Quantum Ising chain, Majorana fermions and tunable square qubits with quantum phase-slip

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with
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Karlsruhe Institute of Technology

Saclay – Delft connection
25+ years

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Single Cooper-Pair Tunneling in Small-Capacitance Junctions

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(Received 2 April 1990)

We present observations of charging effects for Cooper pairs in short linear arrays of small-capacitance Josephson junctions. Current-voltage characteristics show a Coulomb gap for Cooper-pair tunneling when the charging energy exceeds the Josephson coupling energy. In a double junction a zero-voltage current is observed that is modulated by a gate voltage applied to the metal island between the junctions. For longer arrays a crossover from Coulomb blockade of Copper-pair tunneling to a supercurrent is observed when the ratio of Josephson coupling to charging energy is increased.

We are much indebted to D. V. Averin, M. H. Devoret, D. Esteve, M. Peters, U. Geigenmüller, G. Schön, B. van Wees, and P. Hadley for enlightening discussions. We thank the Commissariat à l'Energie Atomique for hospitality during several visits. This work is supported

CONTROLLED TRANSFER OF SINGLE CHARGE CARRIERS

C. Urbina, H. Pothier, P. Lafarge, P.F. Orfila, D. Esteve and M. Devoret
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and
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Abstract

We have designed and operated two devices, the turnstile and the pump, that transfer electrons one by one. They are both based on the existence of stable electrostatic configurations in arrays of ultrasmall tunnel junctions. While the turnstile only works in the normal state the pump could in principle achieve the transfer of single Cooper pairs.

cannot be absorbed. There is a finite tunneling rate only if V_j lies close to V_j^c, within an energy interval determined by the Josephson coupling energy and the fluctuation spectrum of the electromagnetic environment[6].

The turnstile

The turnstile consists of four nominally identical normal thank you for the collaboration

keep going, all of you
for the next 30 years

arXiv:cond-mat/0108266v2
19 Aug 2001

Quantum spin chains and Majorana states in arrays of coupled qubits

L. S. Levitov[1], T. P. Orlando[2], J. B. Majer[3], J. E. Mooij[3]
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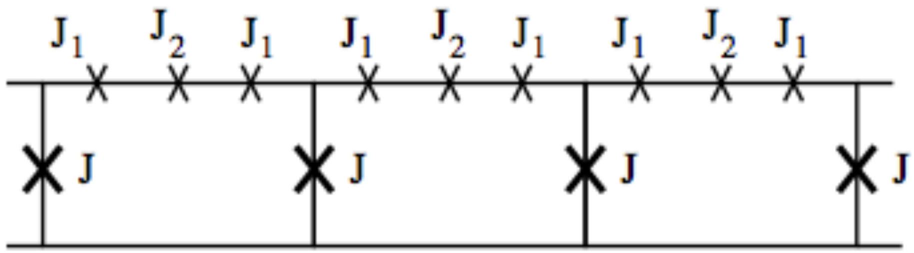
(3) *Applied Physics and DIMES, Delft Technical University, P.O.Box 5046, 2600 GA Delft, the Netherlands*



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Quantum spin chains and Majorana states in arrays of coupled qubits

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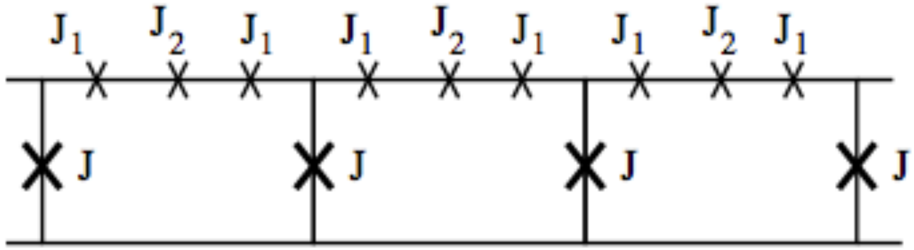
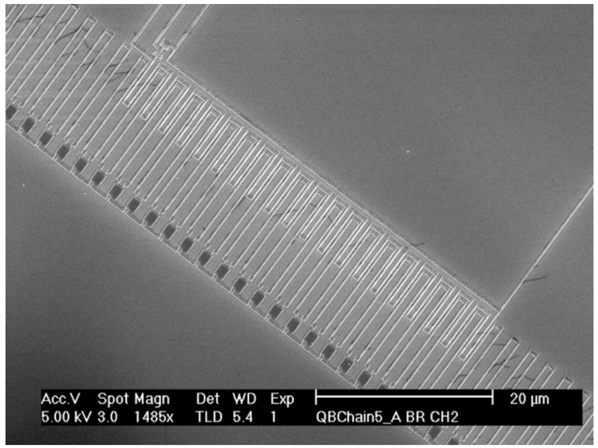


Quantum state transfer in arrays of flux qubits

A Lyakhov and C Bruder
Department of Physics and Astronomy, University of Basel,
Klingelbergstr. 82, 4056 Basel, Switzerland
E-mail: Andriy.Lyakhov@unibas.ch

New Journal of Physics **7** (2005) 181



Floor Paauw 2008

4 (2014) 5535
You, Wang, Zhang, Nori

SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
QUBITS
QUANTUM INFORMATION

Encoding a qubit with Majorana modes in superconducting circuits

J. Q. You[1,2], Z. D. Wang[3], Wenxian Zhang[4] & Franco Nori[2,5]

Ising chain

one-dimensional array of ½ spins, one polarization

$$H = -J\sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z - h\sum_i \sigma_i^z - \Delta\sum_i \sigma_i^x$$

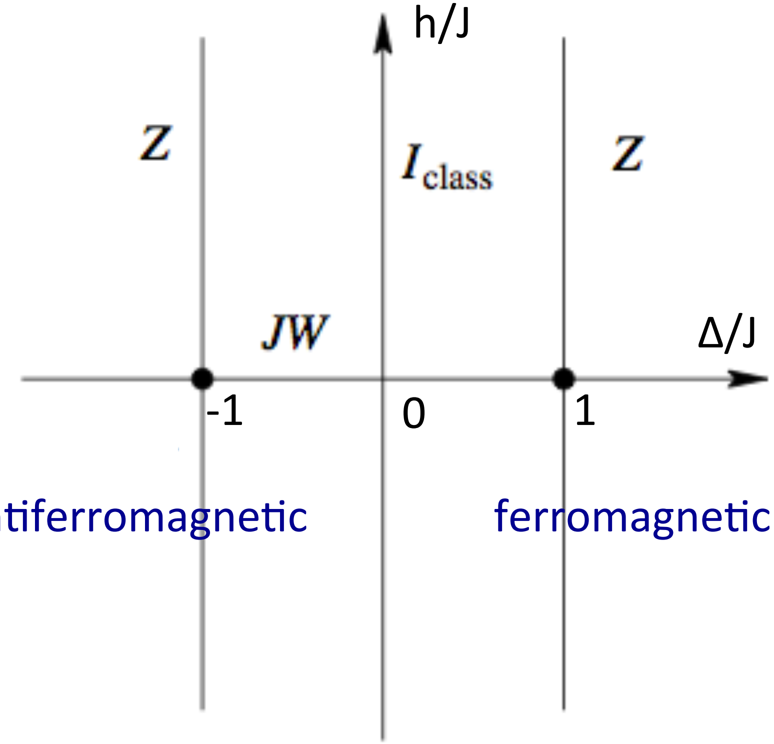
J: exchange constant, interaction between nearest neighbors

J>0 ferromagnetic

J<0 antiferromagnetic

h: applied magnetic field

Δ : on-site quantum transitions



h=0, |Δ/J|<1:
Jordan-Wigner transformation

h=0

$$H = -J\sum_{\langle i,j\rangle}\sigma_i^z\sigma_j^z - \Delta\sum_i \sigma_i^x$$

mapping from ↑↓ spins at fixed positions to spinless fermions that can hop along the chain

Jordan-Wigner transformation (1928)

$$\sigma_i^x = 2a_i^\dagger a_i - 1$$

$$\sigma_i^z = (a_i + a_i^\dagger)\prod_{j<i}\sigma_j^x$$

$$H = -\sum_i J(a_i - a_i^\dagger)(a_{i+1} + a_{i+1}^\dagger) - 2\Delta a_i^\dagger a_i$$

$$\left\{a_i, a_j\right\} = 0$$

$$\left\{a_i^\dagger, a_j\right\} = \delta_{ij}$$

h=0

$$H = -J\sum_{\langle i,j\rangle}\sigma_i^z\sigma_j^z - \Delta\sum_i \sigma_i^x$$

mapping from ↑↓ spins at fixed positions to
spinless fermions that can hop along the chain
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$$\{a_i, a_j\} = 0$$

$$\{a_i^\dagger, a_j\} = \delta_{ij}$$

h=0

$$H=-J\sum_{\langle i,j\rangle}\sigma_i^z\sigma_j^z-\Delta\sum_i\sigma_i^x$$

Jordan-Wigner transformation

$$\sigma_i^x=2a_i^\dagger a_i-1$$

$$\sigma_i^z=(a_i+a_i^\dagger)\prod_{j<i}\sigma_j^x$$

$$H=-\sum_i J(a_i-a_i^\dagger)(a_{i+1}+a_{i+1}^\dagger)-2\Delta a_i^\dagger a_i$$

$$\left\{a_i,a_j\right\}=0$$

$$\left\{a_i^\dagger,a_j\right\}=\delta_{ij}$$

Majorana fermions:

$$\gamma_j^A=\frac{1}{\sqrt{2}}(a_j+a_j^\dagger)$$

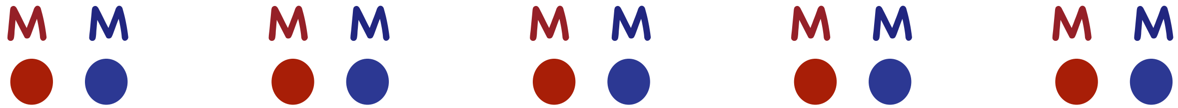
$$\gamma_j^B=\frac{1}{i\sqrt{2}}(a_j-a_j^\dagger)$$

$$\{\gamma_j^a,\gamma_{j'}^{a'}\}=\frac{1}{2}\delta_{aa'}\delta_{jj'}$$

$$\gamma_j^a\gamma_j^a=\frac{1}{2}$$

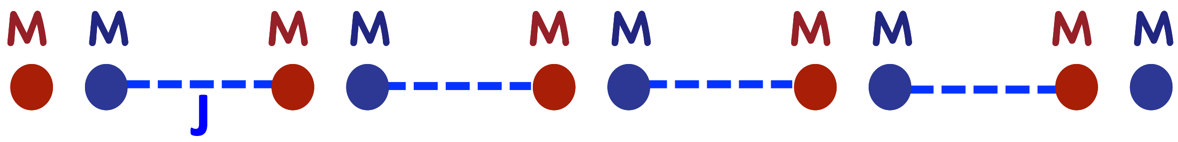
$$H=-2i\sum_{j=1}^{n}\left(J\gamma_j^B\gamma_{j+1}^A-\Delta\gamma_j^B\gamma_j^A\right)$$

Majorana chain

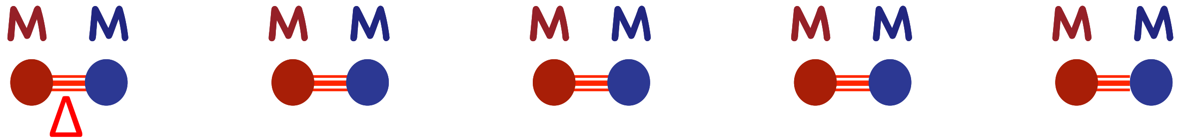


$$H = -2i \sum_{j=1}^{n} \left(J \gamma_j^B \gamma_{j+1}^A - \Delta \gamma_j^B \gamma_j^A \right)$$

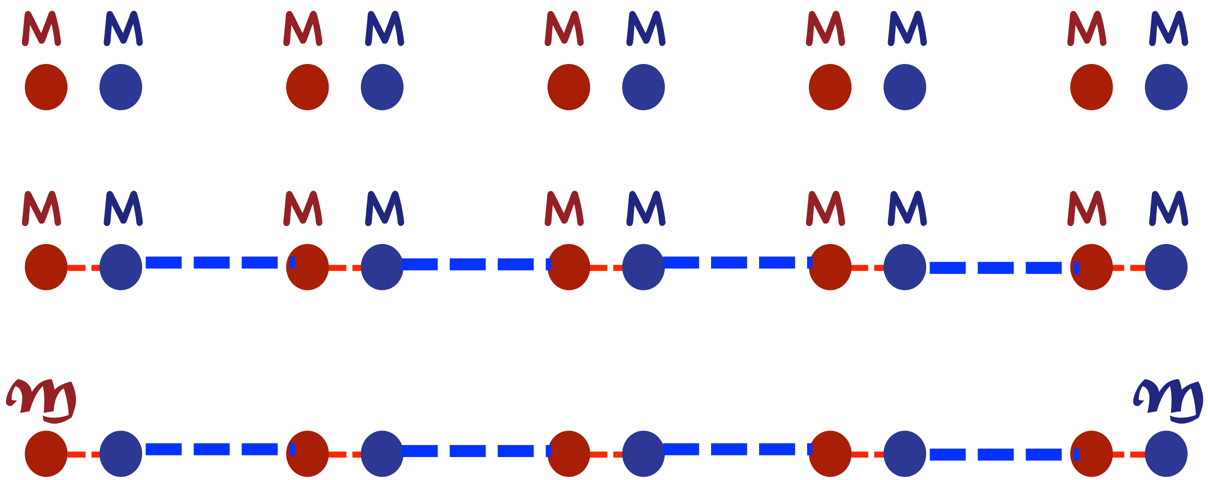
Majorana chain

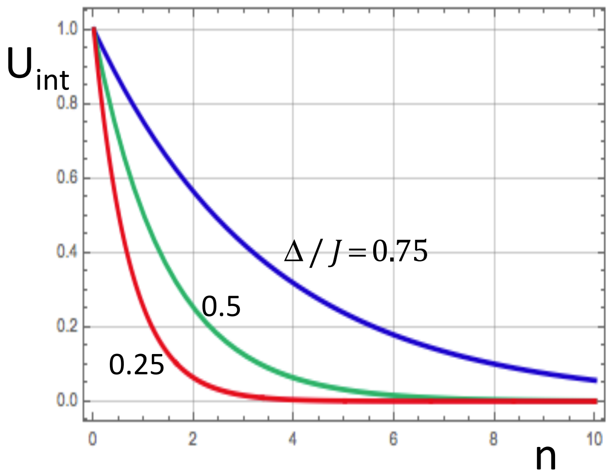


Majorana chain

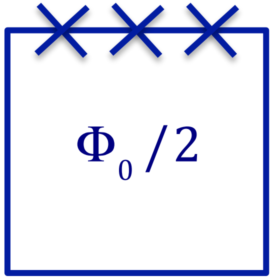


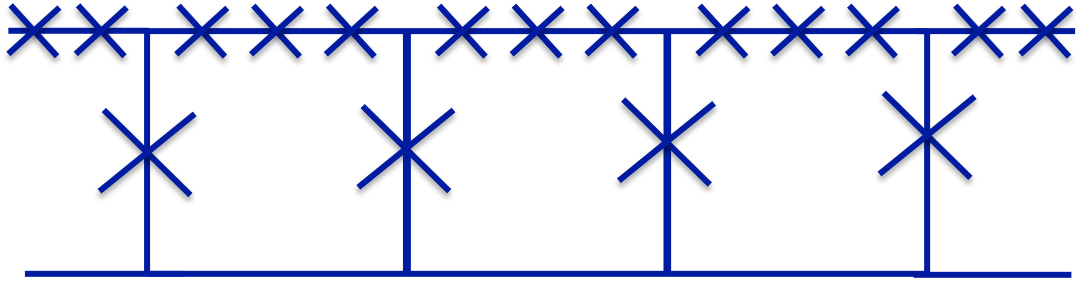
Majorana chain

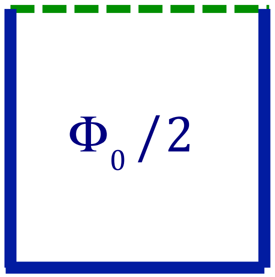




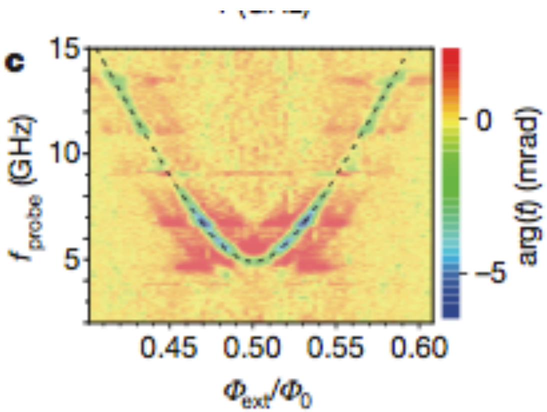
flux qubit with Josephson junctions



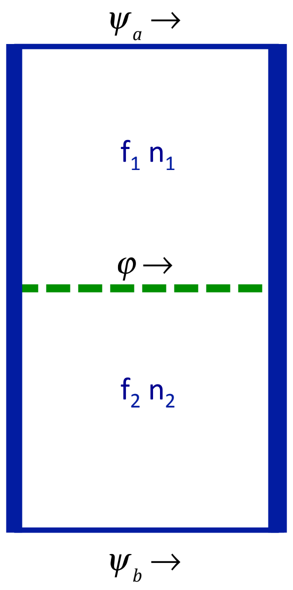




flux qubit with quantum phase-slip:
quantum tunneling of a fluxoid across a superconducting nanowire



Astafiev et al. Nature **484**, 355 (2012)



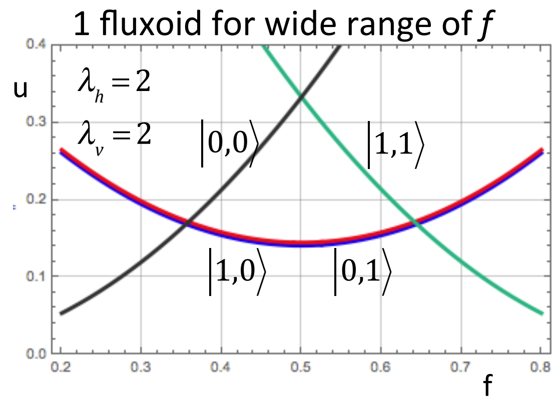
wire: $I = \varphi \Phi_0 / L$

$U = \Phi_0 I \varphi = \varphi^2 \Phi_0^2 / L$

loop: $f = \Phi / \Phi_0$

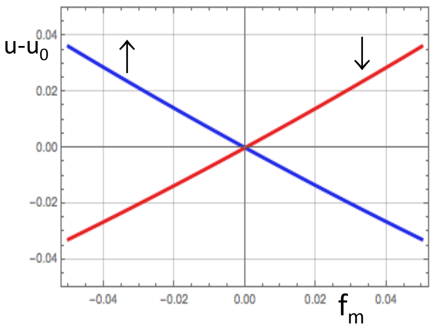
$\sum \varphi = f - n$

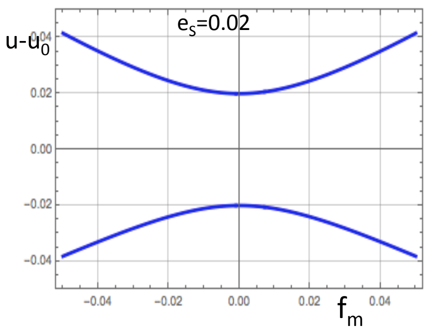
node: $\sum I = 0$



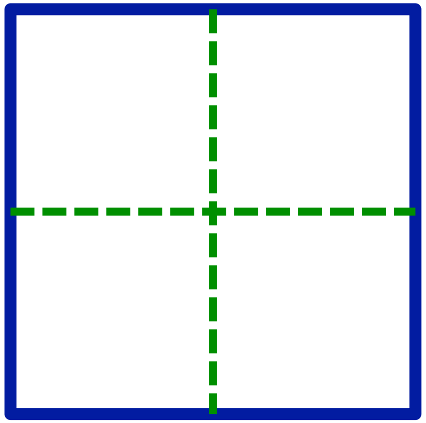
$f_1 = 0.5 + f_m$

$f_2 = 0.5 - f_m$

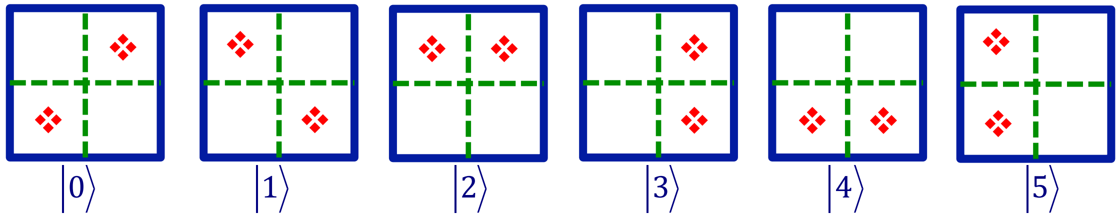




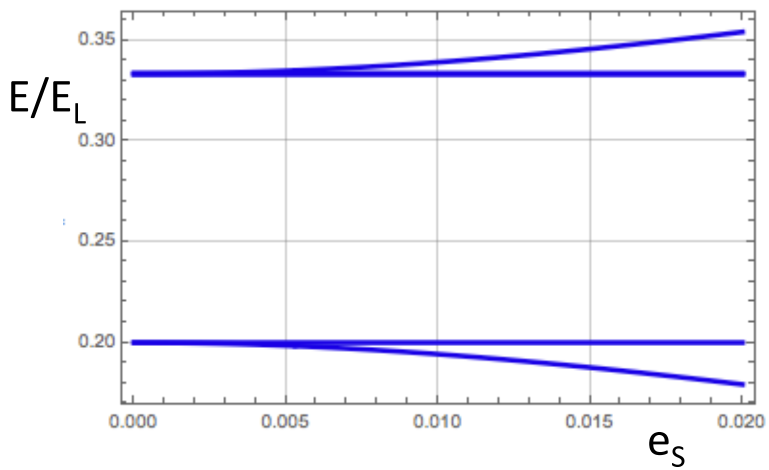
square with 4 loops
f=0.5, 2 fluxoids

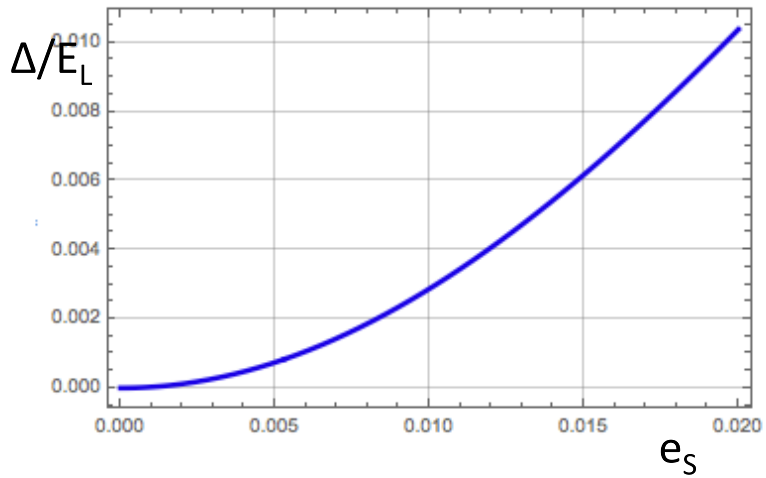


inner wires: quantum phase-slip amplitude E_S
outer wires: phase creep



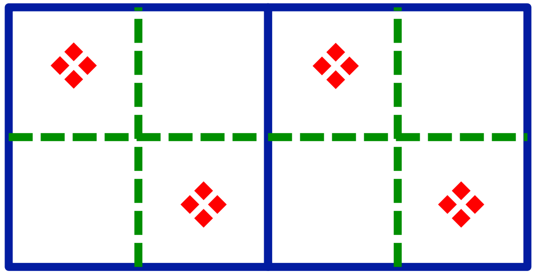
energies normalized to the inductive energy E_L of the QPS wire
$e_S = E_S/E_L$





square QPS flux qubit

ferromagnetic coupling
J= 0.020



energy values
E_L/h can be 500 GHz

J=0.02 means J/h=10 GHz

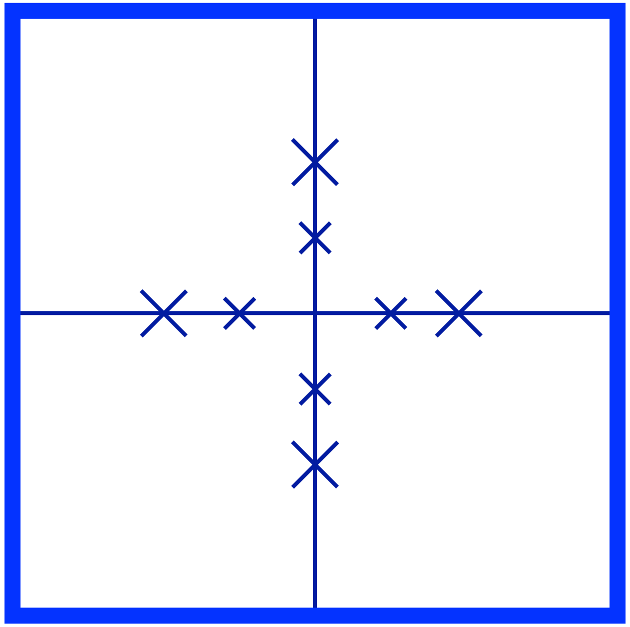
Δ= 0.2 J means Δ/h= 2 GHz

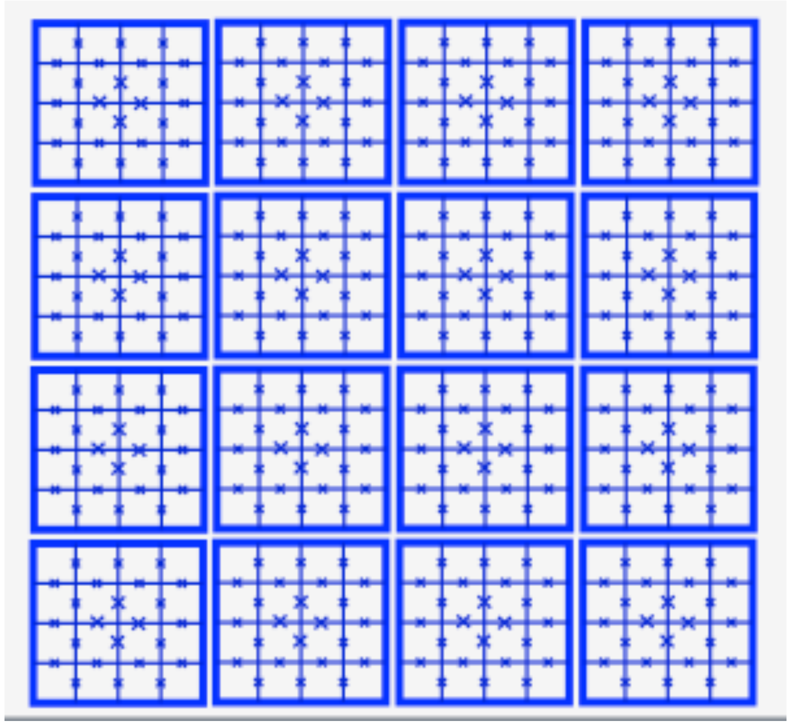
no influence of charges
  no islands
  wavelength of plasma oscillations much larger than sample size

no influence of H, dH/dx or dH/dy

but
  quantum phase-slip untested

why not with Josephson junctions?





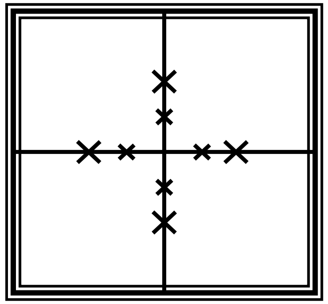
Bilbao 2012
Quantum Simulation conference

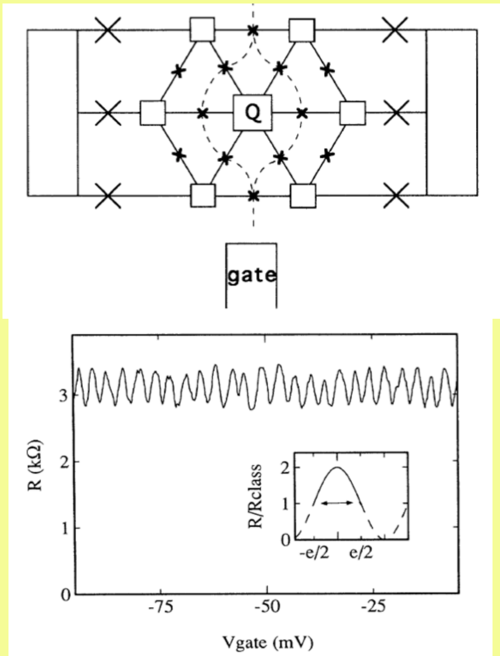
Aharonov Casher effect

quantum calculation Jos Thijssen

5 degrees of freedom,

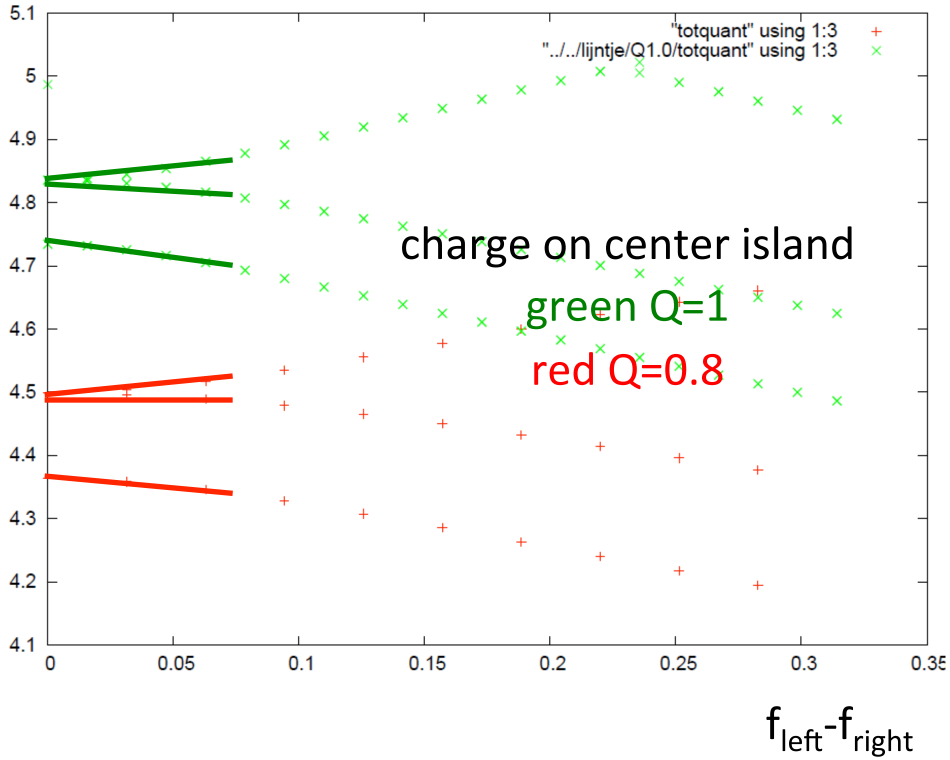
9 variables, 9^5 basis vectors



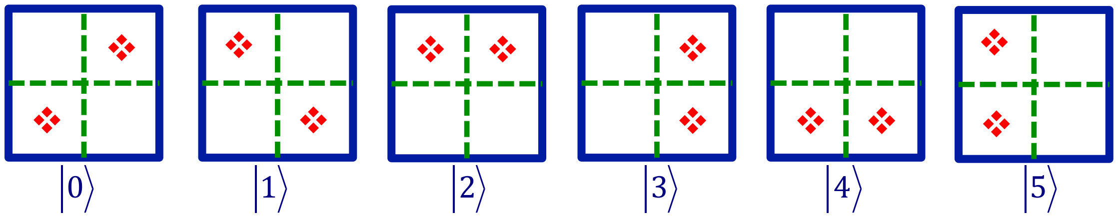


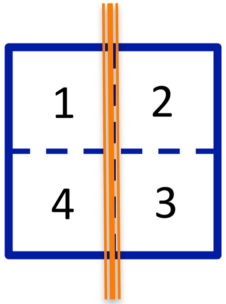
Wiveka Elion et al. (1993)

3 lowest energy levels

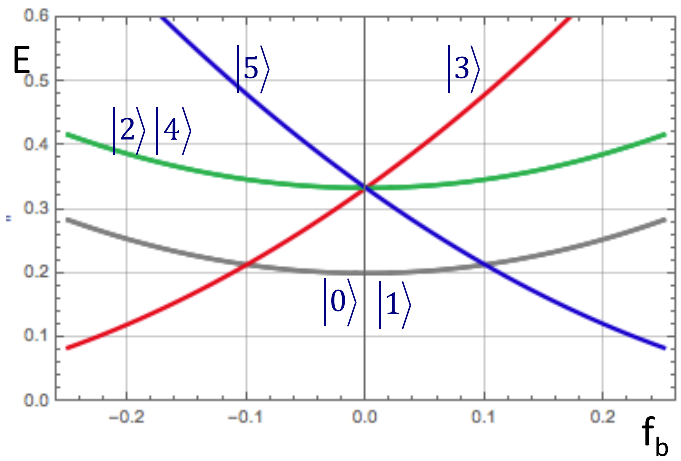


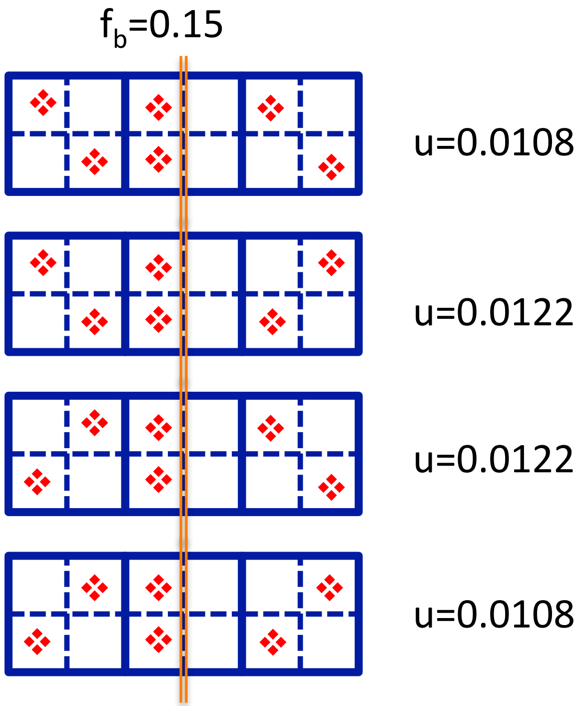
fade-out

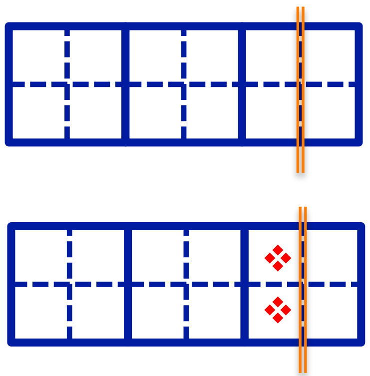


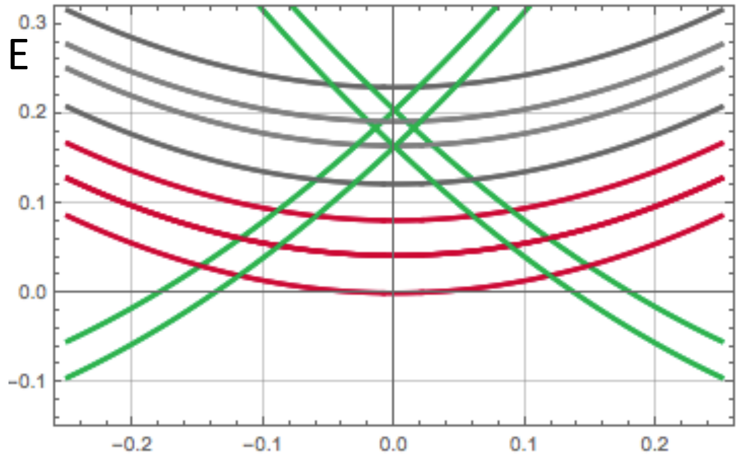


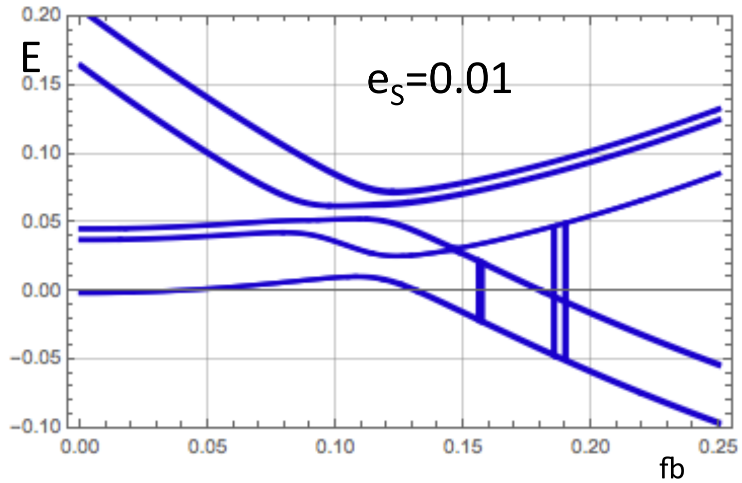
$f_1=0.5+f_b$
$f_2=0.5-f_b$
$f_3=0.5-f_b$
$f_4=0.5+f_b$



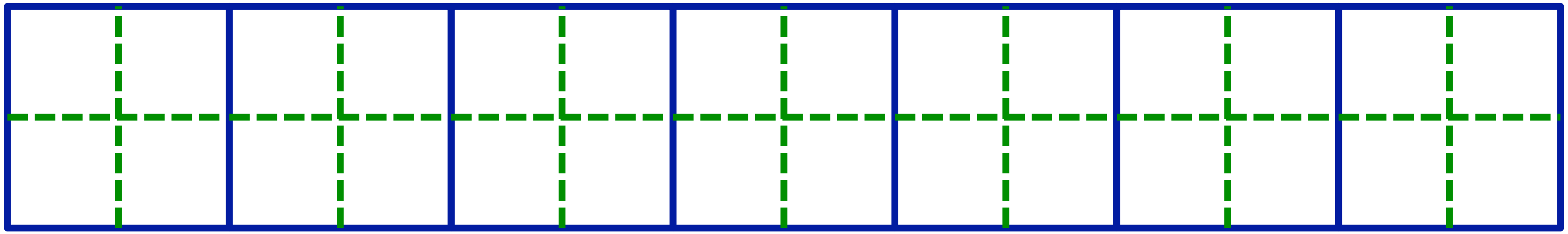



3 qubits
2 qubits


E
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.1
0.0
0.1
0.2


E
e_S=0.01
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
0.00
0.05
0.10
0.15
0.20
0.25
fb

7 qubit chain



7 qubits, 128 classical states

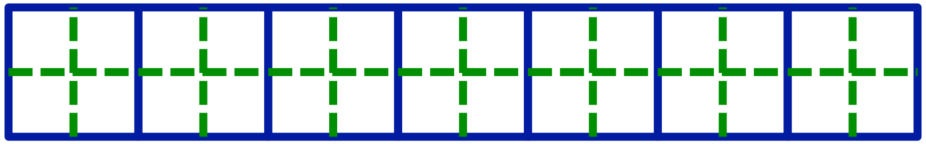
each state:
68 phase values
28 loop equations
40 node equations

E=0,		2 states
E=0.042	(2J)	12 states
E=0.085	(4J)	32 states
E=0.126	(6J)	36 states
E=0.168	(8J)	32 states
E=0.204	(10J)	12 states
E=0.245	(12J)	2 states

lower energy states:

ground states
0000000 1111111

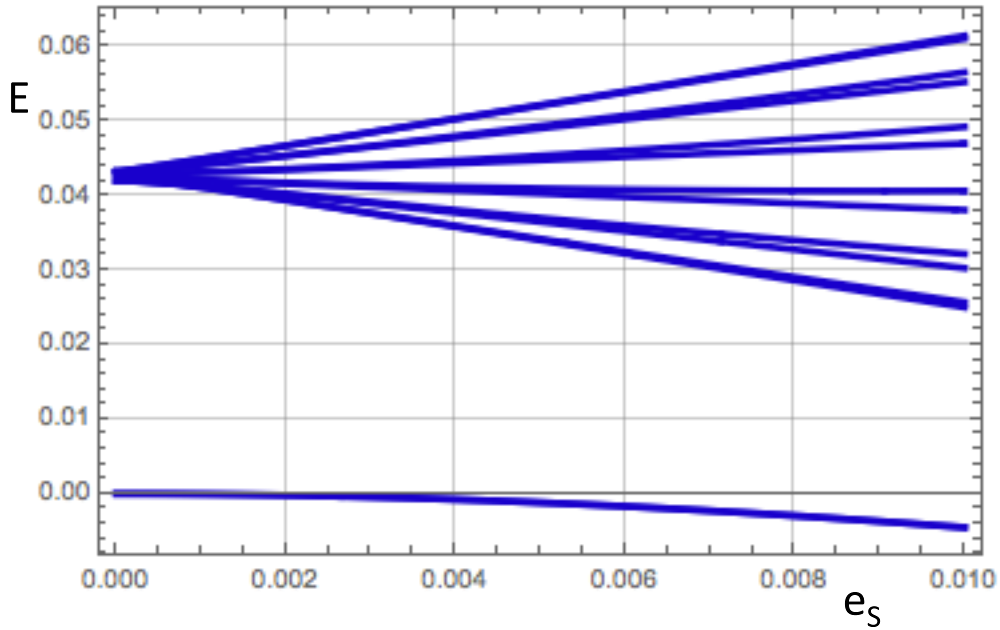
energy between 0.0420 and 0.0432
1000000 0000001 0111111 1111110
1100000 0000011 0011111 1111100
1110000 1111000 0001111 1111000

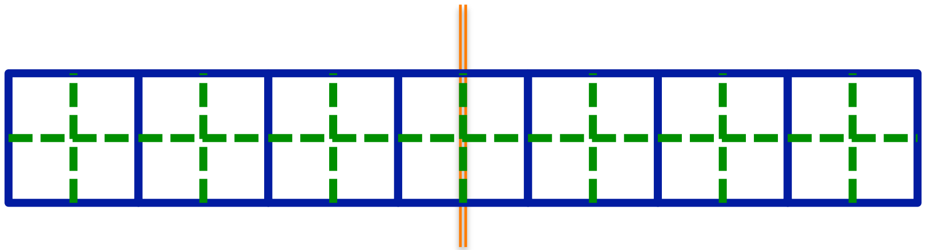


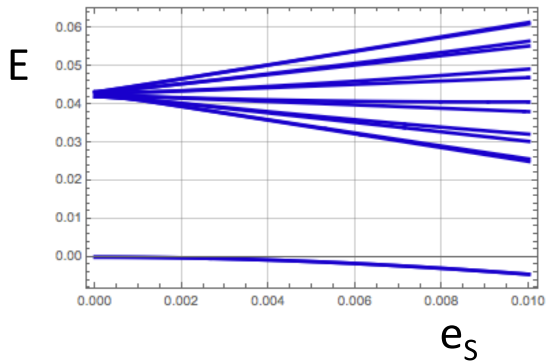
lower energy states:

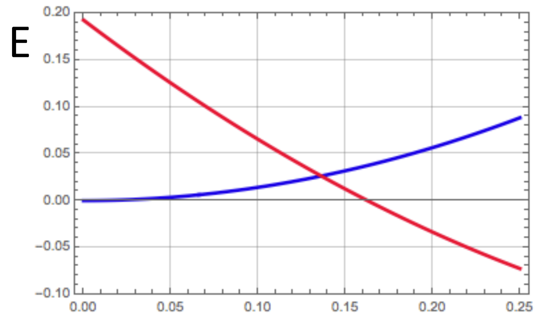
ground states
0000000 1111111

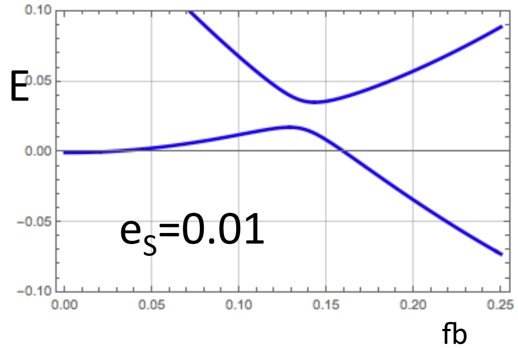
energy between 0.0420 and 0.0432
1000000 0000001 0111111 1111110
1100000 0000011 0011111 1111100
1110000 1111000 0001111 1111000

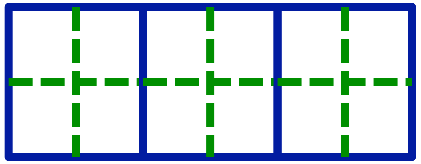


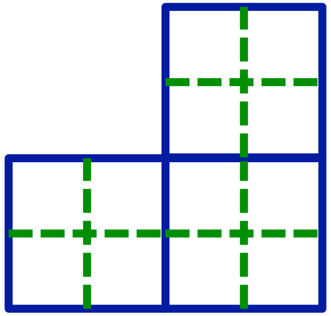


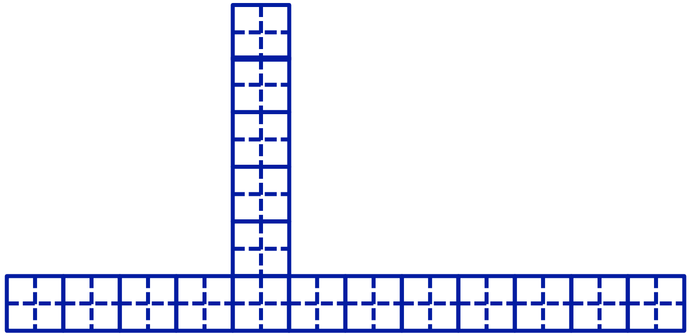

E
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.000
0.002
0.004
0.006
0.008
0.010
e_S


E
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
0.00
0.05
0.10
0.15
0.20
0.25


E
0.10
0.05
0.00
−0.05
−0.10
e_S=0.01
0.00
0.05
0.10
0.15
0.20
0.25
fb







3 squares straight

$u_{\uparrow\uparrow\uparrow}=0$

$u_{\uparrow\uparrow\downarrow}=0.0419$

$u_{\uparrow\downarrow\uparrow}=0.0811$

$u_{\uparrow\downarrow\downarrow}=0.0419$

$u_{\downarrow\uparrow\uparrow}=0.0419$

$u_{\downarrow\uparrow\downarrow}=0.0811$

$u_{\downarrow\downarrow\uparrow}=0.0419$

$u_{\downarrow\downarrow\downarrow}=0$

3 squares corner

$u_{\uparrow\uparrow\uparrow}=0$

$u_{\uparrow\uparrow\downarrow}=0.0389$

$u_{\uparrow\downarrow\uparrow}=0.0820$

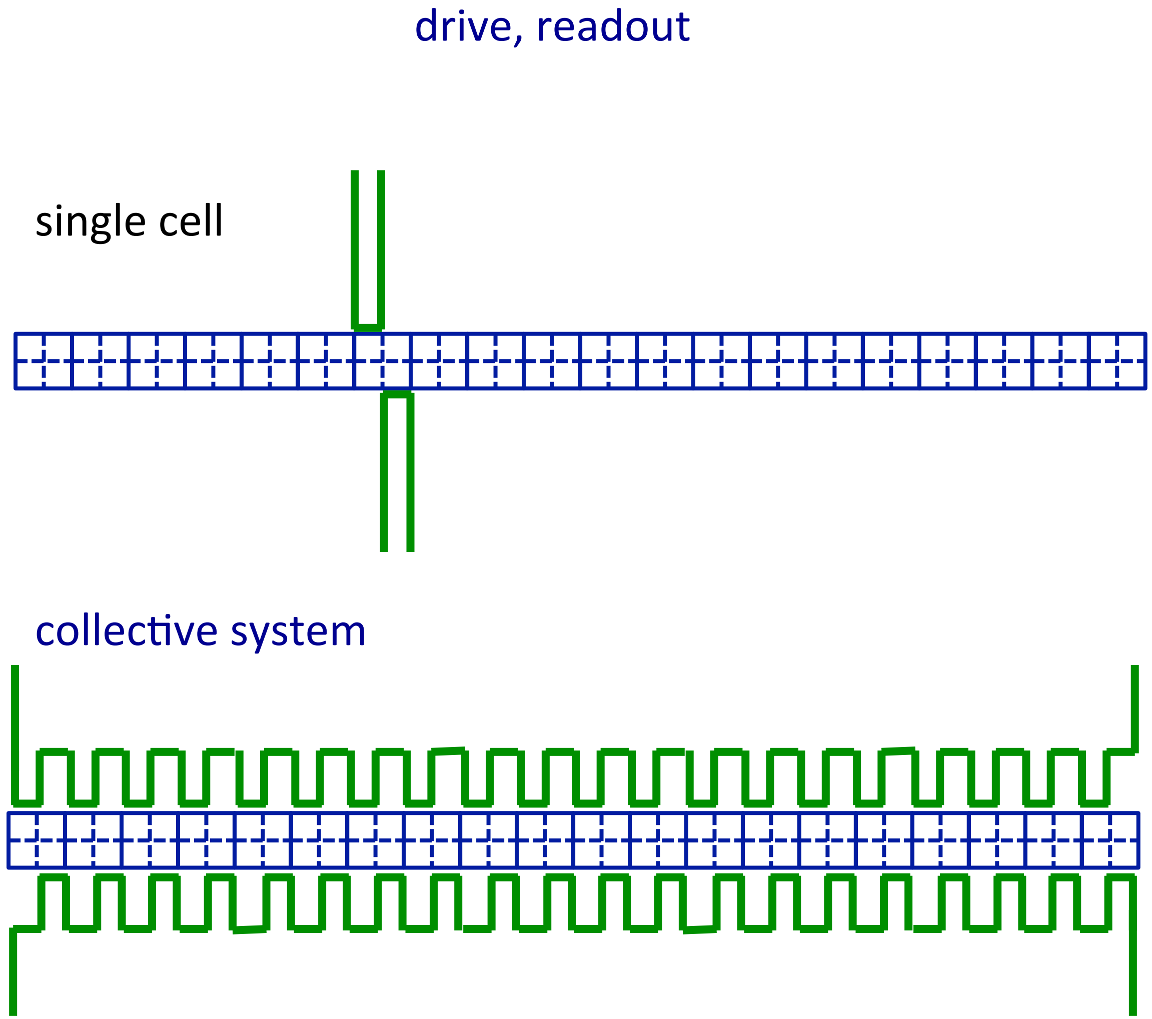
$u_{\uparrow\downarrow\downarrow}=0.0389$

$u_{\downarrow\uparrow\uparrow}=0.0389$

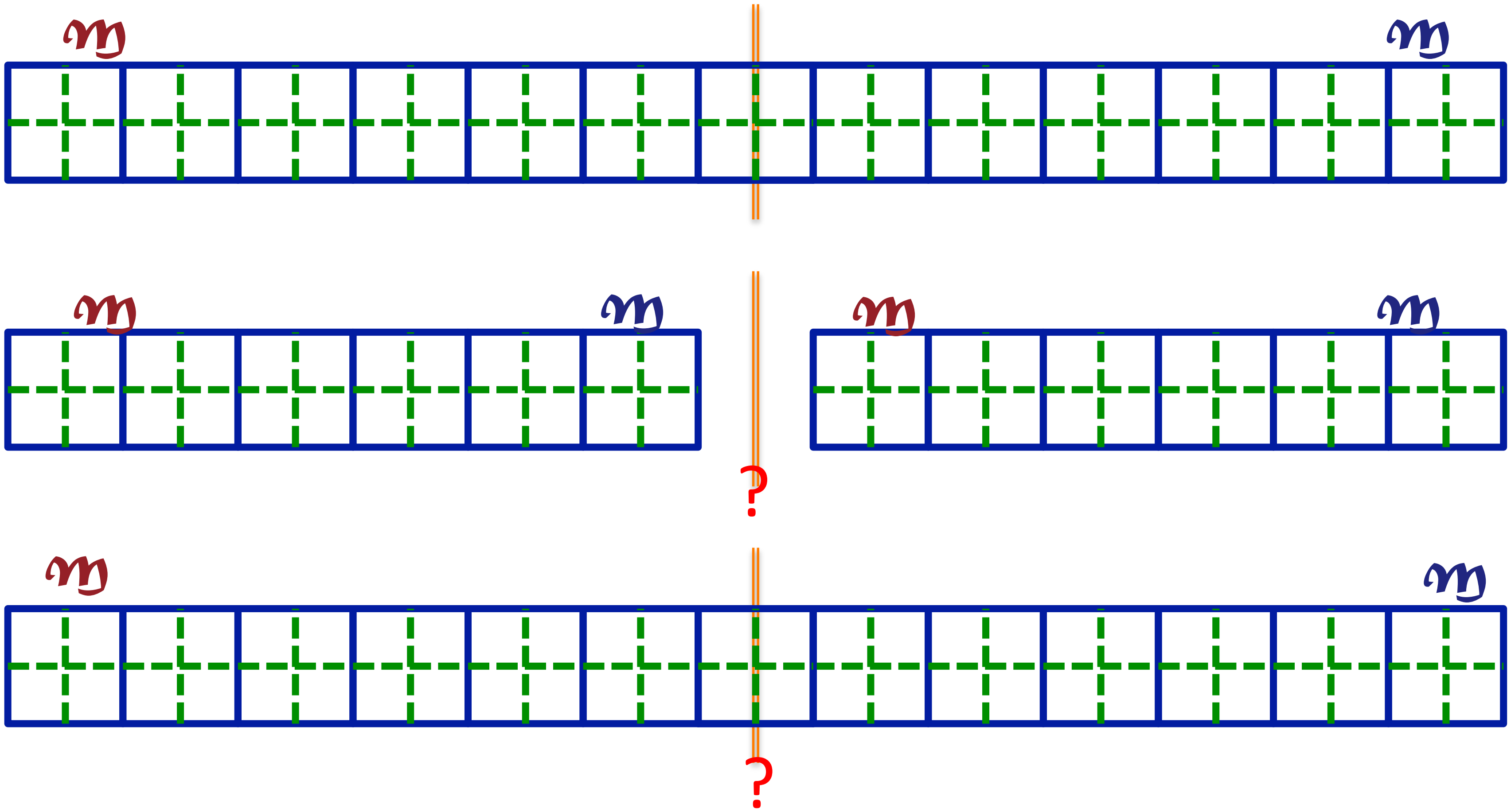
$u_{\downarrow\uparrow\downarrow}=0.0820$

$u_{\downarrow\downarrow\uparrow}=0.0389$

$u_{\downarrow\downarrow\downarrow}=0$


drive, readout
single cell
collective system

fusion



conclusions

aspects of Majorana physics can be studied in quantum Ising chains

Ising chains can be realized with coupled superconducting qubits

square 4-cell qubits with quantum phase-slip nanowires are in principle ideally suited (experimental test needed)
- not sensitive to offset charges or nonlocal magnetic fields
- adiabatic fade-out/in of individual qubits is possible