Skoltech
Skolkovo Institute of Science and Technology

Energy Colloquium

Quantum engineering:

Theory, design and promise of quantum coherent macroscopic structures

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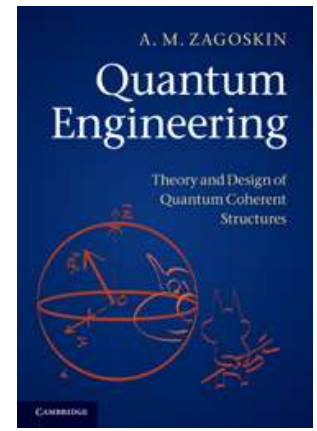
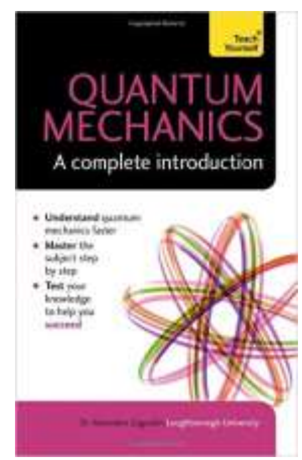
September 15, 2015

My background





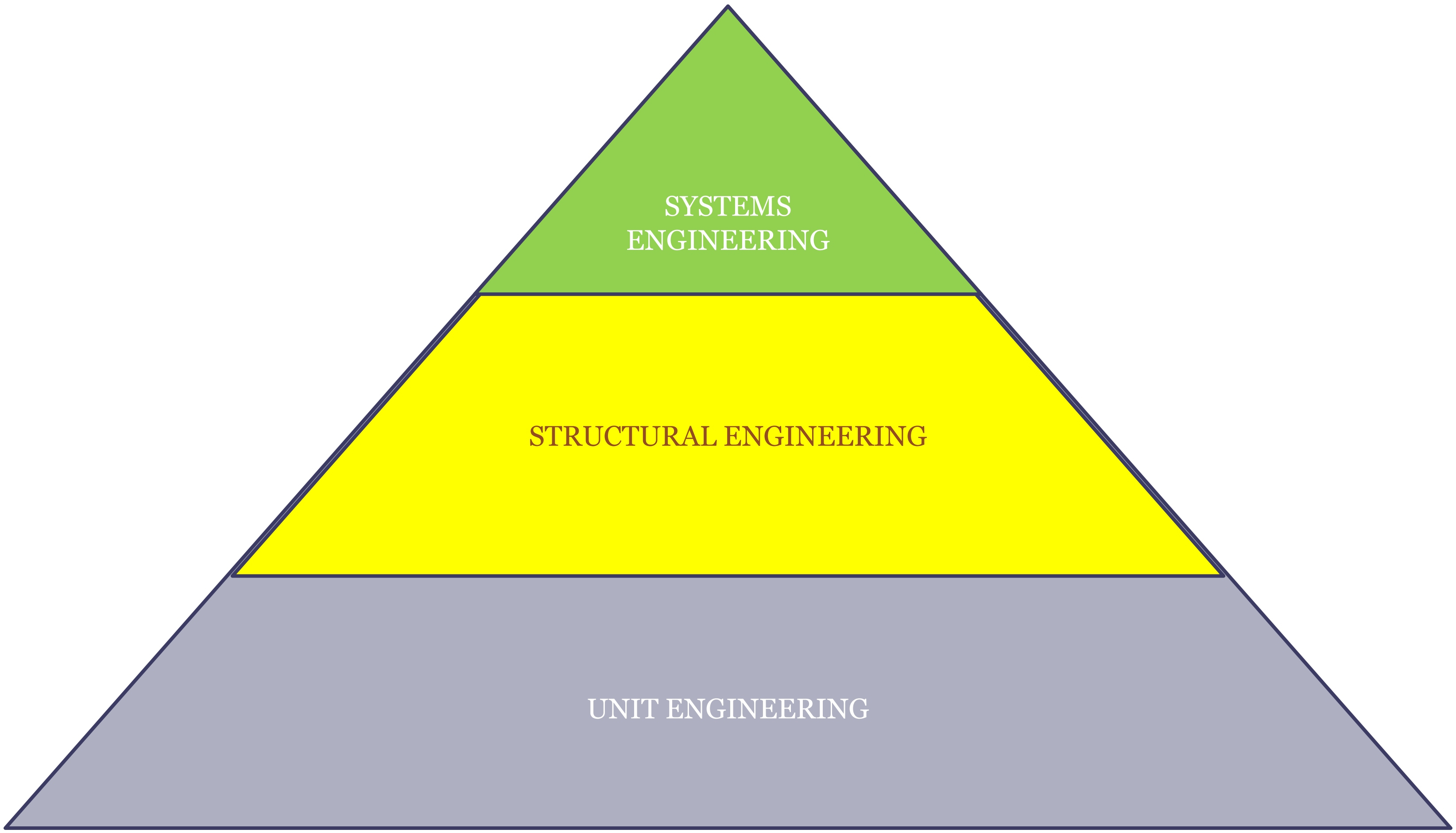
http://journal.frontiersin.org/journal/ict/section/quantum-computing

- The fabrication and control of macroscopic artificial quantum structures, such as qubits, qubit arrays, quantum annealers and, recently, quantum metamaterials, have witnessed significant progress over the last 15 years. This was a surprisingly quick evolution from theoretical musings to what can now be called *quantum engineering*. The development of this discipline will play the decisive role in the "second quantum revolution".

What is “engineering”?

- Accommodating incompatible requirements
- Using “rule-of-thumb” estimates for characterizing and predicting the system’s performance and reliability
- Heuristics
- Scaling
- “Engineering is about building reliable structures using non-reliable components”

Engineering



First quantum revolution

- Semiconductors
  - Tunnelling
  - Band theory
- Lasers
  - Photon – atom interactions
  - Rate equations
- Superconductors
  - Cooper effect
  - Josephson effect

First quantum revolution

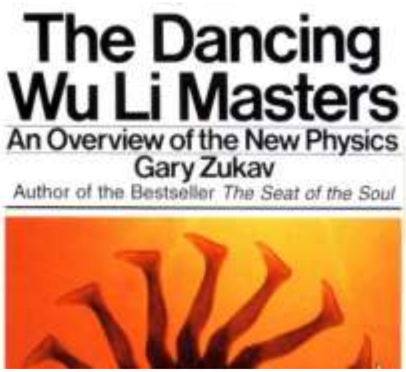
- did *not* produce macroscopic quantum coherent systems
  - quantum superpositions and entanglement in these systems involve only a *small* number of *microscopic* quantum states

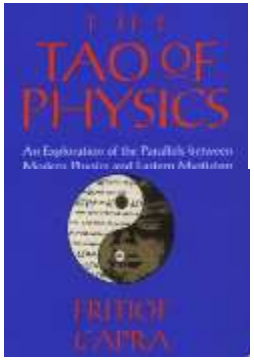
Philosophy of quantum mechanics

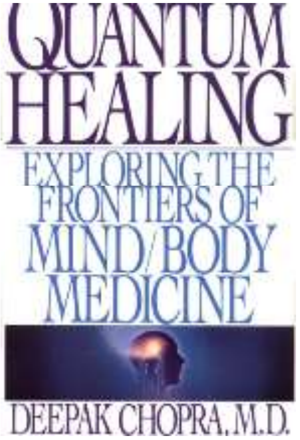
- Copenhagen interpretation
- Many worlds
- Environmental decoherence
- Consistent histories
- Pilot wave
- ?
- “Shut up and calculate!”

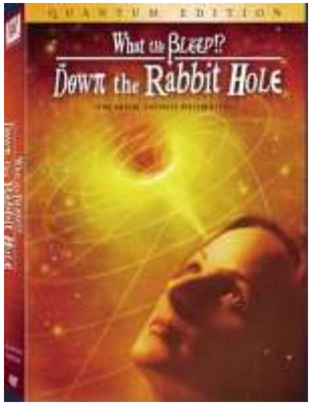
…and all that Capra

- All popularizations of quantum mechanics are wrong
- Some are much more wrong than others





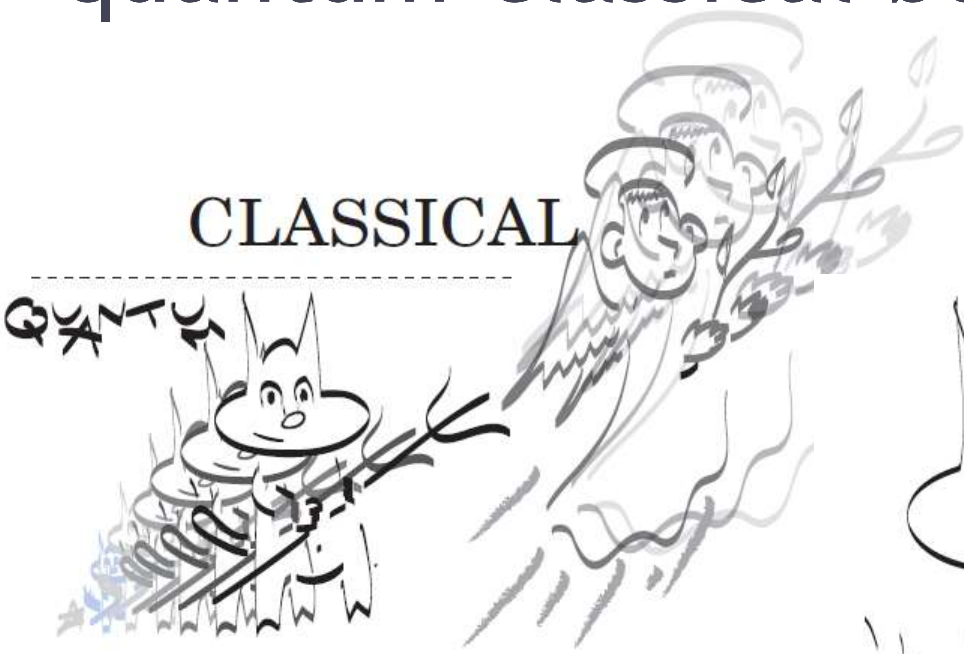




- "Amount of knowledge the ancients did not possess was obviously very significant"
    - Attributed to Mark Twain


Find this Jigsaw Puzzle at www.JigsawGallery.com

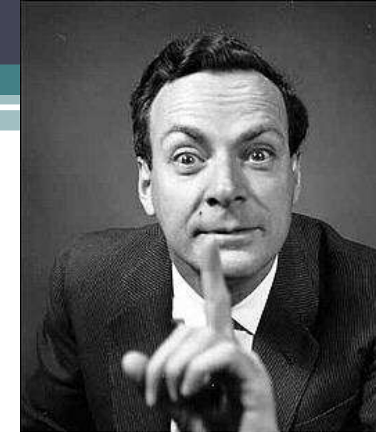
Copenhagen vs. Schengen quantum-classical boundary



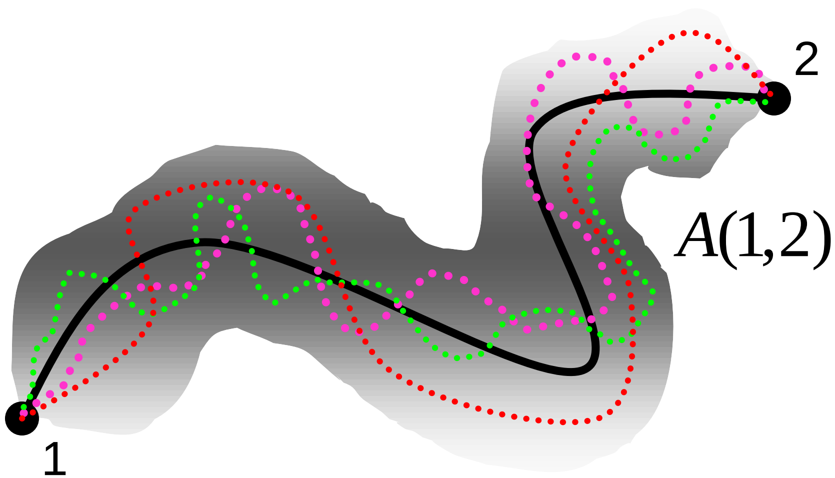
Second quantum revolution

- Use of *essentially quantum* properties of macroscopic quantum coherent devices
    - Entanglement
    - Quantum superposition
    - Quantum coherences

Richard Feynman (1918 – 1988)

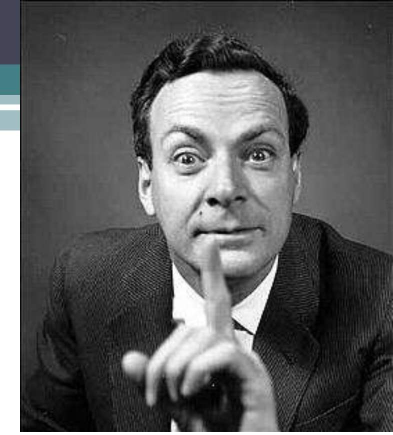


- Path integral formulation: relates quantum to classical mechanics via variational principle
  - Heron – Fermat – Lagrange – Hamilton – Dirac



$$A(1,2) = \int Dx(t)\exp\left[-i\,\frac{S[x(t),\dot{x}(t)]}{\hbar}\right]$$

Richard Feynman (1918 – 1988)



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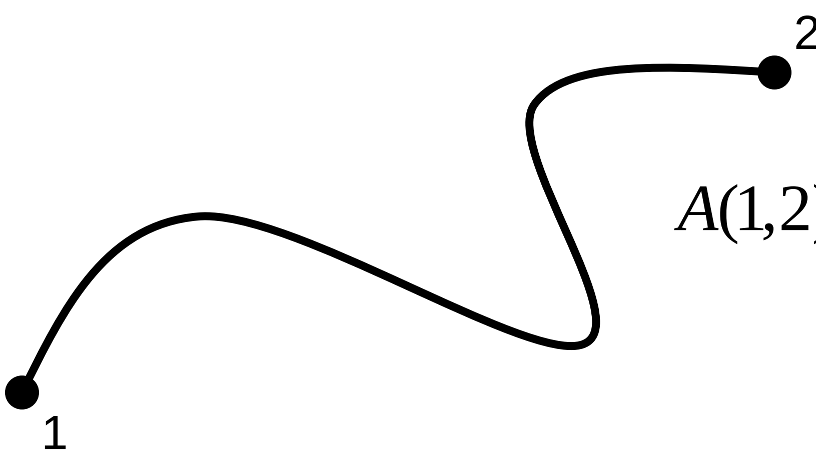
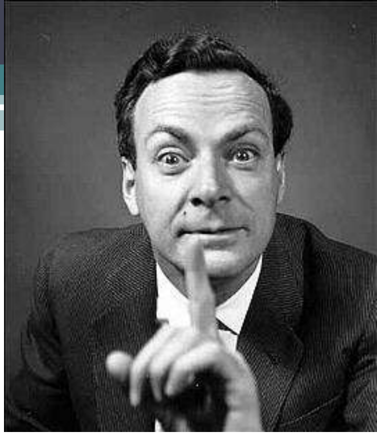


$$A(1,2) = \int Dx(t) \exp\left[-i \frac{S[x(t), \dot{x}(t)]}{\hbar} \right]$$



Richard Feynman (1918 – 1988)

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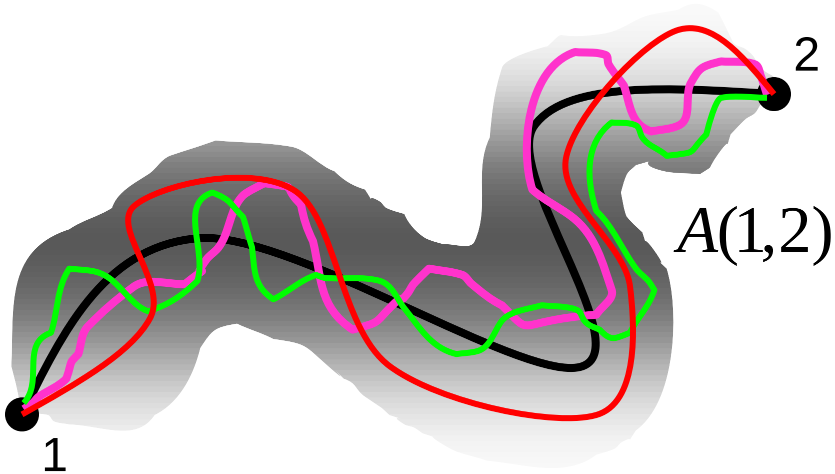

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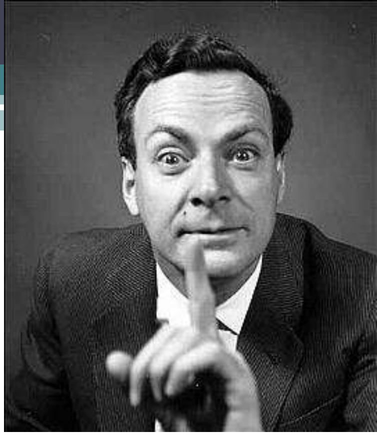
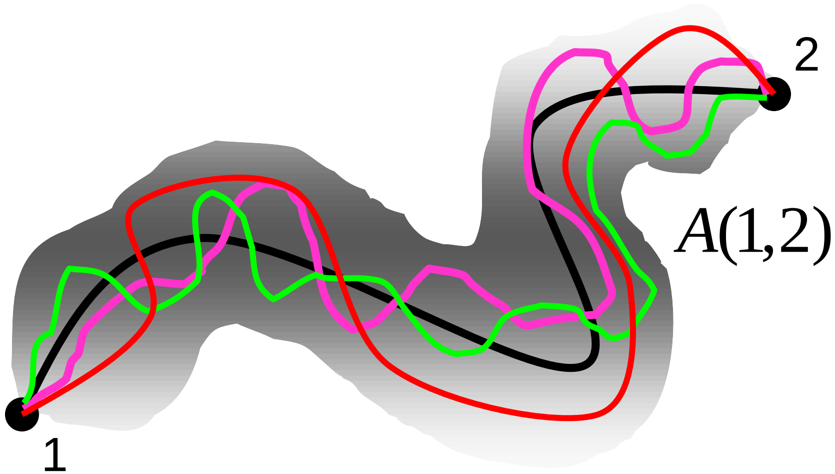
Richard Feynman (1918 – 1988)



- An *efficient* modelling of a quantum system by classical means is IMPOSSIBLE



$$A(1,2) = \int Dx(t) \exp\left[-i \frac{S[x(t), \dot{x}(t)]}{\hbar}\right]$$

“Standard” quantum computing

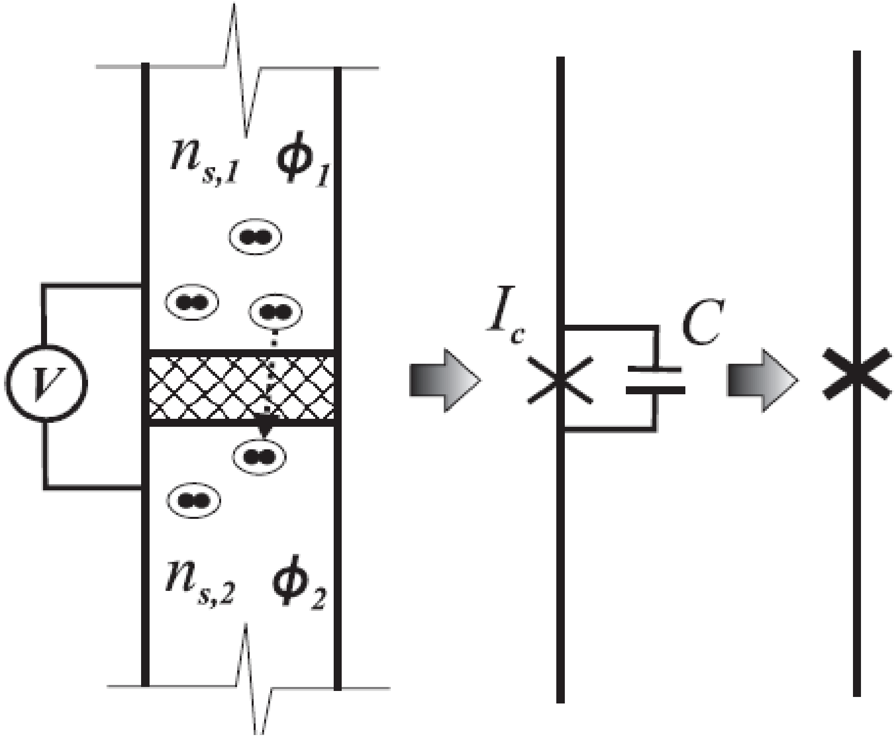
- Precise single and two-qubit quantum manipulations
- Qubit lifetime much shorter than the computational run
- Ergo:
  - Quantum error correction
  - Ancilla qubits, additional operations
  - More noise, shorter lifetime
  - Topological protection etc promising, but…

On s’engage et puis on voit

Why superconducting Josephson qubits?

- Energy gap suppresses decoherence due to quasiparticles
- Superconducting phase is a macroscopic quantum variable related to directly observable quantities: electric charge (Cooper pairs' number) and current

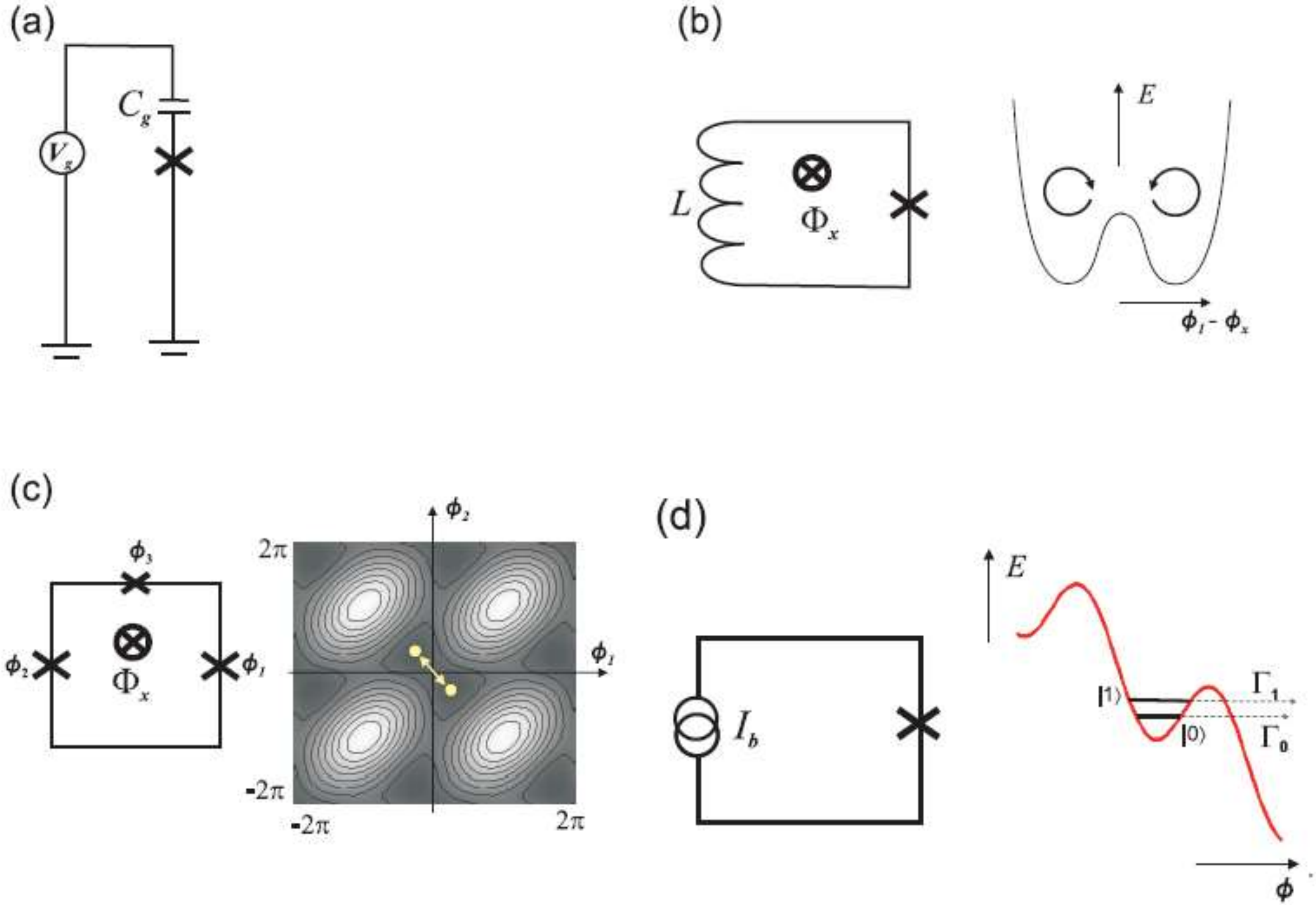
Josephson effect: an Übercrash course



$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\sqrt{n_{s,1}}e^{i\phi_1}\\ \sqrt{n_{s,2}}e^{i\phi_2}\end{pmatrix} = \begin{pmatrix} eV & K \\ K & -eV \end{pmatrix}\begin{pmatrix}\sqrt{n_{s,1}}e^{i\phi_1}\\ \sqrt{n_{s,2}}e^{i\phi_2}\end{pmatrix}$$

$$I_J = I_c \sin\phi; \quad \dot{\phi} = 2eV/\hbar.$$

Superconducting qubits



From Zagoskin & Blais, “Superconducting qubits”, *Physics in Canada*, Dec 2007

Digression: How catty are the qubits?

- How to distinguish a linear superposition from a mixture?
  - Take N' identical bosons and compute reduced density matrix for $N \odot N'$
  - Reduced entropy $S_N = -\mathrm{tr}\, \rho_N \ln \rho_N$
  - $\delta_N = S_N / \min_{(M)} (S_M + S_{N-M})$
  - "Disconnectivity" D is the largest integer N for which δ_N is smaller than some small a
  - For 2 bosons:
    - product state: D=1
    - mixture: D=1
    - linear superposition: D=2

Leggett, Suppl. Prog. Theor. Phys. 69 (1980) 80-100

Digression: How catty are the qubits?

- Supercurrent per se is not "catty"
  - E.g., Josephson effect

$$\Psi(1,2,\ldots N) = A\prod\left(a\psi_L(j)+b\psi_R(j)\right) \sim \left(a\psi_L + b\psi_R\right)^N$$

  - We need rather ("crudely and schematically")

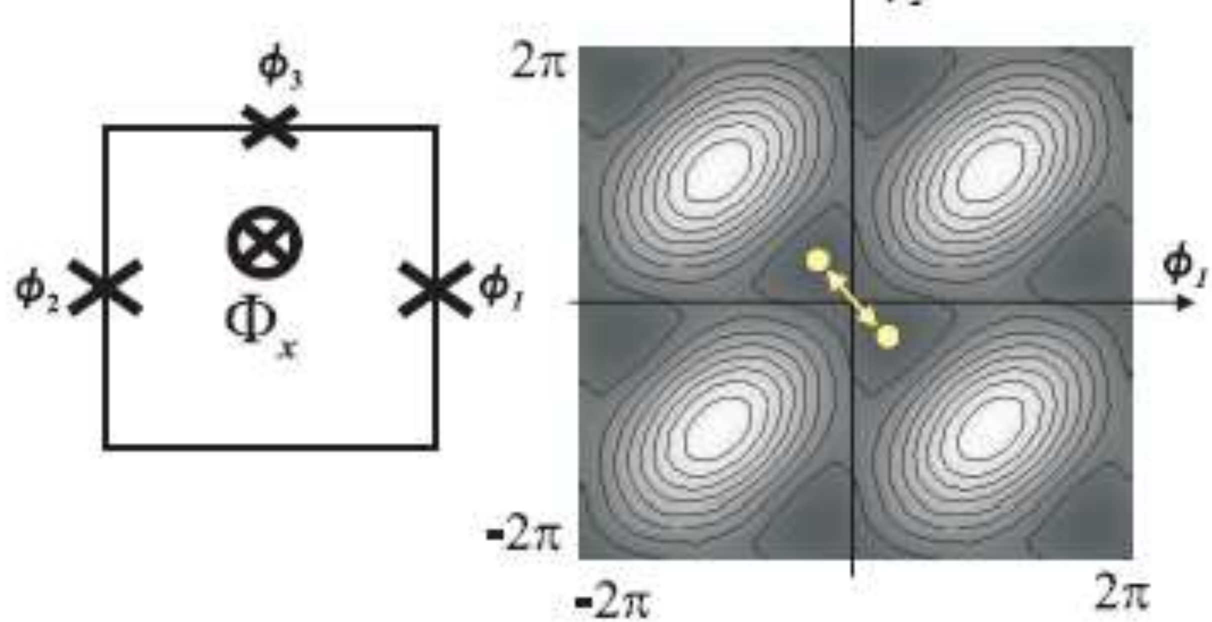
$$\Psi(1,2,\ldots N) \sim a\left(\psi_L\right)^N + b\left(\psi_R\right)^N$$

Leggett, Suppl. Prog. Theor. Phys. 69 (1980) 80-100

Charge qubits

- Superposition of states with N and N+1 Cooper pairs
  - Only two one-particle states differ
  - D~2

Flux qubits



- One island's phase is fixed, two are in a *superposition* of states with different phases:

$$\Psi(1,2,\ldots N) \sim a\left(\psi_{\phi 1}\right)^N + b\left(\psi_{\phi 2}\right)^N$$

  - Number of one-particle states involved:

$$N \sim n_e \Omega \sim 10^{22}\,\mathrm{cm}^{-3} \times \left(10\mu\mathrm{m} \times 1\mu\mathrm{m} \times 0.1\mu.\quad\right) \sim 10^{10}$$

QED with superconducting qubits

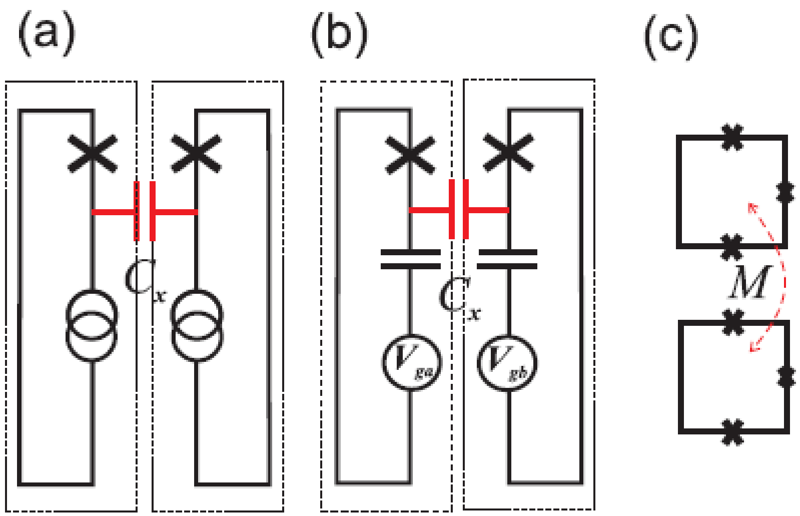
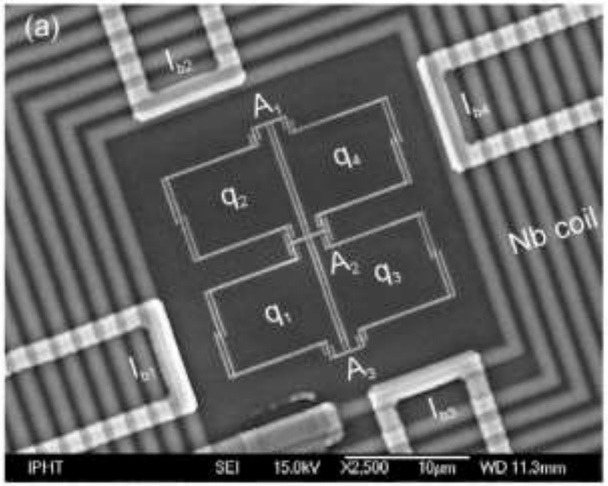


FIG. 3: (a) Phase qubits and (b) charge qubits coupled through a capacitor. (c) Flux qubits coupled through the mutual inductance M.

From Zagoskin & Blais, “Superconducting qubits”, *Physics in Canada*, Dec 2007



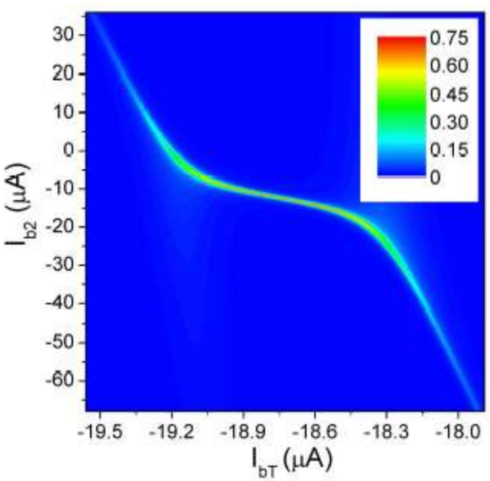
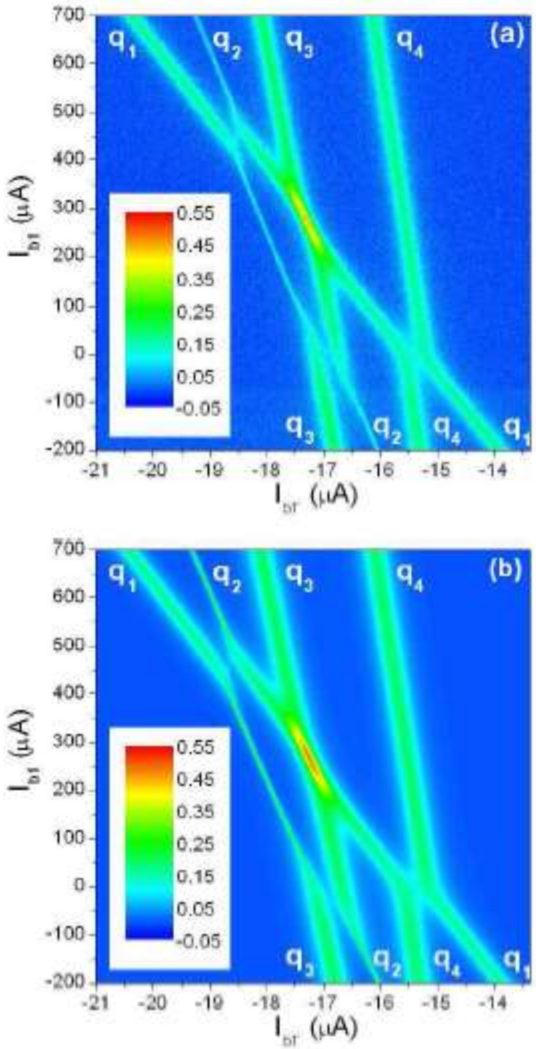
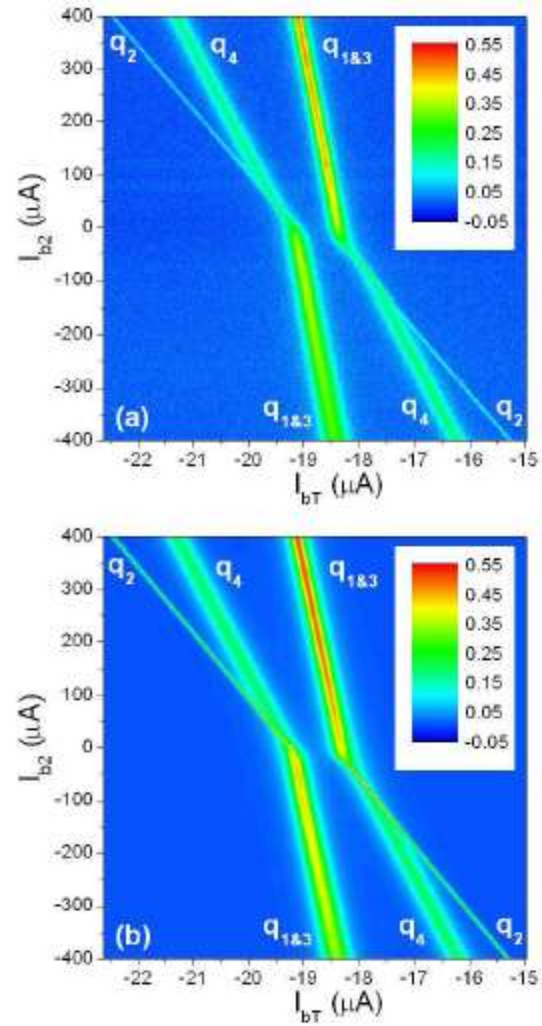


FIG. 1: Entanglement $\mathcal{R}(\psi)$ of the ground state of the four-qubit experimental system described in [20]. The abcissa is the global bias applied to all qubits, and the ordinate is the bias current applied to qubit two. The maximum entanglement value is 0.75 ± 0.05.





M. Grajcar et al., Phys. Rev. Lett. 96, 047006 (2006);
P.J. Love et al., Quant. Inf. Proc. 6, 187 (2007).

QED with superconducting qubits

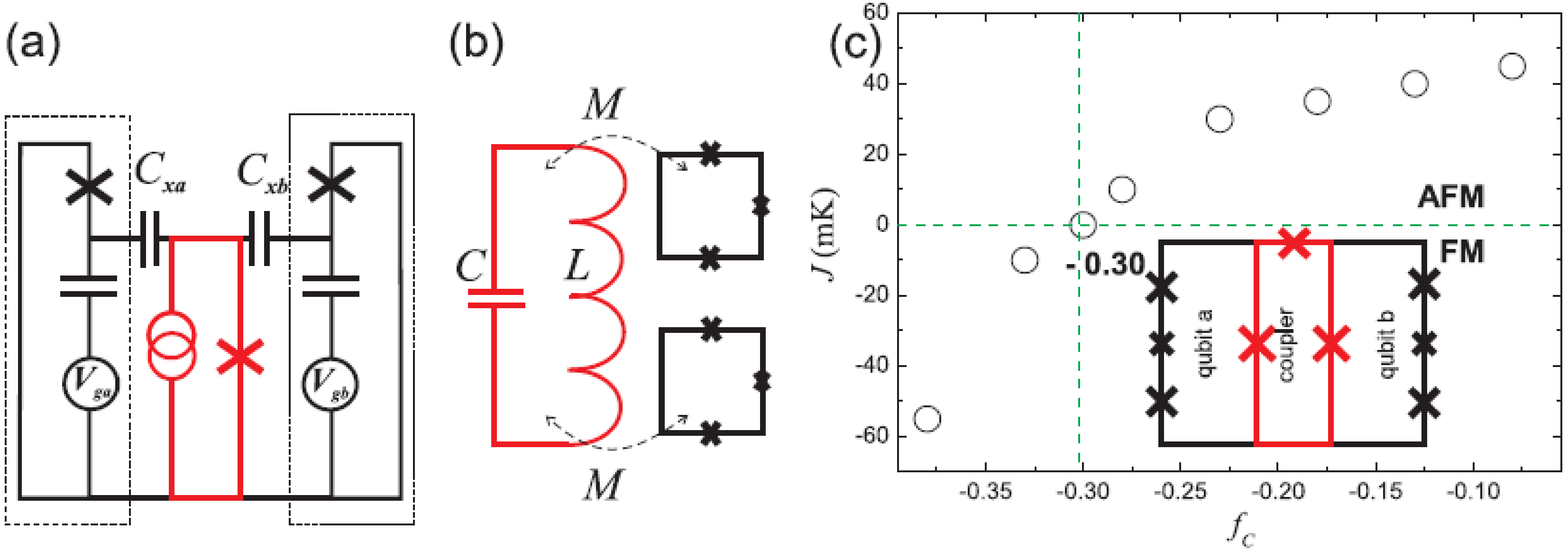


FIG. 4: (a) Charge qubits coupled through a tunable bus circuit (red) (adapted from Ref. [44]). (b) Flux qubits coupled through an LC circuit (red). (c) Tunable coupling of two flux qubits (adapted from Ref. [51]). The coupling is tuned between ferro- and antiferromagnetic by changing the magnetic flux, $\Phi = f_C \Phi_0$, through the coupler (red). Dots show the experimental data.

From Zagoskin & Blais, "Superconducting qubits", *Physics in Canada*, Dec 2007

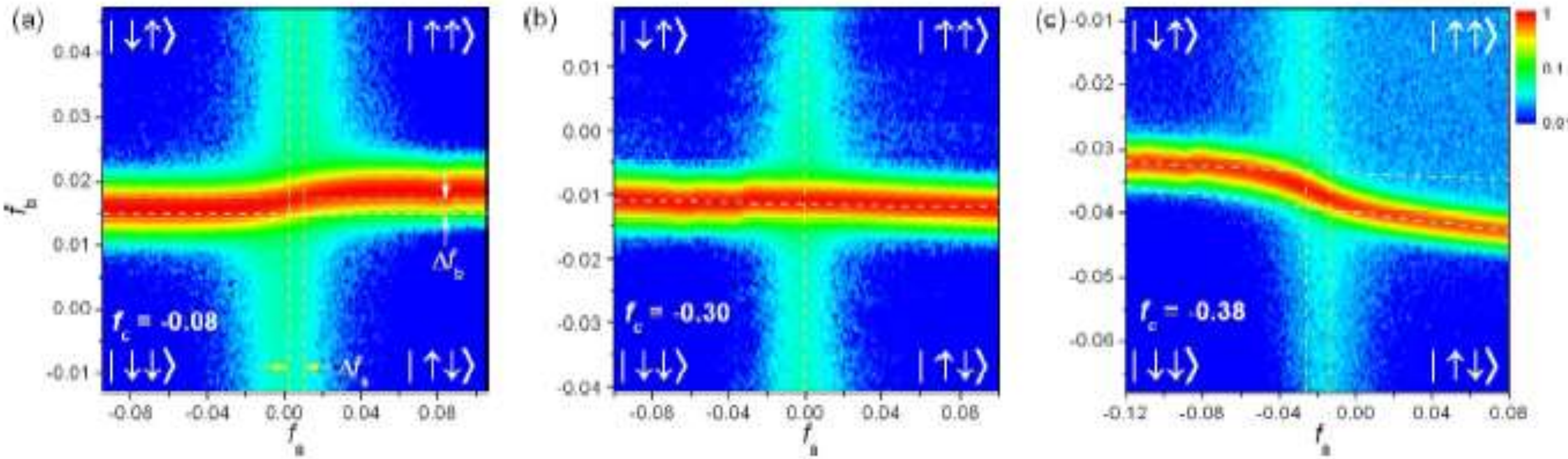


FIG. 3: $-\tan\theta(f_a, f_b)$ for sample 1 at coupler bias $f_c = -0.08$, -0.30, and -0.38, with a manifest change in coupling sign. A theory fit as in Fig. 4 yields couplings $J = 45$, 0, and -55 mK. The excess response in the $|\uparrow\uparrow\rangle$ quadrant for $f_c = -0.38$ is due

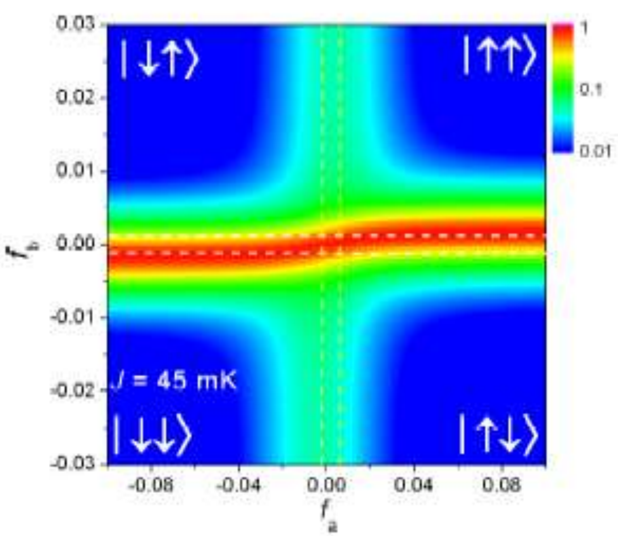
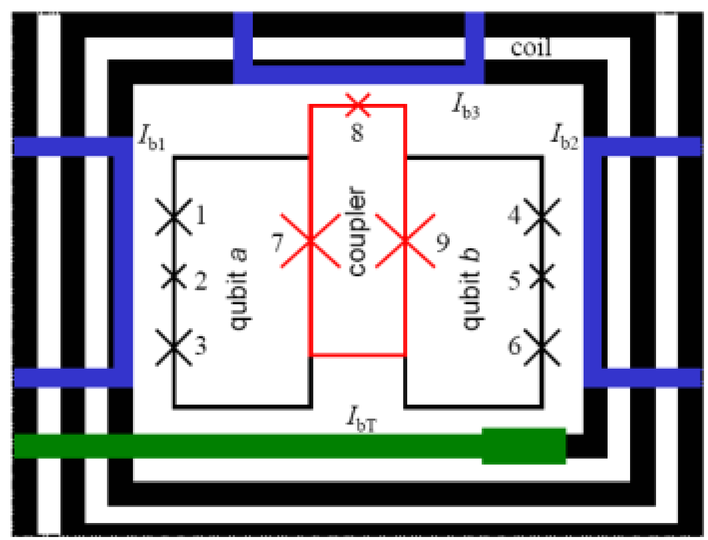
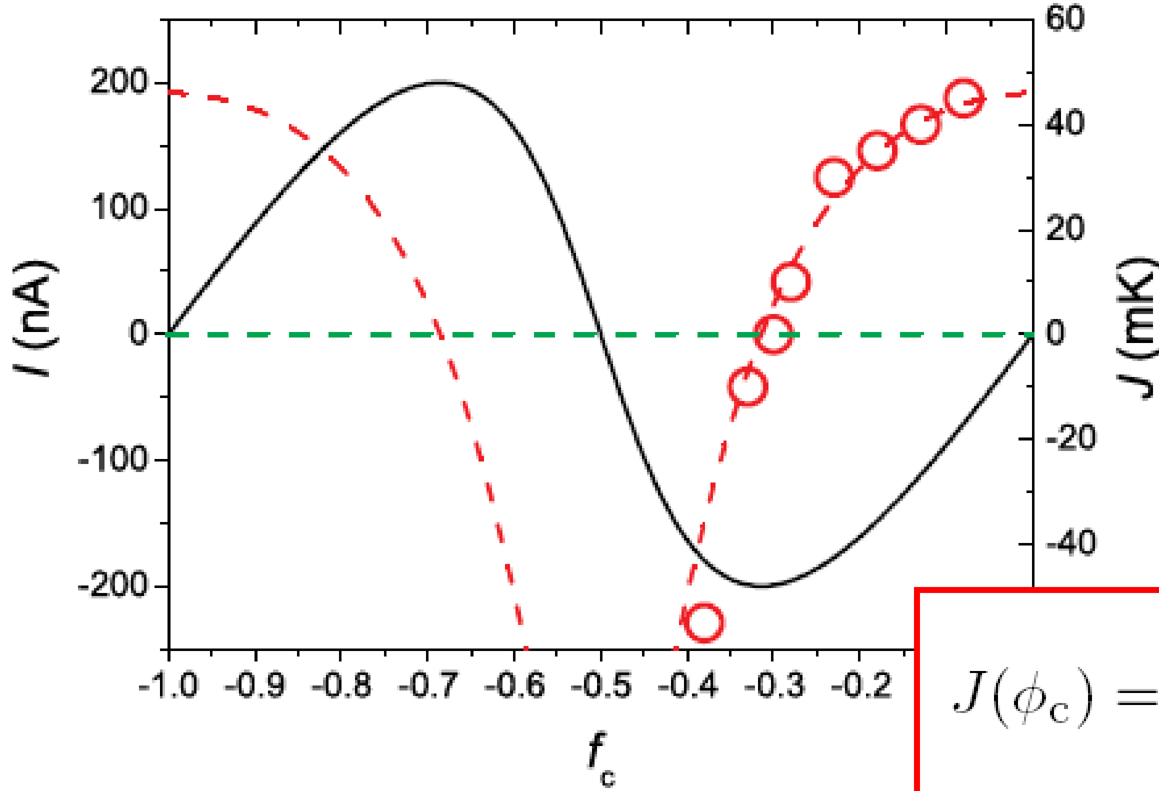


FIG. 4: Theoretical fit for Fig. 3a. The extracted parameters are $T_{\rm eff} = 70$ mK, $\Delta_a = 300$ mK, $I_{pa} = 75$ nA, $\Delta_b = 55$ mK, $I_{pb} = 180$ nA, and $J(-0.08) \approx 45$ mK.



S.H.W. van de Ploeg et al., Phys. Rev. Lett. 98, 057004 (2007)



$$J(\phi_c) = \frac{\hbar}{2e} \frac{I'(\phi_c)}{I_c^2 - I(\phi_c)^2} I_{pa} I_{pb}$$

FIG. 2: Black: the current–flux relation $I(f_c)$ of a coupler with $\alpha_c = S_8/S_9 = 0.2$ and $I_c = 1\ \mu A$. Red-dashed line: the coupling energy $J(f_c)$ obtained from Eq. (3) using this $I(f_c)$ and the loop currents $I_{pa,b}$ found independently from the qubit response. Circles: experimental $J(f_c)$ obtained from Fig. 3.

S.H.W. van de Ploeg et al., Phys. Rev. Lett. 98, 057004 (2007)

QED with superconducting qubits

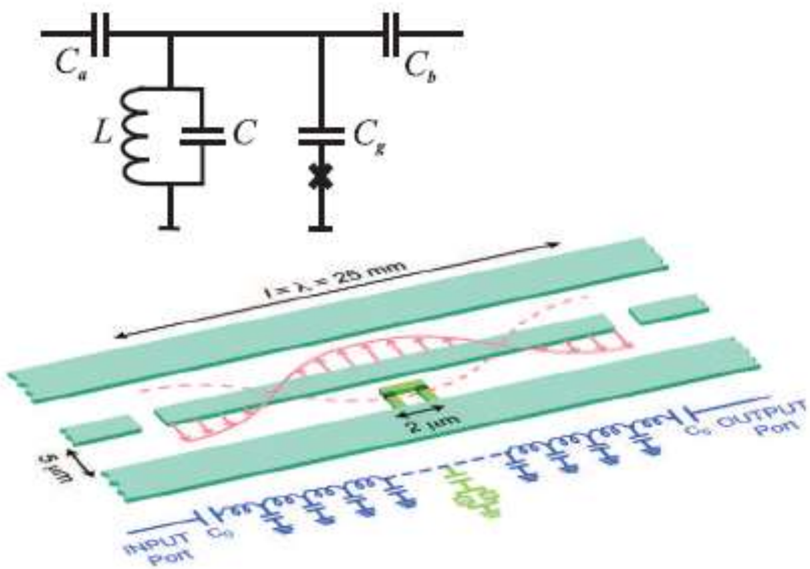


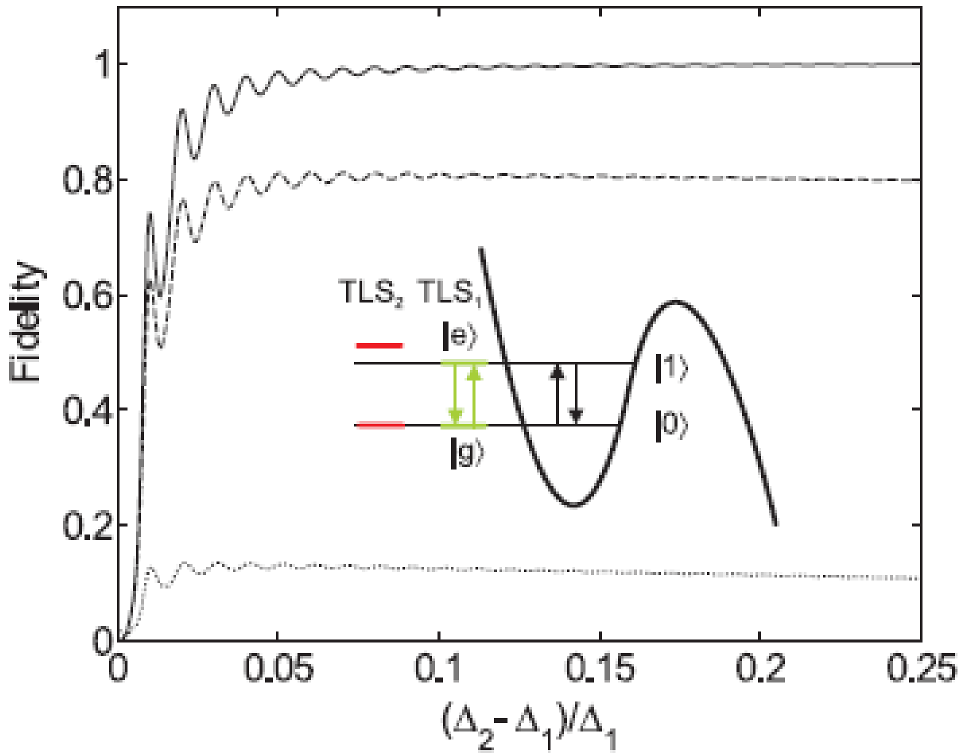
FIG. 5: Circuit QED (adapted from Ref.[70]): a charge qubit coupled to a strip line, and the simplified scheme of the system (inset).

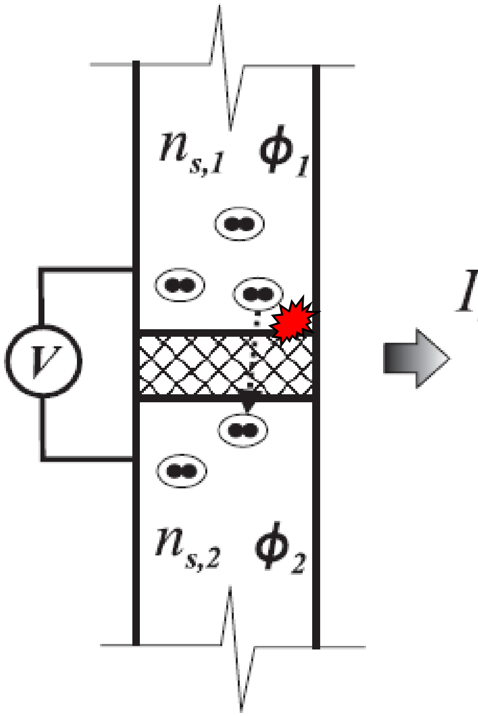
Sources of decoherence

- Intrinsic noise
  - Thermal (quasiparticles in JJ and substrate)
  - 1/f noise
- External noise
  - Ambient EM fields
  - Control and readout circuits

1/f noise: two-level systems

- Using TLS for quantum information processing





Zagoskin, Ashhab, Johansson & Nori, PRL 97 (2006) 07001

Using TLS for quantum information processing

- Decoherence time is $\sim T_{qb}$, not $\sim T_{qb}/N$

$$H_{\text{eff}} = \frac{1}{2}\sum_{j=1}^{N} \hbar\omega_j \sigma_z^j + \sum_{k>j=1}^{N} g_{jk}\sigma_y^j \sigma_y^k.$$

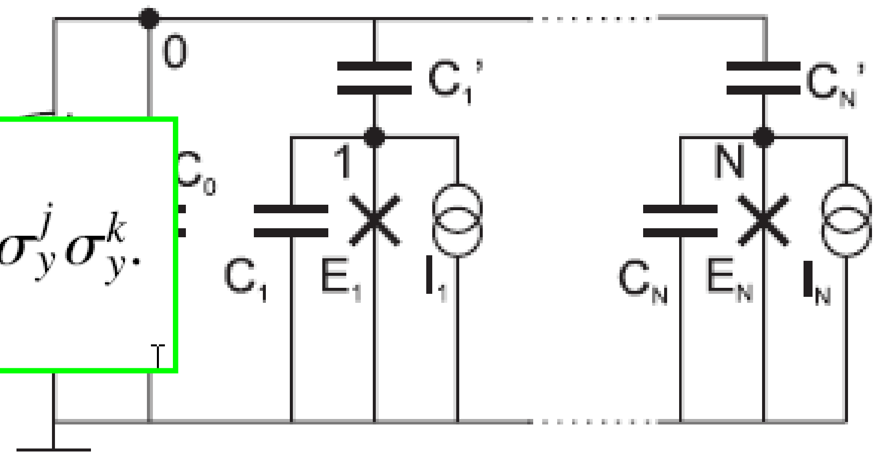
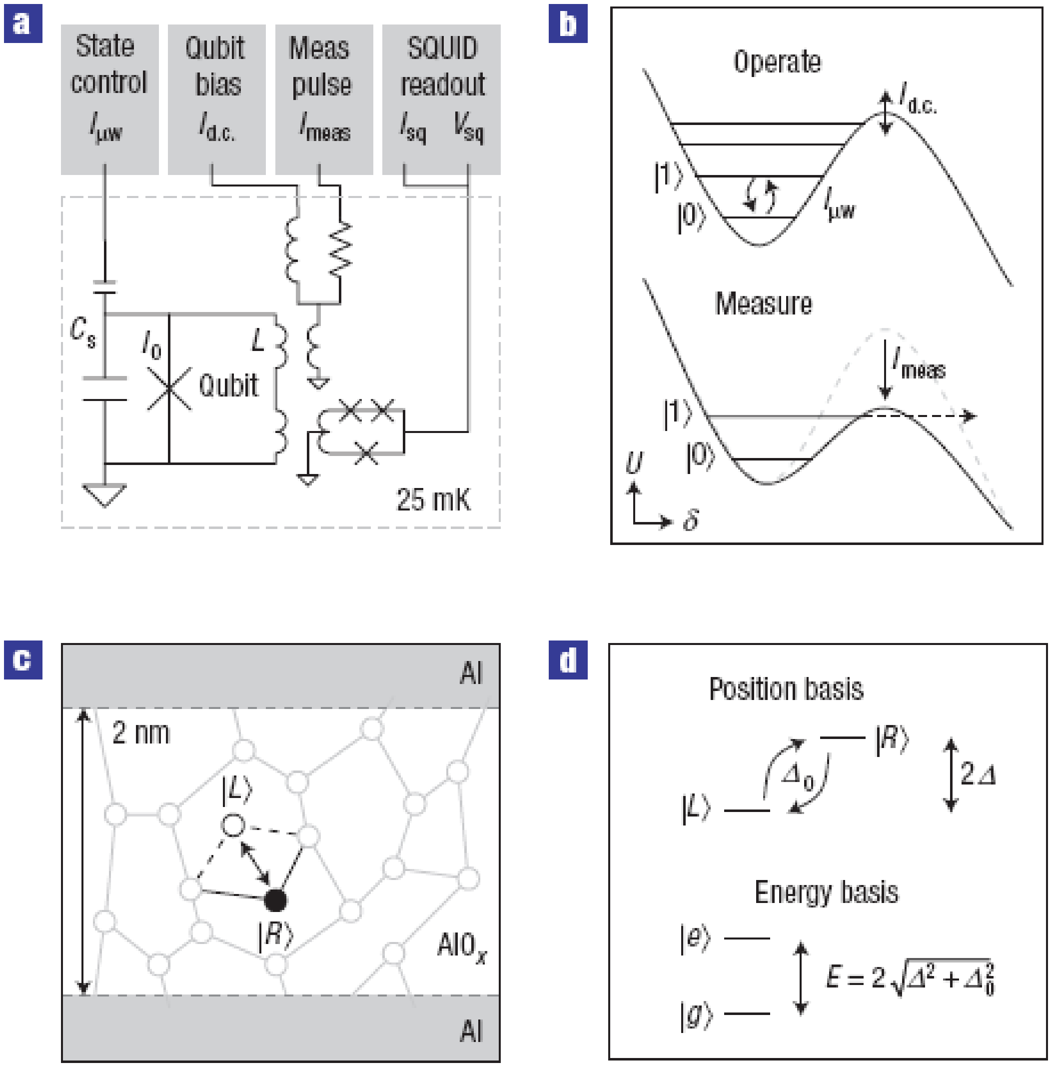


FIG. 2. Scalability of the structure: Two-qubit operations between the TLSs on different CBJJs ($j = 1, \ldots, N$) are enabled by the common LC circuit, which is capacitively coupled to the CBJJs. The Josephson energy, capacitance, and bias current of the jth CBJJ are E_j, C_j, and I_j, respectively.

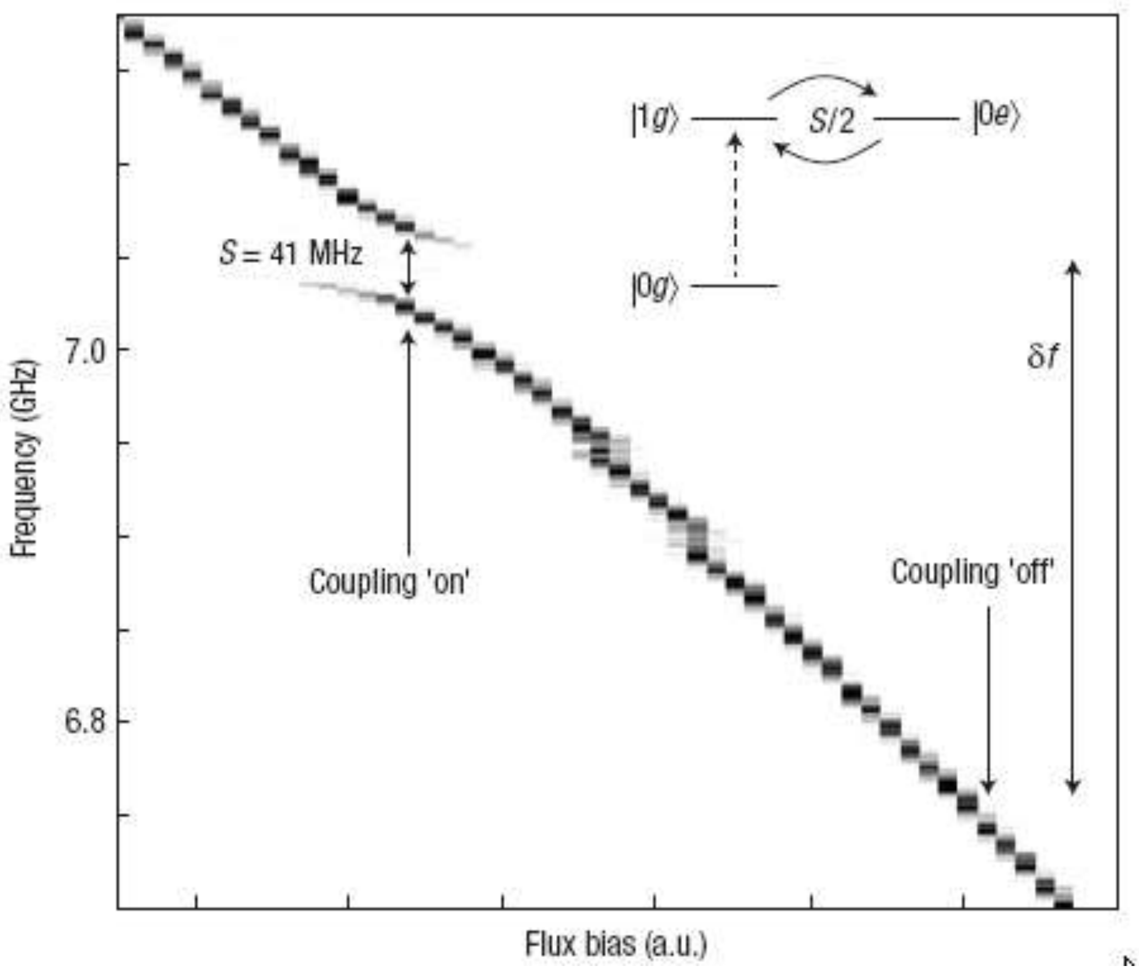
Zagoskin, Ashhab, Johansson & Nori, PRL 97 (2006) 07001

Using TLS for quantum information processing: first experimental realization

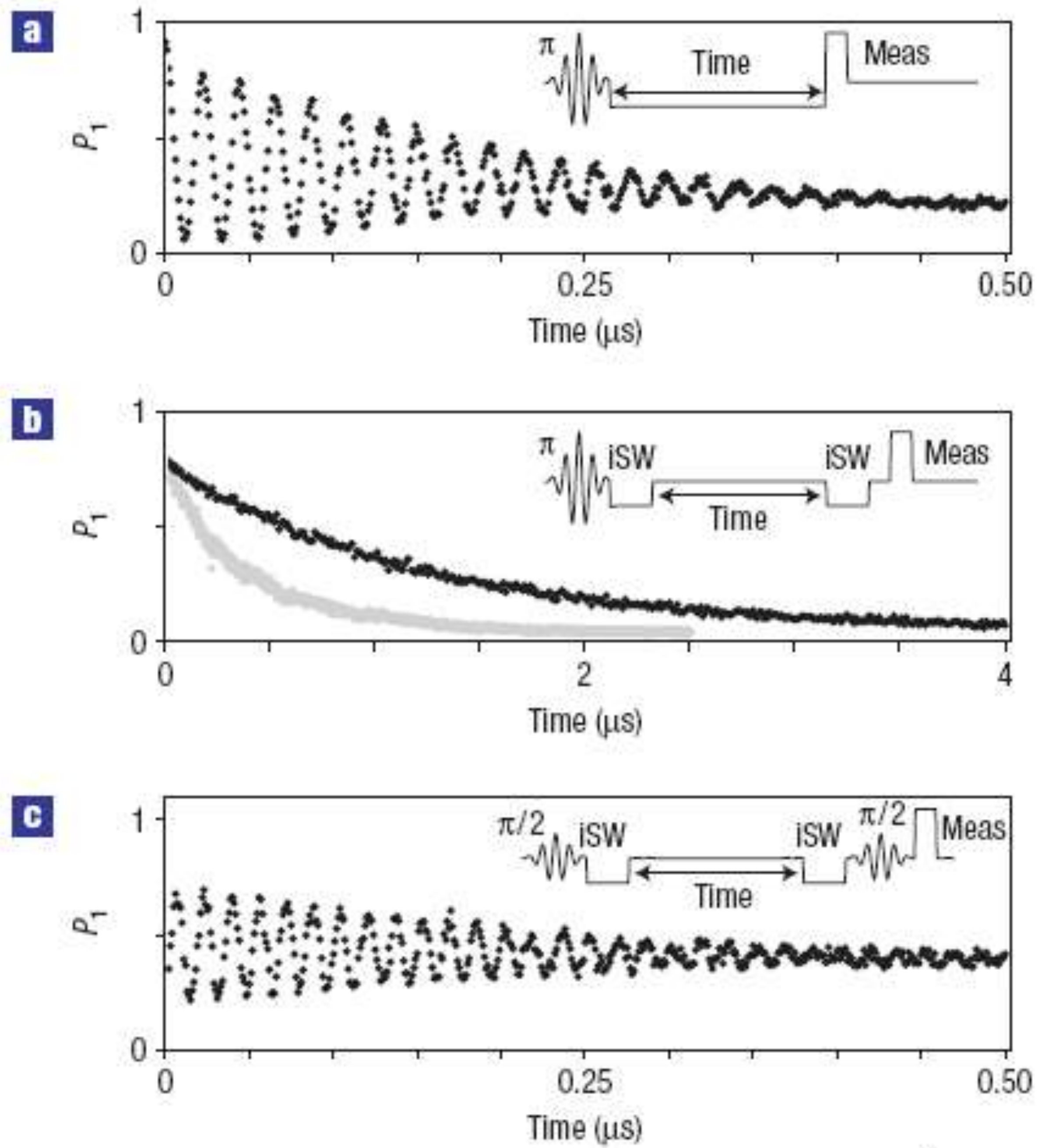


Neely et al., Nature Physics 4 (2008) 523

Using TLS for quantum information processing: first experimental realization



Neely et al., Nature Physics 4 (2008) 523



Neely et al., Nature Physics 4 (2008) 523

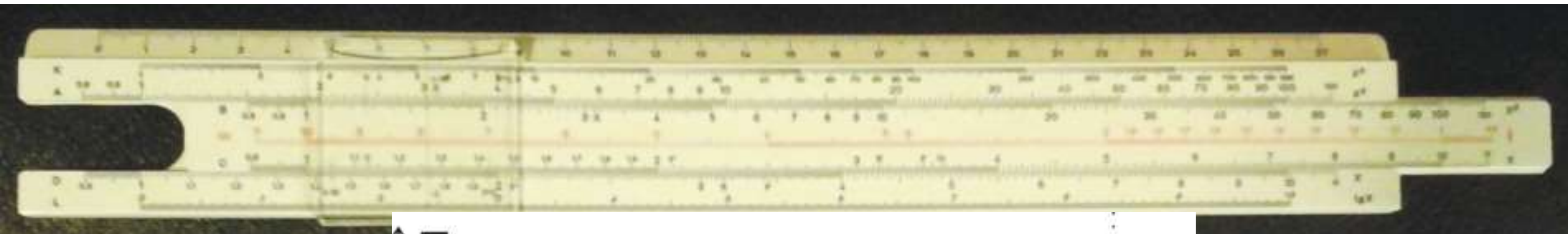
Drastic improvement in quality of superconducting qubits

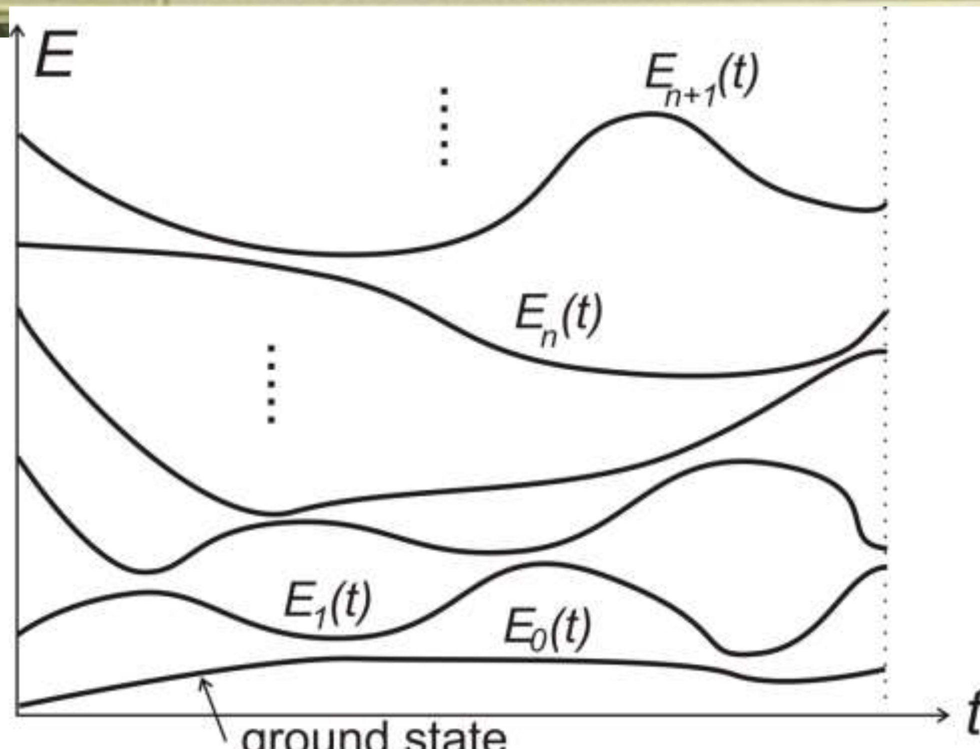
- 1999 – <10 ns
- 2015 – >100 µs
- manipulation time - nanoseconds

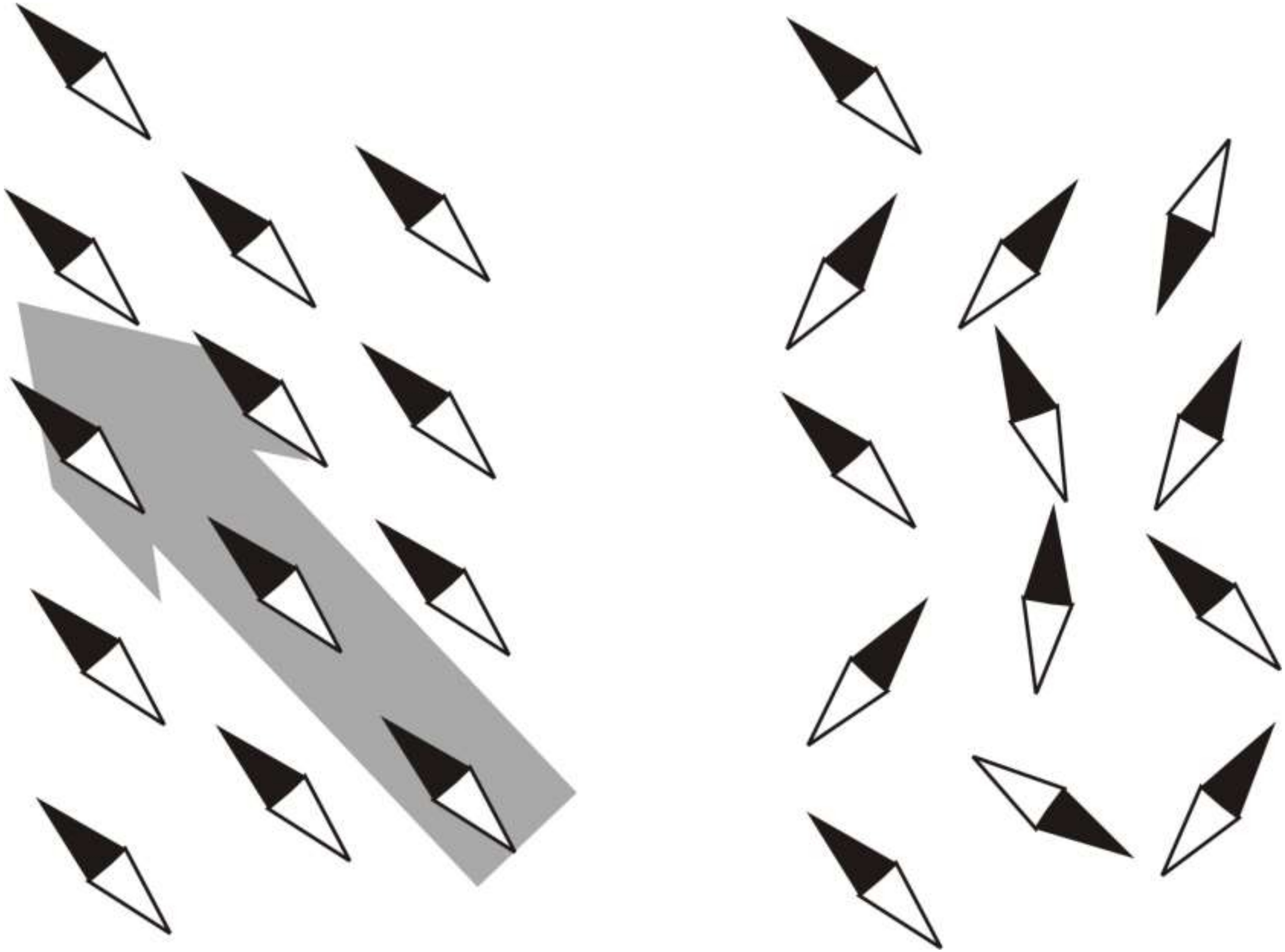
…still short of what is needed for a universal digital quantum computer

Hard to build a Pentium(TM) with steam age technology

Quantum Slide Rules: Adiabatic quantum computing







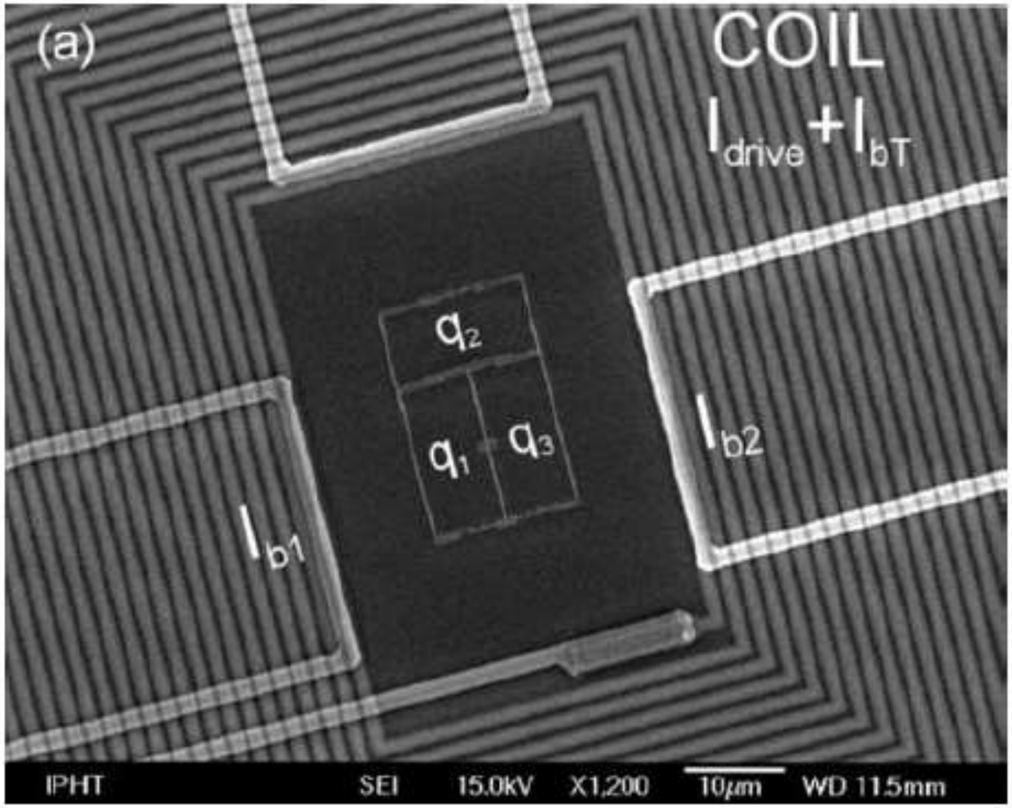
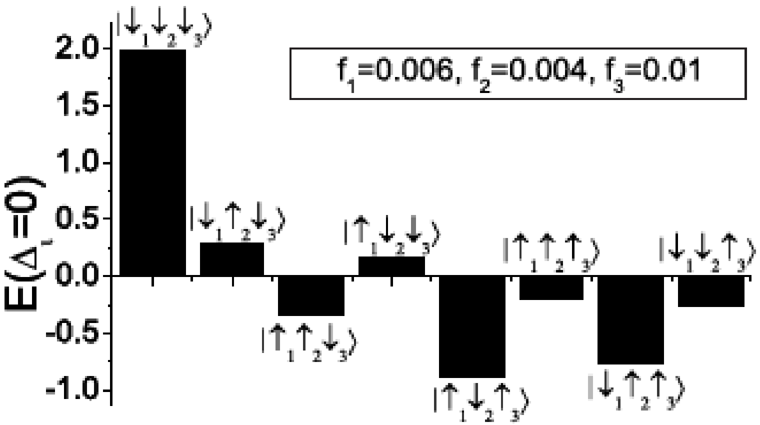


Fig. 6.7. An experimental circuit for the realization of a $(N = 3)$ maxcut adiabatic quantum algorithm (from van der Ploeg et al., 2006, © 2007 IEEE, with permission). Aluminium persistent current qubits are placed inside a niobium pickup coil; the tuning fluxes, f_{qj}, $j = 1,2,3$ (in units of Φ_0), are induced by the currents in Π-shaped bias lines. The qubits are antiferromagnetically coupled through shared Josephson junctions and (to a lesser degree) mutual inductances. The quantum state of the qubits was determined using the impedance measurement technique (IMT). The circuit parameters, $J_{12} = J_{23} = J_{13} = 610$ mK, $\Delta_1 = \Delta_2 = \Delta_3 = 70$ mK, as well as its effective temperature, were determined from fitting the IMT data



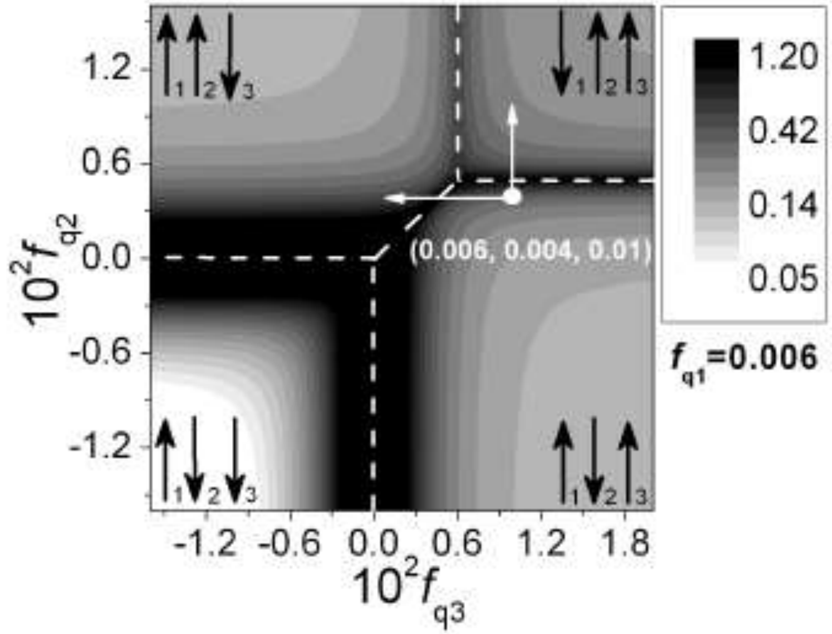


Fig. 6. $-\tan\Theta(f_{q2}, f_{q3})$ at $f_{q1} = 0.006$. The tank's response is calculated for $\Delta_1 = \Delta_2 = \Delta_3 = 96$ mK, $J_{12} = J_{13} = J_{23} = 300$ mK, $I_{p1} = I_{p3} = 350$ nA, $I_{p2} = 420$ nA, and $T = 10$ mK. The white dashed lines denote the cross-overs between the different classical states. At the white dot $(0.006, 0.004, 0.01)$ the MAXCUT problem with the solution $|\uparrow_1\downarrow_2\uparrow_3\rangle$ is encoded, see Fig. 5. The solid arrows show the directions in which the read-out should be carried out in order to reconstruct this state.

Van der Ploeg et al., ASC 2006; A. Izmalkov et al., Europhys. Lett. 76 (2006) 533

Approximate AQC – a possible application?

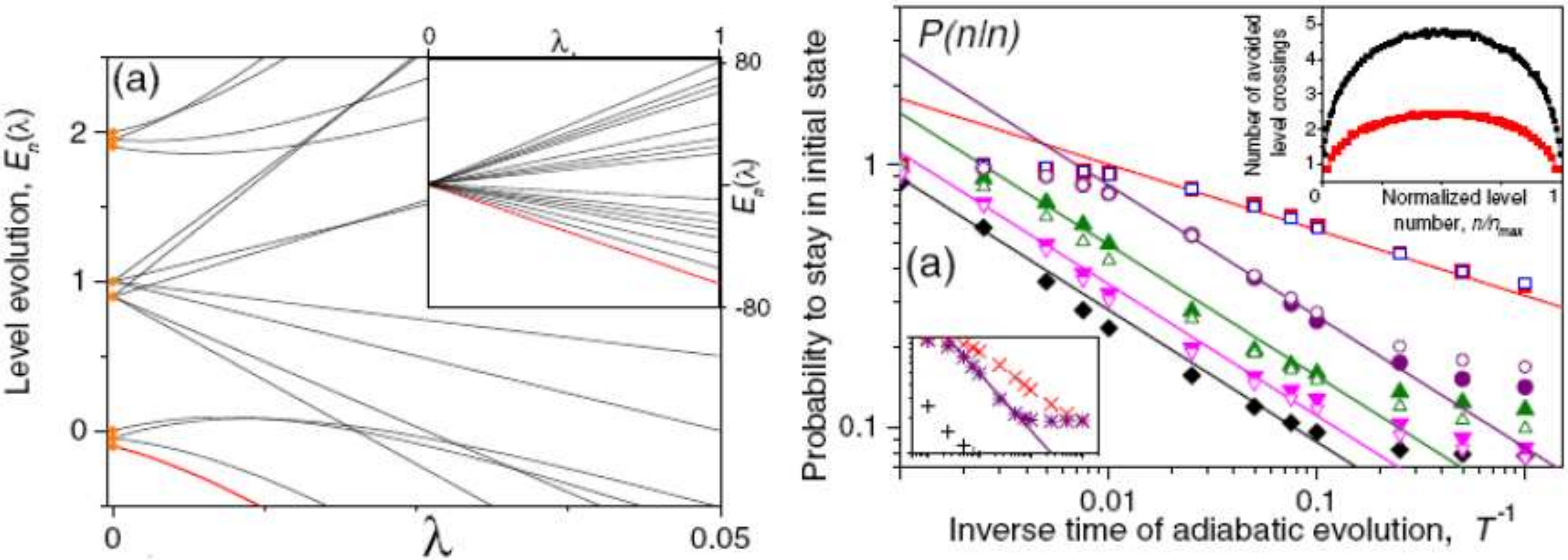
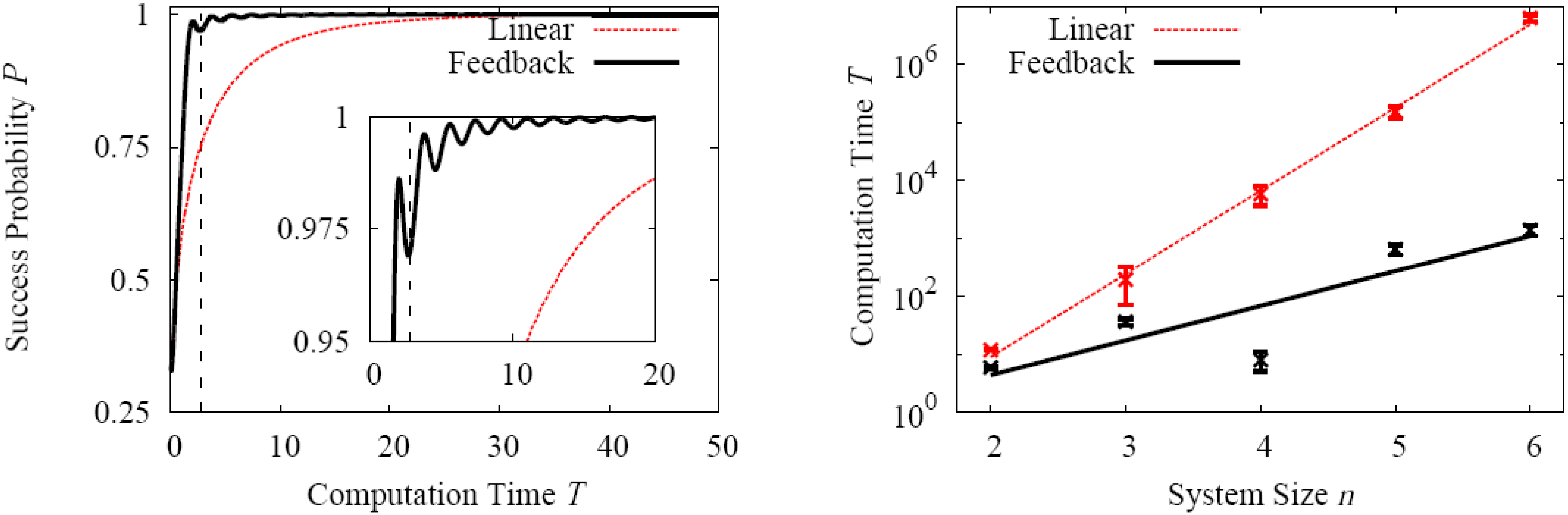


Fig.2.3. Modeling adiabatic quantum evolution in a qubit register.
(Left) Simulation of the CNOT gate for the operation |00> -> |00> (involving 4 qubits). (Rght) Average probability P(n|n) for the system to remain in the initial state |n>, as a function of 1/T (evolution speed), during the adiabatic evolution, for the number of energy levels N=50. Different symbols correspond to different initial states. Left inset: Same for N=150 levels. Right inset: Average number of avoided level crossings during the evolution for N=50 (red) and N=150 (black) states in the system. From [A.M. Zagoskin et al., Phys. Rev. Lett. 98, 120503 (2007)].

Feedback-controlled adiabatic quantum computation



R.D. Wilson, A.M. Zagoskin, S. Savel'ev, and M.J. Everitt; Franco Nori (2012)

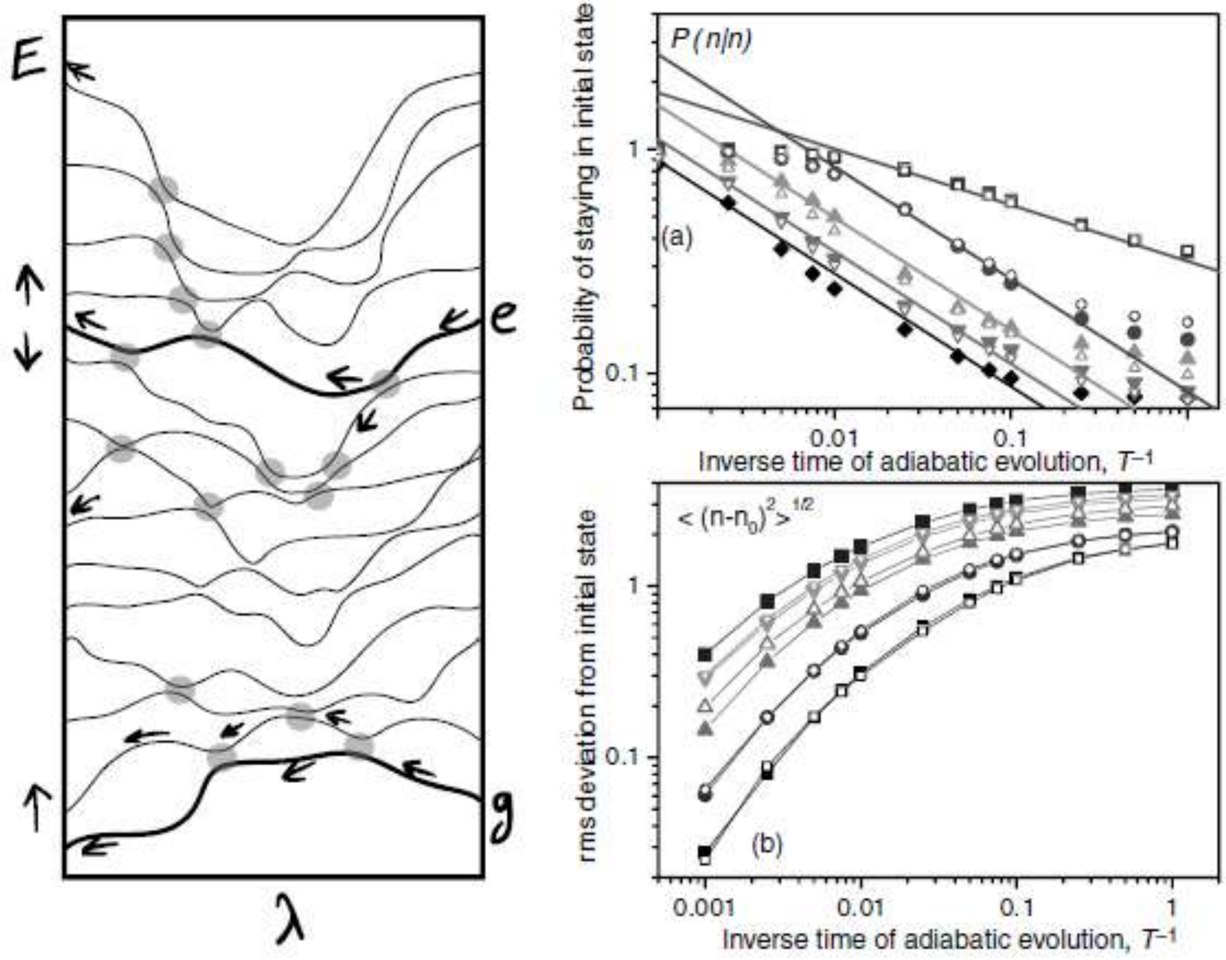


Fig. 6.10. Approximate adiabatic quantum computing (AAQC). (Left) During quasiadiabatic evolution the system can deviate from the initial ground (g) or excited (e) state via a series of Landau–Zener transitions (grey circles), in a process similar to a random walk. (Right) Probability of staying in the same state (a) and the r.m.s. deviation from the initial state (b) as a function of the inverse evolution time for Hamiltonians from the GUE of random matrix theory (reprinted with permission Zagoskin et al., 2007, © 2007 American Physical Society; cf. Eq. (6.63)). Different symbols correspond to different initial energy eigenstates.

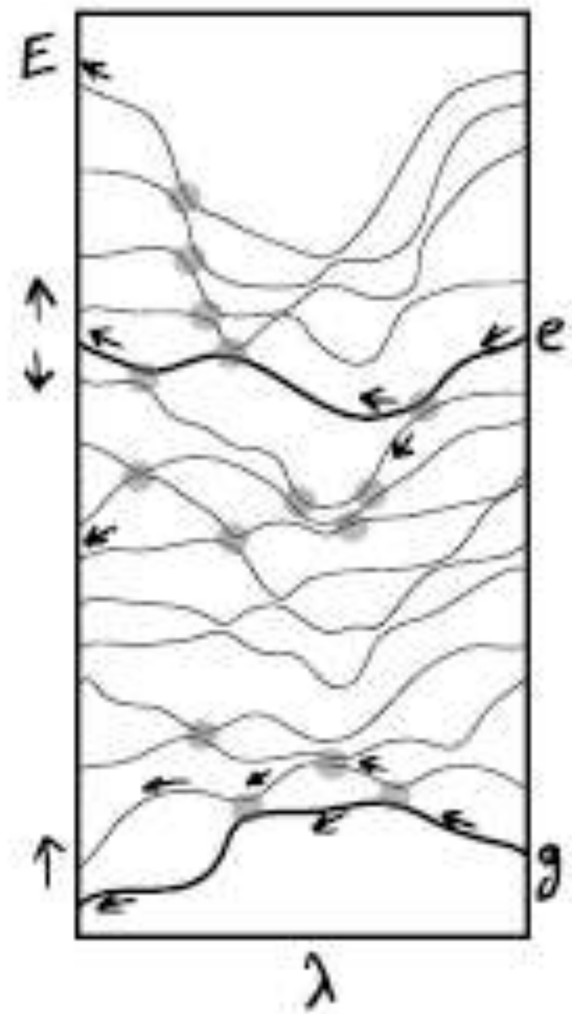
How far do we get from the initial state?

- "LZ diffusion"

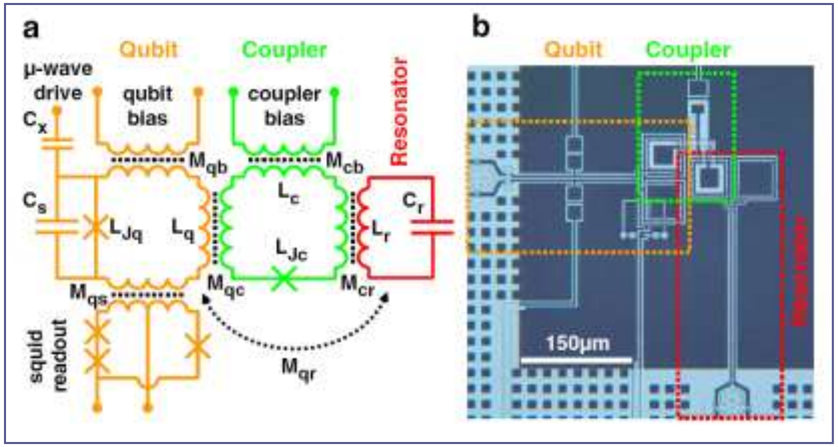
$$\left\langle (n - n_0)^2 \right\rangle_{\lambda=1} = pk|_{\lambda=1} = pN$$

  - N – number of anticrossings per energy level

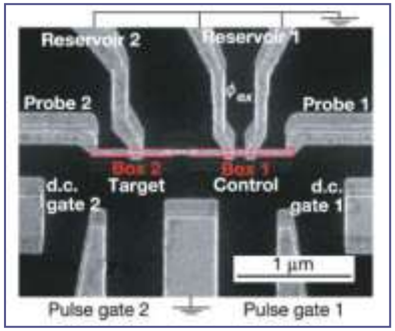
$$\Delta n = \sqrt{\langle n^2 \rangle} \propto \mathrm{e}^{-\alpha T_A}$$



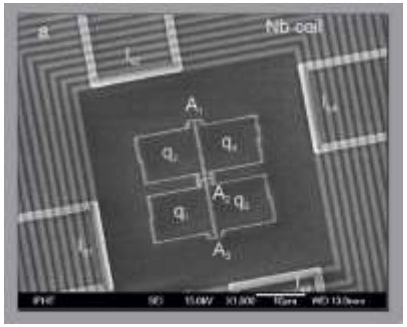
From single qubits to Schrödinger's elephants



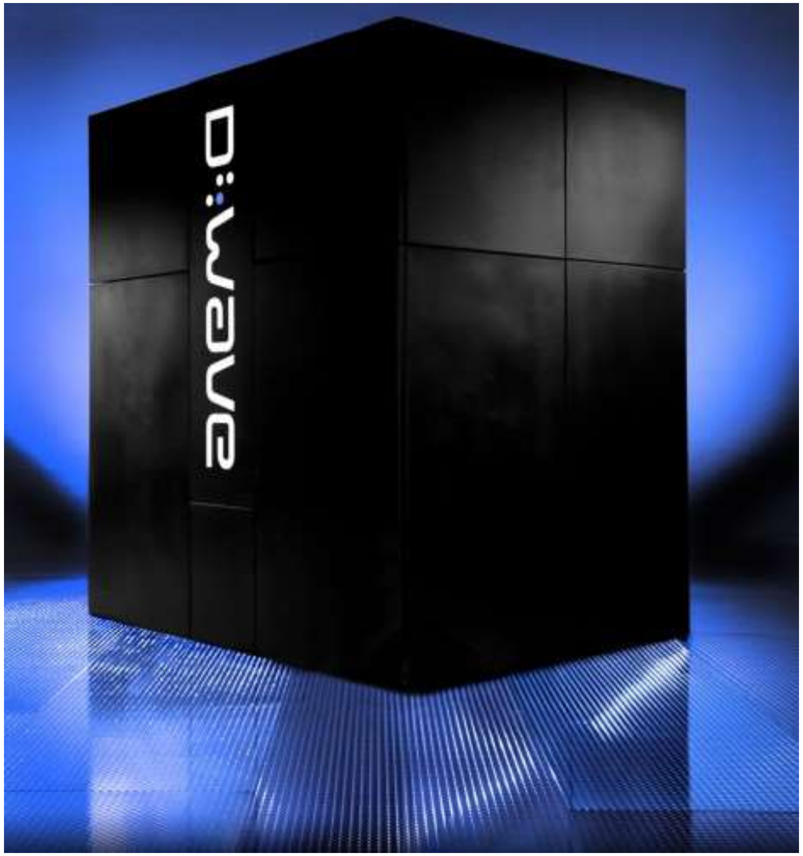
Phase qubit: Allman et al., 2010



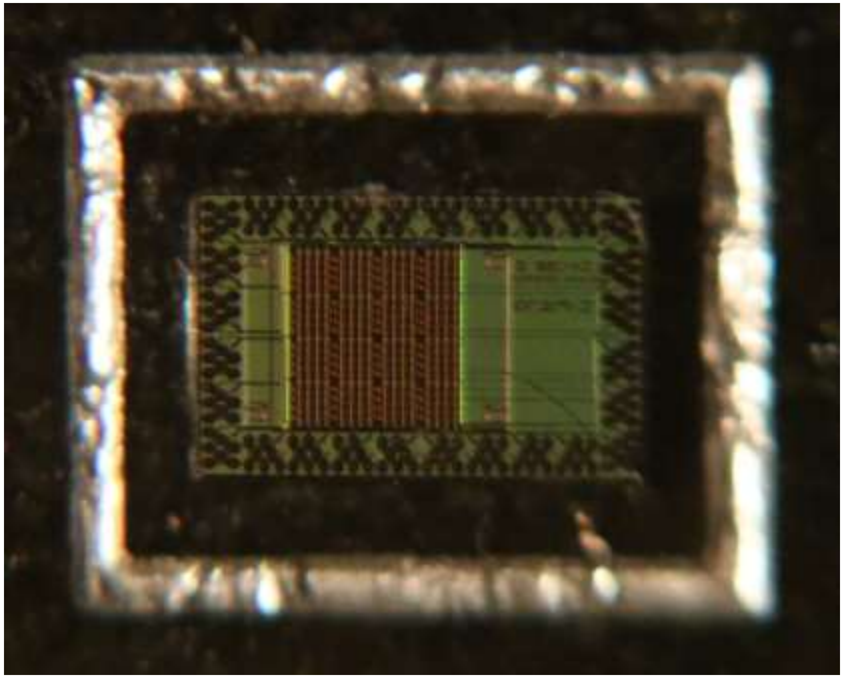
Charge qubits: Yamamoto et al., 2003



Flux qubits: Grajcar et al., 2006




D:Wave
The Quantum Computing Company™
Thank You to Our Investors, Board and Staff
For Being Part of the First D-Wave System Sale
This Rainier 128 Qubit Quantum processor is from the same wafer lot fabricated and used in the very first D-Wave One system delivered for customer use in December, 2010.
This chip is certified to have been cooled to 20 degrees milli-Kelvin.



D-Wave controversy

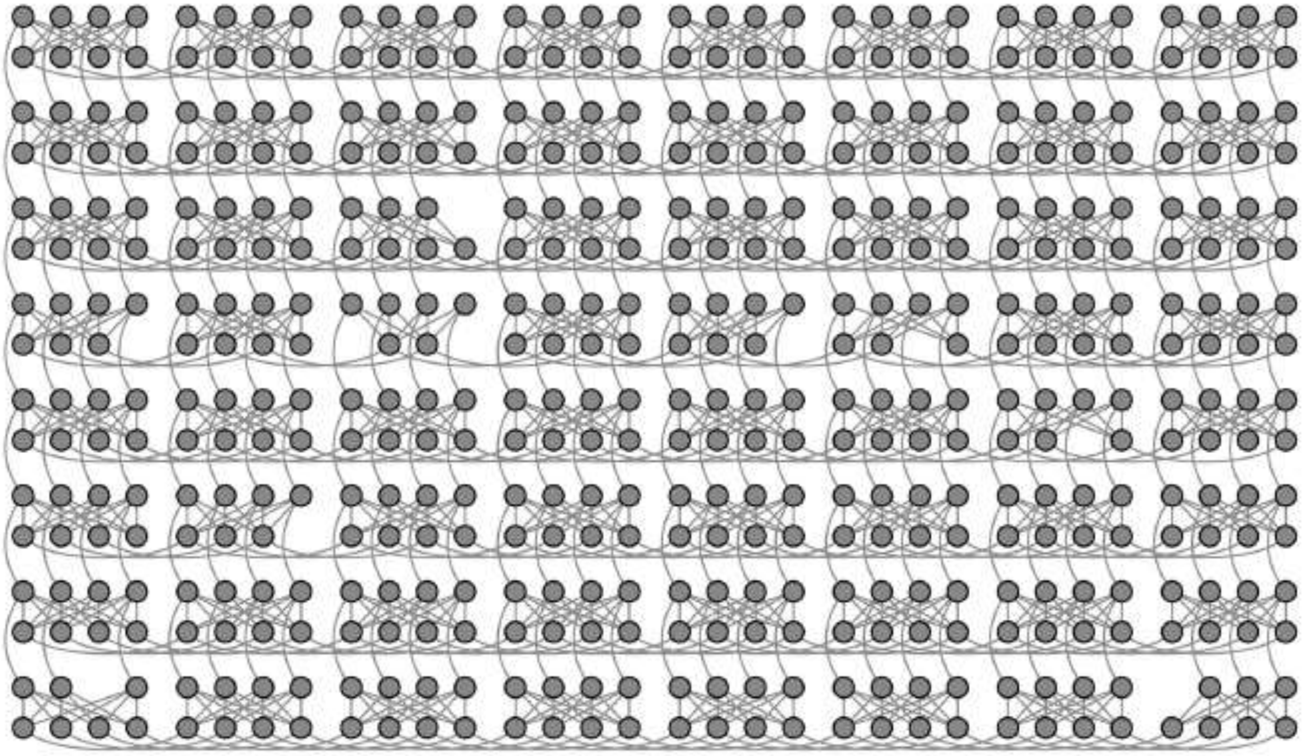
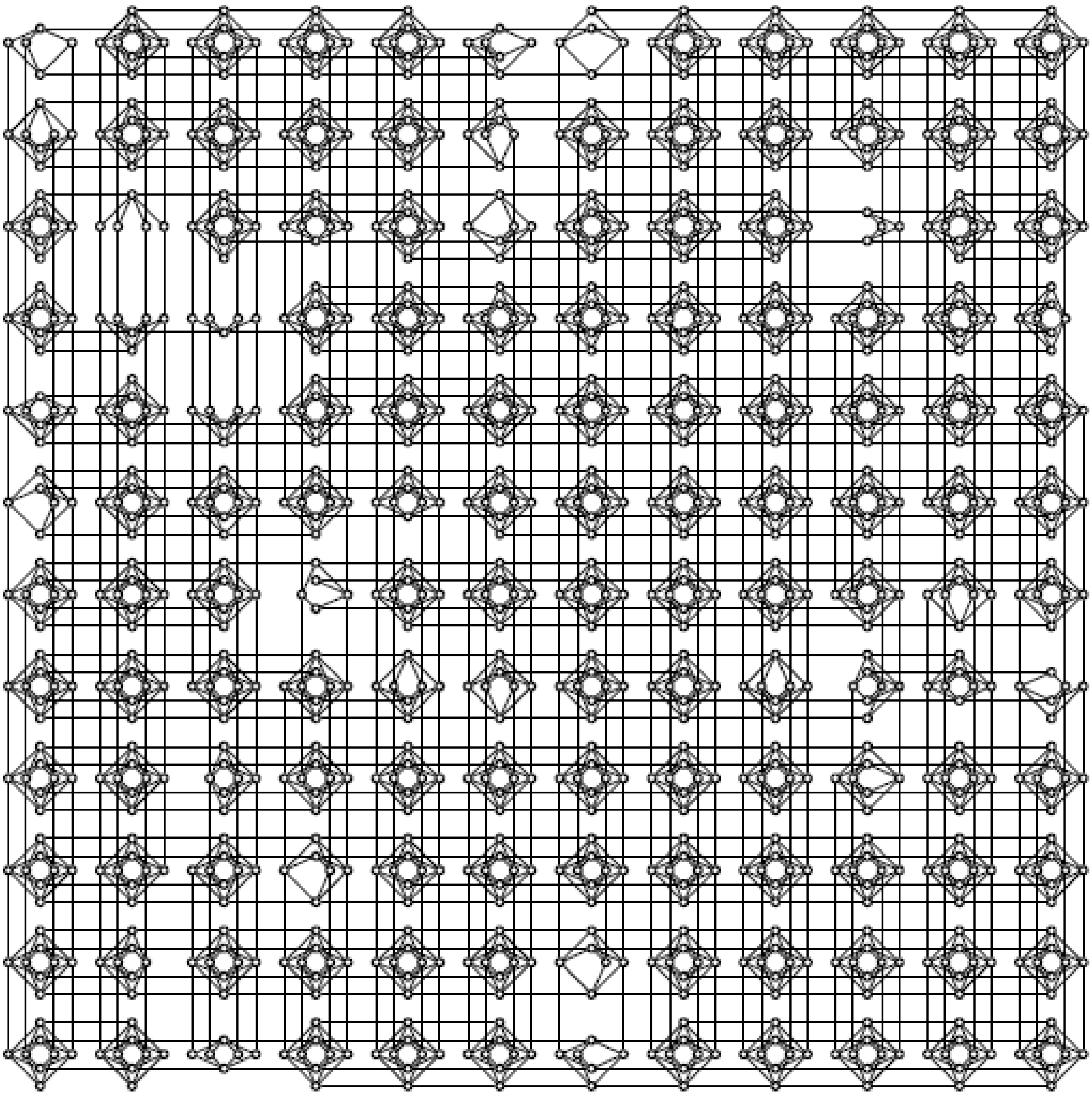


FIGURE 1 | D-Wave's recent generation Chimera connectivity graph $\mathcal{G}$. Vertices indicate spin-valued variables represented by programmable qubits (h_i's), and edges indicate programmable couplers ($J_{i,j}$'s). $\mathcal{G}$ is a lattice of $K_{4,4}$ unit cells where missing qubits are the result of fabrication defects.

D-Wave controversy

- World's biggest collection of qubits
  - Current version of D-Wave 2X had 1152 qubits, 1097 operational
- Quantum operation confirmed for 8-qubit register
- Operation consistent with both quantum and classical models
- Decoherence time of a qubit much shorter than the adiabatic evolution time
- How to tell whether it is quantum, and if so, is it quantum enough?
- 3000× SNAFU
- Recent data (C. Williams at Oxford): N-qubit system with E couplers stays within $\sqrt{N+E}$ from the ground state – consistent with the LZ diffusion picture
- Latest: King et al., "TTT-benchmarking" – faster than conventional algorithms on classical computers

Latest generation Chimaera C_{12}

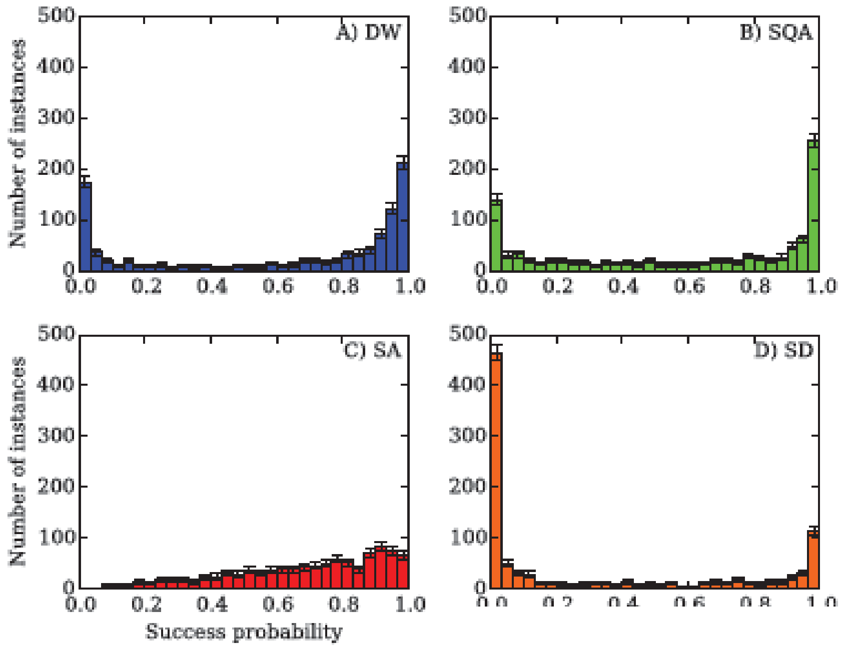


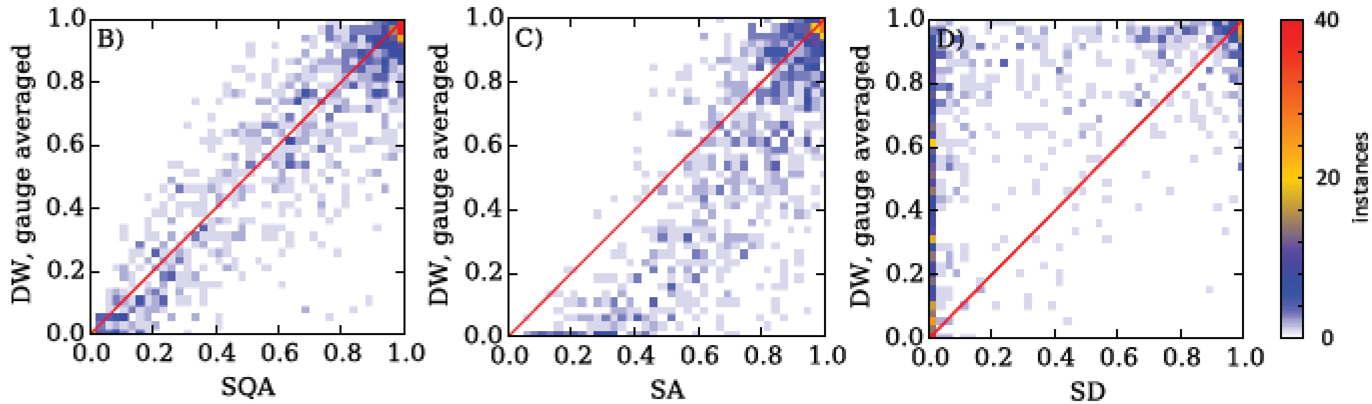
King et al. arxiv 1508.05087

“Time-To-Target” – essentially the same approach as AAQC

- How fast another algorithm can produce the same degree of accuracy (King et al. arxiv 1508.05087)
- BUT:
  - DOES IT REALLY MATTER?
  - “Speed-up” is – scientifically – a minor and ill-defined question compared to the one of “degree of quantumness”

Boixo, S. *et al.* Evidence for quantum annealing with more than one hundred qubits. *Nature Physics* **10**, 218–224 (2014).





frontiers in PHYSICS

ORIGINAL RESEARCH ARTICLE
published: 05 September 2014
doi: 10.3389/fphy.2014.00052

Classical signature of quantum annealing

John A. Smolin * and Graeme Smith

IBM Research, Yorktown Heights, NY, USA

Edited by:
Jacob Biamonte, Institute for Scientific Interchange Foundation, Italy

Reviewed by:
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Scott Aaronson, Massachusetts Institute of Technology, USA

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A pair of recent articles [1, 2] concluded that the D-Wave One machine actually operates in the quantum regime, rather than performing some classical evolution. Here we give a classical model that leads to the same behaviors used in those works to infer quantum effects. Thus, the evidence presented does not demonstrate the presence of quantum effects.

Keywords: quantum annealing, decoherence, quantum computing, D-Wave, adiabatic quantum computing

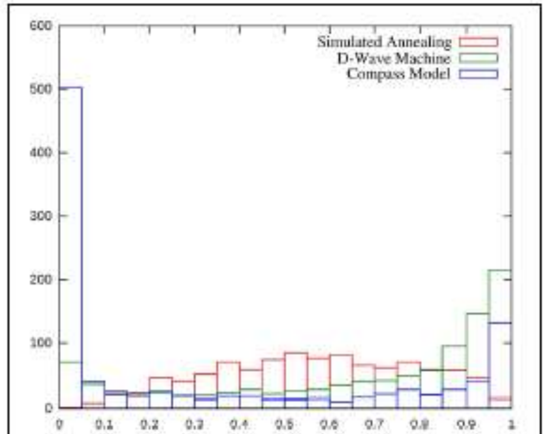
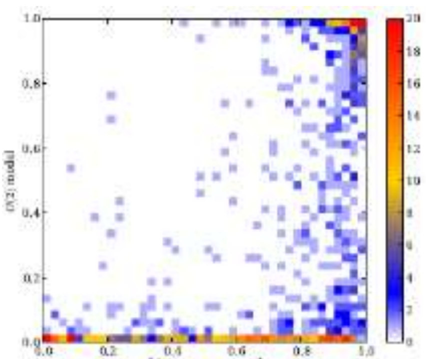
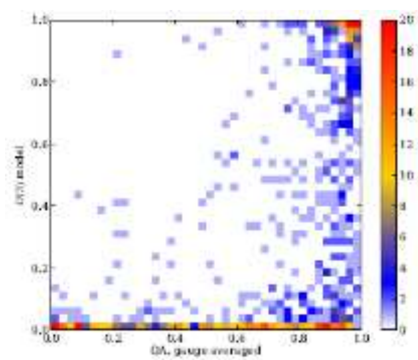
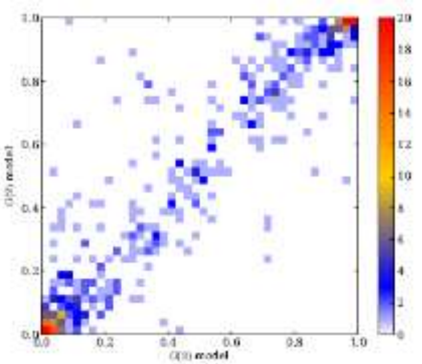


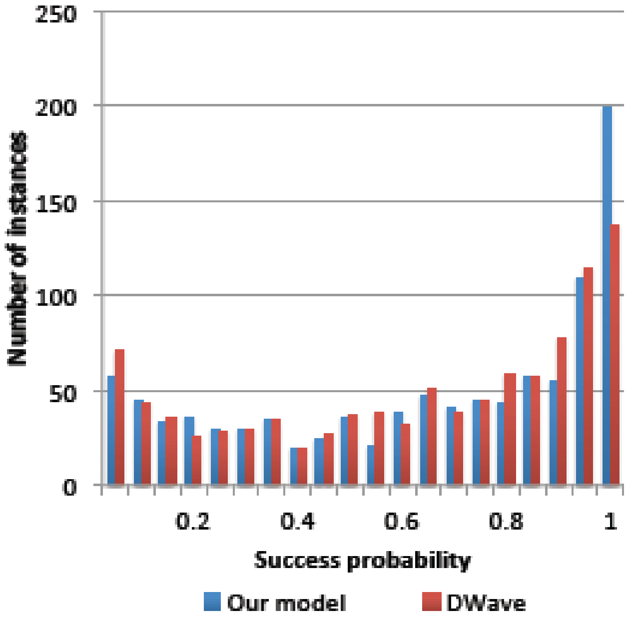
FIGURE 3 | Results of 1000 spin glass instances, each run 100 times on a noisy simulation of the classical compass model with $T = 1000$. A bimodal distribution is observed, with a clear separation between easy and hard instancesd with high and low success probabilities respectively. The noise applied was random kicks to each $\dot{\theta}$ at $t = 10, 20, \ldots, 1000$ uniformly chosen between ± 0.0015. The results are compared to the experimental data of Boixo et al. [2] and to an illustrative run of simulated annealing.

Wang L, Roennow T, Boixo S, Isakov S, Wang Z, Wecker D, et al. Comment on: “Classical signature of quantum annealing.” arXiv:1305.5837 (2013).

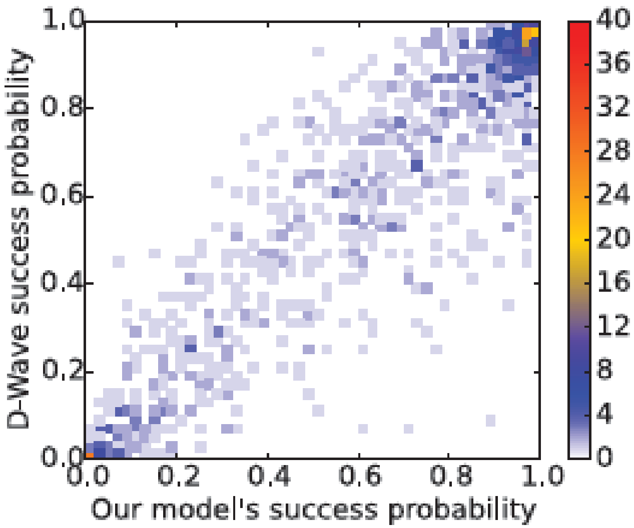


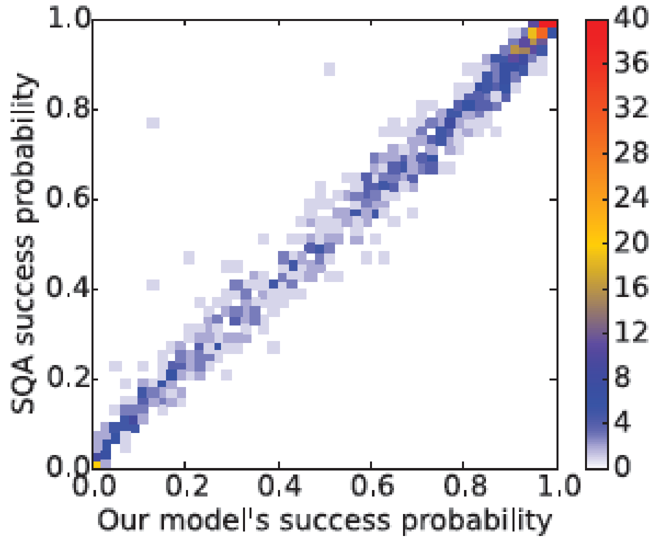






Shin S, Smith G, Smolin J, Vazirani U. How "Quantum" is the D-Wave machine? arXiv:1401.7087 (2014).





Grand Challenge

frontiers in PHYSICS

PERSPECTIVE ARTICLE
published: 30 May 2014
doi: 10.3389/fphy.2014.00033

How to test the "quantumness" of a quantum computer?

Alexandre M. Zagoskin[1,2*], Evgeni Il'ichev[3], Miroslav Grajcar[4], Joseph J. Betouras[1] and Franco Nori[2,5]

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[2] *Center for Emergent Matter Science, RIKEN, Saitama, Japan*
[3] *Quantum Detection, Leibnitz Institute of Photonic Technology, Jena, Germany*
[4] *Department of Experimental Physics, Comenius University, Bratislava, Slovakia*
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Recent devices, using hundreds of superconducting quantum bits, claim to perform quantum computing. However, it is not an easy task to determine and quantify the degree of quantum coherence and control used by these devices. Namely, it is a difficult task to know with certainty whether or not a given device (e.g., the D-Wave One or D-Wave Two) is a quantum computer. Such a verification of quantum computing would be more accessible if we already had some kind of working quantum computer, to be able to compare the outputs of these various computing devices. Moreover, the verification process itself could strongly depend on whether the tested device is a standard (gate-based) or, e.g., an adiabatic quantum computer. Here we do not propose a technical solution to this quantum-computing "verification problem," but rather outline the problem in a way which would help both specialists and non-experts to see the scale of this difficult task, and indicate some possible paths toward its solution.

Keywords: quantum computing, adiabatic quantum computing, quantum coherence, quantum annealing, D-Wave Systems, quantum simulations, quantum speed-up

Grand Challenge

frontiers in
ICT

SPECIALTY GRAND CHALLENGE ARTICLE
published: 22 October 2014
doi: 10.3389/fict.2014.00002

The grand challenge of quantum computing: bridging the capacity gap

Alexandre Zagoskin*

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Edited and reviewed by:
Tobias Lindstrom, National Physical Laboratory, UK

Keywords: Quantum computing, quantum simulation, quantum engineering, testing limits of applicability of quantum mechanics, quantum metamaterials

The fabrication and control of macroscopic artificial quantum structures, such as qubits (Mooij et al., 1999; Nakamura et al., 1999; Friedman et al., 2000), qubit arrays (Johnson et al., 2011; Barends et al., 2014), quantum annealers (Boixo et al., 2013) and, recently, quantum metamaterials (Macha et al., 2014), have wit- mechanics for large enough systems, we will be unable to discover them because of our inability to tell what exactly quantum mechanics *would* predict.

Let us take the optimistic view that quantum computing is not *fundamentally* restricted by, for example, the size of a system capable of demonstrating quantum amenable to the approaches that have proven to work very well in numerous applications in condensed matter physics and quantum statistical mechanics.

Therefore, with such earlier breakthroughs in mind, the task at hand will be difficult yet not impossible, and more than worth the effort.

Why now?

- Fabrication of multiqubit arrays with controlled macroscopic quantum coherence now possible
- Current theoretical methods at their limit and new approaches are urgently needed
- Applications (part of "quantum technologies 2.0"):
    - Integrated quantum limited detection and image processing
    - Quantum optimization
    - Quantum simulation
    - Quantum communication

Quantum engineering for QT2.0

- Quantum UNIT engineering
  - Qubits
  - Couplers
    - **DONE – engineers can take over (at least with superconducting qubits)**
- Quantum STRUCTURAL engineering
  - Multiqubit structure
    - design
    - control
    - performance
    - characterization
    - reliability
    - scalability
      - **ONLY STARTED – theory lags behind (capacity gap)**
- Quantum SYSTEMS engineering
  - Integrating different quantum and classical systems and optimizing human interface
    - **IRRELEVANT at the moment**

Quantum structural engineering – the critical challenge for QT2.0

- Accommodating incompatible requirements
- Using “rule-of-thumb” estimates for characterizing and predicting the system’s performance and reliability
- Heuristics
- Scaling
- “Engineering is about building reliable structures using non-reliable components”
- **And now do all this for a macroscopic quantum coherent structure!**

Bridging the gap

- Develop *efficient* methods of predicting behaviour of *large quantum* systems using *classical* means – without violating Feynman's dictum
  - Statistical predictions – for classes of systems, valid on average
  - Extension of methods of quantum many-body theory and quantum statistics
  - How exactly?

For example…

- Pechukas-Yukawa (generalized Calogero-Sutherland)

$$\frac{d}{d\lambda}x_m = v_m;\ \frac{d}{d\lambda}v_m = 2\sum_{m\neq n}\frac{|l_{mn}|^2}{(x_m - x_n)^3};\ \frac{d}{d\lambda}l_{mn} = \sum_{k\neq m,n} l_{mk}\, l_{kn}\left(\frac{1}{(x_m - x_k)^2} - \frac{1}{(x_k - x_n)^2}\right) ($$

where $x_n(\lambda) = E_n(\lambda)$, $v_n(\lambda) = \langle n|ZH_b|n\rangle$, and $l_{mn}(\lambda) = (E_m(\lambda) - E_n(\lambda))\langle m|ZH_b|n\rangle$. Equations (2) describe the classical Hamiltonian dynamics of a 1D gas with repulsion, where λ plays the role of time, and the nth "particle" has a position $x_n(\lambda)$ and velocity $v_n(\lambda)$. The particle-particle repulsion is determined by the "relative angular momenta" $l_{mn}(\lambda)$.

Zagoskin, Savel'ev and Nori, PRL **98**, 057004 (2007)

- and the corresponding BBGKY chain:

$$\left[\frac{\partial}{\partial\lambda}+v\frac{\partial}{\partial x}\right]f_1(x,v,n)=2\frac{\partial}{\partial v}\sum_m\int dl\,dy\,du\frac{|l|^2}{(y-x)^3}f_2(x,v,n;y,u,m;l).$$

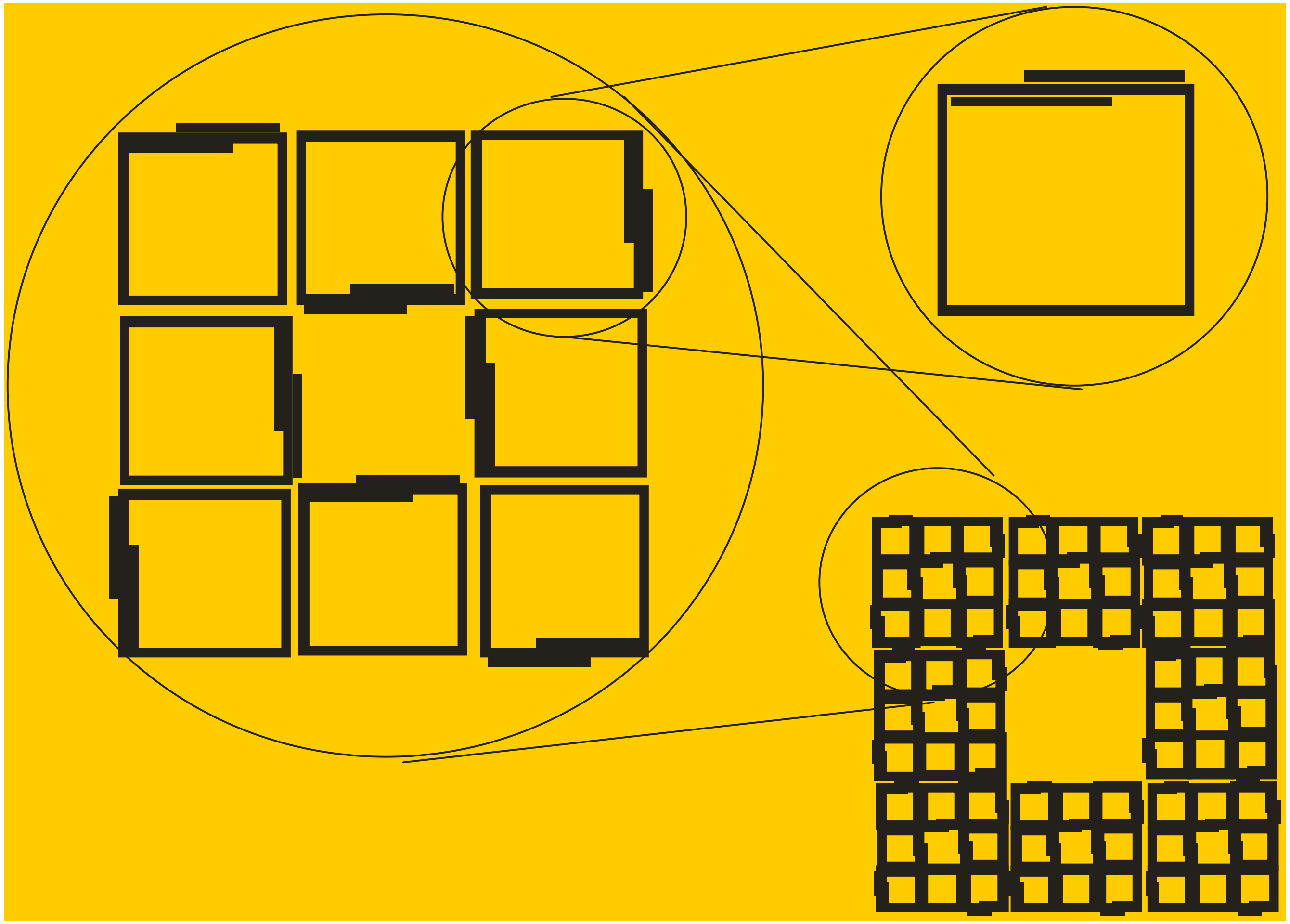
$$\left[\frac{\partial}{\partial\lambda}+v\frac{\partial}{\partial x}-2\Gamma\left(\sum_m\mathcal{P}\int\,dy\,du\,\frac{f_1(y,u,m)}{(y-x)^3}\right)\frac{\partial}{\partial v}\right]f_1(x,v,n)=I_{\mathrm{St}}$$

Zagoskin, Savel’ev and Nori, PRL **98**, 057004 (2007)

Or: scaling approach

- and the use of scale models based, e.g., on quantum metamaterials


CNOT



Quantum metamaterials:

- Artificial optical media that have the following properties:
  - They are composed of quantum coherent unit elements with engineered parameters
  - Quantum states of these elements can be controlled
  - The whole structure can maintain global quantum coherence for longer than the traversal time of a relevant electromagnetic signal

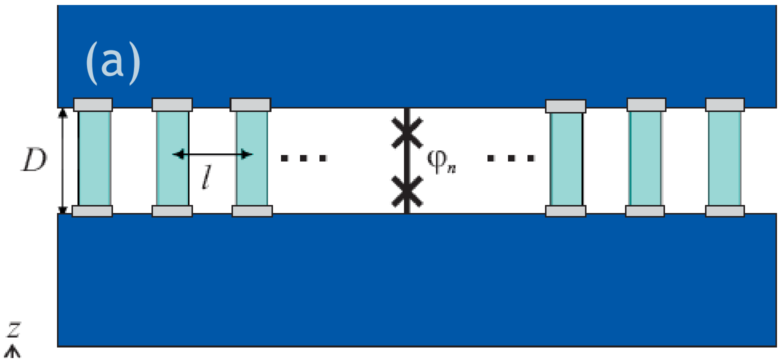
Rakhmanov, Zagoskin, Saveliev & Nori, Phys. Rev. B 77, 144507 (2008)

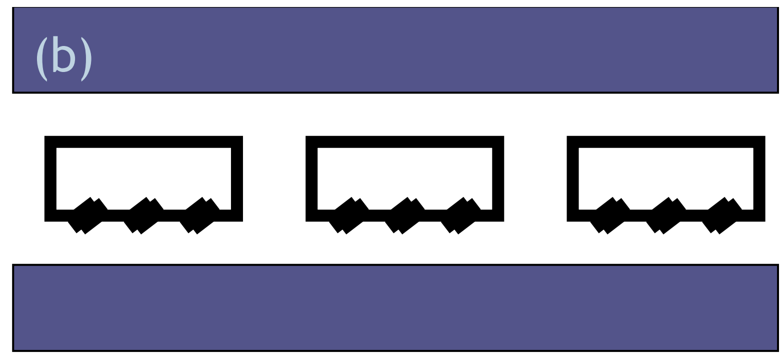
- A quantum metamaterial is an ideal testing bed for the development of quantum engineering and QT2.0
  - Simpler
  - Promising applications
    - Imaging
    - Sensing
    - Testing limits of quantum mechanics

  - An AQC can be considered a special case of a (very complex) quantum metamaterial

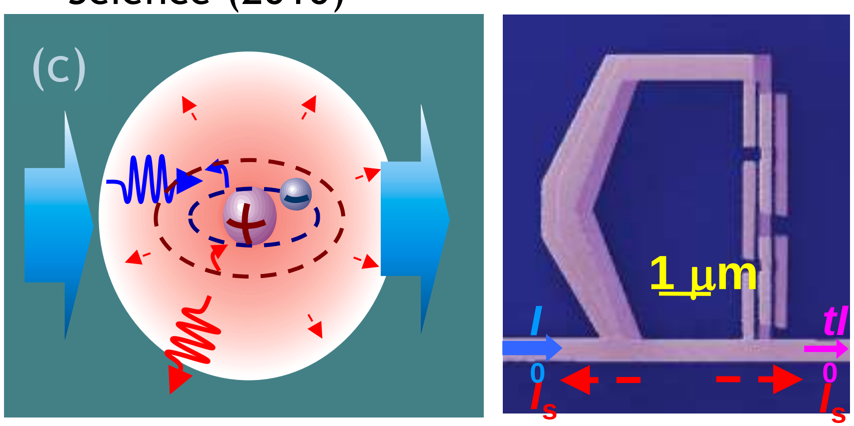
QMMs from 2008 to 2014

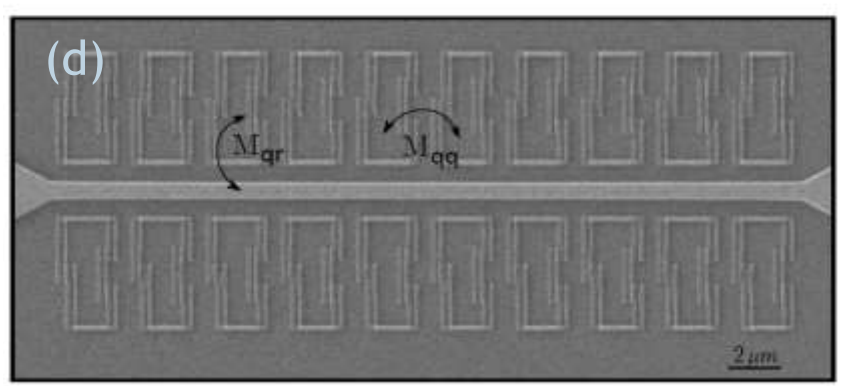
- Theoretical proposal:
- Rakhmanov, Zagoskin, Saveliev & Nori, Phys. Rev. B **77**, 144507 (2008)
- Zagoskin, Rakhmanov, Saveliev & Nori, Phys. Stat. Solidi B **246**, 955 (2009)



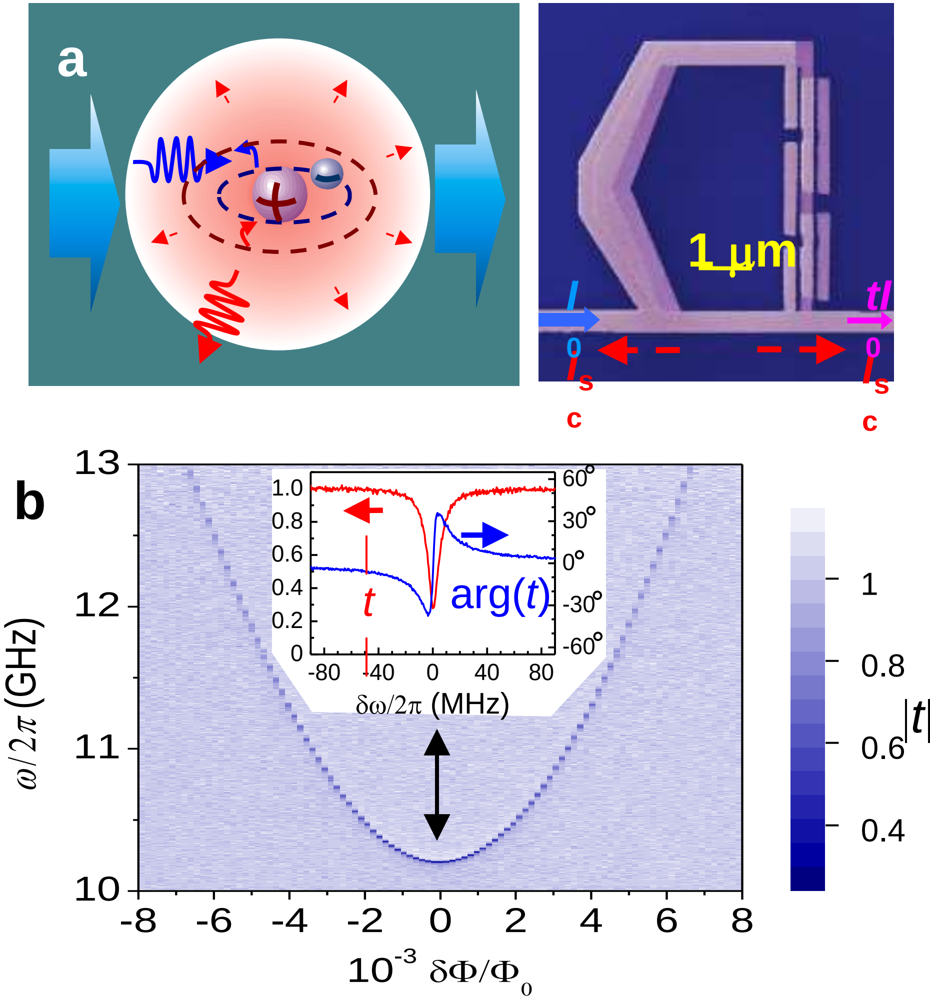


- Proof of principle: Astafiev, Zagoskin et al., Science (2010)
- Experimental prototype: Macha et al. (2013)





Proof-of-principle test

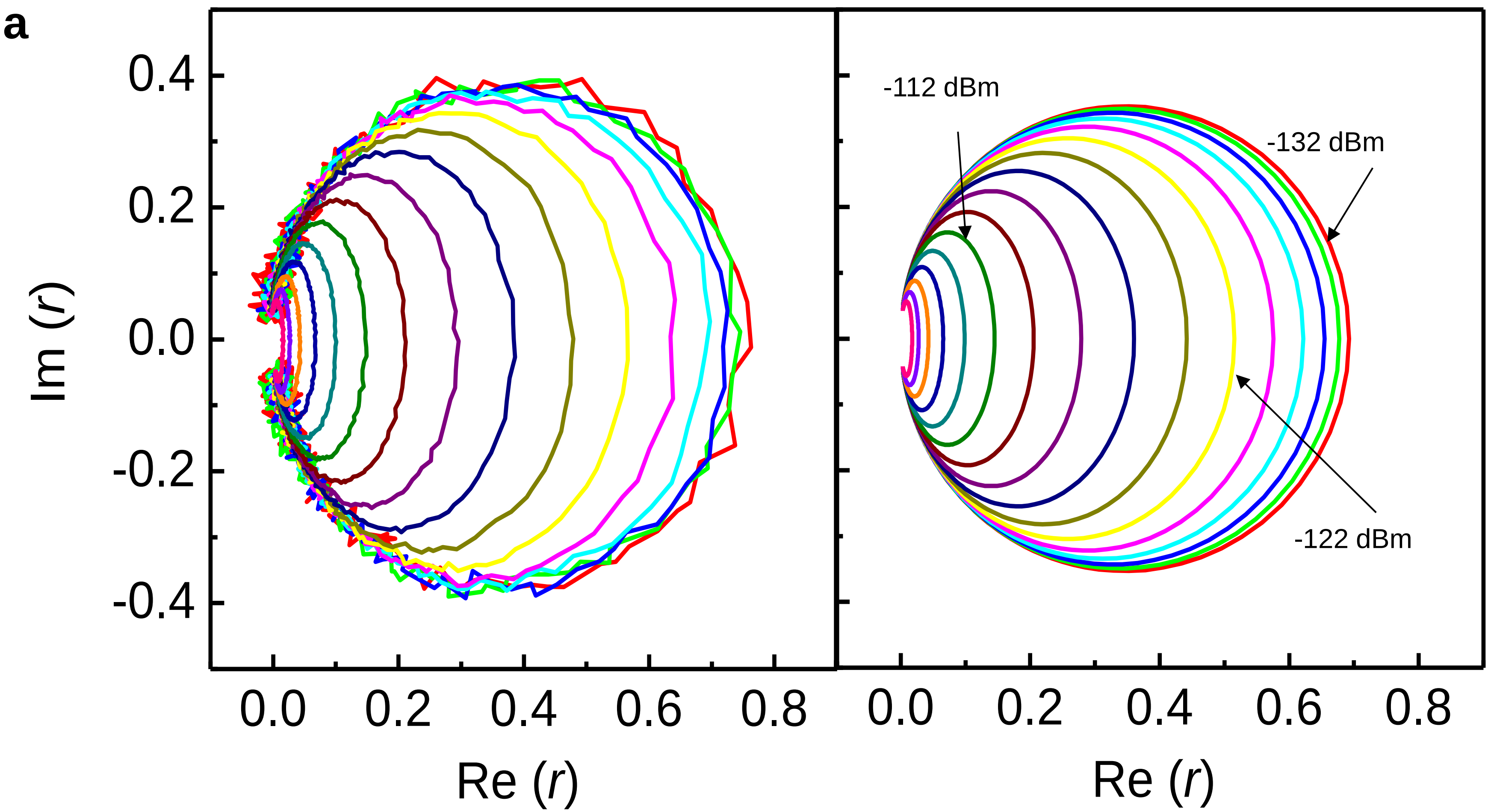


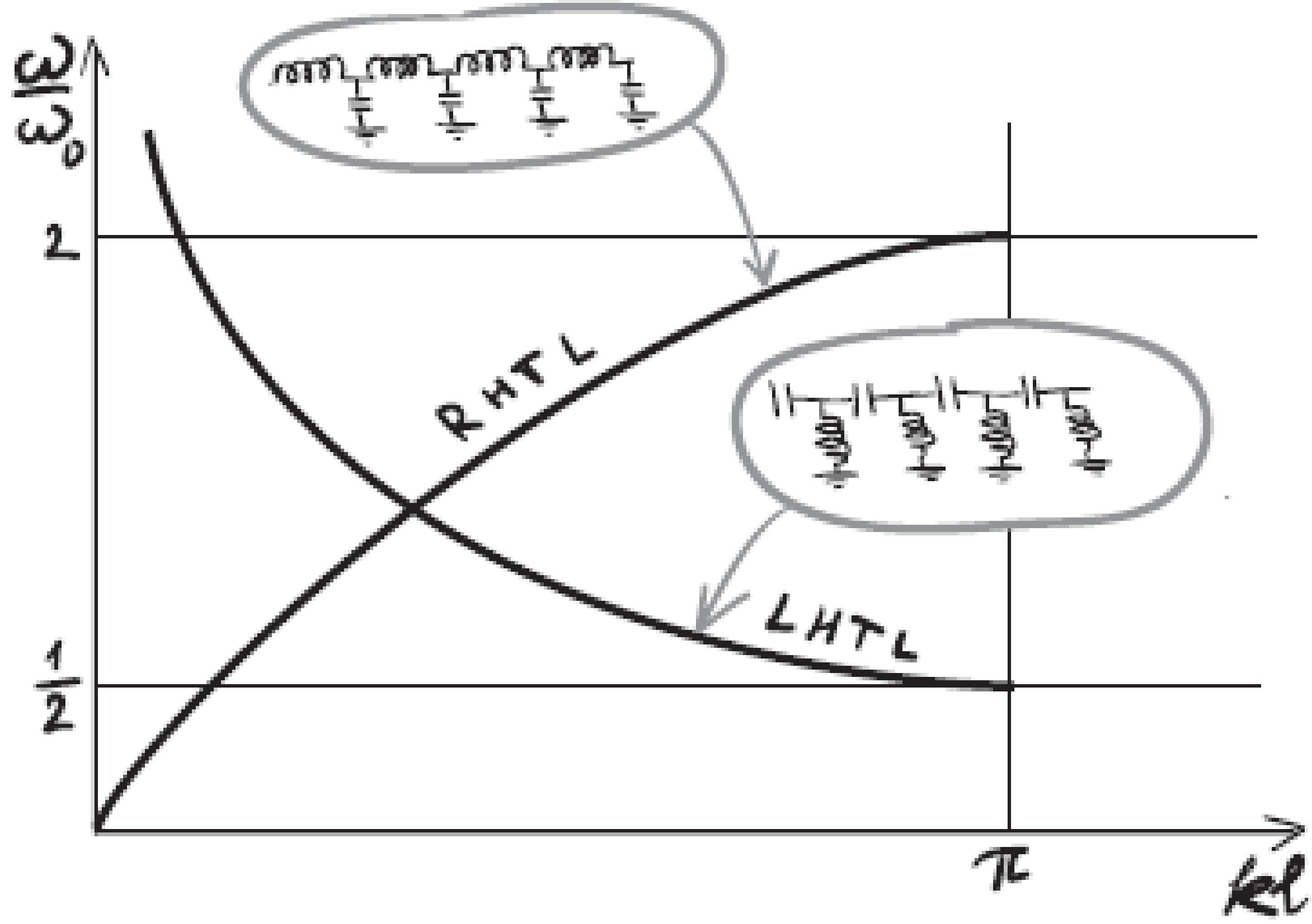
f_0 = 10.204 GHz

I_p = 195 nA

Astafiev, Zagoskin et al., Science (2010)

Elastic scattering





$$\omega^2(k) = \frac{2L_x^{-1}(1-\cos kl) + L_y^{-1}}{2(C_x/c^2)(1-\cos kl) + C_y/c^2}$$

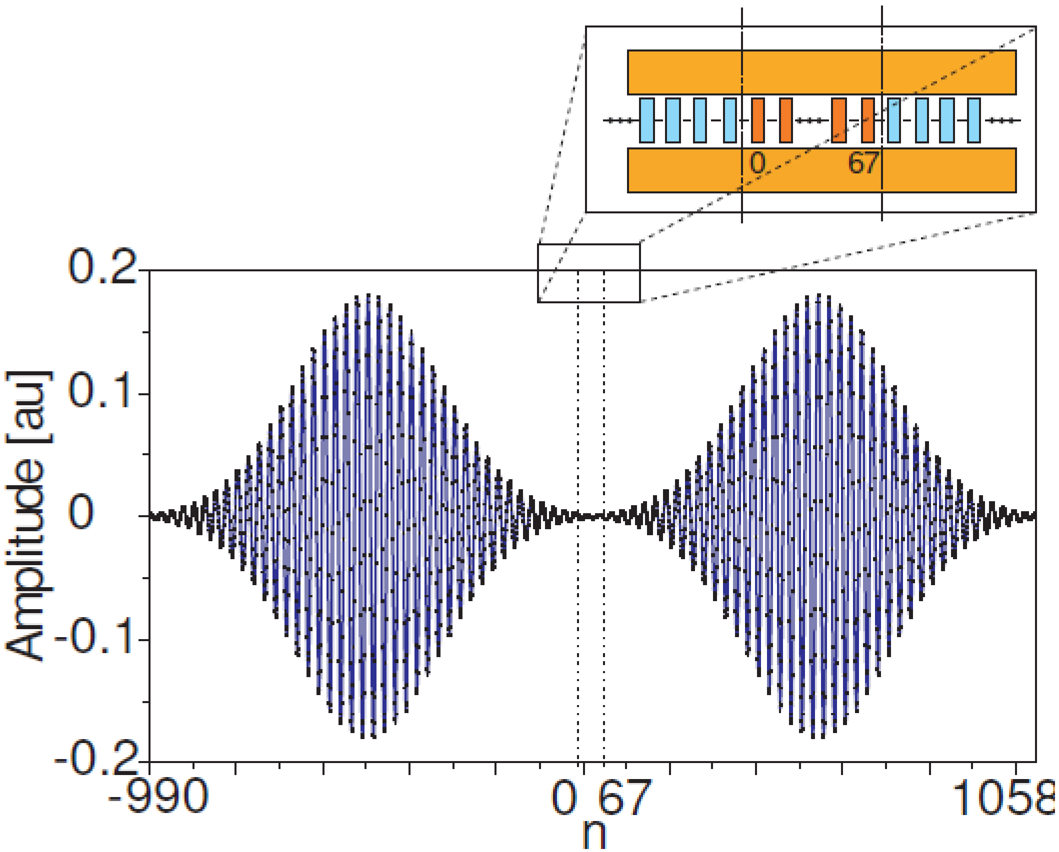
“Ambidextrous quantum metamaterial”

$$(\mathrm{RHTL}):\ \frac{L_x^{-1}}{L_y^{-1}} > \frac{C_x}{C_y};\ (\mathrm{LHTL}):\ \frac{L_x^{-1}}{L_y^{-1}} < \frac{C_x}{C_y}$$

$$2(1-\cos k_c l)\delta L_x^{-1} = -\delta L_y^{-1}$$

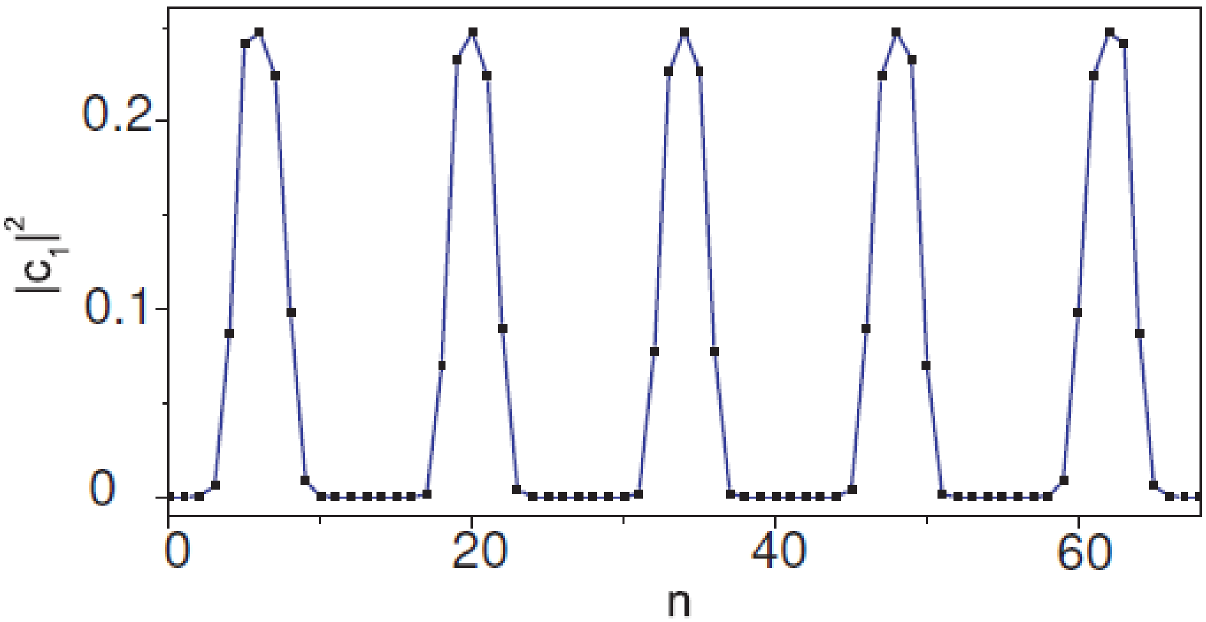
The system can be in a superposition of left- and right-handed states

Initialization of a1D quantum metamaterial



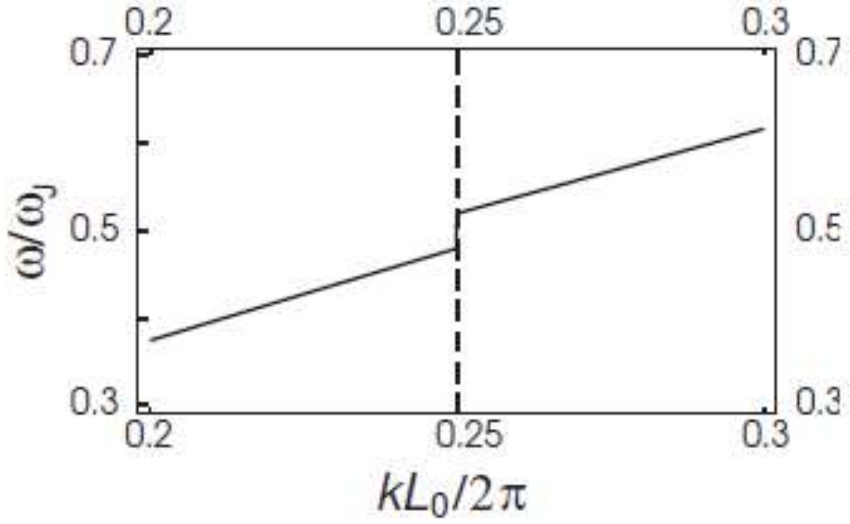
Shvetsov, Satanin, Nori, Saveliev and Zagoskin (2013)

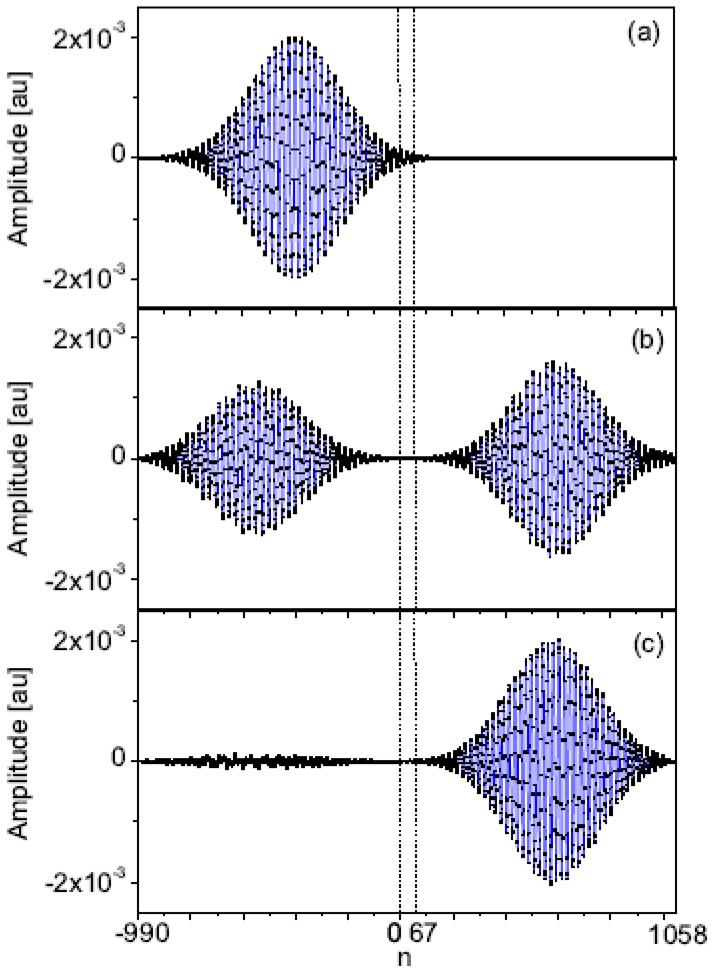
Initialization of a1D quantum metamaterial



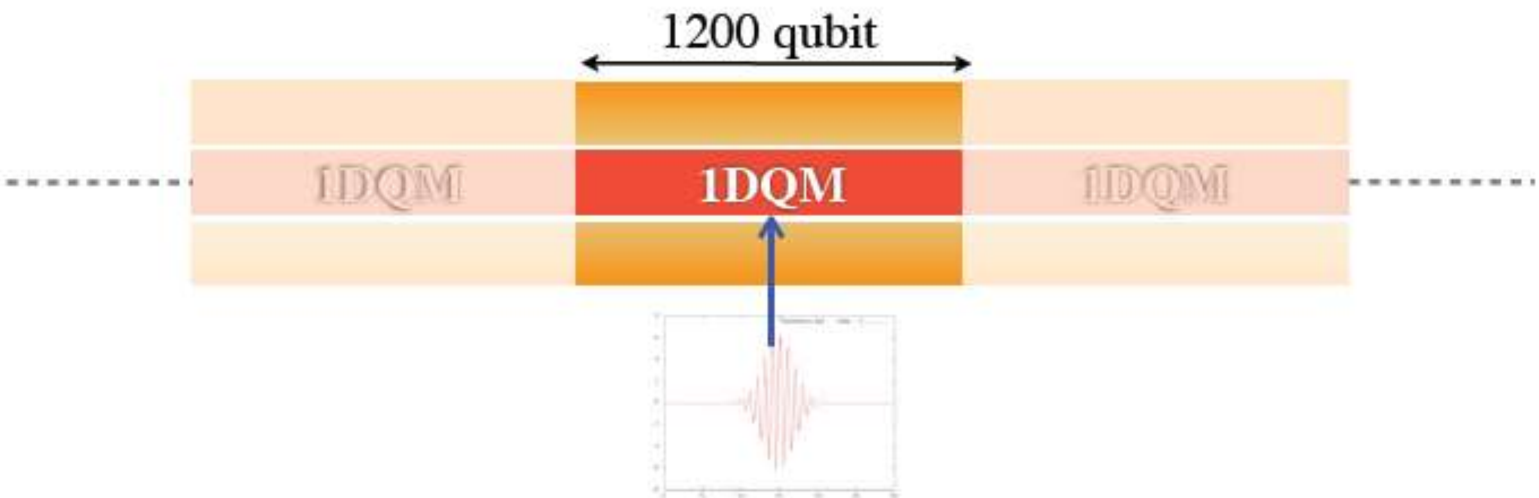
Shvetsov, Satanin, Nori, Saveliev and Zagoskin (2013)

Pulse propagation through the 1D metamaterial





Lasing in a 1D quantum metamaterial



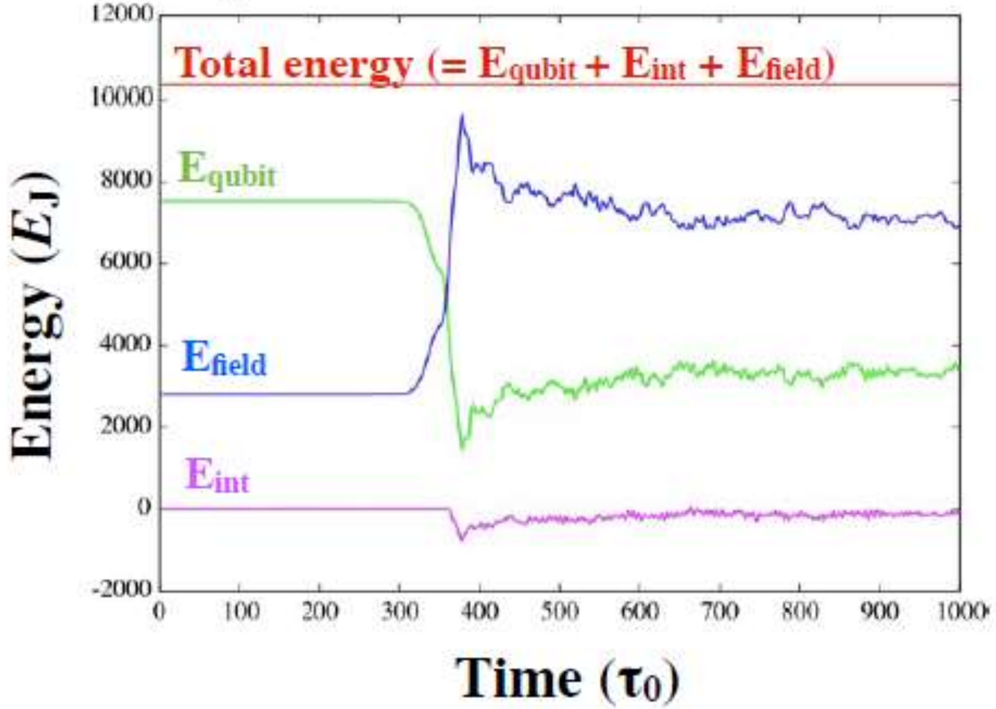
- We apply Gaussian pulse at the middle of the 1DQM.
- Initial condition: $C_1^n = 1,\ C_0^n = 0$ (all states are in the excited state)
- Boundary condition: Periodic boundary condition

$$a_{z,1} = a_{z,n},\ a_{z,0} = a_{z,n-1}$$

Asai et al. (2014)

Time evolution of energy

$$< \mathcal{H} >= E_J \sum_n \left(\langle \Psi_n^s | H_{n,0}^{qubit} | \Psi_n^s \rangle + \langle \Psi_n^s | H_{n,int}^{qubit} | \Psi_n^s \rangle + H_n^{EM} \right)$$



Energy transfer from Qubits to EM fields occurs around 300~400 τ_0.

Asai et al. (2014)

MIT Technology Review

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VIEW

Emerging Technology From the arXiv
September 30, 2013

World's First Quantum Metamaterial Unveiled

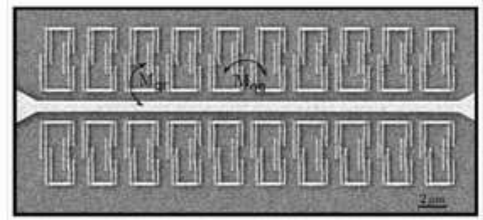
German researchers have designed, built, and tested the first metamaterial made out of superconducting quantum resonators.

LENTA.RU Наука и техника
15 ОКТЯБРЯ 2013, ВТОРНИК, 22:02

Все · Оружие · Гаджеты · Софт · Наука · Техника · Космос

20:35, 30 сентября 2013

Российские физики создали первый в мире квантовый метаматериал

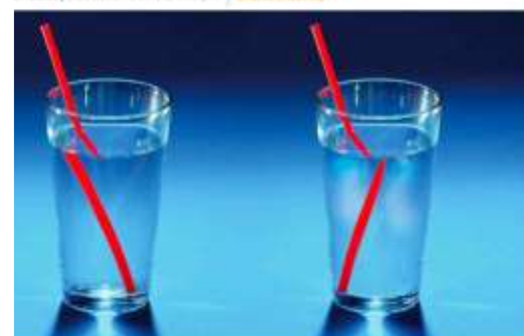


20 С-образных кубитов по обеим сторонам резонатора, электронная микрофотография
Изображение: Pascal Macha et al., 2013, arXiv:1309.5266

Российско-германская группа физиков под руководством Алексея Устинова из Российского квантового центра создала первый в мире
…атериал на основе твердотельных сверхпроводящих
…ание появилось в виде препринта в архиве Корнельского
…аботе также пишет блог Technology Review.

…first quantum metamaterial raises more …stions than it answers

9 Comments



…This Article

German material scientists have created the world's first quantum metamaterial. This new material

nature COMMUNICATIONS

ARTICLE

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Implementation of a quantum metamaterial using superconducting qubits

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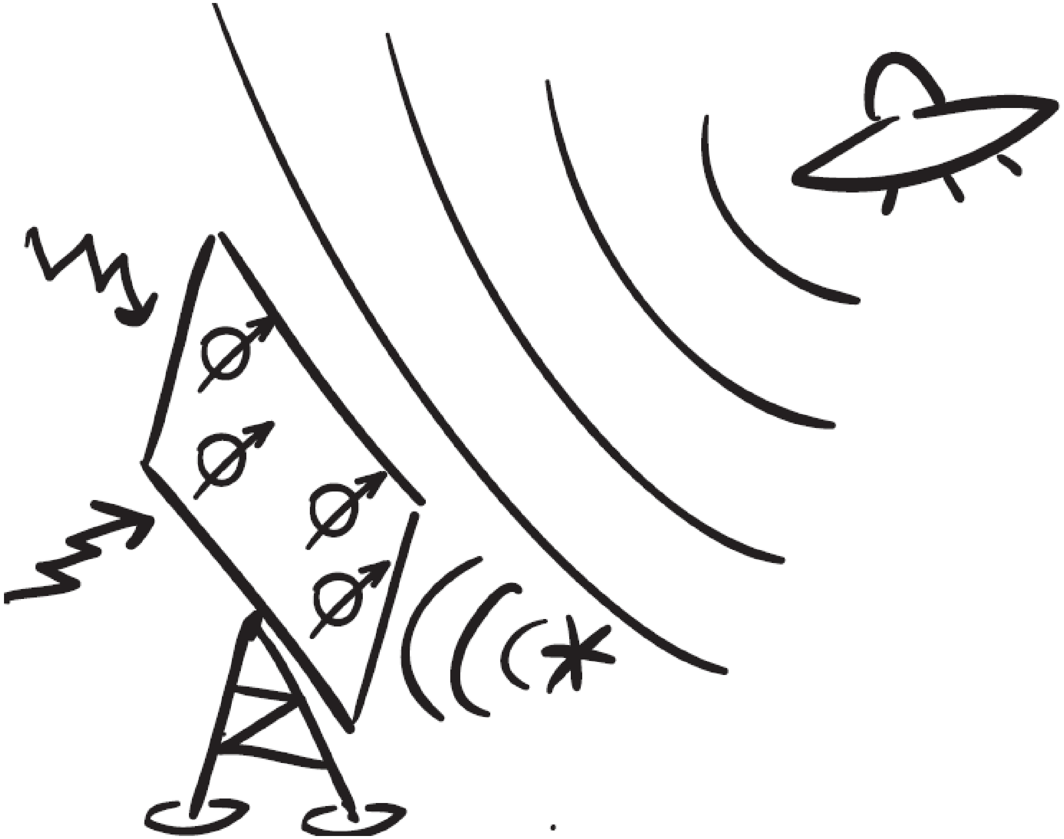
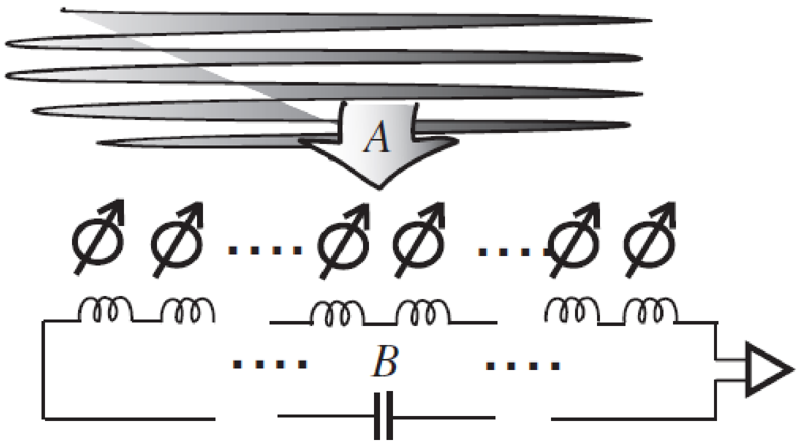
Detecting a single photon's wavefront



Zagoskin, Wilson, Everitt, Saveliev, Gulevich, Allen, Dubrovich and Il'ichev (Scientific Reports, 2013)

Model Hamiltonian



$$H = H_a + V_a + H_{qb} + V_b + H_b.$$

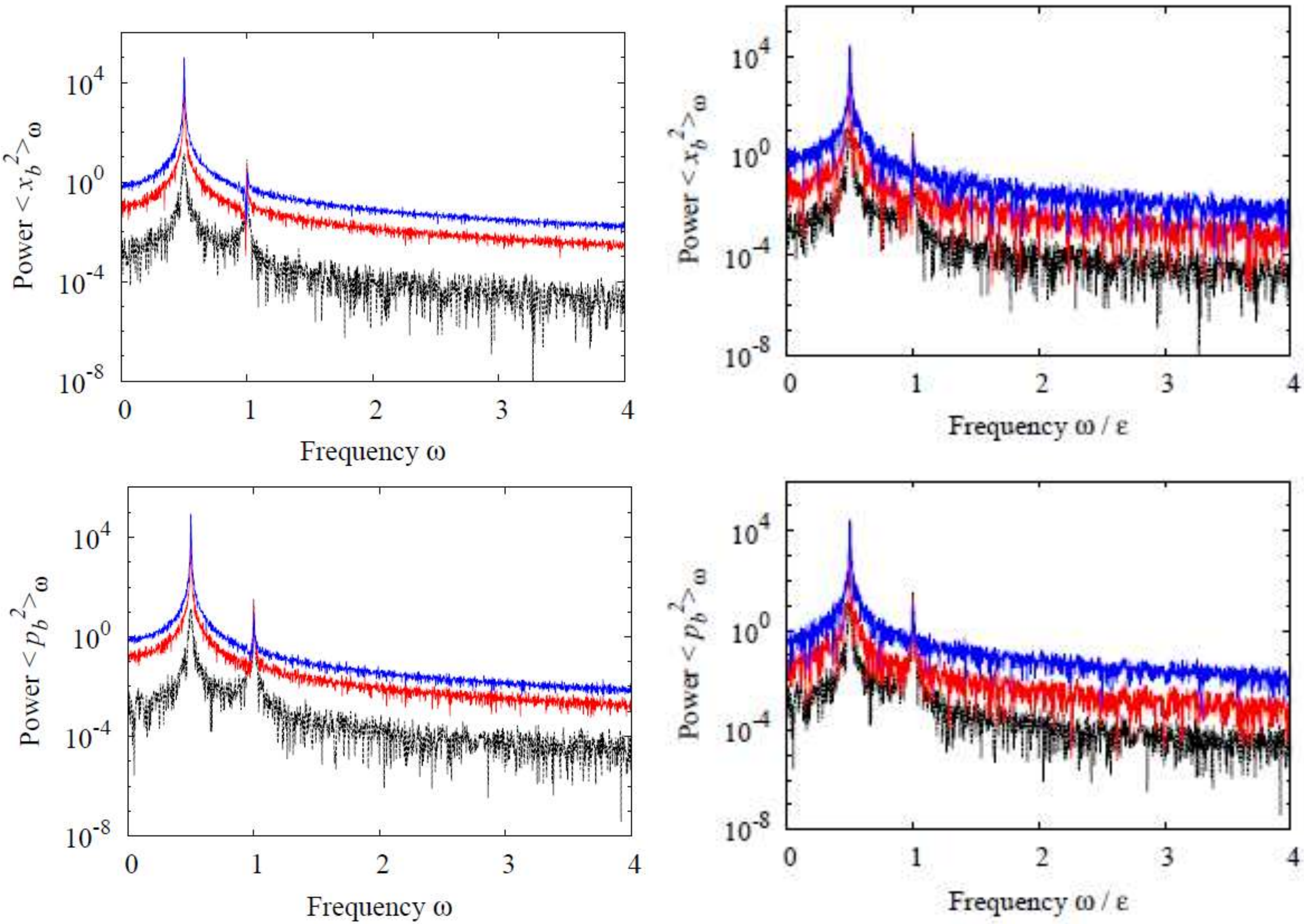
$$H_a = \omega_a(a^\dagger a + 1/2) + f(t)(a^\dagger + a)$$

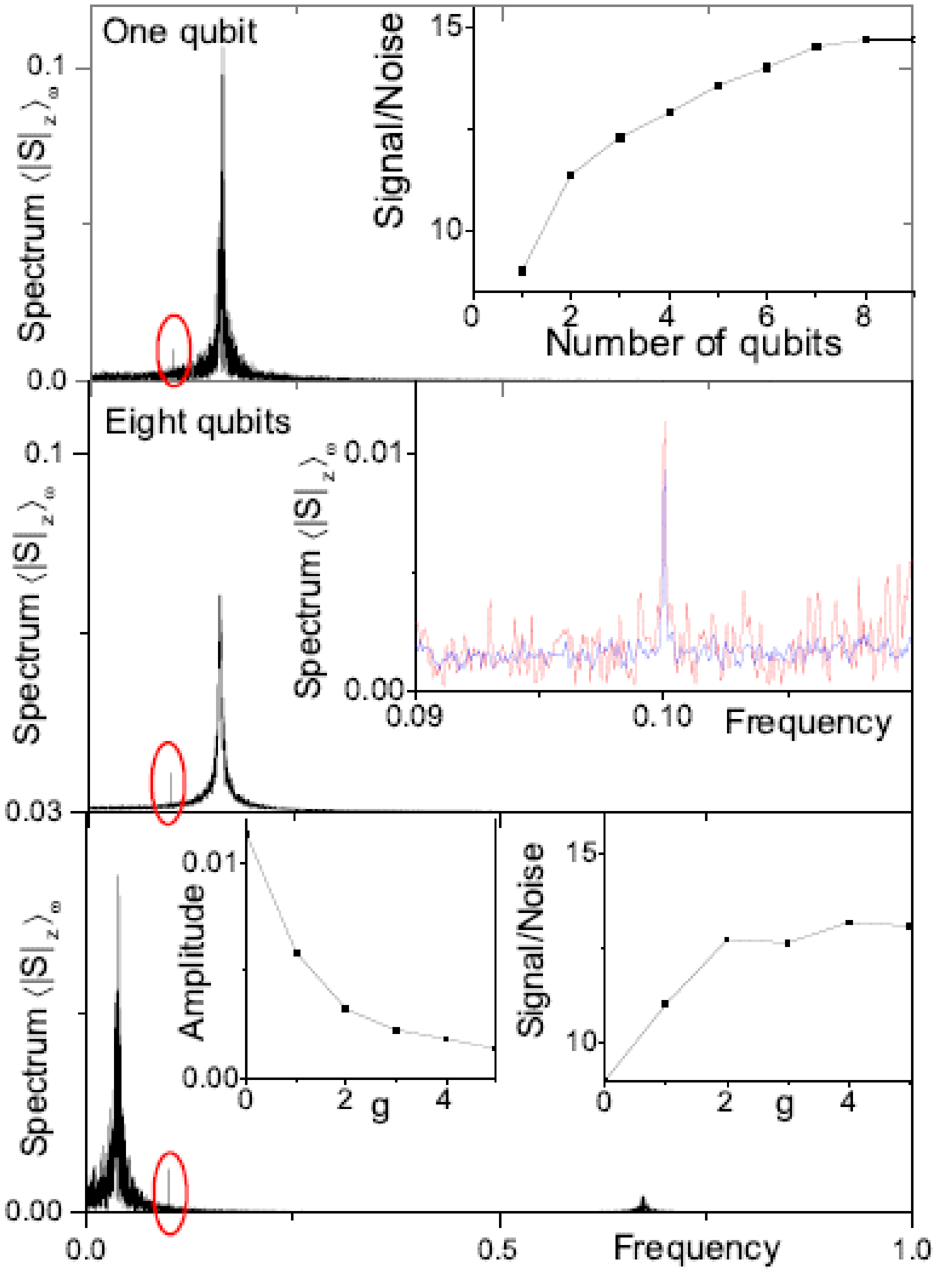
$$H_{qb} = \left(-\frac{1}{2}\right)\sum_{j=1}^{N}\left(\Delta_j \sigma_j^x + \varepsilon_j \sigma_j^z\right)$$

$$H_b = \omega_b(b^\dagger b + 1/2) + h(t)(b^\dagger + b)$$

$$V_a = \sum_j g_j^a (a^\dagger + a)\sigma_j^x, \;\; V_b = \sum_j g_j^b (b^\dagger + b)\sigma_j^x$$

Signal spectra for coherent (left) and Fock (right) input states




One qubit
Spectrum $\langle|S|_z\rangle_\infty$
0.1
0.0
Signal/Noise
15
10
0
2
4
6
8
Number of qubits
Eight qubits
0.1
0.03
Spectrum $\langle|S|_z\rangle_\infty$
0.01
0.00
0.09
0.10
Frequency
0.00
Amplitude
0.01
0.00
0
2
g
4
Signal/Noise
15
10
0
2
g
4
0.0
0.5
Frequency
1.0

“Quantum imaging algorithms”

(a) the original image I

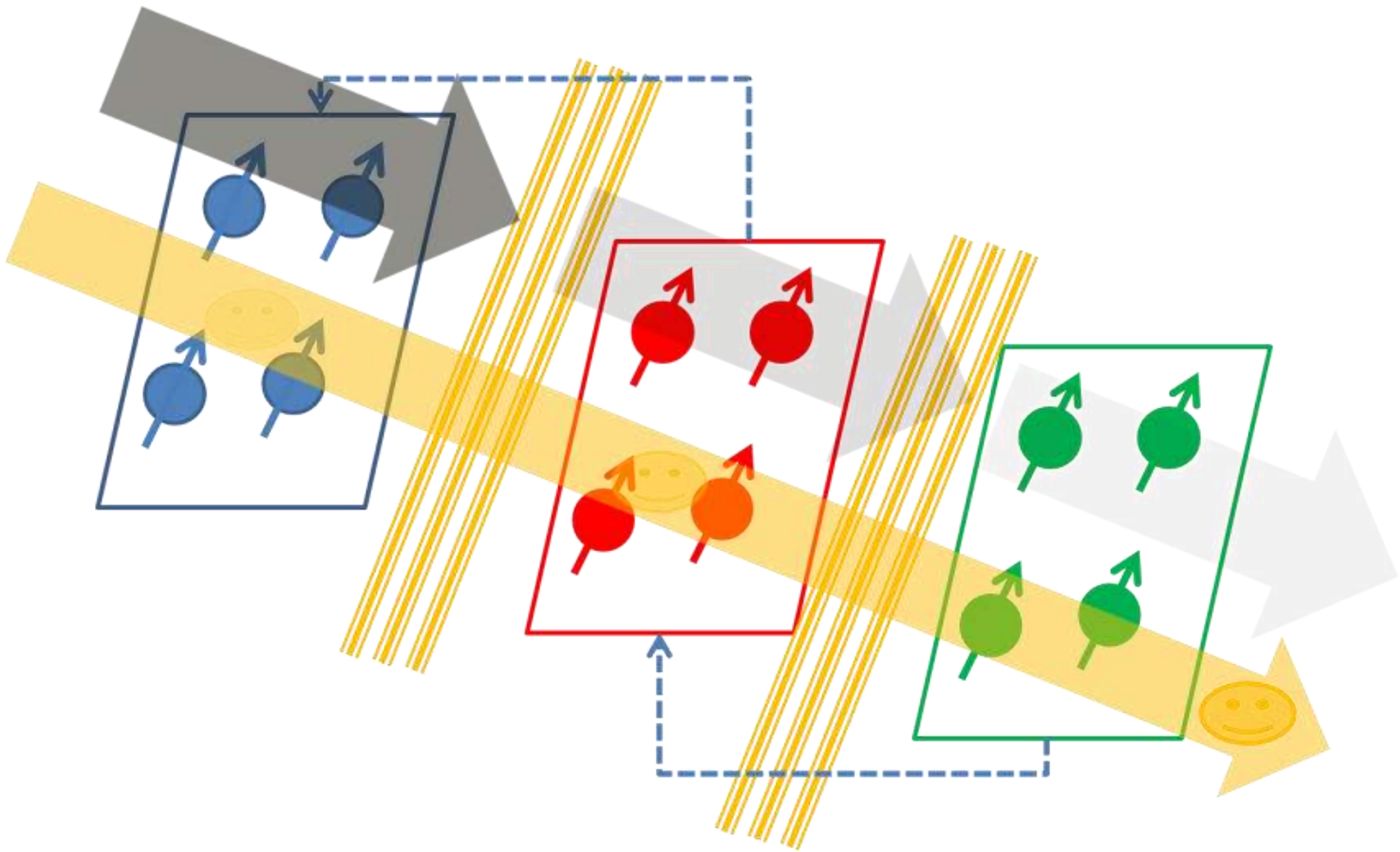
(b) noisy image, In = I+80*randn

(c) image post-processed via the Lindblad flow, T=18

(d) image after a longer run of post-processing, T=36

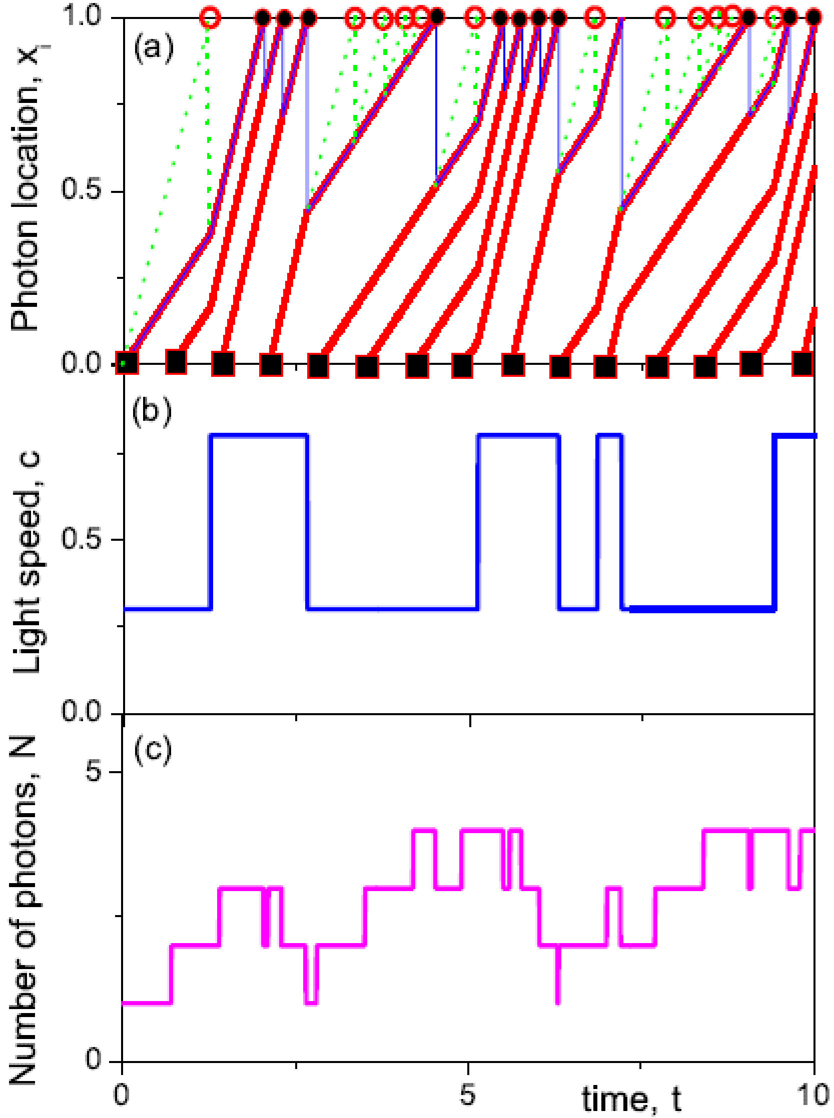
A. Sowa (2014)

Hardware implementation: “Quantum perceptron”



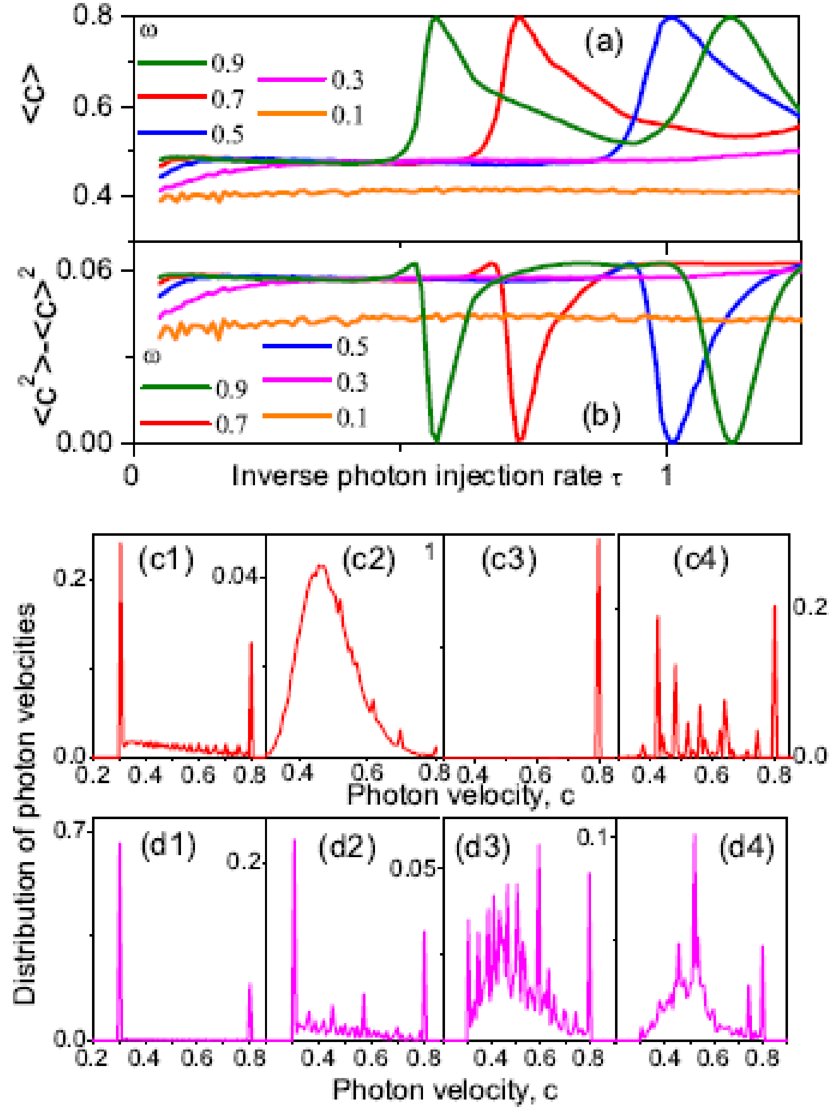
Rigid quantum metamaterials

- (Saveliev and Zagoskin)



Rigid quantum metamaterials

- (Saveliev and Zagoskin)



On-going research

- General theory of partially quantum coherent structures
  - Generalization of methods of quantum many-body theory
  - Dynamic scaling theory of partially coherent structures
    - Collaboration: Loughborough, Cambridge, Boston, Dresden (EPSRC grant, 2015-2018)

Plans

- Quantum metamaterials
  - 2D and 3D quantum metamaterials
  - Optical lattices-based quantum metamaterials
  - Ambidextrous 1D and 2D quantum metamaterials
  - Multifocal devices
  - Quantum limited detectors (including medical applications)
  - Quantum-classical transition research

Conclusions

- Research in quantum engineering (as applied to quantum metamaterials, adiabatic quantum computing and related areas) has the potential for both fundamental breakthroughs and developing disruptive new technologies, new IP and business opportunities

- The research bridges quantum information science, condensed matter physics, physics of metamaterials, quantum optics, and quantum physics, and is expected to have significant impact on chemical, biological and medical research and technologies

- Quantum engineering cannot yet be separated from science and can only be developed as a part and parcel of research of macroscopic quantum coherent systems