

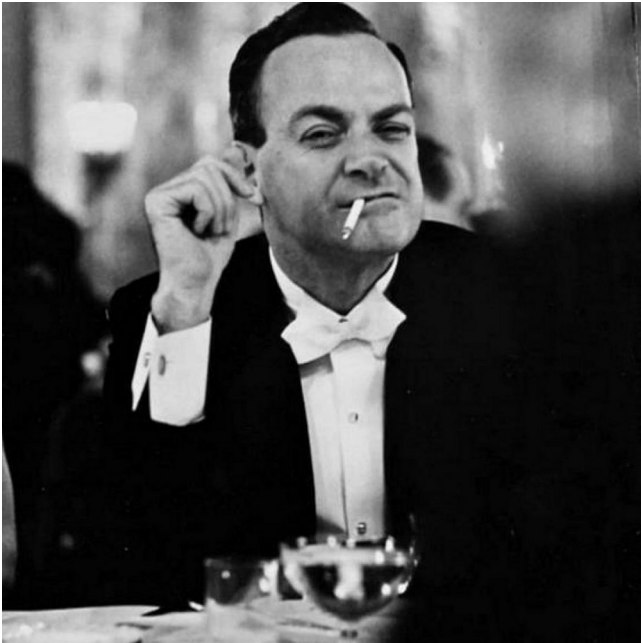
Superconducting Quantum Computer Hardware

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11/30/23



Quantum Computing Fundamentals



“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical.”

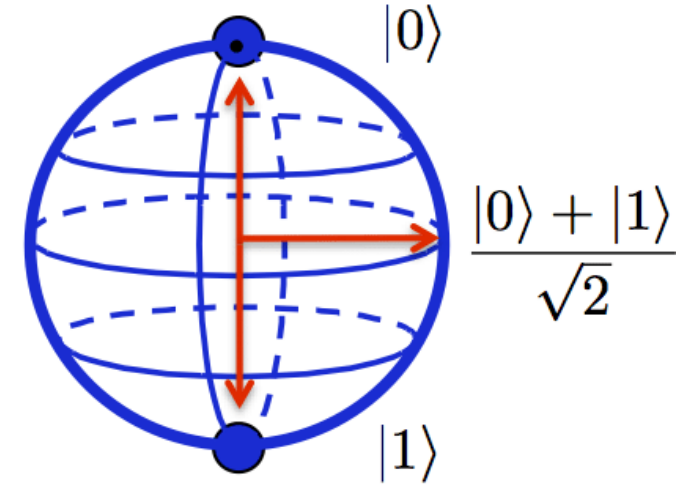
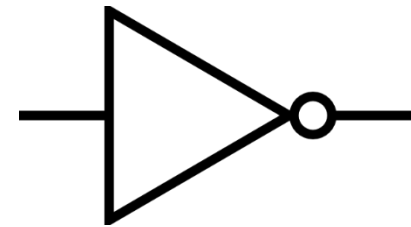
- Breaking cryptography
- Machine learning
- Optimization

● 0

● 1

Classical Bit

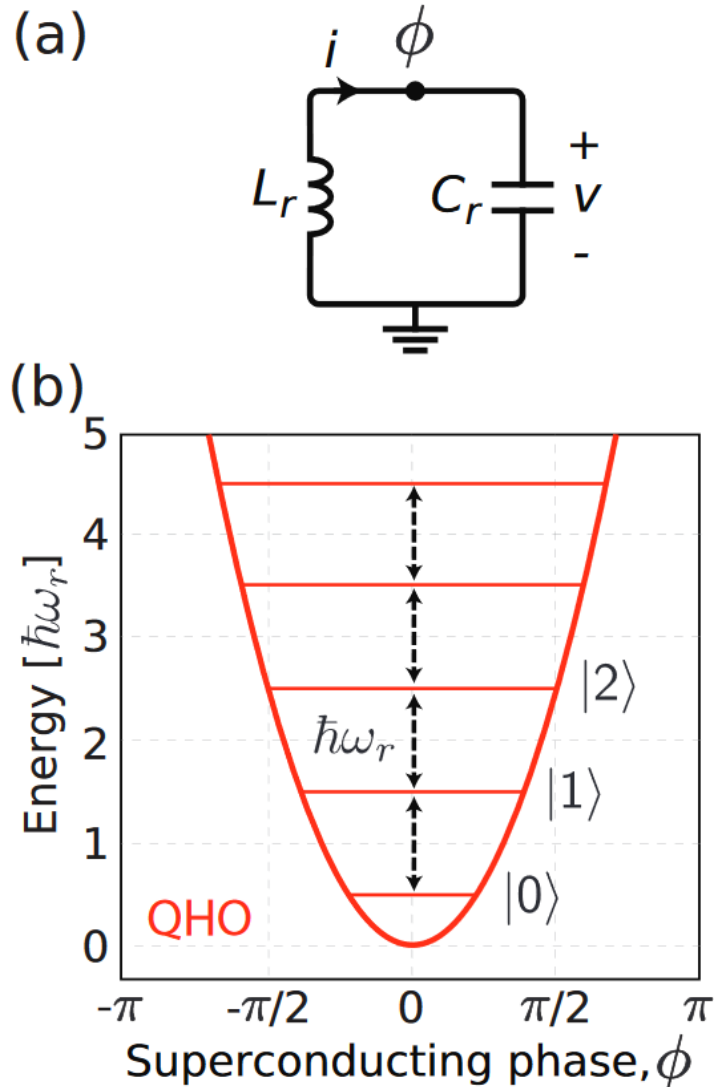
In	Out
0	1
1	0



Qubit



Qubit Circuit



$$U = \frac{1}{2}LI^2 + \frac{1}{2}CV^2$$

$$V_L = -L \frac{dI_L}{dt}$$

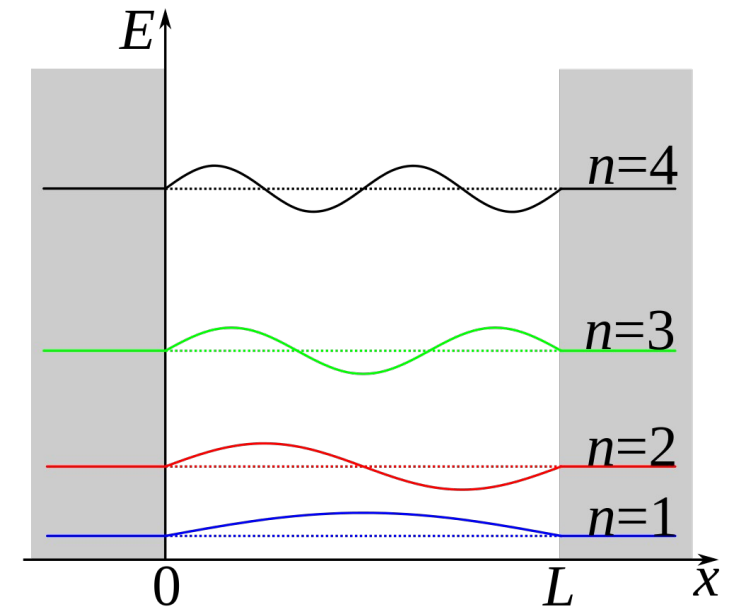
$$I_L = -\frac{1}{L} \int_{-\infty}^t V_L(t') dt$$

$$\Phi(t) = \int_{-\infty}^t V(t') dt'$$

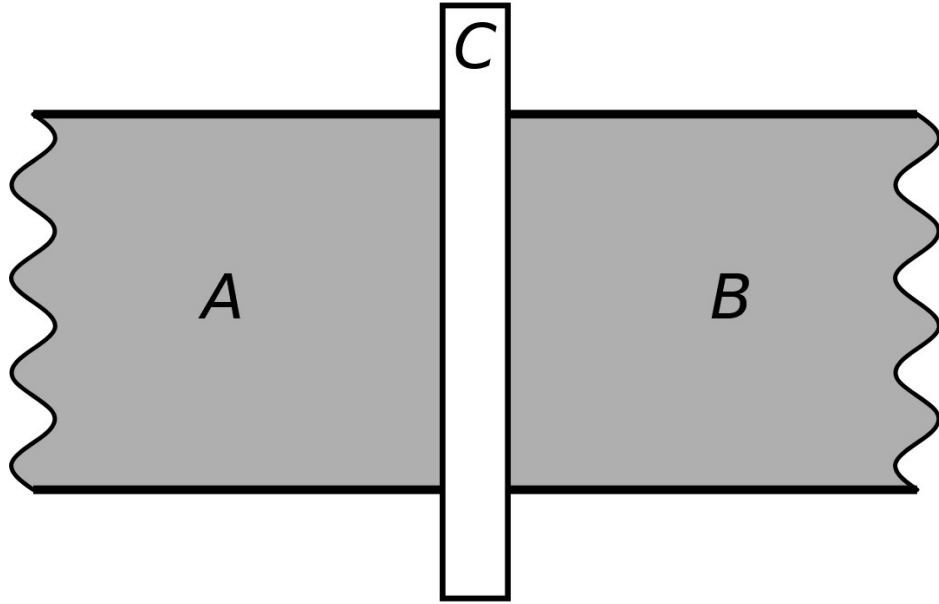
$$\phi = \frac{2\pi}{\Phi_0} \Phi$$

$$U = \frac{1}{2} \left(\frac{\Phi_0}{2\pi} \right)^2 \frac{1}{L} \phi^2 + \frac{1}{2} C \left(\frac{\Phi_0}{2\pi} \right)^2 \left(\frac{d\phi}{dt} \right)^2$$

$$\hat{H} = \hbar\omega (\hat{a}^\dagger \hat{a} + 1/2)$$



Josephson Junction



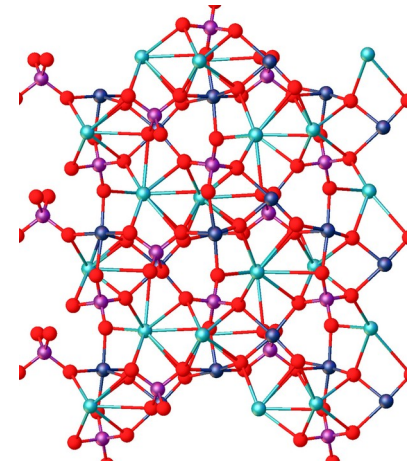
$$\frac{\partial \phi}{\partial t} = \frac{2eV(t)}{\hbar}$$

$$I(t) \propto \dot{n}_A(t) = I_c \sin(\phi(t))$$

$$\begin{aligned} E(\phi) &= -\frac{\Phi_0 I_c}{2\pi} \cos(\phi) \\ &= -\frac{\Phi_0 I_c}{2\pi} \left(1 - \phi^2/2 + \phi^4/24 + \dots\right) \end{aligned}$$

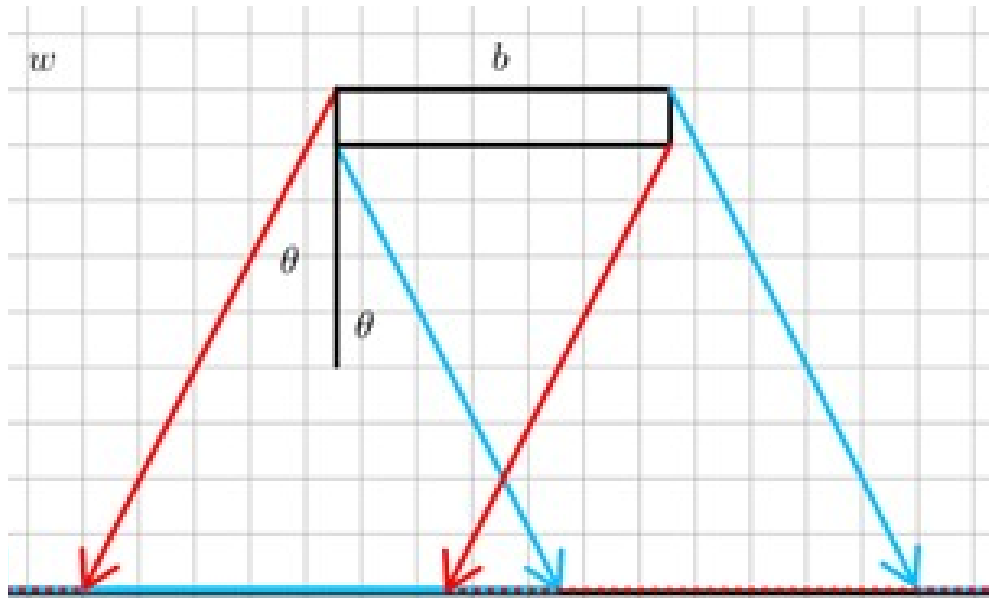
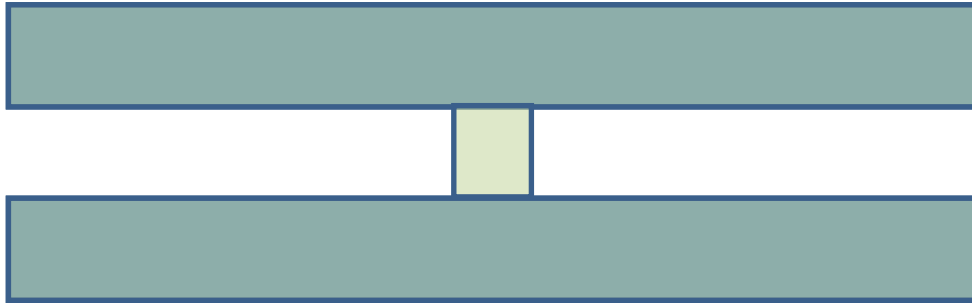
$$\begin{aligned} \psi_A &= \sqrt{n_A} e^{i\phi_A} \\ \psi_B &= \sqrt{n_B} e^{i\phi_B} \\ i\hbar \frac{\partial}{\partial t} \begin{pmatrix} \sqrt{n_A} e^{i\phi_A} \\ \sqrt{n_B} e^{i\phi_B} \end{pmatrix} &= \begin{pmatrix} eV & K \\ K & -eV \end{pmatrix} \begin{pmatrix} \sqrt{n_A} e^{i\phi_A} \\ \sqrt{n_B} e^{i\phi_B} \end{pmatrix} \end{aligned}$$

$$L(\phi) = \frac{L_J}{\cos(\phi)}$$

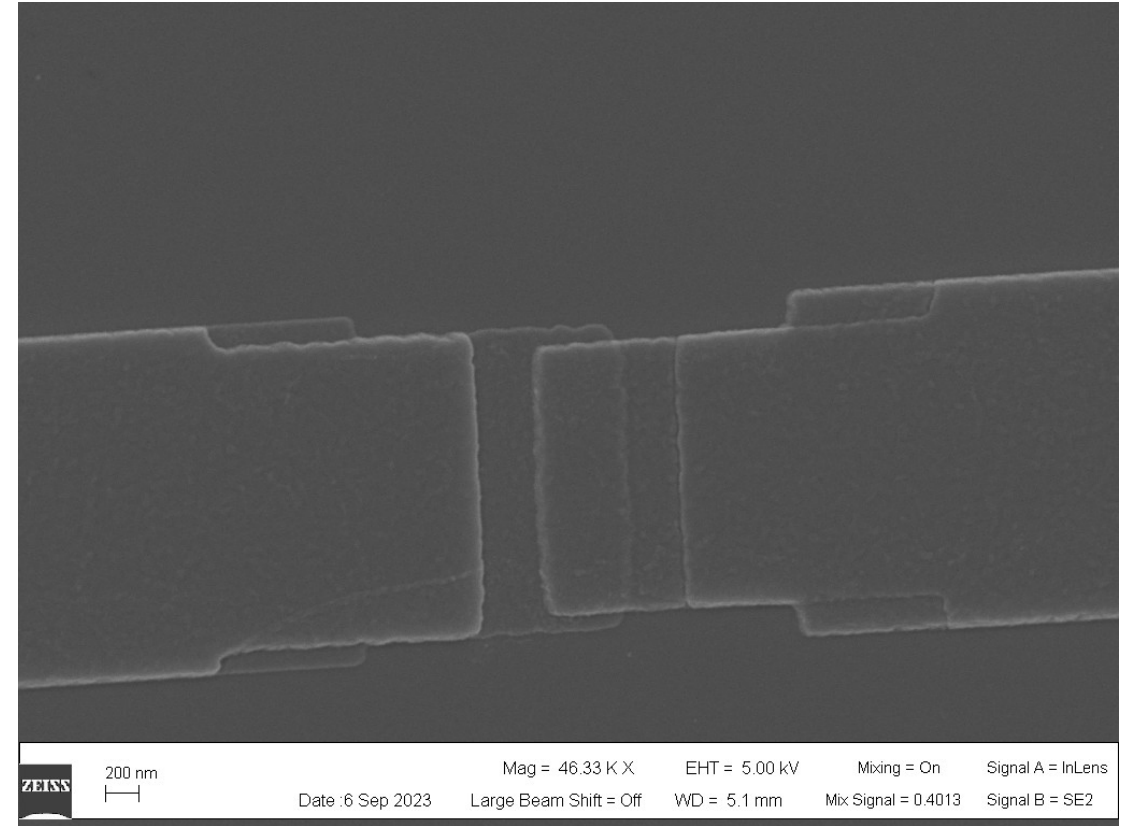


JJ Fabrication

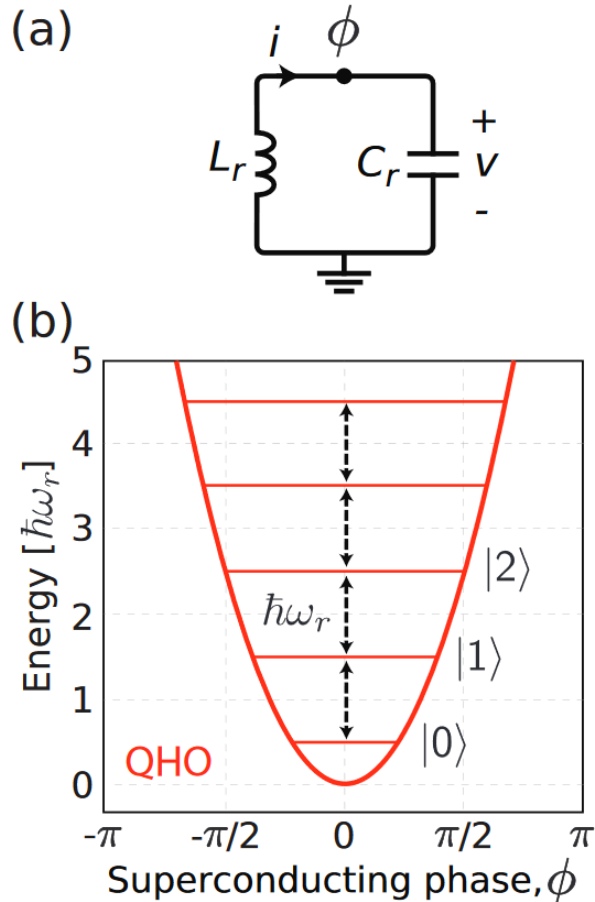
Top View



Side View

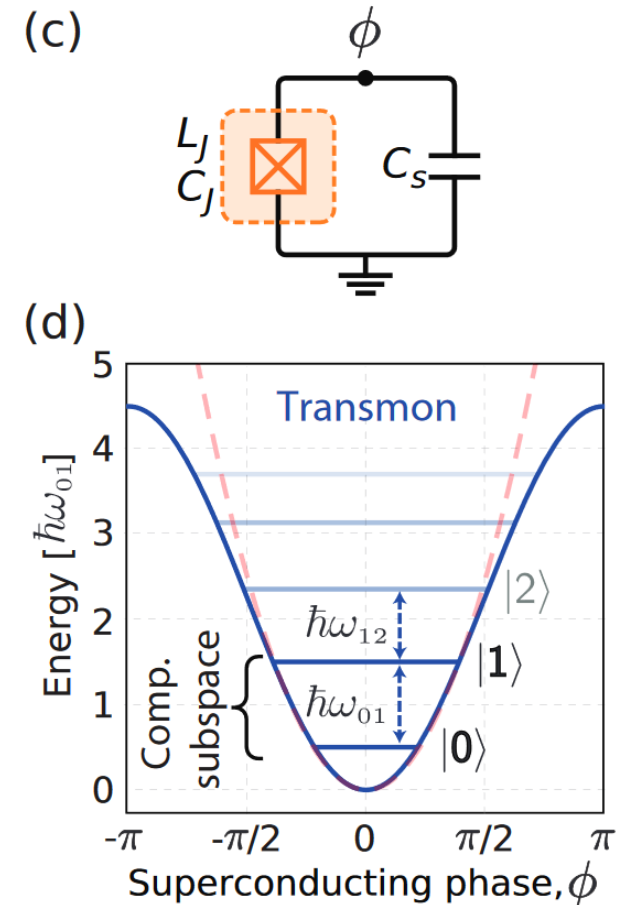


Transmon Qubit



$$U = \frac{1}{2} \left(\frac{\Phi_0}{2\pi} \right)^2 \frac{1}{L} \phi^2 + \frac{1}{2} C \left(\frac{\Phi_0}{2\pi} \right)^2 \left(\frac{d\phi}{dt} \right)^2$$

$$\hat{H} = \hbar\omega \left(\hat{a}^\dagger \hat{a} + 1/2 \right)$$



$$U = -\frac{\Phi_0 I_c}{2\pi} \cos(\phi) + \frac{1}{2} C \left(\frac{\Phi_0}{2\pi} \right)^2 \left(\frac{d\phi}{dt} \right)^2$$

$$\hat{H} = \hbar\omega \left(\hat{a}^\dagger \hat{a} + \frac{\alpha}{2} \hat{a}^{\dagger 2} \hat{a}^2 + \dots \right)$$

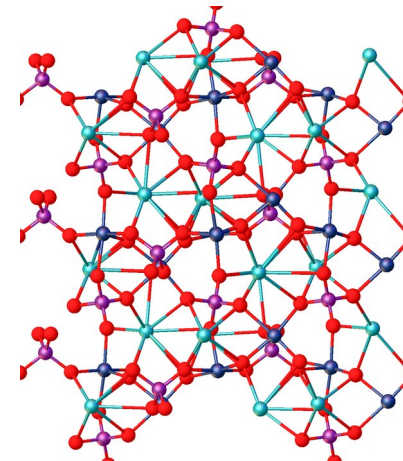
Quantum-Limited Parametric Amplification

- GHz;



$$L(\phi) = \frac{L_J}{\cos(\phi)}$$

$$P = \epsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \dots)$$



$$\hat{H}_I = \hbar g(\hat{a}^2 \hat{b}^{\dagger 2} + \hat{a}^{\dagger 2} \hat{b}^2)$$

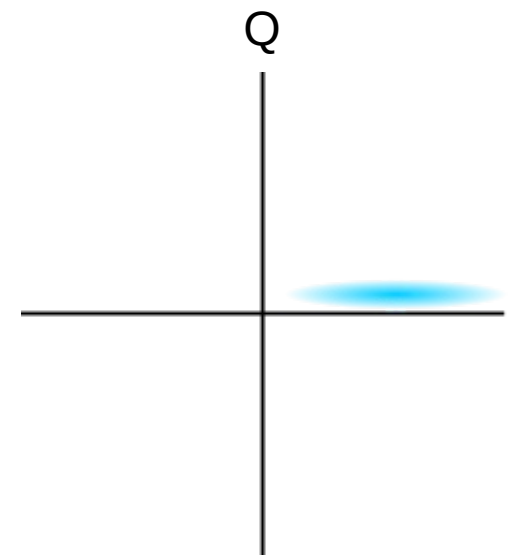
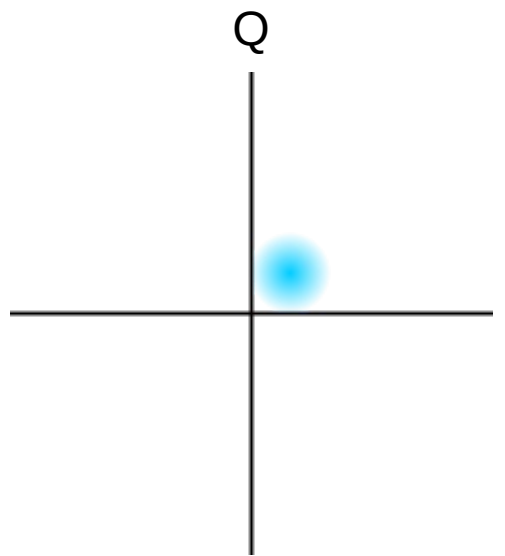
$$\hat{U}(t) = \exp[-i(\hbar g(\hat{a}^2 \hat{b}^{\dagger 2} + \hat{a}^{\dagger 2} \hat{b}^2))t/\hbar]$$

$$\hat{U}(t) = \exp[-i(\hbar g(\hat{a}^2 \beta^{*2} + \hat{a}^{\dagger 2} \beta^2))t/\hbar]$$

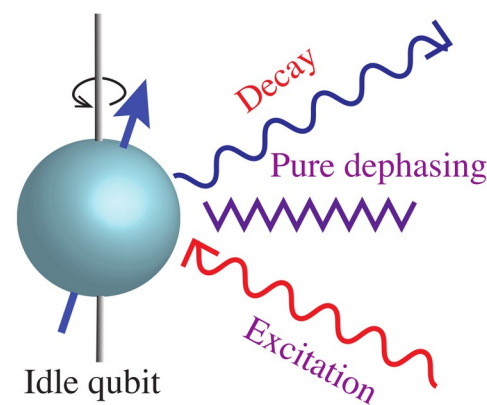
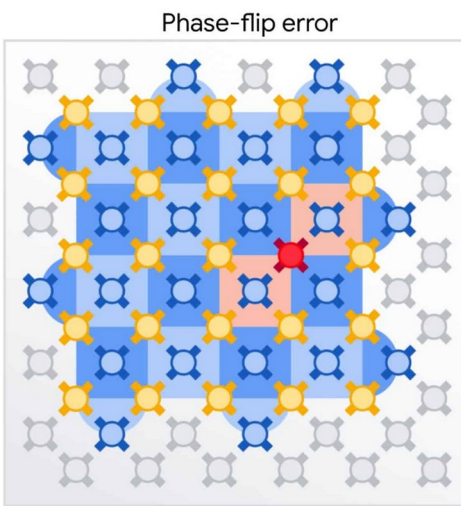
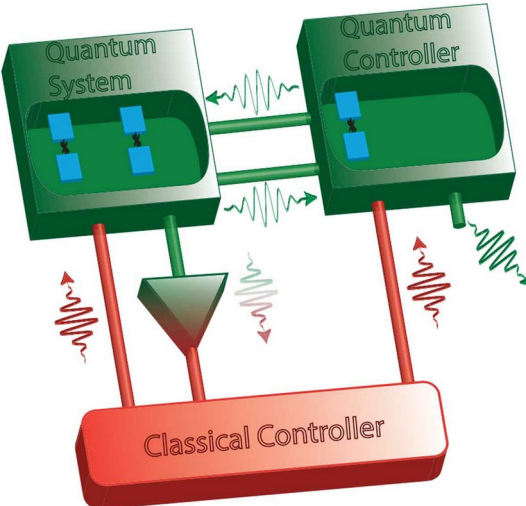
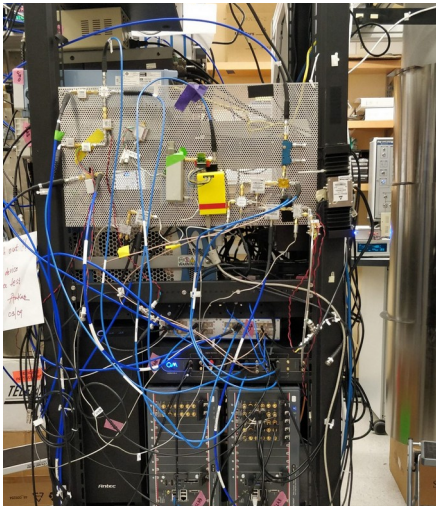
$$\hat{S}(\zeta) = \exp\left[-\frac{\zeta}{2}\hat{a}^{\dagger 2} + \frac{\zeta^*}{2}\hat{a}^2\right]$$

$$\hat{S}^\dagger(\zeta)\hat{a}\hat{S}(\zeta) = \hat{a} \cosh(|\zeta|) - e^{i\theta}\hat{a}^\dagger \sinh(|\zeta|)$$

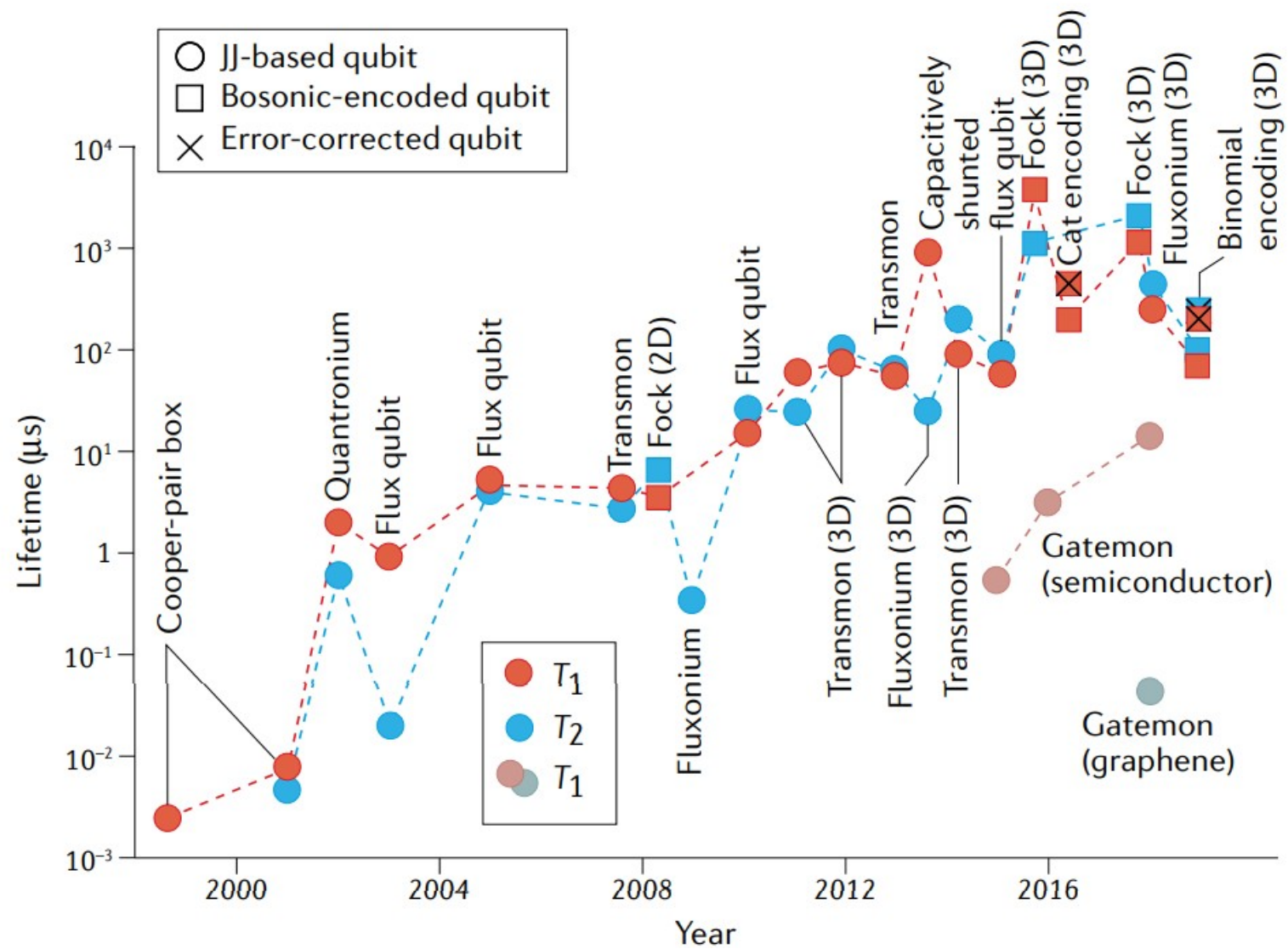
$$\hat{S}^\dagger(\zeta)\hat{a}^\dagger\hat{S}(\zeta) = \hat{a}^\dagger \cosh(|\zeta|) - e^{i\theta}\hat{a} \sinh(|\zeta|)$$



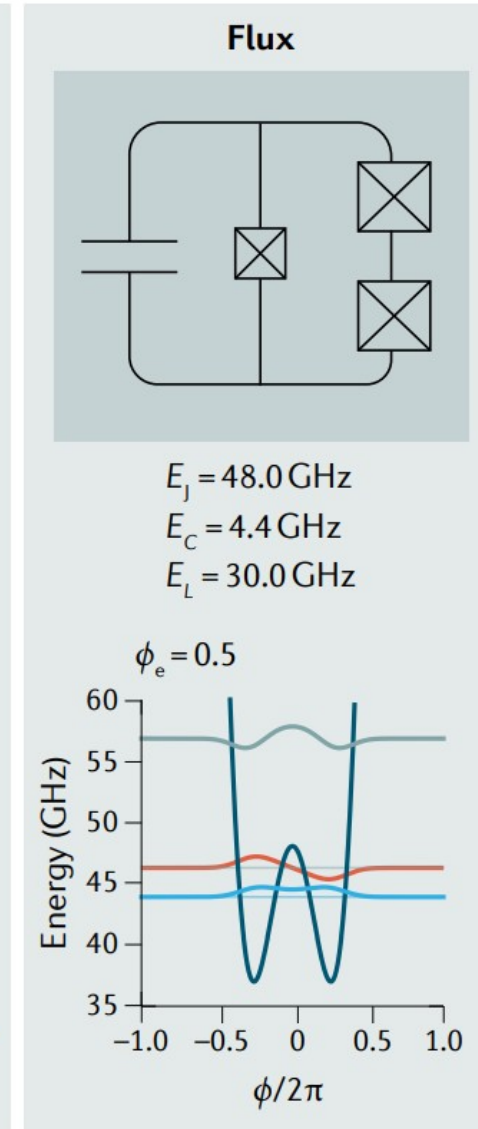
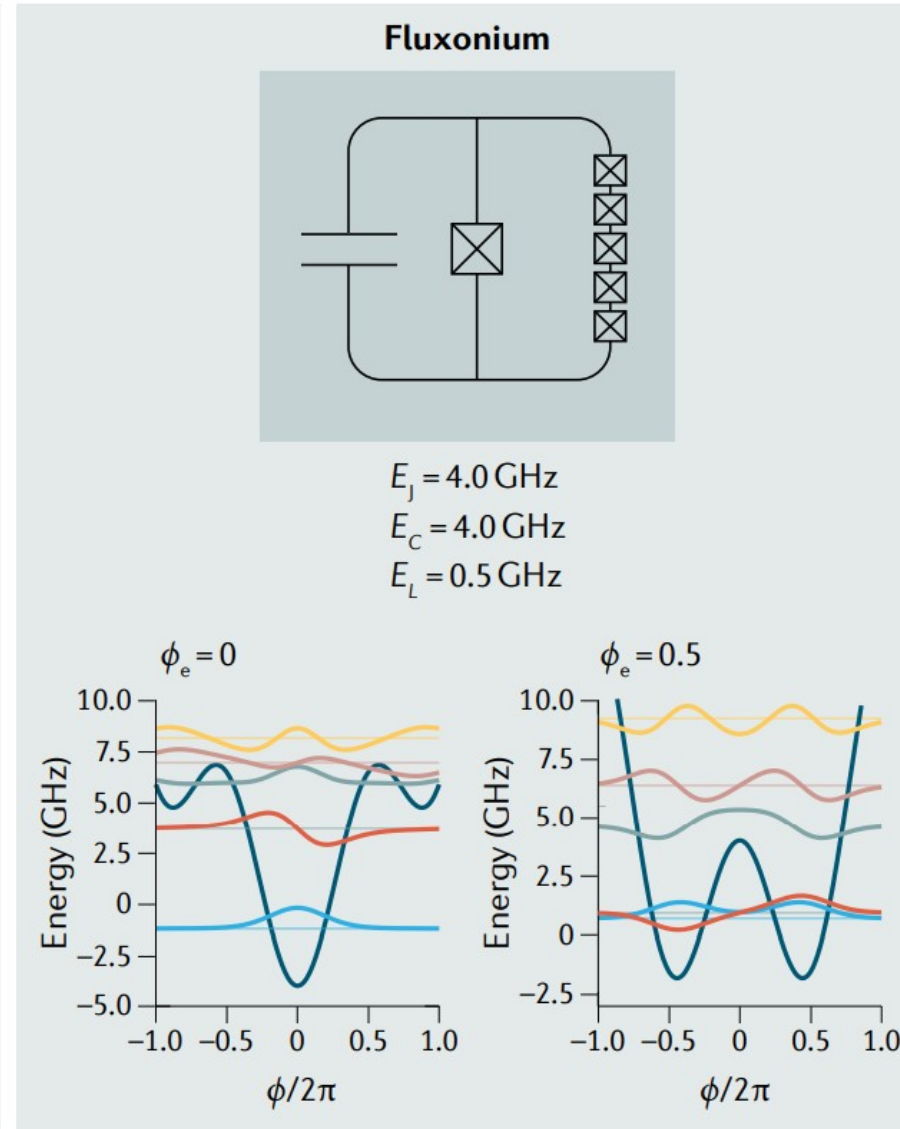
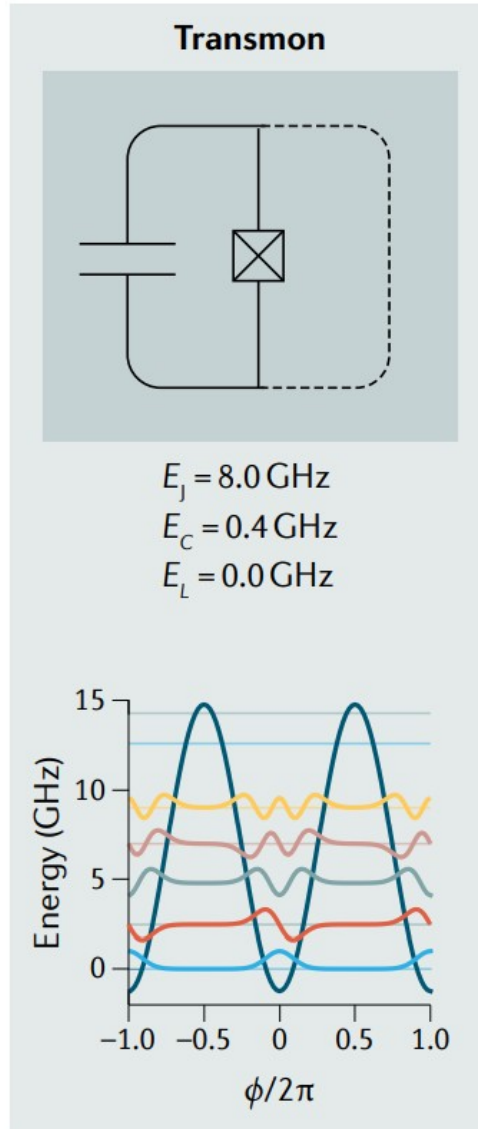
Challenges of Superconducting Quantum Computing

Qubit Quality	Error Correction	Qubit Control	Scaling
<ul style="list-style-type: none">- Qubit lifetime is in the microsecond regime- Error rates are high for computation  <p>The diagram shows a blue sphere representing an 'Idle qubit' on a vertical axis. Three wavy arrows originate from the sphere: a blue arrow labeled 'Decay' pointing upwards and to the right, a purple arrow labeled 'Pure dephasing' pointing horizontally to the right, and a red arrow labeled 'Excitation' pointing downwards and to the right.</p>	<ul style="list-style-type: none">- Error correction has not yet been proven at scale  <p>The diagram is titled 'Phase-flip error' and shows a grid of qubits. Most qubits are blue or yellow, but one central qubit is red, indicating an error. The grid is surrounded by a larger, fainter grid of grey qubits.</p>	<ul style="list-style-type: none">- Low-latency control on the order of nanoseconds  <p>The diagram shows a 'Quantum System' and a 'Quantum Controller' connected by two green lines. Below them is a 'Classical Controller' connected to the quantum system by two red lines. Wavy arrows indicate communication between the components.</p>	<ul style="list-style-type: none">- One qubit requires multiple control wires and several room temperature electronics  <p>A photograph showing a complex hardware setup for quantum computing, featuring a dense network of blue and black cables connected to various electronic components and a large metal cryostat.</p>

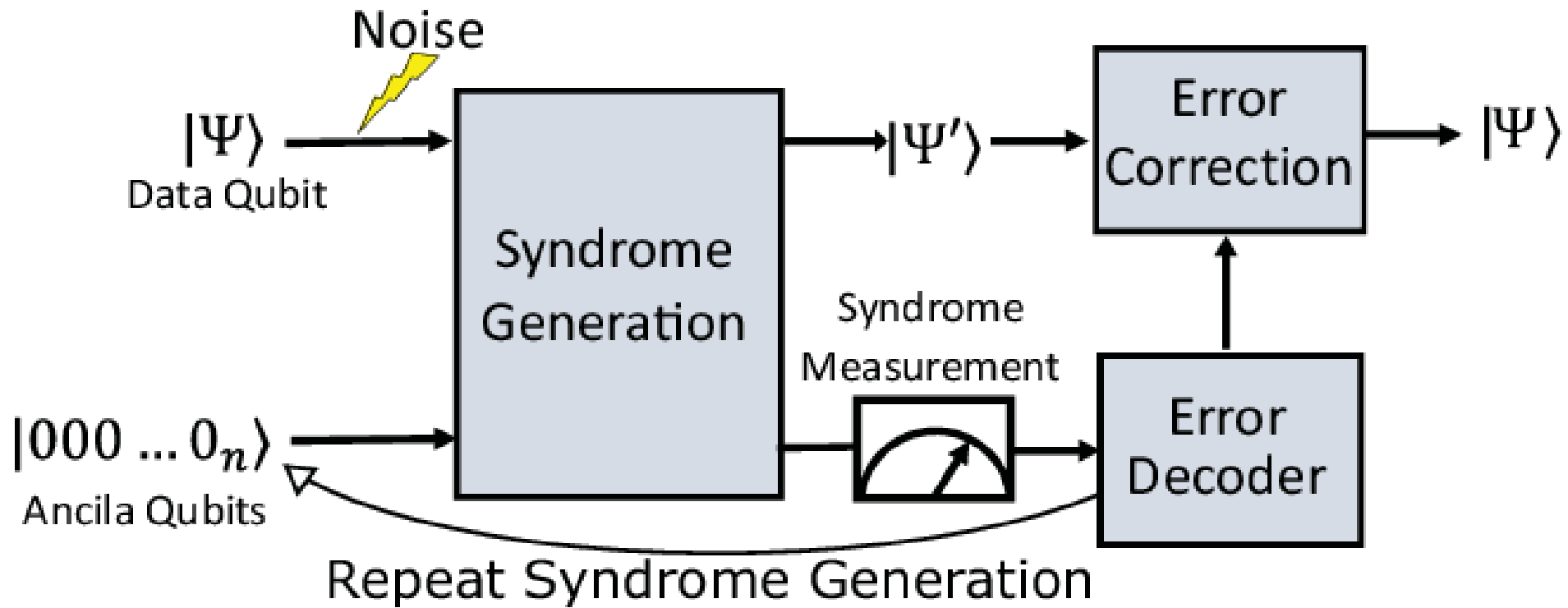
Novel qubit architectures



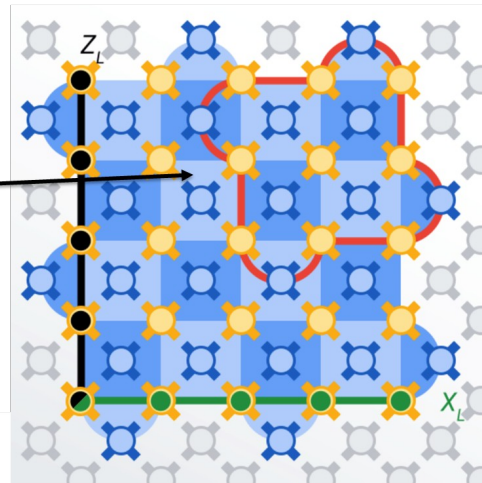
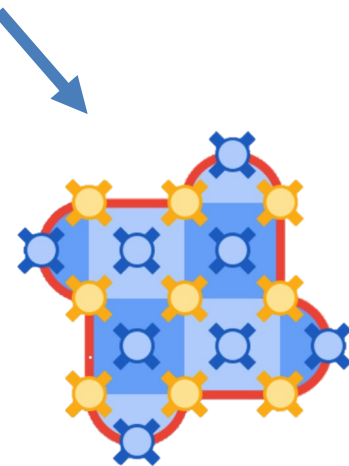
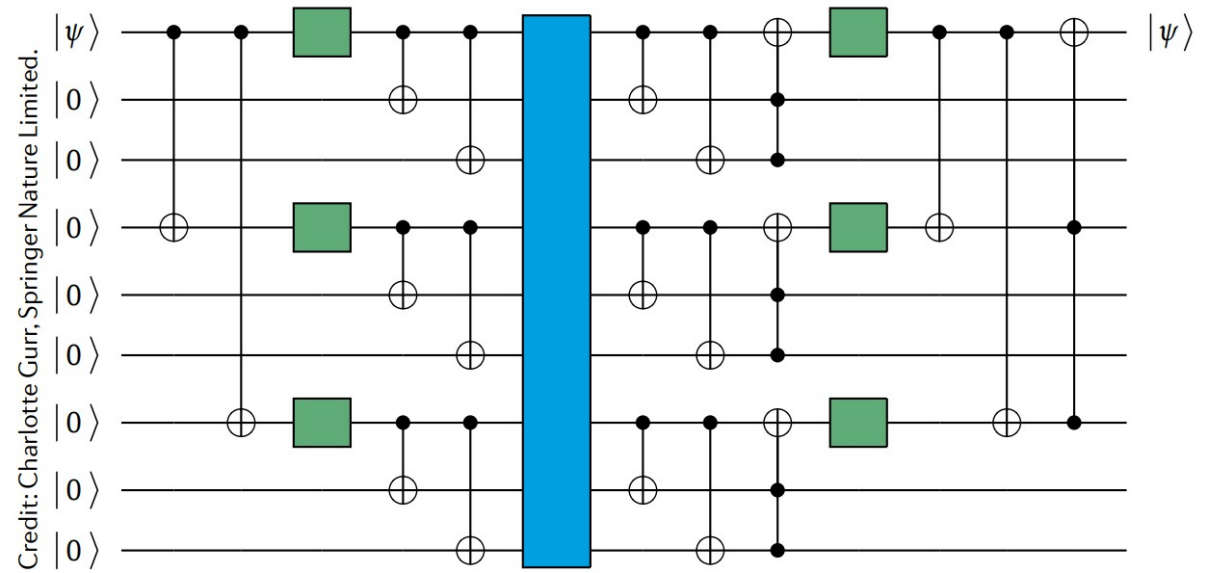
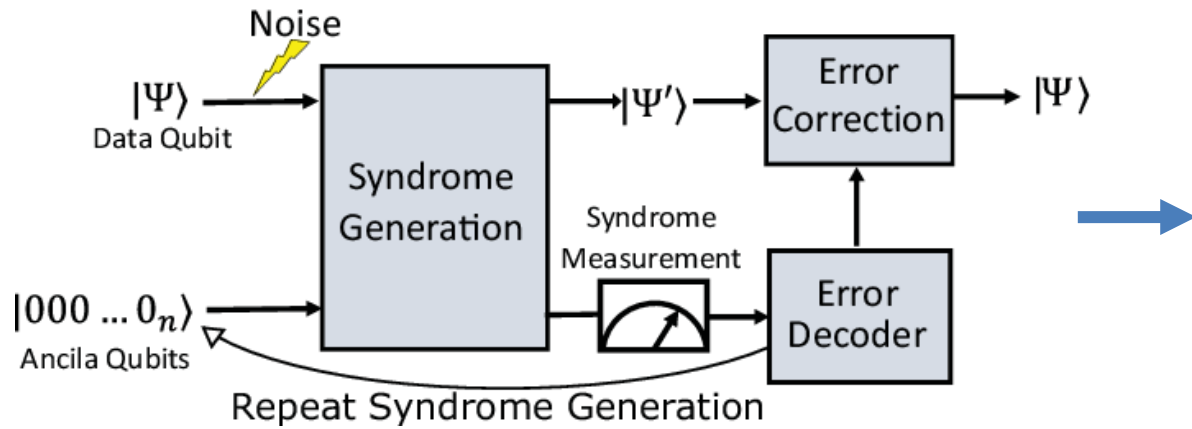
Novel qubit architectures



Quantum Error Correction

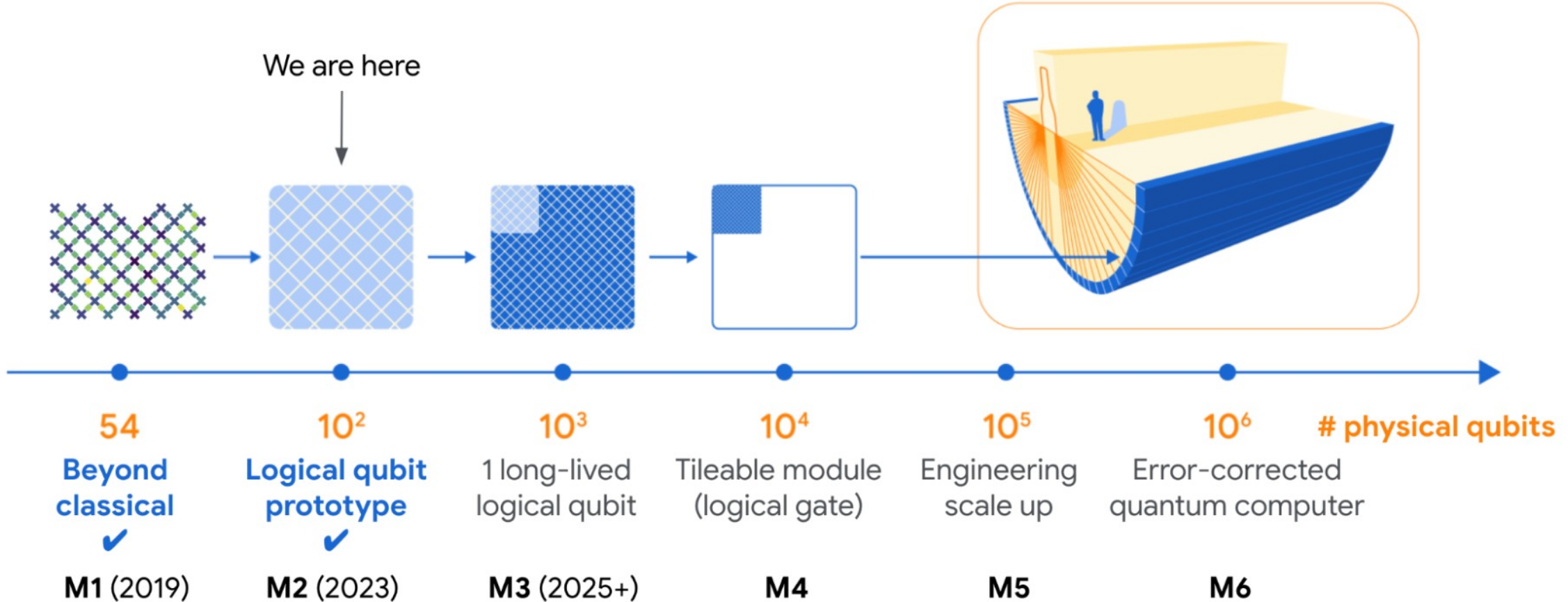


Quantum Error Correction

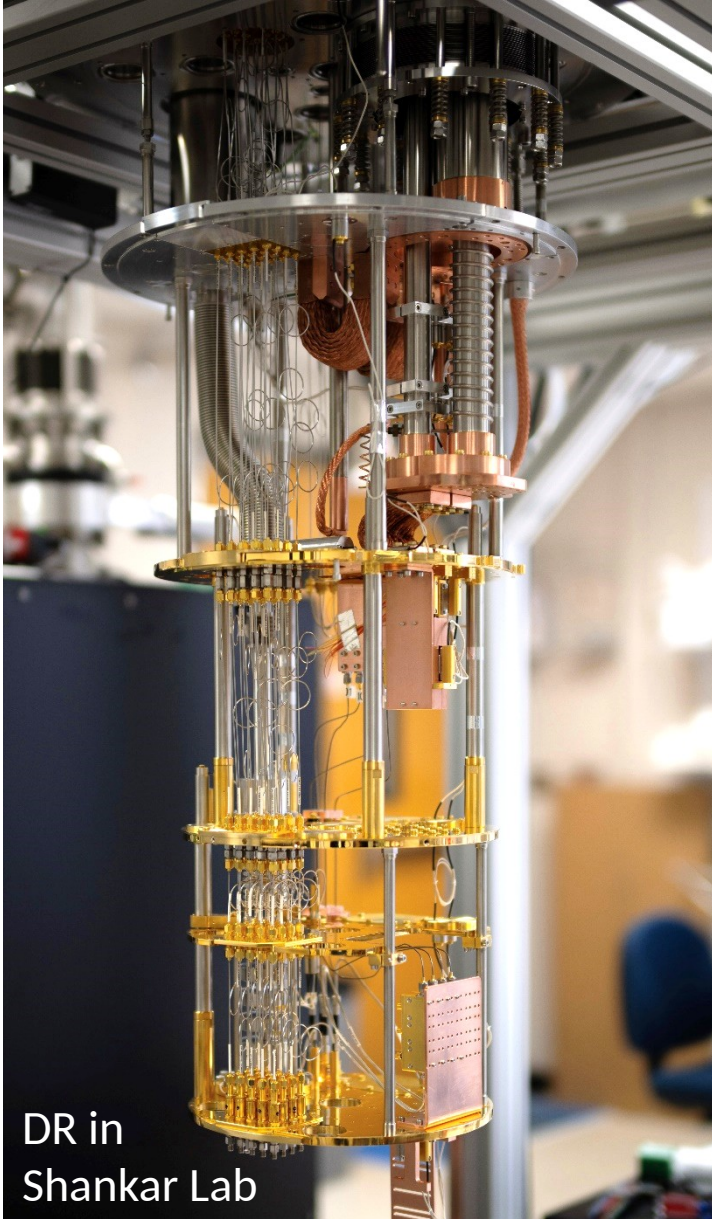


-  Data qubit (d^2)
-  Measure qubit ($d^2 - 1$)
-  Unused
-  Subset distance-3

Quantum error correction	–	Enabled	At scale
# Physical qubits	10 – 100	100 – 1000	$10^4 – 10^6$
# Logical qubits	–	1	10 – 1000+
Logical error	10^{-3}	$10^{-2} – 10^{-6}$	$10^{-6} – 10^{-12}$



Cool it down!



DR in
Shankar Lab

< 20 mK

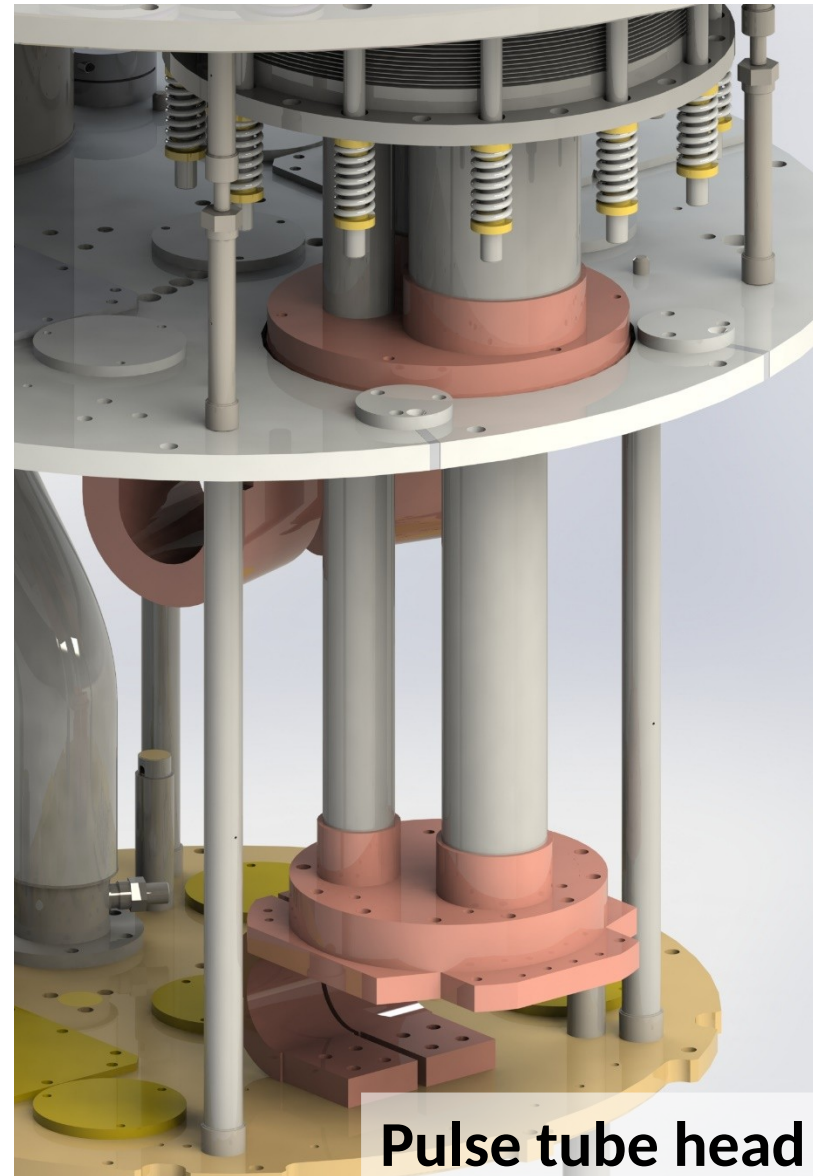
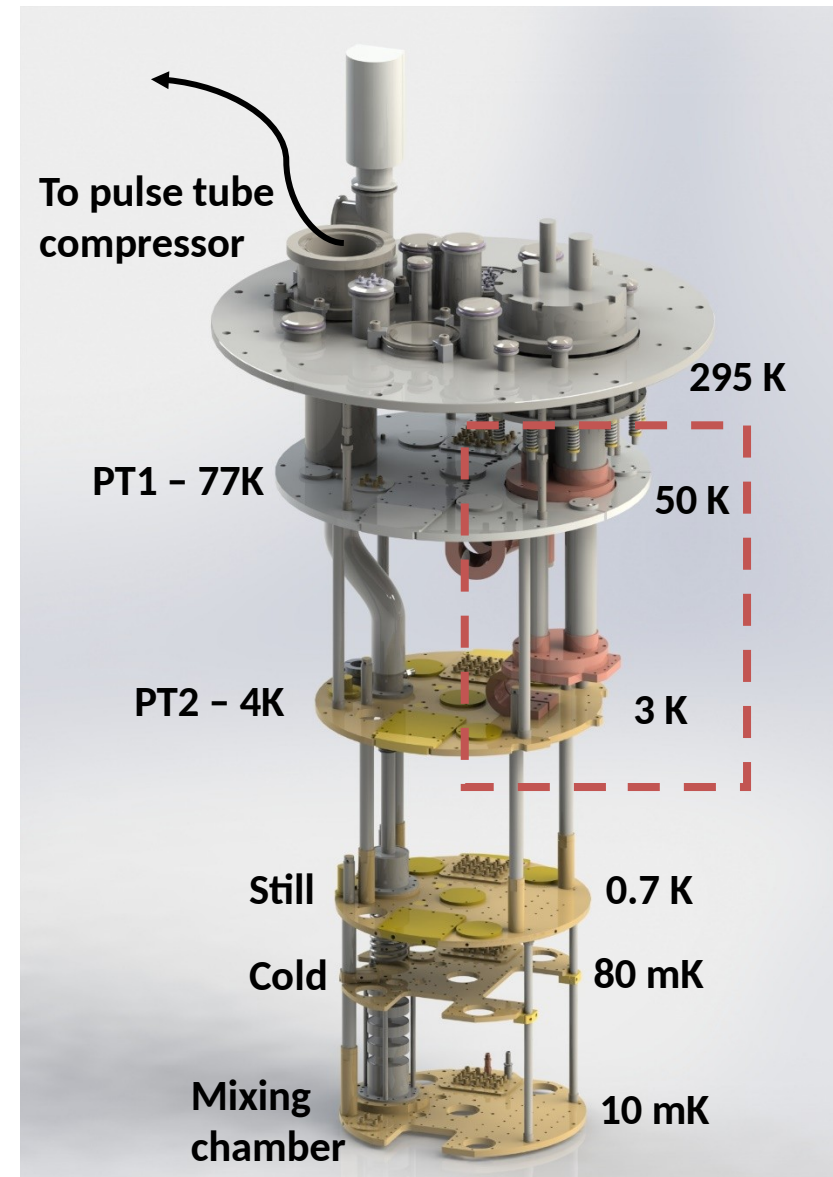
**Dilution
refrigerator**

\$ 500,000



Bluefors DR
SolidWorks render

How does it work? -- a two step cooling

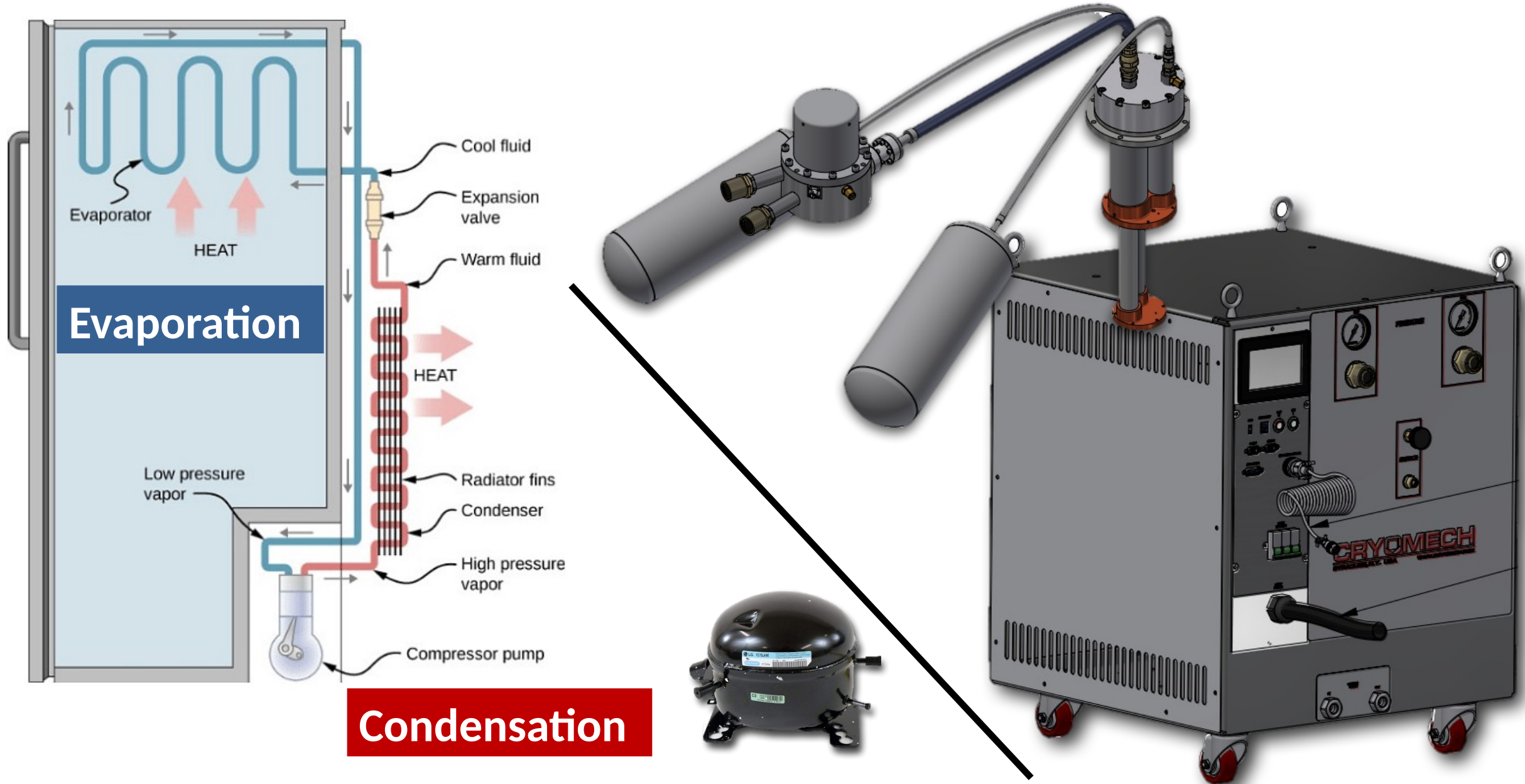


Step one:
Traditional, ~ 3K
Liquify Helium mixture

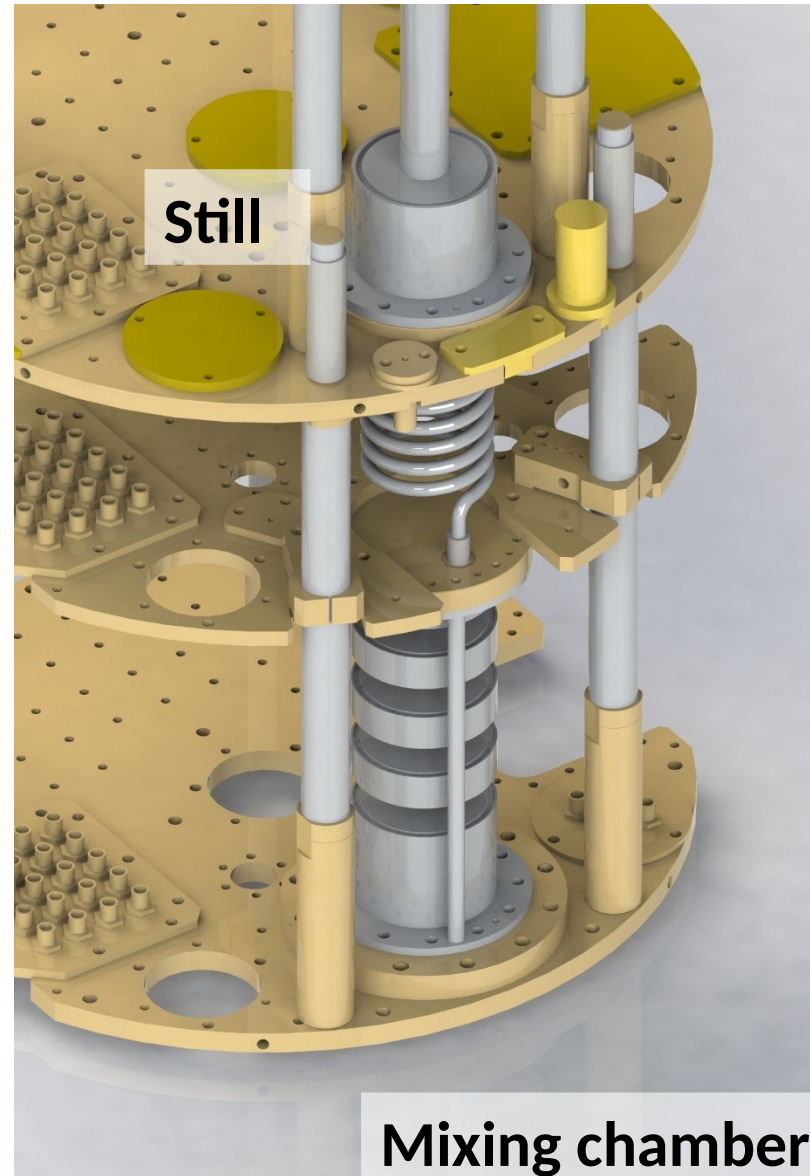
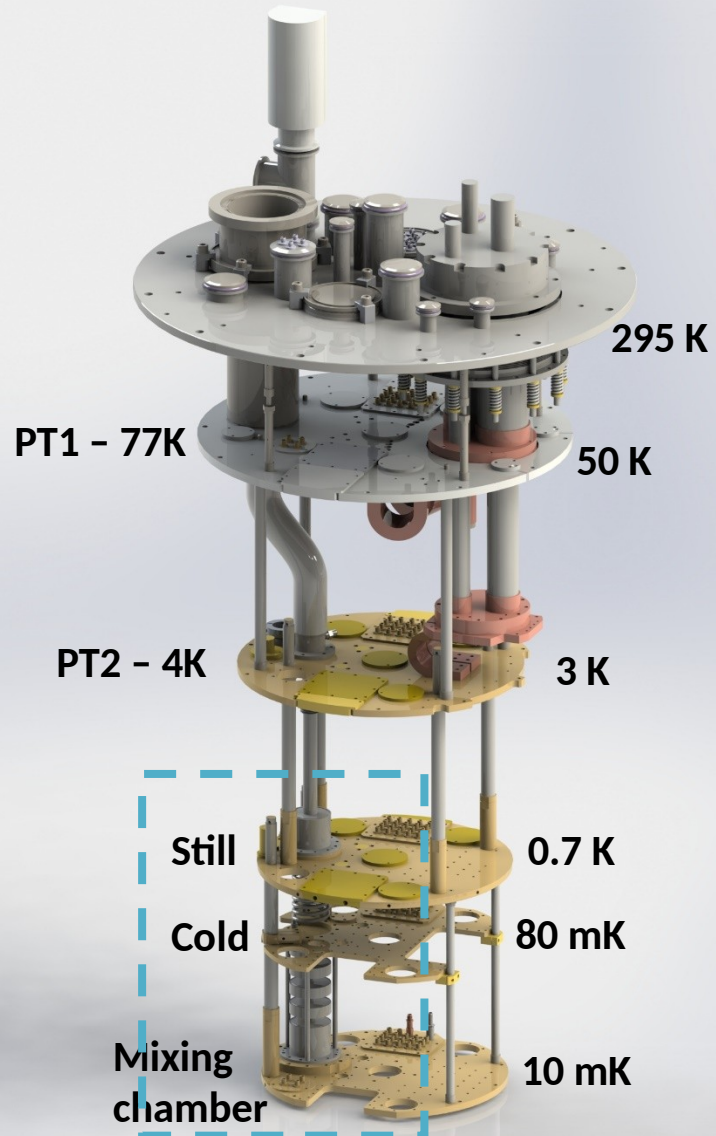
Helium:
lowest boiling point
substance

^3He : 3.19 K
 ^4He : 4.23 K

Pulse tube compressor



How does it work? -- a two step cooling



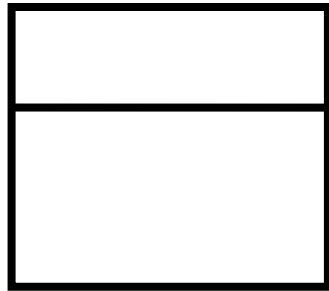
Step two:
Cool down to < 20 mK
Mixing ^3He and ^4He

Record: 1.75 mK
Cooling power:
0.5 mW at 100 mK



NDR: 50.9 μK
Laser cooling: 700 nK
Lowest: 37 pK

^3He and simplified DR

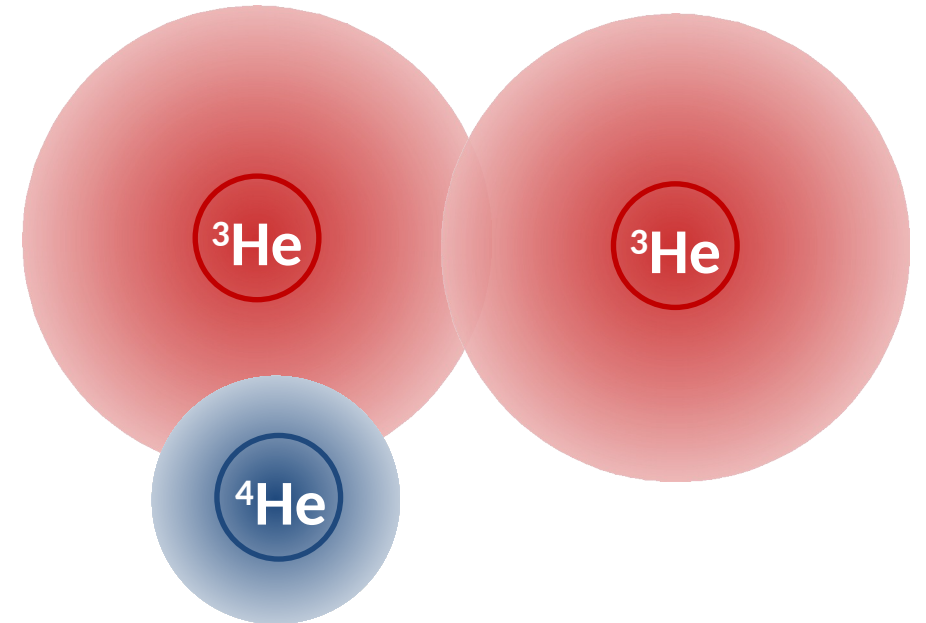


Concentration

Dilute 6.6%



$$dS = \frac{\delta Q}{T}$$



D. Cousins et al., Journal of Low Temperature Physics 114, 547–570 (1999)

D. Christian et al., PRL 127.10 (2021)

D. Nguyen et al., J. Phys.: Conf. Ser. 400 052024 (2012)

Shankar Group

