SRF technology for Quantum Computing and Dark Matter Searches

David van Zanten

SQMS - Fermilab

December 8th 2023

SQMS

A DOE National QIS Research Center

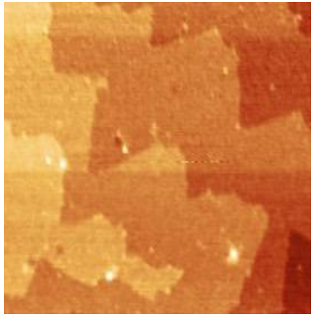
34
Partner Institutions

500+
Collaborators

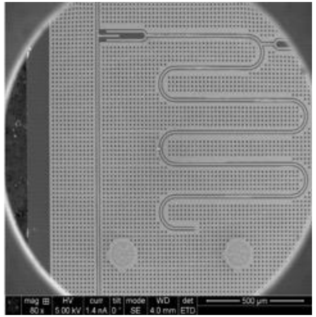
SQMS MISSION Achieve transformational advances in the major cross-cutting challenge of understanding & eliminating decoherence mechanisms in superconducting devices, enabling construction and deployment of superior **quantum systems for computing & sensing**.

SQMS Science & Technology Innovation Chain

Materials → High-coherence devices → Systems integration → New platforms for quantum tech → Quantum advantage



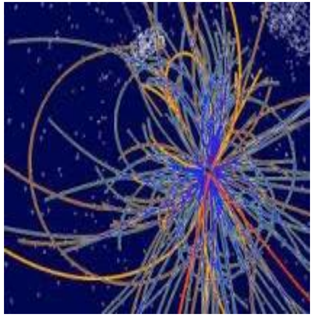
Developing full understanding of decoherence sources



Demonstrating devices with systematically higher T1 & T2

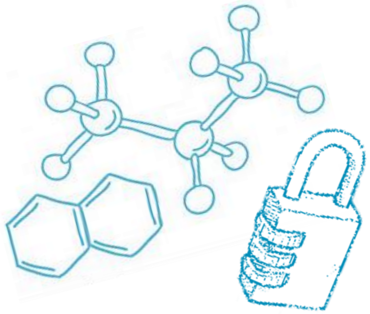
Integrating devices into quantum processors

Deploying large scale quantum cryogenics facilities

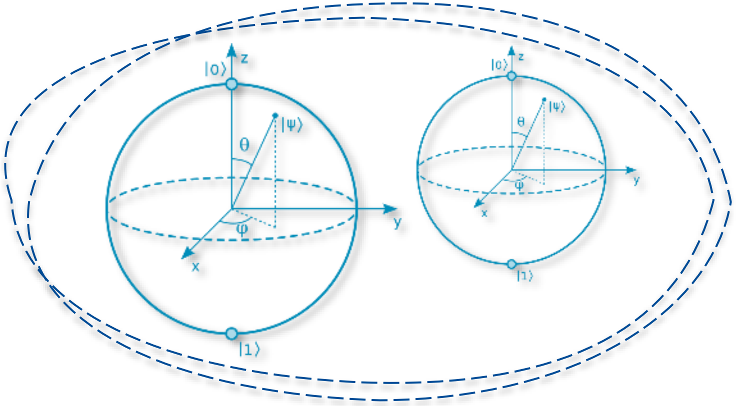


Demonstrating quantum advantage

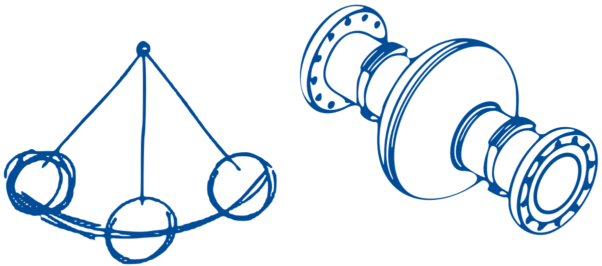
SQMS bridges the gap between ideas and large-scale realizations via unique center-wide coordinated approaches



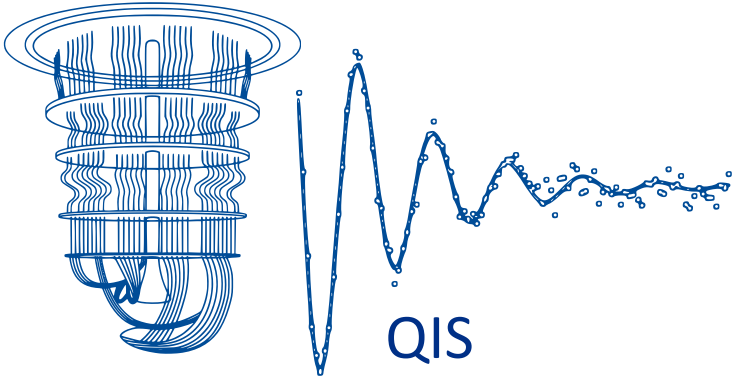
Motivation for QIS



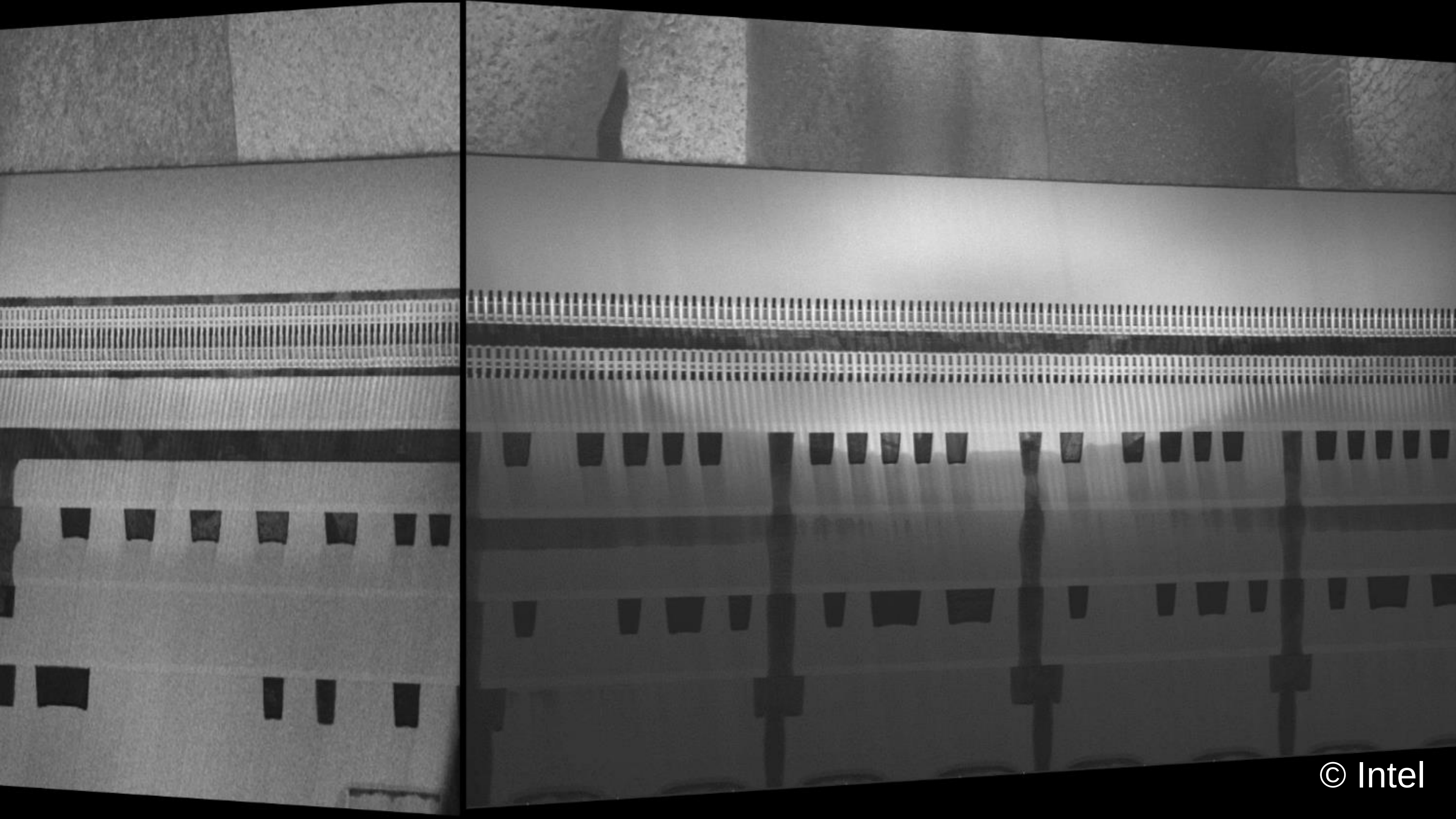
Quantum computing



Quantum hardware

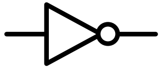


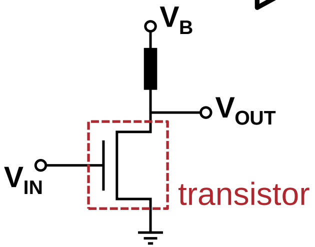
QIS



Classical computing

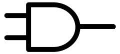
NOT-gate

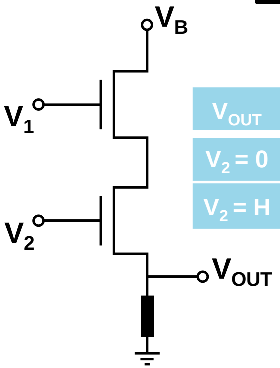




$$V_{IN} = H \rightarrow V_{OUT} = 0$$
$$V_{IN} = 0 \rightarrow V_{OUT} = H$$

AND-gate





V_{OUT}	$V_1 = 0$	$V_1 = H$
$V_2 = 0$	0	0
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Classical computing

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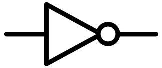

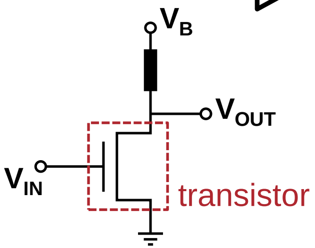

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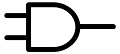

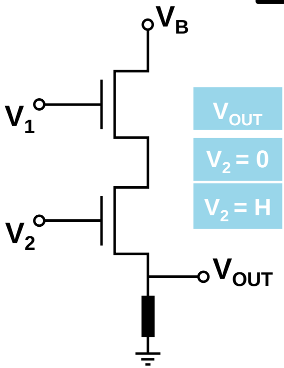

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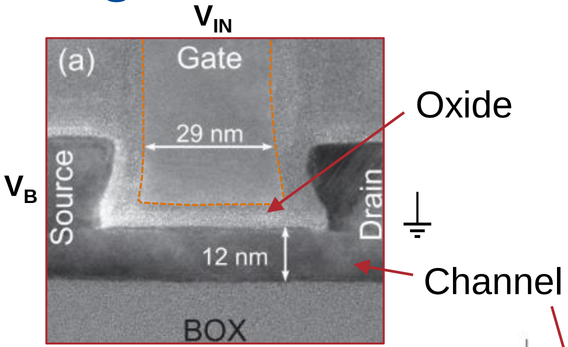
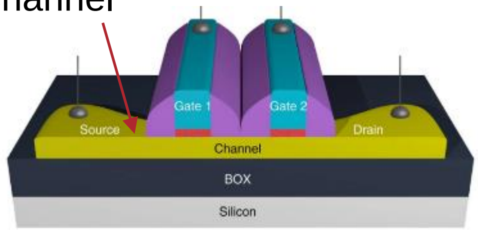
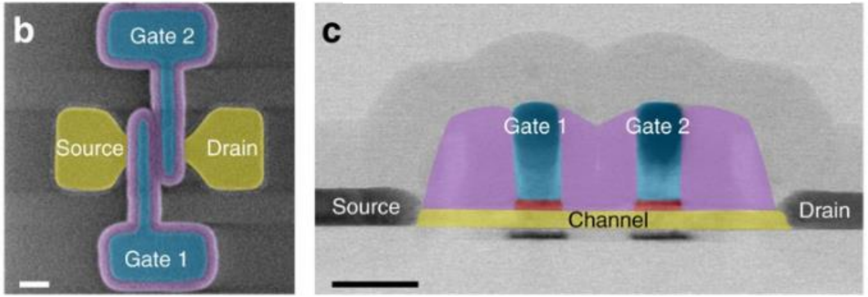


Roche, B., et al. *APL* (2012)





Maurand, R., et al. *Nat. Comm.* (2016)

Classical computing

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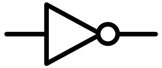

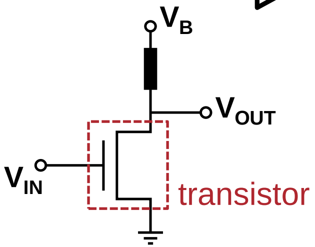

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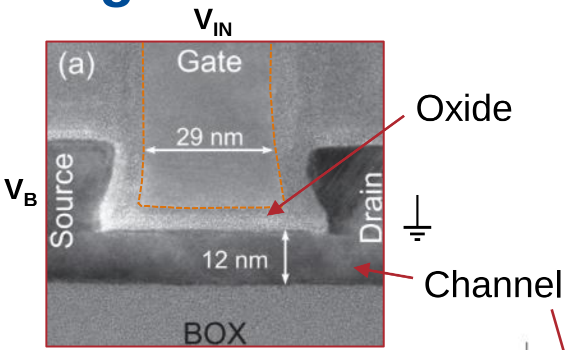

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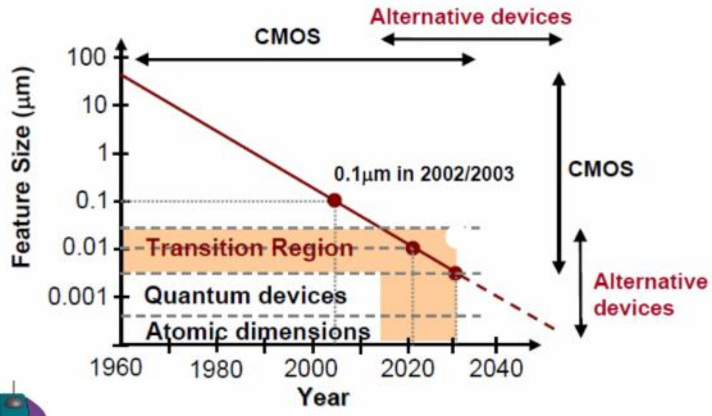

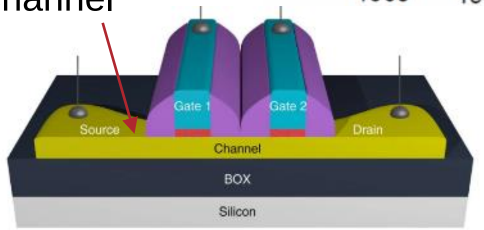

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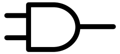

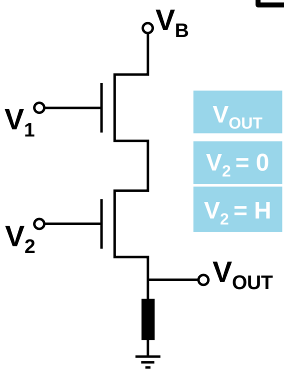

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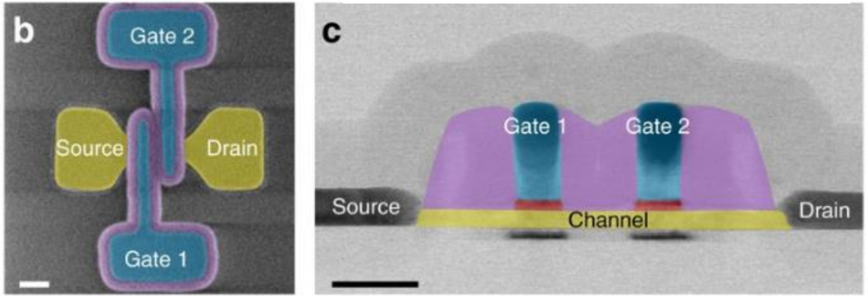

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Classical computing

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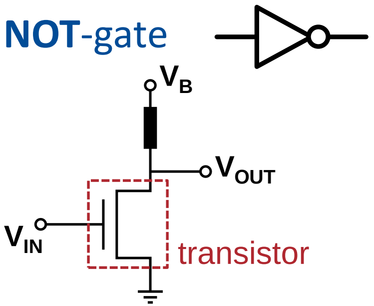

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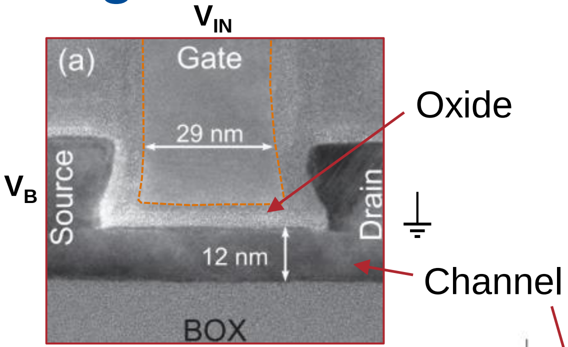

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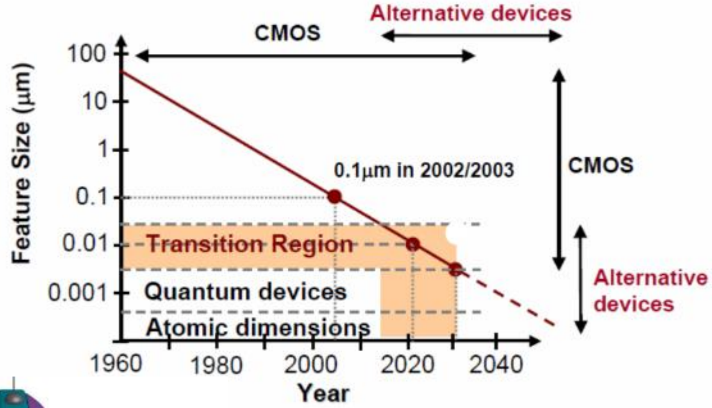

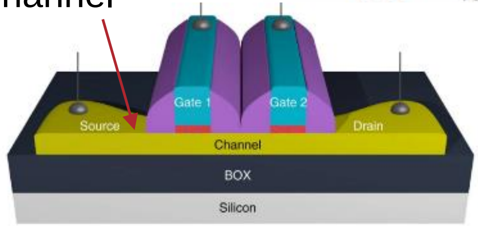

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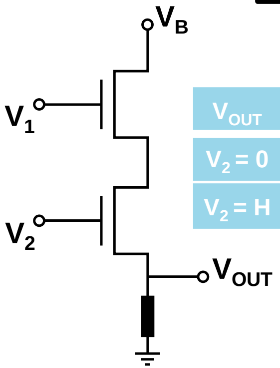

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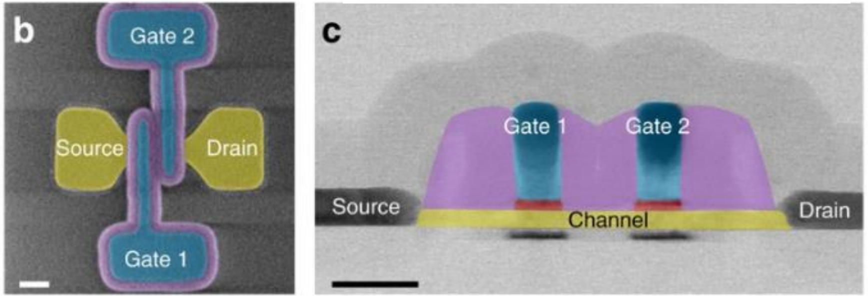

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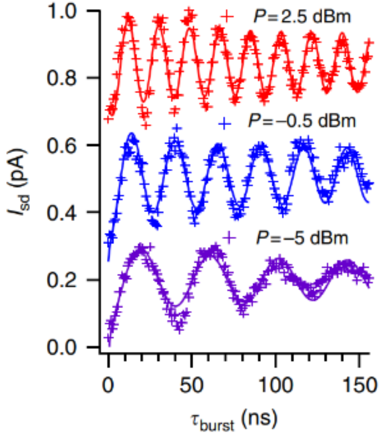
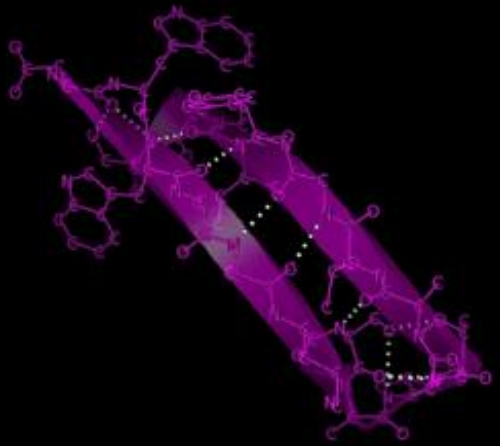
Quantum!

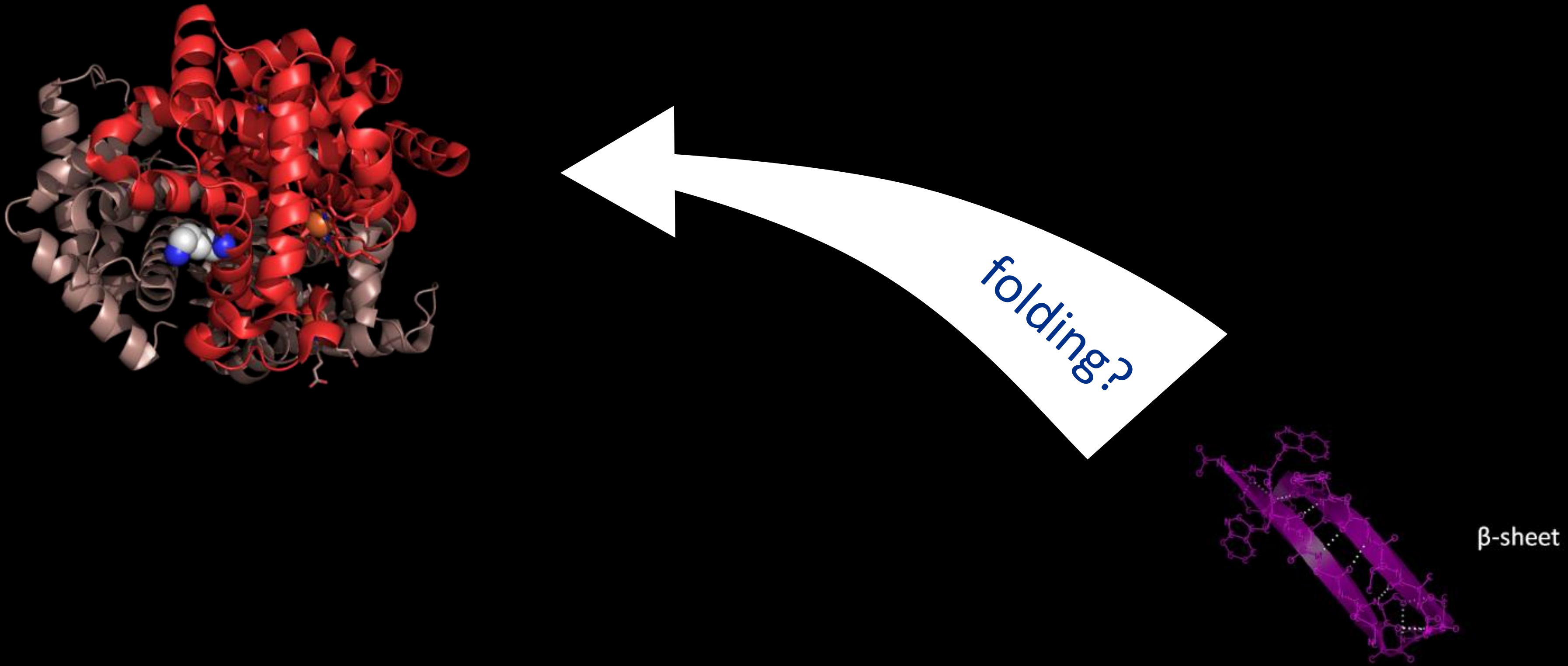


Protein folding



β-sheet

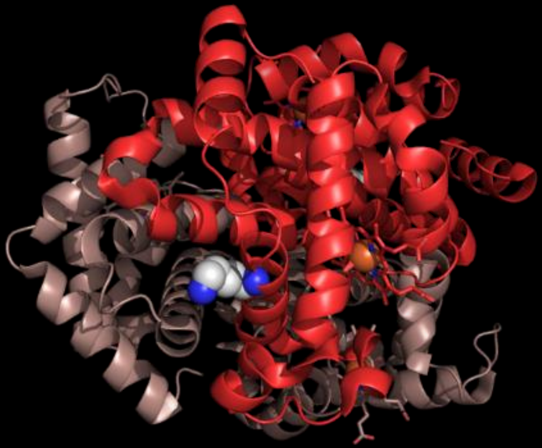
Protein folding

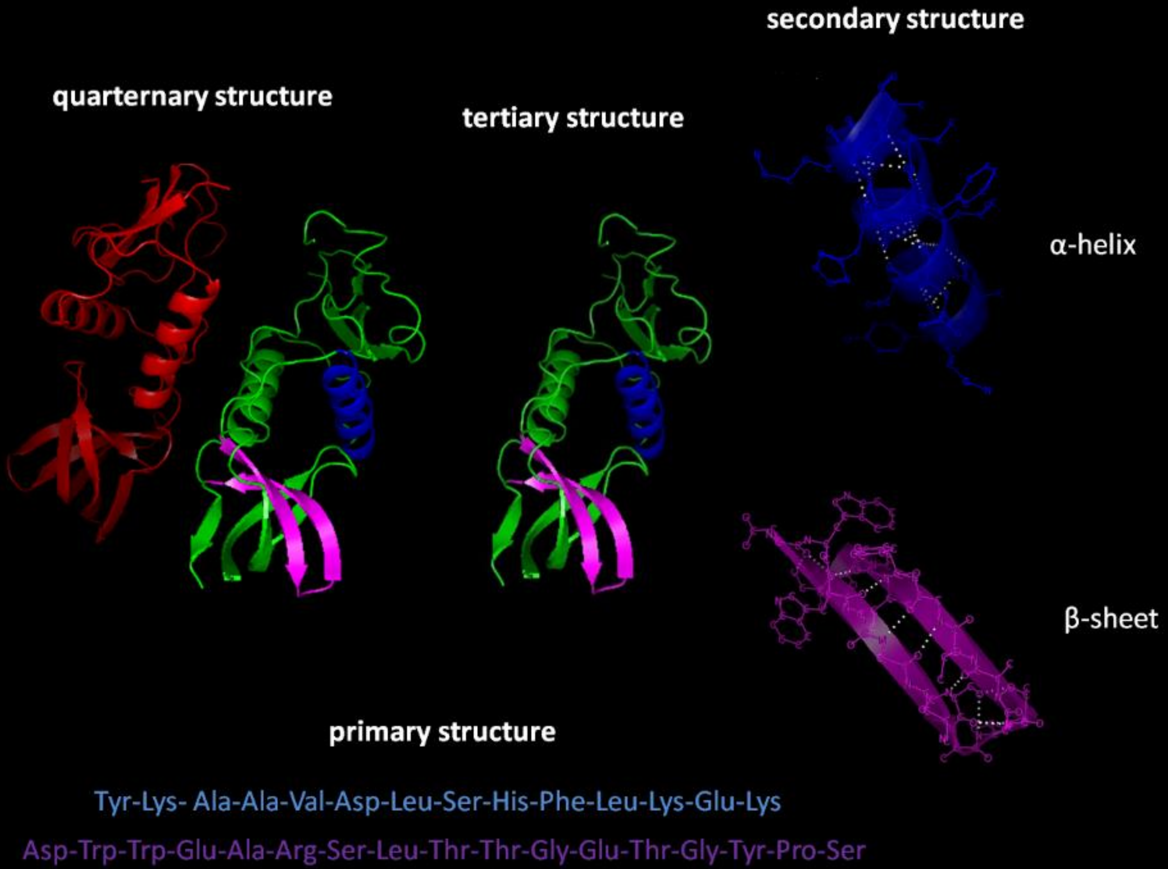


Tyr-Lys- Ala-Ala-Val-Asp-Leu-Ser-His-Phe-Leu-Lys-Glu-Lys

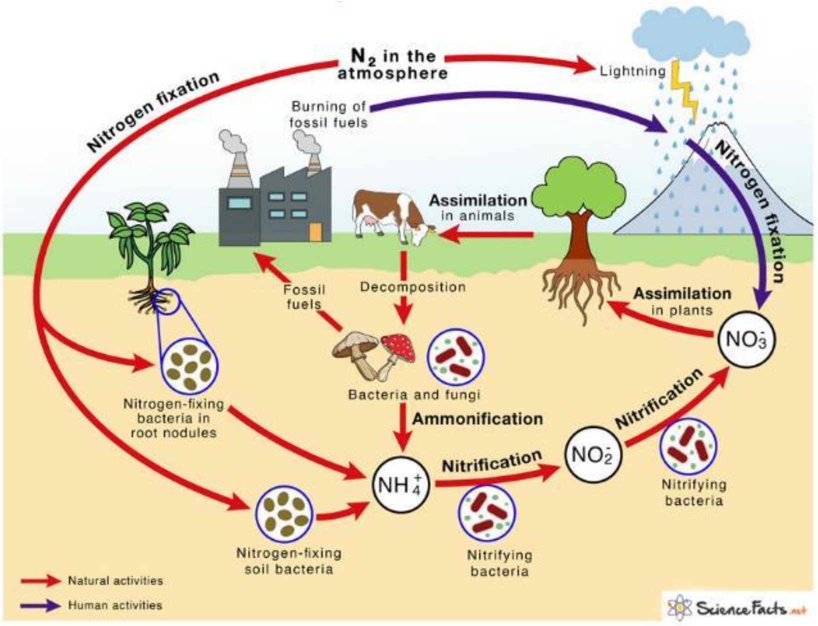
Asp-Trp-Trp-Glu-Ala-Arg-Ser-Leu-Thr-Thr-Gly-Glu-Thr-Gly-Tyr-Pro-Ser

Protein folding



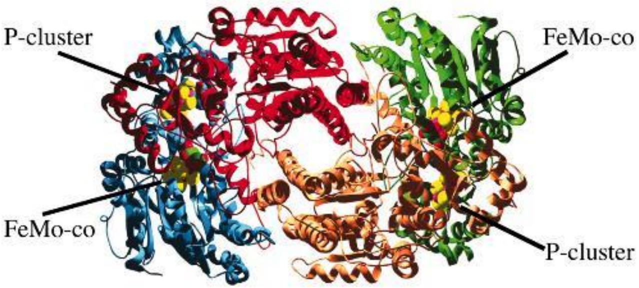


Nitrogenase (nitrogen fixation)



Binding of N_2 into e.g. ammonia

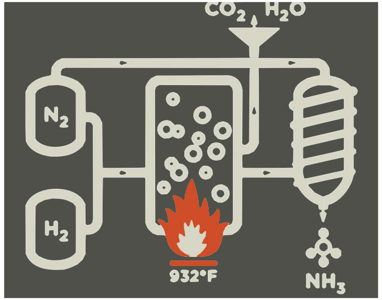
Nitrogenase (enzyme)



Natural in bacteria

VERSUS

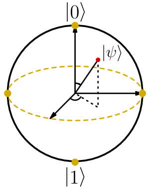
2% of world total energy consumption



Haber – Bosch process

What is a qubit?

- For each possible answer (right or wrong) we need a unique waveform
- The superposition concept of QM gives *N* waveforms, where *N* are the number of eigenstates

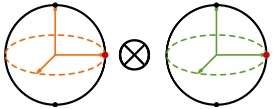


N = 2 (qubit)

$$|\boldsymbol{\psi}\rangle = \cos(\boldsymbol{\theta})\,|\mathbf{0}\rangle + e^{i\boldsymbol{\varphi}}\sin(\boldsymbol{\theta})|\mathbf{1}\rangle$$

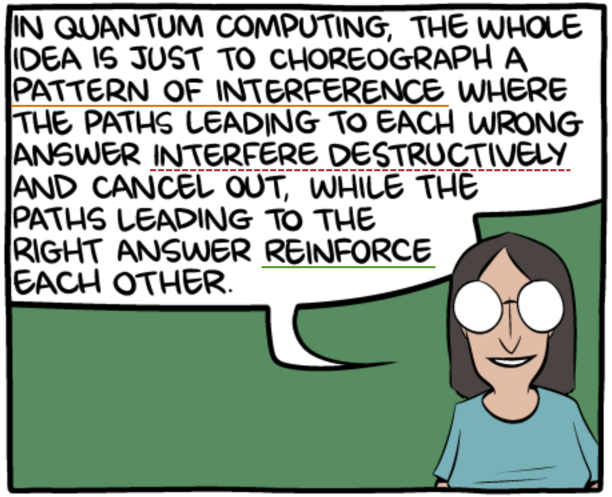
$$= c_1|\mathbf{0}\rangle + c_2|\mathbf{1}\rangle$$

- The entanglement concept of QM allows to construct 2^M waveforms, where M is the number of entangled objects



M = 2

$$c_1|\mathbf{00}\rangle + c_2|\mathbf{01}\rangle + c_3|\mathbf{10}\rangle + c_4|\mathbf{11}\rangle$$



www.smbc-comics.com/comic/the-talk-3

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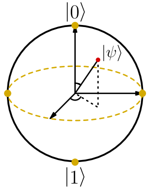

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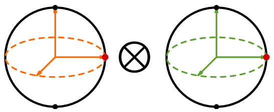

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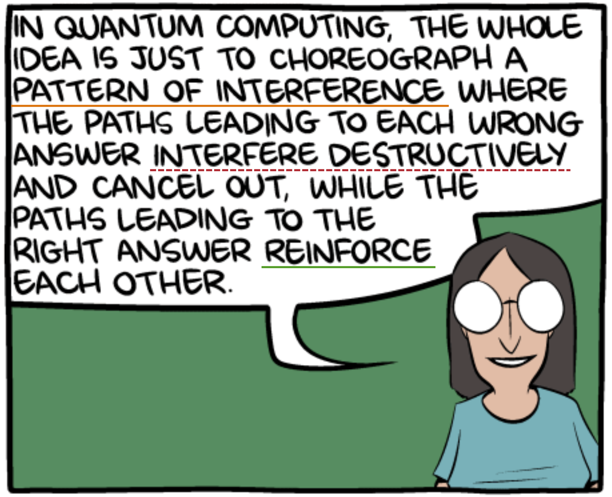

www.smbc-comics.com/comic/the-talk-3

Measurement yields either 'basis' state with **probability**:

$$P_{|i\rangle} = |c_i|^2$$

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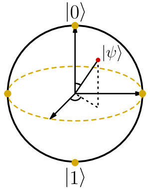

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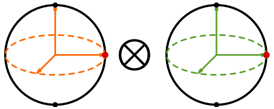

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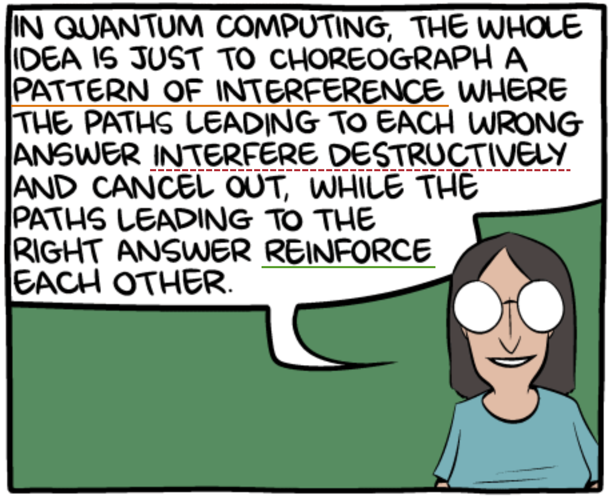
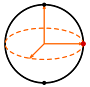
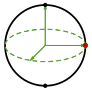


www.smbc-comics.com/comic/the-talk-3

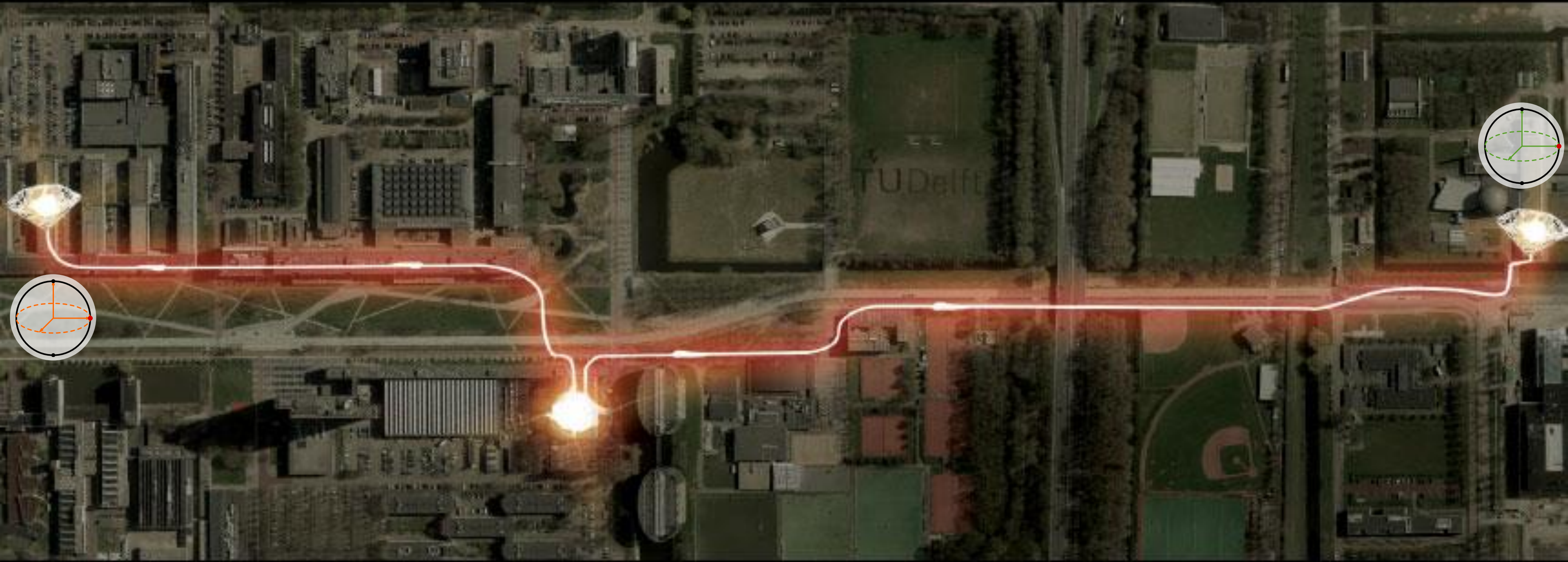
Consider the superposition

$$|\Phi\rangle = c_1|\mathbf{00}\rangle + c_4|\mathbf{11}\rangle$$

Measurement of  → $|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$

collapses  to either $|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$

Spooky action on a distance



Quantum parallelism

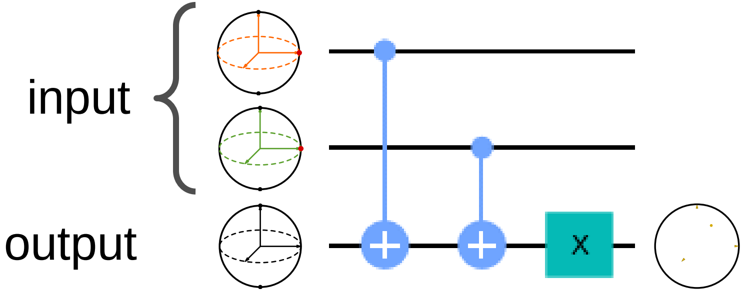
Consider an arbitrary operation $f(x)$…

Classical operation:

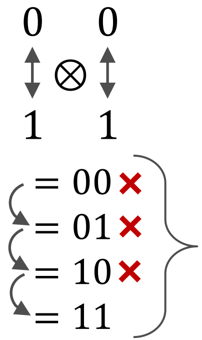
calculate sequentially $f(00)$, $f(01)$, ..

Quantum operation:

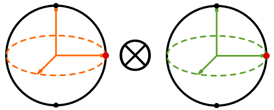
apply $f(|\psi\rangle)$ and measure



Classical bit



Quantum bit



$$|\psi\rangle = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} \equiv \begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \end{bmatrix} = \begin{bmatrix} 00 \\ 01 \\ 10 \\ 11 \end{bmatrix}$$

$|\psi\rangle_O = |0\rangle$ $|\psi\rangle_O = |1\rangle$

$$\begin{matrix} & 0 & 1 & 2 & 3 & 0 & 1 & 2 & 3 \\ |\psi\rangle_{IN} = & [\mathbf{1} & 0 & 0 & 0 & 0 & 0 & 0 & 0] \\ |\psi\rangle_{OUT} = & [0 & 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0] \end{matrix}$$

single input computation

$$|000\rangle \rightarrow |100\rangle$$

output input

Quantum parallelism

Consider an arbitrary operation $f(x)$…

Classical operation:

calculate sequentially $f(00)$, $f(01)$, ..

Quantum operation:

apply $f(|\boldsymbol{\psi}\rangle)$ and measure

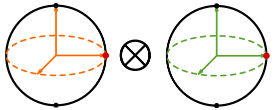
Classical bit

$0 \updownarrow \otimes \updownarrow 0$ / $1 \quad 1$

$= 00$ ✗
$= 01$ ✗
$= 10$ ✗
$= 11$

⇒

Quantum bit



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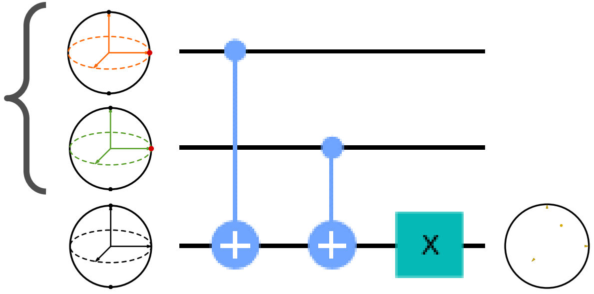
input

output



$|\boldsymbol{\psi}\rangle_{\boldsymbol{O}} = |\mathbf{0}\rangle$ $\quad$ $|\boldsymbol{\psi}\rangle_{\boldsymbol{O}} = |\mathbf{1}\rangle$

$0 \;\; 1 \;\; 2 \;\; 3 \quad 0 \;\; 1 \;\; 2 \;\; 3$

$$|\boldsymbol{\psi}\rangle_{\boldsymbol{IN}} = [0 \;\; \mathbf{1} \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$

$$|\boldsymbol{\psi}\rangle_{\boldsymbol{OUT}} = [0 \;\; \mathbf{1} \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$

single input computation

$$|\mathbf{001}\rangle \rightarrow |\mathbf{0}00\rangle$$

output $\quad$ input

Result contains both input & output

Quantum parallelism

Consider an arbitrary operation $f(x)$…

Classical operation:

calculate sequentially $f(00)$, $f(01)$, ..

Quantum operation:

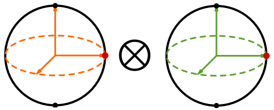
apply $f(|\boldsymbol{\psi}\rangle)$ and measure

Classical bit

$0 \updownarrow 1 \otimes 0 \updownarrow 1$

= 00 ✗
= 01 ✗
= 10 ✗
= 11

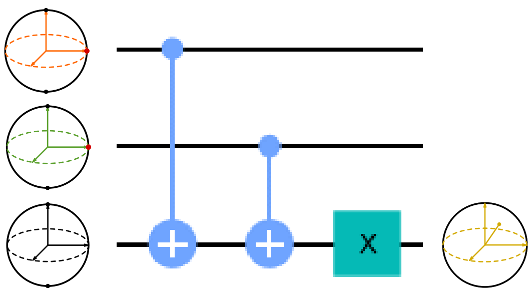
Quantum bit



$$|\boldsymbol{\psi}\rangle = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} \equiv \begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \end{bmatrix} = \begin{bmatrix} 00 \\ 01 \\ 10 \\ 11 \end{bmatrix}$$

input

output



$|\boldsymbol{\psi}\rangle_{\boldsymbol{O}} = |\boldsymbol{0}\rangle$ $|\boldsymbol{\psi}\rangle_{\boldsymbol{O}} = |\boldsymbol{1}\rangle$

0 1 2 3   0 1 2 3

$$|\boldsymbol{\psi}\rangle_{\boldsymbol{IN}} = [\boldsymbol{1}\ \ \boldsymbol{1}\ \ \boldsymbol{1}\ \ \boldsymbol{1}\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$|\boldsymbol{\psi}\rangle_{\boldsymbol{OUT}} = [0\ \ 1\ \ 1\ \ 0\ \ 1\ \ 0\ \ 0\ \ 1]$$

$|0\rangle|0\rangle$ $|1\rangle$ $|1\rangle$

parallel computation!

Quantum parallelism

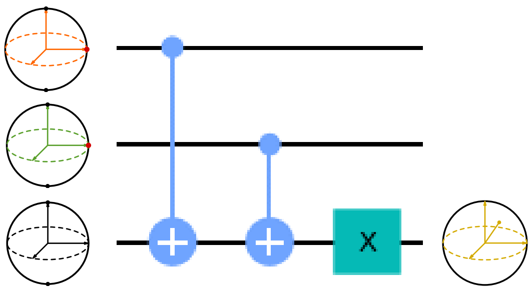
Consider an arbitrary operation $f(x)$…

Classical operation:
calculate sequentially $f(00)$, $f(01)$, ..

Quantum operation:
apply $f(|\psi\rangle)$ and **measure**

input

output

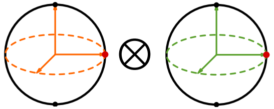


Classical bit

$0 \updownarrow \otimes 0 \updownarrow 1 \quad 1$

$= 00$ ✗
$= 01$ ✗
$= 10$ ✗
$= 11$

Quantum bit



$$|\psi\rangle = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} \equiv \begin{bmatrix} 0 \\ 1 \\ 2 \\ 3 \end{bmatrix} = \begin{bmatrix} 00 \\ 01 \\ 10 \\ 11 \end{bmatrix}$$

$|\psi\rangle_O = |0\rangle$ $|\psi\rangle_O = |1\rangle$

0 1 2 3   0 1 2 3

$$|\psi\rangle_{IN} = [1 \;\; 1 \;\; 1 \;\; 1 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$

$$|\psi\rangle_{OUT} = [0 \;\; 1 \;\; 1 \;\; 0 \;\; 1 \;\; 0 \;\; 0 \;\; 1]$$

$|0\rangle|0\rangle$ $|1\rangle$ $|1\rangle$

parallel computation!

Quantum measurements

Consider an arbitrary operation $f(x)$…

Classical operation:

calculate sequentially $f(00)$, $f(01)$, ..

Quantum operation:

apply $f(|\psi\rangle)$ and **measure**

$$|\psi\rangle_O = |0\rangle \quad |\psi\rangle_O = |1\rangle$$

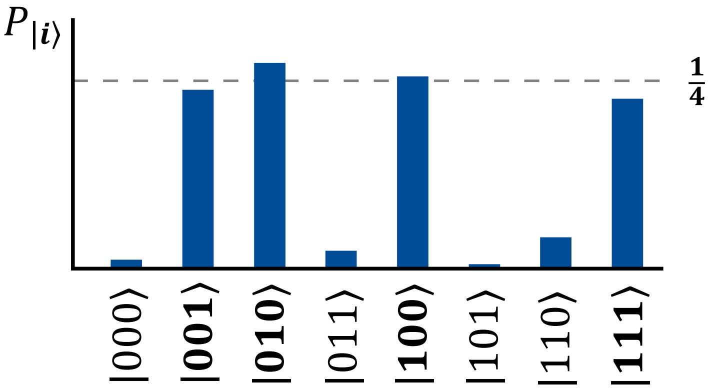
$$\begin{matrix} & 0 & 1 & 2 & 3 & 0 & 1 & 2 & 3 \\ |\psi\rangle_{IN} = & [1 & 1 & 1 & 1 & 0 & 0 & 0 & 0] \\ |\psi\rangle_{OUT} = & [0 & \underline{\mathbf{1}} & \underline{\mathbf{1}} & 0 & \underline{\mathbf{1}} & 0 & 0 & \underline{\mathbf{1}}] \end{matrix}$$

$$P_{|1\rangle} = P_{|2\rangle} = P_{|0\rangle} = P_{|3\rangle} = \frac{1}{4}$$

Measurements return single state with probability

$$P_{|i\rangle} = |c_i|^2$$

Quantum algorithms need to be **repeated** to collect **measurement statistics**!



Quantum measurements

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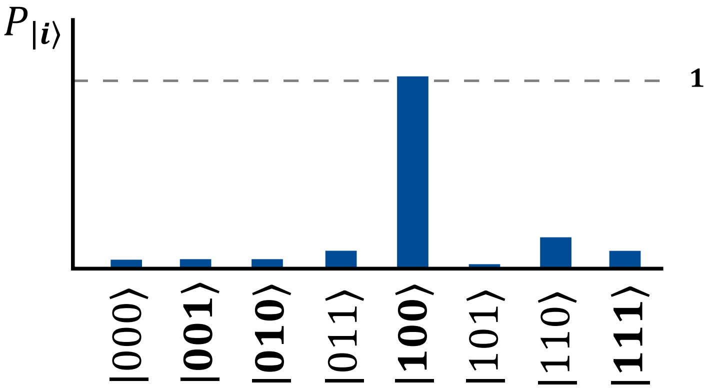
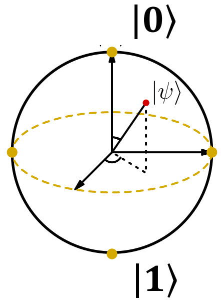


Quantum challenges

State decoherence



$$|\boldsymbol{\psi}\rangle = \cos(\theta)\,|\mathbf{0}\rangle + e^{i\varphi}\sin(\theta)|\mathbf{1}\rangle$$

Relaxation: $\theta \xrightarrow{time} 0$

determined by ‘environment’

Metric: T_1

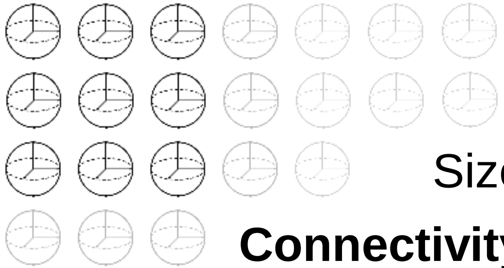
Dephasing: $\varphi \xrightarrow{time}$ random

determined by qubit ‘stability’

Metric: T_φ

$$\frac{\mathbf{1}}{\boldsymbol{T_2}} = \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{T_1}} + \frac{\mathbf{1}}{\boldsymbol{T_\varphi}}$$

Scaling



Size

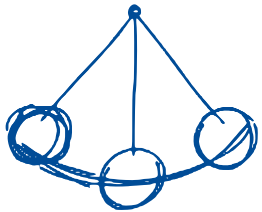
Connectivity

Entanglement

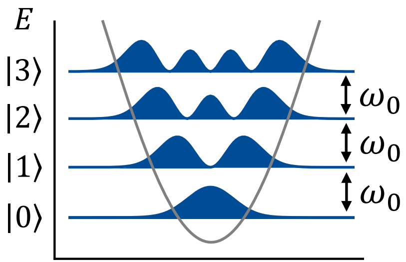
Reproducibility

Preparation-time of entangled state cannot exceed qubit coherence

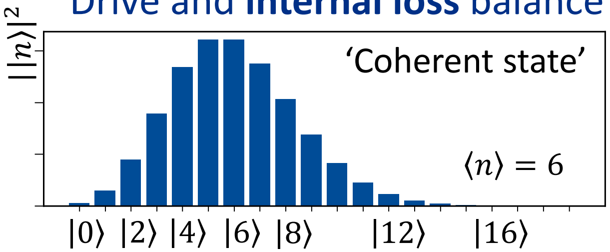
What are qubit actually?



For any harmonic oscillator (LC circuit, 3D cavity, …)

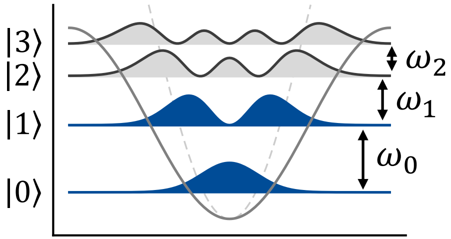


Drive and **internal loss** balance

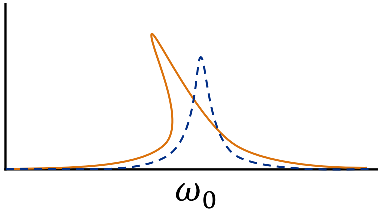


No control of superposition state :/

Slightly anharmonic oscillator (Duffing oscillator)



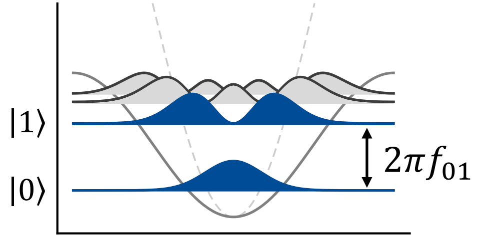
Frequency 'pull' with power

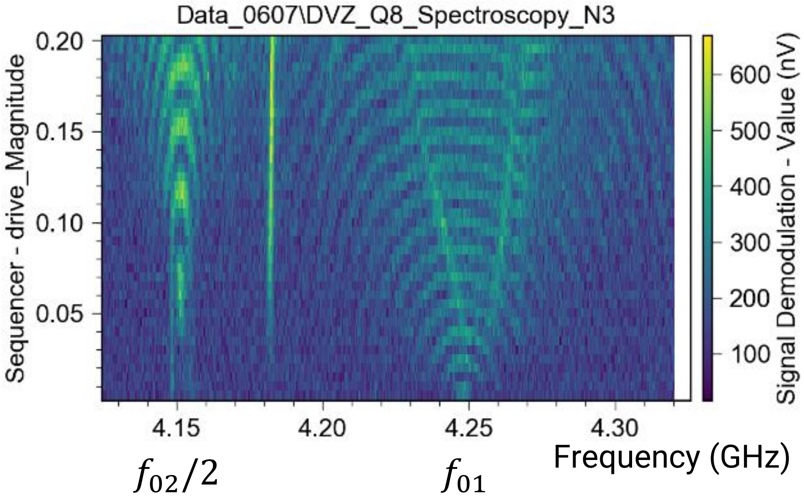


No control of superposition state :/

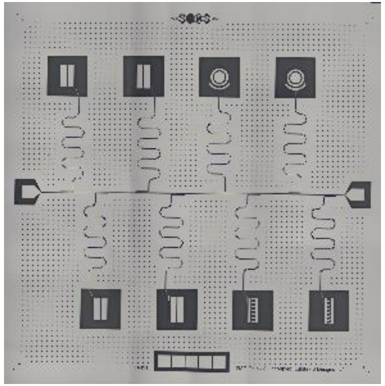
State control of a qubit?

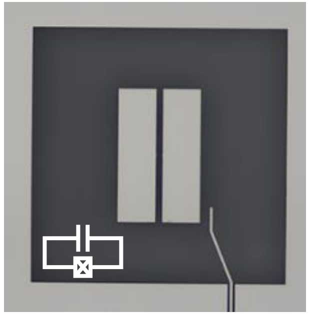
Strongly anharmonic oscillator (qubit)

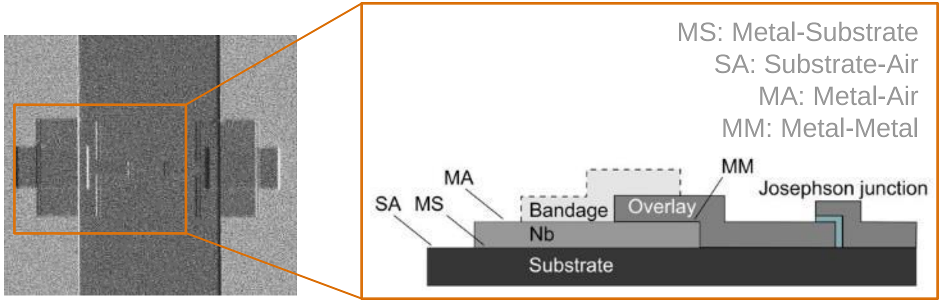




Single qubit control using Rabi-osc. ☺





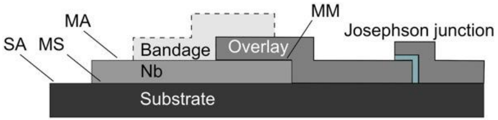


Understanding and improving 2D qubit coherence

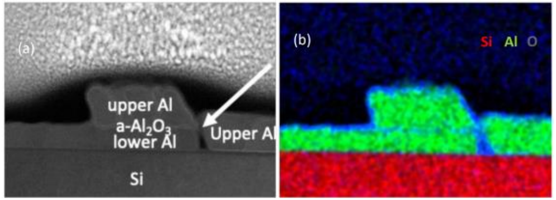
Advanced and extensive material characterization

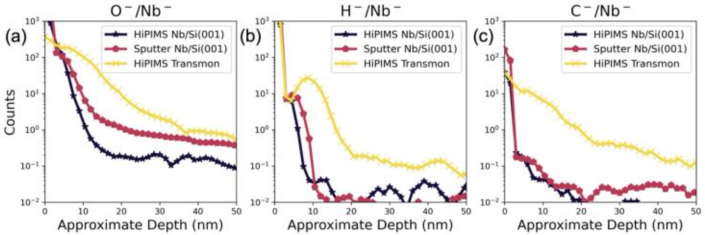
Study the ‘good vs bad’ performing qubits

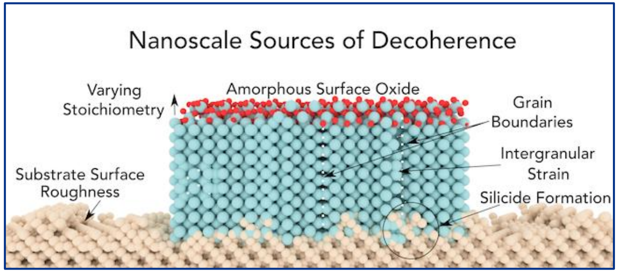
- Cryogenic TEM, AFM, MFM
- Cryogenic XRD, XRR
- Cryogenic TOF-SIMS
- XPS
- Raman
- AP tomography
- THz spectroscopy
- Magnetic-optical img.
- β-NMR, muSR

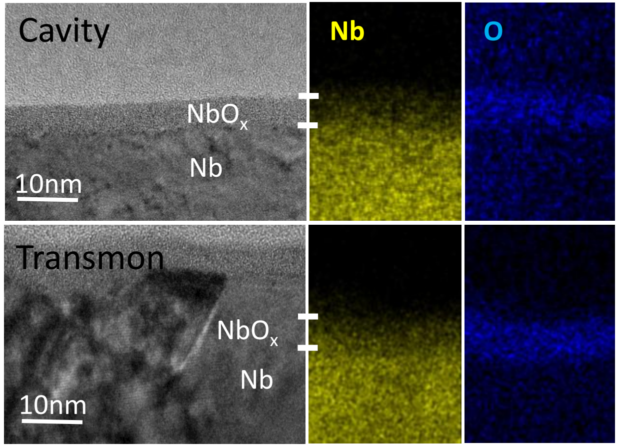


MS: Metal-Substrate | SA: Substrate-Air
MA: Metal-Air | MM: Metal-Metal









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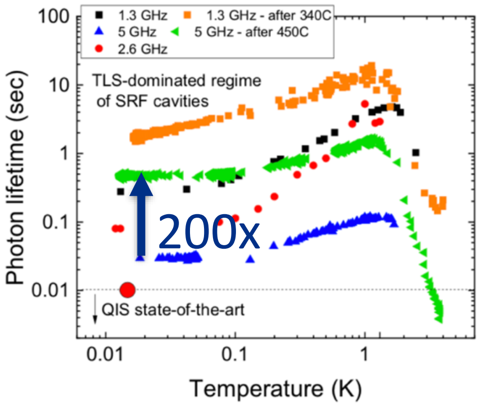
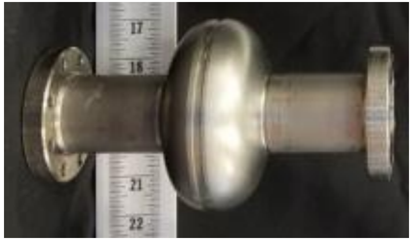
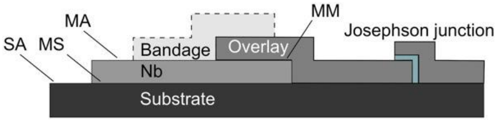
Understanding and improving 2D qubit coherence

A. Romanenko et al, Phys. Rev. Applied **13**, 034032, 2020







MS: Metal-Substrate | SA: Substrate-Air
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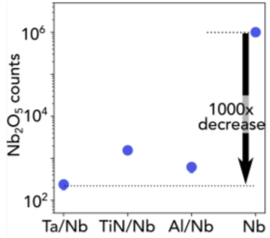
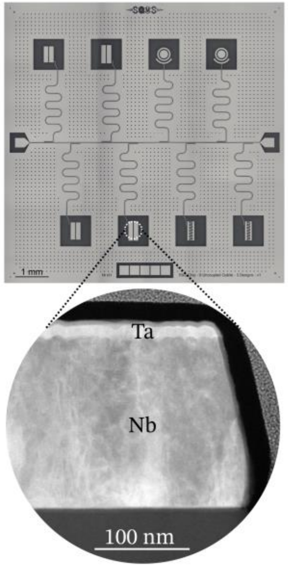
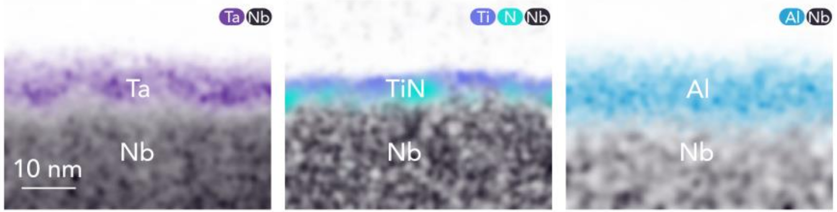
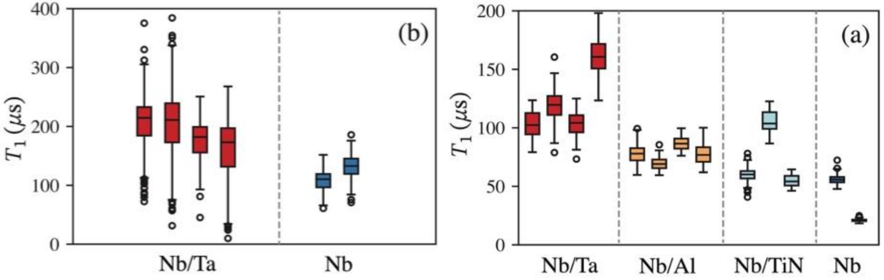
Compare coherence improvements using identical chip-design across the team.

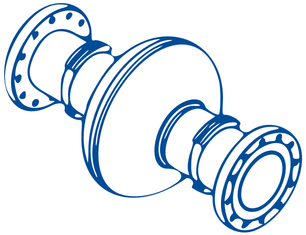


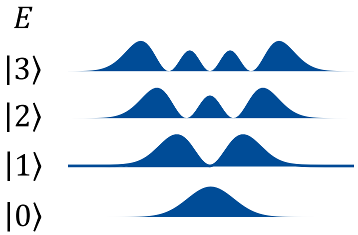






Superconducting qudits?

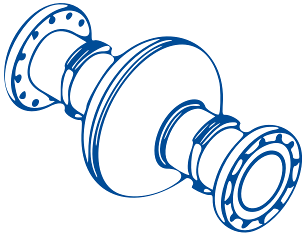


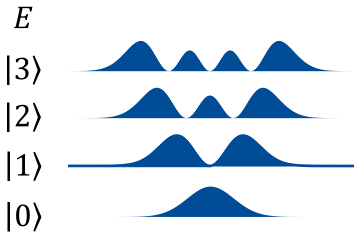


$$|\boldsymbol{\psi}\rangle = c_1|\mathbf{0}\rangle + c_2|\mathbf{1}\rangle + \cdots + c_n|\boldsymbol{n}\rangle$$

A superposition of number of n photons…
'encodes' $\log_2 n$ qubits

Superconducting qu<u>d</u>its?





$$|\boldsymbol{\psi}\rangle = c_1|\mathbf{0}\rangle + c_2|\mathbf{1}\rangle + \cdots + c_n|\boldsymbol{n}\rangle$$

A superposition of <u>number of n photons…</u>
'encodes' $\log_2 n$ qubits

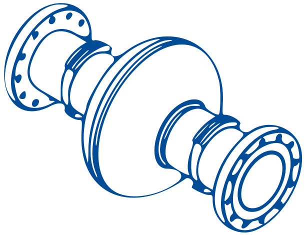
If *frequency* is **small**, *temperature* **must** be **low** $\leftarrow E = hf$ (Einstein)

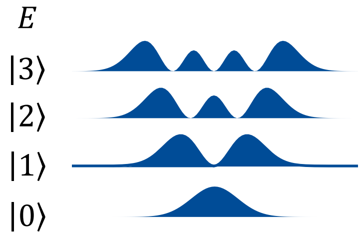
$E = k_B T$ (Boltzman)

Relaxation time

$$\boldsymbol{T^1_{|n\rangle} = \frac{1}{n} T^1_{|0\rangle}}$$

Superconducting qu<u>d</u>its?





$$T^{1}_{|0\rangle} \approx 1\ \mathbf{s}!$$

$$|\boldsymbol{\psi}\rangle = c_1|\mathbf{0}\rangle + c_2|\mathbf{1}\rangle + \cdots + c_n|\boldsymbol{n}\rangle$$

A superposition of <u>number of n photons…</u>
'encodes' $\log_2 n$ qubits

If *frequency* is **small**,
temperature **must** be
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$E = k_B T$ (Boltzman)

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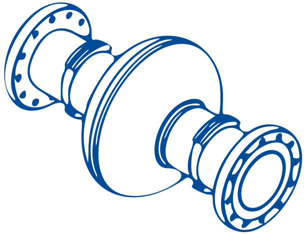
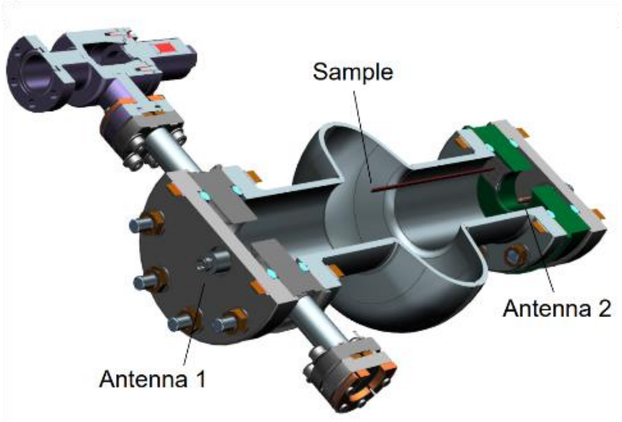
Superconducting qu<u>d</u>its

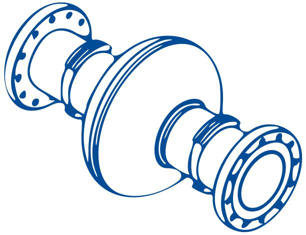


$\otimes$

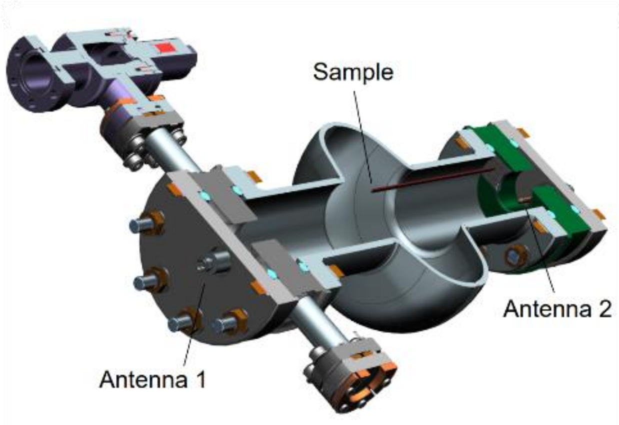
$$|\boldsymbol{\psi}\rangle_{\boldsymbol{Q}} \otimes |\boldsymbol{\psi}\rangle_{\boldsymbol{C}} = (q_1|\mathbf{0}\rangle + q_2|\mathbf{1}\rangle) \otimes (c_1|\mathbf{0}\rangle + c_2|\mathbf{1}\rangle + \cdots + c_n|n\rangle)$$



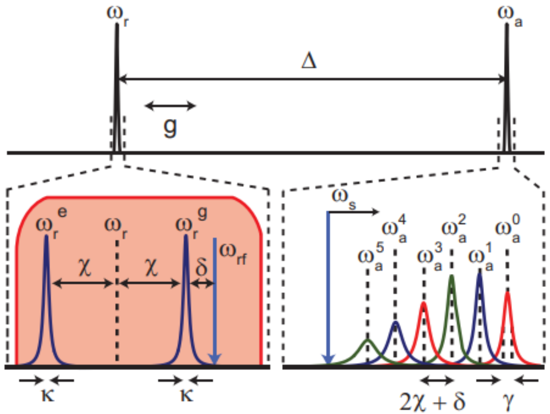
Superconducting qudits



$\otimes$



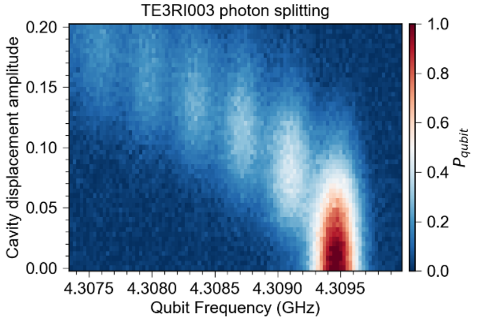
$$|\psi\rangle_Q \otimes |\psi\rangle_C = (q_1|\mathbf{0}\rangle + q_2|\mathbf{1}\rangle) \otimes$$
$$(c_1|\mathbf{0}\rangle + c_2|\mathbf{1}\rangle + \cdots + c_n|n\rangle)$$

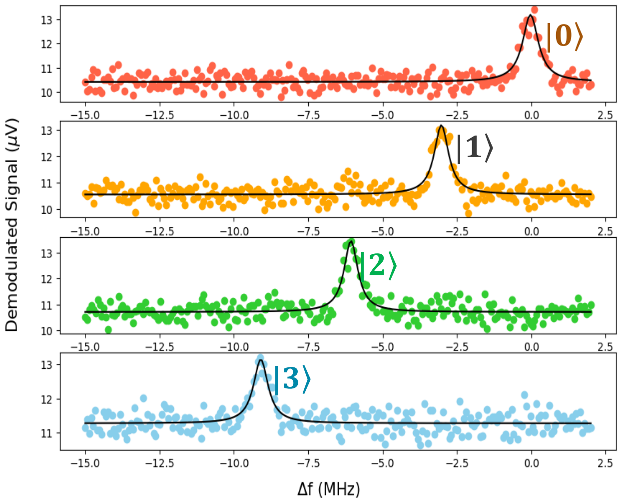


Weak **off-resonance** coupling facilitates **selective** cavity state-control using the **(ancilla) qubit**!

Cavity frequency becomes qubit-state dependent and visa-versa

Superconducting qudits





Ancilla (qubit)

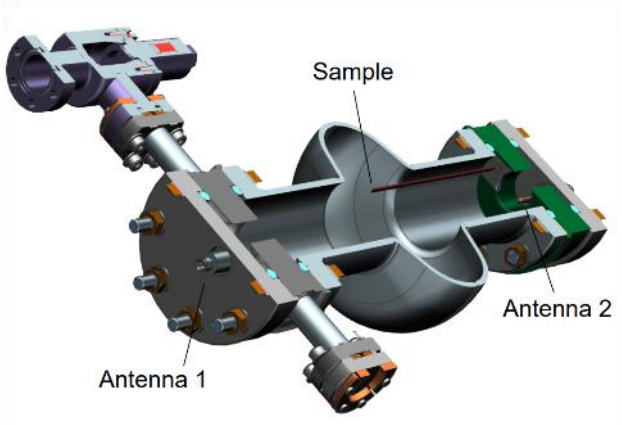
$T_1 \approx 110$ μs

$T_2 \approx 100$ μs

Cavity (qudit)

$T_1 \approx 3.2$ **ms**

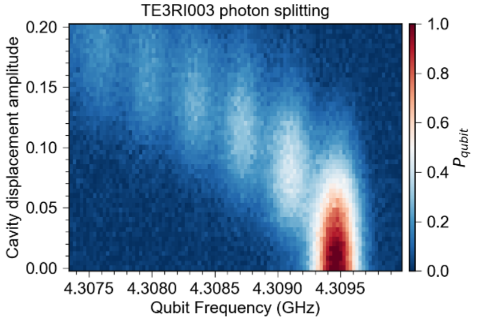
$T_2 \approx 1.5$ **ms**

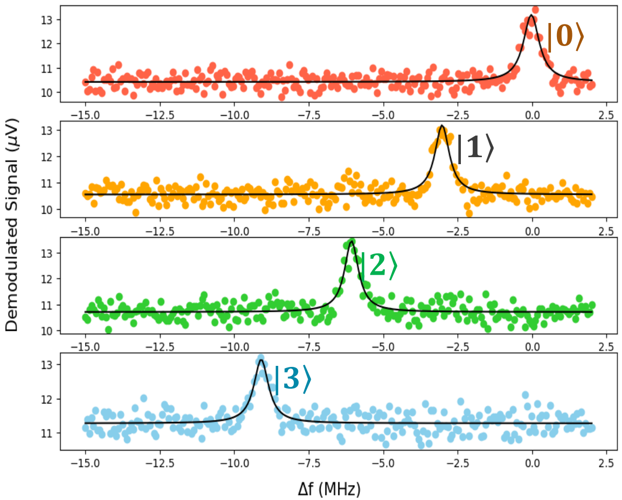


Weak **off-resonance** coupling facilitates **selective** cavity state-control using the **(ancilla) qubit**!

Cavity frequency becomes qubit-state dependent and visa-versa

Superconducting qu<u>d</u>its





Ancilla (qubit)

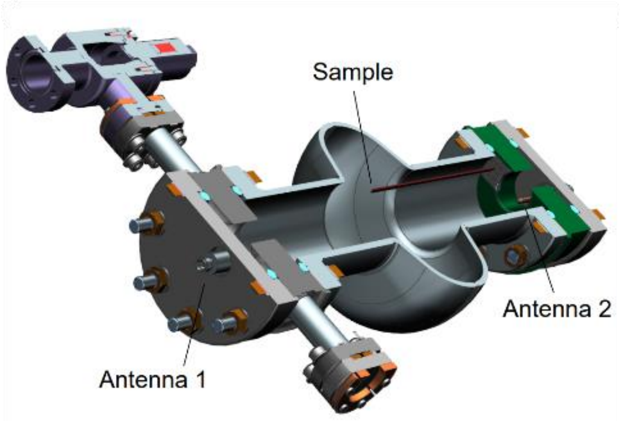
$T_1 \approx 110\ \mu s$

$T_2 \approx 100\ \mu s$

Cavity (qudit)

$T_1 \approx 3.2$ **ms**

$T_2 \approx 1.5$ **ms**

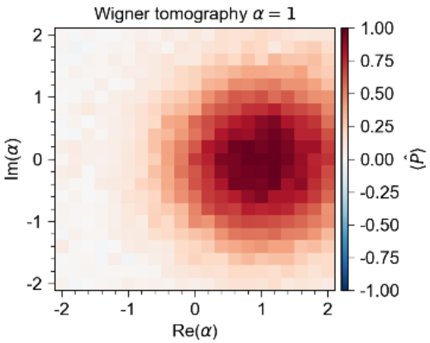


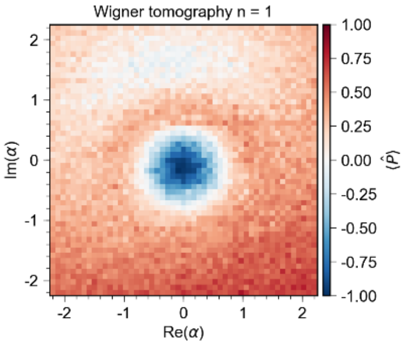
Weak **off-resonance** coupling facilitates **selective** cavity state-control using the **(ancilla) qubit**!

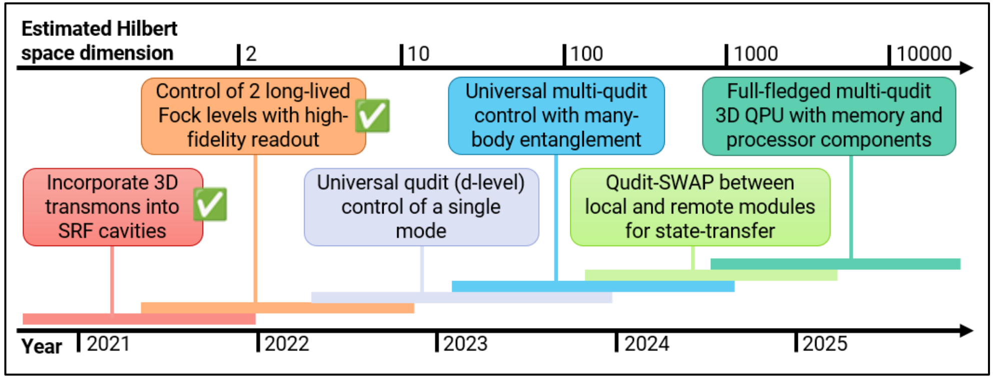
Cavity frequency becomes qubit-state dependent and <u>visa-versa</u>

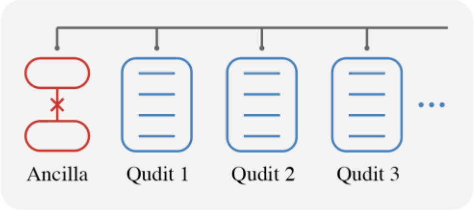
Photon counting!

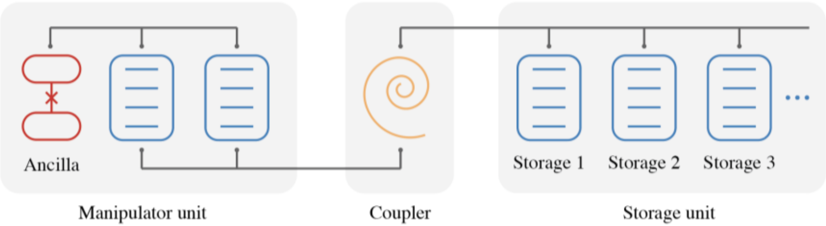
Towards a 3D cavity QPU

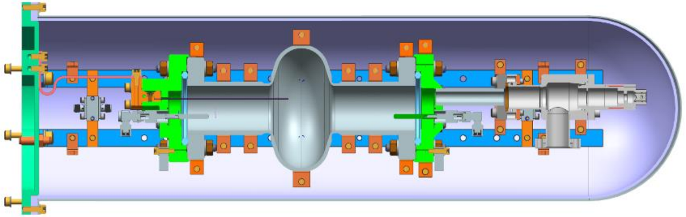












Challenges lying ahead

- **Device performance improvements**
- Scalable qudit architecture
- Quantum error-correction
- Error-correction for qudits
- Large scale cryogenics at **sub**-20 mK
- Time-domain RF electronics for 500k+ channels
- Quantum communication

Challenges lying ahead

my view

- **Device performance improvements**
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- Error-correction for qudits
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- Time-domain RF electronics for 500k+ cha
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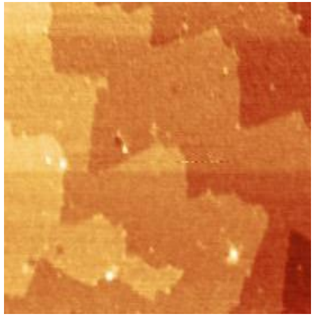
Requires large-scale systematic research into materials, fabrication, design and operation, similar to the SQMS effort or even bigger.

- Qubit T1 → 10 ms or more
- Qudit T1 → 10 s or more

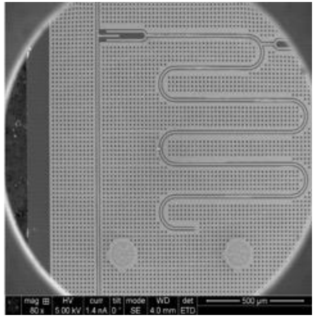
Devices must be T1 - limited!

SQMS Science & Technology Innovation Chain

Materials → High-coherence devices → Systems integration → New platforms for quantum tech → Quantum advantage



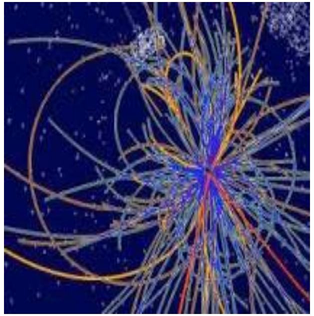
Developing full understanding of decoherence sources



Demonstrating devices with systematically higher T1 & T2

Integrating devices into quantum processors

Deploying large scale quantum cryogenics facilities



Demonstrating quantum advantage

SQMS bridges the gap between ideas and large-scale realizations via unique center-wide coordinated approaches

SQMS

A DOE National QIS Research Center

34
Partner Institutions

500+
Collaborators

Fermilab · Northwestern University · rigetti · AMES National Laboratory · NASA Ames Research Center · NIST

Colorado School of Mines (Earth • Energy • Environment) · Coppin State University · FormFactor™ · Goldman Sachs · Illinois Institute of Technology · INFN

Jefferson Lab · Johns Hopkins University · Lockheed Martin · Lawrence Livermore National Laboratory · LSU · NPL National Physical Laboratory

NYU · Royal Holloway University of London · Rutgers The State University of New Jersey · Spelman College · Stanford · Temple University · Unitary Fund

The University of Arizona · University of Colorado Boulder · UIC University of Illinois Chicago · University of Illinois Urbana-Champaign · University of Michigan

University of Minnesota Driven to Discover® · Università di Pisa · USC University of Southern California · University of Waterloo | IQC Institute for Quantum Computing

SQMS MISSION [excerpt] Achieve transformational advances in the major cross-cutting challenge of understanding & eliminating decoherence mechanisms in superconducting devices, enabling construction and deployment of superior quantum systems for computing & sensing.

The Quantum Garage

- 8 XLD DRs
- 64 parallel experiments
- for 6 scientific thrusts