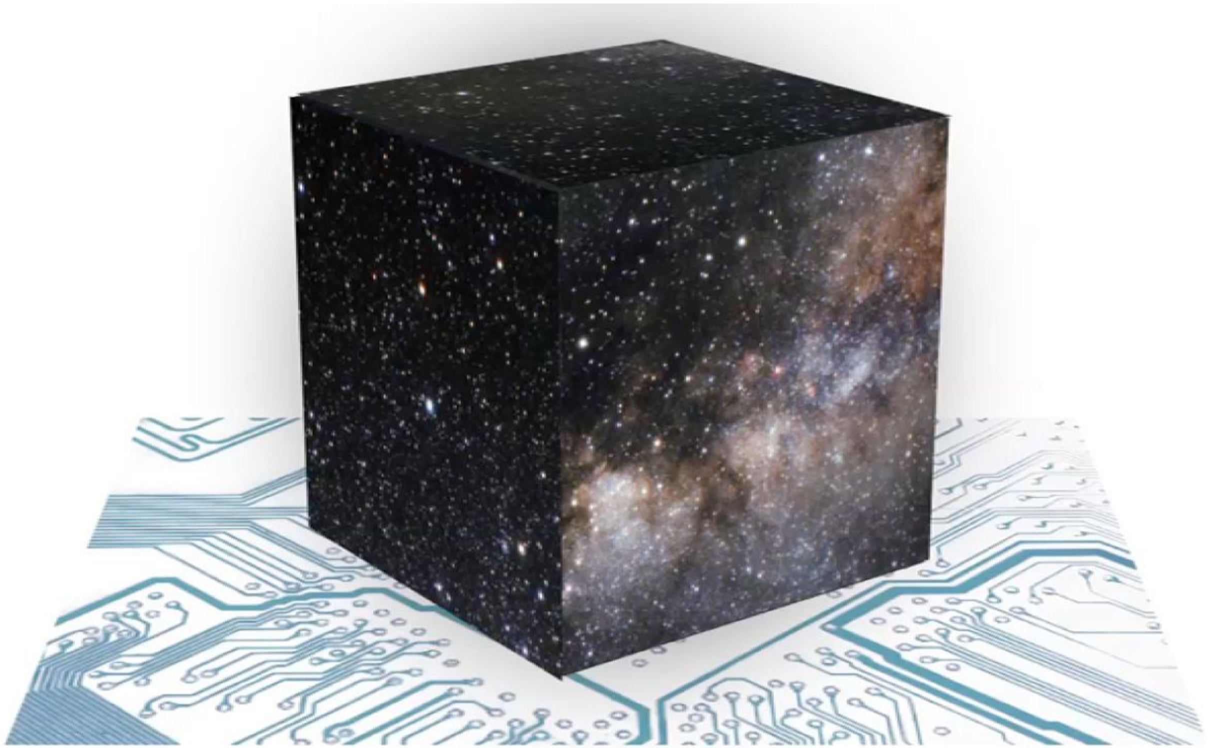
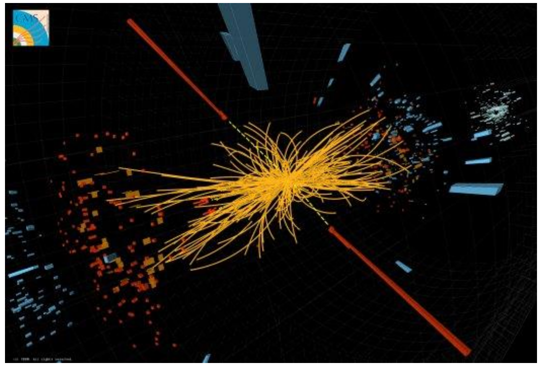
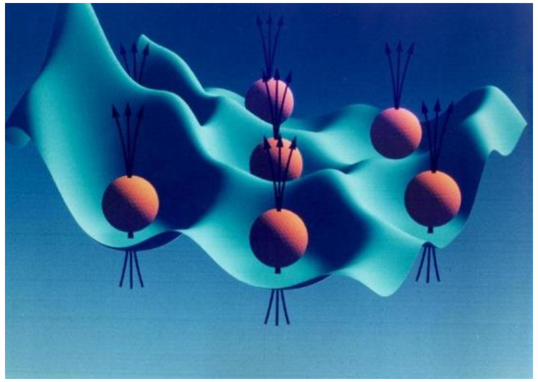
Our Quantum Future



INSTITUTE FOR QUANTUM INFORMATION AND MATTER

John Preskill
Caltech Associates
1 November 2023

Frontiers of Physics

short distance	long distance	complexity
		
Higgs boson	Large scale structure	“More is different”
Neutrino masses	Cosmic microwave background	Many-body entanglement
Supersymmetry	Dark matter	Phases of quantum matter
Quantum gravity	Dark energy	Quantum computing
String theory	Gravitational waves	Quantum spacetime

Two fundamental ideas

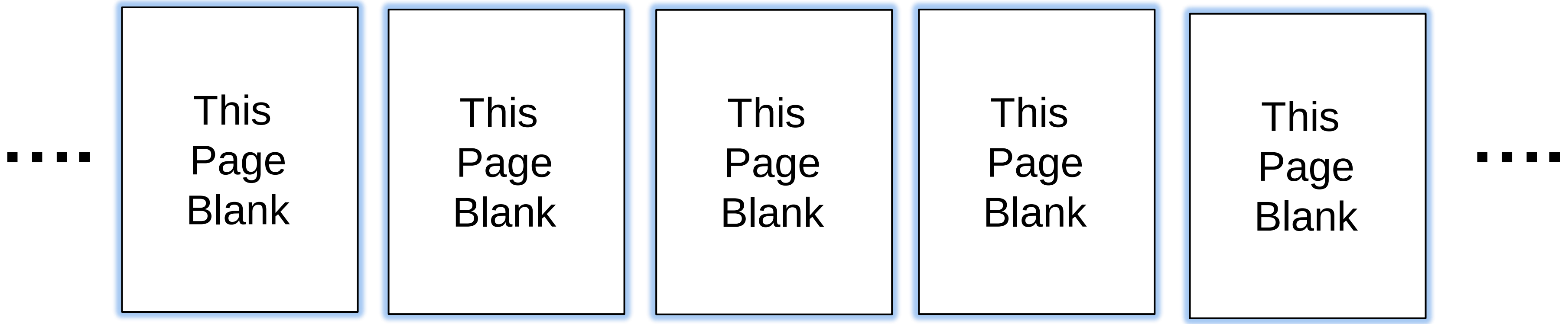
(1) *Quantum complexity*

Why we think quantum computing is powerful.

(2) *Quantum error correction*

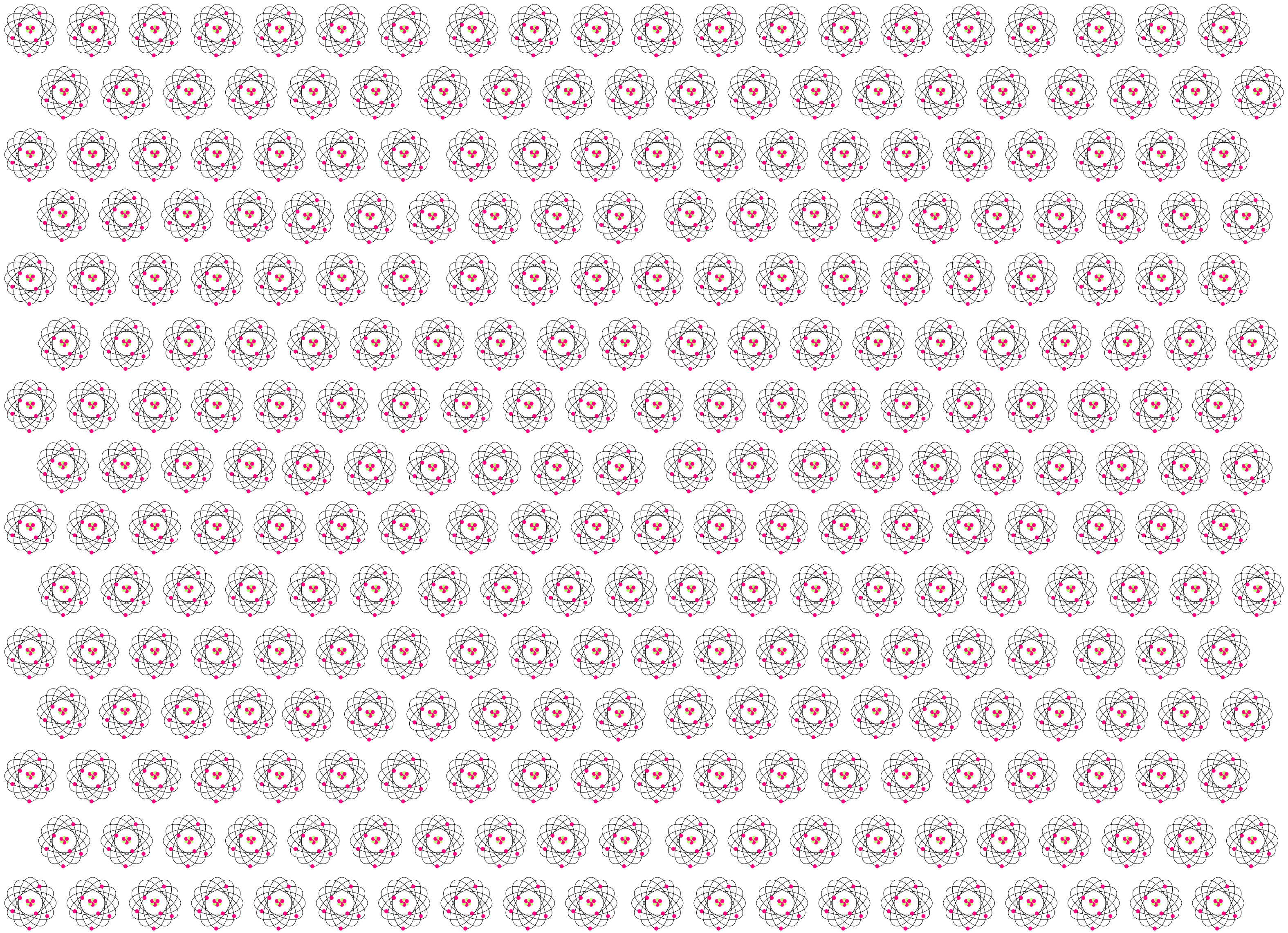
Why we think quantum computing is scalable.

Quantum entanglement



Nearly all the information in a typical entangled “quantum book” is encoded in the correlations among the “pages”.

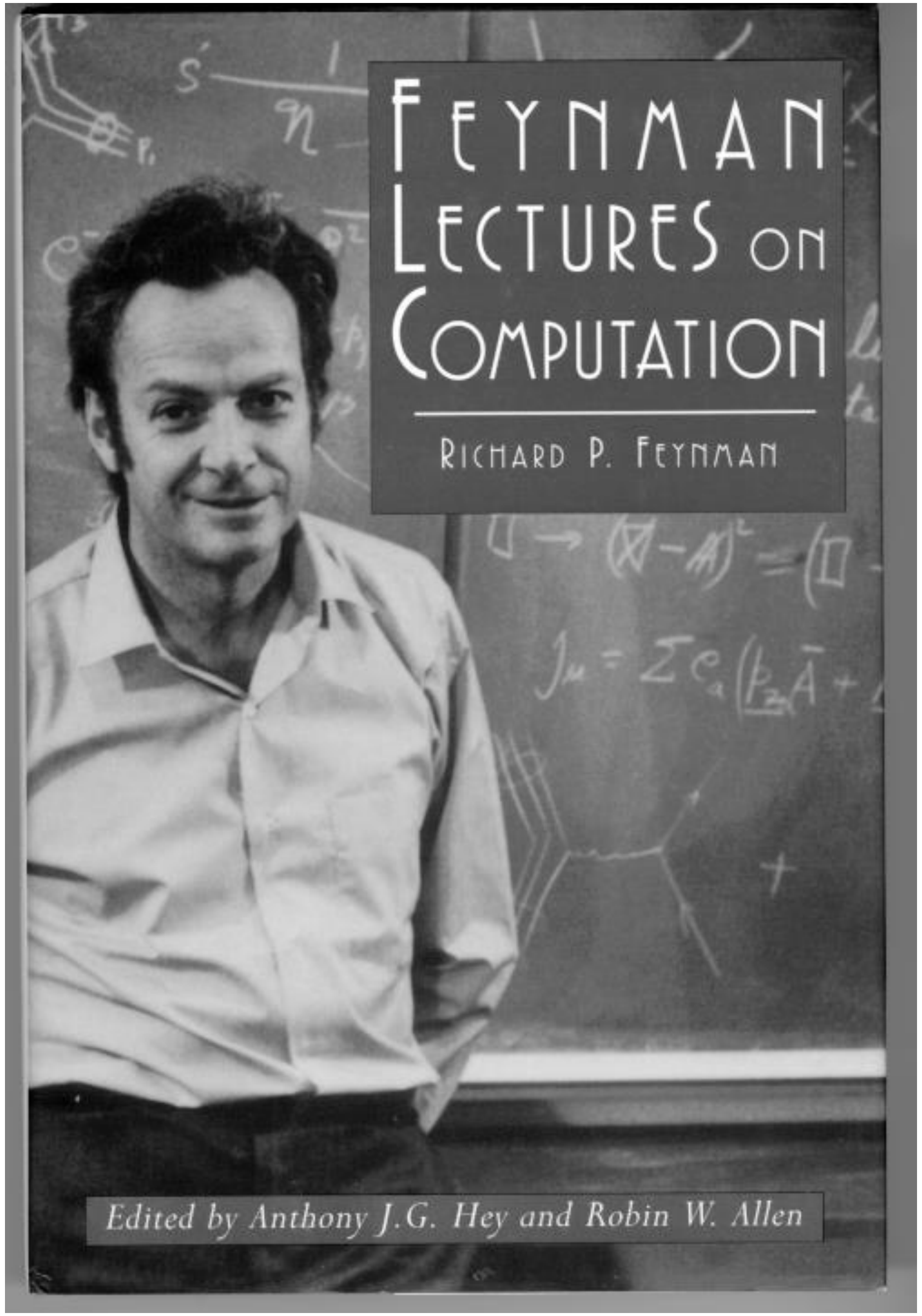
You can't access the information if you read the book one page at a time.

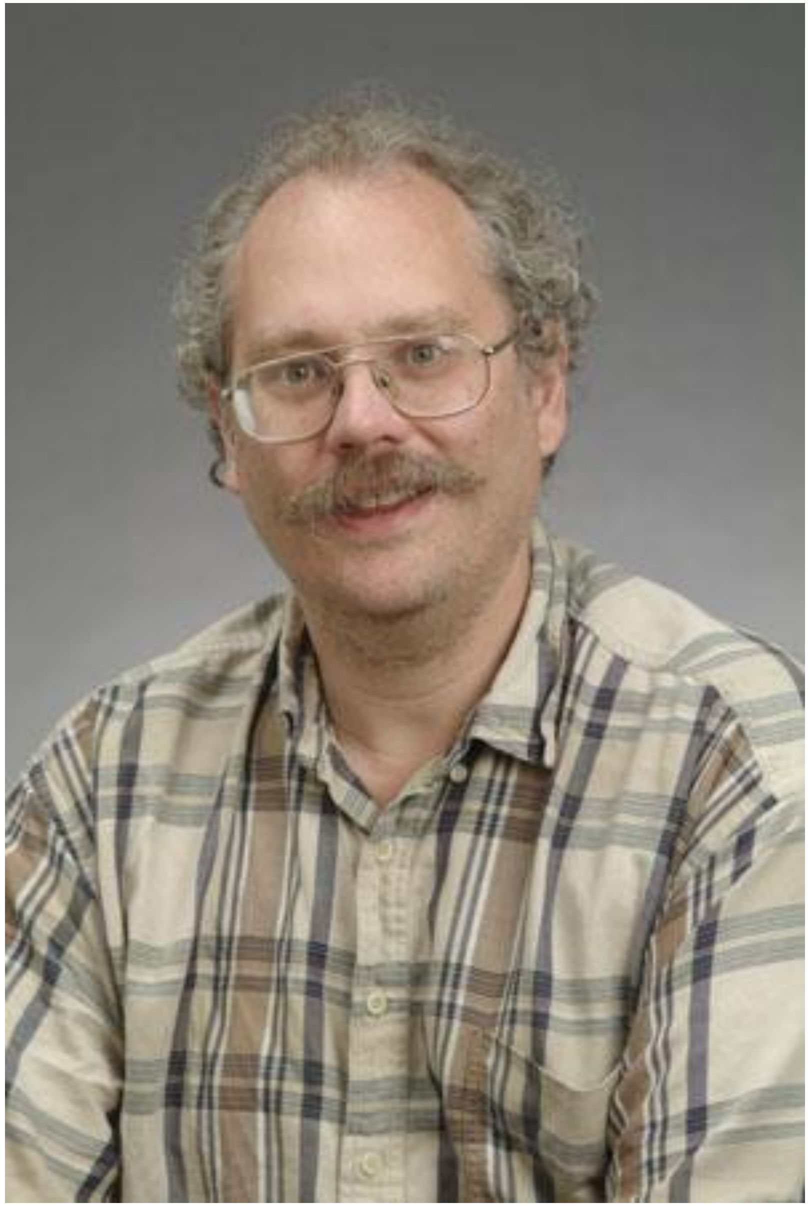


A complete description of a typical quantum state of just 300 qubits requires more bits than the number of atoms in the visible universe.

Richard Feynman

"You can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind."





Peter Shor

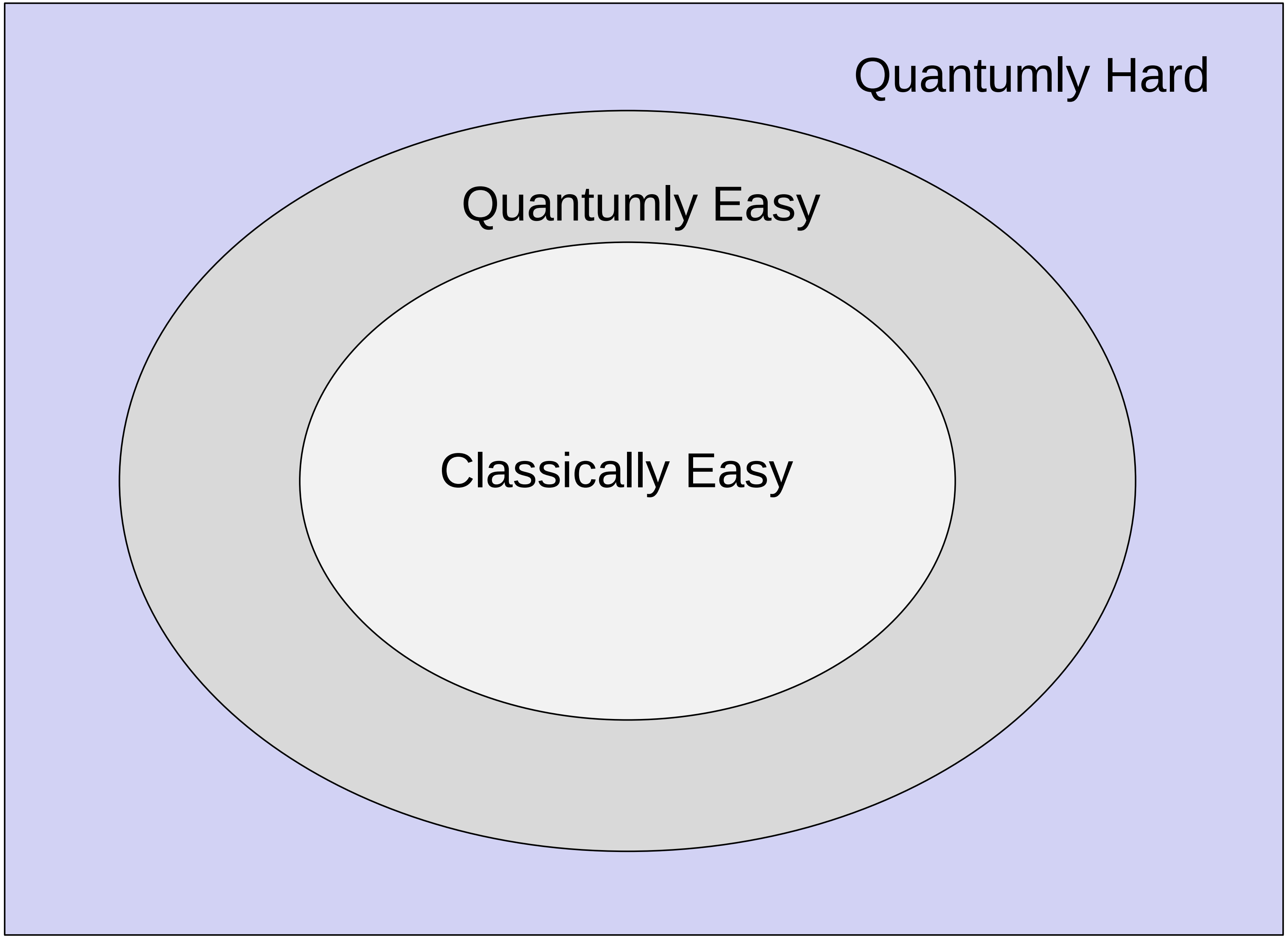
"These algorithms take a number of steps polynomial in the input size, for example, the number of digits of the integer to be factored."

Why we think quantum computing is powerful

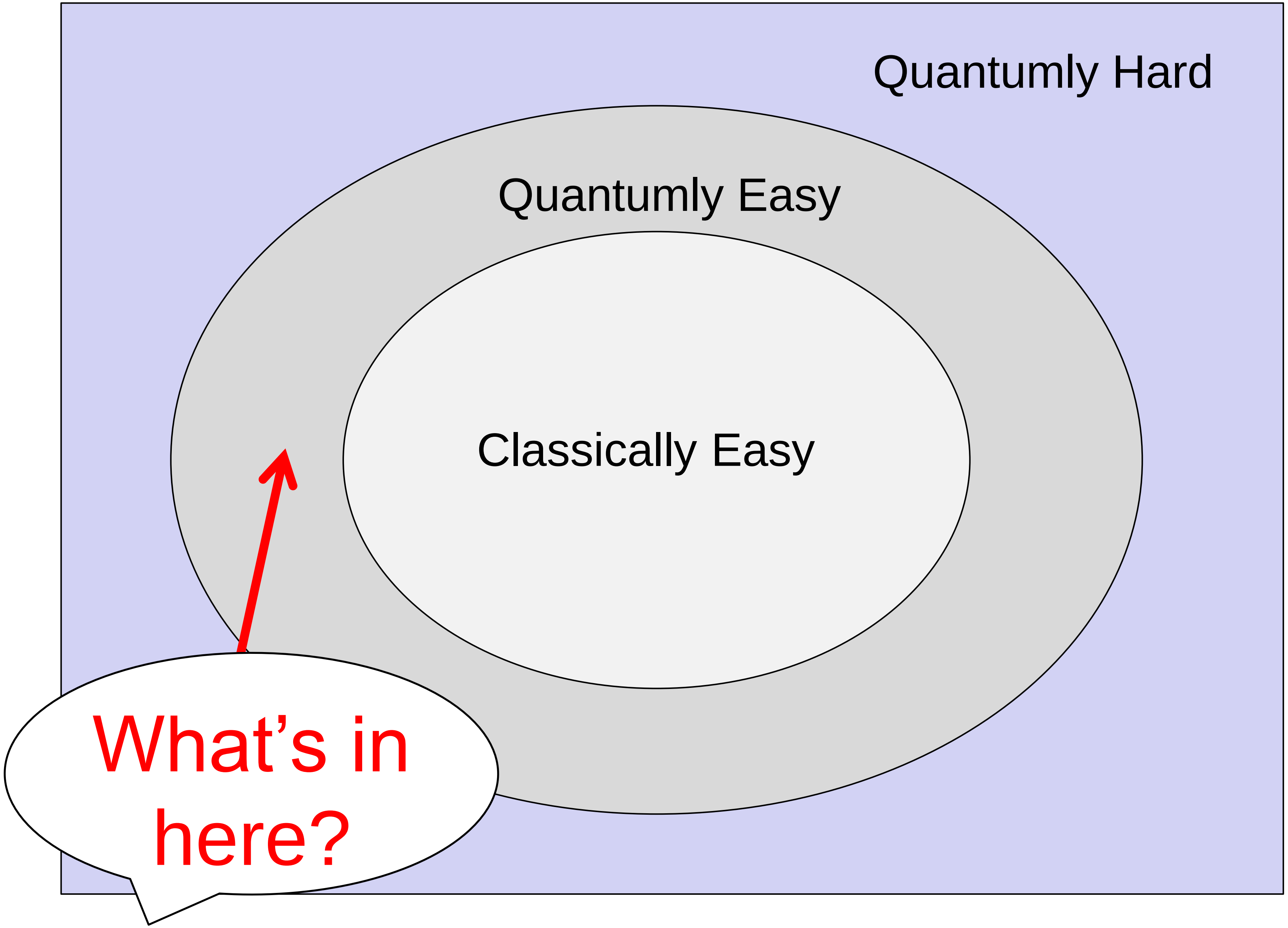
(1) Some problems are believed to be hard for conventional computers, yet would be easy for quantum computers. Factoring is the best known example.

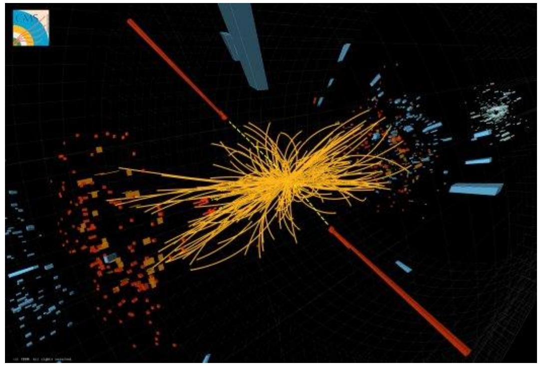
(2) We don't know how to simulate a quantum computer efficiently using a conventional computer.

Problems

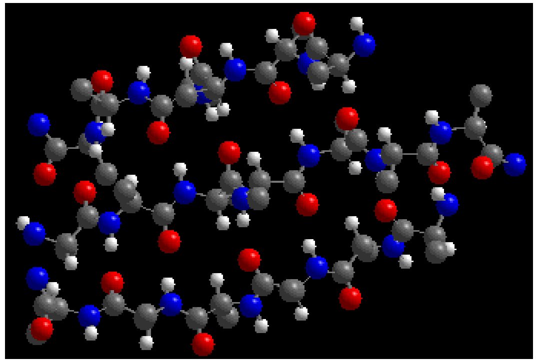


Problems

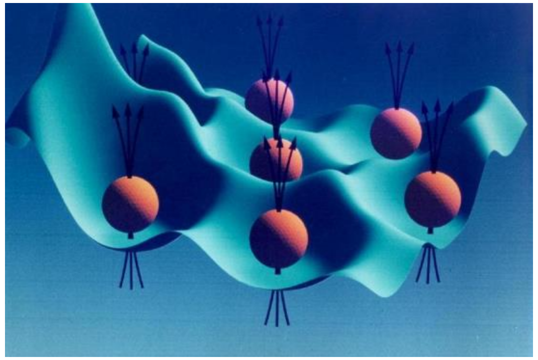

Quantumly Hard
Quantumly Easy
Classically Easy
What's in here?



particle collision



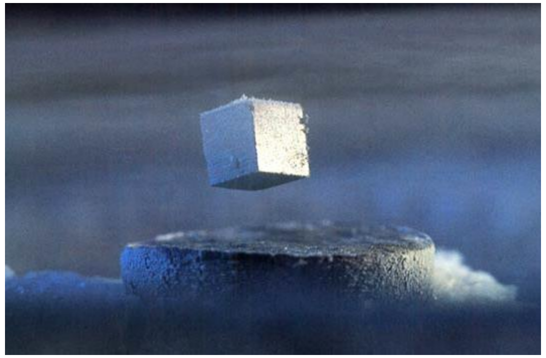
molecular chemistry



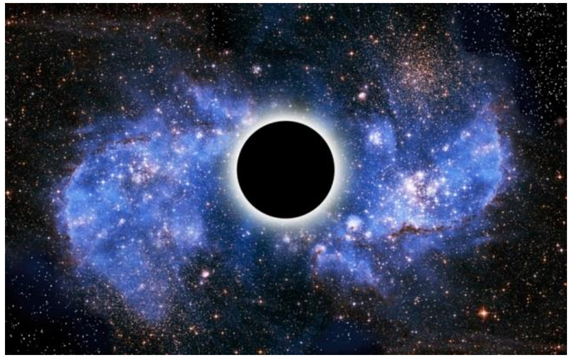
entangled electrons

A quantum computer can simulate efficiently any physical process that occurs in Nature.

(Maybe. We don’t actually know for sure.)

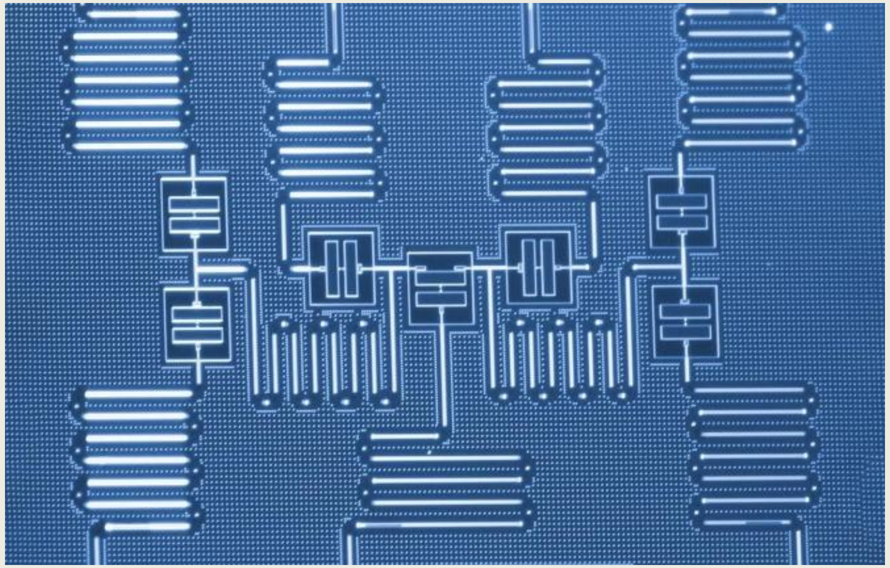


superconductor

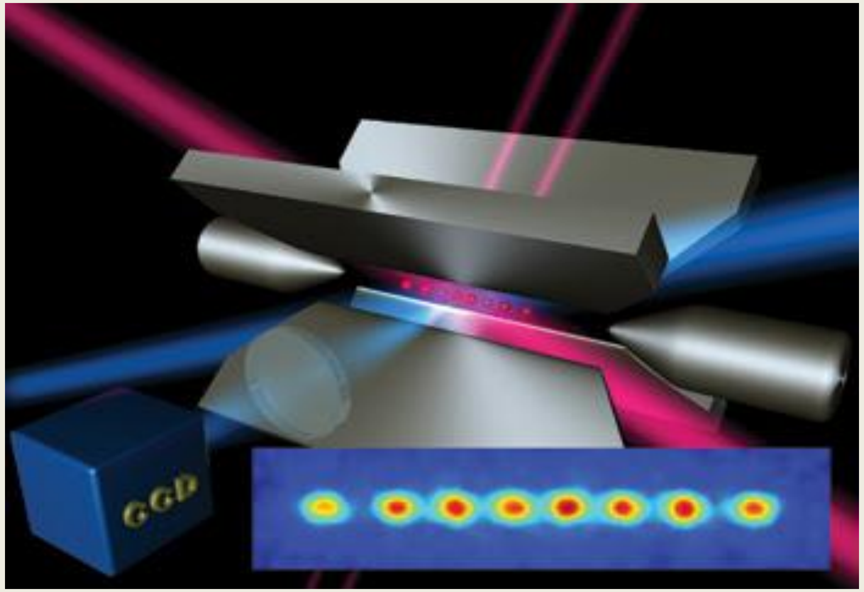


black hole

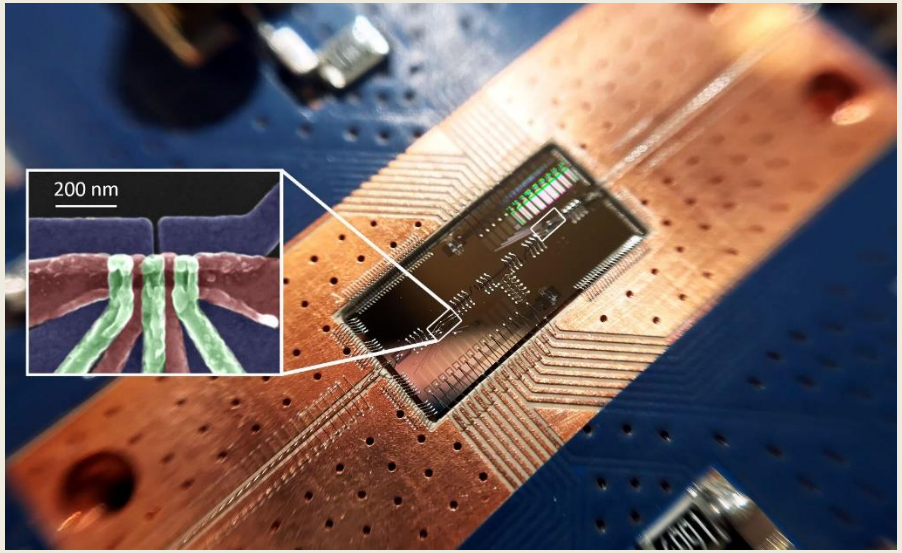
early universe



superconducting qubits



trapped atoms/ions



silicon spin qubits

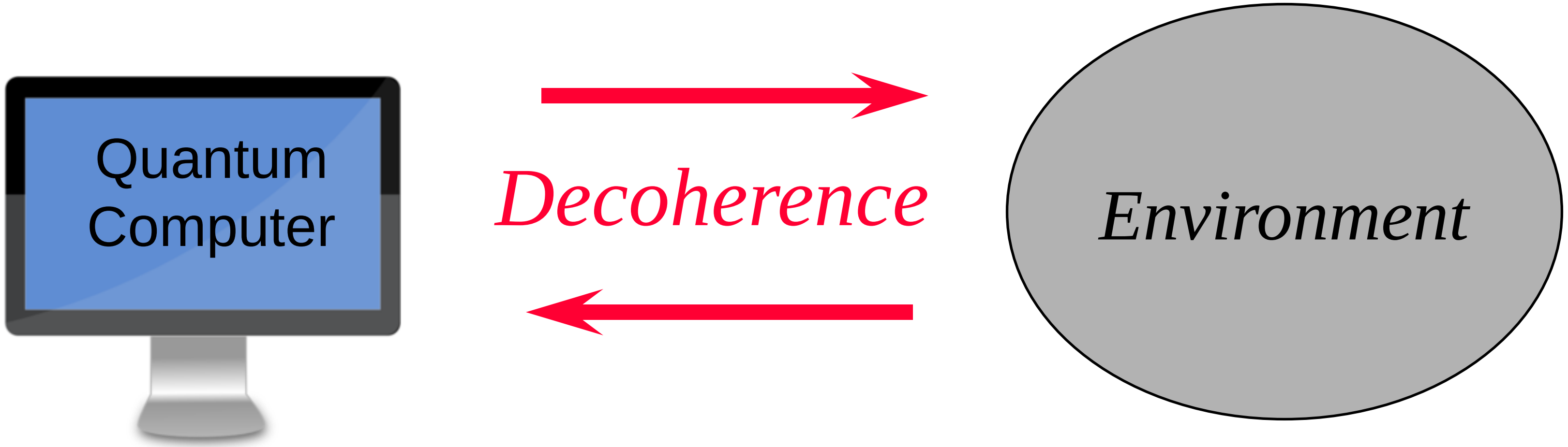
photonics

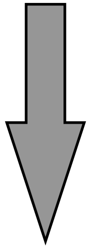
Why quantum computing is hard

We want qubits to interact strongly with one another.

We don’t want qubits to interact with the environment.

Except when we control or measure them.

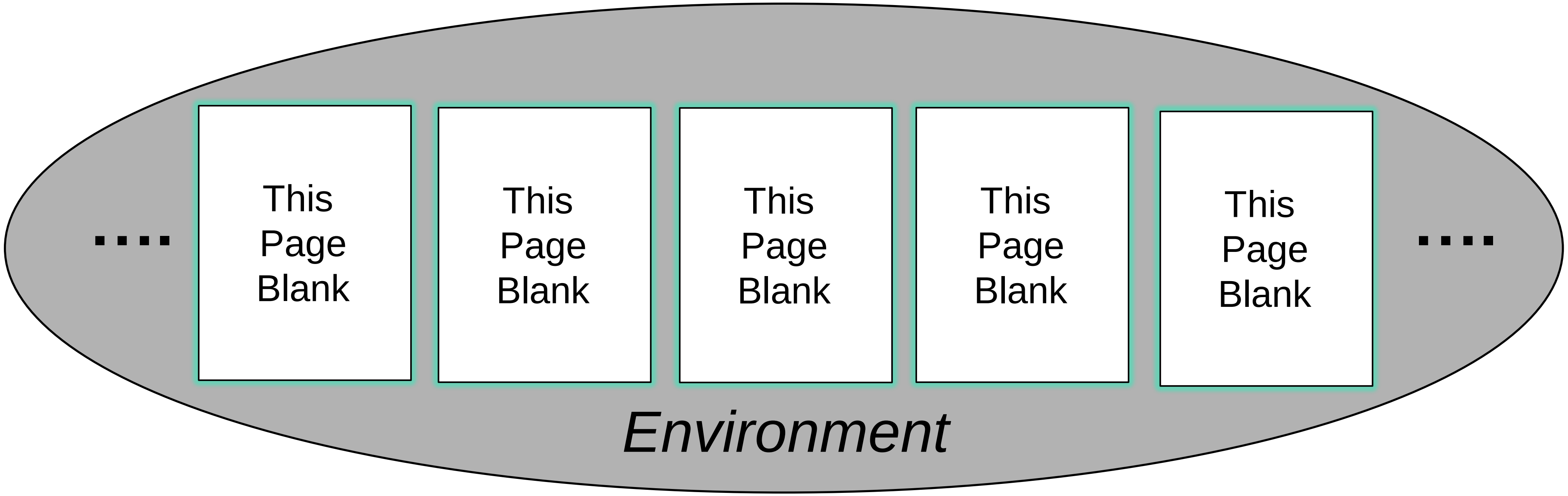




ERROR!

To resist decoherence, we must prevent the environment from “learning” about the state of the quantum computer during the computation.

Quantum error correction



The protected "logical" quantum information is encoded in a highly entangled state of many physical qubits.

The environment can't access this information if it interacts locally with the protected system.

Alexei Kitaev

"Such computation is fault-tolerant by its physical nature."

Quantum computing in the NISQ Era

The (noisy) 100 qubit quantum computer has arrived.
(*NISQ* = noisy intermediate-scale quantum.)

NISQ devices cannot be simulated by brute force using the most powerful currently existing supercomputers.

Noise limits the computational power of NISQ-era technology.

NISQ will be an interesting tool for exploring physics. It *might* also have other useful applications. But we're not sure about that.

NISQ will not change the world by itself. Rather it is a step toward more powerful quantum technologies of the future.

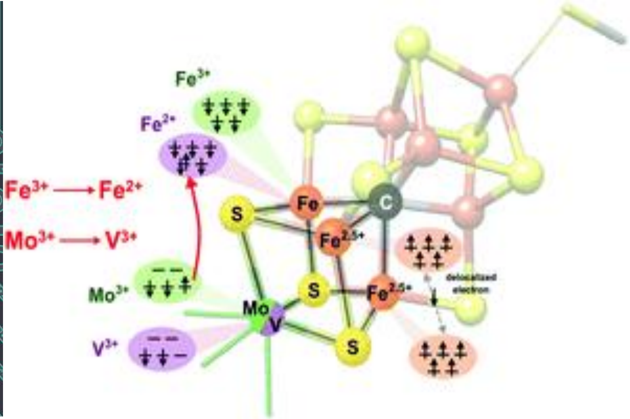
Applications of Quantum Computing

Cryptography

Break 2048 RSA

~ 6000 qubits

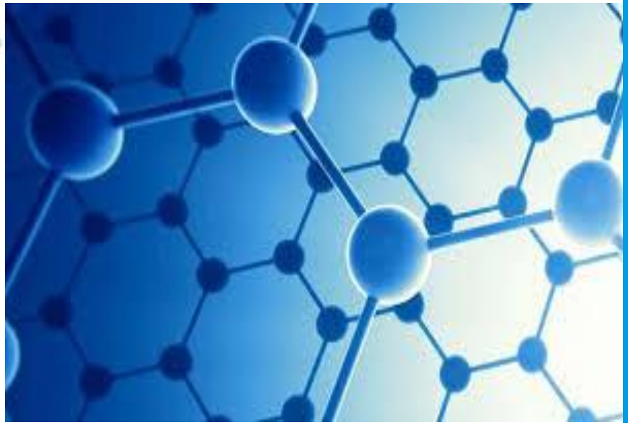
Physics/Chemistry



Simulate FeMoco

~ 200 qubits

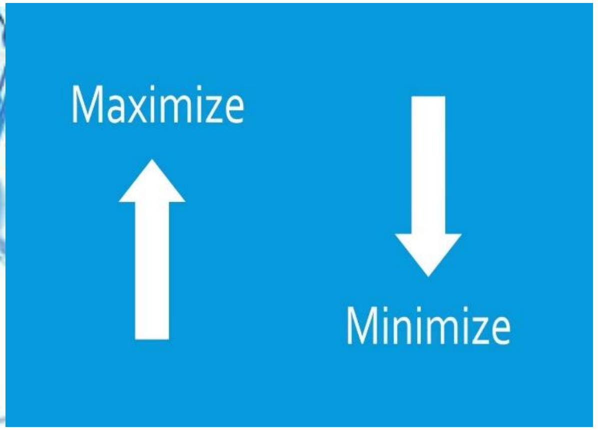
Materials Science



Simulate High-T_c superconductors

~ 70 qubits

Optimization



Scheduling, ranking, learning

~ 100 qubits (?)

Catch: perfect qubits with no noise

Applications of Quantum Computing

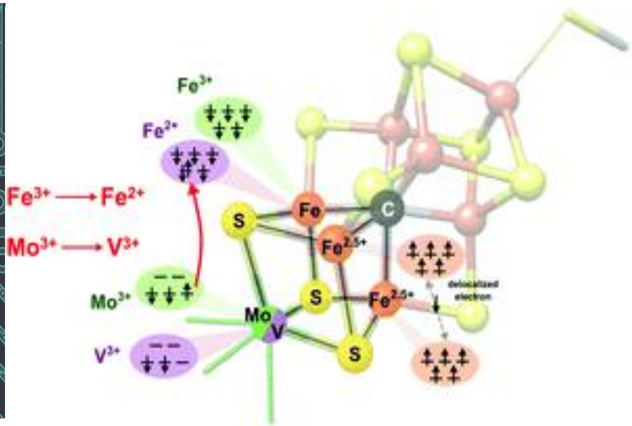
Cryptography

Break 2048 RSA

~

~10M qubits

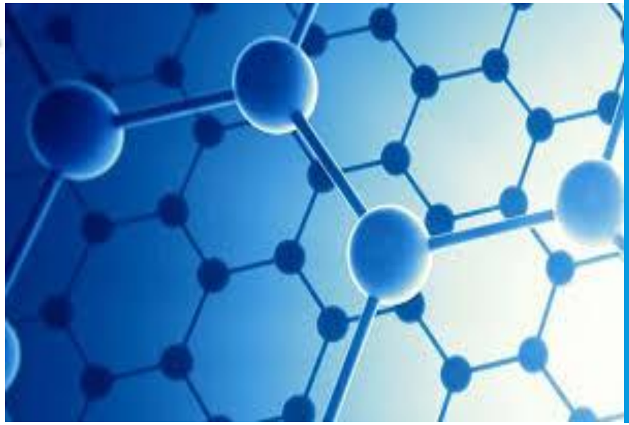
Physics/Chemistry



Simulate FeMoco

~ 1M qubits

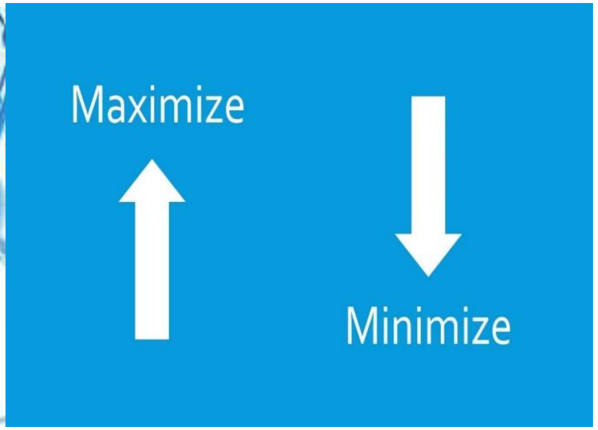
Materials Science



Simulate High-T_c superconductors

~ 100k qubits

Optimization



Scheduling, ranking, learning

~ 1M qubits (?)

Qubits with 0.1% error rate

Open Questions

How will we scale up to quantum computing systems that can solve hard problems?

What are the important applications for science and for industry?

Fueling (US) progress in quantum science and technology

Universities

Caltech, Yale, Maryland, Duke, Chicago, Berkeley, MIT, Harvard, Stanford, Princeton, Colorado, Illinois, Wisconsin, …

National Laboratories

Berkeley Lab, Oak Ridge, Argonne, Fermilab, Brookhaven, SLAC, Sandia, Los Alamos, NIST, …

Priorities

Scientific discovery, new applications, future technologies, workforce training, infrastructure, large-scale engineering, economic competitiveness, national security, international cooperation, …

Industry

IBM, Google, Microsoft, Intel, Amazon, Honeywell, Northrop Grumman, Raytheon, Alibaba, many startups, …

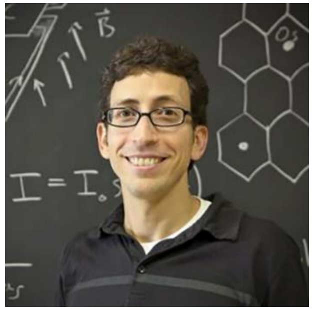
Prospects for the next 5 years

- Encouraging progress toward scalable fault-tolerant quantum computing.
- Scientific discoveries enabled by programmable quantum simulators and circuit-based quantum computers.
- Advances in quantum metrology from improved control of quantum many-body systems.

IQIM

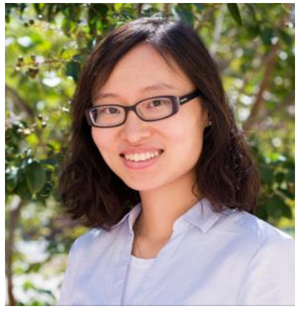
INSTITUTE FOR QUANTUM INFORMATION AND MATTER

Some IQIM Core Faculty who have joined Caltech since 2012


Jason Alicea
Theory, 2012
(Physics)


David Hsieh
Experiment, 2012
(Physics)


Andre Faraon
Experiment, 2012
(Applied Physics)

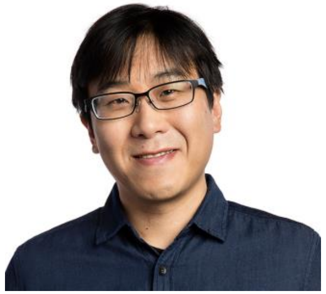

Xie Chen
Theory, 2014
(Physics)


Thomas Vidick
Theory, 2014
(Physics)


Manuel Endres
Experiment, 2016
(Physics)


Fernando Brandão
Theory, 2016
(Physics)


Stevan Nadj-Perge
Experiment, 2016
(Applied Physics)

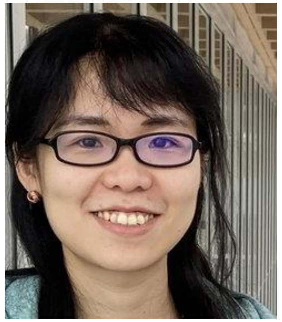

Garnet Chan
Theory, 2016
(Chemistry)


Joseph Falson
Experiment, 2020
(Materials Science)


Urmila Mahadev
Theory, 2020
(Computer Science)


Mohammad Mirhosseini
Experiment, 2020
(Electrical Engineering)


Lee McCuller
Experiment, 2022
(Physics)


Linda Ye
Experiment, 2023
(Physics)

More hires are in the works …

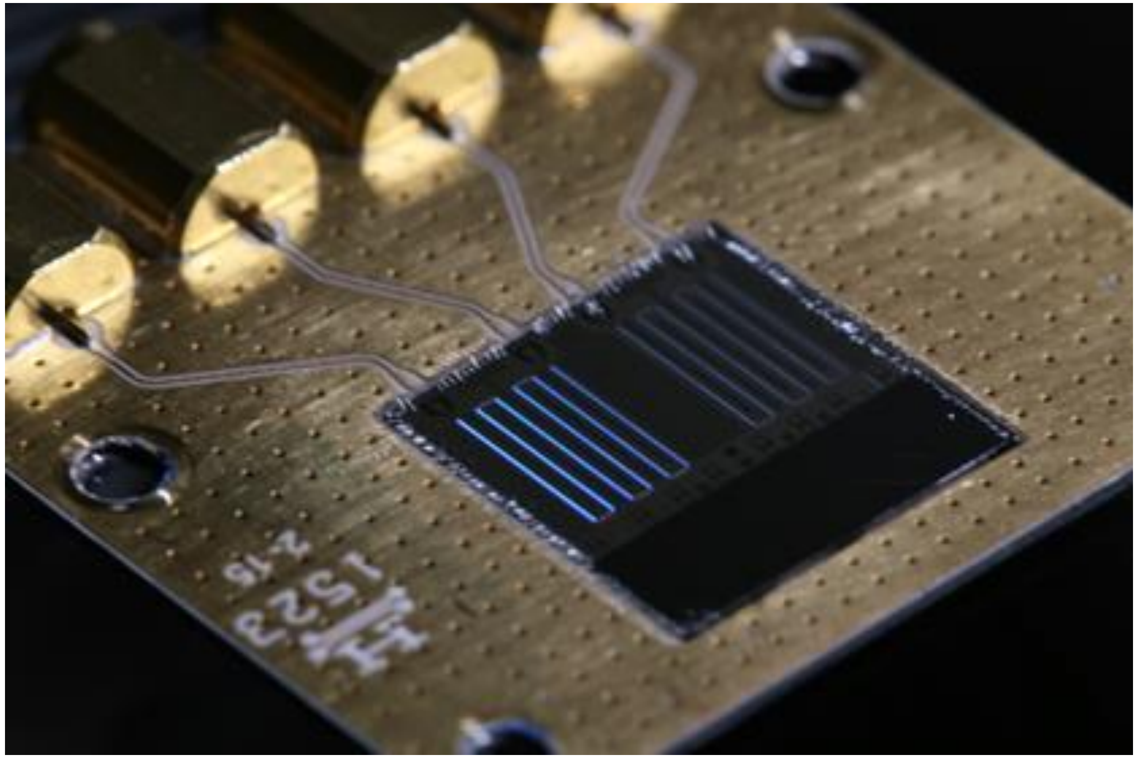
Former IQI(M) postdocs leading research in theoretical quantum information science

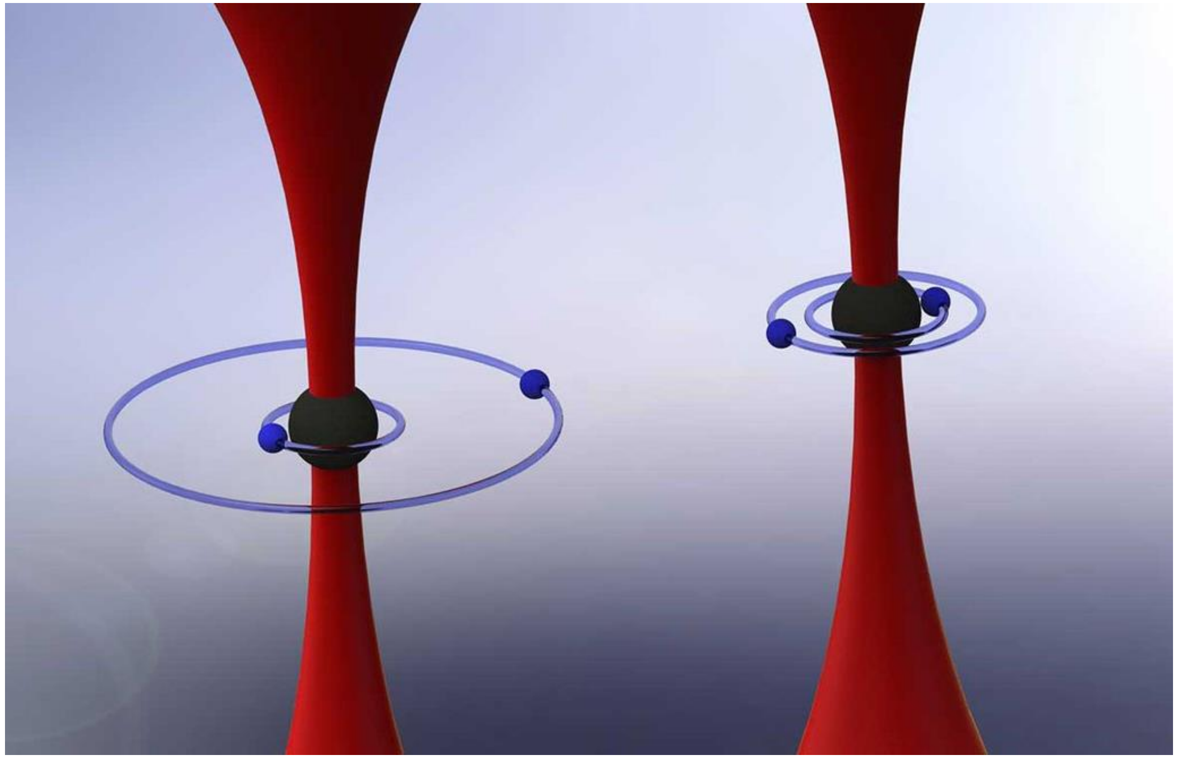
Gorjan Alagic	NIST	Hrant Gharibyan	BlueQubit	Anand Natarajan	MIT
Victor Albert	NIST	Andru Gheorghiu	Chalmers	Ashwin Nayak	Waterloo
Eddy Ardonne	Nordita	András Gilyén	Rényi Institute	Fernando Pastawski	PsiQuantum
Dave Bacon	Google	Alexei Gorshkov	NIST	Stefano Pironio	Brussels
Ning Bao	Northwestern	David Gosset	Waterloo	David Poulin	Sherbrooke
Salman Beigi	IPM	Zhengcheng Gu	Hong Kong	Robert Raussendorf	UBC
Mario Berta	Aachen	Sean Hallgren	Penn State	Ben Reichardt	USC
Robin Blume-Kohout	Sandia	Patrick Hayden	Stanford	Burak Şahinoğlu	PsiQuantum
Sougato Bose	UC London	Alexander Jahn	FU Berlin	Grant Salton	AWS
Sergio Boixo	Google	Stacey Jeffery	CWI	Norbert Schuch	Vienna
Sergey Bravyi	IBM	Liang Jiang	Chicago	Yaoyun Shi	Alibaba
Charles Cao	Virginia Tech	T. Jochym-O'Connor	IBM	Kirill Shtengel	UC Riverside
Matthias Caro	Warwick	Stephen Jordan	Microsoft	Yuan Su	Microsoft
Darrick Chang	ICFO	Kohtaro Kato	Osaka	Kristan Temme	IBM
Andrew Childs	Maryland	Natalie Klco	Duke	Barbara Terhal	Delft
Elizabeth Crosson	UNM	Robert Koenig	Munich	Frank Verstraete	Cambridge
Nicolas Delfosse	Microsoft	Liang Kong	Tsinghua	Guifre Vidal	Google
Abhinav Deshpande	IBM	Richard Kueng	JKU Linz	Ling Wang	Beijing
Andrew Doherty	Sydney	Debbie Leung	Waterloo	Stephanie Wehner	Delft
Luming Duan	Tsinghua	Netanel Lindner	Technion	Pawel Wocjan	UC Florida
Glen Evenbly	AWS	Yi-Kai Liu	NIST	John Wright	Berkeley
Omar Fawzi	ENS Lyon	Angelo Lucia	Madrid	Jon Yard	Waterloo
Lukasz Fidkowski	U. Washington	Saeed Mehraban	Tufts	Beni Yoshida	Perimeter
Steve Flammia	AWS	Spiros Michalakis	Caltech	Shengyu Zhang	CUHK / Tencent
Tuvia Gefen	Hebrew U.	Ash Milsted	AWS	Sisi Zhou	Perimeter

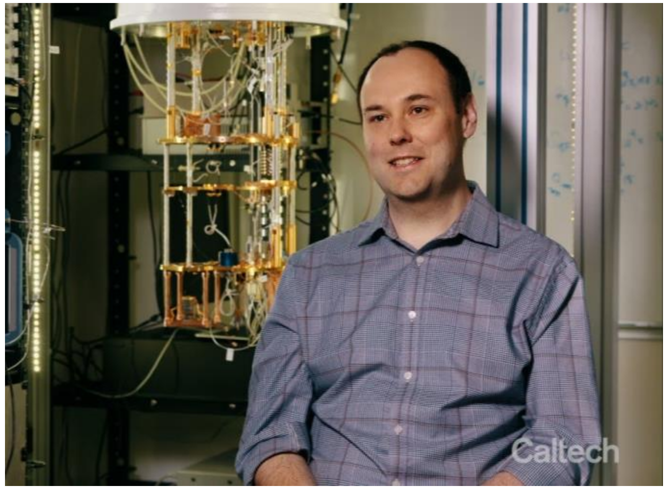
75 former IQI(M) postdocs holding faculty positions (or the equivalent).

38 US, 8 Canada, 19 Europe, 6 Asia, 1 Australia, 3 Middle East.

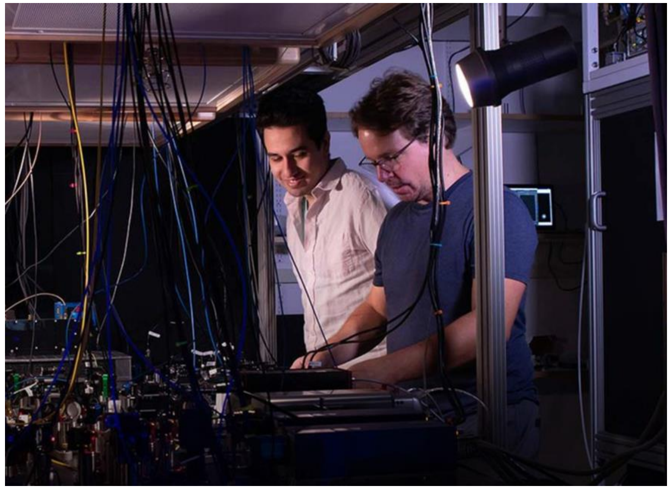
Of 38 in US: 16 at universities, 17 in industry, 5 at national labs





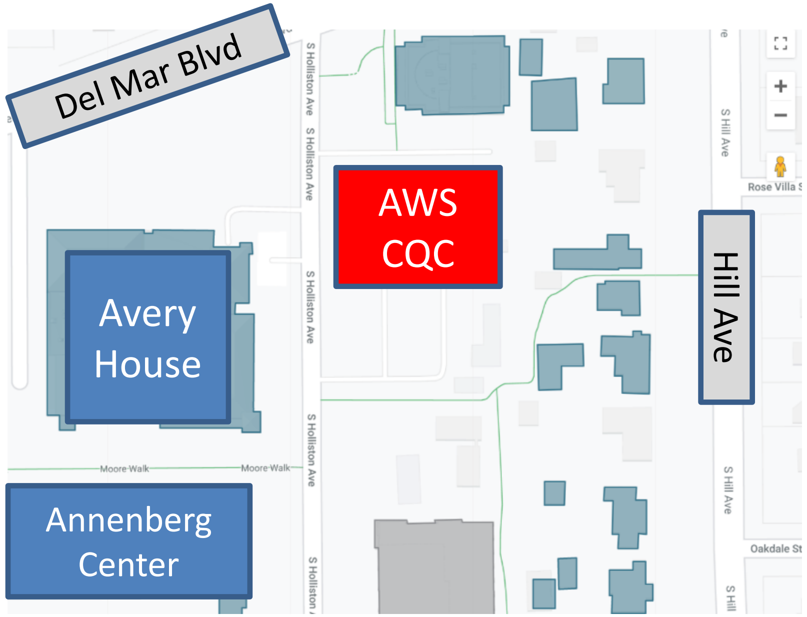


Oskar Painter
Superconducting
Qubits



Manuel Endres
Atomic Qubits

AWS Center for Quantum Computing at Caltech



Oskar Painter

Fernando Brandão

Led by Caltech faculty (Painter and Brandão)

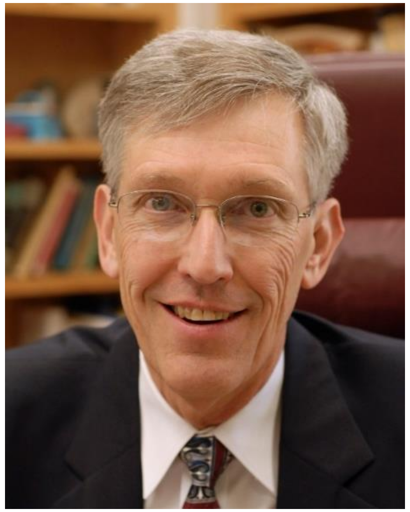
Leveraging technology and ideas developed at Caltech

Sponsored research and extensive collaboration

Surpassing the "standard" quantum limit on measurement precision

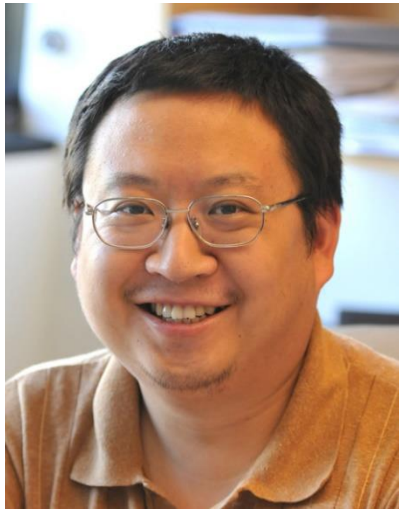
LIGO

Kip Thorne



Jeff Kimble

Rana Adhikari

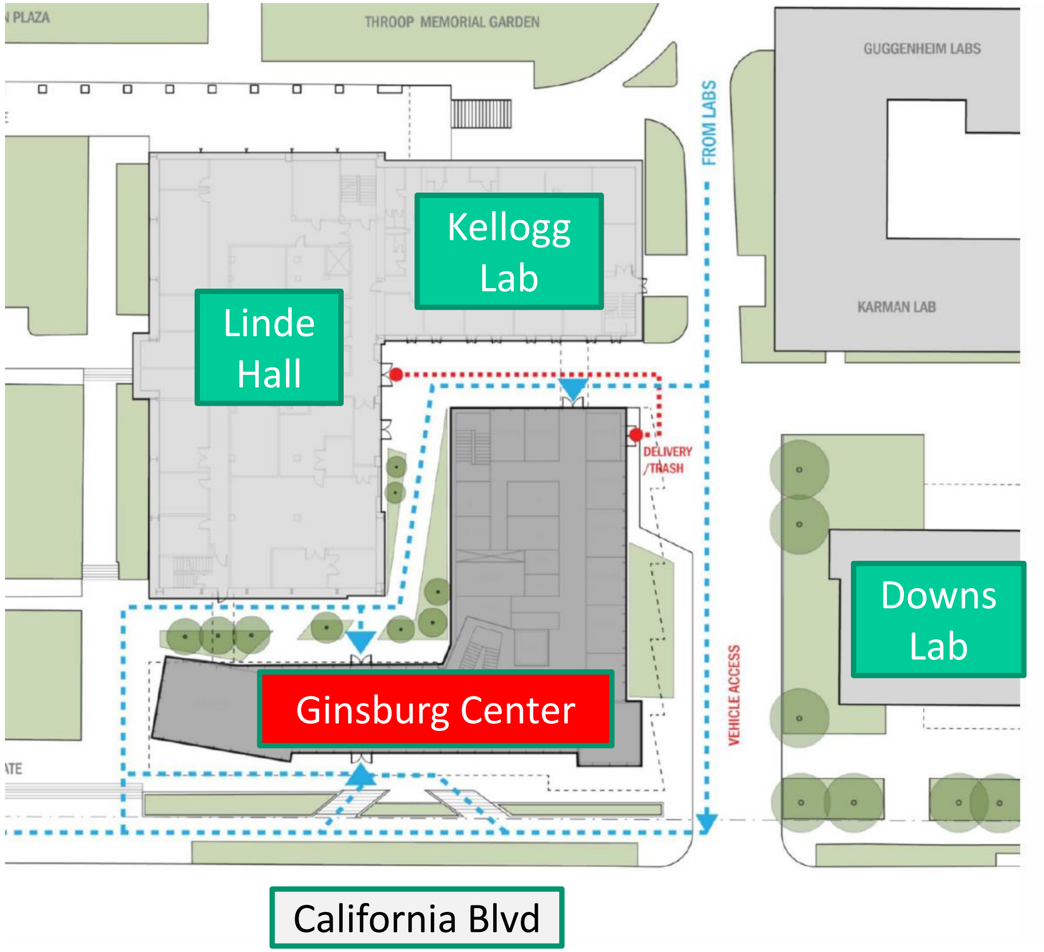


Yanbei Chen

Lee McCuller

Ginsburg Center for Quantum Precision Measurement

Opens 2025. Architectural firm: HOK



Adjacent to Linde, Kellogg, Downs. Seamless cutting-edge laboratory space conducive to intellectual interaction and collaboration, and high-quality contiguous office space for theorists and experimentalists, establishing a vibrant hub for quantum research on campus.