MANIC DEPRESSIVE PHASES

POTENTIAL AND LIMITATIONS OF QUANTUM COMPUTING

JENS EISERT, FREIE UNIVERSITÄT BERLIN

Updated McKinsey analysis for the third annual *Quantum Technology Monitor* reveals that four sectors—chemicals, life sciences, finance, and mobility—are likely to see the earliest impact from quantum computing and could gain up t[…] $2 trillion by 2035 (see sidebar "What is quantum technology?").

Gastkommentar

Handelsblatt

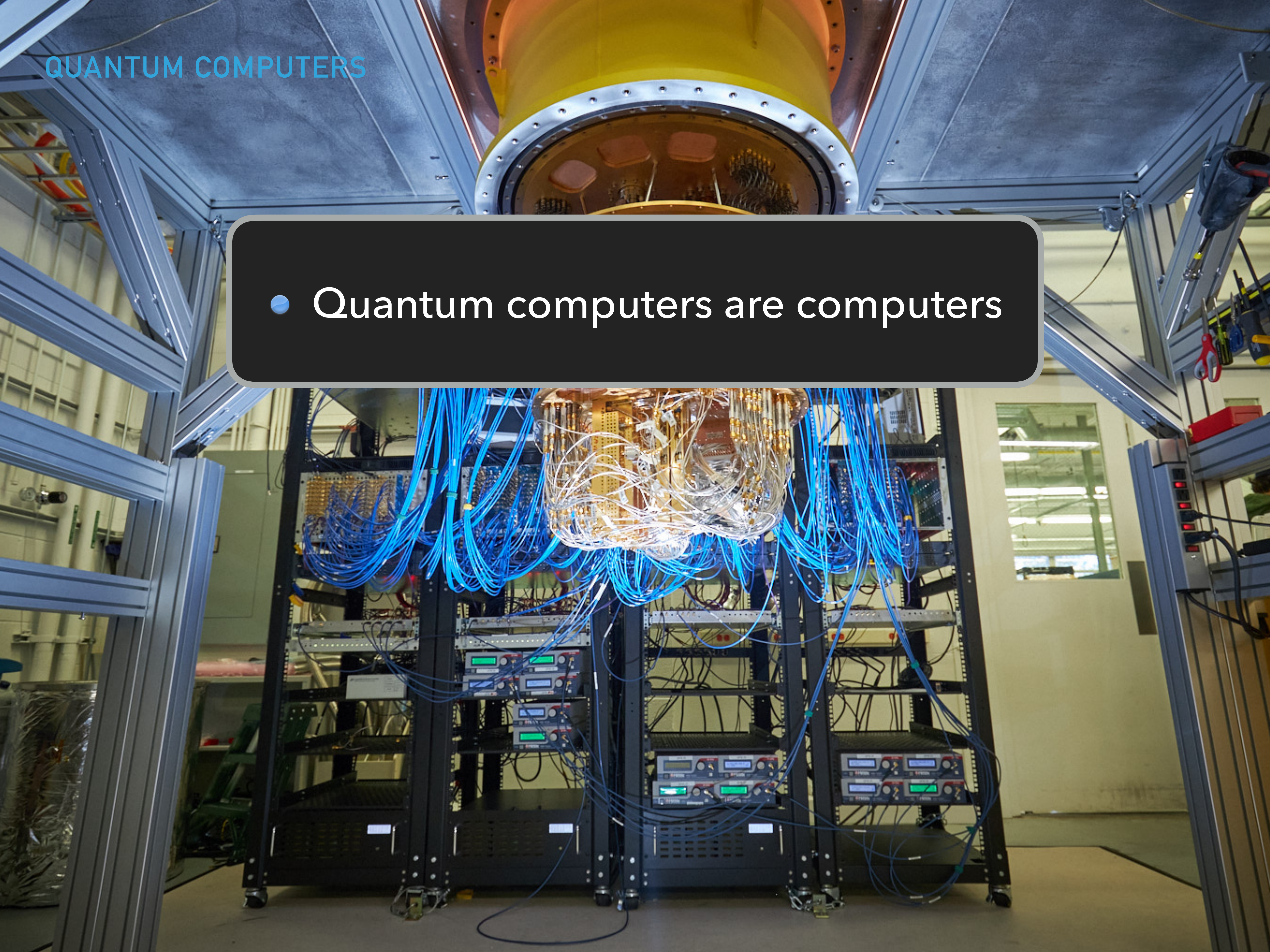
Quantum Computing beschleunigt rasant alle Prozesse

Nach der Künstlichen Intelligenz sind Supercomputer die

POTENTIAL AND LIMITATIONS OF QUANTUM COMPUTING

QUANTUM COMPUTERS

- Quantum computers are computers



- Quantum computers are computers

QUANTUM MECHANICS

- Quantum mechanics is a physical theory

- Quantum mechanics is a physical theory
- Theory of atoms, molecules and light quanta

- Developed 1925-1928

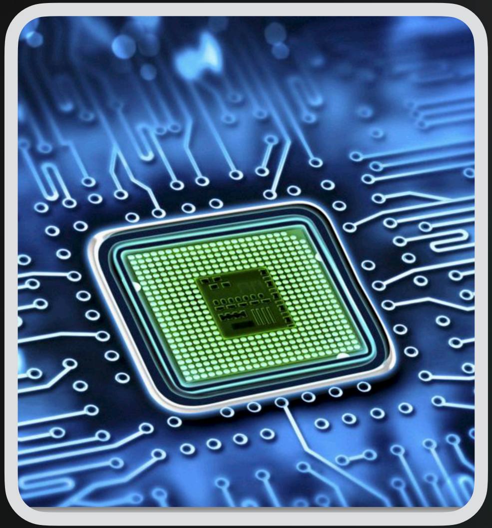
WERNER HEISENBERG

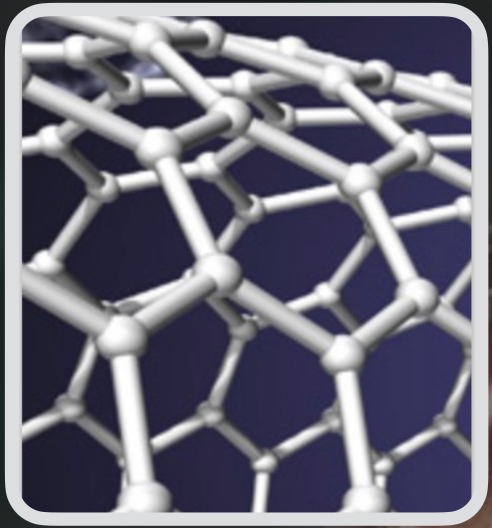
ERWIN SCHRÖDINGER

PAUL DIRAC

QUANTUM MECHANICS

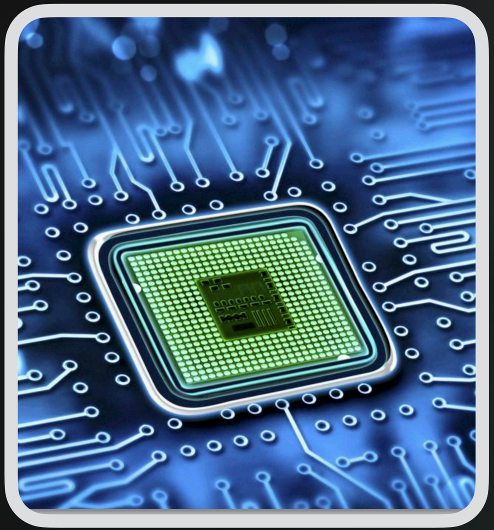
- Developed 1925-1928
- Basis of semiconductors, materials science, lasers

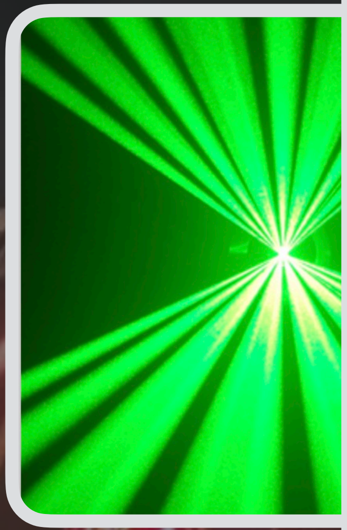




QUANTUM MECHANICS

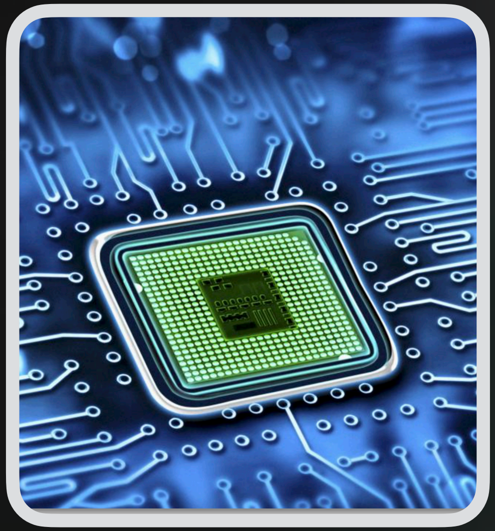
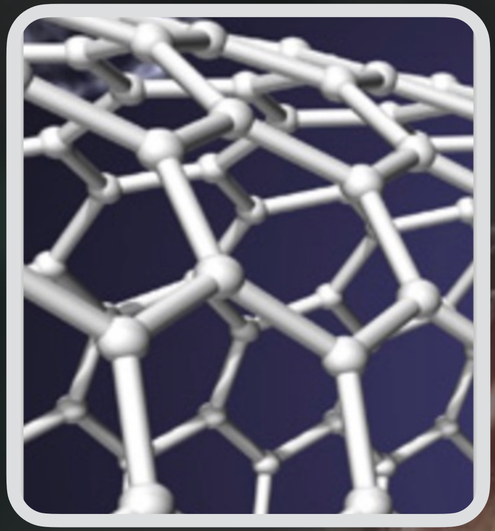
- Developed 1925-1928
- Basis of semiconductors, materials






- First quantum revolution

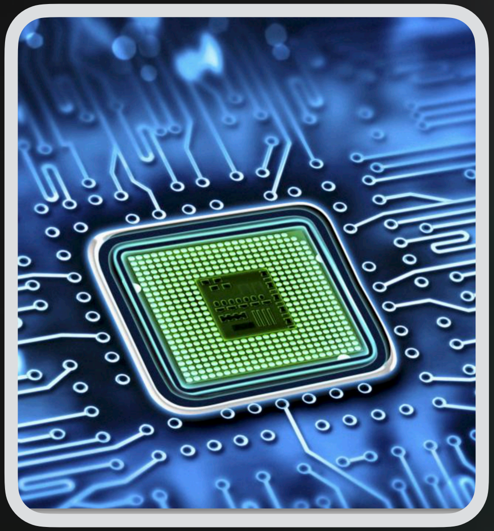
- Developed 1925-1928
- Basis of semiconductors, materials science, lasers

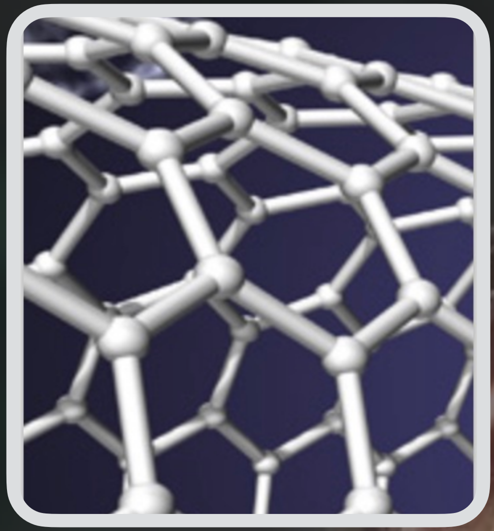
  

- Fine structure constant 7,297.352.566.4(17) x 10^{-3}

QUANTUM MECHANICS

- Developed 1925-1928
- Basis of semiconductors, materials science, lasers





- Fine structure constant 7,297.352.566.4(17) x 10^{-3}
- Radically different from classical physics

RANDOMNESS

- Measurement outcomes are random

- Measurement outcomes are random

- Randomness is known to us

… but it has an explanation

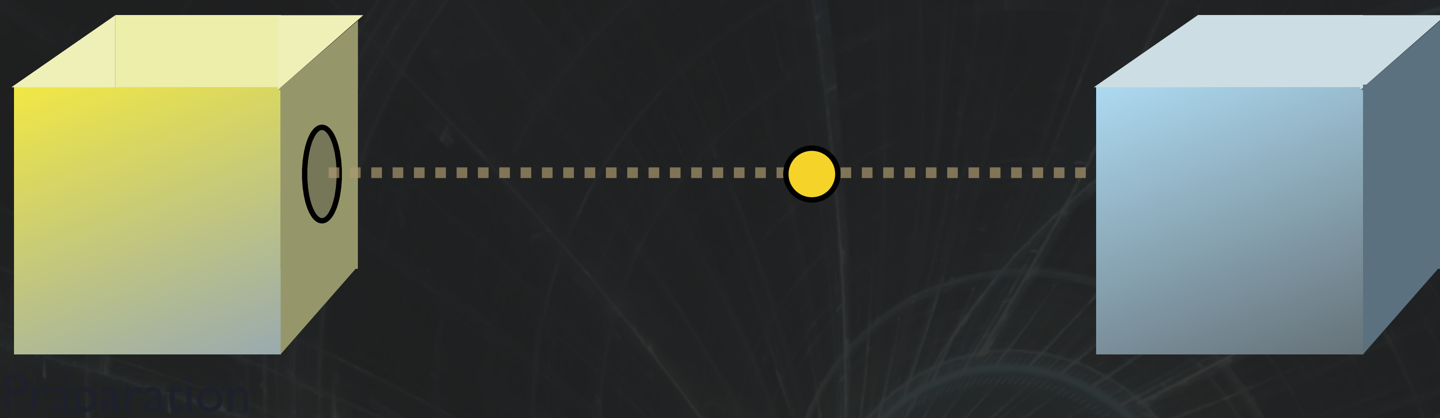
0 1 1 0 1 0

- Randomness is known to us

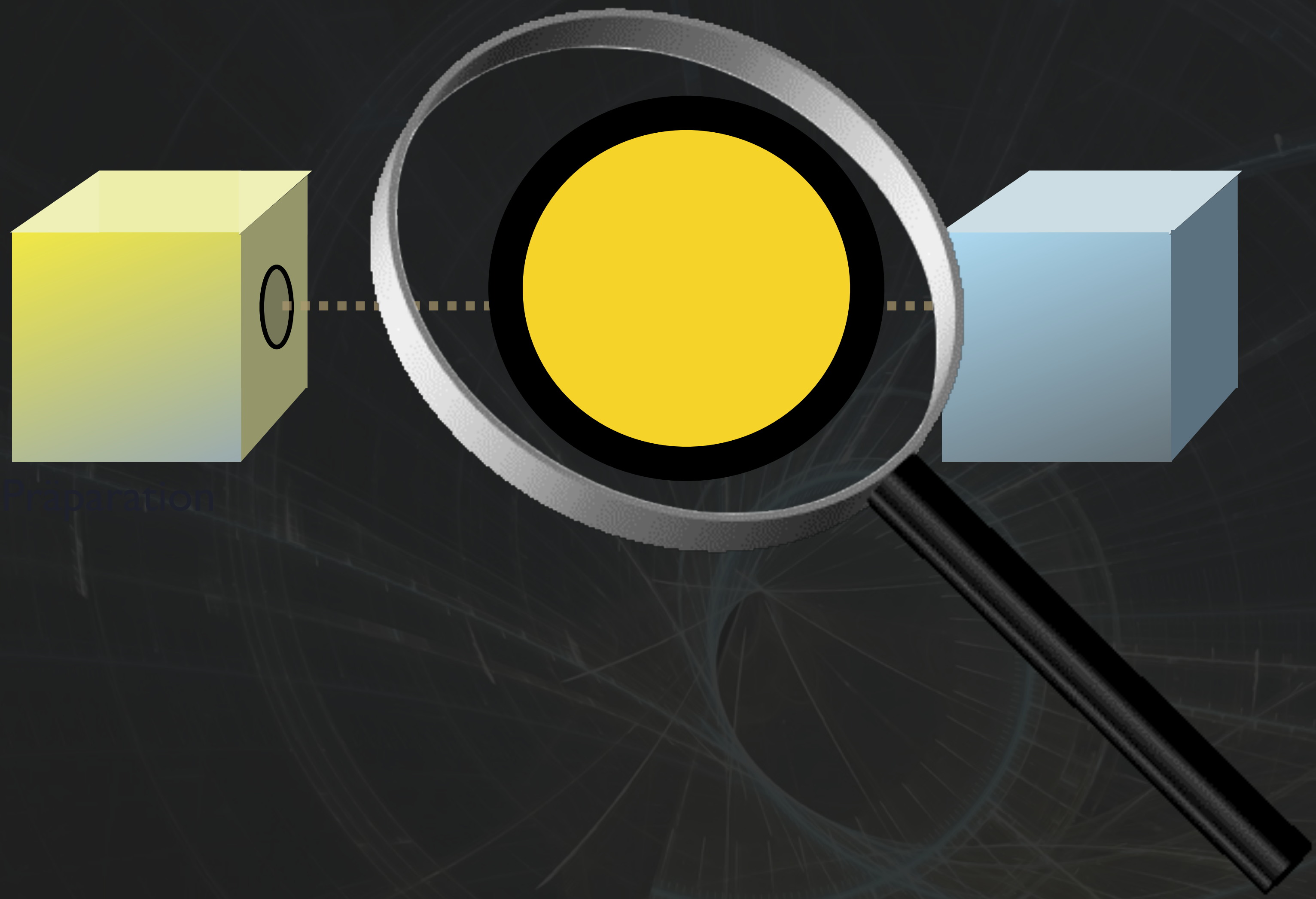
… but it has an explanation

RANDOMNESS IN QUANTUM MECHANICS

- The randomness of quantum mechanics is absolute



- The randomness of quantum mechanics is absolute



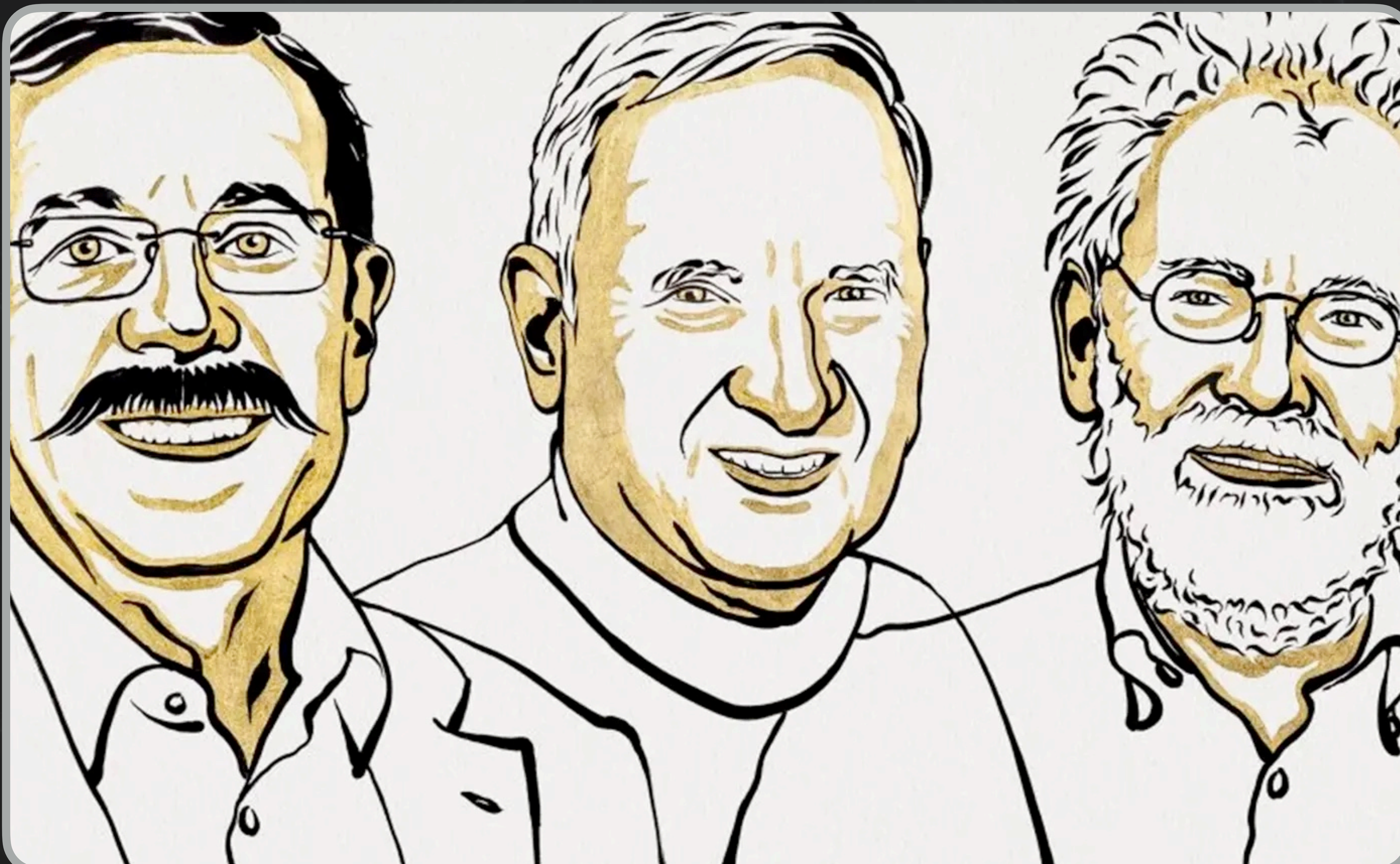
RANDOMNESS IN QUANTUM MECHANICS

- The randomness of quantum mechanics is absolute

- Bell's inequality is violated (assumption of local hidden variables)

$$P(a,b|A,B) = \int d\lambda p(\lambda)\chi_A(a,\lambda)\chi_B(b,\lambda)$$

- The randomness of quantum mechanics is absolute



ALAIN ASPECT, JOHN CLAUSER, ANTON ZEILINGER

UNCERTAINTY

UNCERTAINTY

UNCERTAINTY

- No measurements without disturbance

SUPERPOSITION

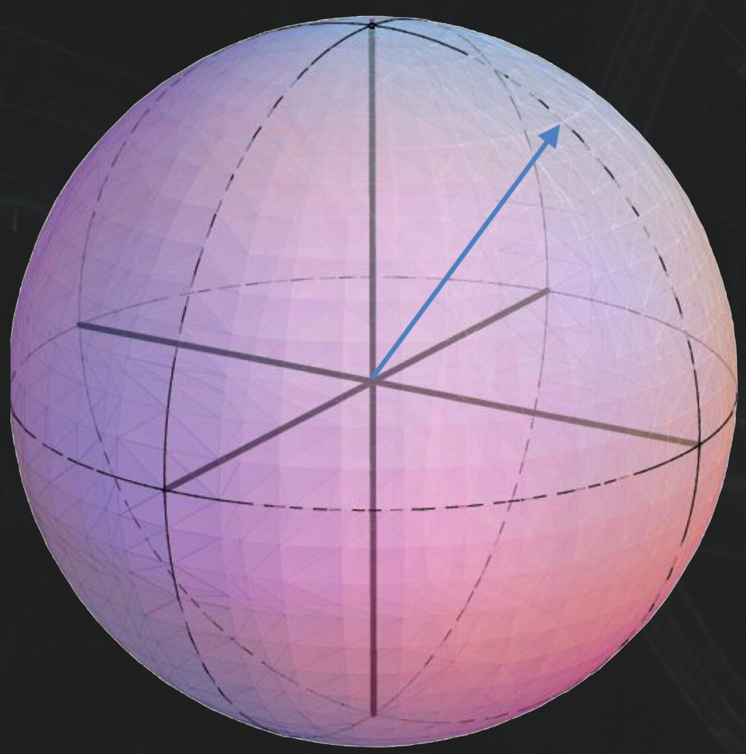
SUPERPOSITION PRINCIPLE

1

0

SUPERPOSITION PRINCIPLE

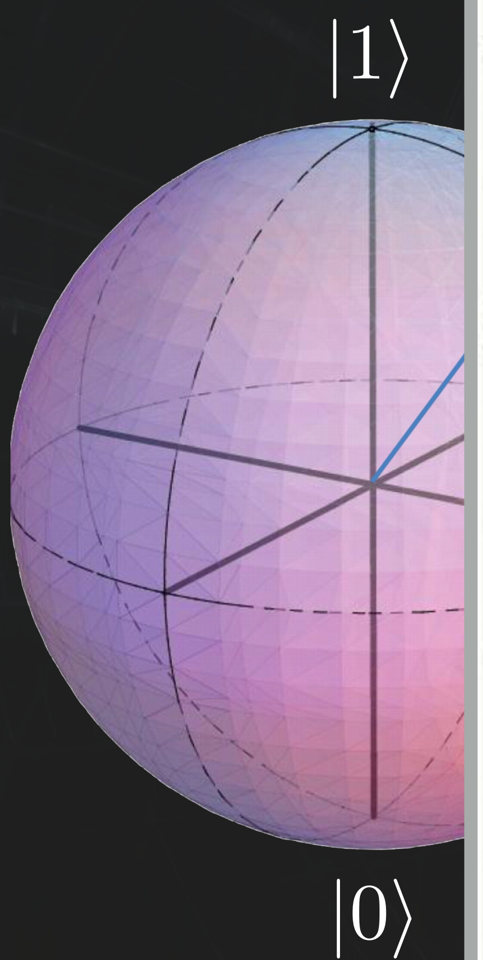
$|1\rangle$

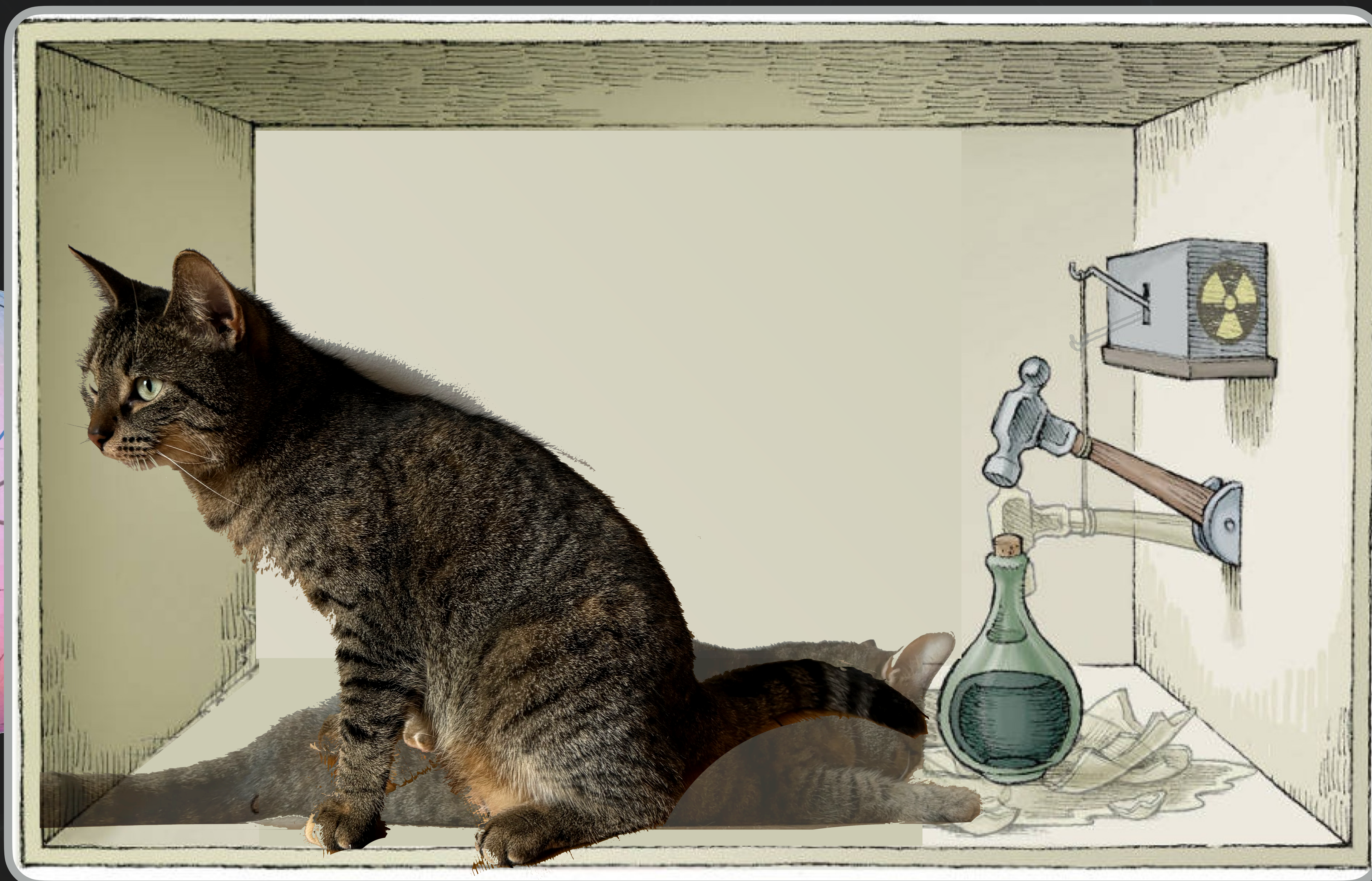


$|0\rangle + |1\rangle$

$|0\rangle$

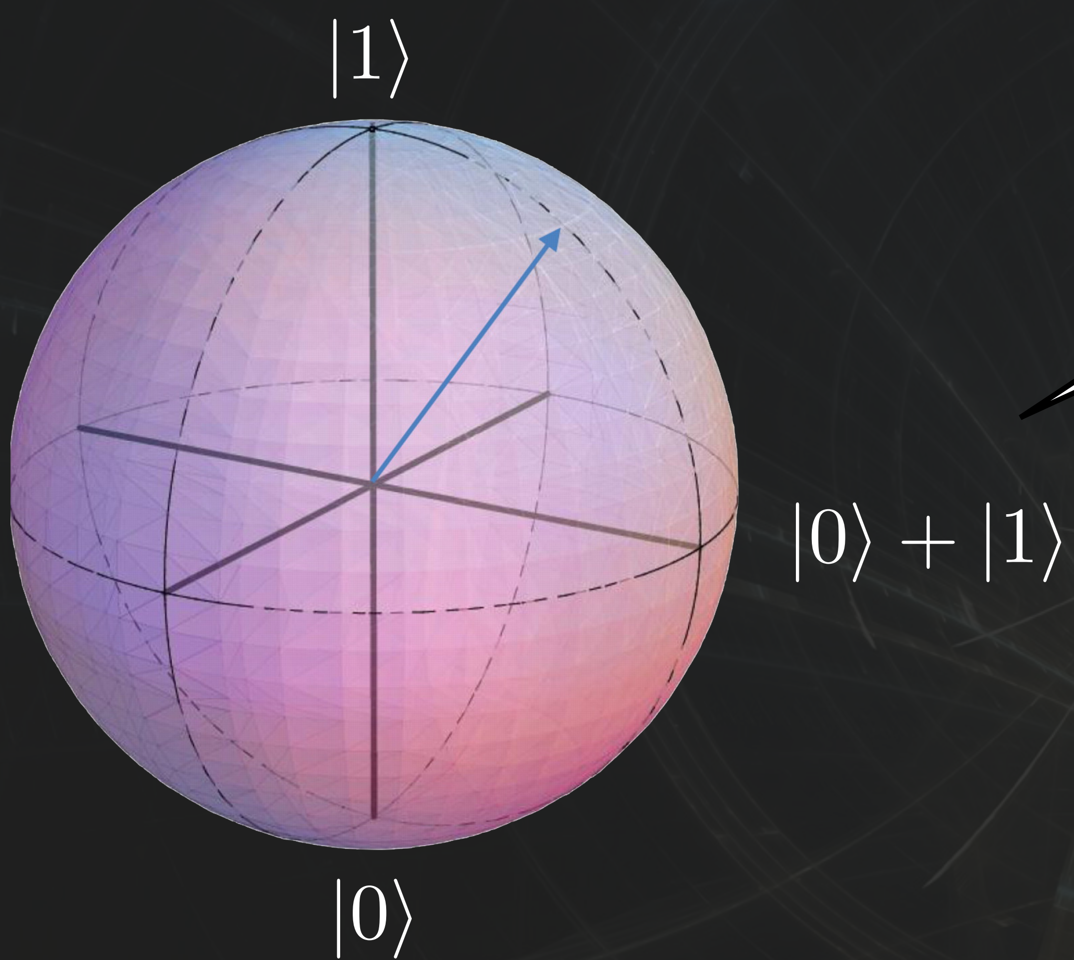
SUPERPOSITION PRINCIPLE

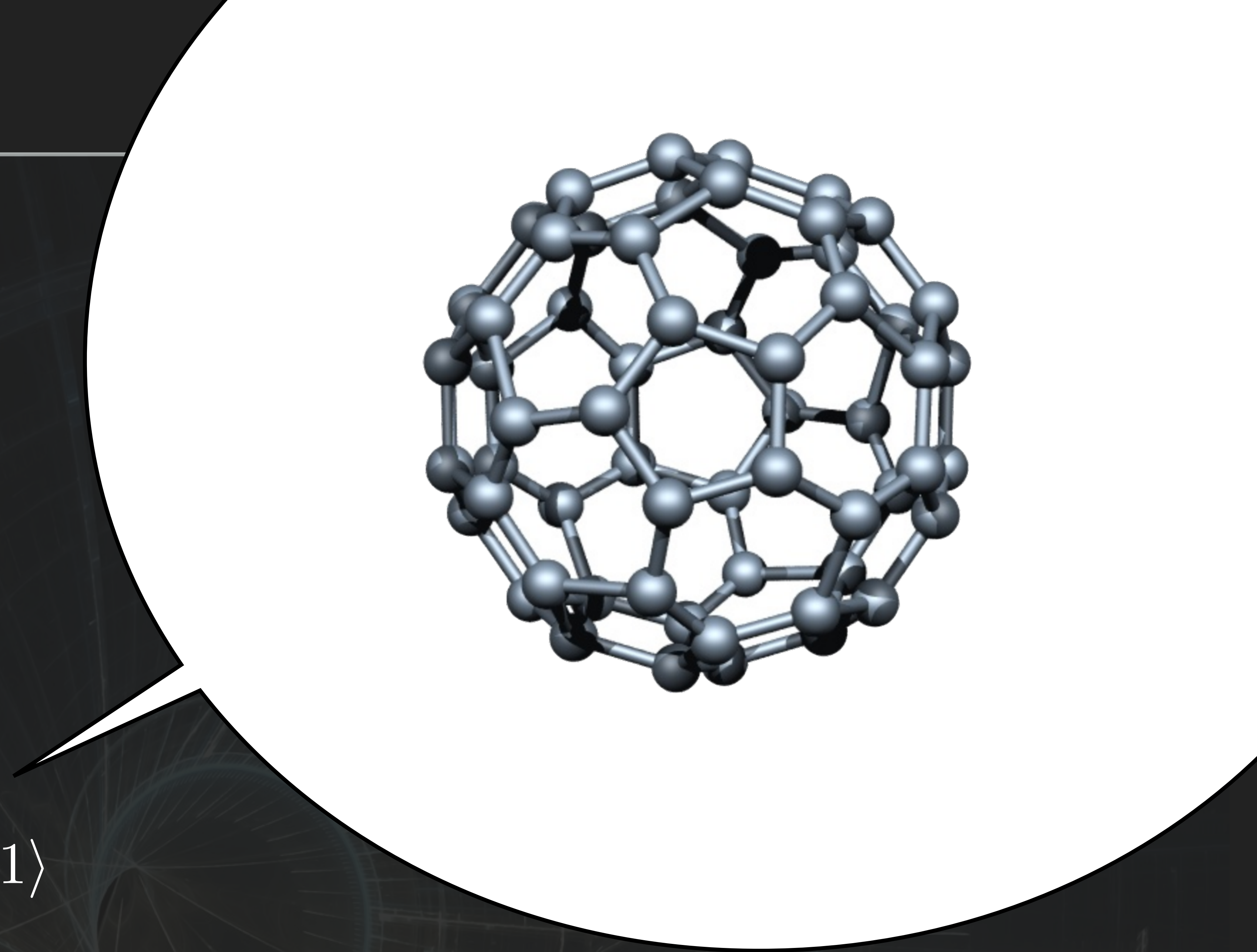




SCHRÖDINGER'S CAT

SUPERPOSITION PRINCIPLE



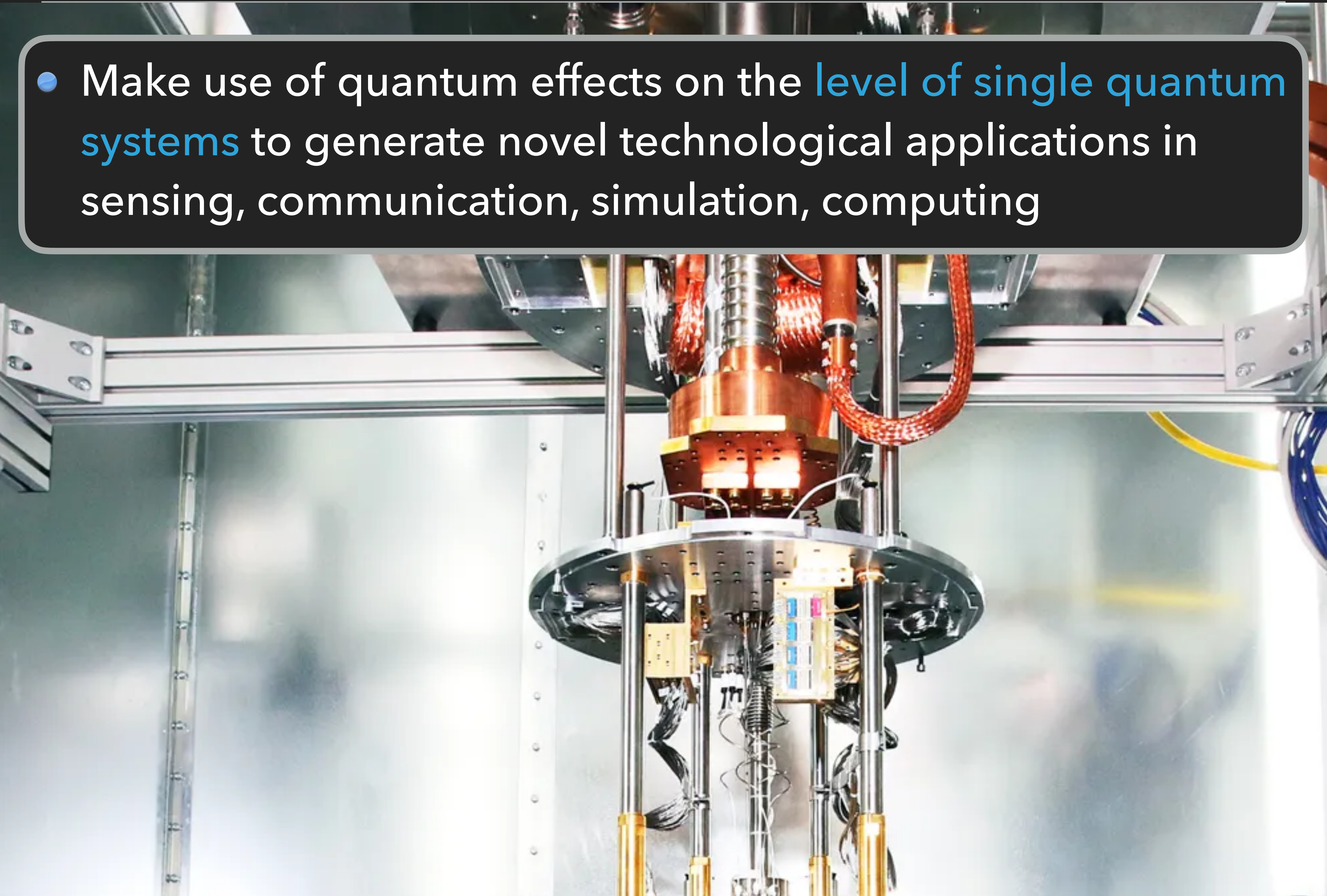


- Systems can be in ‘many states at once’

DEVELOPMENT OF QUANTUM COMPUTING

SECOND QUANTUM REVOLUTION

- Make use of quantum effects on the level of single quantum systems to generate novel technological applications in sensing, communication, simulation, computing



QUANTUM COMPUTERS

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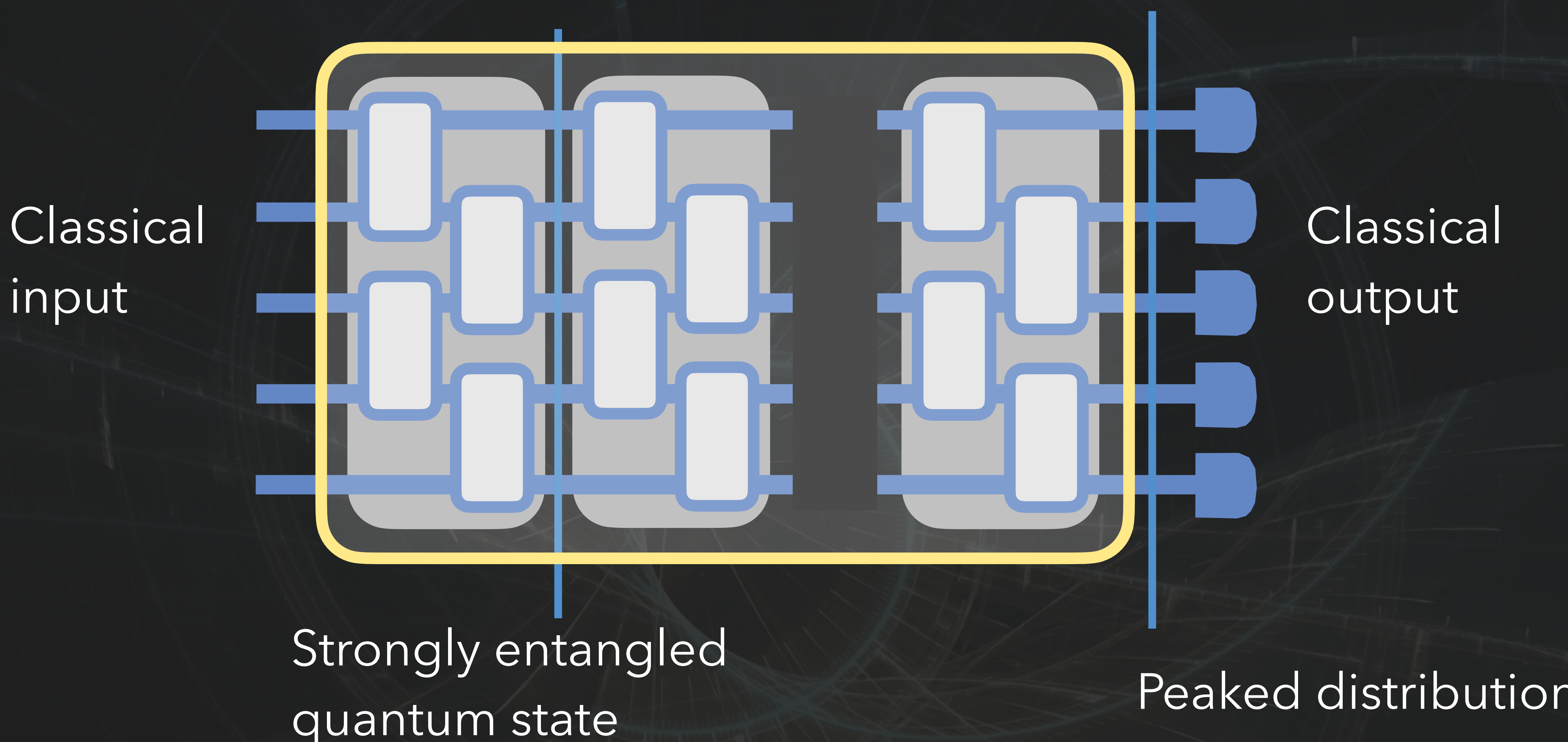
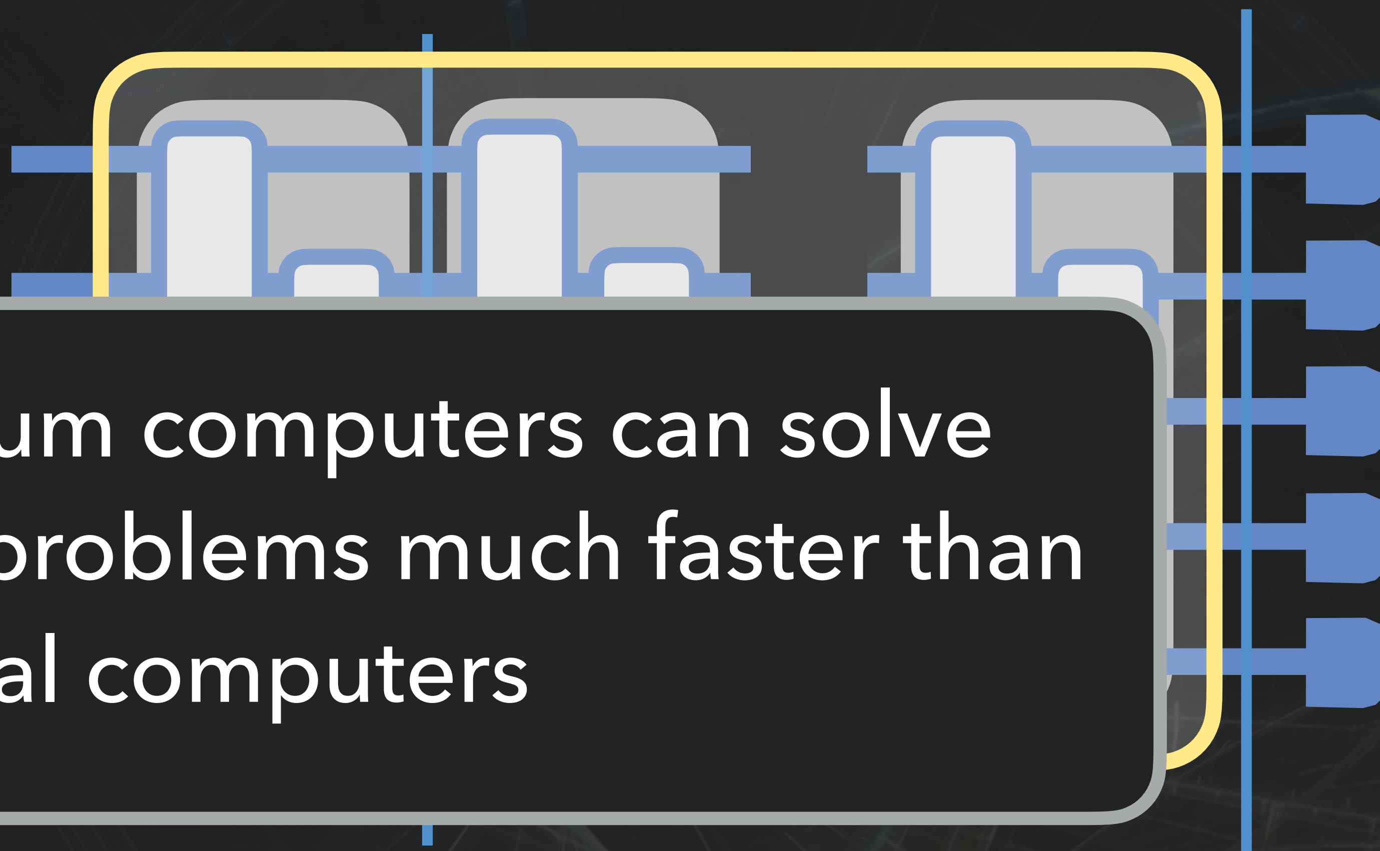


- Constituents can be in a superposition of classical alternatives

$$\alpha|0,1,0,1,0,0,1,1\rangle + \beta|1,1,0,0,1,1,1,0\rangle + \gamma|0,0,1,0,0,1,1,1\rangle + \ldots$$

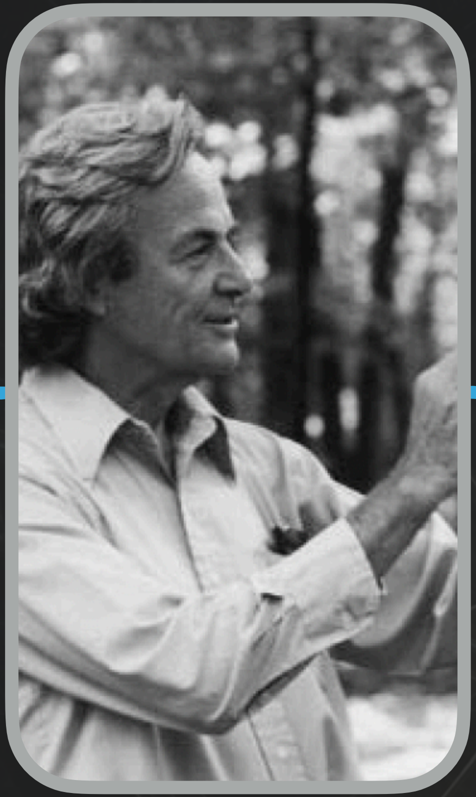
QUANTUM COMPUTERS

- Quantum computers are computers

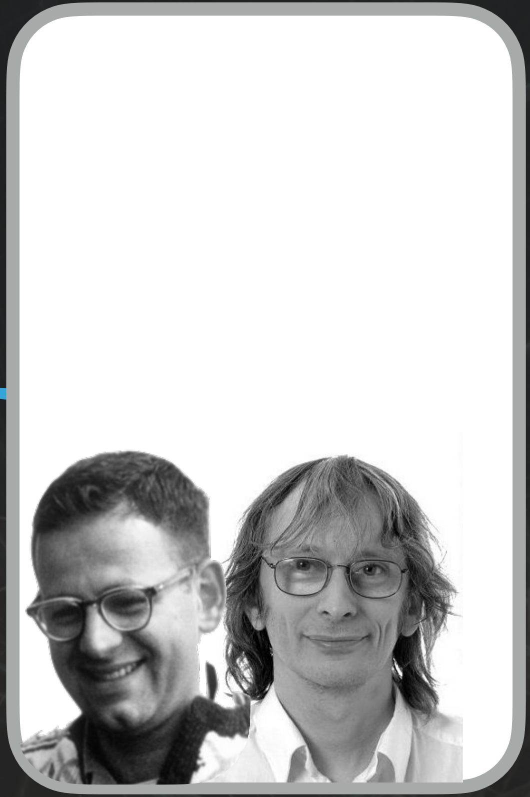


- Quantum computers can solve some problems much faster than classical computers

- Initially a conceptual idea



RICHARD FEYNMAN



PAUL BENIOFF
DAVID DEUTSCH

1982

Feynman, Int J Th Phys 21, 467 (1982)
Benioff, J Stat Phys 22, 563 (1980)
Deutsch, Proc R Soc Lond A 400, 1818 (1985)

- Initially a conceptual idea

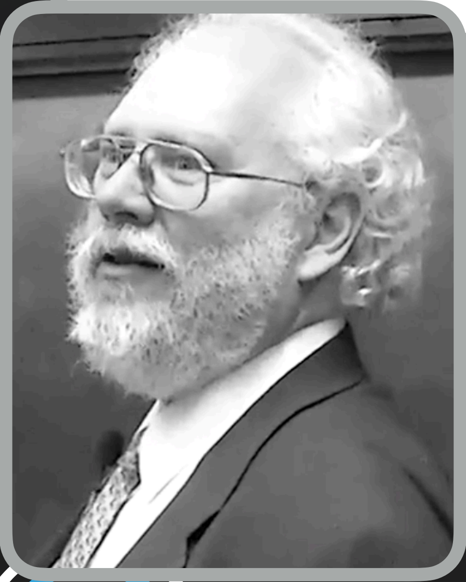
- A factor of a number N can be found if one knows a period p of

$$f(x) = a^x \mathrm{mod} N$$

- Periods can be found with the quantum Fourier transform

$$\sum_{i=0}^{n-1} x_i |i\rangle \mapsto \sum_{i=0}^{n-1} y_i |i\rangle \text{ with } y_k = \frac{1}{\sqrt{n}} \sum_{j=0}^{n-1} x_j e^{2\pi i j k / n}$$

Shor, SIAM J Comp 26, 148 (1997)



PETER SHOR

- Solves factoring in $O((\log N)^3)$ time
- Best classical

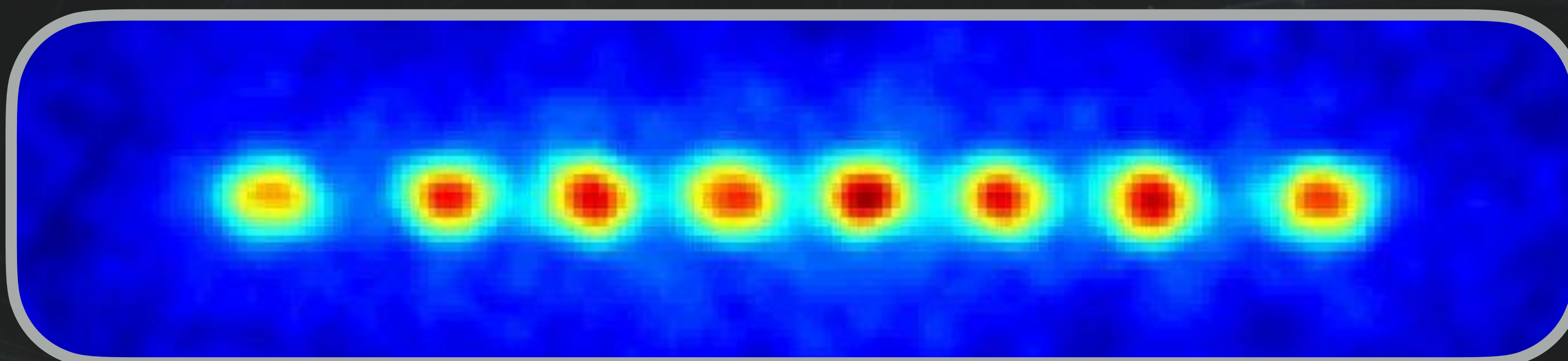
$$\exp(O((\log N)^{1/3}(\log \log N)^{2/3}))$$

1982

1997

QUANTUM COMPUTERS

- Experimental progress harder to come by

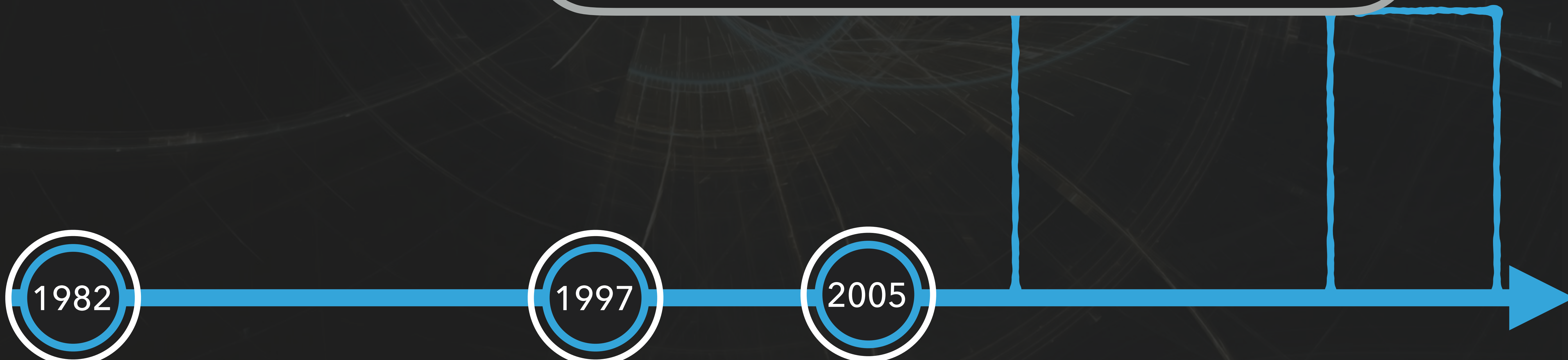


QUANTUM BYTE WITH IONS

QUANTUM COMPUTERS

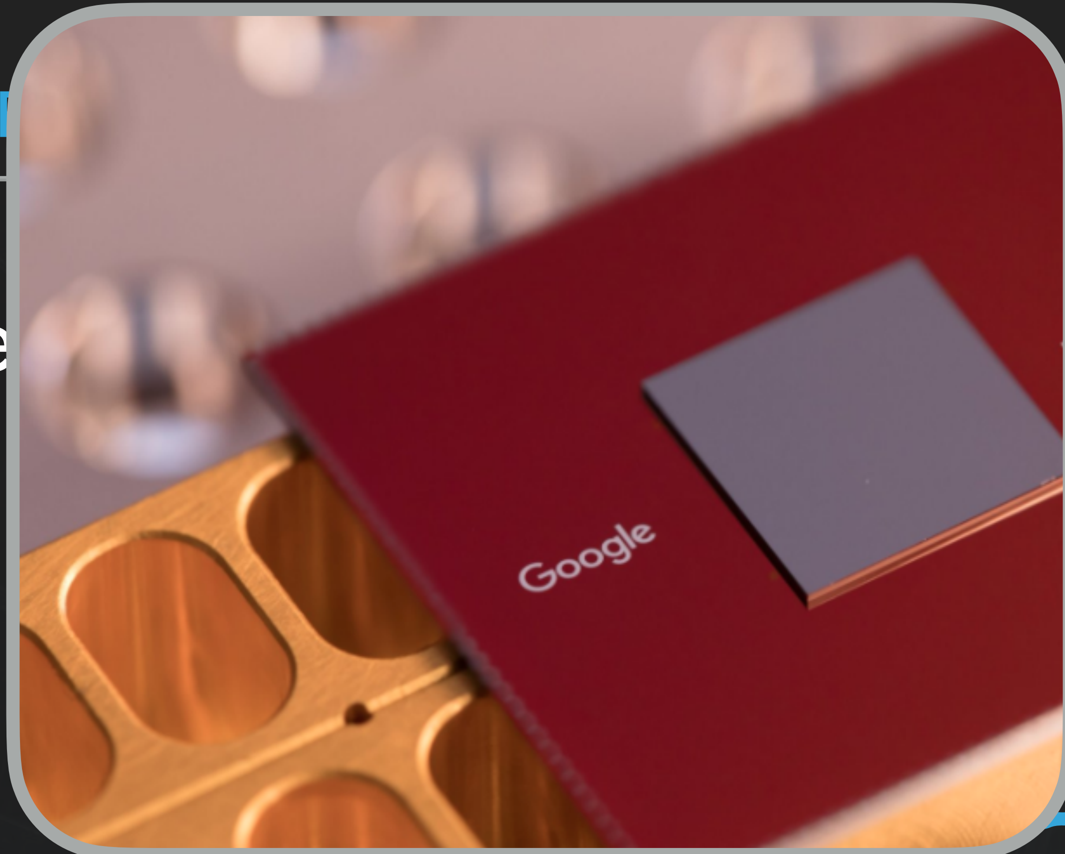
- Some quantum algorithms known

- Linear systems of equations
  Harrow, Hassidim, Lloyd, Phys Rev Lett 15, 150502 (2009)
- Semi-definite programming
  Brandão, Kalev, Li, Lin, Svore, Wu, arXiv:1710.02581 (2017)
- Harmonic oscillators
  Babbusch, Berry, Kothari, Somma, Wiebe, Phys Rev X 13, 041041 (2023)

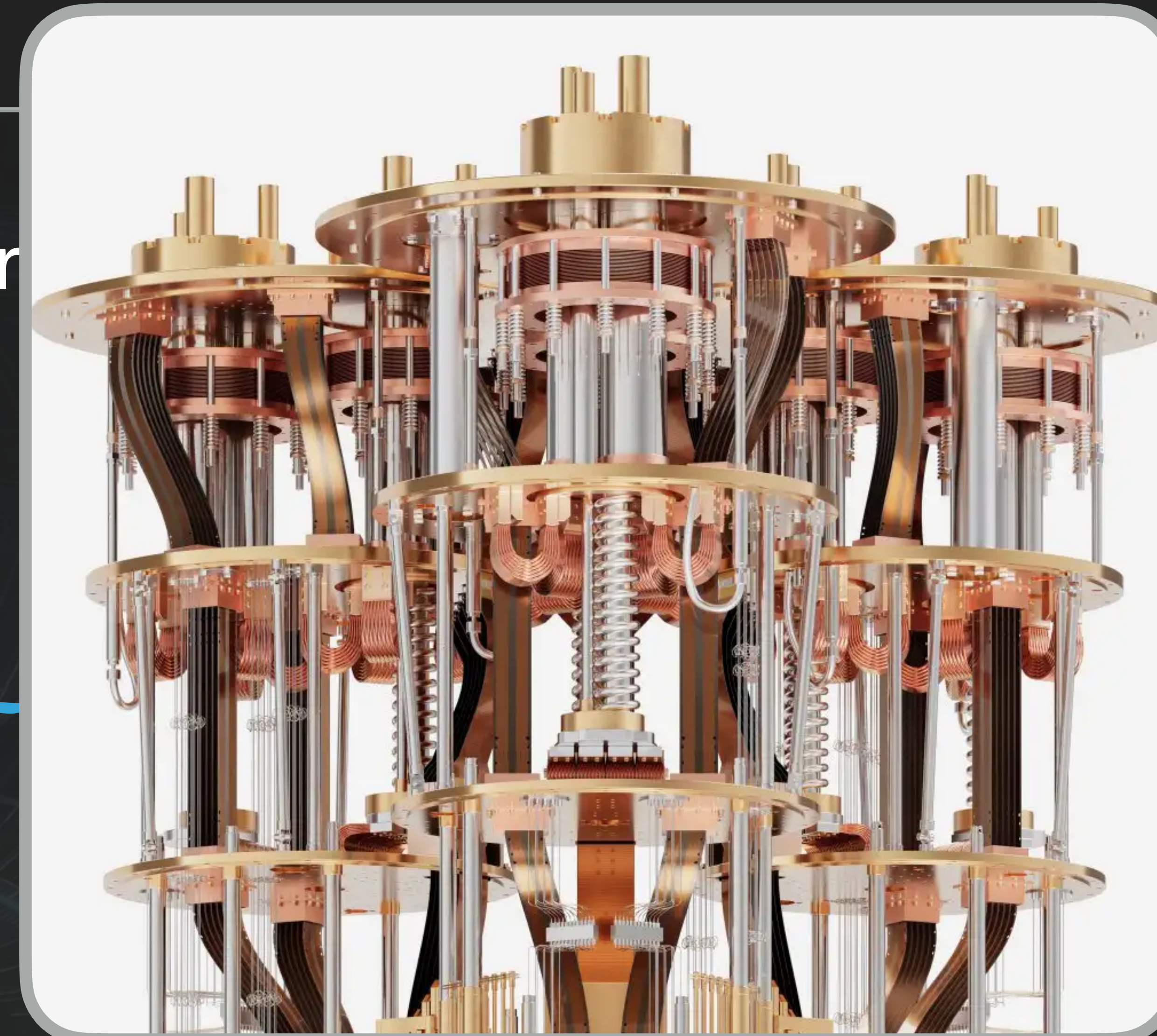


EXPE

- Ve ... per

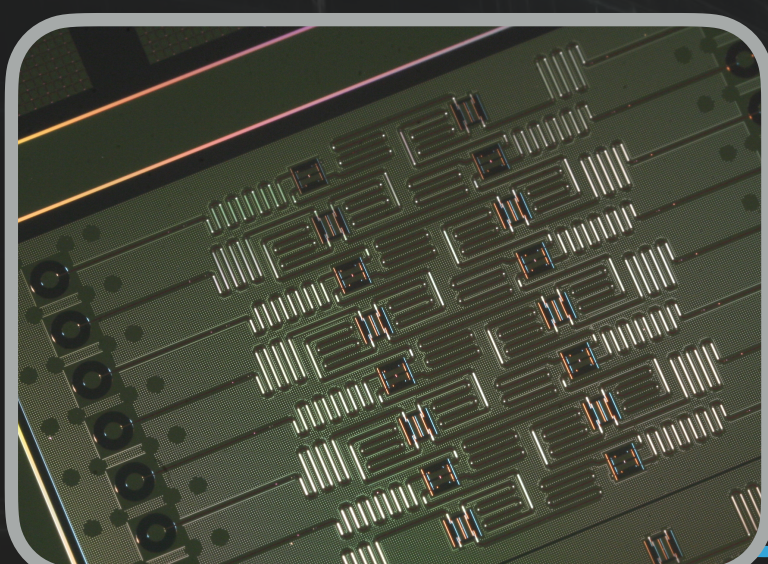


GOOGLE 128 QUBIT BRIZZLECONE



IBM 1221 QUBITS

IBM 50 QUBITS



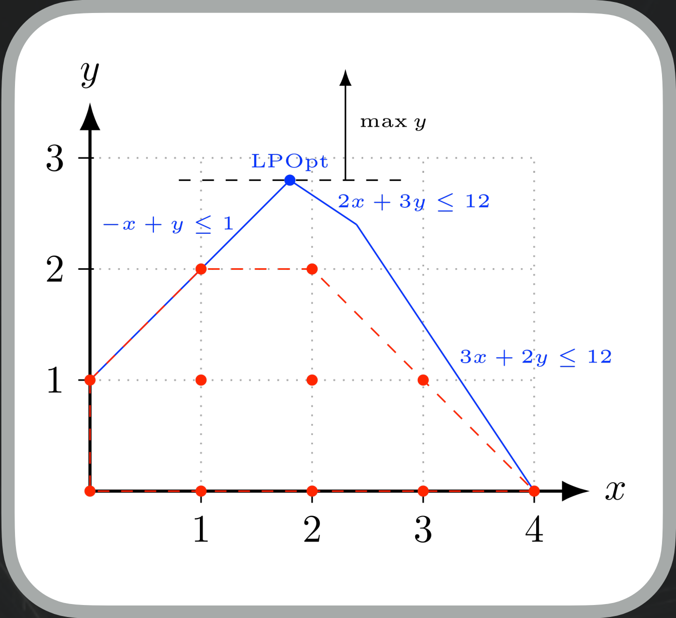
IBM 16 SUPERCONDUCTING QUBITS

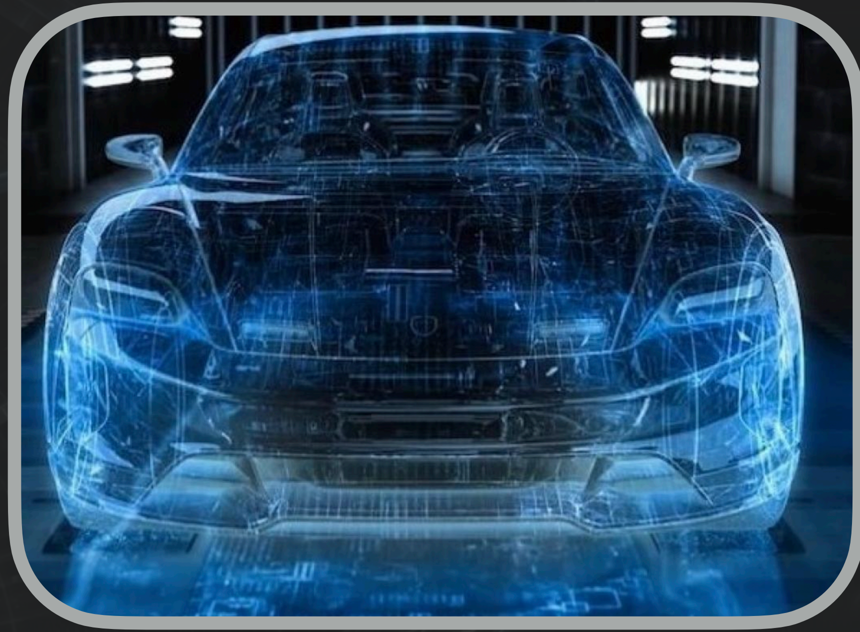
1982 — 1997 — 2005 — 2017 — 2019 — 2024

- Are there quantum advantages in optimization and machine-learning?

- Ubiquitous in industrial applications - but usually NP-hard

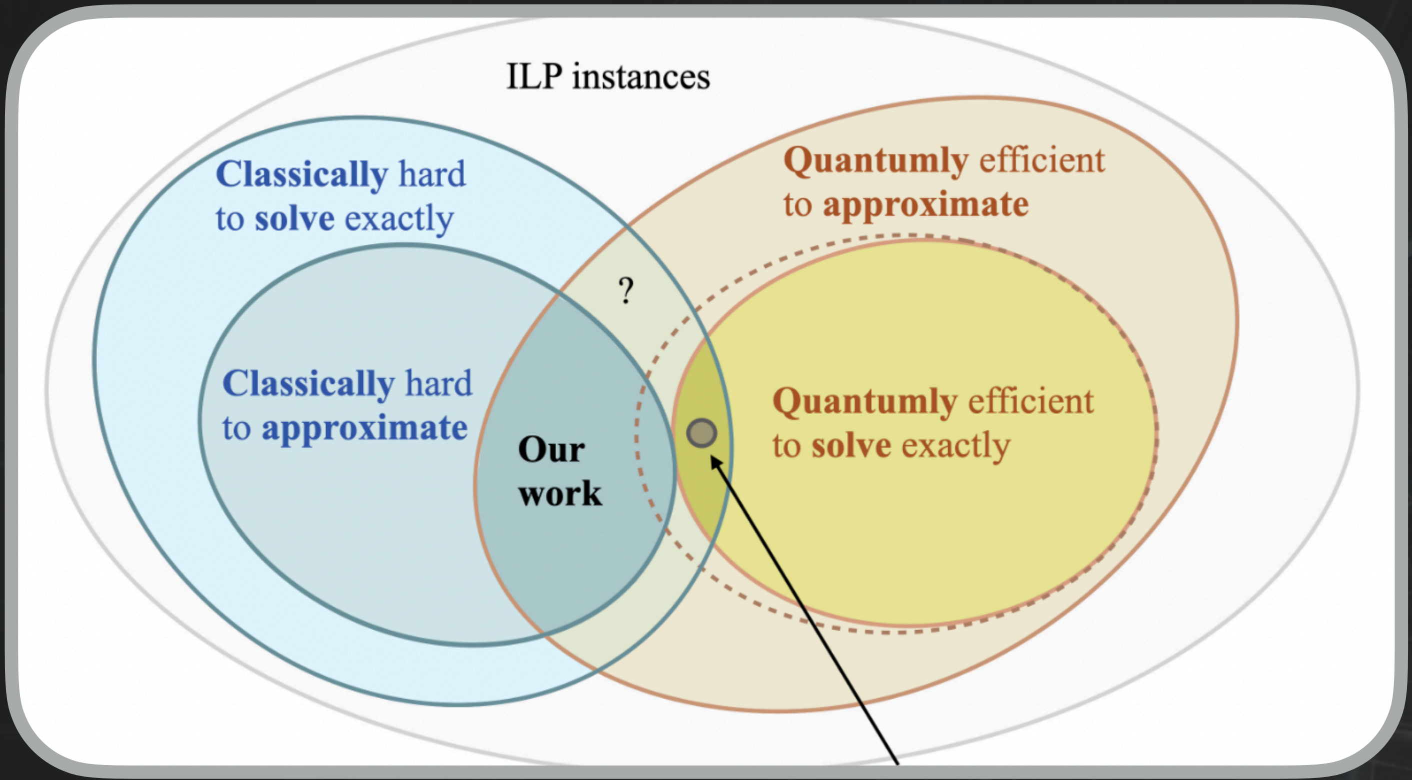
$$
\begin{aligned}
&\text{maximize} && \mathbf{c}^{\mathrm{T}}\mathbf{x} \\
&\text{subject to} && A\mathbf{x} \leq \mathbf{b}, \\
& && \mathbf{x} \geq \mathbf{0}, \\
&\text{and} && \mathbf{x} \in \mathbb{Z}^n,
\end{aligned}
$$





- Can we hope for quantum advantages?

- In principle, yes

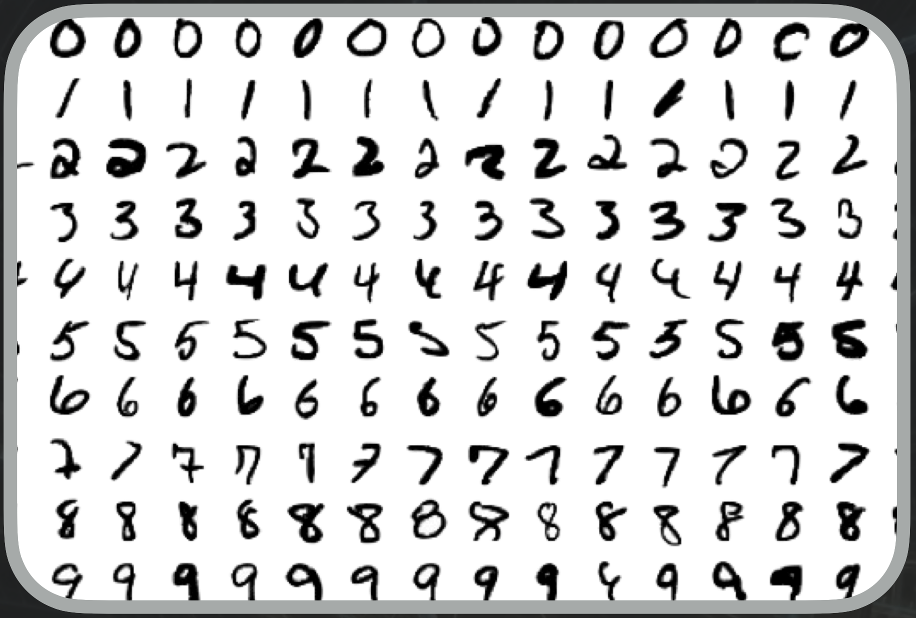


Pirnay, Ulitzsch, Wilde, Eisert, Seifert, arXiv:2212.08678, Science Advances (2024)
Szegedy, arXiv:2212.12572 (2022)

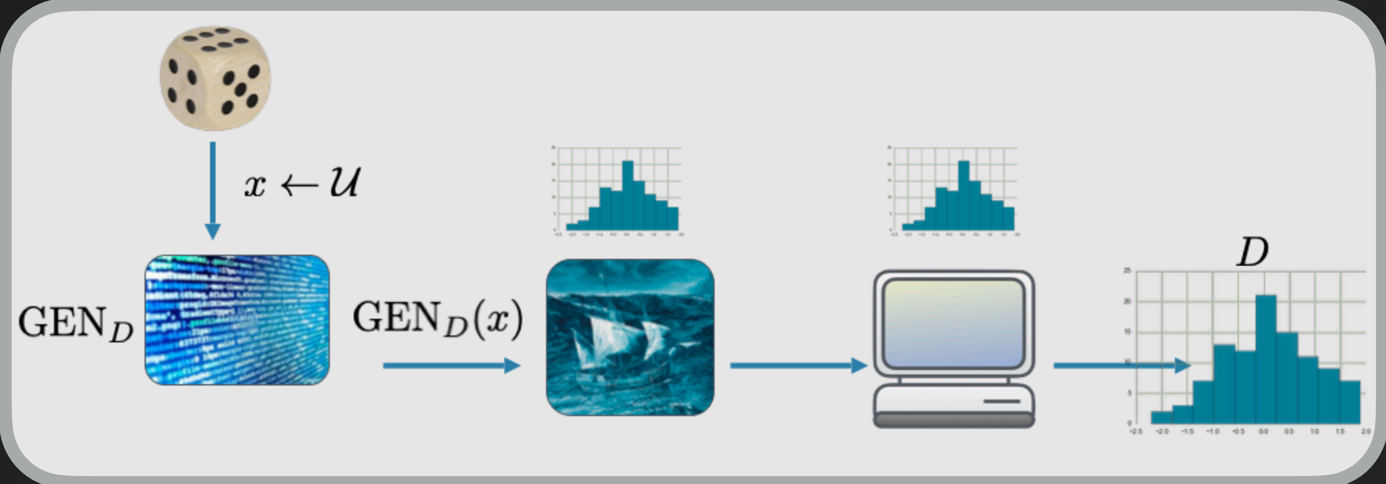
- Quantum computers can efficiently approximate instances of integer programming that are classically hard to approximate
- Race for variational algorithms open

Farhi, Goldstone, Gutmann, Zhou, Quantum 6, 759 (2022)
Zhou, Wang, Choi, Pichler, Lukin, Phys Rev X 10, 021067 (2020)

- How about machine learning?



- Again, yes



Pirnay, Sweke, Eisert, Seifert, Phys Rev A 107, 042416 (2023)
Liu, Arunachalam, Temme, Nature Phys 17, 1013 (2021)
Sweke, Seifert, Hangleiter, Eisert, Quantum 5, 417 (2021)

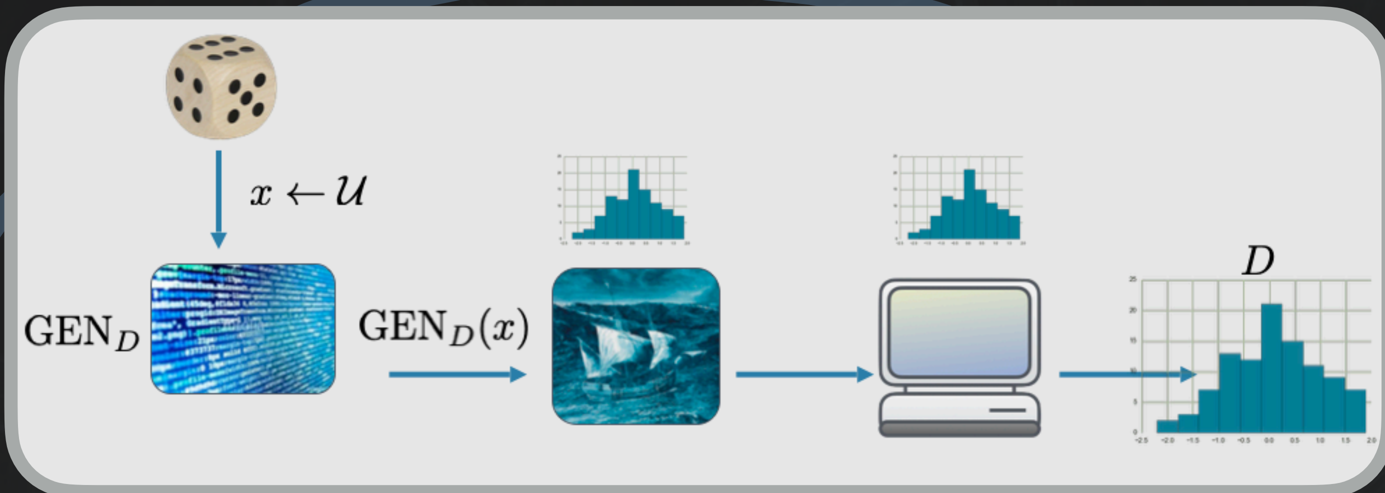
- Quantum computers can learn structured distributions superpolynomially better

- **"Probably approximately correct" learning of distribution classes**
  - A distribution class $\mathcal{C}$ is efficiently PAC learnable w.r.t. distance d if there is an algorithm $\mathcal{A}$ which for every $D \in \mathcal{C}$ and every $\epsilon, \delta > 0$ given access to an oracle $O(D)$, outputs in time $\mathrm{poly}(|D|, 1/\epsilon, 1/\delta)$
  - with probability at least $1-\delta$ ("probably") a generator $\mathrm{GEN}_{D'}$ of a distribution D' such that

$$d(D, D') < \epsilon$$

("approximately correct")

- Again, yes



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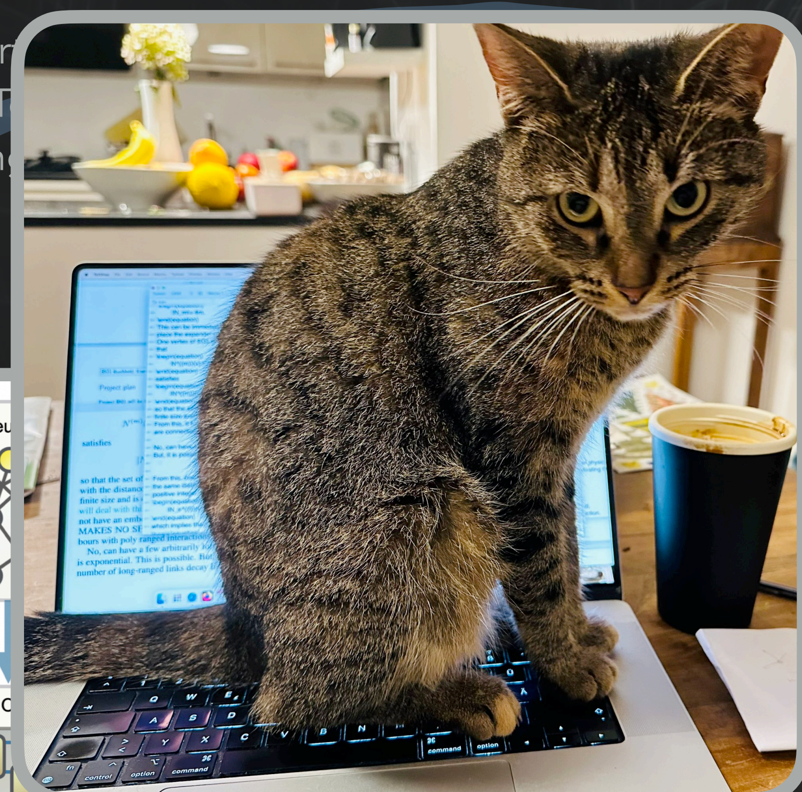
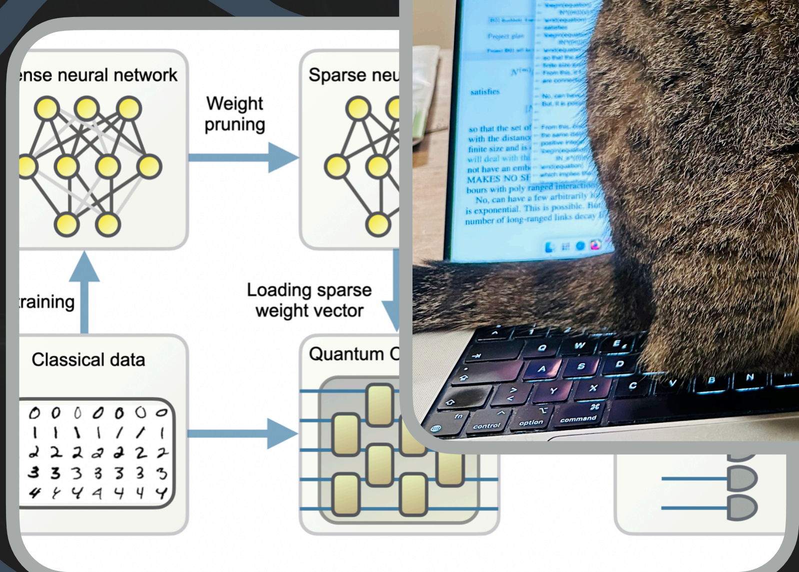
Pirnay, Sweke, Eiser
Liu, Arunachalam, T
Sweke, Seifert, Han





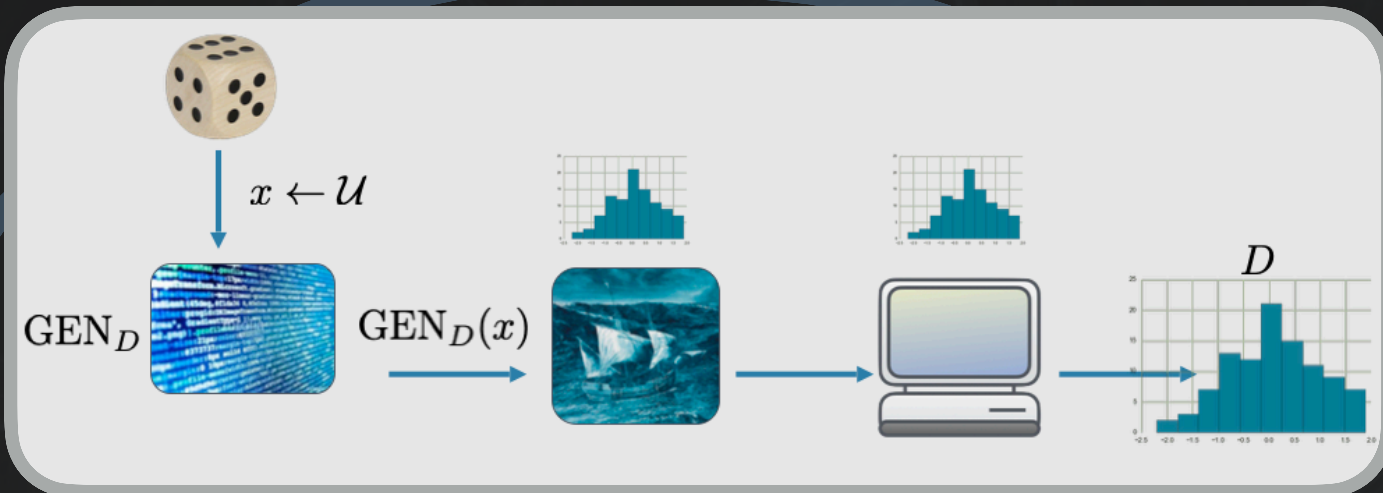
ustrial applications, can train
lassical sparse networks

narks of models with 7
up to 103 million parameters

Liu, Liu, Liu, Ye, Wang, Alexeev, Eisert, Jiang, Nature Comm 15, 434 (2024)

MACHINE LEARNING

- Again, yes



Pirnay, Sweke, Eisert, Seifert, Phys Rev A 107, 042416 (2023)
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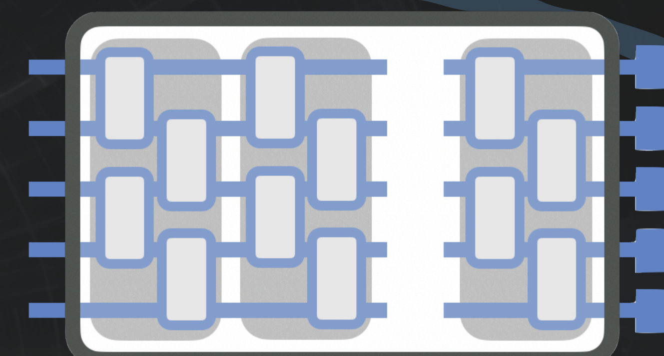
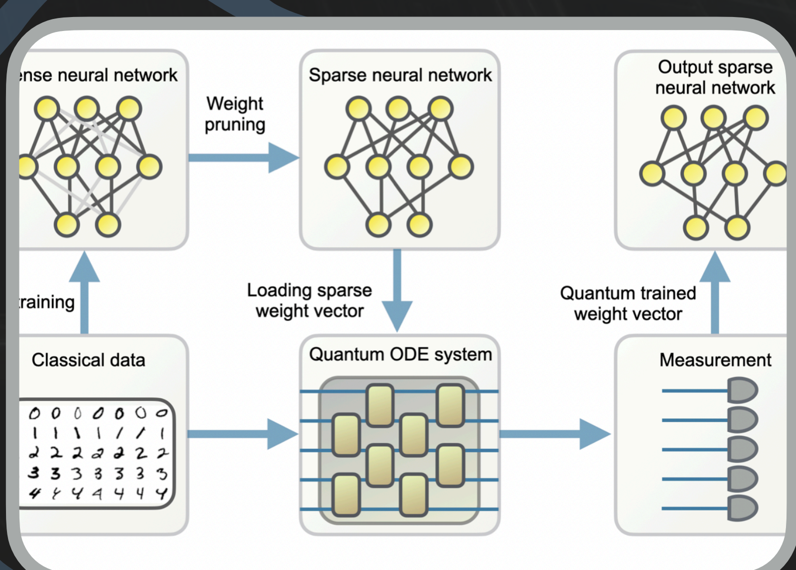


- Short circuits help

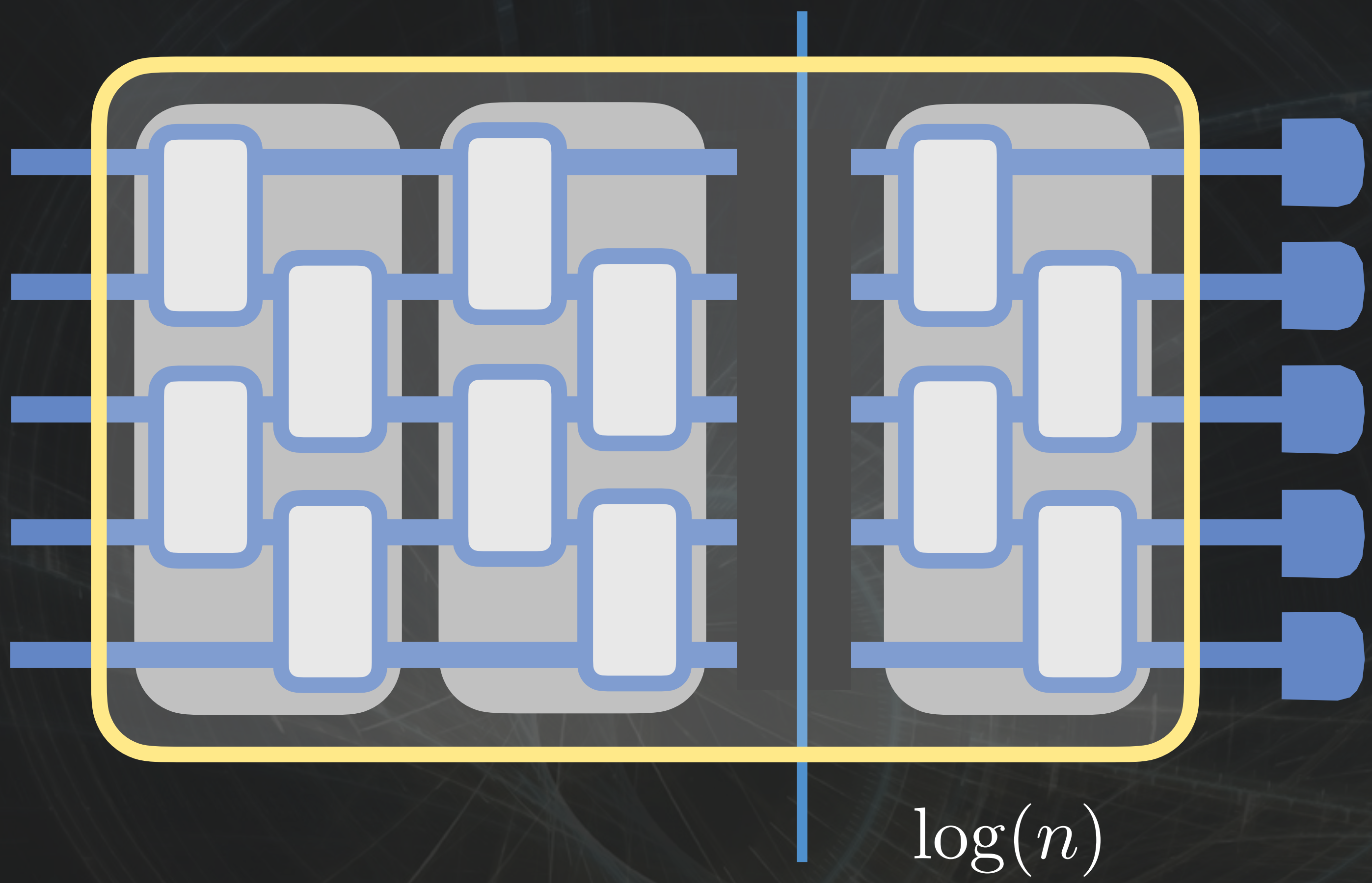
Pirnay, Seifert, Eisert, Jerbi (2024)



- For industrial applications, can train better classical sparse networks
- Benchmarks of models with 7 up to 103 million parameters

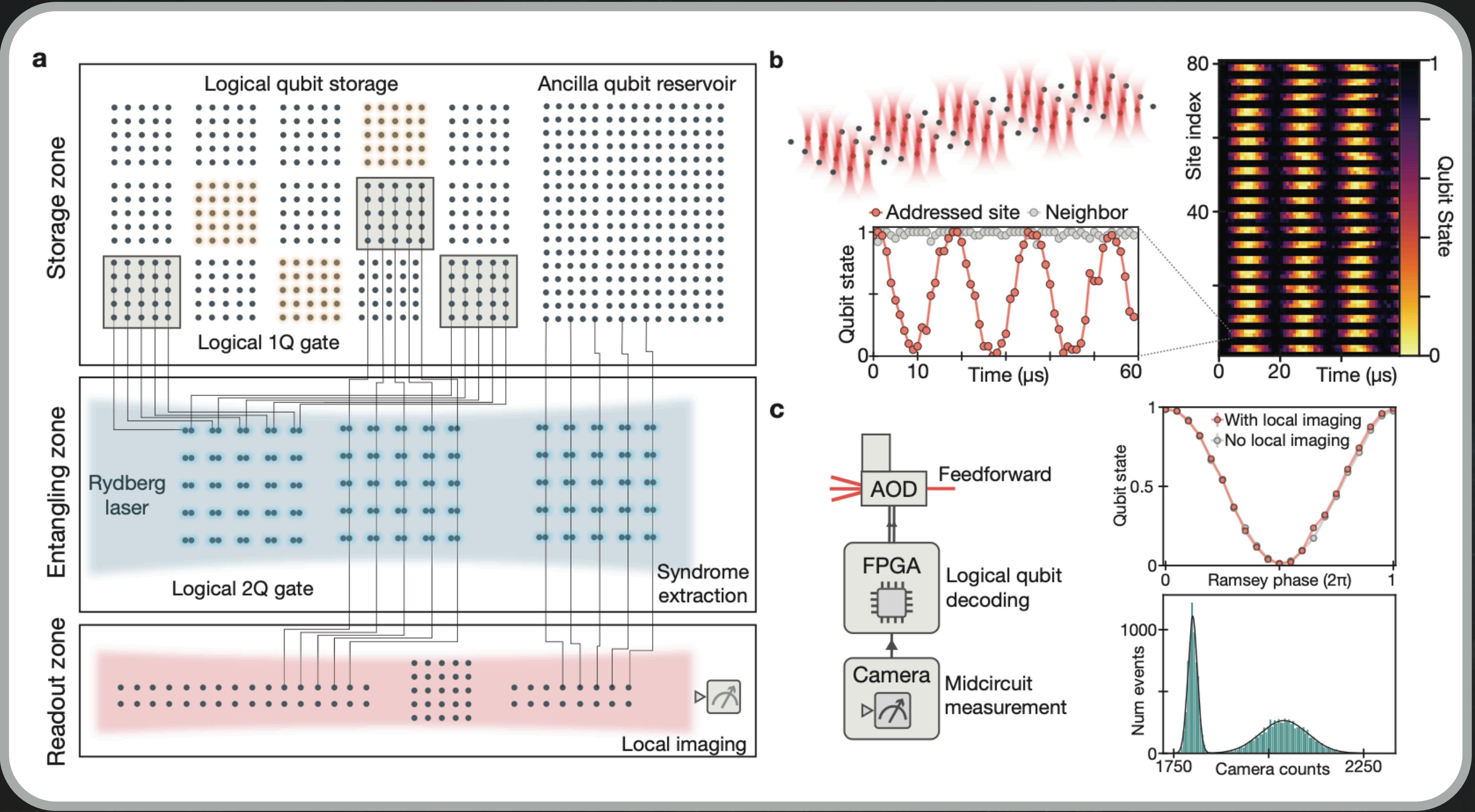
Liu, Liu, Liu, Ye, Wang, Alexeev, Eisert, Jiang, Nature Comm 15, 434 (2024)

- Short circuits do not seem to offer advantages



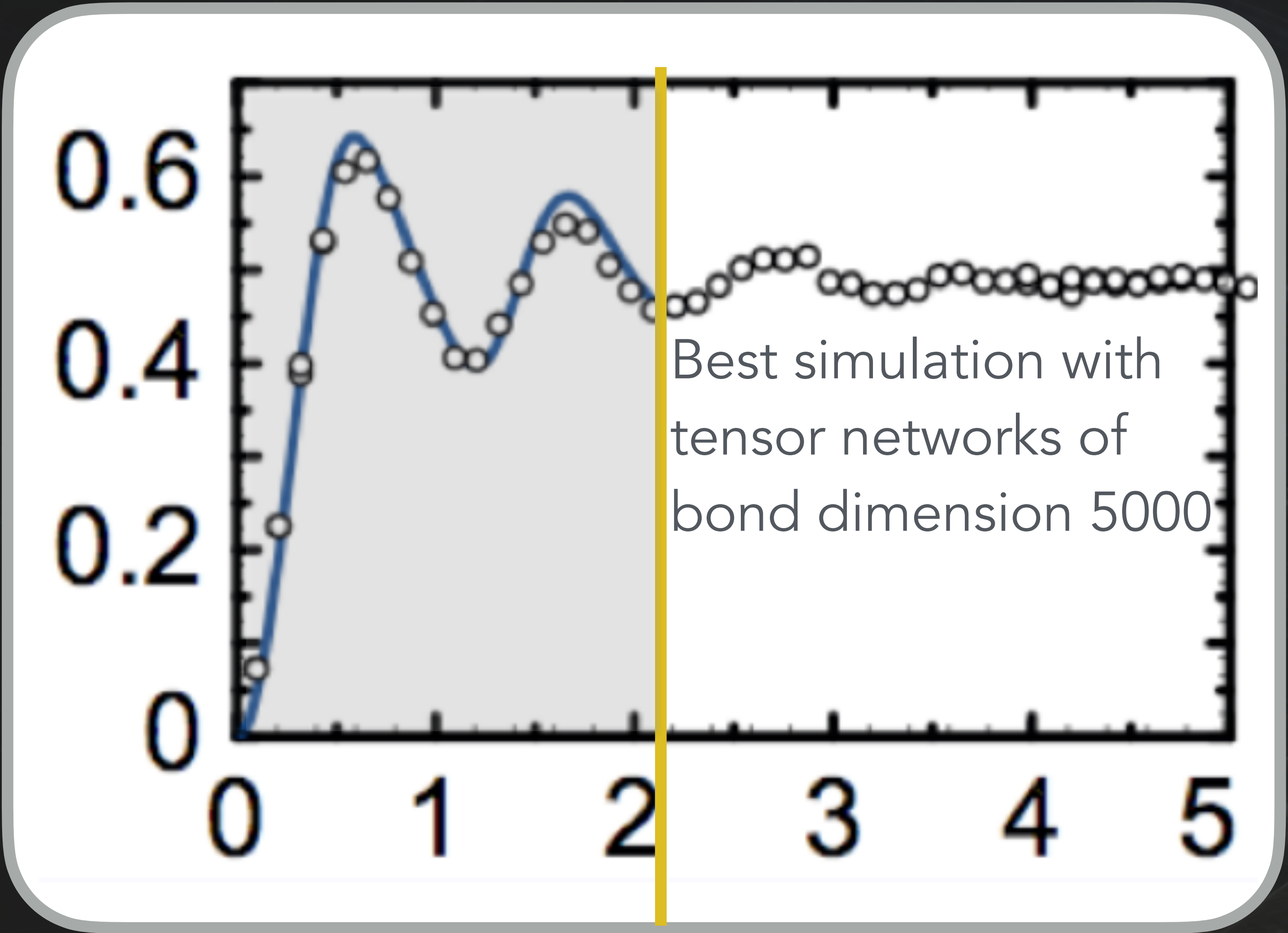
Quek, Stilck França, Khatri, Meyer, Eisert, Nature Phys (2024)
Stilck Franca, Garcia-Patron, Nature Phys 17, 1221 (2021)
Deshpande, Niroula, Shtanko, Gorshkov, Fefferman, Gullans, PRX Quantum 3, 040329 (2022)
Mele, Angrisani, Ghosh, Khatri, Eisert, Stilck Franca, Quek, arXiv:2403.13927 (2024)

- But there have been huge breakthroughs in error correction



Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, Nature 626, 58 (2024)

- Quantum simulations: Quantum materials are hard to be simulated (1 Mio CPU hours per day)
- Idea: Simulate with quantum systems



Trotzky, Chen, Flesch, McCulloch, Schollwoeck, Eisert, Bloch, Nature Phys 8, 325 (2012)

- **Quantum simulations:** Quantum materials are hard to be simulated (1 Mio CPU hours per day)
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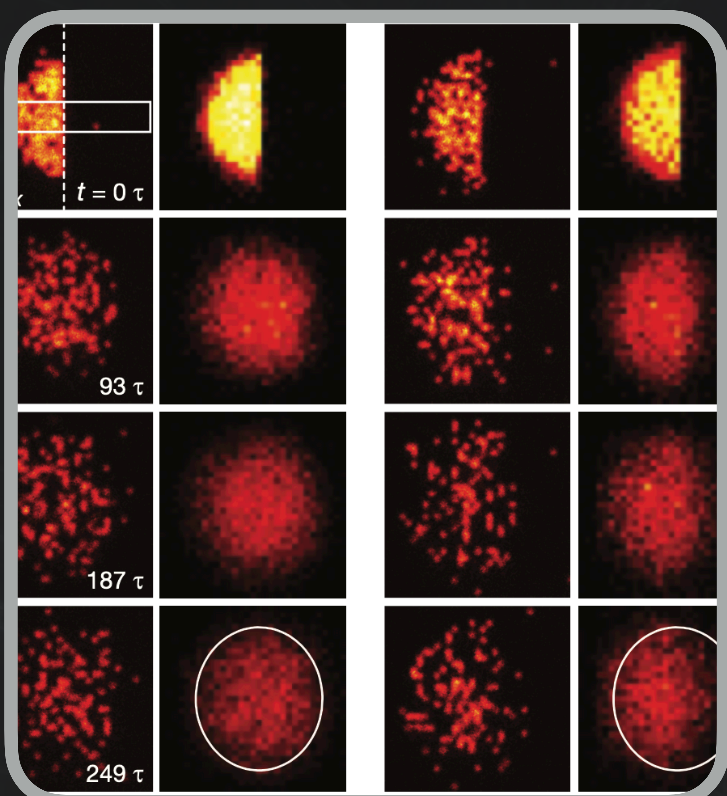
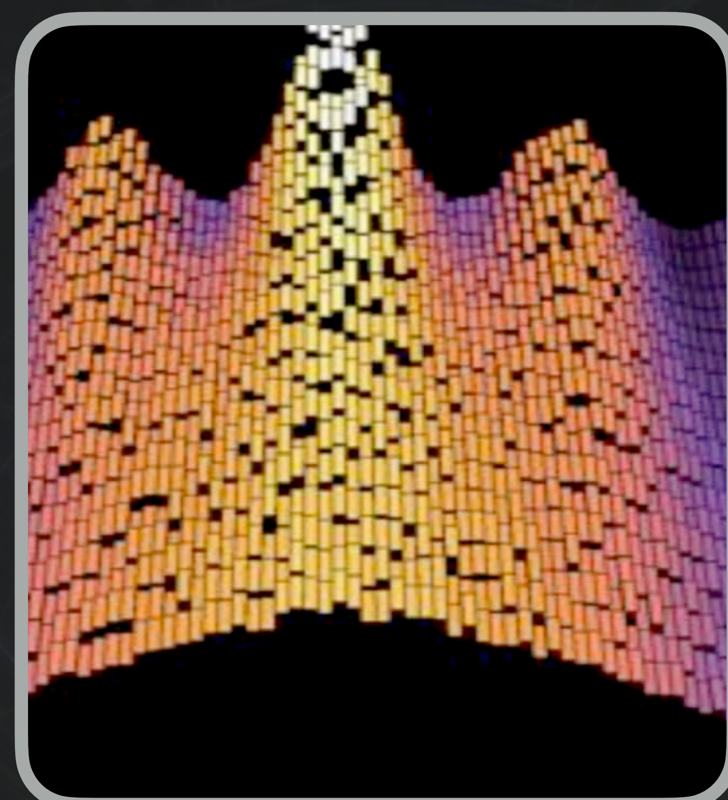


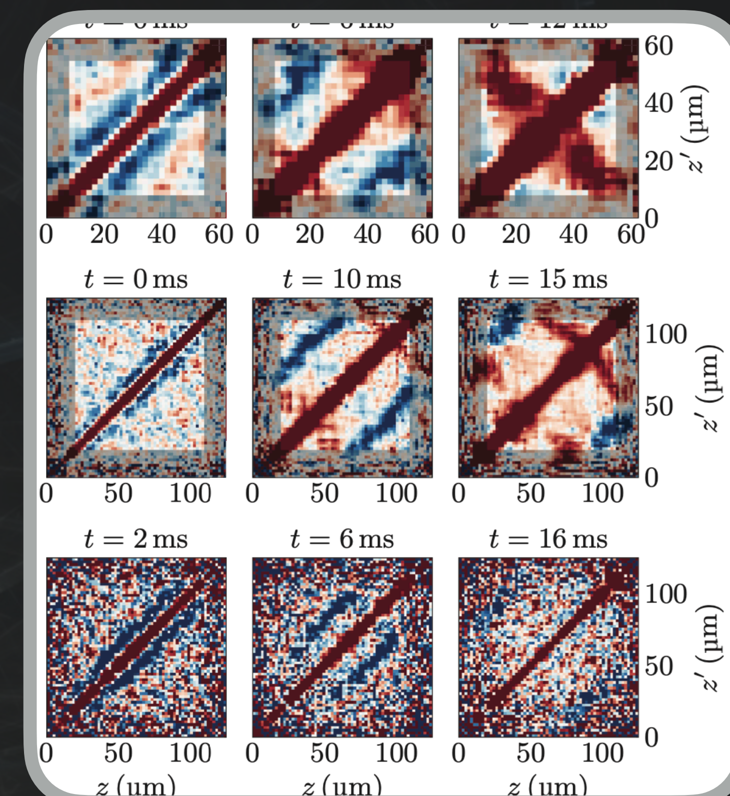
MANY-BODY LOCALIZATION

Choi, Hild, Zeiher, Schauss, Rubio-Abadal, Yefsah, Khemani, Huse, Bloch, Gross, Science 352, 1547 (2016)



STATISTICAL PHYSICS

Schweigler, Gluza, Tajik, Sotiriadis, Cataldini, Ji, Møller, Sabino, Rauer, Eisert, Schmiedmayer, Nature Phys 17, 559 (2021)

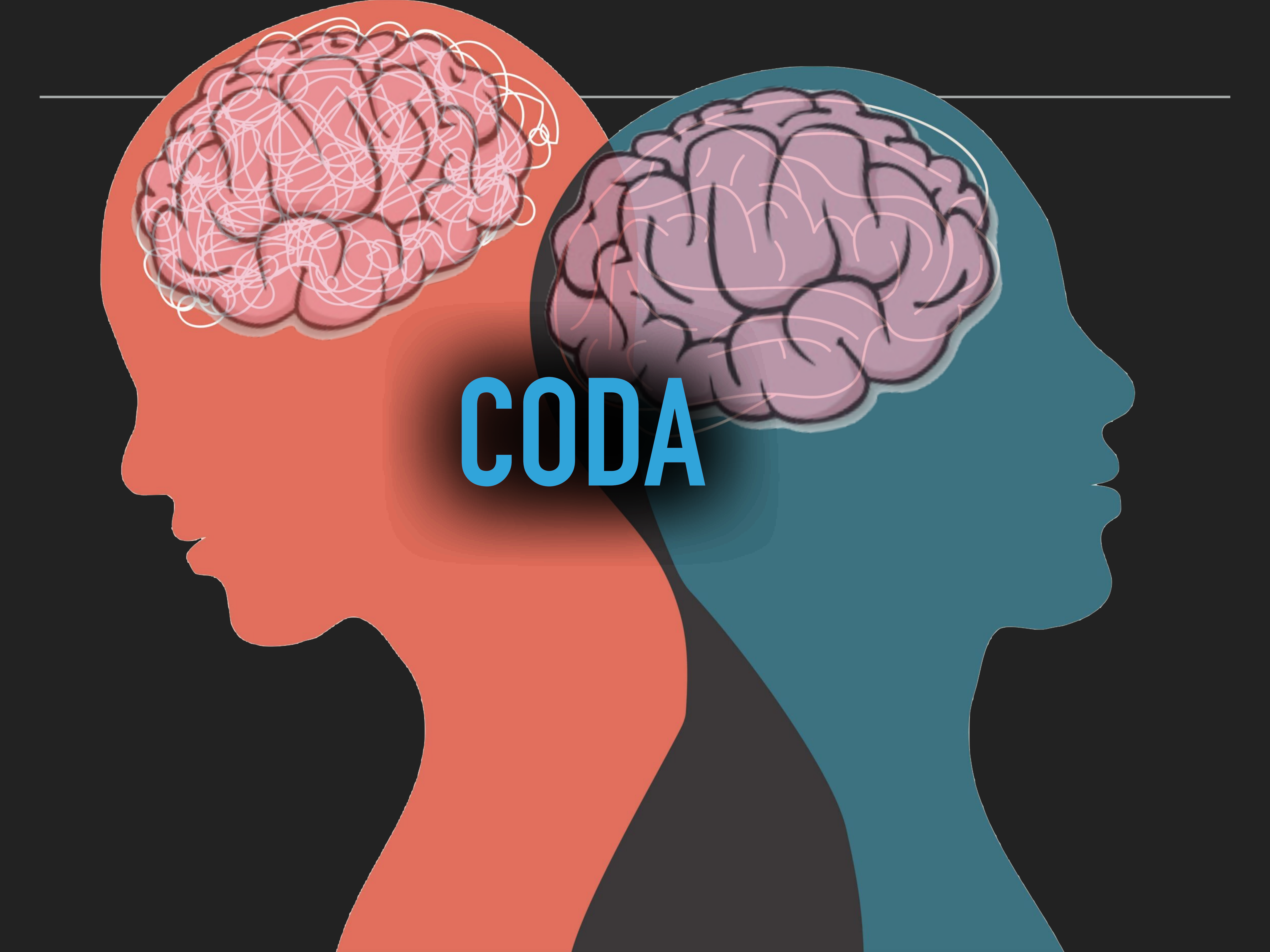


CURVED SPACETIMES

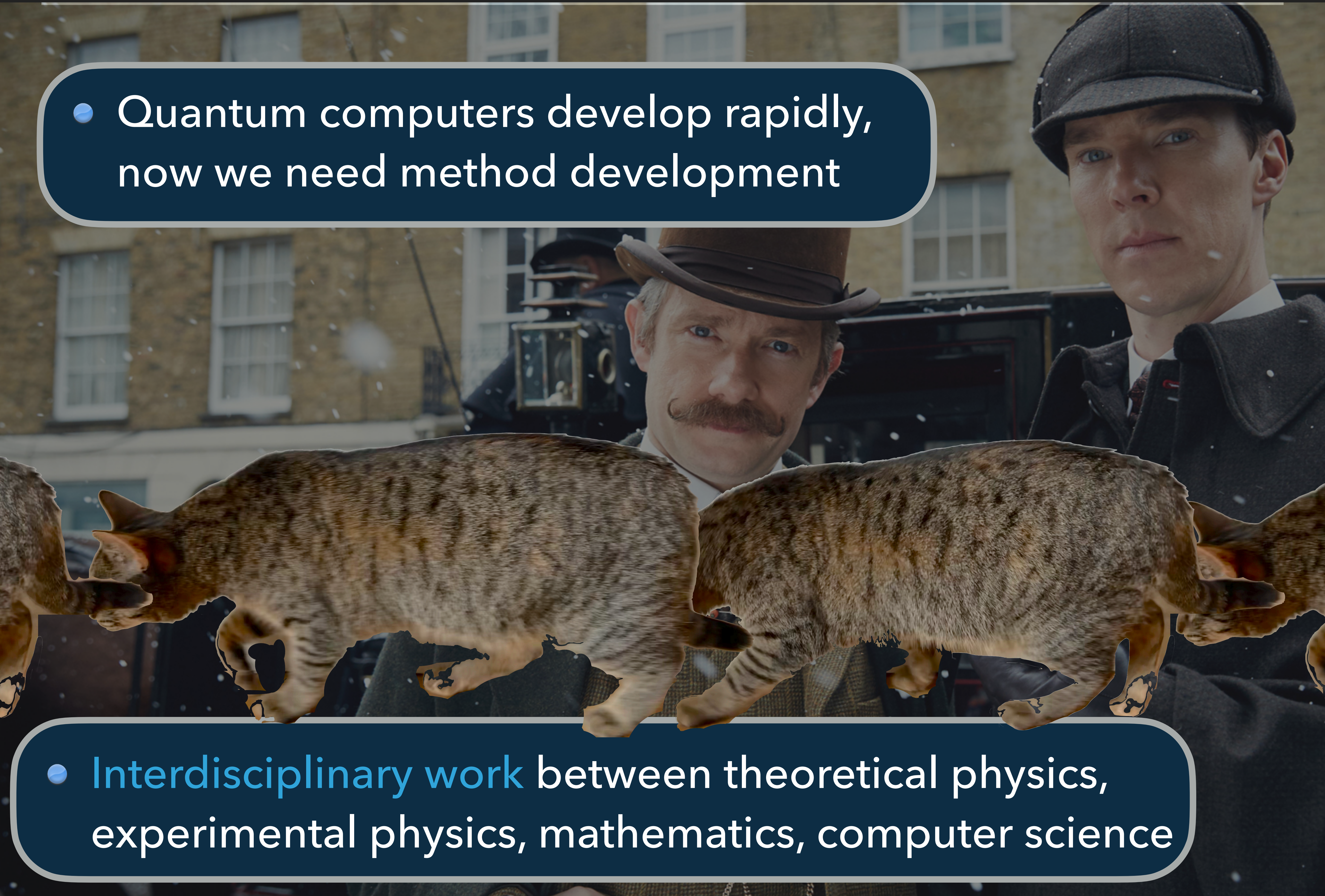
Tajik, Gluza, Sebe, Schüttelkopf, Cataldini, Sabino, Møller, Ji, Erne, Guarnieri, Sotiriadis, Eisert, Schmiedmayer, PNAS 120, e2301287120 (2023)

SMALL QUANTUM COMPUTERS AND SIMULATORS

- Quantum simulators can beat the best supercomputers, but it remains a race

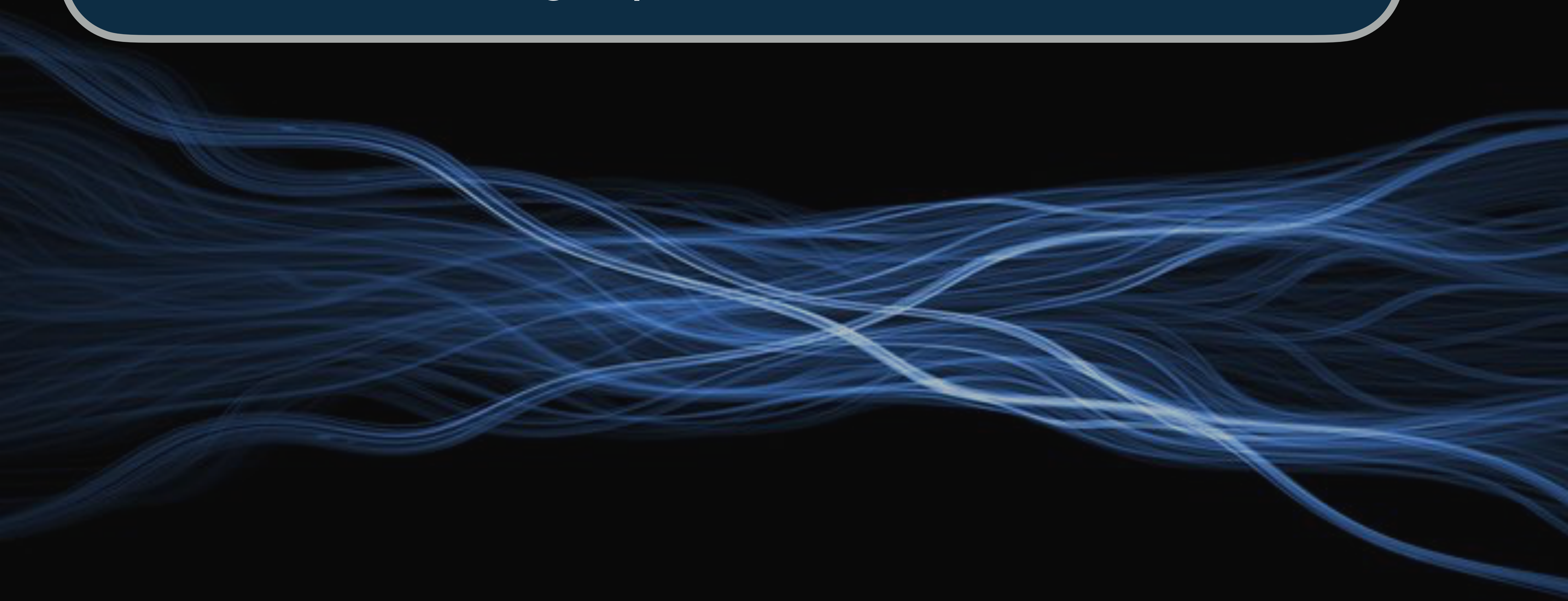

CODA

CODA



- Quantum computers develop rapidly, now we need method development
- Interdisciplinary work between theoretical physics, experimental physics, mathematics, computer science

- Quantum computers will disrupt supercomputing
- Applications in simulation, materials science, machine learning, optimization



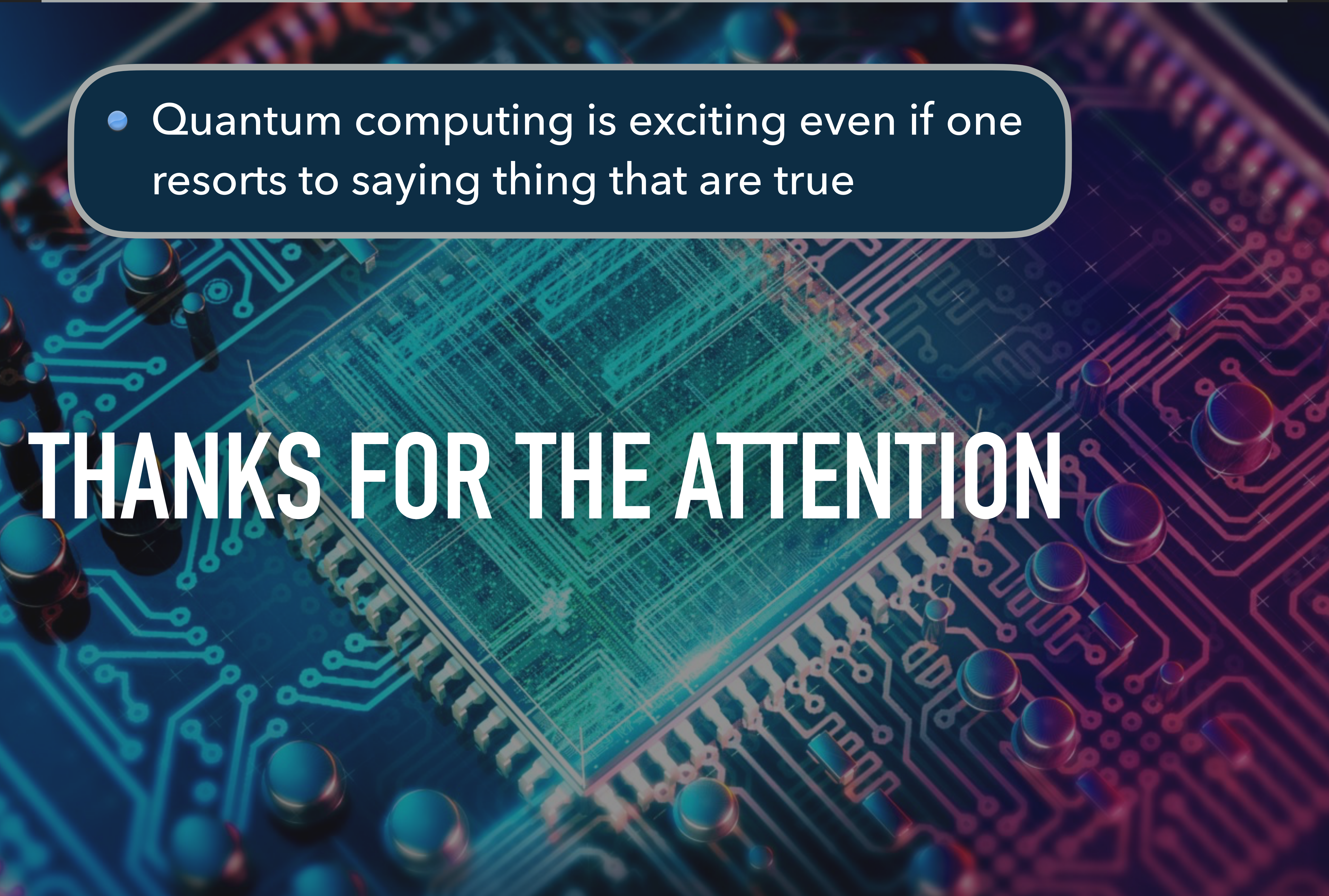
- Quantum flagship of EU supports with 1 Mrd Euros
- German government (BMBF, BMWK) with 2 Mrd Euros
- Bavaria (Munich Quantum Valley)
- Berlin (Berlin Quantum) with 26 Mio Euros

QUANTUM FLAGSHIP

Munich Quantum Valley

Bundesministerium für Bildung und Forschung

- Quantum computing is exciting even if one resorts to saying thing that are true



THANKS FOR THE ATTENTION