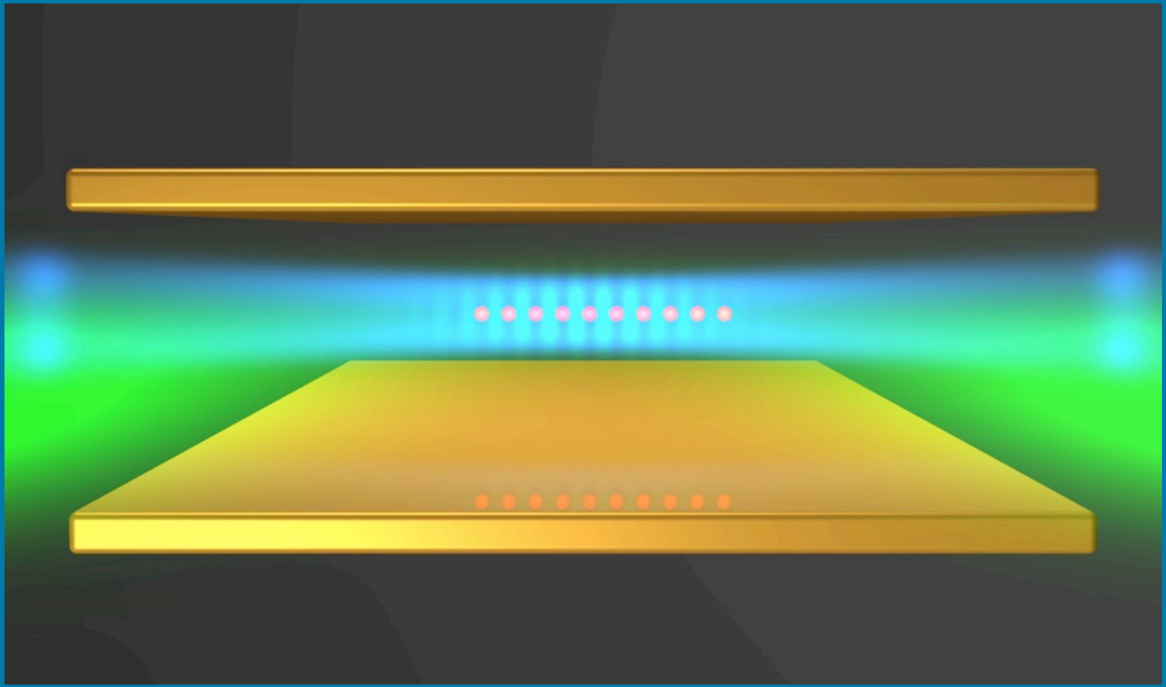
Towards Quantum Simulation with Circular Rydberg Atoms

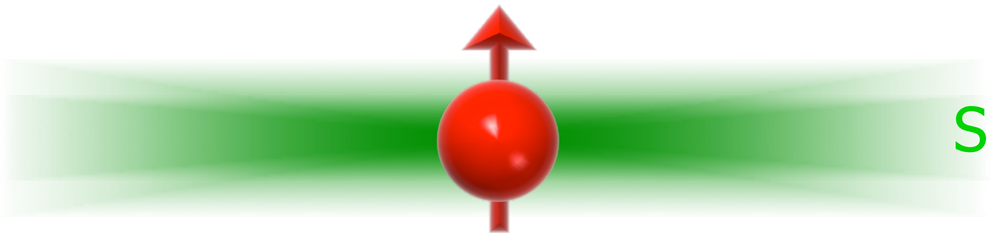


Clément Sayrin
Laboratoire Kastler Brossel

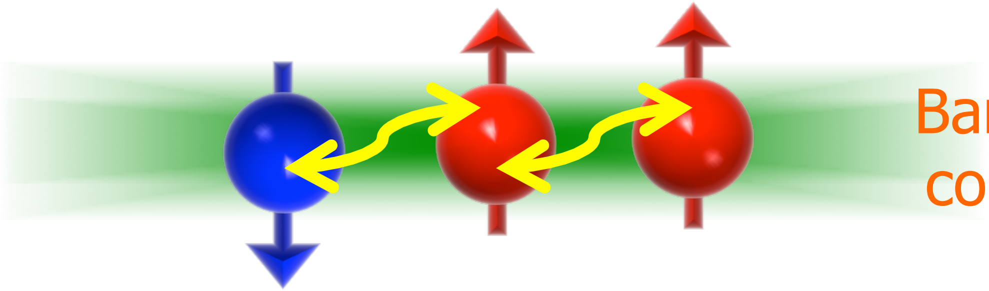
ICQSIM, 15/11/2017

Quantum simulations of spin-systems

Simulations with computer?



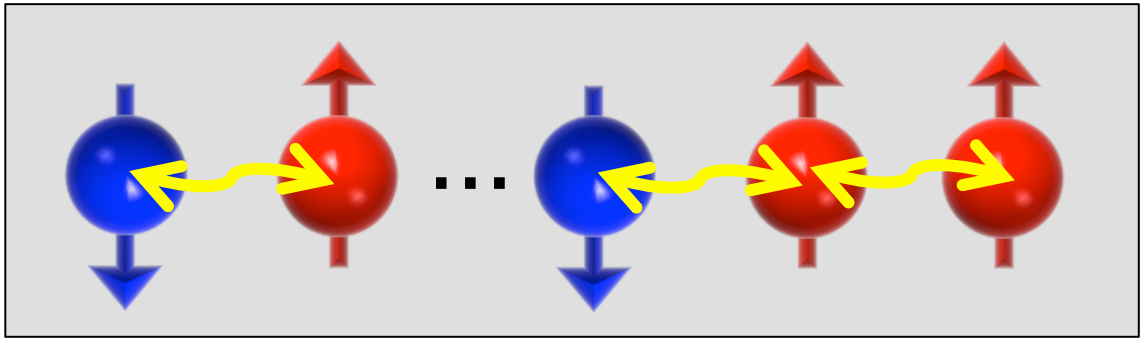
Simple



Barely more complicated

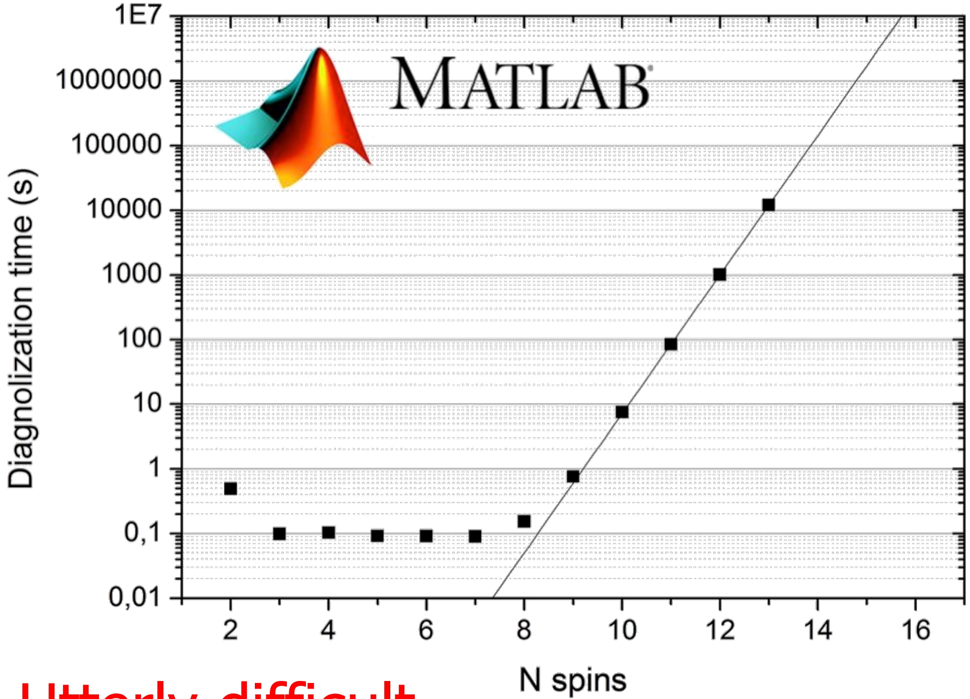
Impossible!

Utterly difficult



Quantum simulations of spin-systems

Simulations with computer?



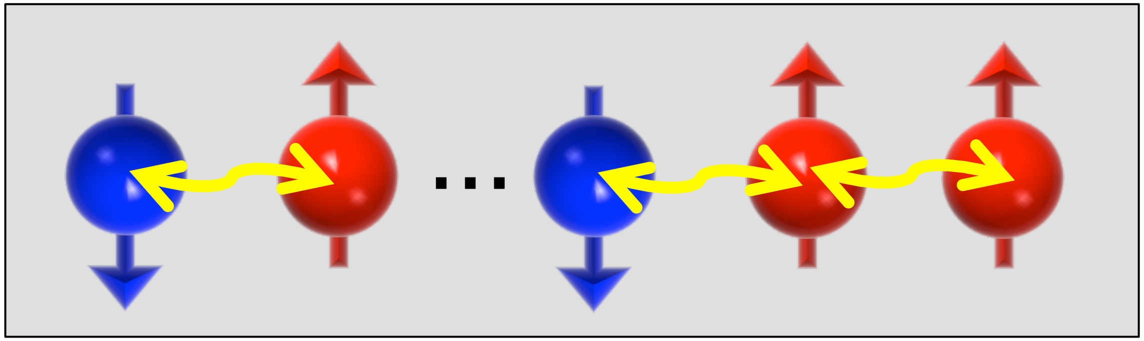
N = 10 → ~ 7 s

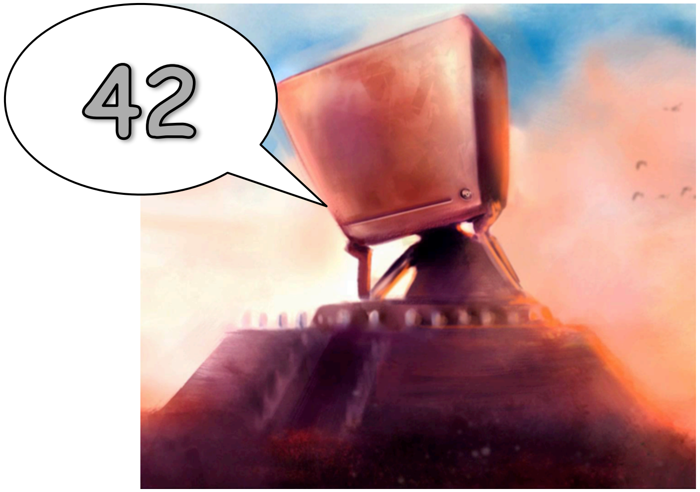
N = 13 → ~ 3 h

N = 16 → ~ 8 months

N = 40 → ~ 4 10^{25} years

Utterly difficult





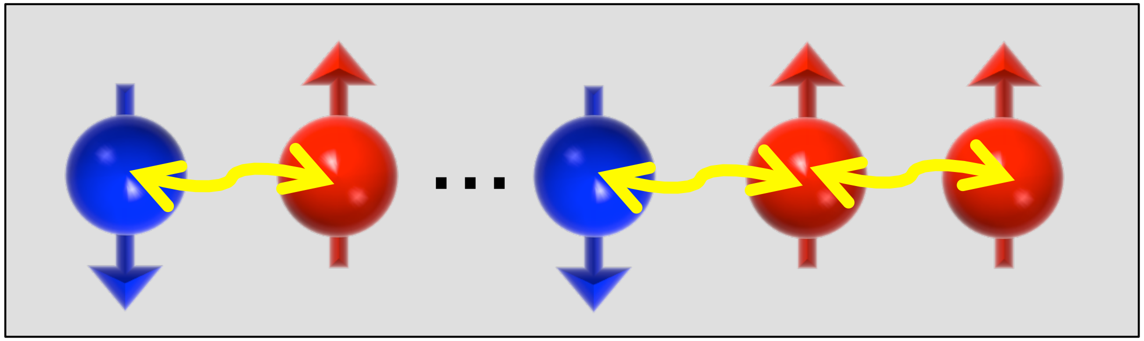
Quantum simulations

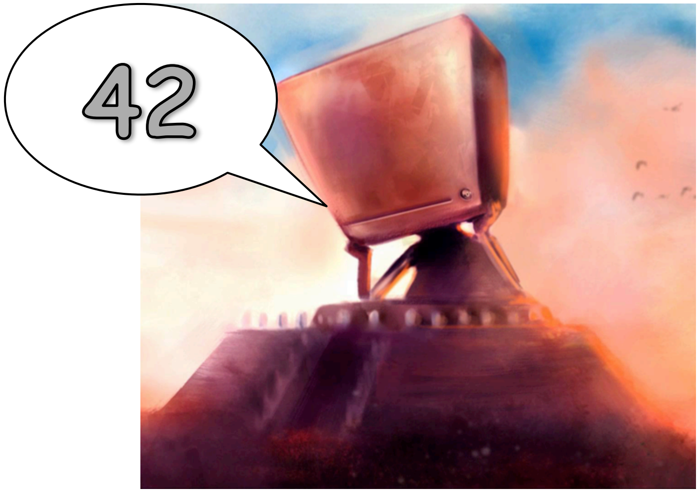
Simulations with computer?

Linear chain of N spins-1/2:

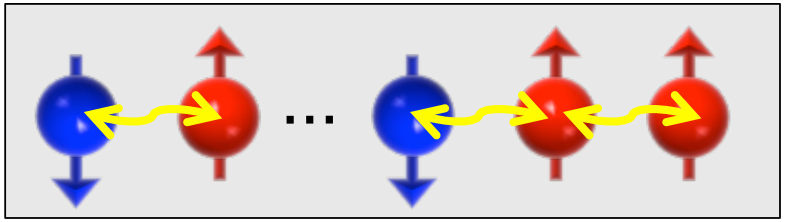
- Exact diagonalization: N ~ 36
- Ground-state: well-known via powerful numerical techniques (DMRG)
- Dynamics… tricky! Few tens of interaction cycles only.

Utterly difficult



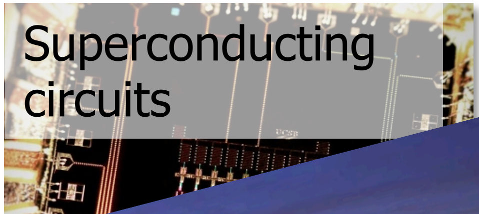


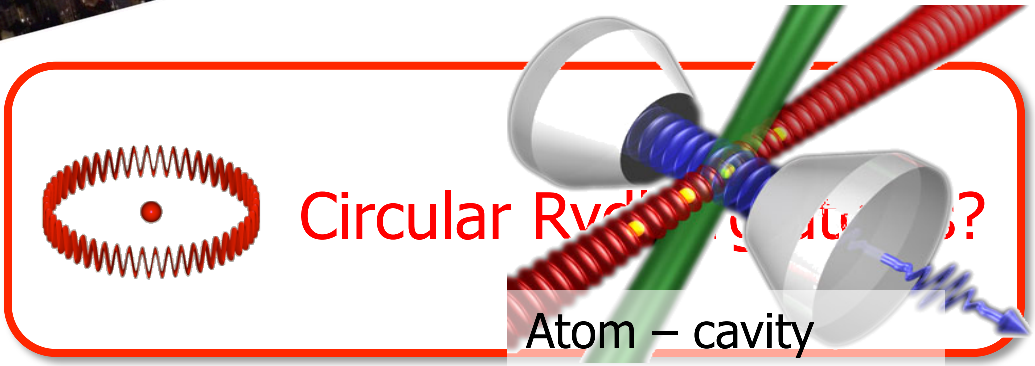
Quantum simulations



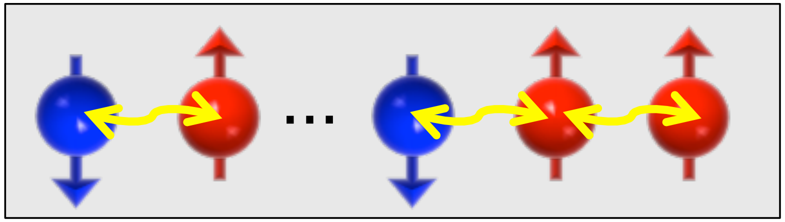
How to simulate?

Use a **mod**





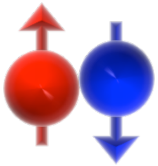
Objective



Simulation of a chain of interacting spins-1/2

Requirements?

- Spin 1/2



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

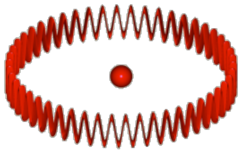
→ Observe many interaction cycles

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

Circular Rydberg atoms $|nC\rangle$

Rydberg atoms

- Very high principal quantum number, n
- Circular levels: maximum angular momentum $l = |m| = n-1$



Large orbit $r_n \sim n^2\, a_0$

→ Huge electric dipole matrix elements

- ➢ Well coupled to the microwave electromagnetic field
- ➢ Strong dipole – dipole interactions!

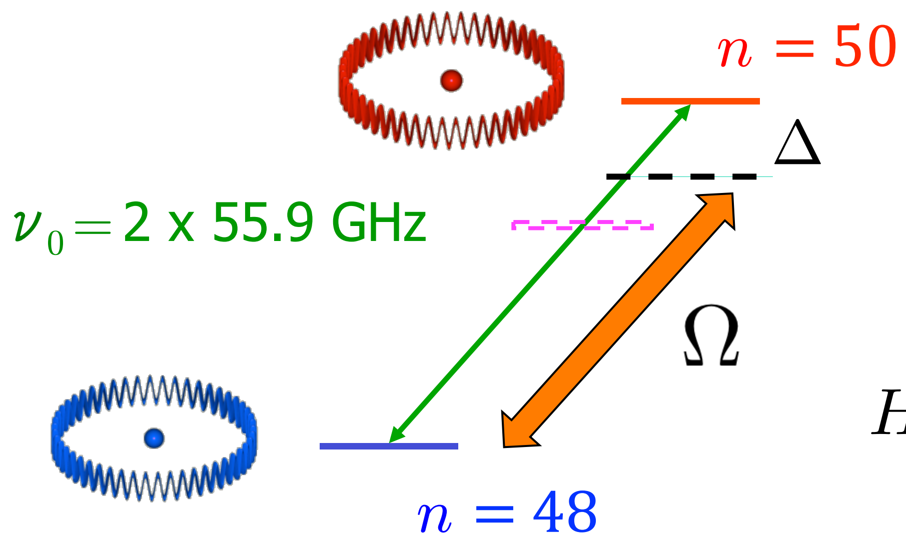
\+ Long lifetimes: Several 100μs for low l levels

Several 10 ms for circular levels

Circular Rydberg atoms

Simulating a spin 1/2

- Two circular Rydberg levels $|nC\rangle$ $|(n+2)C\rangle$ + near-resonant drive



$$H_0 = \frac{h\nu_0}{2}\sigma^z$$

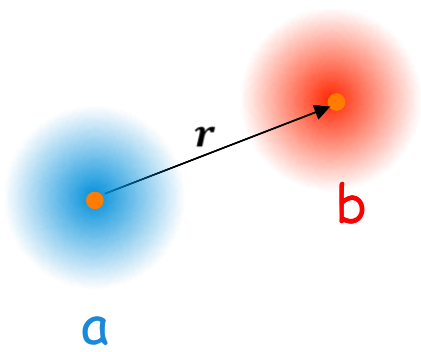
$$H_0 + H_{\mathrm{ext}} = \frac{h\Delta}{2}\sigma^z + \frac{h\Omega}{2}\sigma^x$$

Power and frequency of the microwave source

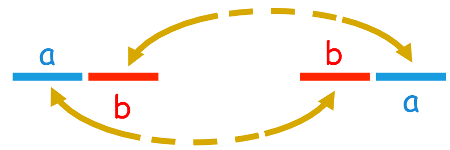
Longitudinal magnetic field

Transverse magnetic field

Dipole-dipole interaction

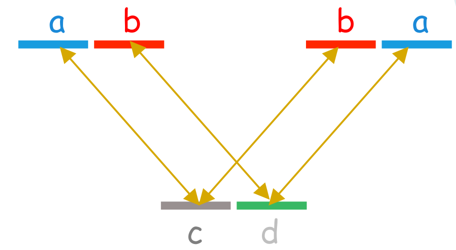


Off-diagonal terms



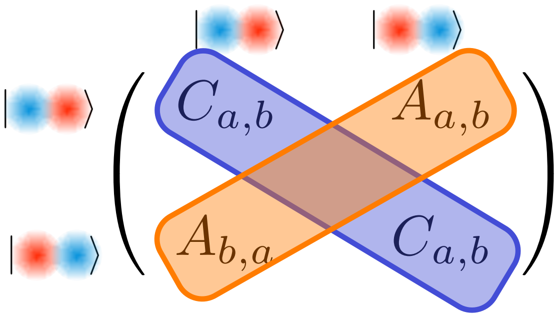
Exchange interaction

$\Delta m = 2$

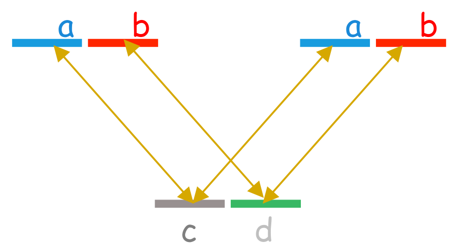


$H_{\text{int}} =$

$\sim \hat{d}_1 \hat{d}_2 / r^3$



Diagonal terms



Direct interaction

Second order, van der Waals interactions

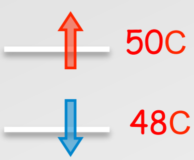
$$J_z, \; J \propto 1/r^6$$

Nearest-neighbour interactions

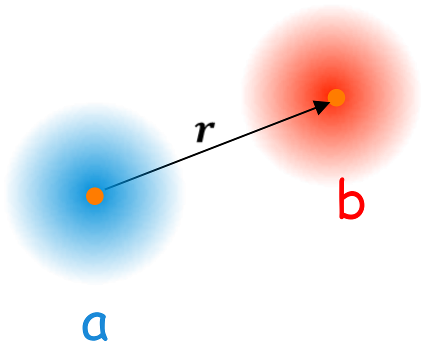
Mapping to a spin interaction

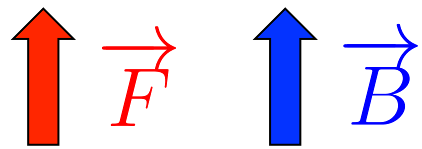
Diagonal terms $J_z \, \sigma_1^z \sigma_2^z$

Off-diagonal terms $J \left(\sigma_1^x \sigma_2^x + \sigma_1^y \sigma_2^y \right)$

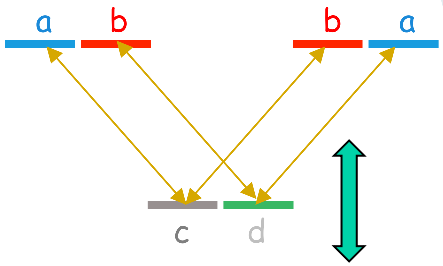


Tunable spin – spin interaction





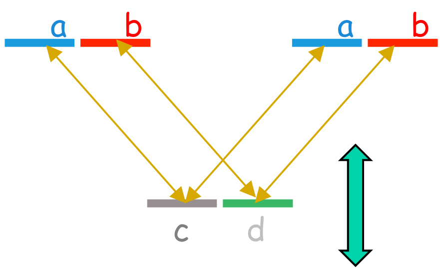
Exchange interaction



- Tunable dipole – dipole interaction:

  A_6 and C_6 coefficients depend on F, B

- Tunable spin – spin interaction:

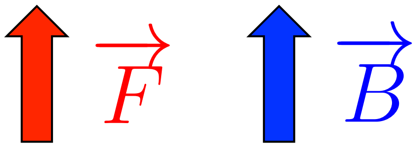


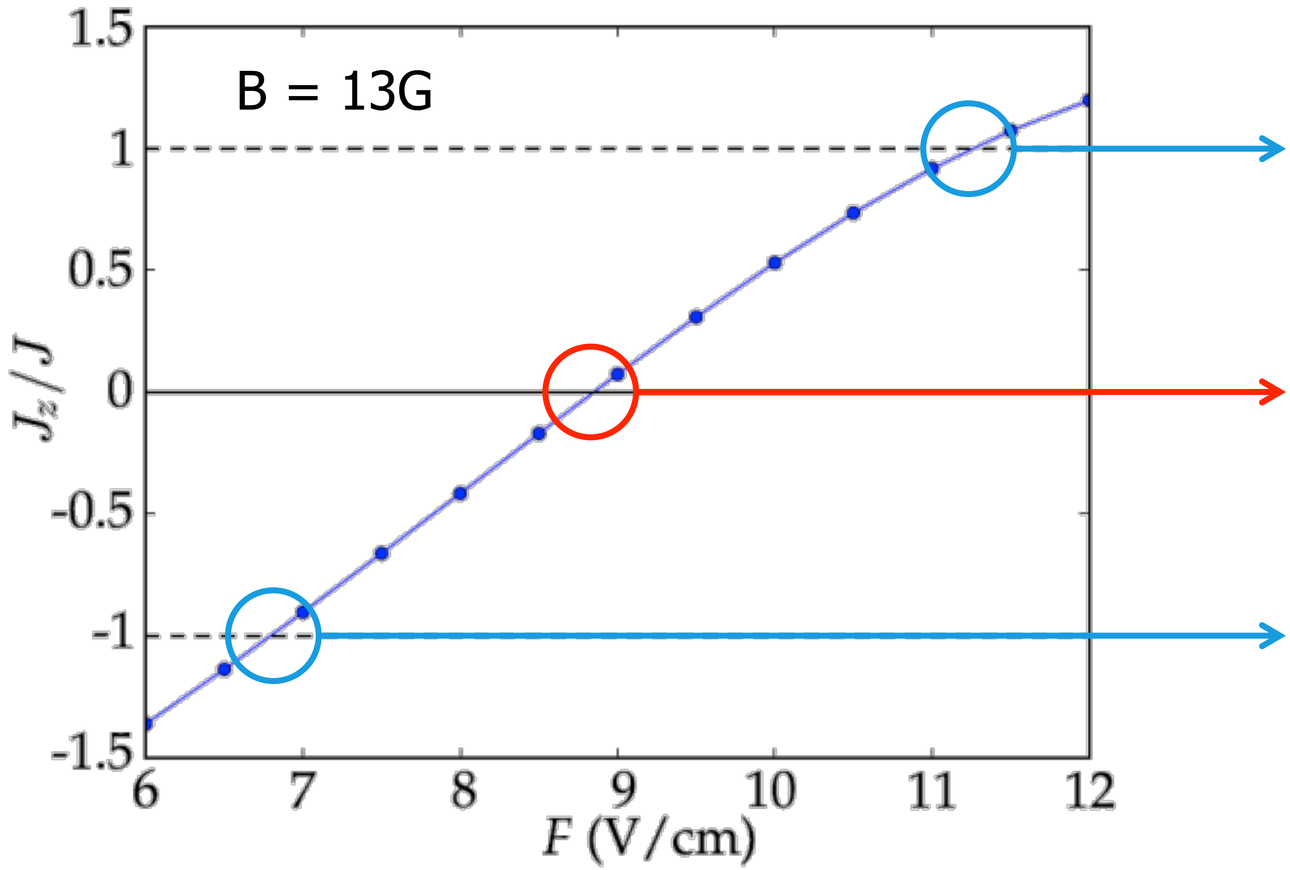
Direct interaction

$$J = \frac{A_{6,48-50}}{2r^6} \qquad J_z = \frac{C_{6,48-48} - 2C_{6,48-50} + C_{6,50-50}}{4r^6}$$

J is nearly constant… … but Jz varies significantly!

Tunable spin – spin interaction



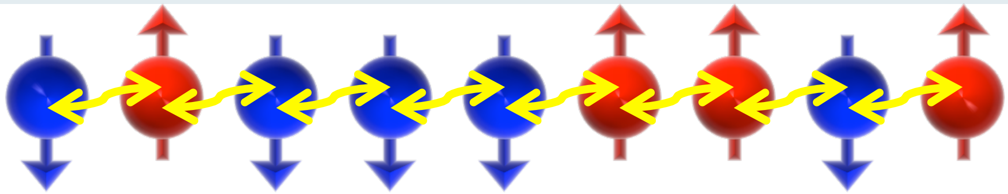


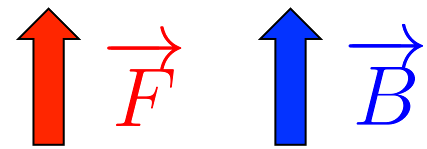
Jz = +J :
Isotropic model

Jz = 0 :
Pure XY interaction

Jz = -J :
Isotropic model

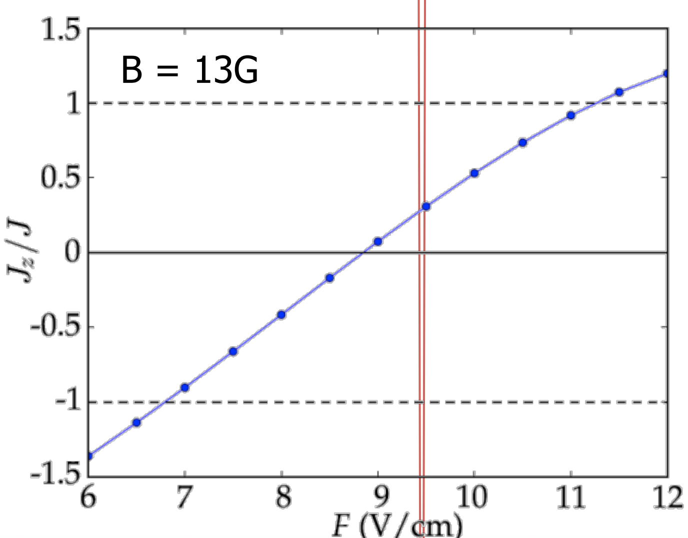
Tunable XXZ Hamiltonian





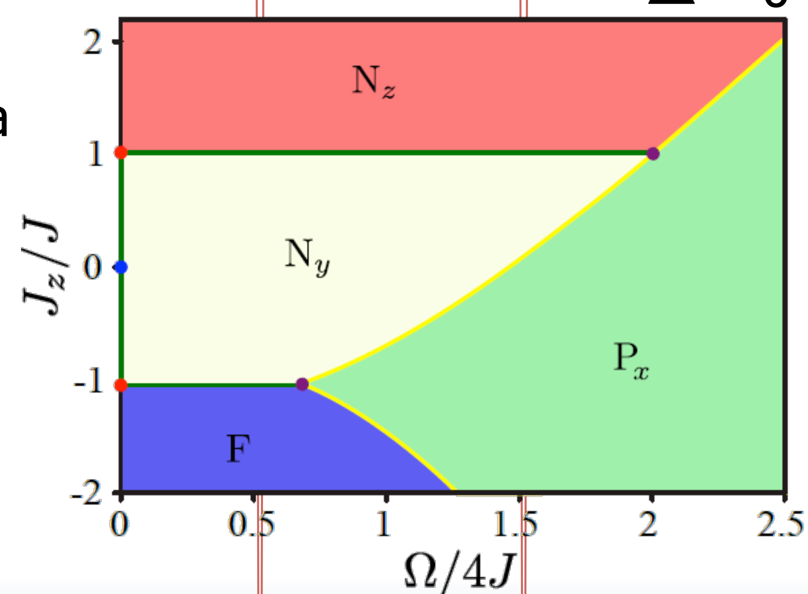
$$H/h = \underbrace{J_z \sum_j \sigma_j^z \sigma_{j+1}^z}_{\text{Longitudinal spin coupling}} + \underbrace{J \sum_j \left(\sigma_j^x \sigma_{j+1}^x + \sigma_j^y \sigma_{j+1}^y\right)}_{\text{Transverse spin coupling}} + \underbrace{\frac{\Delta}{2} \sum_j \sigma_j^z}_{\text{Longitudinal B field}} + \underbrace{\frac{\Omega}{2} \sum_j \sigma_j^x}_{\text{Transverse B field}}$$

Tunable interactions



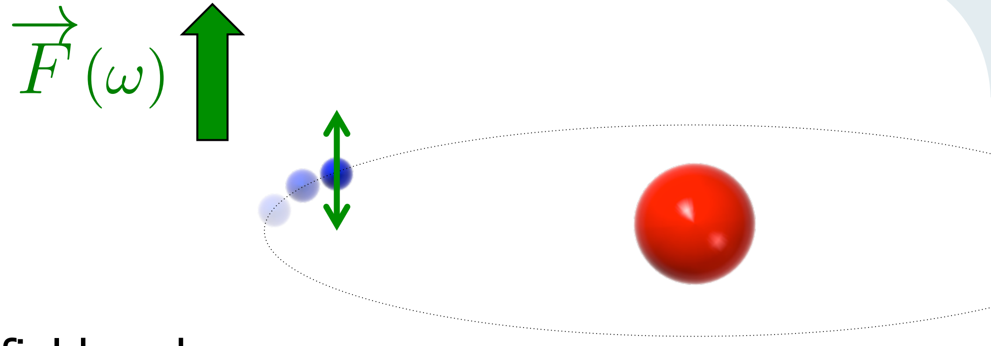
Exploration of a rich phase diagram

$\Delta = 0$



Trapping Rydberg atoms

Ponderomotive potential

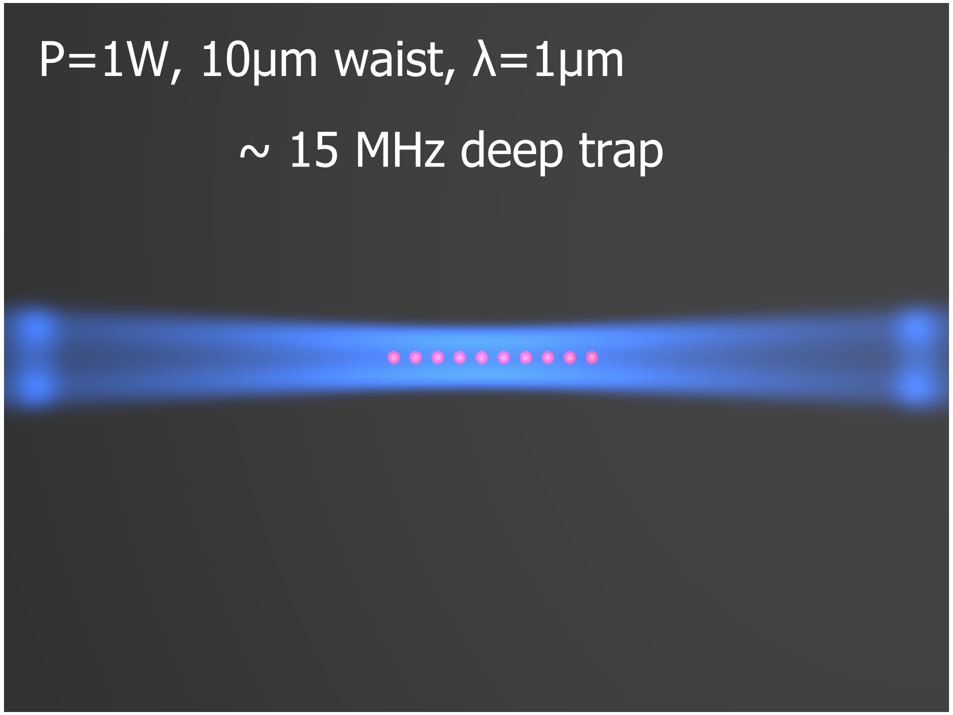


- Valence electron is almost free
- Positive ponderomotive energy

$$\mathcal{E} = \frac{e^2}{2m_e\varepsilon_0 c\,\omega_L^2} I$$

→ Low field seeker

- Laguerre-Gauss beam
- Transverse confinement



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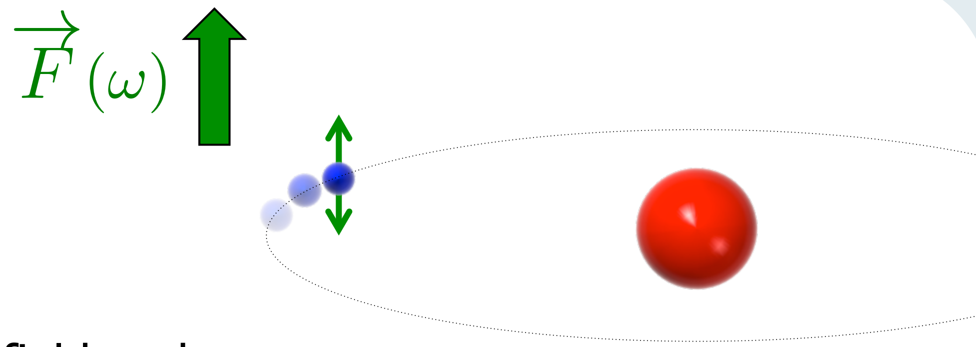

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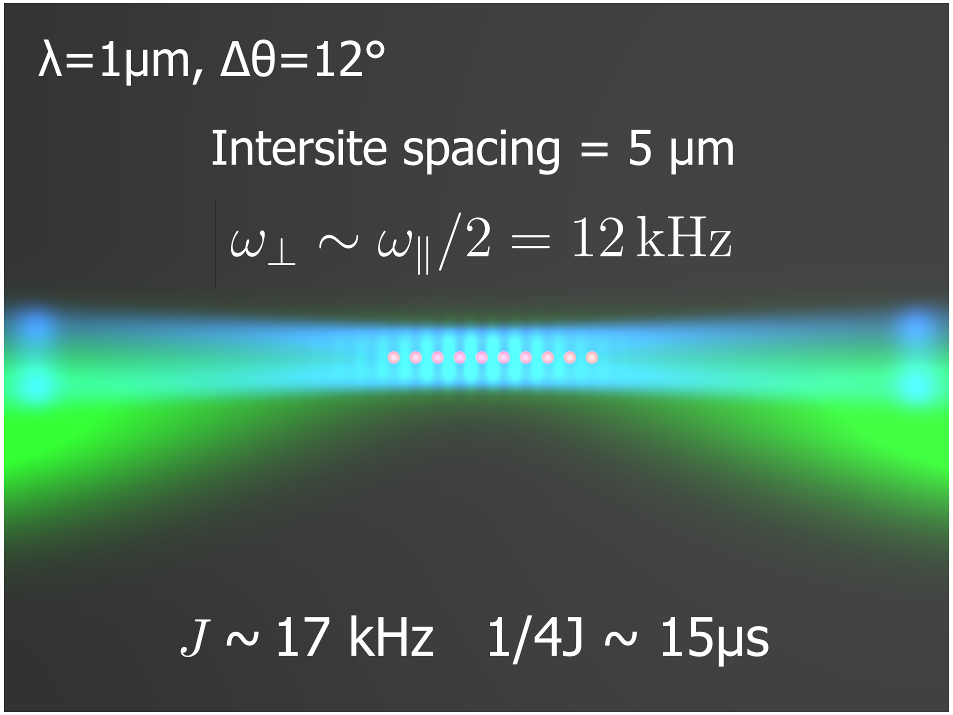
$$\mathcal{E} = \frac{e^2}{2m_e\varepsilon_0 c\,\omega_L^2} I$$

→ Low field seeker

- Laguerre-Gauss beam
- Transverse confinement

- Crossed Gaussian beams
- Longitudinal confinement
- Tunable interatomic distance



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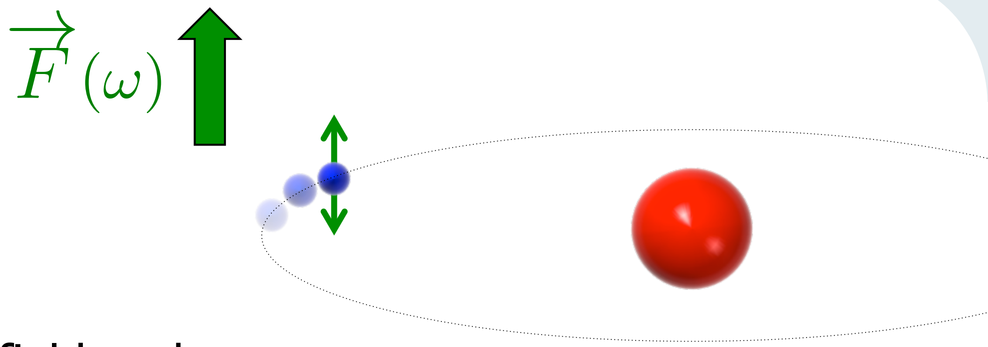
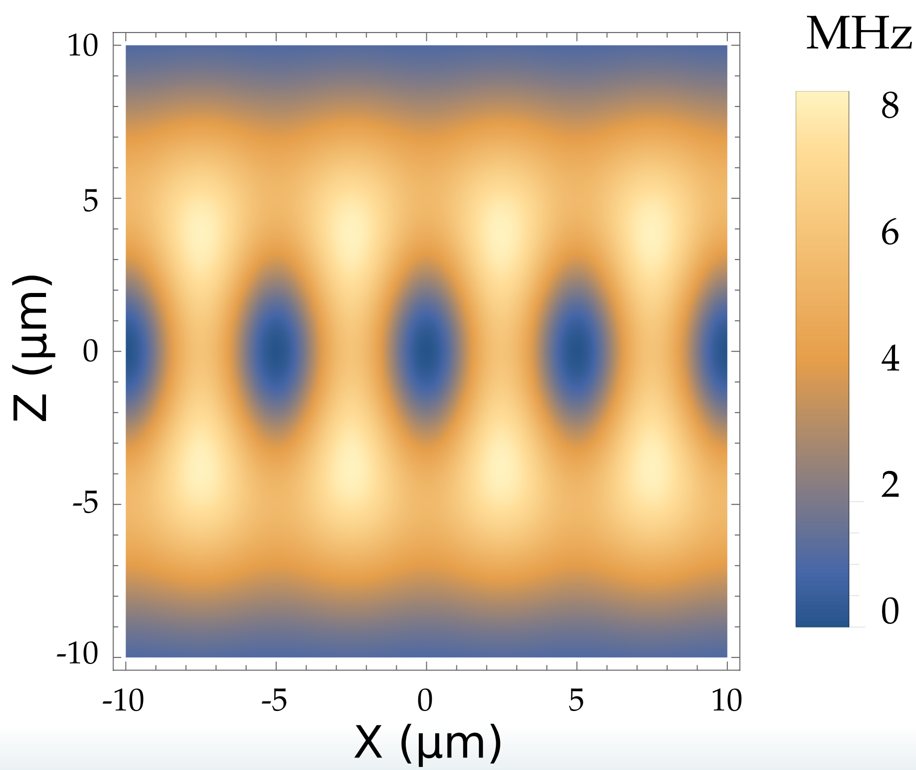
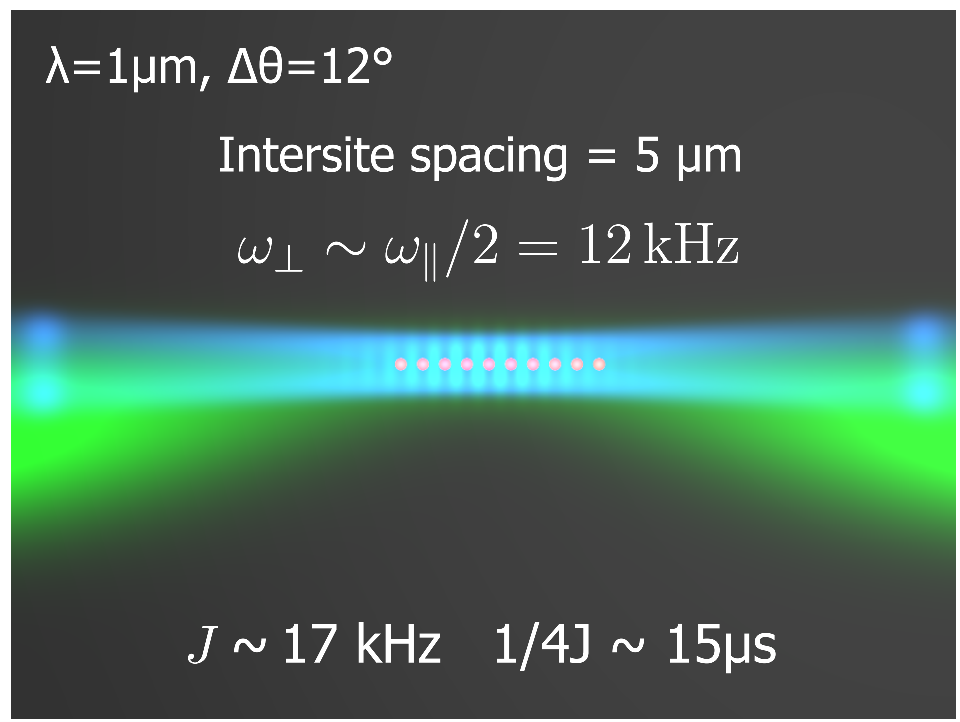


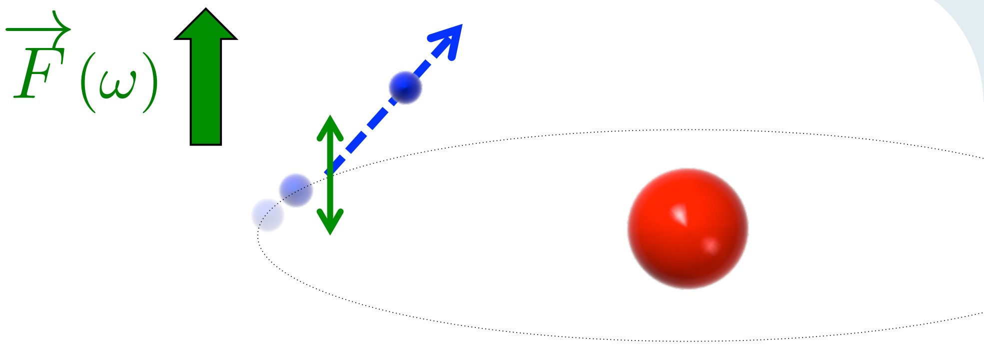




Trapping Rydberg atoms

Ponderomotive potential

- Valence electron is almost free
- Positive ponderomotive energy
- MHz-deep lattices



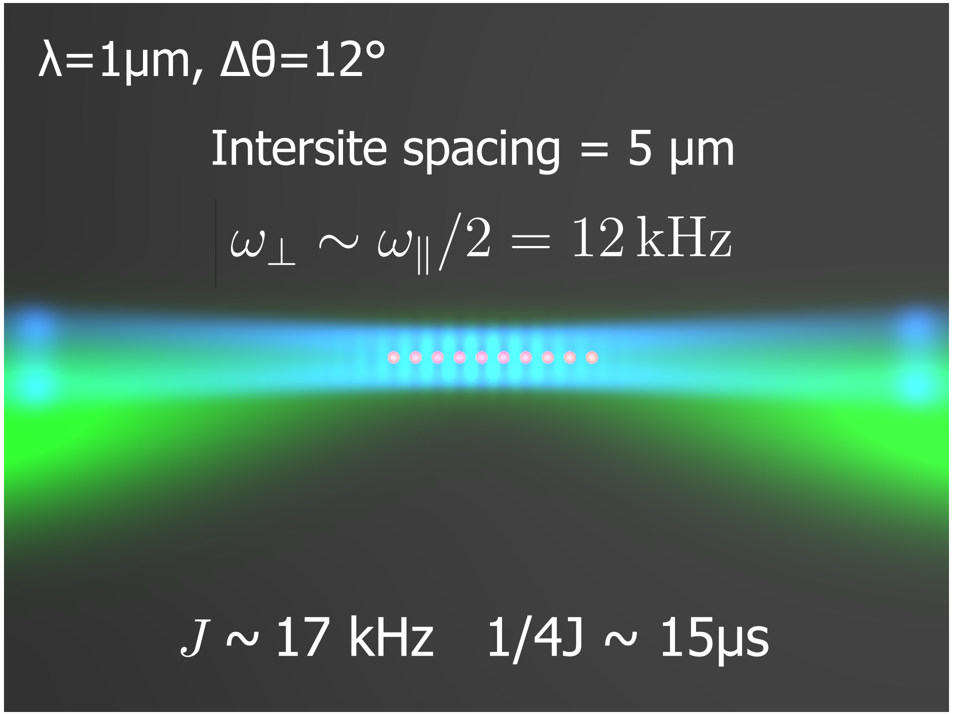
Photoionization?

- Detrimental for low-l levels

  lifetimes ~ few 10 µs

- Negligible for circular levels!

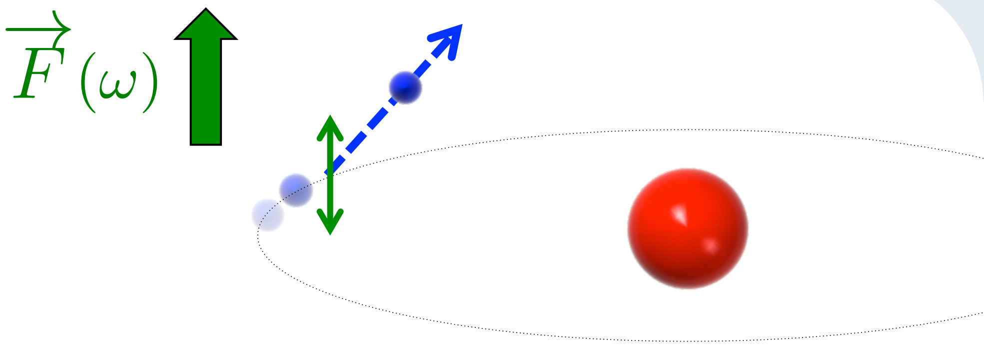
  cross-section ~ 10^{-175} m^2



Trapping Rydberg atoms

Ponderomotive potential

- Valence electron is almost free
- Positive ponderomotive energy
- MHz-deep lattices
- No photoionization



Coherence?

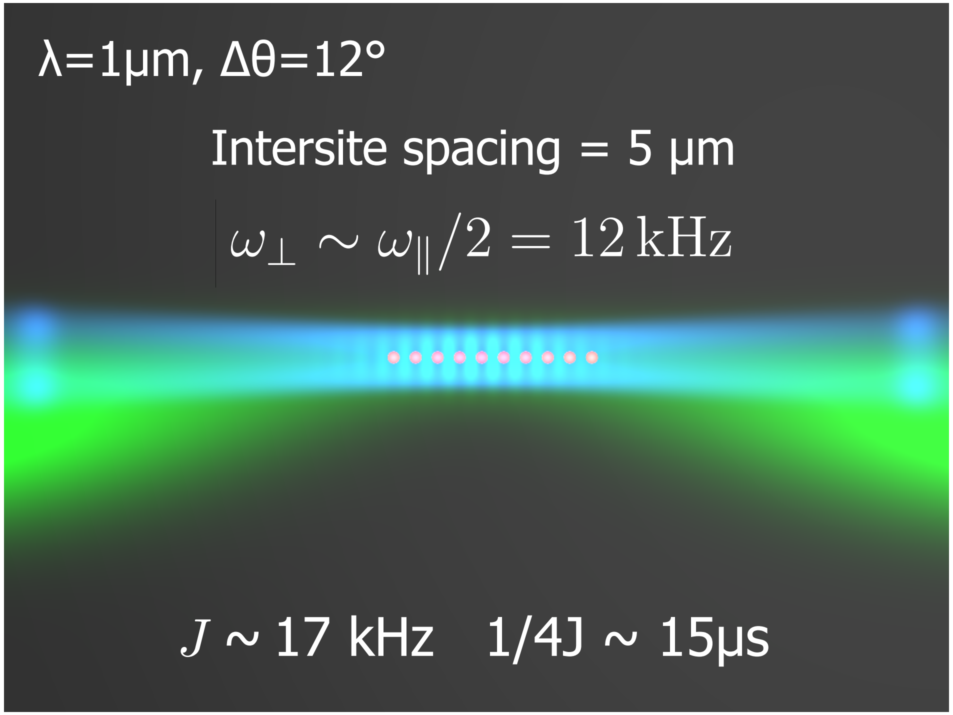
- Potential almost independent of the circular Rydberg level

    Ground-state extension ~ 50 nm

    Electron-orbit radius ~ 250 nm

→ Potential is averaged over the orbit

- Estimated coherence time ~ 0.2 s

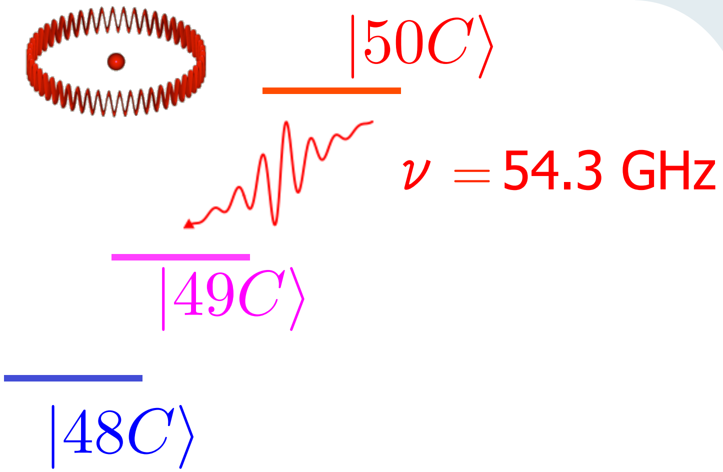


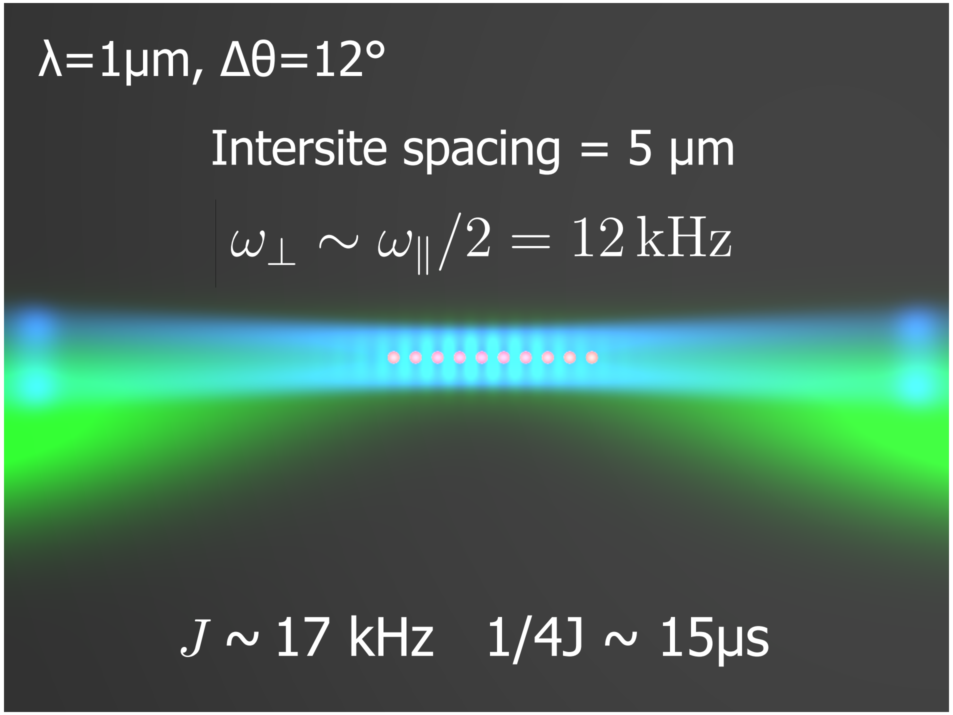
Keeping Rydberg atoms

Radiative decay

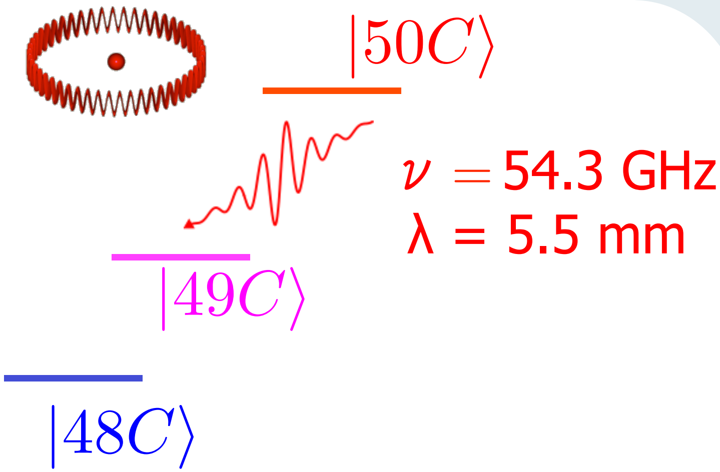
- Unique decay channel $|nC\rangle \to |(n-1)C\rangle$
- Long natural lifetime ~ 30ms

  … only 0.75ms for a 40-atom chain





Keeping Rydberg atoms



Radiative decay

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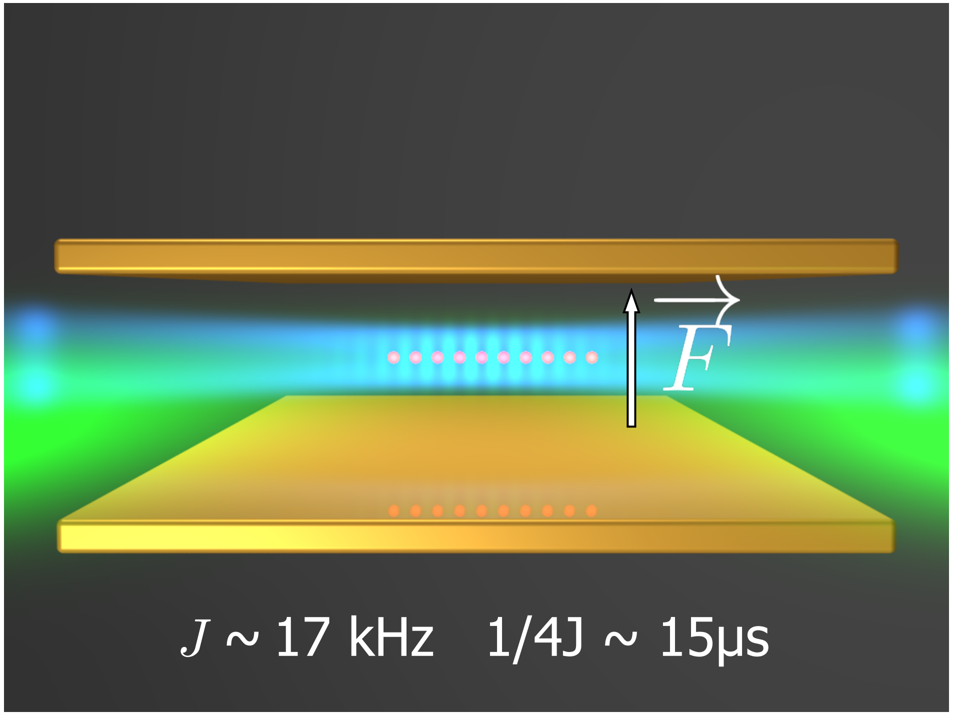
Inhibition of spontaneous emission

- Plane-parallel capacitor, $D \leq \lambda/2$
- Emission of σ^+ polarized photon is inhibited



D. Kleppner [PRL **55**, 2137 (1985)]

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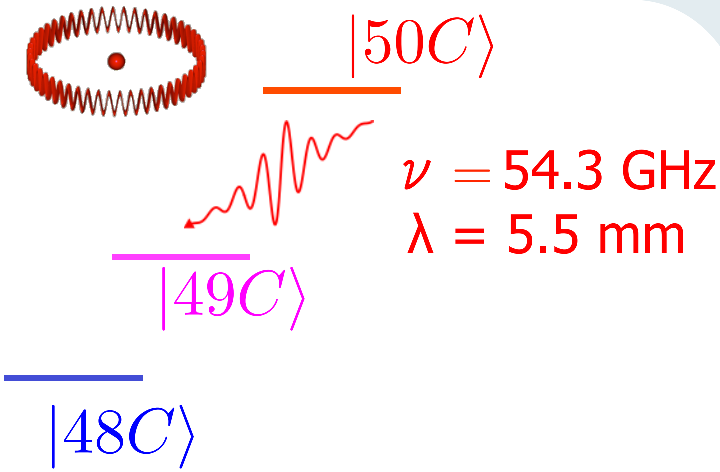

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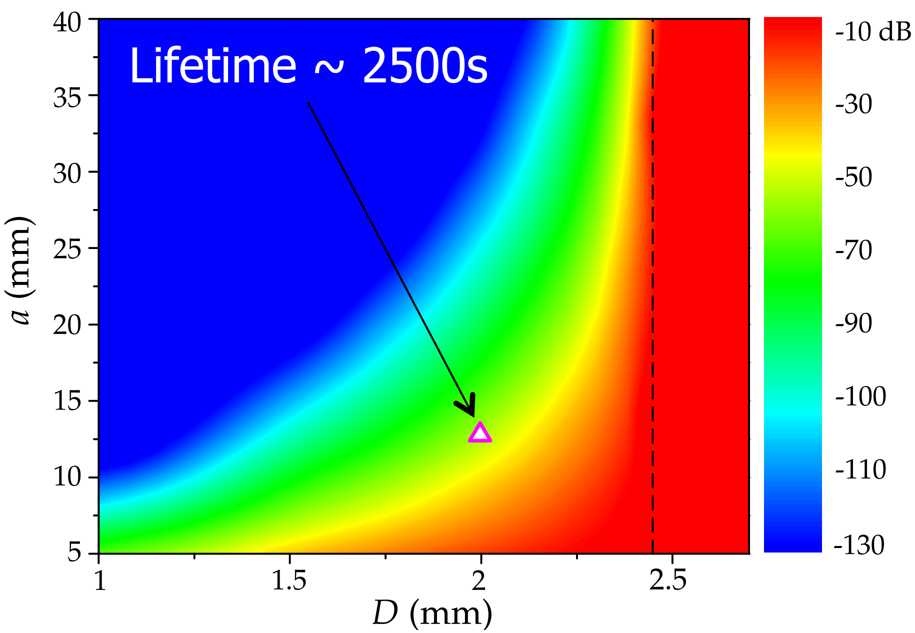
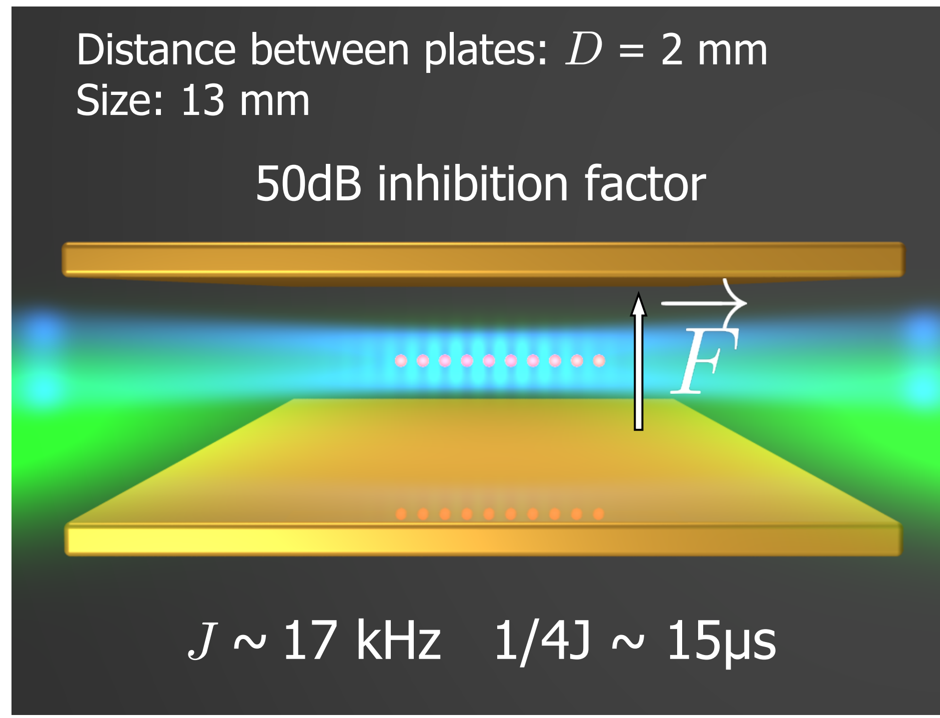




Keeping Rydberg atoms

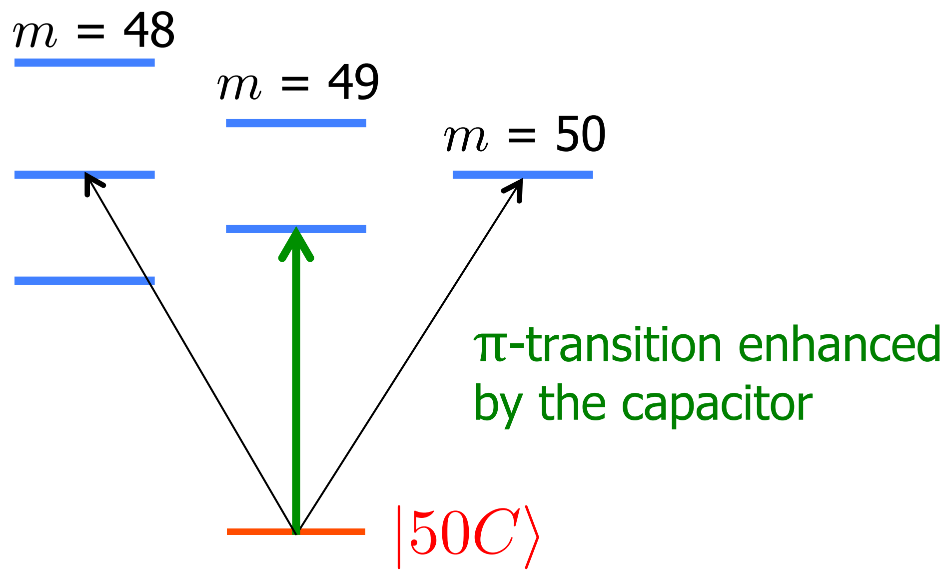
Limitations of the lifetime

- Background gas collisions: 10^{-14} mbar required to reach 400s lifetime

→ accessible in a cryostat environment

- Blackbody induced processes

→ cryogenic temperature required: T ~ 0.5K



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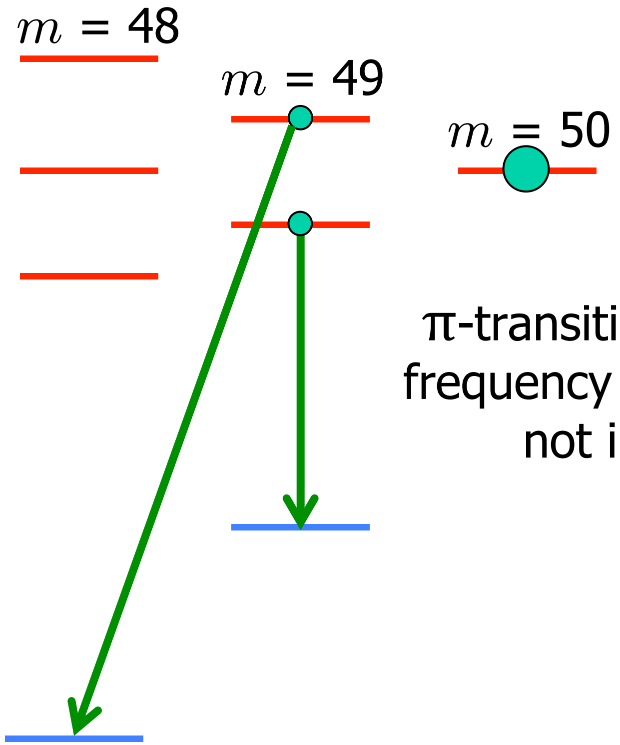
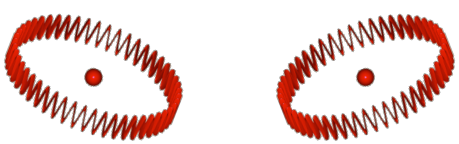


π-transition and high-frequency transition are not inhibited

- Interaction-induced level mixing



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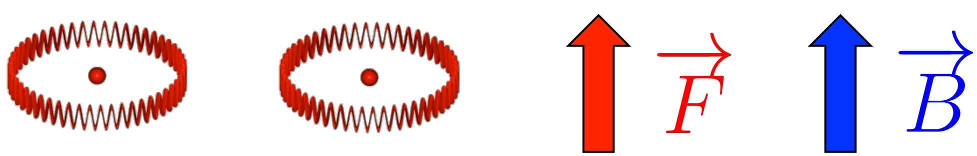
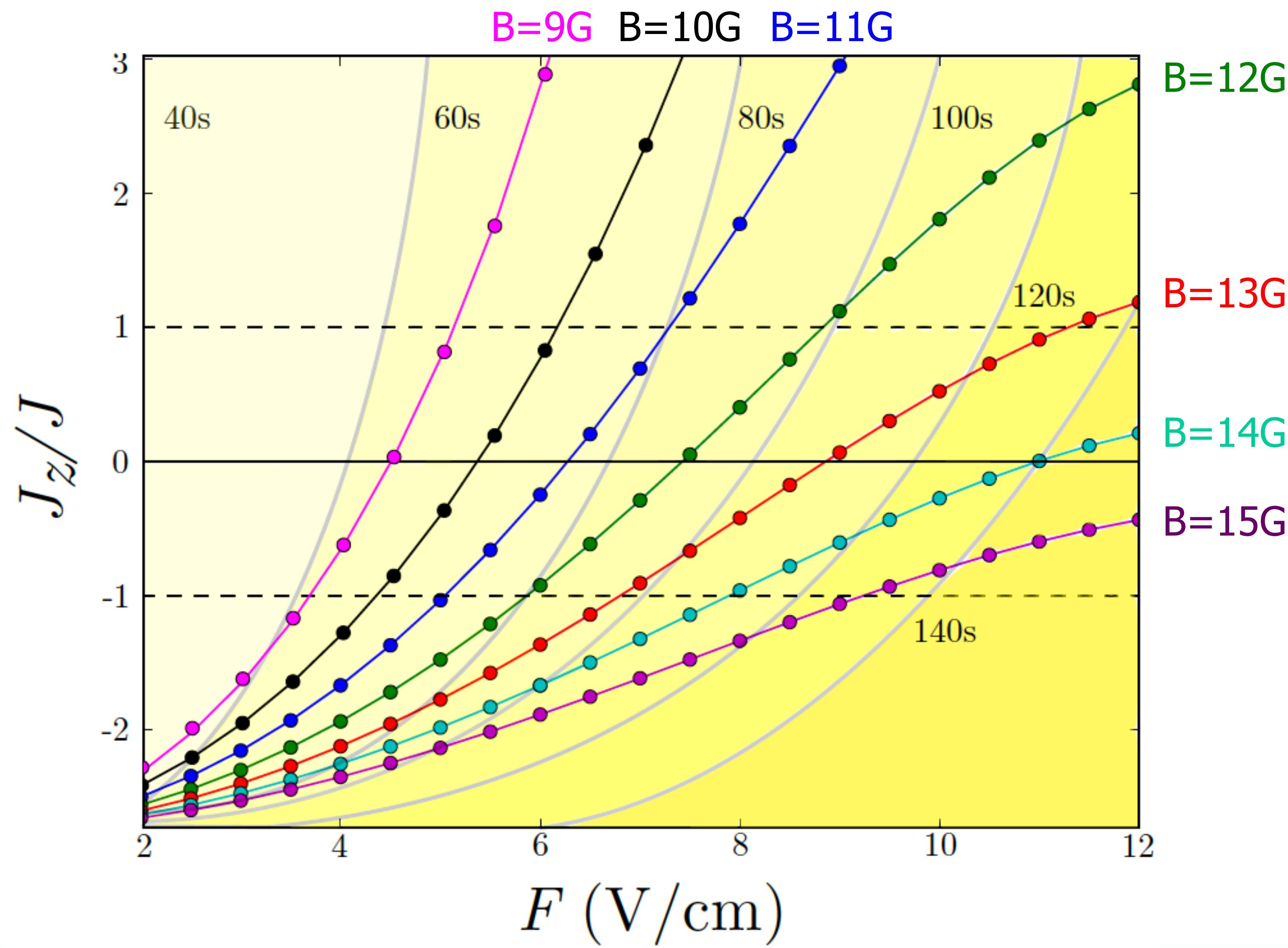


Competition with the tuning of the interaction?

Keeping Rydberg atoms



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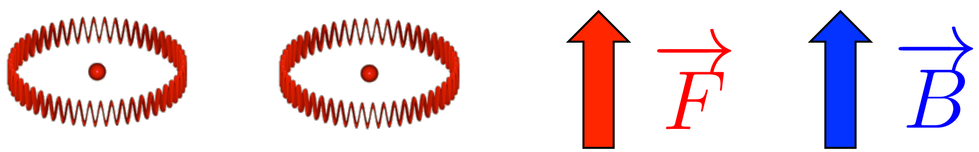
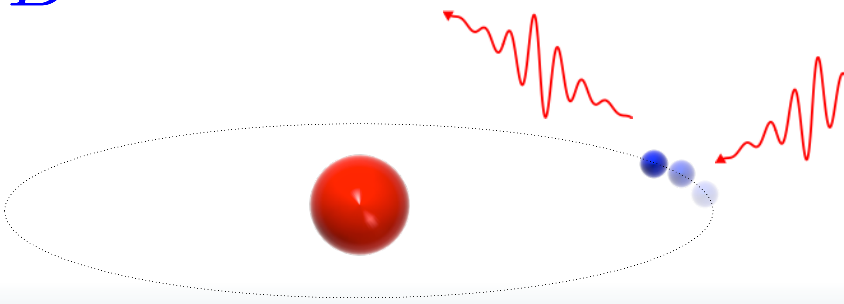


- Compton elastic diffusion of trap photons?



Keeping Rydberg atoms

Summary

Cause	Lifetime (s)	
Residual spontaneous emission	2500	13mm square plates separated by 2mm
Blackbody induced processes	630	T ~ 0.5K
Level mixing	88	B > 9G / F >2V/cm
Photoionization	∞	
Collisions with background gas	400	P ~ 10^{-14} mbar
Compton elastic diffusion	> 180	P = 0.5W
Predicted lifetime	**47**	

with J ~ 17 kHz 1/4J ~ 15μs

Single atom lifetime ~ 50 s

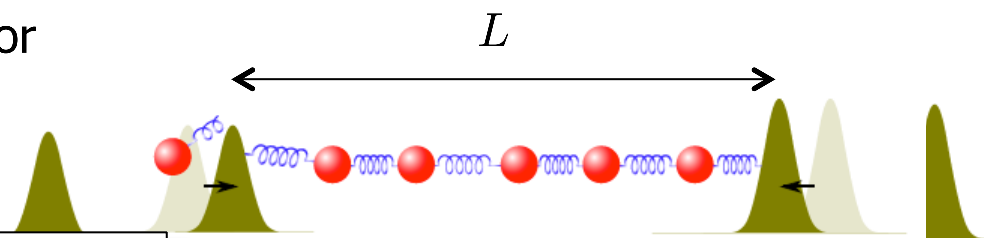
40-atom chain lifetime ≥ 1 s

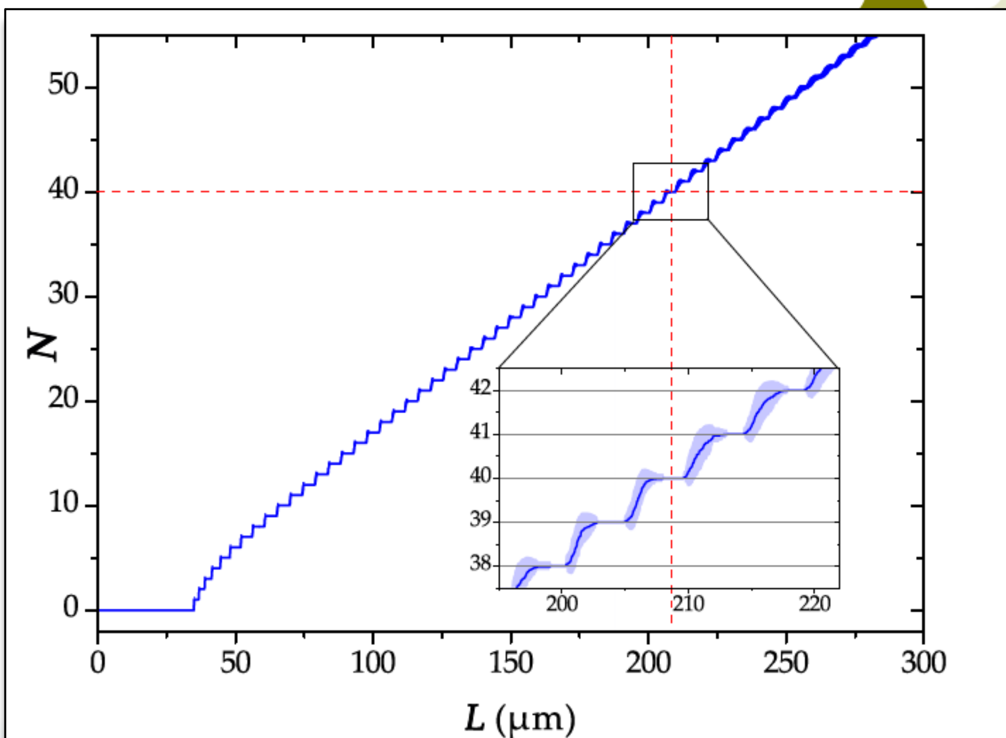
→ ~ 10^5 interaction cycles!

Chain preparation

Deterministic chain evaporation

- Cloud of cold atoms, near quantum degeneracy
- Excitation of Rydberg states and "circularization" inside the capacitor
- Evaporation of the chain



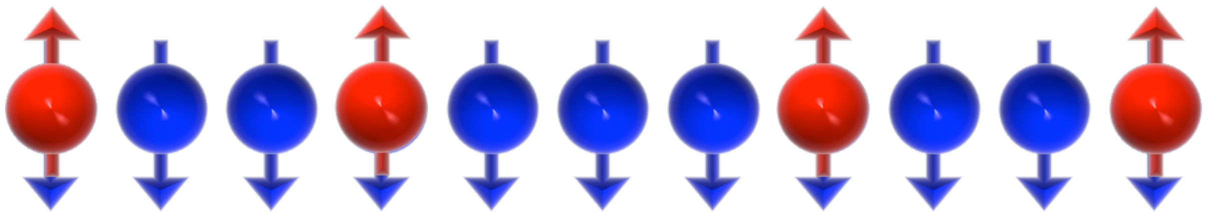


Properties

- 40-atom chain prepared in ~ 1s
- Variant of evaporative cooling:
  4 quanta of vibration
  100 nm position dispersion

Example of measurements

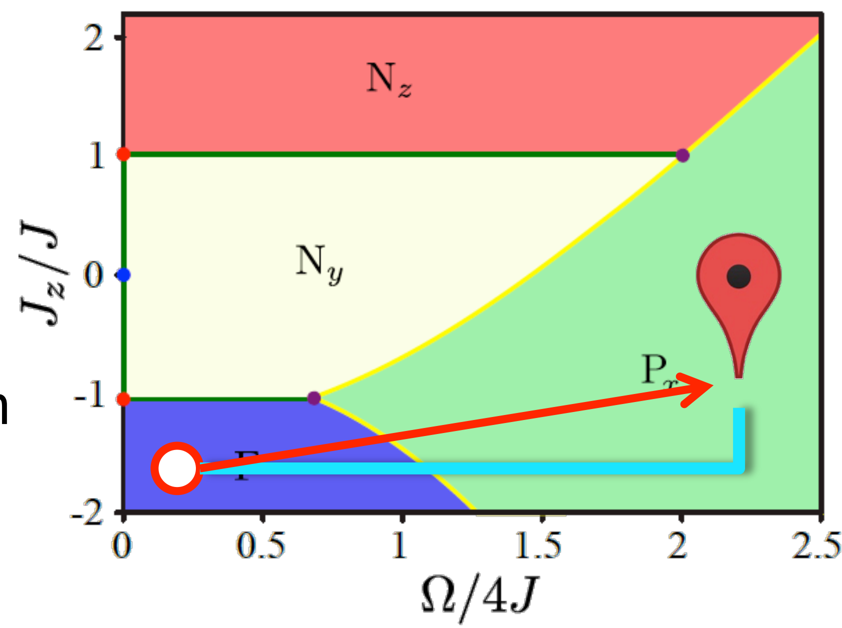
- Chain initialization: all atoms in the same spin state
- Flipping some atoms: atoms at the end of the chain (with single neighbour)



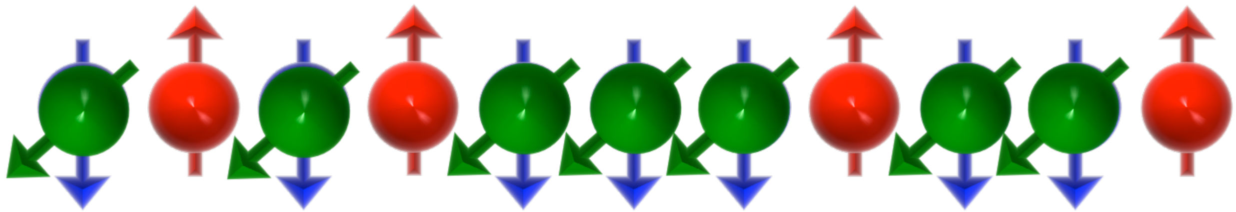
Example of measurements

- Chain initialization: all atoms in the same spin state
- Flipping some atoms: atoms at the end of the chain (with single neighbour)

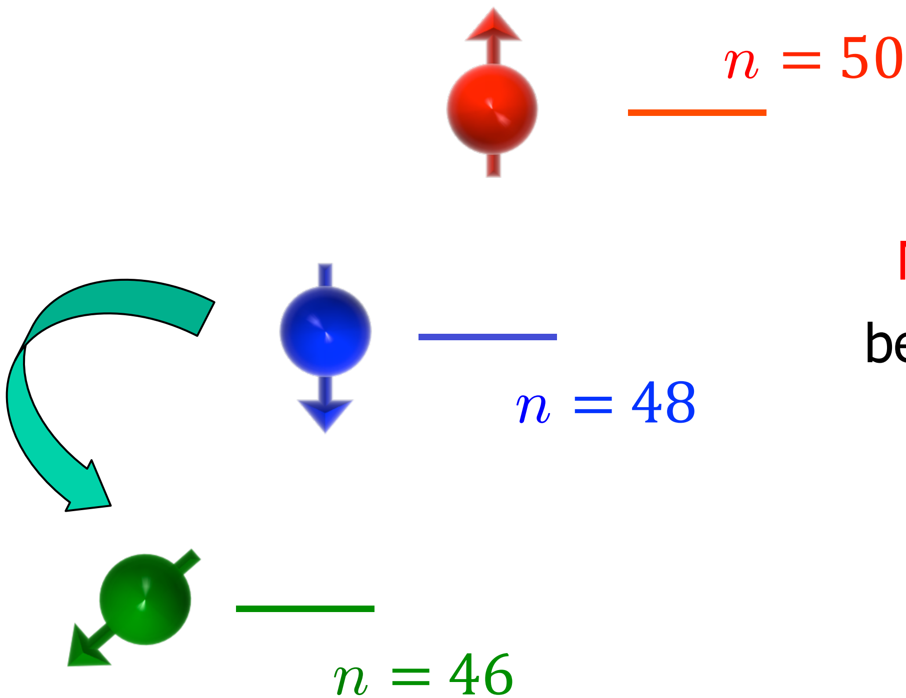
- Moving through the phase diagram:
  - ➢ Initial state in the ground state of the ferromagnetic phase
  - ➢ Adiabatic evolution: reconstruction of the phase diagram
  - ➢ Quenches: return to equilibrium, excitations…



Example of measurements



- At the end of the sequence: freeze the spin dynamics



Negligible exchange interaction

between $|n = 50>$ and $|n = 46>$

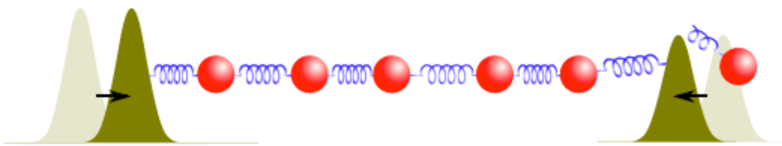
$J_{46\text{-}50}$ is in the mHz-range

Example of measurements

Measurement of spin observables

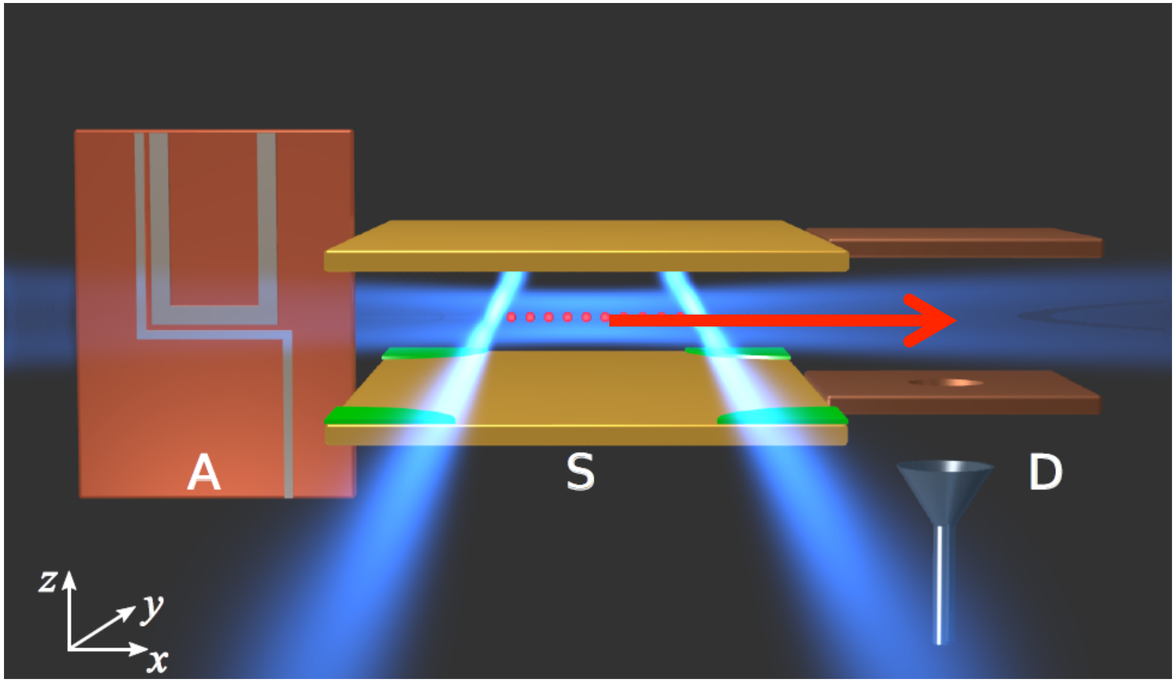
- State-selective field ionization → Measurement of σ^Z
- Evaporation procedure is resumed

→ All atoms are detected one after the other



- Measurement of any spin component up to a global rotation of the spins

- Measurement of all spin correlations between every atoms

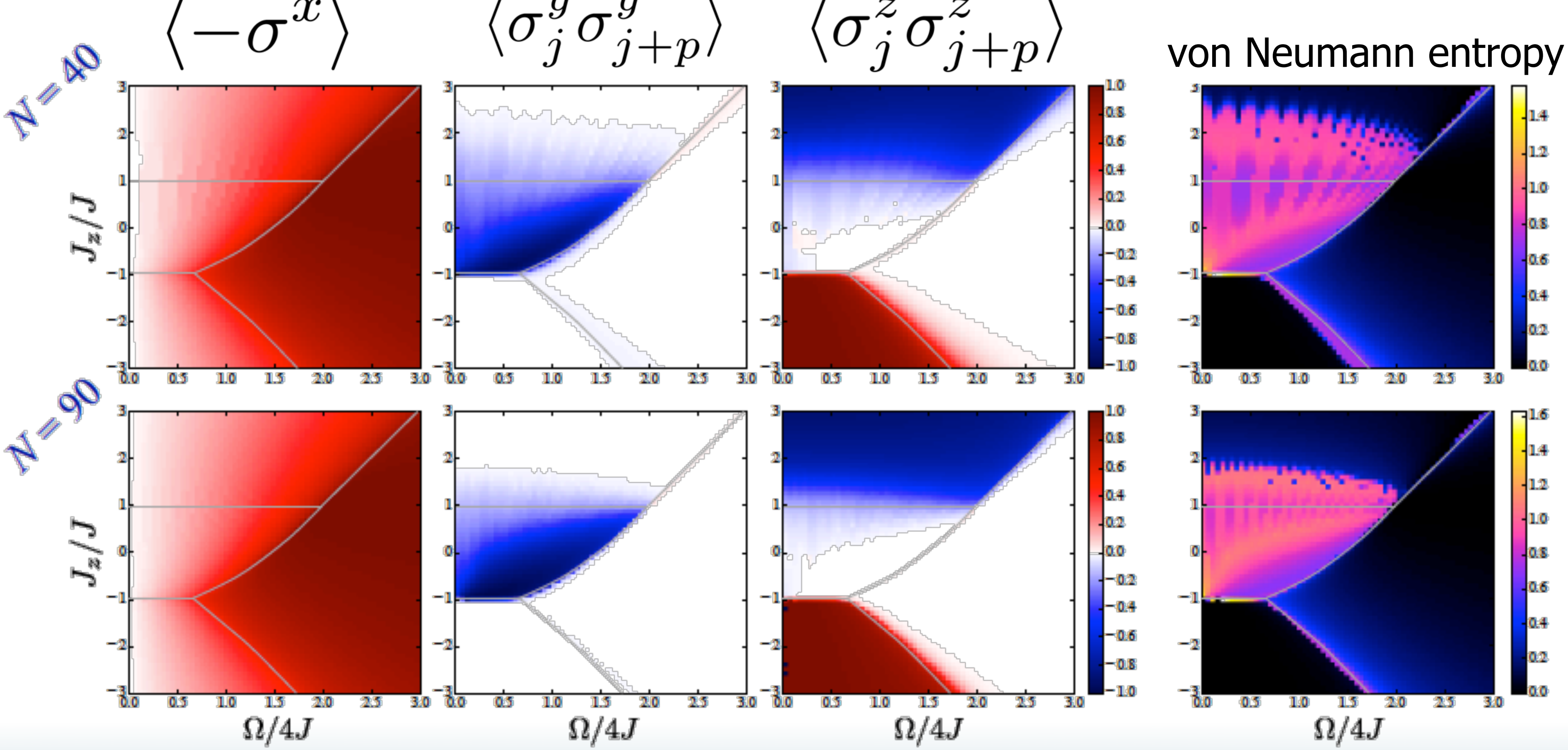


Reconstruction of the phase diagram

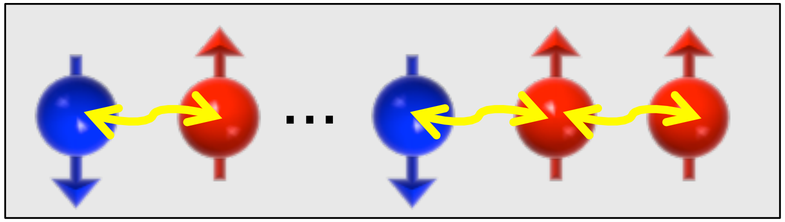
Numerical simulations

G. Roux, LPTMS (Orsay)

- Spin populations and correlations reveal the phase transitions
- Limited finite-size effects already with N=40 atoms



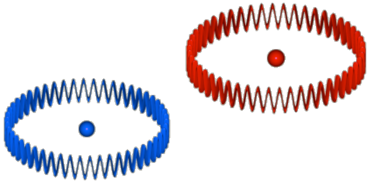
Summary



Simulation of a chain of interacting spins-1/2

Circular Rydberg atom quantum simulator

- Spin 1/2



- Defect free chain of 40 spins

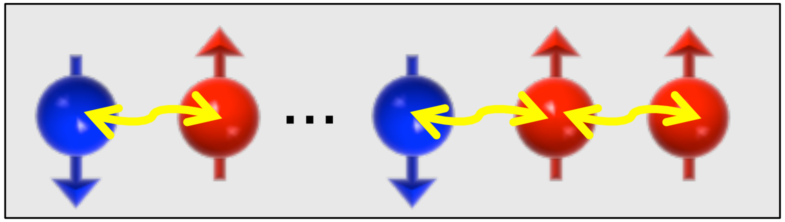
- Long chain lifetime (~ 1s) and strong nearest-neighbour interactions (~15μs)

→ Observation of 10^5 interaction cycles

- Fully tunable XXZ Hamiltonian

T. L. Nguyen et al., arXiv:1707.04397

Summary



Simulation of a chain of interacting spins-1/2

Circular Rydberg atom quantum simulator

- Exploration of long-term dynamics: return to equilibrium after a quench, quantum thermodynamics
- Effects of disorder
- Coupling to a common bosonic bath (motion)
- High frequency modulation: Floquet engineering
- Extension to 2D-protocols (e.g., spin-1 physics)

T. L. Nguyen et al., arXiv:1707.04397

Thank you!

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