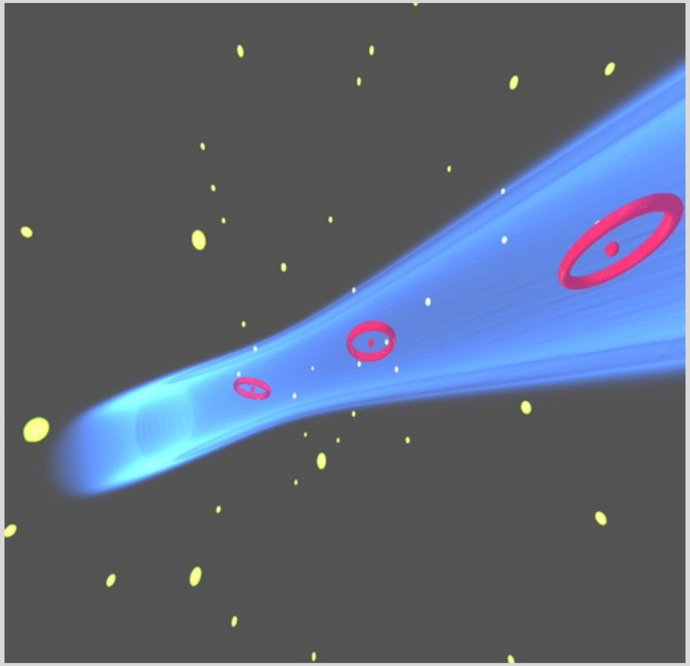


Trapped Circular Rydberg Atoms for Quantum Simulation
Quantum Non-Demolition Detection and Optical Manipulations

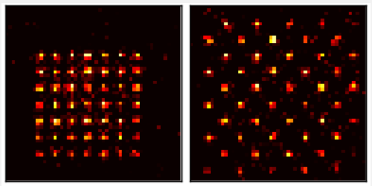
Michel Brune

Laboratoire Kastler Brossel
Physique quantique et applications

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

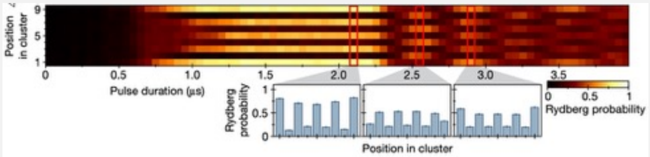
QubitAF

Neutral atoms in optical tweezers

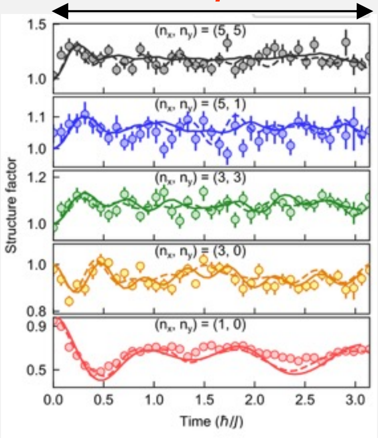


IOGS Palaiseau
Labuhn et al.,
Science **354**
(2016)

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



~10μs



C. Chen et al.
Arxiv2311.1172
6
IOGS Palaiseau

Quantum simulations up to 256 atom on **3-10μs timescale**

→Arbitrary arrays of dipole traps filled with one atom per site

→Use of strong dipole or Van der Waals interaction between Rydberg atoms to perform quantum gates or synthetize spin Hamiltonians with a high degree of control

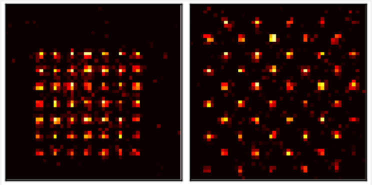
→Beautiful achievements in the field of quantum simulation and quantum computing

Where is the limit?

→timescale of Rydberg levels lifetime

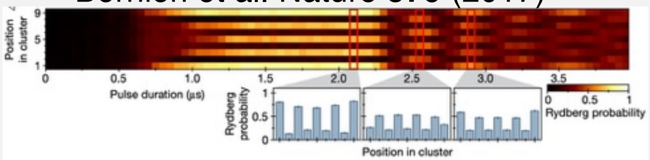
Goal going to **100 times longer timescales** using **circular Rydberg atoms**

Why using Circular Rydberg levels for QS?

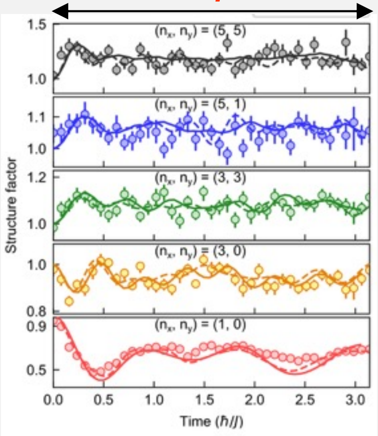


Labuhn et al., Science **354** (2016)

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



~10μs

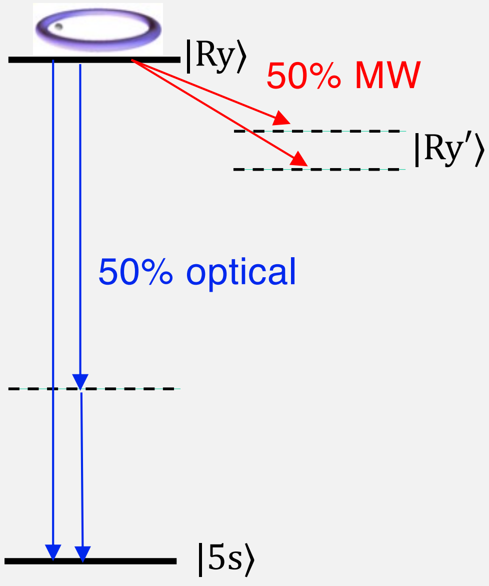


C. Chen et al. Arxiv2311.11726

Quantum simulations up to 256 atom on **3-10μs timescale**

Timescale limitation:

- Radiative lifetime

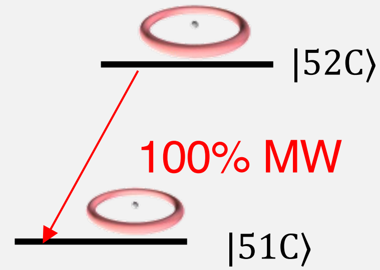


Low-ℓ Rydberg levels

$\tau \simeq 100\ \mu s$ (n=50-80)

Circular levels

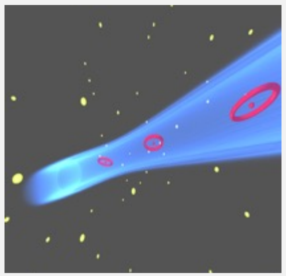
|m| = l = n-1|



Only one MW decay channel at 0K

$\tau \simeq$ **10 ms** (n=50-54) at 4 K

→Cryogeny needed



→build a quantum simulator based on **trapped circular** Rydberg atoms

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

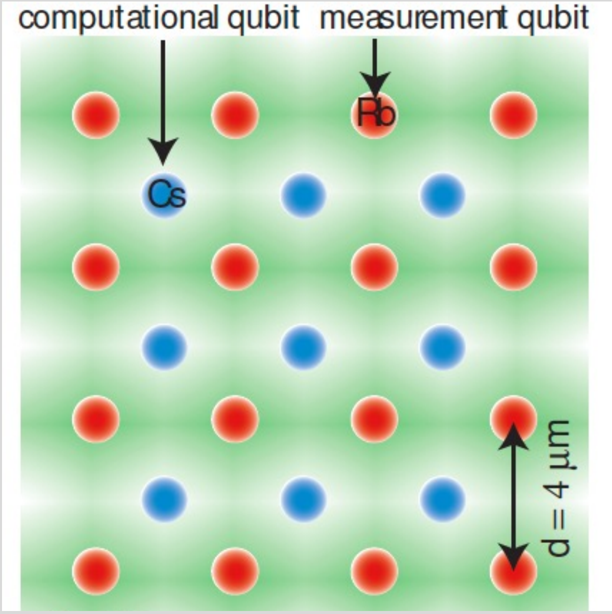
M. Brune

J.M. Raimond

S. Haroche

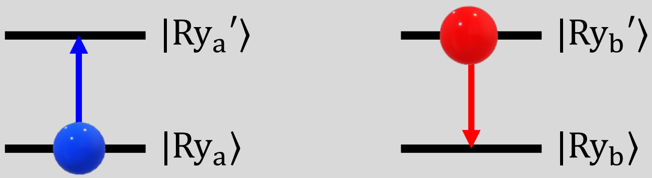
Dual Rydberg platform for preparing and detecting circular atoms

Dual species



*I. Beterov and M. Saffman, PRA **92**, 042710 (2015)*

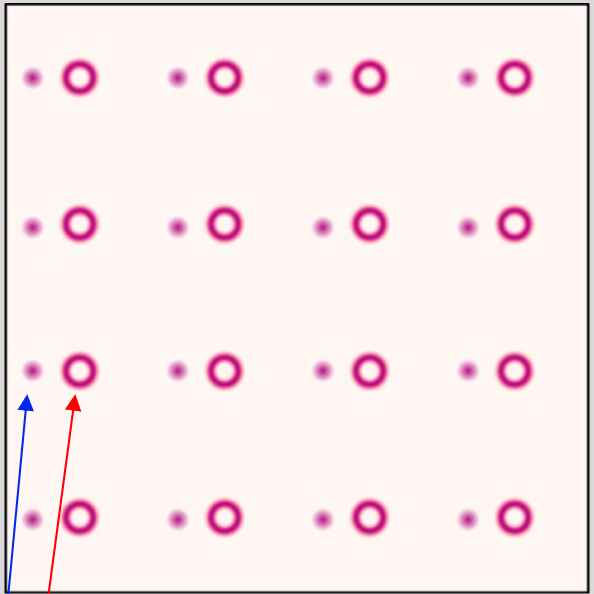
Interspecies Förster resonance

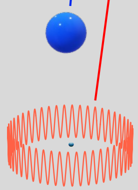


S. Anand… H. Bernien, Nat. Phys. (2024)

$|Ry_b'\rangle$

Dual Rydberg





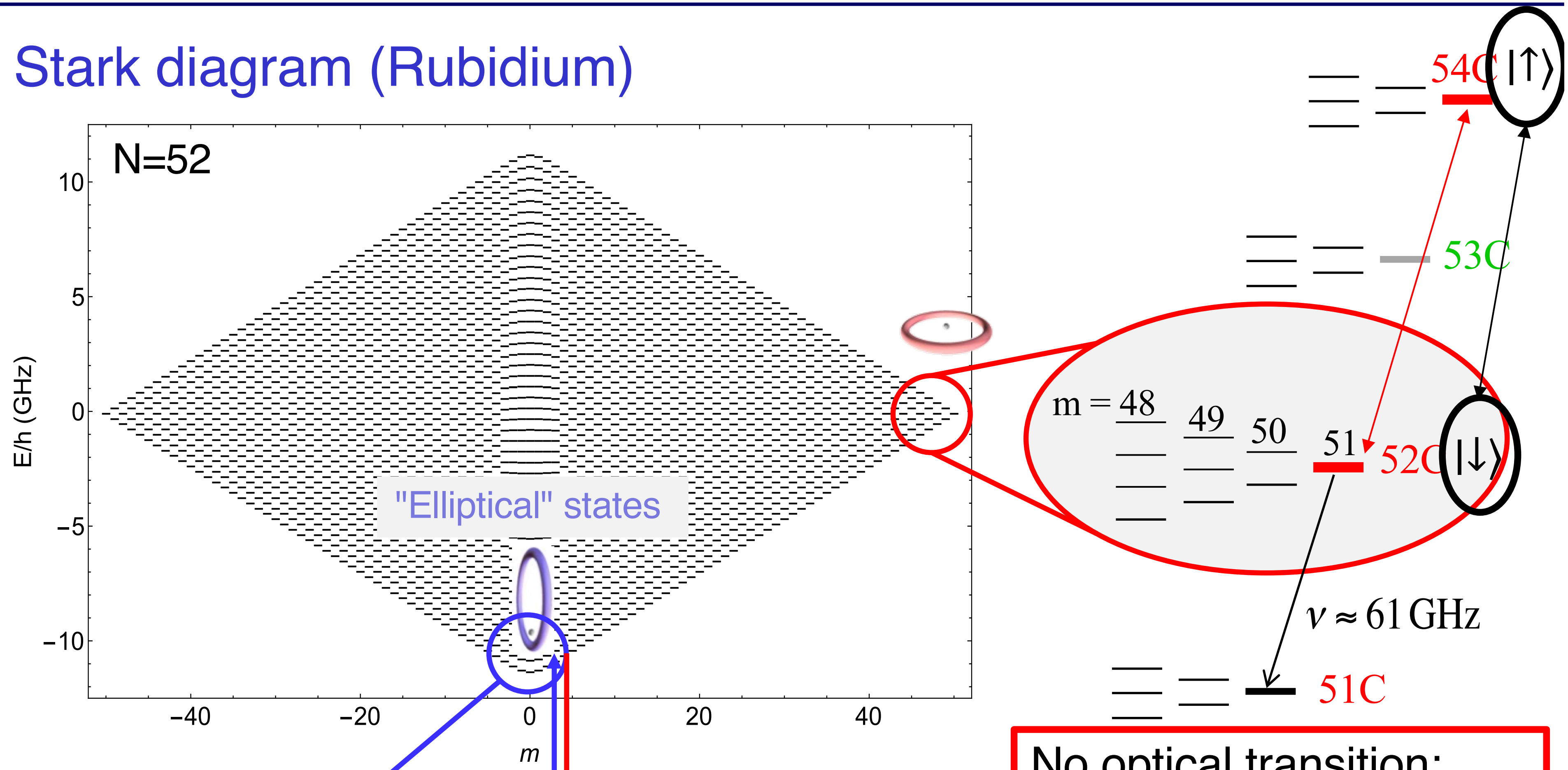
Ancila qubit: **low l Rydberg levels**

Logical qubit: **circular Rydberg levels**

Laser addressing of ancilla provides
- Local QND measurement of circular qubit
- Local manipulation of circular qubit

Low-l to circular Rydberg levels

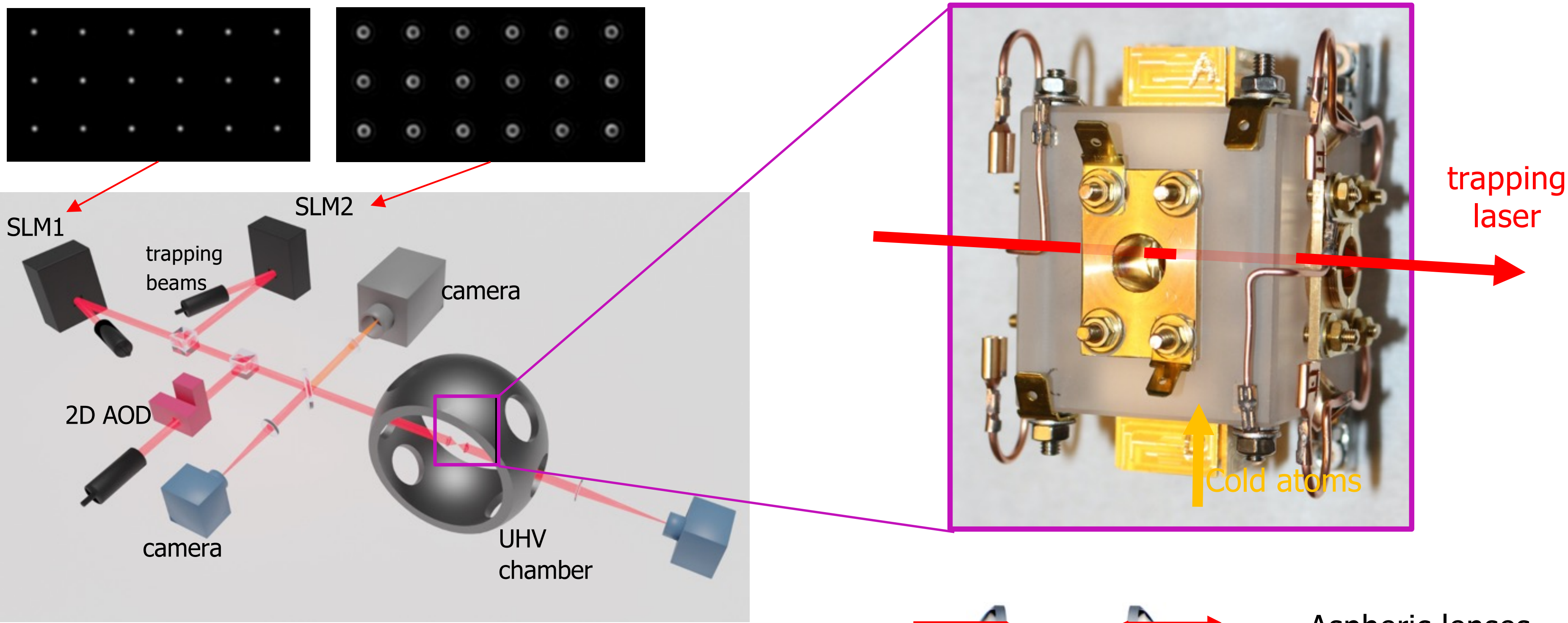
- Stark diagram (Rubidium)

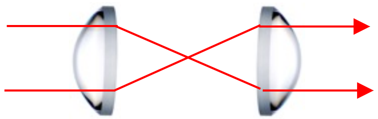


Low-ℓ levels:
Laser accessible
➞direct optical manipulations
Optically addressed quantum gates

No optical transition:
🙂 long lifetime
😟 difficult detection and local addressing
➞use of ancillae atoms solves both problems

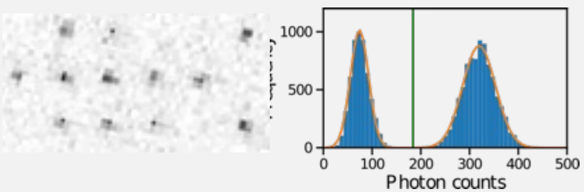
Room temperature setup





Aspheric lenses
NA=0.35

Ground state atom imaging



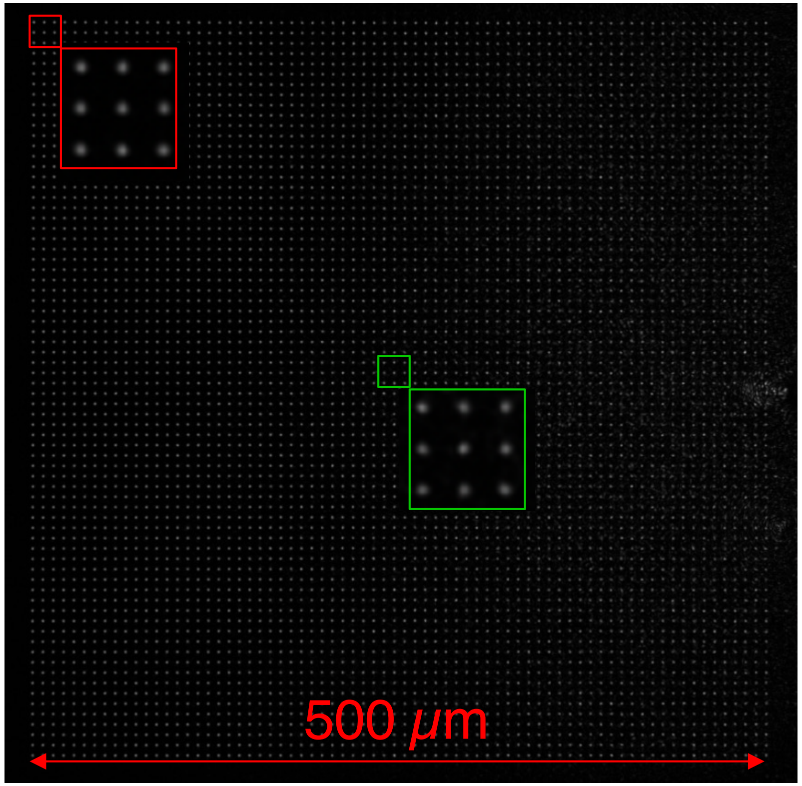
Single atom
detection

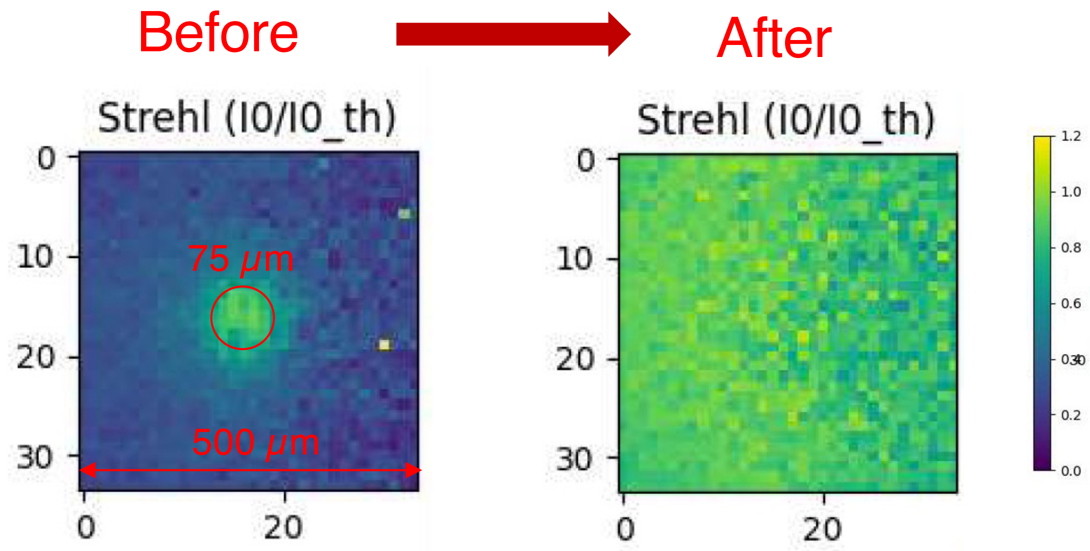
- Spatial Light Modulators (SLM) prepares arrays of optical tweezers
- Atoms at $\approx 15\mu\mathrm{K}$
- Lattice sites separated by $7 - 20\ \mu\mathrm{m}$

Holographic Field-Dependent Aberration Compensation

- Aspherical lenses
  - Perfect focus at focal point on axis
  - Large field-dependent aberrations: Coma > Astigmatism > …others

100*100 array, step 5 μm





→ 500 μm diffraction limited field of view!

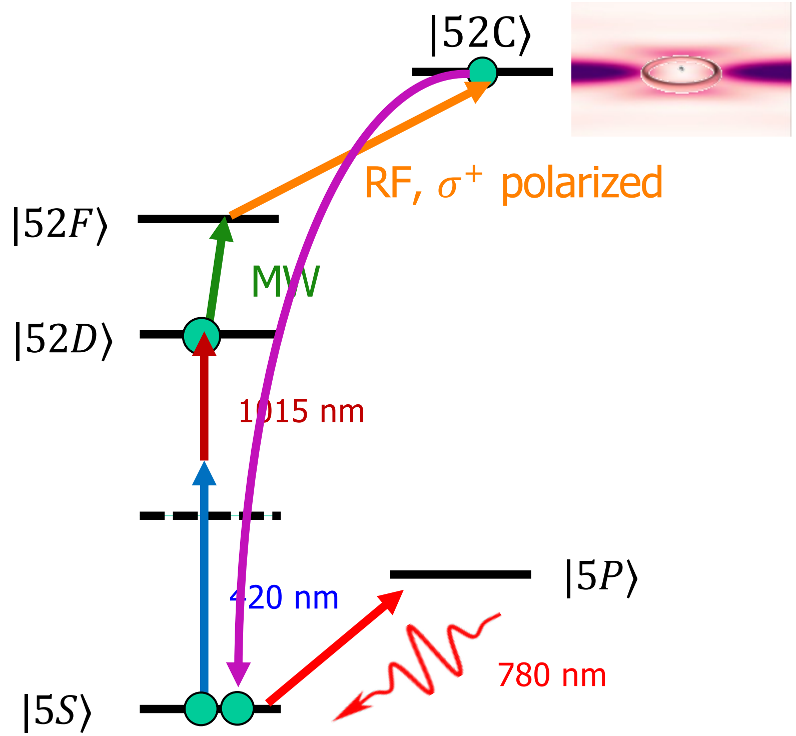
Patented

Y. Machu et al. in preparation

Rydberg excitation and destructive detection

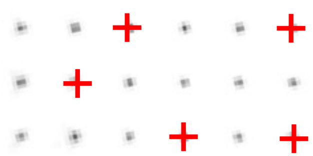
Circular state preparation

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



Destructive detection method DM

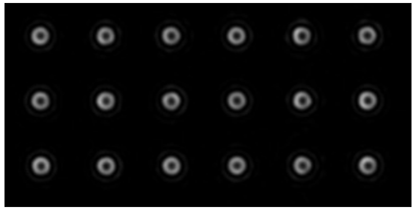
fluorescence imaging after decircularization

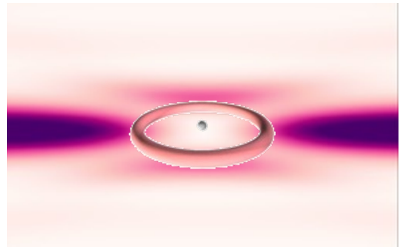


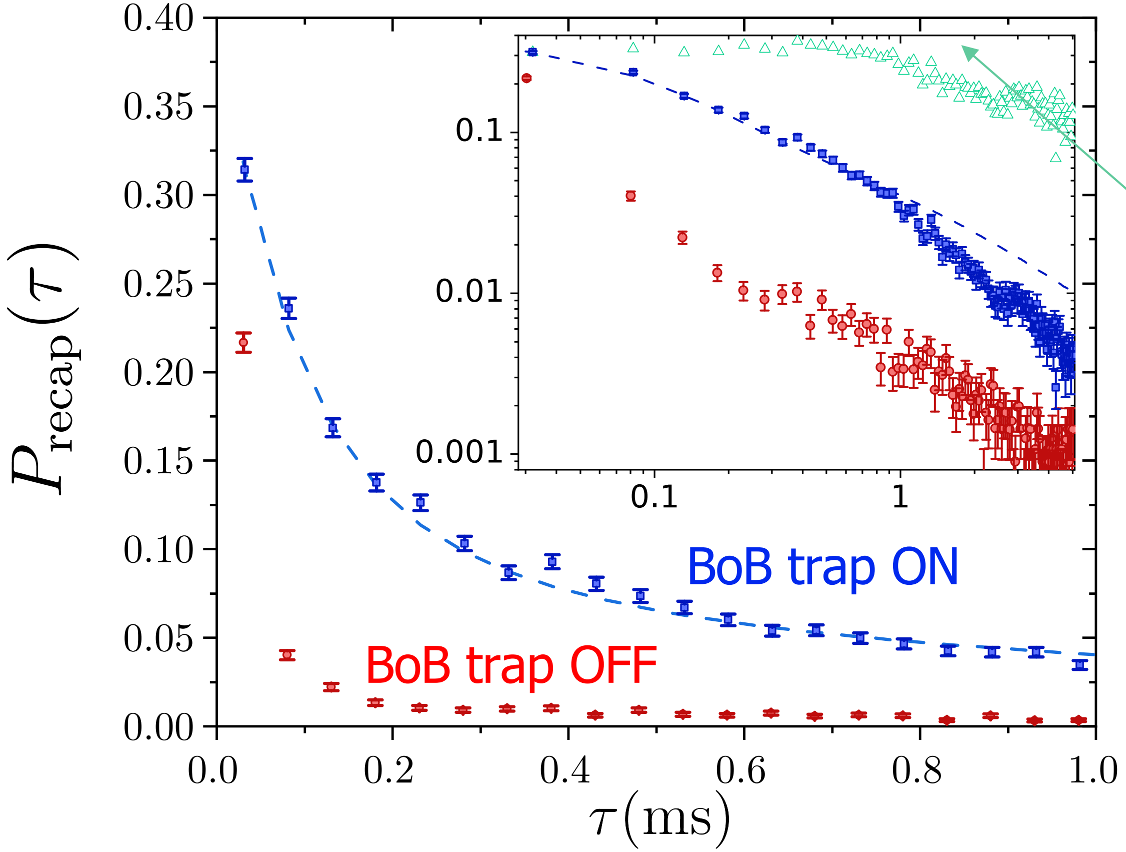
Only 52C trapped circular atoms are finally recaptured and detected by fluorescence

Circular atom trapping

18 BOB array
20 mW per BOB







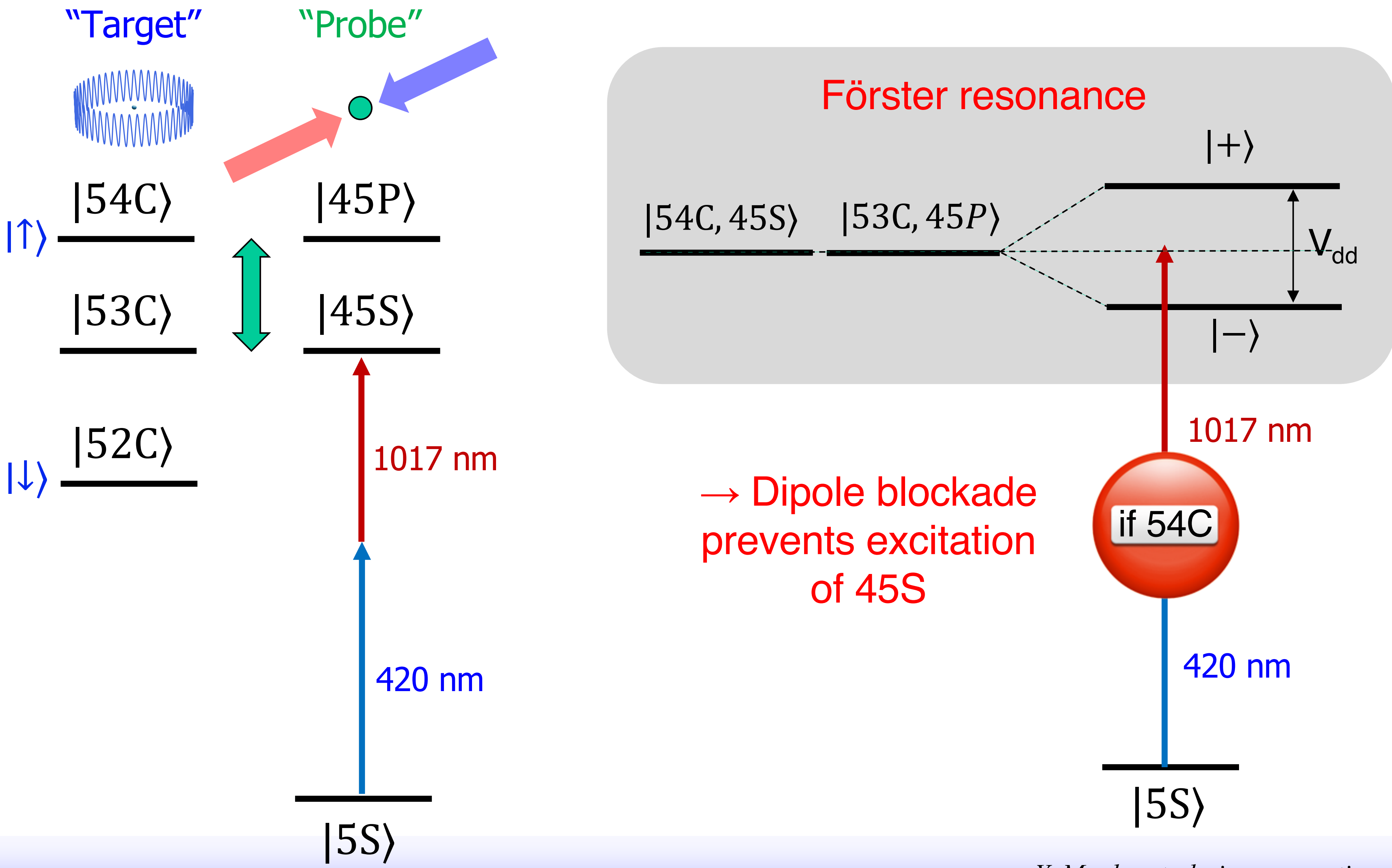
Lifetime corrected data

Blackbody-limited lifetime
125 μs

➞ BB decay corrected
trapping lifetime ≃ 5 ms

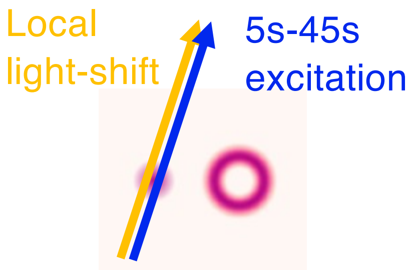
Optical QND detection of Circular atoms

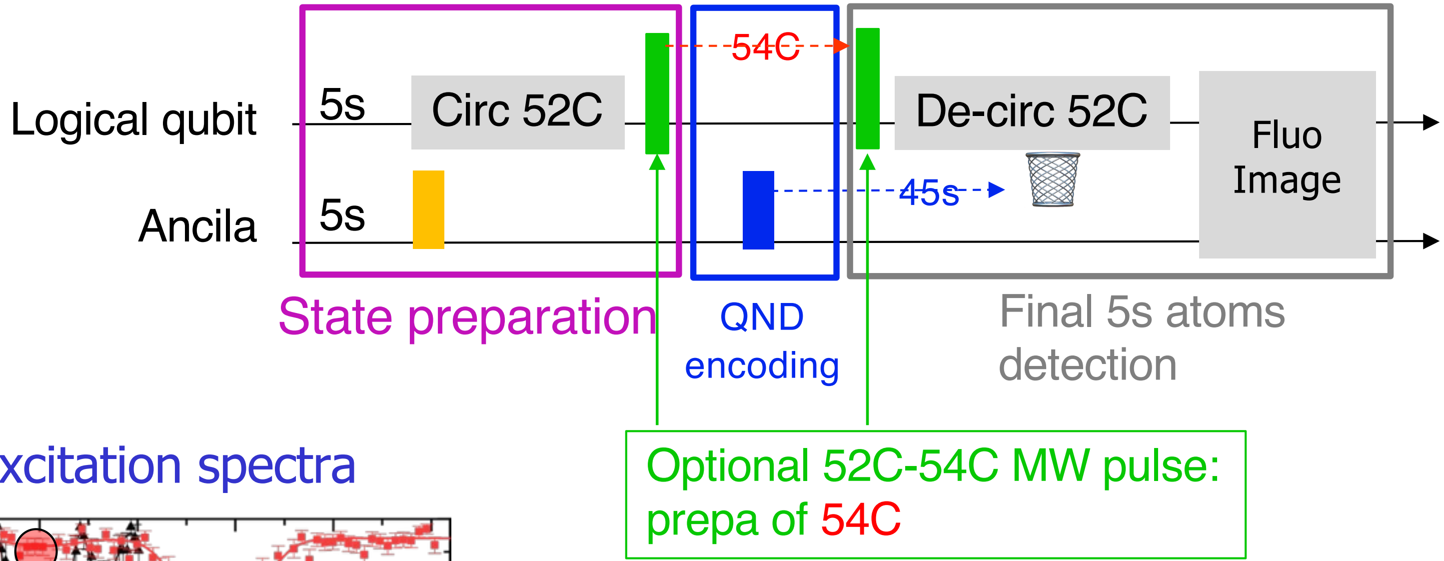
- **Principle**: use Förster resonance



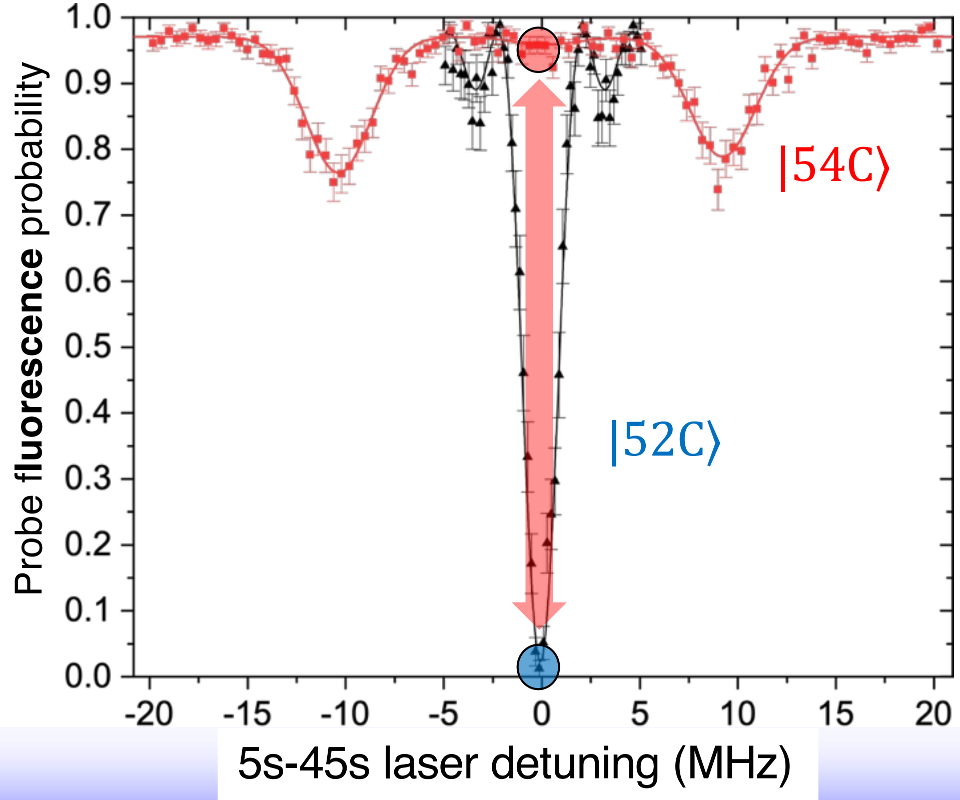
Y. Machu et al., in preparation

Probe excitation blockade observation





$|45S\rangle$ **probe** excitation spectra

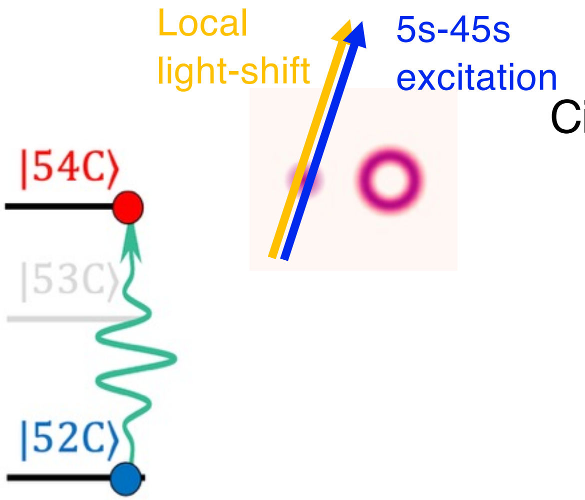


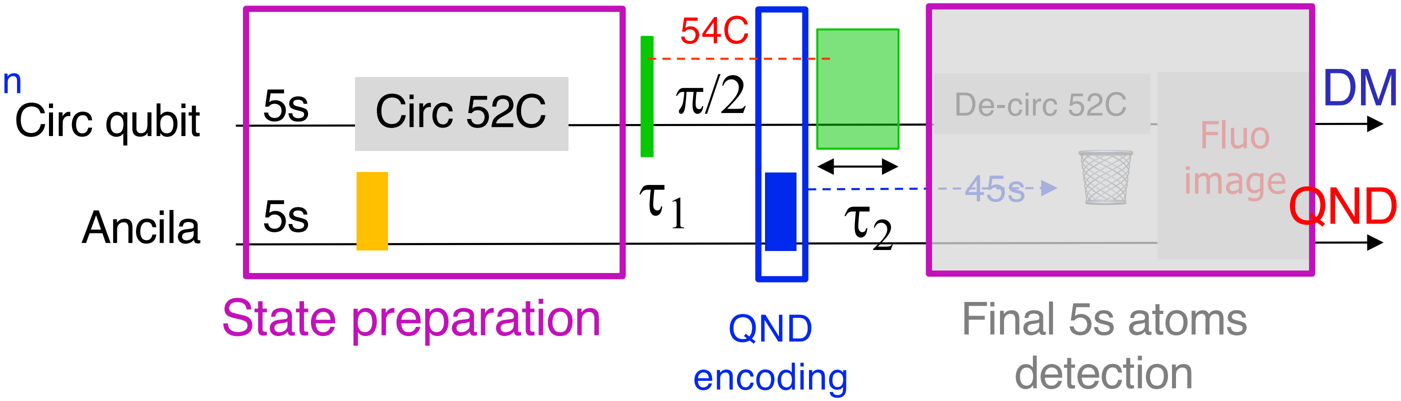
- 52C preparation: no Blockade, the probe disappears at resonance
- 54C preparation: blockade, the probe remains in 5s and is detected
  The circular atom is still there

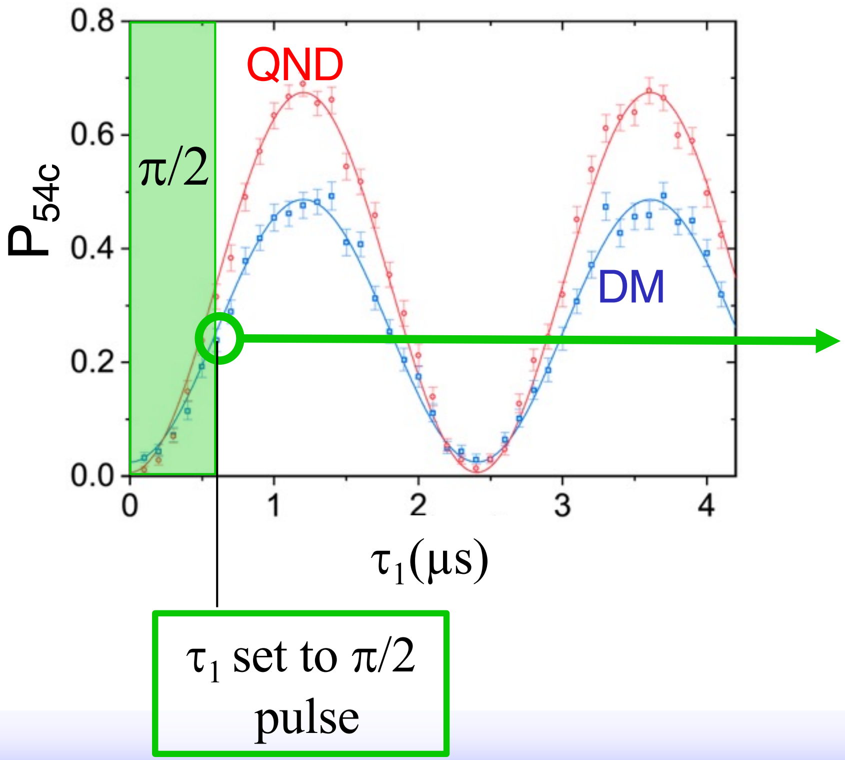
→ **QND** detection of 52C-54C with 97-96% fidelity

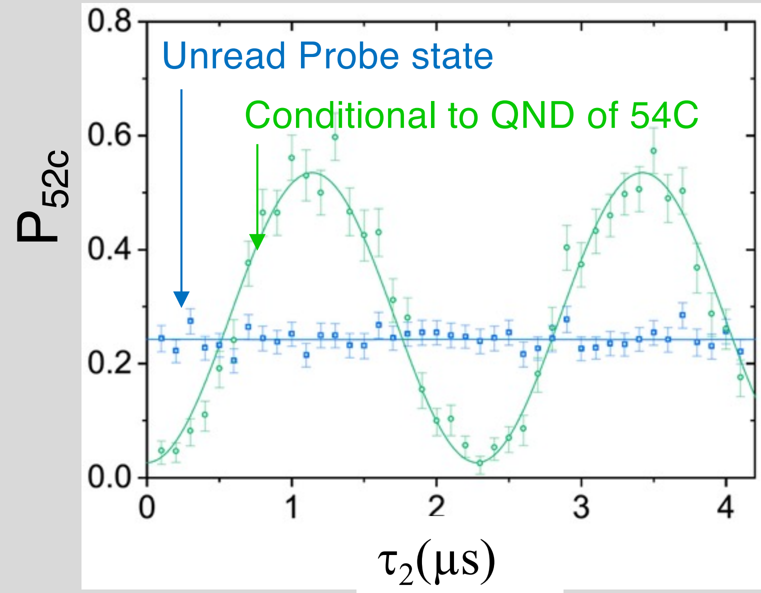
Y. Machu et al., arXiv:2509.24691

Rabi oscillation QND detection









Unread prob: circ qubit in a statistical mixture

→ No Rabi oscillations

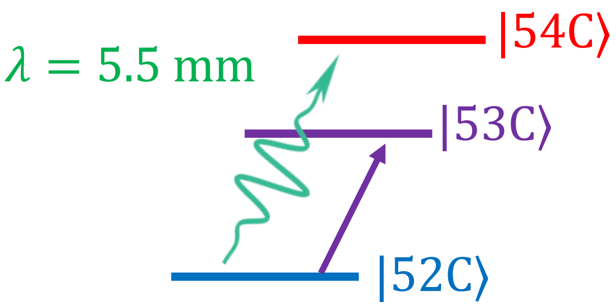
Probe detection projects circ qubit on 54C

→Rabi oscillation starts again

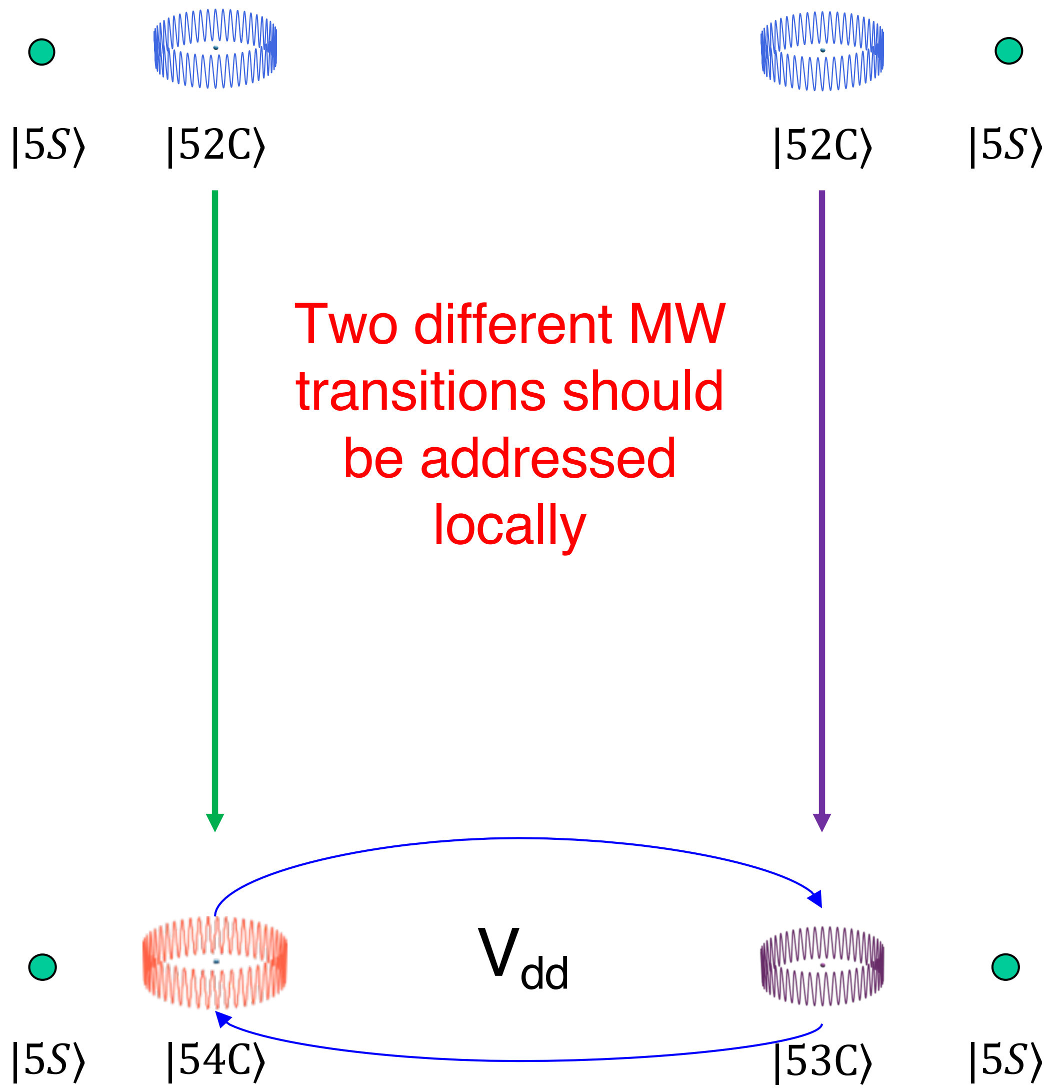
Y. Machu et al., in preparation

Observing exchange between two circular atoms

Initial state: $|52C\rangle \otimes |52C\rangle$



Target state: $|54C\rangle \otimes |53C\rangle$



Observing exchange between two circular atoms

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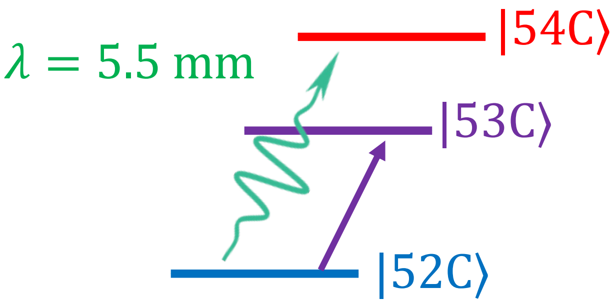
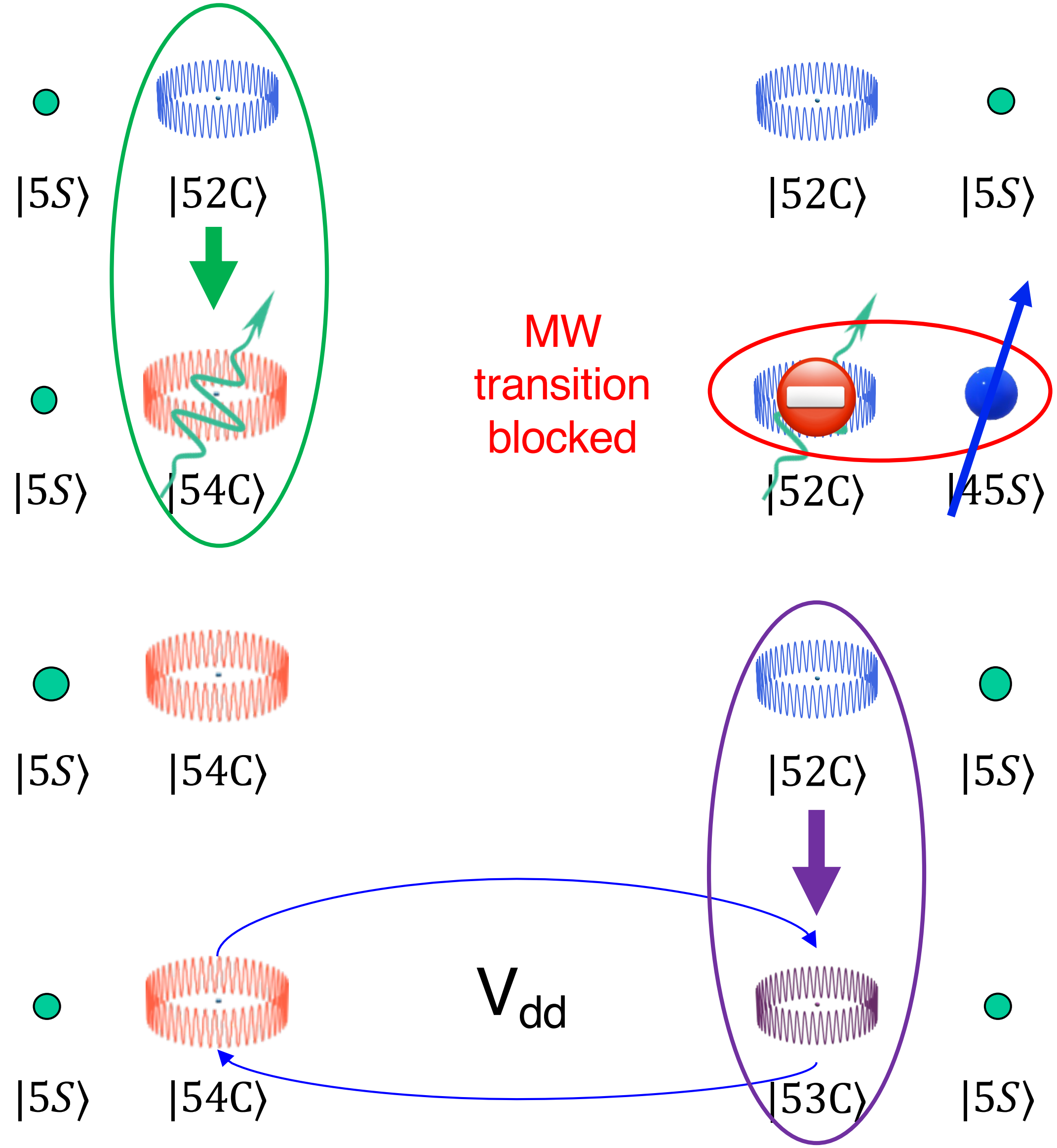
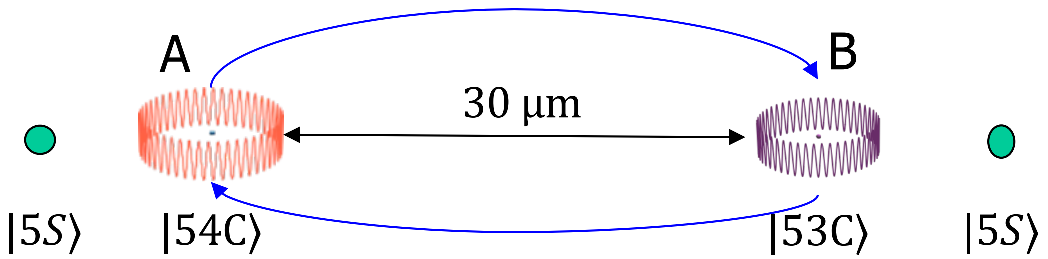


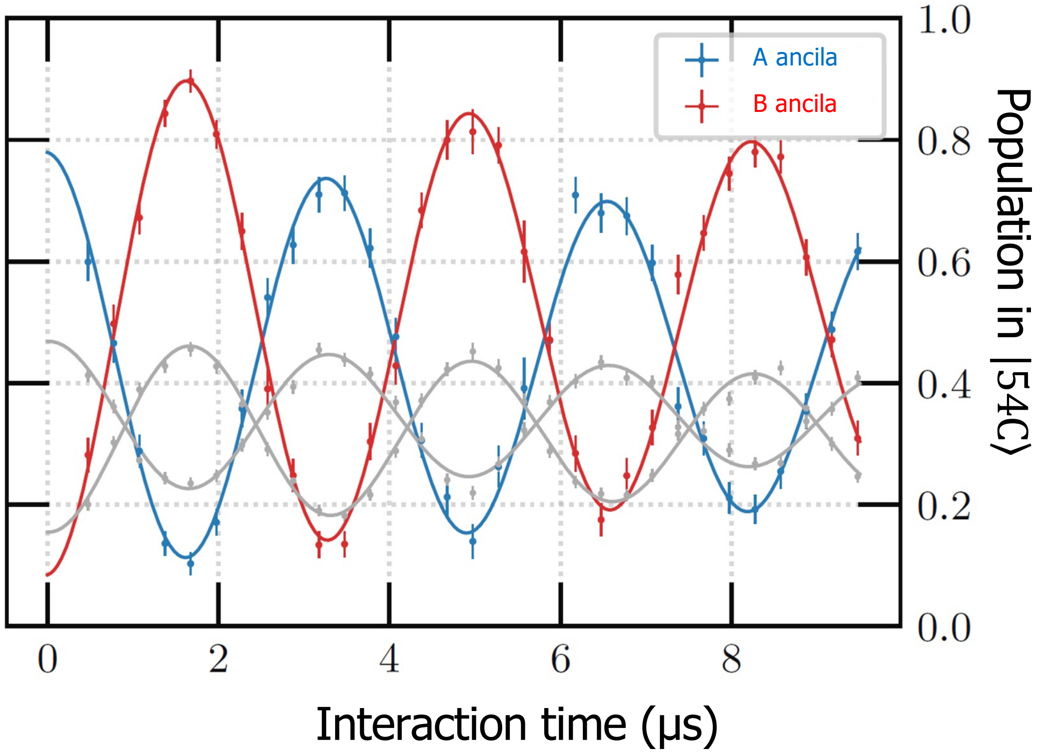
Target state: $|54C\rangle \otimes |53C\rangle$



Target state prepared with two ancilae for QND measurement of circular atoms

Flip-flop oscillations

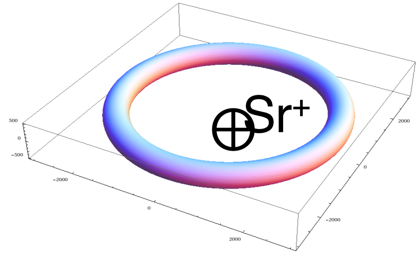


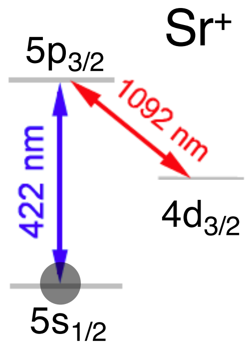


- Flip-flop oscillations at $\Omega/2\pi = 303(2)\text{kHz}$
- Post-selection used: presence of the two circular state heralded by "erasure measurement"

Circular Rydberg atoms of Strontium

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





Léa Lachaud
Baptiste Muraz
Matis pépin

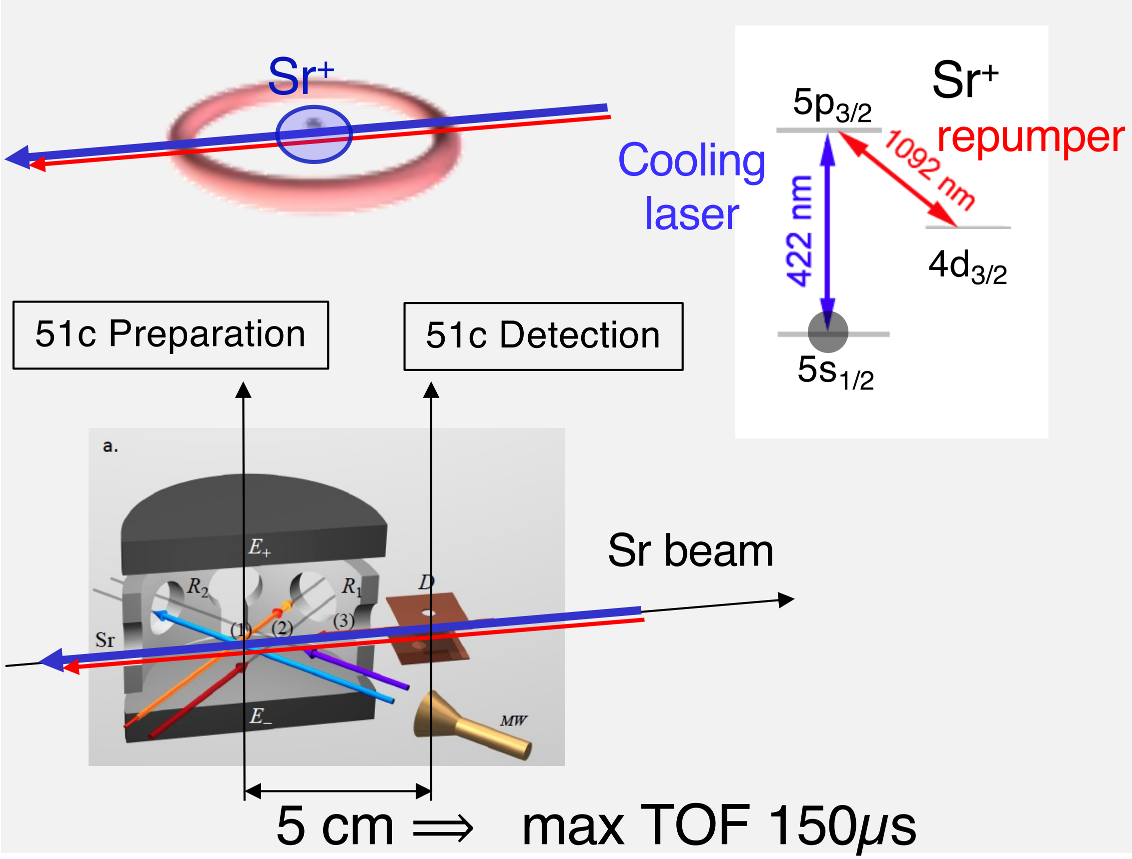
Jean-Michel Raimond
MB

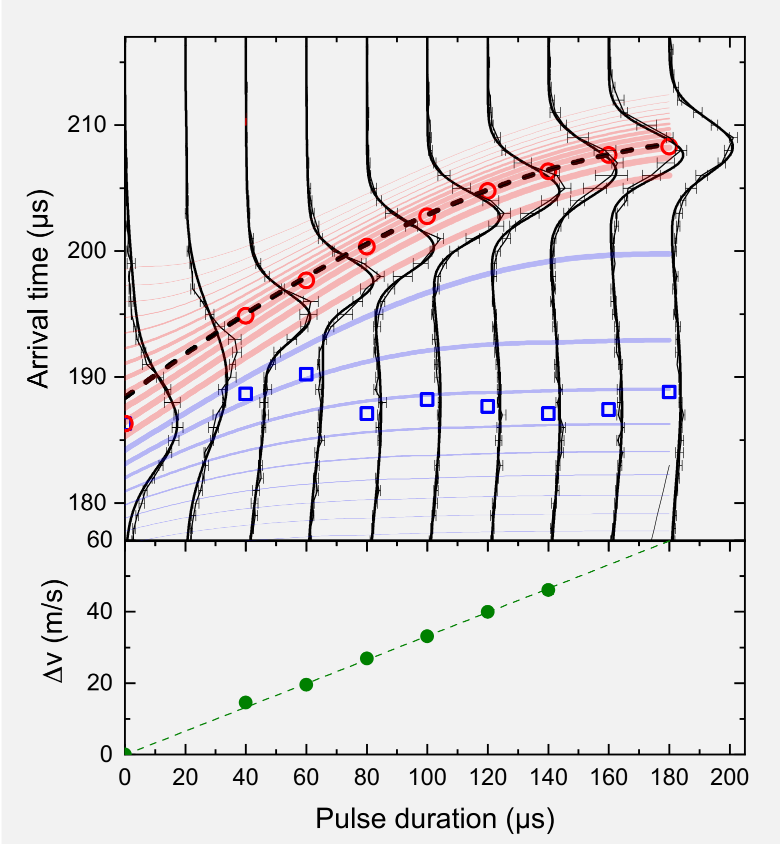
- *RC Teixeira et al. PRL. 125, 263001 (2020)*
Preparation of Long-Lived, Non-Autoionizing Circular Rydberg States of Strontium
- *Nature Physics, **18**, 502 (2022)*
Optical coherent manipulation of alkaline-earth circular Rydberg states
- *MW spectroscopy of Stark levels of Sr, in preparation*
- *L.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

Laser cooling of a Sr atomic beam

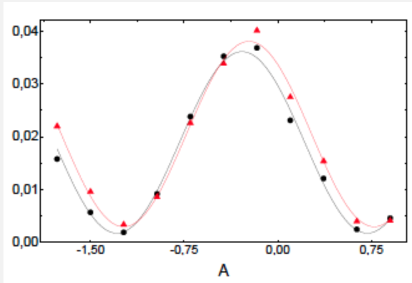
L. Lachaud et al. arXiv:2406.01396

Circular Sr atom cooling using ionic core transition



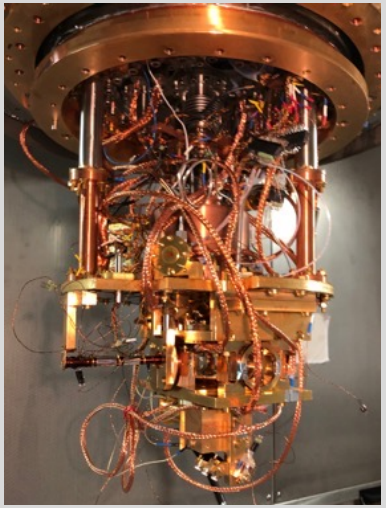


- with slowing lasers, 51C atoms are detected later
  $\Delta V = 40$ m/s, 4000 scattered photons
- Negligible decoherence

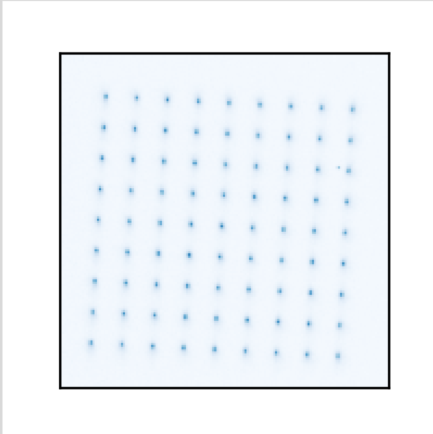


Ramsey fringes on the 51c-49c transition

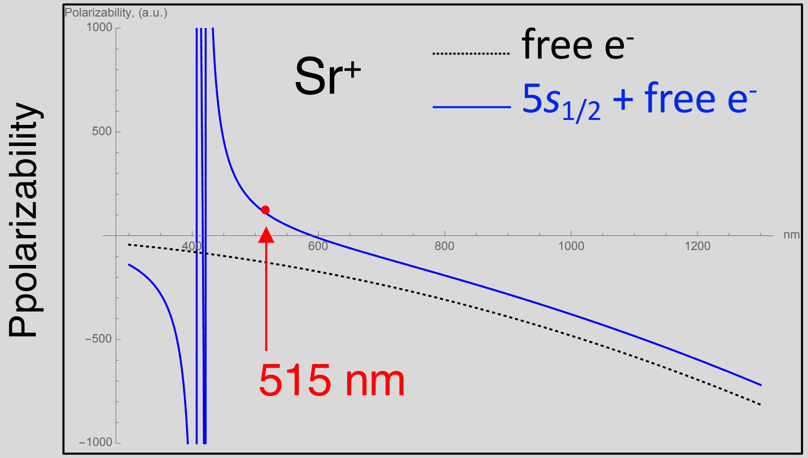
Trapped Sr circular atoms at 4K



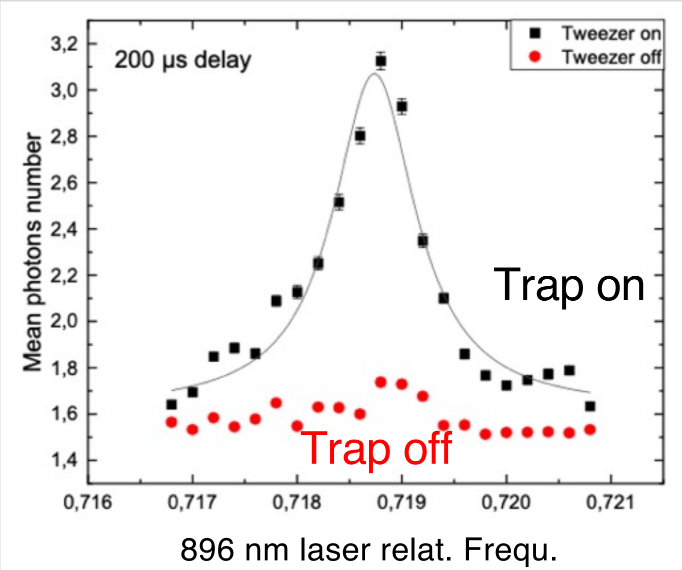
Cryogenic setup

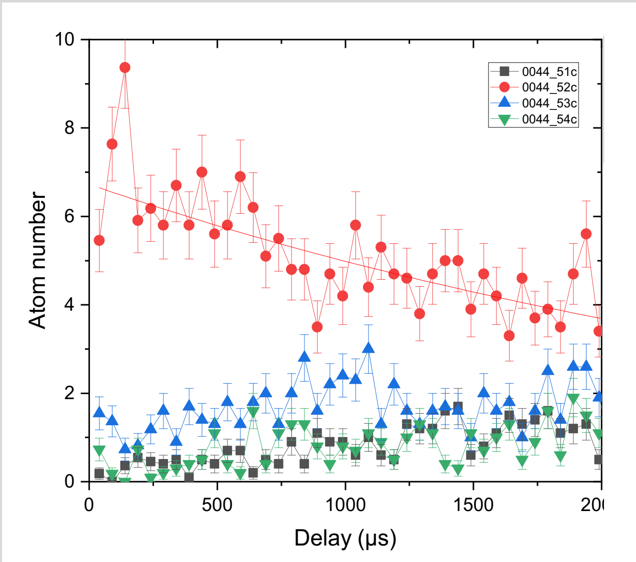


Single Sr atom array



Trapping laser wavelength



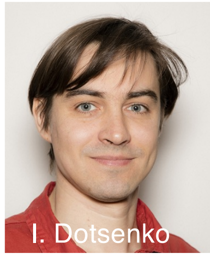


Estimated lifetime
τ ~ 3 ms

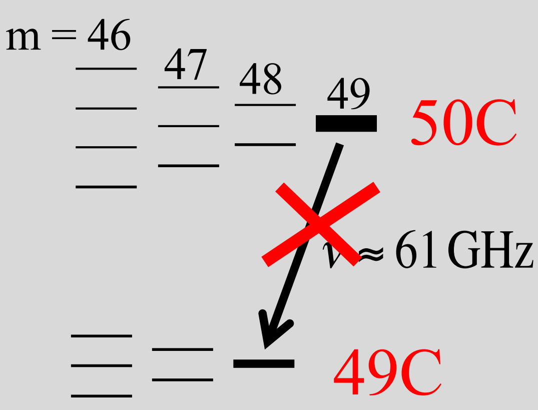
30 times better than
at room-temperature

515 nm laser rapping of Sr circular atoms

Circular atoms living even longer: 1 minute?



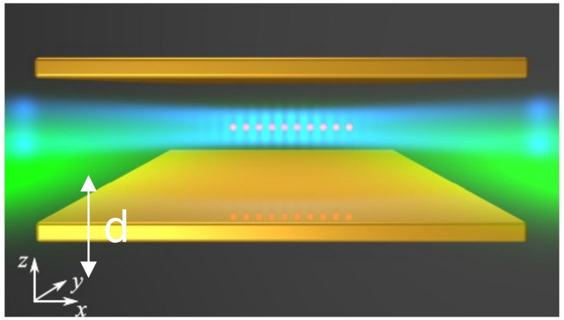
Now professor in Toulouse



Only one, MW, decay channel

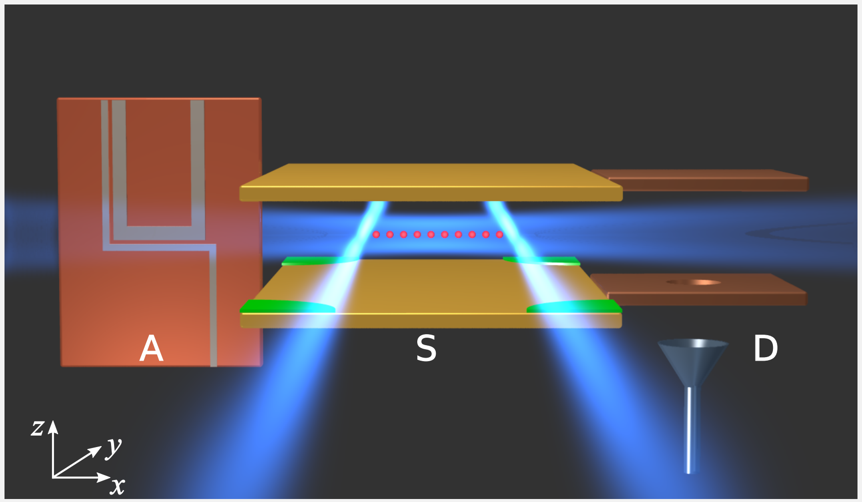
… Rubidium with even longer lifetime:
spontaneous emission inhibition

(D. Kleppner 1981)



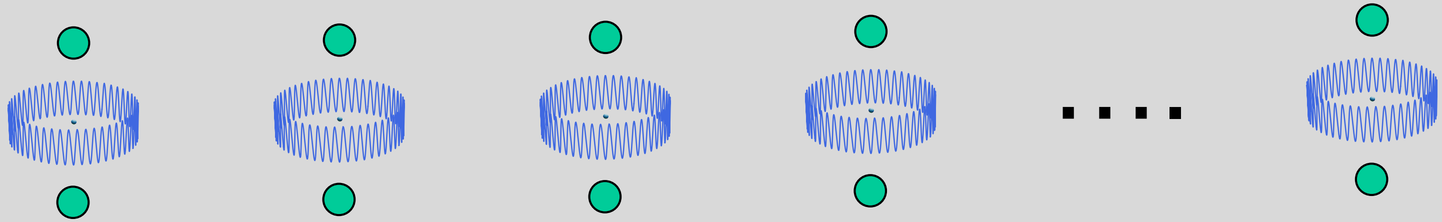
Atoms trapped between two planar electrode with d < $\lambda/2$

Lifetime **up to 1 min** !



Phys. Rev. X 8, 011032 (2018)

Next with rubidium circular atoms?

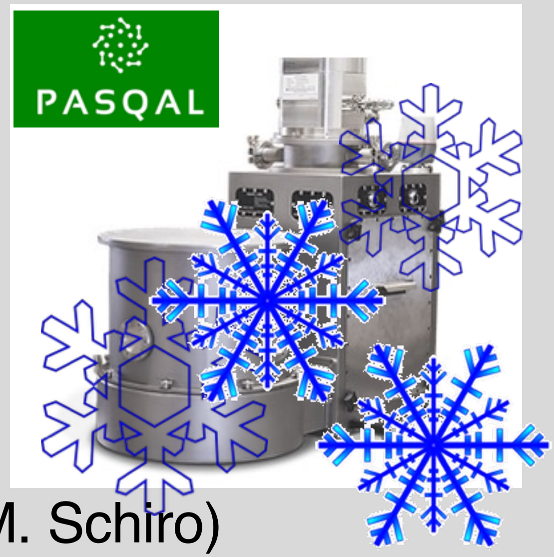


→ Quantum simulations of exchange Hamiltonian H_{XY} in a 10-100 atoms chain

→ use local probes for space/time correlation function measurement

- Observe propagation of excitation
- Effect of disorder, localization

Longer term: switch to cryogenic temperature



Circular atom lifetime 100 μs → 10 ms

→ Observe long timescale dynamics

- Spin glasses
- Out of equilibrium dynamics, quench,
- Slow thermalization
- Measurement induced phase transitions (collab M. Schiro)

Rydberg Atom team at LKB

Rubidium team

C. Sayrin

Yohann Machu (PASQAL)

Andrés Durán Hernández

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