Quantum computing and quantum machine learning:
NISQ

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[https://www.umb.ch/blog/news/detail/quantencomputing-fuer-den-praktischen-einsatz-rueckt-naeher]

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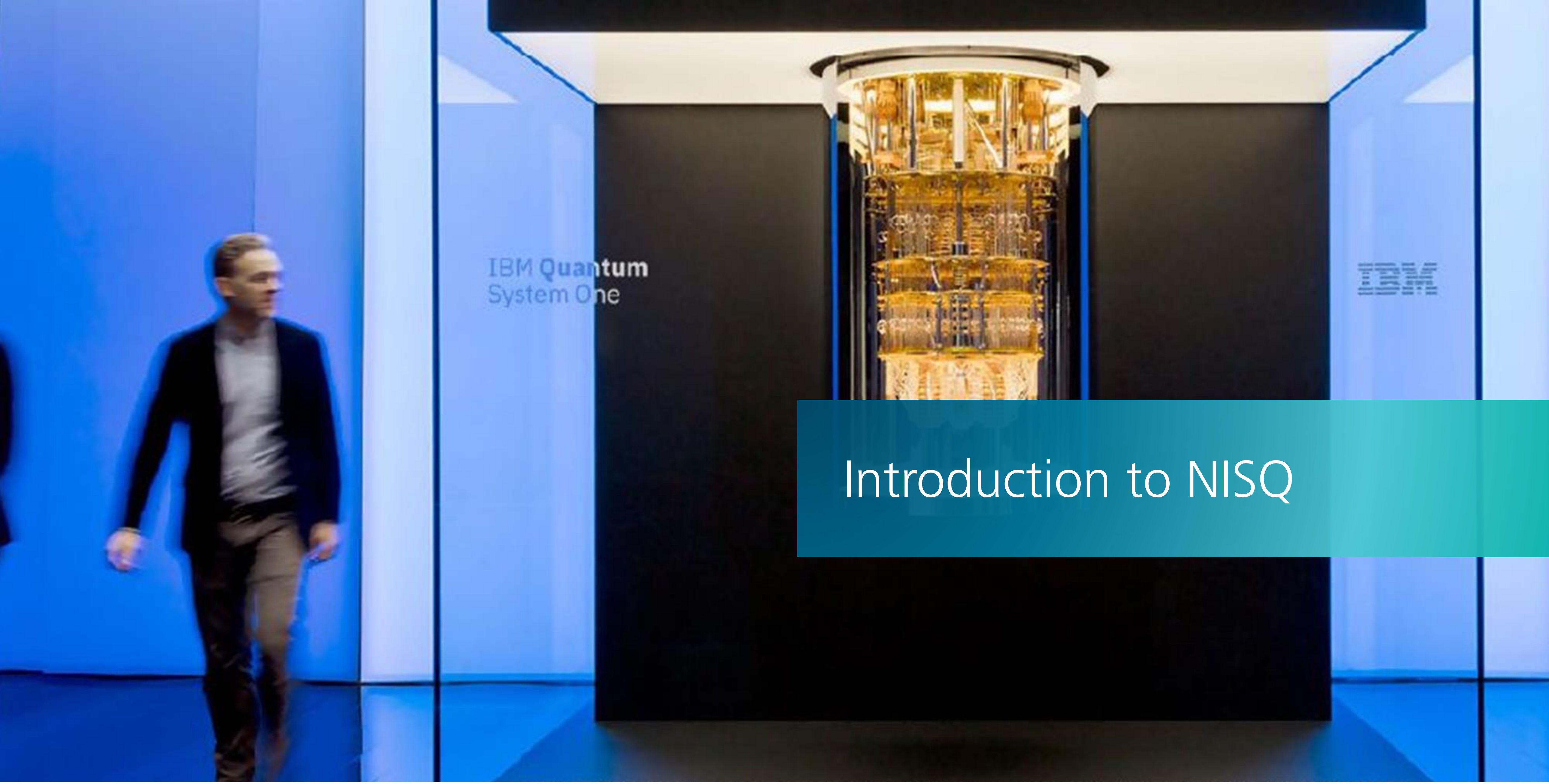
NISQ computing

1. Introduction to NISQ & variational algorithms
2. Noise & error mitigation
   a) Noise types
   b) How severe is the problem?
   c) Mitigation schemes

Continued by an introduction to solving optimization problems with quantum computers



Introduction to NISQ

Noisy Intermediate-Scale Quantum (NISQ) Computing

Fault-tolerant quantum computing requires too many qubits and gates for presently available quantum computers

Algorithms typically assume so-called **logical** qubits, instead available: **physical** qubits

Physical qubits are affected by various errors and have a certain **decoherence** time

Gate operations are equally affected by errors, as well as the measurements

To realize 1 logical qubit, many 10 – 1000 physical qubits required

[Frank Leymann and Johanna Barzen 2020 Quantum Sci. Technol. 5 044007]

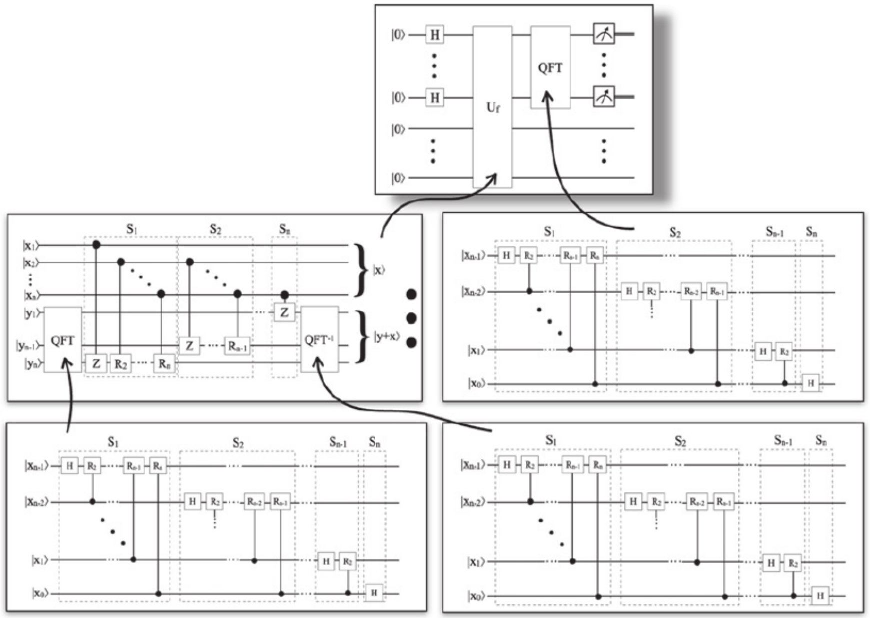
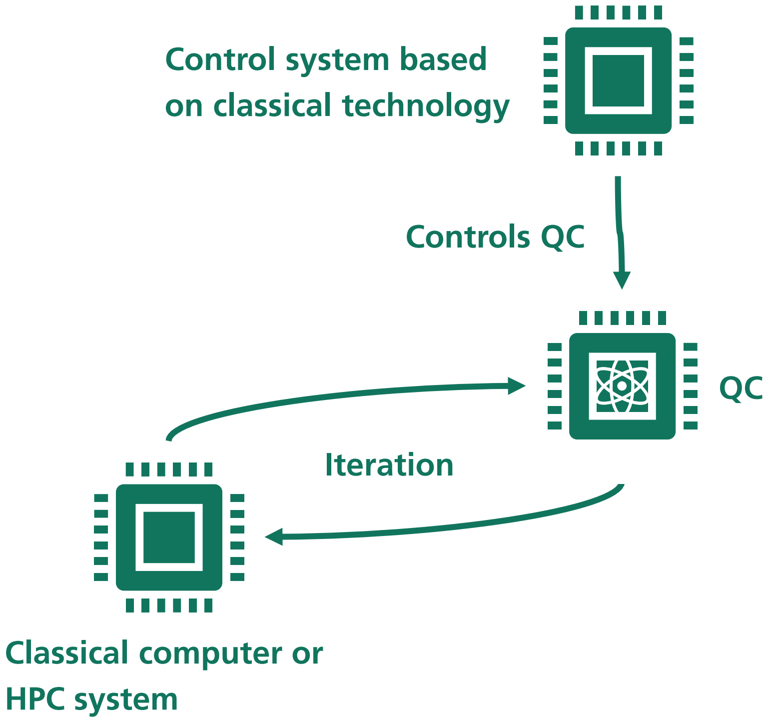


Figure 8. (Partial) expansion of black box functions of the Shor algorithm.

How to design algorithms in the NISQ era?

Situation:
- Limited number of qubits
- Limited conectivity
- Various noise sources, and no error correction (only error mitigation)

Requirements on the QAlg:
- Shallow circuits: limited number of qubits + limited depth
- Hybrid algorithms: Calculations of **limited size, but high complexity** on a quantum computer with a close **iteration** with a classical computer or a High Performance Computing (HPC)-system (for e.g., updates of parameters)
- Close integration with classical computers!



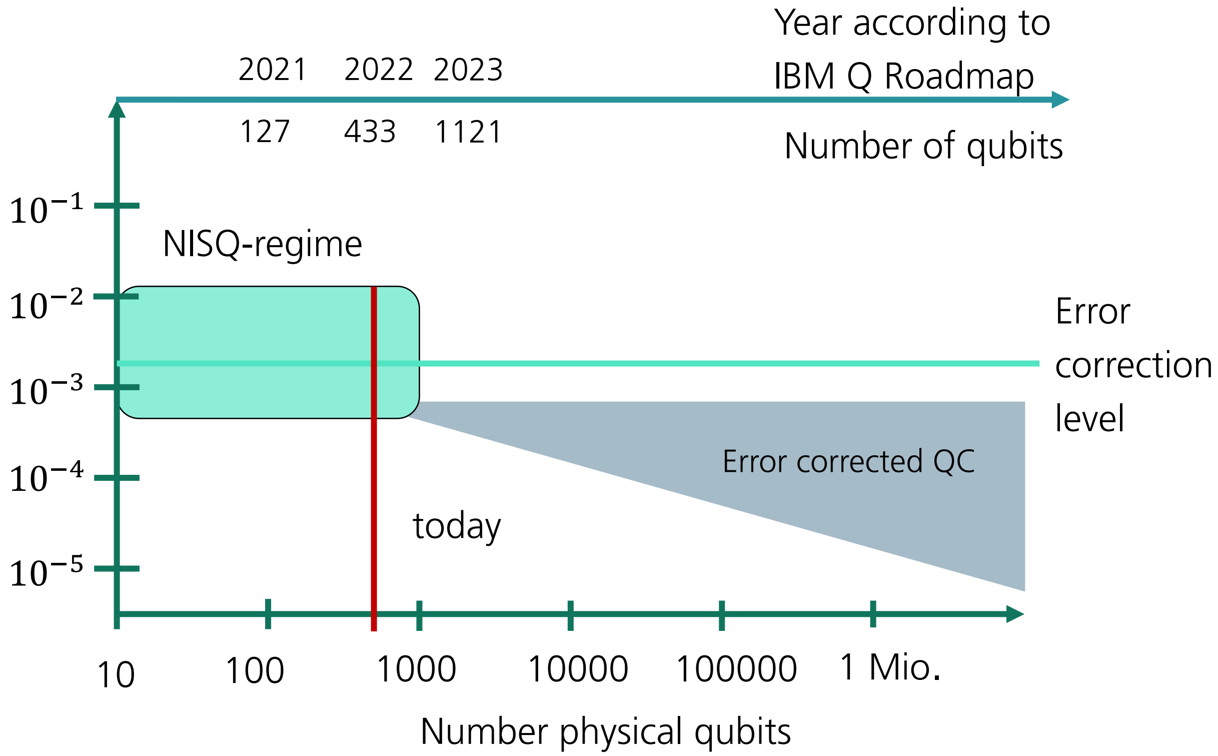
What is required to get a practical quantum advantage?

What is a practical quantum advantage and where do we expect it?

Quantum advantage shown in academic examples – see Google Sycamore – or on the algorithmic side (e.g. Shor's algorithm, Grover's algorithm)

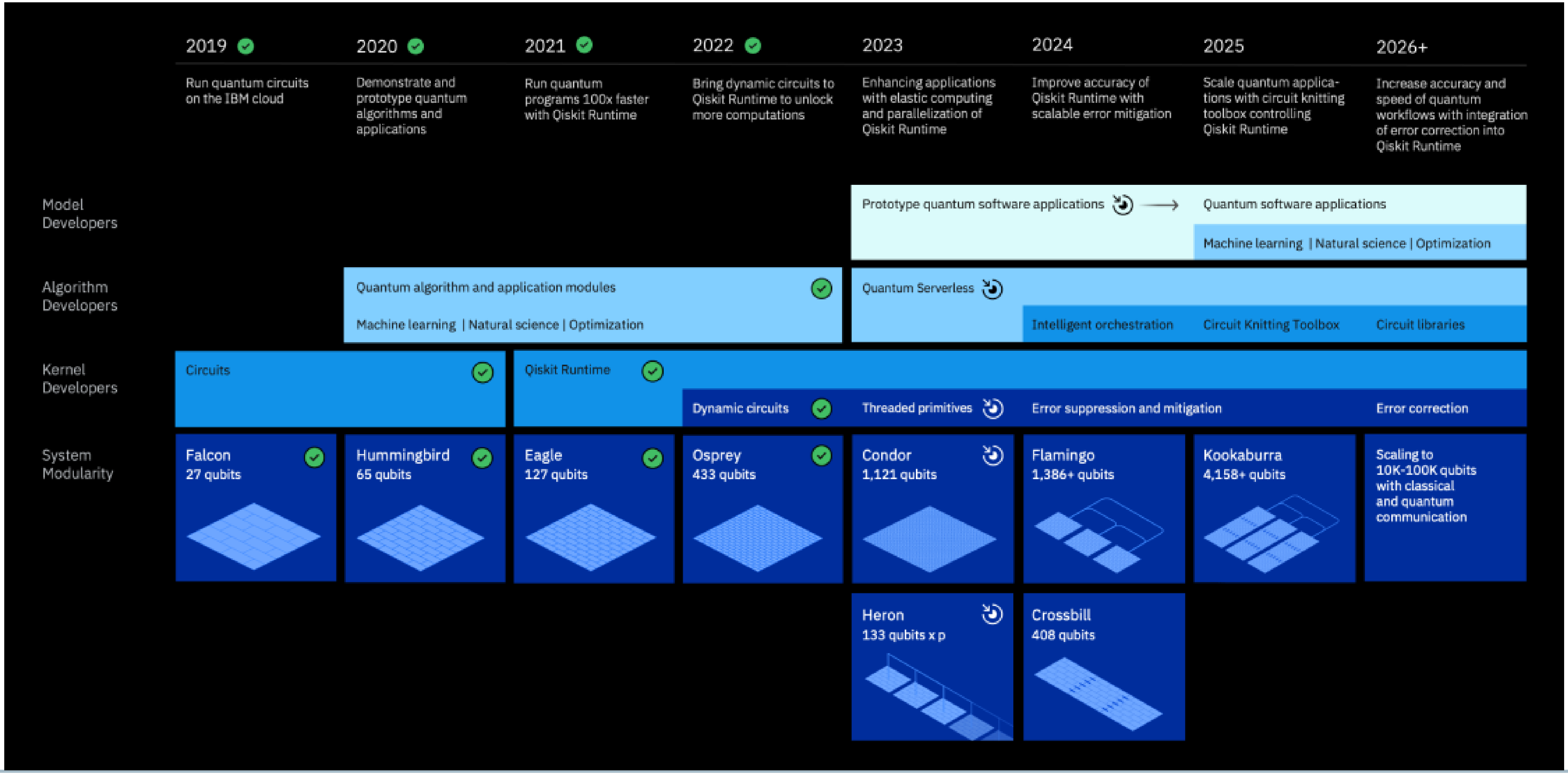
For a practical quantum advantage required:

- Ability to compute ‚real-life' problems, i.e. working on potentially messy and/or large/complicated datasets or tasks
  - Limitations by present size of QPUs and quality.
  - Noise, connectivity between qubits….
  - Data encoding into QPU
- Identification of areas where QC useful + definition of appropriate metrics
  - Simulation, optimization, quantum machine learning



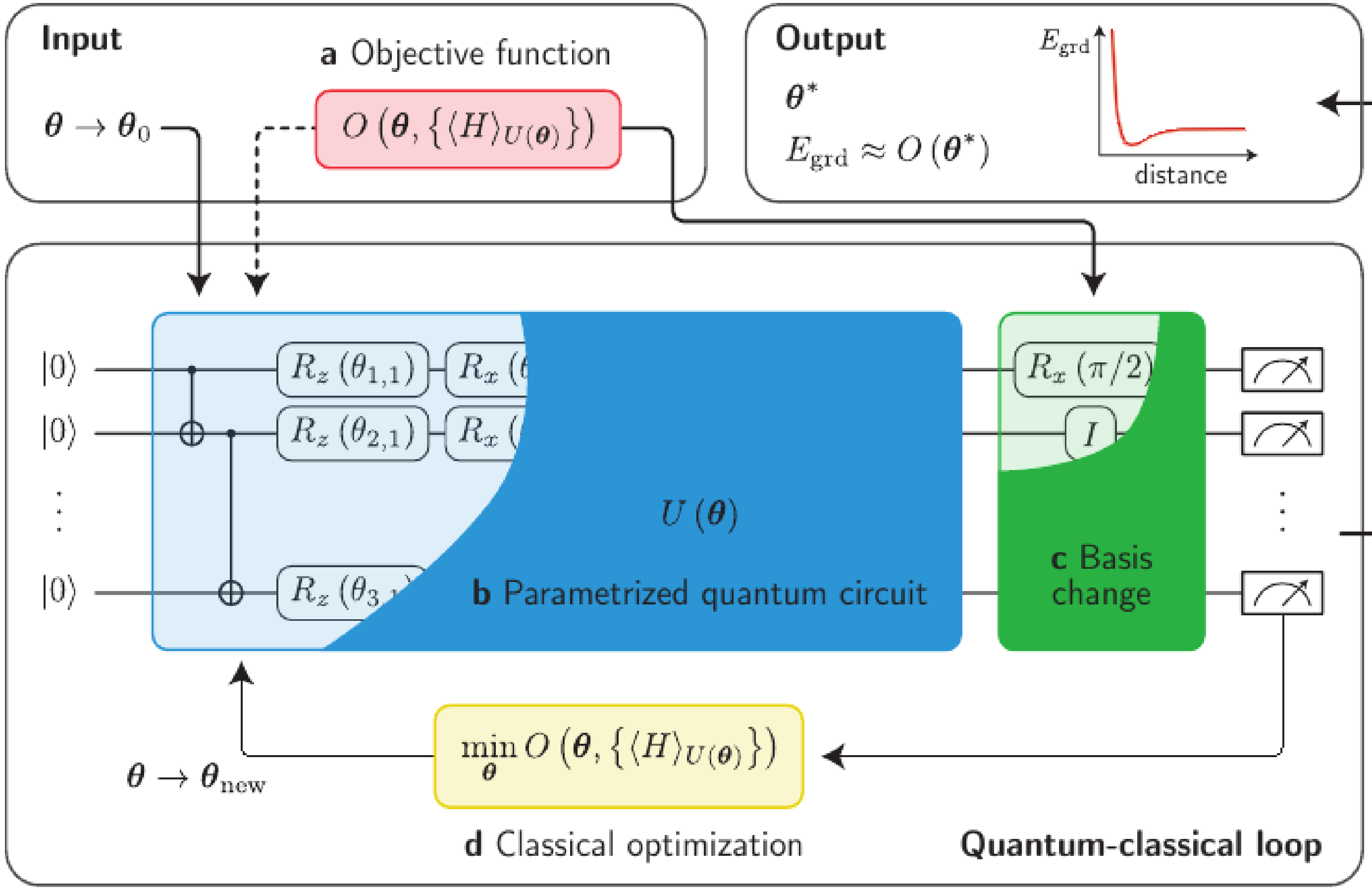
Sources:
Preskill, 2018, https://arxiv.org/abs/1801.00862
Combarro, 2020, A Practical Introduction to Quantum Computing: From Qubits to Quantum Machine Learning and Beyond
IBM Roadmap 2021, https://research.ibm.com/blog/quantum-development-roadmap

Example: IBM roadmap



[https://www.ibm.com/quantum/roadmap]

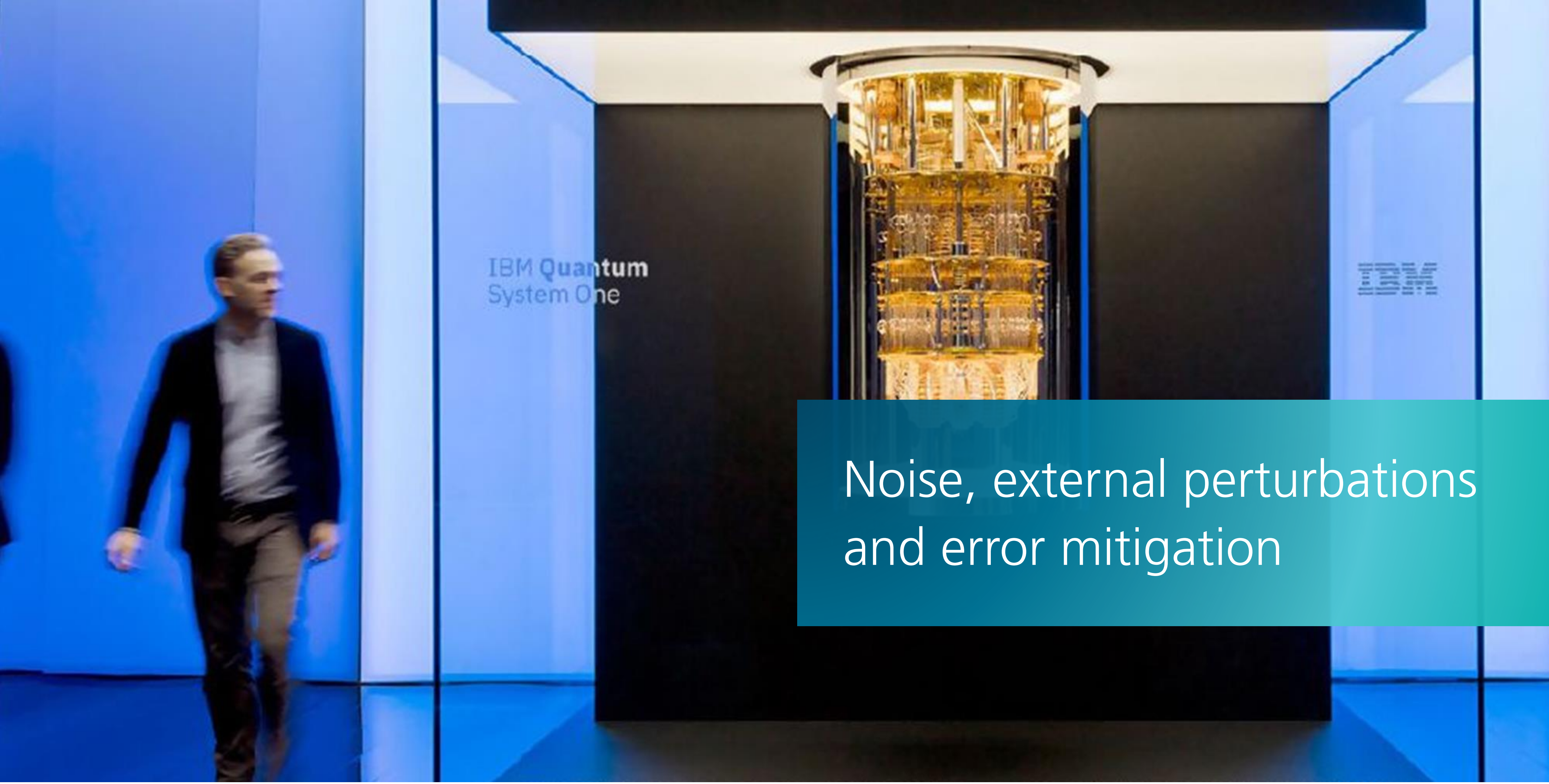
The general working of variational quantum algorithms



[K. Bharti et al., Noisy intermediate-scale quantum (NISQ) algorithms, https://arxiv.org/abs/2101.08448]

Components of variational algorithms

- **Objective function**: Encoding the problem to be solved
- **Cost function**: Function be minimized (by a variational approach)
- **Parametrized quantum circuit** (PQC):
  - With tunable parameters θ to minimize the objective
  - Mesurement: Measurement + basis transformation; input to the cost function
- **Classical optimizer**



Noise, external perturbations and error mitigation

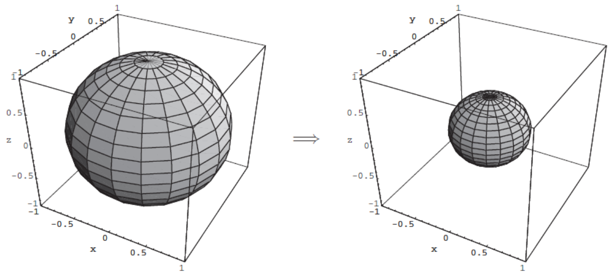
Noise types affecting quantum computers

Different sources of noise affect the calculations on QC:

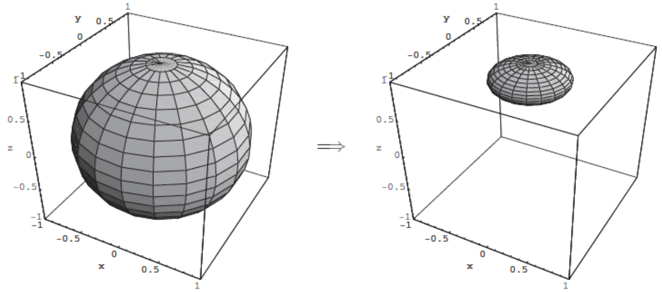
- **Coherent noise**
  (reversible, e.g. by miscalibrated gates)

- **Incoherent noise**:
  - **Readout noise/ Bit flips**
    (Flips the result of the measurement)
  - **Depolarizing noise**
    (a qubit state loses its information due to interactions with the environment)
    - Both phase and superposition lost
  - **Amplitude and phase damping noise**
    (Energy dissipation to the environment)
  - **Phase flip**
    (Change of the phase of the qubit)

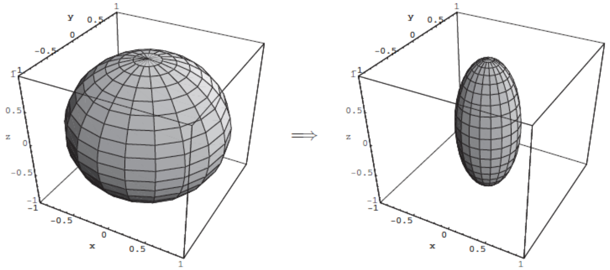
  - **Shot noise** (stochastic, due to the finite number of states)



Depolarizing noise



Amplitude damping



Phase flip

[Nielsen & Chuang]

Cosmic rays and radiation leading to catastrophic bursts

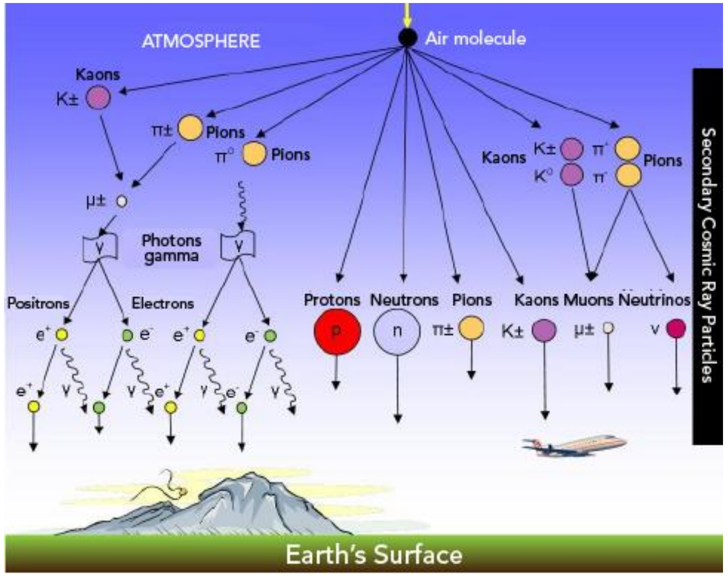
[M. McEwan et al., Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits, Nature Physics 18, 107-111 (Jan 2022)]

Production of high-energetic muons and gamma rays by cosmic rays

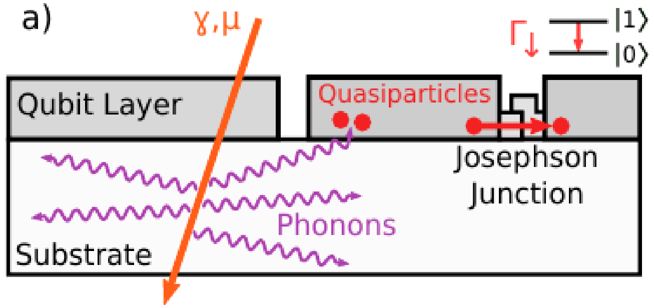
μ, γ from cosmic rays (+ other radiation) may strike superconducting QC chip

Interaction with the matter of the superconducting QC chip:

- Deposition of the energy 100 keV – 1 MeV and therefore >> energy scale of the qubits ~ 25 μeV
- μ, γ inonize substract
- Production of phonons with long lifetime
- Phonons break up Cooper pairs
- + Quasiparticles may tunnel Josephson junction -> resulting in a potential avalanche of quasiparticles
- **Result**: Chip-wide suppression of qubit coherence -> Failure



[https://letstalkscience.ca/educational-resources/backgrounders/what-are-cosmic-rays]



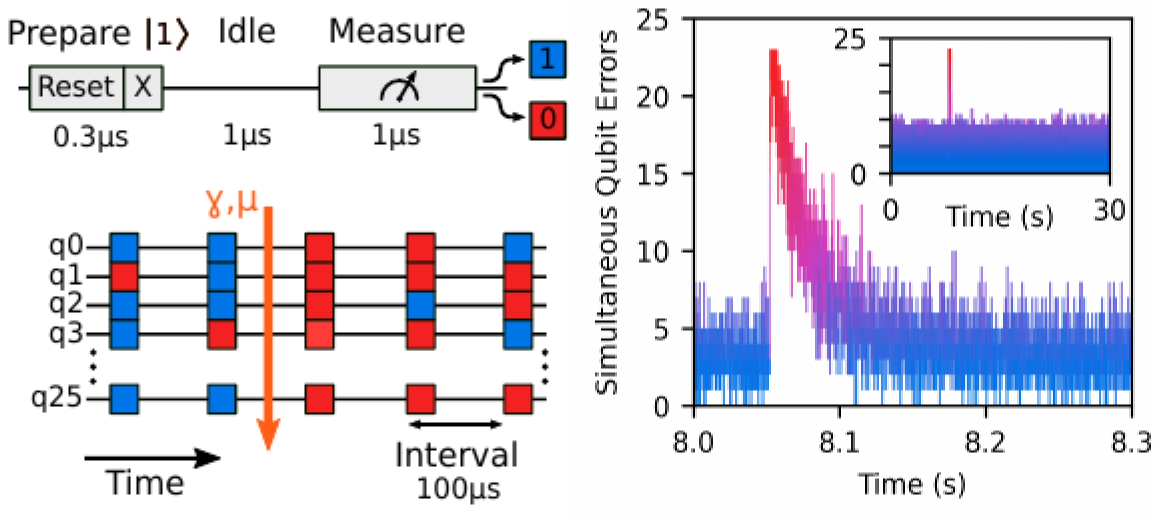
[M. McEwan et al., Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits, Nature Physics 18, 107-111 (Jan 2022)]

Experimental setup

Experiments executed on the Google Sycamore Processor, using 26 qubits with the couplings between the qubits turned off.

Rapid Repetitive Correlated Sampling

- All qubits prepared in state |1>
- Allowed to be idle for 1 µs, then measurement
- Cycles repeated at intervals of 100 µs
- Counts additional errors above decoherence and readout fidelities that are expected.



[M. McEwan et al., Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits, Nature Physics 18, 107-111 (Jan 2022)]

Results

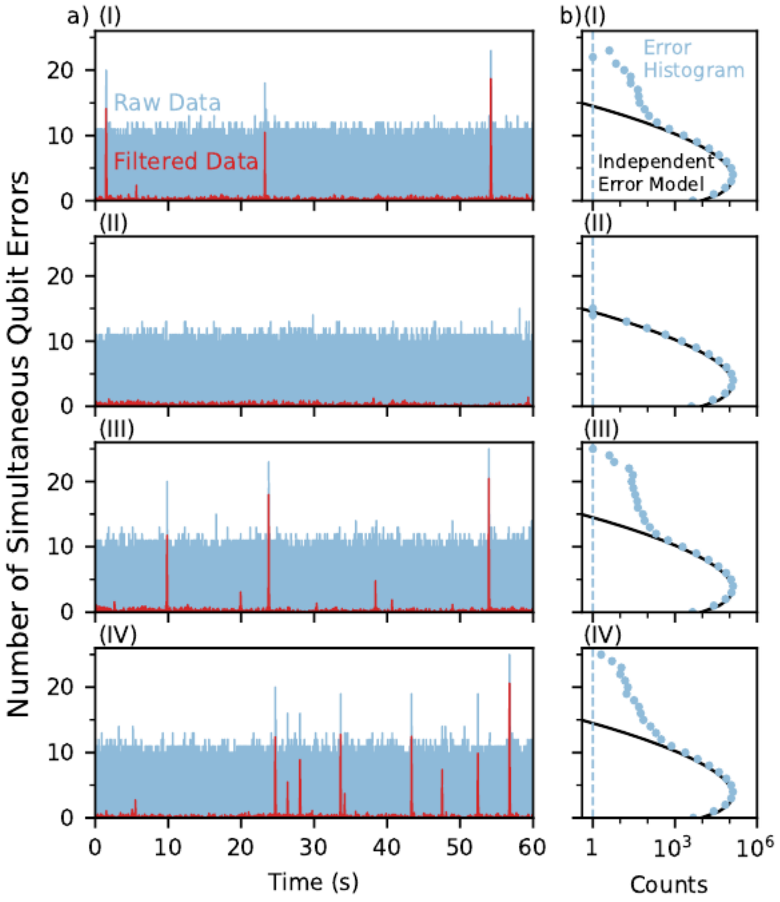
Different datasets taken and analyzed.

Approx. 1 event every 10s

Impact of cosmic rays clearly visible comparing to situation without an event present

Impact of cosmic rays particularly problematic for QAlgs running a couple of hours

Mitigation techniques from astroparticle physics detectors may be helpful in mitigating errors



Impact of noise on the QAOA algorithm

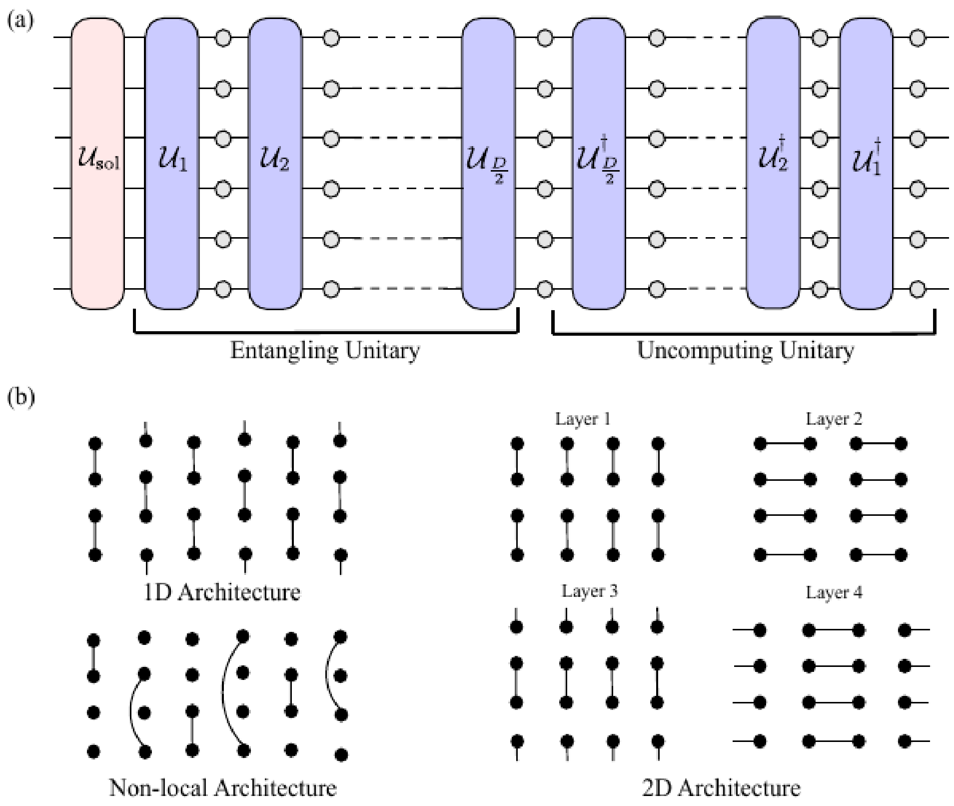
[G. Gonzalez-Garcia et al., Error propagation in NISQ devices for solving classical optimization problems, PRX Quantum 3, 040326]

Noise may impact the trainability of variational algorithms + influence the result quality

Which circuit length and depth is acceptable to still obtain good results?

Theoretical analysis by G. Gonzalez-Garcia et al.:
- Build a model of random circuits
- Start with product states, apply entanglement, disentangle to another product state, measure

Finding: The noise propagates quickly through the circuit



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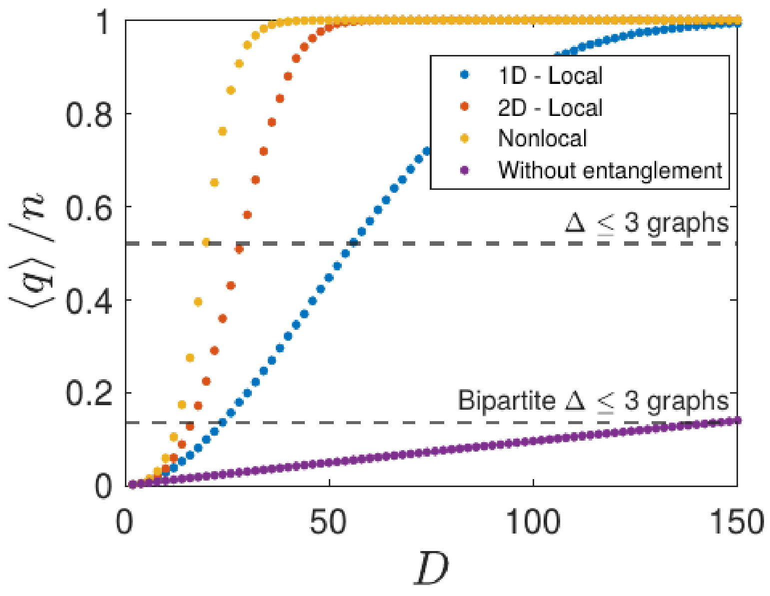
Findings

[G. Gonzalez-Garcia et al., Error propagation in NISQ devices for solving classical optimization problems, PRX Quantum 3, 040326]

Which noise level p is acceptable to obtain a solution to QAOA within a certain multiplicative error of its true solution?

Allowed circuit depths depending on the chip architecture (1D or 2D):

- Maximum circuit depth allowed (*n*: system size):
  - 1D: $\max(O\left(p^{-\frac{1}{2}}\right), O(1/(pn)))$
  - 2D: $\max(O\left(p^{-\frac{1}{3}}\right), O(1/(pn)))$



As soon as half of the qubits depolarized, the average quality of the solution is worse than the quality of the classical solution

A good solution requires a computation ~without errors **-> an error rate below $p \sim 1/(nD)$ is required** (D is the depth of the circuit)

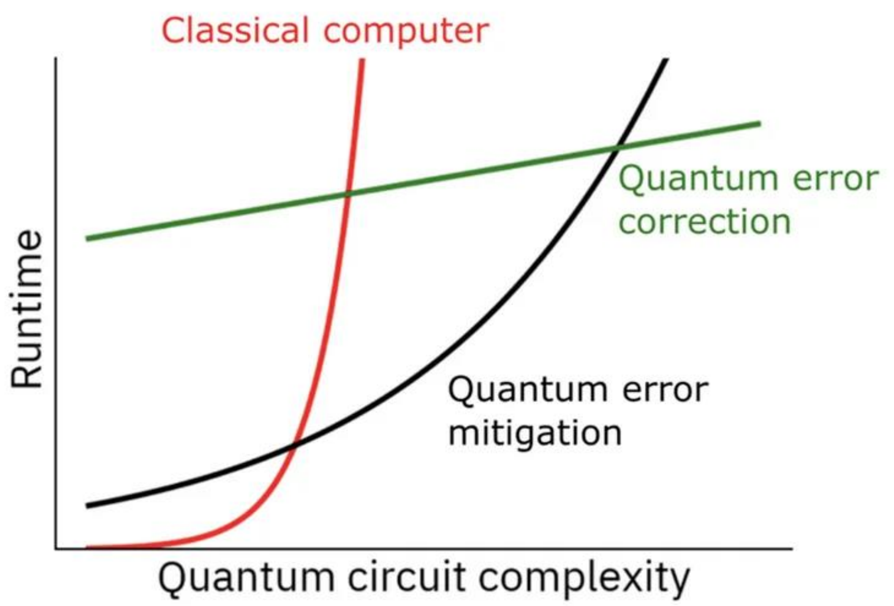
Error mitigation

Why we need it + definition

Noise presents a significant limitation to what we can currently calculate on QC

How can we solve this problem?

- **Alternative** (shorter and small) **algorithms** (quantum advantage unclear)
- **Quantum error correction**:
  - Correction schemes implemented on QC; results in more physical qubits required
  - Various ideas exist
  - Threshold theorem (Aharonov + Ben-Or 1997 + Kitaev 1997):
    - If errors can be reduced below a certain threshold, circuits of arbitrary length possible despite noisy hardware
- **Quantum error mitigation**:
  - Classical post-processing of algorithms to reduce the noise-induced bias
  - Only effective for an ensemble of circuits, the individual result of a circuit evaluation can be worse!



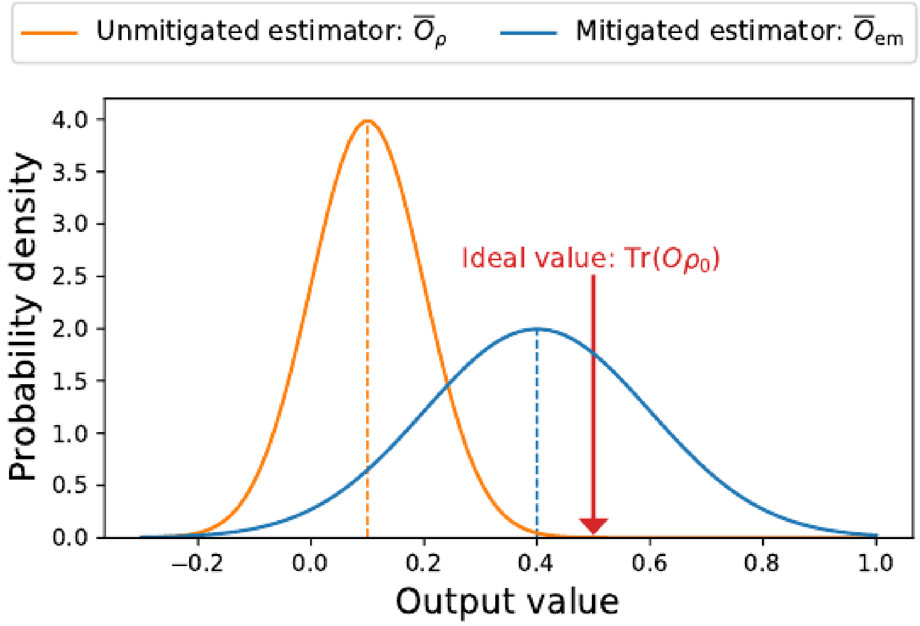
[https://research.ibm.com/blog/gammabar-for-quantum-advantage]

Impact of quantum error mitigation

In general quantified by the impact on the expectation value and the variance of an operator

- The ideal result would be $tr(O\rho_0)$
- Instead of the operator O we rather get the estimator $\hat{O}$
- Calculate:
  - Mean square error: $MSE[\hat{O}] = \mathbb{E}\left[\left(\hat{O} - tr(O\rho_0)\right)^2\right] = Bias[\hat{O}]^2 + Var[\hat{O}]$
  - Variance: $\mathrm{Var}[\hat{O}] = \mathbb{E}[\hat{O}] - \mathbb{E}[\hat{O}]^2$

Noise shifts the mean with respect to ideal value + broadens the variance.
Error mitigation reduces the shifts, but broadens the variance further. (Reason: the error mitigation essentially constructs a more complicated estimator)



[Z. Cal et al, Quantum Error Mitigation, arXiv:2210.00921 [quant-ph]]

Example for an error mitigation technique

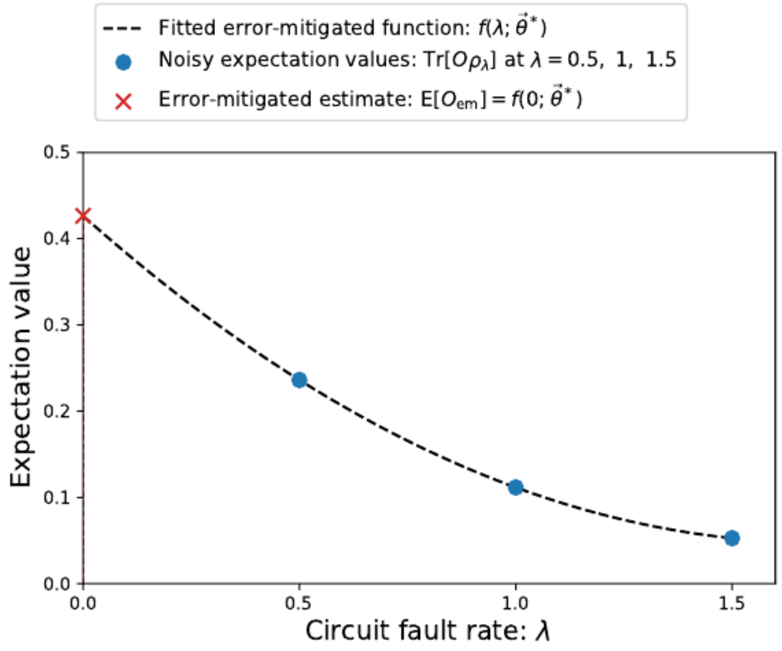
Zero-noise extrapolation

Assume that a circuit has a fault rate of λ for a obtaining a state ρ_λ

This means $tr(O\rho_\lambda)$ is a function of λ

Idea of the zero-noise extrapolation:

- Measure $tr(O\rho_\lambda)$ at the smallest circuit fault rate possible
- Measure $tr(O\rho_\lambda)$ at increasing circuit fault rates (boosted error rates)
- Fit $tr(O\rho_\lambda)$ as function of λ
- (Different fit functions may be applicable depending on the situation)
- Extrapolate to λ = 0



[Z. Cal et al, Quantum Error Mitigation, arXiv:2210.00921 [quant-ph]]

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