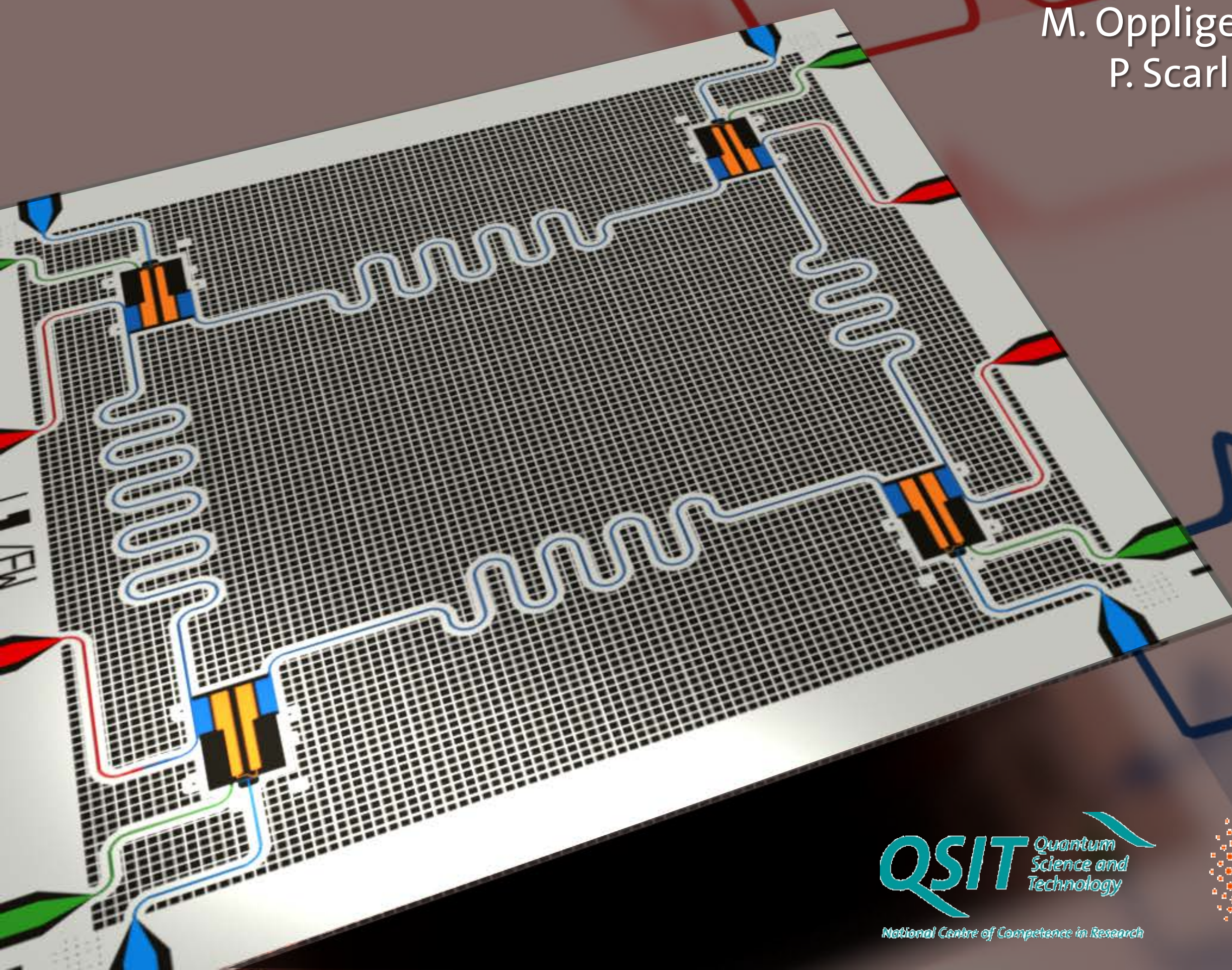
Quantum Physics with Superconducting Qubits

Andreas Wallraff *(ETH Zurich)*
www.qudev.ethz.ch

Science Team:
J.-C. Besse, M. Collodo, S. Garcia, S. Gasparinetti,
J. Heinsoo, S. Krinner, P. Kurpiers, P. Magnard
M. Oppliger, M. Pechal, A. Potocnik, Y. Salathe,
P. Scarlino, M. Stammeier, A. Stockklauser,
T. Thiele, T. Walter
Technical Team:
M. Frey, T. Hofmaenner, J. Luetolf
(ETH Zurich)



FN SNF
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QSIT Quantum Science and Technology
National Centre of Competence in Research
erc
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Former group members now
Faculty/PostDoc/PhD/Industry

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M. Allan (Leiden)
M. Baur (ABB)
J. Basset (U. Paris Sud)
S. Berger (AWK Group)
R. Bianchetti (ABB)
D. Bozyigit (MIT)
C. Eichler (Princeton)
A. Fedorov (UQ Brisbane)
A. Fragner (Yale)
S. Filipp (IBM Zurich)
J. Fink (IST Austria)
T. Frey (Bosch)
M. Goppl (Sensirion)
J. Govenius (Aalto)
L. Huthmacher (Cambridge)
D.-D. Jarausch (Cambridge)
K. Juliusson (CEA Saclay)
C. Lang (Radionor)
P. Leek (Oxford)
P. Maurer (Stanford)
J. Mlynek (Siemens)
M. Mondal (Johns Hopkins)
M. Pechal (Stanford)
G. Puebla (IBM Zurich)
A. Safavi-Naeini (Stanford)
L. Steffen (AWK Group)
T. Thiele (UC Boulder)
A. van Loo (Oxford)
S. Zeytinoğlu (ETH Zurich)

Collaborations with (groups of):

A. Blais (Sherbrooke)
C. Bruder (Basel)
M. da Silva (Raytheon)
L. DiCarlo (TU Delft)
K. Ensslin (ETH Zurich)
J. Faist (ETH Zurich)
J. Gambetta (IBM Yorktown)
K. Hammerer (Hannover)
T. Ihn (ETH Zurich)
F. Merkt (ETH Zurich)
L. Novotny (ETH Zurich)
T. J. Osborne (Hannover)
B. Sanders (Calgary)
S. Schmidt (ETH Zurich)
R. Schoelkopf (Yale)
C. Schoenenberger (Basel)
E. Solano (UPV/EHU)
W. Wegscheider (ETH Zurich)

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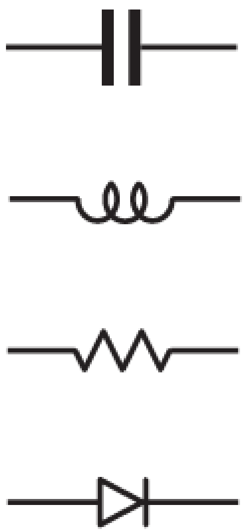
Swiss Federal Institute of Technology Zurich
QSIT Quantum Science and Technology
National Centre of Competence in Research
QED Circuit and Cavity Quantum Electrodynamics
SOLID
erc
Seventh Framework Programme
GEOMDISS
aqute
scaleQIT

Conventional Electronic Circuits

basic circuit elements:

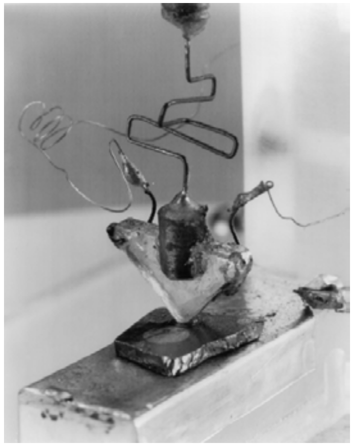


basis of modern information and communication technology

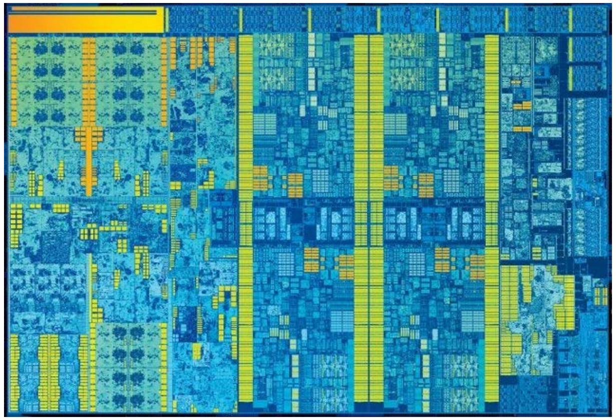
properties :

- classical physics
- no quantum mechanics
- no superposition or entanglement
- no quantization of fields

first transistor at Bell Labs (1947)



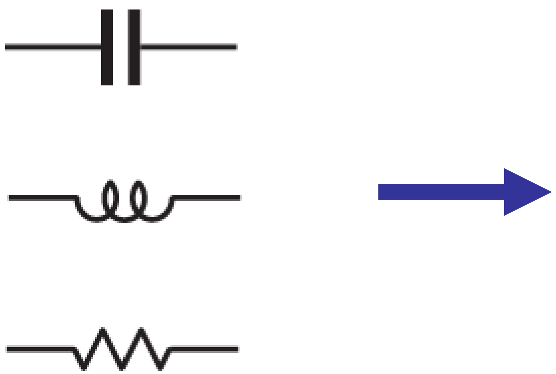
Intel Core i7-6700K Processor



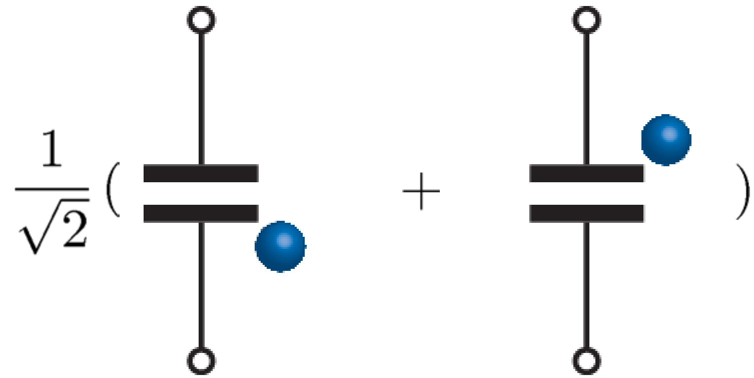
smallest feature size 14 nm
clock speed ~ 4.2 GHz
> 3. 10^9 transistors
power consumption > 10 W

Classical and Quantum Electronic Circuit Elements

basic circuit elements:



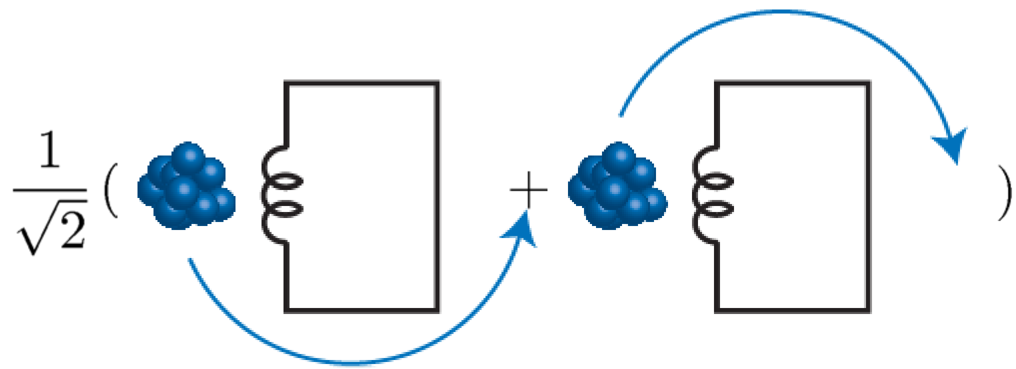
charge on a capacitor:



quantum superposition states of:

- charge q
- flux ϕ

current or magnetic flux in an inductor:

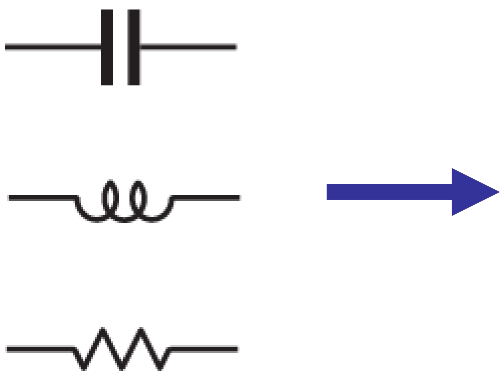


commutation relation (c.f. *x*, *p*):

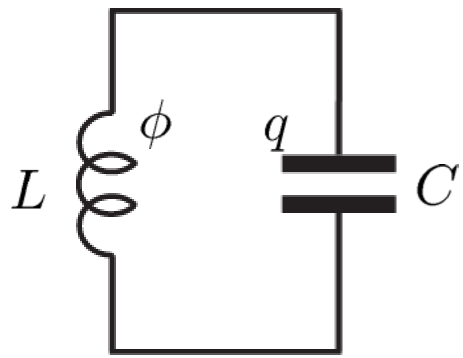
$$\left[\hat{\phi}, \hat{q}\right] = i\hbar$$

Constructing Linear Quantum Electronic Circuits

basic circuit elements:



harmonic LC oscillator:



$$\omega = \frac{1}{\sqrt{LC}} \sim 5\,\mathrm{GHz}$$

classical physics:

$$H = \frac{\phi^2}{2L} + \frac{q^2}{2C}$$

quantum mechanics:

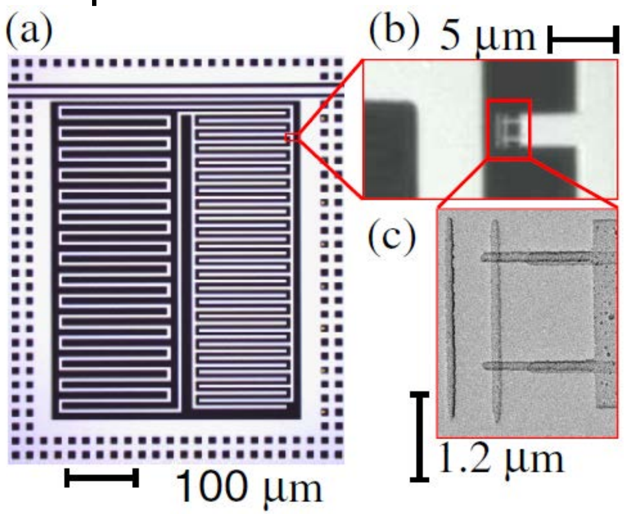
$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{q}^2}{2C} = \hbar\omega(\hat{a}^\dagger \hat{a} + \frac{1}{2}) \qquad \left[\hat{\phi}, \hat{q}\right] = i\hbar$$

energy:

Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

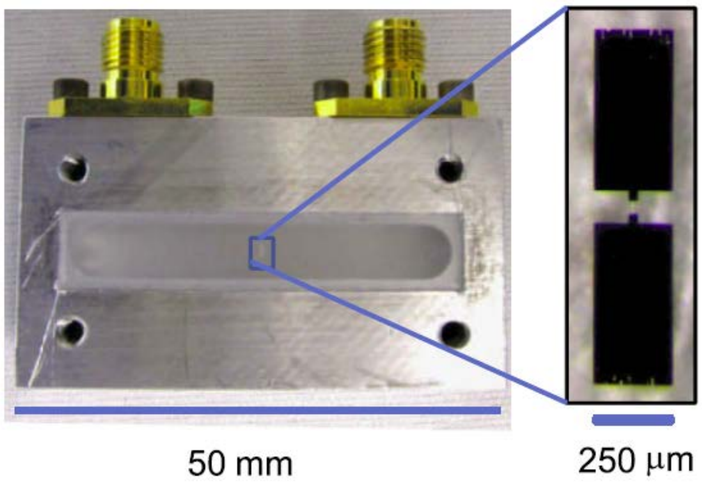
Flavors of Superconducting Harmonic Oscillators

lumped element resonator:



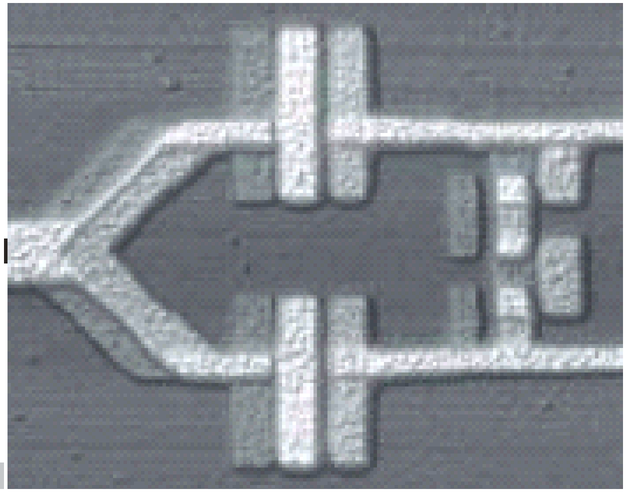
Z. Kim *et al.*, *PRL* 106, 120501 (2011)

3D cavity:



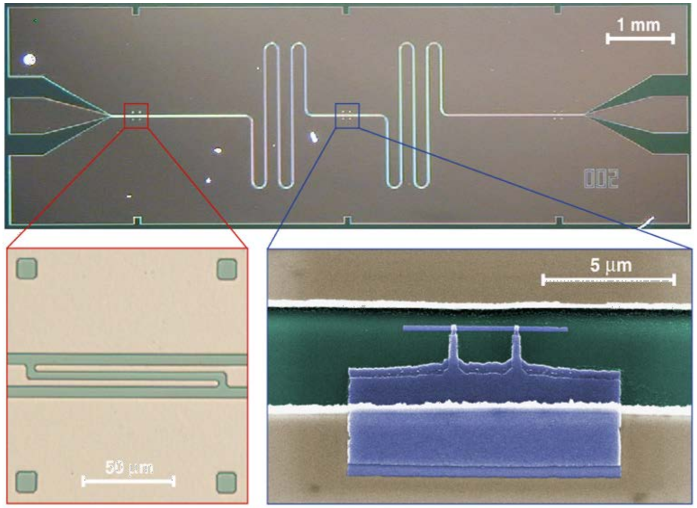
H. Paik *et al.*, *PRL* 107, 240501 (2011)

weakly nonlinear junction:



I. Chiorescu *et al.*, *Nature* 431, 159 (2004)

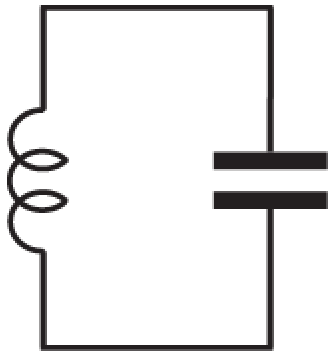
planar transmission line resonator:



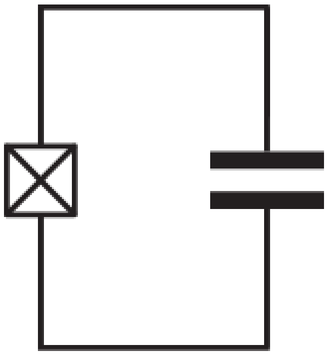
A. Wallraff *et al.*, *Nature* 431, 162 (2004)

Linear vs. Nonlinear Superconducting Oscillators

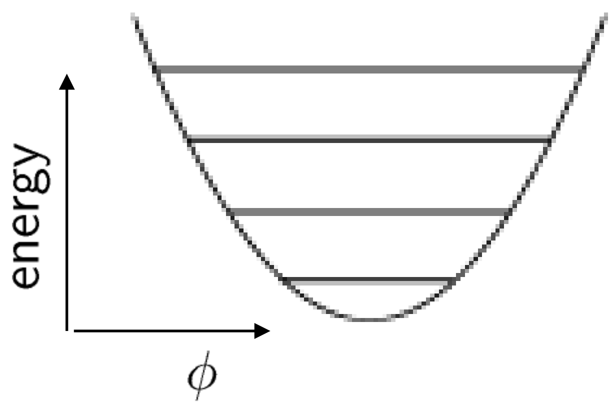
LC resonator:

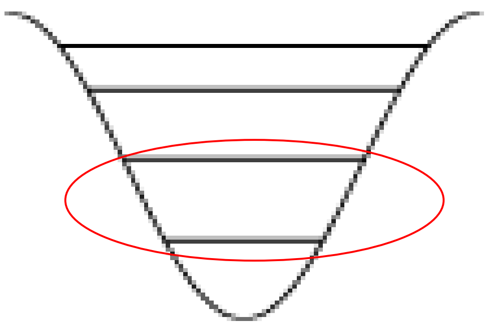


Josephson junction resonator:
Josephson junction = nonlinear inductor



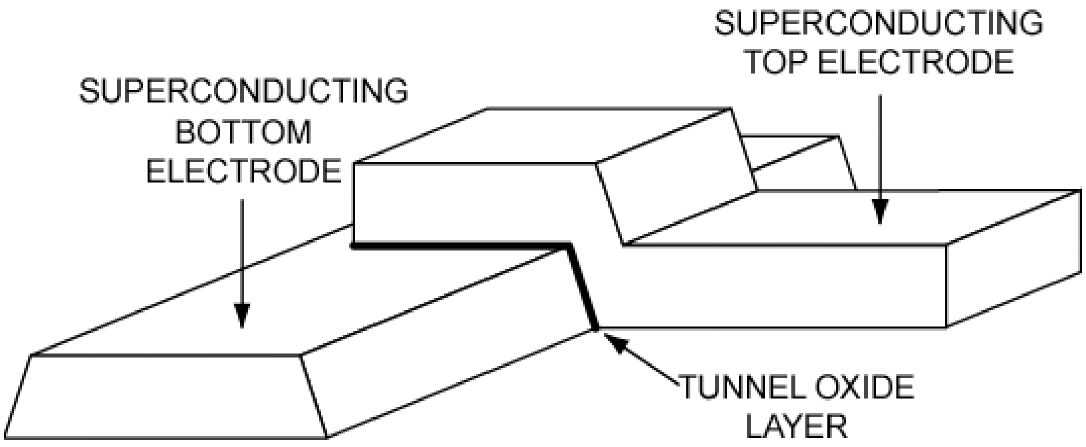
anharmonicity defines effective two-level system





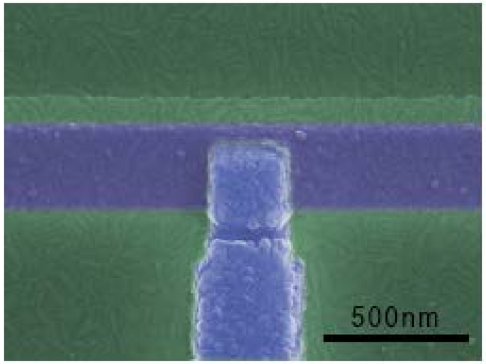
A Low-Loss Nonlinear Element

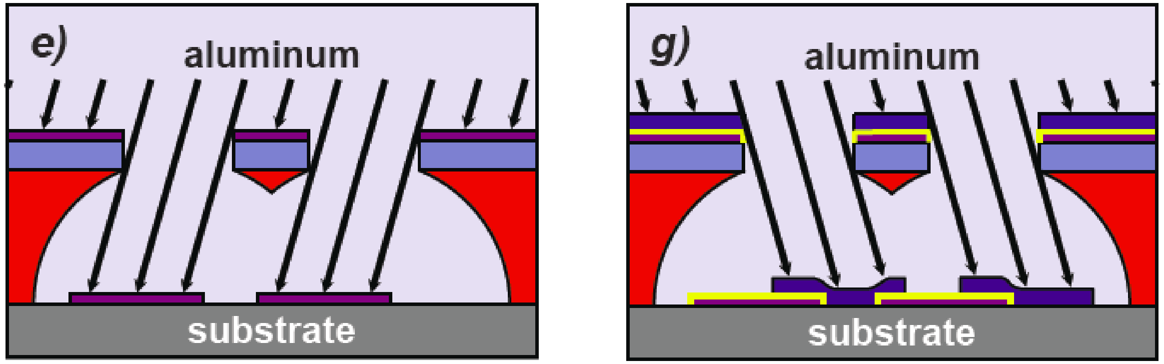
a (superconducting) Josephson junction:



- superconductors: Nb, Al
- tunnel barrier: AlO_x

Josephson junction fabricated by shadow evaporation:





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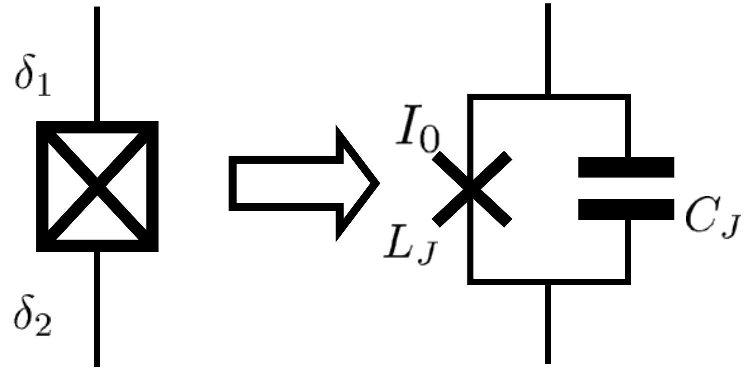
M. Tinkham, *Introduction to Superconductivity* (Krieger, Malabar, 1985).

The Josephson Junction as an ideal Non-Linear Inductor

a nonlinear inductor without dissipation



Josephson relations:

$$I = I_0 \sin\delta = I_0 \sin\left[2\pi\phi(t)/\phi_0\right]$$

$$V = \frac{\phi_0}{2\pi}\dot{\delta} = \dot{\phi}$$

nonlinear current/phase relation

gauge inv. phase difference:

$$\delta = \delta_2 - \delta_1 = 2\pi\phi(t)/\phi_0$$

specific Josephson inductance L_{J0}

Josephson inductance:

$$V = -L_J\dot{I} = \frac{\phi_0}{2\pi I_0}\frac{1}{\cos\delta}\dot{I}$$

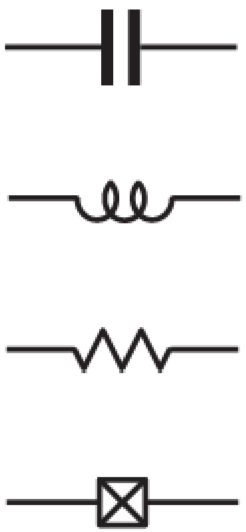
specific Josephson energy E_{J0}

Josephson energy:

$$E_J = \int VI dt = \frac{I_0\phi_0}{2\pi}\cos\delta$$

Constructing Non-Linear Quantum Electronic Circuits

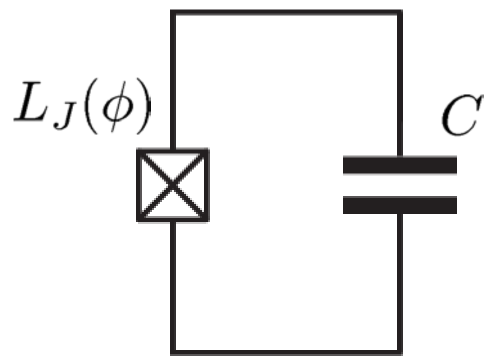
circuit elements:



Josephson junction:

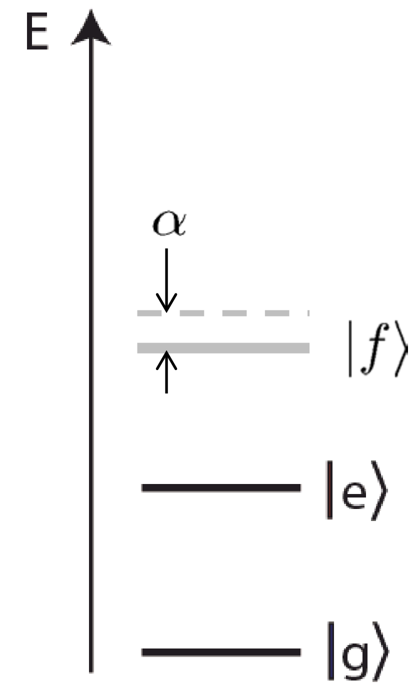
a non-dissipative nonlinear element (inductor)

anharmonic oscillator:



$$H \approx \hbar(\omega_{ge}\,\hat{b}^\dagger\hat{b} - \frac{\alpha}{2}\,\hat{b}^{\dagger 2}\hat{b}^2)$$

non-linear energy level spectrum:

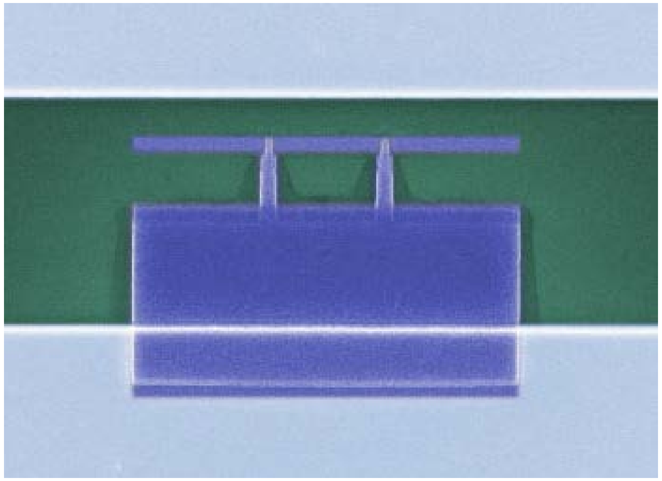


electronic artificial atom

Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

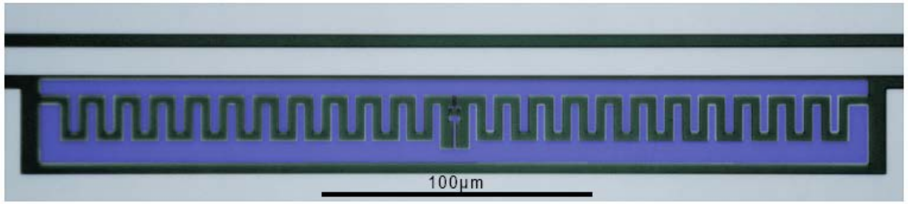
Flavors of Superconducting Artificial Atoms

Cooper pair box:



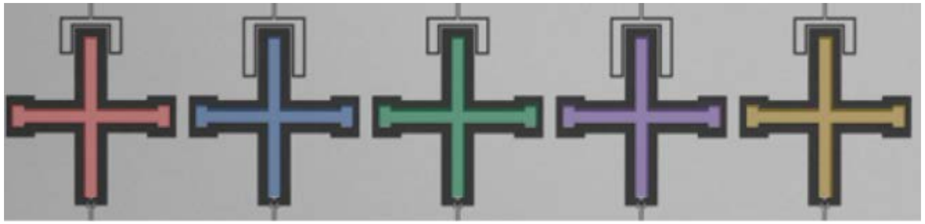
Bouchiat et al., *Physica Scripta* T76, 165 (1998).

Transmon:



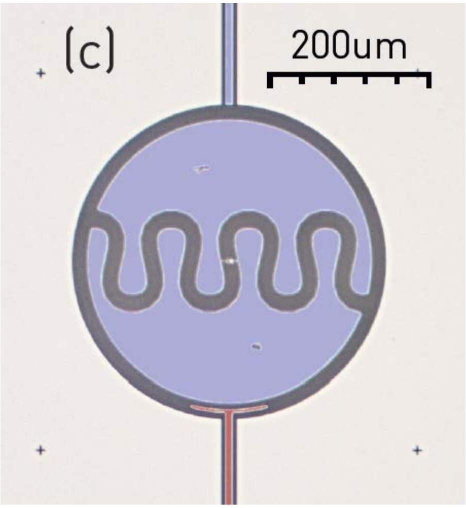
J. Koch *et al.*, PRA 76, 042319 (2007)

Xmons:



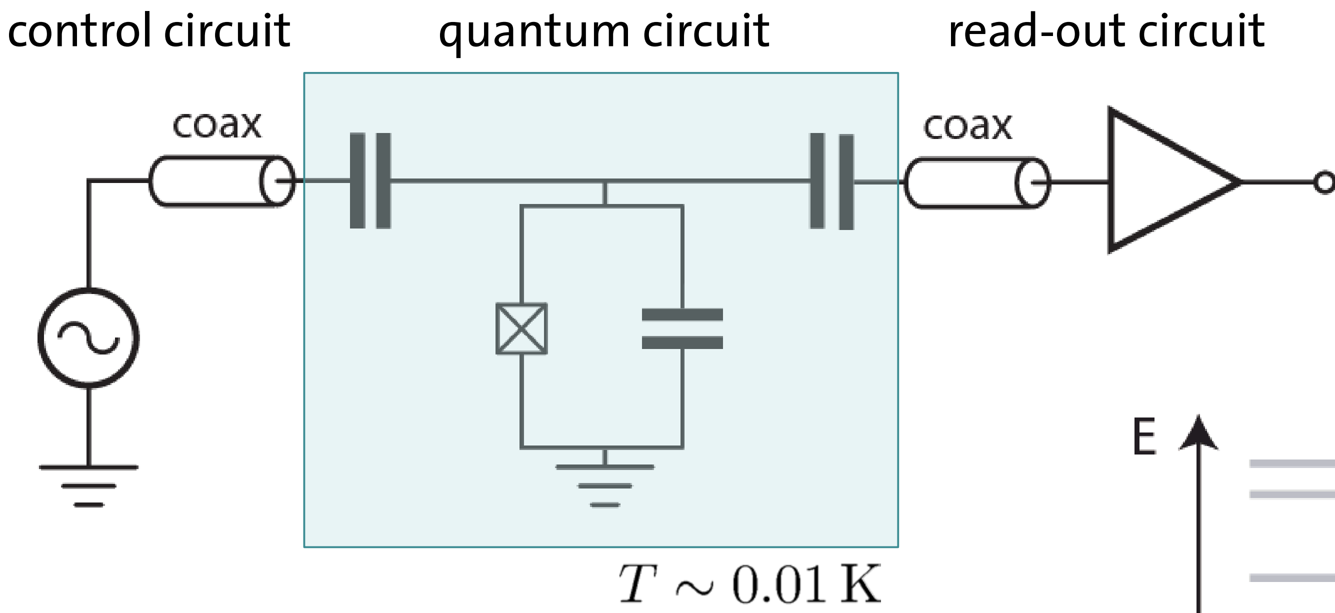
Barends *et al.*, *Phys. Rev. Lett.* 111, 080502 (2013)

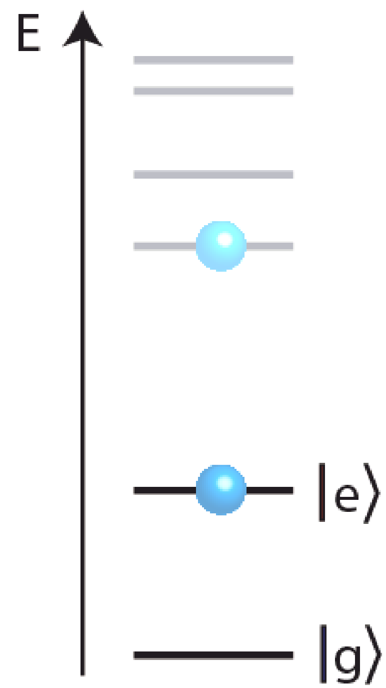
(Jellymon):



Pechal *et al.*, *arXiv:*1606.01031 (2016)

How to Operate Circuits in the Quantum Regime?



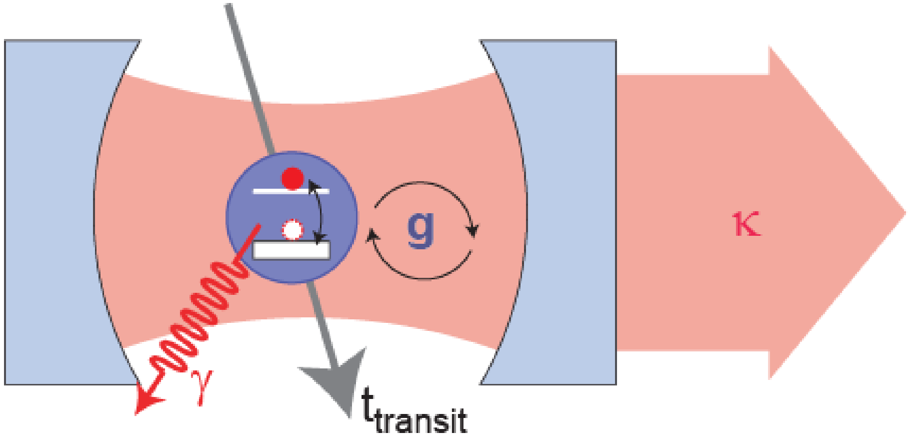


recipe:

- avoid dissipation
- work at low temperatures
- isolate quantum circuit from environment

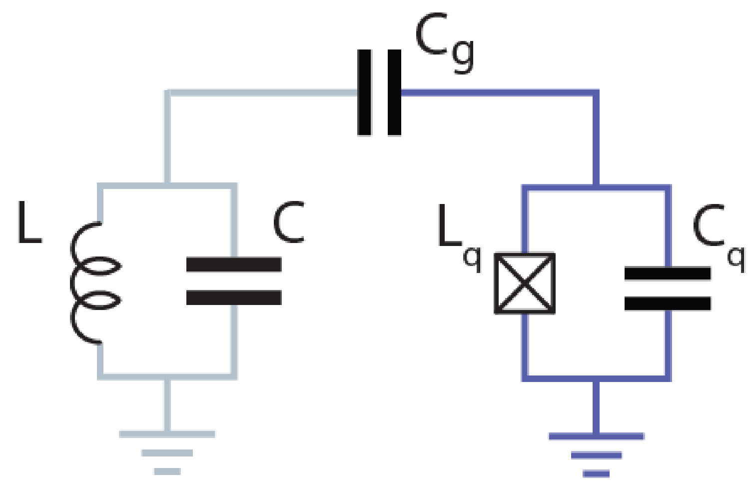
Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411174* (2004)

Cavity QED with Superconducting Circuits



coherent quantum mechanics
with individual photons and qubits ...

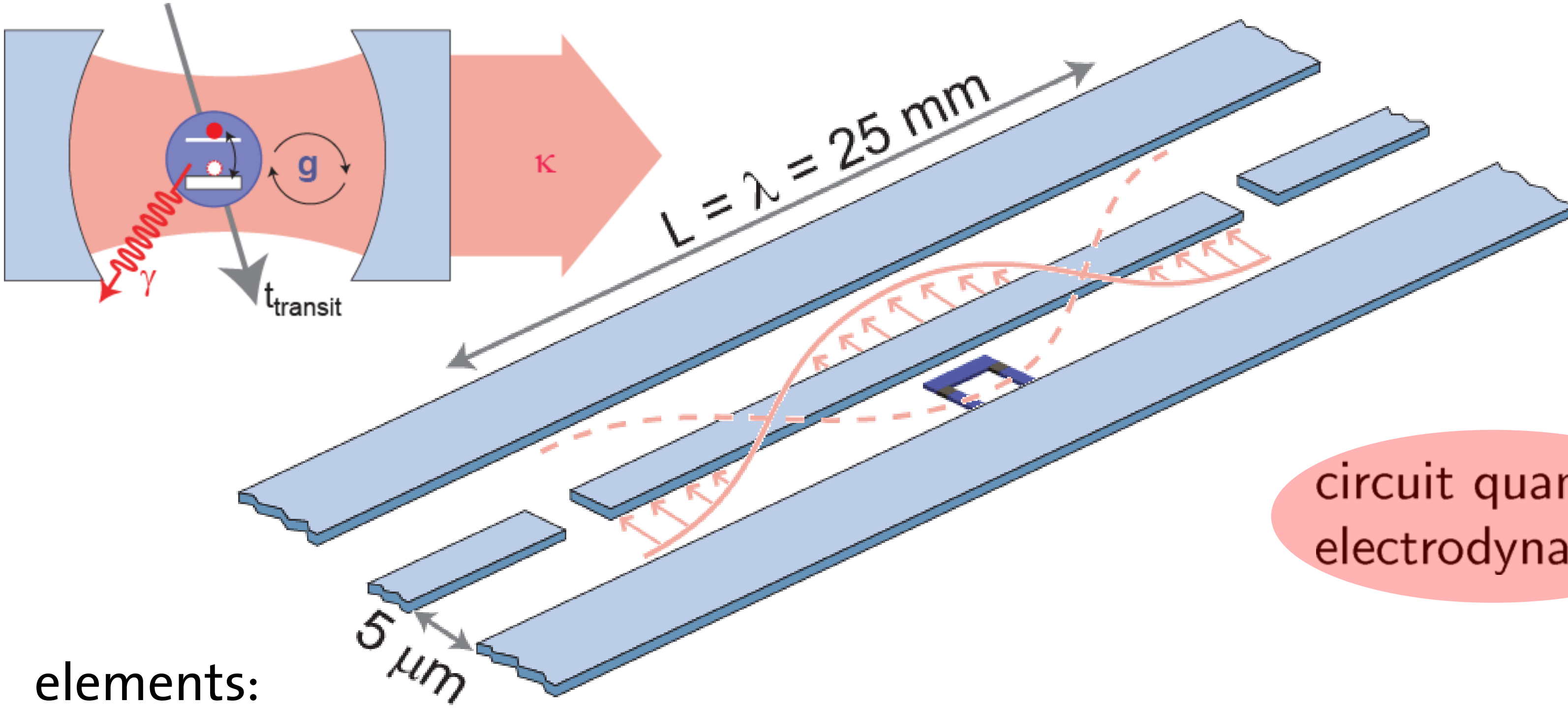
... basic approach:



What is this good for?

- Isolating qubits from their environment
- Maintain addressability of qubits
- Reading out the state of qubits
- Coupling qubits to each other
- Converting stationary qubits to flying qubits

Cavity QED with Superconducting Circuits



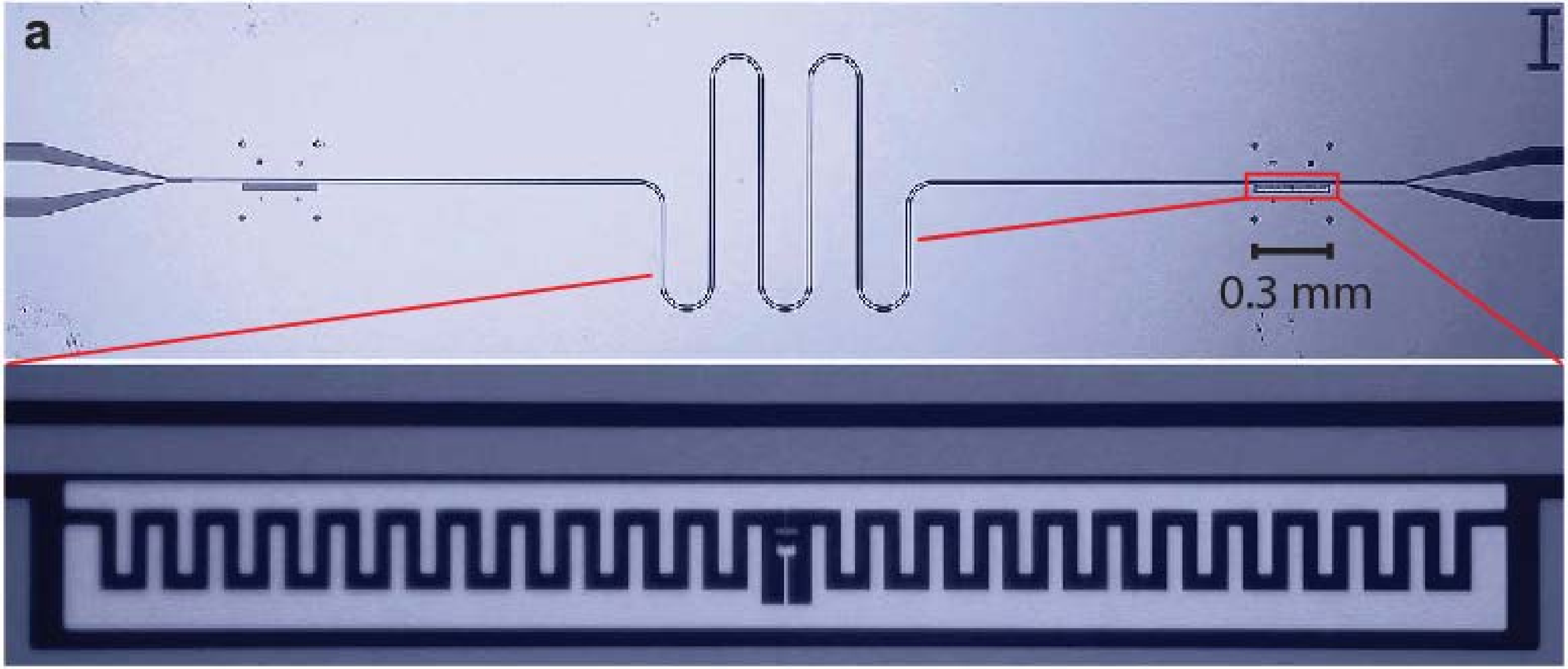
circuit quantum electrodynamics

elements:

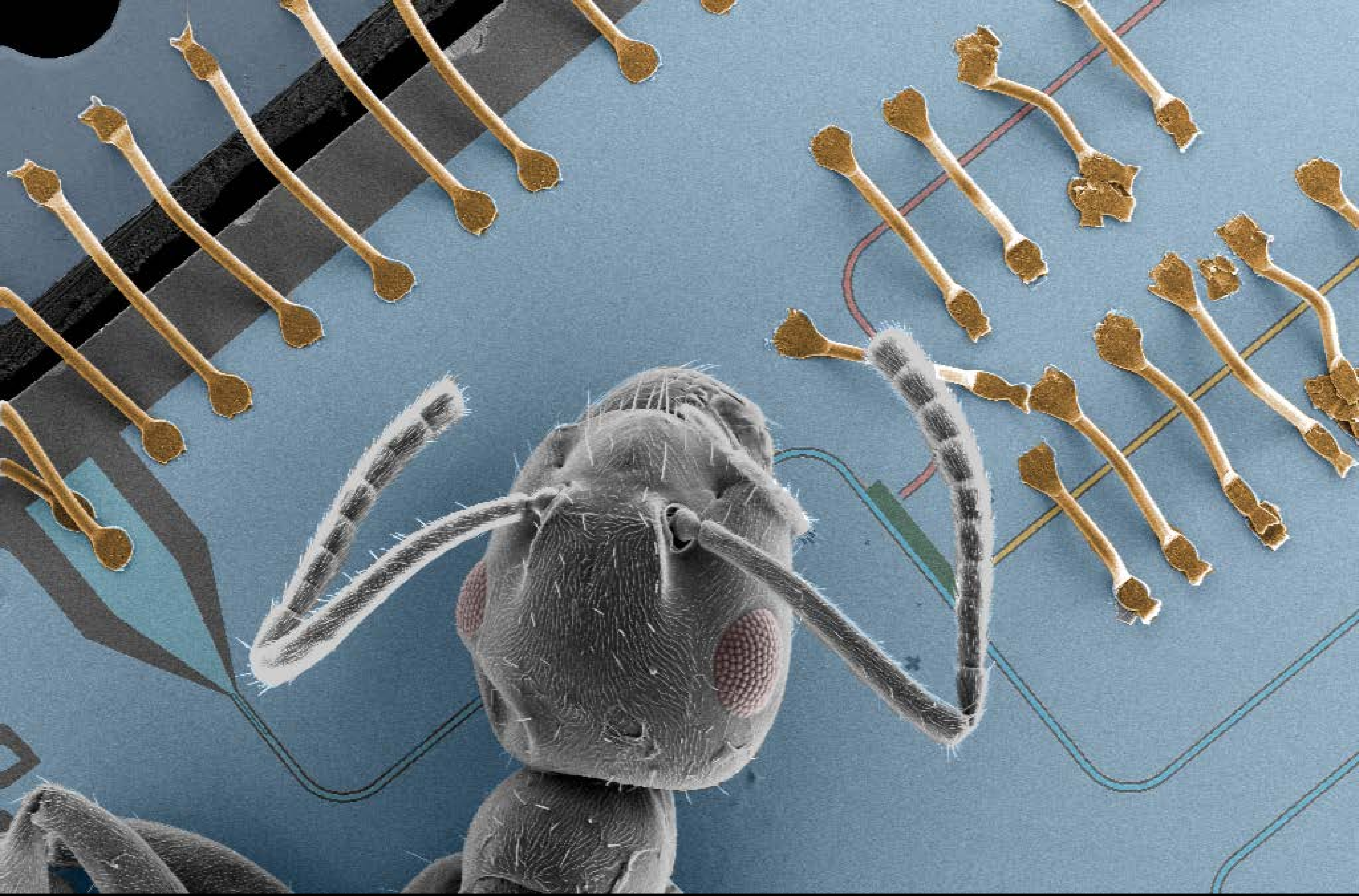
- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_o and long photon life time $1/\kappa$
- the atom: a superconducting qubit with large dipole moment d and long coherence time $1/\gamma$ and fixed position ...
- ... or any microscopic/macroscopic quantum element or ensemble thereof with an appreciable dipole moment

A. Blais, *et al.*, *PRA* 69, 062320 (2004)
A. Wallraff *et al.*, *Nature (London)* 431, 162 (2004)
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* 451, 664 (2008)

Realization



device fabrication: L. Frunzio et al., IEEE Trans. on Appl. Supercon. 15, 860 (2005)



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Swiss Federal Institute of Technology Zurich

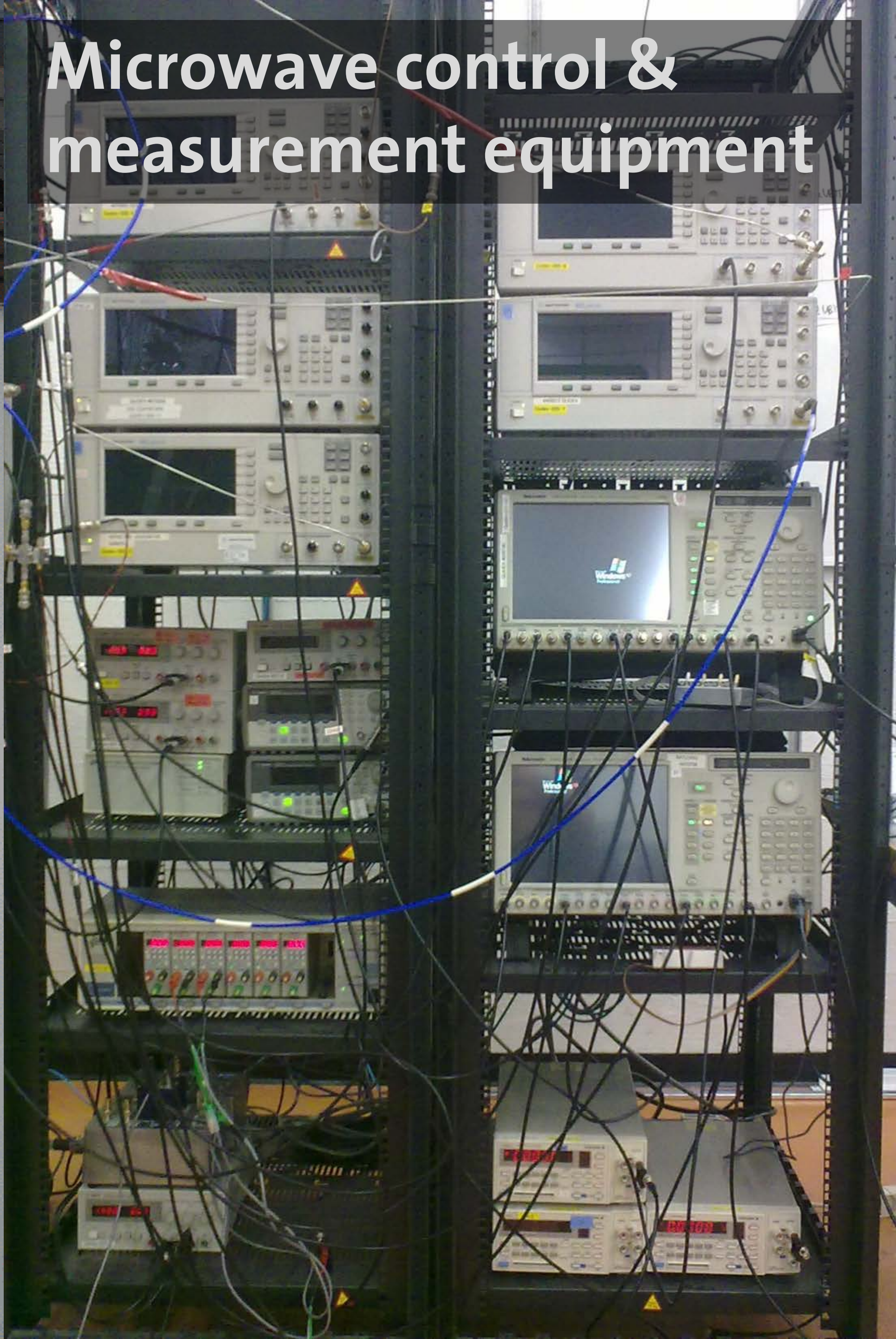
J. Mlynek *et al.,* Quantum Device Lab, ETH Zurich (2012)

Sample Mount

M. Peterer *et al.*, Quantum Device Lab, ETH Zurich (2012)

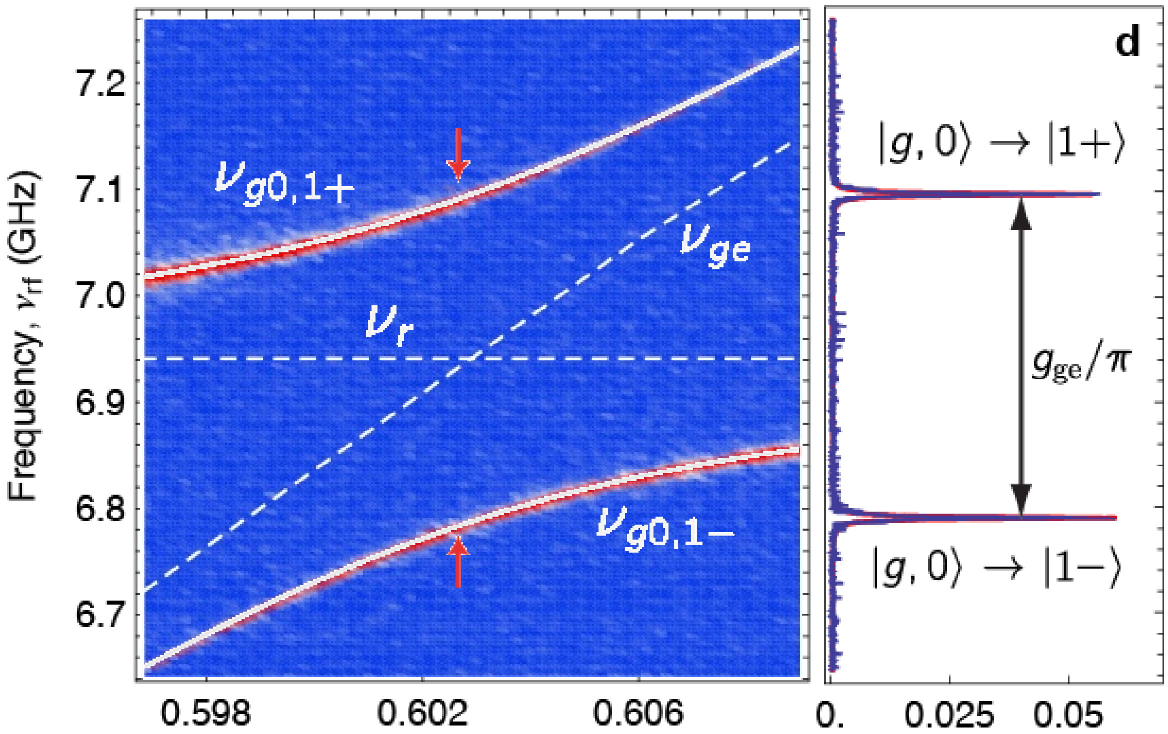
Cryostate for temperatures down to 0.02 K

Microwave control & measurement equipment



Resonant Vacuum Rabi Mode Splitting ...

... with one photon (*n=1*):

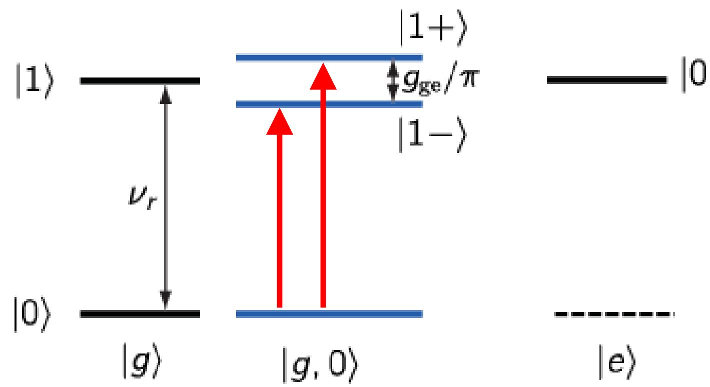


very strong coupling:

$$g_{ge}/\pi = 308\,\mathrm{MHz}$$

$$\kappa, \gamma < 1\ \mathrm{MHz}$$

$$g_{ge} \gg \kappa, \gamma$$



forming a 'molecule' of a qubit and a photon

first demonstration in a solid: A. Wallraff et *al.*, *Nature (London)* 431, 162 (2004)

this data: J. Fink et al., *Nature (London)* 454, 315 (2008)

R. J. Schoelkopf, S. M. Girvin, *Nature (London)* 451, 664 (2008)

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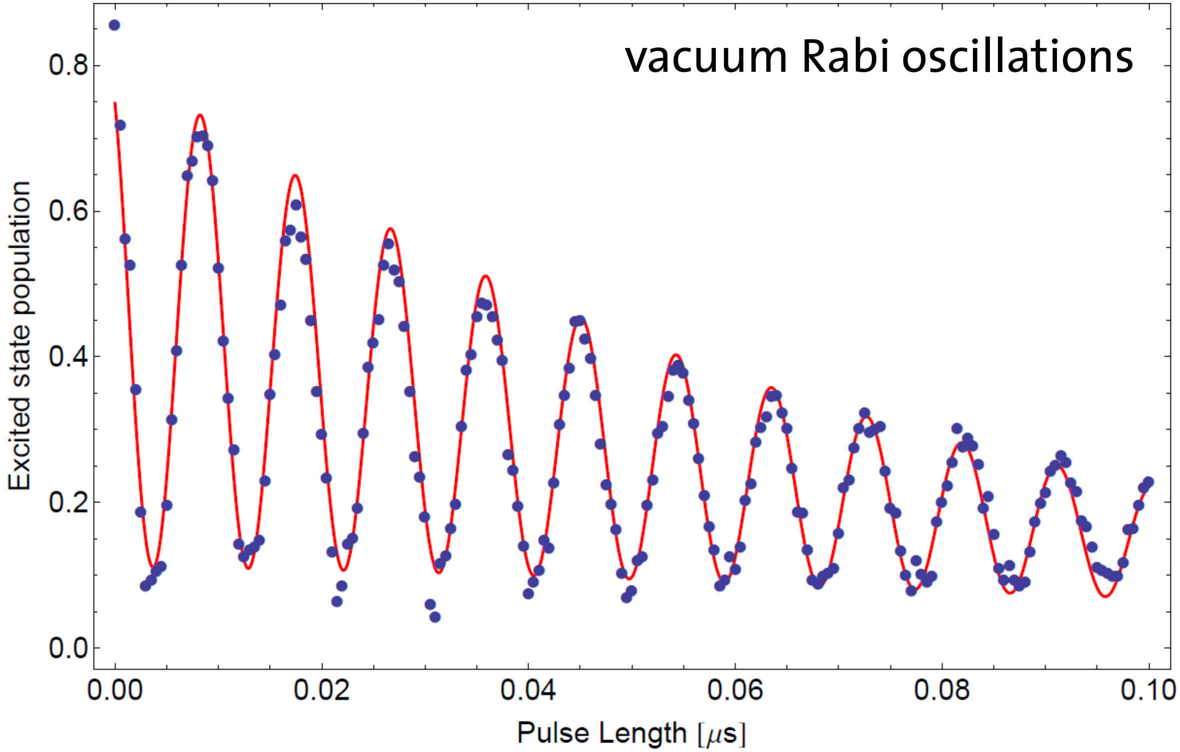

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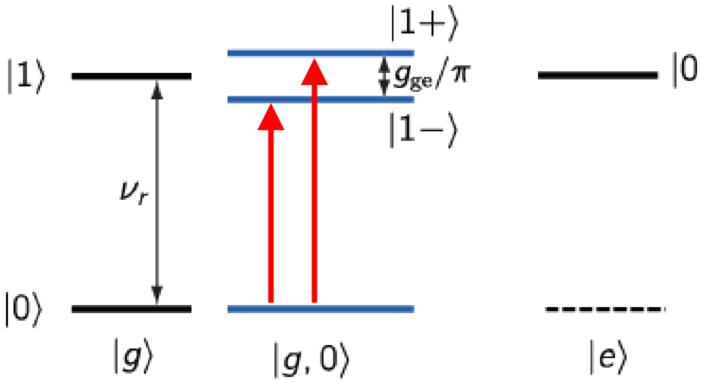

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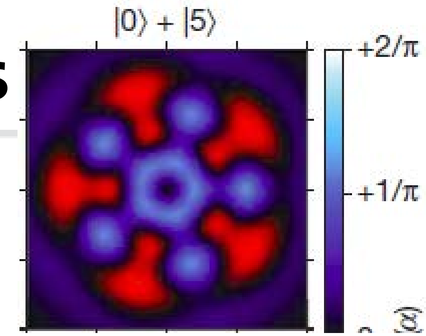
this data: J. Fink et al., *Nature (London)* 454, 315 (2008)

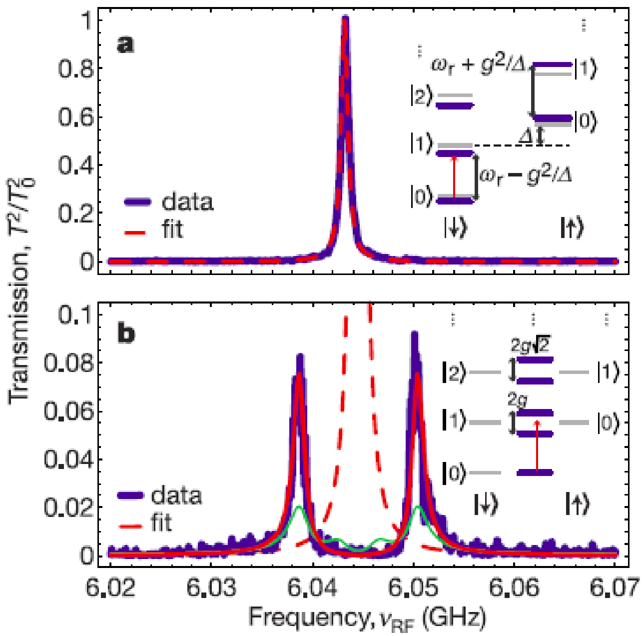
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* 451, 664 (2008)

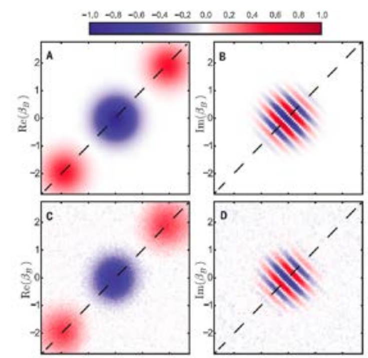
Quantum Optics with Supercond. Circuits



Strong Coherent Coupling

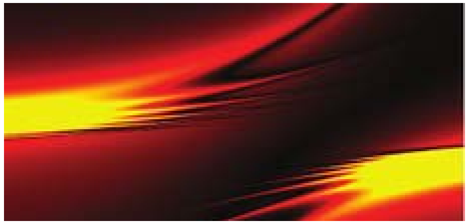
Chiorescu *et al.*, *Nature* 431, 159 (2004)
Wallraff *et al.*, *Nature* 431, 162 (2004)
Schuster *et al.*, *Nature* 445, 515 (2007)





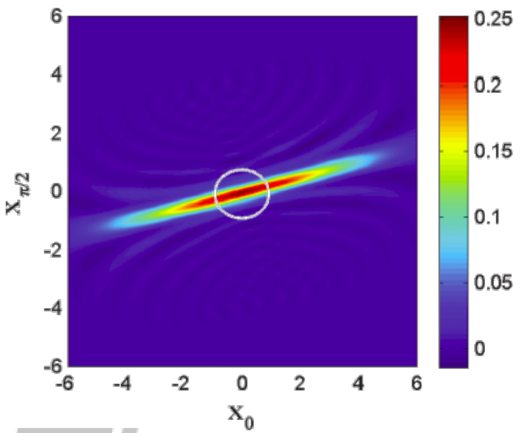
Root n Nonlinearities

Fink *et al.*, *Nature* 454, 315 (2008)
Deppe *et al.*, *Nat. Phys.* 4, 686 (2008)
Bishop *et al.*, *Nat. Phys.* 5, 105 (2009)



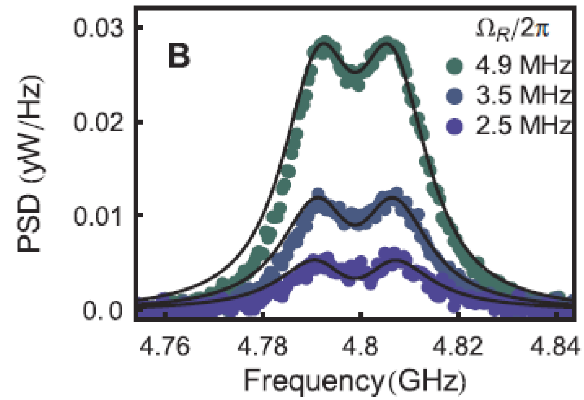
Microwave Fock and Cat States

Hofheinz *et al.*, *Nature* 454, 310 (2008)
Hofheinz *et al.*, *Nature* 459, 546 (2009)
Kirchmair *et al.*, *Nature* 495, 205 (2013)
Vlastakis *et al.*, *Science* 342, 607 (2013)
Wang *et al.*, Science 352, 1087 (2016)



Parametric Amplification & Squeezing

Castellanos-Beltran *et al.*, *Nat. Phys.* 4, 928 (2008)
Abdo *et al.*, *PRX* 3, 031001 (2013)

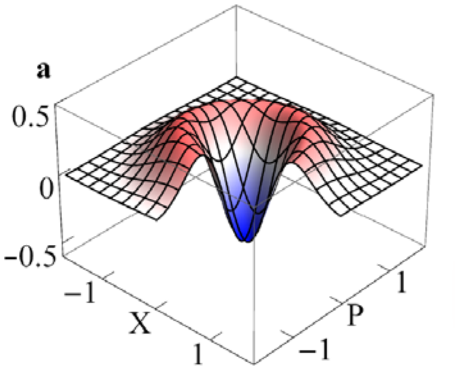


Waveguide QED – Qubit Interactions in Free Space

Astafiev *et al.*, *Science* 327, 840 (2010)
van Loo *et al.*, *Science* 342, 1494 (2013)

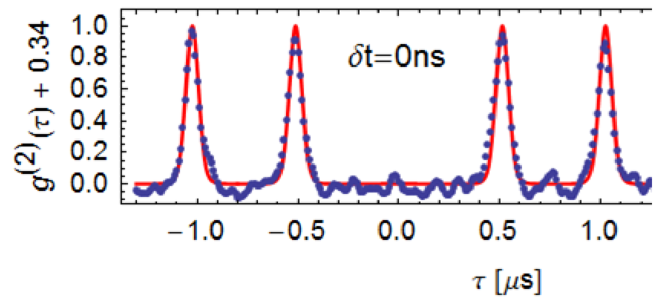
Experiments with Propagating Microwaves

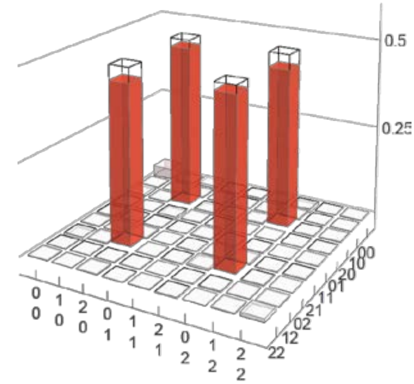
Full state tomography and Wigner functions of propagating photons



Eichler *et al., PRL* 106, 220503 (2011)

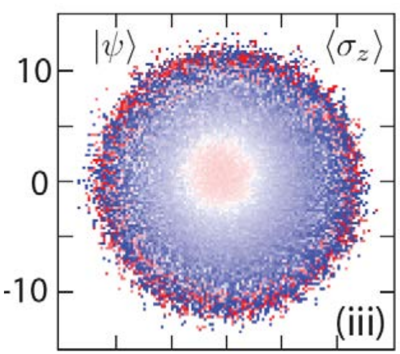
Hong-Ou-Mandel: Two-photon interference incl. msrmnt of coherences at microwave freq.

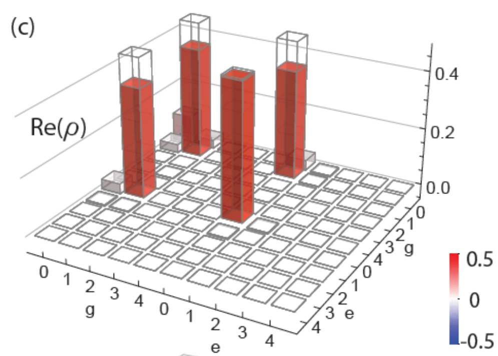




Lang *et al.*, *Nat. Phys.* 9, 345 (2013)

Preparation and characterization of qubit-propagating photon entanglement

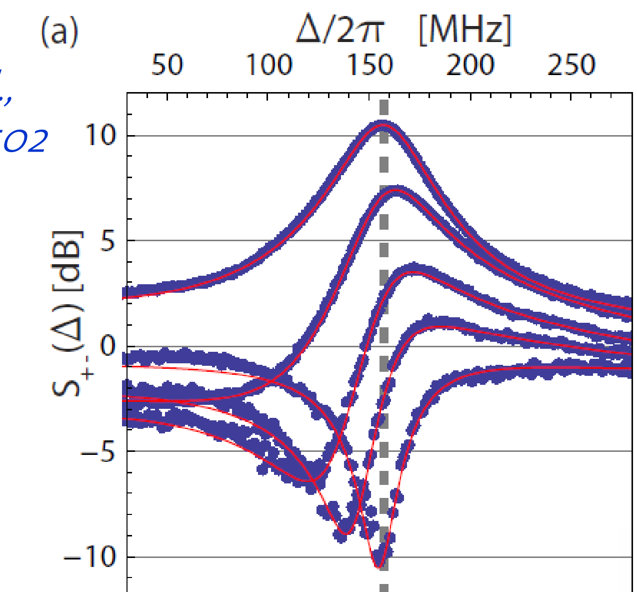




Eichler *et al., PRL* 109, *240501* (2012)
Eichler *et al., PRA* 86, 032106 (2012)

Squeezing in a Josephson parametric dimer

Eichler *et al., PRL* 113, *110502* (2014)

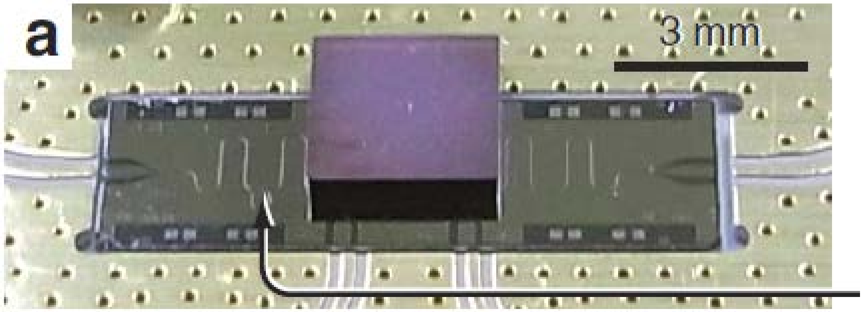


Hybrid Systems with Superconducting Circuits

Spin Ensembles: e.g. NV centers

D. Schuster *et al.*, *PRL* 105, 140501 (2010)

Y. Kubo *et al.*, *PRL* 105, 140502 (2010)



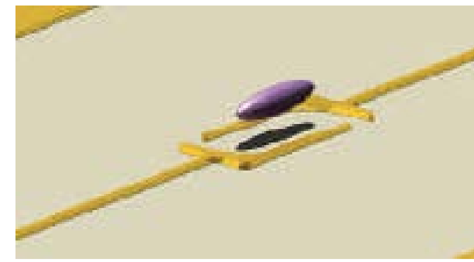
Polar Molecules, Rydberg, BEC

P. Rabl *et a*l, *PRL* 97, 033003 (2006)

A. Andre *et a*l, *Nat. Phys.* 2, 636 (2006)

D. Petrosyan *et al*, *PRL* 100, 170501 (2008)

J. Verdu *et al*, *PRL* 103, 043603 (2009)

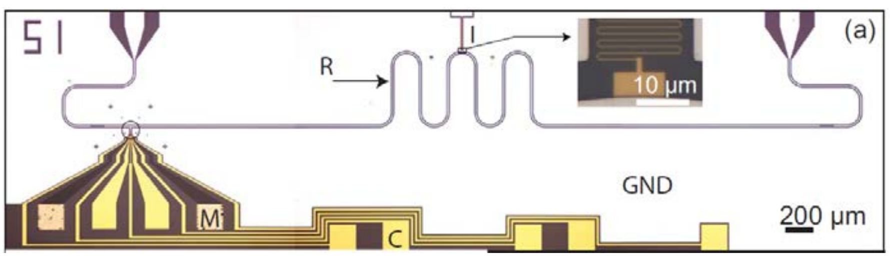


CNT, Gate Defined 2DEG, or nanowire Quantum Dots

M. Delbecq *et al.*, *PRL* 107, 256804 (2011)

T. Frey *et al.*, *PRL* 108, 046807 (2012)

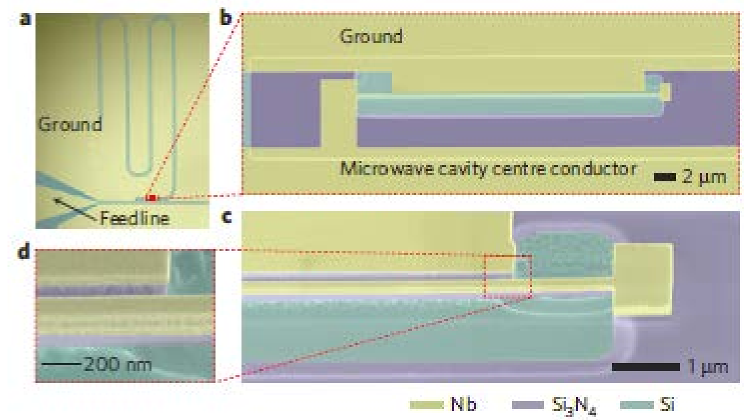
K. Petersson *et al.*, *Nature* 490, 380 (2013)



Nano-Mechanics

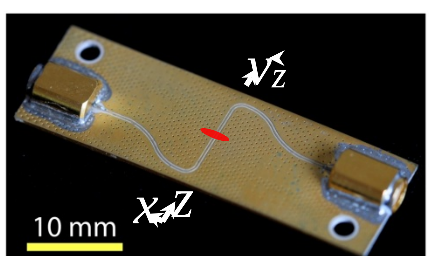
J. Teufel *et al.*, *Nature* 475, 359 (2011)

X. Zhou *et al.*, *Nat. Phys.* 9, 179(2013)



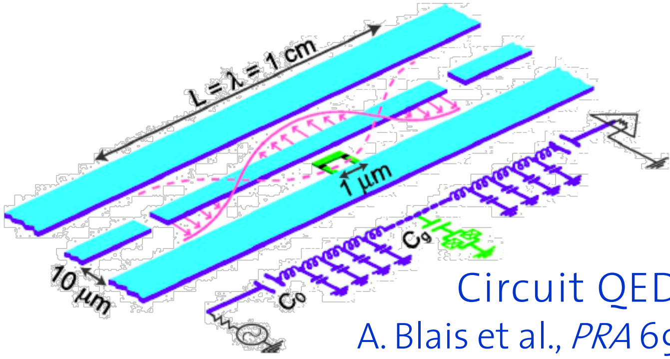
Rydberg Atoms

S. Hogan *et al.*, *PRL* 108, 063004 (2012)



... and many more

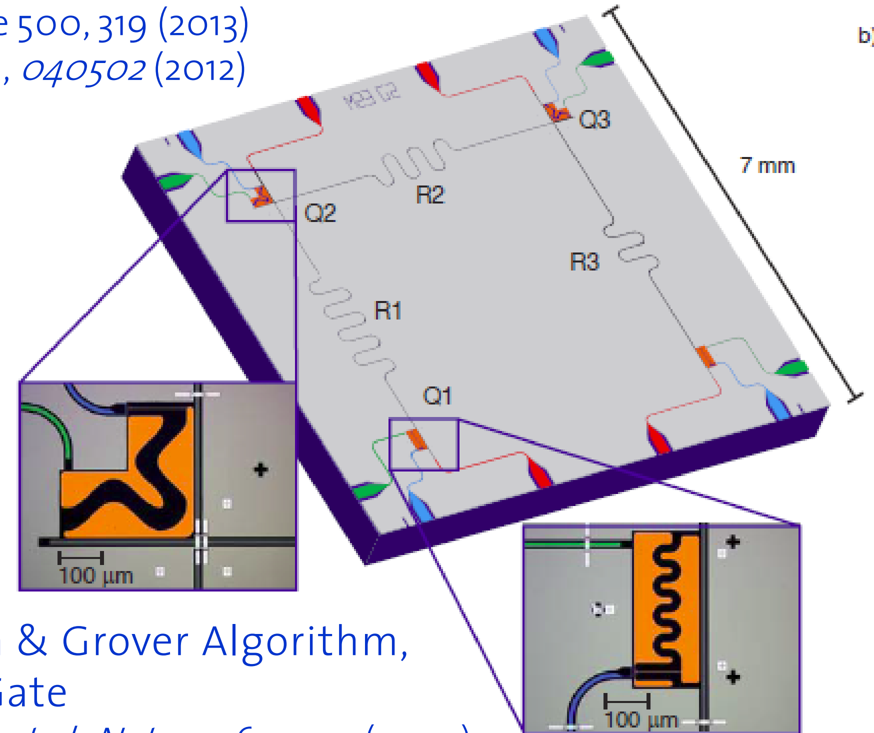
Quantum Computing with Superconducting Circuits



Teleportation

L. Steffen *et al., Nature* 500, 319 (2013)

M.. Baur *et al., PRL* 108, *040502* (2012)



Circuit QED Architecture

A. Blais et al., *PRA* 69, 062320 (2004)

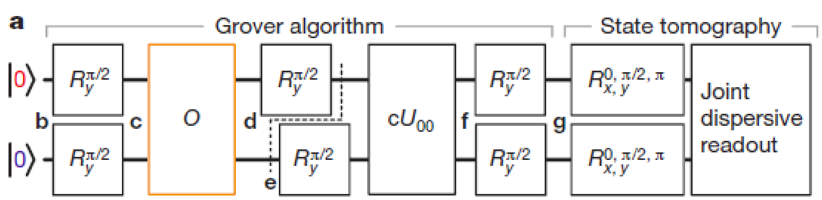
A. Wallraff *et al., Nature* 431, 162 (2004)

M. Sillanpaa *et al., Nature* 449, 438 (2007)

H. Majer *et al., Nature* 449, 443 (2007)

M. Mariantoni *et al., Science* 334, 61 (2011)

R. Barends *et al., Nature* 508, 500 (2014)



Deutsch & Grover Algorithm, Toffoli Gate

L. DiCarlo *et al., Nature* 460, 240 (2009)

L. DiCarlo *et al., Nature* 467, 574 (2010)

A. Fedorov *et al., Nature* 481, 170 (2012)

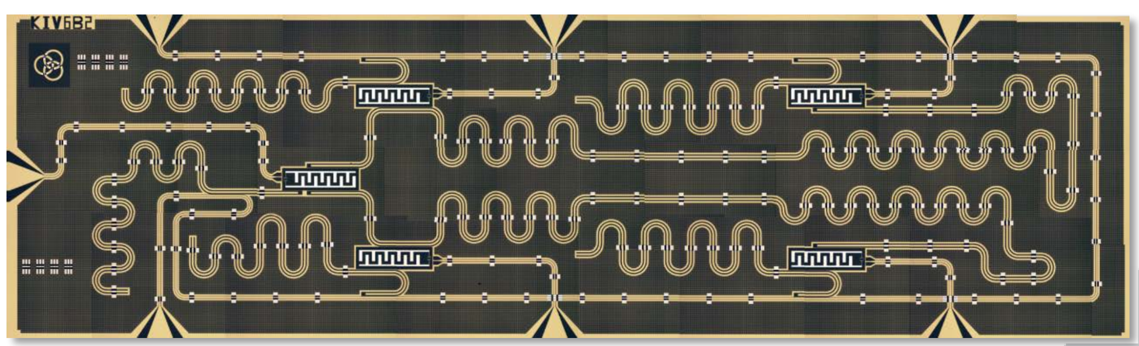
Error Correction

M. Reed *et al., Nature* 481, 382 (2012)

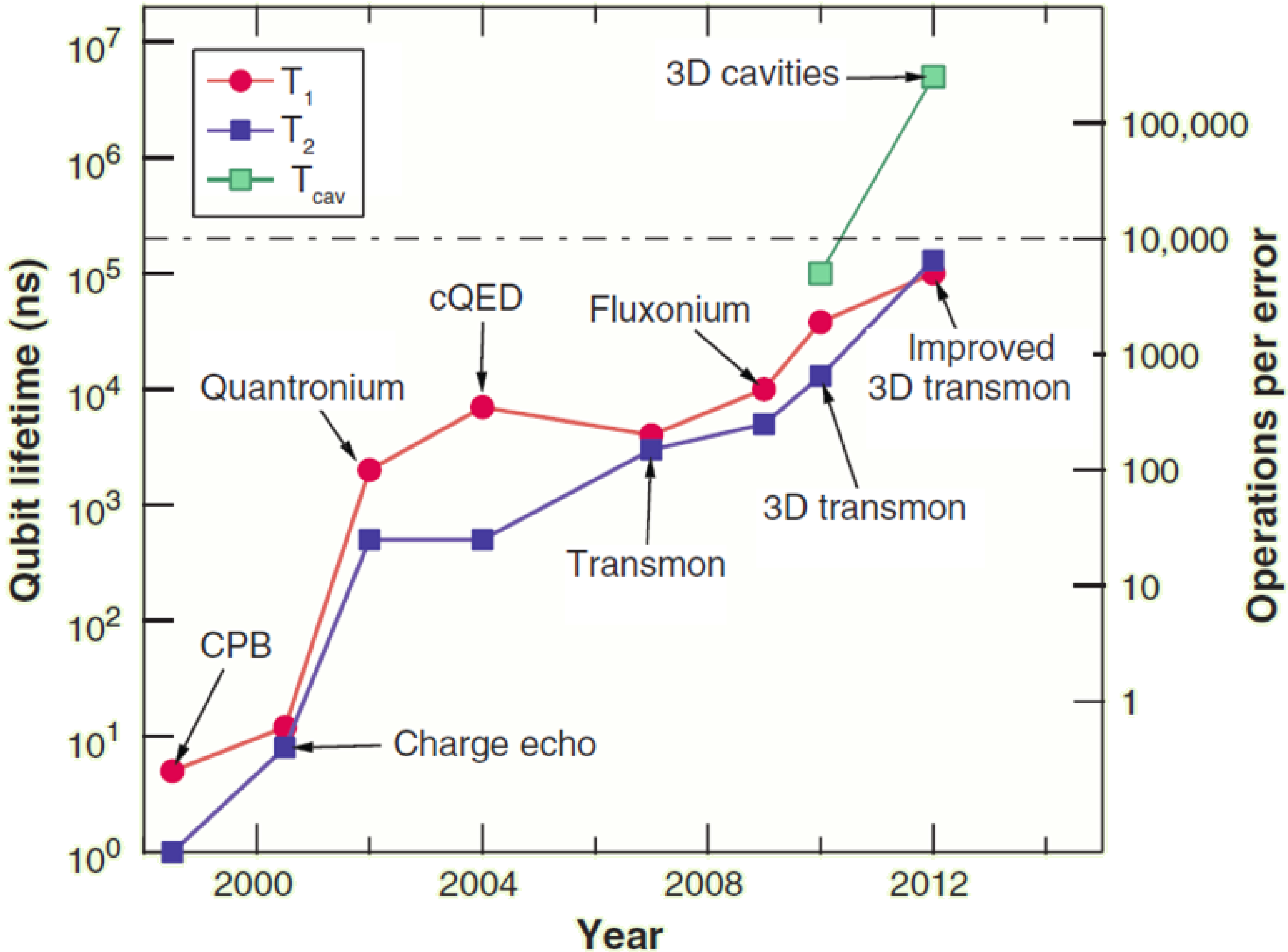
Corcoles et al., *Nat. Com.* 6, 6979 (2015)

Ristè et al., *Nat. Com.* 6, 6983 (2015)

Kelly et al., *Nature* 519, 66-69 (2015)

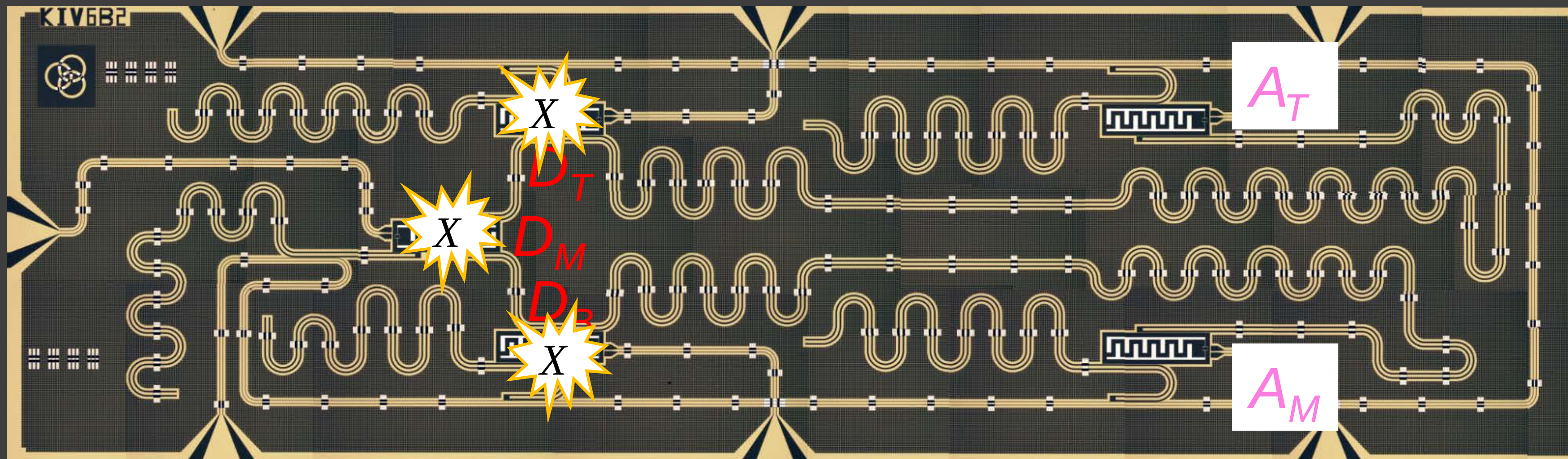


10⁵ Improvement in Coherence Time in 13 Years



M. Devoret, R. Schoelkopf *Science* 339, 1169 (2013)

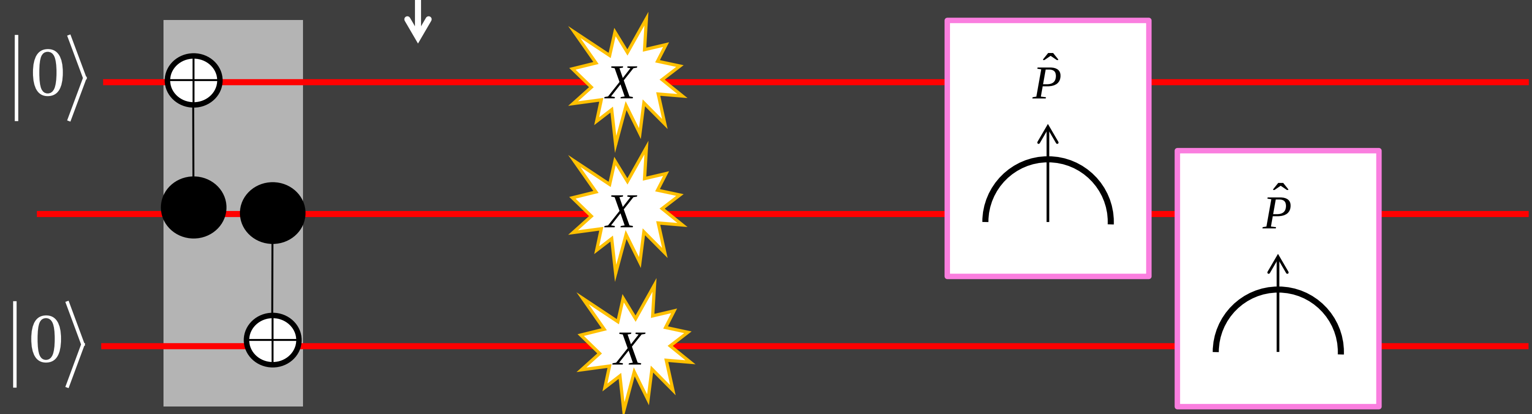
Recent Progress in Quantum Error Correction



$$\alpha|000\rangle + \beta|111\rangle$$

encode

Discretize, signal errors using quantum parity checks

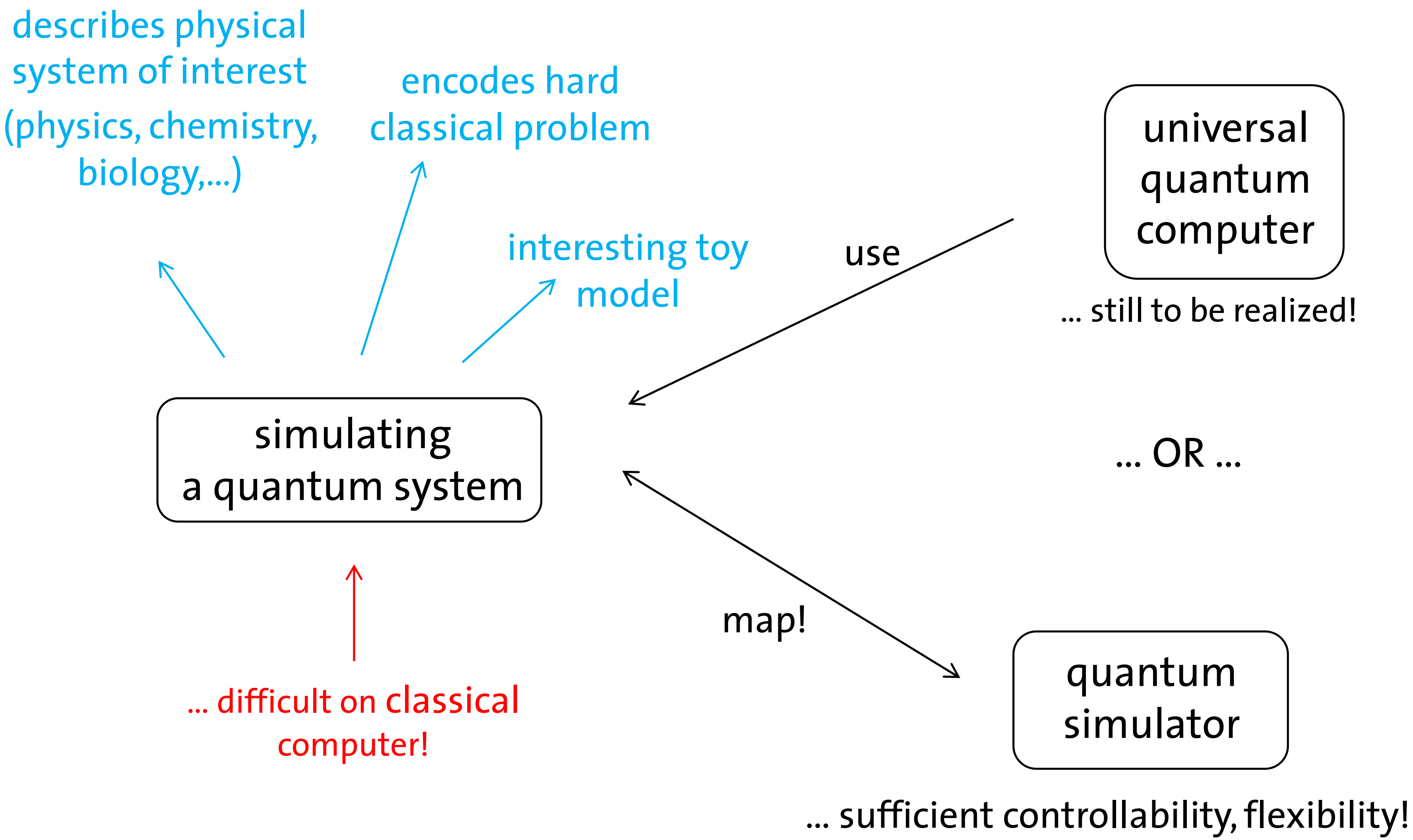


IBM: Corcoles *et al.*, *Nat. Com.* **6**, 6979 (2015), ArXiv:1410.6419

QuTech: Ristè, Poletto, Huang *et al.*, *Nat. Com.* **6**, 6983 (2015), ArXiv:1411.5542

UCSB/Google: Kelly *et al.*, *Nature* **519**, 66-69 (2015), ArXiv:1411.7403

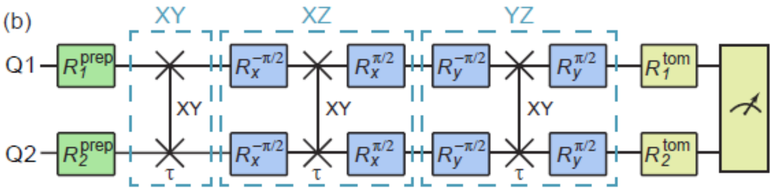
Quantum Simulation



Feynman, *Int. Journal of Th. Phys.* 21, 467 (1982)
Llloyd, *Science* 273, 5278 (1996)

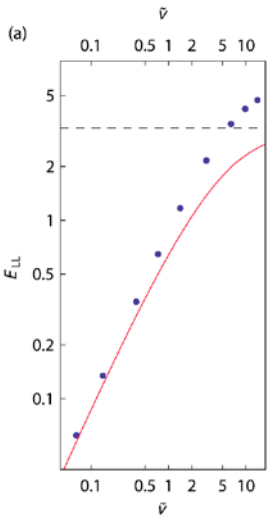
Quantum Simulation with Superconducting Circuits

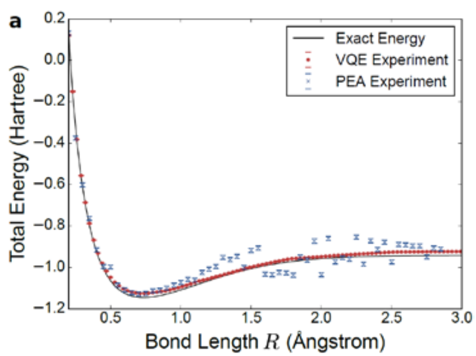
Digital simulation of exchange, Heisenberg, Ising spin models



Salathe *et al.*, *PRX* 5, 021027 (2015)

Quantum simulation of correlated systems with variational Ansatz

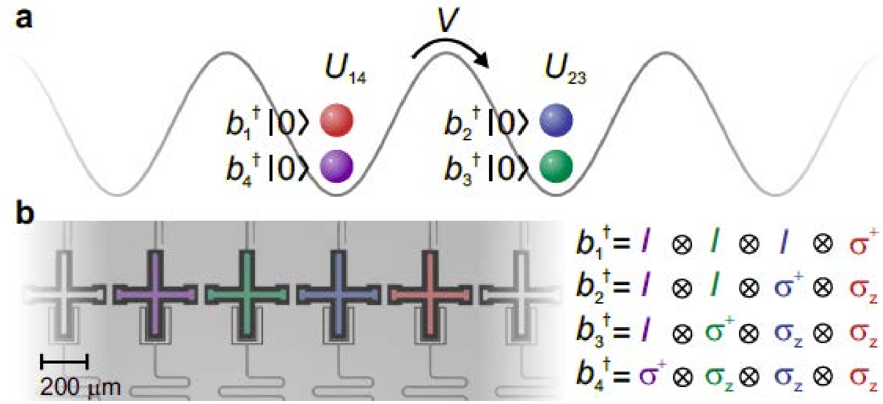




Eichler *et al.*, *Phys. Rev. X* 5, 041044 (2015)

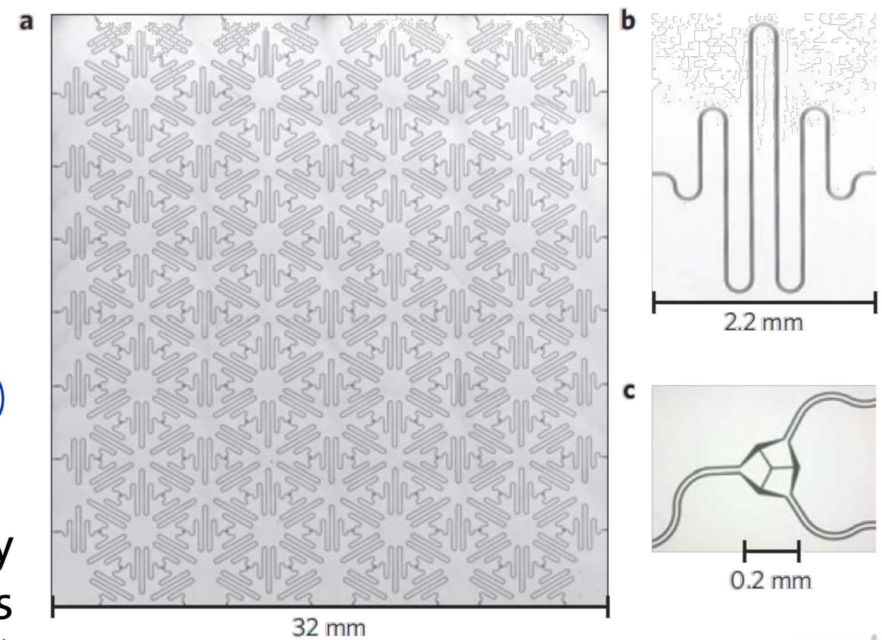
O'Malley *et al.*, *arXiv*:1512.06860 (2015)

... two-mode fermionic Hubbard models



Barends *et al.*, *Nat. Com.* 6, 7654 (2015)

Analog simulations with cavity and/or qubit arrays

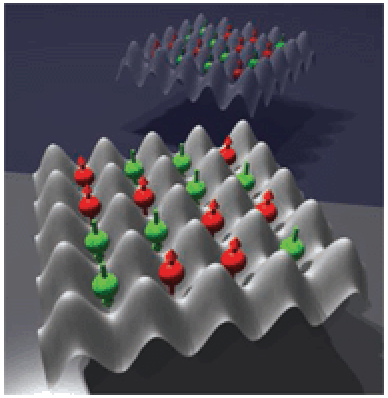


Houck *et al.*, *Nat Phys.* 8, 292 (2012)

Raftery *et al.*, *Phys. Rev. X* 4, 031043 (2014)

Systems for Quantum Simulation

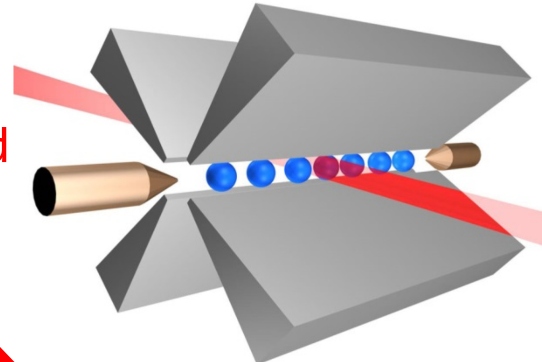
Ultracold gases



Bloch et al.,
Nat. Phys. 8, 267 (2012)

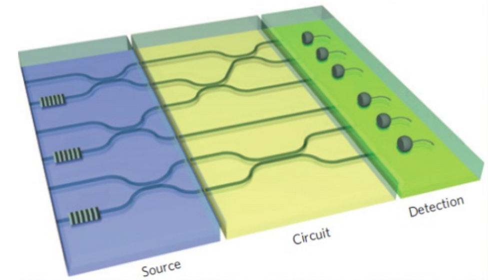
more established

Trapped ions



Blatt & Roos,
Nat. Phys. 8, 277 (2012)

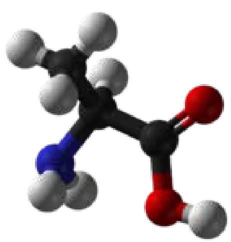
Optical photons



Aspuru-Guzik & Walther,
Nat. Phys. 8, 258 (2012)

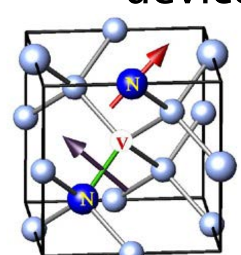
under development

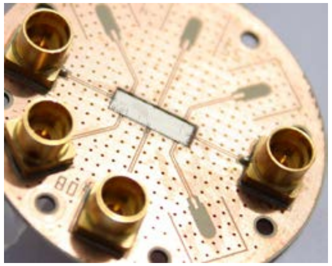
Nuclear magnetic resonance



Vandersypen & Chuang,
RMP 76, 1037 (2004)

Solid state quantum devices

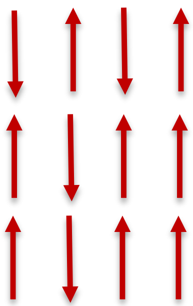




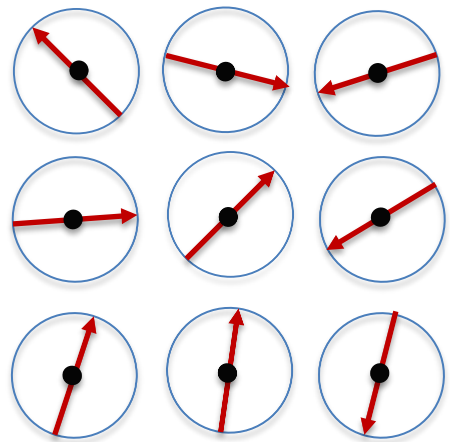
Georgescu et al., *RMP* 86, 153 (2014)

Digital Quantum Simulation of Spin Models

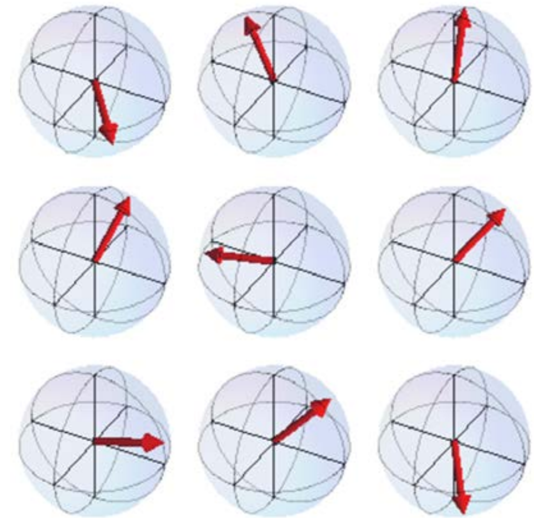
Ising (up-down)



XY (Compass)



XYZ (Heisenberg)



interaction term

$$J \sum_{(i,j)} \sigma_i^x \sigma_j^x$$

$$\sum_{(i,j)} J_x \sigma_i^x \sigma_j^x + J_y \sigma_i^y \sigma_j^y$$

$$\sum_{(i,j)} J_x \sigma_i^x \sigma_j^x + J_y \sigma_i^y \sigma_j^y + J_z \sigma_i^z \sigma_j^z$$

+ magnetic field term, e.g. $B \sum_{i=1}^{n} \sigma_i^z$

Potential applications in physics, chemistry and material science.

Number of spins > 100 → classical simulations intractable

Digital Quantum Simulation

model Hamiltonian
to be realized in ‘software’

realizable in ‘hardware’

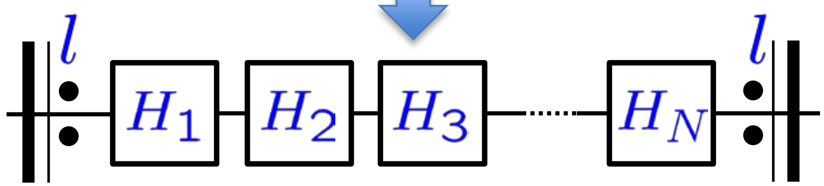
$$H = \sum_{k=1}^{N} H_k$$

time evolution:

Suzuki-Lie-Trotter approximation

higher-order terms

$$\exp(-iHt) = \left(\prod_{k=1}^{N} \exp(-iH_k t/l) \right)^l + E(t,l)$$



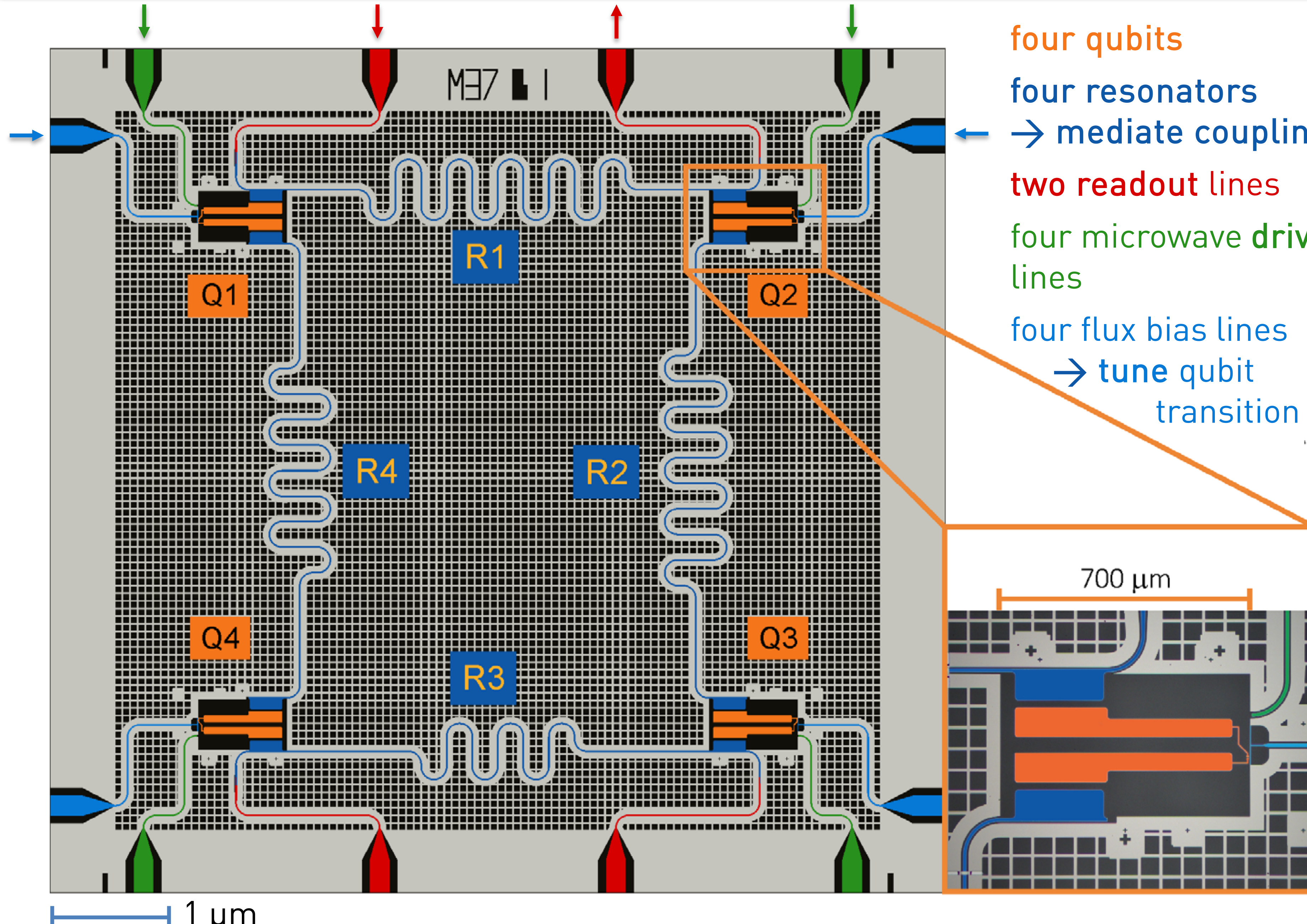
“digital quantum simulation”

$E(t,l) \to 0$ if $l \to \infty$

works for all Hamiltonians with local interactions (universal)

Lloyd, S. *Science* **273**, 1073 (1996)

4 Qubit Device with Nearest Neighbor Connectivity



four qubits

four resonators
→ mediate coupling

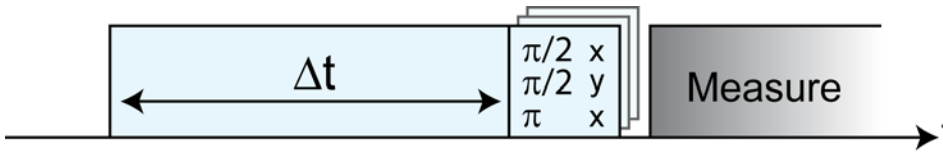
two readout lines

four microwave **drive** lines

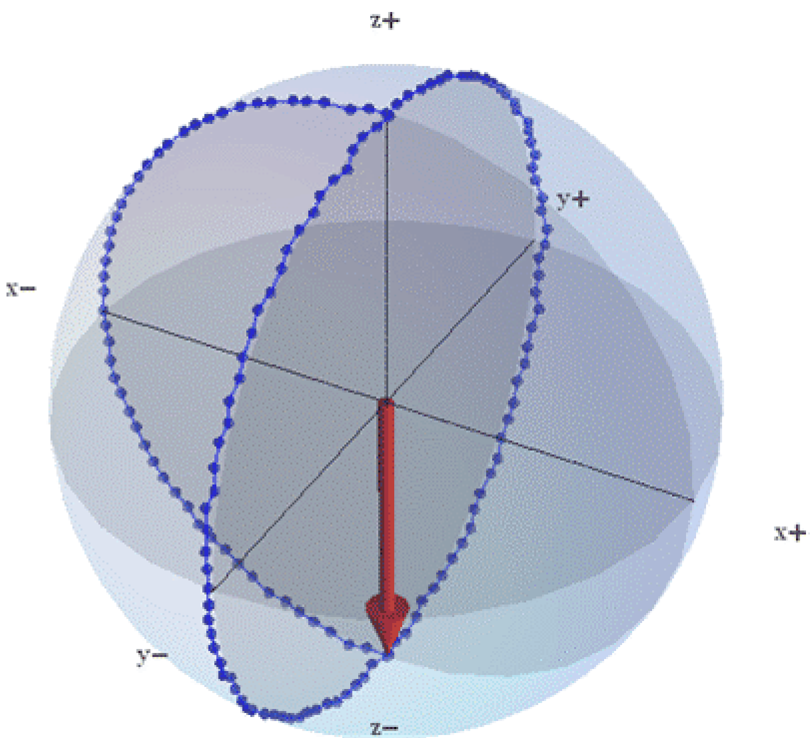
four flux bias lines
→ **tune** qubit transition

Single Qubit Gates

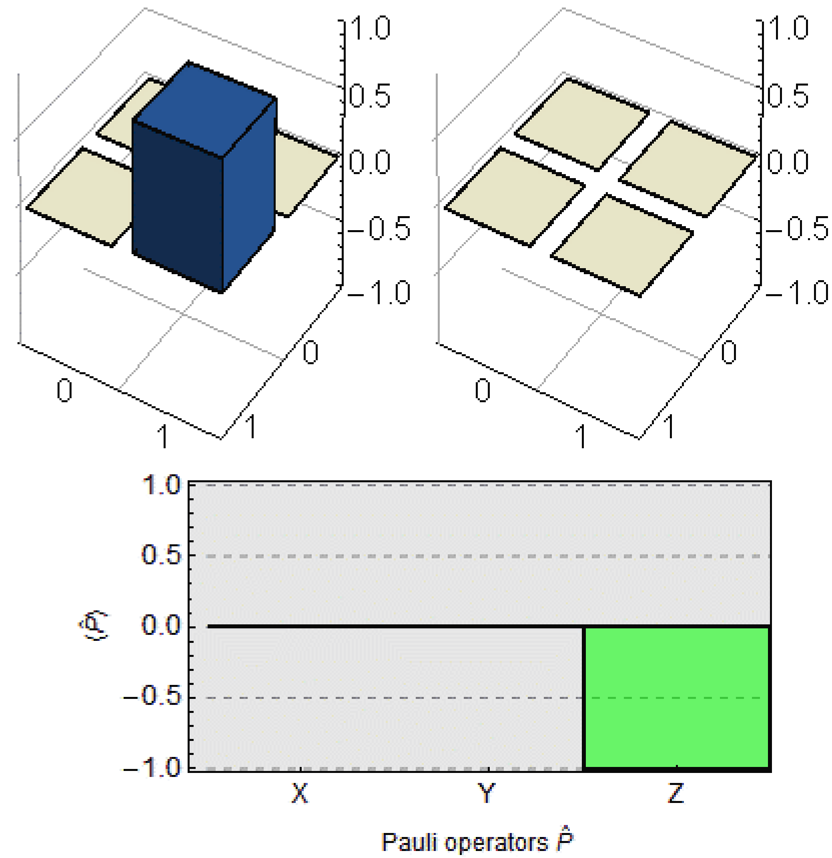
Pulse sequence for qubit rotation and readout:



experimental Bloch vector:



experimental density matrix and Pauli set:

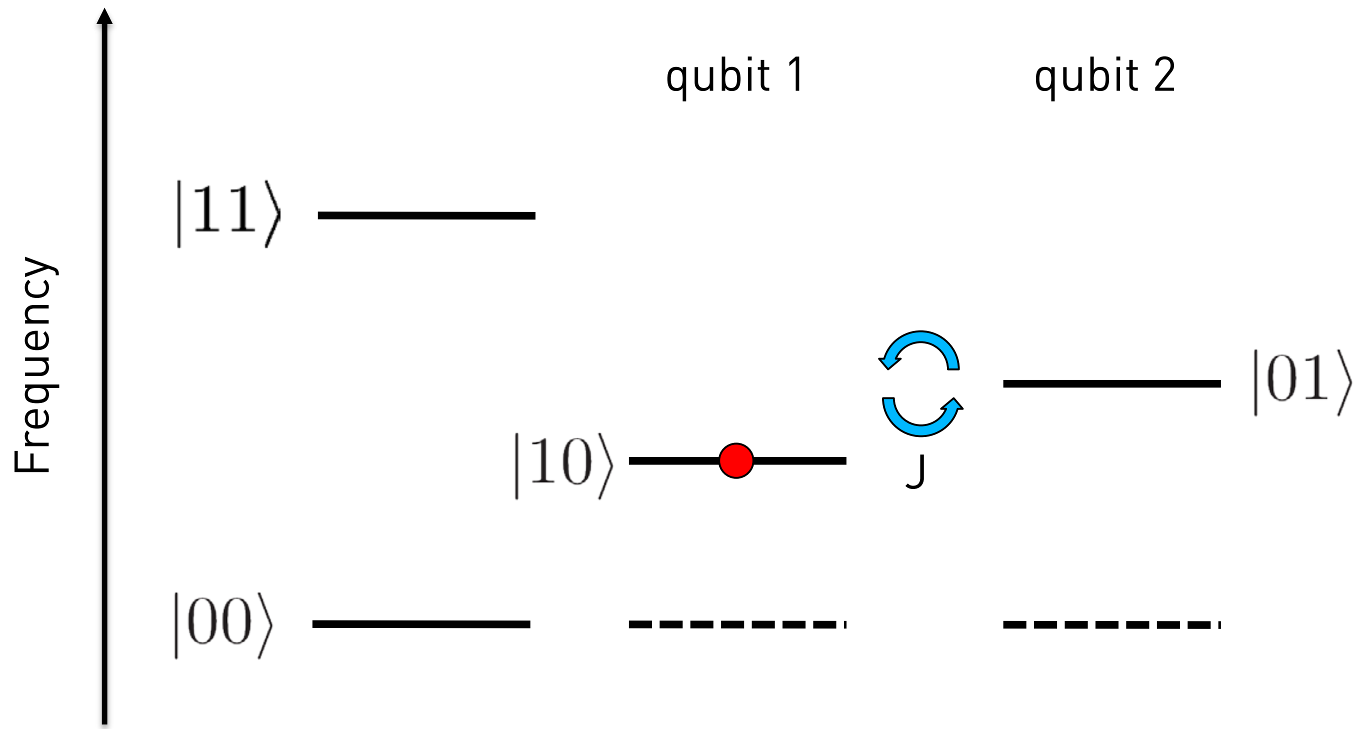


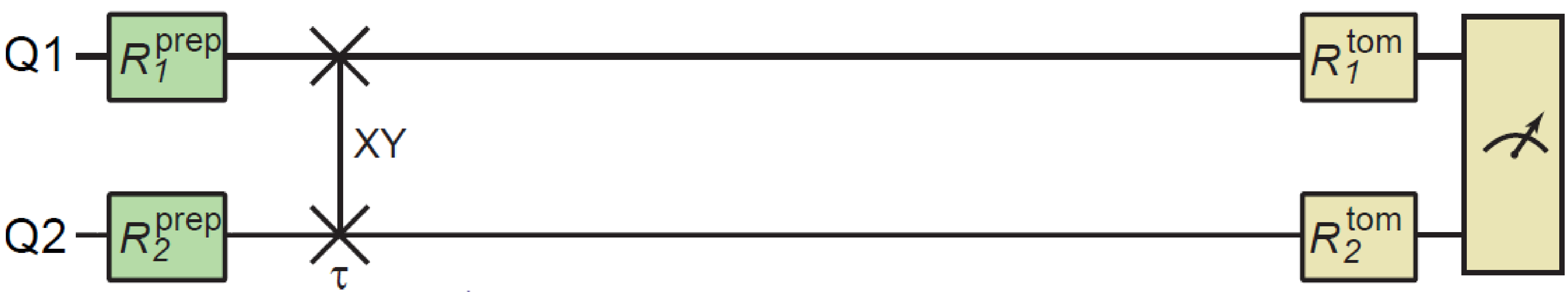
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

XY Interaction (Hardware) Controlled by Detuning

$$H_{2Q} = -\frac{1}{2}\omega_1\hat{\sigma}_1^z - \frac{1}{2}\omega_2\hat{\sigma}_2^z + J\left(\hat{\sigma}_1^+\hat{\sigma}_2^- + \hat{\sigma}_1^-\hat{\sigma}_2^+\right)$$

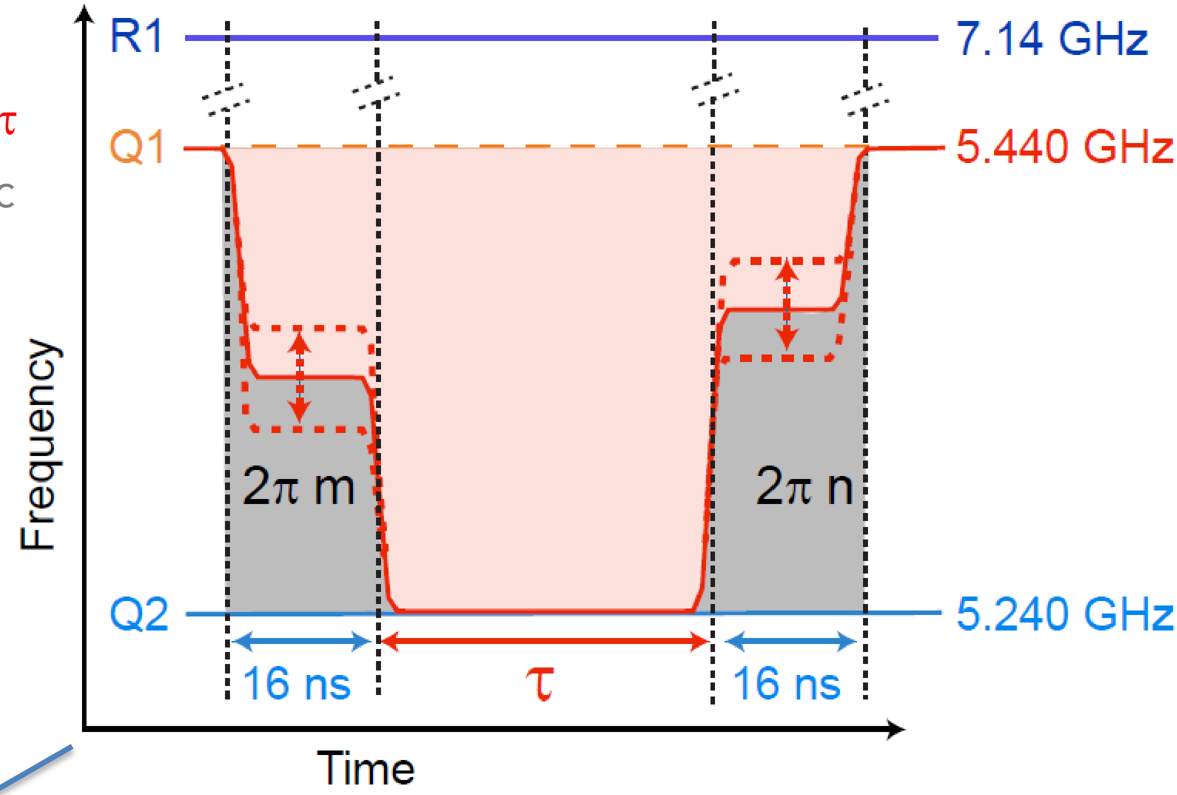




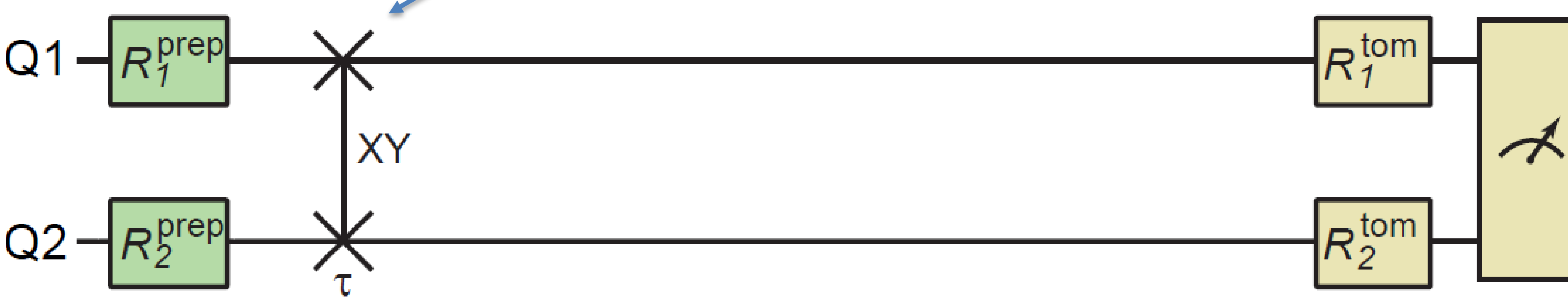
Frequency Control through Flux Bias

Profile of flux pulse:

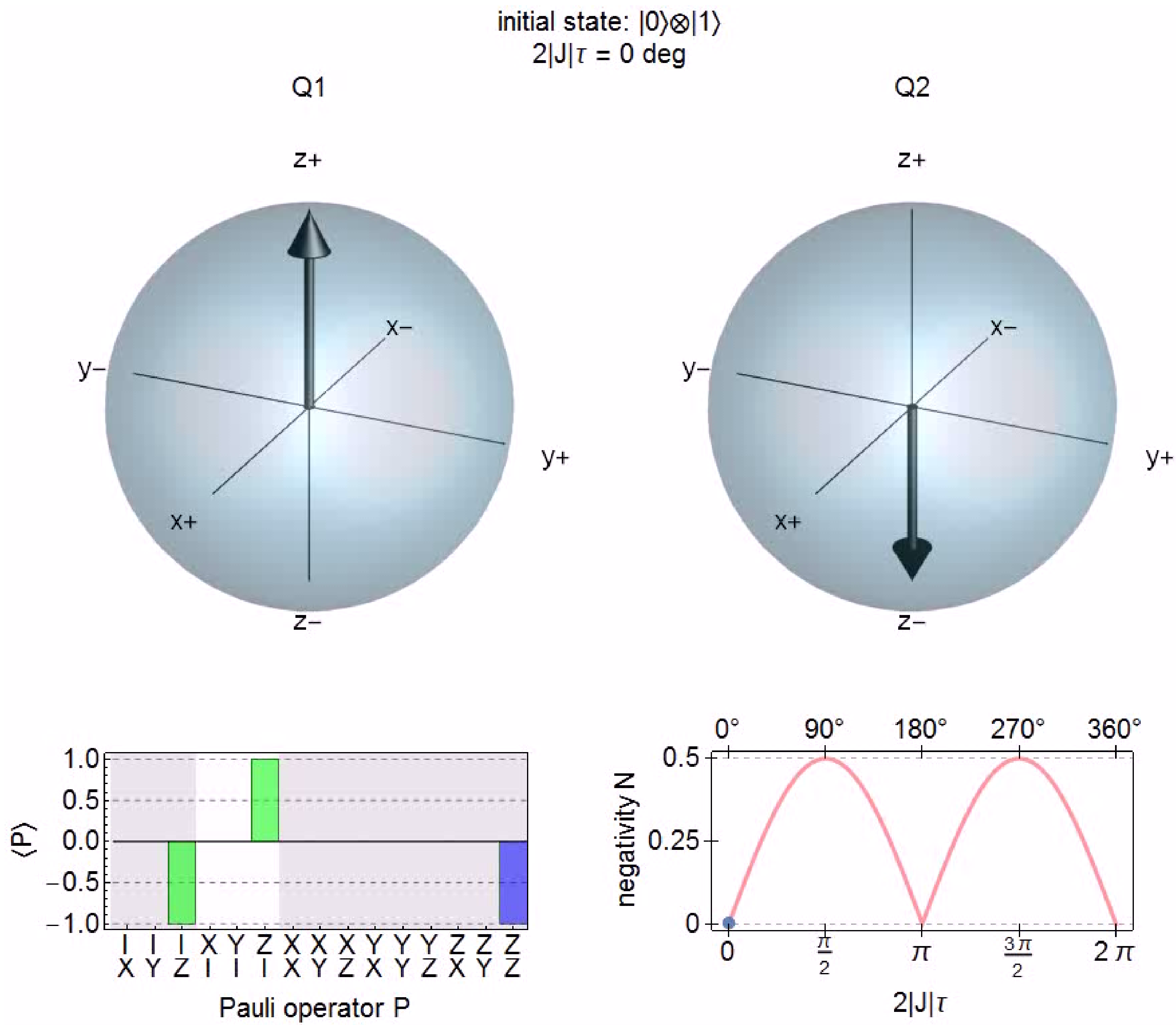
- tunable interaction time τ
- compensation of dynamic phase



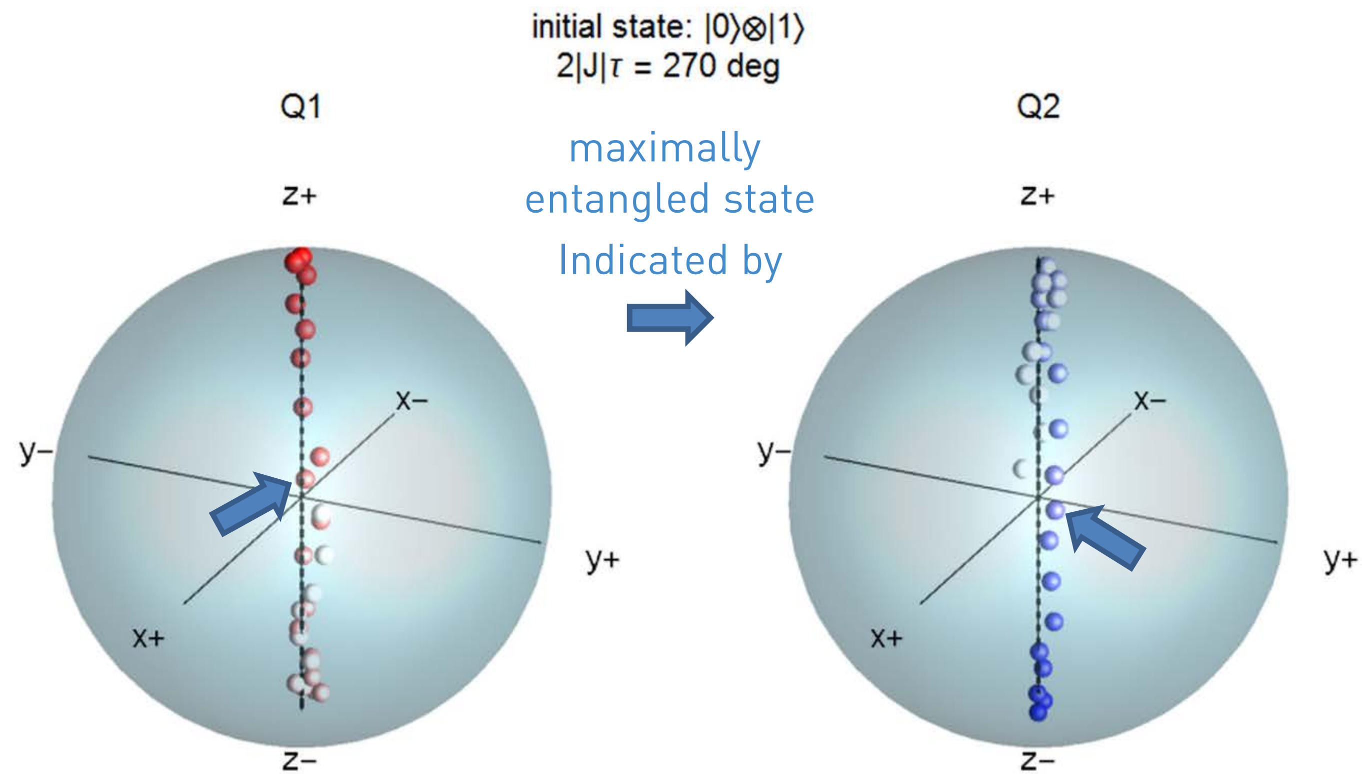
Circuit representation of gate sequence:



XY Interaction: Calculation

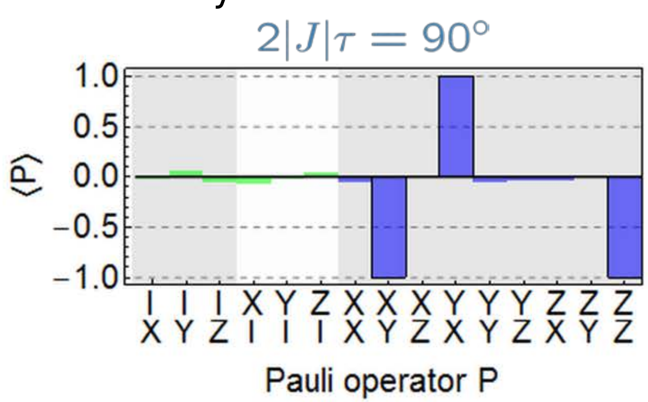


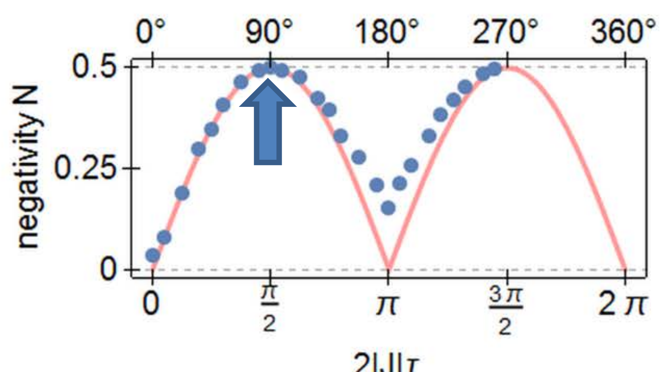
XY Interaction: Experimental Data



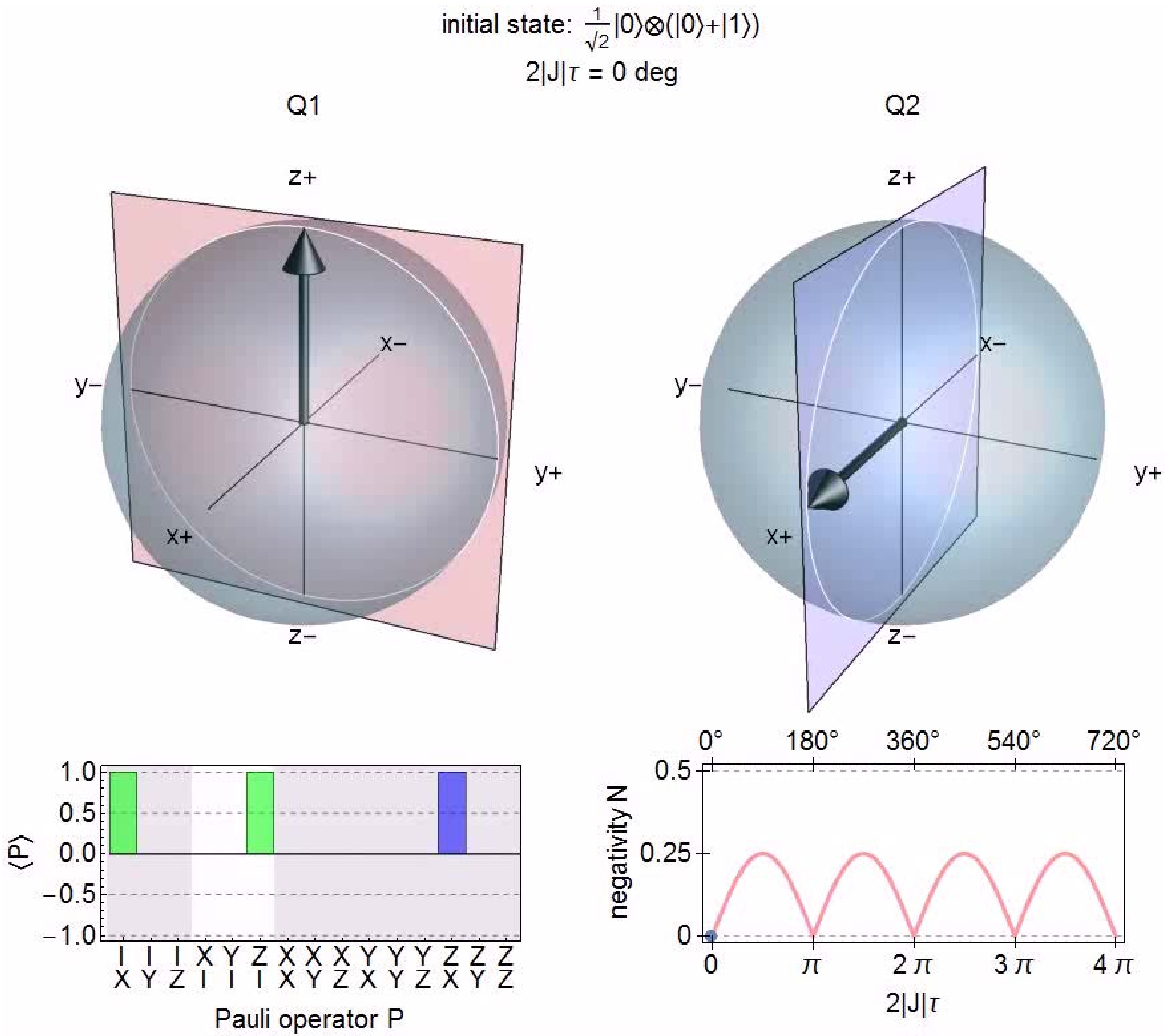
maximally entangled state Indicated by

state fidelity: 99.7 %





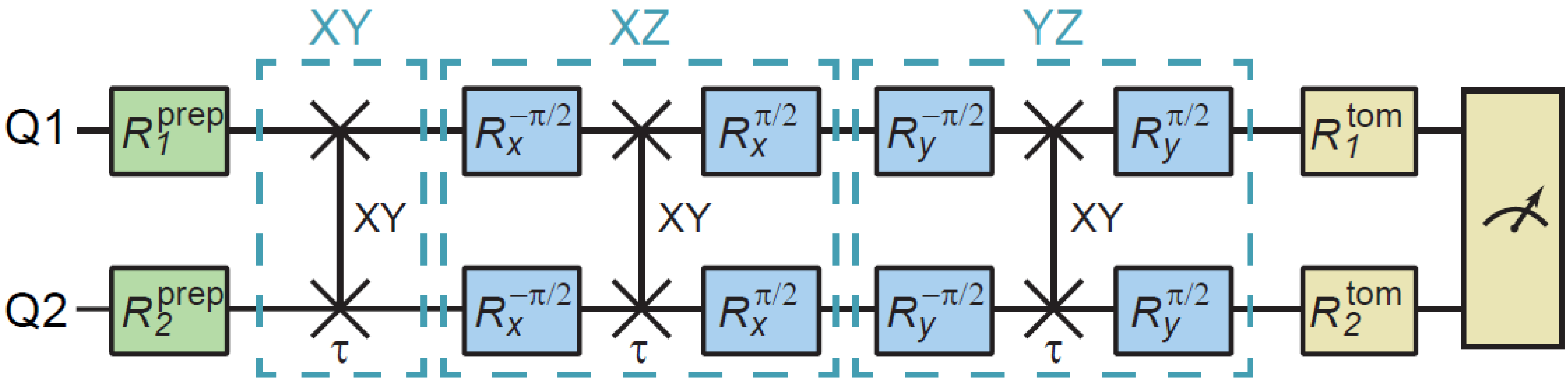
XY Interaction: Calculation



Digital Simulation of Heisenberg XYZ Interaction

Hamiltonian to be simulated: $H_{xyz} = J(\sigma_1^x \sigma_2^x + \sigma_1^y \sigma_2^y + \sigma_1^z \sigma_2^z)$

Gate sequence:



operators commute

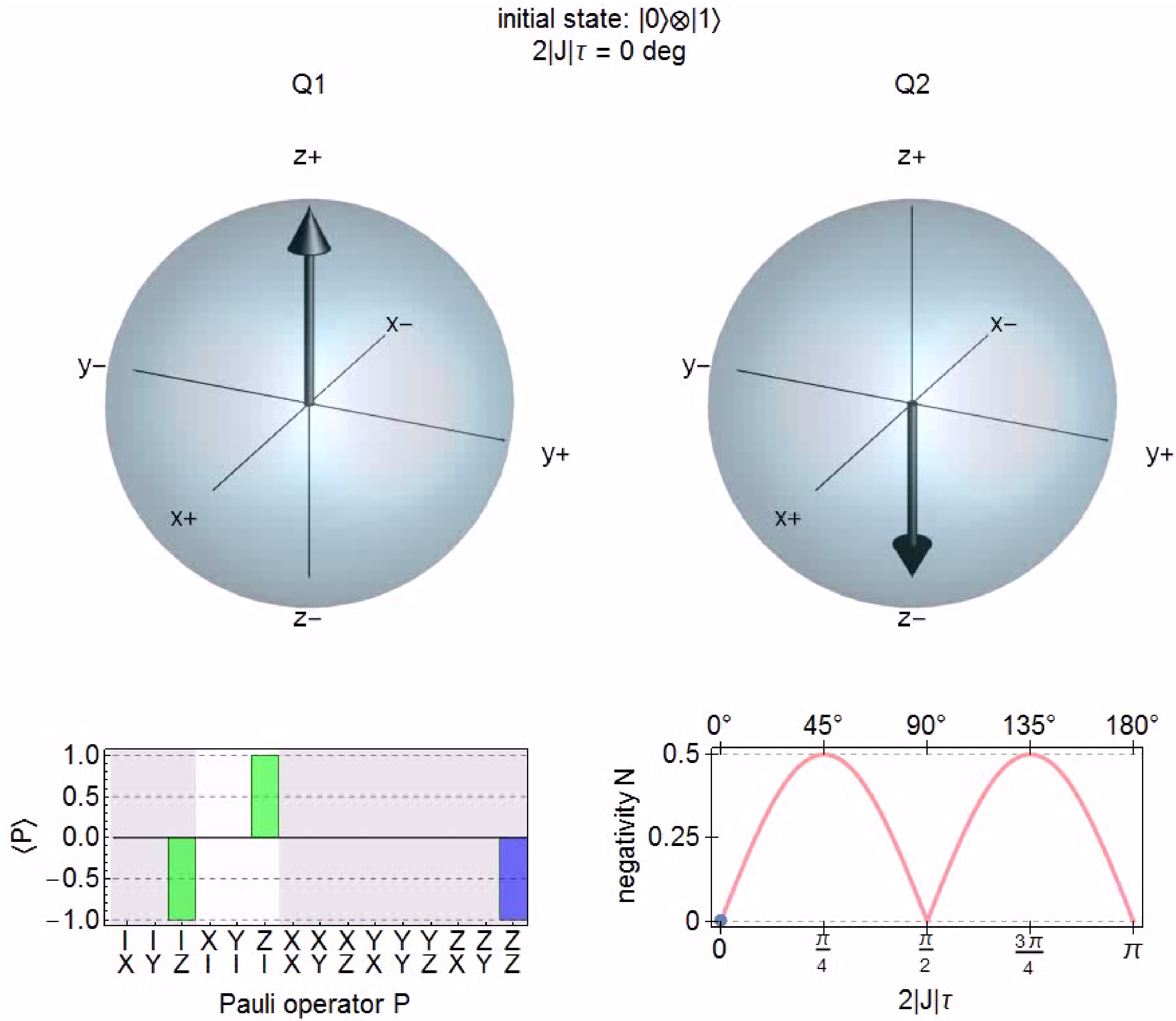
-> no Trotter decomposition required, exact result in one step

$$e^{-iH\tau} = e^{-iH_{yz}\tau} e^{-iH_{xz}\tau} e^{-iH_{xy}\tau}$$

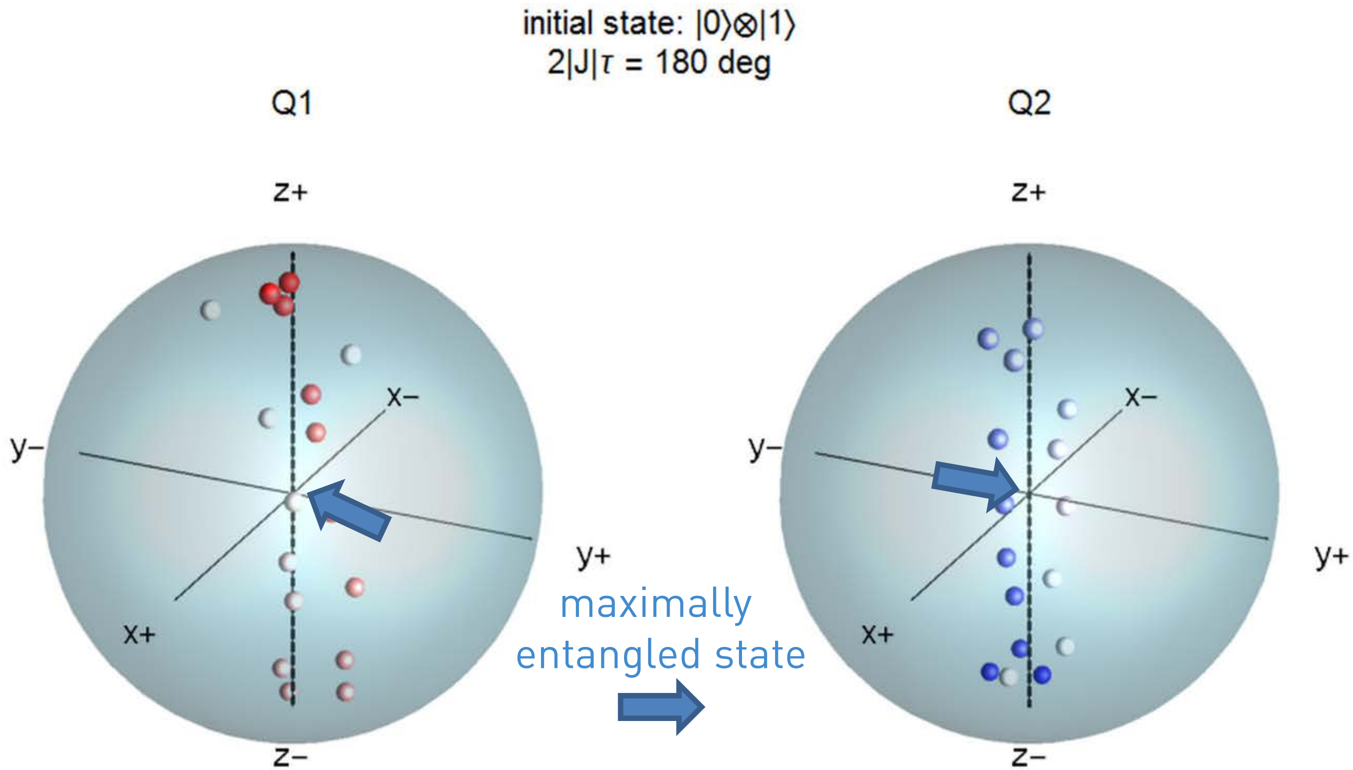
$$= e^{-i(H_{yz}+H_{xz}+H_{xy})\tau} = e^{-i\ H_{xyz}\tau}$$

Las Heras, U., et al. *Phys. Rev. Lett.* **112,** 200501 (2014)

Heisenberg XYZ Interaction: Calculation

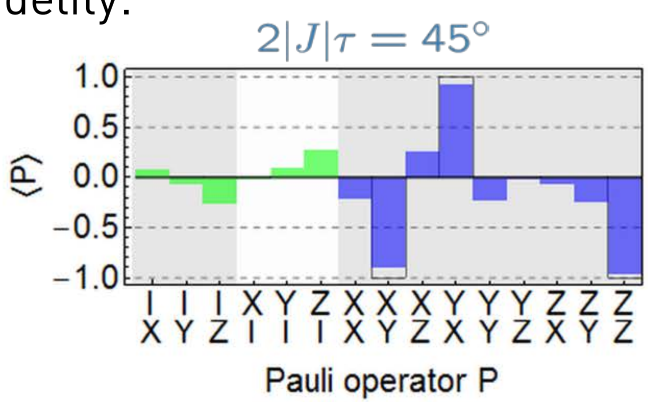


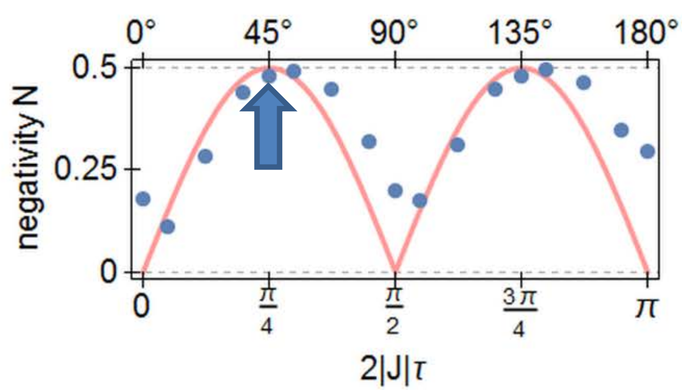
Heisenberg XYZ Interaction: Experimental Data



maximally entangled state

state fidelity:
94.7 %





Salathé, Y. *PRX* **5**, 021027 (2015)

Heisenberg XYZ Interaction: Calculation

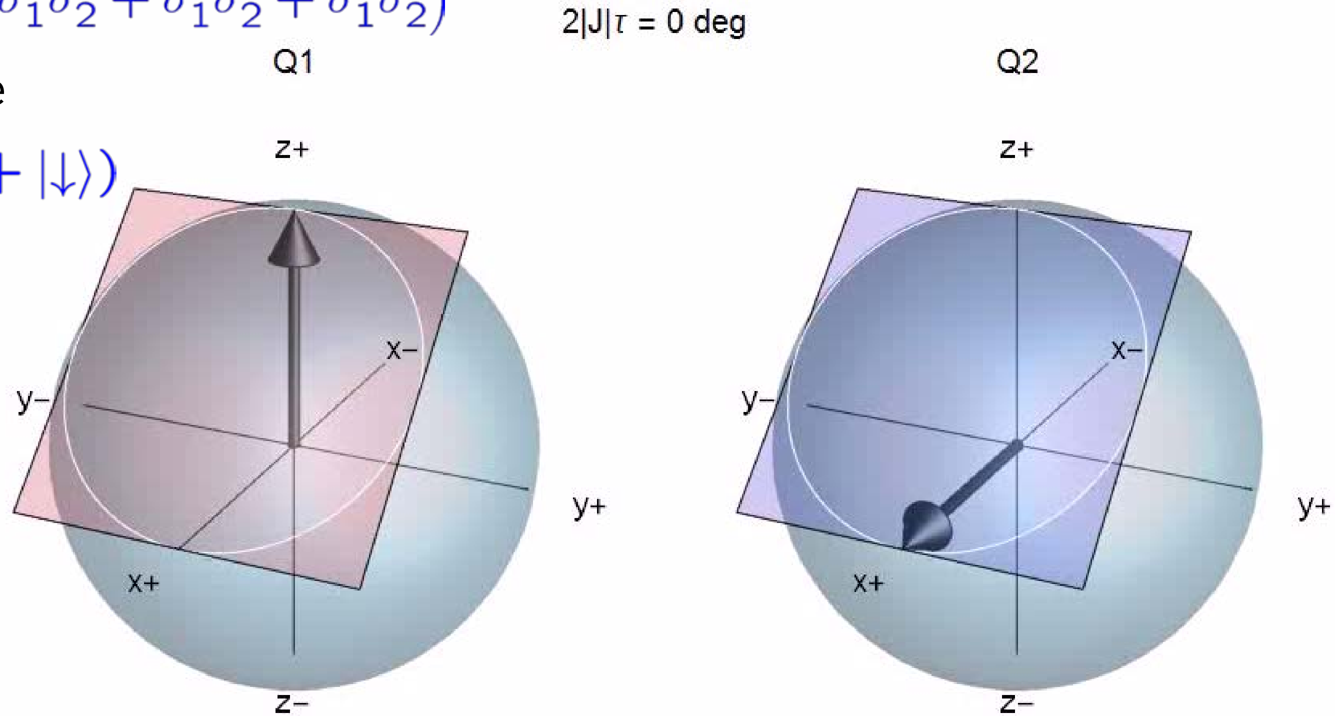
$$H_{xyz} = J\left(\sigma_1^x\sigma_2^x + \sigma_1^y\sigma_2^y + \sigma_1^z\sigma_2^z\right)$$

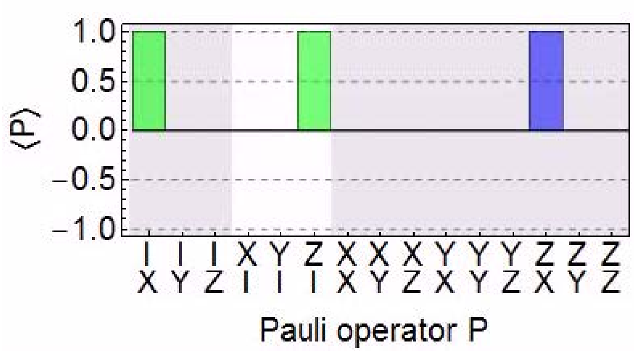
initial state

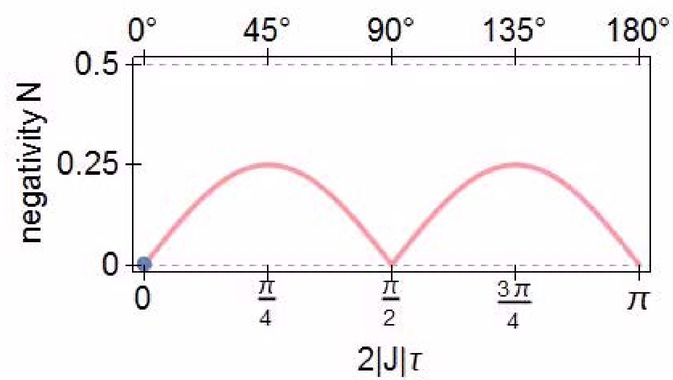
$$\frac{1}{\sqrt{2}}|\uparrow\rangle(|\uparrow\rangle + |\downarrow\rangle)$$

red: Q1

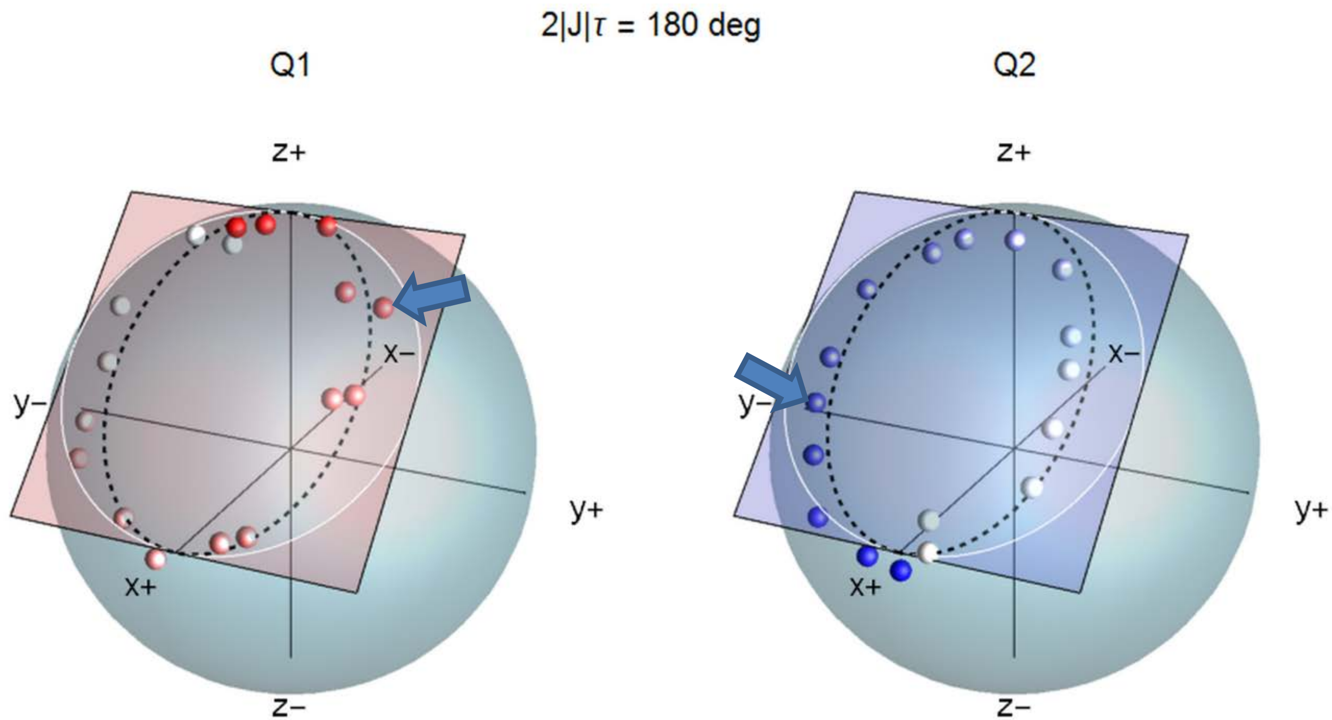
blue: Q2



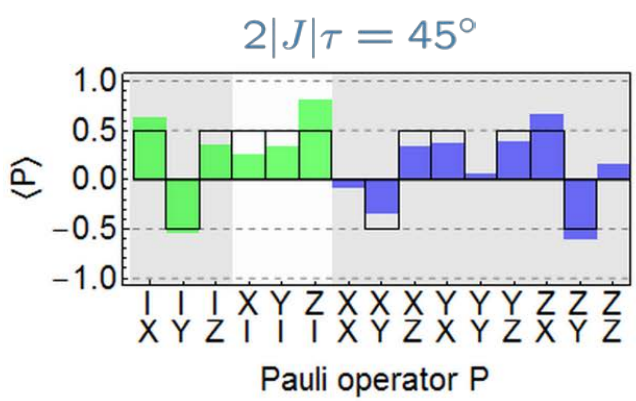


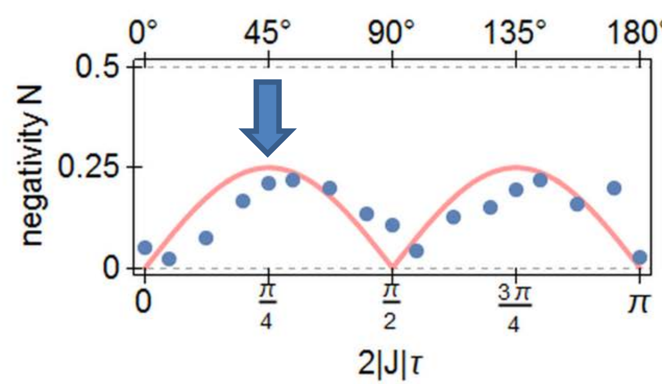


Heisenberg XYZ Interaction: Experimental Data



state fidelity: 95.3 %





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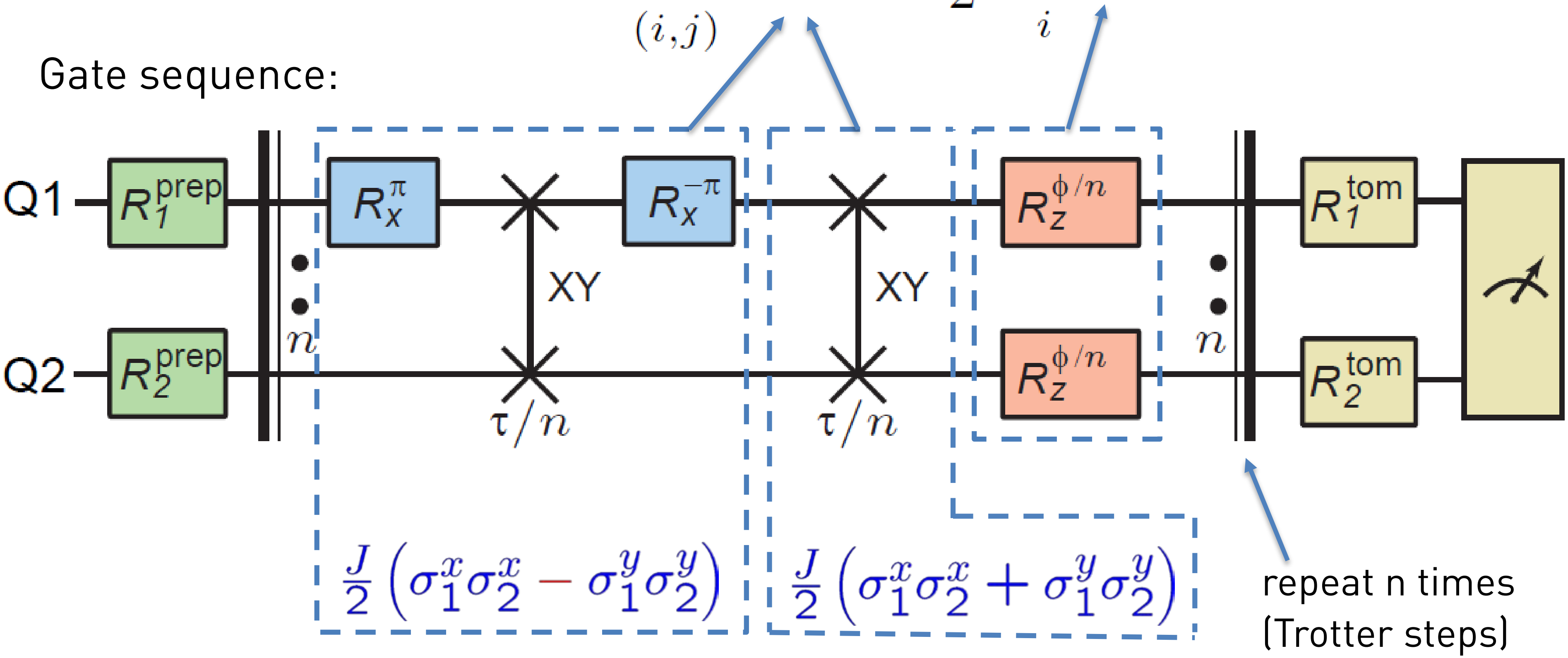
Ising Model with External Field

Hamiltonian to be simulated:

$$H_I = J \sum_{(i,j)} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z$$

Gate sequence:



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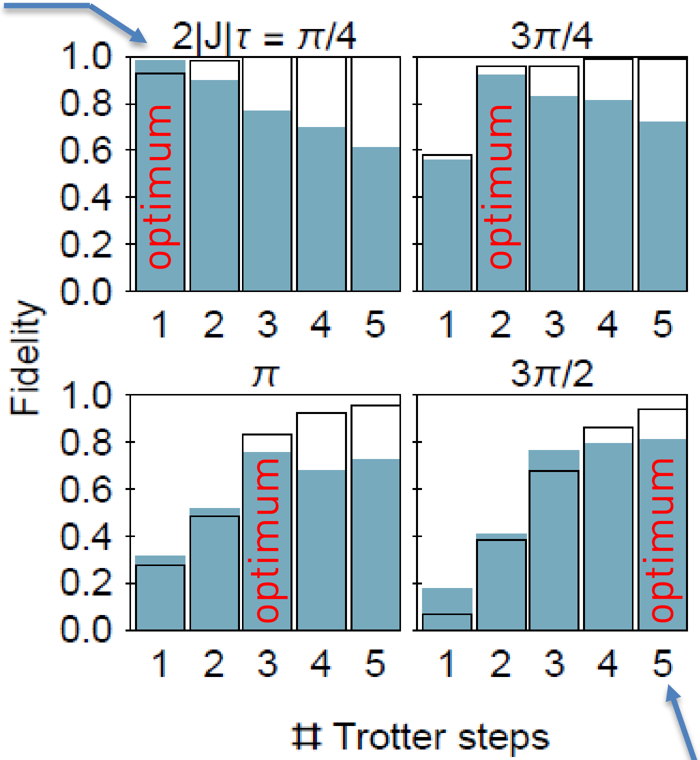
Fidelity of Simulation *vs.* Trotter Step and Int. Angle

Fidelity of simulated state: $F = \left(\mathrm{Tr}\sqrt{\sqrt{\hat{\rho}_{\mathrm{theo}}}\hat{\rho}_{\mathrm{meas}}\sqrt{\hat{\rho}_{\mathrm{theo}}}}\right)^2$

fewer Trotter steps needed for **small** phase angles (higher-order terms are less important)

Optimal final state fidelity reached at **finite** number of Trotter steps due to limited fidelity individual gates



wire frame: ideal Trotter fidelity

colored bars: experimental fidelity

more Trotter steps needed for **large** interaction phase angles (higher order terms are important)

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Summary and Outlook

Conclusions:

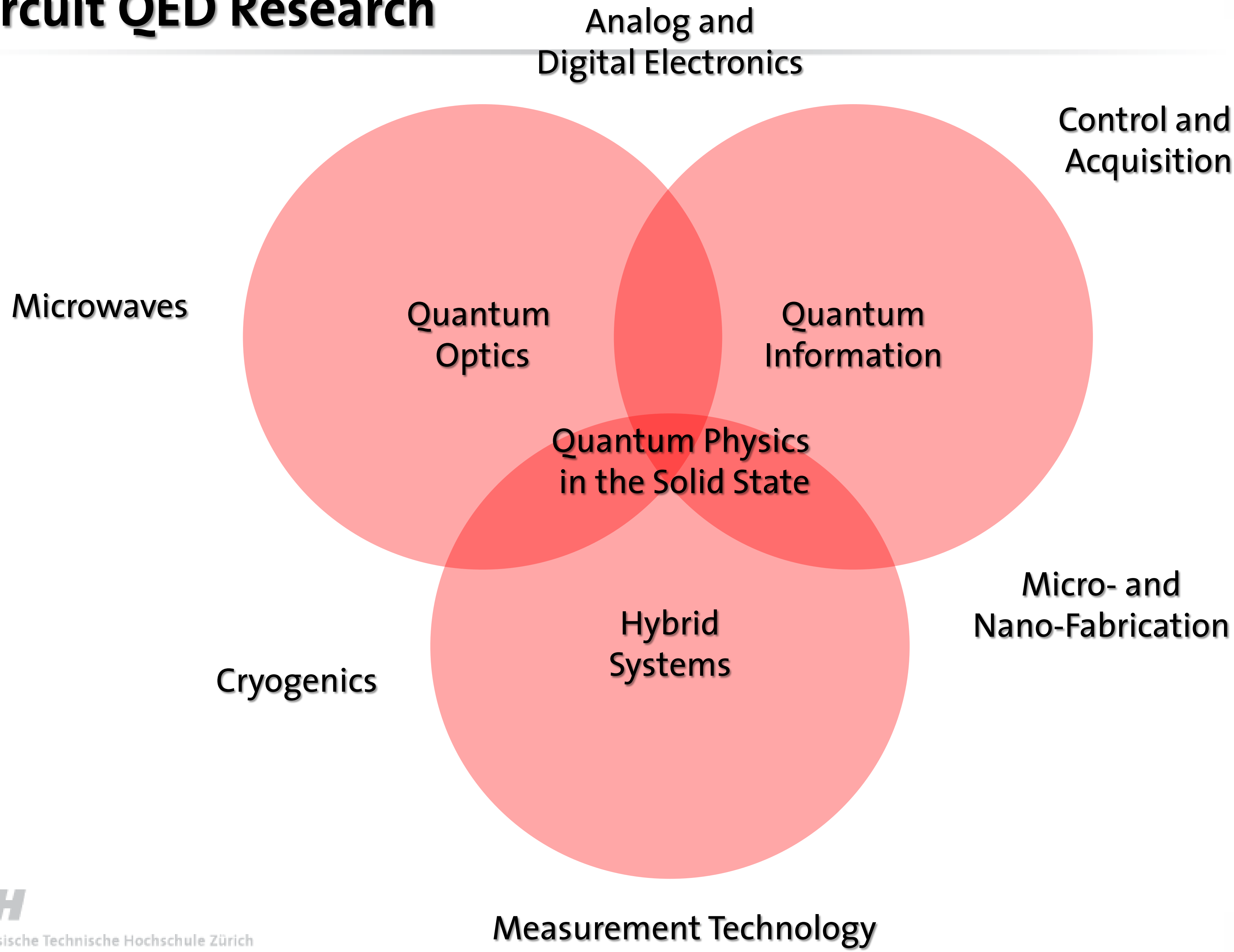
- one of the first digital quantum simulation with superconducting qubits
- simulated time-evolution of paradigmatic spin models
- typical state fidelities above 80% for XYZ and Ising
- used up to 10 two-qubit gates with a continuous interaction parameter combined with 25 single-qubit gates
- challenge: gate calibration with continuous control parameter

Interesting perspectives:

- simulation of Hamiltonians with local interactions using Trotter decomposition
- combine analog and digital methods
- explore time-dependent Hamiltonians
- use bosonic building blocks explicitly
- expand to larger number of spins

Collaboration: Salathé, Mondal, Oppliger, Heinsoo, Kurpiers, Potočnik, Mezzacapo, Las Heras, Lamata, Solano, Filipp, Wallraff *Phys. Rev. X* **5**, 021027 (2015)

Circuit QED Research



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incl. undergrad and summer students

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