

Dipartimento di Fisica
Università di Firenze

Quantum information with ultracold atoms

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Conferenza Dipartimento di Fisica

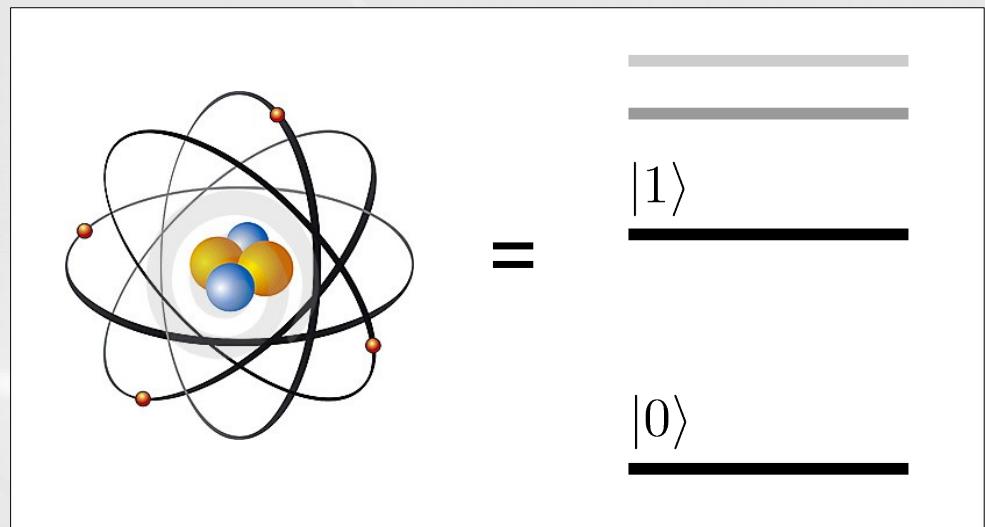
Quantum information with ultracold atoms

Using single neutral atoms to store and manage quantum information

- simple systems
- well-defined internal states
- atomic physics technology

Applications:

- quantum computing
- multi-particle entanglement
- ...



Two major requirements:

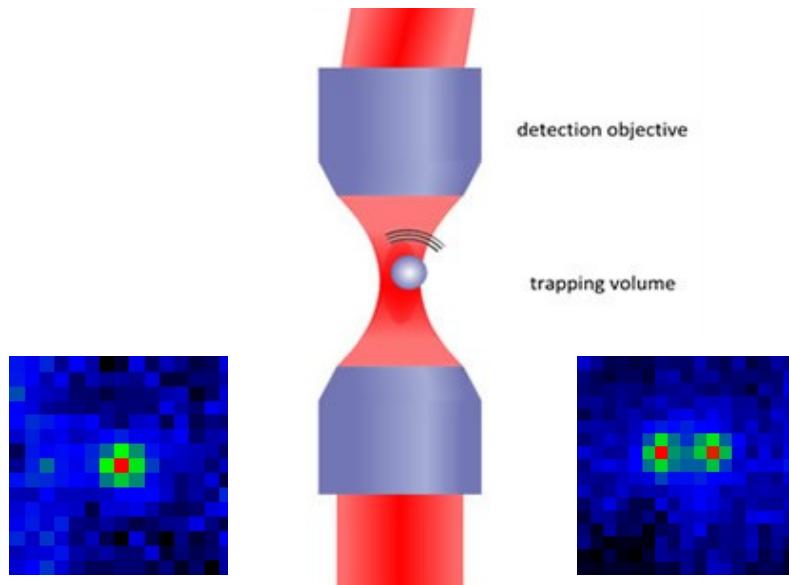
- **ability to manipulate and detect single qubits**
- **need of long coherence times**

Different approaches

bottom-up approach

(Institut d'Optique, Bonn, ...)

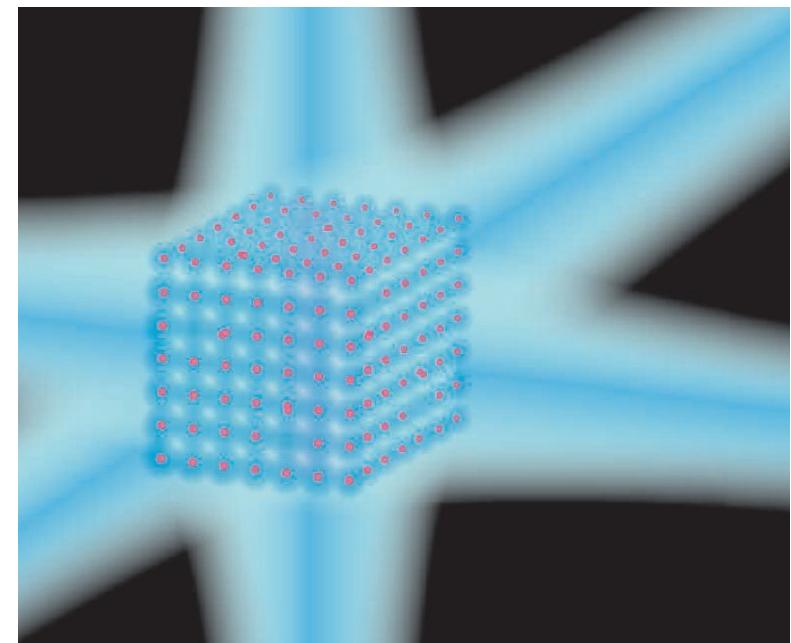
single-atom optical traps
“optical tweezers”



top-down approach

(Florence, MPQ, ETH, MIT, ...)

quantum gases in optical lattices

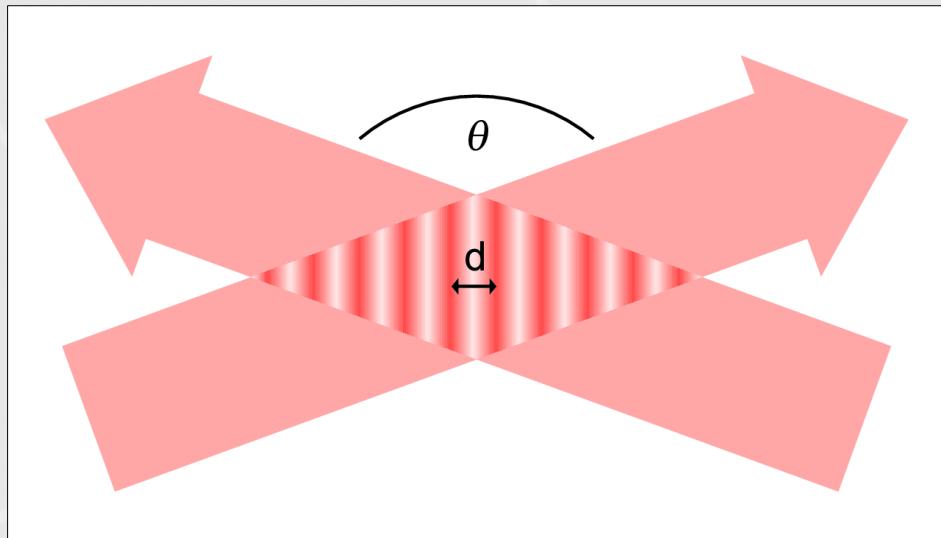


single-atom manipulation for free
difficult scalability

good scalability for free
single-site addressing difficult

Optical lattices

Interfering coherent laser beams provide a standing wave



periodic defect-free potentials

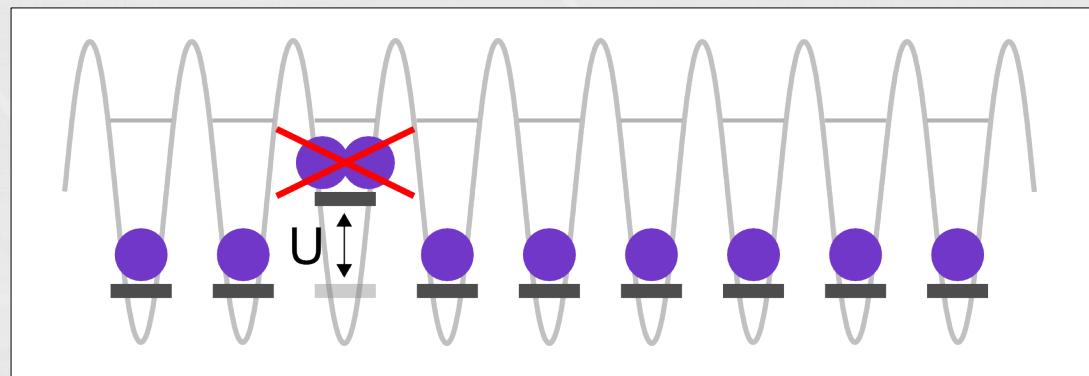
- quantum simulation of cond-mat systems
- interferometry, precision measurements
- optical metrology
- quantum information

Creating quantum registers

Starting from a degenerate quantum gas (BEC, Fermi gas) at ~ 100 nK we can fill an optical lattice with exactly one atom per lattice site

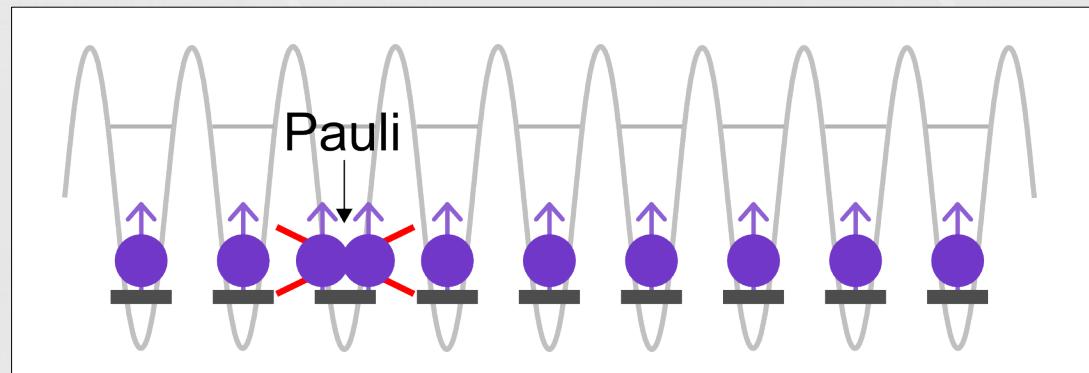
strong repulsive interactions
between bosons

MOTT INSULATOR



spin polarized fermions

BAND INSULATOR

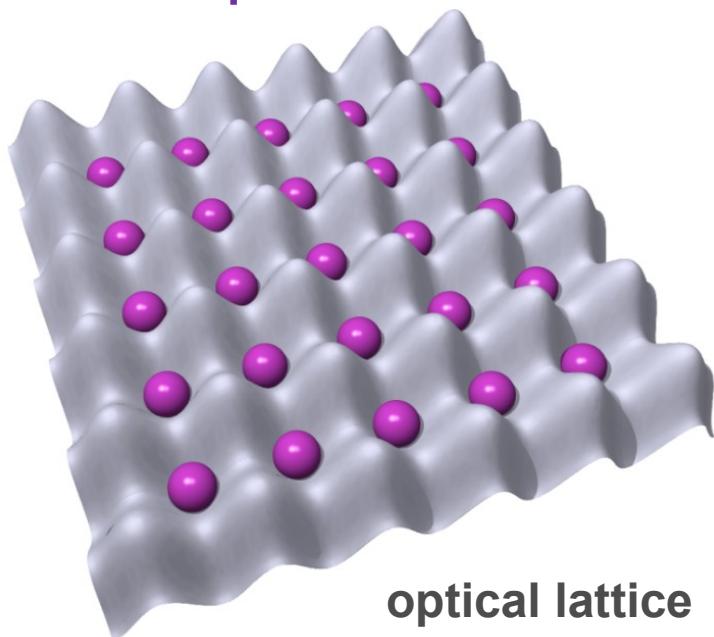


Single site addressing

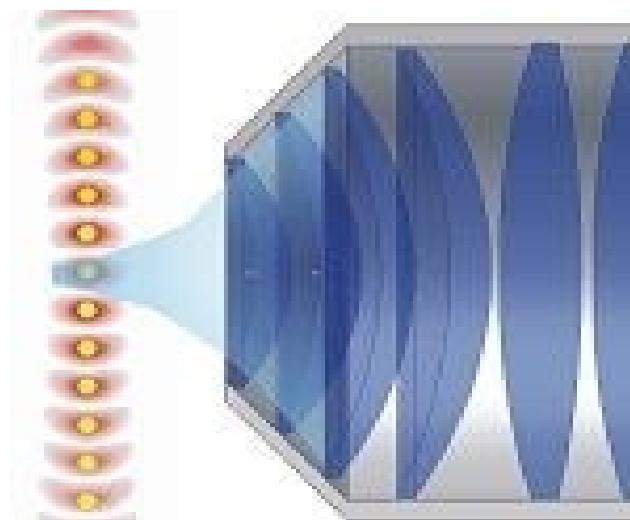
Quantum register with atoms trapped in optical lattices

High-res imaging + optical tweezing for addressing and manipulating qubits

atoms = qbits



r/w addressability and manipulation

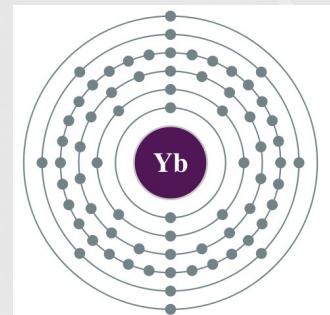


microscope objective

Ytterbium

Ytterbium (Yb) is a good candidate for quantum information processing with neutral atoms:

- Several stable isotopes
- Rich level structure (metastable states)
- Optical clocks technology



hydrogen 1 H 1.007	yttrium 3 Li 6.941	beryllium 4 Be 8.012
lithium 11 Na 22.990	magnesium 12 Mg 24.305	
potassium 19 K 39.098	calcium 20 Ca 40.078	
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	
cesium 55 Cs 132.91	barium 56 Ba 137.33	
francium 87 Fr 223	radium 88 Ra 226	
lanthanide series		
lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91
neodymium 60 Nd 144.24	europium 61 Eu 150.38	thulium 62 Tm 151.96
promethium 63 Pm 145.91	gadolinium 64 Gd 151.96	dysprosium 65 Dy 162.50
samarium 66 Sm 150.38	erbium 67 Er 161.97	ytterbium 68 Yb 173.04
europium 63 Eu 151.96	ytterbium 69 Yb 173.04	brownium 70 Bn 173.04
actinide series		
actinium 89 Ac 227	thorium 90 Th 232.04	protactinium 91 Pa 231.04
thorium 90 Th 232.04	neptunium 92 Np 238.03	plutonium 93 Pu 244.04
protactinium 91 Pa 231.04	americium 94 Am 243.04	curium 95 Cm 247.04
curium 92 Cm 247.04	berkelium 96 Bk 247.04	californium 97 Cf 251.04
berkelium 93 Bk 247.04	curium 98 Es 250.04	fonderium 99 Fm 257.04
curium 94 Cm 250.04	curium 100 Md 256.04	bohrium 101 No 258.04

Name
Symbol
Atomic number
Atomic weight
Electron configuration

Ytterbium
Yb
70
173.04
[Xe]4f¹⁴6s²

Stable isotopes

168 ^{Yb}	0.13%	I=0
170 ^{Yb}	3.04%	I=0
171 ^{Yb}	14.28%	I=1/2
172 ^{Yb}	21.83%	I=0
173 ^{Yb}	16.13%	I=5/2
174 ^{Yb}	31.83%	I=0
176 ^{Yb}	12.76%	I=0

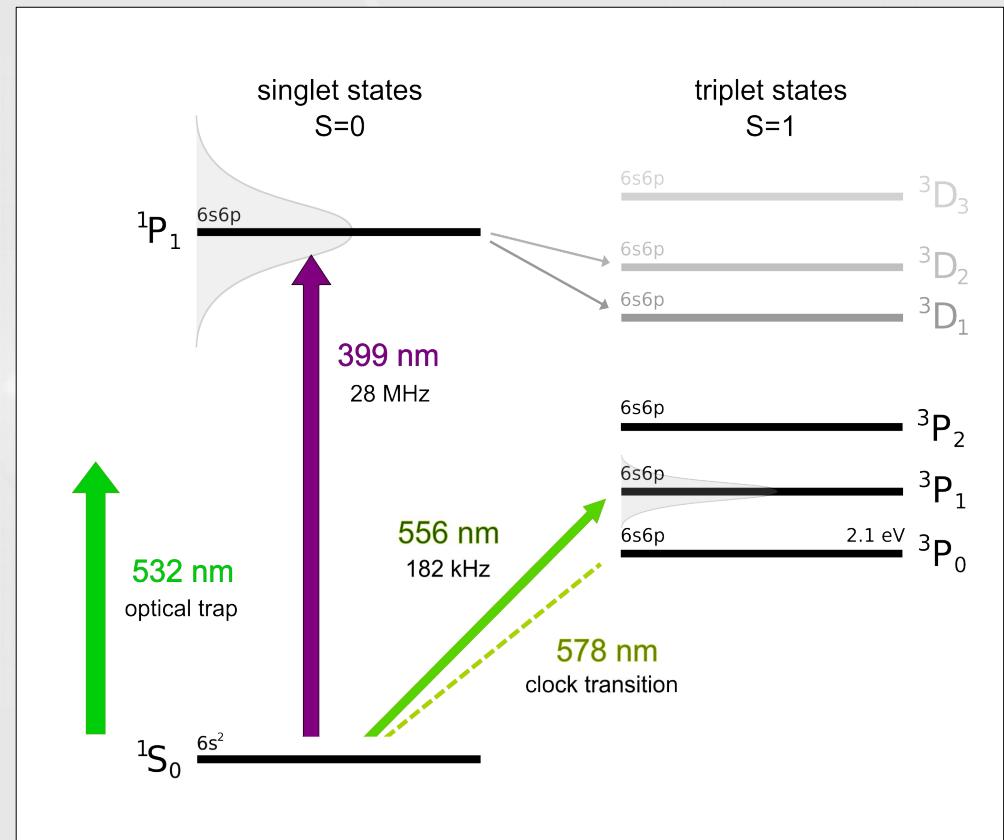
Ytterbium

As true alkaline-earth atoms ytterbium has a two-electron structure:

- metastable triplet ($S=1$) states
- ground state with $J=0$
- intercombination clock transition

Ytterbium cooling:

- Yb atomic beam
- Zeeman slower @ 399 nm
- Green MOT @ 556 nm
- Optical trap @ 532 nm



Development of novel laser sources (INO-CNR)

Electronic qubits

- Using the $^1S_0 = |0\rangle$ and $^3P_0 = |1\rangle$ as logical states of the qubit

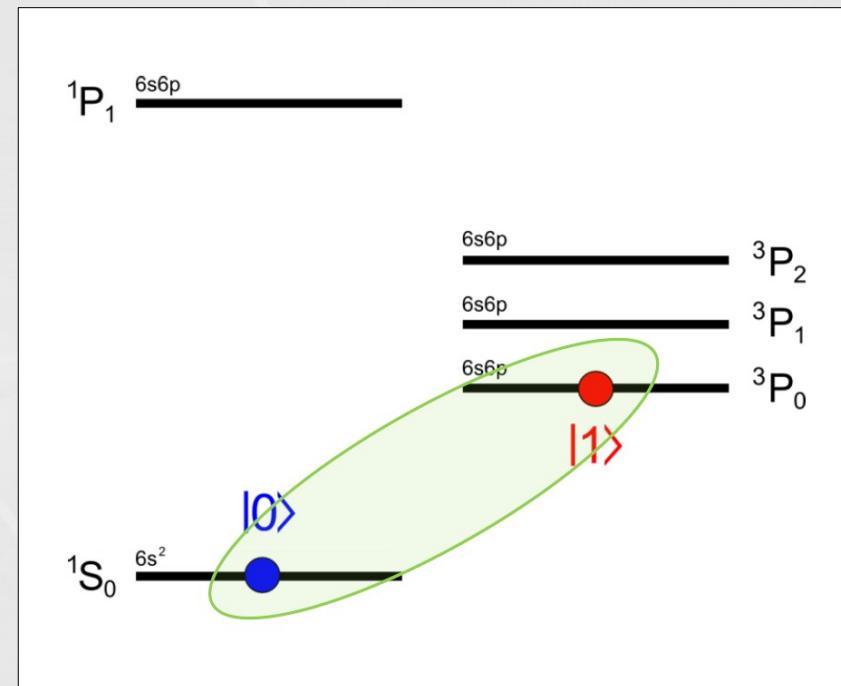
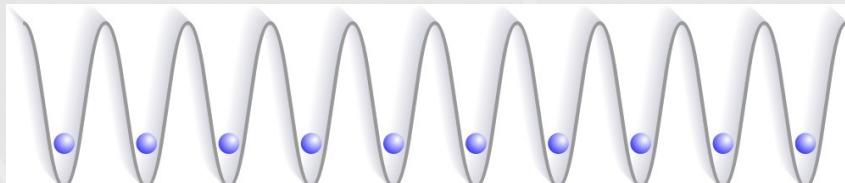
Optical atomic clock technology

Ultranarrow intercombination transition
(doubly-forbidden)



Extremely long coherence times in the superposition $\alpha|0\rangle + \beta|1\rangle$

State-independent quantum register at the magic wavelength $\lambda = 752$ nm



Nuclear qubits

- Storing qubits in the nuclear spin state of a fermionic isotope

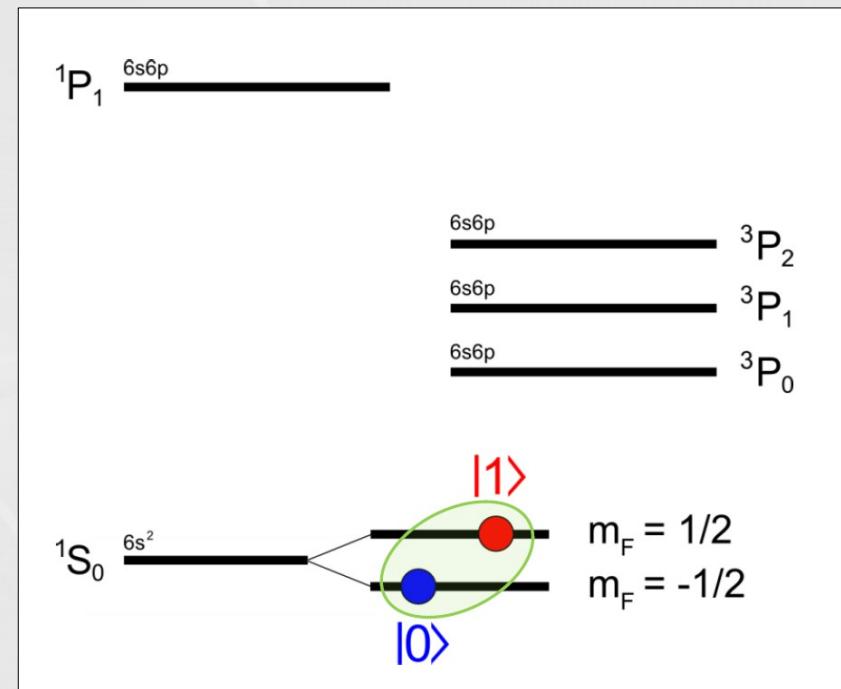
No coupling between nuclear spin and electronic degrees of freedom

Magnetic moment of the fermionic isotopes in the states 1S_0 and 3P_0 is entirely due to the nuclear spin ($J=0$)



Long coherence times

Very small sensitivity (10^3 - 10^4 less than alkalis) to magnetic field fluctuations



Quantum gates with ultracold collisions

Example of implementation of a quantum gate for identical fermionic particles

Symmetrization of the wavefunction:

$$|0,0\rangle = \Psi_-(x_1, x_2)|\uparrow, \uparrow\rangle$$

$$|0,1\rangle = [\Psi_-(x_1, x_2)|\chi_T\rangle + \Psi_+(x_1, x_2)|\chi_S\rangle] / \sqrt{2}$$

$$|1,0\rangle = [\Psi_-(x_1, x_2)|\chi_T\rangle - \Psi_+(x_1, x_2)|\chi_S\rangle] / \sqrt{2}$$

$$|1,1\rangle = \Psi_-(x_1, x_2)|\downarrow, \downarrow\rangle$$

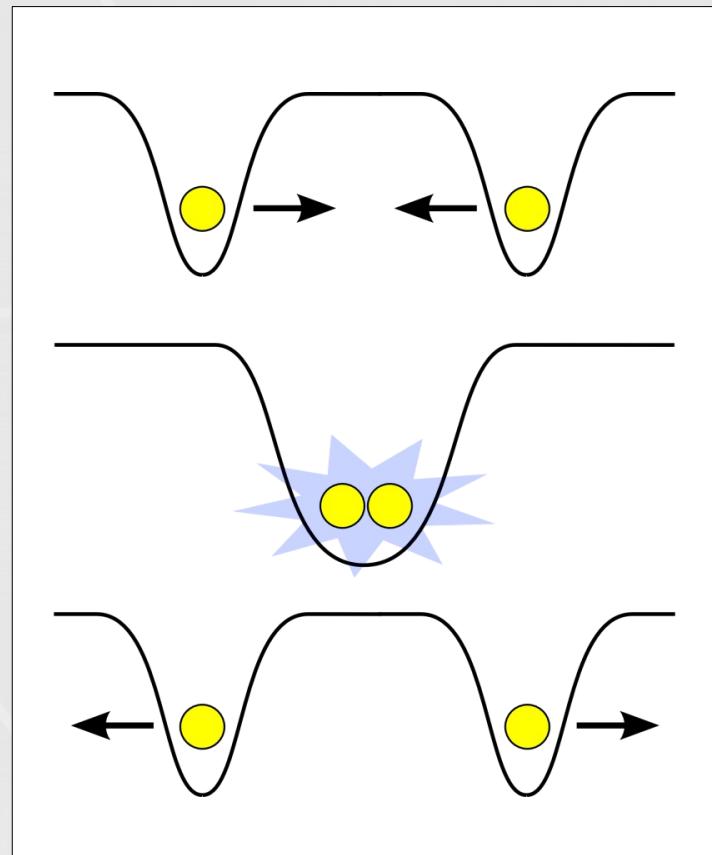
$$|\chi_S\rangle = (|\uparrow, \downarrow\rangle - |\downarrow, \uparrow\rangle) / \sqrt{2} \rightarrow \text{collisional phase-shift}$$

$$|\chi_T\rangle = (|\uparrow, \downarrow\rangle + |\downarrow, \uparrow\rangle) / \sqrt{2} \rightarrow \text{no collisional phase-shift}$$

Implementation of the $\sqrt{\text{SWAP}}$ gate:

$$\sqrt{\text{SWAP}}|0,1\rangle = (|0,1\rangle + i|1,0\rangle) / \sqrt{2}$$

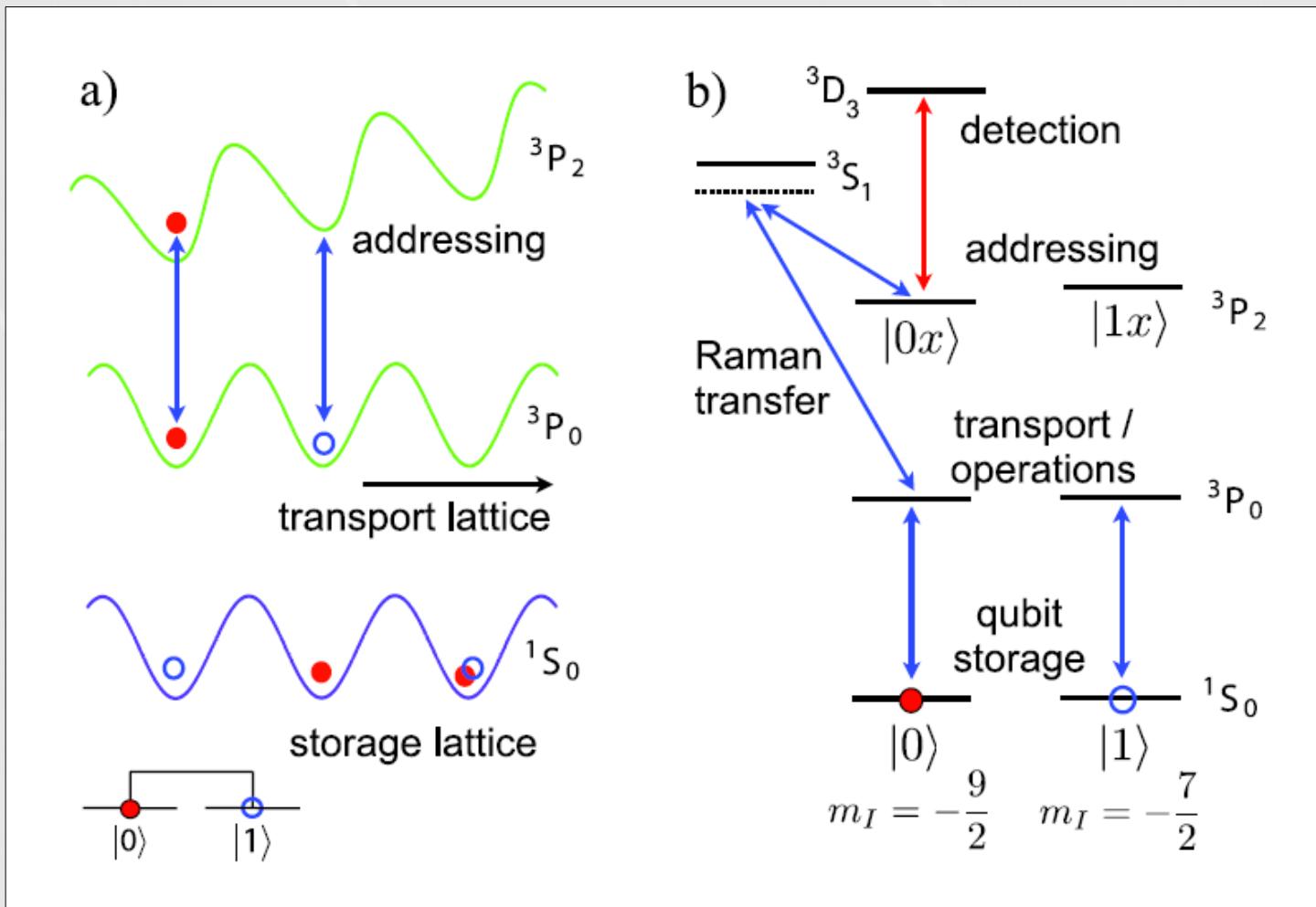
$$(\sqrt{\text{SWAP}})^2|0,1\rangle = i|1,0\rangle$$



Quantum computing with alkaline-earth atoms

Quantum computing with alkaline-earth-metal atoms

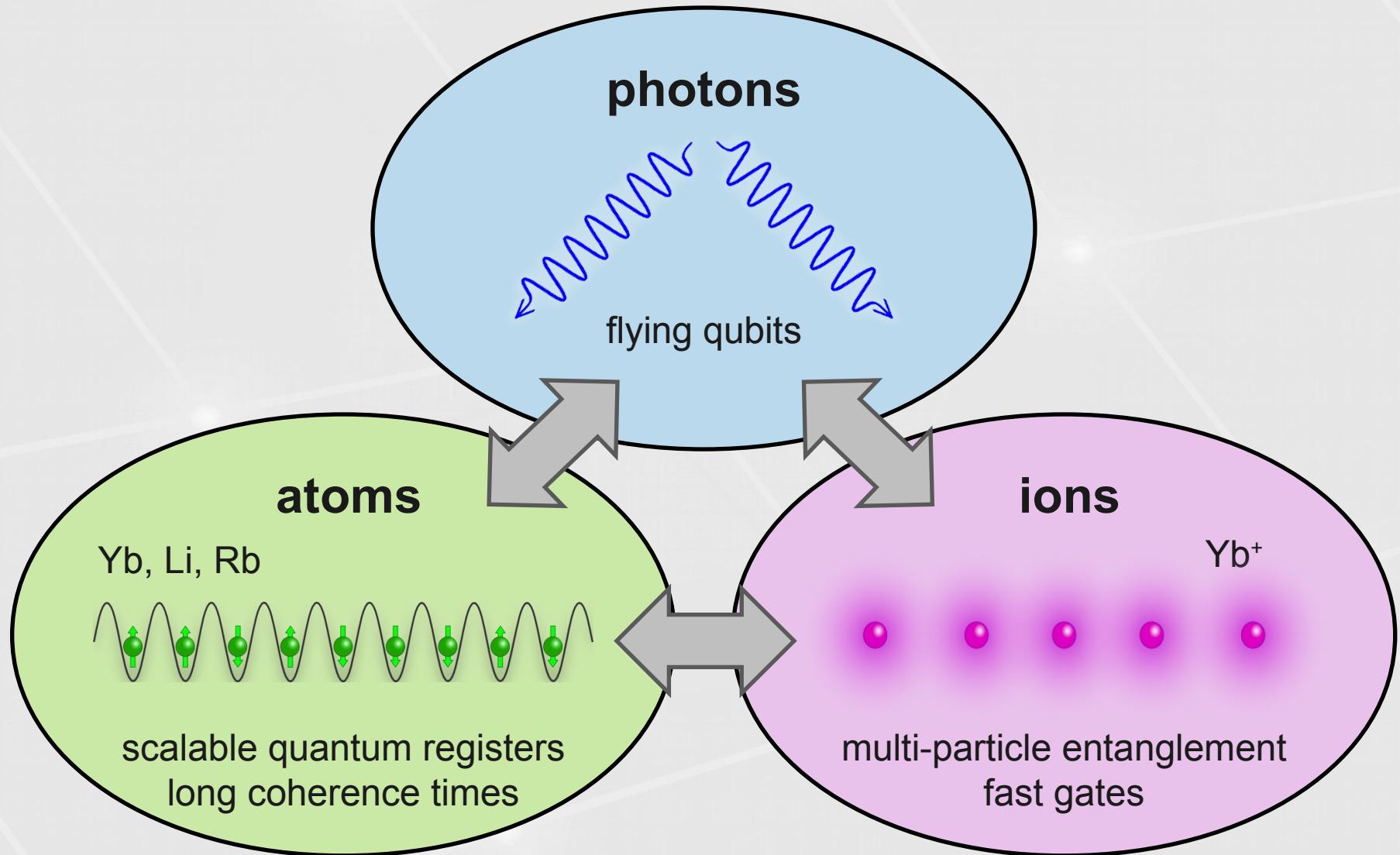
A. Daley, M. M. Boyd, J. Ye, P. Zoller, PRL **101**, 170504 (2008)



Quantum interfaces

Connecting different quantum systems

Hybrid systems for QIPC



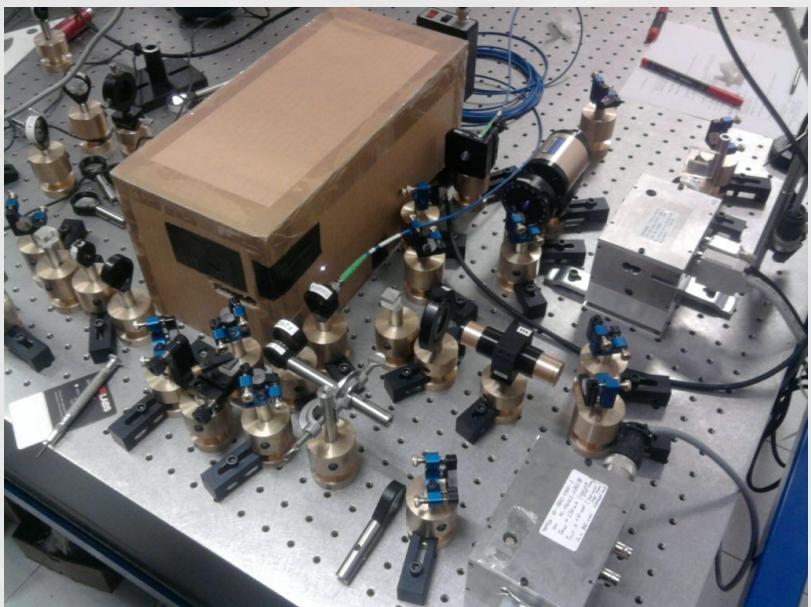
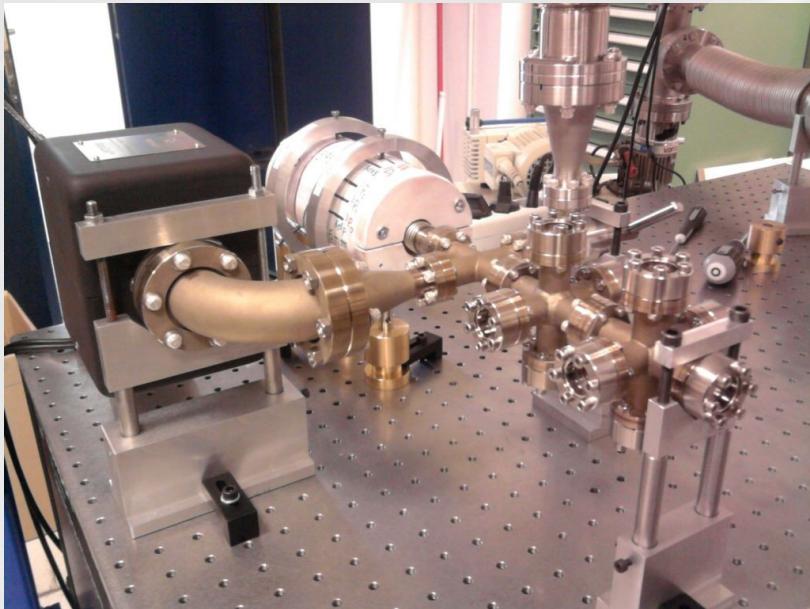
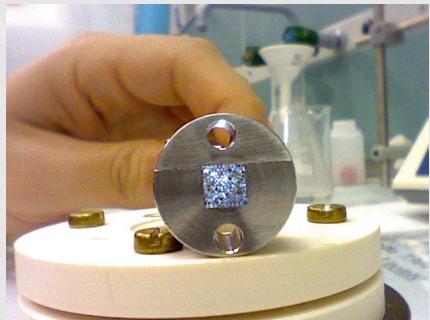
Where?

LAB. 69 – Dipartimento di Fisica
Massimo Inguscio's lab (ex-helium)



What?

LAB. 69 – Dipartimento di Fisica



Who? & How?

Fundings:

- IIT – ENCORE Seed Project
- EU FP7 – AQUTE Integrated Project
- MAE – Progetto UVICOLS



People:

- | | |
|-----------------------|------------------------|
| • Florian Schaefer | LENS (postdoc) |
| • Jacopo Catani | INO-CNR (postdoc) |
| • Leonardo Fallani | Dipartimento di Fisica |
| • Massimo Inguscio | Dipartimento di Fisica |
| • Pablo Cancio Pastor | INO-CNR |
| • Giovanni Giusfredi | INO-CNR |
| • Paolo De Natale | INO-CNR |
| • Chiara D'Errico | (now at MIT) |

No requests for department workshops

