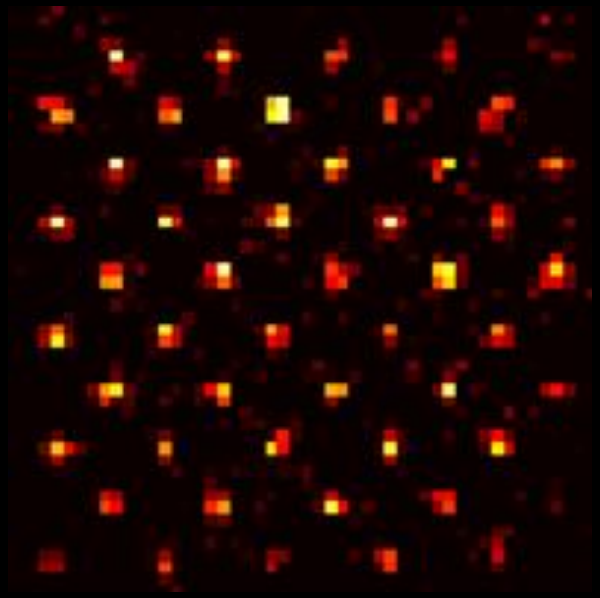
Quantum simulation of spin Hamiltonians in arrays of single Rydberg atoms: recent results, work in progress, and new tools

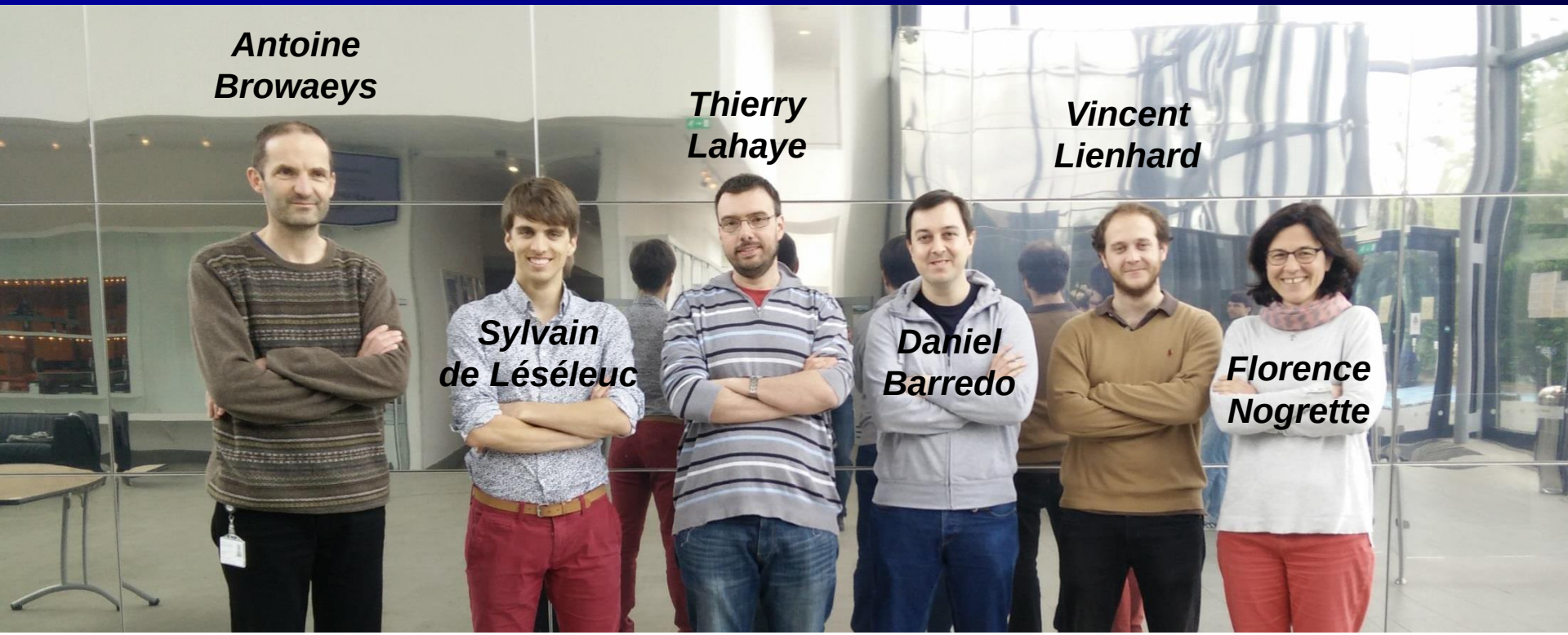
Thierry Lahaye

Laboratoire Charles Fabry,
CNRS, Institut d'Optique, Palaiseau, France



Frontiers of interacting systems of Rydberg atoms
ITAMP, 1-2 June 2017

The Rydberg team in Palaiseau



Former members:
A. Vernier, L. Béguin, H. Labuhn, S.Ravets

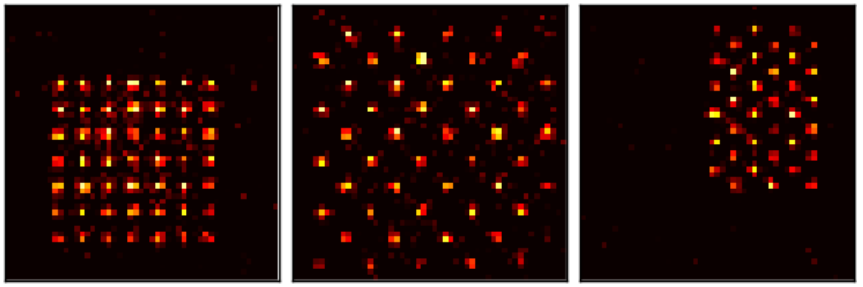
Group website: https://atom-tweezers-io.org/

Funding:

Our experimental platform

- **Arrays of single atoms with arbitrary geometries**

  Spacing: a few microns



- **Strong interactions via Rydberg excitation**

U / h ~ 1-10 MHz for R ~ 5-10 µm

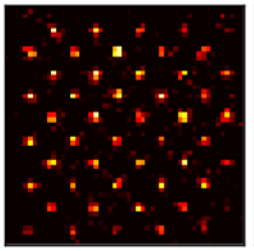
Implement spin models

Ising (vdW interactions), XY (resonant dipole-dipole interaction),…

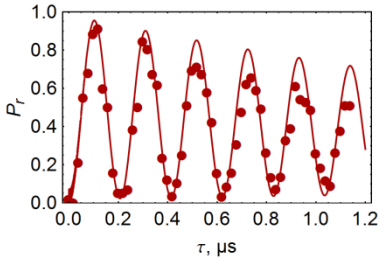
(…but also quantum gates!)

Outline

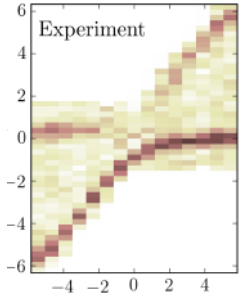
1. Setup and recent results



2. Understanding imperfections

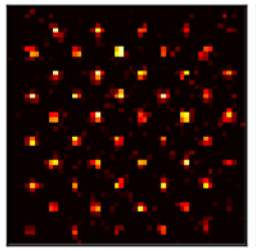


3. Some new tools

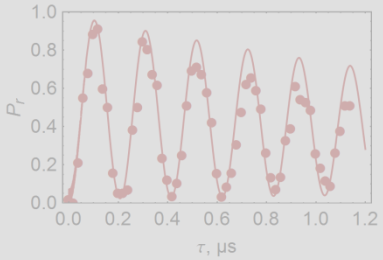


Outline

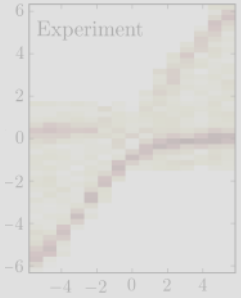
1. Setup and recent results



2. Understanding imperfections

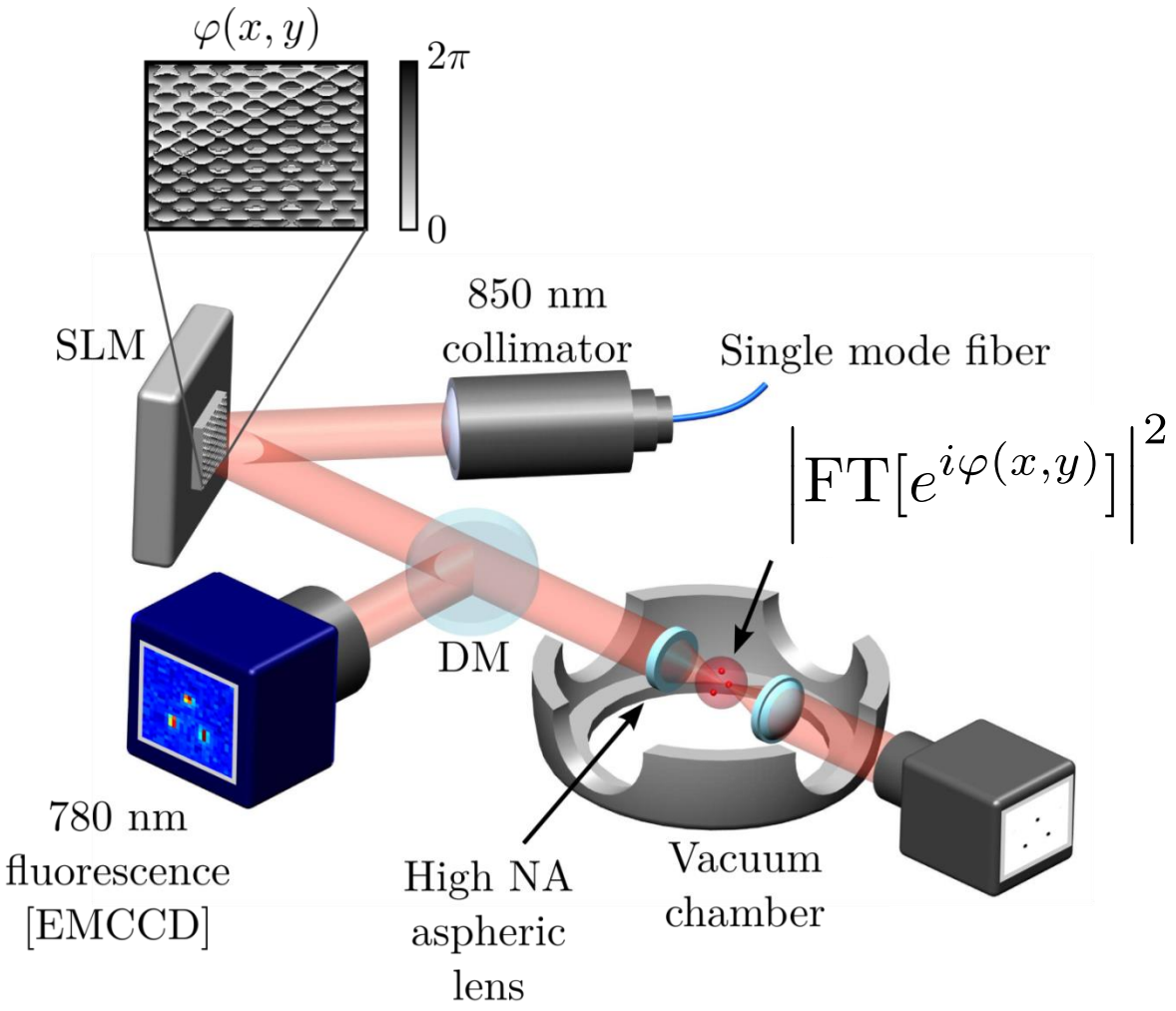


3. Some new tools



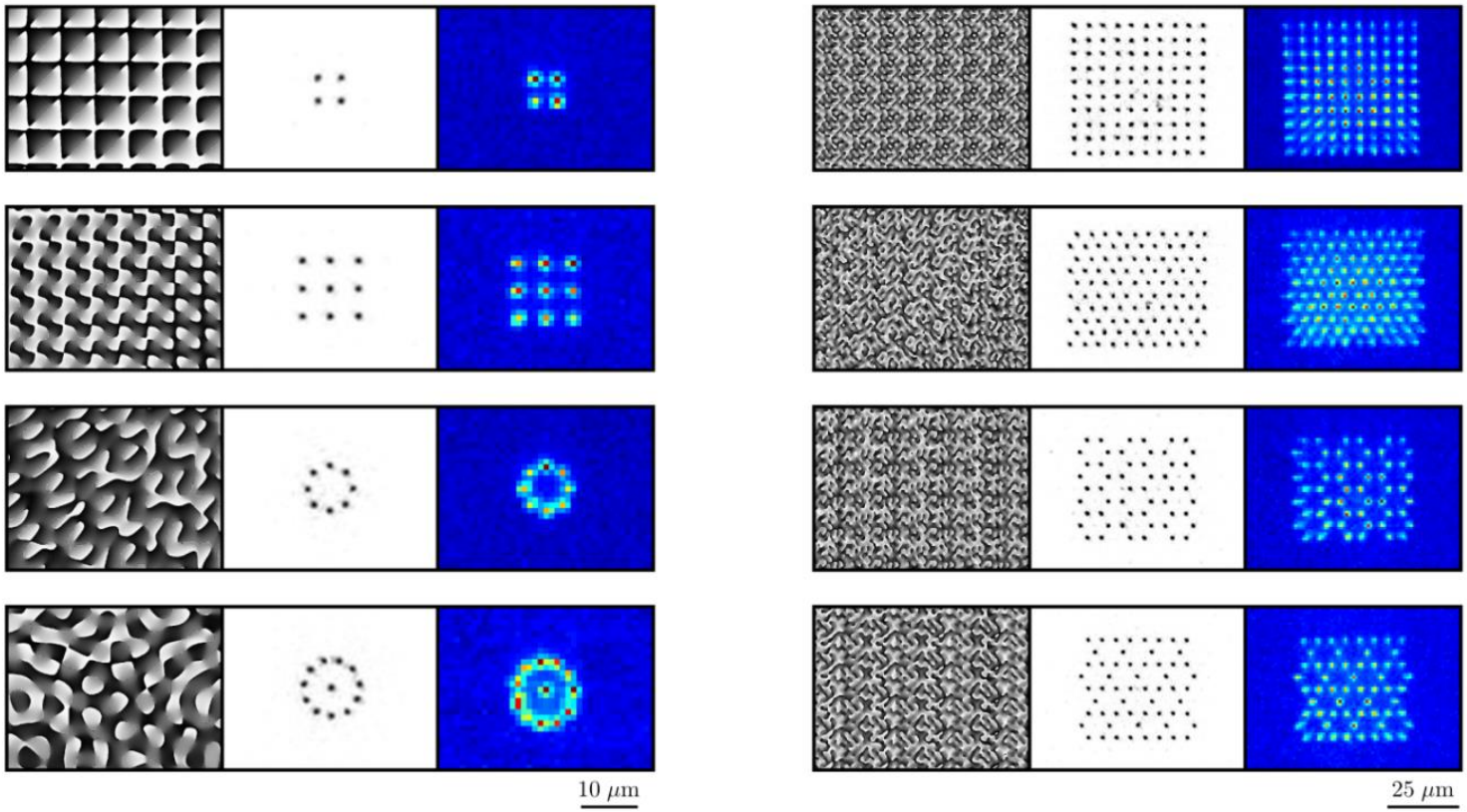
2D arrays of single atoms

Arrays of microtraps with an SLM



+ 8 independent electrodes under vacuum to control electric field

A gallery of arrays

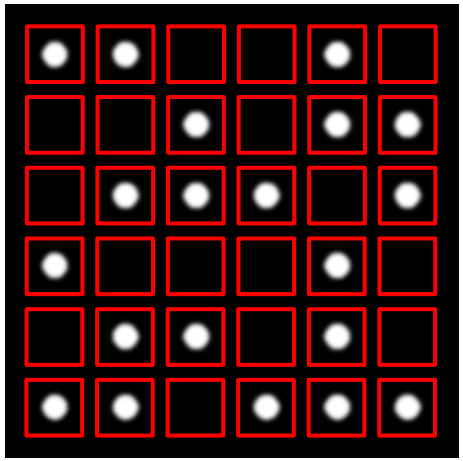


- Distance between neighboring traps down to 3 μm
- Highly uniform trap depths
- Easily reconfigurable

F. Nogrette *et al.*, Phys. Rev. X **4**, 021034 (2014).

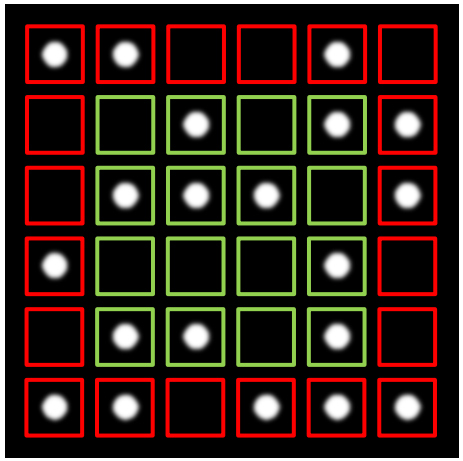
Active sorting of the atoms in the arrays

Initial atom distribution (stochastically filled)



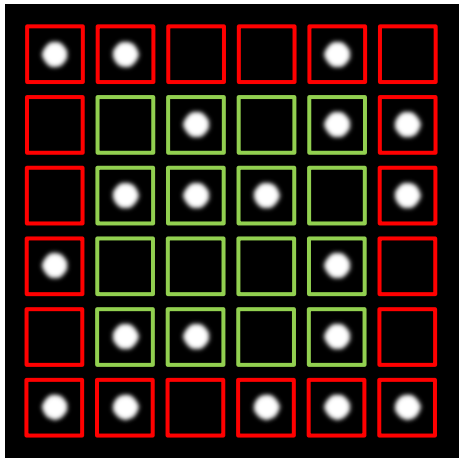
Active sorting of the atoms in the arrays

Initial atom distribution (stochastically filled)

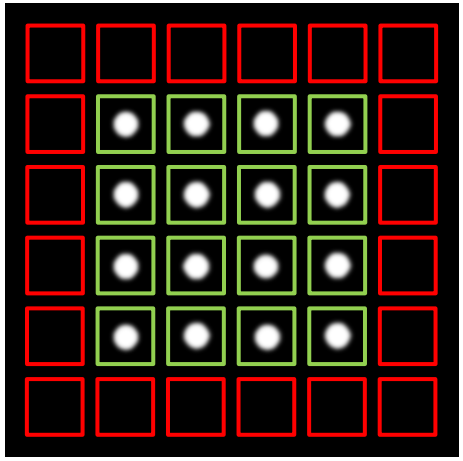


Active sorting of the atoms in the arrays

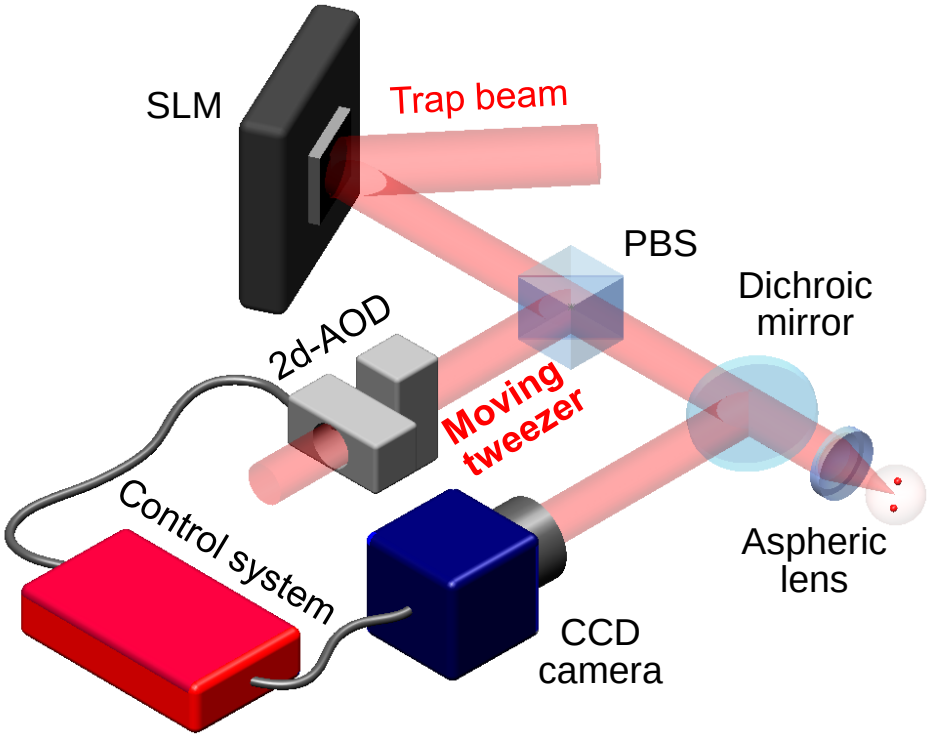
Initial atom distribution (stochastically filled)



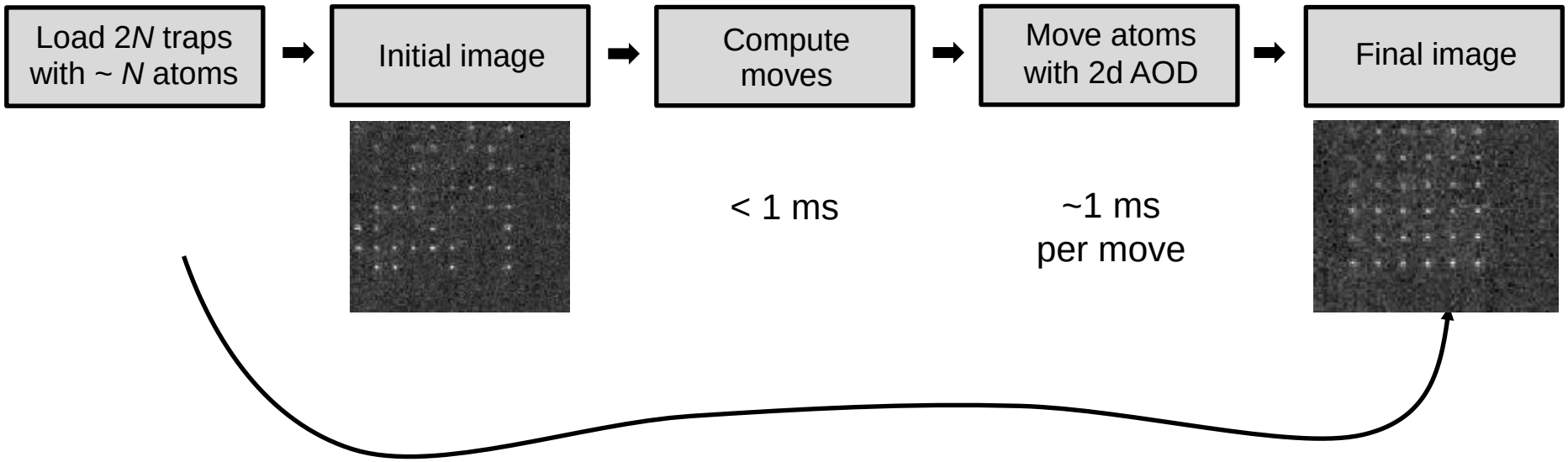
Target atom distribution (ordered array)



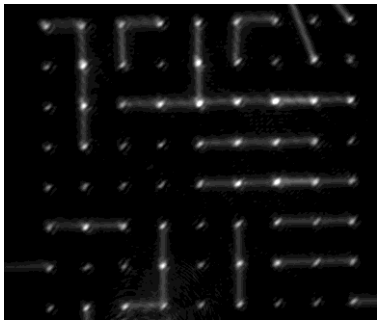
How? Moving optical tweezers!



Assembly sequence for a target of *N* traps

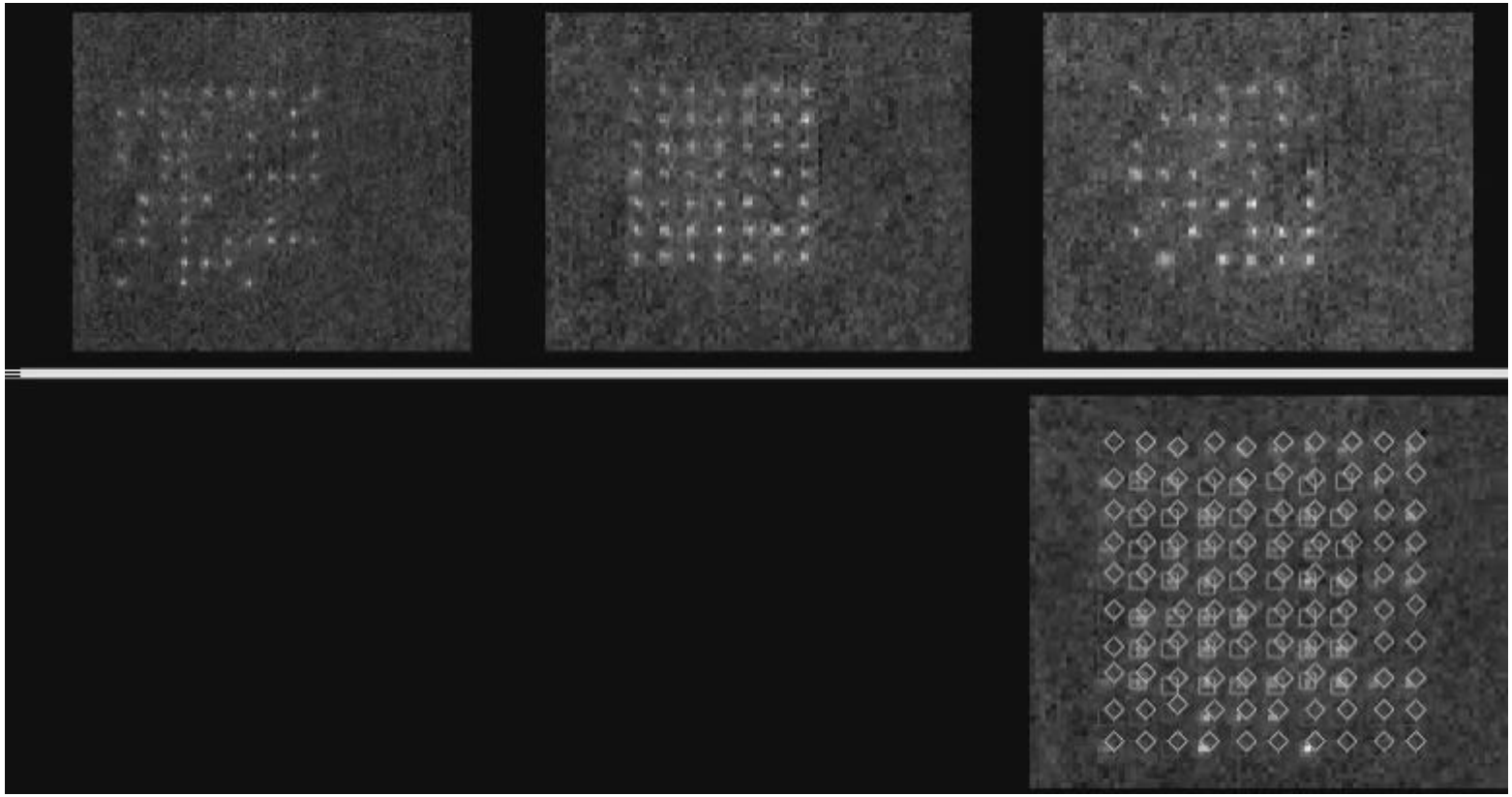


Total assembly time ~ 50 to 100 ms



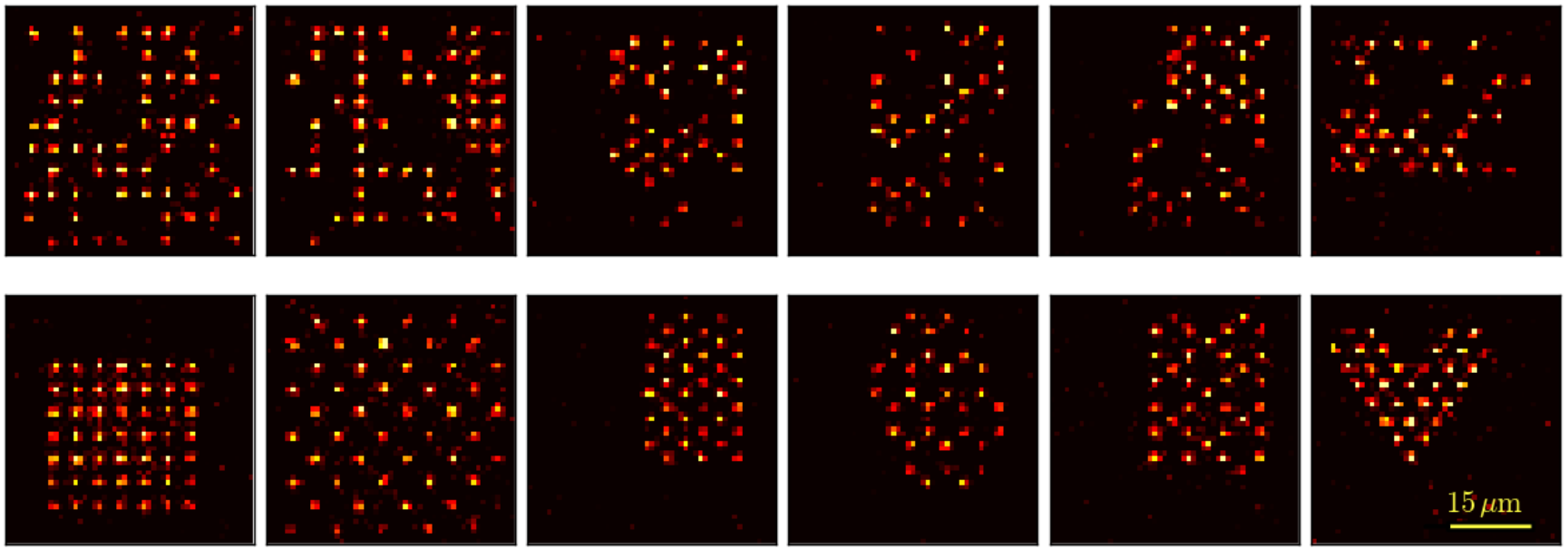
Assembly of a 7x7 square array

Before sorting | After sorting | After Rydberg excitation



Gallery of arrays

(single-shot images)



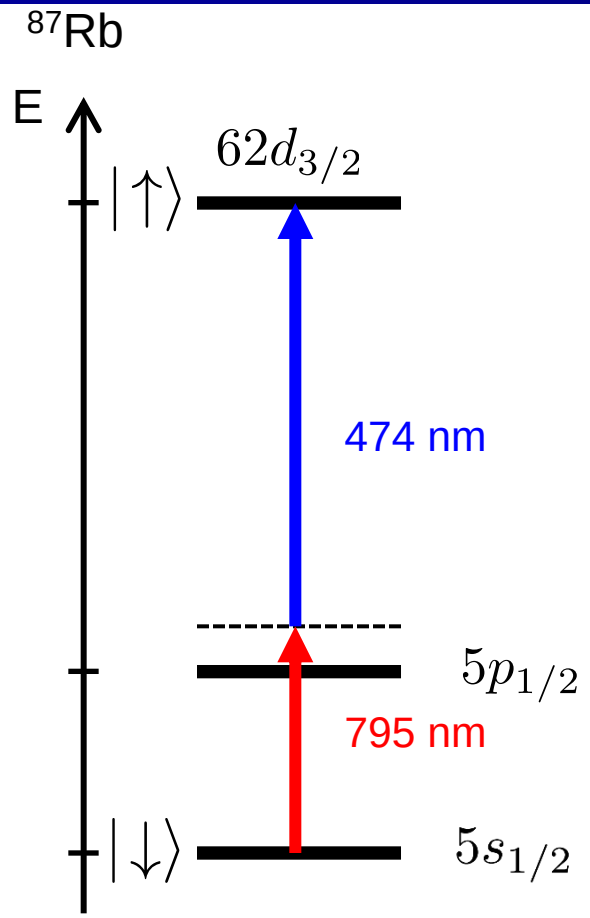
- Fully loaded arrays up to 50 atoms
- 98% filling fraction at ~ 1/s repetition rate
- 100% filling every ~ 2-5 sec

Barredo, de Léséleuc, *et al.*, Science **354**, 1021 (2016)

Related work at Harvard in 1D: Science **354**, 1024 (2016)

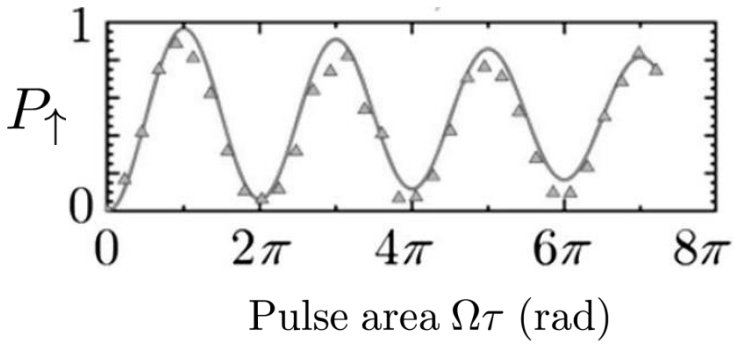
Rydberg atoms & their interactions

Coherent manipulation of Rydberg states

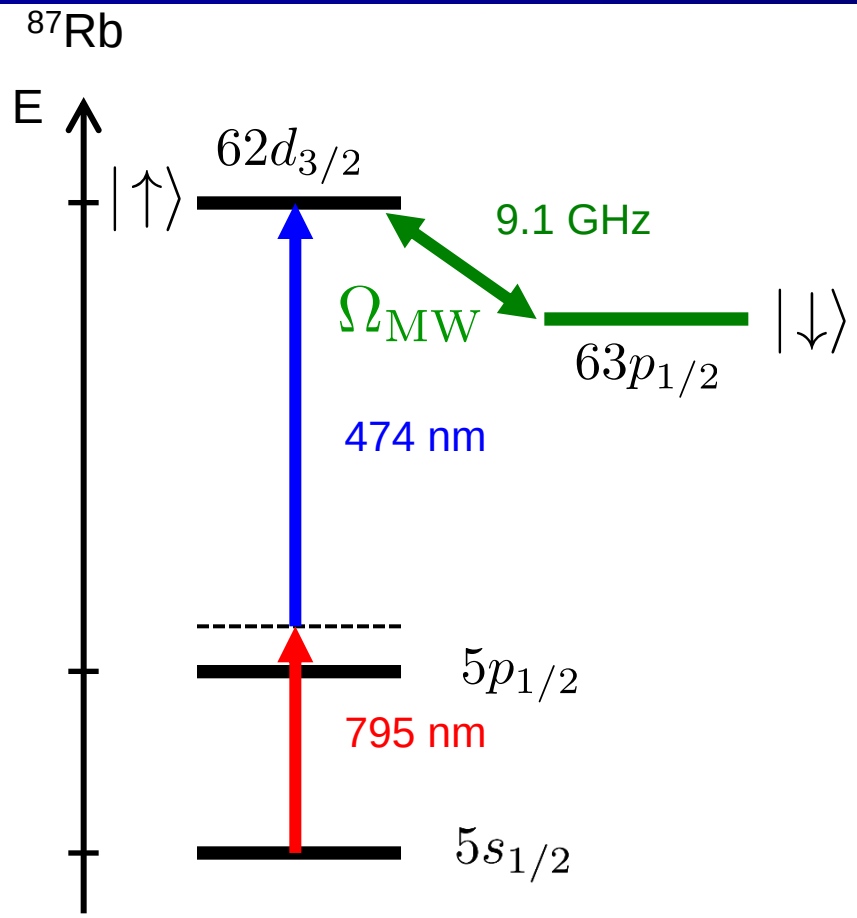


Single atom ⇒ repeat 100 times

Optical excitation $\Omega/(2\pi) \sim 1\,\mathrm{MHz}$

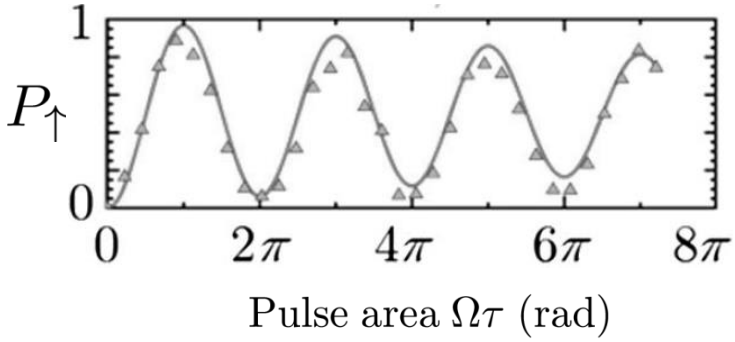


Coherent manipulation of Rydberg states

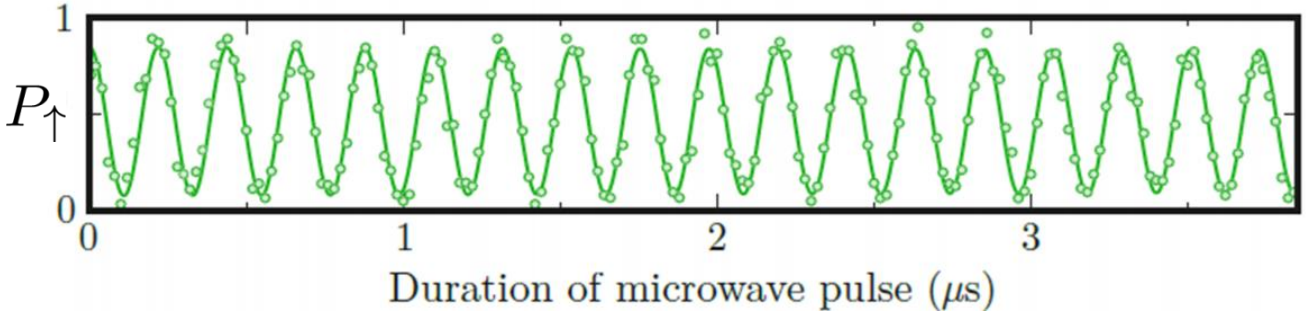


Single atom ⇒ repeat 100 times

Optical excitation $\Omega/(2\pi) \sim 1\,\mathrm{MHz}$

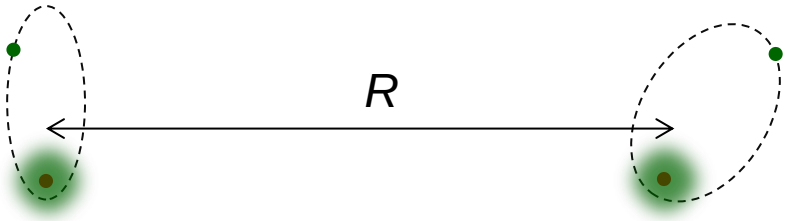


Microwave transfer



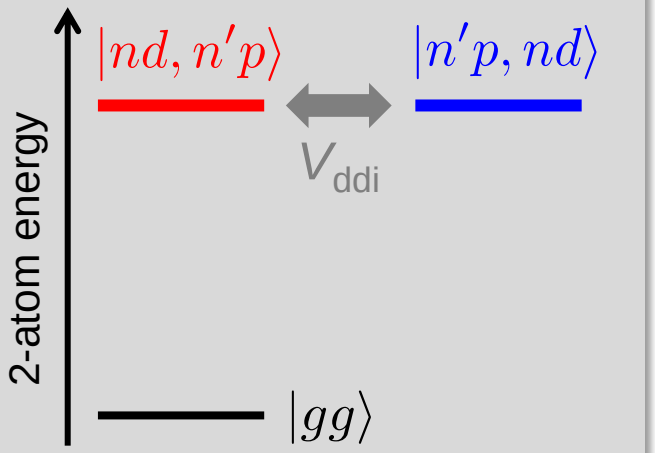
D. Barredo *et al.*,
PRL **114**, 113002 (2015)

Interactions between Rydberg atoms



$$\hat{V}_{\mathrm{ddi}} = \frac{1}{4\pi\varepsilon_0}\frac{\hat{\boldsymbol{d}}_1\cdot\hat{\boldsymbol{d}}_2 - 3(\hat{\boldsymbol{d}}_1\cdot\hat{\boldsymbol{n}})(\hat{\boldsymbol{d}}_2\cdot\hat{\boldsymbol{n}})}{R^3}$$

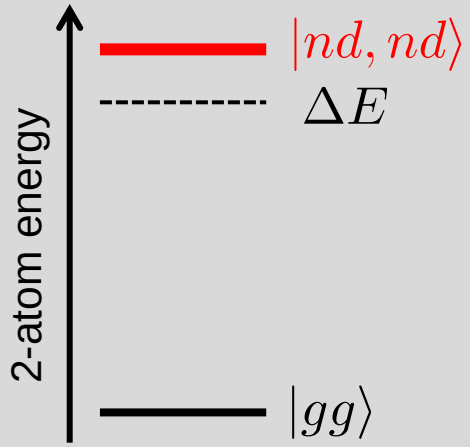
Resonant interaction



$$V \sim \frac{C_3}{R^3}$$

XY interaction (flip-flop)

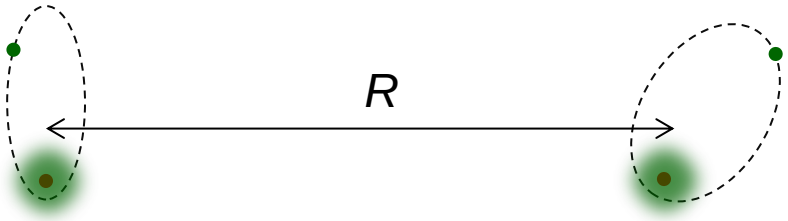
van der Waals



$$\Delta E \sim \frac{C_6}{R^6}$$

Ising-like interaction

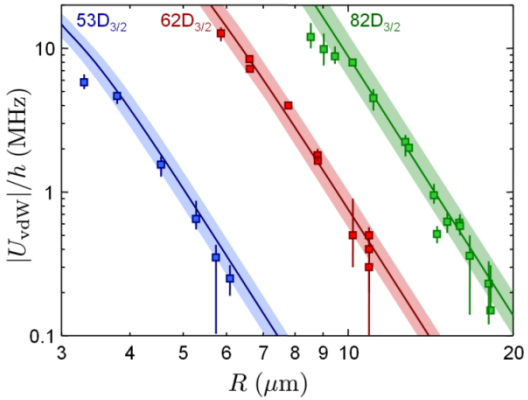
Interactions between two Rydberg atoms in the lab



$$\hat{V}_{\mathrm{ddi}} = \frac{1}{4\pi\varepsilon_0}\frac{\hat{\boldsymbol{d}}_1\cdot\hat{\boldsymbol{d}}_2 - 3(\hat{\boldsymbol{d}}_1\cdot\hat{\boldsymbol{n}})(\hat{\boldsymbol{d}}_2\cdot\hat{\boldsymbol{n}})}{R^3}$$

van der Waals

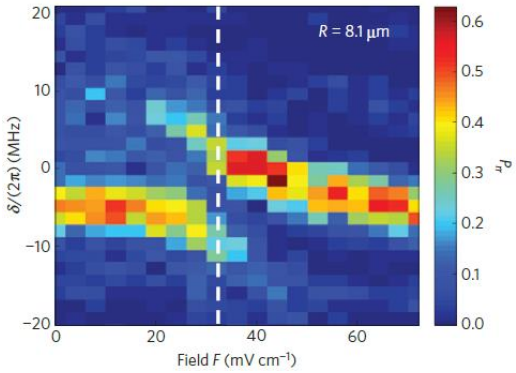
$U \sim 1/R^6$



Béguin *et al.*, PRL 2013

Förster resonance

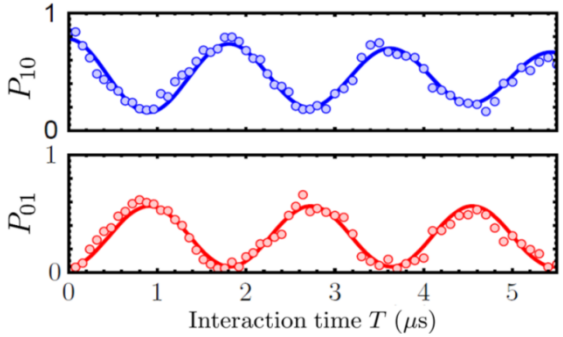
$U \sim 1/R^3$



Ravets *et al.*, Nature Phys. 2014

Resonant dipole-dipole interaction

$U \sim 1/R^3$

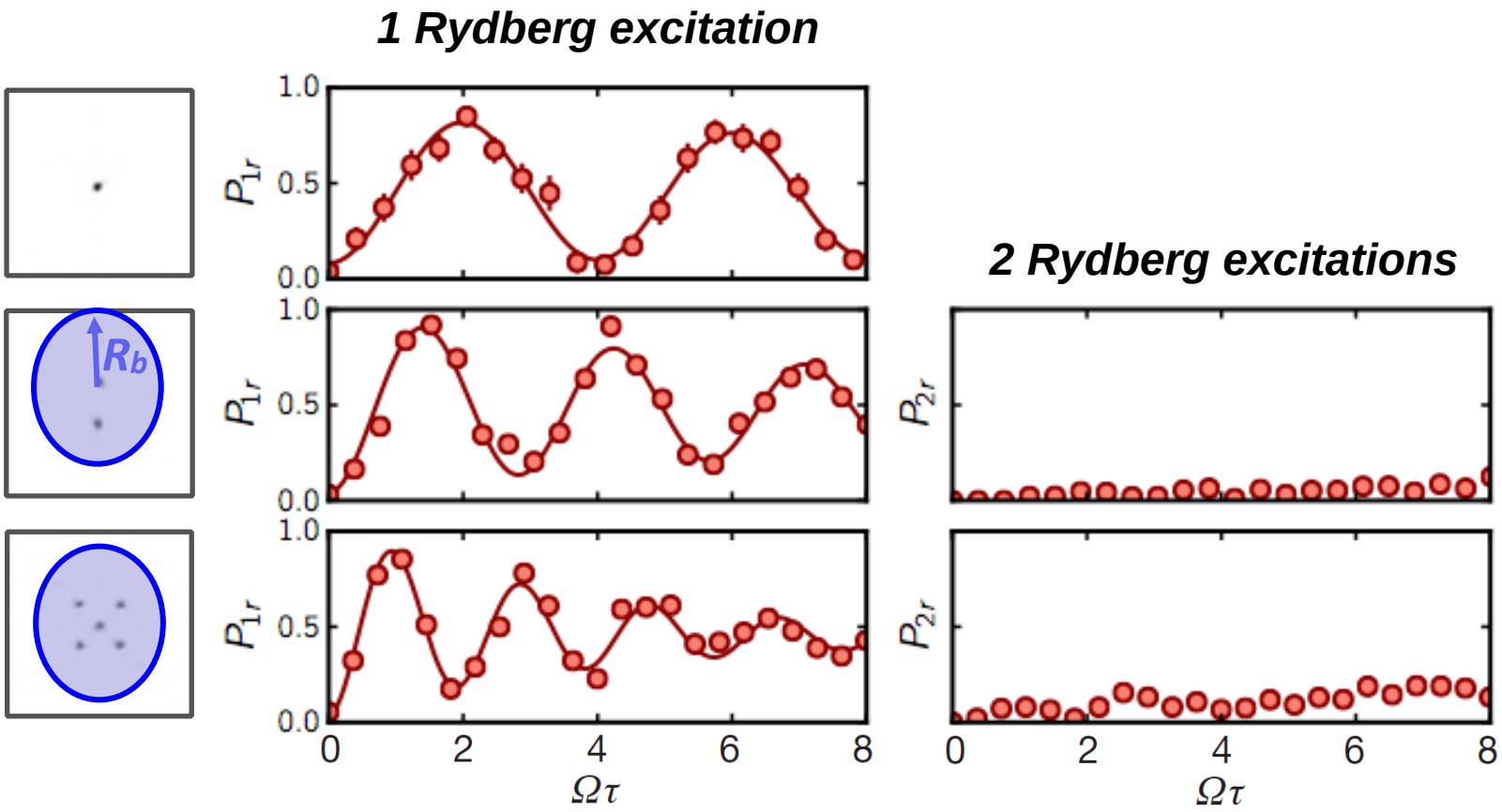


Barredo *et al.*, PRL 2015

Review: A. Browaeys *et al.*, J. Phys. B **49**, 152001 (2016)

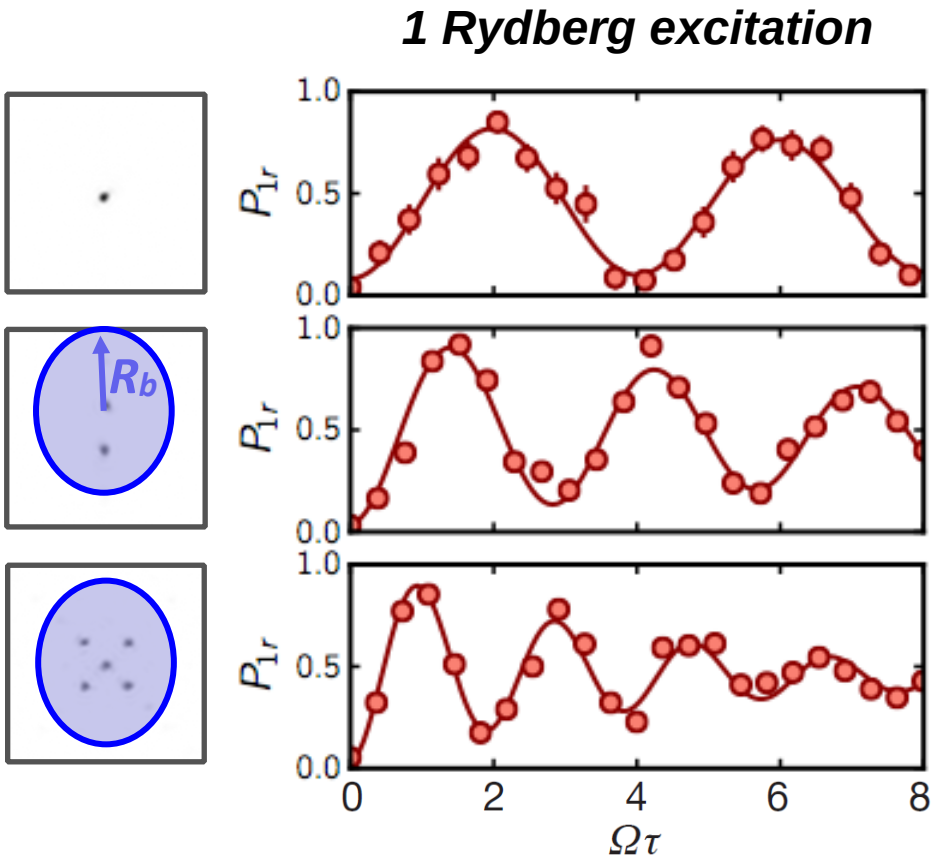
Rybderg blockade and Ising-like spin Hamiltonians

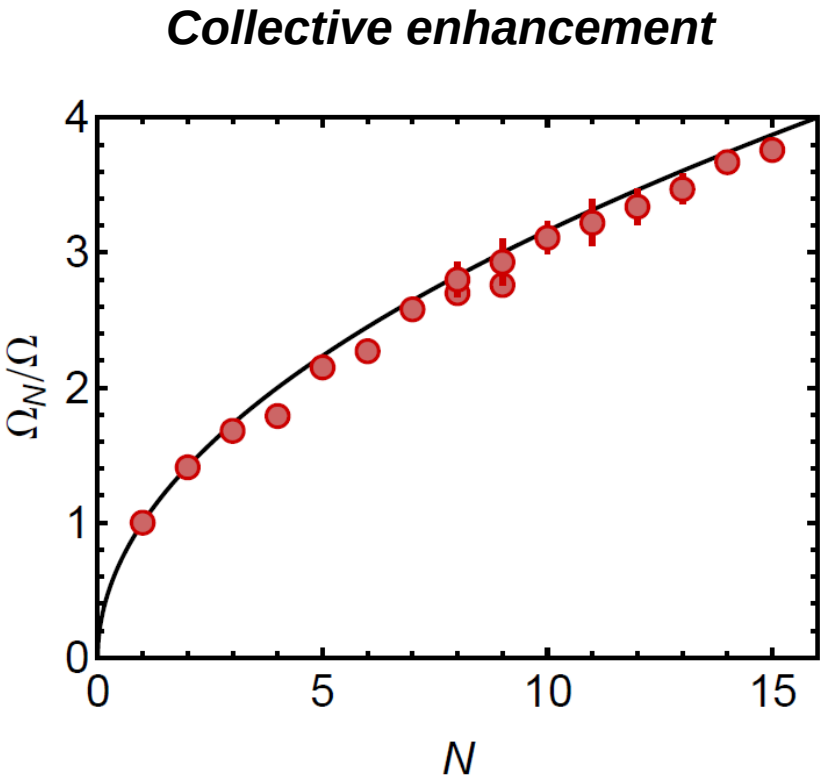
Collective excitation & Rydberg blockade



H. Labuhn *et al*., Nature **534**, 667 (2016)

Collective excitation & Rydberg blockade



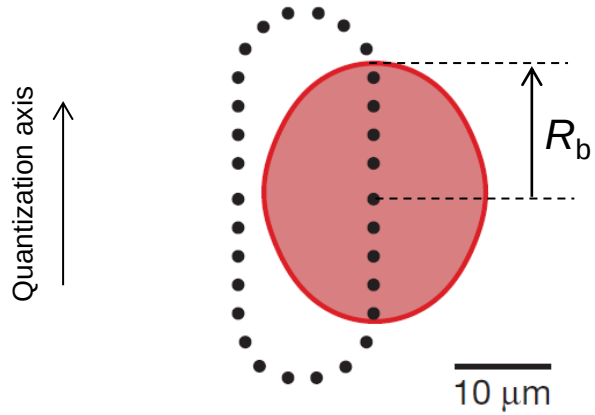


H. Labuhn *et al.*, Nature **534**, 667 (2016)

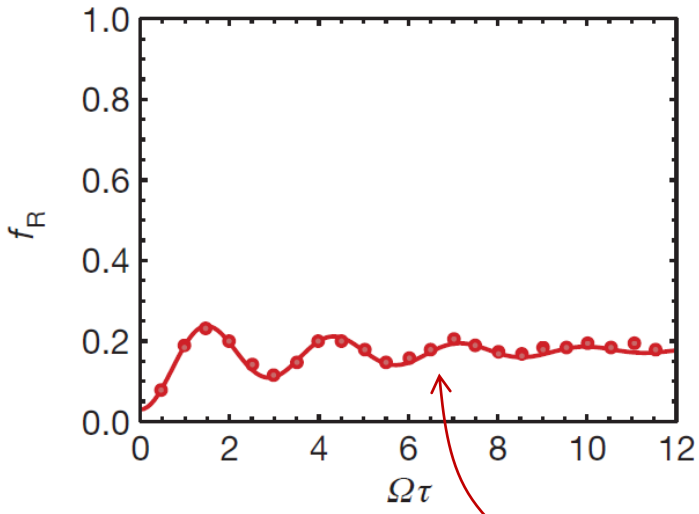
Quench of Ising-like spin Hamiltonians

1D chain with periodic boundary conditions
20 atoms

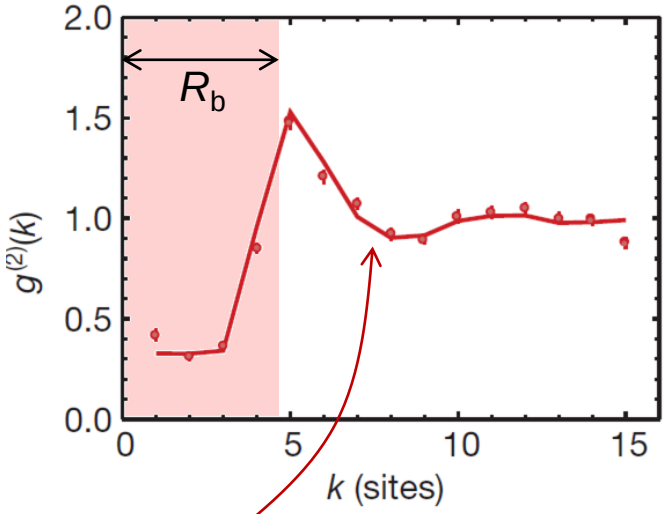
$$H = \sum_i \frac{\hbar\Omega}{2}\sigma_x^i + \sum_{i<j} V_{ij} n^i n^j$$



Magnetization



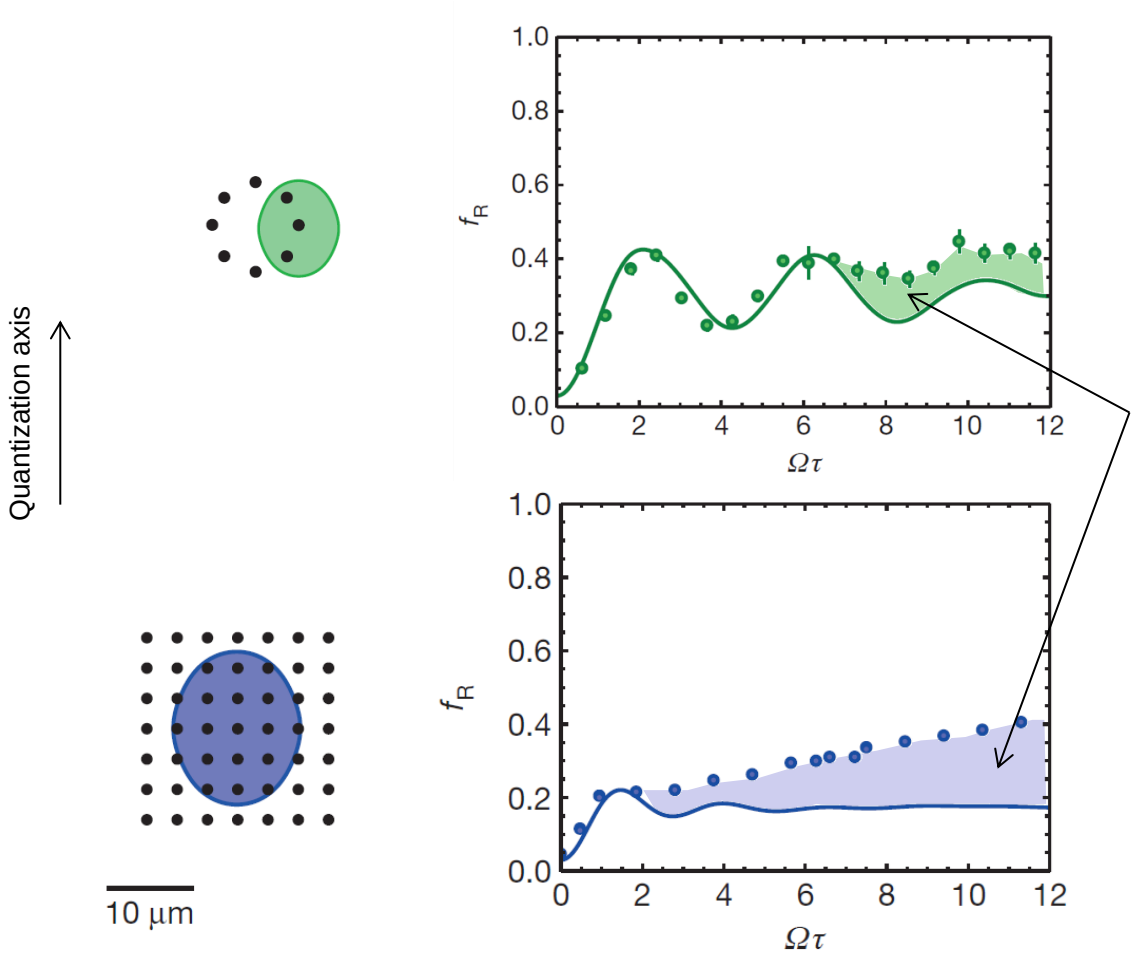
Spin-spin correlation function



Spin ½ model, no adjustable parameter
(calculations by Tommaso Macrì)

H. Labuhn *et al.*, Nature **534**, 667 (2016)

Quench of Ising-like spin Hamiltonians



Stronger anisotropy

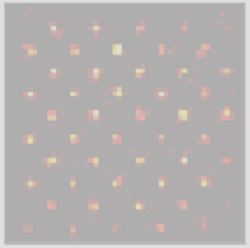
Excess of Rydberg atoms at long times as compared to prediction of spin ½ model

Effect of multilevel structure of $D_{3/2}$ Rydberg states?

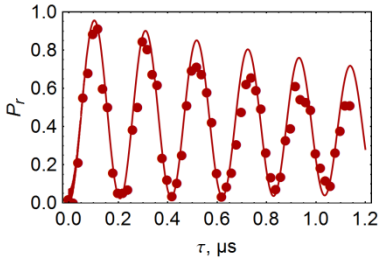
H. Labuhn *et al.*, Nature **534**, 667 (2016)

Outline

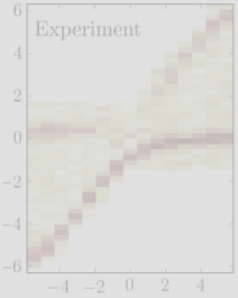
1. Setup and recent results



2. Understanding imperfections



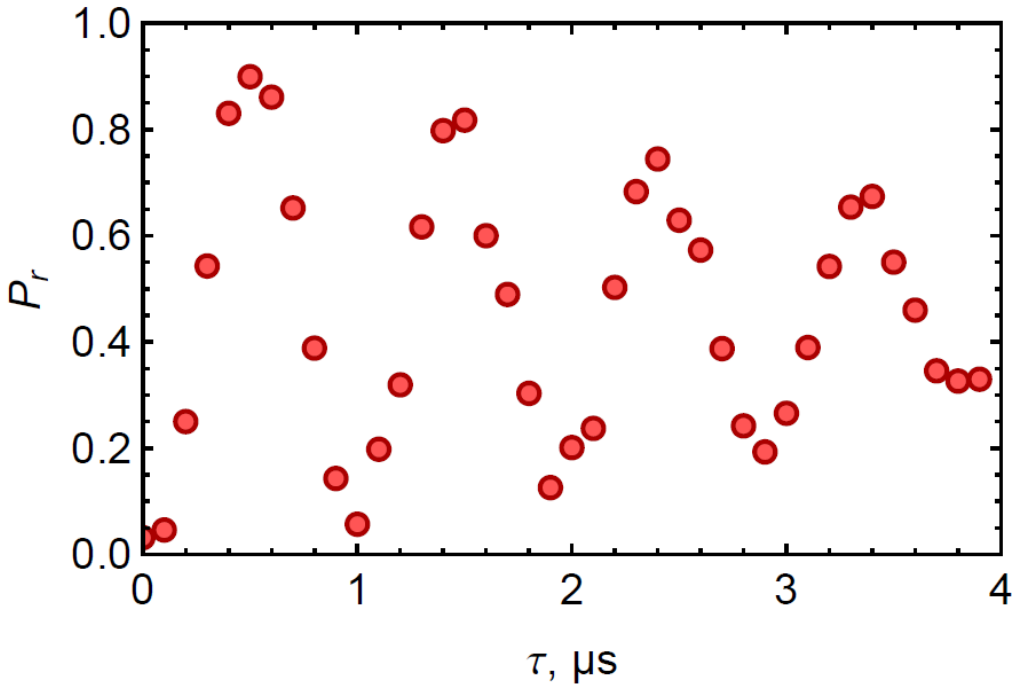
3. Some new tools



Imperfections at the single-particle level

Understanding the damping of Rabi oscillations $|g\rangle \leftrightarrow |r\rangle$

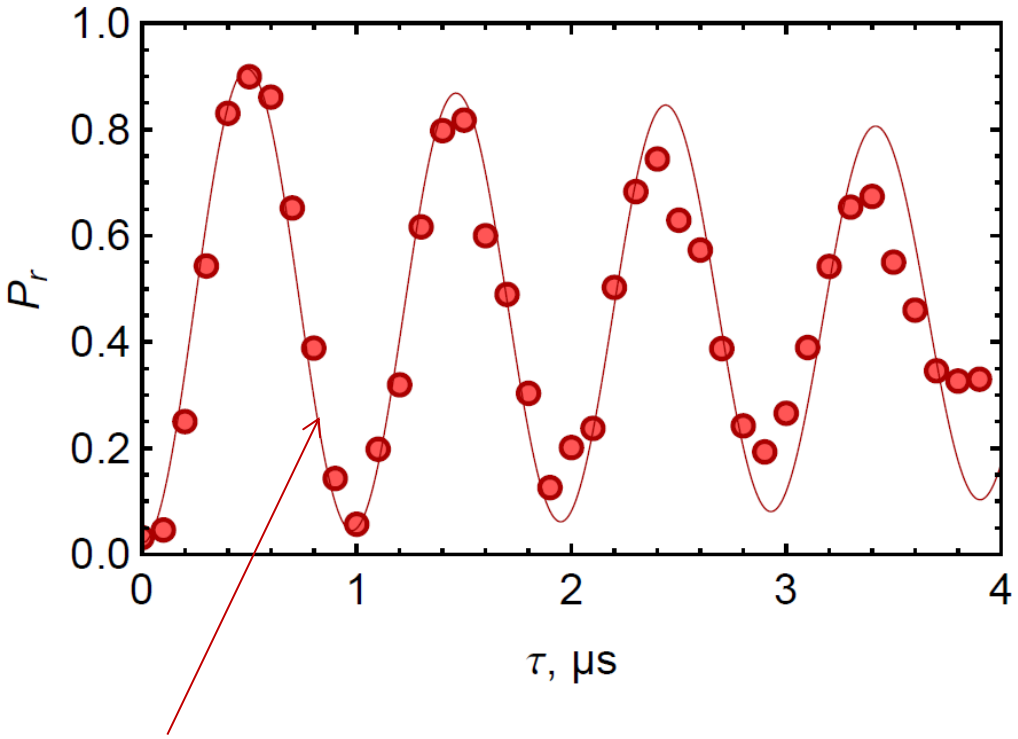
Typical Rabi oscillation to $61D_{3/2}$ for a single atom:



1/e damping time ~ 5 μs. Where does this come from?

Understanding the damping of Rabi oscillations $|g\rangle \leftrightarrow |r\rangle$

Typical Rabi oscillation to $61D_{3/2}$ for a single atom:



Model including a, b, c, d. No adjustable parameter.

Combination of several small effects:

a. Doppler effect

b. Spontaneous emission via $5P_{1/2}$ state

c. Laser phase noise

d. Imperfection in optical pumping and in detection

More details in the "decoherence" session…

Imperfect blockade for nD states due to anisotropic vdW interactions

Breakdown of Rydberg blockade

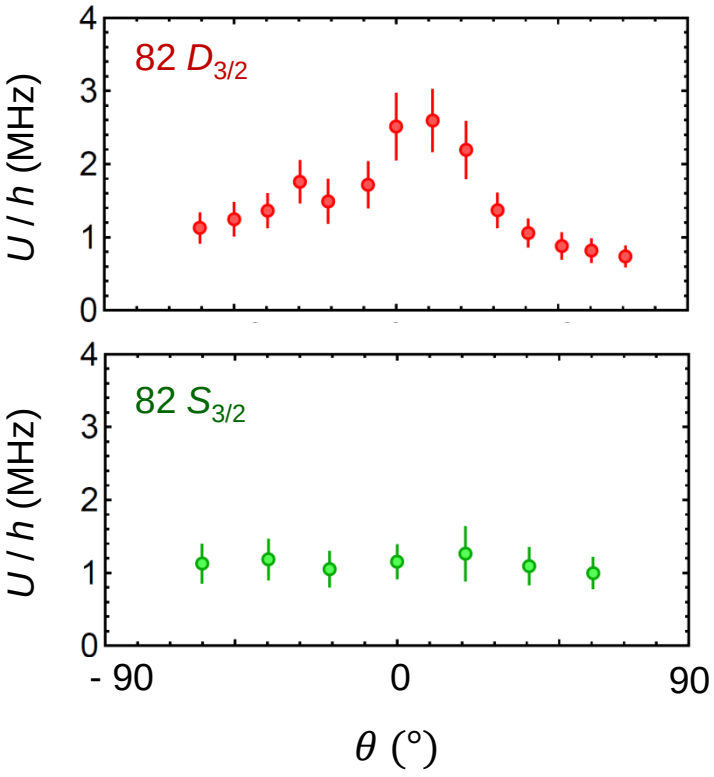
Rybderg atoms have *many* levels…

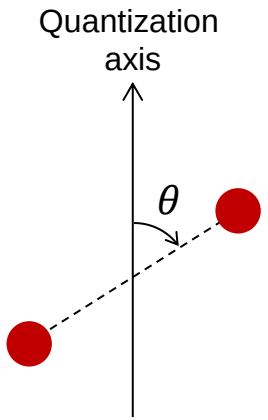
…which can lead to a breakdown of the blockade:

- ***Zeeman degeneracies***
  T. G. Walker and M. Saffman, Phys. Rev. A **77**, 032723 (2008).
- ***'Three-body' interactions close to Förster resonances***
  T. Pohl and P.R. Berman, Phys. Rev. Lett. **102**, 013004 (2009).
- ***Molecular resonances***
  A. Derevianko *et al.*, Phys. Rev. A **92,** 063419 (2015).

Understanding the imperfect blockade for D states

- nD$_{3/2}$ states: 4 Zeeman sublevels
- For an atom pair not aligned with quantization axis, vdW interaction is a 16 x 16 matrix
- Simplest approach: Anisotropic, effective C_6 coefficient





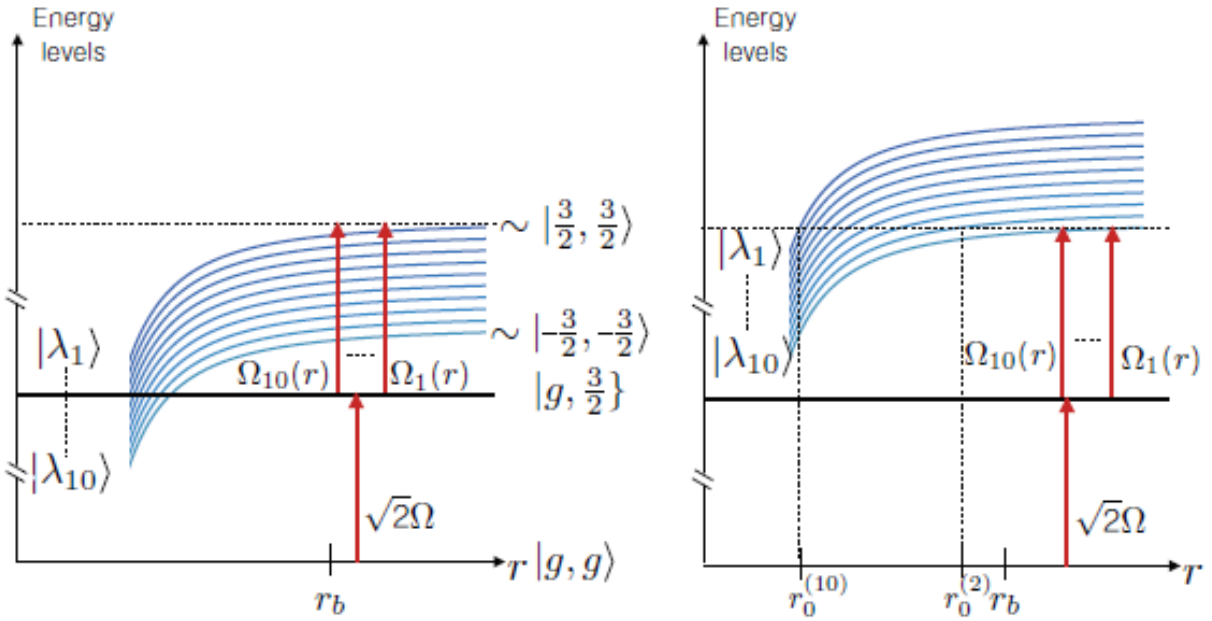
Barredo *et al.*, PRL **112** 183002 (2014)

Vermersch *et al.*, PRA **91** 023411 (2015)

Effect of a B-field

- B-field: Zeeman effect splits $n\mathrm{D}_{3/2}$,$n\mathrm{D}_{3/2}$ manifold

- If vdW and Zeeman effect have opposite signs, breakdown of blockade at some ***magic distances***

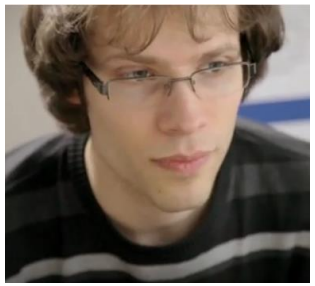


Vermersch *et al.*, PRA **91** 023411 (2015)

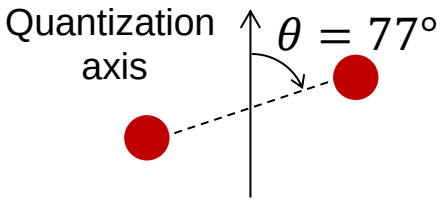
E-field also matters!

S. Weber *et al.*, arXiv:1612.08053

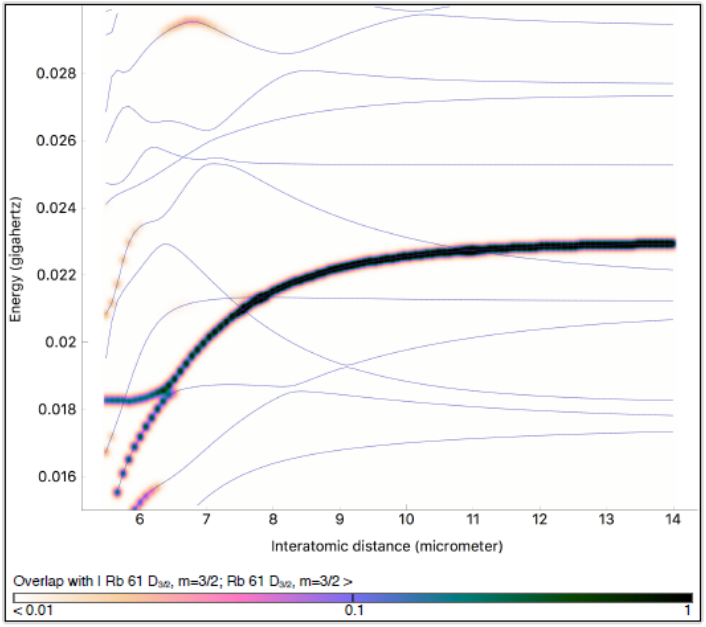
Pair interaction calculator
https://pairinteraction.github.io



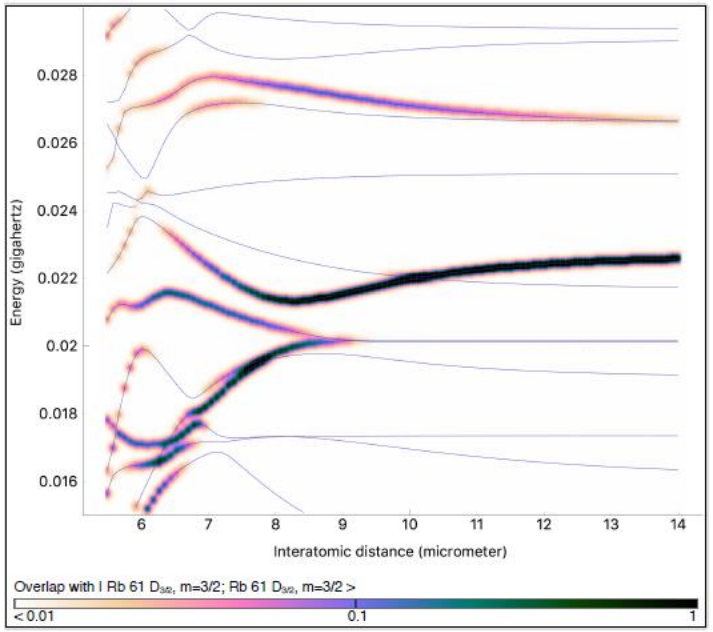
Hans-Peter Büchler Sebastian Weber



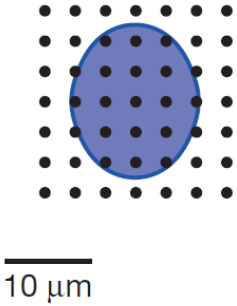
B = 6.9 G
E = 0 mV/cm



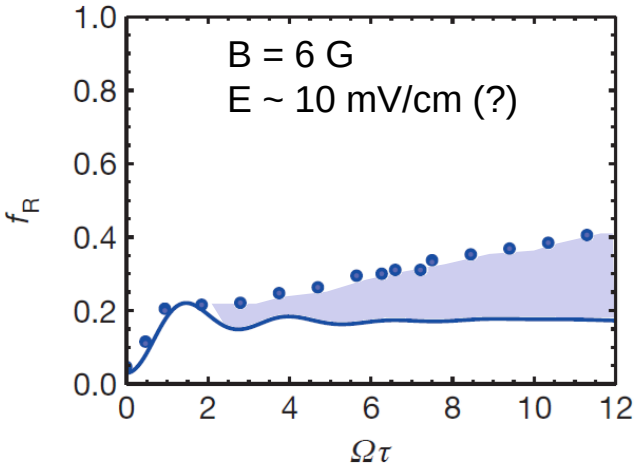
B = 6.9 G
E = 20 mV/cm



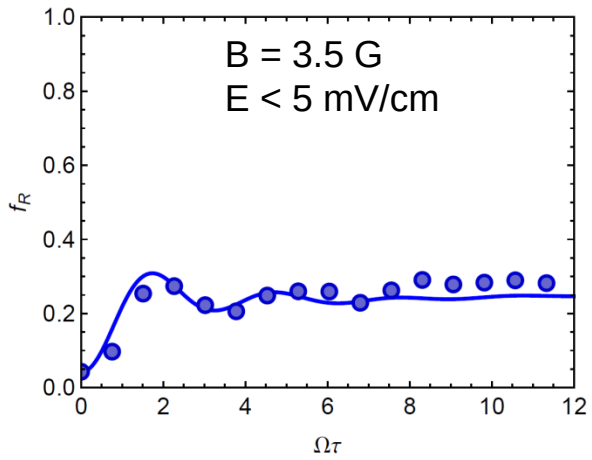
Back to the the 7x7 array…



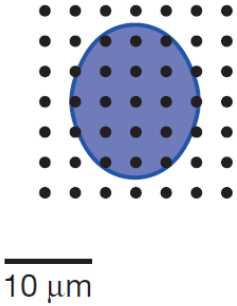
Before…



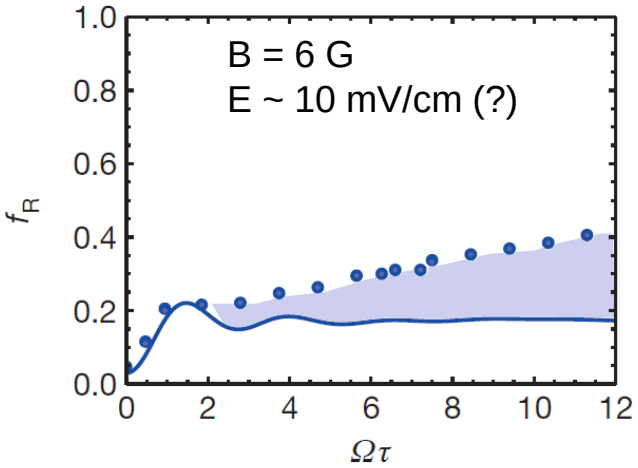
After…



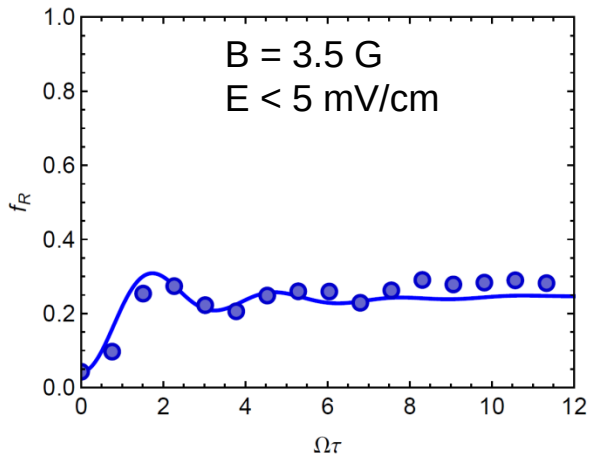
Back to the the 7x7 array…

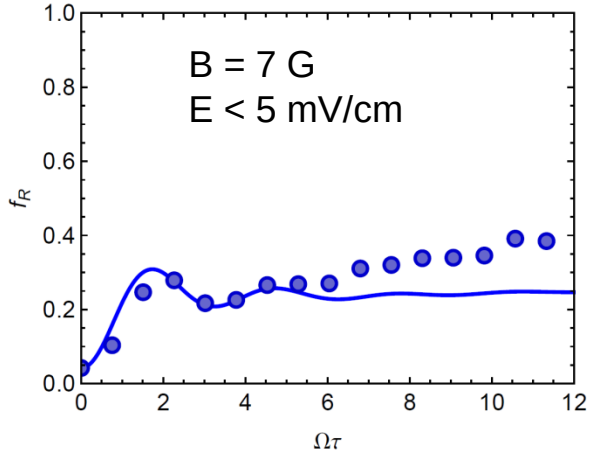


Before…



After…

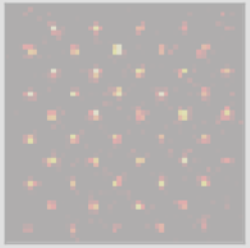




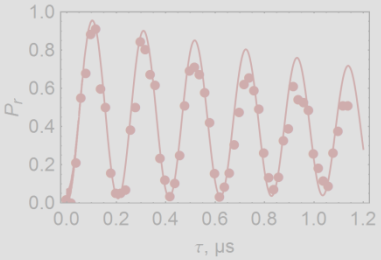
'Safe' region in parameter space (*E*, *B*, θ) is quite small (especially for high n)

Outline

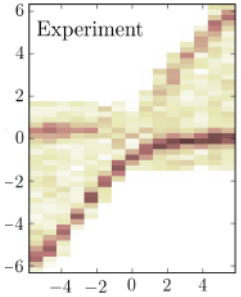
1. Setup and recent results



2. Understanding imperfections



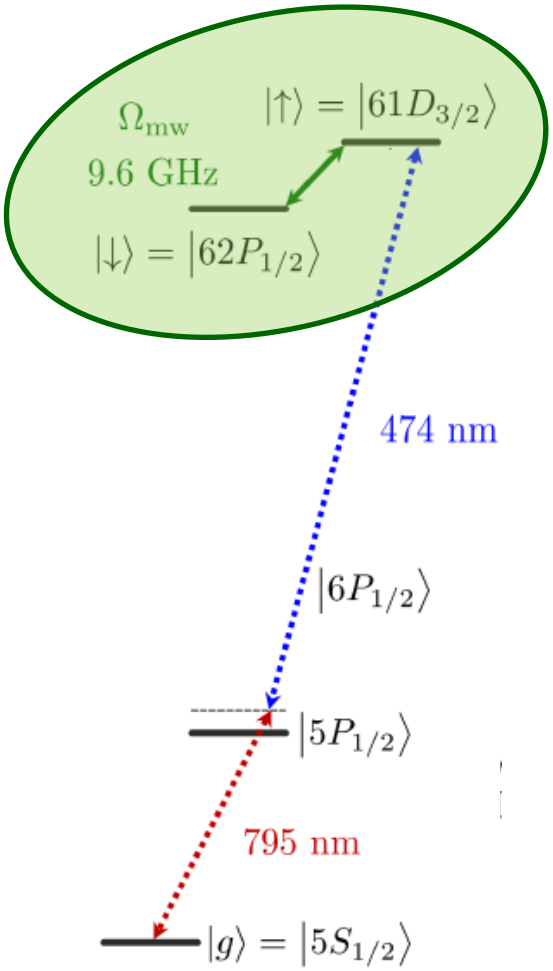
3. Some new tools

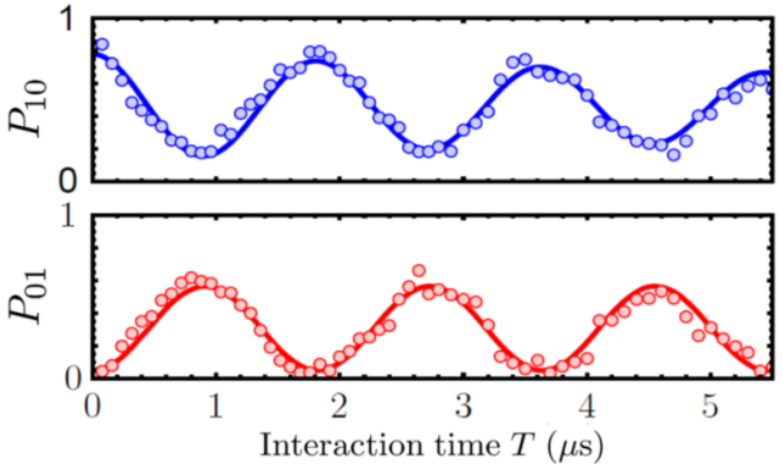


Local optical control of XY interactions

Local optical control of the resonant DDI

Resonant dipole-dipole coupling $|\uparrow\downarrow\rangle \leftrightarrow |\downarrow\uparrow\rangle$ ***Spin exchange, always "on"***





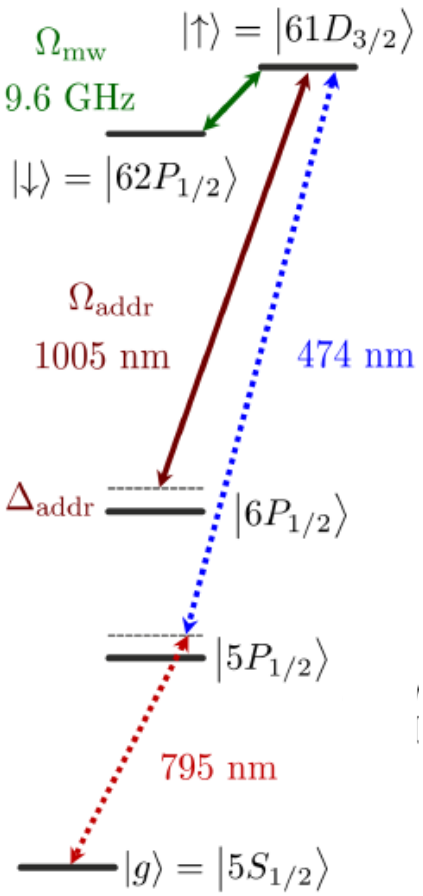
Barredo *et al.*, PRL 2015

How to control this interaction?

Local optical control of the resonant DDI

Resonant dipole-dipole coupling $|\uparrow\downarrow\rangle \leftrightarrow |\downarrow\uparrow\rangle$ ***Spin exchange, always "on"***

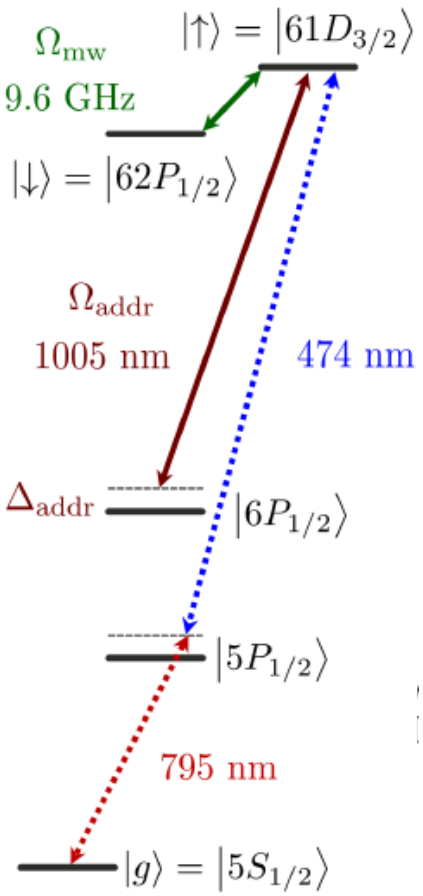
Apply selective lightshift on $|\uparrow\rangle$ with beam at 1005 nm!

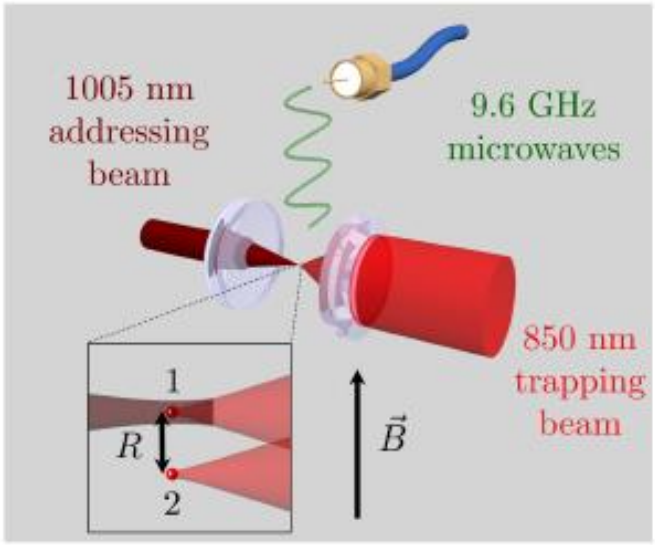


Local optical control of the resonant DDI

Resonant dipole-dipole coupling $|\uparrow\downarrow\rangle \leftrightarrow |\downarrow\uparrow\rangle$ ***Spin exchange, always "on"***

Apply selective lightshift on $|\uparrow\rangle$ with beam at 1005 nm!

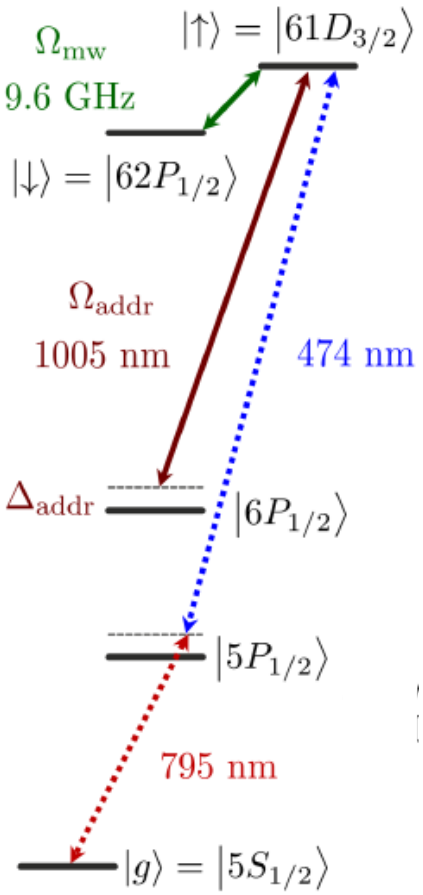


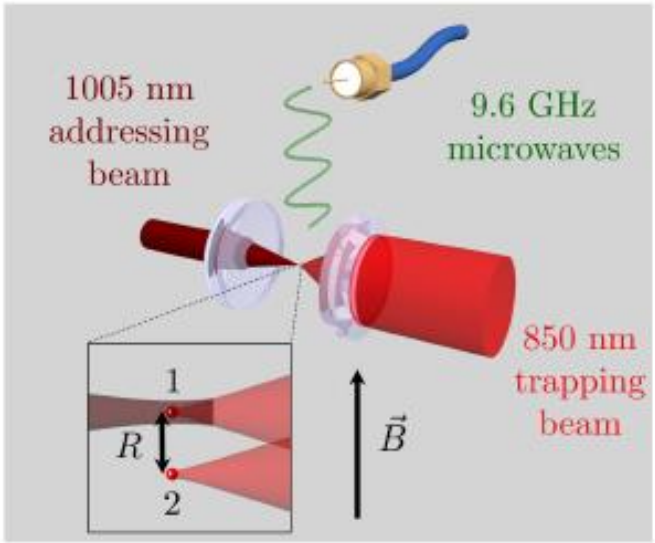


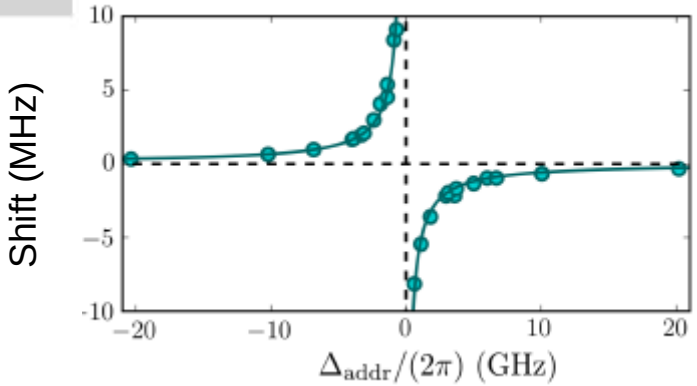
Local optical control of the resonant DDI

Resonant dipole-dipole coupling $|\uparrow\downarrow\rangle \leftrightarrow |\downarrow\uparrow\rangle$ ***Spin exchange, always "on"***

Apply selective lightshift on $|\uparrow\rangle$ with beam at 1005 nm!

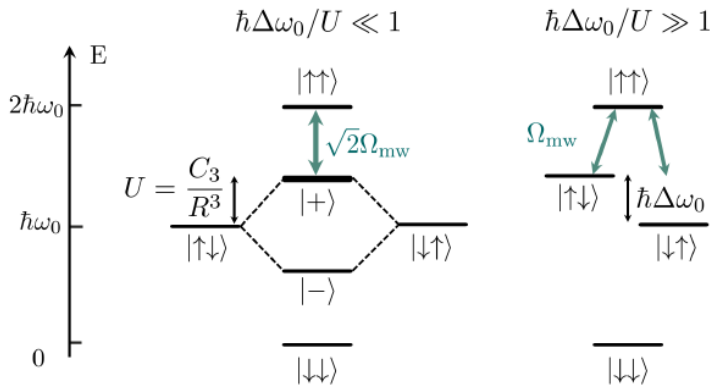




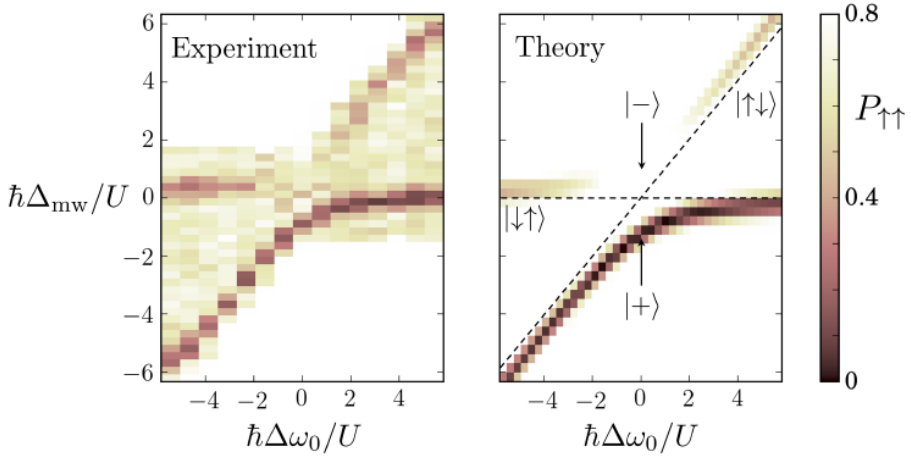


Two atoms

Controlling a two-spin system

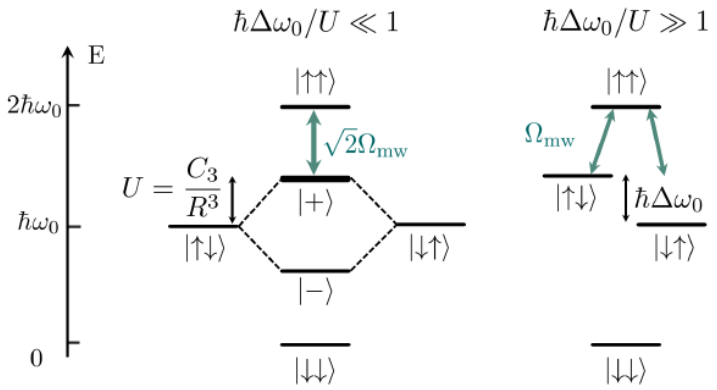


Microwave spectroscopy starting in $|\uparrow\uparrow\rangle$

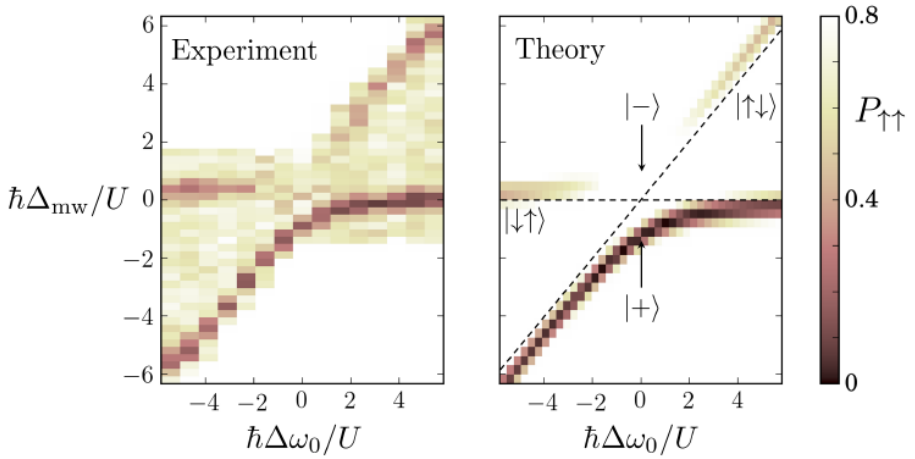


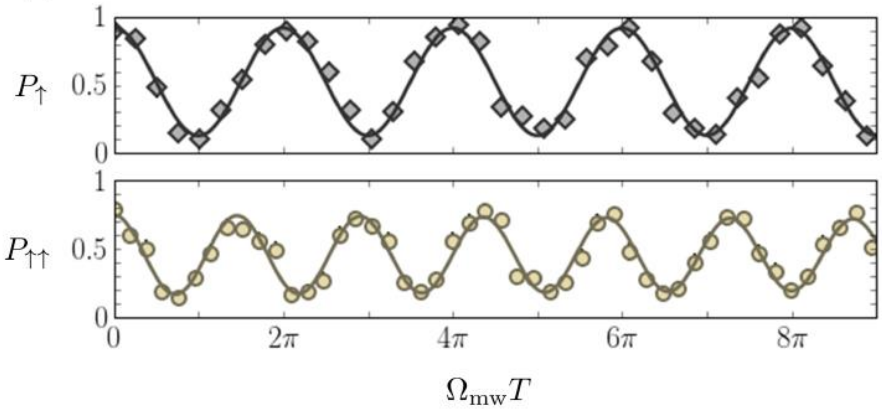
Two-spin system

Controlling a two-spin system



Microwave spectroscopy starting in $|\uparrow\uparrow\rangle$



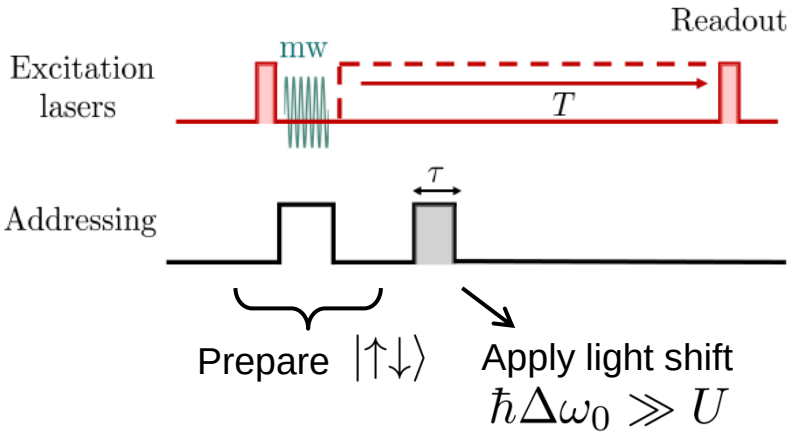


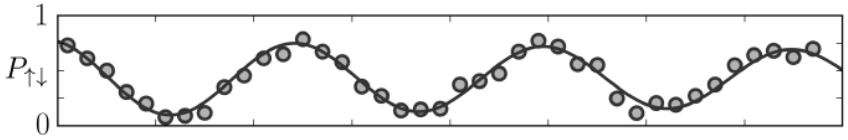
Collective, mw-driven Rabi oscillation between $|\uparrow\uparrow\rangle$ ***and***

$$|+\rangle = \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}$$

Freezing at will the interaction

Experimental sequence:

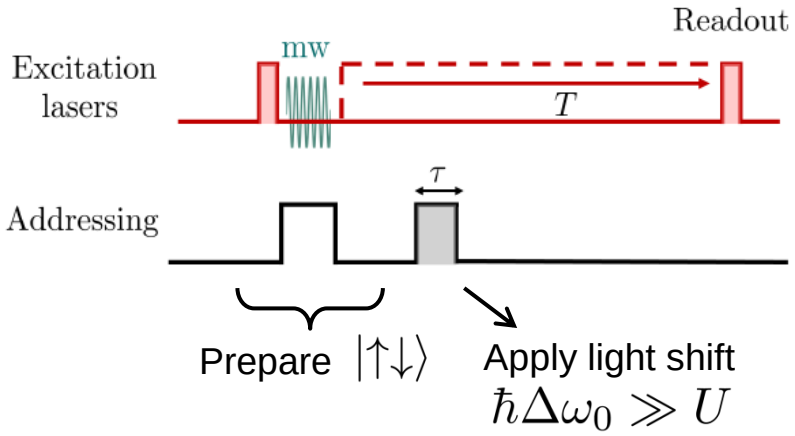


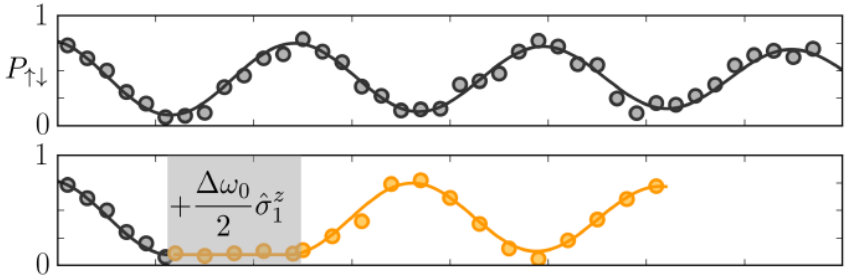


No addressing: regular spin exchange

Freezing at will the interaction

Experimental sequence:



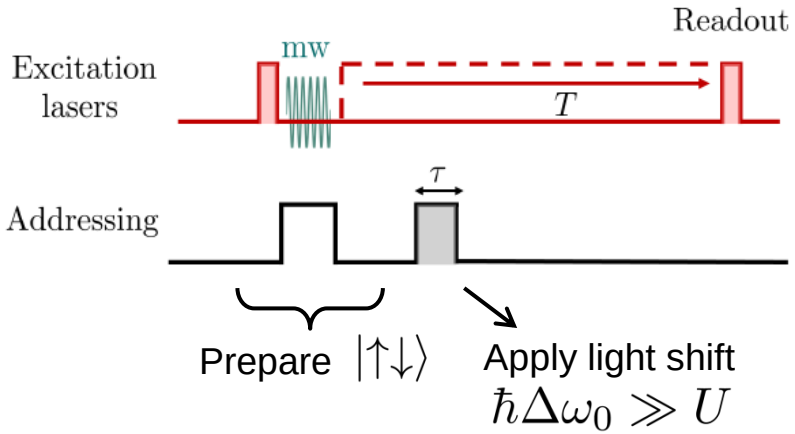


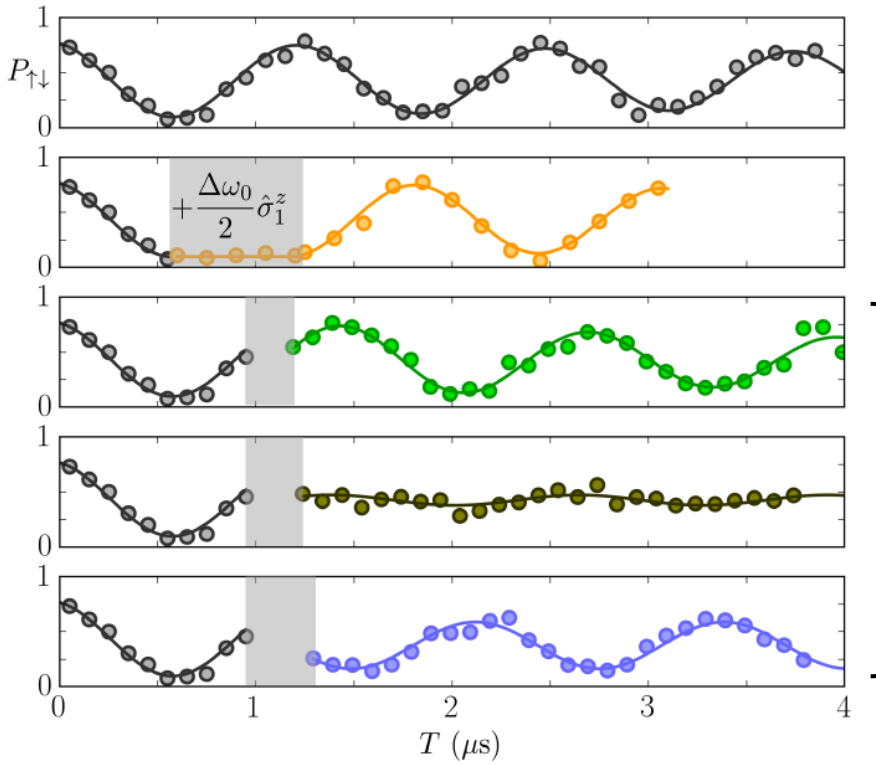
No addressing: regular spin exchange

Freeze dynamics of $|\downarrow\uparrow\rangle$

Freezing at will the interaction

Experimental sequence:





No addressing: regular spin exchange

Freeze dynamics of $|\downarrow\uparrow\rangle$

Freeze a superposition:
influence of the dynamical phase $\Delta\omega_0\tau$

de Léséleuc *et al.*, arXiv:1705:03293

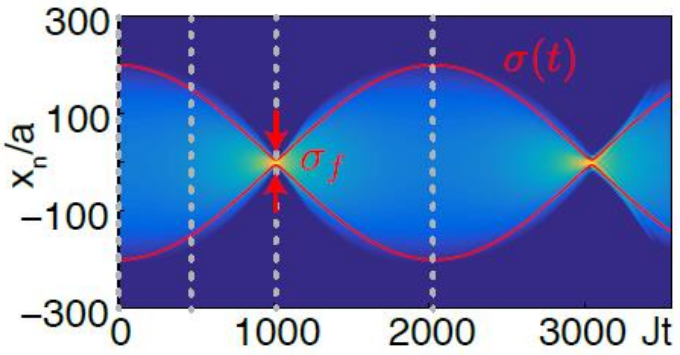
Future applications?

Combining several beams at 1005 nm (e.g. with an SLM)

- ‘Quantum spin lensing’

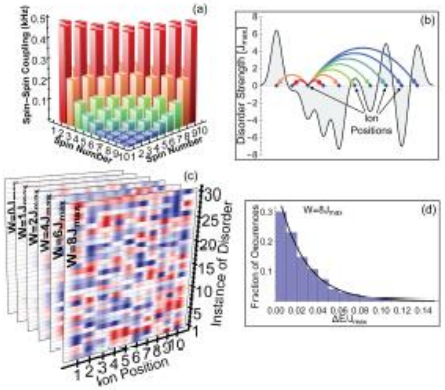
  A. W. Glätzle *et al.*, arXiv:1704.08837

$$\hat{H} = -J \sum_n \left[\hat{\sigma}_+^{(n)} \hat{\sigma}_-^{(n+1)} + \text{H.c.} \right] + \sum_n V_n \hat{\sigma}_z^{(n)}$$

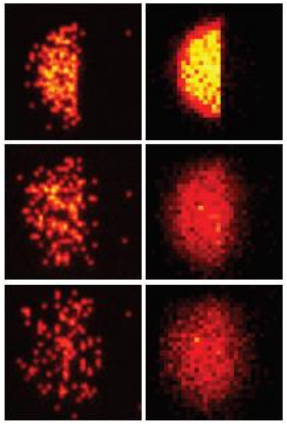


- Controlled disorder: Many-body localization for XY model

Ising 1d (JQI)



Bose-Hubbard 2d (Munich)…



Outlook: Beyond 2D

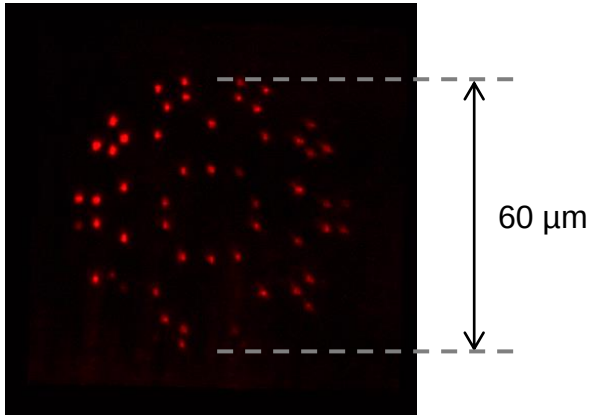
3D holographic arrays

3D arrays of traps

R. Di Leonardo, F. Ianni, and G. Ruocco,
Computer generation of optimal holograms for optical trap arrays,
Optics Express **15**, 1913 (2007)

Work in progress…

Rb_{60} ‘fullerene’



- Long exposure fluorescence imaging (average filling)
- Imaged “slice-by-slice”
- Atom assembler: in progress

Thanks for your attention!