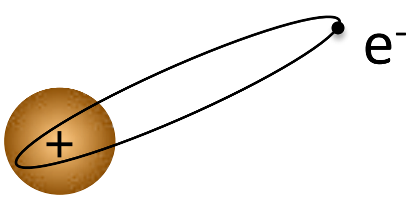
UNIVERSITÉ PARIS SUD

INSTITUT d'OPTIQUE GRADUATE SCHOOL

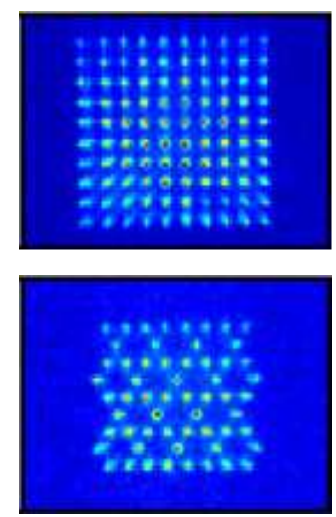
CNRS dépasser les frontières

Experimental investigation of dipole-dipole interactions between a few Rydberg atoms



Antoine Browaeys

Laboratoire Charles Fabry,
Institut d'Optique, CNRS, FRANCE



The "Quantum Optics – Atom" group at Institut d'Optique

Stephan Jennewein | Sylvain Ravets | A B | Yvan Sortais | Thierry Lahaye

Henning Labuhn | Daniel Barredo | Joseph Pellegrino | Ronan Bourgain | Lucas Béguin | Florence Nogrette

DGA | TRIANGLE DE LA PHYSIQUE | IFRAF | COHERENCE | erc

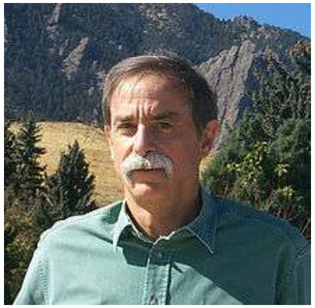
Quantum state engineering

Current status

☑ Isolate and control ≤ 10 individual quantum systems

H. Dehmelt

1989



S. Haroche D. Wineland

2012

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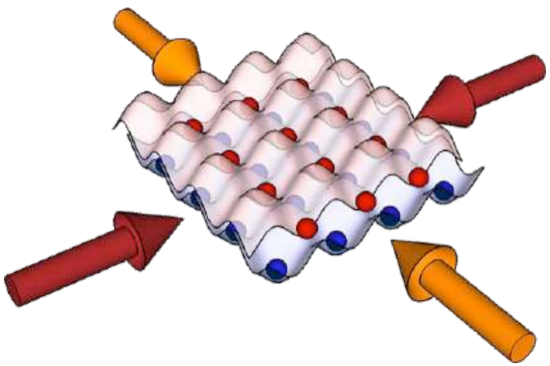
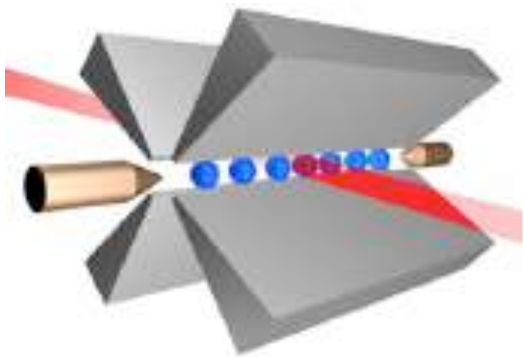
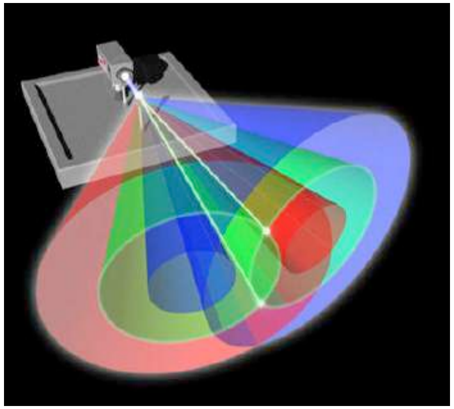
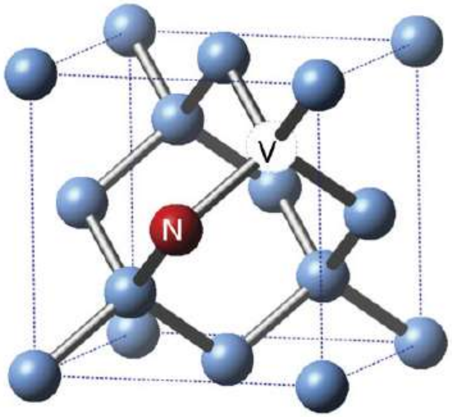
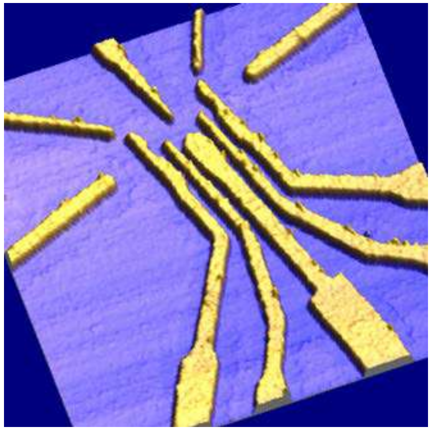

Neutral atoms

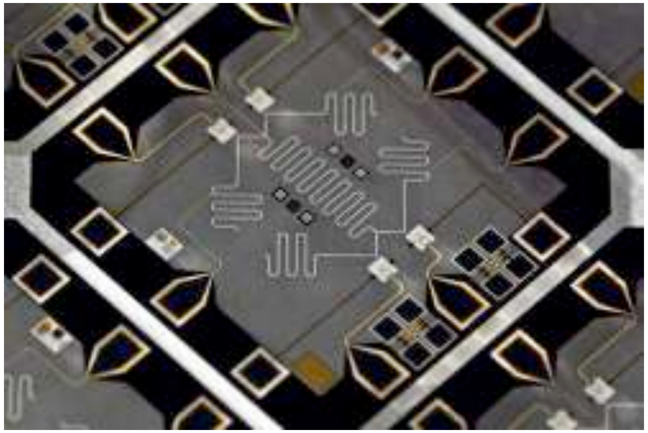

Ions


Photons



NV centers


Quantum dots


Superconducting qubits

Quantum state engineering

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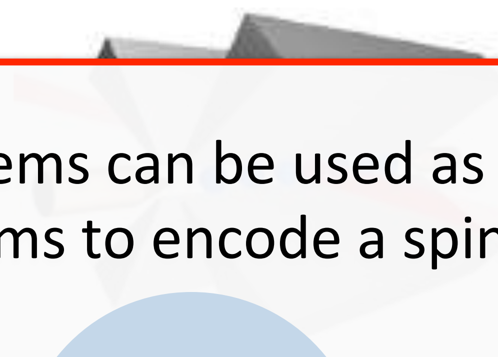
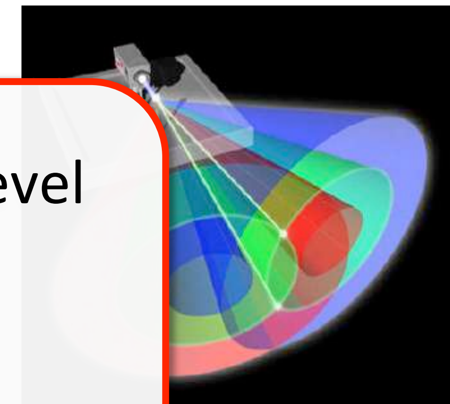
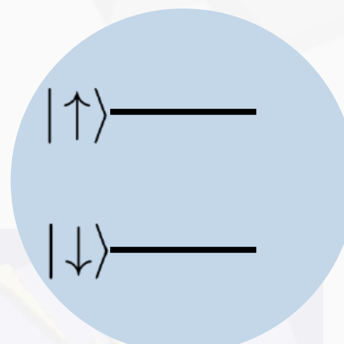
Neutral atoms

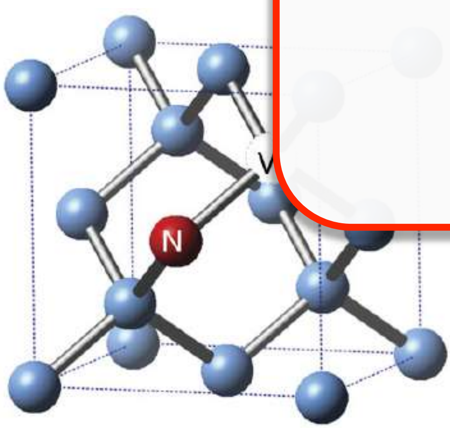




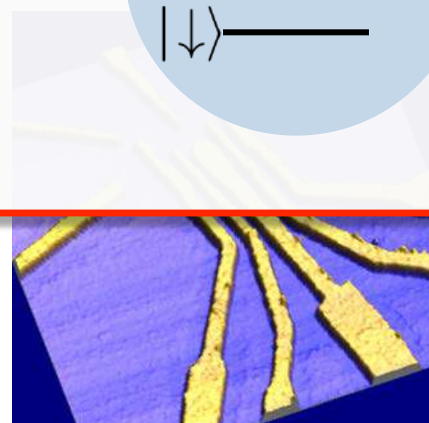
Photons

All those systems can be used as two-level systems to encode a spin:

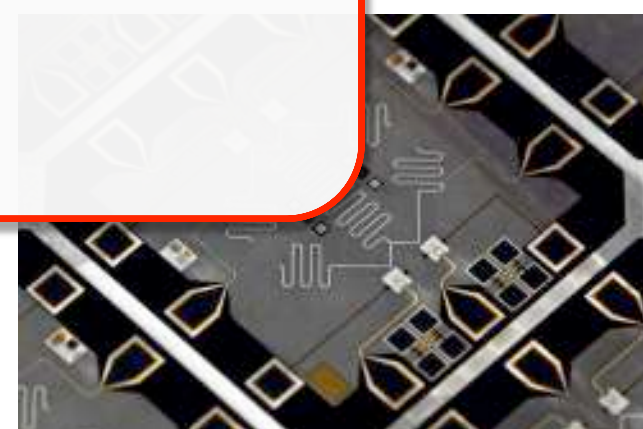




NV centers



Quantum dots



Superconducting qubits

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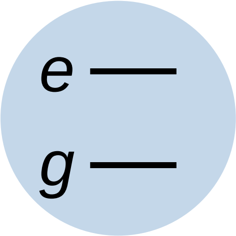
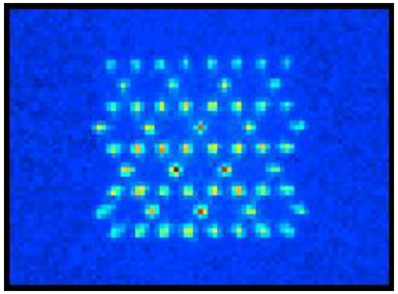


☑ Control their interactions ⇒ **entanglement**



Challenge: extend to "many" particles (≥ 10 - 100)

Applications:

Quantum simulation

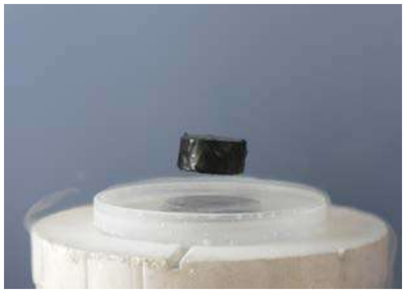
Quantum computation

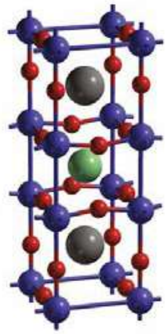
Quantum metrology

Application to quantum simulation

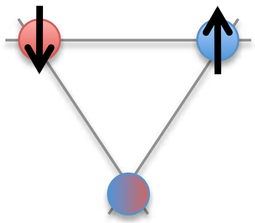
Quantum many-body problems

High-T_c superconductivity

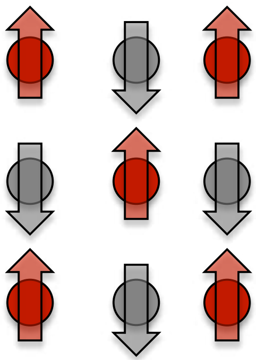




Quantum magnetism



Typical examples of many-body Hamiltonians: spin Hamiltonians

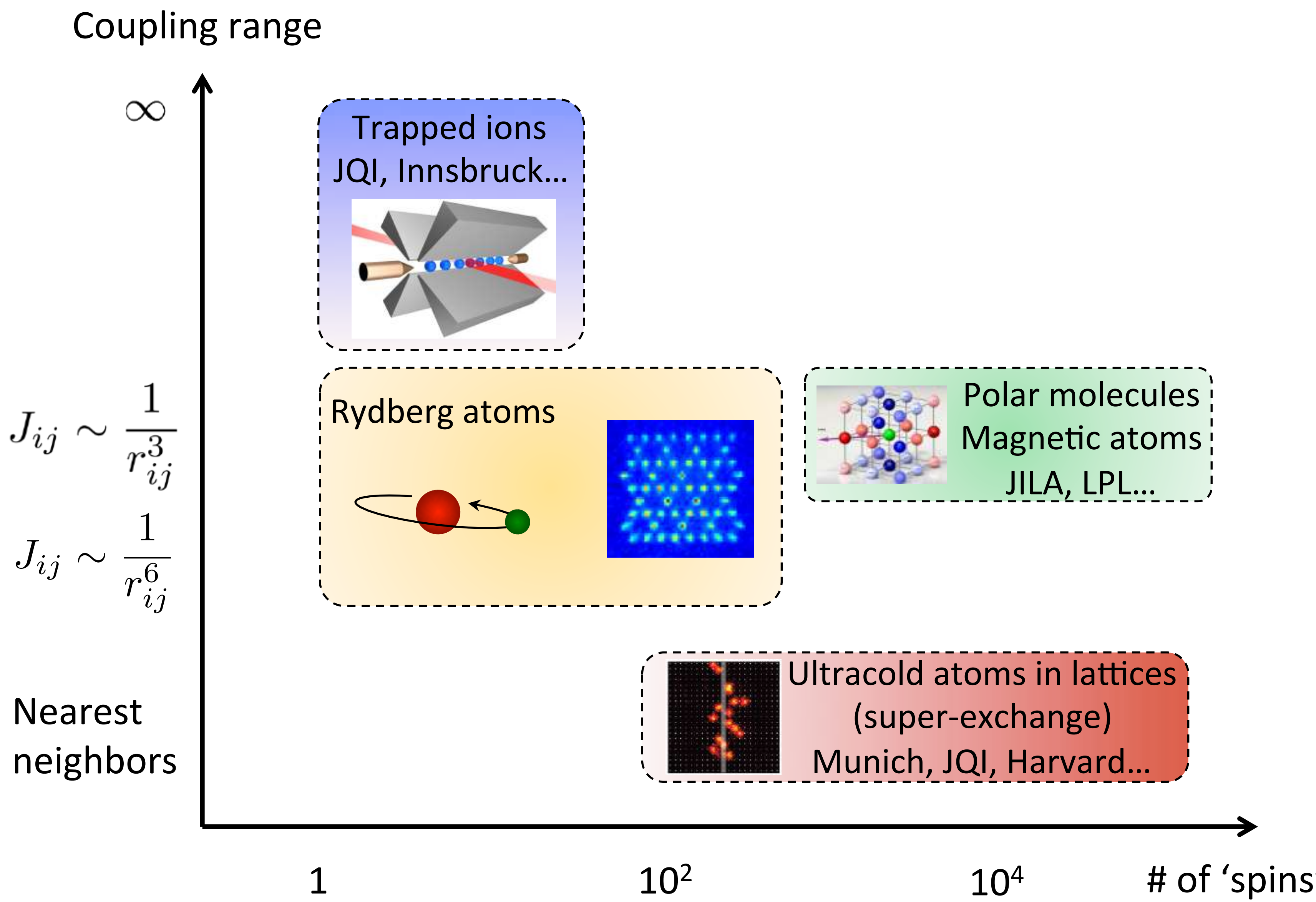


Ising $$H_z = \sum_{i \neq j} J_{ij} \hat{S}_i^z \hat{S}_j^z$$

XY model $$H_{XY} = \sum_{i \neq j} J_{ij} \left(\hat{S}_i^+ \hat{S}_j^- + \hat{S}_i^- \hat{S}_j^+ \right)$$

Open questions (long-range interaction) for N > 30:
phase diagram, dynamics, role of anisotropy…

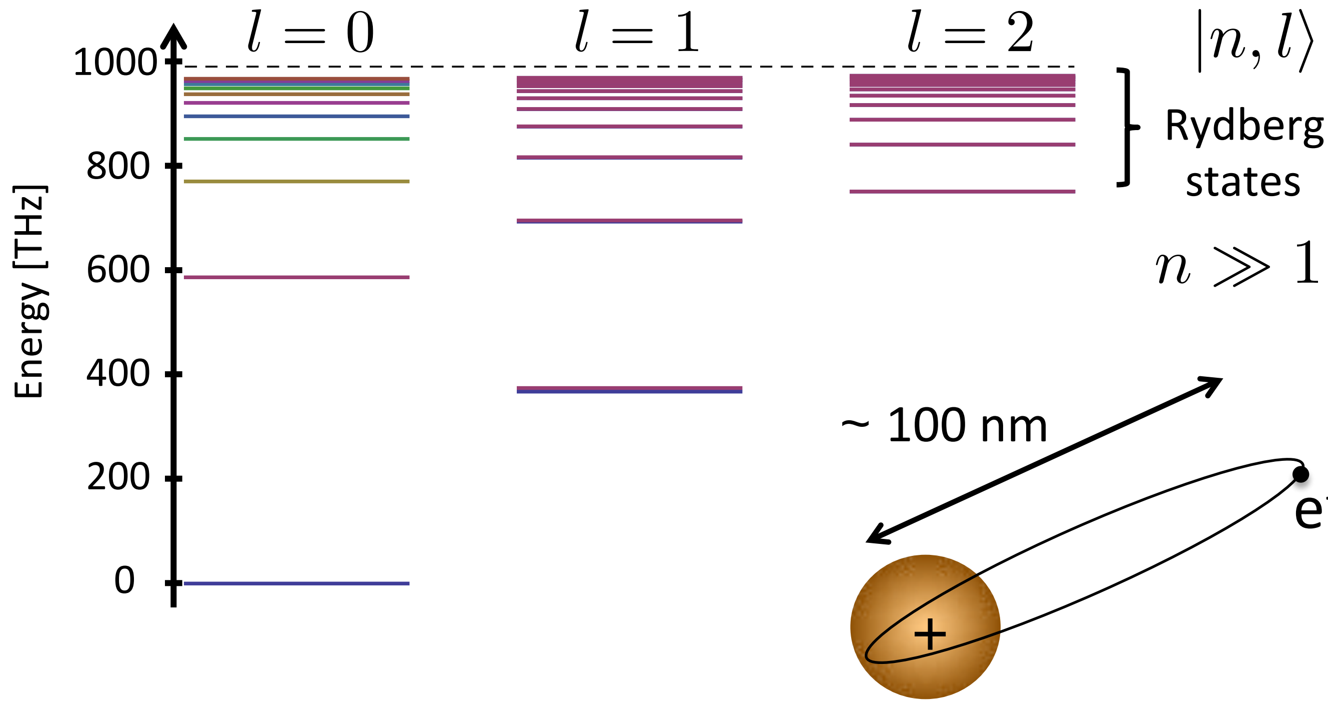
Spin Hamiltonians in AMO physics



See e.g. Hazzard et al, arXiv:406.0937

"Rydberg atoms"

Johannes Rydberg
1854-1919

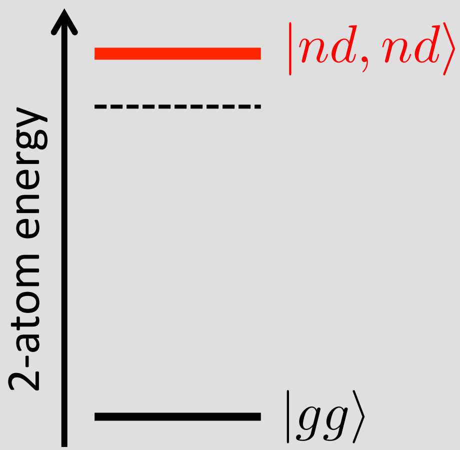


1. Long lifetime $\tau \sim n^3 \Rightarrow$ *n* > 60, τ > 100 μs
2. Large transition dipole: $d[(n,l) \rightarrow (n, l \pm 1)] \sim n^2 e a_0$
3. Large polarizability: $\alpha \sim n^7 \Rightarrow$ large AC & DC Stark shift

Rydberg atoms and their interaction

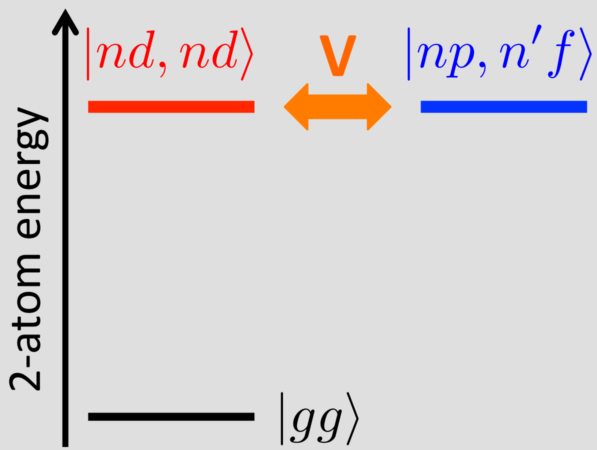
$$\hat{V} \sim \frac{\hat{d}_A \hat{d}_B}{4\pi\epsilon_0 R^3}$$

van der Waals



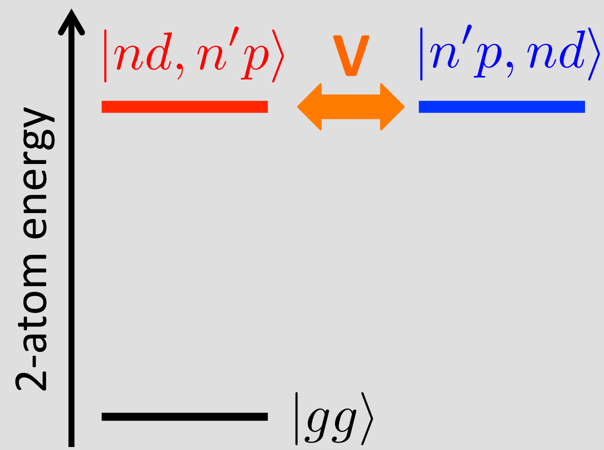
$$H = \frac{C_6}{R^6} S_A^z S_B^z$$

Förster resonance



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

Resonant interaction

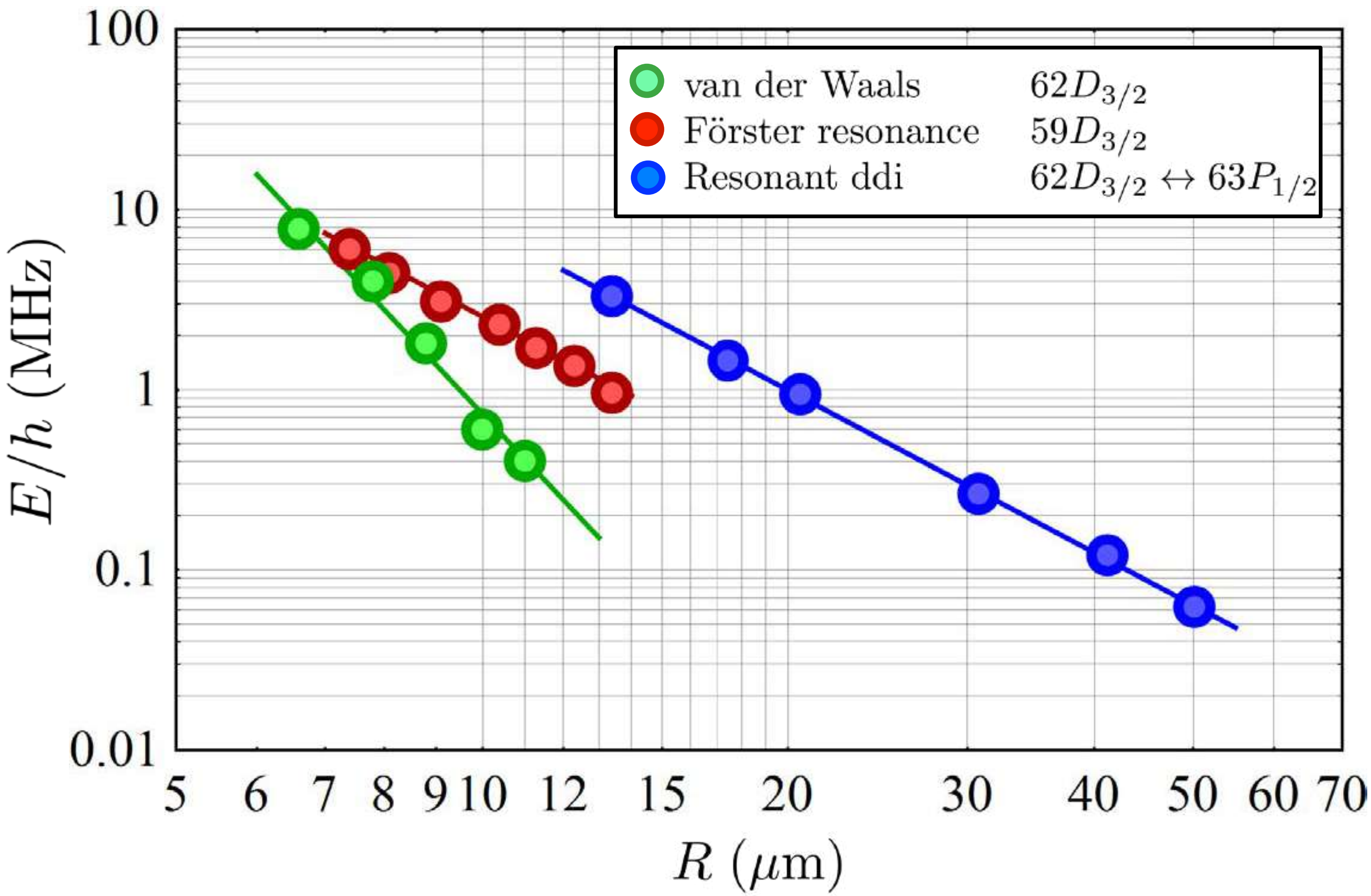


$$H = \frac{C_3}{R^3} \left(S_A^+ S_B^- + S_A^- S_B^+\right)$$

P. Zoller, M. Lukin, M. Saffman (2000’s), Moelmer, Pupillo…

Büchler, PRL **109**, 025303 (2012); Rey, arXiv:1406:4758 …Lesanovsky, Pohl, Zoller, Lewenstein…

Overview: measured interaction between 2 Rydberg atoms



$$n \sim 60, R \sim 10\,\mu\mathrm{m} \Rightarrow V \sim h \times 1 - 10\,\mathrm{MHz}$$

Outline

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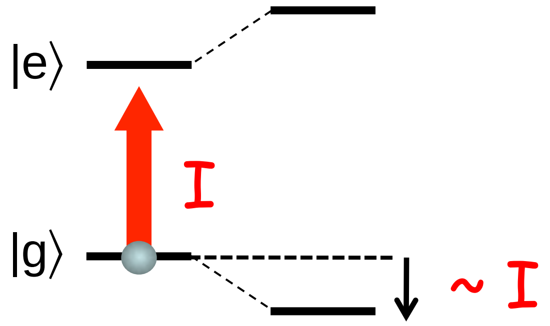
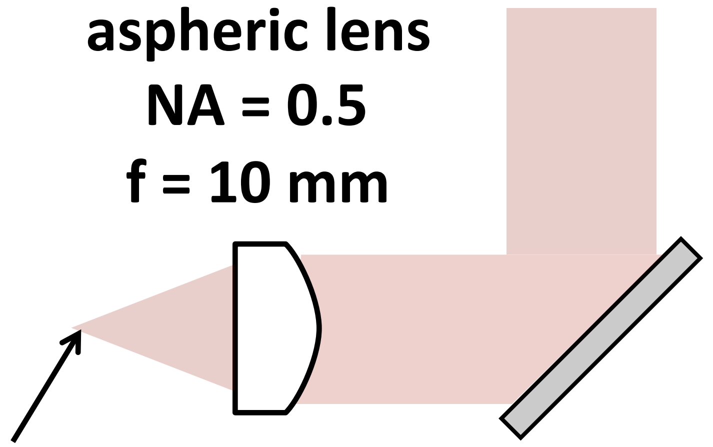
Microscopic optical dipole trap for single atom trapping

Non-resonant atom-laser interaction
⇒ **light-shift**

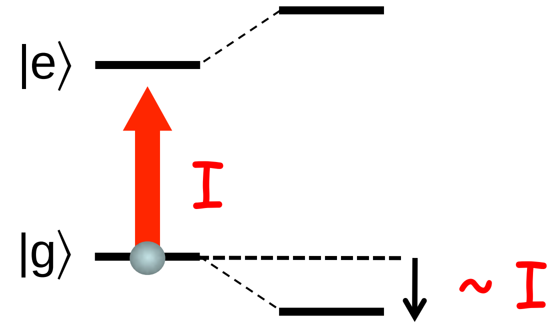


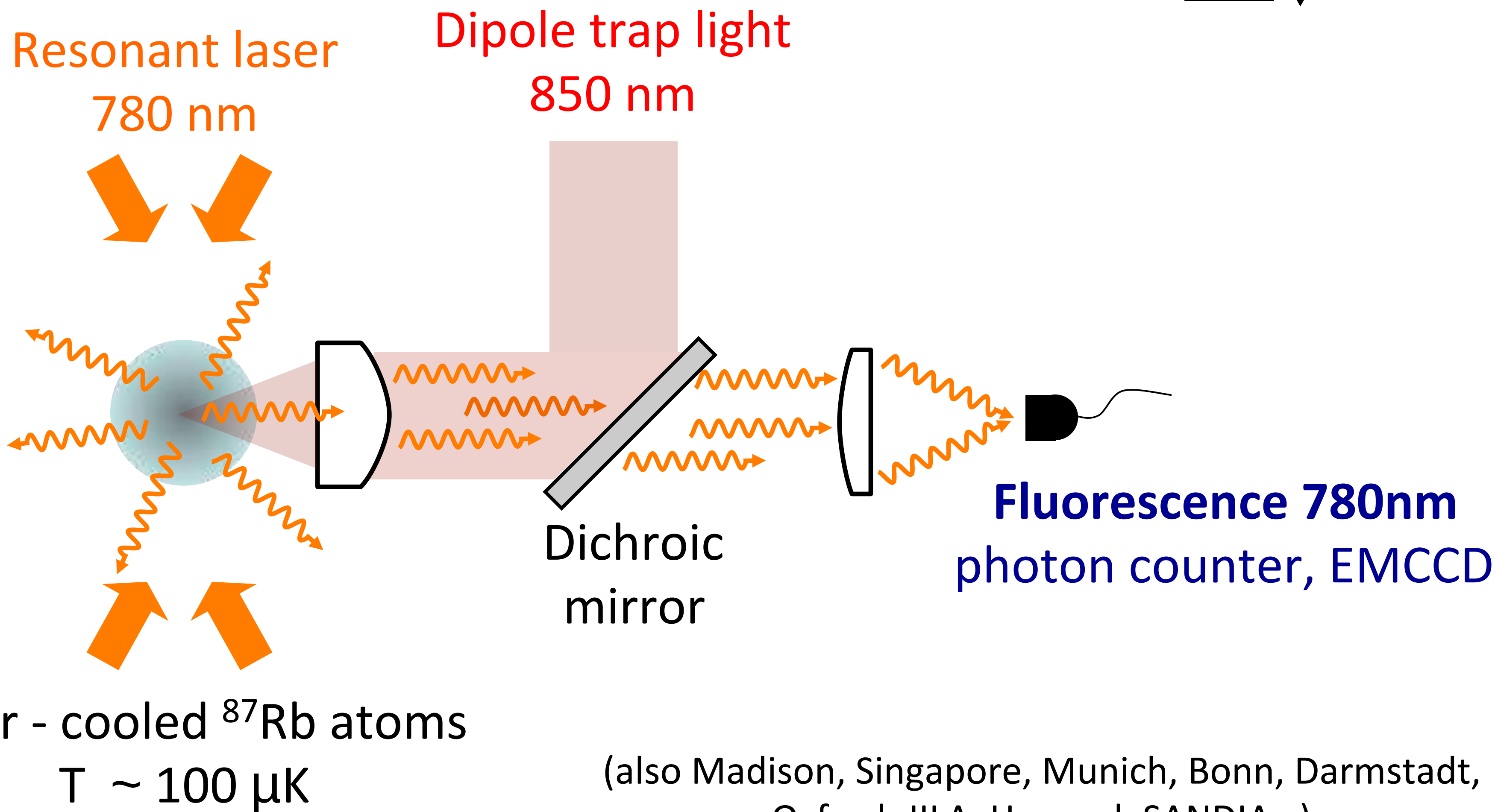


(also Madison, Singapore, Munich, Bonn, Darmstadt, Oxford, JILA, Harvard, SANDIA…)

Microscopic optical dipole trap for single atom trapping

Non-resonant atom-laser interaction
$\Rightarrow$ **light-shift**





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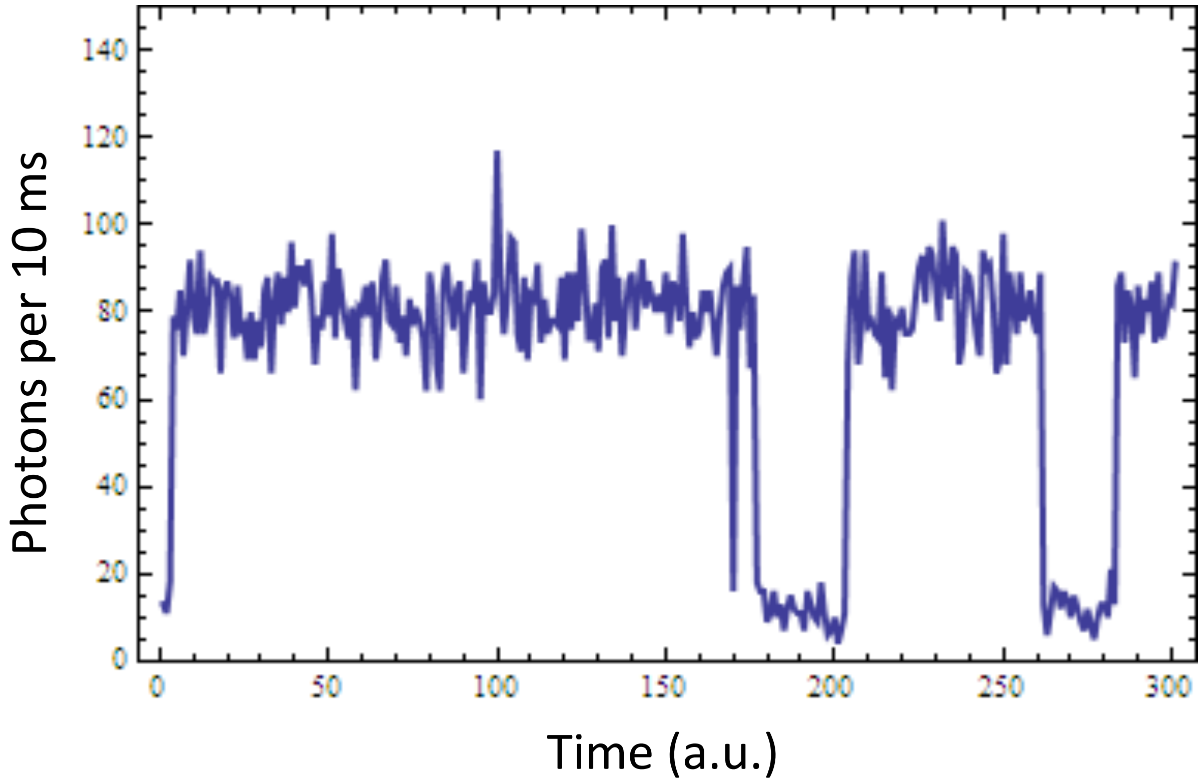
Fast light-assisted collision prevents two atoms at the same time…

Fluorescence @ 780 nm induced by the cooling lasers



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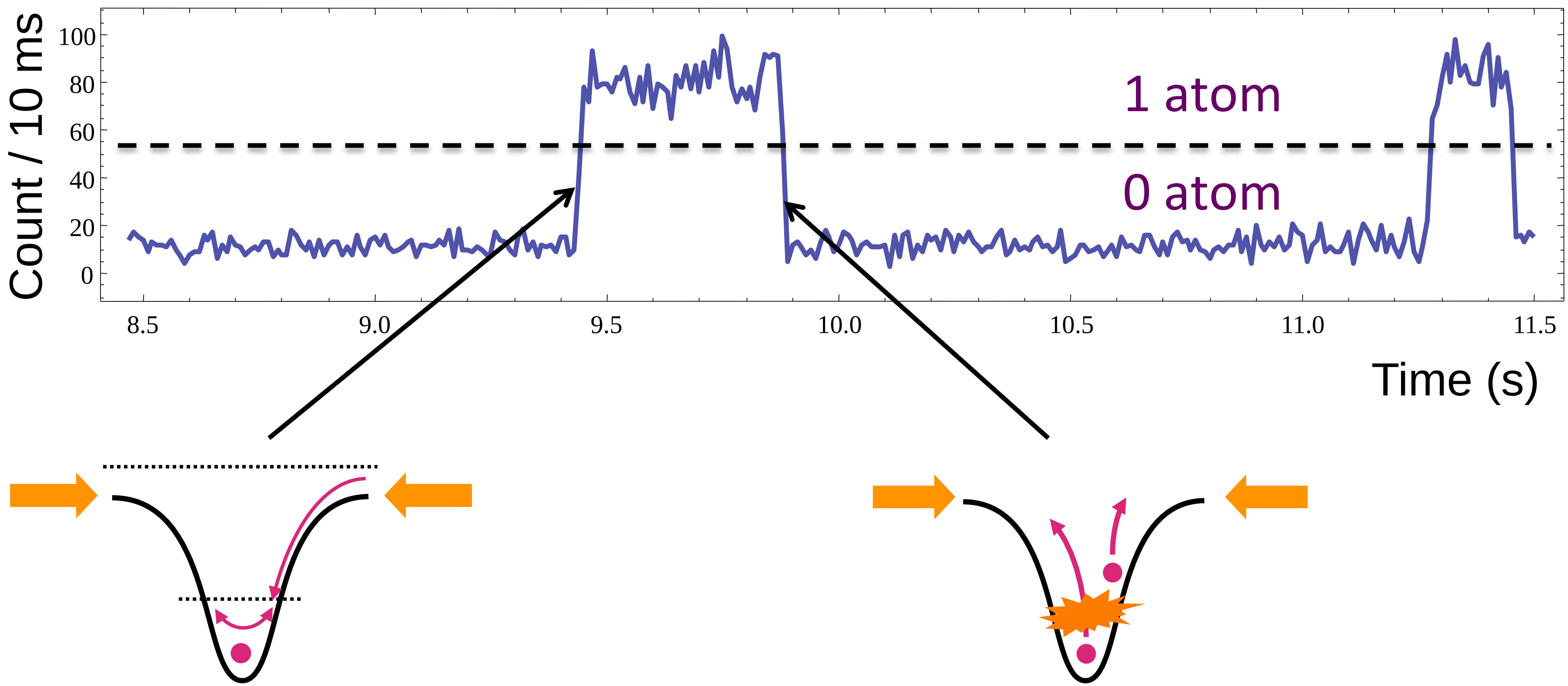


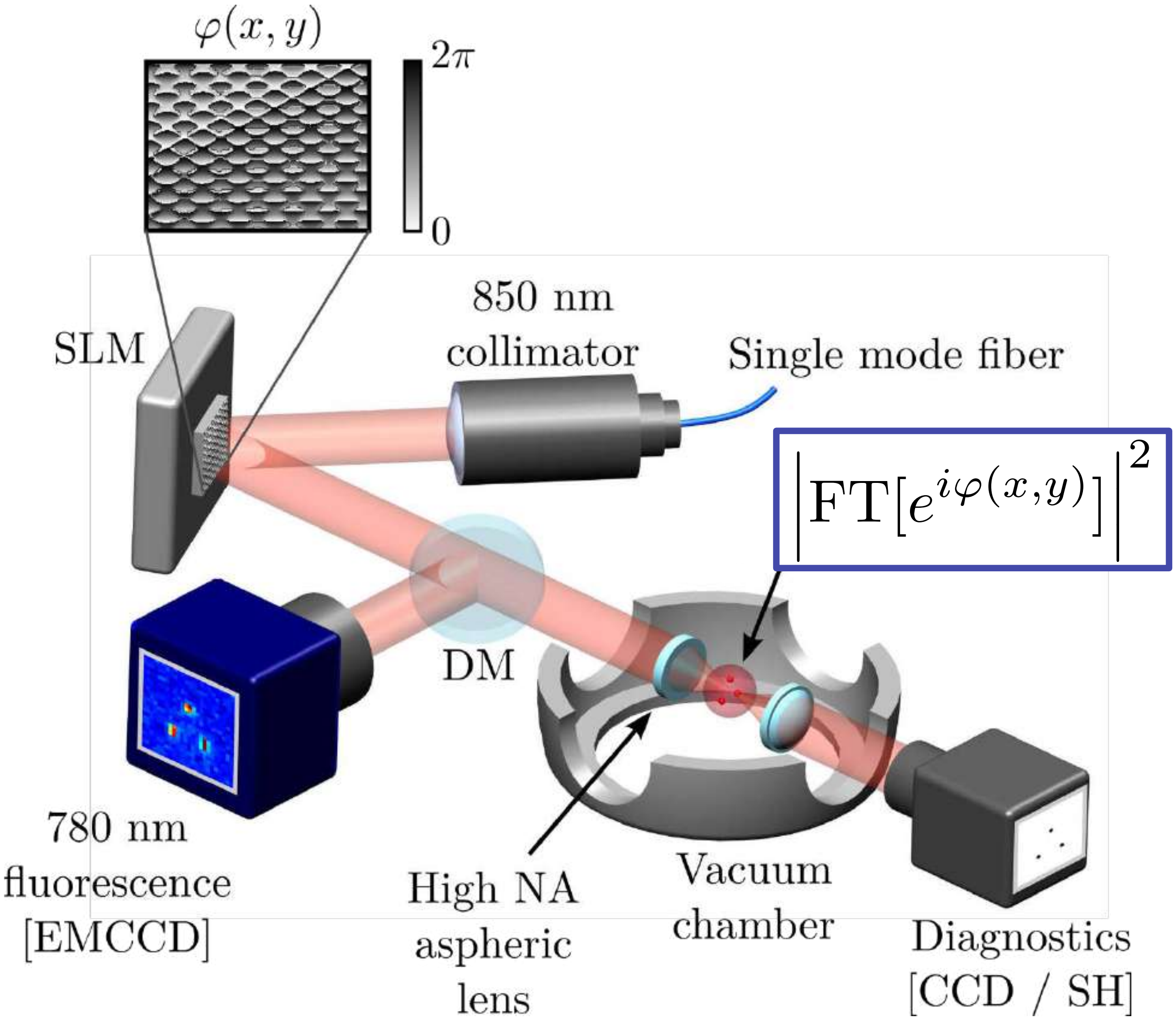
NON deterministic single-atom source ($E/k_B \approx 50\ \mu K$)

Probability to get one atom in a trap = 1/2

Schlosser *et al.*, Nature **411**, 1024 (2001)

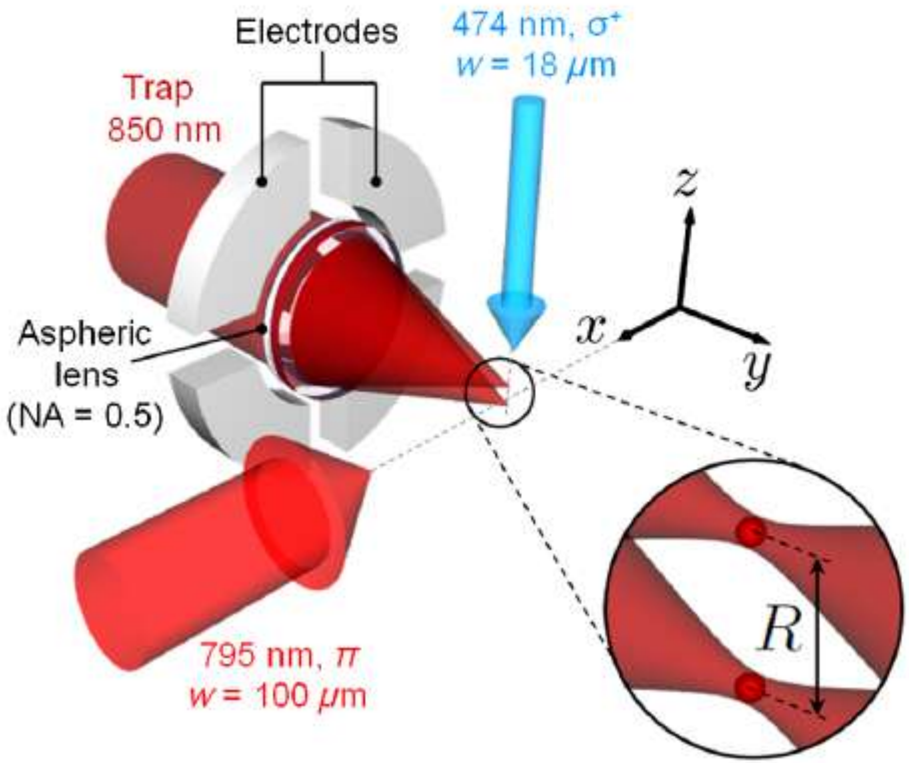
Sortais *et al.*, PRA **75**, 013406 (2007)

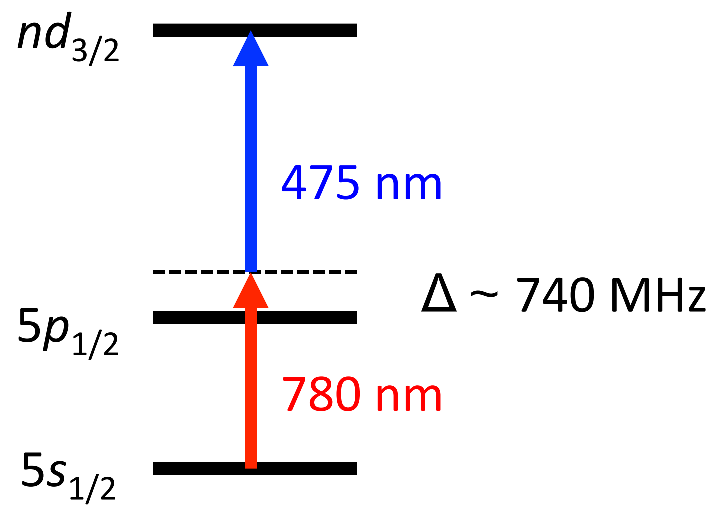
Two and three traps: Spatial Light Modulator



Rydberg excitation and detection

T. A. Johnson *et al.*, PRL **100**, 113003 (2008)
Miroshnychenko, PRA **82**, 023623 (2010)

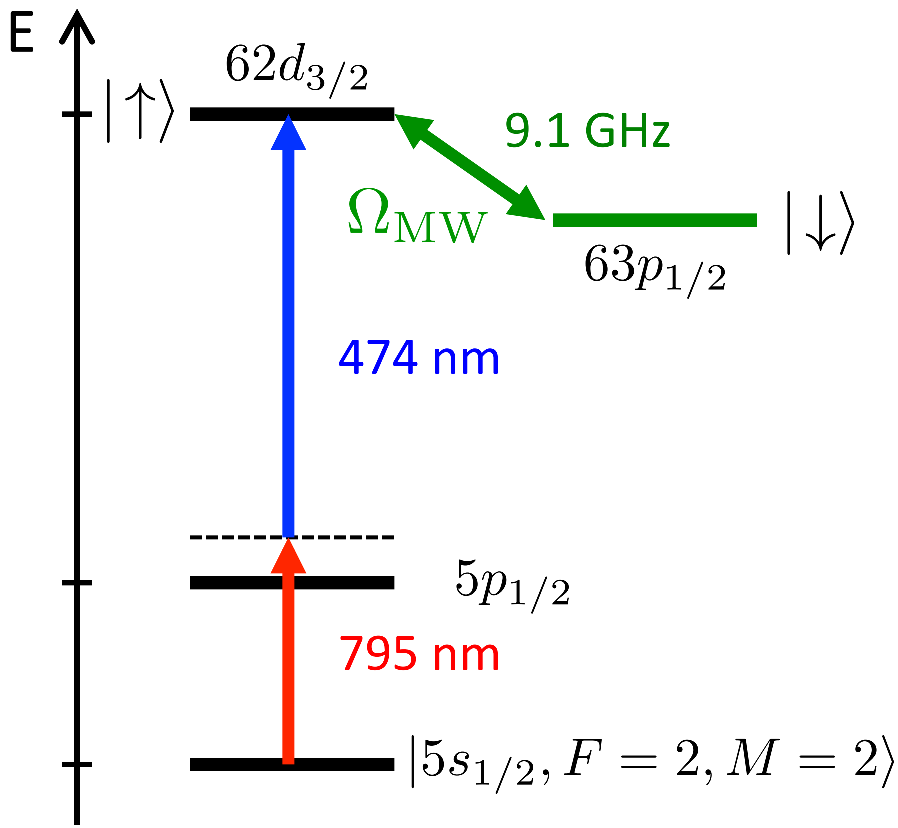




- Two-photon excitation: *n* = 50 - 100
- $\Omega / 2\pi = 0.5 – 5$ MHz

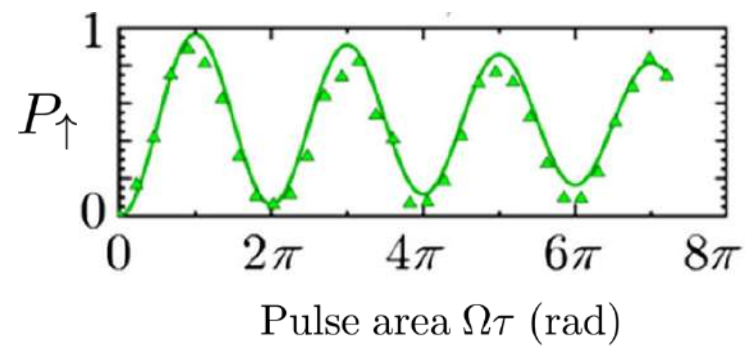
- Control of **electric fields** by 8 electrodes
- Rydberg signal: **loss of atom from trap**, no recapture at the end (95% fidelity)

Coherent manipulations of Rydberg state (single atom)



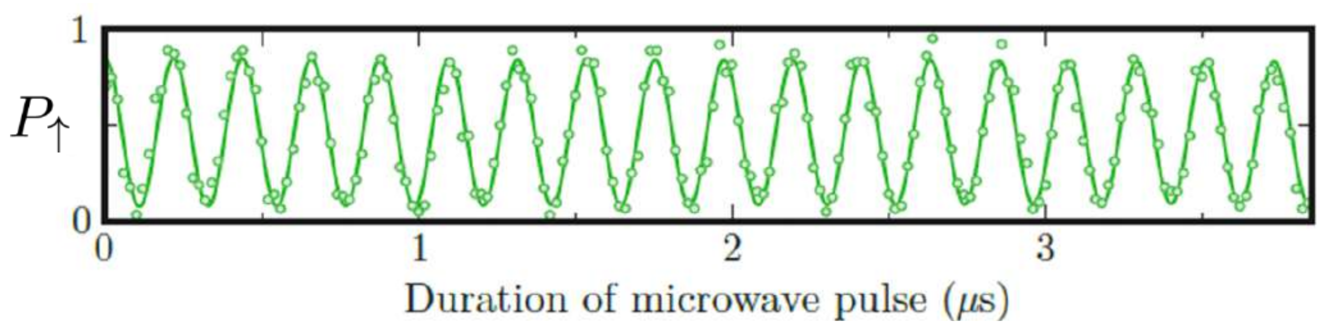
Single atom ⇒ repeat 100 times

Optical excitation



Microwave transfer

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



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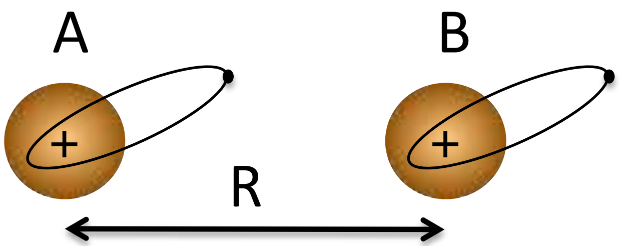
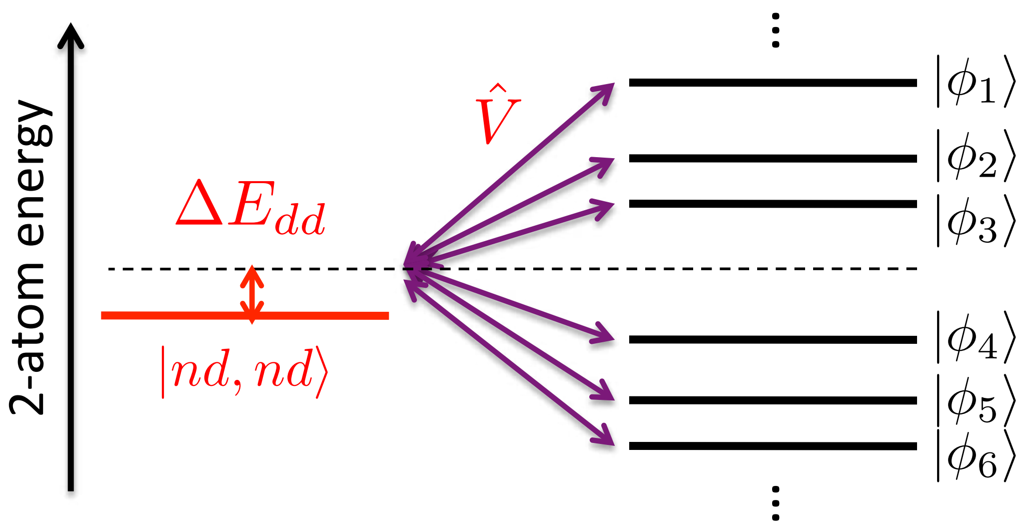
Van der Waals interaction



$$\hat{V} = \frac{1}{4\pi\epsilon_0 R^3} \left(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{d}}_B - 3(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{r}})(\hat{\mathbf{d}}_B \cdot \hat{\mathbf{r}}) \right)$$

2-atom basis: $\{|\phi_{nn'}\rangle = |n,l\rangle \otimes |n',l'\rangle\}$



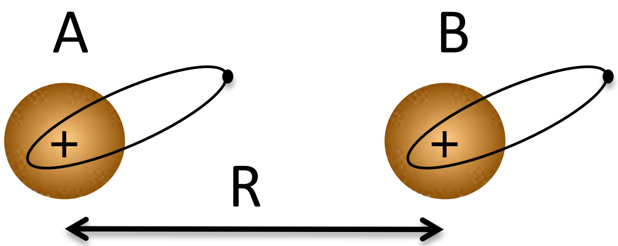
Van der Waals regime:

$$\Delta E_{dd} = \sum_{|\phi\rangle} \frac{|\langle \phi|\hat{V}|dd\rangle|^2}{E_\phi - E_{dd}} = \frac{C_6}{R^6}$$

Scaling law: $C_6 \propto n^{11}$

Interaction in Rydberg state = **10^{11}** x ground state interaction!!

Van der Waals interaction



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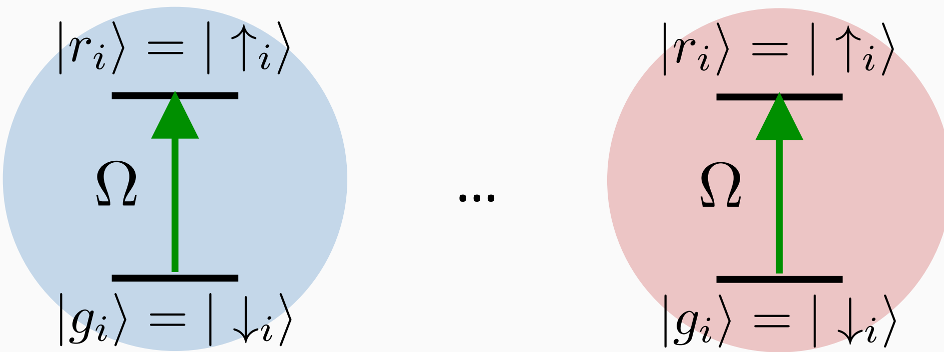
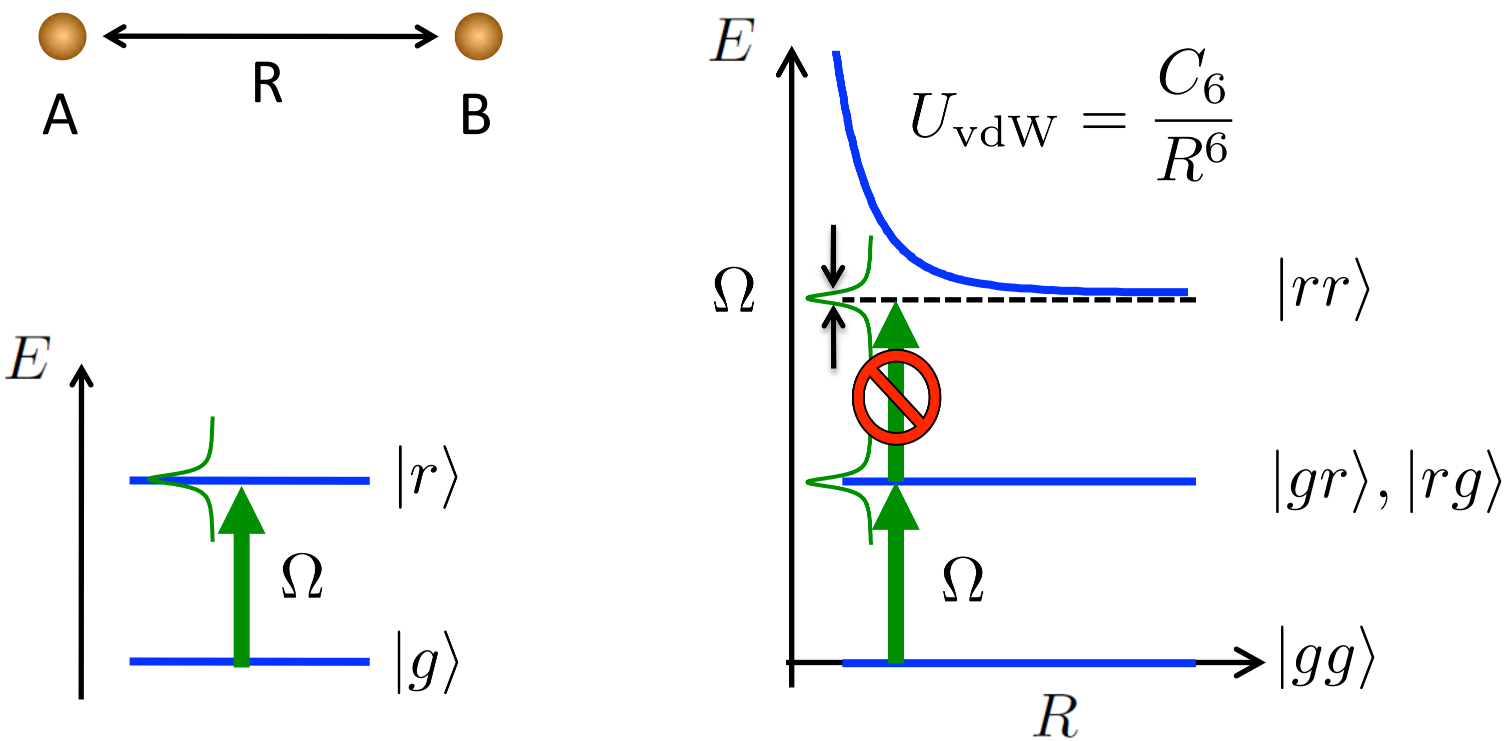


Implement: $$\hat{H} = \hbar\Omega \sum_i \hat{S}_x^{(i)} + \sum_{i \neq j} \frac{C_6}{R_{i,j}^6} \hat{S}_z^{(i)} \hat{S}_z^{(j)}$$

(Ising Hamiltonian)

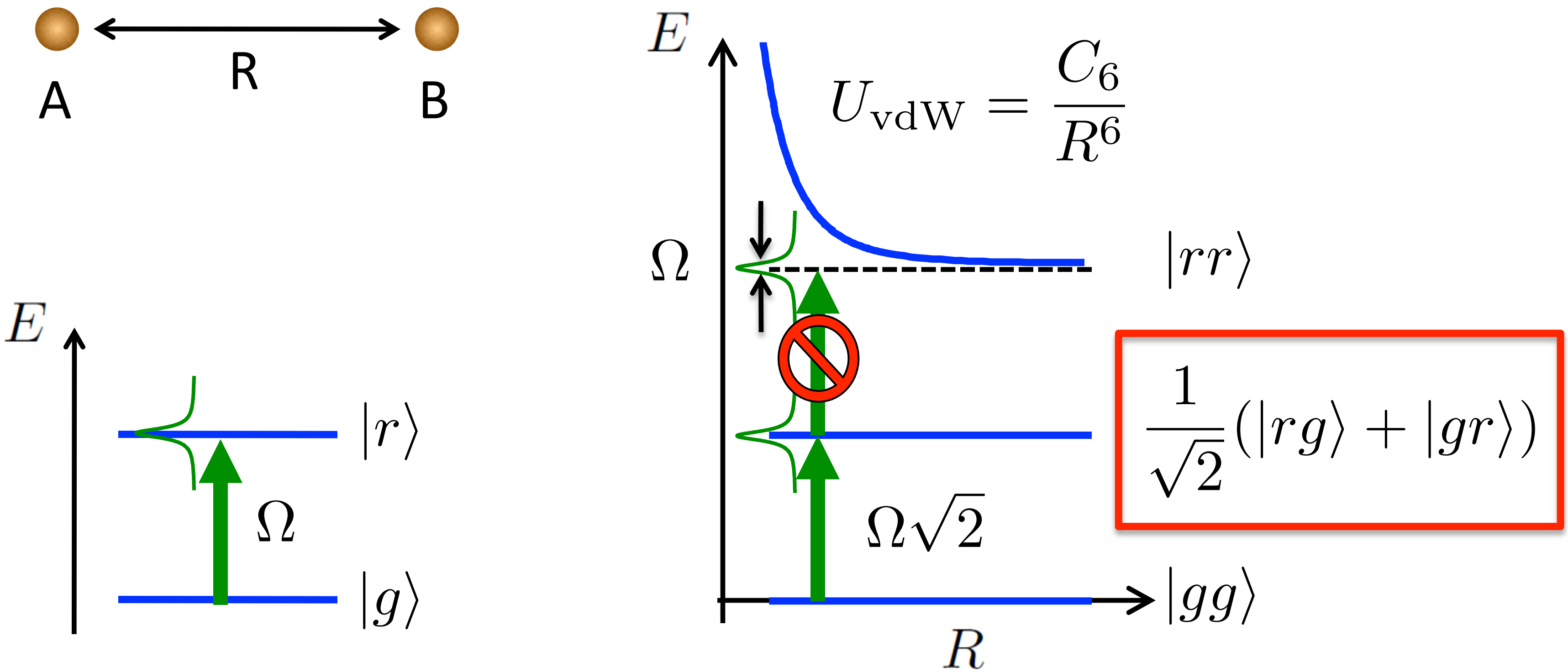
Collective excitation of two interacting Rydberg atoms



If $\hbar\Omega \ll U_{\mathrm{vdW}}$: no excitation of $|rr\rangle$ $\Rightarrow$ **blockade**

D. Jaksch, *et al.*, PRL **85**, 2208 (2000)
M. D. Lukin, *et al.*, PRL **87**, 037901 (2001)

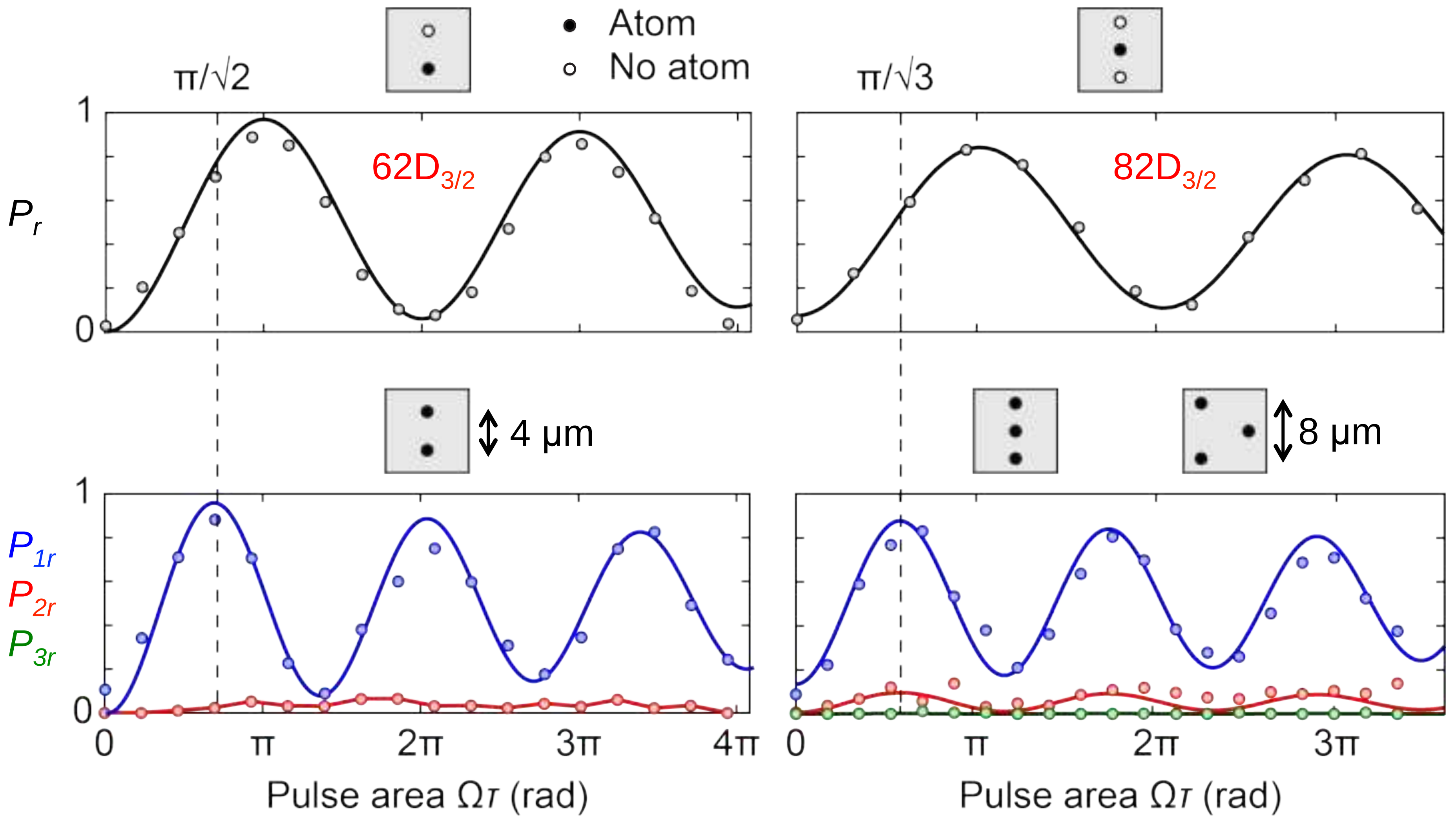
Collective excitation of two interacting Rydberg atoms



Collective oscillation between $|gg\rangle$ and $\frac{1}{\sqrt{2}}(|rg\rangle + |gr\rangle)$

with coupling $\Omega\sqrt{2}$ (N atoms $\Rightarrow$ $\Omega\sqrt{N}$)

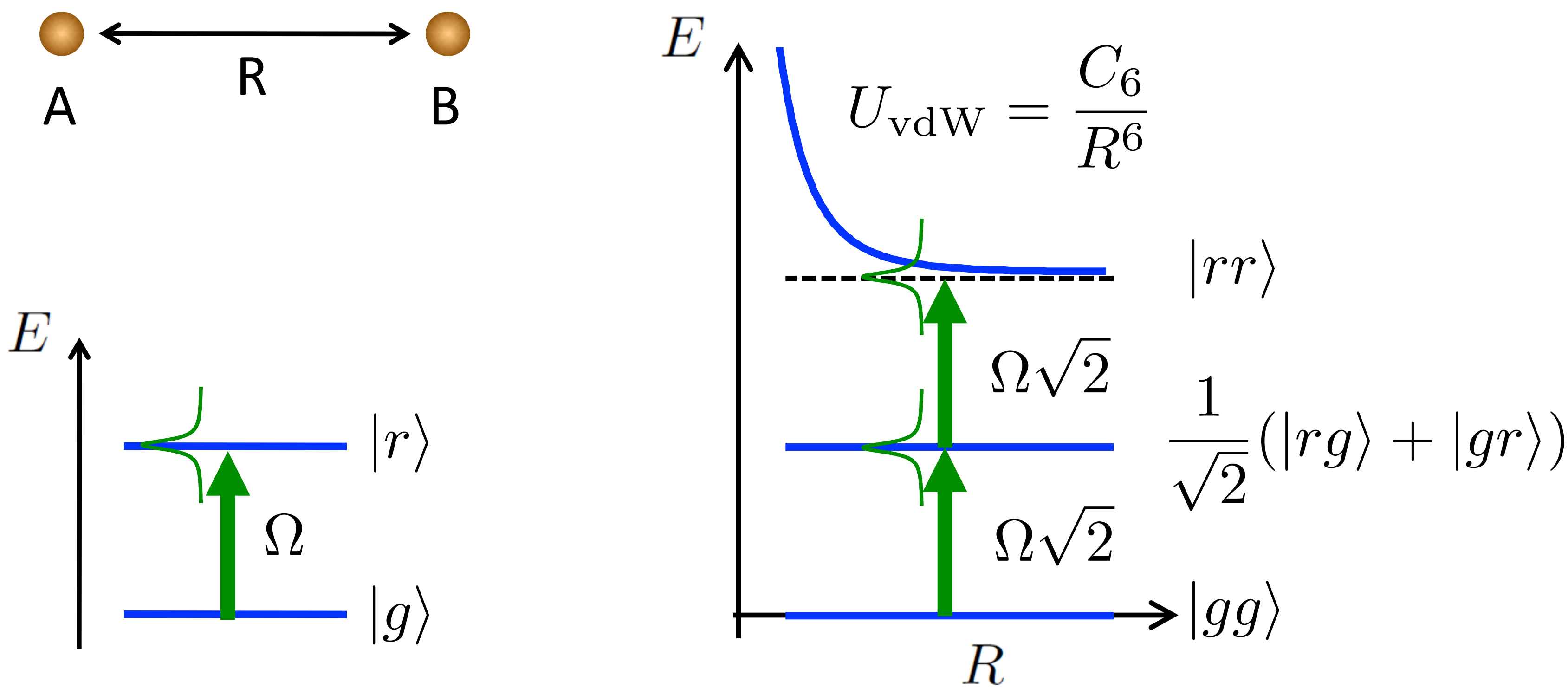
Full blockade with 2 and 3 atoms



L. Béguin *et al.*, PRL **110**, 263201 (2013)
Early demonstrations: Gaétan, Nat. Phys. **5**, 115 (2009); Urban, Nat. Phys. **5**, 110 (2009)

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

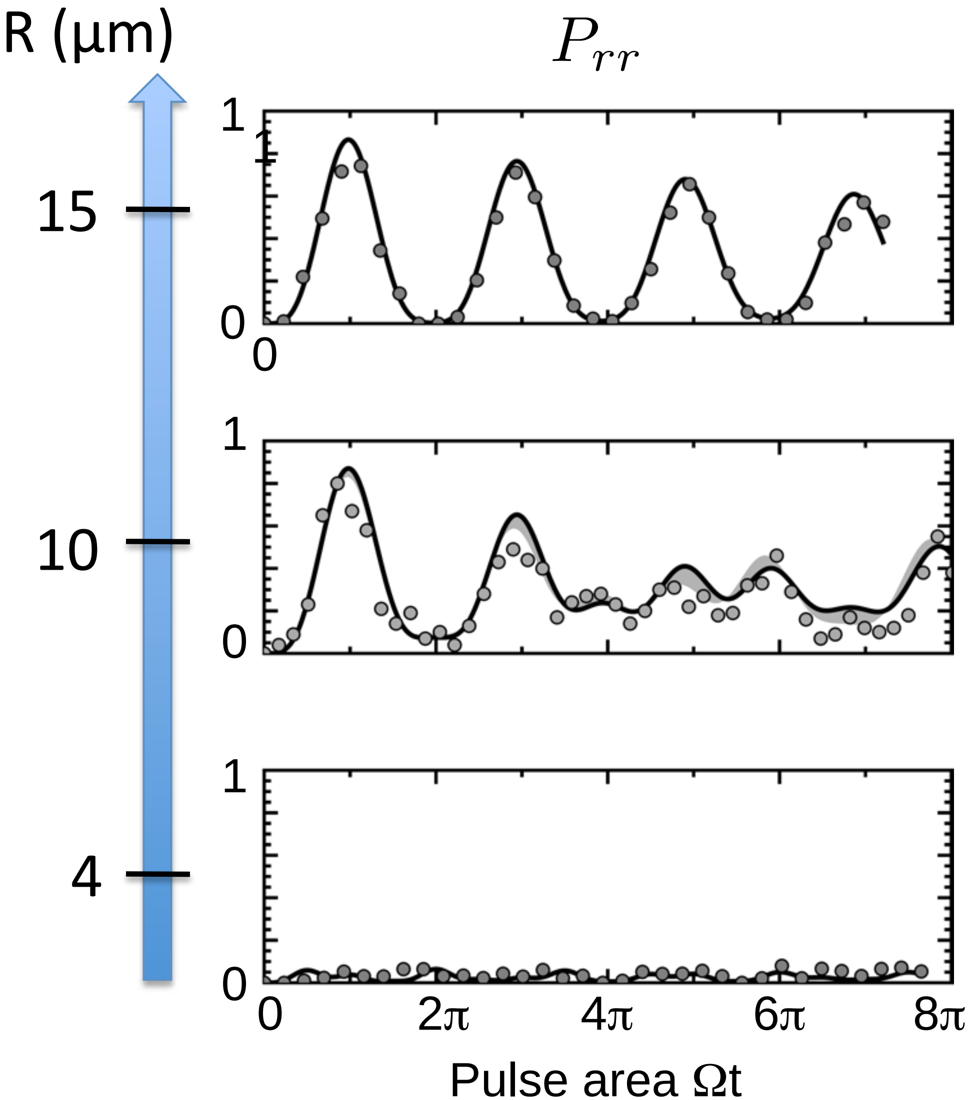
Collective excitation of two interacting Rydberg atoms



If $\hbar\Omega \approx U_{\mathrm{vdW}}$: dynamics involves Ω **and** U_{vdW} ⇒ **partial blockade**

$$|\psi(t)\rangle = \alpha(t)|gg\rangle + \beta(t)\frac{1}{\sqrt{2}}(|rg\rangle + |gr\rangle) + \gamma(t)|rr\rangle$$

From the blockade to the partial blockade ($62d_{3/2}$)

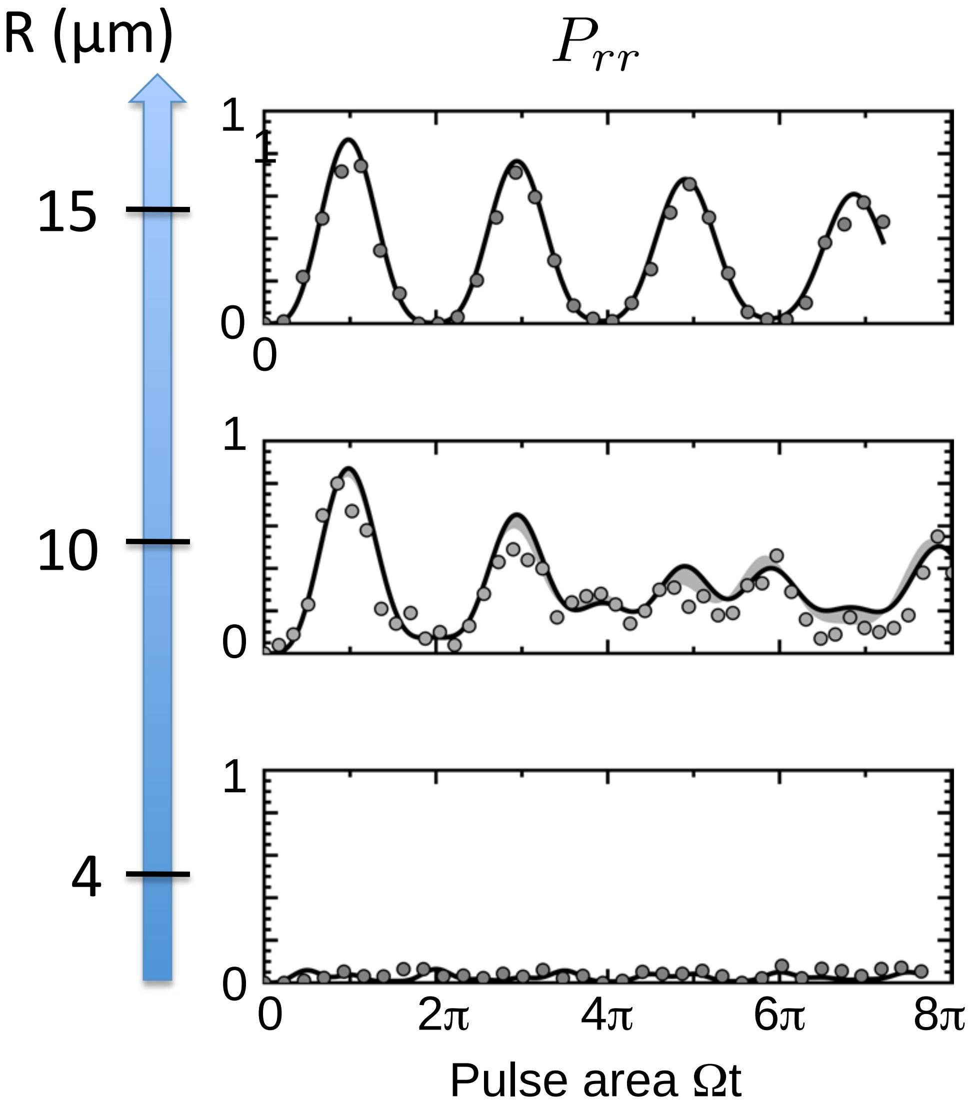


$\hbar\Omega \gg U_{\rm vdW}$

$\hbar\Omega \approx U_{\rm vdW}$

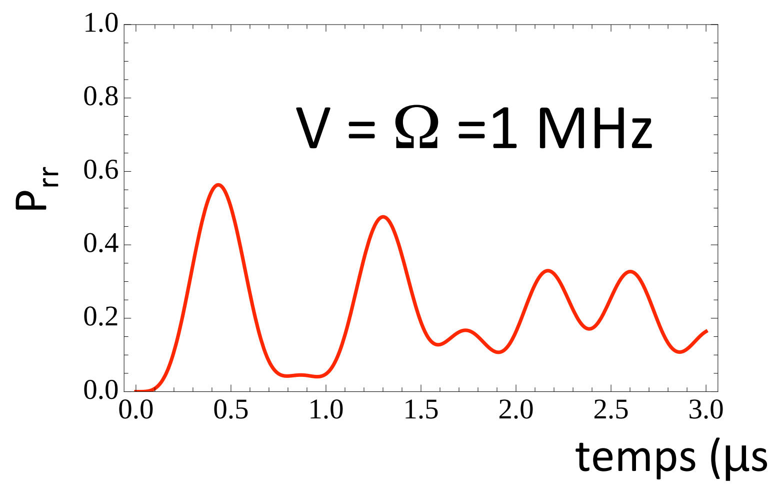
$\hbar\Omega \ll U_{\rm vdW}$

From the blockade to the partial blockade ($62d_{3/2}$)



$\hbar\Omega \gg U_{\mathrm{vdW}}$

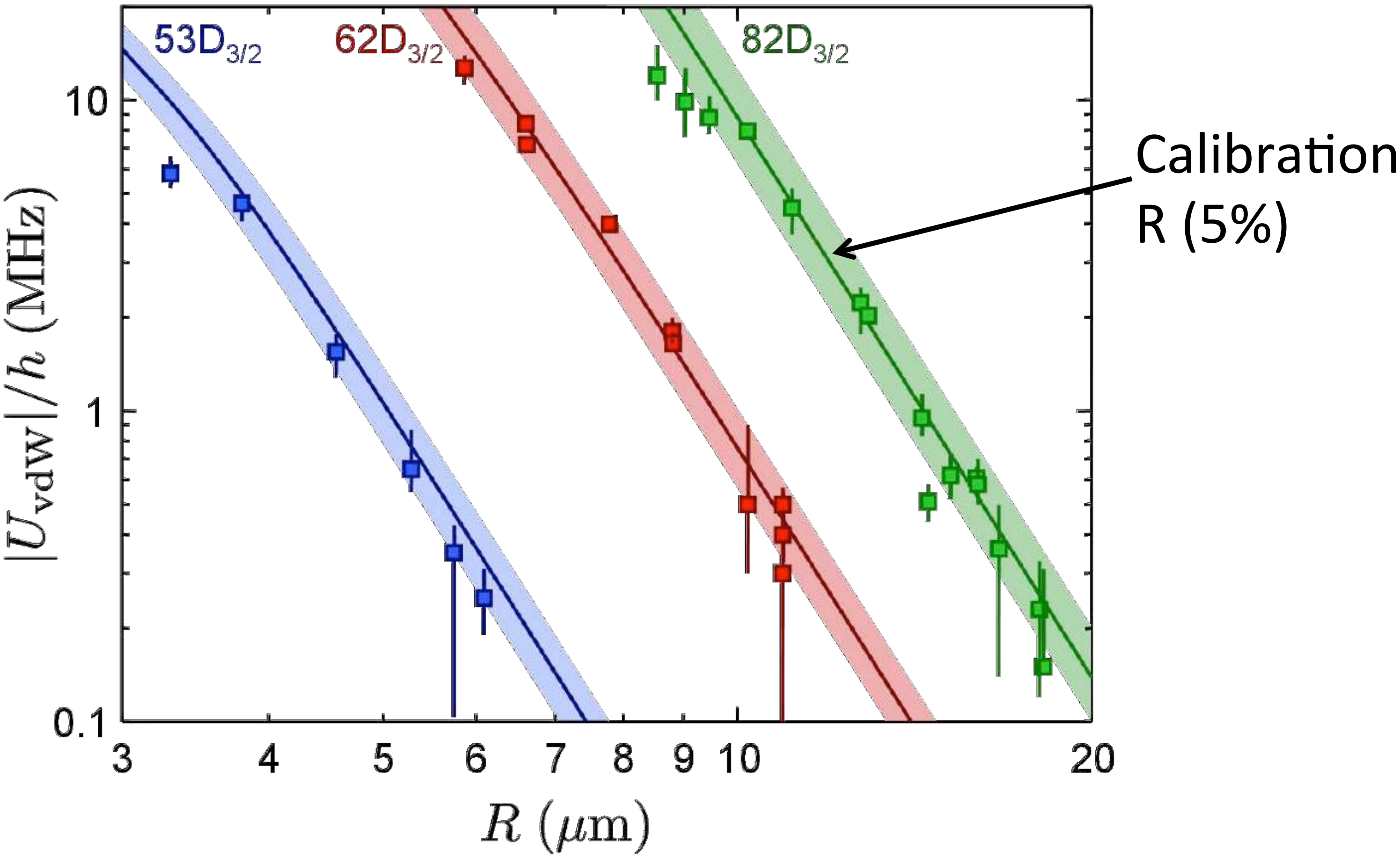
Théorie (eq. Schrödinger)



$\hbar\Omega \ll U_{\mathrm{vdW}}$

Fit $\Rightarrow$ extract U_{vdW}

Measuring U_{vdW} vs distance



Theory curves: direct diagonalization (dipole-dipole interaction)

No adjustable parameter

Béguin *et al.*, PRL **110,** 263201 (2013).

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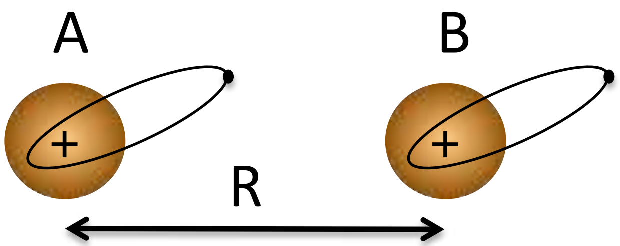
From van der Waals to resonant interaction



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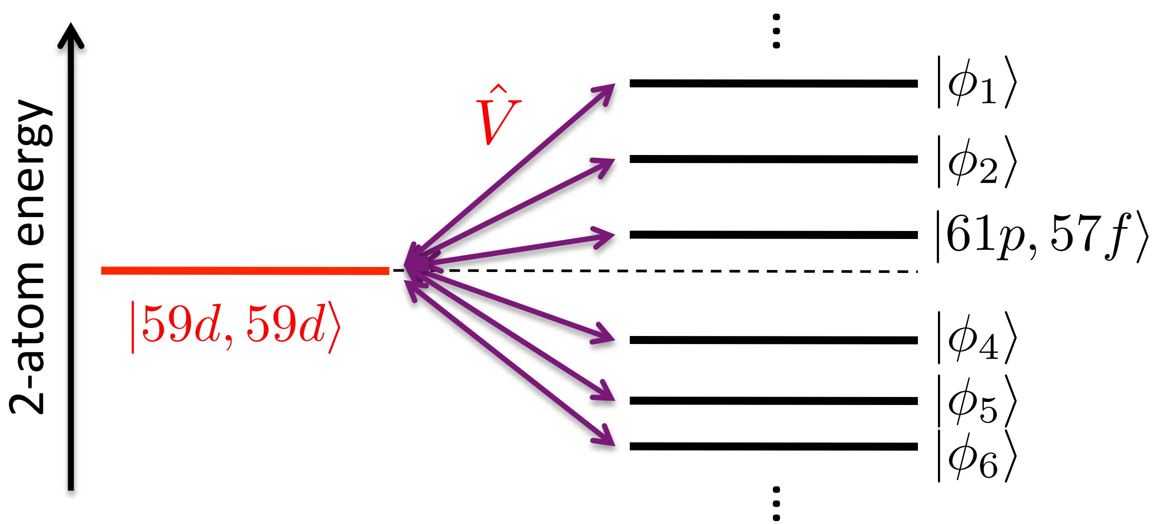
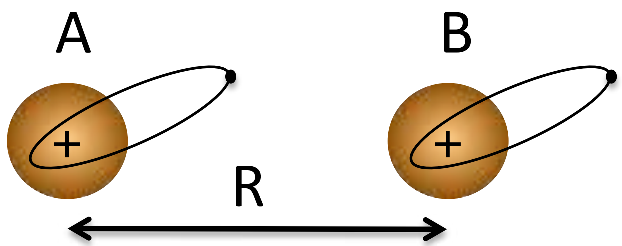


From van der Waals to resonant interaction



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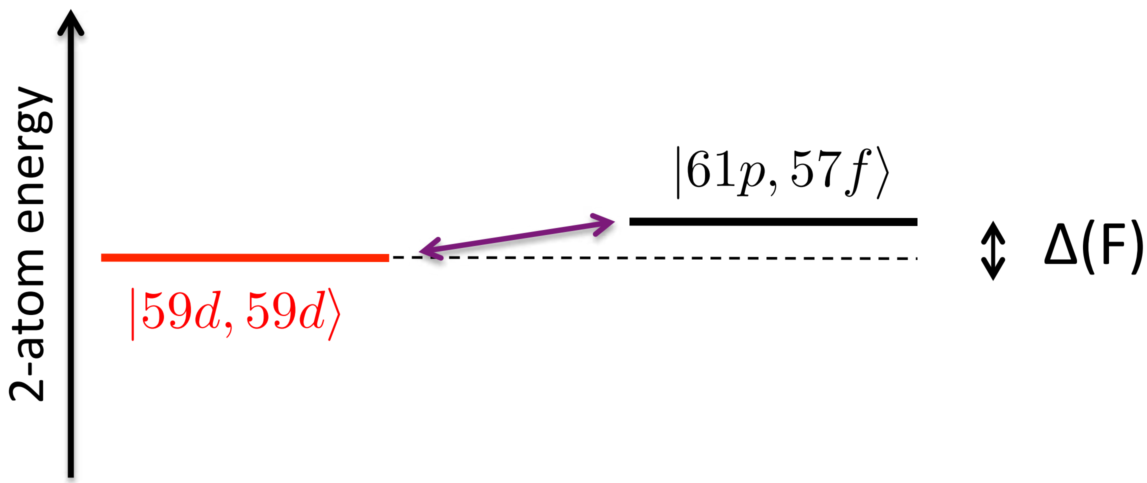


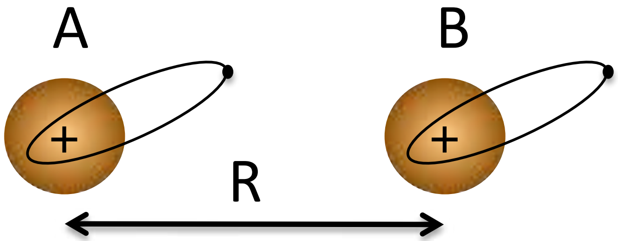
Relative Stark shift

Tune Δ(DC-Field)

Förster resonance

Walker&Saffman J. Phys. B 2005

From van der Waals to resonant interaction



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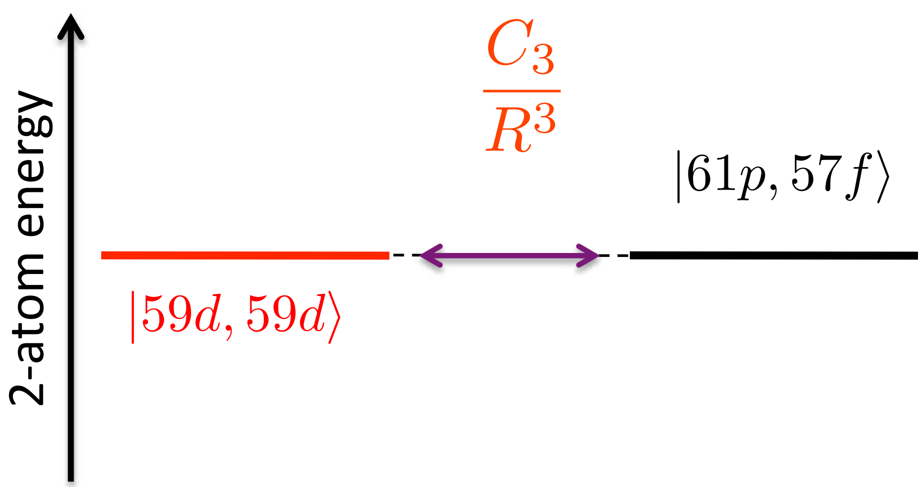

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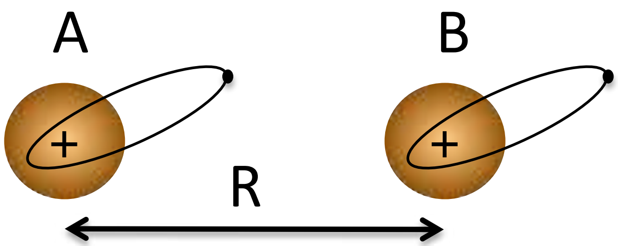

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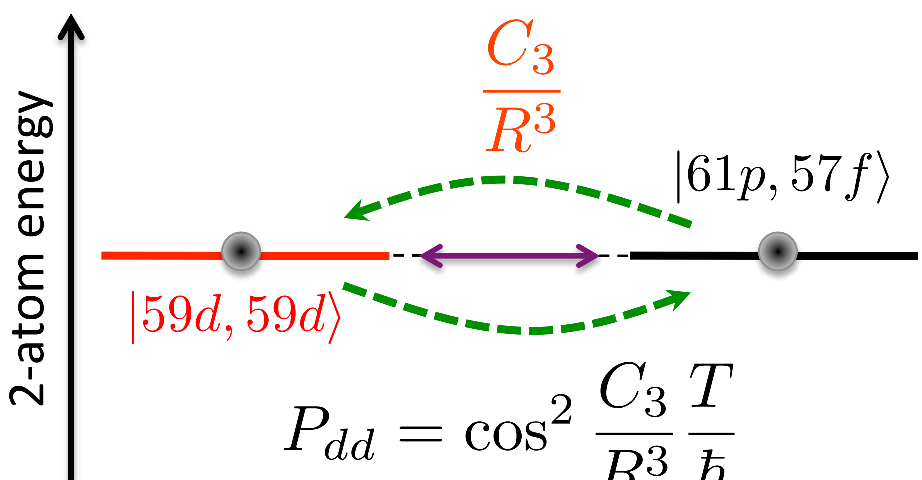
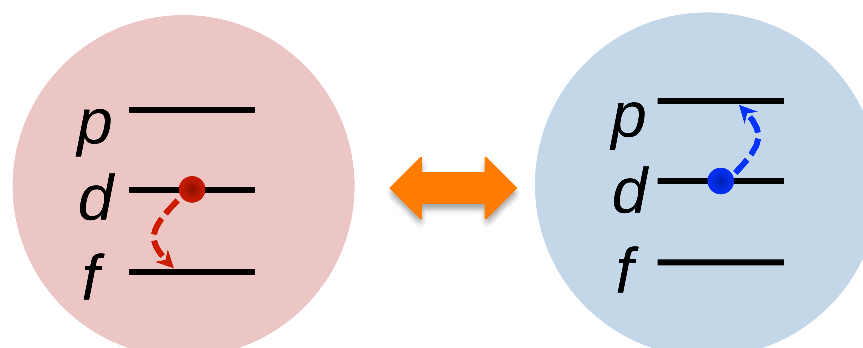


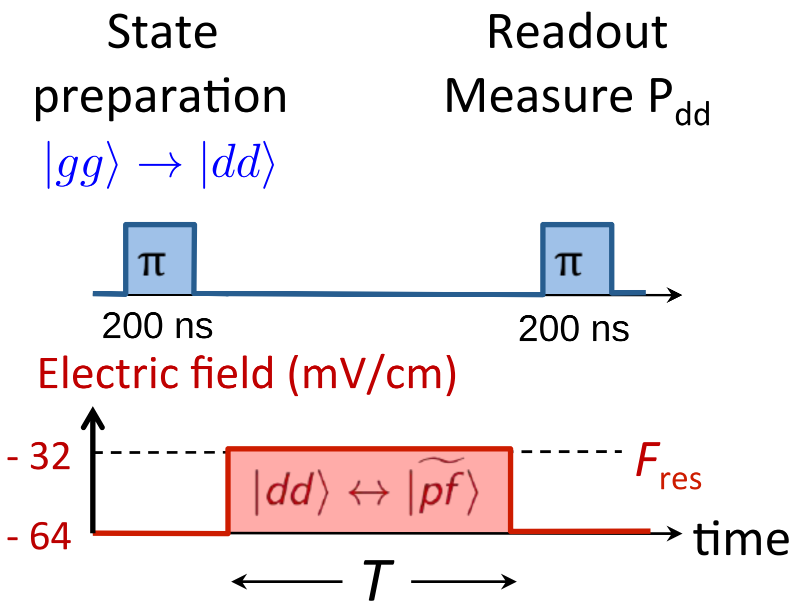
$$P_{dd} = \cos^2 \frac{C_3}{R^3}\frac{T}{\hbar}$$

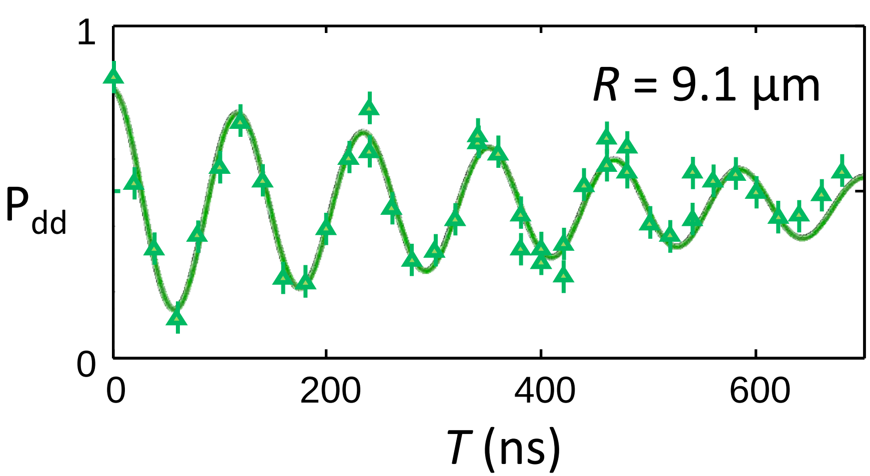


Earlier works in ensembles: T. Gallagher, P. Pillet, T. Pfau, G. Raithel…

Coherence "hidden": random positions of the atoms.

Observation of "Förster oscillations" between two atoms





S. Ravets *et al.*, Nat. Phys. **10**, 914 (2014)

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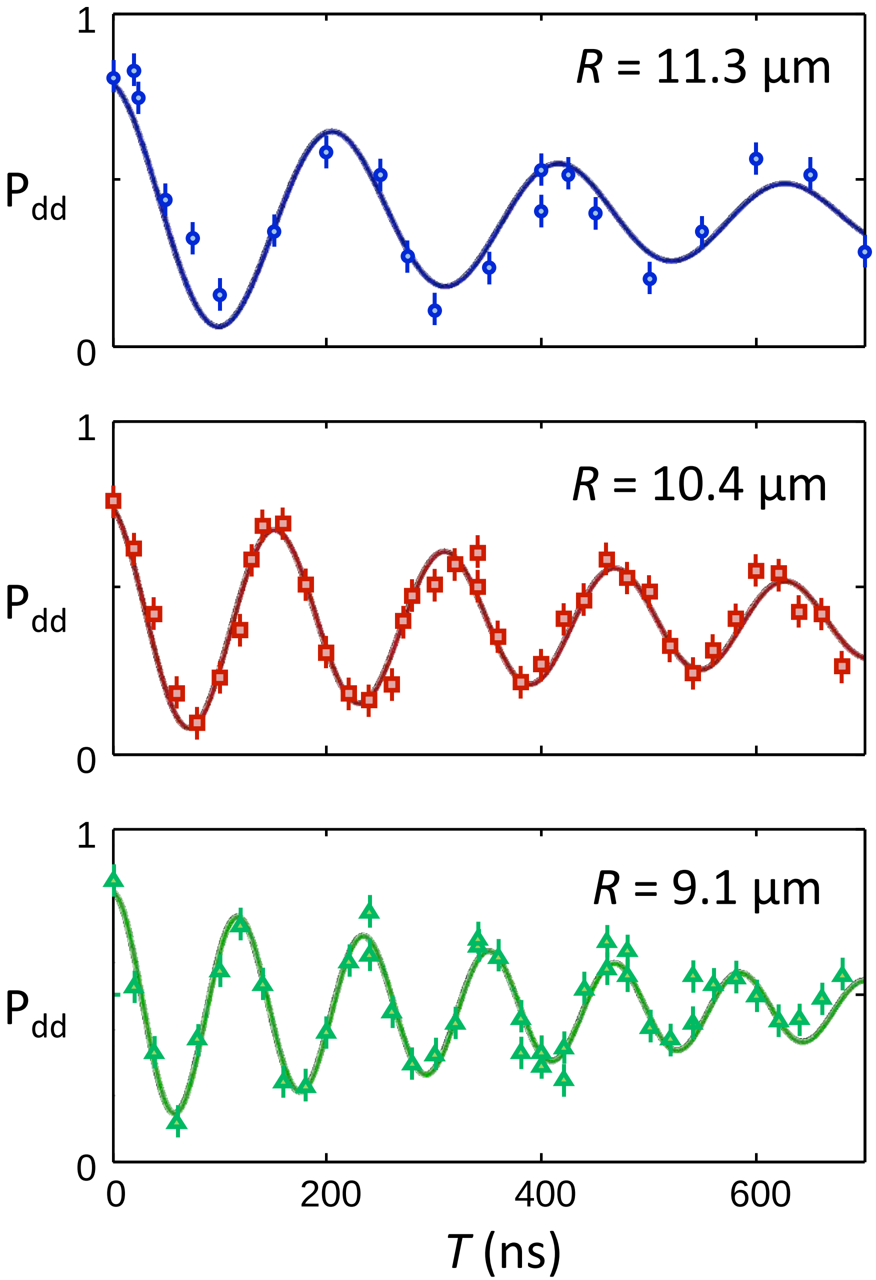

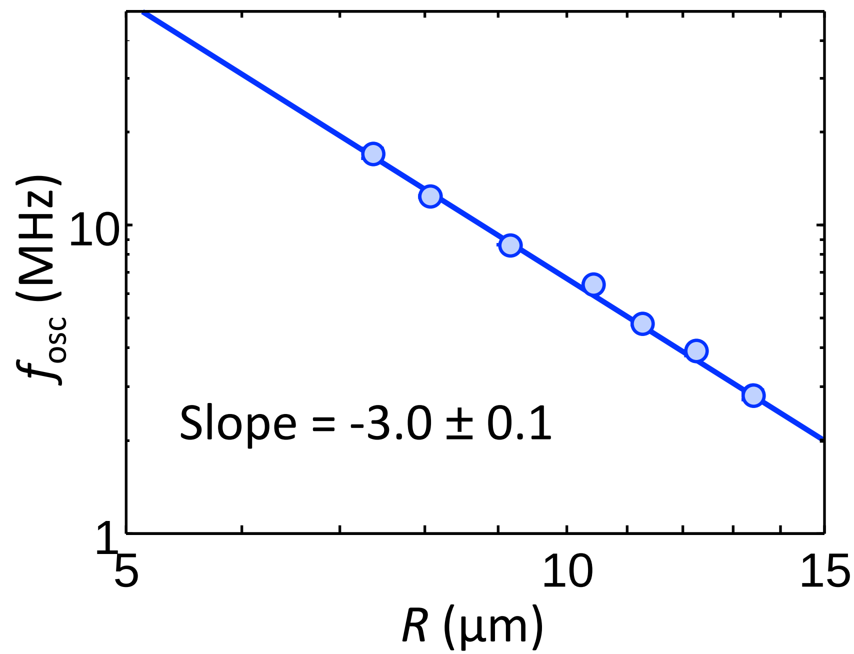

$$C_{3,\mathrm{exp}} = 2.39 \pm 0.03 \ \mathrm{GHz}.\mu\mathrm{m}^3$$

$$C_{3,\mathrm{th}} = 2.54 \ \mathrm{GHz}.\mu\mathrm{m}^3$$

S. Ravets *et al.*, Nat. Phys. **10**, 914 (2014)

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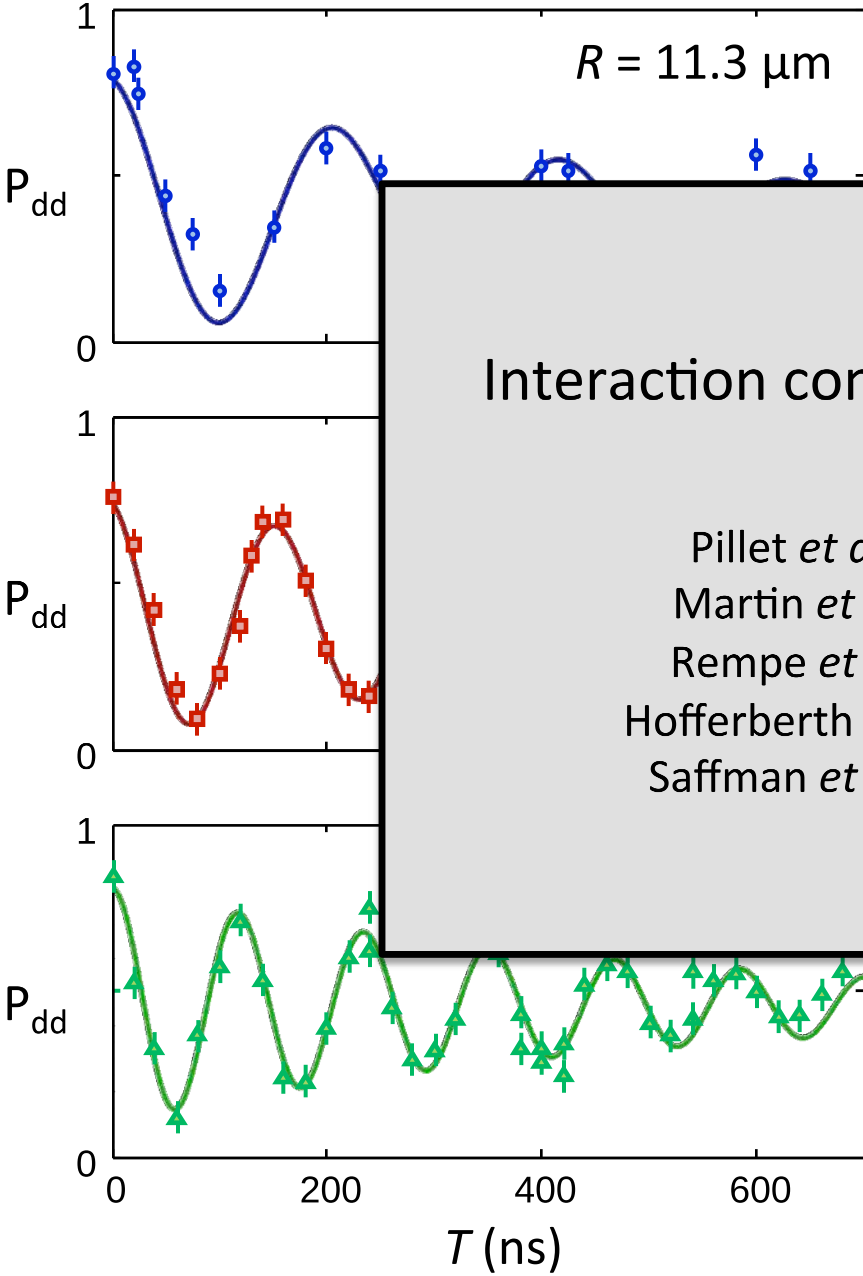

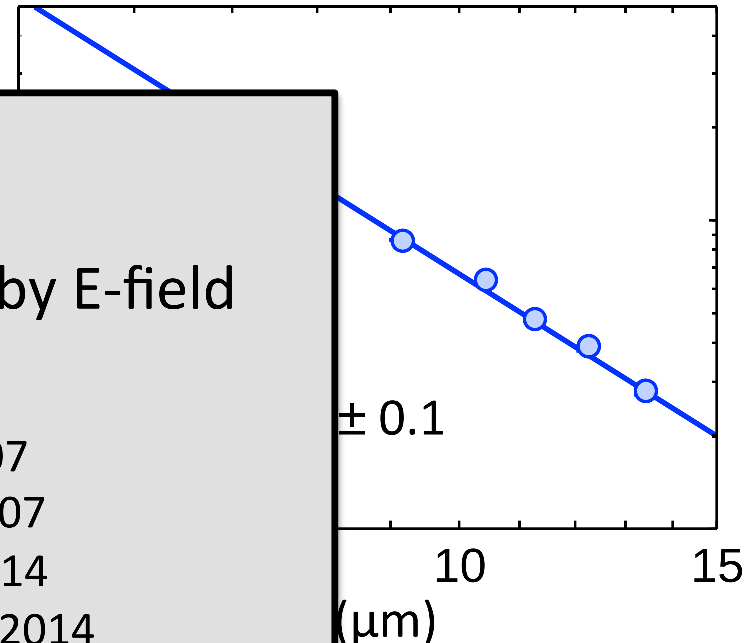

Interaction controlled by E-field

Pillet *et al.*, PRL 2007
Martin *et al.*, PRL 2007
Rempe *et al.*, PRL 2014
Hofferberth *et al.*, PRL 2014
Saffman *et al.*, RMP 2010

$0.03\ \mathrm{GHz}.\mu\mathrm{m}^3$

$$C_{3,\mathrm{th}} = 2.54\ \mathrm{GHz}.\mu\mathrm{m}^3$$

S. Ravets *et al.*, Nat. Phys. **10**, 914 (2014)

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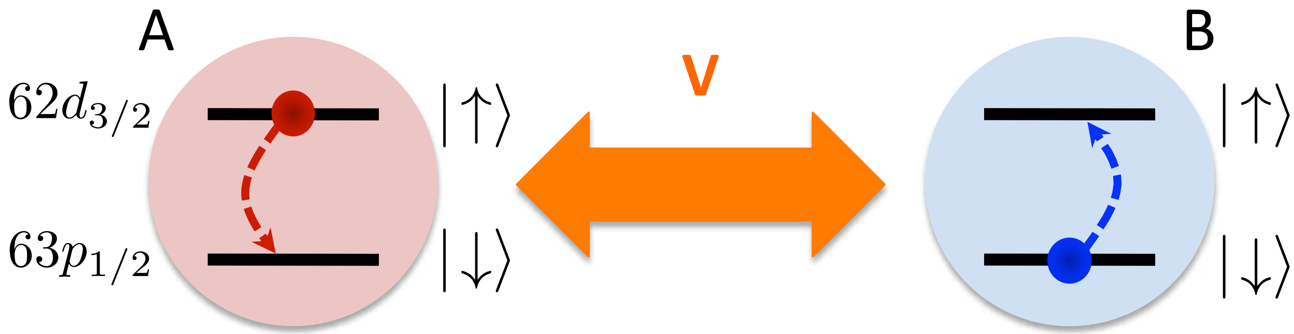
4. Resonant dipole-dipole interaction in small spin chains

5. Towards "many" atoms: hol… atoms

In collaboration with C.S. Adams
(visiting in Palaiseau, April 2014)

Resonant interaction between two different Rydberg states



"Pseudo-spins" coupled by $V = \dfrac{1}{4\pi\epsilon_0}\dfrac{d^2}{R^3}$ with $d = \langle\uparrow|\hat{D}_q|\downarrow\rangle$

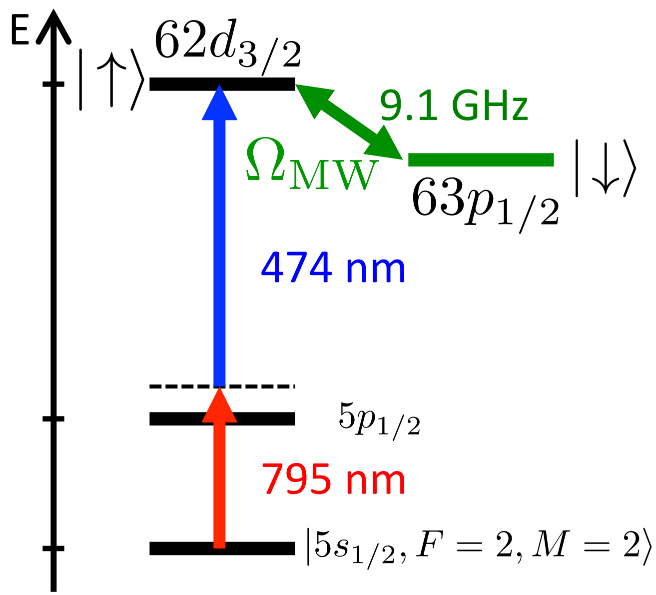
$$\hat{H} = V\left(\hat{S}_A^+\hat{S}_B^- + \hat{S}_A^-\hat{S}_B^+\right)$$ in $\{|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle\}$ basis

Non-radiative energy "exchange" or "spin exchange"

Earlier works in ensembles: Gallagher, Pillet, Pfau, Weidemüller…

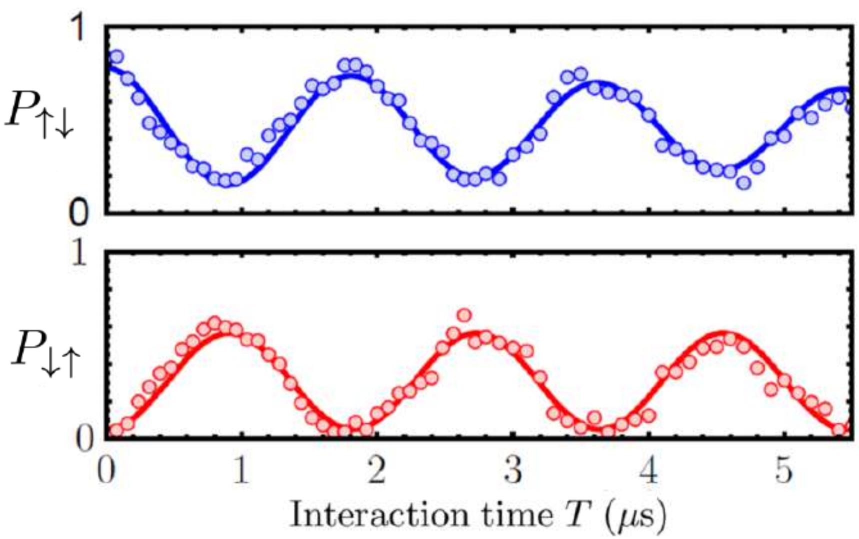
Coherence "hidden": random positions of the atoms.

Observation of spin exchange between 2 atoms (R = 30 µm)

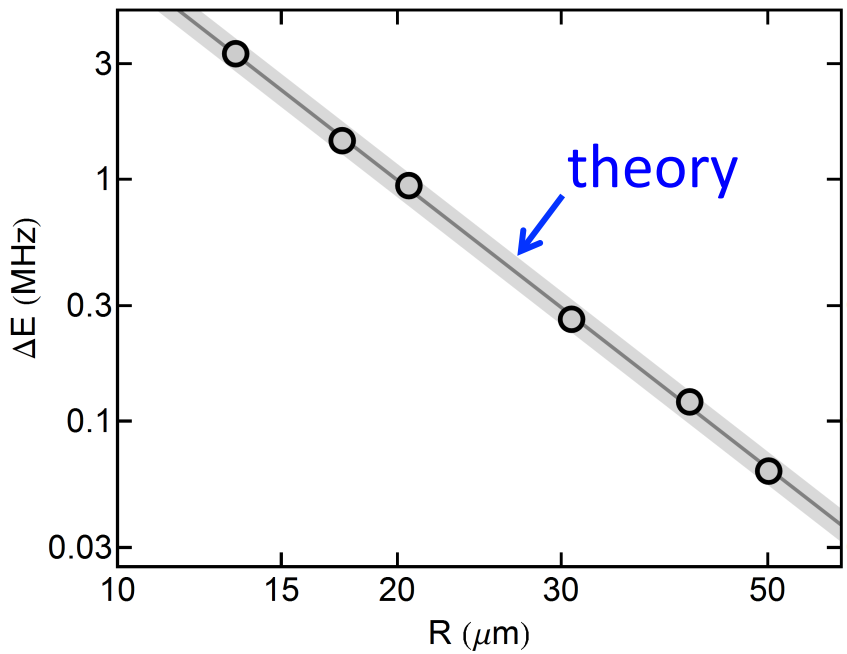


Prepare $|\uparrow\downarrow\rangle$ using microwaves + addressing beam [Labuhn, PRA **90**, 023415 (2014)]

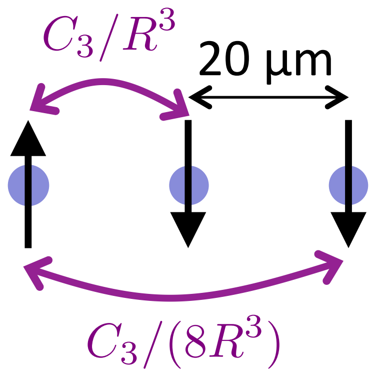
Readout: de-excite $|\uparrow\rangle$ to ground state



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

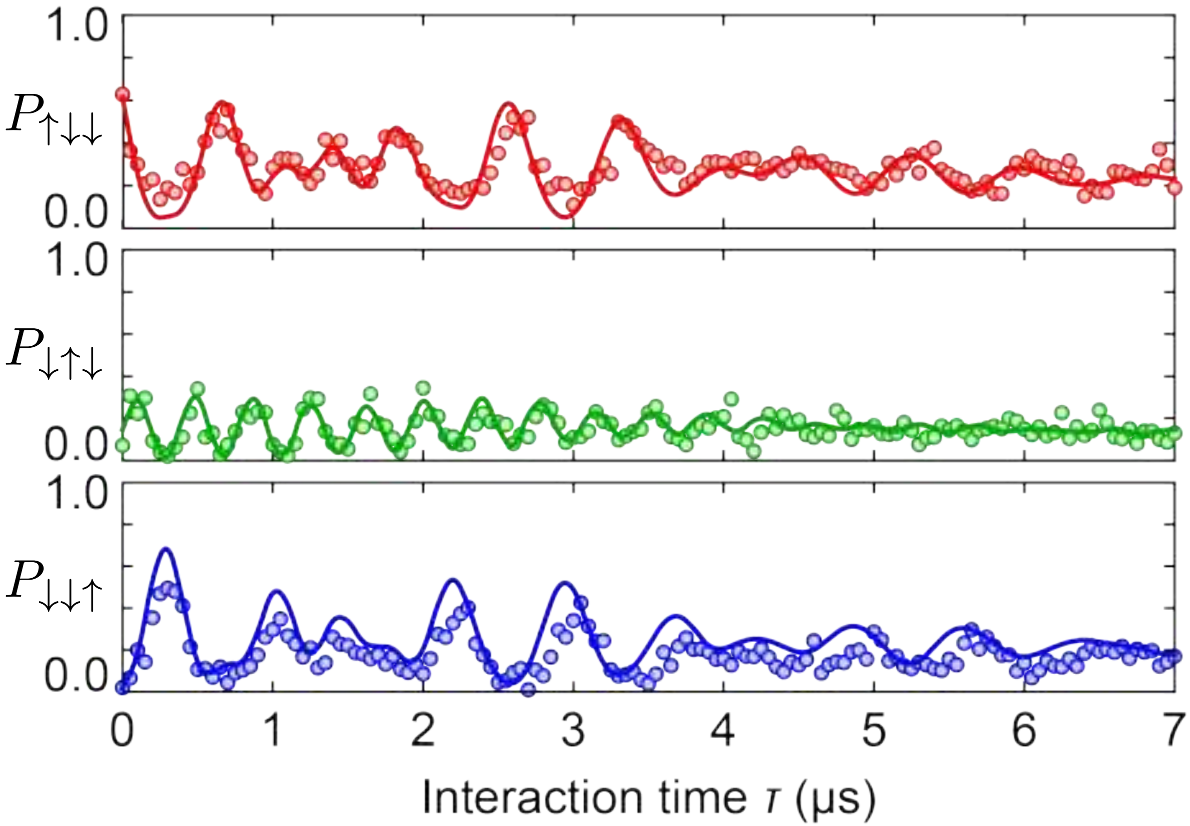


Observation of spin exchange in a 3-atom chain



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

Prepare $|\uparrow\downarrow\downarrow\rangle$ at $t = 0$,
and let the system evolve



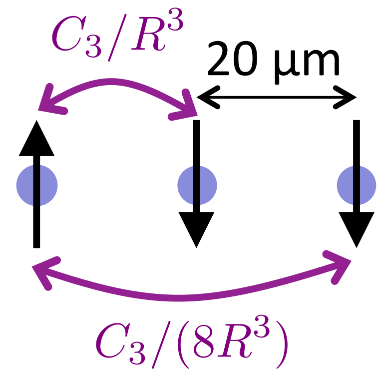
Solid lines: simulation using XY Hamiltonian and known imperfections.

Damping: temperature (30 – 50 µK)

No adjustable parameter

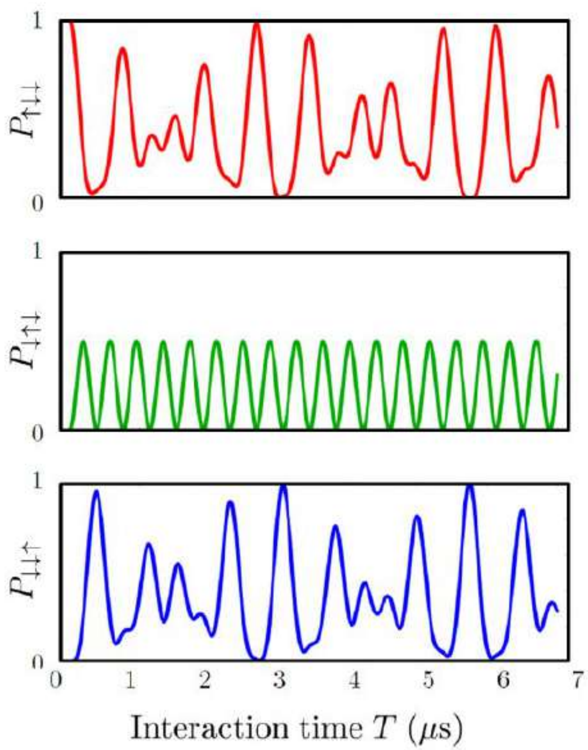
Optical lattices Nat. Phys. **9**, 235 (2013) ; trapped ions Nature, **511**, 198 & 202 (2014)

Three-atom "spin-chain": what to expect (theory) ?



Prepare $|\uparrow\downarrow\downarrow\rangle$ at $t = 0$,
and let the system evolve

1/R³ interaction

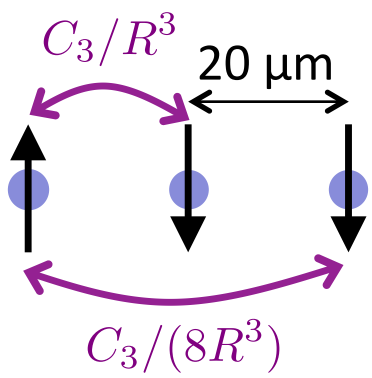


2 off-diagonal couplings: V & V / 8

⇒ eigenvalues (incommensurate):

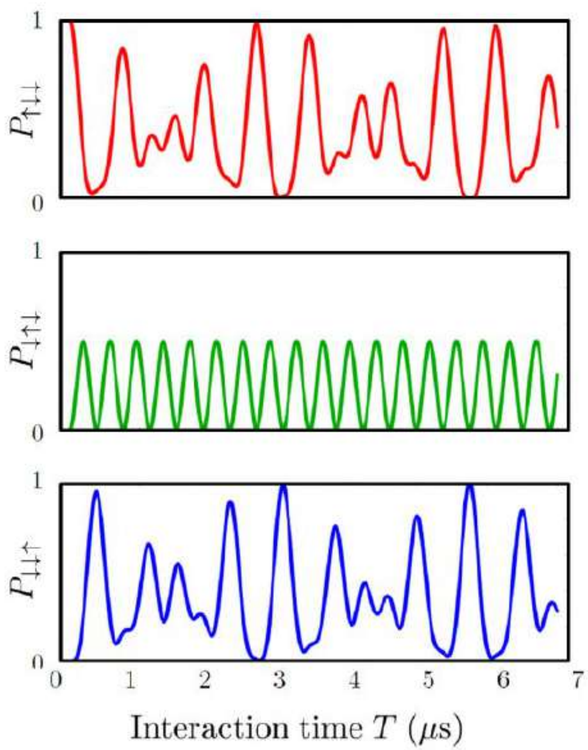
$$\frac{V}{16}\left(1+3\sqrt{57}\right)\ ,\ \frac{V}{16}\left(1-3\sqrt{57}\right)\ ,\ -\frac{V}{8}$$

Three-atom "spin-chain": what to expect (theory) ?

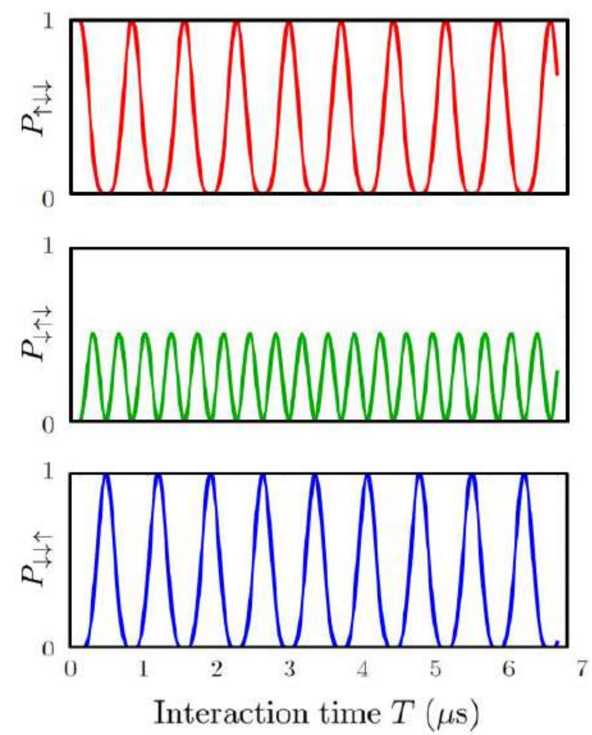


Prepare $|\uparrow\downarrow\downarrow\rangle$ at $t = 0$,
and let the system evolve

$1/R^3$ interaction



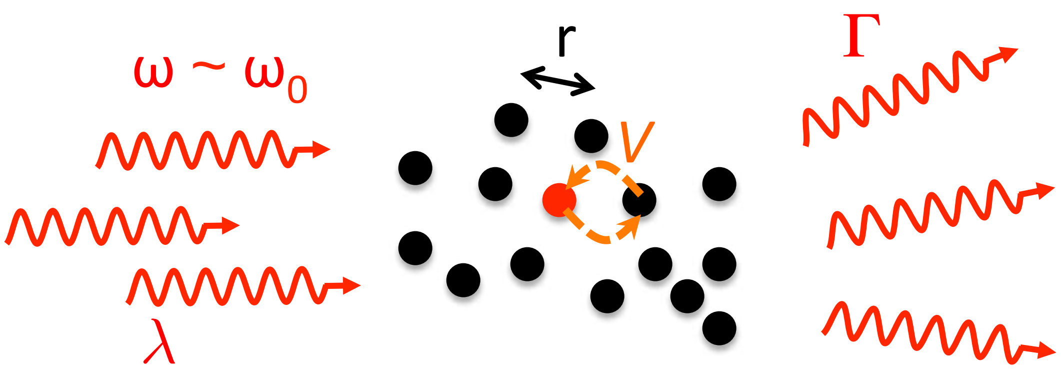
Nearest-neighbor only

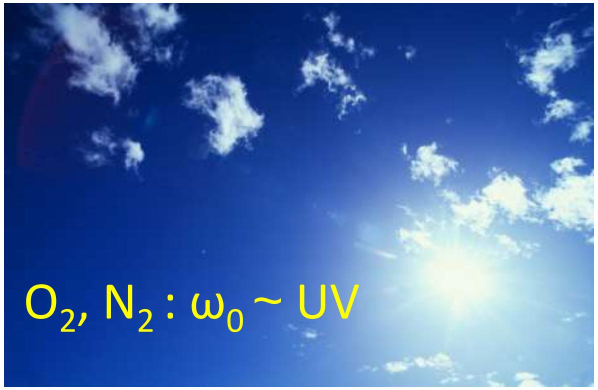


Resonant energy exchange around us…

1. Near-resonance light scattering in dense media

Ensemble of two level-atoms (frequency ω_0, linewidth Γ)





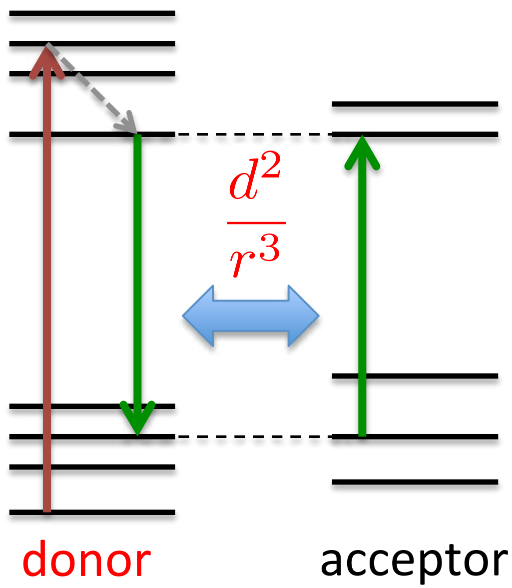
Non-radiative energy redistribution. Rate: $\frac{V}{\hbar}$ $\Rightarrow$ modifies scattering

Javanainen PRL **112**, 113603 (2014) ; Pellegrino, PRL **113**, 133602 (2014)

Resonant energy exchange around us…

2. Energy transport in biological systems

FRET



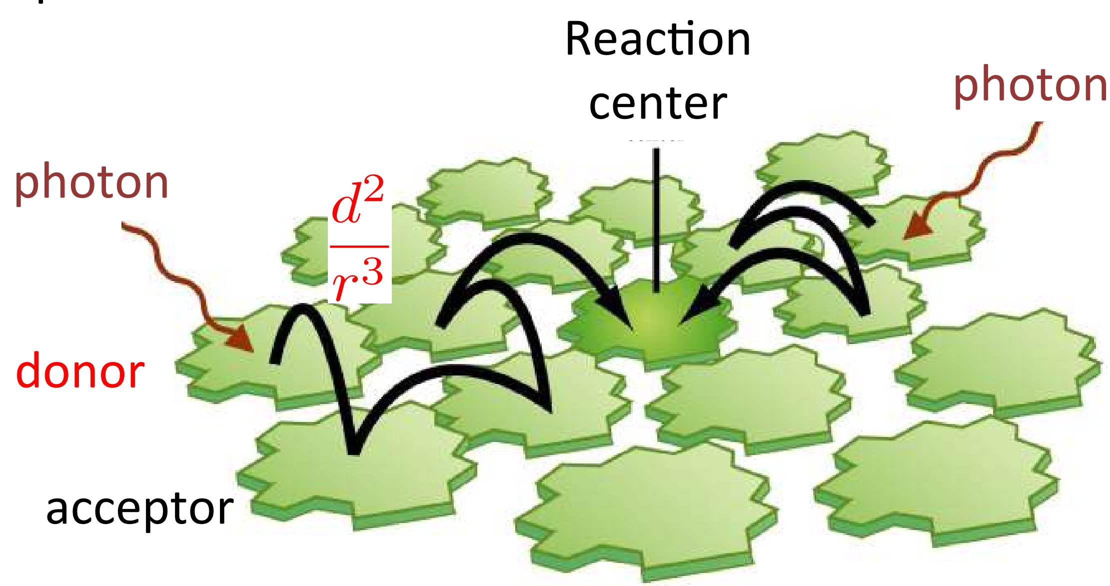
$$k_{tr} = \frac{1}{\tau}\left(\frac{R_0}{r}\right)^6 \propto \left(\frac{d^2}{r^3}\right)^2$$

F. Perrin (1933), Oppenheimer (1941)
Th. Förster (1946)

Clegg, *The History of FRET* (2006)

Photosynthesis:

QE > 90%



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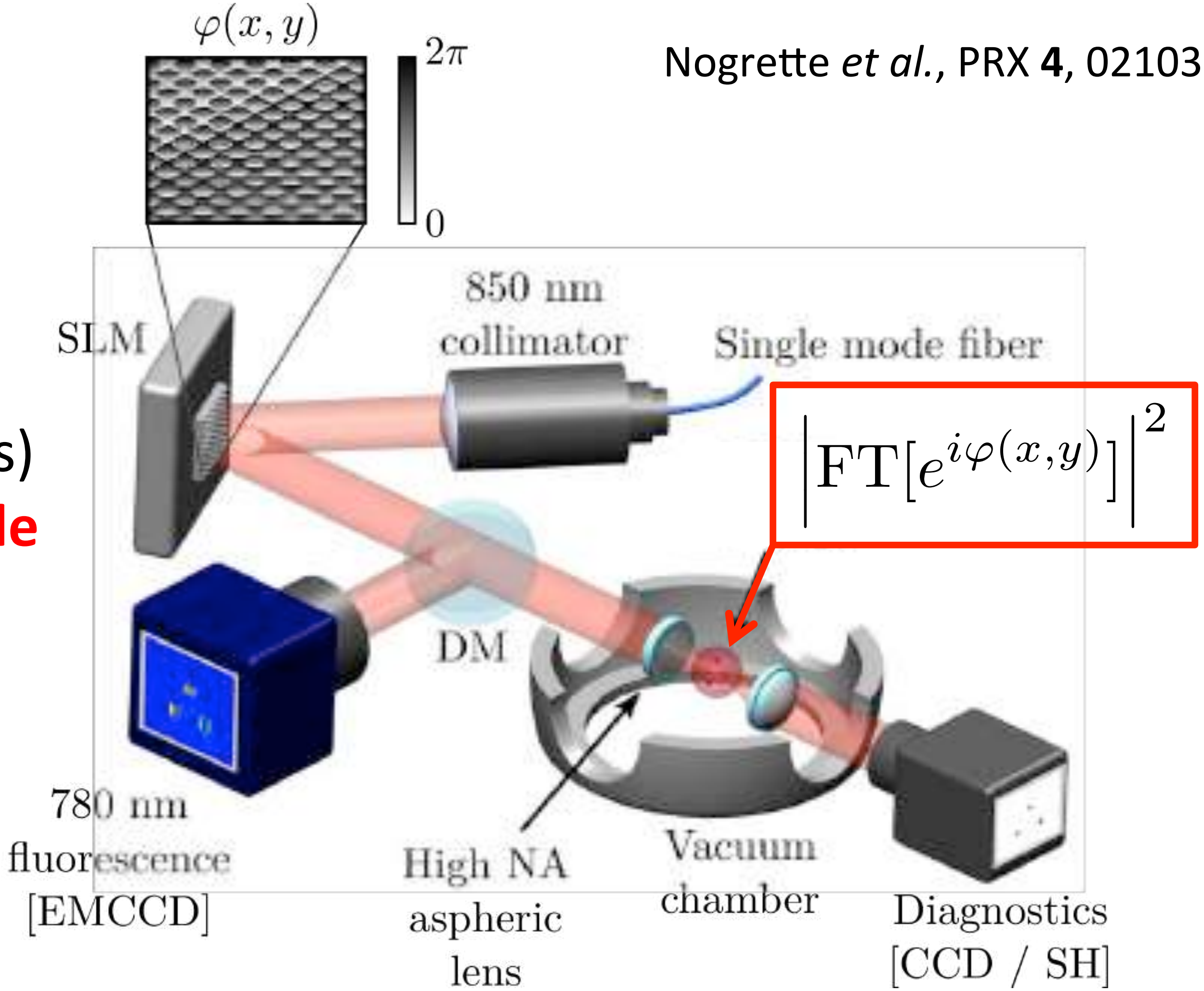
5. Towards “many” atoms: holographic 2D arrays of individual atoms

Holographic 2D arrays of optical tweezers

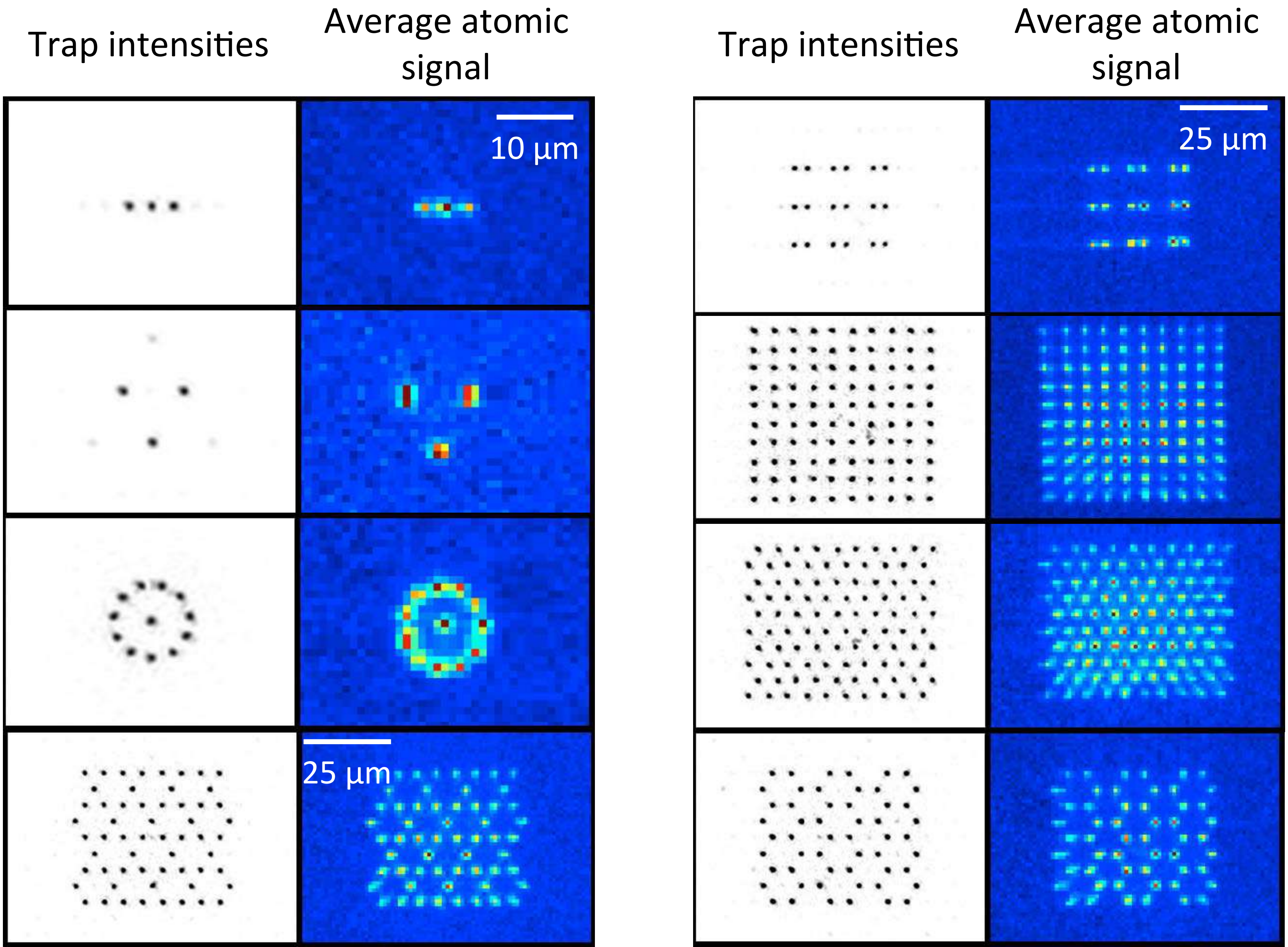
Nogrette *et al.*, PRX **4**, 021034 (2014)

Spatial Light Modulator (liquid crystals)
Reconfigurable

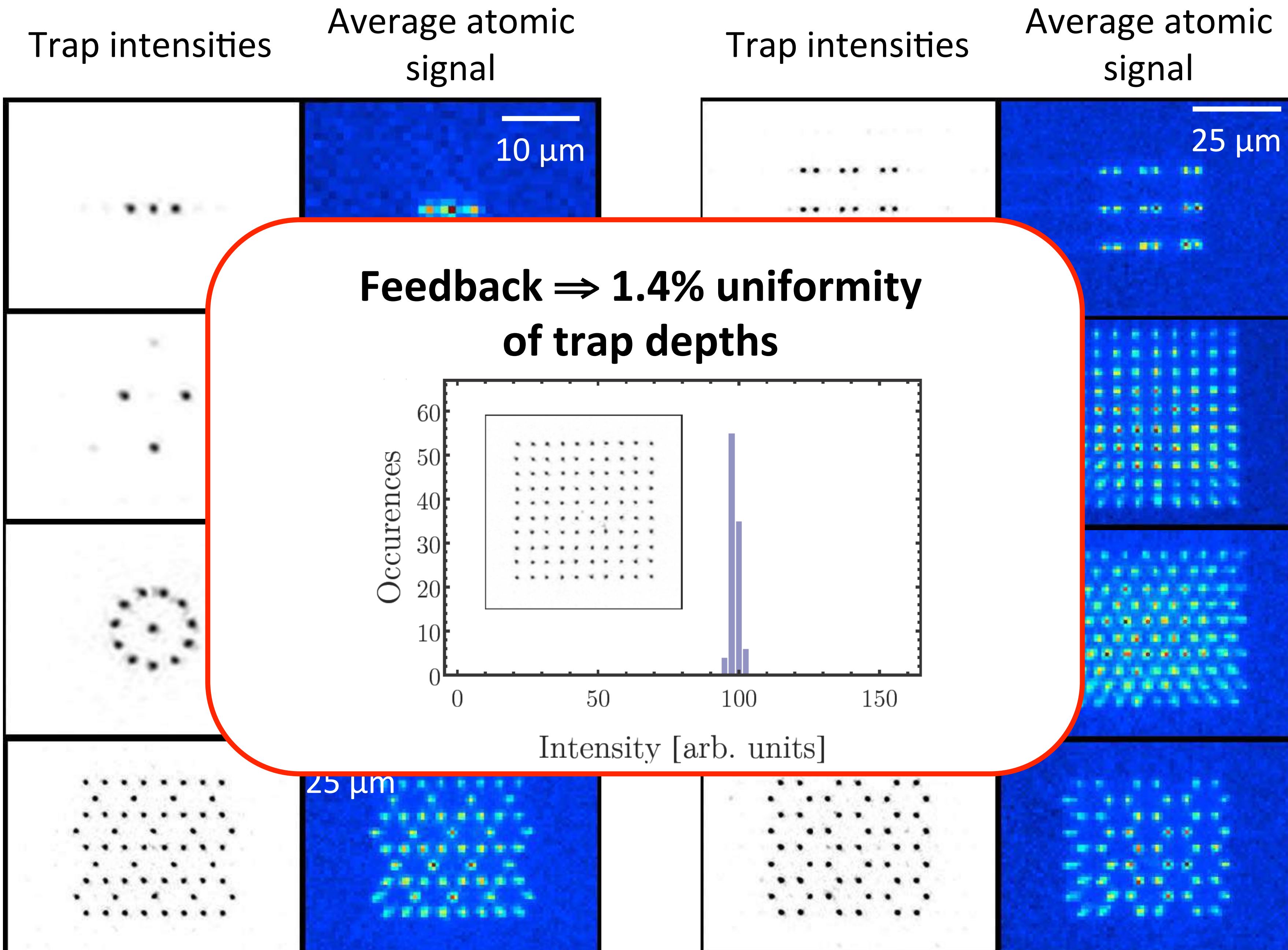


1. Iterative algorithms to obtain the desired intensity pattern (Gerchberg - Saxton)
2. Measure pattern ⇒ **feedback** to improve array "quality"

Gallery of 2D arrays of tweezers

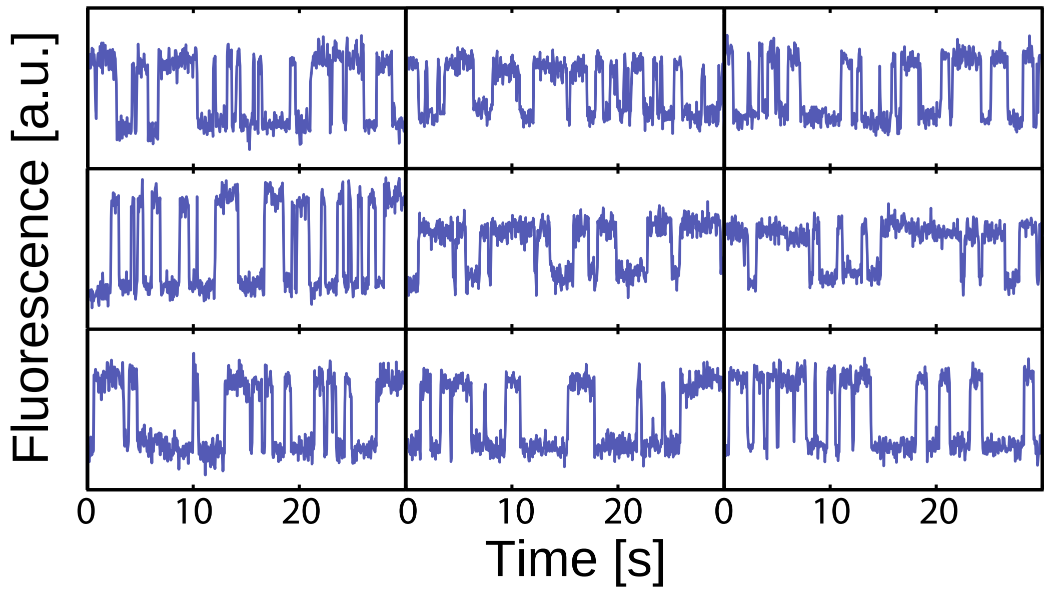


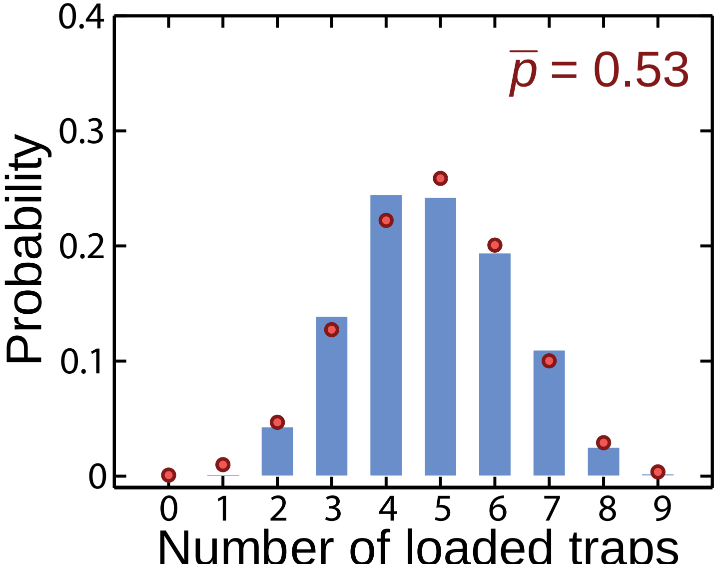
Gallery of 2D arrays of tweezers



Arrays of optical tweezers with individual atoms

Signal on each pixel of the CCD



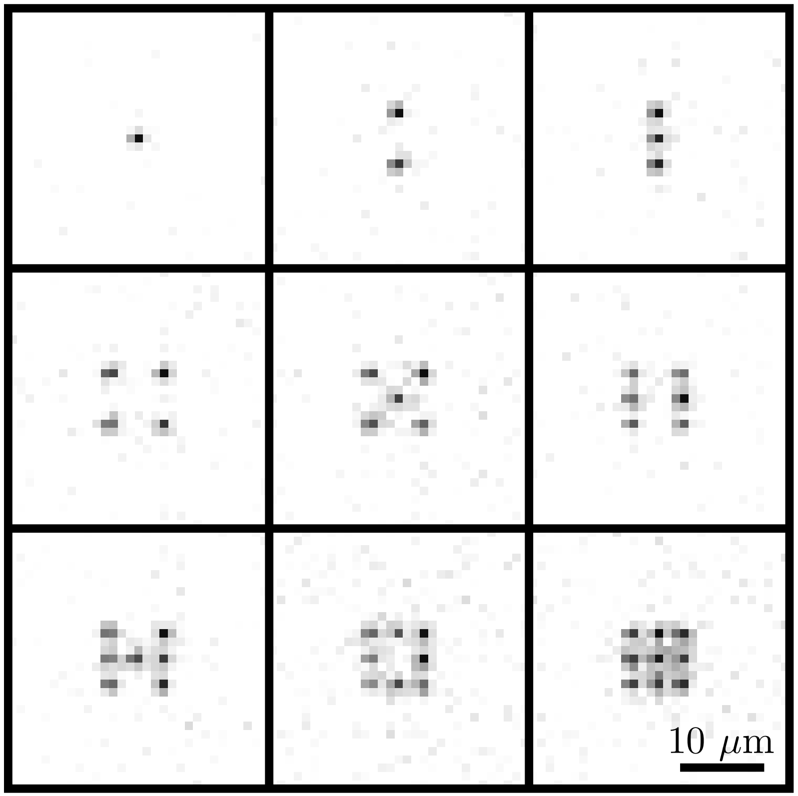


Nogrette *et al.*, PRX **4**, 021034 (2014)

Non-deterministic loading:
all traps filled with proba p^N

Deterministic loading:
Grünzweig, Nat. Phys. **6**, 951 (2010)
Ebert, PRL **112**, 043602 (2014)

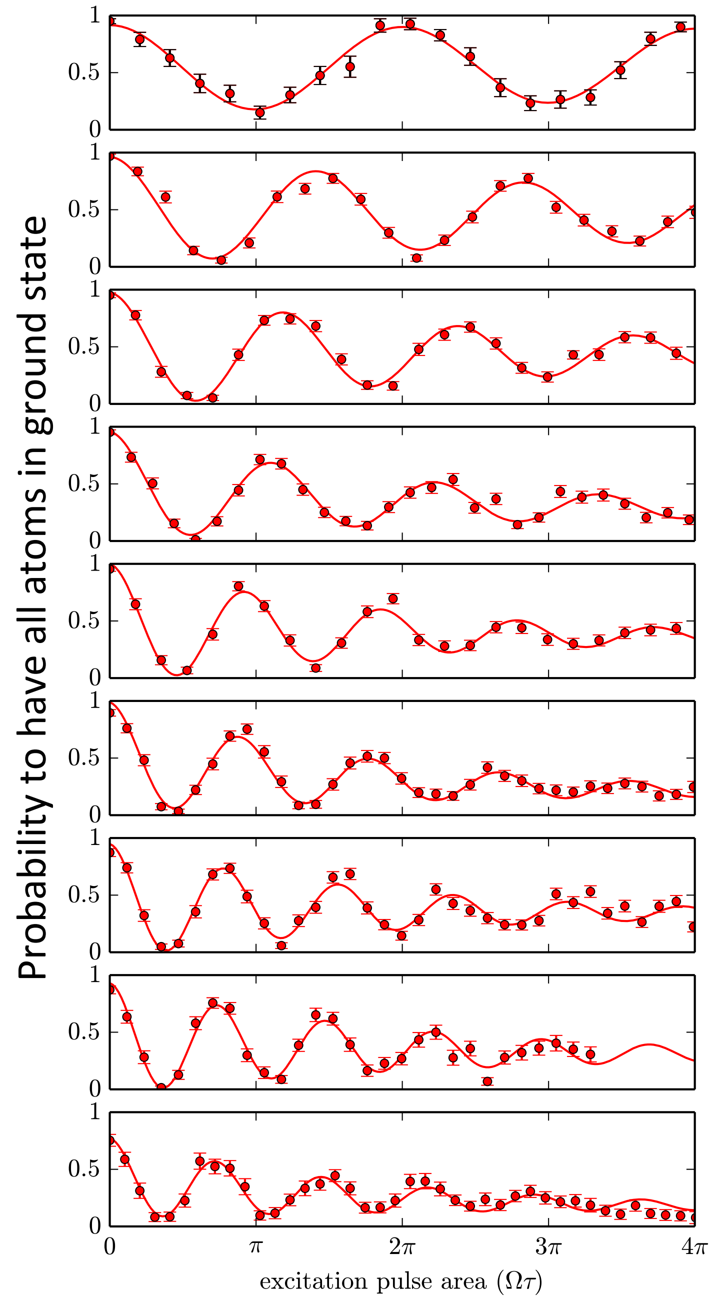
Collective excitation in "large" arrays (preliminary…)



Deterministic loading

(N = 9 every 100 s ⇒ 36 hours!)

$100d_{3/2}$



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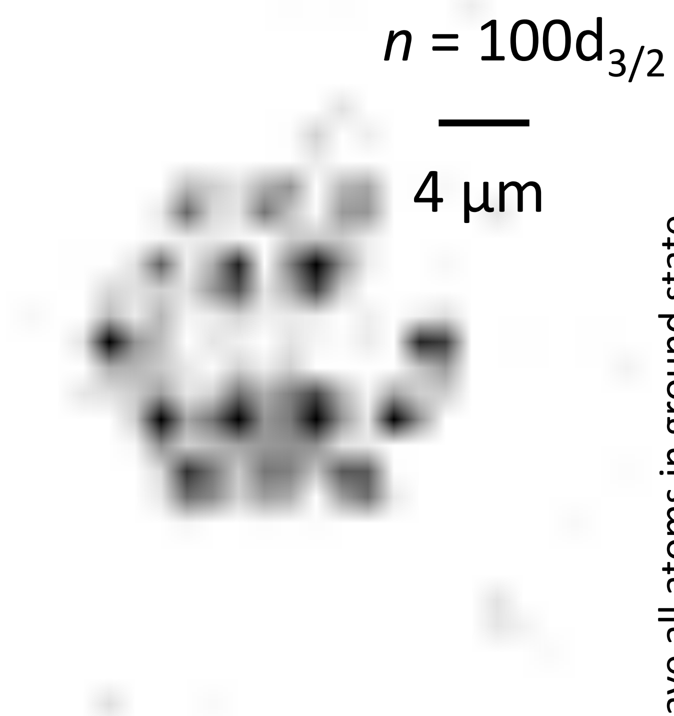
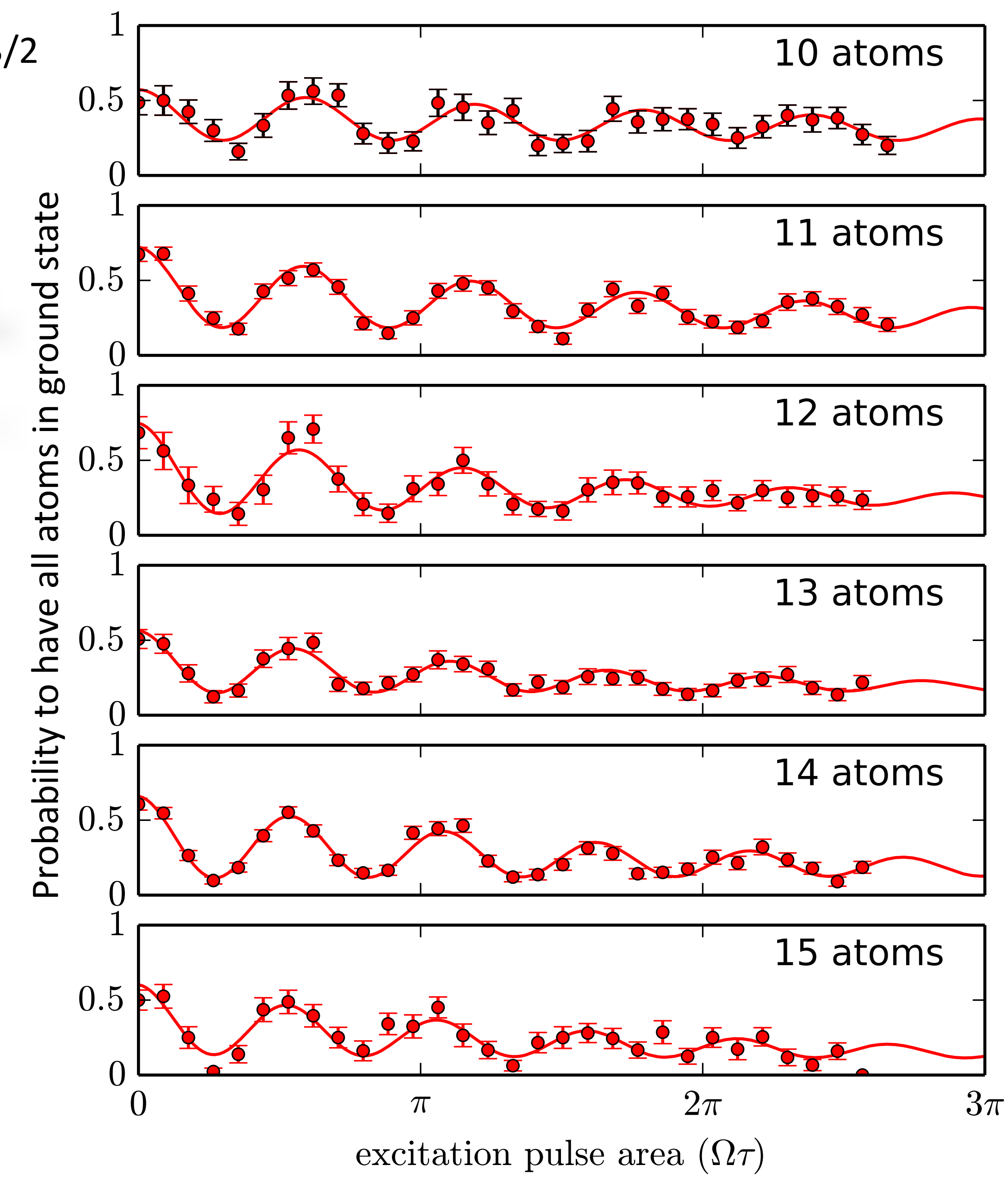


Triangular array

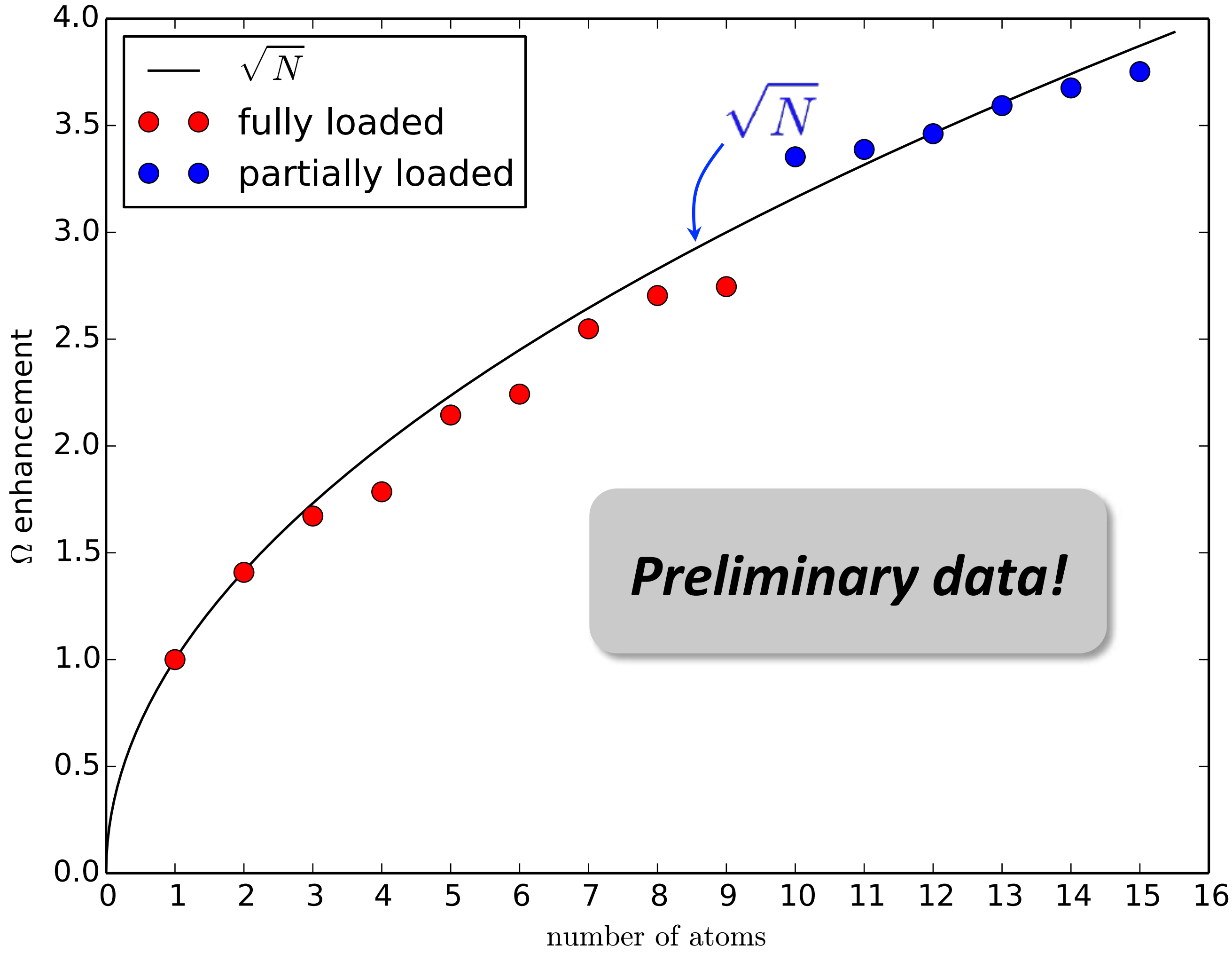
19 traps

Trigger on N atoms
(N = 10 every 1s)



Collective excitation in "large" arrays (preliminary…)

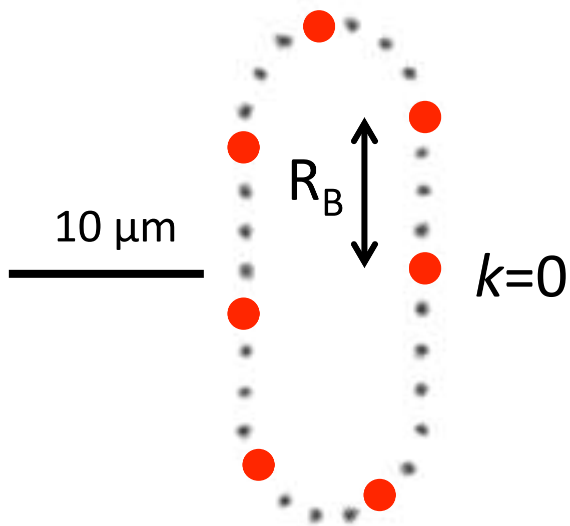
Collective Rabi frequency

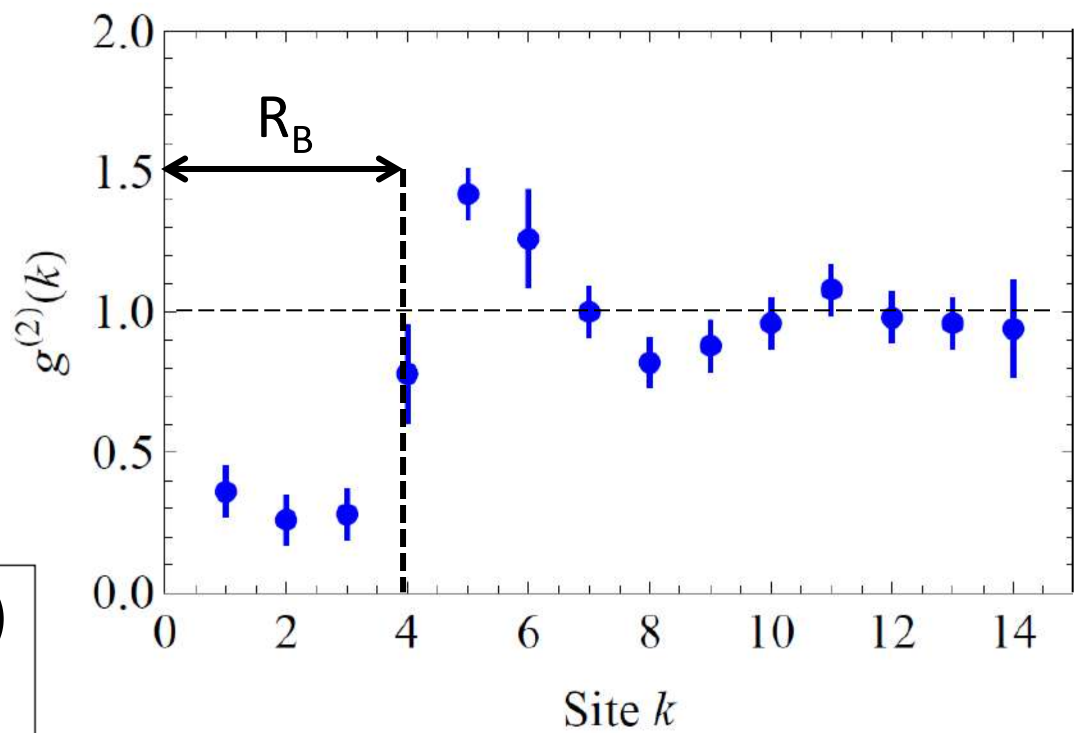


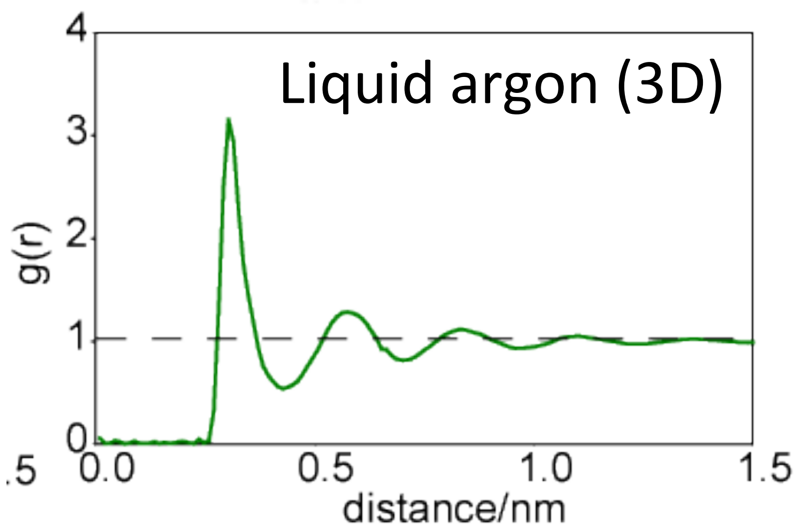
Pair correlation function in a 1D Ising spin chain

Sparsely loaded ring (30 traps, > 20 atoms)

Preliminary data!







http://rkt.chem.ox.ac.uk

Also in Munich (2D) Nature 2012

Conclusion

Manipulation of Rydberg interactions with 2-3 atoms

1. Van der Waals
2. Control interaction by E-field
3. Resonant interaction

$\Rightarrow$ **Engineer Hamiltonians**

$$\hat{H} = \sum_{i,j} \frac{C_6}{R_{i,j}^6} \hat{S}_i^z \hat{S}_j^z$$

van der Waals

$$\hat{H} = \sum_{i,j} \frac{C_3}{R_{i,j}^3} \left(\hat{S}_i^+ \hat{S}_j^- + \hat{S}_i^- \hat{S}_j^+ \right)$$

X-Y exchange

Future directions: arrays of ~ 10 – 20 atoms

1. Study of elementary few-body systems with long range interaction: spectroscopy, phase diagrams, dynamics…
2. **Transition** 2 body – few body physics
3. Transport in ordered or disordered arrays