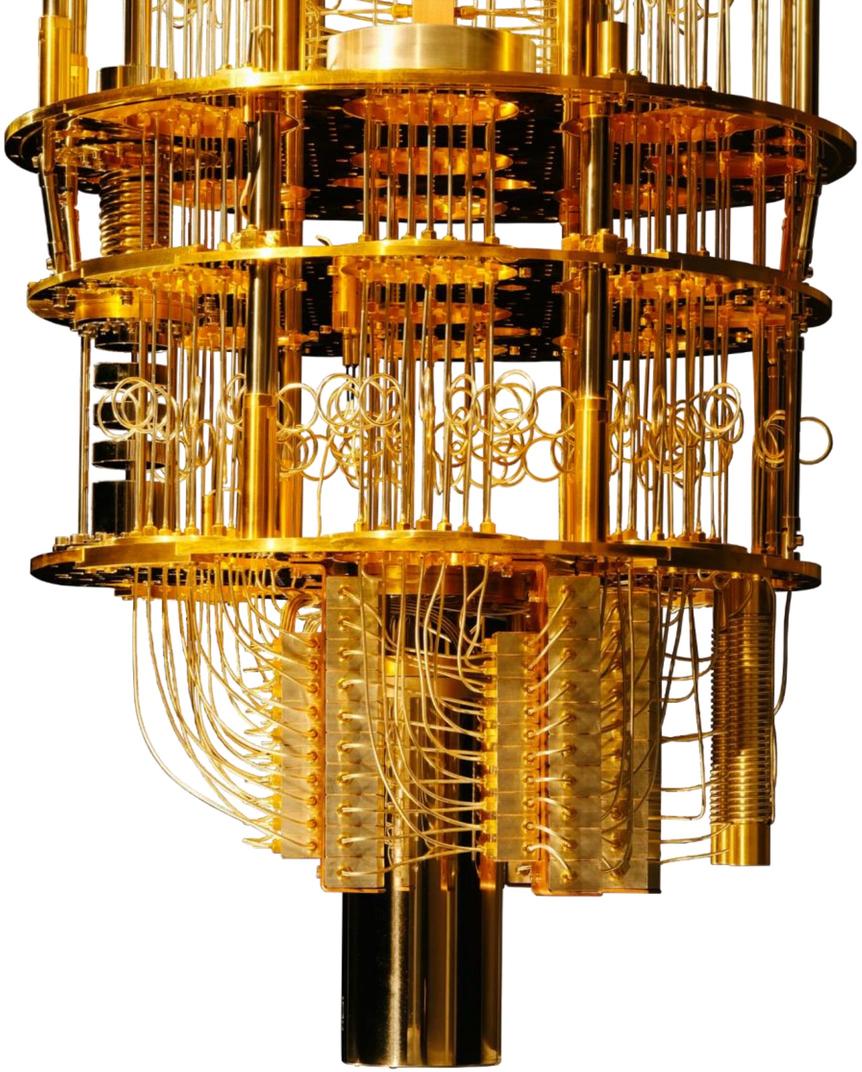

# Quantum Noises and Mitigation Techniques

Mohammad Halataei

Shahid Beheshti University

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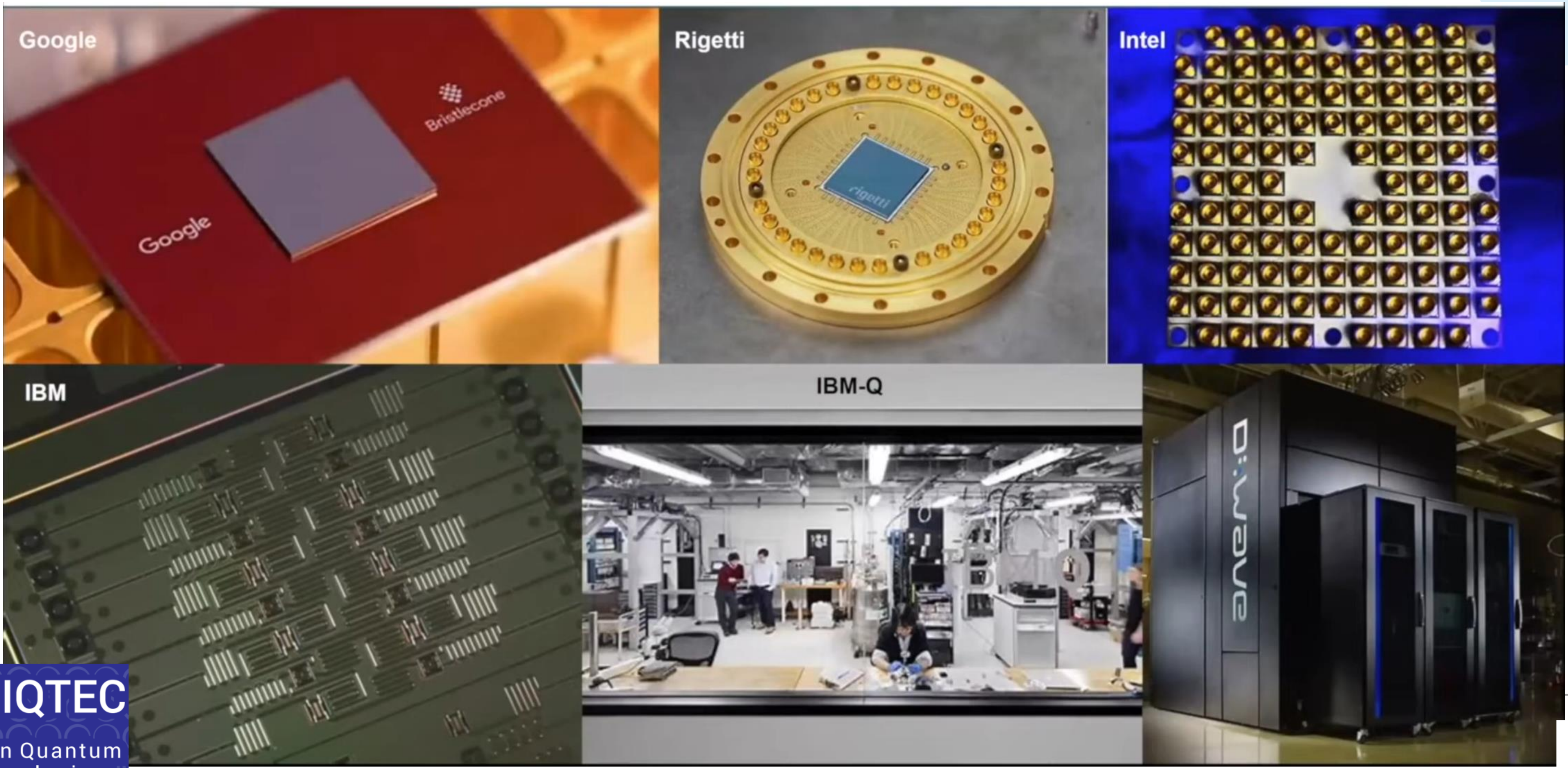
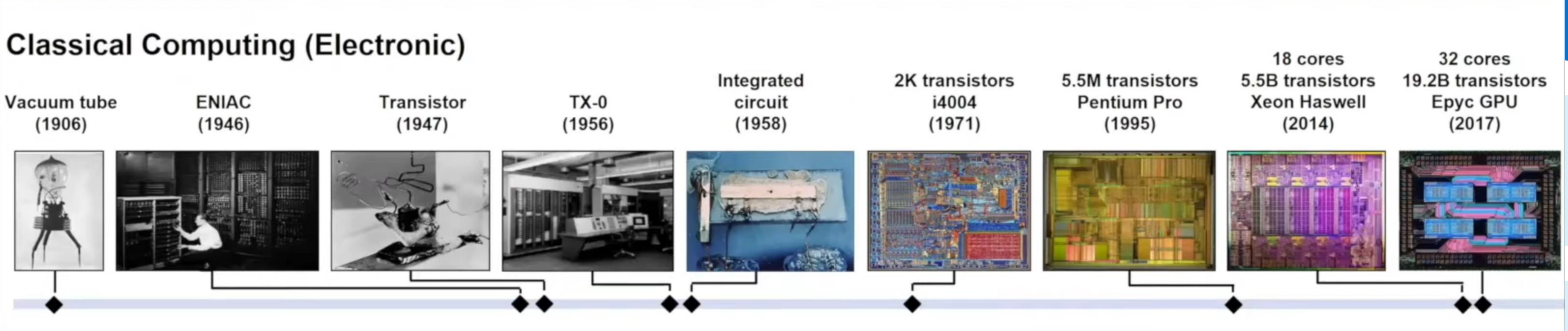
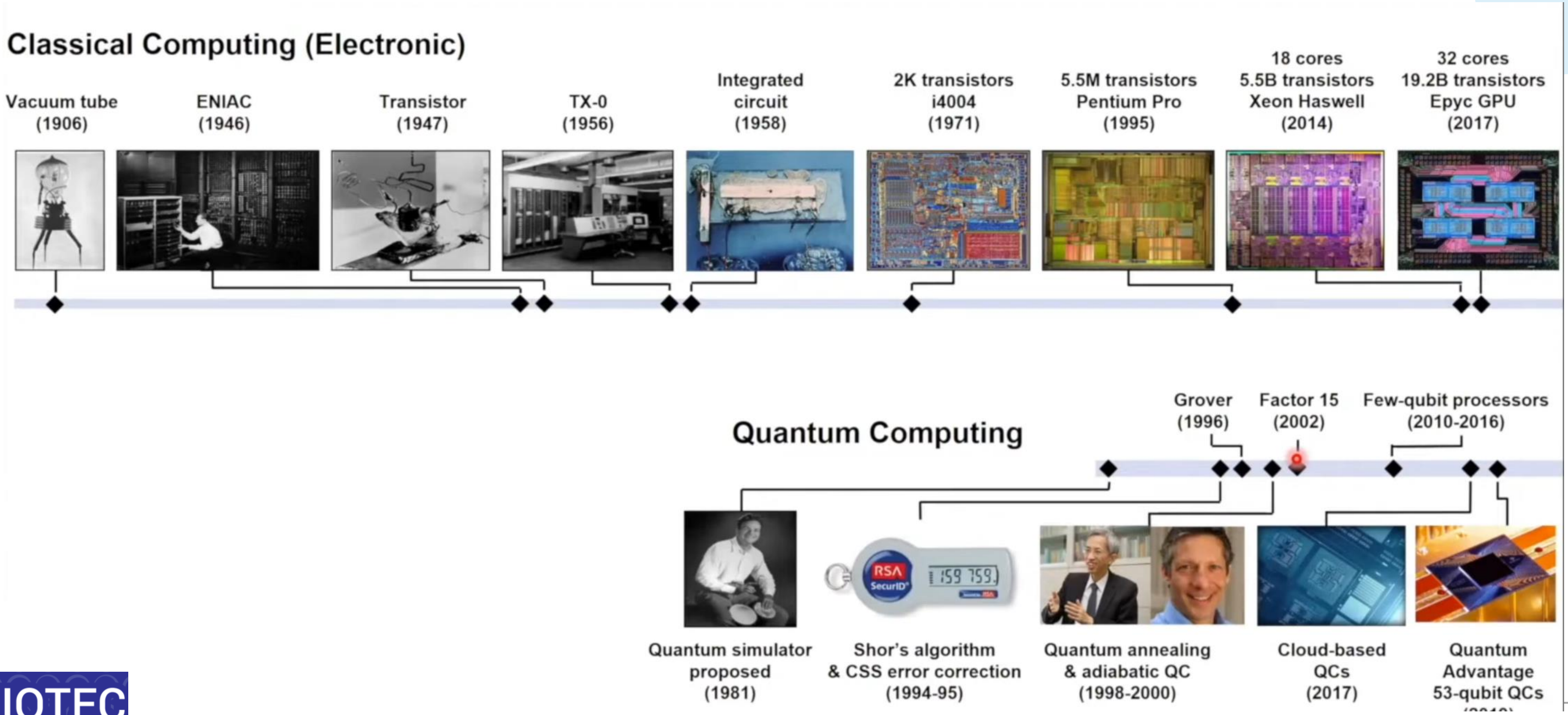
# Superconducting Qubits – Exciting Time!



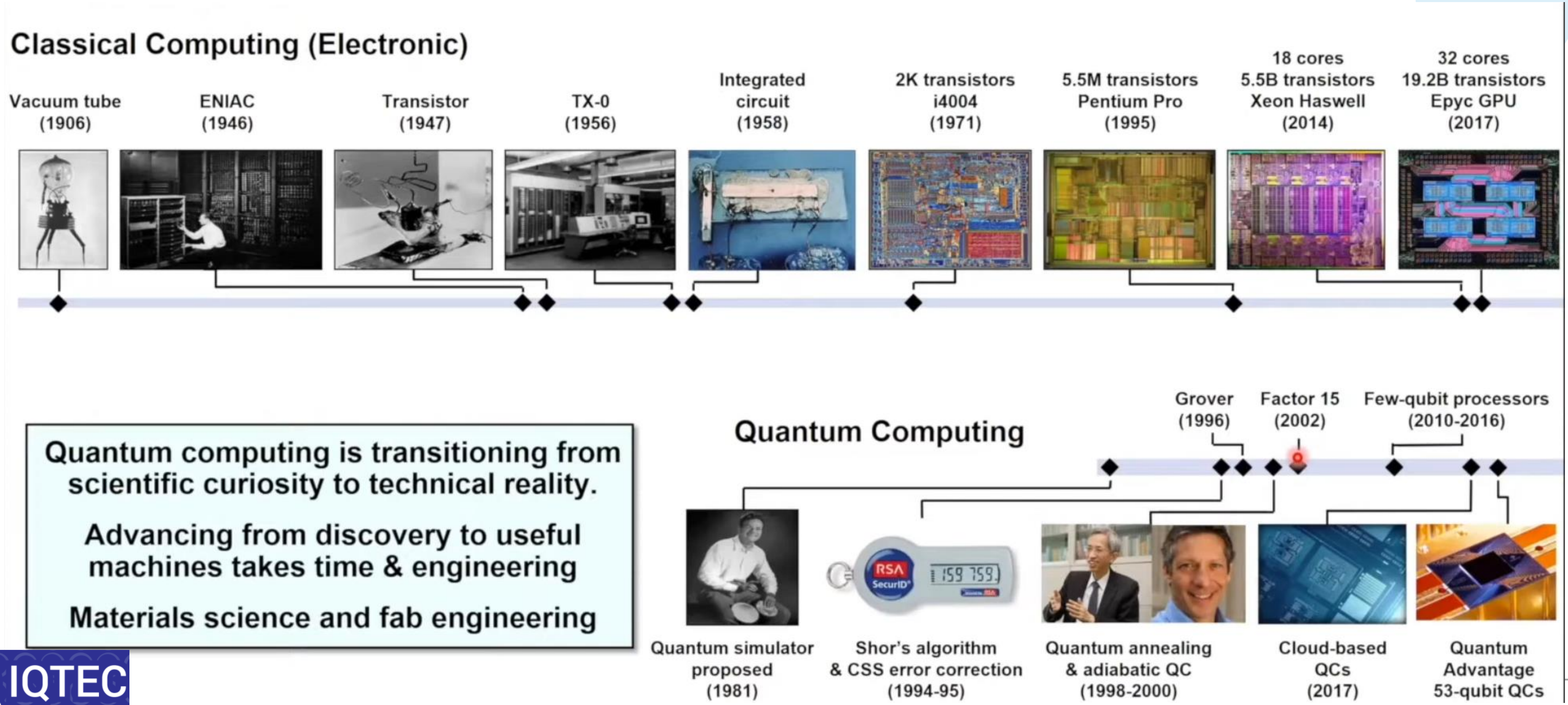
# Computing Development Timeline



# Computing Development Timeline



# Computing Development Timeline



## Classical Computing (Electronic)

- Vacuum tube (1906)
- ENIAC (1946)
- Transistor (1947)
- TX-0 (1956)
- Integrated circuit (1958)
- 2K transistors i4004 (1971)
- 5.5M transistors Pentium Pro (1995)
- 18 cores 5.5B transistors Xeon Haswell (2014)
- 32 cores 19.2B transistors Epyc GPU (2017)

## Quantum Computing

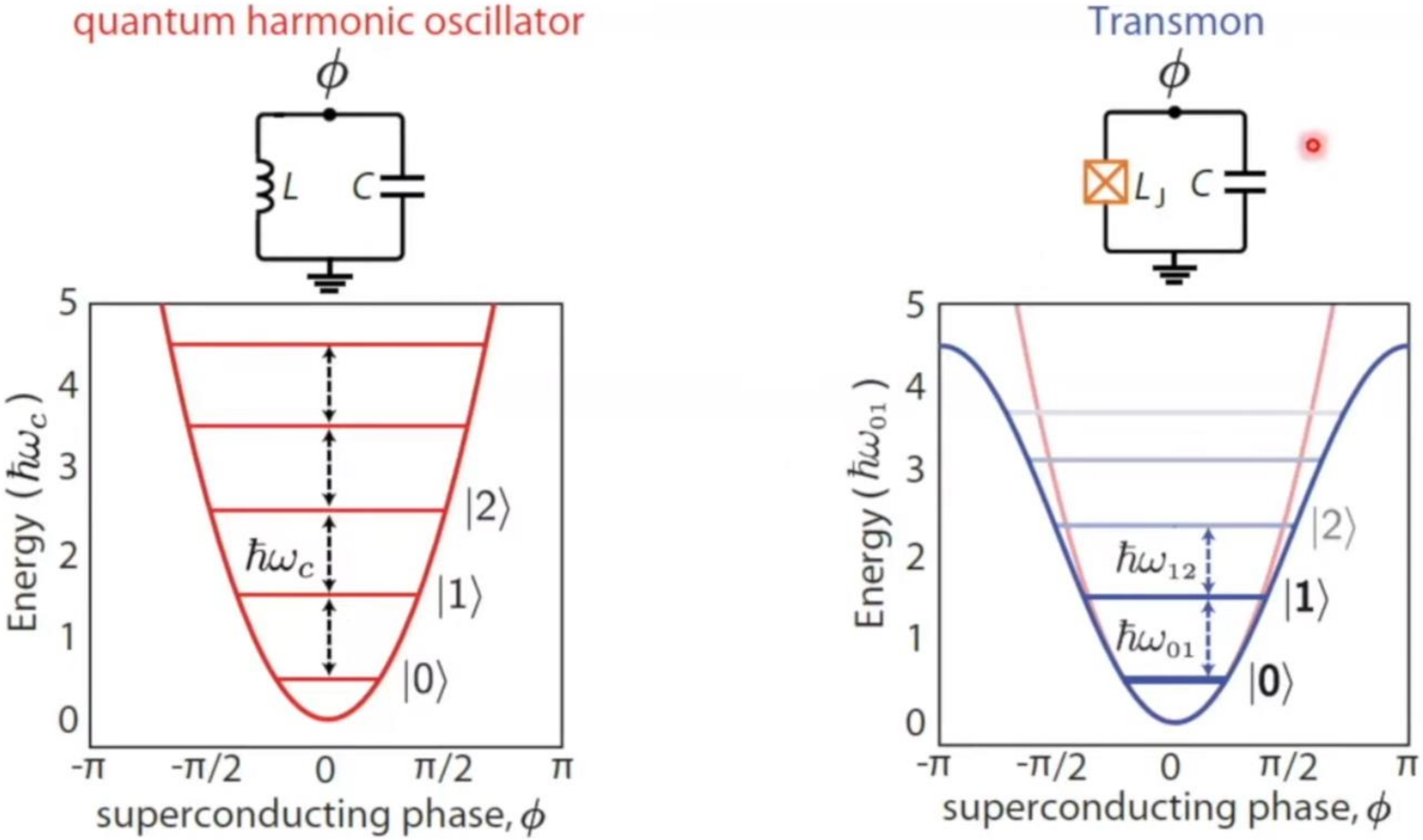
- Quantum simulator proposed (1981)
- Shor's algorithm & CSS error correction (1994-95)
- Grover (1996)
- Quantum annealing & adiabatic QC (1998-2000)
- Factor 15 (2002)
- Few-qubit processors (2010-2016)
- Cloud-based QCs (2017)
- Quantum Advantage 53-qubit QCs

Quantum computing is transitioning from scientific curiosity to technical reality.

Advancing from discovery to useful machines takes time & engineering

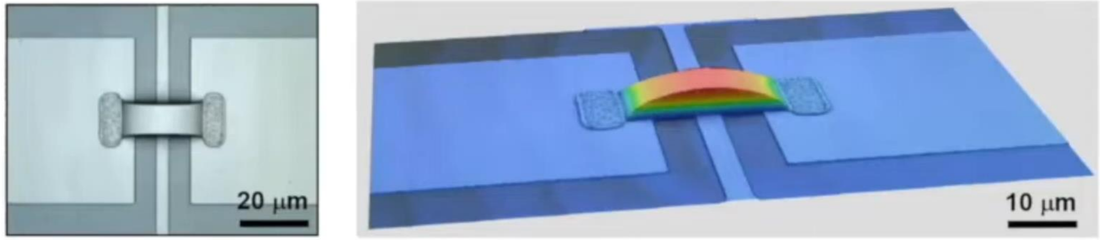
Materials science and fab engineering

# How to Build a Superconducting Qubits

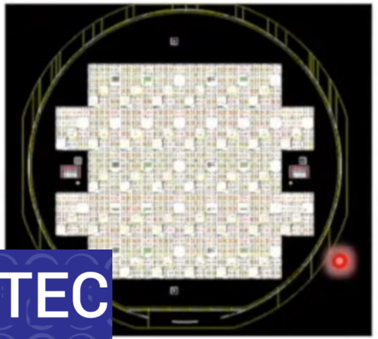


# Fabrication Engineering

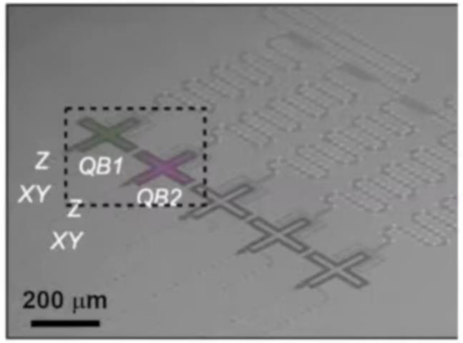
- **Manufactured/designed qubits**
- **Lithographic scalability (silicon)**



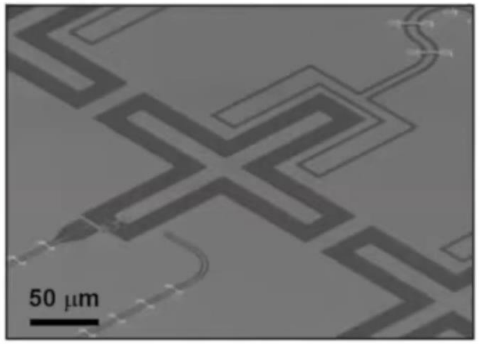
**High-coherence air-gap cross-overs
(optical microscope and confocal images)**



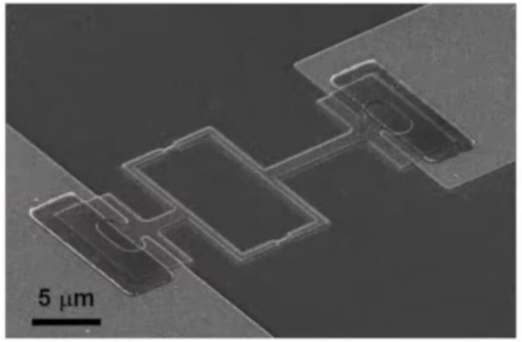
**200-mm wafers
(49 Reticles × 16 chips)**



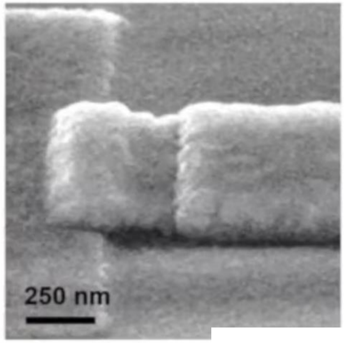
**5-Transmon chip with
readout resonators**



**Transmon capacitor
and control lines**



**Tunable transmon qubit
loop with junctions**

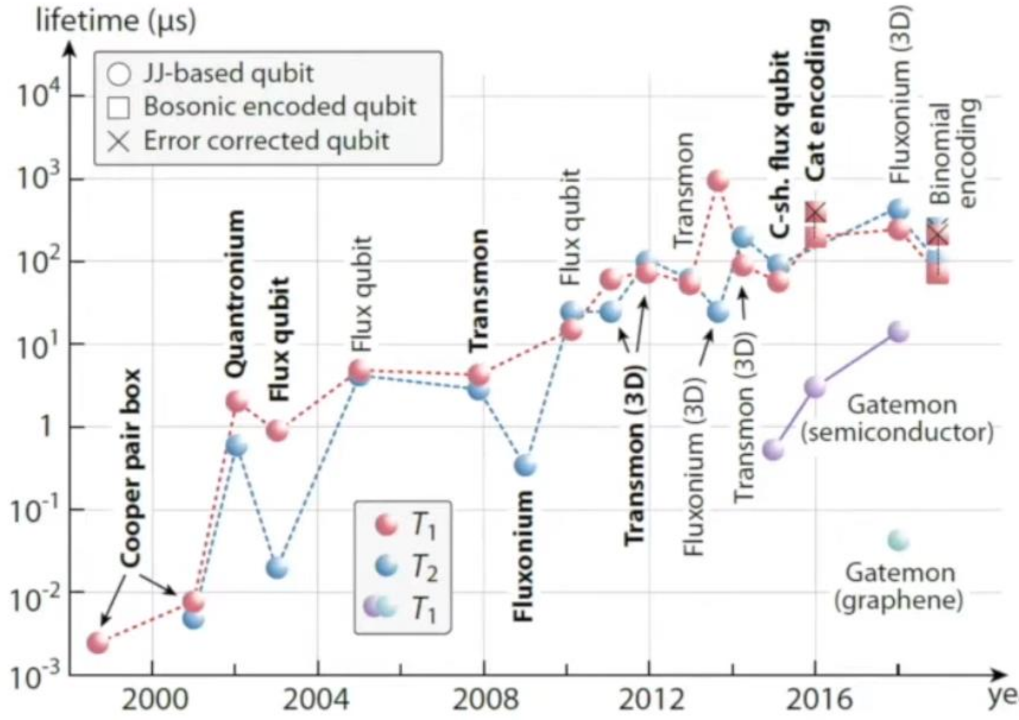


**Josephson junctions
(aluminum)**

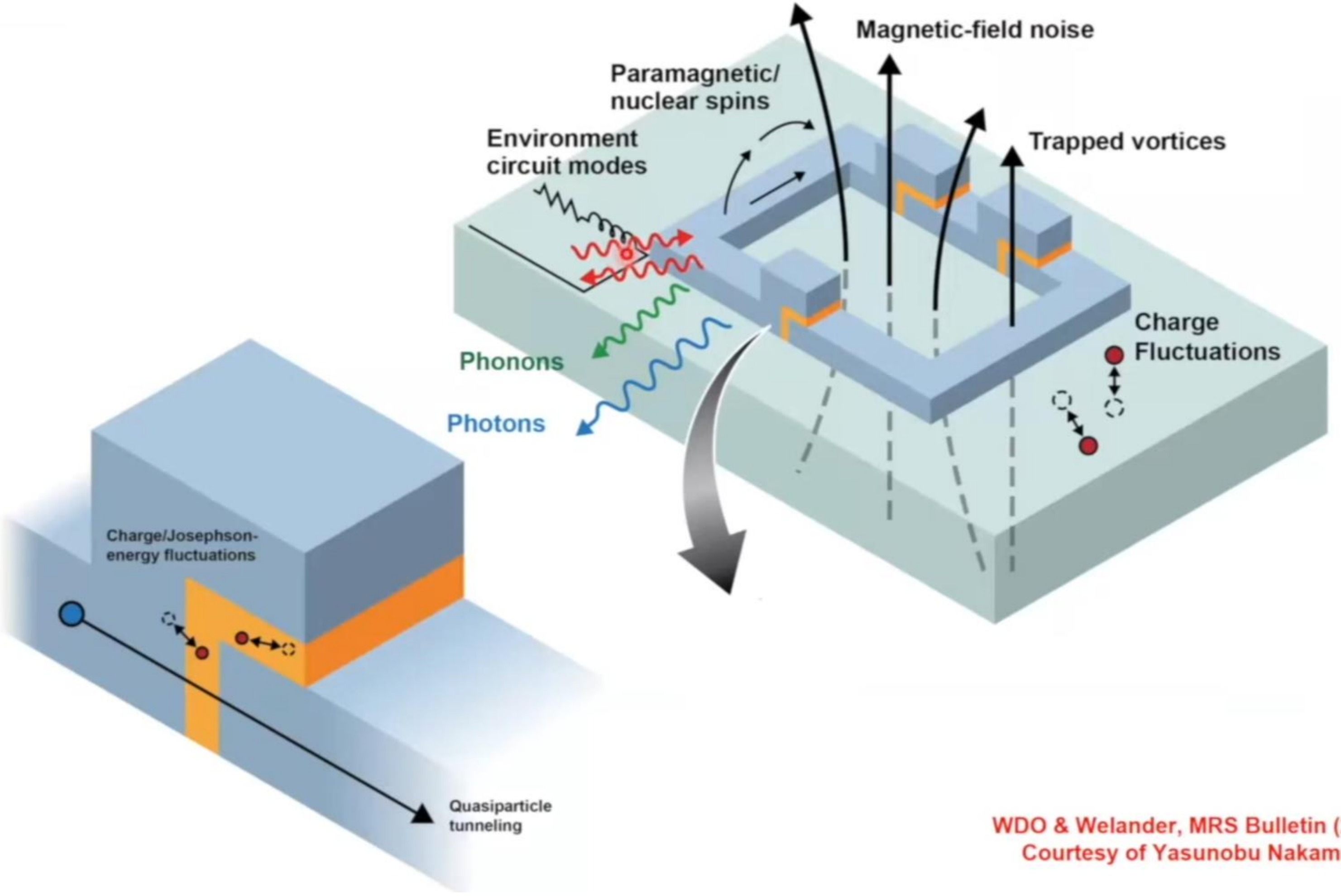
# Engineering Improved Coherence

- Remarkable improvement in $T_{1,2}$
  - Materials
  - Fabrication
  - Design

“Moore’s Law” for $T_2$

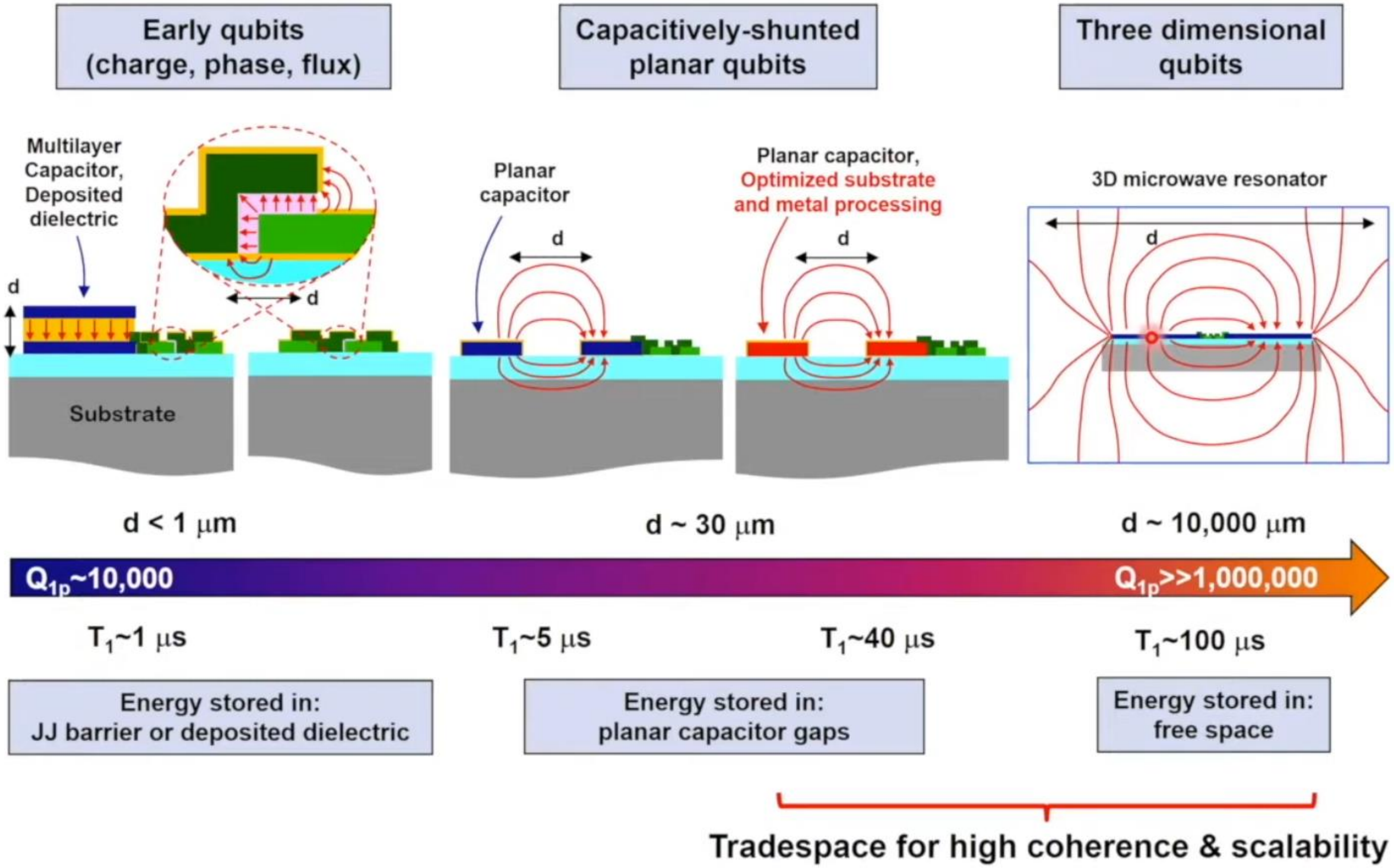


# Improving Coherence

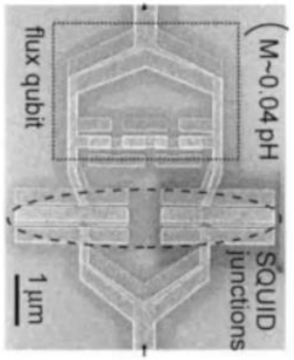


WDO & Welander, MRS Bulletin (2013);
Courtesy of Yasunobu Nakamura

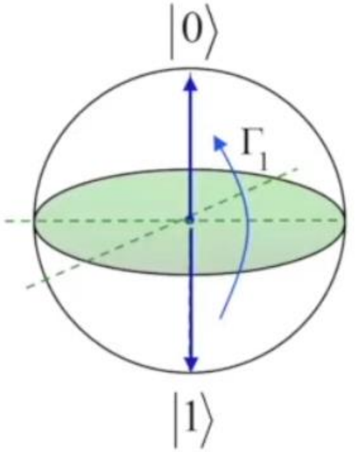
# Design Work-Arounds



# Coherence Times

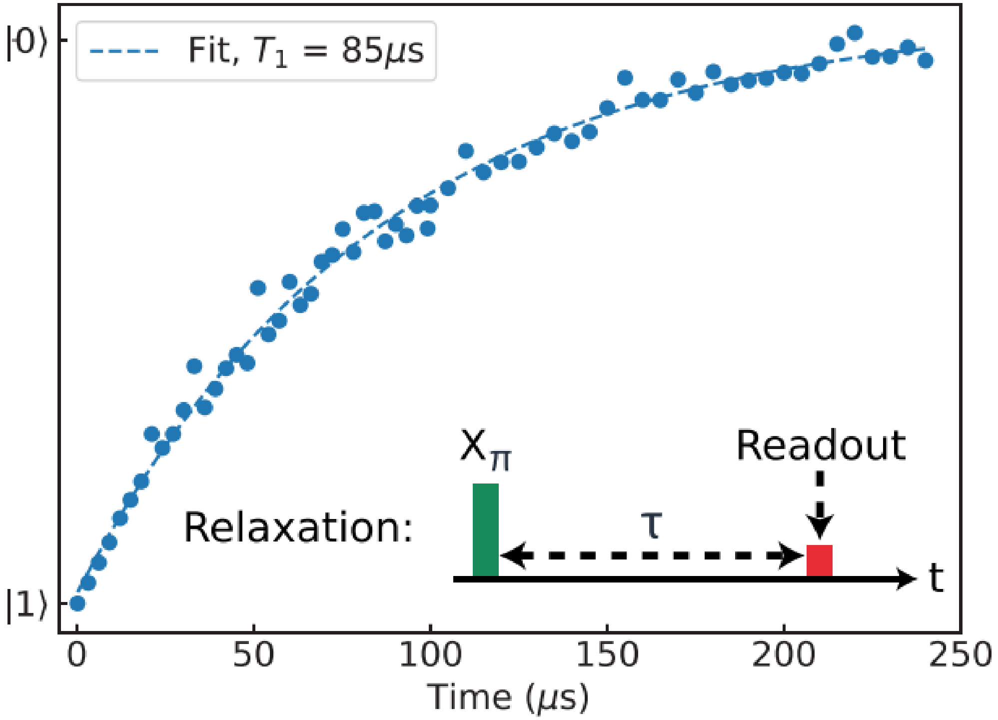


- **Relaxation rate:** $\Gamma_1 = 1/T_1$



# Measuring $T_1$

- How to measure?
  - Excite using a $X_\pi$ pulse
  - Measure after time $\tau$ during which spontaneous decay occurs
  - Probability of measuring ground or excited state depends on polarization
  - Repeat many times!
  - Estimate $T_1$ by taking ensemble average



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Kjaergaard, M., Yan, F., Orlando, T.P., Gustavsson, S. and Oliver, W.D., 2019. A quantum engineer's guide to superconducting
lied physics reviews*, 6(2).

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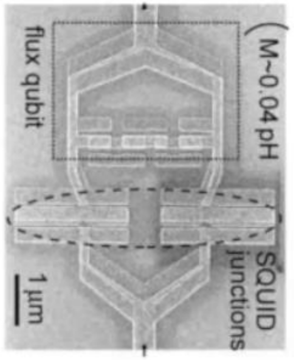
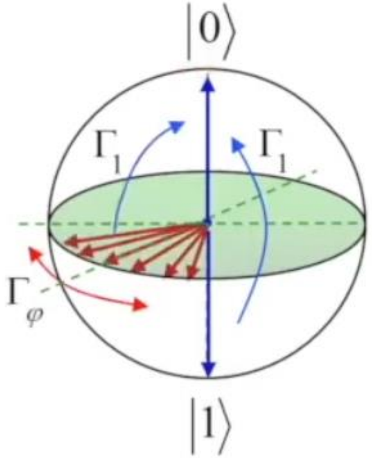
# Coherence Times

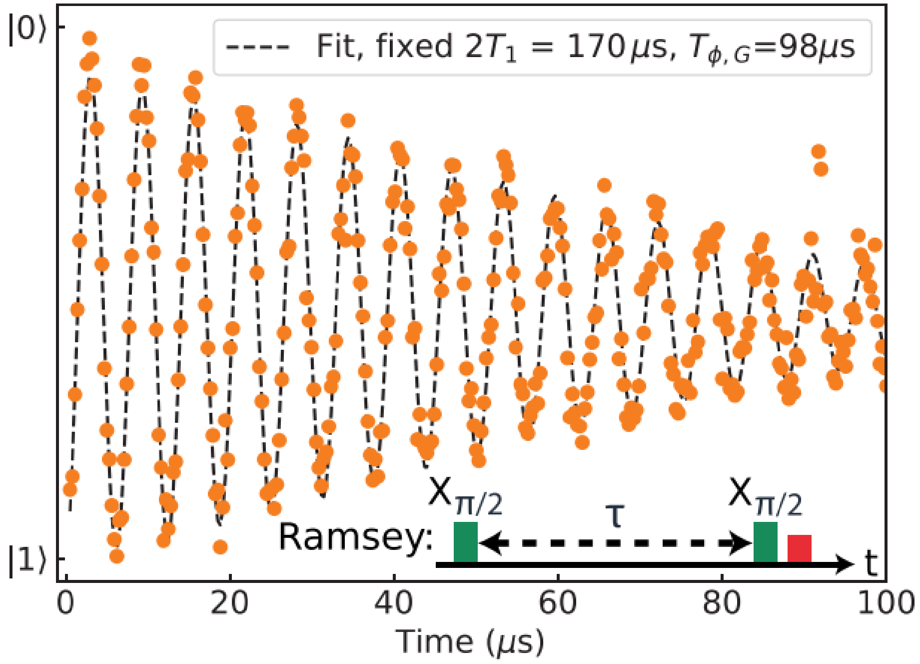


- **Relaxation rate:** $\Gamma_1 = 1/T_1$
- **Decoherence rate:** $\Gamma_2 = \dfrac{1}{T_2} = \dfrac{1}{2T_1} + \dfrac{1}{T_\varphi}$
- **Dephasing rate:** $\Gamma_\varphi = 1/T_\varphi$



# Measuring $T_2$

- Send a $X_{\pi/2}$ pulse to put Bloch Vector on the equator
- Since the carrier frequency $\omega_d$ and qubit frequency $\omega_q$ may differ by $\delta\omega$, the Bloch Vector will precess around z-axis, thus the oscillation of the Ramsey Experiment
- After time $\tau$, another $X_{\pi/2}$ pulse will put the vector back on the z-axis
- Then we estimate $T_2$ by taking the ensemble average of measurements
- Dephasing is usually faster than relaxation!



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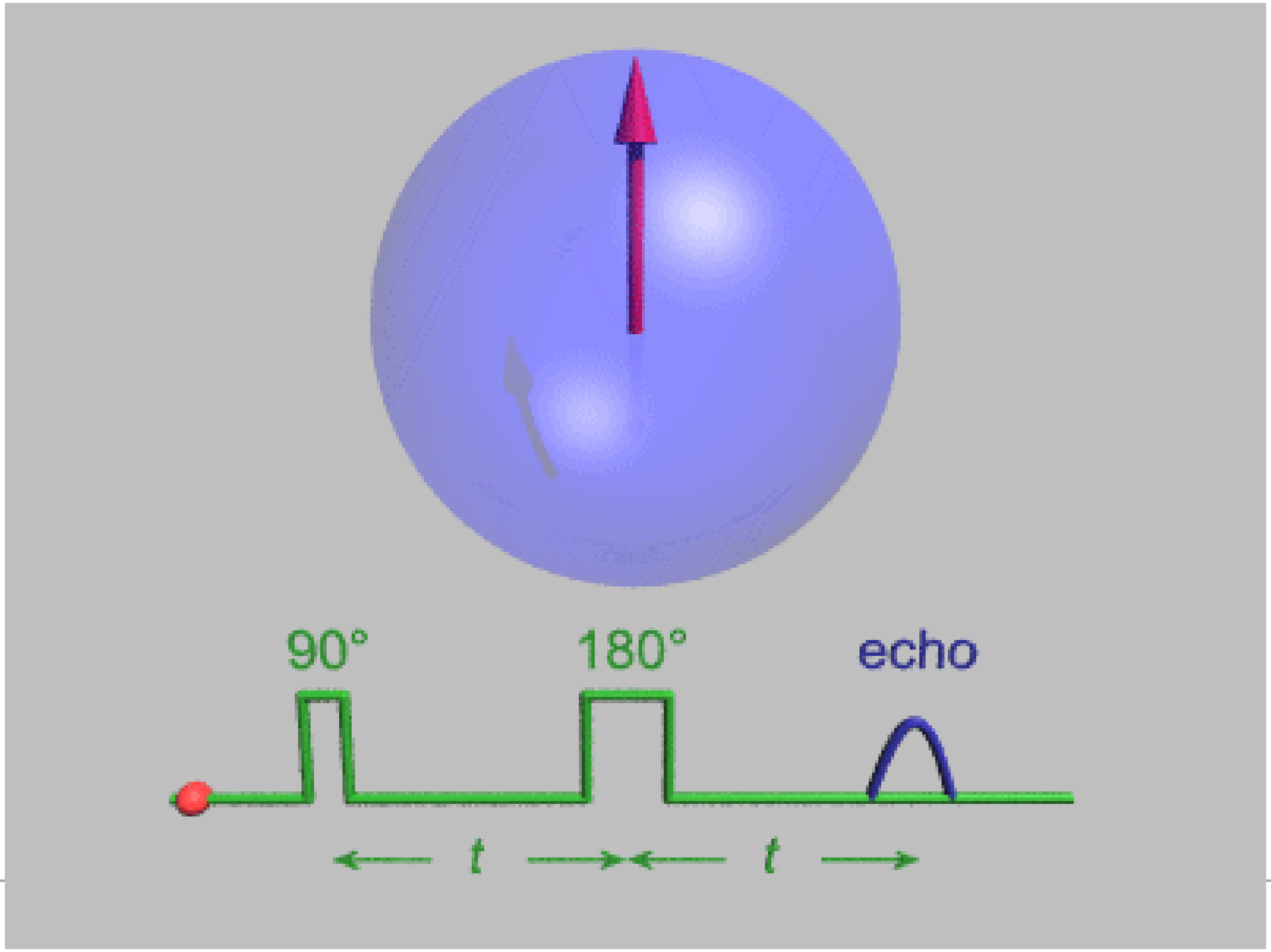
Kjaergaard, M., Yan, F., Orlando, T.P., Gustavsson, S. and Oliver, W.D., 2019. A quantum engineer's guide to superconducting
lied physics reviews, *6*(2).

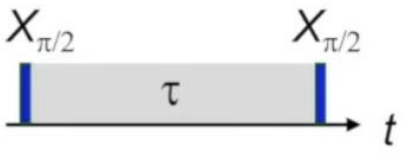
# Spin Echo

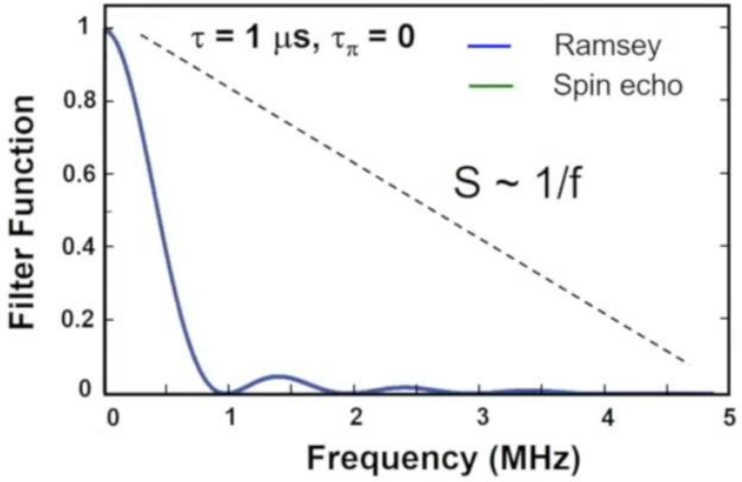


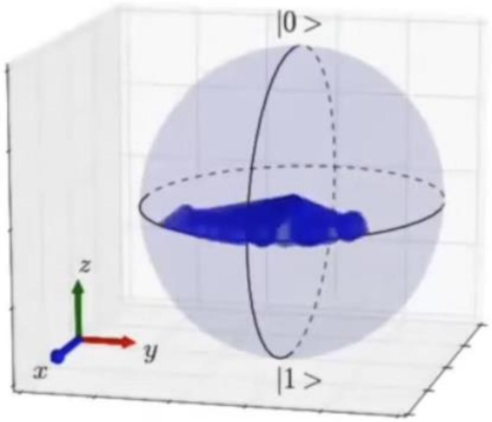
# Dynamical Decoupling

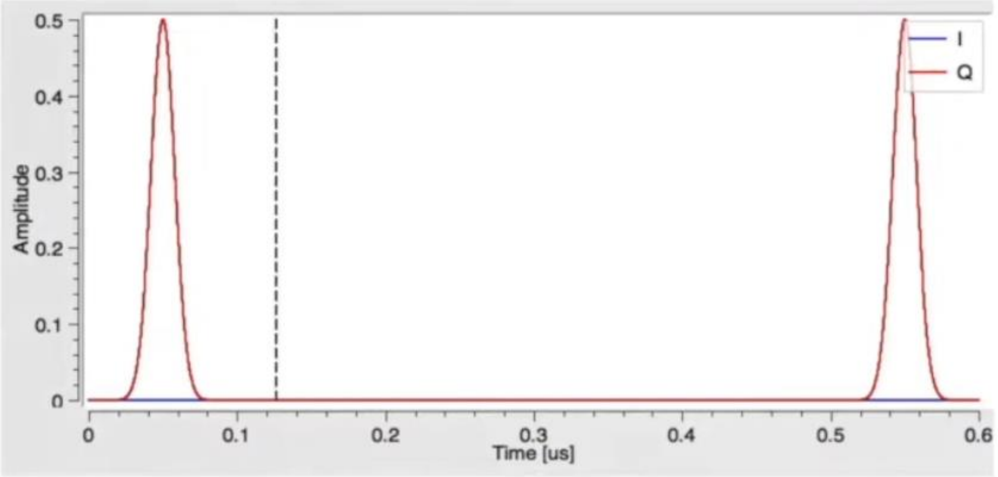
NO Dynam. Decoup.

(Ramsey, N=0)

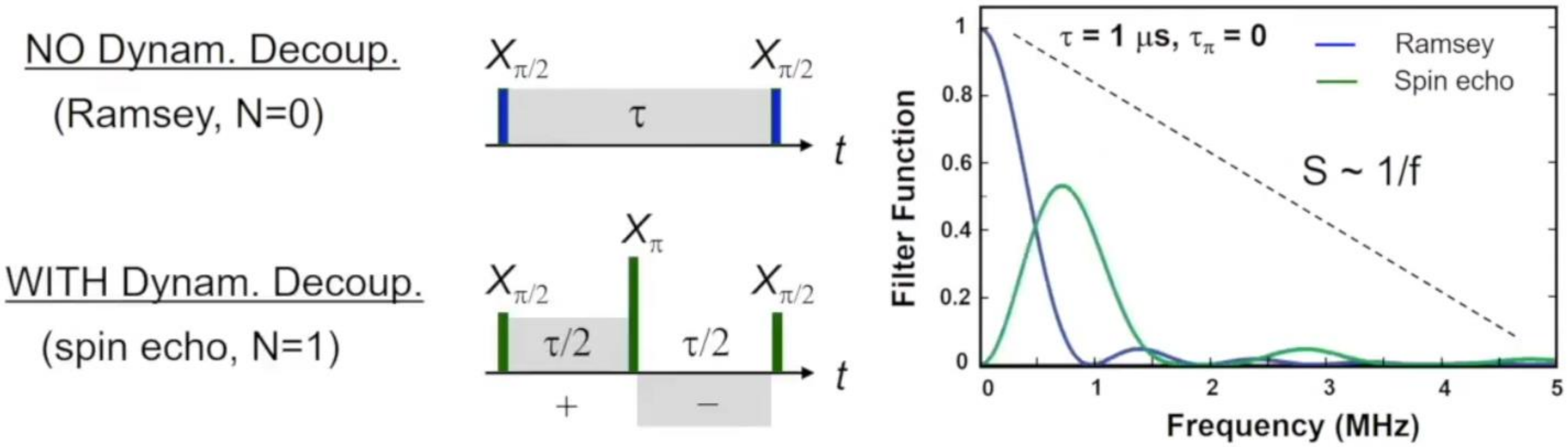


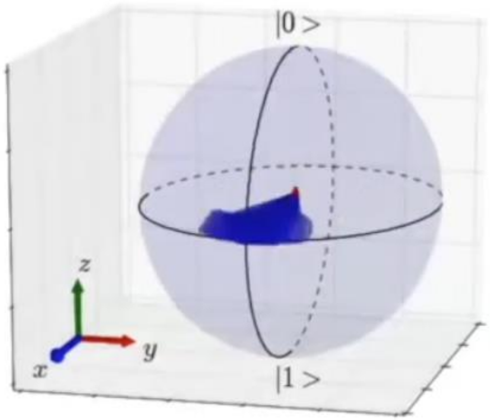


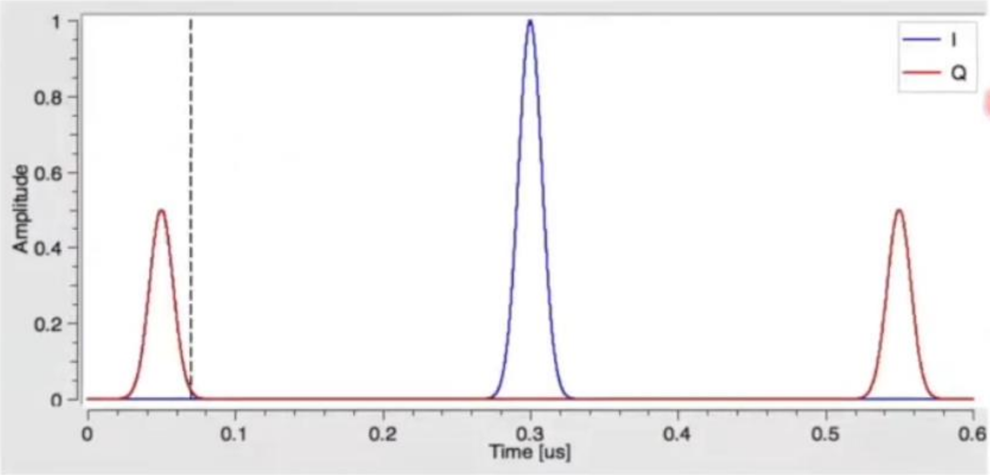




# Dynamical Decoupling

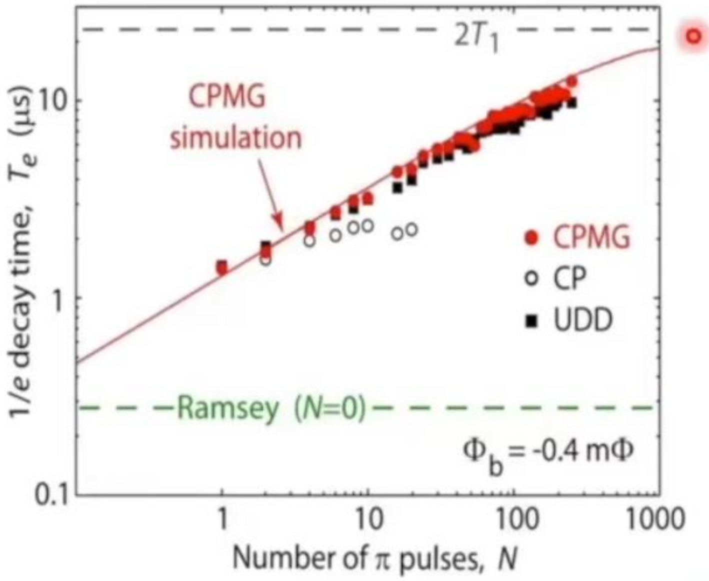




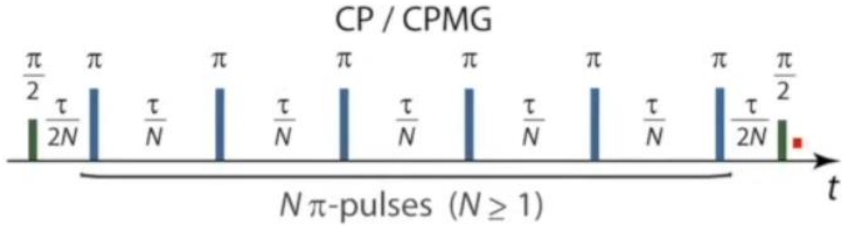


# Dynamical Decoupling

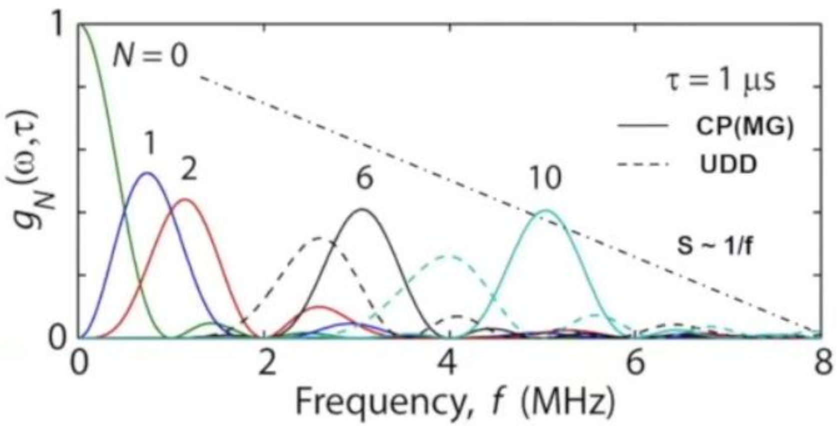
**Engineered Error Mitigation:**
**Dynamical Decoupling**
(improves the physical qubit error rate)



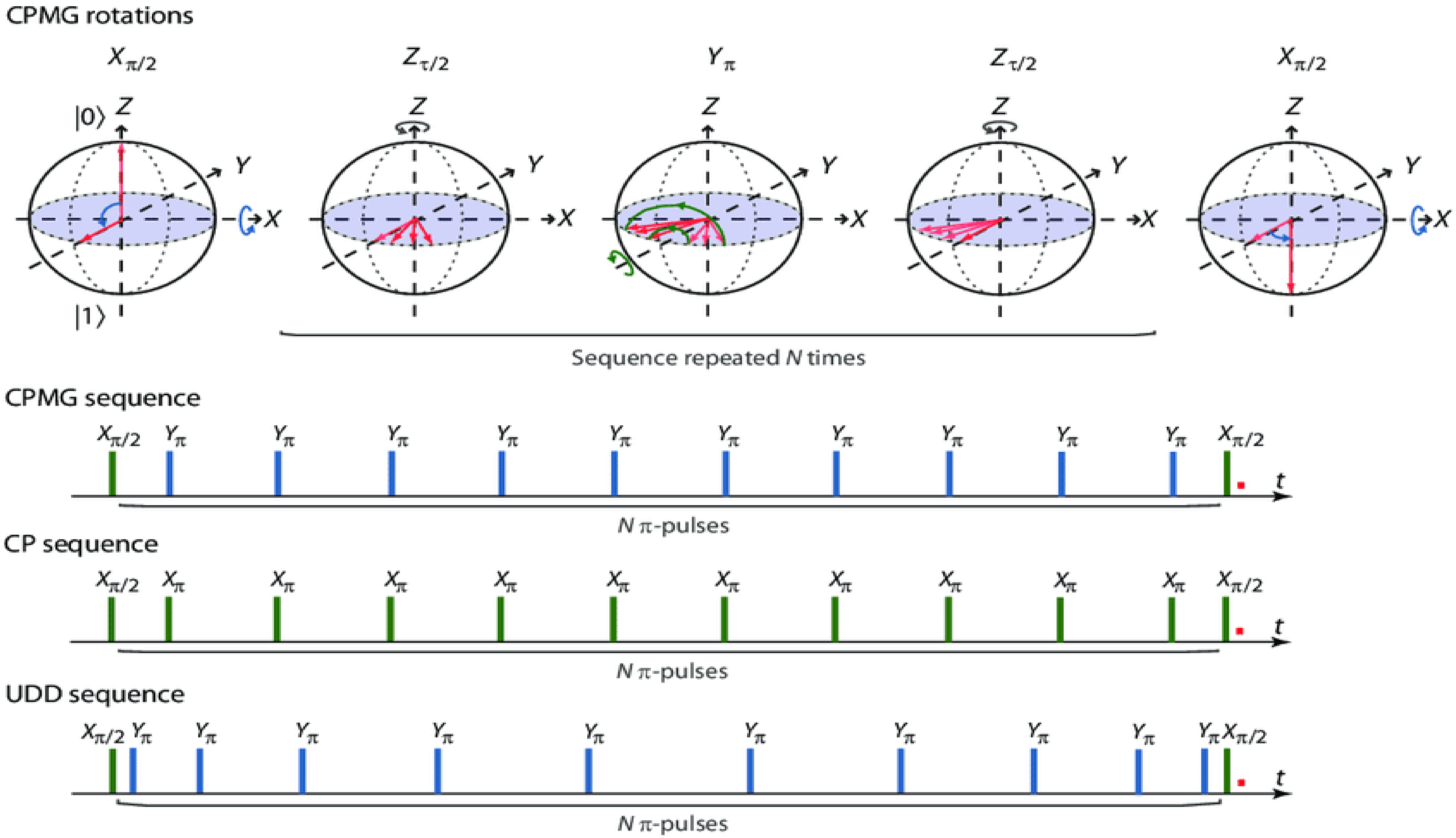
**Carr – Purcell (– Meiboom – Gill) Sequence**



**Noise-Shaping Filter Functions**



# Dynamical Decoupling



# Hardware-based Noise Mitigation Techniques

- ❑ Improvements in materials and fabrication
  - Substrate cleaning and annealing
  - Optical surface treatments
  - Quasiparticle traps
- ❑ Design improvements
- ❑ Dynamical error suppression
- ❑ Cryogenic engineering
  - More efficient heat sinks
  - Absorptive black material for thermal photons
  - Additional cavity filters

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Kjaergaard, M., Yan, F., Orlando, T.P., Gustavsson, S. and Oliver, W.D., 2019. A quantum engineer's guide to superconducting
*lied physics reviews*, *6*(2).

# Algorithmic noise mitigation techniques

- Zero Noise Extrapolation (ZNE)
- Machine Learning Quantum Error Mitigation (ML-QEM)

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Kjaergaard, M., Yan, F., Orlando, T.P., Gustavsson, S. and Oliver, W.D., 2019. A quantum engineer's guide to superconducting
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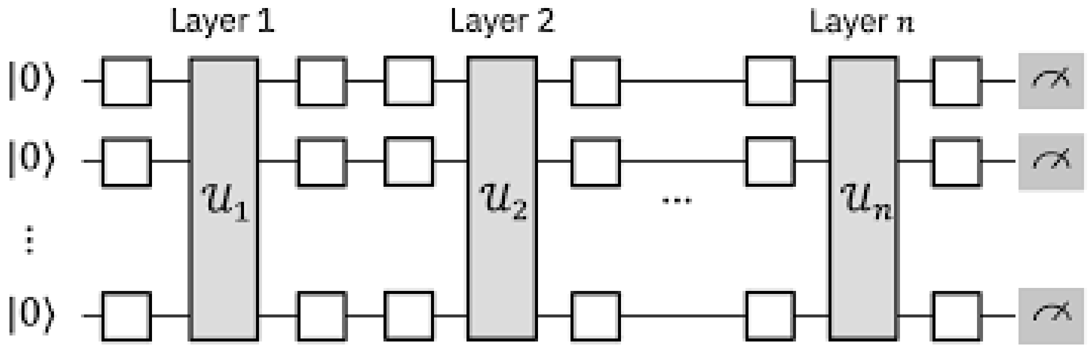
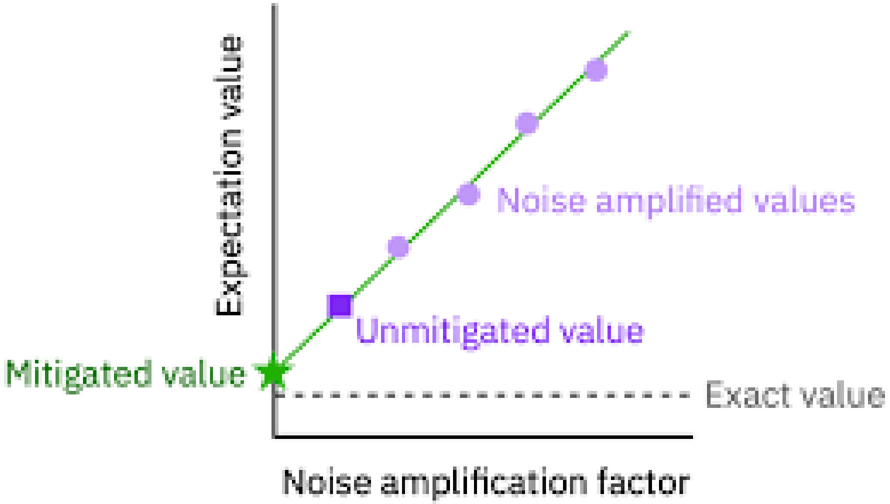
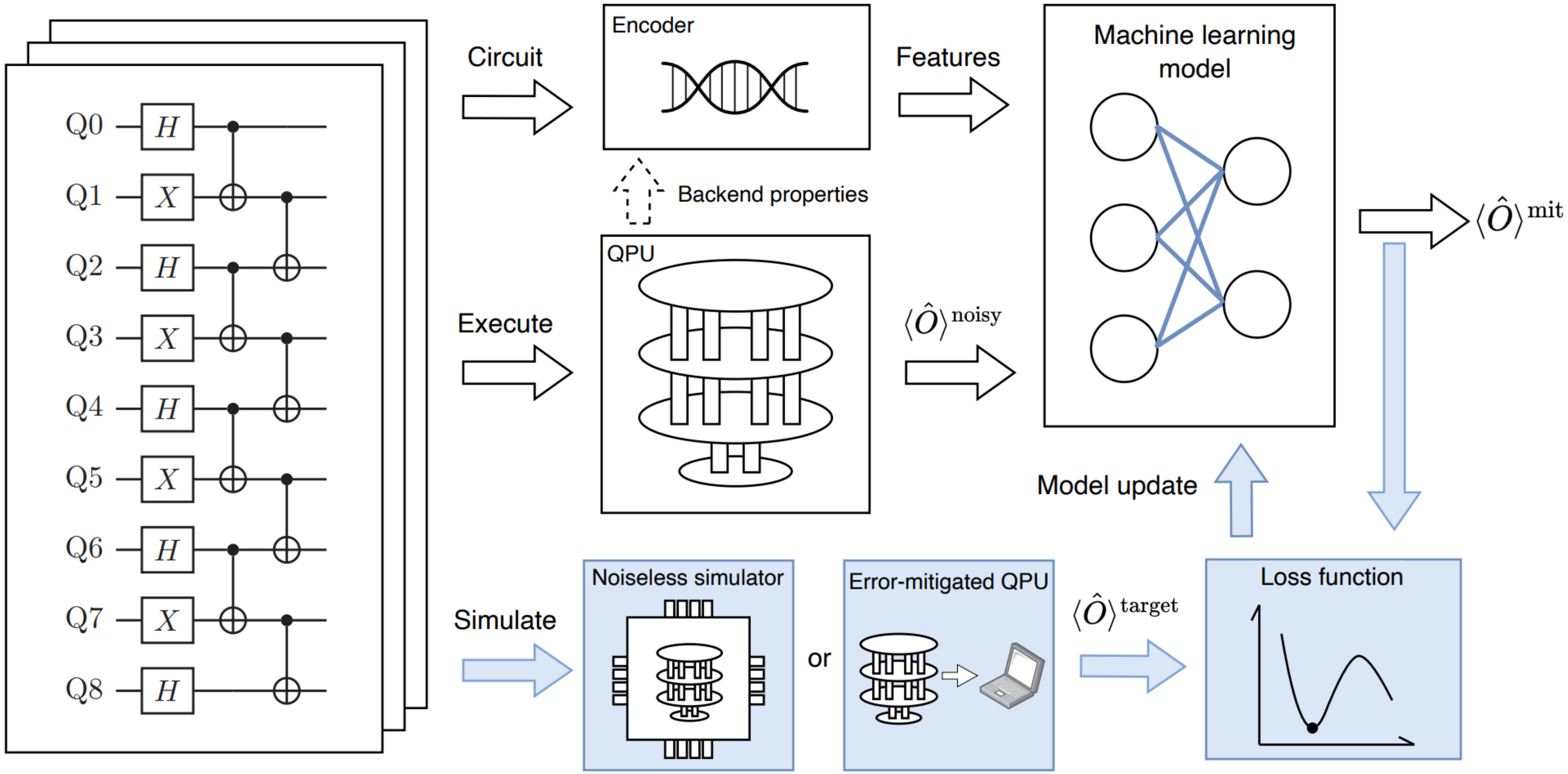
# Zero Noise Extrapolation



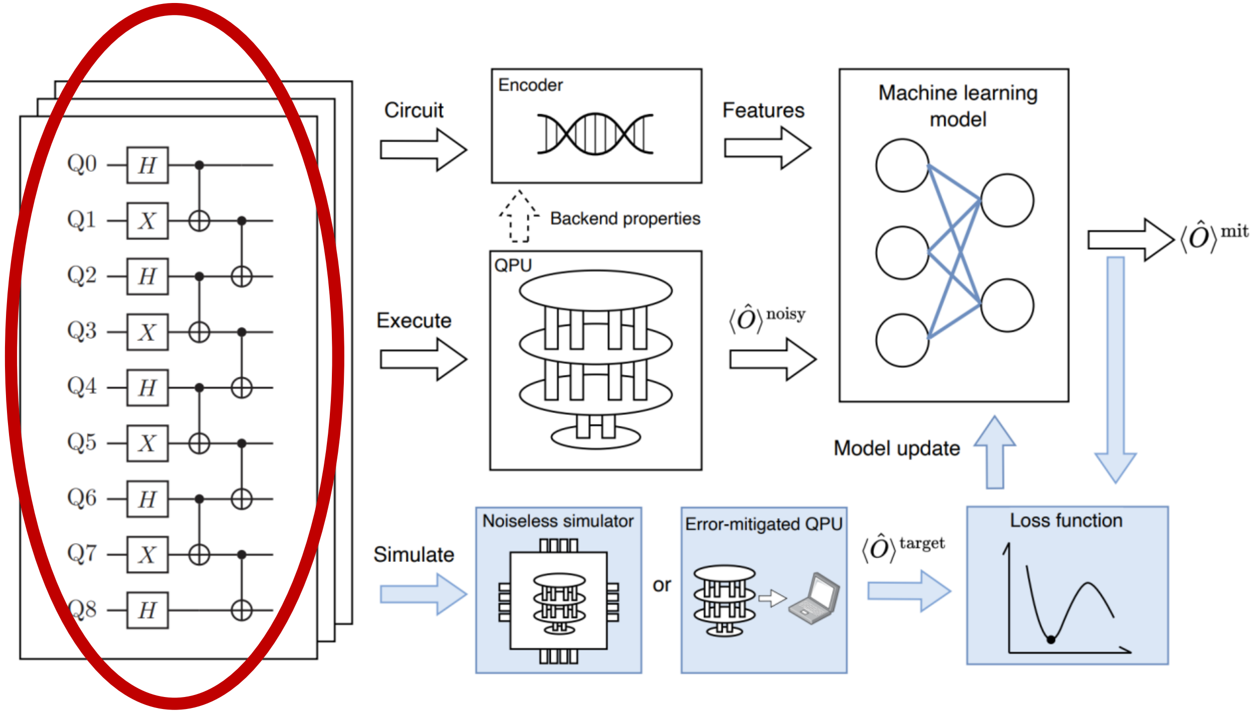


# Error Mitigation with Machine Learning



ang, D.S., Sitdikov, I., Salcedo, C., Seif, A. and Minev, Z.K., 2023. Machine learning for practical quantum error
*arXiv preprint arXiv:2309.17368*.

# Error mitigation with machine learning



A quantum circuit (left) is passed to an encoder (top) that creates a feature set for the ML model (right) based on the circuit and the quantum processor unit (QPU) targeted for execution. The model and features are readily replaceable.

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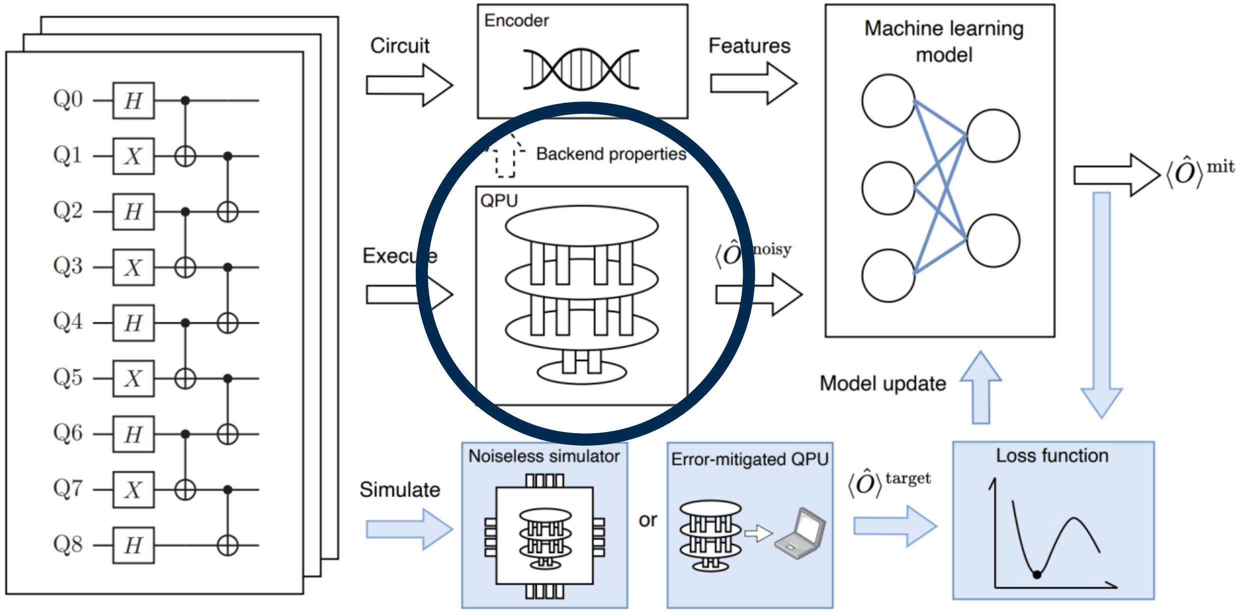
ang, D.S., Sitdikov, I., Salcedo, C., Seif, A. and Minev, Z.K., 2023. Machine learning for practical quantum error *arXiv preprint arXiv:2309.17368*.

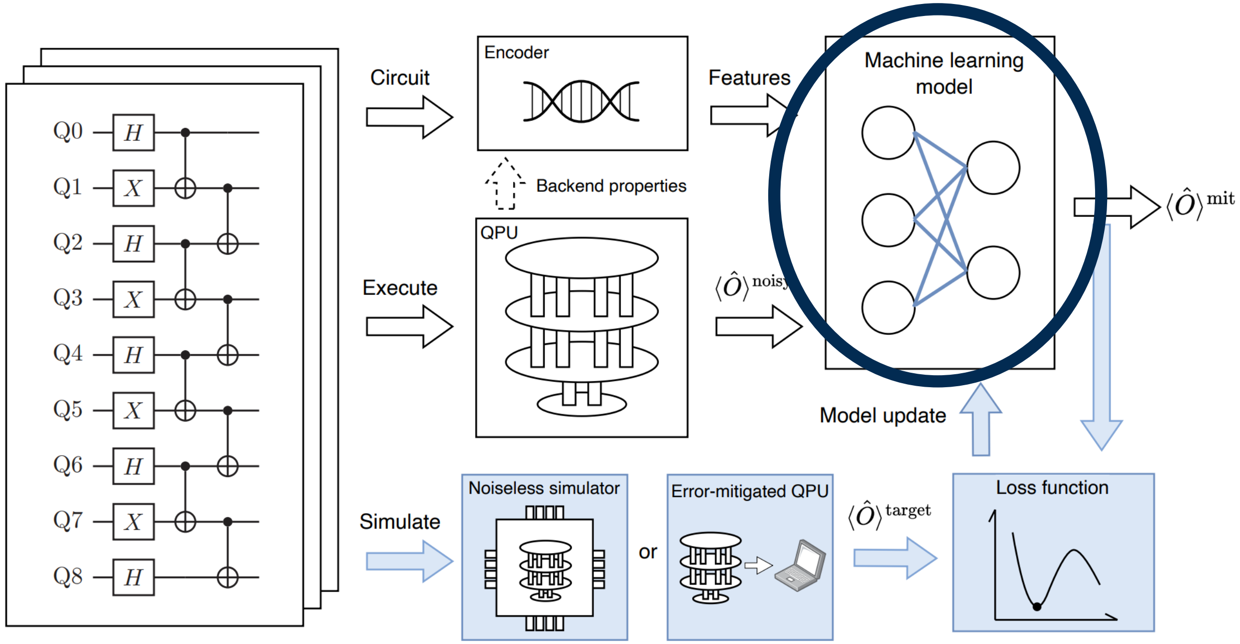
# Error mitigation with machine learning



The executed noisy expectation values ⟨O⟩-noisy (middle) serve as the input to the model whose aim is to predict their noise-free value ⟨O⟩-mit

ang, D.S., Sitdikov, I., Salcedo, C., Seif, A. and Minev, Z.K., 2023. Machine learning for practical quantum error
*arXiv preprint arXiv:2309.17368*.

# Error mitigation with machine learning



To achieve this, the model is trained beforehand against target values $\langle O \rangle$ target of example circuits. These are obtained either using noiseless simulations in the case of small-scale, tractable circuits or using the noisy QPU in conjunction with a conventional error mitigation strategy in the case of large-scale, intractable circuits. The training minimizes the loss function, typically the mean square error

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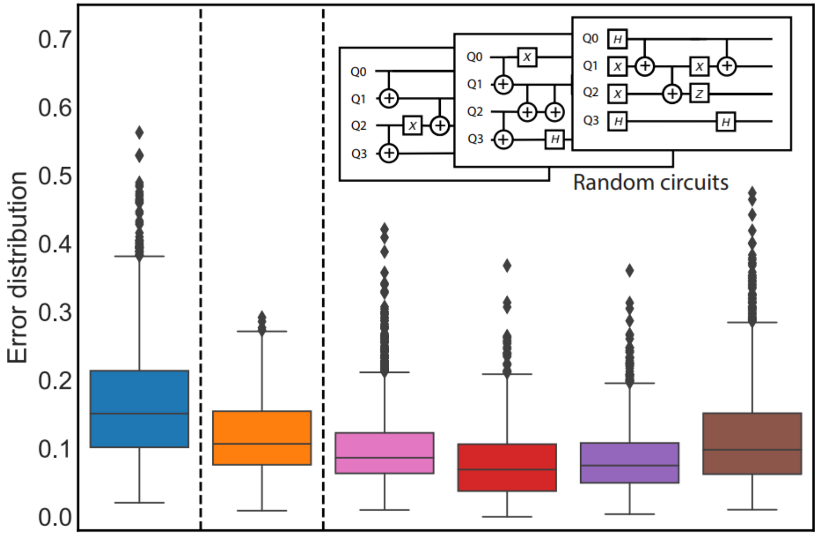
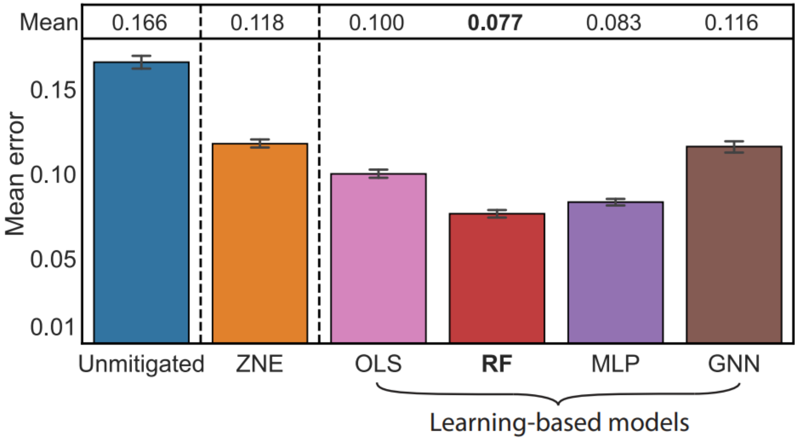
*arXiv preprint arXiv:2309.17368.*

# Error mitigation with machine learning

- Random circuits
- Trotterized dynamic of the 1D Ising spin chain
- These two classes play the role to simulate the noise on the small scale of them
- In the study of Trotterized circuits, the performance of the methods is also studied in the absence and presence of readout error or coherent noise, in addition to incoherent noise.





ang, D.S., Sitdikov, I., Salcedo, C., Seif, A. and Minev, Z.K., 2023. Machine learning for practical quantum error *arXiv preprint arXiv:2309.17368*.

# Conclusion

- Building hardware takes time. But we should enter the race now before it’s too late!
- Noise is one of the main obstacles in the way of building a quantum computer. But we are improving noise mitigation techniques every year.
- Hardware noises can be addressed by improvement in materials, fabrication, and designs.
- We also came to invent dynamical suppression techniques.
- Lastly machine learning has also come to enhance the quantum computing era.