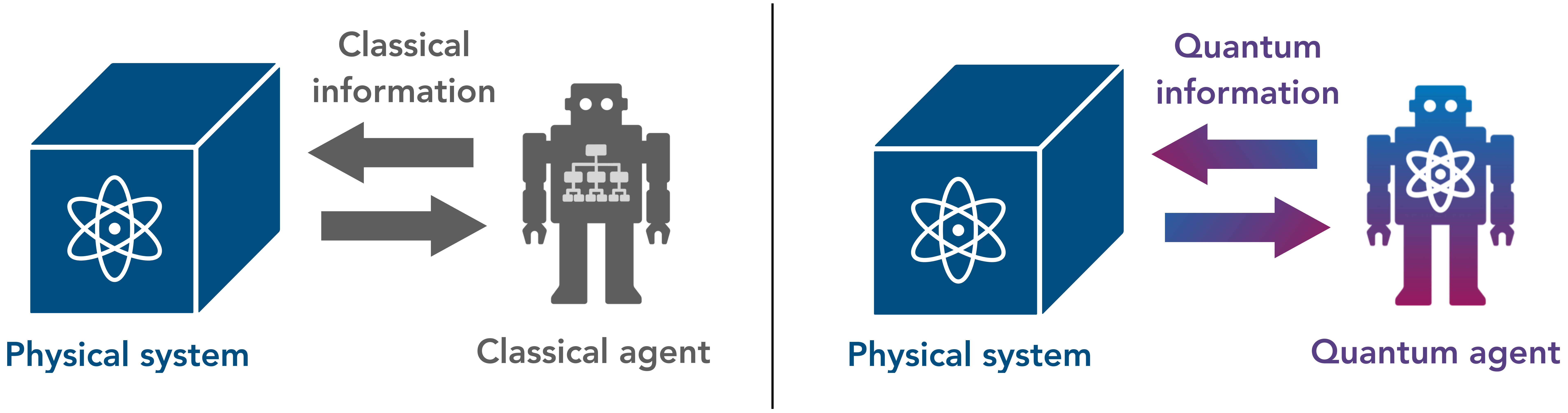
Ph 220: Lecture 20

Next Steps for Quantum x AI

Classical vs Quantum AI

- What are the **advantages** of **quantum AI agents** over **classical AI**?
- Could quantum technology fundamentally alter our ability to **learn** about the world?

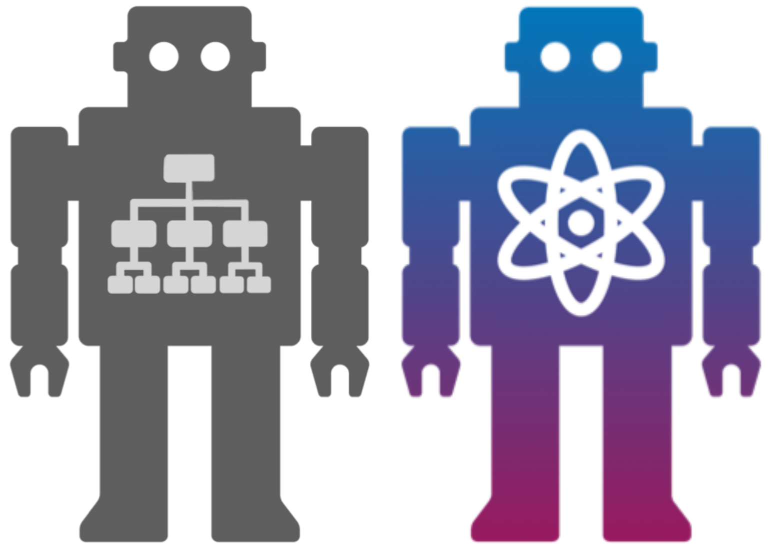


Exponential quantum advantage

Exponential quantum advantage

Predicting many incompatible observables

To predict all Pauli observables $\{I, X, Y, Z\}^{\otimes n}$,
classical agent needs $\Omega(2^n)$ **experiments**,
quantum agent only needs $\mathcal{O}(n)$ **experiments**.



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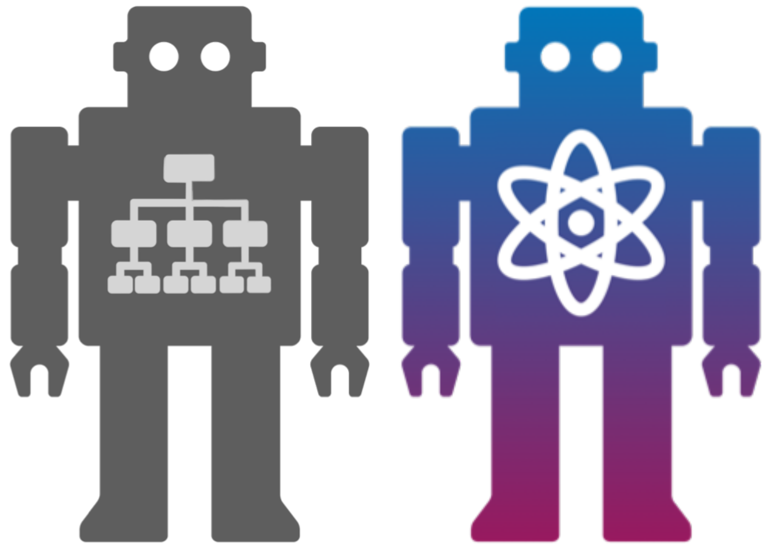
Performing quantum PCA

To estimate property of principal component, classical agent needs **exponential time**, quantum agent needs **polynomial time**.



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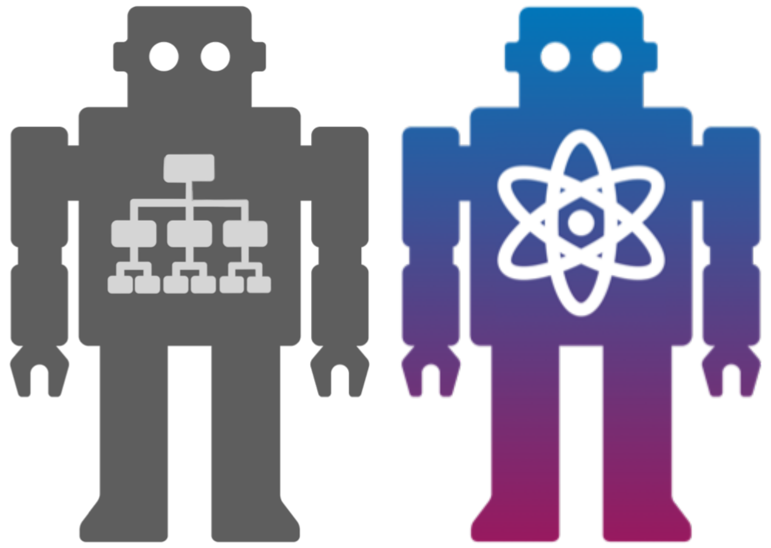
Uncovering symmetry in dynamics

Classifying dynamics with or without time-reversal
symmetry gives **exponential advantage**.



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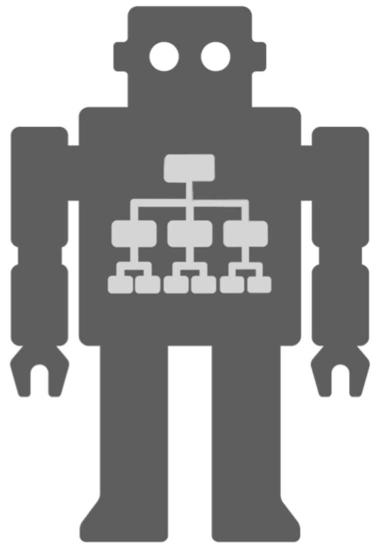
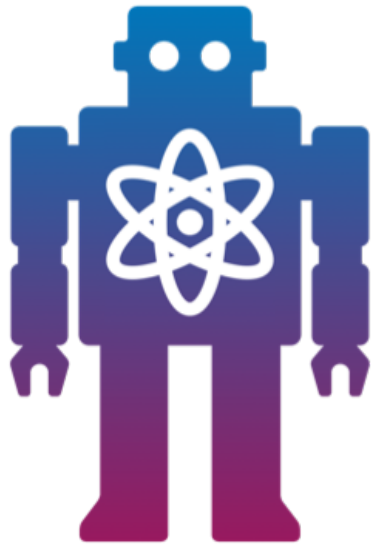
Uncovering symmetry in dynamics

Classifying dynamics with or without time-reversal symmetry gives **exponential advantage**.

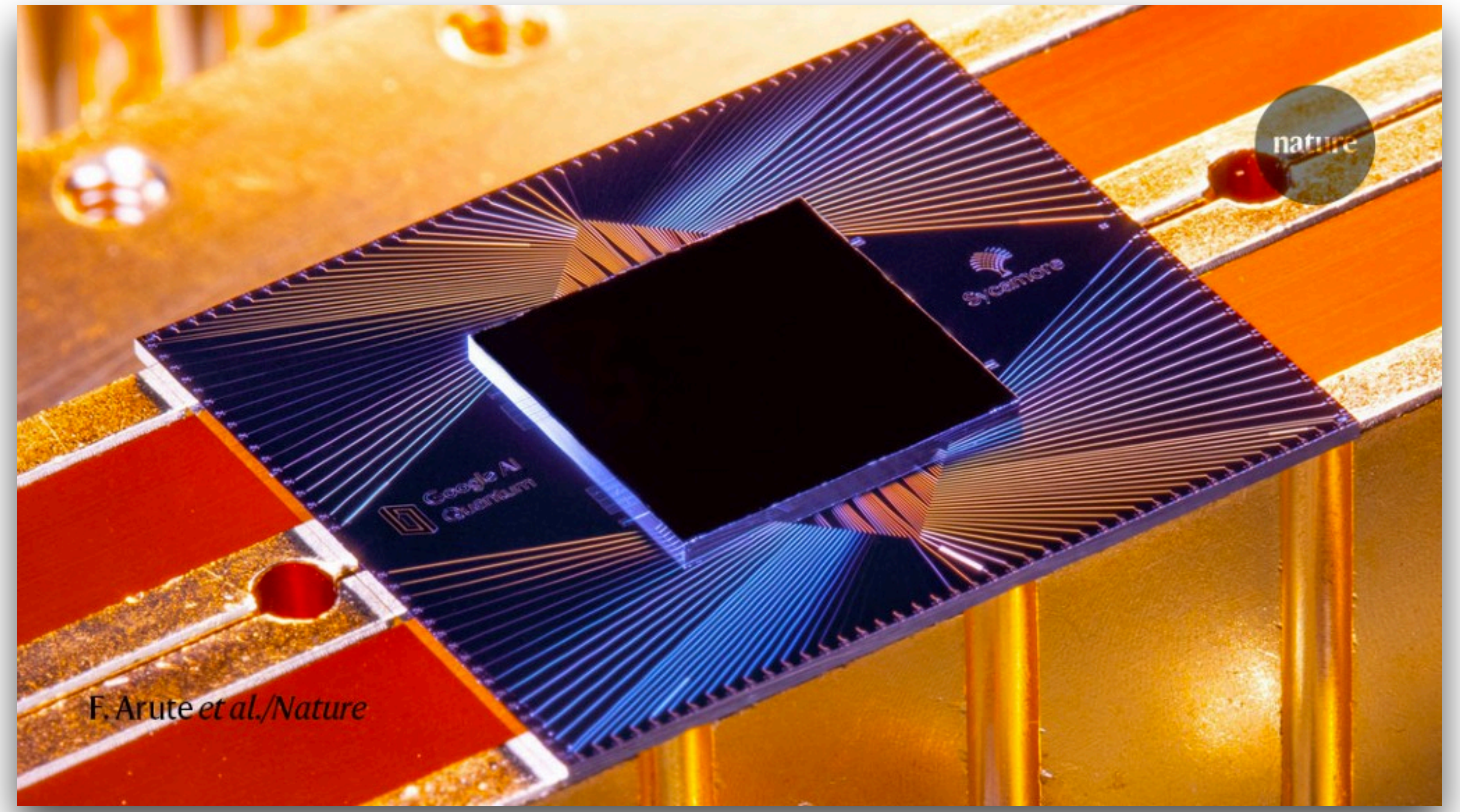
Learning physical dynamics

To learn a polynomial-time quantum process,
a classical agent requires **exponential experiments**,
a quantum agent only needs **polynomial experiments**.

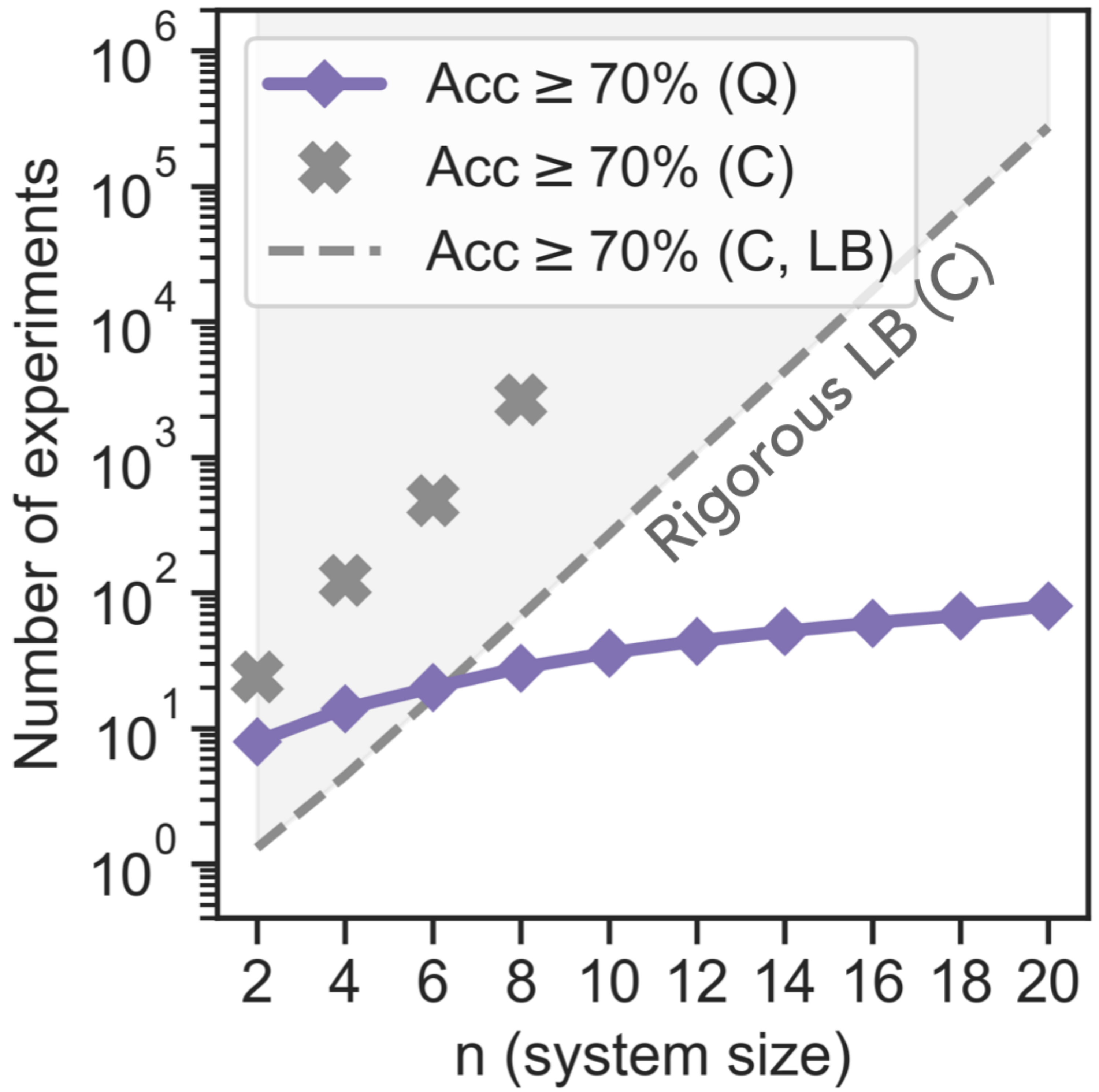



Demonstration on Sycamore:
Quantum advantage in learning states

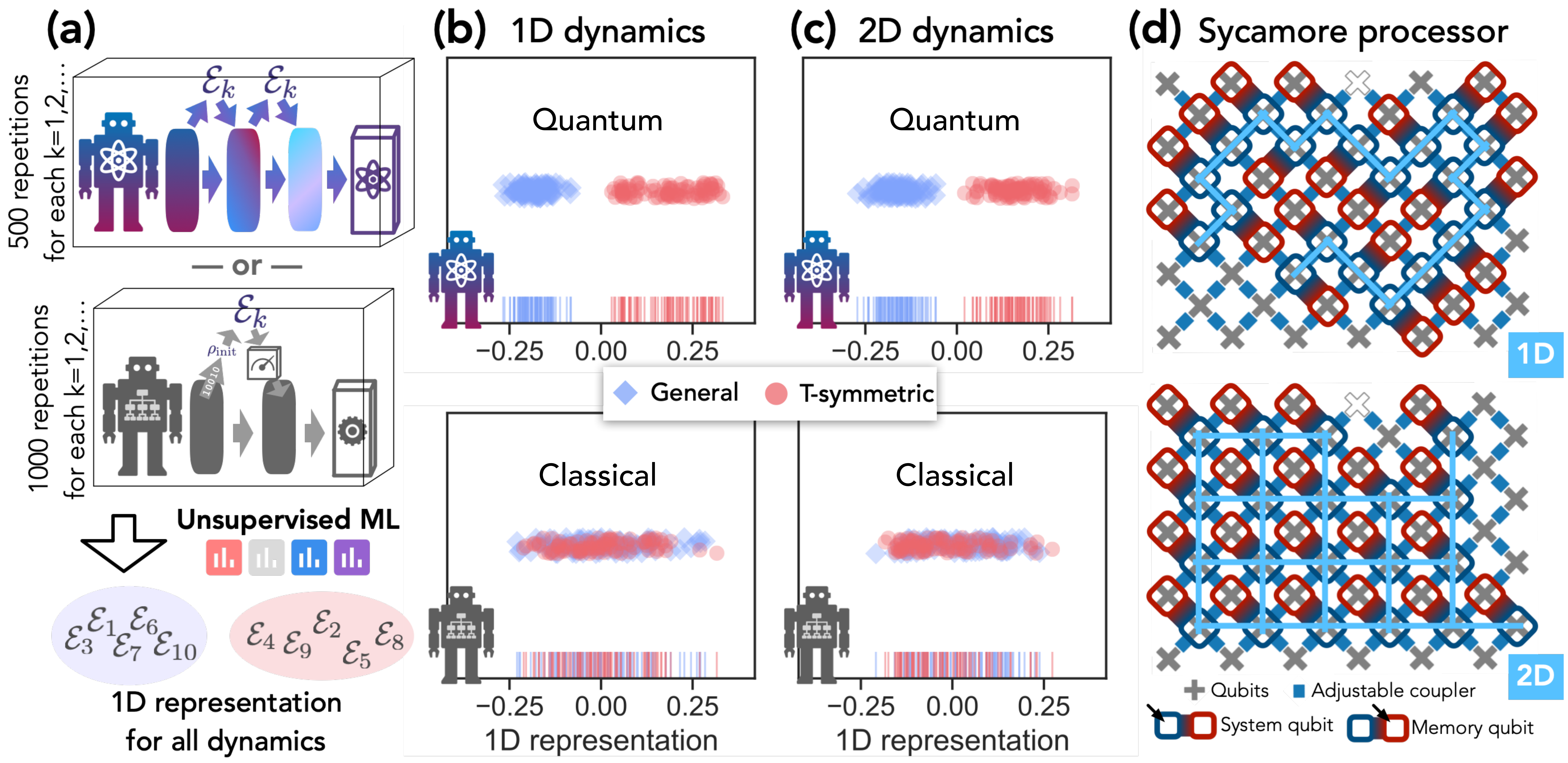
Utilizing a total of 40 qubits



Sycamore Processor



Demonstration on Sycamore: Quantum advantage in learning dynamics



What we learned so far

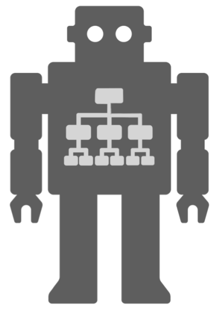
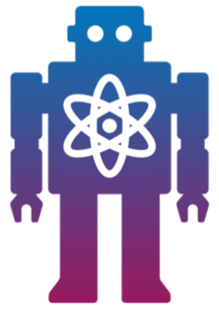
What we learned so far

- ✤ How to efficiently learn in the quantum universe?

What we learned so far

✤ **How to efficiently learn in the quantum universe?**

We have seen how to learn fields, states, unitaries, Hamiltonians, devices

( via randomized measurement,  via gentle entangled measurement)

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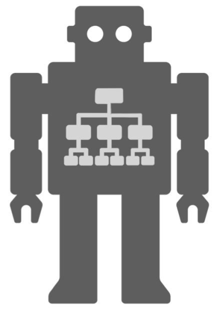
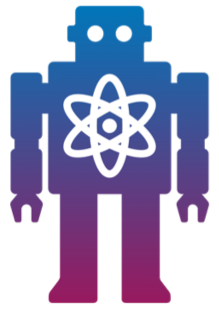
( via randomized measurement,  via gentle entangled measurement)

Mathematical tools: concentration inequality, Weingarten calculus, gentle measurements, matrix analysis.

What we learned so far

- ✤ What physical phenomena can quantum machines learn?

What we learned so far

✤ **What physical phenomena can quantum machines learn?**

Evolution time, causal structure, entanglement, topological order, noise in state/measurement are **quantumly hard** to feel/see/measure/learn.

What we learned so far

- ✤ **What physical phenomena can quantum machines learn?**

  Evolution time, causal structure, entanglement, topological order, noise in state/measurement are **quantumly hard** to feel/see/measure/learn.

  Mathematical tools: cryptography, purification, pseudorandom states and unitaries, representation theory.

What we learned so far

- When can quantum machines learn/predict better than classical?

What we learned so far

✤ **When can quantum machines learn/predict better than classical?**

QNNs can learn to generate classically hard distributions.

Quantum AI can learn exponentially faster than classical AI in quantum tasks.

What we learned so far

✤ **When can quantum machines learn/predict better than classical?**

QNNs can learn to generate classically hard distributions.

Quantum AI can learn exponentially faster than classical AI in quantum tasks.

Mathematical tools: teleportation/MBQC, quantum complexity theory, learning tree, uncertainty principle.

Where do we go from here?

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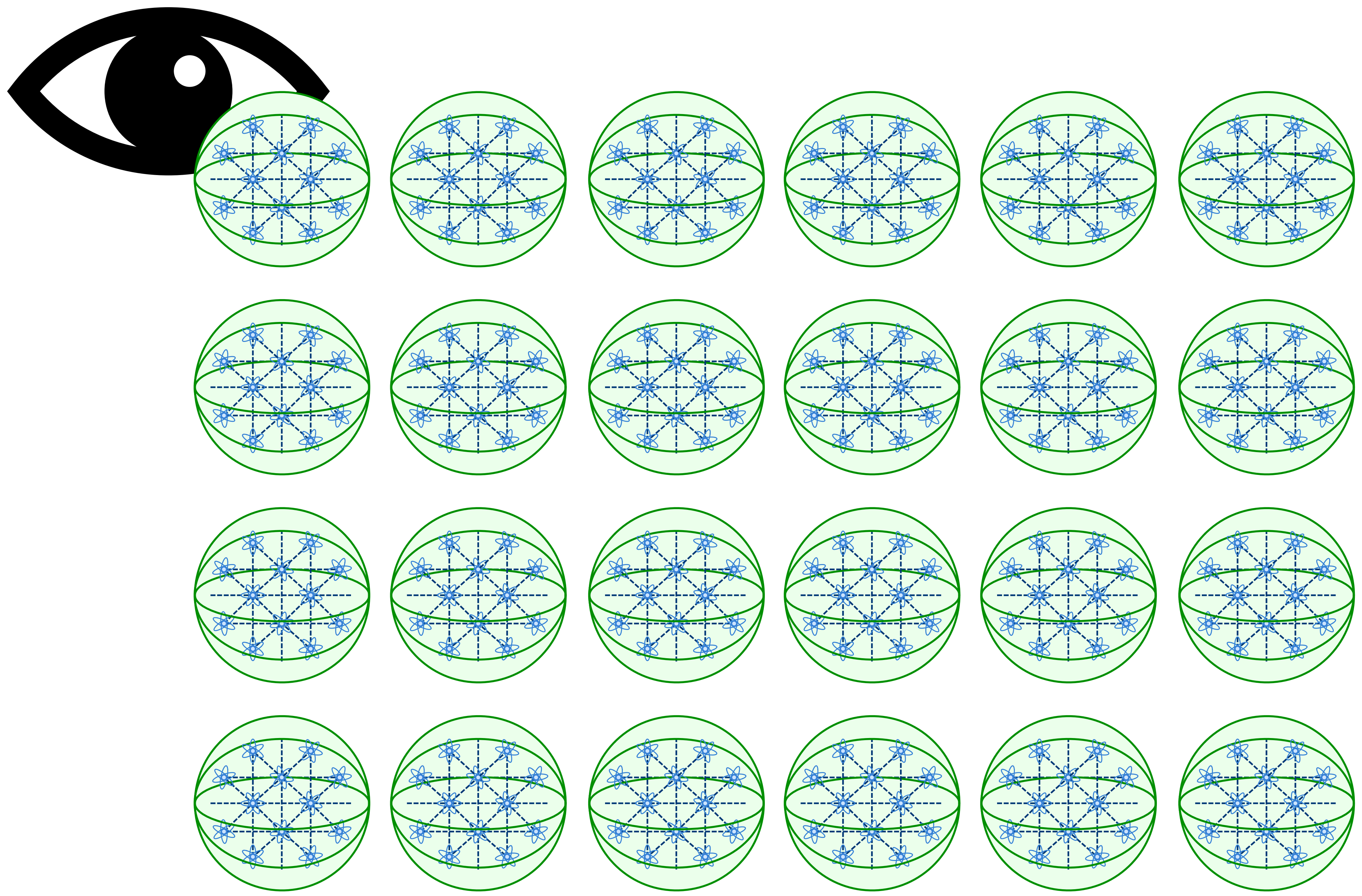
- **AI for Quantum Technology:**

  How to accelerate/automate quantum technology with AI?

Where do we go from here?

✤ **AI for Quantum Technology:**

How to **accelerate/automate** quantum technology with AI?



Where do we go from here?

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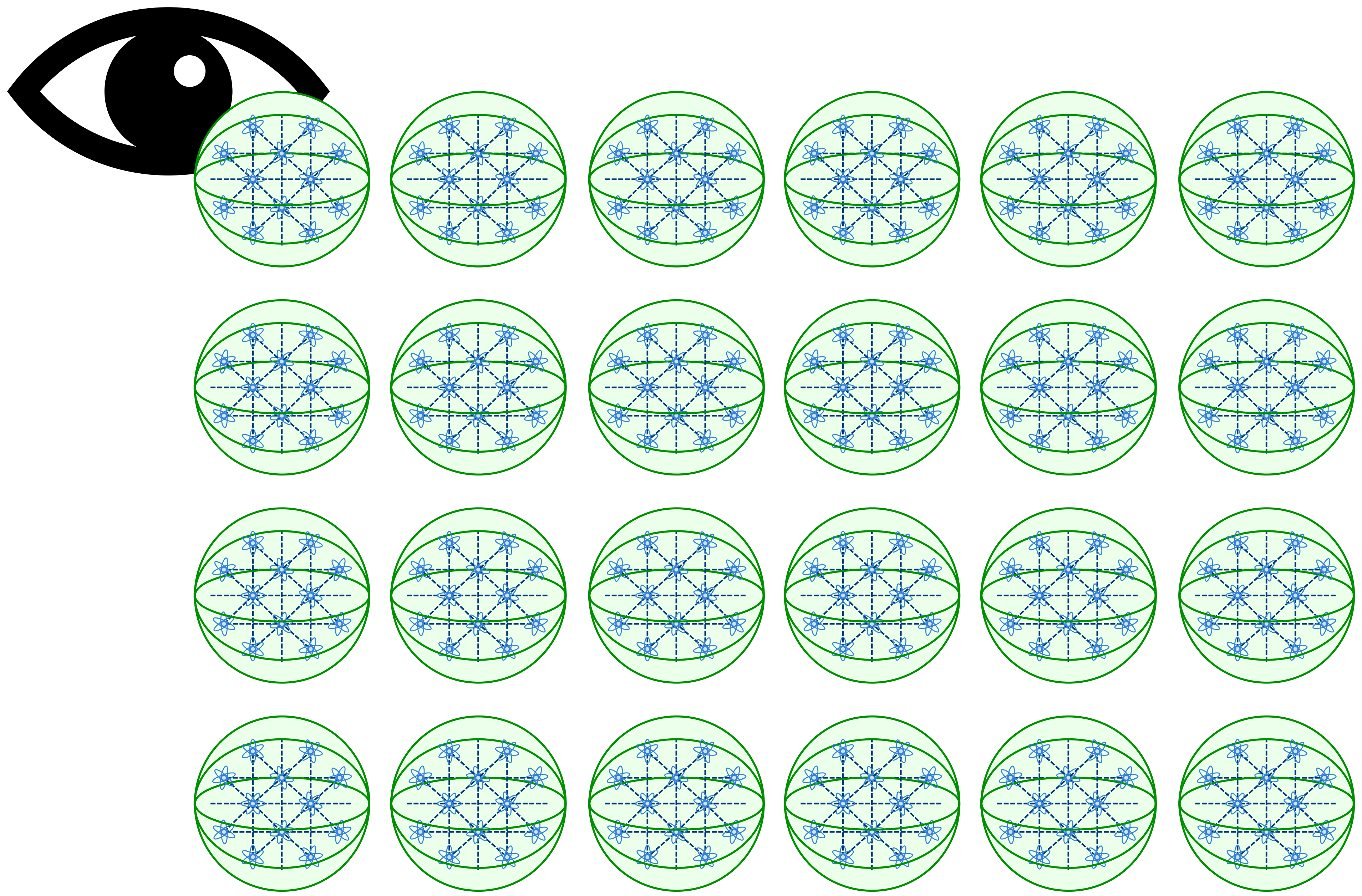
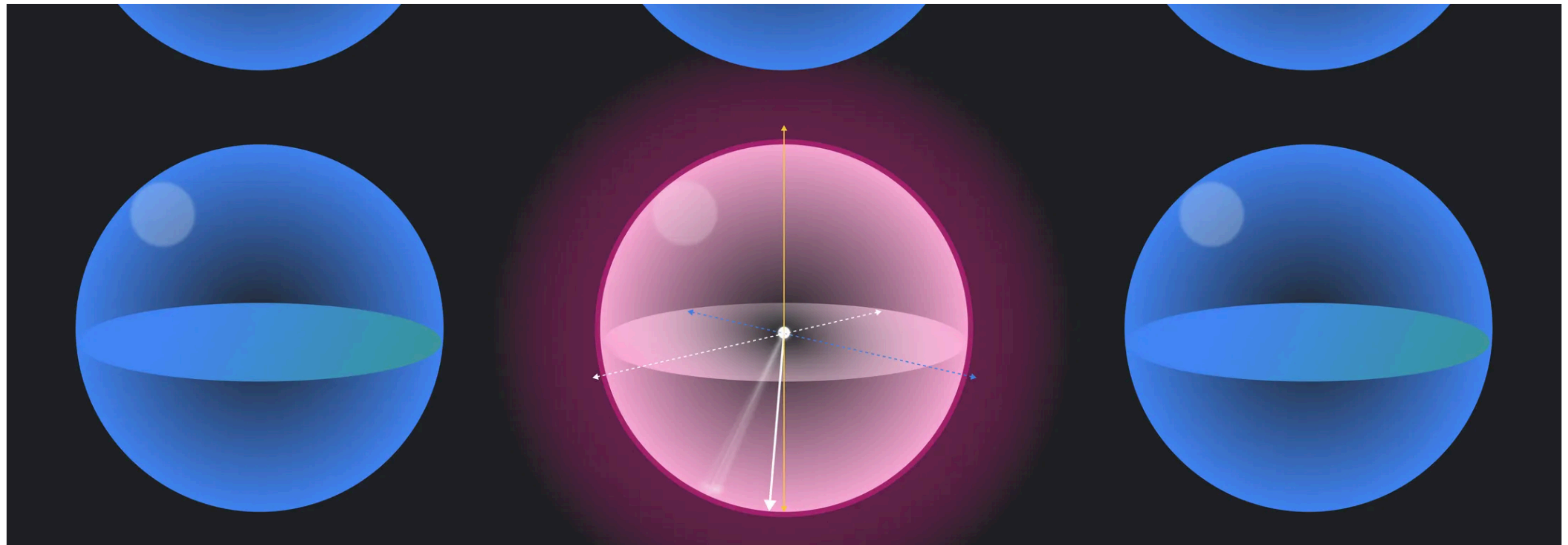
How to **accelerate/automate** quantum technology with AI?



AlphaQubit tackles one of quantum computing's biggest challenges

G Google DeepMind and Quantum AI teams

Share



Where do we go from here?

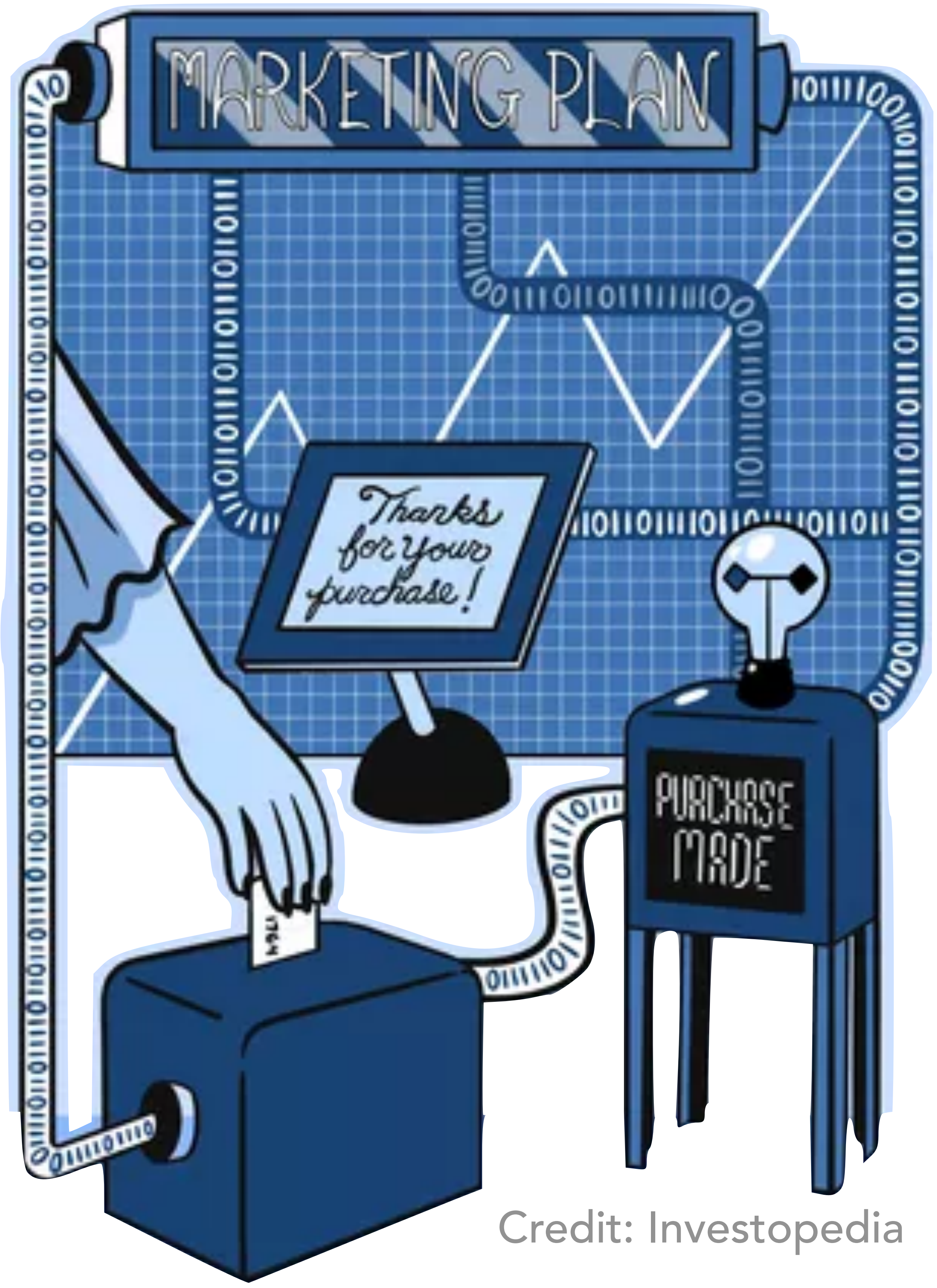
- ✤ **AI for Quantum Technology:**

  How to **accelerate/automate** quantum technology with AI?

- ✤ **Quantum Advantage for Classical AI:**

  Can quantum machines achieve **significant advantage** in learning problems arising from **classical ML/AI**?

Quantum Advantage for Analyzing Classical Data



Credit: Investopedia

Quantum AI

Question:

Can quantum AI offer useful advantage in analyzing large amount of classical data?

Quantum Advantage
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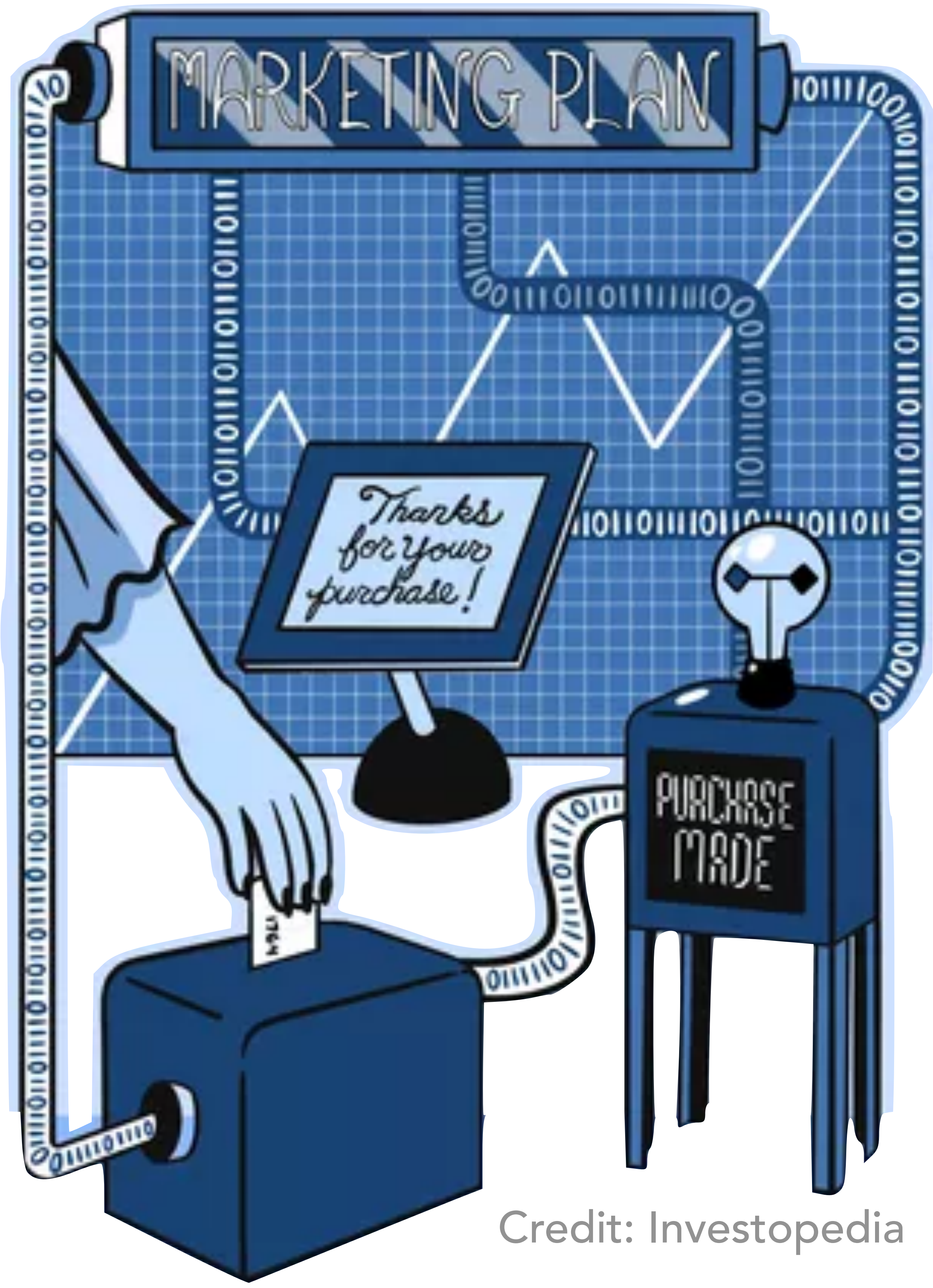

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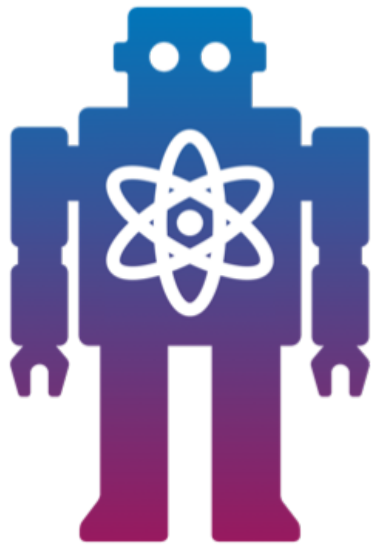

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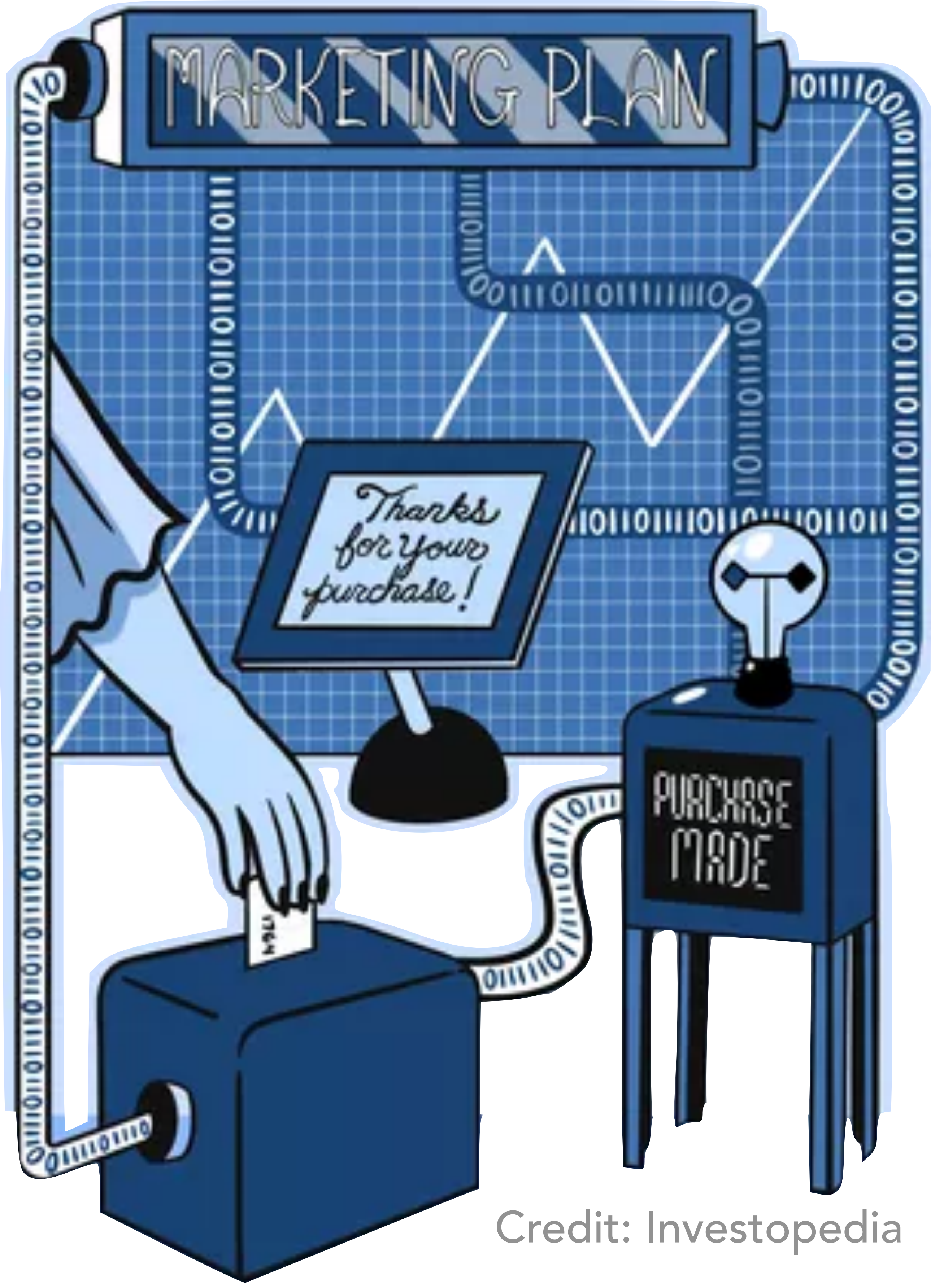
Existing QML algorithms does not seem useful.

Quantum Advantage for Analyzing Classical Data



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Quantum AI

Data loading problem

(data loading $\gg$ computation)

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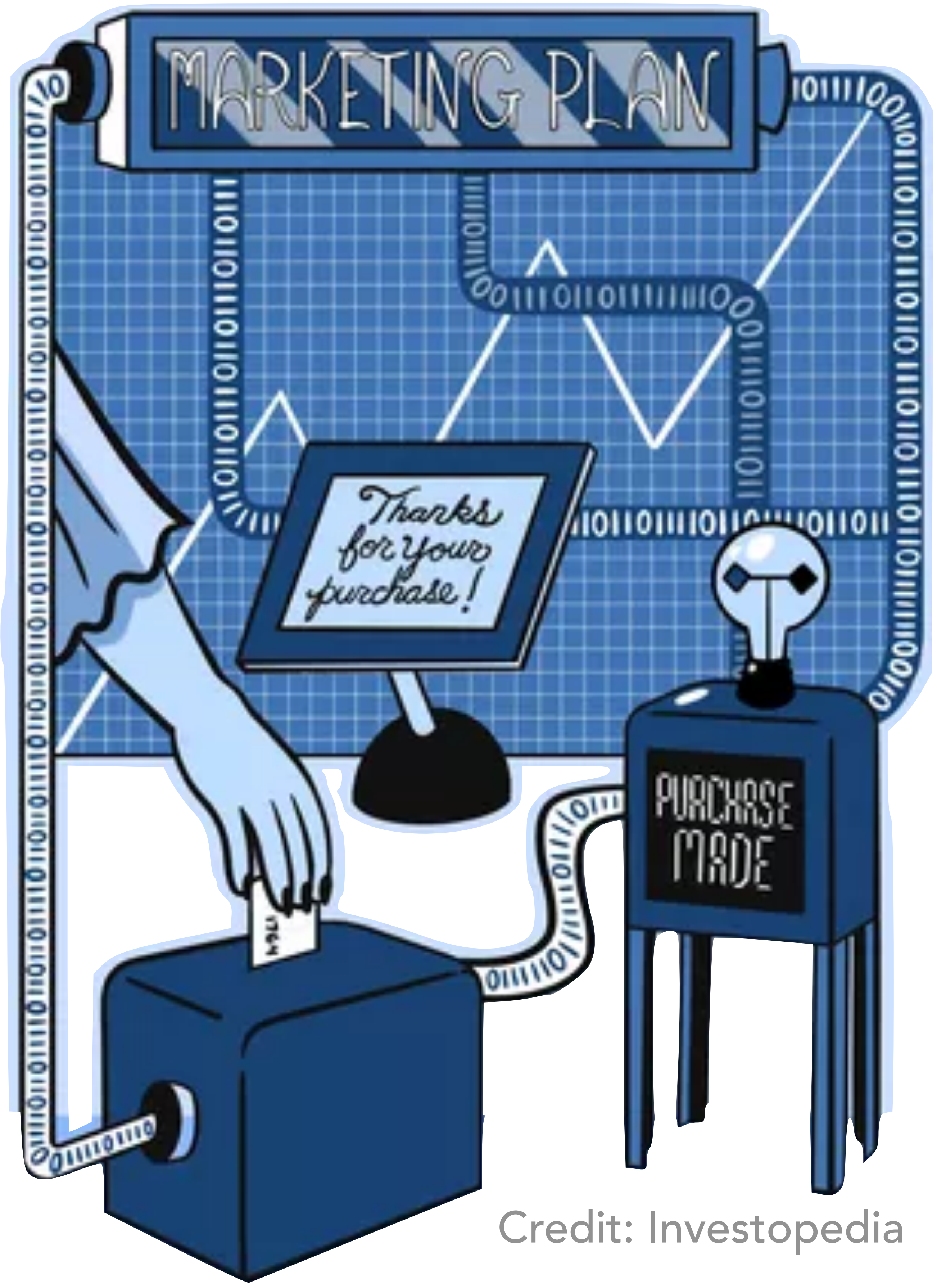

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Exponentially large **QRAM**

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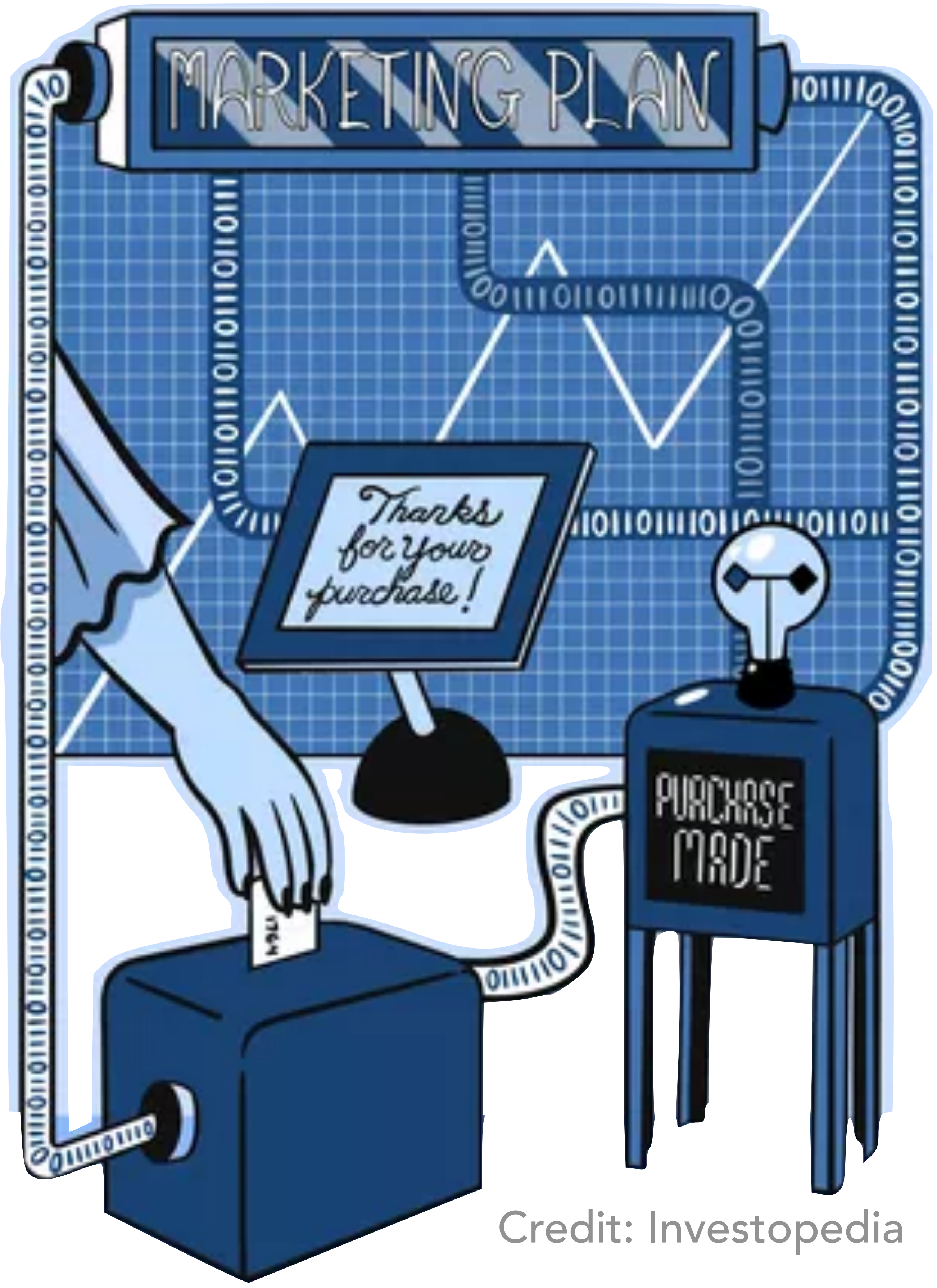

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Quantum AI

Data loading problem
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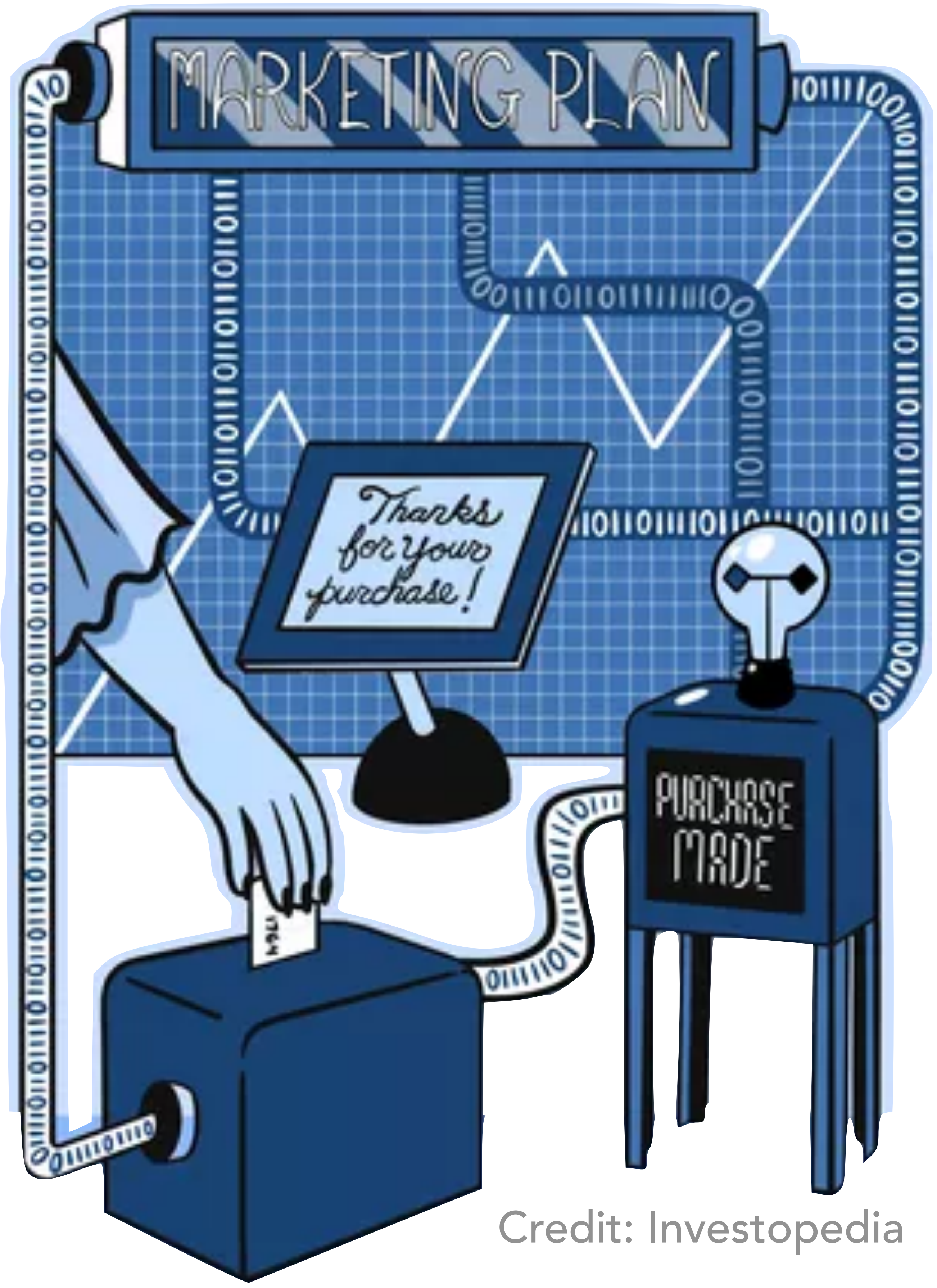
Exponentially large **QRAM**

Only **polynomial** speedup
(dequantization)

Quantum Advantage for Analyzing Classical Data



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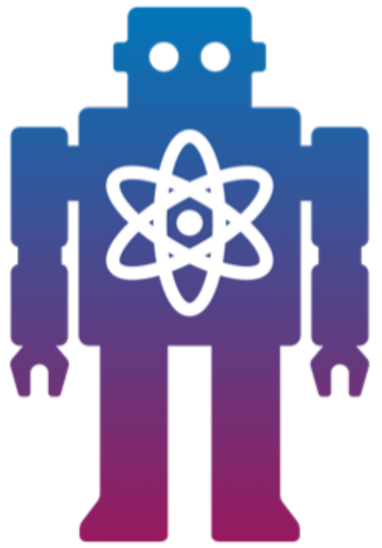

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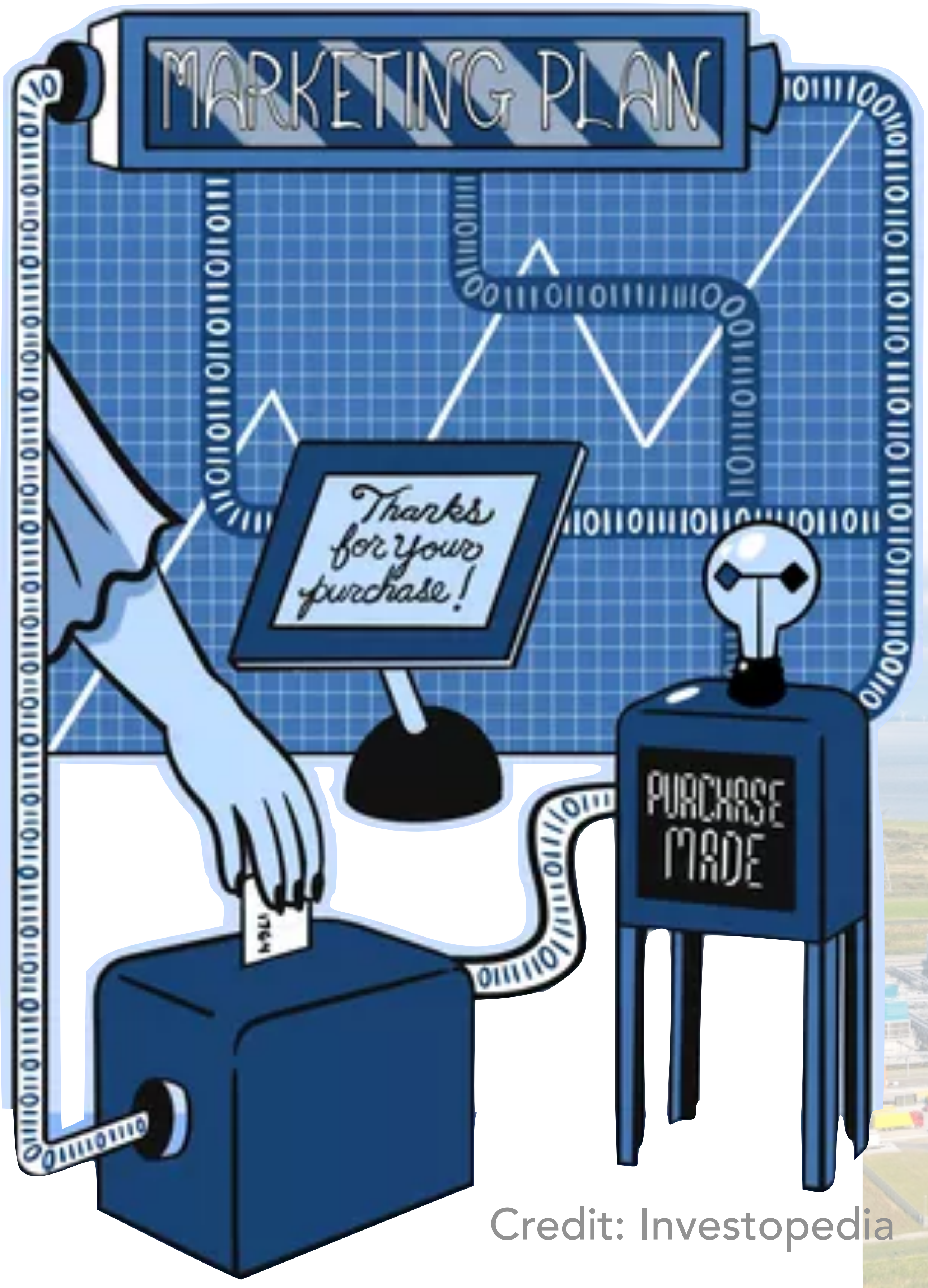

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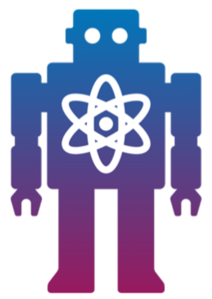
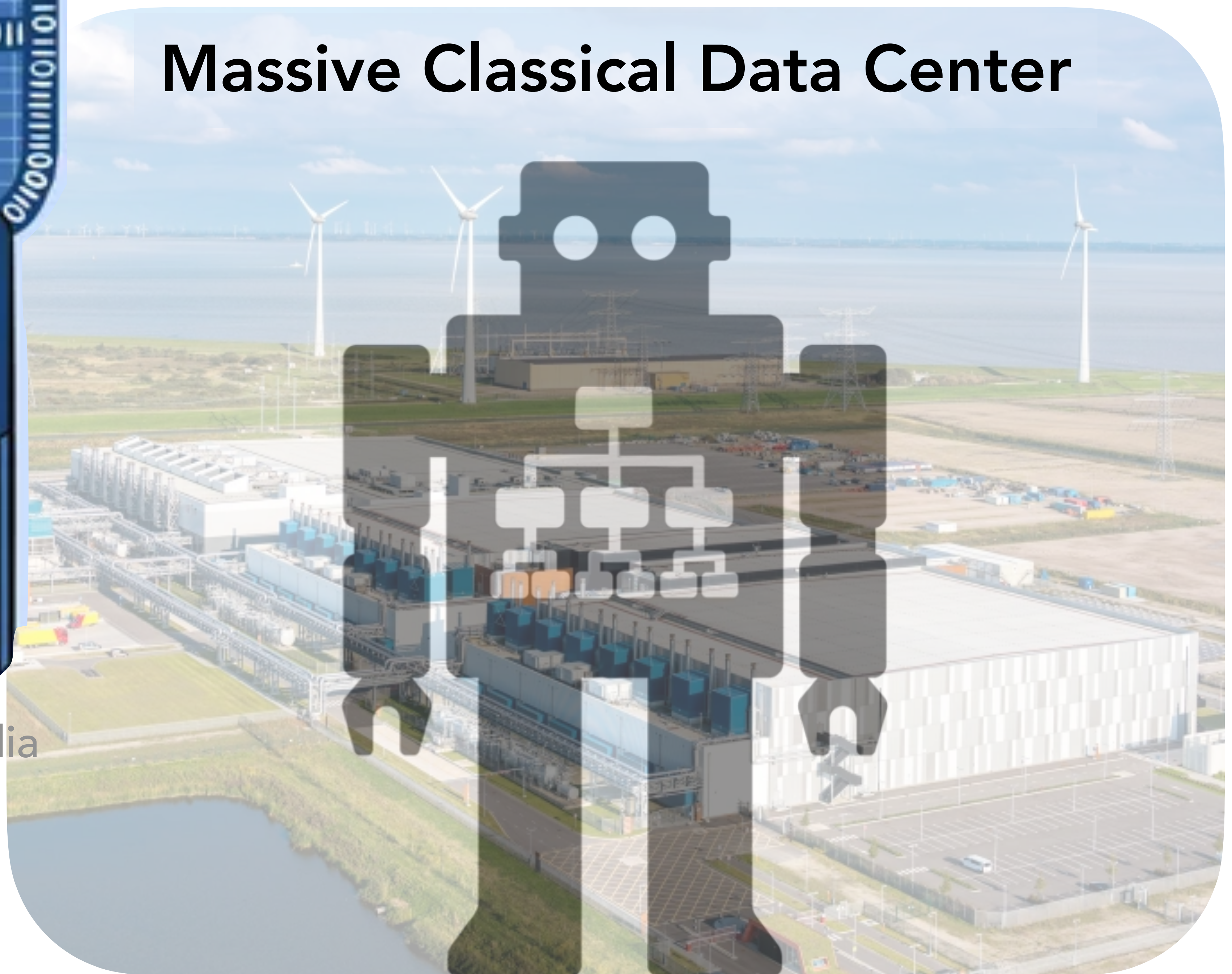


Tiny Quantum AI running on 100 logical qubit chip

v.s.



Massive Classical Data Center

Question:

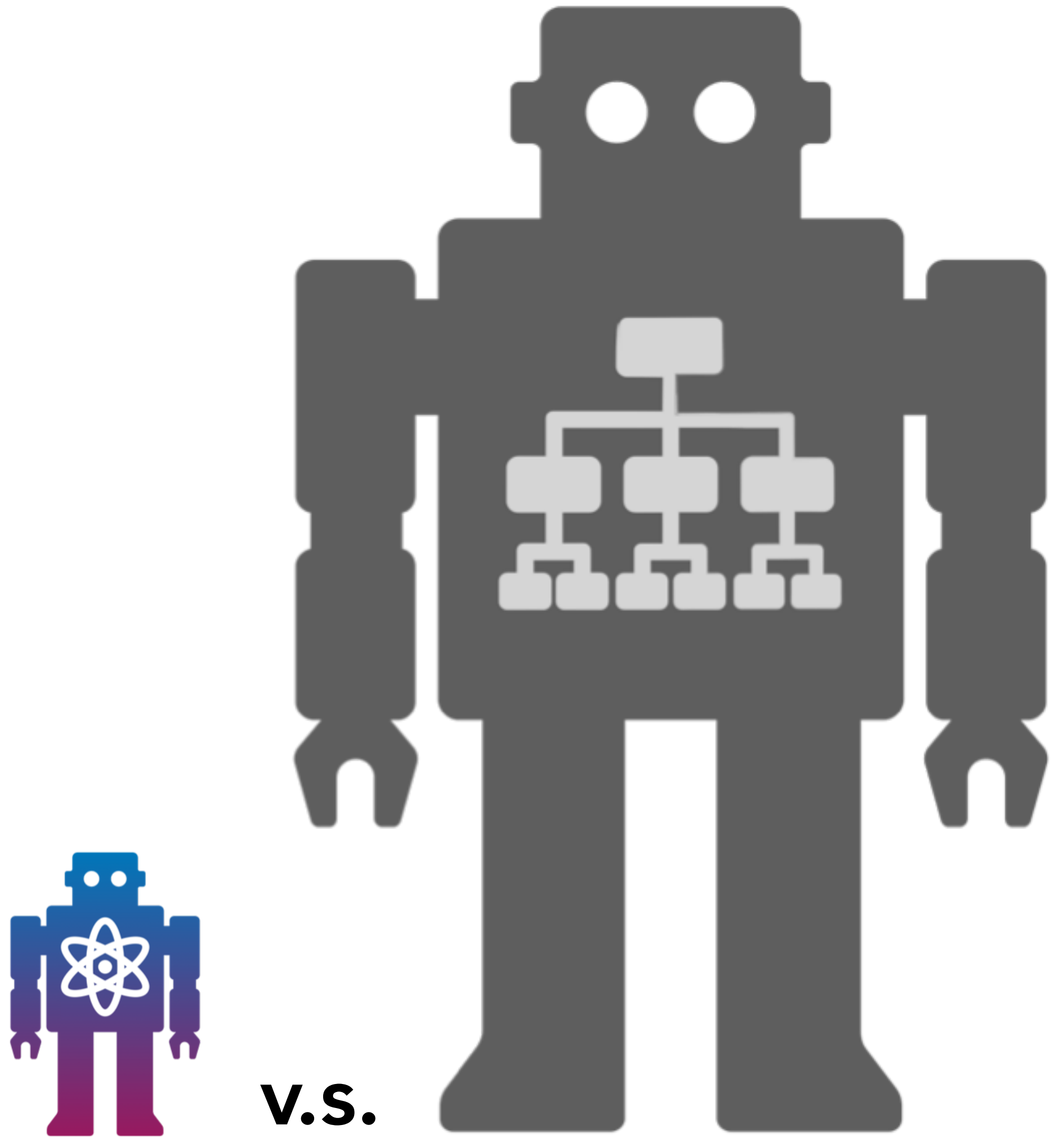
Can QML running on **small** quantum chips **outperform** **exponentially** larger classical machines?

Quantum Advantage for Analyzing Classical Data

User data, internet data, sensor data, financial data, consumer data, market data, …

Classical Data Samples

$z \sim \mathscr{D}$



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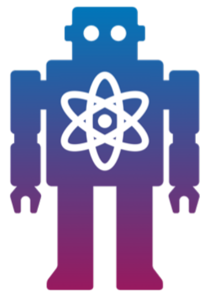

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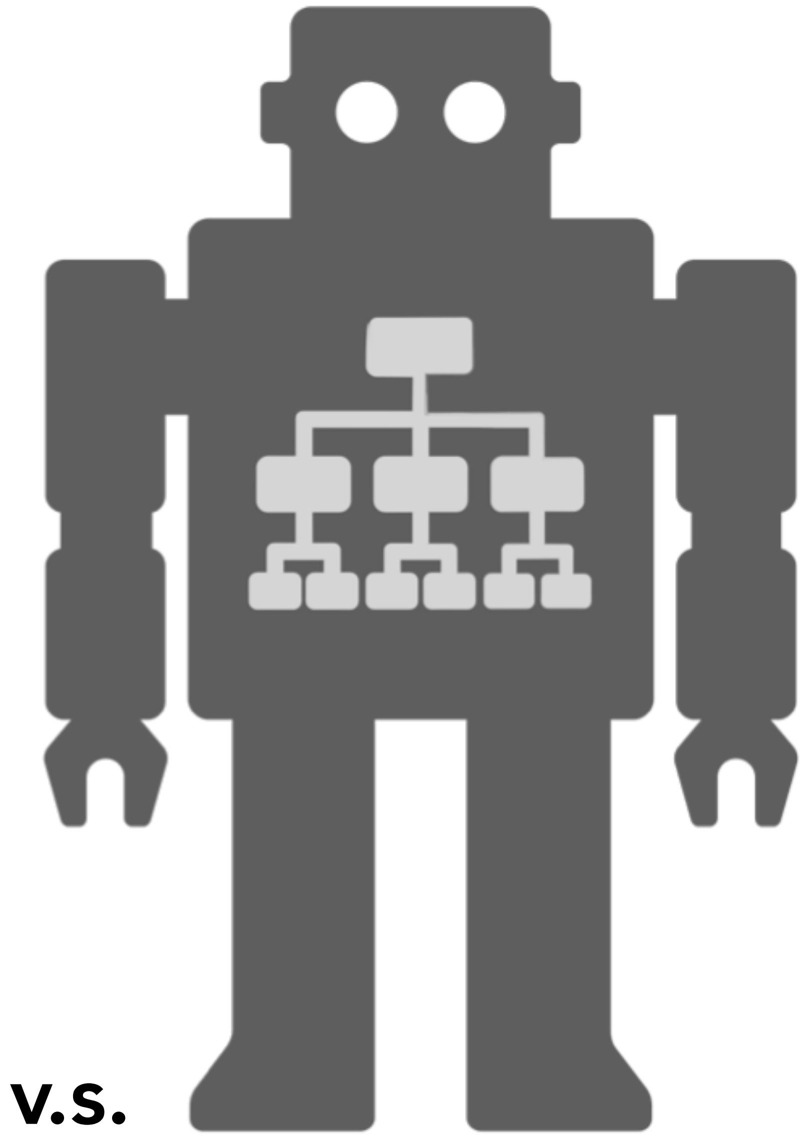

Massive
Classical AI

High-level algorithmic idea:

Quantum Advantage for Analyzing Classical Data

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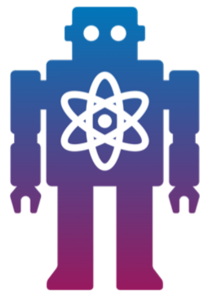
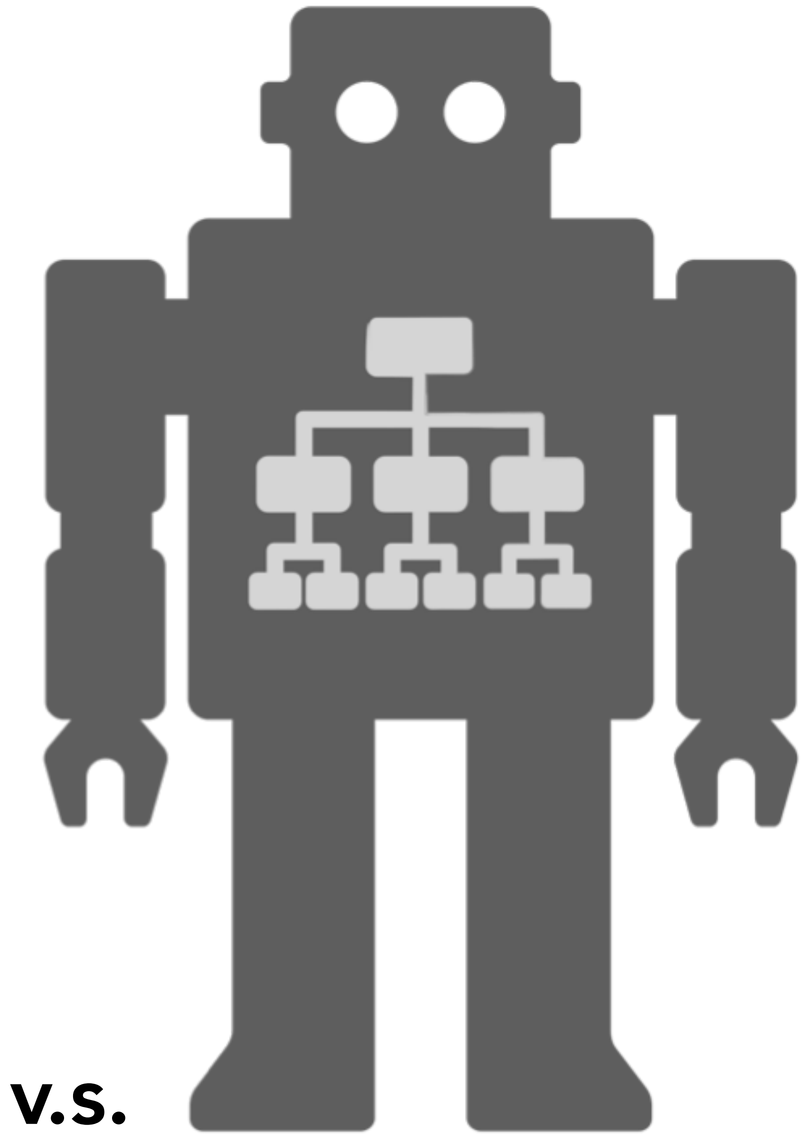


Tiny Quantum AI

v.s.



Massive Classical AI

High-level algorithmic idea:

(1) Get data sample $z \sim \mathscr{D}$

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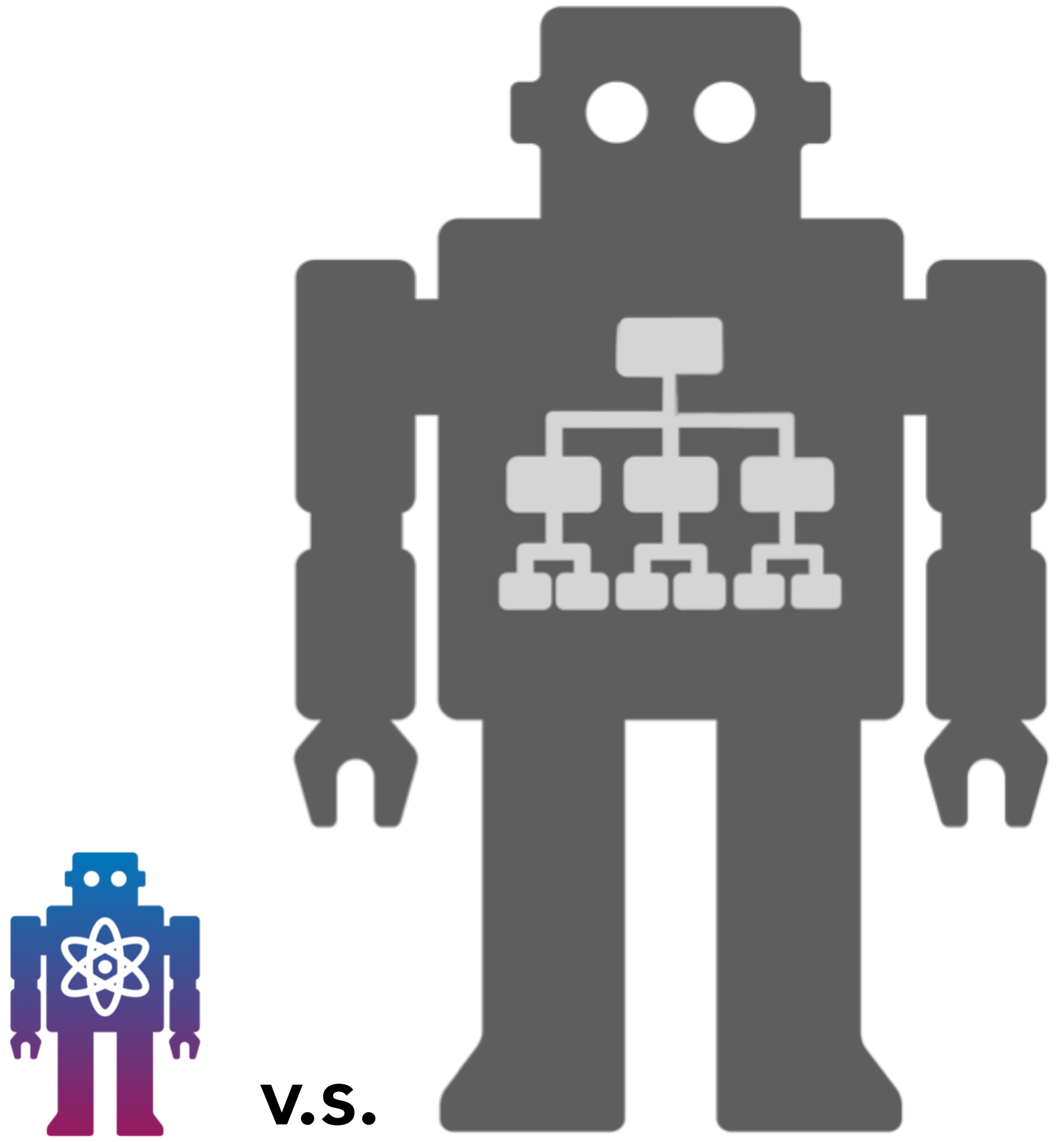

Tiny
Quantum AI

v.s.

Massive
Classical AI

High-level algorithmic idea:

(1) Get data sample $z \sim \mathscr{D}$

(2) Create Hamiltonian term h_z

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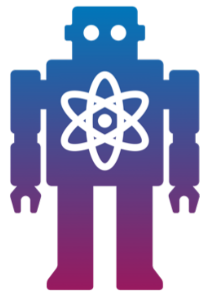

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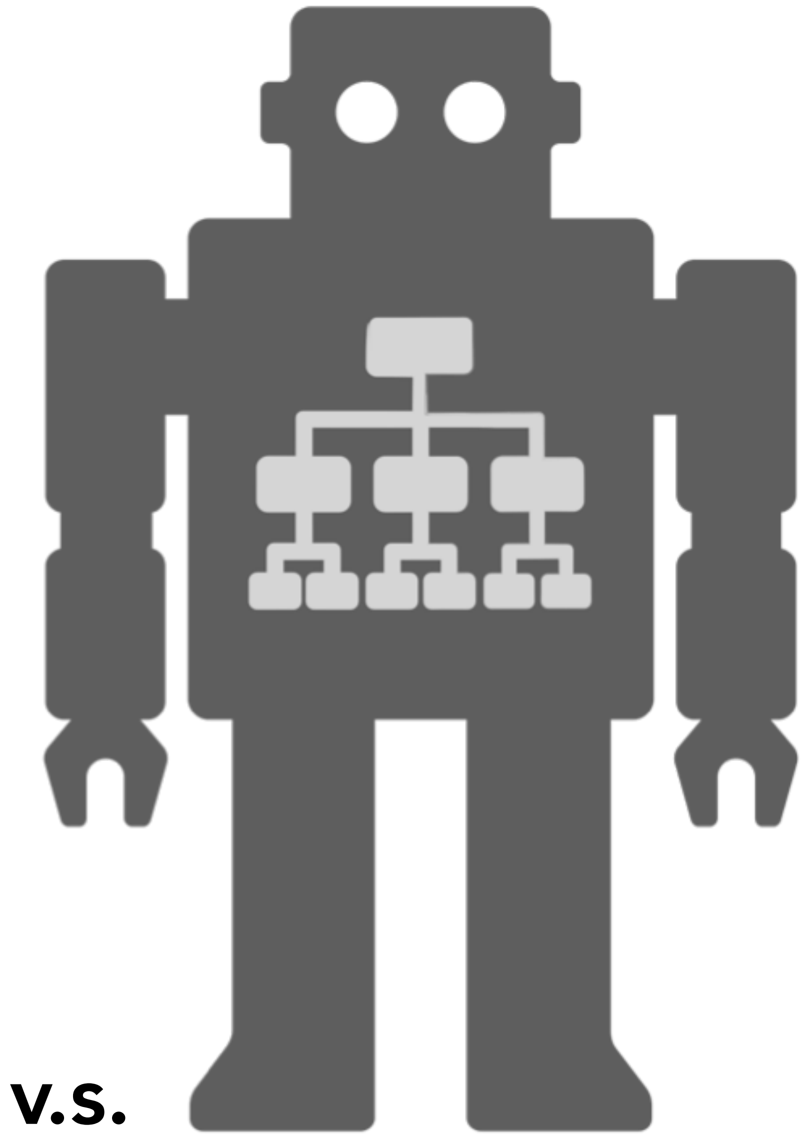


Massive Classical AI

High-level algorithmic idea:

(1) Get data sample $z \sim \mathscr{D}$

(2) Create Hamiltonian term h_z

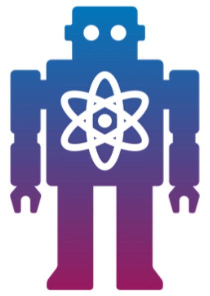
(3) Evolve under $e^{-i\Delta t \cdot h_z}$

Quantum Advantage for Analyzing Classical Data

User data, internet data, sensor data, financial data, consumer data, market data, …

Classical Data Samples

$z \sim \mathscr{D}$



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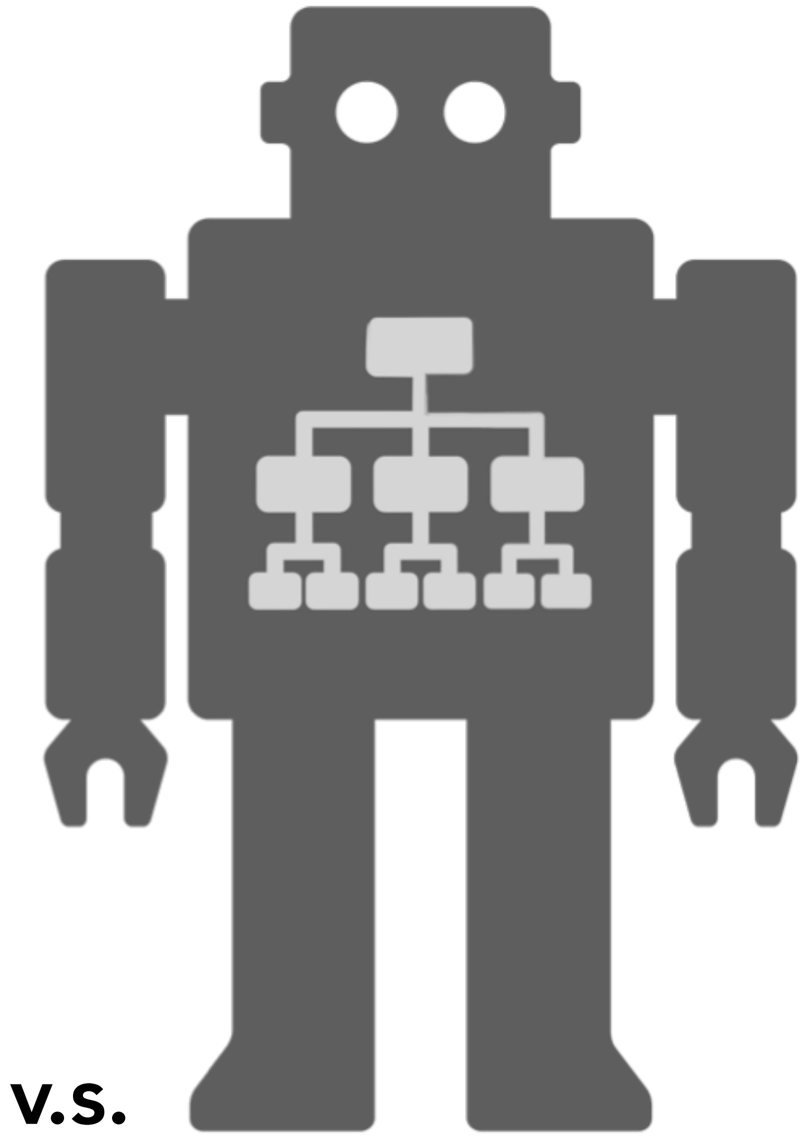

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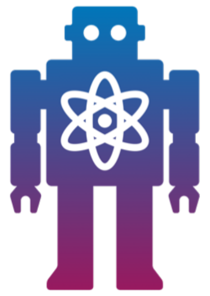

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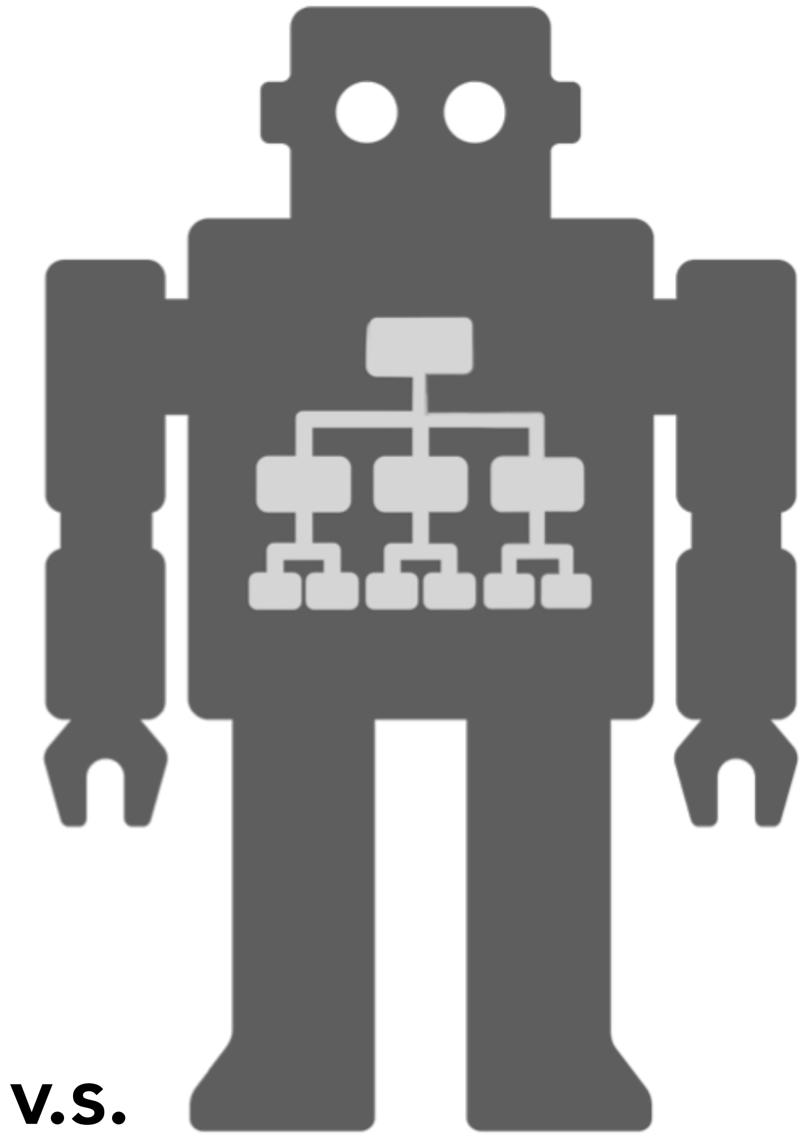

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High-level algorithmic idea:

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(2) Create Hamiltonian term h_z

(3) Evolve under $e^{-i\Delta t \cdot h_z}$

(4) Repeat

After seeing some samples, the random unitary converges to $e^{-it \cdot \mathbb{E}_{z \sim \mathscr{D}}[h_z]}$ for a tunable t.

Quantum Advantage for Analyzing Classical Data

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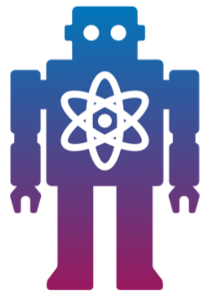

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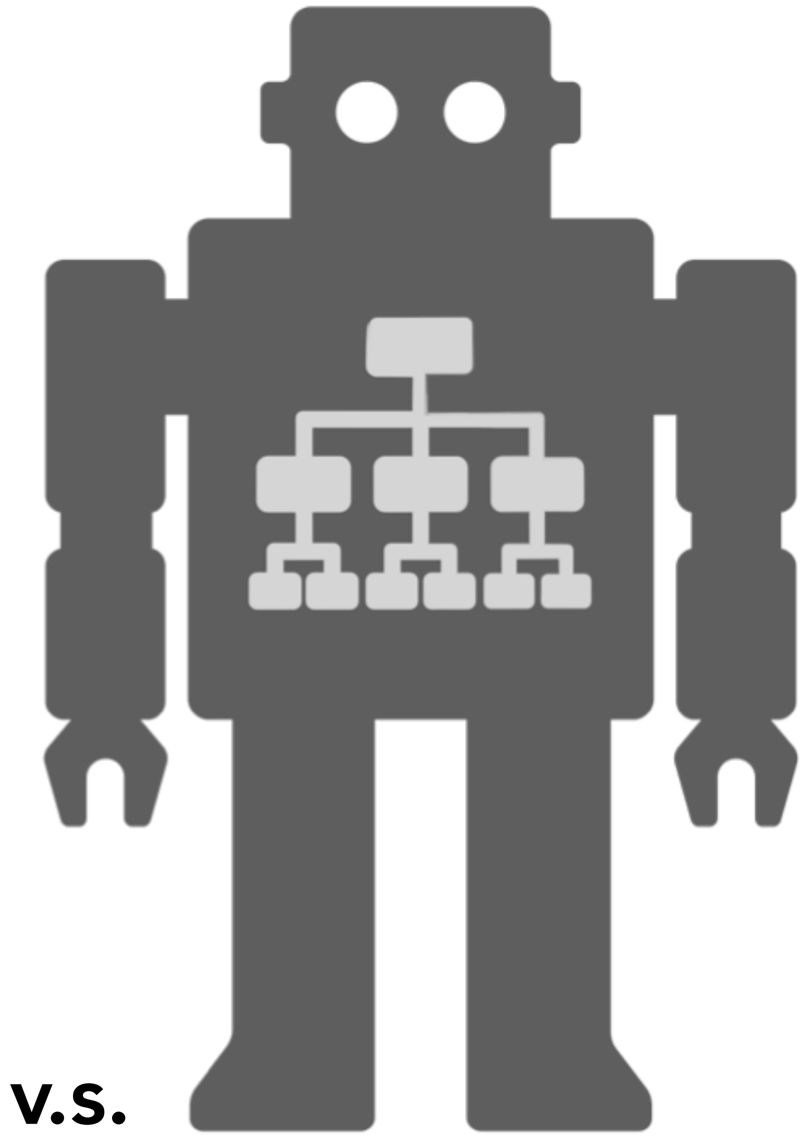

Massive Classical AI

Central Idea:

Replace **QRAM** with a **quantum oracle** sketched from classical data samples.

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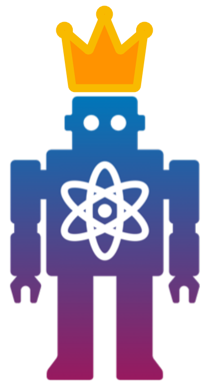

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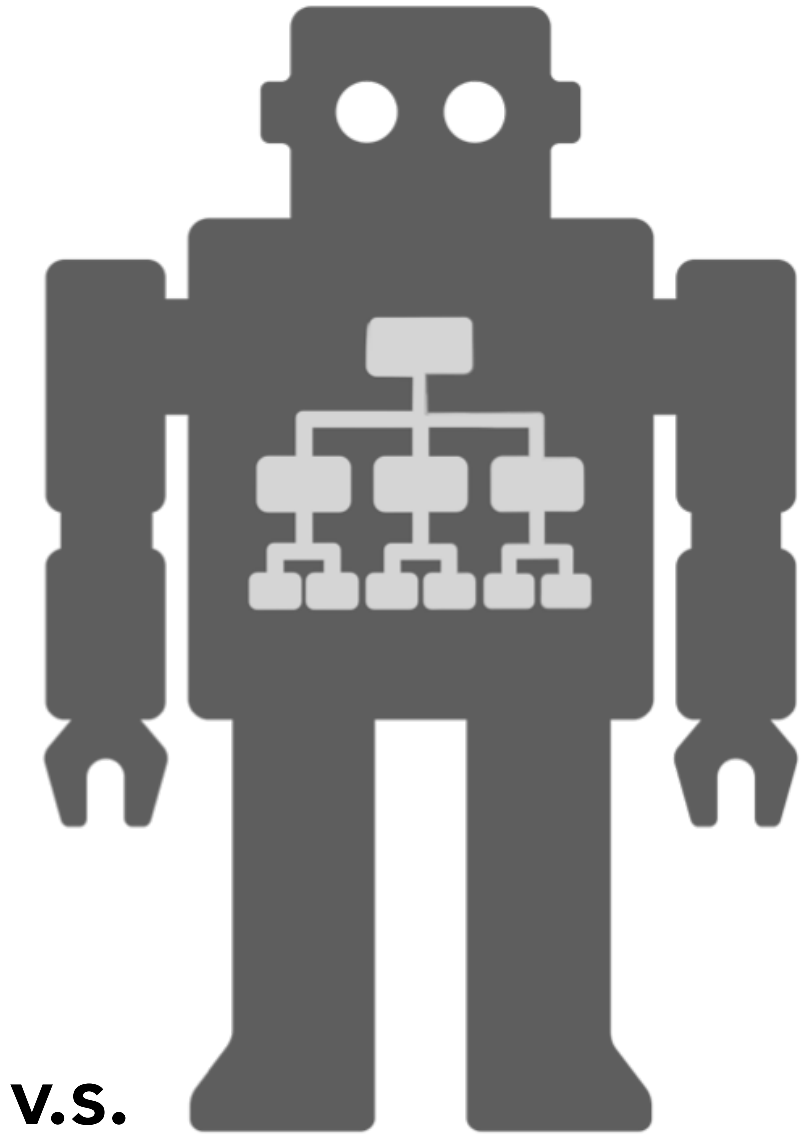


Massive Classical AI

Claim:

With $\mathcal{O}(N)$ samples, $\mathrm{poly}(\log N)$**-qubit machine** can solve SVM, PCA, … **better** than any **classical machines** with $\mathcal{O}(N^{0.99})$ **bits.**

Where do we go from here?

- **AI for Quantum Technology:**

  How to **accelerate/automate** quantum technology with AI?

- **Quantum Advantage for Classical AI:**

  Can quantum machines achieve **significant advantage** in learning problems arising from **classical ML/AI**?

Where do we go from here?

✤ **Physics of Learning:**

What are the **fundamental limit** in **space**, **time**, and **energy** governing **any** physical system that can learn?

Where do we go from here?

- **Physics of Learning:**

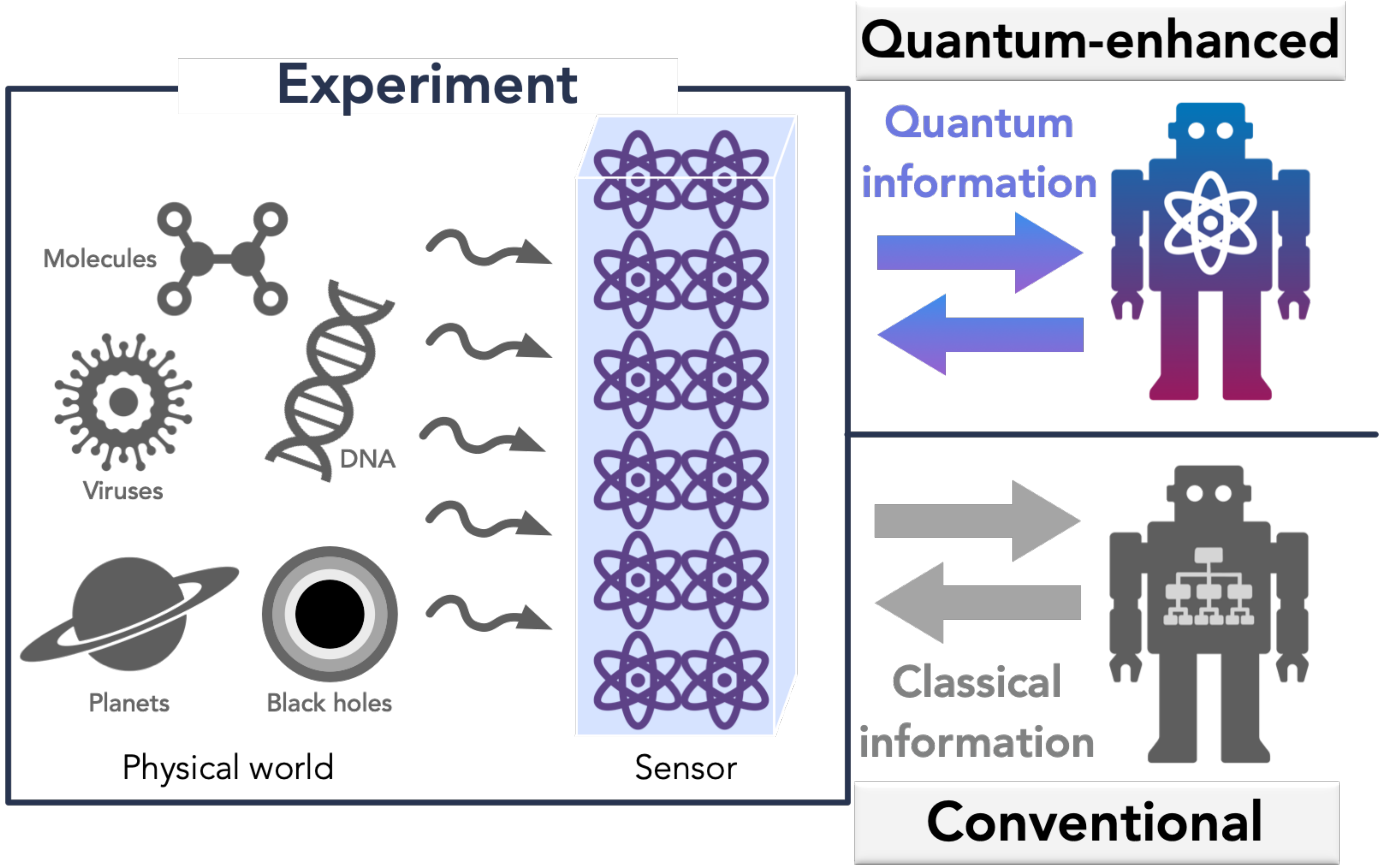
  What are the fundamental limit in space, time, and energy governing **any** physical system that can learn?

- **Quantum AI Discovery:**

  How can quantum machines learn to discover new physics?

Sensing Classical Fields

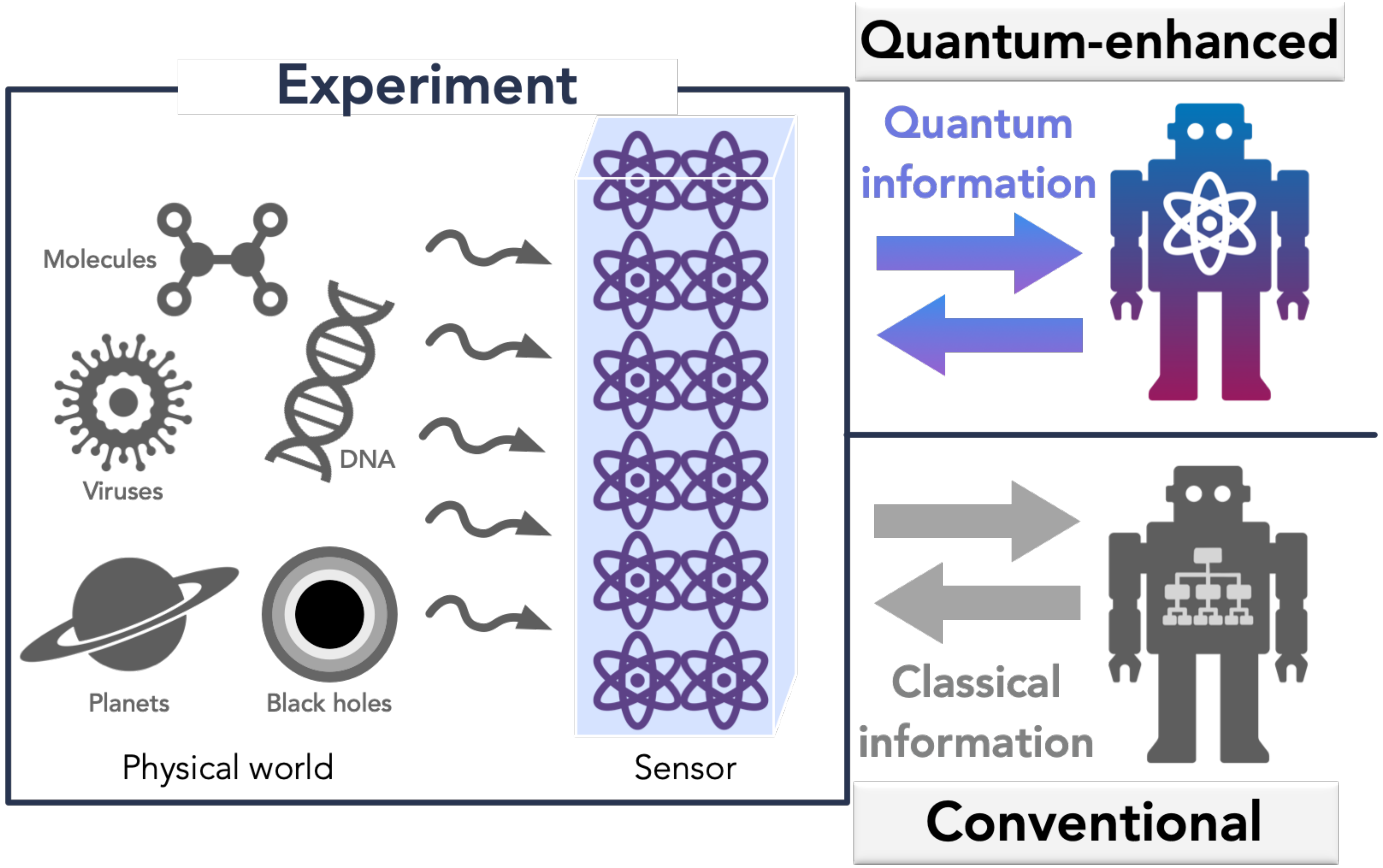
- **Sensing classical fields** has wide-ranging applications.



Sensing Classical Fields

- **Sensing classical fields** has wide-ranging applications.
- **Applications:**

  Probing material properties,



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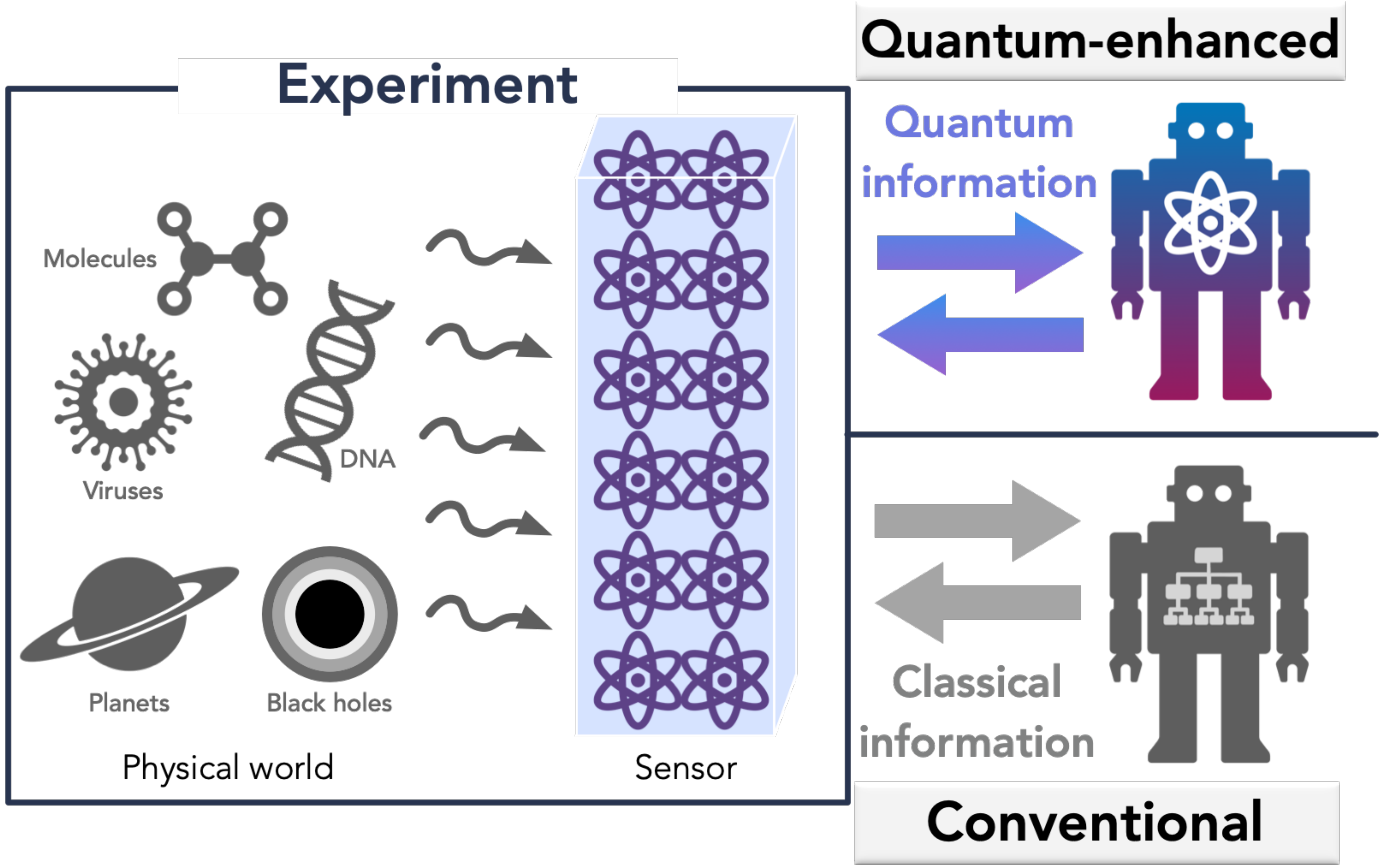

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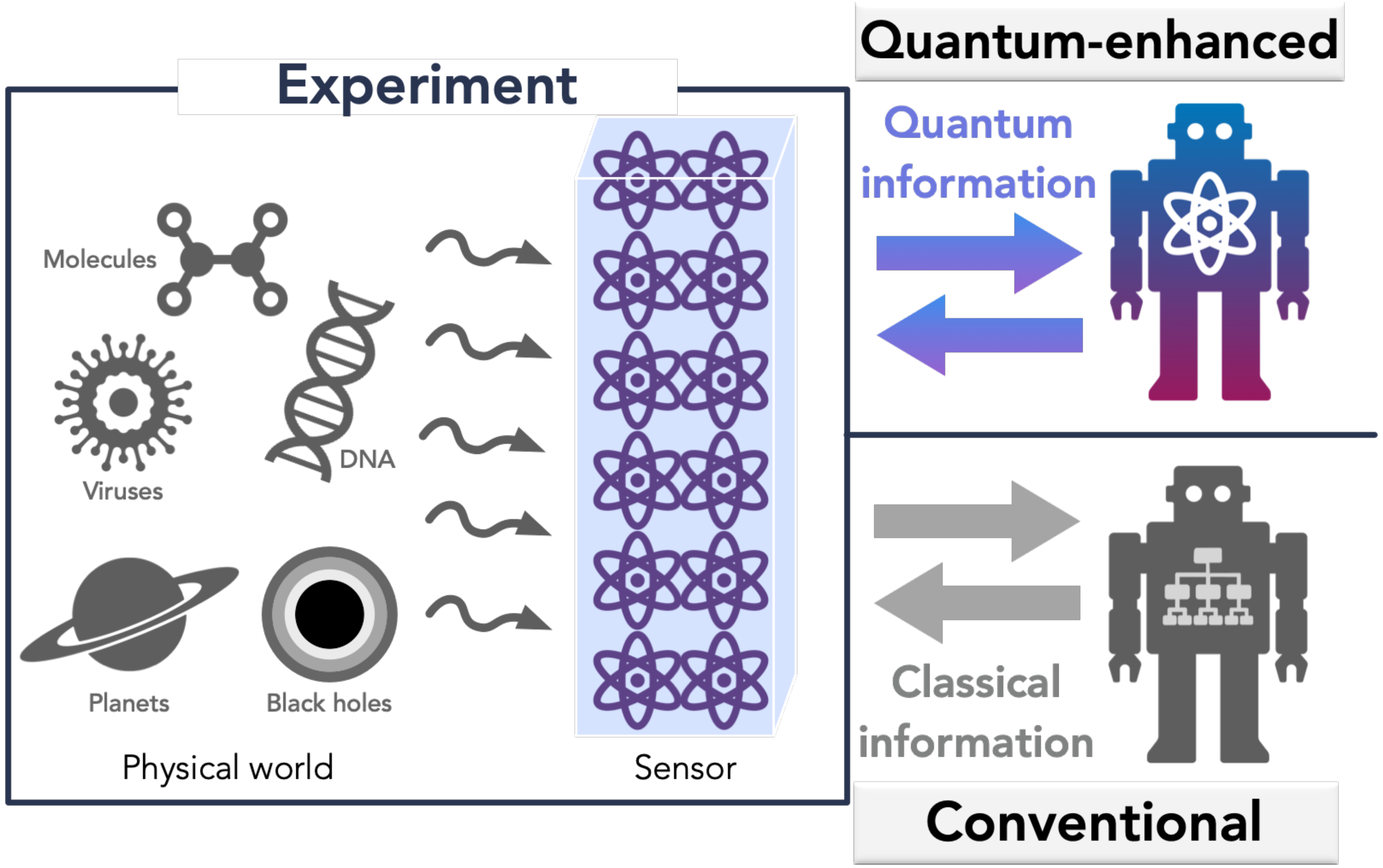

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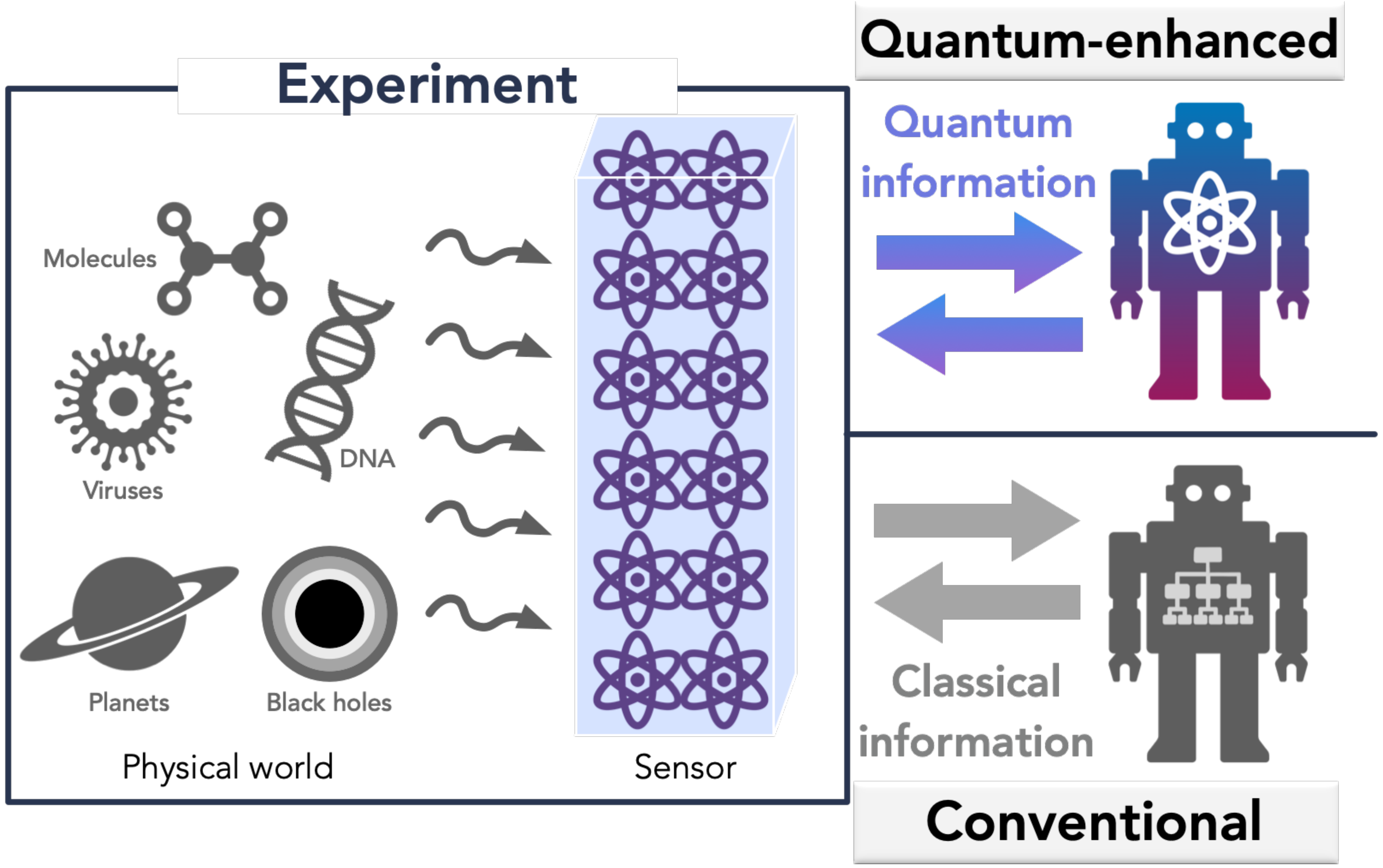
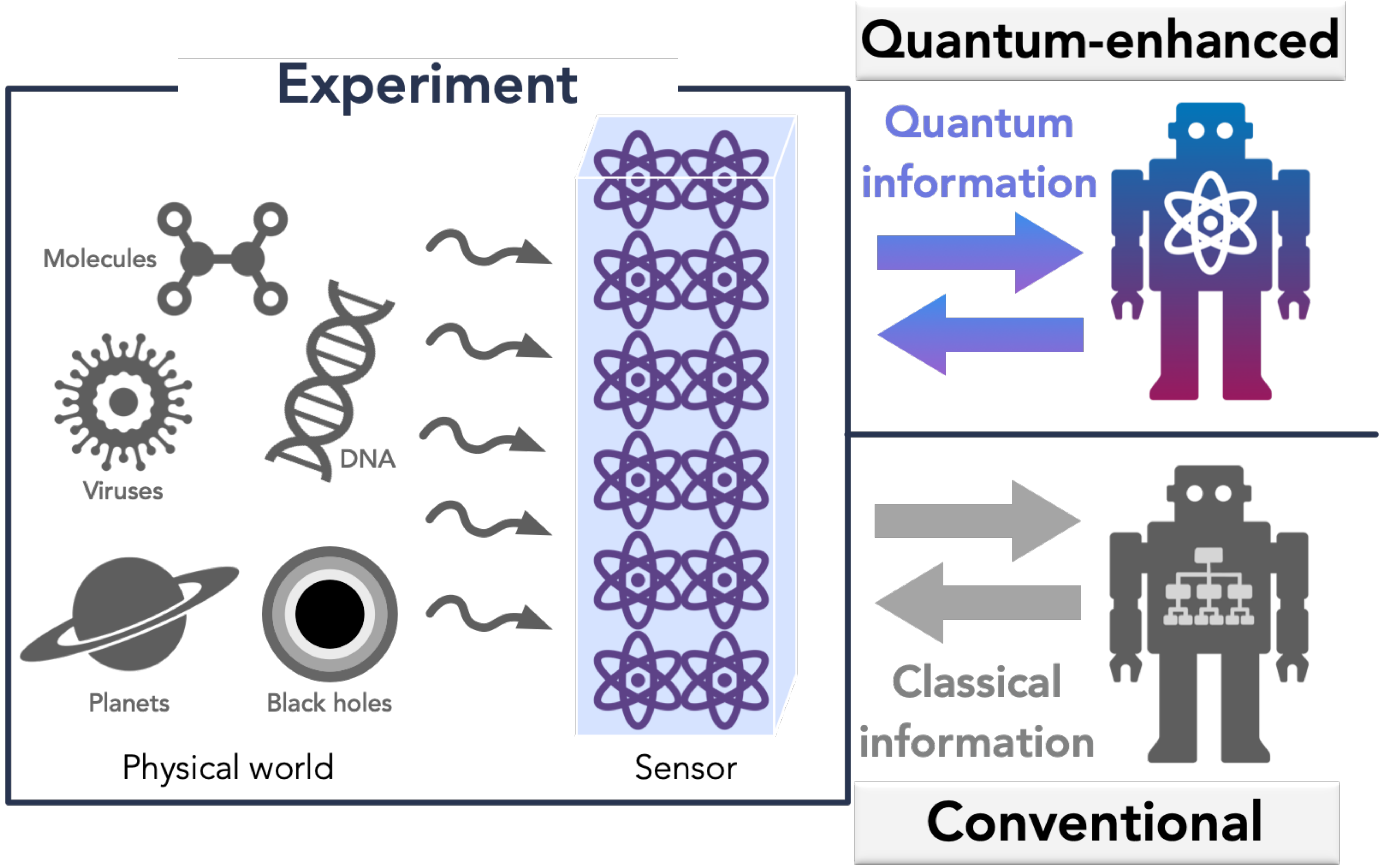
  Detecting **dark matter**, …



Sensing Classical Fields

- **Simplest task (from Lec. 1):**

$$B(t) = B \text{ vs } B(t) = 0$$



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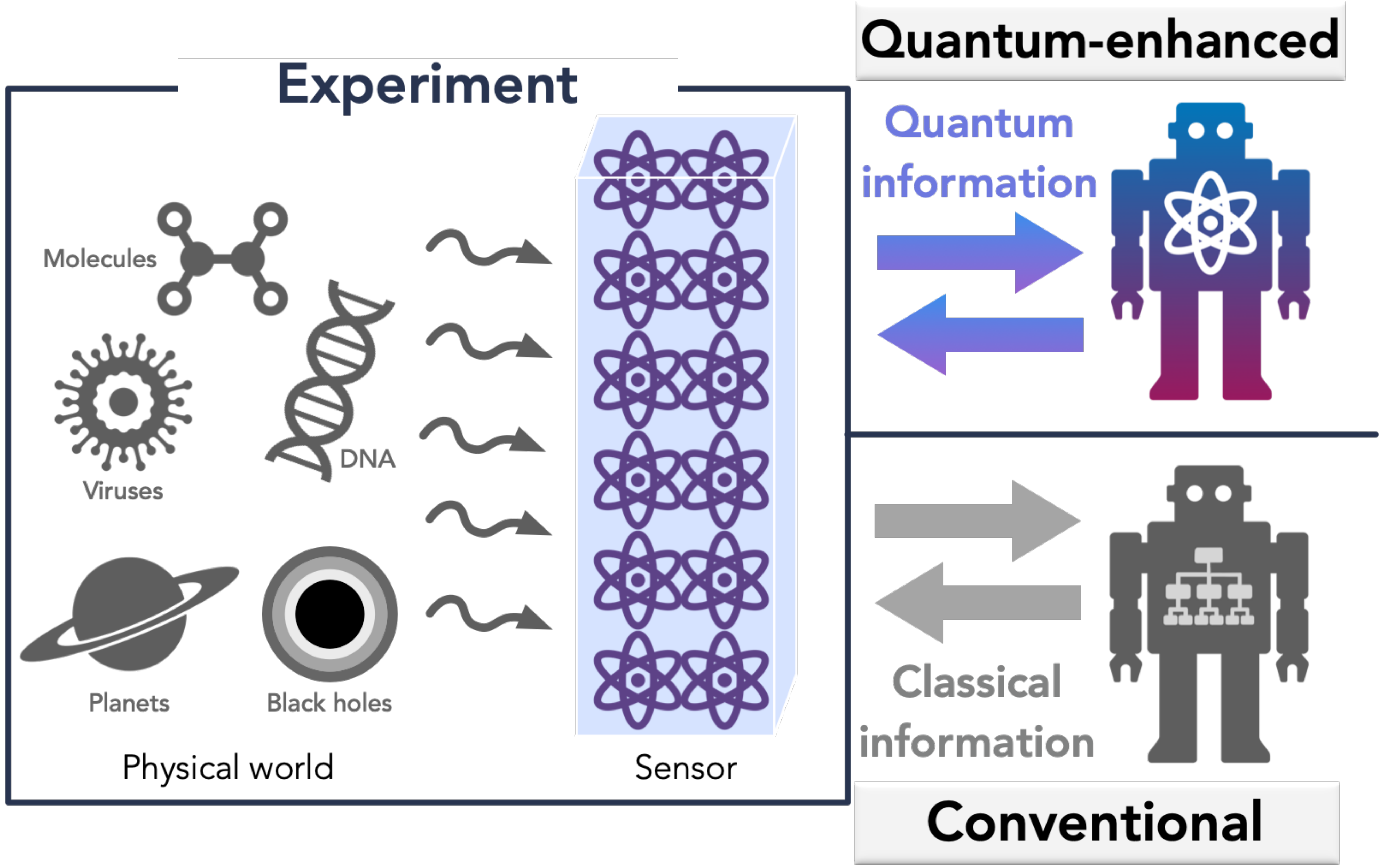

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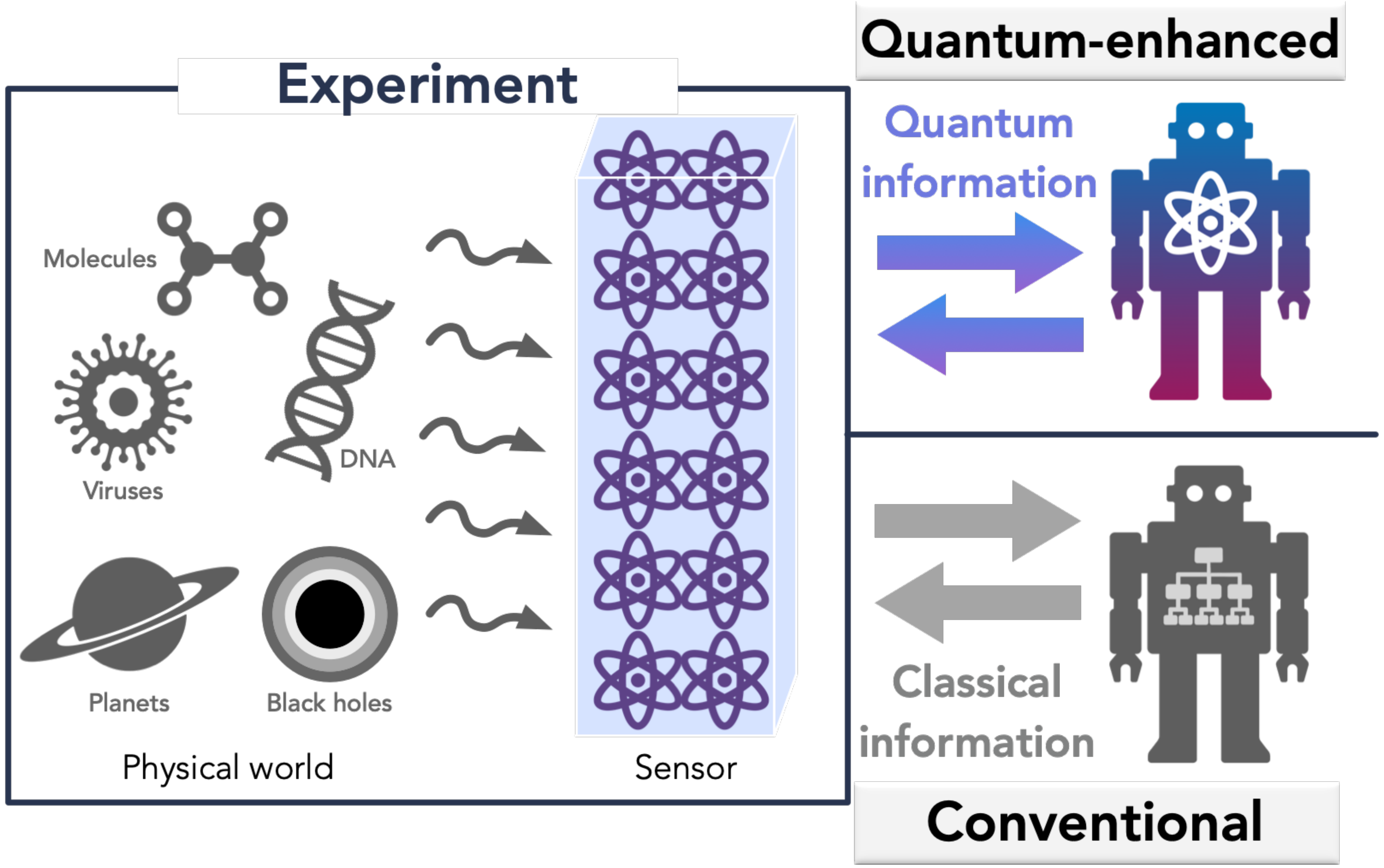

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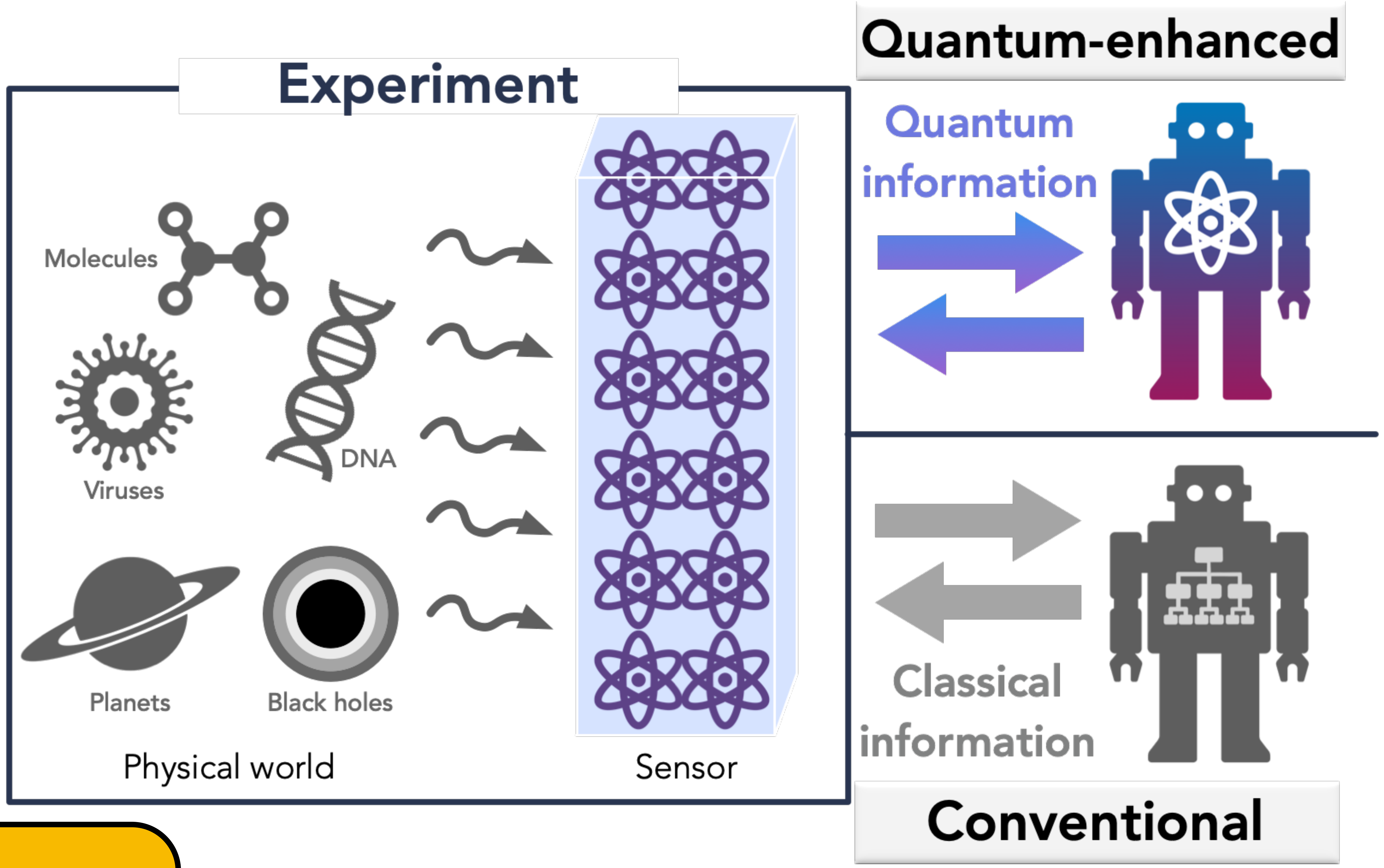
This optimality has spawn the field of **quantum sensing**



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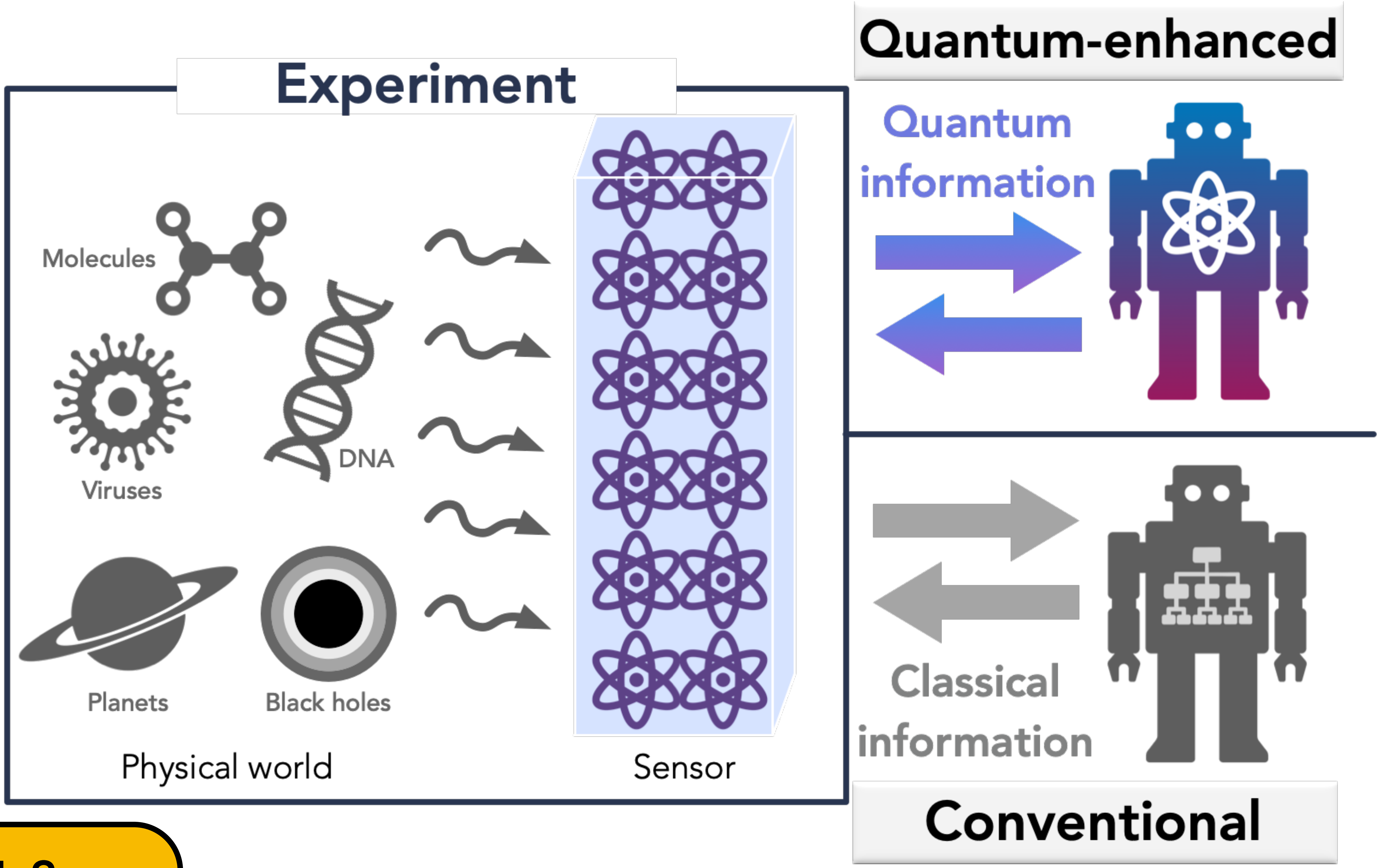
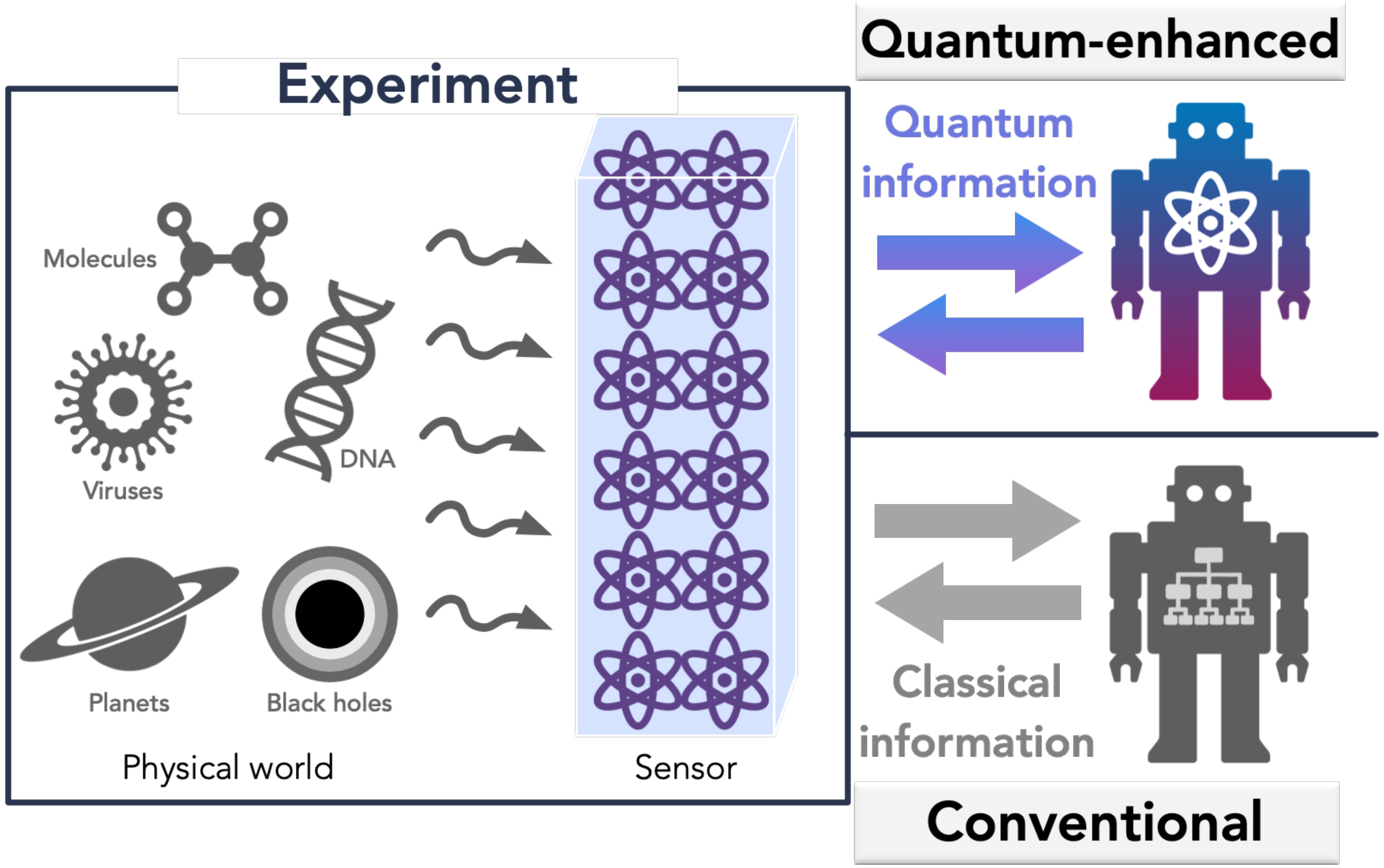
But **no need** for quantum AI & the speedup is just quadratic.



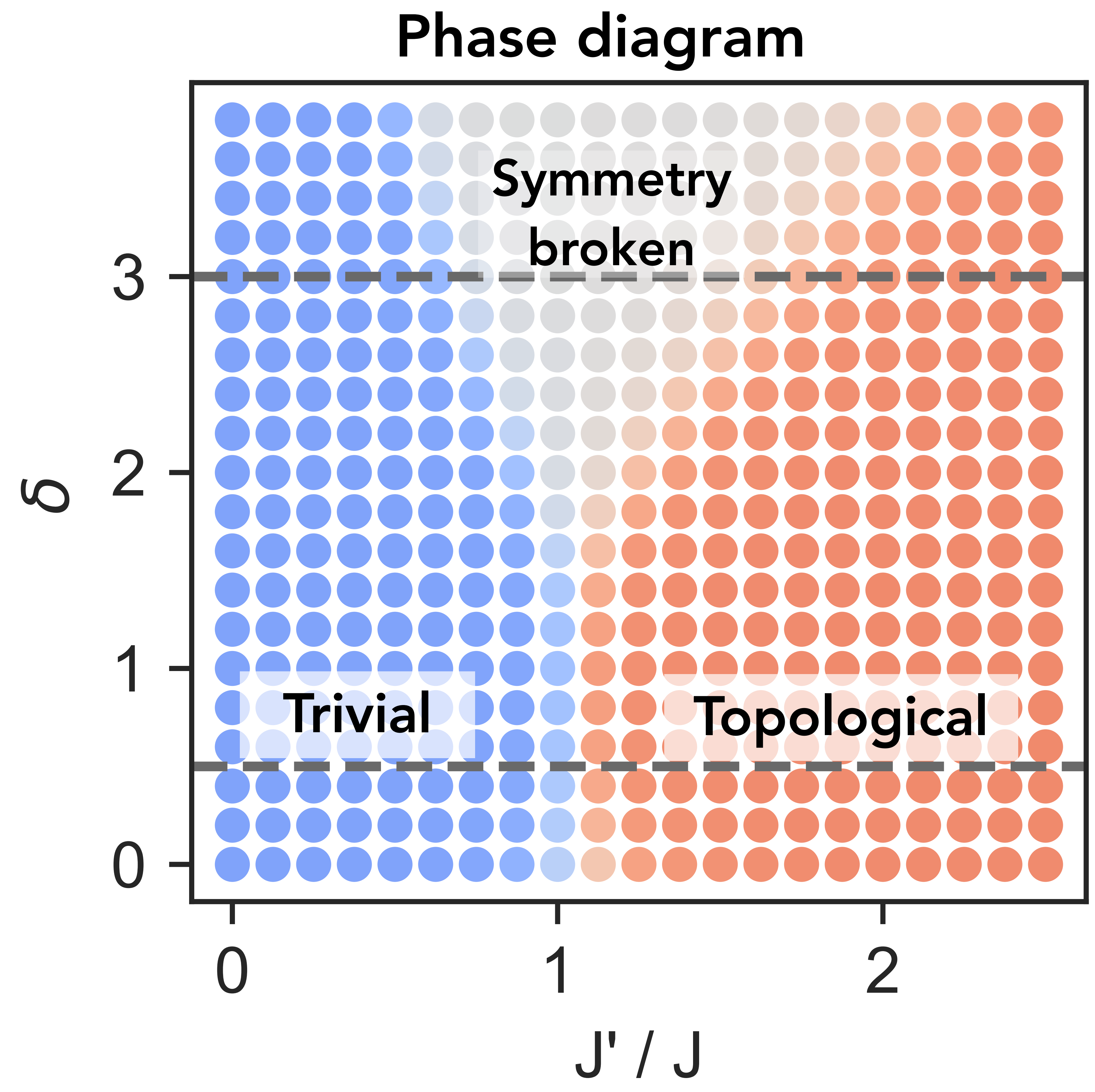
Sensing Classical Fields

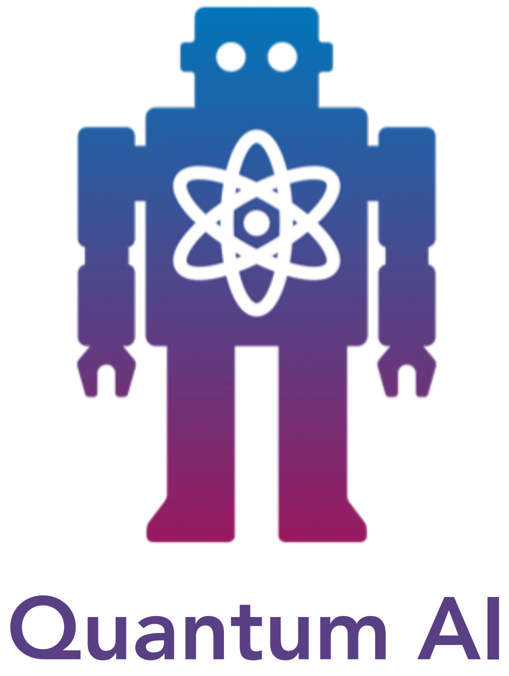
Question:

Can quantum AI offer superpolynomial quantum advantage in sensing classical fields?



Discovering New Phases of Matter





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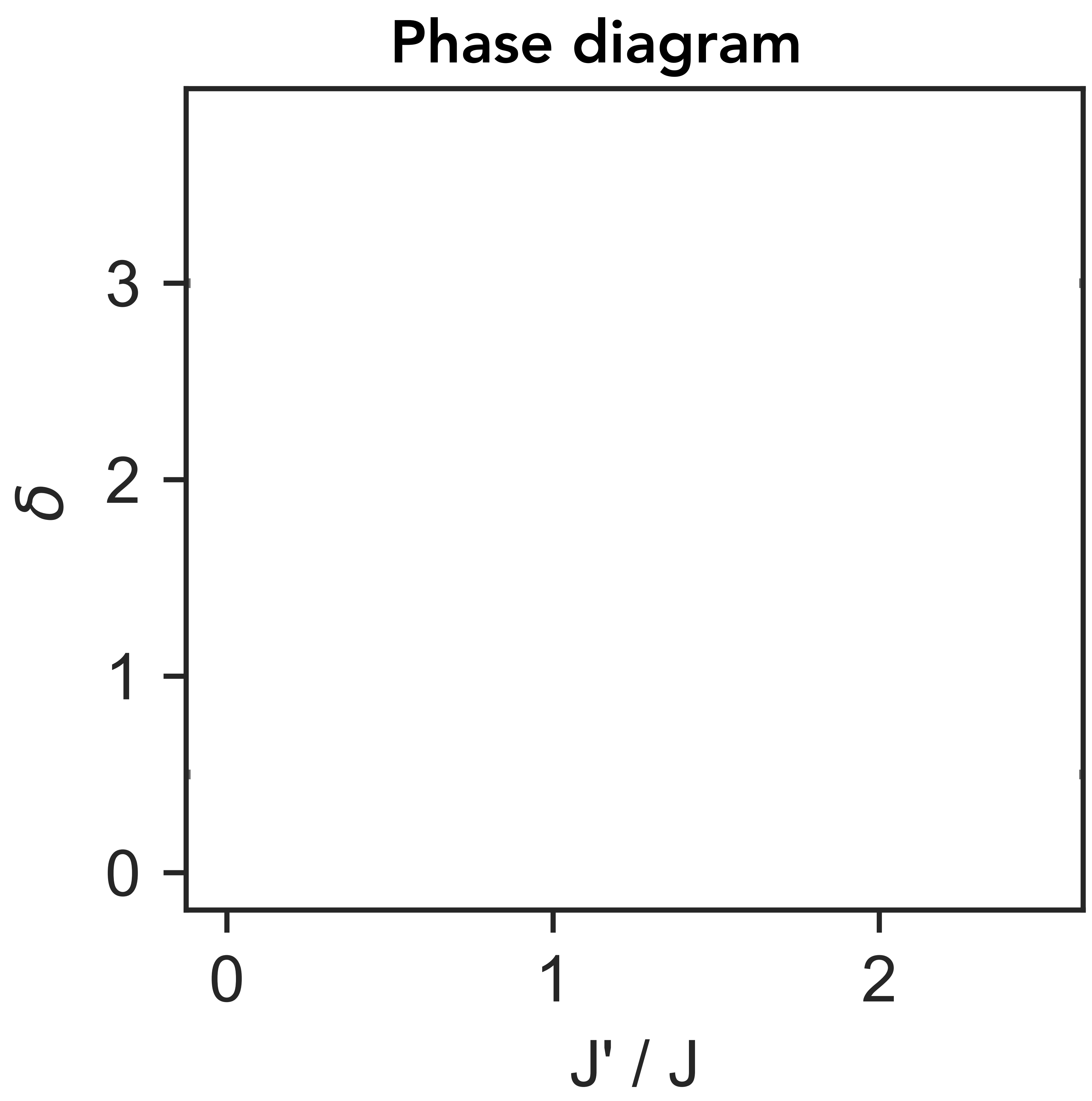
How can quantum AI discover phases of matter on its own?

Discovering New Phases of Matter



Quantum AI

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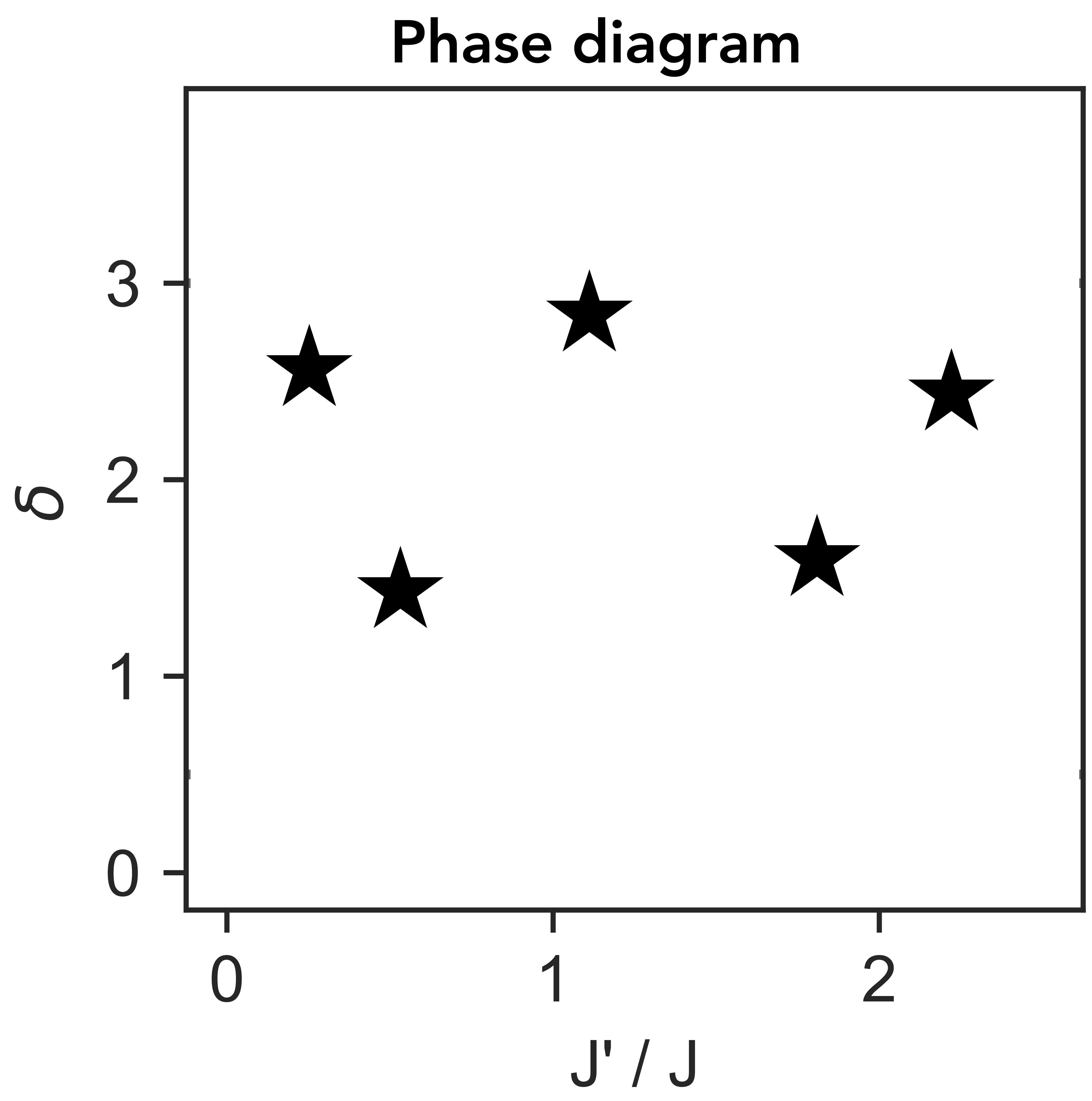
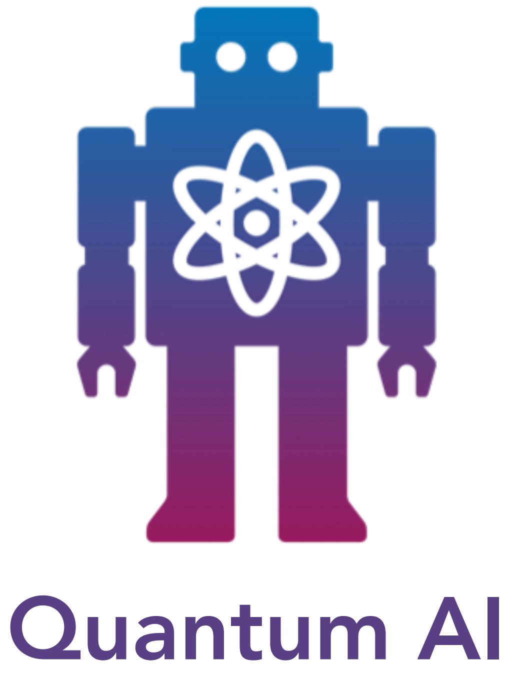


★ : ground states we found on QC



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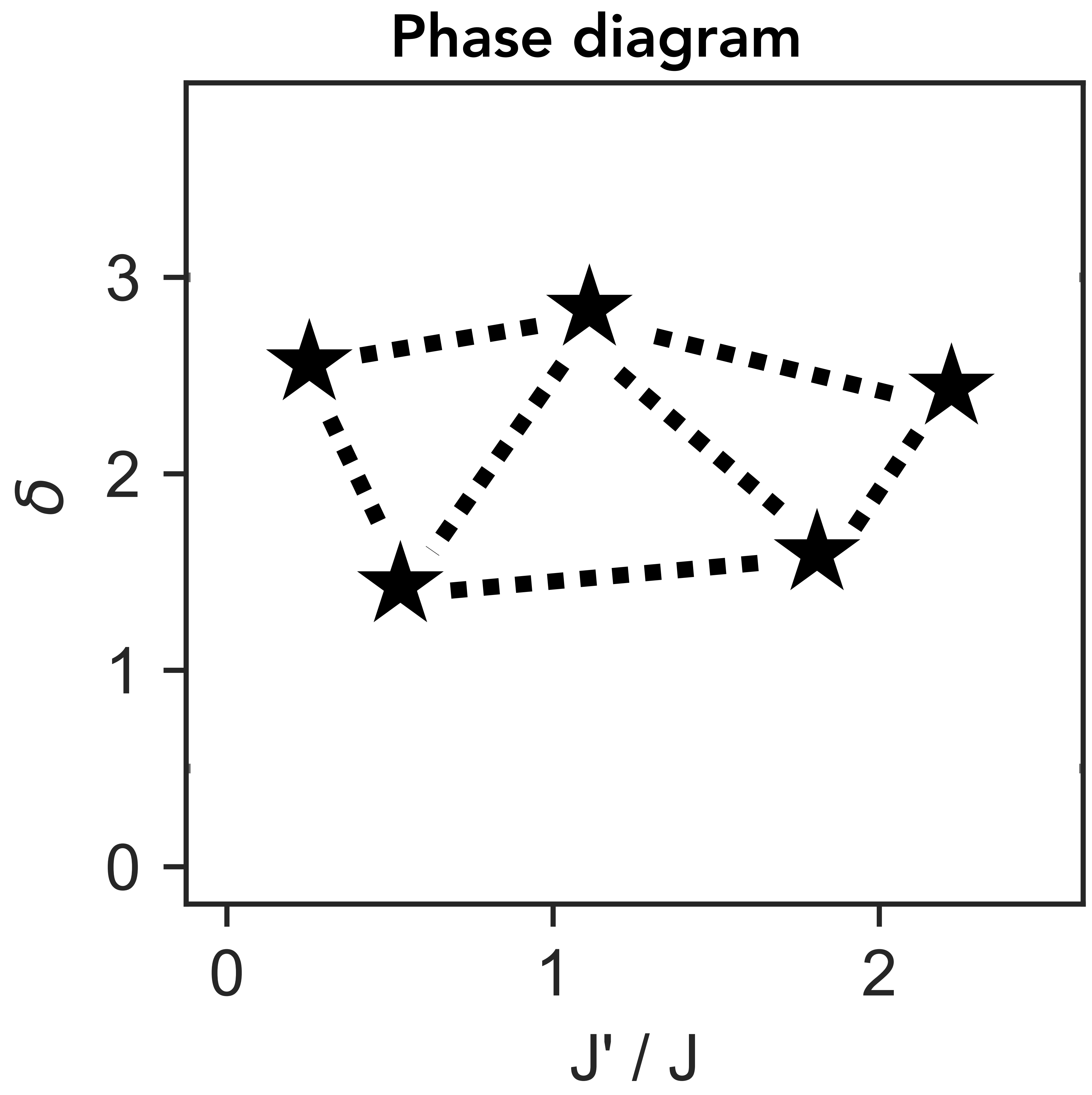

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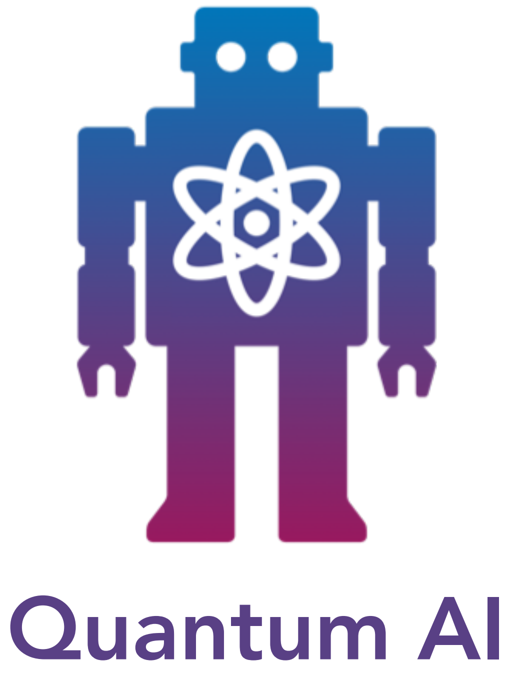

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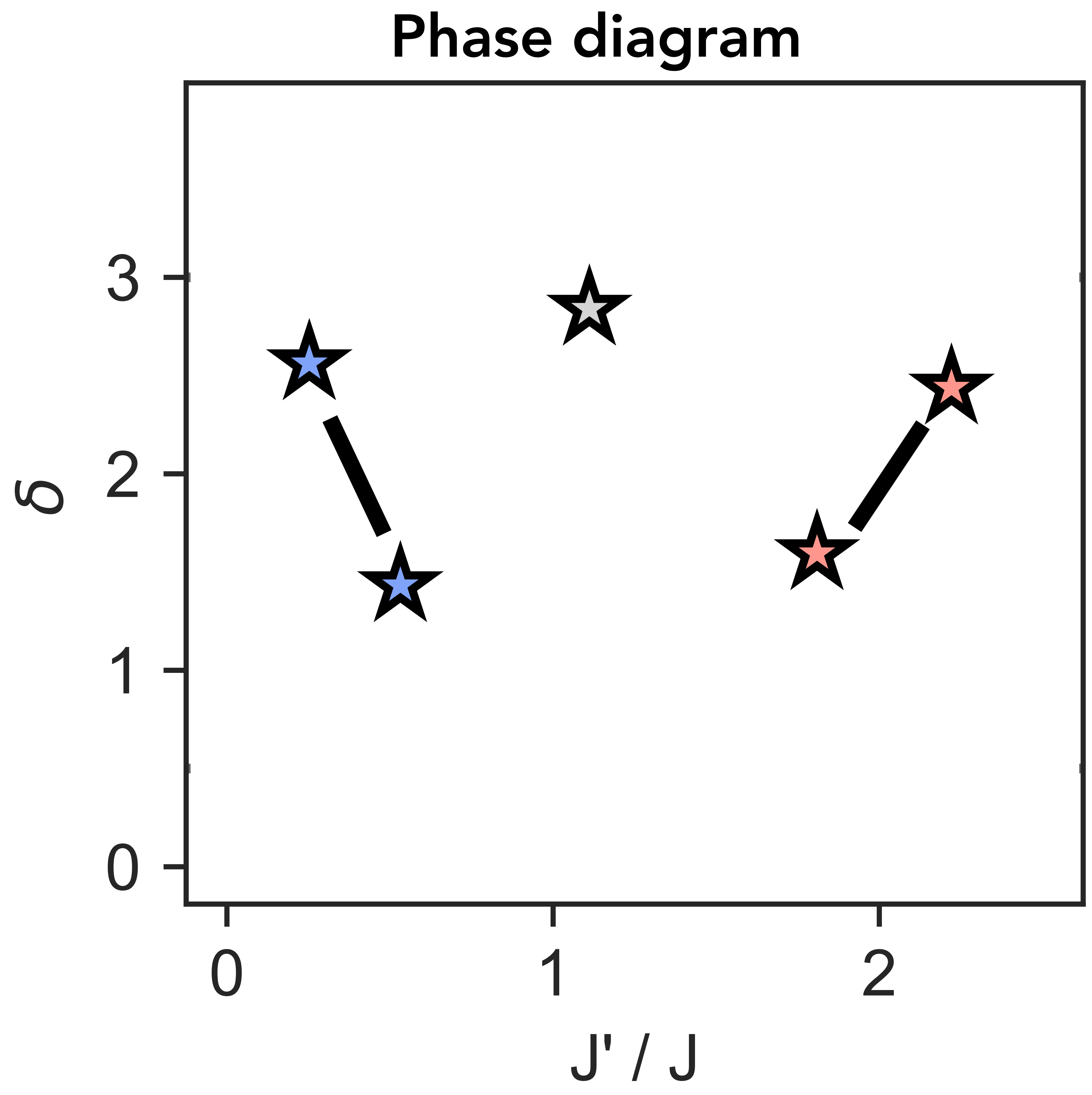
Can quantum AI tell if **two states** are in the same phase or not?

Discovering New Phases of Matter



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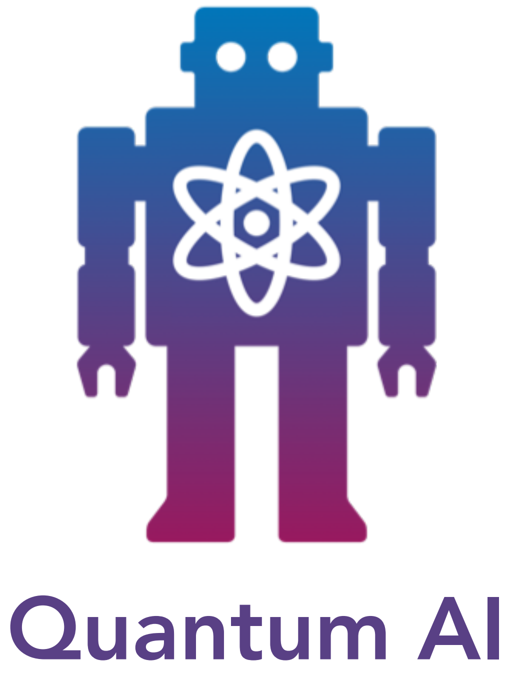

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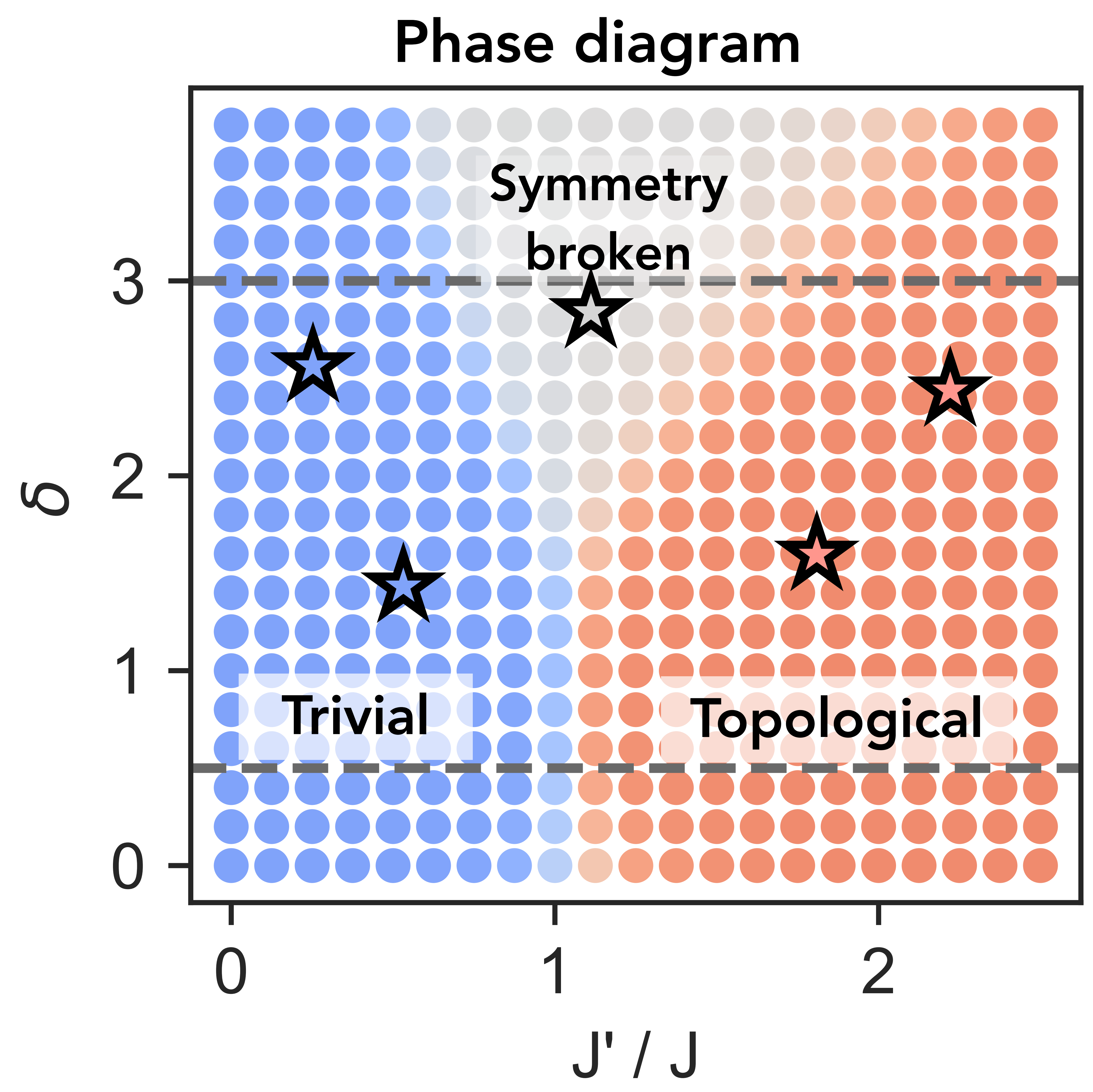

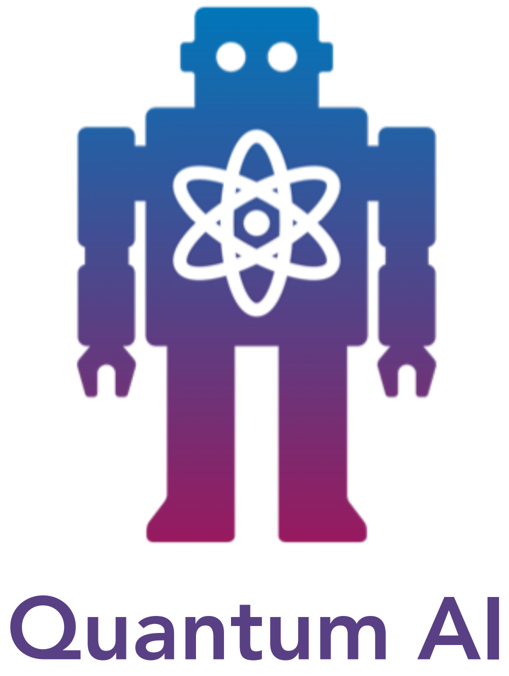

If yes, quantum AI can **discover new phases** by mapping out the entire phase diagram.

Long-term ambitions

1. Develop our understanding of learning to accelerate/automate science.
2. Build a **quantum machine** capable of learning and discovering new facets of our universe beyond humans and classical machines.



AI imagination of itself learning and discovering new facets of our quantum universe