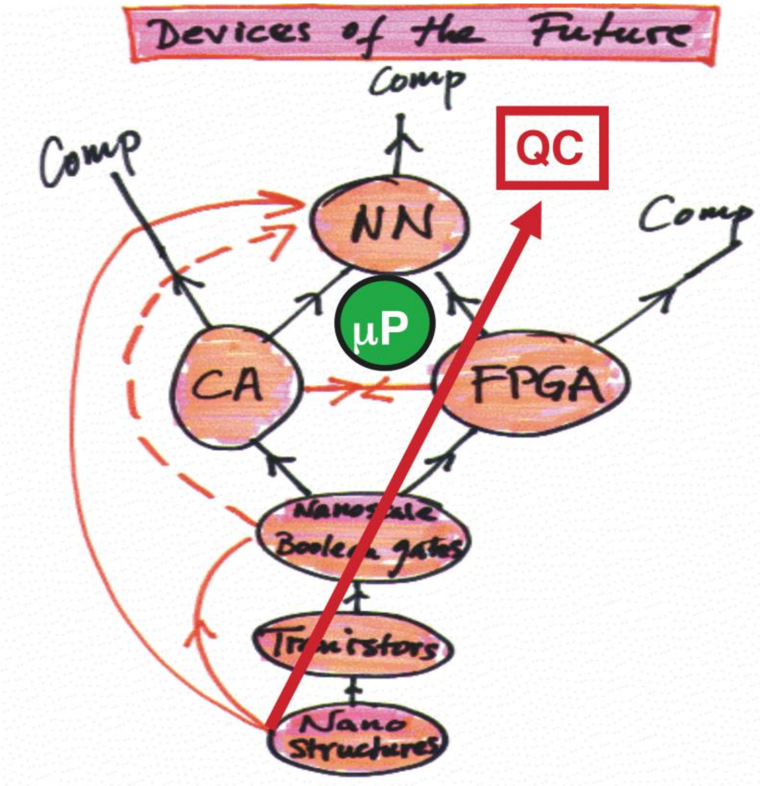
Solid State Quantum Computing



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About this presentation …..

(1) Overview of qubits

(2) Focus on solid-state qubits

(3) Focus on superconducting qubits

(4) Glimpse of a SWOT analysis

(5) Examples of the state of the art

(6) Detailed discussion of the SWOT table

(7) About quantum error correction

(8) Comments on previous benchmarking ….

(9) Comments on Flagship-type efforts …..

QIP main qubit concepts

QIP = Quantum Information Processing
4,5,6 = Solid-state QIP

(1) Ion qubits in electrostatic/dynamic traps

(2) Atom qubits in crossed-laser traps

(3) Spin qubits in molecules

(4) Quantum dots (QD)

(5) Spin qubits in solids

(6) Superconducting Josephson junction (JJ) qubits and circuits

(7) Photonic flying qubit circuits

Current status of QIP

There are no (solid-state) quantum computers - yet.

QIP experiments are going on with 10-15 (spin) qubits in molecules (NMR) and ion traps, and there is steady progress in many areas, but competitive QIP still far(?) away.

Focus on hybrid systems to profit from the best properties not found simultaneously in pure systems:
High speed (operation)
Long coherence time (memory)

Focus on quantum simulators (QS) to simulate static and dynamical properties of small physical and chemical systems with useful accuracy.

Current status of solid-state QIP

Solid-state systems may have an edge via technological scalabililty.

Solid-state qubits comprise: superconducting Josephson-junction (SC-JJ) based (charge, flux and phase), quantum dot (QD) (charge, spin), and impurities (electron spin and nuclear spin) in crystallites and in molecules.

[In principle one might add atoms and ions in solid-state microtraps.]

Present most successful approaches are **JJ-based Transmon qubit - resonator (cQED) systems (30 mK)** and **spin-based NV centers in diamond (300 K)**. The recent development is impressive and promising.

Solid-state QC – a first SWOT analysis

Strengths

- 2D/3D Cavity/circuit QED-cQED
- 3D Transmon qubits, T2≈100 μs
- [2D Transmon qubits, T2≈2-4 μs]
- Hybrid devices demonstrated
- No known physical barriers
- Microwave engineering problem
- **Technological scalability**

Weaknesses

- All DiVincenzo criteria not yet fulfilled
- Coherence time still too short
- Only 5-10 qubit systems in the near term
- **Scaling of comput. functionality unknown**
- Limited number of useful problems
- Long-term evolution needed
- Efficient QEC still in the future
- Solid-state systems way behind ion traps

Opportunities

- To engineer a small functional QS
- To implement the surface code and demonstrate QEC
- To implement optimal control
- To develop a multi-qubit QS that beats a classical computer.
- To develop classical-quantum hybrid/embedded systems
- To develop generic QIP
- To establish Q-technologies

Threats

- QEC cannot be implemented in practice
- QIP applications have no practical importance
- QS cannot cannot beat classical computers
- QIP/QS remain advanced scientific "toys"

Present focus areas

- **Teleportation**
- **Measurement-based feedback and feed-forward**
- **Quantum error correction**
- **Simulation of quantum system**

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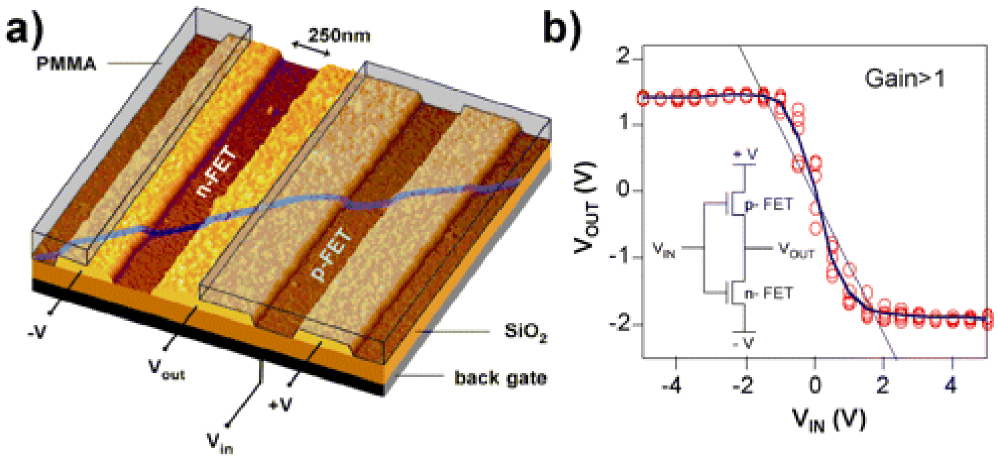
The next 4-5 years may be decisive

Great progress can be expected

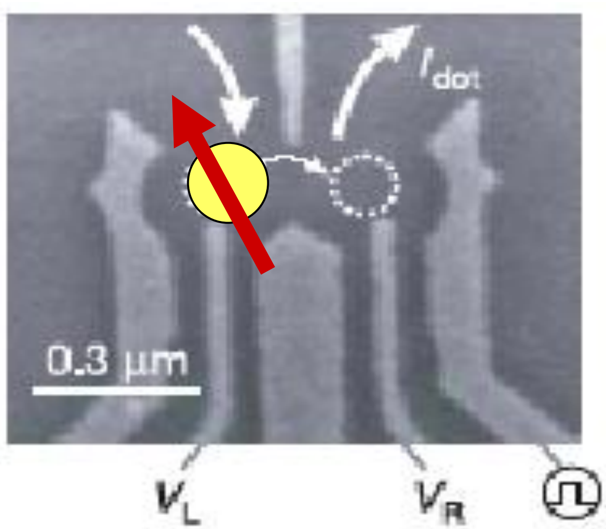
May reveal the timescale for competitive QIP:

5-10-20-50-…. years ??

Classical vs Quantum bits



Logic levels
"0" and "1"
Low/high voltages
V0/V1

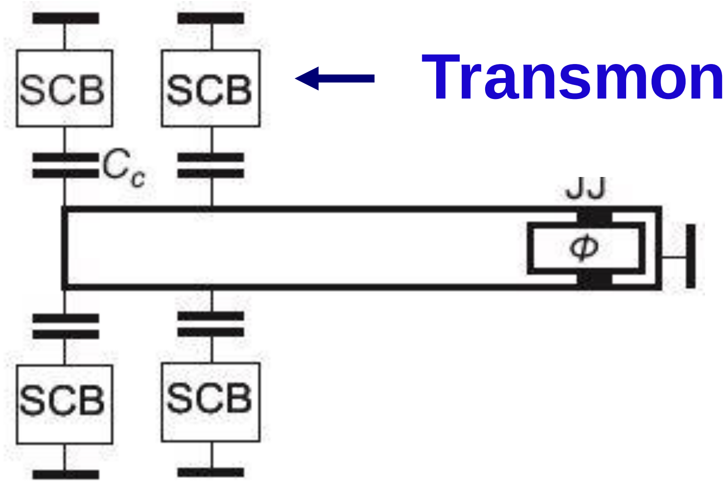


Logic levels
|0> and |1>
Quantum energy levels, states

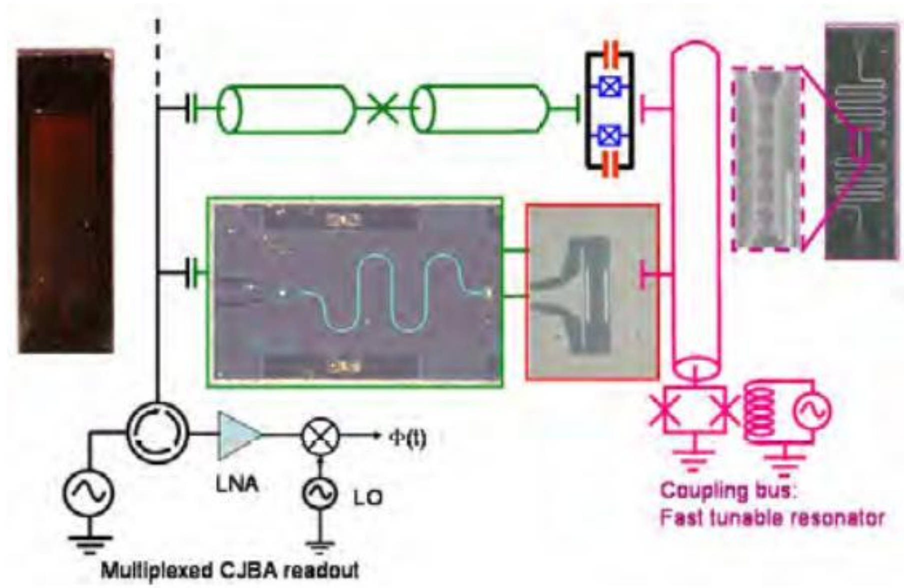
E1, |1>

E0, |0>

JJ core technologies



Transmon



2-level system:

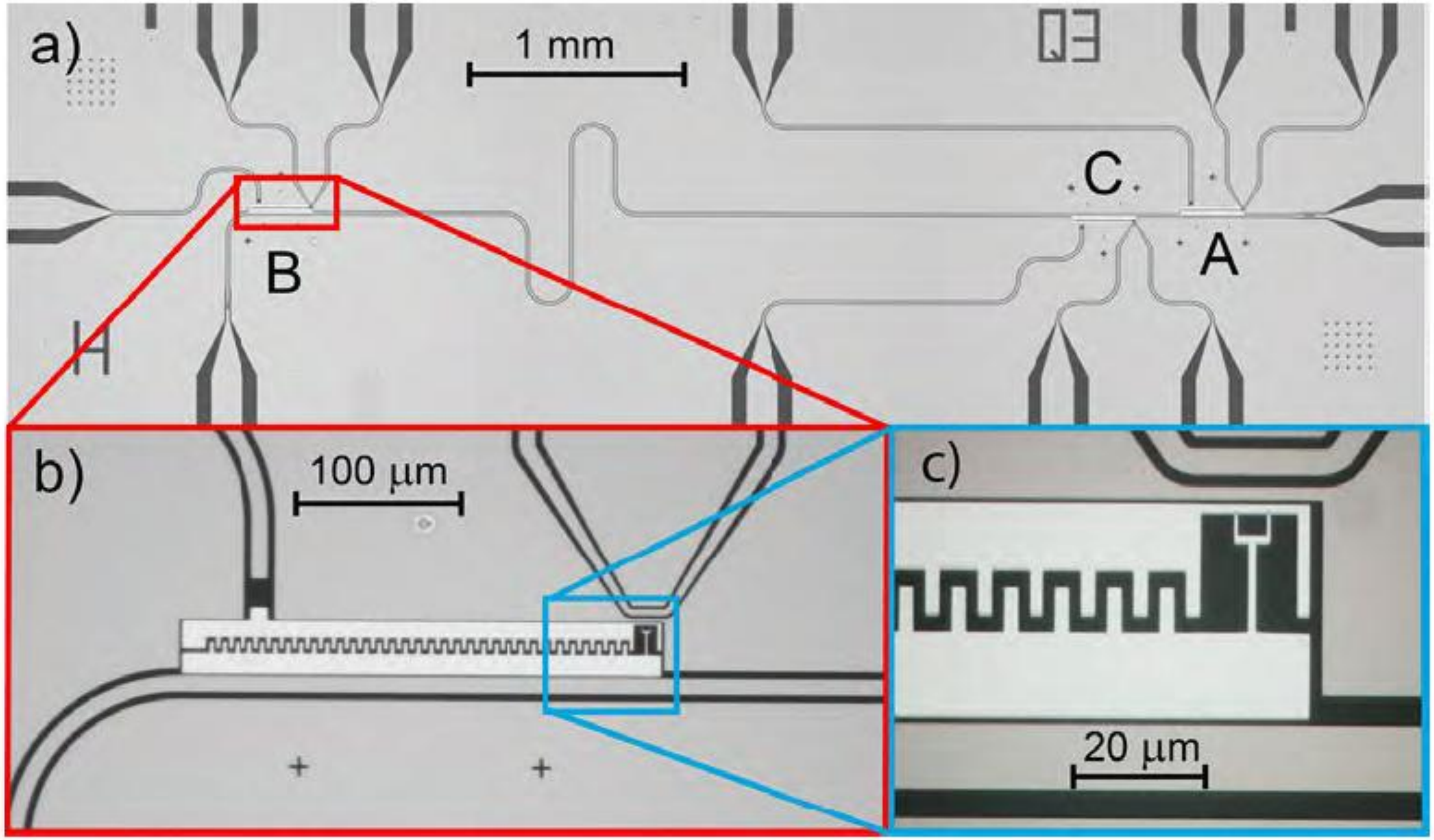
Superposition state: $|\psi\rangle = a_0\,|0\rangle + a_1\,|1\rangle$

N qubits -->> Superposition of 2^N eigenstates:
Multi-qubit configuration interaction (CI)

$$|\psi\rangle = a_0\,|0..00\rangle + a_1\,|0..01\rangle + a_2\,|0..10\rangle + a_3\,|0..11\rangle + \ldots + a_{(2^N-1)}\,|1..11\rangle$$

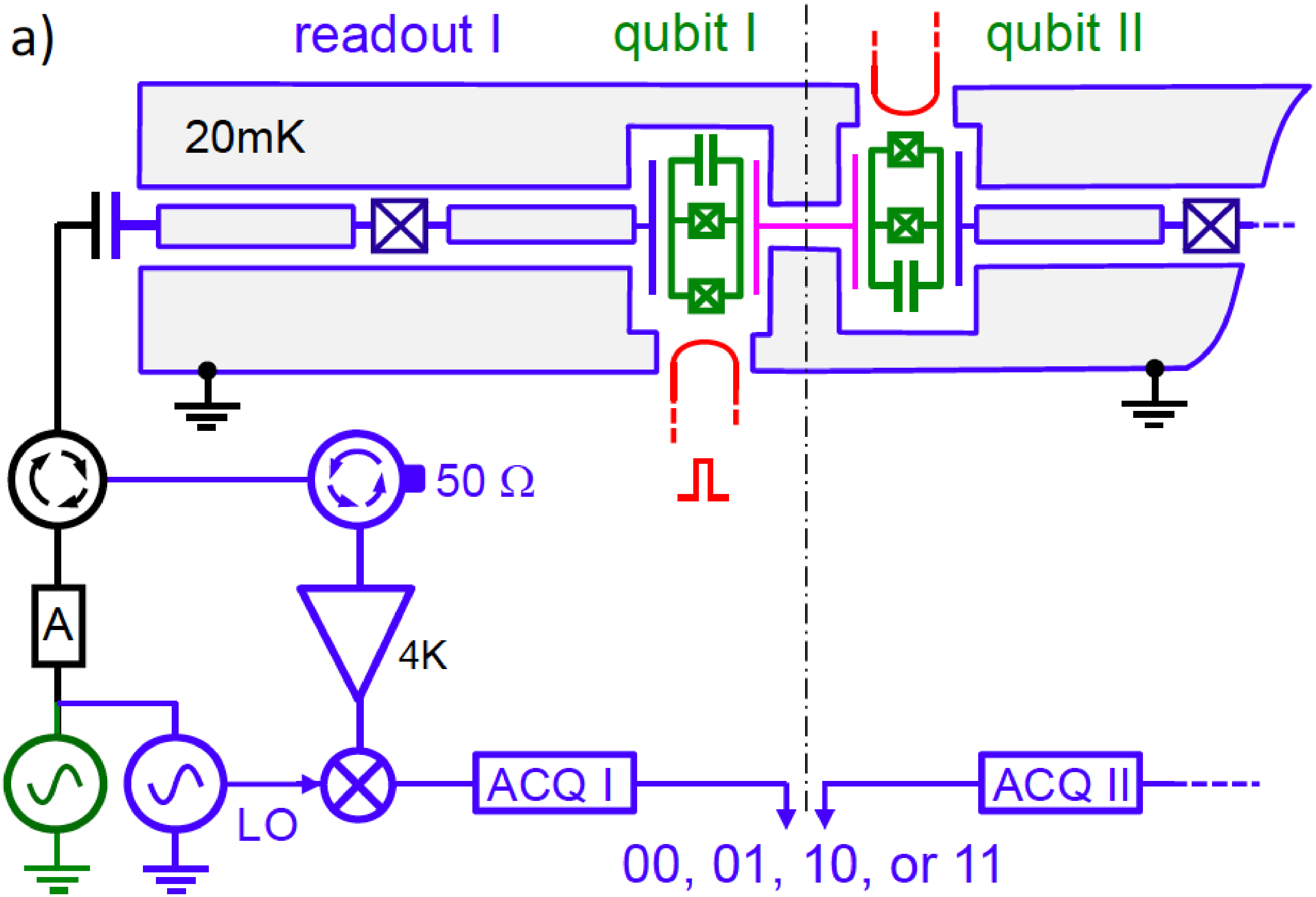
Coherent N-bit memory
Parallellism (superposition) and entanglement (non-product state)

JJ core technologies



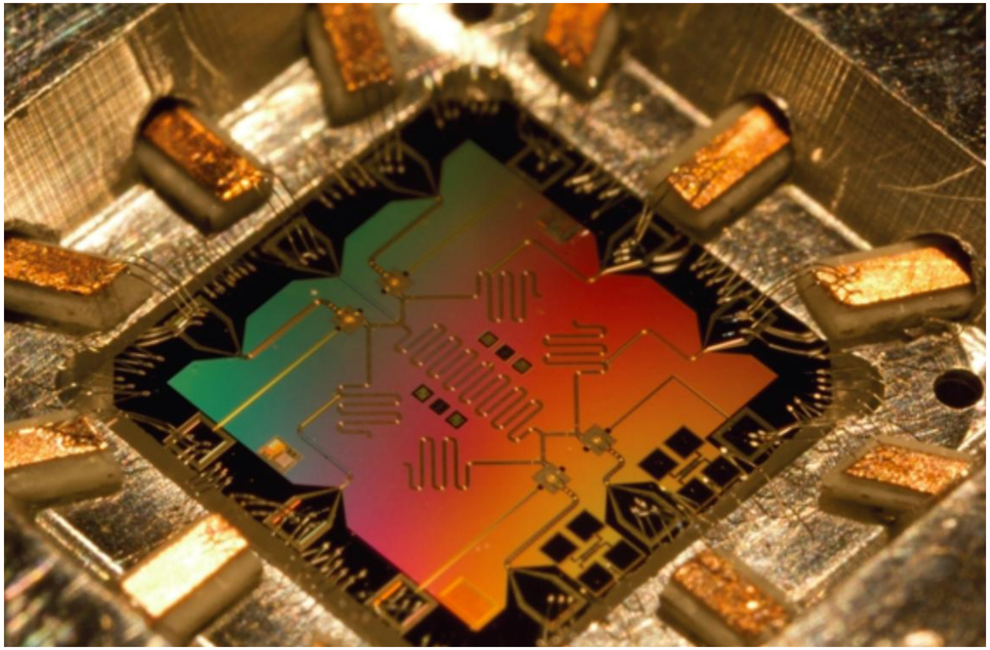
Wallraff group, ETH, Zürich (2011)

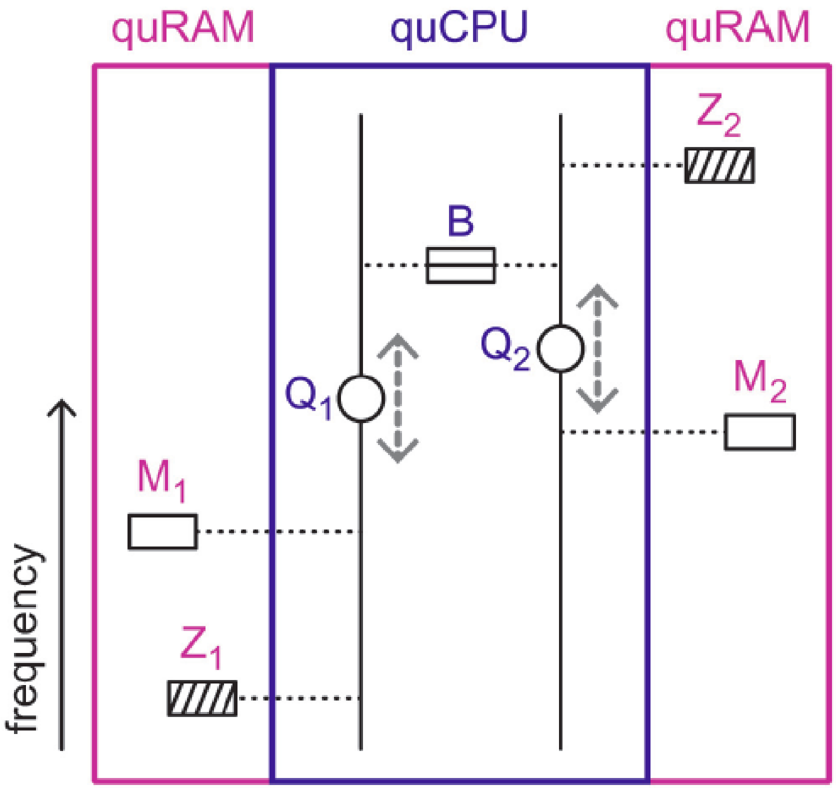
JJ core technologies



Quantronics group, CEA-Saclay, France (2011)

JJ core technologies – phase qubits



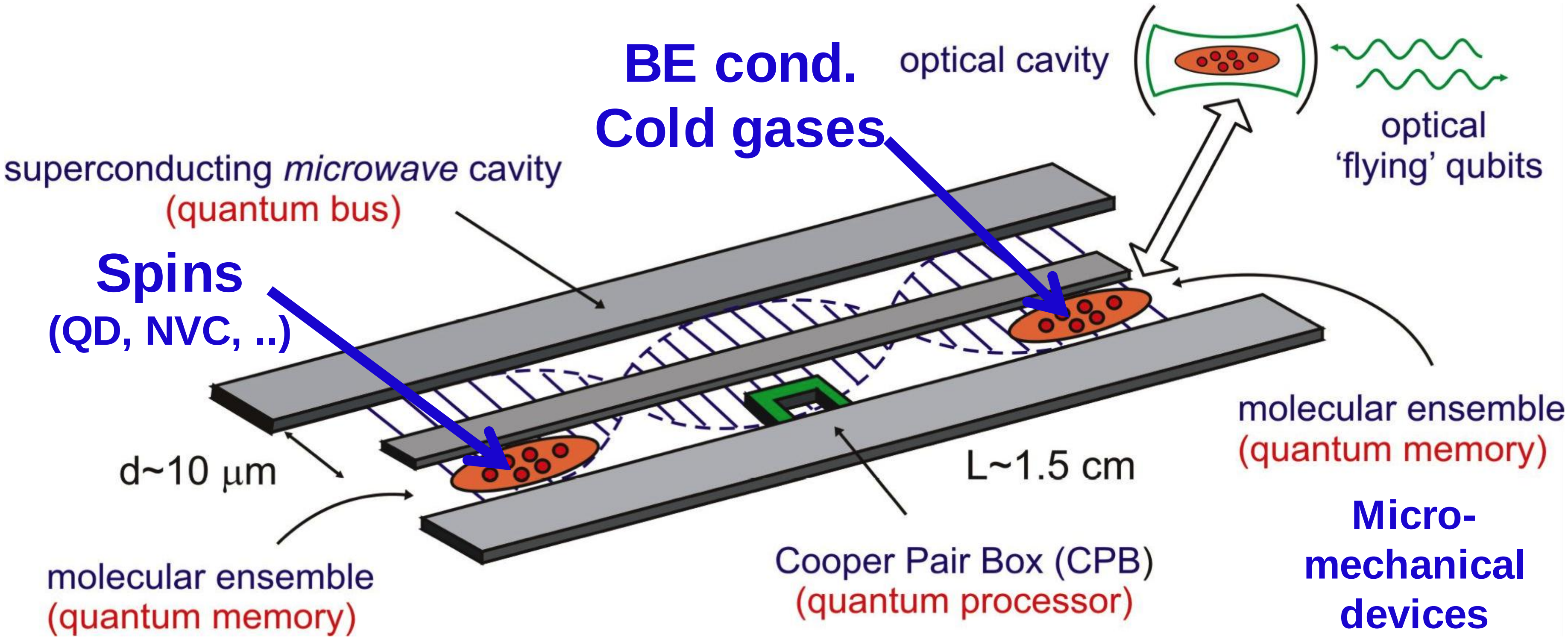


Qubits: phase qubits
Memory: high-Q resonators
Switchable couplings

Martinis group, UCSB, CA, USA (2011)

Hybrid devices

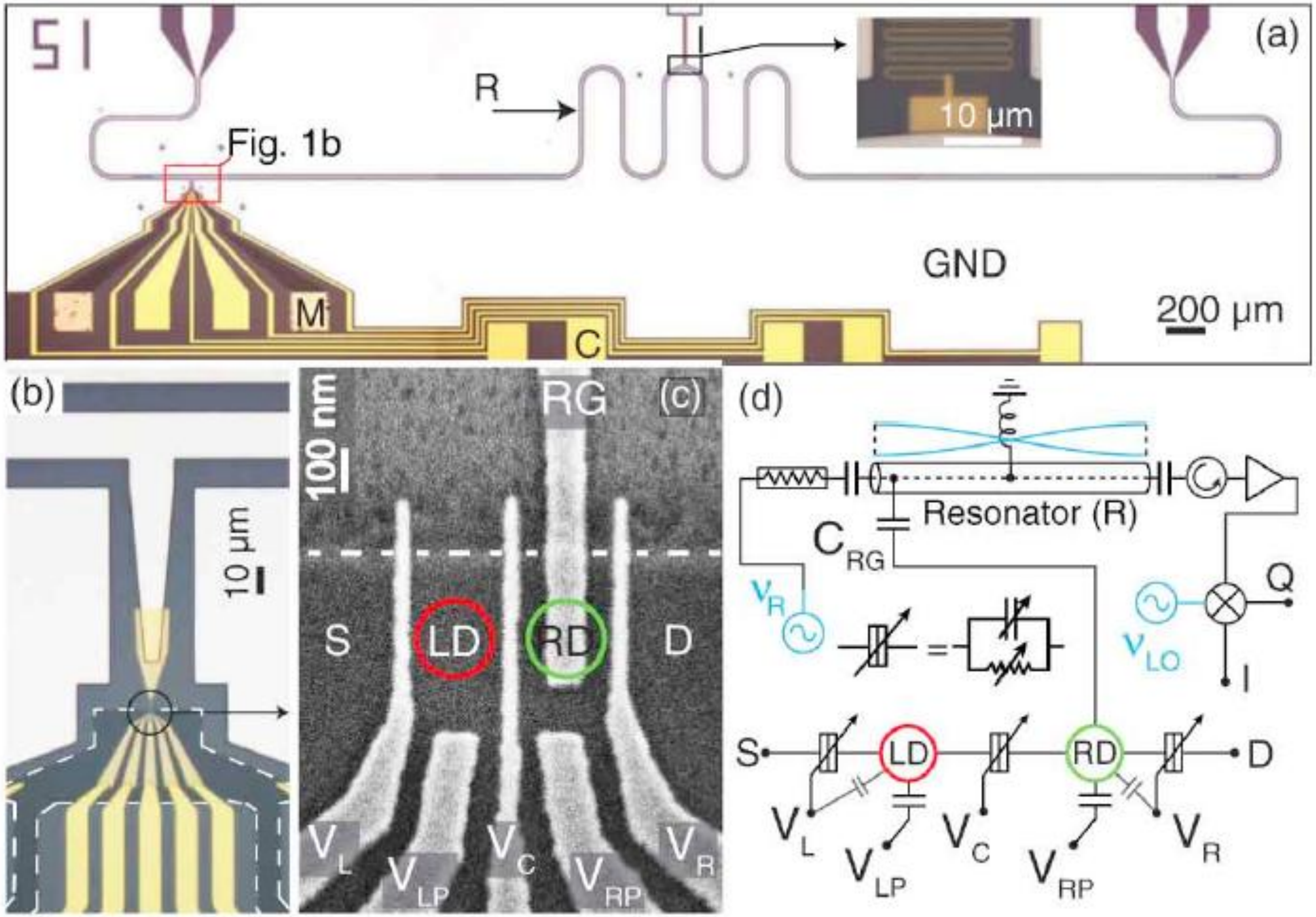
Processing - memory - communication – collaboration
The only realistic option for non-toy QIP ?



Josephson junctions (JJ)

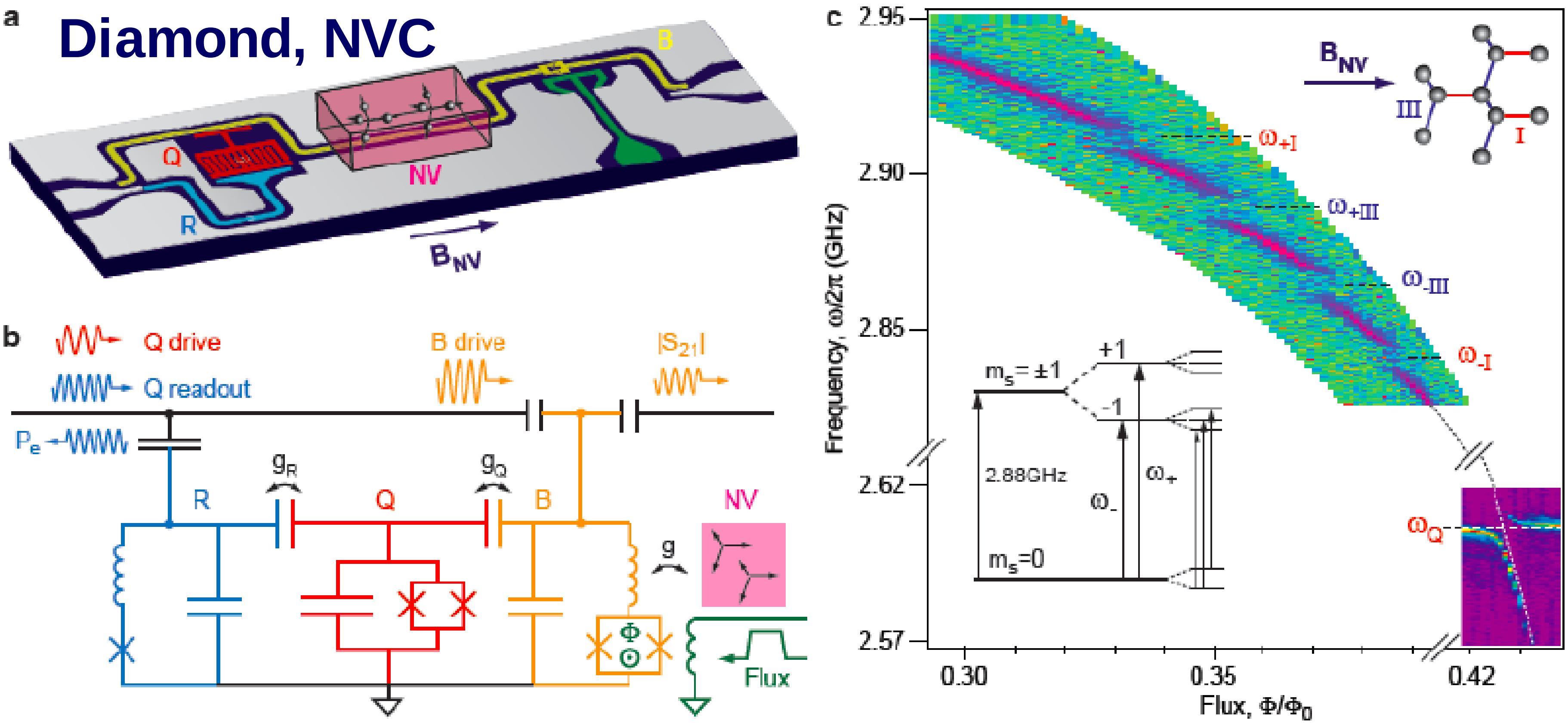
Picture adapted from Peter Zoller et al.

QIP hybrid devices, state of the art



Wallraff/Ensslin groups, ETH, Zürich (2011)

QIP hybrid devices, state of the art



Quantronics group, CEA-Saclay, France (2011)

Diamond, NVC for RT QIP: Wrachtrup group, Stuttgart; Hanson, Delft; Lukin group, Harvard; Awschalom group, UCSB; ….

Solid state of the art of Q-algorithms

Bell states	Martinis' group, UCSB
State tomography	Schoelkopf's/Devoret's group, Yale
Gate tomography	Wallraff's group, ETH, Zürich
Bell inequalities	Quantronics group, CEA-Saclay
GHZ/W states	IBM, Yorktown Heights
Deutsch-Jozsa	Wrachtrup's group, Stuttgart (Diamond, NVC)
Grover	Lukin's group, Harvard (Diamond, NVC)
Measurement-based state initialization	L. DiCarlo et al., Delft
Measurement-based feedback	

Solid-state QC –SWOT analysis

Strengths
- 2D/3D Cavity/circuit QED-cQED
- 2D Transmon qubits, T2≈5 μs
- 3D Transmon qubits, T2≈100 μs
- Hybrid devices demonstrated
- No known physical barriers
- Microwave engineering problem
- Nanofabrication, e-beam litho
- Technological scalability

Weaknesses
- All DiVincenzo criteria not yet fulfilled
- Coherence time still too short
- Only 5-10 qubit systems in the near term
- No generic computational functionality
- Limited number of useful problems
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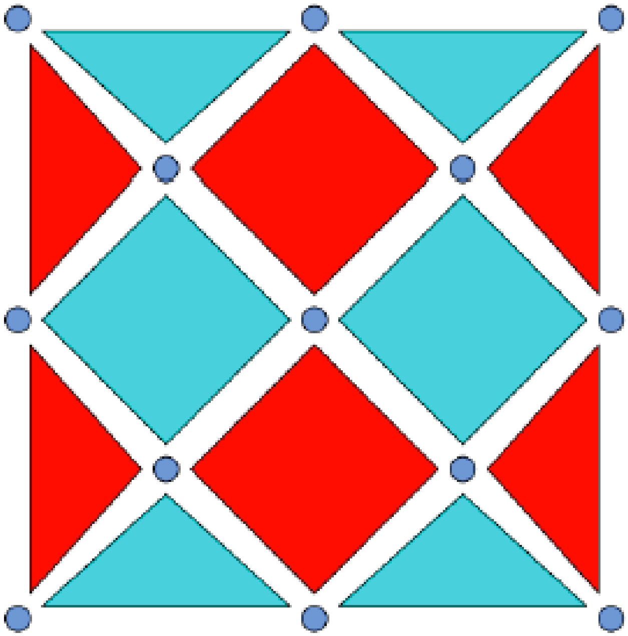
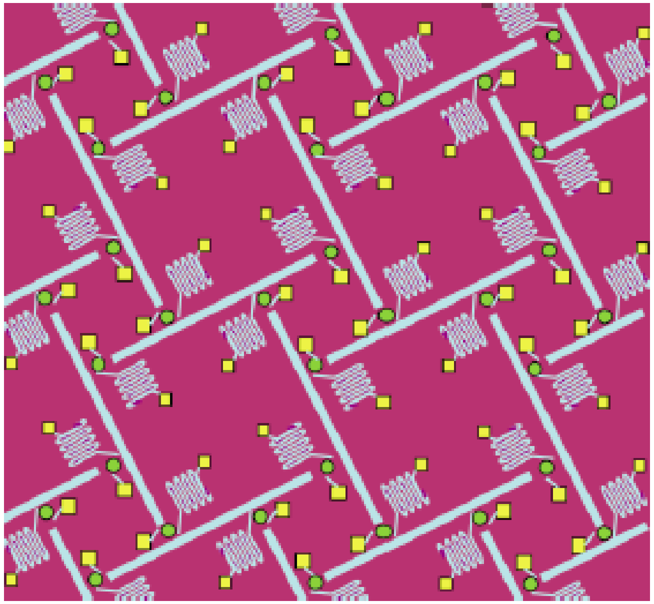
Threats
- QEC cannot be implemented in practice
- Coherence time too short for implementation of the measurements and operations needed to maintain coherence and to produce meaningful computation/simulation
- QIP applications have no practical importance
- QS cannot cannot beat classical computers
- QIP/QS remain advanced scientific “toys”

The million dollar question …..

Will the surface code make QEC possible?

13 qubits + acillas; 4-qubit parity measurements





From D. DiVincenzo (2009)
A US collaboration (IBM and others) are determined to develop and test this approach within 4 years

QIP qubit devices, state of the art

	JJ Tmon Transmon	JJ Fx Flux	JJ Phs Phase	QD spin GaAs	NVC spins diamond	Ion trap
Qubit # operated	4	4 (80)	3	2	3 (6)	14
1q gates	Yes	Yes	Yes	Yes	Yes	Yes
T1 (relaxation)	2 μs	1 μs [3]	0.6 μs [5]	1 s	100 s	~1 s
T2 (decoherence)	2 μs			1 μs	2 ms	~1 ms
$T2_{Echo}$	5 μs	20 μs [18]	0.3 μs [5]	1 μs	2 ms	~1 s
T2 (3D)	95 μs					
T_{op}, *1q*	1 ns	1 ns		50 ns 4 ps (optical)	3 ns	μs
2q gates	Yes	Yes	Yes	Yes	Yes	Yes
T_{op}, *2q*	1-2 ns	1-2 ns	1-2 ns	200 ps	1 μs	μs
Nq direct coupling	2	2	3	2	> 3	> 8
Nq-CPW/resonator coupling (cQED)	3-4	?	?	0	0	0
Readout	Cavity, disp Osc, disp Fidelity for 1q >>98%	Osc, disp Osc, switch Fidelity for 1q >> 90%	Direct Osc, disp	Electrical Fidelity 1q > 98% Also optical	Optical	Optical
Nq individ readout	4	?	3	2	1 ?	?

QIP algorithms, state of the art

	JJ Tmon Transmon	JJ Fx Flux	JJ Phs Phase	QD spin GaAs	NVC spins diamond	Ion trap
Interfacing	Tmon-CPW-NVC	?	Phs-CPW	spin-photon	CPW-NVC	
Hybrid devices	None	None	None	None	None	None
Technological scalability	Yes	Yes	Yes?	Unknown	Yes?	Unknown
Computational scalability	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Bell state	Yes	Yes	Yes	No	Yes	Yes
State tomography	Yes	No	Yes	No	Yes	Yes
Gate tomography	Yes	No	Yes	No	Yes	Yes
Bell inequalities	Yes	No	Yes	No	Yes	Yes
GHZ, W states	Yes	No	Yes	No	Yes	Yes
Deutsch-Jozsa	Yes	No	Yes?	No	No ?	Yes
Teleportation	No	No	No	No	No	Yes
Grover (Search)	Yes	No	No	No	No	Yes
Shor (Factorization)	No	No	No	No	No	QFT
QEC (Quantum Error Correction)	Yes (1 step)	No	No	No	No	Yes (3 steps)