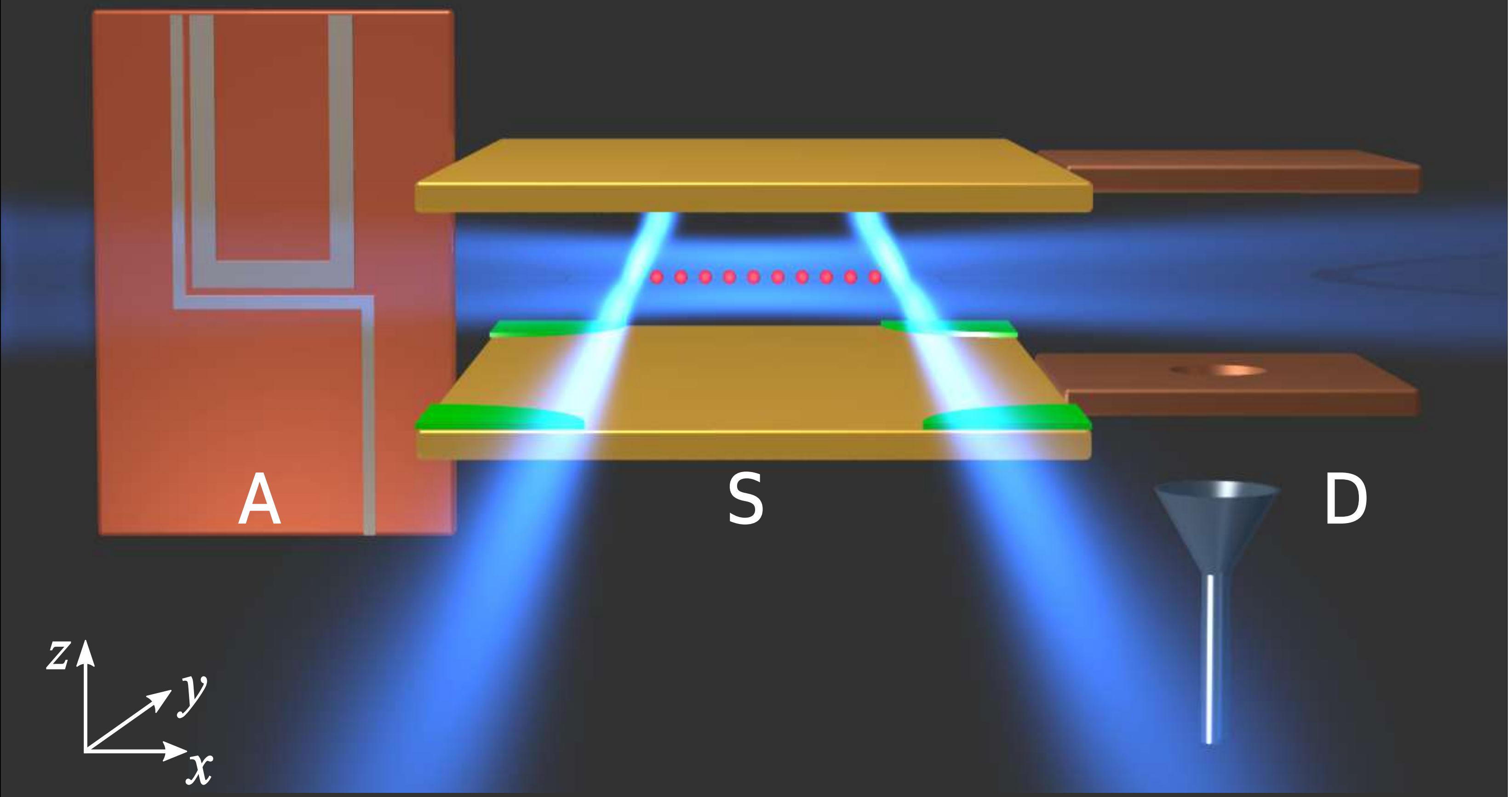
Sao Paulo ICPT School, Sept, 2019



From cavity QED to quantum simulations with Rydberg atoms

Lecture 5

Michel Brune

Laboratoire Kastler Brossel
Physique quantique et applications

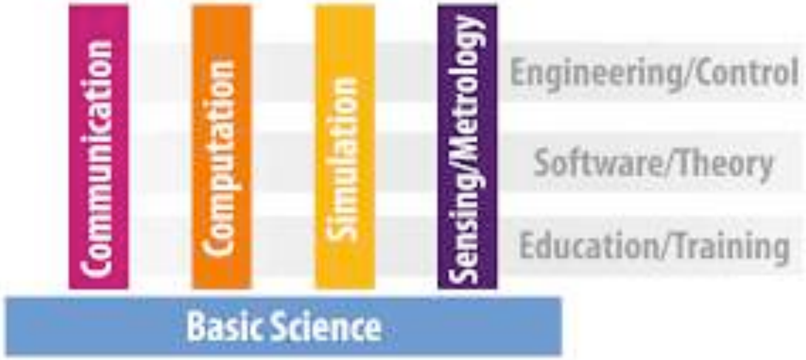
École Normale Supérieure, CNRS,
Université Pierre et Marie Curie,
Collège de France, Paris

Quantum simulation

- Quantum technologies

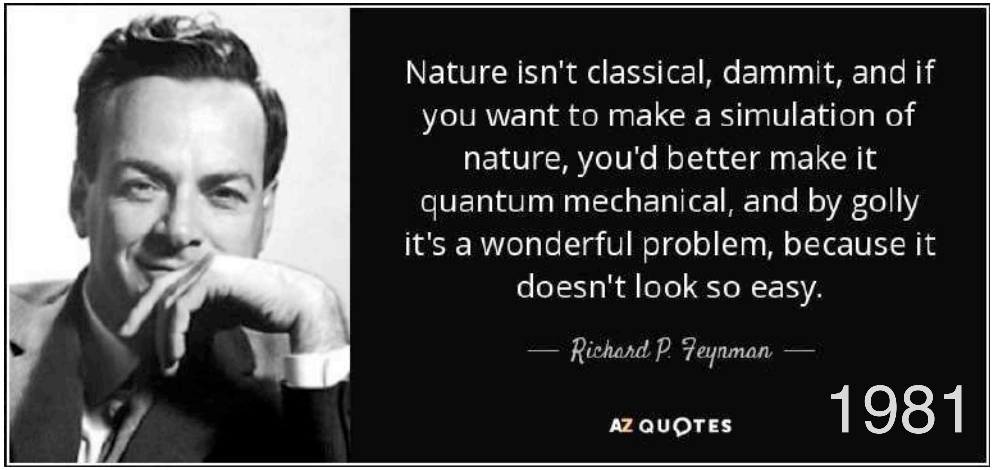
  EU Flagship

  QUANTUM
  FLAGSHIP



- **Quantum simulation:**

use a well controlled "synthetic" quantum system in order to address complex many-boby problems of solid-state physics



Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

— Richard P. Feynman —

AZ QUOTES

1981

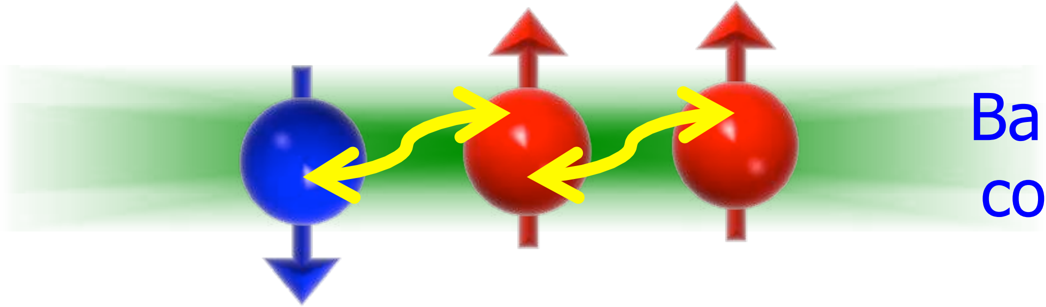
  - ❑ High degree of control of parameters in a range not accessible in the real system
  - ❑ Access to local physical properties at the level of individual elementary elements -> measurement of any correlation function

➙ Seems much "easier" than quantum computation

Quantum simulations of spin-systems

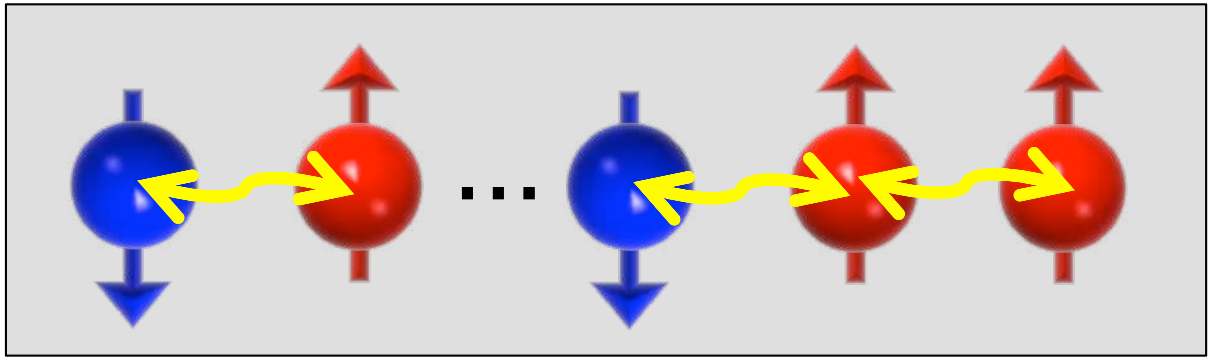
Simulations with computer?

Simple



Barely more complicated

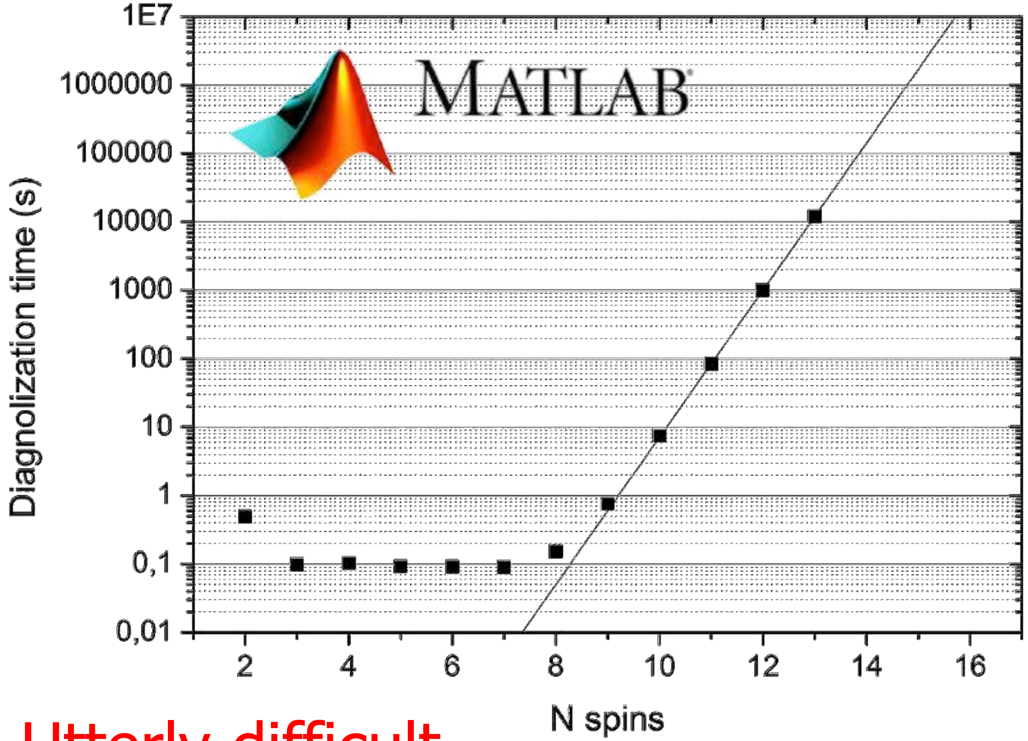
Utterly difficult



Impossible!

Quantum simulations of spin-systems

Simulations with computer: face exponential size of Hilbert space



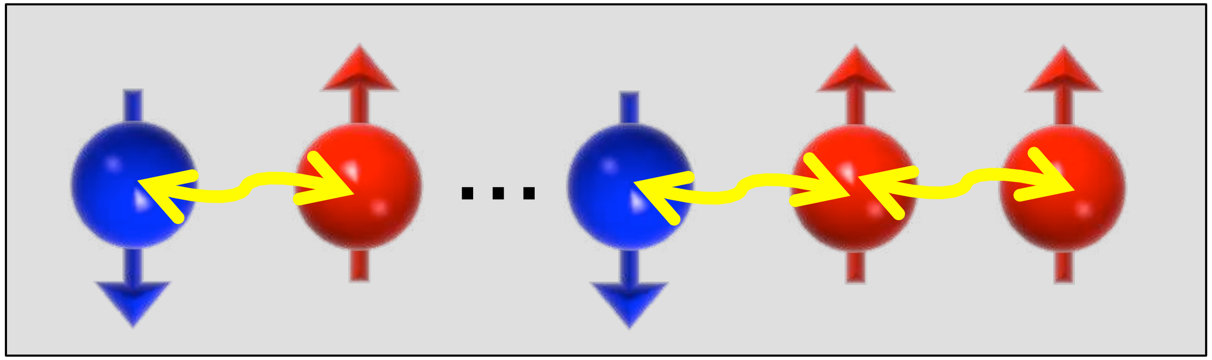
N = 10 → ~ 7 s

N = 13 → ~ 3 h

N = 16 → ~ 8 months

N = 40 → ~ 4 10^{25} years

Utterly difficult



Impossible!

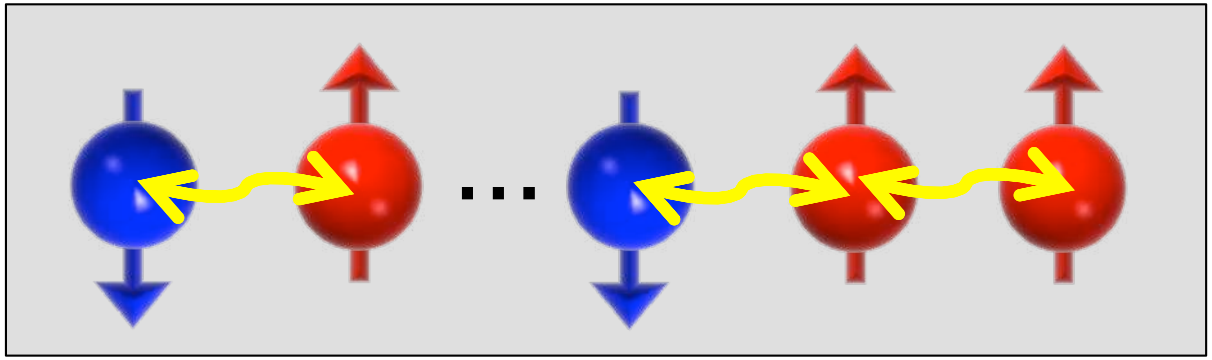
Quantum simulations

Simulations with computer?

Linear chain of N spins-1/2:

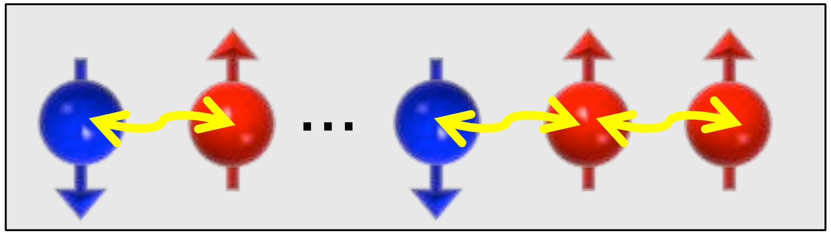
- Exact diagonalization: N ~ 36 (present performance)
- Ground-state: well-known via powerful numerical techniques (DMRG)
- Dynamics… tricky! Few tens of interaction cycles only.

Utterly difficult



Impossible!

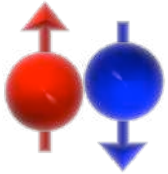
Spin chain quantum simulation



Simulation of a chain of interacting spins-1/2

Requirements?

- Spin 1/2

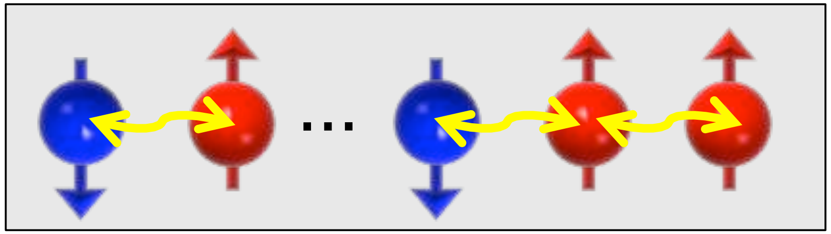


- Defect free chain of spins preparation
- Long lifetime and strong interaction

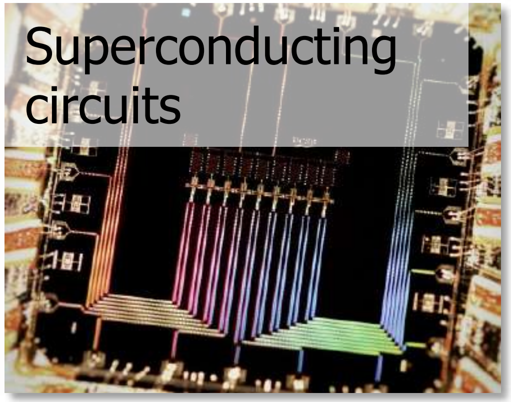
→ Observe many interaction cycles

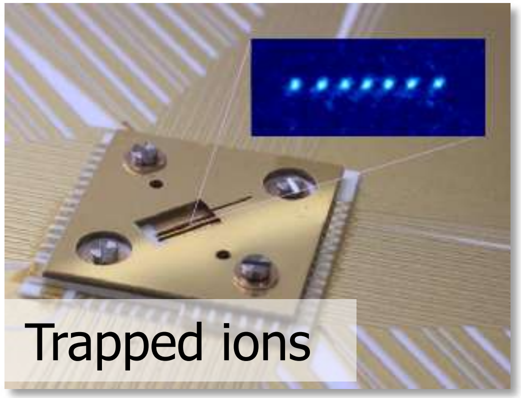
- Fully tunable Hamiltonian $H = H_0 + H_{\text{ext}} + H_{\text{int}}$

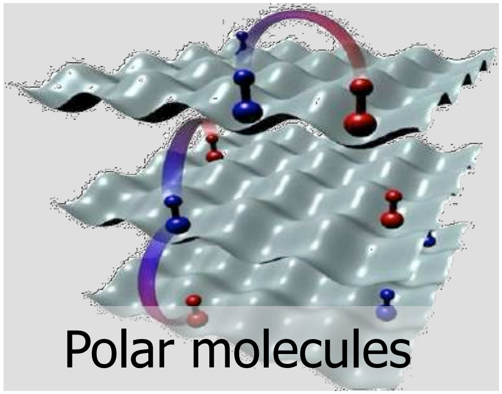
Quantum simulations: various systems

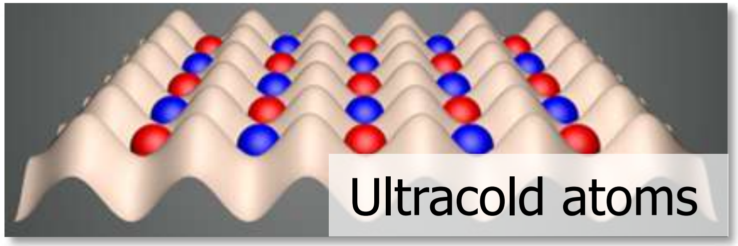


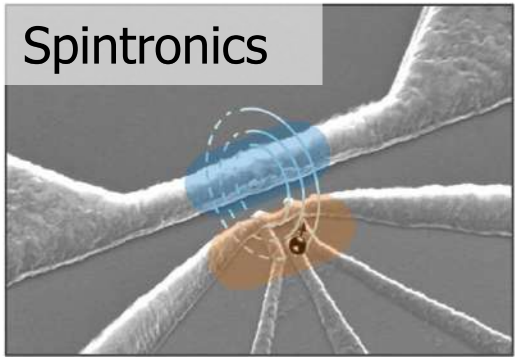
How to simulate?

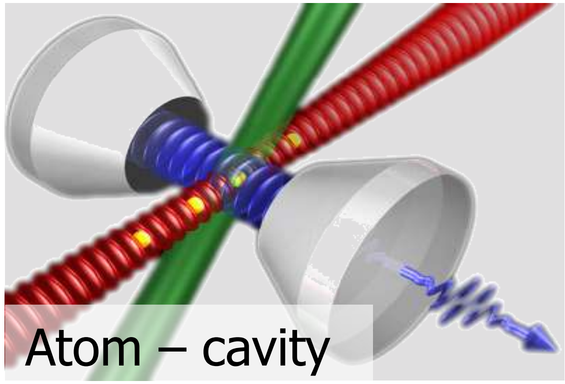

Superconducting circuits

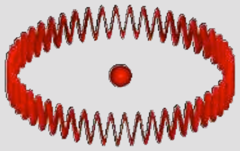

Trapped ions


Polar molecules


Ultracold atoms

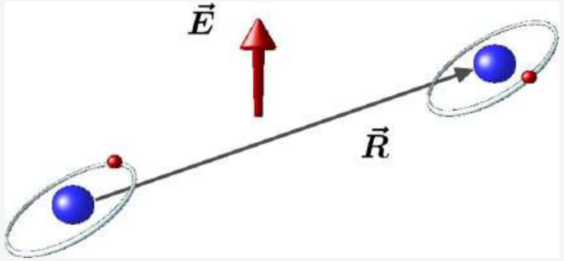

Spintronics


Atom – cavity


Rydberg atoms?

Rydberg atoms dipole-dipole interaction

Dipole interaction



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

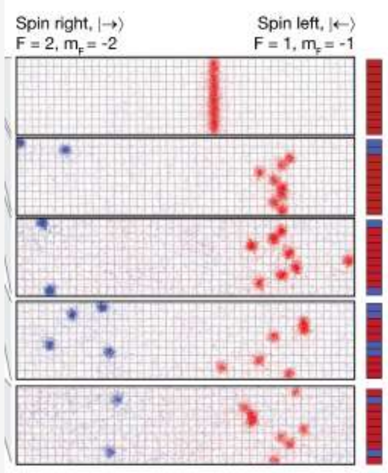
Rydberg atoms have large dipole: $d=q\ a_0\ n^2 \simeq 2000$ a.u. for $n=50$

➞ coupling strength in the MHz range at a distance $d=5\ \mu$m
Typically 10^{11} times larger than for ordinary atom

➞ fast quantum gates and quantum simulation as compared with the dissipation timescales

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

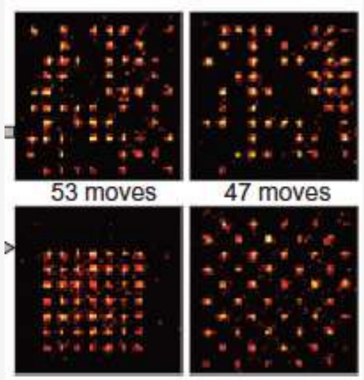
$$\tau_{loss} \approx 130 \mu s$$

→ Filling factor smaller than 1

I. Bloch, C. Gross

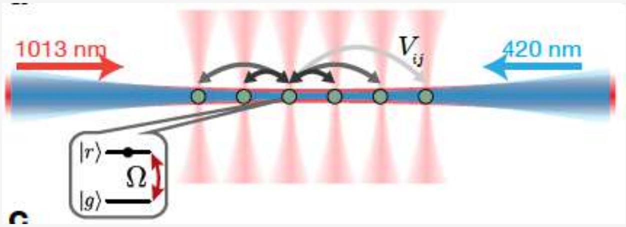
arXiv:1705.08372

- 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

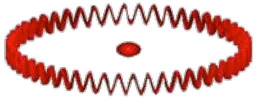
Rydberg atoms quantum simulator

- 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)



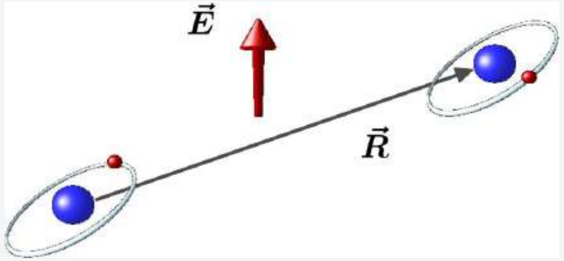
  - ❑ Long natural lifetime, 25 ms for n=48
    - → Spontaneous emission can even be supressed
  - ❑ Large orbit $r_n \sim n^2 a_0$ → Huge electric dipole matrix elements
  - → Strong dipole – dipole interactions
  - ❑ Can be trapped without ionizing

T.L. Nguyen et al, PRX 2018

→ good candidates for building a quantum simulator

Dipole interaction between circular atoms

Dipole interaction

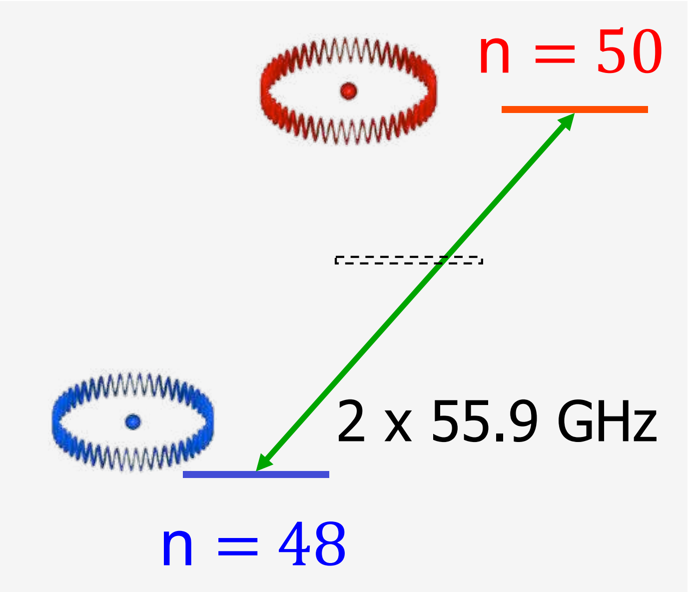


$$V_{dd}=\frac{q^2}{4\pi\varepsilon_0 r^3}\left(\vec{r}_1.\vec{r}_2-3\left(\vec{r}_1.\frac{\vec{r}}{r}\right).\left(\vec{r}_2.\frac{\vec{r}}{r}\right)\right)$$

$|nC,nC\rangle$ 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

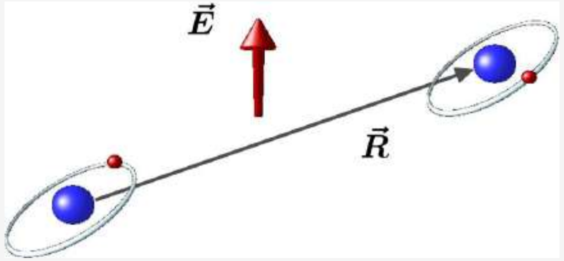


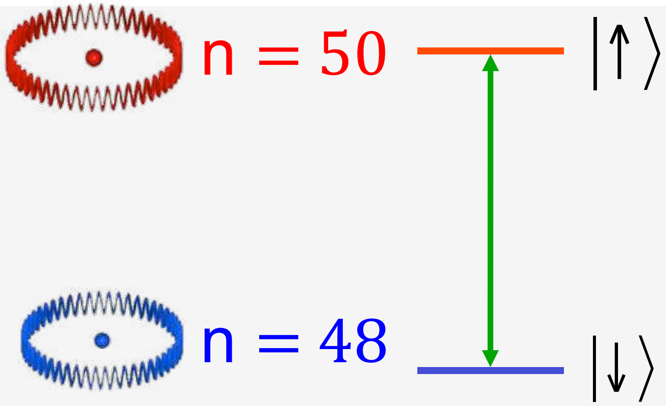
Large n → more BB radiation
→ shorter lifetime
Small n → lower interaction

→ chose 48C and 50C

XXZ spin chain model

Dipole interaction





Next-neighbor spin chain hamiltonian

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

X or Z fields
→result from
microwave dressing:

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

Ising

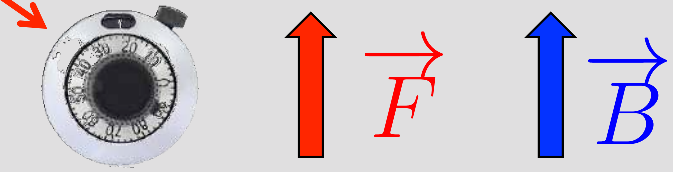
exchange

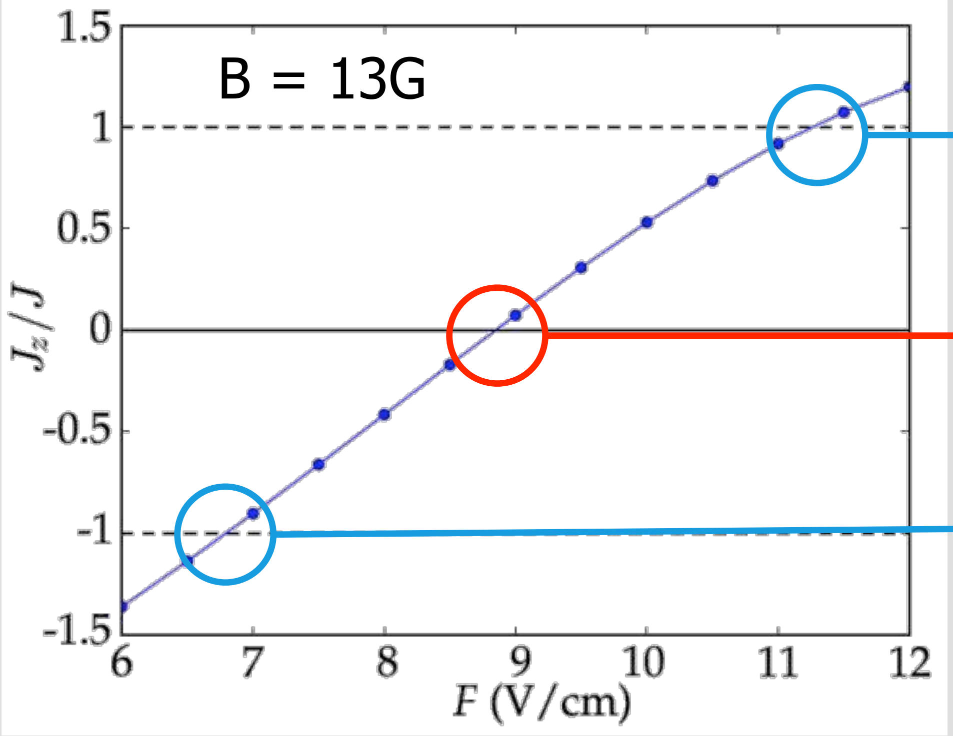
Tunability of XXZ Hamiltonian

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

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

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

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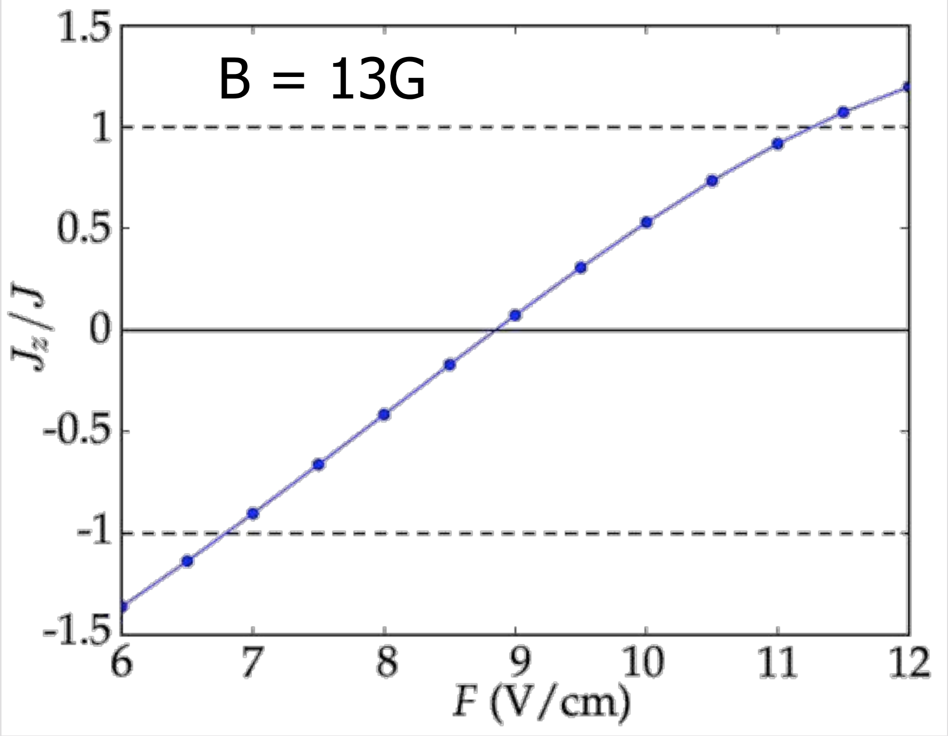

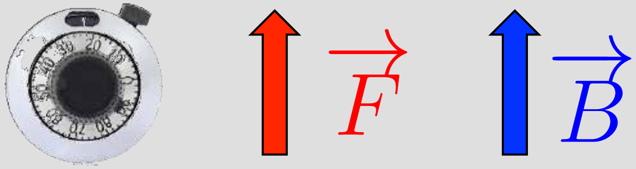

- Interaction strength
  - ❑ J= 17 kHz for d= 5 μm,
  - ❑ Spin exchange time 1/4J in the 10 μs range

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

Tunability of XXZ Hamiltonian

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

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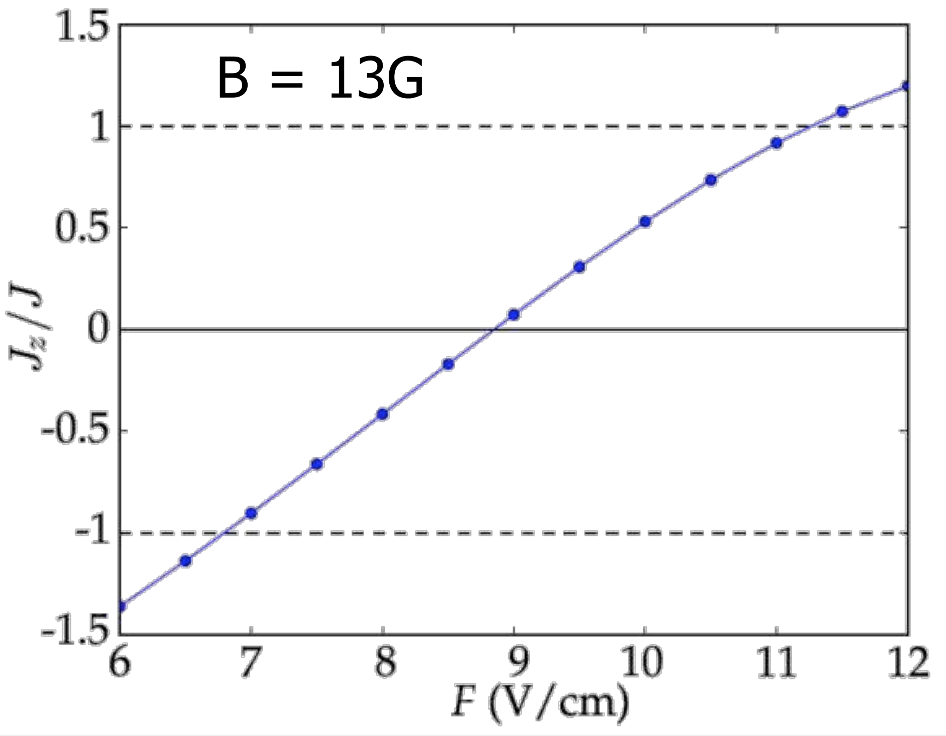
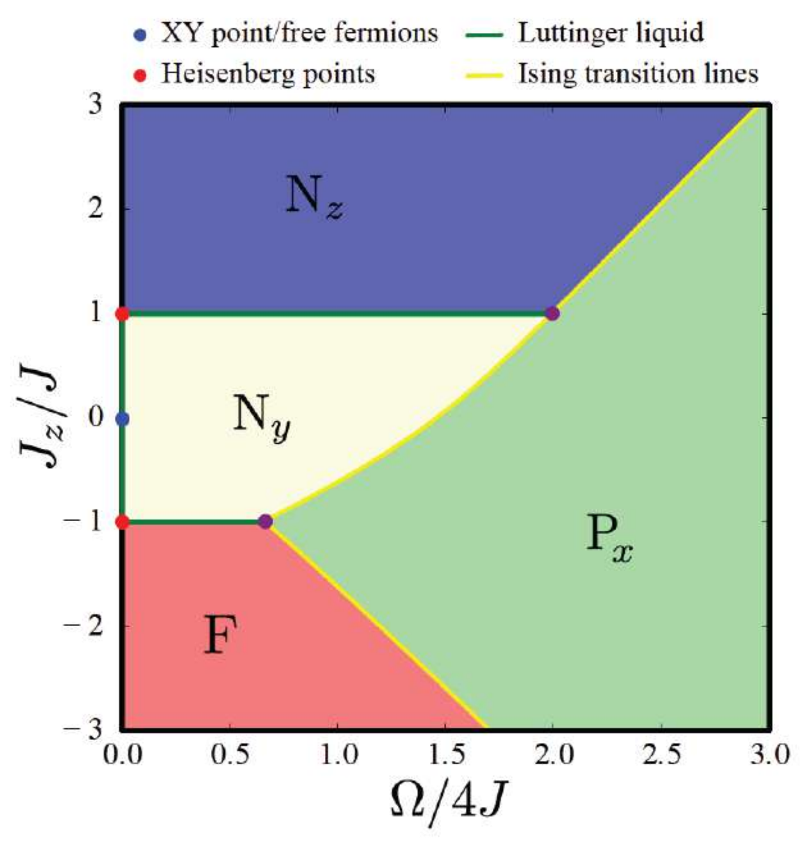


Phase diagram at Δ=0

(Guillaume Roux LPTMS)



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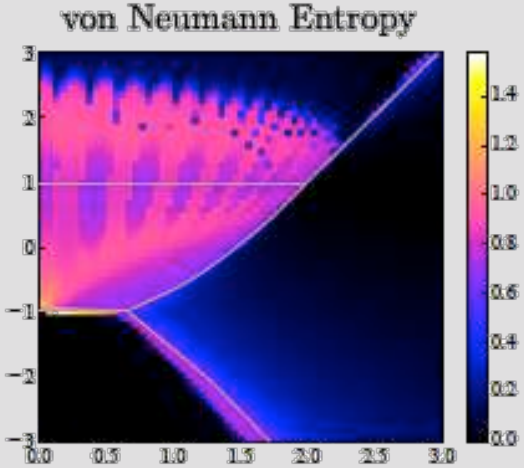
→explore phase diagram by adiabatic variation of parameters as a benchmark

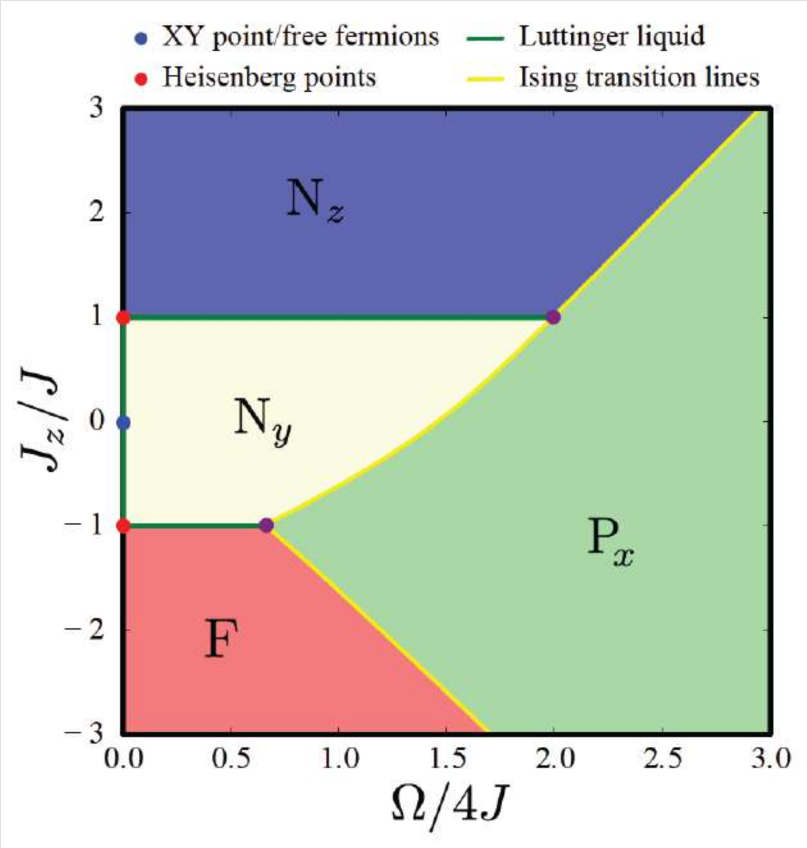
Collaboration with G. Roux (LPTMS, Paris Saclay)



DMRG calculations with 40 atoms

Phase diagram at Δ=0

(Guillaume Roux LPTMS)



Tunable XXZ spin chain model

Next-neighbor spin chain hamiltonian

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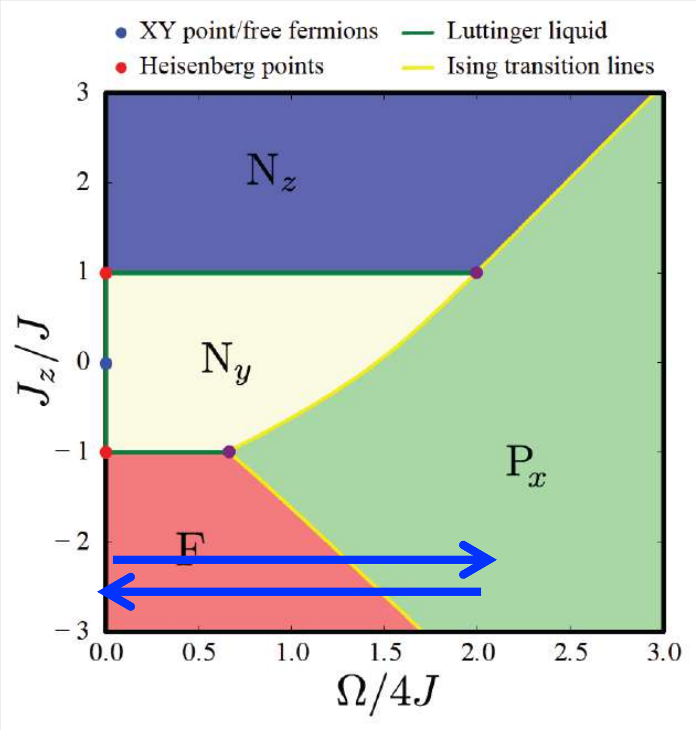
Phase diagram at Δ=0

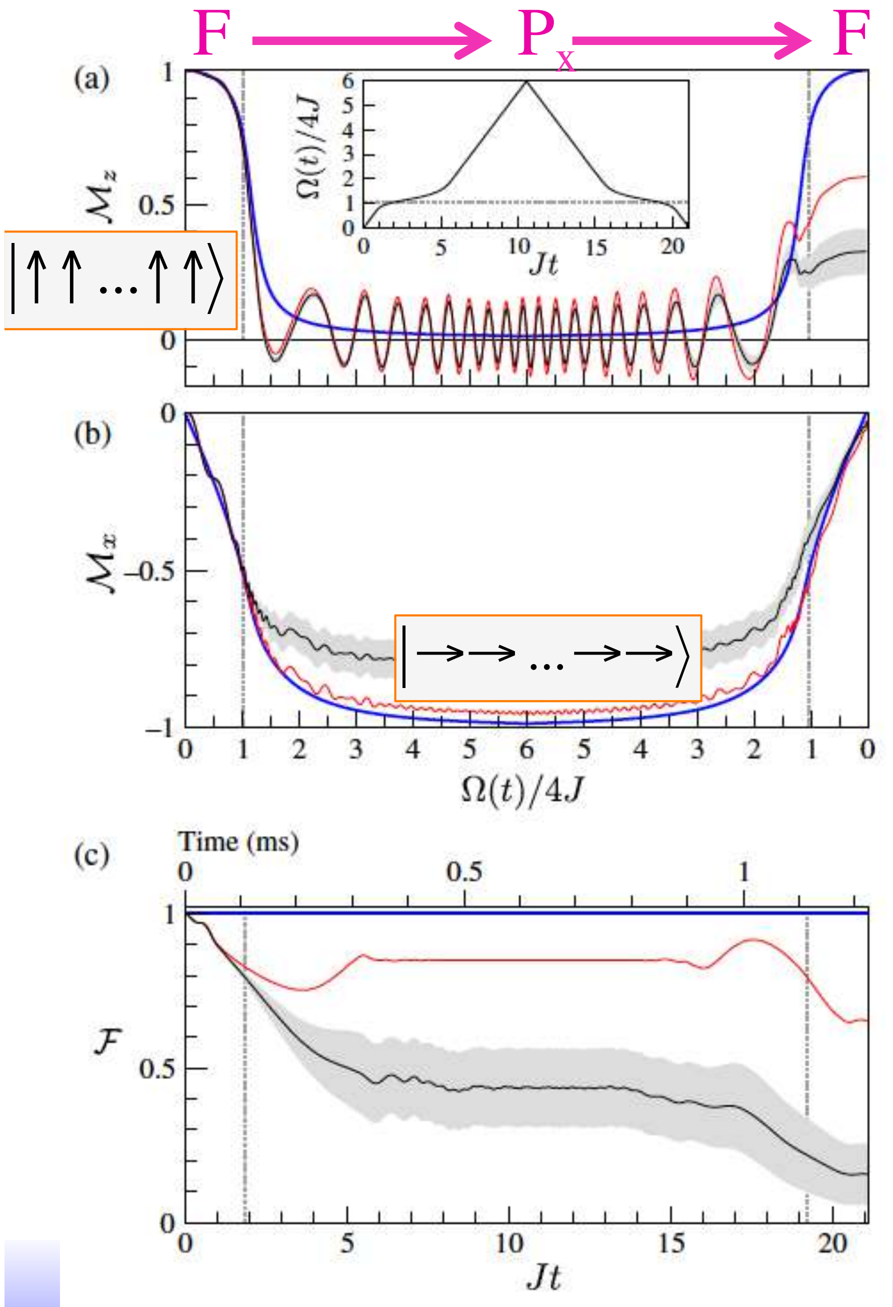
(Guillaume Roux LPTMS)



- F: ferromagnetic, all spin // Z
- P: paramagnetic, all spin // X
- $N_{x,y}$: Néel phases, altenated spin up-down along X or Y

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

Exact simulation of adiabatic phase transitions



Simulation for 14 spin
Including residual motion

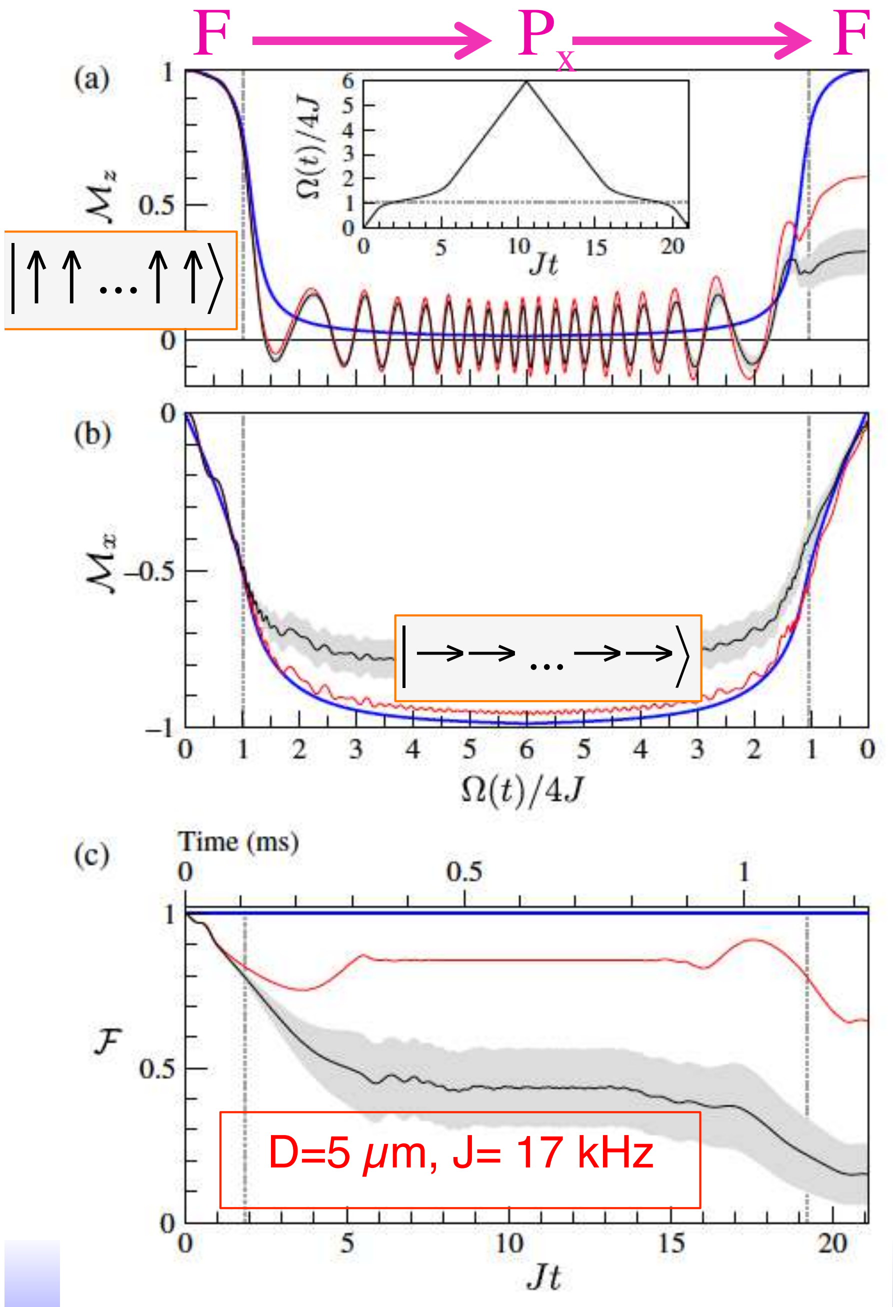
Exact ground state
Adiab evol, no motion
Adiab evol+motion

D=5 μm, J= 17 kHz

➞ fidelity strongly affected by residual atomic motion

PRX 2018, arXiv 1707.04397

Exact simulation of adiabatic phase transitions

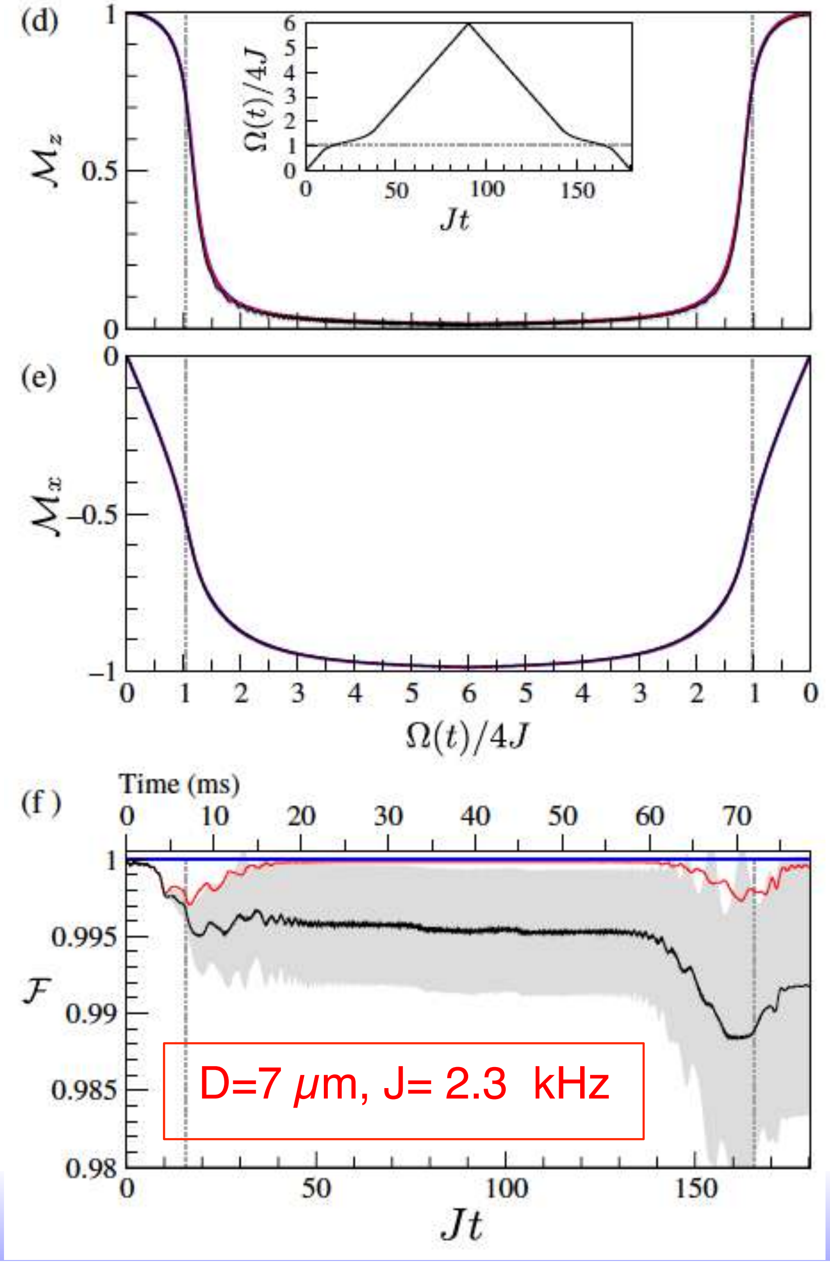


$F \longrightarrow P_x \longrightarrow F$

$|\uparrow\uparrow \dots \uparrow\uparrow\rangle$

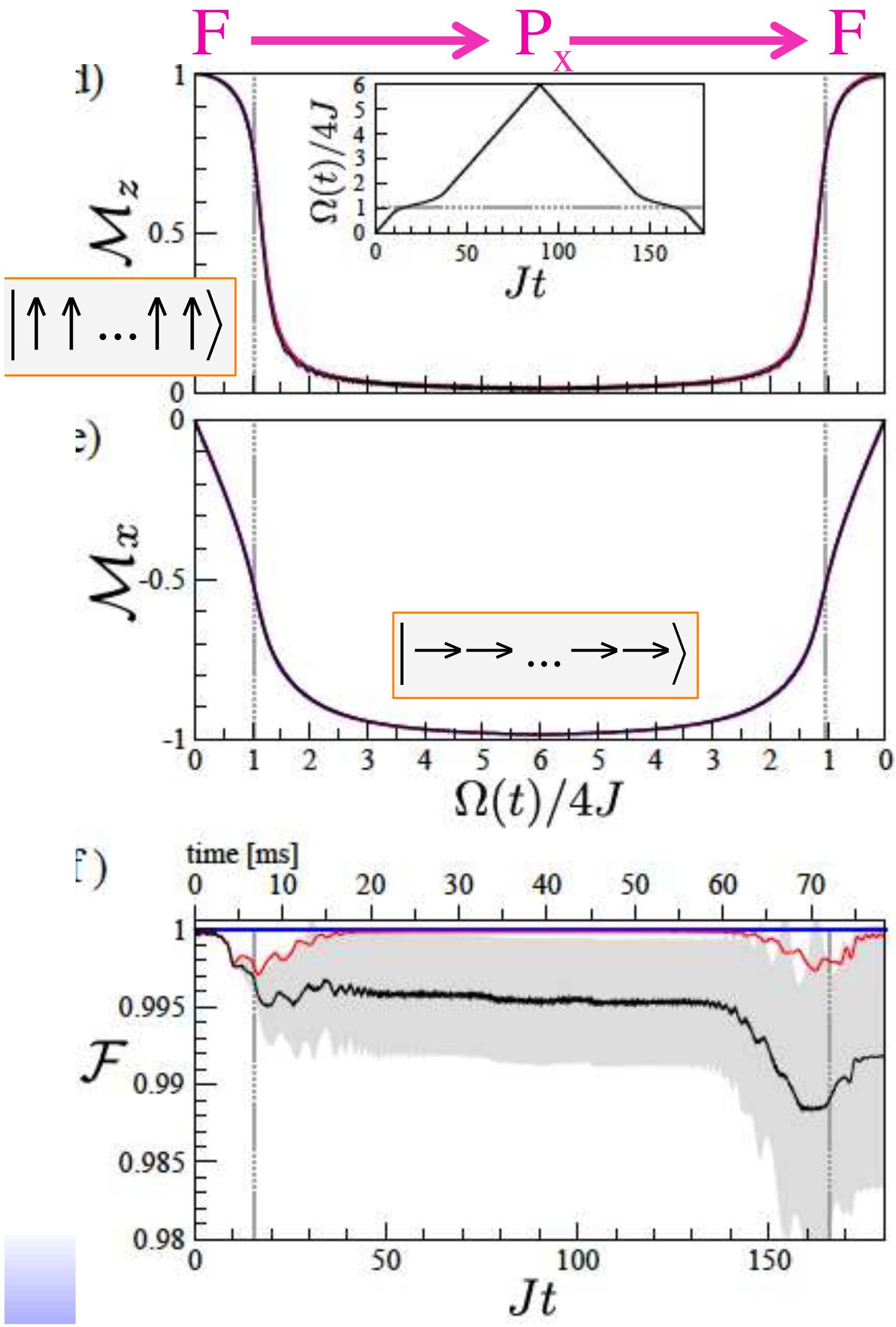
$|\rightarrow\rightarrow \dots \rightarrow\rightarrow\rangle$

D=5 μm, J= 17 kHz



D=7 μm, J= 2.3 kHz

Exact simulation of adiabatic phase transitions



Simulation for 14 spin
Including residual motion

d=7 μm, J= 2.3 kHz

For slox spin coupling wrt vibrationnal mo

→ nearly perfect preparation of phase P_X

→ fidelity weakly affected by residual atomic motion

PRX 2018, arXiv 1707.04397

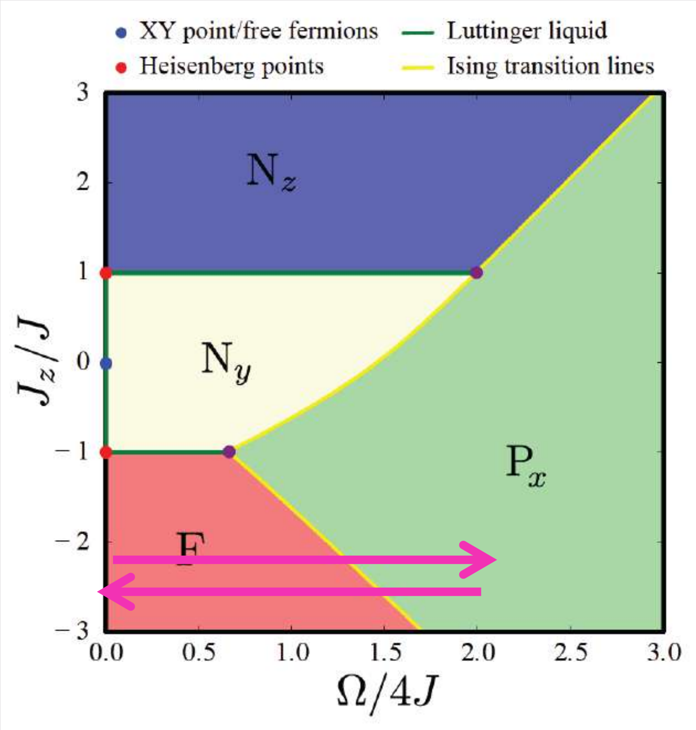
Tunable XXZ spin chain model

Next-neighbor spin chain hamiltonian

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

Phase diagram at Δ=0

(Guillaume Roux LPTMS)



- ➙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

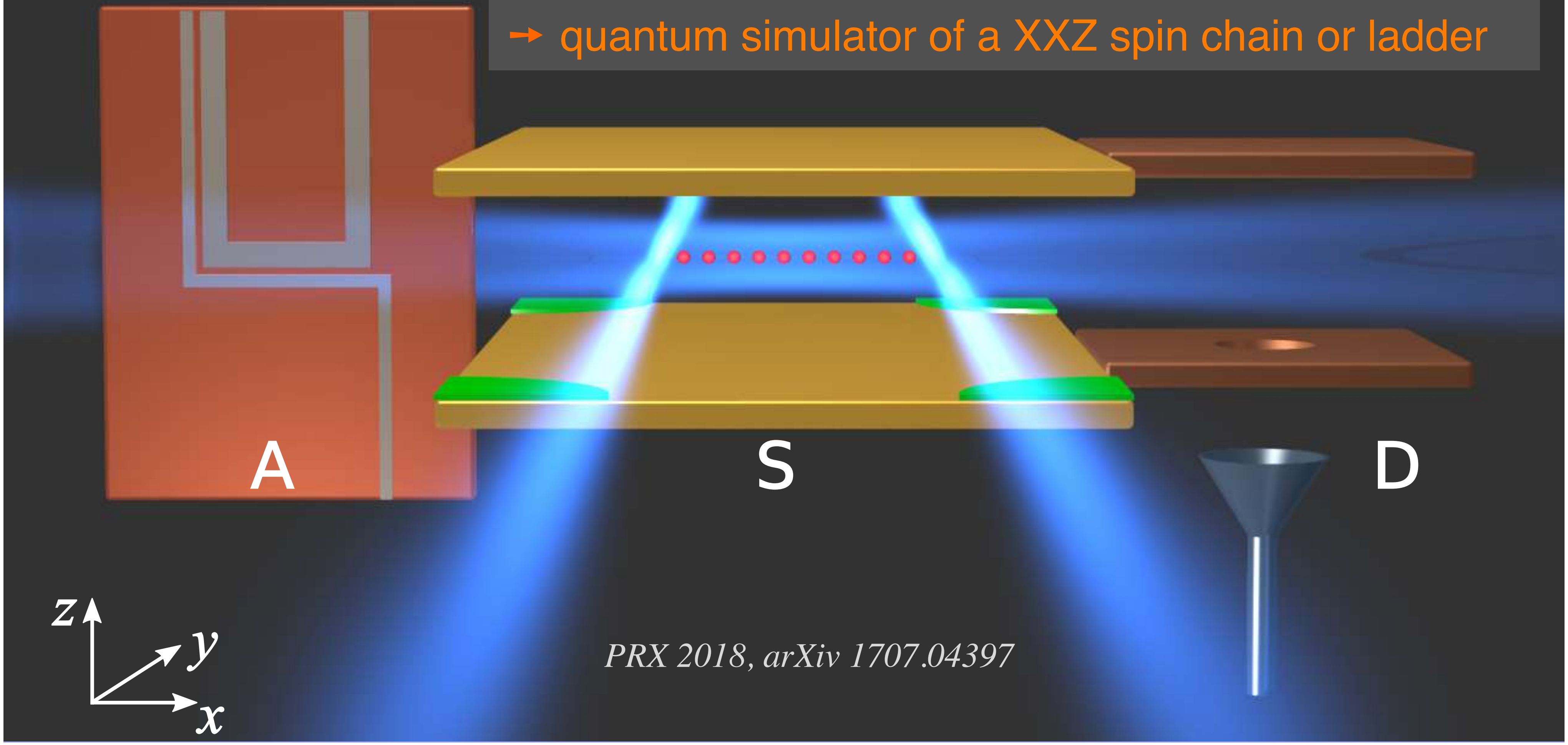
Trapped circular Rydberg atoms

- 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

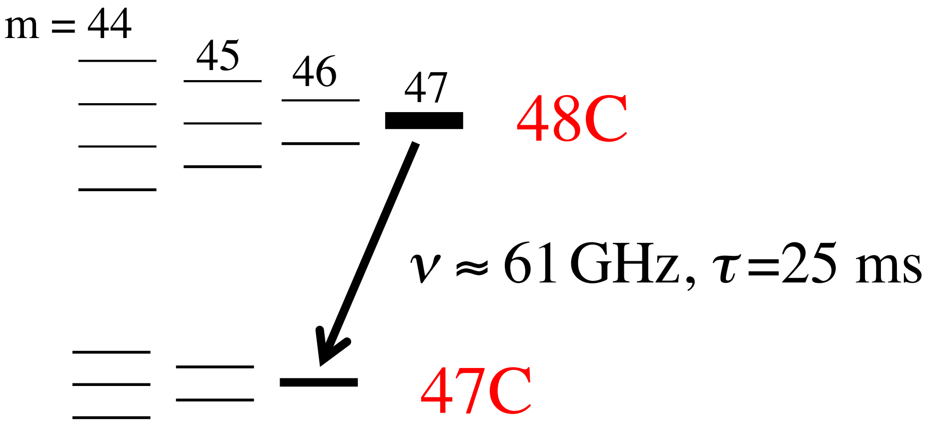


PRX 2018, arXiv 1707.04397

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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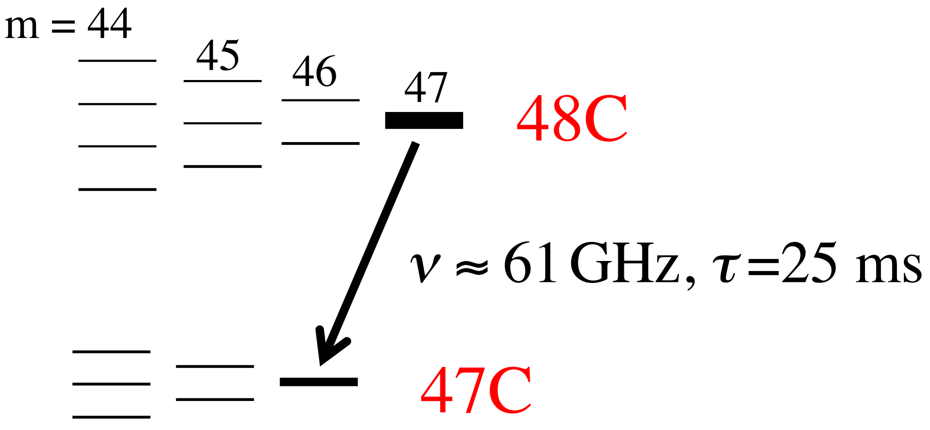
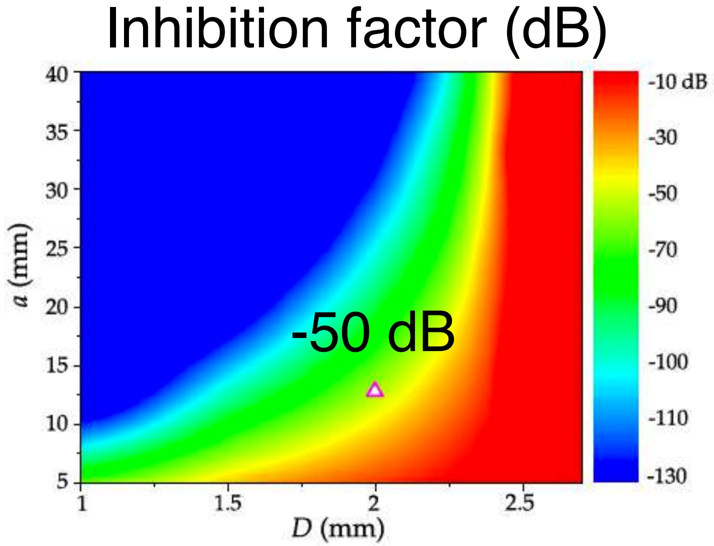
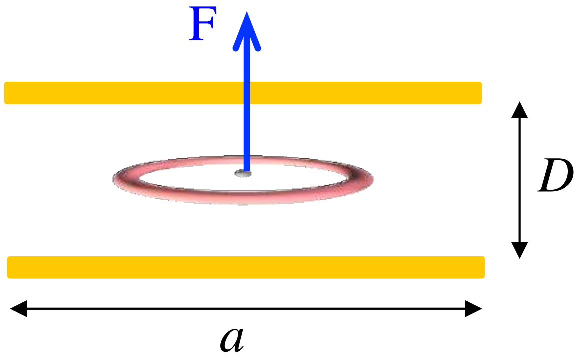




- Spontaneous emission inhibition

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

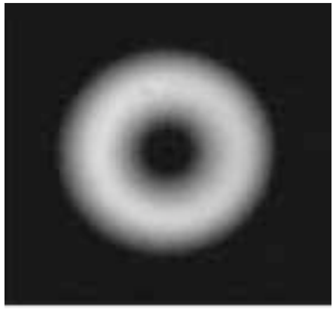
- ❑ Emission inhibited in a capacitor below cut-off.



→ 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

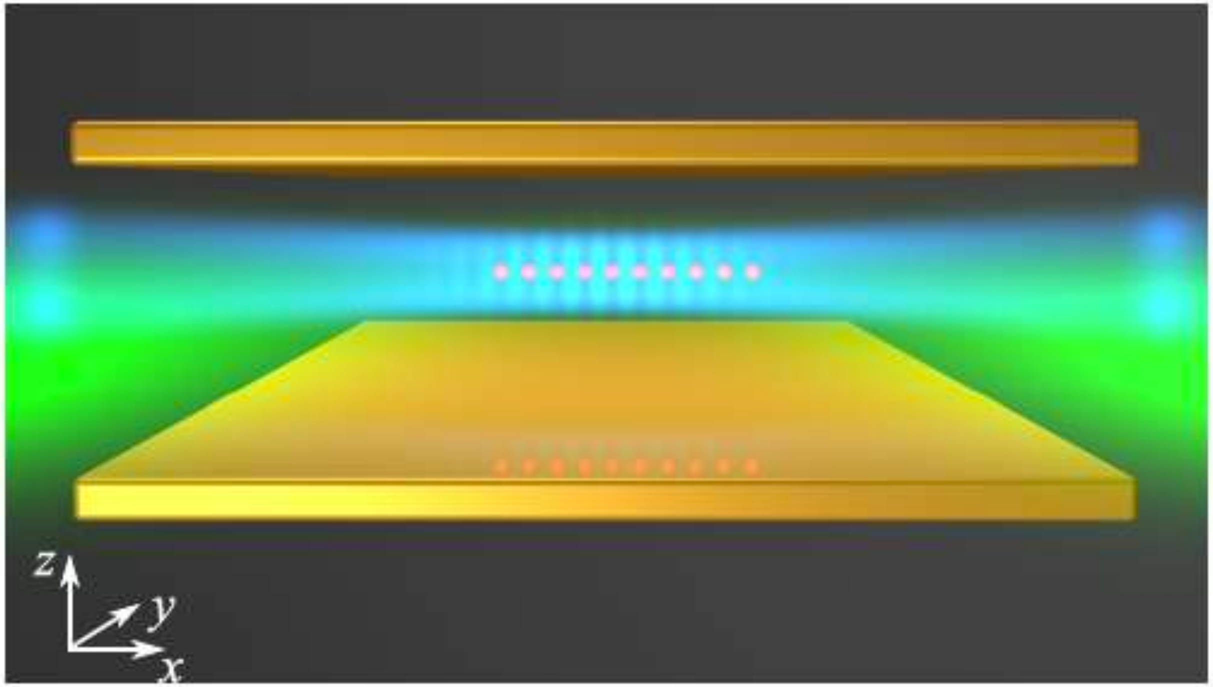
  - ❑ Impervious to photoionization

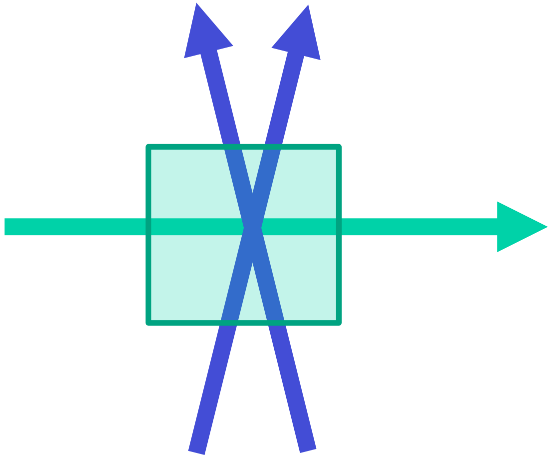
    → severe limitation for low *l* states

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

A simple trap geometry for a 1-D lattice

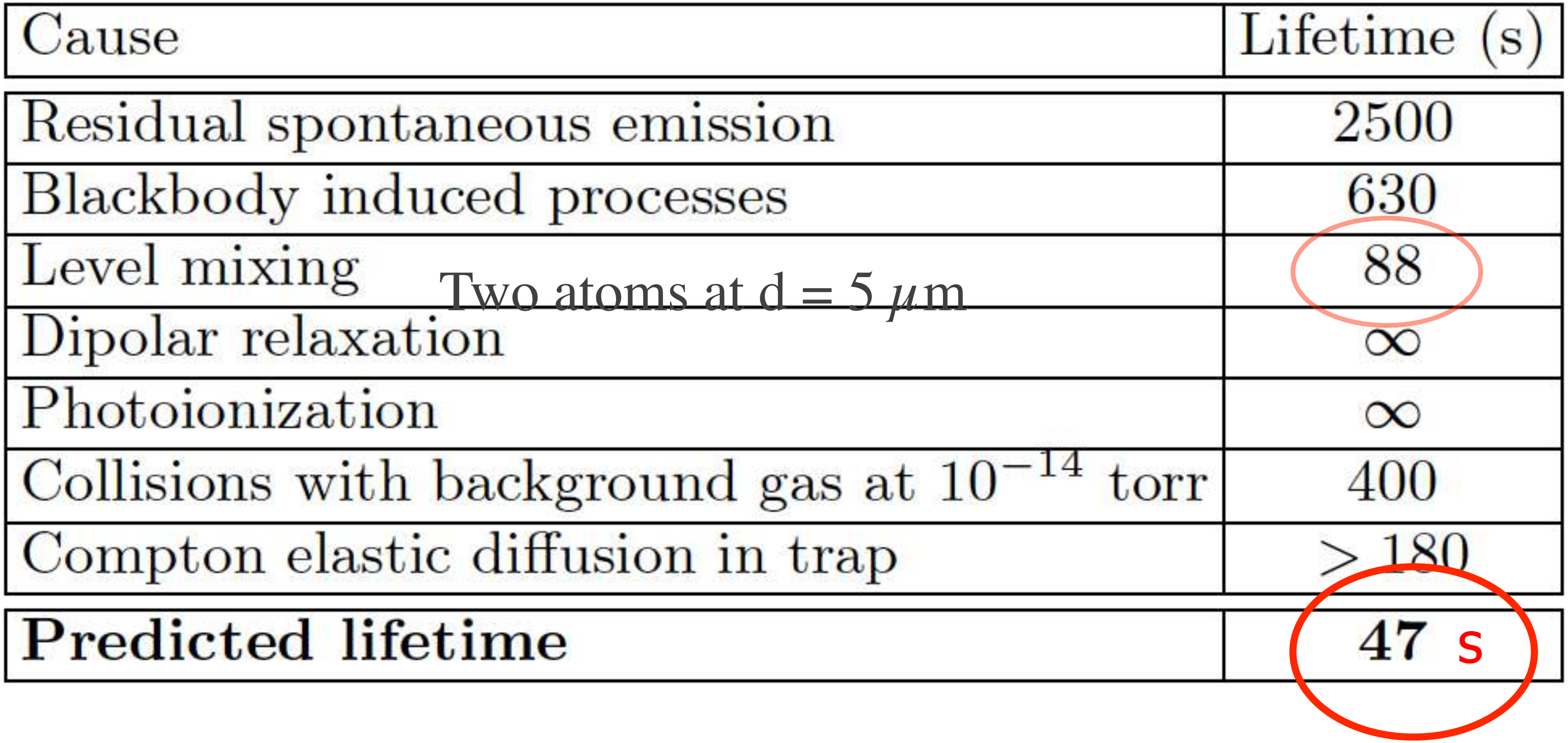
- Trapping lasers at 1 μm





- ☐ 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

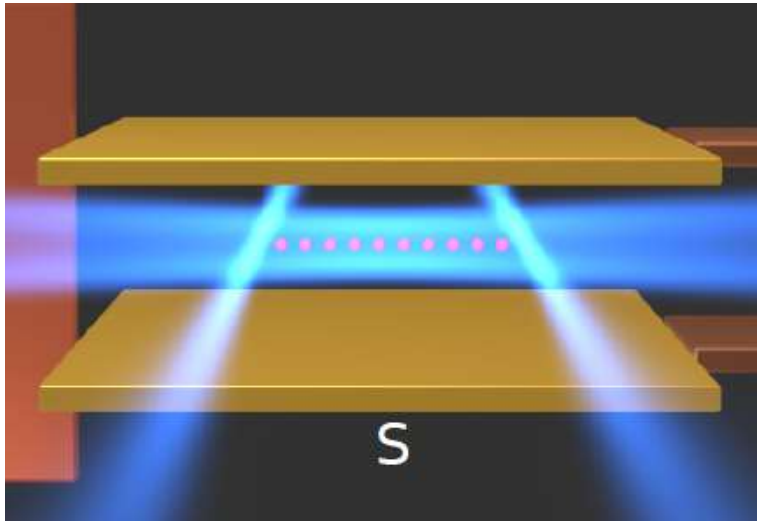
This corresponds to 10^4-10^5 exchange time

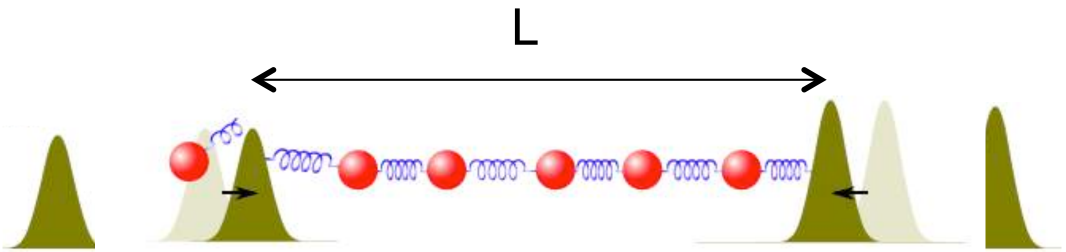
Deterministic chain preparation

- 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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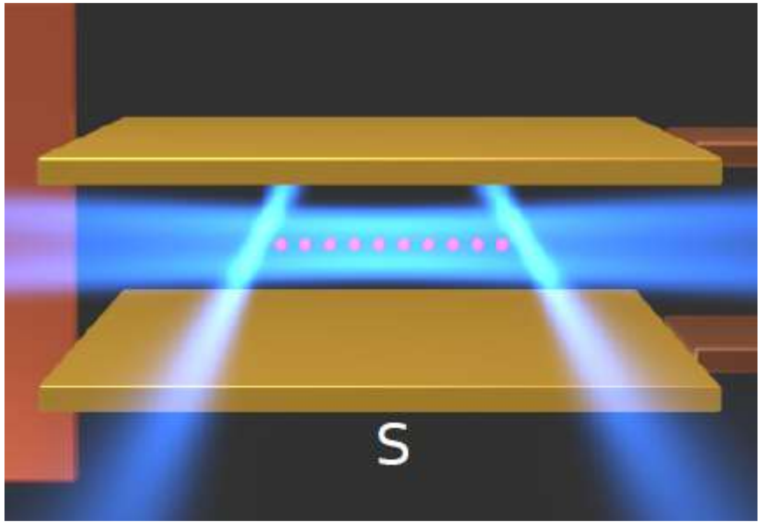

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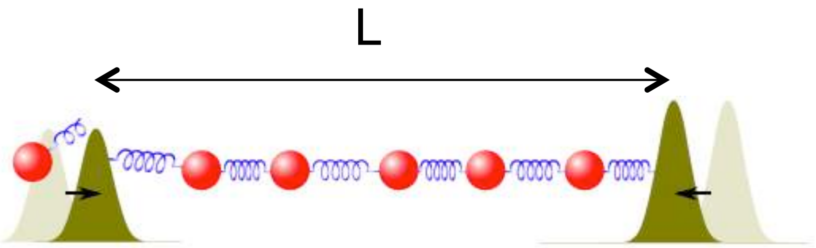
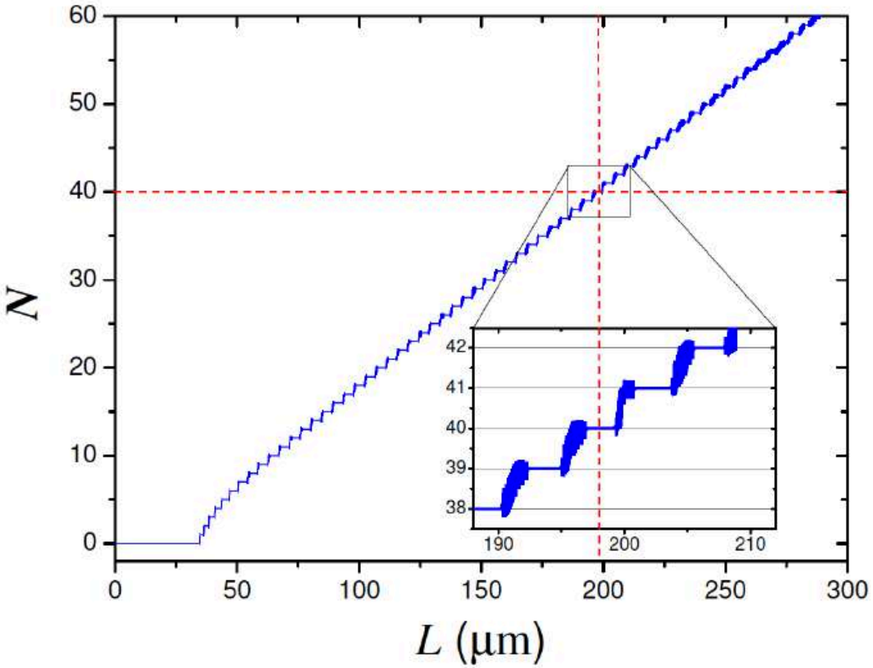
Deterministic chain preparation up to ~40



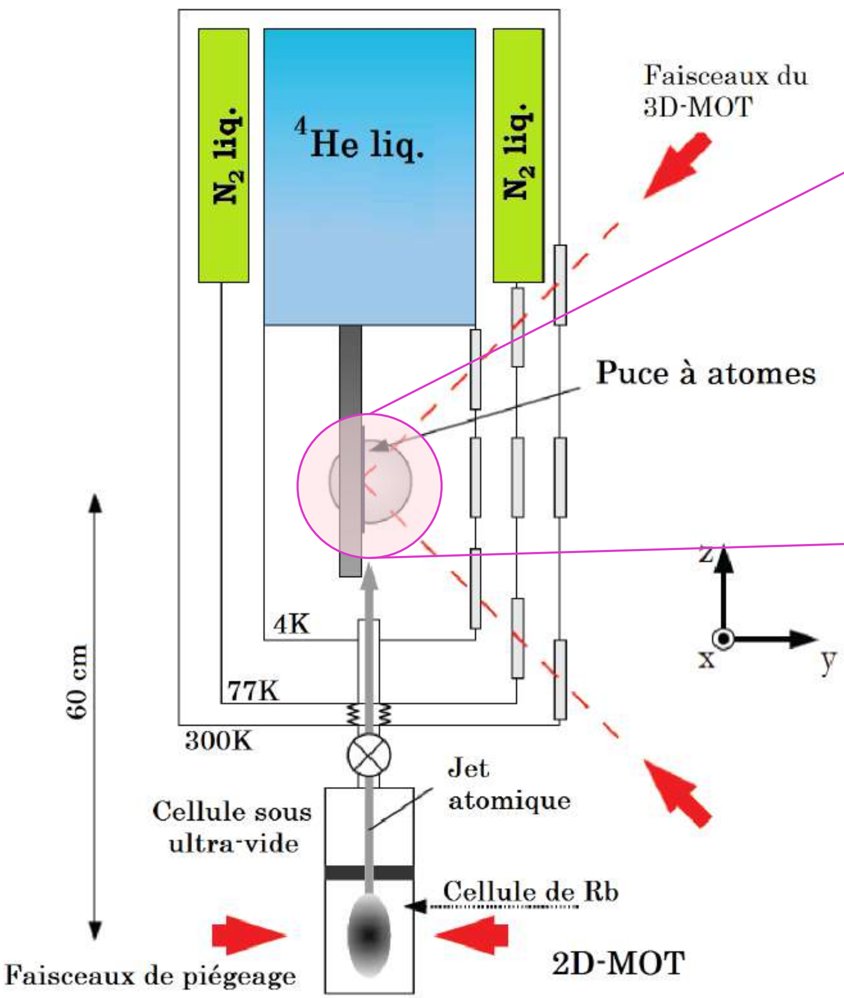


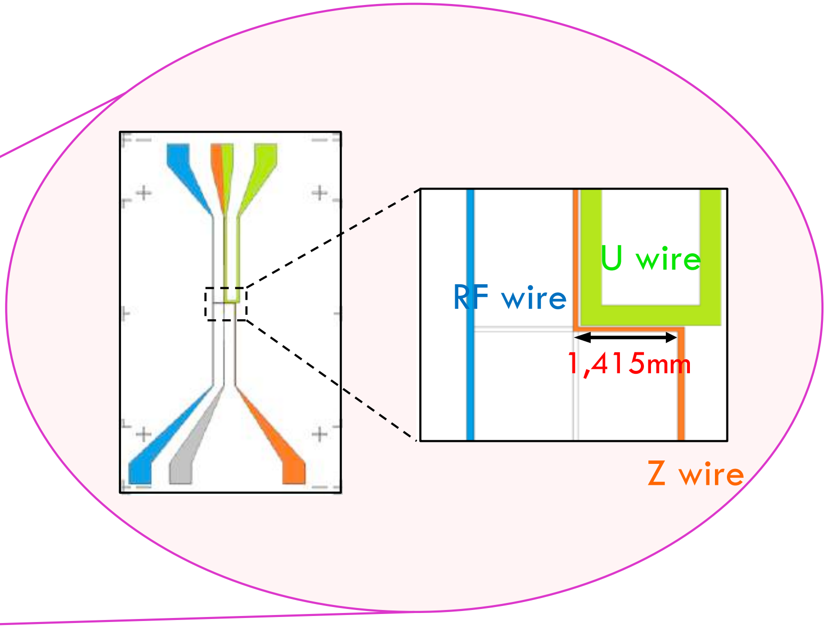
➞Efficient evaporative cooling cooling

Final motion amplitude close to ground state

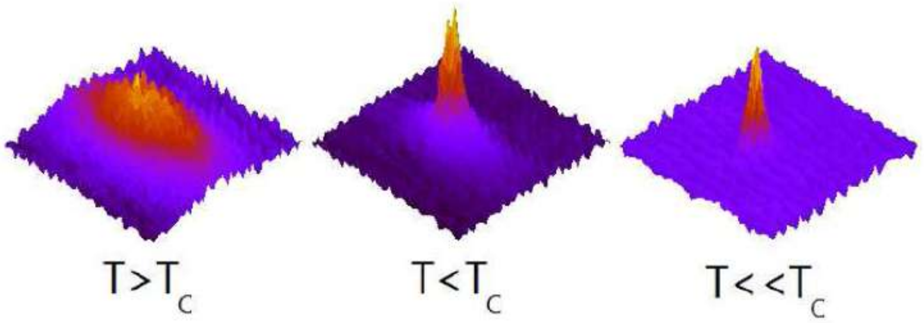
Thermodynamic description: collab. with David Papoulard (Univ. Cergy)

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

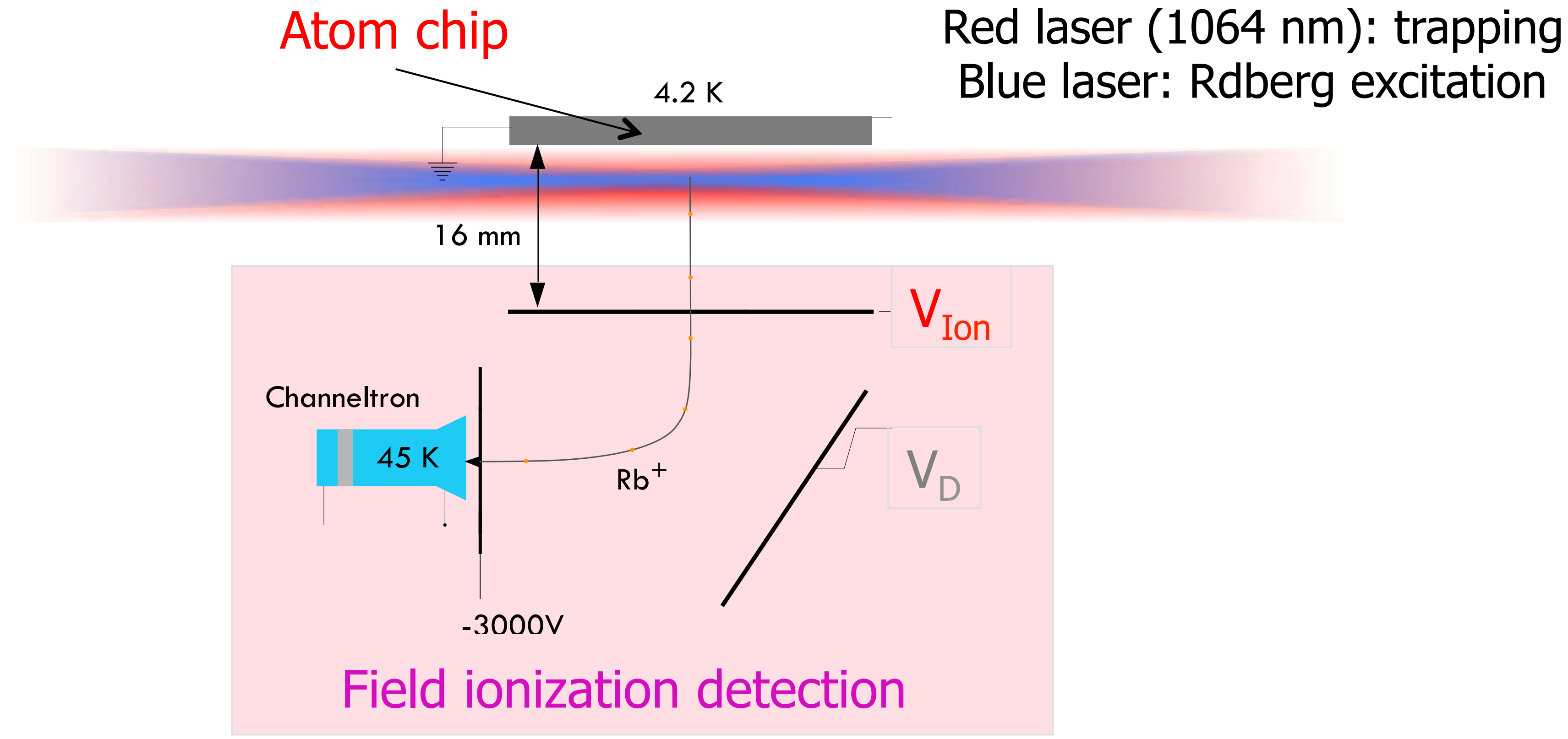
*Roux et al. EPL **81**, 56004 (2008)*

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



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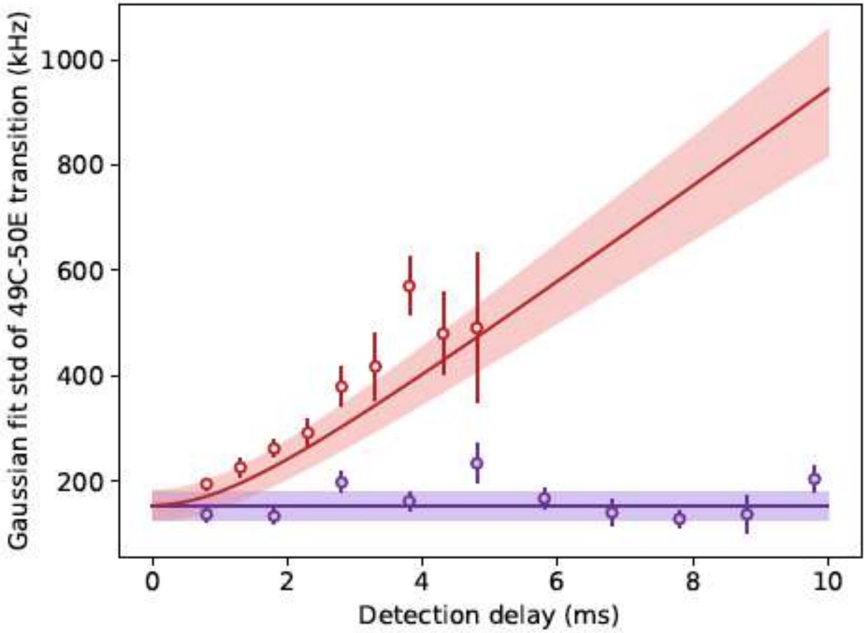
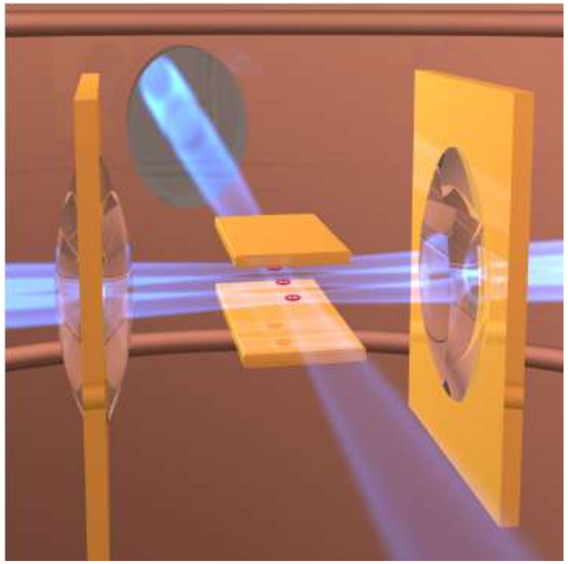
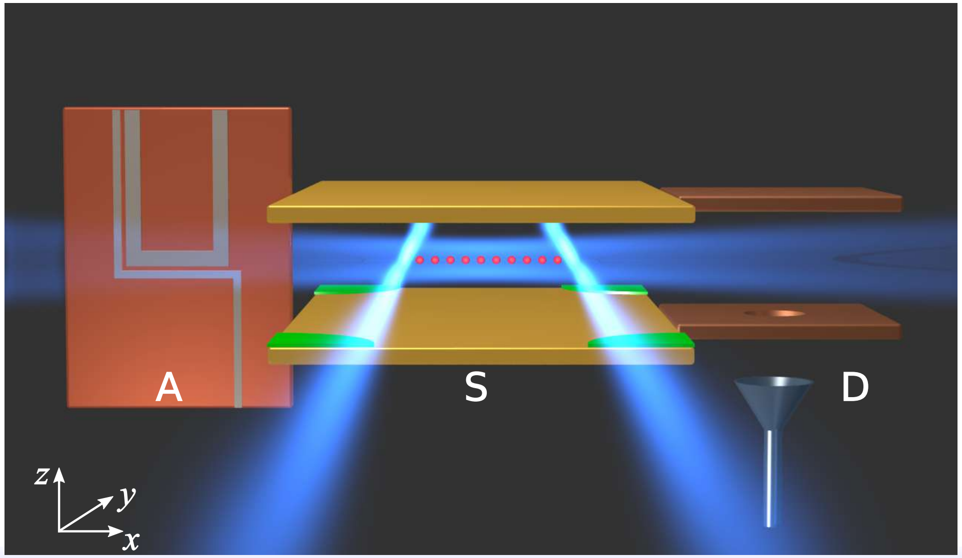


Trapping inhibits
thermal expansion of
circular Rydberg atoms

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 LKB-ENS cavity QED team

- Staring, in order of apparition

- Serge Haroche
- Michel Gross
- Claude Fabre
- Philippe Goy
- Pierre Pillet
- Jean-Michel Raimond
- Guy Vitrant
- Yves Kaluzny
- Jun Liang
- Michel Brune
- Valérie Lefèvre-Seguin
- Jean Hare
- Jacques Lepape
- Aephraim Steinberg
- Andre Nussenzveig
- Frédéric Bernardot
- **Paulo Nussenzveig**
- Laurent Collot
- Matthias Weidemuller
- François Treussart
- Abdelamid Maali
- David Weiss
- Vahid Sandoghdar
- Jonathan Knight
- Nicolas Dubreuil
- Peter Domokos
- Ferdinand Schmidt-Kaler
- Jochen Dreyer
- Peter Domokos
- Ferdinand Schmidt-Kaler
- Ed Hagley
- Xavier Maître
- Christoph Wunderlich
- Gilles Nogues
- Vladimir Ilchenko
- Jean-François Roch
- Stefano Osnaghi
- Arno Rauschenbeutel
- Wolf von Klitzing
- Erwan Jahier
- Patrice Bertet
- Alexia Auffèves
- Romain Long
- Sébastien Steiner
- Paolo Maioli
- Philippe Hyafil
- Tristan Meunier
- Perola Milman
- Jack Mozley
- Stefan Kuhr
- Sébastien Gleyzes
- Christine Guerlin
- Thomas Nirrengarten
- Cédric Roux
- Julien Bernu
- Ulrich Busk-Hoff
- Andreas Emmert
- Adrian Lupascu
- Jonas Mlynek
- Igor Dotsenko
- Samuel Deléglise
- Clément Sayrin
- Xingxing Zhou
- Bruno Peaudecerf
- **Raul Teixeira**
- Sha Liu
- Theo Rybarczyk
- Carla Hermann
- Adrien Signolles
- Adrien Facon
- Stefan Gerlich
- Than Long Nguyen

- Eva Dietsche
- Dorian Grosso
- Frédéric Assémat
- Athur Larrouy
- Valentin Métillon
- Tigrane Cantat-Moltrecht

Collaboration: L Davidovich, N. Zaguri, P. Rouchon, A. Sarlette, S Pascazio, K. Mölmer, C. Koch …

Cavity technilogy: CEA Saclay, Pierre Bosland

The team

+ open post-doc positions…

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Cavity QED
I. Dotsenko (two cavity)
S. Gerlich, T. Rybarczyk,
M. Penasa, V. Métillon

S. Gleyzes (slow atoms)
D. Grosso, E.K. Dietsche,
F. Assemat

Superconducting atom chip
Spin simulator
C. Sayrin
Thanh Long Nguyen
T. Cantat-Moltrecht
R. Cortinas
B. Ravon

Quantum metrology
S. Gleyzes
A. Signoles, A. Facon,
E.K. Dietsche, A. Larrouy

Collaborations:

Feedback: P. Rouchon, M. Mirrahimi, A. Sarlette, Ecole des Mines Paris

QZD: P. Facchi, S. Pascazio Uni. Bari

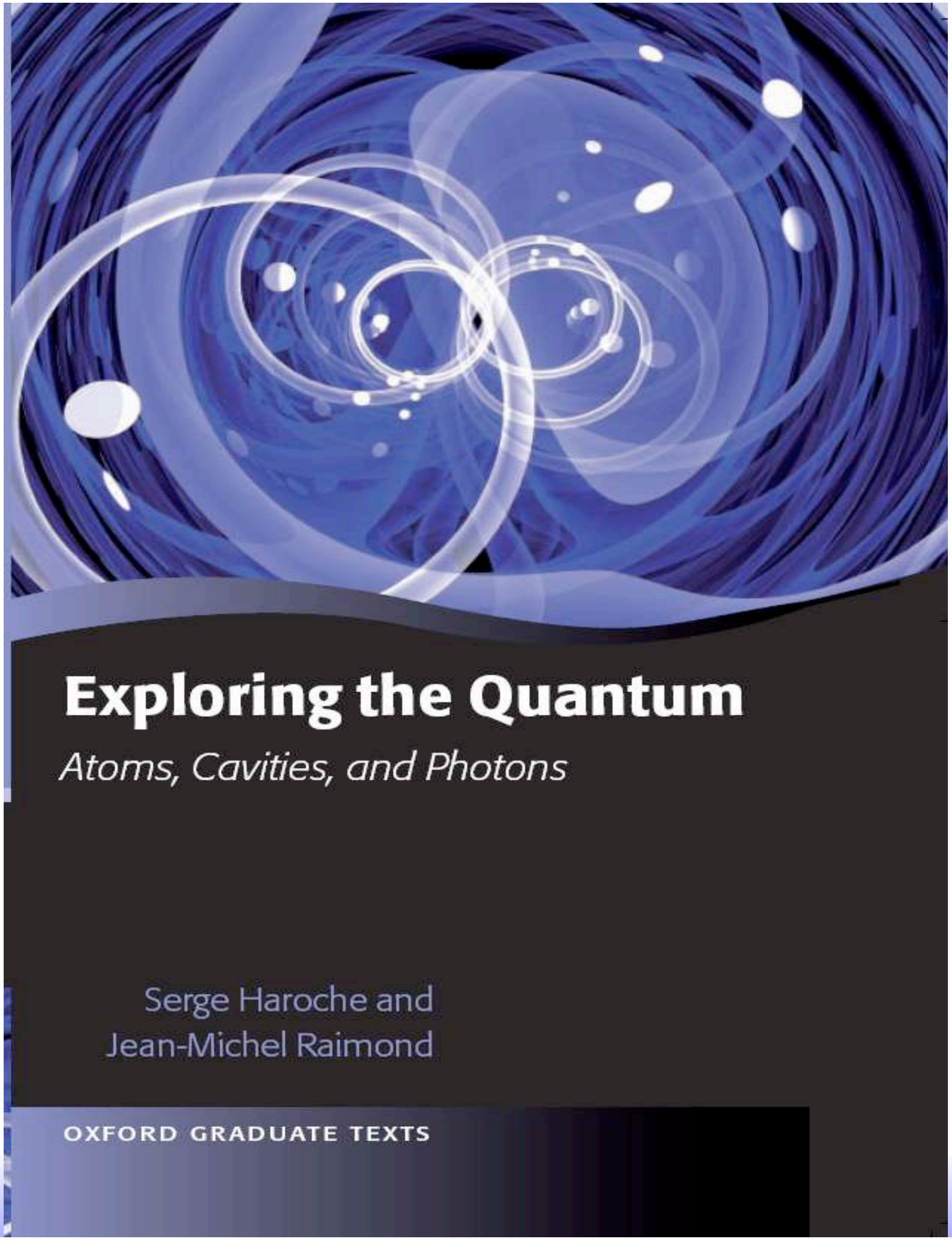
Past Quantum State: K. Mölmer

Spin chain: G. Roux, T. Jolicoeur, LPTMS

A work starting in 1991

Jean-Michel Raimond **Serge Haroche** **Michel Brune**

For more…



Exploring the Quantum

Atoms, Cavities, and Photons

Serge Haroche and
Jean-Michel Raimond

OXFORD GRADUATE TEXTS