Ultracold Atoms as Quantum Simulators: From Phase Transitions to Quantum Computation

Symposium and Training Workshop on Quantum Information & Technologies

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Pune

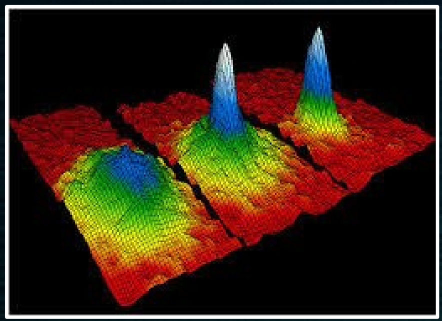
Outline of the talk

- Introduction and Motivation
- Basics
  - Ultracold Atoms
  - Optical Lattices
  - Classical vs. Quantum Phase Transitions
  - Probing techniques
- Applications
  - Quantum computing
- Challenges and Future directions
- Summary

Motivation & Relevance

- Discover new phenomenon / phases of matter
- To get new insights and design better quantum materials
  - can overcome challenges associated with the complexity of interactions, mixing up of effects, tuning of parameters, impurity effects, etc.
- Technological importance
  - Quantum computing
  - Quantum sensors (atomic interferometers, metrology, etc.)
  - Quantum memories (storage systems)
  - Lossless power transmission - high T_c superconductivity
  - Precision measurements (atomic clocks, GPS devices)

How cold are ‘ultracold atoms’ ?



Ultracold matter

Outer space

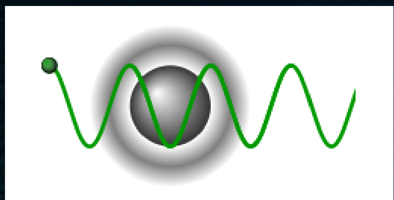
Earth’s surface

Centre of the Sun

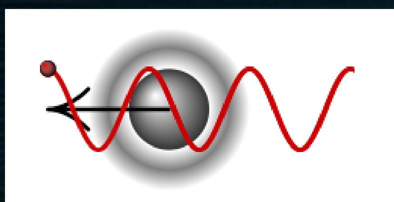
Ultracold matter	Outer space	Earth’s surface	Centre of the Sun
10^{-9} K	2.7 K	300 K	10^{7} K
0.001 m/s	40 m/s	400 m/s	70,000 m/s

Speed of atoms

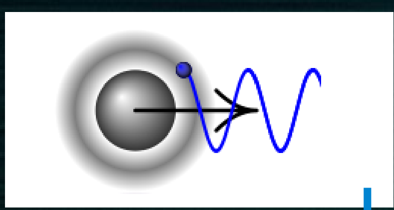
Laser cooling



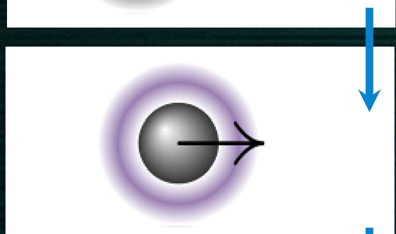
- A stationary atom sees the laser neither red- nor blue-shifted and does not absorb the photon.



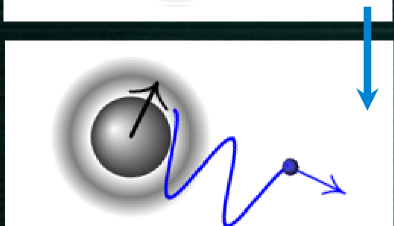
- An atom moving away from the laser sees it red-shifted and does not absorb the photon.



- An atom moving towards the laser sees it blue-shifted and absorbs the photon, slowing the atom.



- The photon excites the atom, moving an electron to a higher quantum state.

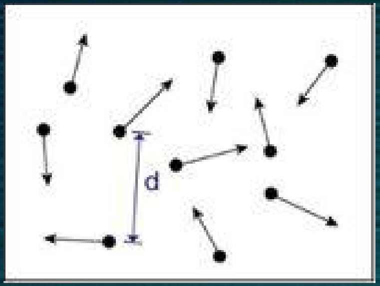


- The atom re-emits a photon in a random direction. Because of this randomness there is no net change in momentum over many absorption-emission cycles. But the final momentum of atom now reduces in the direction opposite to the laser beam.

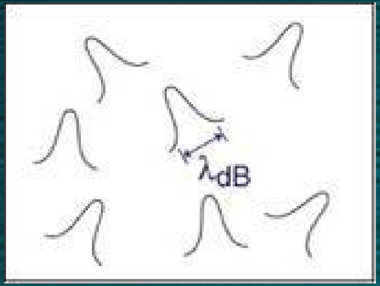
*Nobel Prize (1997) : Steven Chu, Claude Cohen-Tannoudji, William D. Phillips

What happens at ultracold temperatures?

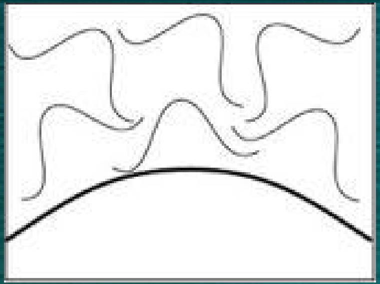
- At high temperatures atoms are far apart and behave like billiard balls.



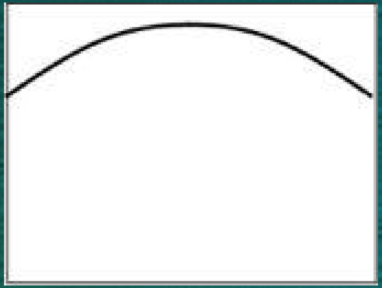
- Upon decreasing the temperature, the de Broglie wavelength (λ_{dB}) increases (scales as $T^{-1/2}$).



- Eventually this wavelength becomes comparable with the inter-particle separation (d).



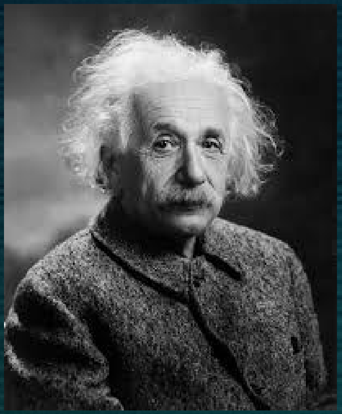
- At this point the single particle wave functions get smeared and a giant matter wave emerges.



- Bose-Einstein Condensate formation!!

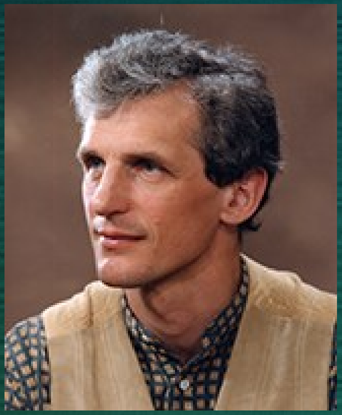
Bose-Einstein Condensation

Theoretical prediction : S. N. Bose and A. Einstein in 1924

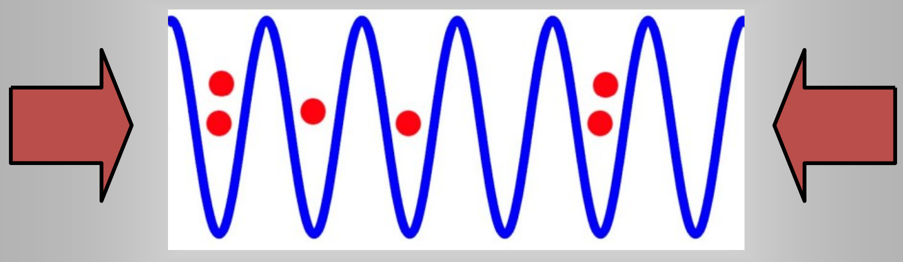
First lab realization : E. Cornell, C. Wieman and W. Ketterle in 1995



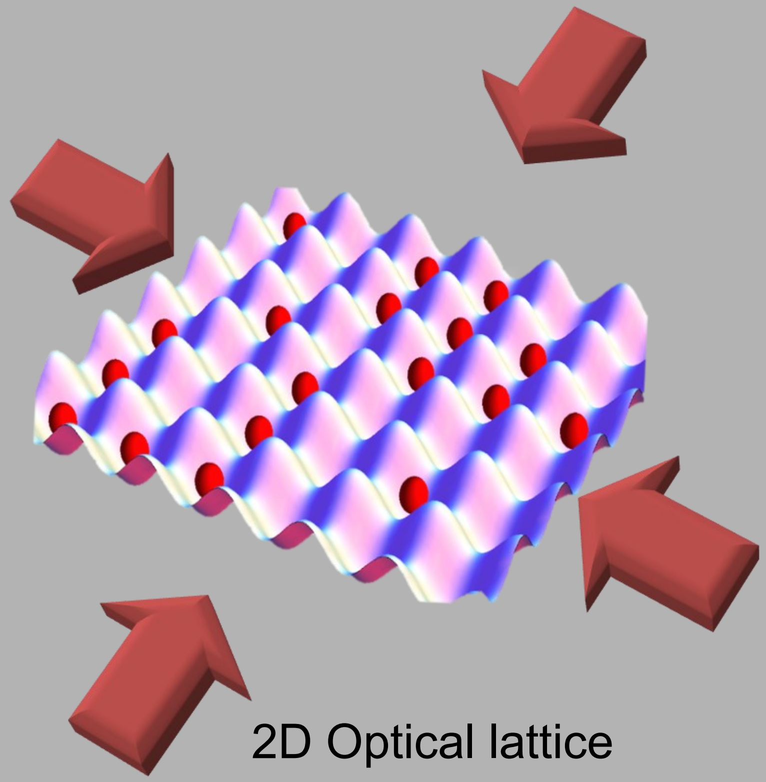


*Nobel Prize (2001)

Optical Lattices



1D Optical lattice



2D Optical lattice

- Optical potential wells created by the interference of counter-propagating laser beams.
- Can trap neutral atoms via polarization effects.
- Spacing between lattice sites is of the order of 500–1000 nm.
- Lattice depth, geometry, dimensionality can be fully controlled.
- The interaction between the atoms can be made repulsive or attractive.

Idea

* Ultracold Atoms in Optical Lattices can be used to mimic real materials *

Atoms play the role of electrons

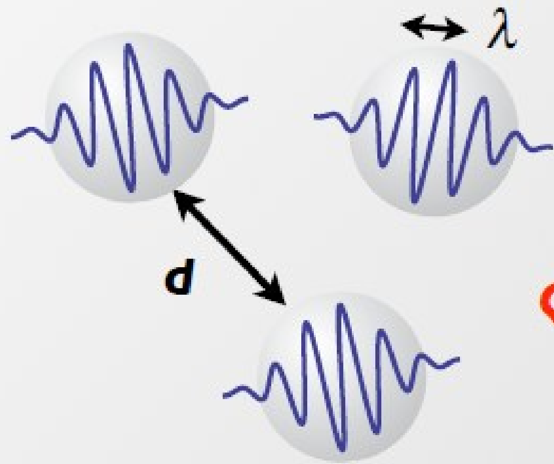
and

Optical lattice plays the role of crystal lattice.

Why this idea works?

Quantum Regime

$$\lambda/d \gtrsim 1$$

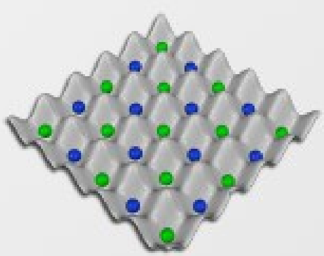


de Broglie Wavepackets

Universality of Quantum Mechanics!

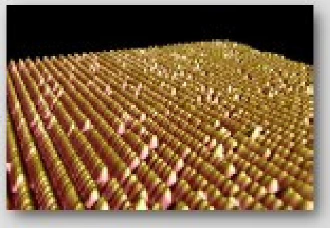
Ultracold Quantum Matter

- ***Densities:*** ***$10^{14}/cm^3$***
  (100000 times thinner than air)
- ***Temperatures:*** ***few nK***
  (100 million times lower than outer space)



Real Materials

- ***Densities:*** ***10^{24}-$10^{25}/cm^3$***
- ***Temperatures:*** ***mK – several hundred K***

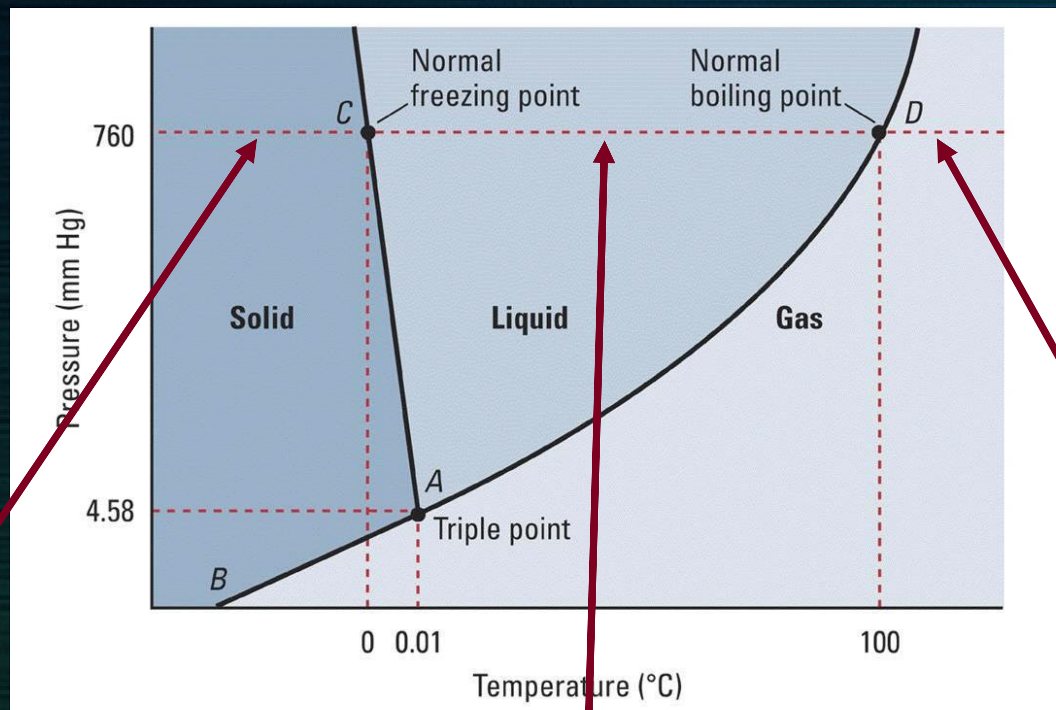


(Neuchatel)

Same λ/d !

Classical vs. Quantum Phase Transitions

P-T phase diagram for water



Bose-Hubbard model

Bosons in an optical lattice can be described by the Bose-Hubbard model:

$$H = -t \sum_{\langle i,j \rangle} (\hat{a}_i^\dagger \hat{a}_j + \text{H.c.}) + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)$$

kinetic energy potential energy

t : hopping between nearest-neighboring sites ⟨ i, j ⟩

a ($a^\dagger$) : annihilation (creation) operator

U : on-site interaction

n : number operator

U/t << 1 : Superfluid (SF)

U/t >> 1 : Mott insulator (MI)

$$\text{Density} = \frac{\text{Total no. of atoms}}{\text{Total no. of sites}}$$

$$|\Psi_{SF}\rangle \sim \left(\sum_{i=1}^{M} a_i^\dagger\right)^N |0\rangle$$

$$|\Psi_{MI}\rangle \sim \prod_{i=1}^{M} (a_i^\dagger)^n |0\rangle$$

MI phase arises only at integer densities.

Phase diagram can be obtained numerically by using a suitable method like Density Matrix Renormalization Group (DMRG), Mean-field theory (MFT), etc.

Bose-Hubbard model

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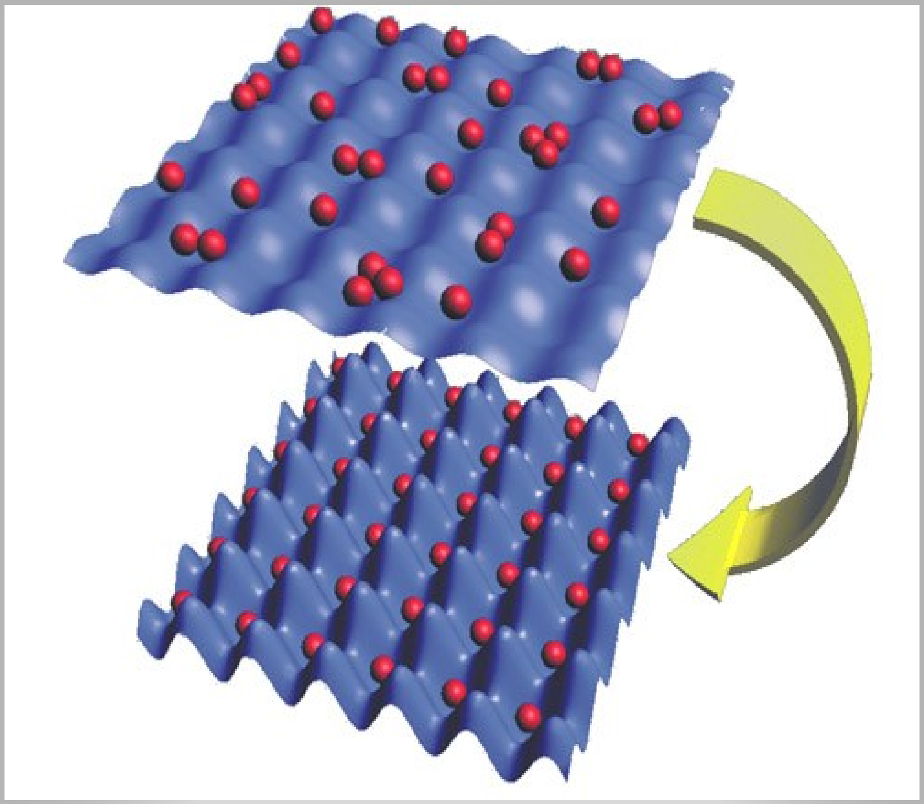
$$H = -t \sum_{\langle i,j \rangle} (\hat{a}_i^\dagger \hat{a}_j + \text{H.c.}) + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)$$

- Controlled by lattice depth
- Strength $\propto \alpha |E|^2$
- Vary I => vary t

- Two-body interaction
- U $\propto a_s$ (scattering length)
- Tuned using magnetic fields (Feshbach resonance)

Superfluid to Mott insulator transition



Superfluid (top) to Mott-insulator (bottom) transition in a 2D optical lattice at density (ρ) = 1.0

- Particles are weakly interacting in the superfluid phase and have long range coherence. A single atom can be thought to be delocalized across the whole lattice.
- By tuning the lasers we can vary the ratio (U/t).
- If potential wells become deep enough, atoms can not overcome the energy barriers and get localized to individual lattice sites. This results in the Mott-insulator phase.

*First experimental demo. : Markus Greiner, et al, ***Nature 415, (2002)***

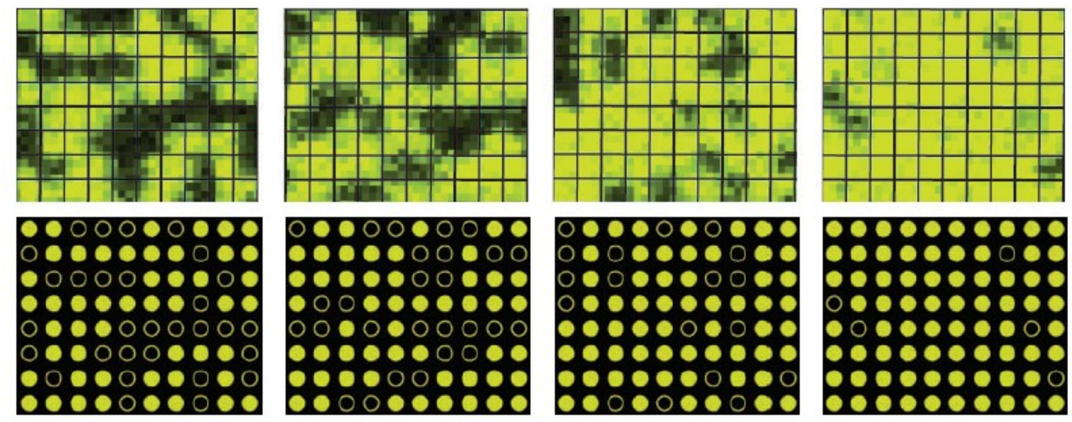
Measurement techniques

- Imaging – absorption imaging, fluorescence, etc.
- Time-of-flight method
- Spectroscopic techniques
- Single site imaging – quantum gas microscopes

Lattice depth increases

Probing the Superfluid–to–Mott Insulator Transition at the Single-Atom Level

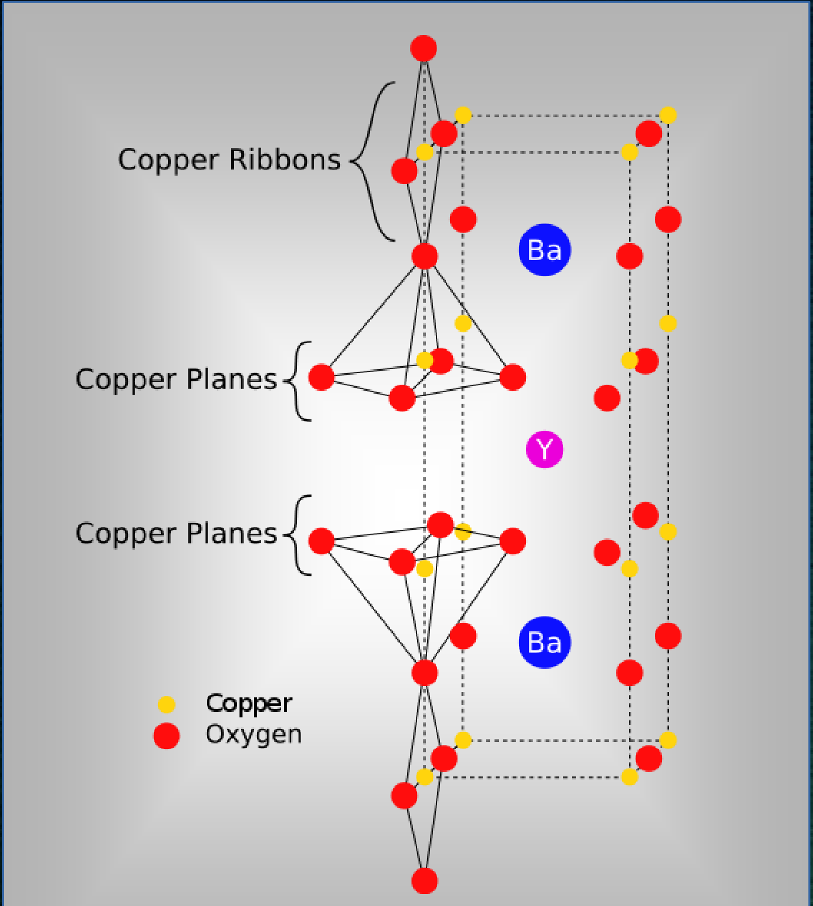
W. S. Bakr
Science 329, 5991, 547 (2010)



Single site imaging of atom number fluctuations across the SF - MI transition

Applications

Applications : Material Science



Structure of Yttrium Barium Copper Oxide (a superconductor)

High temperature superconductivity

Superconductors are materials that conduct electricity with no resistance.

-desirable : room temperature superconductivity

-applications : lossless transmission, medical applications, etc.

Ultracold atoms in optical lattices:

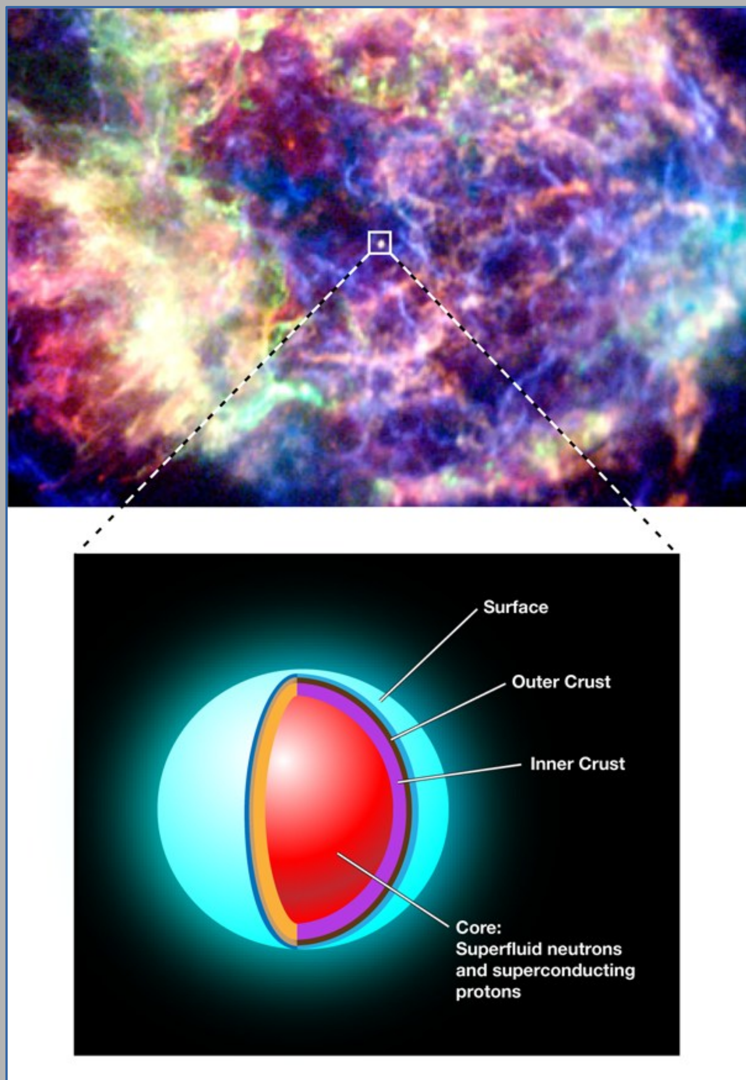
-very clean systems

-easy to manipulate

-mimic desirable properties / structures

-design better superconductors

Applications : Astrophysics



(Top) X-ray image of the Cassiopeia A supernova remnant.
(Bottom) Drawing showing the different layers of a neutron star.

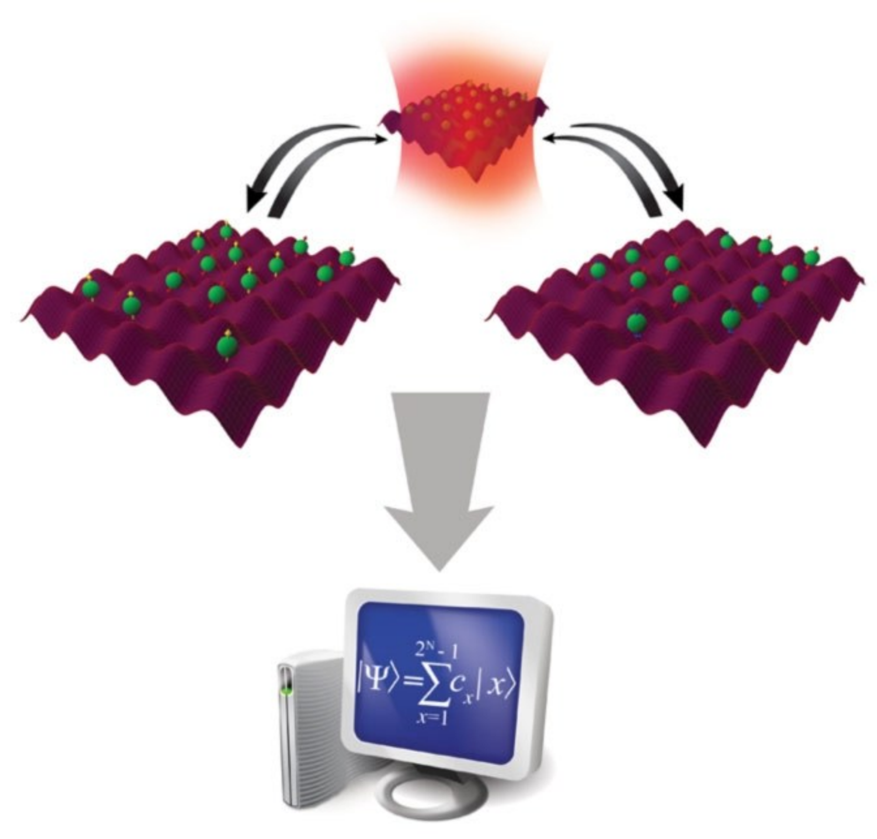
Astrophysical phenomenon

Cassiopeia A in the Cassiopeia constellation is a neutron star. Based on the observed cooling rate of the star, astrophysicists believe the neutrons in its core to be in a superfluid state.

Neutron stars are the compact remnants of certain supernova explosions. They are born from the catastrophic gravitational collapse of the iron core of massive stars at the end point of their evolution.

At optimum temperature, pressure and desnisties, neutrons may form pairs. These composite pairs are bosons that can behave coherently on a very large scale and the nucleon condensate can flow without any viscosity, ***analogous to a superfluid***.

Applications : Quantum Computing



Lattice-based quantum computer (concept)
Lasers used to precisely detect, measure, or manipulate atoms in lattices.

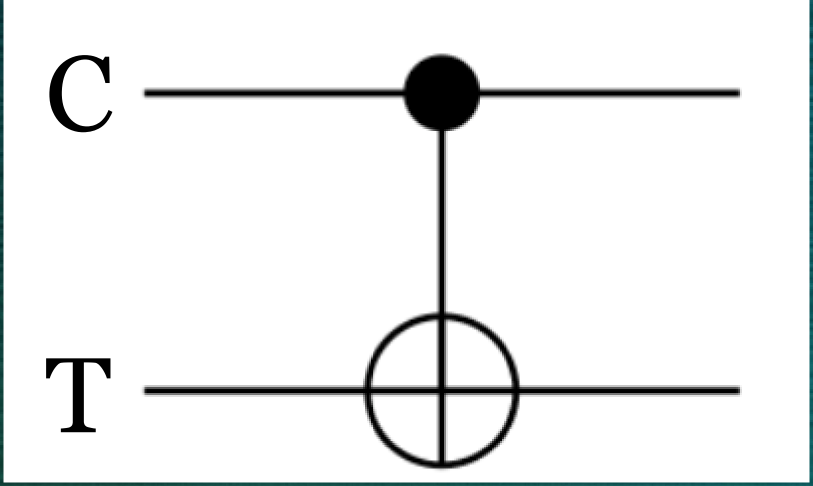
- Neutral atom quantum computing: array of trapped atoms.
- Atoms used as qubits: internal hyperfine states = $|0\rangle$, $|1\rangle$.
- Rydberg excitation for interaction and entangling gates. (Rydberg atoms : atoms with long range dipole-dipole interaction)
- Programmable arrays: optical tweezers place atoms precisely.
- Readout using **site-resolved imaging** via quantum gas microscopes.
- Companies : PASQAL, ColdQuanta, QuEra.

QC : Gate Operation examples

- Single-qubit gate : microwave or Raman transition between two hyperfine levels (e.g. in Rb, Cs) => manipulate the state to $|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$
- Two-qubit gate : Rydberg blockade mechanism
  An atom in a Rydberg state can shift the energy level of a neighbouring atoms => prevents the other atom from being excited to the same Rydberg state = conditional shift (change)

Before		After	
Control	Target	Control	Target
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$

CNOT gate



QC : Gate Operation examples

Demonstration of a Neutral Atom Controlled-NOT Quantum Gate

L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson, T. G. Walker, and M. Saffman

Phys. Rev. Lett. 104, 010503 (2010)

Published January 8, 2010

Entanglement of Two Individual Neutral Atoms Using Rydberg Blockade

T. Wilk, A. Gaëtan, C. Evellin, J. Wolters, Y. Miroshnychenko, P. Grangier, and A. Browaeys

Phys. Rev. Lett. 104, 010502 (2010)

Published January 8, 2010

- By combining the conditional phase shifts with single-qubit operations, a CNOT gate or other two-qubit gates can be implemented.
- Implement CNOT and CZ gates using pulse sequences.

Neutral-atoms based QC

PASQAL

Rubidium atoms
100+ gate-based qubits, 300 in analogue mode
Focus on quantum simulation and differential equations

QuEra Computing Inc.

Rubidium atoms
256–336 qubits (analogue), working toward gate-based
Focus on optimization (QUBO) problems, many-body physics

atom computing

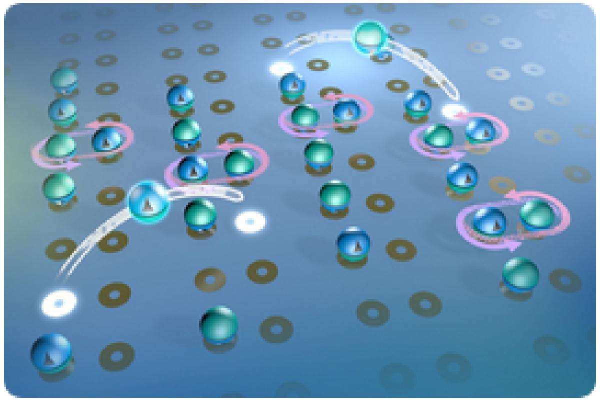
Strontium / Ytterbium atoms
1,000+ qubit arrays (nascent stages)
Long coherence times (tens of seconds)

Infleqtion

Rubidium / Cesium
~100 qubits
Focus on quantum sensing and atomic clock products

Neutral-atoms based QC

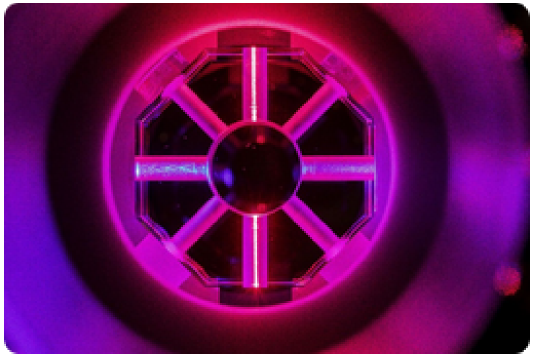
FermiQP – Fermion Quantum Processor



The FermiQP project focuses on the development of a novel quantum-processor architecture and its demonstration in the laboratory. The new architecture is intended to create advantages that no other platform can offer, first and foremost the possibility of using a quantum machine in two fundamentally different operating modes: An analogue mode, in which a quantum advantage is expected in the short term for specific questions in the field of quantum materials, as well as a digital mode, in which the processor is universally programmable. The analogue mode directly utilizes the fermionic nature of the processor to efficiently explore quantum materials. The digital mode offers competitive scalability, full parallelizability of all qubit operations and full connectivity of the processor.

Neutral-atoms based QC

MUNIQC-Atoms – Munich Quantum Valley Quantum-Computer Demonstrators



The MUNIQC-Atoms project aims to realize a neutral-atom-based quantum processor with up to 400 qubits encoded in strontium atoms. It targets the full quantum- computing stack from low-level atomic hardware to its integration into high-performance computing environments. While the TAQC consortium conducts research also in alternative approaches to neutral-atom quantum computing, MUNIQC-Atoms pur-sues the rapid construction of a neutral-atom-based quantum-computing demonstrator with state-of-the-art components.

Advantages

Lattice Architecture

Atoms arranged in 1D/2D/3D optical lattices

Geometries: square, triangular, hexagonal, superlattices, etc.

High Scalability

Optical lattices can trap **thousands to millions of atoms**.

Regular, defect-free arrays achievable with Bose/Fermi insulators or rearranged tweezer arrays.

Long Coherence Times

Hyperfine states are extremely **stable,** coherence time if the order of **seconds**.

Measurements

Fluorescence detection allows high-fidelity measurement (>99%).

Low Cross-Talk

Atoms interact only when designed to — naturally **low cross-talk** between qubits.

Challenges and Future directions

Challenges

Decoherence:

Atom loss, spontaneous emission, and technical noise limit coherence time.
Need for ultra-stable laser systems and vacuum environments.

Precise Control of Interactions:

Feshbach resonances require magnetic field precision.
Need better tuning for long-range interactions (e.g., dipolar atoms or Rydberg states).

Future Directions

Hybrid Platforms:

Combine atoms with **superconducting circuits**, or **photonics**.

Topological and Exotic Phases:

Simulation of robust and noise resistant phases for fault tolerant QC.

Quantum Networks:

Link multiple optical lattice setups via photonic interconnects for distributed quantum computing.

To summarize…

- Ultracold atoms can be used to **study condensed-matter quantum many-body systems**, which are **hard to simulate otherwise**. They also allow us to study phenomenon from other domains.

- On the QC side, cold atoms in optical lattices can be used as robust **programmable simulators**, with **dynamic control, scalability, high fidelity, and accurate measurements**.

- Despite technical challenges, the **synergy of experiment and theory**, makes this a **rich and evolving frontier**.

- Collaboration between science and engineering fields is the key for rapid advancements in these fields.