Quantum Computing Tutorial (Part 2)

Adam Lyon
Academic Lecture Series
18 December 2018

Outline

- Can we relate the Quantum Mechanics of Quantum Computing to some physics system that a physicist knows? *
- Short review of popular public toolkits
- Hands on with QISKit (IBM)
- Teleportation (and experiments) *
- How do superconducting quantum computers work? *
- Fermilab's involvement with Quantum Information Science

* = by popular request

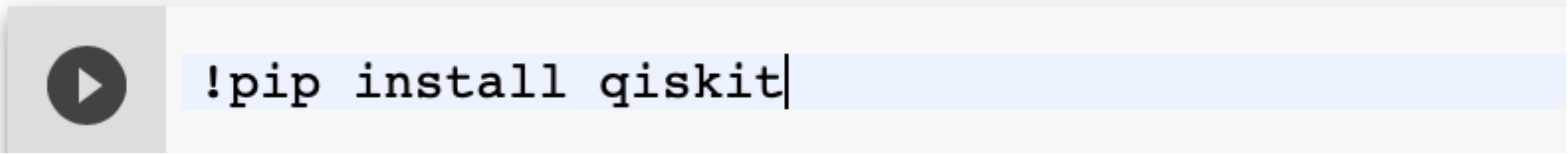
Please do this if you are following along…

- Using Docker (best)…
  - Start the container

```
cd your/quantumComputing/area
docker run -it --rm -v $PWD:/work -p 8888:8888 lyonfnal/qc-python-ubuntu
git clone https://github.com/Qiskit/qiskit-tutorials.git
<Start JupyterLab>
```

- Using Binder (good)
  - Go to https://github.com/Qiskit/qiskit-tutorials
  - click on the “Launch Binder” badge

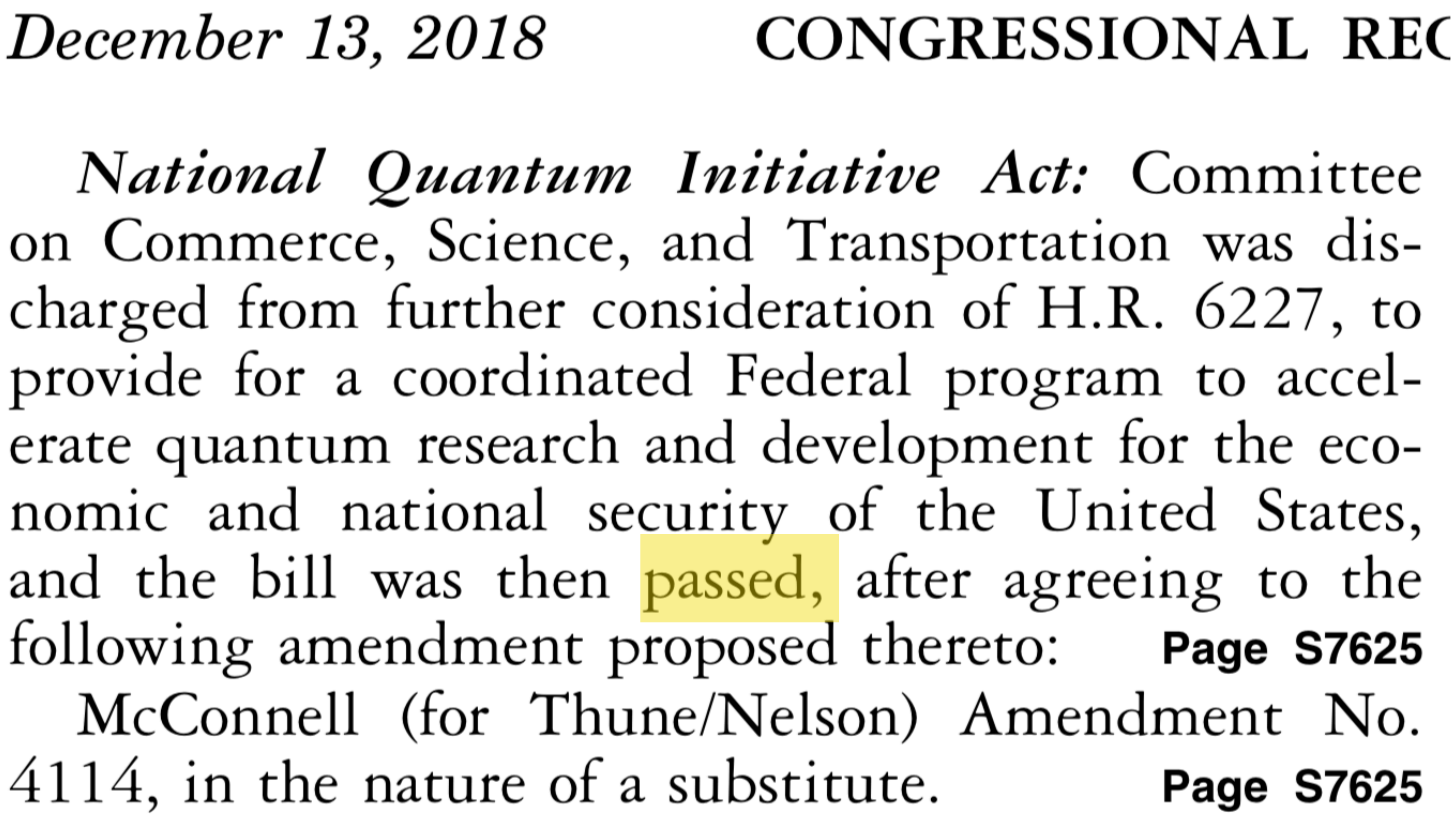
- Using Google Colaboratory (ok)
  - Go to https://colab.research.google.com
  - Click on “GitHub” tab and in the text box put in https://github.com/Qiskit/qiskit-tutorials
  - You will likely need to add a cell and run …



```
!pip install qiskit
```

Some (good) news…

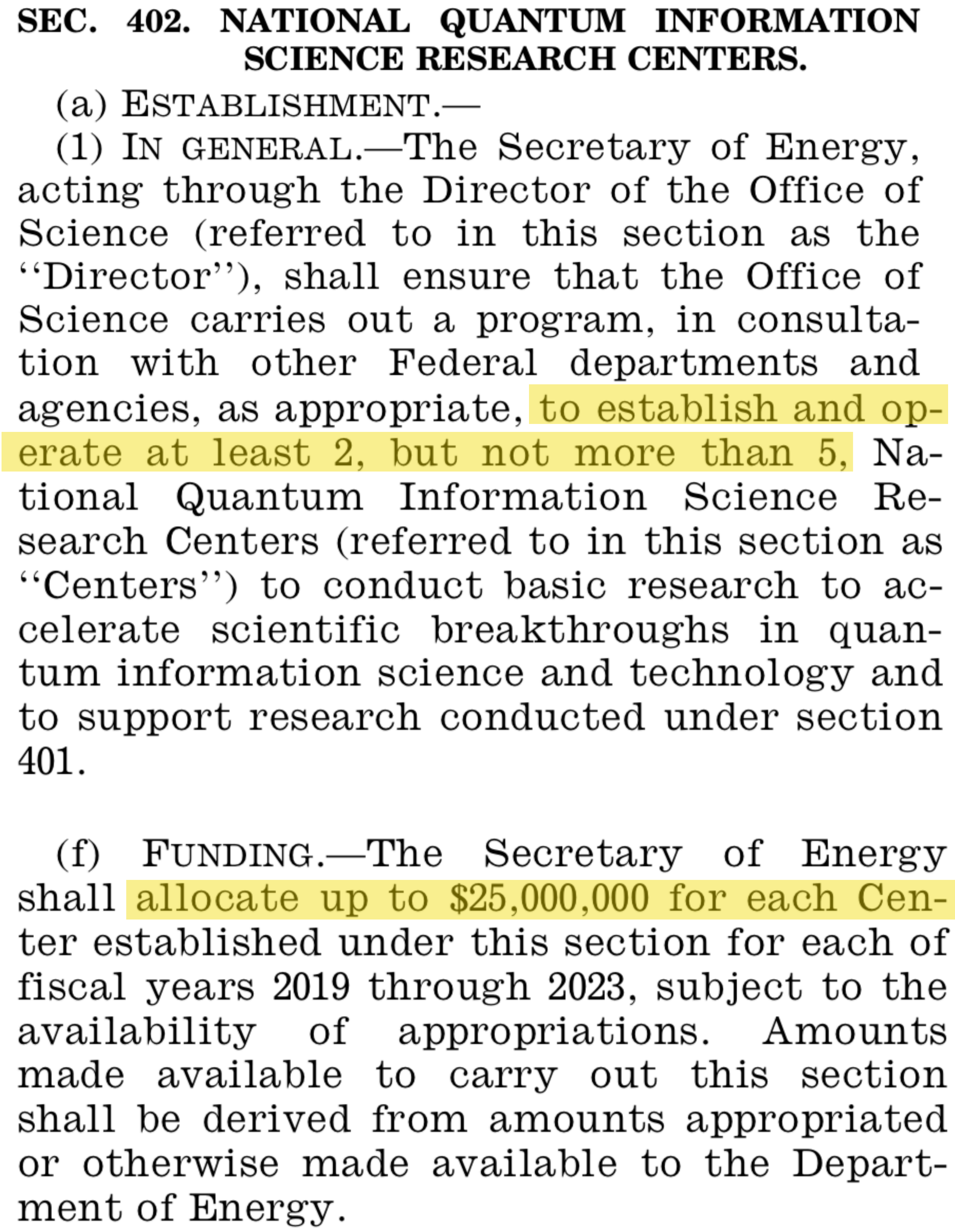
National Quantum Initiative Passed the Senate last Thursday!



December 13, 2018 CONGRESSIONAL REC

National Quantum Initiative Act: Committee on Commerce, Science, and Transportation was discharged from further consideration of H.R. 6227, to provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States, and the bill was then passed, after agreeing to the following amendment proposed thereto: **Page S7625**

McConnell (for Thune/Nelson) Amendment No. 4114, in the nature of a substitute. **Page S7625**



SEC. 402. NATIONAL QUANTUM INFORMATION SCIENCE RESEARCH CENTERS.

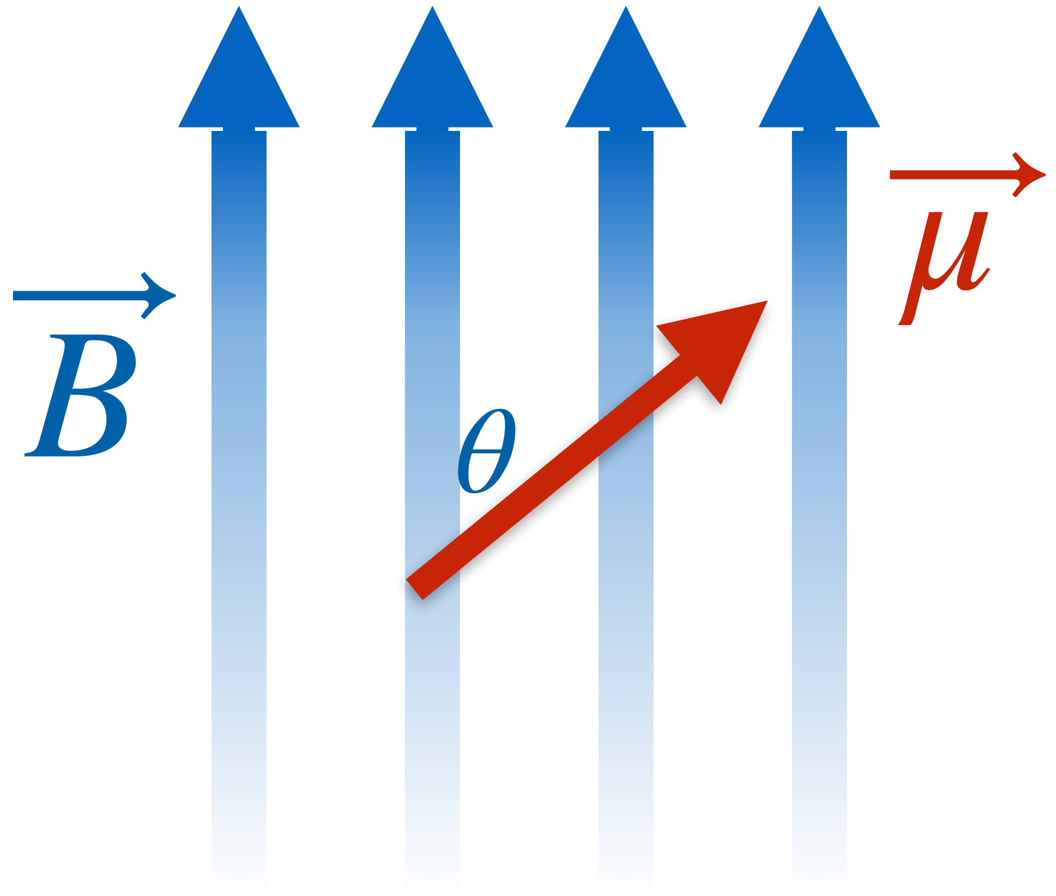
(a) ESTABLISHMENT.—

(1) IN GENERAL.—The Secretary of Energy, acting through the Director of the Office of Science (referred to in this section as the ‘‘Director’’), shall ensure that the Office of Science carries out a program, in consultation with other Federal departments and agencies, as appropriate, to establish and operate at least 2, but not more than 5, National Quantum Information Science Research Centers (referred to in this section as ‘‘Centers’’) to conduct basic research to accelerate scientific breakthroughs in quantum information science and technology and to support research conducted under section 401.

(f) FUNDING.—The Secretary of Energy shall allocate up to $25,000,000 for each Center established under this section for each of fiscal years 2019 through 2023, subject to the availability of appropriations. Amounts made available to carry out this section shall be derived from amounts appropriated or otherwise made available to the Department of Energy.

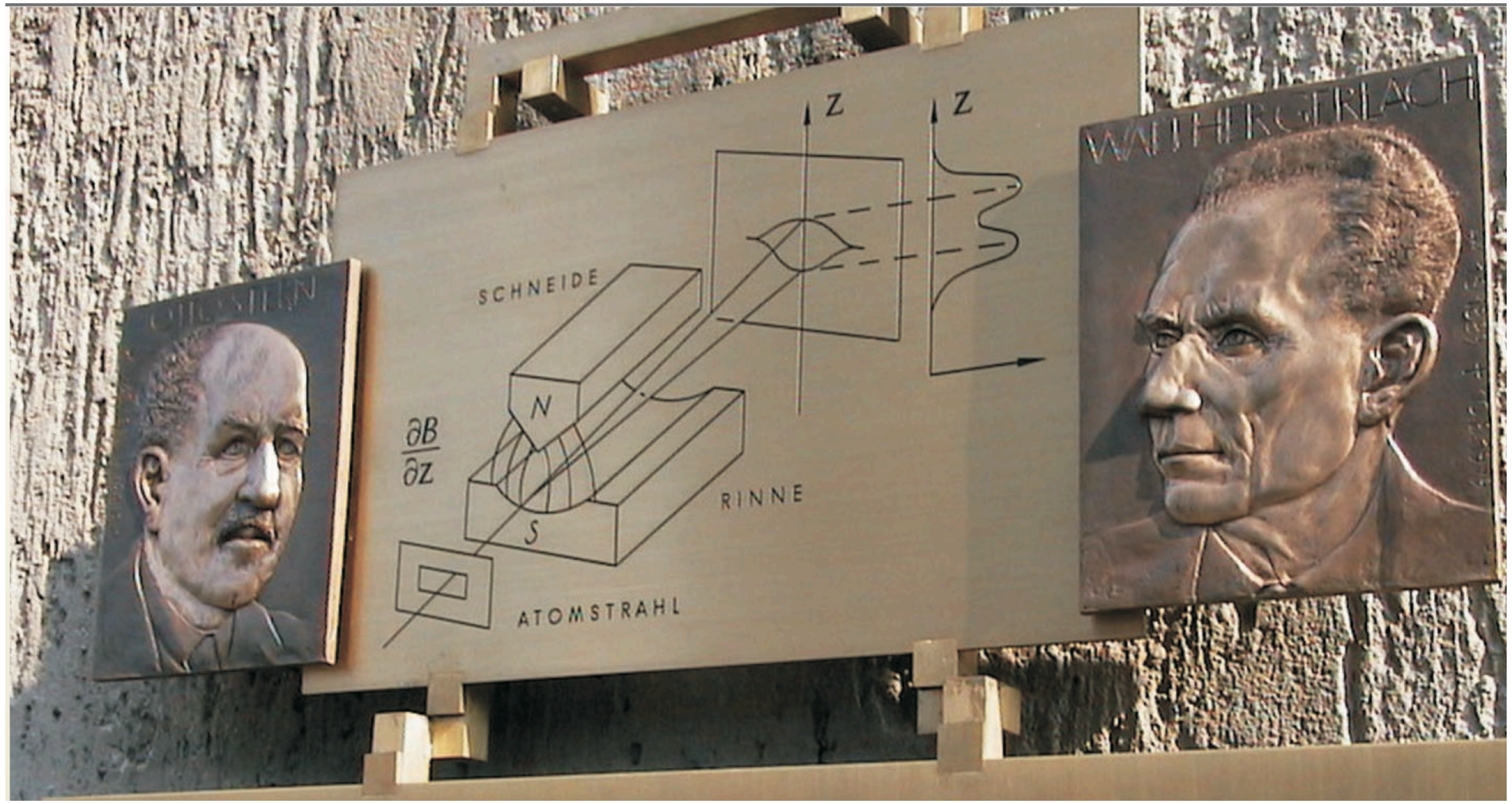
Quantum Mechanics of Quantum Computing for real

- Electron spins…. Are they quantized?
- Potential energy of magnetic dipole in magnetic field $U = -\vec{\mu} \cdot \vec{B}$
- Force on the dipole is $F = -\nabla U = \nabla(\vec{\mu} \cdot \vec{B})$
- If the magnetic field points up and is, conveniently, $\vec{B} = B_0 z\hat{z}$
- So, $F = \nabla(\vec{\mu} \cdot \vec{B}) = \nabla(\mu_z B_0 z) = \mu B_0 \cos(\theta)\,\hat{z}$
- Dipoles aligned with field are pushed up, anti-aligned are pushed down
- Is electron spin classical or quantum?

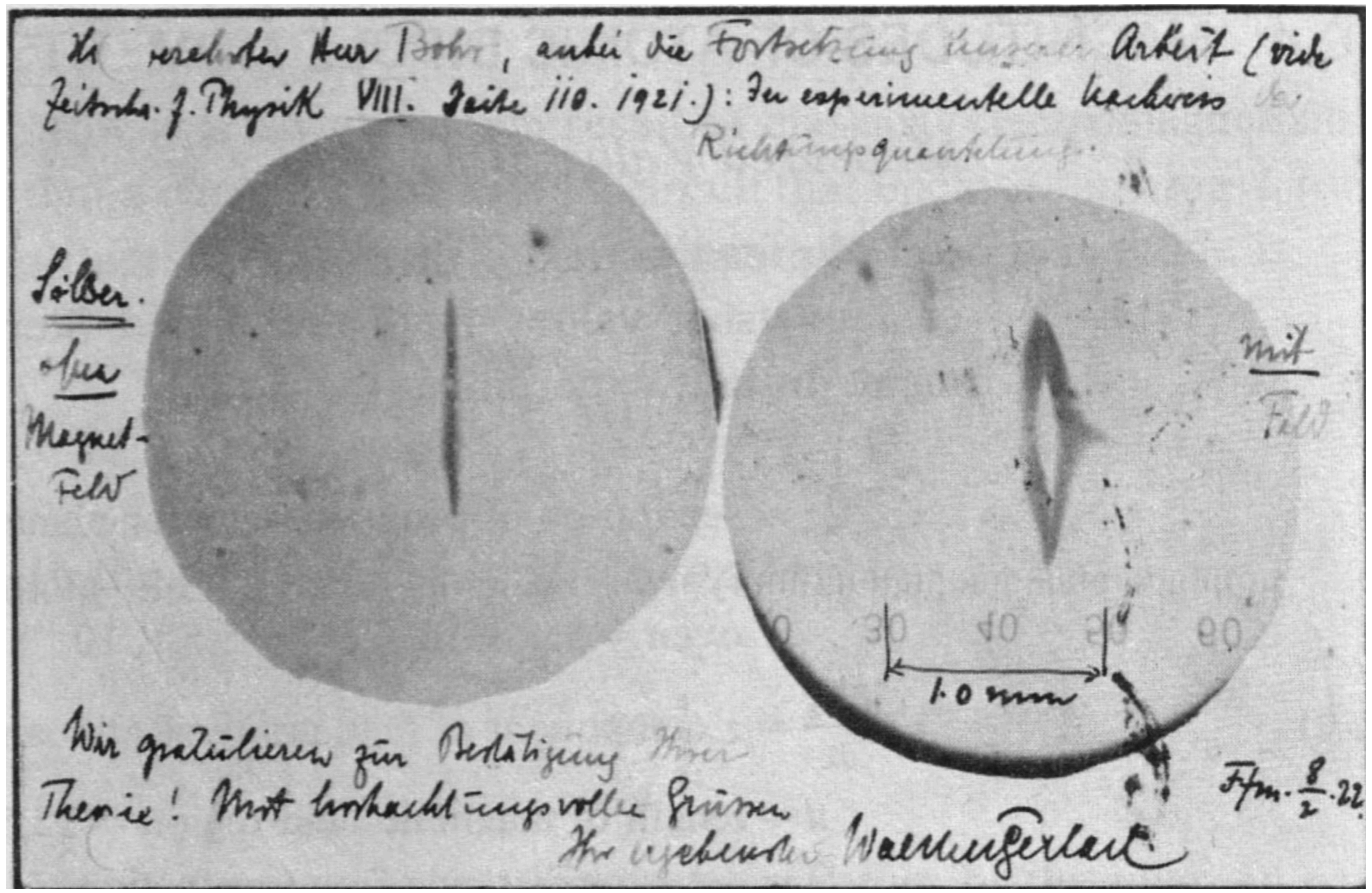


Following Whaley, Young & Sarovar Chem/CS/Phys191 Berkeley

Stern-Gerlach Experiment (1922)



No B B



Hochverehrter Herr Bohr, anbei die Fortsetzung unserer Arbeit (vide Zeitschr. f. Physik VIII. Seite 110. 1921.): Der experimentelle Nachweis der Richtungsquantelung.

Silber. ohne Magnet-Feld

mit Feld

0 30 40 80 90

1.0 mm

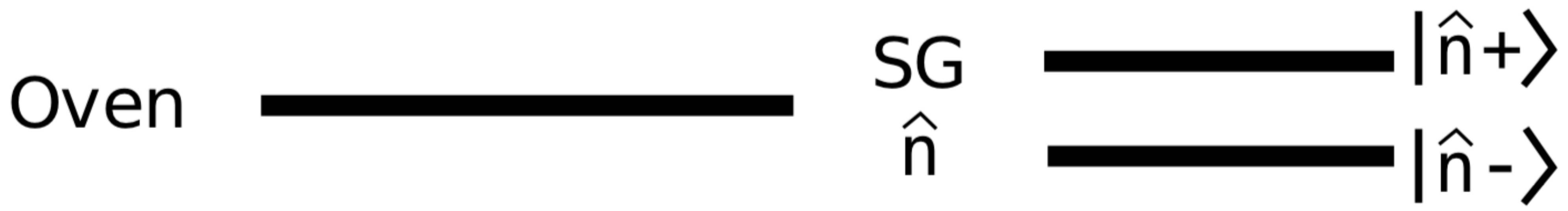
Wir gratulieren zur Bestätigung Ihrer Theorie! Mit hochachtungsvollen Grüssen Ihr ergebenster Walther Gerlach

Ffm. 8/2.22

Physics Today, December 2003

- With silver atoms - demonstrated spatial quantization of magnetic moment
- Uhlenbeck & Goudsmit explained effect as quantized electron spin (1925)
  - Intrinsic angular momentum, not orbital

Spins are a two-state system



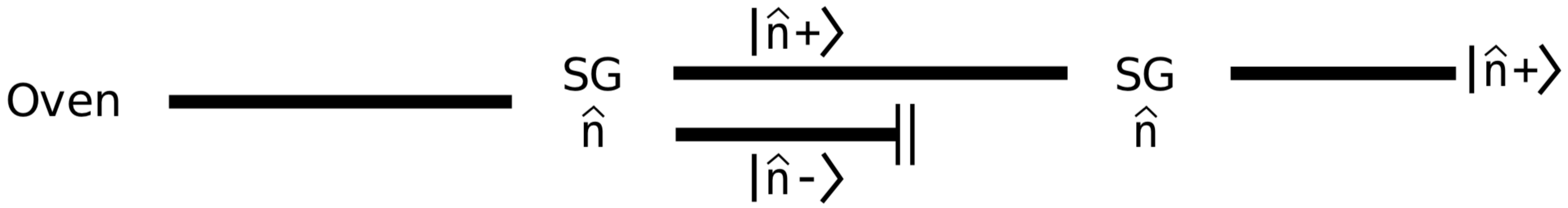
Oven

SG $\hat{n}$

$|\hat{n}+\rangle$

$|\hat{n}-\rangle$

Let’s chain SG experiments, looking at just the upper output from the first



Oven

SG $\hat{n}$

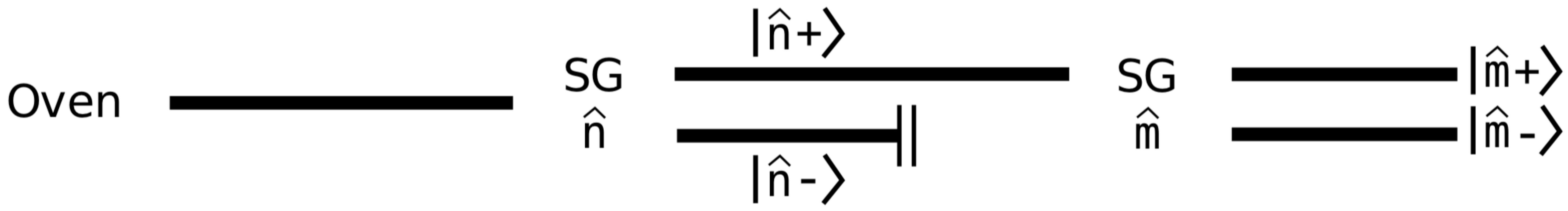
$|\hat{n}+\rangle$

$|\hat{n}-\rangle$

SG $\hat{n}$

$|\hat{n}+\rangle$

We get one beam. Kinda boring. Let’s rotate the 2nd SG device



Oven

SG $\hat{n}$

$|\hat{n}+\rangle$

$|\hat{n}-\rangle$

SG $\hat{m}$

$|\hat{m}+\rangle$

$|\hat{m}-\rangle$

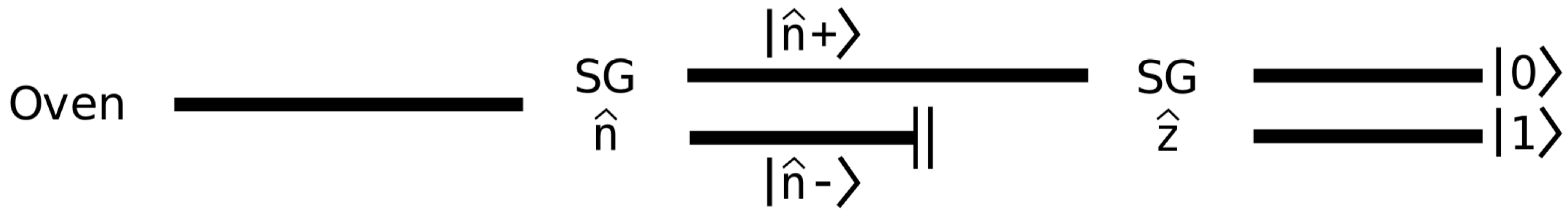
We get two beams again with

$$P(|\hat{n}+\rangle \rightarrow |\hat{m}+\rangle) = (1/2)(1 + \hat{n} \cdot \hat{m})$$

$$P(|\hat{n}+\rangle \rightarrow |\hat{m}-\rangle) = (1/2)(1 - \hat{n} \cdot \hat{m})$$

Bases

- For convenience, pick a basis $|\hat{z}\pm\rangle$ where $|\hat{z}+\rangle = |0\rangle$, $|\hat{z}-\rangle = |1\rangle$
- So $|\hat{n}+\rangle = \alpha|0\rangle + \beta|1\rangle$
- Look at……………………..



- What are α and β ?
- Given $|\hat{n}+\rangle$, probability for measuring $|0\rangle$ is

$$P(0, |\hat{n}+\rangle) = |\langle 0|\hat{n}\rangle|^2 = |\alpha\langle 0|0\rangle + \beta\langle 0|1\rangle|^2 = |\alpha|^2 = \frac{1}{2}(1 + \hat{n}\cdot\hat{z}) = \frac{1}{2}(1+\cos\theta)$$

$|\alpha| = \cos(\theta/2)$ and can also find that $|\beta| = \sin(\theta/2)$

- Introducing phases and eventually get

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

- And we've reproduced the Bloch Sphere for a single qubit

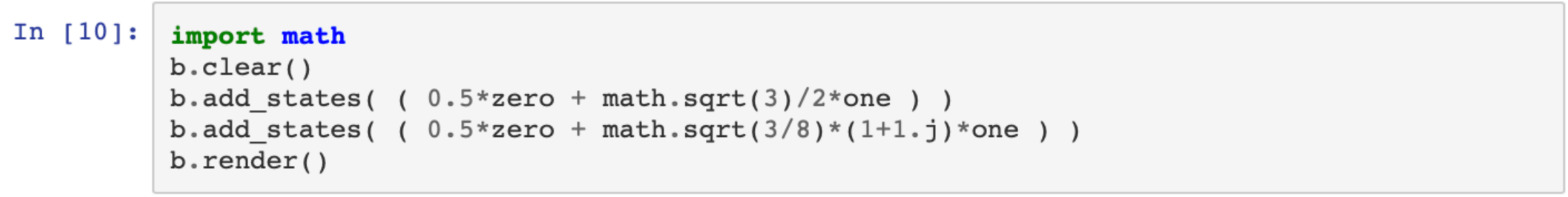
Bloch sphere

We can recast $|\psi\rangle = \alpha|0\rangle > +\beta|1\rangle$ as $|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$

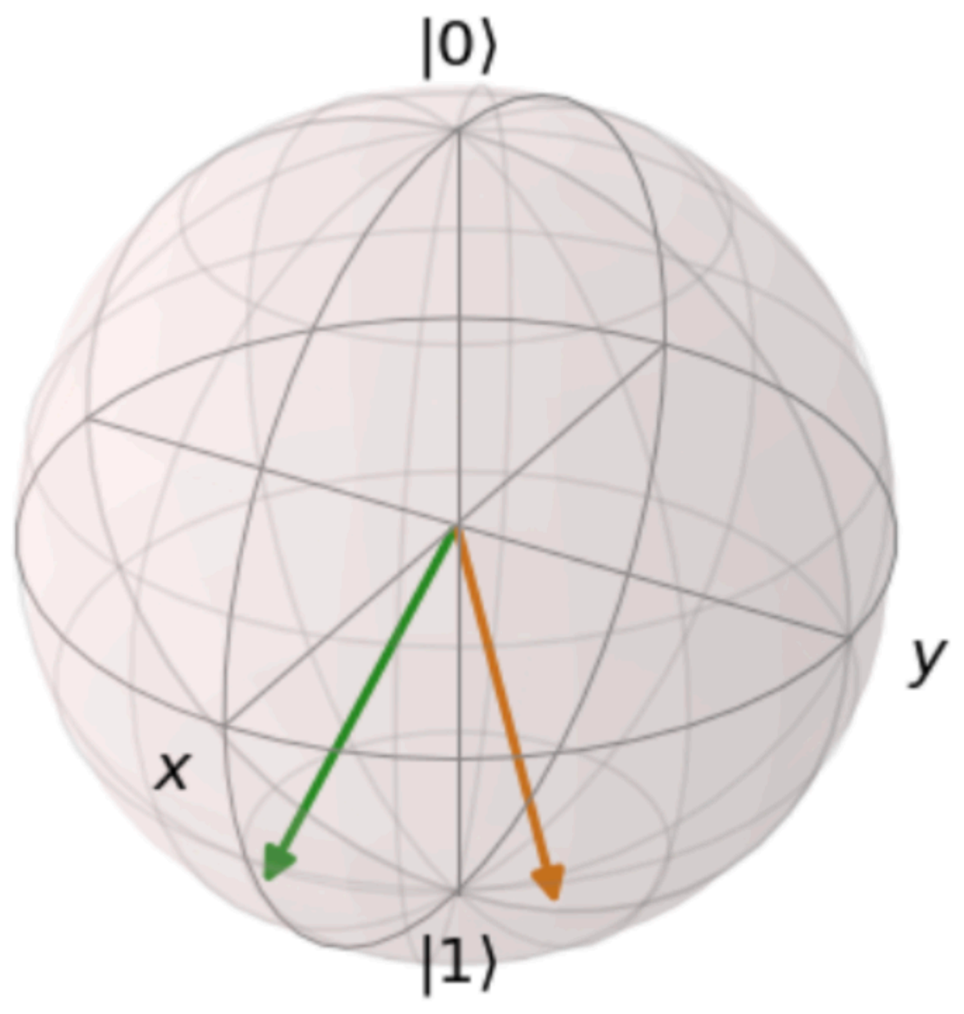
Another superposition:

$|\psi\rangle = R_{\pi/3}|0\rangle = \frac{1}{2}|0\rangle + \frac{\sqrt{3}}{2}|1\rangle; P(0) = 1/4, P(1) = 3/4$

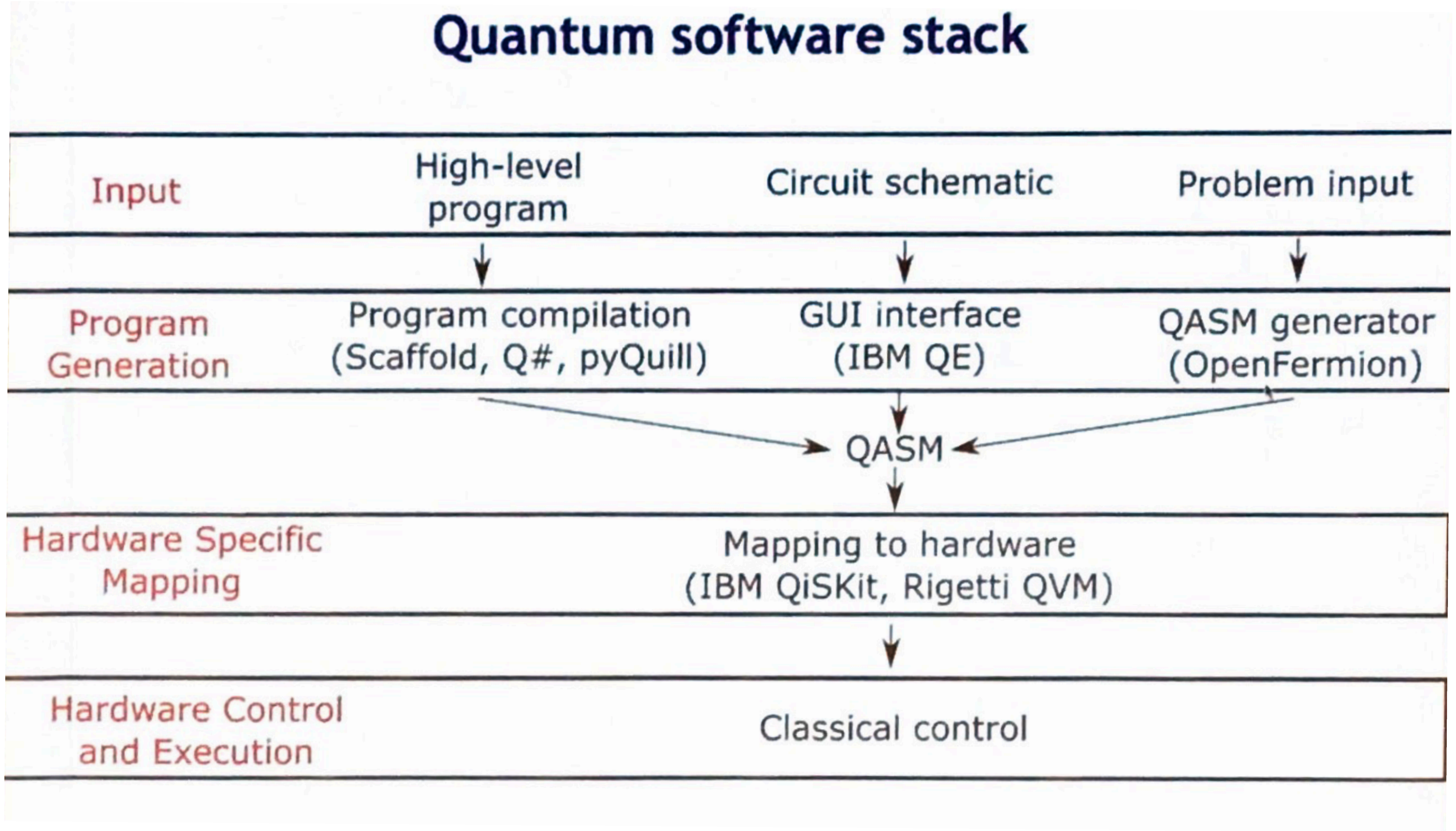
And add a relative phase... $|\psi'\rangle = \frac{1}{2}|0\rangle + \sqrt{\frac{3}{8}}(1+i)|1\rangle; P(0) = 1/4, P(1) = 3/4$



```
In [10]: import math
         b.clear()
         b.add_states( ( 0.5*zero + math.sqrt(3)/2*one ) )
         b.add_states( ( 0.5*zero + math.sqrt(3/8)*(1+1.j)*one ) )
         b.render()
```



Quantum Software (from Yuri Alexeev/ANL)



Quantum software stack

Input	High-level program	Circuit schematic	Problem input
Program Generation	Program compilation (Scaffold, Q#, pyQuill)	GUI interface (IBM QE)	QASM generator (OpenFermion)
		QASM	
Hardware Specific Mapping	Mapping to hardware (IBM QiSKit, Rigetti QVM)		
Hardware Control and Execution	Classical control		

Quantum Computing Toolkits

- Lots of big players (and a few smaller ones)

Google

Cirq

OpenFermion

ProjectQ

Powerful open source software for quantum computing

Microsoft | Quantum

Q#

rigetti

pyQuil

IBM

QISKit

QuTiP

Quantum Toolbox in Python

- Why are there so many? All of these providers are looking for customers and applications!

IBM made a board game

ENTANGLION

The World’s First Open Source Quantum Board Game. Master New Galaxies in Your Quest to Construct a Quantum Computer!

2 PLAYERS

AGES 14+

~45 MINUTES

Quantum Computing Toolkits

- All have very good documentation. QisKit has a collection of notebooks
- Different levels of computing:
  - Lowest - IBM is coming out with a module that will allow you to manipulate the microwave pulses
  - Assembly - QASM - the “compiled” output - you can program in this if you want, but why?
  - Gate Level - Google’s *Cirq,* IBM's *QISKit Terra,* Rigetti’s *pyquil* [python]
    Microsoft Q# (.net based language)
  - Application Level - *OpenFermion*, IBM’s *QISKit Aqua*, Rigetti’s *Forrest*
    Quantum Chemistry and optimization

- Backends:
  - All of the above offer simulators that are closely tied to the toolkits - laptop or cloud
  - Stand-alone simulator Atos Quantum Learning Machine (46 qubits)
  - Actual Quantum Computing Hardware (e.g. IBM Quantum Experience), Partnerships

IBM's QISKit

- The docker container has all of the toolkits mentioned above except the ones from Rigetti (can't just download them). Q# is in a separate container.

- QISKit has lots of tutorials in Jupyter Notebooks
  - More so than any other toolkit, AFAIK
  - Best way to get started, IMHO

- You (yes you) can run on a real Quantum Computer
  IBM Q Experience

- But QISKit is undergoing an upheaval to new version. But let's try it…

QISKit Tutorials

- `qiskit → basics → getting_started_with_qiskit_terra`
- `qiskit → terra → summary_of_quantum_operations`
- `community → terra → qis_info → …`

Tutorial

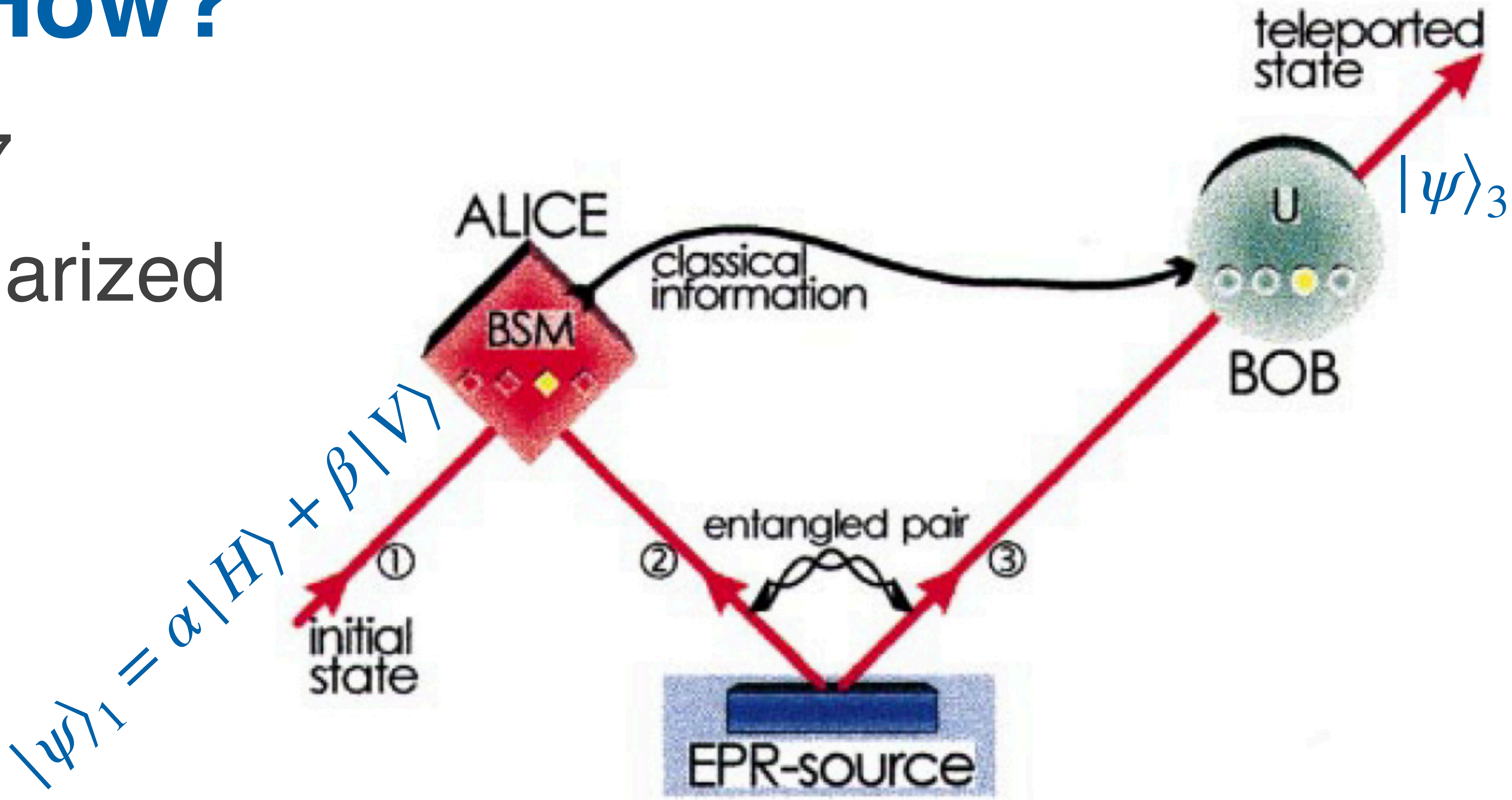
- [added after the fact]
- We went through the “Getting Started with QISKit Terra” notebook
- We were particularly interested in running on the 14 qubit Quantum machine and looking at noise for a 3-qubit EPR state. Seemed like the states with |0> had less noise than states with |1>

Quantum Teleportation - How?

Bouwmeester *et. al.*, Nature, 1997

Photons are horizontal/vertical polarized
or in superposition

Note that we’ve chosen one of the four EPR pairs for a reason (asymmetric; changes sign on interchanging particles)



$$|\psi\rangle_1 = \alpha|H\rangle + \beta|V\rangle$$

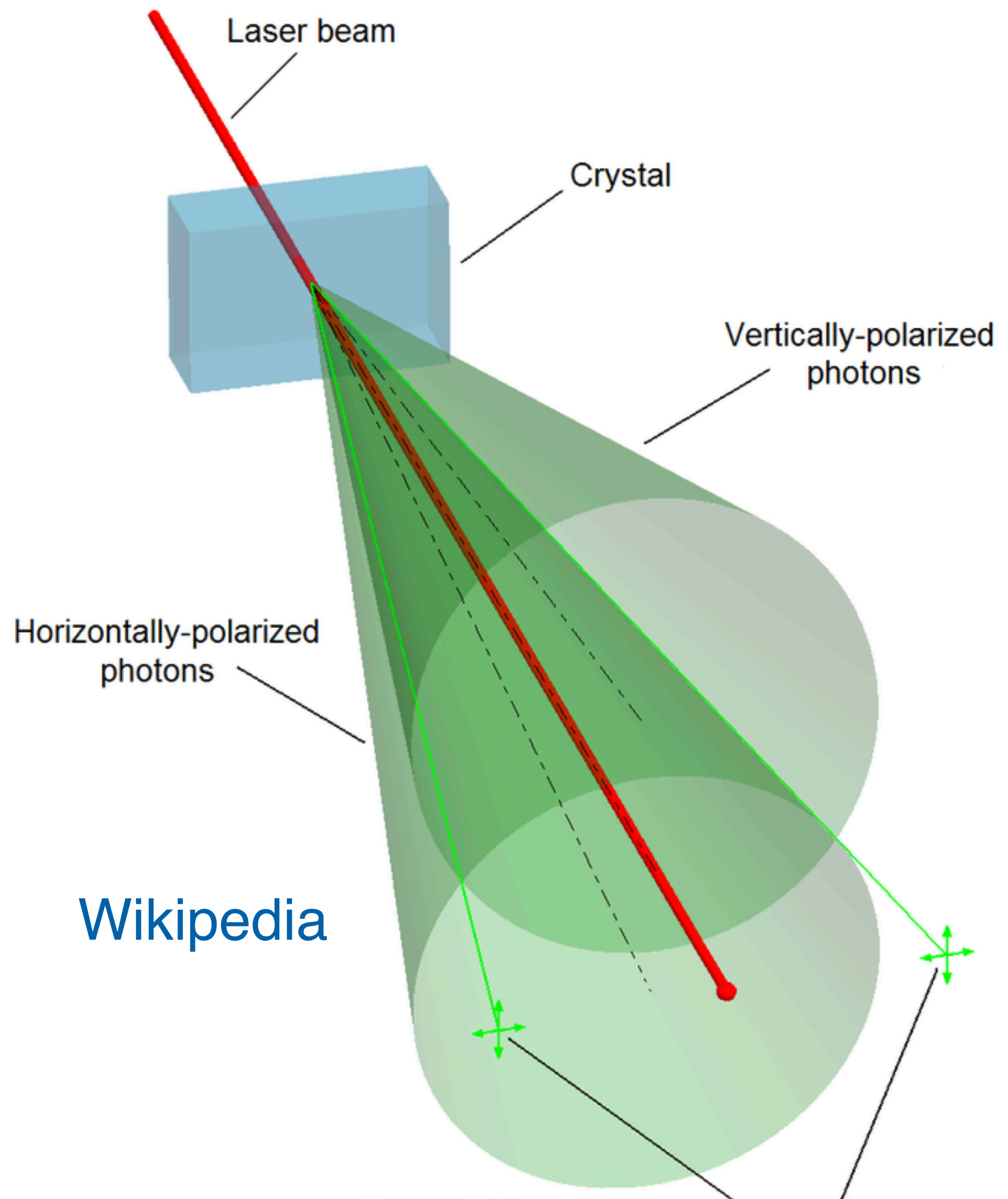
$$|\psi\rangle_3$$

$$|\psi^-\rangle_{23} = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$$

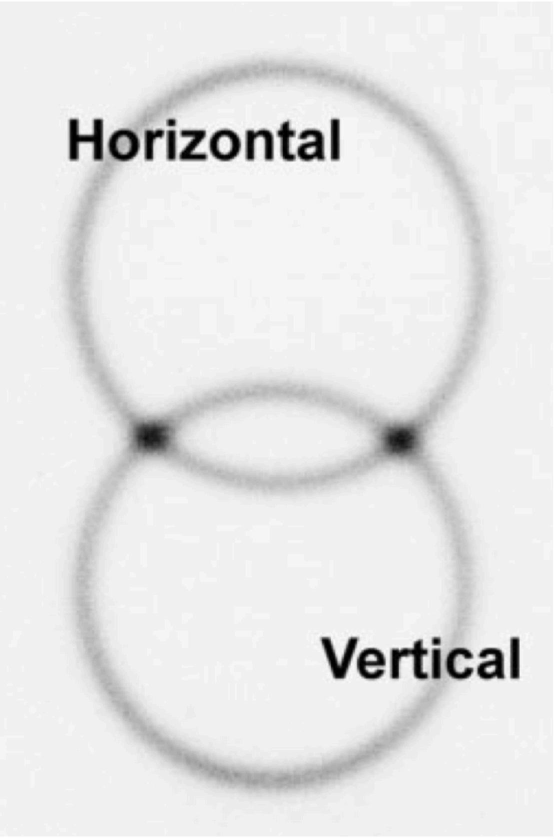
Alices has photons 1 & 2, Bob has photon 3.

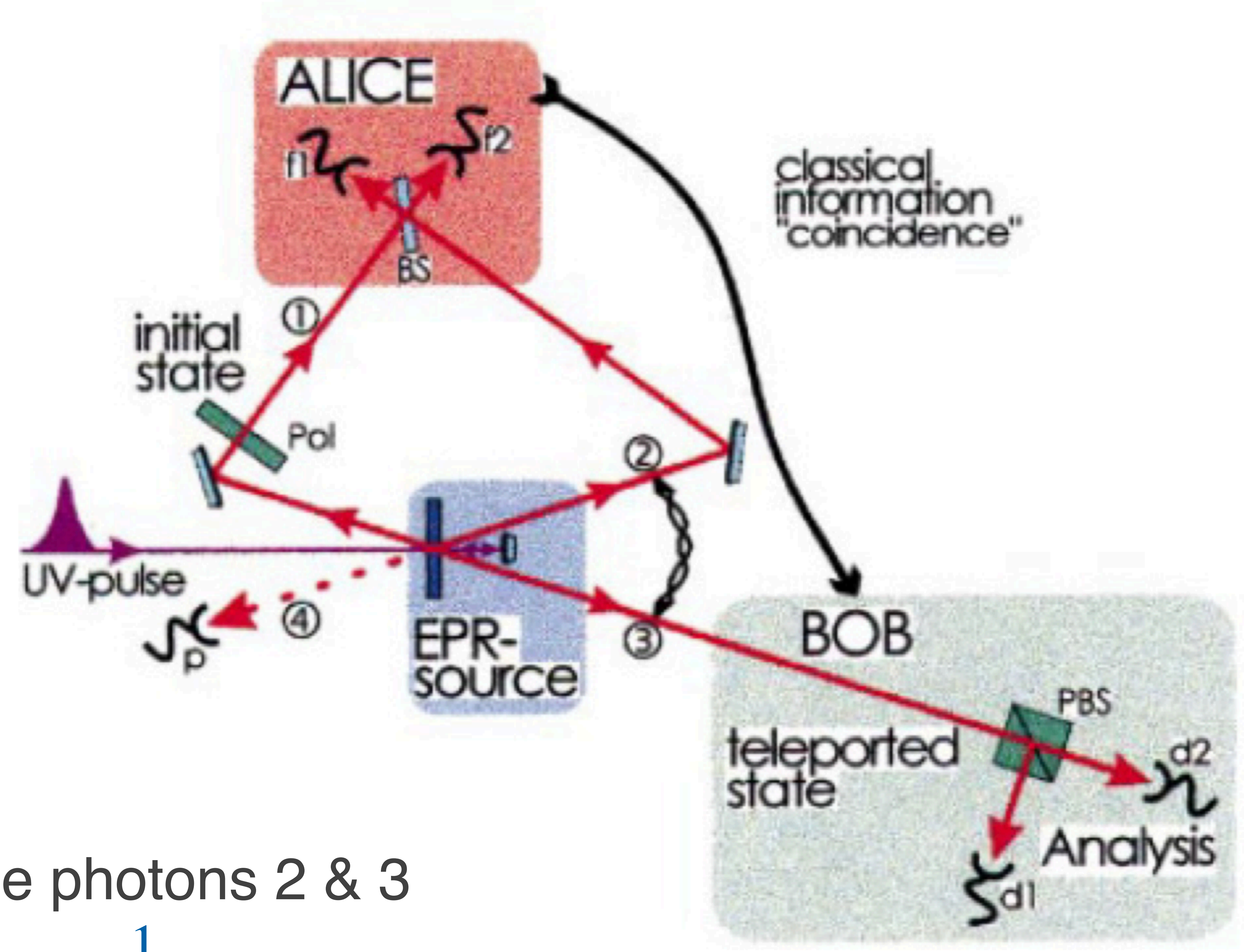
Quantum Teleportation in the lab

- Start with a UV pulse and send through a nonlinear crystal
  - BBO (Beta Barium Borate)
  - Spontaneous Parametric Down-conversion
    - Most of the beam goes straight through but some light gets split into correlated photon pairs of opposite polarization - form cones
    - Where cones meet, get EPR photon pairs



Wikipedia





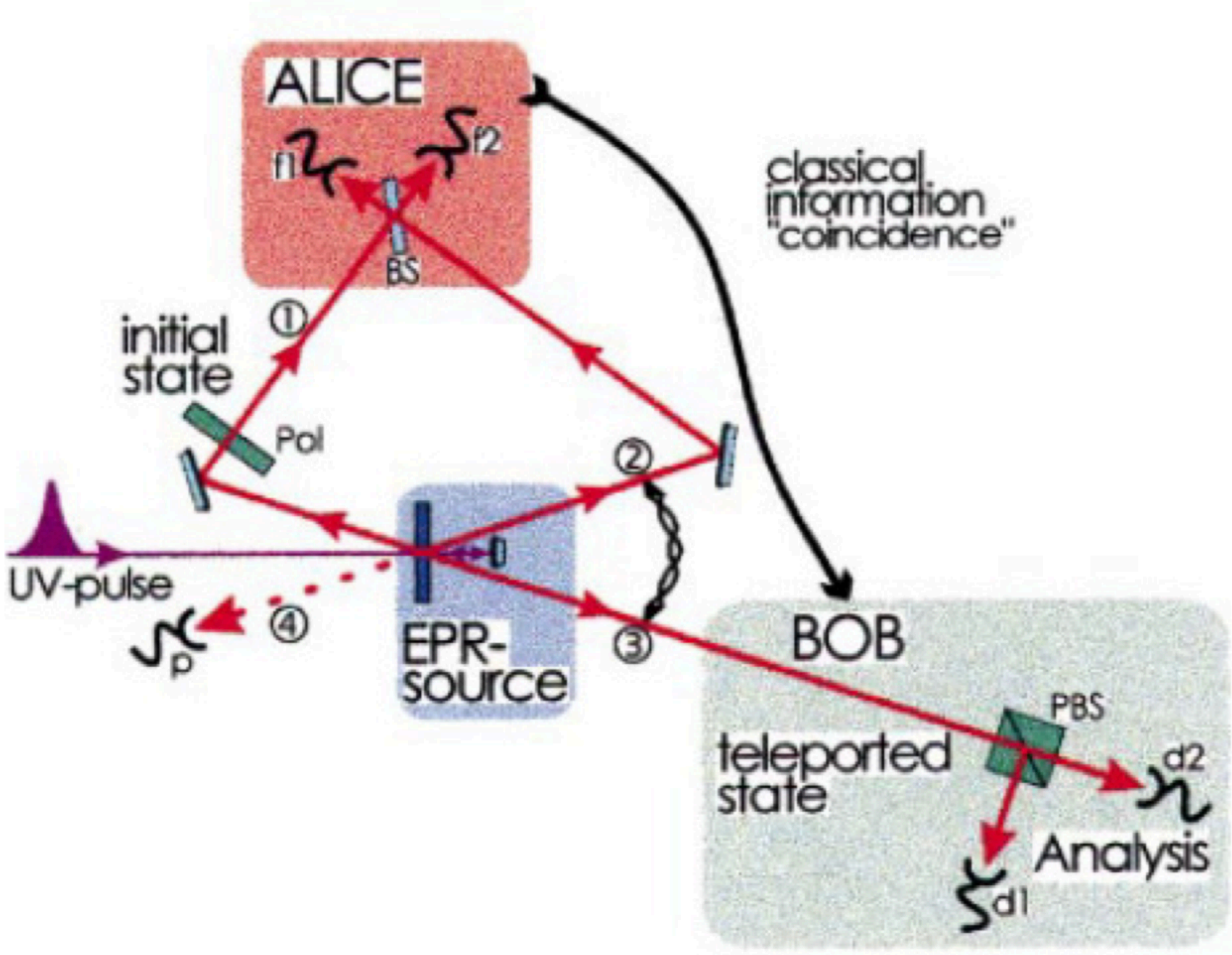
- Create photons 2 & 3

$$|\psi^-\rangle_{23} = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$$

- Retroflect the main beam back through crystal to make photons 1 & 4 (#4 is just an indicator)

Quantum Teleportation in the lab

- Alice sends photon #1 through a polarizer to make the initial state
- Now photon #1 and #2 (from the EPR pair) goes through a beam splitter putting them in superposition
- Now Alice measures her state and tells Bob
  - It turns out that only the asymmetric bell state reflects and both detectors f1 and f2 are hit in coincidence
  - If non-asymmetric bell state appears, then BOB throws his photon away
  - So this works 25% of the time



- Bob will now have the state (throw away phase) $|\psi\rangle_3 = \alpha|H\rangle + \beta|V\rangle$
- Teleportation!!!

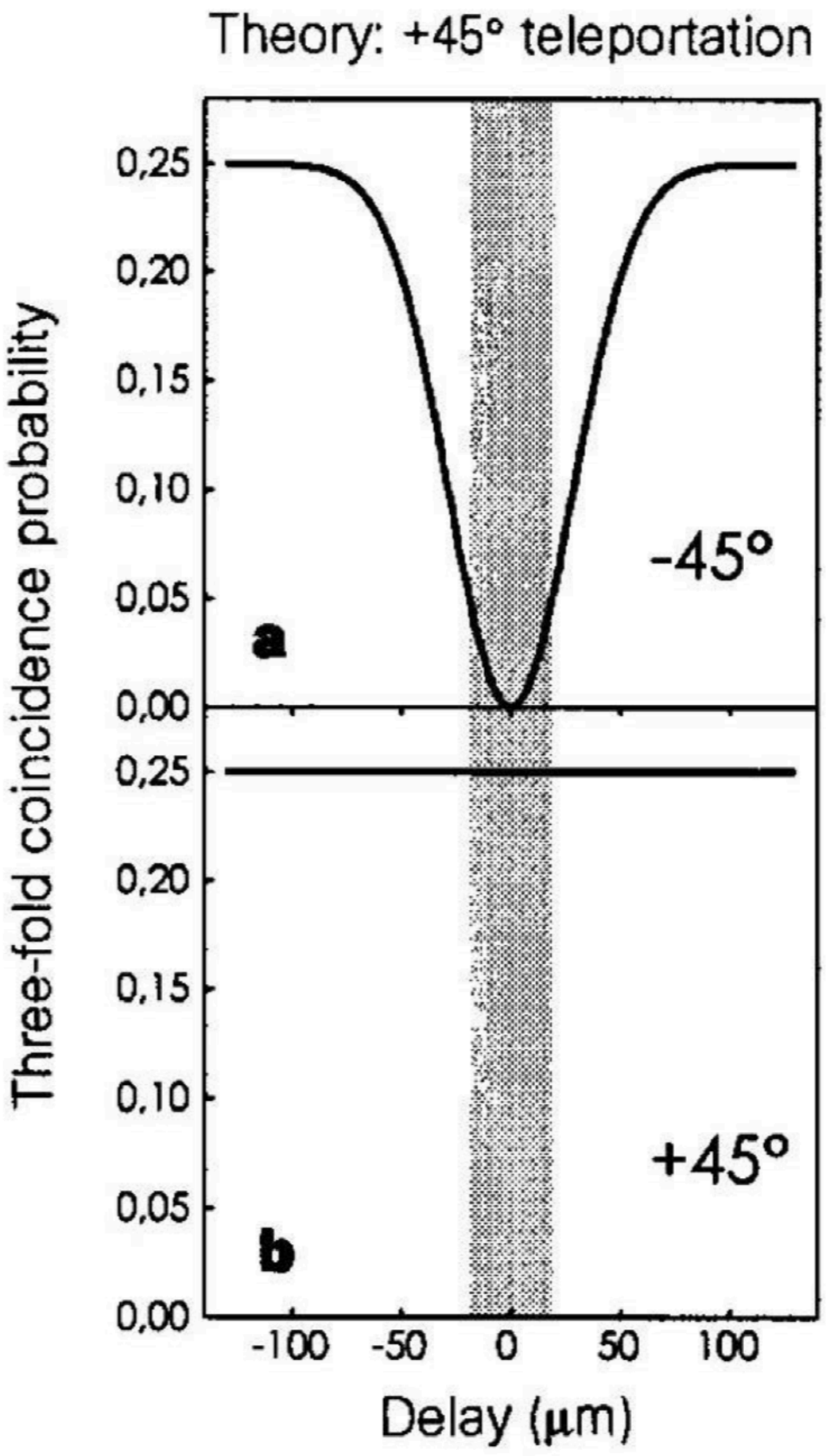
Testing Teleportation

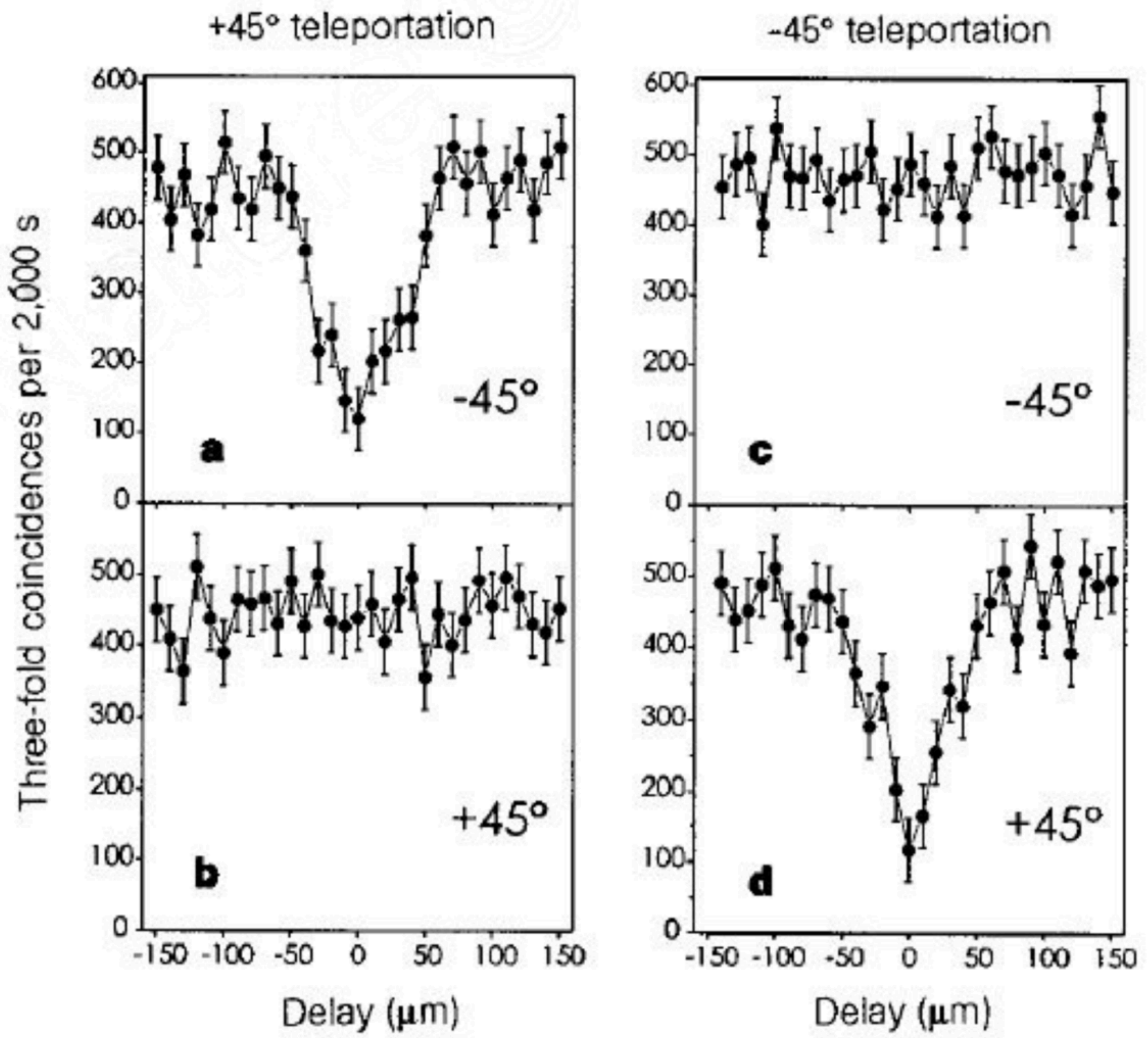
- Teleportation should work in any basis.
  - Don’t test {H,V} - those are preferred by our experiment
  - Instead try {–45°, +45°} polarizations and a superposition (circular polarization)

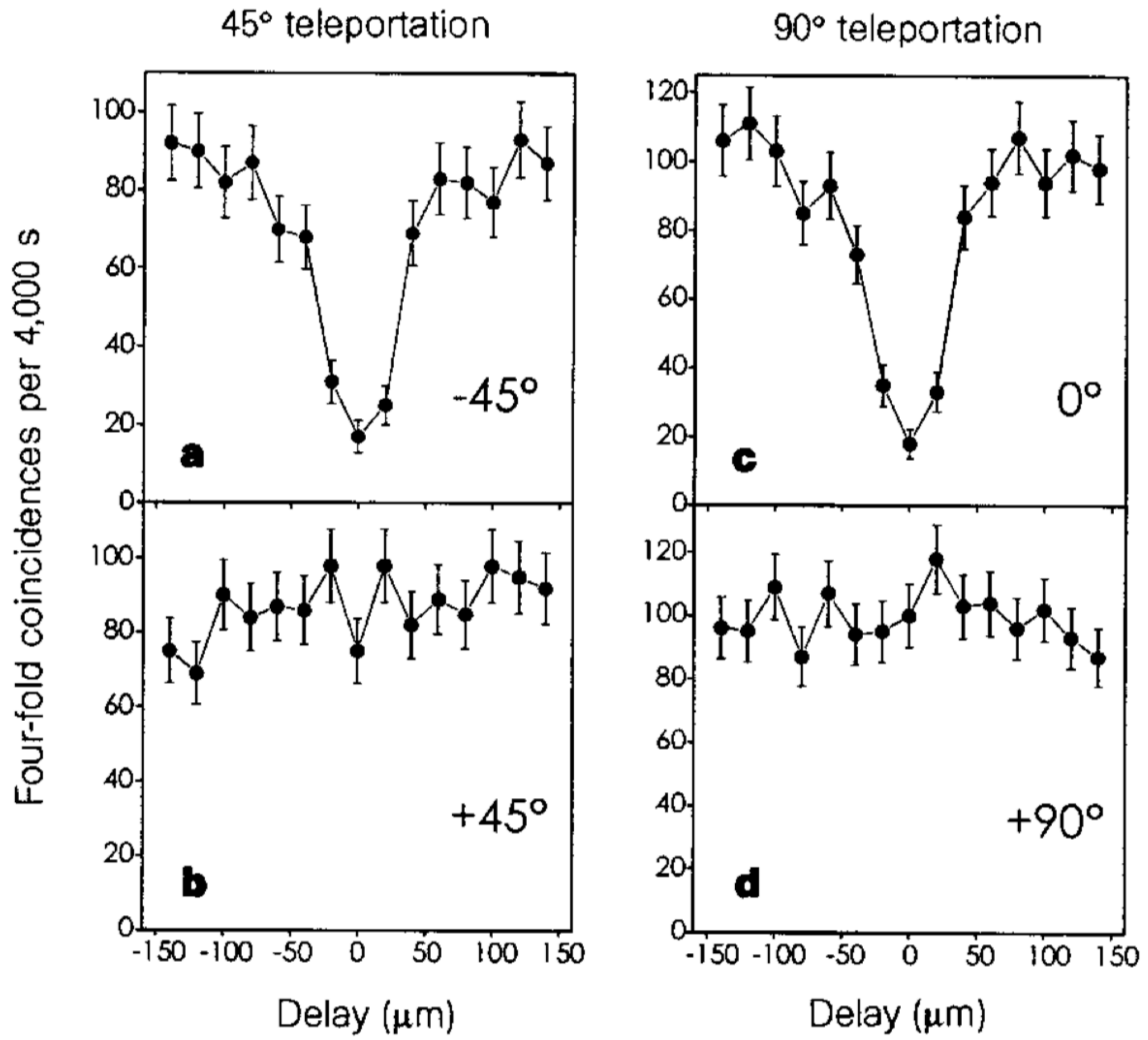
- For +45°, Alice adjusts her polarizer to make +45° polarization
  - If f1 & f2 fire, then Bob’s photon is polarized at +45°. Pass it through a polarized beam splitter and detectors behind. The +45° detector should fire 25% of the time. The –45° detector should fire 0% of the time

  - Teleportation depends on photon 2 arriving at Alice’s beam splitter at the same time as photon 1. We can ruin this coincidence by moving the retroflection mirror.
    - Ruined teleportation makes random states. So both +45° and -45° detectors fire 25% of the time

Results







Spurious 3-fold coincidences subtracted

Require 4-fold coincidence (no subtraction)

Urban teleportation

FIG. 1. **Aerial view of Calgary.** Alice is located in Manchester, Bob at the University of Calgary (UofC), and Charlie in a building next to City Hall in Calgary downtown. The teleportation distance — in our case the distance between Charlie and Bob — is 6.2 km. All fibres belong to the Calgary telecommunication network but, during the experiment, they only carry signals created by Alice, Bob or Charlie and were otherwise "dark".

Raju Valivarthi, et. al., *Quantum teleportation across a metropolitan fibre network* (ArXiv)

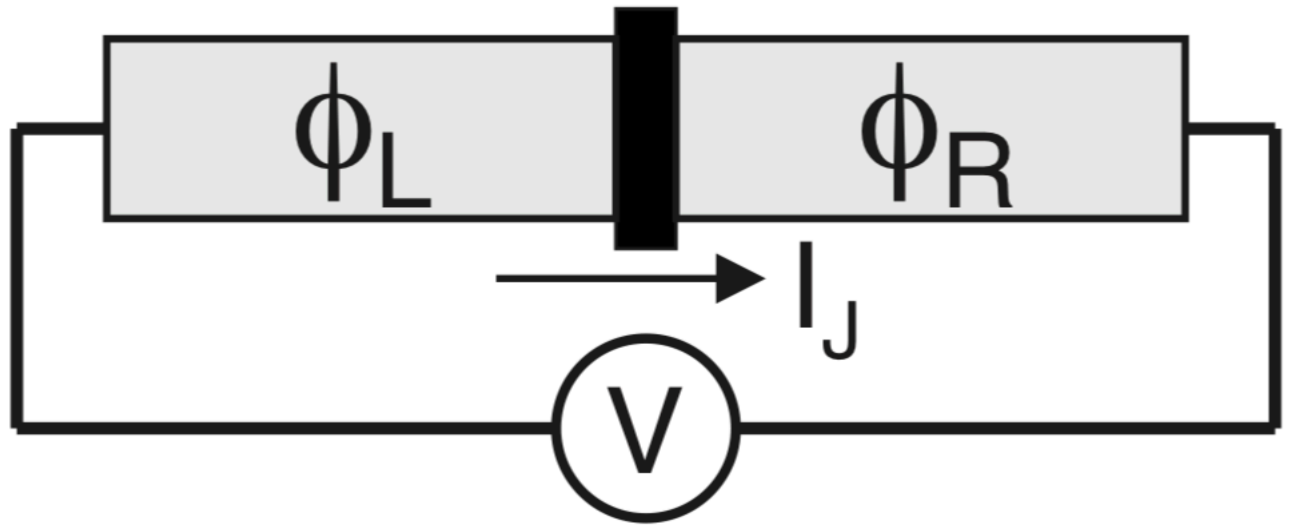
Fermilab and Argonne are doing such experiments too (see towards the end of the talk)

How do Quantum Computers Work?

- Requirements
  - Qubits need some kind of physical representation and maintain quantum properties
  - We must be able to manipulate their quantum evolution (e.g. a transistor isn't a qubit)
  - We must be able to prepare their initial states and measure their final states

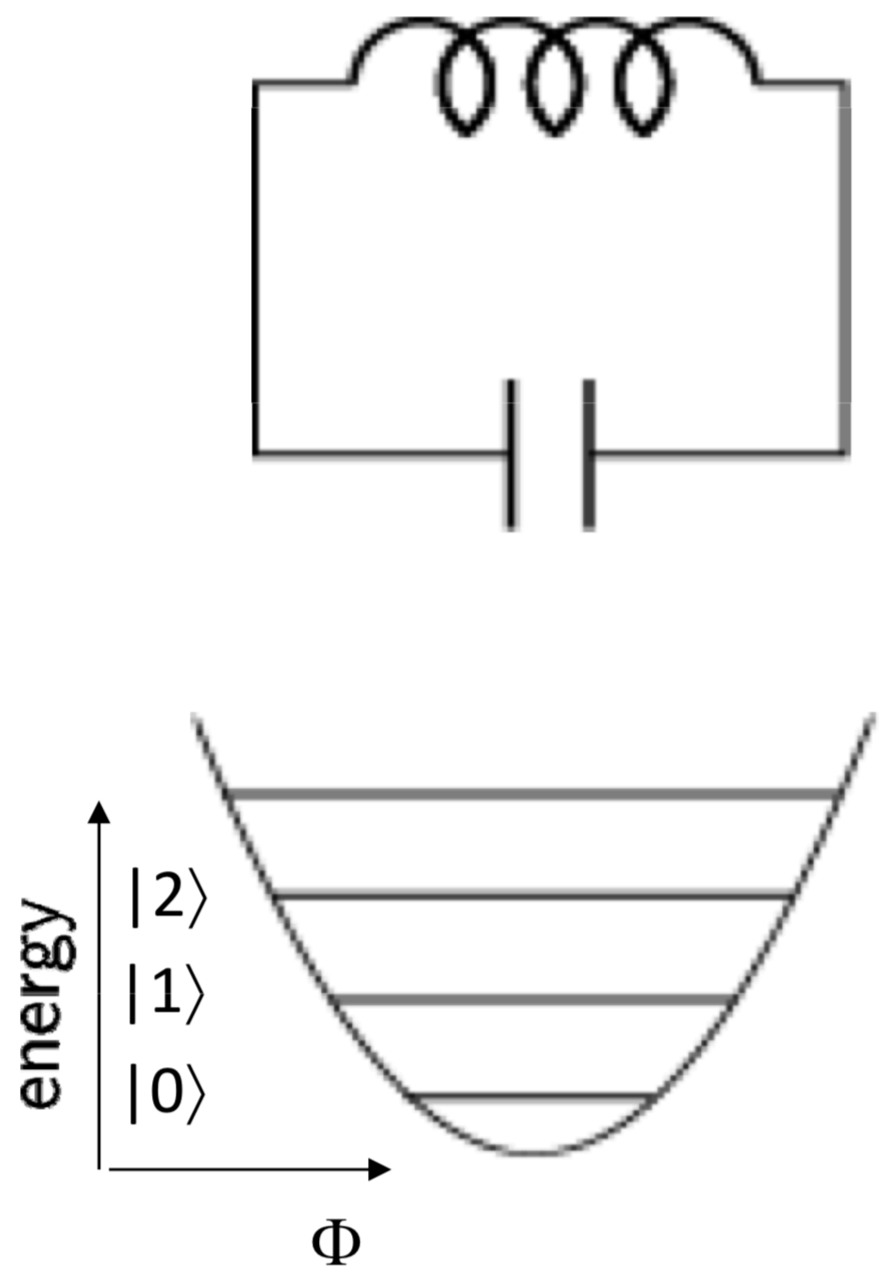
- Noise is the enemy
  - T_1 Energy relaxation time (a physical system will "relax" back to the ground state if given enough time)
  - T_2 Decoherence/Dephasing (intrinsic and external coupling leading to energy loss, ruining the quantum state; no system is perfectly closed)
  - Initial state fidelity, gate fidelity, measurement fidelity (how often you got the right thing)
  - Gate time is important … must be able to execute many gates before quantum state is lost to noise

Superconducting Qubits (Artificial Atoms)



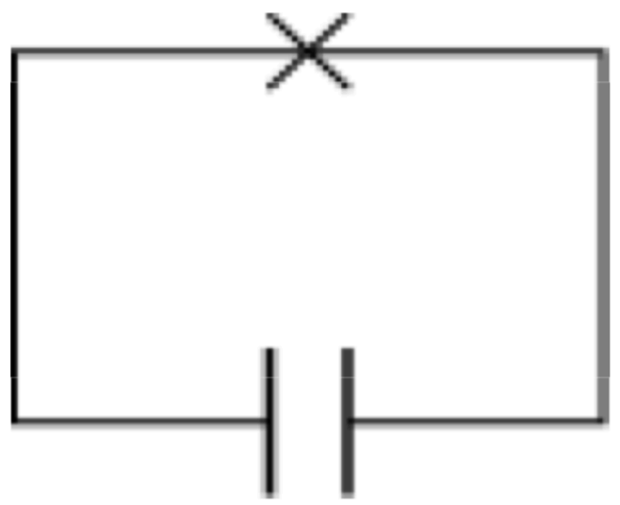
- Superconducting Josephson Junction
  - Super-current tunnels through barrier between two superconductors
  - Combined with a capacitor — make a resonator
  - Josephson junction provides non-linearity to make anharmonic oscillator
  - States $|g\rangle, |e\rangle, |f\rangle$ (ground, excited, leakage)
  - Excited - ground ~ 5 GHz for 10s miliKelvin
  - Microwave pulse rotates in Bloch Sphere:
    - Frequency $\omega_d = Freq(|e\rangle - |g\rangle)$
    - Axis selected by quadrature amplitude modulation
    - Angle set by pulse duration

LC resonator

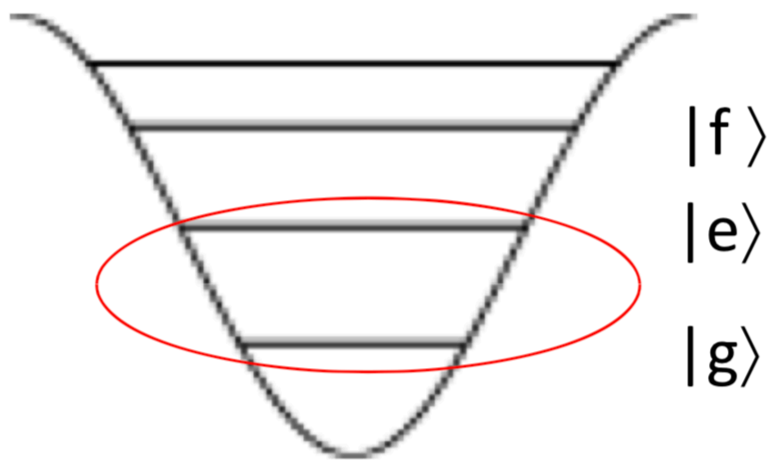


Josephson junction resonator

Josephson junction = nonlinear inductor



anharmonicity → effective two-level system

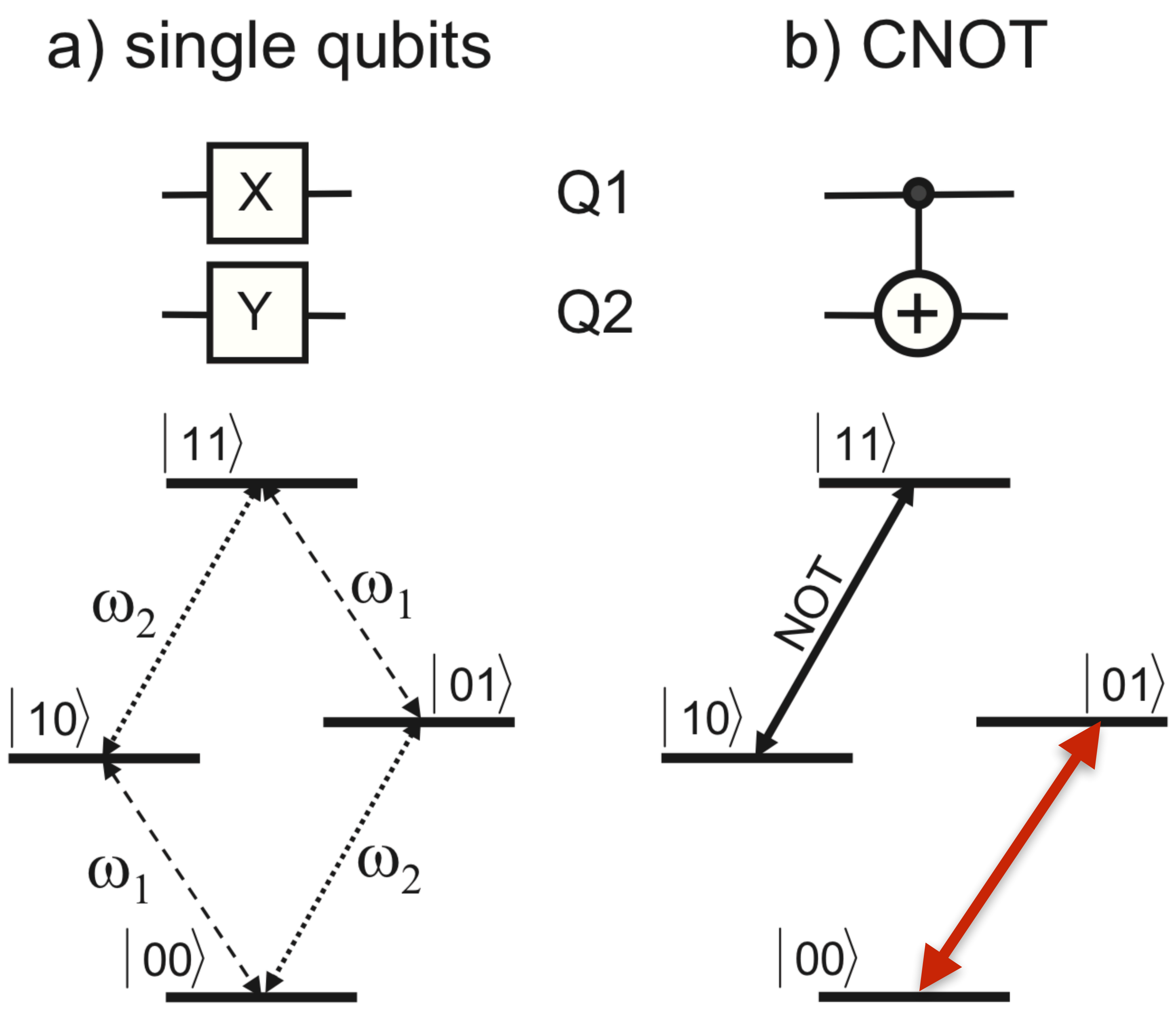


Superconducting Qubits

- QAM $\mathscr{E}(t) = \mathscr{E}^x(t)\cos(\omega_d t) + \mathscr{E}^y(t)\sin(\omega_d t)$
- Hamiltonian: $H^R = (\omega - \omega_d)\,|\,1\rangle\langle 1\,| + \frac{1}{2}(\mathscr{E}^x(t)\sigma_x + \mathscr{E}^y(t)\sigma_y)$
- If only rotate about x axis for time t$_g$ $U_x = \exp\left(\frac{-i}{\hbar}\int_0^{t_g} H^R dt\right) = \exp\left(-i\int_0^{t_g} \mathscr{E}^x(t)dt \cdot \sigma_x/2\right)$
- This is the same as Rotation operator $R_x(\theta)$ by $\theta = \int_0^{t_g} \mathscr{E}^x(t)dt$
- This is universal since any $U = R_x(\theta_1)\ R_y(\theta_2)\ R_x(\theta_3)$
- 2-qubit gates for those that are coupled with capacitor or with a quantum “bus” - microwave cavity quantum harmonic oscillator
- Measurement with microwave resonator with resonance frequency shifted by qubit state

Making a CNOT gate

From Martinis (2012)



Cannot work due to Degeneracy

Instead, couple the qubits so that the frequencies are different

But now we have more frequencies and this isn't *scalable* to large number of qubits

Solution is to select qubit coupling when needed

CNOT implemented by tuning $\omega_1 = \omega_2$ making $|01\rangle$ and $|10\rangle$ swap

Then apply single qubit gates to get CNOT

OR - use cross resonance effect:

Drive control qubit at the frequency of target qubit…

Conditions rotation of target on state of control

[Not scalable]

Calibration is crucial

- Need to tune pulse waveforms for qubit controls (frequency, phase, time)
- Calibrations depend on other calibrations
- Parameters drift over time
- Different cases - single qubit gates, multi-multi-quit gates, etc
- Takes a significant amount of time

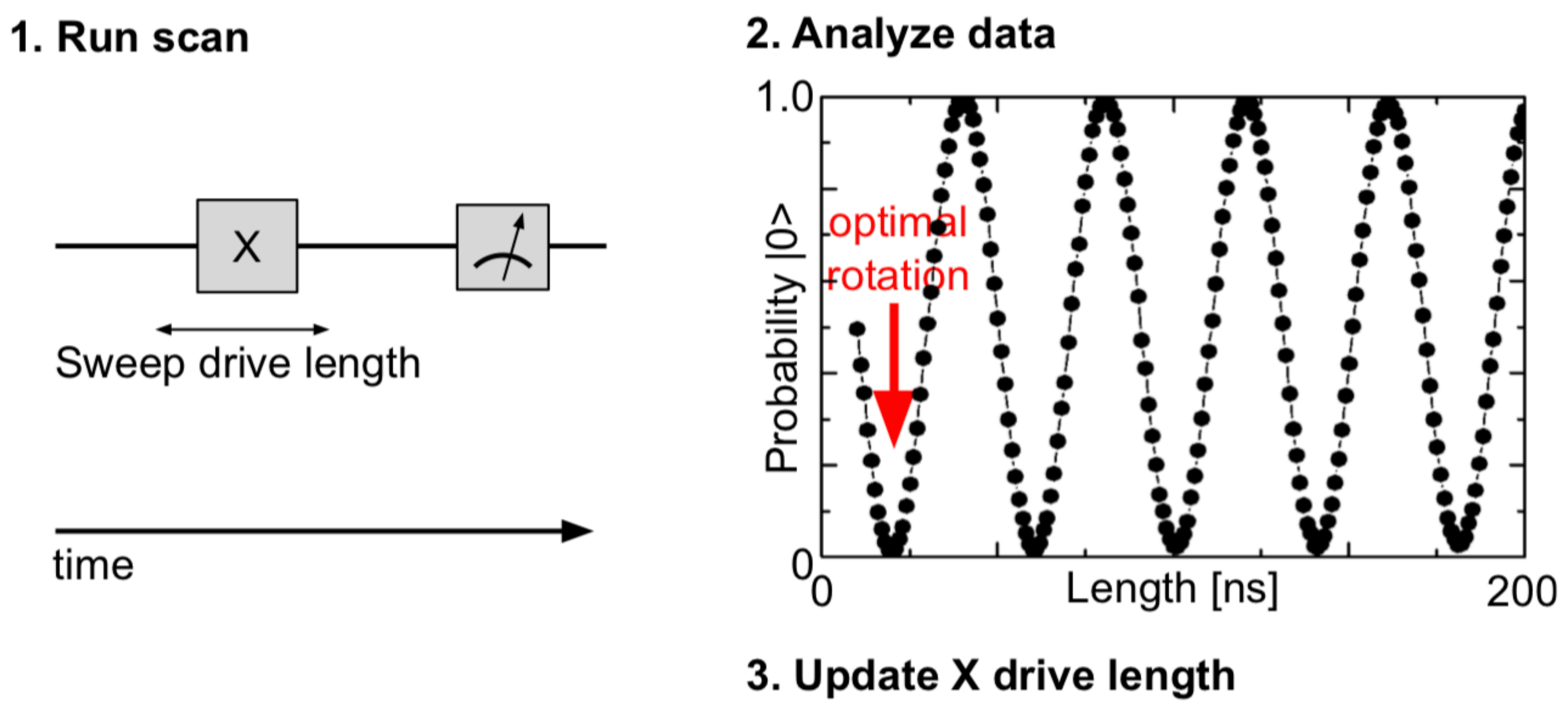
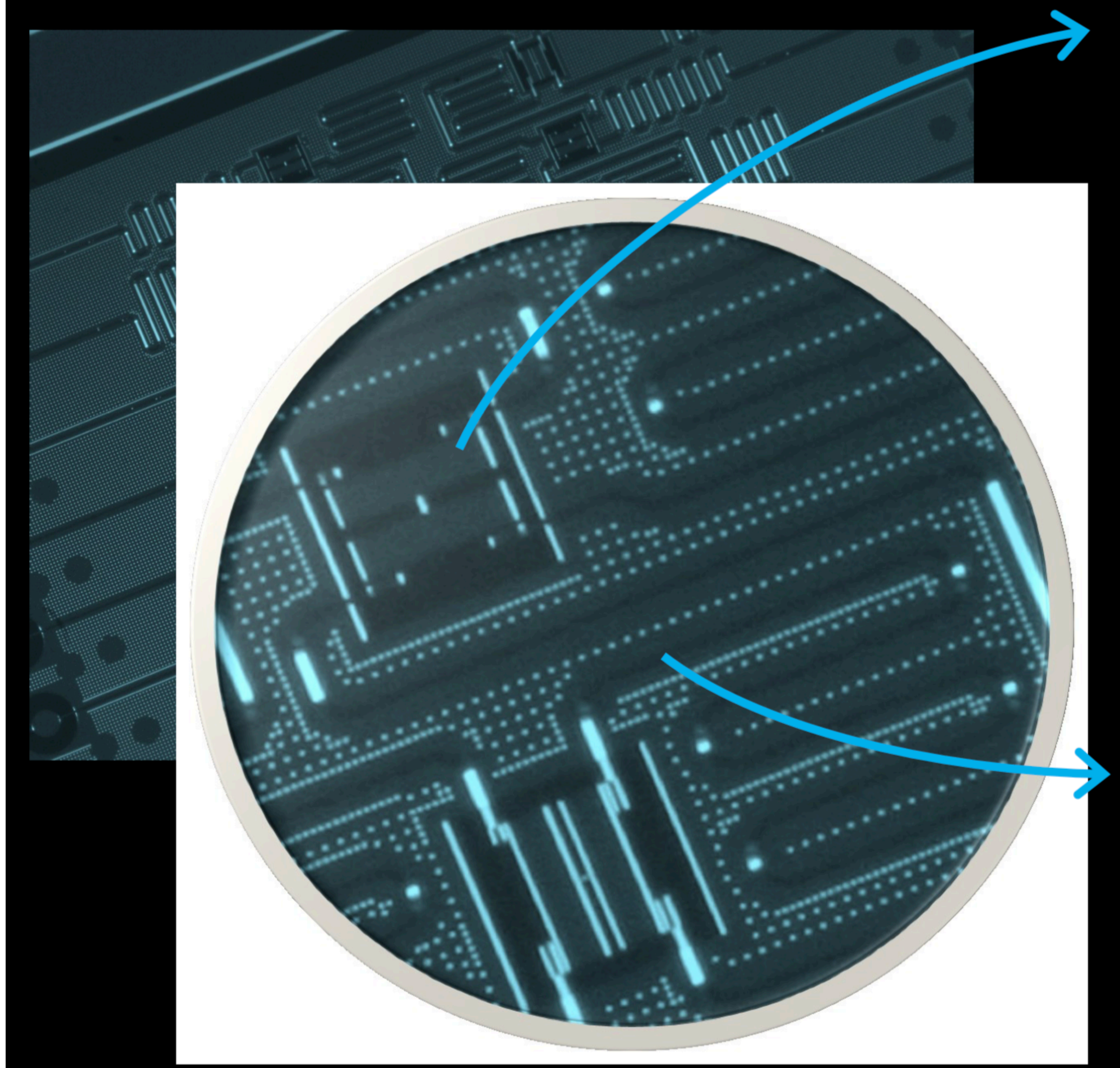


FIG. 1. **An example of a rabi driving cal.** (1) The rabi driving scan is performed, consisting of a collection of experiments, where each experiment has a single drive length, and the average probability of the $|0\rangle$ state is measured. (2) The data is analyzed, and the optimal drive length is determined. (3) The qubit parameter for the driving length of an X pulse is updated to the optimal value.

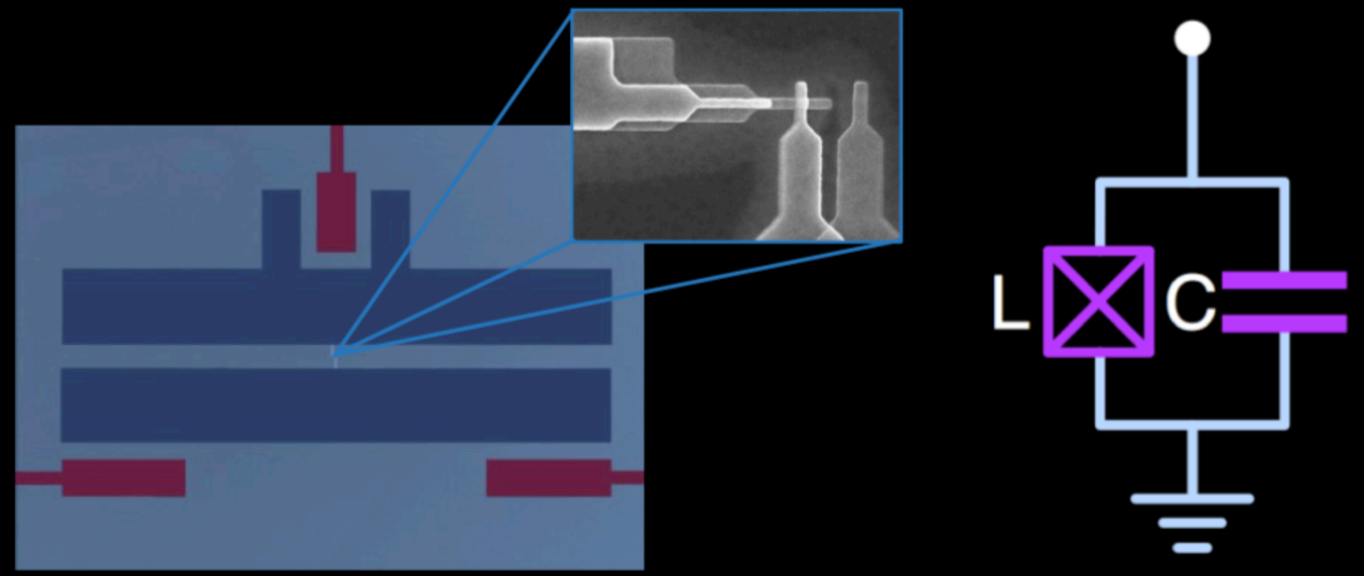
Kelly *et. al.*, *Physical qubit calibration on a directed acyclic graph*, 2018

What do these things look like?



Superconducting qubit

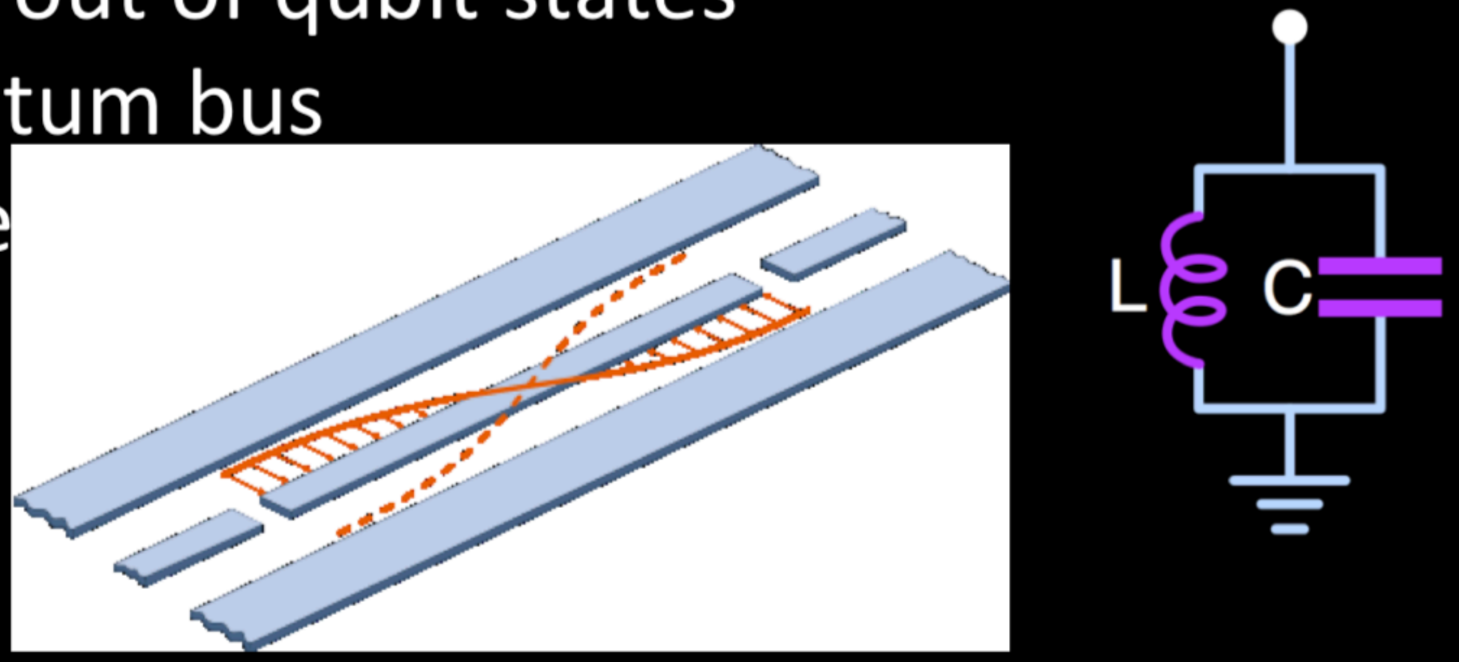
- quantum information carrier



$E_{01} \approx 5\ \mathrm{GHz} \approx\ 240\ \mathrm{mK}$

Microwave resonator:

- read-out of qubit states
- quantum bus
- noise



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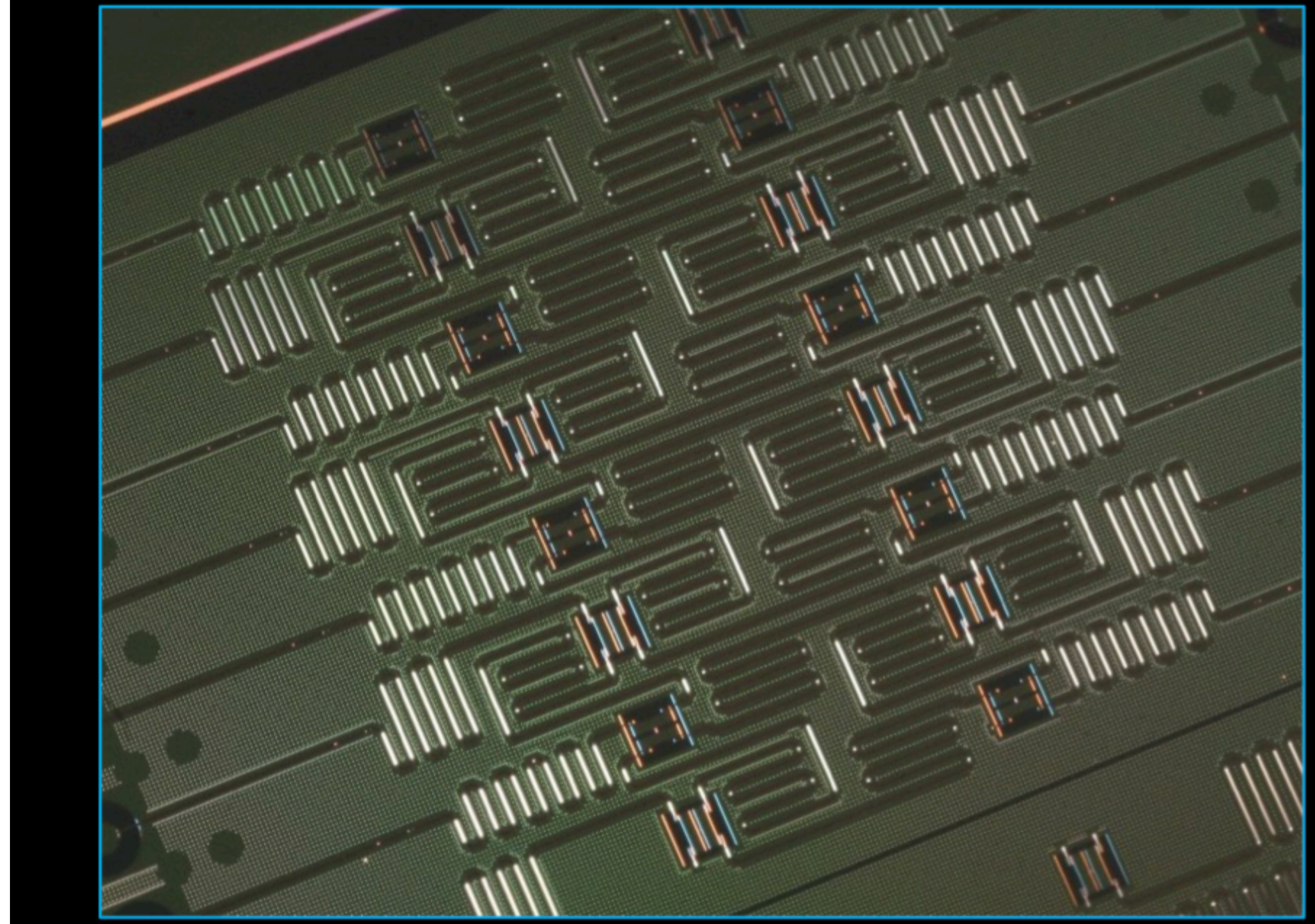
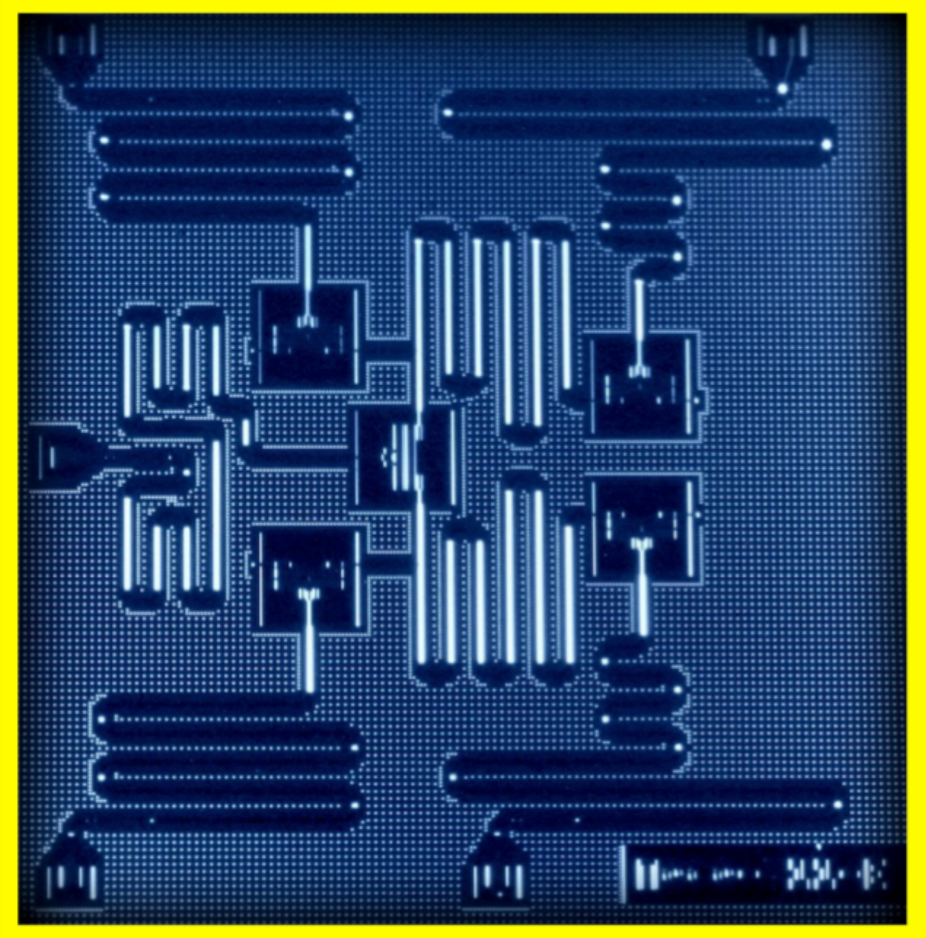
IBM qubit processor architectures

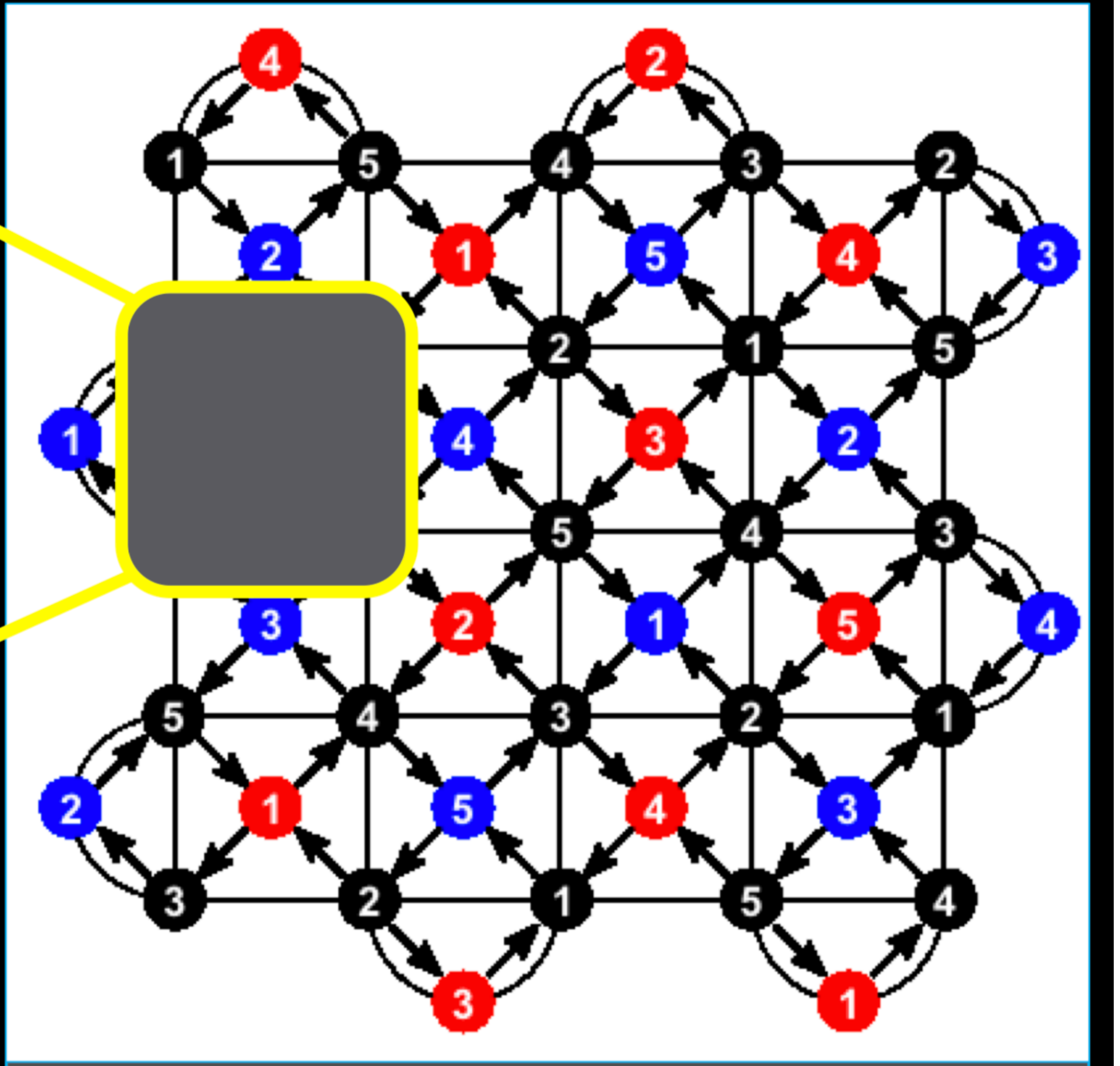
IBM Q experience (publicly accessible)

16 Qubits (2017)



5 Qubits (2016)

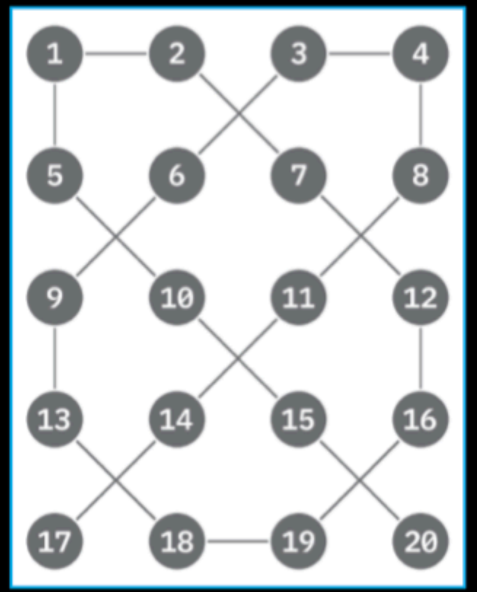




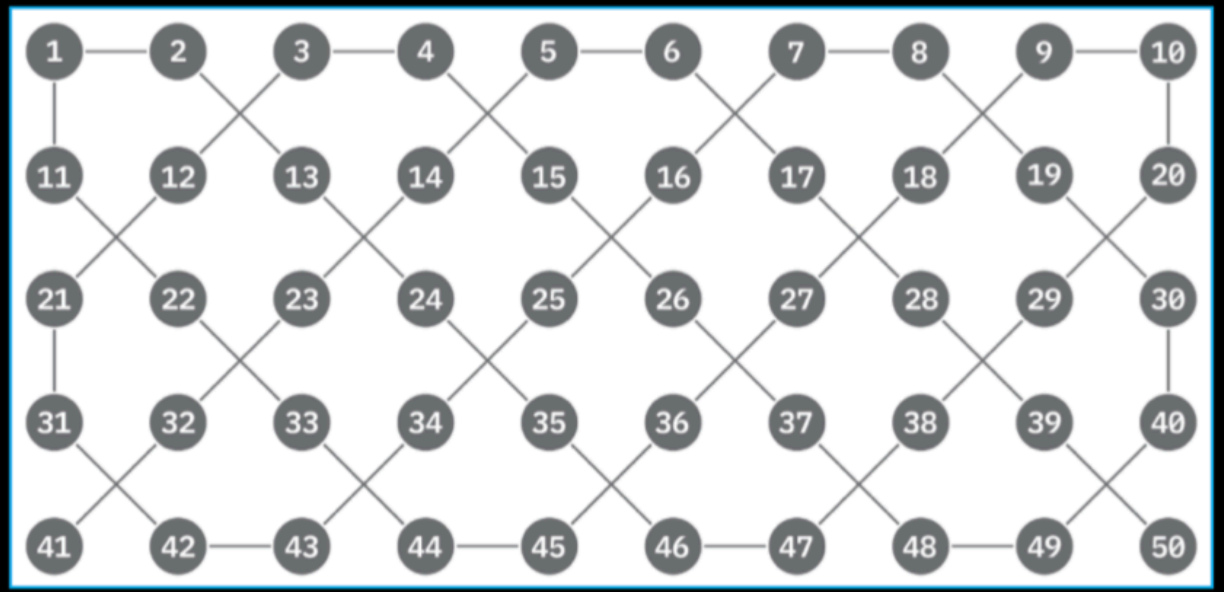
Latticed arrangement for scaling

IBM Q commercial

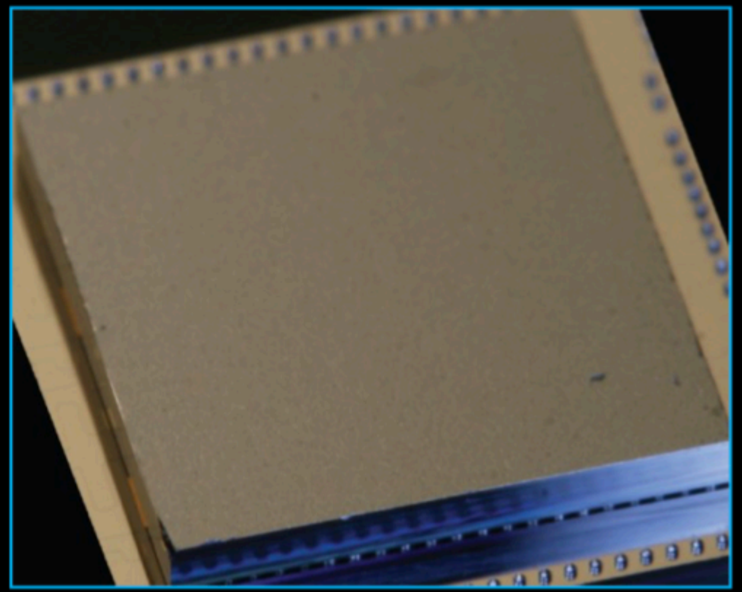
20 Qubits



50 Qubit architecture (2017)



Package



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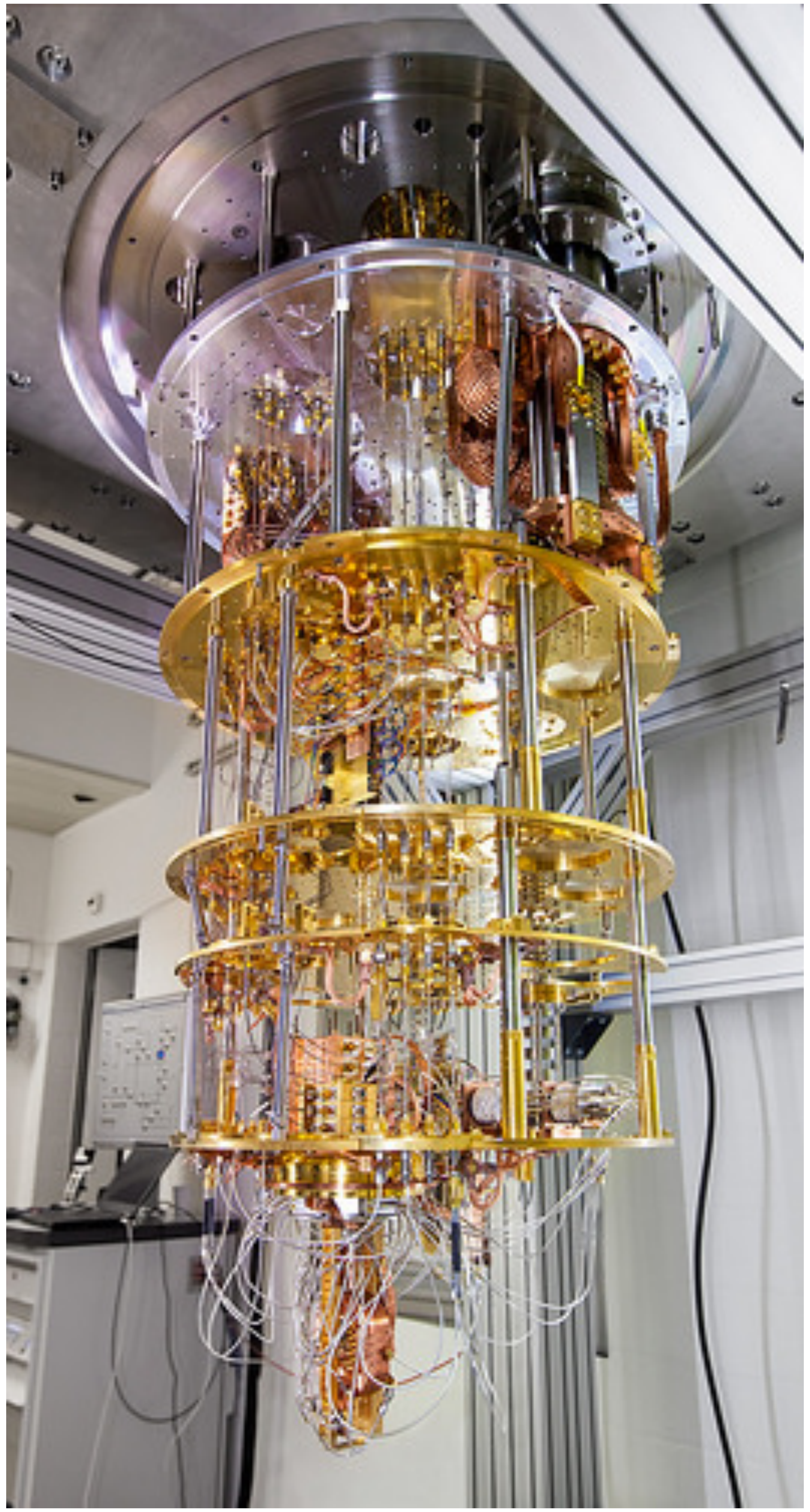
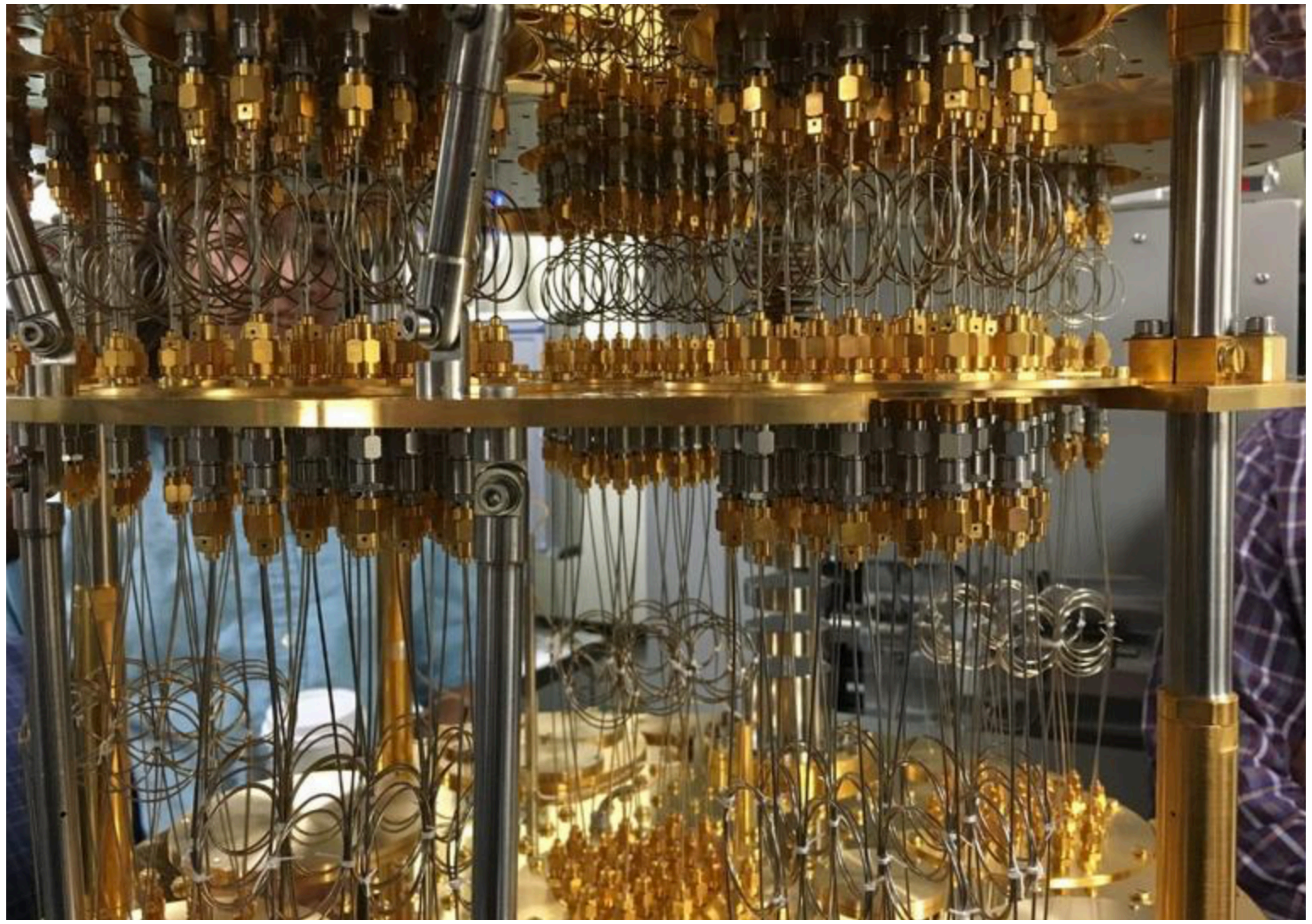
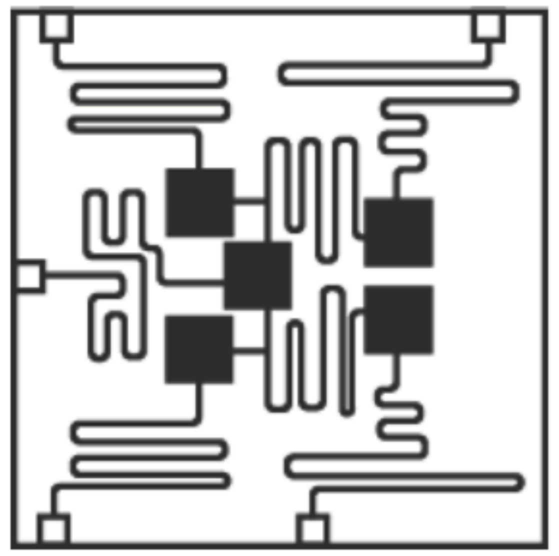
Cool Pictures

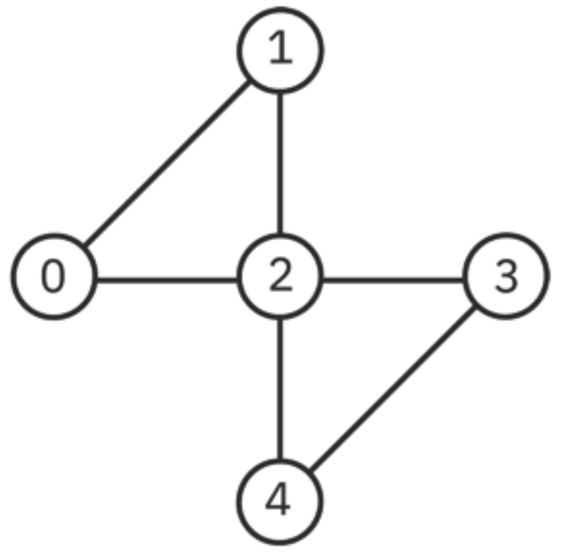


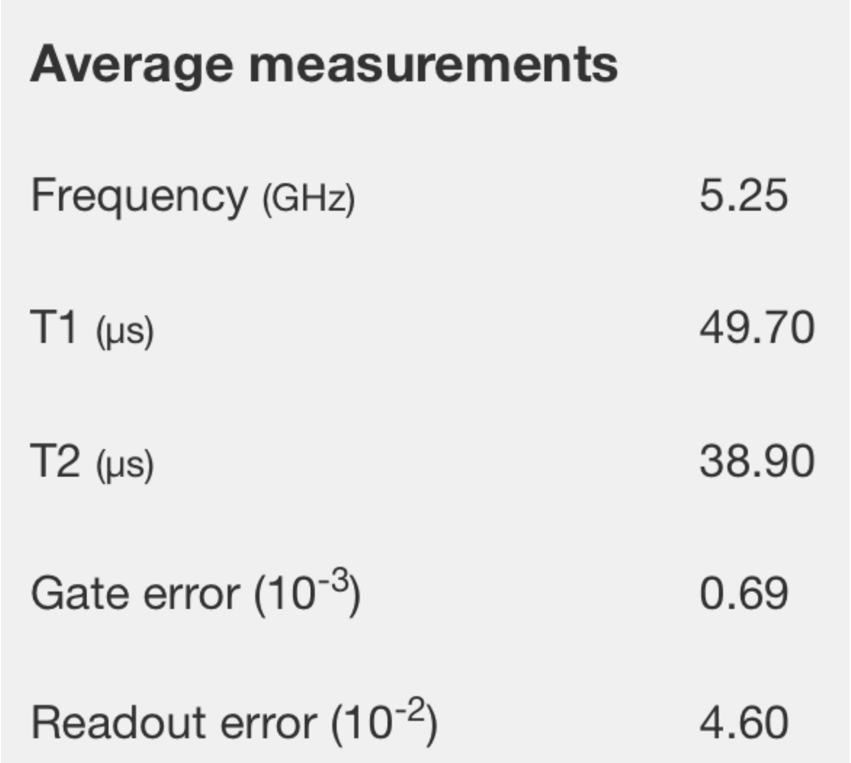


IBM QC Machine information (Public web)

- 5 Qubit Tenerife

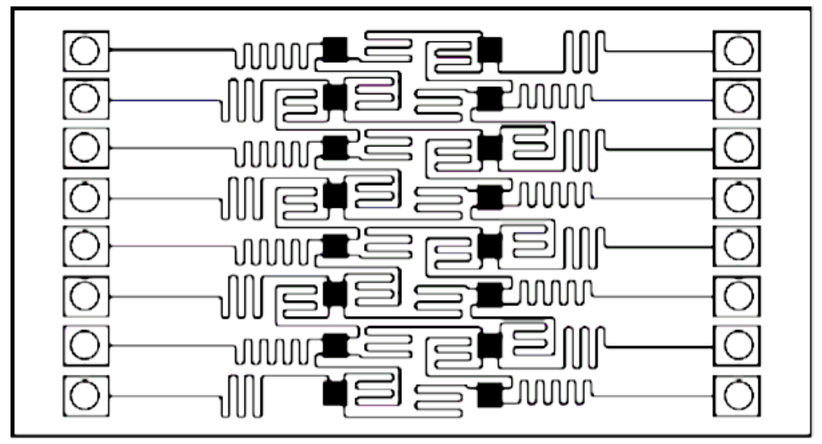


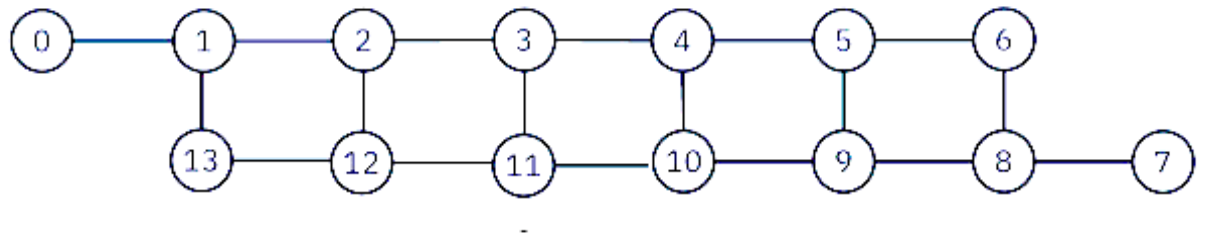


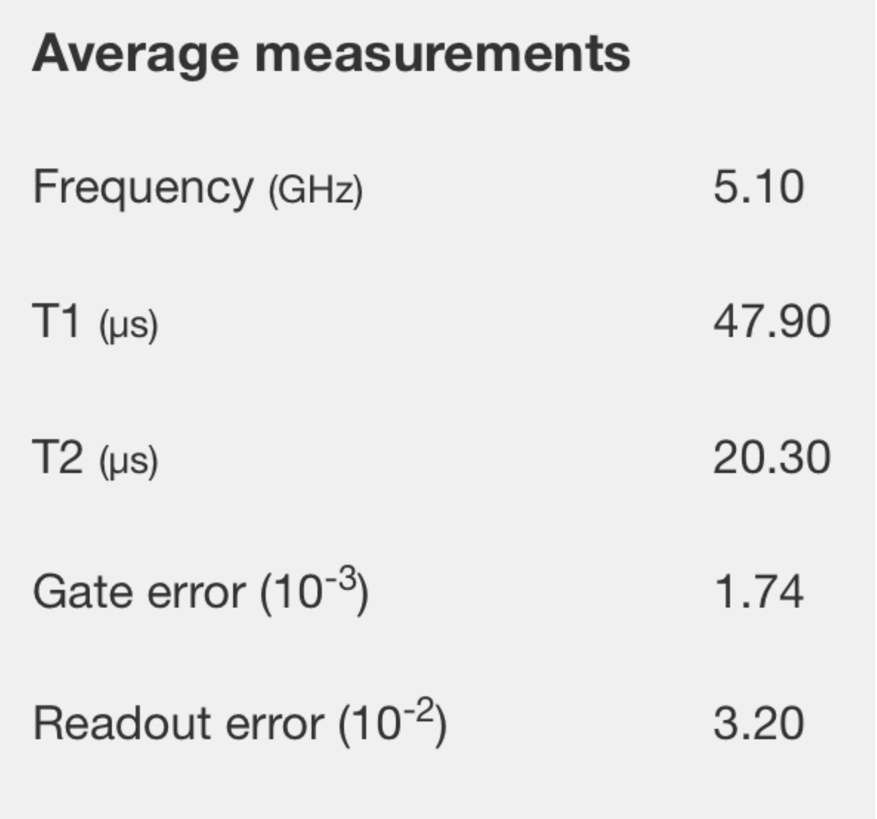


Average measurements	
Frequency (GHz)	5.25
T1 (µs)	49.70
T2 (µs)	38.90
Gate error (10^{-3})	0.69
Readout error (10^{-2})	4.60

- 14 Qubit Melbourne

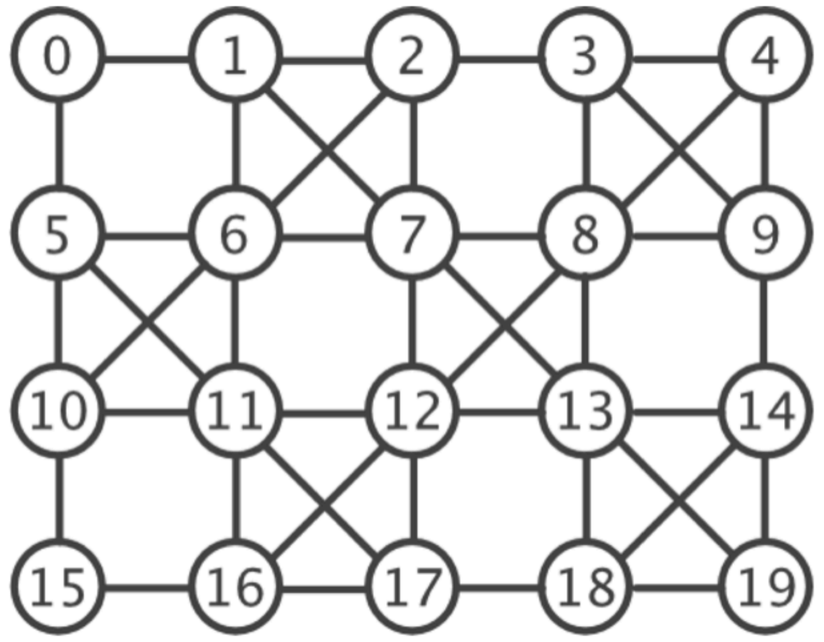


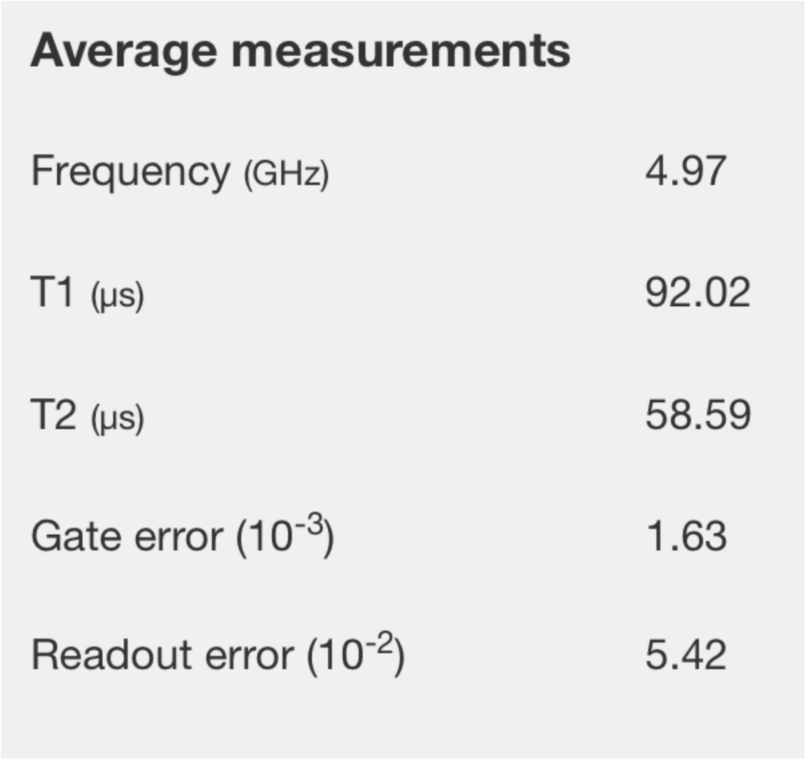




Average measurements	
Frequency (GHz)	5.10
T1 (µs)	47.90
T2 (µs)	20.30
Gate error (10^{-3})	1.74
Readout error (10^{-2})	3.20

- 20 Qubit Tokyo

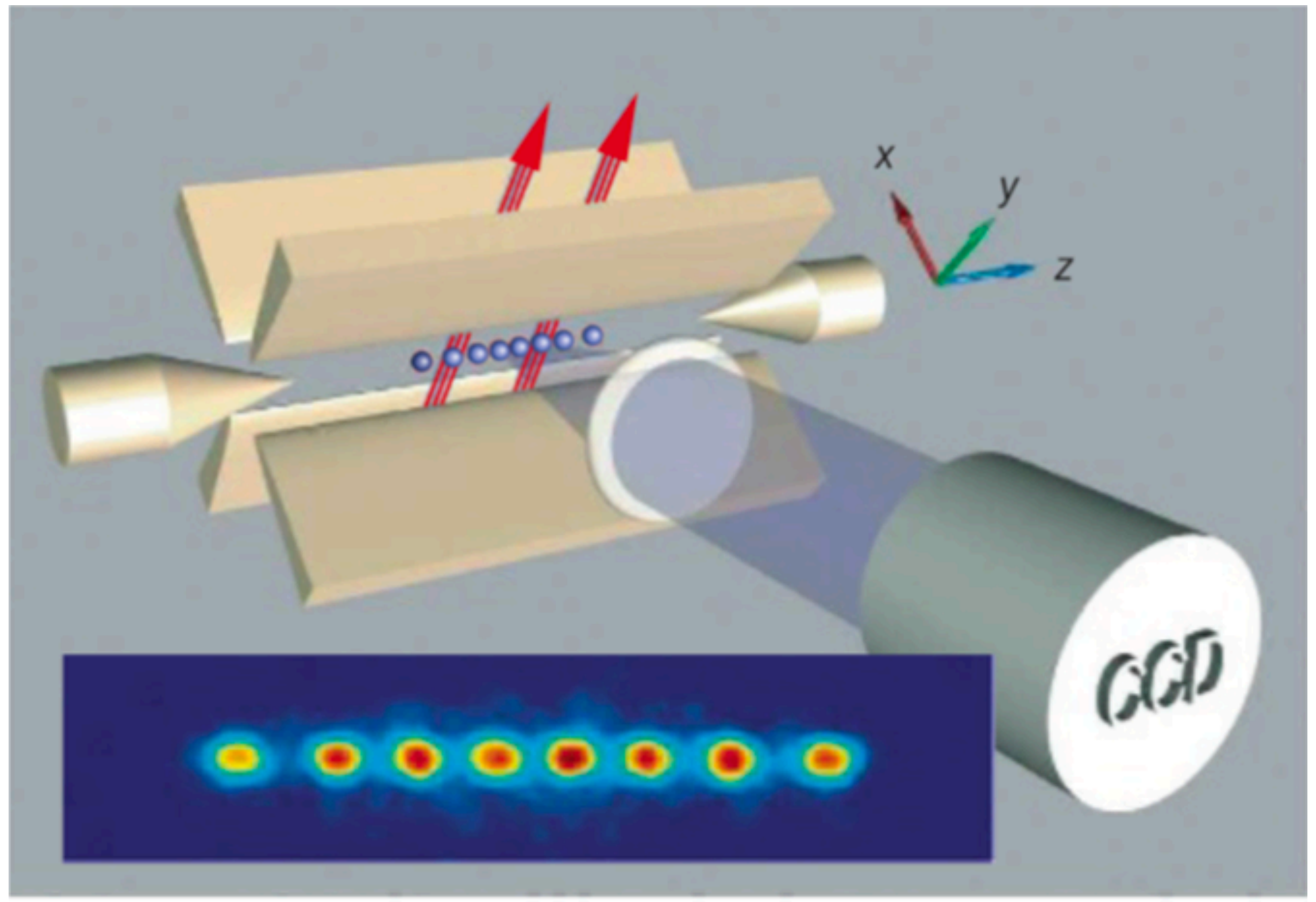


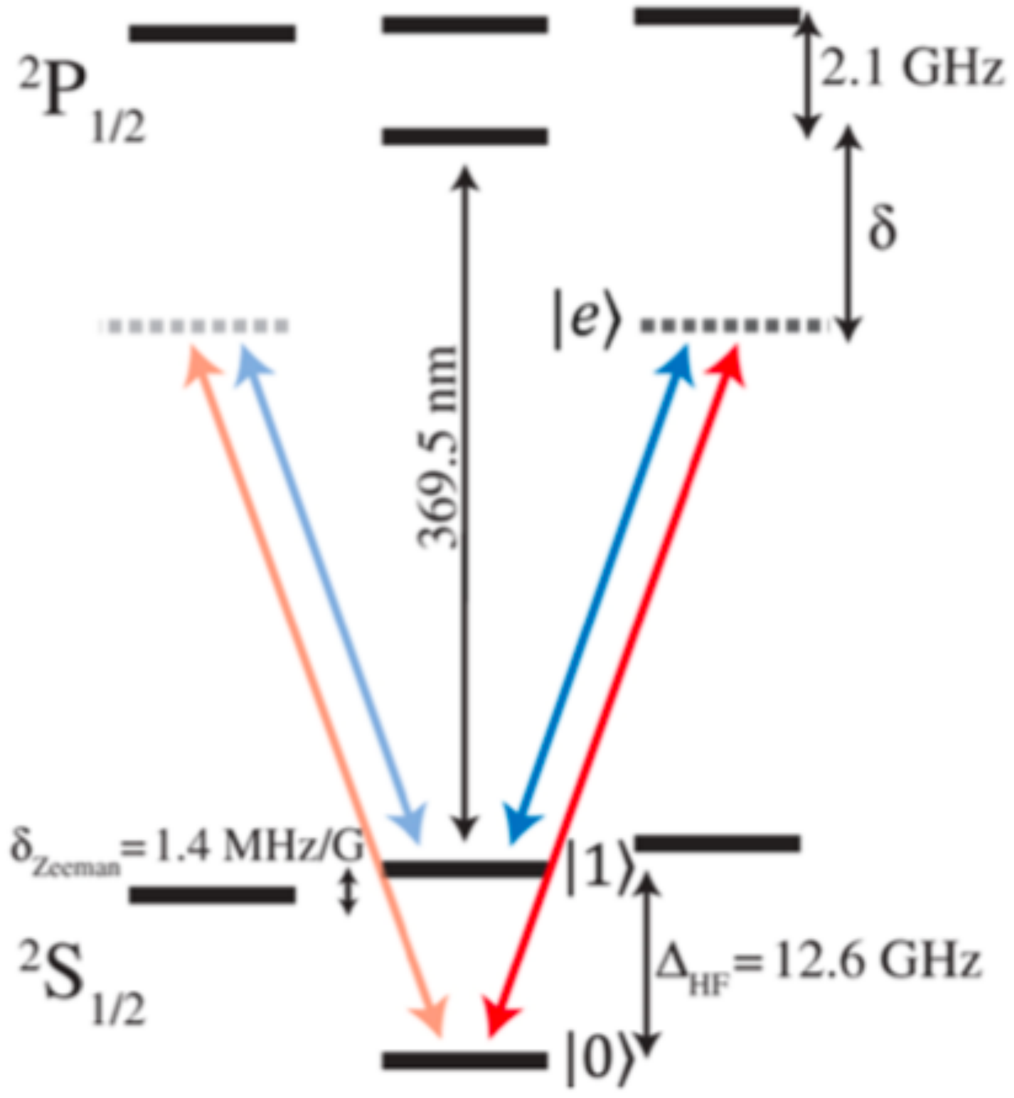


Average measurements	
Frequency (GHz)	4.97
T1 (µs)	92.02
T2 (µs)	58.59
Gate error (10^{-3})	1.63
Readout error (10^{-2})	5.42

Other technologies (Humble et. al., 2018)

- Ions

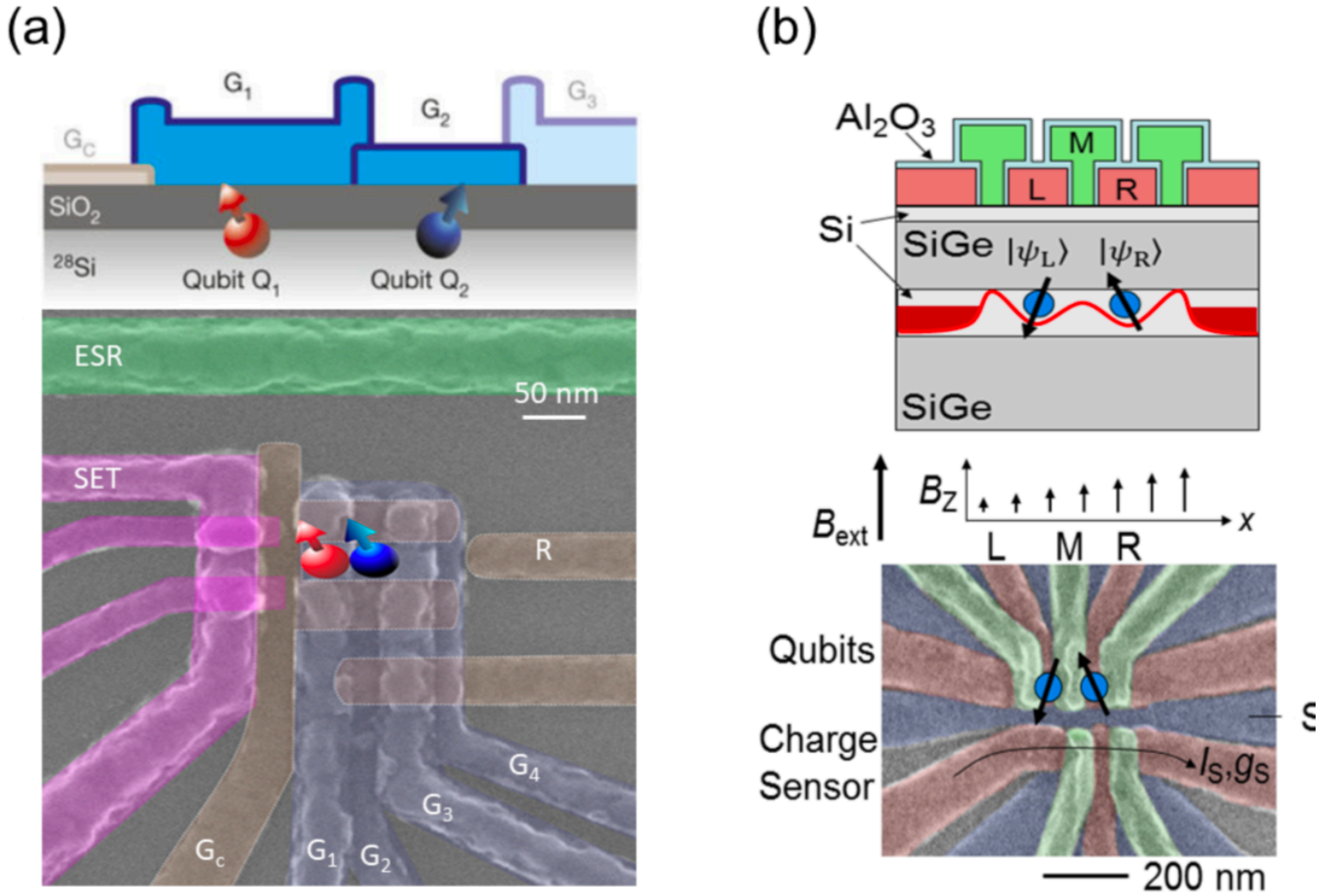




IONQ

- ~ 150 qubits in 2019
- T1 ~ 100 ms
- T2 ~ very long

- Silicon Spin States



- T1 ~ 1 s
- T2 ~ 0.2 ms

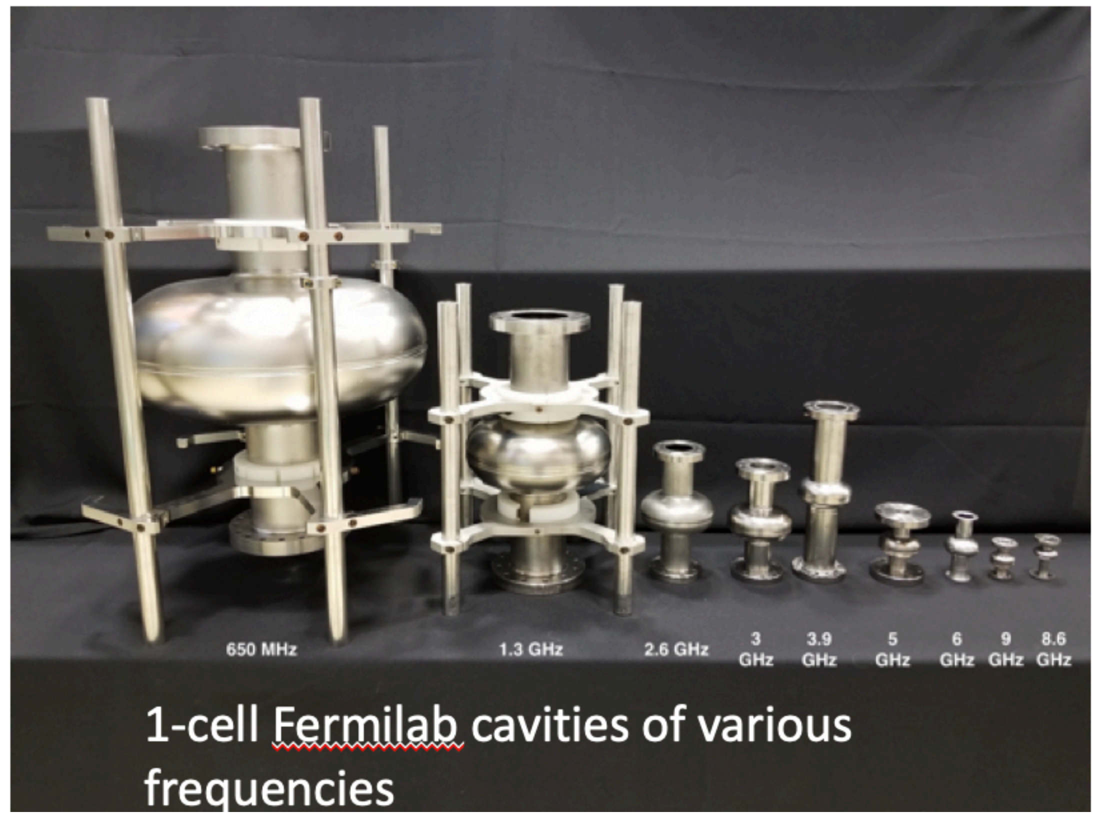
Fermilab QIS Involvement (very briefly) [PGS talk at SC18]

- Fermilab has unique capabilities to be leveraged by QIS
- Sensing and metrology, Communication, Computing

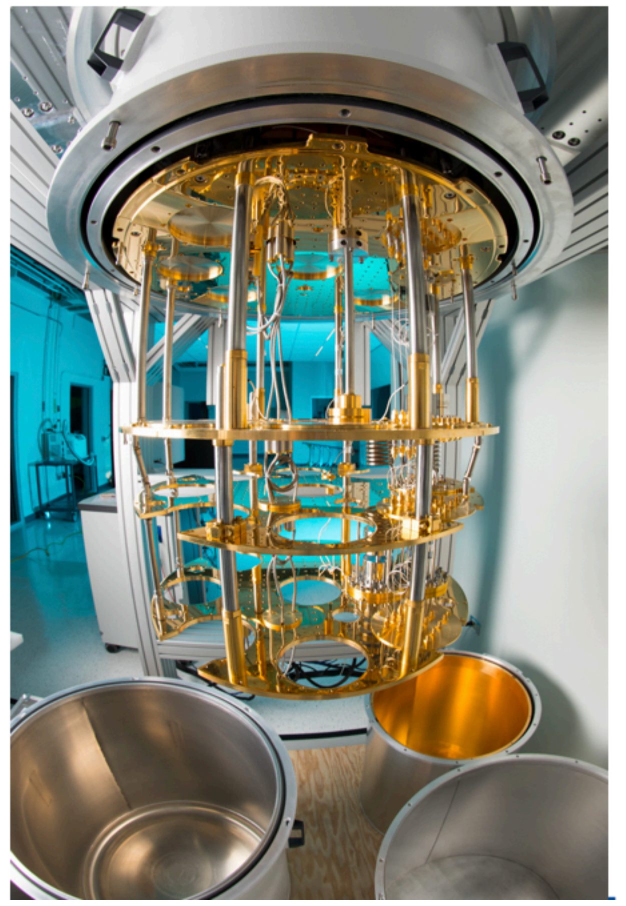
- SRF Cavities

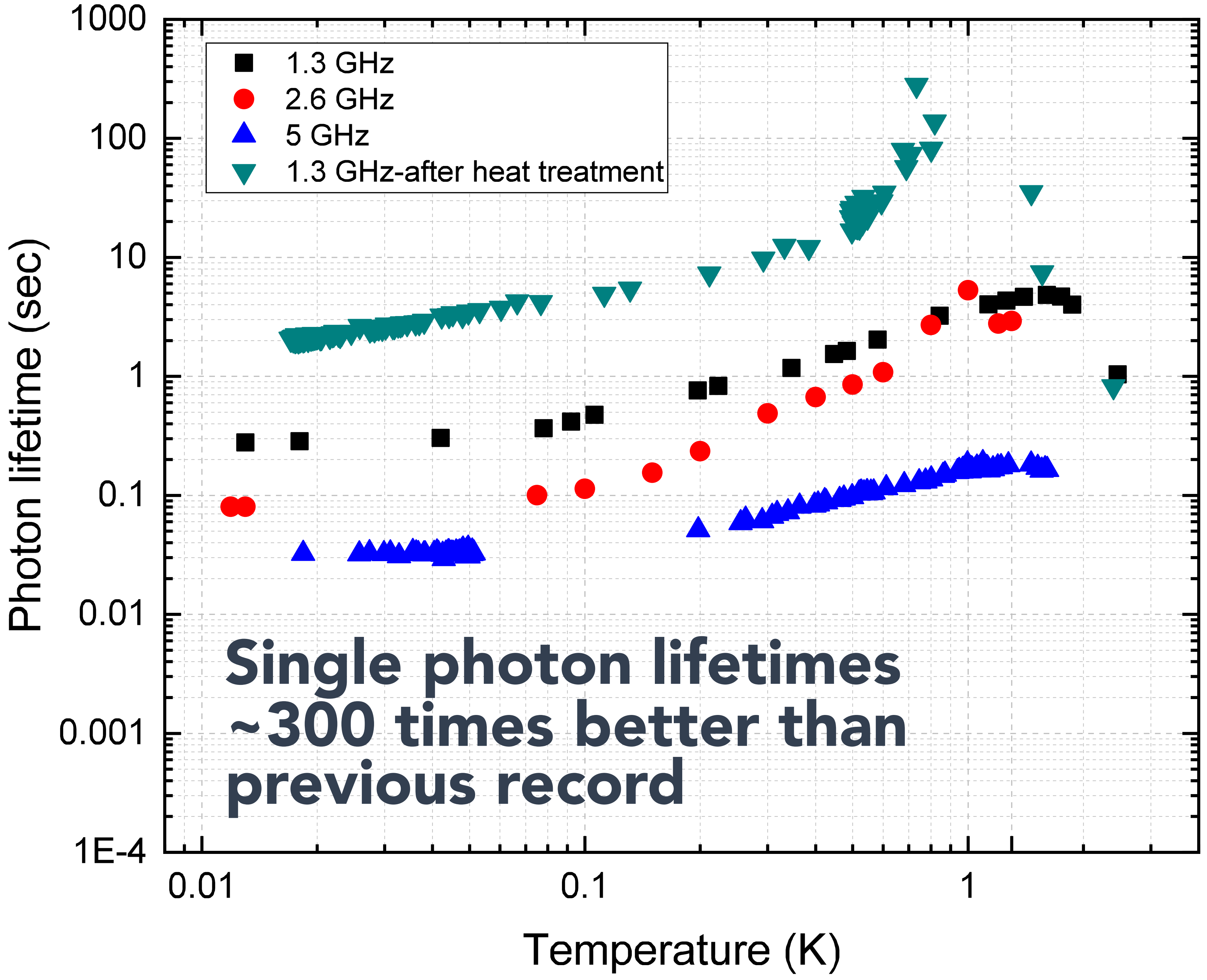
Challenges:

- For accelerators we want high gradients → as many photons as possible; for QC applications we want to manipulate cavity states at the **single photon** level
- Accelerators operate at temperatures around 2K, QC systems around 20 milliKelvin

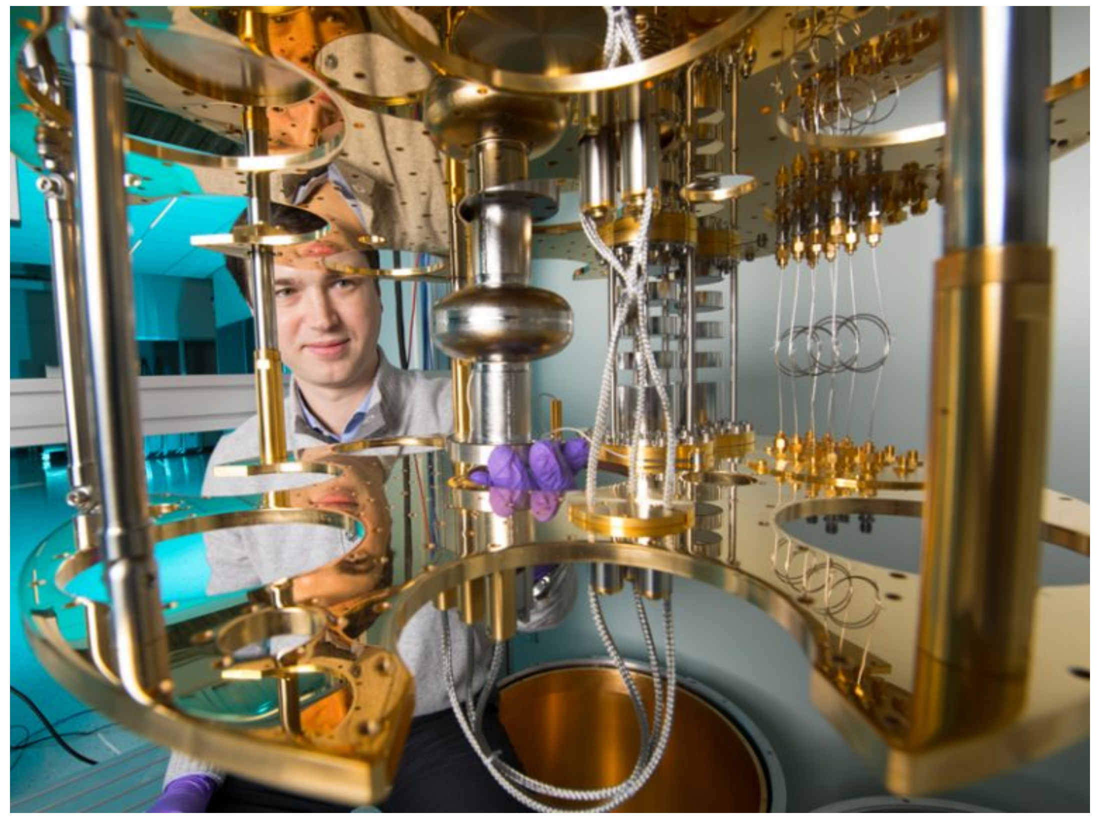


1-cell Fermilab cavities of various frequencies





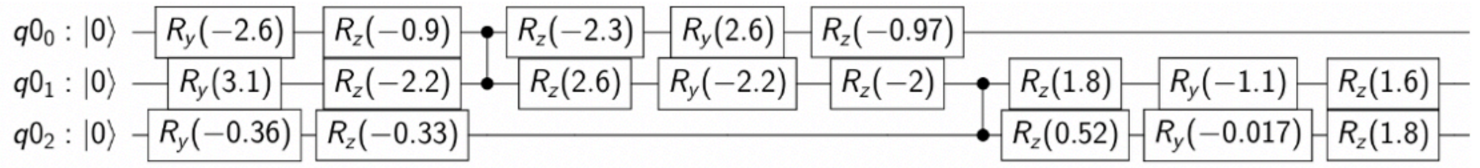
Single photon lifetimes ~300 times better than previous record



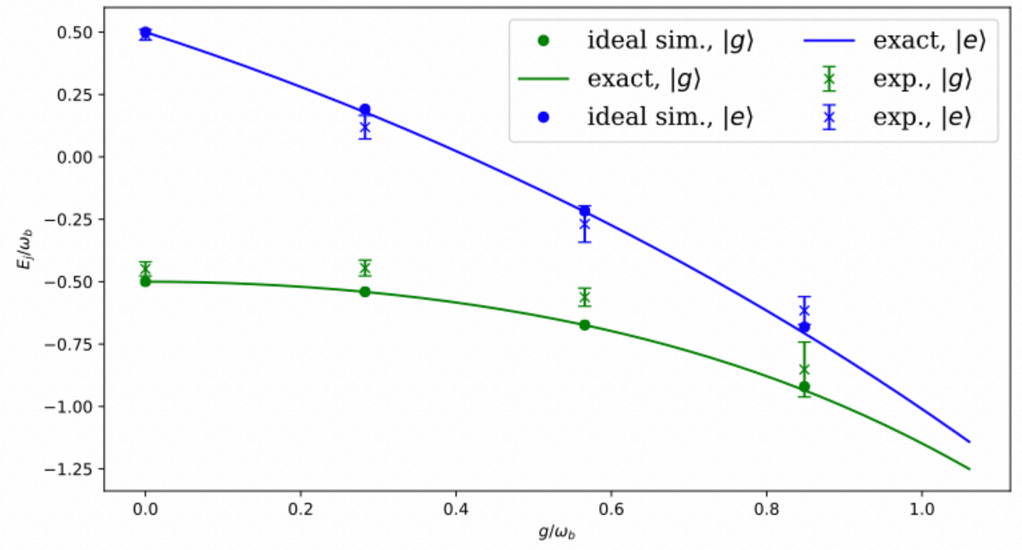
HEP Applications on Quantum Computers

- New approach for fermion-boson interacting systems
- Optimization problems
- Machine Learning (!!)
- Interfaces and workflows
- Tutorials and training (e.g. this - via an LDRD)

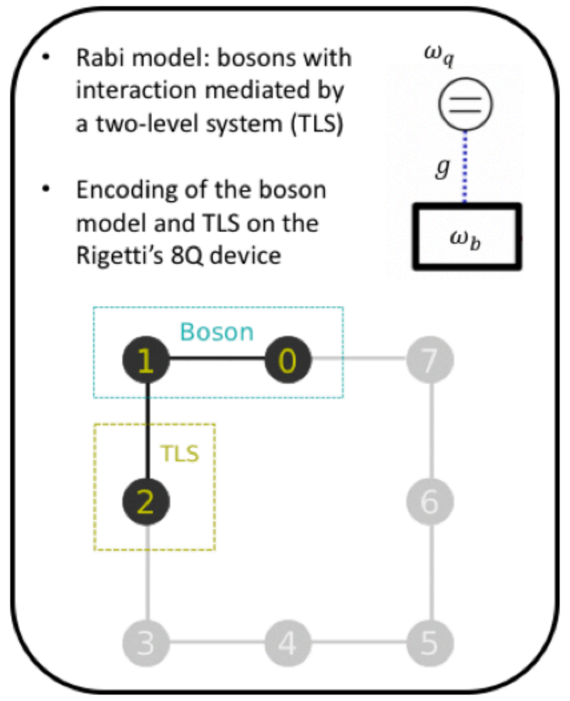
- Quantum-classical hybrid algorithm
  - quantum: efficient measurement of trial-state energy
  - classical: gradient-based algorithm to update trial state
- Trial state parameterized by a quantum circuit



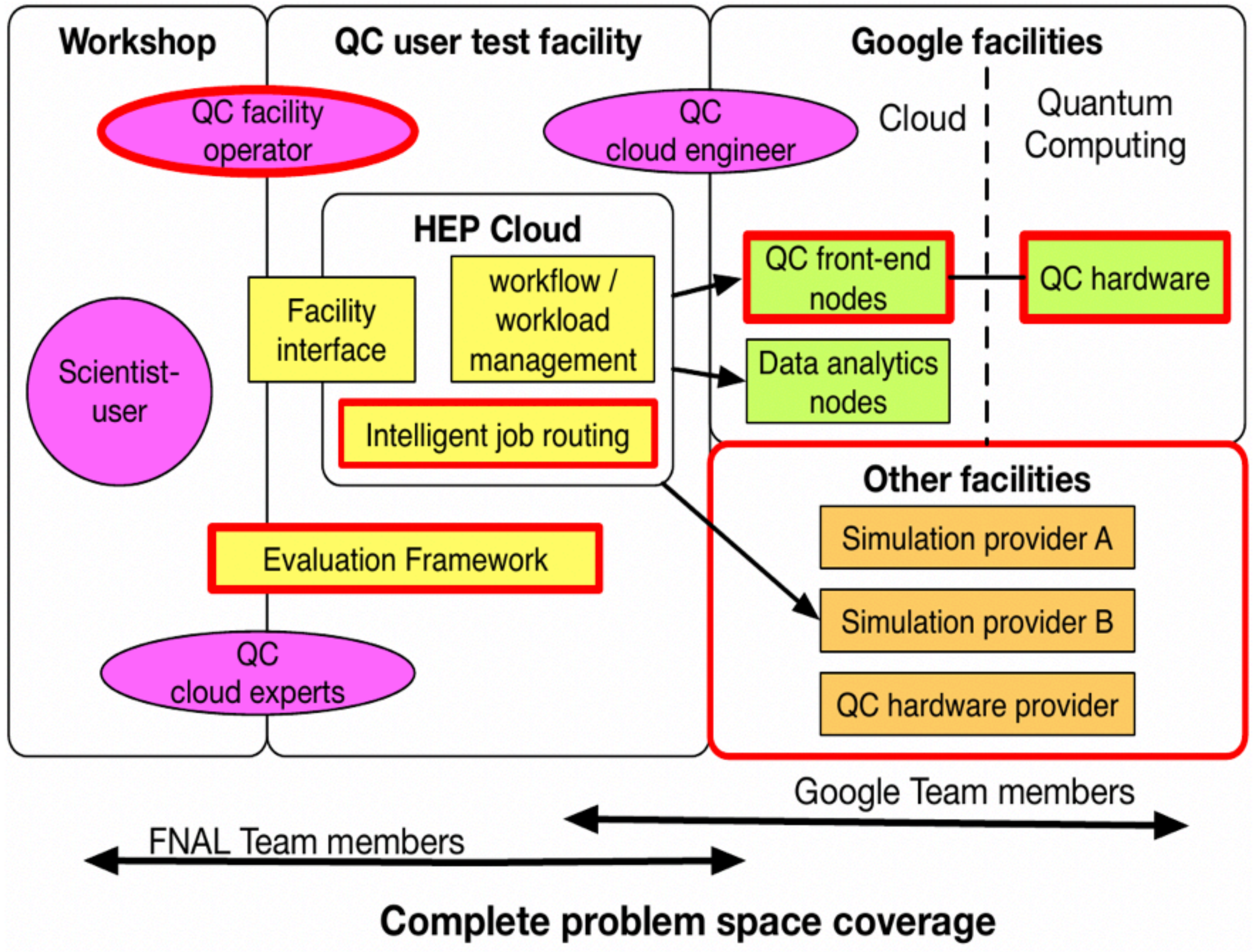
- Implementation on Rabi-model (boson coupled to spin)



Algorithm verification using simulators, also tested on Rigetti's 8Q device



- Rabi model: bosons with interaction mediated by a two-level system (TLS)
- Encoding of the boson model and TLS on the Rigetti's 8Q device



Workshop

QC user test facility

Google facilities

QC facility operator

QC cloud engineer

Cloud

Quantum Computing

HEP Cloud

Facility interface

workflow / workload management

Intelligent job routing

QC front-end nodes

QC hardware

Data analytics nodes

Scientist-user

Other facilities

Simulation provider A

Simulation provider B

QC hardware provider

Evaluation Framework

QC cloud experts

Google Team members

FNAL Team members

Complete problem space coverage

Quantum Communications

- Fermilab Quantum Teleportation Experiment (FQNET)

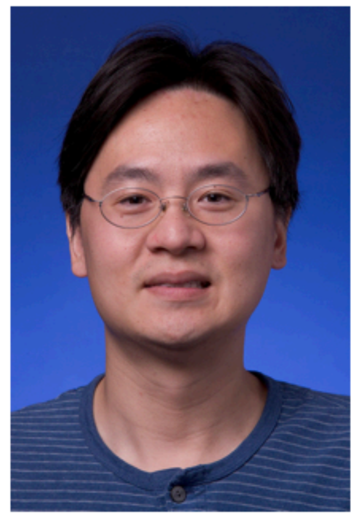
Baseline equipment for teleportation in place

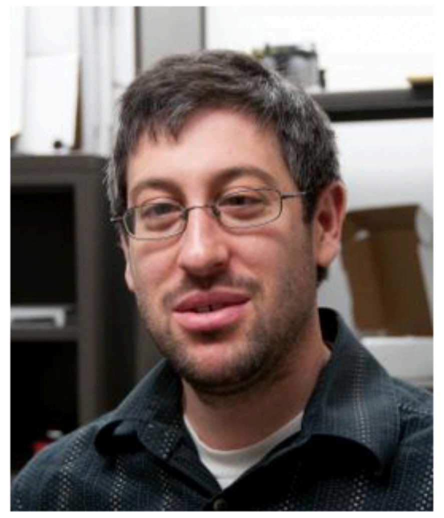
System commissioning underway

Use dark fiber between Argonne and Fermilab (~30mi)

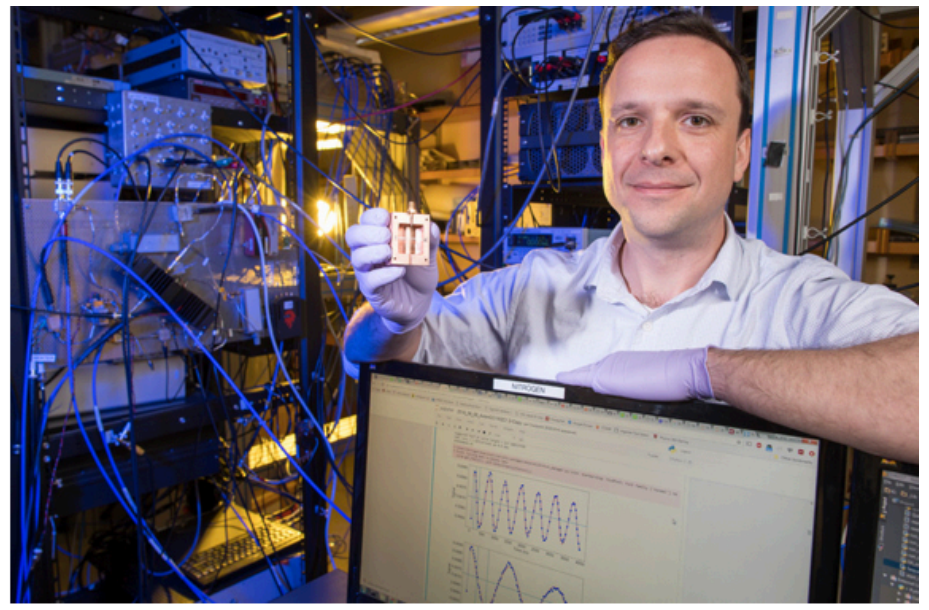
Quantum Sensors

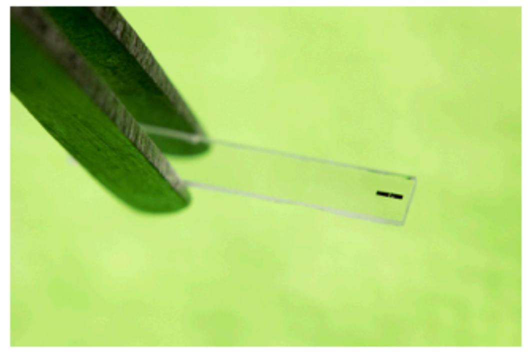
Qubit-based single microwave photon sensors for axion detection

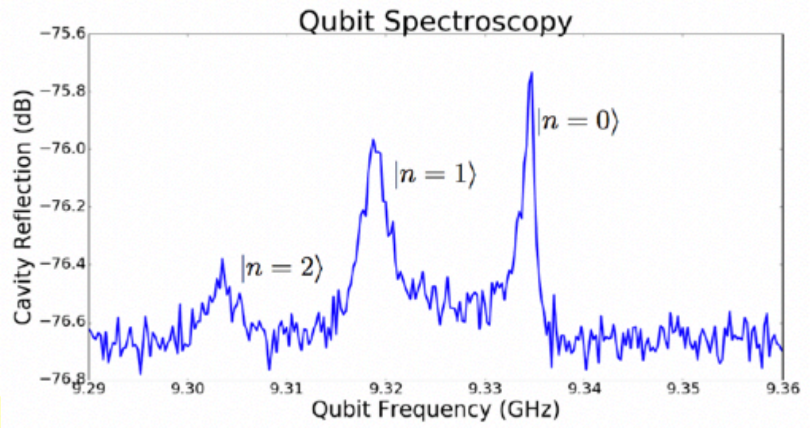

Aaron Chou

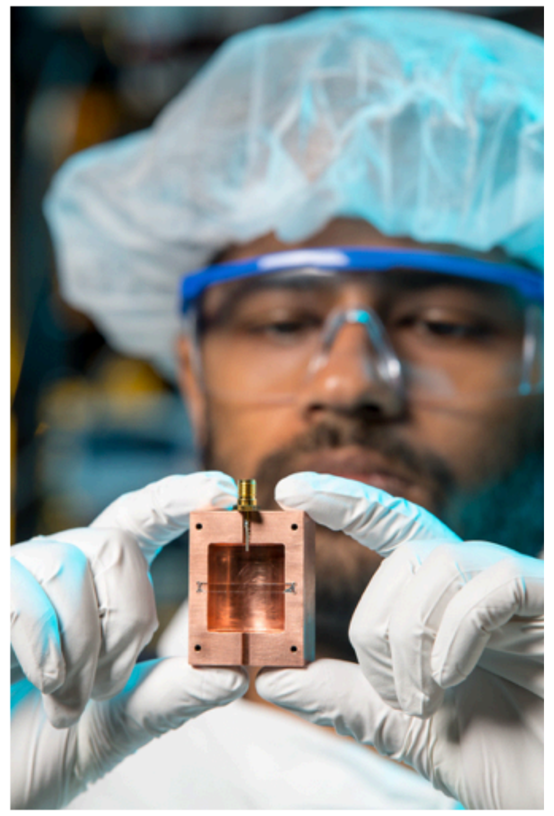

David Schuster(UC)


Konrad Lehnert U.Colorado/NIST


Daniel Bowring, Fermilab
2018 Early Career Award

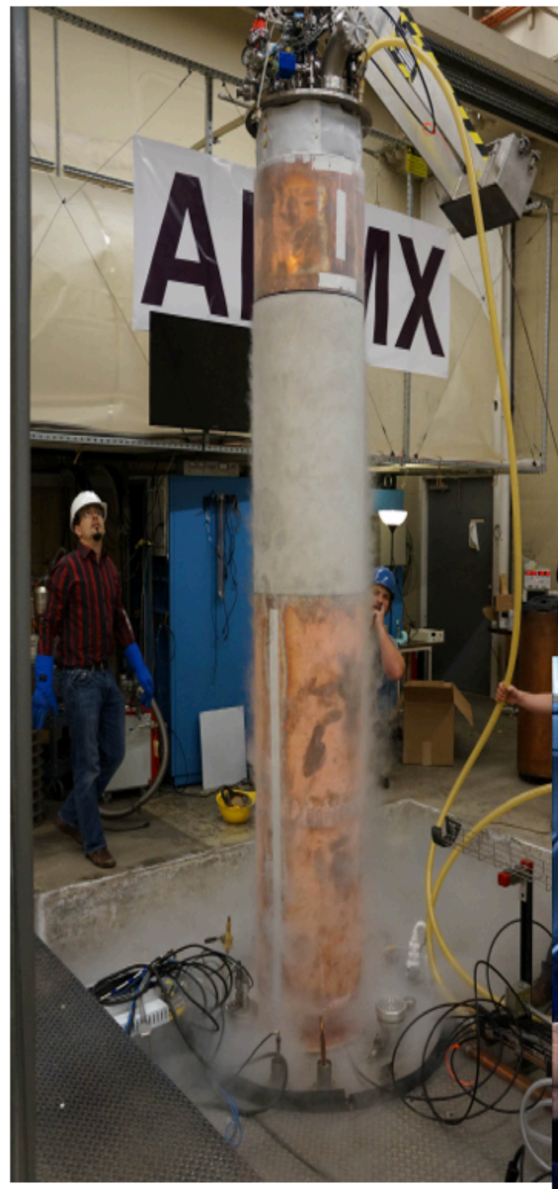

New Fermilab test stand incorporates magnet into a dilution refrigerator for R&D on qubit-cavity systems for a next generation dark matter experiment.




Grad student Akash Dixit installing a prototype detector in a 10 mK test stand in the Schuster Lab.

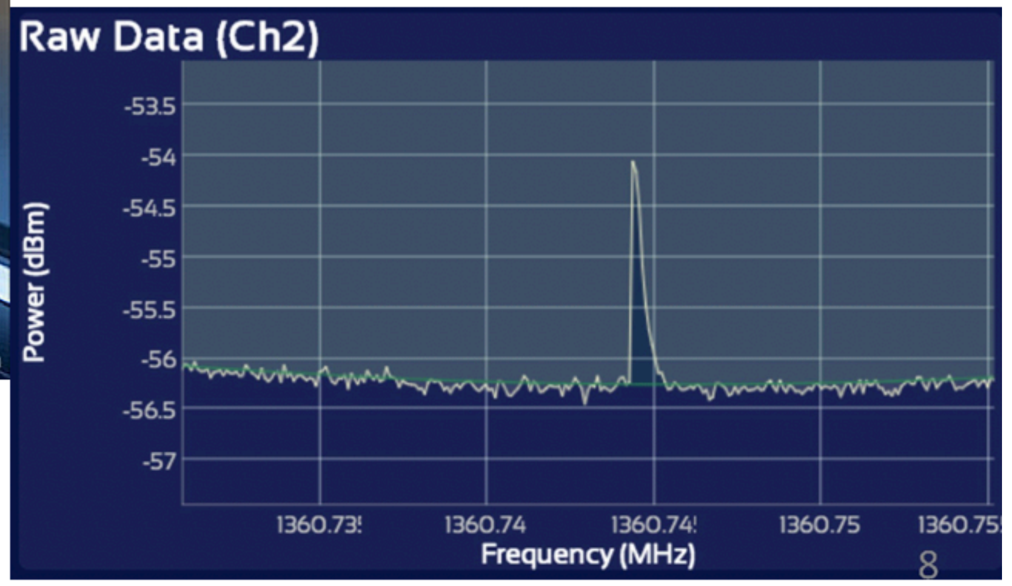
A resonant cavity "axion" dark matter search proceeds by tuning the radio frequency of the cavity and checking to see if you can hear the dark matter "radio broadcast" above the static noise

- The "static" of the radio is thermal photons + quantum noise



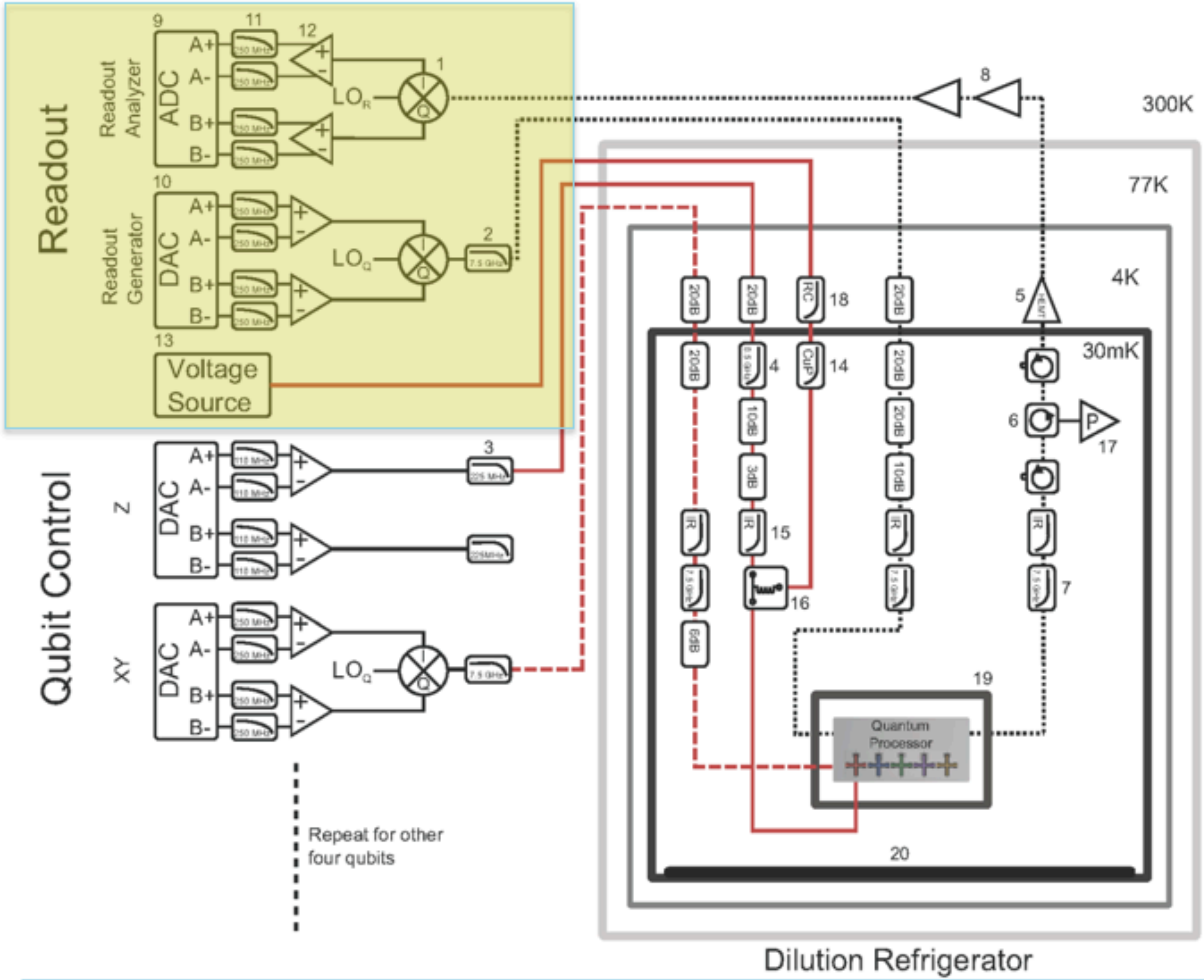
ADMX Experiment at U.Washington

Simulated axion signal from ADMX



Quantum Controls … leverage expertise in MKIDS

SQubit RF readout and control



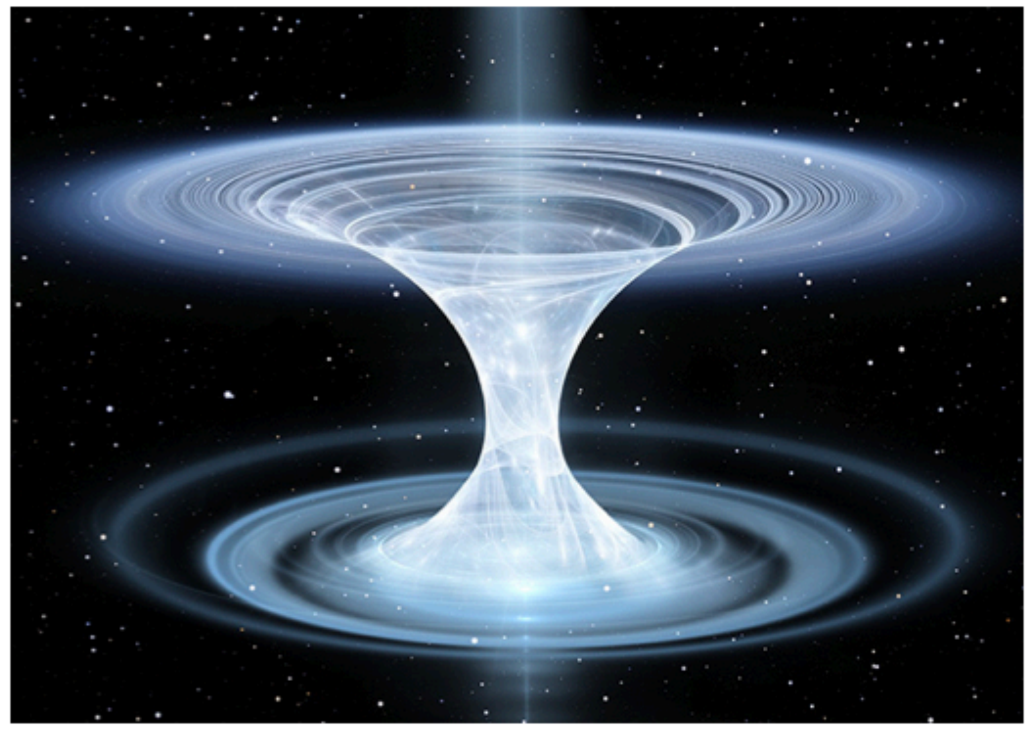
In the light yellow block there are the functions already covered by fMESSI1.

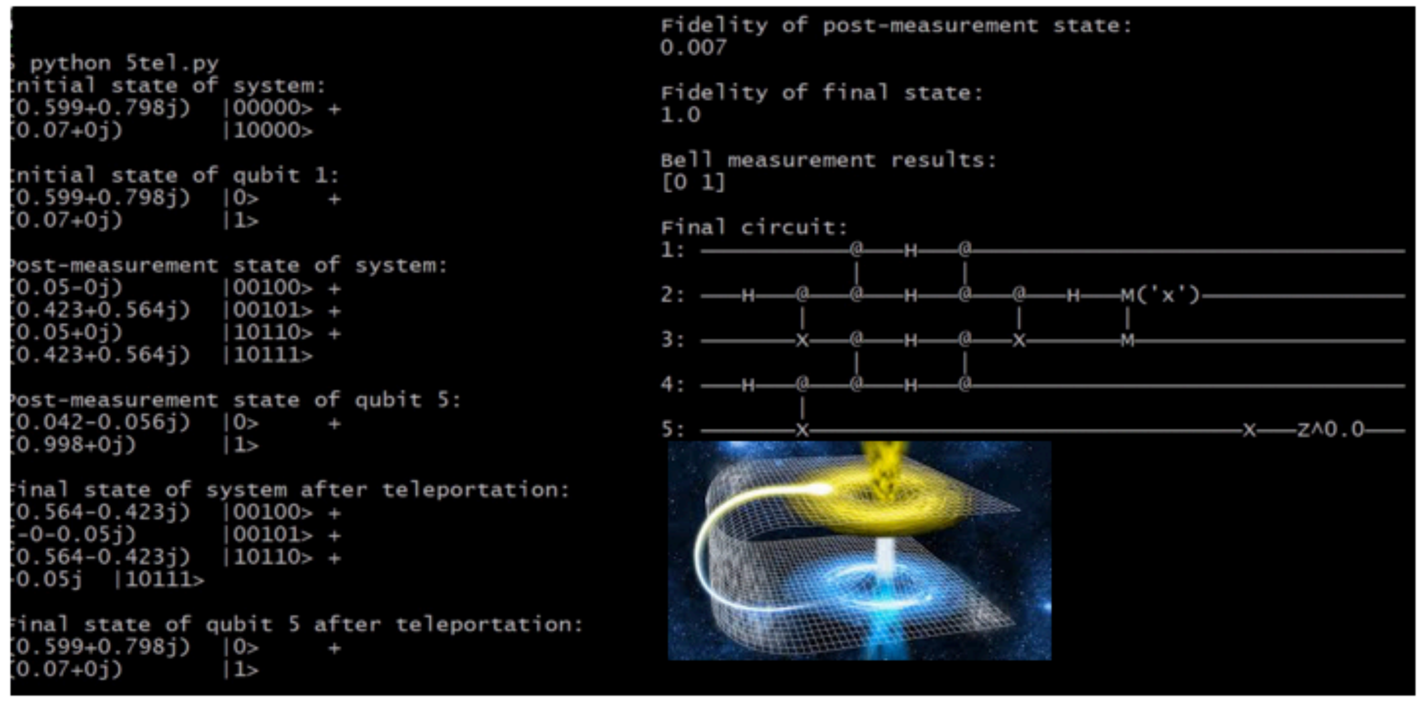
The readout "measures" the qubit state using its dispersive coupling to a RF resonator.

Theory

Driving HEP Science: Entanglement as Probe of Space-Time

- Recent HEP theoretical work shows that a pair of entangled black holes can be connected by a **wormhole**
- This has been shown to be **a special kind of quantum teleportation**, that should be reproducible for smaller quantum systems in the lab
  - Implementation of protocols on available quantum computers
  - FQNET is developing the technology required for to perform the first experiments with wormhole teleportation protocols





```
 python 5tel.py
nitial state of system:
(0.599+0.798j)  |00000> +
(0.07+0j)       |10000>

nitial state of qubit 1:
(0.599+0.798j)  |0>     +
(0.07+0j)       |1>

ost-measurement state of system:
(0.05-0j)       |00100> +
(0.423+0.564j)  |00101> +
(0.05+0j)       |10110> +
(0.423+0.564j)  |10111>

ost-measurement state of qubit 5:
(0.042-0.056j)  |0>     +
(0.998+0j)      |1>

inal state of system after teleportation:
(0.564-0.423j)  |00100> +
-0-0.05j)       |00101> +
(0.564-0.423j)  |10110> +
0.05j  |10111>

inal state of qubit 5 after teleportation:
(0.599+0.798j)  |0>     +
(0.07+0j)       |1>
```

```
Fidelity of post-measurement state:
0.007

Fidelity of final state:
1.0

Bell measurement results:
[0 1]

Final circuit:
1: ───────────@───H───@───────────────────────────────
              │       │
2: ───H───@───@───H───@───@───H───M('x')──────────────
          │               │       │
3: ───────X───@───H───@───X───────M───────────────────
              │       │
4: ───H───@───@───H───@───────────────────────────────
          │
5: ───────X───────────────────────────────X───Z^0.0───
```

The end

- There’s a lot to learn about Quantum Computing (we just scratched the surface)

- There’s an enormous amount of activity in the field

- A lot of expectations and hype, but a lot of promise

- Fermilab is uniquely situated to participate in QIS. We bring our expertise to benefit QIS Research, and we bring QIS Research to benefit our HEP science

More references

- Chem/CS/Phys191(2014) Lecture Notes
- S. Gilbert Technology Overview Talk, 2010 (pdf)
- Buluta *et. al., Natural and artificial atoms for quantum computation,* 2011 (ArXiv)
- S. Filipp, *Quantum computing with superconducting qubits – Towards useful applications,* 2018 (pdf)
- G. Wendin, *Quantum Information Processing with Superconducting Circuits,* 2017 (ArXiv)
- T. Humble *et. al., Quantum Computing Circuits and Devices,* 2018 (ArXiv)