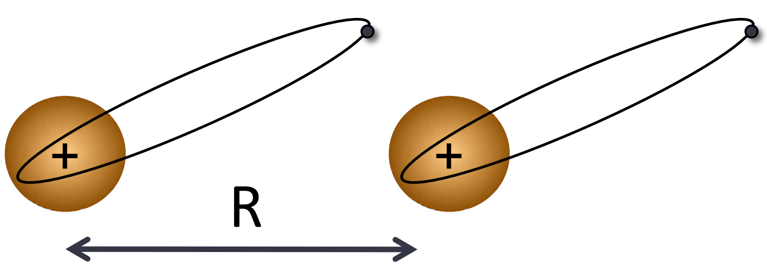
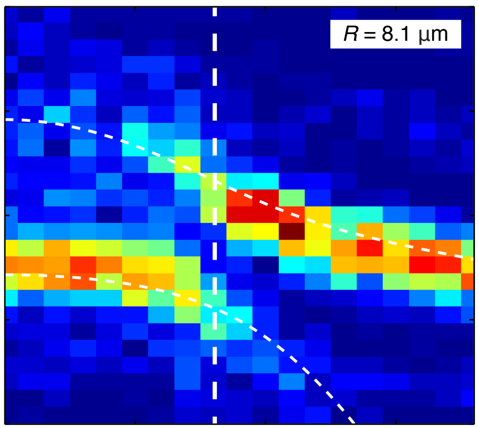
Resonant Interactions between two Rydberg Atoms

Sylvain Ravets, Henning Labuhn, Daniel Barredo, Thierry Lahaye, Antoine Browaeys





July, 2014

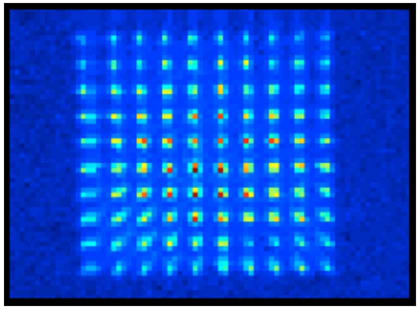
Quantum state engineering with individual neutral atoms

- Quantum information, metrology, simulation (entangled states ⇒ interaction)

  M. Saffman *et al.*, Rev. Mod. Phys. **82** (2010)

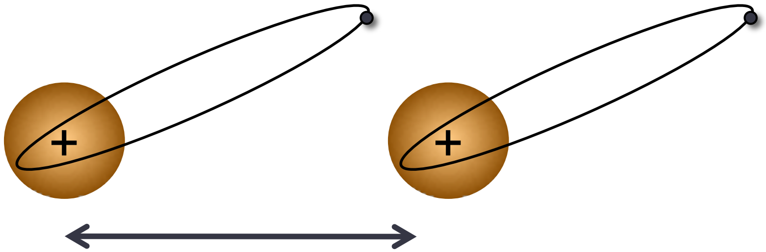
- Isolate and control single atoms:
  - Arrays of traps

    d ~ a few microns



- Interaction: Rydberg atoms

  n >> 1
  Large dipole moments

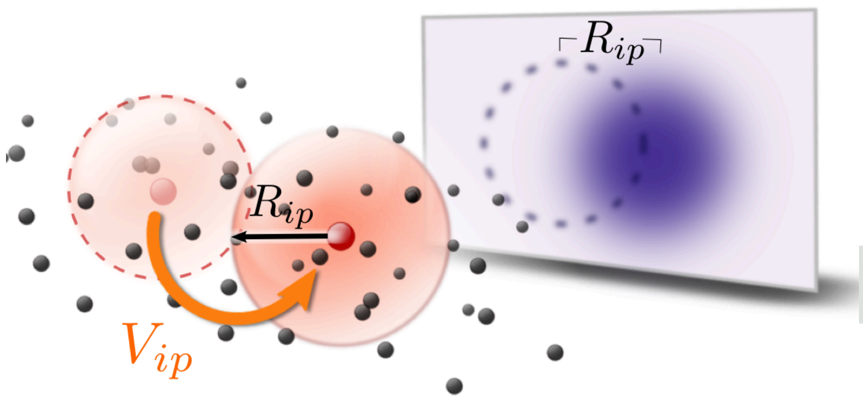


Resonant dipole-dipole interactions between Rydberg atoms

- Need for strong and tunable interactions
  ➔ use resonant interactions ($\propto 1/R^3$) controlled by electric fields (Förster resonance).

See Gallagher, Pillet, Saffman, Pfau, Weidemüller,…

- Leads to energy transport in disordered media.



G. Günter, *et al.* Science **342** (2013)

- Indirect evidences of coherence at resonance:

M. Mudrich, *et al.* Phys. Rev. Lett. **95** (2005)

J. Nipper, *et al.* Phys. Rev. Lett. **108** (2012)

Our setup

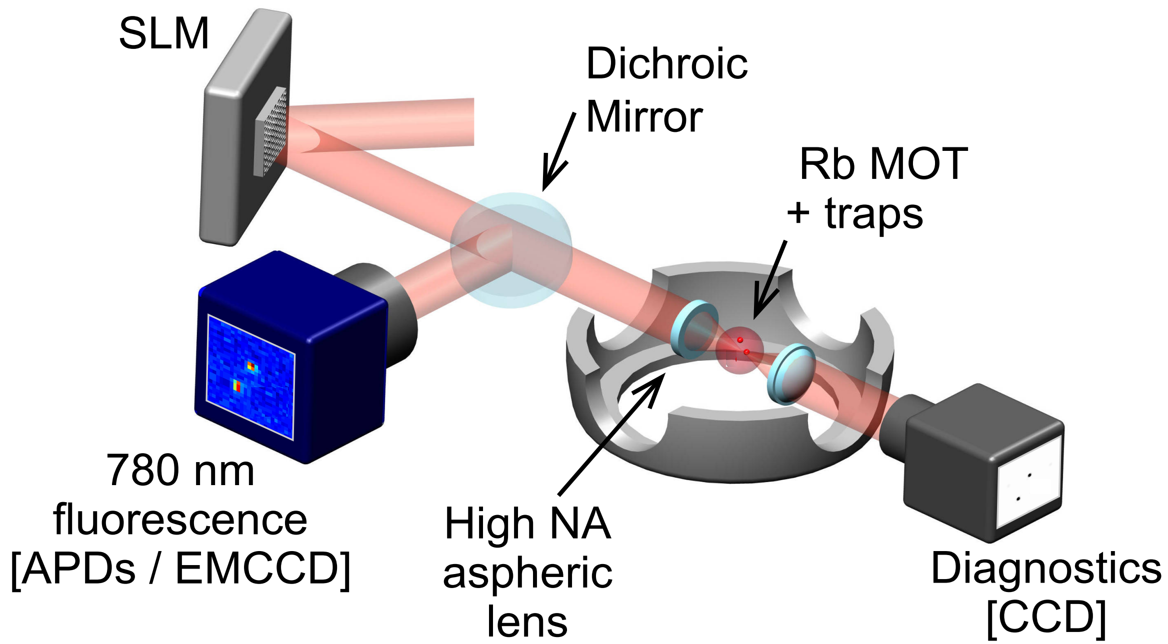
Production of traps arrays

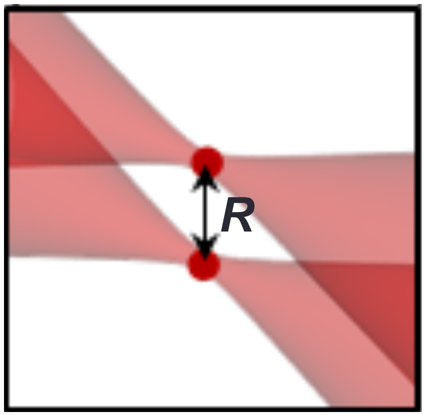
Control of electric fields

Excitation to Rydberg states

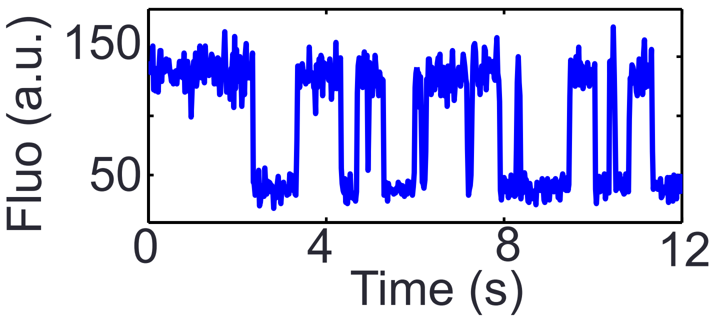
Single atoms in microscopic dipole traps

- ~1μm dipole trap: only one atom trapped due to light-assisted collisions
- Spatial Light Modulator: easily reconfigurable trap geometry



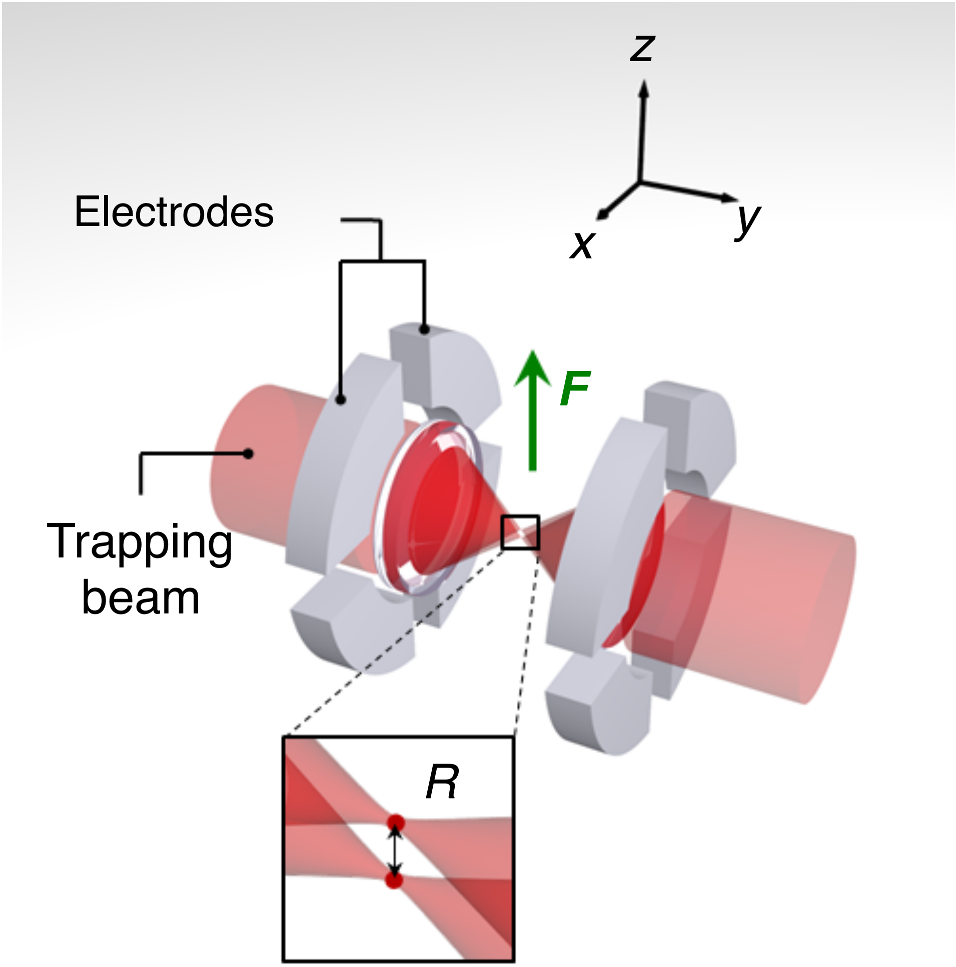


- Detection: collect fluorescence (780 nm)



Schlosser *et al.,* Nature **411** (2001)
Sortais *et al.,* Phys. Rev. A **75** (2007)
Nogrette *et al.*, Phys. Rev. X **4** (2014)

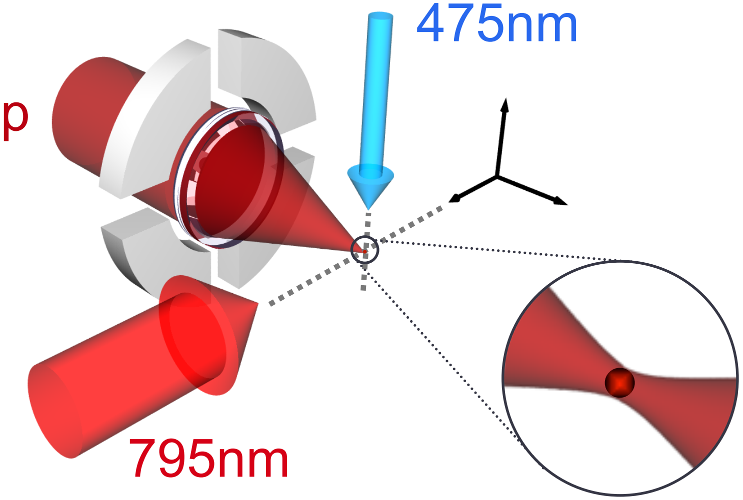
Control of static electric fields

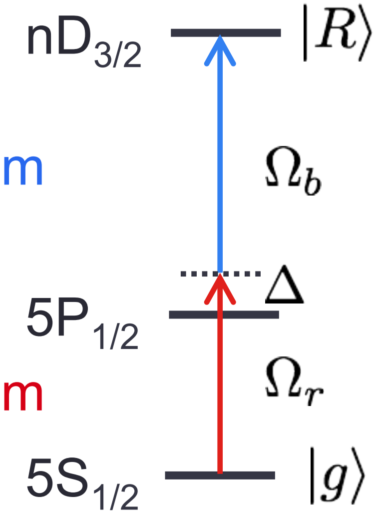


- Rydberg states : high polarizability / sensitivity to electric fields
- Control of *E*-field: 8 electrodes (compensation, **control of interaction**)

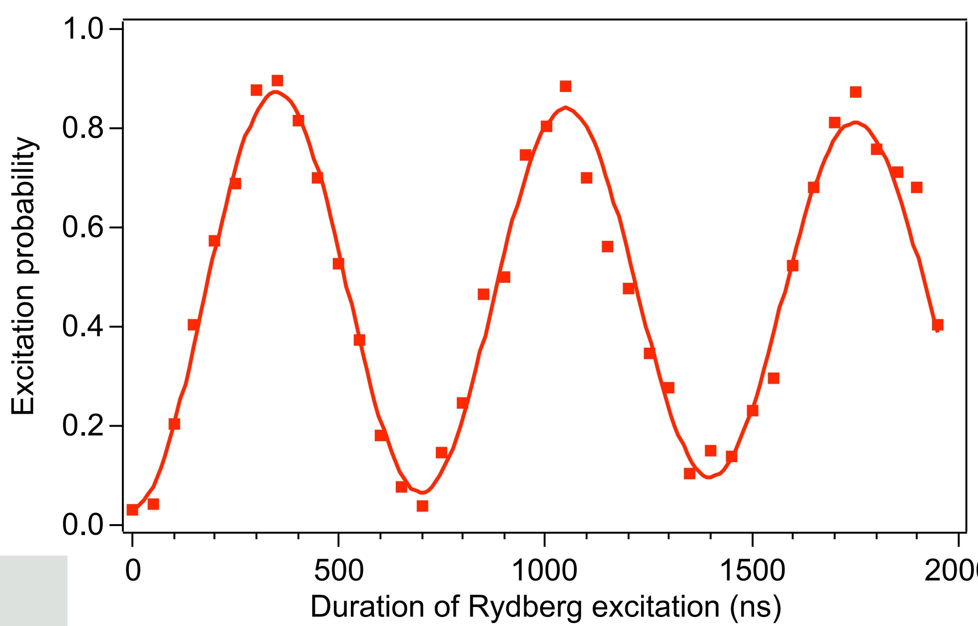
See also: Löw, *et al.*, J. Phys. B: At. Mol. Opt. Phys. **45** (2013)

Single atom Rydberg excitation





- Example of a one-atom Rabi oscillation to $59D_{3/2}$:

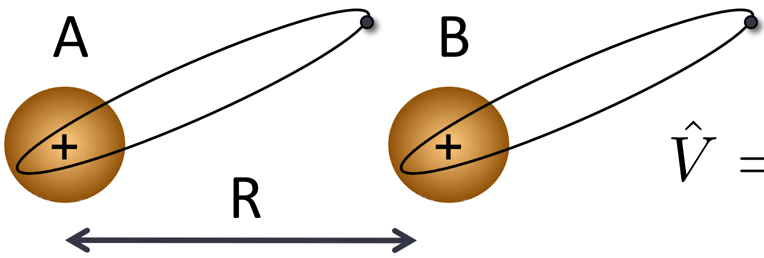


Y. Miroshnychenko, *et al.*, PRA **82** (2010)
Early results at Wisconsin: PRL **100** (2008)

Resonant Interaction between two Rydberg Atoms

Tuning two atoms to a Förster resonance

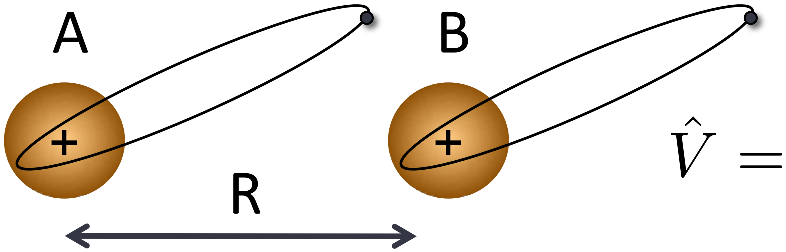
Interactions between two Rydberg atoms



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

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

Interactions between two Rydberg atoms



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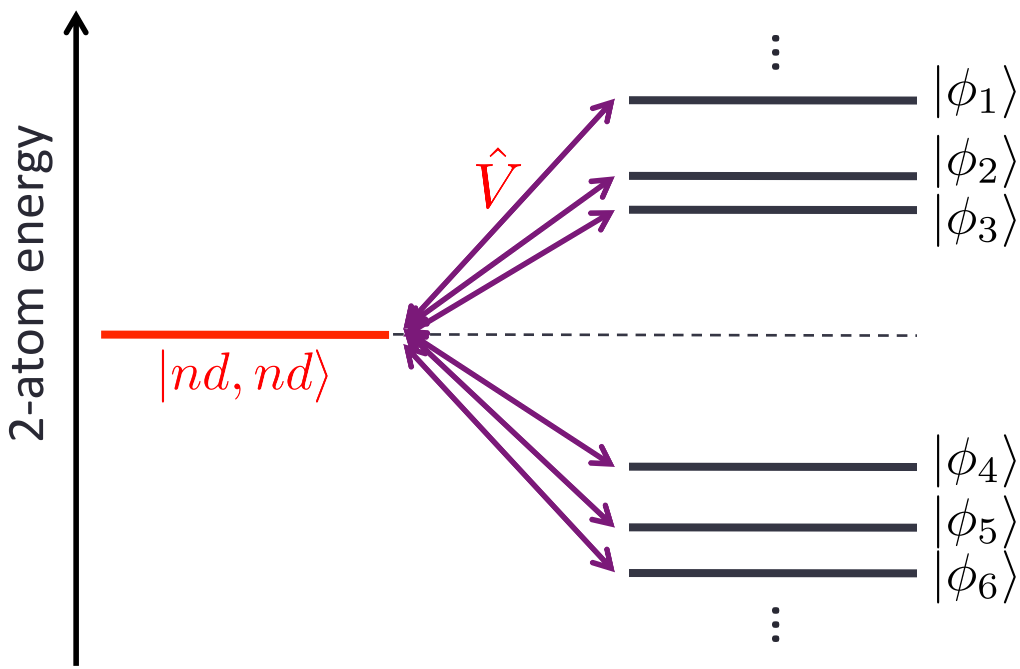
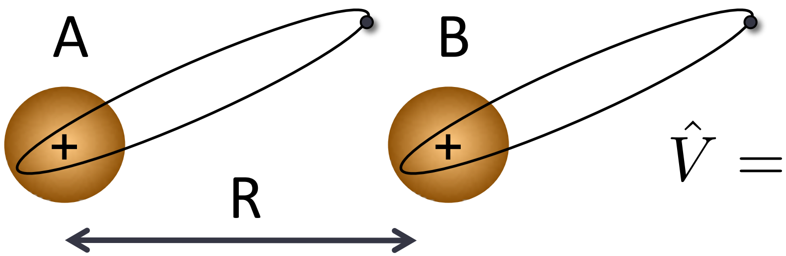


Van der Waals regime:

$$\Delta E_{dd} = \frac{C_6}{R^6}$$

Tuning two atoms to resonance



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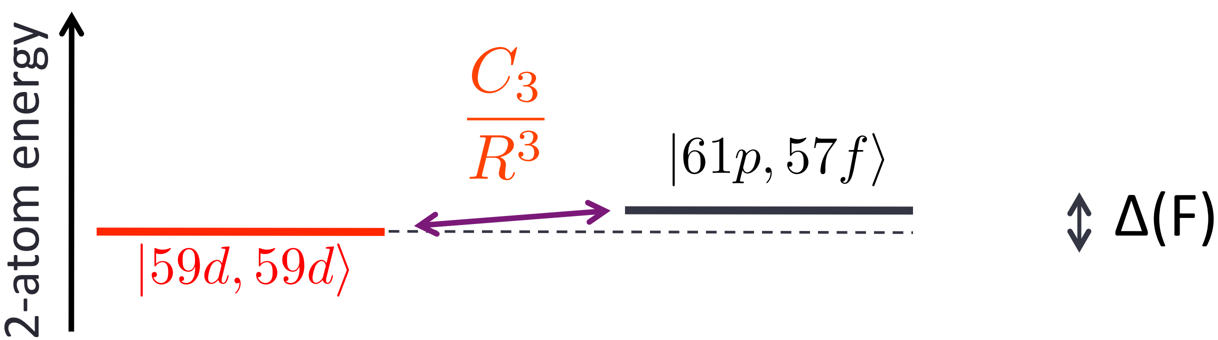
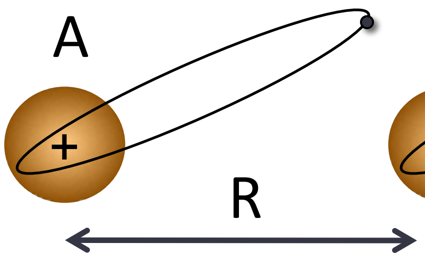


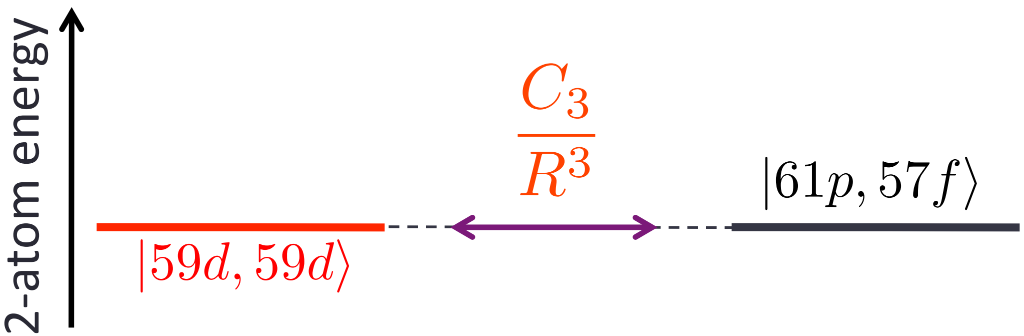
Tune Δ(F): relative Stark shift

Tuning two atoms to resonance



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

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

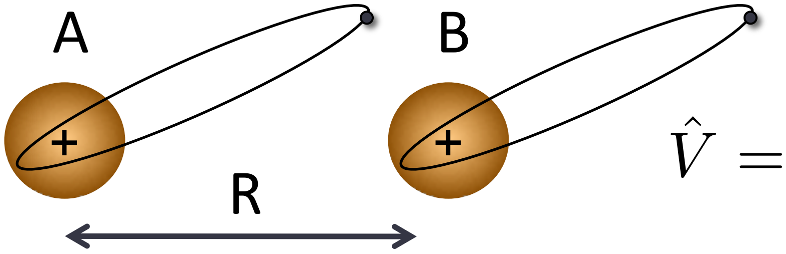


$F = F_{res}$ (35mV/cm)

« Förster resonance »

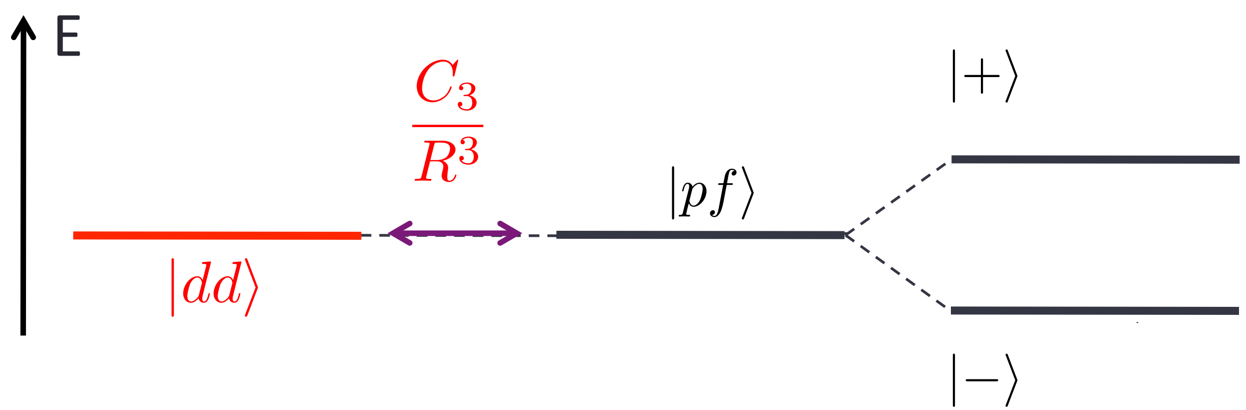
See Gallagher, Pillet, Saffman, Pfau…

Tuning two atoms to resonance



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

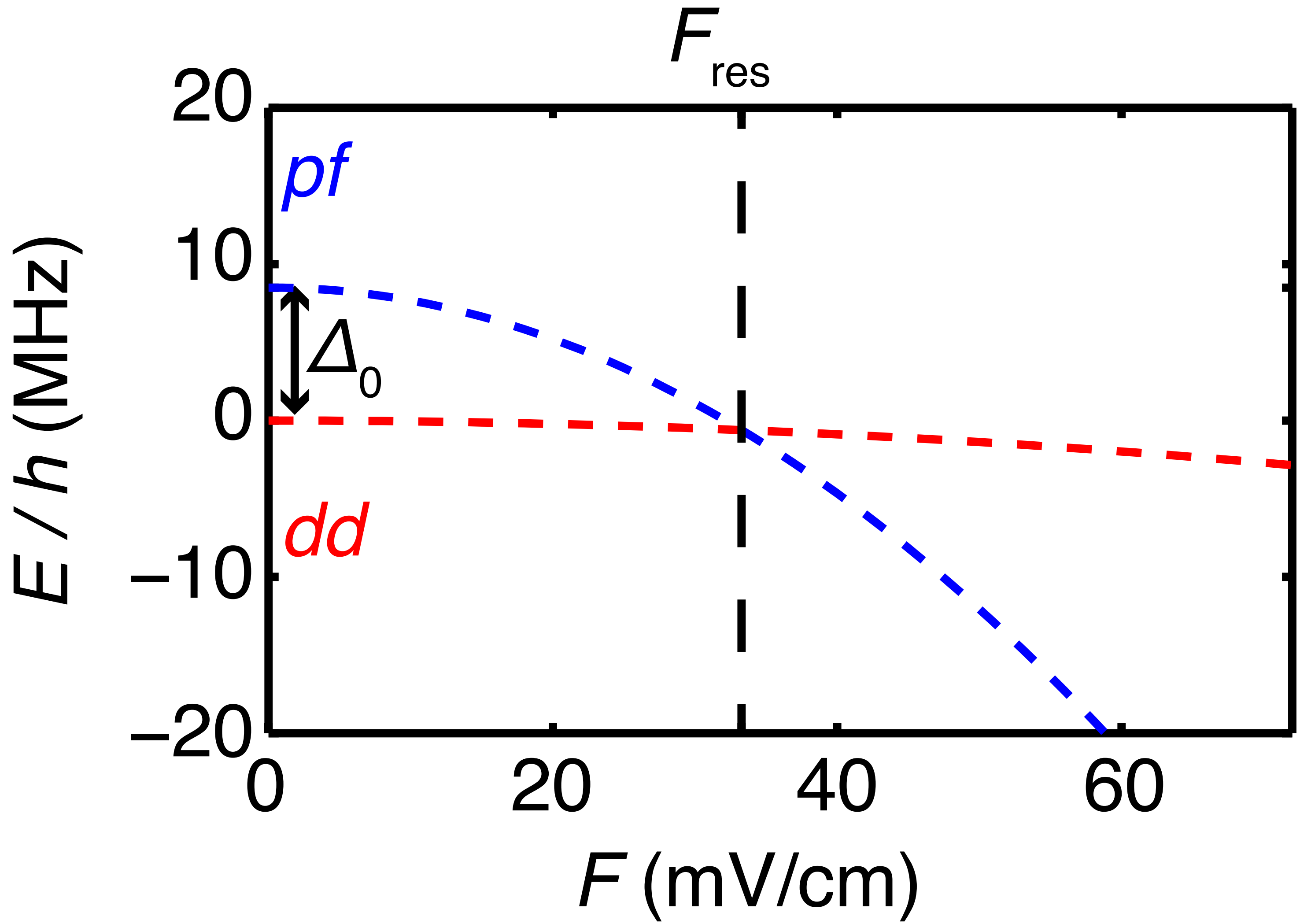
2-atom basis: $\{|\phi_{nn'}\rangle = |n,l\rangle \otimes |n',l'\rangle\}$



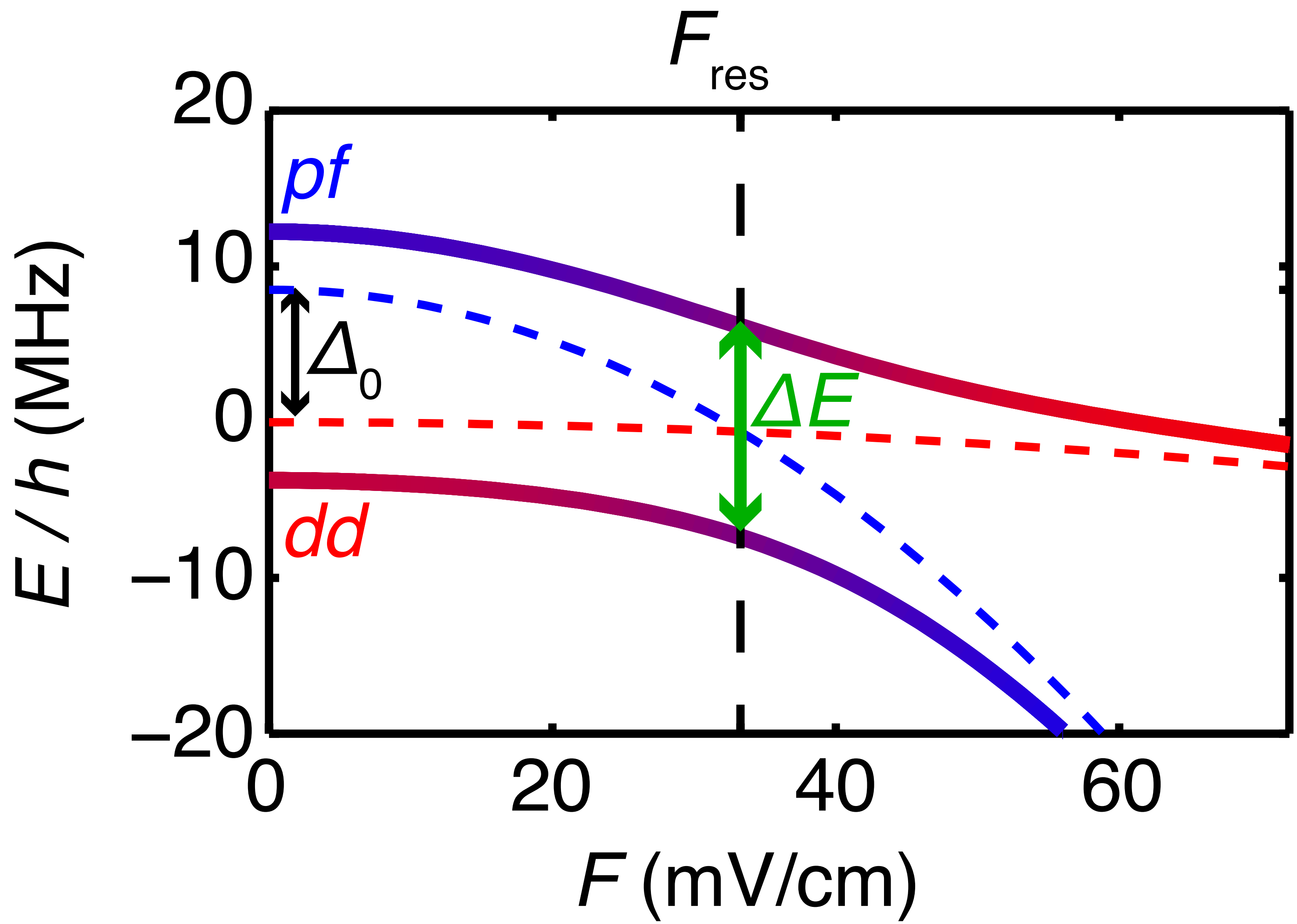
$$\Delta E_{\pm} \simeq \pm \frac{C_3}{R^3}$$

Förster resonance between two atoms

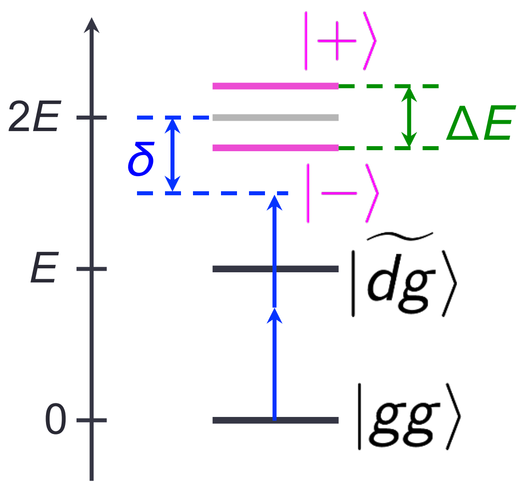
- Stark-shift of the levels in the absence of coupling:

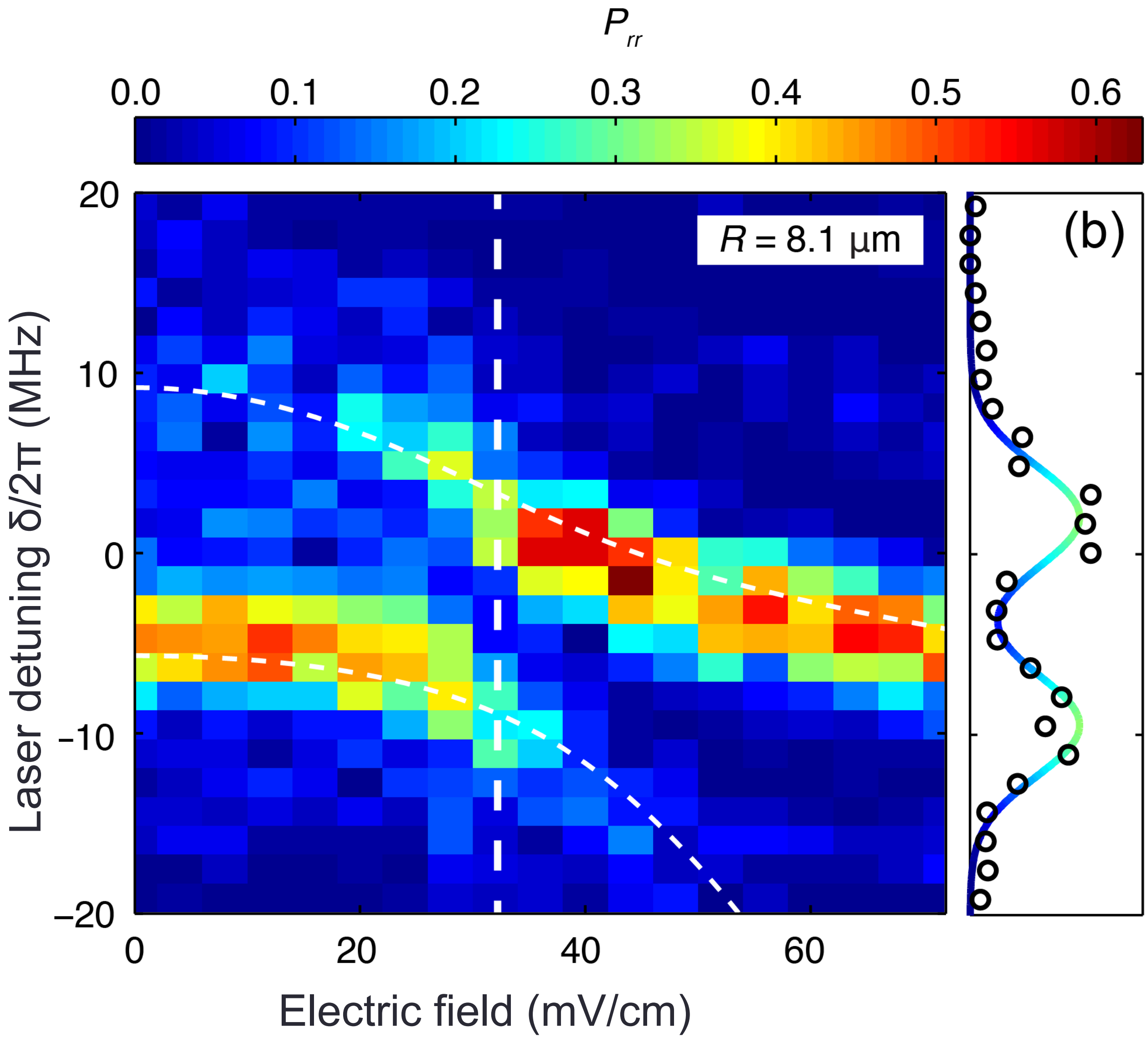


Förster resonance between two atoms



Spectroscopy of the interacting system



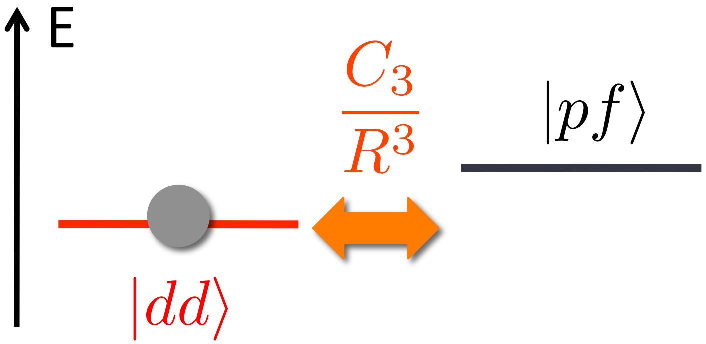


Ravets, *et al.* arXiv:1405.7804

Coherence at a Förster Resonance

Measuring the Förster oscillation between two atoms

Coherent oscillation at resonance



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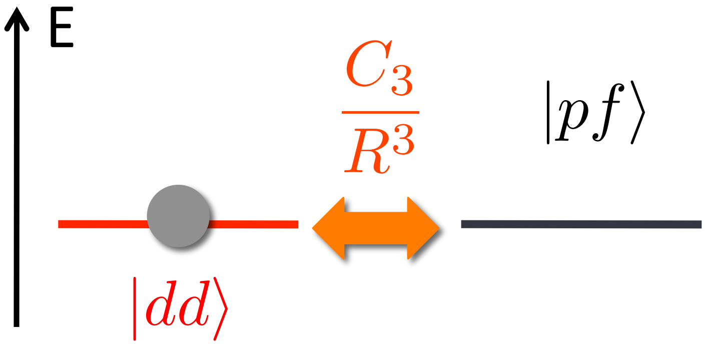
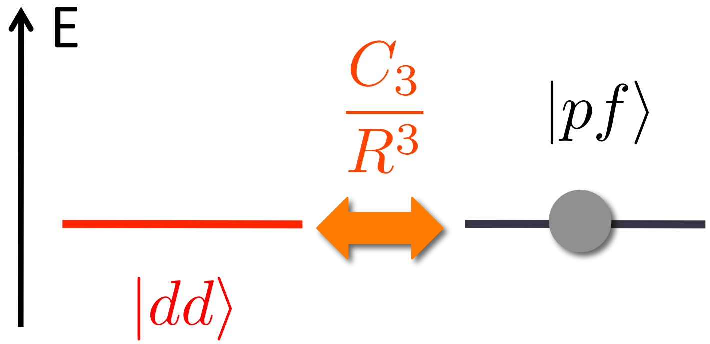
Coherent oscillation at resonance



Expect: $P_{dd} = \cos^2 \frac{C_3}{R^3} \frac{t}{\hbar}$

Ravets, *et al.* arXiv:1405.7804

Coherent oscillation at resonance



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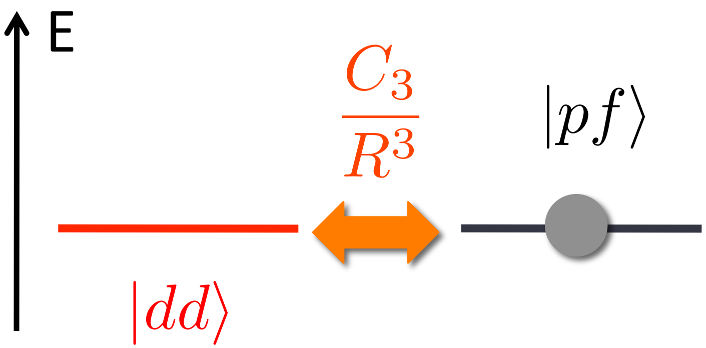
Coherent oscillation at resonance



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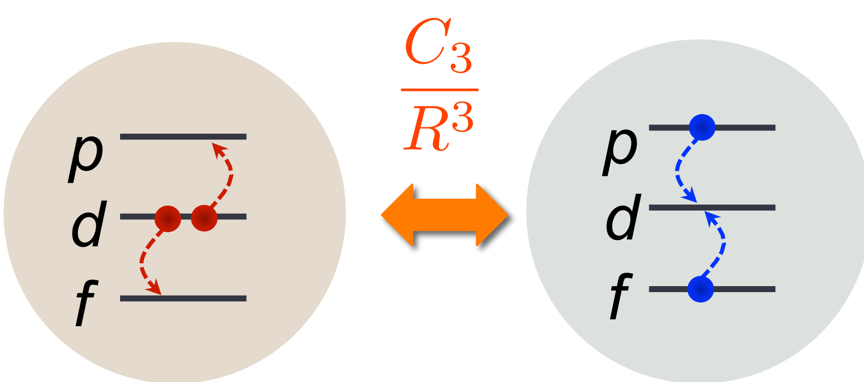

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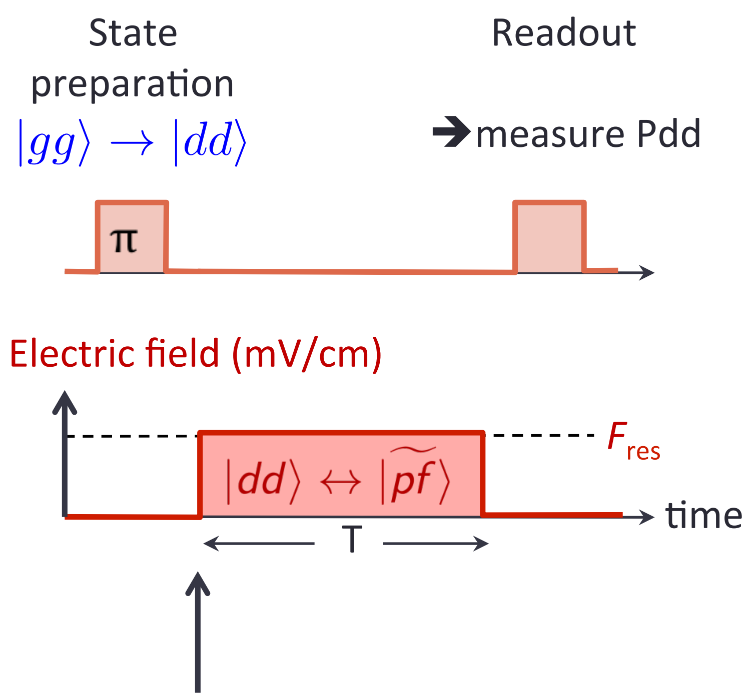
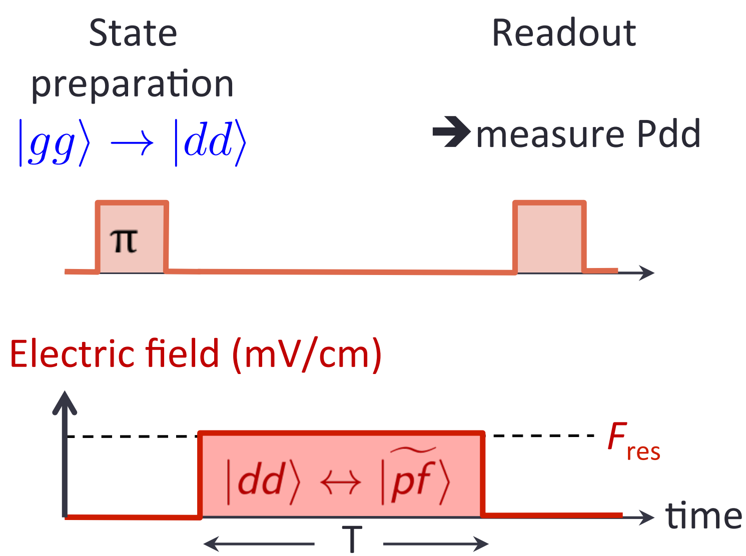
Observation of Forster oscillations

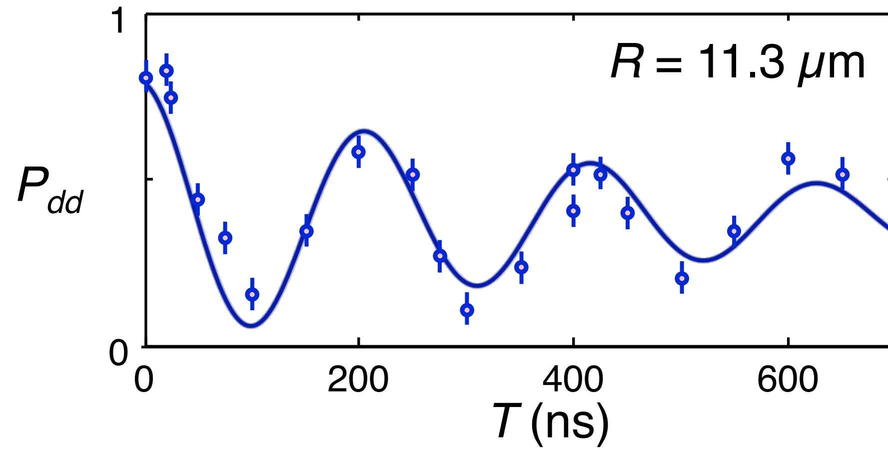


Switch on the interaction

Ravets, *et al.*, arXiv:1405.7804

Observation of Forster oscillations

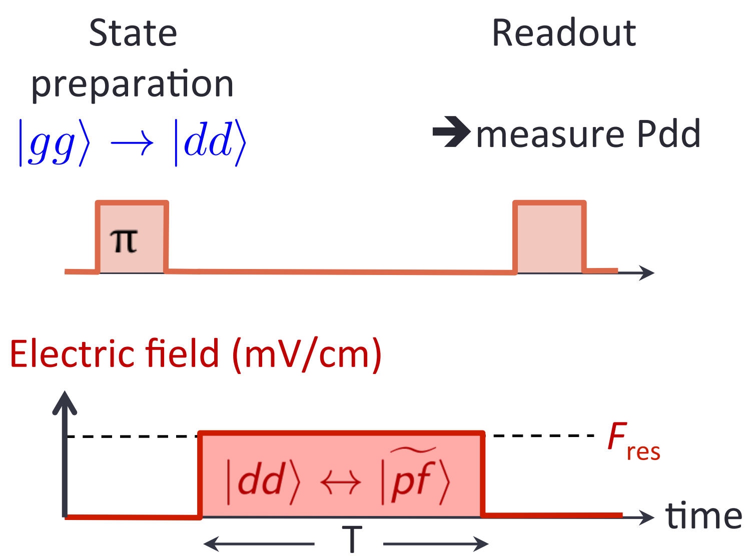


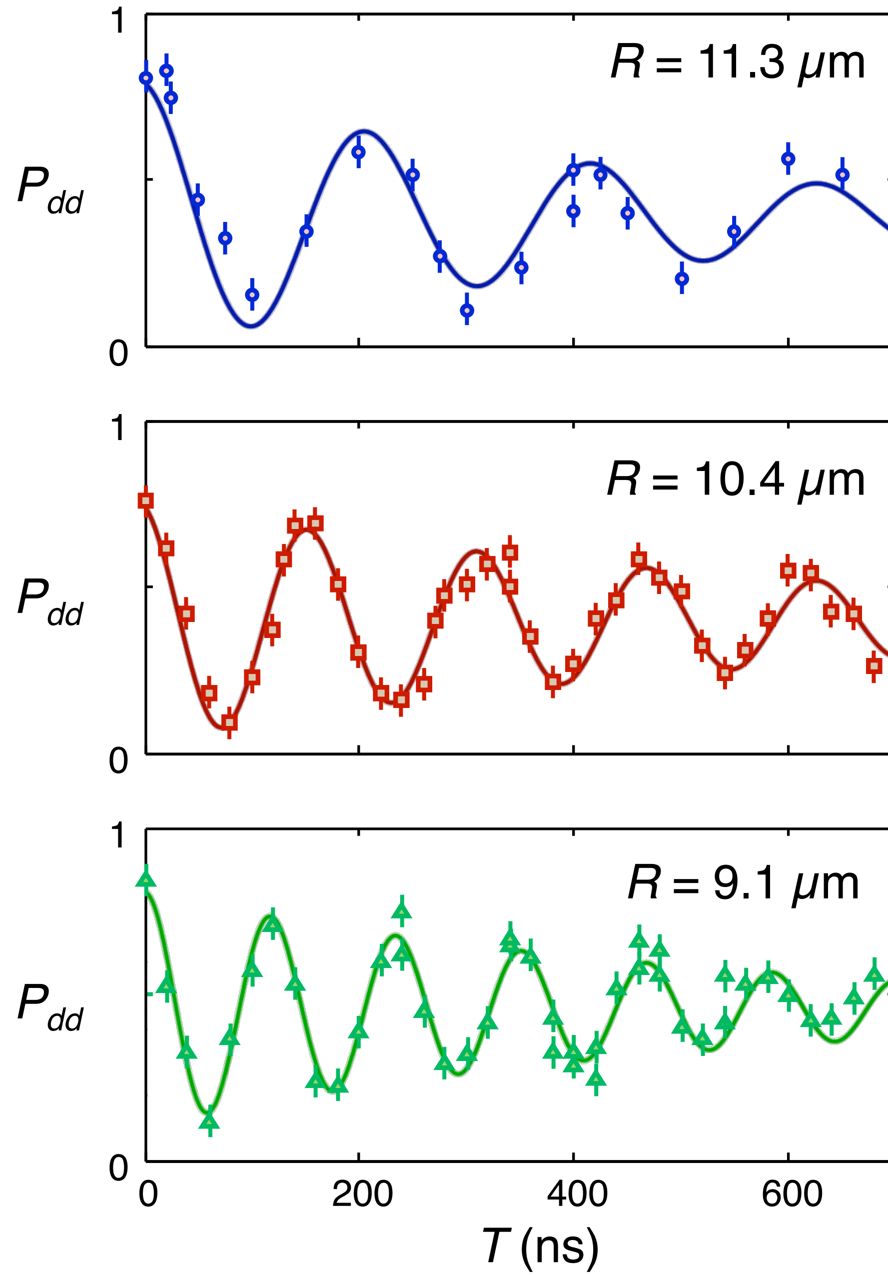


~10 MHz interaction for atoms separated by ~10 μm

Ravets, *et al.*, arXiv:1405.7804

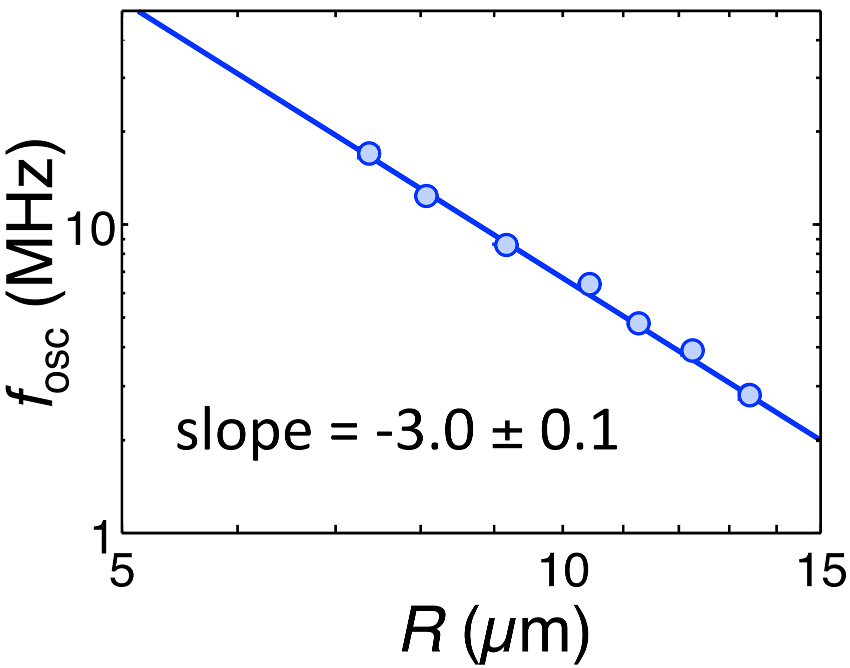
Observation of Forster oscillations

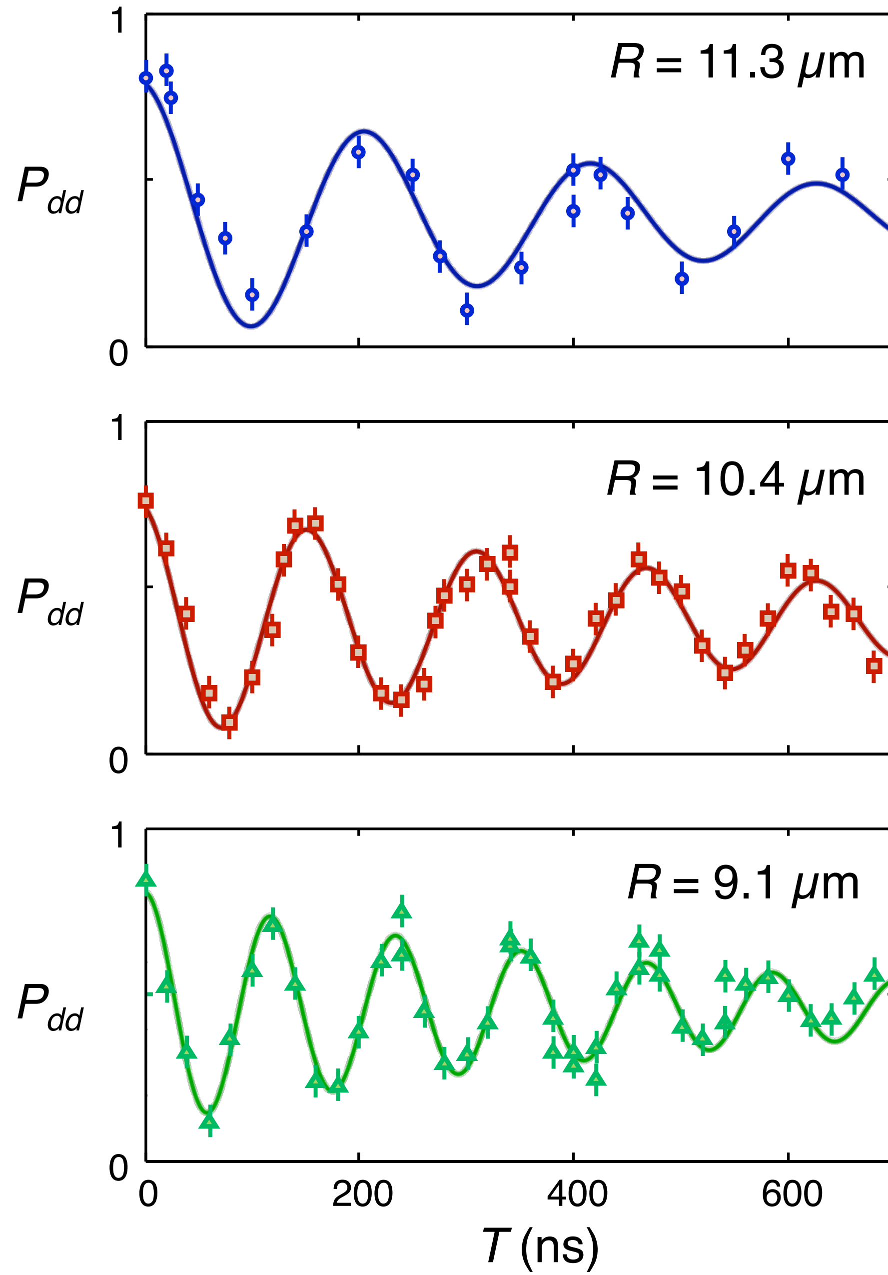




Ravets, *et al.*, arXiv:1405.7804

Measurement of the interaction energy





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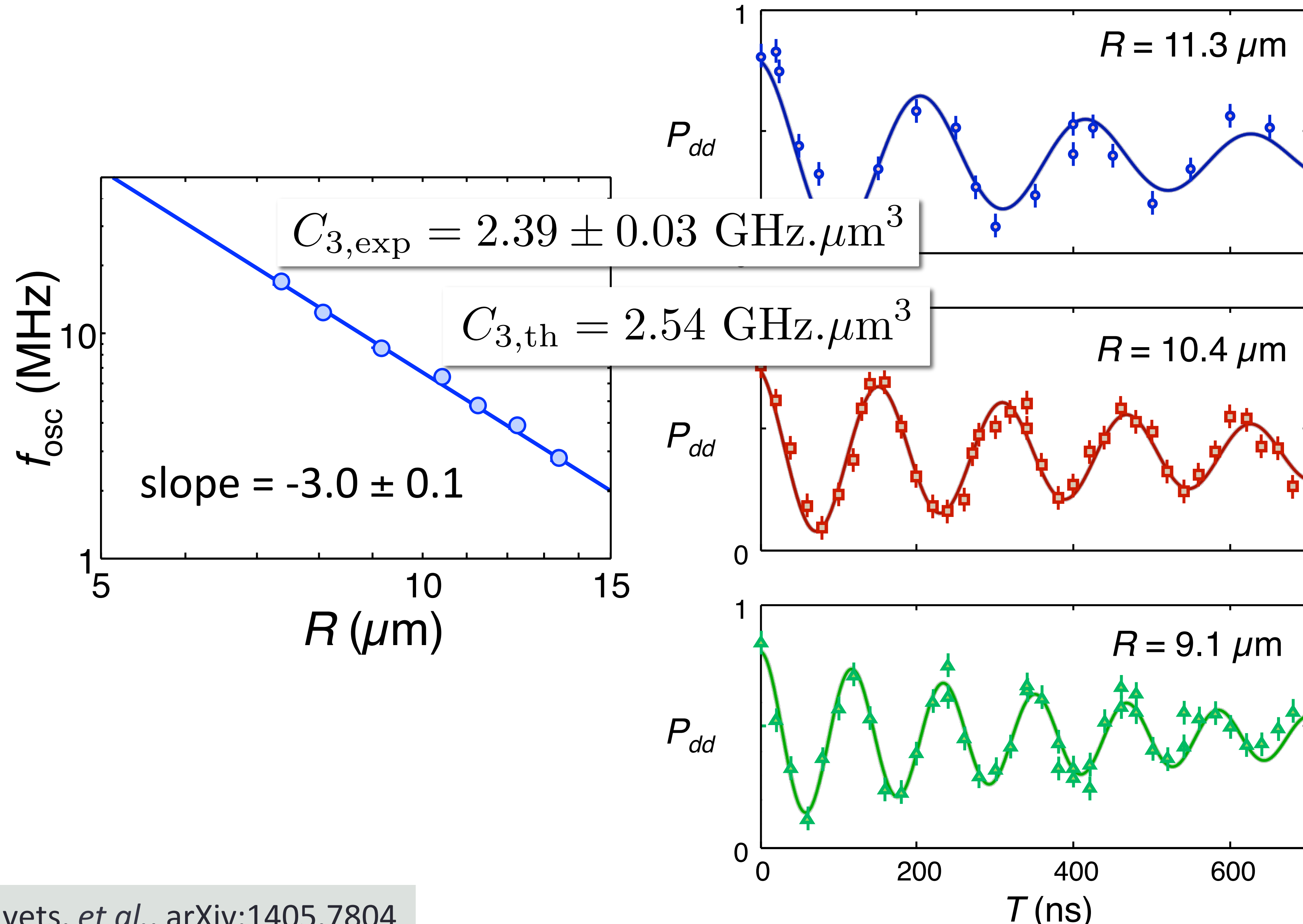


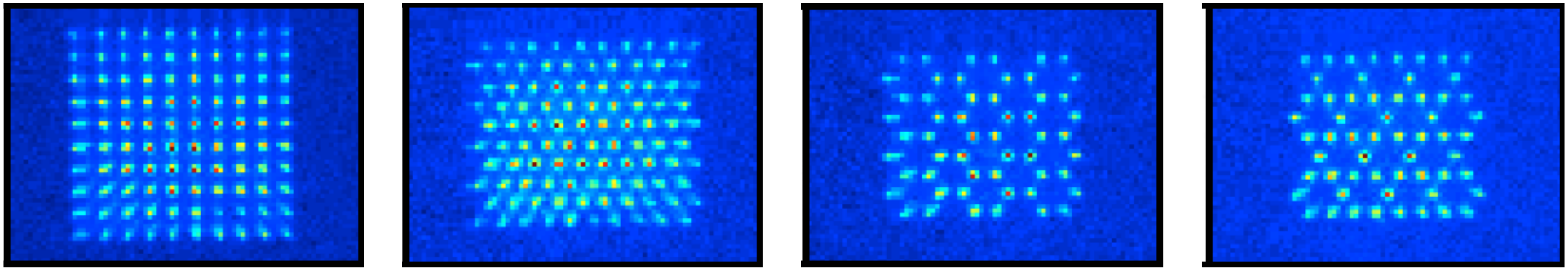
$$C_{3,\mathrm{exp}} = 2.39 \pm 0.03 \ \mathrm{GHz}.\mu\mathrm{m}^3$$

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

Ravets, *et al.*, arXiv:1405.7804

Outlook

- Larger arrays ~ 50 atoms



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

- Quantum simulation of spin Hamiltonians, coherent energy transfer… in many-body systems.