

Ultracold atoms as a quantum simulation platform for 2D many-body systems

Patricia Christina Marques Castilho

São Carlos Physics Institute, University of São Paulo (IFSC-USP)

FAPESP Week Germany

March 25th-26th 2025



IFSC UNIVERSITY
OF SÃO PAULO
São Carlos Institute of Physics



2D K
Lab

Quantum technology in São Carlos

The city of São Carlos and its Universities



Location: ~ 250 km from São Paulo

Population: ~ 250.000 habitants

Two public universities:

- University of São Paulo (USP)



IFSC UNIVERSITY
OF SÃO PAULO
São Carlos Institute of Physics

- Federal University of São Carlos (UFSCar)



Quantum technology in São Carlos

Research interests

Physics:

- NV-centers
- Photonic devices
- Cold and ultracold atoms
- NMR (education)
- ...

Engineering:

- Sensors
- Quantum computation

Undergrad program on quantum
engineer

Start-ups

Embrapa

Agrotechnology

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Prof. V. S. Bagnato

BEC lab

Rb BEC

Na BEC



Prof. E. A. L. Henn

Dy lab

Dy BEC

+ Ion trap
(starting)



Prof. L. Marcassa

Ryd lab

Ryd Rb
sensing



Prof. P. C. M. Castilho

2D lab

2D K



Prof. P. Courteille

Sr lab

Sr 1
Light-matter

Sr 2
gravimeter



Prof. R. C. Teixeira

Clock lab

Clock



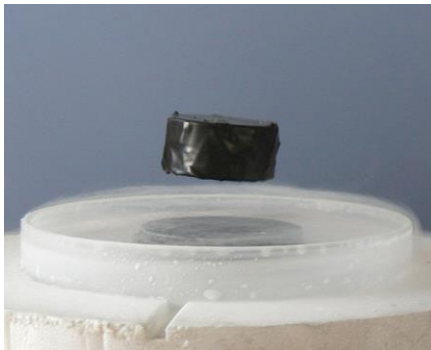
Prof. D. V. Magalhães

+ Theory group

USP & UFSCar

Modeling real materials

E.g.: Superconductors



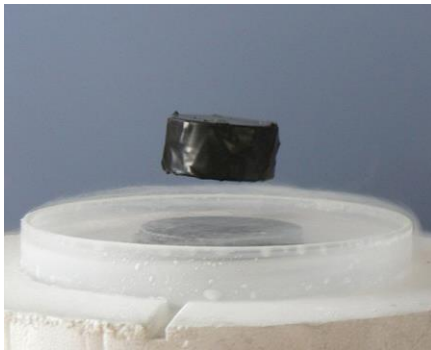
Many-body systems with strongly correlated particles (interact)

$$N \sim N_A \sim 10^{23} \text{ particles/mol}$$

Solid: movement of electrons inside the material

Modeling real materials

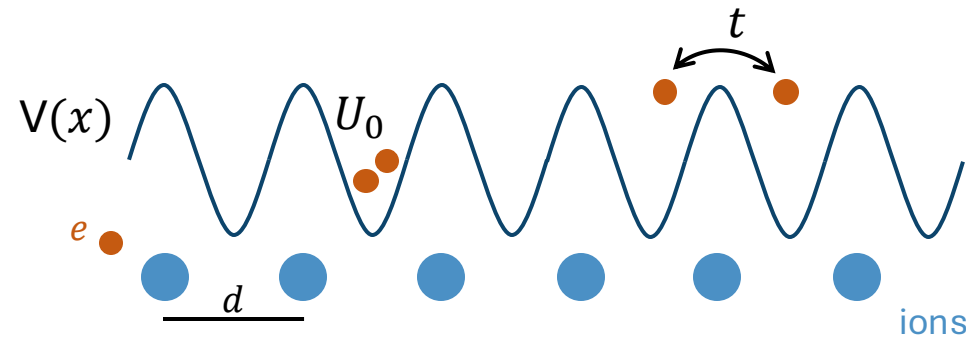
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Interaction: U_0

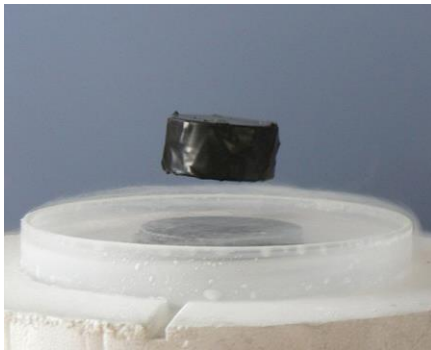
Tunneling: t



Competition
between these
energies

Modeling real materials

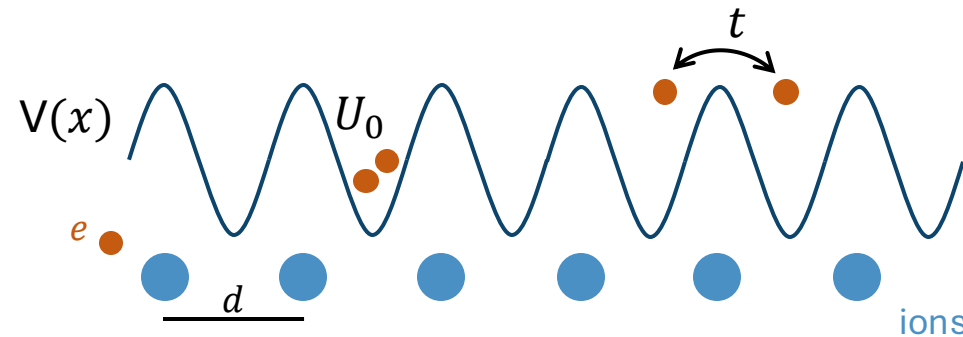
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Degree of freedom of electrons: 2 internal states (spins)



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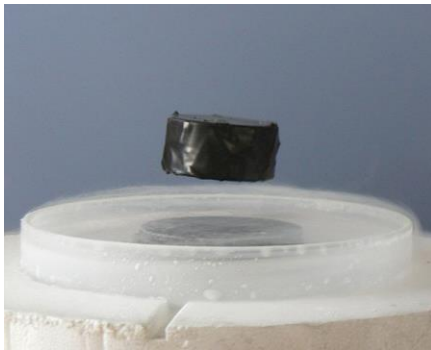
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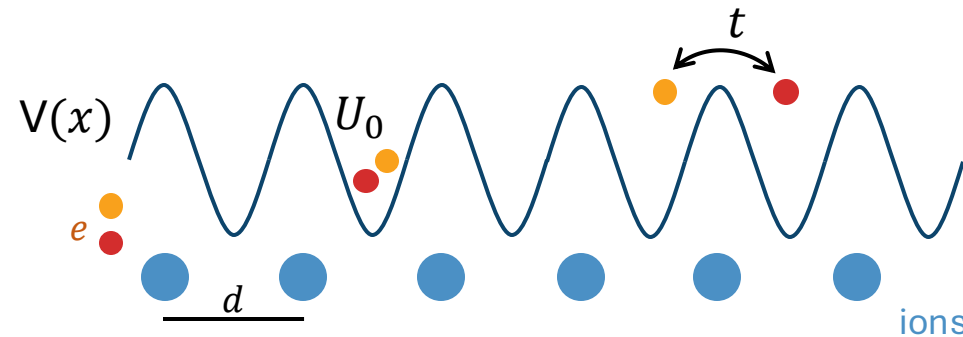
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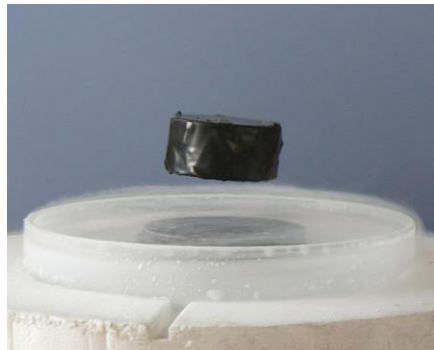
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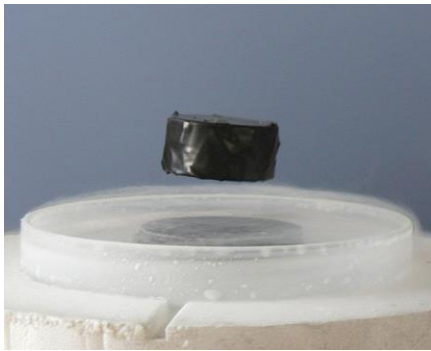
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Numerical simulations

Each electron can have 2 degrees of freedom

Modeling real materials

E.g.: Superconductors



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Classical systems

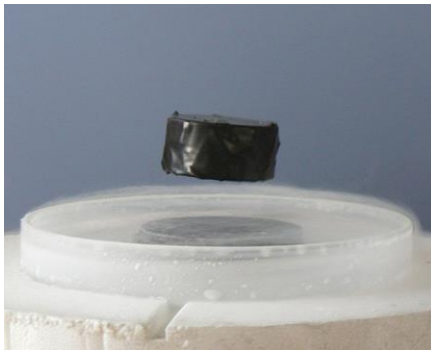
N -particles $\rightarrow$ system's dimension = $2N$

Quantum systems (spin-1/2)

N -particles $\rightarrow$ system's dimension = 2^N

Modeling real materials

E.g.: Superconductors



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Classical systems

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Quantum systems (spin-1/2)

N -particles $\rightarrow$ system's dimension = 2^N

# of particles	1	5	10	20
Classical system	2	10	20	40
Quantum system	2	32	1024	>1 million!

Limit $\sim N = 40$ spins!!!

Simulating with Quantum Computers

Not yet a reality...

- N -particles $\rightarrow$ N -**qubits**
- Few **logical** qubits ~ 40
Most qubits perform operations and error correction (ancillas)
- Development of quantum protocols
- Quantum supremacy achieved only at specific cases



Google quantum computer



Microsoft: Majorana 1

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A long way to go in simulating many-body quantum systems



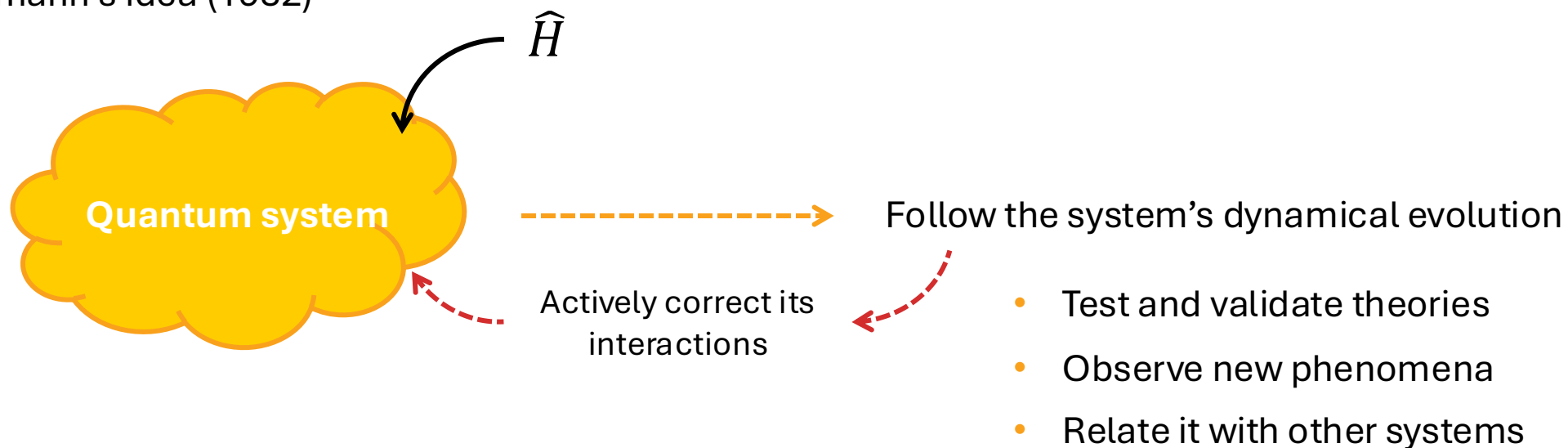
Google quantum computer



Microsoft: Majorana 1

Quantum simulator platforms

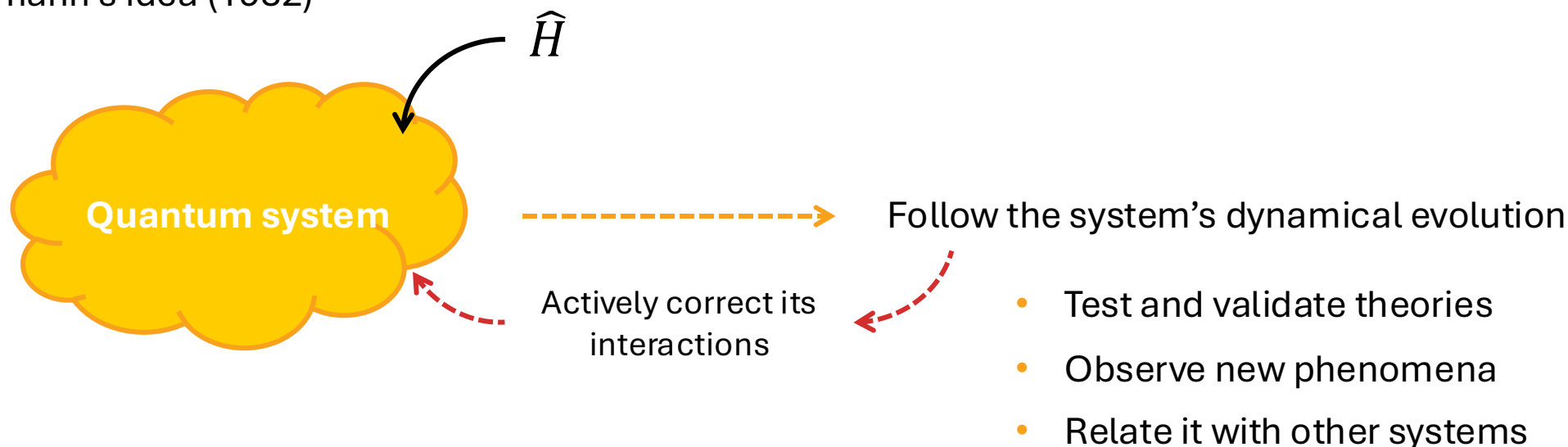
Feynman's idea (1982)*



*R. P. Feynman. Simulating Physics with computers. *Int J Theor Phys* **21**, 467–488 (1982).

Quantum simulator platforms

Feynman's idea (1982)*



Very powerful approach: many particles $\sim 10^3 - 10^4$ particles

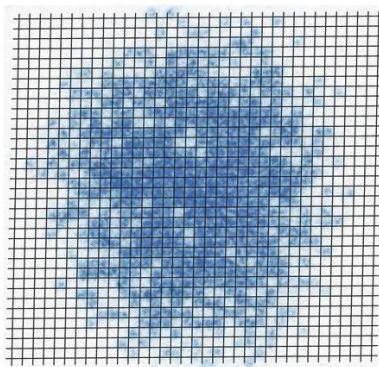
Not universal: restricted to what can be done in the laboratory

Quantum simulator platforms

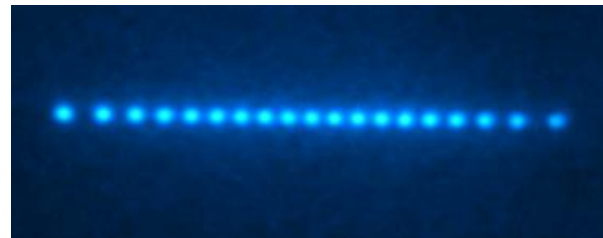
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Different experimental platforms:

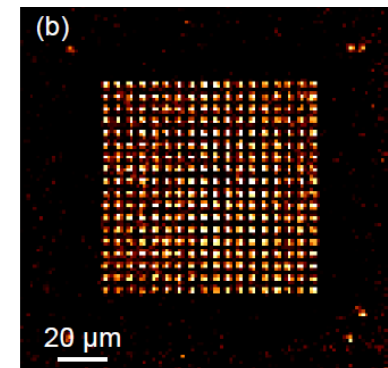
Optical lattices



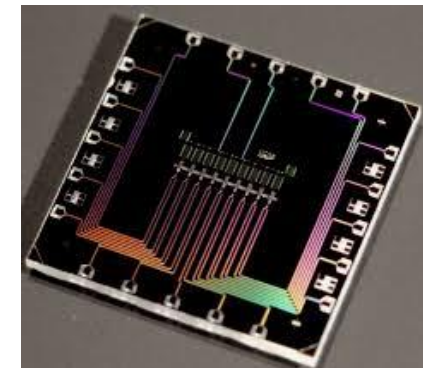
Ion traps



Rydberg atoms



Superconducting devices



Many groups all around the world

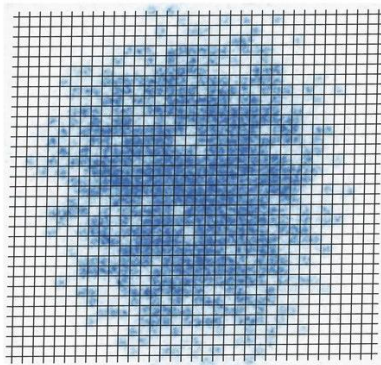
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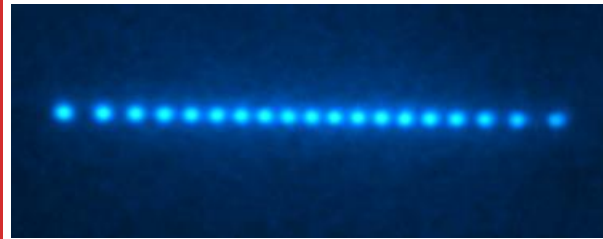
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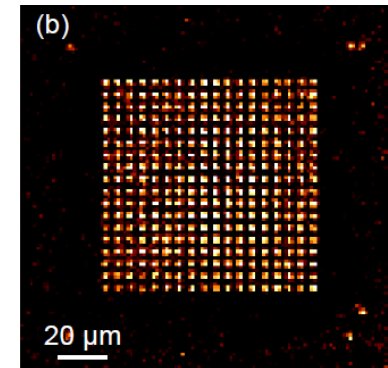
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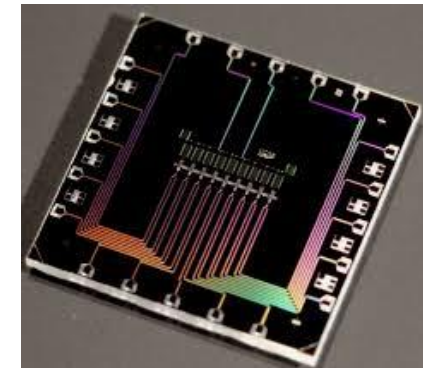
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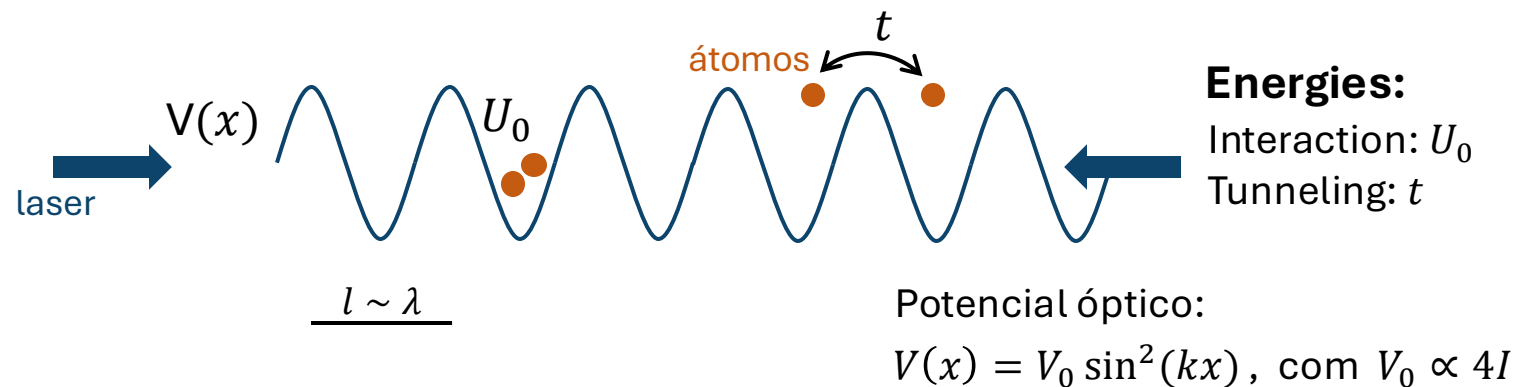


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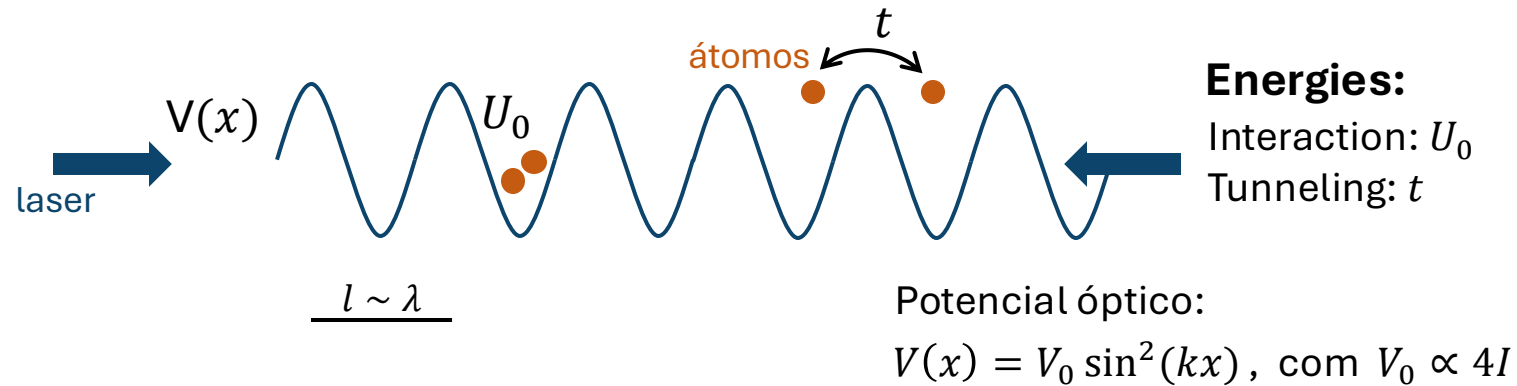
Neutral atoms in optical lattices

Ultracold atoms trapped by interfering laser beams

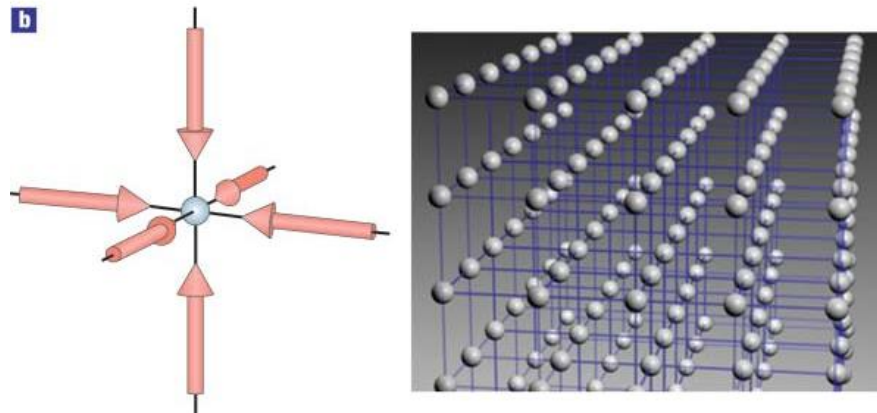


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Extending this idea to 3D...



3D squared optical lattice

+ many other lattice's configurations!

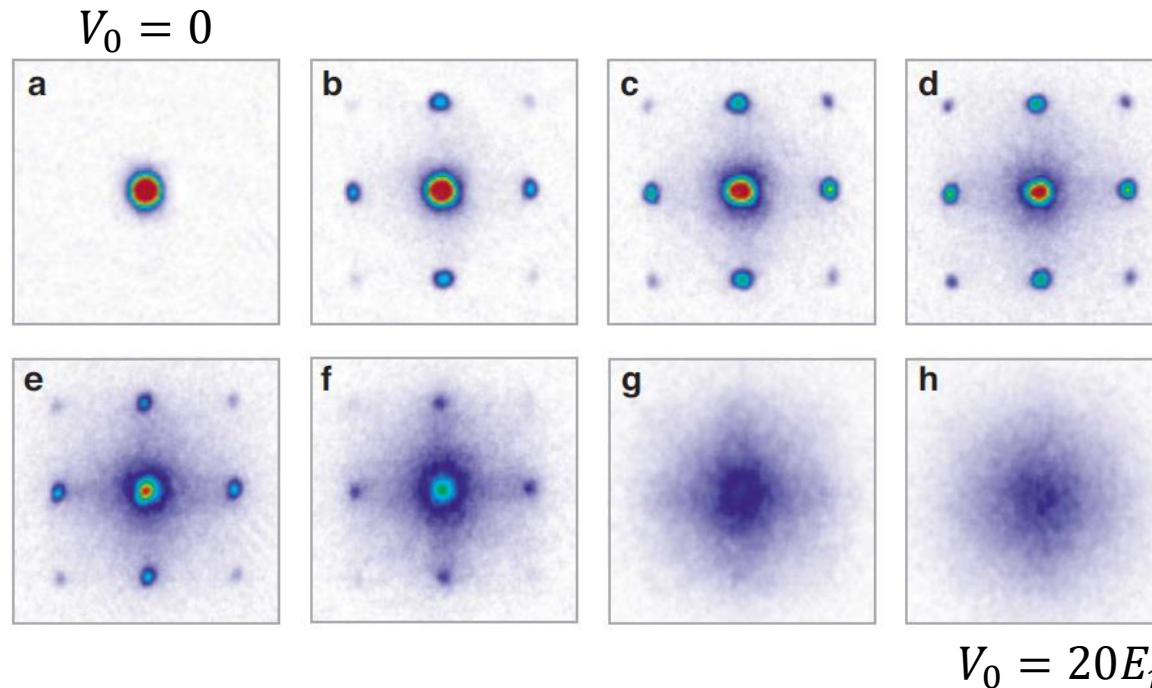
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Pioneer experimental work: superfluid to Mott insulator transition



Immanuel Bloch
Max-Planck-Institute of
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M. Greiner *et al.* *Nature* **415**, 39 (2002)

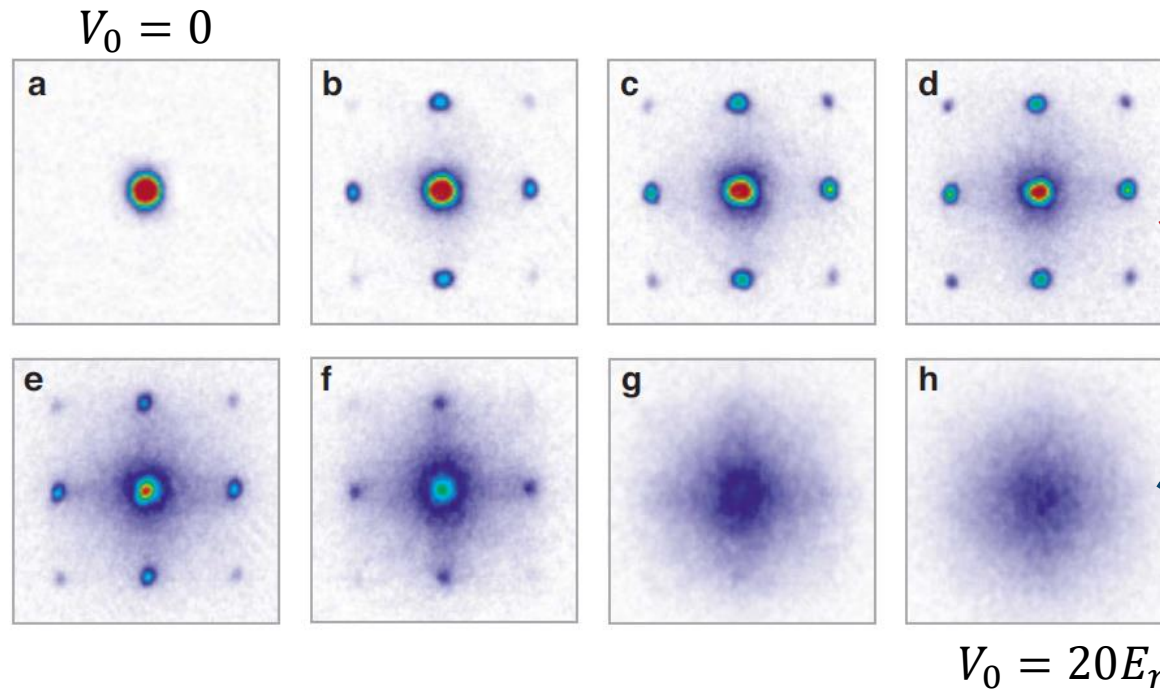
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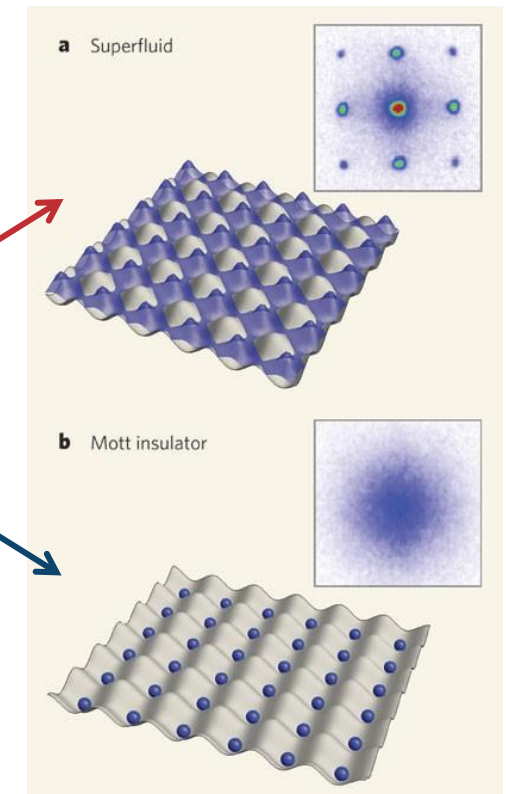
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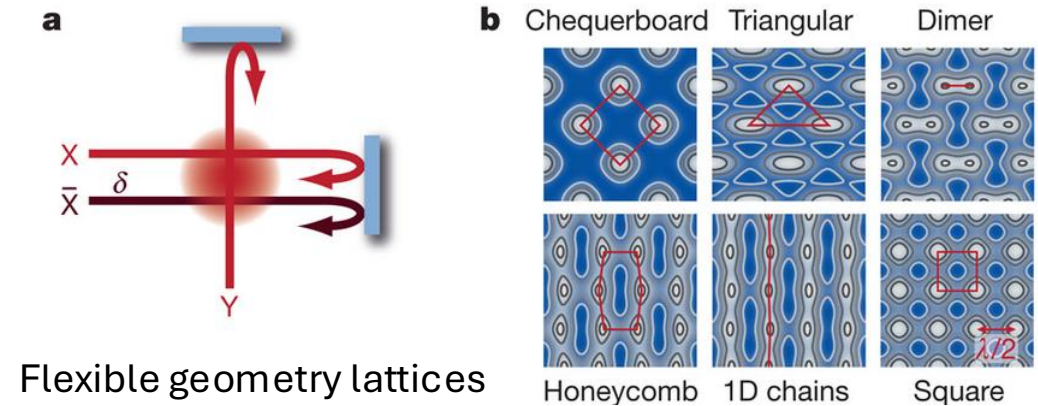
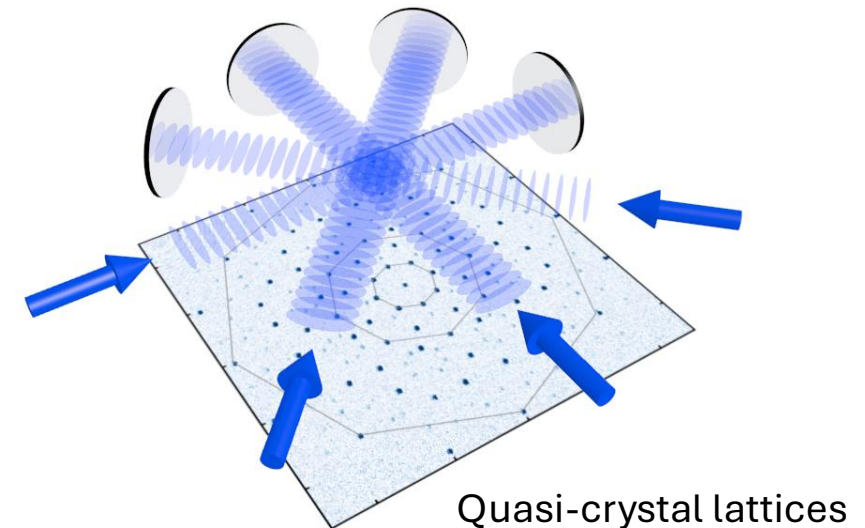


Features of atoms in optical lattices

Why these system are interesting for quantum simulation?

1. Statistics: bosons, fermions or mixtures
2. Manipulate the internal state
3. Control and engender atomic interactions
4. Static or moving particles
5. Few thousand of particles
6. Full control over the lattice potential

Different crystal-like structures changing the number and angle of the laser beams



Latest achievements

Potential engineering:

Single site dressing

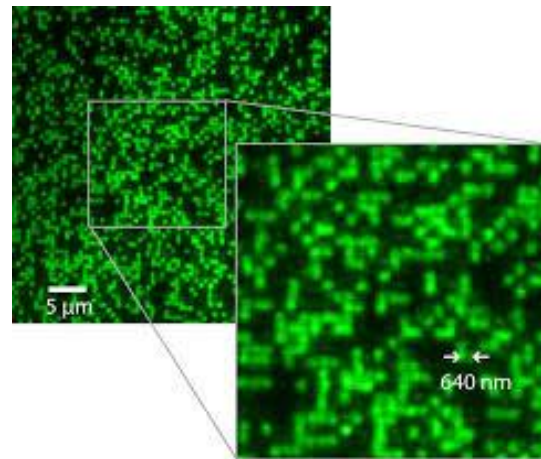
Large uniform systems with variable geometries

Detection: Quantum gas microscope

Review: C. Gross *et al. Nature Physics* **17**, 1316 (2021)

Single atom detection

State-resolved imaging



Single-atom resolution

Latest achievements

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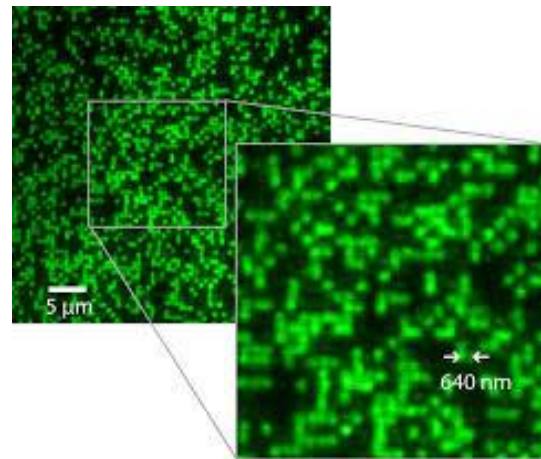
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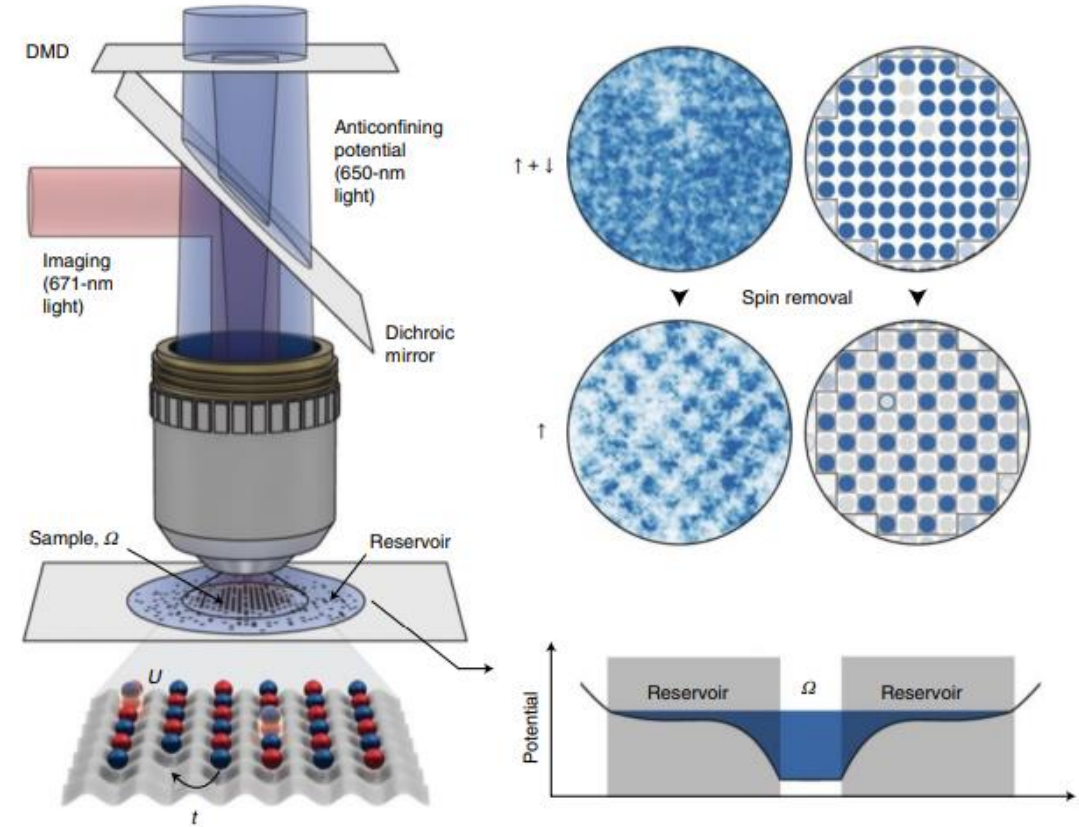
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Single-atom resolution



A. Mazurenko et al. *Nature* **545**, 462 (2017)

Latest achievements

Potential engineering:

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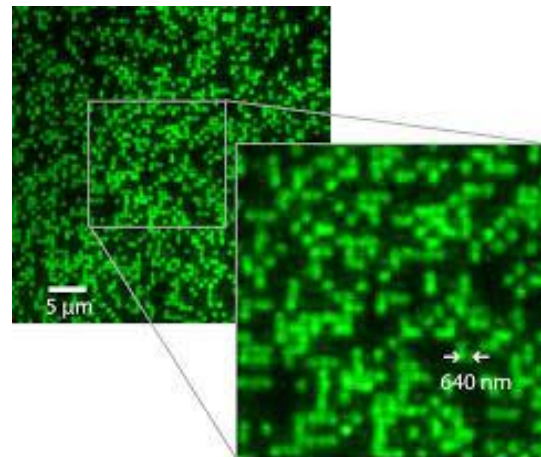
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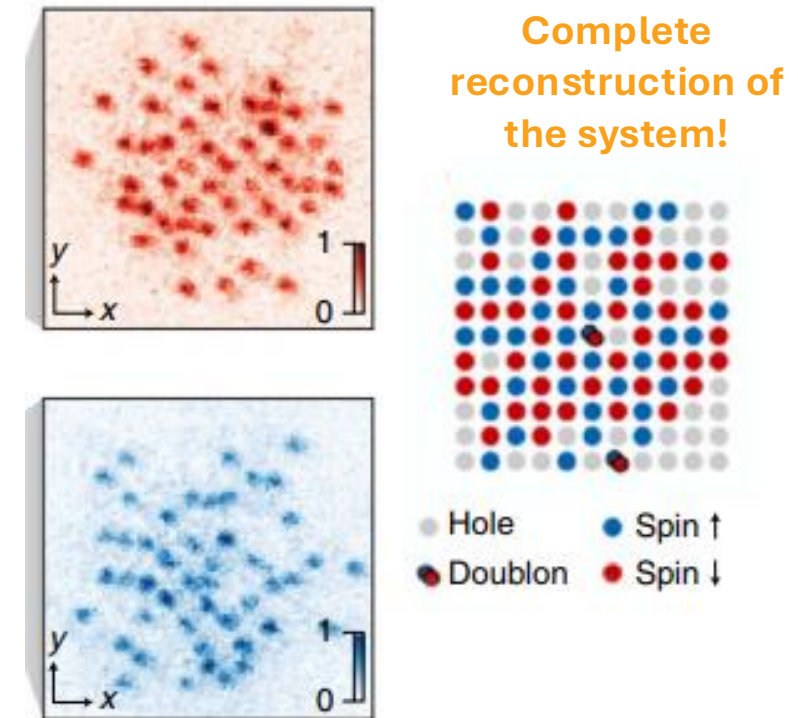
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Single-atom resolution



J. Koepsell et al. *Phys. Rev. Lett.* **125**, 010403 (2020)

2D optical lattices in Brazil

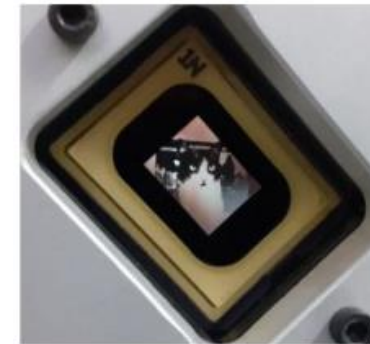
Explore the role of **perturbations** and **disorder** in many-body 2D systems

Get closer to real materials

How to do it?

Combine standard optical lattices with a **DMD**

Local perturbations and static and
dynamic disorder



Array of independently
controlled micromirrors

2D K
Lab

2D optical lattices in Brazil

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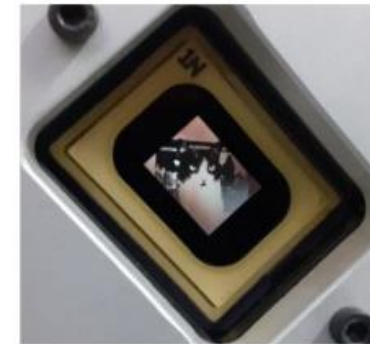
Local perturbations and static and
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Open questions:

- Many-body Anderson localization in 2D
- Dynamics of holes and doublons
- Phase-diagram with disorder

New states of matter?

2D K
Lab



Array of independently
controlled micromirrors

New experimental setup

Started in January 2024

2D K
Lab

January 2024



May 2024



February 2025

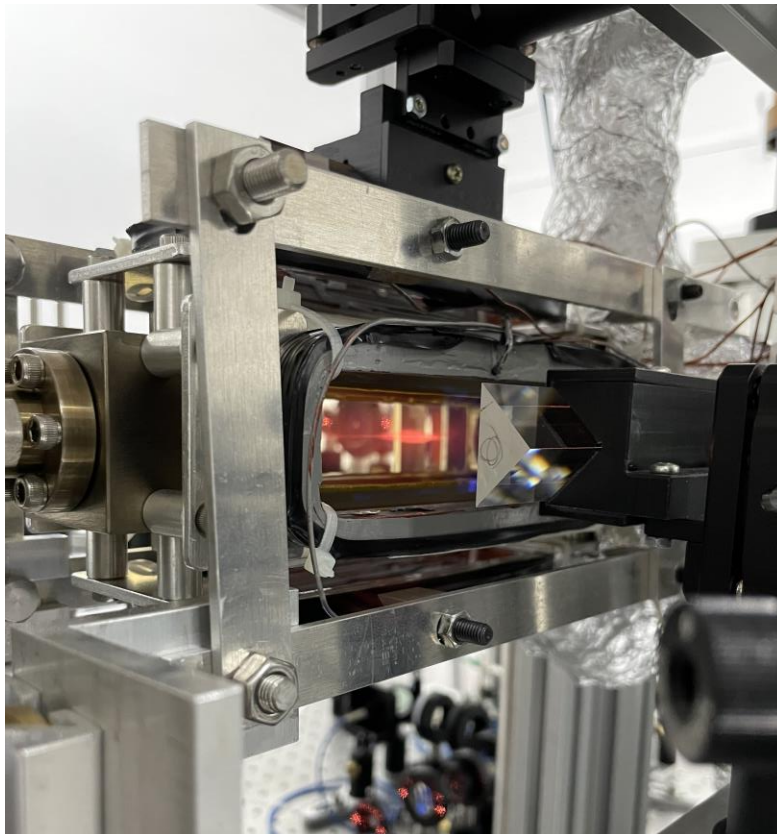


New experimental setup

Achieved all initial laser cooling steps

2D K
Lab

2D-MOT



3D-MOT



Large size MOT ~ 10 mK

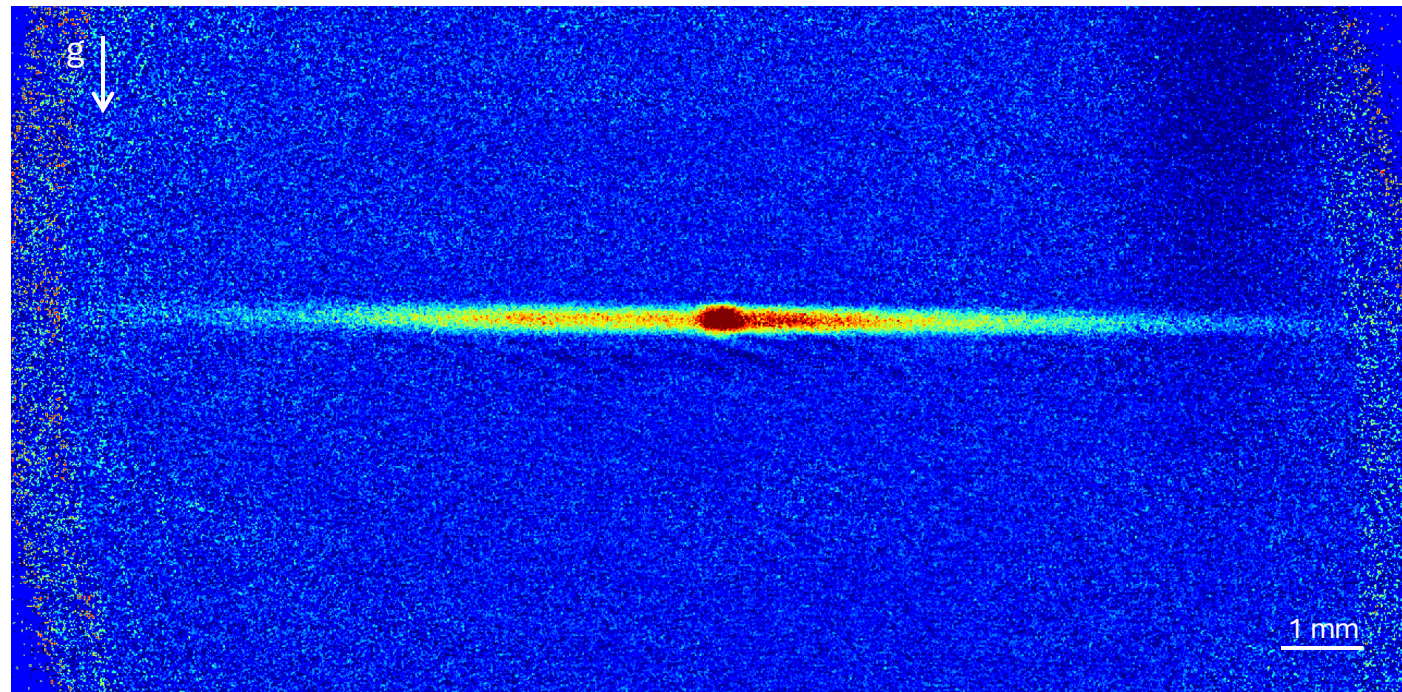
After gray molasses

2×10^8 atoms at ~ 6 μ K

New experimental setup

Now: atoms in the crossed ODT

2D K
Lab



$$\begin{cases} N \sim 2 \times 10^6 \text{ atoms} \\ T \sim 10 \mu\text{K} \end{cases}$$

Starting point to cool the atoms down to Bose-Einstein condensation and tune atomic interactions.

New experimental setup

2D K Lab team

P. C. M. Castilho

PhD students:

P. H. C. Cunha

G. T. Belumat

Undergrad students:

L. P. Balan

N. B. Cristiano

T. E. S. Silva

I. Y. D. Acosta

Visiting professor:

M. Nuñez-Portela (Colombia)
(Ago-Dec 2024)



2D K
Lab



@2DKLab

www.ifsc.usp.br/~pcastilho

Thank you



2D K
Lab



 @2DKLab

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Going back to a quantum computer...

Ultracold atom based platform

Rydberg atoms in optical tweezers

Pioneers: A. Broaueys (Paris) and M. Lukin (Cambridge, US)

Lukin's group:

Nature **620**, 58-65 (2024)

Article

Logical quantum processor based on reconfigurable atom arrays

<https://doi.org/10.1038/s41586-023-06927-3>

Received: 21 October 2023

Accepted: 1 December 2023

Published online: 6 December 2023

Open access

 Check for updates

Dolev Bluvstein¹, Simon J. Evered¹, Alexandra A. Geim¹, Sophie H. Li¹, Hengyun Zhou^{1,2}, Tom Manovitz¹, Sepehr Ebadi¹, Madelyn Cain¹, Marcin Kalinowski¹, Dominik Hangleiter³, J. Pablo Bonilla Ataides¹, Nishad Maskara¹, Iris Cong¹, Xun Gao¹, Pedro Sales Rodriguez², Thomas Karolyshyn², Giulia Semeghini⁴, Michael J. Gullans³, Markus Greiner¹, Vladan Vuletić⁵ & Mikhail D. Lukin^{1✉}

Suppressing errors is the central challenge for useful quantum computing¹, requiring quantum error correction (QEC)^{2–6} for large-scale processing. However, the overhead in the realization of error-corrected ‘logical’ qubits, in which information is encoded across many physical qubits for redundancy^{2–4}, poses substantial challenges to large-scale logical quantum computing. Here we report the realization of a programmable quantum processor based on encoded logical qubits operating with up to **280 physical qubits**. Using logical-level control and a zoned architecture in reconfigurable neutral atom arrays⁷, our system combines high

Going back to a quantum computer...

Ultracold atom based platform

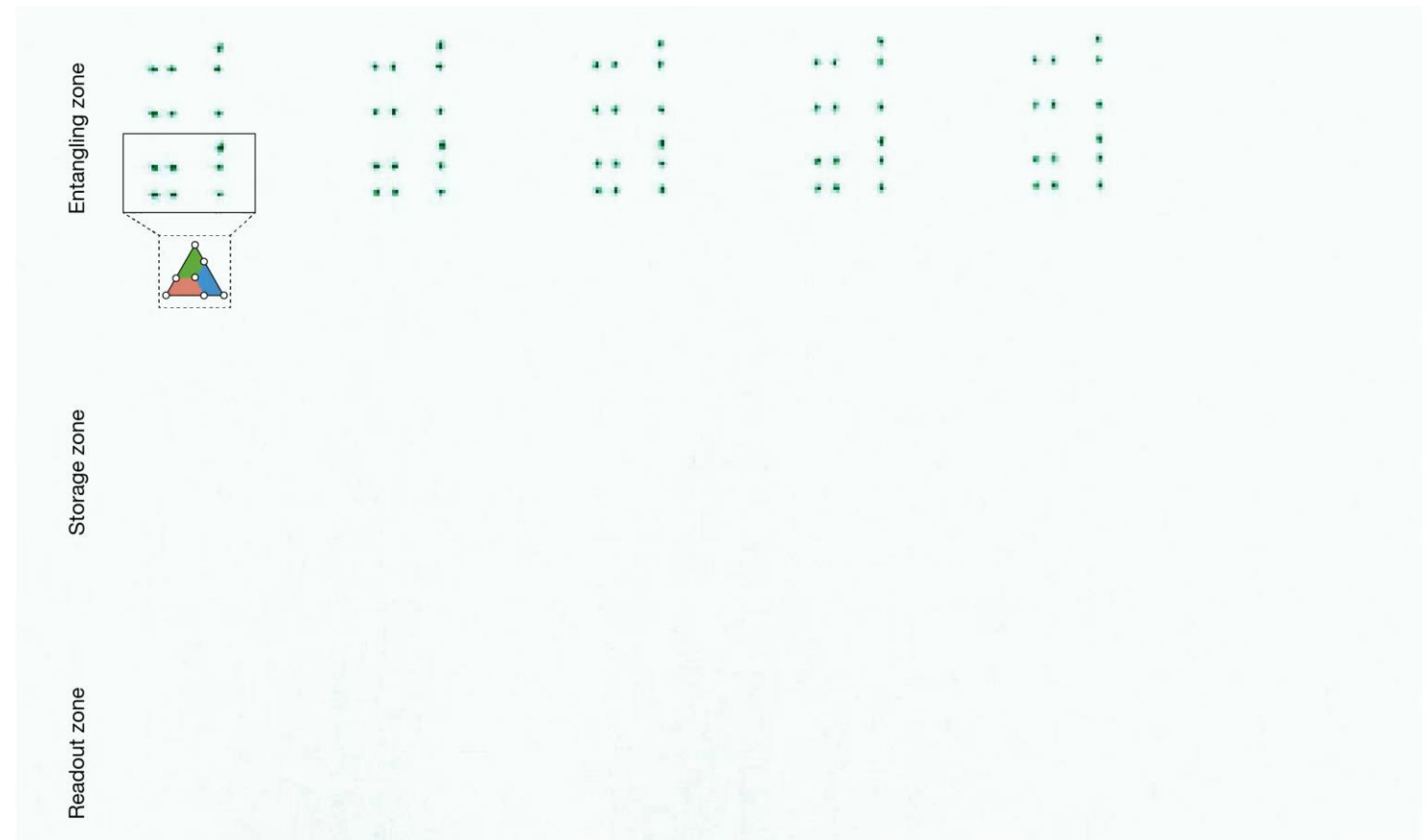
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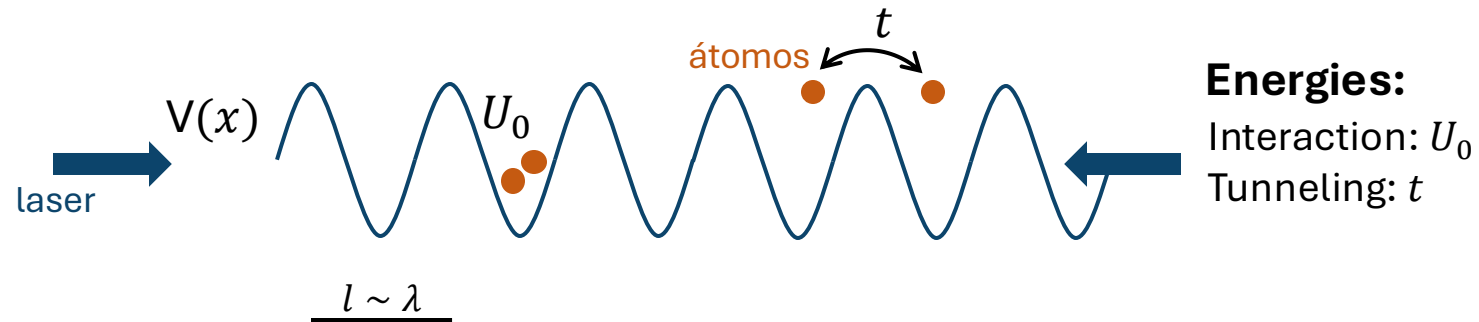
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**Ultracold atom platforms are
great for quantum simulation
and computation!**



Neutral atoms in optical lattices

Ultracold atoms trapped by interfering laser beams



Potencial óptico:

$$V(x) = V_0 \sin^2(kx), \text{ com } V_0 \propto 4I$$

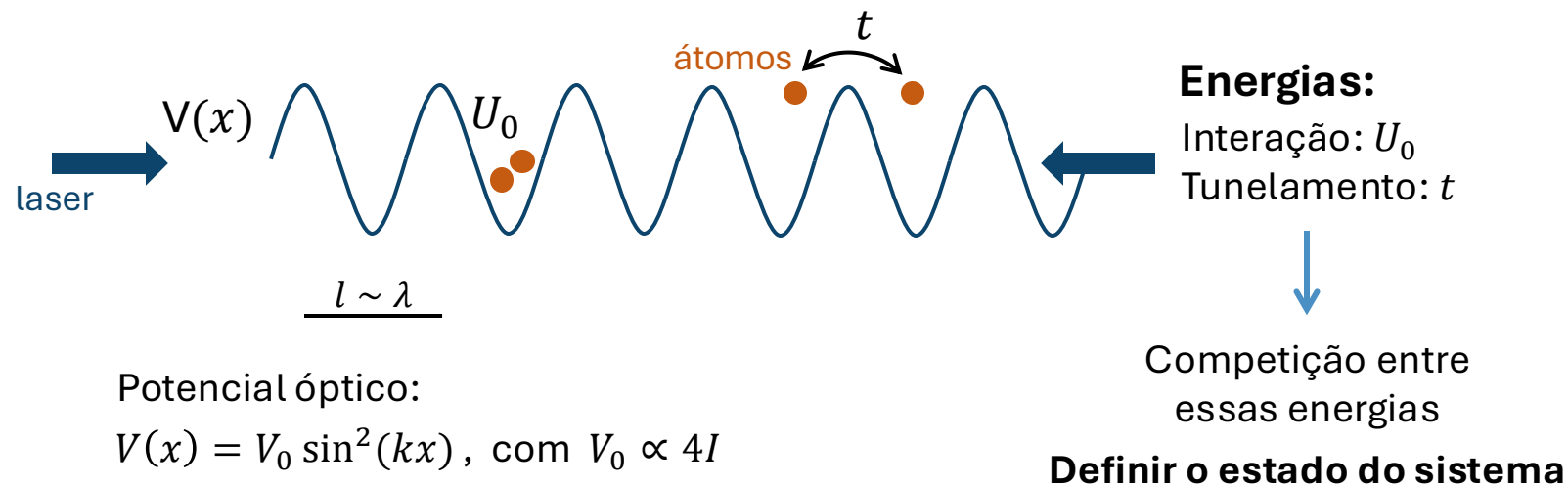
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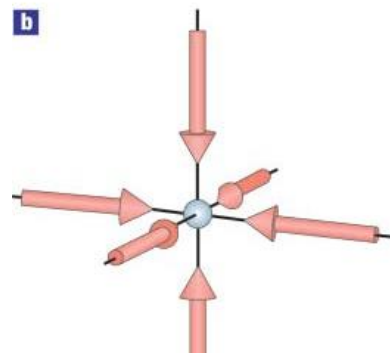
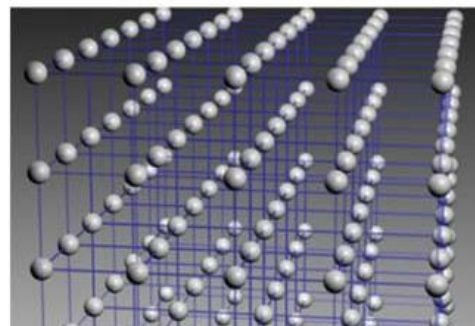


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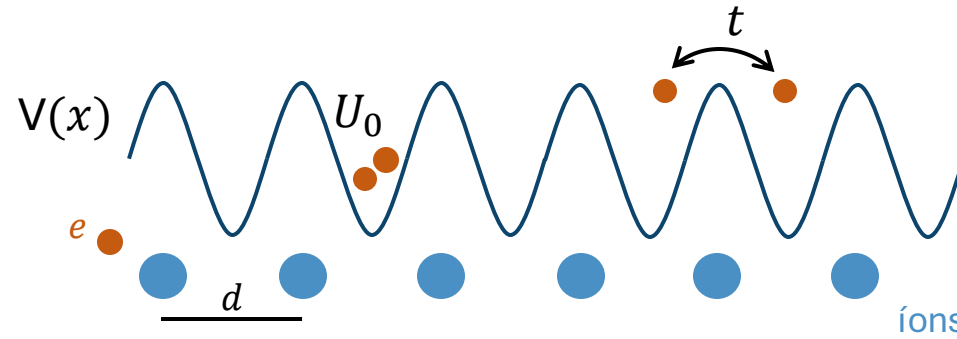
Átomos em redes ópticas

Interferência de feixes de laser



I. Física da matéria condensada

Sólidos: rede cristalina definida pelos íons do material



Energias:

Interação: U_0

Tunelamento: t



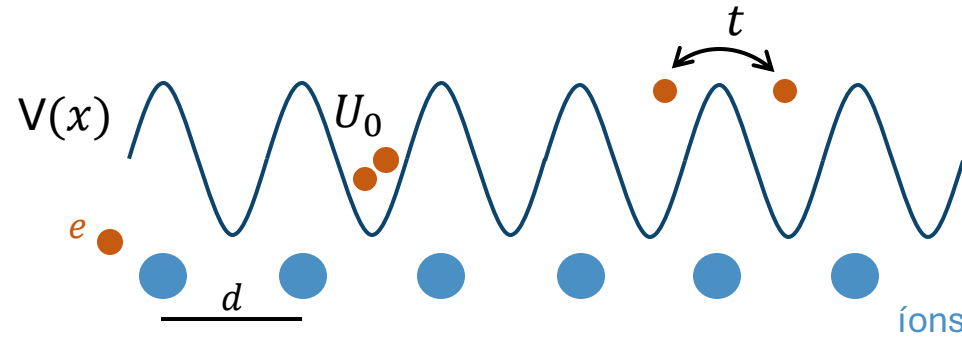
Competição entre
essas energias

Definir o estado do sistema

**Emular tal modelo com átomos
ultrafrios?**

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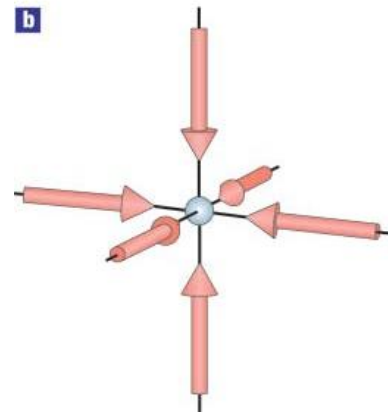
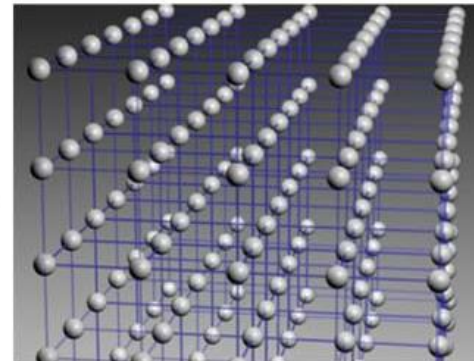
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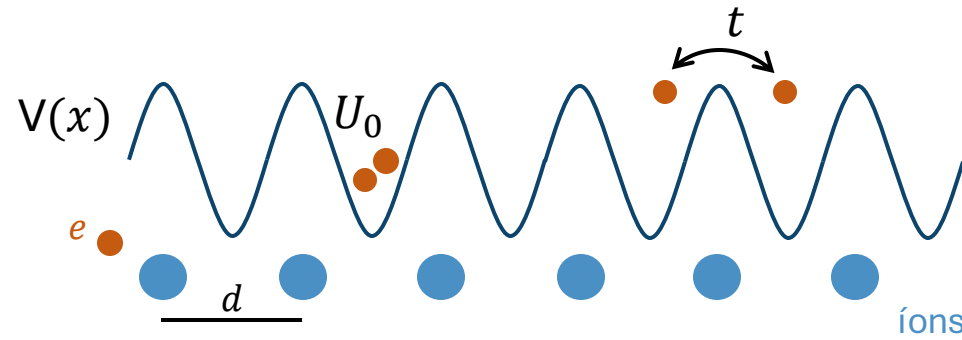
Interferência de feixes de laser



Rede óptica tridimensional

Átomos ultrafrios em redes ópticas

Átomos em redes ópticas:



Energias:

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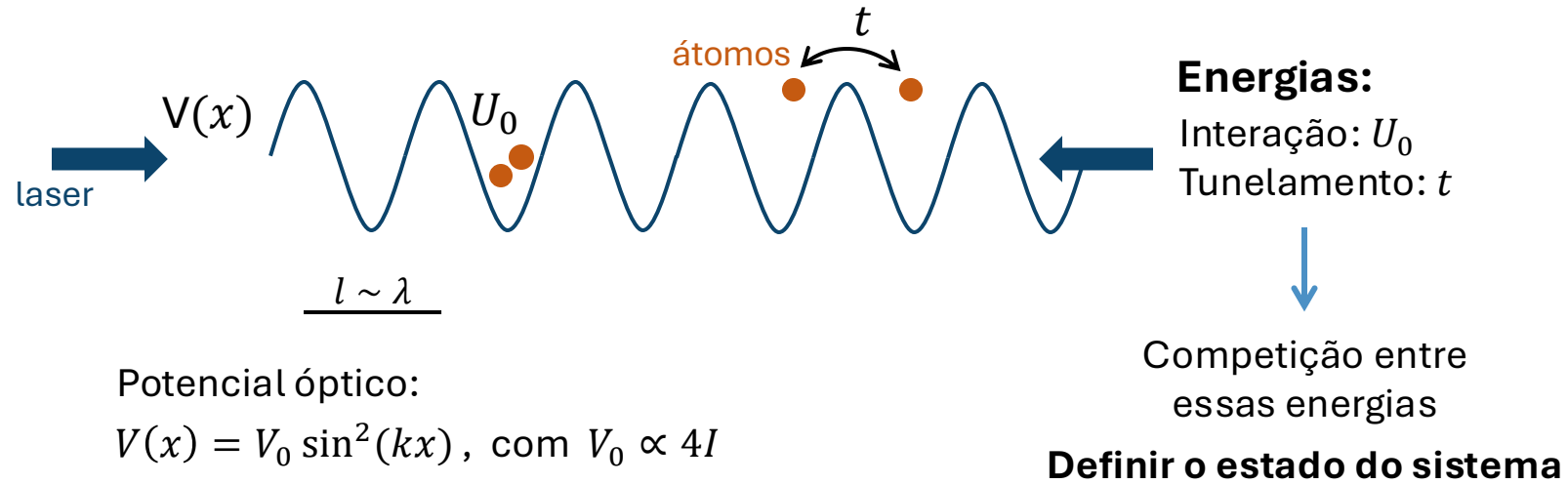


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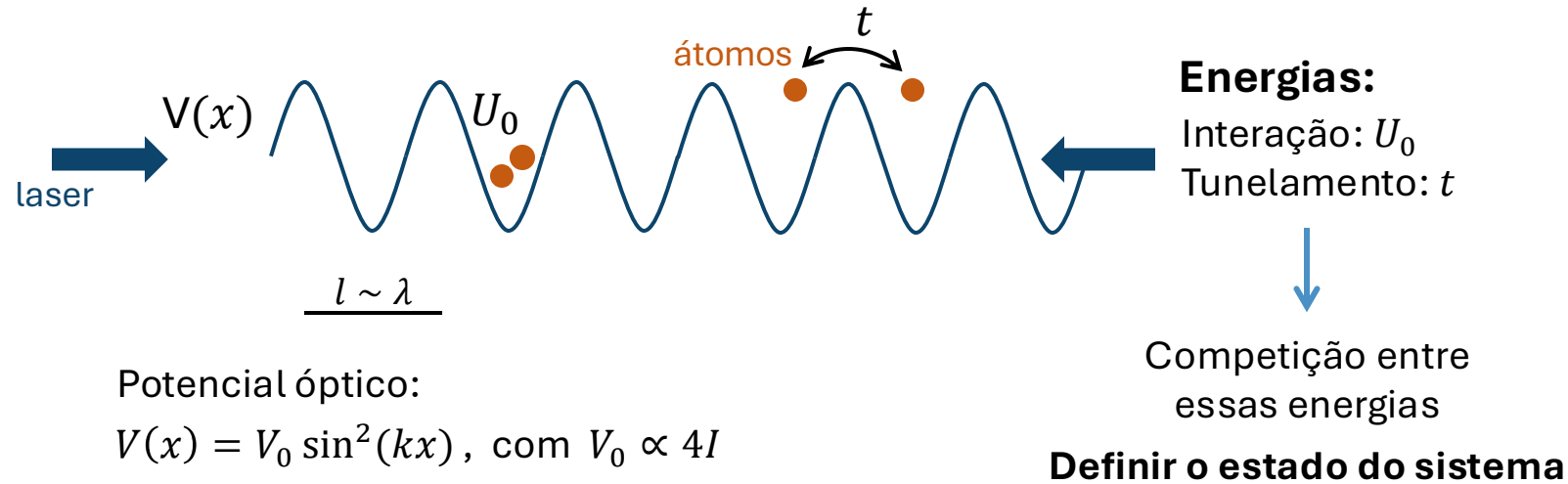
Átomos ultrafrios em redes ópticas

Átomos em redes ópticas:



Átomos ultrafrios em redes ópticas

Átomos em redes ópticas:



Variando V_0 podemos **permitir** ou **suprimir** tunelamento!

Átomos delocalizados
 “viajando” pela rede

Átomos localizados confinados
 em poços específicos
(sistemas isolados)

Transição superfluido e isolante de Mott



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WEEK
GERMANY

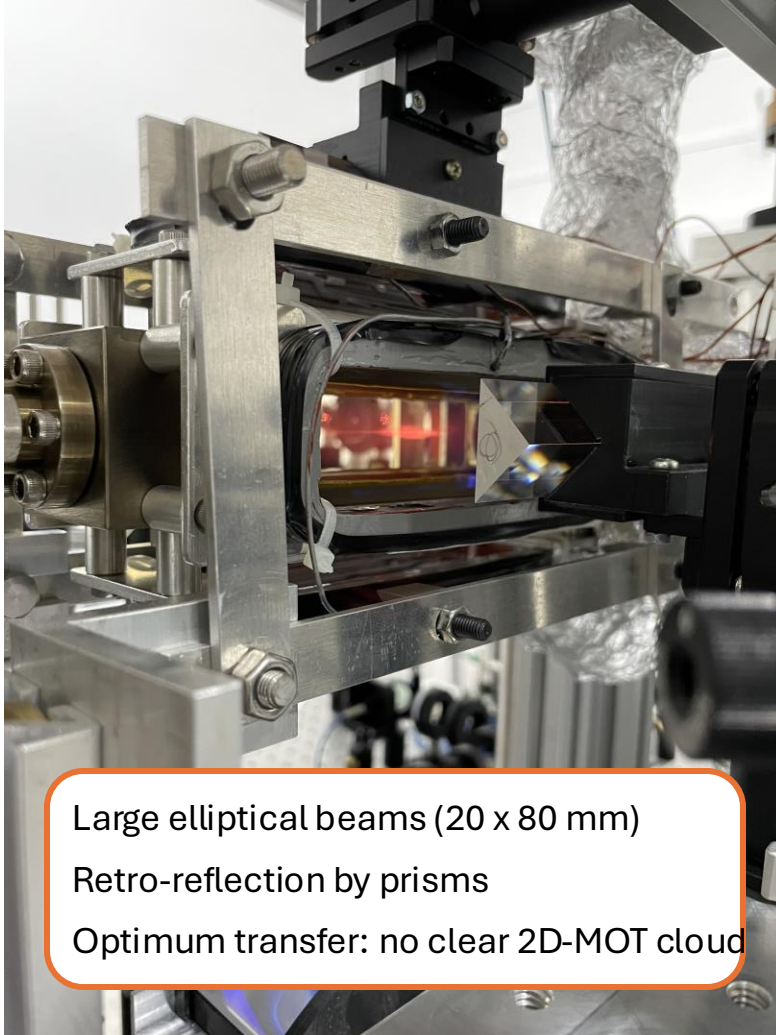
March 25-26th, 2025



Experimental status

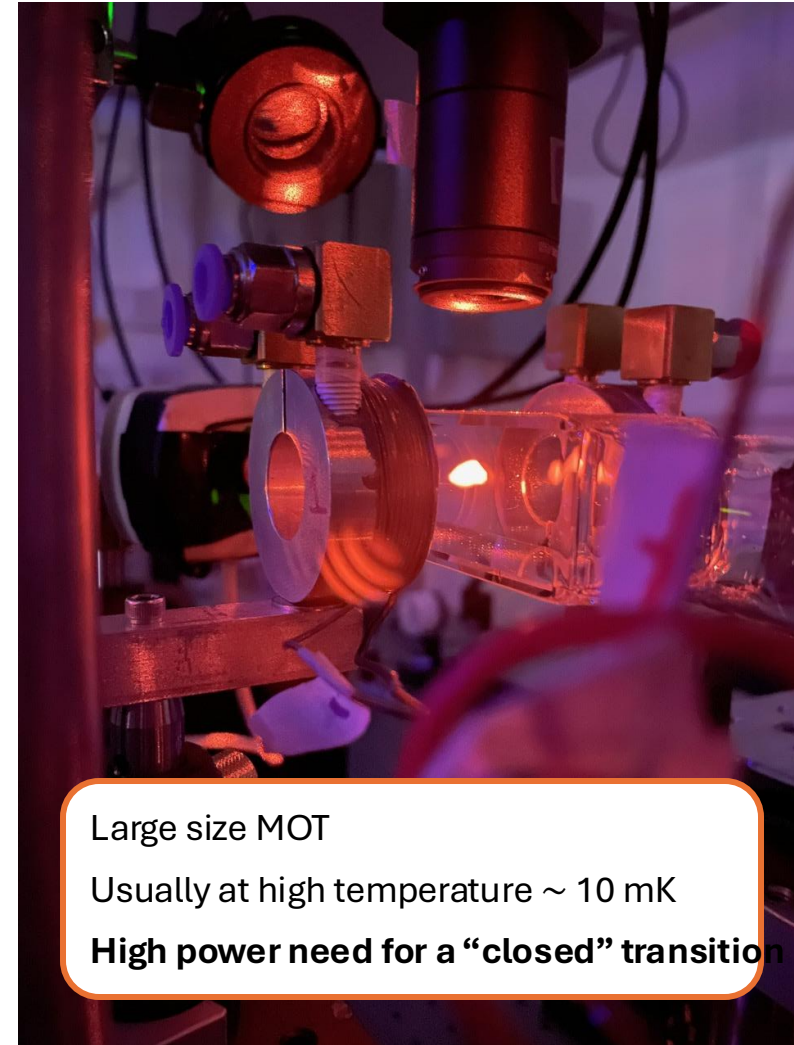
Initial laser cooling steps

2D-MOT



Large elliptical beams (20 x 80 mm)
Retro-reflection by prisms
Optimum transfer: no clear 2D-MOT cloud

3D-MOT

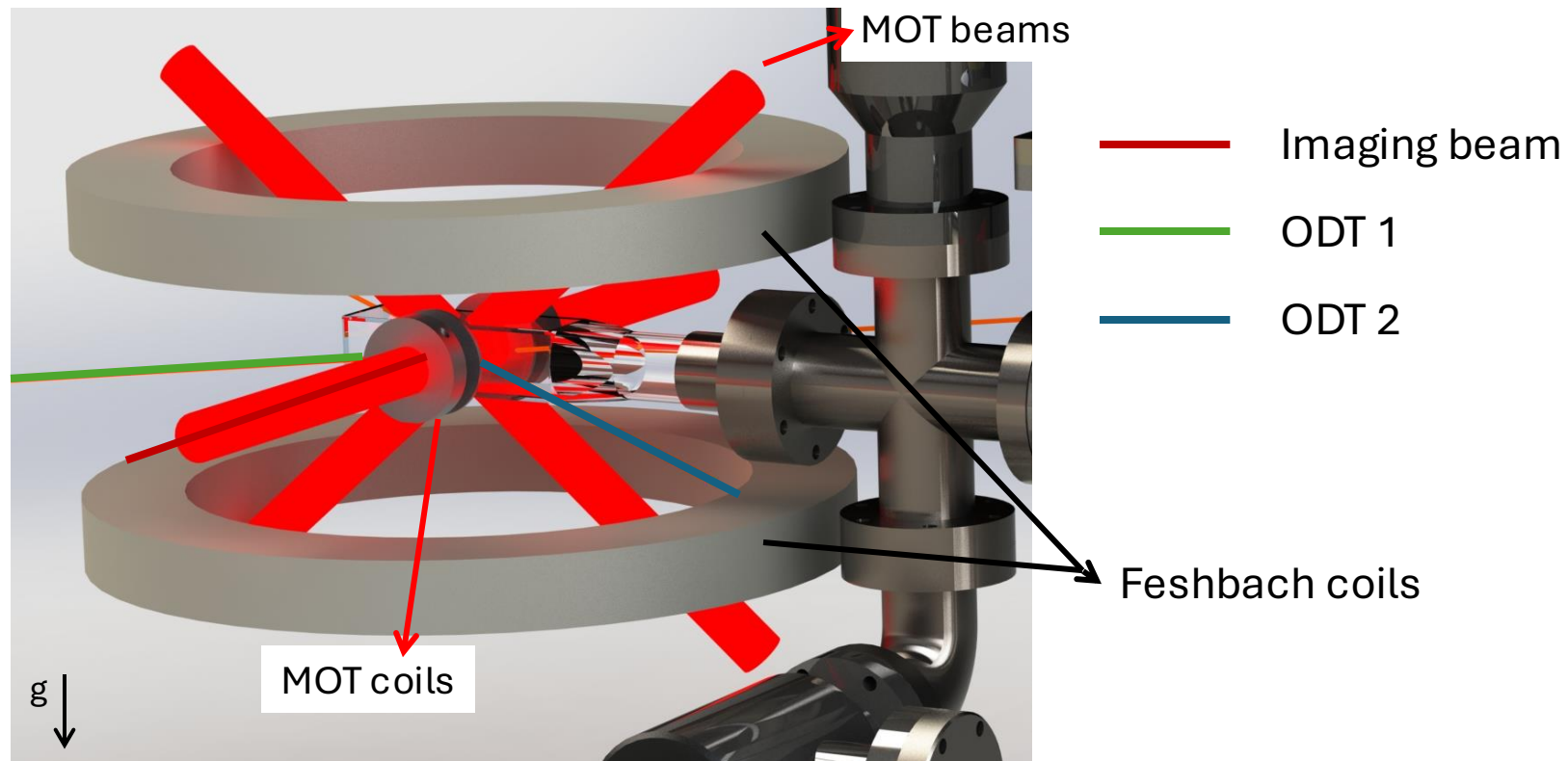


Large size MOT
Usually at high temperature ~ 10 mK
High power need for a “closed” transition

Experimental status

Loading a crossed optical dipole trap (ODT)

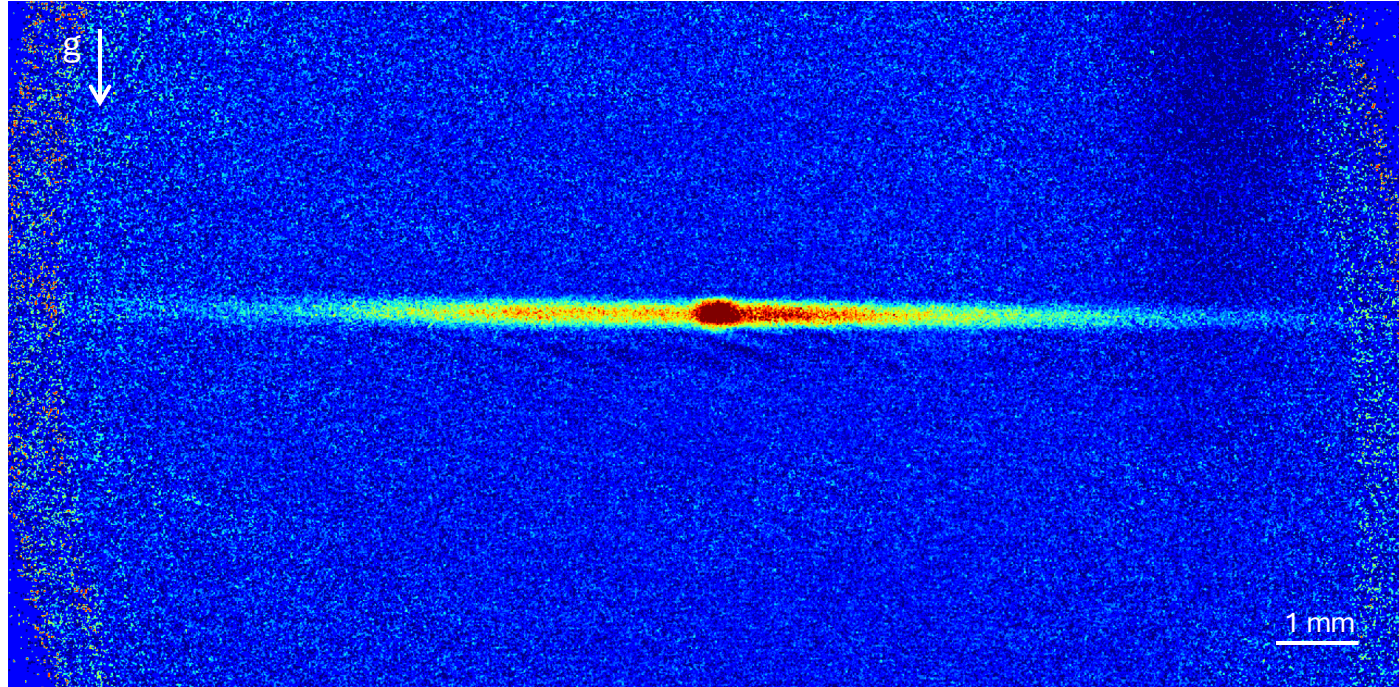
Crossed ODT: setup around the glass cell



Experimental status

Loading a crossed optical dipole trap (ODT)

Crossed ODT: absorption image of the atoms



$$\begin{cases} N \sim 2 \times 10^6 \text{ atoms} \\ T \sim 10 \mu\text{K} \end{cases}$$

Starting point to cool the atoms
up to Bose-Einstein
condensation and tune atomic
interactions.