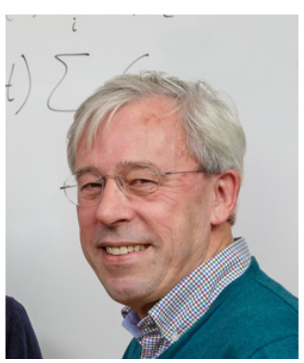
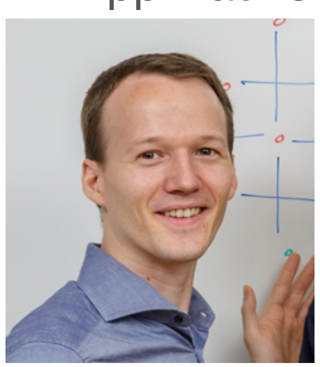
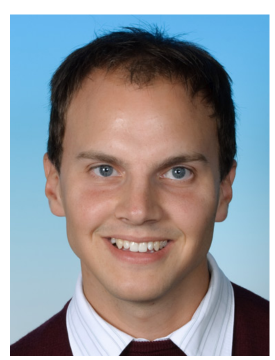
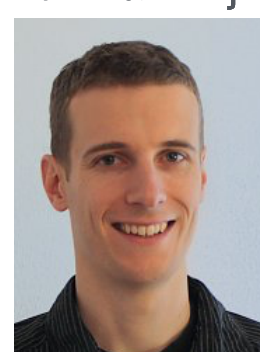
Hauser-Raspe Foundation

Adiabatic Quantum Computing with Parity Constraints

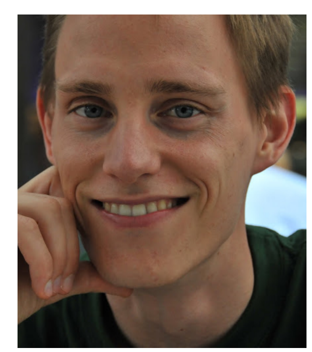
Wolfgang Lechner

Peter Zoller

Philipp Hauke


Sci. Adv. 1, 1500838 (2015).

Alex Glätzle

Rick van Bijnen


arXiv:1611.02594 (2016)

Martin Leib


arXiv:1604.02359(2016)

Markus Heyl

Lars Bonnes


arXiv:1411.7933 (2014)

KITP, Designer Quantum Systems Out of Equilibrium, 15th Nov. 2016

Quantum Computing

- Entanglement
- Superposition
- Measurement

… as a resource.

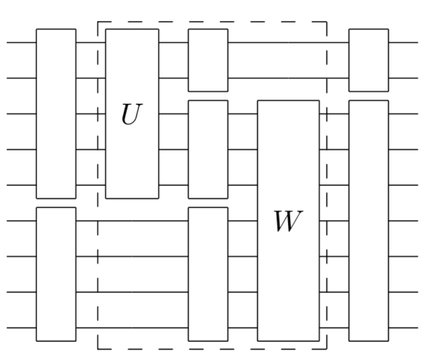
Universal Quantum Computer

Quantum Simulation

e.g. Hubbard Model

$$H = -t \sum_{\langle i,j \rangle} a_i^\dagger a_j + \frac{U}{2} \sum_i \hat{n}_i \left(\hat{n}_i - 1 \right) - \mu \sum_i \hat{n}_i$$

Gate Models



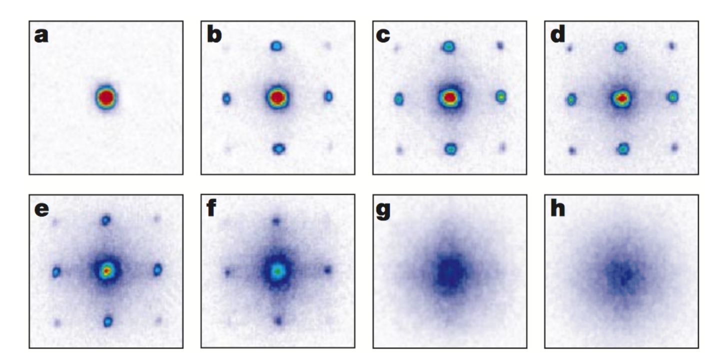
One-Way Quantum Computing

Raussendorf, Briegel PRL (2001).

P. Walther et. al Nature (2005).

Adiabatic Quantum Computing

Farhi et. al., Science (2001).



D Jaksch, et. al. PRL 81, 3108 (1998).

M. Greiner, et. al. Nature, 415 (2002).

Adiabatic Quantum Computing

H. Nishimori et. al., PRE **58**, 5355 (1998).
E. Farhi et. al., Science **292**, 472 (2001).

$$H(t) = \left(1 - \frac{t}{T}\right) H(0) + \frac{t}{T} H_p$$

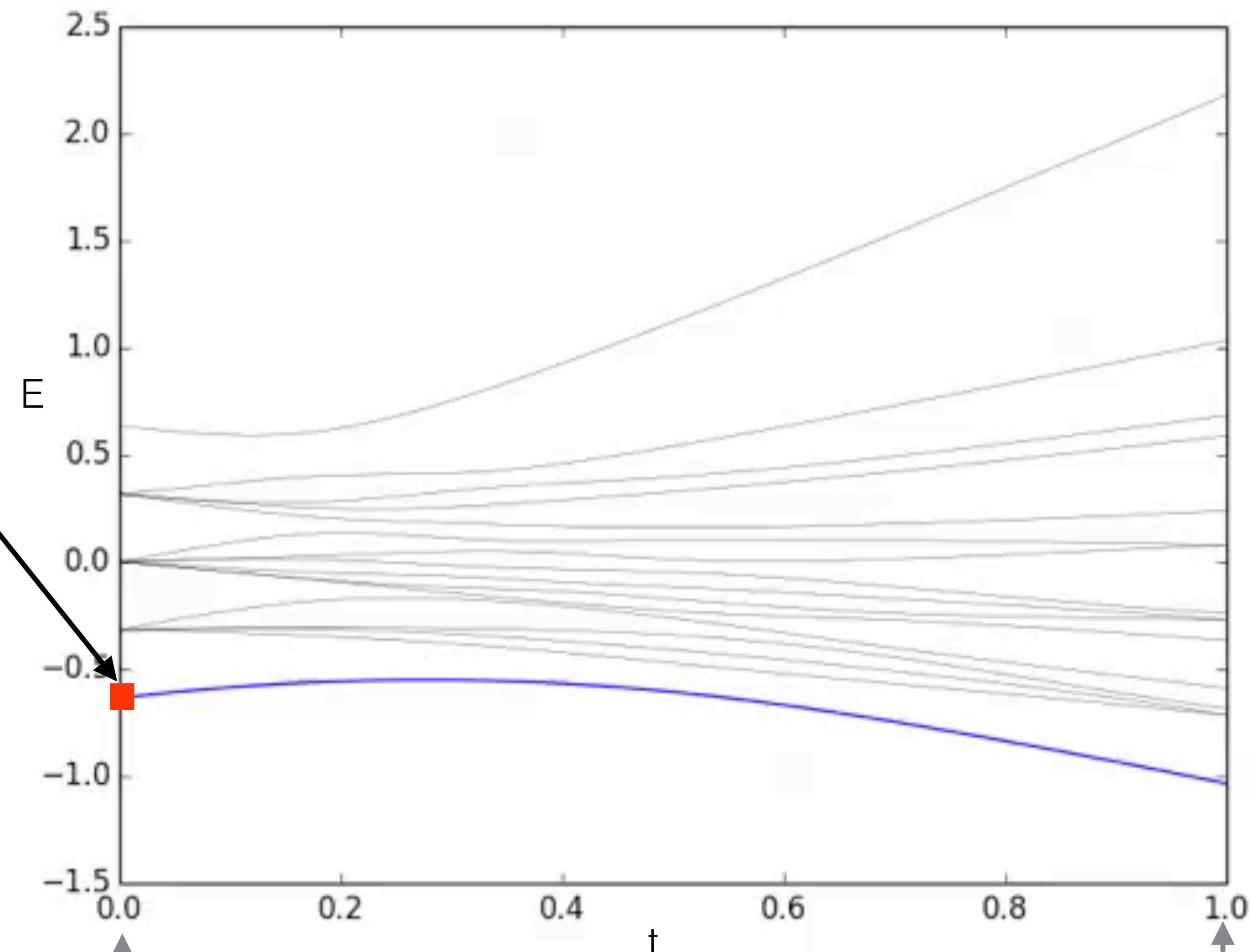
Trivial initial Hamiltonian   Problem Hamiltonian

1. Prepare System in $|\psi_0\rangle$ which is the ground state of H(0)

2. Slowly evolve the system with

$$|\psi(t)\rangle = e^{-i\int_0^t H(t)dt}|\psi_0\rangle$$

3. Due to the adiabatic theorem, the final state is the ground state of H_p



$$H_0 = \sum_i^N \sigma_x^{(i)}$$

$$H_p = \sum_{i<j} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}$$

Adiabatic Quantum Computing

H. Nishimori et. al., PRE **58**, 5355 (1998).
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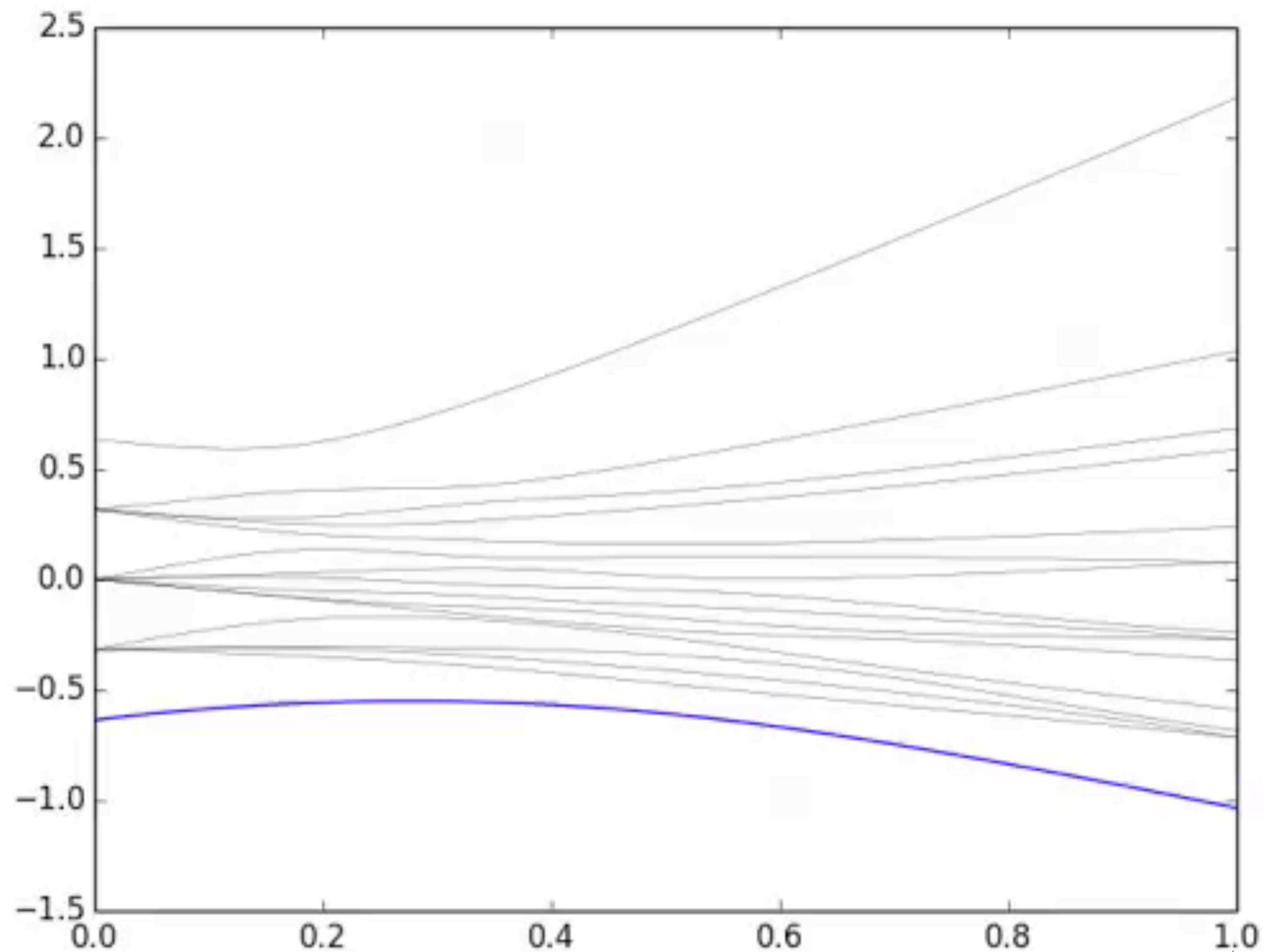


$$H_0 = \sum_i^N \sigma_x^{(i)}$$

$$H_p = \sum_{i<j} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}$$

Adiabatic Quantum Computing

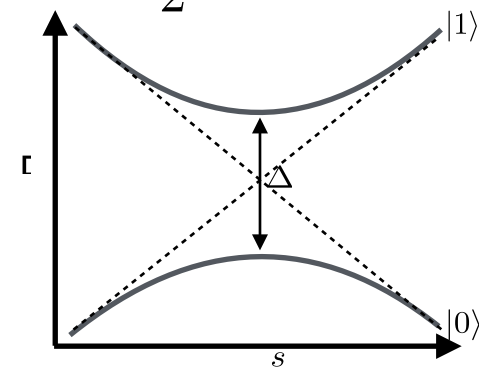
- Adiabaticity:

mapping function s(t) $i\frac{ds}{dt}\frac{d}{ds}|\psi(s)\rangle = H(s)|\psi(s)\rangle$

$$\frac{1}{\tau(s)} = \frac{ds}{dt} \ll \frac{\Delta^2}{|\frac{d}{ds}H(s)|}$$

Landau-Zener problem

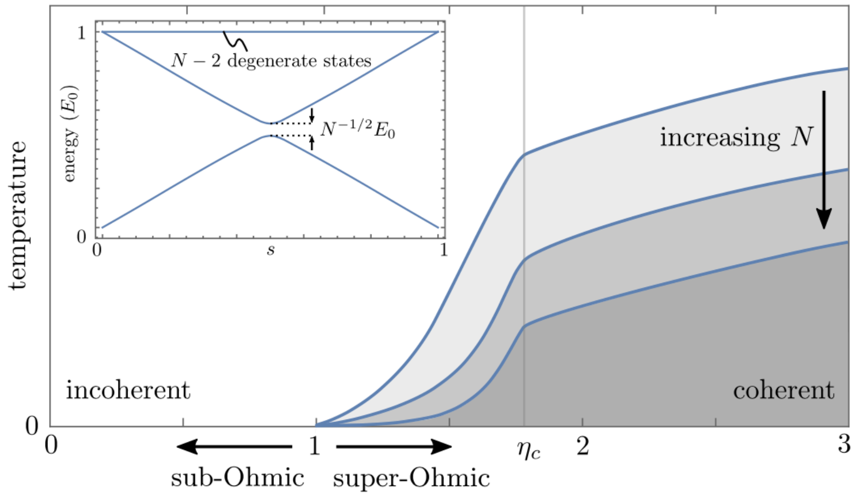
$$H(t) = \frac{1}{2}(1-s)\Delta\sigma_x + \frac{1}{2}s\sigma_z$$



- Coherence:

D. Wild, S. Gopalakrishnan, M. Knap, N. Y. Yao, M. D. Lukin
Phys. Rev. Lett. , 117, 150501 (2016).

- only scalable at zero-temperature
- at finite temperature, error correction is needed



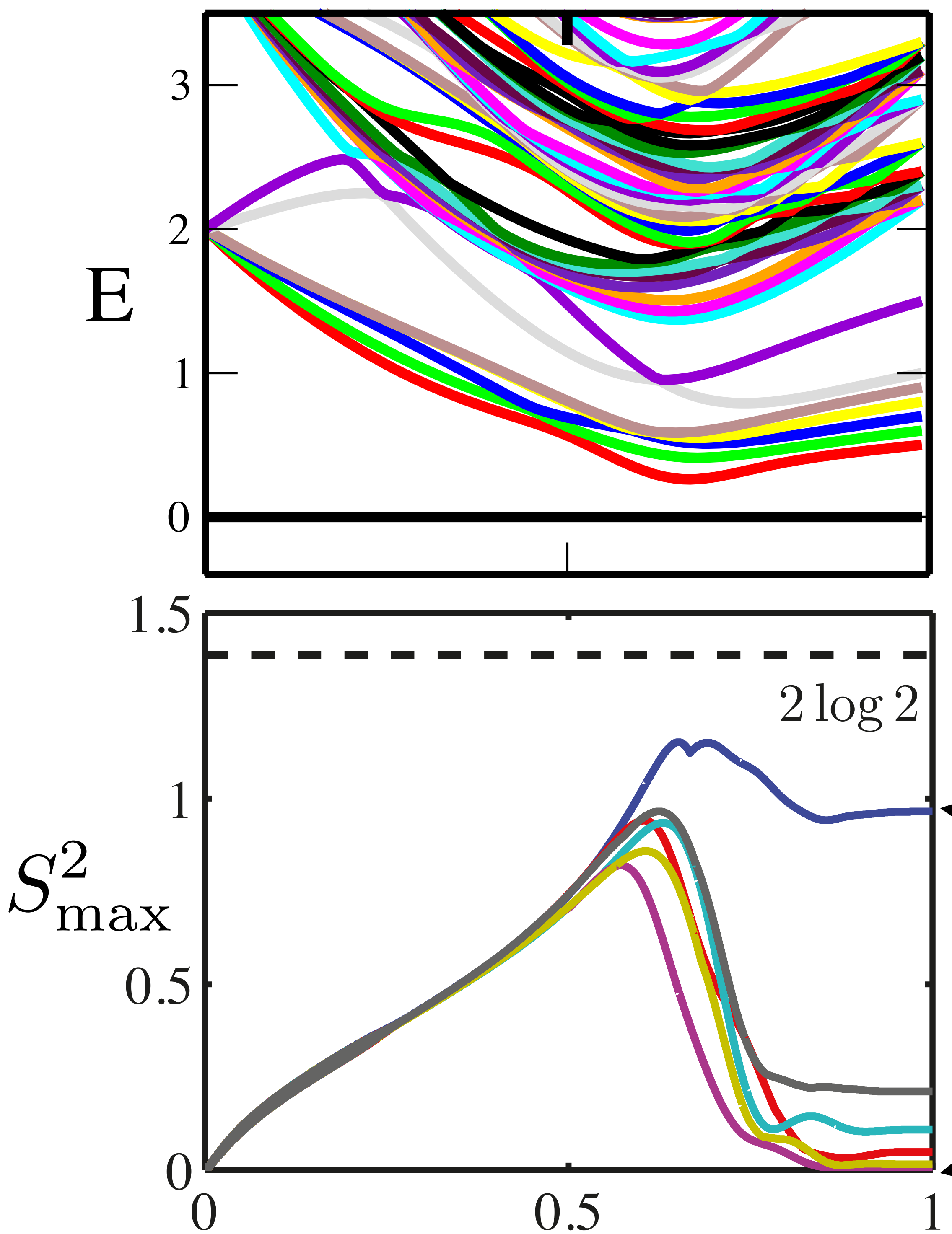
- Universality:

- Any gate model can be simulated with an adiabatic quantum computer.
  Aharanov et. al. SIAM Review 50, 755 (2008).

- Grover Algorithm can be implemented optimally $\mathcal{O}(\sqrt{N})$.
  Fahri and Gutmann, Phys. Rev. A 57, 2403 (1998).

Adiabatic Quantum Computing

- Entanglement as a resource:



$$\mathcal{H}(t) = A(t)\sum_{i}^{N} b_i \sigma_x^{(i)} + B(t)\left[\sum_{i=1}^{N} h_i \sigma_z^{(i)} + \sum_{i=1}^{N}\sum_{j=1}^{i} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}\right]$$

e.g : Entanglement Entropy:

$$S = -\mathrm{Tr}\left[\rho_A \log \rho_A\right] \qquad \rho_A = \mathrm{Tr}_B\left[\rho\right]$$

Maximum of S for each combination of bipartition A and B at each time:

$$S^2_{\max}(t) = \max S(A, B)$$

non-adiabatic (irreversible)

adiabatic (reversible)

P. Hauke, L. Bonnes, M. Heyl and WL, Front. Phys. 3, 21 (2015).

Adiabatic Quantum Computing

- Infinite Range Spin glass

$$\mathcal{H}(t) = A(t)\sum_{i}^{N} b_i \sigma_x^{(i)} + B(t)\left[\sum_{i=1}^{N} h_i \sigma_z^{(i)} + \sum_{i=1}^{N}\sum_{j=1}^{i} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}\right]$$

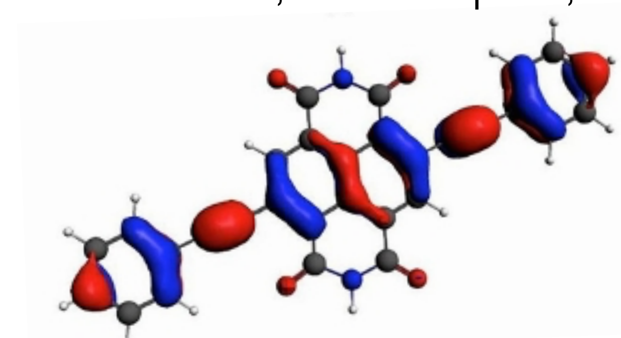
NP-hard problems

A. Lucas, *Frontiers in Physics* ***2****, 00005 (2014).*

- Traveling Salesman
- Knapsack
- Minimal Spanning Tree
- Number Partitioning
- Graph Coloring
- 3SAT
- Graph Partition
- …

Quantum Chemistry

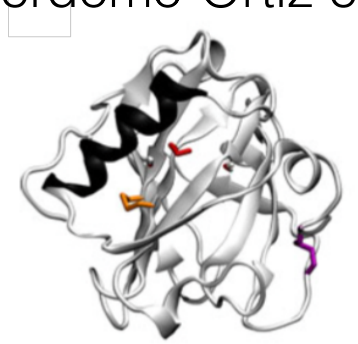
R. Babbush et. al., Sci. Rep. 4, 6603 (2014).



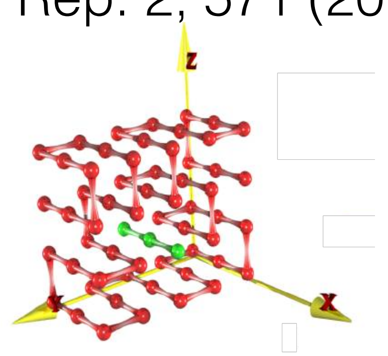
Picture: E. Meijer, University of Amsterdam.

Protein Folding

A. Perdomo-Ortiz et. al., Sci. Rep. 2, 571 (2012).



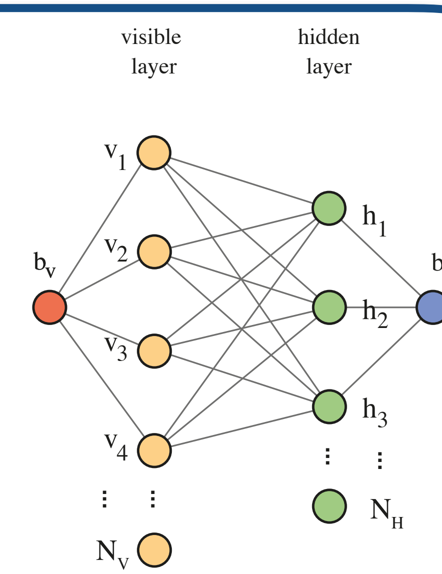
e.g. beta-lactoglobolin (milk protein)
Picture: Peter Bolhuis



I. Coluzza, et.al. Biophys. J. (2007).

Machine Learning

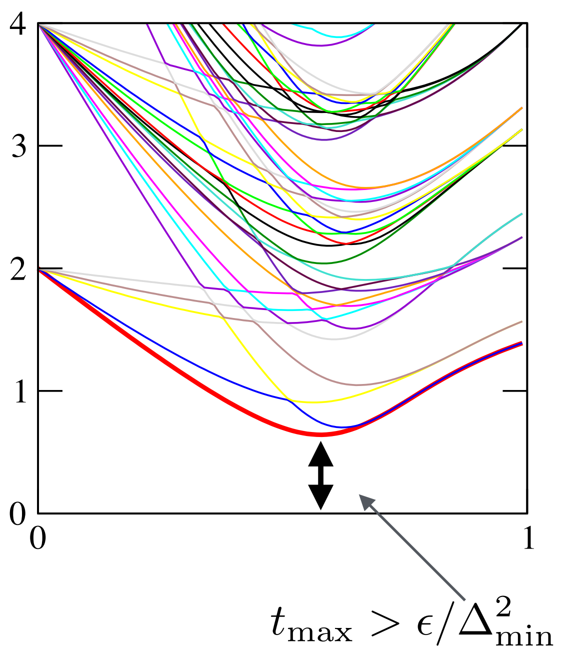
G. Hinton et. al.,
Restricted Boltzmann Machines



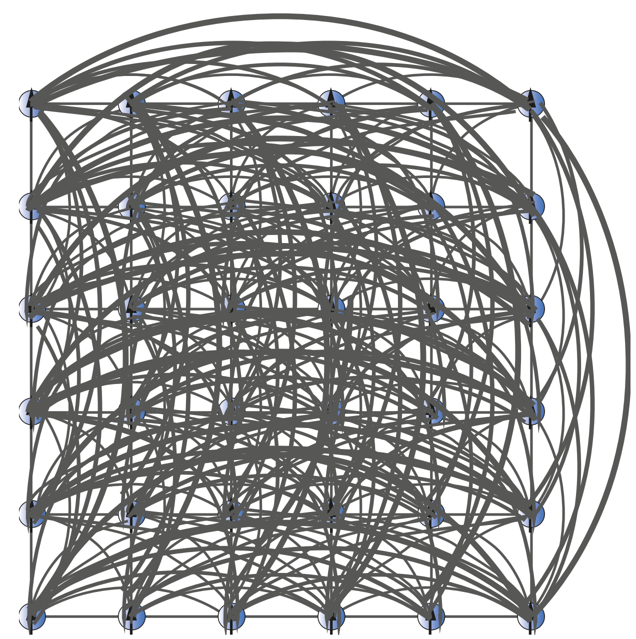
Adiabatic Quantum Computing

Challenges:

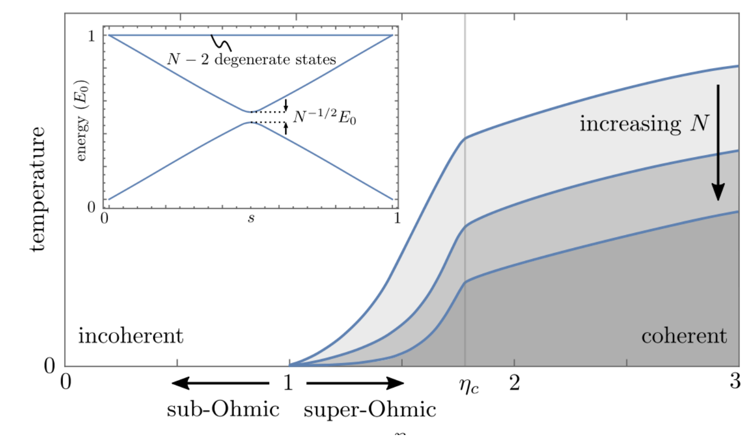
Minimal gap



Connectivity

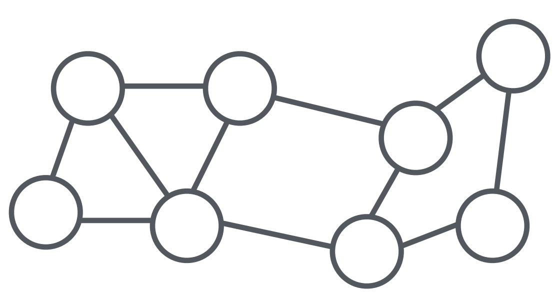


Finite temperature

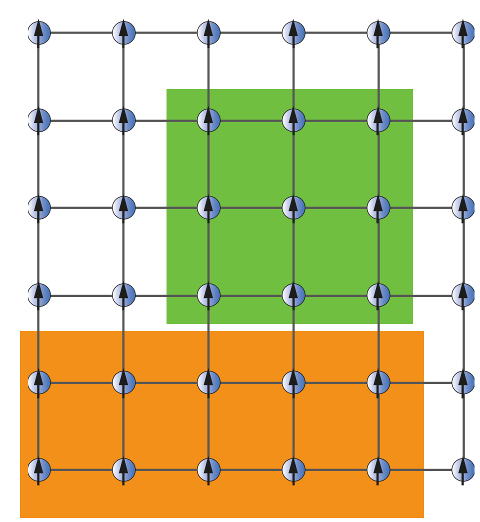


D. Wild et. al.,
Phys. Rev. Lett. , 117, 150501 (2016).

n-body terms

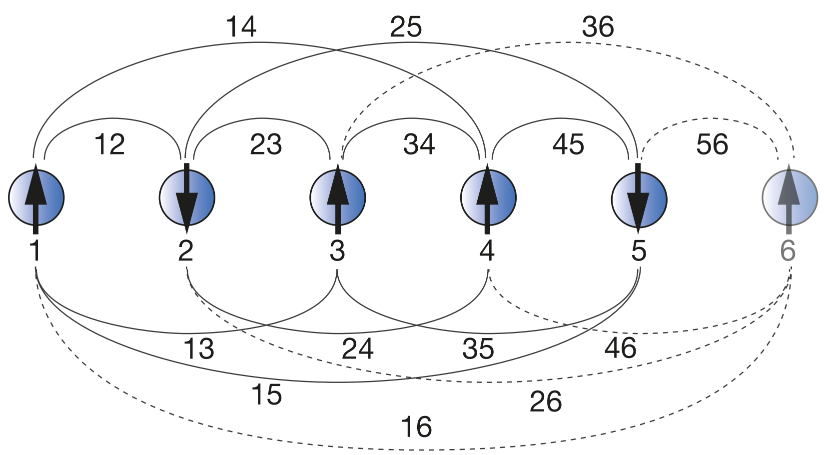


Fault tolerance



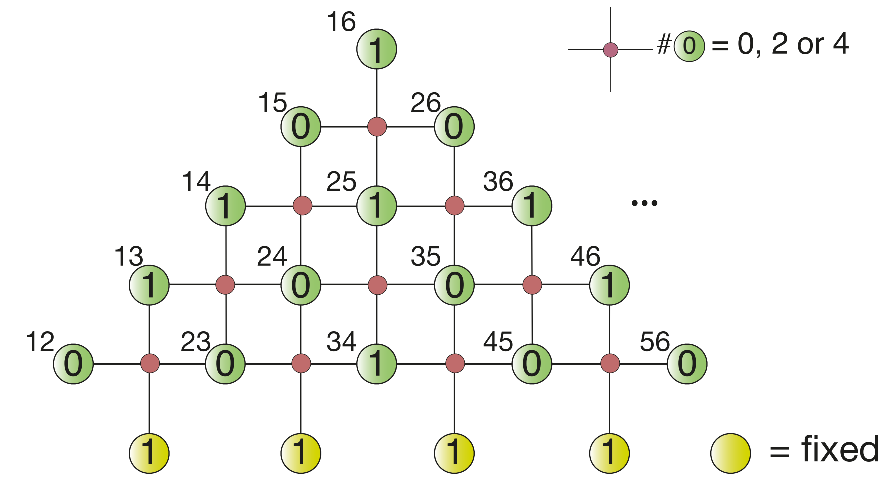
Parity Adiabatic Quantum Computing

Spin glass paradigm



$$\mathcal{H}(t) = A(t)\sum_{i}^{N} b_i\sigma_x^{(i)} + B(t)\left[\sum_{i=1}^{N} h_i\sigma_z^{(i)} + \sum_{i=1}^{N}\sum_{j=1}^{i} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}\right]$$

Parity constraints

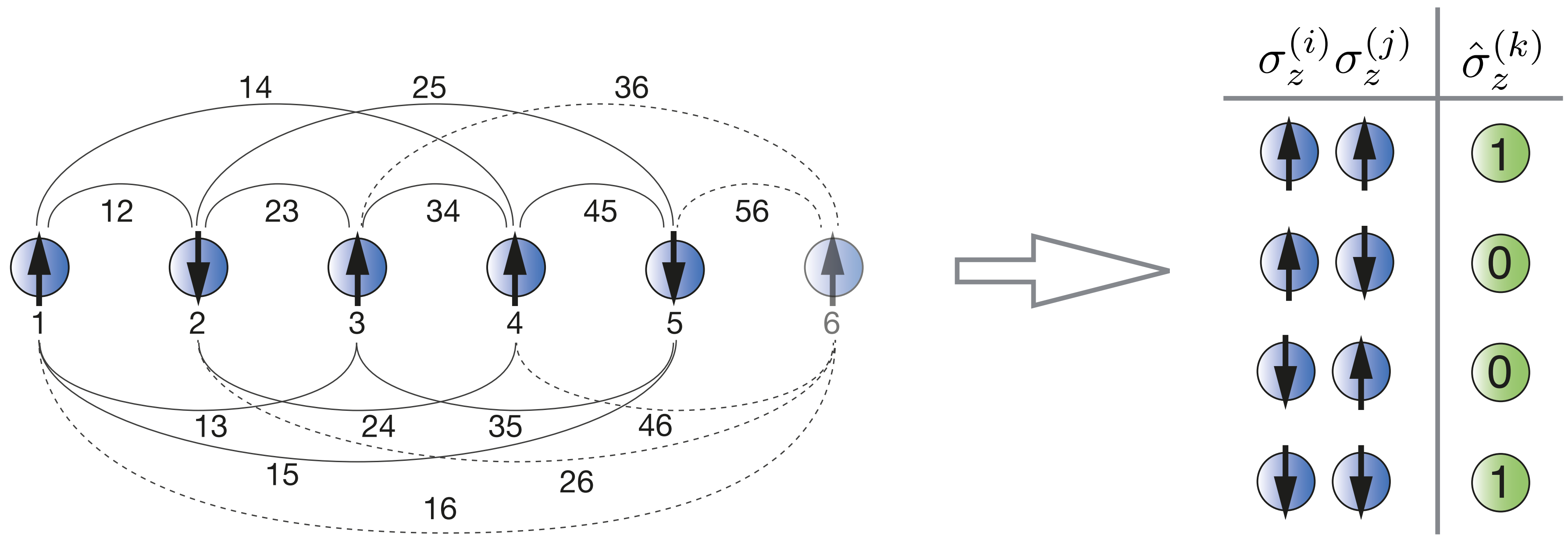


$$\mathcal{H}(t) = A(t)\sum_{i=1}^{K} b_i\sigma_x^{(i)} + B(t)\sum_{i=1}^{K} J_i\sigma_z^{(i)} + C(t)\sum_{l=1}^{K-N} C_l$$

WL, P. Hauke, P. Zoller, Science Advances 1, 1500838 (2015).

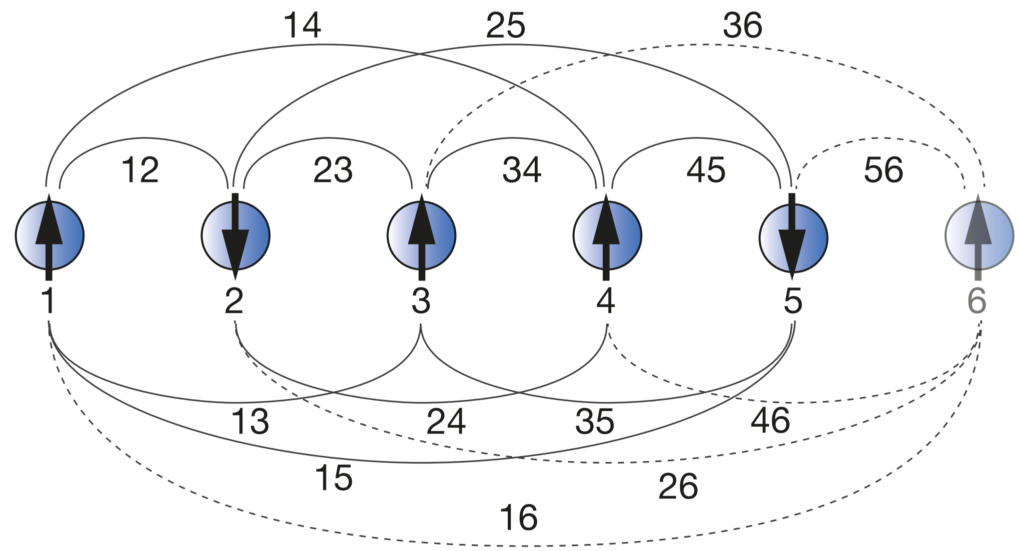
- abstraction of logical from physical qubits
- encode **all-to-all interaction matrix** in local fields
- architecture comprises **problem-independent**, **local interaction**
- can be realized in current **qubit platform**
  (e.g. flux qubits, transmon qubits, ultracold atoms, hybrids systems,…)
- **classical error tolerance** from redundant encoding
- **k-body terms**

All-to-all programmable architecture



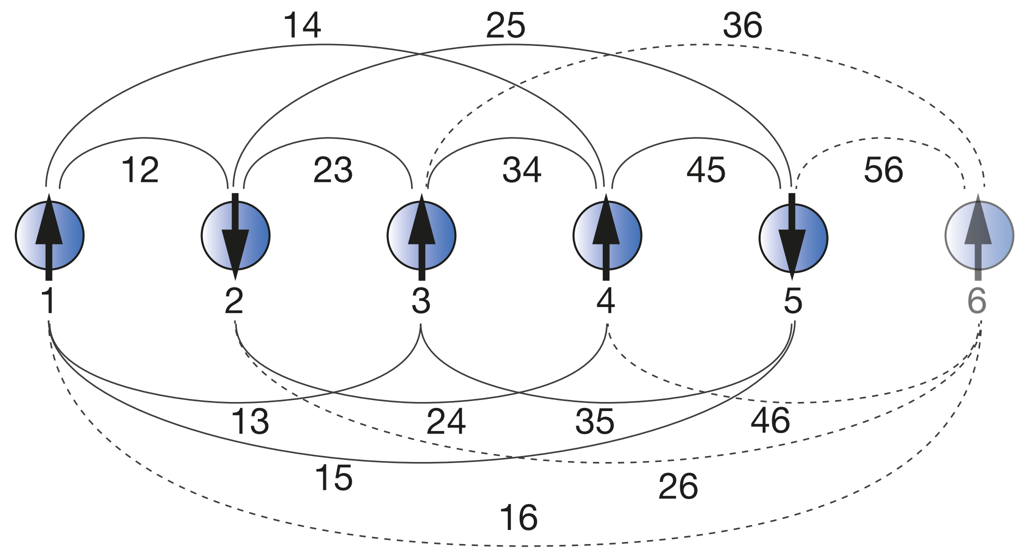
Physical qubits $\hat{\sigma}_z^{(k)}$ represent parity of **logical qubits.**

All-to-all programmable architecture



$$\mathcal{H} = \sum_{i=1}^{N} \sum_{j=1}^{i} J_{ij} \sigma_z^{(i)} \sigma_z^{(j)} \Longrightarrow \sum_{i=1}^{K} J_i \hat{\sigma}_z^{(i)}$$

All-to-all programmable architecture



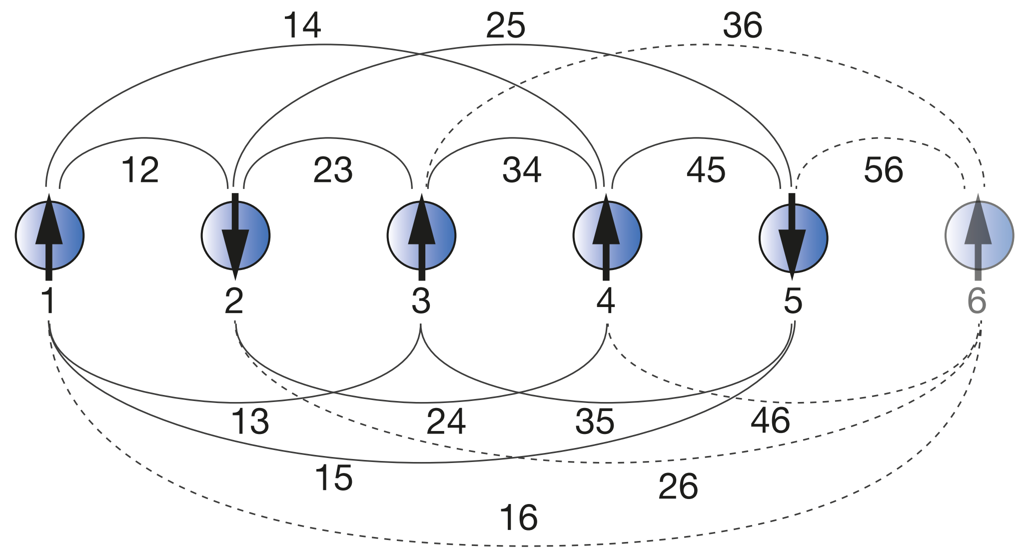
$$\mathcal{H} = \sum_{i=1}^{N} \sum_{j=1}^{i} J_{ij} \sigma_z^{(i)} \sigma_z^{(j)} \Longrightarrow \sum_{i=1}^{K} J_i \hat{\sigma}_z^{(i)}$$

N degrees of freedom

$$K = \frac{N(N-1)}{2}$$

degrees of freedom

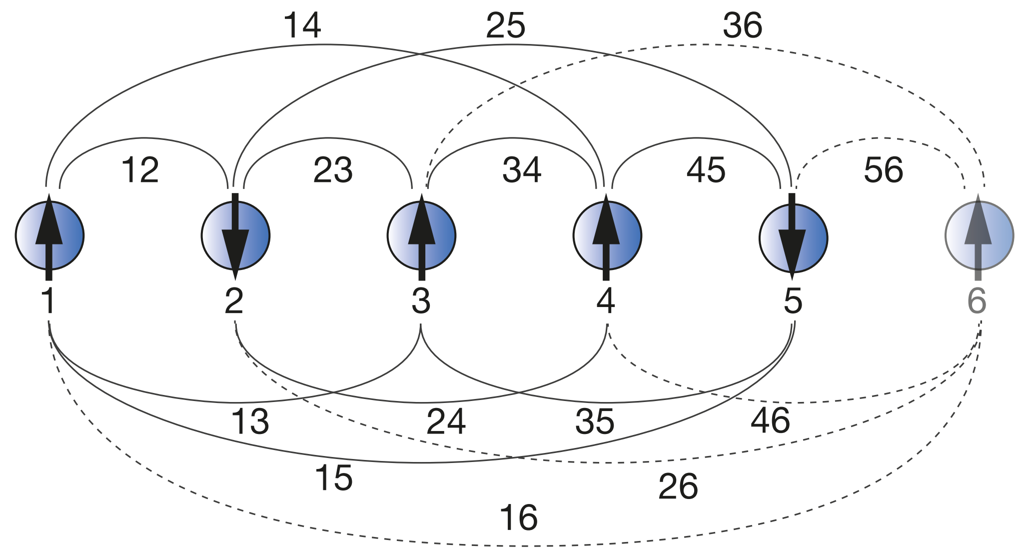
All-to-all programmable architecture



$$\mathcal{H} = \sum_{i=1}^{N} \sum_{j=1}^{i} J_{ij} \sigma_z^{(i)} \sigma_z^{(j)} \Longrightarrow \sum_{i=1}^{K} J_i \hat{\sigma}_z^{(i)} + \sum_{l=1}^{K-N} C_l$$

K-N constraints

All-to-all programmable architecture



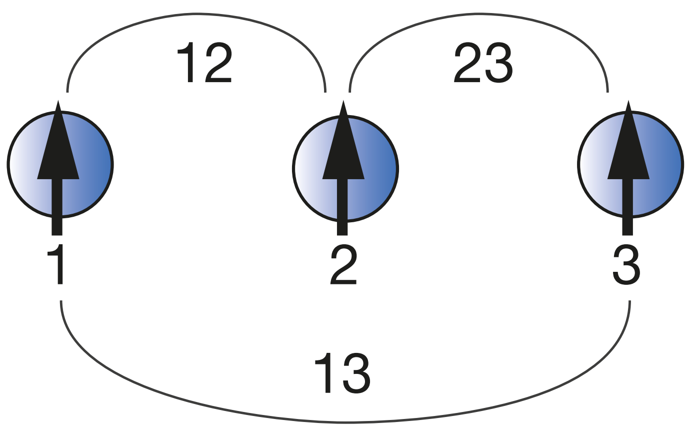
$$\mathcal{H} = \sum_{i=1}^{N}\sum_{j=1}^{i} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)} \Longrightarrow \sum_{i=1}^{K} J_i \hat{\sigma}_z^{(i)} + \sum_{l=1}^{K-N} C_l$$

K-N constraints

What are these constraints?

Constraints

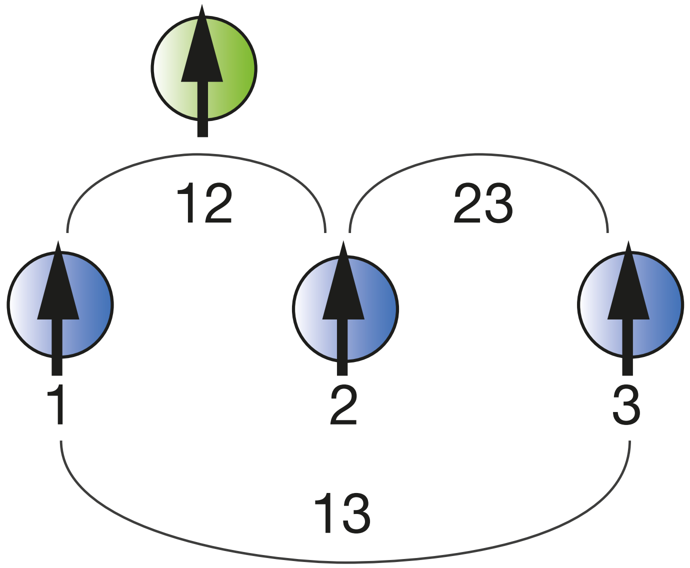
Conditions on closed loops



$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(3)}$	$\hat{\sigma}_z^{(12)}$	$\hat{\sigma}_z^{(13)}$	$\hat{\sigma}_z^{(23)}$
1	1	1			

Constraints

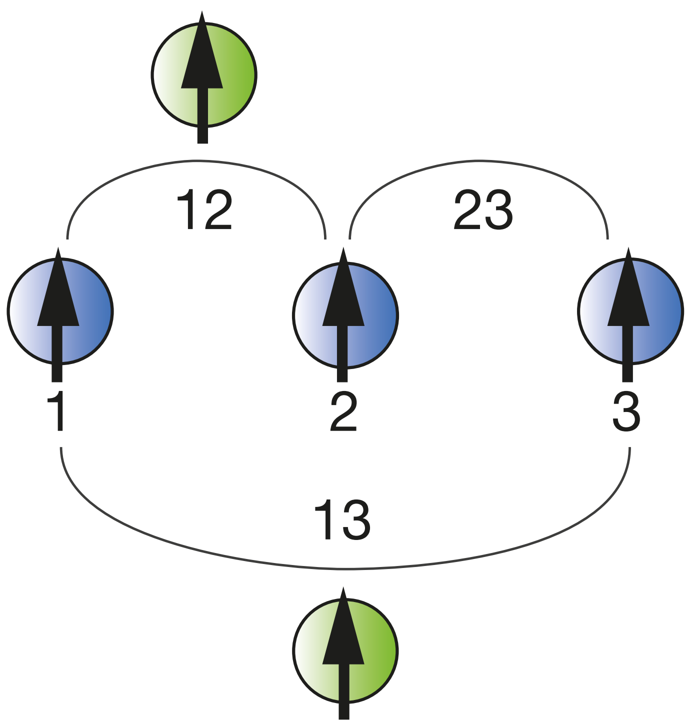
Conditions on closed loops



$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(3)}$	$\hat{\sigma}_z^{(12)}$	$\hat{\sigma}_z^{(13)}$	$\hat{\sigma}_z^{(23)}$
1	1	1	1		

Constraints

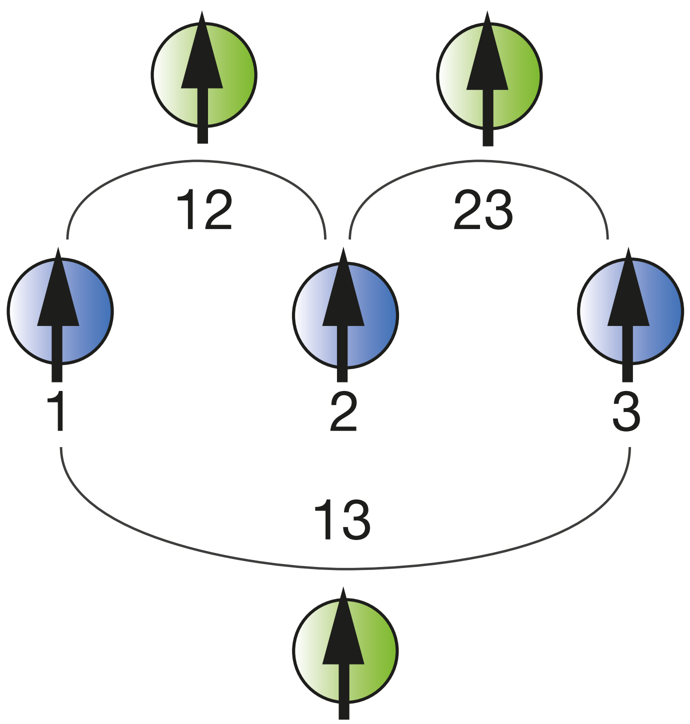
Conditions on closed loops



$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(3)}$	$\hat{\sigma}_z^{(12)}$	$\hat{\sigma}_z^{(13)}$	$\hat{\sigma}_z^{(23)}$
1	1	1	1	1	

Constraints

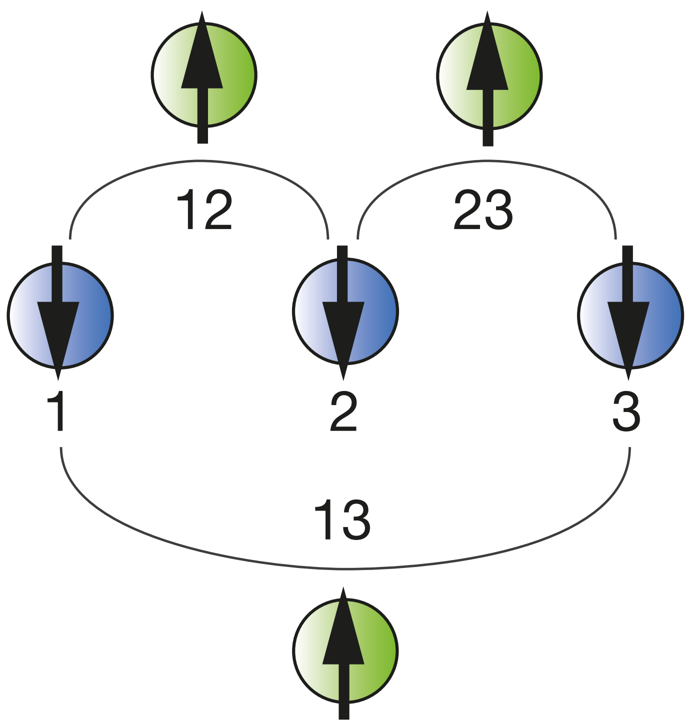
Conditions on closed loops



$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(3)}$	$\hat{\sigma}_z^{(12)}$	$\hat{\sigma}_z^{(13)}$	$\hat{\sigma}_z^{(23)}$
1	1	1	1	1	1

Constraints

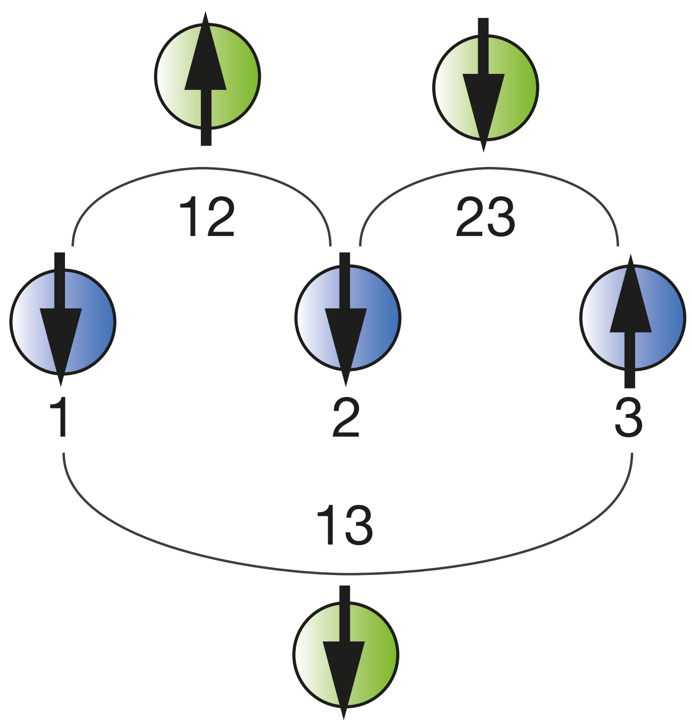
Conditions on closed loops



$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(3)}$	$\hat{\sigma}_z^{(12)}$	$\hat{\sigma}_z^{(13)}$	$\hat{\sigma}_z^{(23)}$
1	1	1	1	1	1
0	0	0	1	1	1

Constraints

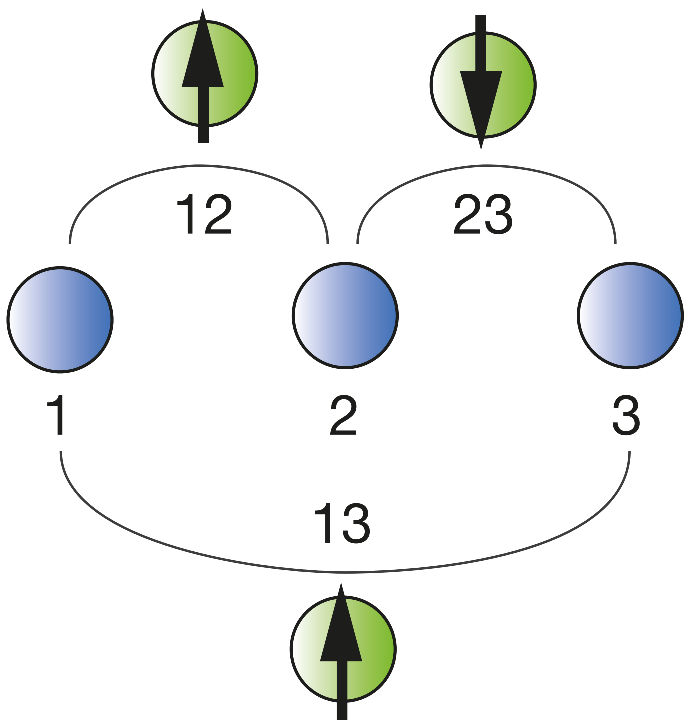
Conditions on closed loops



$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(3)}$	$\hat{\sigma}_z^{(12)}$	$\hat{\sigma}_z^{(13)}$	$\hat{\sigma}_z^{(23)}$
1	1	1	1	1	1
0	0	0	1	1	1
0	0	1	1	0	0

Constraints

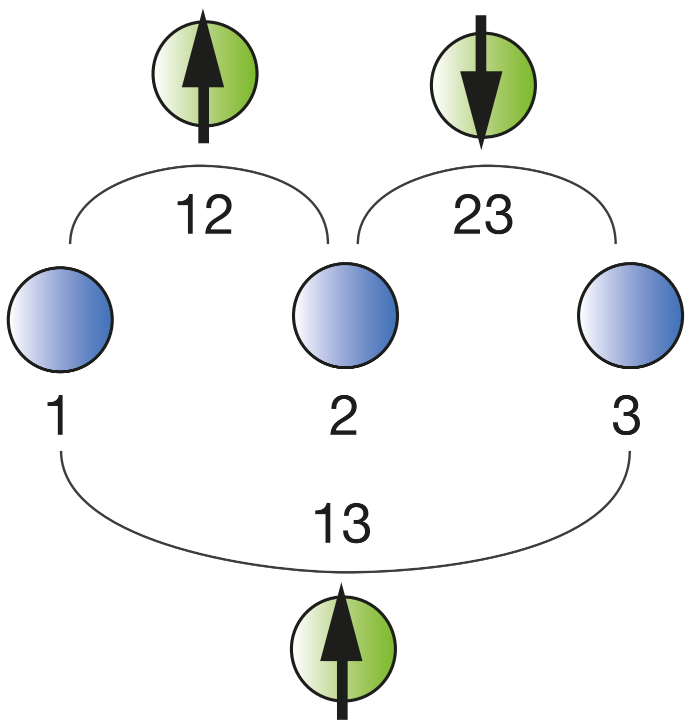
Conditions on closed loops



$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(3)}$	$\hat{\sigma}_z^{(12)}$	$\hat{\sigma}_z^{(13)}$	$\hat{\sigma}_z^{(23)}$
1	1	1	1	1	1
0	0	0	1	1	1
0	0	1	1	0	0
	…			…	
			1	1	0

Constraints

Conditions on closed loops

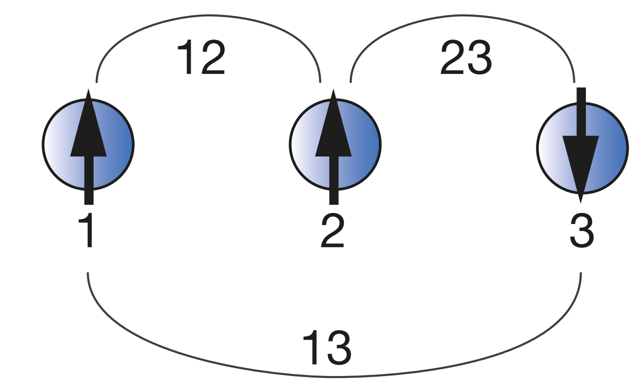


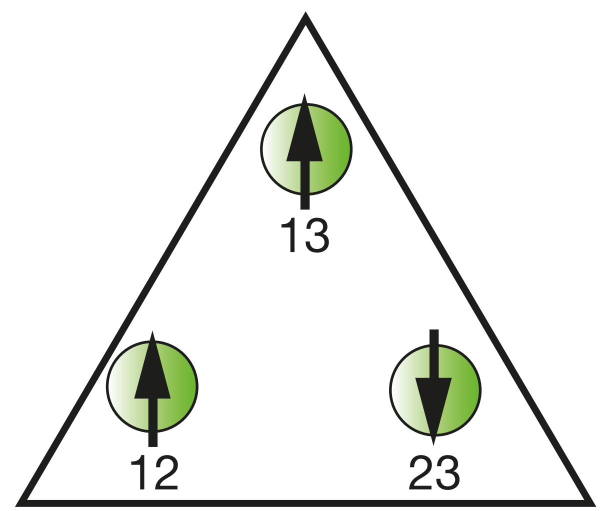
$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(3)}$	$\hat{\sigma}_z^{(12)}$	$\hat{\sigma}_z^{(13)}$	$\hat{\sigma}_z^{(23)}$
1	1	1	1	1	1
0	0	0	1	1	1
0	0	1	1	0	0
	$\dots$			$\dots$	
			1	1	0

In **each closed loop**, the number of **spin-down** has to be an **even** number or 0.

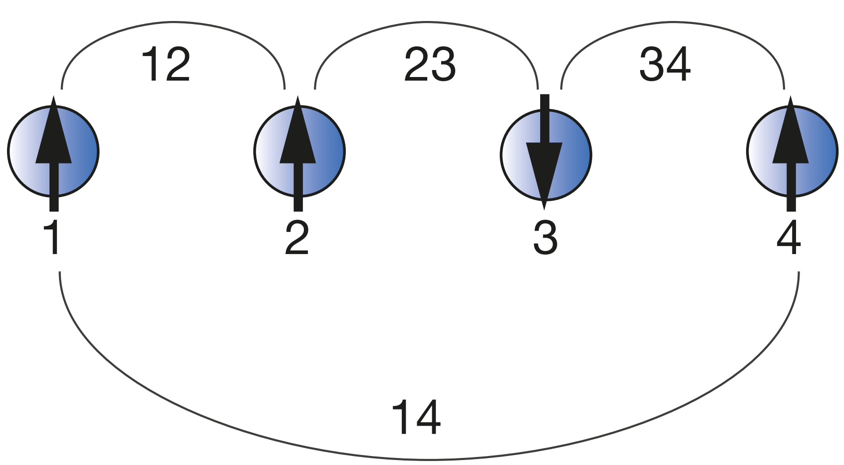
Constraints (Implementation)

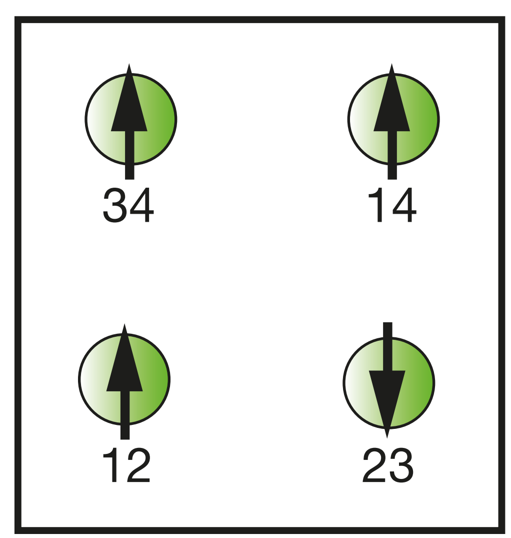
Logical Qubits	Physical Qubits





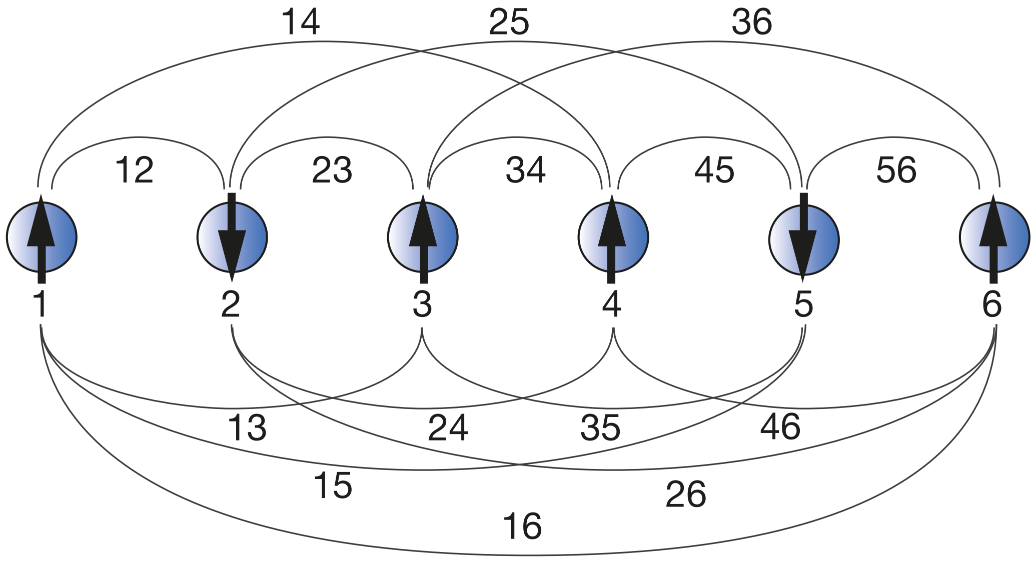
$$C_l = -C\hat{\sigma}_z^{(12)}\hat{\sigma}_z^{(23)}\hat{\sigma}_z^{(13)}$$





$$C_l = -C\hat{\sigma}_z^{(12)}\hat{\sigma}_z^{(23)}\hat{\sigma}_z^{(34)}\hat{\sigma}_z^{(14)}$$

Constraints



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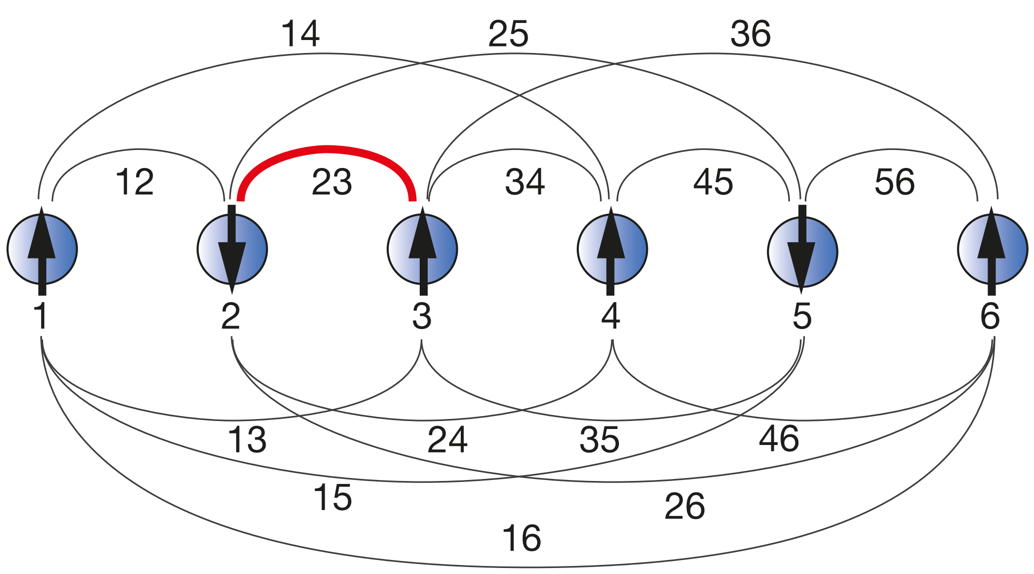

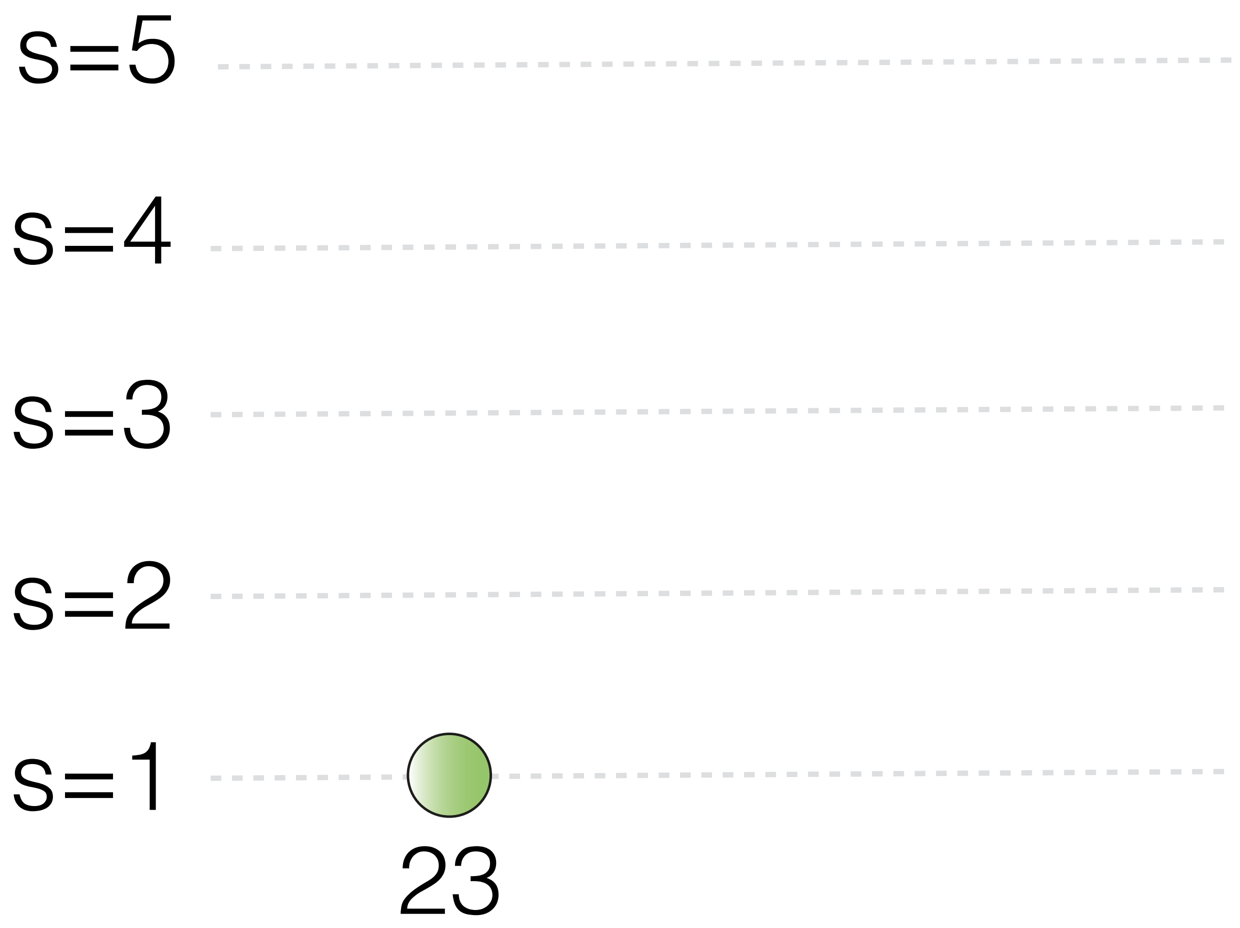

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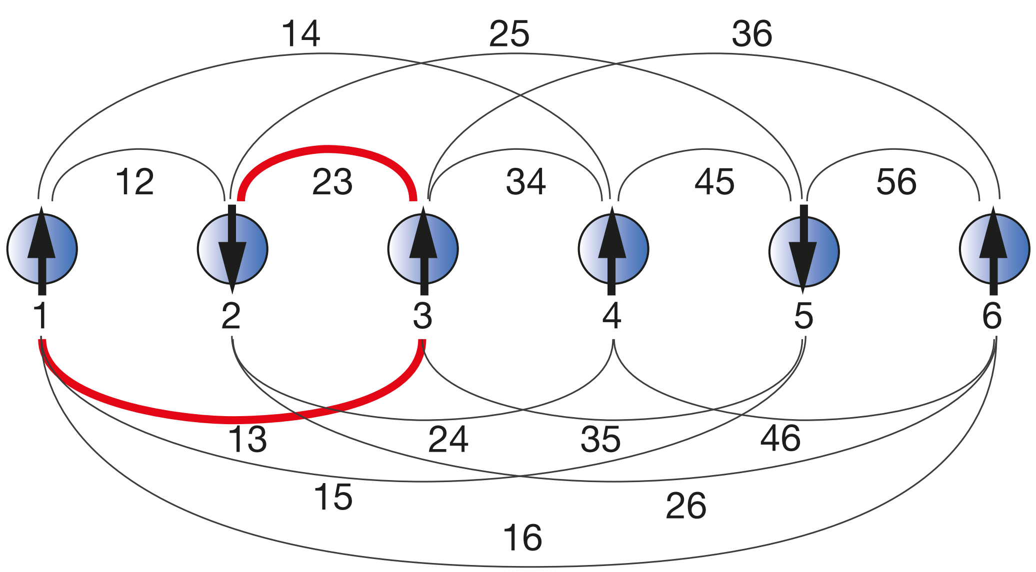

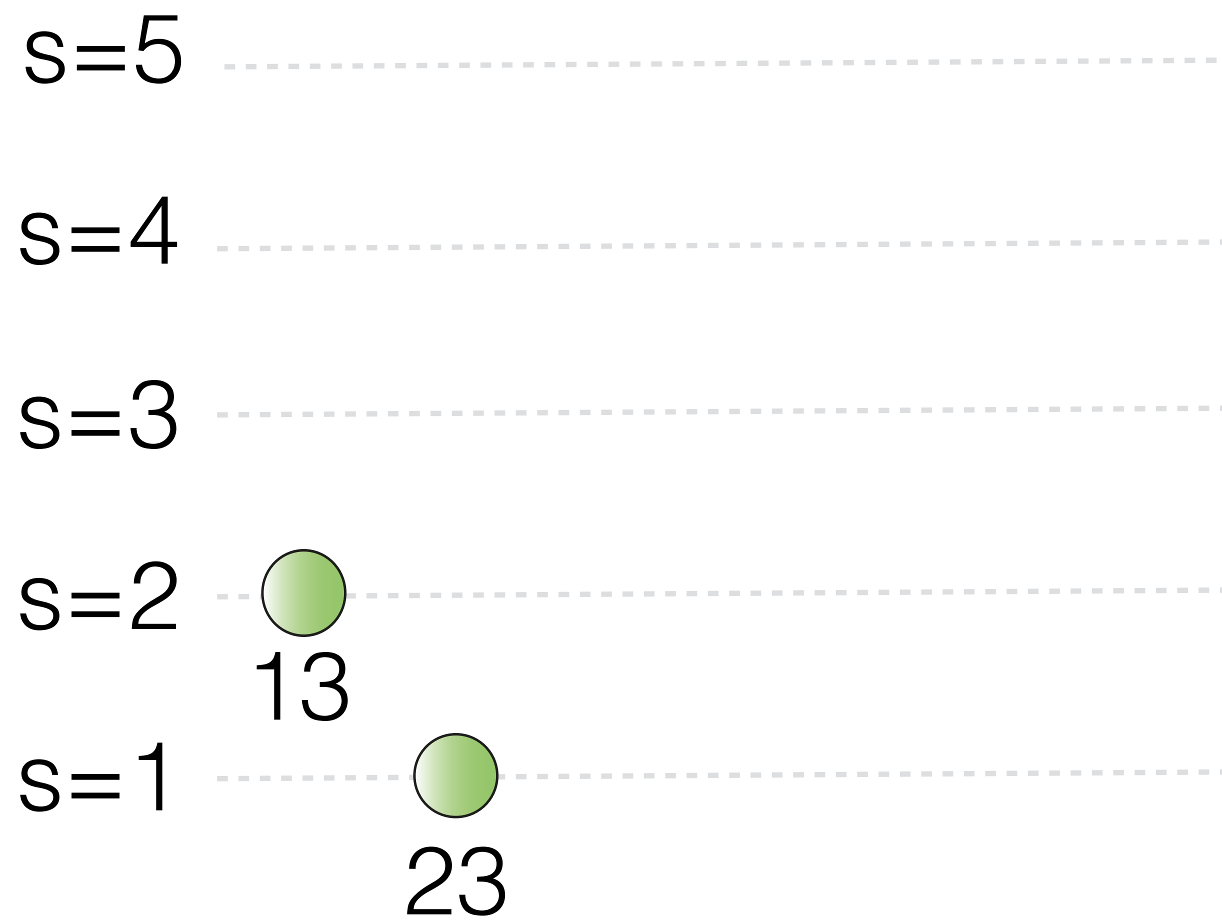

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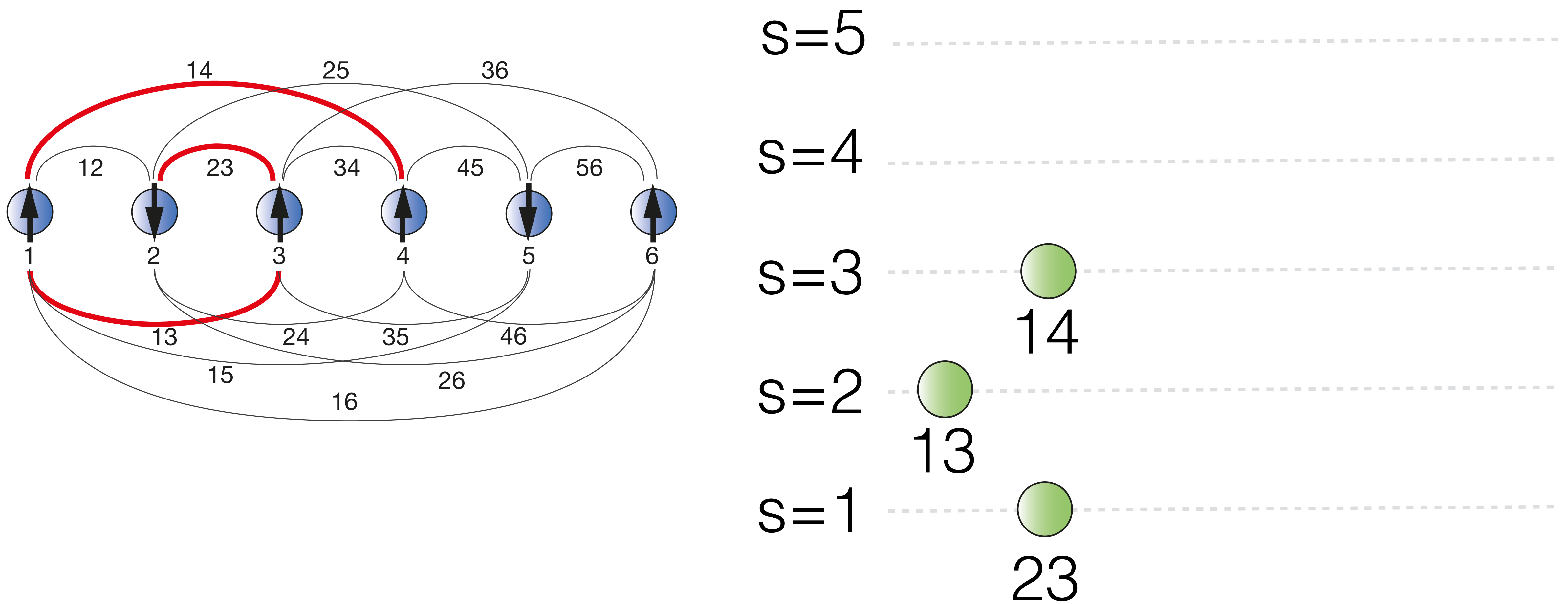
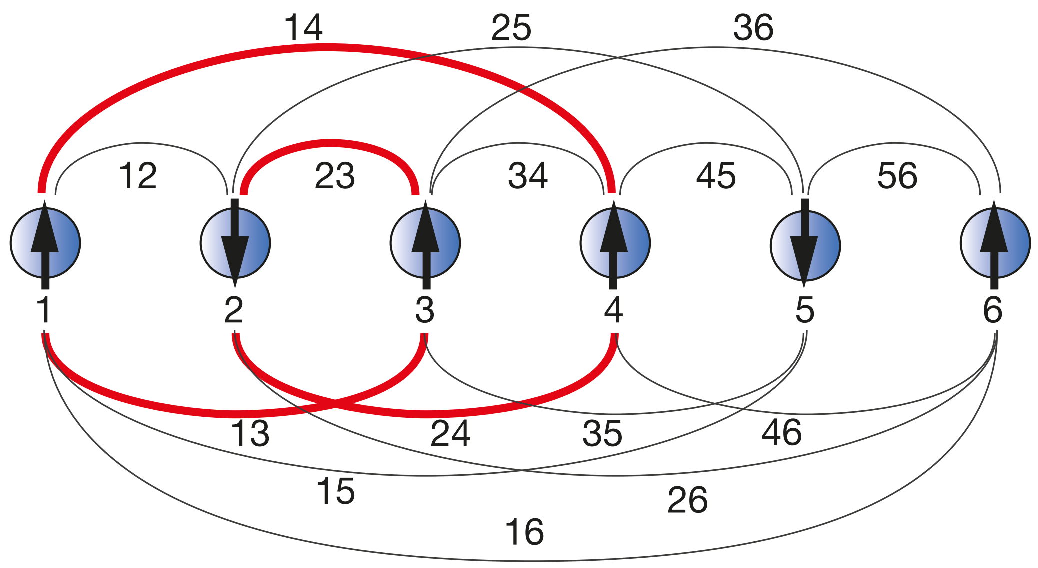
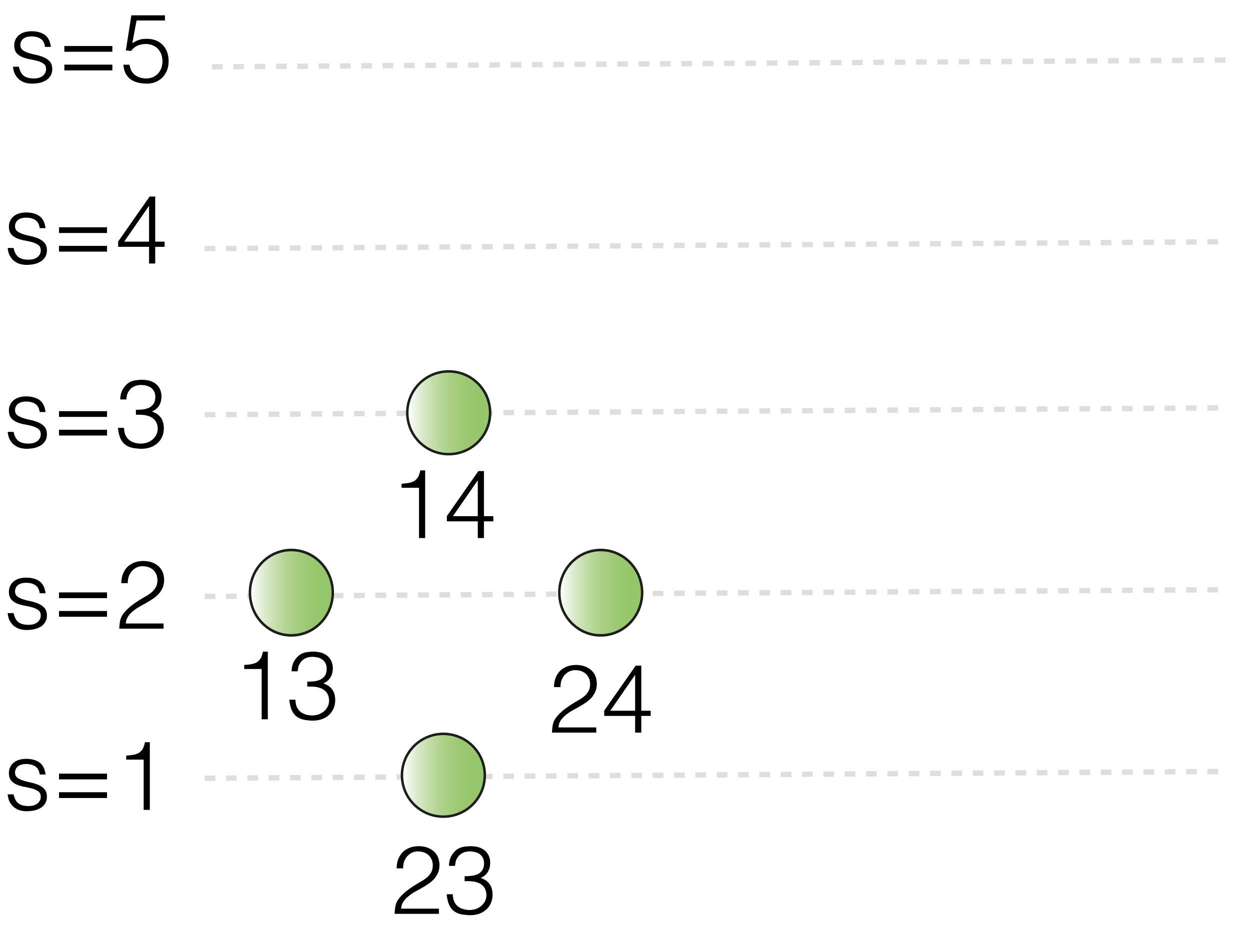


Constraints





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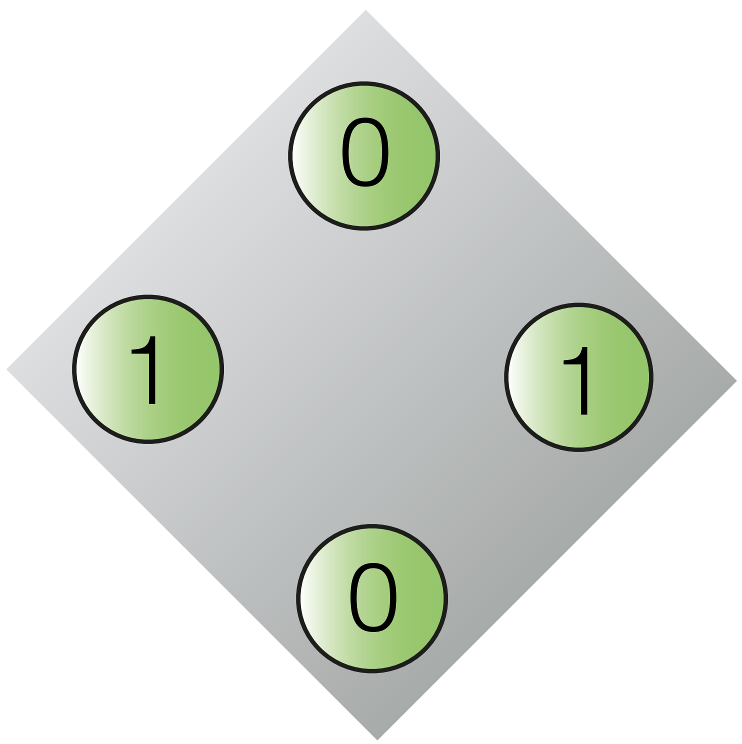
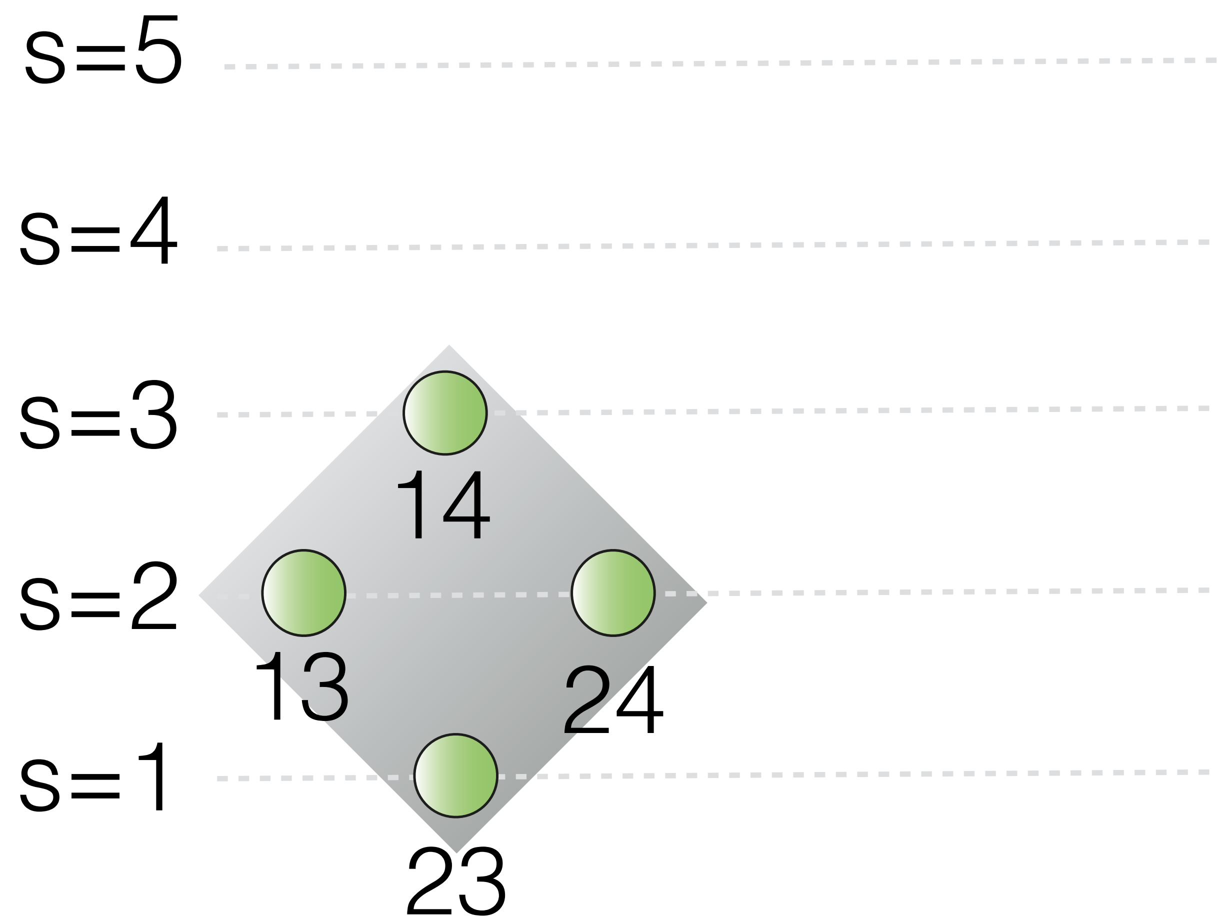
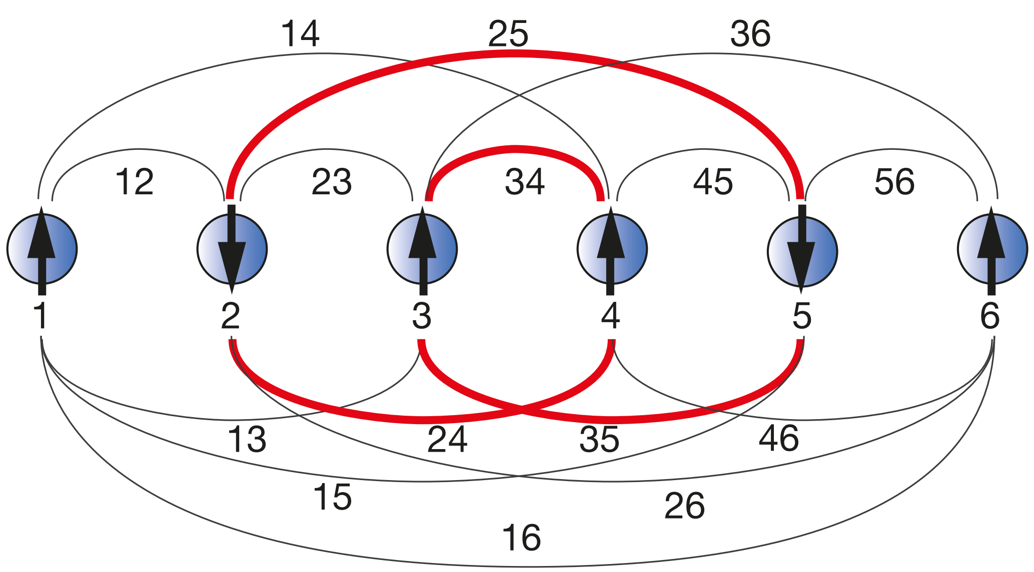


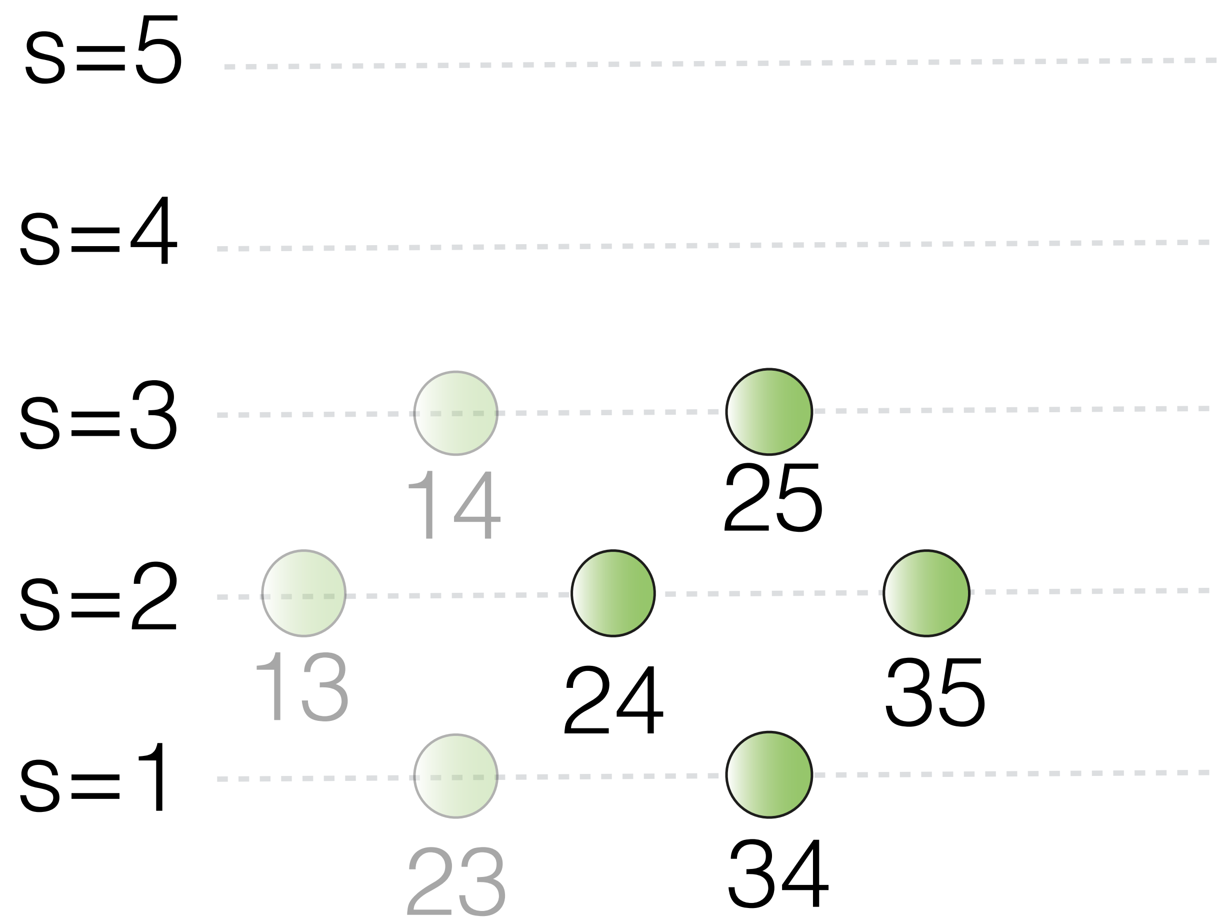
Number of spin-down
is even



$$C_l = -C\left(\sum_{m=n,e,s,w} \tilde{\sigma}_z^{(l,m)} + S_z^l\right)^2 = -C\tilde{\sigma}_z^{(l,n)}\tilde{\sigma}_z^{(l,e)}\tilde{\sigma}_z^{(l,s)}\tilde{\sigma}_z^{(l,w)}$$

Constraints





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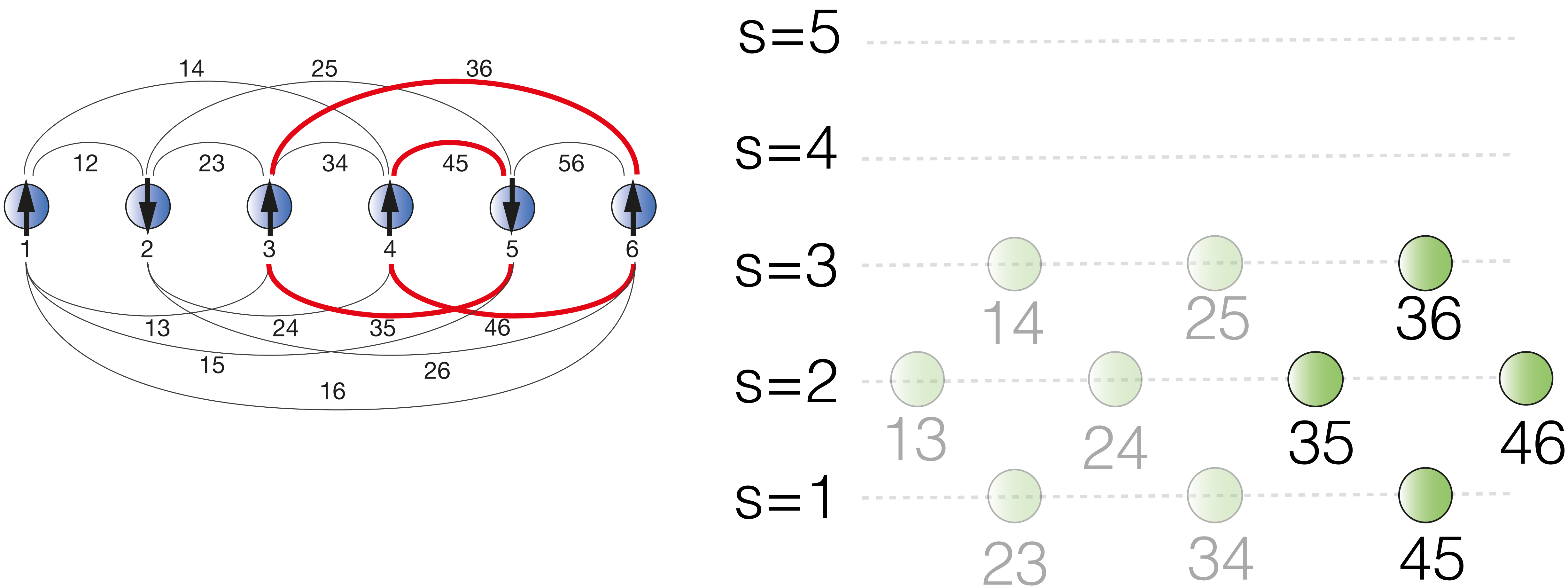

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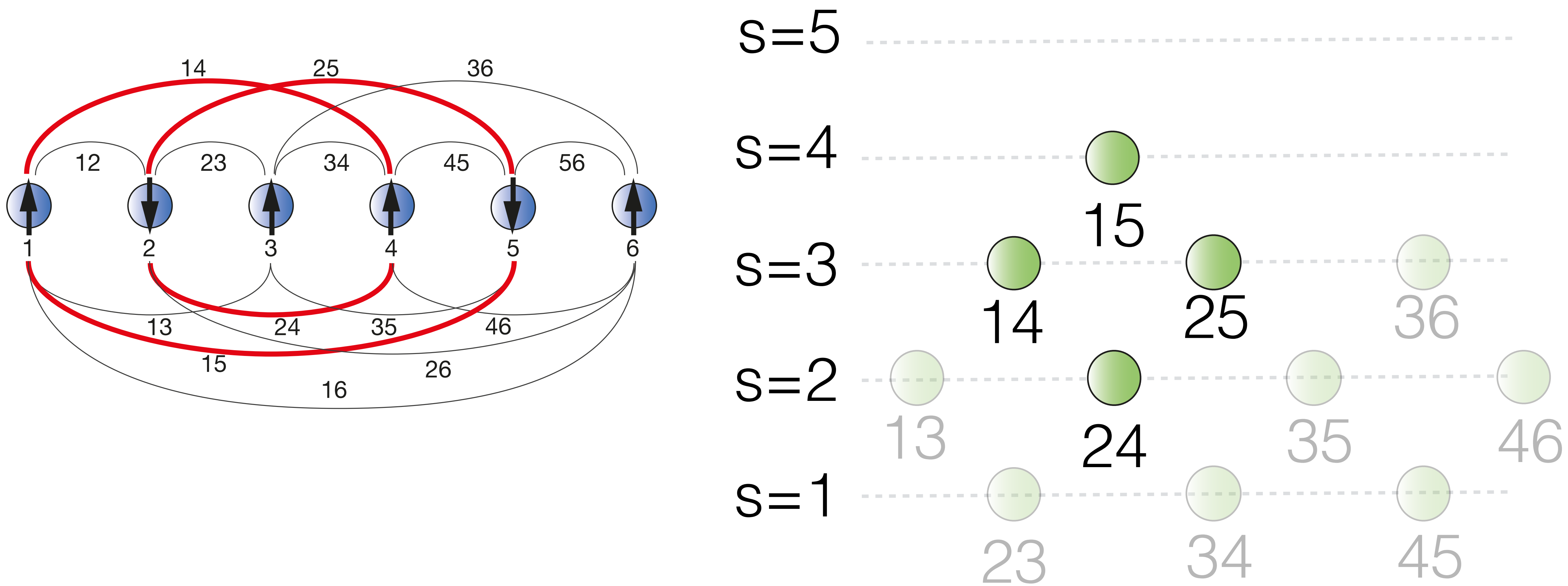

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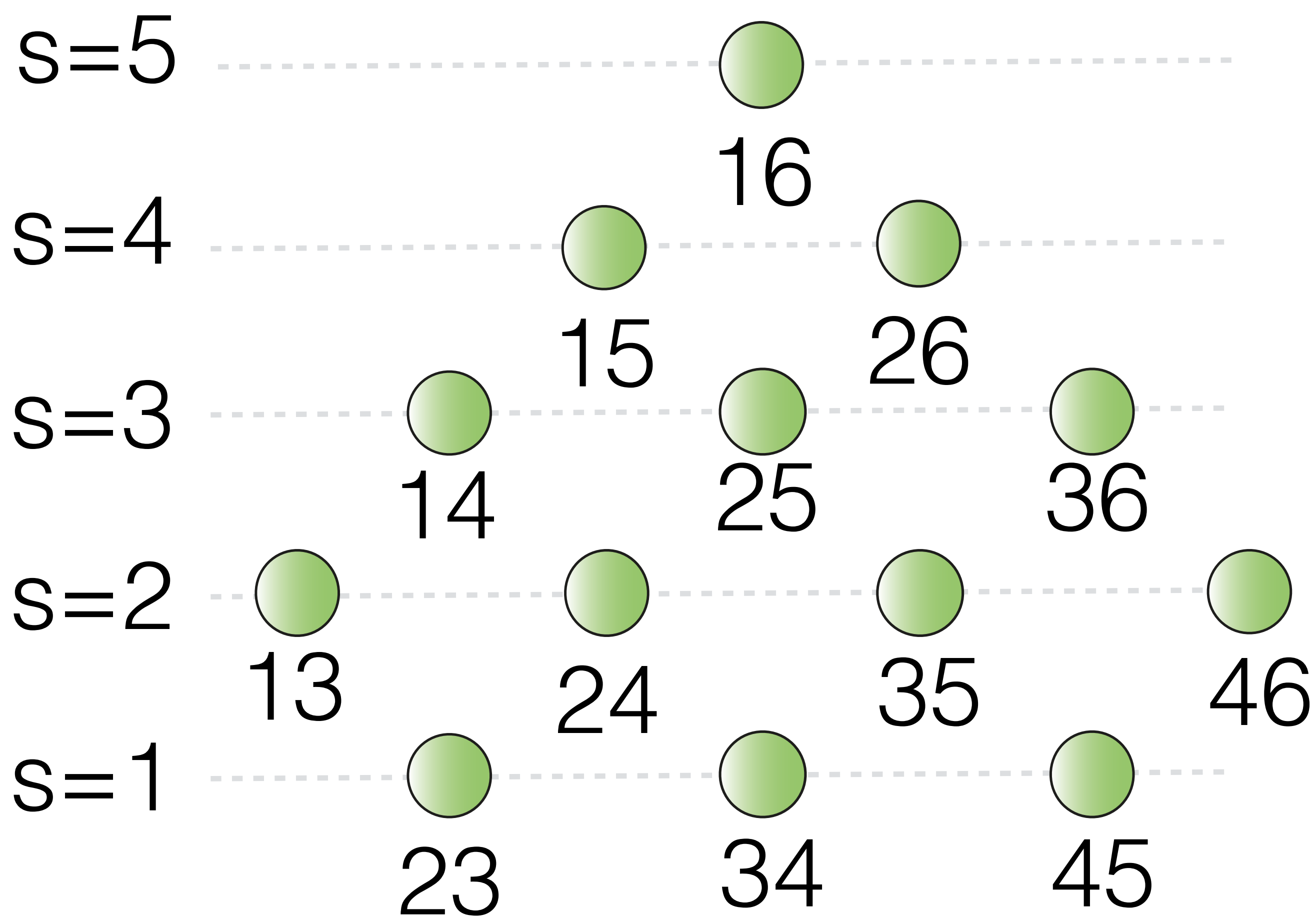
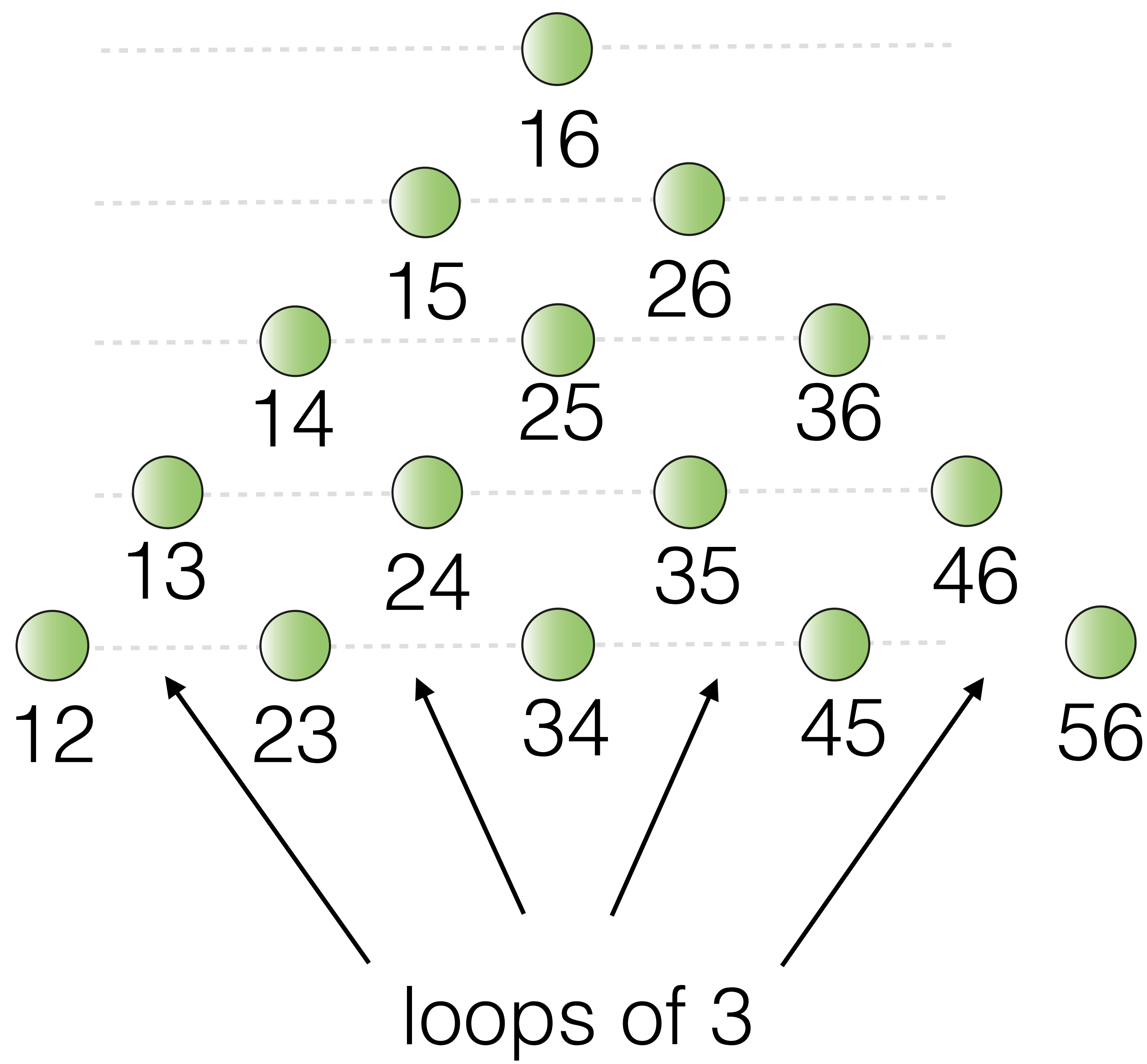


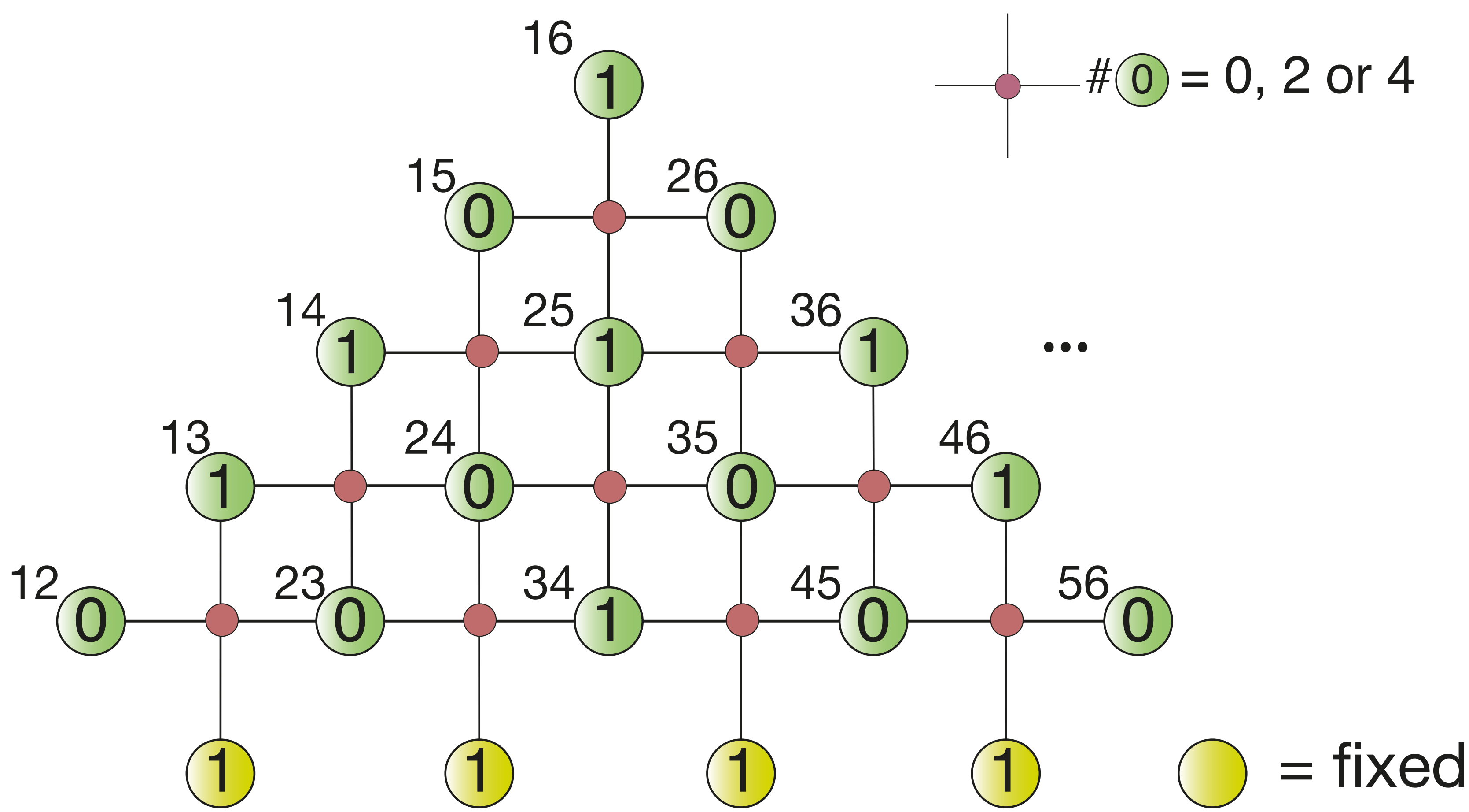
Constraints



Parity AQC

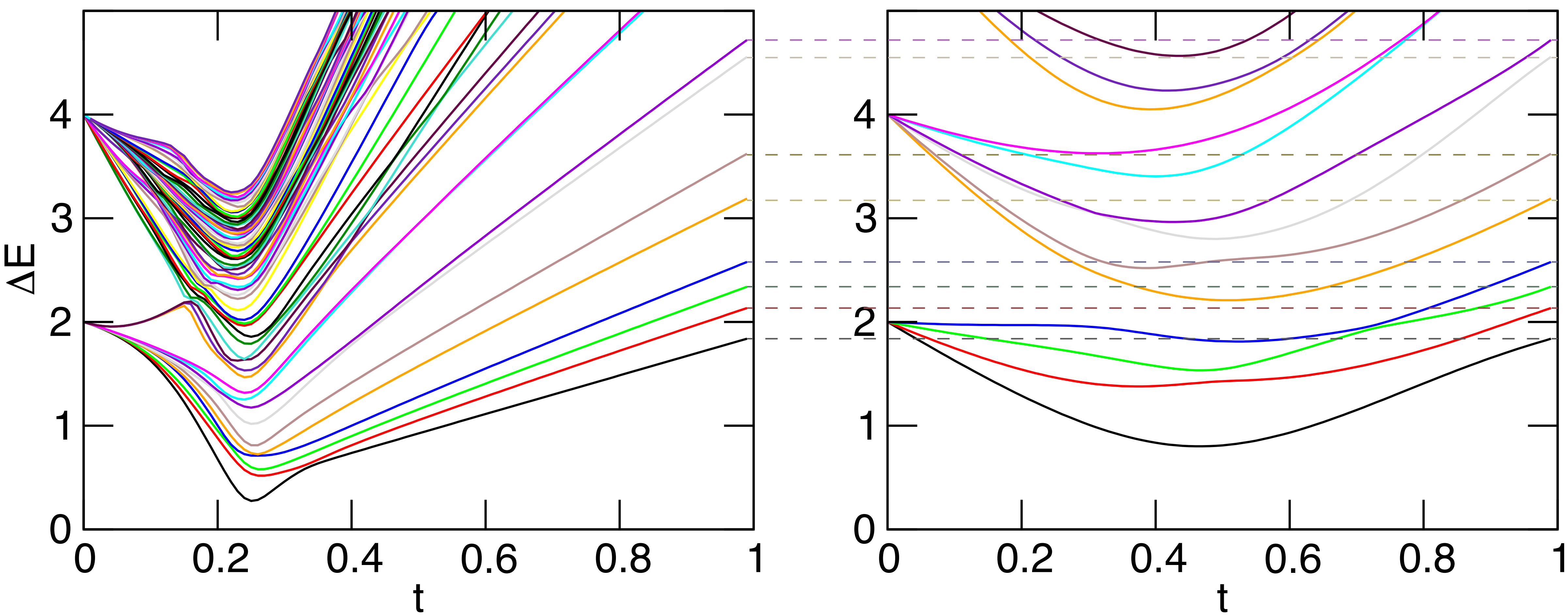
$$\mathcal{H}(t) = A(t)\sum_{i=1}^{K} b_i \sigma_x^{(i)} + B(t)\sum_{i=1}^{K} J_i \sigma_z^{(i)} + C(t)\sum_{l=1}^{K-N} C_l$$

$$K = \frac{N(N-1)}{2} \qquad C_l = -C\tilde{\sigma}_z^{(l,n)}\tilde{\sigma}_z^{(l,e)}\tilde{\sigma}_z^{(l,s)}\tilde{\sigma}_z^{(l,w)}$$



Spectrum

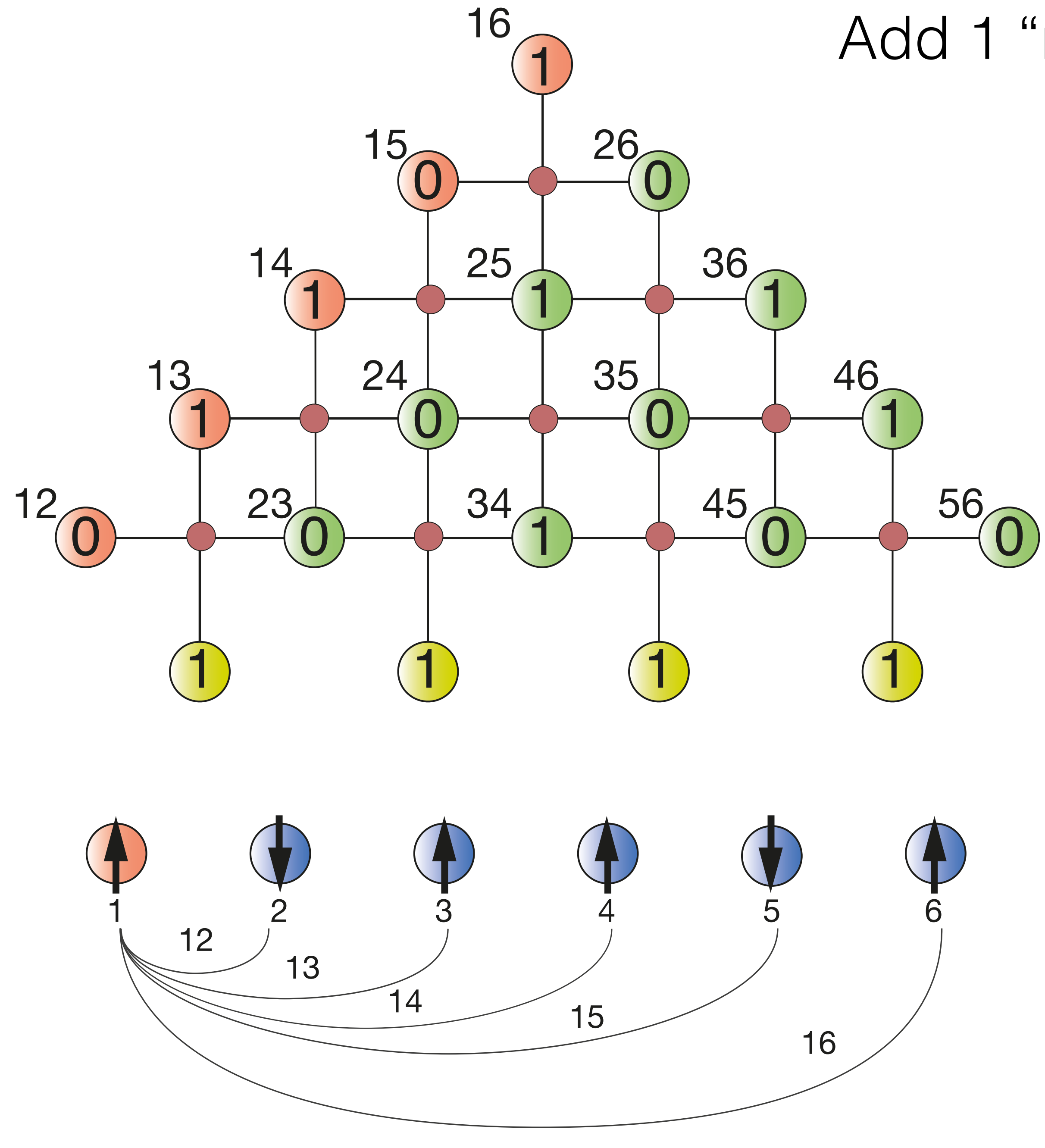
$$H(t) = A(t) \sum_{k=1}^{K} h_k \tilde{\sigma}_x^{(k)} + B(t) \left[\sum_{k=1}^{K} J_k \tilde{\sigma}_z^{(k)} + \sum_{l=1}^{K-N} C_l \right]$$



Magnetic Field term

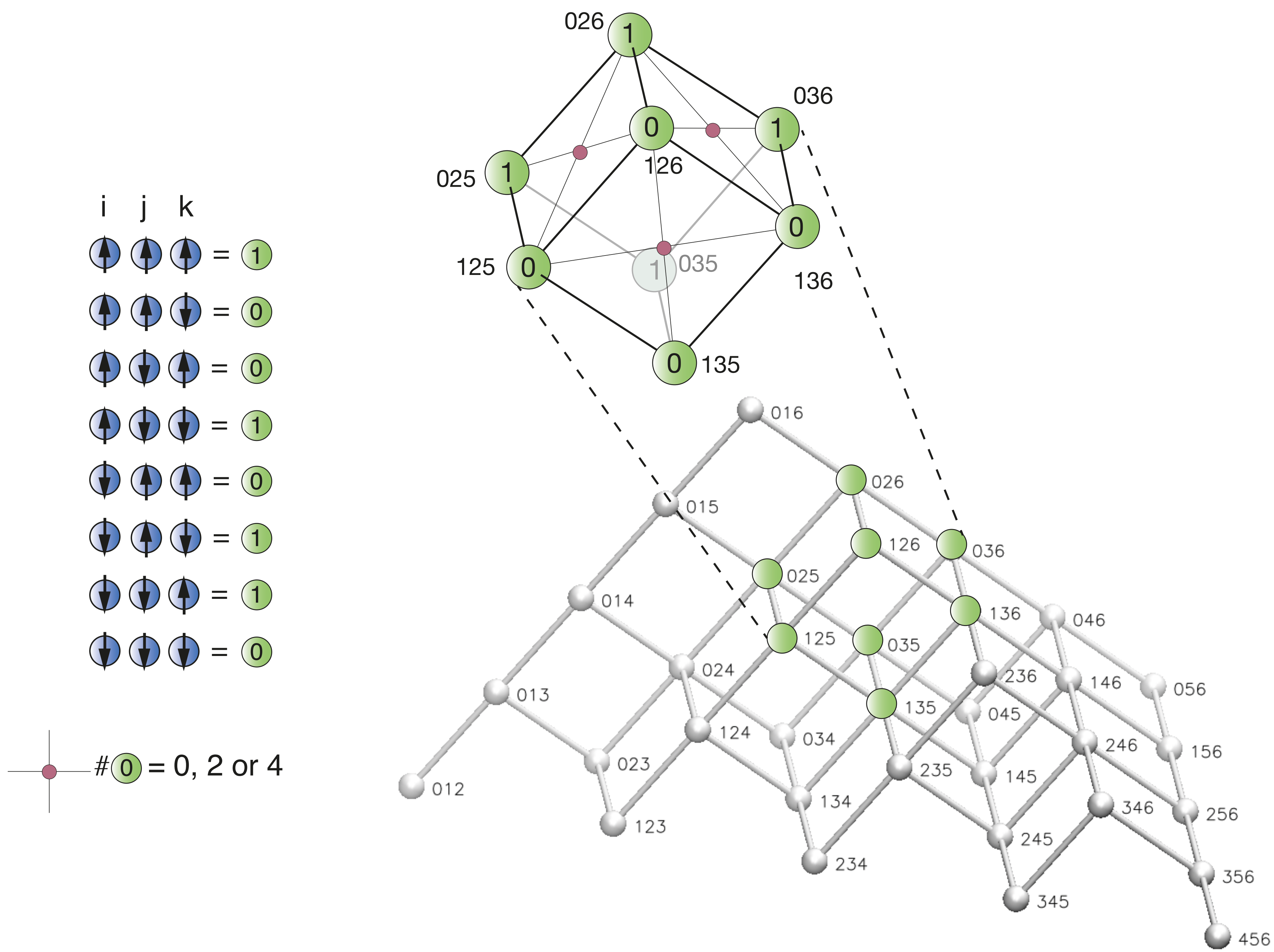
$$H = \sum_{i=1}^{N} h_i \sigma_z^{(i)} + \sum_{i=1}^{N} \sum_{j=1}^{i} J_{ij} \sigma_z^{(i)} \sigma_z^{(j)}$$

Add 1 “row” of qubits.



Three-Body interactions

$$H = \sum_{i=1}^{N} h_i \sigma_z^{(i)} + \sum_{i=1}^{N} \sum_{j=1}^{i} J_{ij} \sigma_z^{(i)} \sigma_z^{(j)} + \sum_{i}^{N} \sum_{j}^{i} \sum_{k}^{j} J_{ijk} \sigma_z^{(i)} \sigma_z^{(j)} \sigma_z^{(k)}$$



Error correction

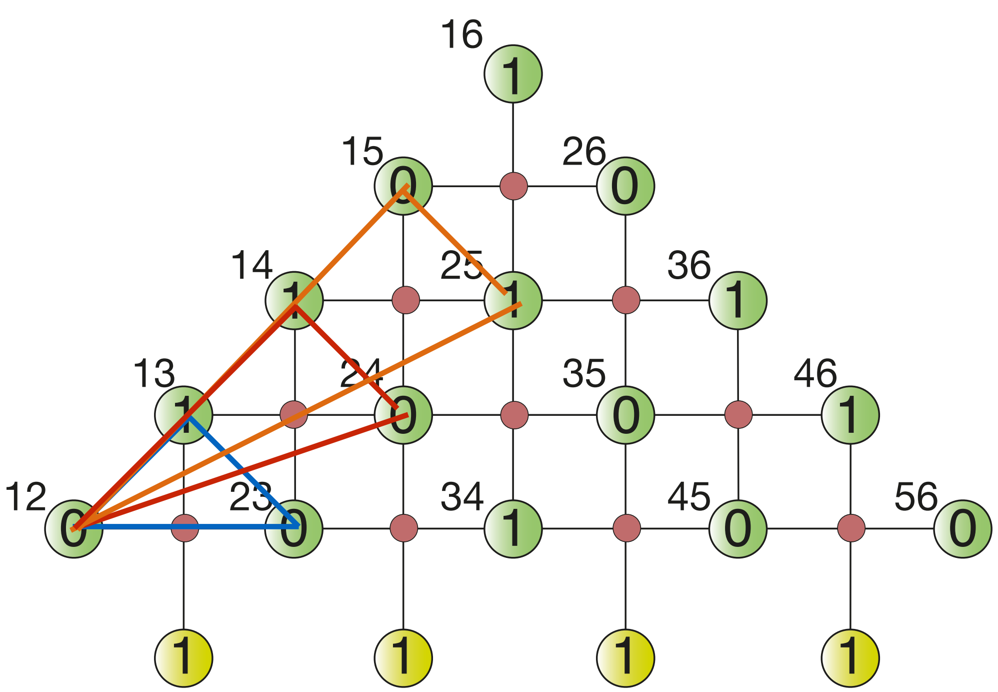
Fernando Pastawski, John Preskill, Physical Review A 93, 052325 (2015).

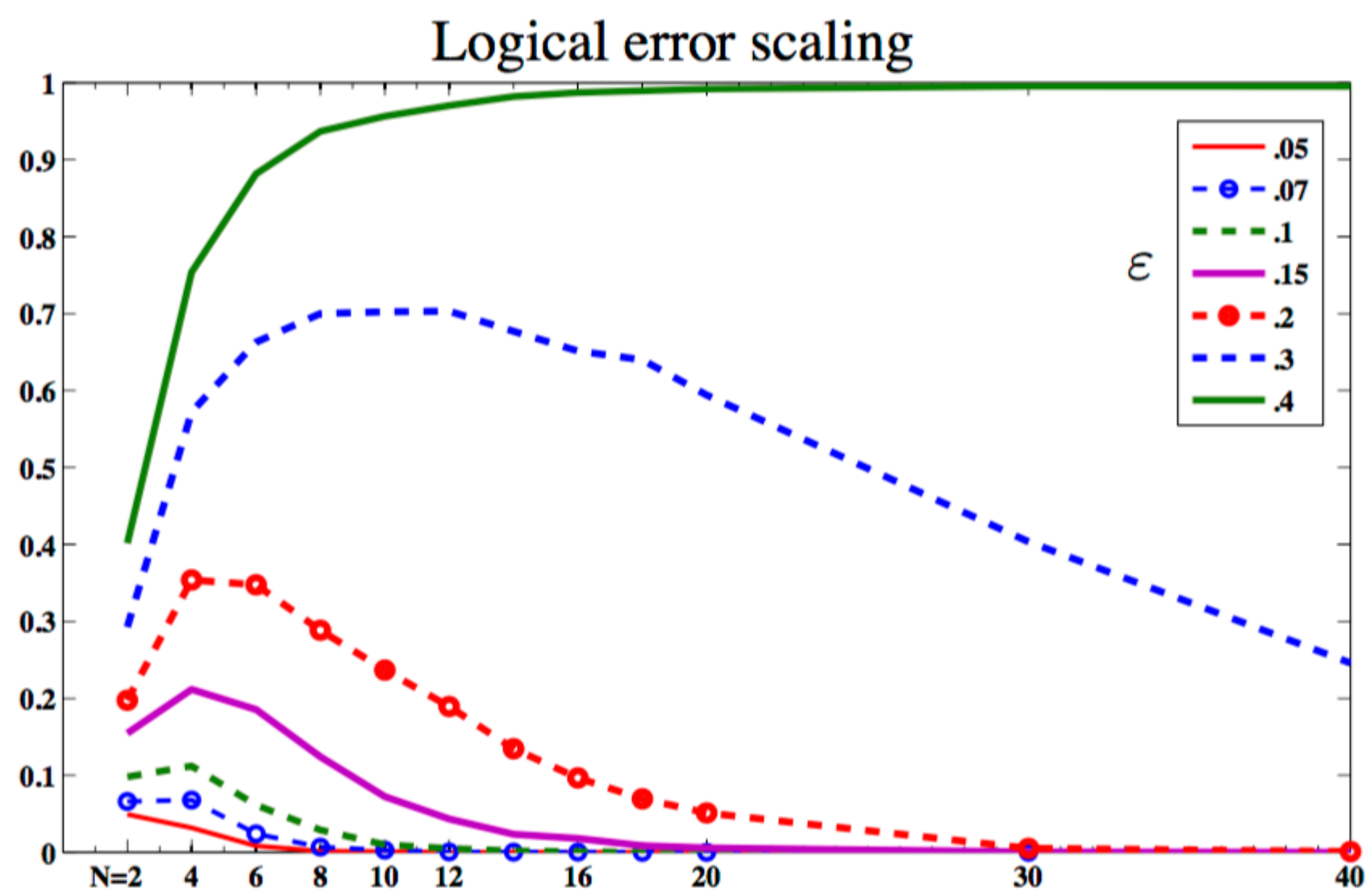
Belief propagation algorithm

Parity is preserved for any closed loop: $0 = (12) \oplus (23) \oplus (13) = (12) \oplus (24) \oplus (14) = ... = (12) \oplus (2N) \oplus (1N)$

Estimate value of (12) from

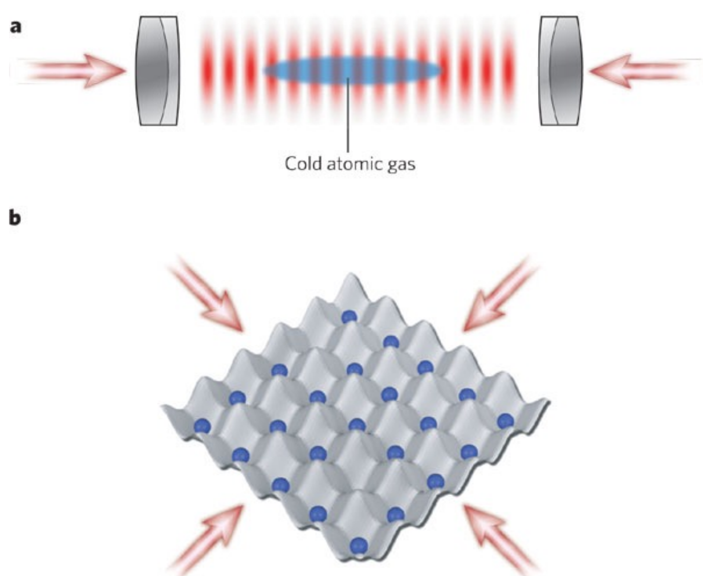
$$g_{12} = (23) \oplus (13) = (24) \oplus (14) = ... \quad \text{loops of 3}$$
$$g_{12} = (23) \oplus (34) \oplus (14) = (23) \oplus (35) \oplus (15) = ... = \quad \text{loops of 4}$$
$$g_{12} = (23) \oplus (34) \oplus (45) \oplus (15) = ... \quad \text{loops of 5}$$
$$\ldots$$





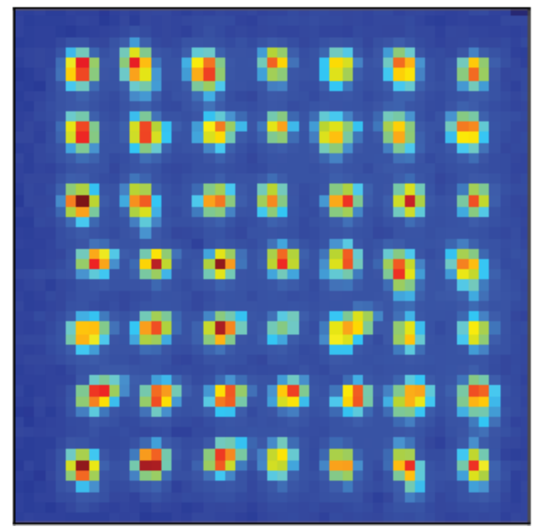
New platforms for Quantum Annealing

Ultracold atoms in optical lattices



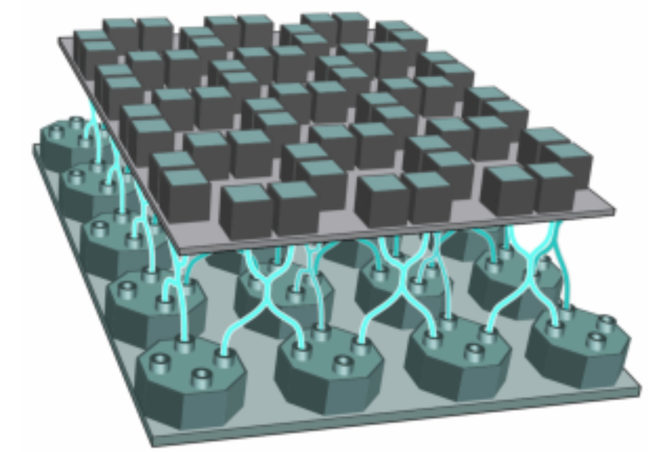
Bloch, Munich

Rydberg atoms



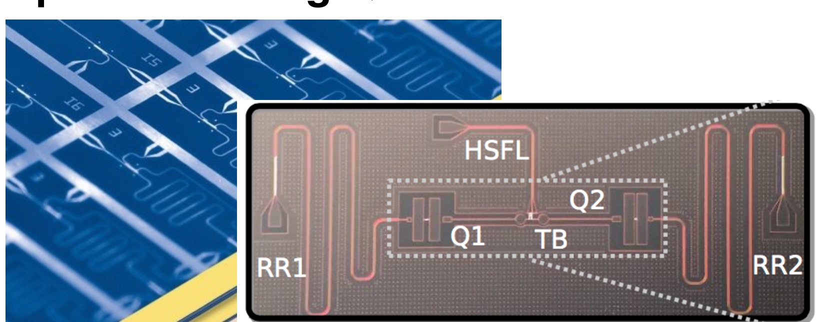
Saffman, Madison

Hybrid Ion-traps



S. Benjamin, Oxford

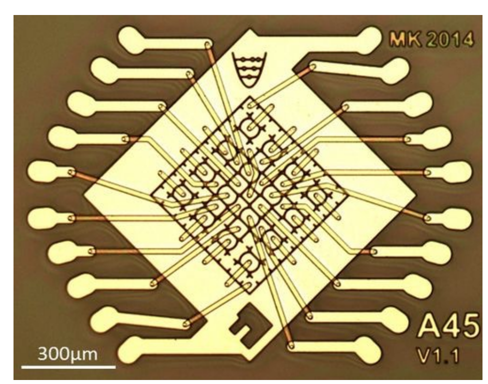
Superconducting Qubits



Filipp , IBM

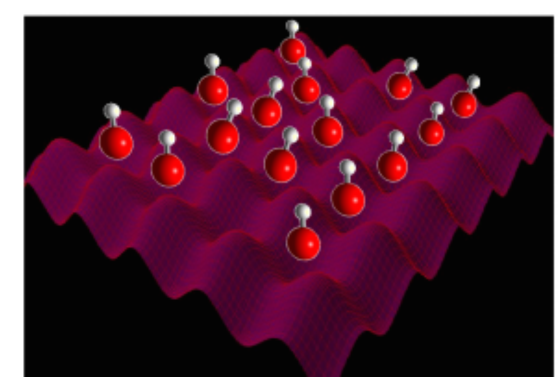
A. Wallraff

Ions in surface traps



Blatt, Innsbruck

Polar Molecules



J. Ye, Boulder

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A. Glätzle, R. van Bijnen, P. Zoller and WL, arXiv:1611.02594 (2016).

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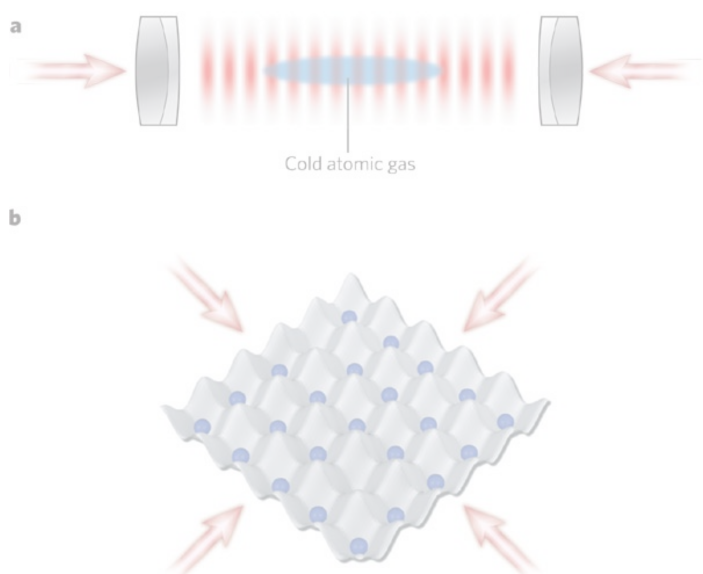
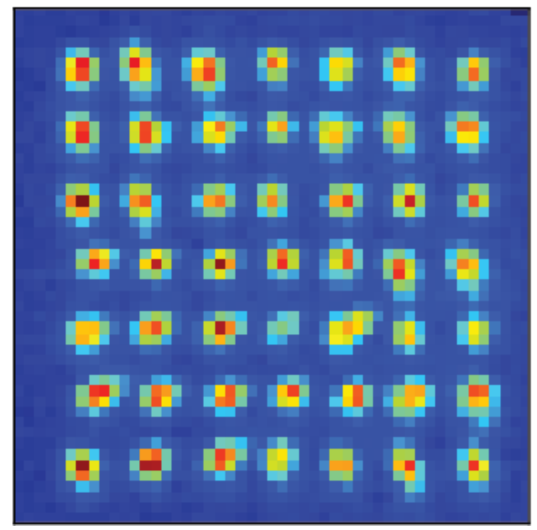


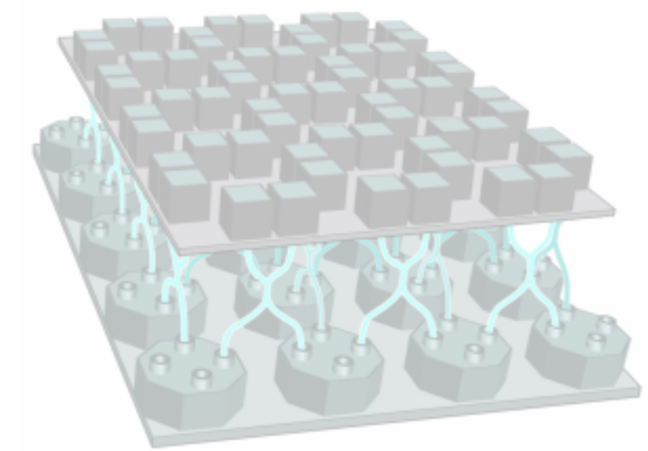
Bloch, Munich

Rydberg atoms



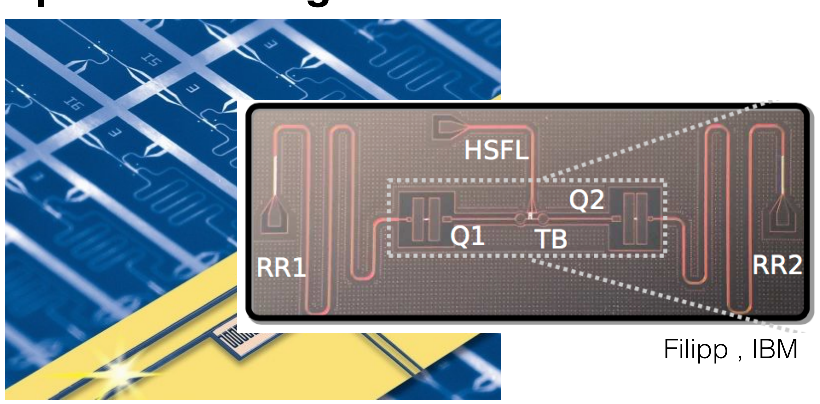
Saffman, Madison

Hybrid Ion-traps



S. Benjamin, Oxford

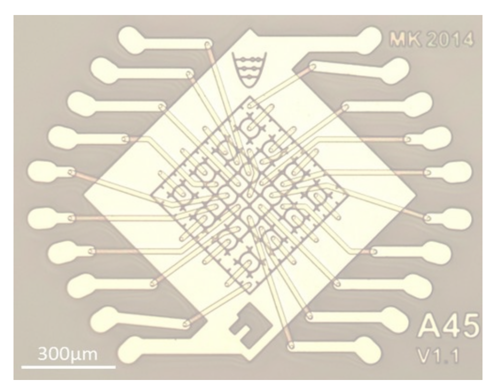
Superconducting Qubits



Filipp , IBM

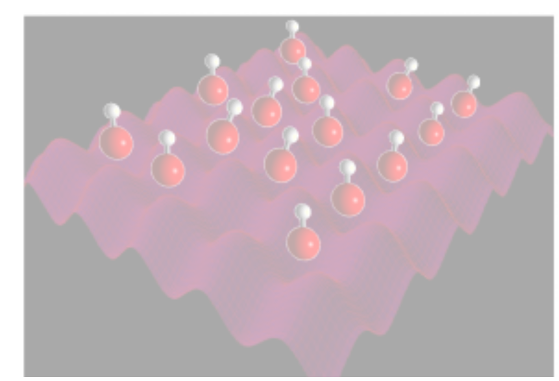
A. Wallraff

Ions in surface traps



Blatt, Innsbruck

Polar Molecules

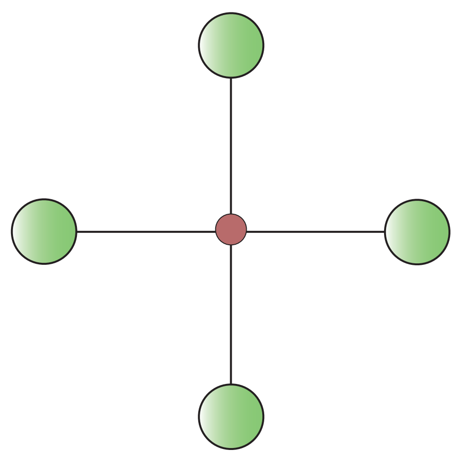


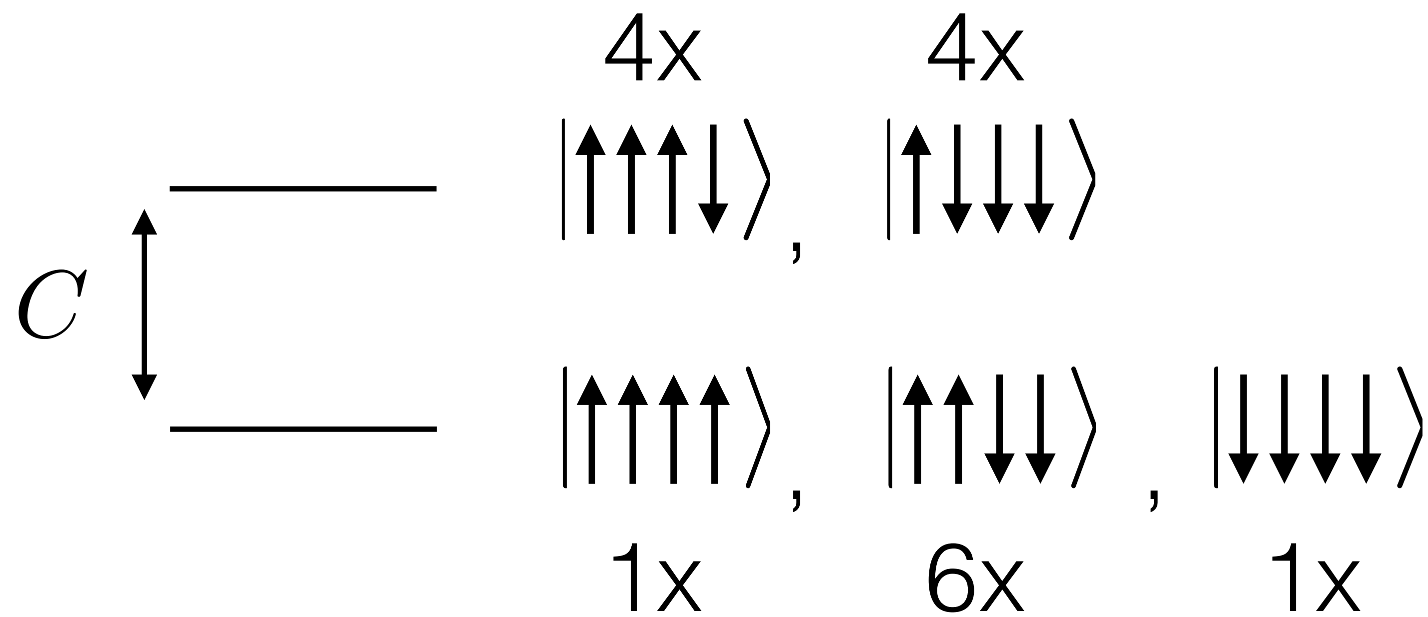
J. Ye, Boulder

Martin Leib, P. Zoller, and WL, arXiv:1604.02359(2016).

Strategies for constraint design with Rydberg atoms

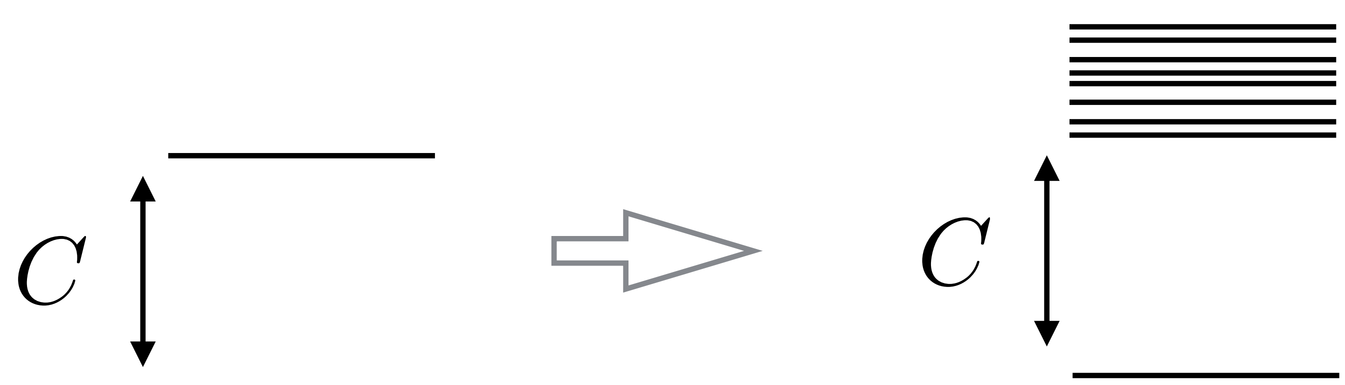
4-body constraints





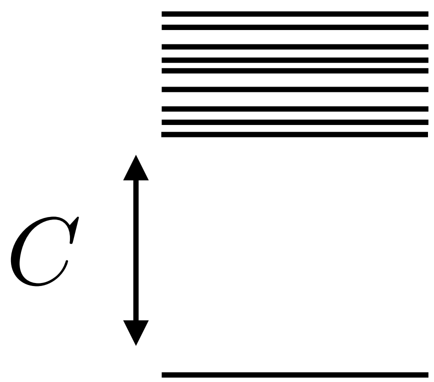
$$H_c = -C\sigma_z^1\sigma_z^2\sigma_z^3\sigma_z^4$$

Unphysical states do not matter



Strategies for constraint design with Rydberg atoms

Andrea Rocchetto, Simon C. Benjamin and Ying Li, Science Advances 2, e1601246 (2016).



even parity

$|\uparrow\uparrow\uparrow\uparrow\rangle, |\uparrow\uparrow\downarrow\downarrow\rangle, |\downarrow\downarrow\downarrow\downarrow\rangle$

$$\sum_{i}^{4} \sigma_z^{(i)}$$

↑

-4,0,4

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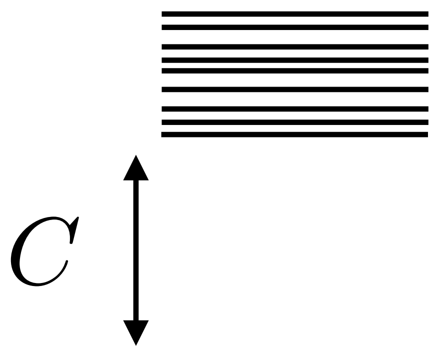


even parity

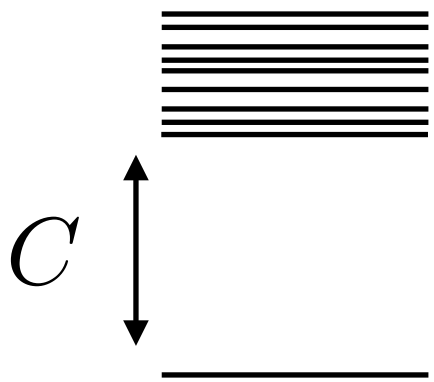
$|\uparrow\uparrow\uparrow\uparrow\rangle, |\uparrow\uparrow\downarrow\downarrow\rangle, |\downarrow\downarrow\downarrow\downarrow\rangle$

$$S = \left(4S_z + \sum_i^4 \sigma_z^{(i)} \right)^2$$

qutrit -4,0,4

Strategies for constraint design with Rydberg atoms

Andrea Rocchetto, Simon C. Benjamin and Ying Li, Science Advances 2, e1601246 (2016).

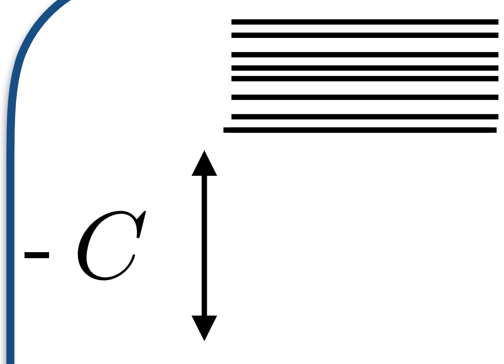


even parity

$|\uparrow\uparrow\uparrow\uparrow\rangle, |\uparrow\uparrow\downarrow\downarrow\rangle, |\downarrow\downarrow\downarrow\downarrow\rangle$

$$S = \left(4S_z + \sum_i^4 \sigma_z^{(i)}\right)^2$$

qutrit -4,0,4



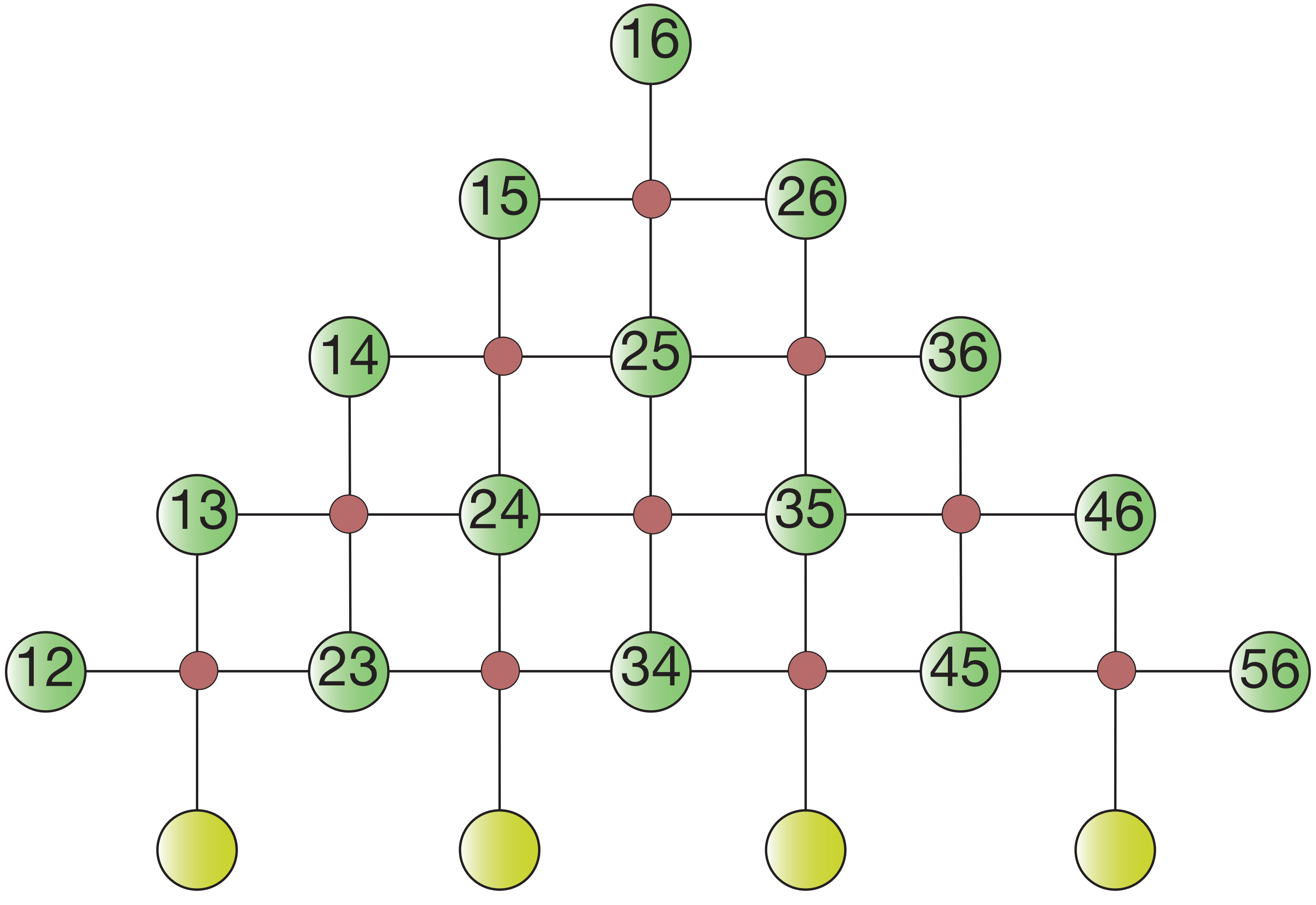
odd parity

$|\uparrow\uparrow\uparrow\downarrow\rangle, \quad |\uparrow\downarrow\downarrow\downarrow\rangle$

$$S = \left(2\sigma_z^{(a)} + \sum_i^4 \sigma_z^{(i)}\right)^2$$

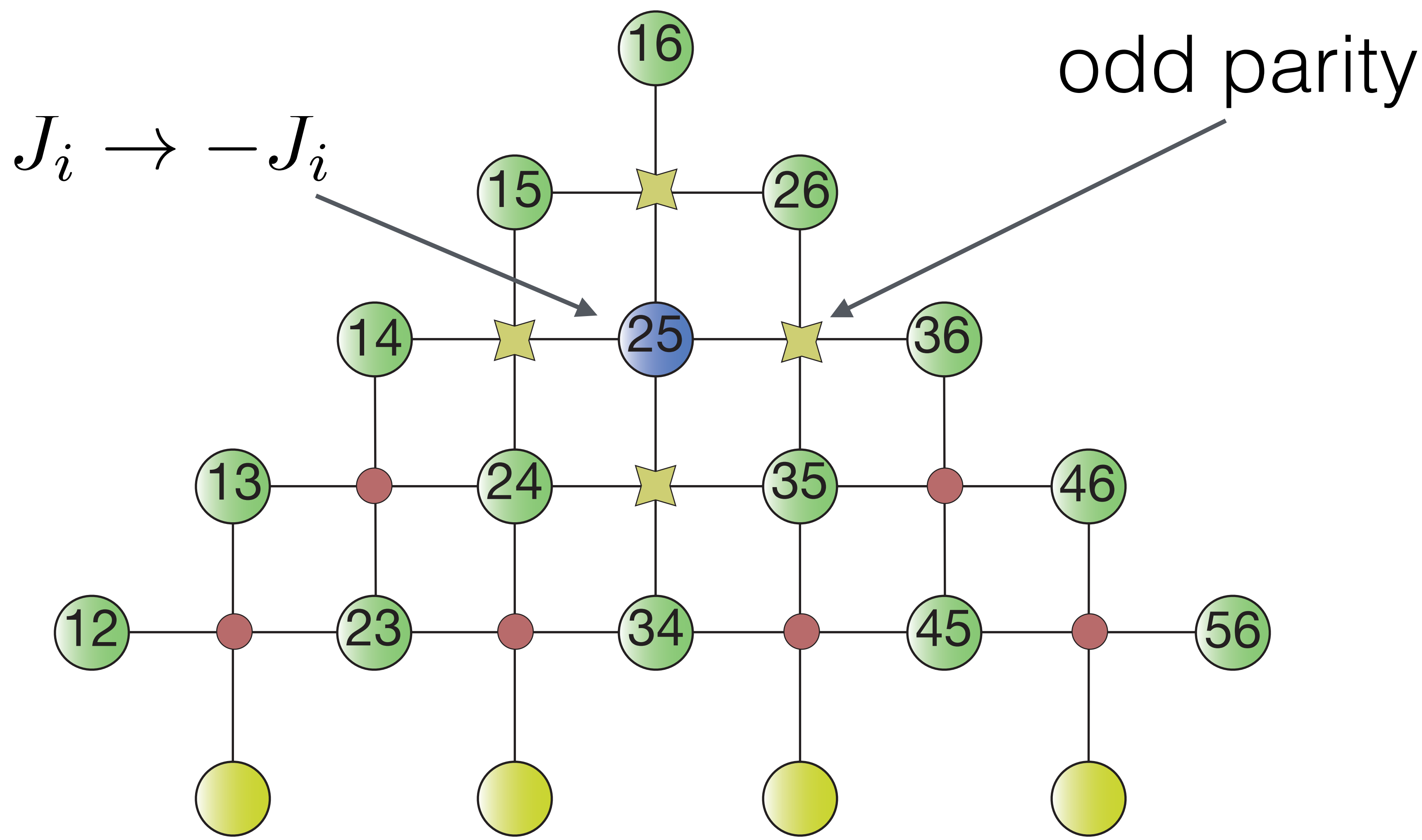
qubit -2,2

Odd parity representation



Odd parity representation

Andrea Rocchetto, Simon C. Benjamin and Ying Li, Science Advances 2, e1601246 (2016).



Odd parity representation

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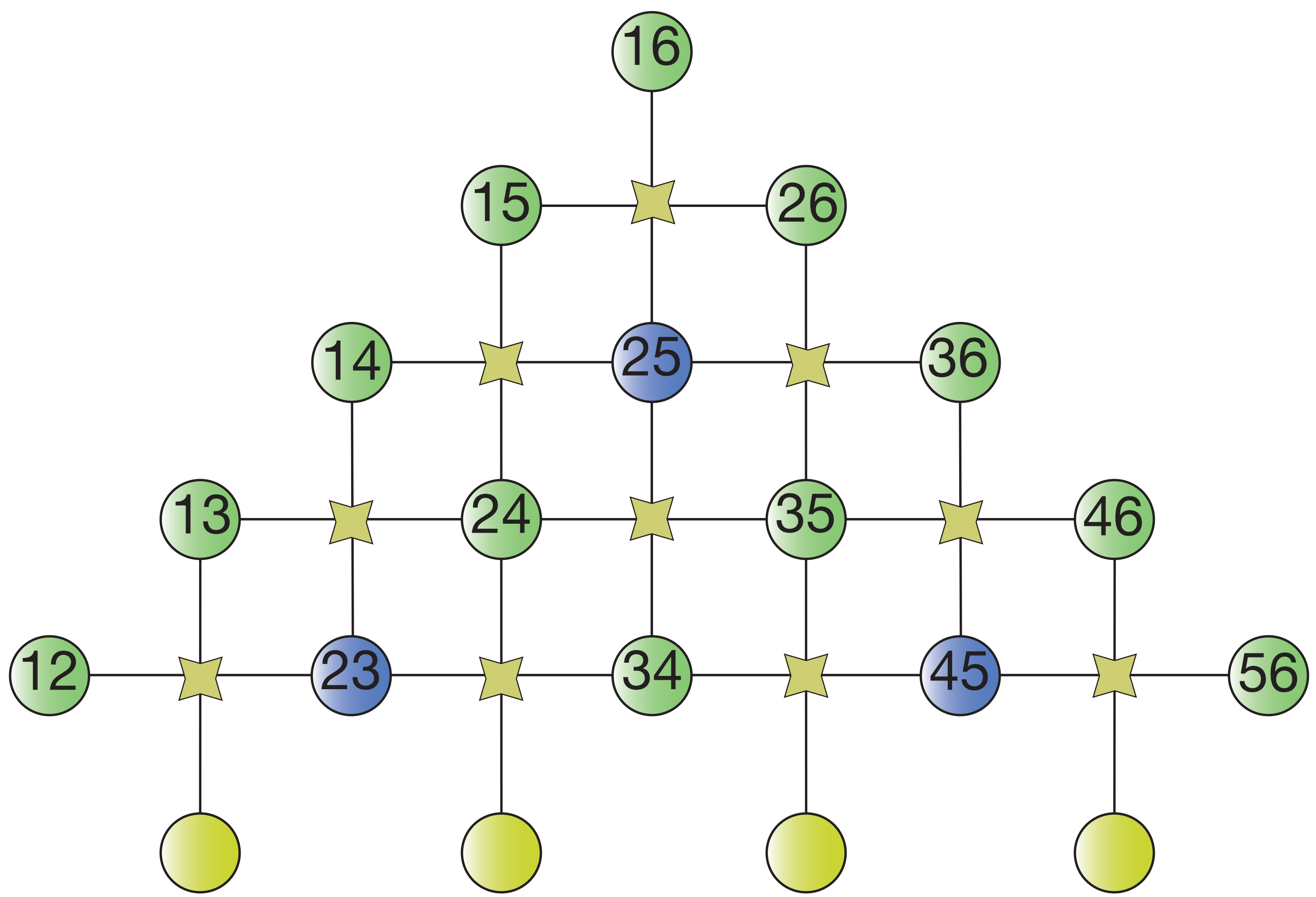
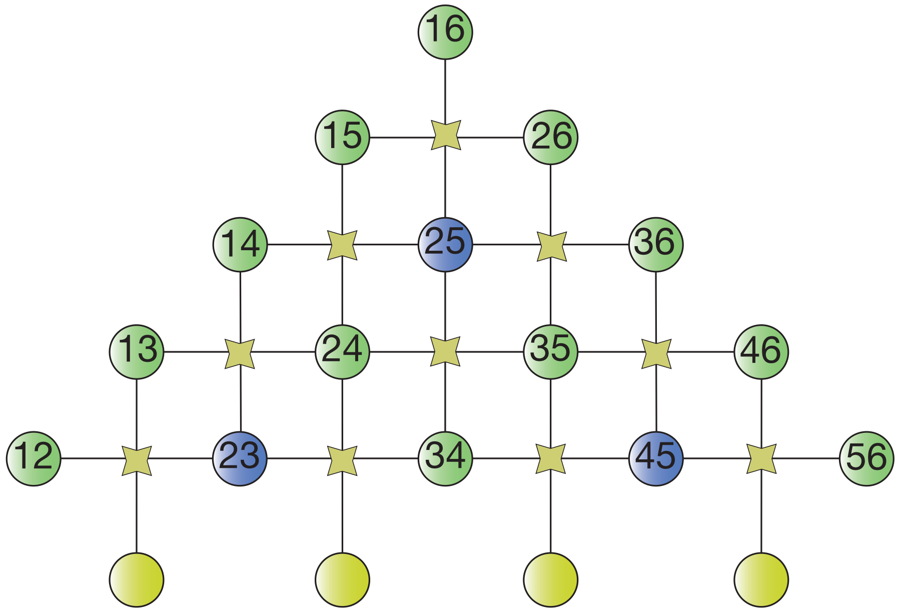
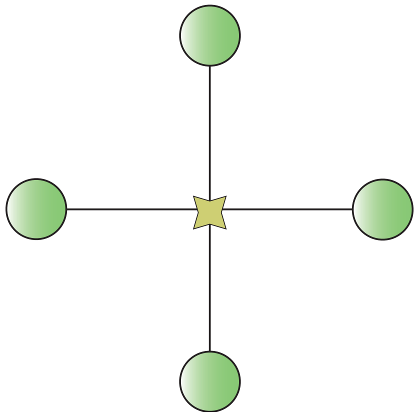


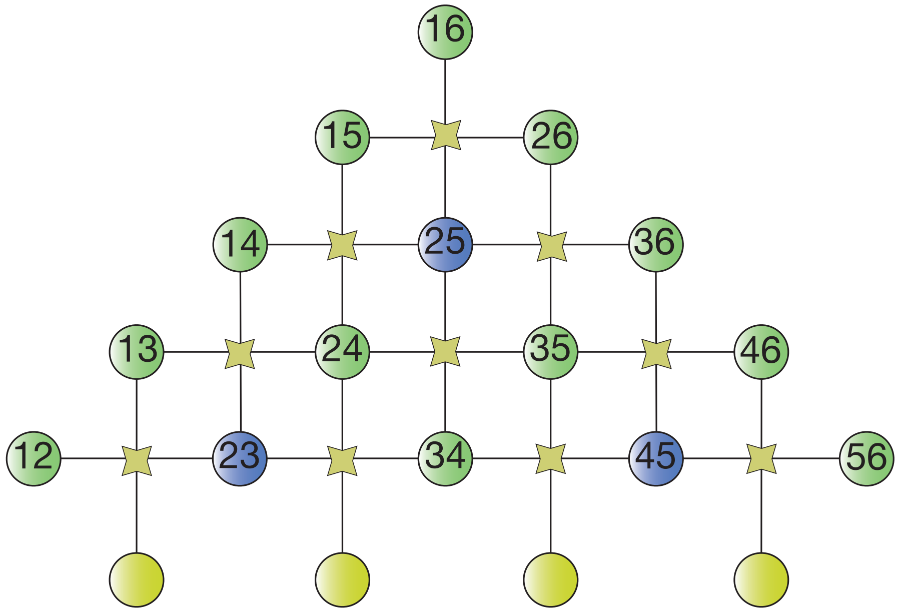
Odd parity representation

$$S = \left(2\sigma_z^{(a)} + \sum_i^4 \sigma_z^{(i)} \right)^2$$



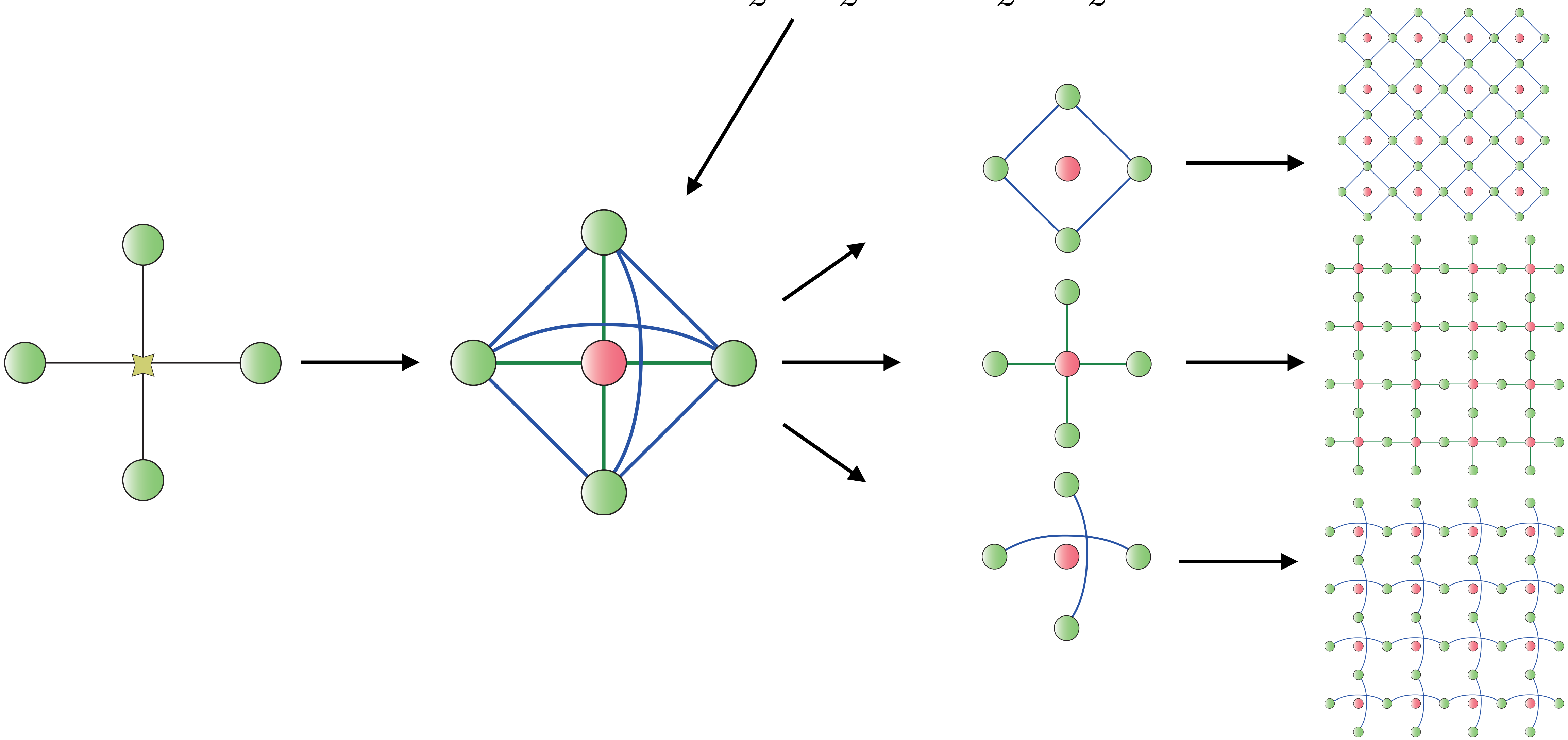


Odd parity representation

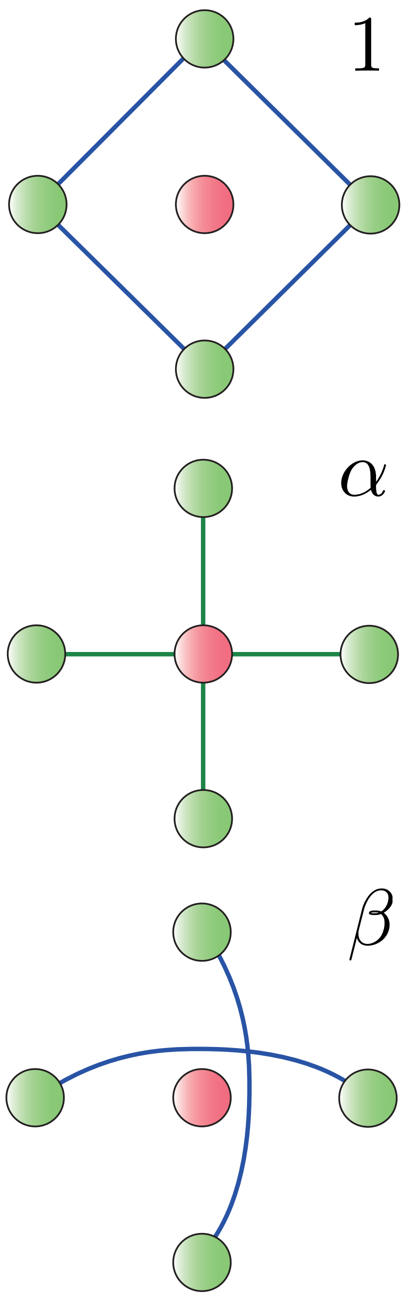


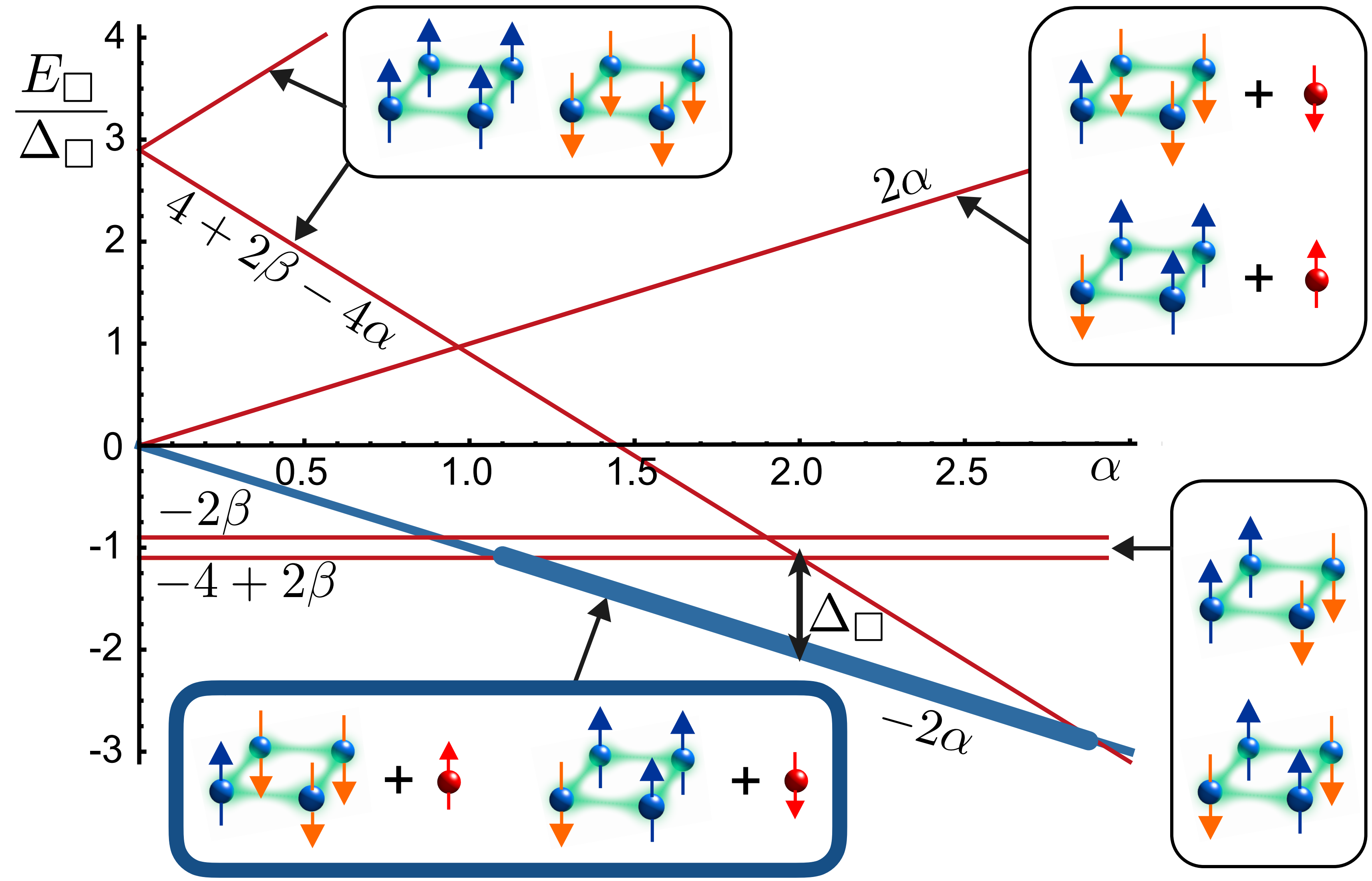
$$S = \left(2\sigma_z^{(a)} + \sum_i^4 \sigma_z^{(i)} \right)^2$$

$$2\sigma_z^{(a)}\sigma_z^{(1)} + 2\sigma_z^{(a)}\sigma_z^{(2)} + 2\sigma_z^{(a)}\sigma_z^{(3)} + 2\sigma_z^{(a)}\sigma_z^{(4)} +$$
$$\sigma_z^{(1)}\sigma_z^{(2)} + \sigma_z^{(1)}\sigma_z^{(3)} + \sigma_z^{(1)}\sigma_z^{(4)} + \sigma_z^{(2)}\sigma_z^{(3)} +$$
$$\sigma_z^{(2)}\sigma_z^{(4)} + \sigma_z^{(3)}\sigma_z^{(4)}$$



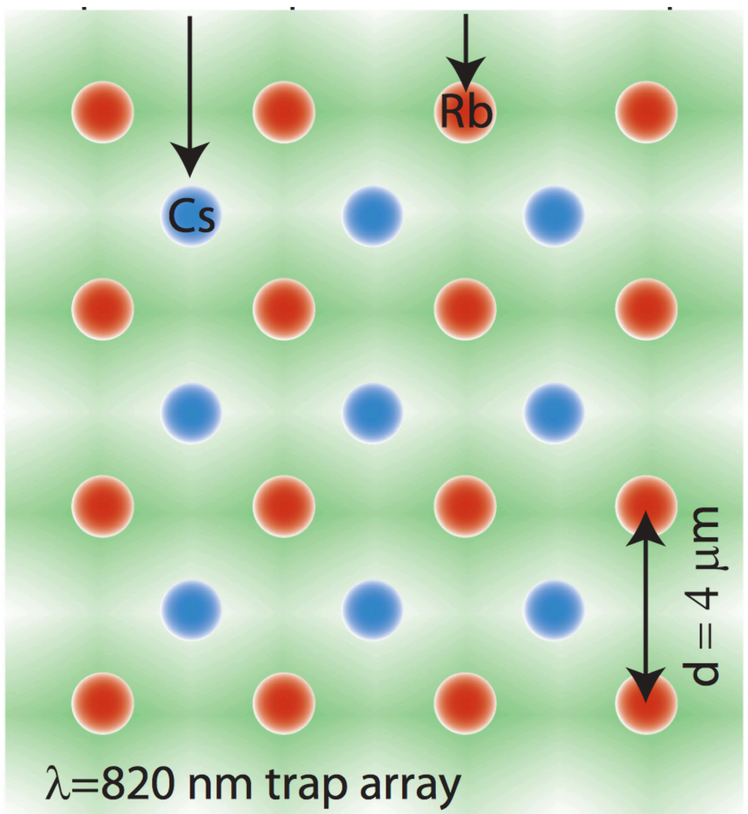
Error Robustness



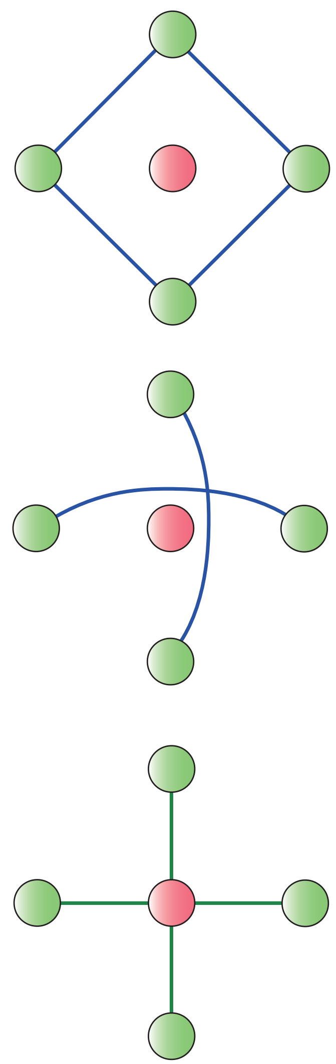


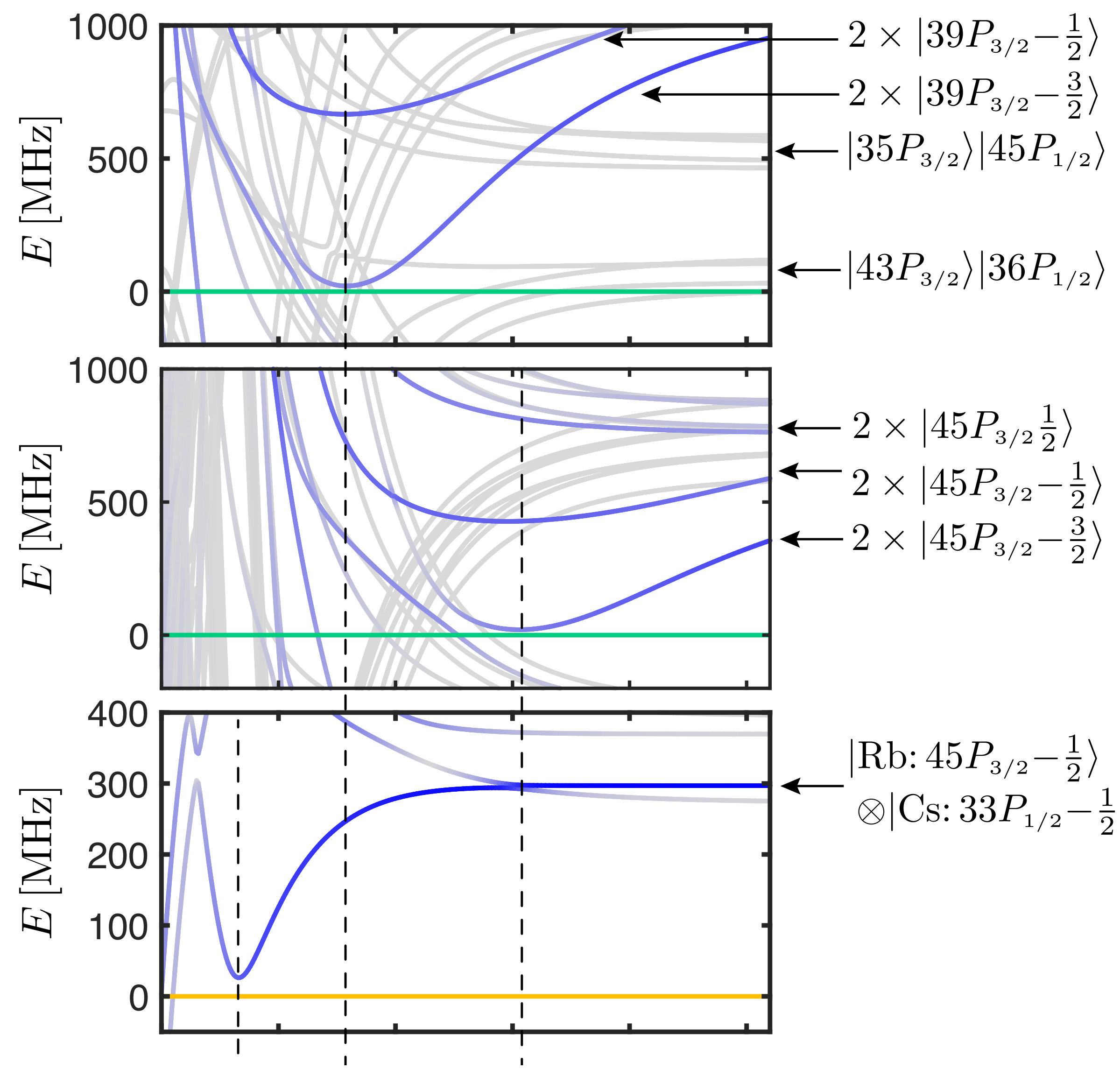
Neutral Atoms in Optical Lattices

A. Glätzle, R. van Bijnen, P. Zoller and WL, arXiv:1611.02594 (2016).



I. I. Beterov and M. Saffman,
Phys. Rev. A 92, 042710 (2015).





$$\hat{H} = \hat{H}_A^{(1)} \otimes \hat{I} + \hat{I} \otimes \hat{H}_A^{(2)} + \hat{V}_{dd}$$

R. M. W. van Bijnen and T. Pohl
Phys. Rev. Lett. **114**, 243002 (2015)

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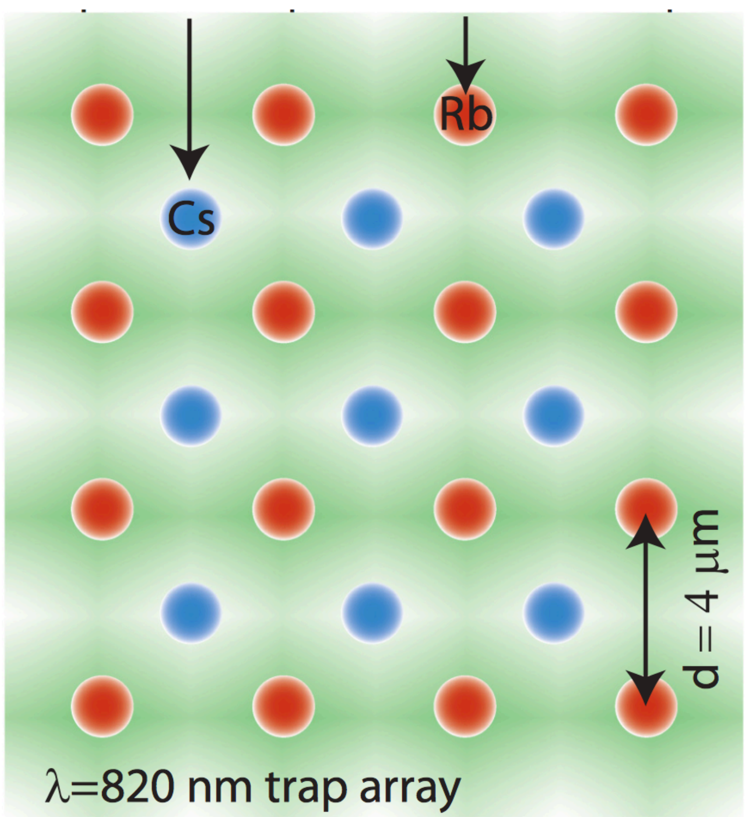
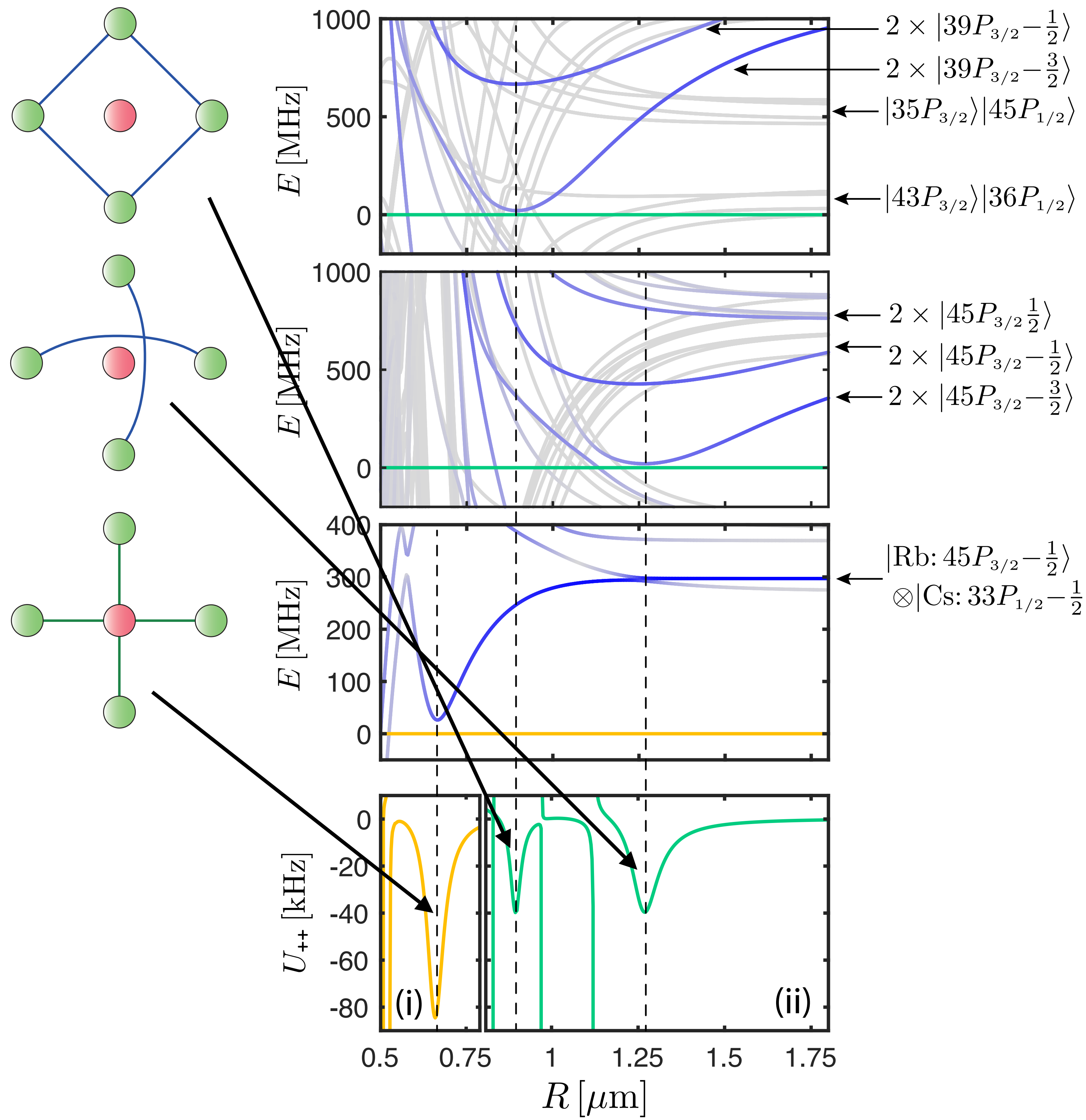
A. Glätzle, R. van Bijnen, P. Zoller and WL, arXiv:1611.02594 (2016).

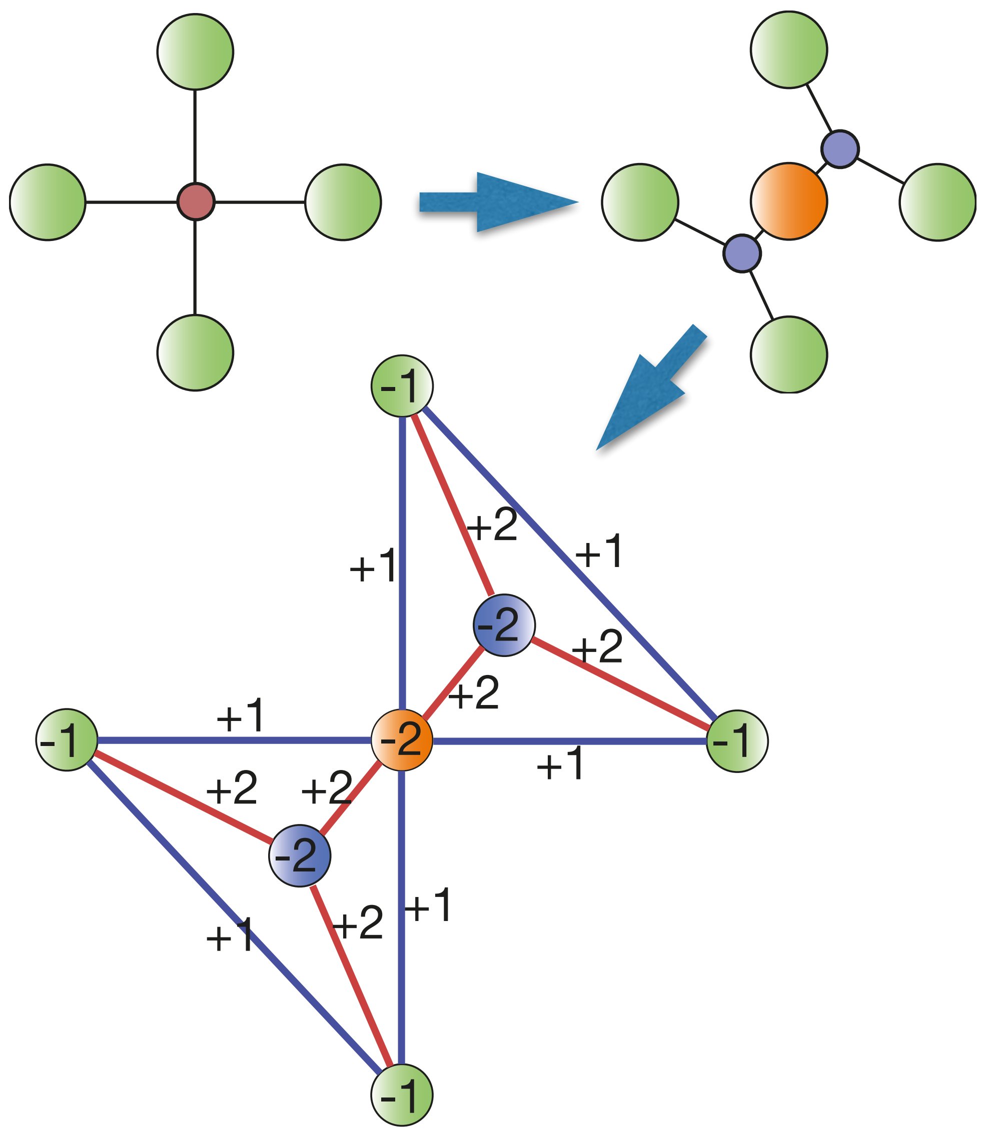


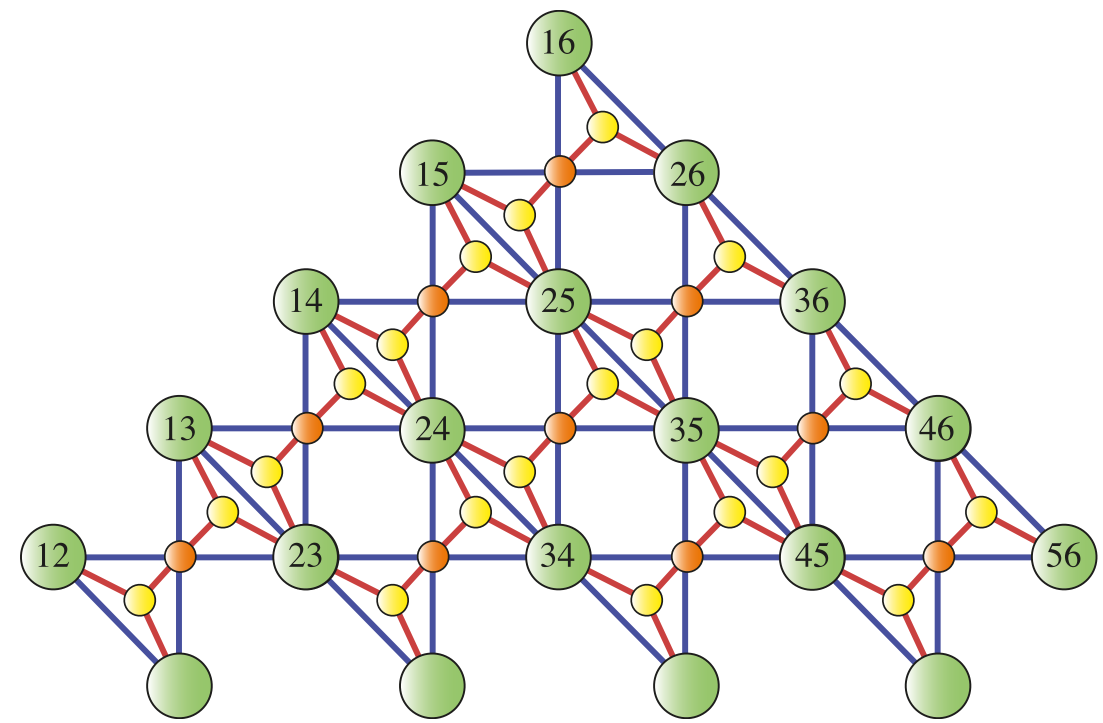
I. I. Beterov and M. Saffman, Phys. Rev. A 92, 042710 (2015).



Transmon Implementations

Martin Leib, P. Zoller, WL, arXiv:1604.02359(2016).



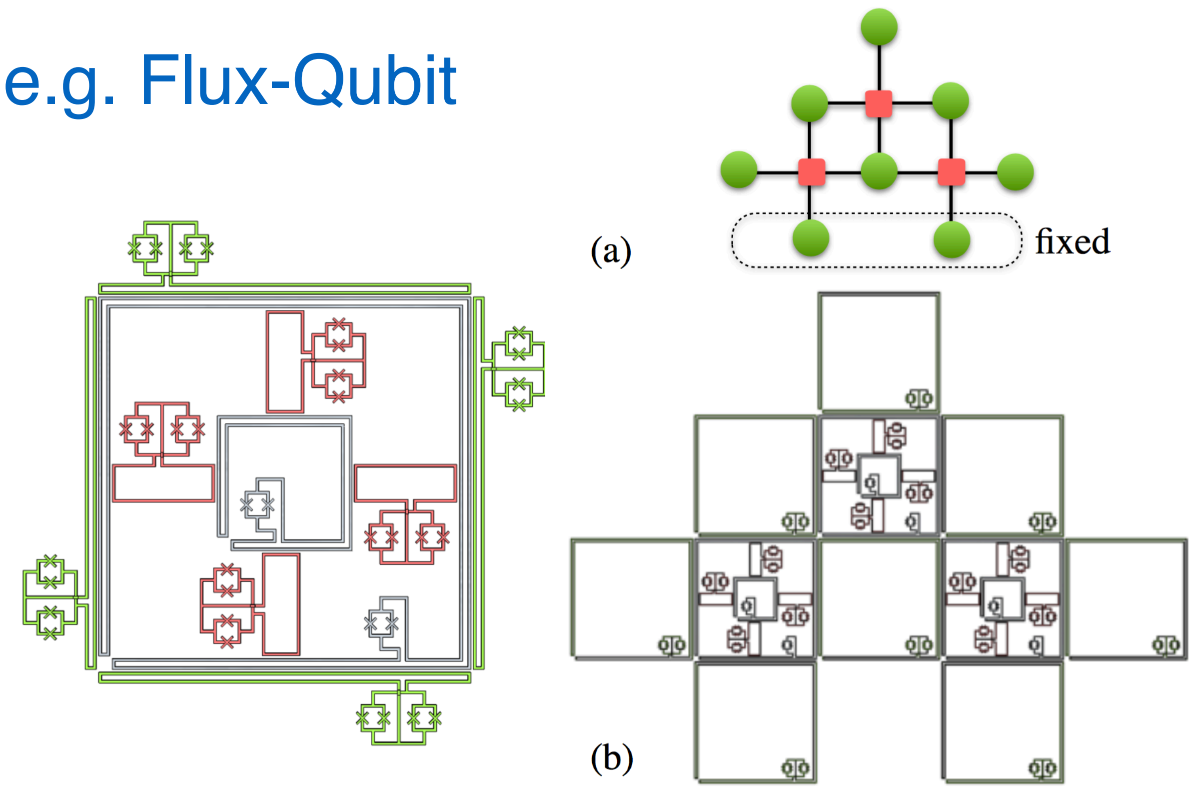


- rotating frame
- only **pair interactions**
- **no crossings**
- all **local fields** have the **same sign**
- all **interactions** have the **same sign**
- programming [0,2]

$$\sigma_z^{(1)}\sigma_z^{(2)}\sigma_z^{(3)} \rightarrow \quad \sigma_z^{(1)}\sigma_z^{(2)} + \sigma_z^{(2)}\sigma_z^{(3)} + \sigma_z^{(3)}\sigma_z^{(1)} + \sum_{i=1}^{3}[2\sigma_z^{(i)}\sigma_z^{(a)} - \sigma_z^{(i)}] - 2\sigma_z^{(a)}$$

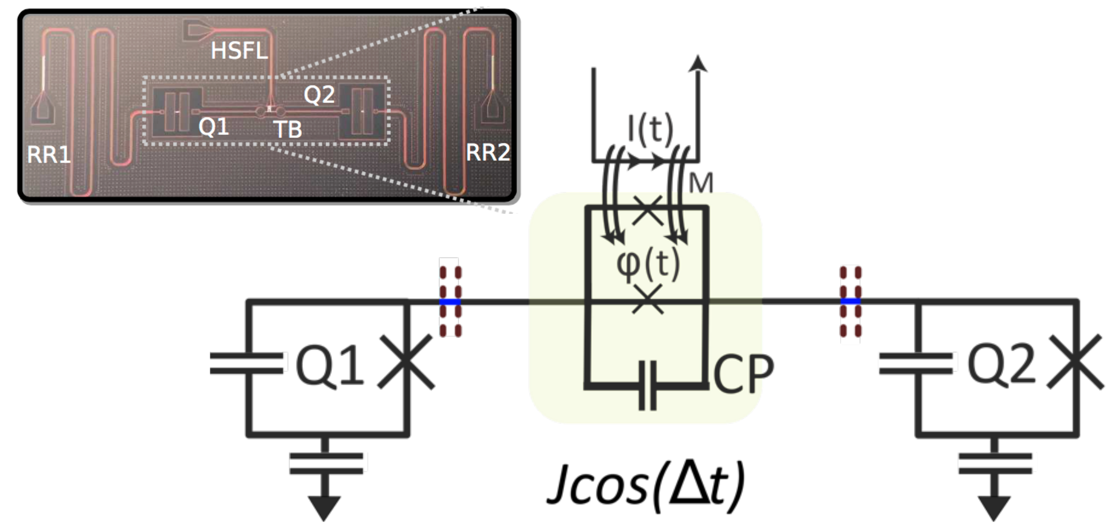
Quantum Circuit for LHZ

e.g. Flux-Qubit



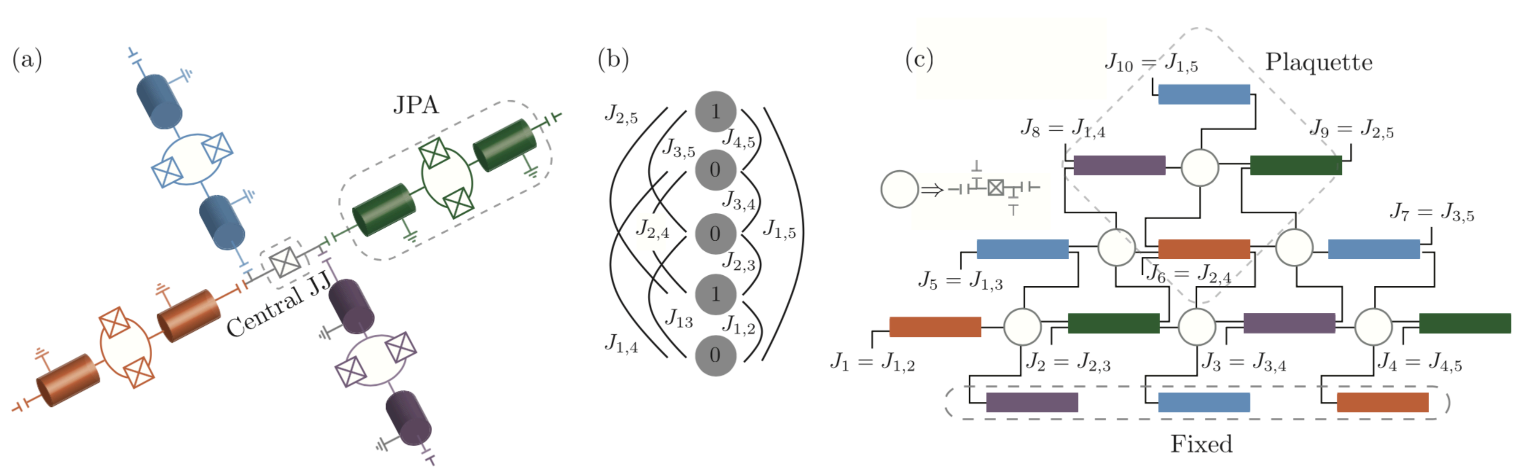
Nicholas Chancellor, Stefan Zohren, Paul A. Warburton arXiv:1603:09521 (2016).

e.g. Driven fixed frequency Transmons



D. C. McKay, S. Filipp, A. Mezzacapo, F. Solgun, J. Chow, and J. M. Gambetta. arXiv:1604.03076 (2016).

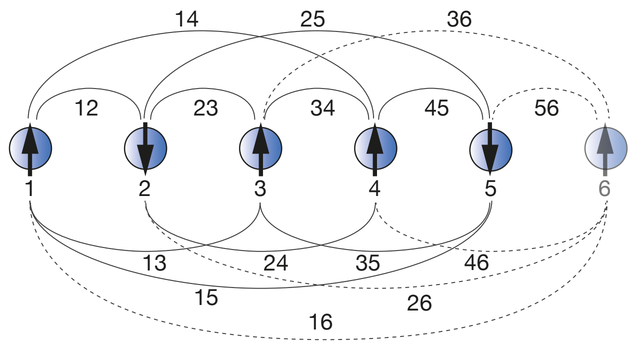
e.g. Driven Kerr-nonlinearities

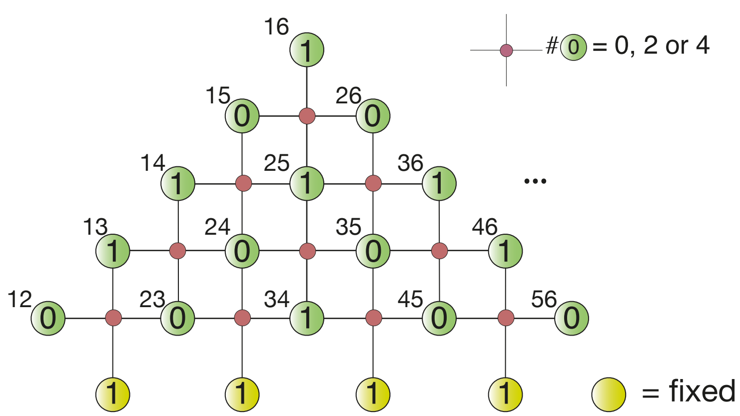


Shruti Puri, Christian Kraglund Andersen, Arne L. Grimsmo, Alexandre Blais, arXiv:1609.07117 (2016).

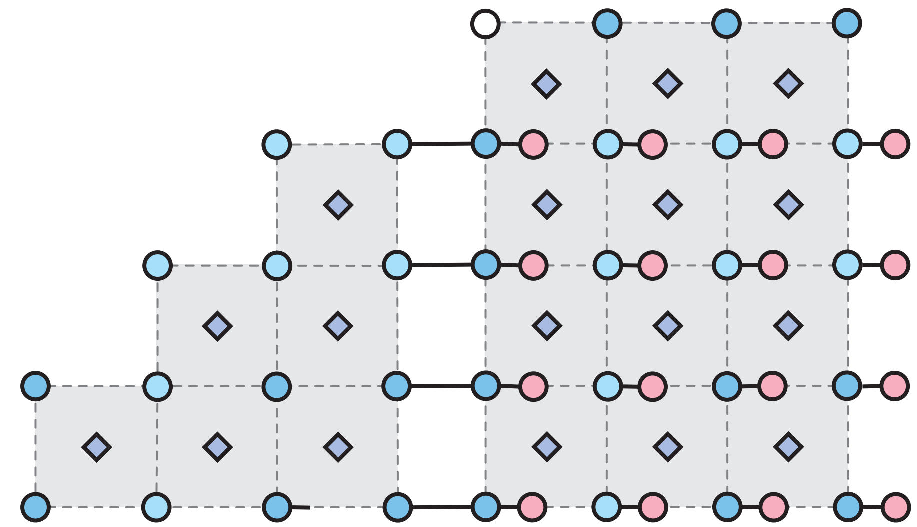
Outlook

Infinite range spin-glass vs. finite range lattice gauge



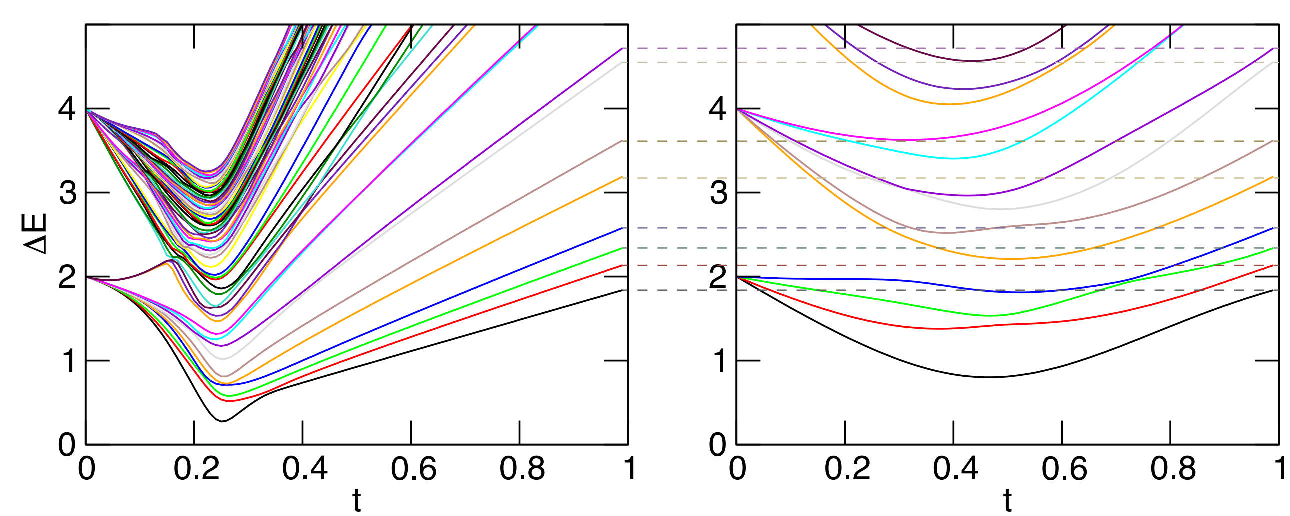


Quantum Machine Learning



Dynamical Weights

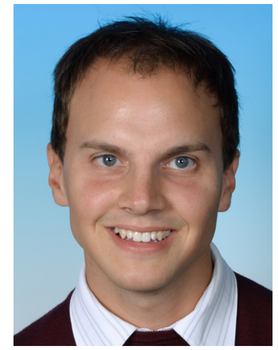
Coherent Annealing



Peter Zoller

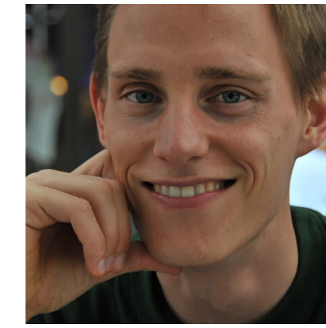
Philipp Hauke

Alex Glätzle

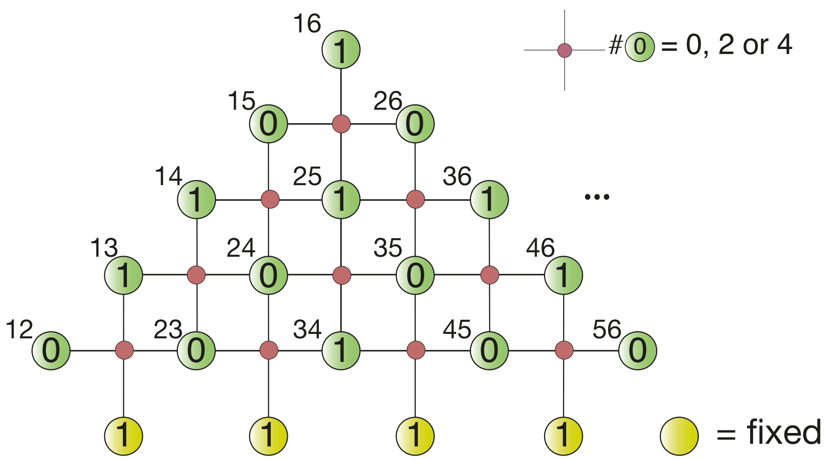


Rick van Bijnen

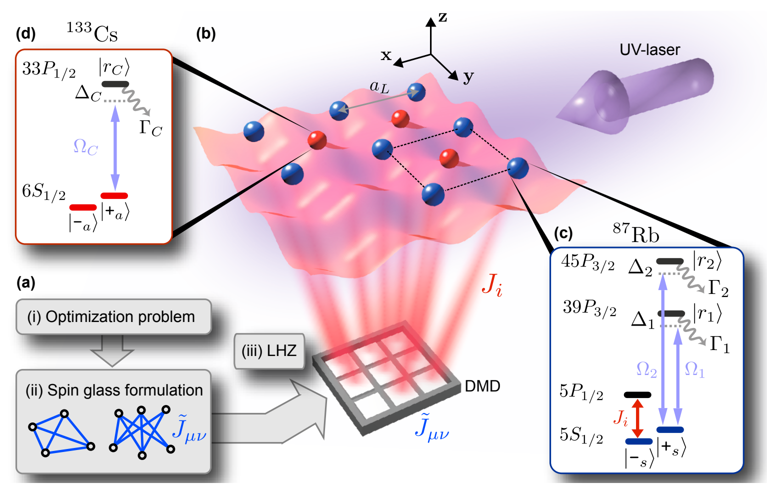
Martin Leib



Science Advances 1, 1500838 (2015).



arXiv:1611.02594 (2016).



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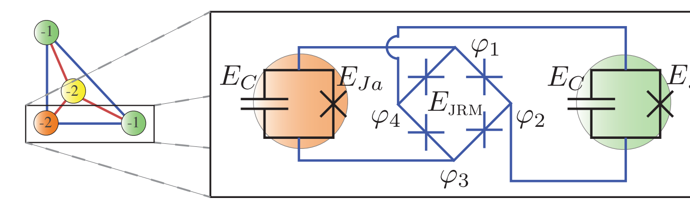
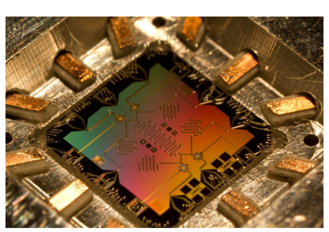
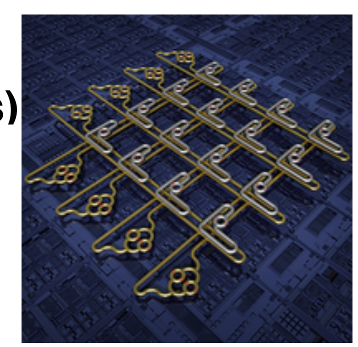


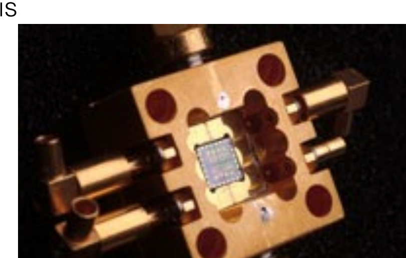
Superconducting Qubits (Transmons)



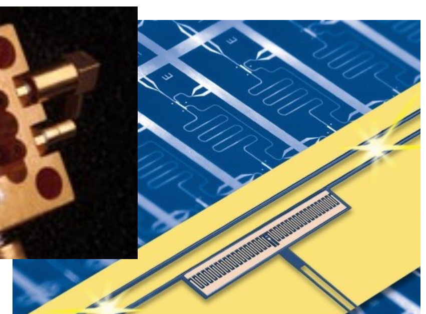
J. Martinis



S. Boixo

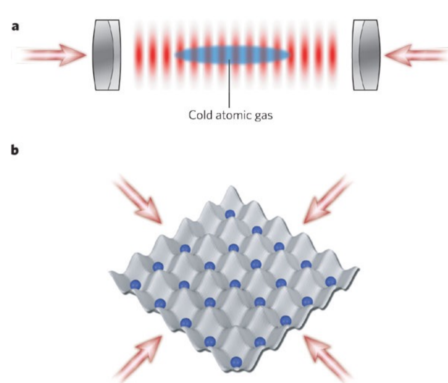


W. Oliver



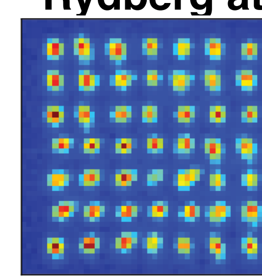
A. Wallraff

Ultracold atoms in optical lattices



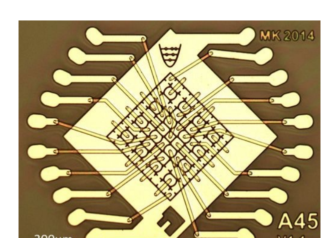
I. Bloch group, *Nature* ***453***, *016*

Rydberg atoms



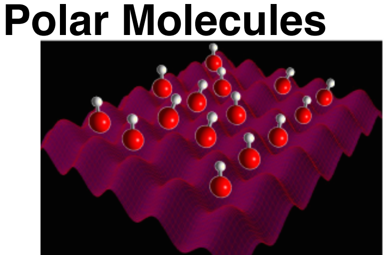
Saffman, Madison

Ions in surface traps



Blatt.

Polar Molecules



J. Ye.