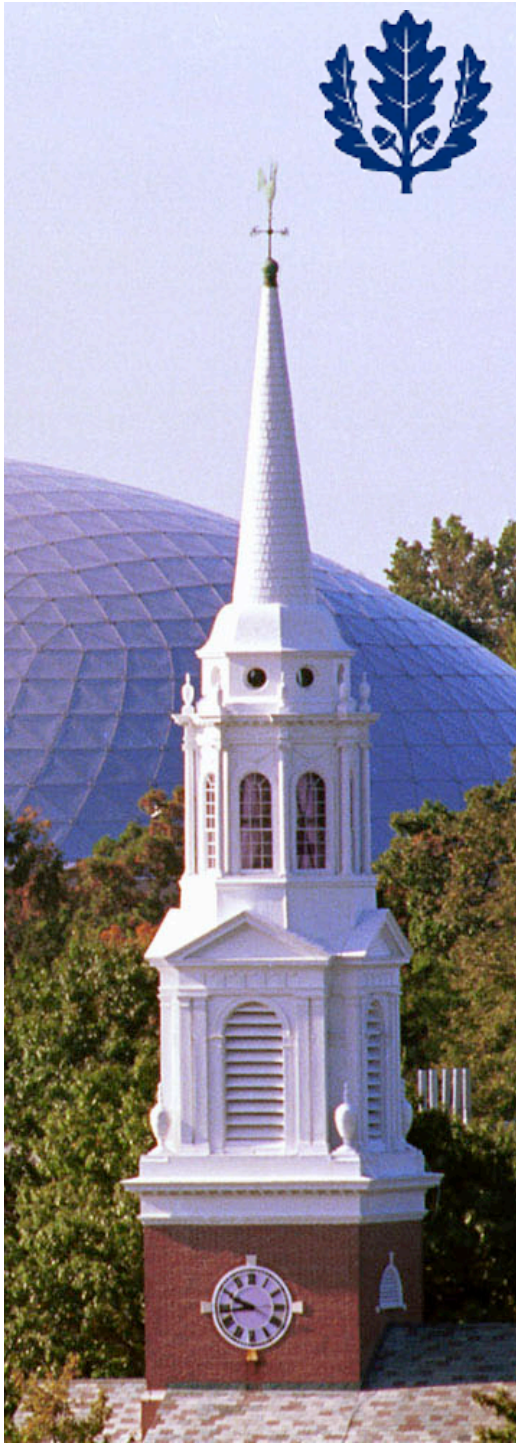


University of Connecticut

Aspen Center for PHYSICS

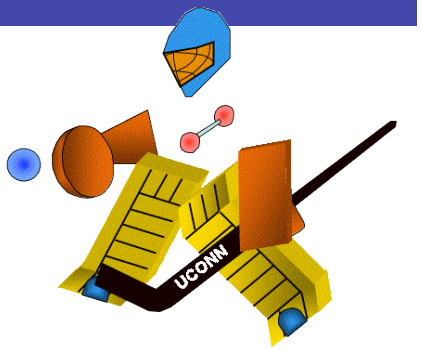
Workshop on
Quantum Simulation/Computation
with Cold Atoms and Molecules

AMO Tutorial 2: cold atoms

by Robin Côté

Aspen, Wednesday June 3 2009

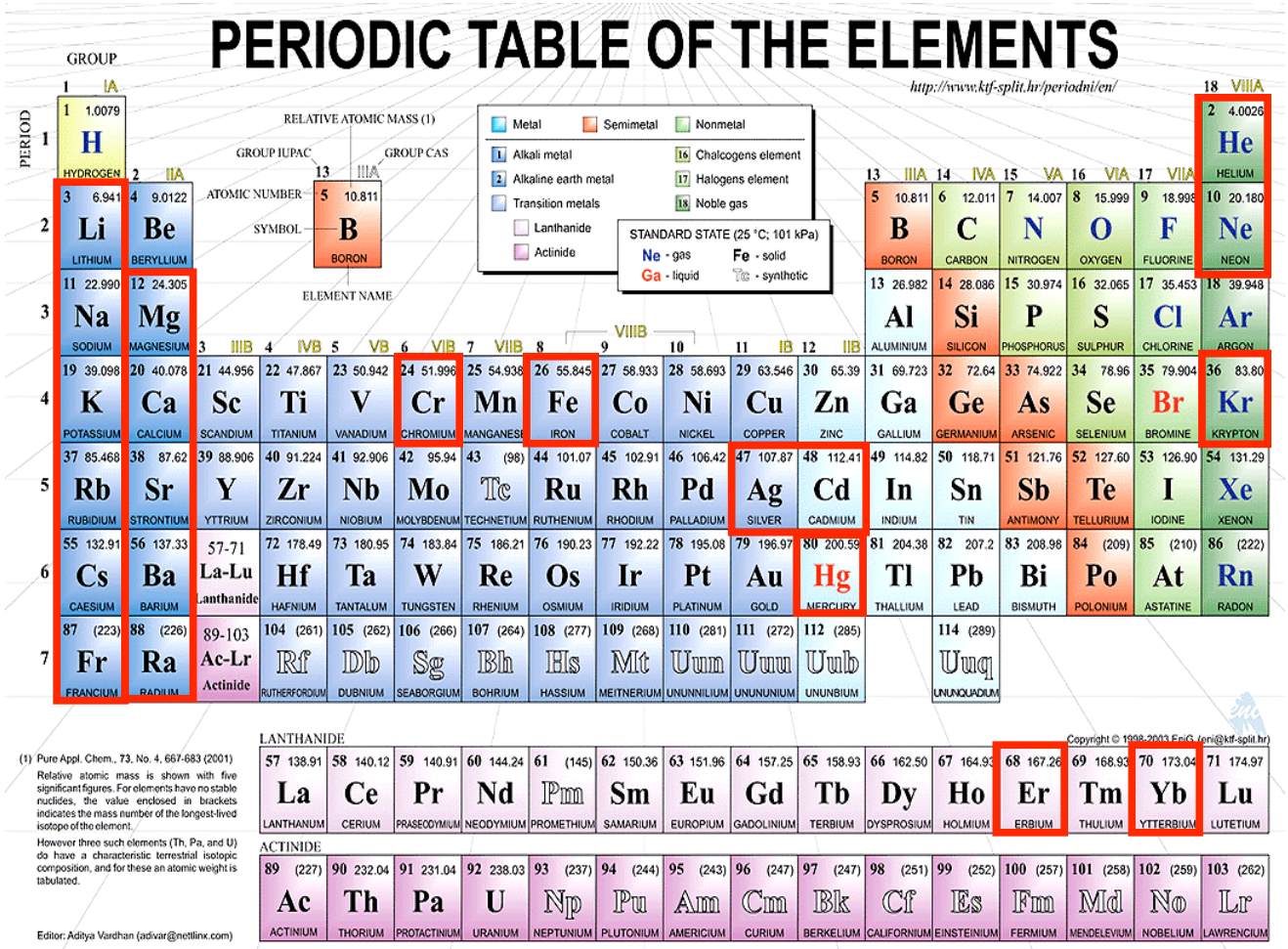
Outline



- Introduction/motivation
  - Property wish list
- Overview of AMO platforms
- Trapped ion / atom-ion systems
- **Cold atoms**
  - **Rydberg atoms**
- Cold molecules
- Other applications
- Concluding remarks

Cold Atoms

- The list is growing



-2-level cycling transitions

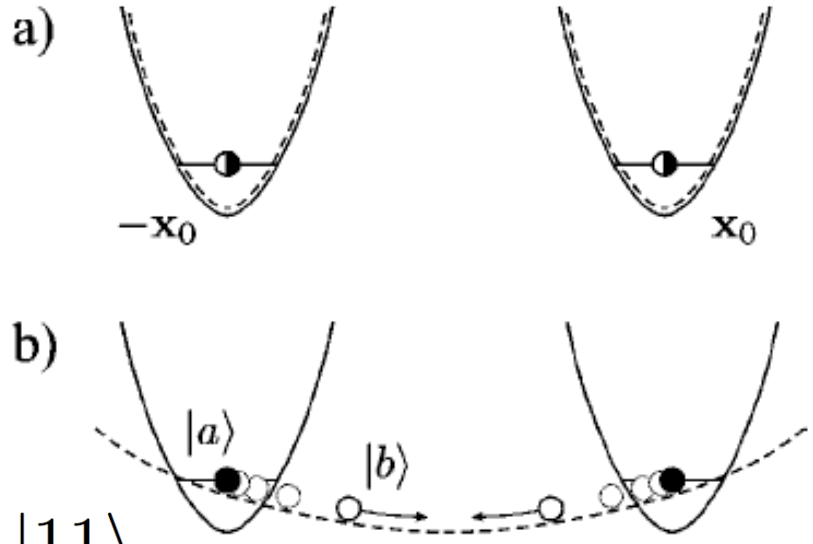
-available transitions

Quantum computer wish list

- Stable trapping/storage
- Addressable qubits
- Gates between (separated) qubits
- Long coherence-, short interaction-times
- Scalability
- Strong, switchable interaction
- Readout/initialization

Collisional gate

- Phase gate
  - Each site initially in super-position of $|0\rangle$ and $|1\rangle$



$$|A\rangle \sim |0\rangle_A + |1\rangle_A$$
$$|B\rangle \sim |0\rangle_B + |1\rangle_B$$
$$|Q\rangle \sim |00\rangle + |01\rangle + |10\rangle + |11\rangle$$

- Change the trap for state $|1\rangle$
  - Collision induce a phase

$$|Q\rangle \sim |00\rangle + |01\rangle + |10\rangle + e^{i\phi}|11\rangle$$

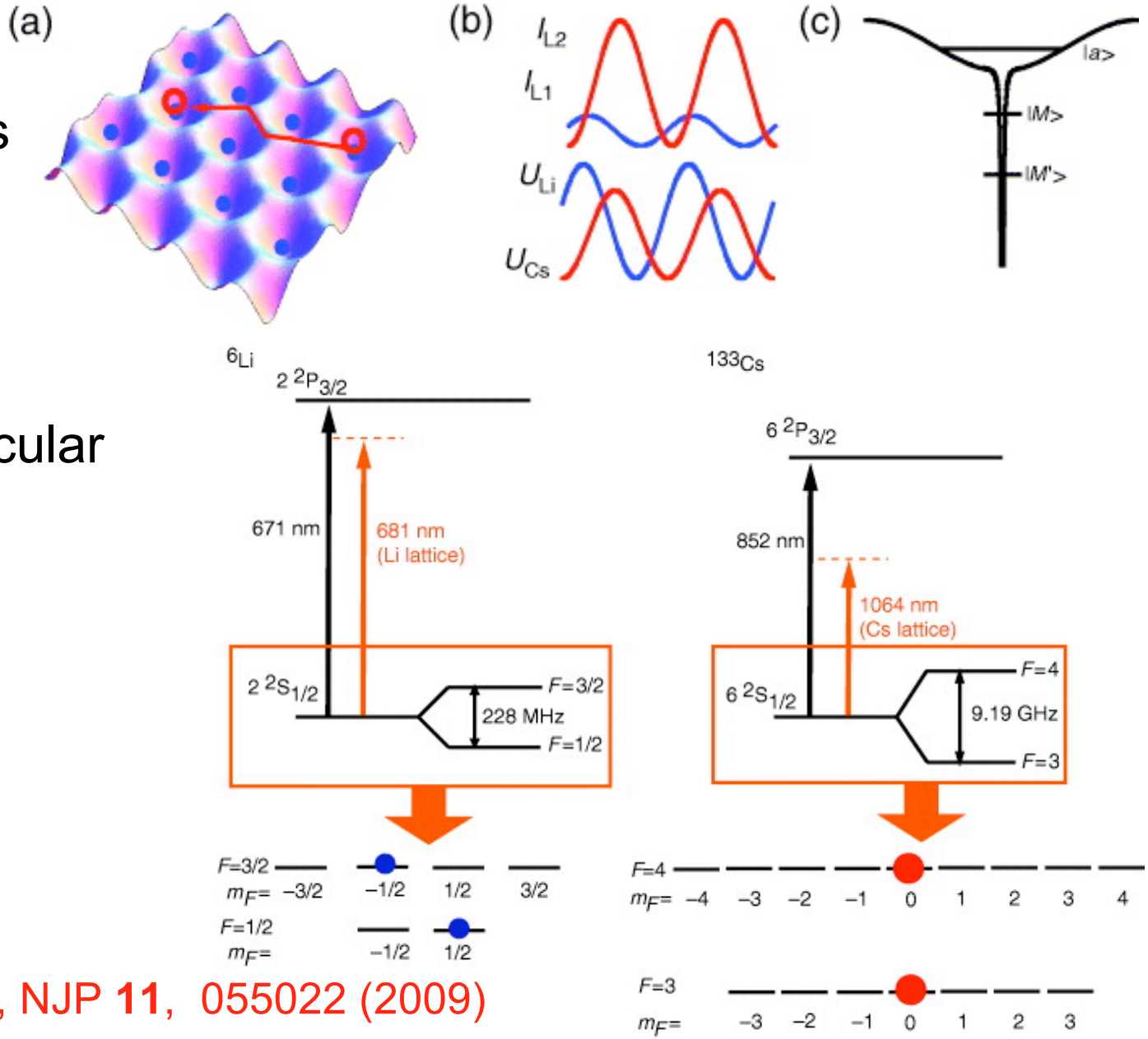
- $\phi = \pi$: phase gate

$$|Q\rangle \sim |00\rangle + |01\rangle + |10\rangle - |11\rangle$$

Cirac-Zoller, PRA 61, 022304 (2000)

Using a mixture

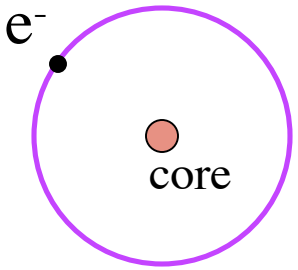
- C. Chin
  - ^{6}Li and ^{133}Cs
- Not exactly collisional
  - Needs molecular states



C. Chin & co-workers, NJP **11**, 055022 (2009)

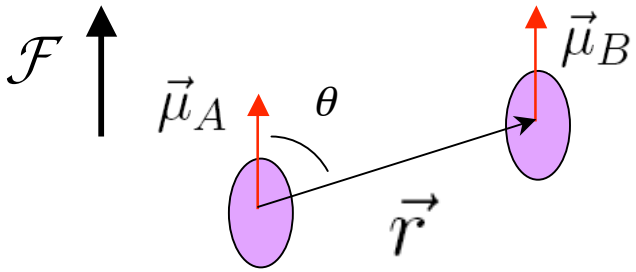
Rydberg Atoms

- Alkali atoms are good candidates to encode qubits:
  - Measurement high quantum efficiency: e.g., cycling transition.
  - Easy cooling and trapping
  - Low decoherence times.



- Rydberg atoms resemble hydrogen atom:
  - Radius and dipole moment scale as n^2
  - Energy $\propto 1/(n-\delta_{n,\ell})^2$, quantum defect $\delta_{n,\ell}$
- Long lifetimes $\propto n^3$. *50p*, τ=238 μs (τ =.02 μs for *5p*)
- Large polarizability $\propto n^7$: Stark mixing other ℓ by electric fields $\mathcal{F}$

$$|\,49p\,\rangle = \alpha\,|\,49p\rangle + \beta\,|\,49s\rangle + \ldots \text{ with } \beta = 0.11\,\mathcal{F} \Rightarrow \tilde{\mu}_{pp} = 2\alpha\,\beta\,\mu_{sp}$$



$$V_{d-d} = \frac{\vec{\mu}_A \cdot \vec{\mu}_B}{r^3} - 3\frac{(\vec{r}\cdot\vec{\mu}_A)(\vec{r}\cdot\vec{\mu}_B)}{r^5}$$

Long-range wells

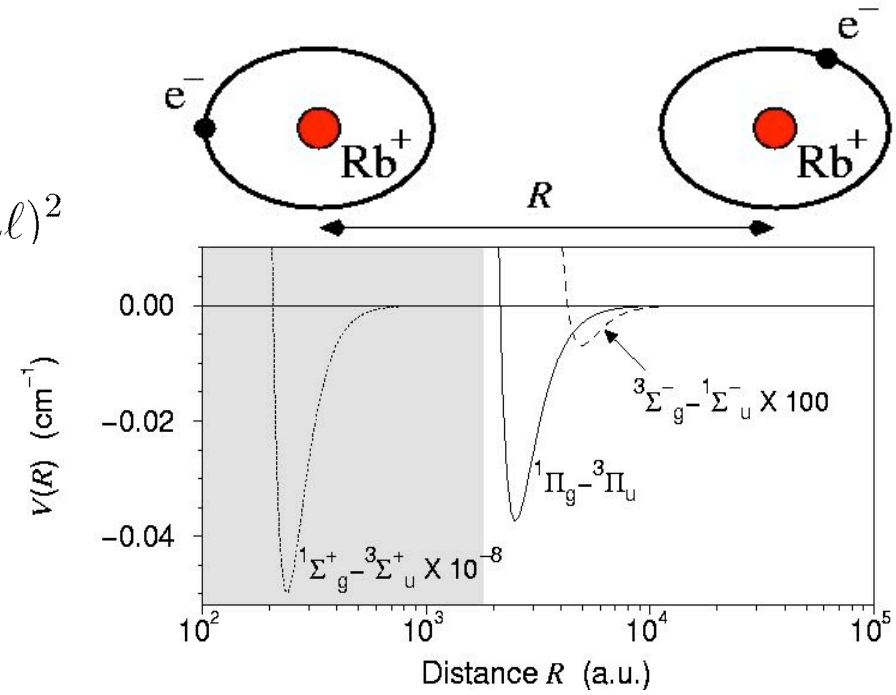
- Higher dispersion terms
  - *np+ns* or *np+nd* :

$$V(R) = \frac{C_3}{R^3} \quad \text{with} \quad C_3 = A(np|r|n\ell)^2$$

  - *np+np* :

$$V(R) = -\frac{C_5}{R^5} - \frac{C_6}{R^6} - \frac{C_8}{R^8}$$

$$C_3 \propto n^4 \ , \ C_5 \propto n^8$$
$$C_6 \propto n^{11} \ , \ C_8 \propto n^{15}$$



- Combination of coefficients can lead to long-range wells
  - "stable" if electron wave functions do not overlap (non-shaded region)
  - very extended molecules (few μm or more) : macrodimers
  - shallow wells can exist only in ultracold regime
    - n=70: D_e~300 kHz and R_e~100,000 a_0 (100 levels spaced by a few kHz)

C. Boisseau, I. Simbotin, & R. Côté, PRL **88**, 133004 (2002)

Mixed states

- When $\left|\frac{C_6}{R^6}\right| \sim \Delta E$, need to include couplings between states splitted by ΔE at $R \to \infty$

- Simple treatment with *np*+*np* and *ns*+*n'*s asymptotes
  - E.g., atomic states for *70p*+*70p* and *70s*+*71s mix*
  - Asymptotic form of electronic wave functions of atom pairs

    $|pp(1)\rangle$, $|pp(2)\rangle$ and $|ss'\rangle$ contain dipole-dipole terms
  - Need to diagonalize interactions (with correct symmetries and dipole moments)

$$\begin{pmatrix} 0 & 0 & AR^{-3} \\ 0 & 0 & BR^{-3} \\ AR^{-3} & BR^{-3} & \Delta E \end{pmatrix}$$

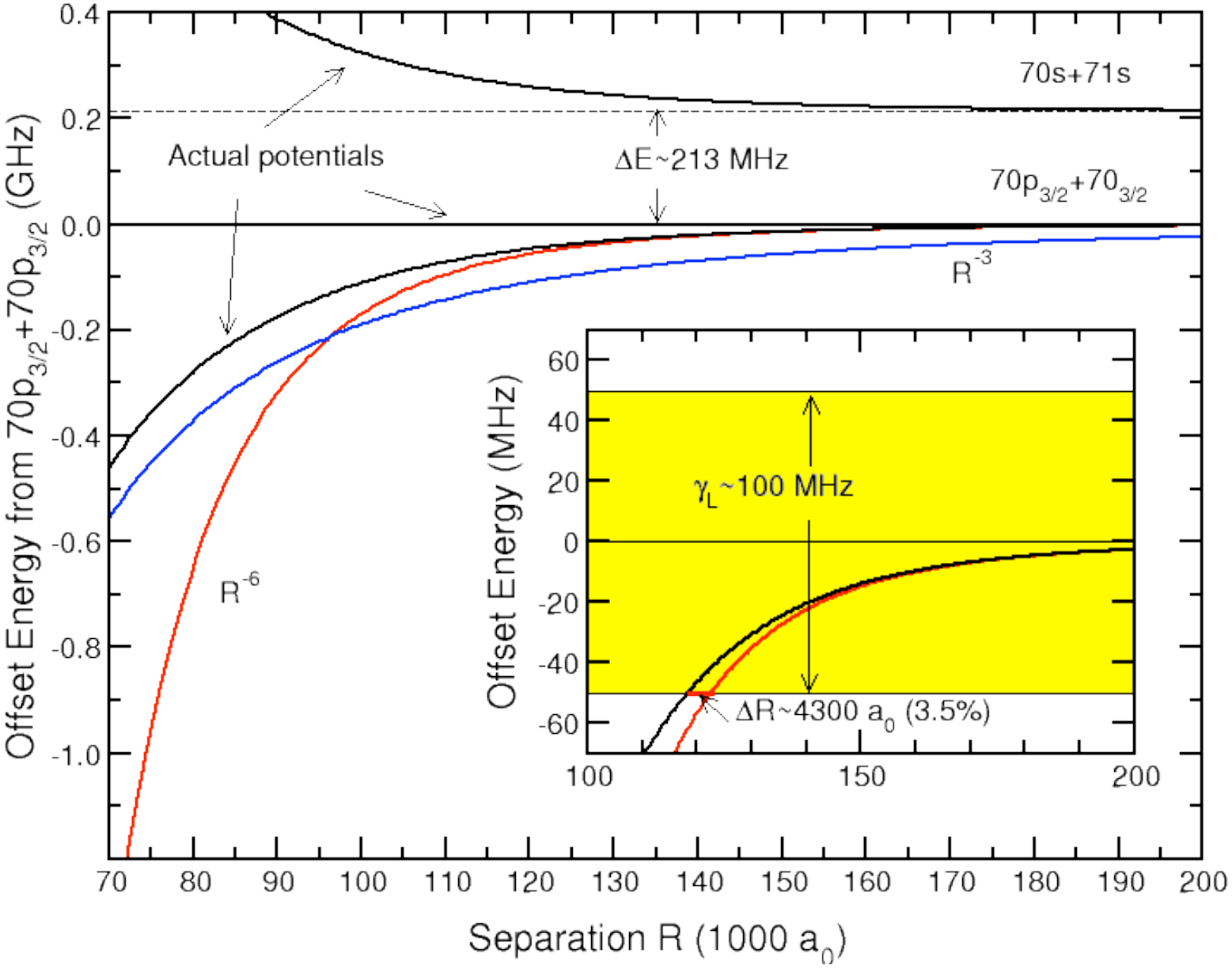
$$A = \frac{2}{3}\mu_{ps}\mu_{ps'}$$

$$B = \frac{4}{3\sqrt{2}}\mu_{ps}\mu_{ps'}$$

$$\Delta E \sim 213 \text{ MHz}$$

K. Singer, J. Stanojevic, M. Weidemüller, and R. Côté, J. Phys. B **38**, S295 (2005).

Coupled potential curves



Application: Phase Gate

- "Simple" phase control gate
  - use atoms in an optical lattice
  - state prepared by Raman pulses

$$|A\rangle = \frac{1}{\sqrt{2}}\{\,|0\rangle + |1\rangle\,\}$$

$$|B\rangle = \frac{1}{\sqrt{2}}\{\,|0\rangle + |1\rangle\,\}$$

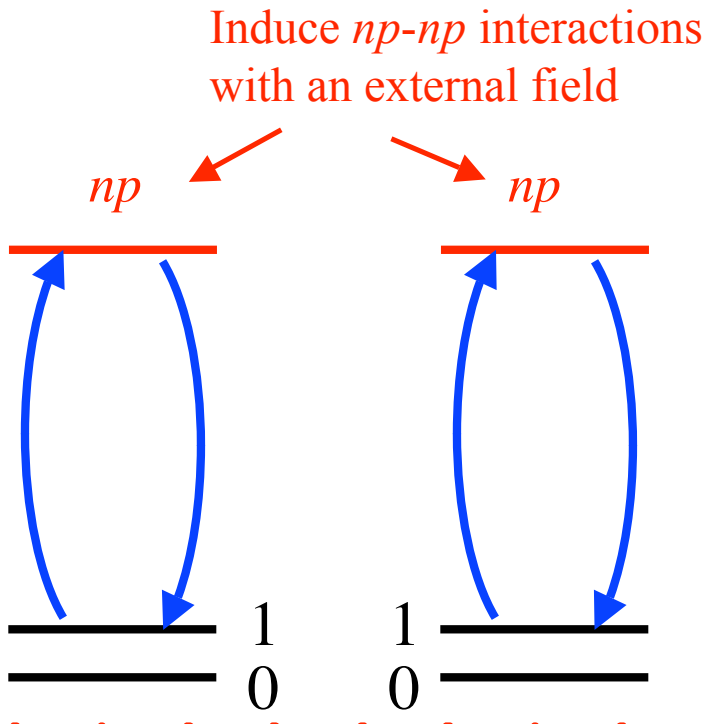
- Two-qubit state

$$|Q\rangle \neq |A\rangle \otimes |B\rangle$$

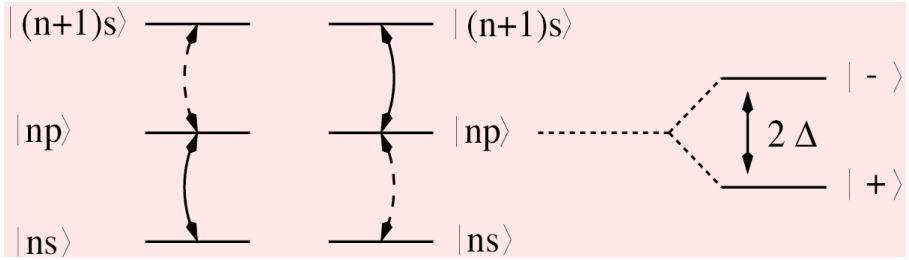
$$|Q\rangle = |00\rangle + |01\rangle + |10\rangle - |11\rangle$$

- Possible also with excitation blockade
  - strong dipole-dipole interactions
  - degenerate states split
  - laser pulse sequence gives a phase gate

D. Jaksch *et al.*, PRL **85**, 2208 (2000).

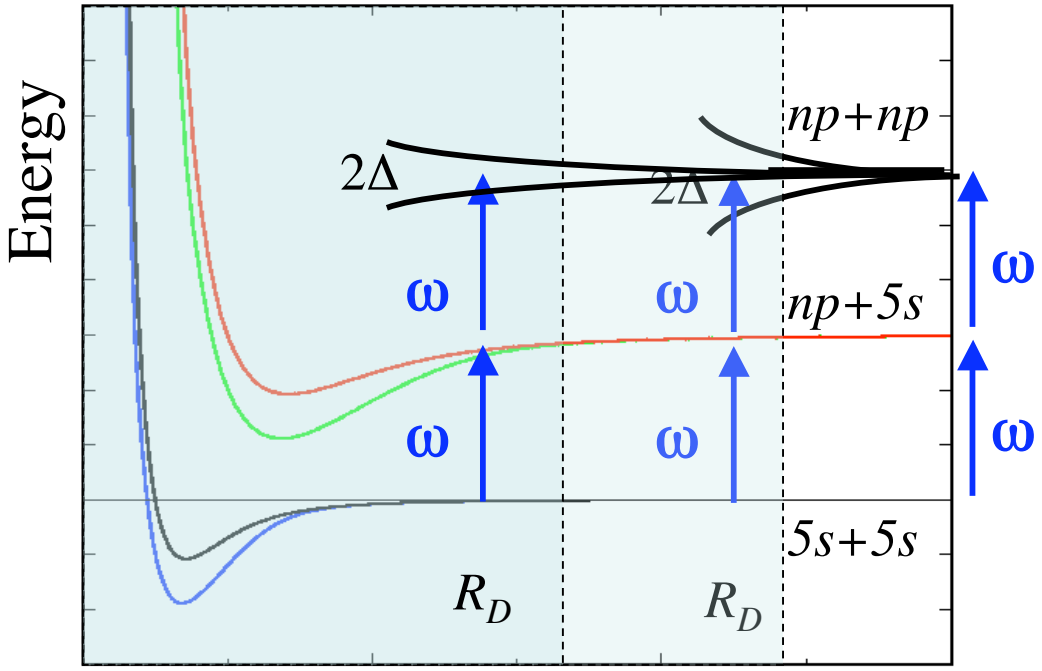


$\phi=\pi$ for $\tau=5.3\mu$sec
(n=50, R=25 μm, $\mathcal{F}$=3 V/cm)



Application: Excitation Blockade

- van der Waals $\propto n^{11}$
  - interactions shift the two-photon resonance
- Low n or densities
  - Weak interactions between Rydberg atoms
  - 2-photon resonance is shifted at "small" R
  - below R_D , excitation of 2 Rydberg atoms (or more) is prohibited
  - Isolated atom behavior

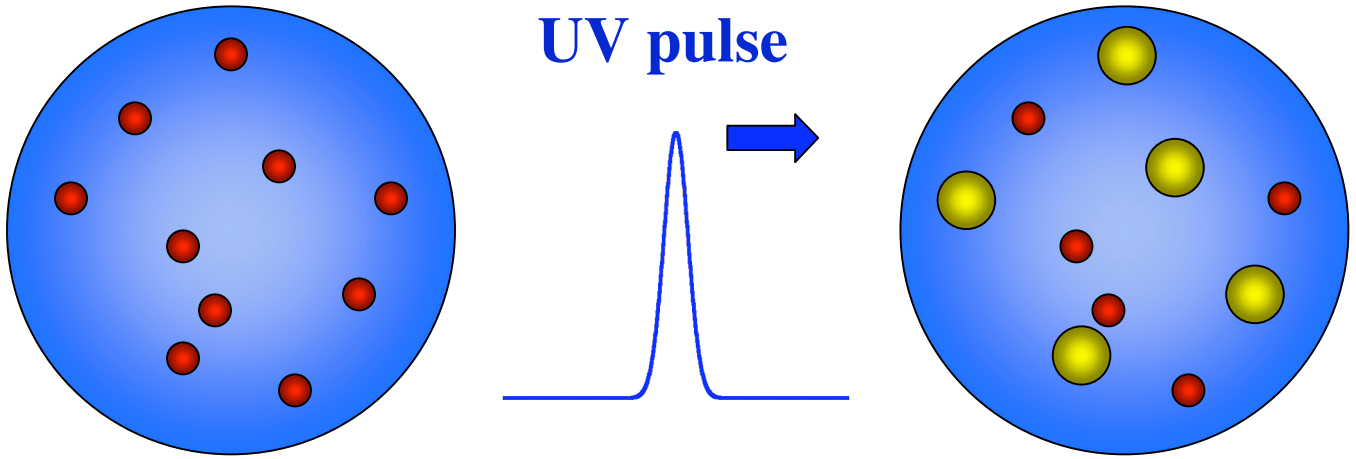


- large n or densities
  - strong molecular interactions
  - resonance shifted at large R
  - *Blockaded* behavior

A sketch

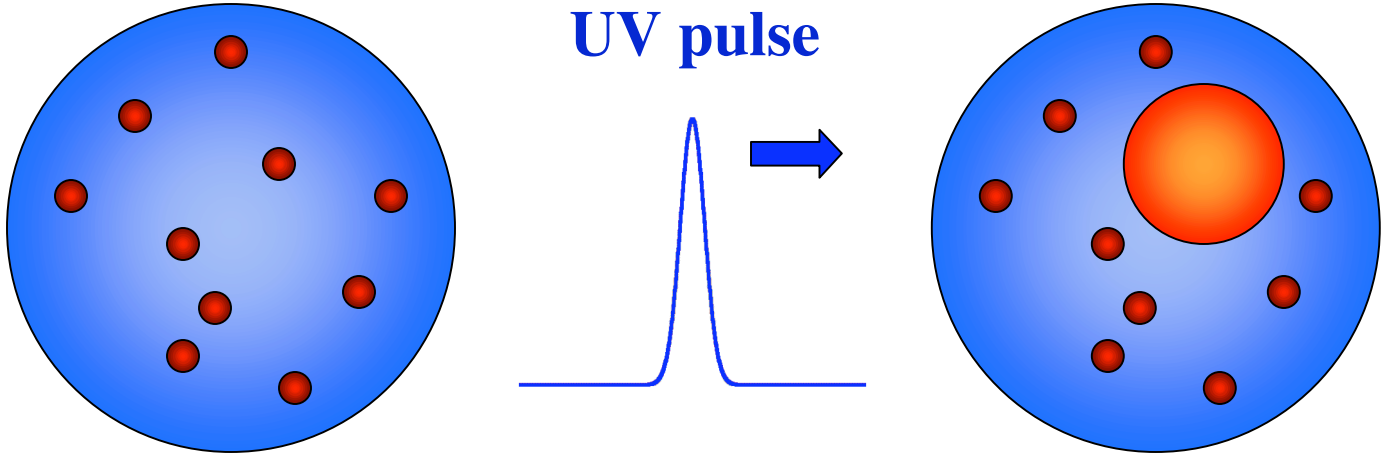
Isolated atom behavior

Weak interactions/low n



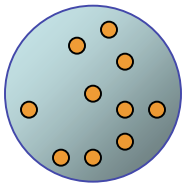
Blockaded atom behavior

Strong interactions/high n



Blockade & gates

- Ensemble of atoms
  - few μm in size
  - 10-100 atoms



- Collective states

  $|g\rangle$: All atoms in ground state.

  $|q^n\rangle$: Collective state of n-atoms in q.

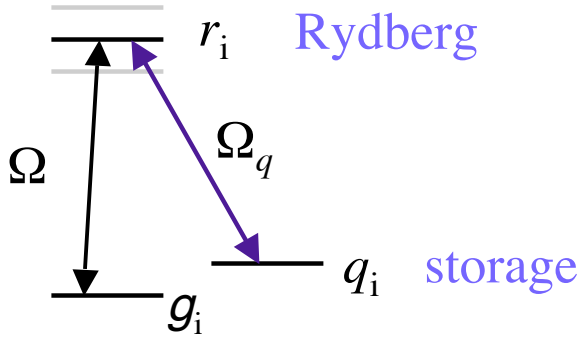
  $|r^1\rangle$: Only one excitation allowed in r.

- Prepare initial state

$$|g\rangle \overset{\Omega\sqrt{N}}{\rightarrow} |r^1\rangle \overset{\Omega_q}{\rightarrow} |q^1\rangle$$

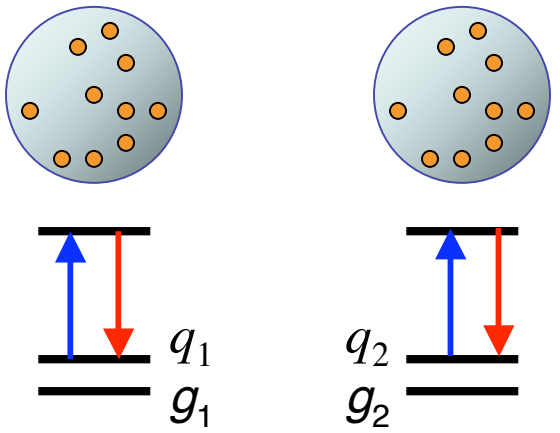
  - Based on conditional excitation
  - Ensemble behaves as a "super-atom"

- Single-atom levels:



- Phase gate

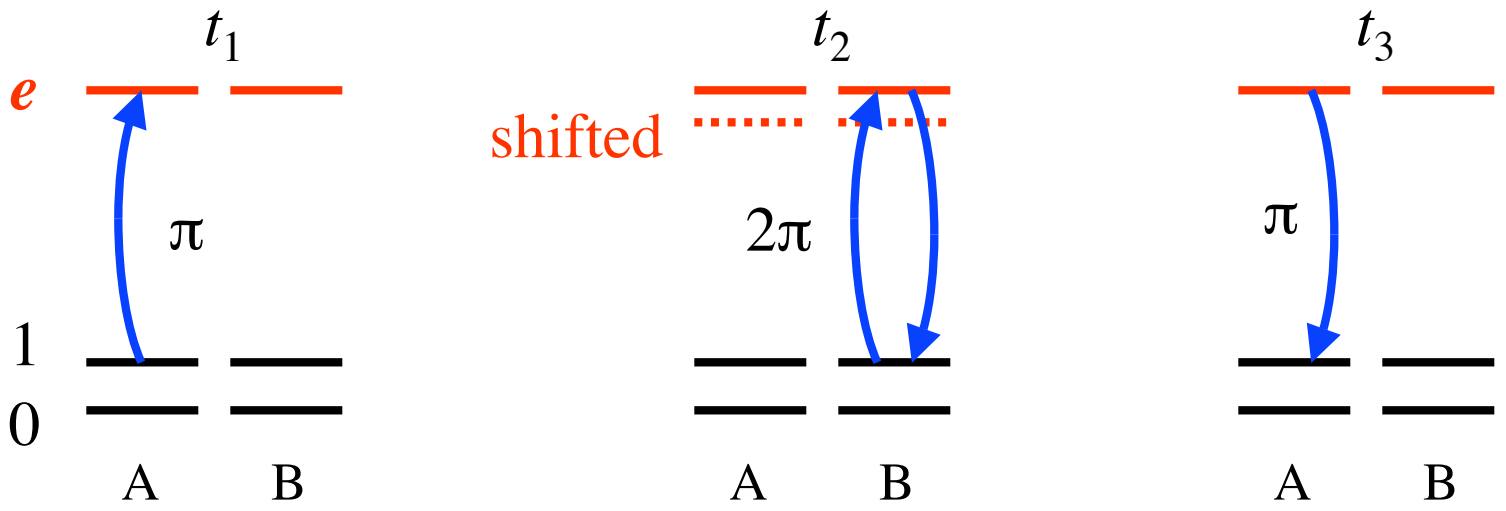
$$|g_1g_2\rangle \rightarrow |g_1g_2\rangle \quad |g_1q_2\rangle \rightarrow |g_1q_2\rangle$$
$$|q_1g_2\rangle \rightarrow |q_1g_2\rangle \quad |q_1q_2\rangle \rightarrow -|q_1q_2\rangle$$



M.D. Lukin, M. Fleischhauer, R. Côté, L.M. Duan, D. Jaksch, J.I. Cirac, and P. Zoller, PRL **87**, 037901 (2001)

Gate using Blockade

- If sites individually addressable and shift large



$$|Q_0\rangle = |00\rangle + |01\rangle + |10\rangle + |11\rangle$$

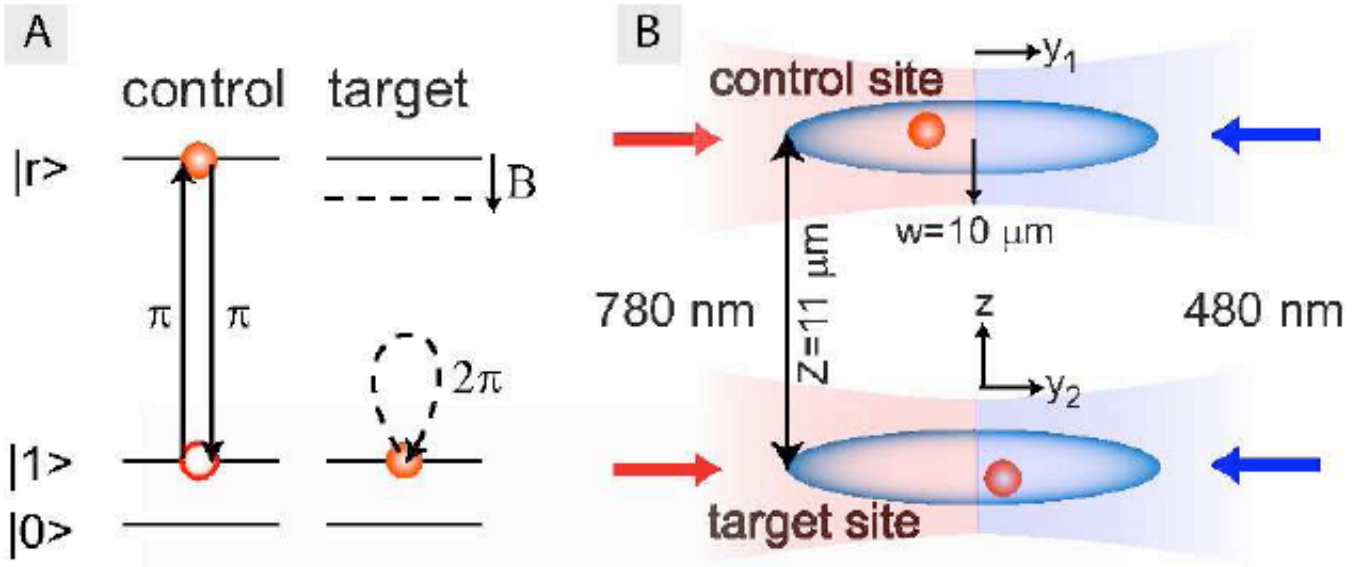
$$|Q_1\rangle = |00\rangle + |01\rangle + i|e0\rangle + i|e1\rangle$$

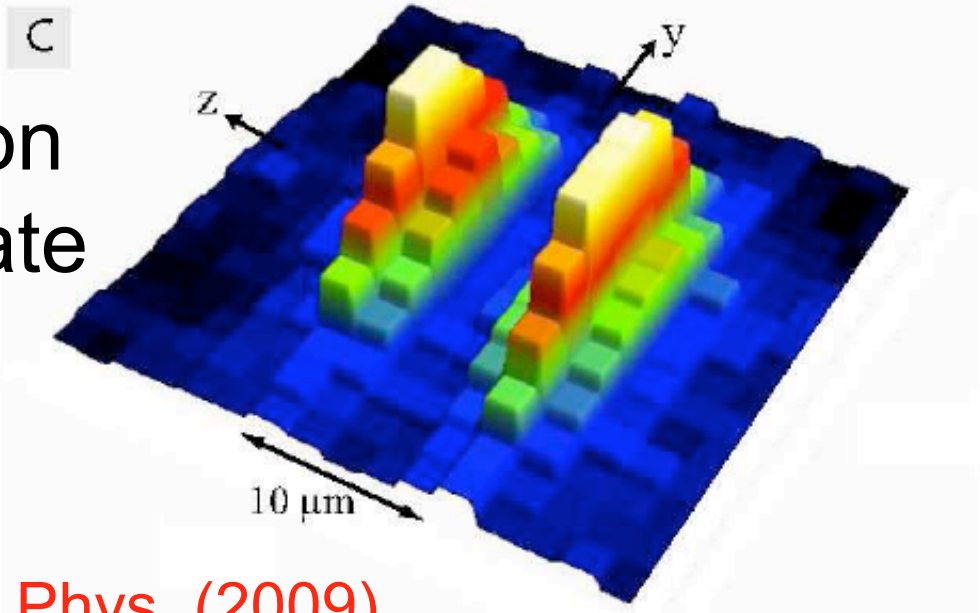
$$|Q_2\rangle = |00\rangle + i^2|01\rangle + i|e0\rangle + \boxed{i|e1\rangle} \leftarrow \text{blockaded}$$

$$|Q_3\rangle = |00\rangle + i^2|01\rangle + i^2|10\rangle + i^2|11\rangle$$
$$= |00\rangle - |01\rangle - |10\rangle - |11\rangle$$

D. Jaksch *et al.*, PRL **85**, 2208 (2000).

Observation with 2 atoms



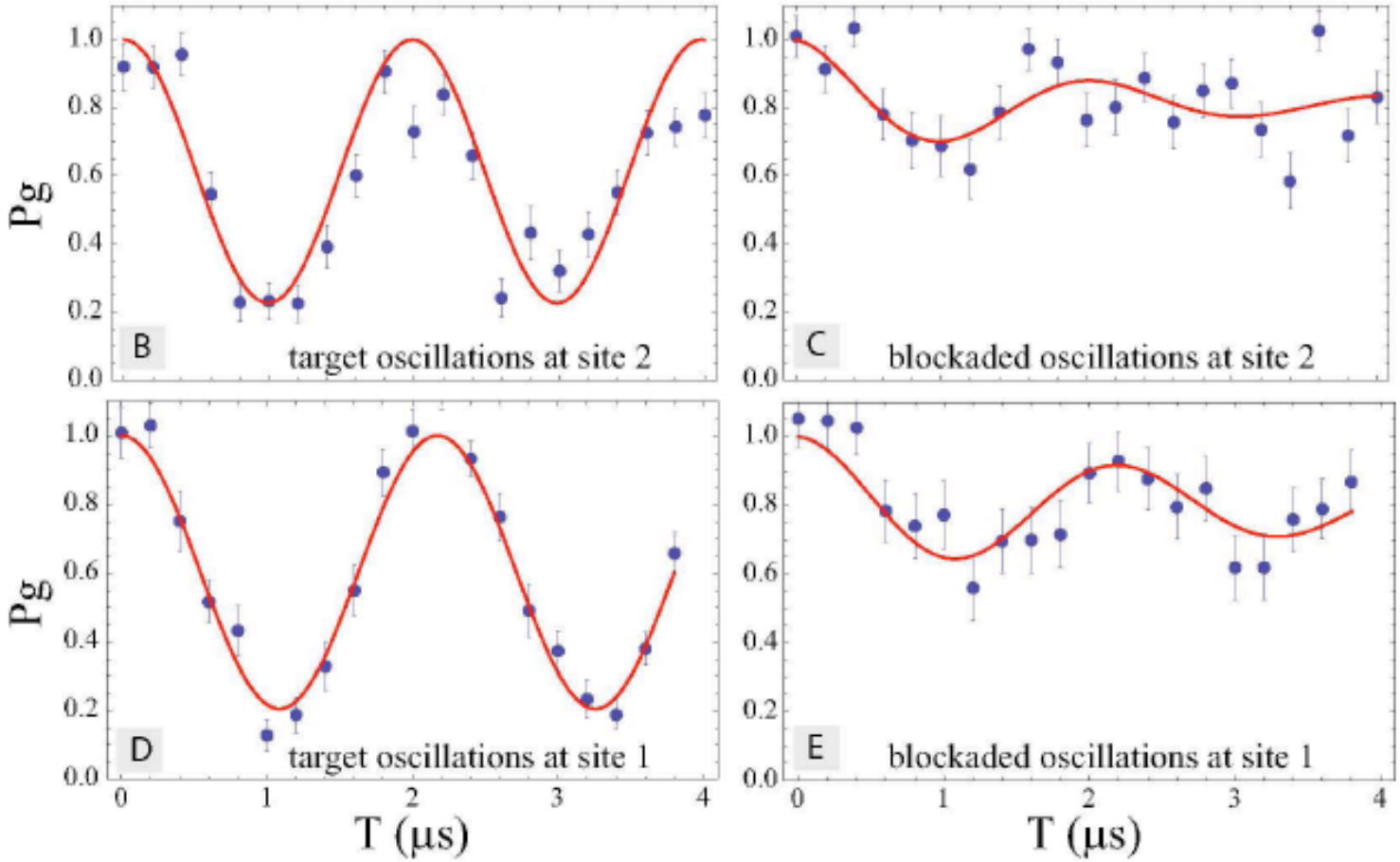


- Target excitation depends on state of control

E. Urban et al., Nature Phys. (2009).

Results

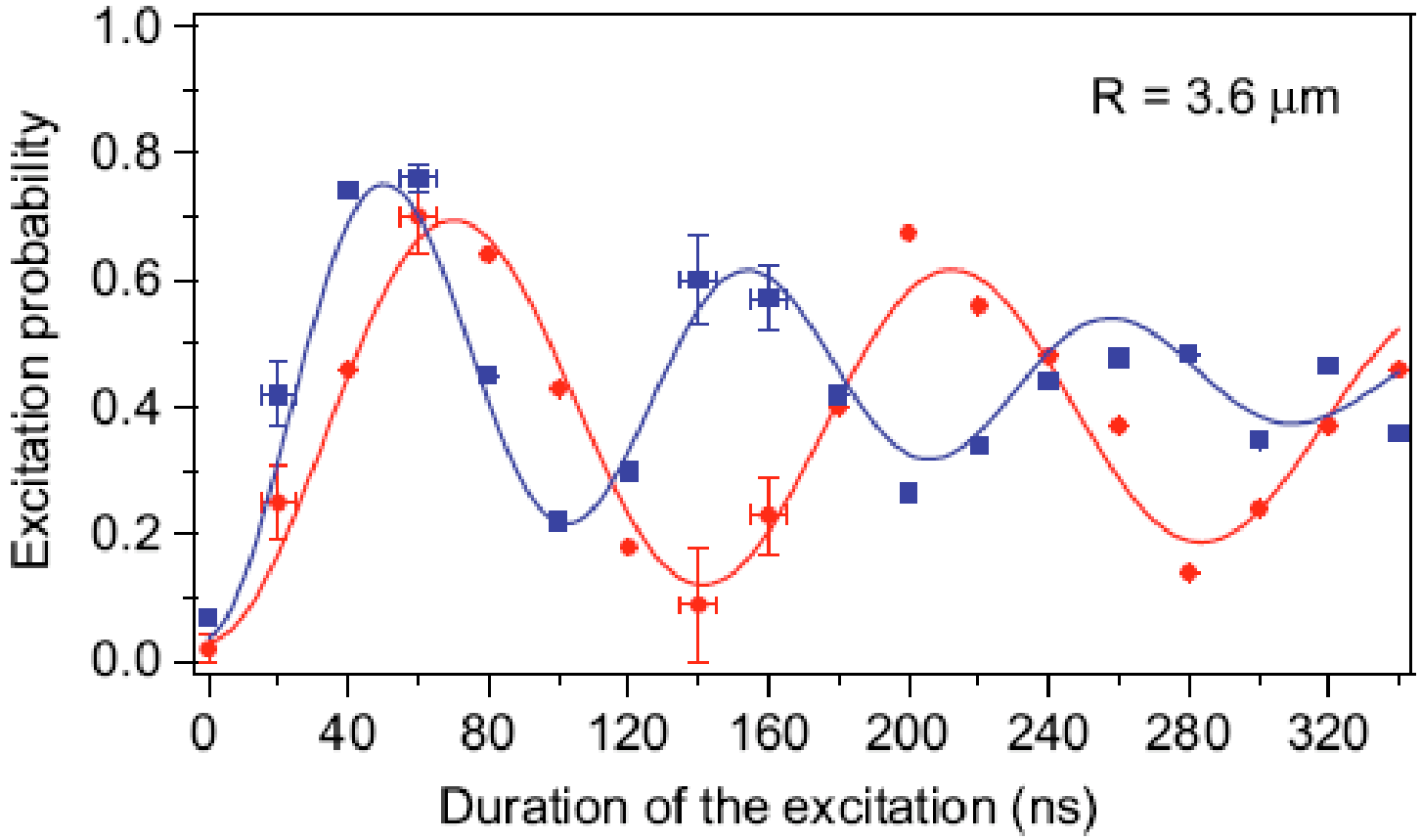
- If control is excited (n=79)
  - Lower probability of exciting the target



E. Urban et al., Nature Phys. (2009).

Many-body excitation

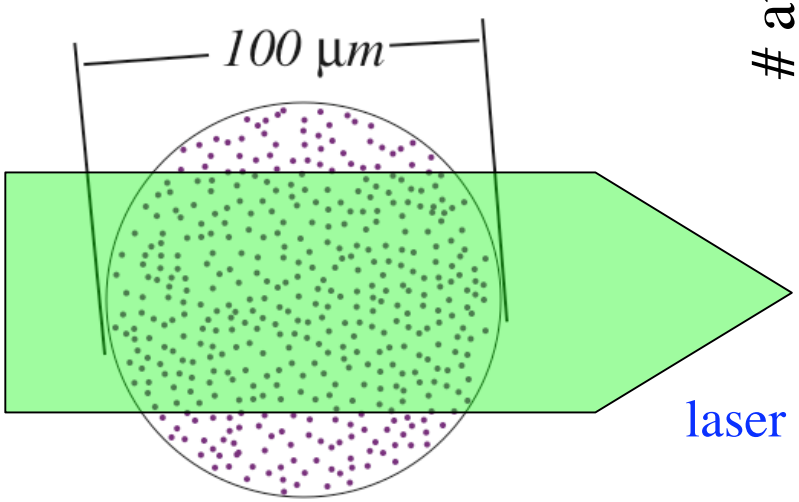
- When 2 atoms are excited in $58d_{3/2}$
  - Rabi frequency is $\sqrt{2}\,\Omega$

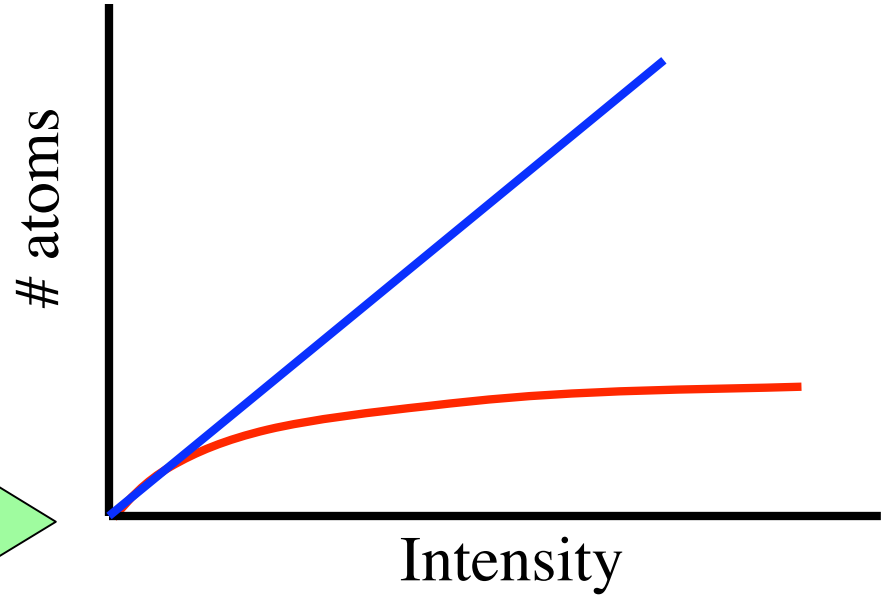


A. Gaëtan et al., Nature Phys. (2009).

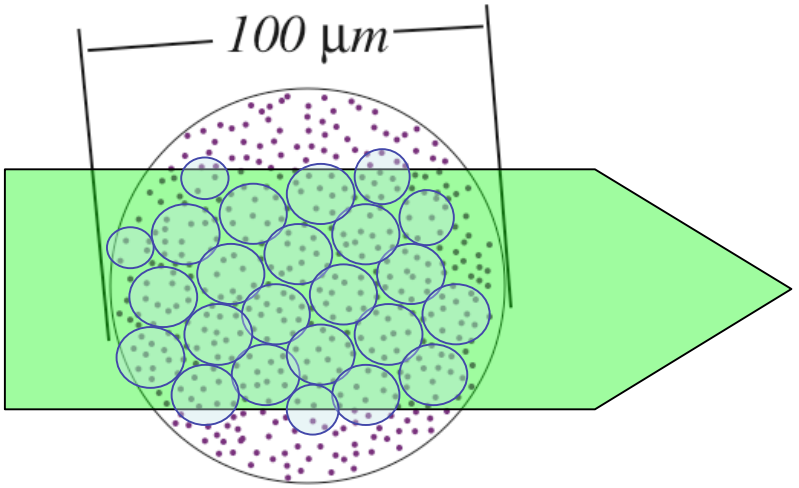
About a larger sample ?

- low *n* or densities
  - isolated atom behavior





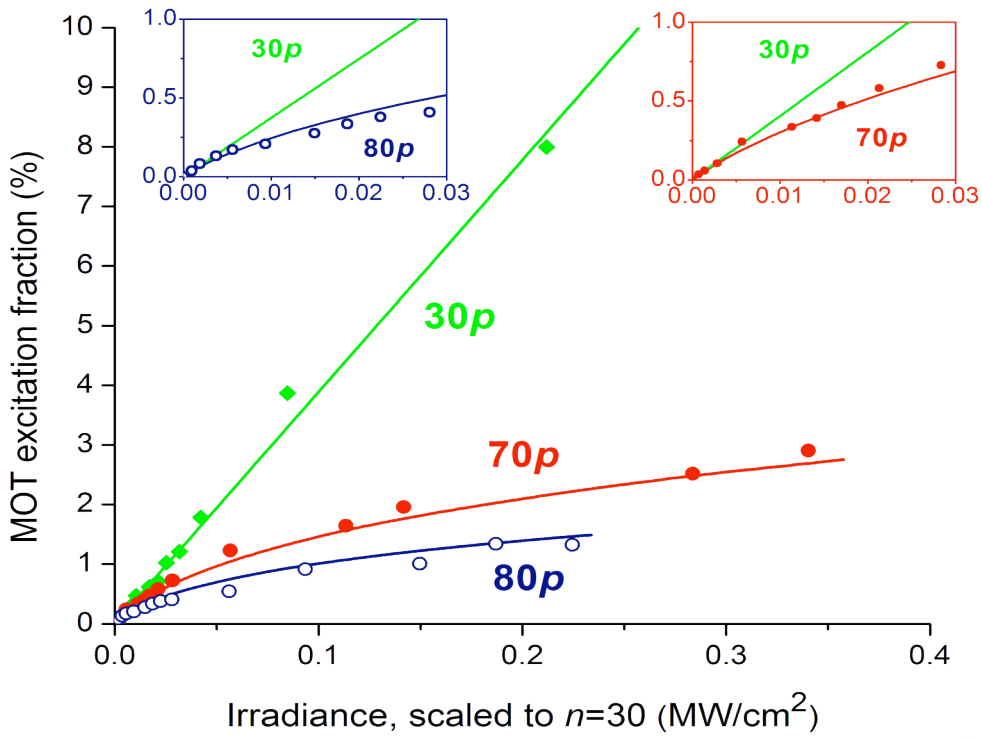
laser pulse



- large *n* or densities
  - locally blockaded domains

Measurements

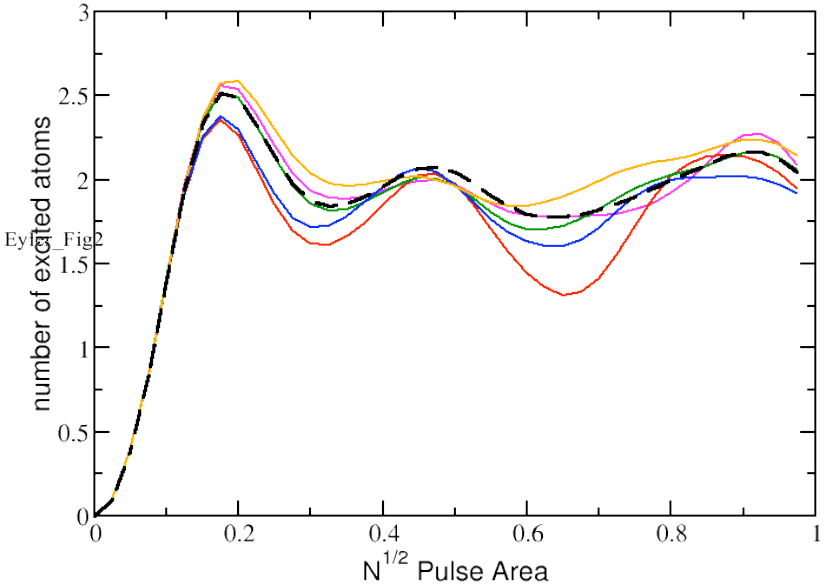
- Excitation blockade:



D. Tong *et al.*, PRL **93**, 063001 (2004).
K. Singer, *et al.*, PRL **93**, 163001 (2004).

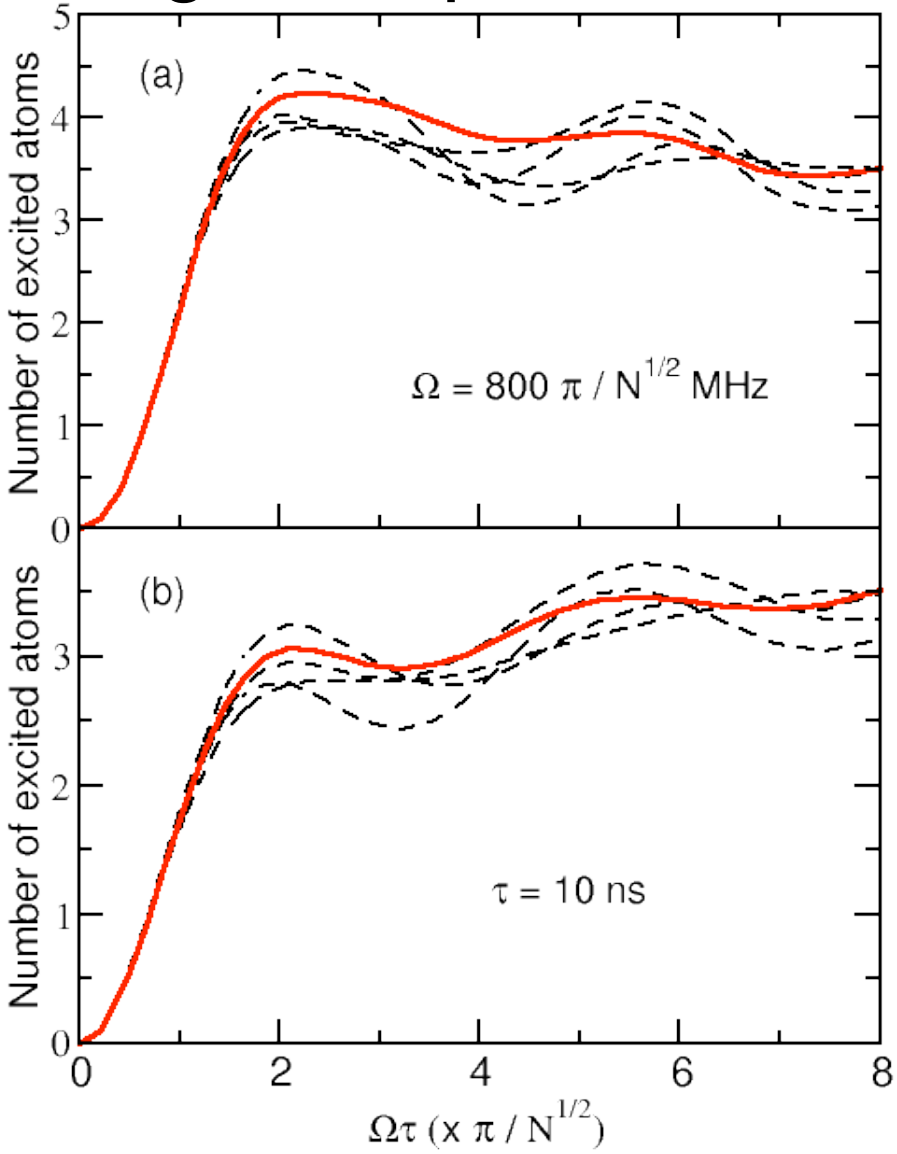
- Dipole blockade
  - observed by Pillet

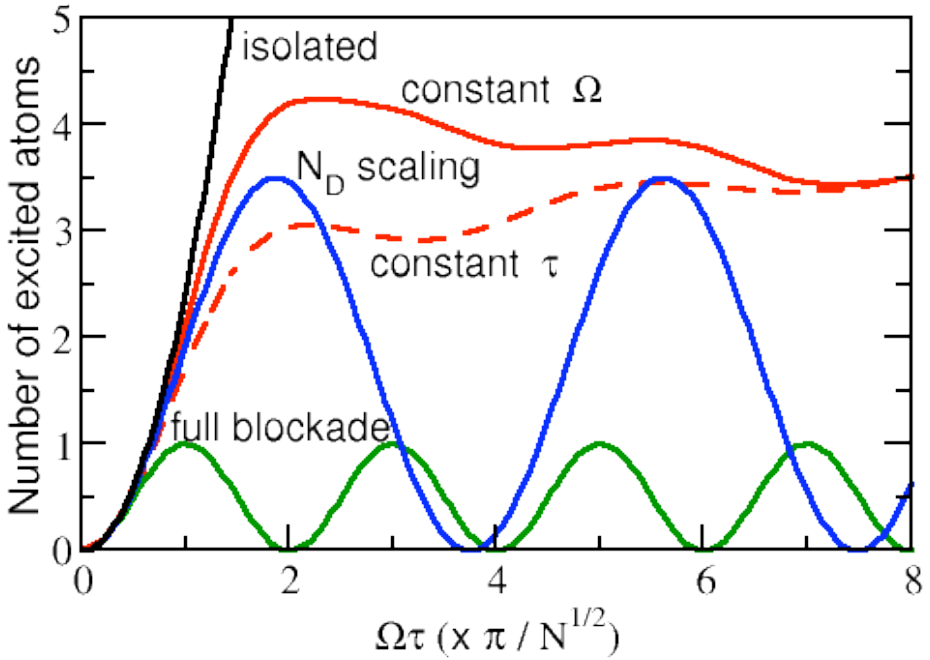
- Many-body oscillation
  - difficult in large sample
  - Pfau in Rb BEC
  - n=90, 70 atoms, 10^{11} cm^3, τ = 10 ns



Results from simulations

- Large sample: 70 atoms and up to 7 excitations





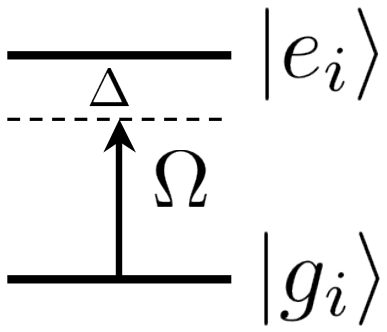
- 70p atoms
  - Rabi frequency scales $\sqrt{N_D}\ \Omega$

Many-body treatment

- Hamiltonian with 2-level atom *i*

$$H = \Delta \sum_{i=1}^{N} \hat{\sigma}^i_{ee} - \frac{\Omega}{2} \sum_{i=1}^{N} \left(f(t) \hat{\sigma}^i_{eg} + f^*(t) \hat{\sigma}^i_{ge} \right)$$

$$+ \sum_{i \neq j > i} \kappa_{ij} \hat{\sigma}^i_{ee} \hat{\sigma}^j_{ee}$$



- With definitions

$$\hat{\sigma}^i_{eg} \equiv |e_i\rangle\langle g_i|$$

$$\kappa_{ij} = \frac{C_6}{R^6_{ij}}$$

$$f(t) = e^{-t^2/\sigma^2 - i\beta t^2}$$

Simplification

- Equation of motion for σ-operators
- Removing the Δ term using new scaled variables

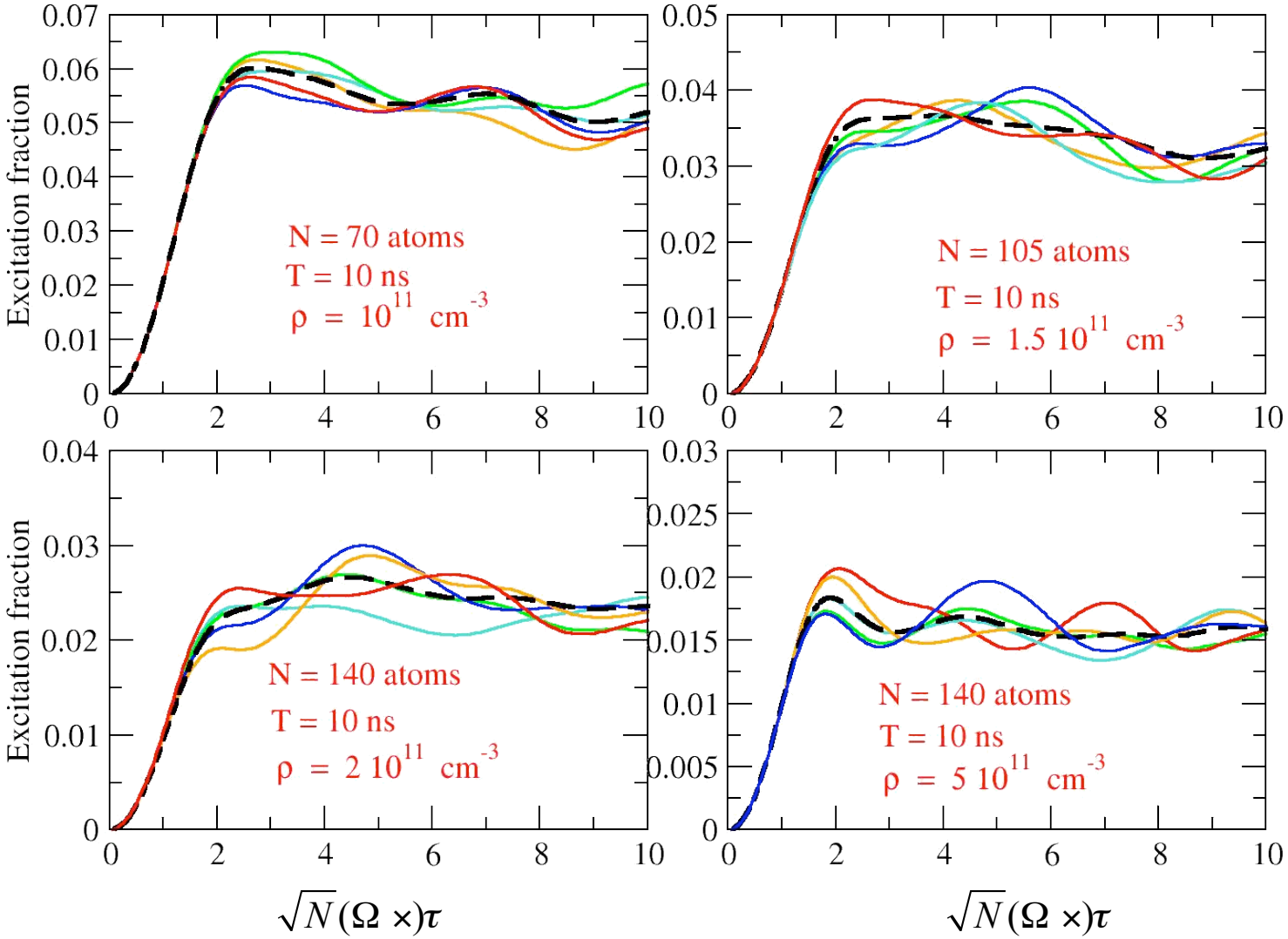
$$\tau = t/\sigma \quad , \quad \omega = \Omega\sigma \quad , \quad k_{ij} = \kappa_{ij}\sigma \quad , \quad \delta = \Delta\sigma$$

$$\frac{d\hat{\sigma}^i_{ee}}{d\tau} = i\frac{\omega}{2}\left[g(\tau)\hat{\sigma}^i_{eg} - g^*(\tau)\hat{\sigma}^i_{ge}\right]$$

$$\frac{d\hat{\sigma}^i_{eg}}{d\tau} = i\frac{\omega}{2}g^*(\tau)\left[2\hat{\sigma}^i_{ee} - 1\right] + i\sum_{j\neq i} k_{ij}\hat{\sigma}^i_{eg}\hat{\sigma}^j_{ee}$$

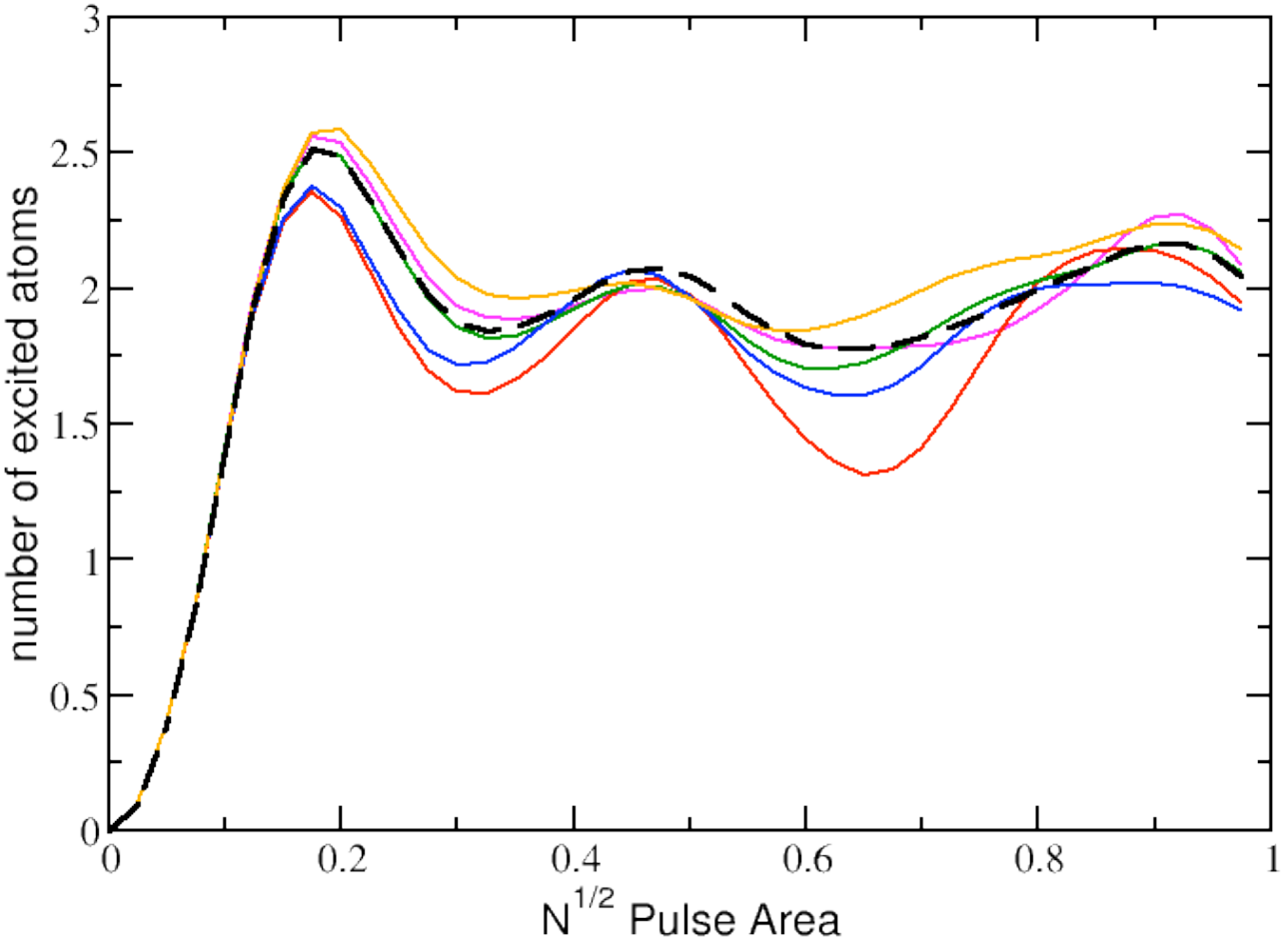
- where $g(\tau) = f(\tau)e^{i\delta\tau}$

Time dependence



Stronger interactions

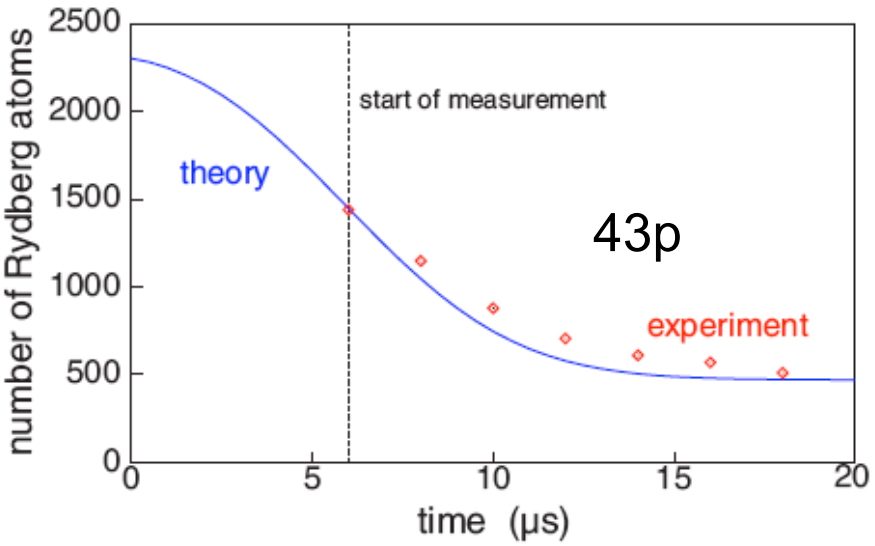
- Time-dependent with n=90
  - 70 atoms
  - $\rho = 10^{11}$ cm^{-3}
  - τ = 10 ns
  - Square pulse
  - V~(8 μm)^3



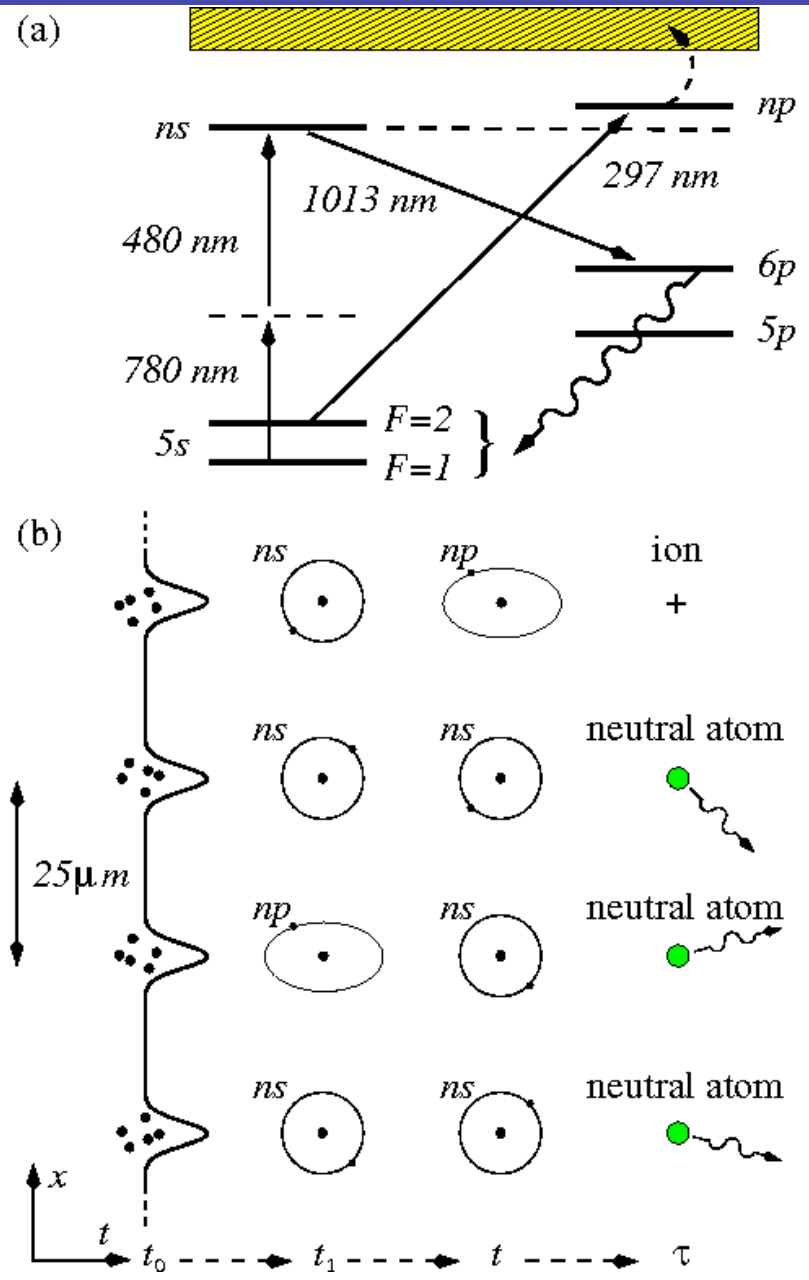
  - Fewer excitations (~ 2)

Other studies

- Quantum random walk
  - Diffusion of excitation
  - Prepare using blockade
  - Freiburg and Dresden
- Superradiance

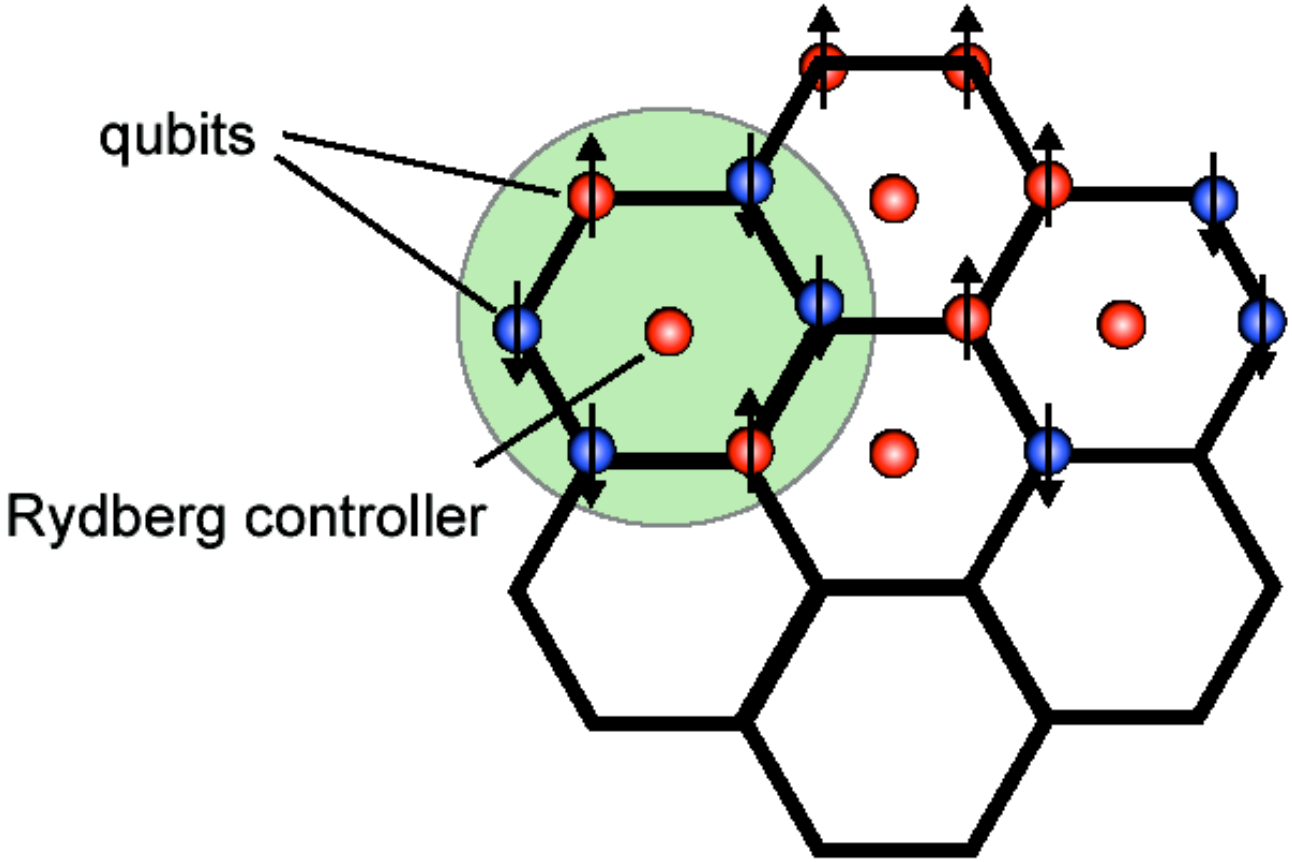


T. Wang et al., PRA 75, 033802 (2007).



Other applications

- Exotic many-body spin systems
  - Kitaev toric code

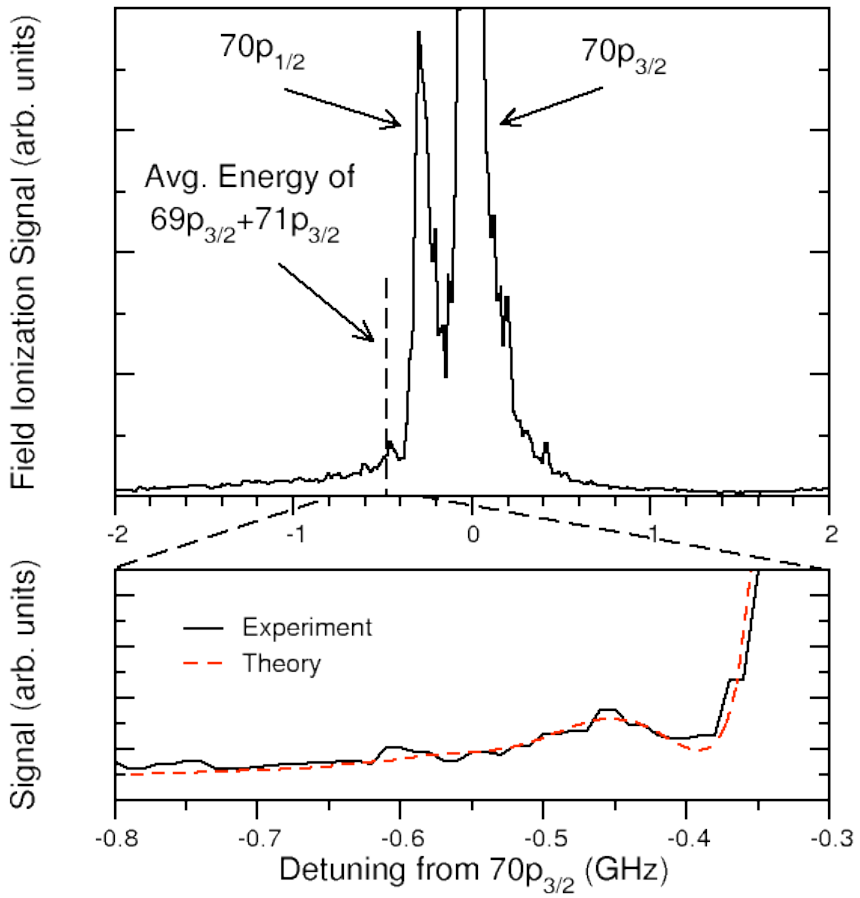


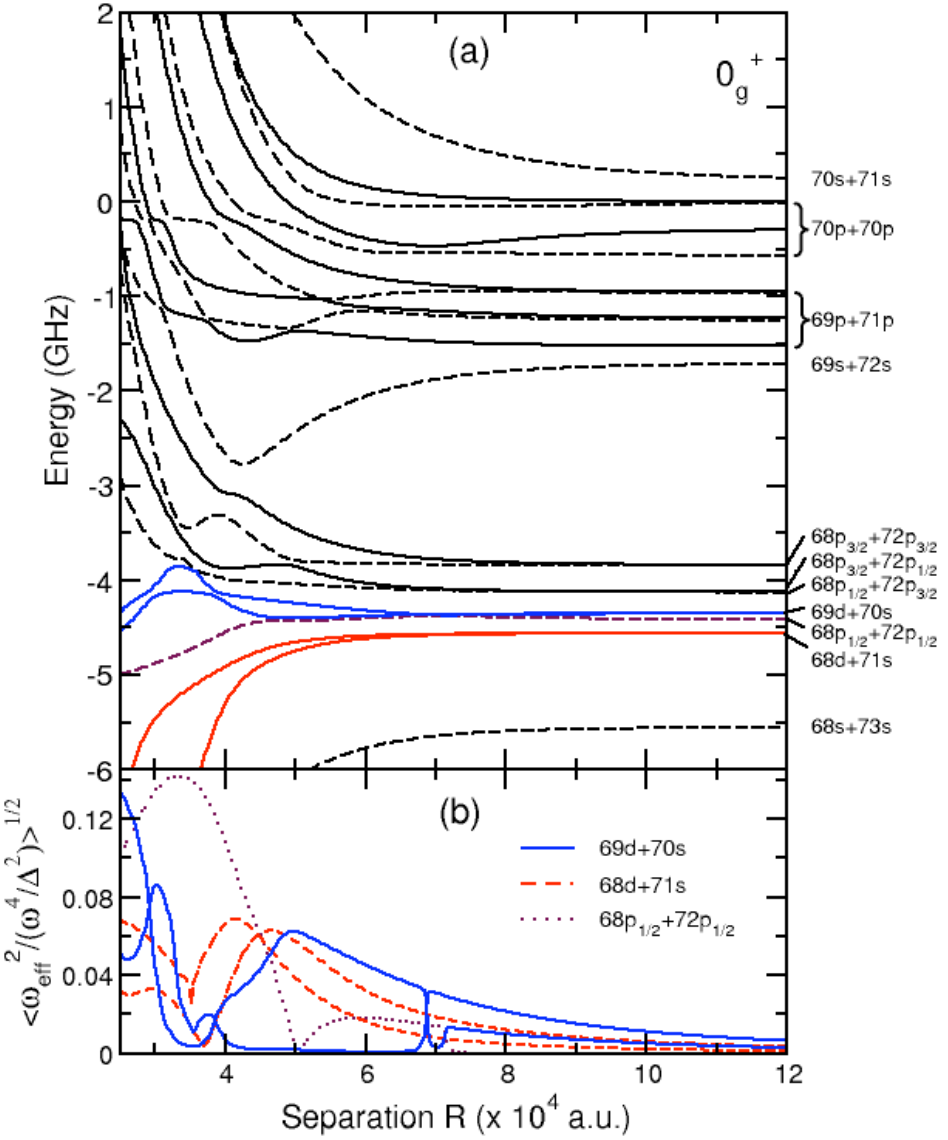
P. Zoller, talk at NSF sponsored workshop (April 2009).

PA in Rydberg gases

- Molecular resonance
  - Curve mixing

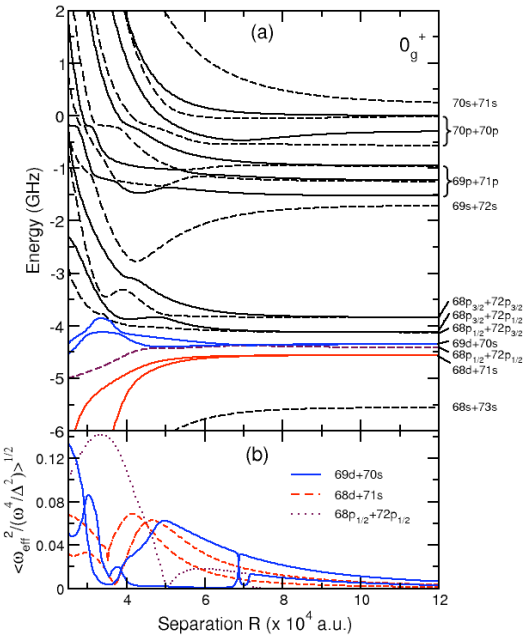
S.M Farooqi *et al.*, PRL **91**, 183002 (2003).
J. Stanojevic *et al.*, EPJD **40**, 3 (2006).

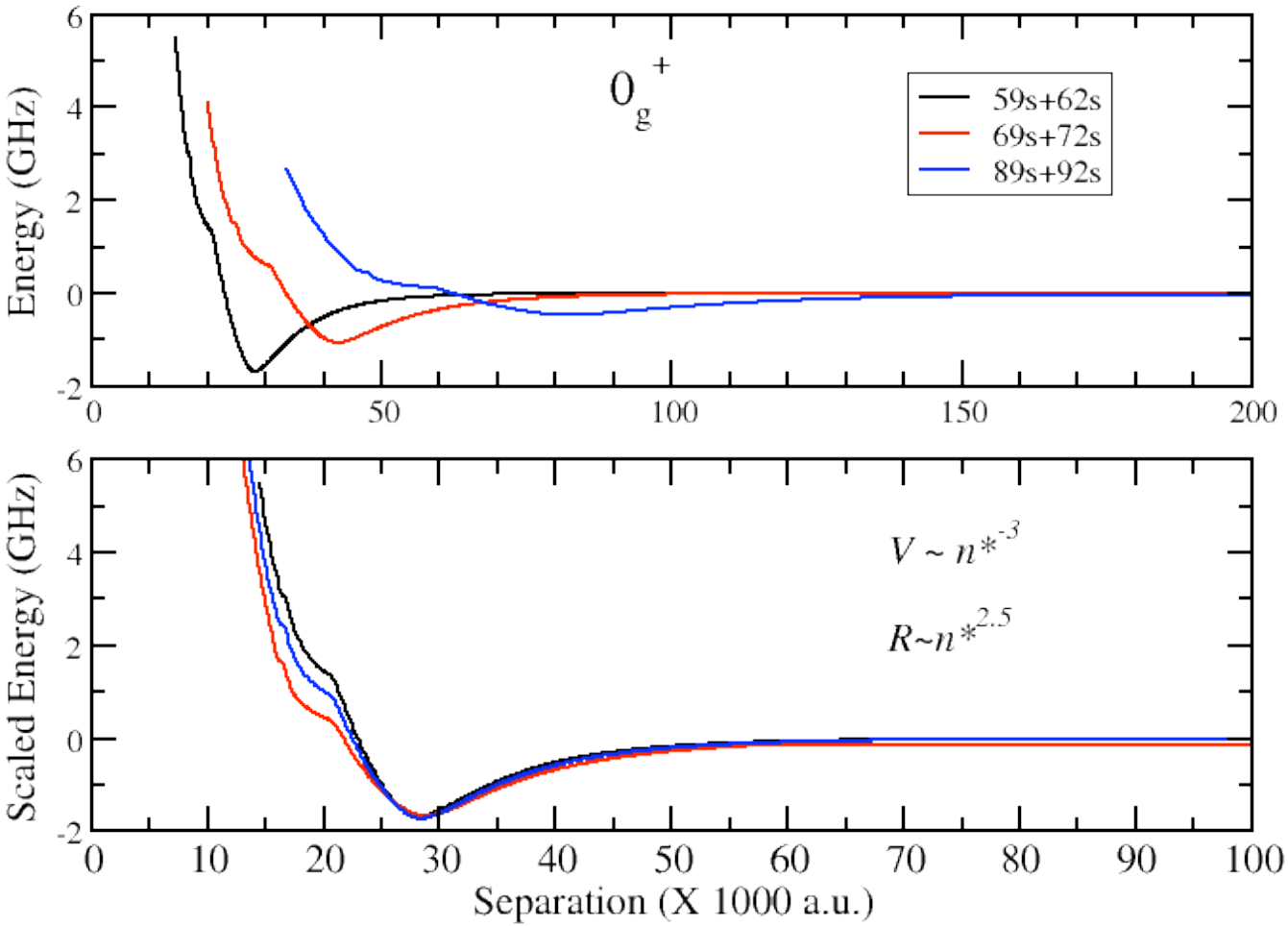




Potential wells

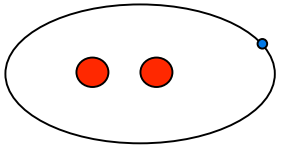
- s+s' & p+p' mixing ⇒ wells at shorter separation
  - "macrodimers" (ex., n=70 ⇒ R_e = 103 000 a.u.)
- Scaling
  - $R_e \sim n^{*2.5}$
  - $D_e \sim n^{*-3}$

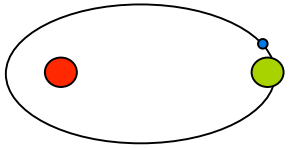




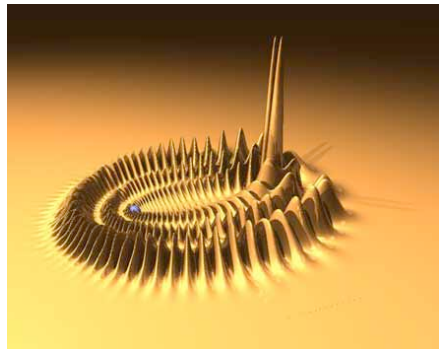
Application: Rydberg Molecules

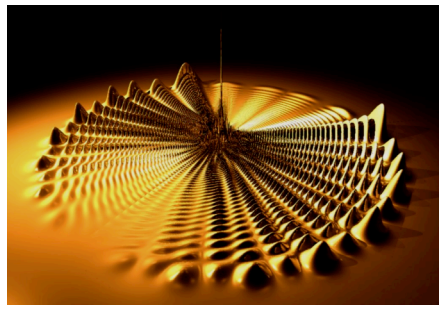
- "Common" case
  - Tight molecular ion core
  - Loosely bound electron

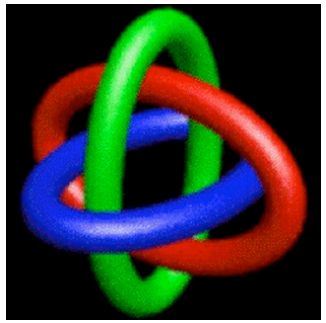




- Interested in excited molecules with *large* internuclear separation *R*
- *Giant* Helium dimers produced by $He(2^3S\uparrow)+He(2^3P\uparrow)$
  - R ~ 150 - 1150 a_0 and binding energy 1-2 GHz
    [Leonard *et al.*, Phys. Rev. Lett. **91**, 073203 (2003)]
- *Trilobite* or *butterfly* states (Greene et al.)
  - One atom excited and one in ground state
  - Electron scatters from neutral ground atom
    - Binding energies ~ 2GHz at n=70
    - Typical R_e: 500 a_0
- Borromean states (J.M. Rost)

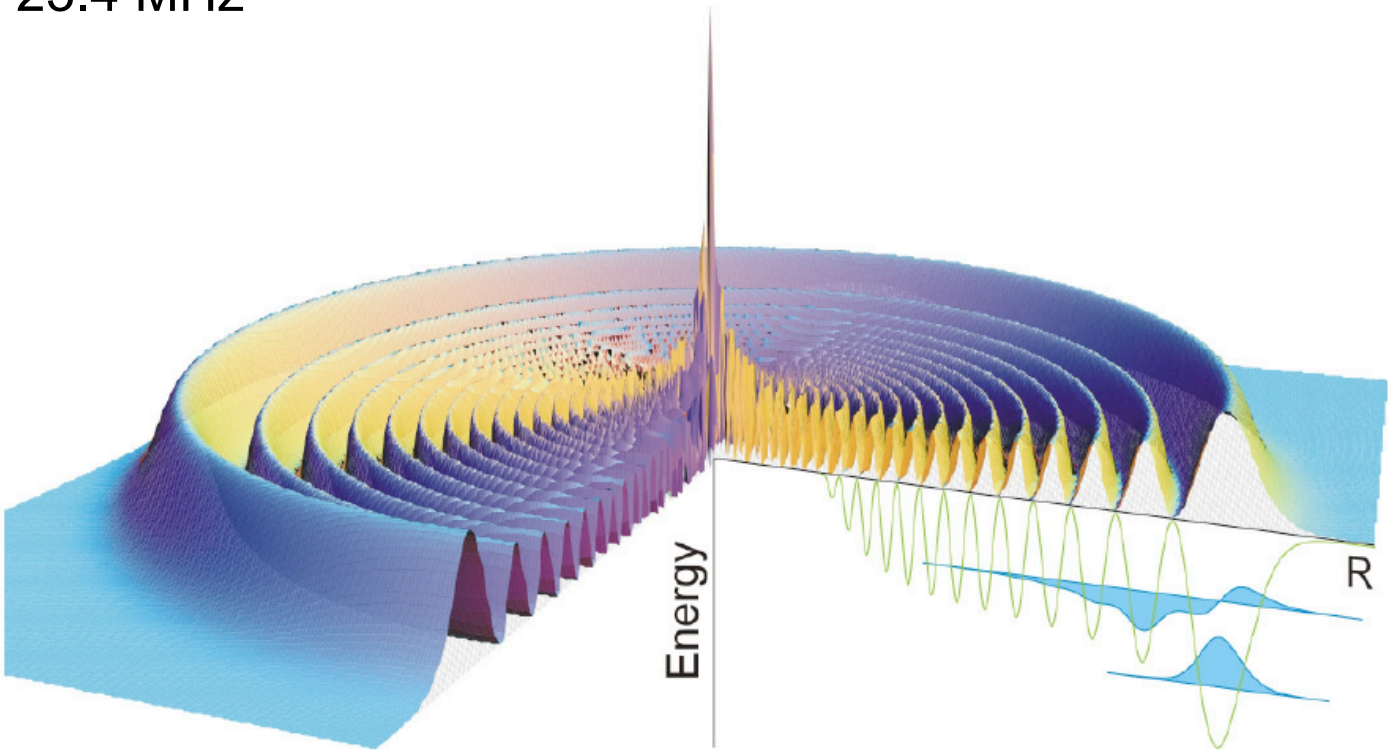






Recent measurements

- Density function for 5s-35s
  - Bound levels observed
    - R~1900 a.u.
    - v=0 at -23.4 MHz



T. Pfau's group, in Nature (2009).

Quick break

- To refresh yourself