Interacting Laser-Trapped Circular Rydberg Atoms

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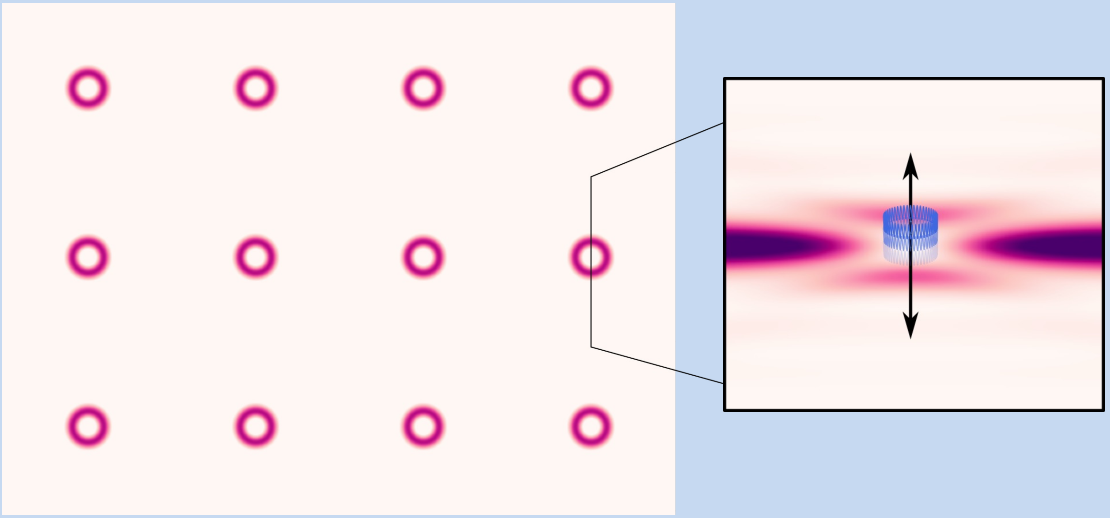
April 05, 2024



Circular Rydberg atoms

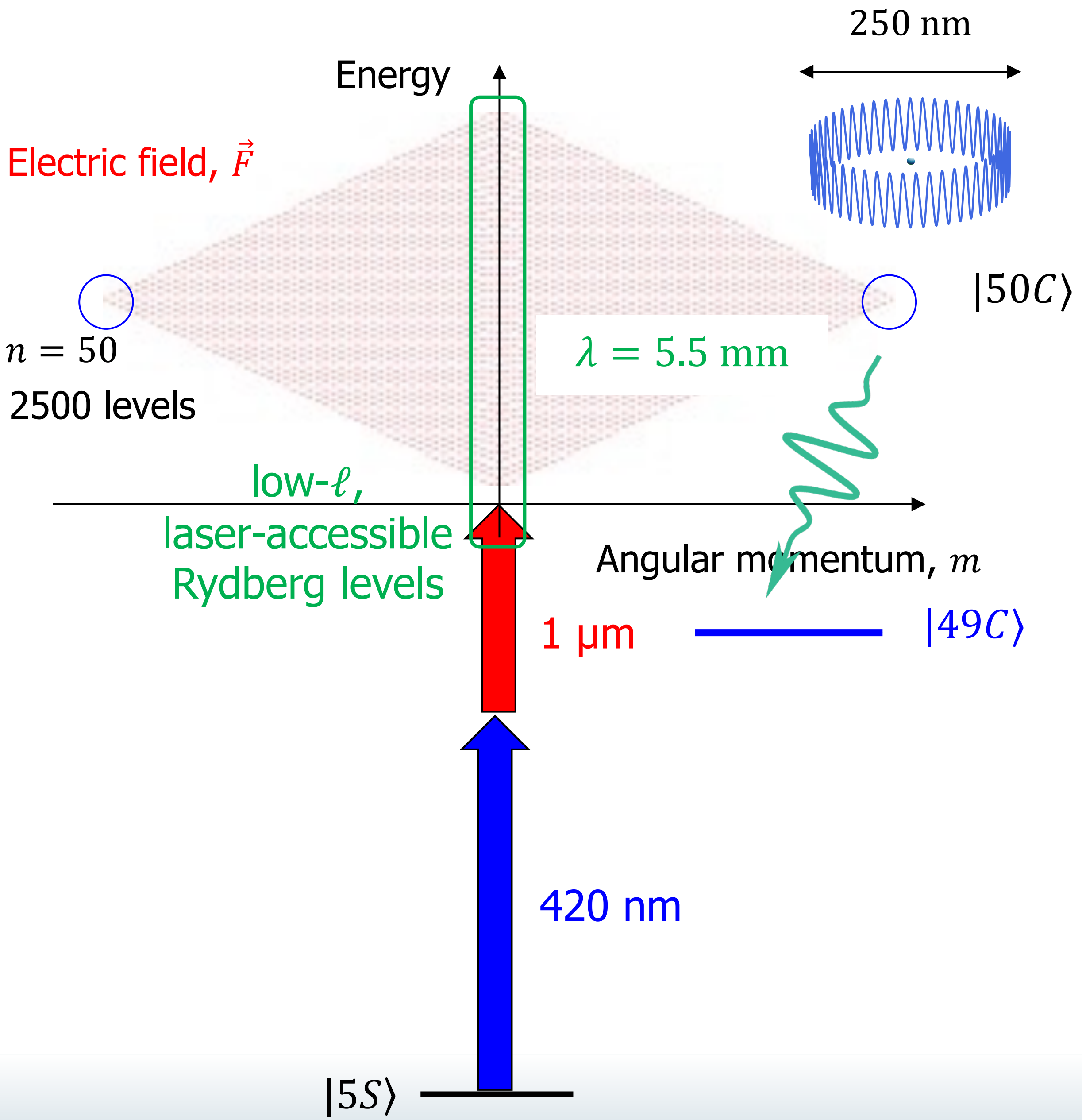
- High principal quantum number: $n \gg 1$
- Circular Rydberg levels:
  maximum angular momentum $\ell = |m| = n - 1$
- Giant hydrogenoid atoms: size $\sim n^2 a_0$

Large electric polarizability

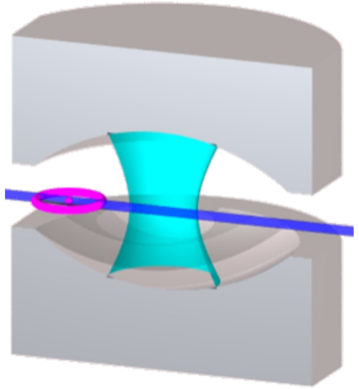
- Strong coupling to DC or RF/MW fields
- Strong dipole-dipole interactions between two Rydberg atoms

Long natural lifetimes ($n{\sim}50$)

- Low-ℓ levels, $\tau \propto n^3 \sim 200\ \mu\mathrm{s}$: optical transitions
- Circular levels, $\tau \propto n^5 \sim 30\ \mathrm{ms}$: MW transition



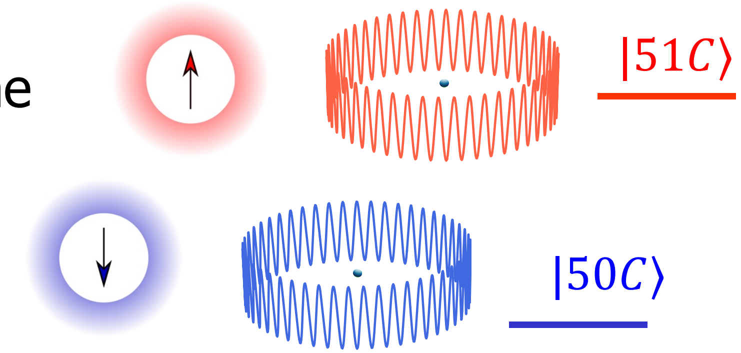
Strong coupling to electromagnetic fields



- Cavity-QED experiments in the strong coupling regime

  Individual circular Rydberg atoms interacting with a microwave cavity mode

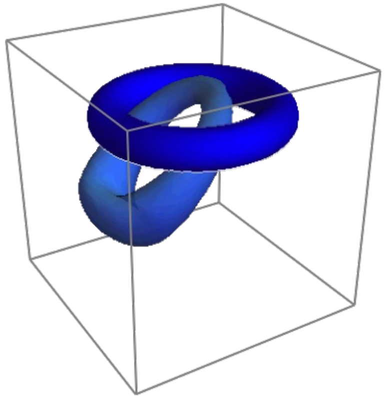
  S. Haroche, RMP **85**, 1083 (2013)



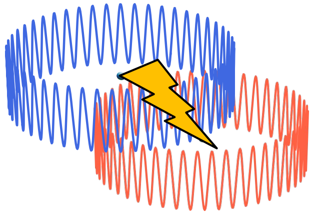
- Electro-magnetometry with circular Rydberg atoms

  A. Facon et al., Nature **535**, 7611 (2016)

  E. Dietsche et al., Nat. Phys. **15**, 326 (2019)



… but no interactions so far



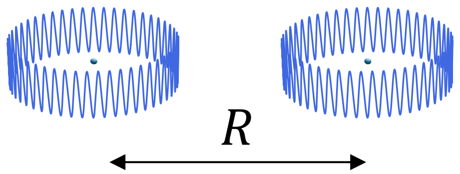
Interactions between circular Rydberg atoms

second-order
van der Waals interaction

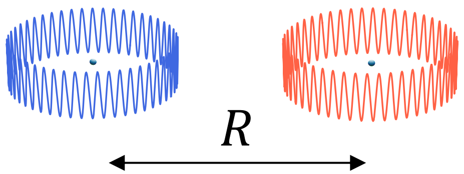
first-order dipole-dipole or
second-order vdW interaction

$J_z \sigma_1^z \sigma_2^z$

Ising interaction



$E \propto 1/R^6$



$\Delta n = 1 \Rightarrow E \propto 1/R^3$ **XX Hamiltonian**

$\Delta n = 2 \Rightarrow E \propto 1/R^6$ **XXZ Hamiltonian**

$J\left(\sigma_1^x \sigma_2^x + \sigma_1^y \sigma_2^y\right)$

Spin-exchange interaction

Simulated Hamiltonian

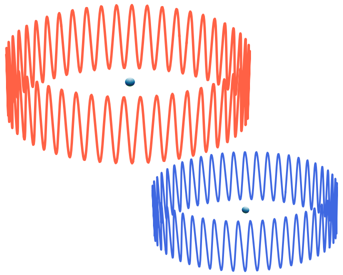
$$H_0 + H_{\text{ext}} = \frac{h\Delta}{2}\sigma^z + \frac{h\Omega}{2}\sigma^x + J_z \sigma_1^z \sigma_2^z + J\left(\sigma_1^x \sigma_2^x + \sigma_1^y \sigma_2^y\right)$$

Fictitious magnetic fields — Ising interaction — Spin-exchange interaction

Quantum simulation with circular Rydberg atoms

- Long lifetime, τ
  100-fold improvement w.r.t. low-ℓ levels
- Large interaction frequencies, Ω
  equivalent to low-ℓ levels

→ 100-fold improvement in figure of merit: $\Omega \times \tau \gg 1$
~ # observable interaction cycles

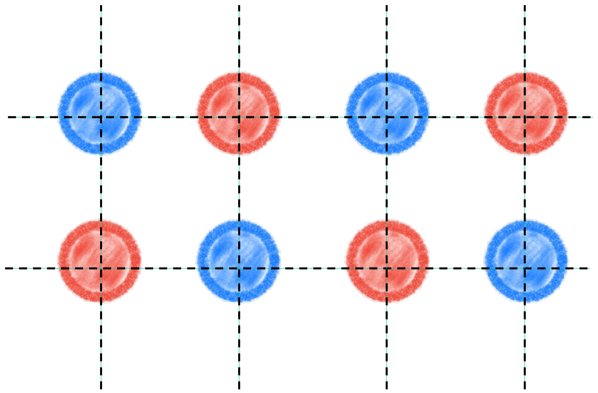


Limitations in computation time

- Laser-accessible, low-ℓ Rydberg levels

→ 100-atom simulator:
an atom is lost within ~1μs

- Rydberg atoms are not trapped
- With $\Omega/2\pi$ in the 1–10 MHz range,
  a few interaction cycles can be observed



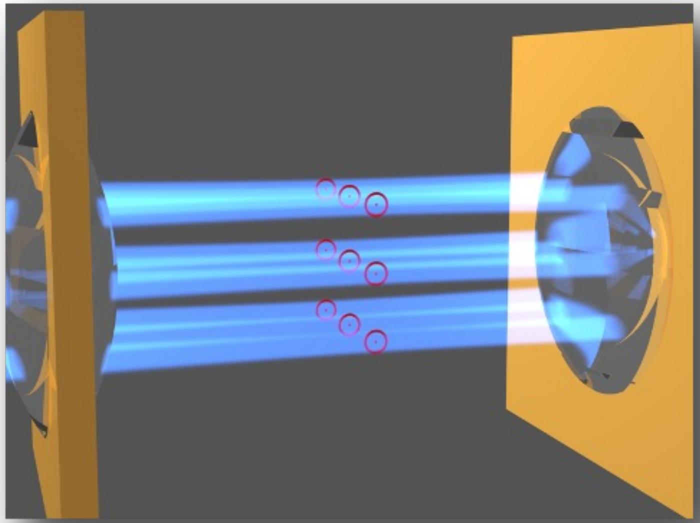
Circular Rydberg atoms?

- Improved adiabaticity
- Simulation of quantum dynamics
  - Propagation of excitation/correlations
  - Slow phenomena, e.g. thermalization

Outline

New experimental platform

- Array of laser-trapped individual circular Rydberg atoms



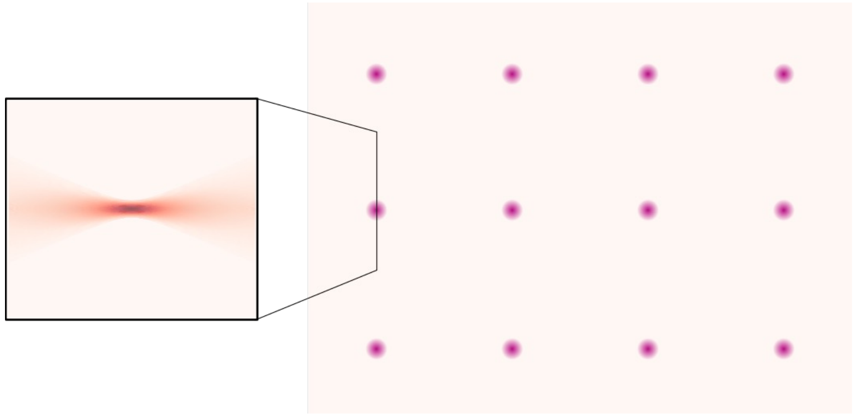
Dipole-dipole interactions

- Measurement of the first-order dipole-dipole interactions between circular Rydberg atoms

Detection and control

- Spatial and level-selective manipulation and detection of circular Rydberg atoms

Laser-trapping of circular Rydberg atoms

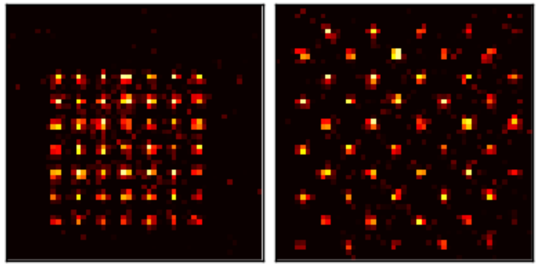


Optical tweezers

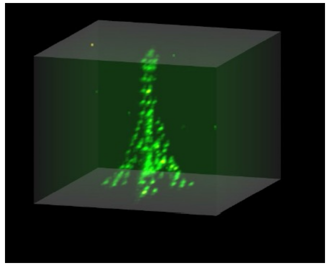
- Tightly-focused Gaussian beams
- Collisional blockade regime

- Arbitrary, defect-free arrays of laser-trapped ground-state atoms
- … but inefficient for Rydberg levels of alkali atoms

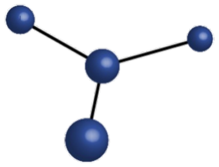
Endres et al., Science **354**, 1024–1027 (2016)



Barredo et al., Science **354**, 6315 (2016)



Barredo et al., Science **561**, 79 (2018)



M. Kim et al., PRX Q **1**, 020323 (2020)

Laser trapping of circular Rydberg atoms

Ponderomotive (repulsive) potential

S. K. Dutta… G. Raithel, PRL **84**, 5551 (2000)

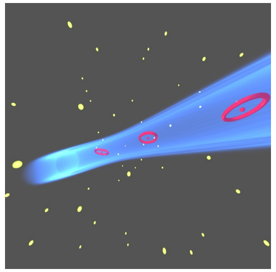
- Almost-free Rydberg electron repelled by light field
- Requires intensity minima
- Nearly state-insensitive traps
- Circular states: no photo-ionization!

Previous works

Circular levels, 2D trap

Laguerre-Gauss beam

R. Cortiñas *et al.*, PRL (2020)

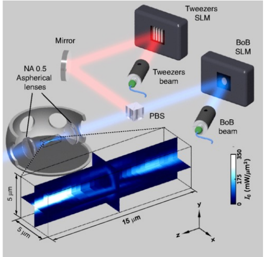


low-ℓ levels, 3D trap

"Bottle" beams

D. Barredo… A. Browaeys, T. Lahaye, PRL (2020)

+ T. M. Graham… M. Saffman, PRL (2020)

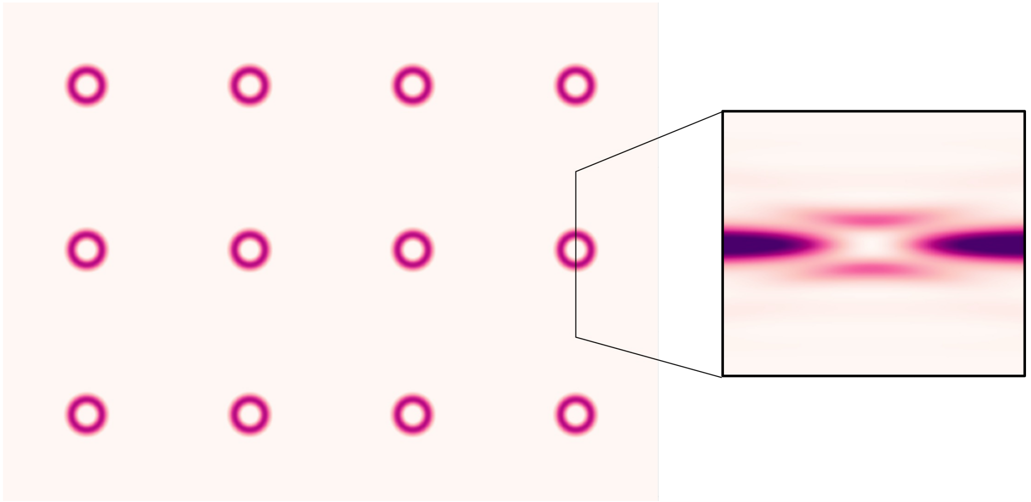


Regular array of circular Rydberg atoms

A repulsive trap for Rydberg atoms

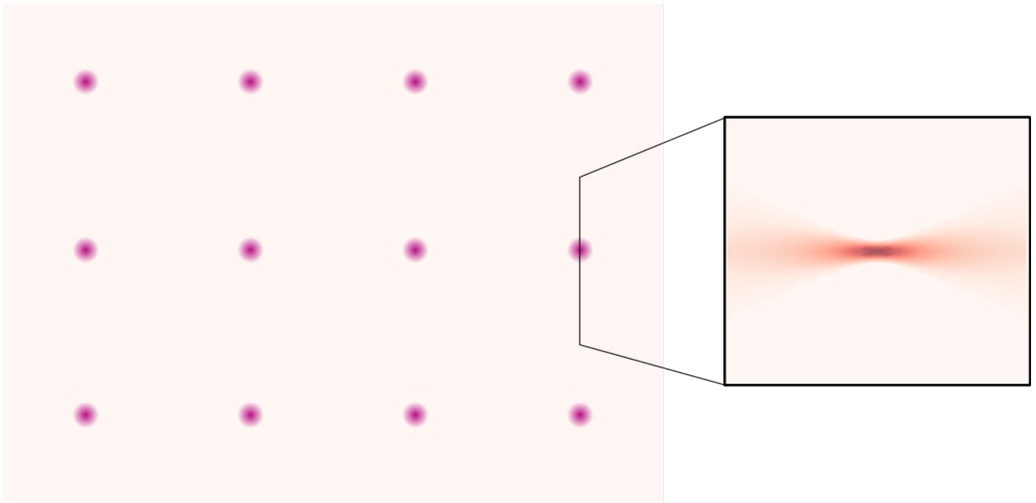
- 3D trap is required: optical bottle beams
- IOGS experiment: 3D trapping of low-ℓ Rydberg levels

D. Barredo… A. Browaeys, T. Lahaye, PRL (2020)



An attractive trap for ground-state atoms

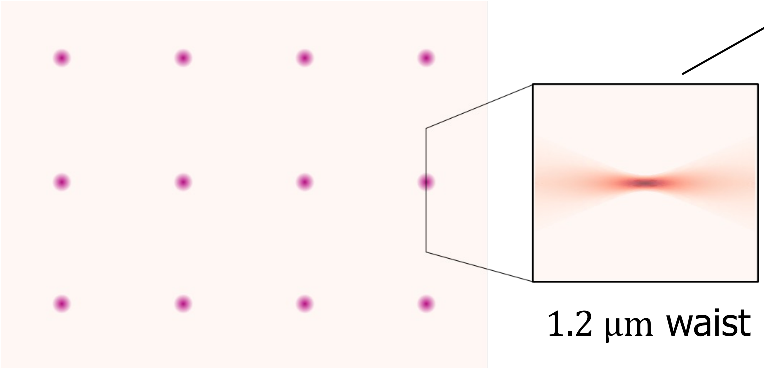
- Pre-order the atoms with arrays of optical tweezers
- Properly align the two arrays to excite Rydberg atoms in the bottle beams



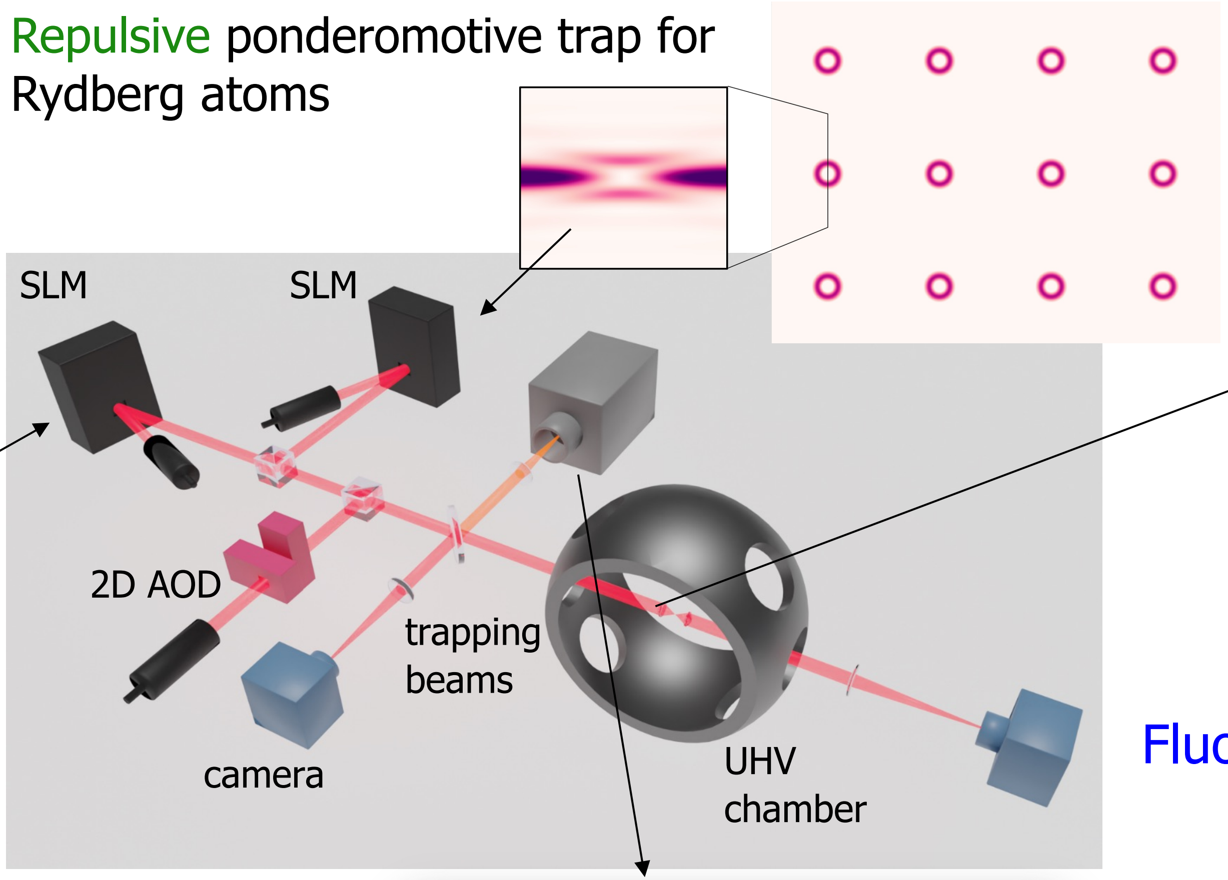
Experimental setup

Room-temperature setup

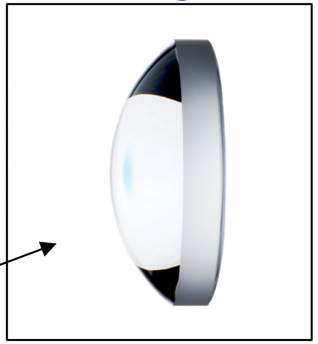
Attractive red-detuned dipole traps for ground-state atoms



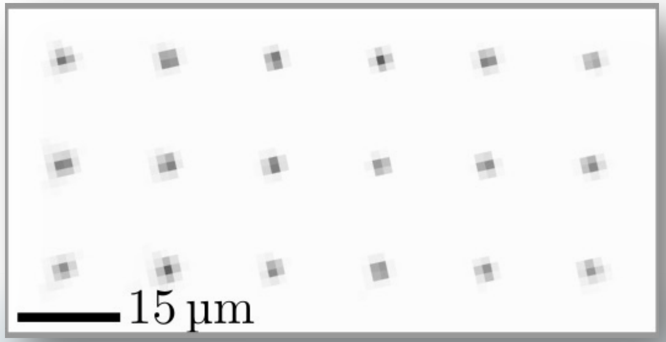
Repulsive ponderomotive trap for Rydberg atoms



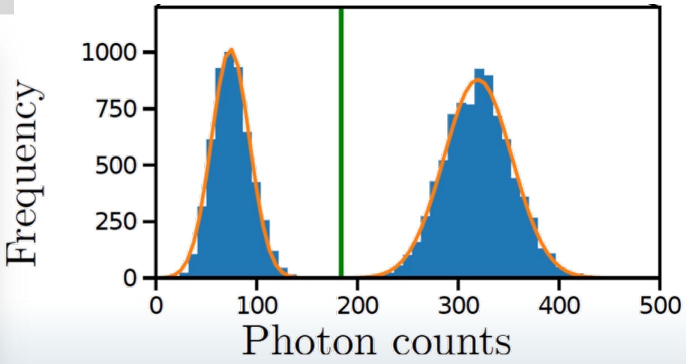
tightly focusing lens



- Spatial light modulator: trap engineering and aberration correction
  Y. Machu et al., filed patent (2023)
- Individual cold atoms in optical tweezers



Fluorescence imaging



Rydberg excitation and trapping

Ground state

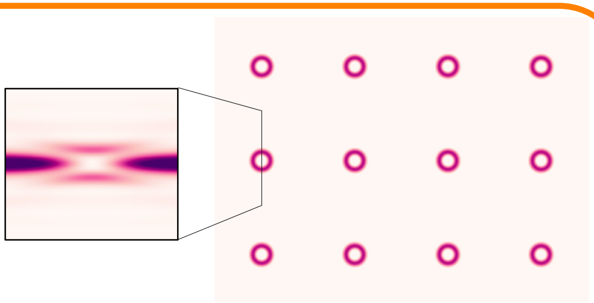
- Laser-cooling
- Fluorescence imaging

Rydberg excitation

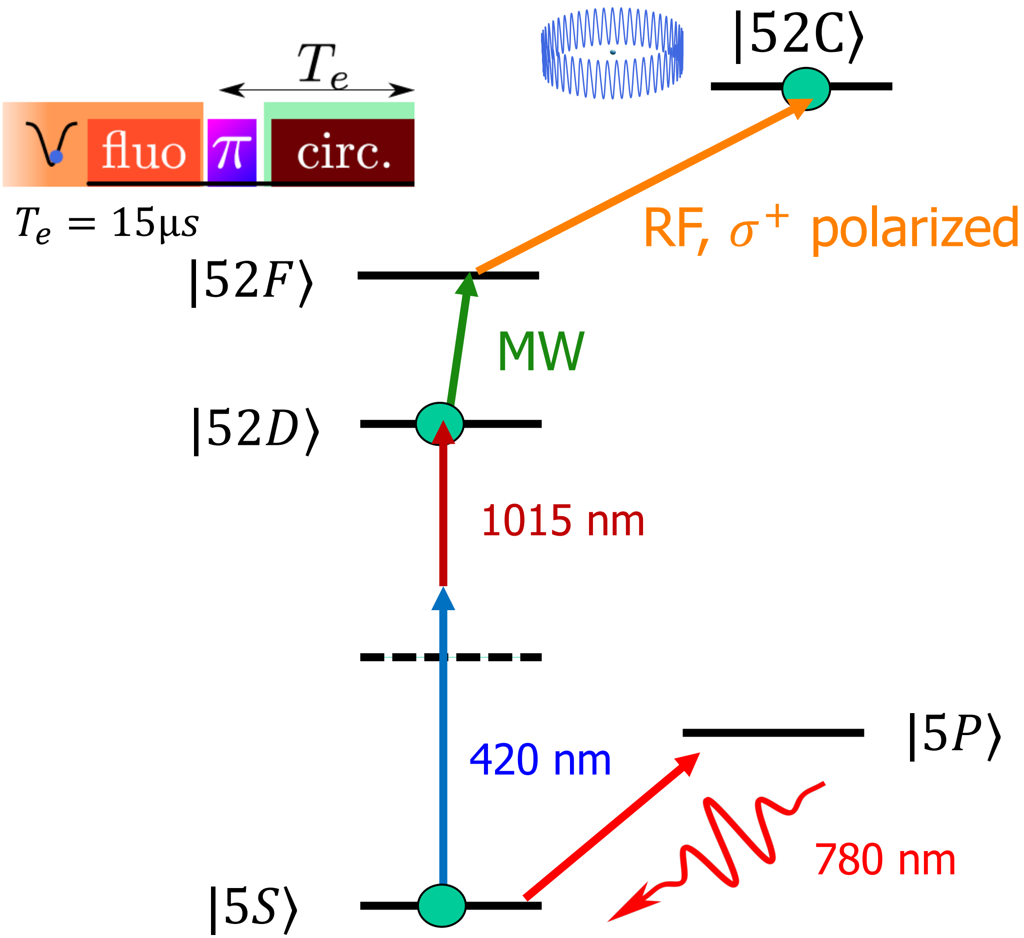
- 2-photon excitation to $52D$ Rydberg level

Circular state preparation

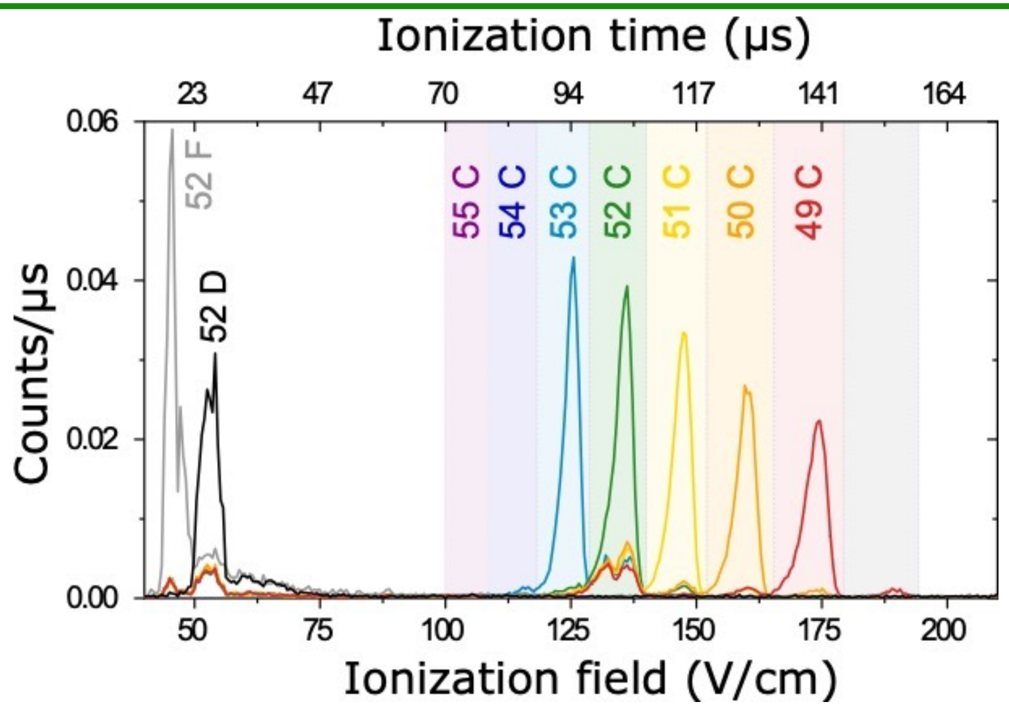
- Bottle beam traps
- MW + RF transitions
- No optical transition in circular state



Detection?



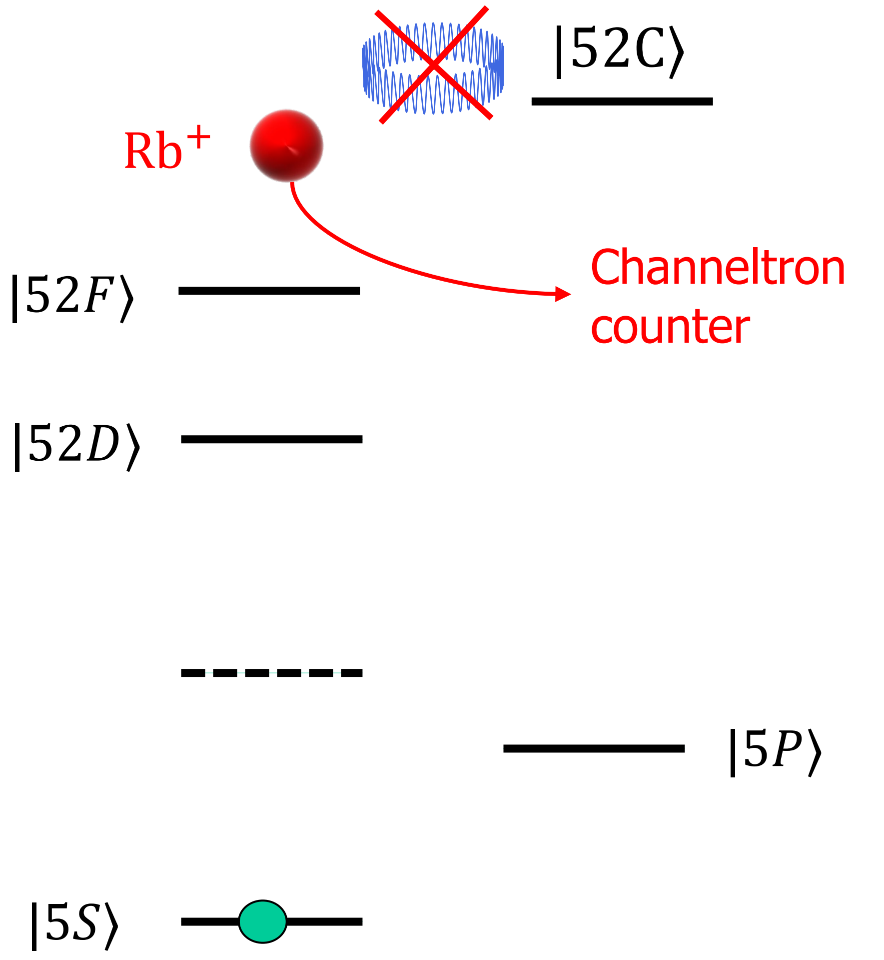
Circular state detection



T. Cantat-Moltrecht et al., PRR **2**, 022032(R) (2020)

- Strong electric field ionizes the circular Rydberg levels
- Rb ions detected by a channeltron

Field-ionization detection

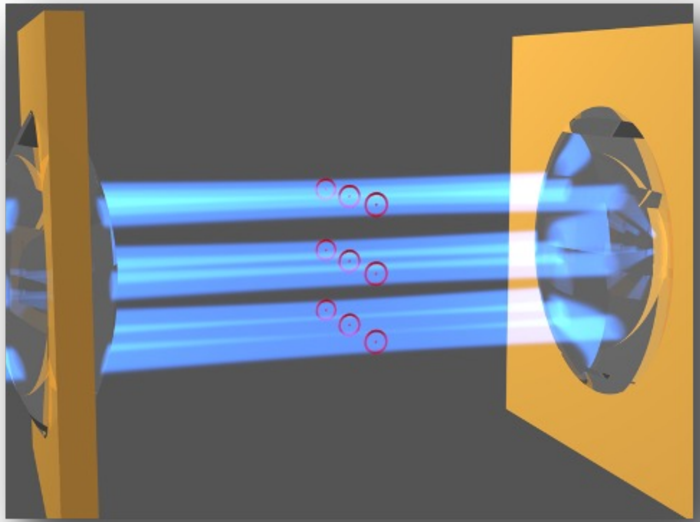


Level-selective, destructive measurement

Outline

New experimental platform

- Array of laser-trapped individual circular Rydberg atoms



Dipole-dipole interactions

- Measurement of the first-order dipole-dipole interactions between circular Rydberg atoms

Detection and control

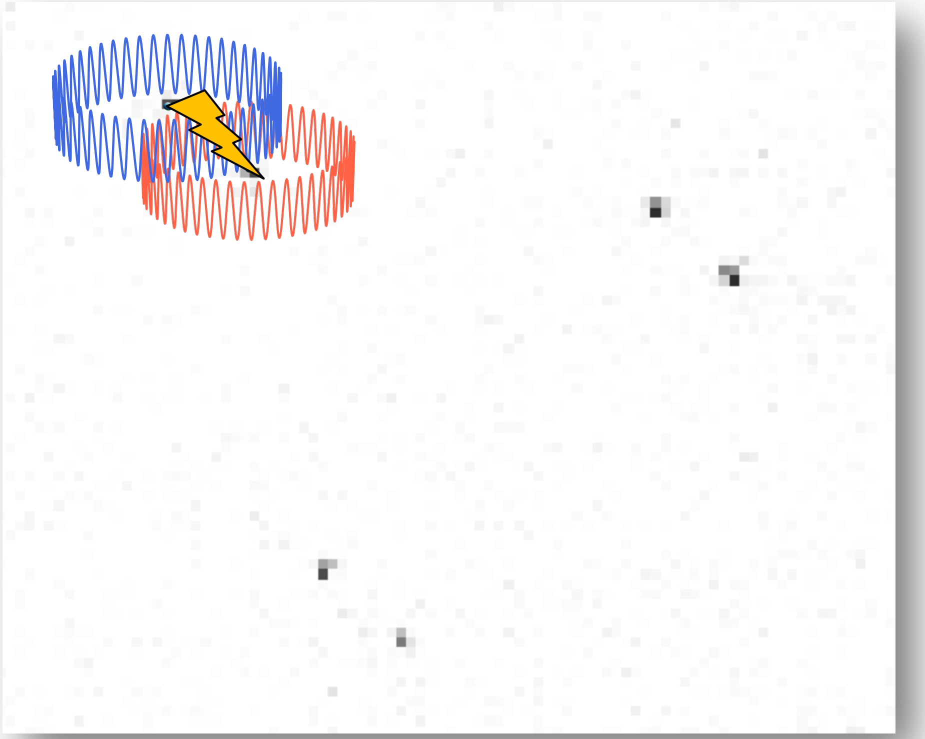
- Spatial and level-selective manipulation and detection of circular Rydberg atoms

Interacting circular Rydberg atoms

Probe the interaction between two atoms in circular states ?

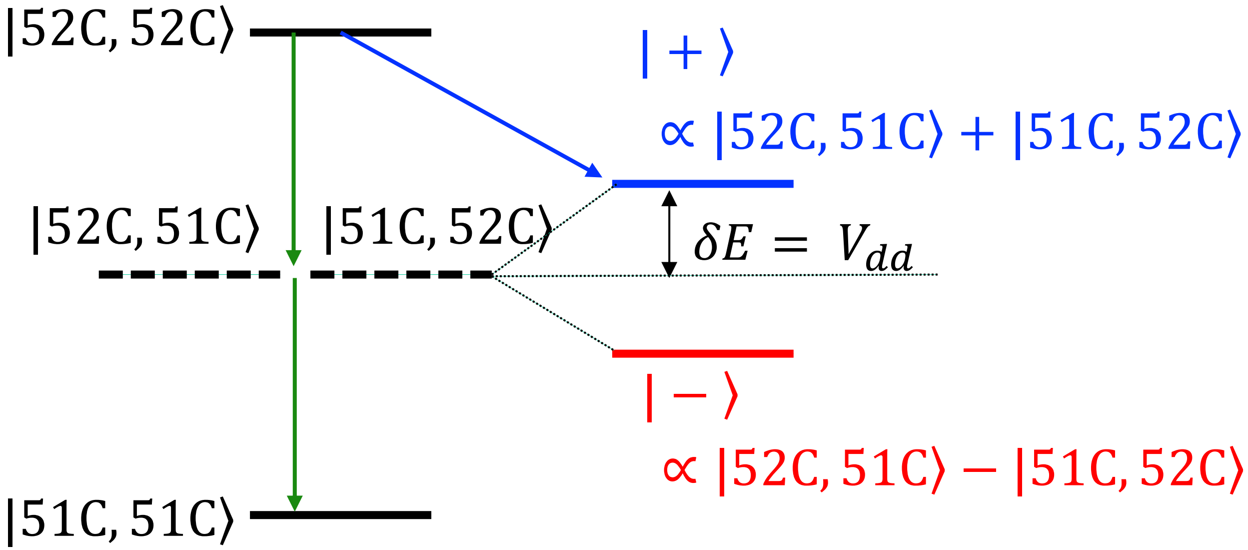
- Prepare array of pairs of atoms

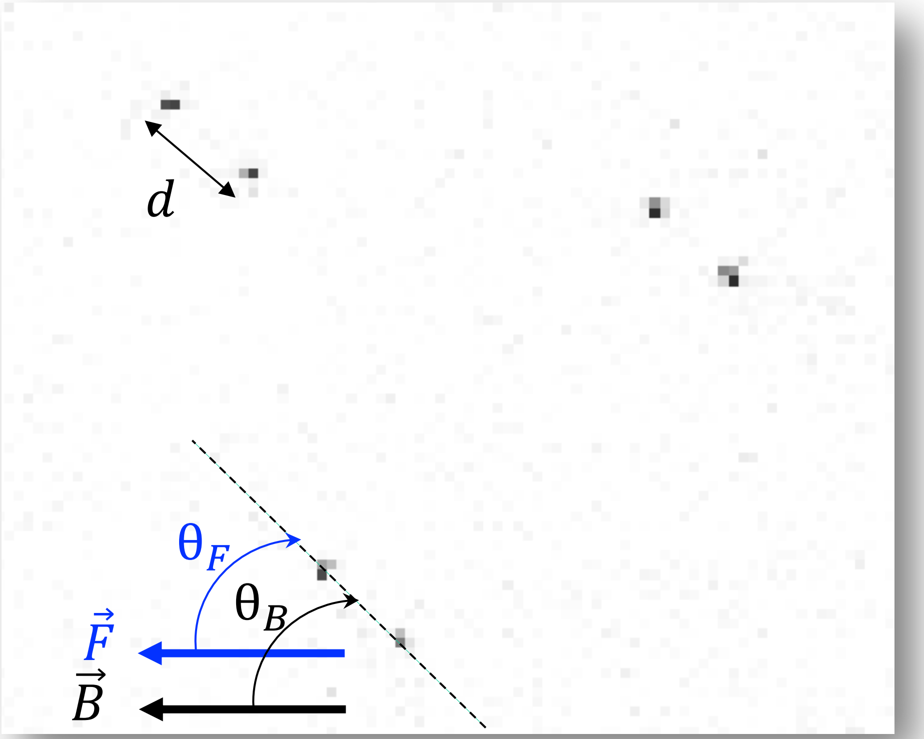
- Probe the "strong" dipole-dipole interaction between $|nC\rangle$ and $|(n+1)C\rangle$



Interacting circular Rydberg atoms

- Pairs of atoms prepared in $|52C, 52C\rangle$
- Microwave spectroscopy reveals pair interactions



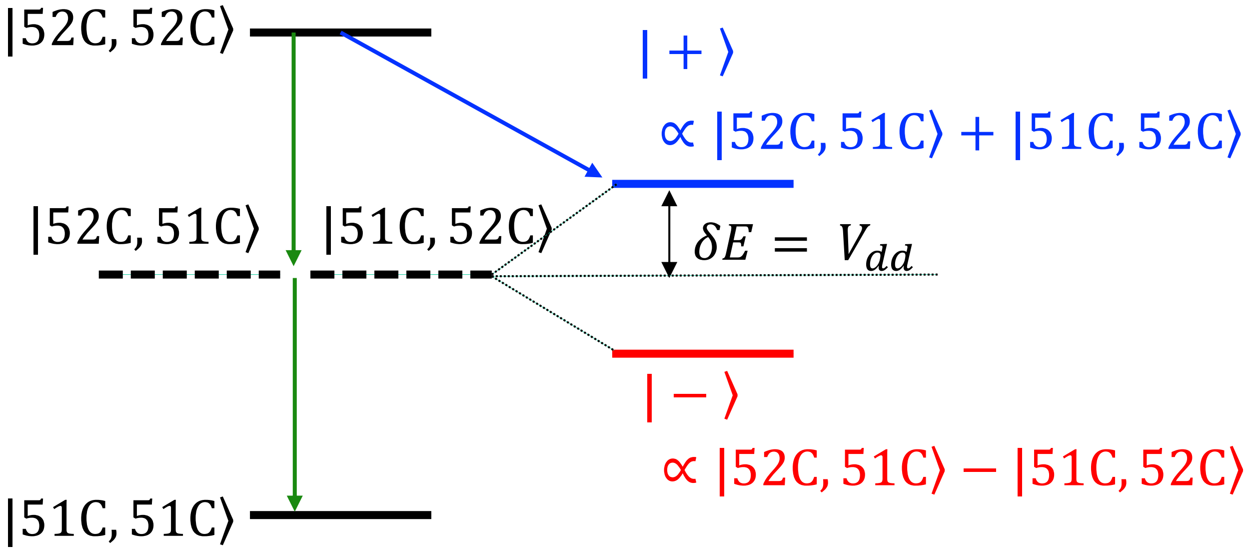


Starting configuration: $\theta_F = \theta_B$

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

Interacting circular Rydberg atoms

- Pairs of atoms prepared in $|52C, 52C\rangle$
- Microwave spectroscopy reveals pair interactions



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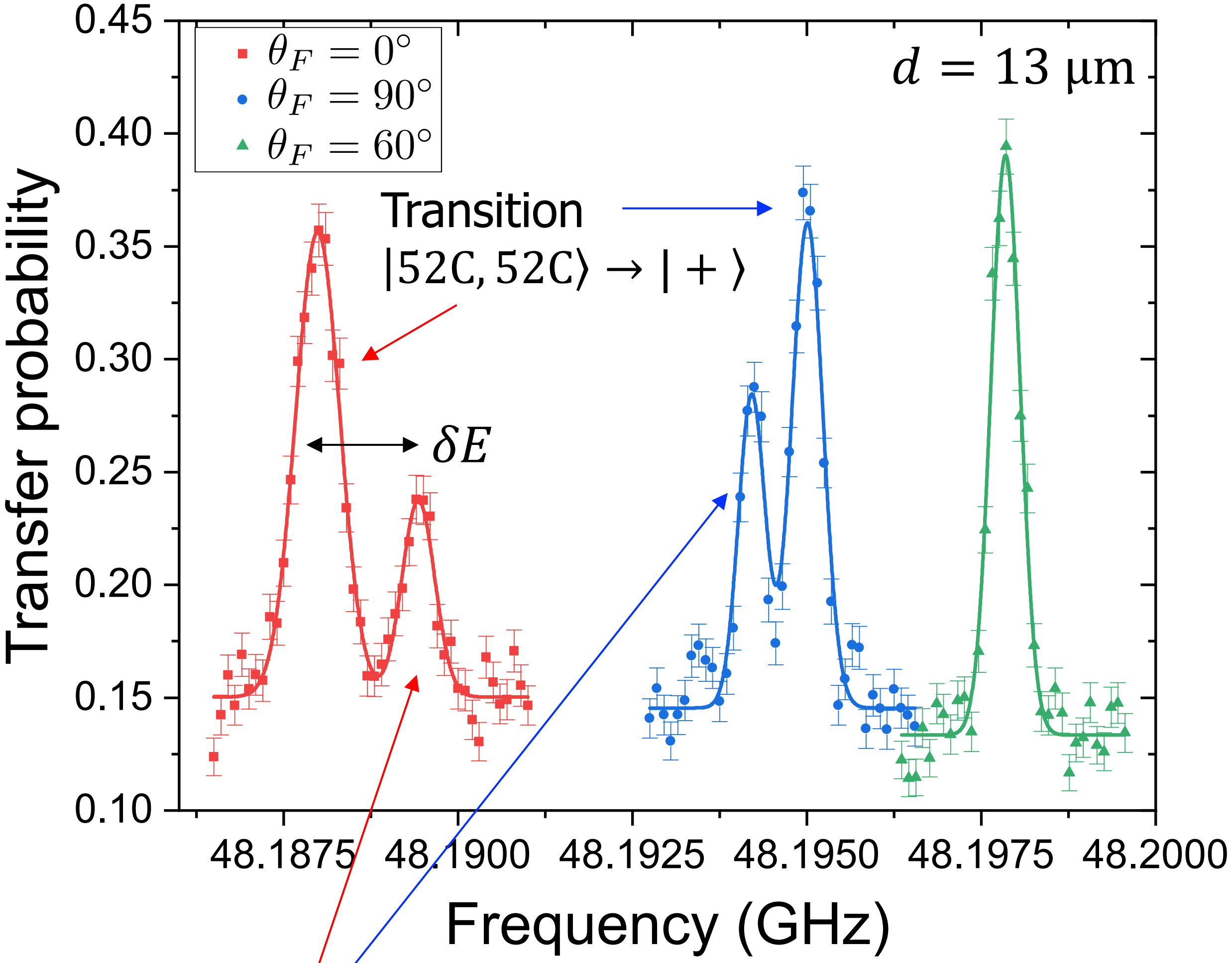
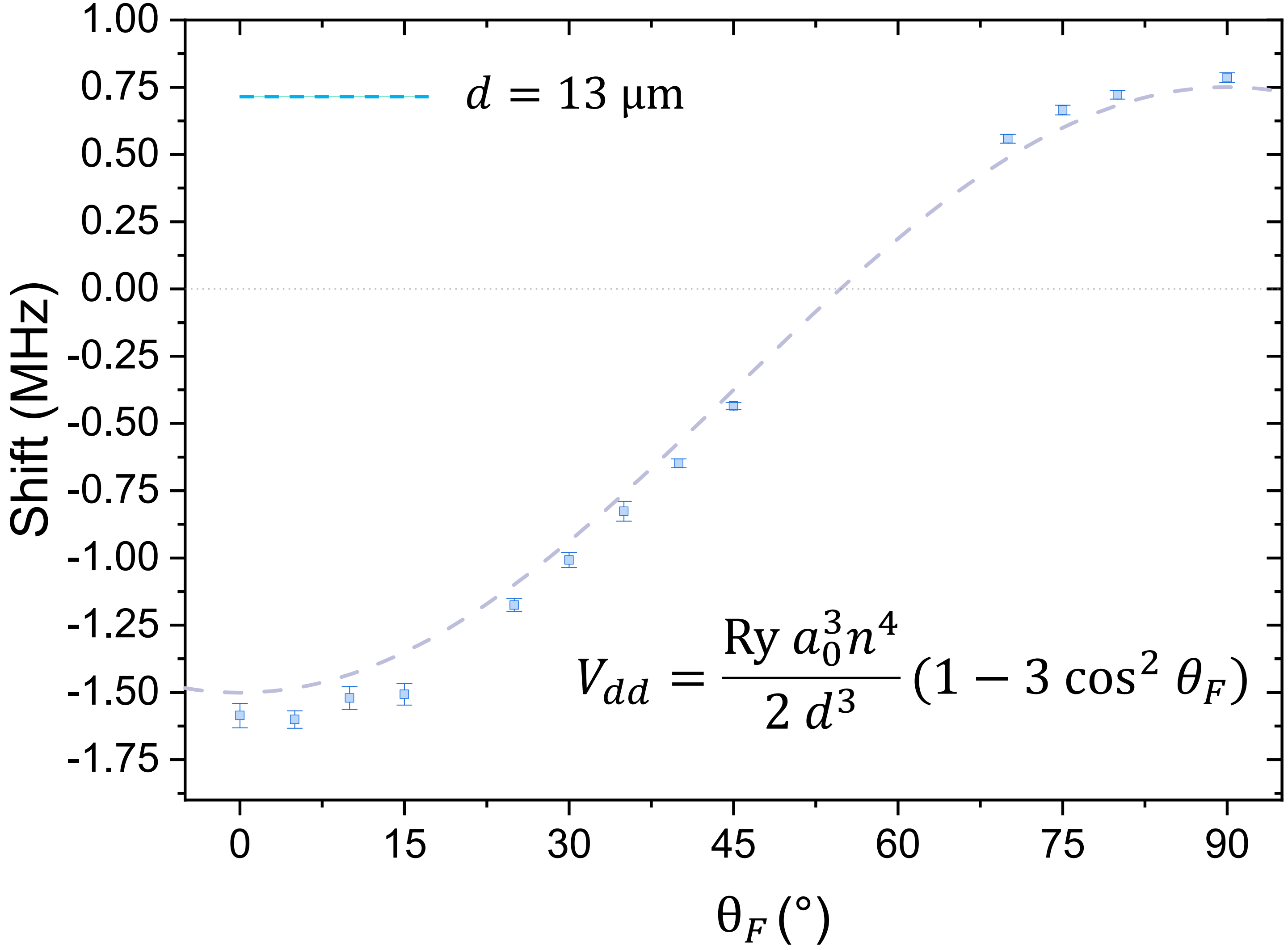
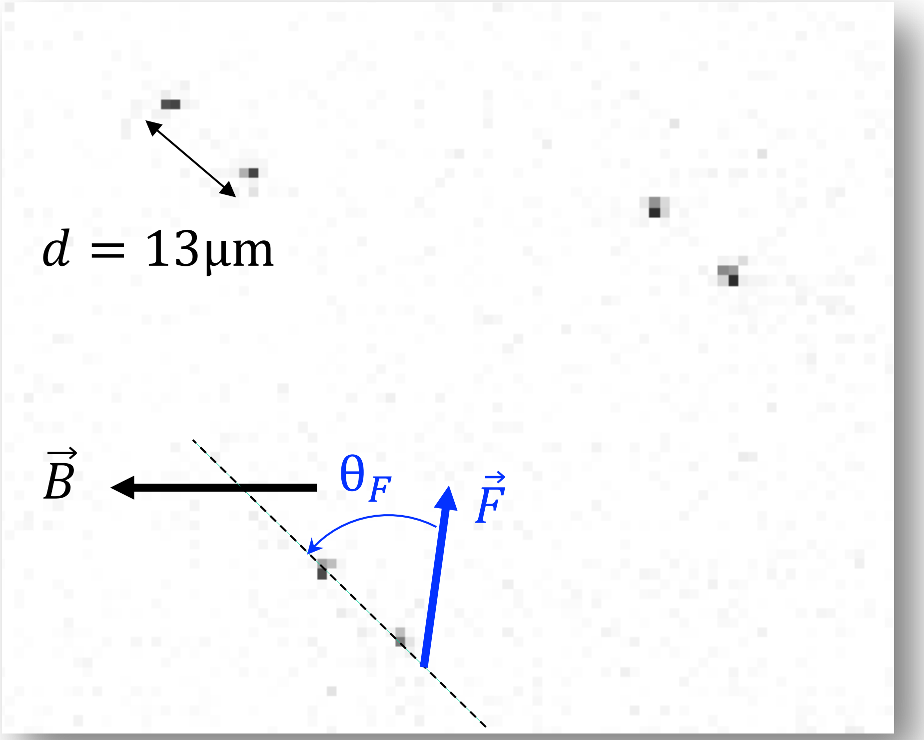


- Single atom
- Two photon transition $|52C, 52C\rangle \rightarrow |51C, 51C\rangle$

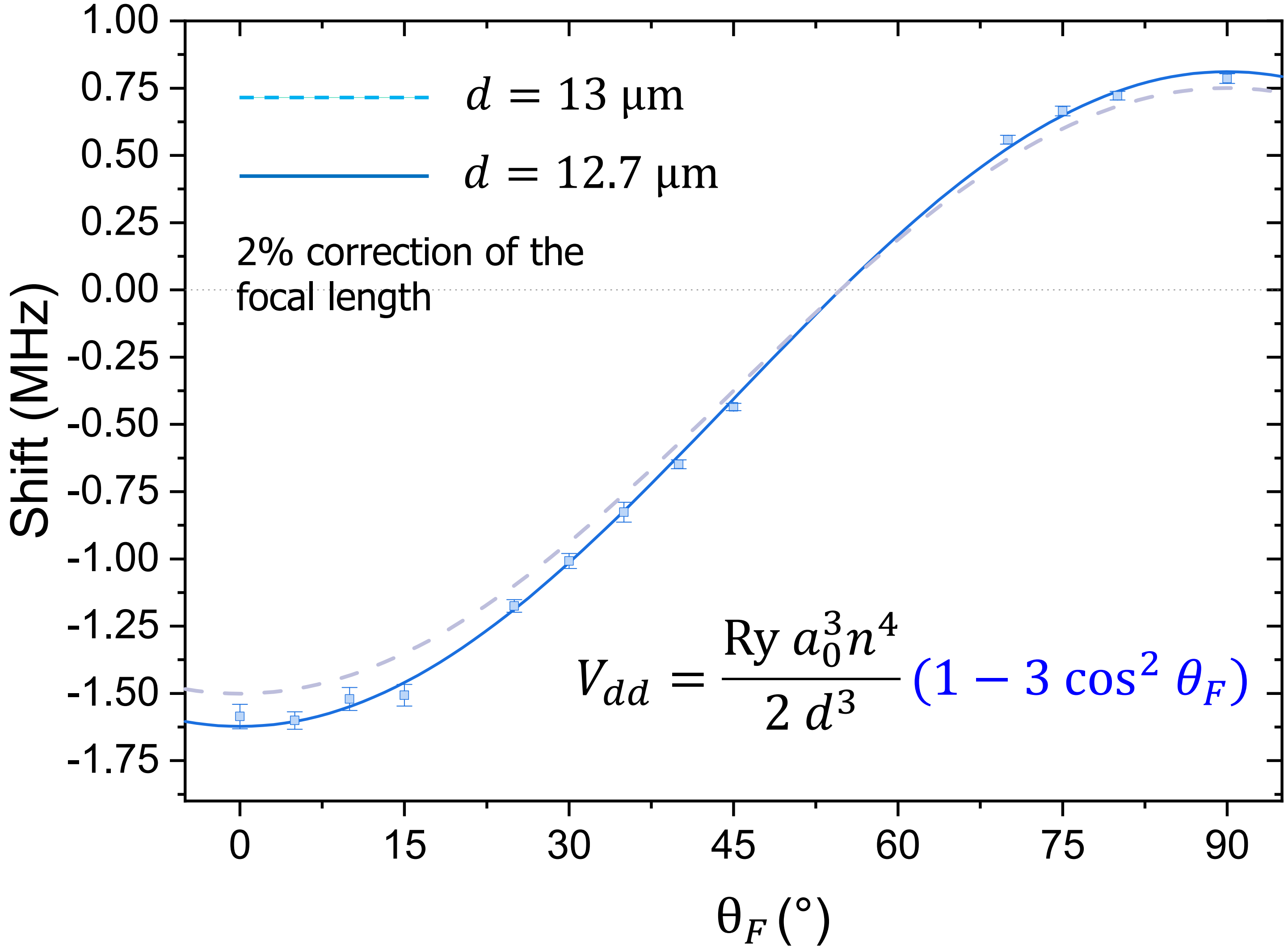
Interacting circular Rydberg atoms



Collab. With D. Papoular, LPTM (Cergy)



Interacting circular Rydberg atoms



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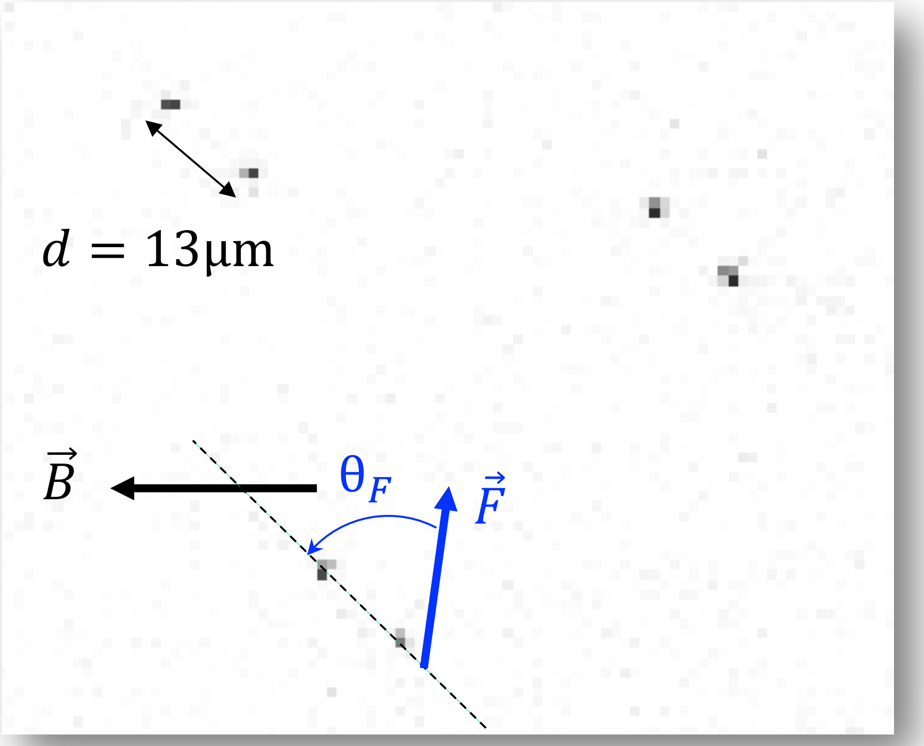
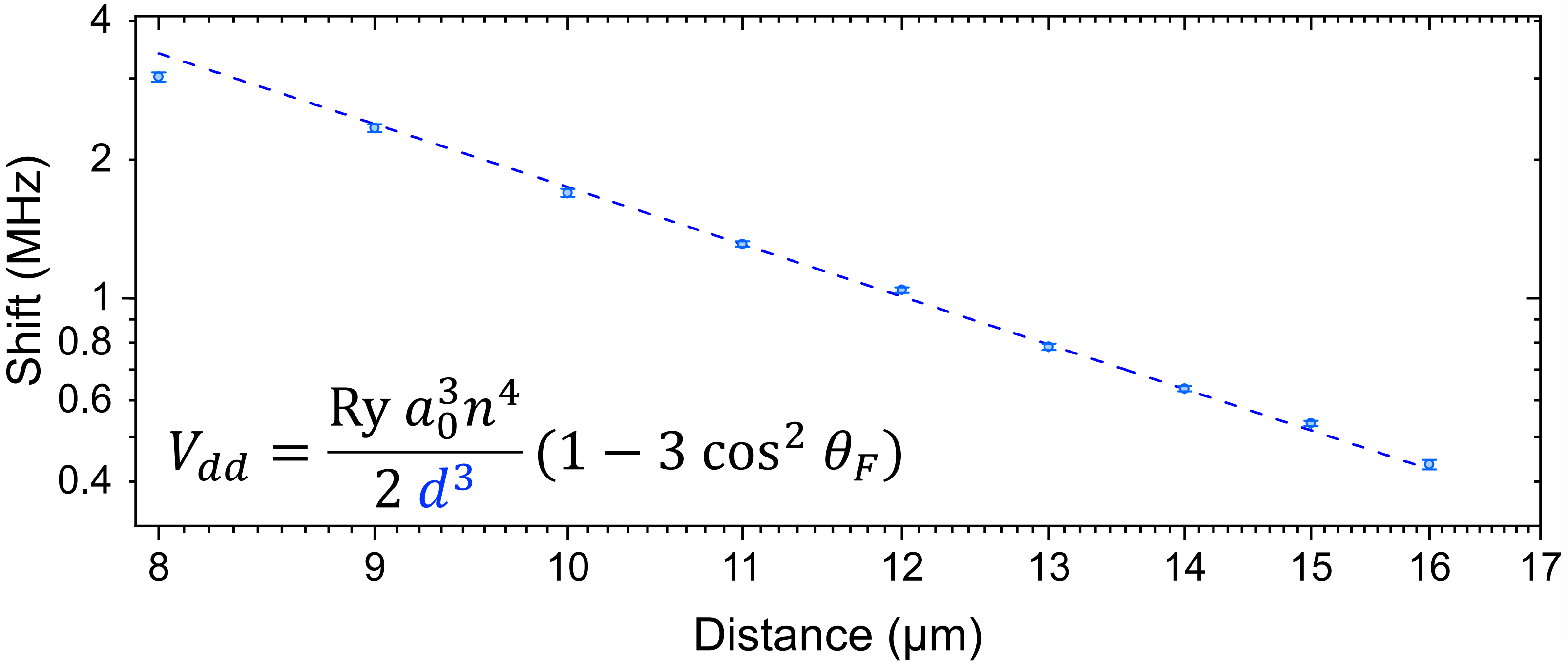
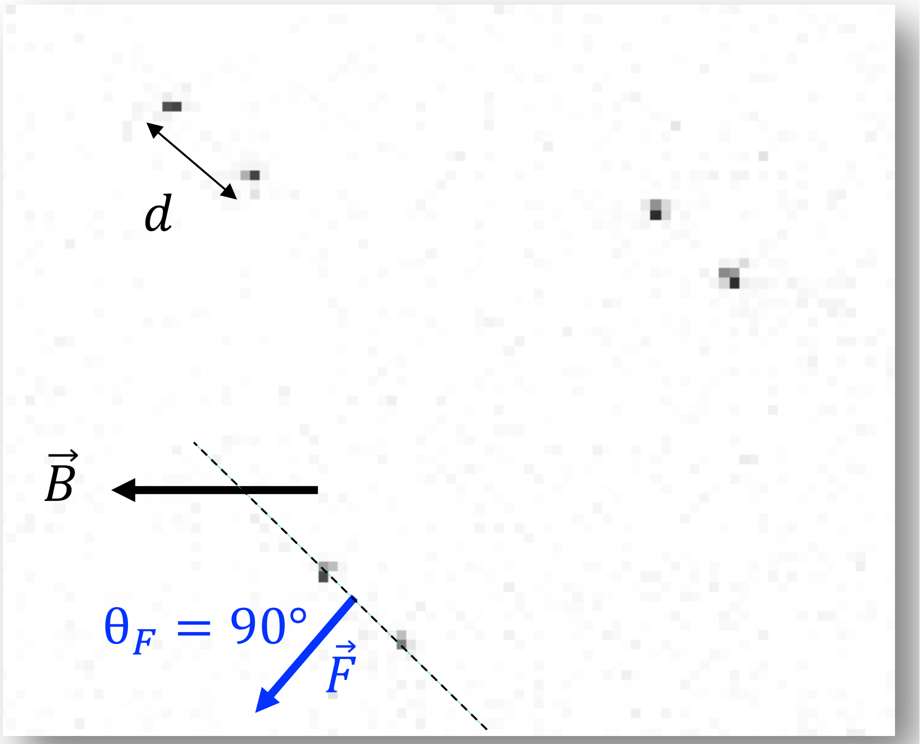


P. Méhaignerie et al., in prep.

Interacting circular Rydberg atoms





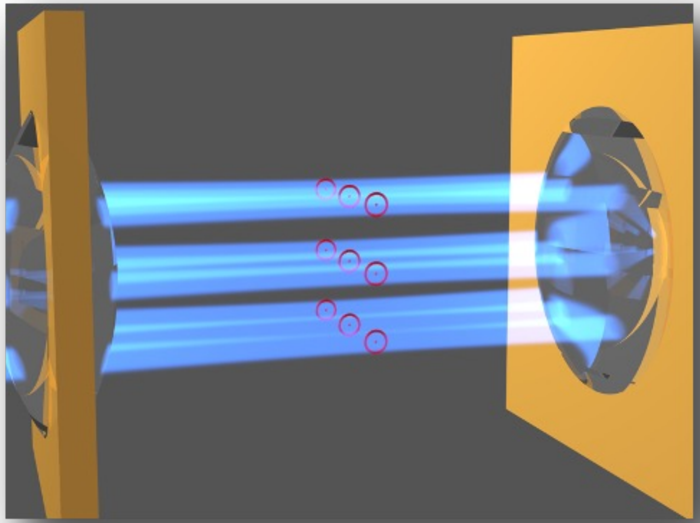
Full characterization of dipole-dipole interaction between circular Rydberg atoms

P. Méhaignerie et al., in prep.

Outline

New experimental platform

- Array of laser-trapped individual circular Rydberg atoms



Dipole-dipole interactions

- Measurement of the first-order dipole-dipole interactions between circular Rydberg atoms

Detection and control

- Spatial and level-selective manipulation and detection of circular Rydberg atoms

Problem: no optical transition…

Optical detection of circular states

- Circular state preparation reversed
- Atom recaptured in optical tweezers

→ Level selective: $|52C\rangle$ only is detected

Spatially selective: fluorescence imaging

- Used to demonstrate laser-trapping of circular states

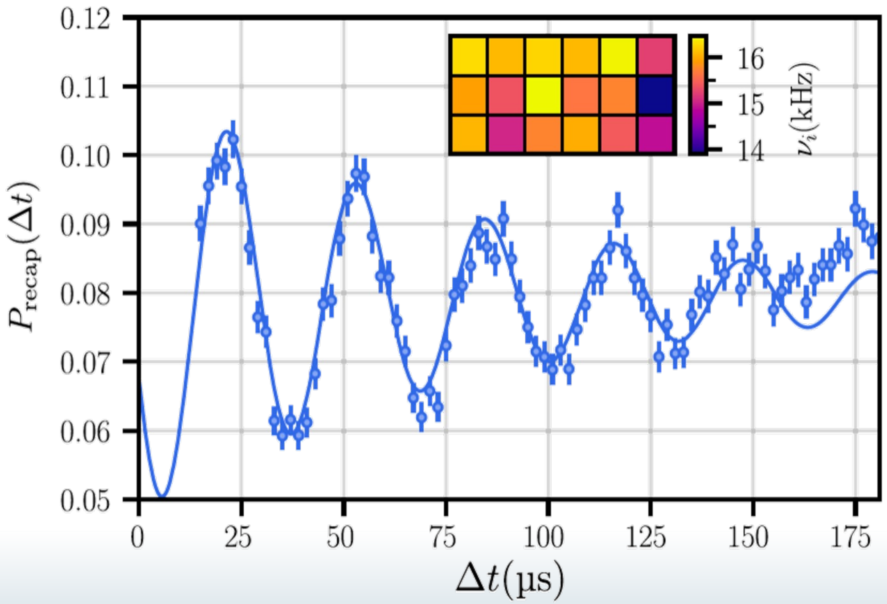
B. Ravon et al., PRL **131**, 093401 (2023)

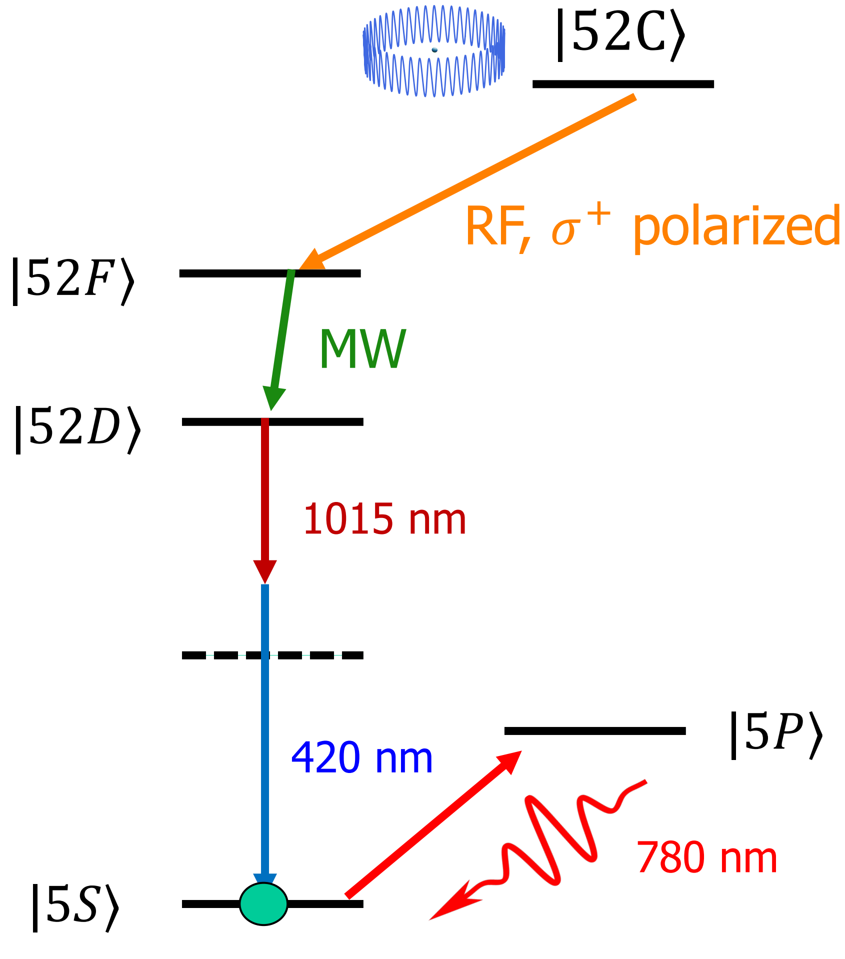
Power: $20\ \mathrm{mW}$ / site

Trap depth: $70\ \mu\mathrm{K}$

$$\nu_{\mathrm{trap}} = 15.8\ \mathrm{kHz}$$

$$\Delta\nu_{\mathrm{trap}} = 0.6\ \mathrm{kHz}$$





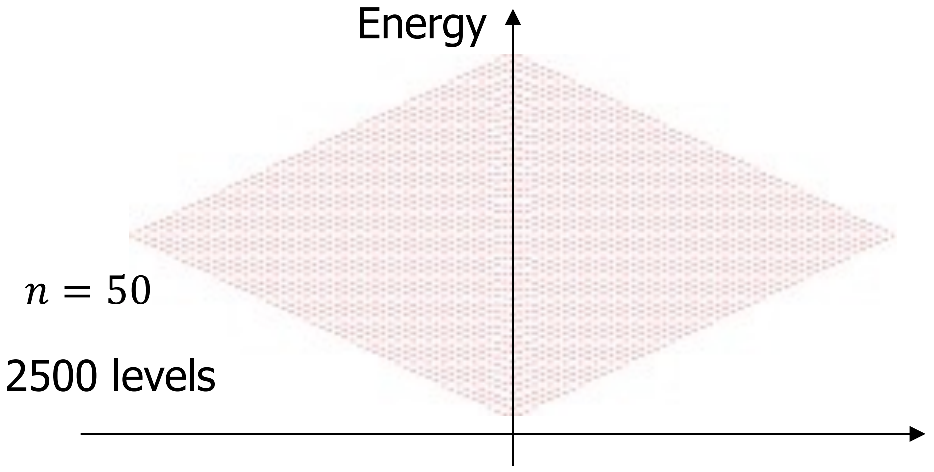
Summary and outlook

Quantum simulations with circular Rydberg atoms

- Spin dynamics under the XX or XXZ Hamiltonians

- Exploit the large Rydberg multiplicity
  - Simulation of large-spin Heisenberg Hamiltonians
  - Simulation of quantum field theories

  A. Kruckenhauser… P. Zoller, Quantum Sc. And Tech. **8**, 015020 (2022)



- Explore the coupling between spin and motion

  P. Méhaignerie et al., Phys. Rev. A **107**, 063106 (2023)

  ➡ already observed with two atoms

  P. Méhaignerie et al. (in prep.)

In collaboration with G. Roux
LPTMS (Orsay)

Thank you!

Brice Ravon
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Gautier Creutzer
Aurore-Alice Young

Maxime Favier (NPL)

C. Sayrin
M. Brune
J.M. Raimond

B. Ravon et al., PRL **131**, 093401 (2023)
P. Méhaignerie et al., PRA **107**, 063106 (2023)
P. Méhaignerie et al., in preparation
Y. Machu et al., in preparation