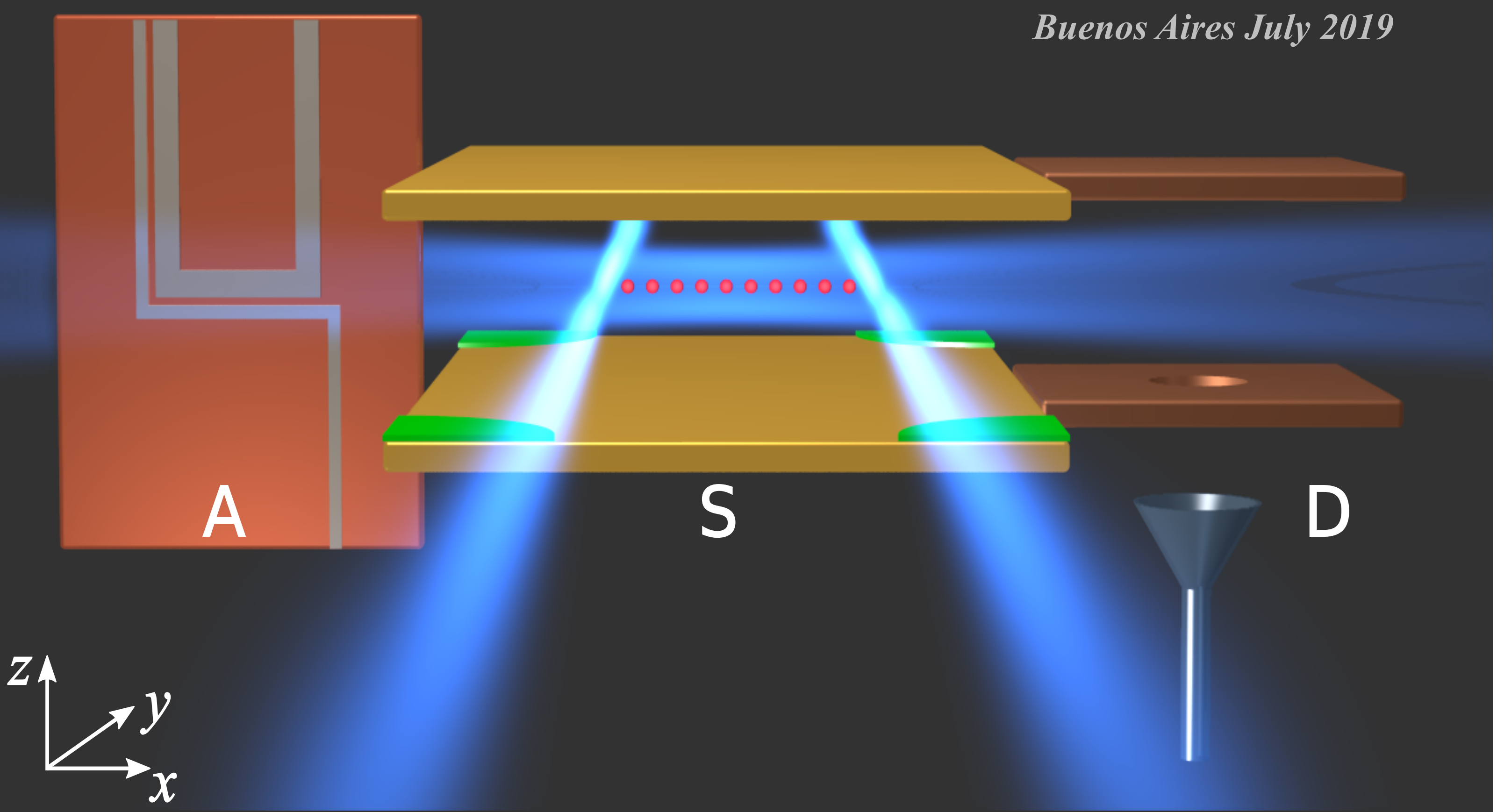
Giambiani Winter School
Buenos Aires July 2019



From cavity QED to quantum simulations with Rydberg atoms
Lecture 3

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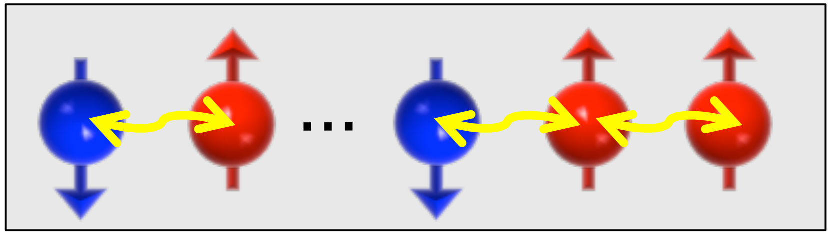
Physique quantique et applications

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

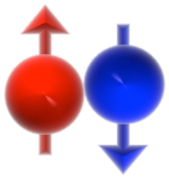
Spin chain quantum simulation



Simulation of a chain of interacting spins-1/2

Requirements?

- Spin 1/2



- Defect free chain of spins preparation

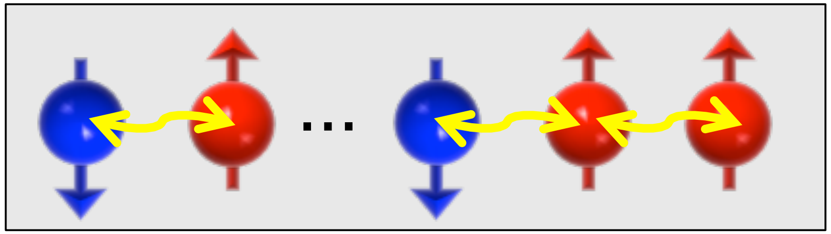
- Long lifetime and strong interaction

→ Observe many interaction cycles

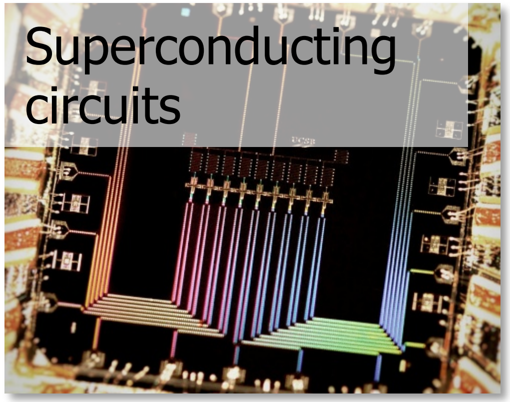
- Fully tunable Hamiltonian $H = H_0 + H_{\mathrm{ext}} + H_{\mathrm{int}}$

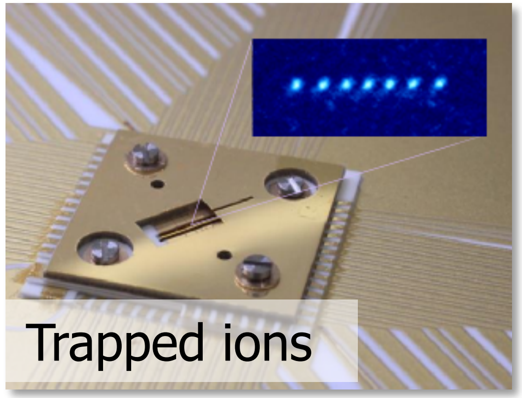


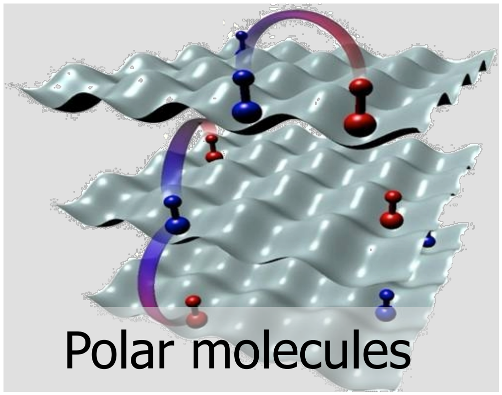
Quantum simulations: various systems

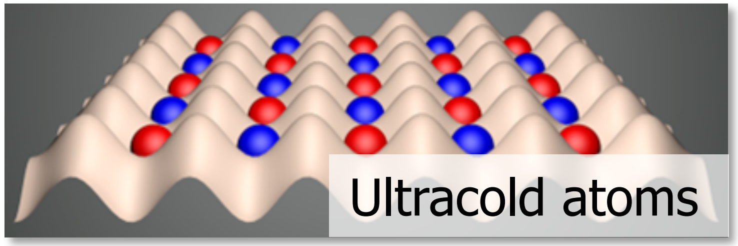


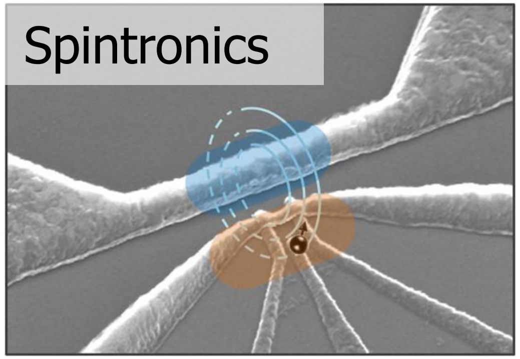
How to simulate?

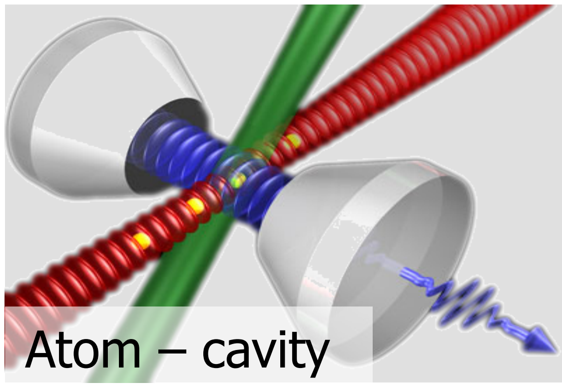


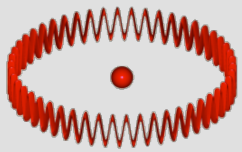








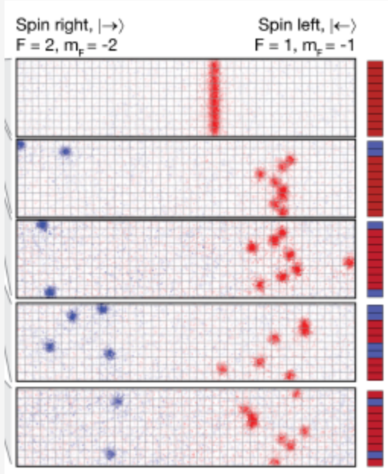




Rydberg atoms?

Present Rydberg atom based quantum simulators

- MOT insulator of ground state atoms + Rydberg dressing



→ dynamic of a linear 10 atom Ising spin chain

→ simulation duration limited by blackbody induced Rydberg losses

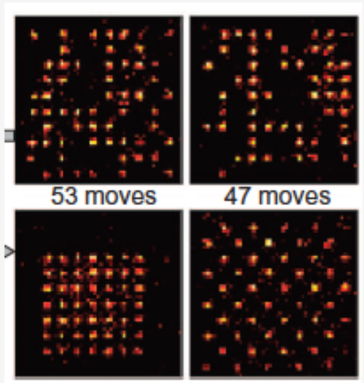
$$\tau_{loss} \approx 130\mu s$$

→Filling factor smaller than 1

I. Bloch, C. Gross

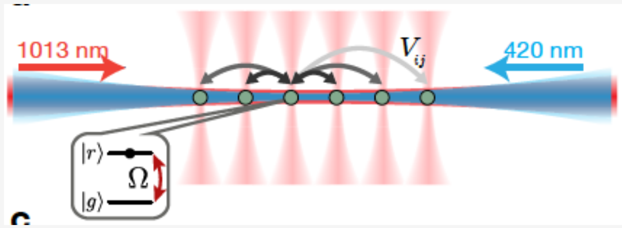
arXiv:1705.08372

- Single trapped ground state atoms in optical tweezers



Science **354,** 1021 (2017)
49 atom array

A. Browayes Paris-Saclay



arXiv:1707.04344
51 atom linear trap

M. Lukin Harward-MIT

The Rydberg state is not trapped →simulation limited to few μs timescale

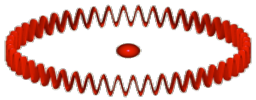
Rydberg atoms quantum simulator

- Two main limitations for low angular momentum Rydberg states (S, P, D laser accessible levels)
  - ❑ Finite Rydberg state lifetime (100 μs for laser accessible states)
    - ➞ And blackbody induced transfers
  - ❑ Atomic motion
    - ➞ An even more severe limitation to the useful time

  Reduced but not cancelled by Rydberg dressing of ground states

  E. A. Goldschmidt, Phys. Rev. Lett. 116, 113001 (XXX)

- Circular Rydberg atoms (L=lml=n-1)



  - ❑ Long natural lifetime, 25 ms for n=48
    - ➞ Spontaneous emission can even be supressed
  - ❑ Large orbit $r_n \sim n^2 a_0$ ➞ Huge electric dipole matrix elements

  ➞ Strong dipole – dipole interactions

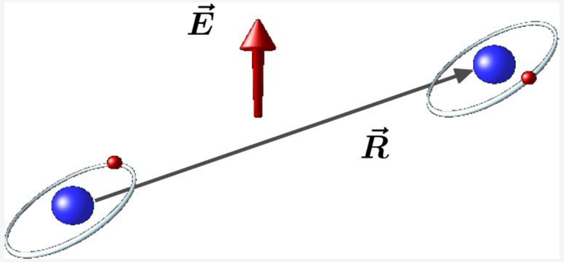
  - ❑ Can be trapped without ionizing

  T.L. Nguyen et al, PRX 2018

➞ good candidates for building a quantum simulator

Dipole interaction between circular atoms

Dipole interaction

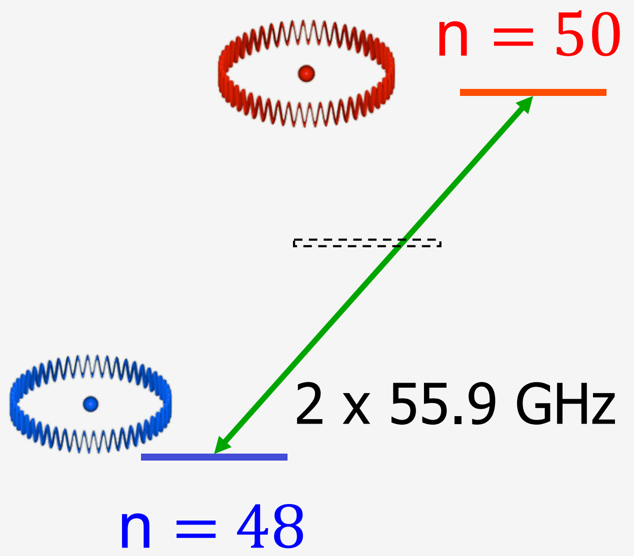


$$V_{dd} = \frac{q^2}{4\pi\varepsilon_0 r^3}\left(\vec{r}_1.\vec{r}_2 - 3\left(\vec{r}_1.\frac{\vec{r}}{r}\right).\left(\vec{r}_2.\frac{\vec{r}}{r}\right)\right)$$

$|nC,nC\rangle$ van der Waals interaction $\frac{C_6}{R^6}$

$|nC,n'C\rangle \Leftrightarrow |n'C,nC\rangle$ exchange interaction

- n'=n+2 A_6/R^6 same order of magnitude as vdW

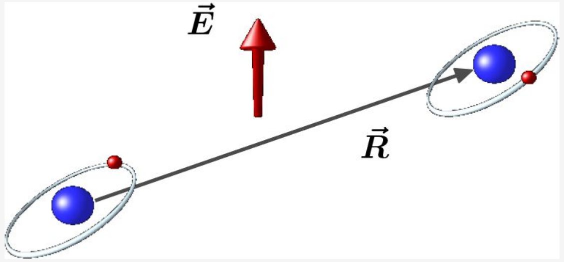


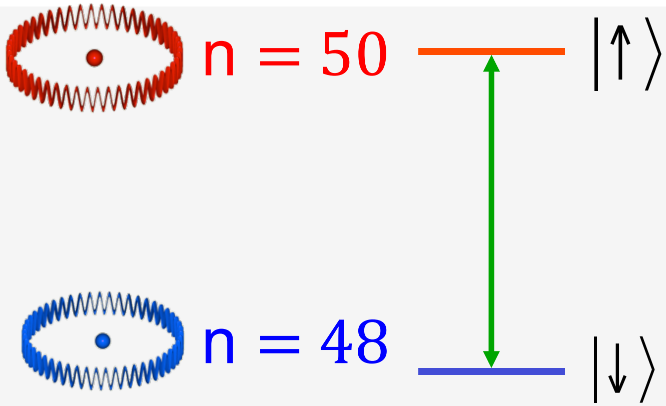
Large n → more BB radiation
→ shorter lifetime
Small n → lower interaction

→ chose 48C and 50C

XXZ spin chain model

Dipole interaction





Next-neighbor spin chain hamiltonian

$$\frac{H}{h} = \frac{\Delta}{2}\sum_{j=1}^{N}\sigma_j^Z + \frac{\Omega}{2}\sum_{i=1}^{N}\sigma_j^X + J_Z\sum_{j=1}^{N-1}\sigma_j^Z\sigma_{j+1}^Z + J\sum_{j=1}^{N-1}(\sigma_j^X\sigma_{j+1}^X + \sigma_j^Y\sigma_{j+1}^Y)$$

X or Z fields
→result from
microwave dressing:

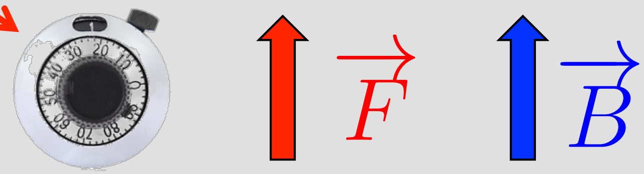
- $\Delta = \omega_0 - \omega_{mw}$
- Ω: MW Rabi frequency

Ising

exchange

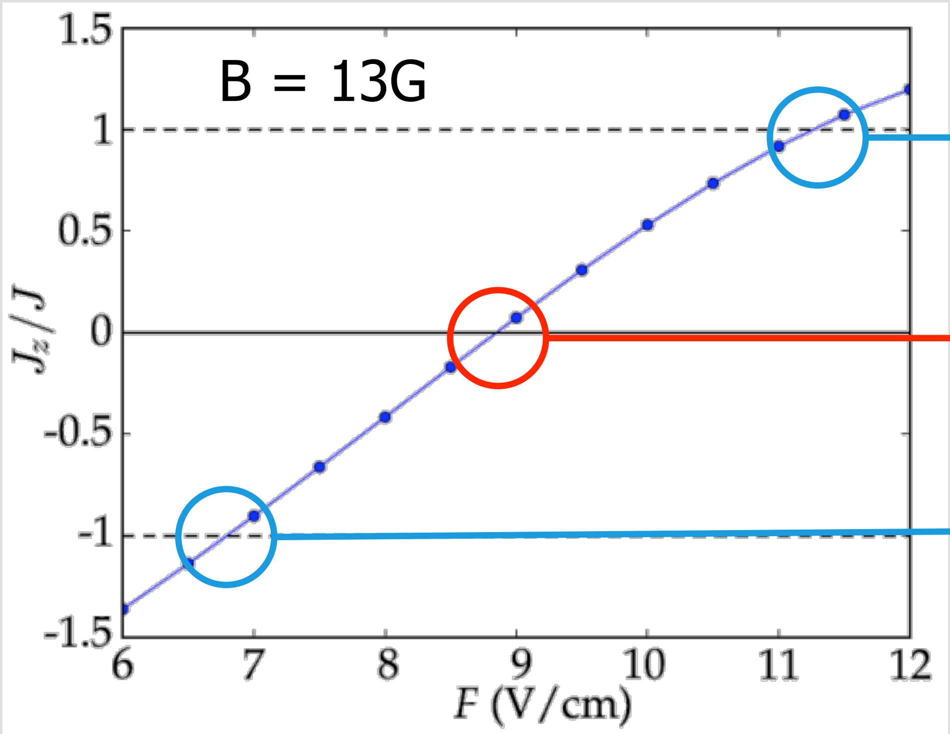
Tunability of XXZ Hamiltonian

$$\frac{H}{h} = \frac{\Delta}{2}\sum_{j=1}^{N}\sigma_j^Z + \frac{\Omega}{2}\sum_{i=1}^{N}\sigma_j^X + J_Z\sum_{j=1}^{N-1}\sigma_j^Z\sigma_{j+1}^Z + J\sum_{j=1}^{N-1}(\sigma_j^X\sigma_{j+1}^X + \sigma_j^Y\sigma_{j+1}^Y)$$



Coupling tunability:

- J nearly constant
- J_z tuned with electric and magnetic fields



Jz = +J :
Isotropic model

Jz = 0 :
Pure XY interaction

Jz = -J :
Isotropic model

Tunability of XXZ Hamiltonian

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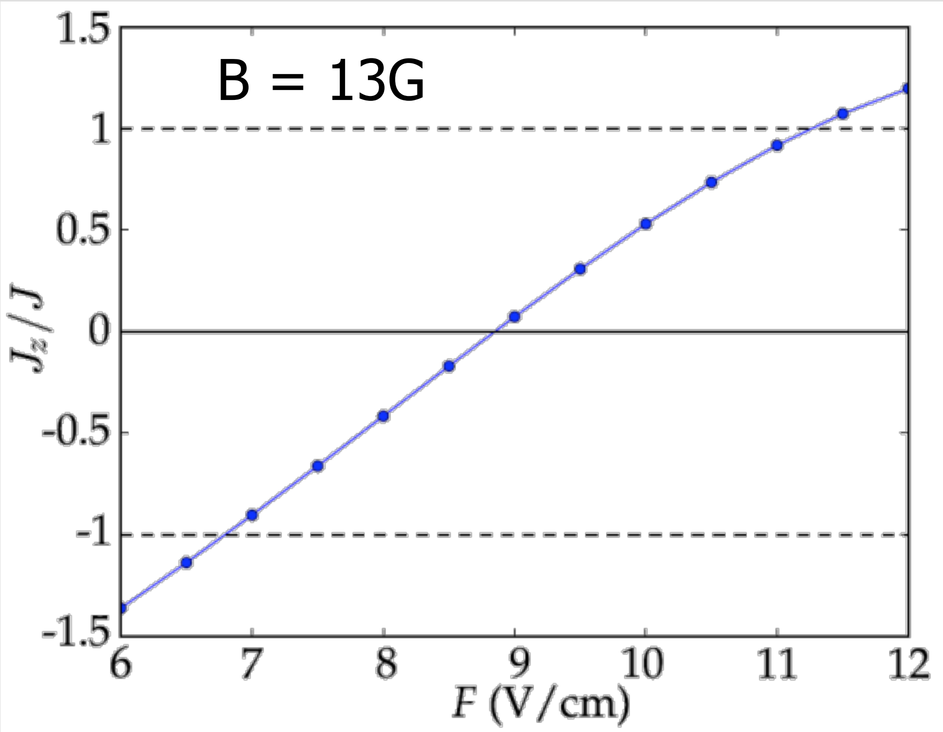

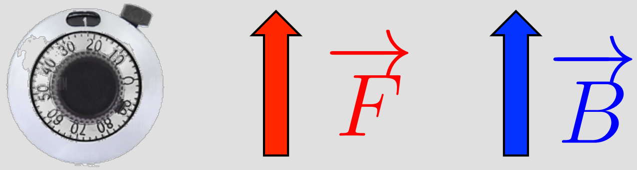

- Interaction strength
  - J= 17 kHz for d= 5 μm,
  - Spin exchange time 1/4J in the 10 μs range

➙ Trapping time of 1s for a 40 atoms chain is 10^5 exchange times!

Tunability of XXZ Hamiltonian

$$\frac{H}{h} = \frac{\Delta}{2}\sum_{j=1}^{N}\sigma_j^Z + \frac{\Omega}{2}\sum_{i=1}^{N}\sigma_j^X + J_Z\sum_{j=1}^{N-1}\sigma_j^Z\sigma_{j+1}^Z + J\sum_{j=1}^{N-1}(\sigma_j^X\sigma_{j+1}^X + \sigma_j^Y\sigma_{j+1}^Y)$$

Coupling tunability:

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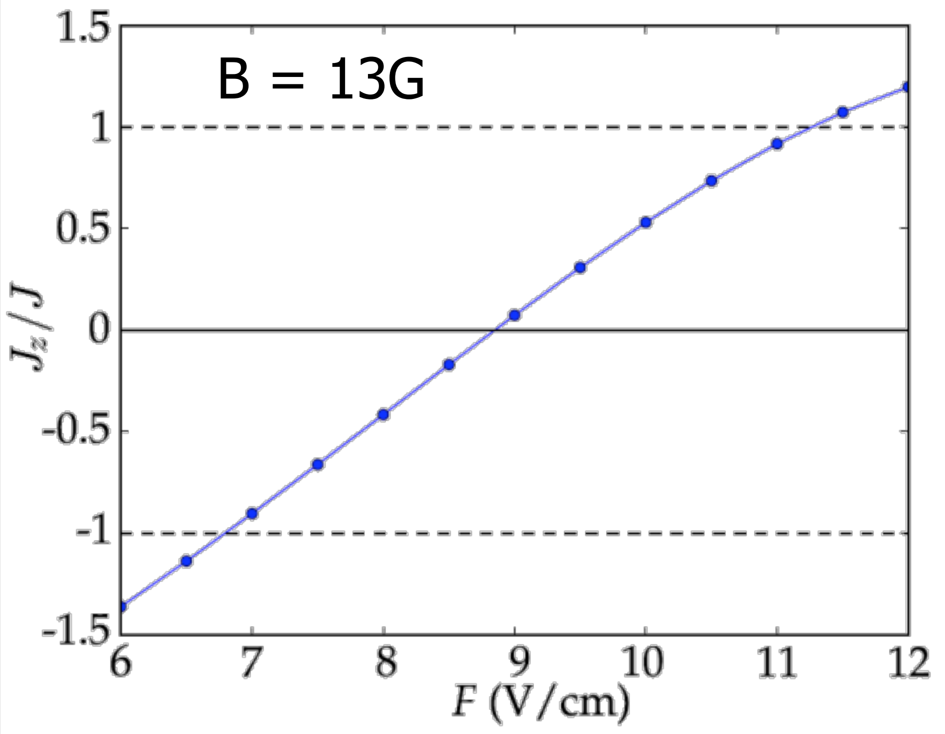
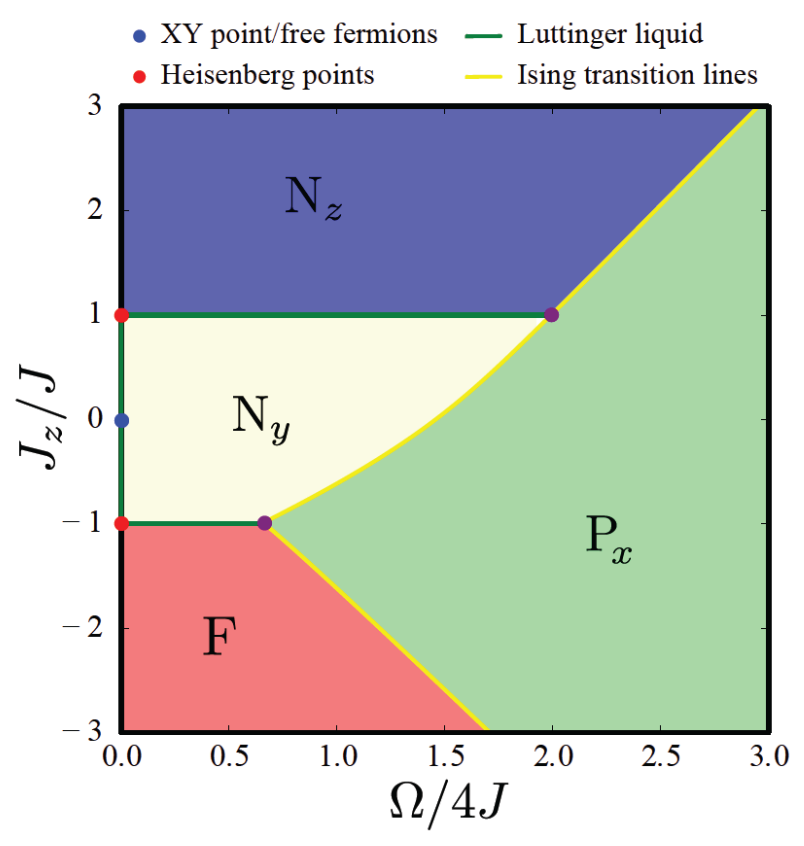


Phase diagram at Δ=0

(Guillaume Roux LPTMS)



Tunable XXZ spin chain model

Next-neighbor spin chain hamiltonian

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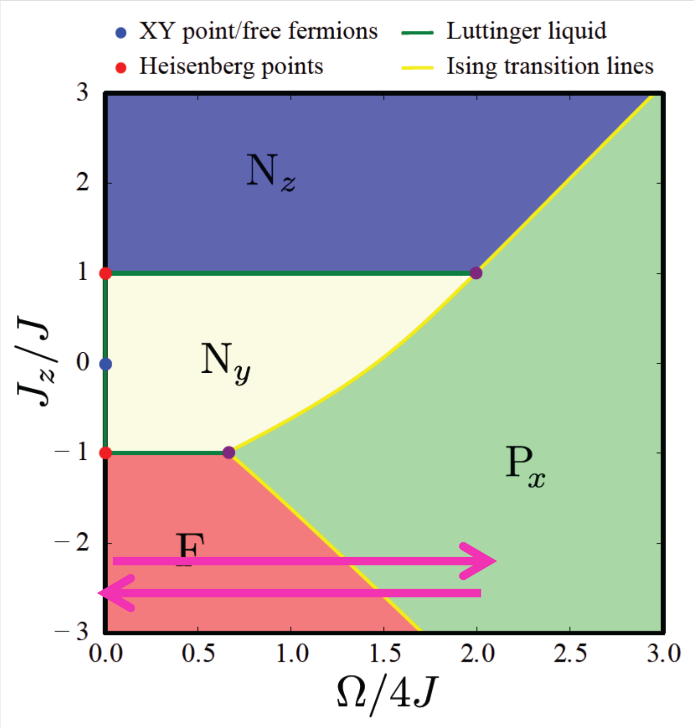
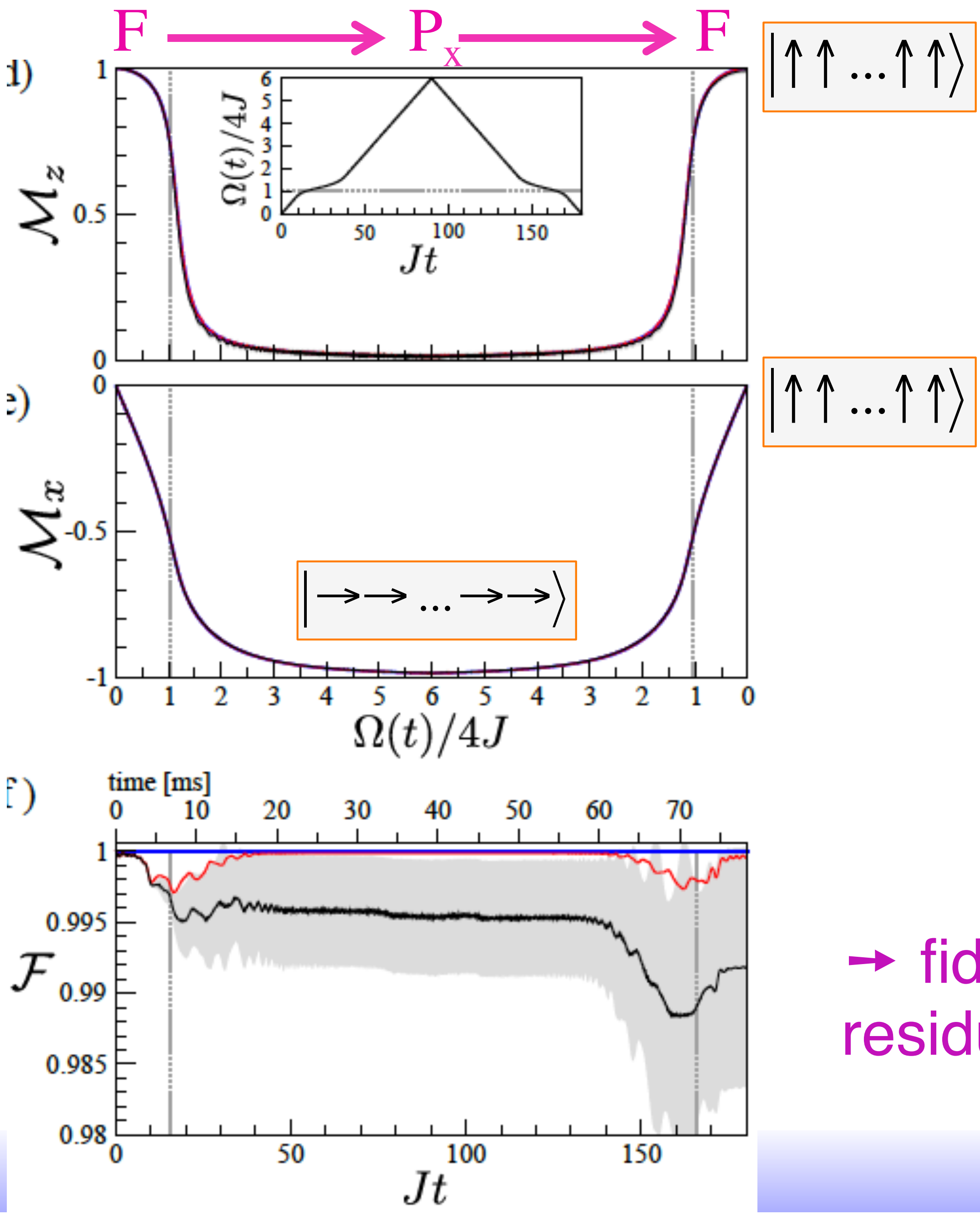


→explore phase diagram by adiabatic variation of parameters as a benchmark

Exact simulation of adiabatic phase transitions



Simulation for 14 spin
Including residual motion

d=7 μm, J= 2.3 kHz

Same values of order parameter as in the exact ground state

→ nearly perfect preparation of phase P_X

→ fidelity weakly affected by residual atomic motion

arXiv 1707.04397

Tunable XXZ spin chain model

Next-neighbor spin chain hamiltonian

$$\frac{H}{h} = \frac{\Delta}{2}\sum_{j=1}^{N}\sigma_j^Z + \frac{\Omega}{2}\sum_{i=1}^{N}\sigma_j^X + J_Z\sum_{j=1}^{N-1}\sigma_j^Z\sigma_{j+1}^Z + J\sum_{j=1}^{N-1}(\sigma_j^X\sigma_{j+1}^X + \sigma_j^Y\sigma_{j+1}^Y)$$

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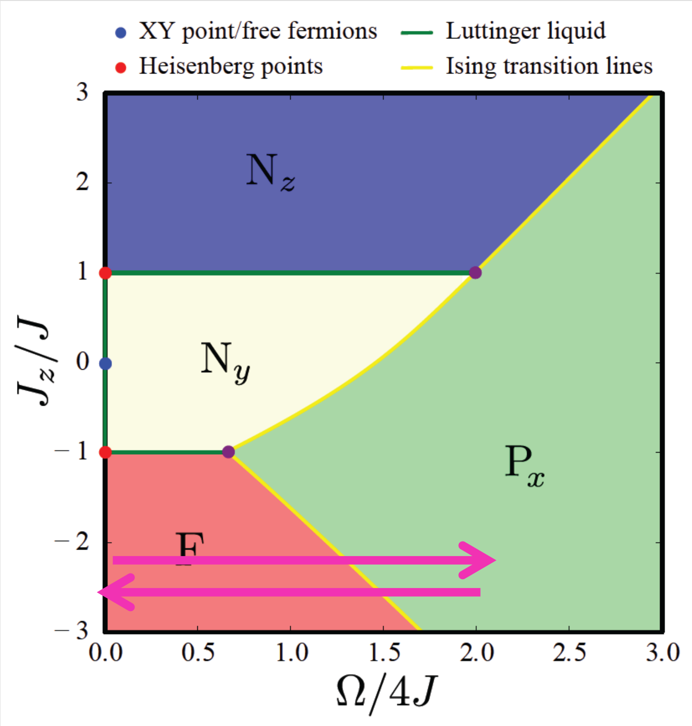


➞explore phase diagram by adiabatic variation of parameters as a benchmark

➞study quenches: defects generation (Kibble-Zurek)

➞study transport: MBL with controlled disorder and interactions

➞spin ladder: study Haldane phase of effective spin 1

...

General scheme of trapped Rydberg atom simulator

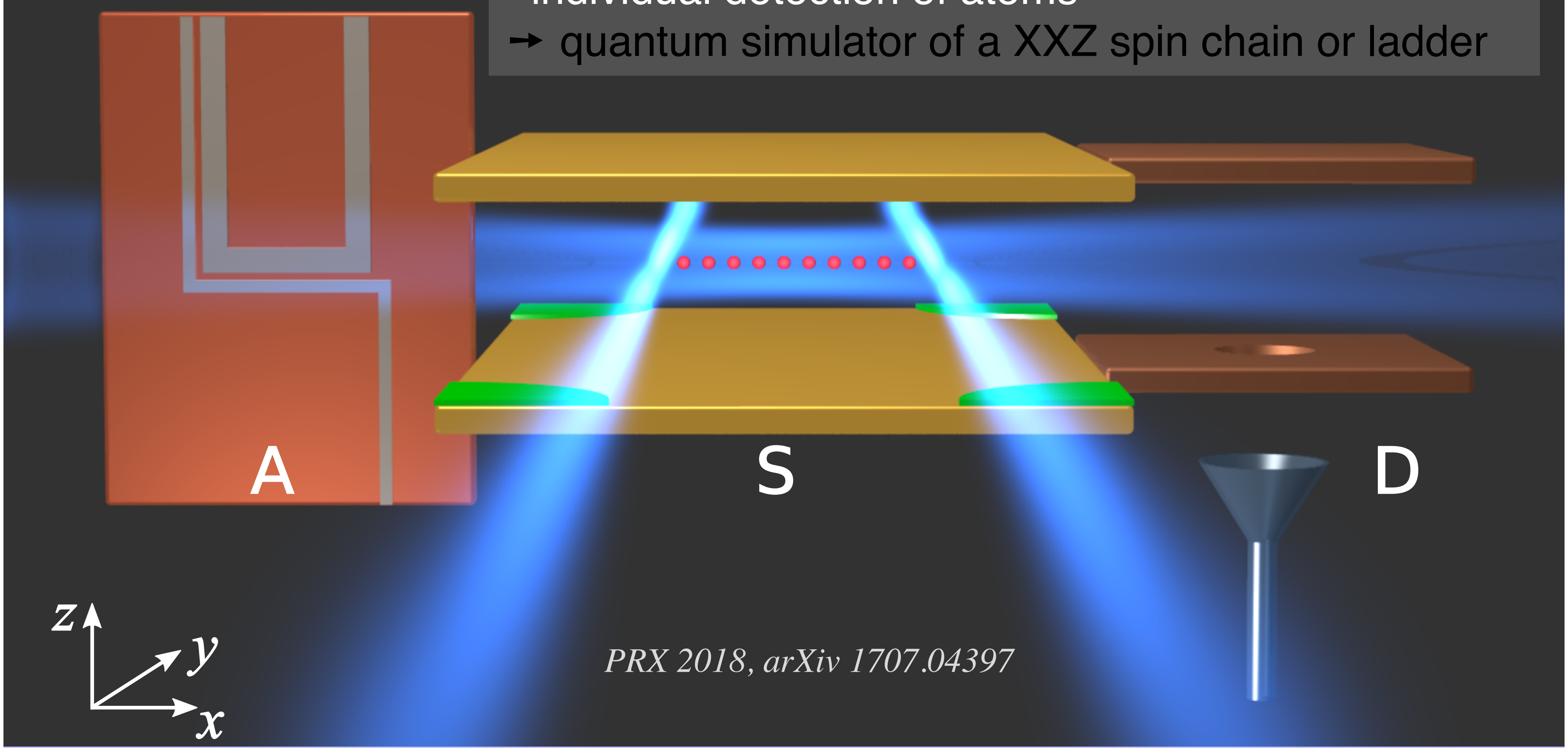
Trapped circular Rydberg atoms

- inhibited spontaneous emission $\tau \simeq 1$ min
- ponderomotive laser trap

→ perfect 1D lattice of 40 atoms

- individual detection of atoms

→ quantum simulator of a XXZ spin chain or ladder

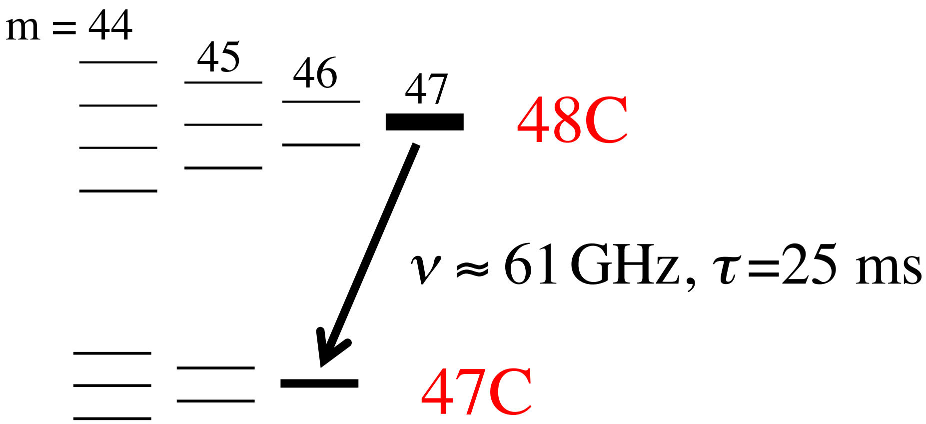


PRX 2018, arXiv 1707.04397

Circular Rydberg Atoms (CRA): spontaneous emission inhibition

- CRA decay channel:

microwave spontaneous emission on a σ^+ transition, 25 ms lifetime for 48C



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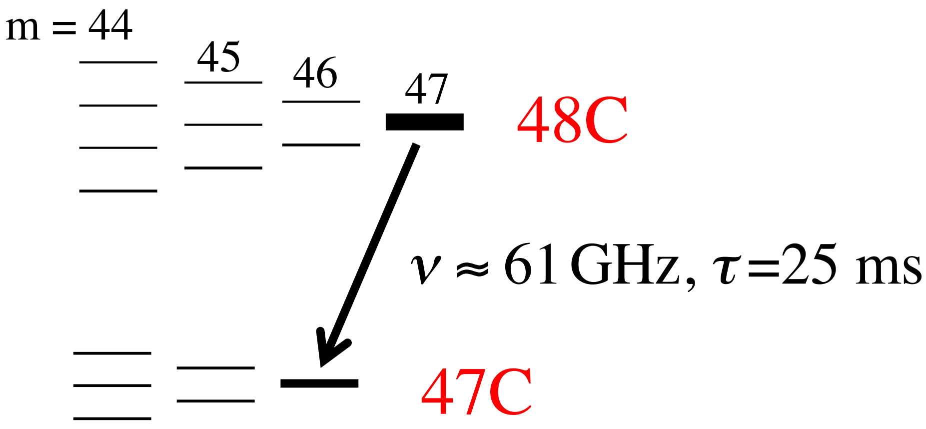
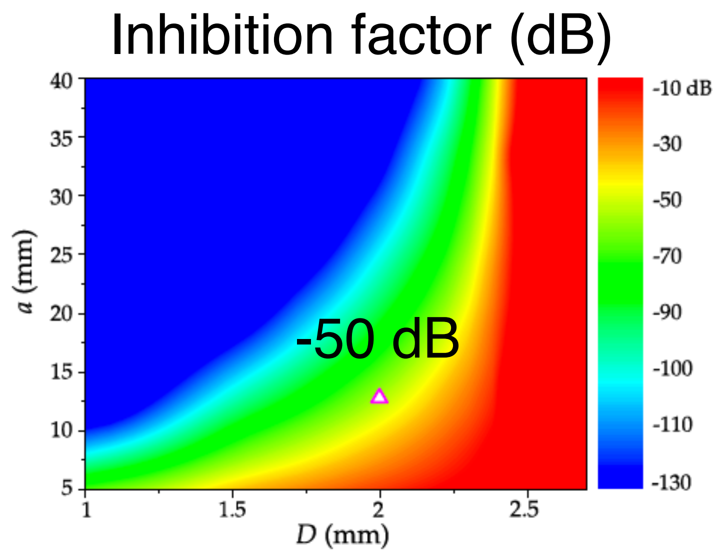
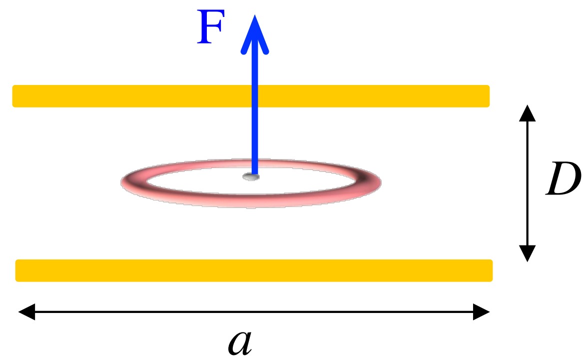




- Spontaneous emission inhibition

D. Kleppner Phys. Rev. Lett. 47, 233 (1981)

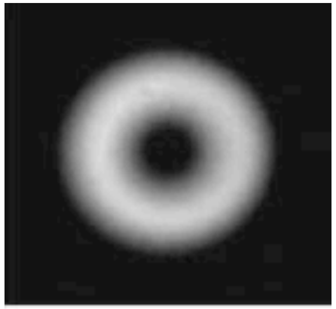
❑ Emission inhibited in a capacitor below cut-off.



➞ 2500 s life in a 13 x 2 mm capacitor !

laser trapping circular states

S. K. Dutta et al. Phys. Rev. Lett. 85, 5551
Raithel group



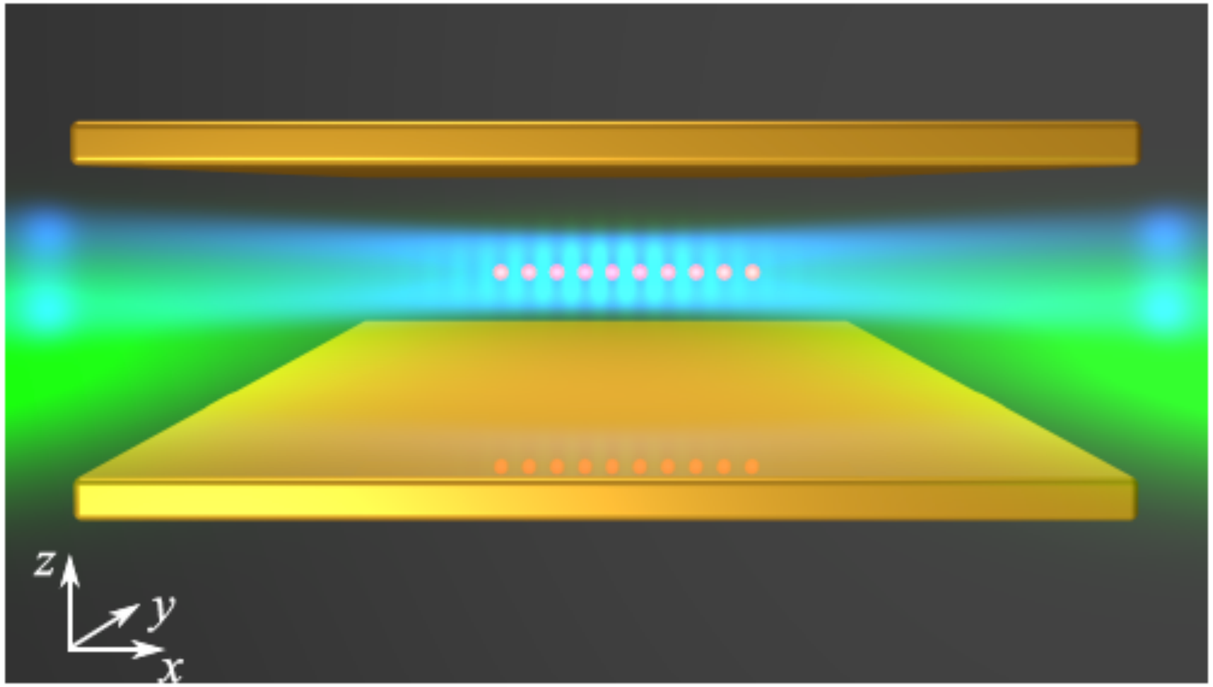
- Circular states can be laser-trapped !
  - ❑ Ponderomotive electron energy:
    - ➞ atoms are low-field seekers

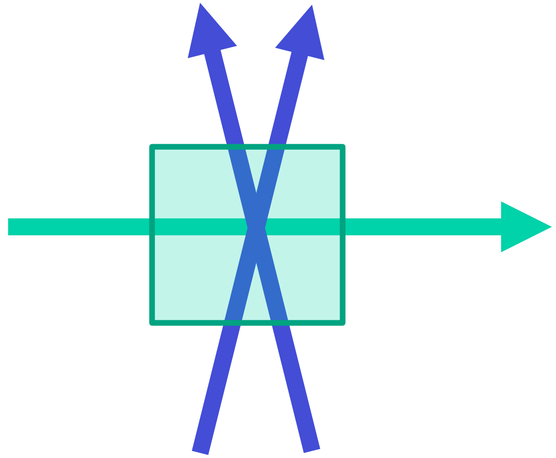
      Trapped in vortex beam
    - ➞ a deep trap
      - ~ similar polarizability as ground state Rubidium at 1 μm wavelength
  - ❑ Trapping almost independent of principal quantum number
    - ➞ Low trap-induced decoherence
  - ❑ Impervious to photoionization
    - ➞ severe limitation for low *l* states

      Saffman et al. Phys. Rev. A 72, 022347

A simple trap geometry for a 1-D lattice

- Trapping lasers at 1 μm





- ❑ LG mode along Ox (transverse trap)
- ❑ Two Gaussian beams at a small angle

  ➞ Longitudinal lattice with an adjustable spacing

  – d= 5 to 7 μm

  – 24 kHz longitudinal oscillation frequency

Expected lifetime limit for trapped atoms

Cause	Lifetime (s)
Residual spontaneous emission	2500
Blackbody induced processes	630
Level mixing	88
Dipolar relaxation	∞
Photoionization	∞
Collisions with background gas at 10^{-14} torr	400
Compton elastic diffusion in trap	> 180
Predicted lifetime	**47** s

Two atoms at d = 5 μm

For 50 atoms, less than one atom lost in 1s

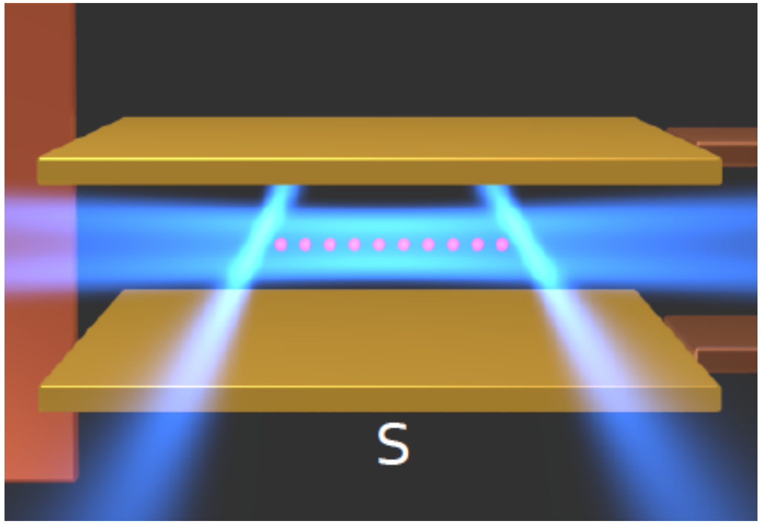
This corresponds to 10^4-10^5 exchange time

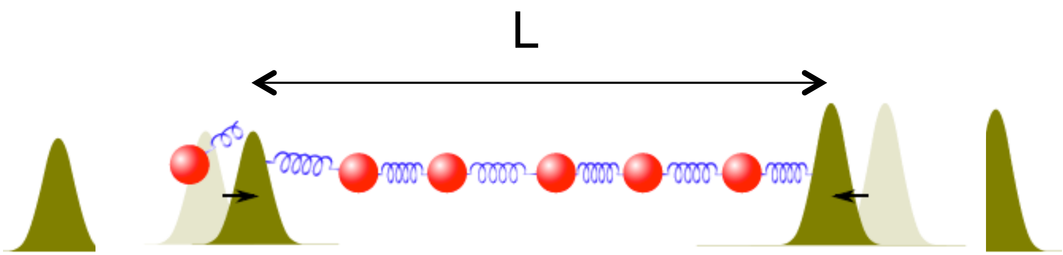
Deterministic chain preparation

- Van der Waals evaporation
  - LG and "plug beams trap
    - ➞ One weak, one strong
  - Load ~ 100 circular atoms
  - Compress the trap: atom evaporate
  - Classical simulation

➞Final atom number determined by trap length

Deterministic chain preparation up to ~40





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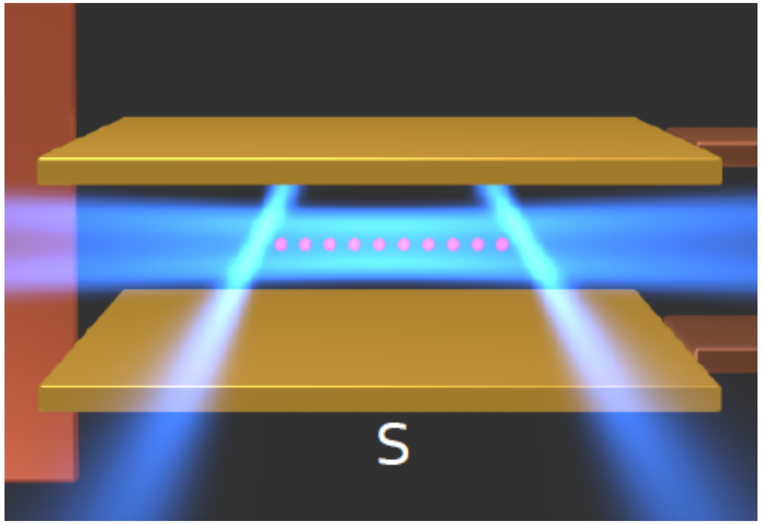
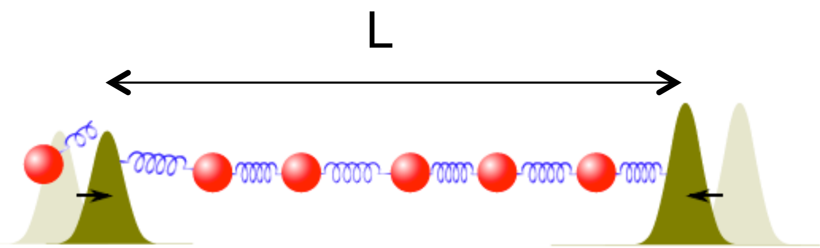
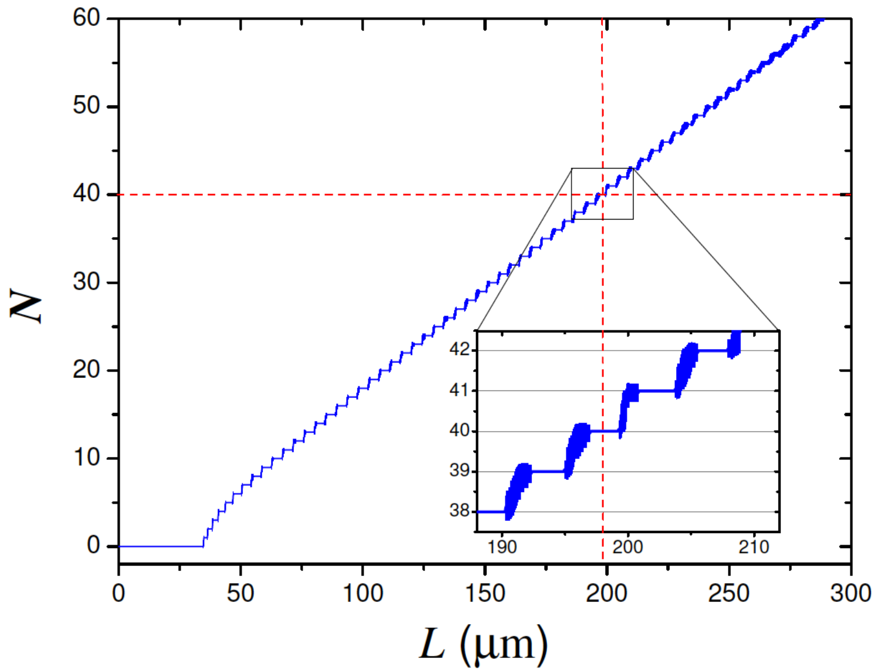






➞Efficient evaporative cooling cooling

Final motion amplitude close to ground state

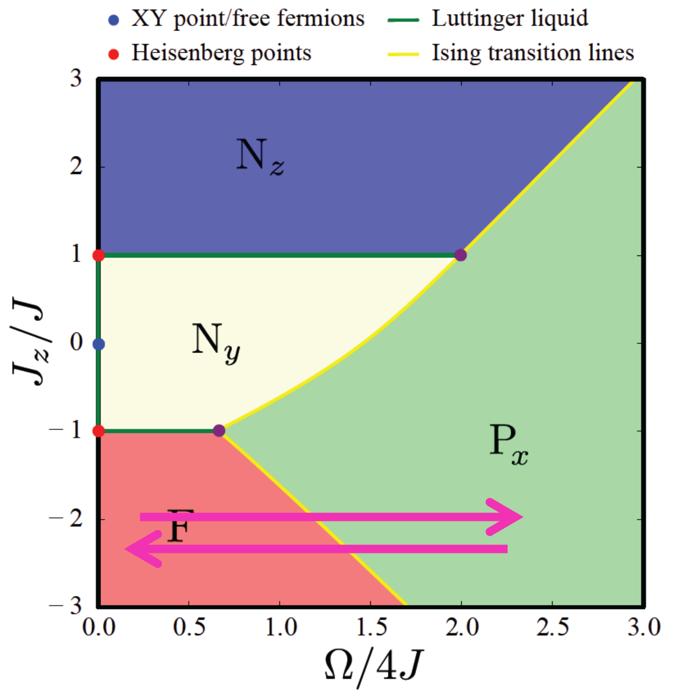
Thermodynamic description: collab. with David Papoulard (Univ. Cergy)

Perspectives for circular atom QS

- Adiabatic exploration of the phase diagram

→ Benchmark

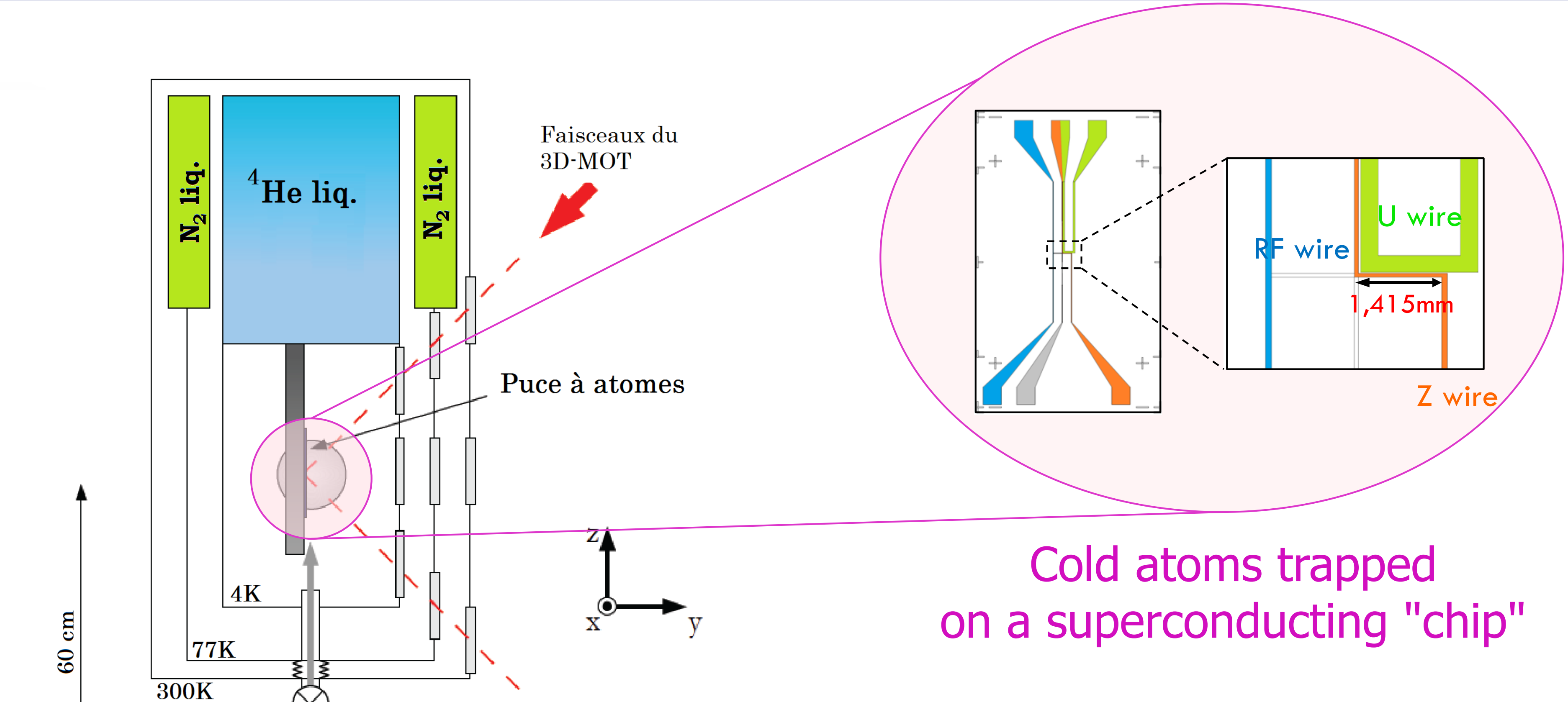
- Adding disorder with a speckle field
  - Bose glass physics
  - Many-body localization
- Fast variations of Hamiltonian
  - Quenches, Excitation spectroscopy,
  - Floquet engineering



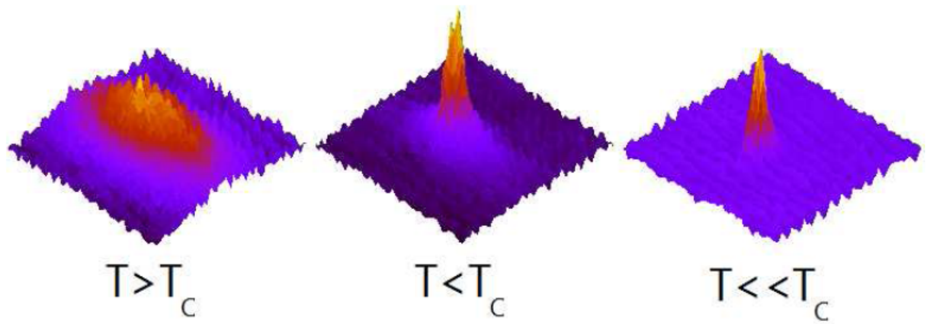
- Study of slow processes: thermalization, spin glass
- In 2D: Ladder geometry and Haldane physics
  - Bringing two chains together
    - → Maps onto Haldane physics: topological order

→ Let us build the circular Rydberg atom simulator

Present experiment: ultracold Rydberg atoms on a chip



Cold atoms trapped
on a superconducting "chip"



Rubidium atoms

➔ evaporative cooling down to 10^4 atom BEC

*Roux et al. EPL **81**, 56004 (2008)*

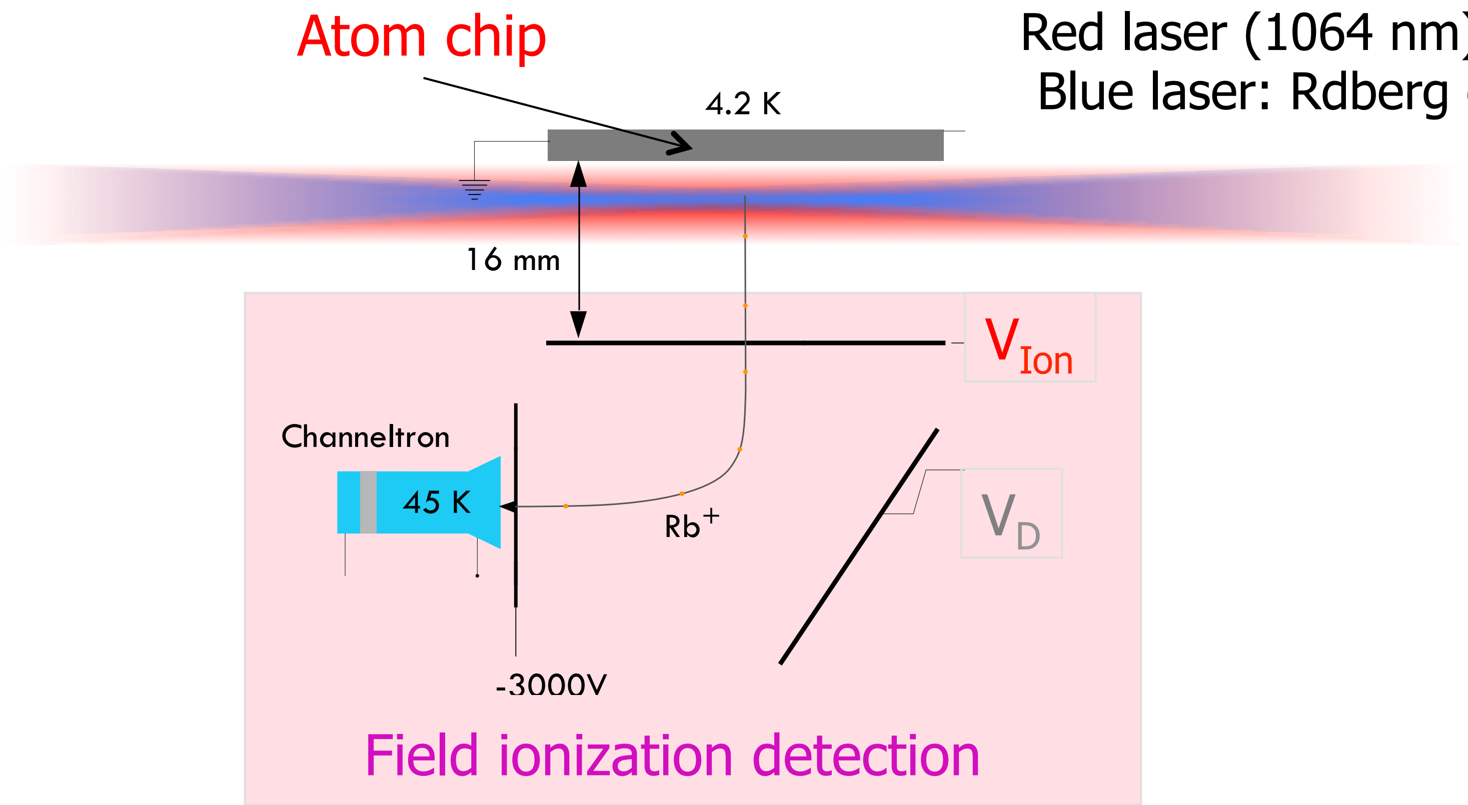
Circular atom traping: first demonstration

- Microwave spectroscopy in a gradient of electric field:

➟ the linewidth of the resonance reflects the spatial extension of the circular atom sample

➟ time of fly measurement with and without trapping

Red laser (1064 nm): trapping
Blue laser: Rdberg excitation



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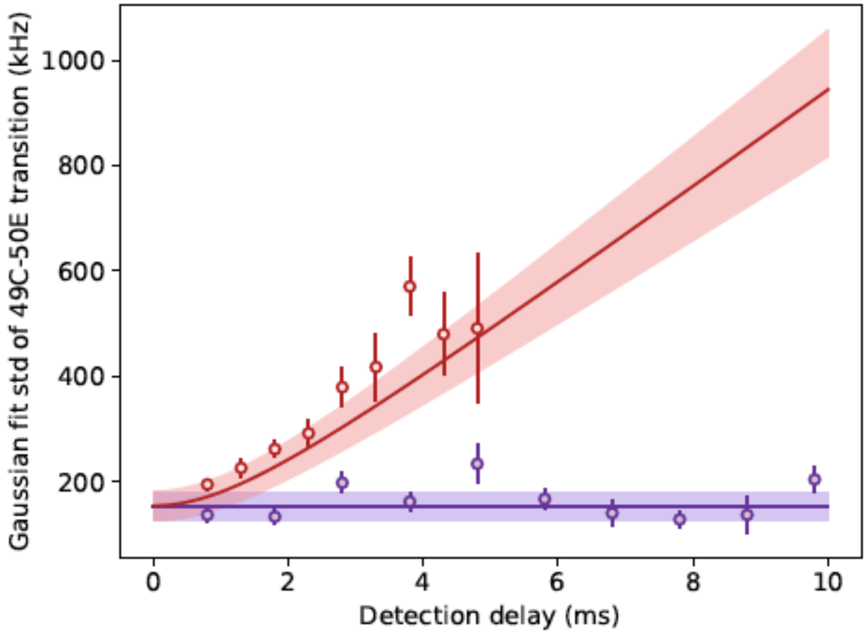
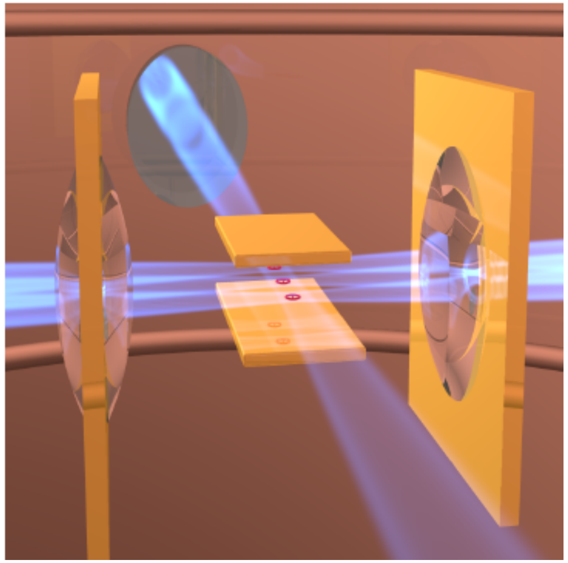
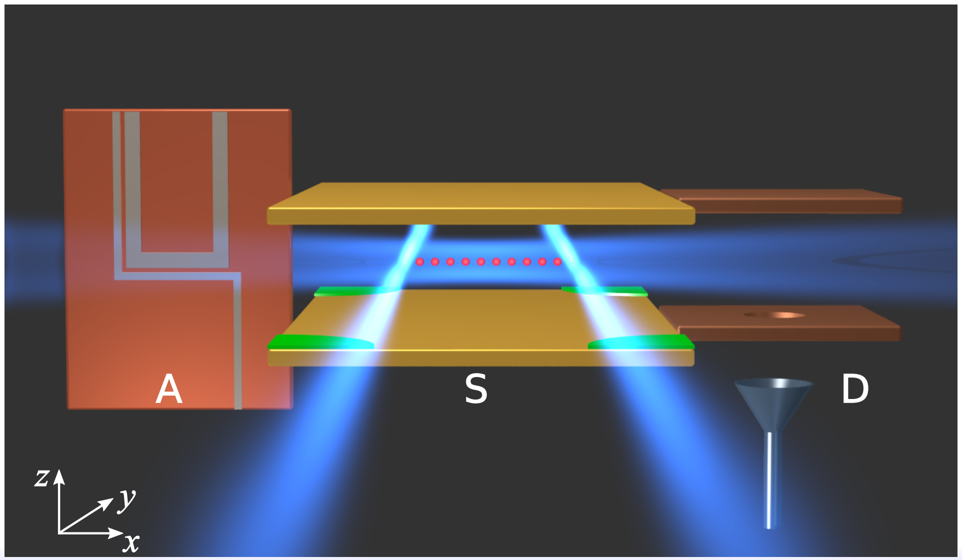


Trapping inhibits thermal expansion of circular Rydberg atoms

Trapped Rydberg atoms quantum simulator



1- Simple setup: trapping single CRA in optical tweezers 2D geometry, no control of spontaneous emission



2- Demonstrate 1-10 min inhibition of spontaneous emission for a single trapped atom

3- Put everything together!

The team

+ open post-doc positions…

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