Quantum Computing: Underneath the hood

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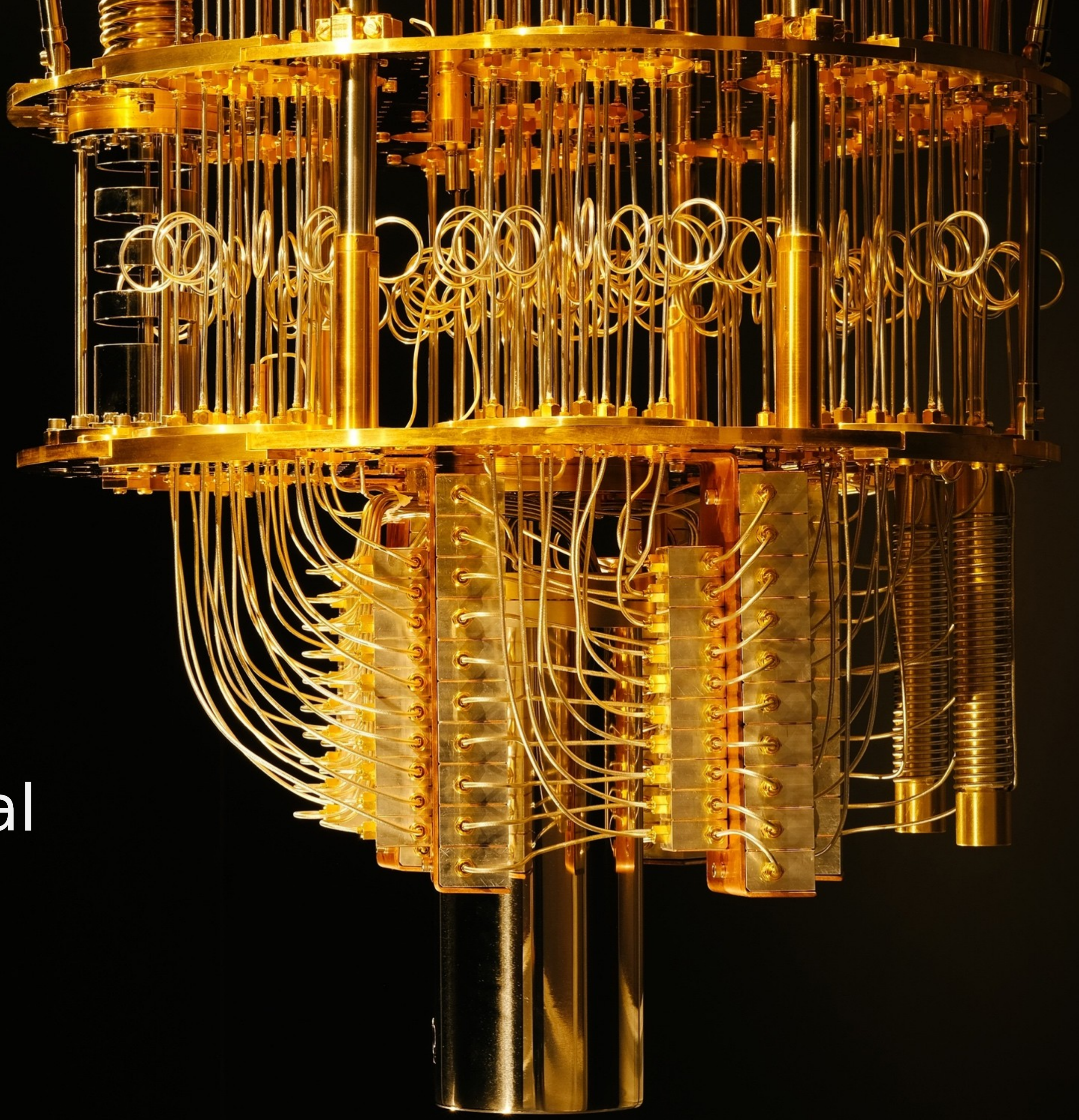
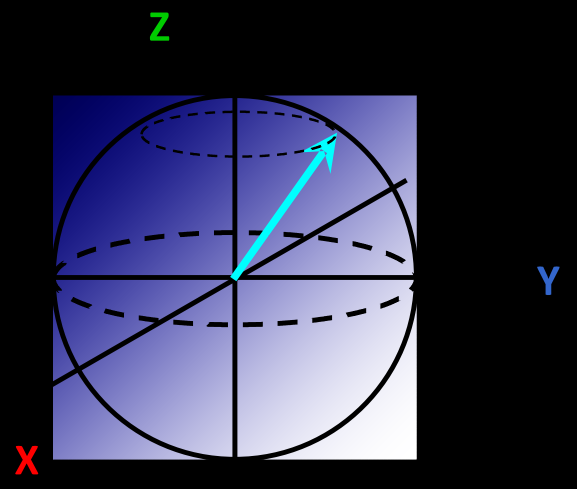
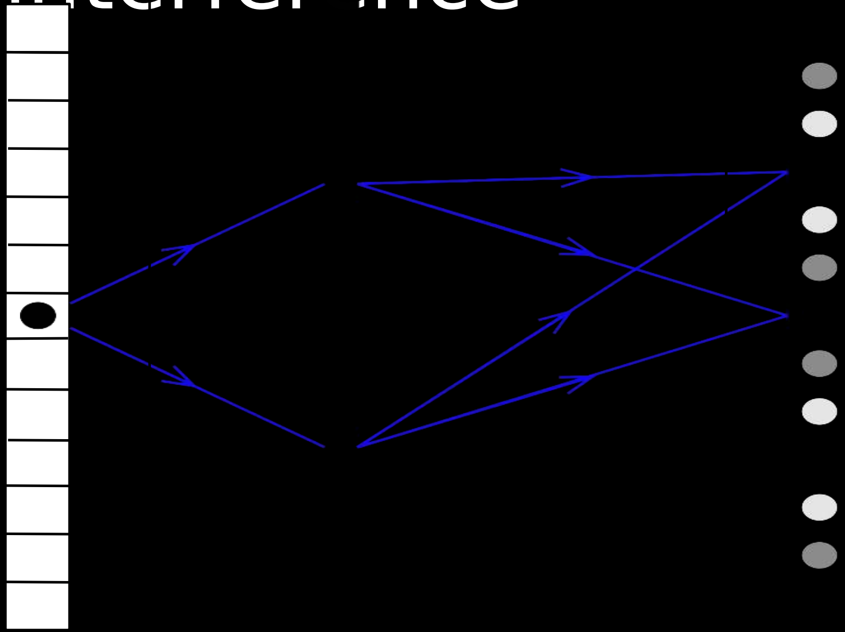
Hotchips 2020

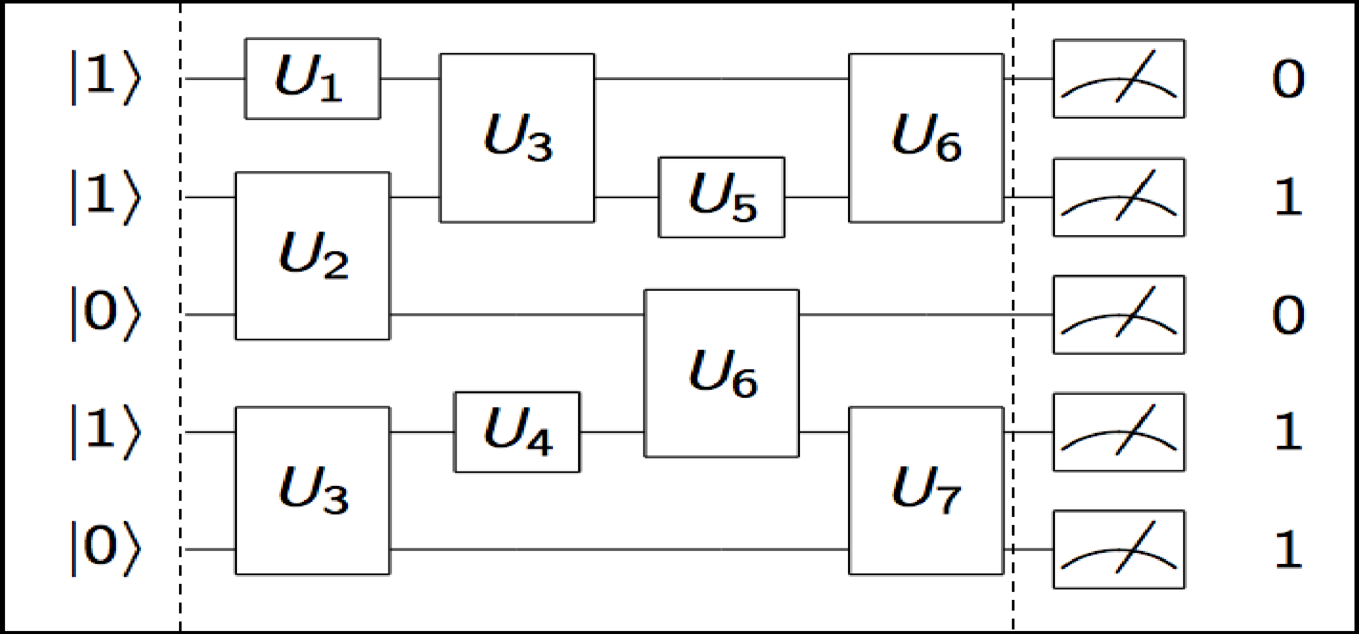


The Quantum Bit



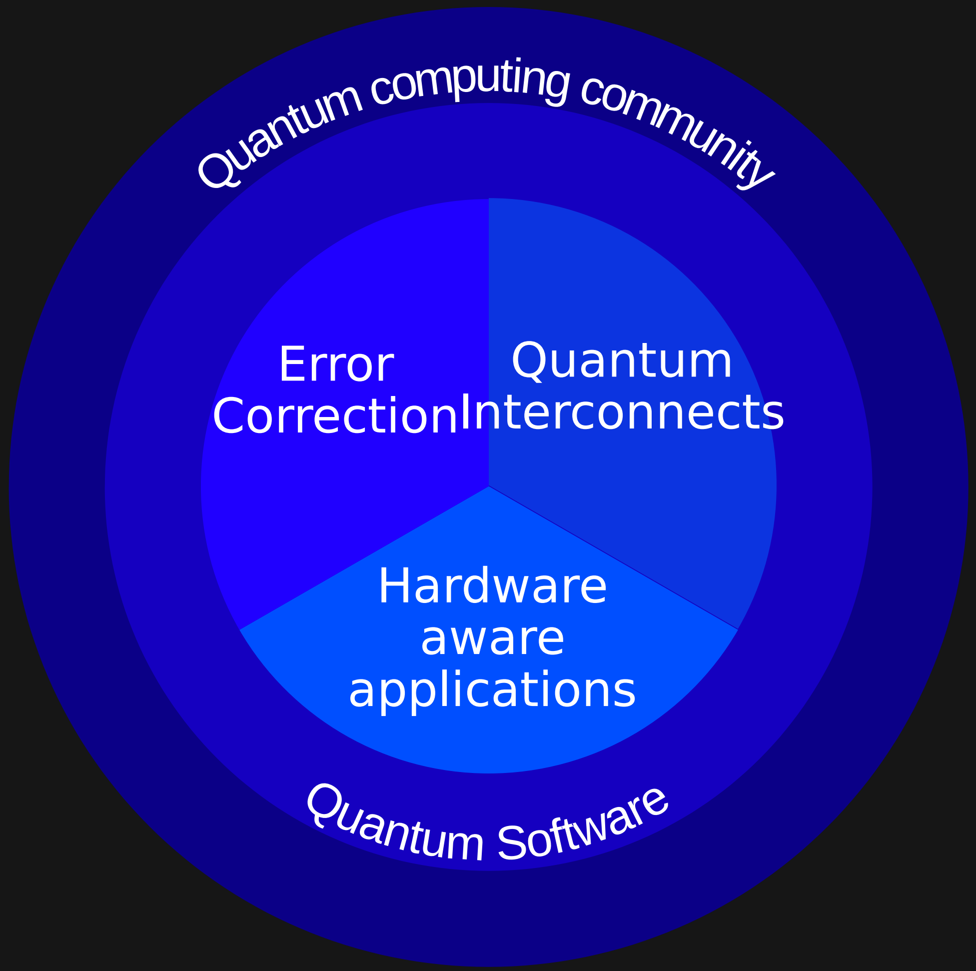
Quantum Computing: Extra power from interference





- Many computational paths from the initial state to each final state
- Each path accumulates a complex phase, e.g.
- Output probability is concentrated at the final states where (almost) all paths arrive with (approximately) the same phase.

The pillars of quantum computing



At the Core is hardware development

Improved fundamentals
- *coherence*
- *gate fidelity*
- *high on/off ratio*
- *Junction physics*

Improved systems
- *packaging and integration*
- *stable and reliable control systems*

Error correction
- *More efficient codes (long range interactions)*
- *Codes co-designed with hardware*

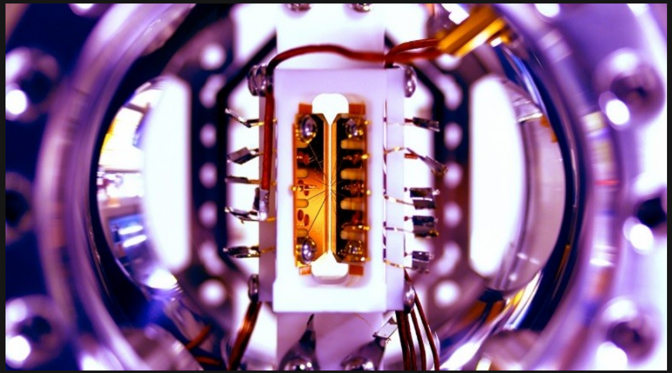
Quantum interconnects
- *Coupling to flying qubit*
- *Distributed compilers and correction*

Hardware aware applications
- *Based on complexity of underlying circuit*
- *Hardware co-designed with circuit*

Quantum Computing Technologies

What's your favorite qubit?

Ions



Credit: S. Debnath and E. Edwards/JQI
Monroe Group, University of Maryland/JQI

Photons

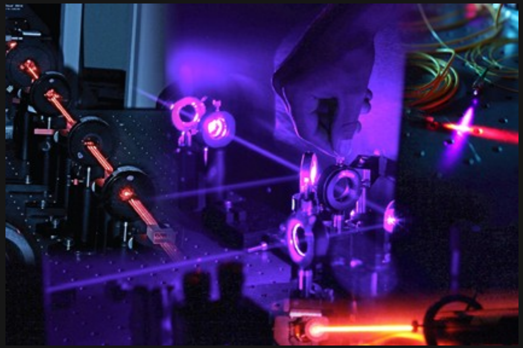


Image from the Centre for Quantum Computation & Communication Technology, credit Matthew Broome

Nanowires

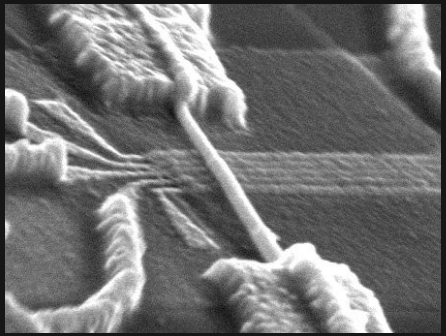


Image from Kouwenhoven Group, Delft

Neutral Atoms

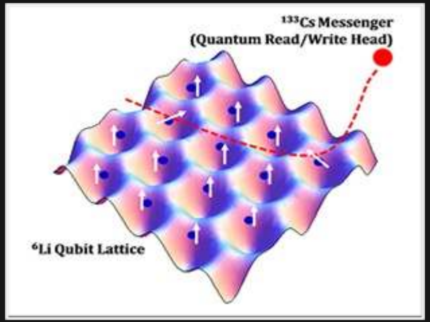
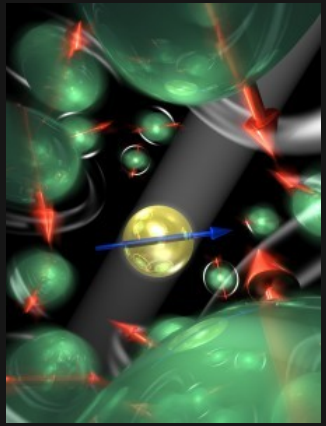


Image from Cheng Group, University of Chicago

Solid-state defects



NV Centers, Phosphorous in Si, SiC defects, etc.

Image from Hanson Group, Delft

Quantum dots

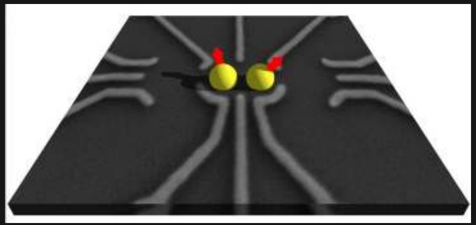
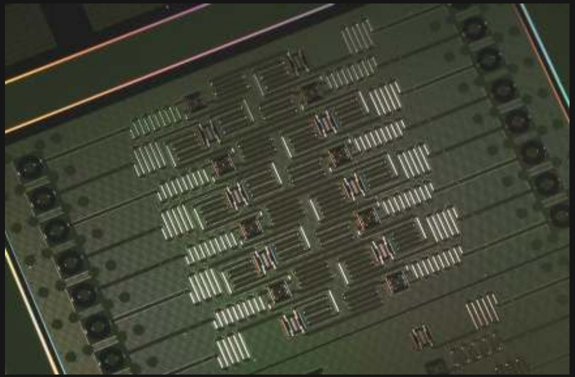
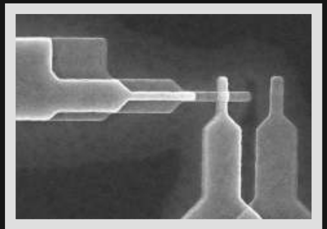


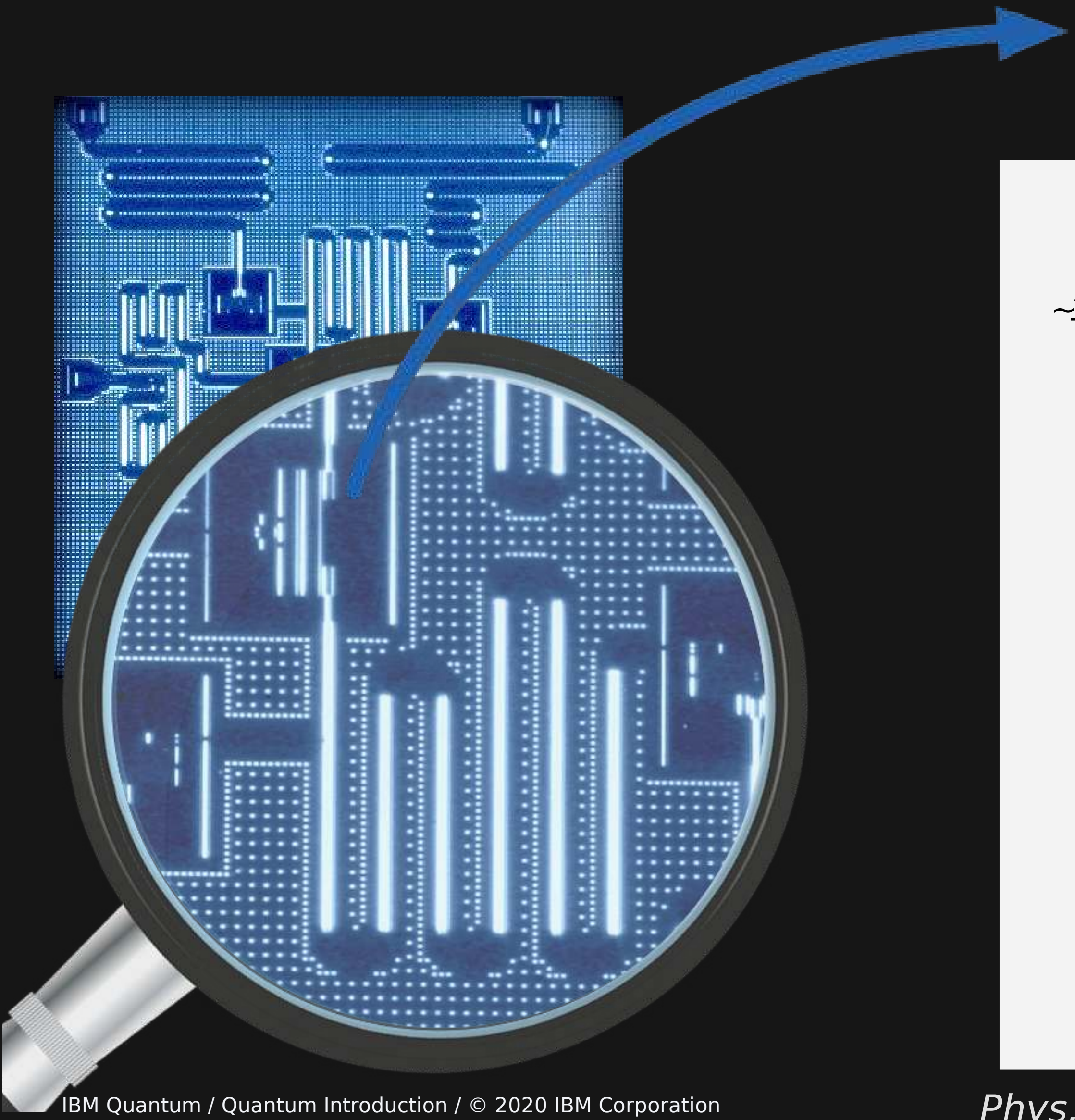
Image from Univ. Basel

Superconducting Circuit





The Transmon



Superconducting Qubit:

Josephson Junction as a non-linear inductor

SC → $\Psi_1 = e^{i\phi_1}$

~1nm barrier →

SC → $\Psi_2 = e^{i\phi_2}$

"Josephson Phase"

$\delta = \phi_1 - \phi_2$

→

$V = (\Phi_0 / 2\pi)\, \dot{\delta}$

$I_J = I_0 \sin \delta$

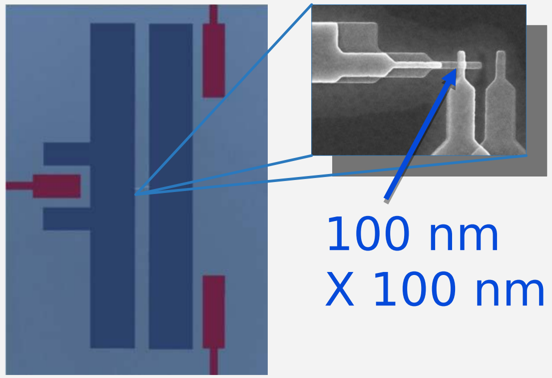
Josephson Relations

→

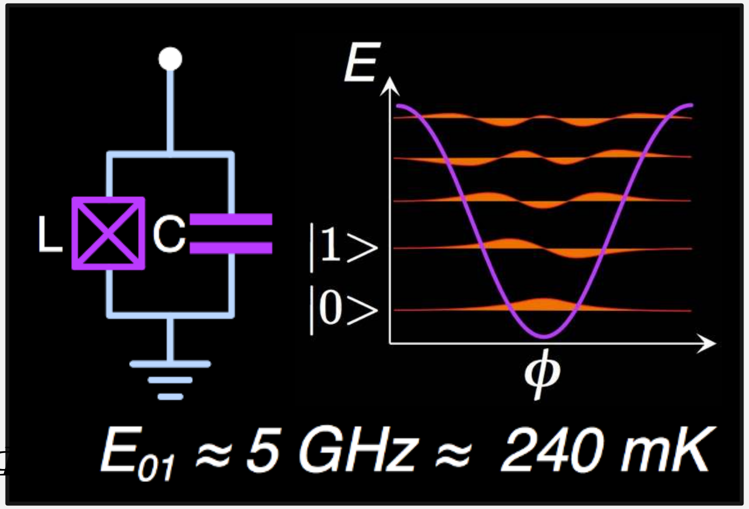
$\frac{dI}{dt} = \frac{1}{L} V(t)$

$L = \frac{\Phi_0}{2\pi I_0 \cos(\delta)}$

Non-linear inductor



$H = q^2 + Cos($



~300MHz anharmonicity

Phys. Rev. A **76**, 04319 (2007)

Qubits and Errors

A qubit is a quantum two-level system

Finite qubit coherence times

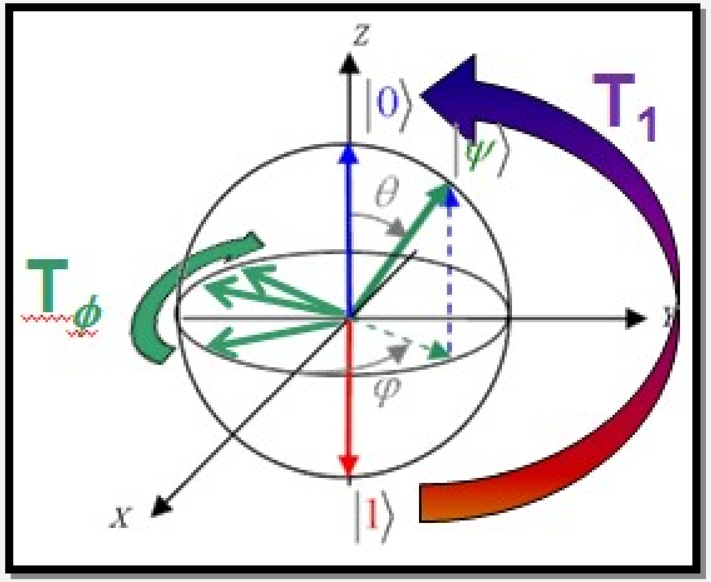
- T1: relaxation (dissipation - think resistor)
- Tf: dephasing (randomization of f)
    - Results from measurement (intentional or not)
- T2: parallel combination of above,

Imperfect control pulses

Spurious inter-qubit couplings

Imperfect qubit state measurements

➢ **Errors unavoidable —**
Will they destroy our computation?



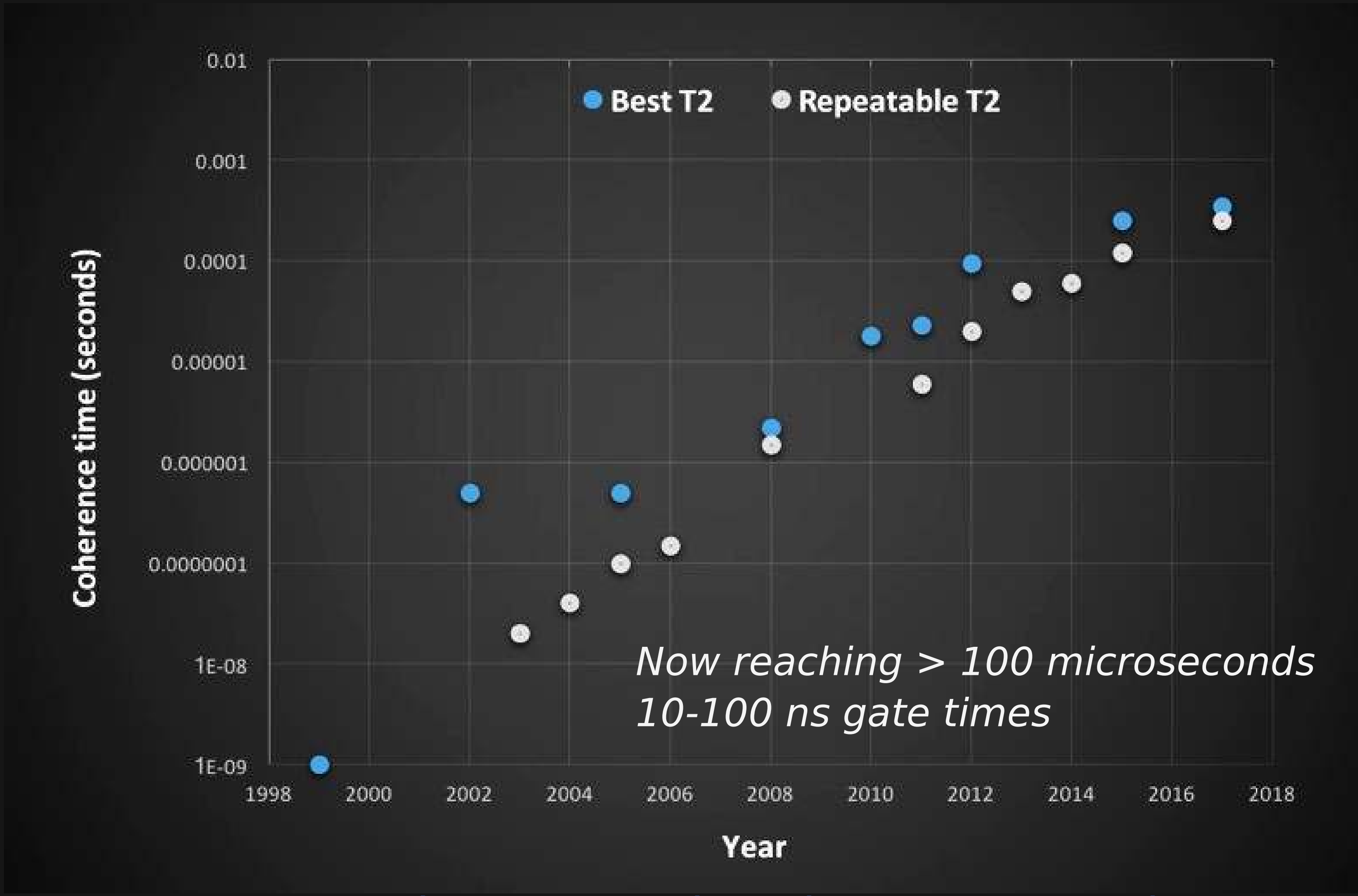
$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

Yes but there is error correction

Coherence times of superconducting qubits

Developments to extend coherence times

- Materials e.g. [2]
- Design and geometries e.g. [3]
- 3D transmon [4]
- IR Shielding [5,6],
- Cold normal metal cavities and cold qubits [7]
- High Q cavities [8]
- Titanium Nitride (collaboration with David Pappas @ NIST Boulder) [9] …
- ***Remarkable progress over the past decade***



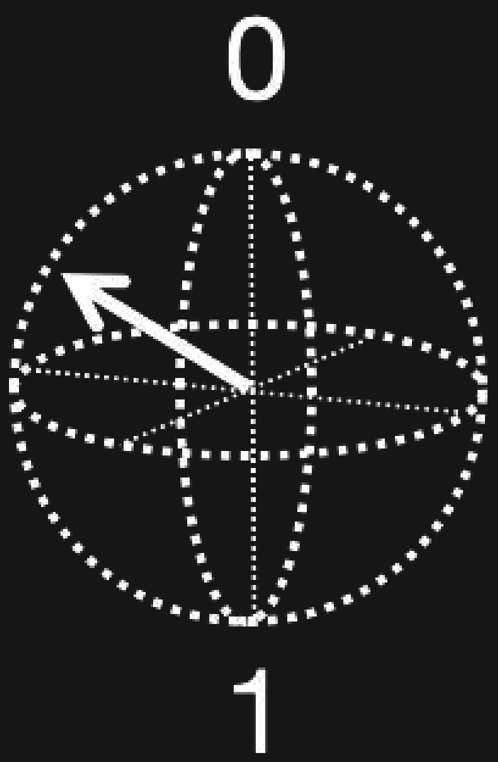
Steady progress in coherence over the years

But still need ~ 1 more order of magnitu

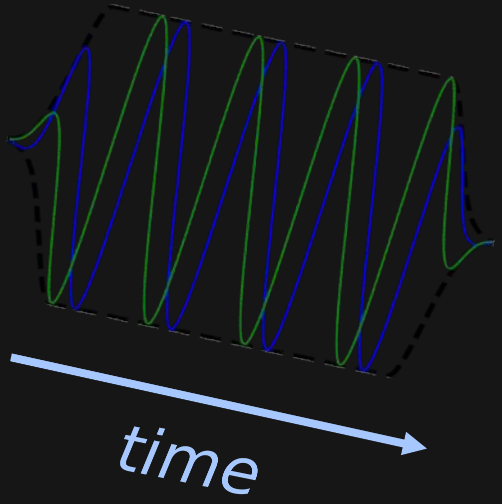
[2] J. Martinis et al., PRL 95 210503 (2005)
[3] K. Geerlings et al., APL 192601 (2012)
[4] H. Paik et al., PRL 107, 240501 (2011)
[5] R. Barends et al., APL 99, 113507 (2011)
[6] A. Corcoles et al., APL 99, 181906 (2011)
[7] C. Rigetti et al., PRB 86, 100506 (2012)
[8] M. Reagor et al., arXiv:1302.4408 (2013)
[9] J. Chang et al. APL 103, 012602 (2013)

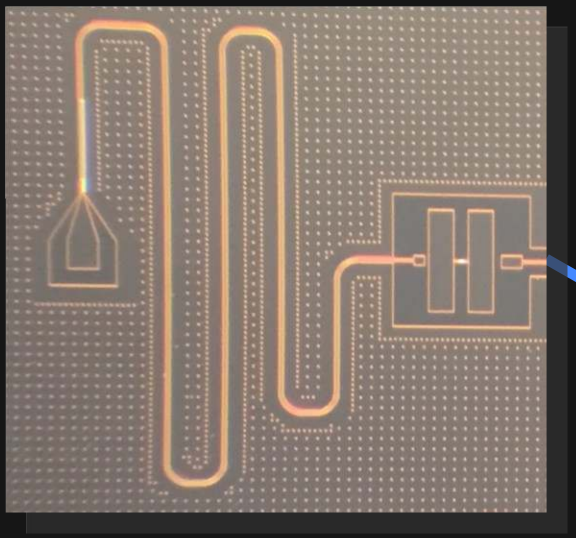
Controlling the Qubit State

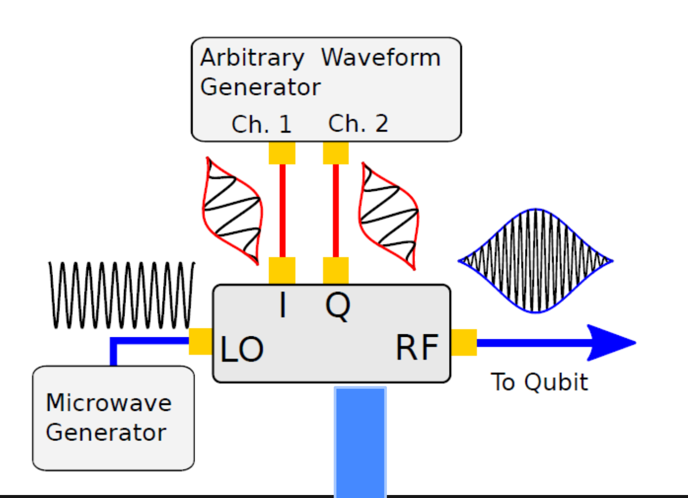
$$|\Psi\rangle = \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle$$

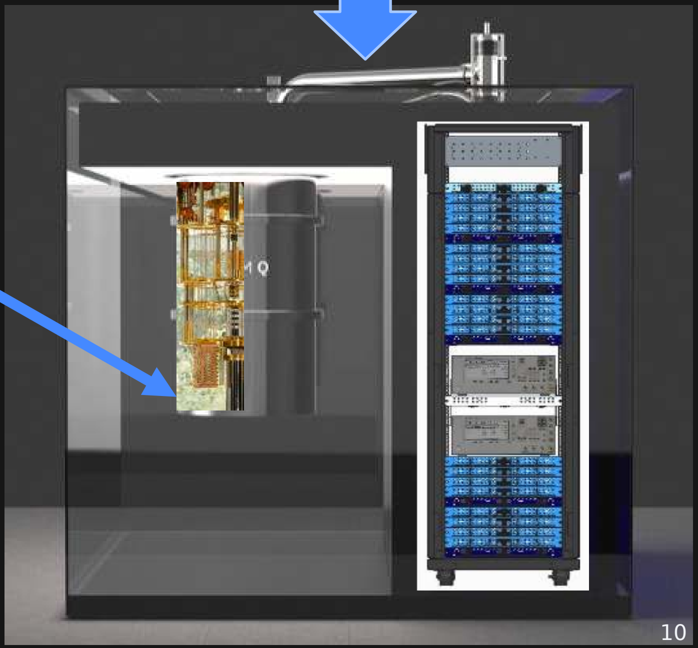


Drive around the Bloch sphere using microwave pulses (typically 10-50ns @ 5GHz)

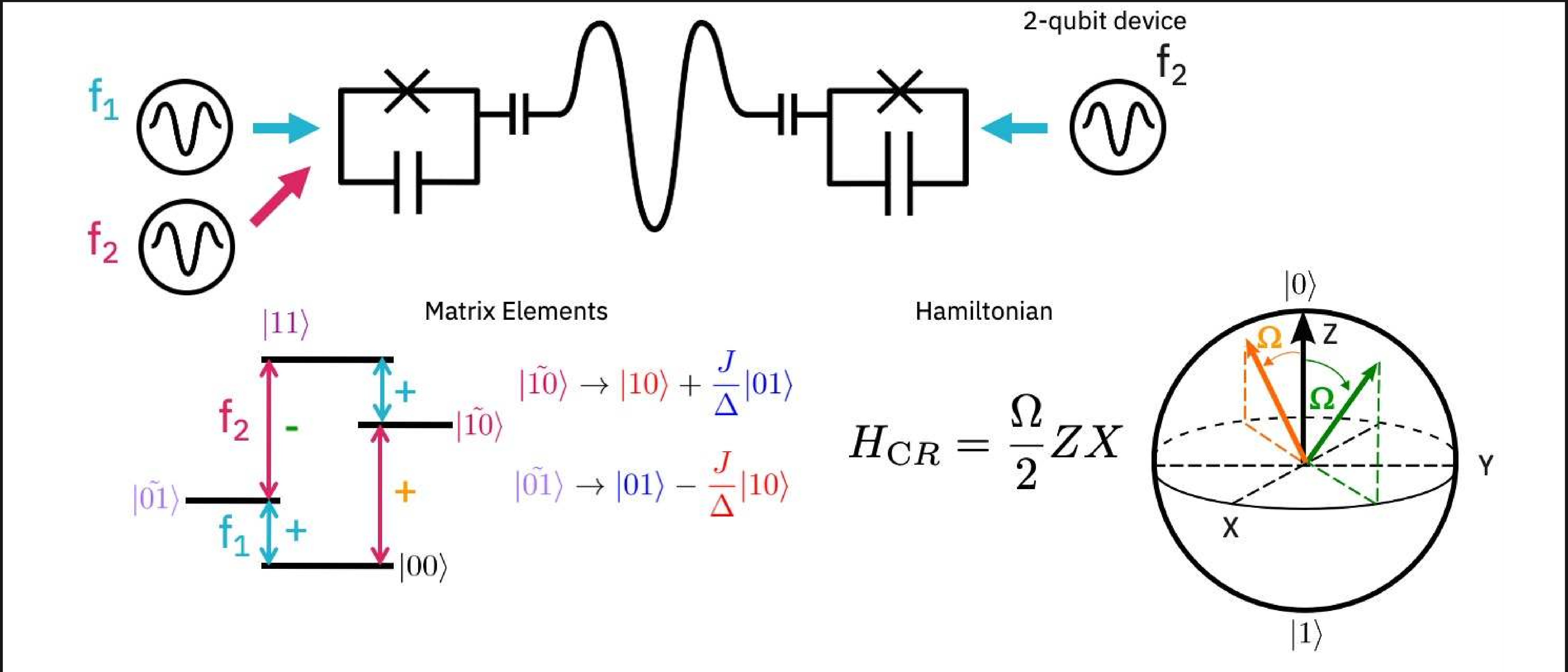








Two-qubit gates: Cross resonance



Theory: C. Rigetti and M. Devoret, Phys. Rev. B 81, 134507 (2010) Experiment J. Chow et al., Phys. Rev. Lett. 107, 080502 (2011)

Cross resonance: What can go wrong?

Always on ZZ between every qubit pair

Trying ways to eliminate this but residual ZZ will always be present

Strong microwave drive

T1 and T2 not what we think during the gate?

Stark shift on the control

ZI

Stark shift on spectator qubits

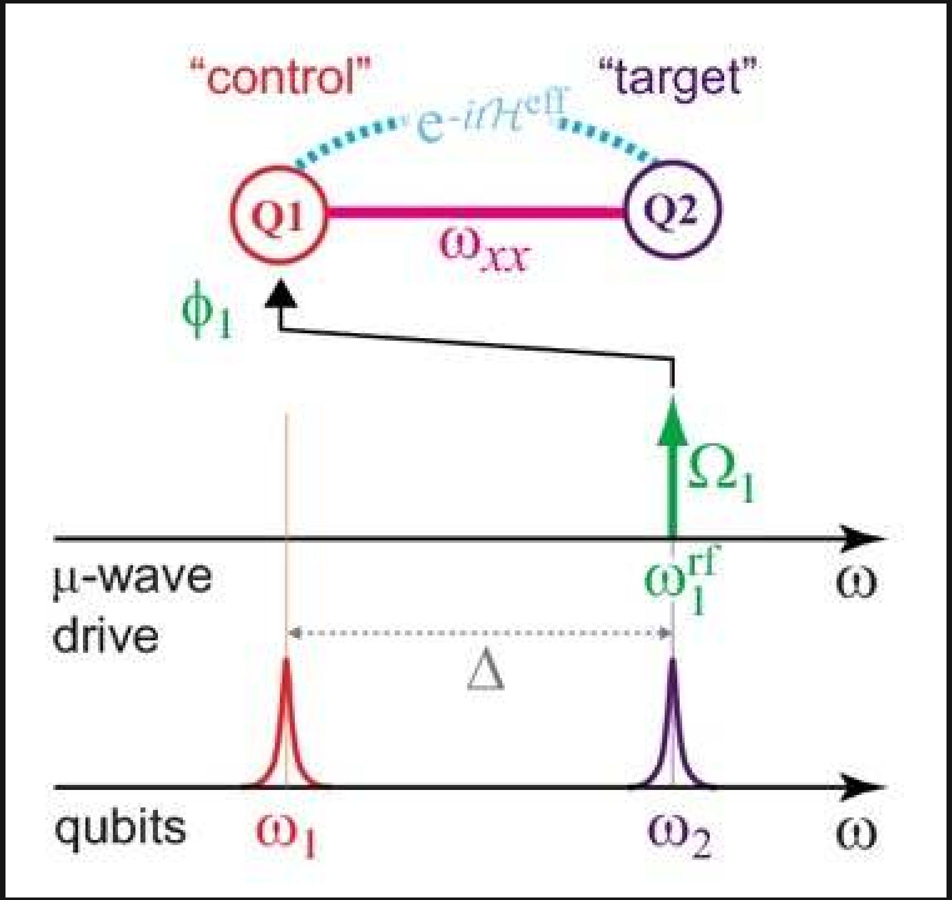
Any qubit coupled to C or T gets a Z

Z on random qubit in presence of cross-talk

Refocusing schemes can mitigate some of the Z errors (including ZZ) but residual commutator errors remain (e.g. ZY, etc)

Leakage

Rigetti and Devoret, PRB **81**, 134507 (2010)



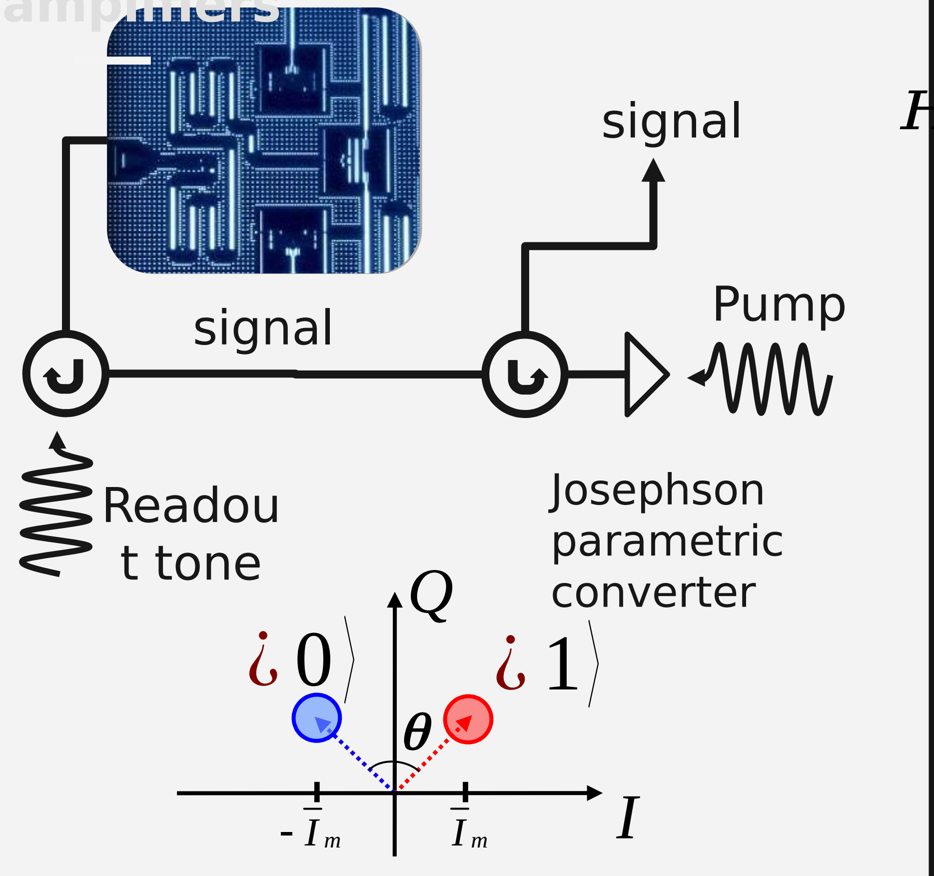
Drive Q1 at the frequency of Q2

H=a*ZX+b*IX

High-fidelity single-shot readout

IBM **Quantum**

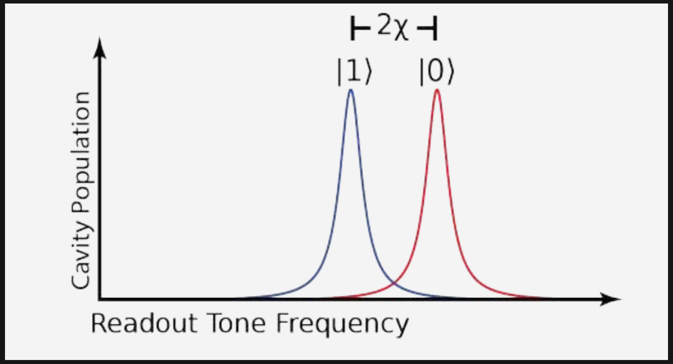
Use quantum-limited amplifiers



Need to detect small signals (-130 dBm)

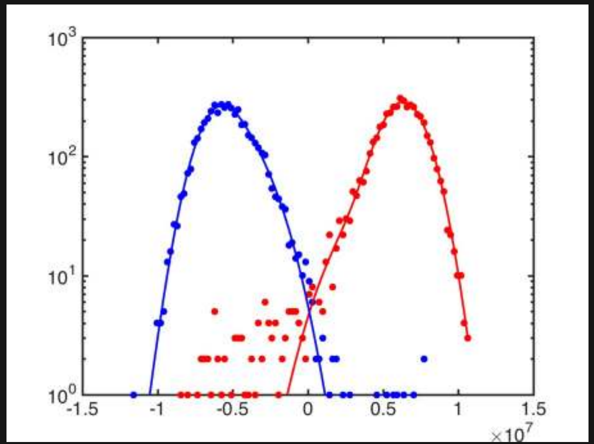
Dispersive Limit

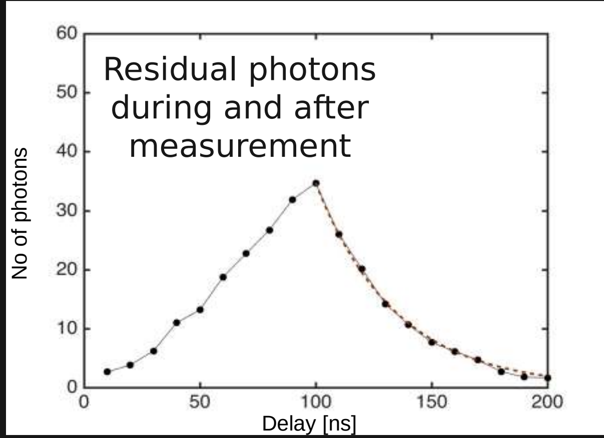
$$H=(\omega ¿¿ C+\chi\sigma^z)a^\dagger a+\frac{\omega_Q}{2}\sigma^z$$



Qubit Frequency (GHz)	Readout Frequency (GHz)	κ/2p (MHz)	2χ/2π (MHz)	T_1 average (μs)	T2 echo average (μs)
5.249	6.838	4.60	1.70	**33.9 ± 0.27**	**39.4 ± 0.6**

Total latency: 470 ns, readout fidelity ~0.99

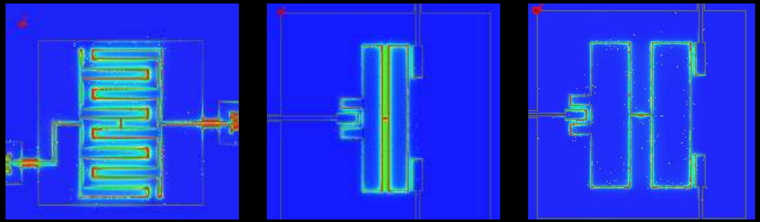




Coherence

Understanding how the qubit couples to the environment.

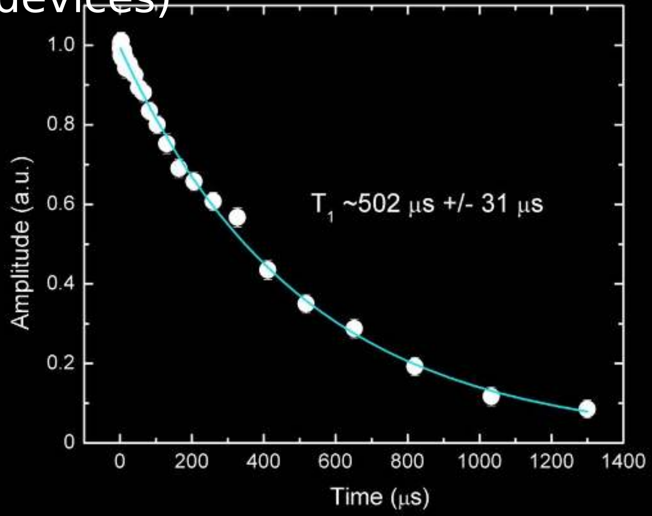
Example surface loss



Q~200-500k Q~1-1.5M Q~1.5-2.4M

Gambetta et al, IEEE Trans. Appl. Supercond. 27 (2017)

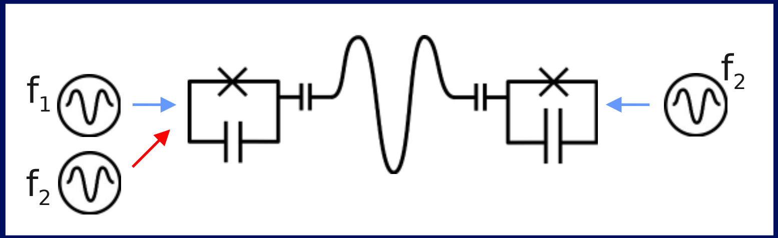
Current best (single qubit devices)



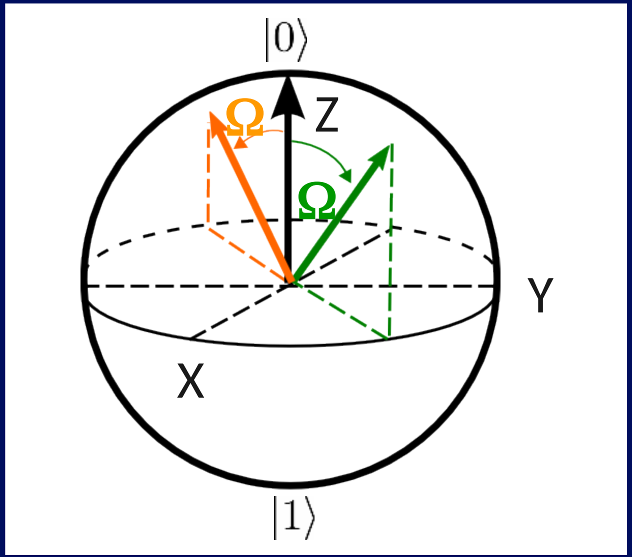
Single and two-qubit gates

DRAG and advanced calibration

F. Motzoi *et al.*, PRL. 103, 110501 (2009)
S. Sheldon et al., PRA 93, 012301 (2016)



Cross resonance interaction used for the two-qubit gate



C. Rigetti and M. Devoret, *PRB* **81**, 134507 (2010)

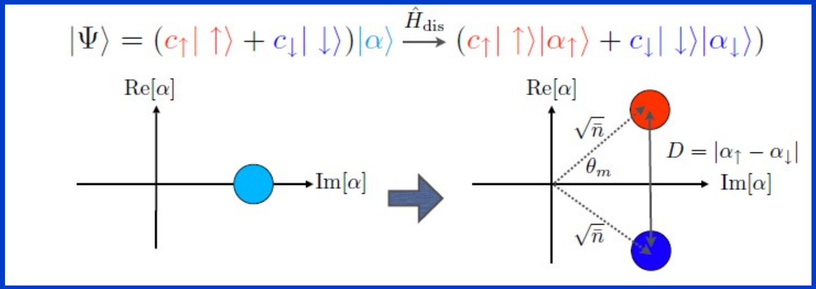
Current limited two-qubit 99.1%

Sheldon et al. Phys. Rev. A 93, 060302(R) [2016]

Measurement

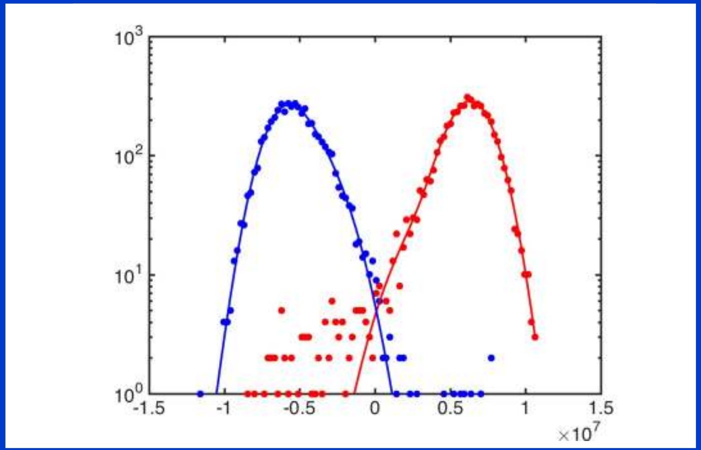
Dispersive Limit of a resonator-qubit JC Hamiltonian

$$H=(\omega ¿¿ C+\chi \sigma^{Z})a^{\dagger}a+\frac{\omega_Q}{2}\sigma^{Z}¿$$



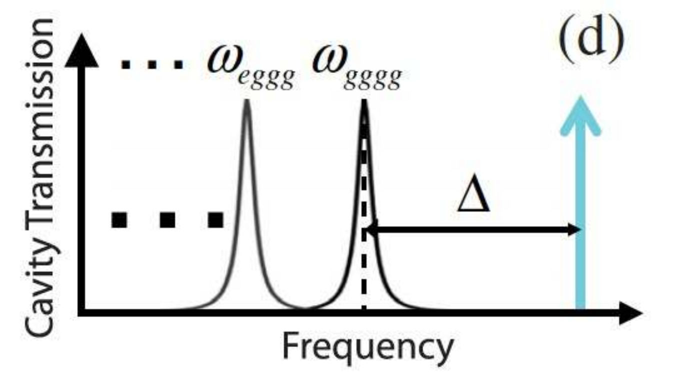
Gambetta et al. PRA, **77,** 012112 (2008

Quantum limited amplifiers give 99% assignment fidelity in 500ns



Alternative Gates

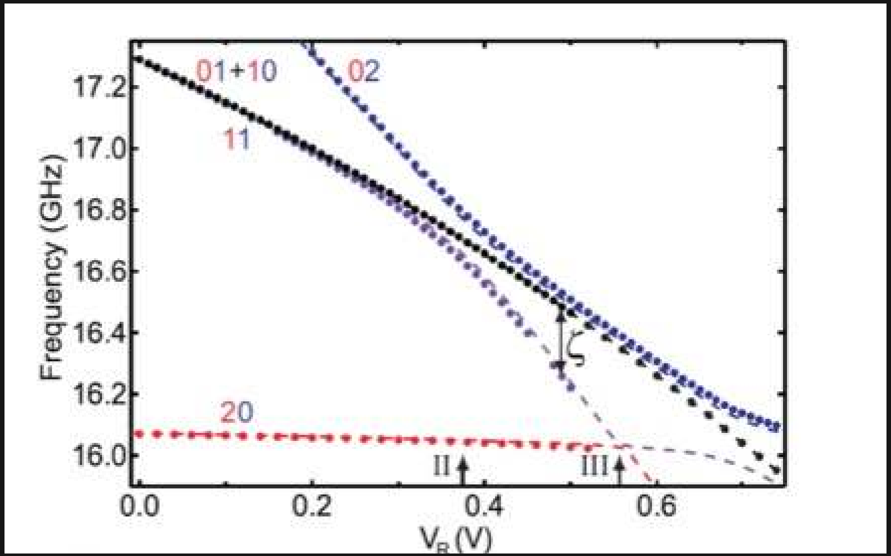
RIP



Phys. Rev. Lett. **117**, 250502 (2016)

- Drive coupling cavity at detuned frequency
- Turn on ZZ coupling
- Requires high quality factors

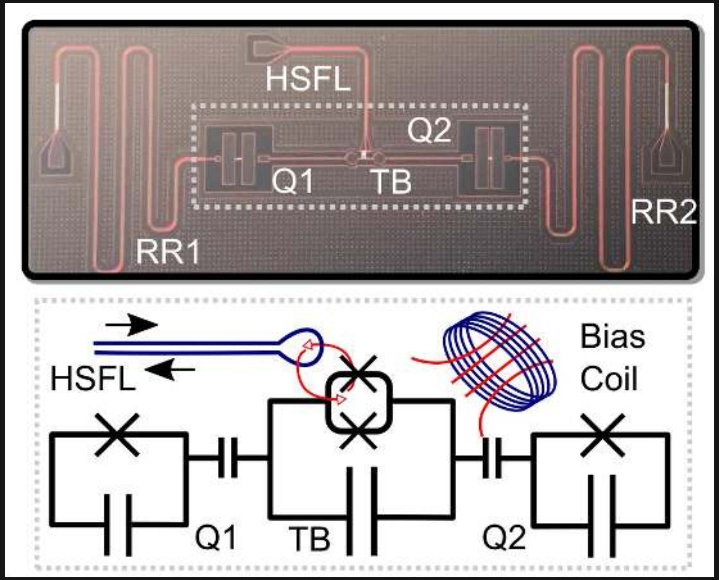
Flux based / tunable



DiCarlo et al., Nature 460, 240-244 (2009)

- Turn on ZZ by tuning qubits or coupler
- Swap 11 -> 20 and back

Btune gate



McKay et al., Phys. Rev. App. 6, 064007 (2016)

- Drive coupler at difference of qubit frequencies

Two-qubit gates

Table 1 State of the art high-fidelity two-qubit gates in superconducting qubits

Acronym[a]	Layout[b]	First demonstration [Year]	Highest fidelity [Year]	Gate time
CZ (ad.)	T–T	DiCarlo et al. (71) [2009]	99.4%† Barends et al. (3) [2014]	40 ns
			99.5%† Kjaergaard et al. (72) [2019]	60 ns
$\sqrt{\text{iSWAP}}$	T–T	Neeley et al. (80)° [2010]	90%⋆ Dewes et al. (73) [2014]	31 ns
CR	F–F	Chow et al. (74) [2011]	99.1%† Sheldon et al. (5) [2016]	160 ns
$\sqrt{\text{bSWAP}}$	F–F	Poletto et al. (75) [2012]	86%⋆ ibid.	800 ns
MAP	F–F	Chow et al. (76) [2013]	87.2%⋆ ibid.	510 ns
CZ (ad.)	T–(T)–T	Chen et al. (55) [2014]	99.0%† ibid.	30 ns
RIP	3D F	Paik et al. (77) [2016]	98.5%† ibid.	413 ns
$\sqrt{\text{iSWAP}}$	F–(T)–F	McKay et al. (78) [2016]	98.2%† ibid.	183 ns
CZ (ad.)	T–F	Caldwell et al. (79) [2018]	99.2%† Hong et al. (6) [2019]	176 ns
CNOT_L	BEQ-BEQ	Rosenblum et al. (13) [2018]	∼99%□ ibid.	190 ns
CNOT_{T-L}	BEQ-BEQ	Chou et al. (81) [2018]	79%⋆ ibid.	4.6 µs

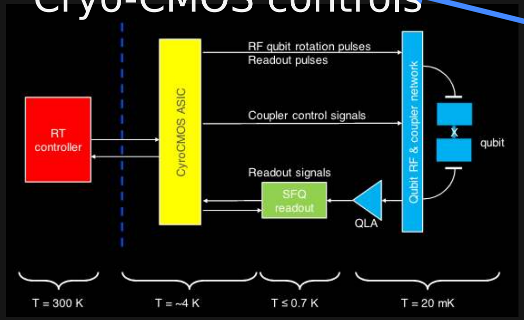
Kjaergaard et al., Annual Reviews of Condensed Matter Physics 11, 369-395 (2020)

Quantum Hardware Challenges

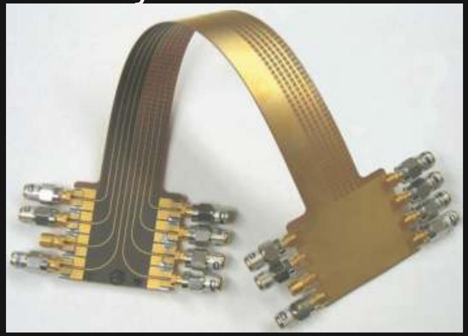
Room temp electronics
(stable, low-noise, cost)

Inside the Cryo Dilution Fridge

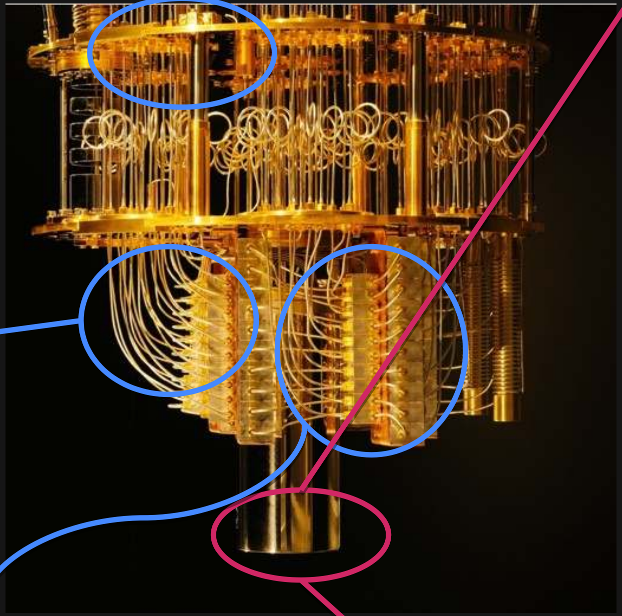
Cryo-CMOS controls



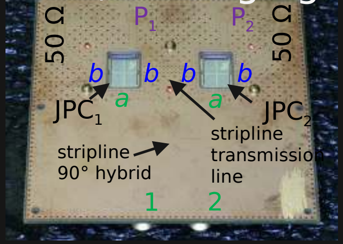
Cryo flex lines



Harris et al., Review of Scientific Instruments 83, 086105 (2012)

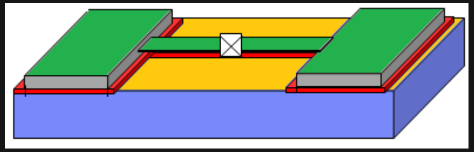


Amplifiers, Attenuators, Isolators, Packaging

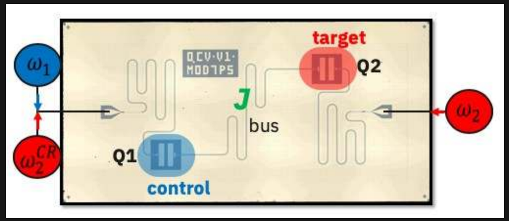


Processor, device development

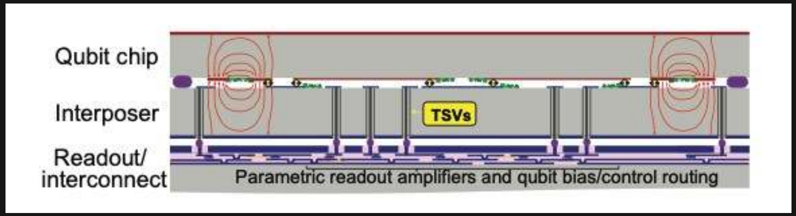
Coherence, junctions, materials



Better two-qubit gates



Packaging



Rosenberg et al., npj Quantum Information volume 3, Article number: 42 (2017)

Randomized Benchmarking {M}

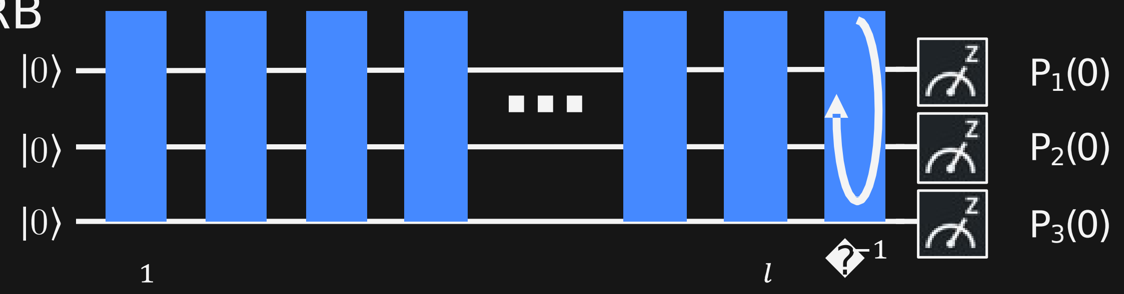
1. Select l Cliffords (from the n-qubit group) randomly and calculate the inversion gate
2. Starting in |0> measure the polarization of each qubit after application of the sequence
3. Average over many different random sequences (“seeds”)
4. Fit to $A*\alpha^n+B$
   Error is related to α as $d/(d-1)*(1-\alpha)$

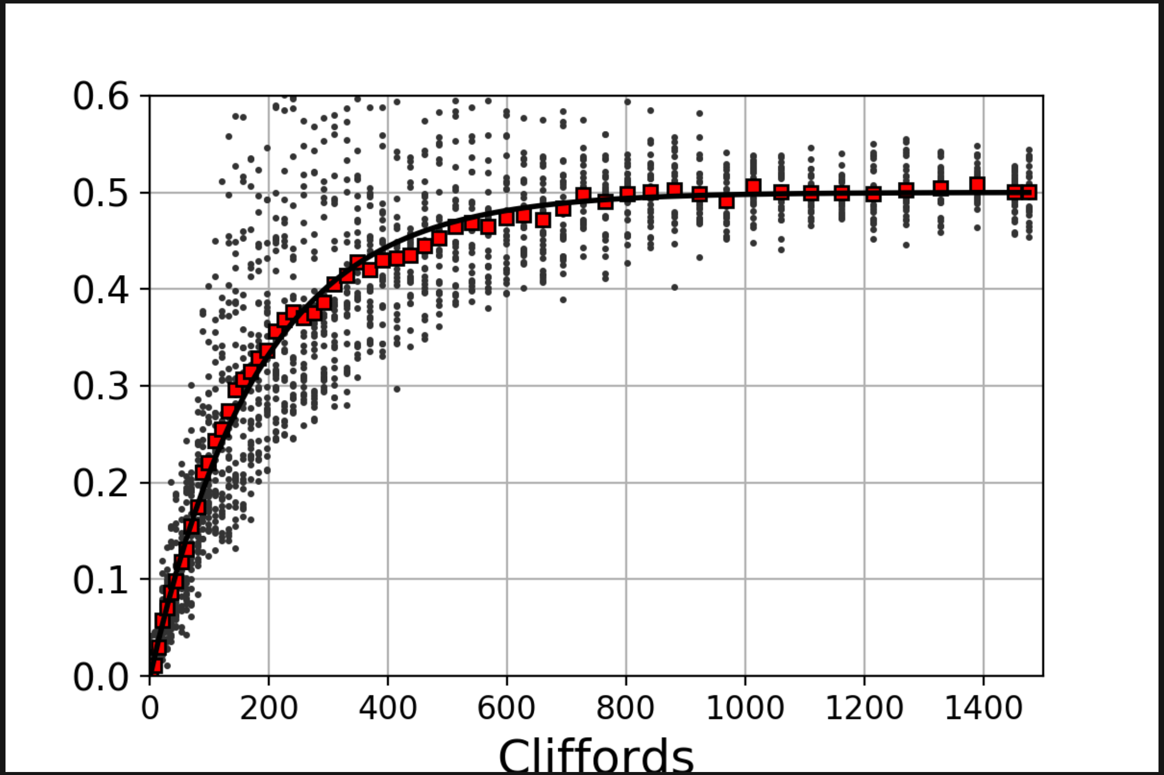
N	Cliffords
1	24
2	11,520
3	92,897,280
4	12,128,668,876,800

Eaaswar Magesan, J. M. Gambetta, and Joseph Emerson, “Scalable and robust randomized benchmarking of quantum processes,” Phys. Rev. Lett. 106 , 180504 (2011)

IBM **Quantum**

Standard N-Qubit RB





Conclusions

- Lots of progress over the past decade
- Approximately 50-qubit devices can be build with “good” fidelity
- Many significant scaling challenges left
- Error correction important long term

At the Core is hardware development

Improved fundamentals
coherence
gate fidelity
high on/off ratio
Junction physics

Improved systems
packaging and integration
stable and reliable control systems

Error correction
More efficient codes (long range interactions)
Codes co-designed with hardware

Quantum interconnects
Coupling to flying qubit
Distributed compilers and correction

Hardware aware applications
Based on complexity of underlying circuit
Hardware co-designed with circuit


IBM Q
IBM
HELIUM
HELIUM

IBM Q Experience

Launched May 4, 2016

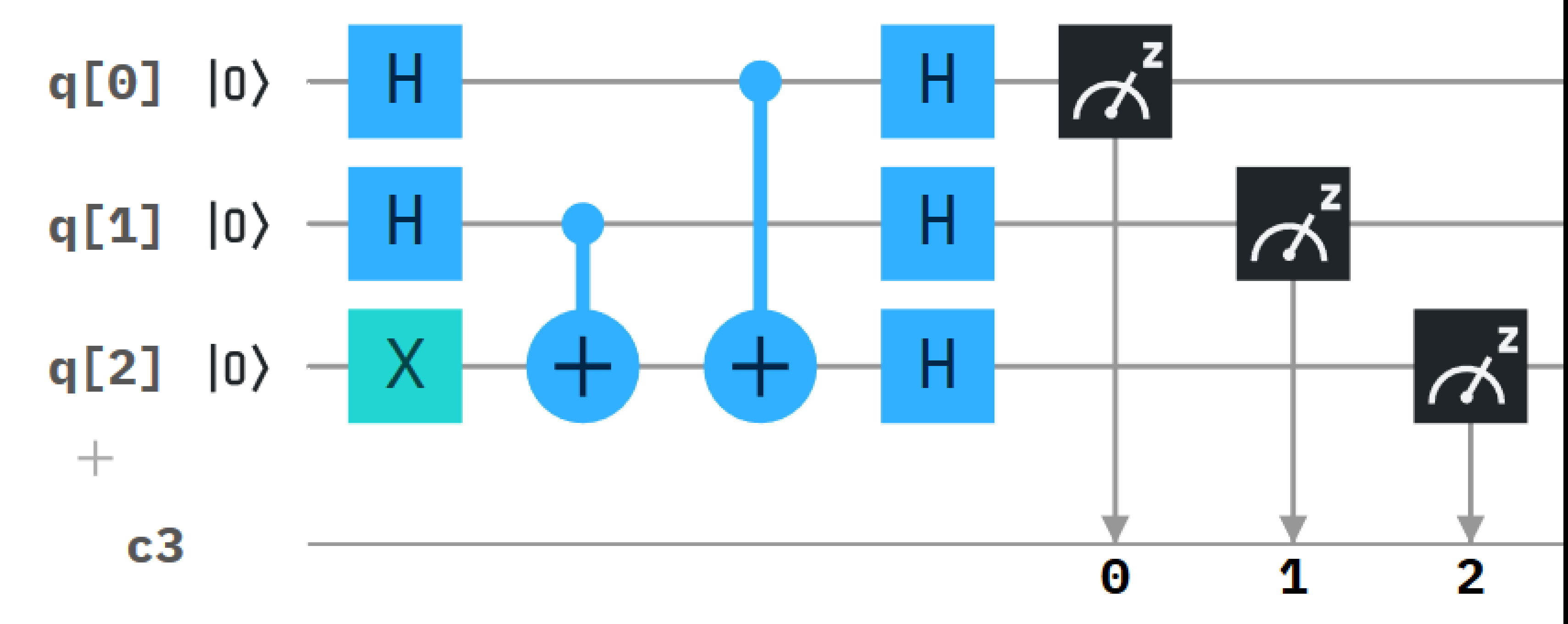
Free, cloud-based GUI and programmatic access to small quantum devices and simulators

Detailed user guide with example algorithms

> 160,000 users

> 20 million experiments

Writing quantum circuits: the "quantum score"



- "Textbook" way of showing quantum circuits
- Conducive to user-friendly drag-and-drop interface
- Useful for beginners studying simple circuits
- Becomes unmanageable for large/complex circuits

Writing quantum circuits: OpenQASM

- Text-based circuit representation
- Equivalent to quantum score
  - The OpenQASM at right represents the quantum score on the previous slide
- Good for sending basic commands to a quantum computer
- Not useful for writing circuits manually, but amenable to programmatic generation

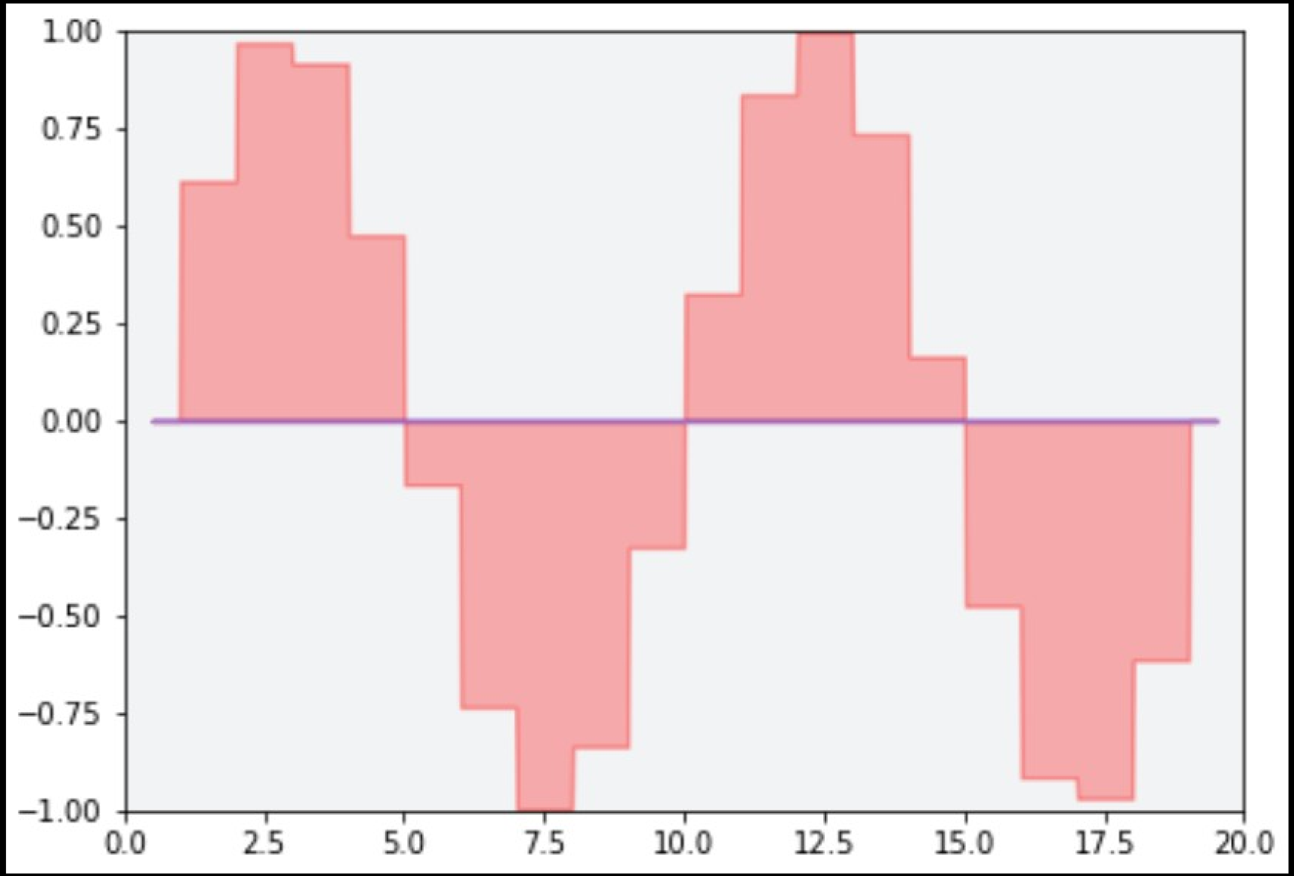
Full specification: arxiv.org/pdf/1707.03429.pdf

```
include "qelib1.inc";

qreg q[3];
creg c[3];

h q[0];
h q[1];
x q[2];
cx q[1],q[2];
cx q[0],q[2];
h q[0];
h q[1];
h q[2];
measure q[0] -> c[0];
measure q[1] -> c[1];
measure q[2] -> c[2];
```

Writing quantum circuits: OpenPulse

- An even lower level than OpenQASM: direct control over the analog pulses being sent to control and measure the qubits

- Programmatic generation is critical for building even the simplest circuits



arxiv.org/pdf/1905.02666.pdf

IBM Quantum Platform + Full Qiskit Stack

Applications

Applications
Chemistry, AI, Optimization, Finance

Algorithms
QPE, Grover, HHL, QSVM, VQE, QAOA, ...

Noise, V&V, Error Correction
Benchmarking, Volume, Mitigation

} Ignis, Aqua

Quantum Circuits

Pulse Level Control

Transpile

3rd Party Plugins
Transpilers, Visualizers, Circuit Constructors

} Terra (Circuits)

Open Network Interface/API
arXiv:1809.03452

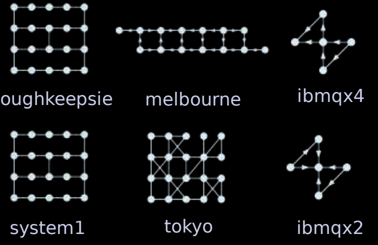
Queueing Job Control

Authenticaton User/Group Management

3rd Party Plugins
Languages, Toolkits

} Network/API Layer

Hardware



+8 more

Simulators (Aer)

statevector, unitary
stabilizer, t-gate,
tensor network

Third Party

QuTech-Delft (cloud)
JKU DD Simulator
QCGPU Statevector Simulator
Alpine Quantum Technologies (ions)

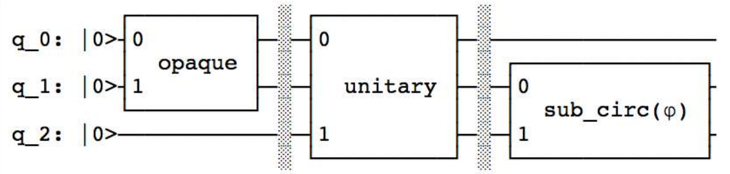
} Backends

https://qiskit.org

Circuit-Level Interface


```python
from qiskit.circuit import QuantumCircuit, Gate, Parameter
from qiskit.quantum_info.operators import Operator

# define circuit without register
circ = QuantumCircuit(3)

# add an opaque gate
opaque_gate = Gate(name='opaque', num_qubits=2, params=[])
circ.append(opaque_gate, [0, 1])
circ.barrier()

# add a unitary operator
sigma_x = np.array([[0, 1], [1, 0]])
sigma_y = np.array([[0, -1j], [1j, 0]])
matrix = np.kron(sigma_x, sigma_y)
unitary = Operator(matrix)
circ.append(unitary, [0, 2])
circ.barrier()

# add a subroutine and parametrize it
sub_circ = QuantumCircuit(2, name='sub_circ')
sub_circ.h(0)
phi = Parameter('φ')
sub_circ.crz(phi, 0, 1)
sub_circ.t(0)
sub_inst = sub_circ.to_instruction()
circ.append(sub_inst, [1, 2])
```

```python
circ.draw()
```



Decompose

```python
circ = circ.decompose()
```

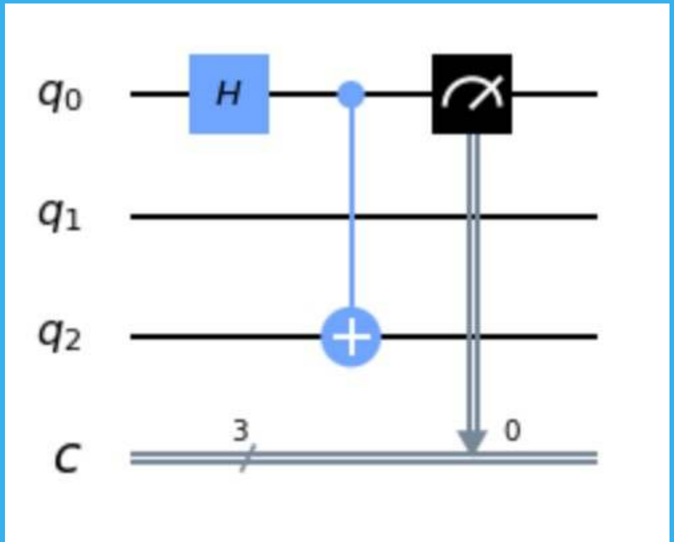
Bind Parameters

```python
circ = circ.bind_parameters({phi: 1.57})
```

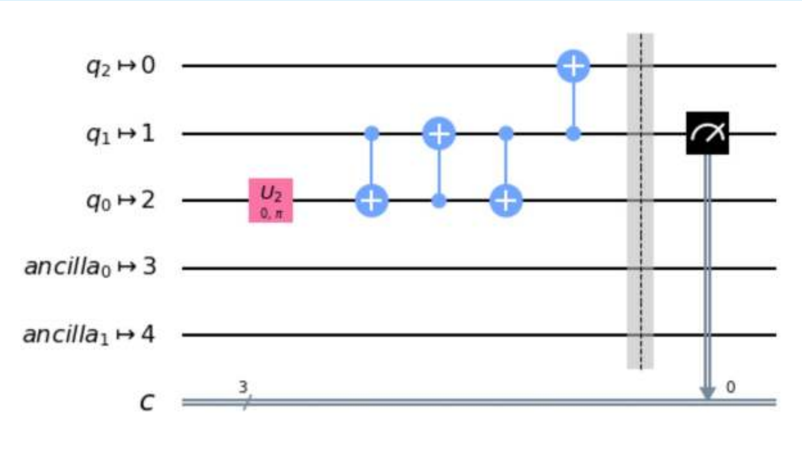
Qiskit Compilation Pipeline

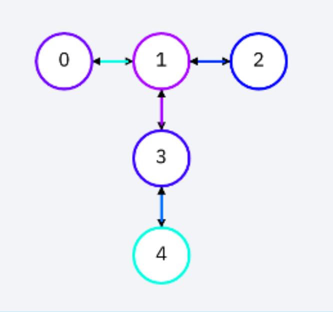
IBM **Quantum**

```
qc=QuantumCircuit(3,3)
qc.h(0)
qc.cx(0,2)
qc.measure(0,0)
qc.draw(output='mpl')
```

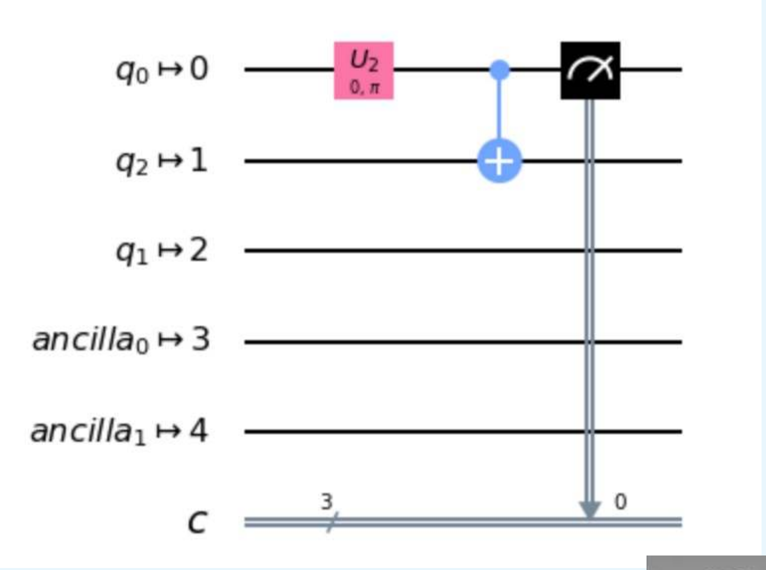



```
backend = provider.get_backend('ibmq_london')
qc_device = transpile(qc, backend)
display(qc_device.draw(output='mpl'))
```





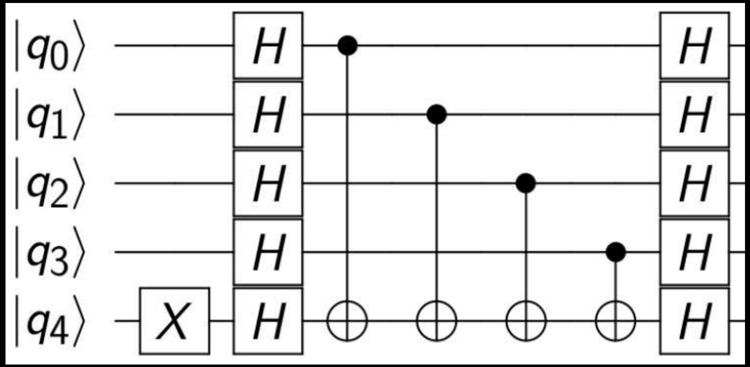

```
backend = provider.get_backend('ibmq_london')
qc_device = transpile(qc, backend,optimization_level=3)
display(qc_device.draw(output='mpl'))
```

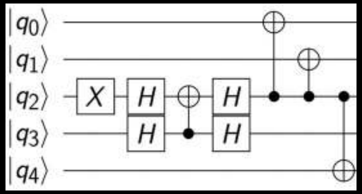


The Importance of the Transpiler

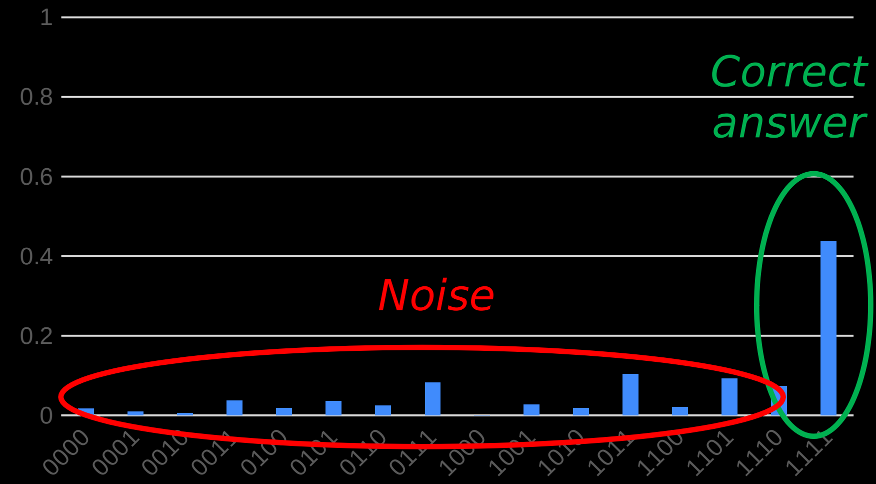
IBM **Quantum**

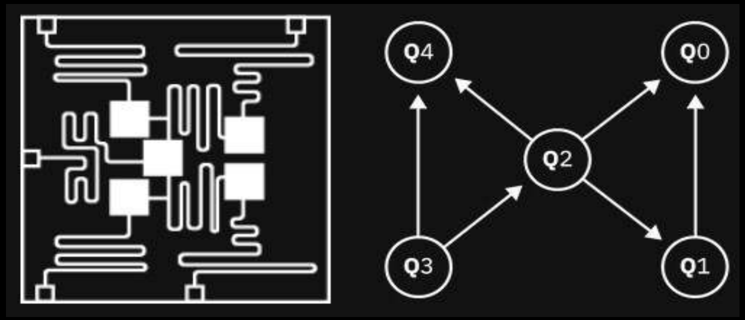
Programmed Circuit





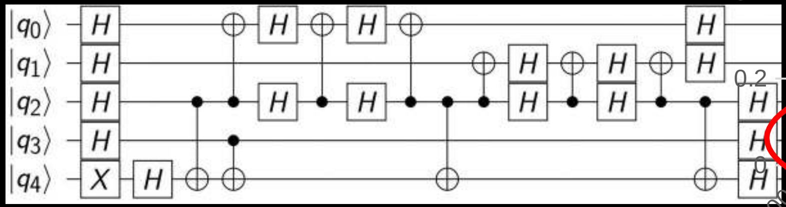
Good Compiler

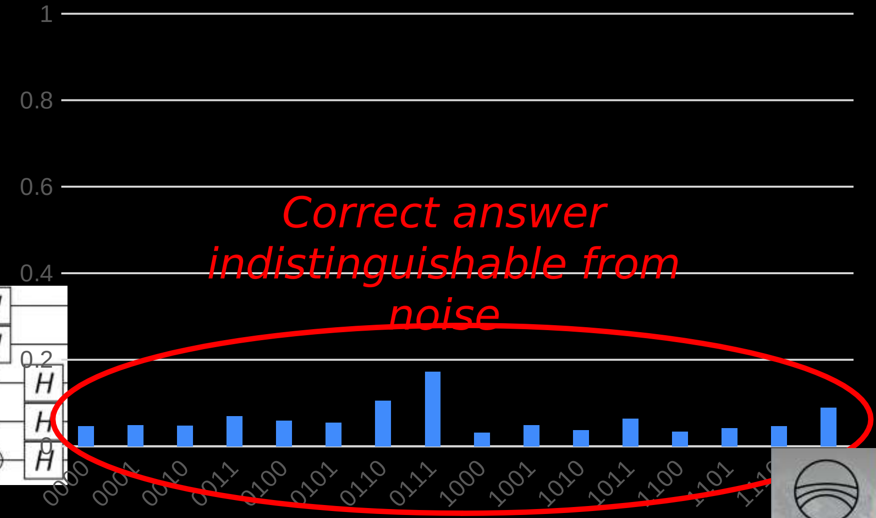




Device

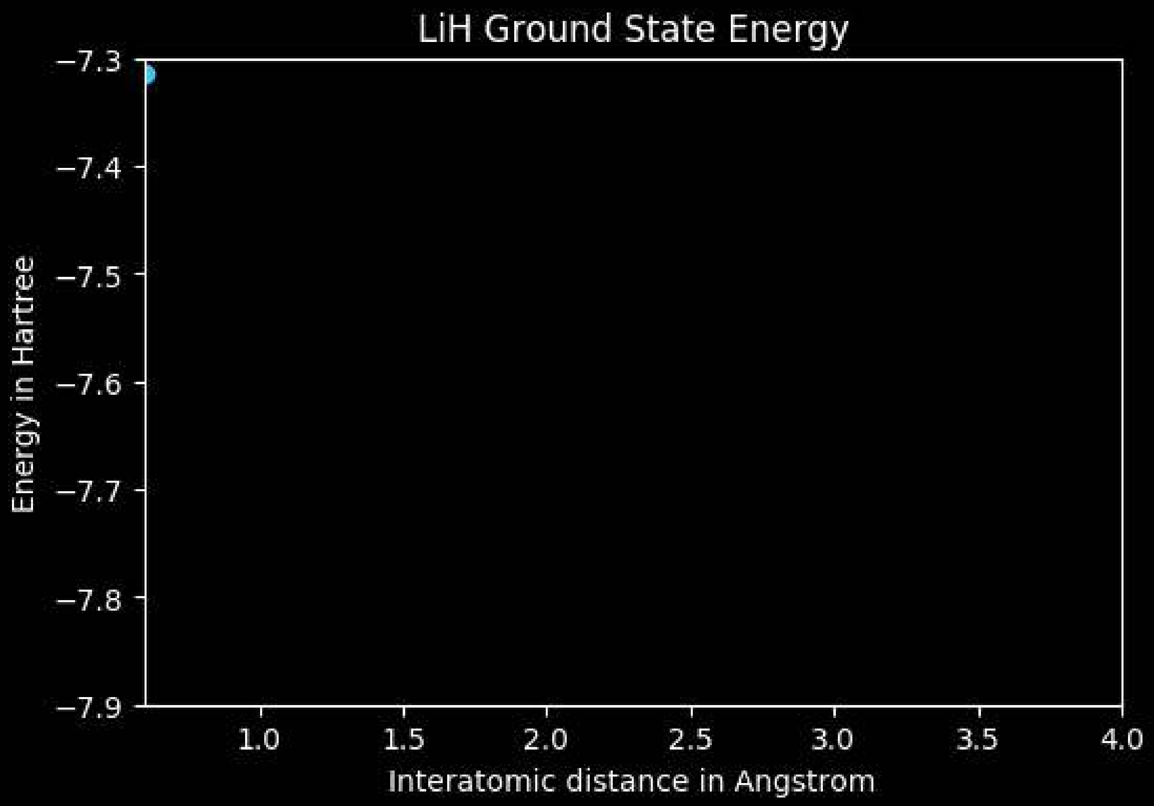
Bad Compiler





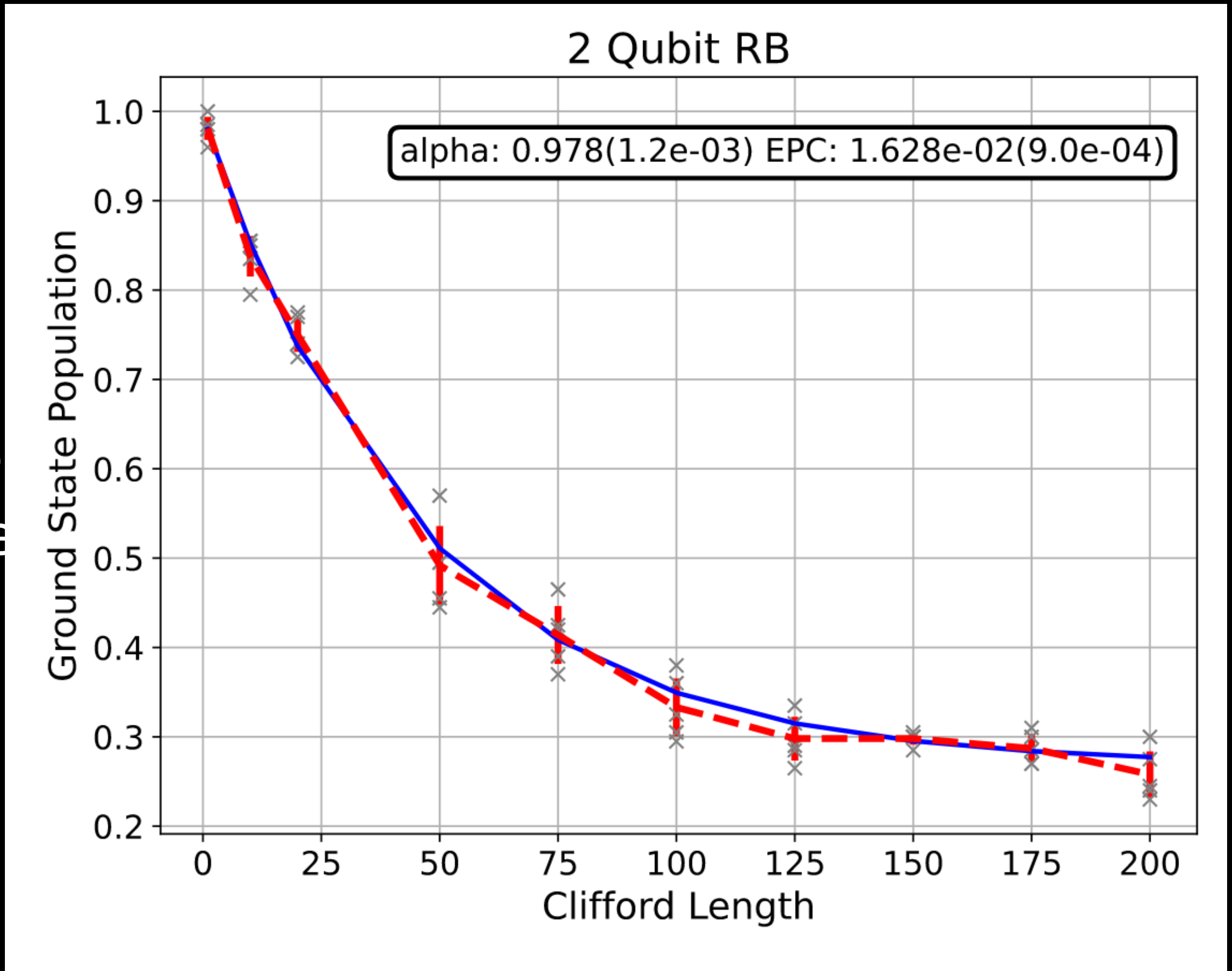
Qiskit Aqua

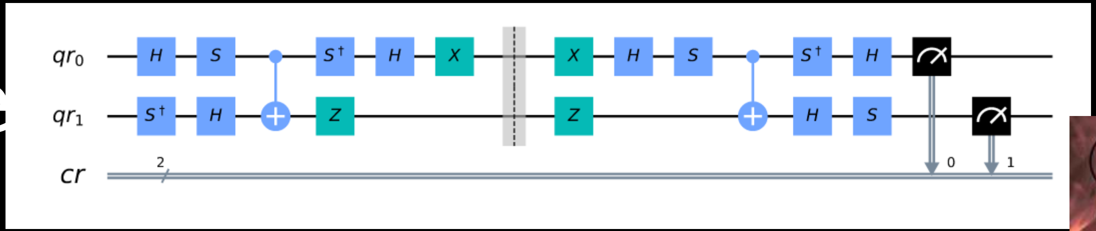
- High-level, application-specific modules in finance, chemistry, optimization, and AI
- Interfaces with domain-specific packages e.g. PySCF for chemistry
- Implements hybrid classical-quantum algorithms such as VQE



Qiskit Ignis: Features

- Characterization
  - Coherence (T1 and T2)
  - Gates (amplitude and angle calibratio
  - Hamiltonian (ZZ crosstalk measureme
- Mitigation
  - Measurement error mitigation
- Verification
  - Quantum volume
  - Randomized benchmarking
- Tomography (state and proce

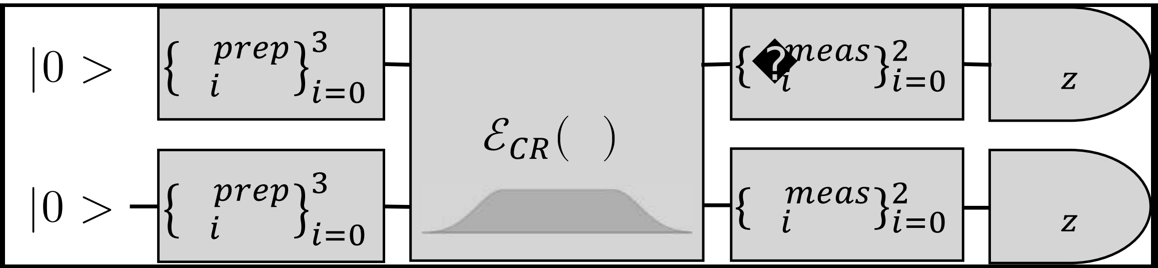


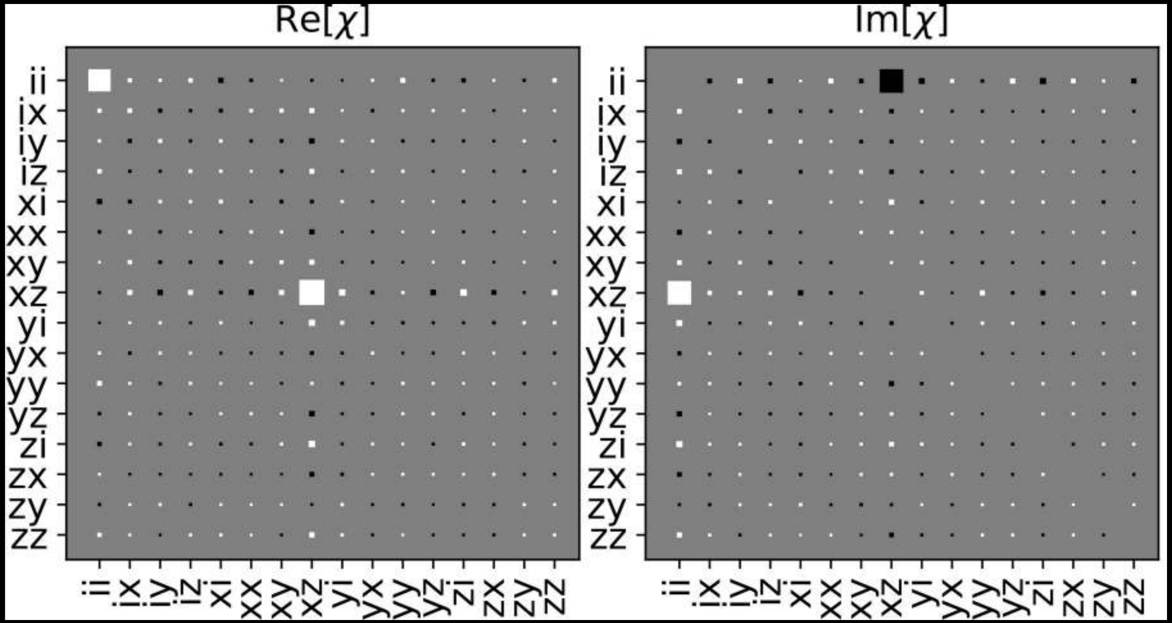


Calibrating and Benchmarking CR

IBM **Quantum**

```
defaults = backend.defaults()
config = backend.configuration()

cr_pulse = gaussian_square(duration, amp, sigma, risefall)

sched = Schedule()
sched += cr_pulse(ControlChannel(1))

inst_map = defaults.instruction_schedule_map
inst_map.add('CR', [1, 0], sched)
basis_gates += config.basis_gates + ['CR']

qr = QuantumRegister(2)
circuit = QuantumCircuit(qr)
circuit.append(Gate('CR', 2, []), qargs=[qr[1], qr[0]])

qpt_circs = process_tomography_circuits(circuit, [qr[0], qr[1]])
qpt_circs_transpiled = transpile(qpt, backend, basis_gates)
qpt_scheds = schedule(qpt_circs_transpiled, backend, inst_map)
result = execute(qpt_sches, backend).result()
qpt_tomo = ProcessTomographyFitter(result, qpt_circs)
```

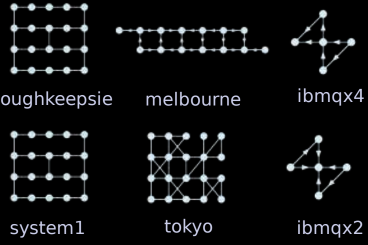




IBM Quantum Platform + Full Qiskit Stack

Applications

Ignis / Aqua	**Applications** Chemistry, AI, Optimization, Finance	**Algorithms** QPE, Grover, HHL, QSVM, VQE, QAOA, ...	**Noise, V&V, Error Correction** Benchmarking, Volume, Mitigation	
Terra (Circuits)	Quantum Circuits	Pulse Level Control	Transpile	3rd Party Plugins: Transpilers, Visualizers, Circuit Constructors
Network/API Layer	Open Network Interface/API arXiv:1809.03452	Queueing Job Control	Authenticaton User/Group Management	3rd Party Plugins: Languages, Toolkits
Backends	Hardware	Simulators (Aer)	Third Party	



+8 more

statevector, unitary
stabilizer, t-gate,
tensor network

QuTech-Delft (cloud)
JKU DD Simulator
QCGPU Statevector Simulator
Alpine Quantum Technologies (ions)

https://qiskit.org

200+ Papers and Counting

IBM **Quantum**

Performing Quantum Computing Experiments in the Cloud

Simon J. Devitt
Center for Emergent Matter Science, RIKEN, Wakoshi, Saitama 315-0198, Japan.
(Dated: September 2, 2016)

A quantum teleportation experiment for undergraduate students

S. Fedortchenko*

Braiding Majoranas in a five qubit experiment

James R. Wootton
Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

PHYSICAL REVIEW A 94, 012314 (2016)

Experimental test of Mermin inequalities on a five-qubit quantum computer

Daniel Alsina and José Ignacio Latorre

(Received 25 May 2016; published 11 July 2016)

Violation of Mermin inequalities is tested on the five-qubit IBM quantum computer.

Homomorphic Encryption Experiments on IBM's Cloud Quantum Computing Platform

He-Liang Huang,[1,2] You-Wei Zhao,[2,3] Tan Li,[1,2] Feng-Guang Li,[1,2] Yu-Tao Du,[1,2] Xiang-Qun Fu,[1,2] Shuo Zhang,[1,2] Xiang Wang,[1,2] and Wan-Su Bao[1,2,*]

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PAPER

Entropic uncertainty and measurement reversibility

Mario Berta[1], Stephanie Wehner[2] and Mark M Wilde[3,4]

Demonstration of *entanglement assisted invariance* on IBM's Quantum Experience

Sebastian Deffner
Department of Physics, University of Maryland Baltimore County, Baltimore, MD 21250, USA

Experimental Comparison of Two Quantum Computing Architectures

N. M. Linke,[1] D. Maslov,[2,3] M. Roetteler,[4] S. Debnath,[1] C. Figgatt,[1] K. A. Landsman,[1] K. Wright,[1] and C. Monroe[1,3,5]
[1]*Joint Quantum Institute and Department of Physics,*

Compressed quantum computation using the IBM Quantum Experience

M. Hebenstreit,[1] D. Alsina,[2,3] J. I. Latorre,[2,3] and B. Kraus[1]

Leggett-Garg test of superconducting qubit addressing the clumsiness loophole

Emilie Huffman[1,2] and Ari Mizel[1]

O Computador Quântico da IBM e o *IBM Quantum Experience*

Alan C. Santos*[1]

Quantum state reconstruction made easy: a direct method for tomography

R. P. Rundle,[1] Todd Tilma,[2] J. H. Samson,[1] and M. J. Everitt[1,*]
[1]*Quantum Systems Engineering Research Group & Department of Physics, Loughborough University, Leicestershire LE11 3TU, United Kingdom*
[2]*Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan*

ProjectQ: An Open Source Software Framework for Quantum Computing

Damian S. Steiger,* Thomas Häner,† and Matthias Troyer‡
Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland
(Dated: December 28, 2016)

Quintuple: a Python 5-qubit quantum computer simulator to facilitate cloud quantum computing

Christine Corbett Moran[a,b,*]

Approximate Quantum Adders with Genetic Algorithms: An IBM Quantum Experience

Rui Li[1], Unai Alvarez-Rodriguez[2], Lucas Lamata[2], and Enrique Solano[2,3]
[1]Department of Physics, Zhejiang University, Hangzhou 310027, China

Get started...

`pip install qiskit`

quantum-computing.ibm.com

Qiskit

An open-source quantum computing framework for leveraging today's quantum processors in research, education, and business

Qiskit Terra

A solid foundation for quantum computing

Qiskit Aqua

Algorithms for near-term quantum applications

Qiskit Aer

A high performance simulator framework for quantum circuits

Qiskit Ignis

Understanding and mitigating noise in quantum device