Adiabatic quantum computing with dressed Rydberg atoms

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Krittika Goyal
with Bob Keating, Ivan Deutsch,
Yuan-Yu Jau*, Grant Biedermann* and Andrew Landahl*

University of New Mexico
*Sandia National Laboratories

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UNM

Adiabatic QUantum ARchitectures In Ultracold Systems

Neutral atom theory:

Ivan Deutsch
Krittika Goyal
Bob Keating

UNM

Sandia National Laboratories

AQUARIUS

Andrew Landahl

Solid state effort with quantum dots

Architecture group

Neutral Atom Expt:

Greg Brady, Kevin Fortier, Tom Hamilton, Aaron Hankin, Yuan-Yu Jau, Cort Johnson, Shanalyn Kemme, Michael Mangan, Paul Parazzoli, Peter Schwindt and Grant Biedermann

What is AQC?

- Goal: Solve an optimization problem using Adiabatic Quantum Computation (AQC)

[1] E. Farhi and J. Goldstone, arXiv:quant-ph/0001106v1 (2000).

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- Map on to problem Hamiltonian $H_P \Rightarrow$ *Ground state is the solution*
- Begining Hamiltonian $H_B \Rightarrow$ *Ground state is easy to prepare*
- $H(s) = (1-s)H_B + sH_P$ [1]
  Change s *adiabatically (slowly)* so that system is always in the *ground state* of $H(s)$

[1] E. Farhi and J. Goldstone, arXiv:quant-ph/0001106v1 (2000).

Quadratic Unconstrained Binary Optimization (QUBO)

- The general QUBO problem is to find the $\vec{z} = (z_1, z_2, \ldots, z_n)$ that minimizes the function

$$f(\vec{z}) = \sum_{i=1}^{n} h_i z_i + \sum_{i,j=1}^{n} J_{ij} z_i z_j, \text{ where } z_i \in 0, 1$$

- NP-hard because the number of possible values of $\vec{z}$ scales as 2^n.

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- NP-hard because the number of possible values of $\vec{z}$ scales as 2^n.
- This problem is equivalent to finding the ground state of the Hamiltonian

$$H_P = \sum_{i=1}^{n} h_i \left(\frac{\mathbb{I} - \sigma_z^{(i)}}{2} \right) + \sum_{i,j=1}^{n} J_{ij} \left(\frac{\mathbb{I} - \sigma_z^{(i)}}{2} \right) \otimes \left(\frac{\mathbb{I} - \sigma_z^{(j)}}{2} \right)$$

The z_i have been mapped onto $\left(\frac{\mathbb{I} - \sigma_z^{(i)}}{2} \right)$

Why dressed ground state Rydberg atoms?

- Ground state neutral atoms allow for precise and robust single qubit control.

  D. Schrader PRL **93**, 150501 (2004)

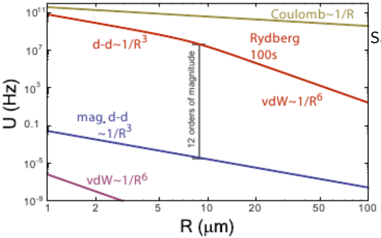
  C. Zhang PRA **74**, 042316 (2006)

  W.Rakreungdet PRA **79**, 022316 (2009)

- Interactions between ground state neutral atoms are very weak, making it hard to implement two qubit gates, without contact interaction

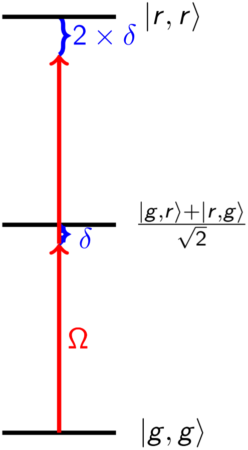
Why dressed ground state Rydberg atoms?

- Ground state neutral atoms allow for precise and robust single qubit control.
- Interactions between ground state neutral atoms are very weak, making it hard to implement two qubit gates, without contact interaction
- Dipole-dipole interactions between Rydberg atoms are several orders of magnitude stronger than ground state neutral atoms.



Saffman, et. al RMP **82, 2313 (2010)**

The Rydberg blockade



- $U_{\rm dd}$ is the interaction energy between two Rydberg atoms.
- Blockade interaction results in entangled state $\frac{|g,r\rangle+|r,g\rangle}{\sqrt{2}}$
- References:Y. Miroshnychenko et al. PRA **82**, 013405 (2010).

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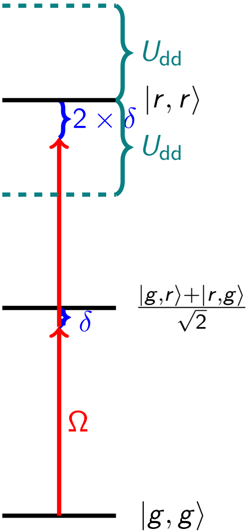

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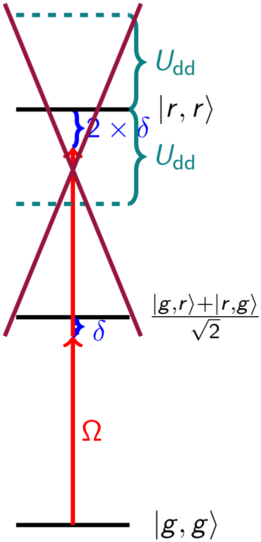

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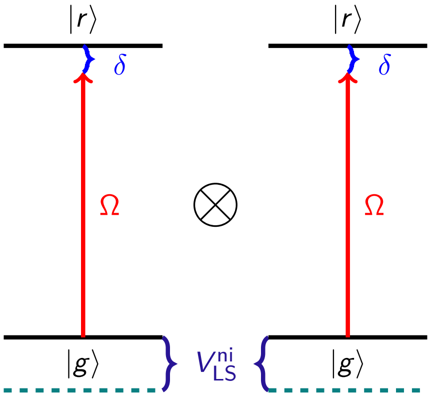
Dressed ground state Rydberg atoms



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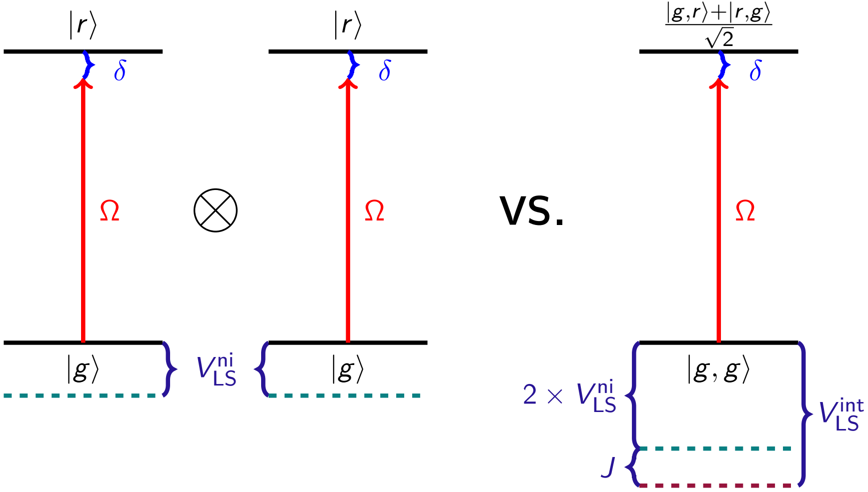

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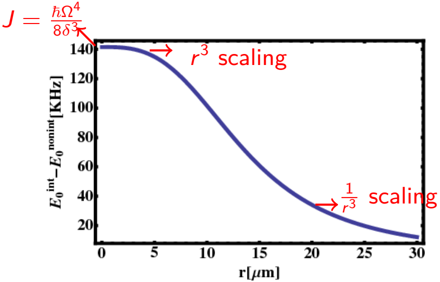
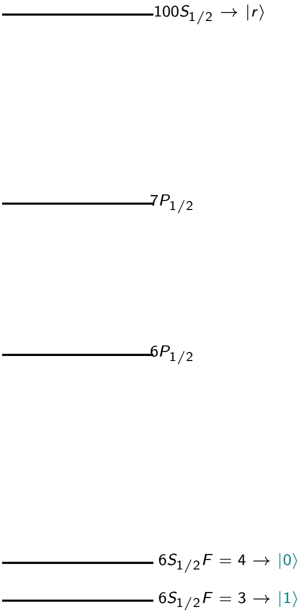


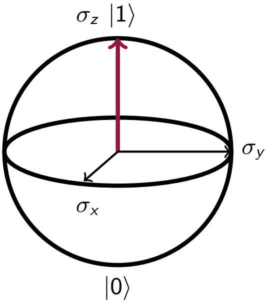
J. E. Johnson and S. L. Rolston, PRA **82** ,033412(2010)

- The interaction is robust to fluctuations in r.
- Dressed ground state Rydberg atoms are easy to trap.
- The interaction can stay on at all times which is required for AQC.

Cs energy level diagram:



- Prepare atoms in $6S_{1/2}F = 3 \rightarrow |1\rangle$ (eigenstate of σ_z)
- Turn on $\pi/2$ microwave pulse $\rightarrow \frac{|0\rangle - |1\rangle}{\sqrt{2}}$ (ground state of σ_x)



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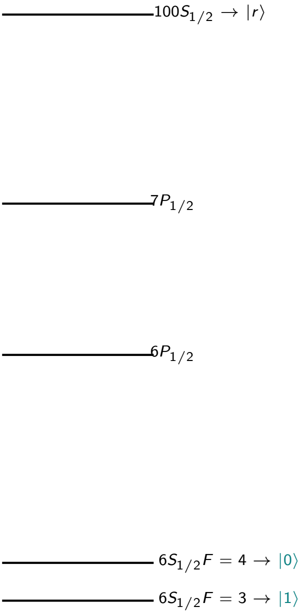

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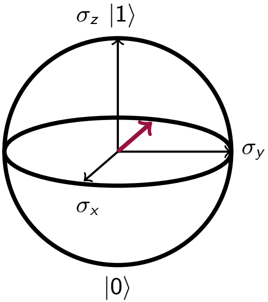

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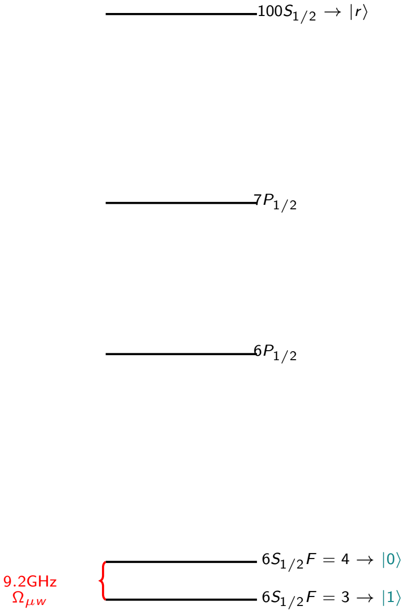

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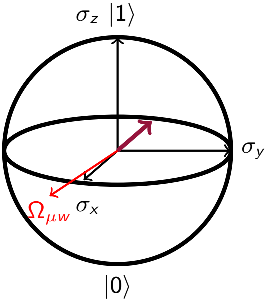
- Turn on the microwaves.

$$H_B = \frac{\hbar\Omega_{\mu w}(t)}{2}\left(\sigma_x^{(1)} + \sigma_x^{(2)}\right)$$



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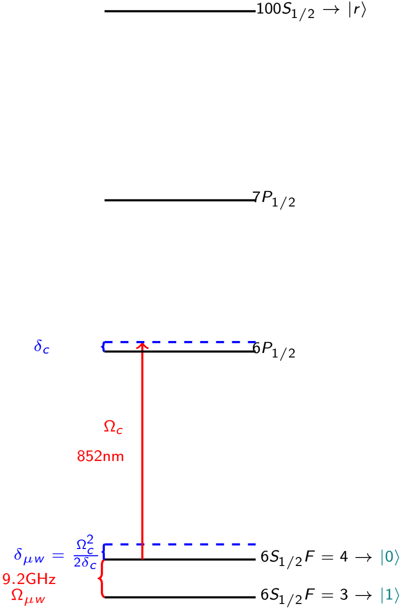

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  $H_B = \frac{\hbar\Omega_{\mu w}(t)}{2}\left(\sigma_x^{(1)} + \sigma_x^{(2)}\right)$
- Turn on the 852 nm laser:

$$-\frac{\hbar}{2}\left(\delta_{\mu w1}(t)\sigma_z^{(1)} + \delta_{\mu w2}(t)\sigma_z^{(2)}\right)$$

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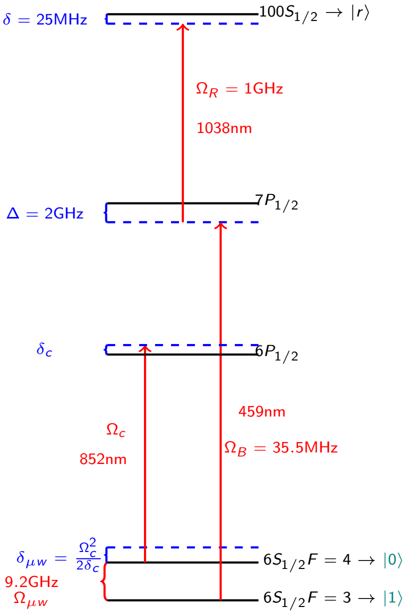

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  $$-\frac{\hbar}{2}\left(\delta_{\mu w1}(t)\sigma_z^{(1)} + \delta_{\mu w2}(t)\sigma_z^{(2)}\right)$$
- Turn on Rydberg lasers:
  $$J(t)\left(\frac{\mathbb{I} - \sigma_z^{(1)}}{2}\right) \otimes \left(\frac{\mathbb{I} - \sigma_z^{(2)}}{2}\right)$$

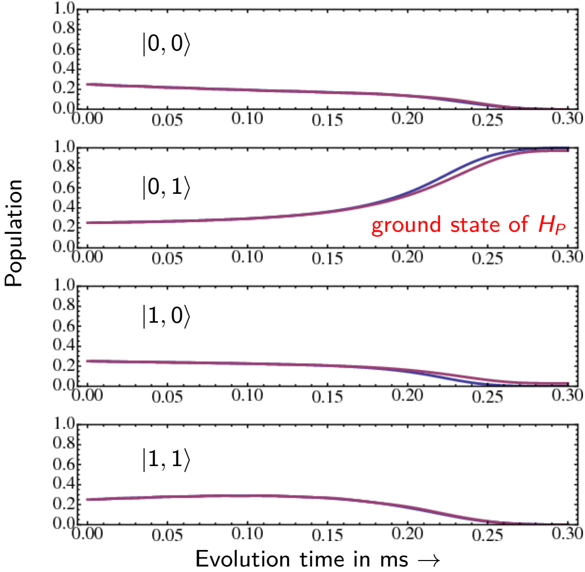
Evolution time: 2 qubit QUBO

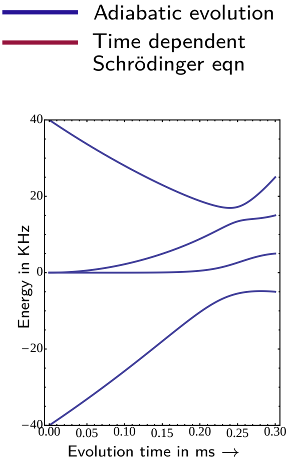
2 qubit QUBO Hamiltonian in KHz:

$$H(t) = 20\left(1 - \frac{t}{t_{\max}}\right)\left(\sigma_x^{(1)} + \sigma_x^{(2)}\right) + 5\frac{t}{t_{\max}}\sigma_z^{(1)} + 10\frac{t}{t_{\max}}\sigma_z^{(2)} + 10\left(\frac{t}{t_{\max}}\right)^2\left(\frac{\mathbb{I} - \sigma_z^{(1)}}{2}\right) \otimes \left(\frac{\mathbb{I} - \sigma_z^{(2)}}{2}\right)$$

Ground state of H_P is $|0, 1\rangle$

Evolution time: 2 qubit QUBO





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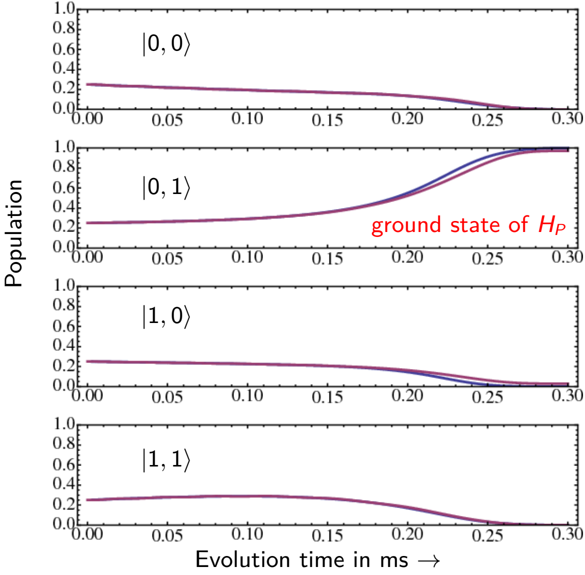
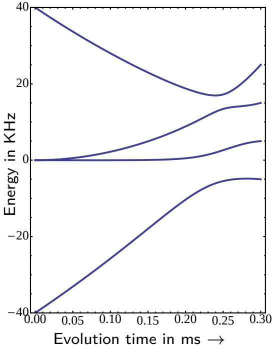


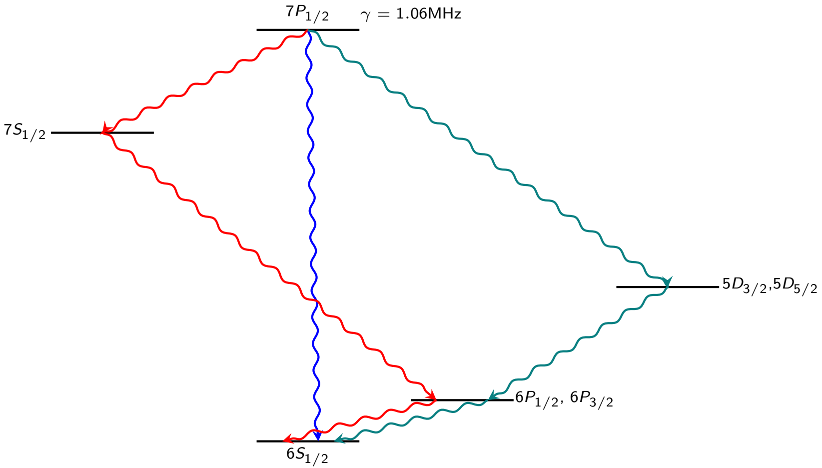
Adiabatic evolution

Time dependent Schrödinger eqn



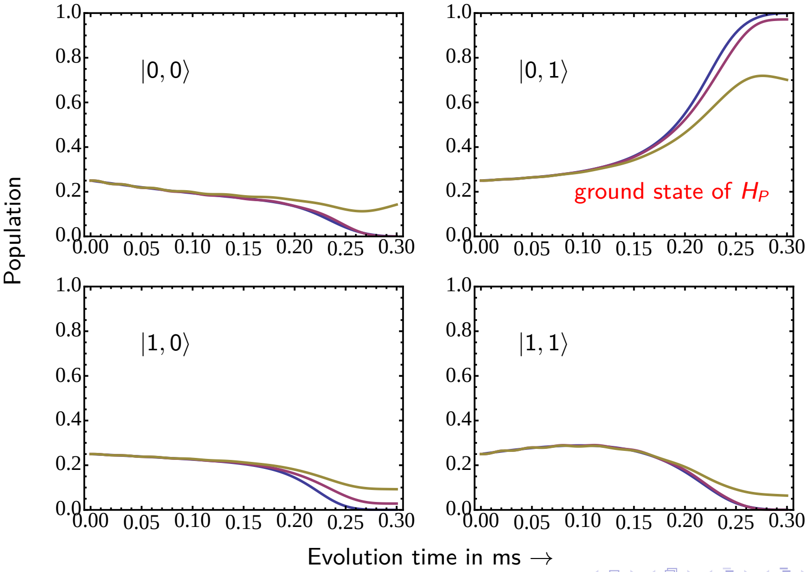
What about photon scattering?

Photon scattering



Photon scattering randomizes qubit, i. e. returns qubit with approximately equal probability to $F = 3$ and $F = 4$ states.

Effect of dissipation

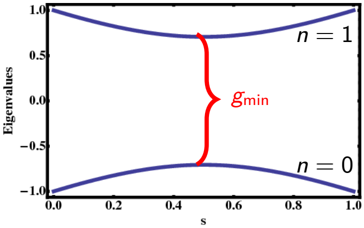


Summary And Outlook

- Experimental scheme for two qubit QUBO problem.
- We need to combat the effects of dissipation.
- Optimize ramp to minimize time required for adiabaticity

How Slowly?

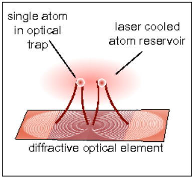
$$H(s) = (1-s)\sigma_x + s\sigma_z$$



- By the adiabatic theorem the timescale for evolution must satisfy $T \gg \frac{\varepsilon}{g_{\min}^2}$ [a], where $\varepsilon = \max \left| \langle n=1; s | \frac{dH(s)}{ds} | n=0; s\rangle \right|_{0<s<1} \approx 1$
- The feasability of AQC depends on the scaling of $g_{\min}$ with number of qubits.

[a] E. Farhi and J. Goldstone, arXiv:quant-ph/0001106v1 (2000).

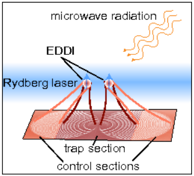
Initialize



Prepare atoms in $6S_{1/2}F = 3 \rightarrow |1\rangle$

Turn on $\pi/2$ microwave pulse $\rightarrow \frac{|0\rangle - |1\rangle}{\sqrt{2}}$

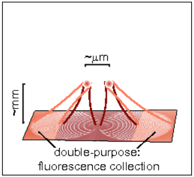
Adiabatic Evolution



Turn on and adiabatically ramp down $\Omega_{\mu w}$

Adiabatically ramp up intensities of all lasers.

State Readout



Evolution time