TEXAS
The University of Texas at Austin

Superconducting Quantum Computer Hardware

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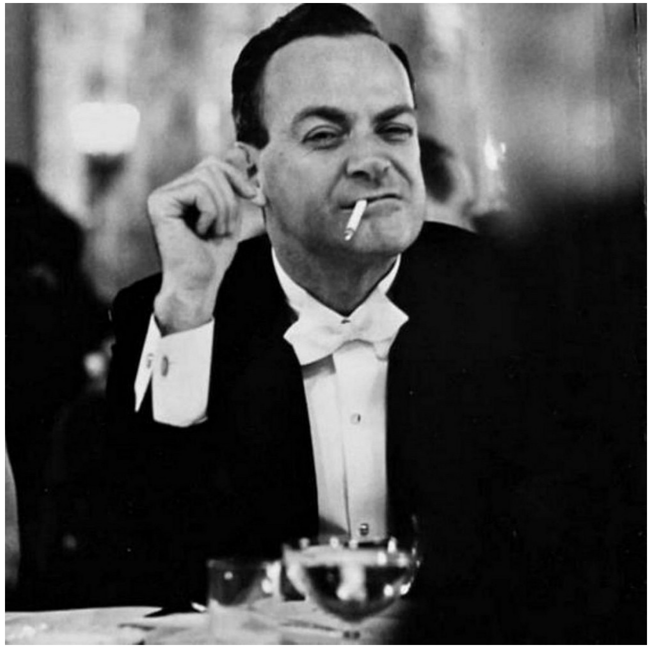
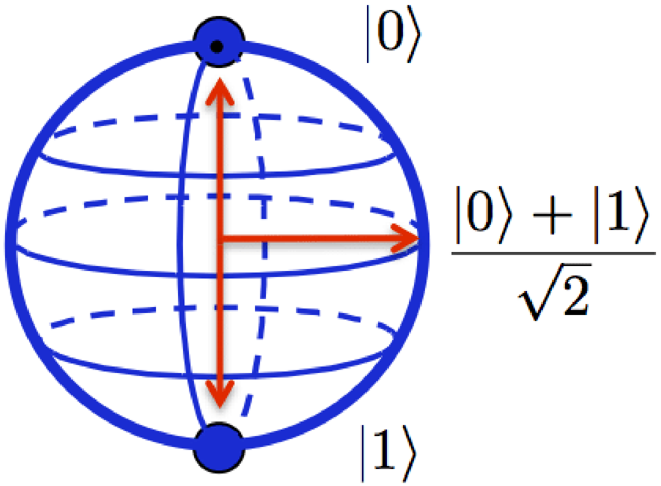
Quantum Computing Fundamentals



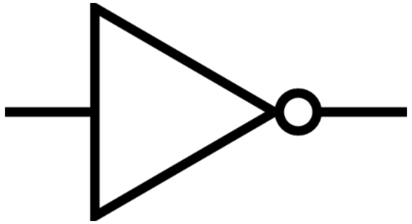
"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical."

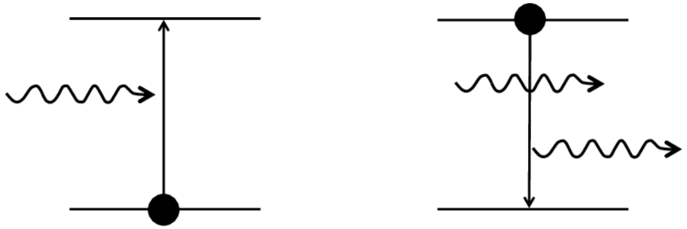
- Breaking cryptography
- Machine learning
- Optimization



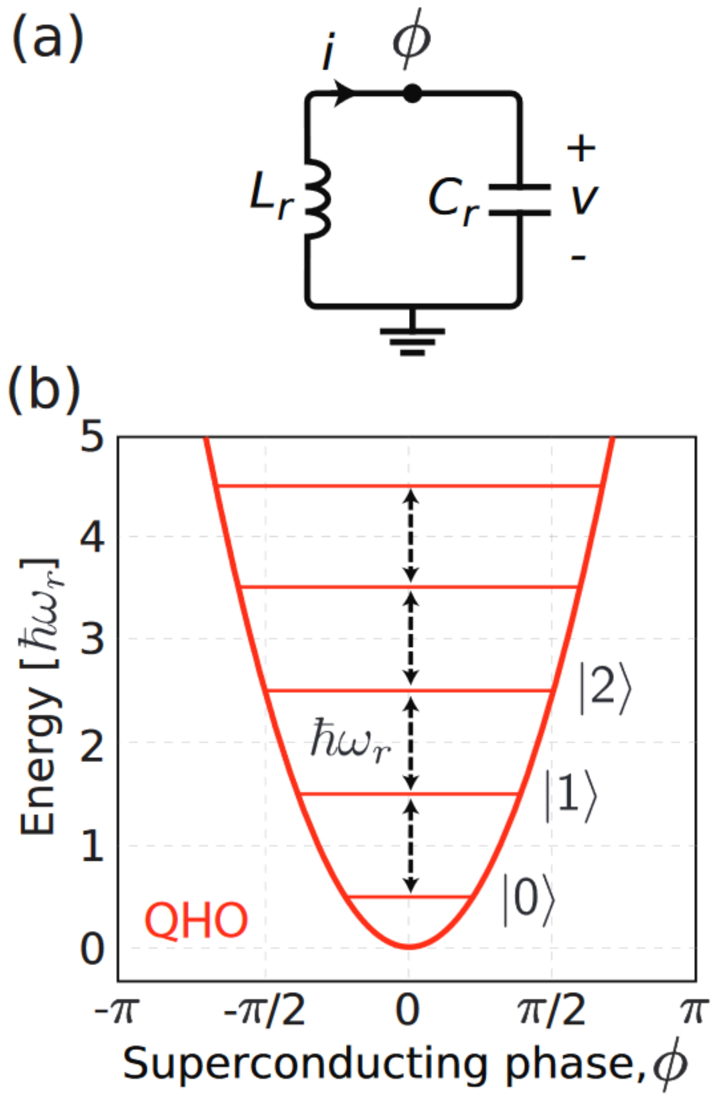
Classical Bit **Qubit**

In	Out
0	1
1	0





Qubit Circuit



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

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

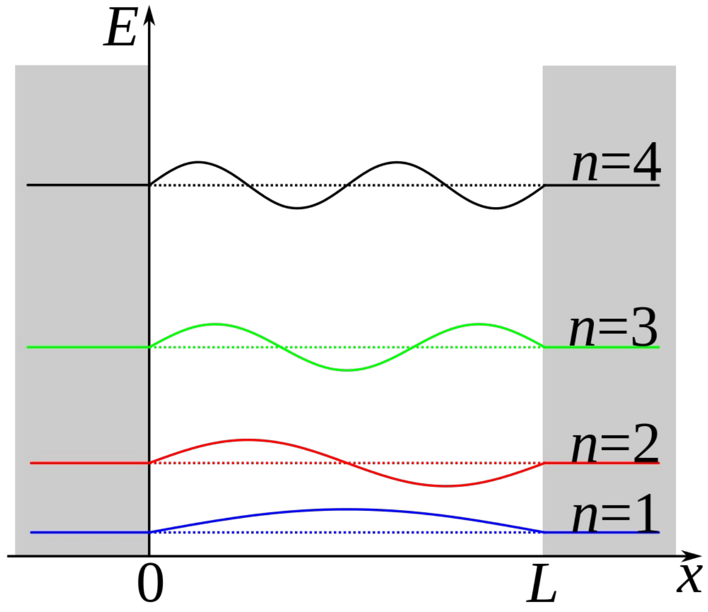
$$I_L = -\frac{1}{L}\int_{-\infty}^{t} V_L(t')dt$$

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

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

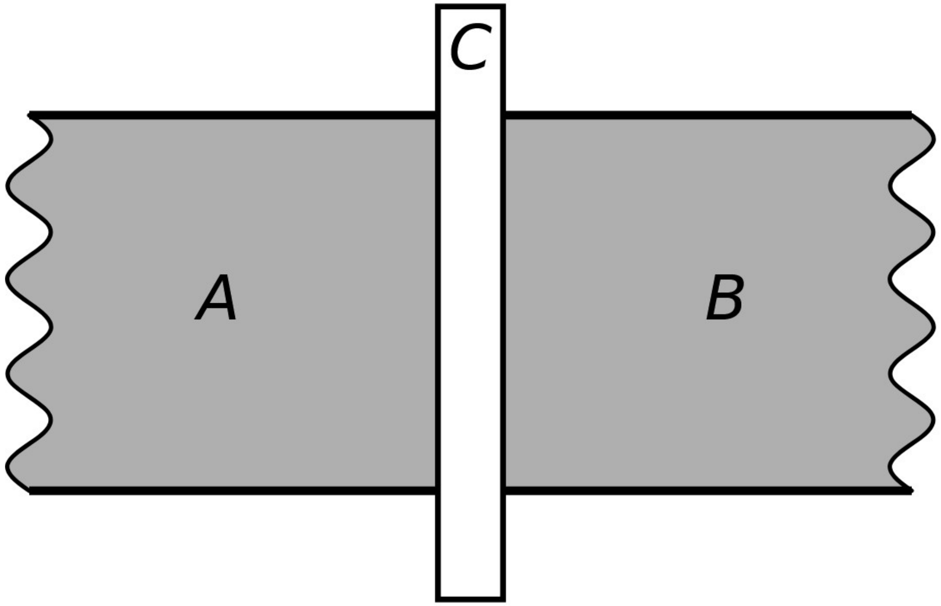
$$U = \frac{1}{2}\left(\frac{\Phi_0}{2\pi}\right)^2 \frac{1}{L}\phi^2 + \frac{1}{2}C\left(\frac{\Phi_0}{2\pi}\right)^2\left(\frac{d\phi}{dt}\right)^2$$

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



Krantz *et al.*, "A quantum engineer's guide to superconducting qubits," Applied Physics Review (2019).

Josephson Junction



$$\psi_A = \sqrt{n_A} e^{i\phi_A}$$

$$\psi_B = \sqrt{n_B} e^{i\phi_B}$$

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

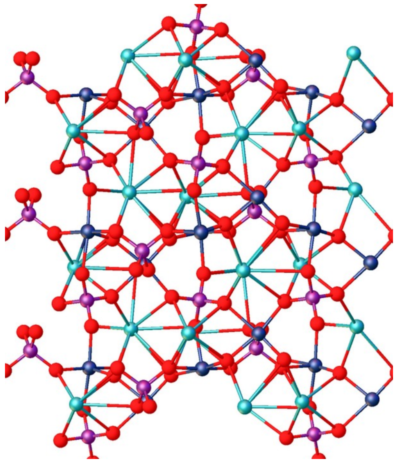
$$\frac{\partial \phi}{\partial t} = \frac{2eV(t)}{\hbar}$$

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

$$E(\phi) = -\frac{\Phi_0 I_c}{2\pi} \cos(\phi)$$

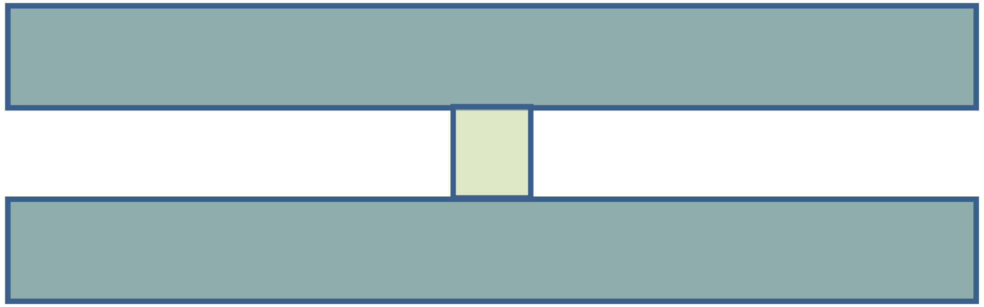
$$= -\frac{\Phi_0 I_c}{2\pi} (1 - \phi^2/2 + \phi^4/24 + \dots)$$

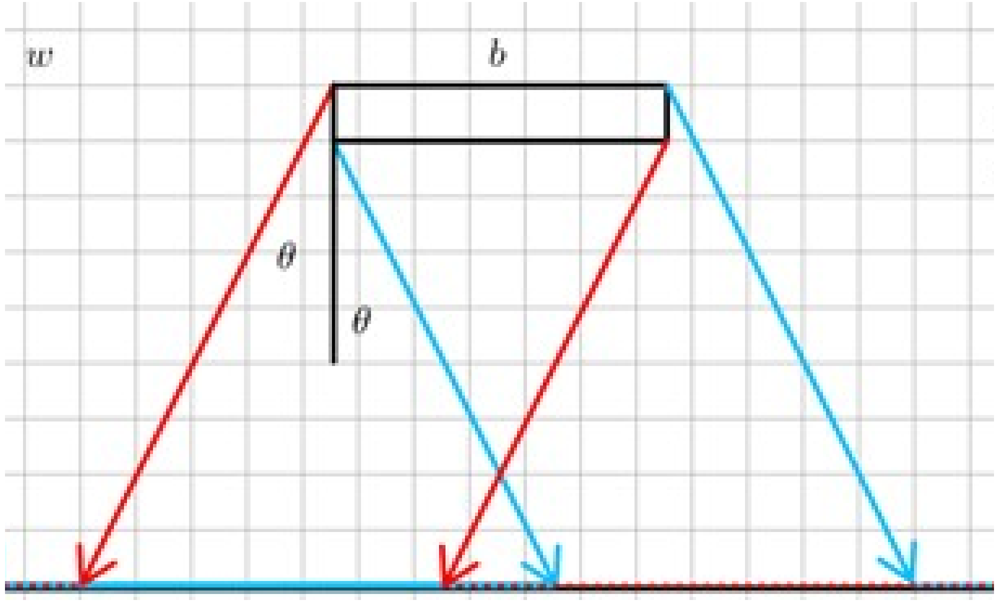
$$L(\phi) = \frac{L_J}{\cos(\phi)}$$



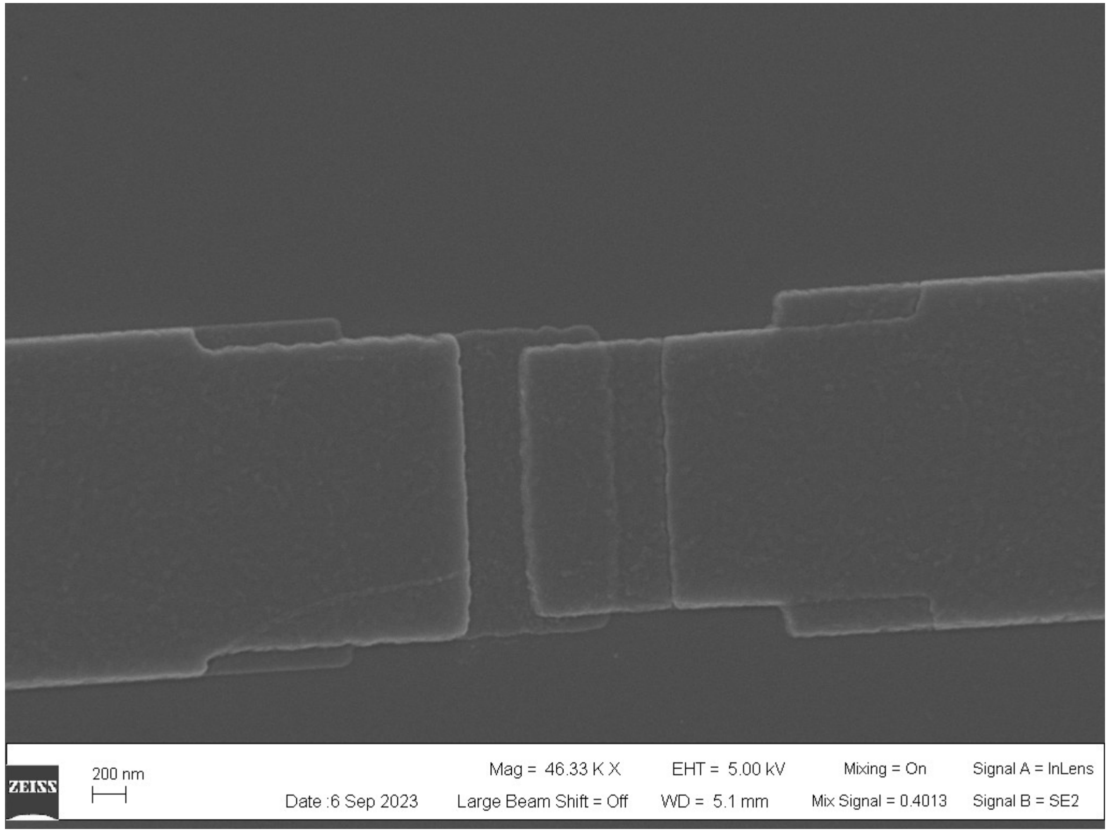
JJ Fabrication

Top View

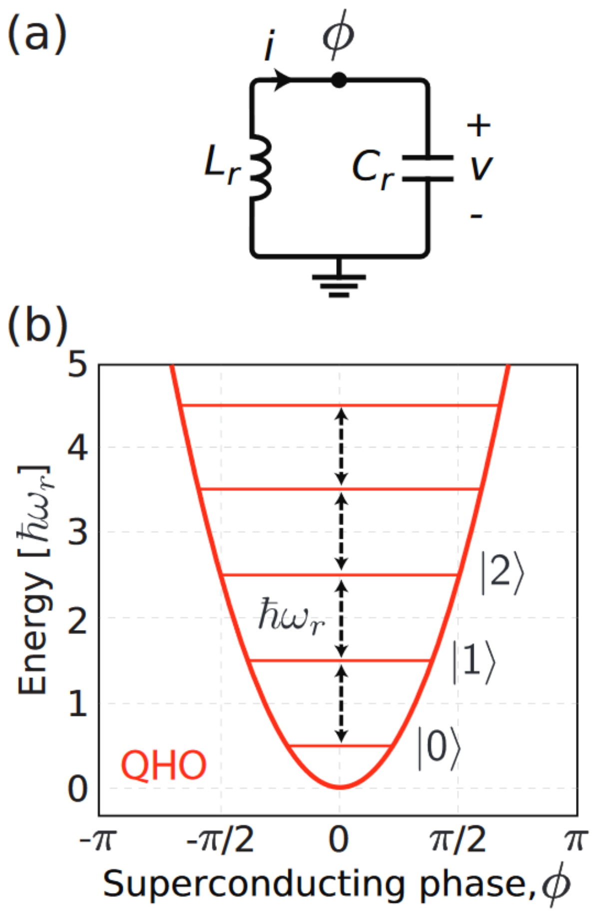


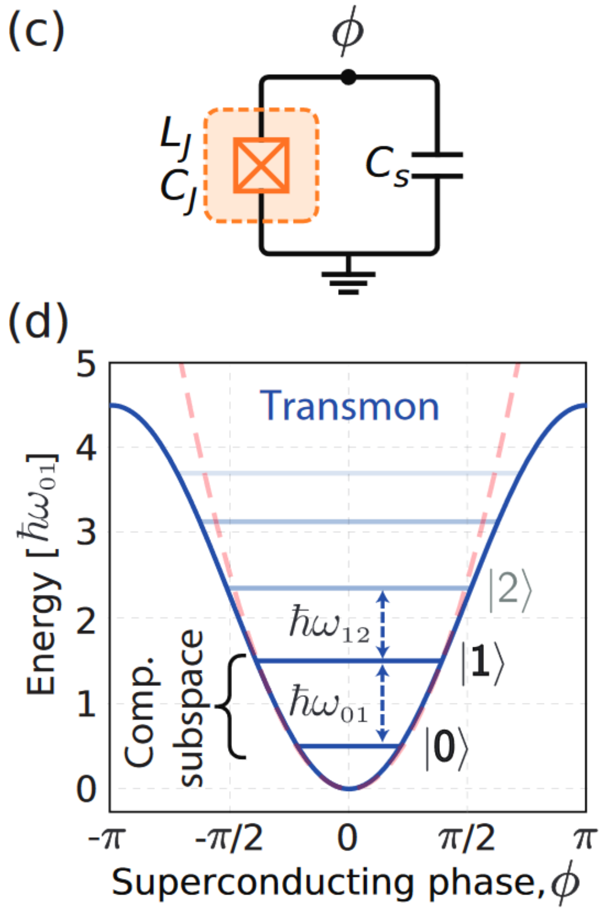


Side View



Transmon Qubit





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

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

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

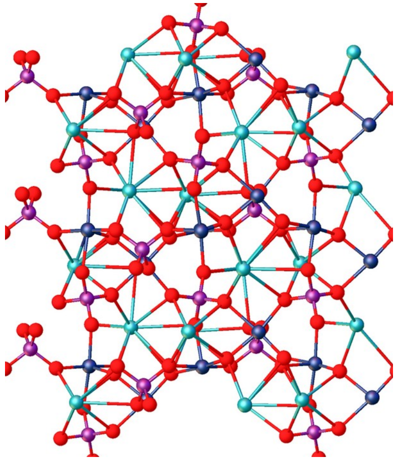
$$\hat{H} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{\alpha}{2}\hat{a}^{\dagger 2}\hat{a}^2 + \dots\right)$$

Quantum-Limited Parametric Amplification

- GHz;

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

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



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

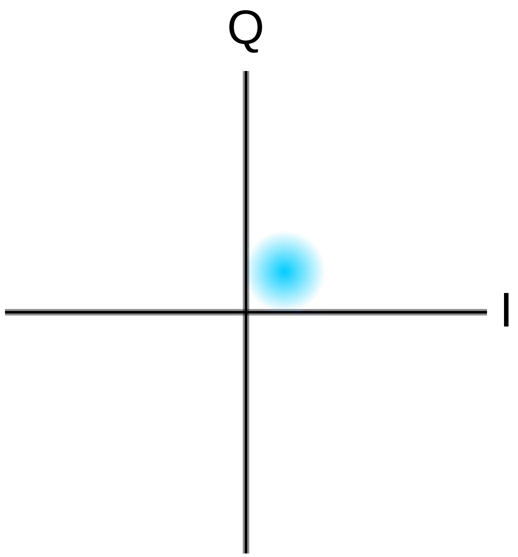
$$\hat{U}(t) = \exp[-i(\hbar g(\hat{a}^2\hat{b}^{\dagger^2} + \hat{a}^{\dagger^2}\hat{b}^2))t/\hbar]$$

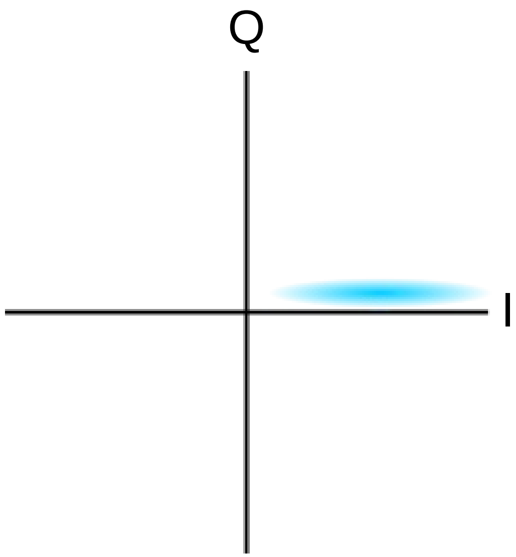
$$\hat{U}(t) = \exp[-i(\hbar g(\hat{a}^2\beta^{*^2} + \hat{a}^{\dagger^2}\beta^2))t/\hbar]$$

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

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

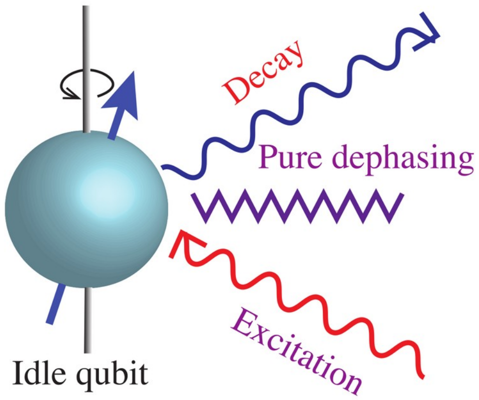
$$\hat{S}^\dagger(\zeta)\hat{a}^\dagger\hat{S}(\zeta) = \hat{a}^\dagger\cosh(|\zeta| - e^{i\theta}\hat{a}\sinh(|\zeta|))$$

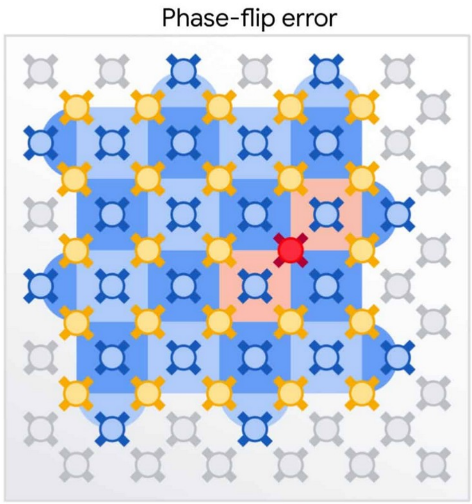


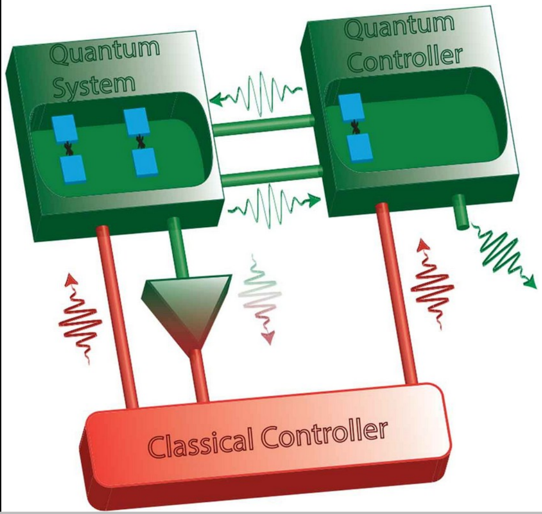


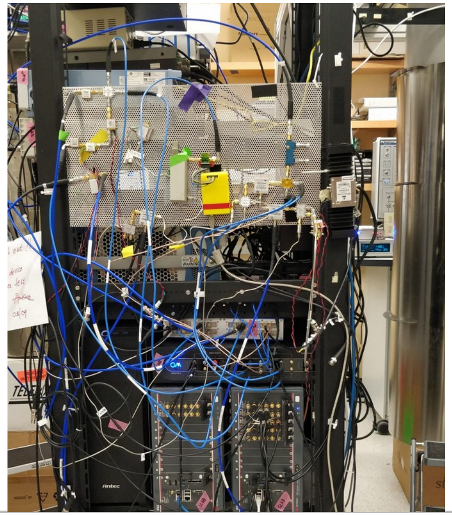
Challenges of Superconducting Quantum Computing

Qubit Quality	Error Correction	Qubit Control	Scaling
- Qubit lifetime is in the microsecond regime - Error rates are high for computation	- Error correction has not yet been proven at scale	- Low-latency control on the order of nanoseconds	- One qubit requires multiple control wires and several room temperature electronics

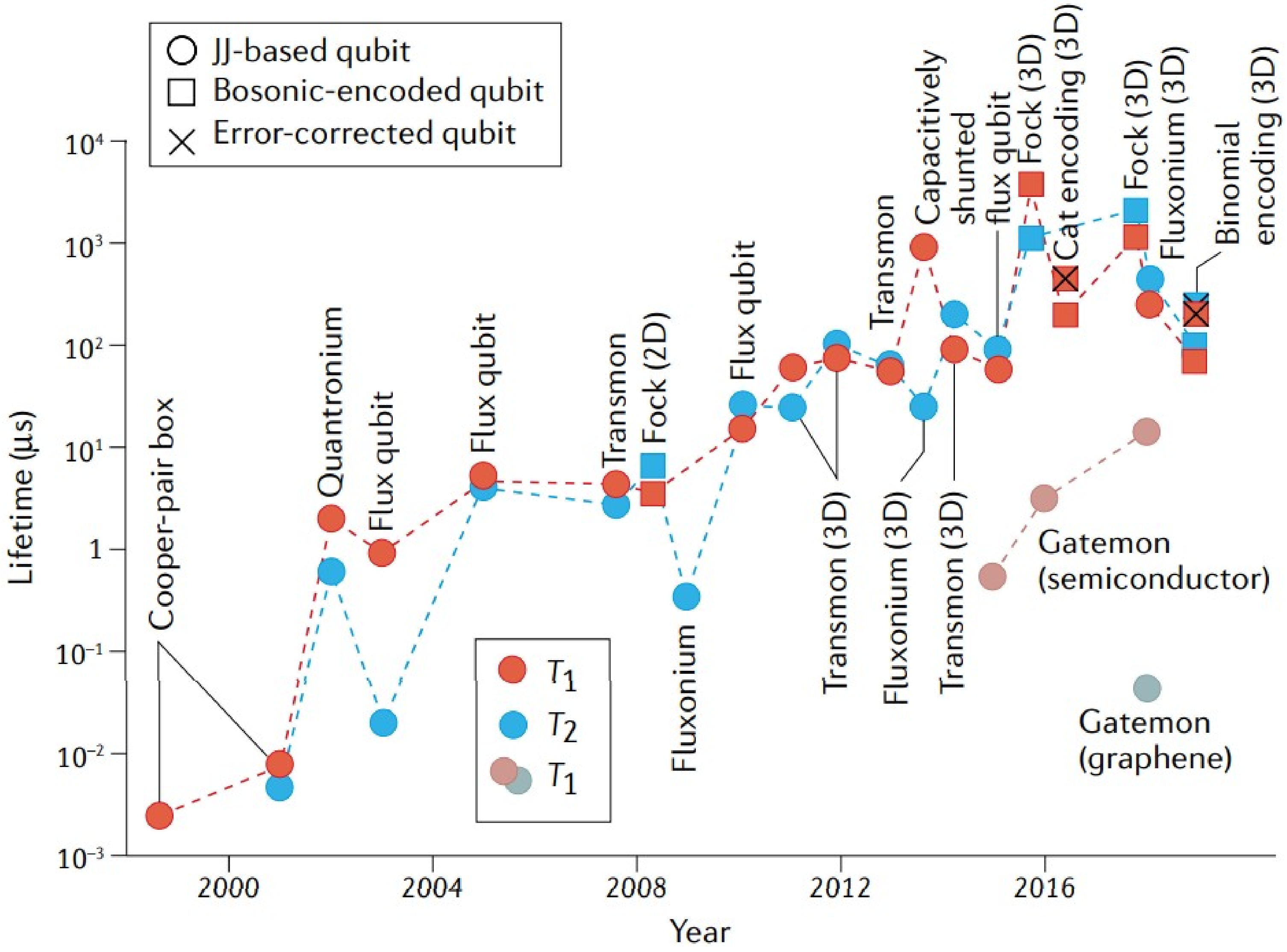






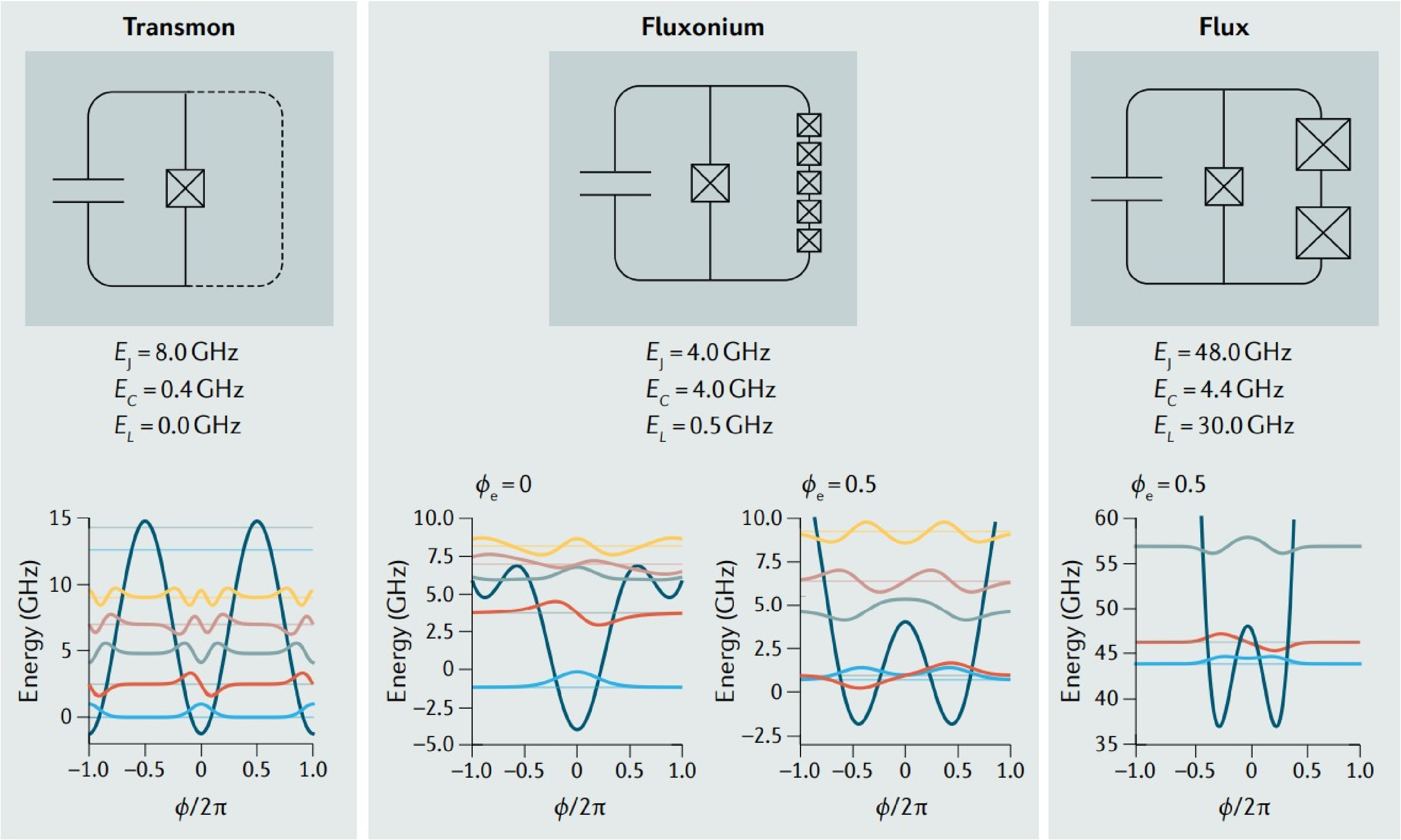


Novel qubit architectures



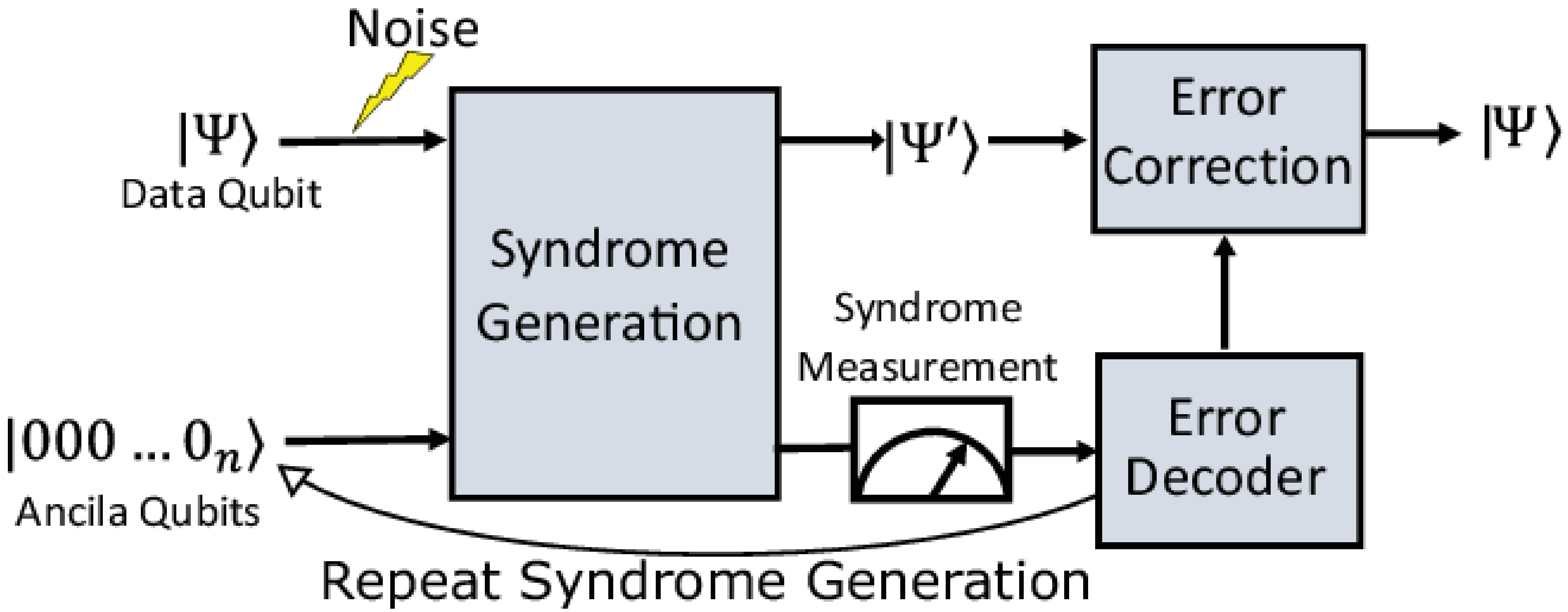
Siddiqi, Nature Reviews (2021).

Novel qubit architectures

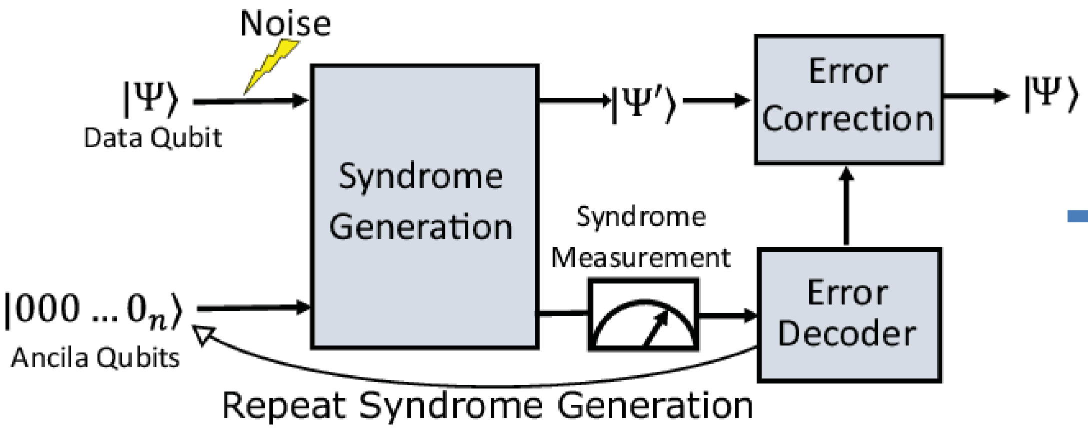


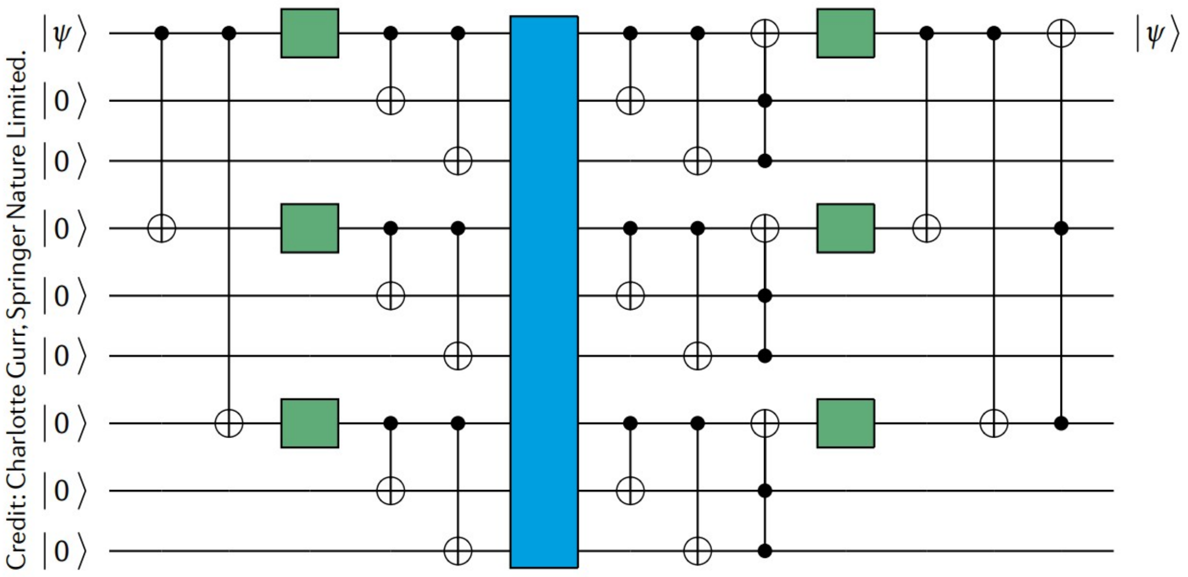
Siddiqi, Nature Reviews (2021).

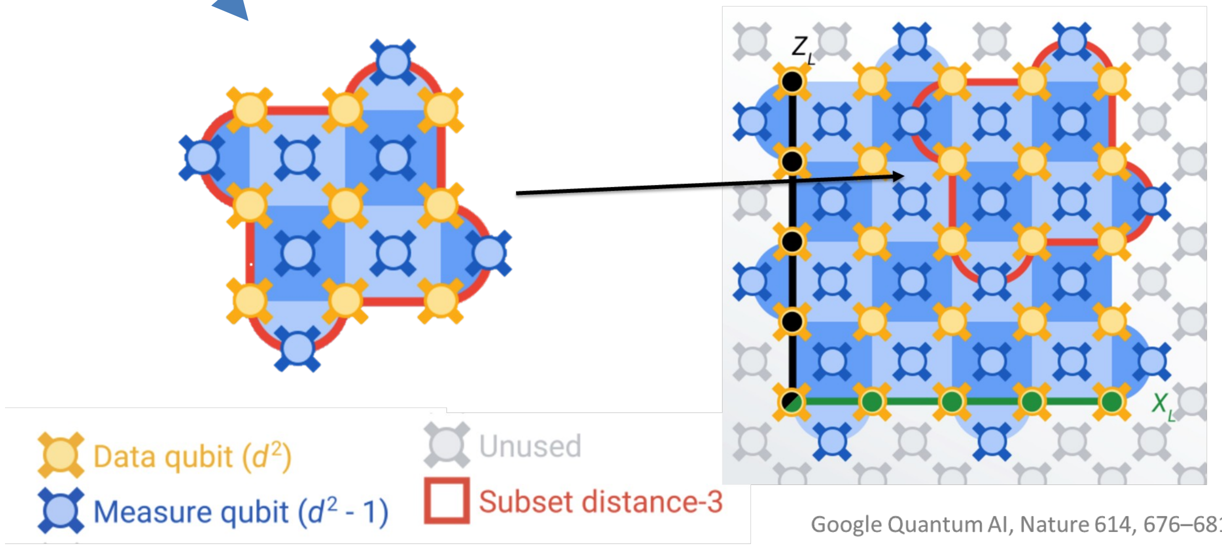
Quantum Error Correction



Quantum Error Correction

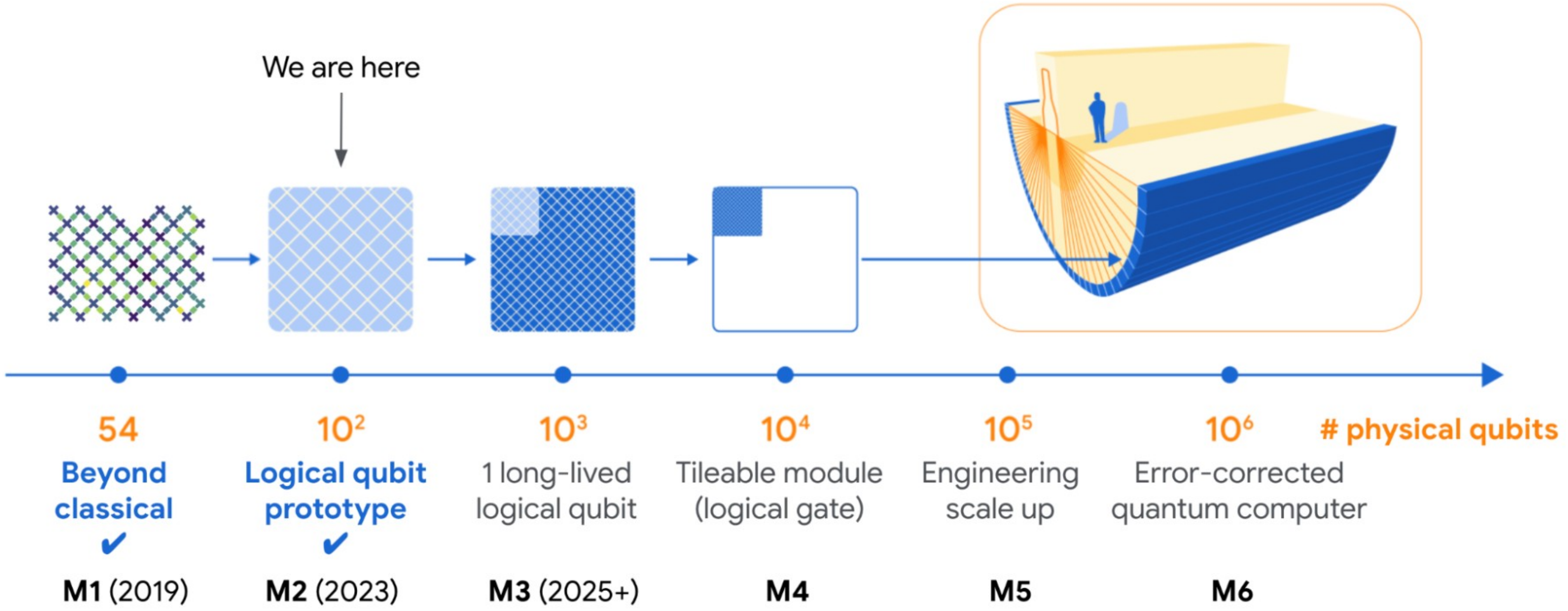




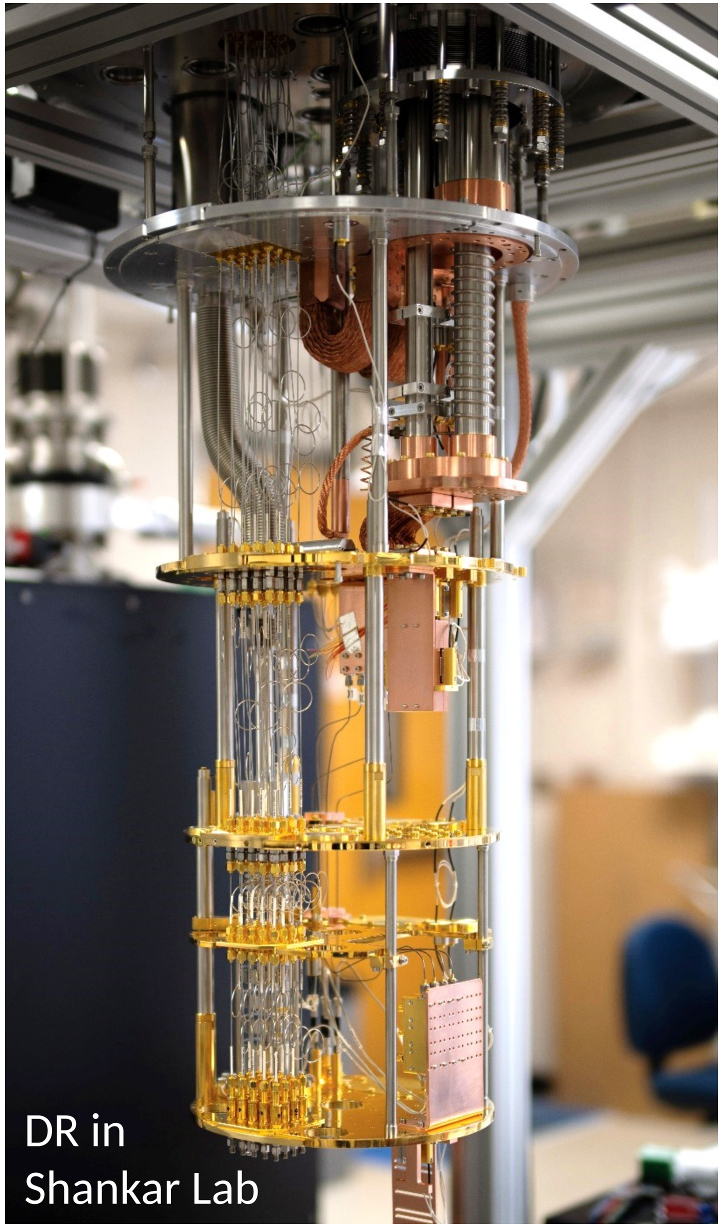


Google Quantum AI, Nature 614, 676–681 (2023).

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!

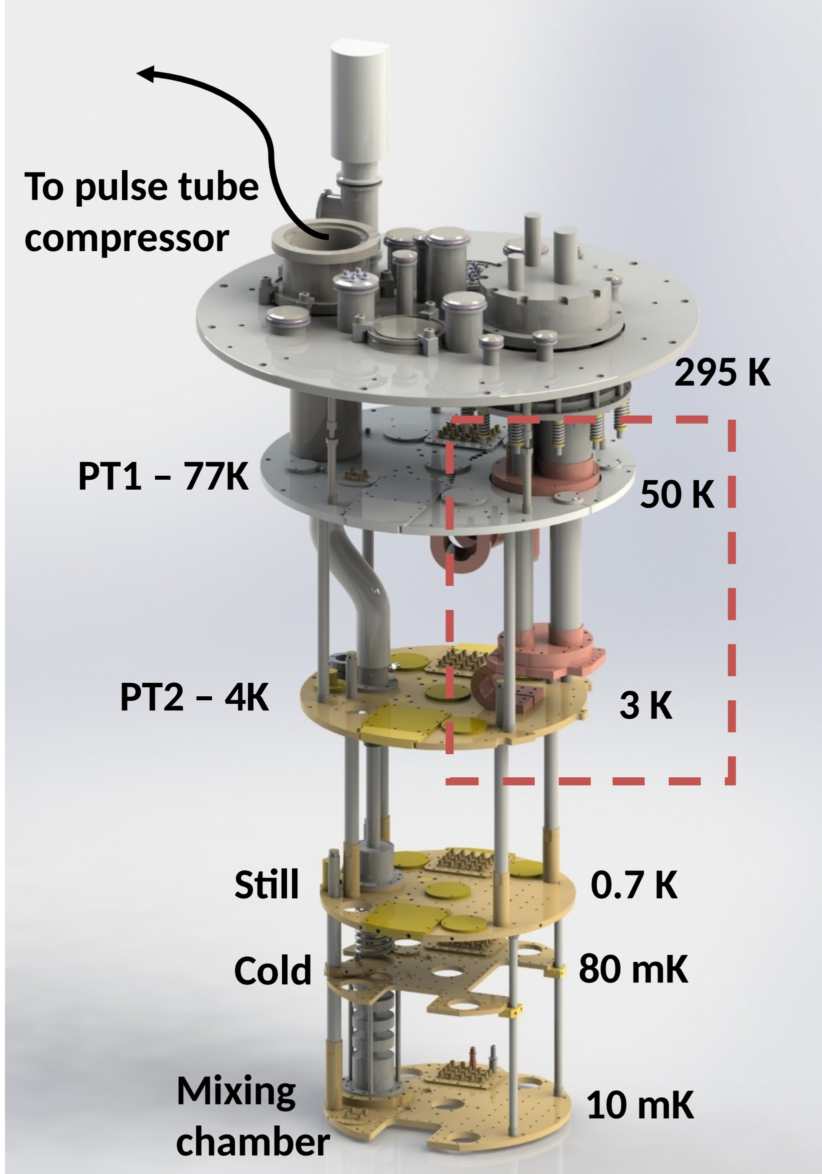


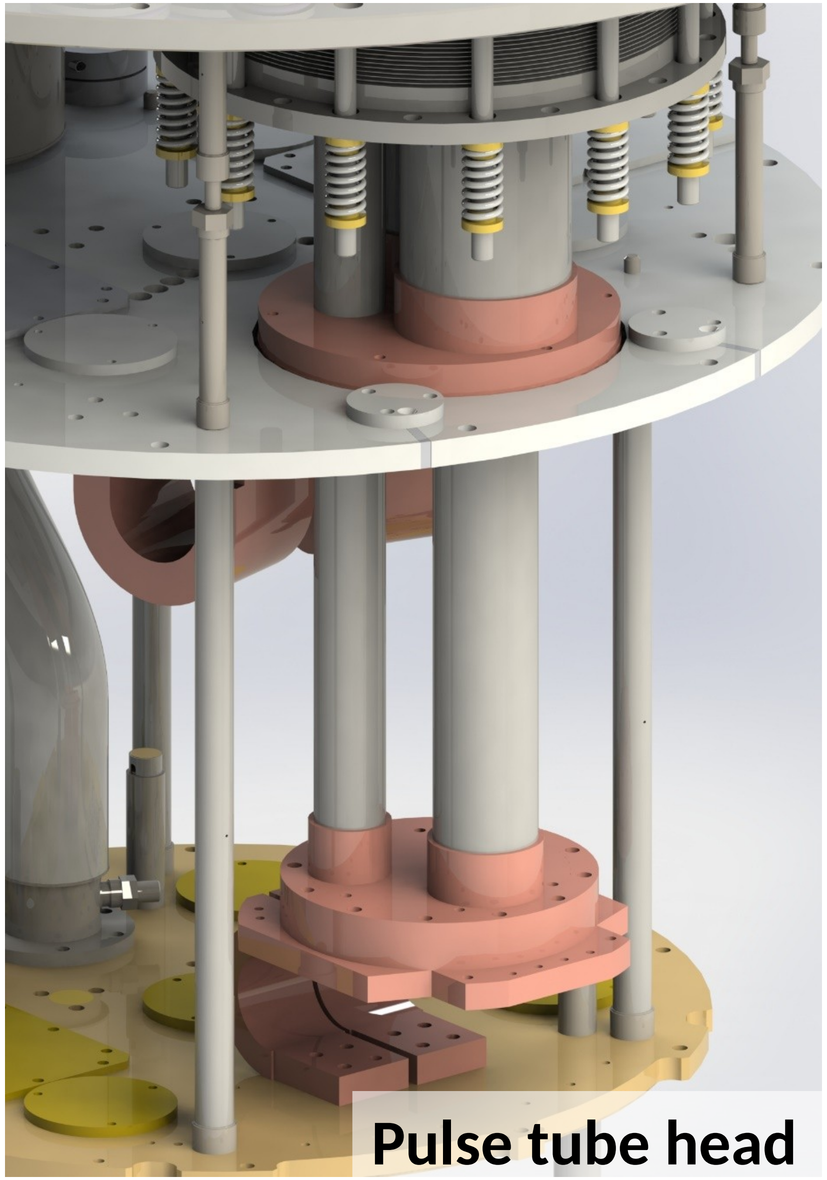
< 20 mK

Dilution refrigerator

$ 500,000

How does it work? -- a two step cooling



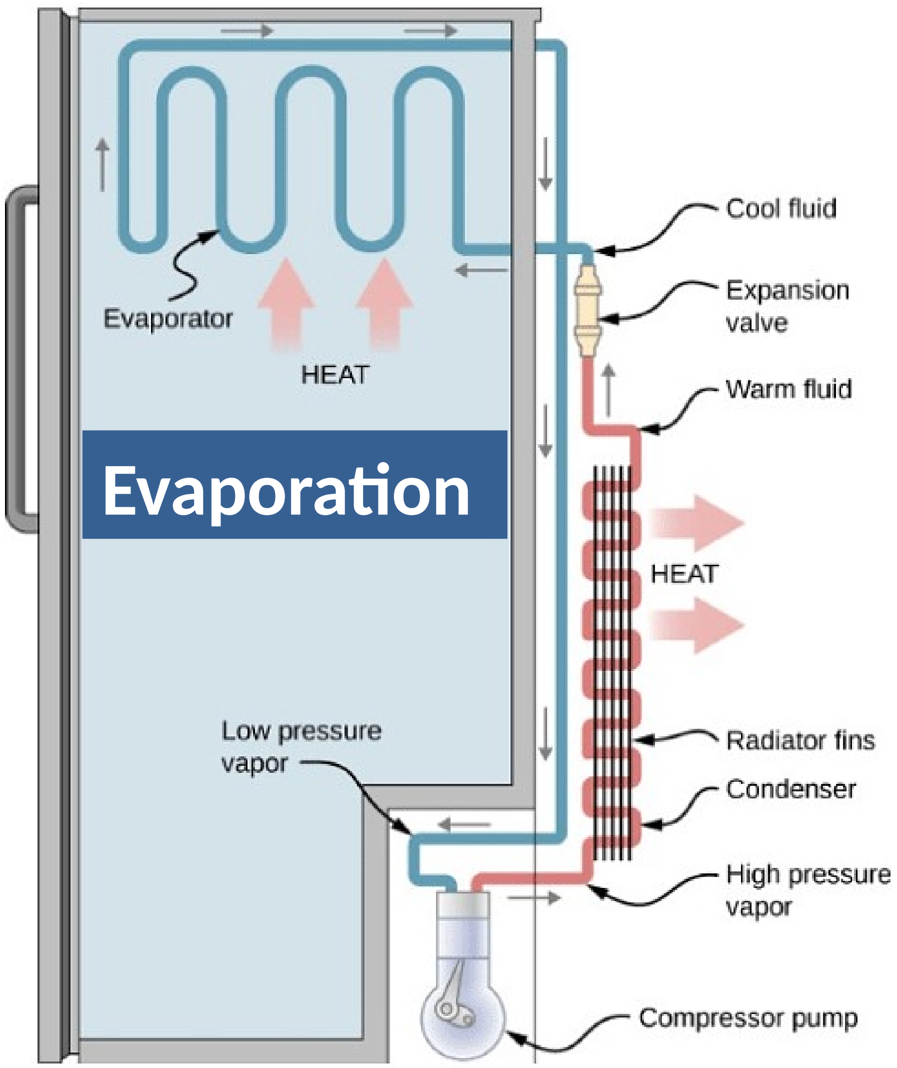


Step one:
Traditional, ~ 3K
Liquify Helium mixture

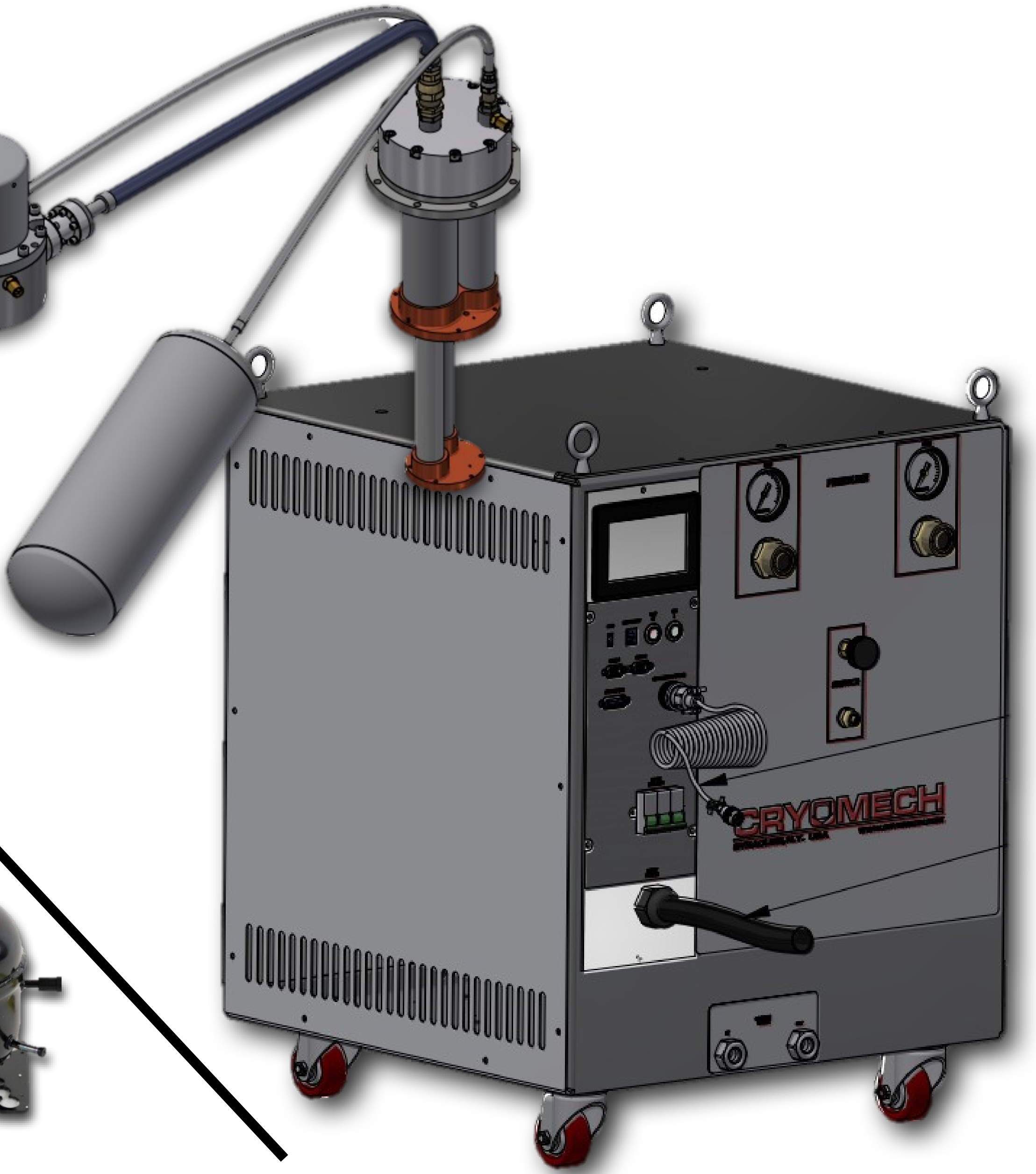
Helium:
lowest boiling point substance

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

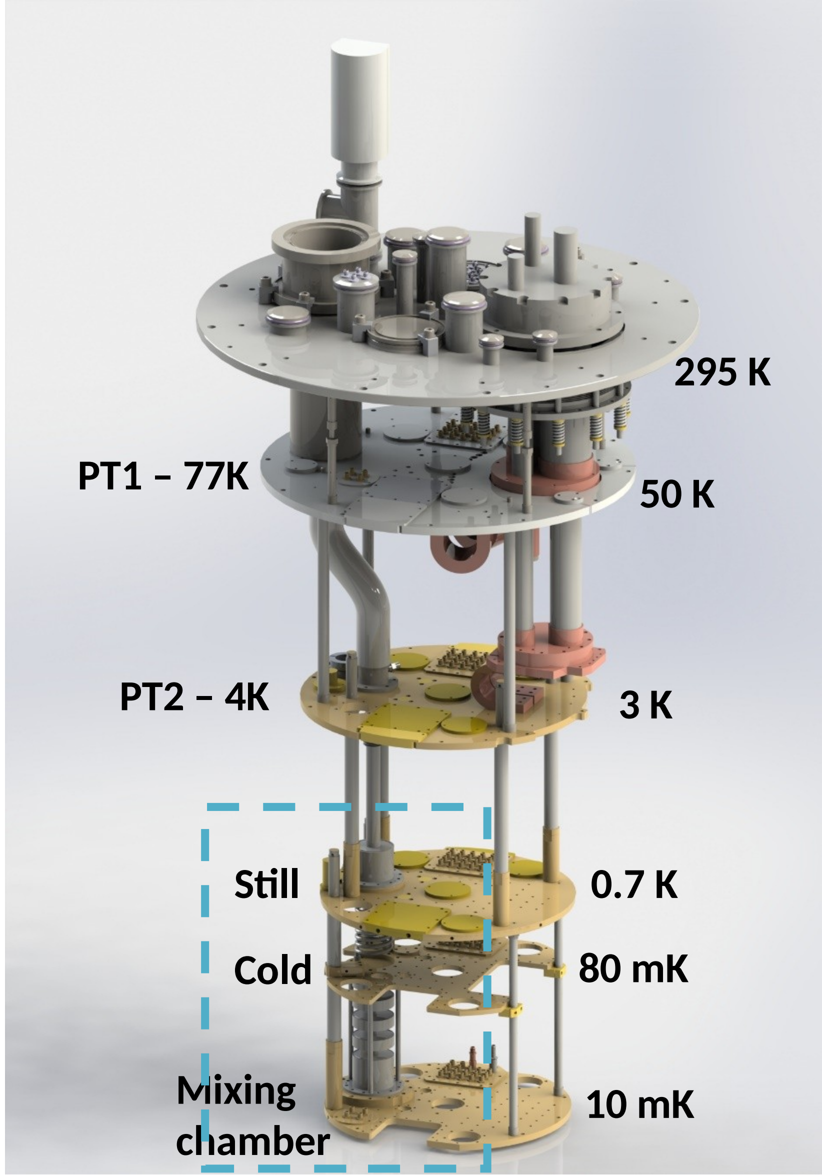
Pulse tube compressor

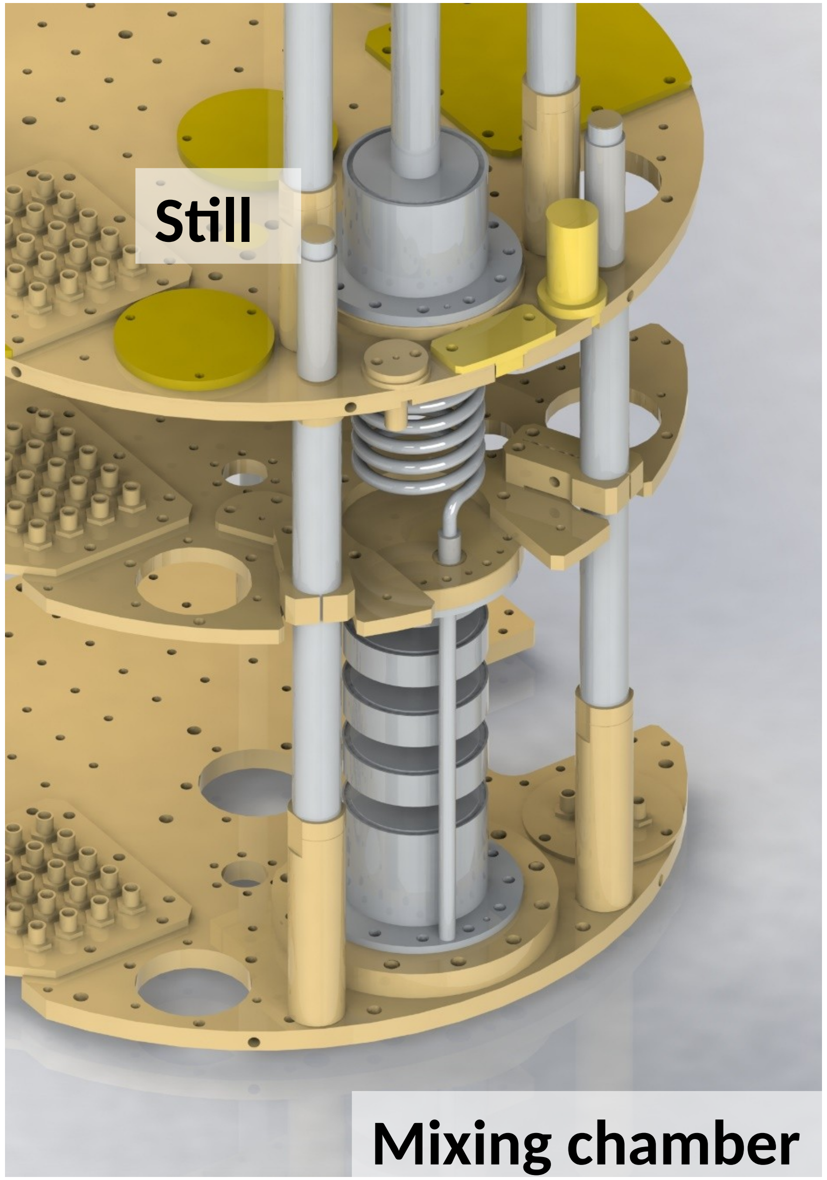


Condensation



How does it work? -- a two step cooling



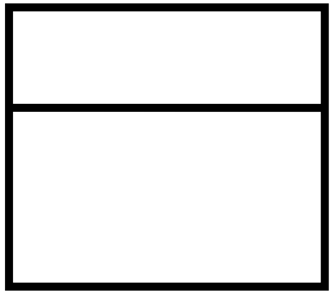


Step two:
Cool down to < 20 mK
Mixing ^3He and ^4He

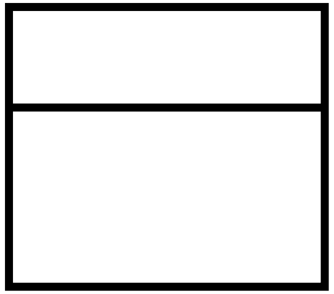
Record: 1.75 mK
Cooling power:
0.5 mW at 100 mK

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

^{3}He and simplified DR

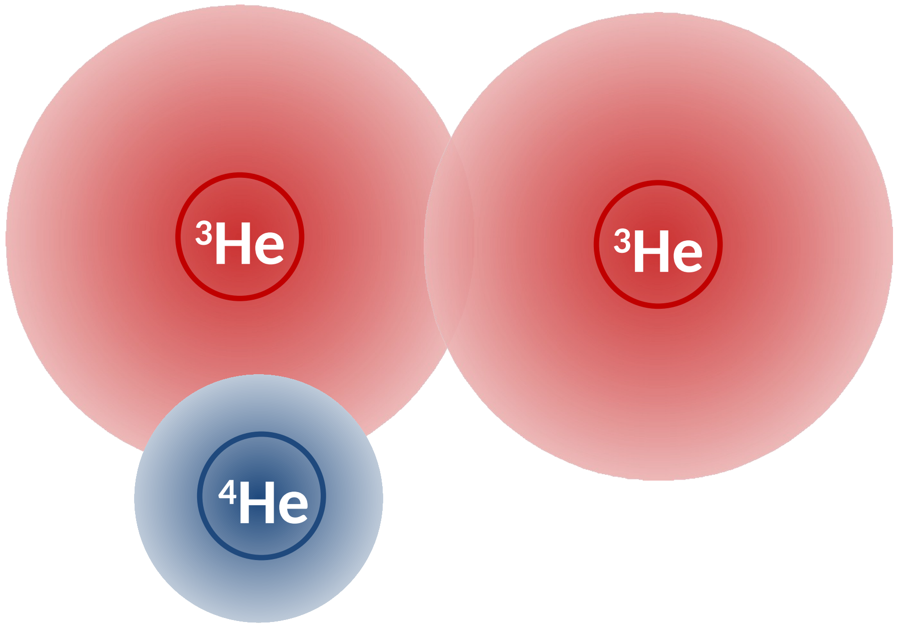


$$dS = \frac{\delta Q}{T}$$



Concentration

Dilute 6.6%



Reference

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