Quantum AI

Quantum computing in industry as a student and as a full-time researcher

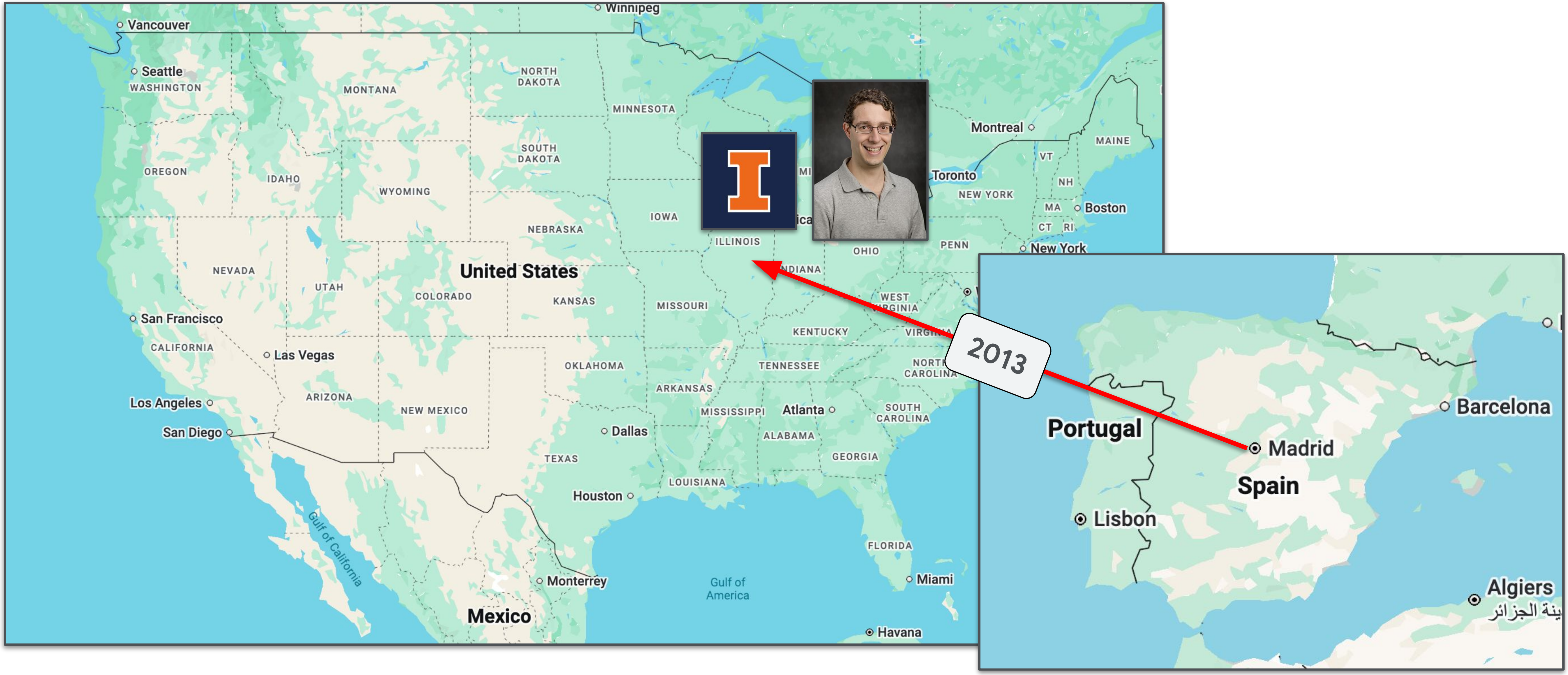
Benjamin Villalonga

Career seminar at UIUC Physics Department
2025-09-11

Google

My path

My path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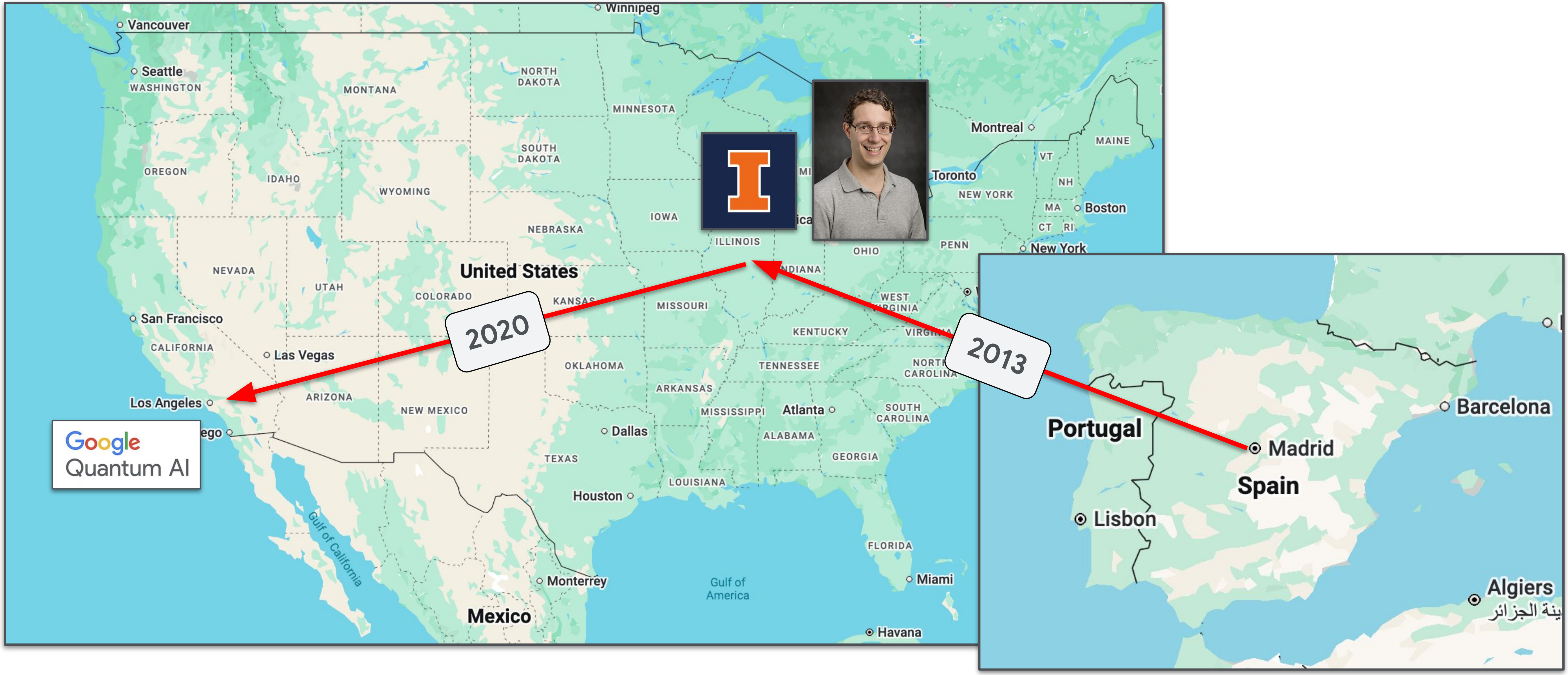
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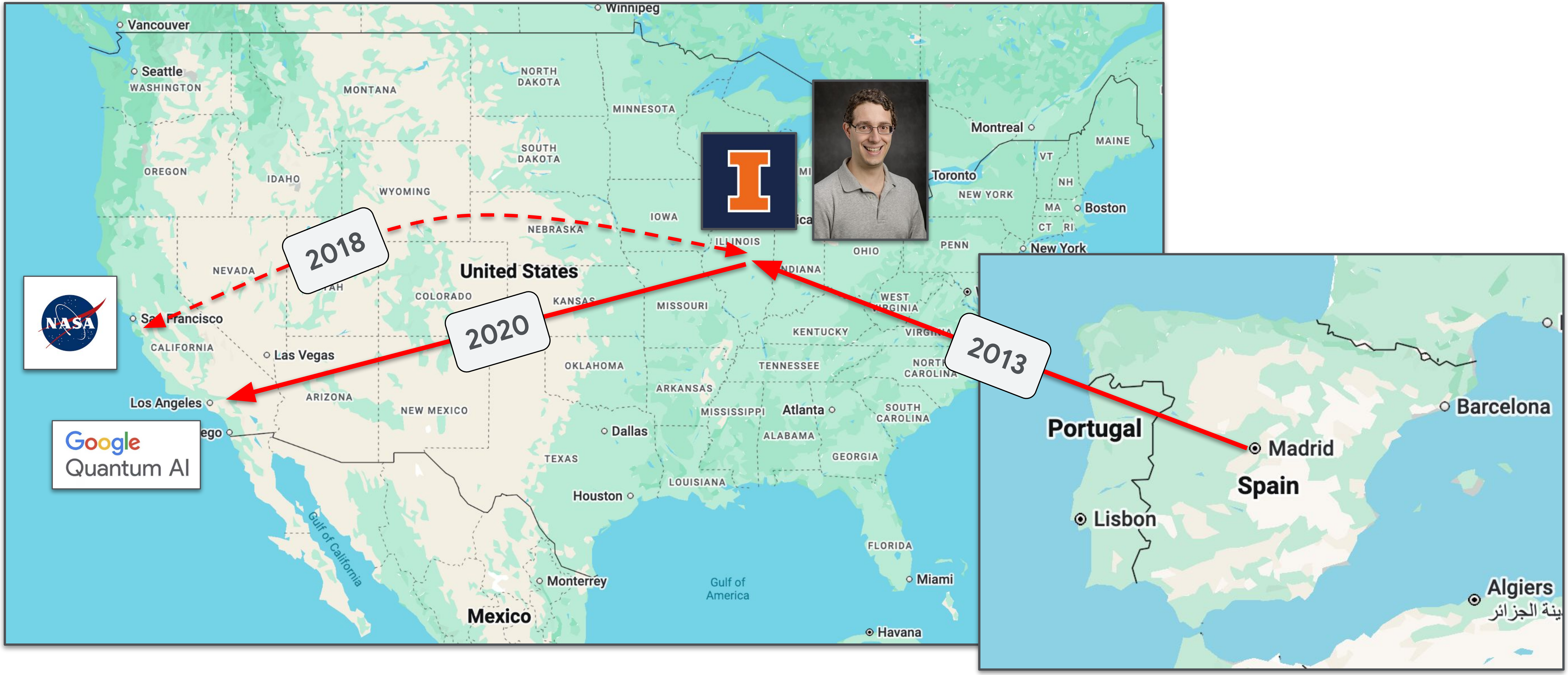
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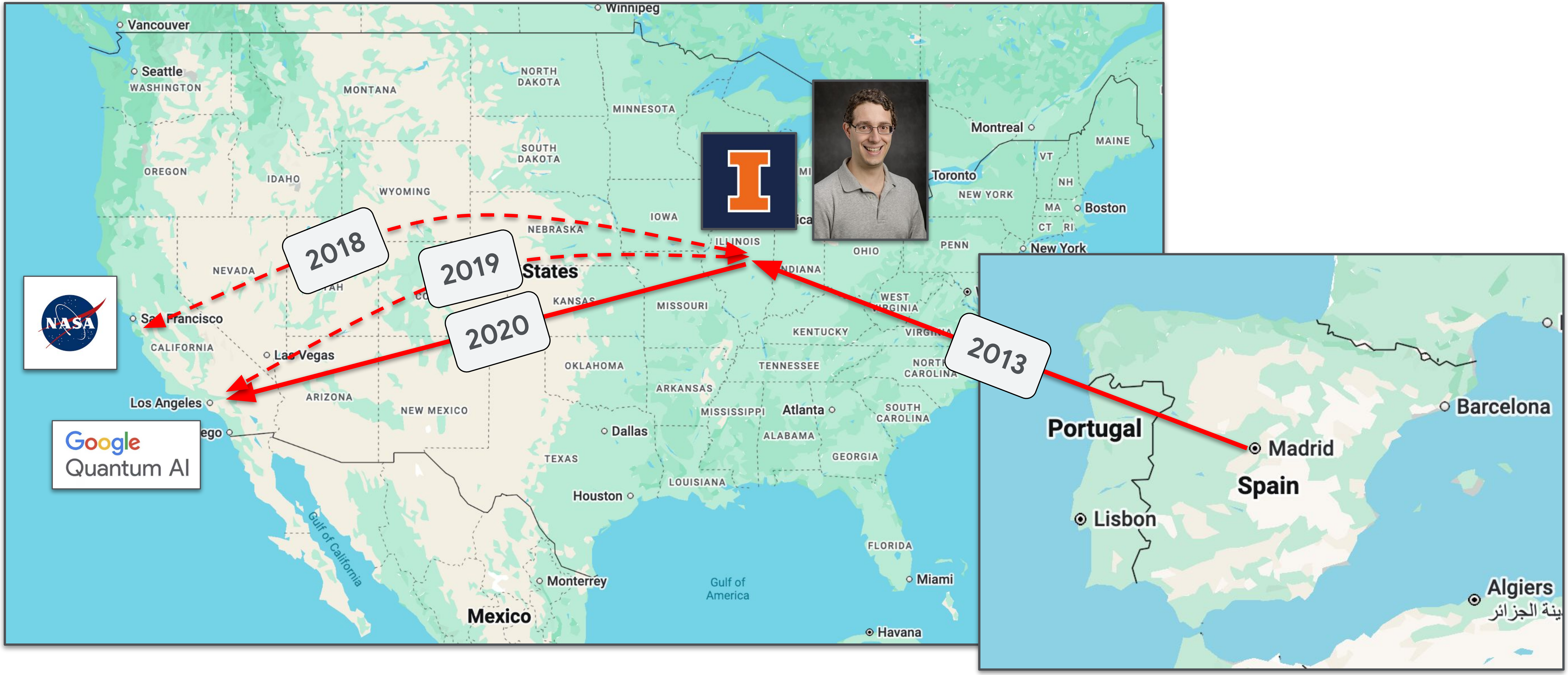
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PhD student

Grad school

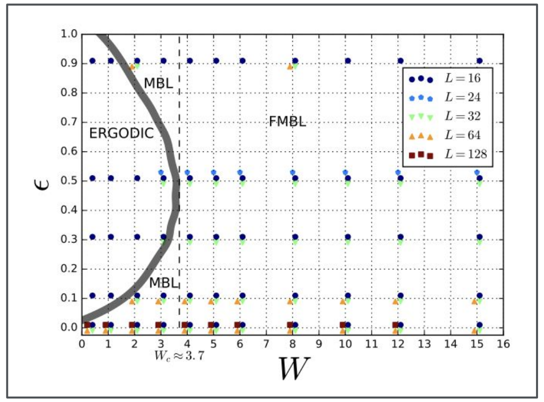
Bryan

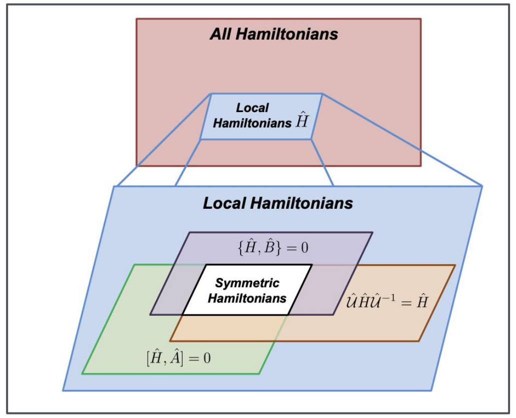
PhD student

Grad school

Many-body localization and other **computational condensed matter problems**

Bryan





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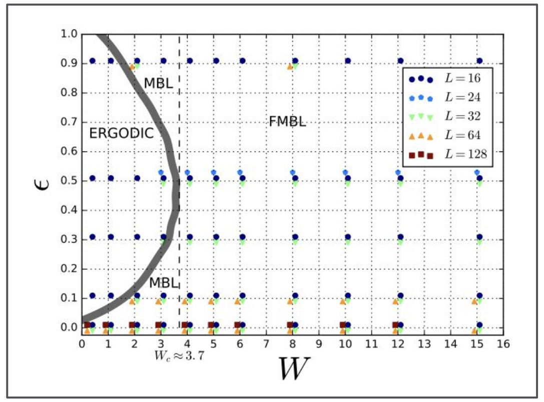
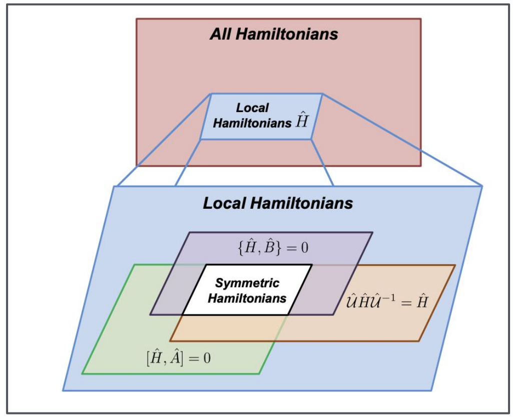
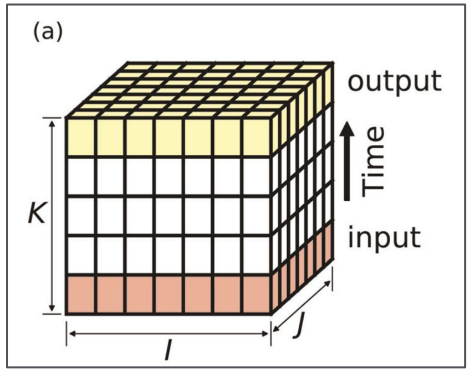




Salvatore



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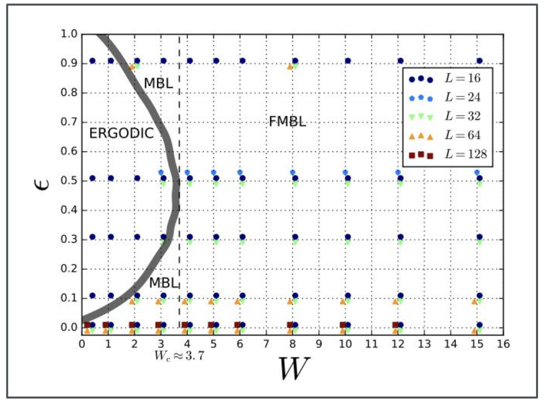

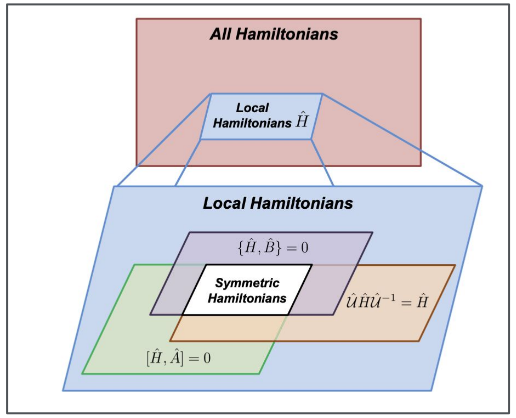

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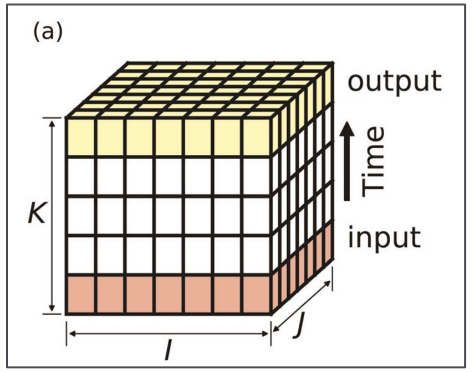


Google Quantum AI

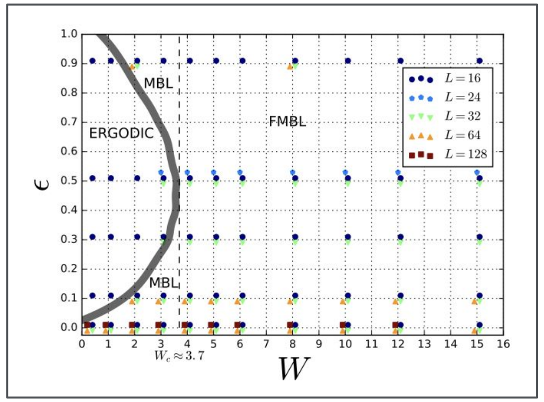
Sergio

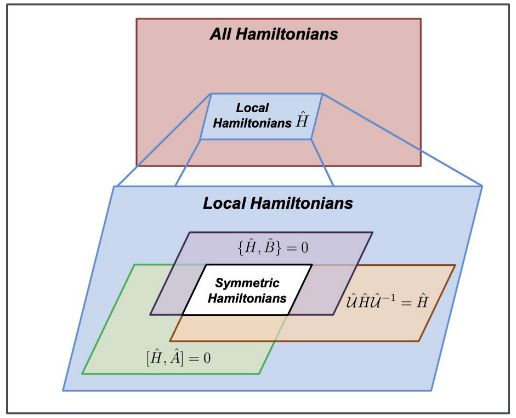
PhD student

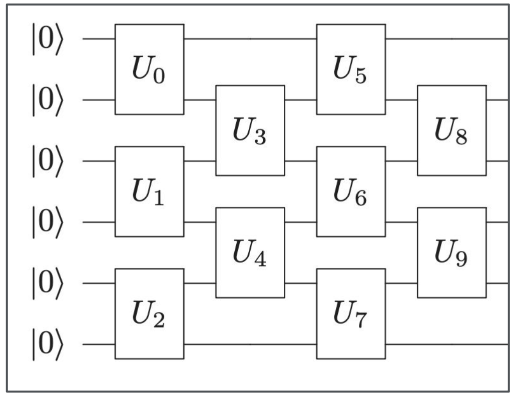
Grad school

Many-body localization and other **computational condensed matter problems** + **quantum information / quantum computing**

Bryan







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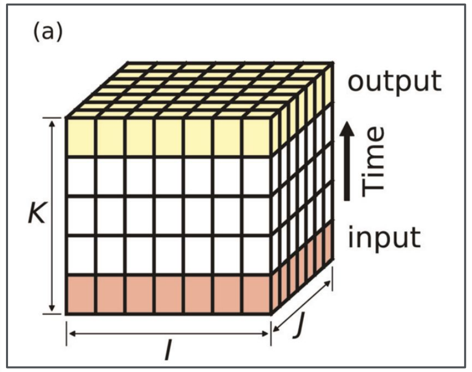

Google Quantum AI

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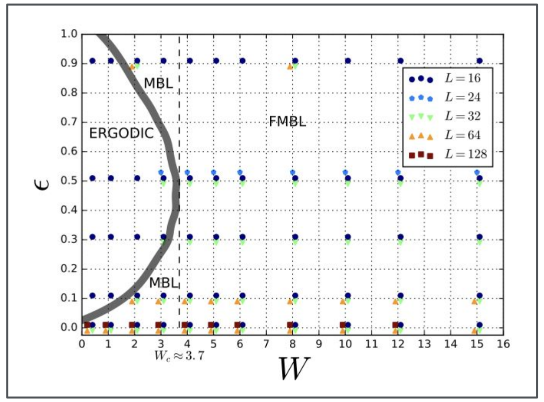

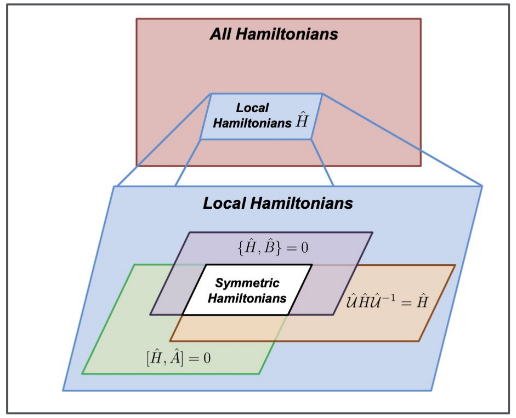

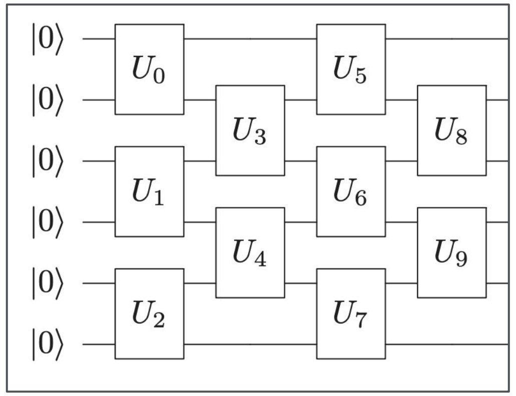

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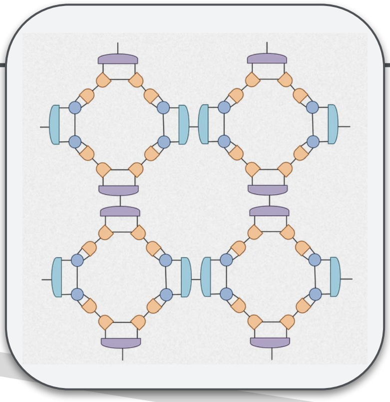
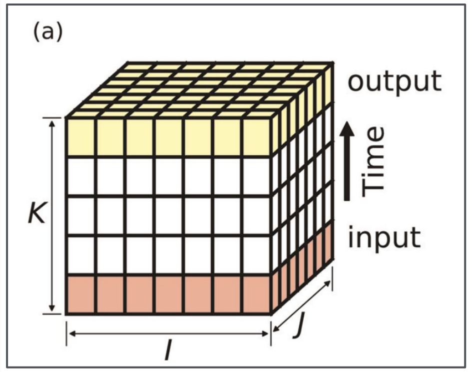


Tensor networks (tensors.net)

Creativity (Gemini)

Salvatore



Google Quantum AI

Sergio

Full time researcher

Google Quantum AI

Full time researcher

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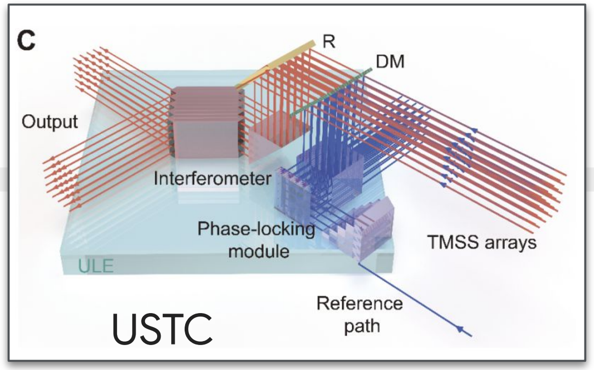
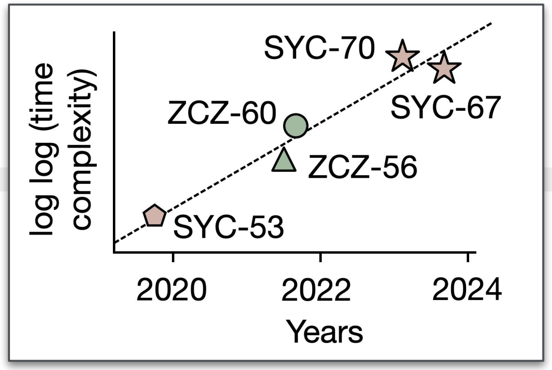
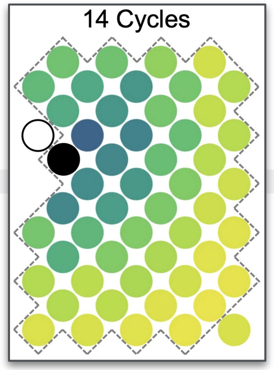
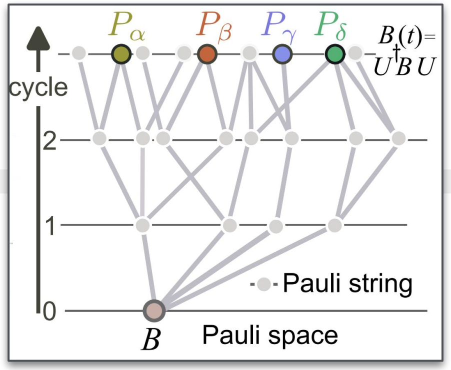
Beyond-classical computations (quantum advantage)









Full time researcher

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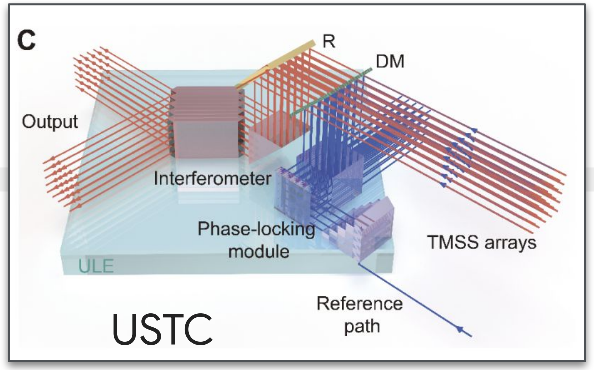
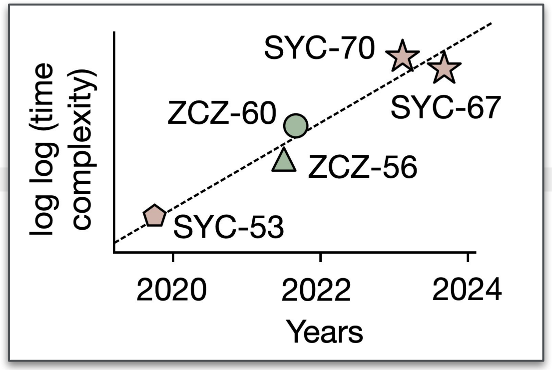
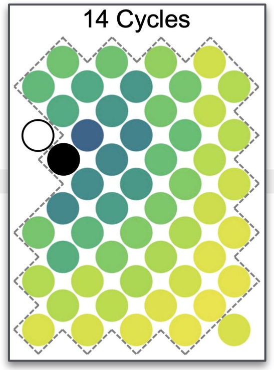
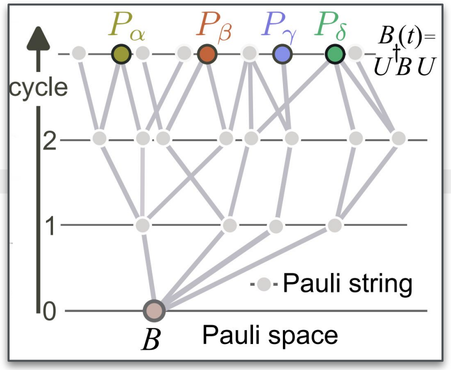
Beyond-classical computations (quantum advantage)

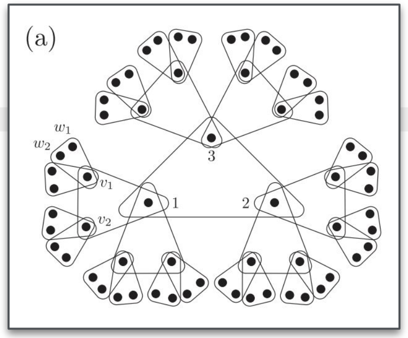


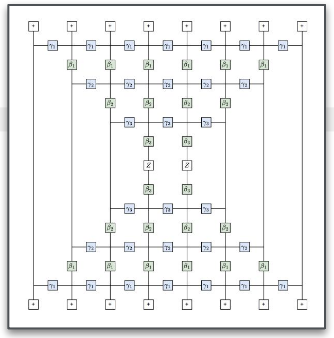






Analysis of quantum algorithms for optimization





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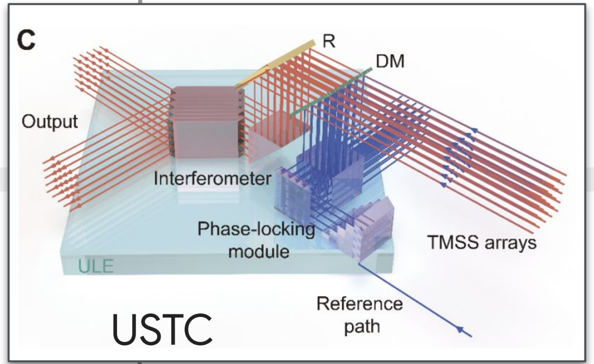
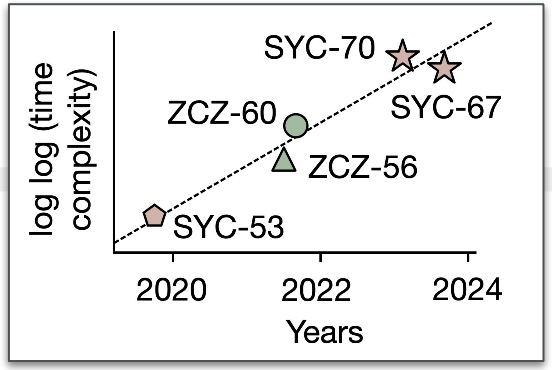
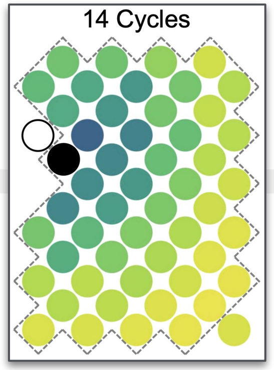
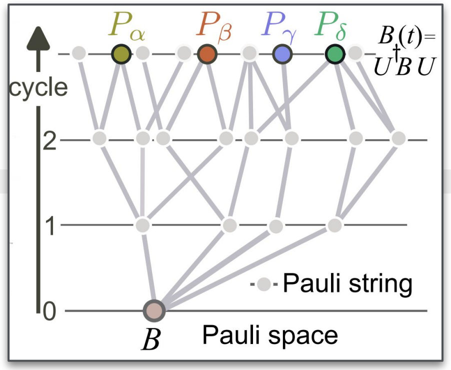
Beyond-classical computations (quantum advantage)









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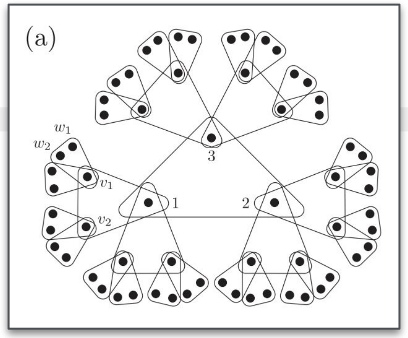
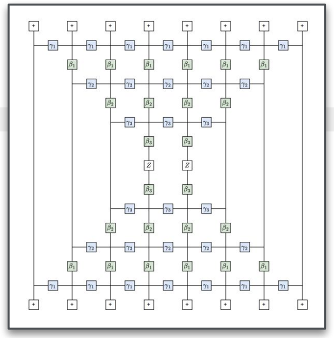
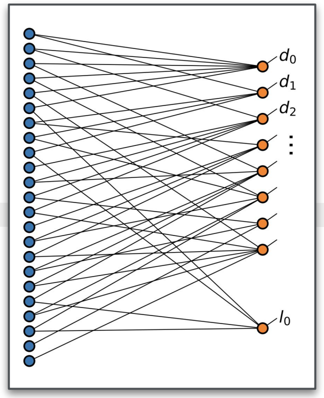




Decoding for quantum error correction experiments



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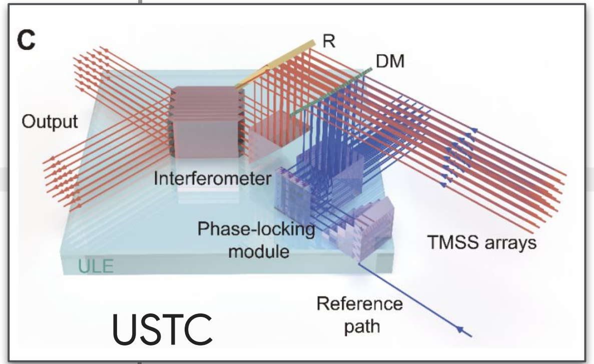
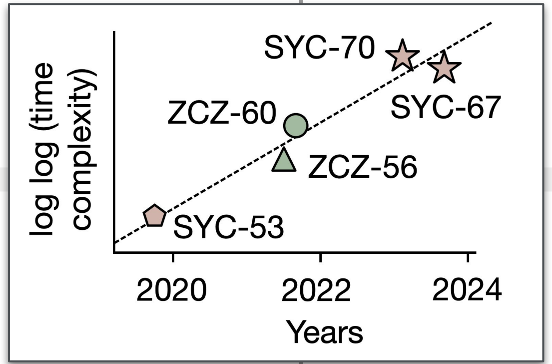
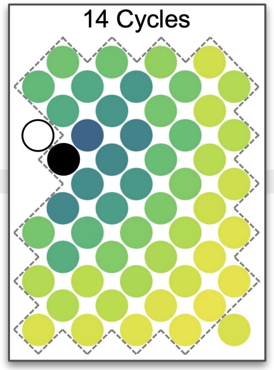
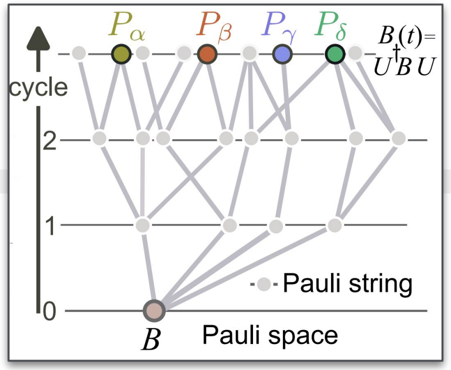
Beyond-classical computations (quantum advantage)









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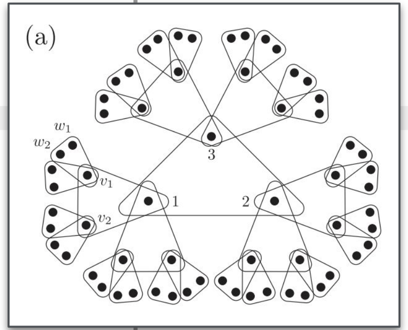

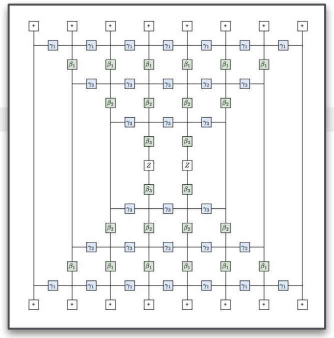

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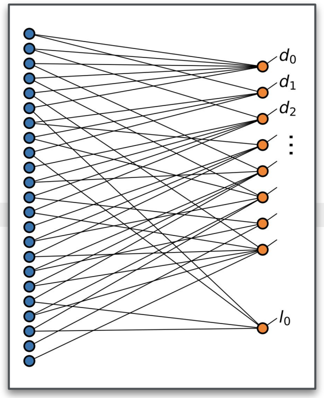
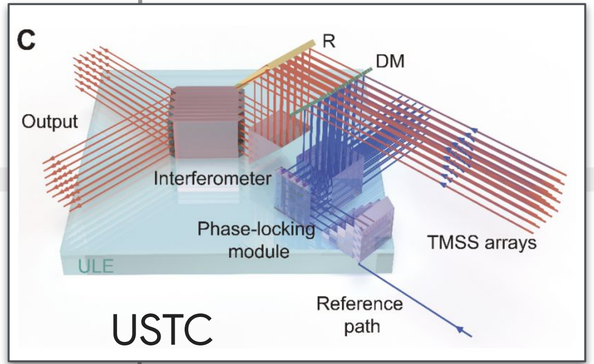


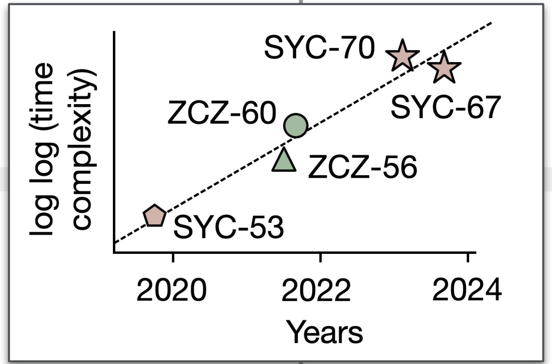
Noisy near term experiments of quantum simulation

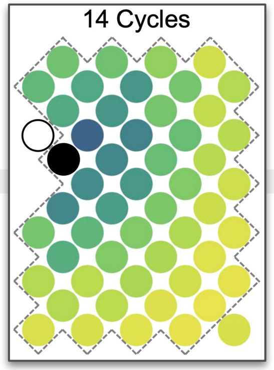
Full time researcher

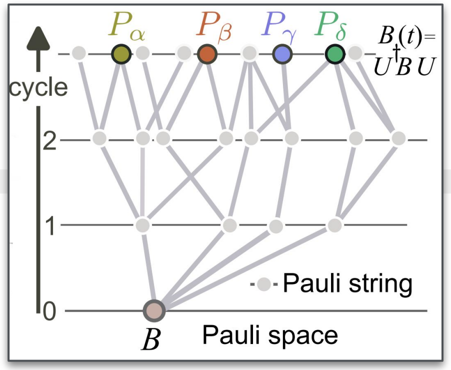
Google Quantum AI

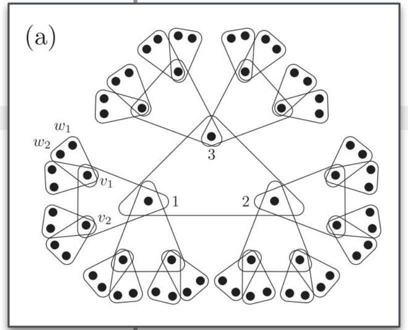
Beyond-classical computations (quantum advantage)

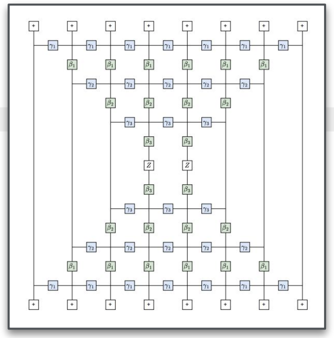




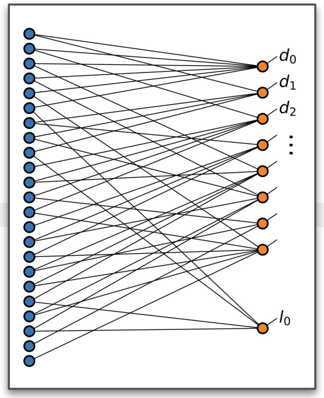








Analysis of quantum algorithms for optimization



Decoding for quantum error correction experiments

Noisy near term experiments of quantum simulation

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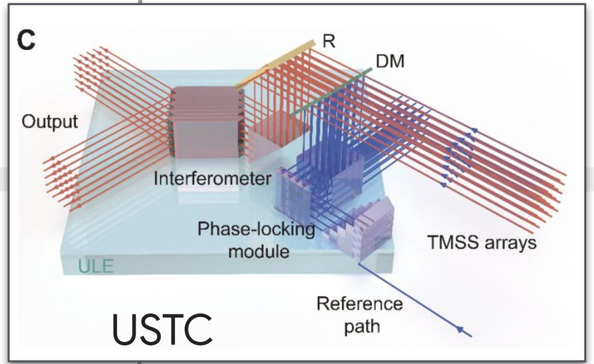
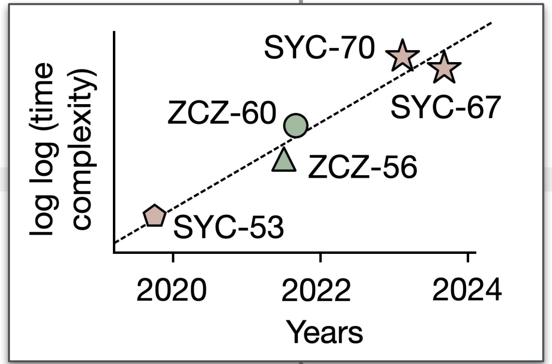
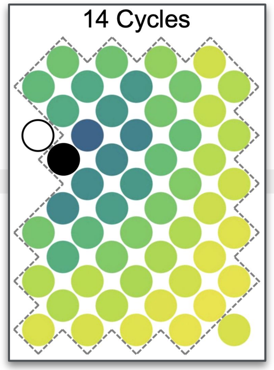
Full time researcher

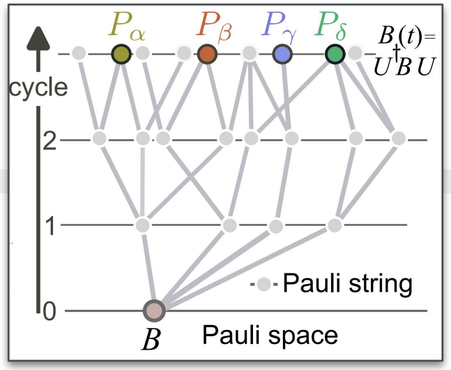
Google Quantum AI

Beyond-classical computations (quantum advantage)









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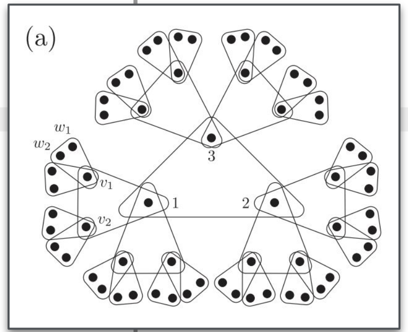

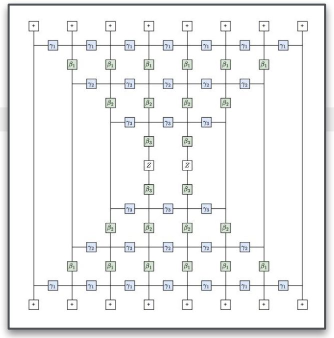

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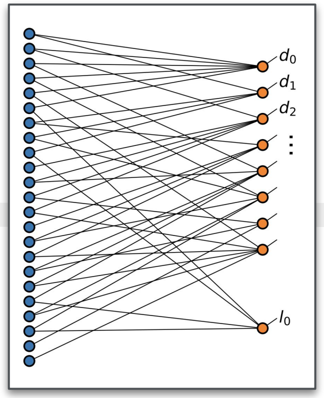

Noisy near term experiments of quantum simulation

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Tensor networks for quantum computing

Nat. Reviews Physics 2025

Lessons (that I constantly forget)

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- **Knowledge and skills accumulate**
  - Anything might be helpful in the future
  - Ideas that you like the most stick longer, more strongly, and have more impact. Try to follow those

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- **Knowledge and skills accumulate**
  - Anything might be helpful in the future
  - Ideas that you like the most stick longer, more strongly, and have more impact. Try to follow those
- **Some of these skills serve as bridges**
  - Learning new areas or changing research directions, projects, positions, ...
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Lessons (that I constantly forget)

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  - Especially in such a *young and interdisciplinary* field: a lot has to be explored, and different ideas or angles might open a lot of room for exploration
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- **Collaborating is key**
  - You learn, network, get unstuck, don’t reinvent the wheel, work on relevant problems, ...
  - With very few examples, good collaborative researchers are much more prolific
  - *Sharing* rather than *jumping on* opportunity to collaborate
  - At the personal level, usually generous researchers get further, both technically and career-wise

Quantum computing and (some of) our work

Our mission is to build quantum computing for otherwise unsolvable problems

Google Quantum AI

A new computational model

A new computational model

Classical physics ↔ classical computers

state	**0**0110
operation (not)	↓
state	**1**01**10**
operation (cnot)	↓
state	001**11**
operation (...)	↓
	...

bits

Microchips, abacus, person+pencil (textbook calculations), ...

A new computational model

Classical physics ↔ classical computers

state	00110
operation (not)	↓
state	10110
operation (cnot)	↓
state	00111
operation (...)	↓
	…

bits

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Quantum physics ↔ quantum computers

```
0.01|00000> - 0.03|00001> - 0.07|00010> + …
                    ↓
0.04|00000> + 0.12|00001> + 0.02|00010> + …
                    ↓
0.20|00000> + 0.00|00001> - 0.16|00010> + …
                    ↓
                    …
```

qubits

Superconducting qubits, trapped ions, photons, neutral atoms, ...

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                    ↓
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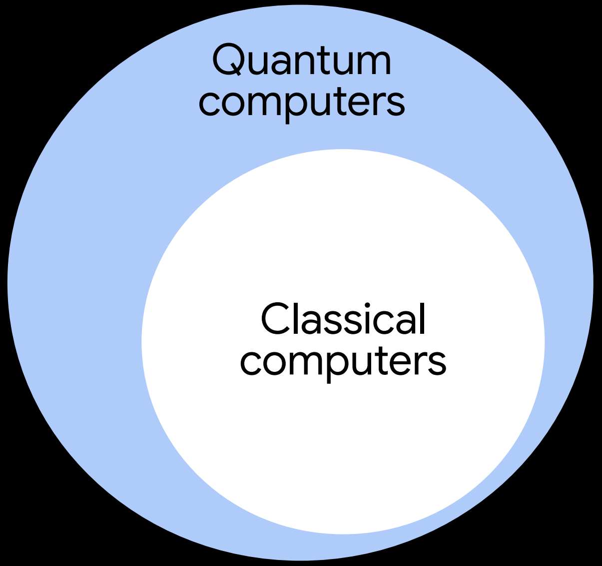
                    ↓
                   ...
```

qubits

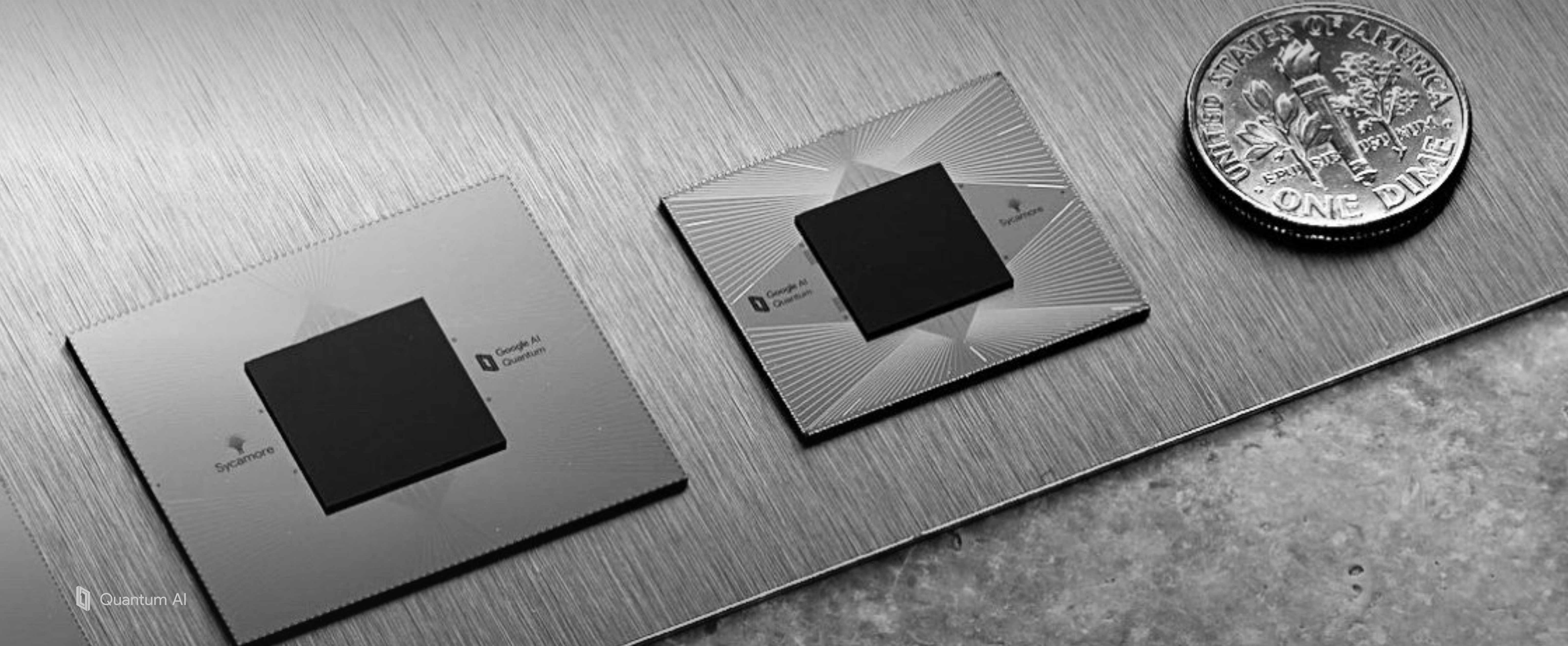
Superconducting qubits, trapped ions, photons, neutral atoms, ...

A computational model *beyond Turing machines*

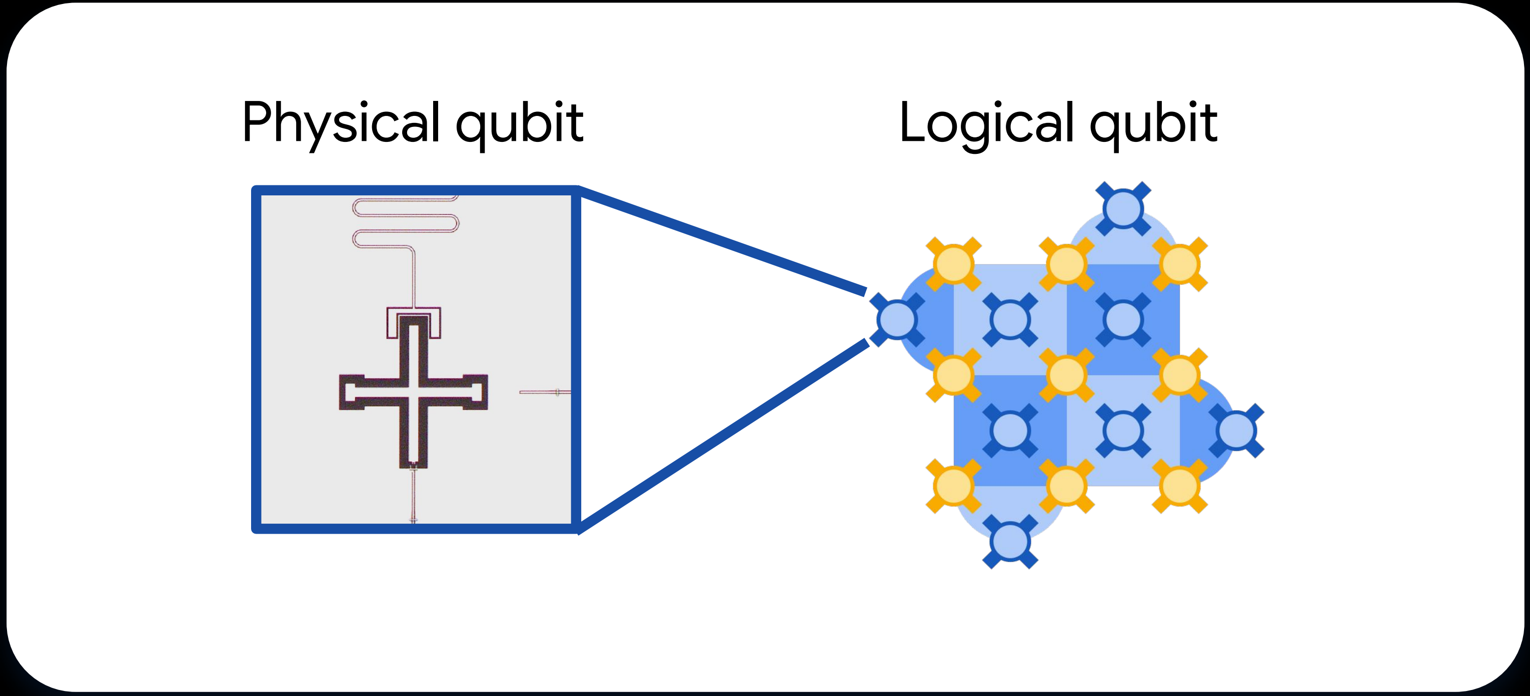
with application in chemistry, materials science, cryptography, optimization, machine learning, ...



Superconducting qubits are printed on a 2D substrate and cooled down to close to near absolute zero temperature



Quantum error correction



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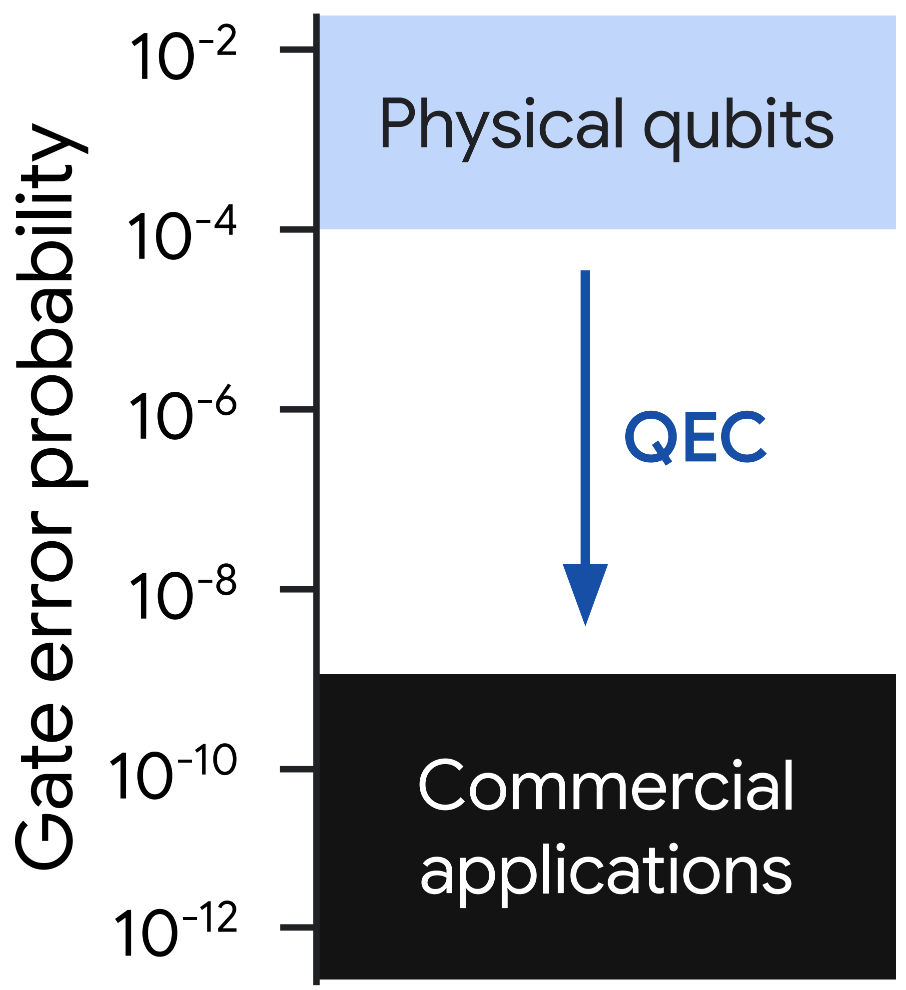

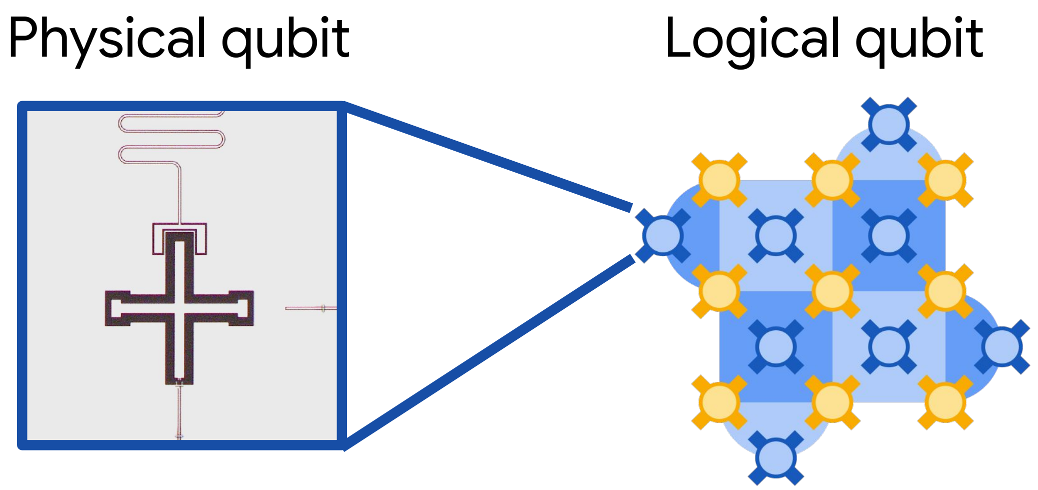

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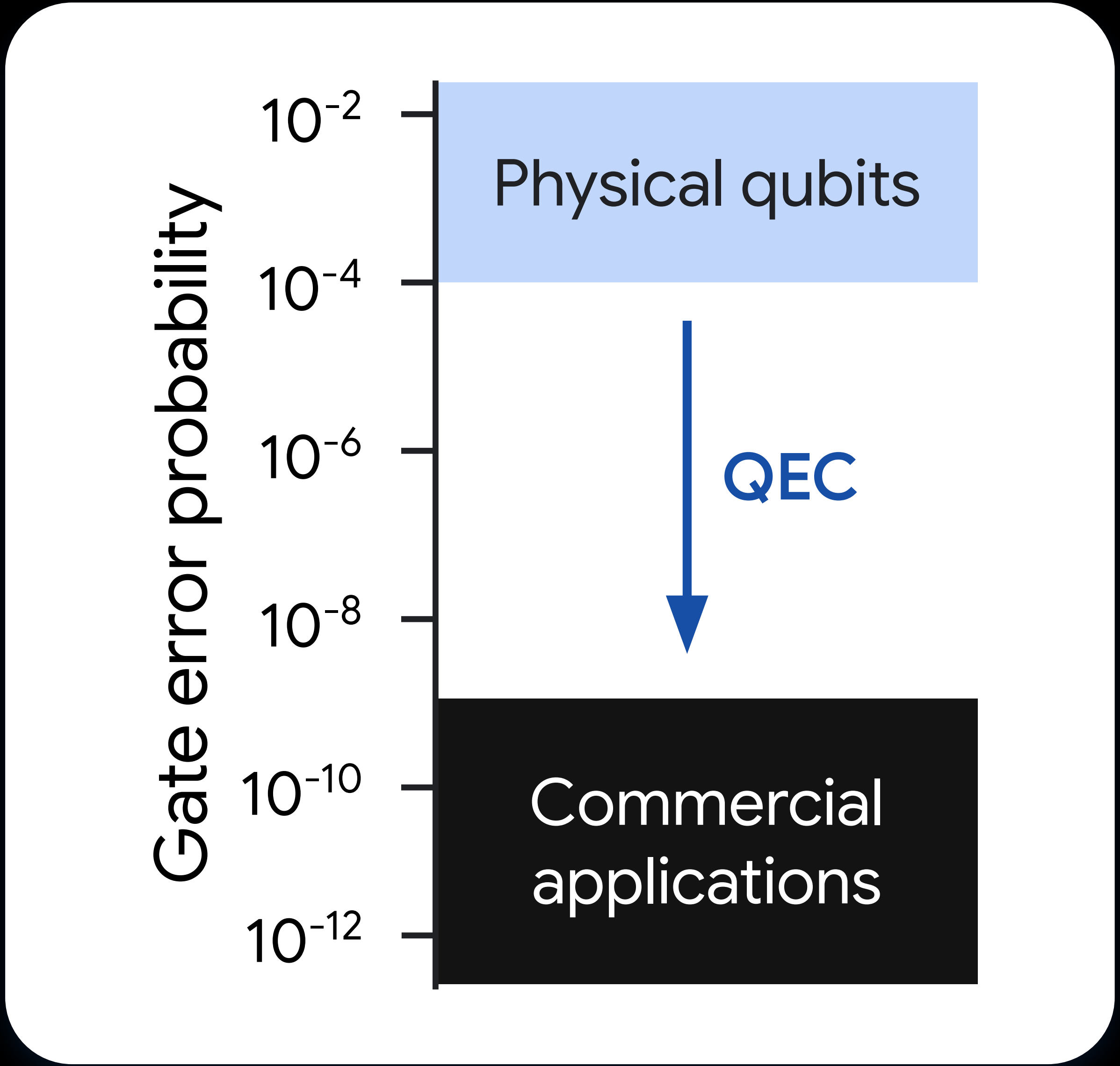

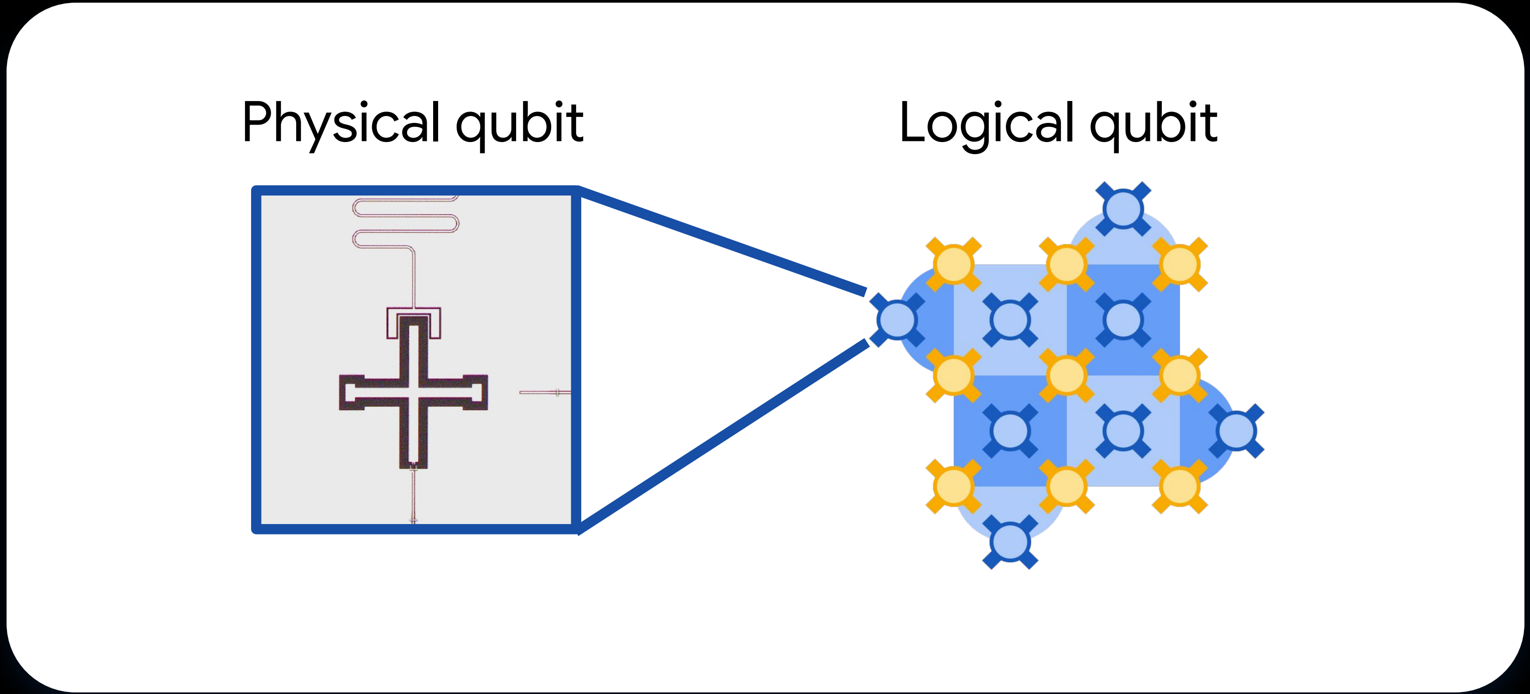

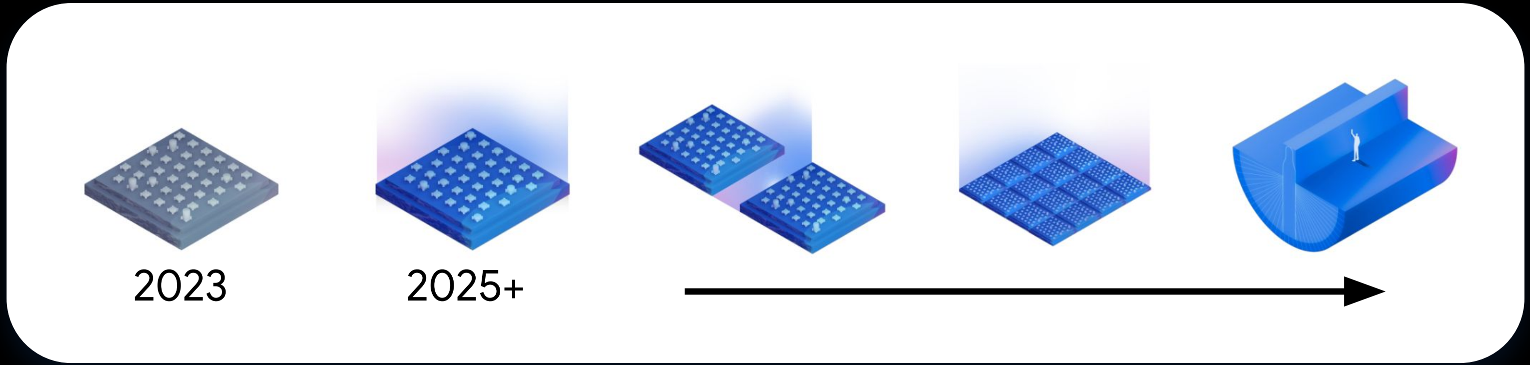

Quantum error correction - progress

Nature, 2023


Article

Suppressing quantum errors by scaling a surface code logical qubit

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Google Quantum AI*

Practical quantum computing will require error rates well below those achievable with physical qubits. Quantum error correction[1,2] offers a path to algorithmically relevant error rates by encoding logical qubits within many physical qubits, for which increasing the number of physical qubits enhances protection against physical errors. However, introducing more qubits also increases the number of error sources, so the density of errors must be sufficiently low for logical performance to improve with increasing code size. Here we report the measurement of logical qubit performance scaling across several code sizes, and demonstrate that our system of superconducting qubits has sufficient performance to overcome the additional errors from increasing qubit number. We find that our distance-5 surface code logical qubit modestly outperforms an ensemble of distance-3 logical qubits on average, in terms of both logical error probability over 25 cycles and logical error per cycle ((2.914 ± 0.016)% compared to (3.028 ± 0.023)%). To investigate damaging, low-probability error sources, we run a distance-25 repetition code and observe a 1.7×10^{-6} logical error per cycle floor set by a single high-energy event (1.6×10^{-7} excluding this event). We accurately model our experiment, extracting error budgets that highlight the biggest challenges for future systems. These results mark an experimental demonstration in which quantum error correction begins to improve performance with increasing qubit number, illuminating the path to reaching the logical error rates required for computation.

Since Feynman's proposal to compute using quantum mechanics[3], many potential applications have emerged, including factoring[4], optimization[5], machine learning[6], quantum simulation[7] and quantum chemistry[8]. These applications often require billions of quantum operations[9–11] and state-of-the-art quantum processors typically have error rates around 10^{-3} per gate[12–17], far too high to execute such large circuits. Fortunately, quantum error correction can exponentially suppress the operational error rates in a quantum processor, at the expense of temporal and qubit overhead[18,19].

Several works have reported quantum error correction on codes able to correct a single error, including the distance-3 Bacon–Shor[20], colour[21], five-qubit[22], heavy-hexagon[23] and surface[24,25] codes, as well as continuous variable codes[26–29]. However, a crucial question remains of whether scaling up the error-correcting code size will reduce logical error rates in a real device. In theory, logical errors should be reduced if physical errors are sufficiently sparse in the quantum processor. In practice, demonstrating reduced logical error requires scaling up a device to support a code that can correct at least two errors, without sacrificing state-of-the-art performance. In this work we report a 72-qubit superconducting device supporting a 49-qubit distance-5 ($d = 5$) surface code that narrowly outperforms its average subset 17-qubit distance-3 surface code, demonstrating a critical step towards scalable quantum error correction.

Surface codes with superconducting qubits

Surface codes[30–34] are a family of quantum error-correcting codes that encode a logical qubit into the joint entangled state of a $d \times d$ square of physical qubits, referred to as data qubits. The logical qubit states are defined by a pair of anti-commuting logical observables X_L and Z_L. For the example shown in Fig. 1a, a Z_L observable is encoded in the joint Z-basis parity of a line of qubits that traverses the lattice from top to bottom, and likewise an X_L observable is encoded in the joint X-basis parity traversing left to right. This non-local encoding of information protects the logical qubit from local physical errors, provided we can detect and correct them.

To detect errors, we periodically measure X and Z parities of adjacent clusters of data qubits with the aid of $d^2 - 1$ measure qubits interspersed throughout the lattice. As shown in Fig. 1b, each measure qubit interacts with its neighbouring data qubits to map the joint data qubit parity onto the measure qubit state, which is then measured. Each parity measurement, or stabilizer, commutes with the logical observables of the encoded qubit as well as every other stabilizer. Consequently, we can detect errors when parity measurements change unexpectedly, without disturbing the logical qubit state.

A decoder uses the history of stabilizer measurement outcomes to infer likely configurations of physical errors on the device. We can then

*A list of authors and their affiliations appears at the end of the paper.

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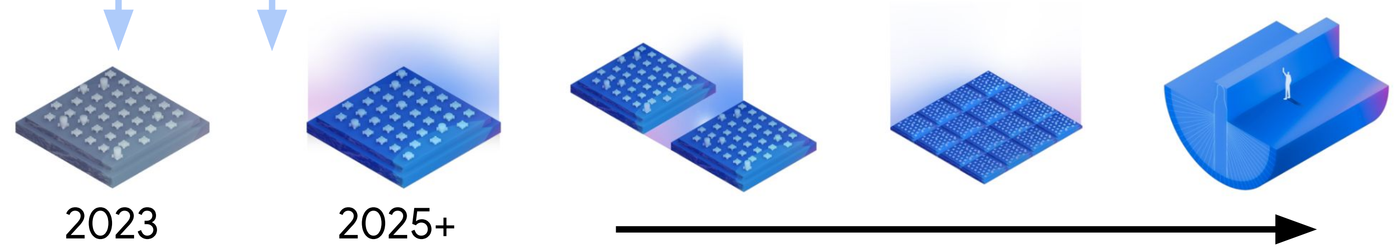
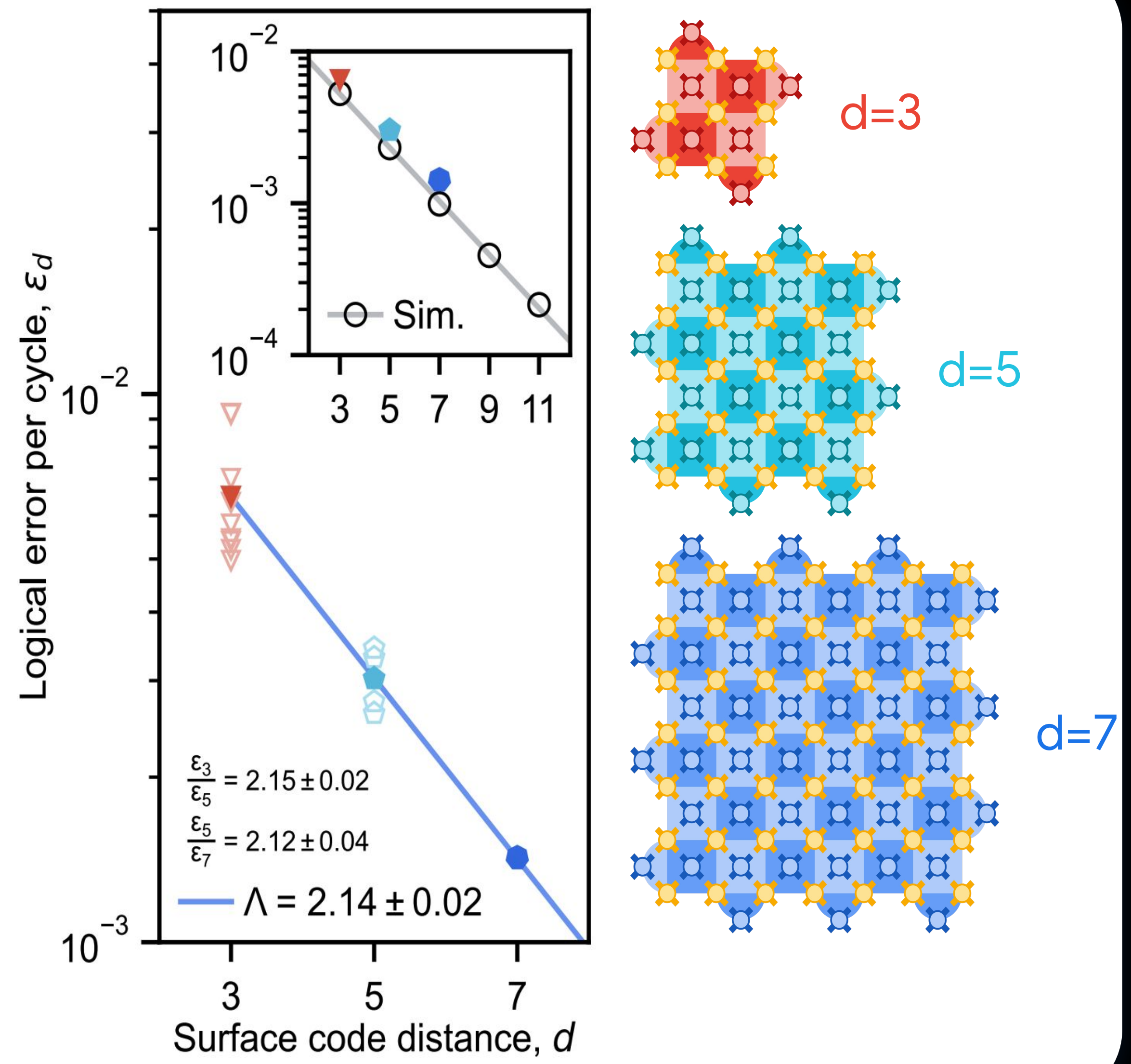
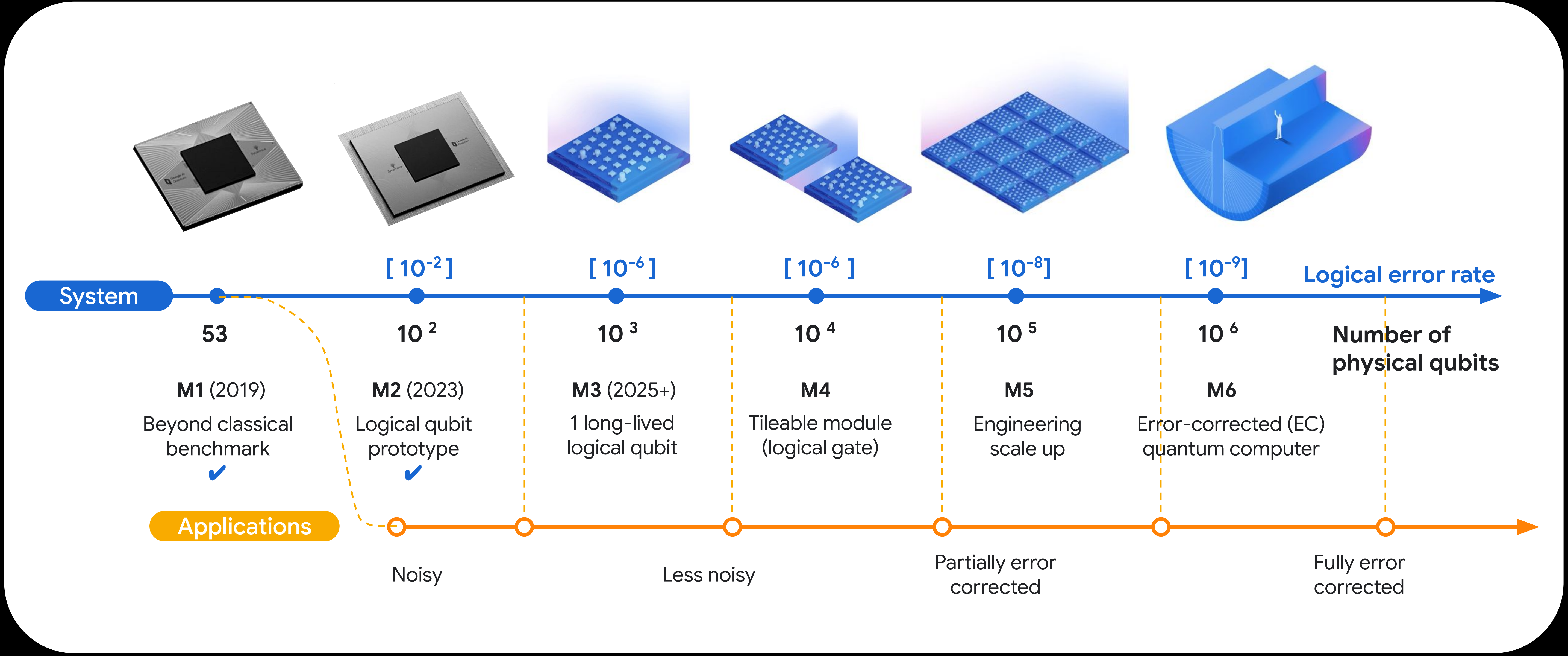
- Logical qubit better than any physical qubit
- 10x reduction compared to 2023

2024





Long term roadmap & near term machines



Can we show *beyond-classical* capabilities before we have a full-scale, error-corrected quantum computer?

Random circuit sampling

Nature, 2019

Article

Quantum supremacy using a programmable superconducting processor

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Random circuit sampling

Nature, 2019

Article

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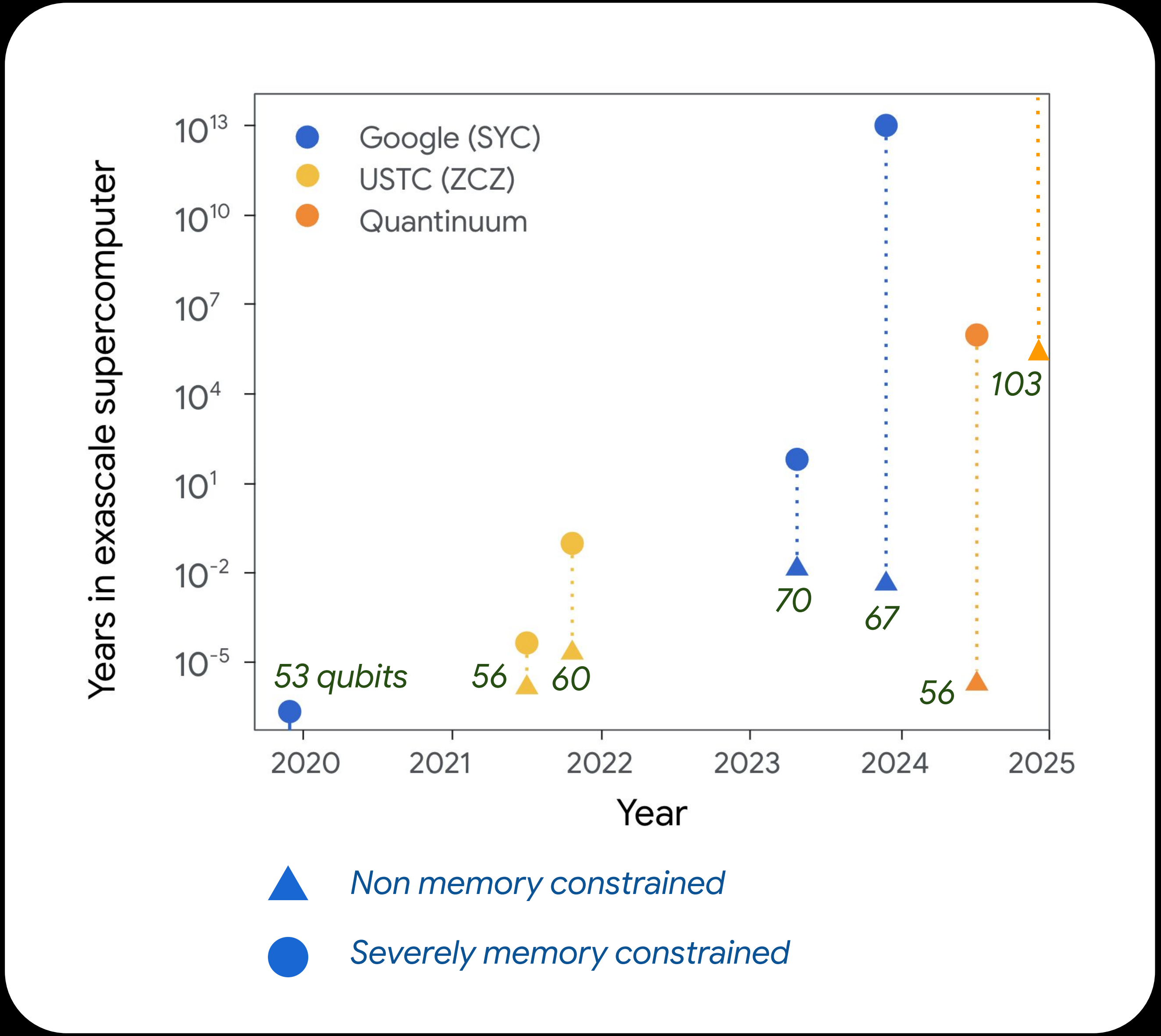
past few years[42–50]. We expect that lower simulation costs than reported here will eventually be achieved, but we also expect that they will be consistently outpaced by hardware improvements on larger quantum processors.

Random circuit sampling - progress



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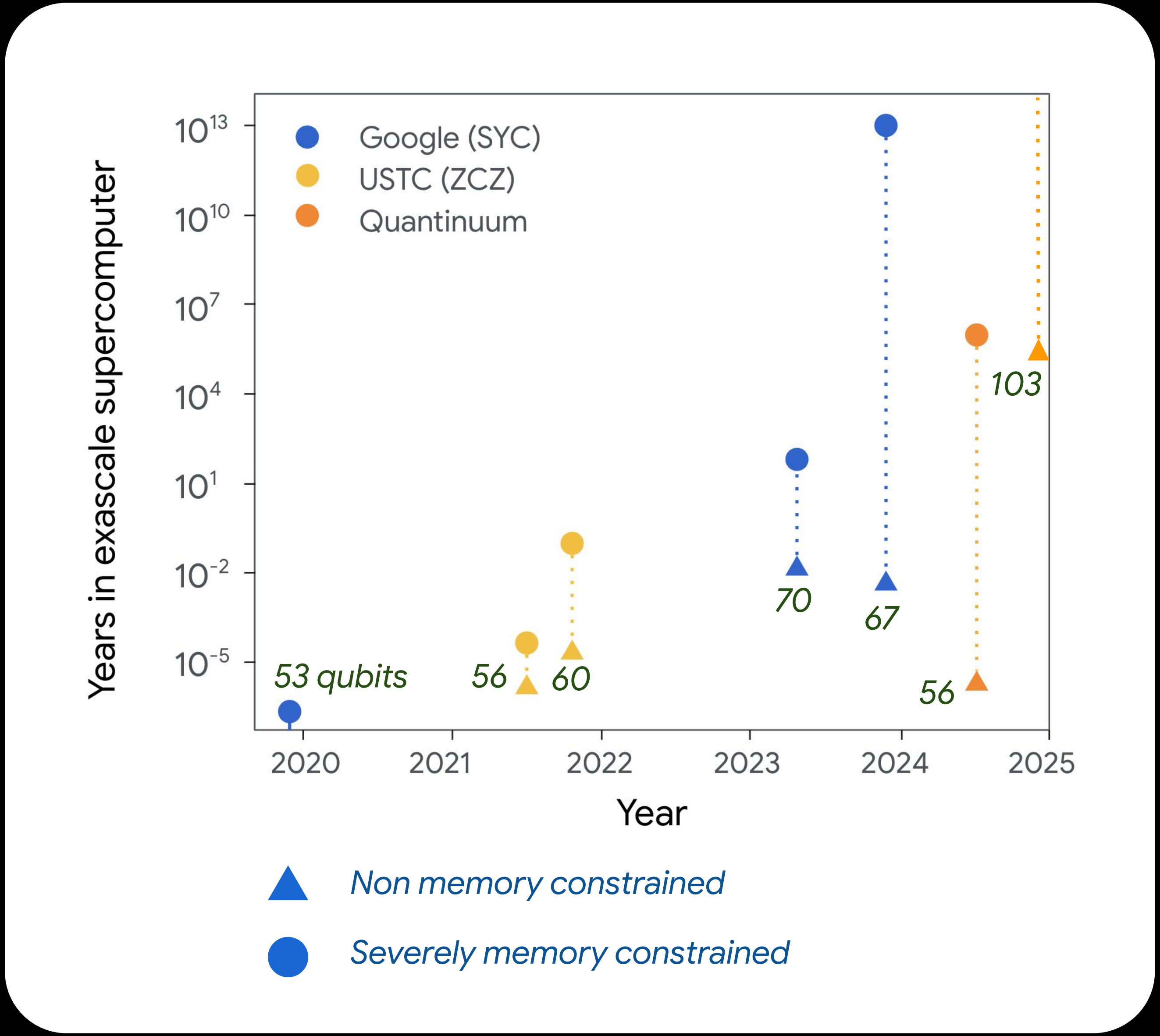


Reduction in *component error rates*

↓

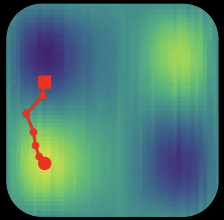
Access to larger computational volumes (number of qubits, computational depth)

↓

Vastly more complex computations

Can we show *beyond-classical* capabilities *with application* before we have a full-scale, error-corrected quantum computer?

Extensive work towards application



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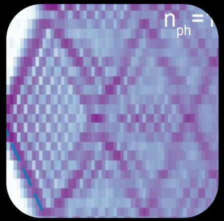

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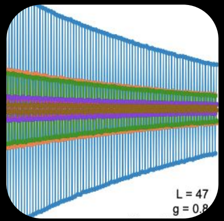

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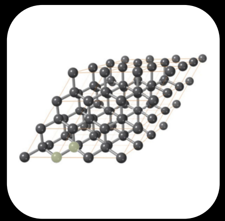

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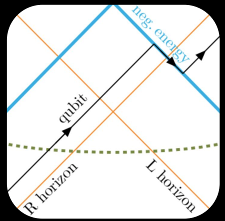

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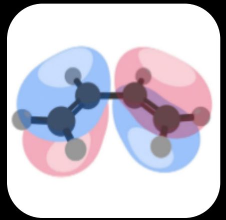

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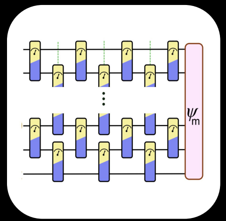

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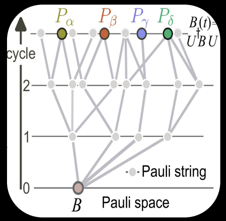

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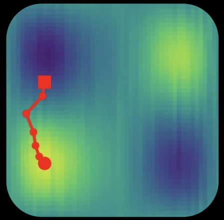

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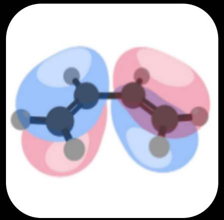

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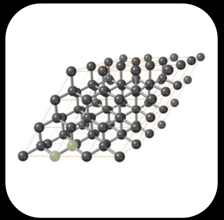

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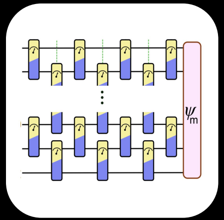

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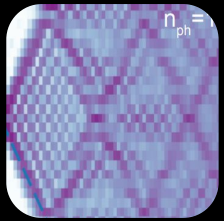

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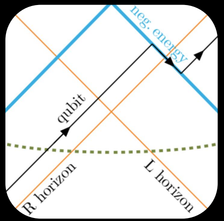

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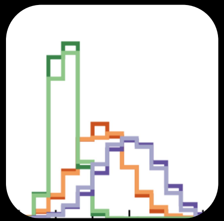

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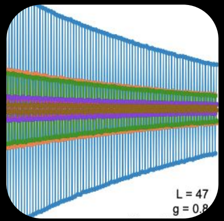

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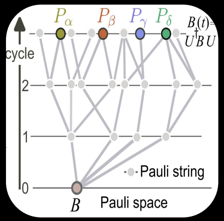

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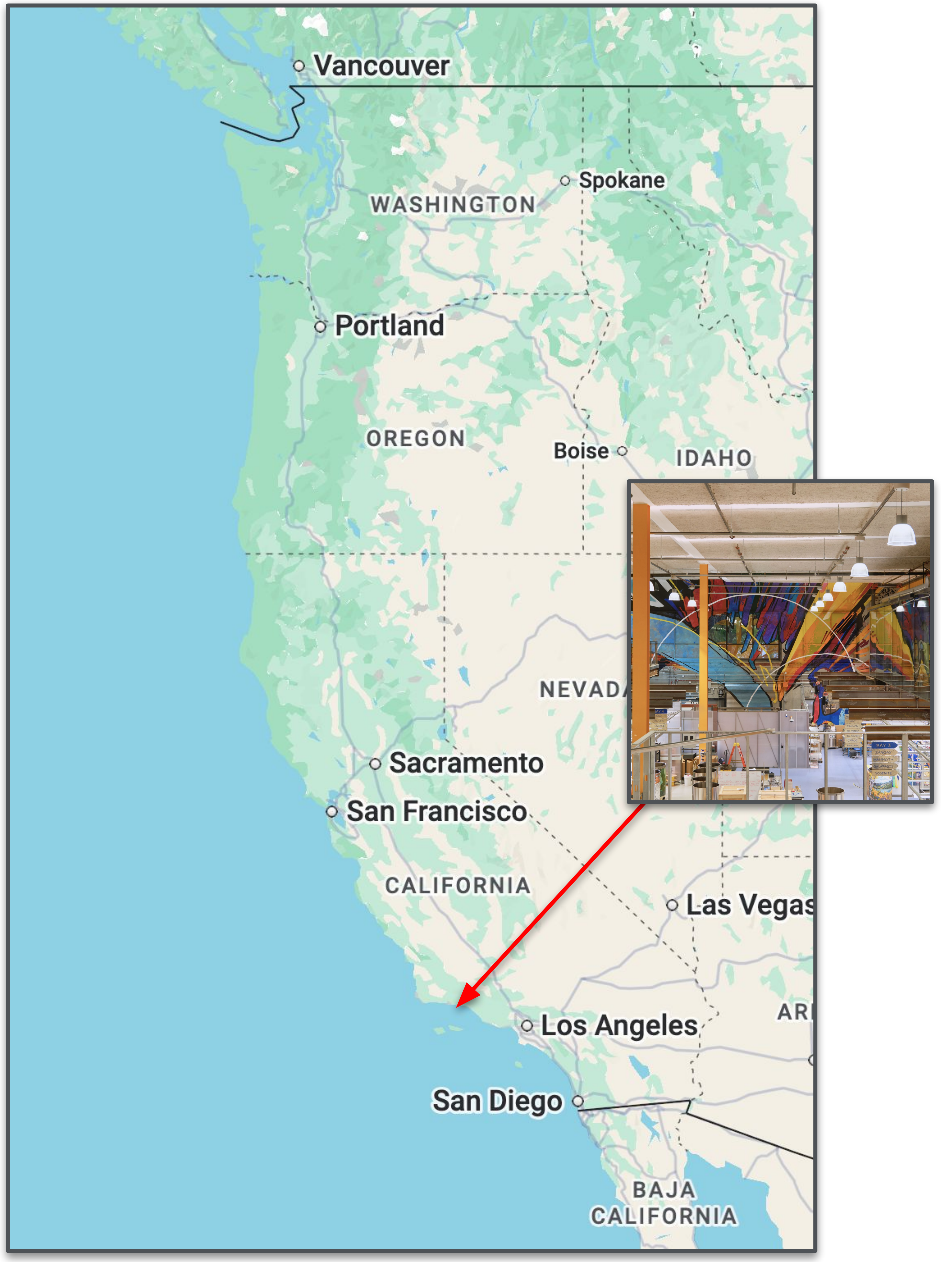
Incremental progress towards *beyond-classical application*

The team

Where is the team?



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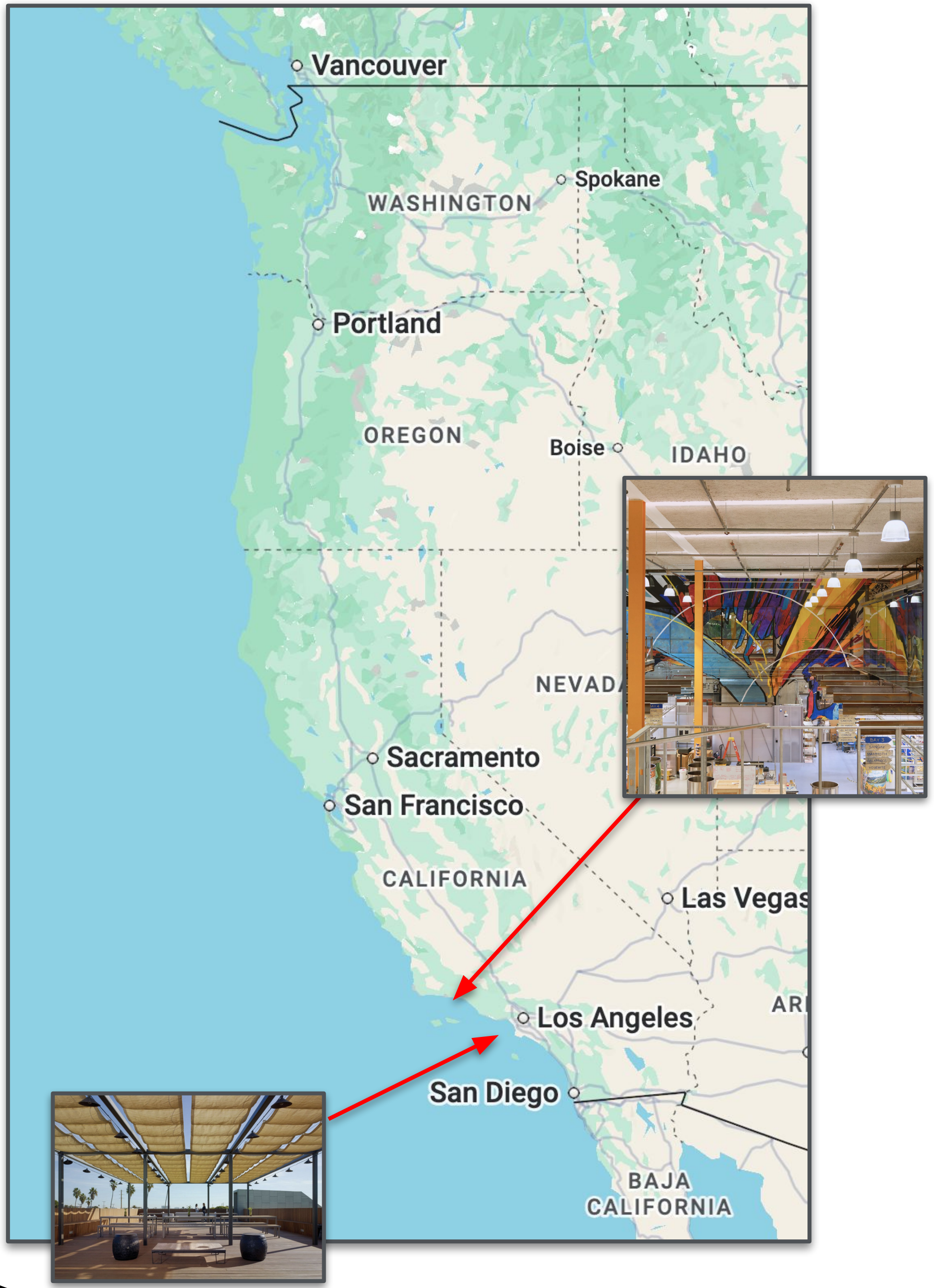

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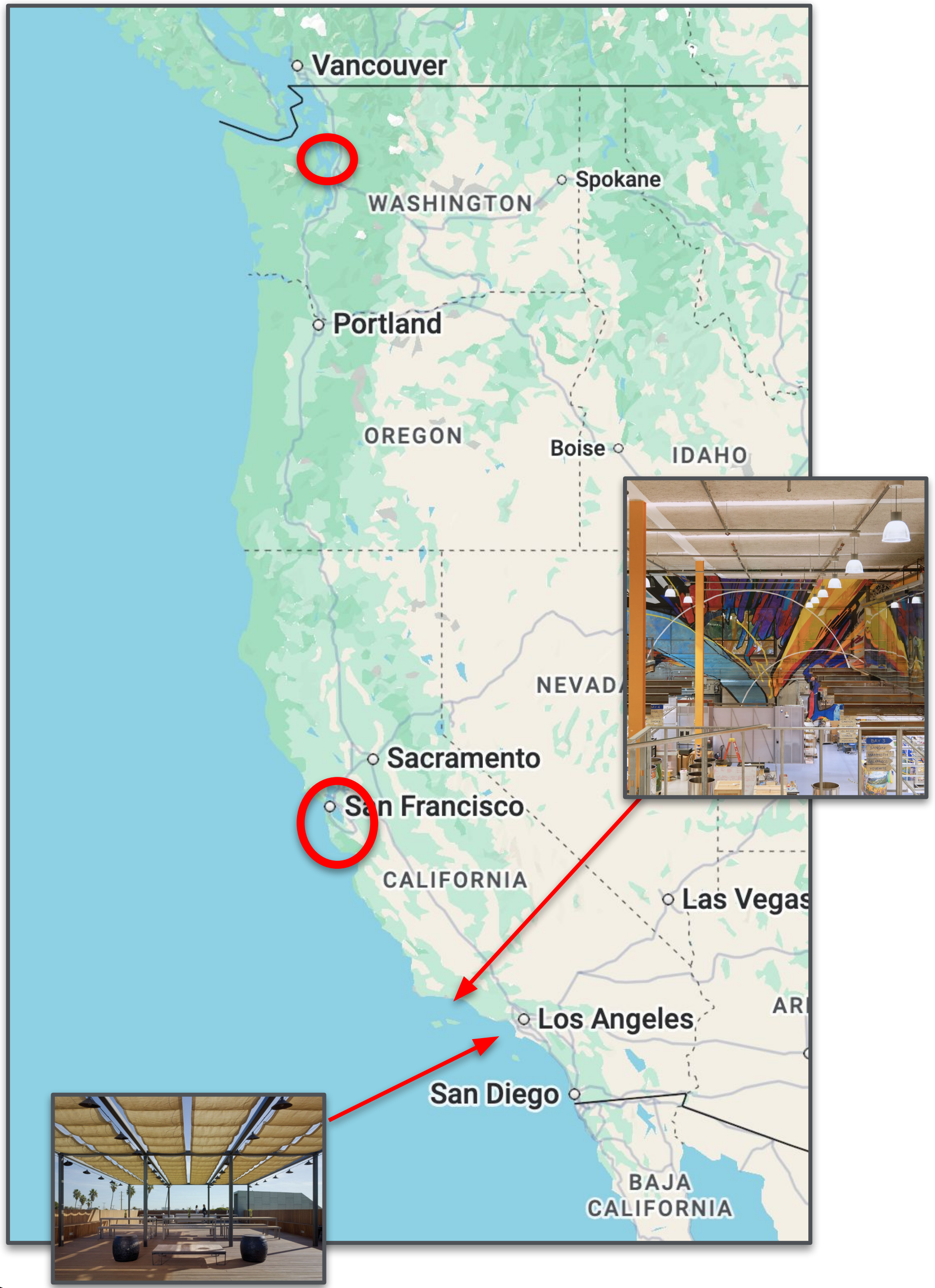

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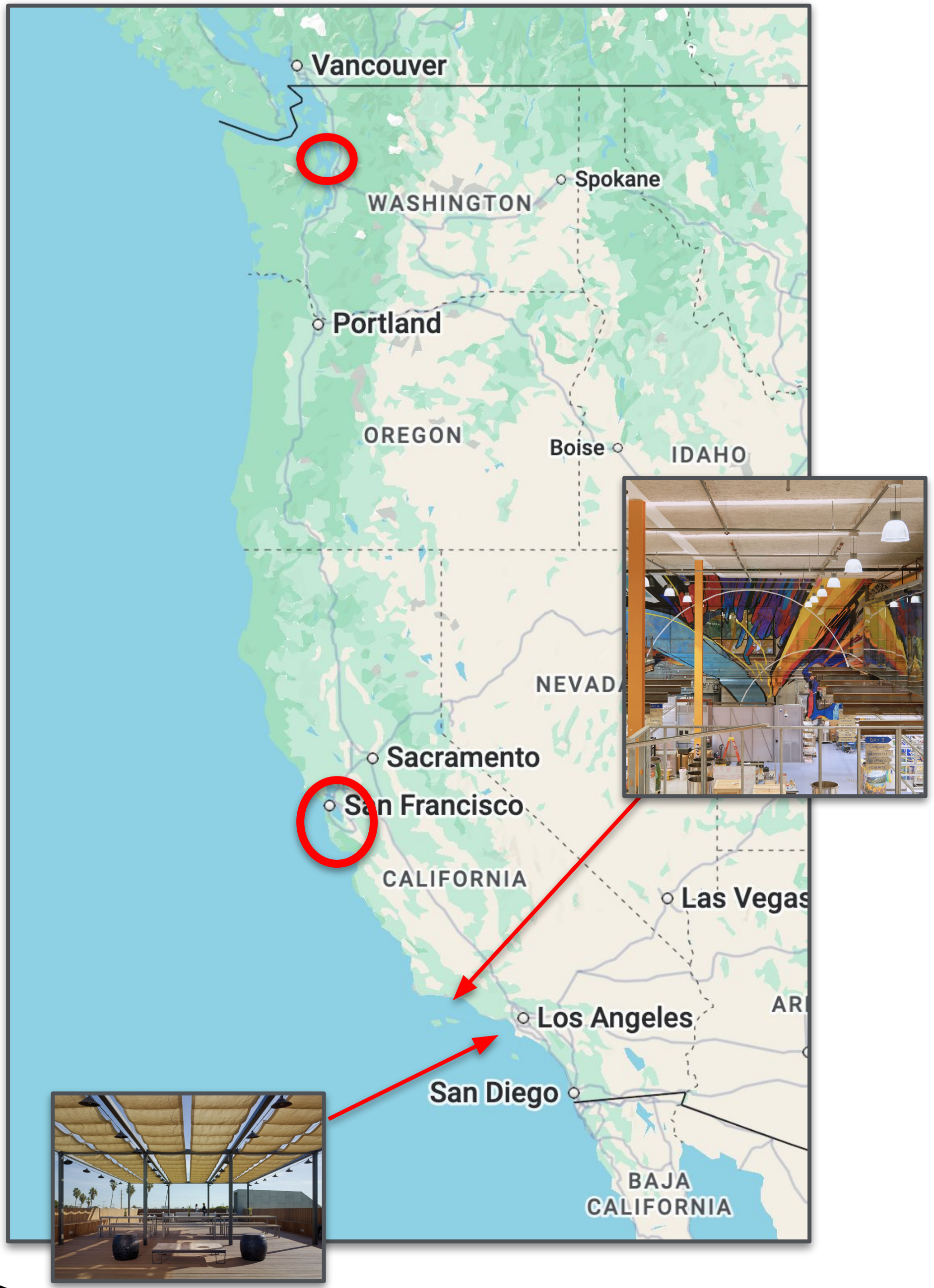

- **Santa Barbara**

  All experimentalists, a lot of theorists/numerics, some software engineers, and other roles.

- **Venice, Los Angeles**

  Theory/numerics, software engineers, and other roles.

- **Bay area (San Francisco and Mountain View)**

  Theory/numerics, software engineers, and other roles.

- **Seattle**

  Mostly software engineers.

- **Other locations**

  A very small number of people work from other locations.

Roles / Backgrounds (non-exhaustive list): research & non-research

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Technical roles

- Fabrication
- Characterization (device and noise modelling) and calibration
- Electronics
- Cryogenics
- Fault-tolerant quantum algorithms
- Near-term quantum applications / quantum simulation
- Computational methods and simulation
- Quantum error correction
- Open source packages (cirq, qualtran, ...)
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Backgrounds

- Experimental condensed matter physics / material science
- Theoretical and computational condensed matter / chemistry
- Quantum optics
- Mathematics
- Statistical mechanics
- Theoretical computer science (complexity theory)
- Software engineering
- Finance (high-frecuency trading)
- Aerospace
- Semiconductor industry
- Machine learning / AI
- ...

Opportunities for students

Student opportunities

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- **Student researcher program:**
  - Flexible appointment: full time/part time and short term/long term
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- **Informal collaborations or other appointments**

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They'll continue doing what they are doing regardless of this opportunity working out. And they show it.

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Puts their foot on the door
Getting started in the field, providing a minor improvement for someone's result, doing an internship at a different place, fixing a bug on an open source project, ...

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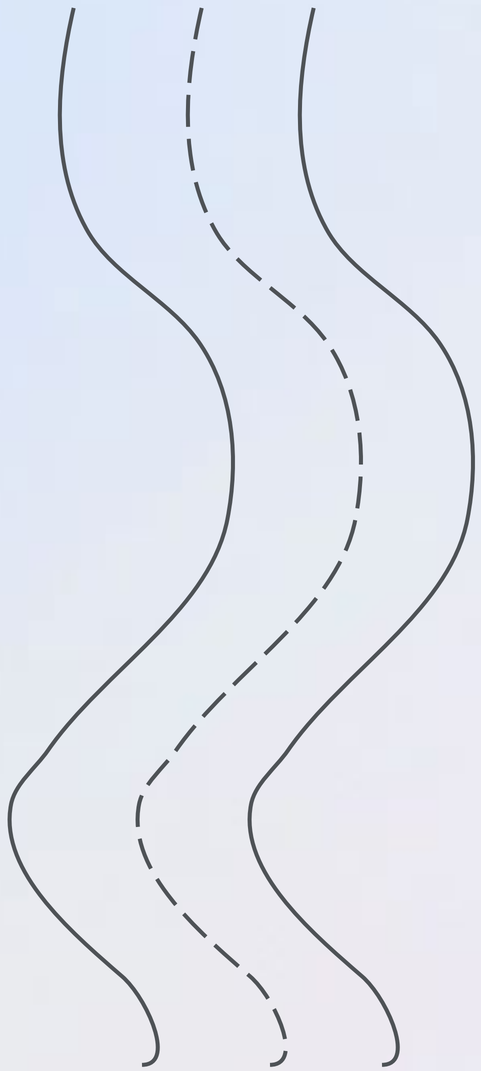
Academia vs Industry

Quantum computing is walking a thin line. It's an exciting time!



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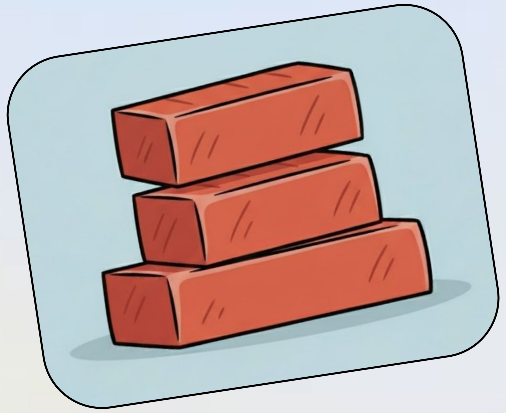
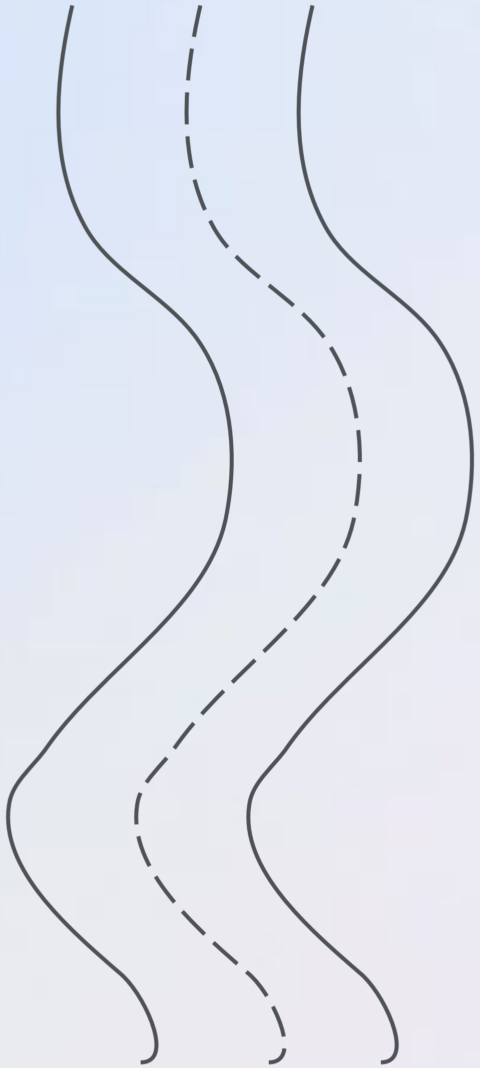
⚠️ Too **pedestrian:** no progress





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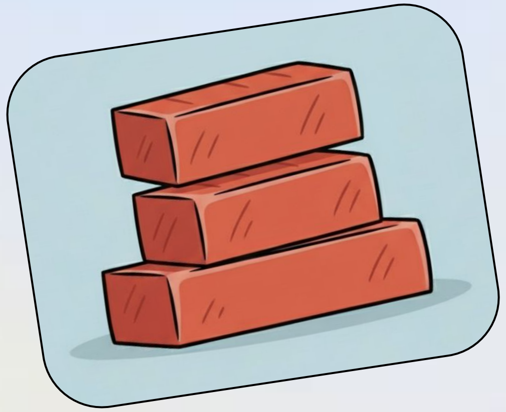

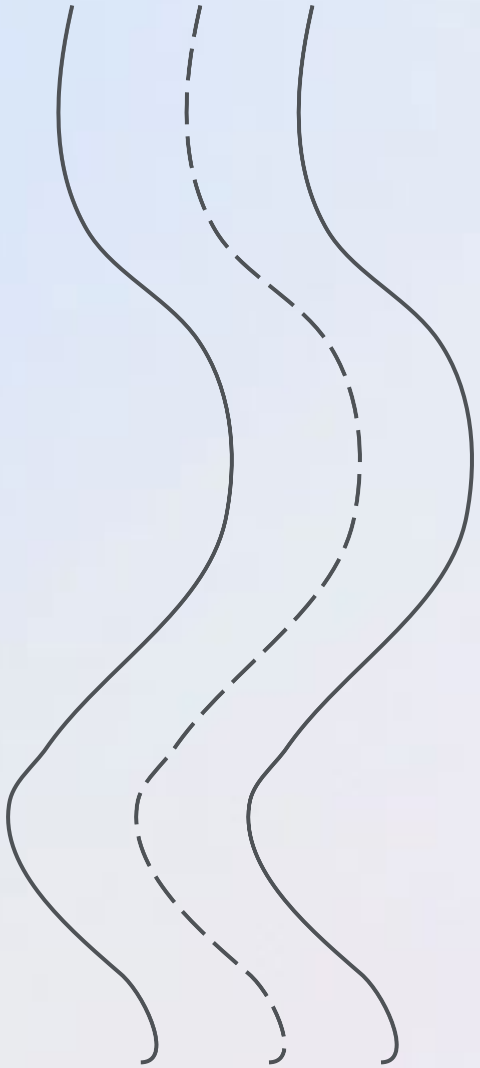

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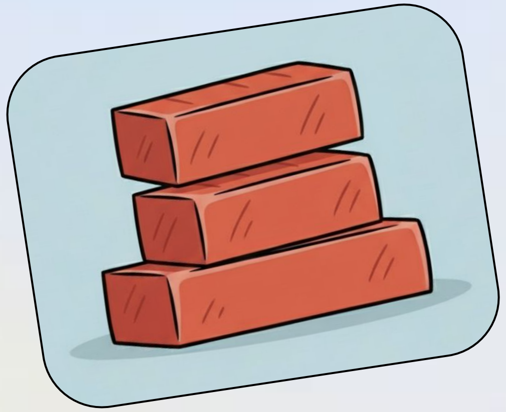

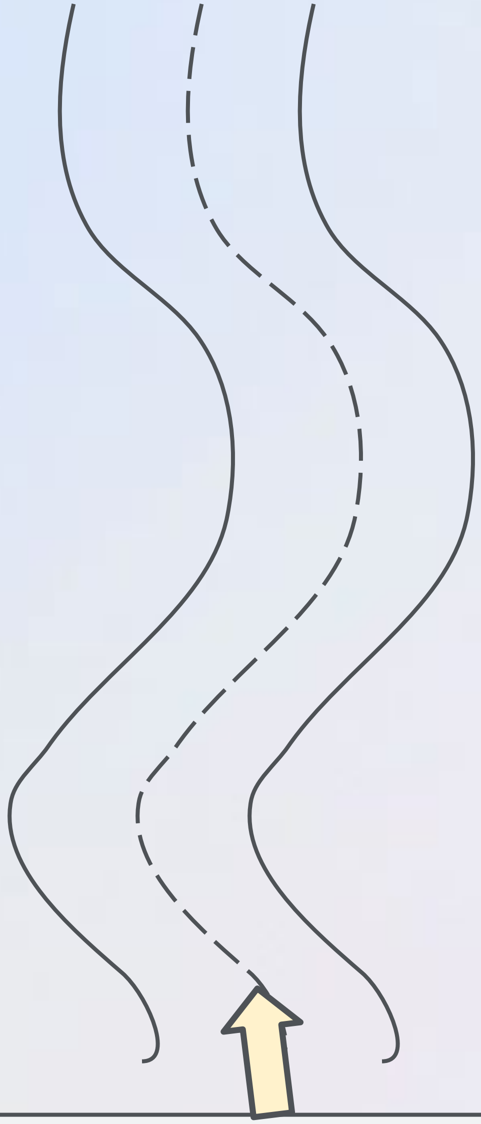

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Management, compromises, vision, resources, expertise, practicality, personal motivation, team motivation, deadlines, competition, applications, talent, expertise, incentives, business/market ...

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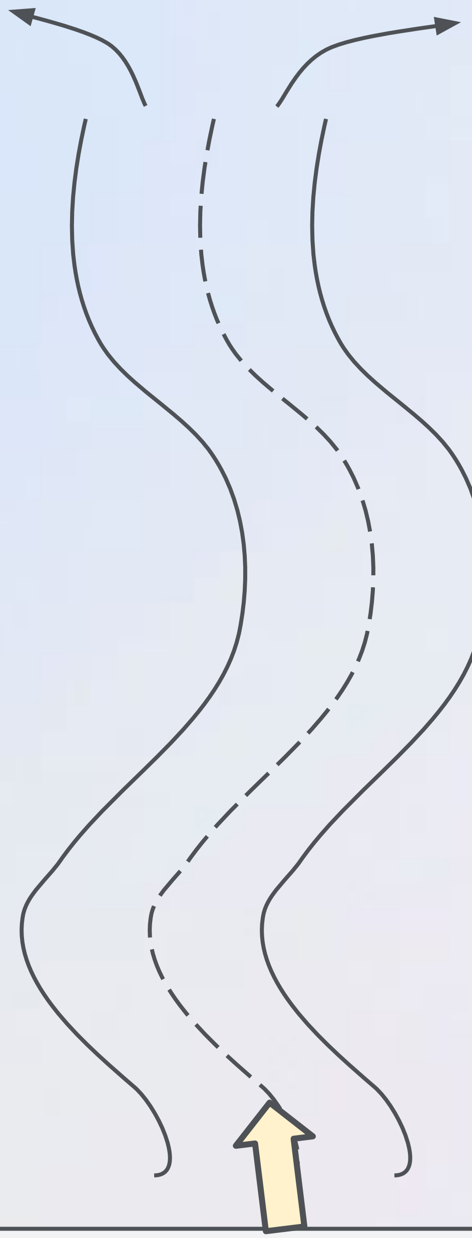
Mature industries

Academia



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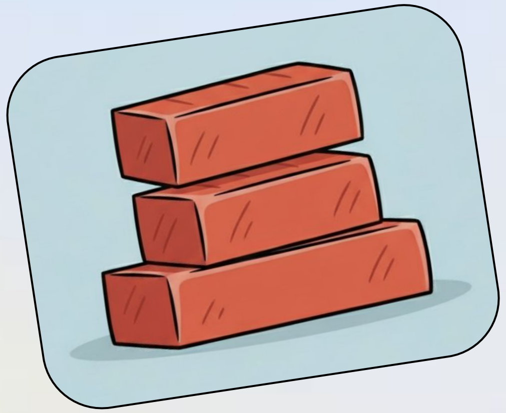

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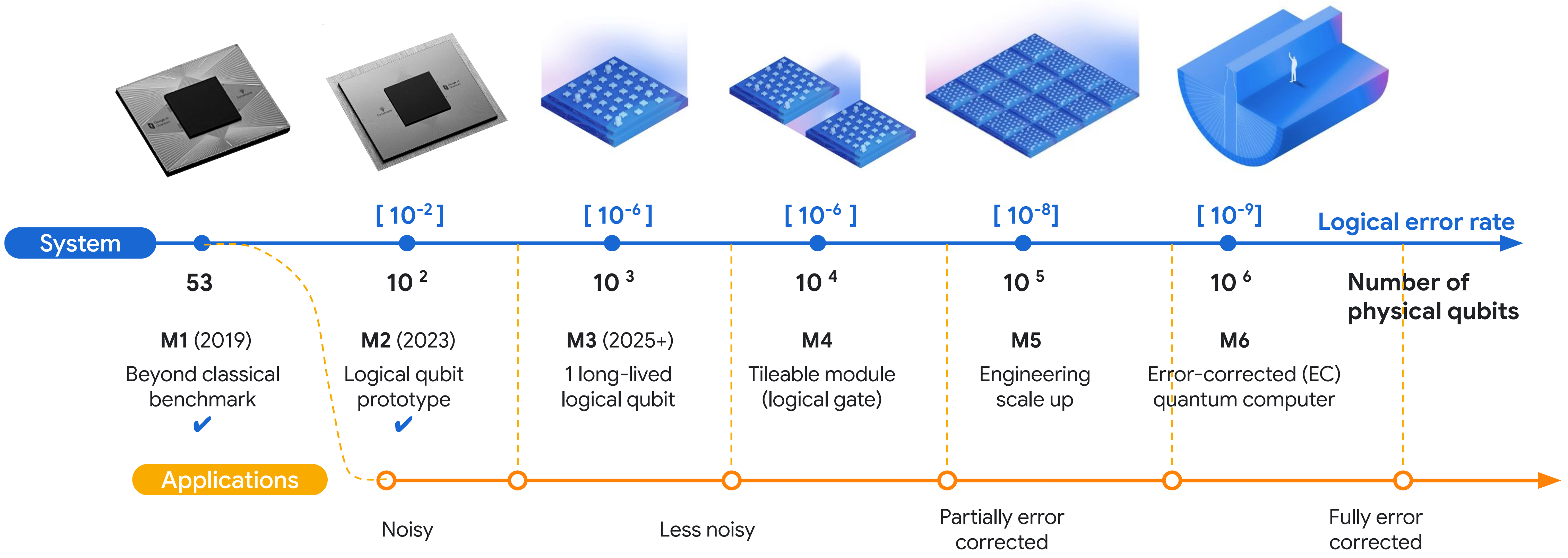
Quantum AI

Our roadmap will need more talented people



Benjamin Villalonga (bcorrea@google.com)

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