JENA IPHT QUANTUM ELECTRONICS

Radio-Frequency Technique for Investigation of Quantum Properties of Superconducting Structures.

E. Il'ichev

Motivation

Demonstration the simplest quantum algorithm by making use of flux qubits

Problem of quantum measurements.

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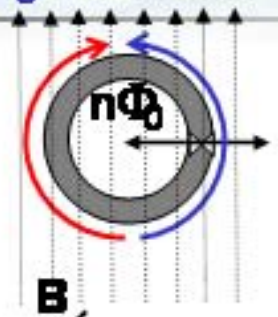
Single-junction interferometer



$$\Phi_0 = \frac{h}{2e}$$

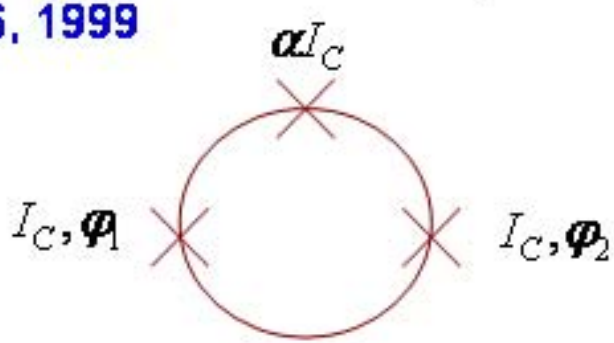
Can exhibit MQT (A. Legget *et al.,)*

Useful device for memory cells

However $\beta = 2\pi L I_C / \Phi_0 > 1$

Solution – for N>3 the ring exhibits hysteresys even for negligible loop inductance (T. Yamashita *et al.*, J. Appl. Phys. **19**, 2519 (1979).)

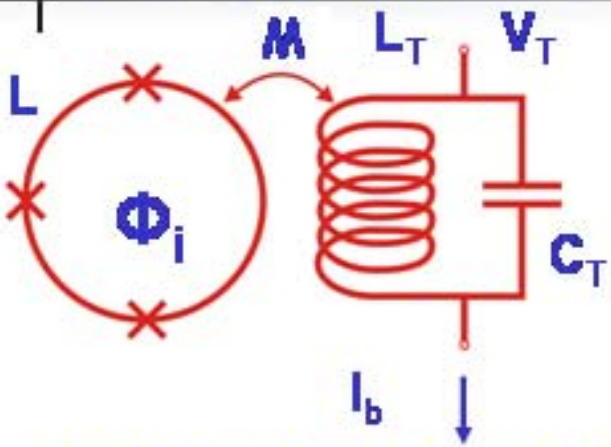
Therefore this structure can be used as qubit J.E. Mooij *et al.*, Science **285**, 1036, 1999



Outline

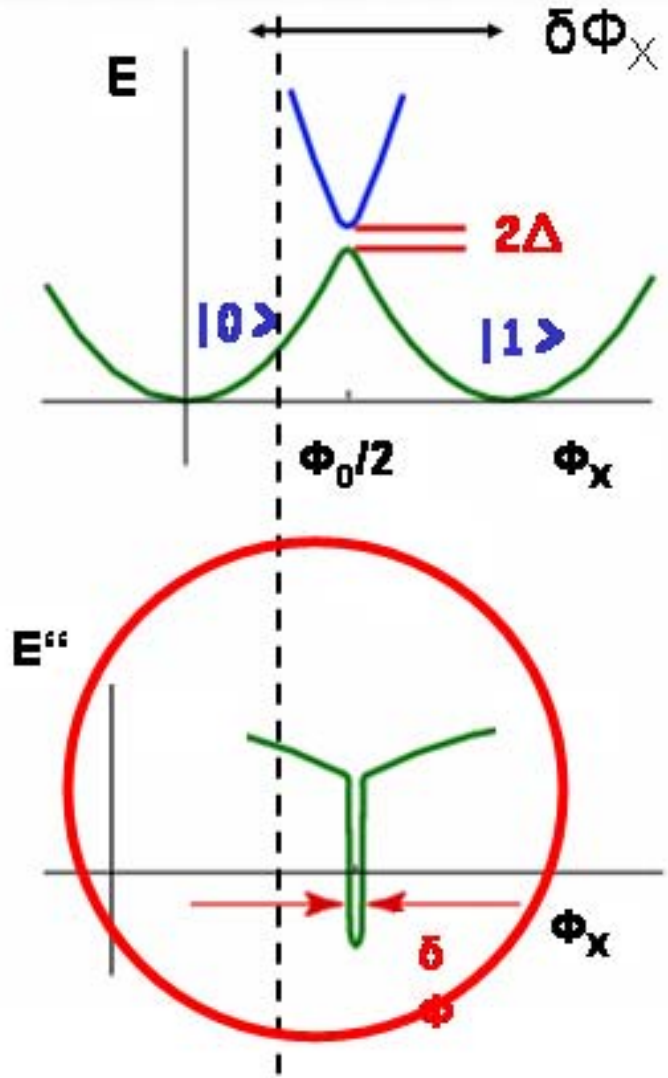
- Readout concept
- Two coupled qubits
- Basic idea of the Adiabatic Quantum Computation
- Three coupled qubits
- Ferromagnetic and antiferromagnetic coupling
- Four coupled qubits with FM and AF coupling

Readout concept



Θ-phase shift between I_b and V_T

$$\tan\theta = k^2 QL \frac{d^2E}{d\Phi^2}$$



Dip:

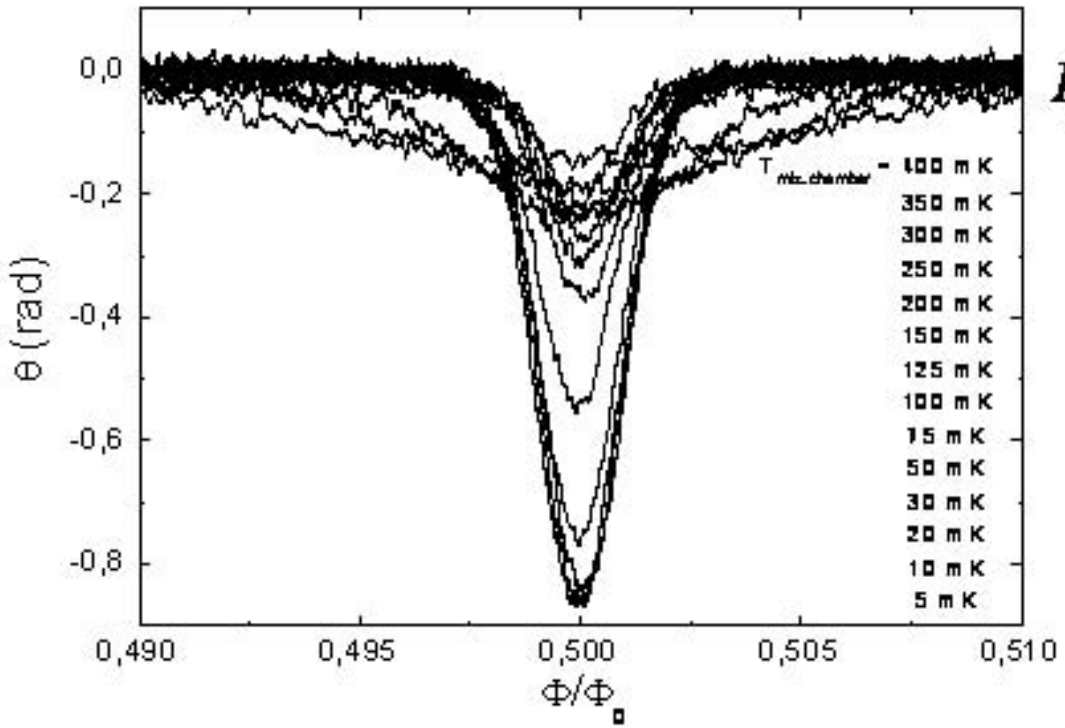
evidence for quantum regime

access to qubit parameters

nondemolition readout of qubit

Results

I_b = 77pA



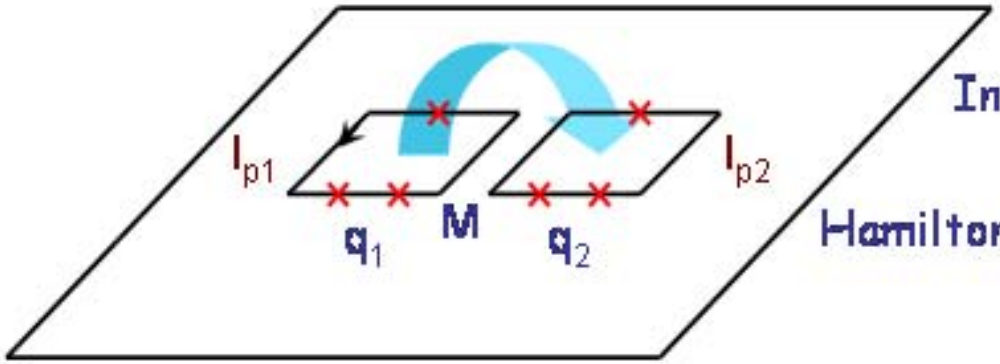
$$I_p = \frac{(\tan\Theta)_{MAX}}{k^2 Q L_q} \cdot \frac{\Phi_0 f_{FWHM}}{2\sqrt{2^{2/3}-1}}$$

$$\Delta = I_p \cdot \frac{\Phi_0 f_{FWHM}}{2\sqrt{2^{2/3}-1}}$$

$$I_p = I_C(1 - 1/4\alpha^2)^{1/2}$$

Ya. S. Greenberg et al., PRB 66, 214525 (2002)
M. Grajcar et al., PRB 69, 060501(R) (2004)

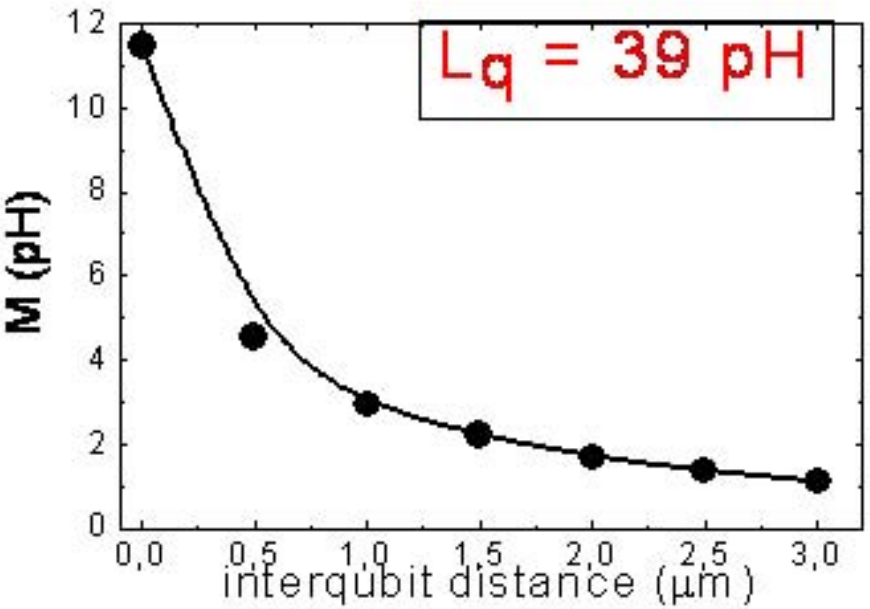
3JJ Flux-qubit; Inductive Coupling



Interaction energy: $J = MI_{p1}I_{p2}$

Hamiltonian: $H_\Sigma = H(q_1) + H(q_2) + J\sigma_1^z\sigma_2^z$

$$H(q_i) = \varepsilon_i\sigma_i^z + \Delta_i\sigma_i^x$$



Drawback

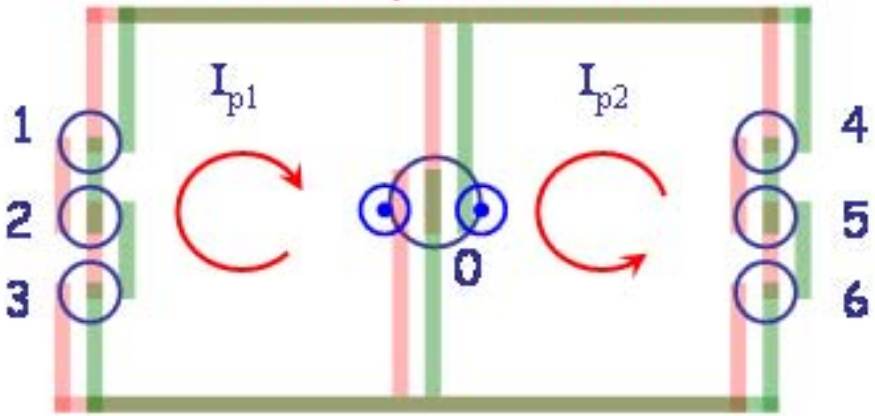
The "size" problem: Coupling energy cannot be made strong enough for small L_q

Interaction energy can be increased if

1. Qubits have shared leg
2. Persistent currents increase

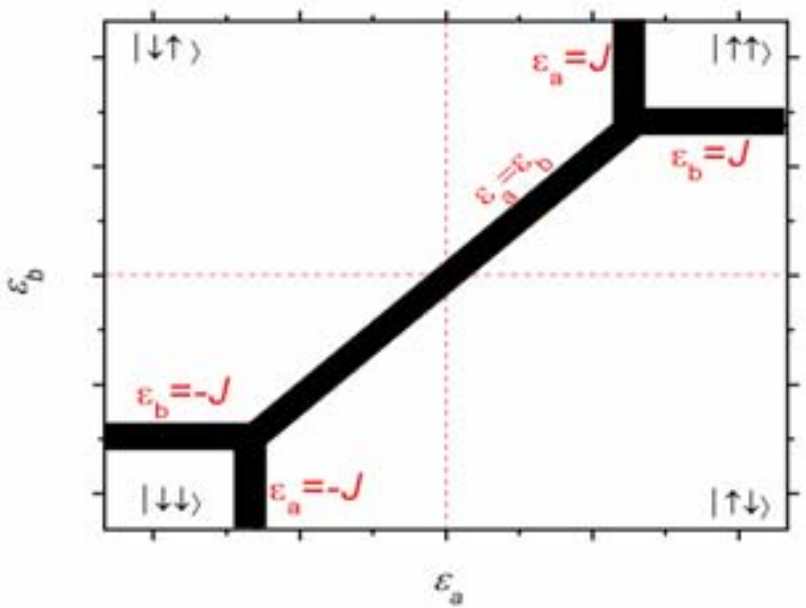
Coupling through a shared Josephson junction

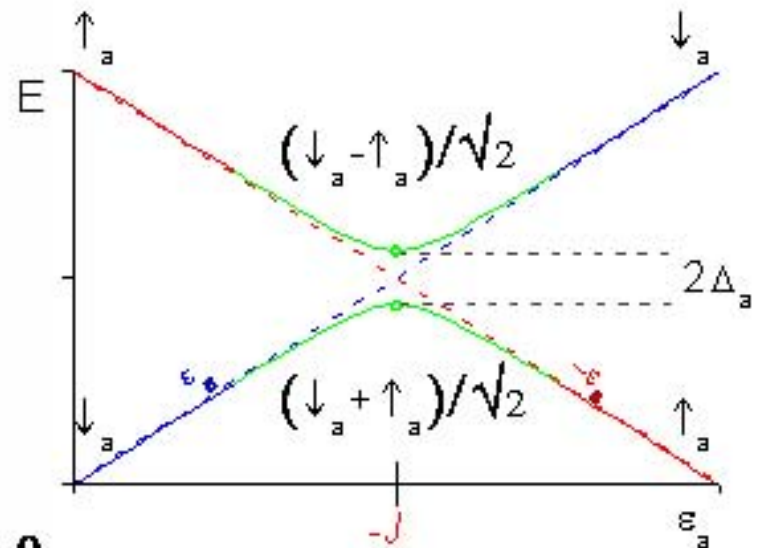
Our implementation



Originally proposed by L.S. Levitov *et al*, *cond-mat*/0108266

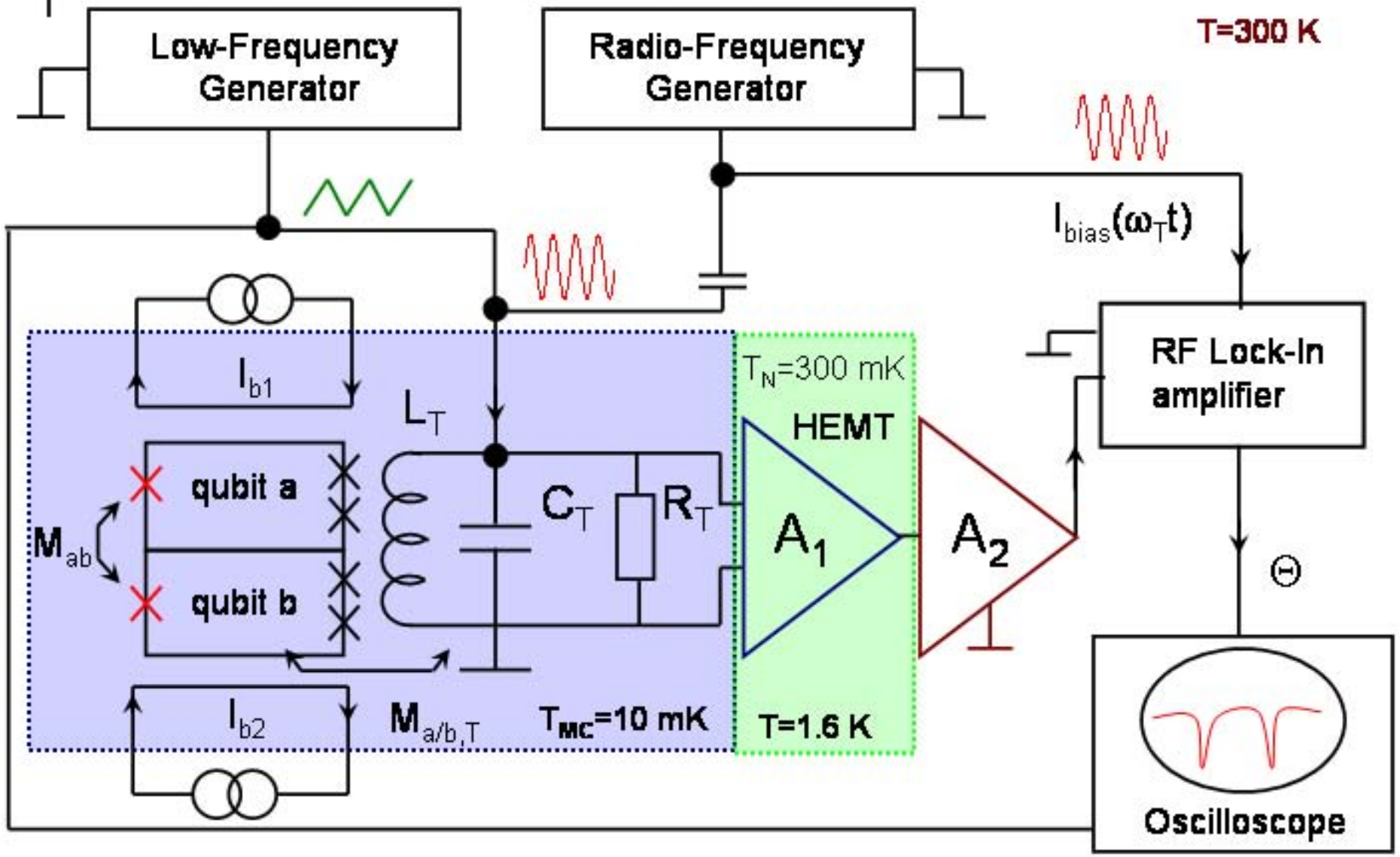
Intuitively: The phase drop over the coupling junction leads to reduction in junctions energy of qubits and increase in Josephson energy of the junction 0.





$\Delta_a \neq 0$

Measurement scheme

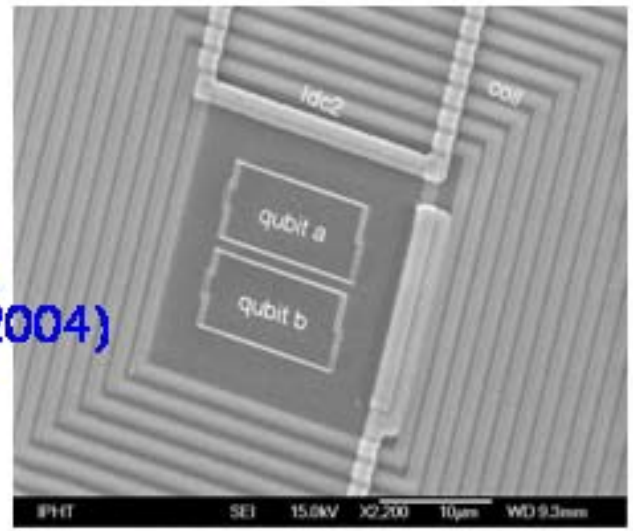


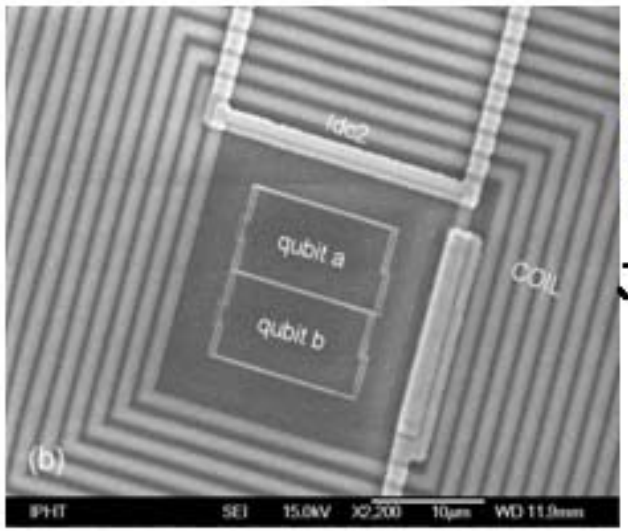
Micrographs

1.

Weak inductive Coupling J=20 mK

A. Izmalkov *et al.*, PRL 93, 037003 (2004)





2.

Strong inductive coupling

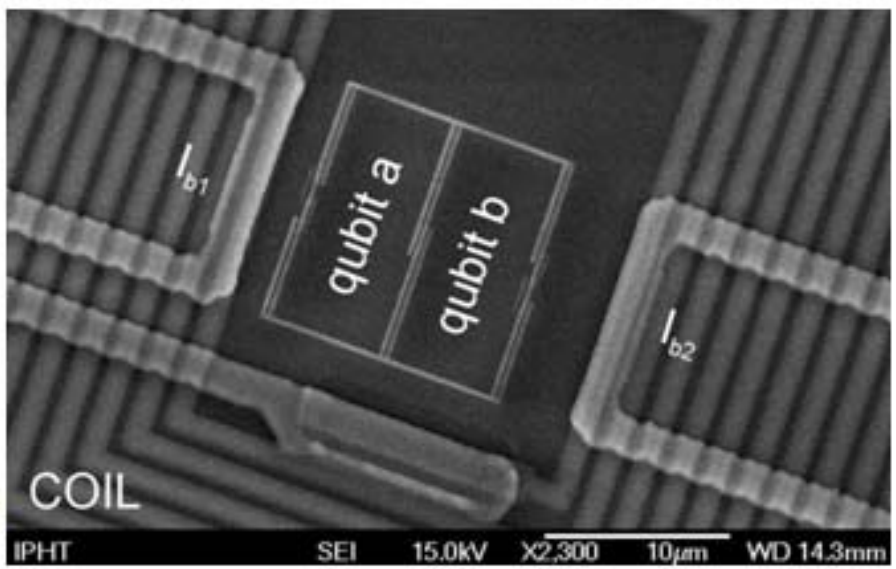
J=150 mK

3,4.

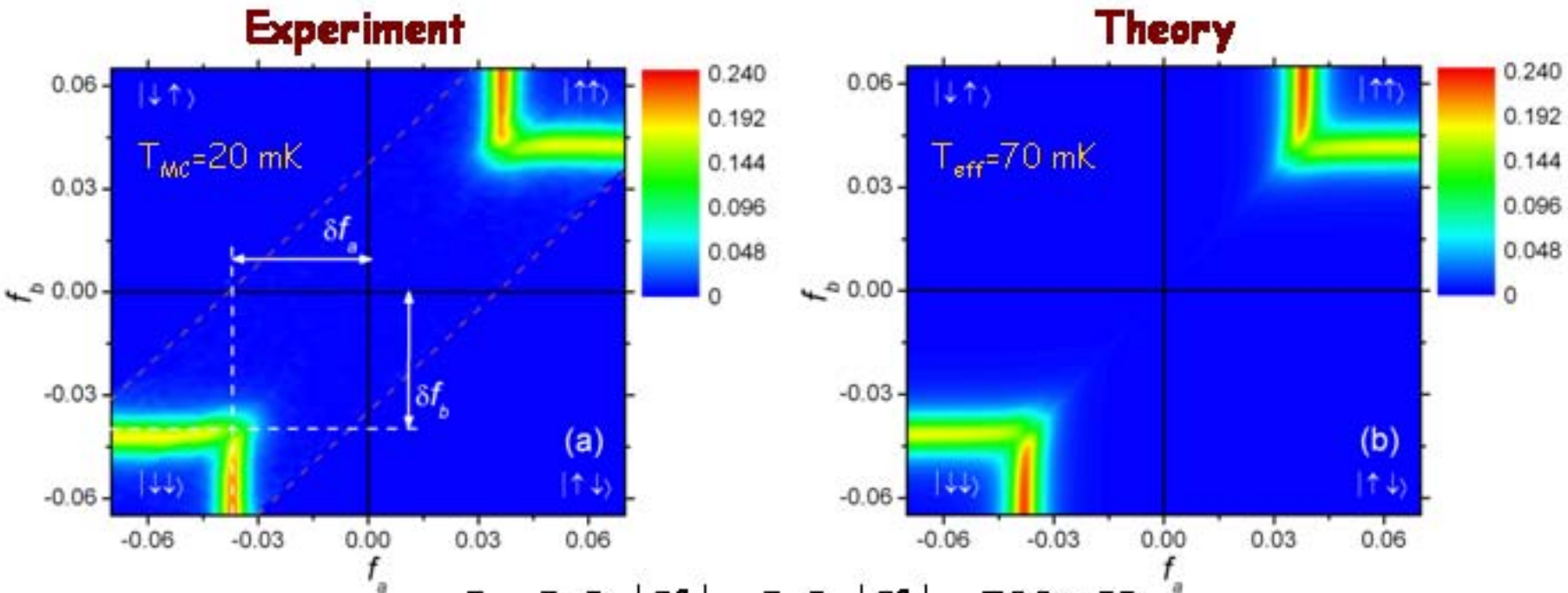
Coupling throug a shared Josephson junction

J=0.7 K, 1.2 K

M. Grajcar, *et al.*, Phys. Rev. B 72, R020503, (2005).



Coupling through a shared Josephson junction.IMT flux diagram.*



$$J = I_a \Phi_0 \left|\delta f_a\right| = I_b \Phi_0 \left|\delta f_b\right| = 700\,\mathrm{mK}$$

Sample No.	S_{J0}, (μm^2)	Δ_a, (mK)	Δ_b (mK)	I_a (nA)	I_b (nA)	J (K)
1	0.3	80	90	120	110	0.7
2	0.15	30	30	150	120	1.2

*M. Grajcar, *et al.*, Phys. Rev. B **72**, 020503 (R), (2005).

Concept of Adiabatic Quantum Computation*

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1. Encode your mathematical problem into the "problem Hamiltonian"

$$H_P = \sum_{i=1}^{N} \varepsilon_i(f_i)\sigma_{z,i} + \sum_{i=1}^{N} \Delta_i \sigma_{x,i} + \sum_{i<j}^{N} J_{i,j}\sigma_{z,i}\sigma_{z,j}$$

2. Make a chip with layout in accordance with the model Hamiltonian (Analogue Computer)

3. Start with initial Hamiltonian H_I in the known ground state $|I\rangle$

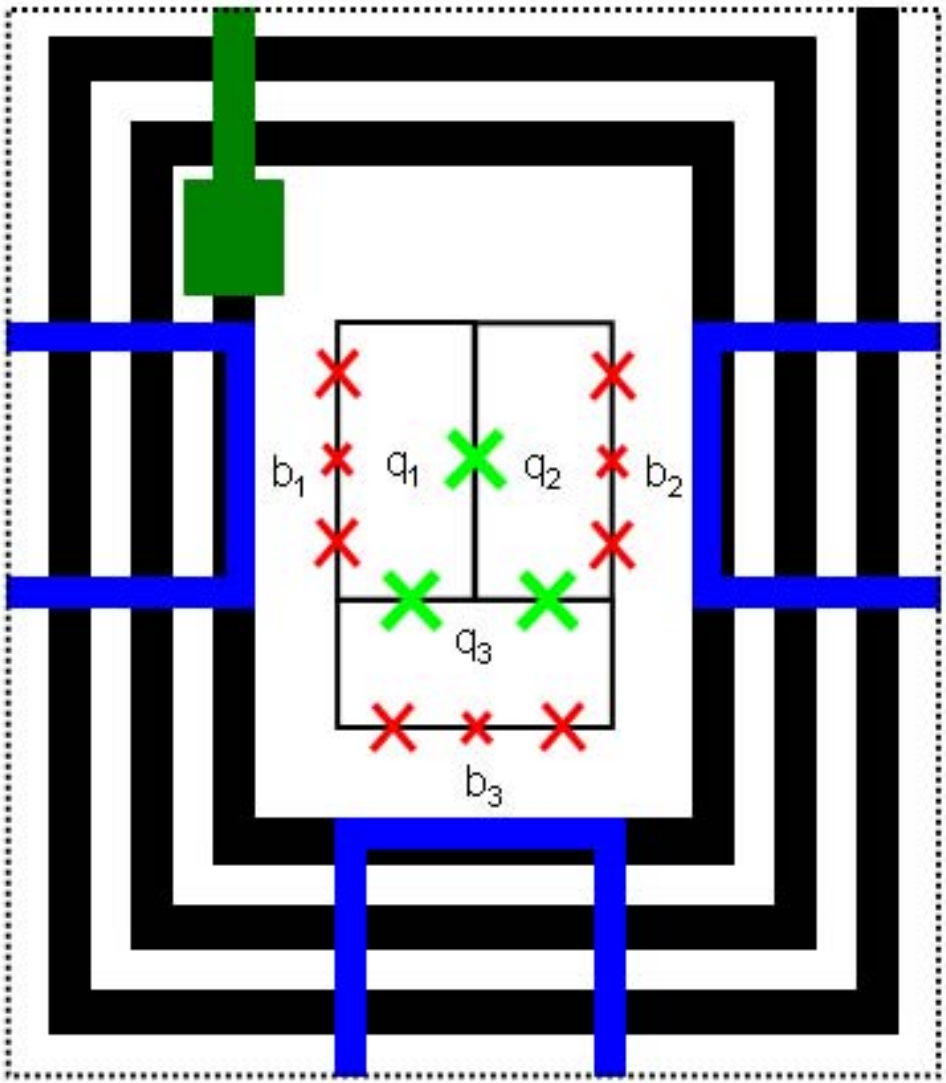
$$H_I = \sum_{i=1}^{N} \varepsilon_i(f_i)\sigma_{z,i}$$

4. Adiabatic evolution from $|I\rangle$ to the <u>unknown</u> ground state $|g\rangle$ of H_P by changing the bias of individual qubits adiabatically

5. Readout the ground state $|g\rangle$ of H_P

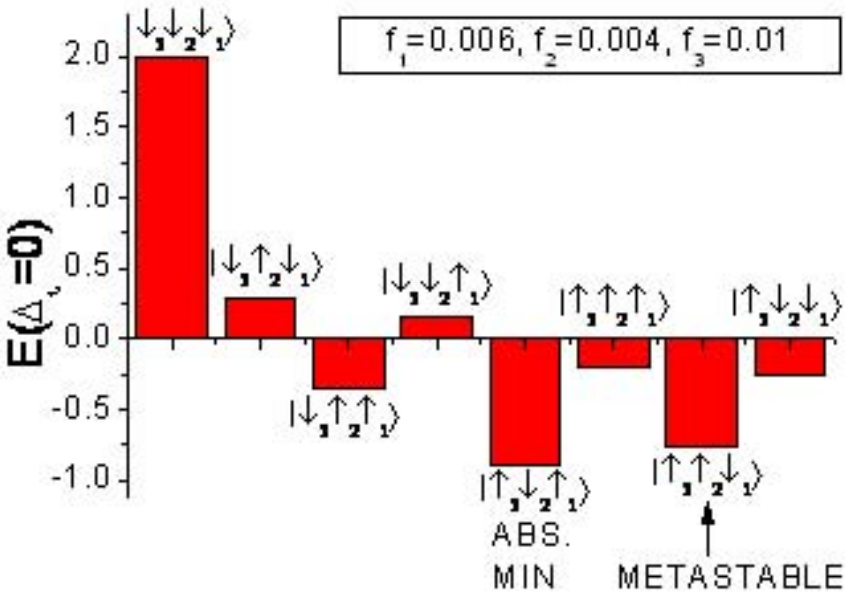
* E. Farhi, J. Goldstone, S. Gutmann, M. Sipser, quant-ph/0001106.

Sample layout



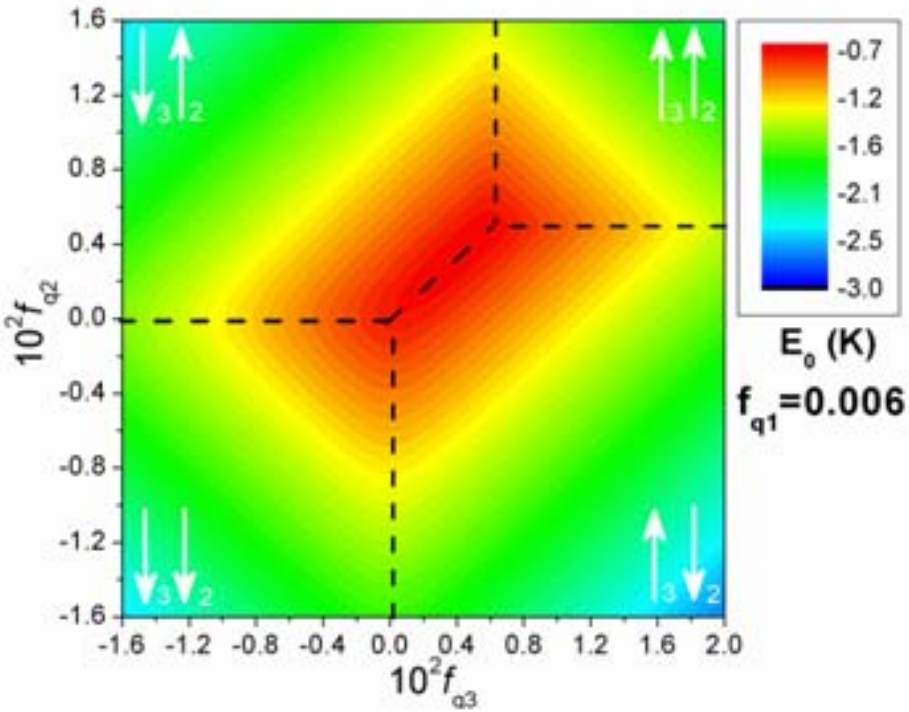
$J_{12}=J_{13}=J_{23}=0.3$ K
$\Delta_1=\Delta_2=\Delta_3=96$ mK
$I_{p1}=I_{p3}=350$ nA, $I_{p2}=420$ nA

If $f_1=6m\Phi_0$, $f_2=4m\Phi_0$, $f_3=10m\Phi_0$
solution is $|\uparrow\downarrow\uparrow\rangle$

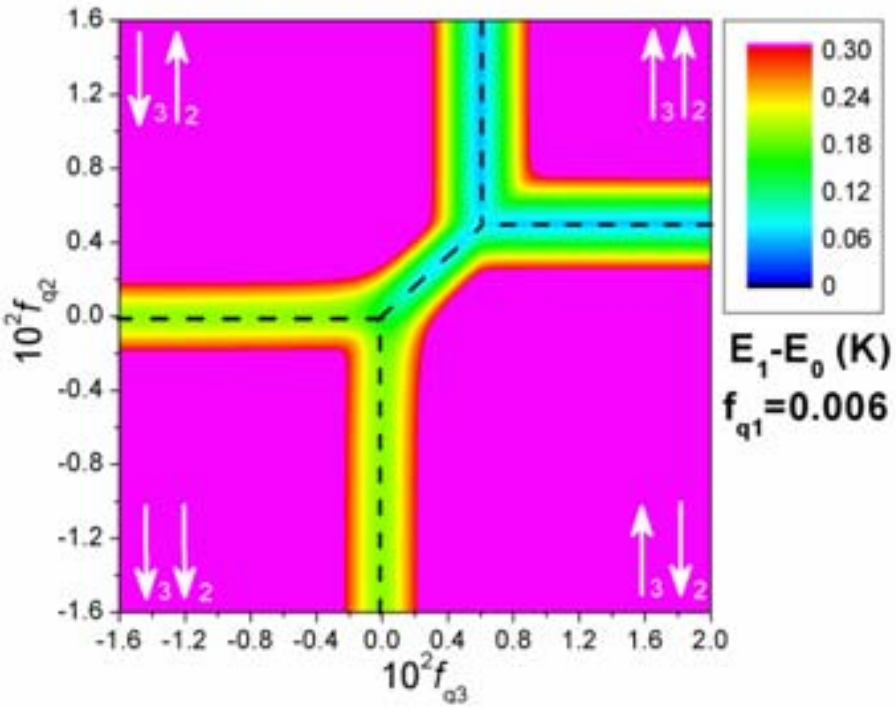


Adiabatic evolution

Energy of the ground state



Spacing between ground and first excited states

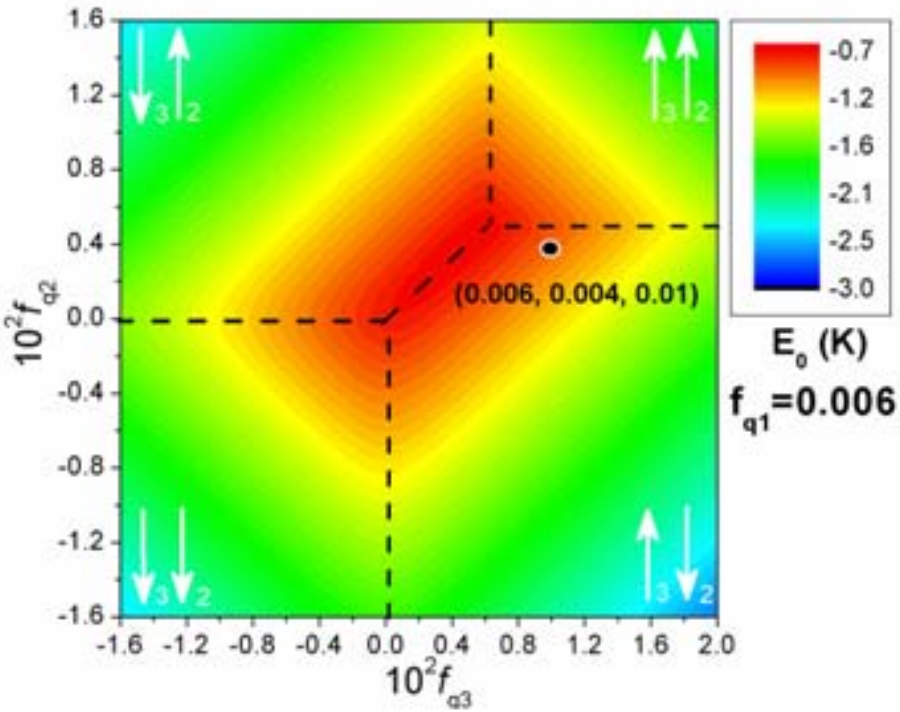


– – – Max curvature of the ground state

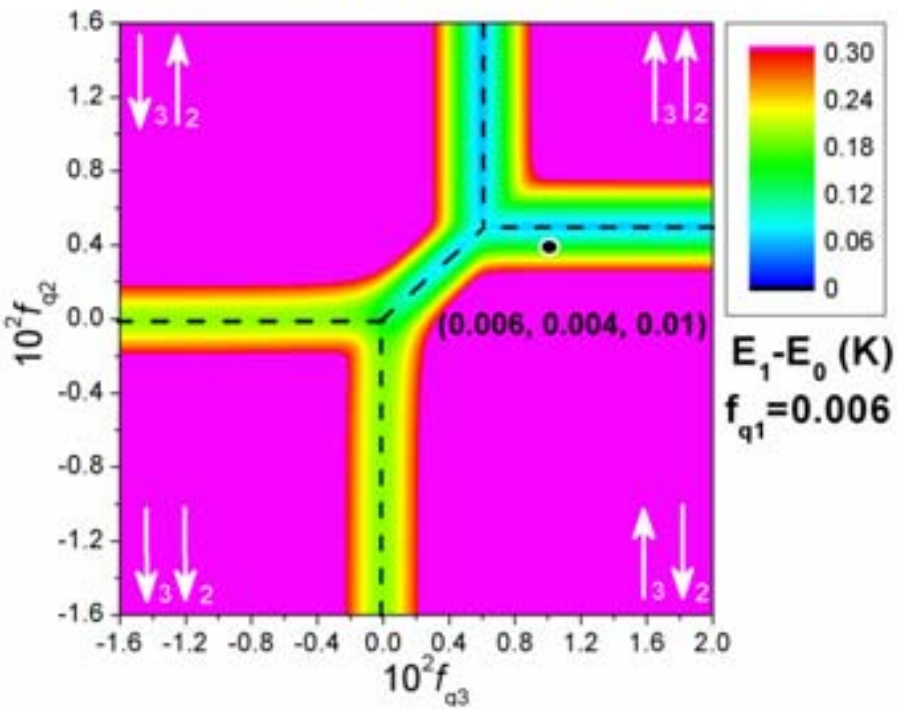
- boundary of the classical stability diagram

Adiabatic evolution

Energy of the ground state



Spacing between ground and first excited states

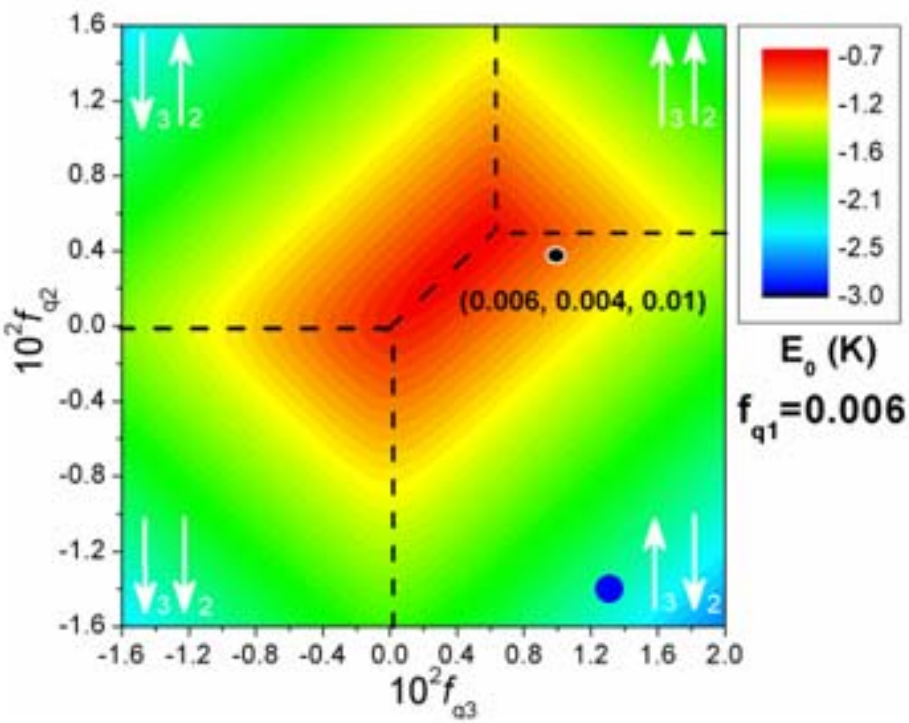


– – – Max curvature of the ground state

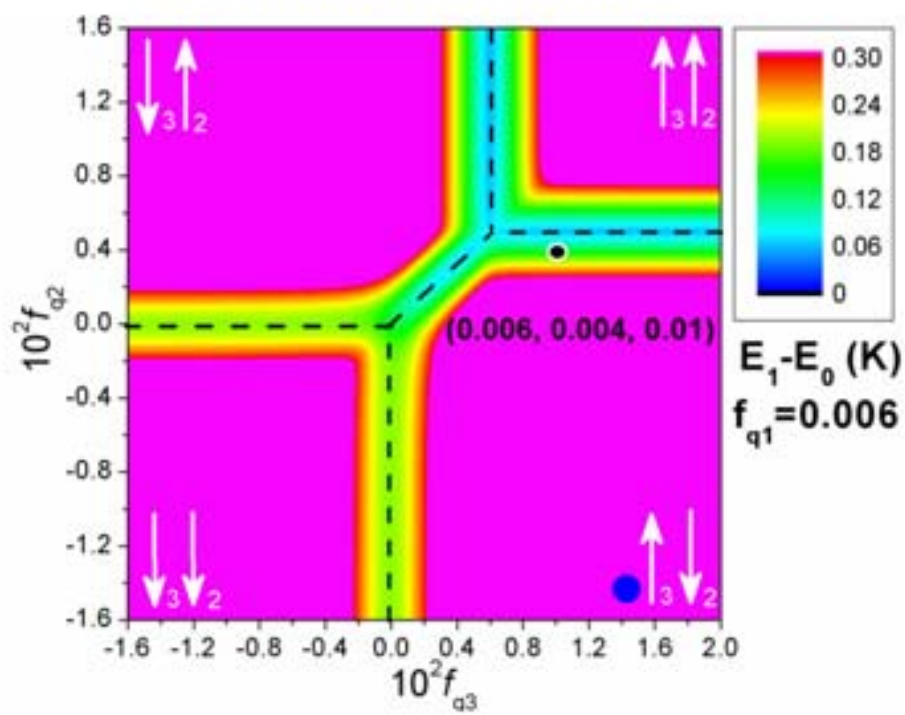
If $f_1=6m\Phi_0$, $f_2=4mF_0$, $f_3=10mF_0$ solution is $|\uparrow\downarrow\uparrow\rangle$

Adiabatic evolution

Energy of the ground state



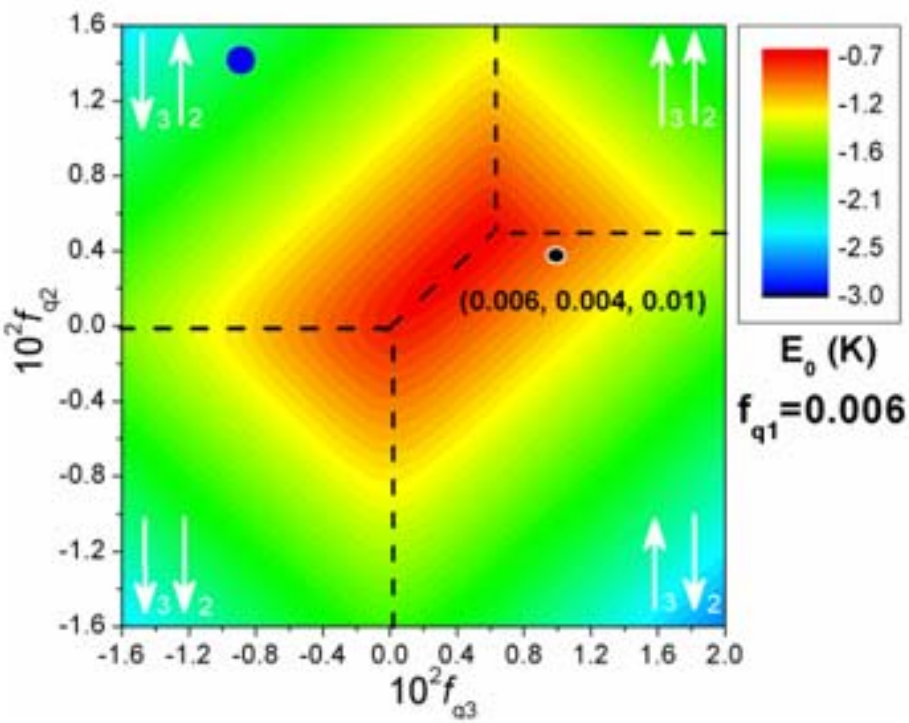
Spacing between ground and first excited states



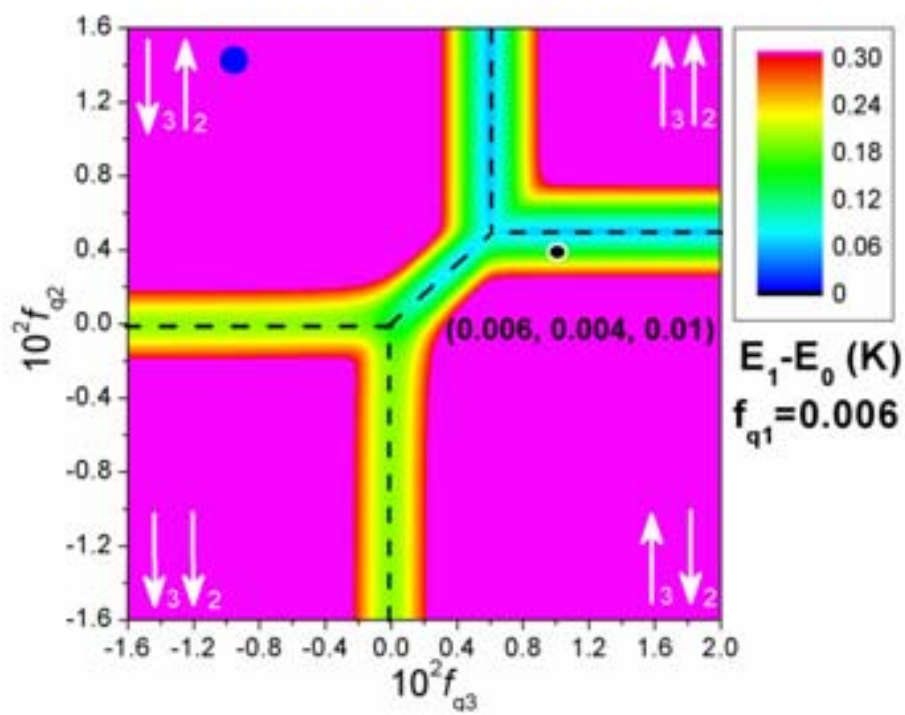
– – – Max curvature of the ground state

Adiabatic evolution

Energy of the ground state



Spacing between ground and first excited states

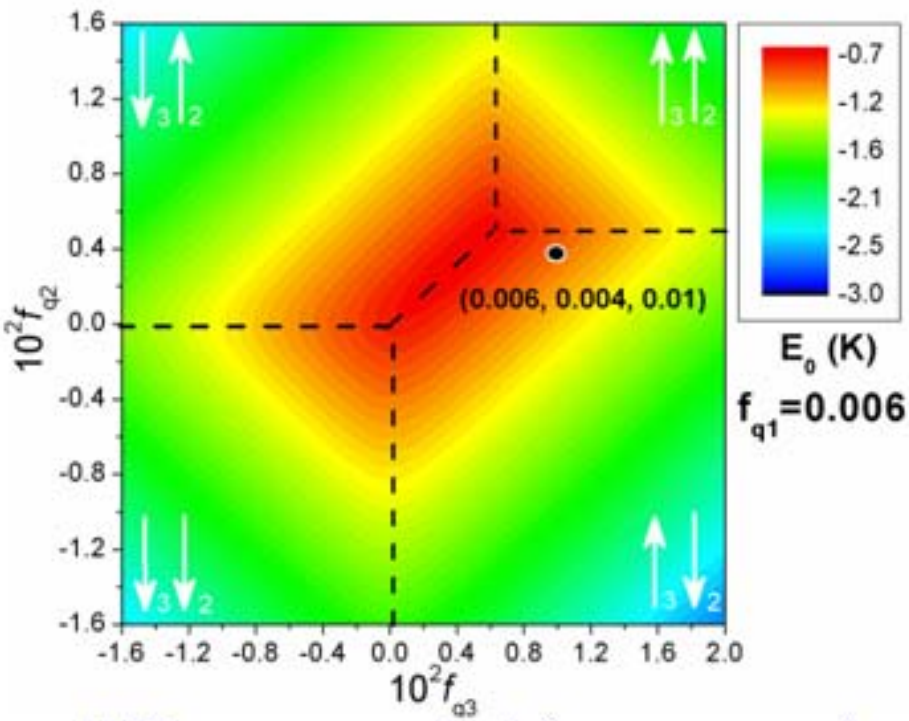


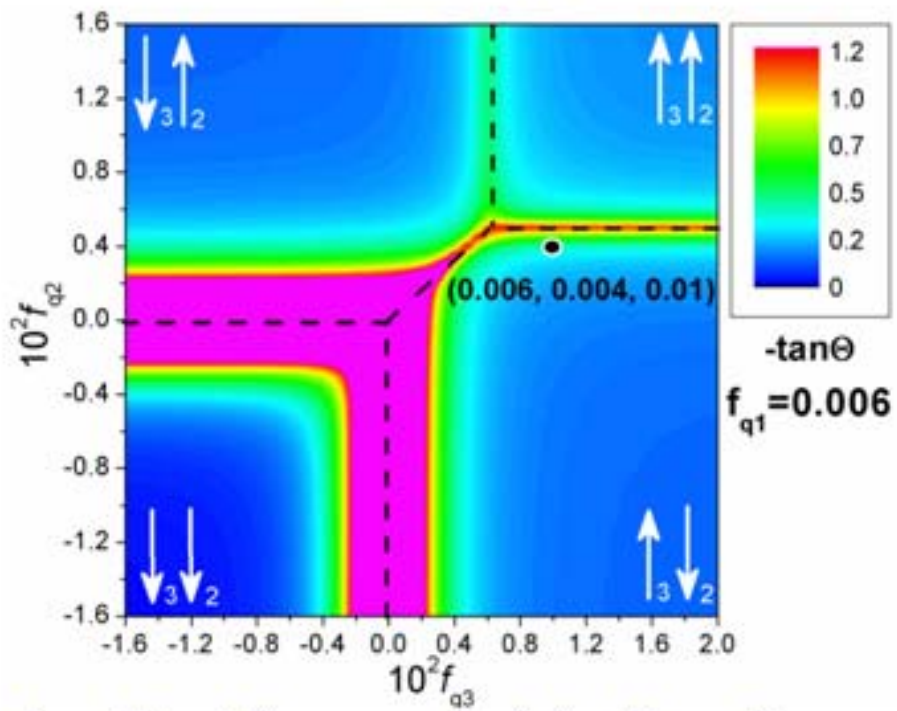
– – – Max curvature of the ground state

Readout (Flux map)

M. Grajcar, A. Izmalkov, E. Il'ichev, *Phys. Rev. B* **71**, 144501 (2005)

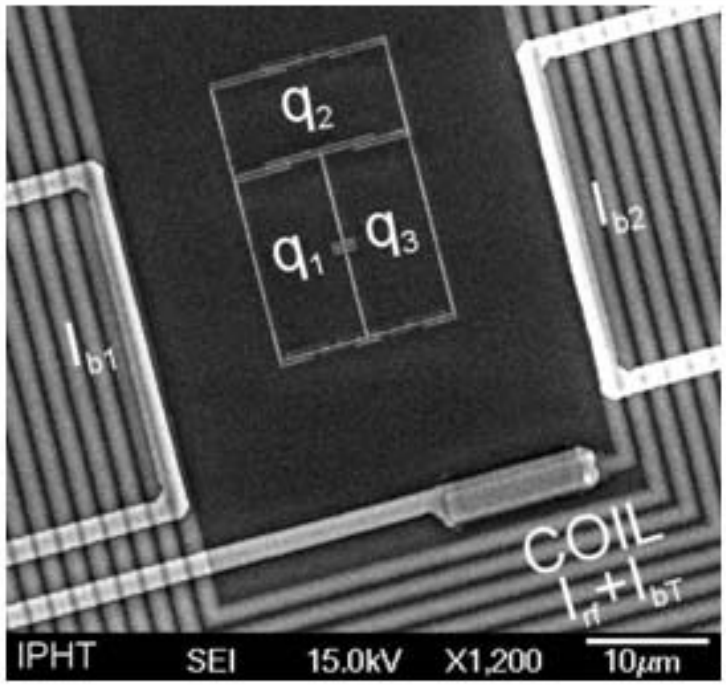
T=10 mK

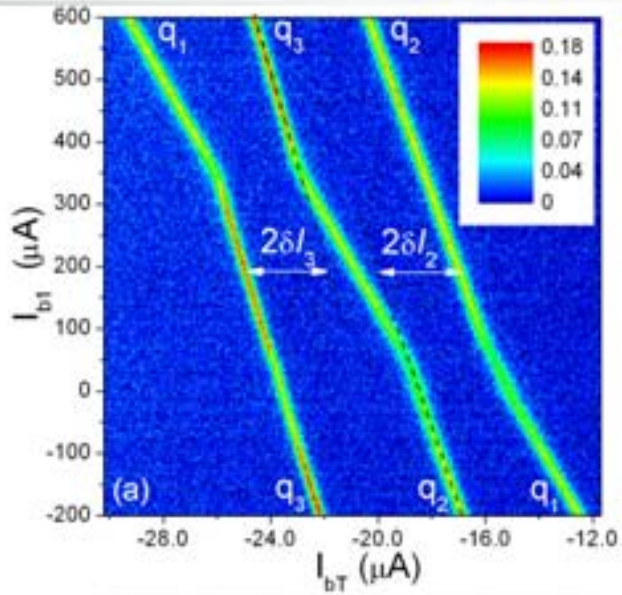


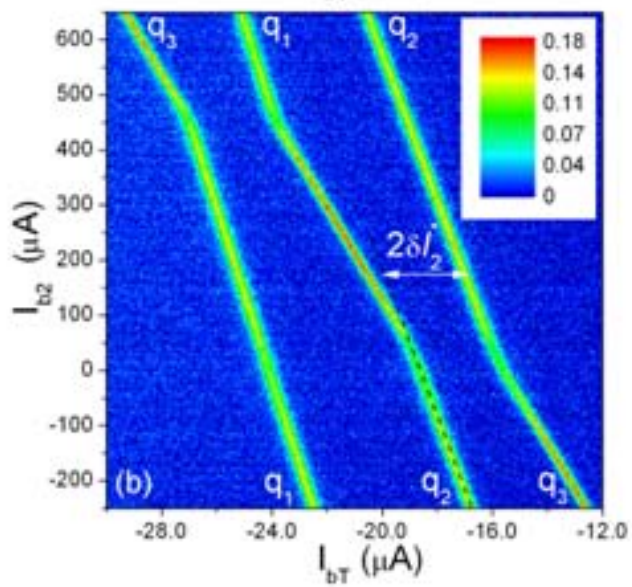


- IMT response depicts max curvature of multiqubit ground state, therefore giving solution AC
- Flux map readout should be quite fast and T_{eff} should be small, in order to prevent temperature transitions to first excited state

Three qubits, preliminary experimental data





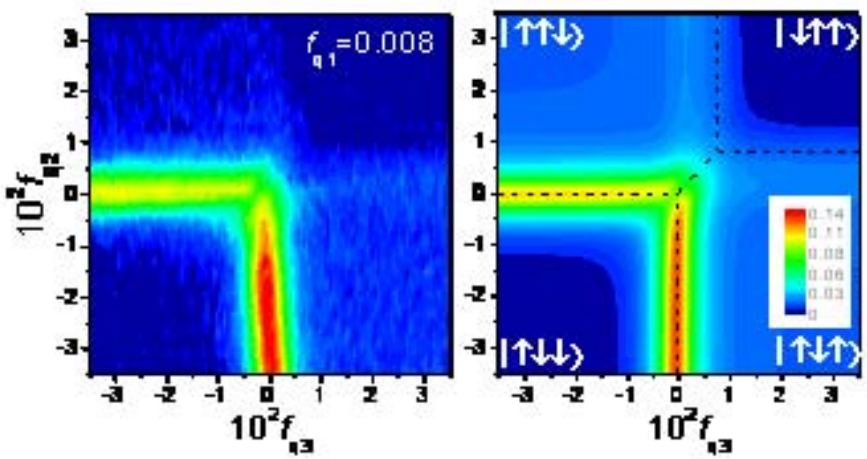


Sample parameters:

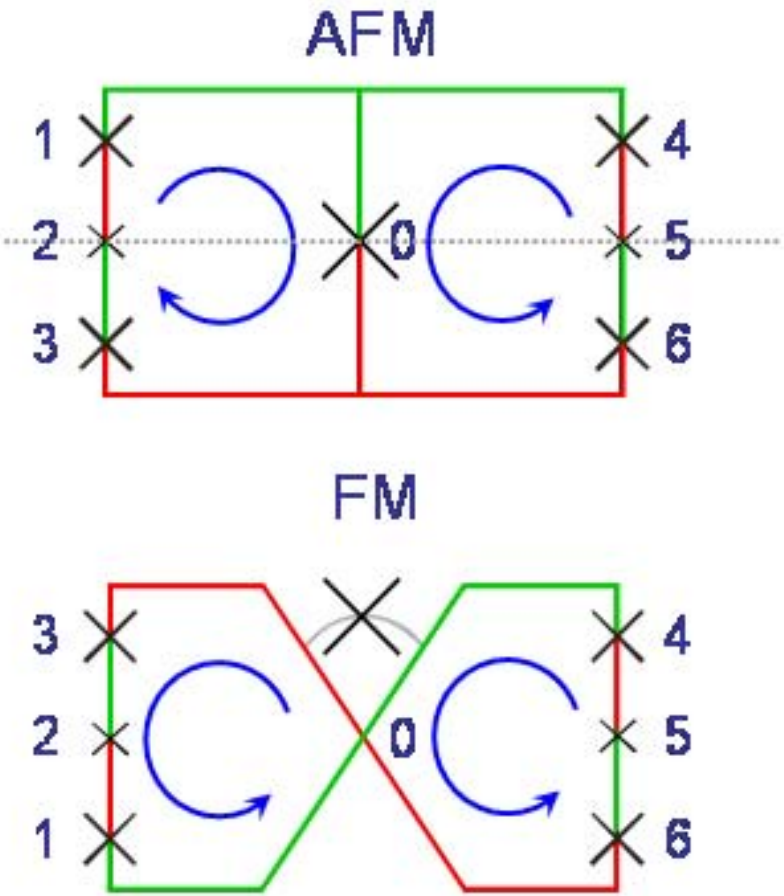
$J_{12}=J_{13}=J_{23}=0.61$ K,
$\Delta_1=\Delta_2=\Delta_3=70$ mK,
$I_{p1}=I_{p2}=115$ nA, $I_{p3}=125$ nA

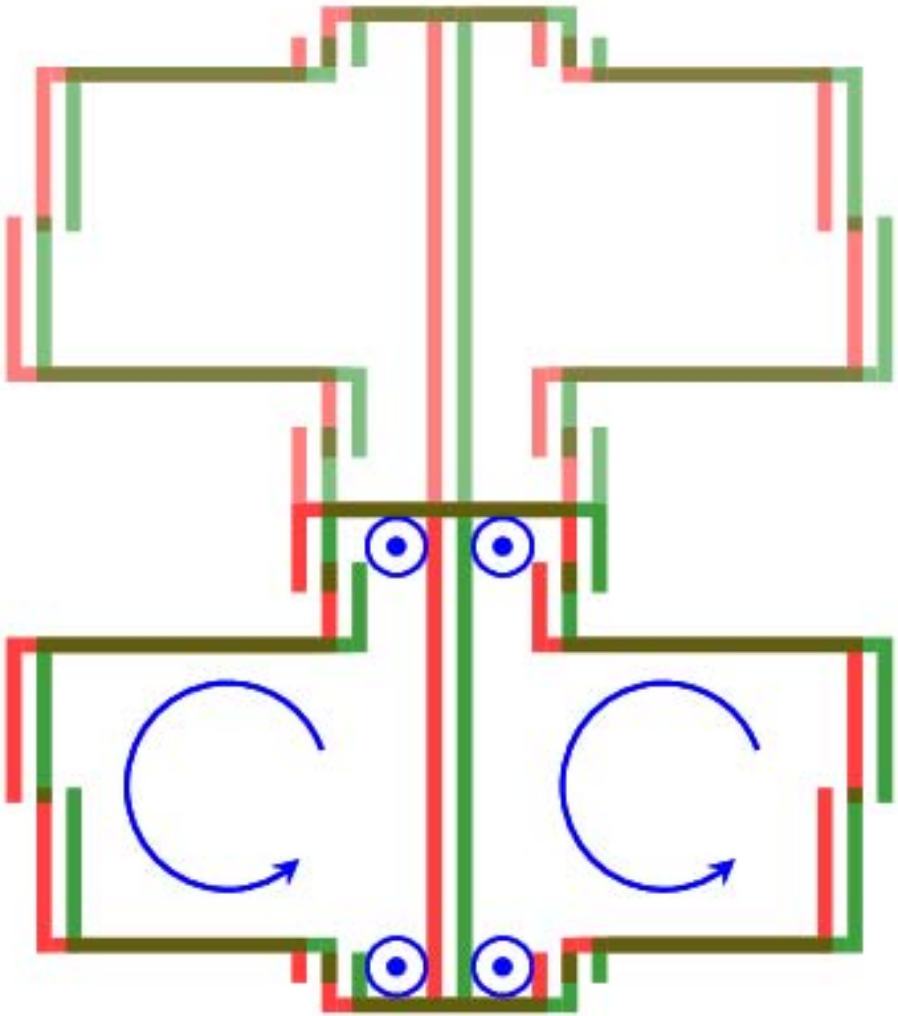
3D susceptibility of three qubit system

Experiment Theory

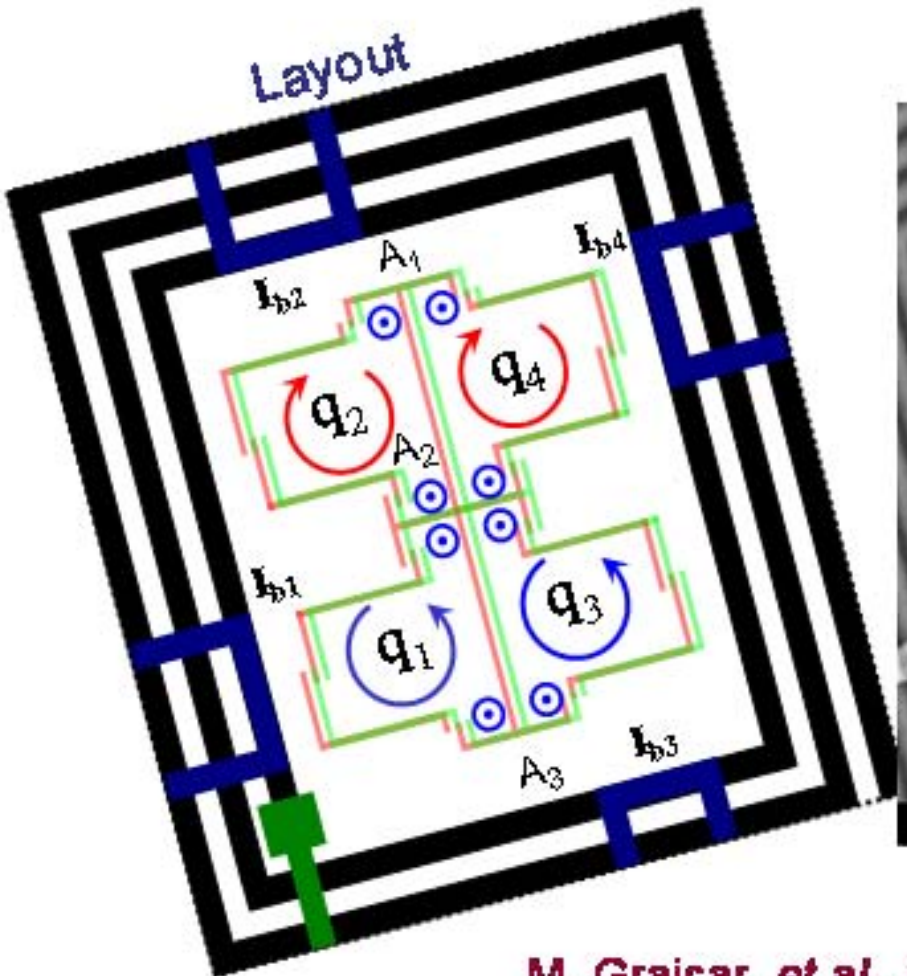


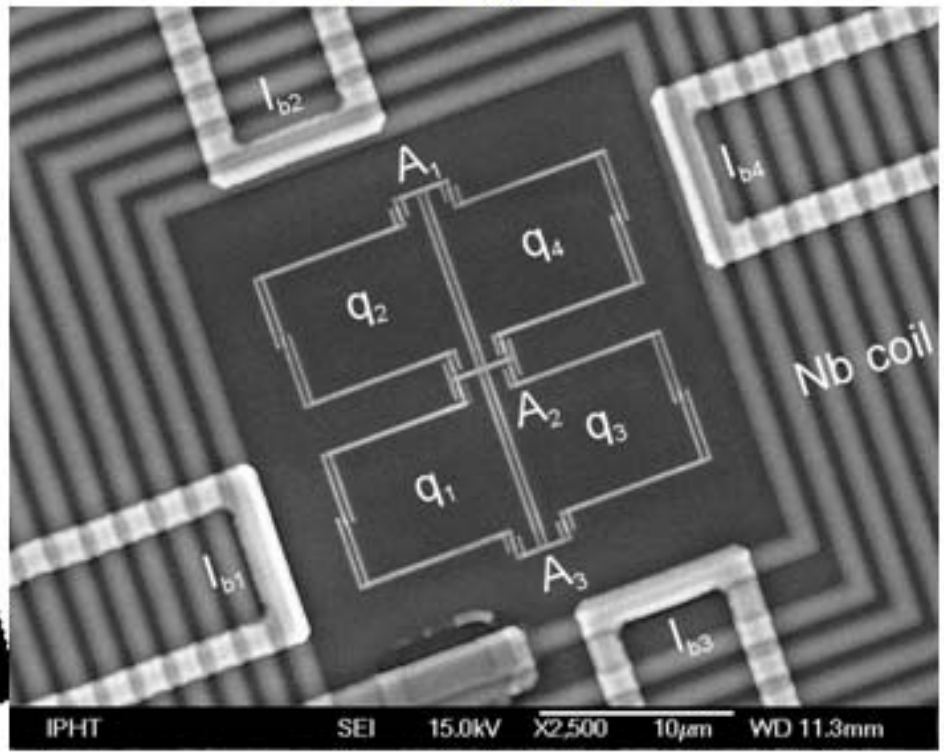
Four qubit sample with mixed couplings. Layout





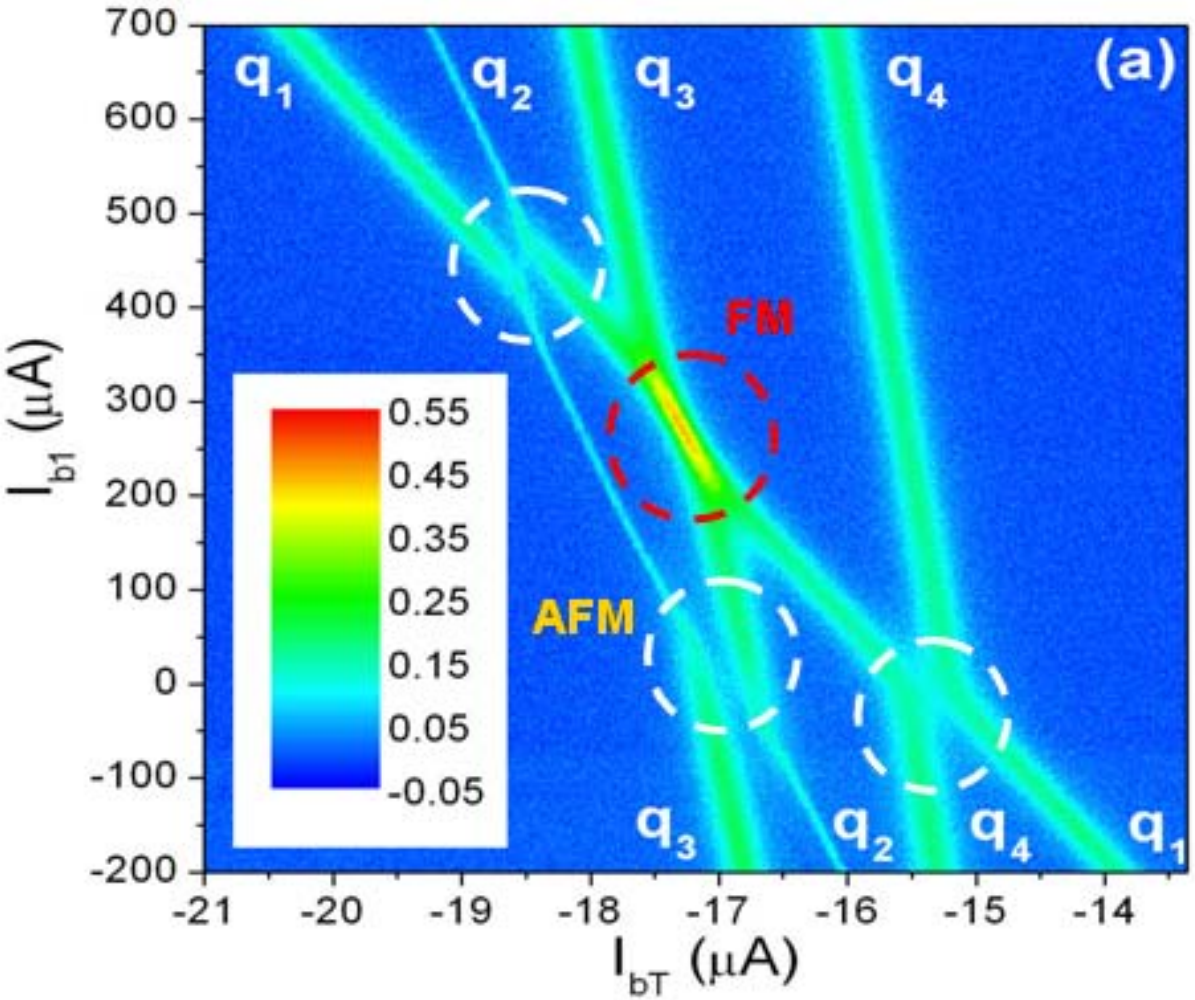
Four qubit sample. Micrograph





M. Grajcar, *et al.*, cond-mat/0509557.

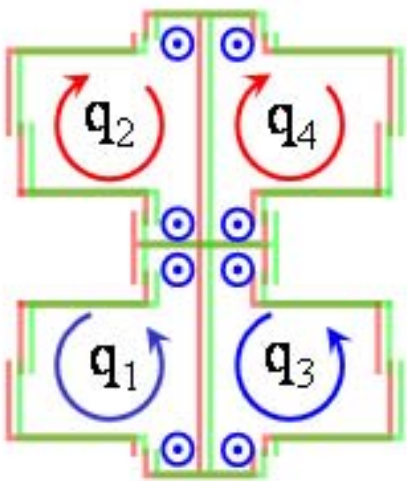
Anti-Ferromagnetic (AFM) and Ferromagnetic (FM) Coupling



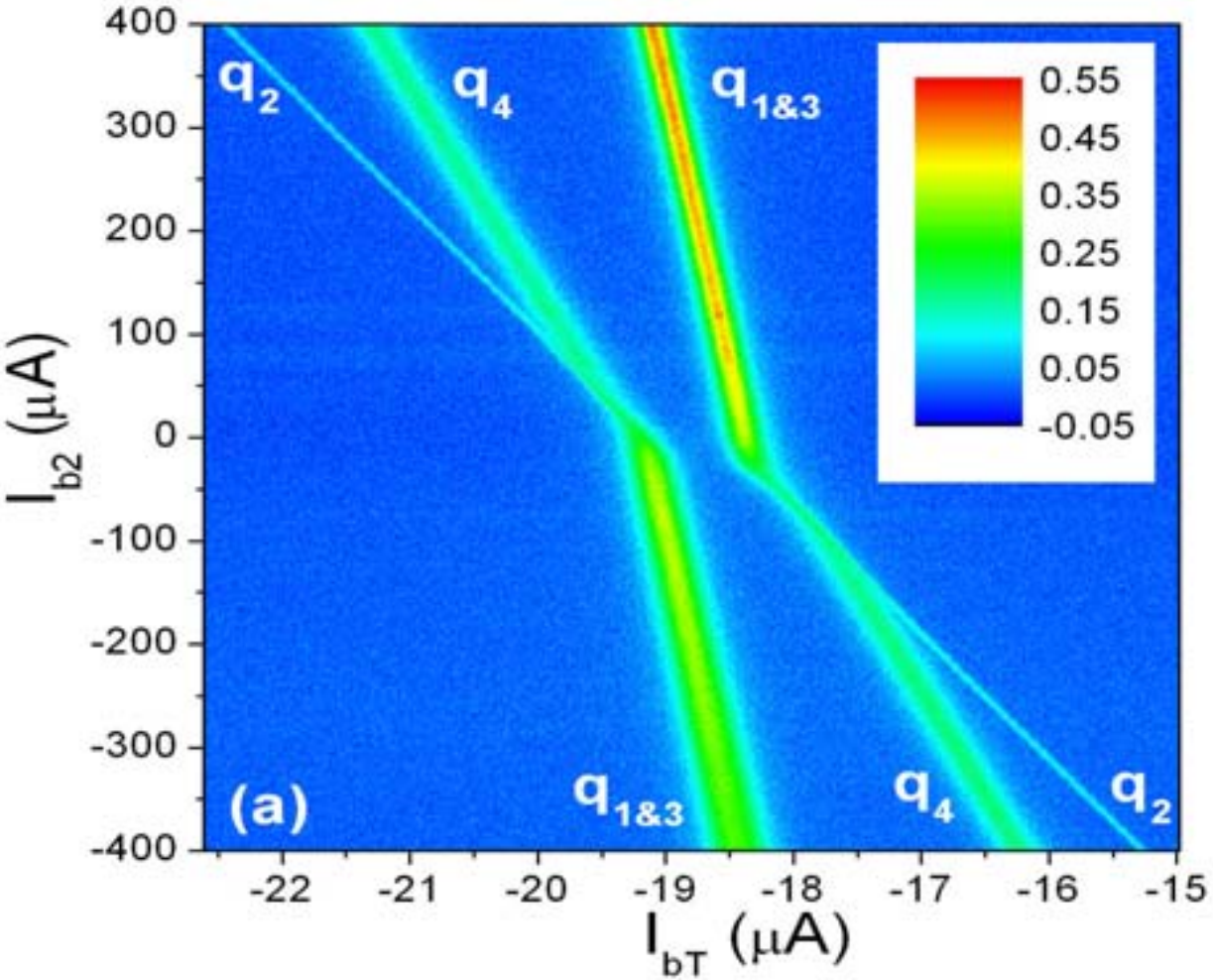
I_{b2}=10 μA

I_{b3}=0 μA

I_{b4}=250 μA



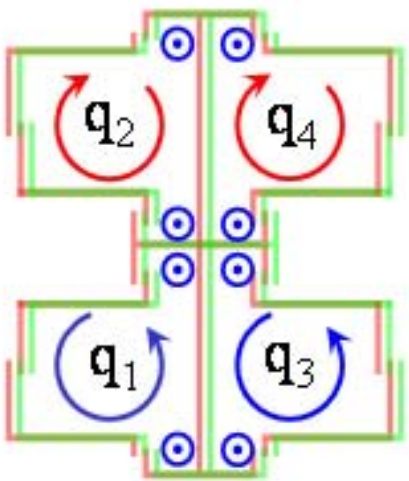
AFM interaction between FM interacting qubit pairs



I_{b1}=-400 μA

I_{b3}= 0 μA

I_{b4}= -50 μA



Theoretical fits

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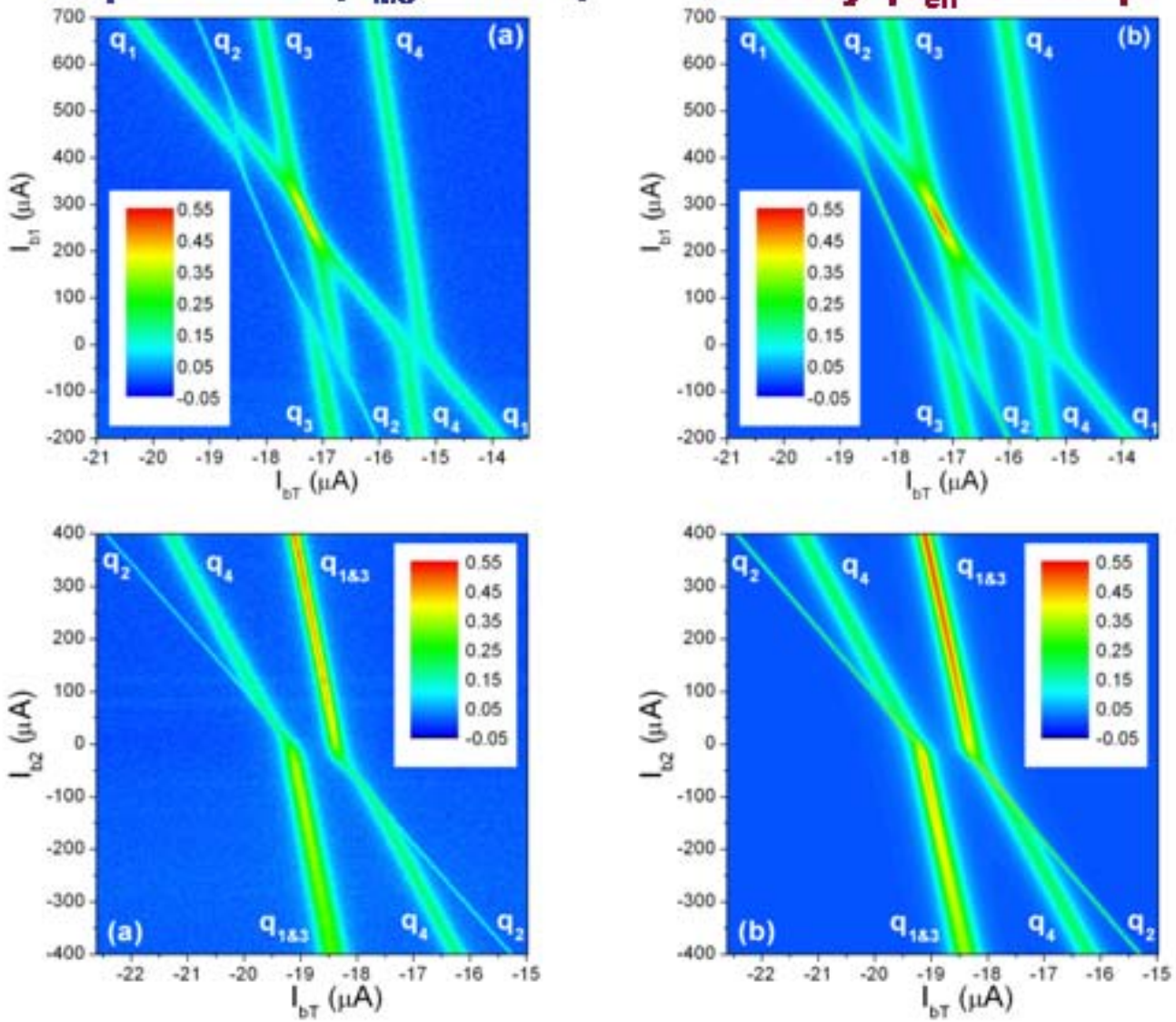
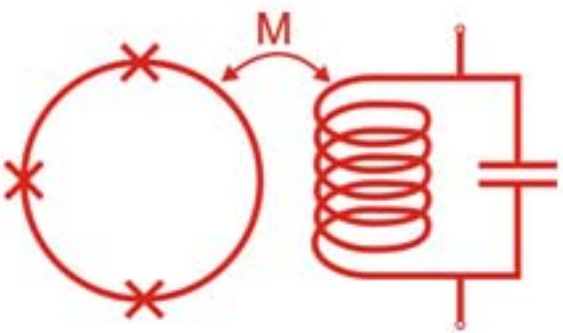
Experiment (T_{MC}=10 mK) **Theory (T_{eff}=70 mK)**



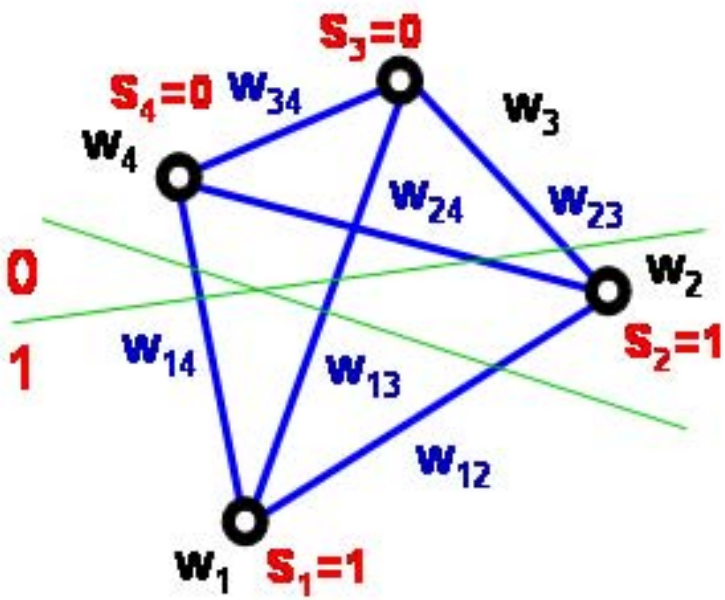
Measurements by making use of:

- (PTB charge qubit) – LC circuit
- (Chalmers charge qubit) – RF SET
- (Sakle quantronium) – LC circuit with JJ
- (Delft flux qubit) – LC circuit with SQUID
- (Yale charge qubit) – strip resonator
- Parametric transduser



1. Encoding MAXCUT problem

Example for 4 nodes



$$P(|s\rangle) = \sum_i w_i s_i + \sum_{i,j} s_i (1 - s_j) w_{i,j}$$

$$\max(P) \text{ for } |s\rangle_{solution} = |0011\rangle \equiv |\downarrow_4 \downarrow_3 \uparrow_2 \uparrow_1\rangle$$

$$H_P = \sum_{i=1}^{N} \varepsilon_i(f_i)\sigma_{z,i} + \sum_{i<j}^{N} J_{i,j}\sigma_{z,i}\sigma_{z,j} + \sum_{i=1}^{N} \Delta_i \sigma_{x,i}$$

Payoff function is encoded in Hamiltonian H_P if $\Delta_i << J_{i,j}$ and

$$\boxed{\varepsilon_i \equiv I_{pi}\Phi_0 f_i = -w_i/2; \; J_{i,j} = w_{i,j}/2}$$

$f_i = \Phi_i / \Phi_0 - 0.5$ - flux through qubit i

H_P – The MAXCUT problem Hamiltonian

$$H_P |g\rangle = E_g |g\rangle$$

M. Steffen *et al.*, *Phys. Rev. Lett.* **90**, 067903 (2003)