LHZ scheme implementation

Abhishek Anand

What we have:

- Machinery to solve QUBOs restricted to unit disk graphs

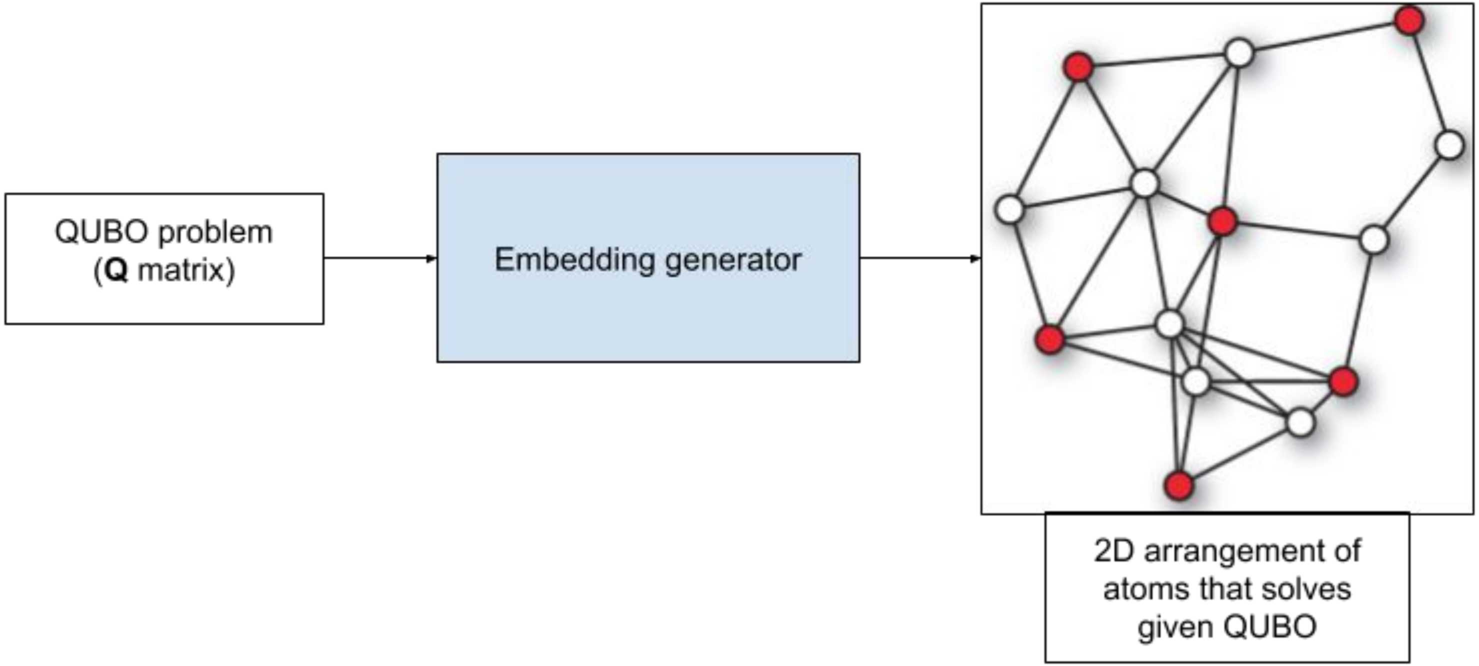
Quantum Optimization for Maximum Independent Set Using Rydberg Atom Arrays

Hannes Pichler,[1,2,*] Sheng-Tao Wang,[2,*] Leo Zhou,[2] Soonwon Choi,[2,3] and Mikhail D. Lukin[2]

What we wish to do:

- Solve arbitrary QUBO on arbitrary graph
- Translate arbitrary graph ⇒ equivalent UD graph

Overview


QUBO problem
(**Q** matrix)
Embedding generator
2D arrangement of
atoms that solves
given QUBO

Attempt 1: [< $O(n^2)$ atoms]

$\boxed{N^2 \text{ non-linear equations with } qN \text{ variables}}$

where q = number of degrees of freedom for each atom:

- x, y coordinate
- n, l, etc.

In general, not solvable for arbitrary set of equations.
Plus, scaling problems (q).

Attempt 2: [O(n^2) atoms: LHZ]

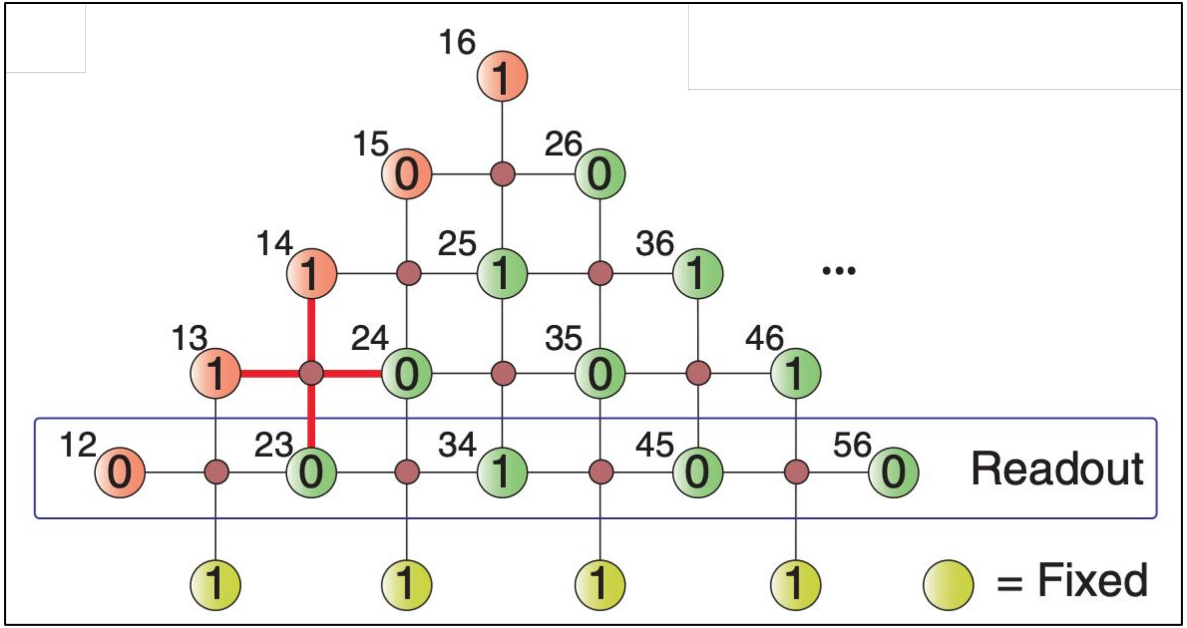
A quantum annealing architecture with all-to-all connectivity from local interactions

Wolfgang Lechner,[1,2*] Philipp Hauke,[1,2] Peter Zoller[1,2]

Core idea: represent each interaction as an atom

Main challenge: as redundancy (each variable represented *n* time),
ensure some constraints

LHZ geometry



LHZ geometry

- Only works with 4 atoms per group (square/rhombus shape) as underlying fact that makes it work is:

$$n^2 = \sum_{i=0}^{n-1} (2n+1)$$

- Only one symmetric position for auxiliary qubit

Why single species/n does not work:

If single species, then:

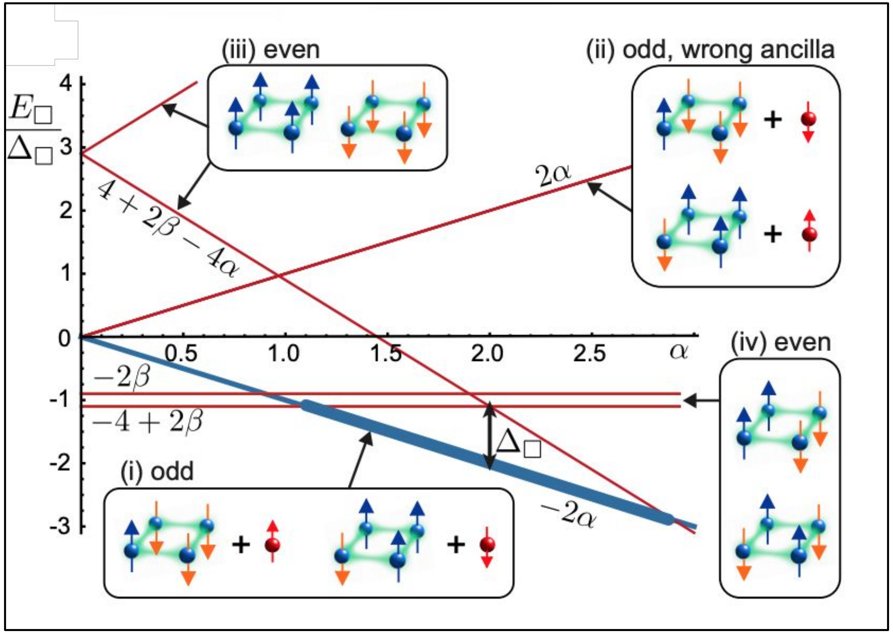
$$V_{a,b} = 8V_{\text{edges}}$$

- where *a* is the auxiliary qubit and *b* is on the corners
- But, for the right degeneracy and energy separation, we want:

$$V_{a,b} = 2V_{\text{edges}}$$

Why single species/n does not work:

$$V_{a,b} = 2V_{\text{edges}}$$



What can we do?

- (Empirically, no proof), all other symmetric configurations with >1 auxiliary qubits suffer from the same problem

- Use qutrits

- Use different species: ^{87}Rb and ^{133}Cs

A Coherent Quantum Annealer with Rydberg Atoms

A. W. Glaetzle,[1,2,*] R. M. W. van Bijnen,[1,2,*] P. Zoller,[1,2] and W. Lechner[1,2,†]

- Use different *n*

Use different *n* (only s-s interactions)

- Find n_1, n_2 analytically by solving:

$$\boxed{\frac{C6_{n_1,n_2}}{\left(\frac{1}{\sqrt{2}}\right)^6} = 2C6_{n_1,n_1}}$$

- Run simulation: **30 < n_1, n_2 < 120**

Use different *n* (Rb)

- l = 0, j = ½, m = ½

- Running simulation: **$10 < n_1, n_2 < 120$, $1.995 < x < 2.005$, $4\ \mu m < r < 25\ \mu m$** where r = distance between physics atoms

- 218 unique configurations possible

- Use cases when *ancillary n* < *physical n* (to prevent ancillary-ancillary interactions)

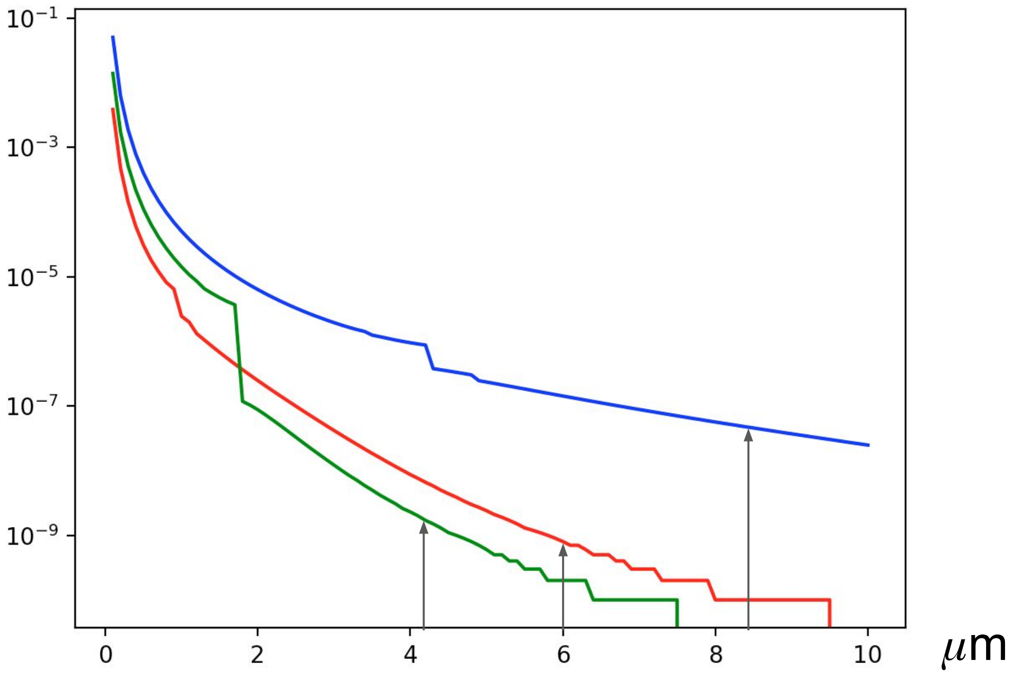
Specific Rb configuration

- Physical ⇒ $|63S_{1/2}>$
- Ancillary ⇒ $|117S_{1/2}>$

- Distance b/w physical ⇒ 6 μm
- Distance b/w ancillary and physical ⇒ 4.24 μm

Interaction trends

Red → physical-physical
Blue → ancillary-ancillary
Green → physical-ancillary



Ancilla-ancilla interactions very strong!

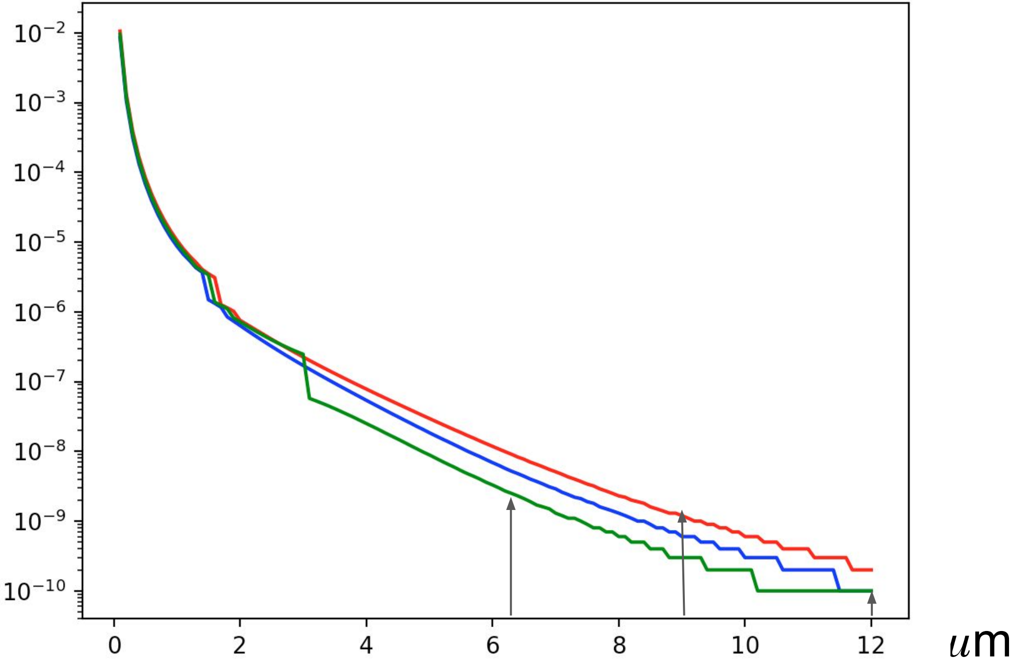
What’s the best we can do with s-s interactions?

- Physical ⇒ $|80S_{1/2}>$
- Ancillary ⇒ $|76S_{1/2}>$

- Distance b/w physical ⇒ 9 μm
- Distance b/w ancillary and physical ⇒ 6.36 μm

Interaction trends

Red → physical-physical
Blue → ancillary-ancillary
Green → physical-ancillary



Still, ancilla-ancilla interactions dominate

Idea: encode ancilla as a p-state

- s-s interactions stronger than s-p
- But, s-p interactions stronger than p-p!

Hence, if we encode ancilla as a p-state, ancilla-ancilla interactions would not dominate.

Optimal s-p Rb configuration

- Physical ⇒ $|100S_{1/2}>$
- Ancillary ⇒ $|80P_{3/2}>$

- Distance b/w physical ⇒ ~6 μm
- Distance b/w ancillary and physical ⇒ ~4.24 μm

- For small system (4 physical + 3 ancilla): **we achieve required parity separation**

To do: full Hamiltonian analysis