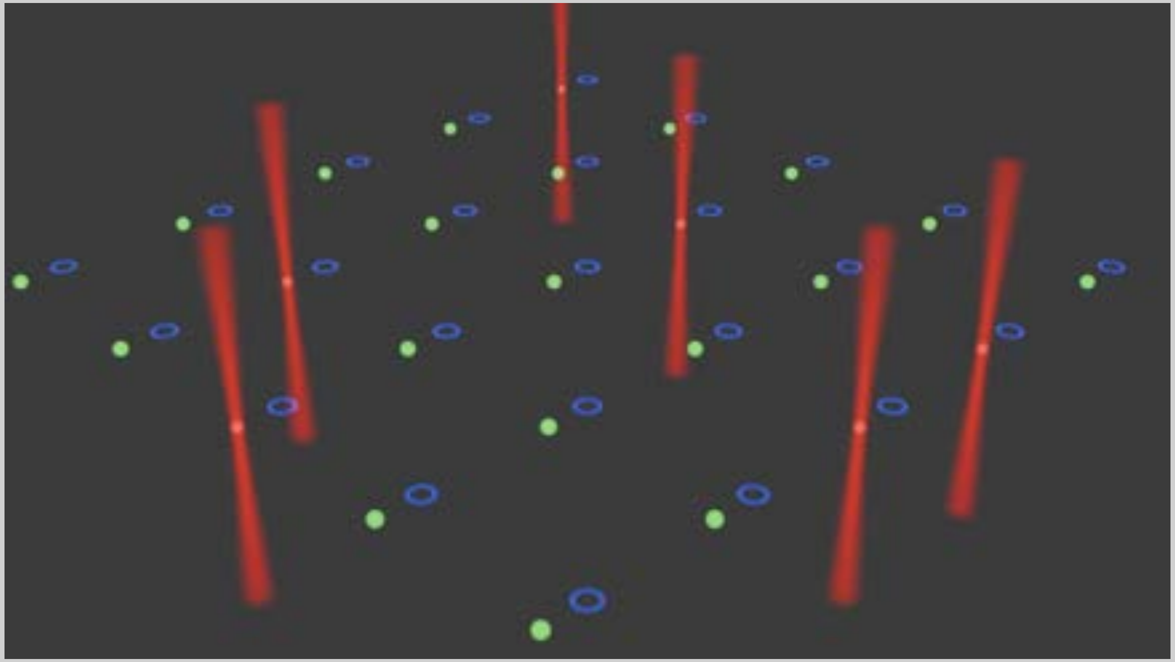
Dynamics and control of classical and quantum systems
Mines_Paris 2-5 June, 2026



Trapped Circular Rydberg Atoms for Quantum Simulation: Quantum Non-Demolition Detection and Optical Manipulations

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Physique quantique et applications

École Normale Supérieure, CNRS,
Université Pierre et Marie Curie,
Collège de France, Paris

QubitAF

Rydberg Atom team at LKB

Rubidium team

C. Sayrin

Yohann Machu (PASQAL)

Andrés Durán Hernández

Gautier Creutzer

Aurore-Alice Young

Abderrahmane Kassid

Strontium team

S. Gleyzes

B. Bakkali-Hassani

Baptiste Muraz

Mathis Pépin

Inhibition team

I. Dotsenko

GuIllaume Cœuret

Ankul Prajapati

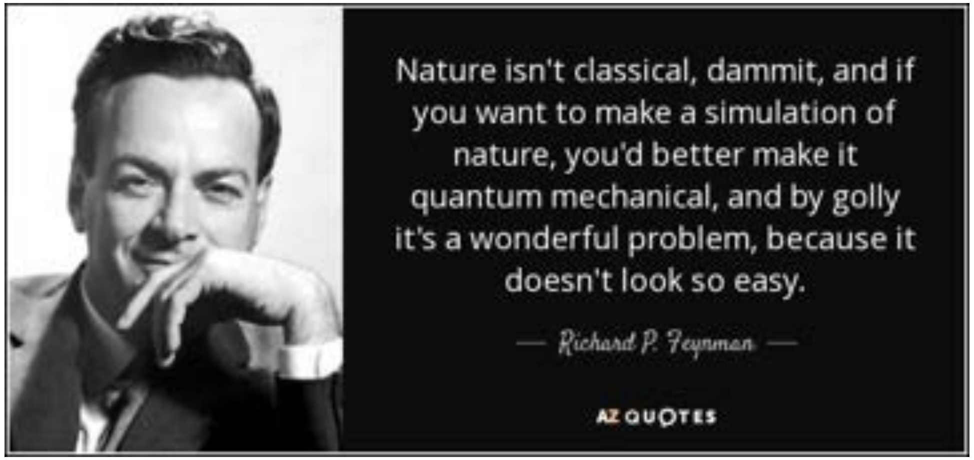
Gauthier Rey

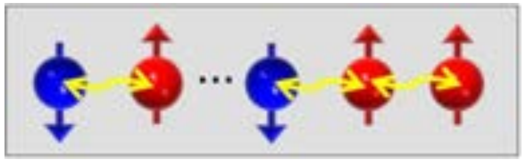
M. Brune

J.M. Raimond

S. Haroche

A quantum simulator: why?





Feynman 1981: in order to understand/simulate complex quantum systems

→ better use a quantum simulator

Based on the assembly of many, individual, well-controlled quantum systems:

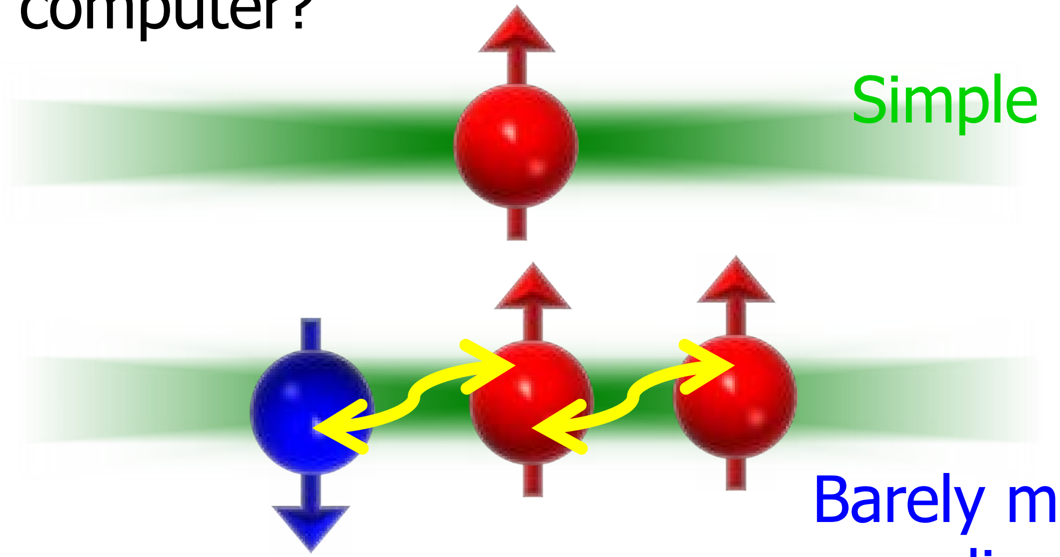
→ “Bottom-up approach”

Advantage of “artificial quantum matter” over real quantum materials:

- local preparation of individual quantum systems
- Large flexibility for control of interaction parameters
- Local measurement of the quantum state of individual constituents.

Quantum simulations of spin-systems

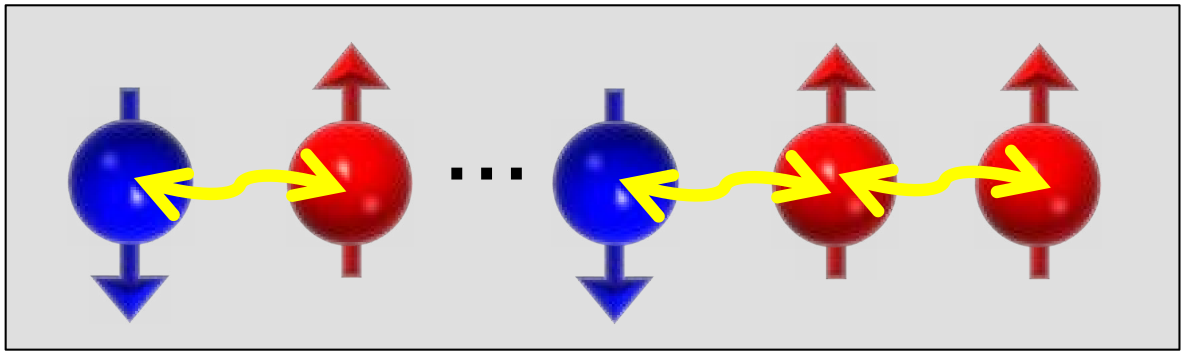
Simulations with computer?



Simple

Barely more complicated

Utterly difficult



Classical simulation ?

Exact simulation limited to **40 spin** by the huge size of Hilbert space:

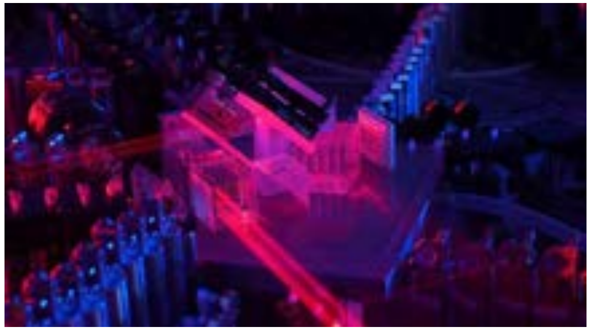
$$2^{40} = 10^{12}$$

complex numbers needed for describing the full quantum state! Does not even fit into supercomputer memory

Impossible!

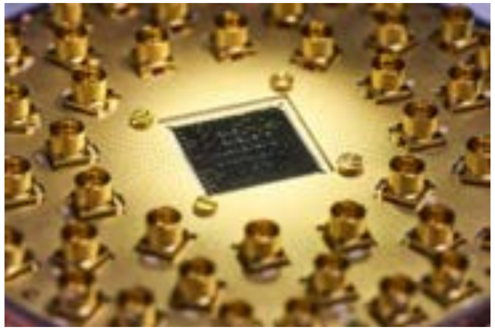
Quantum simulators

Single photons



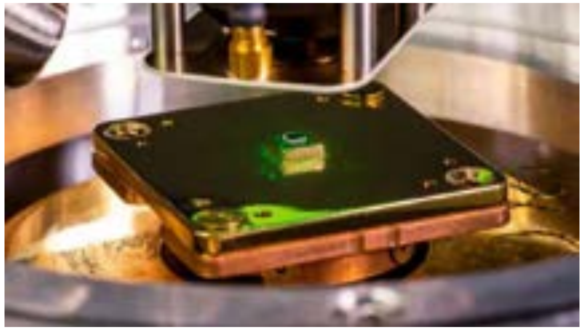
USTC China

Superconductors



ETH Zürich

Diamond colour centres

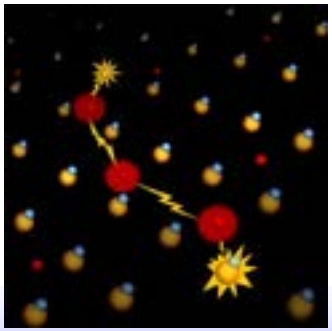


Princeton University

Trapped ions

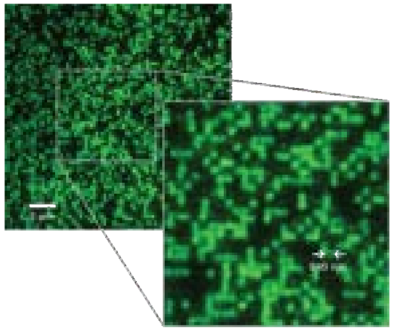
Innsbruck University

Ultracold molecules



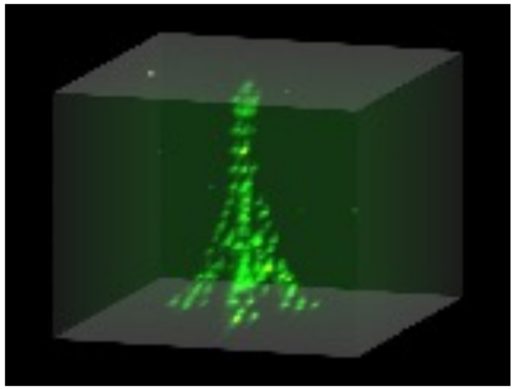
Imperial College

Neutral atoms in optical lattices



Harvard-MIT

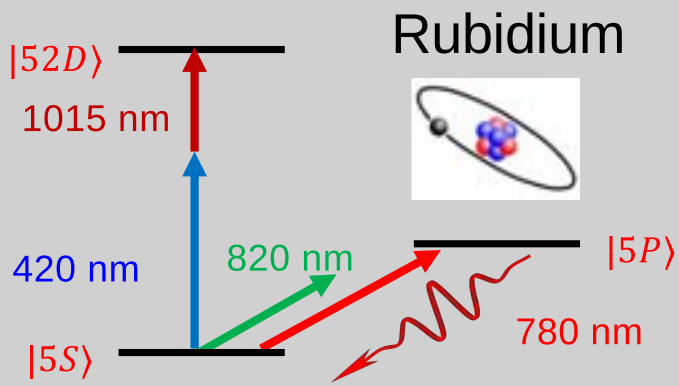
Rydberg atoms in optical tweezers



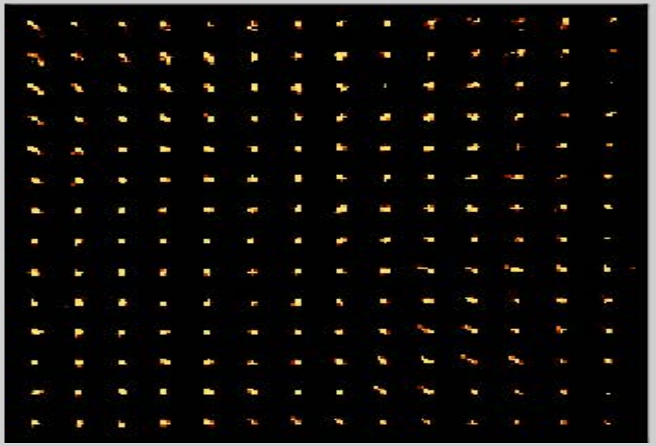
IOGS

Neutral atoms: why do we like them

- All identical, easy to (re)produce
- Coupling to light (lasers):
  - Internal state manipulation
  - Fluorescence detection
  - Optical traps and laser cooling



Individual atoms in optical tweezers



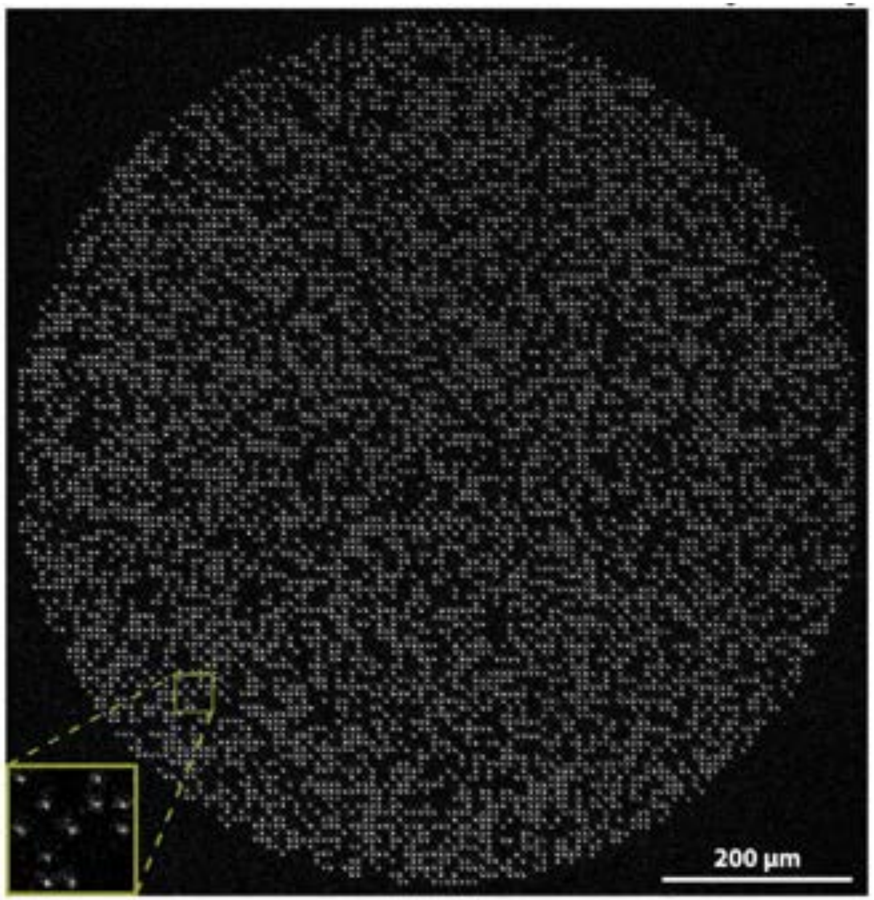
IOGS (Browaeys & Lahaye)

- Tightly-focused Gaussian beams
- At most one atom per trap
- Arbitrary-shape defect-free arrays with up to thousands atoms
- Reconfigurable arrays

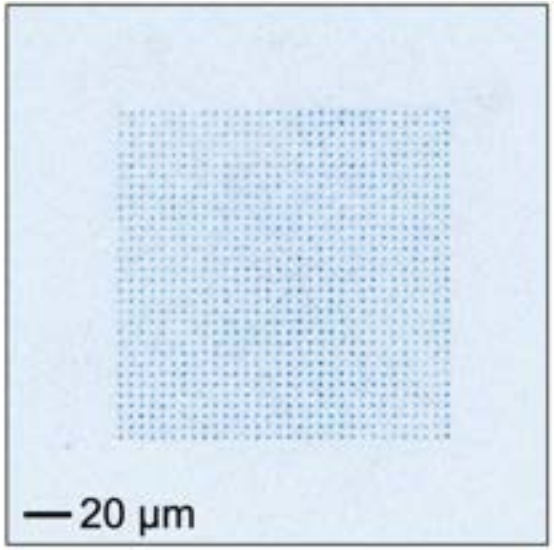
Neutral atoms: why do we like them

State of the art

12000 traps
6000 atoms
Random loading



H. Manetsch…, M. Endres, Nature (2025)



D. Lim et al, PASQAL, arXiv 2026

Defect-free
1024 atoms

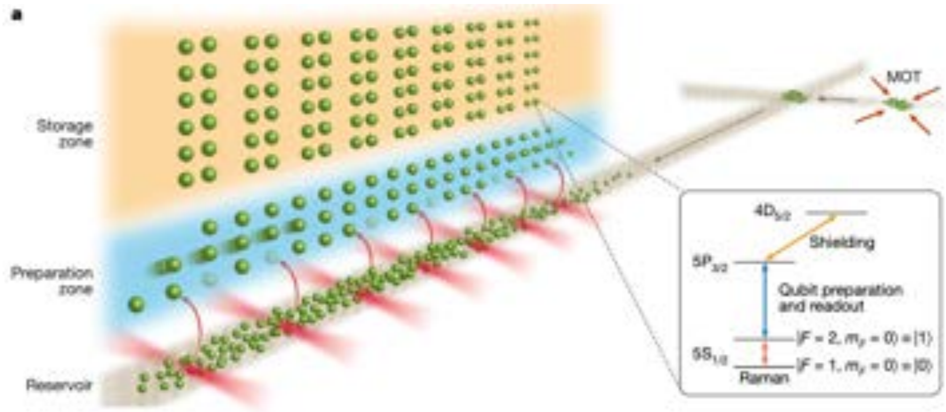
R. Lin…, Lu,Pan, PRL 2025

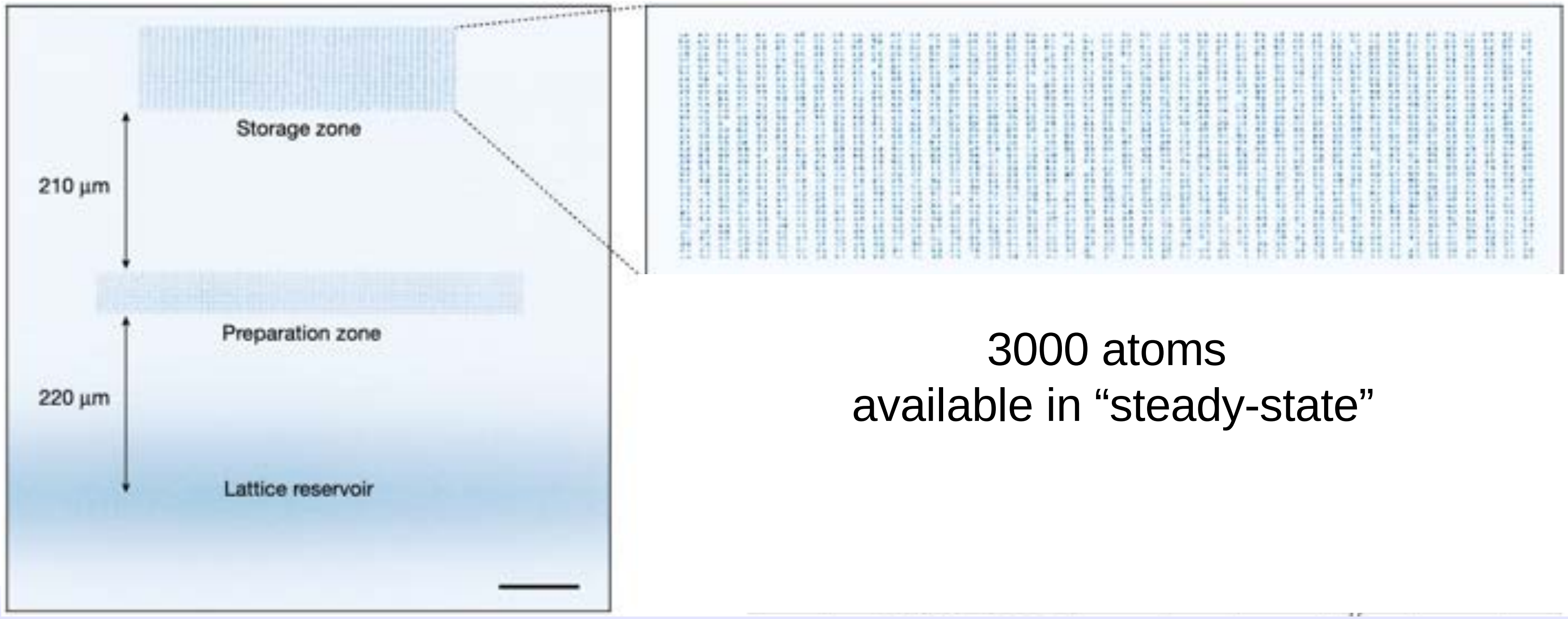
Fast
rearrangement
of up to 2024
atoms

Neutral atoms: why do we like them

Sophysticated continuous reloading architecture

N.C. Chiu, … M. Lukin, Nature 2025

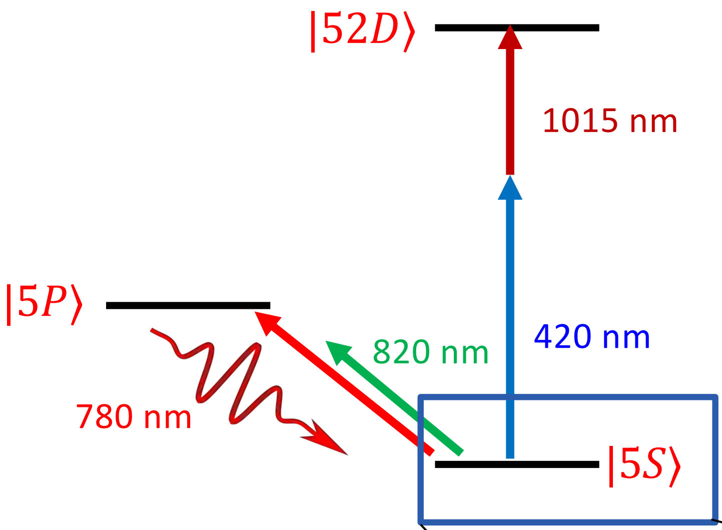




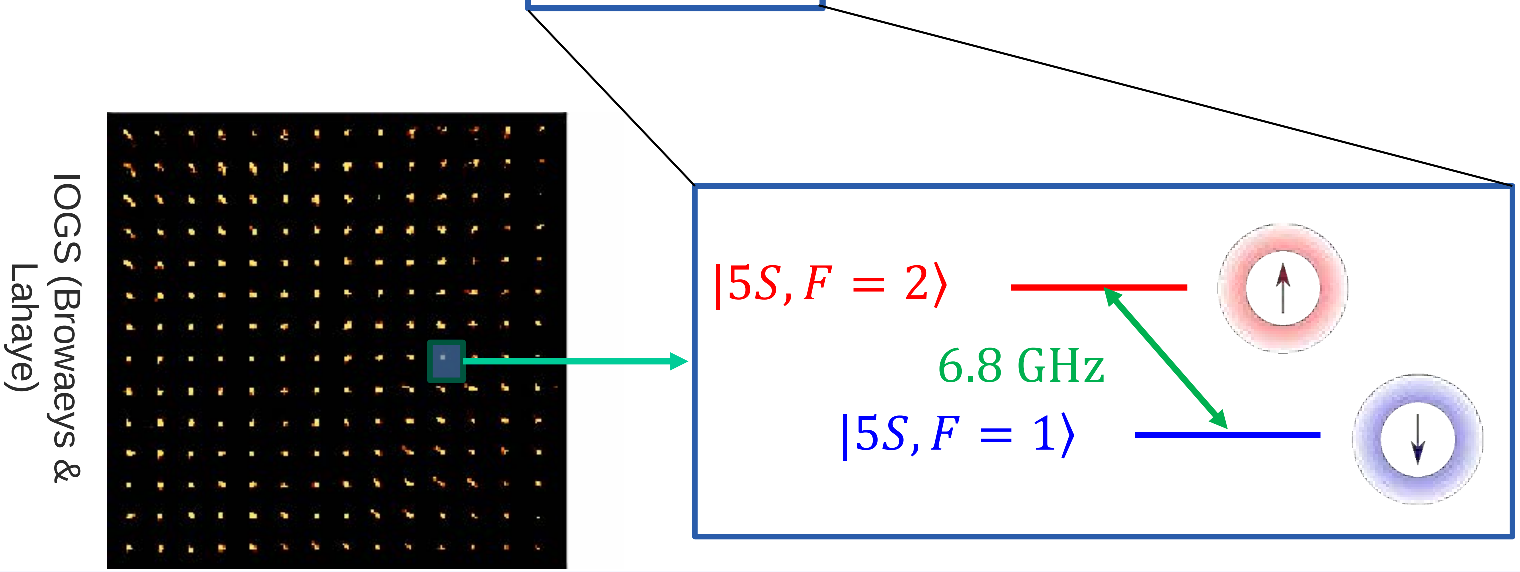
3000 atoms
available in “steady-state”

Neutral atoms: why do we like them

- Ground state: long hyperfine coherence time: > 1 s



- Qubit encoded in hyperfine ground states
- Negligible contact interaction
- Two qubit interactions?



Interactions: Rydberg atoms

Rydberg levels

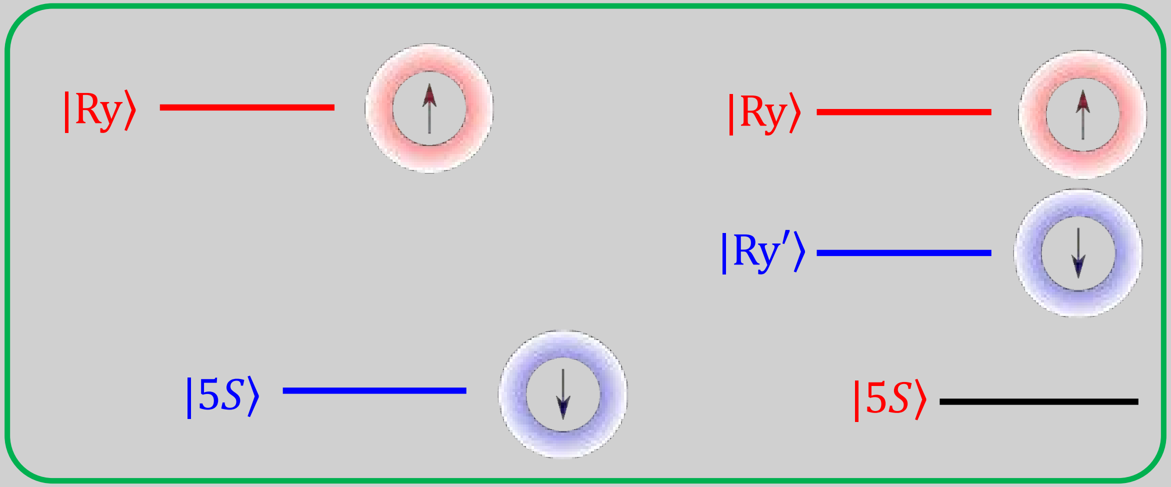
Johannes Rydberg

- **High** principal quantum number: $n \gg 1$
- **Giant hydrogenic atoms**: size $\sim n^2 a_0 \sim 250\ \mathrm{nm}$
- **Strong dipole-dipole interactions** between two Rydberg atoms:

  $\Omega \sim 1 - 10\ \mathrm{MHz}$ at a few microns

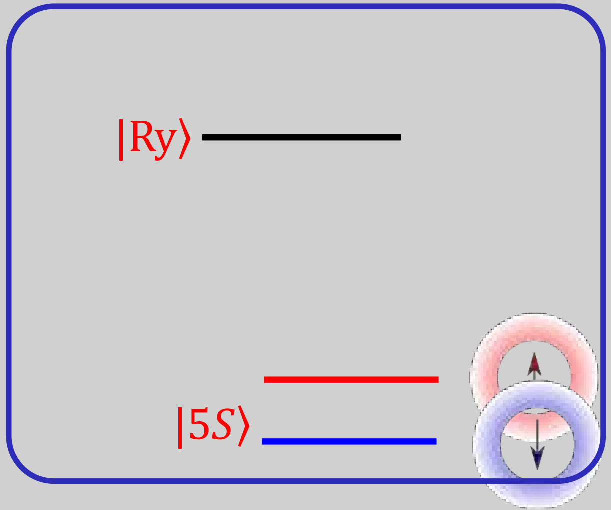
- **Metastable**: lifetimes, $\tau \propto n^3 \sim 200\ \mu\mathrm{s}$

Rydberg-based qubit or spin-1/2

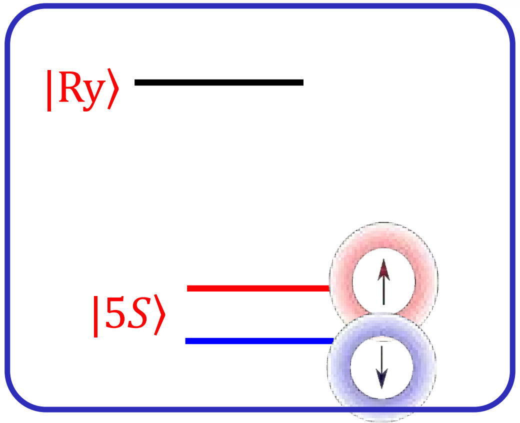


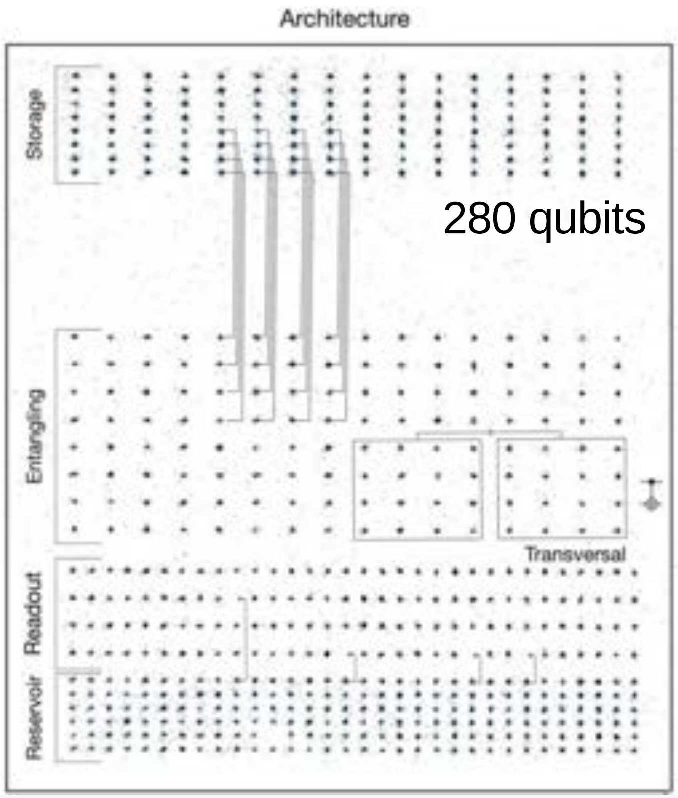
Quantum simulation

Quantum computation



Quantum computing with Rydberg atoms





Reconfigurable quantum processor

- Arrays of few hundreds atoms / physical qubits
- **40 logical qubits**
- Below-threshold quantum error correction
- Dipole blockade ➡ High-fidelity gates: $F \geq 99.5\%$

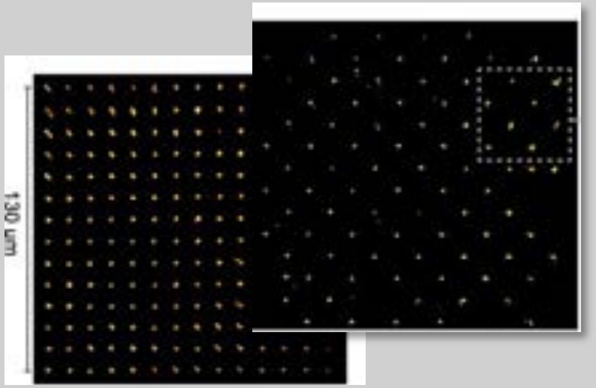
Many labs/companies: Harvard/QuEra (Rb), Princeton (Yb), Caltech (Sr), Madison/Inflection (Cs), Munich/Planqc (Sr), Atom computing (Yb), Pasqal (Rb)

New players: Google (Sr)

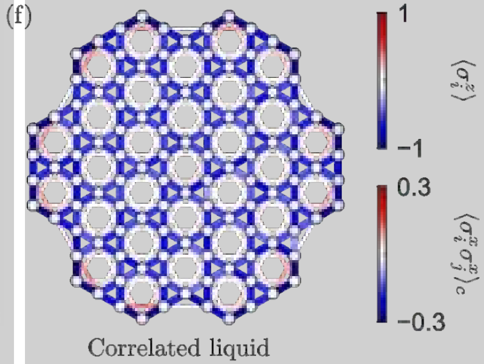
Strong claims: Shor's algorithm, breaking of RSA-2048 with 10 000 atoms

D. Bluvstein et al, Nature 2024, Nature 2025

Quantum simulation with Rydberg atoms



P. Scholl… A. Browaeys, Nature 2021
S. Ebadi… M. Lukin, Nature 2021



G. Bornet… A. Browaeys, arXiv:2602.14323

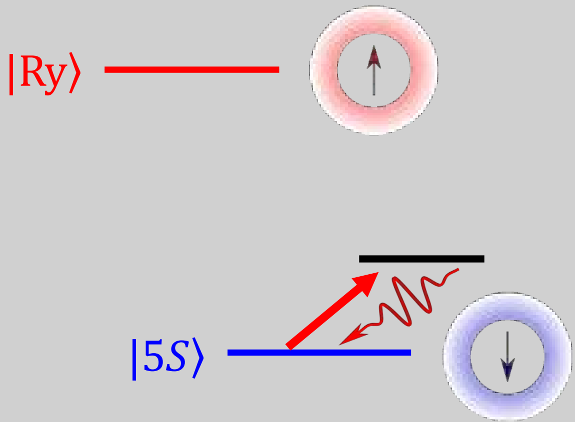
Simulation of quantum magnetism

- Adiabatic phase diagram reconstruction
- Observation of a spin liquid?
- Simulation of "true" material $TmMgGaO_4$

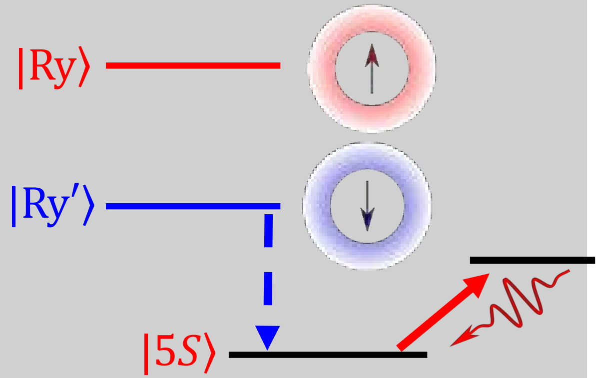
L. Leclerc… A. Browaeys, A. Dauphin (PASQAL) arXiv:2603.20372

Optical measurement and local manipulations

- Final state measurement: destructive fluorescence measurement
- Simulator initialization: local manipulation through focused light beams



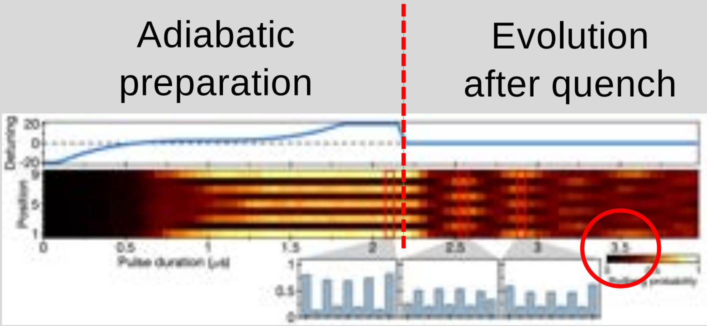
Van der Walls
Ising Hamiltonian



Exchange interaction
XY, XXZ Hamiltonians

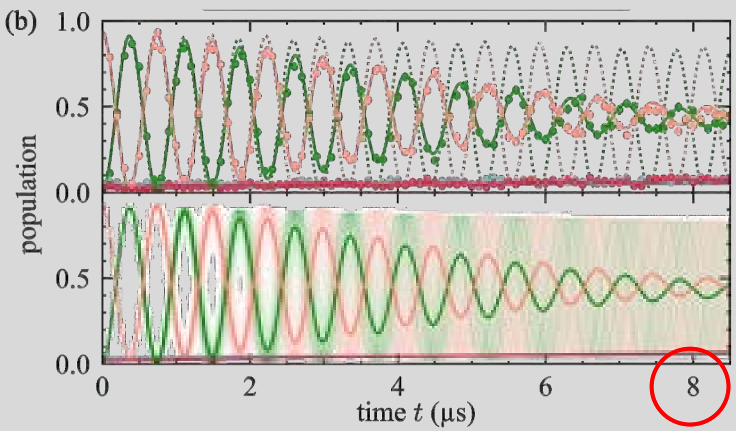
Quantum simulation of dynamics?

Simulation of quench dynamics



Bernien et al. Nature **579** (2017)

Observation of spin-exchange interaction



G. Emperauger,…, T. Lahaye, PRA (2025)

Interaction time limit

- Rydberg atoms are **free flying**

→ Perturbation due to motion within $\lesssim$ 1 μs

- **Lifetime** of optically-accessible Rydberg levels $\tau \sim 100$ μs

→ Effective decay time for N atoms: $\tau/N \lesssim$ 1 μs

- Characteristic interaction frequencies $\Omega \sim 10$ MHz

→ **Few interaction cycles:** $\Omega \times \tau \lesssim 10$

Simulation time
limited to a few μs

Why we prefer circular atoms: Lifetime !

- Rydberg level with **maximal angular momentum:** $m = |\ell| = n - 1$
- **Strong interactions**, similar to low-ℓ levels
- **Long lifetimes**:
  - Low-ℓ levels: MW + optical transitions
    $\tau \propto n^3 \sim 200\ \mu s$:
  - Circular levels : MW transition only
    $\tau \propto n^5 \sim 30$ ms:

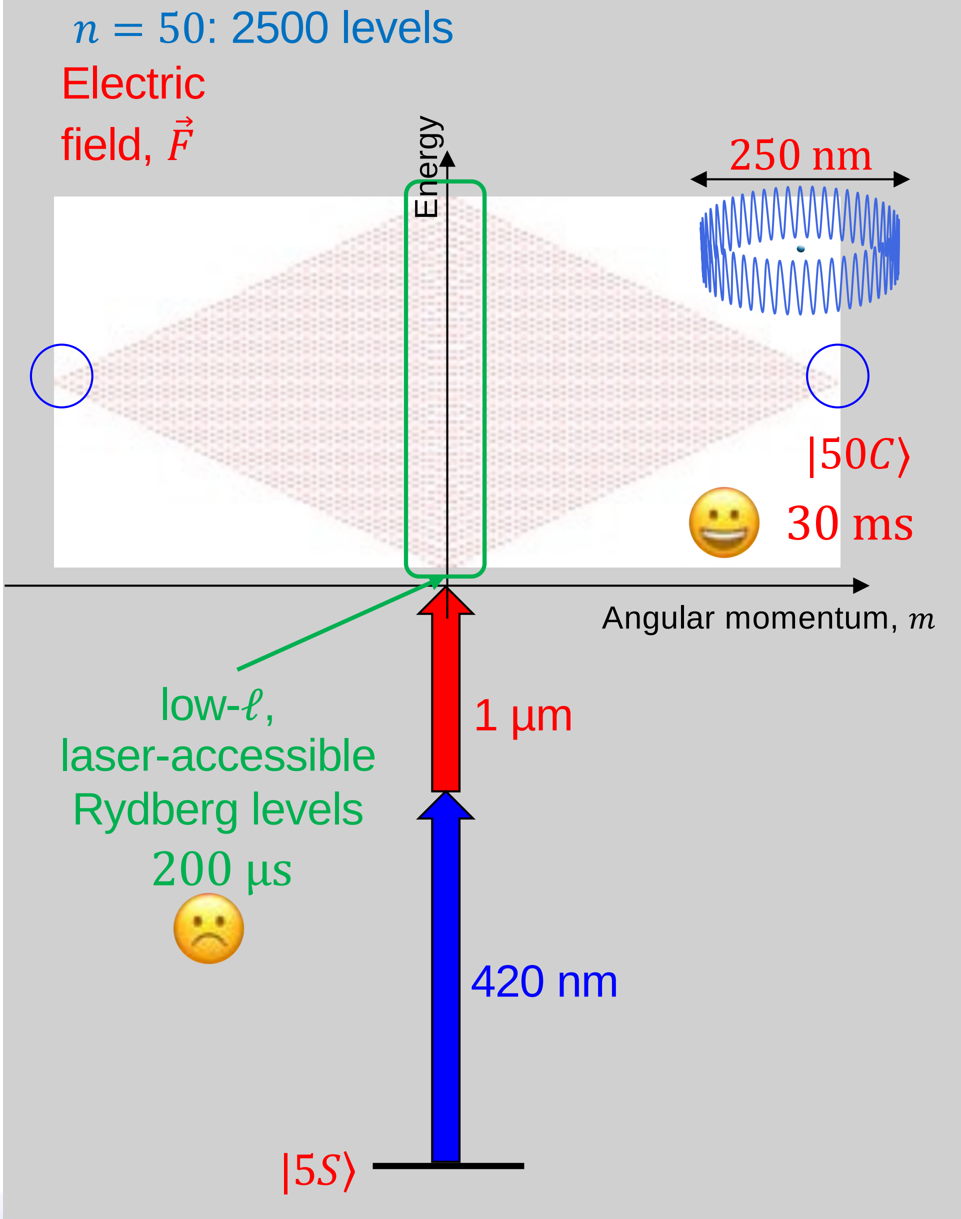
100 fold improvement of $\Omega \times \tau$

No optical transitions…

- Complex preparation
(though long experience in LKB)

- No local measurements
- No local manipulations

A second electron is missing!



Use of a second electron: strontium

S. Gleyzes and B. Bakkali-Hassani (LKB)

- One electron in circular level, one electron in the ground state

  R.C. Teixeira... M. Brune, PRL (2020)

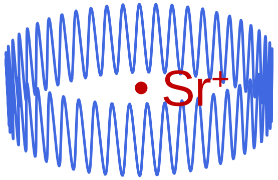
- Optical cooling and detection of circular levels

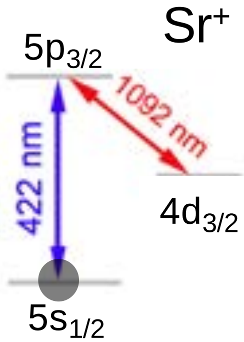
  A. Muni... S. Gleyzes, Nat. Phys. (2022)

- Circular-state-coherence preserving operations on the core electron

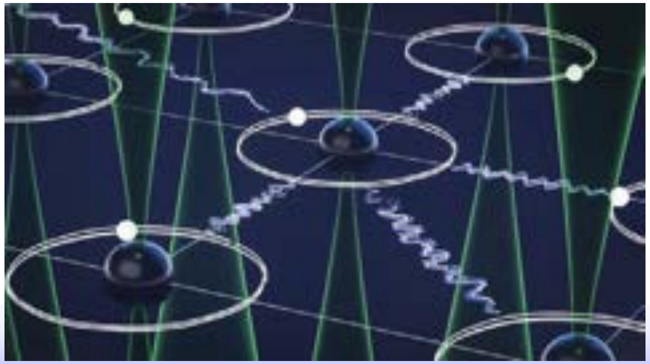
  L. Lachaud... S. Gleyzes, PRL (2024)

  M. Wirth... F. Meinert, PRL (2024)





- Laser-trapping of Rydberg atoms through the ionic core



- Paris team: in preparation
- Stutgart team

  C. Hölzl... F. Meinert, PRX (2024)

Rydberg Atom team at LKB

Rubidium team

C. Sayrin

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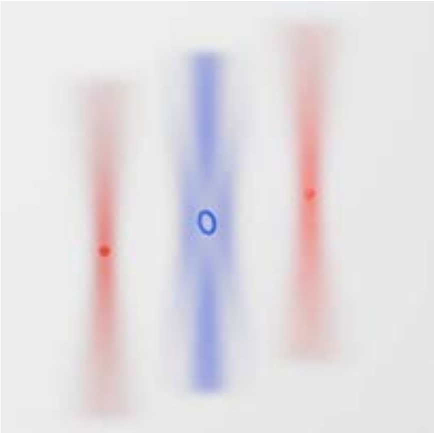
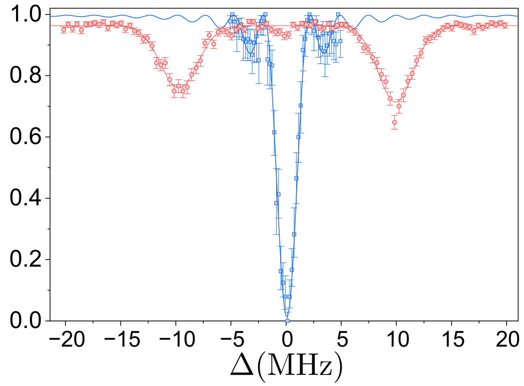
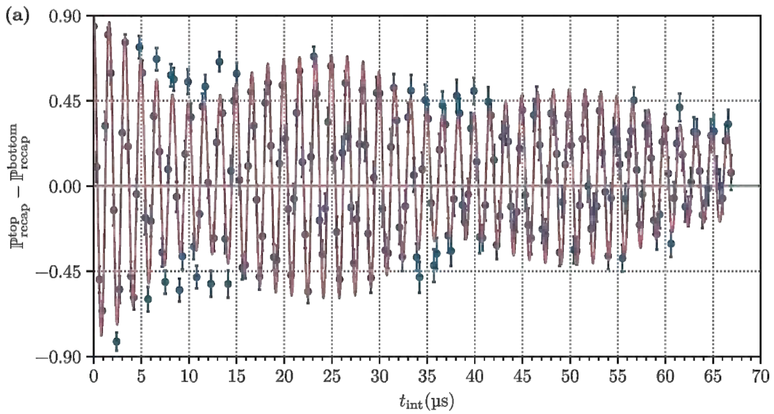
Outline



1. **Hybrid array of laser-trapped Rydberg atoms**

2. QND measurement and local manipulations

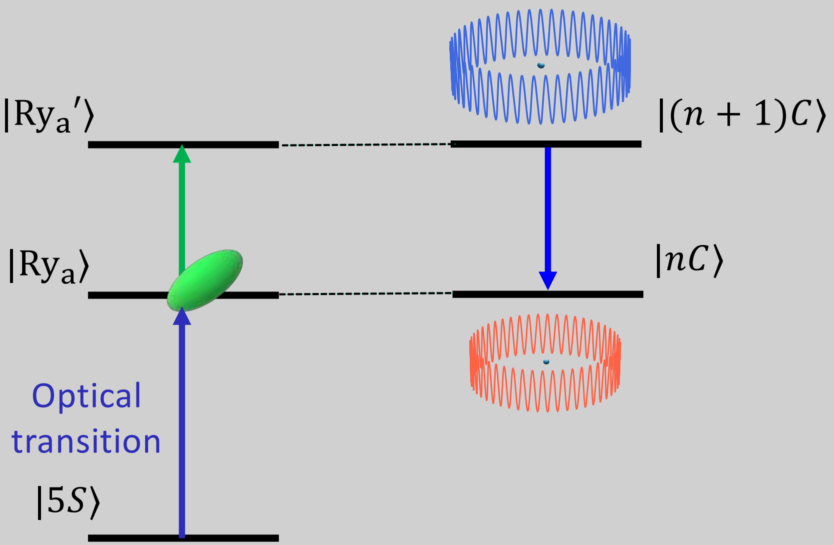




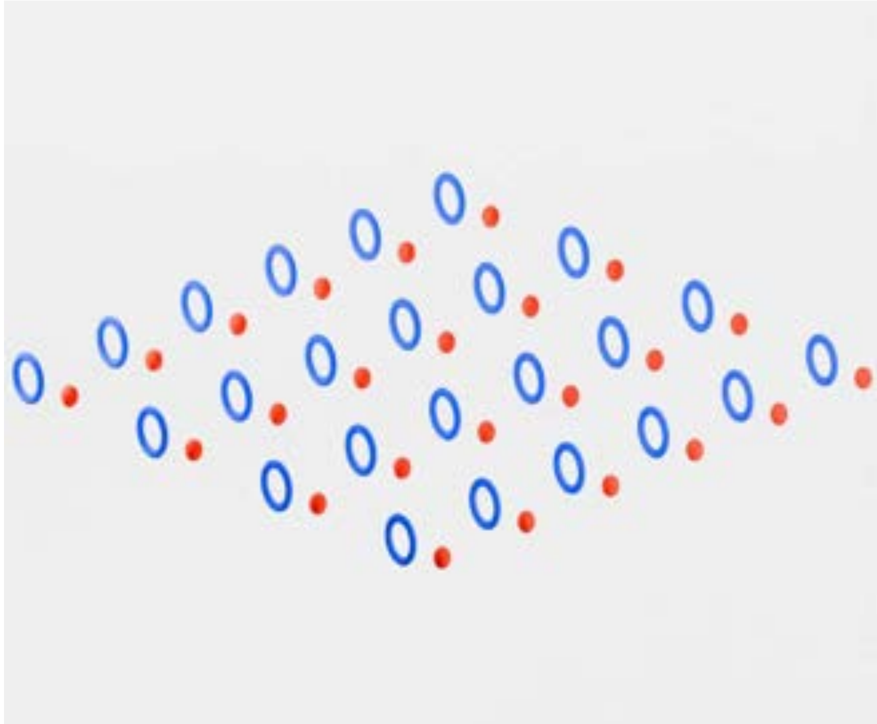
3. Long-lived spin-exchange interaction

Hybrid Rydberg platform

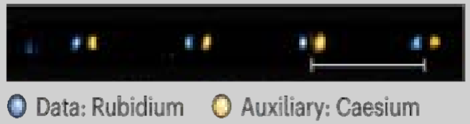
- Data qubits encoded on circular Rydberg levels
- Ancillary qubits encoded on low-ℓ Rydberg levels
- Strong interaction through Förster resonance



- **Quantum non-demolition measurement** and **local manipulation** of circular Rydberg atoms



See also:



- Dual-species experiments

I. Beterov and M. Saffman, PRA (2015)

S. Anand… H. Bernien, Nat. Phys. (2024)

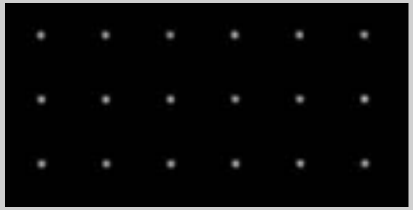
- Rydberg/molecule experiments

C. Zhang and M. Tarbutt, PRX Q (2022)

Arrays of individual (Circular) Rydberg atoms

Ground-state atoms

- Attractive dipole traps
- Array of Gaussian optical tweezers
- Atoms initially loaded in an arbitrary 2D array



Circular Rydberg atoms

- **Repulsive** ponderomotive traps

  S. K. Dutta… G. Raithel, PRL (2000)

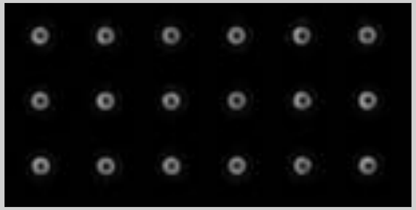
- Array of optical **bottle beams** (BoBs)

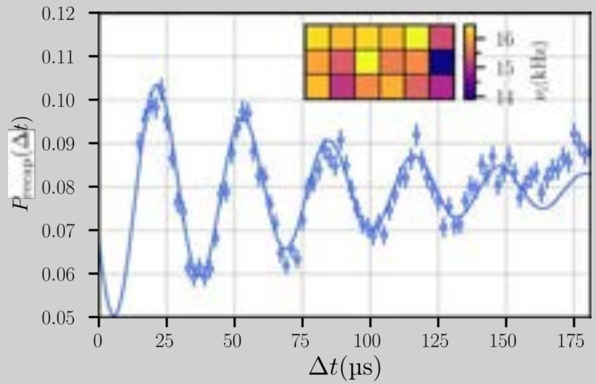
  B. Ravon… C. S., PRL (2023)

- See also:

R. Cortiñas,…, M. Brune, PRL (2020)

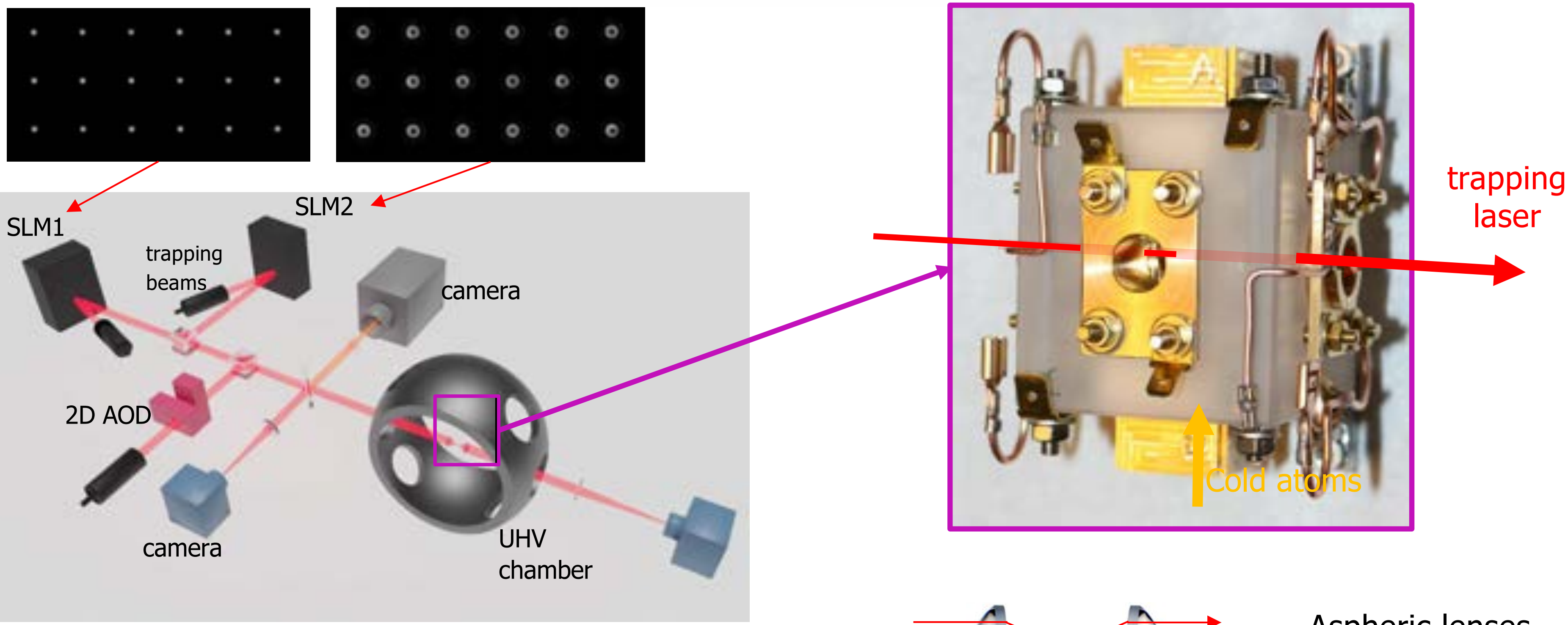
D. Barredo,…, T. Lahaye, PRL (2020)

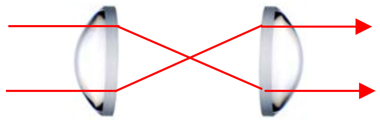




Oscillations of circular atoms in BOB traps

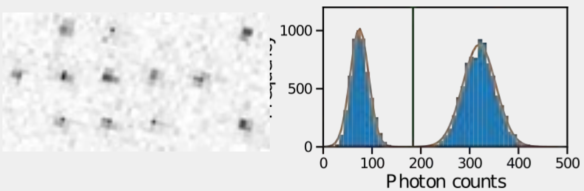
Room temperature setup





Aspheric lenses
NA=0.35

Ground state atom imaging



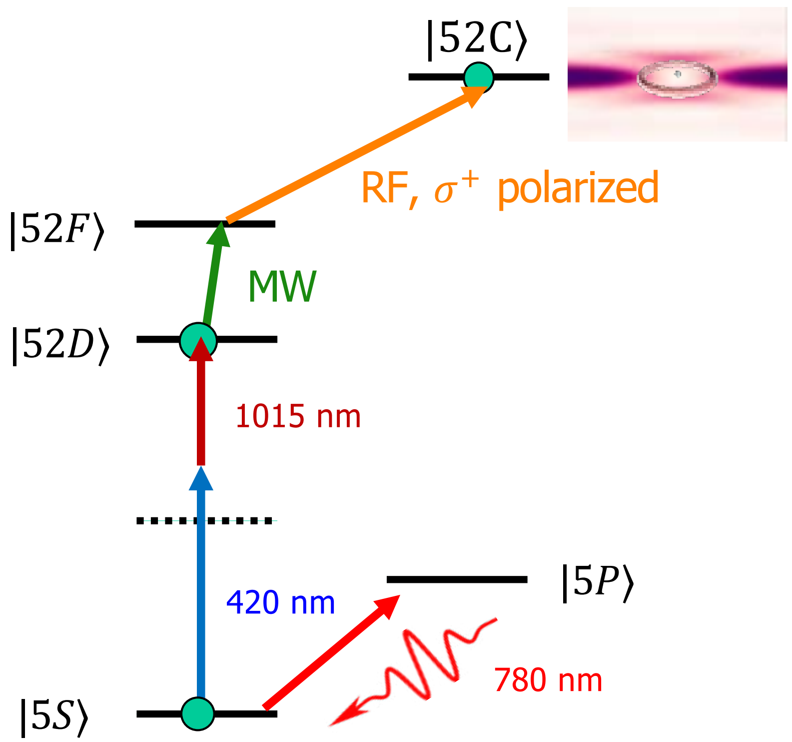
Single atom detection

- Spatial Light Modulators (SLM) prepares arrays of optical tweezers
- Atoms at $\approx 15\mu\mathrm{K}$
- Lattice sites separated by $7 - 20\ \mu\mathrm{m}$

Rydberg excitation and destructive detection

Circular state preparation

- 2-photon excitation to $52D$ Rydberg level
- MW + RF transitions
- No optical transition in circular state



Rydberg excitation and destructive detection

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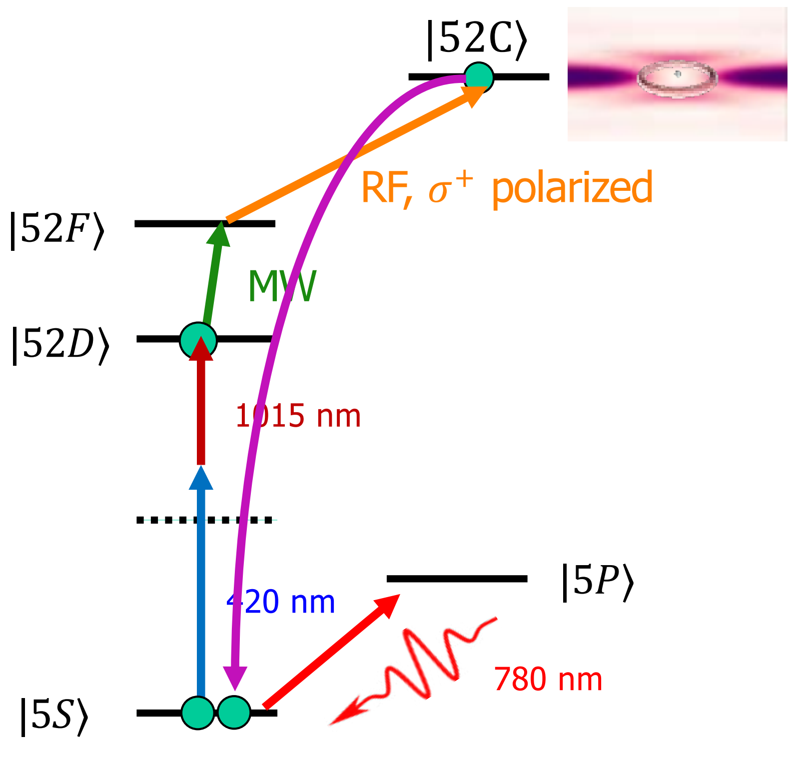
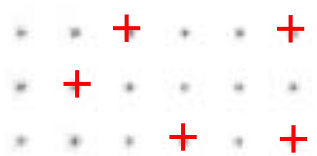


Destructive detection method DM

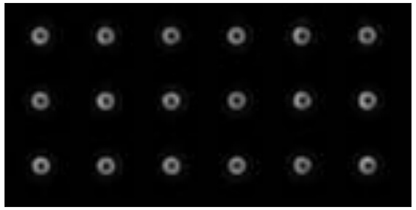
fluorescence imaging after decircularization

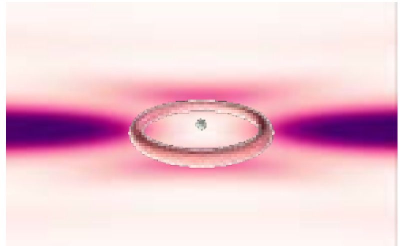


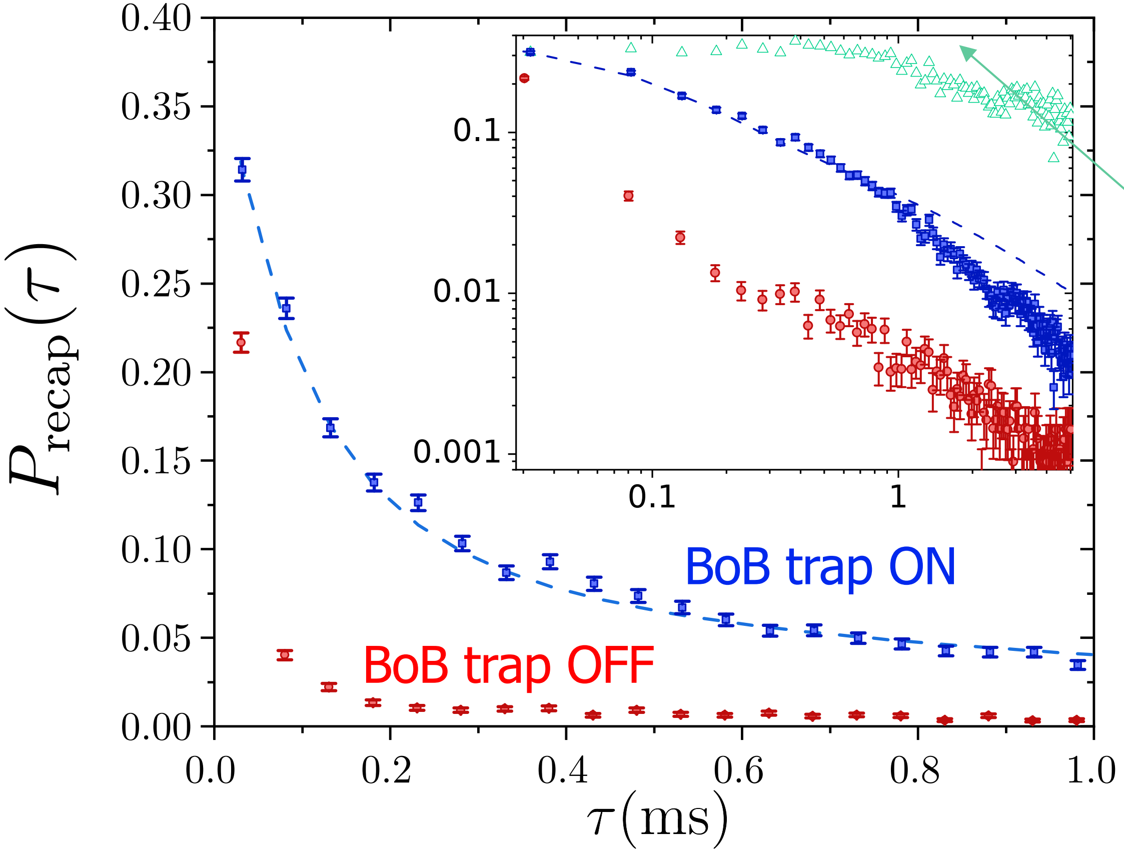
Only 52C trapped circular atoms are finally recaptured and detected by fluorescence

Circular atom trapping

18 BOB array
20 mW per BOB







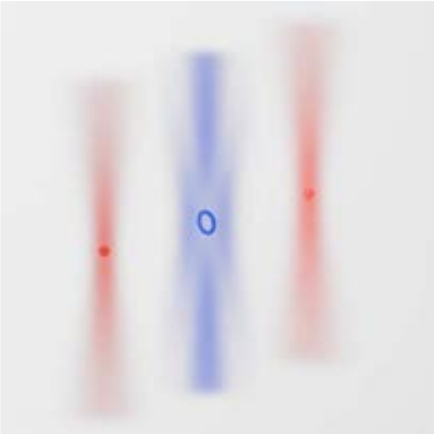
Lifetime corrected data

Blackbody-limited lifetime
125 µs

➞ BB decay corrected
trapping lifetime ≃ 5 ms

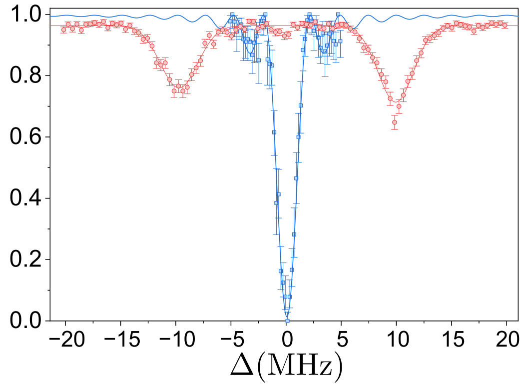
B. Ravon et al., arXiv:2304.04831

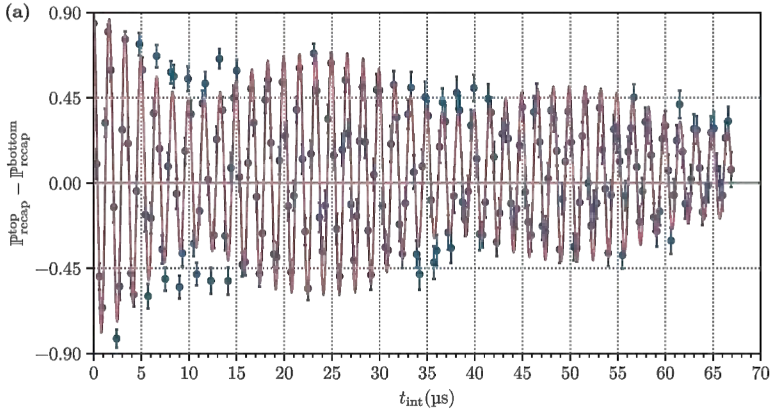
Outline



1. Hybrid array of laser-trapped Rydberg atoms

2. QND measurement and local manipulations

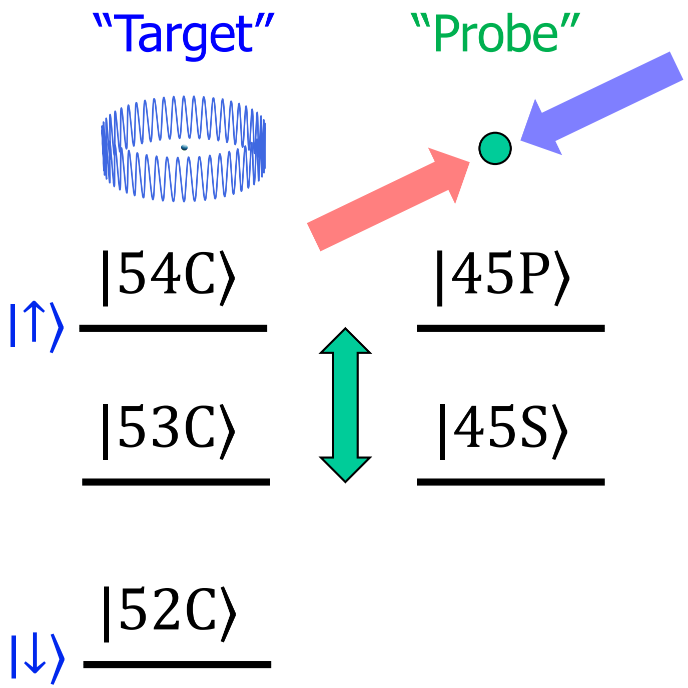


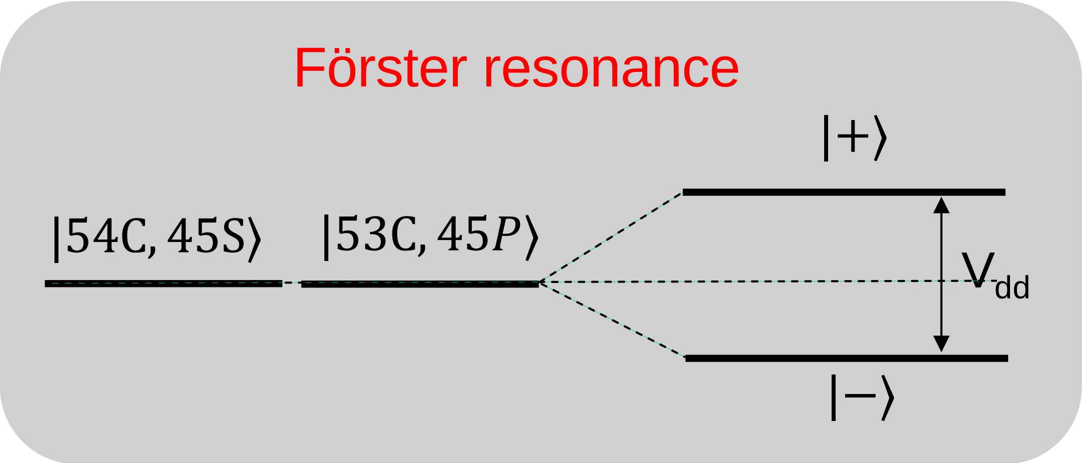


3. Long-lived spin-exchange interaction

Optical QND detection of Circular atoms

- **Principle**: use Förster resonance

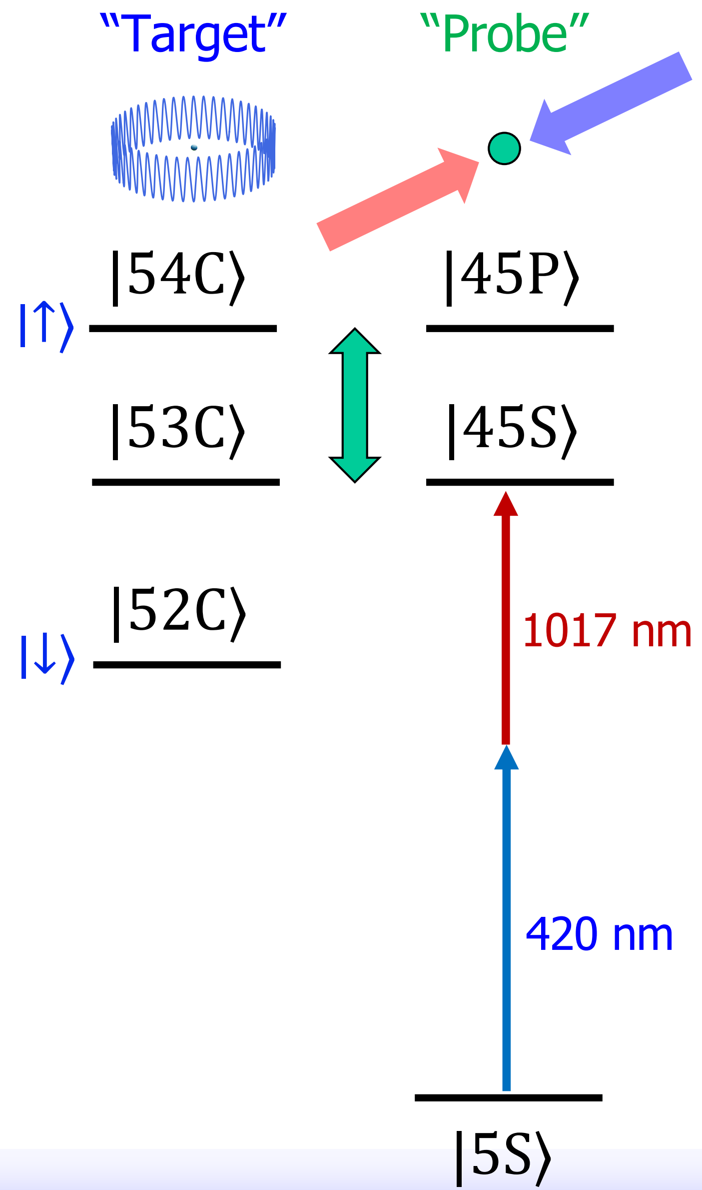


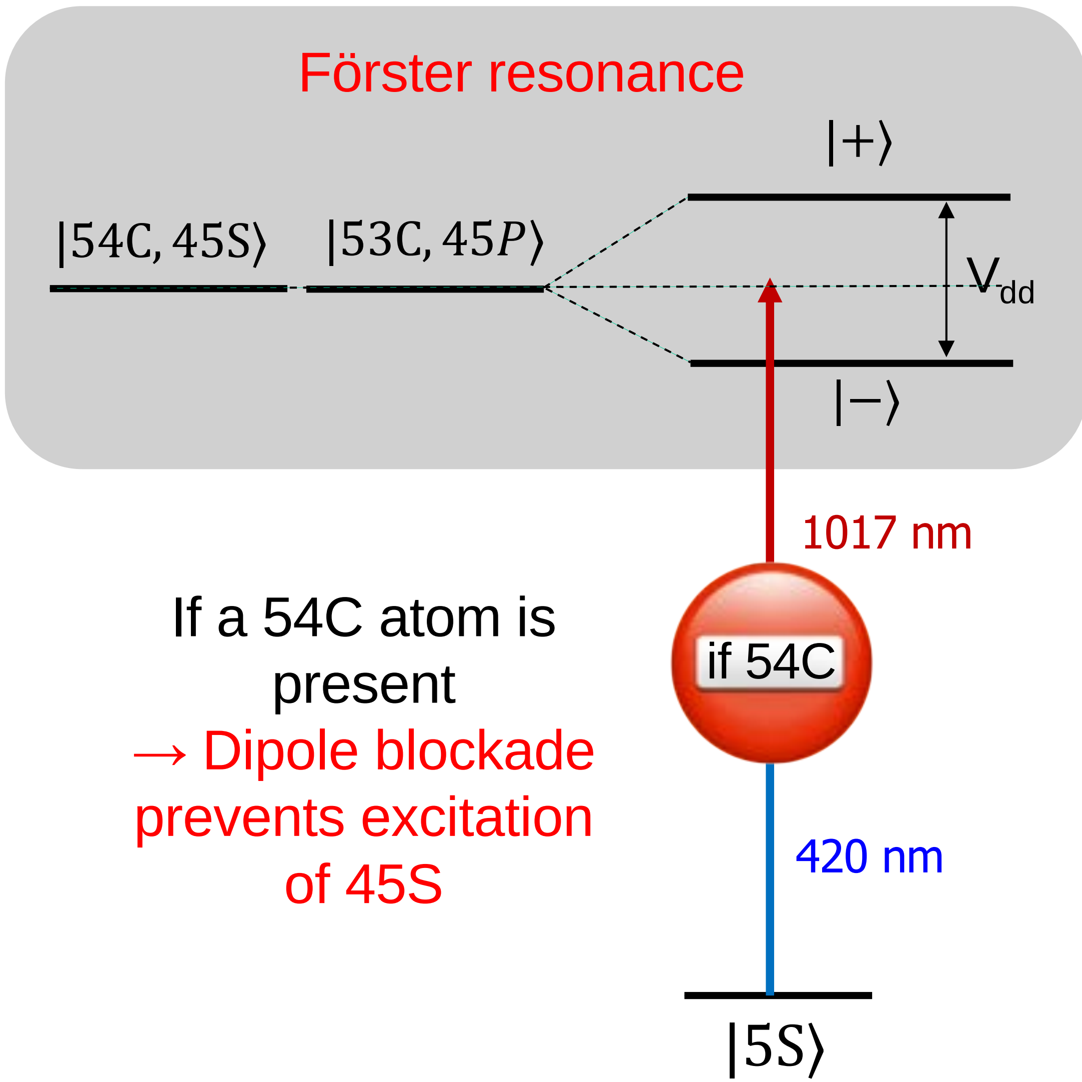


Y. Machu et al., in preparation

Optical QND detection of Circular atoms

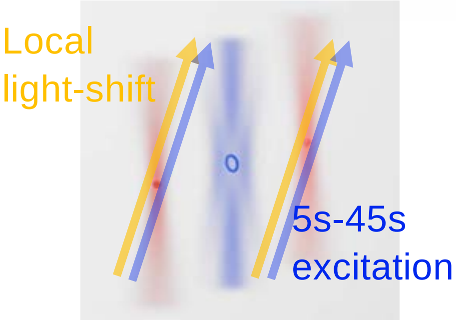
- **Principle**: use Förster resonance

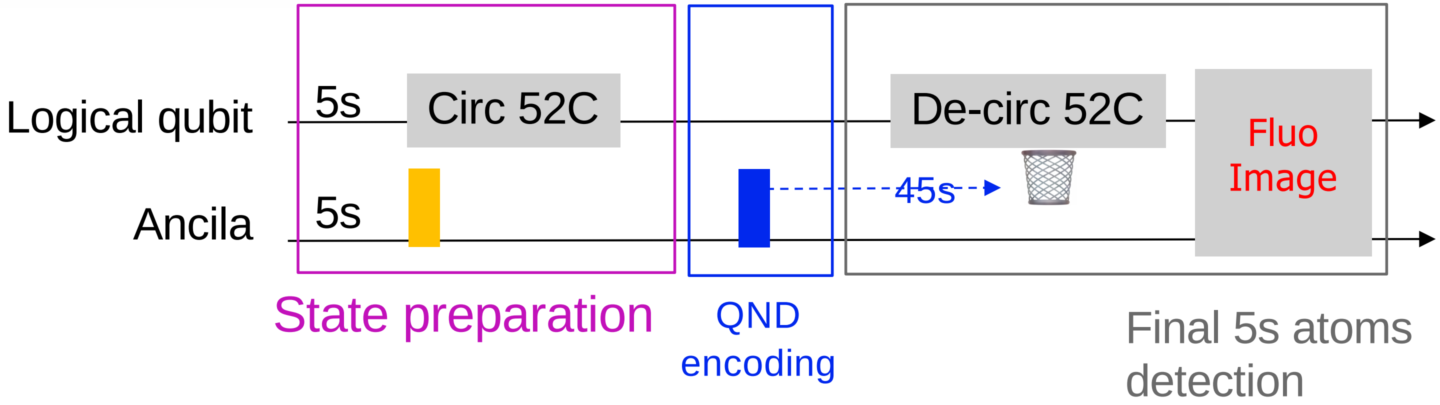




Y. Machu et al., in preparation

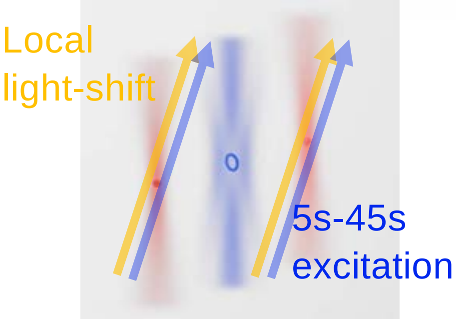
Probe excitation blockade observation

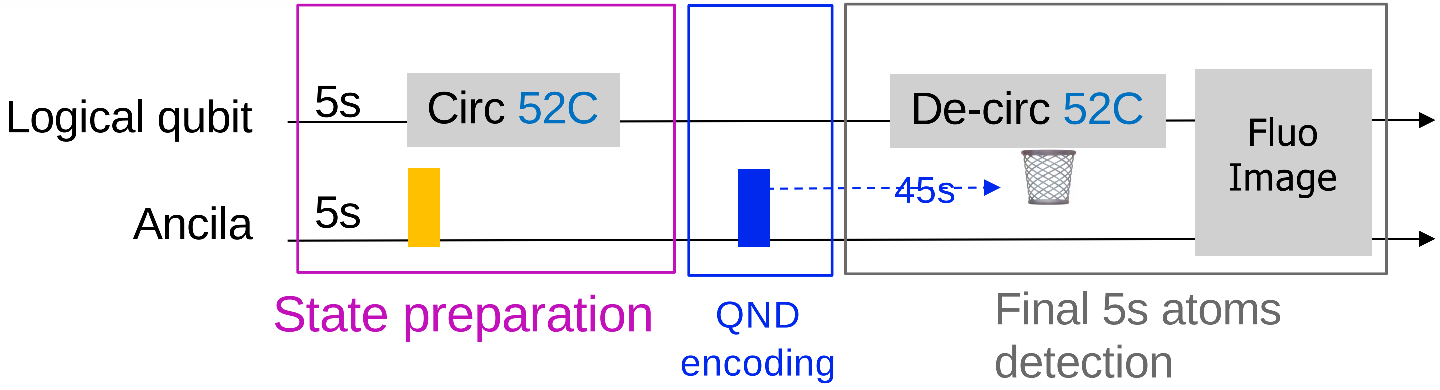


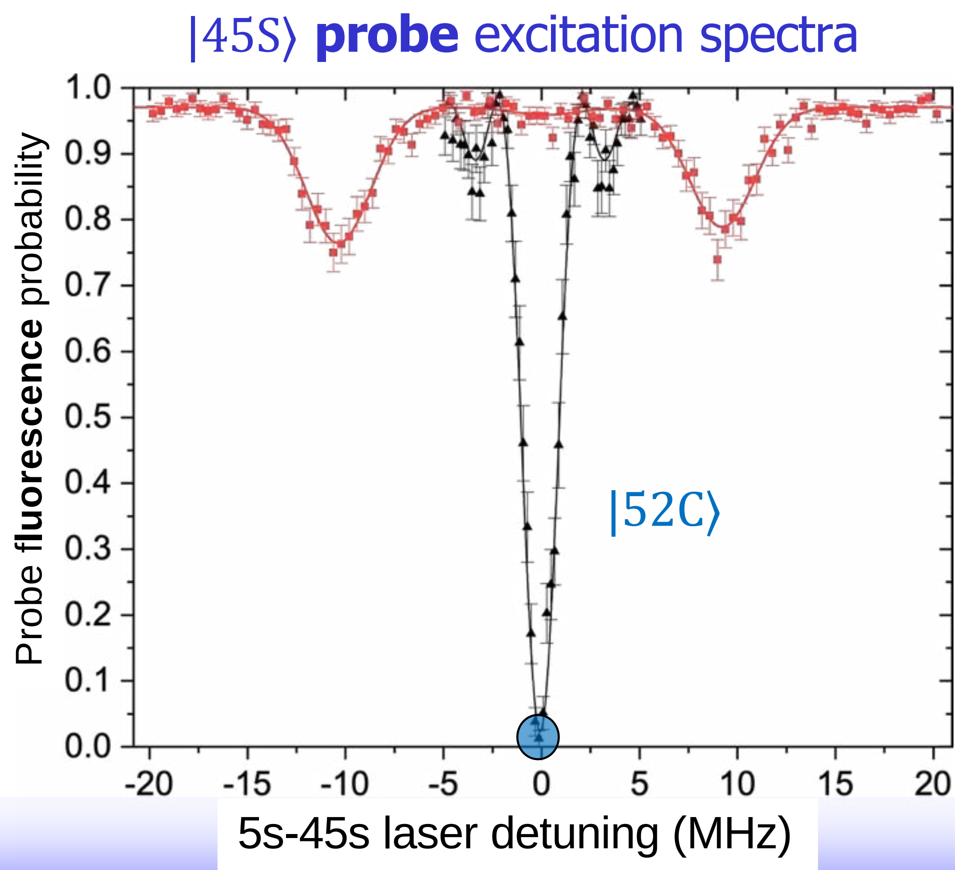


Y. Machu et al. PRX Quantum (2026)

Probe excitation blockade observation







- 52C preparation: no Blockade, the probe disappears at resonance

Y. Machu et al. PRX Quantum (2026)

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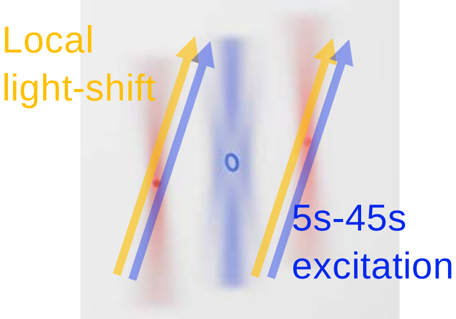
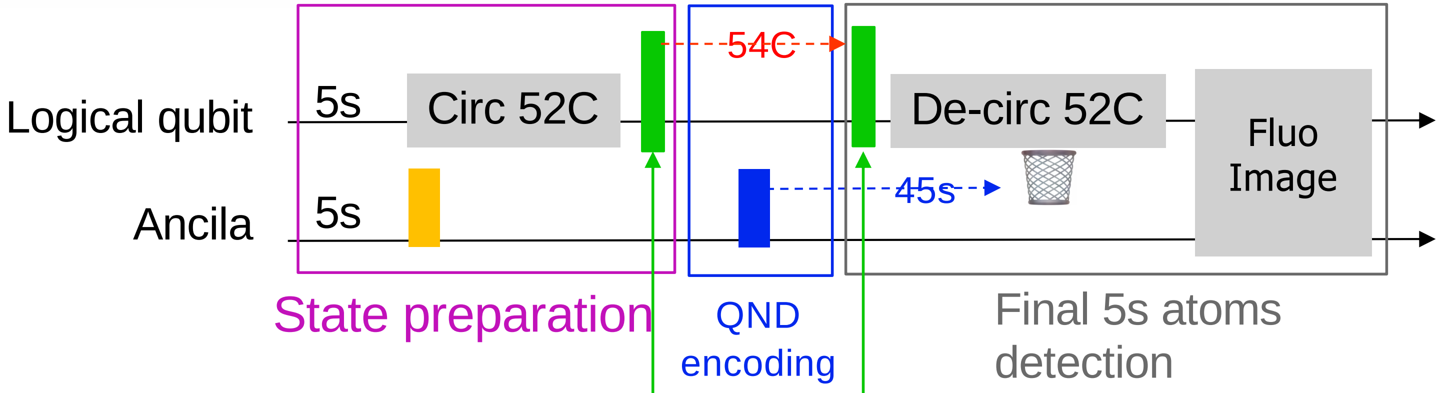
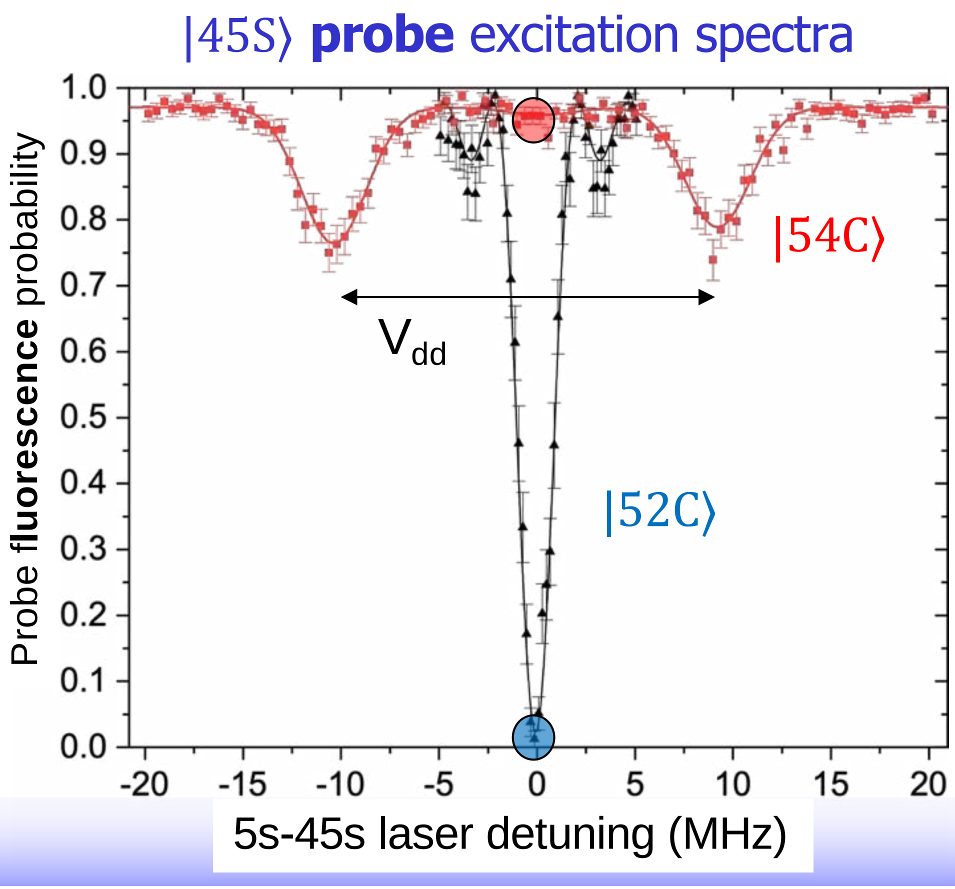


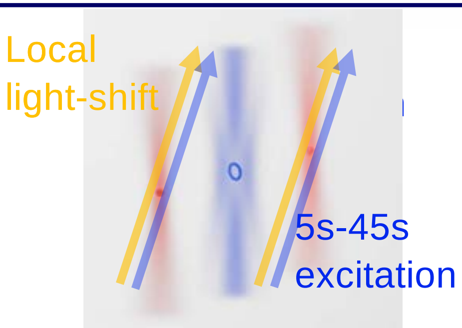


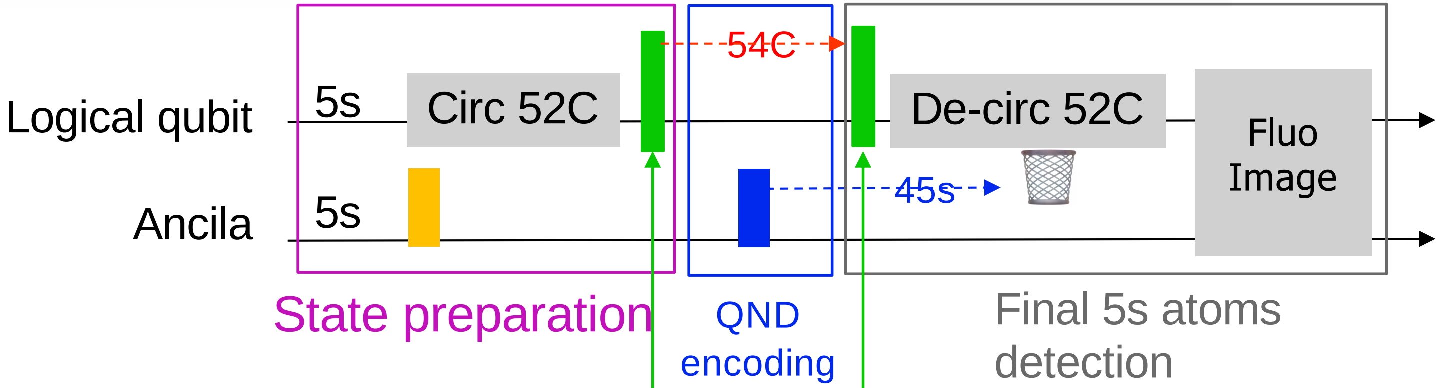


- 52C preparation: no Blockade, the probe disappears at resonance
- 54C preparation: blockade, the probe remains in 5s and is detected
  The circular atom is still there

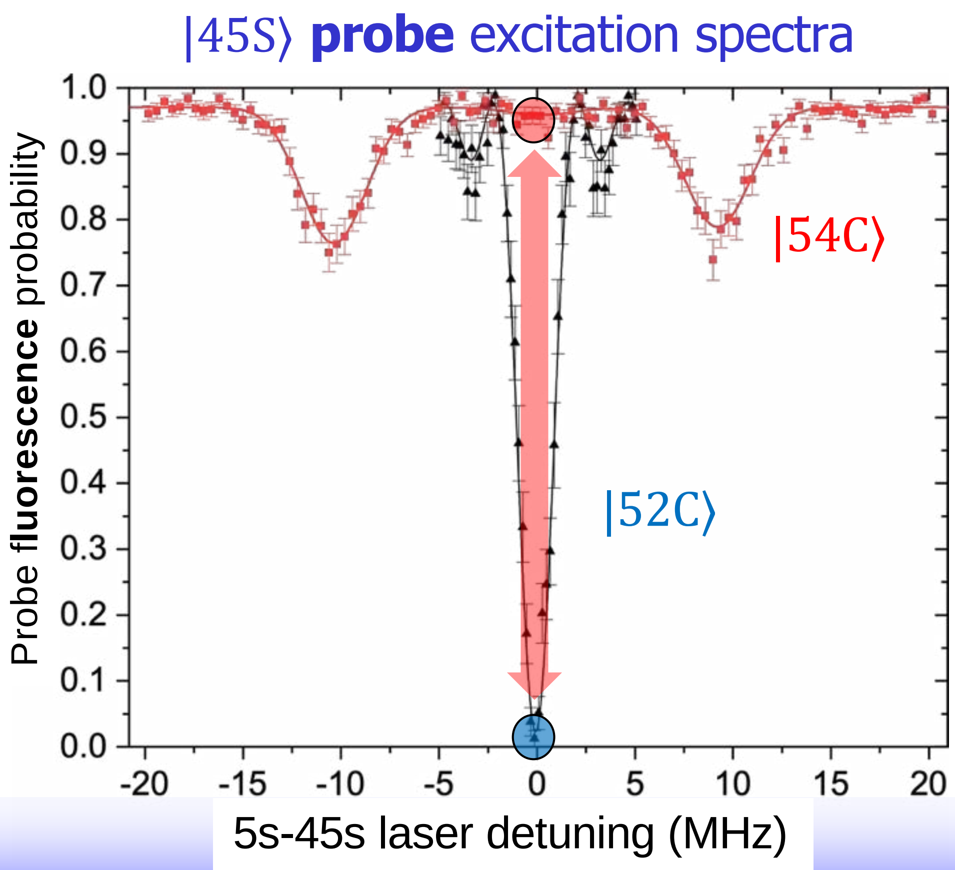
Y. Machu et al. PRX Quantum (2026)

Probe excitation blockade observation





Optional 52C-54C MW pulse: prepa of 54C

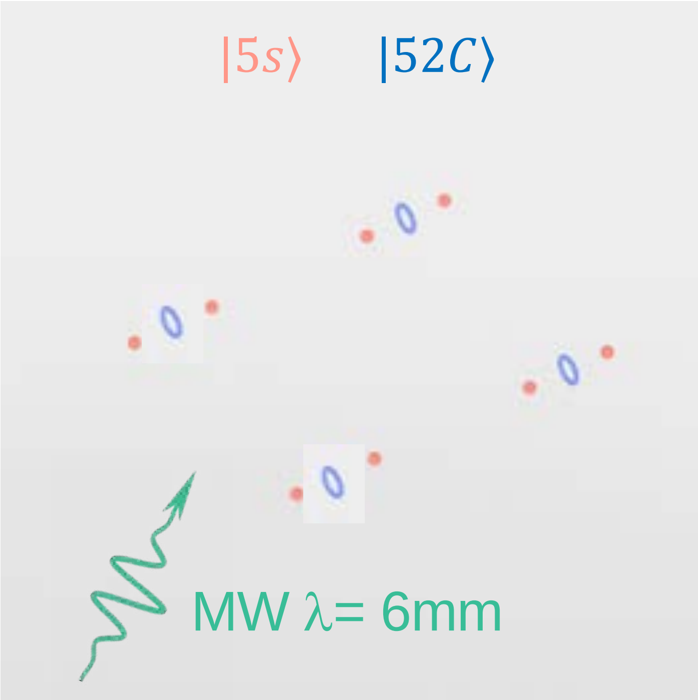


- 52C preparation: no Blockade, the probe disappears at resonance
- 54C preparation: blockade, the probe remains in 5s and is detected
  The circular atom is still there

➙ **QND** detection of 52C-54C with 97-96% fidelity

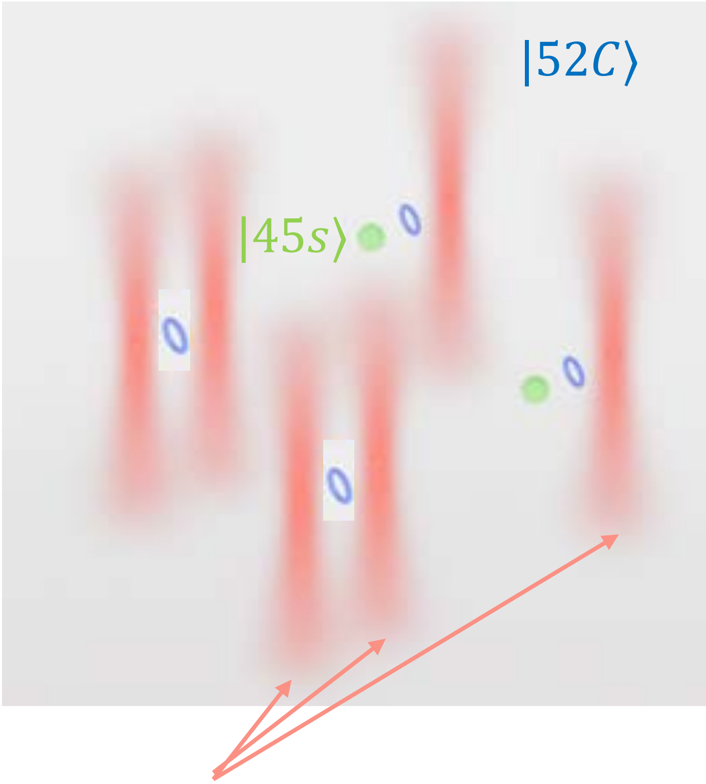
Y. Machu et al. PRX Quantum (2026)

Local control of circular atoms



- Preparation of $|5s\rangle|52C\rangle$

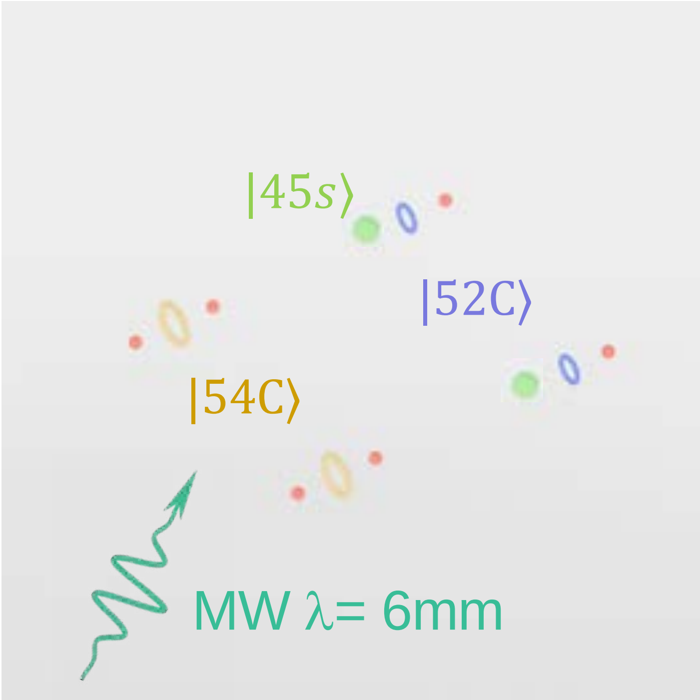
Local control of circular atoms



- Preparation of $|5s\rangle|52C\rangle$
- Local trap-induced light shifts

→ Spatially-selective excitation of ancillae to $|45S\rangle$

Local control of circular atoms



- Preparation of $|5s\rangle|52C\rangle$

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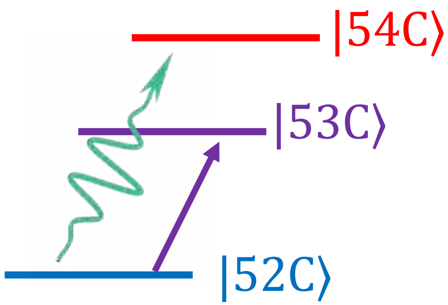
→ Spatially-selective excitation of ancillae to $|45S\rangle$

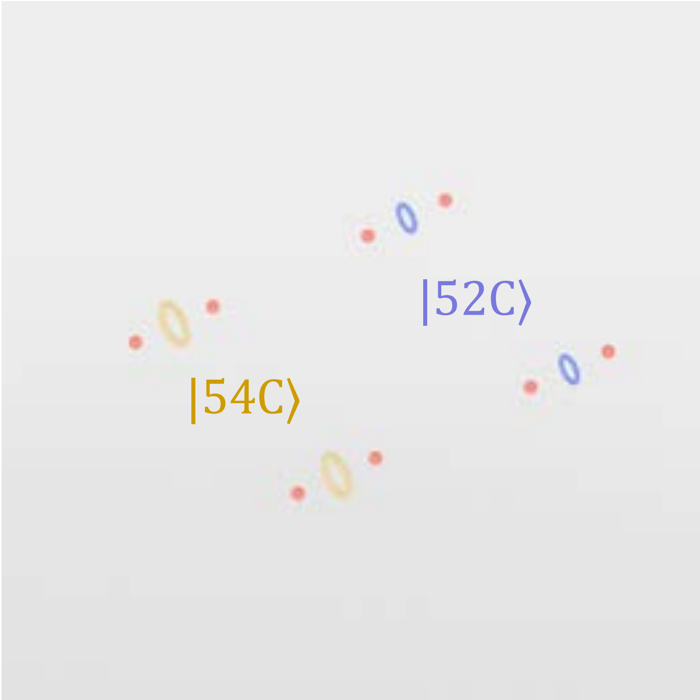
- Rydberg blockade

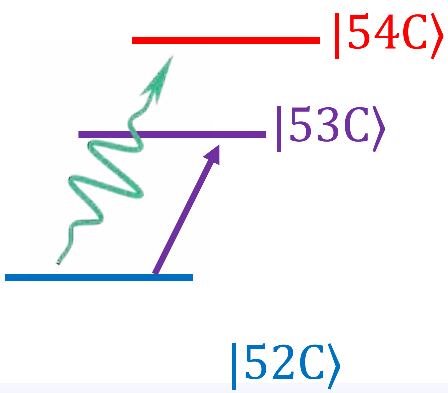
of the MW $|52C\rangle \rightarrow |54C\rangle$ transition



Y. Machu et al. PRX Quantum (2026)

Local control of circular atoms





- Preparation of $|5s\rangle|52C\rangle$
- Local trap-induced light shifts

→ Spatially-selective excitation of ancillae to $|45S\rangle$

- Rydberg blockade

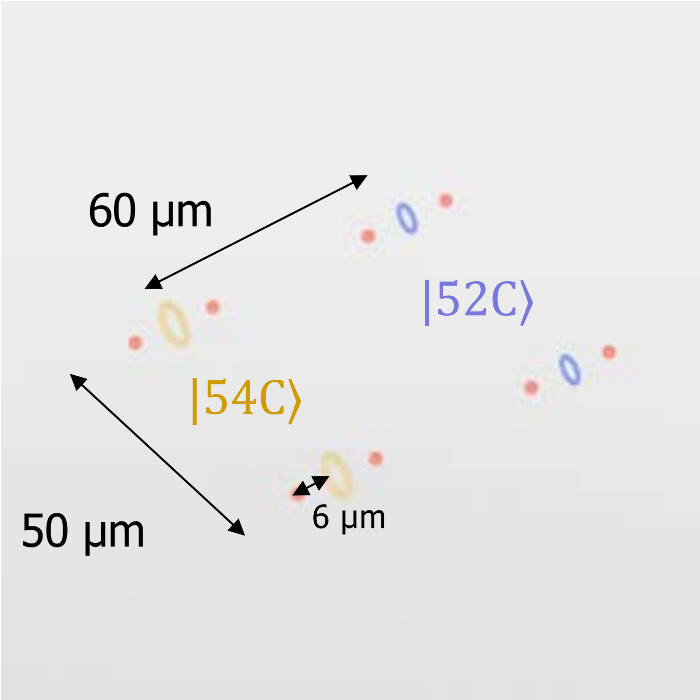
of the MW $|52\mathrm{C}\rangle \to |54\mathrm{C}\rangle$ transition

- De-excitation of the ancillae:

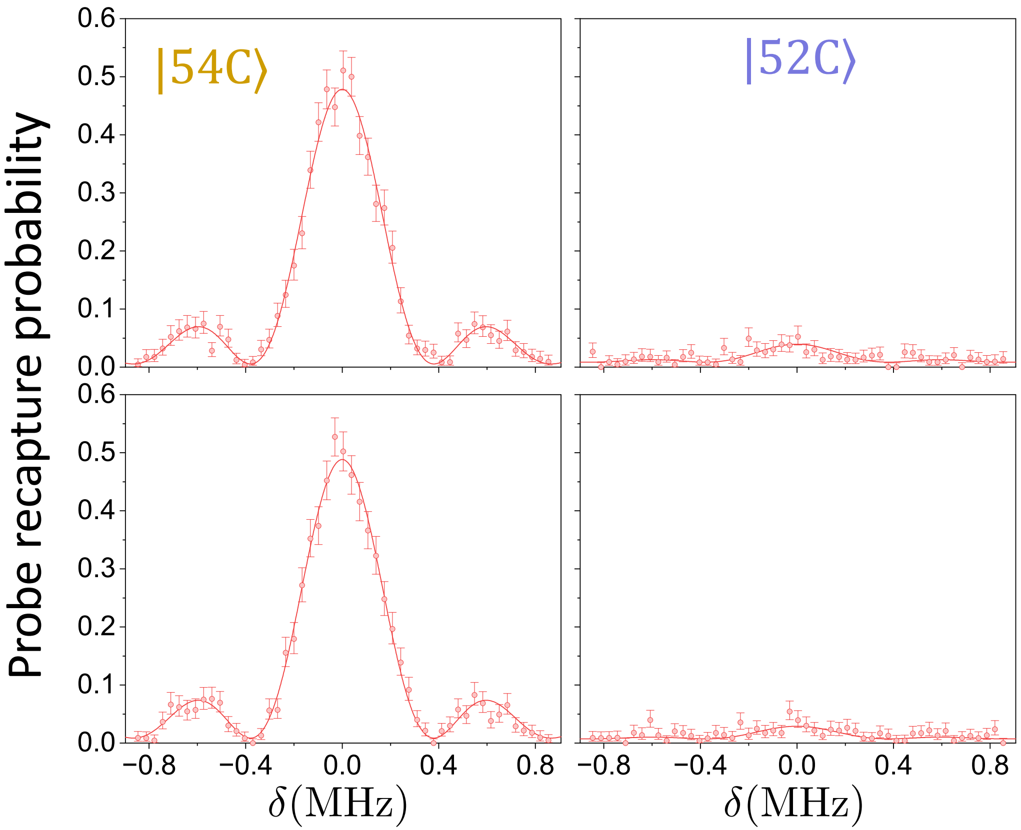
Ancilae ready for QND measurement

- QND measurement using ancillae

Local control of circular atoms



Spatialy-selective spin flips



QND ancillae blocked

QND ancillae Excited in 45s

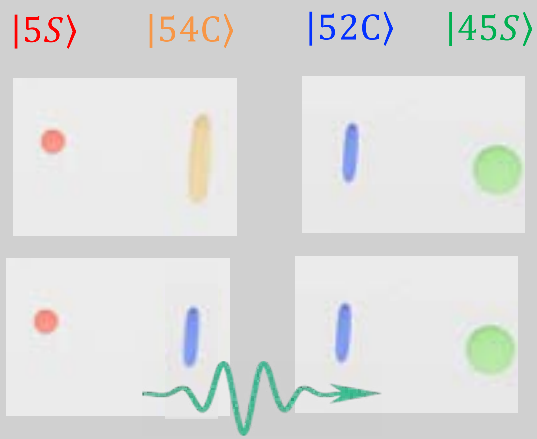
Preparation error detection

QND measurement

- Does not distinguish $|52C\rangle$ from preparation error
- Significant problem with several circular Rydberg atoms… (circutarization efficiency 70%)

Circular Rydberg atom	Ancilla atom	Ancilla detection
$|54C\rangle$	$|5S\rangle$	recaptured / fluorescence
$|52C\rangle$	$|45S\rangle$	lost / no fluorescence
Other	$|45S\rangle$	lost / no fluorescence

Syndrome measurement



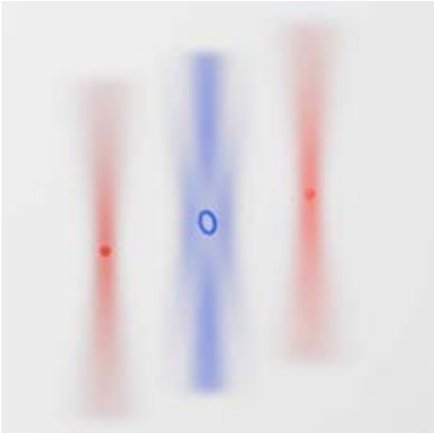
- Operate the ancilla-based measurement
- MW transfer $|54C\rangle \rightarrow |52C\rangle$ blocked for atom in $|52C\rangle$

All circular atoms end up in $|52C\rangle$

Circular Rydberg atom	Ancilla atom	Circular Rydberg atom (after MW pulse)	Circular Rydberg detection	Ancilla detection
$|54C\rangle$	$|5S\rangle$	$|52C\rangle$	recaptured / fluorescence	recaptured / fluorescence
$|52C\rangle$	$|45S\rangle$	$|52C\rangle$	recaptured / fluorescence	lost / no fluorescence
Other	$|45S\rangle$	Other	lost / no fluorescence	lost / no fluorescence

Preparation error **suppressed by post-selection**
Missing circular atoms are not detected after decircularization

Outline



1. **Hybrid array of laser-trapped Rydberg atoms**

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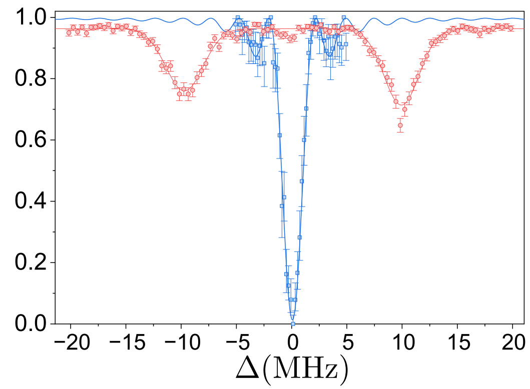
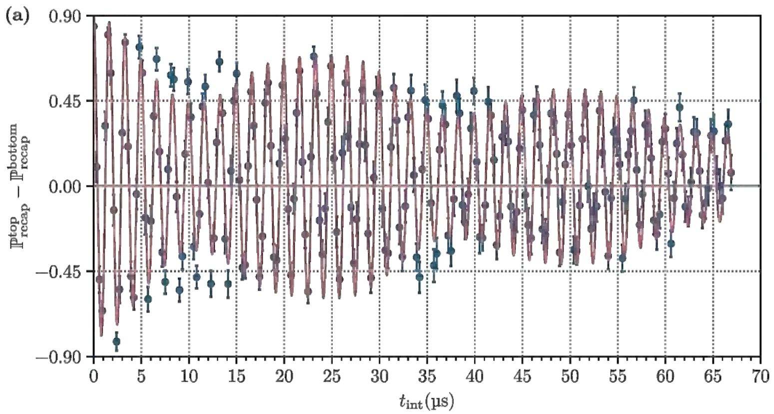
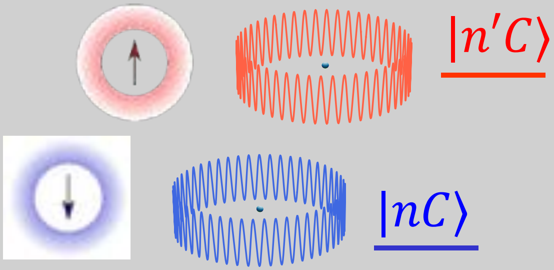




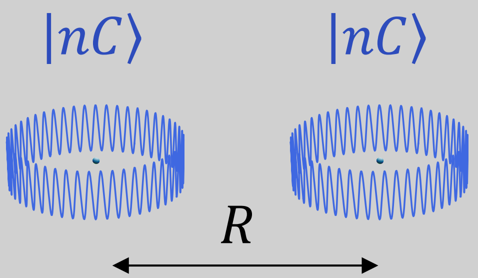
3. Long-lived spin-exchange interaction

Interactions between circular atoms



- Effective spin-1/2 with two circular Rydberg levels
- Interactions similar to low-ℓ Rydberg levels

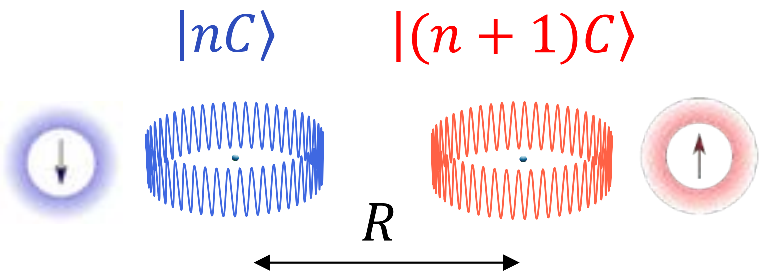
second-order
van der Waals interaction



$$E \propto 1/R^6$$

Ising interaction $J_z \sigma_1^z \sigma_2^z$

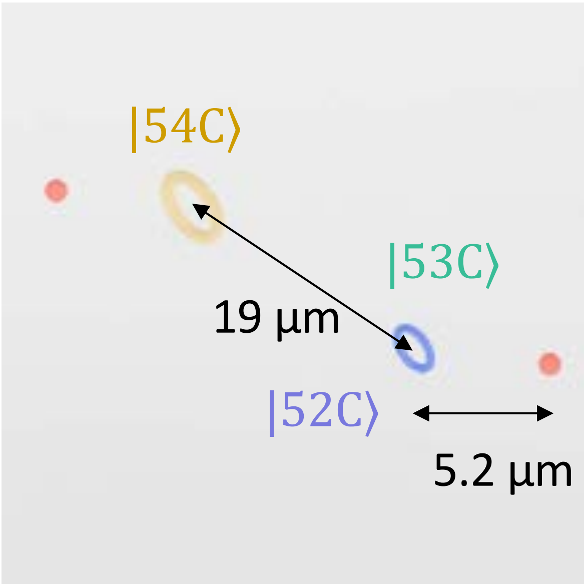
first-order resonant
dipole-dipole interaction

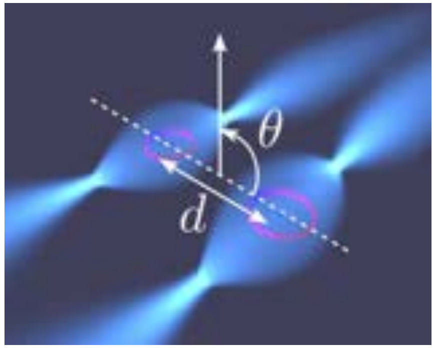


$$E \propto 1/R^3$$

XY interaction
"flip-flop"
$J\,(\sigma_1^x \sigma_2^x + \sigma_1^y \sigma_2^y)$

Spin exchange between laser-trapped circular atoms

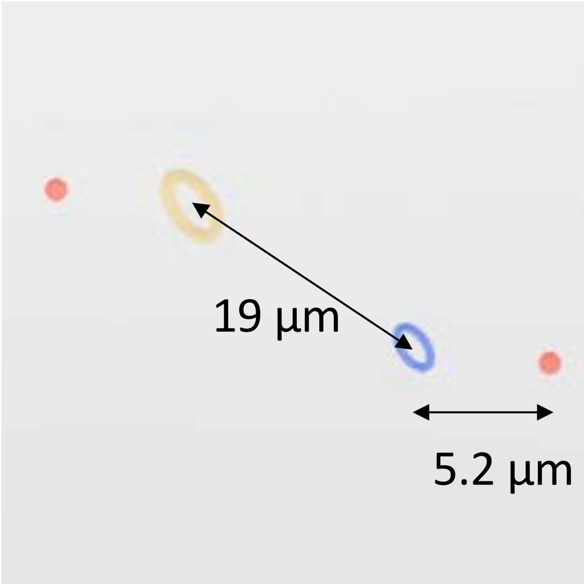


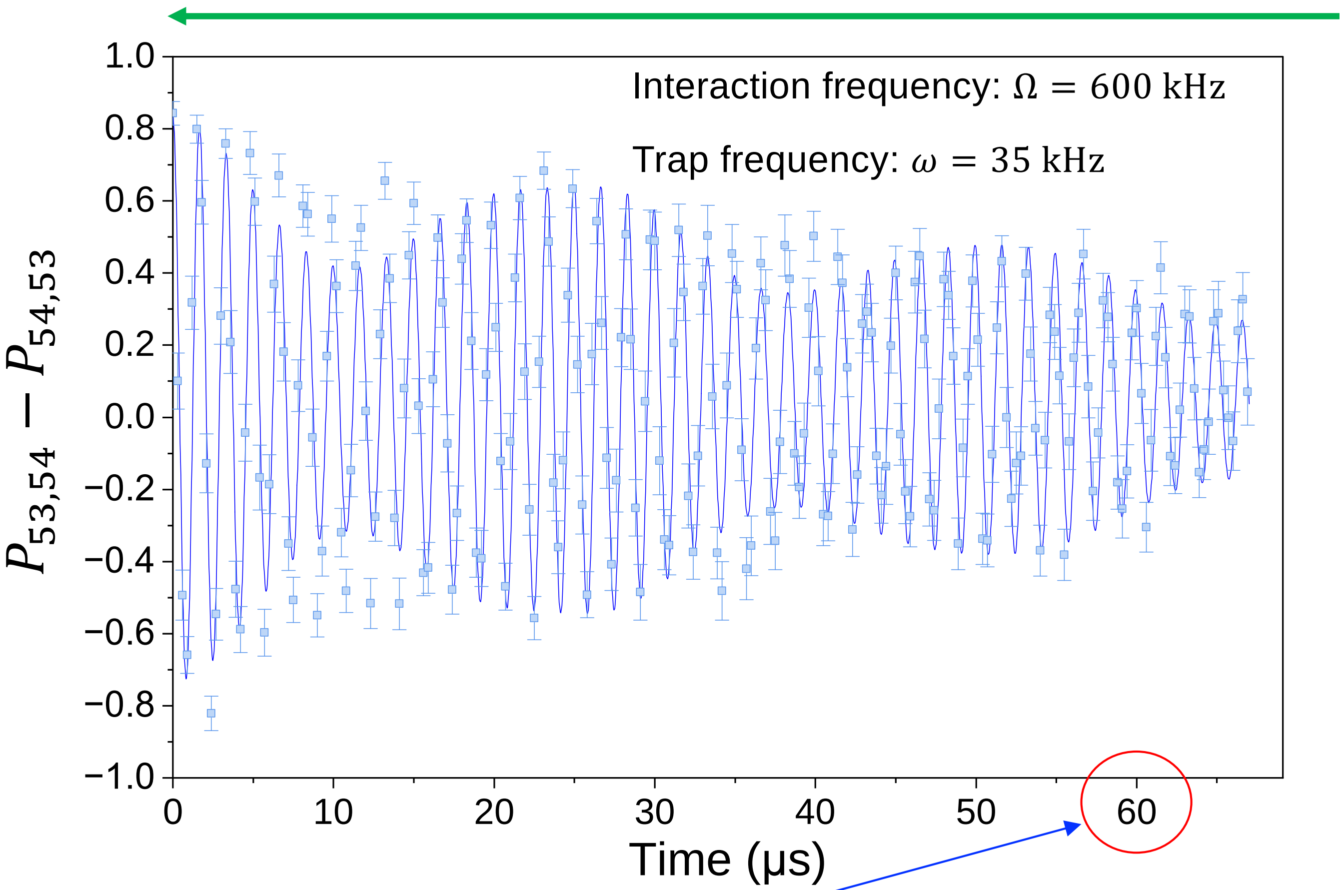


$V_{dd} = C_3\,(1 - 3\cos^2\theta)\,/\,d^3$

- Two circular Rydberg atoms in |52C⟩ and |54C⟩
- Preparation at a "magic angle" (54.7°) no interactions
- MW transfer of |52C⟩ to |53C⟩
- Fast rotation of the electric field turns on / off the interaction

Spin exchange between laser-trapped circular atoms

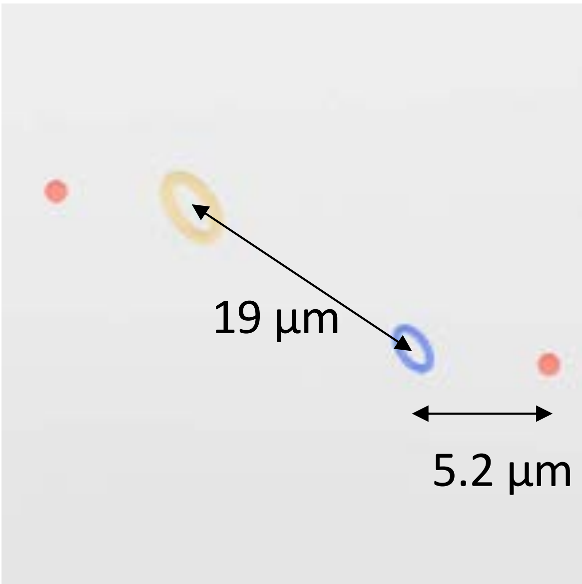




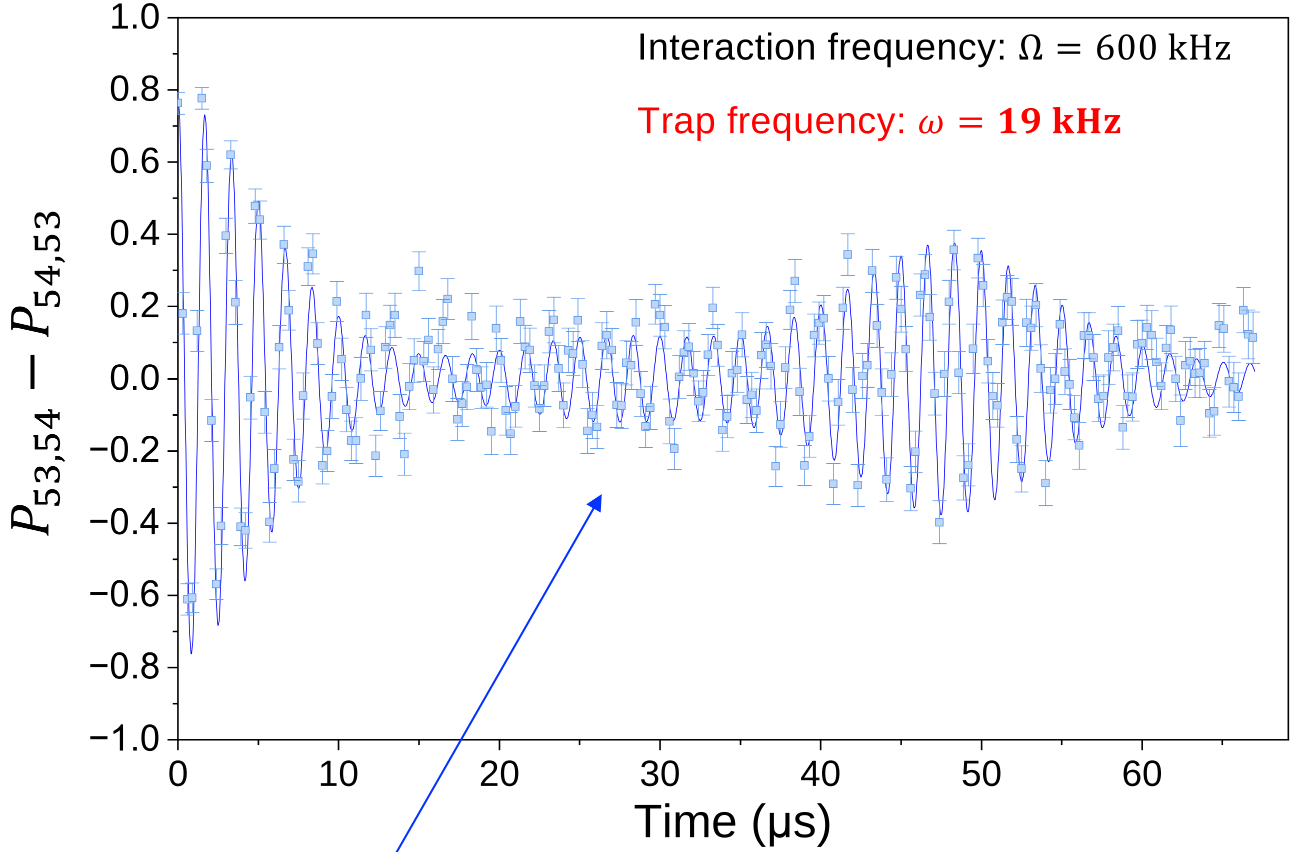
40 interaction cycles
clearly visible over > 60µs

Spin exchange between laser-trapped circular atoms

Exchange in a weaker trap



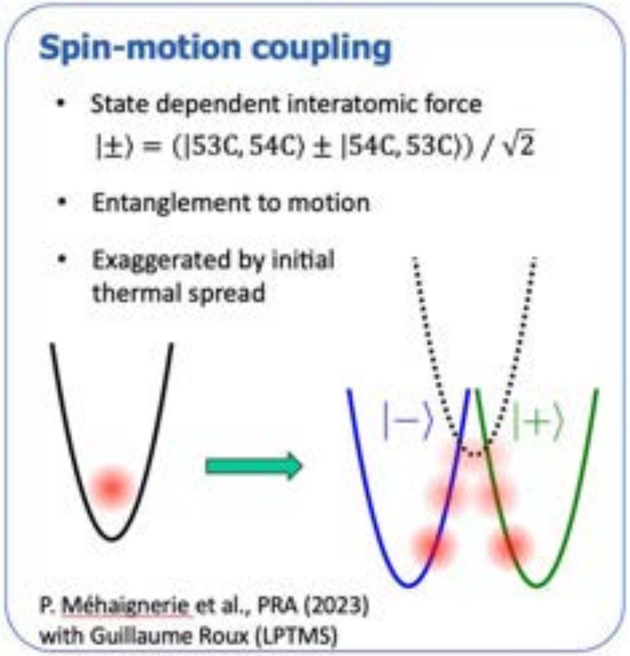
10-fold improvement over state of the art



fast collapse of contrast
before a revival

Spin exchange between laser-trapped circular atoms

Exchange in a weaker trap



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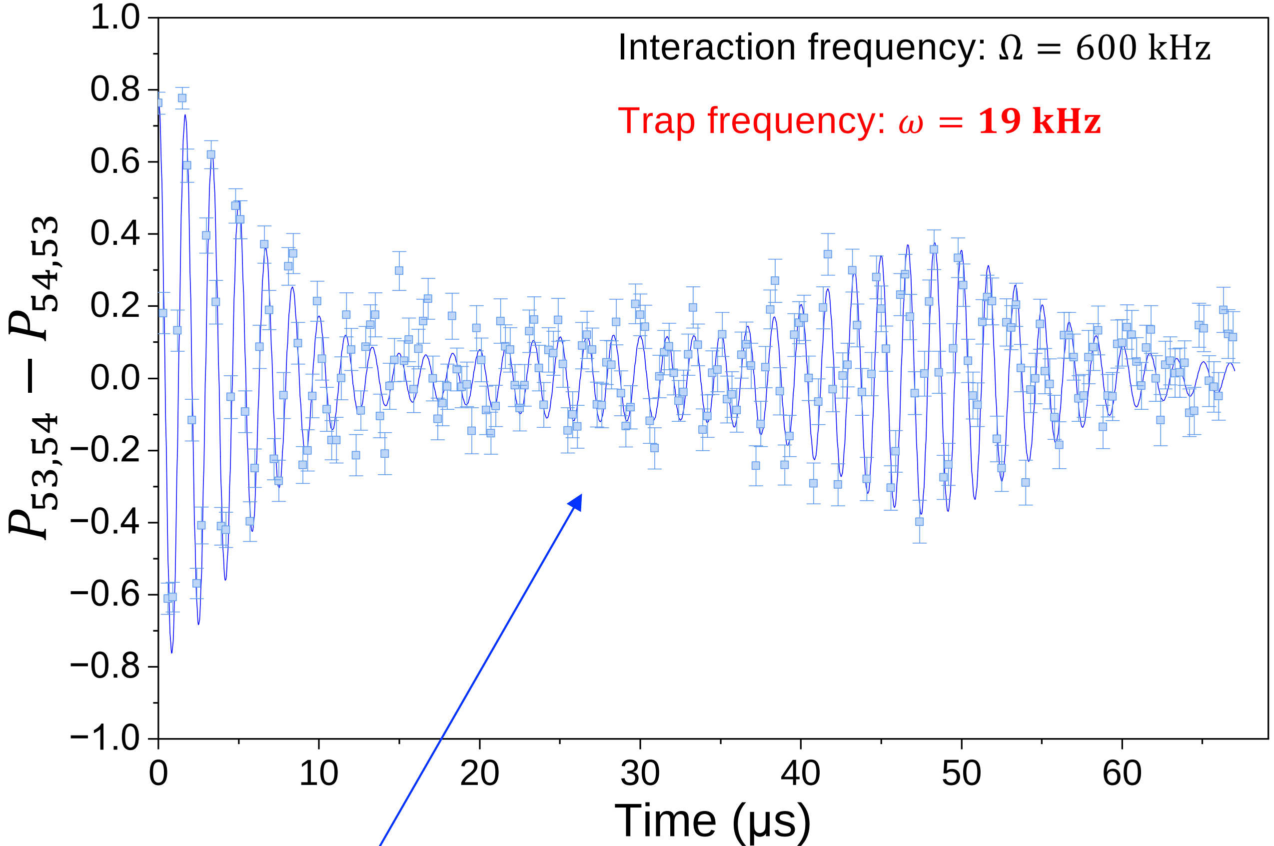


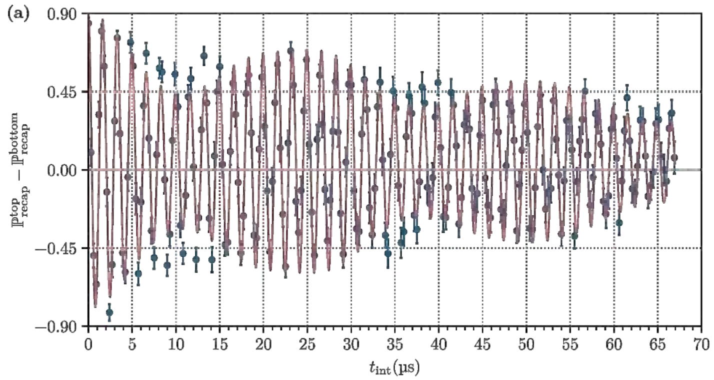
Observation of separation and recombination of spatial wavpacket

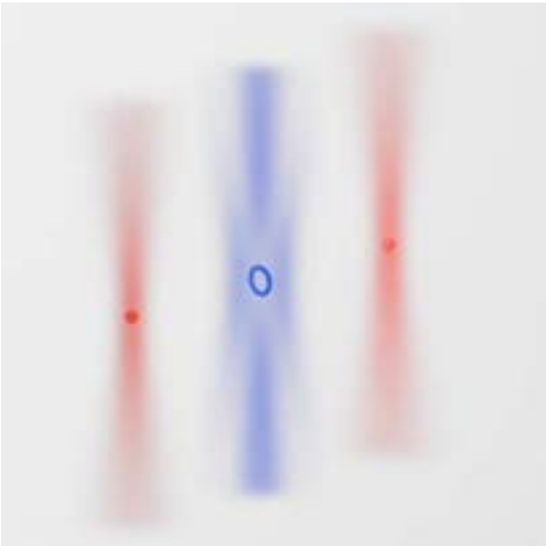
fast collapse of contrast before a revival

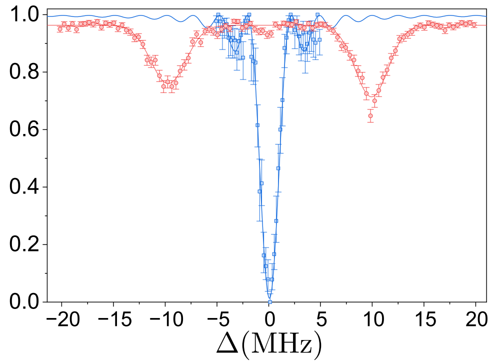
Dual-Rydberg platforM

- Hybrid platform that enables long-duration quantum simulations

- Circular Rydberg atoms: quantum computation or quantum simulation







- Low-ℓ Rydberg atom: ancilla atom for measurement and local control

What to do next?

- Cryogenic environment: long-lifetimes of circular Rydberg levels (~ 10 ms)

- Mid-circuit measurements: explore the interplay between quantum measurement (Zeno effect) and quantum dynamics

➡ Measurement induced quantum phase transitions
see e.g. X. Turkeshi,…, M. Schiró, PRB (2021)

- Ancilla-based control of the interactions: tunability of the interaction range, switchable interactions

➡ T. Botzung, G. Creutzer, C. S., J. Schachemayer, PRR (2026)
arXiv:2508.02815

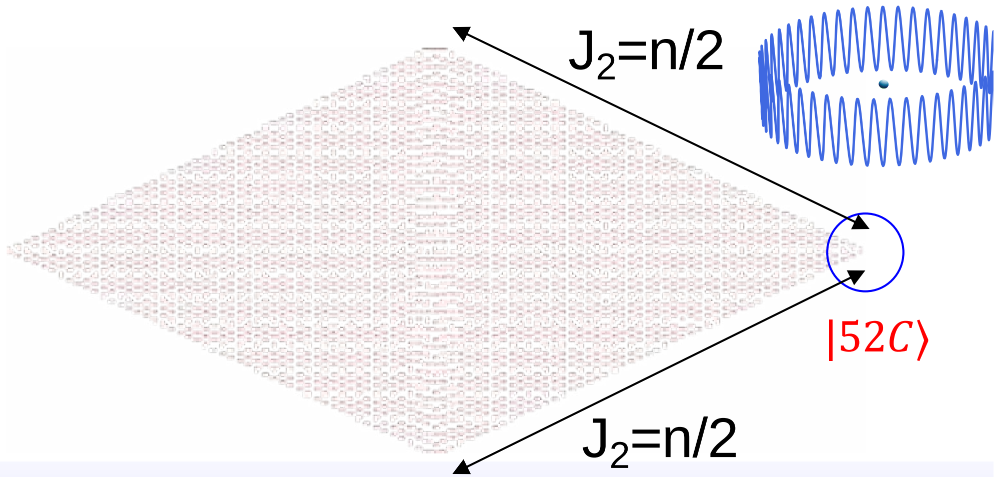
Pasqal

MYCRYOFIRM
CRYOGENIC SOLUTIONS

- Exploit the vast Rydberg manifold:

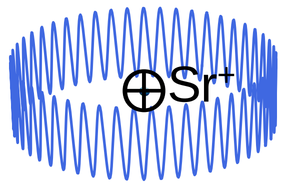
SO4 symmetry of Hydrogen
→ Hidden large spin J1 an j2
→ Large “artificial dimensions

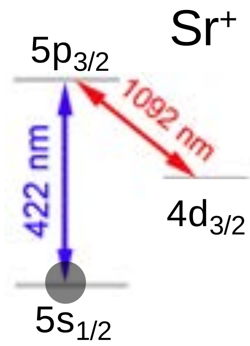
Quantum simulation beyond the spin 1/2



Circular Rydberg atoms of Strontium

S. Gleyzes and B. Bakkali-Hassani (LKB)





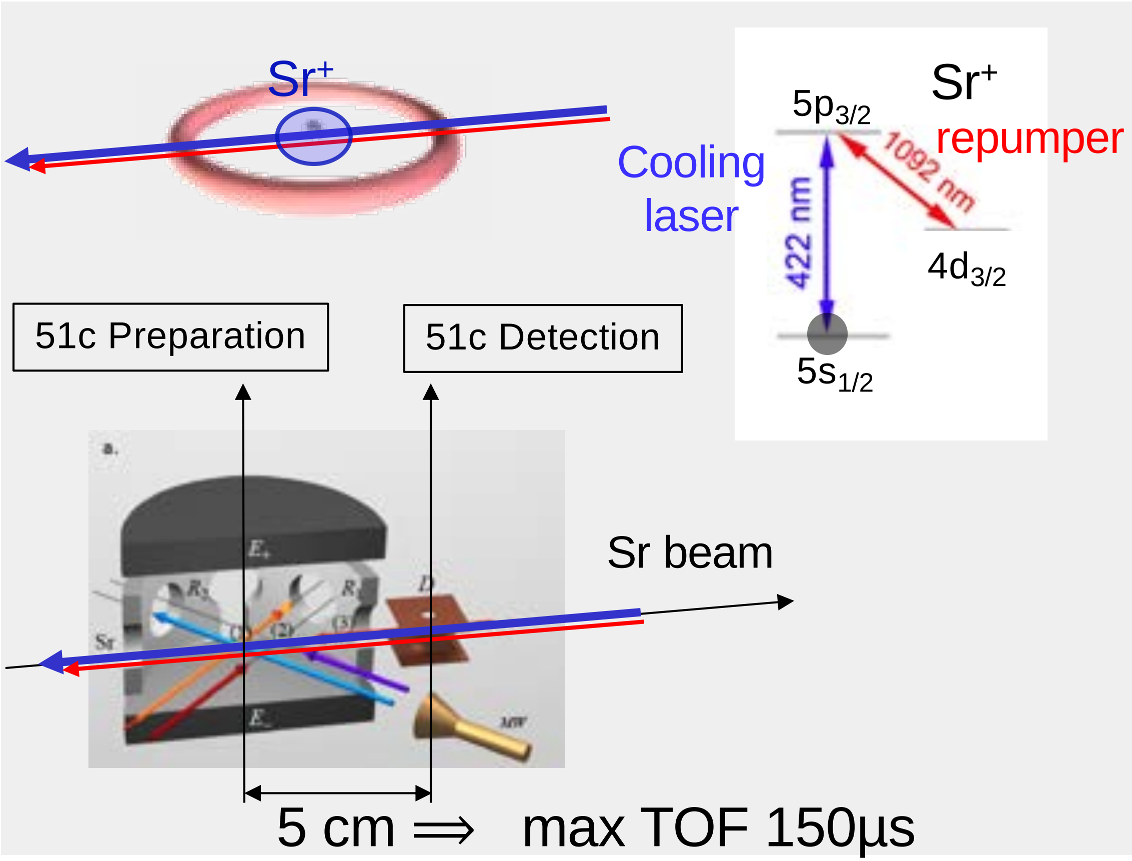
Léa Lachaud
Baptiste Muraz
Matis pépin

Jean-Michel Raimond
MB

- *RC Teixeira et al. PRL. 125, 263001 (2020)*
Preparation of Long-Lived, Non-Autoionizing Circular Rydberg States of Strontium
- *Nature Physics, **18**, 502 (2022)*
Optical coherent manipulation of alkaline-earth circular Rydberg states
- *MW spectroscopy of Stark levels of Sr, in preparation*
- *L. Lachaud et al. arXiv:2406.01396,*
Laser cooling of circular states of Sr ,

Laser cooling of a Sr atomic beam

Circular Sr atom cooling using ionic core transition



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L. Lachaud et al. arXiv:2406.01396

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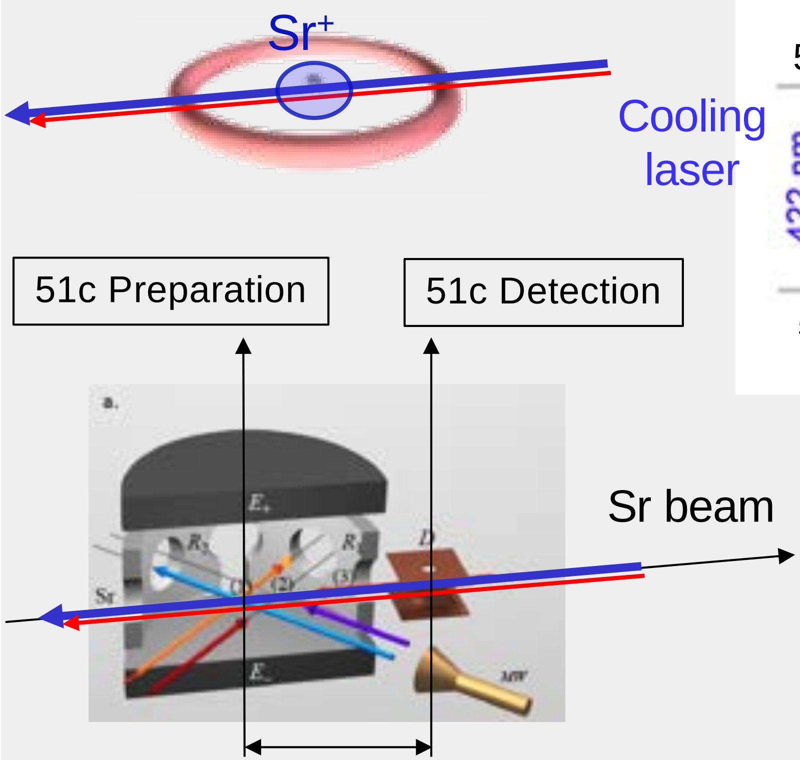
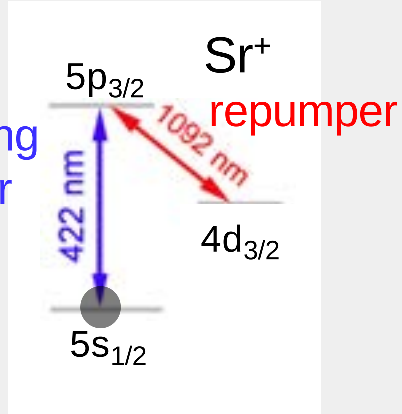
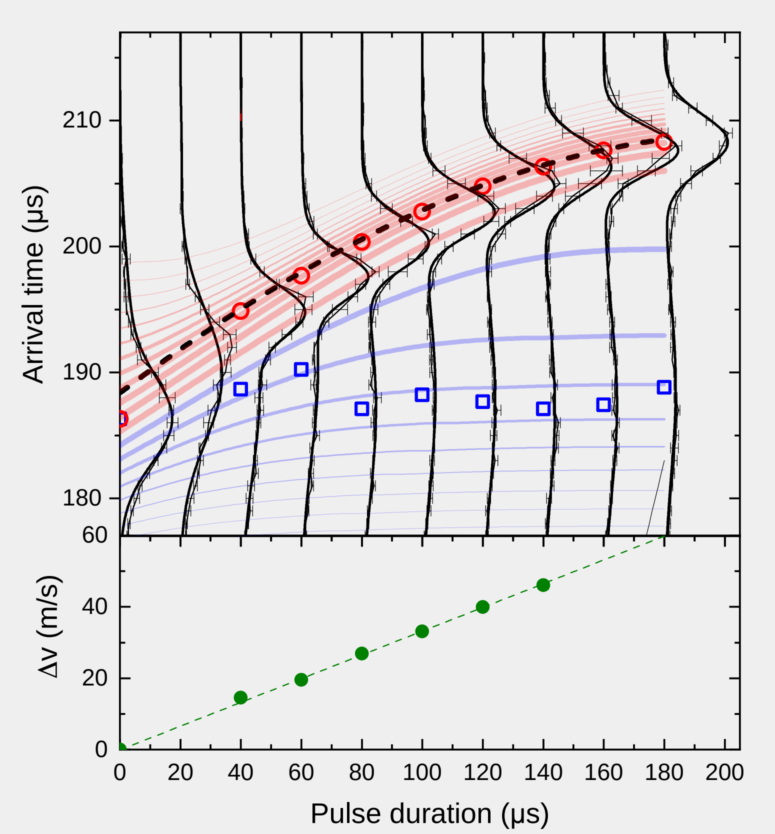




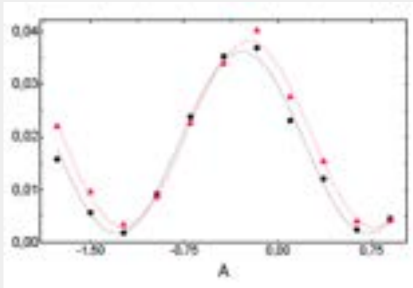
5 cm ⟹ max TOF 150µs



➙ with slowing lasers, 51C atoms are detected later

ΔV= 40 m/s, 4000 scattered photons

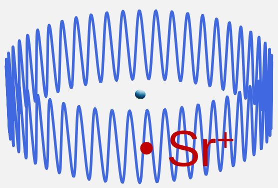
➙ Negligible decoherence



Ramsey fringes on the 51c-49c transition

Rydberg- $4d_{3/2}$ Sr^+ quadrupole interaction

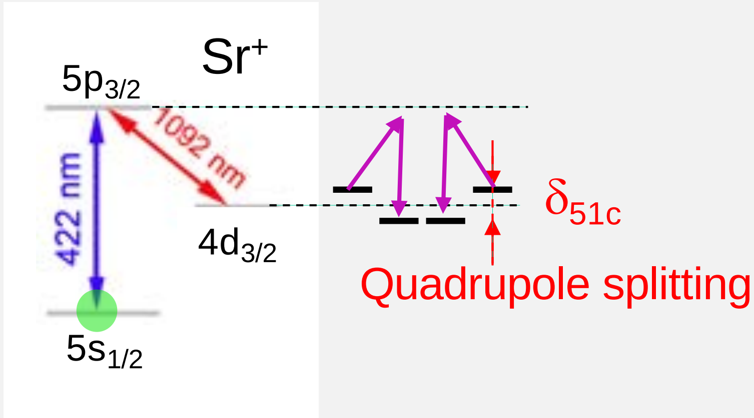
$|4d_{3/2}51c\rangle$



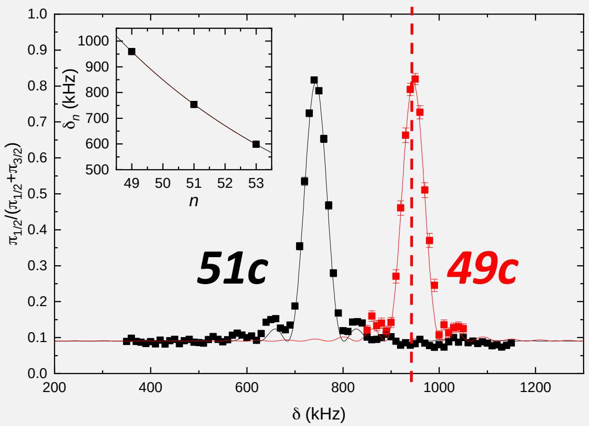
Quadrupole shift

$\delta_{51c} \approx 750$ kHz

Sr+ ion energy levels



Raman spectrum



Nature Physics, **18**, 502 (2022)

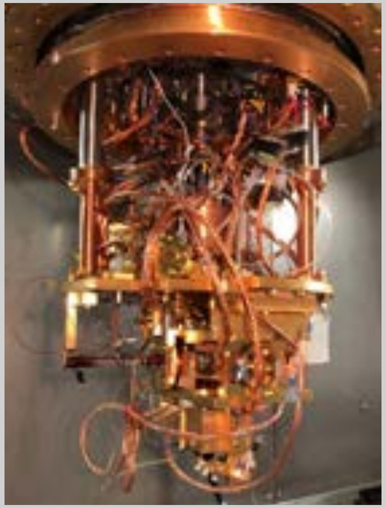
Nc dependence of $m_J = 3/2 \rightarrow m_J = 1/2$ transition

$\Rightarrow$ **Conditional flip of $4d_{3/2}$ sublevels**

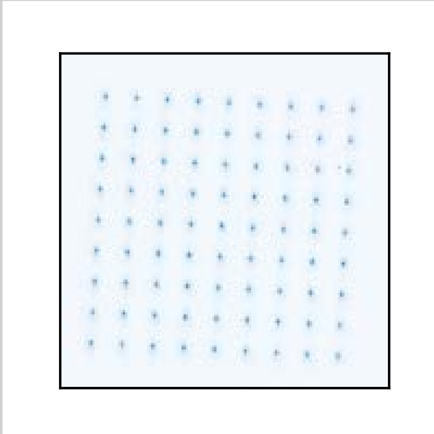
$\Rightarrow$ Encoding/measurement of circular sate using the ionic core state

by optical manipulation of the Sr+ core

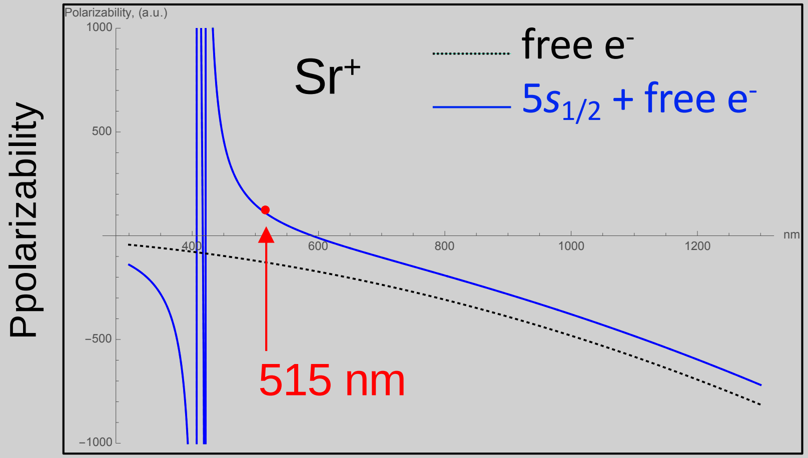
Trapped Sr circular atoms at 4K



Cryogenic setup

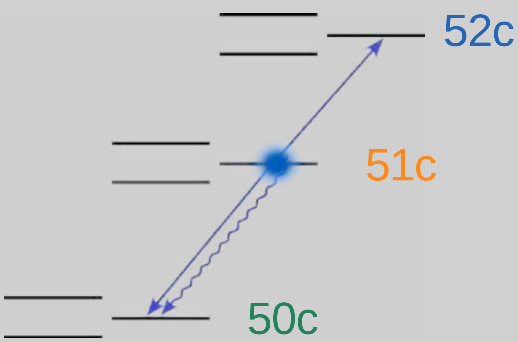


Single Sr atom array



Trapping laser wavelength

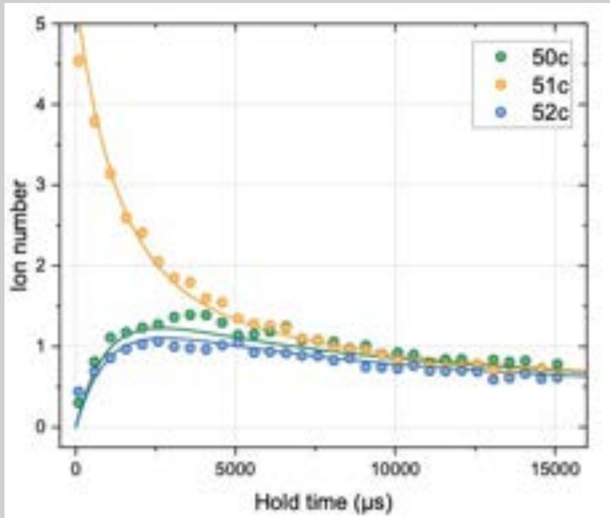
Sr circular atoms trapped with the same tweezers as ground state



Estimated lifetime at 4K

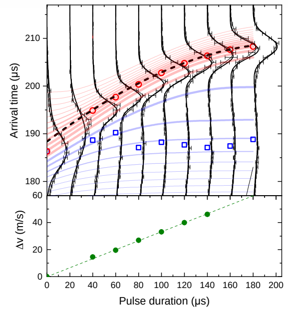
τ ~ 3 ms

Effective BBR temperature 22K

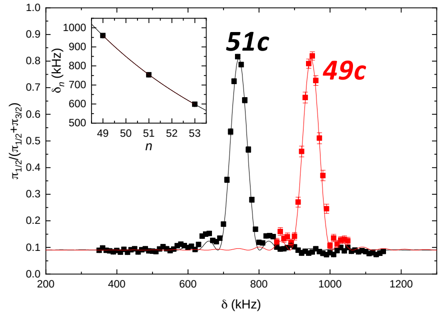


30 times better than at room-temperature

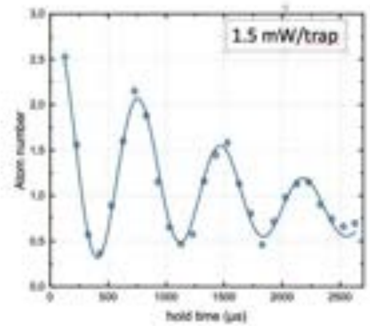
Quantum simulation with SR: Perspectives



- Same trap for ground-state and circular
- Cooling using the ionic core



- Optical manipulation/detection via quadrupole interaction
- Add Singlet-triplet degree of freedom



Next:

- QND detection of the circular sate using core fluorescence
- Quantum simulation with large number of circular atoms

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