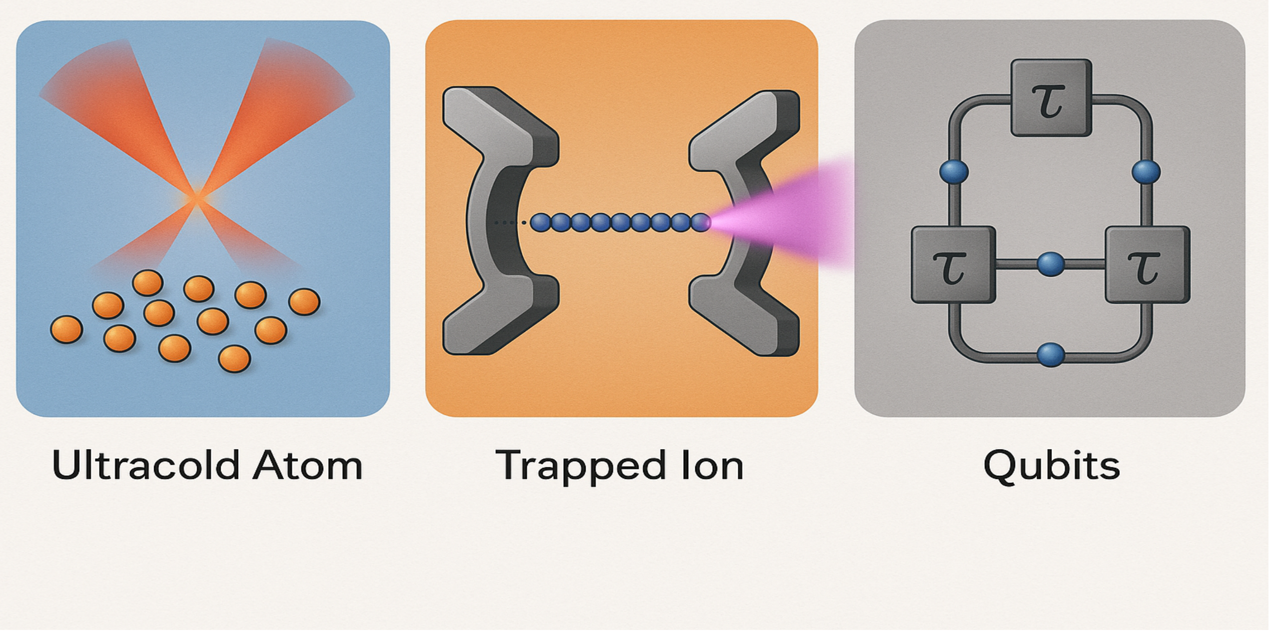


MANY-BODY QUANTUM SENSORS

The Next Frontier In Precision Technology

Debraj Rakshit
Harish-Chandra Research Institute, Allahabad

QIT-2025

IIIT Allahabad

QIC group at HRI (past & present)

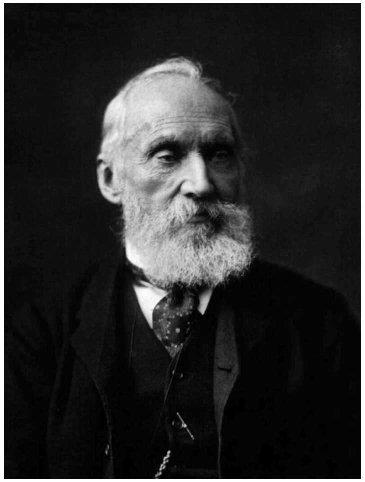
Outline

- From Classical to Quantum
- Quantum Sensing in Action (case studies)
  - Uncertainty as resource
  - Entanglement as resource
- The Theory Behind Quantum Precision (brief review)
- The Next Generation of Quantum Sensors—Quantum Many-Body Sensors
- Quantum Many-Body Systems: Computational Complexity and Beyond
- Quantum Simulators: Ideology and AMO Realizations
- AMO Platforms in Action —
  - Quantum Critical Sensing via Localization in Quasiperiodic Fermionic Lattices
  - Quantum Critical Sensing of Faint Potentials via Tilted Bosonic Lattices
- Critical Quantum Sensors: What Is the Origin of Quantum Advantage?
- Summary and Perspectives

Measurement: Gauge it better to make it better

Measurement: Gauge it better to make it better

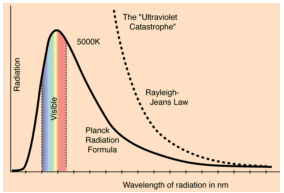
Classical physics at its pinnacle
Impressive achievements with electromagnetism, mechanics, astronomy …

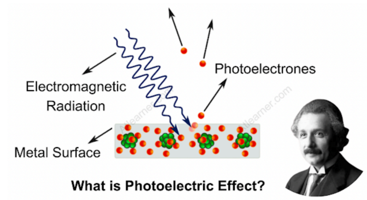


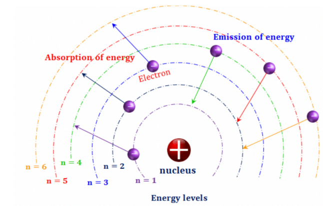
1897 (Lord Kelvin): famously stated, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"

1897: Electron was discovered, beginning of a new era in physics …

Series of experiments gave birth to the Quantum Mechanics







1900 – Planck: Introduced energy quantization to solve blackbody radiation

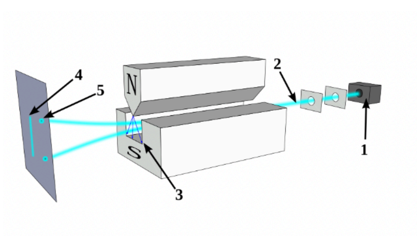
1905 – Einstein: Explained the photoelectric effect using photons

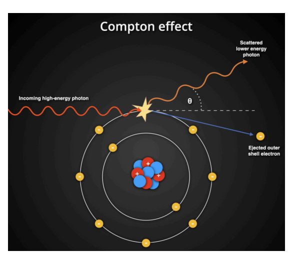
1913 – Bohr: Proposed quantized orbits in the hydrogen atom

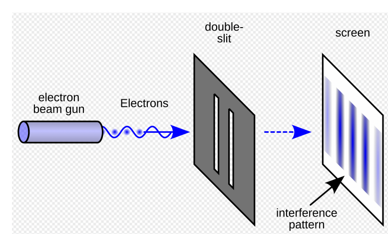
1922 – Stern–Gerlach: Showed spin quantization using silver atoms

1923 – Compton: Demonstrated photon momentum via X-ray scattering

1927 – Double-Slit (Electrons): Revealed superposition through interference pattern







The striking new world of Quantum Mechanics

Quantization

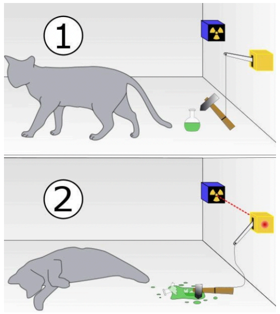
Wave nature of QM

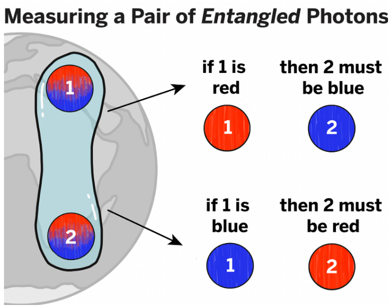
Probabilistic

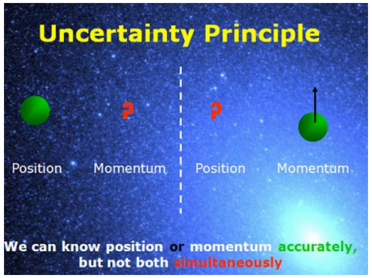
Superposition

Entanglement

Uncertainty





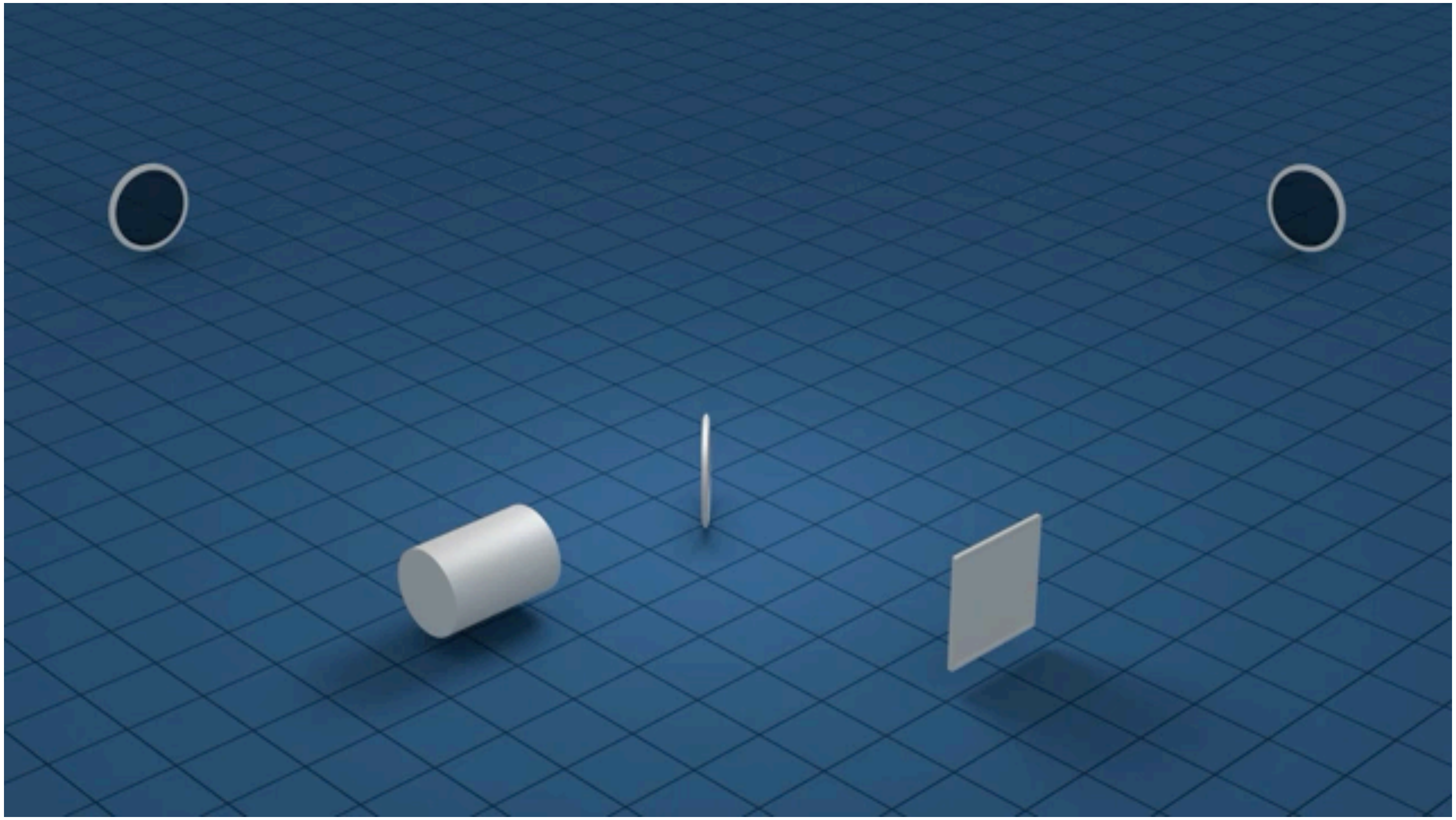


QUANTUM SENSING

—Exploit quantum phenomena for enhanced precision

Quantum Sensing: Example-1 (Detection of gravitational wave at LIGO)

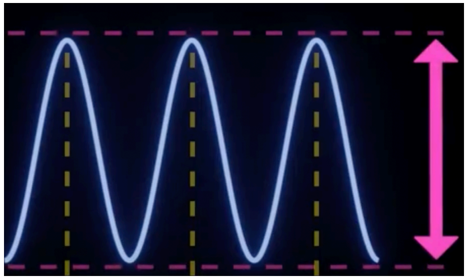
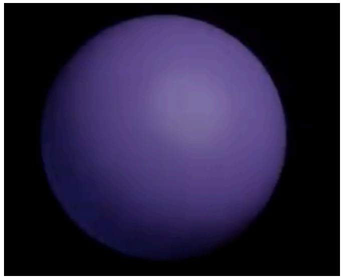
Manipulate **uncertainty** from QM **in light** for in order to make more and more precise measurement



Quantum Sensing: Example-1 (Detection of gravitational wave at LIGO)

Manipulate **uncertainty** from QM **in light** in order to make more and more precise measurement

- LIGO injects **squeezed light**—a special light state with reshaped quantum uncertainty—into its detector
- This squeezes uncertainty in the **phase** (where the signal is) and shifts it into the **amplitude** (less critical)
- The effect is like squeezing a balloon: squeezing one direction expands the other

Quantum Sensing: Example-2 (Detection of Phase)

Manipulate **entanglement** from QM in order to make more and more precise measurement

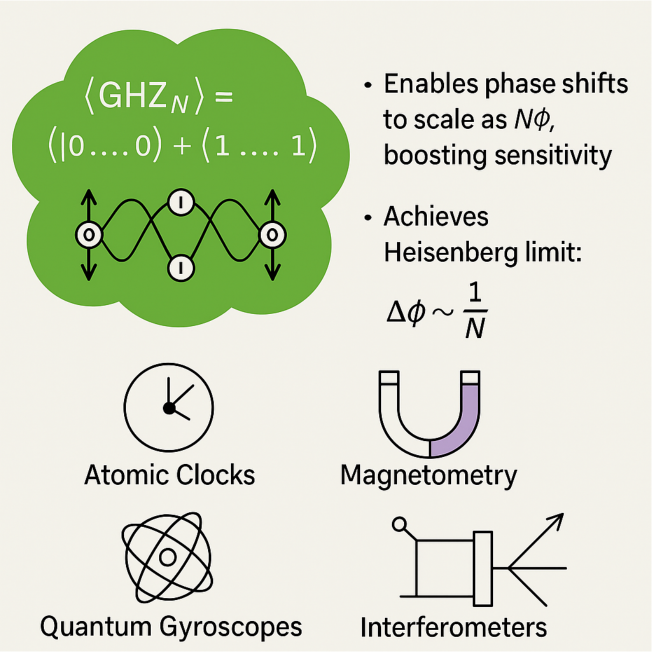
$$\text{GHZ State: } |\mathsf{GHZ}_N\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle^{\otimes N} + |1\rangle^{\otimes N}\right)$$

$$\text{Phase encoding: } |\mathsf{GHZ}_N\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle^{\otimes N} + e^{iN\phi}|1\rangle^{\otimes N}\right)$$

Sensitivity Improvement

Heisenberg limit (with GHZ): $(\Delta\phi)^2 \propto \frac{1}{N^2}$ [variance in ϕ]

Standard quantum limit: $(\Delta\phi)^2 \propto \frac{1}{N}$



Limits of Precision Measurement

—Fundamental bound

Estimation theory (quantum)

Quantum system: A family of quantum states defined on a given Hilbert space $\mathcal{H}$ and labeled by a parameter λ living on a d-dimensional manifold $\mathcal{M}$, with the mapping: $\lambda \mapsto \rho(\lambda)$

Quantum estimator: $\hat{\lambda}$ is a self joint operator → Describes a quantum measurement followed by any classical data processing performed on the outcomes

The ultimate precision attainable by quantum measurements: Quantum Cramer-Rao theorem

$$\Delta^2 \widehat{\lambda_q} \geq F_q(\lambda)^{-1}: \qquad \text{Quantum Cramer} - \text{Rao bound}$$

$\Delta^2 \widehat{\lambda_q}$ ↓ Varience

$F_q(\lambda)$ ↓ Quantum Fisher information – A metric in $\mathcal{M}$

Quantum Cramer – Rao bound ↓ Independent of measurement

$\mathcal{M}$ copies of the state: $\Delta^2 \widehat{\lambda_q} \geq (\mathcal{M} F_q(\lambda))^{-1}$

Quantum estimation: Inferring the estimator and the metric

Given an observable $\hat{O}$, the signal-to-noise ratio (SNR) for estimating the parameter λ as

$$F_o[\lambda] = \lim_{\delta V \to 0} \frac{\left(\frac{d\langle\hat{o}\rangle}{d(\delta\lambda)}\right)^2}{\langle\hat{o}^2\rangle - \langle\hat{o}\rangle^2}$$

↓

Directly related to the mean-square error of the estimator: Useful in parameter estimation

Maximize the SNR over all possible observables → Obtain quantum Fisher Information (QFI):

$$F_q[\lambda] = \max_{\hat{o}} F_o[\lambda]$$

$$F_q = \lim_{\delta\lambda \to 0} \frac{8}{\delta\lambda^2}[1 - F(\rho_\lambda, \rho_{\lambda-\delta\lambda})]$$

Fidelity susceptibility

$$F(\rho, \sigma) = Tr\left(\sqrt{\rho\sqrt{\sigma}\rho}\right)$$

S. L. Braunstein and C. M. Caves, Phys. Rev. Lett. **72**, 3439 1994

QUANTUM MANY-BODY SENSORS

(NEWLY EMERGING IDEAS)

Critical Quantum Sensors (core idea)

Quantum criticality (2nd order, topological, localization transitions)

Characterized by gap-to-gapless transitions, symmetry breaking, long-range correlations

↓

Quantum resources for enhanced precision

Adiabatic quantum sensors:

Enhanced scaling of QFI at criticality: $F_Q \propto L^\beta$

$\beta = 1$: Standard quantum limit
$\beta = 2$: Heisenberg scaling

Syatem-size as a resource

Dynamical quantum sensors:

Involves evolution: $F_Q \propto L^\beta t^\alpha$

Time as resource, along with system-size

Critical Quantum Sensors — What is Quantum Criticality?

Quantum criticality (2nd order, topological, localization transitions)

Characterized by gap-to-gapless transitions, symmetry breaking, long-range correlations

What Is a Phase Transition?

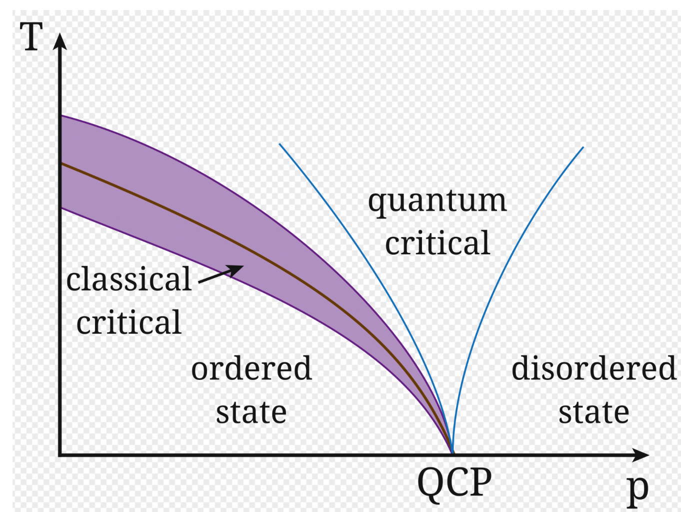
- In classical systems (like water freezing), transitions happen by **thermal fluctuations** at finite temperature.

What Makes Quantum Phase Transitions (QPT) Different?

- **QPTs happen at absolute zero (T = 0)**
- Caused by **quantum fluctuations**, not thermal energy

Key Features of QPT:

- Marked by a **non-analytic change** in the ground state
- Show **critical points** with long-range entanglement
- Governed by **universal scaling laws** and **critical exponents**



Why It Matters:

- Fundamental to understanding **quantum matter**
- Connects to **quantum information**, **entanglement**, and **emergent phenomena**

Critical quantum sensors: Formalism

System size as a resource

Around criticality

$L \to \infty$ → $F_Q[\lambda] \propto |\lambda - \lambda_c|^{\alpha}$

Finite size → $F_Q[\lambda = \lambda_c] \propto L^{\beta}$

$\zeta \sim |\lambda - \lambda_c|^{-\nu}$ → Diverging length scale at criticality

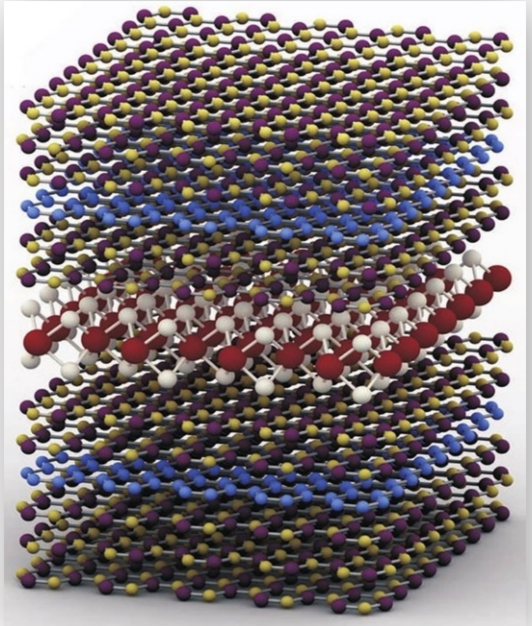
$$F_Q = L^{\alpha/\nu} g[L^{1/\nu}(\lambda - \lambda_c)]$$ → Finite-size scaling Ansatz

$$\beta = \alpha/\nu$$

QUANTUM MANY-BODY SYSTEMS

(COMPUTATION COMPLEXITIES)

SECRET Life of Matter



Efitov's group, ICFO

Physical properties

Energy
Magnetism
Conductivity
Correlations
Entanglement
Dynamics

|0000……0>
|0000.......1>
.
.
.
.
|11111.......1>

$$|\Psi\rangle = C_1 \, |0000\ldots\ldots0\rangle + C_2 \, |0000\ldots\ldots.1\rangle + \ldots\ldots.. + C_N \, |11111\ldots\ldots.1\rangle$$

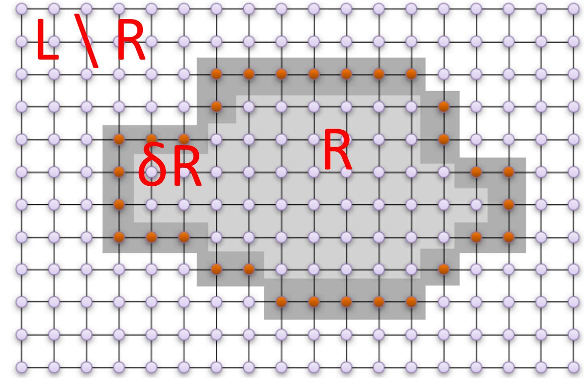
Hilbert space dimension increases as 2^L (NP-hard)

"… cannot be solved accurately when the number of particles exceeds about 10. No computer existing or that will ever exist can break this barrier because it's a catatrophe of dimension ..."

(Pines and Laughlin, 2000)

Direct diagonalization can solve lattice systems with L ~ 30

Many-body Complexity and Information



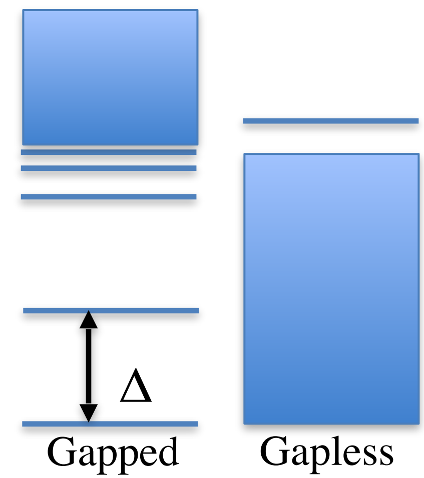
Entanglement entropy

$$|\psi\rangle = \sum_{i_1 i_2 \ldots i_L} c_{i_1 i_2 \ldots i_L} |i_1\rangle |i_2\rangle \ldots |i_L\rangle = \sum_\alpha \Lambda_\alpha |\alpha\rangle_A \otimes |\alpha\rangle_B$$

$$S = -\mathrm{Tr}(\rho_R \log \rho_R) = -\sum_\alpha \Lambda_\alpha^2 \log \Lambda_\alpha^2$$

Local gapped Hamiltonian respect **area law:**

$$S(\rho_R) = O(|\partial R|)$$



1D: $H = \sum_{i \in L} H_{i,i+1}; \| H_{i,i+1} \| \le J$

$\mathrm{S(L) = Const.}$ (Hestings, 07)

Nature's kindness: Entropy is naturally extensive, area law is not

DMRG, MPS….

Only special classes of QMB systems can be solved efficiently

Quantum Simulators: Ideology

There exists may exotic quantum phenomena with important applications

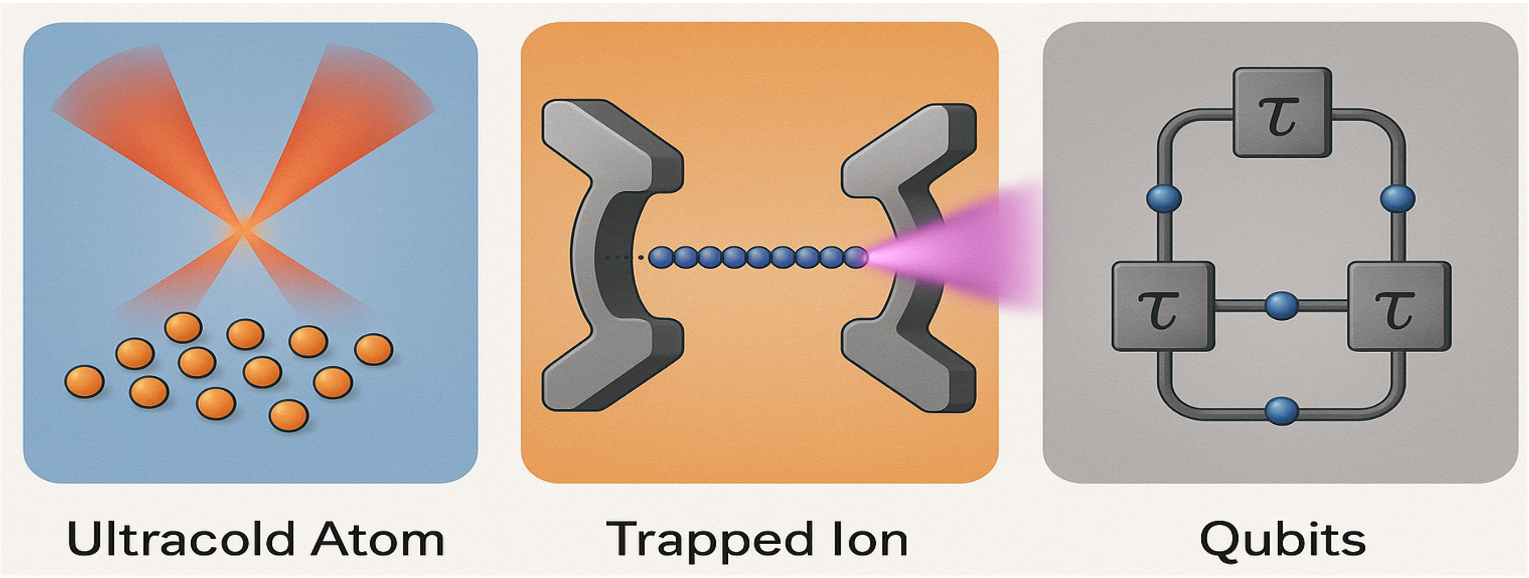
Developing full understandings via classical computer are difficult (often impossible) due to inherent many-body complexity

May be we can use a simpler and better controllable quantum system to simulate and understand the target system. Such a system would thus work as **quantum computer of special purpose**, i.e. QUANTUM SIMULATOR

M Lewenstein, A Sanpera, V Ahufinger, B Damski, A Sen and U Sen, Adv. Phys. 2007
I. Bloch, J. Dalibard, and W. Zwerger, RMP, 2008
M. Lewenstein, A. Sanpera, and V Ahufinger, Oxford University Press, 2012

Quantum Simulations on Physical Platforms

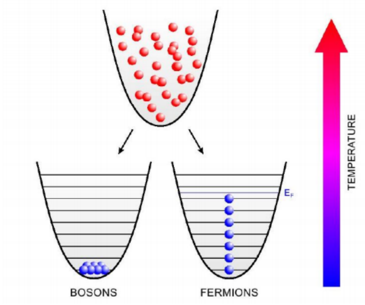
Engineered quantum materials …



AMO PLATFORMS

(AS A NEW CLASS OF QMB SENSING DEVICES)

Neutral Atoms

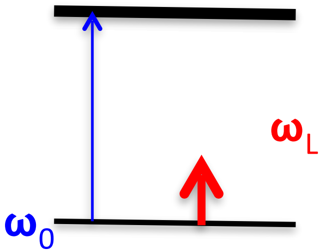


Neutral atoms can be composite bosons or composite fermions

They can be trapped optically via a combination of far detuned laser with spatially varying intensity

$\mathbf{d} = \alpha \mathbf{E}$

$U_{dip} = \mathbf{d} \cdot \mathbf{E}$

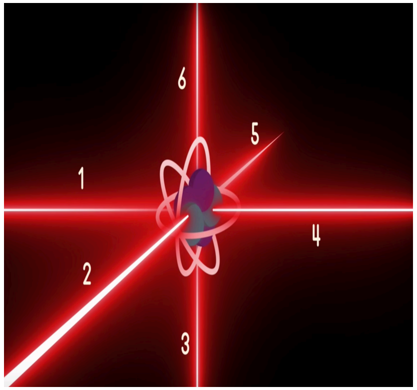


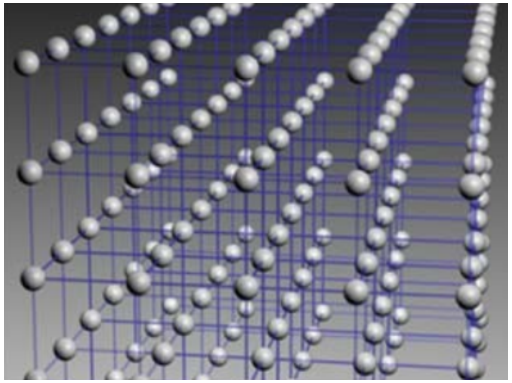
$\Delta = \omega_0 - \omega_L >> \Gamma_0$

They can be cooled to sub-nano temperature via several cooling techniques

They can be loaded into optical lattice

Steven Chu, Claude Cohen-Tannoudji and William D. Phillips 1997 Nobel
Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman 2001 Nobel

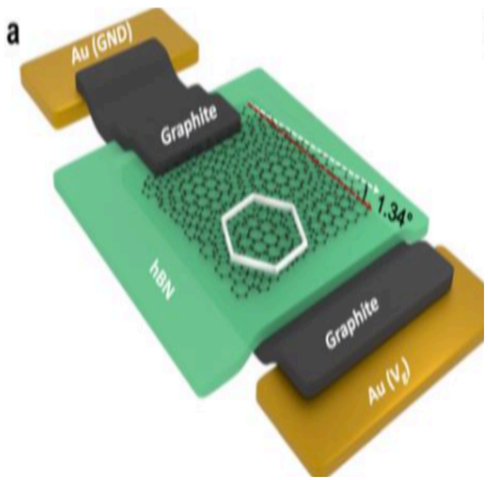




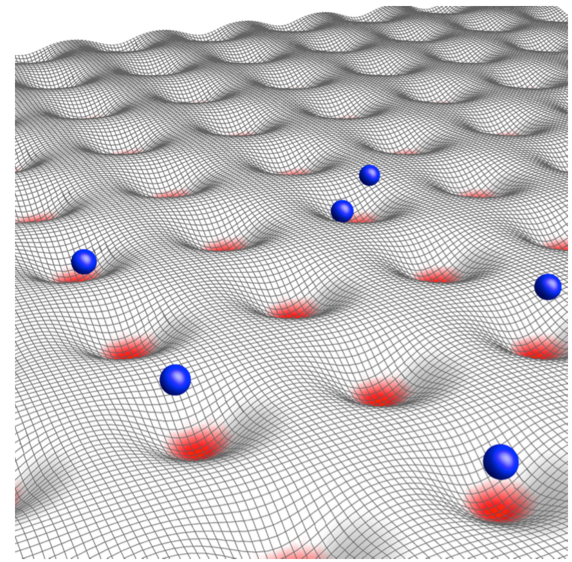
I. Bloch's group

Review: R. Grimm et al., Adv. At. Mol. Opt. Phys. 2000 [for cooling and trapping of neutral atoms]

PRINCIPLE OF EMERGENCE



Efitov's group, ICFO



Periodic potential made by ion <-> Periodic potential made by optical interference

Electron <-> Atom

- ULTRACOLD ATOMS BOUND TO LIGHT
- ION TRAPS
- SUPERCONDUCTING DEVICES
- PHOTONIC DEVICES

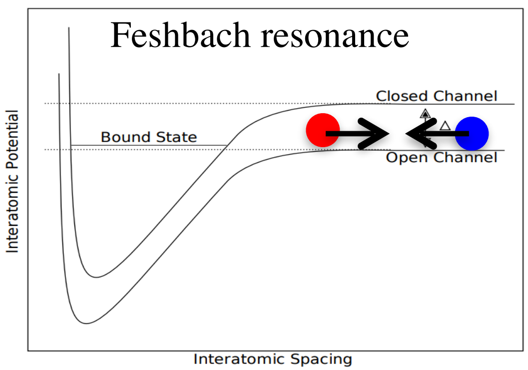
Unprecedented control of cold atoms in optical lattice

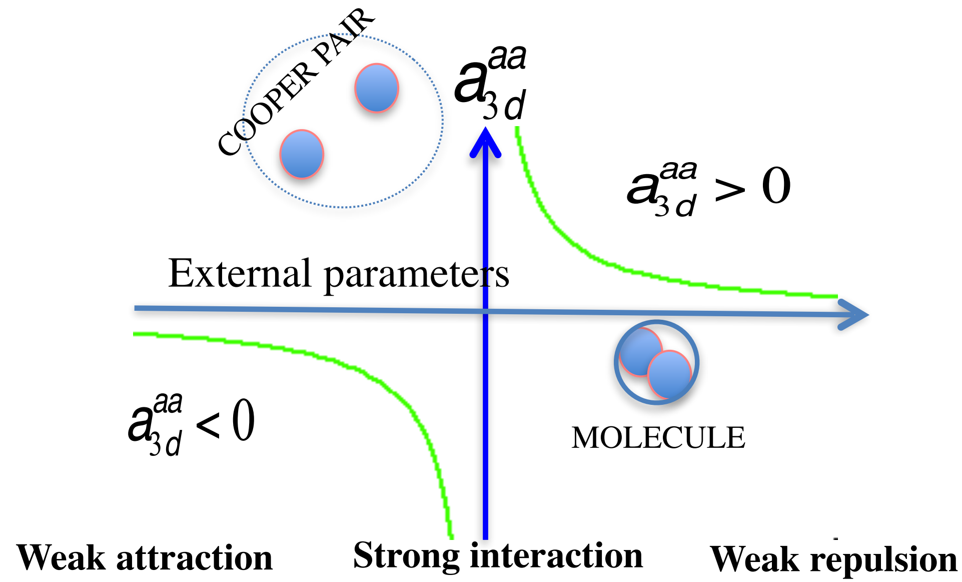
Interaction can be tuned:

Dilute atomic gas (n ~ 10^{12}-10^{15} atoms/cm^3)

- Two-body collisions play important role
- Three-body collisions are rare
- s-wave scattering (Universality)

$$a_s = -\lim_{k \to 0} \frac{\tan(\delta_k)}{k}$$



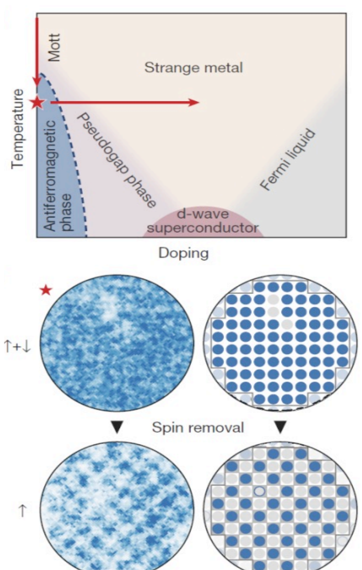


Tunneling can be tuned: Control laser intensity …

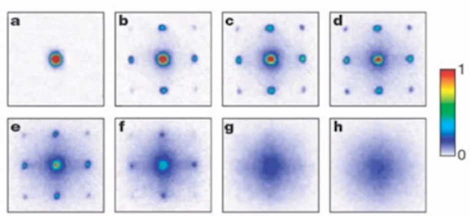
Different statistics: Fermions, bosons, mixture …

Why ultracold atoms?

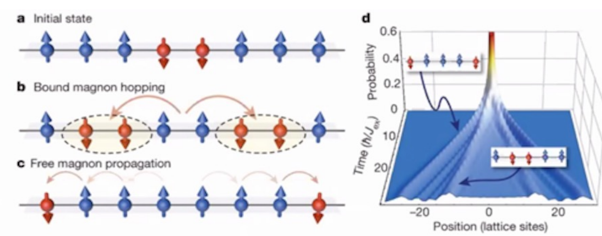
Spectacular success in simulating quantum many-body physics



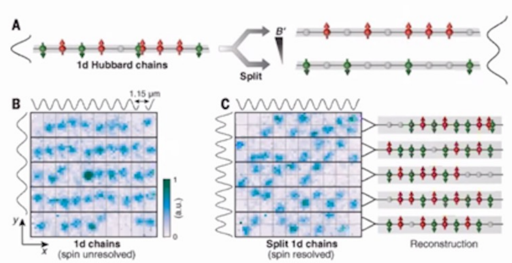
A. Mazurenko et. al., Nature (2017)



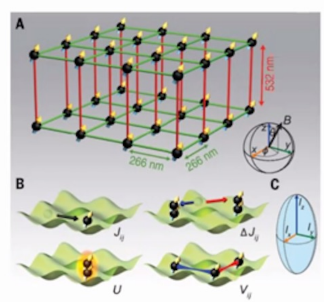
Greiner *et al.* Nature, 415, 2002



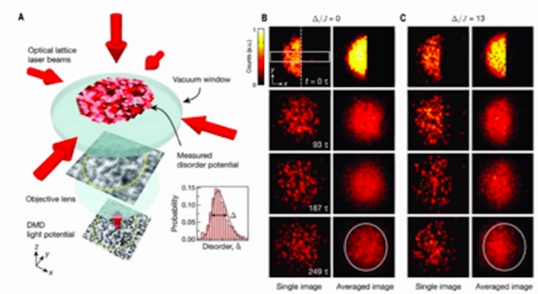
Fukuhara *et al.* Nature, 502, 2013



Boll *et al.* Science, 353, 2016



Baier *et al.* Science, 352, 2016

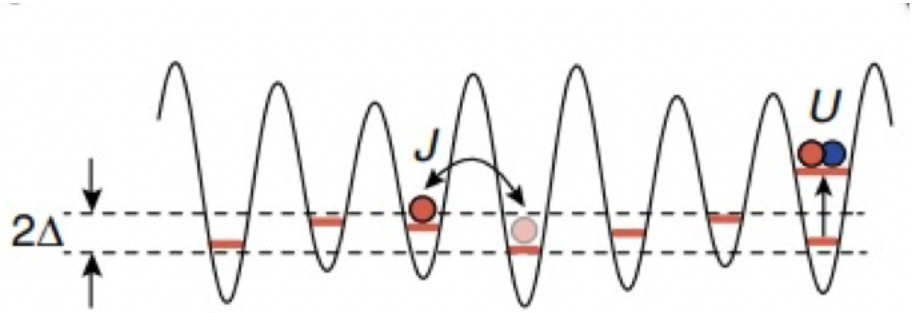


J. Choi *et al.* Science, 352, 2016

AMO PLATFORMS

Ex. 1: Localization in fermonic Quasiperiodic lattice is resource for quantum sensing

Roati et al., *Nature* **453**, 895 (2008) — first observation of localization in quasiperiodic lattice
Schreiber et al., *Science* **349**, 842 (2015) — first realization of MBL with quasiperiodic potential



Localization-delocalization transition

The system

$$\hat{H}_{ni} = -t\sum_i (\hat{c}_i{}^\dagger \hat{c}_{i+1} + h.c.) + V\sum_i \cos(2\pi i\omega)\, \hat{c}_i{}^\dagger \hat{c}_i + \mathrm{U}\sum_i \hat{n}_i \hat{n}_{i+1}$$

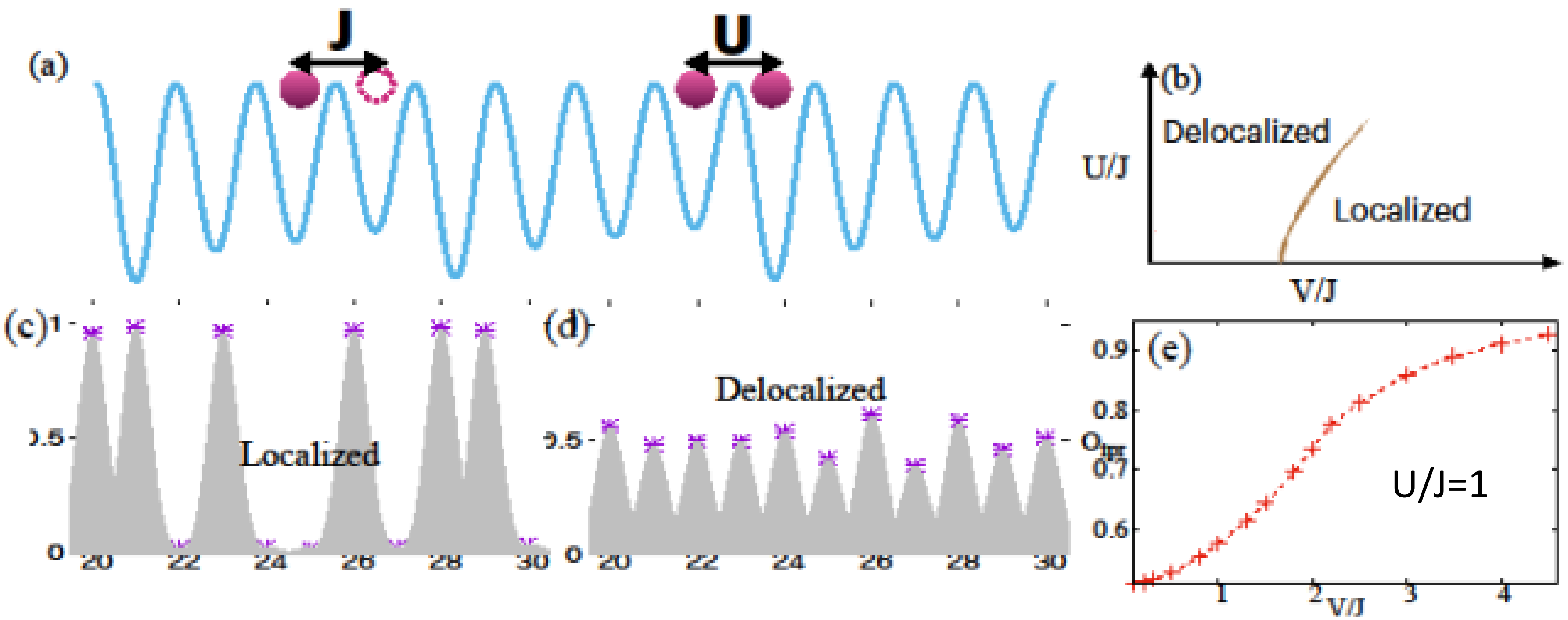
An irrational number

- **Single-particle case:** Characterized by an energy independent localization transitions at a finite modulation strength, $V_c = 2$

A. Sahoo, U. Mishra and D. Rakshit, Localization Driven Quantum Sensing, Phys. Rev. A 109, L030601 (2024)

Fermions in quasiperiodic lattice

Localization-delocalization transition



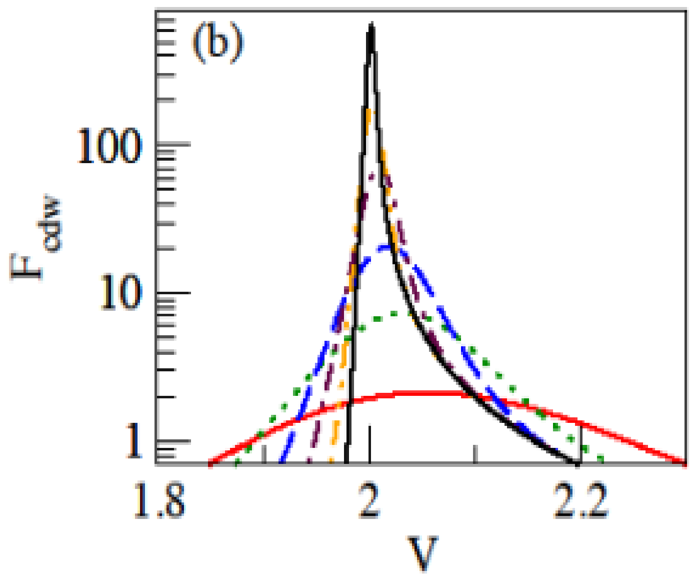
- **Many-body case:** Supports a many-body localization transition at a finite modulation strength, $V_c > 2$

A. Sahoo, U. Mishra and D. Rakshit, Localization Driven Quantum Sensing, Phys. Rev. A 109,

Single-particle case

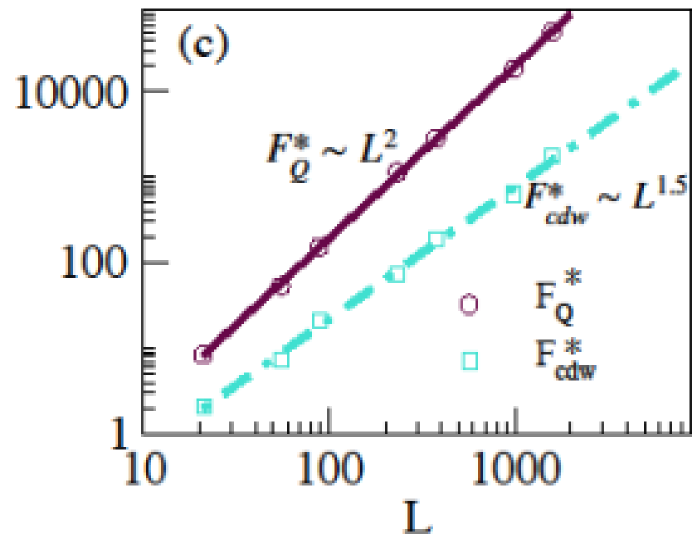
Observable Fisher Information: Scaling

L=21, 55, 89, 233, 377, 987



Charge-density wave operator

$\hat{O}_{cdw} = \frac{1}{n_f} \sum_i (-1)^i \, \hat{c}_i^{\dagger} \hat{c}_i$



- F_{cdw}^* at V^* is well beyond SQL : QUANTUM ADVANTAGE!

A. Sahoo, U. Mishra and D. Rakshit, Localization Driven Quantum Sensing, Phys. Rev. A 109, L030601 (2024)

Many-body case: Half-filled system

Observable Fisher Information: The clue …

Initial state leaves its imprint → Ordering is maintained

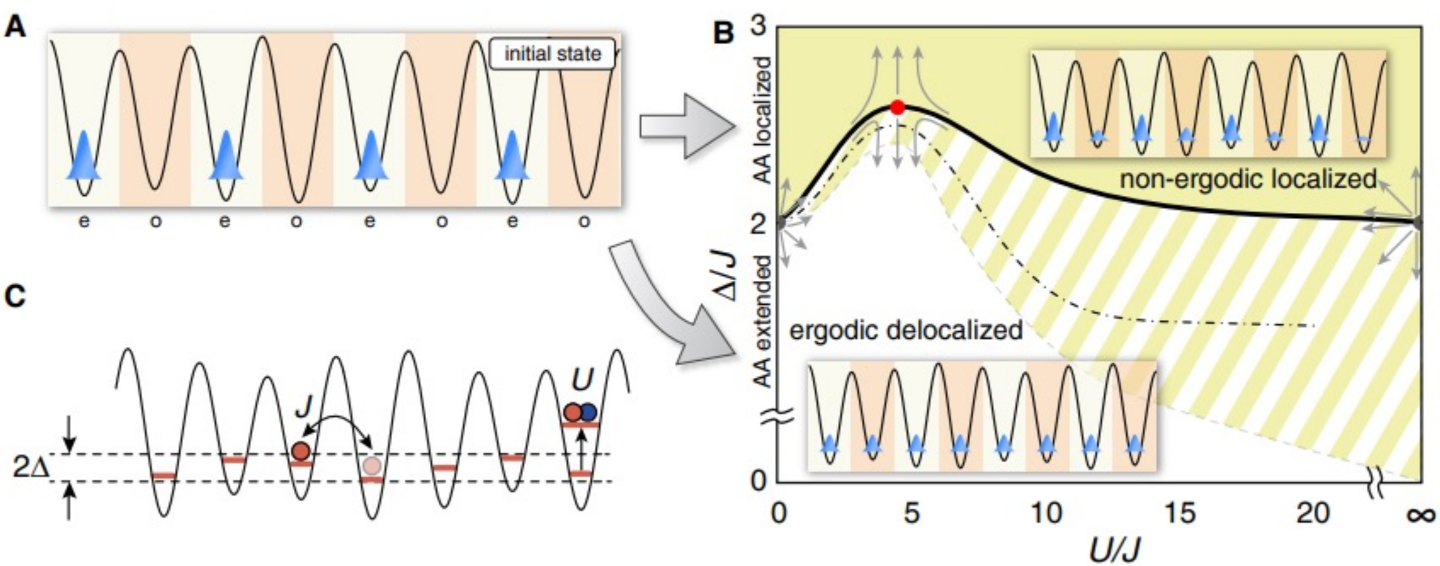
RESEARCH ARTICLE

QUANTUM GASES

Observation of many-body localization of interacting fermions in a quasirandom optical lattice

Michael Schreiber,[1,2] Sean S. Hodgman,[1,2] Pranjal Bordia,[1,2] Henrik P. Lüschen,[1,2] Mark H. Fischer,[3] Ronen Vosk,[3] Ehud Altman,[3] Ulrich Schneider,[1,2,4] Immanuel Bloch[1,2]*

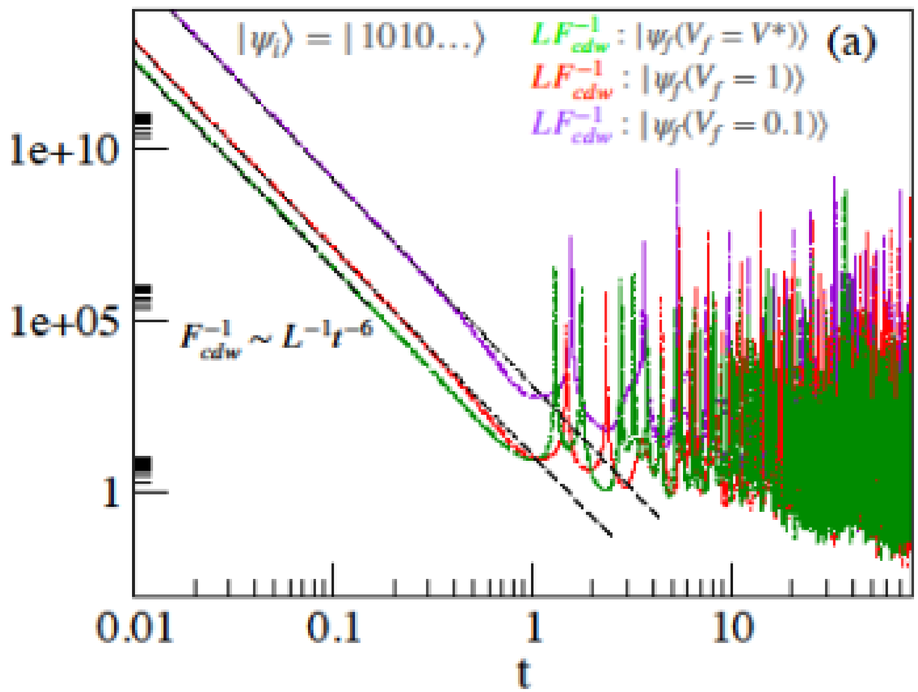
Many-body localization (MBL), the disorder-induced localization of interacting particles, signals a breakdown of conventional thermodynamics because MBL systems do not thermalize and show nonergodic time evolution. We experimentally observed this nonergodic evolution for interacting fermions in a one-dimensional quasirandom optical lattice and identified the MBL transition through the relaxation dynamics of an initially prepared charge density wave. For sufficiently weak disorder, the time evolution appears ergodic and thermalizing, erasing all initial ordering, whereas above a critical disorder strength, a substantial portion of the initial ordering persists. The critical disorder value shows a distinctive dependence on the interaction strength, which is in agreement with numerical simulations. Our experiment paves the way to further detailed studies of MBL, such as in noncorrelated disorder or higher dimensions.



M. Schreiber, …., I. Bloch, Science **349**, 842 (2015)

Engineer dynamical Sensors …

Dynamical sensors: Robustness of scalings



Time dependence of F_{cdw} due to a sudden quench for L= 55, 89 and 233

- Emergent scaling laws are robust against the details of the driving Hamiltonians
- They are robust against the choices of the initial states for F_{H_2}

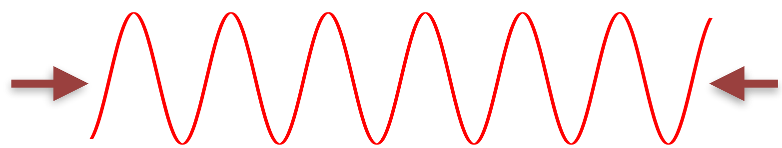
A. Sahoo, U. Mishra and D. Rakshit, Localization Driven Quantum Sensing, Phys. Rev. A 109, L030601 (2024)

Cold Bosons in Optical Lattice

Shallow optical potential ($V_0 \leq 5E_R$)

Continuum Schrödinger or Gross-Pitaevskii equation

$$\hat{H} = \int dx \left[\hat{\psi}^\dagger \left(-\frac{\hbar^2}{2m}\partial_x^2 + V_0 \sin^2(kx) \right) \hat{\psi}(x) + \frac{g}{2}\hat{\psi}^\dagger(x)^2 \hat{\psi}(x)^2 \right]$$



Deep lattice regime ($V_0 \geq 5E_R$)

Bose-Hubbard (tight-binding limit)

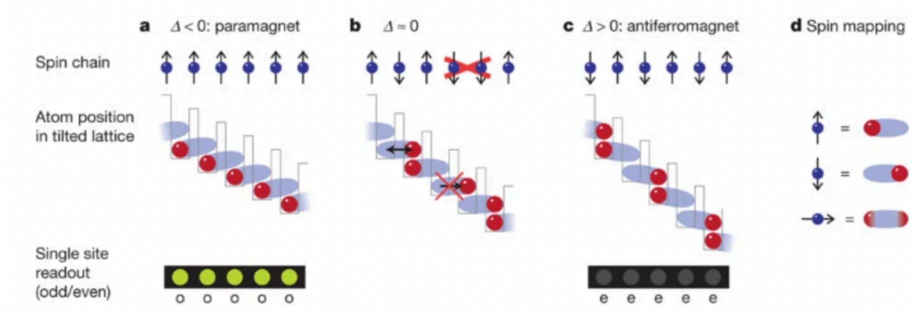
$$\hat{H} = -t \sum \hat{b}_i^\dagger \hat{b}_{i+1} + U \sum \hat{n}_i(\hat{n}_{i+1} - 1)$$

AMO PLATFORMS

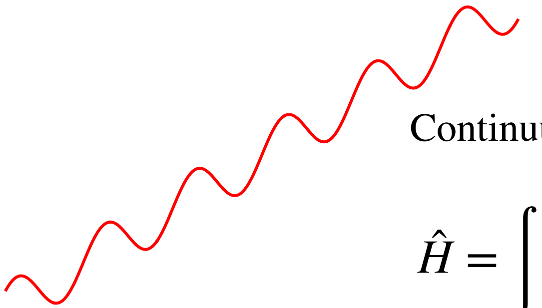
Ex. 2: Stark localization in bosonic tilted lattice—super-Heisenberg scaling and sensing faint potentials (signals)

J. Simon, ….M. Grainer, *Nature* **472**, 307 (2011) → Quantum simulation of a ferromagnetic domain wall using a tilted optical lattice in a 2D setup
A. Rubio-Abadal,…, I. Bloch, C. Gross, *Phys. Rev. X* **9**, 041014 (2019) → Demonstrated many-body localization in a tilted (Stark) optical lattice without disorder
K. Morong,…, C. Monroe, *Nature* **599**, 393 (2021) → Observation of localization due to a linear potential in a clean system (no disorder).

Figure 2: Tilted Hubbard model and mapping to spin model.



Cold Bosons in TILTED Optical Lattice: Stark Localization



Continuum Schrödinger or Gross-Pitaevskii equation **under tilt**

$$\hat{H} = \int dx \left[\hat{\psi}^\dagger \left(-\frac{\hbar^2}{2m}\partial_x^2 + V\sin^2(kx) + V_0|x| \right)\hat{\psi}(x) + \frac{g}{2}\hat{\psi}^\dagger(x)^2\hat{\psi}(x)^2 \right]$$

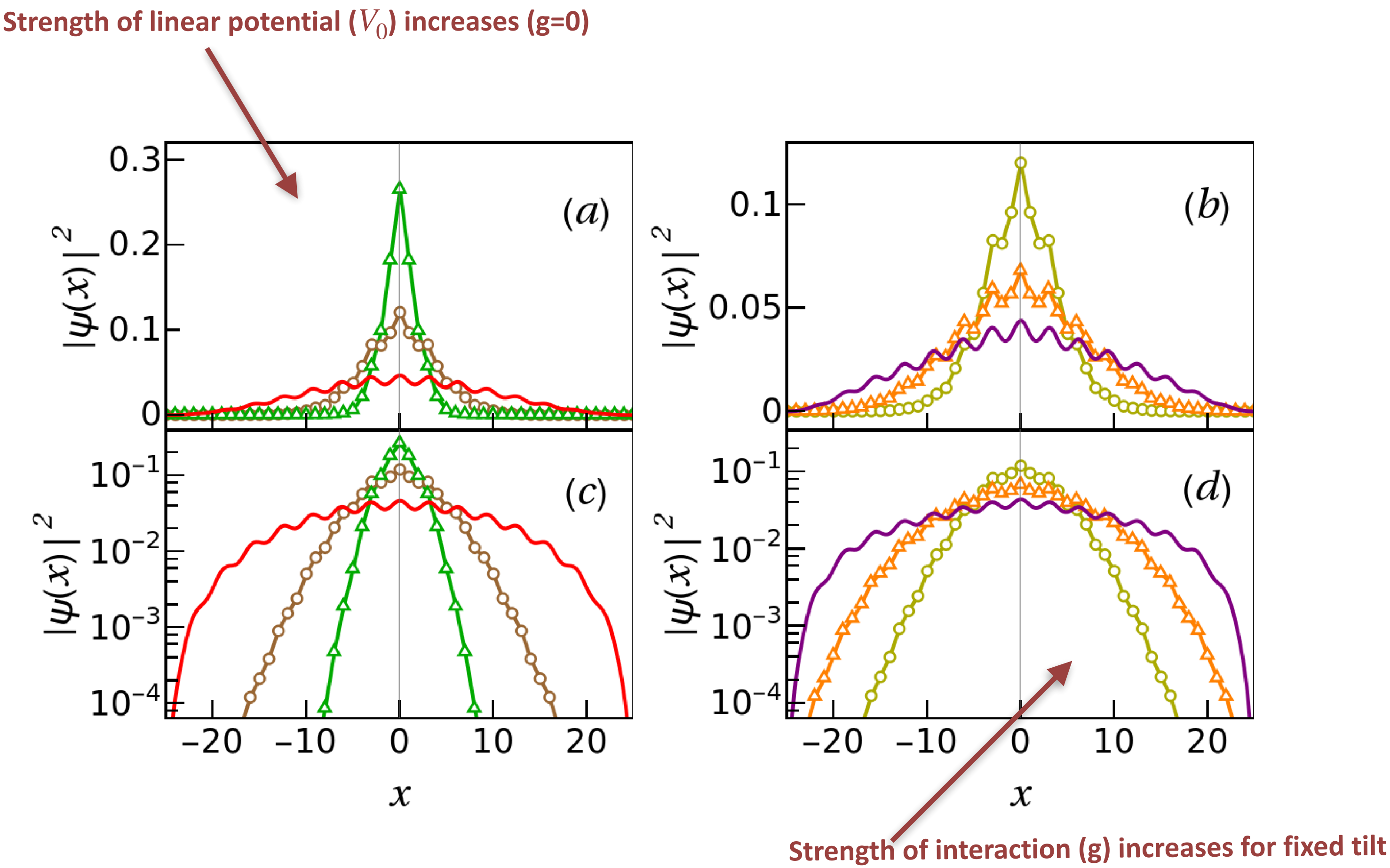
Bose-Hubbard (tight-binding limit) **under tilt**

$$\hat{H} = -t\sum \hat{b}_i^\dagger \hat{b}_{i+1} + U\sum \hat{n}_i(\hat{n}_{i+1} - 1) + V_0\sum i\hat{n}_i$$

Localization in the limit of $V_0 \to 0$ in the thermodynamic limit (non-interacting system)

Cold Bosons in TILTED Optical Lattice: Stark Localization

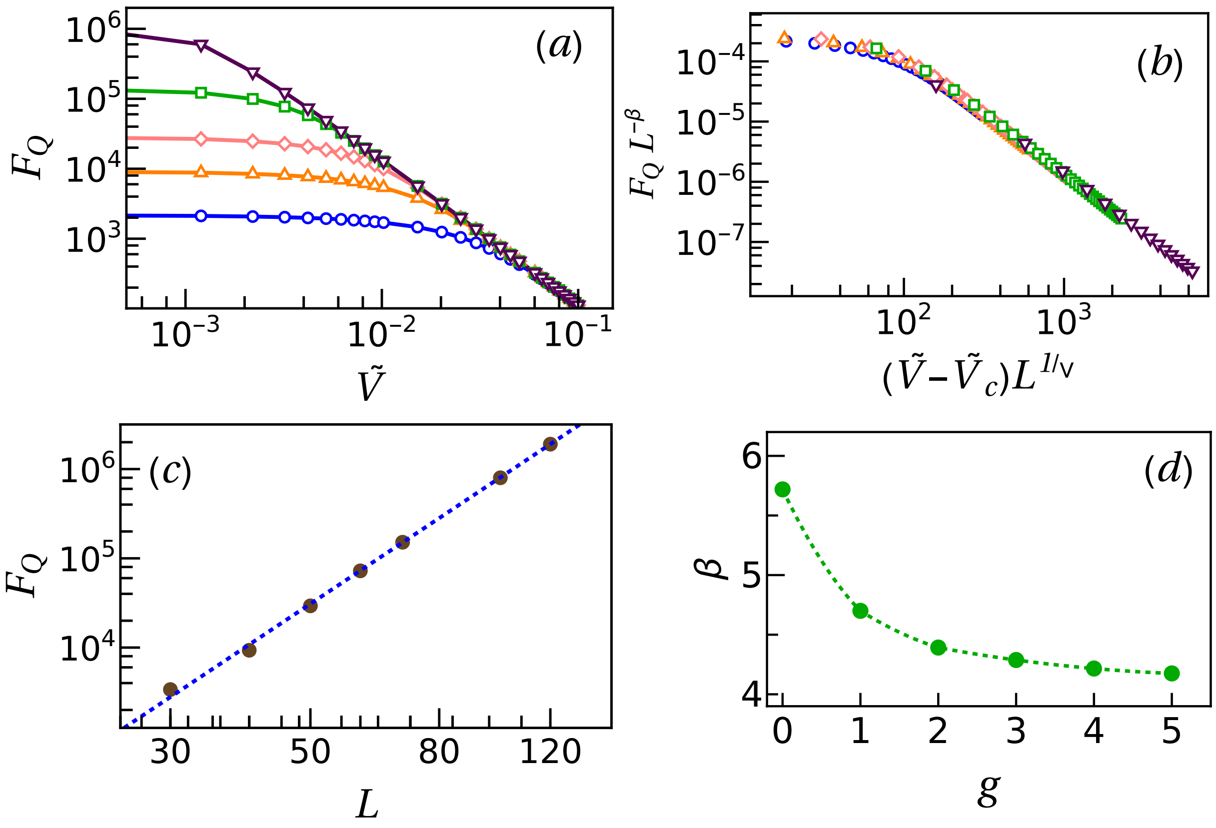
Continuum limit behavior



A. Debnath, M. Gajda and Debraj Rakshit, Tilt-Induced Localization in Interacting Bose-Einstein Condensates for Quantum Sensing, **arXiv:2506.06173**

Cold Bosons in TILTED Optical Lattice: QFI

Quantum sensing of faint signals



$F_Q \sim L^{\beta}$ **: super-Heisenberg scaling**

A. Debnath, M. Gajda and Debraj Rakshit, [Tilt-Induced Localization in Interacting Bose-Einstein Condensates for Quantum Sensing](), **arXiv:2506.06173**

CRITICAL QUANTUM SENSORS —

What is the origin of quantum advantage?

CRITICAL QUANTUM SENSORS—
What is the origin of quantum advantage?

Quantum criticality is associated with many key concepts:

Gap closing, symmetry-breaking, long-range correlations

Until now almost all critical sensors are associated with **gap closing** … $F_Q \leq \frac{L^2}{\Delta^2}$

P. Abiuso, P. Sekatski, J. Calsamiglia, and M. Perarnau-Llobet, PRL **134**, 010801 (2025)

Related references:

V. Montenegro et. al., **Review: Quantum Metrology and Sensing with Many-Body Systems**, Physics Reports 1134, 1(2025)

K. D. Agarwal, S. Mondal, A. Sahoo, D. Rakshit, A. S. De and U. Sen,
Quantum sensing with ultracold simulators in lattice and ensemble systems: a review, arXiv:2507.06348

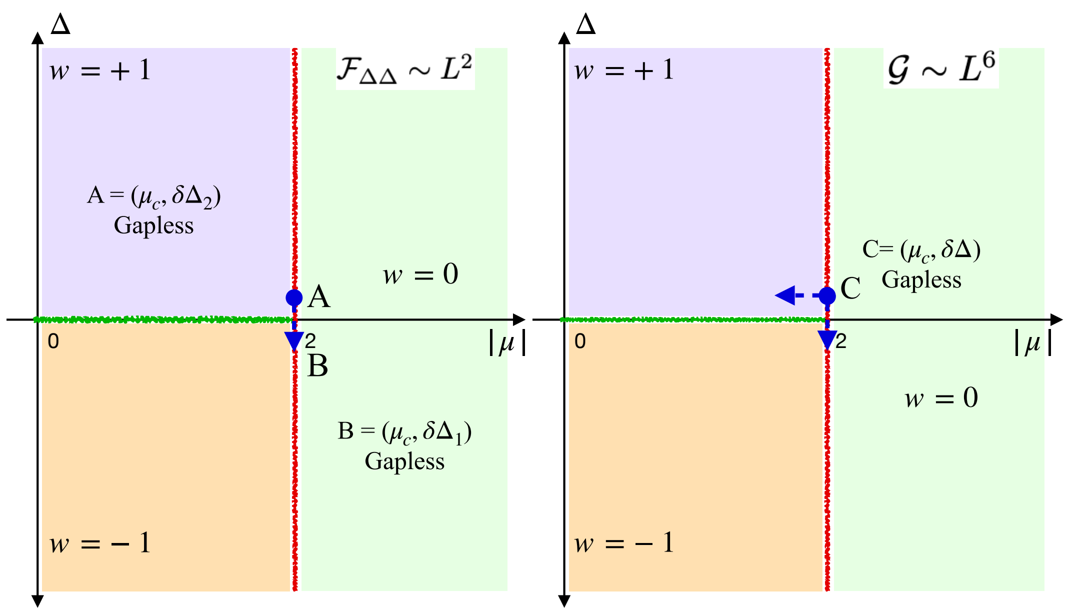
Can symmetry-breaking alone may give rise to quantum advantage?

Kitaev model, 1D p-wave superconductor

$$\hat{H} = \hat{H}_1 + \hat{H}_\Delta$$

$$\hat{H}_1 = -\sum_{j=1}^{L}\left(\hat{c}_j^\dagger \hat{c}_{j+1} + h.c.\right) - \mu \sum_{j=1}^{L}\left(\hat{c}_j^\dagger \hat{c}_j - \frac{1}{2}\right)$$

$$\hat{H}_\Delta = \frac{\Delta}{2}\sum_{j=1}^{L}\left(\hat{c}_j^\dagger \hat{c}_{j+1}^\dagger + h.c.\right)$$



S Mondal, A Sahoo, U Sen and D Rakshit, Multicritical quantum sensors driven by symmetry-breaking, arXiv:2407.14428

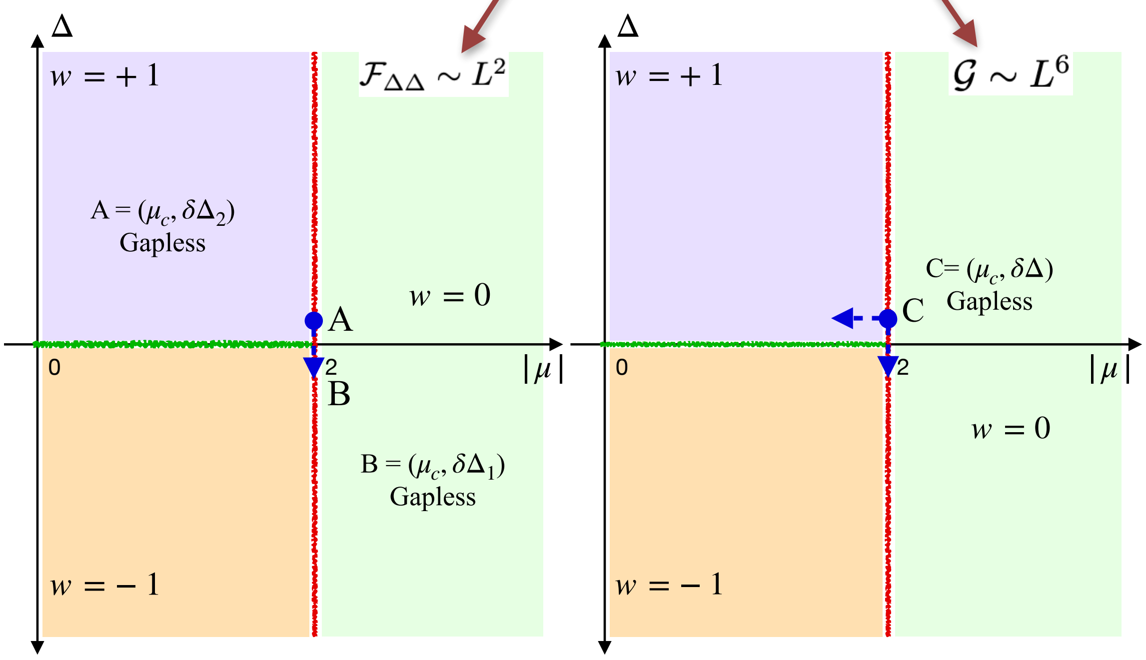
Multi-Critical Multi-Parameter Quantum Sensors Driven by Symmetry-Breaking

Multi-parameter Estimation—

Compute Quantum Fishsher Information Matrix

$$\delta\mu^2 + \delta\Delta^2 \geq \frac{1}{m}\mathcal{G}^{-1}$$

Quantum advantage via symmetry-breaking



S Mondal, A Sahoo, U Sen and D Rakshit, [Multicritical quantum sensors driven by symmetry-breaking](), arXiv:2407.14428

Concluding Remarks

- Engineered quantum materials are used to push boundaries of quantum metrology, where AMO platforms lead the pack

- Utility of quantum phenomena, such as **spin squeezing, quantum criticality, quantum phase transition** (including second-order, topological, and localization transitions), **multicriticality, interferometry, time-crystal, and quantum scar**, along with **quantum coherence, and entanglement**, in diverse quantum metrological protocols including thermometry, inertial sensors, gravimetry, magnetometry, precision clocks

- The true challenge on the experimental front lies in the preparation and control of scalable quantum simulators with long coherence time

- With steady progress in innovative techniques, a promising future awaits in which quantum sensors are poised to achieve near-optimal precision and broad practical impact

THANK YOU