QUANTUM SIMULATION AND COMPUTING

A NEW WAY OF COMPUTING BEYOND SUPERCOMPUTERS

JENS EISERT, FU BERLIN

HARDWARE HACKING, BIG TECH DAY 11

- Gordon Moore (Intel, 1965): Number of transistors in integrated circuits **doubles** approximately every two years


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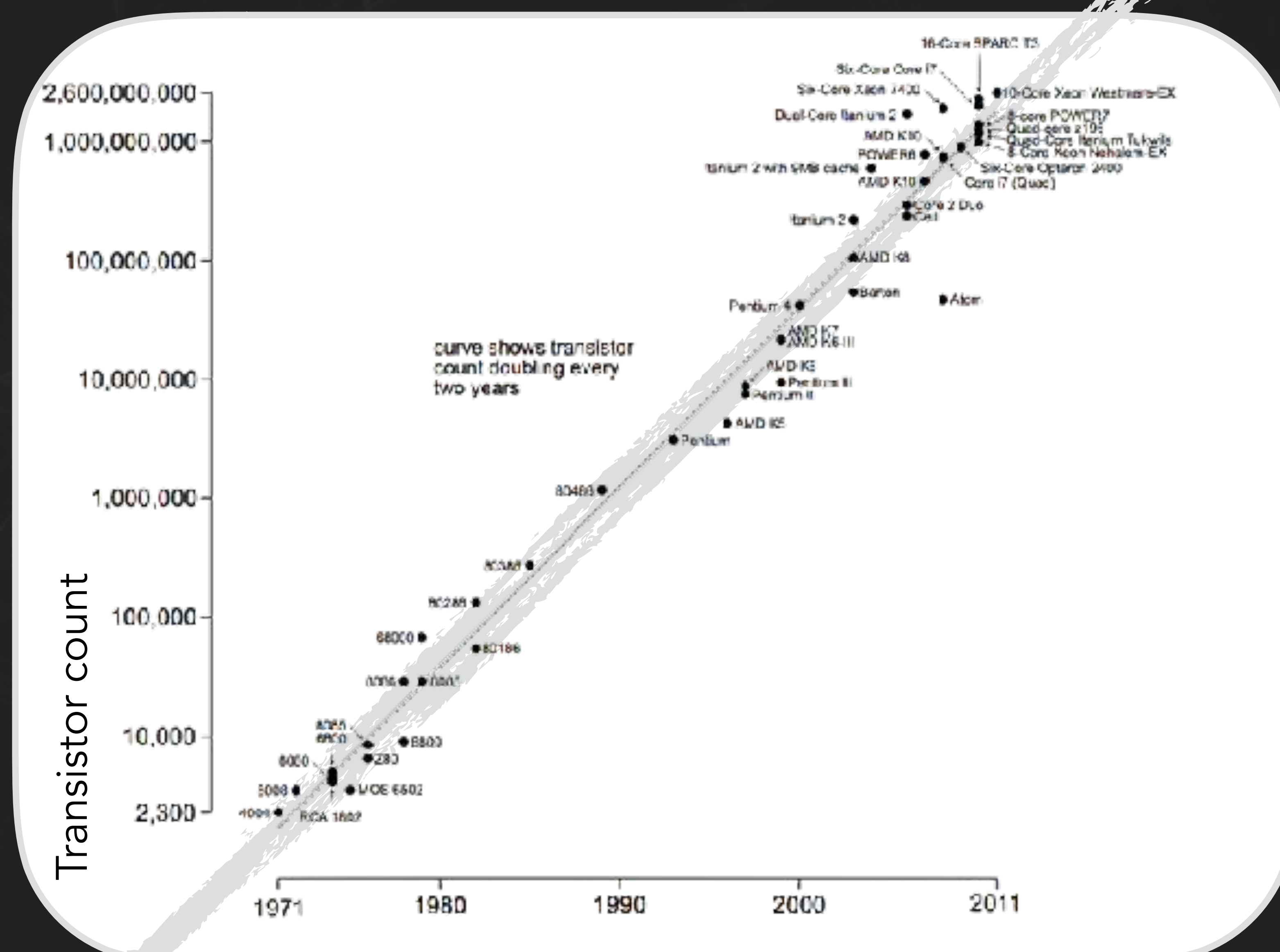
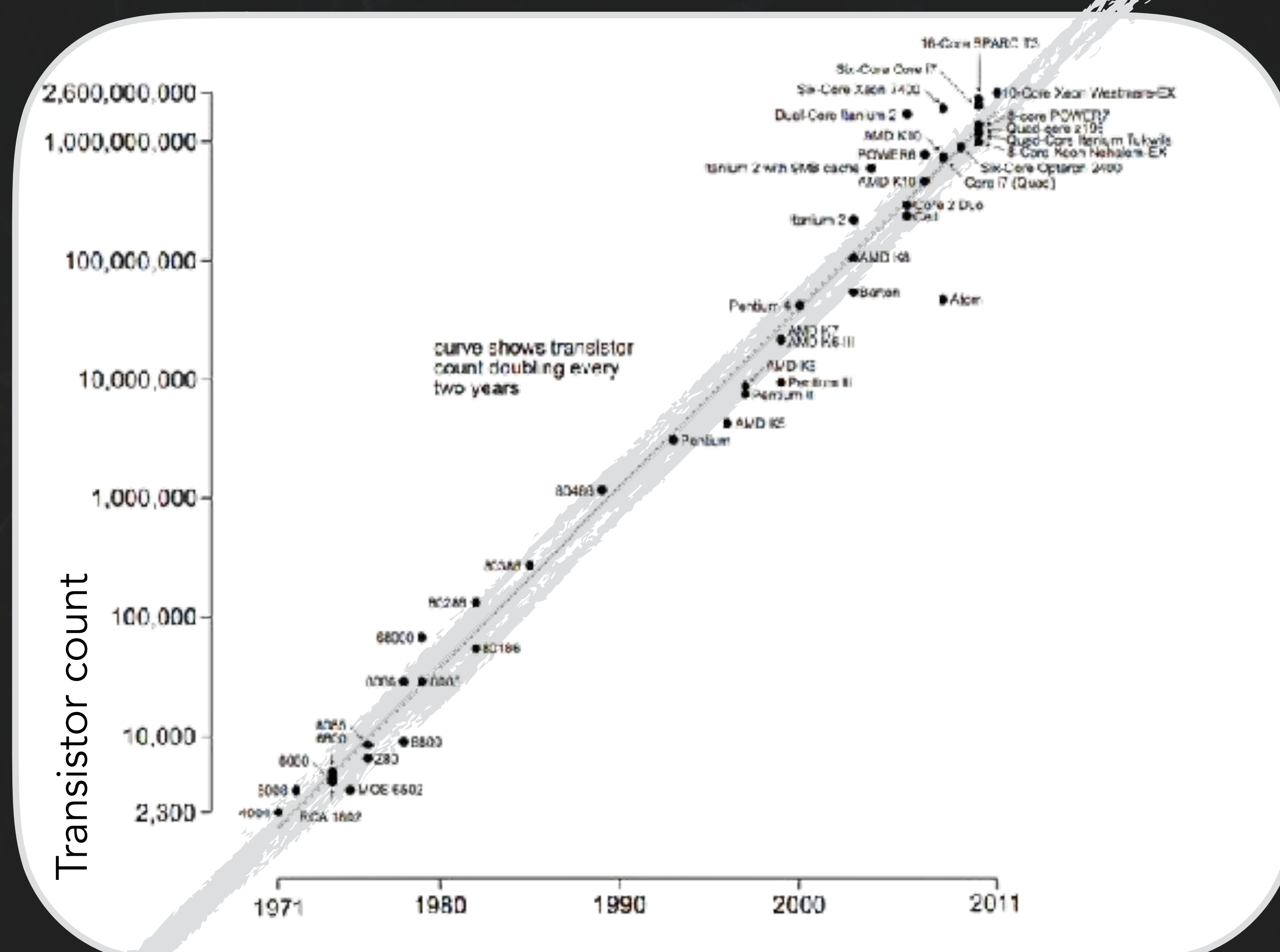


- Gordon Moore (Intel, 1965): Number of transistors in integrated circuits **doubles** approximately every two years
- Minimum feature size down to that of **single atoms**



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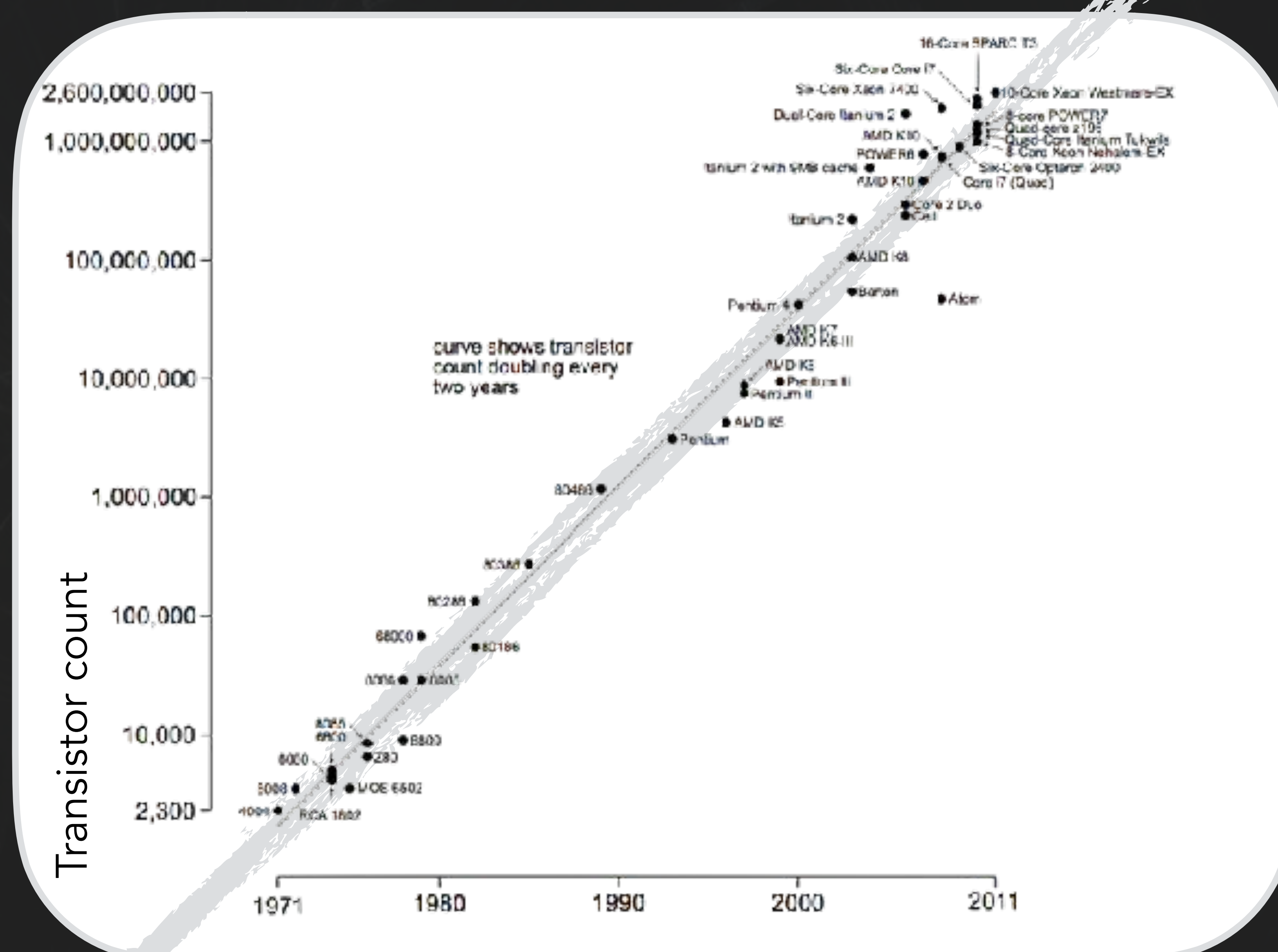
- Different physical laws matter



QUANTUM MECHANICS

- Quantum mechanics is a physical theory

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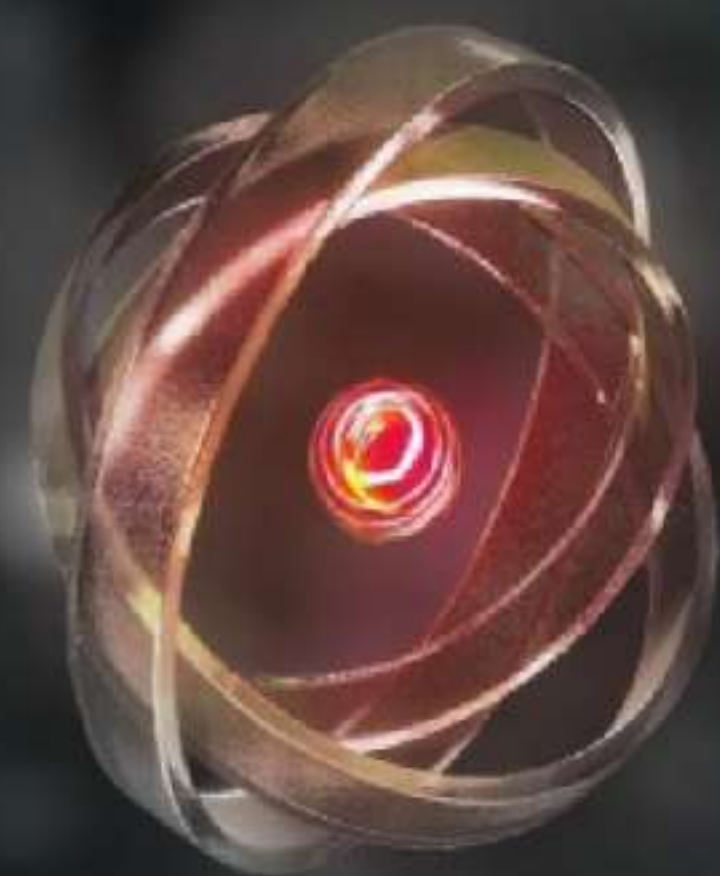
- Theory of atoms, molecules, and light quanta



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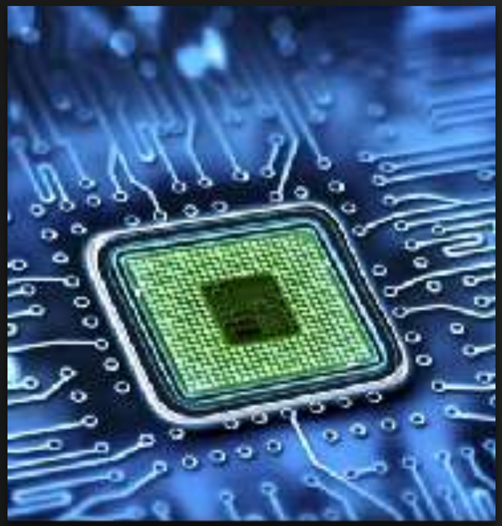
- Basis of **semi-conductors**, **materials science**, **lasers**



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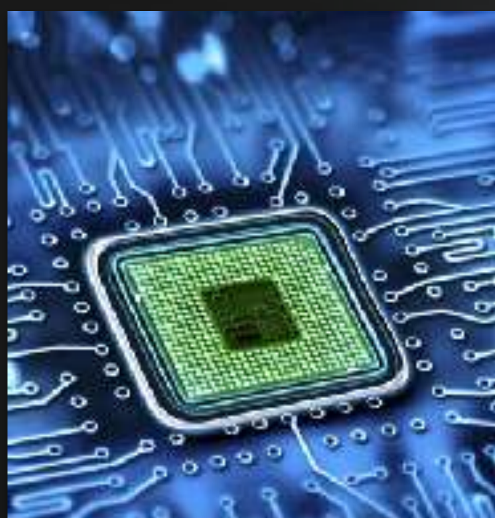

- Fine structure constant: 7,297.352.566.4(17) x 10^{-3}

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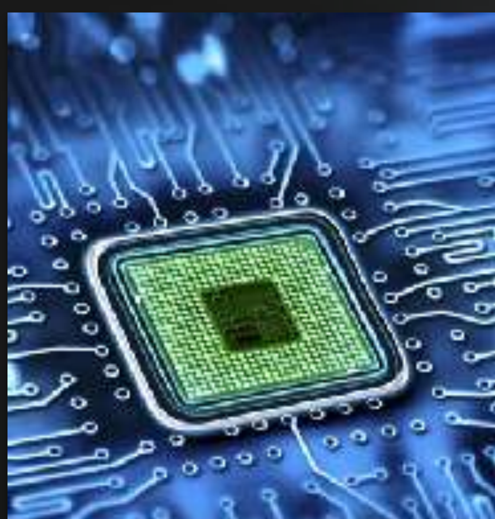

- Fine structure constant: 7,297.352.566.4(17) x 10^{-3}
- Radically different from classical mechanics

RANDOMNESS

- Measurement outcomes are random

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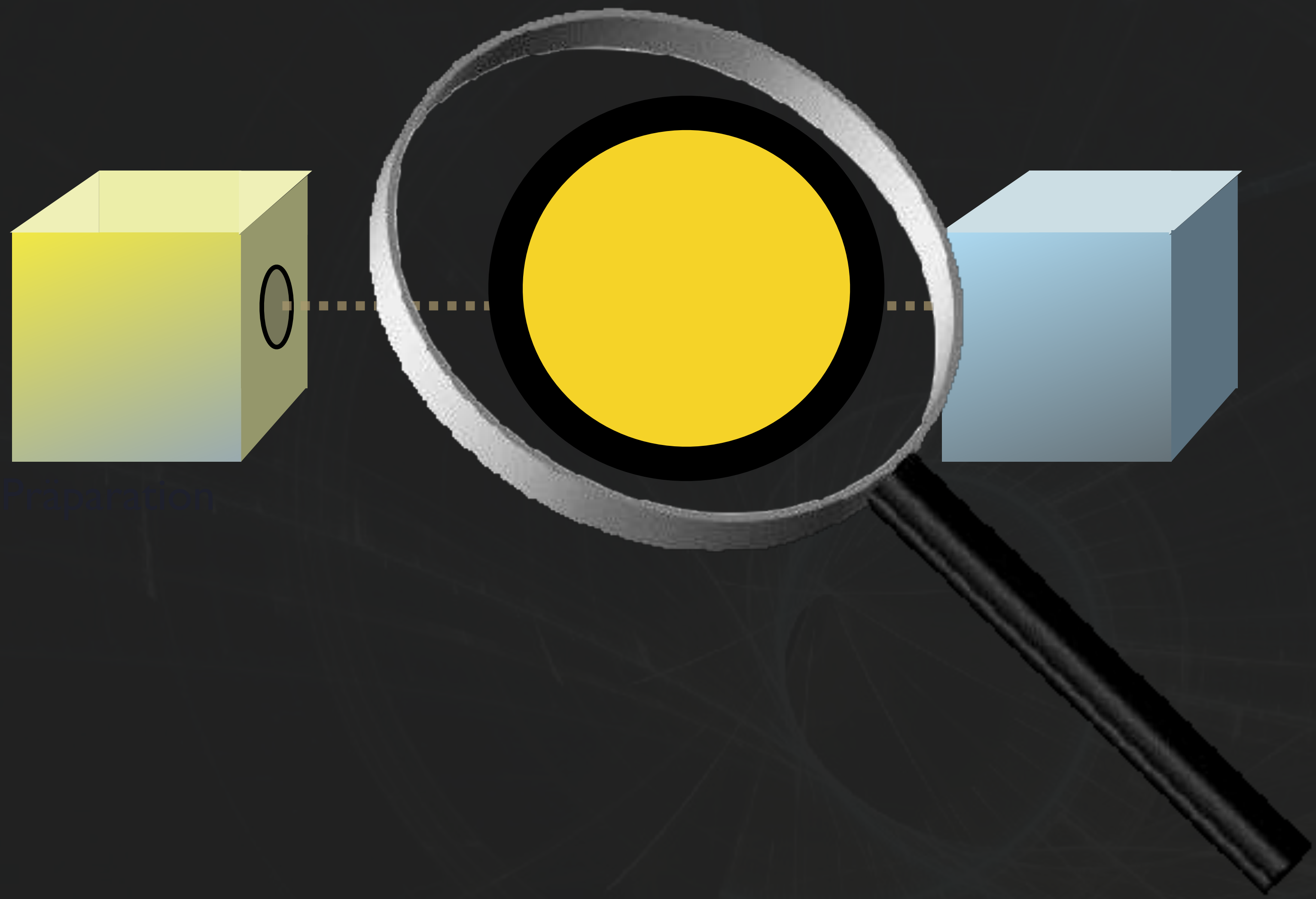
- We are used to randomness…
- … but this has an explanation

- Measurement outcomes are random

- The randomness of quantum mechanics is absolute



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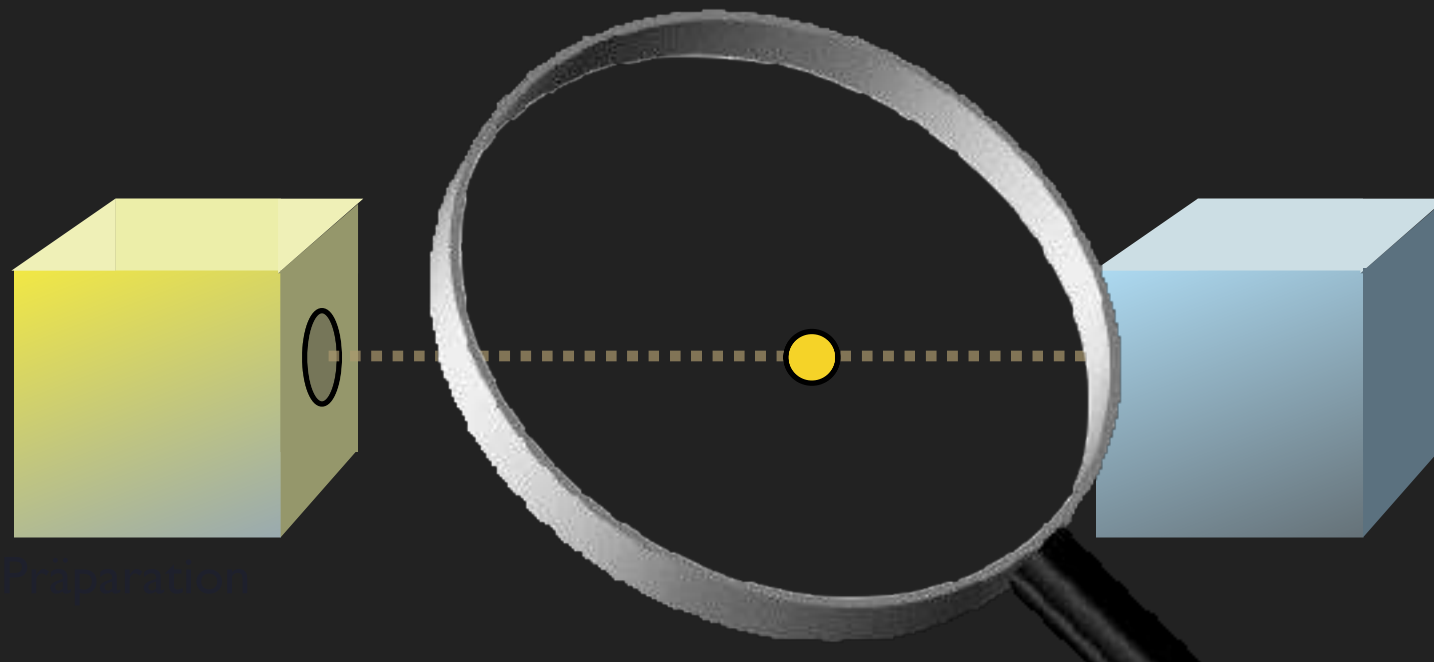

- Bell inequality violated under assumption of local hidden variables

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

UNCERTAINTY

UNCERTAINTY PRINCIPLE

- No measurement without disturbance

SUPERPOSITION

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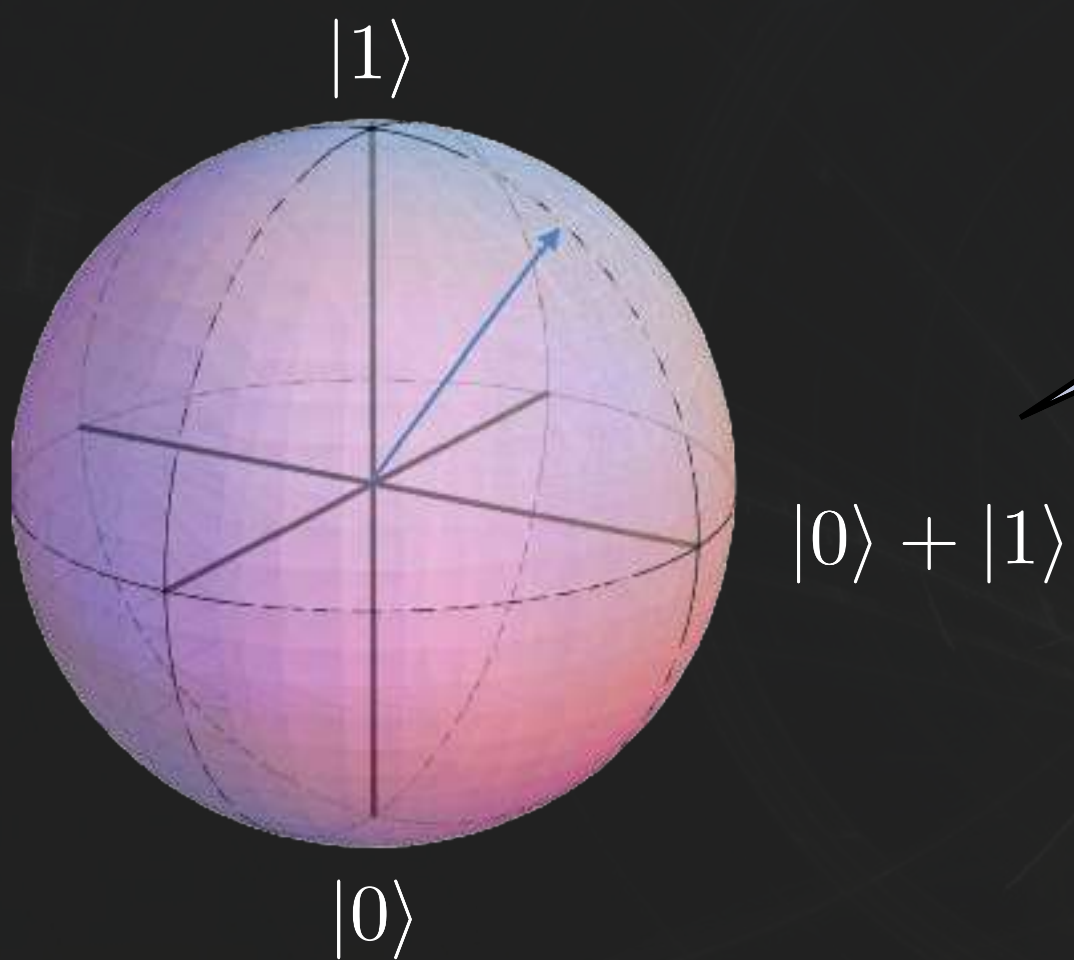
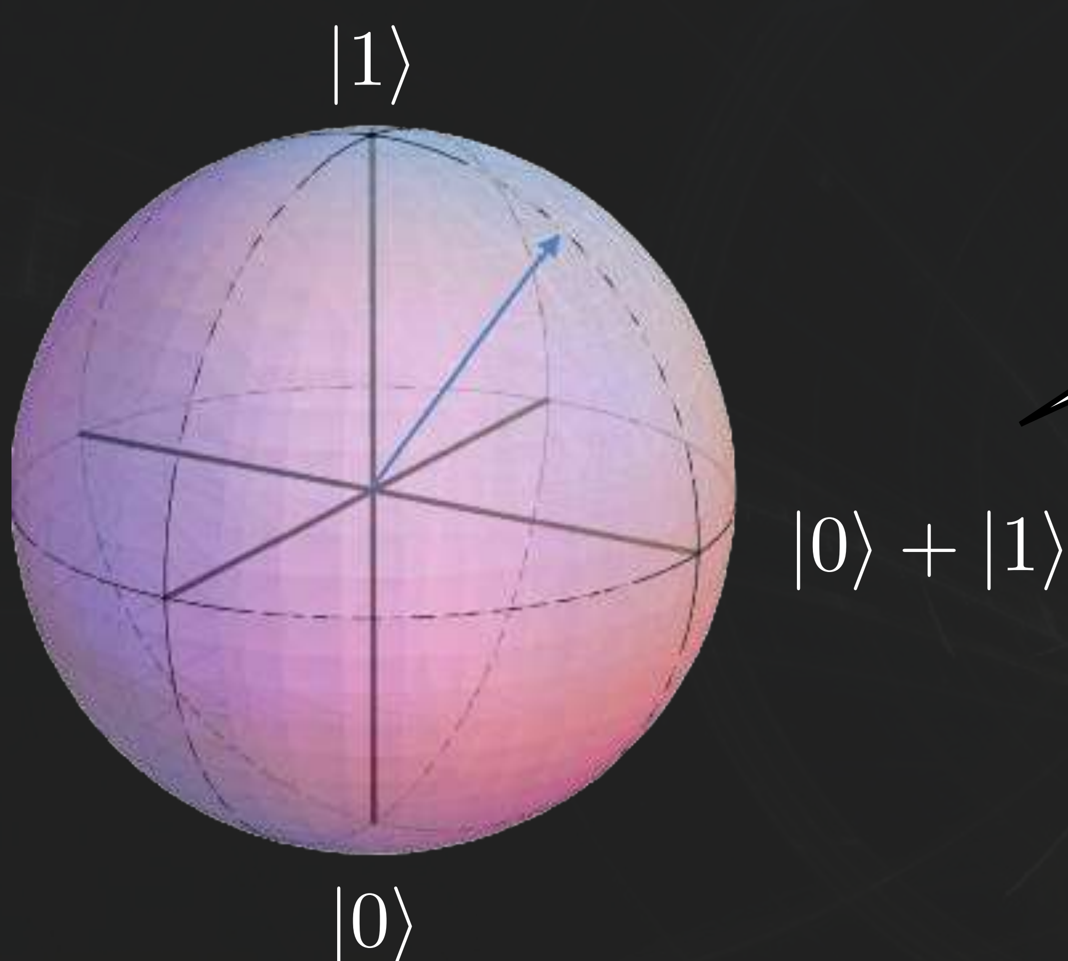
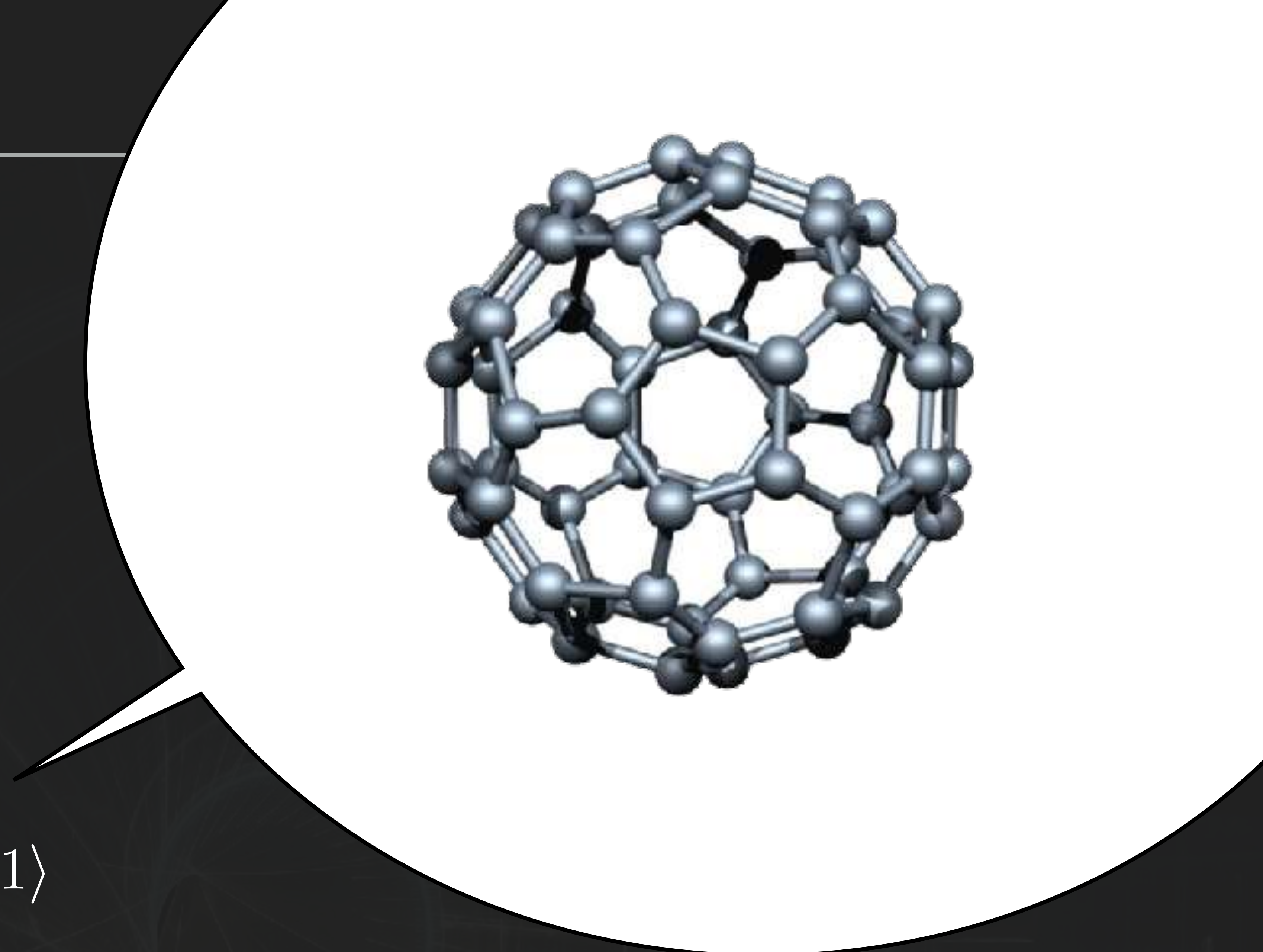


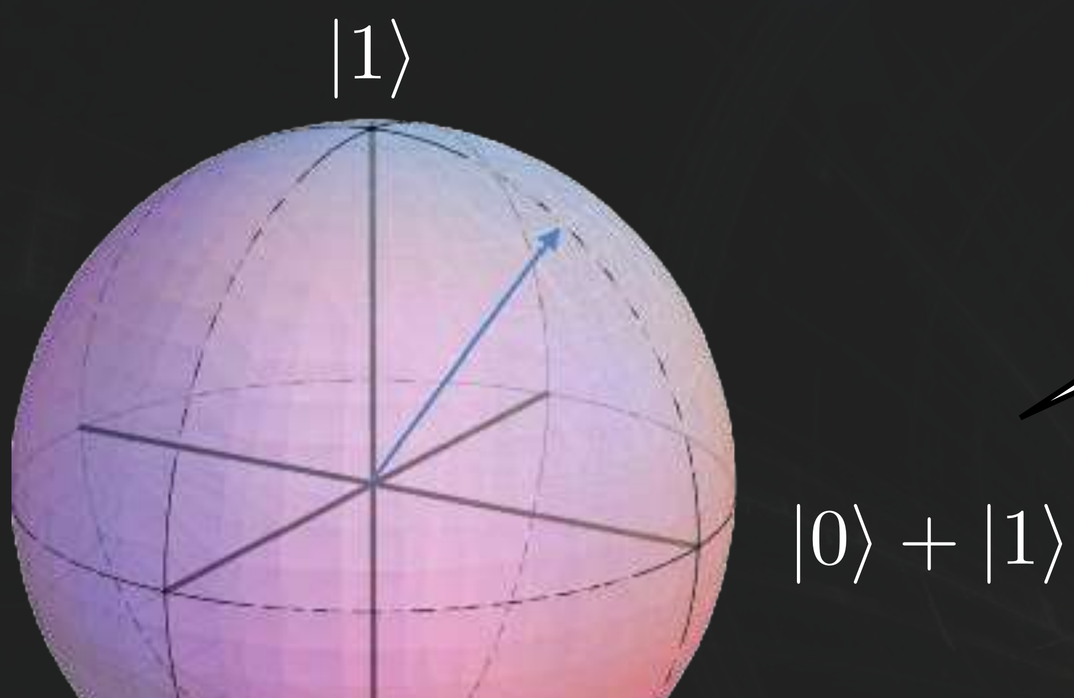
SUPERPOSITION PRINCIPLE

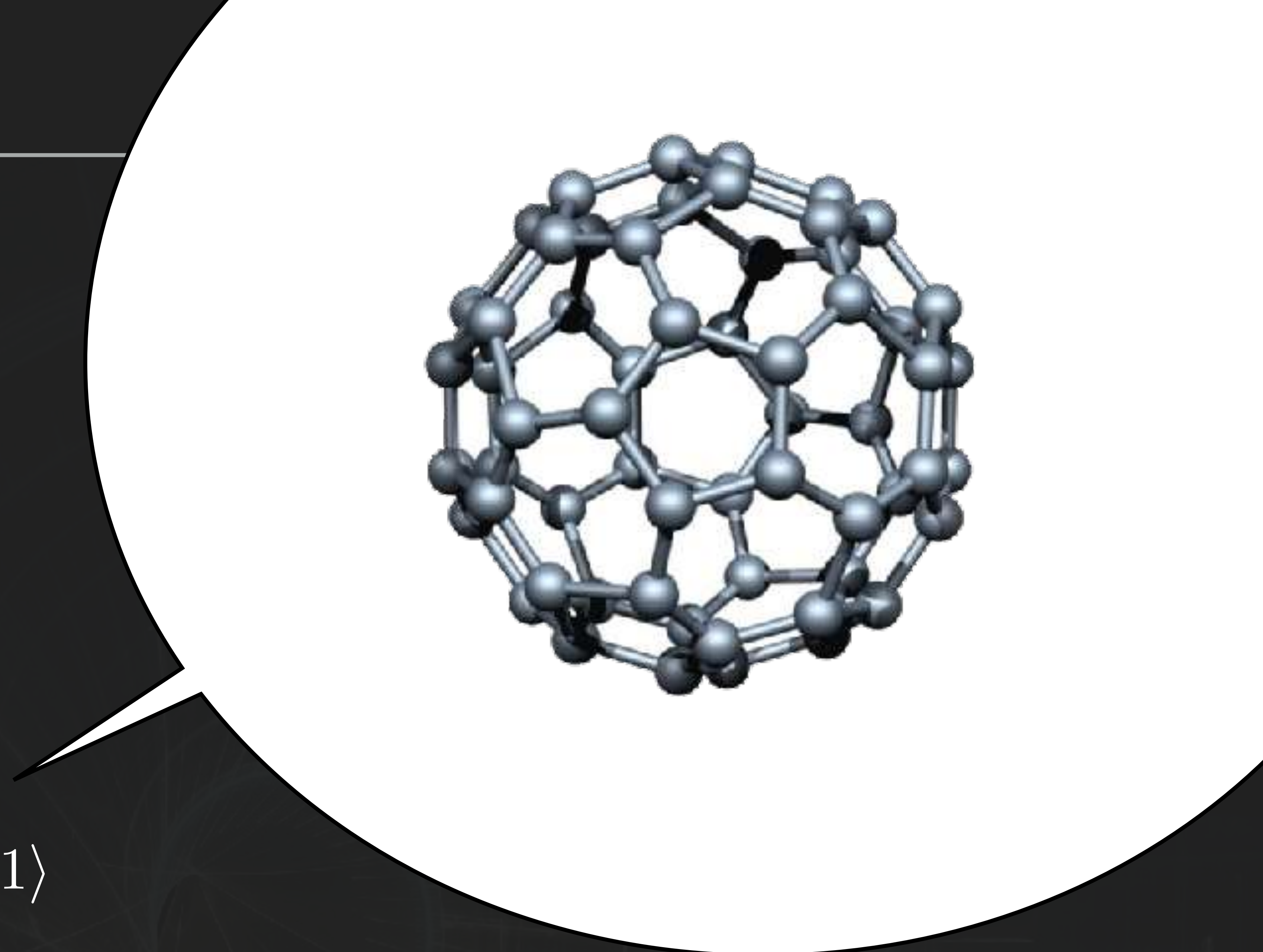




- Systems can be in “many states at once”

SUPERPOSITION PRINCIPLE



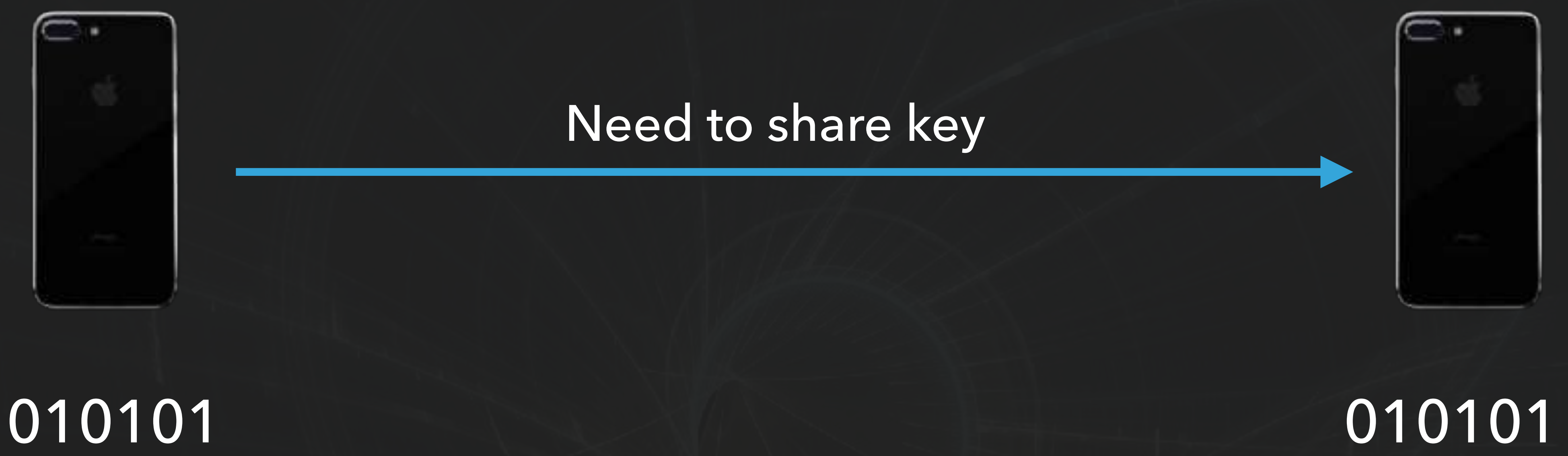


- State space $\{\rho : \rho \geq 0,\ \mathrm{tr}(\rho) = 1\}$ over complex vector space $\mathcal{H}$
- For n spins $\mathcal{H} = \mathbb{C}_2^{\otimes n}$

QUANTUM TECHNOLOGIES

- Make use of quantum effects on the single quantum system level to think of new technologies in communication, sensing, computation, simulation

- Classical key distribution



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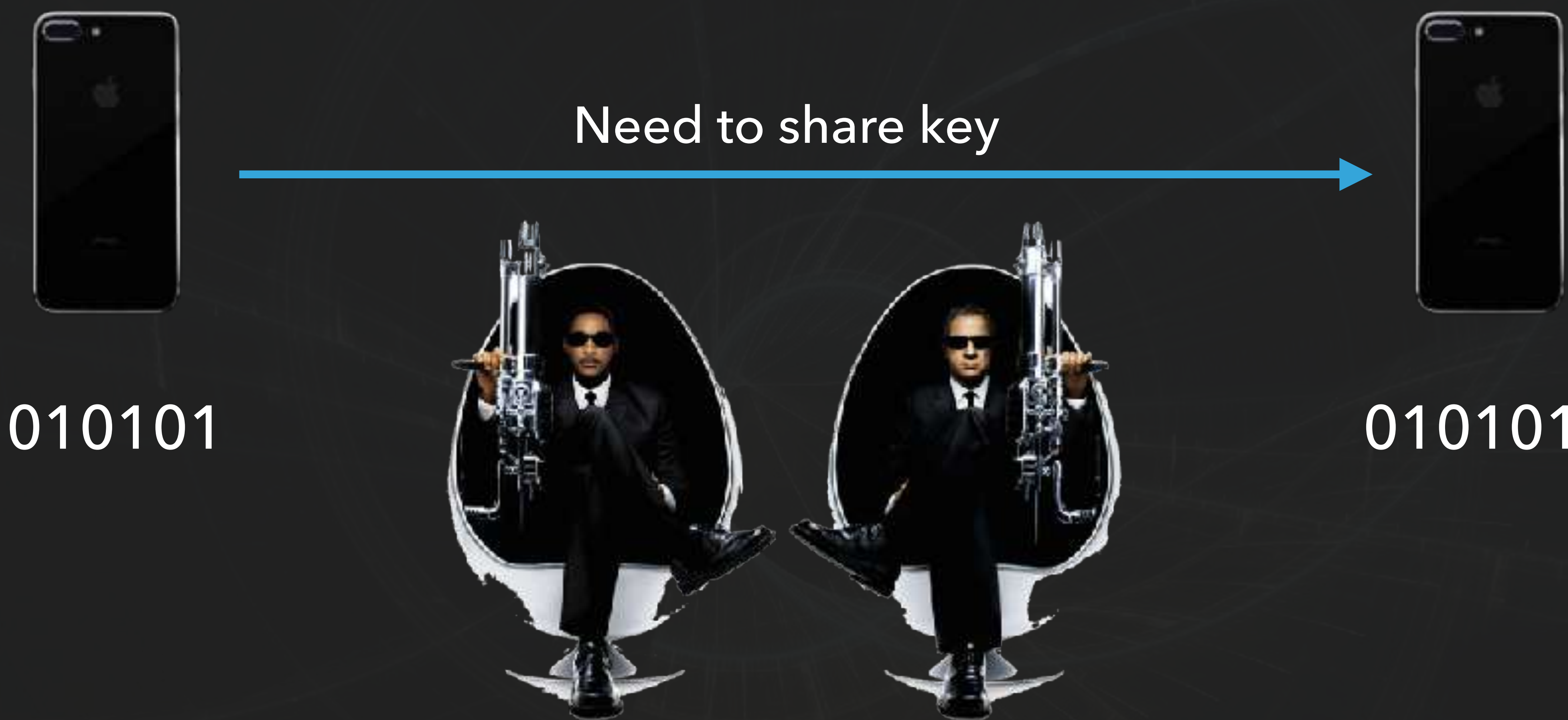

- Quantum key distribution for secure communication

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No information gain without disturbance

- Quantum key distribution for secure communication

Alice’s bit	0	1	1	0	1	0	0	1
Alice’s basis	$+$	$+$	$\times$	$+$	$\times$	$\times$	$\times$	$+$
State	$\uparrow$	$\rightarrow$	$\searrow$	$\uparrow$	$\searrow$	$\nearrow$	$\nearrow$	$\rightarrow$
Bob’s basis	$+$	$\times$	$\times$	$\times$	$+$	$\times$	$+$	$+$
Bob’s result	$\uparrow$	$\nearrow$	$\searrow$	$\nearrow$	$\rightarrow$	$\nearrow$	$\rightarrow$	$\rightarrow$
Public part								
Key	0		1			0		1

- Basis $+$

  $\uparrow = |1\rangle, \; \rightarrow = |0\rangle$

- Basis $\times$

  $\searrow = |0\rangle + |1\rangle, \; \nearrow = |0\rangle - |1\rangle$

SECURE COMMUNICATION

- Quantum key distribution for secure communication

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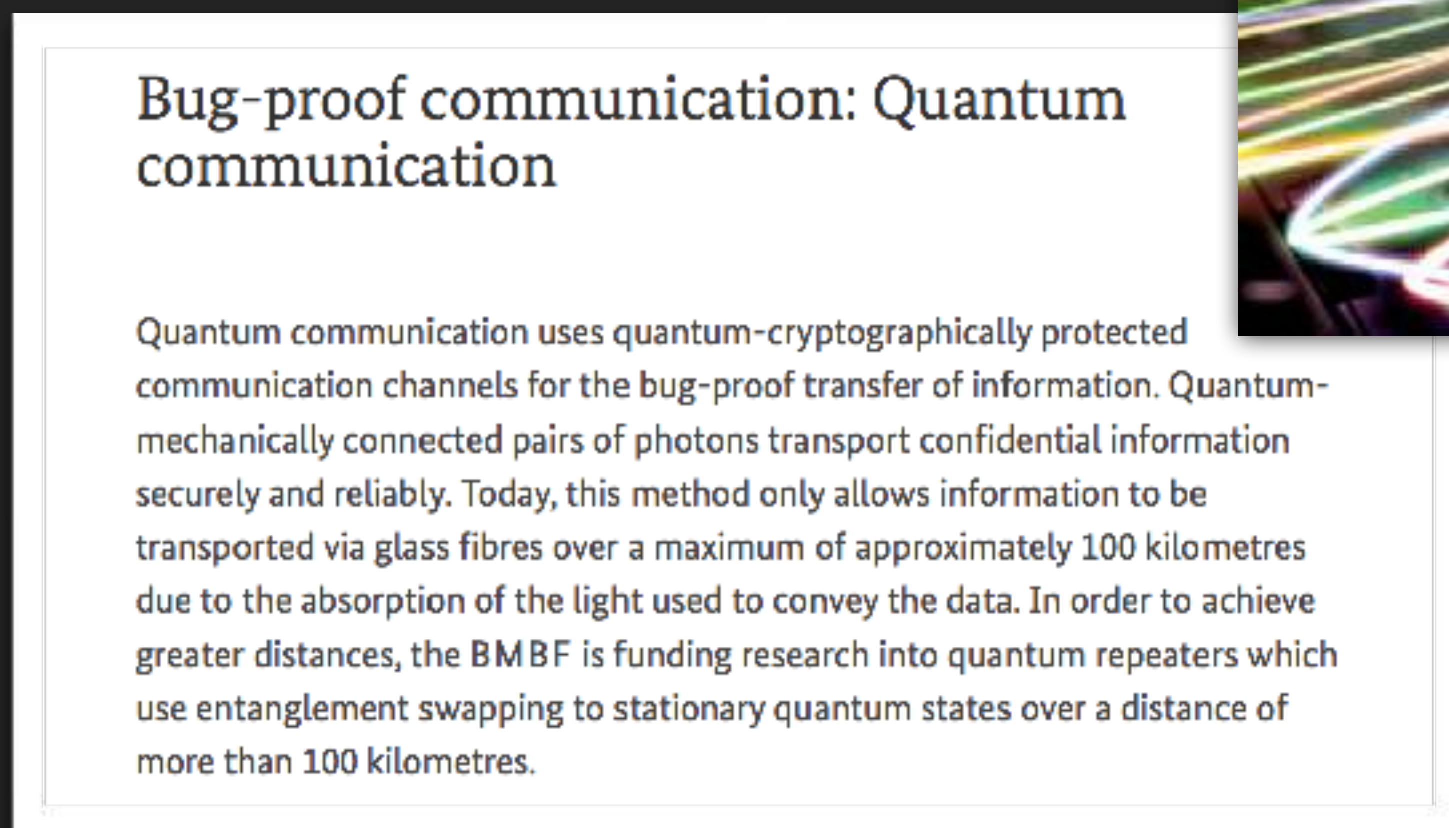
- Security can be proven

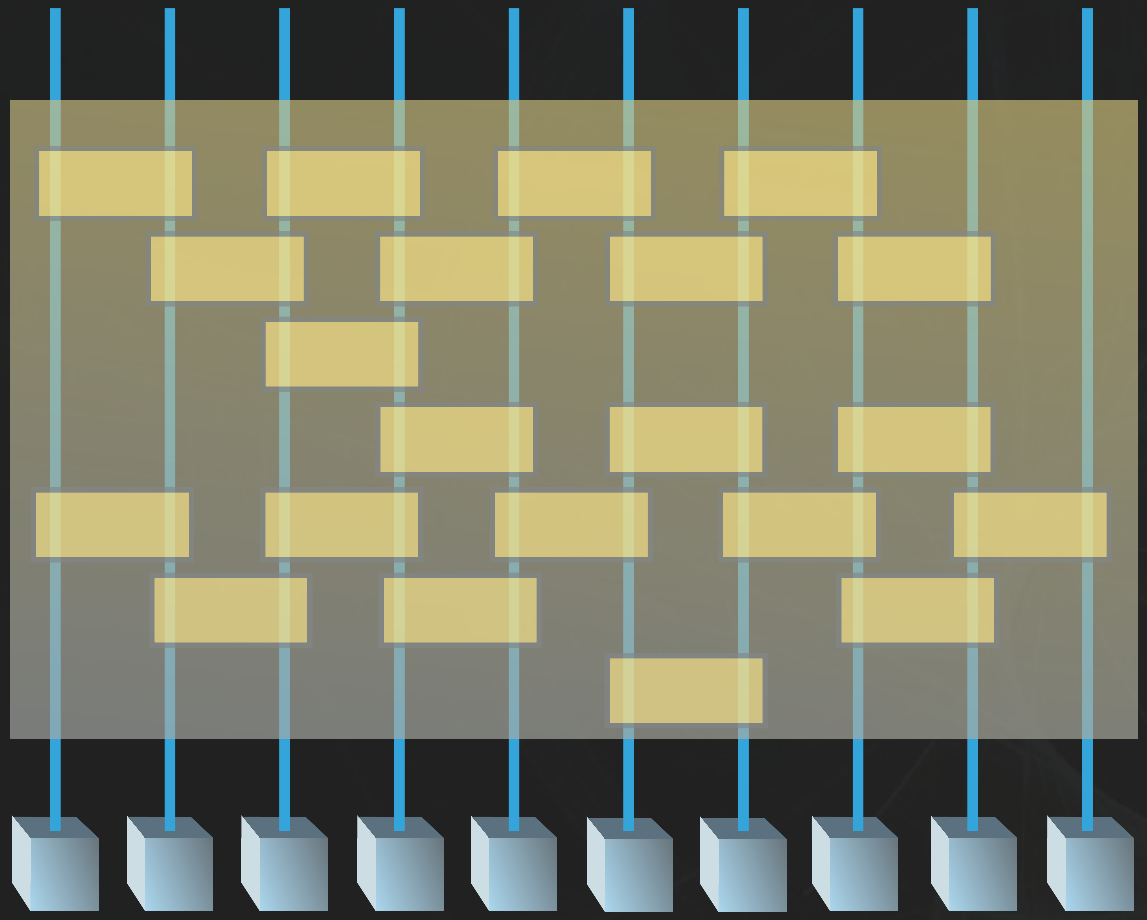


Bug-proof communication: Quantum communication

Quantum communication uses quantum-cryptographically protected communication channels for the bug-proof transfer of information. Quantum-mechanically connected pairs of photons transport confidential information securely and reliably. Today, this method only allows information to be transported via glass fibres over a maximum of approximately 100 kilometres due to the absorption of the light used to convey the data. In order to achieve greater distances, the BMBF is funding research into quantum repeaters which use entanglement swapping to stationary quantum states over a distance of more than 100 kilometres.

QUANTUM COMPUTERS

- Computational devices with single quantum systems



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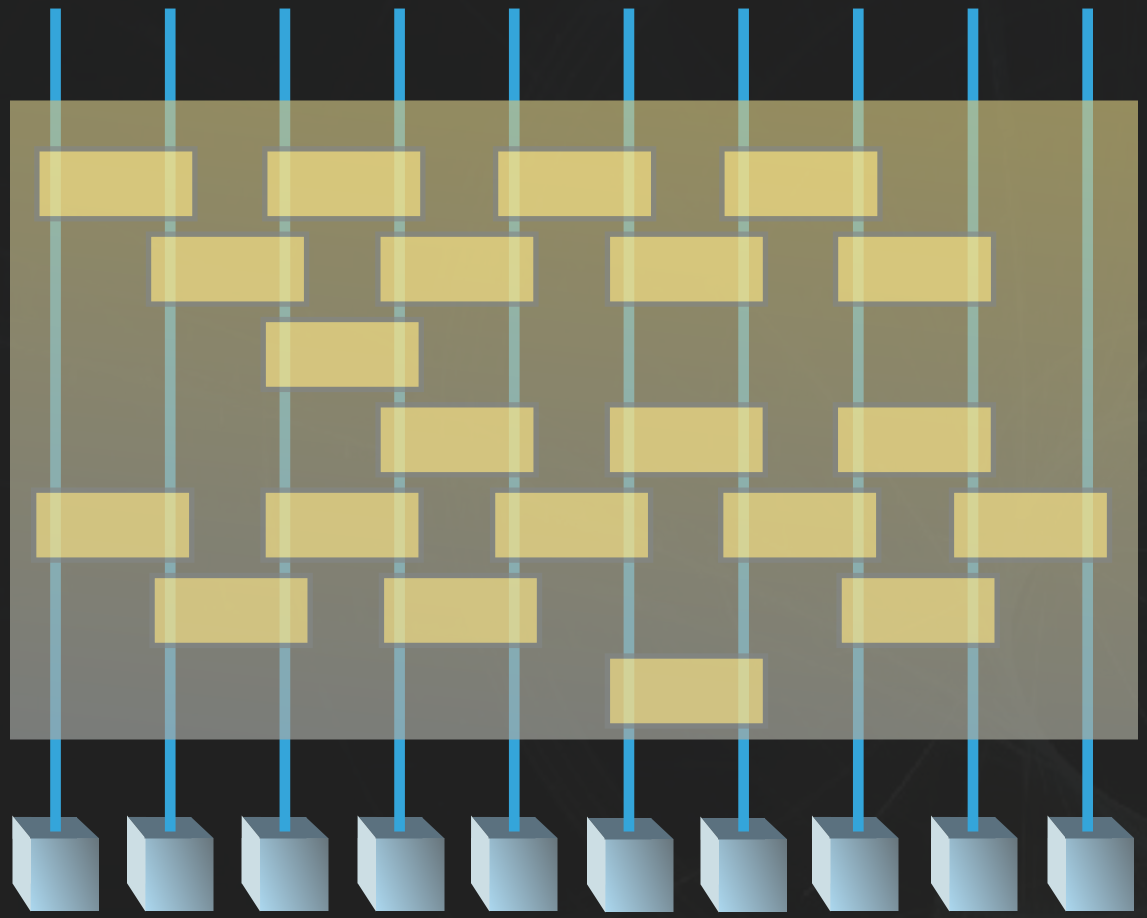
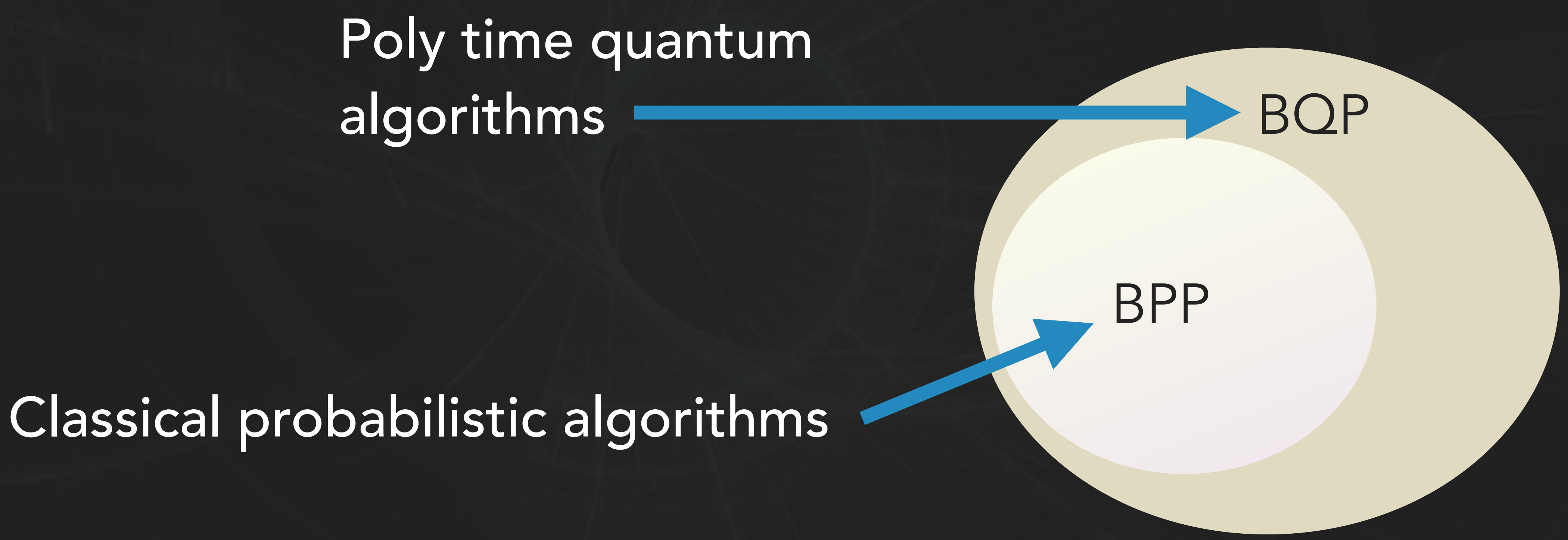


- E.g., 01010011 (bits) replaced by (qubits)

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

- Could solve some problems supercomputers cannot



- E.g., factoring of large products of prime numbers
  - A factor of a large number N can be found if the **period** p of

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

can be identified

  - Periods can be found using 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)

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  - Solves NP problem in poly time: Runtime $O((\log N)^3)$
  - Best known classical algorithm $\exp(O((\log N)^{1/3} (\log \log N)^{2/3}))$
  - Generalised to hidden subgroup problem

Shor, SIAM J Comp 26, 148 (1997)

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- Solving linear systems
  Harrow, Hassidim, Lloyd, Phys Rev Lett 15, 150502 (2009)

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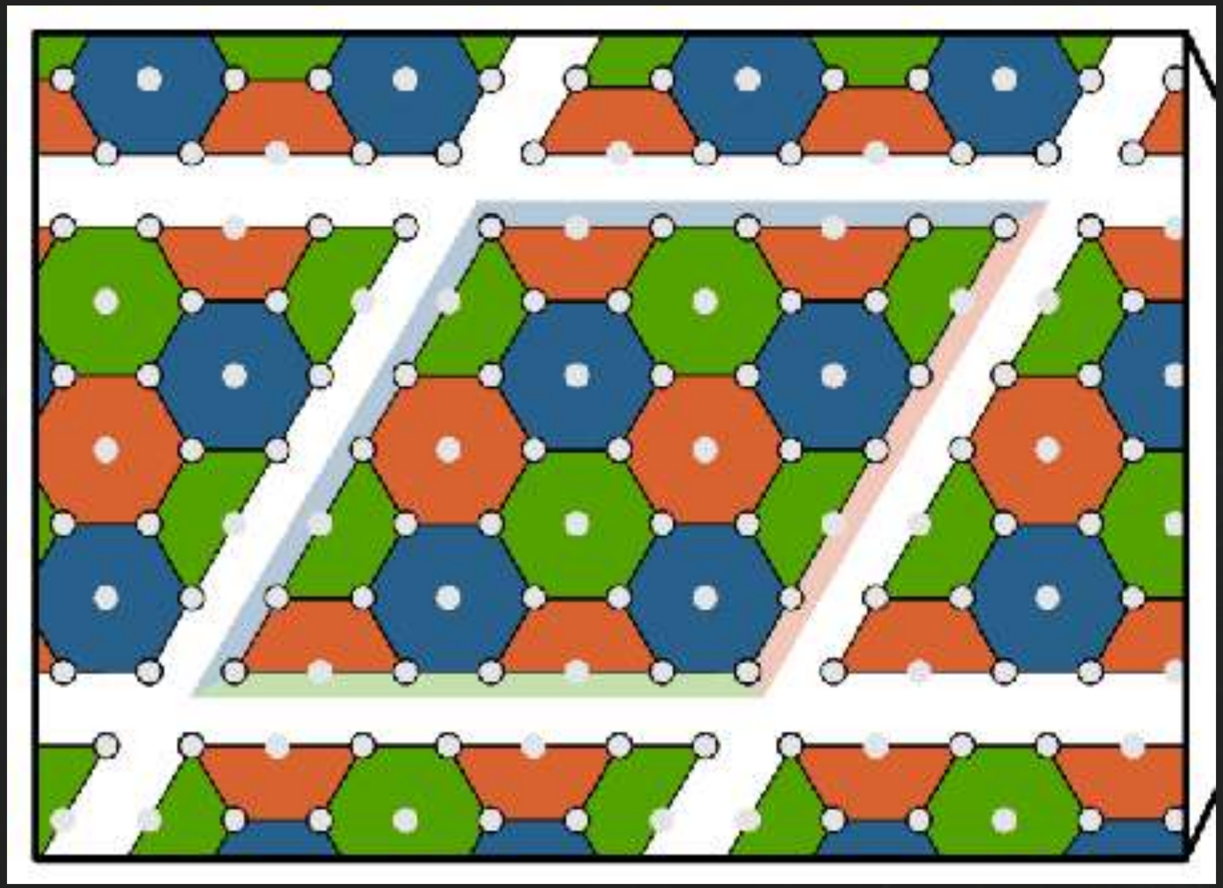
  Shor, SIAM J Comp 26, 148 (1997)
- Solving linear systems
  Harrow, Hassidim, Lloyd, Phys Rev Lett 15, 150502 (2009)
- Spectral analysis
  Steffens, Rebenstrost, Marvian, Eisert, Lloyd, New J Phys 19, 033005 (2017)
- Semi-definite programming
  Brandão, Kalev, Li, Lin, Svore, Wu, arXiv:1710.02581

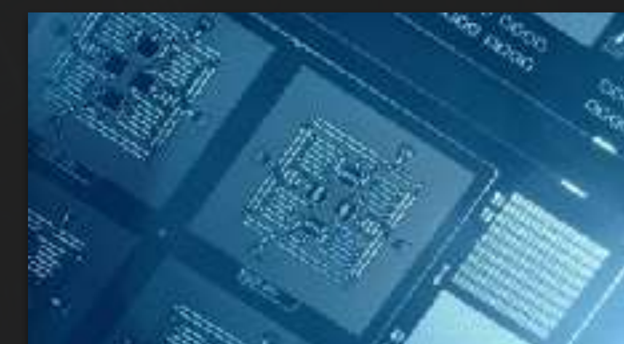
- Can tolerate small errors in all steps (at high cost)



E.g., Litinski, Kesselring, Eisert, von Oppen, arXiv:1704.01589

- The race for building quantum computers
- Not there, but with 50 superconducting qubits taking shape

(IBM)



(Google)

(Rigetti)

(D-wave)

QUANTUM SIMULATORS

- **Quantum simulators:** Not all strongly correlated quantum systems/materials can be classically simulated

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- **Idea:** Simulate quantum systems with quantum systems

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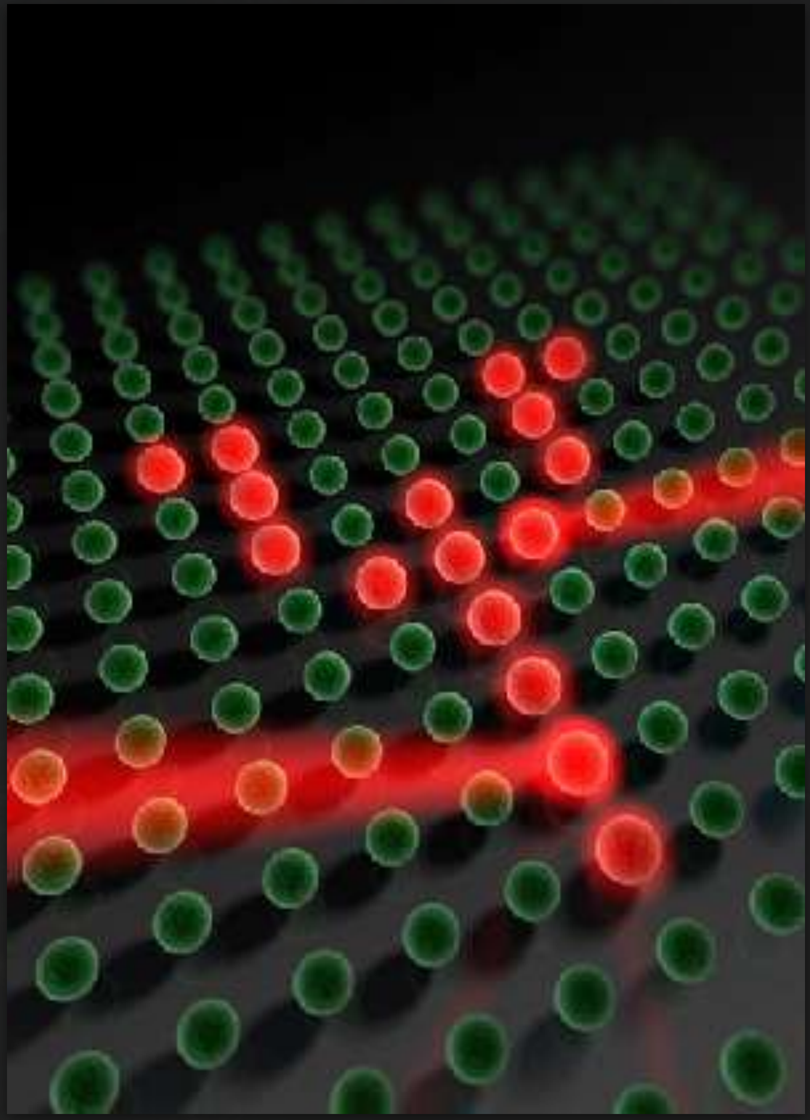
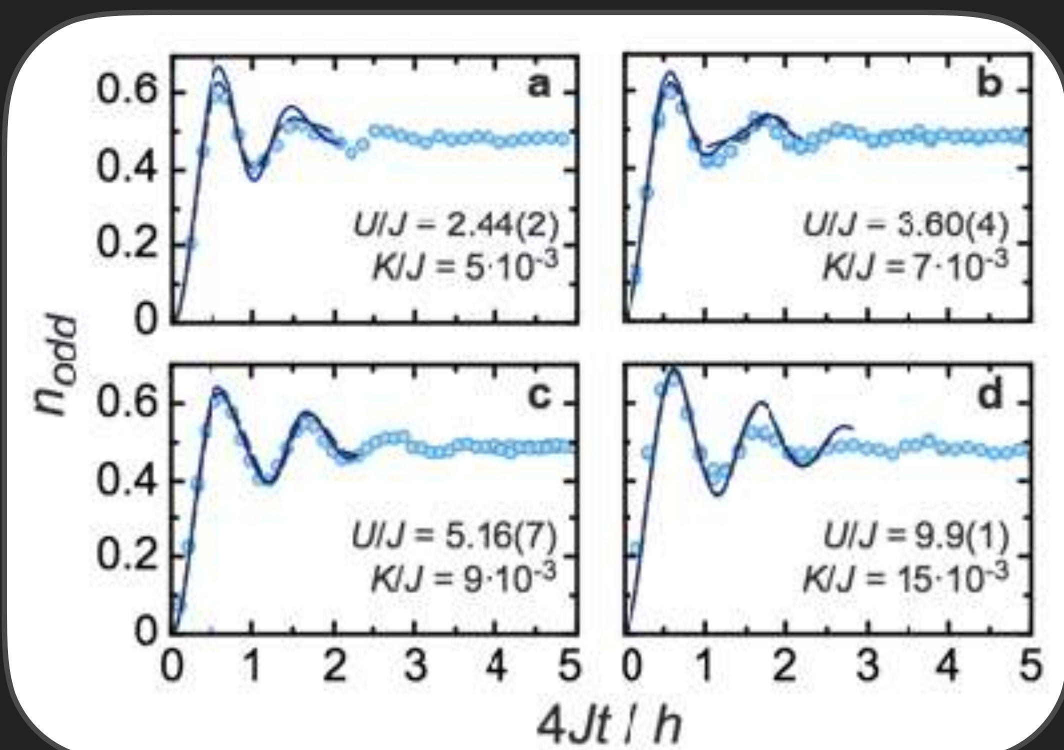


Cold atoms in optical lattices

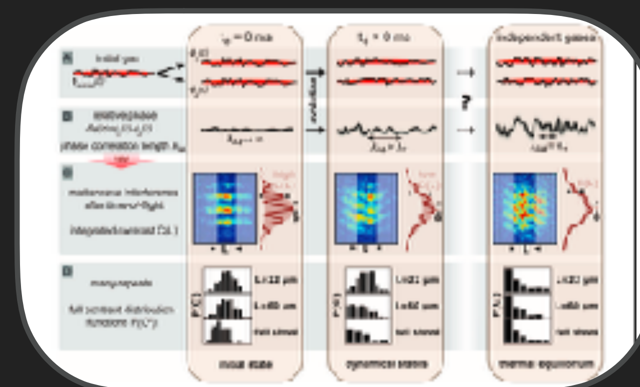
- Simulate interesting physical situations

Equilibration



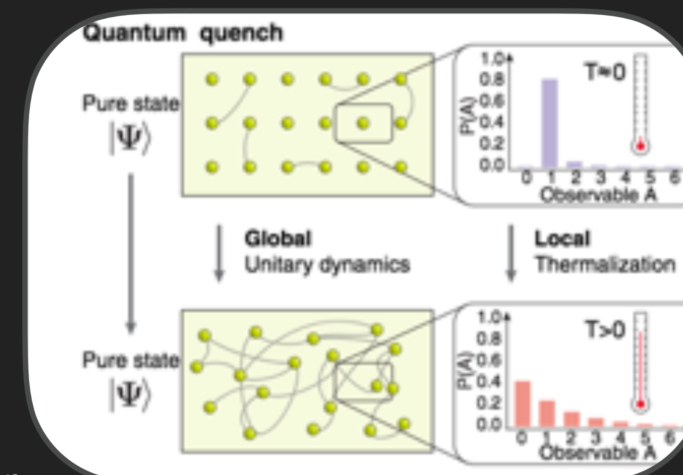
Trotzky, Chen, Flesch, McCulloch, Schollwöck, Eisert, Bloch, Nature Physics 8, 325 (2012)

Pre-thermalization



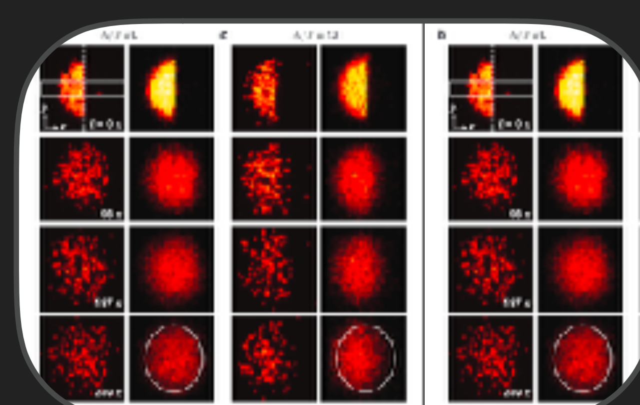
Gring, Kuhnert, Langen, Kitagawa, Rauer, Schreitl, Mazets, Smith, Demler, Schmiedmayer, Science 337, 1318 (2012)

Thermalization



Kaufman, Tai, Lukin, Rispoli, Schittko, Preiss, Greiner, Science 353, 794 (2016)

Many-body localization



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

- Some properties can be obtained beyond supercomputers

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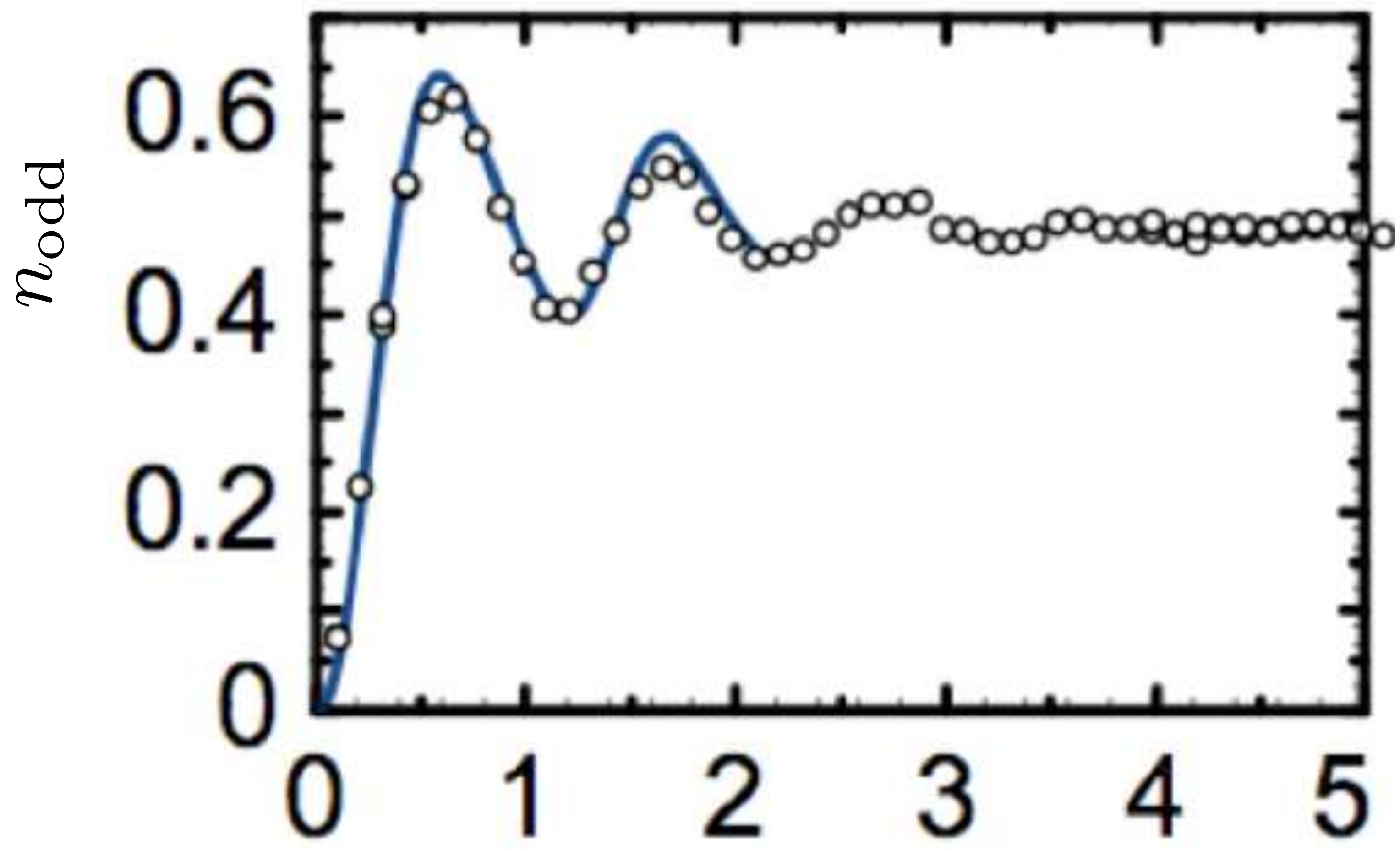
  - Imbalance as function of time for $|\psi(0)\rangle = |0, 1, \ldots, 0, 1\rangle$ under Bose-Hubbard Hamiltonian



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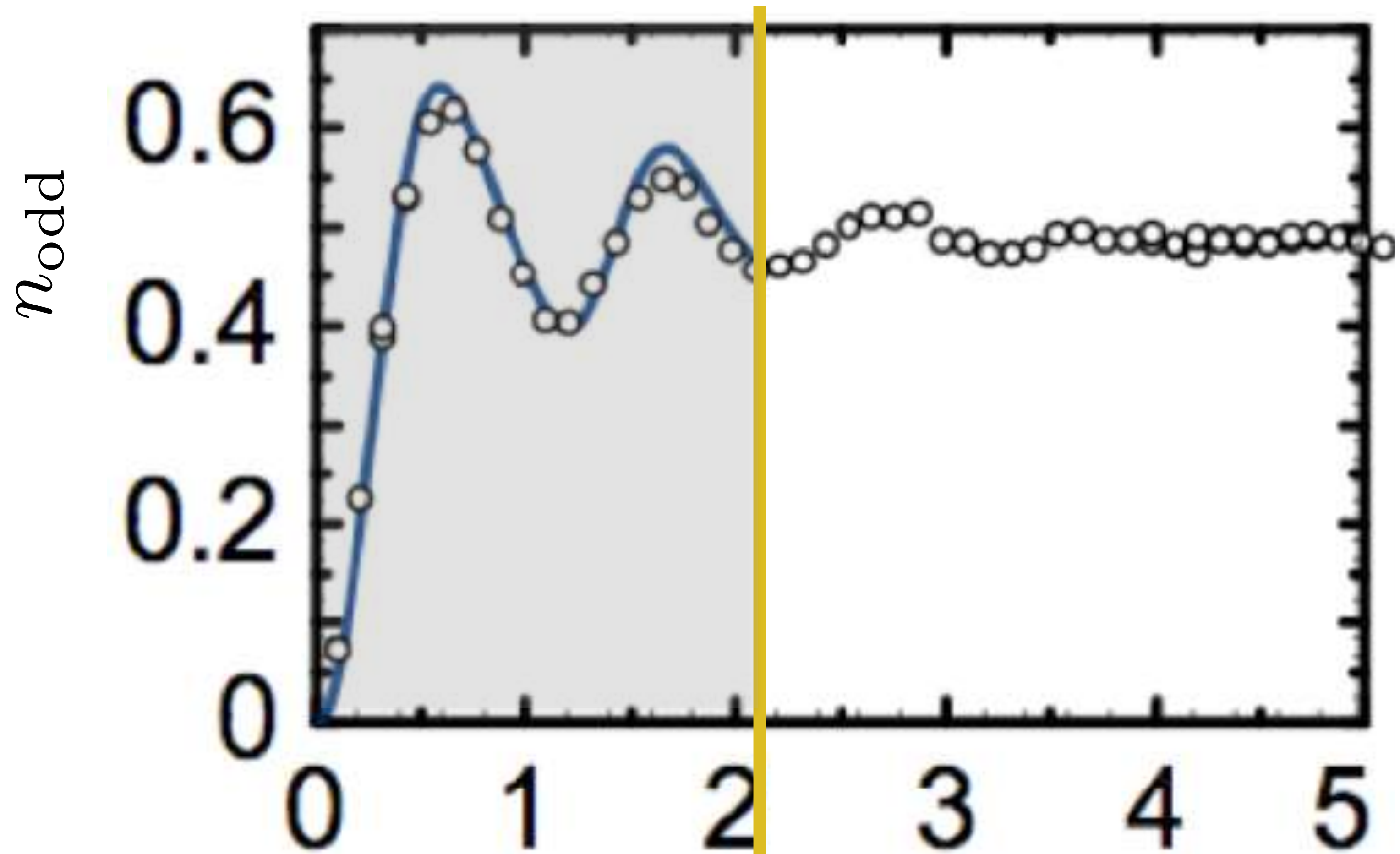

Best available classical matrix-product state simulation, bond dimension 5000

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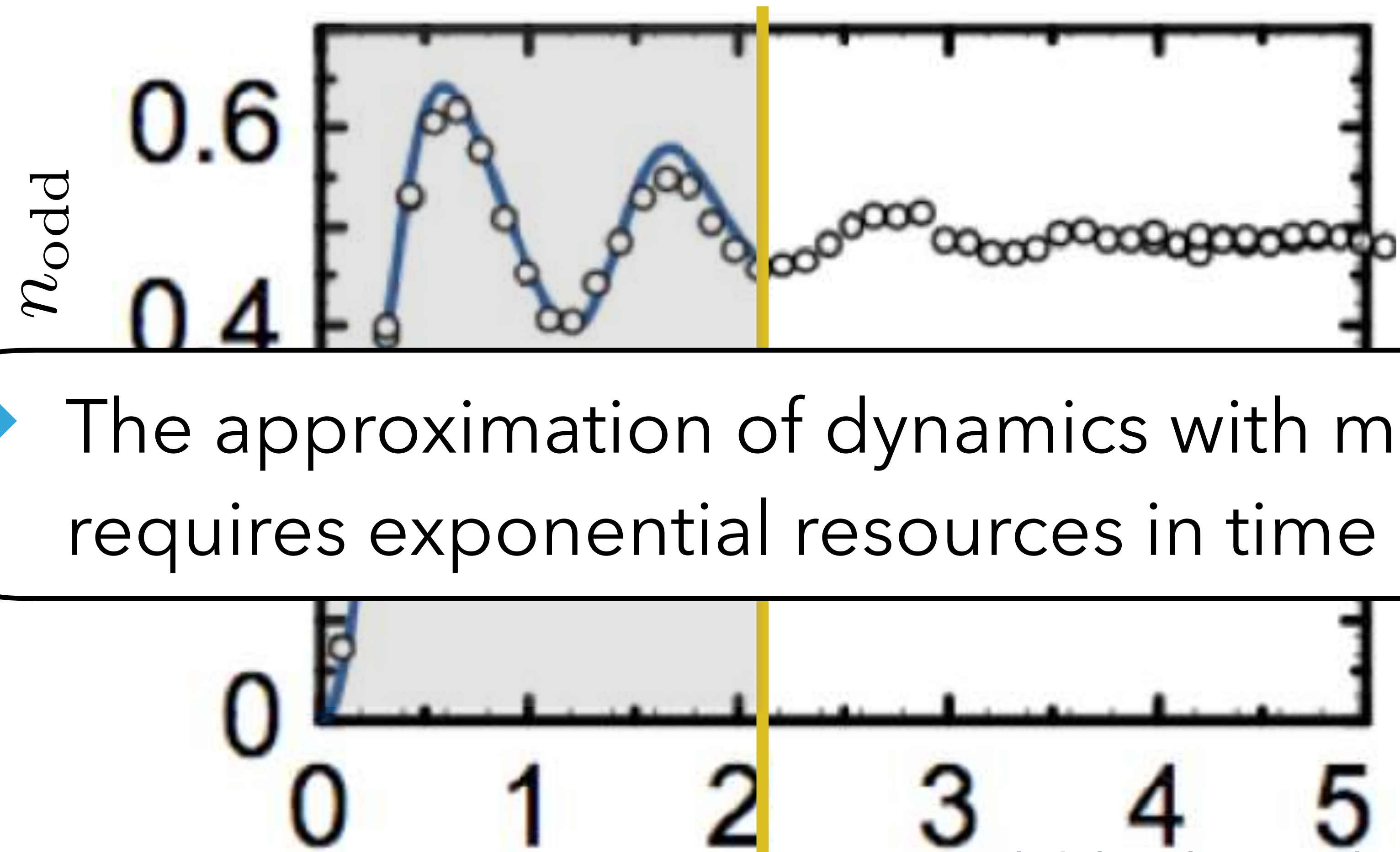

- The approximation of dynamics with matrix-product states requires exponential resources in time

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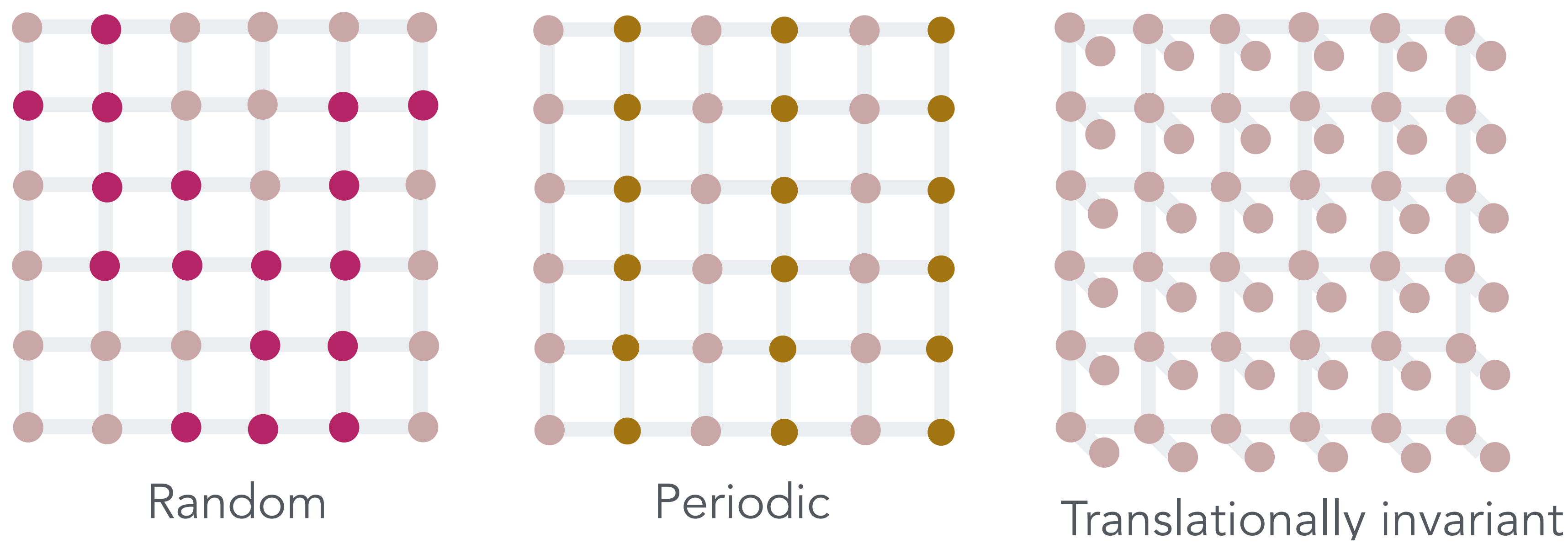
  - Simple Ising nearest-neighbor architectures



Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, Phys Rev X 8, 021010 (2018)

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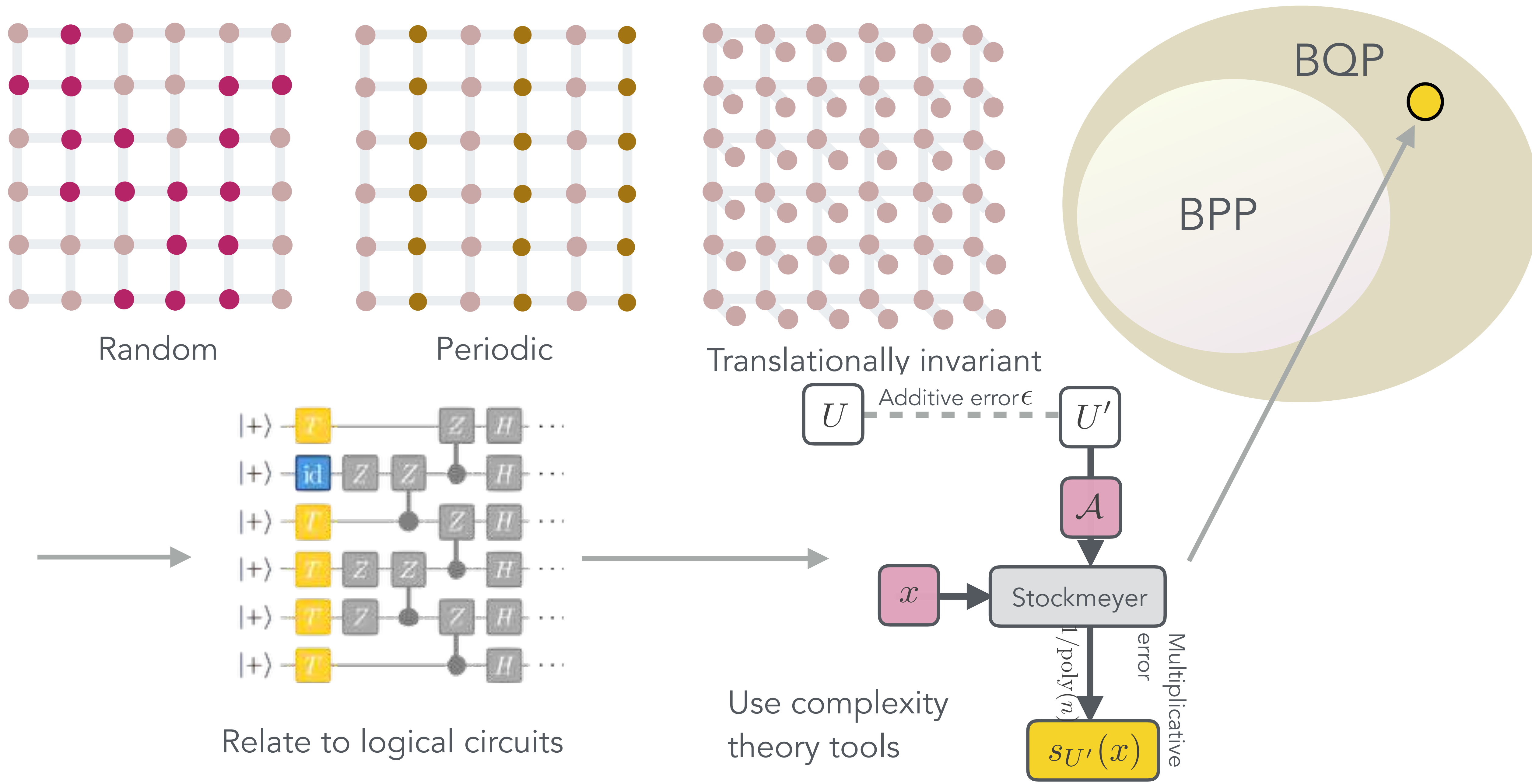

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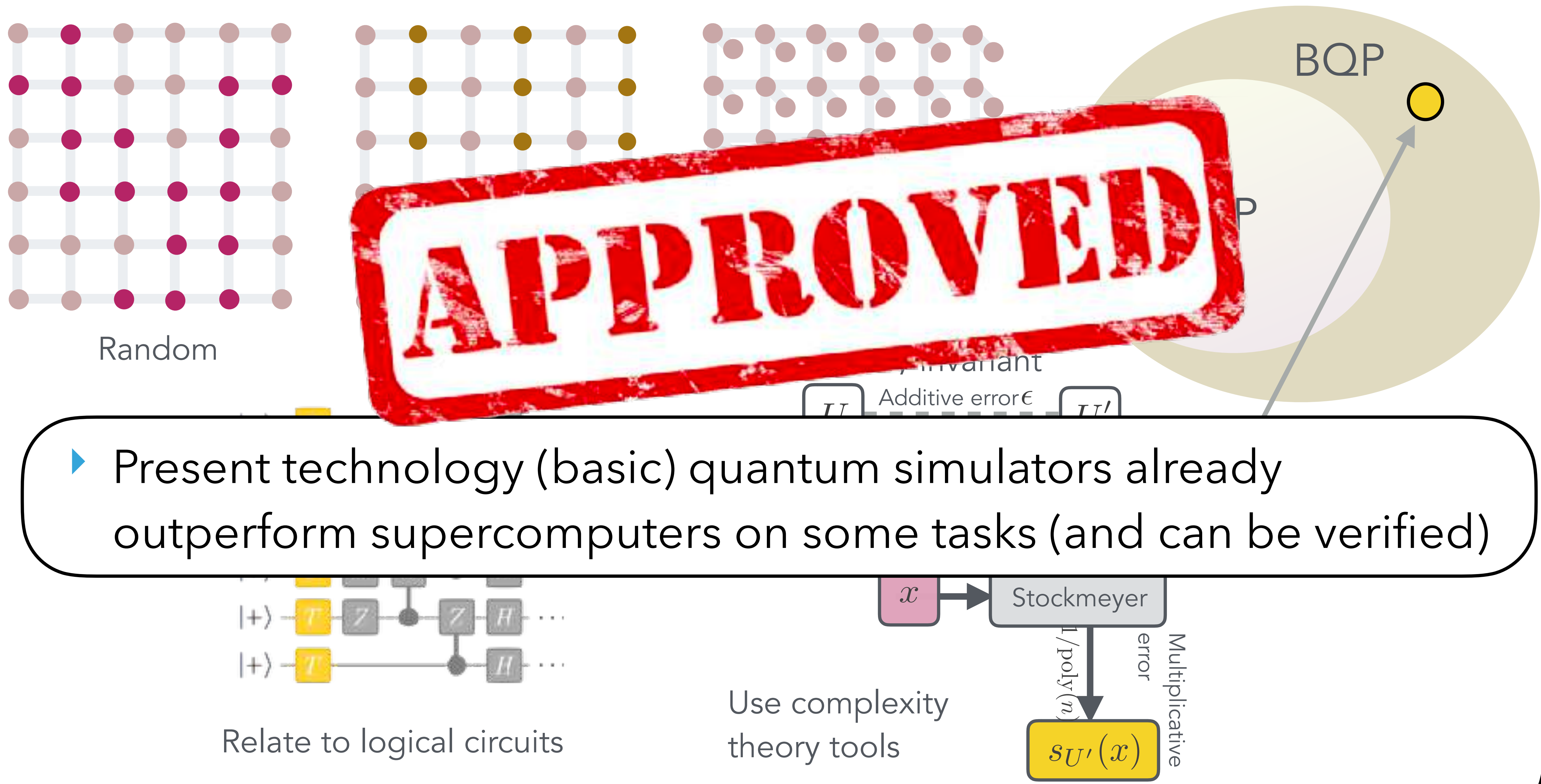
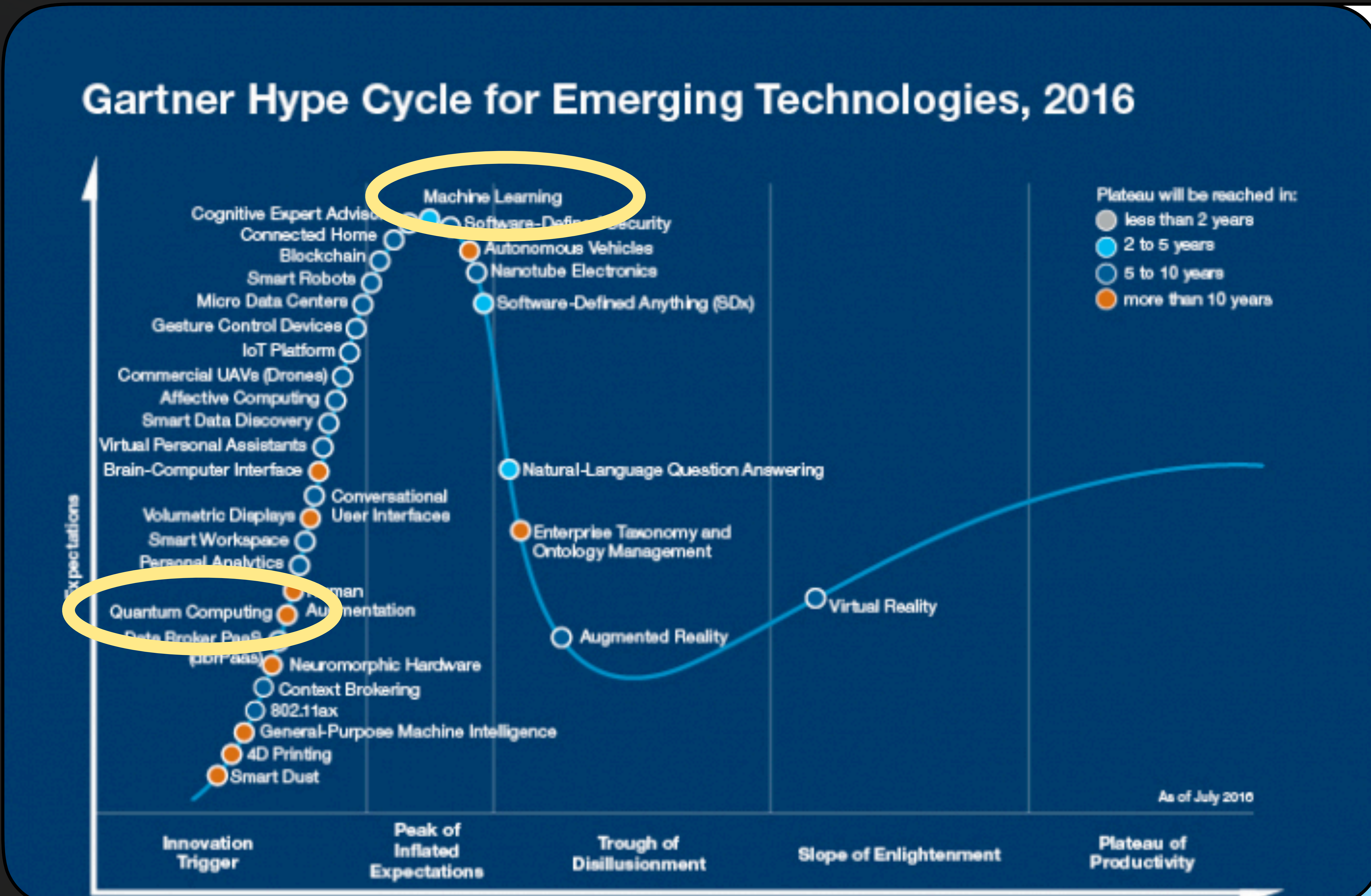


- Present technology (basic) quantum simulators already outperform supercomputers on some tasks (and can be verified)

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, Phys Rev X 8, 021010 (2018)

GETTING GOING...

- 1G€ Euros-Flagship for quantum technologies



- "Quantum computing is exciting even if you restrict yourself to saying things that are true."

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THANKS FOR YOUR ATTENTION