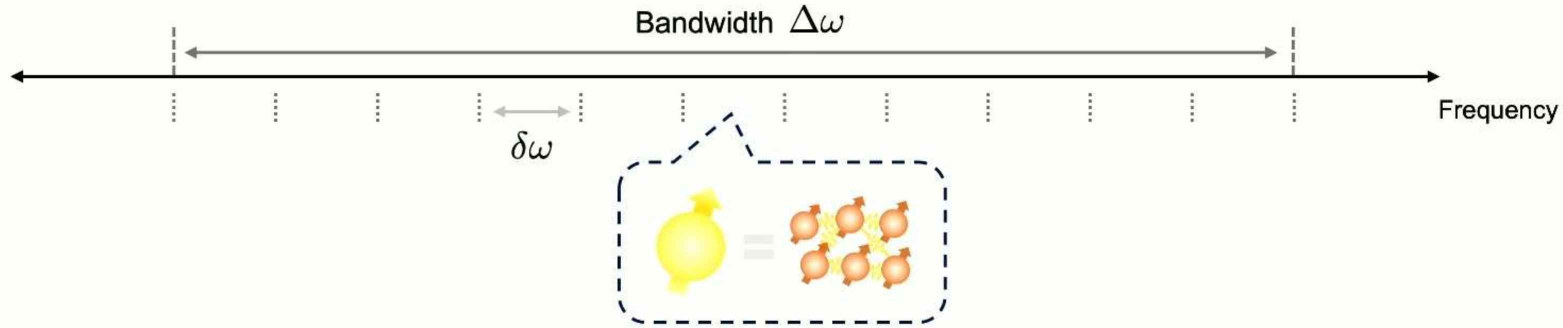
Total sensing time

$$\tau_{\text{conv}} = \frac{\Delta\omega}{(B_{\min})^2}$$

Conventional approach



Conventional approach



Standard Quantum Limit

$$\tau \sim \frac{\Delta\omega}{N\, B_{\min}^2}$$

Heisenberg Limit

$$\tau \sim \frac{\Delta\omega}{N^2\, B_{\min}^2} = \frac{1}{NB_{min}} \times \frac{\Delta\omega}{NB_{min}}$$

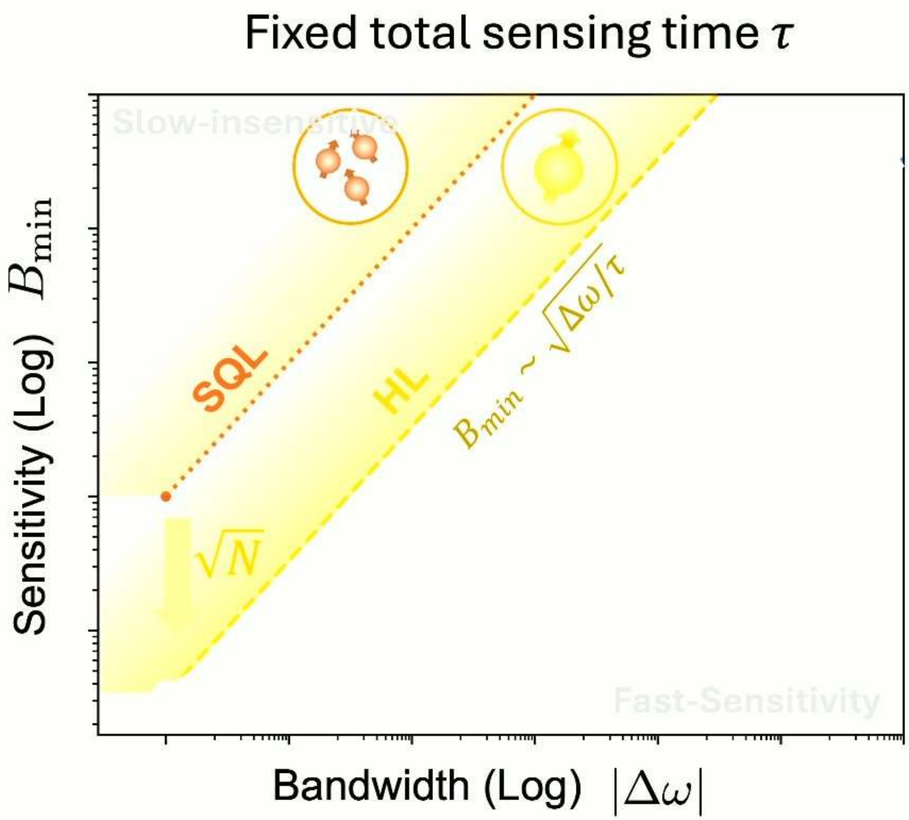
Any conventional approaches*

Minimum time needed scales as

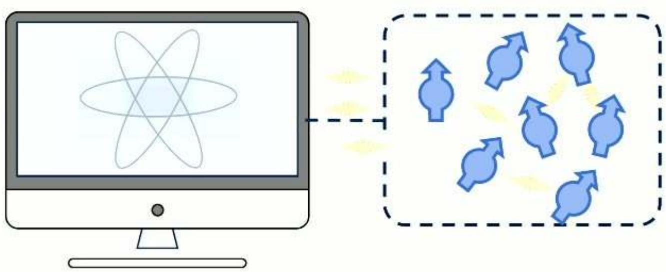
$$\tau_{\mathrm{conv}} = \Omega\left(\frac{1}{NB_{\min}}\left\lceil\frac{\Delta\omega}{NB_{\min}}\right\rceil\right)$$

* See Theorem 3 and Theorem 5 in arXiv:2501.07625

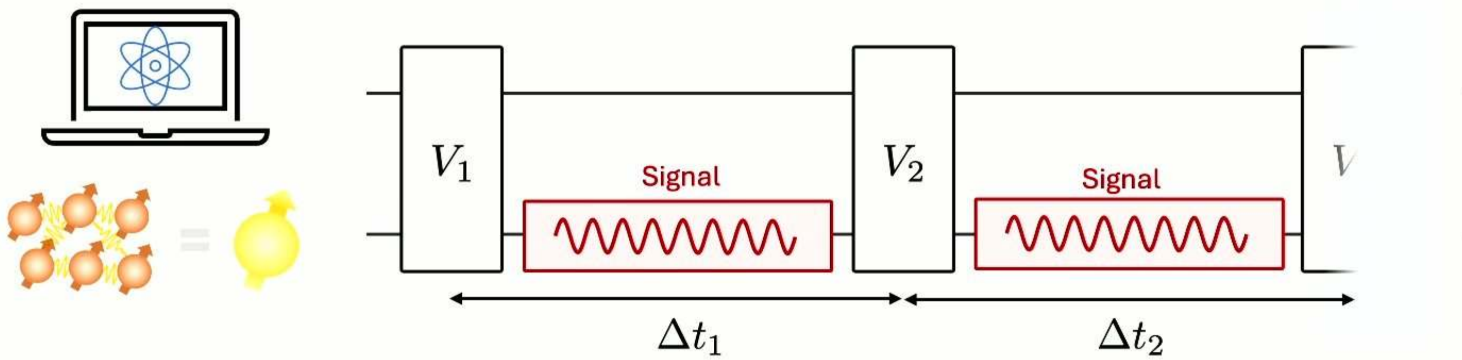
Conventional approach



Quantum Computing Enhanced Sensing



Quantum Computing Enhanced Sensing



- ✓ Infinitely fast gates V_k
- ✓ Infinitely short intervals $\Delta t_k \to 0$

Main results

Quantum Search Sensing (QSS) algorithm solves AC[$B_{\min}, \Delta\omega$] with N sensor particles within time :

$$\tau_{\mathrm{QSS}} = \tilde{O}\left(\frac{1}{NB_{\min}}\sqrt{\frac{\Delta\omega}{NB_{\min}}}\right)$$

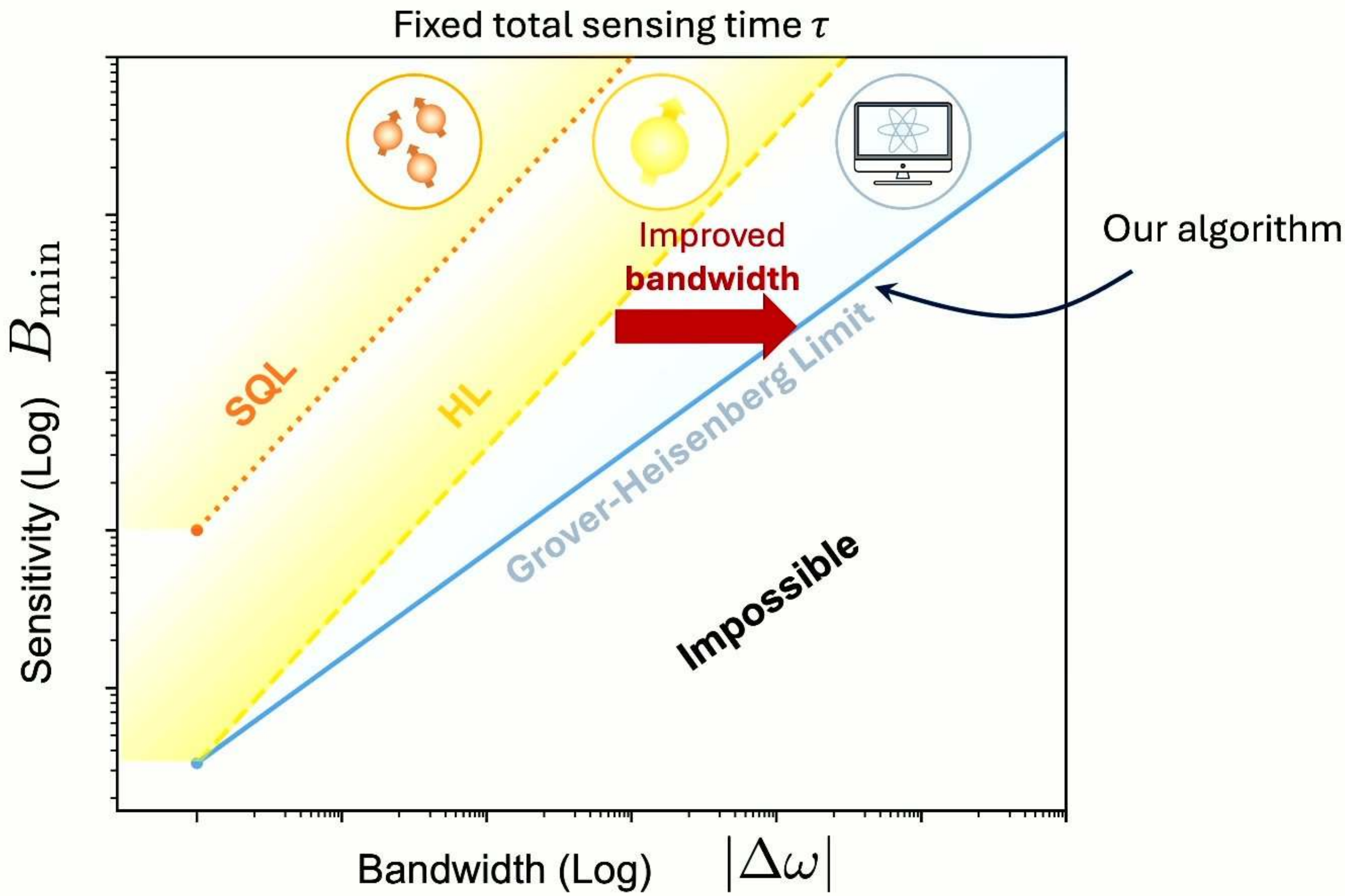
Note: $\tau_{\mathrm{conv}} = O\left(\frac{1}{NB_{\min}}\frac{\Delta\omega}{NB_{\min}}\right)$

No quantum algorithm can solve AC[$B_{\min}, \Delta\omega$] with N sensor particles faster than the fundamental limit :

$$\tau_{\mathrm{GHL}} = \Omega\left(\frac{1}{NB_{\min}}\sqrt{\frac{\Delta\omega}{NB_{\min}}}\right)$$

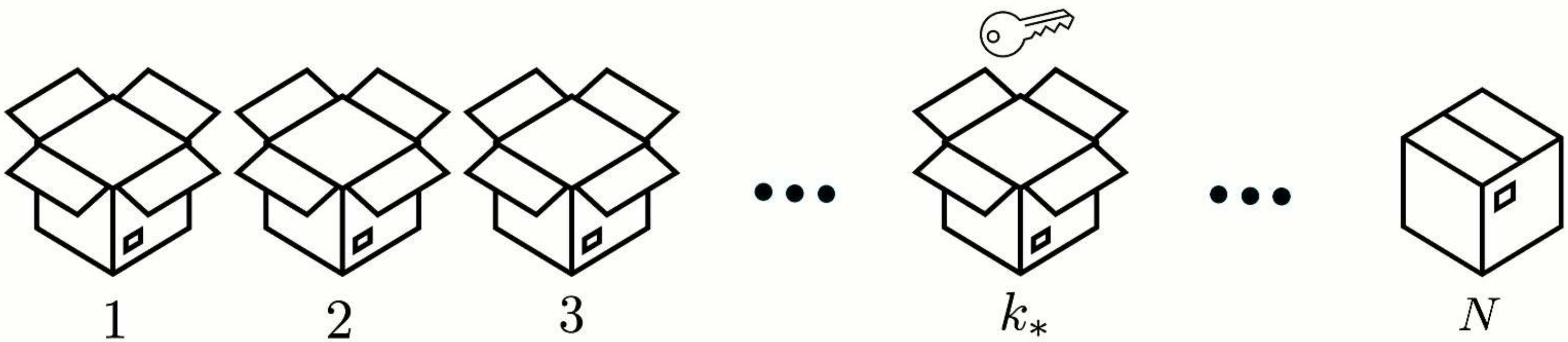
Grover-Heisenberg Limit

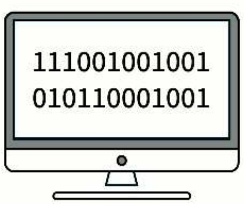
Quantum Search Sensing



Search Problem

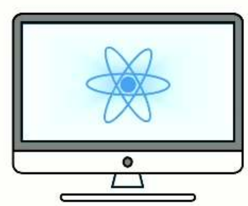
Given N identical boxes, find the “marked” box





Classically, $O(N)$ queries

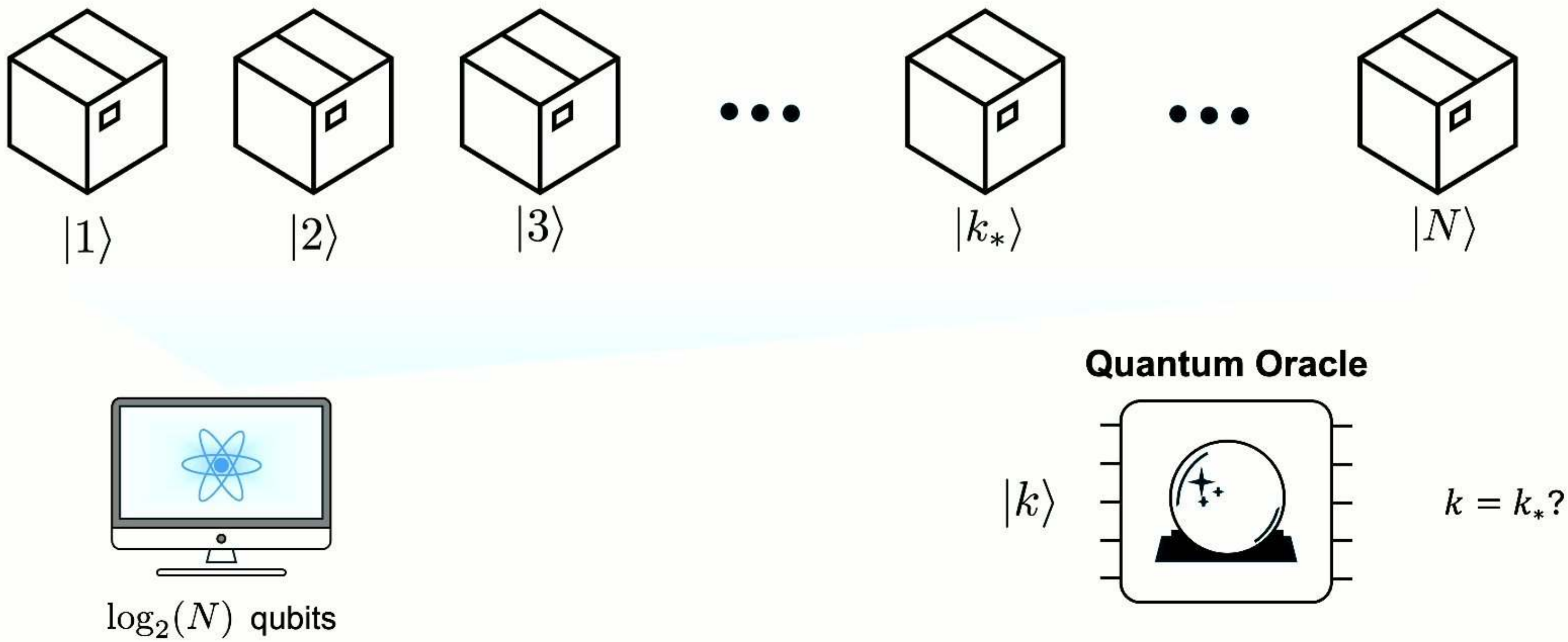
vs.



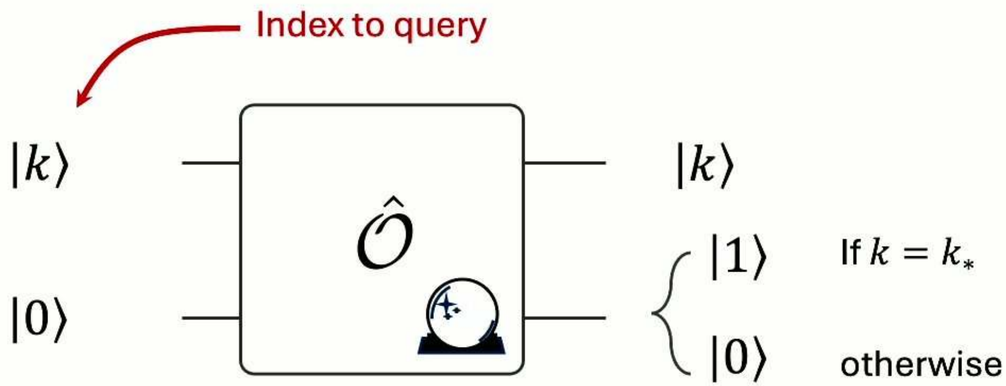
Quantumly, $O(\sqrt{N})$ queries!

Quantum Oracles

What does it mean to query “quantumly?”



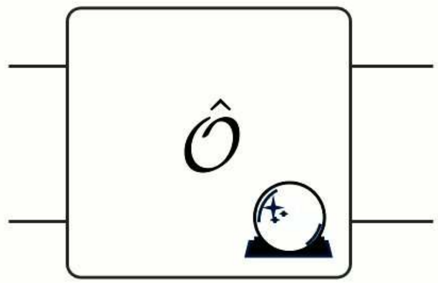
Grover Algorithm requires an Oracle



Grover Algorithm requires an Oracle

$$\sum_k c_k \, |k\rangle$$

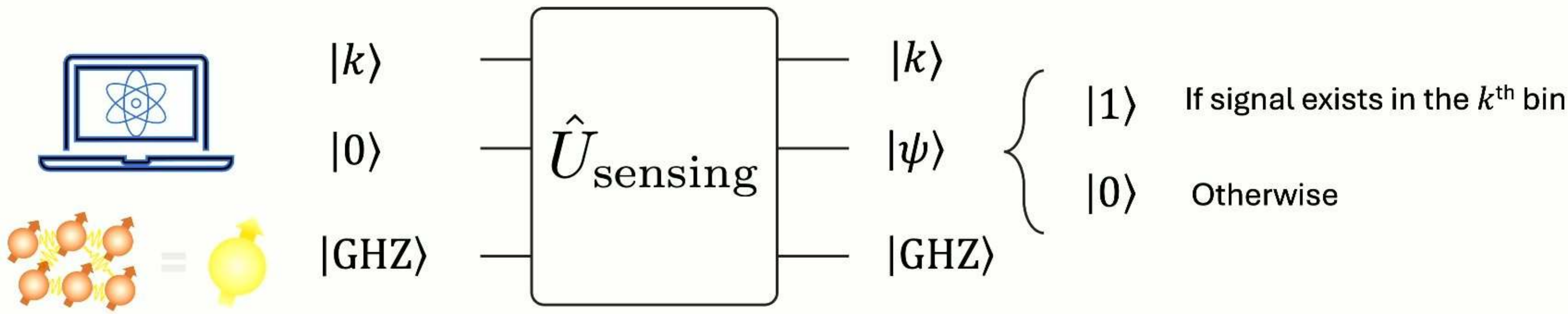
$$|0\rangle$$



$$\sum_{k \neq k_*} c_k |k\rangle \, |0\rangle + c_{k_*} |k_*\rangle |1\rangle$$

Quickly verify the marked element while maintaining coherent superposition

Building an Oracle from Quantum Sensing



Challenges

- Unitary implementation
- Coherent superposition input $|k\rangle$
- Sensors must be decoupled
- High fidelity

More Challenges

$B(t) = B\cos(\omega t + \phi)$

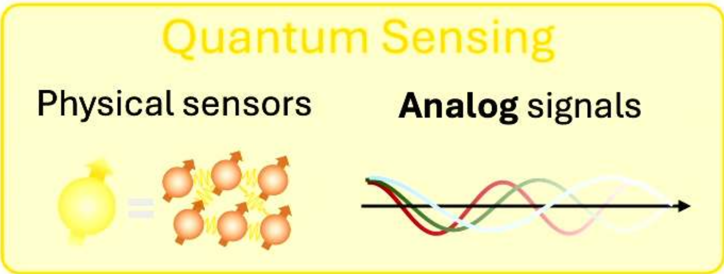
- Unknown B
- Continuous ω
- Unknown ϕ

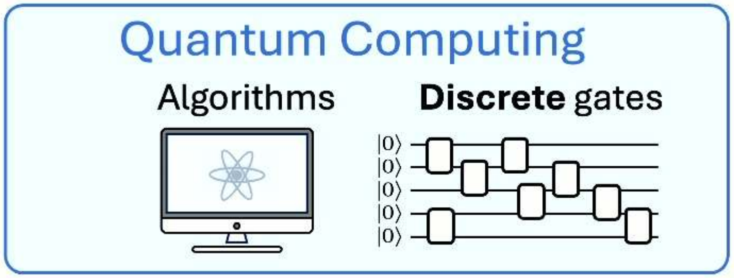
$H_{\mathrm{signal}}(t) = B(t)\,\hat{Z}$

- Analog coupling to signal
- Discrete Oracle output

Key Challenge:

Interfacing quantum sensing and computing

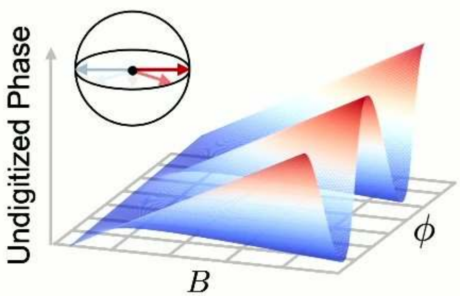




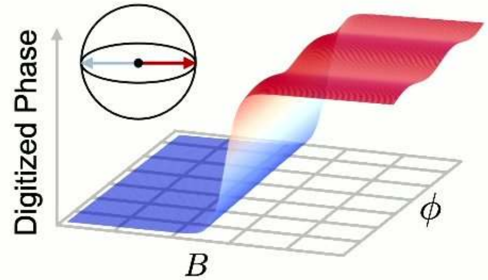
Digitization: interfacing quantum sensors and computers

Unitarily transform analog signals into
high-accuracy discrete operations

Analog response

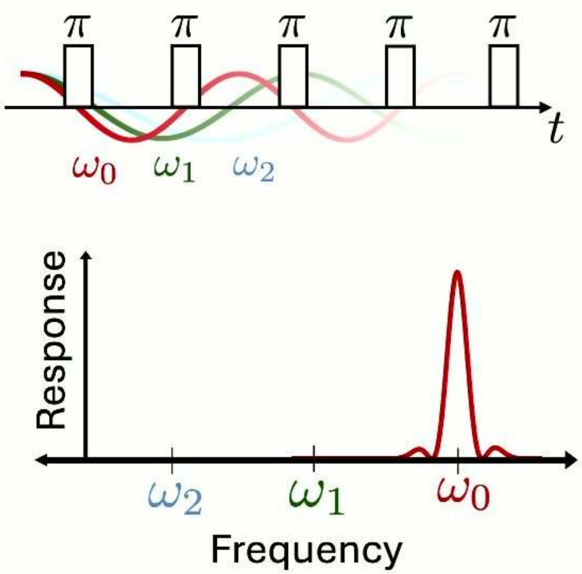


Digitized response

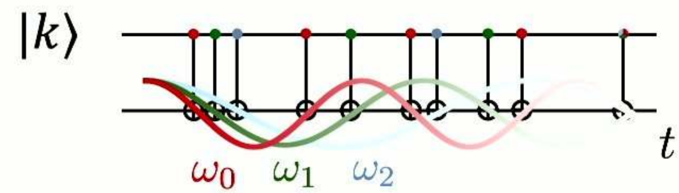


Key Idea 1: Coherent Superposition Sensing

Conventional AC sensing

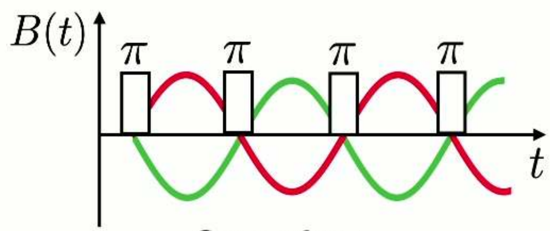


Quantum controlled AC sensing

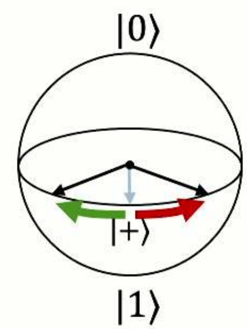


Key Idea 2: Phase Agnostic Sensing

Conventional AC sensing



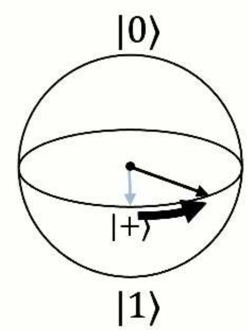
- Same freq.
- Different phase ϕ



- *Unreliable oracle*

What we want

- Same freq.
- Different phase ϕ

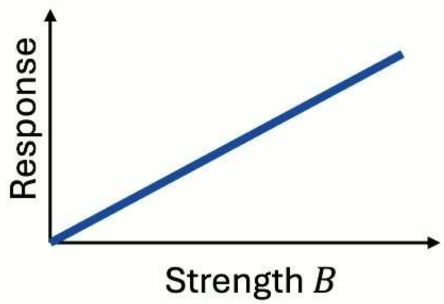


- ***Reliable oracle***

✓ *AC Stark shift*
✓ *(super)adiabatic theorem*

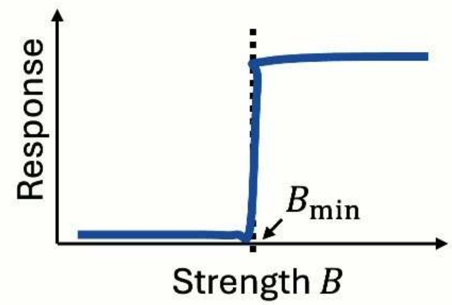
Key Idea 3: Nonlinear Signal Processing

Conventional AC sensing



- *Continuous response*

What we want



✓ *Robust discrete response*

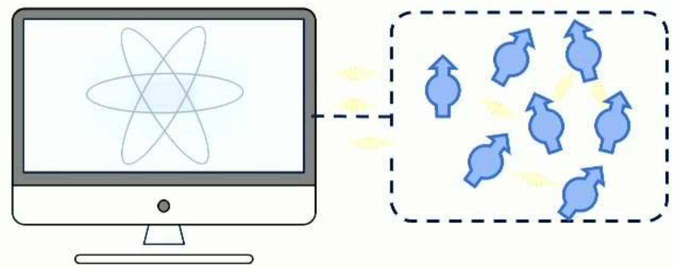
Quantum signal processing

Repeated θ-rotations

$$R_x(\phi_0)\; R_z(\theta)\; \cdots\; R_z(\theta)\; R_x(\phi_L)$$

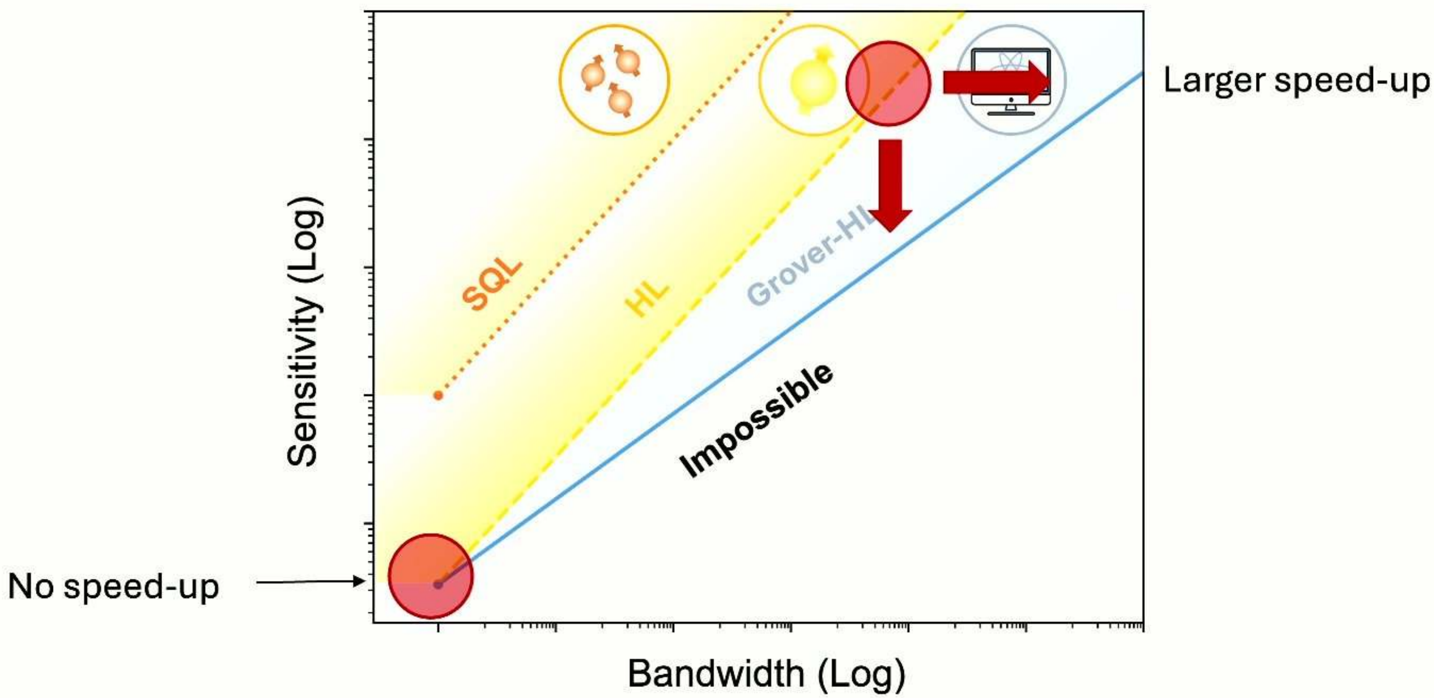
Today's talk

- AC Sensing
- **Quantum Advantage**
- Near-term Experiment
- Discussion



Grover advantage = quadratic speed-up (?)

Computational Time ≠ Sensing Time



Grover advantage = quadratic speed-up (?)

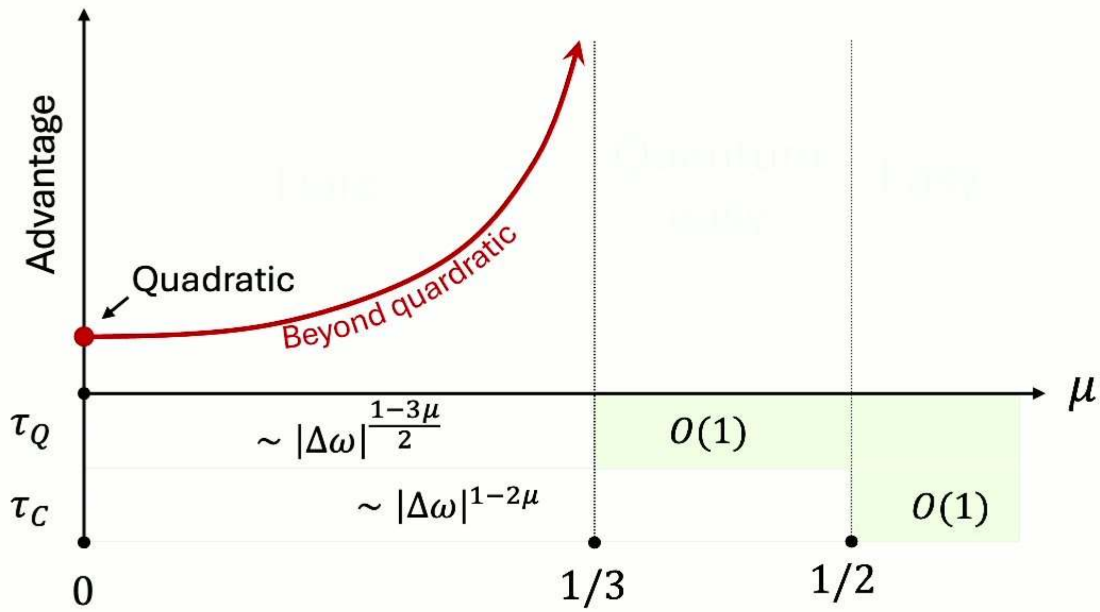
Computational Time ≠ Sensing Time

Structured AC sensing:

$$H(t) = \hbar g_\omega B(t)\, \hat{S}_z$$

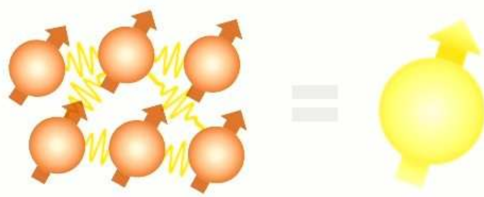
Coupling strength:

$$g_\omega \propto \omega^\mu$$



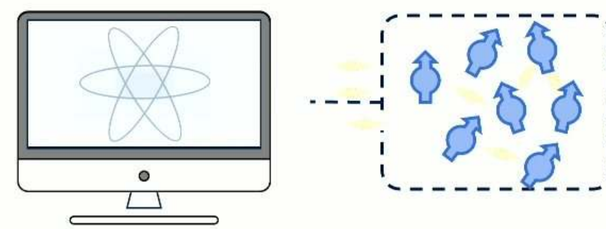
Origin of metrological gain

Entanglement enhanced sensitivity



✓ Collective behaviors

Quantum Search Sensing



Quantum Computation (???)

Necessary Ingredients to Achieve Grover-Heisenberg Limit

- ✓Nonlinear, nonperturbative approach (Theorem 3)
- ✓Long coherent quantum memory (Theorem 4)
- ✓Non-classical control (Theorem 5)

Necessary Ingredients to Achieve Grover-Heisenberg Limit

- ✓Nonlinear, nonperturbative approach (Theorem 3)
- ✓Long coherent quantum memory (Theorem 4)
- ✓Non-classical control (Theorem 5)

Coherent quantum information processing

Nonlinear nonperturbative approach is necessary

Linear (perturbative) approach: $|\Psi(t)\rangle \approx |\Psi_0\rangle + \alpha\, B\, |\Psi_\perp\rangle$

Maximize the coefficient $|\alpha|$ or quantum Fisher Info: $\mathcal{F}_Q \leq 4|\alpha|^2$.

Solving AC$[B_{\min}, \Delta\omega]$ ⟺ $|\alpha\, B_{\min}|^2 = O(1)$ for $\omega \in \Delta\omega$ on average

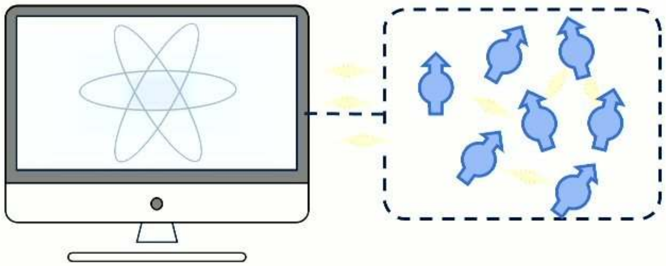
Any QFI-based protocols solving AC$[B_{\min}, \Delta\omega]$ must take time at least :

$$\tau_{\text{conv}} = \Omega\left(\frac{1}{NB_{\min}}\frac{\Delta\omega}{NB_{\min}}\right)$$

Quantum Fisher information is of limited use.

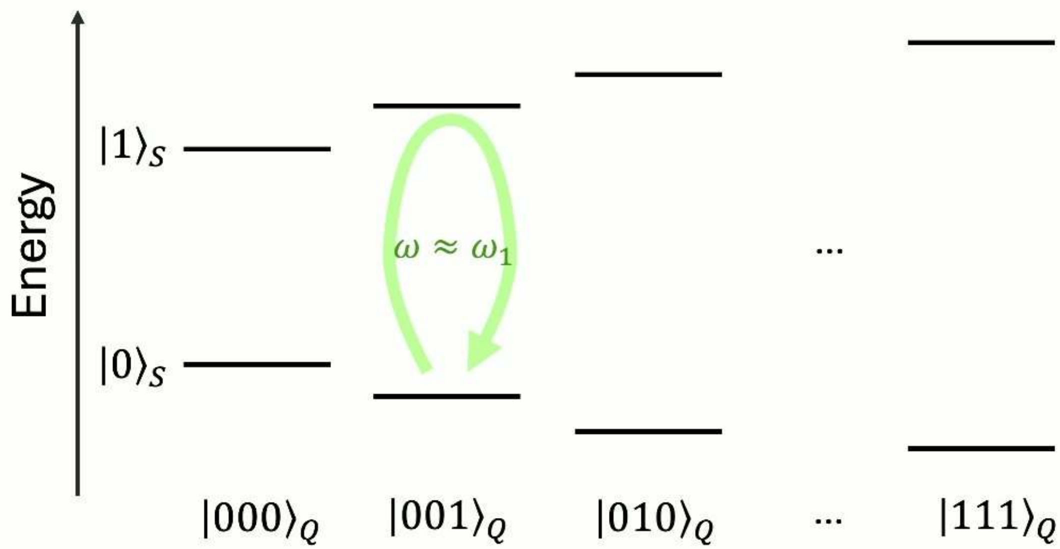
Today's talk

- AC Sensing
- Quantum Advantage
- **Near-term Experiment**
- Discussion & Outlook



Near-term Experimental Implementation

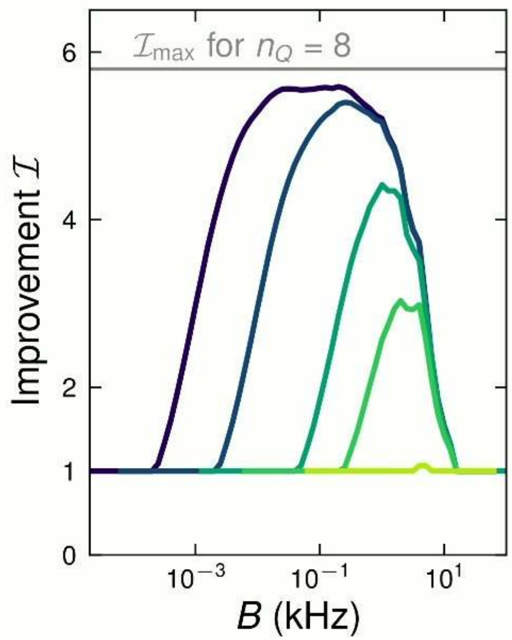
$$H = \frac{\omega_S}{2}\hat{Z}_S + \sum_{i=1}^{N_Q}\frac{J_i}{2}\hat{Z}_s\hat{Z}_{Q,i} = \sum_k \omega_k \hat{Z}_S \otimes |k\rangle\langle k|$$

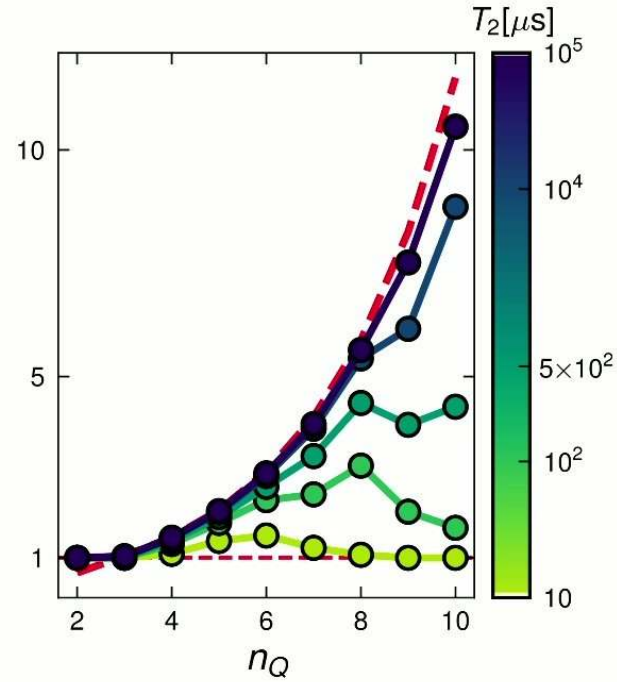


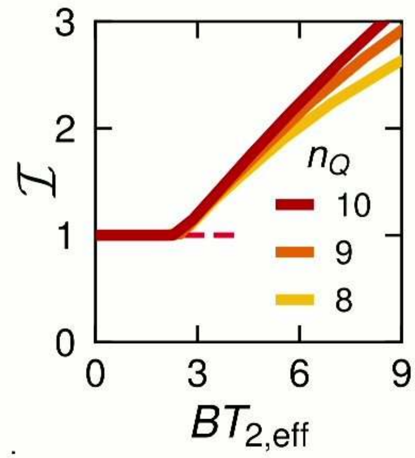
✓ Superposition sensing
✓ Grover reflection operation

NV centers

Improvement $\mathcal{I} = \tau_{\mathrm{conv}}/\tau_{\mathrm{QSS}}$



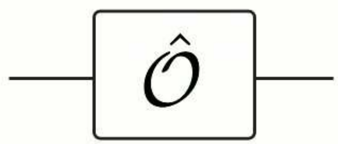




$$\mathcal{I} \sim BT_{2,\mathrm{eff}}$$

Discussion & Outlook

"Nature as Oracle"



Discussion & Outlook

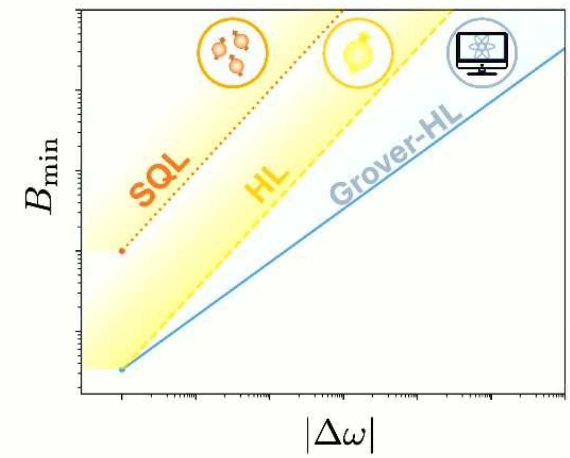
"Robust Interface of Quantum Sensors and Computers"

Summary

Broadband AC sensing

✓ Algorithm: Quantum Search Sensing

✓ Optimality: Grover-Heisenberg Limit



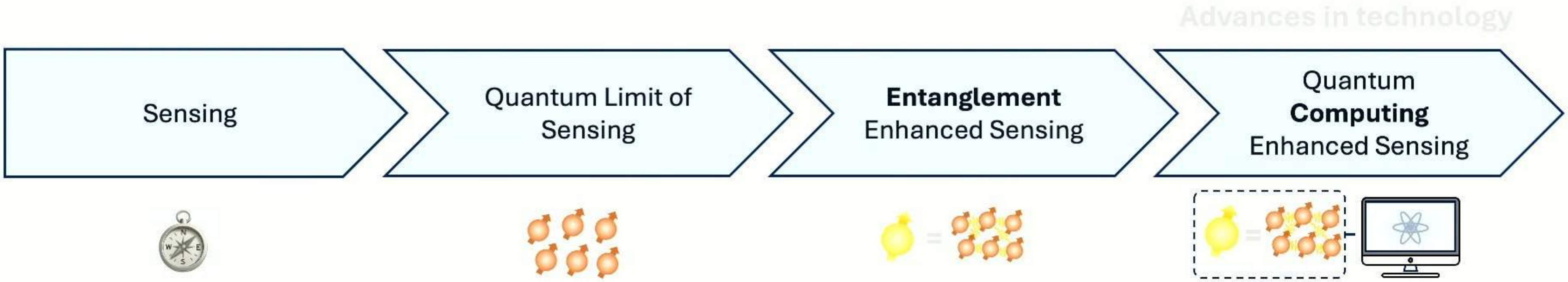
Necessary ingredients

✓ Non-perturbative

✓ Non-classical control

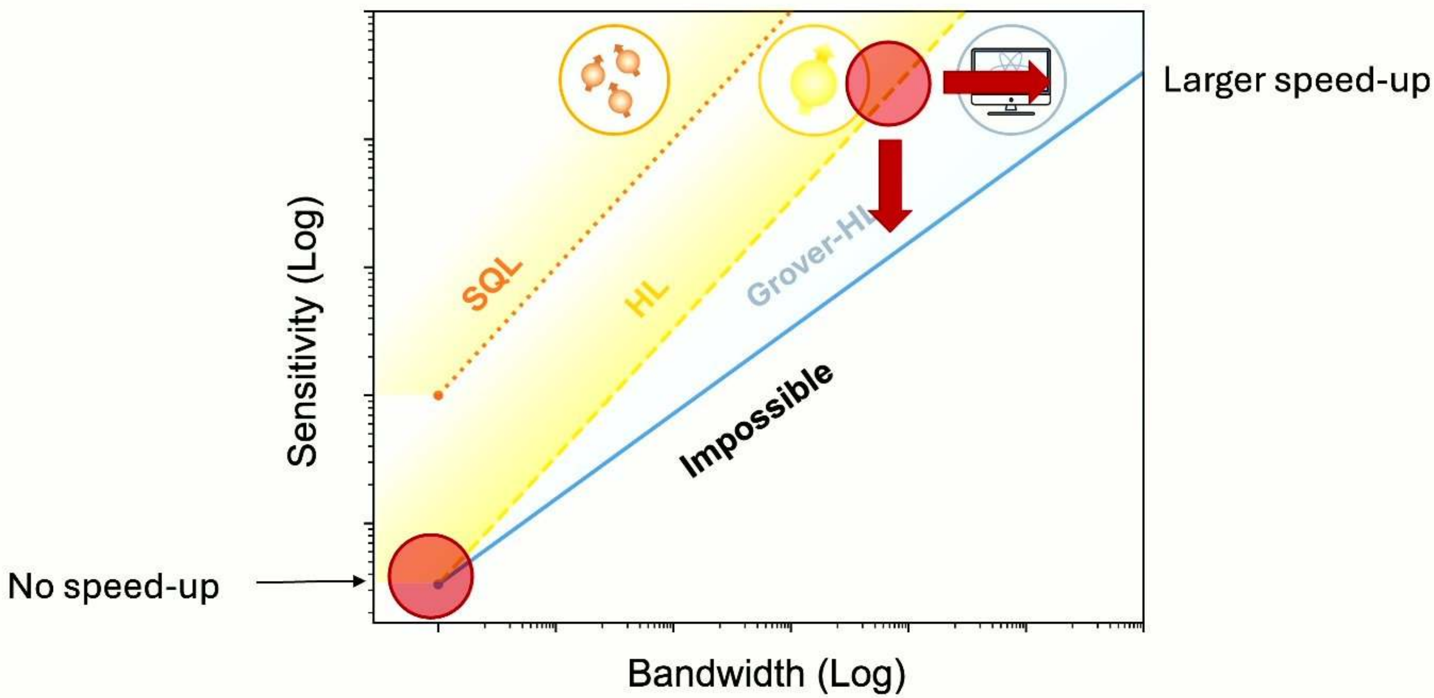
"Digitization"

"Nonlinear signal processing"

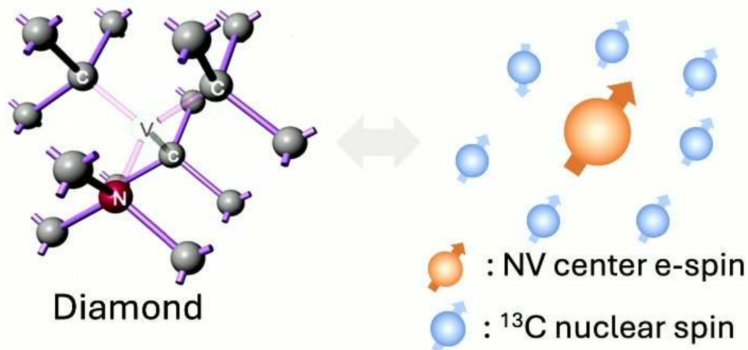


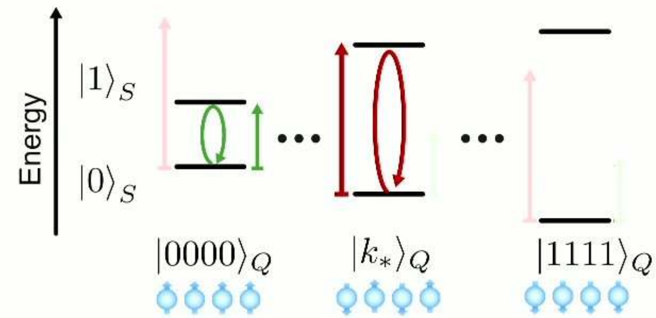
Grover advantage = quadratic speed-up (?)

Computational Time ≠ Sensing Time

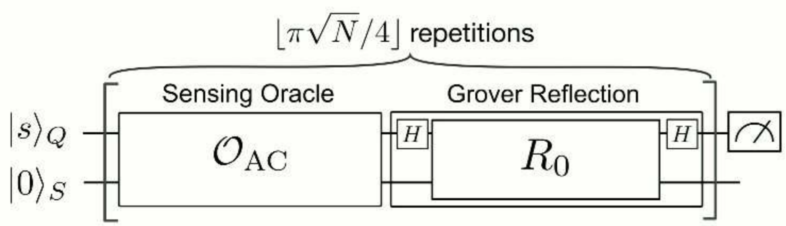


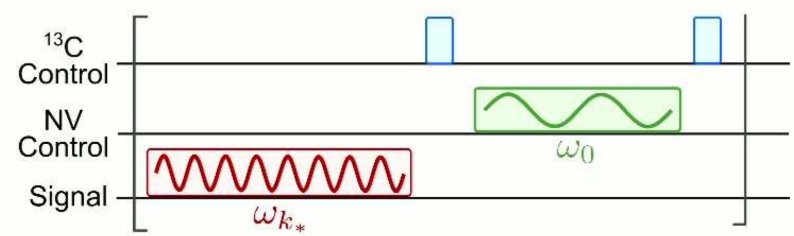
NV centers





Pulse-level implementation of a simplified algorithm*





* If a signal exists, we assume $B = 0$ is known and $\omega \in \{\omega_k\}$.

Discussion & Outlook

"Robust Interface of Quantum Sensors and Computers"