Quantum Software Consortium

Universiteit Leiden

From Quantum Machine Learning to Quantum AI

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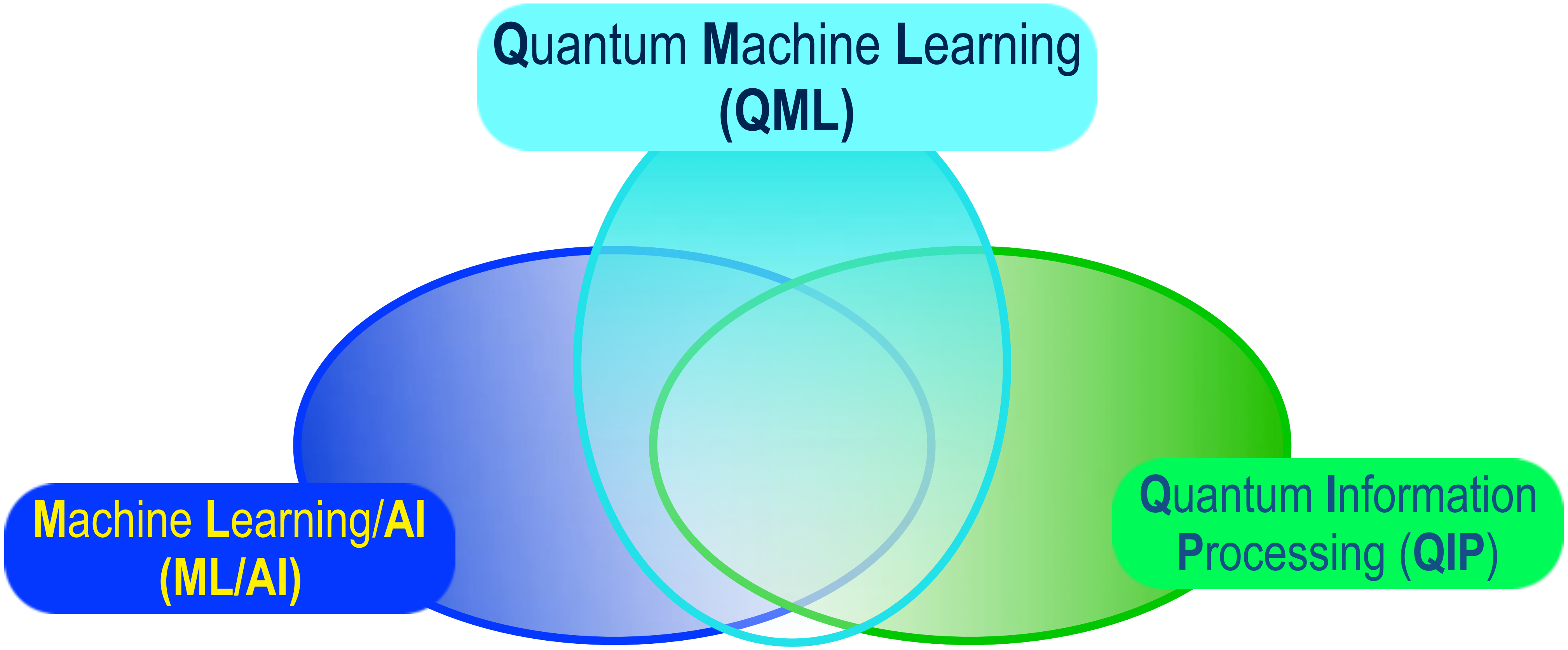
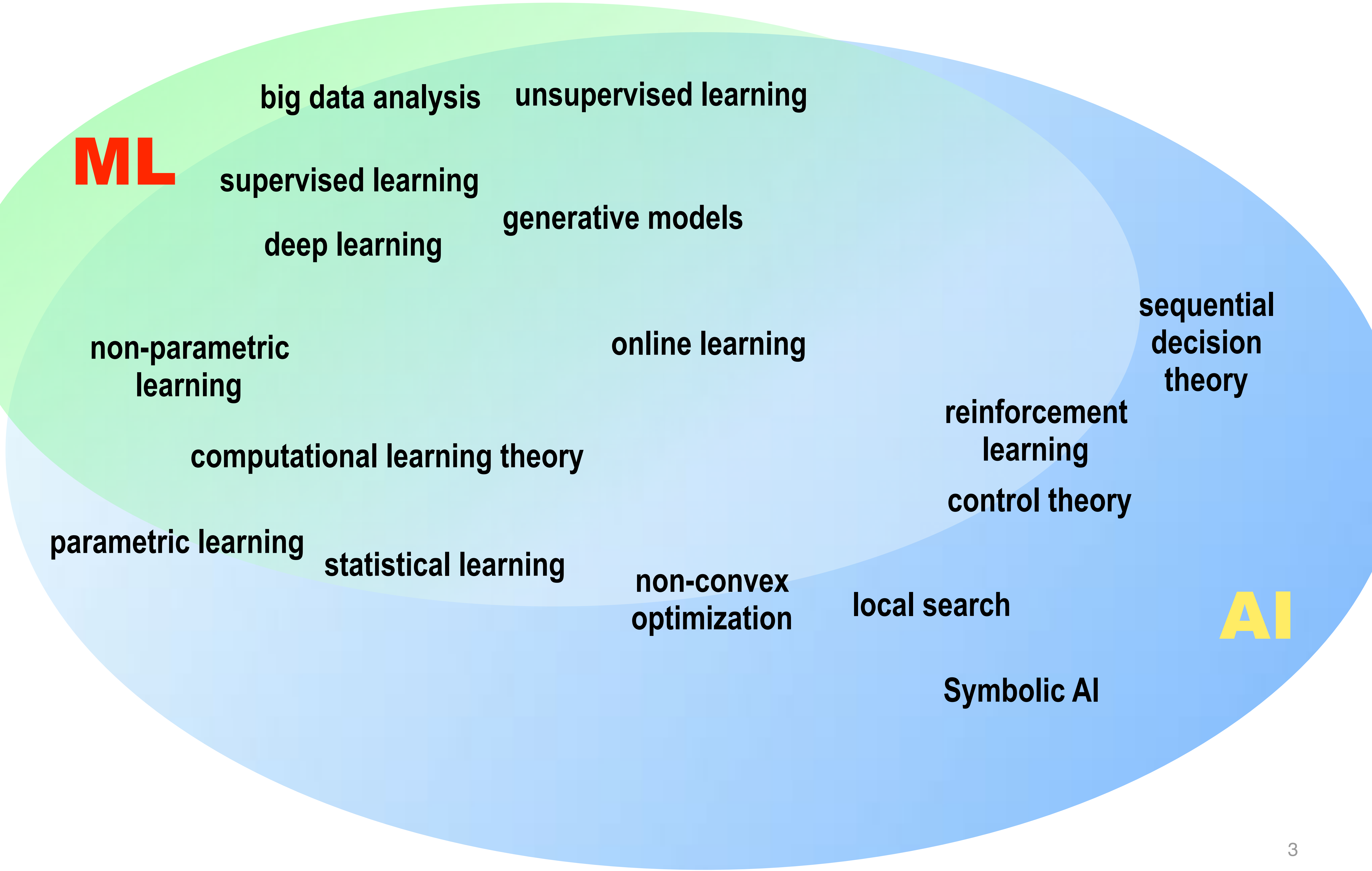


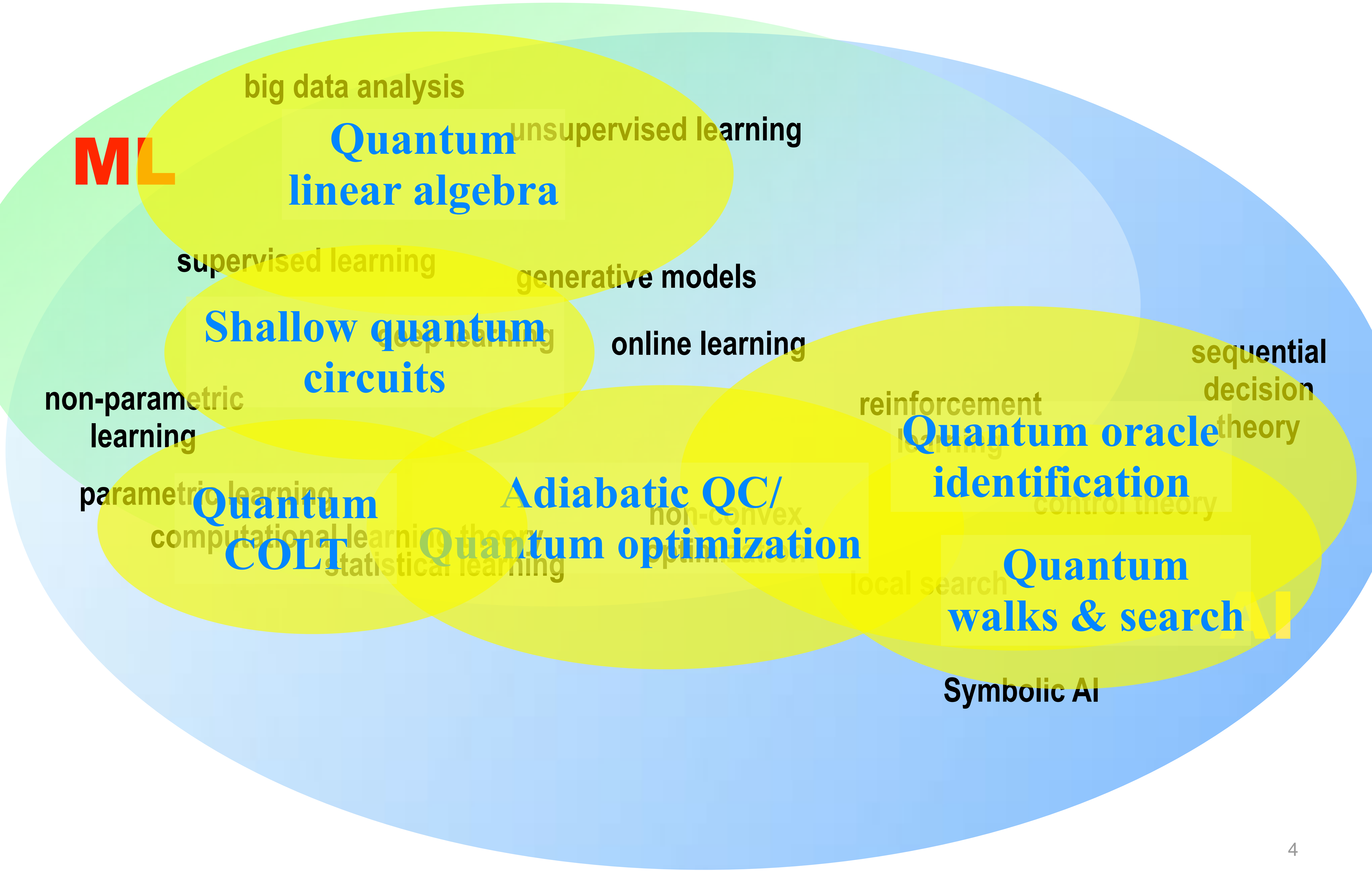
- **ML→QIP** (quantum-applied ML) ['74]
- **QIP→ML** (quantum-enhanced ML) [‘94]

- **QIP↭ML** (quantum-generalized learning) [‘00]
  - ML-insipred QM/QIP
  - Physics inspired ML/AI

Machine learning is not one thing.
AI is not even a few things.



QeML is even more things



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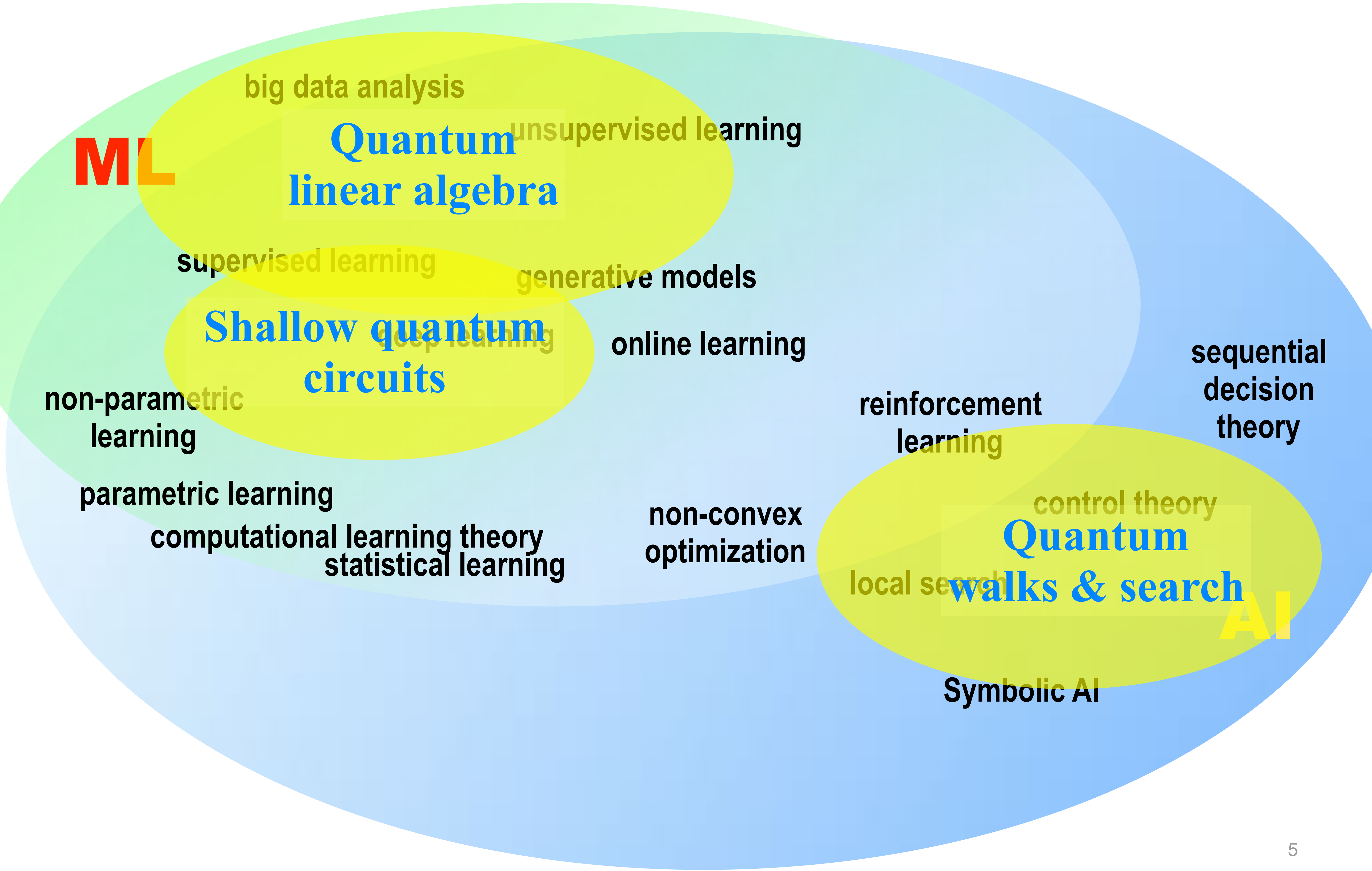
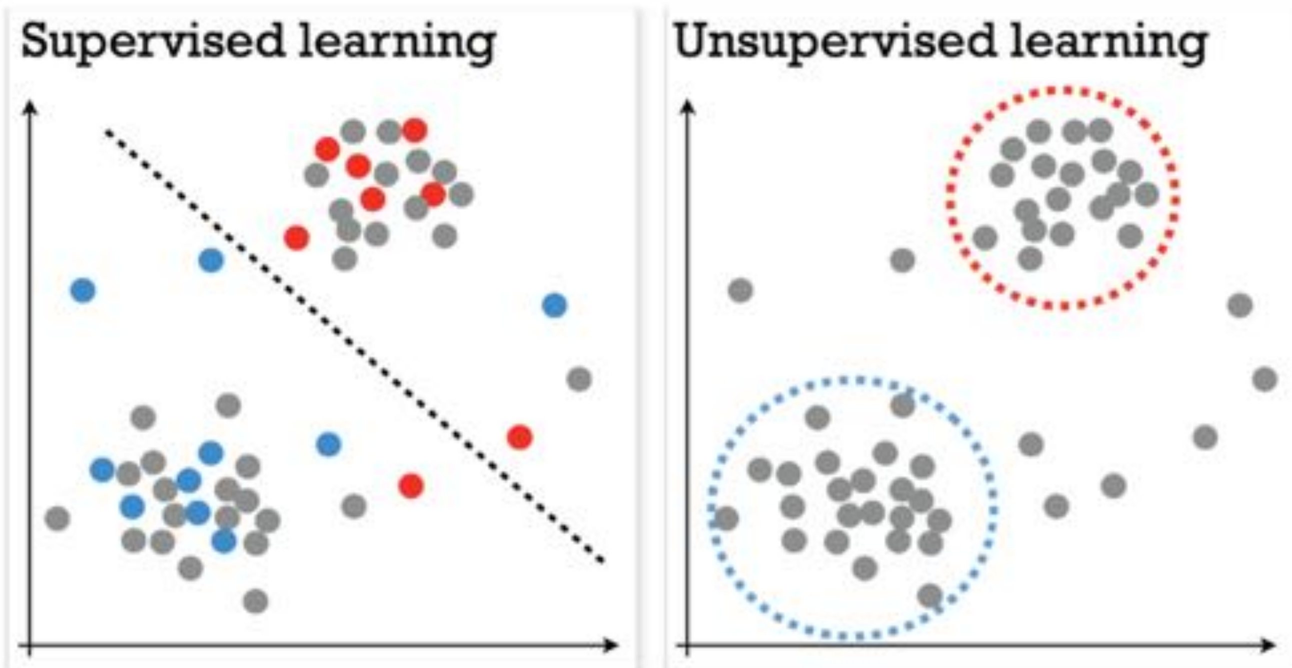


Machine Learning: the **WHAT**



or

Sudo is this a cat?

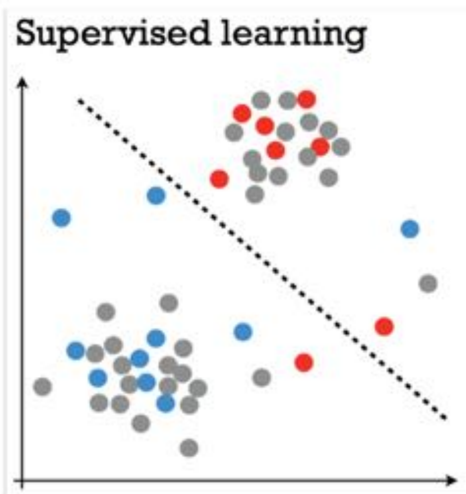
Learning *P(labels|data)* given samples from *P(data,labels)*

-generative models
-clustering (discriminative)
-feature extraction

Sudo make me a cat.
Sudo what is a cat!?

Learning structure in *P(data)* give samples from *P(data)*

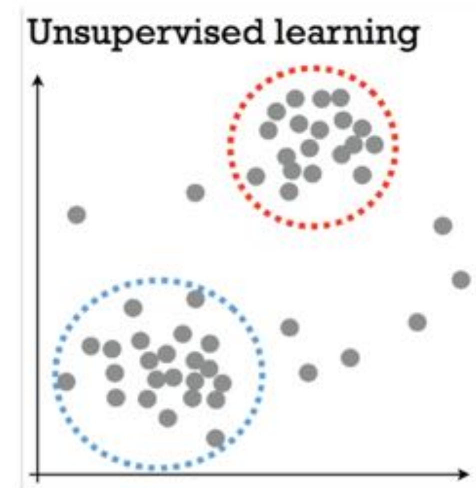
Machine Learning: the **HOW**



output hypothesis *h* on *Data* x *Labels*
approximating P(labels|data)

$$\text{parametrized family } \{h_\theta\}_\theta$$

$$\text{argmin}_\theta \ \text{Err\_training\_set}(\theta) + \text{Reg}(\theta)$$

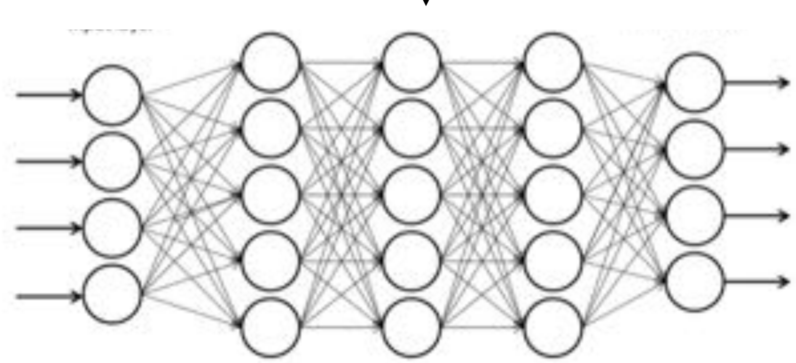


output hypothesis *h* on *Data*
"approximating" P(data)

In practice

model parameters $\boldsymbol{\theta}$

Optimizer



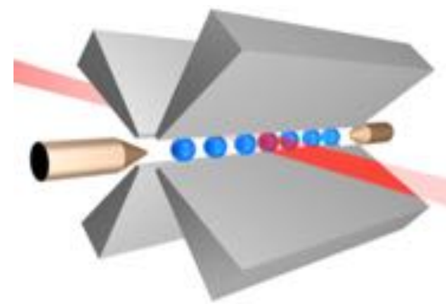
estimate error on sample (dataset)

What about quantum computers?

Quantum computers…

…and physics

-*manipulate* registers of 2-level systems (qubits)



-full description:

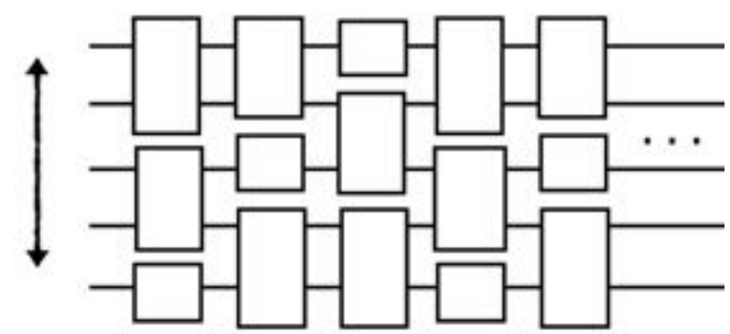
n qubits $\rightarrow$ ***2^n dimensional vector***

-manipulation: acting locally (gates)

…and computer science

-likely can *efficiently* compute more things than classical computers (factoring)
e.g. factor numbers, or generate complex distributions

-even if QC is "shallow"



…and reality

special-purpose
quantum annealers

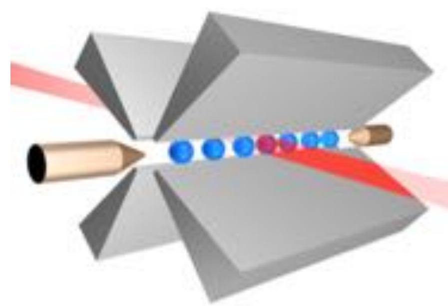
Banana
for scale

cca 50 qubit
all-purpose
noisy

Quantum computers…

...and physics

-*manipulate* registers of 2-level systems (qubits)



-full description:

n qubits → 2^n dimensional vector

...and computer science

-can compute things likely beyond **BPP** (factoring)

-can produce distributions which are hard-to-simulate for classical computers (unless **PH collapses**)

-even if QC is "shallow"

...and reality

special-purpose
quantum annealers

Banana
for scale

cca 50 qubit
all-purpose
noisy

Bottlenecks of ML and the quantum pipeline

a) The optimization bottleneck
b) Big data & comp. complexity
c) Machine learning Models

Bottlenecks of ML and the quantum pipeline

a) The optimization bottleneck — **quantum annealers**

b) Big data & comp. complexity — **universal QC and Q. databases**

c) Machine learning Models — **restricted (shallow) architectures**

Bottlenecks of ML and the quantum pipeline

a) The optimization bottleneck — **quantum annealers**

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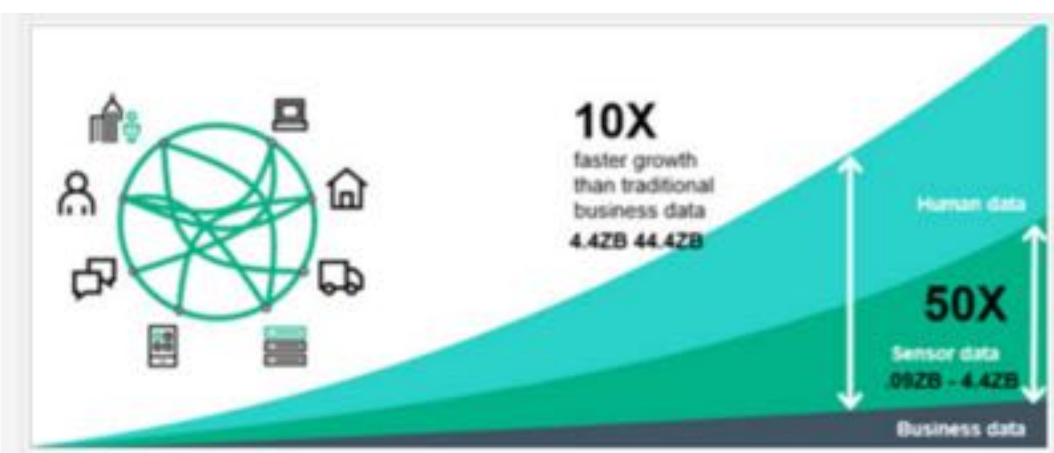
Precursors of Quantum Big Data

<u>Exponential data?</u>

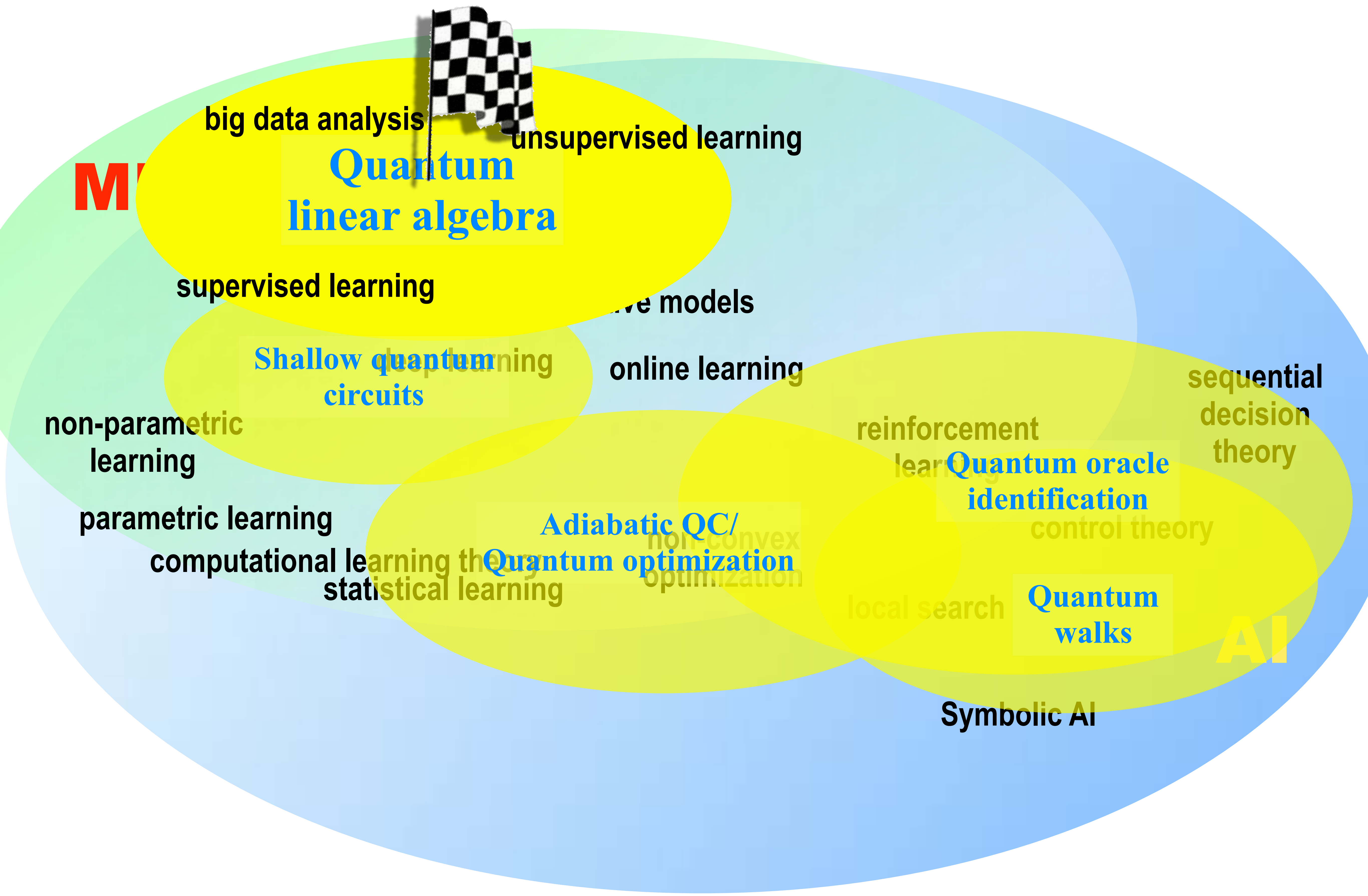


There are many sources that predict exponential data growth toward 2020 and beyond.

+

Much of data analysis is linear-algebra:

regression = Moore-Penrose
PCA = SVD…


big data analysis
unsupervised learning
Quantum linear algebra
supervised learning
ve models
Shallow quantum circuits
deep learning
online learning
non-parametric learning
parametric learning
computational learning theory
statistical learning
Adiabatic QC/ Quantum optimization
non-convex optimization
reinforcement learning
Quantum oracle identification
sequential decision theory
control theory
local search
Quantum walks
AI
Symbolic AI

Enter *quantum linear algebra*

-*n* qubits $\leftrightarrow$ 2^n dimensional vector

-*compute* evolution = *linear algebra*

*-so… evolution of quantum systems *does* linear algebra*

-with ***exponentially large matrices!***

amplitude encoding

$$\mathbf{R}^N \ni \mathbf{x} = (x_i)_i$$

$$\downarrow$$

$$|\psi\rangle \propto \sum_{i=1}^N x_i |i\rangle$$

exp(*n*) amplitudes in *n* qubits

block encoding

$$U|0\rangle|\psi\rangle = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \psi \\ 0 \end{bmatrix} = \begin{bmatrix} A\psi \\ C\psi \end{bmatrix} = |0\rangle A|\psi\rangle + |1\rangle C|\psi\rangle$$

functions of operators

$$f(A)|\psi\rangle = \alpha_0|\psi\rangle + \alpha_1 A|\psi\rangle + \alpha_0 A^2|\psi\rangle \cdots$$

$$\approx A^{-1}|\psi\rangle$$

inner products

$$P(0)_\psi = |\langle 0|\psi\rangle|^2$$

Phys. Rev. Lett. **15**,. 103, 250502 (2009)
arXiv:1806.01838

If this worked literally…this would make us *INFORMATION GODS.*

Prediction: *44 zettabytes by 2020.*

If all data is floats, this is 5.5×10^{21} *float values*

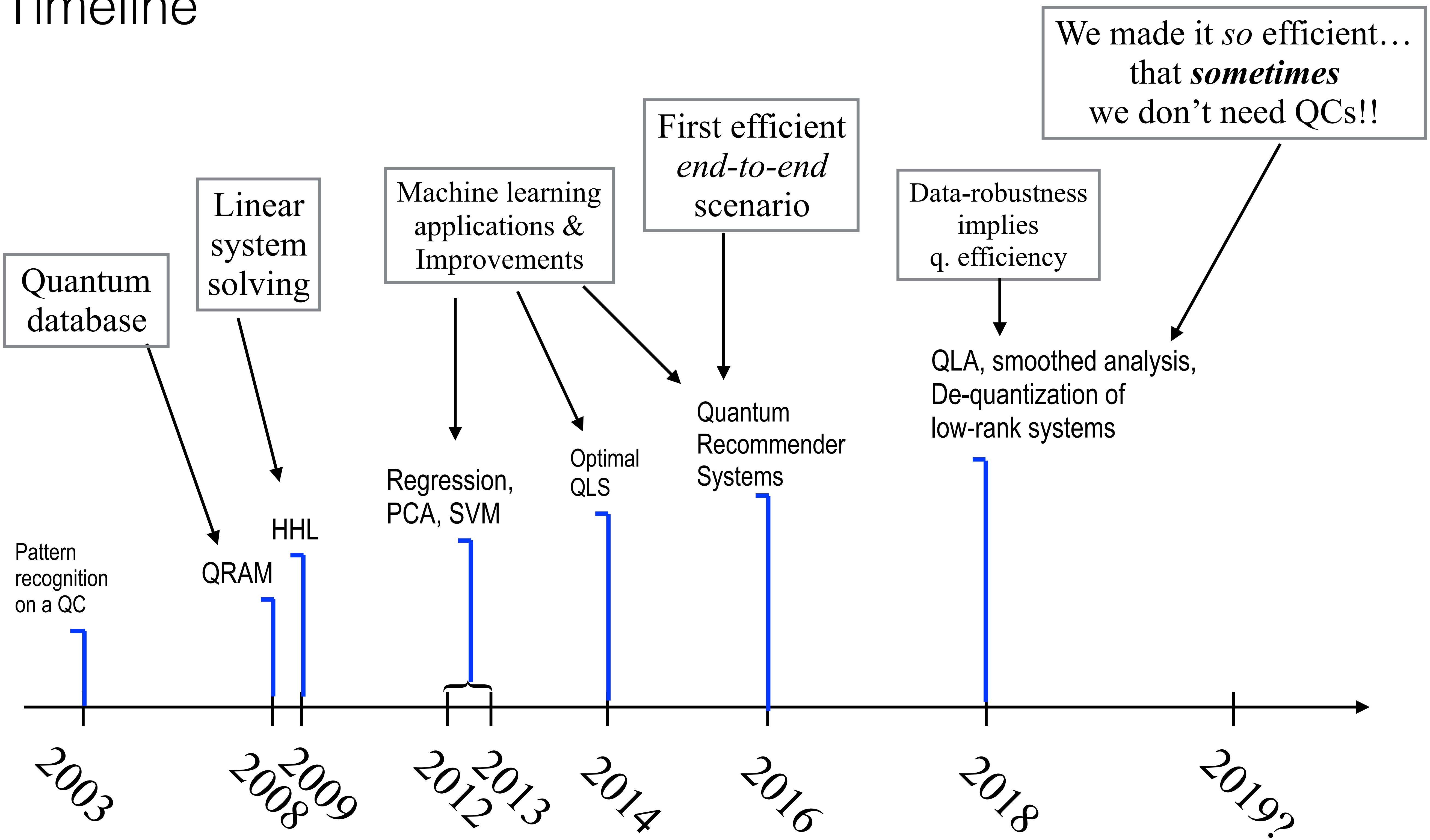
If this worked literally…this would make us *INFORMATION GODS.*

Prediction: *44 zettabytes by 2020.*

If all data is floats, this is 5.5×10^{21} float values

… can be stored in state of 73 qubits (ions, photons….)

Timeline



Quantum database
Linear system solving
Machine learning applications & Improvements
First efficient *end-to-end* scenario
Data-robustness implies q. efficiency
We made it *so* efficient… that ***sometimes*** we don't need QCs!!
Pattern recognition on a QC
QRAM
HHL
Regression, PCA, SVM
Optimal QLS
Quantum Recommender Systems
QLA, smoothed analysis, De-quantization of low-rank systems
2003
2008
2009
2012
2013
2014
2016
2018
2019?

Summary of quantum (inspired) "big data"

The "bad"

*-**not an inexhaustible source** of exponential quantum advantage*

Quantum and classical

*-**exponentially efficient processing***
given suitable databases

Quantum advantages over classical

-Quantum works with full-rank transforms (e.g. Fourier for series)
*-**polynomial advantage** (up to 16 degree difference at the moment)*
-error scaling: exponential precision v.s. poly (in-)precision

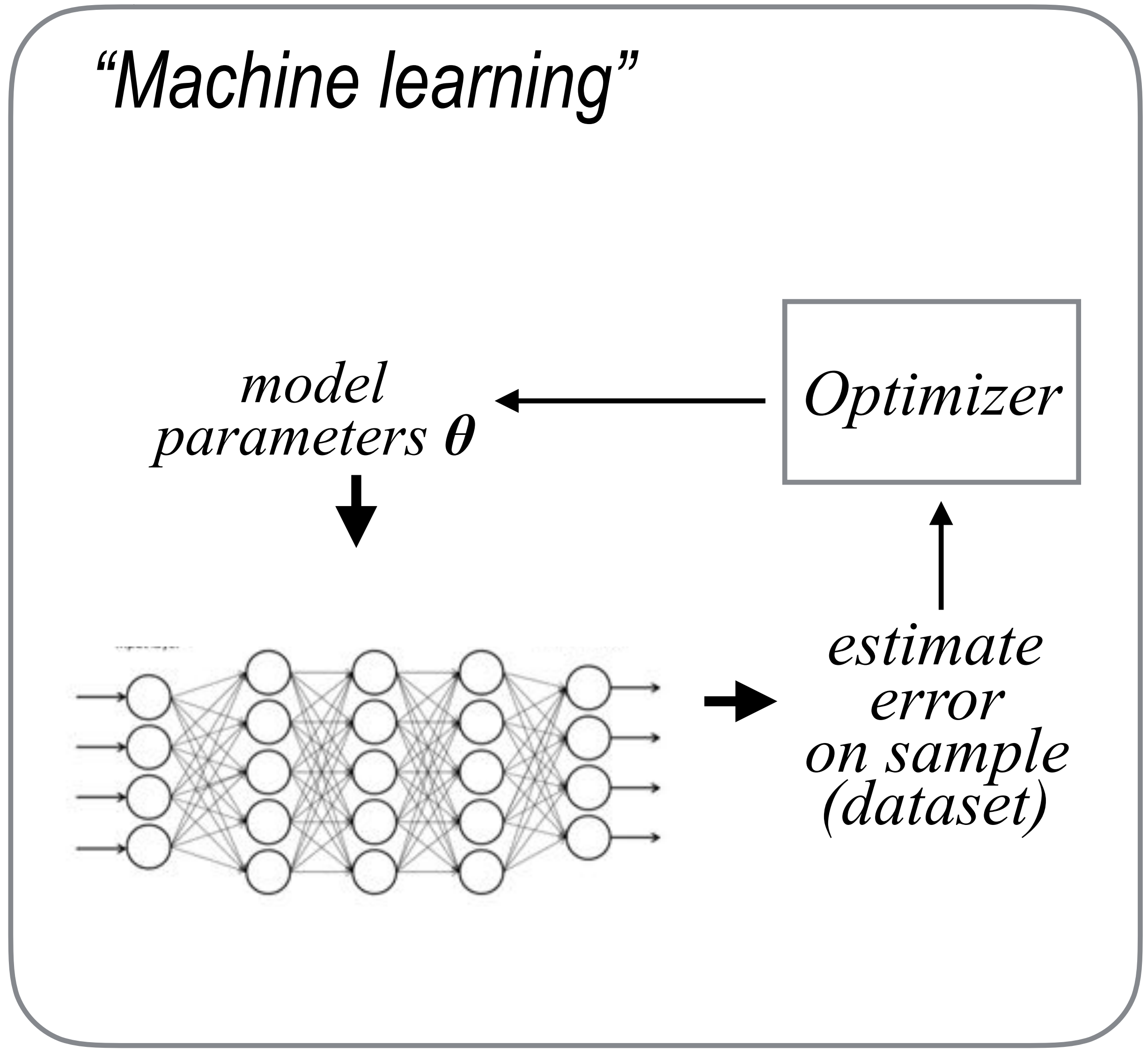
Bottlenecks of ML and the quantum pipeline

a) The optimization bottleneck — **quantum annealers**

b) Big data & comp. complexity — **universal QC and Q. databases**

c) Machine learning Models — **restricted (shallow) architectures**

(Quantum) Machine learning Models



Improving ML == speeding up algorithms… *or is it?*

Machine learning Models matter!

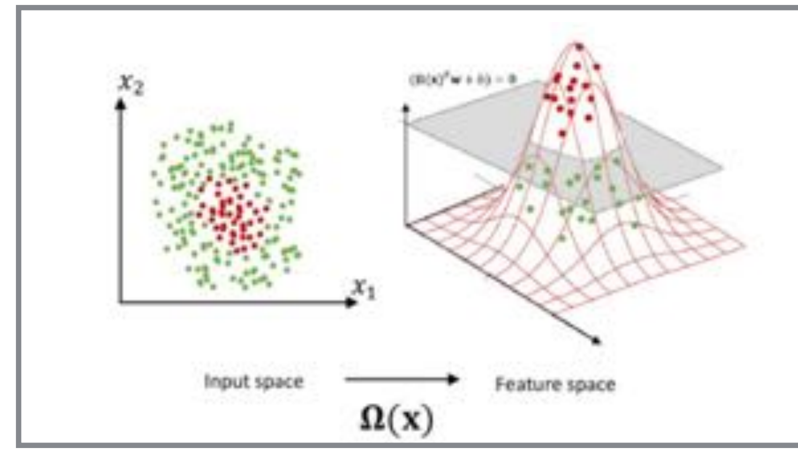
<u>best fit v.s. “generalization performance”</u> or *classifying well* ***beyond the training set***

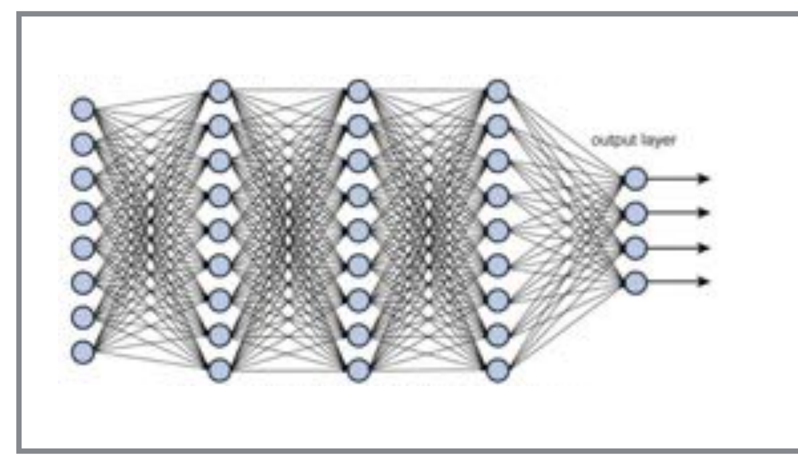
Challenge:

Models:

Data:

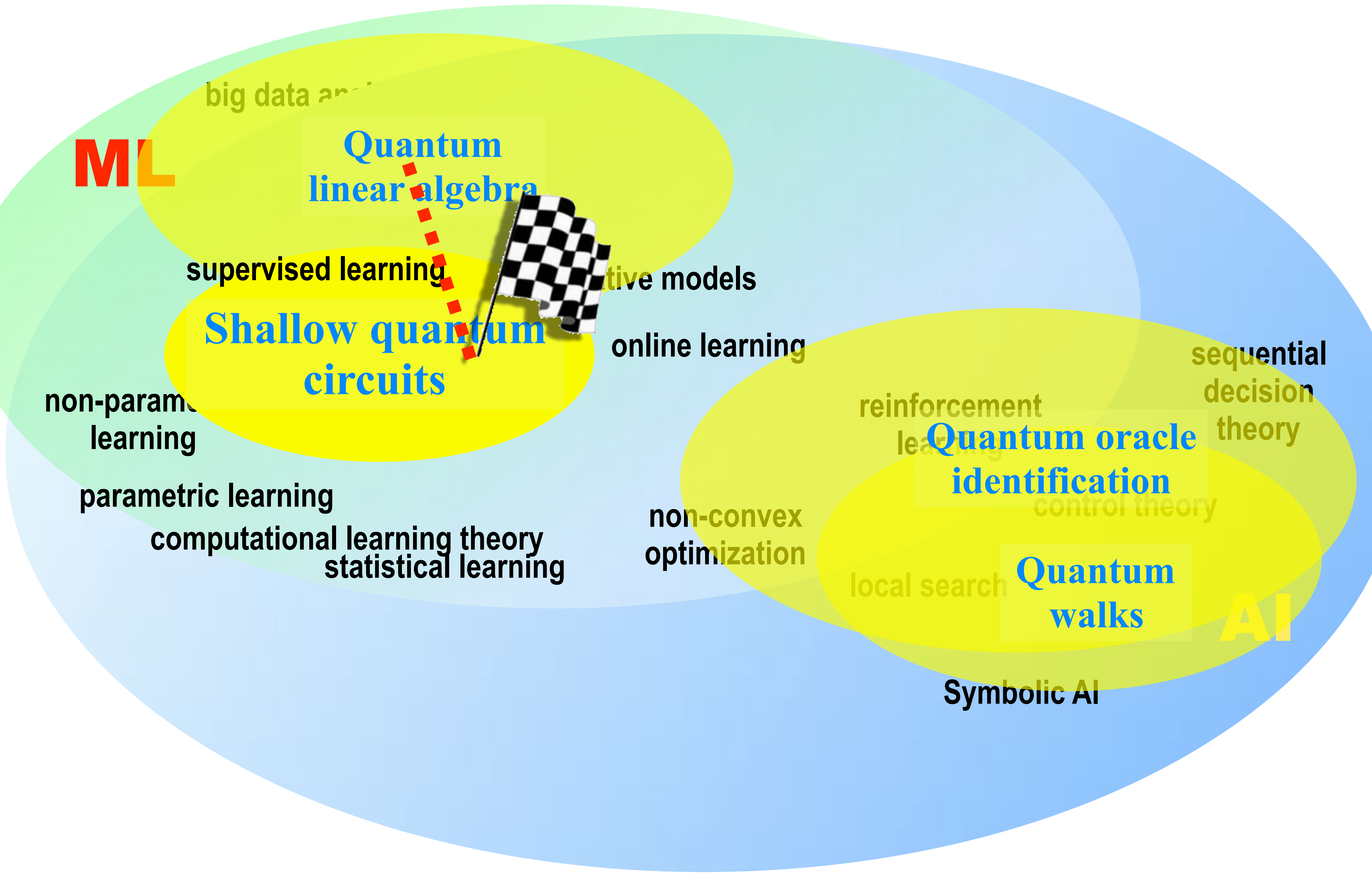
squeek
or
meow?





Not all models (+training algo) are born equal (for *real* datasets)…

Image: 10.1016/j.compstruct.2018.03.007


ML
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Shallow quantum circuits
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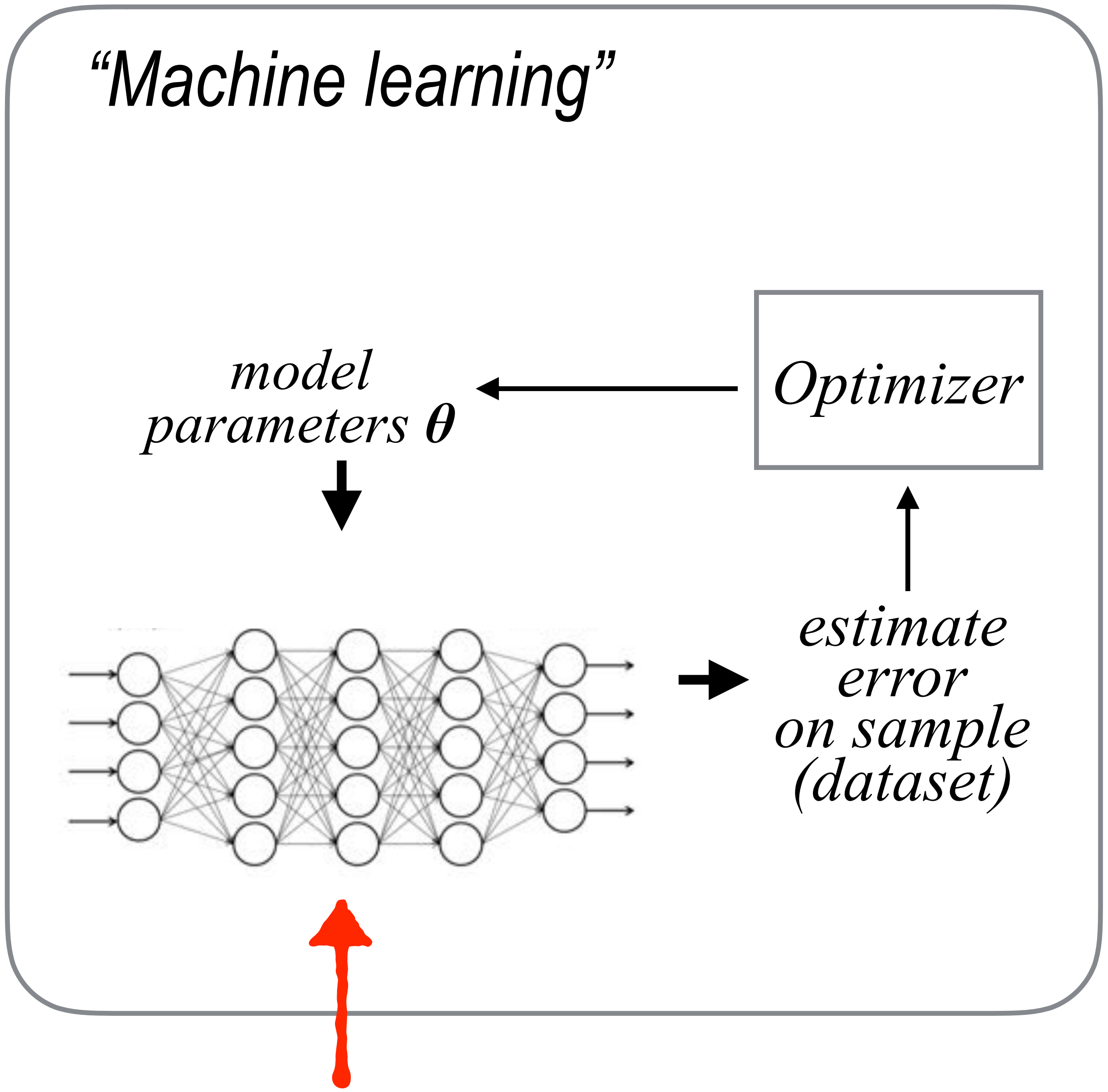
Symbolic AI

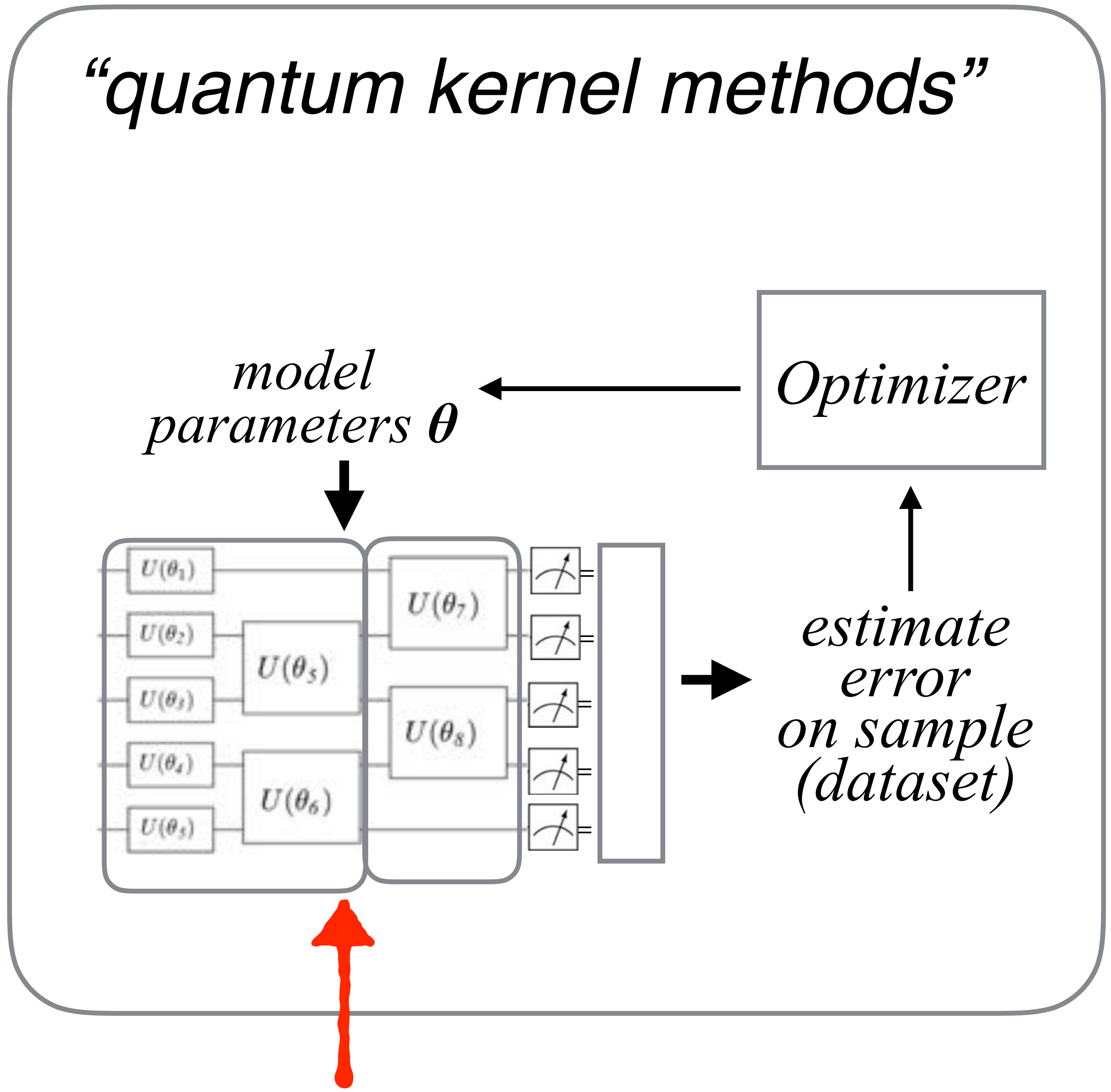
Machine learning Models



family of functions.

if it's "good", we can generalize well

Quantum Machine learning Models



How about "shallow quantum circuits"?
-instead neural network, train a QC!
-related to ideas from
q. condensed-matter physics (VQE)

Phys. Rev. Lett. 122, 040504 2019
Nature 567, 209–212 (2019)
(c.f. Elizabeth Behrman in '90s)

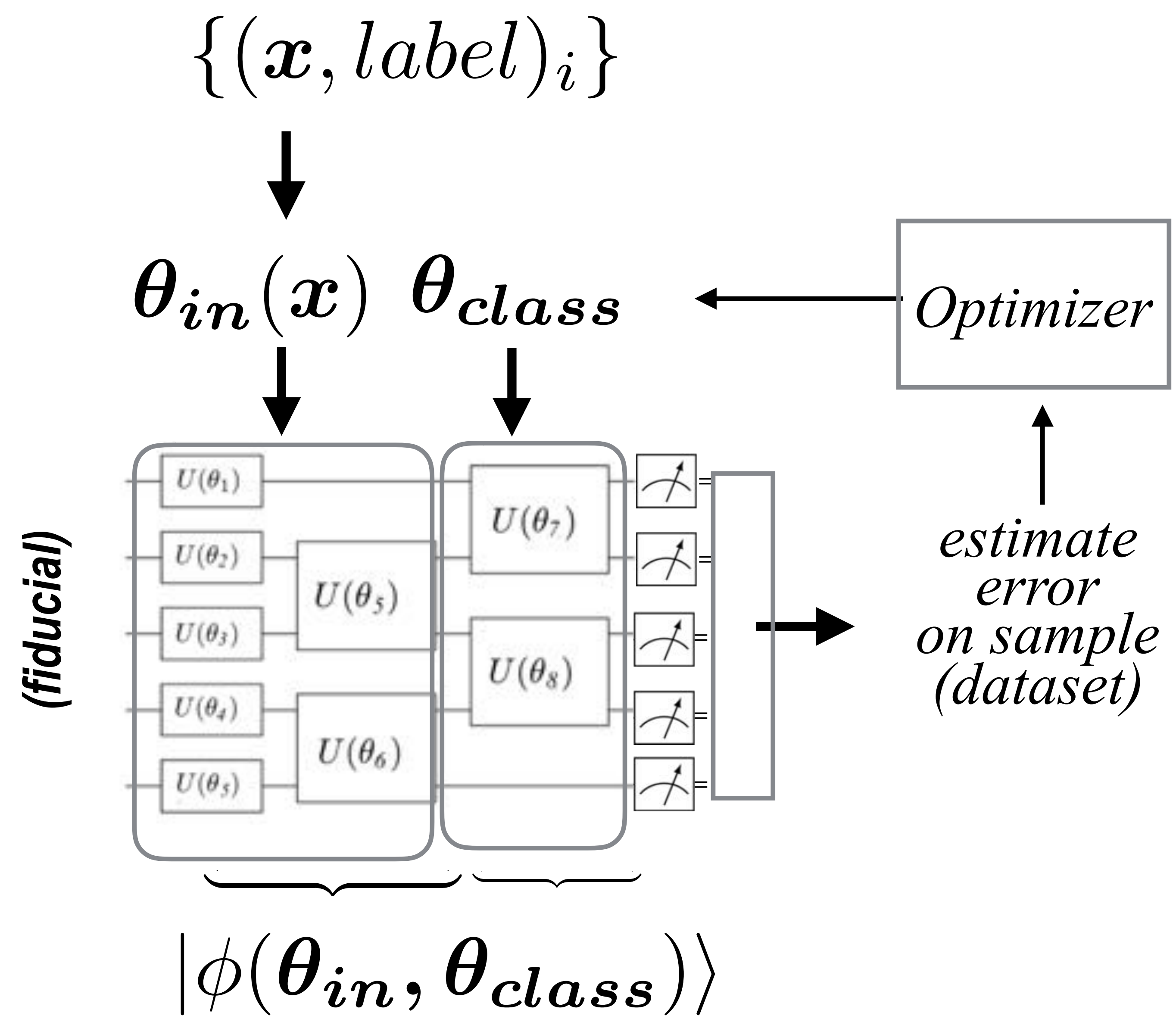
Quantum Machine learning Models
“quantum kernel methods”

<u>The good</u>
- near term architectures
- seems to be ***robust***
  <u>*(noise not inherently critical!)*</u>
- *possibly* ***very expressive***

<u>The neutral</u>
- ***many parameters***
- ***model advantages*** less clear

(*contrast to variational methods!*)

<u>The bad</u>
- ***barren plateaus*** *(also in DNN)*



Phys. Rev. Lett. 122, 040504 2019
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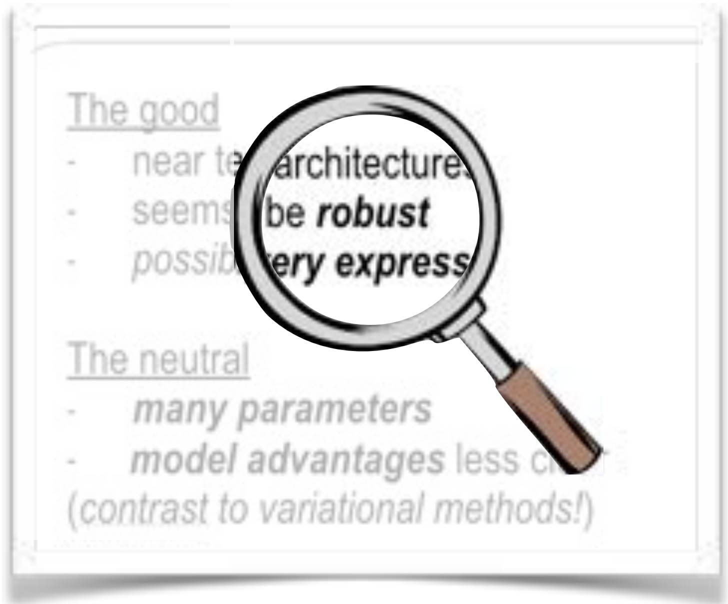
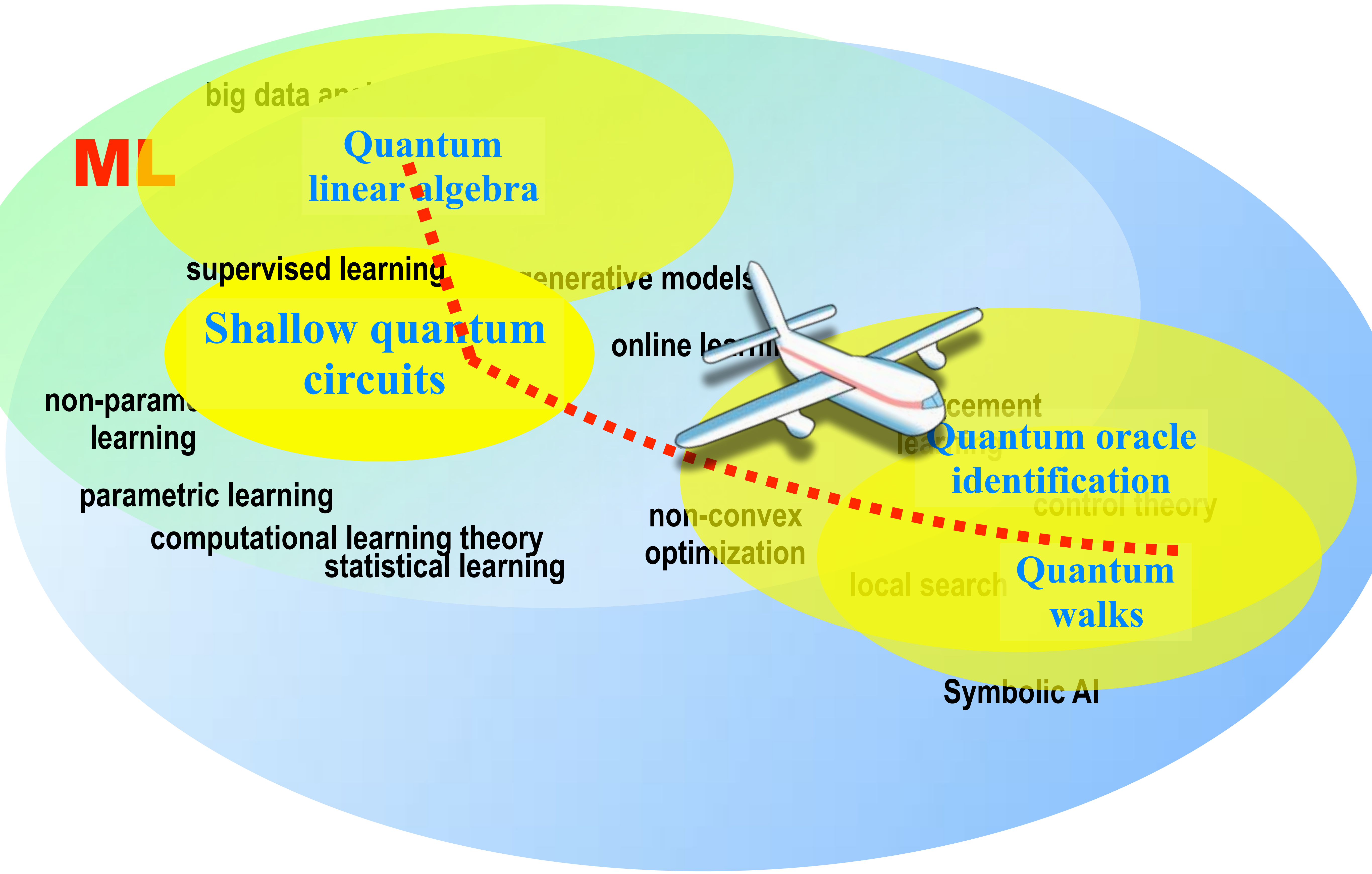
A hope… *killer app for noisy QCs?*



ML good for dealing with noise (in *data*)…
Can QML deal with *its own* noise (in *process*)?

Beyond ML?



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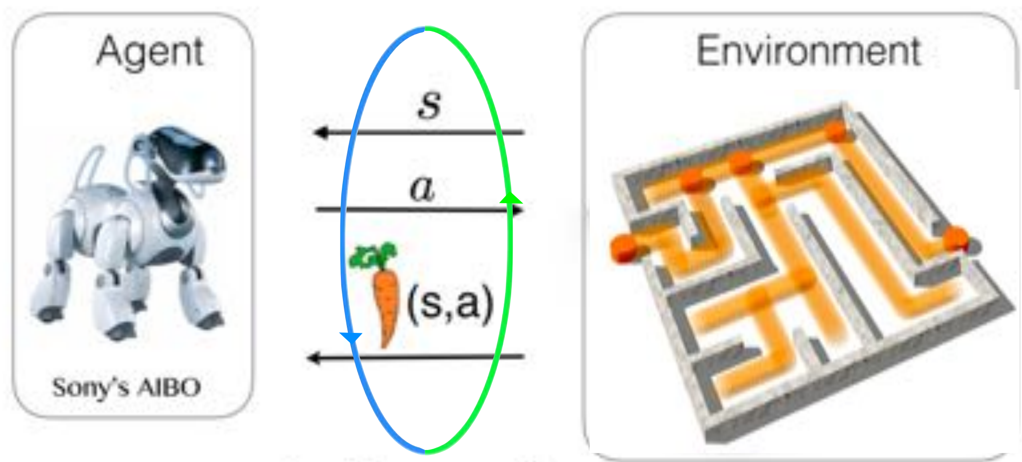
control theory
local search
Quantum walks
Symbolic AI

Quantum-enhanced reinforcement learning



c.f. Briegel

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big data ana

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sequential
decision
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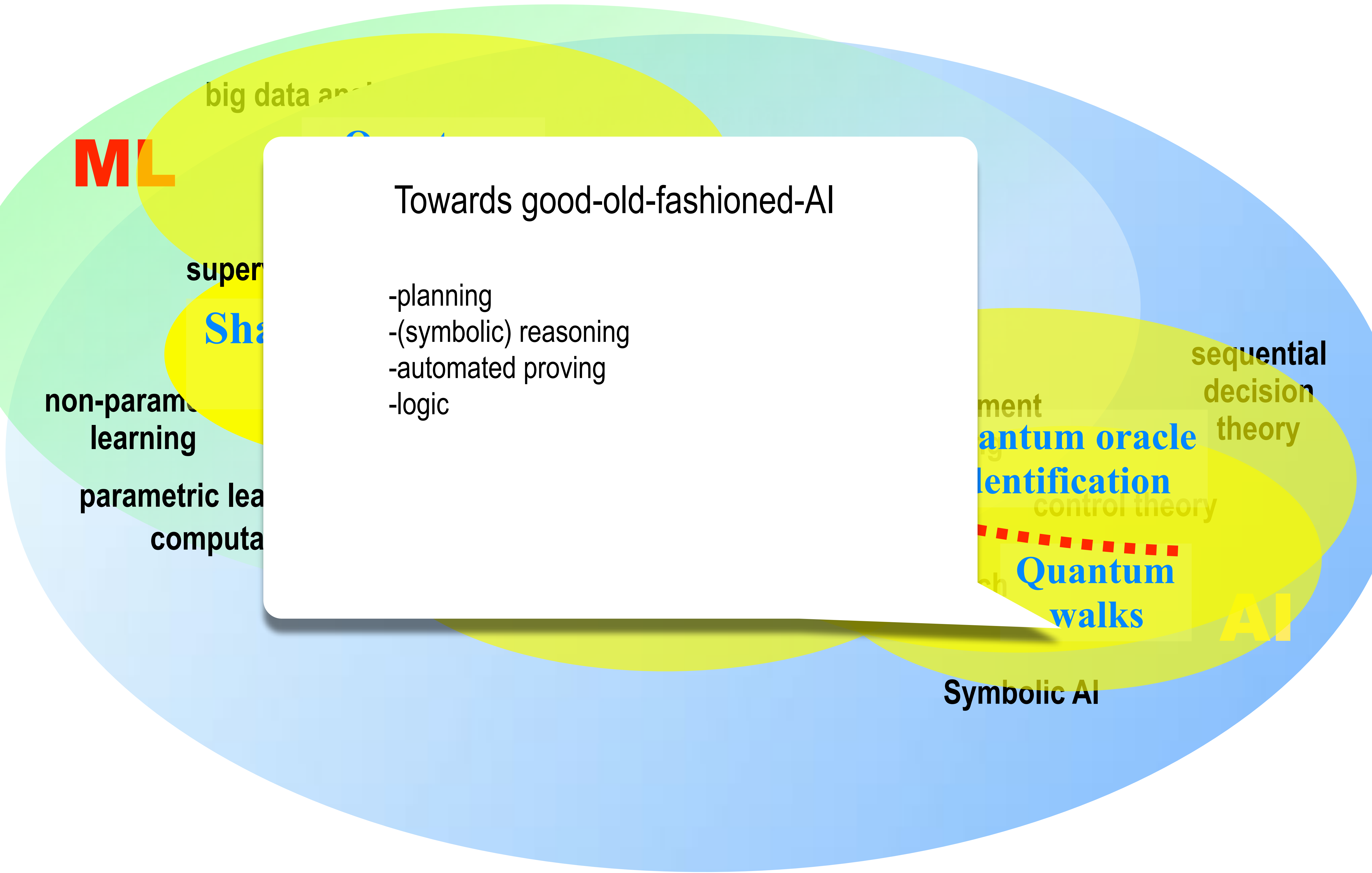


Towards good-old-fashioned-AI

- -planning
- -(symbolic) reasoning
- -automated proving
- -logic

Optimal packing

Shortest tours

$$f(x_1, \ldots, x_n) = (x_1 \vee x_{10} \vee \bar{x}_{51}) \wedge (\bar{x}_3 \vee \bar{x}_{10} \vee \bar{x}_{11}) \wedge (\bar{x}_{11} \vee \bar{x}_{44} \vee \bar{x}_{51}) \cdots$$

Traffic flow optimization

RL and ML

Find a proof of
Riemann's hypothesis
with less than a million lines
(if it exists)?

*finding *good* (not worst case!) solutions to this is central to AI*

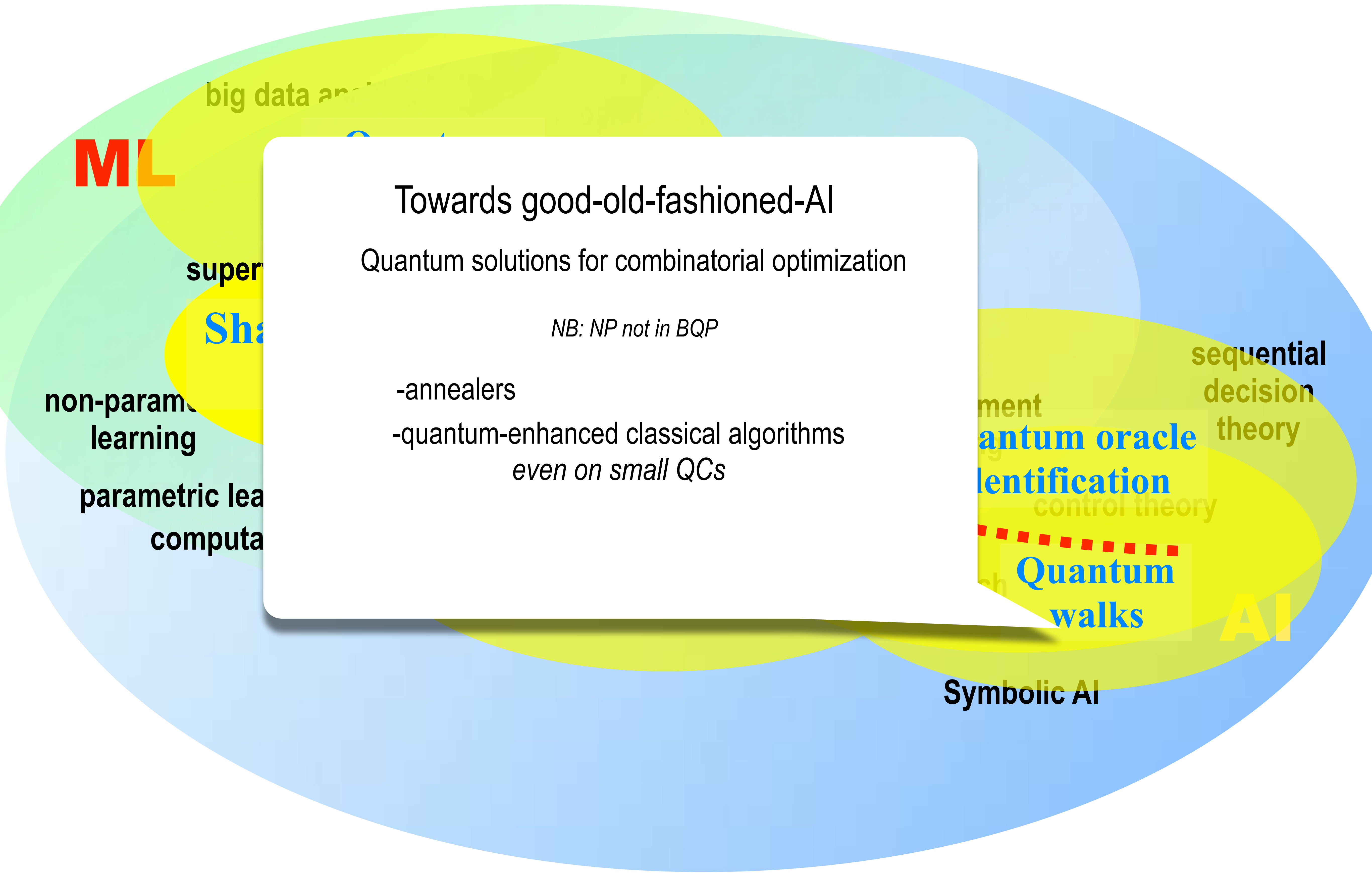
Towards good-old-fashioned-AI

Quantum solutions for combinatorial optimization

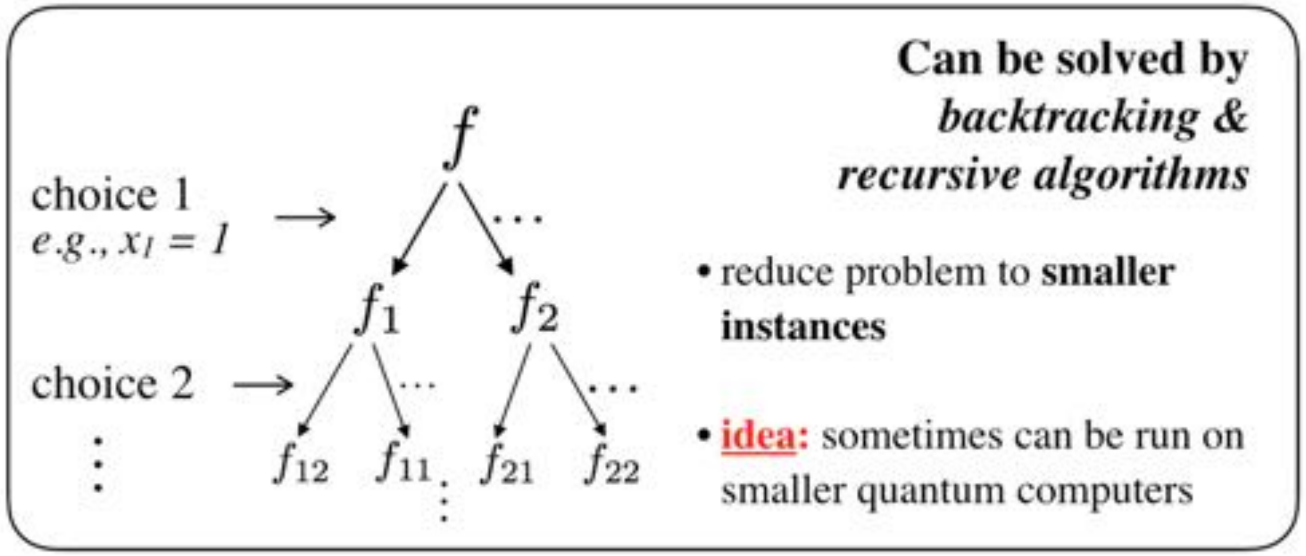
NB: NP not in BQP

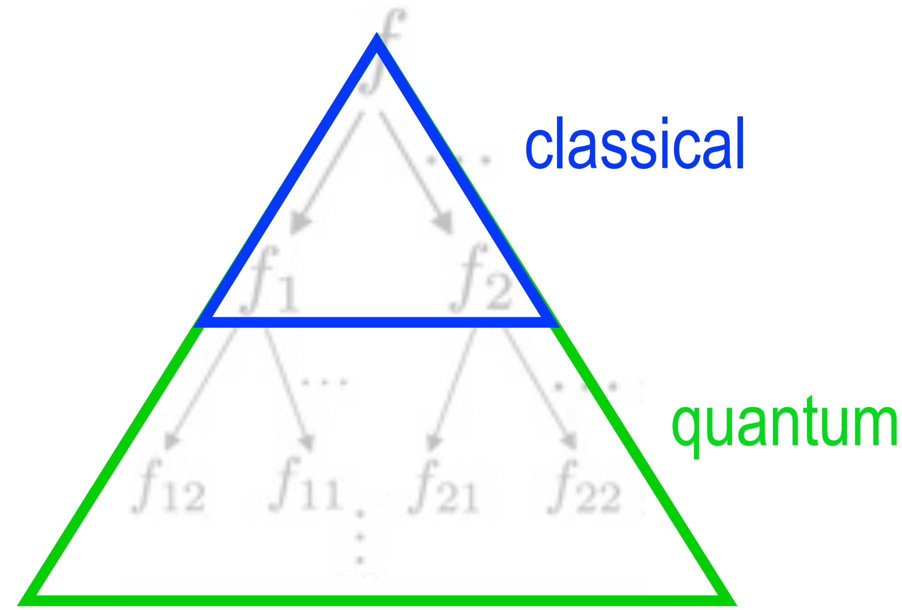
-annealers

-quantum-enhanced classical algorithms
even on small QCs



NP problems on smaller quantum computers



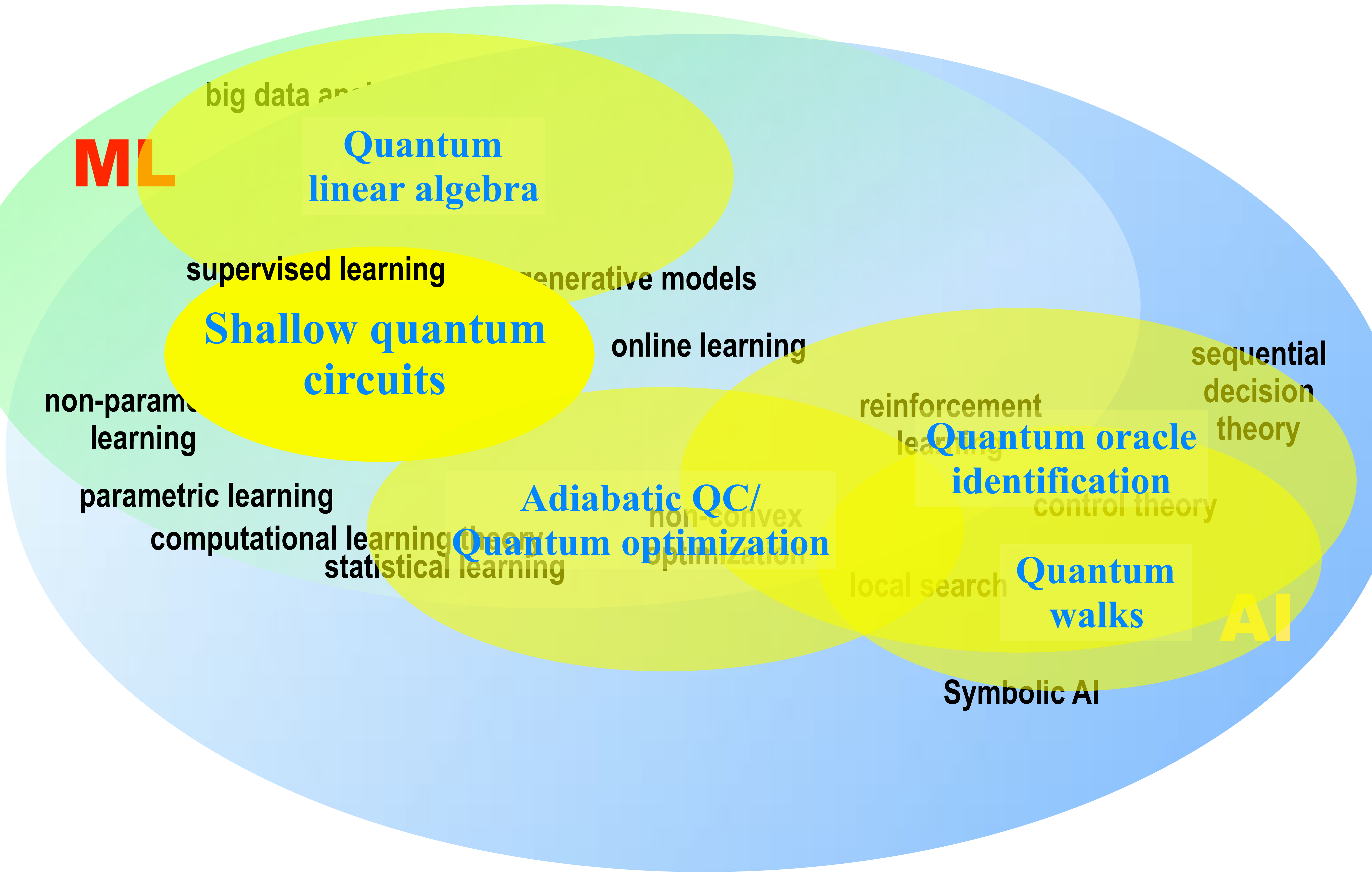


Works because structure is loose

For heuristic solutions… noise may not be a terminal problem

AI as the killer ap?

VD, Ge, Cirac, *Phys. Rev. Lett.* 121, 250501 (2018)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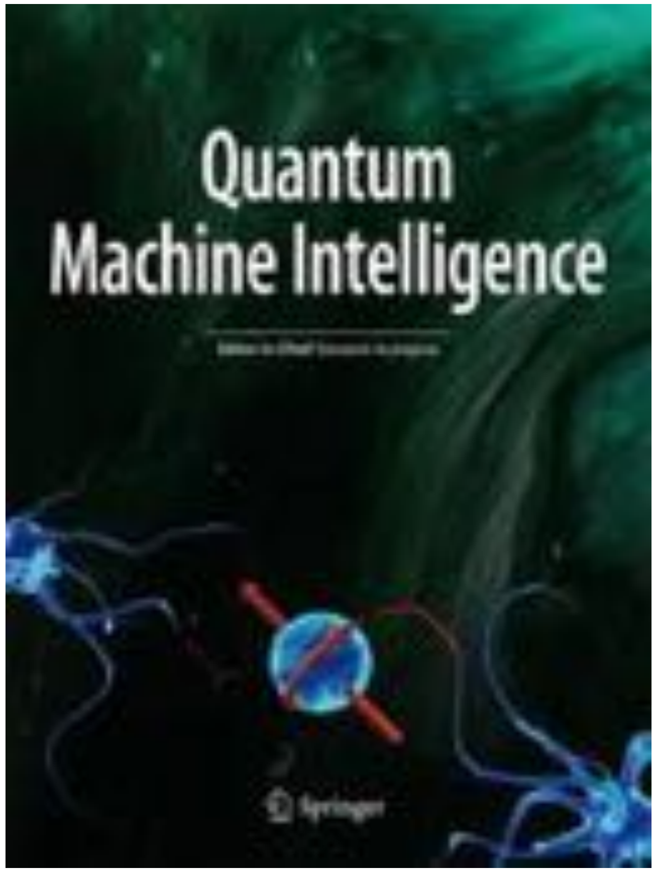

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