

Quantum Computing

Dagli algoritmi all'intelligenza artificiale:
sfide e promesse di una tecnologia emergente



UNIVERSITÀ DI PAVIA
Dipartimento di Fisica

Il regno quantico

?

?

?

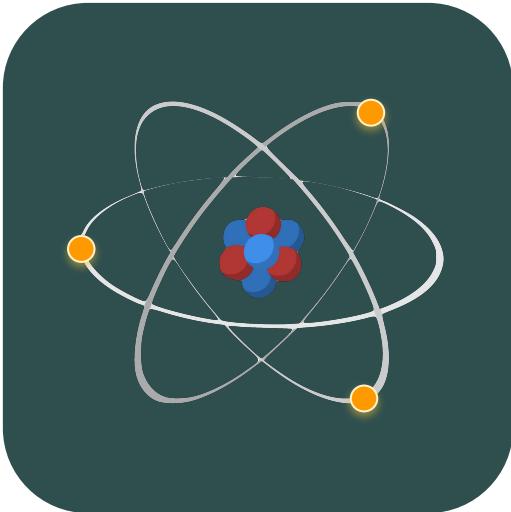
?

?





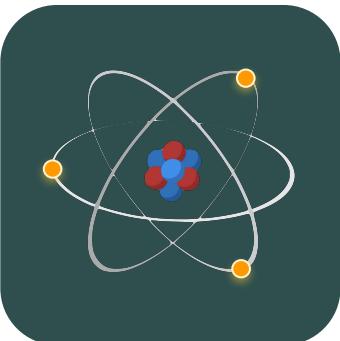
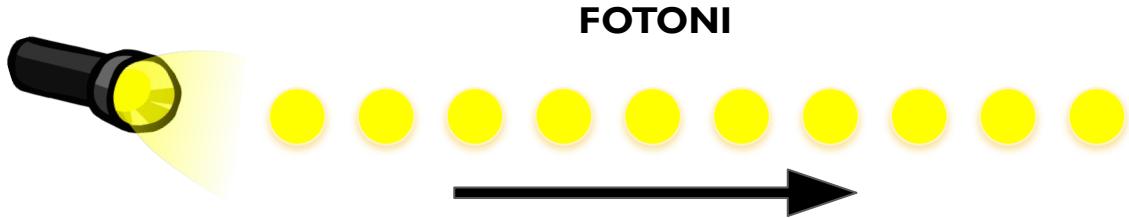
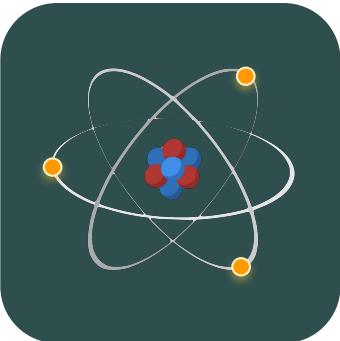
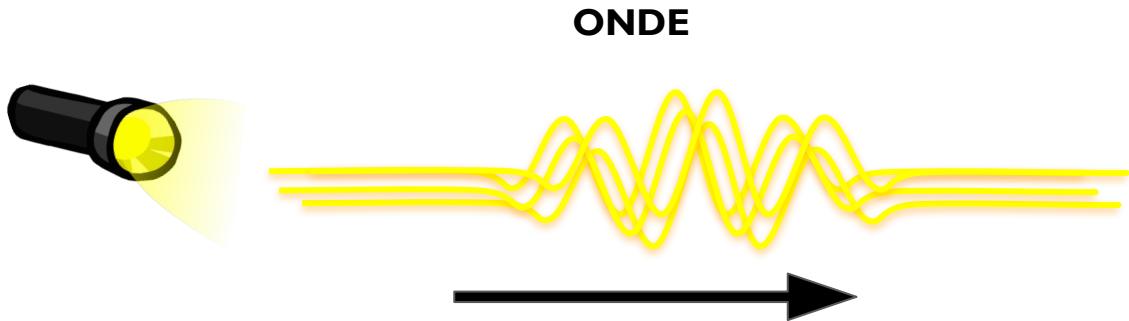
Meccanica Quantistica



Describe fenomeni fisici a scala atomica e subatomica

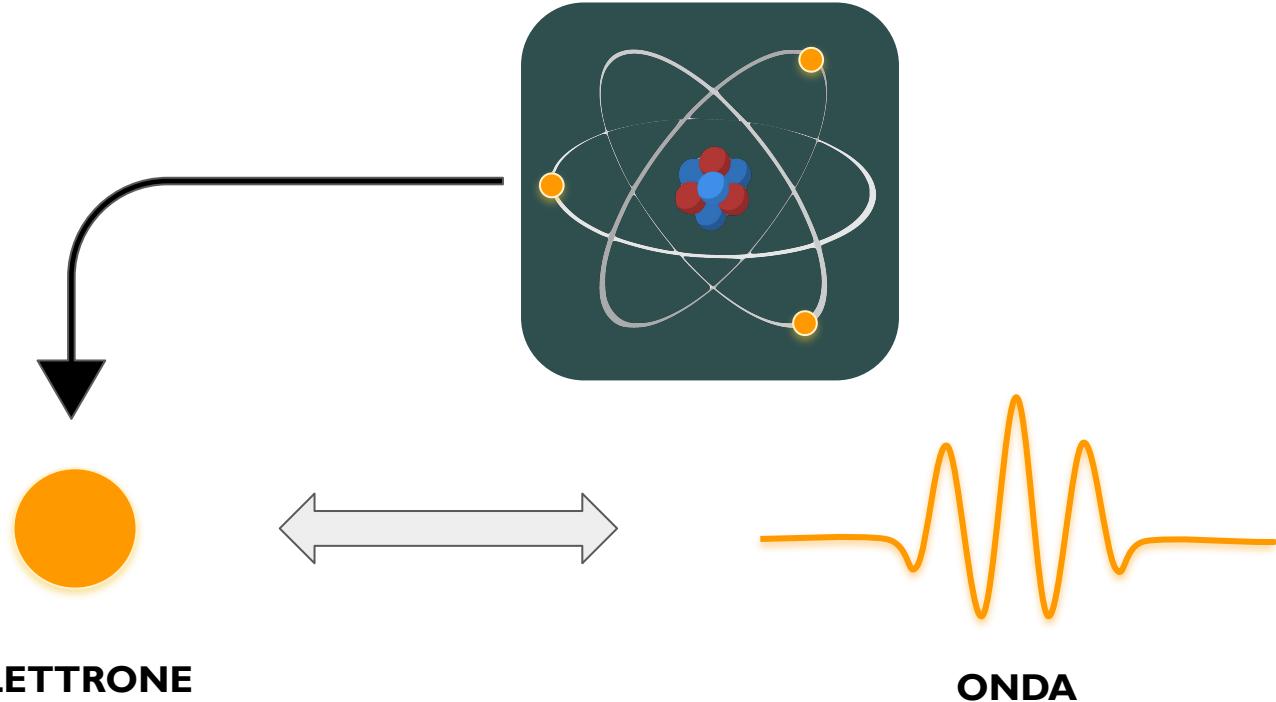


Meccanica Quantistica

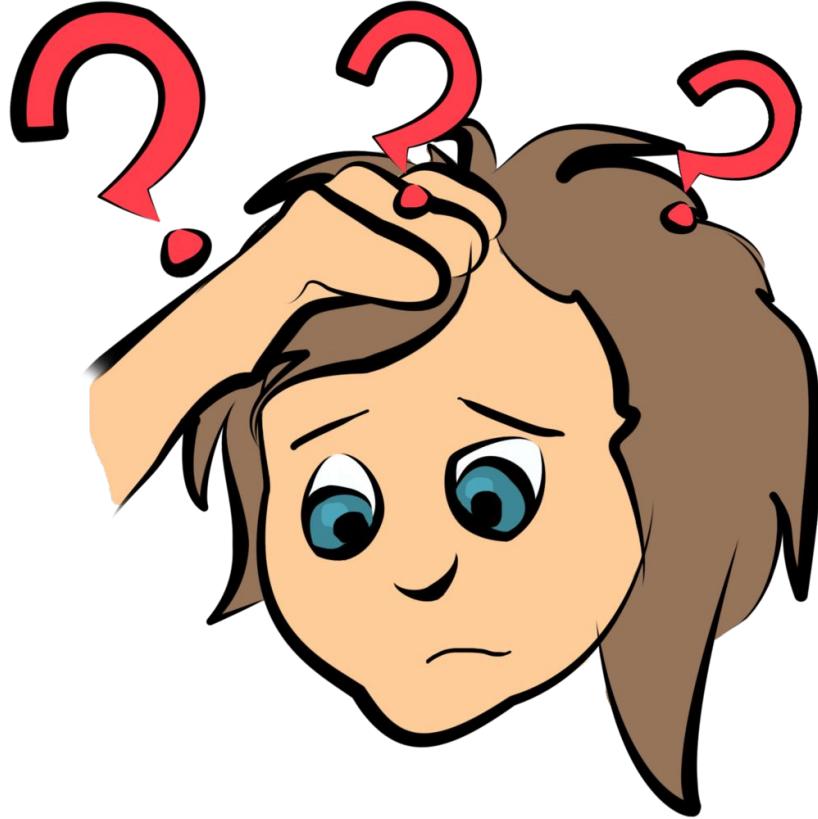




Meccanica Quantistica

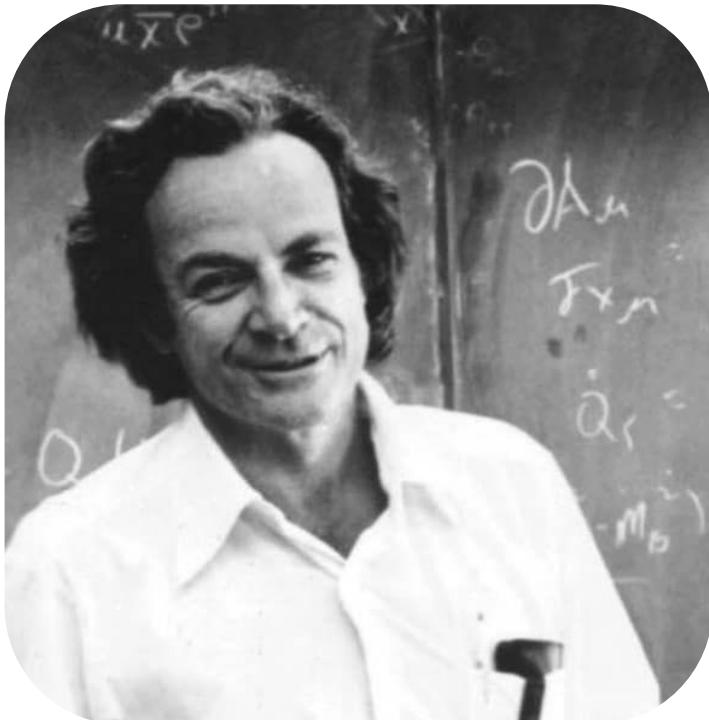


CONFUSI?





Capire la meccanica quantistica



"Se pensi di capire la meccanica quantistica, allora non capisci la meccanica quantistica"

Richard Feynman



La prima proposta di computer quantistico



"La natura non è classica, e se vuoi fare una simulazione della natura, faresti meglio a renderla quantistica... è un problema meraviglioso, perché non sembra così facile."

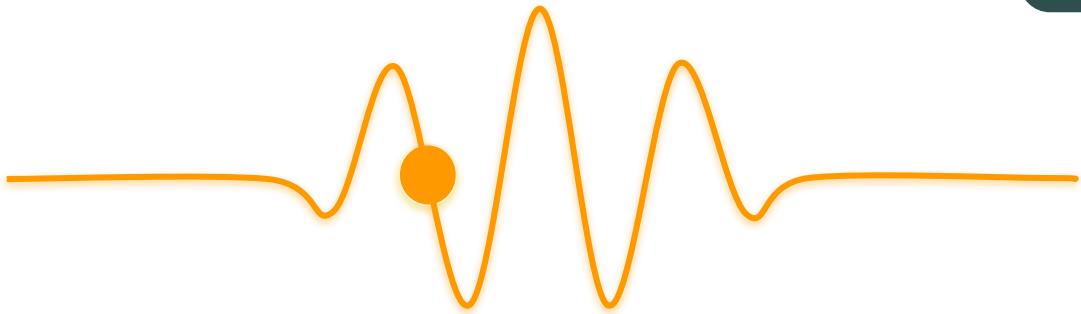
Richard Feynman



Stati quantistici

Funzione d'onda o STATO QUANTISTICO: $|\psi\rangle \rightarrow$

VETTORE

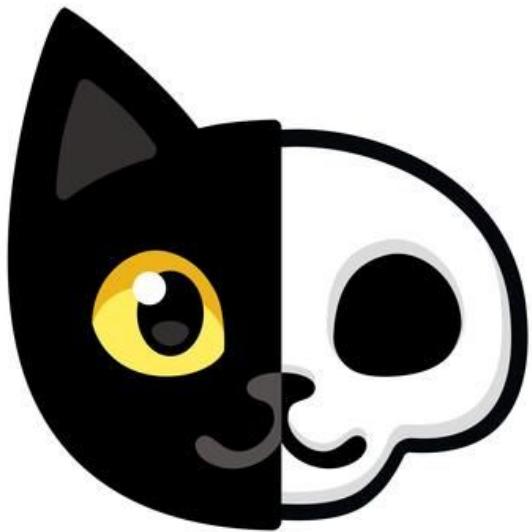


Proprietà Quantistiche di interesse

Sovrapposizione

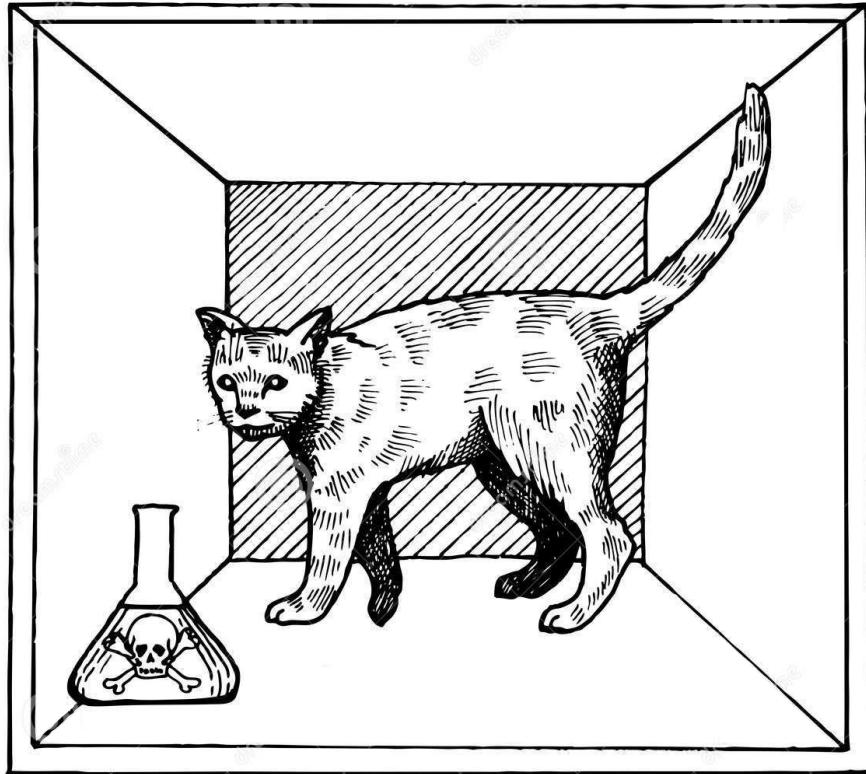
Entanglement

Sovrapposizione





Il Gatto di Schrödinger





Sovrapposizione

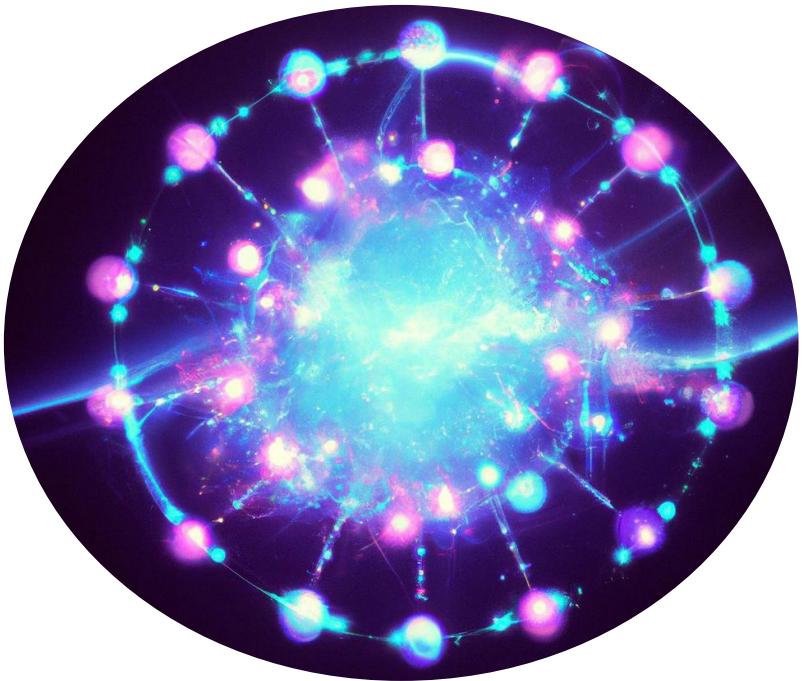
$$|\psi\rangle = a |\text{cat}\rangle + b |\text{skull}\rangle$$

$$a, b \in \mathbb{C}$$

Avrò lo stato $|\text{cat}\rangle$ con probabilità $|a|^2$ e lo stato $|\text{skull}\rangle$ con probabilità $|b|^2$

La Meccanica Quantistica è una teoria
PROBABILISTICA

Entanglement

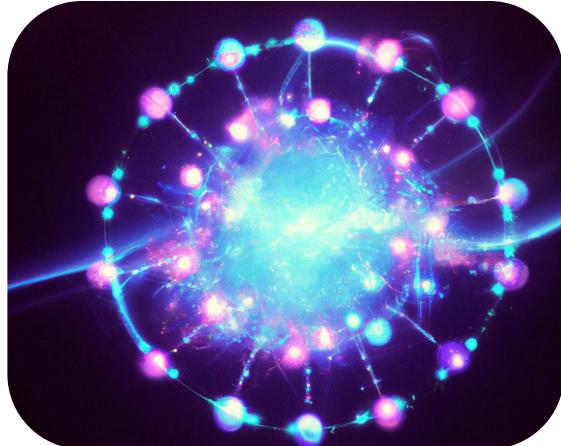
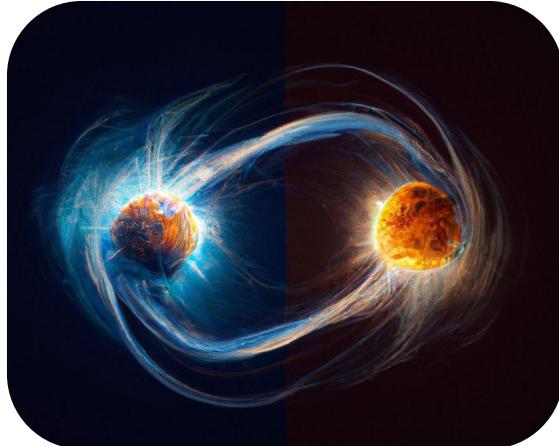




Entanglement

Correlazione **NON-CLASSICA**

I sistemi hanno un'unica funzione d'onda, non ho stati SEPARATI



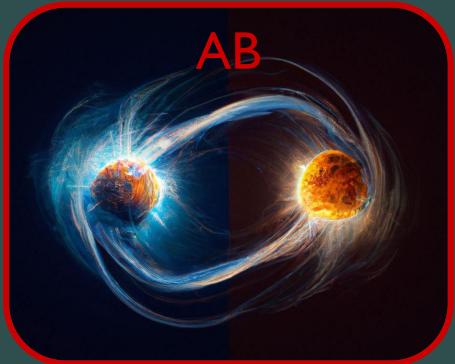


Entanglement

STATI ENTANGLED



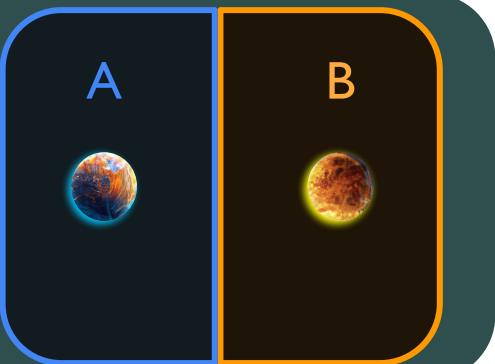
I sistemi hanno un'unica funzione d'onda



STATI SEPARABILI



I sistemi possono essere descritti da
funzioni d'onda distinte



Quantum Information

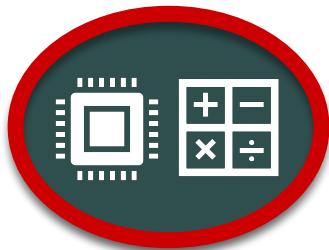




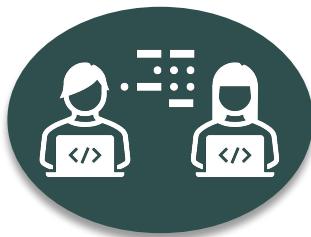
Quantum Information

“... lo studio delle tecniche di elaborazione dell’informazione che possono essere realizzate utilizzando sistemi quantistici”

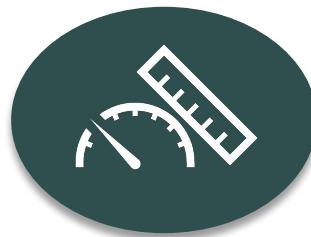
[Nielsen and Chuang “Quantum Computation and Quantum Information” (Cambridge 2010)]



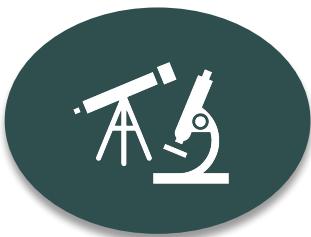
Computing



Comunicazione
& Crittografia



Metrologia



Imaging

E ALTRO ANCORA...



Unità di informazione

BIT

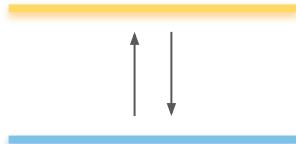


0

1

vs

QUBIT

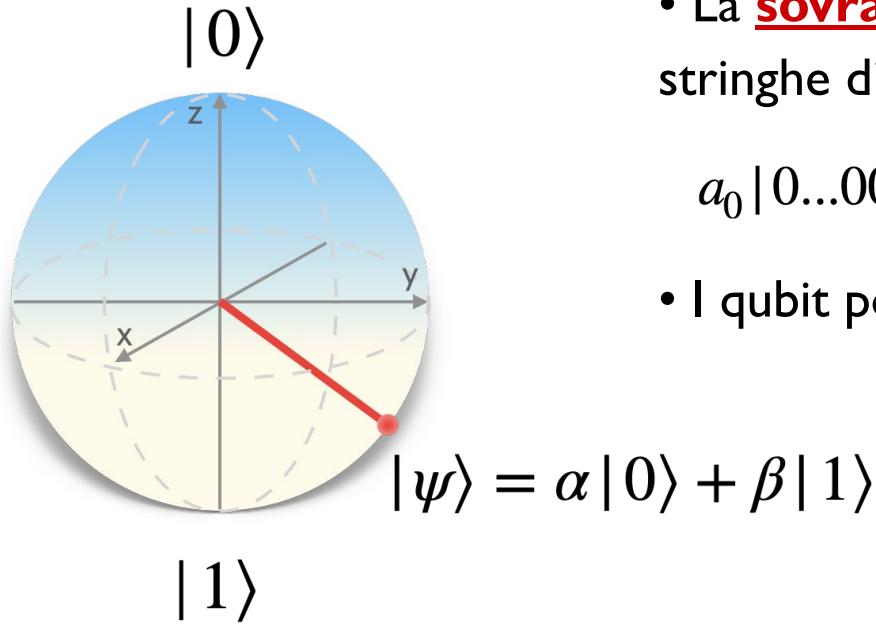


$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$



Quantum Bit



- La **sovraposizione** permette di avere più stringhe di bit contemporaneamente:

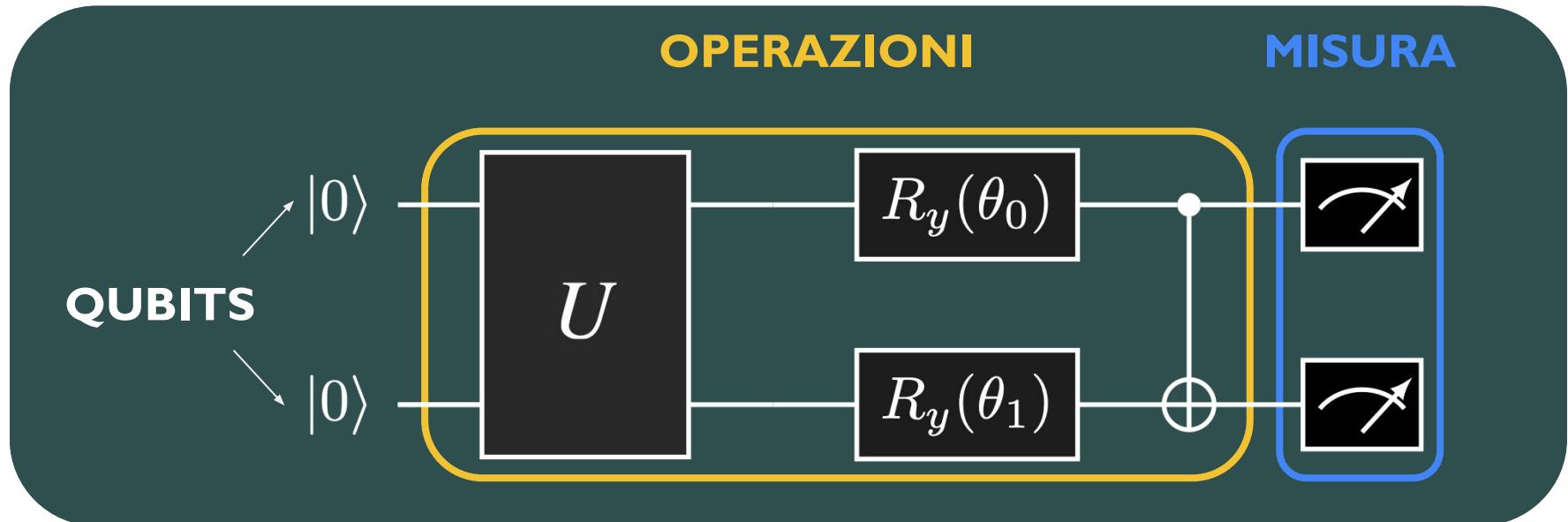
$$a_0|0\dots00\rangle + a_1|0\dots01\rangle + \dots + a_{2^n}|1\dots11\rangle$$

- I qubit possono condividere **entanglement**

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



Il modello circuitale

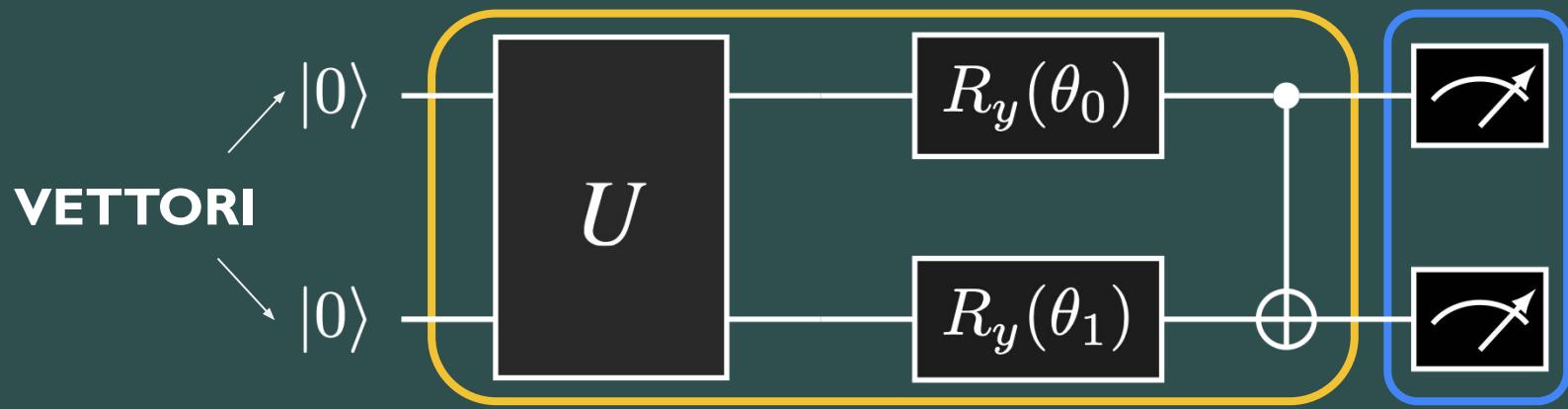


MQ è **PROBABILISTICA** → La misura va ripetuta più volte



Come funziona in pratica?

MOLTIPLICAZIONI DI MATRICI



È ALGEBRA LINEARE!! 



Teletrasporto quantistico

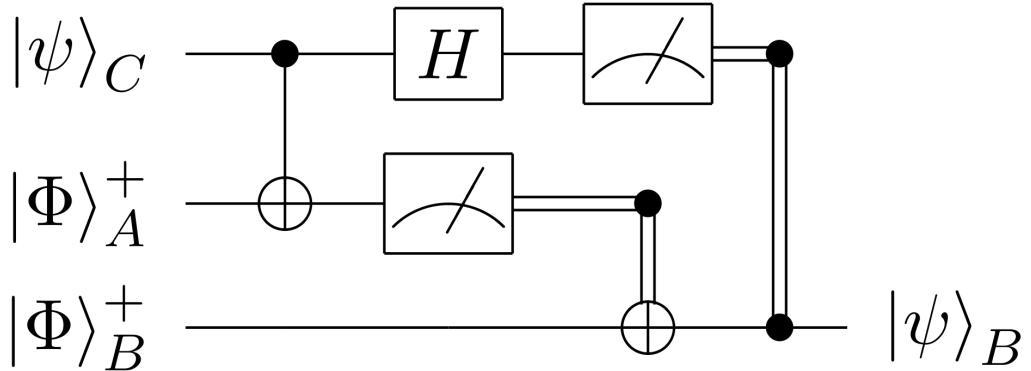


Quello che tutti
vorremmo!





Teletrasporto quantistico



Quello che già
abbiamo!

Teletrasporto di uno STATO fra
due osservatori A e B mediante
scambio di bit classici

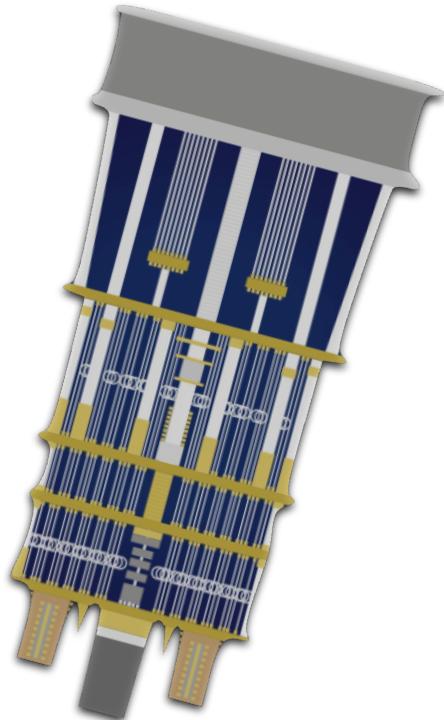
Terra-satellite
500-1400 km



[Nature 549, 70–73 (2017)]



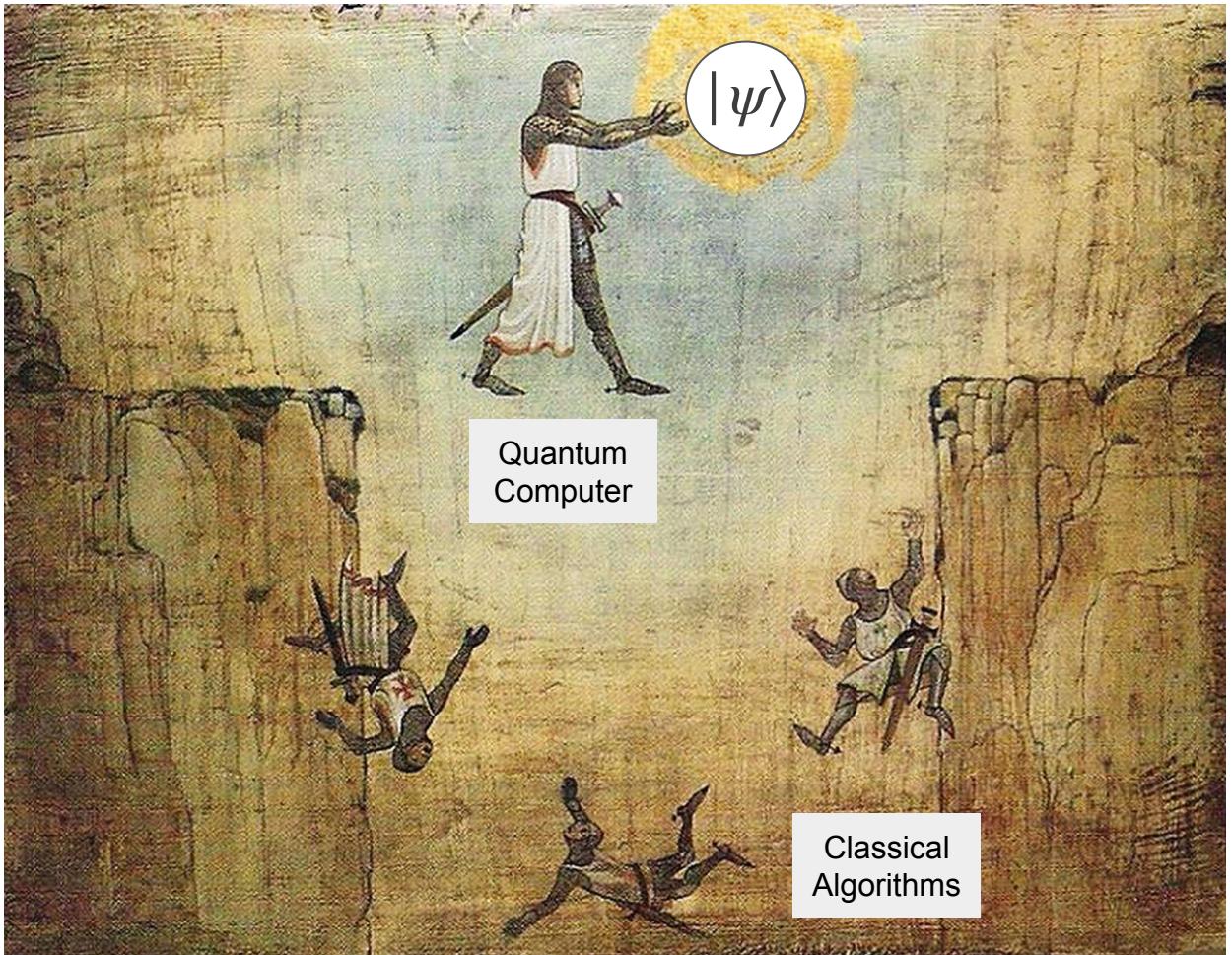
IN THE AGE OF
QUANTUM
COMPUTING



QUANTUM SUPREMACY

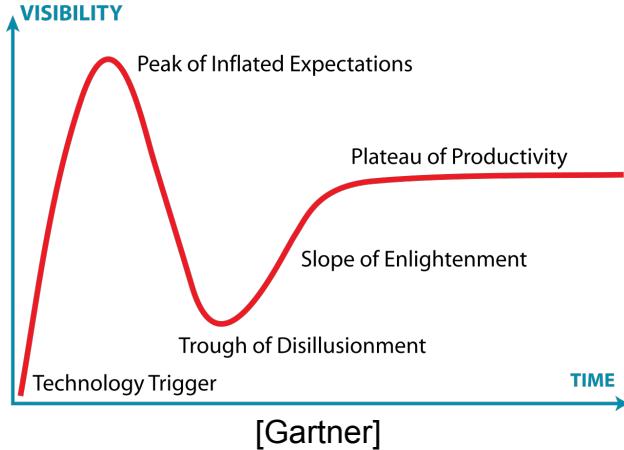
“Gli esperti si aspettano che il quantum computing possa contribuire a comprendere la biologia e l’evoluzione, a curare il cancro, e persino ad adottare misure per invertire il cambiamento climatico”

[Insider]

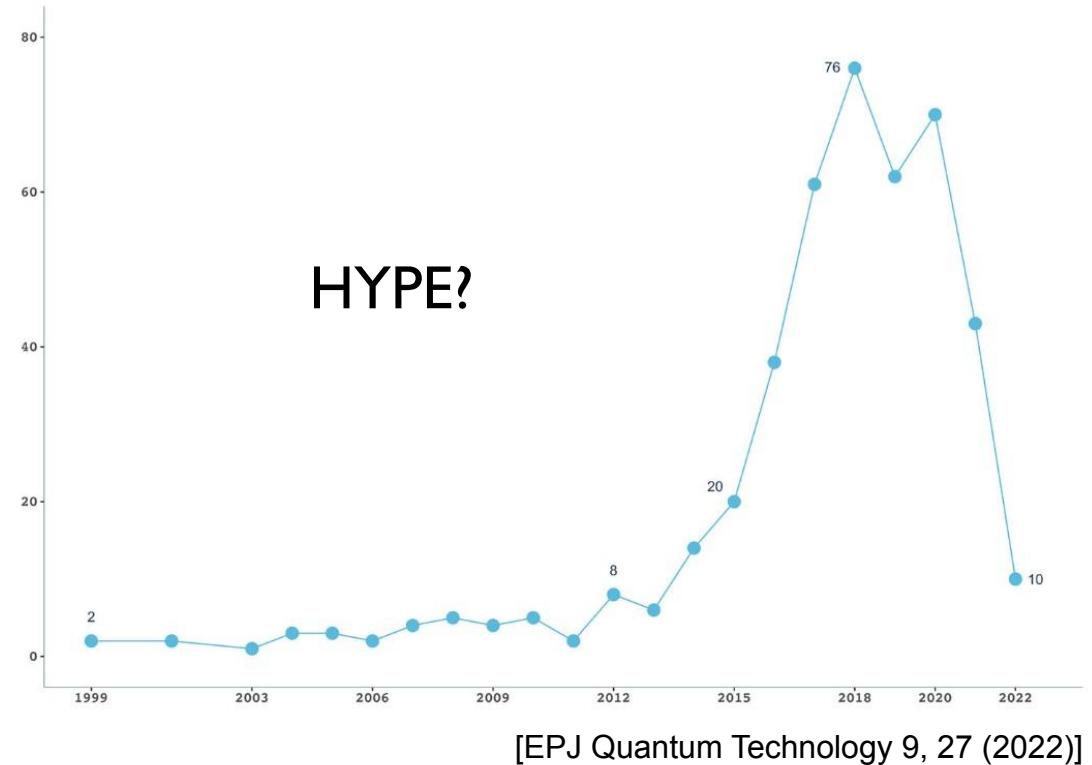


*“Si prevede che il mercato
 del quantum computing
 raggiungerà i 65 Mrd USD
 entro il 2030 dai soli 507
 Mln USD del 2019”*

[P&S Intelligence]



Numero di nuove quantum startups all'anno







Qual è l'obiettivo

QUANTUM
SUPREMACY?

Risolvere un problema con un
numero di risorse inferiori
rispetto a un computer classico

QUANTUM
ADVANTAGE



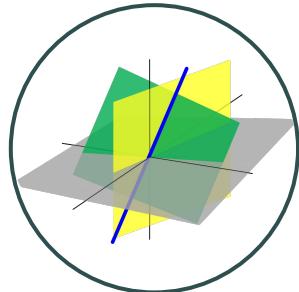
Sovrapposizione



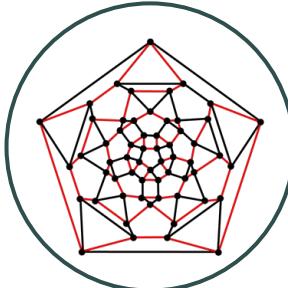
Entanglement



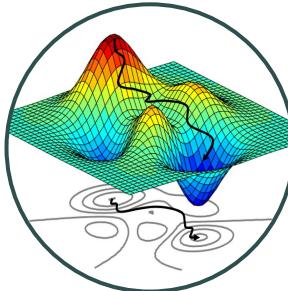
Applicazioni del quantum computing



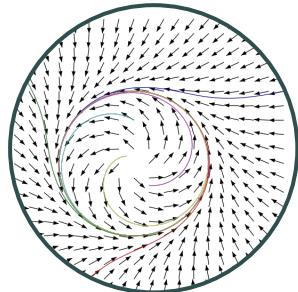
ALGEBRA
LINEARE



CALCOLO
COMBINATORIO



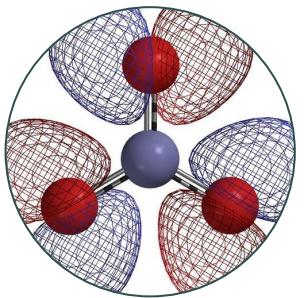
OTTIMIZZAZIONE



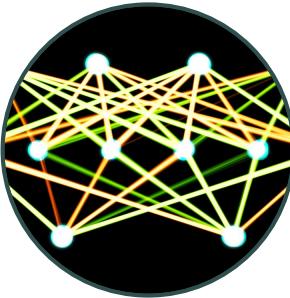
EQUAZIONI
DIFFERENZIALI



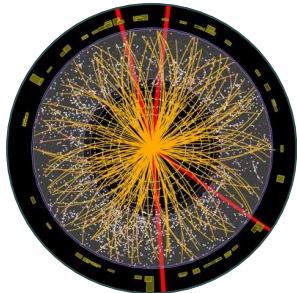
Applicazioni del quantum computing



CHIMICA
QUANTISTICA



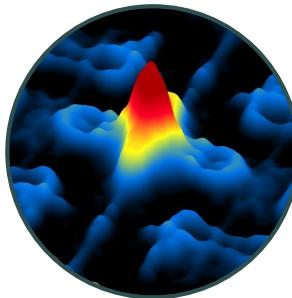
MACHINE
LEARNING



FISICA DELLE
ALTE ENERGIE



FINANZA



FISICA DELLA
MATERIA

E ALTRO ANCORA...



Algoritmo di Bernstein-Vazirani

$(x_1, x_2, \dots, x_N) \rightarrow f \rightarrow \{0, 1\}$

Determinare s ?

$$f(x) = s \cdot x \bmod 2$$

classicamente

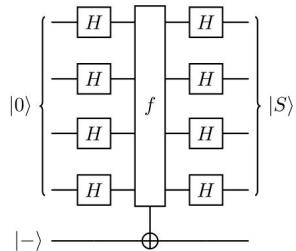
N interrogazioni



N input per determinare
 (s_1, s_2, \dots, s_N)

Bernstein-Vazirani

1 interrogazione



QUANTUM
ADVANTAGE!



Algoritmo di Shor

Fattorizzazione un
numero intero

Quantum advantage

classicamente
~esponenziale



Shor
 $\log N$

IBM Q [Phys. Rev. A 100, 012305 (2019)]

[2001] $15 = 5 \times 3$



[2012] $21 = 7 \times 3$



[2019] $35 = 7 \times 5$



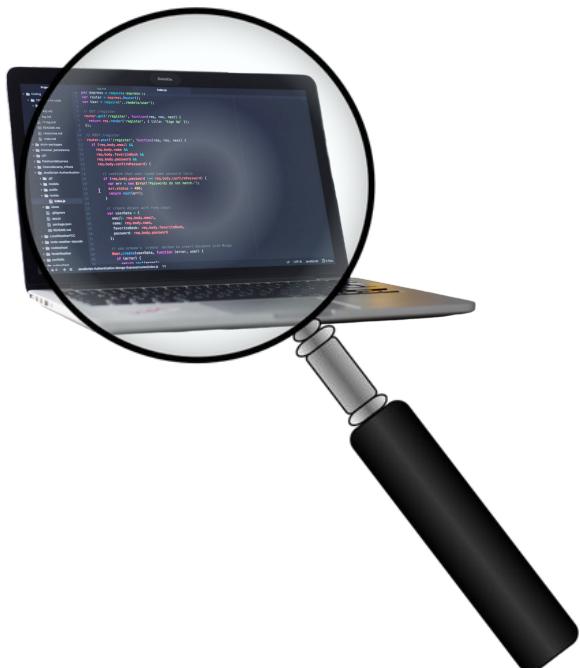
Per quale motivo



Errori hardware...



Tecnologie classiche per la computazione



CPU



HDD



SSD



GPU

Interazione
elettromagnetica per
codificare e manipolare
l'informazione



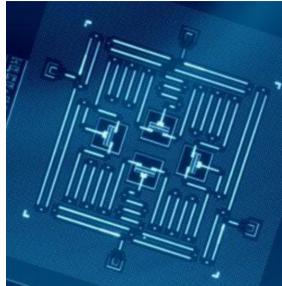
CAMBIAMO SCALA!



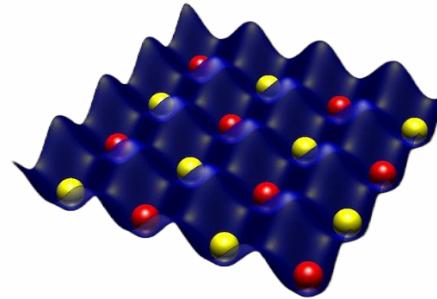


Tecnologie quantistiche per la computazione

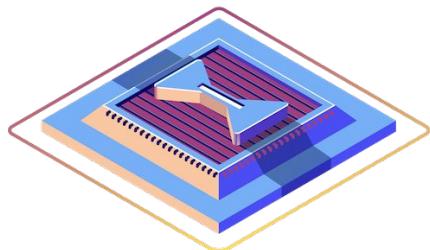
CIRCUITI SUPERCONDUTTORI



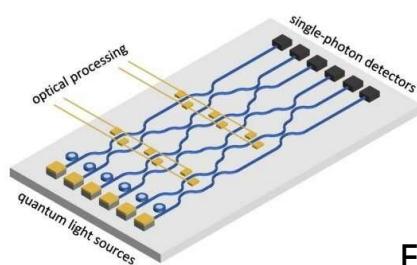
ATOMI NEUTRI



IONI INTRAPPOLATI



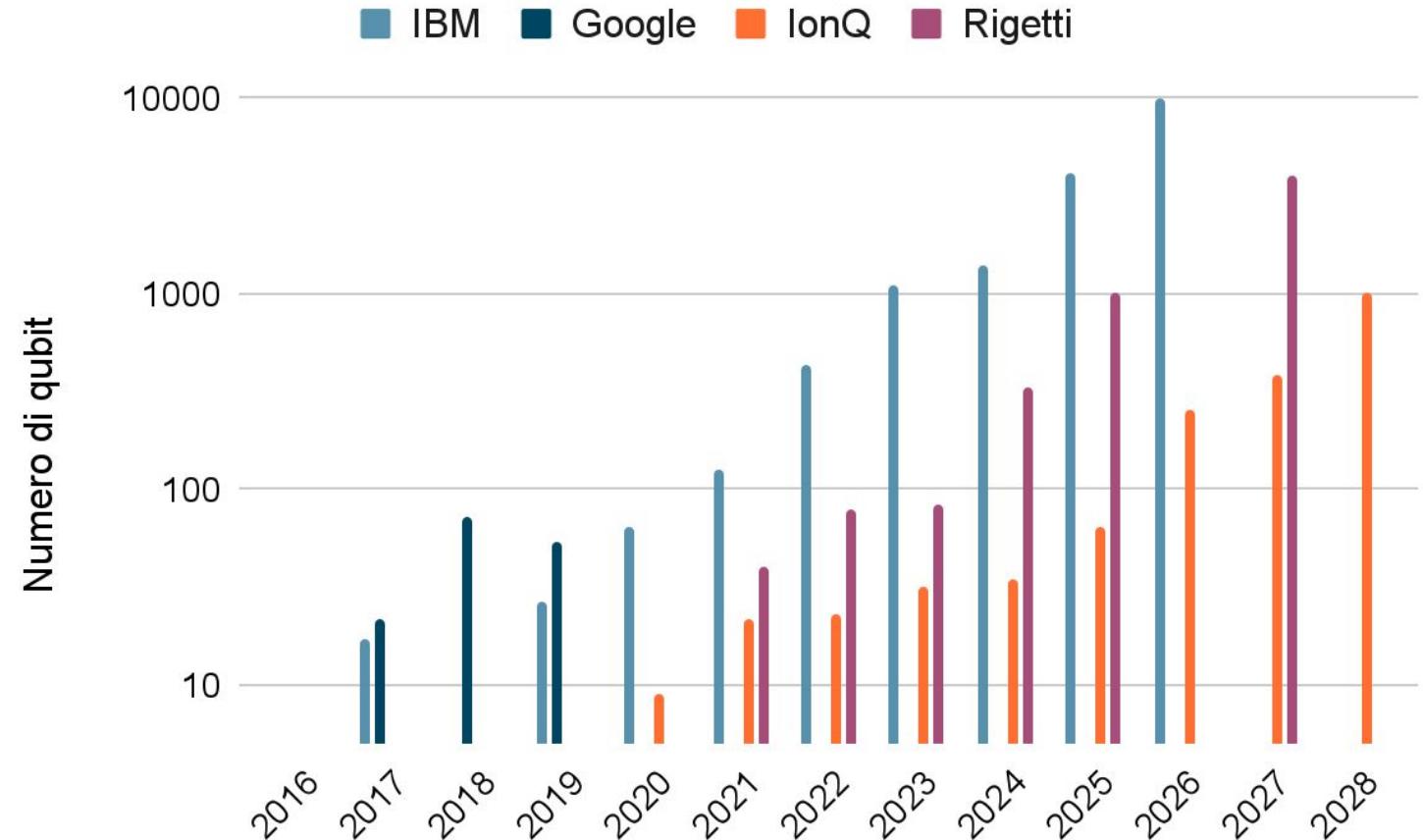
FOTONI



E ALTRO ANCORA...

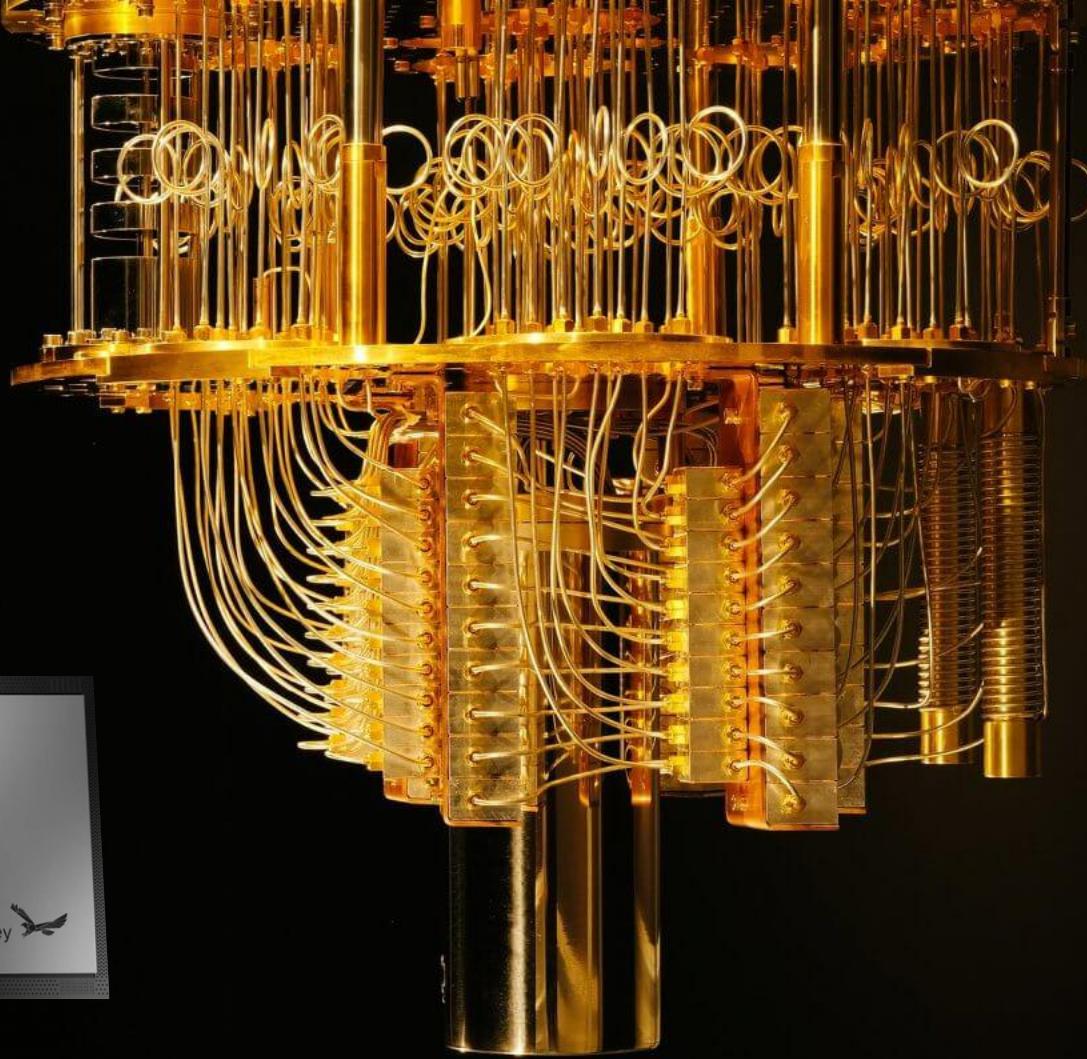
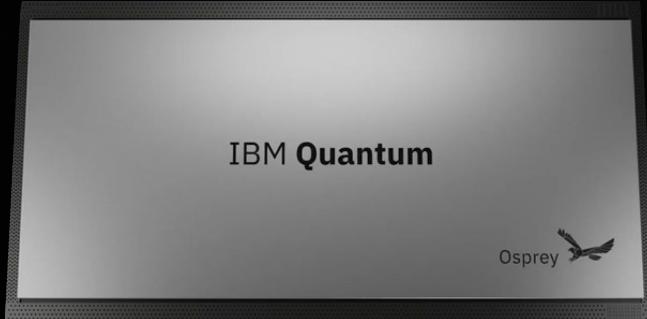


Roadmap



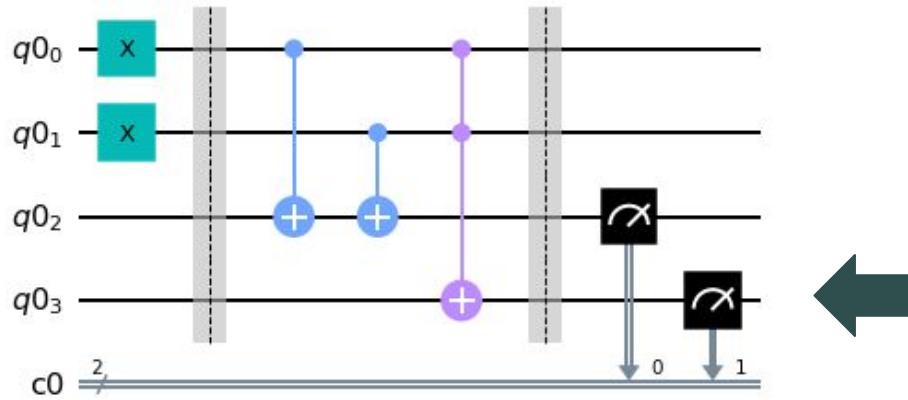


433 qubit





1+1 = ?



Quantum
half-adder

Tabella logica

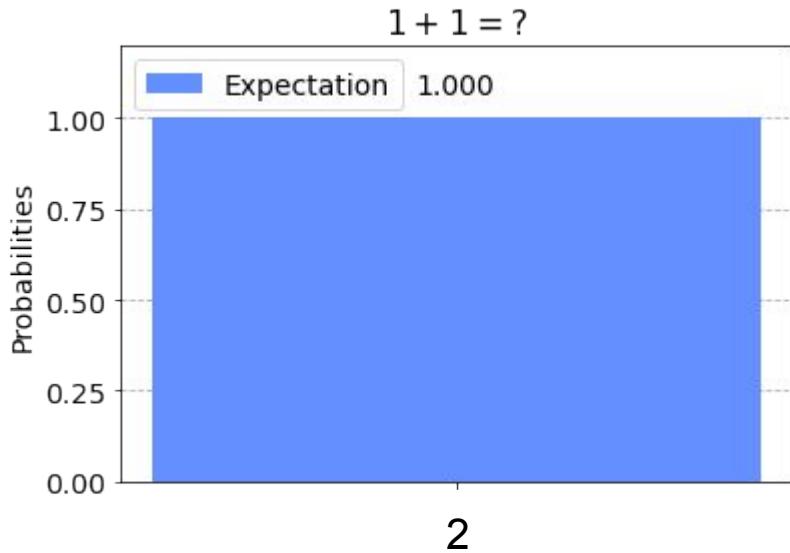
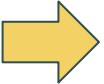
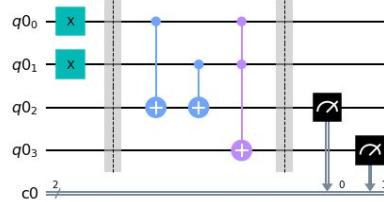
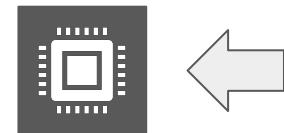
Input 1	Input 2	Output
0	0	0 (00)
0	1	1 (01)
1	0	1 (01)
1	1	2 (10)



Sistema chiuso

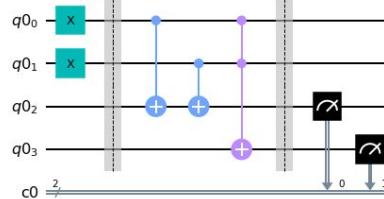
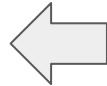
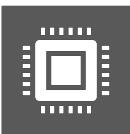


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Sistema aperto

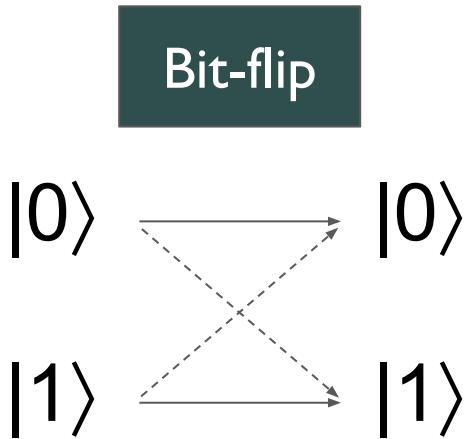




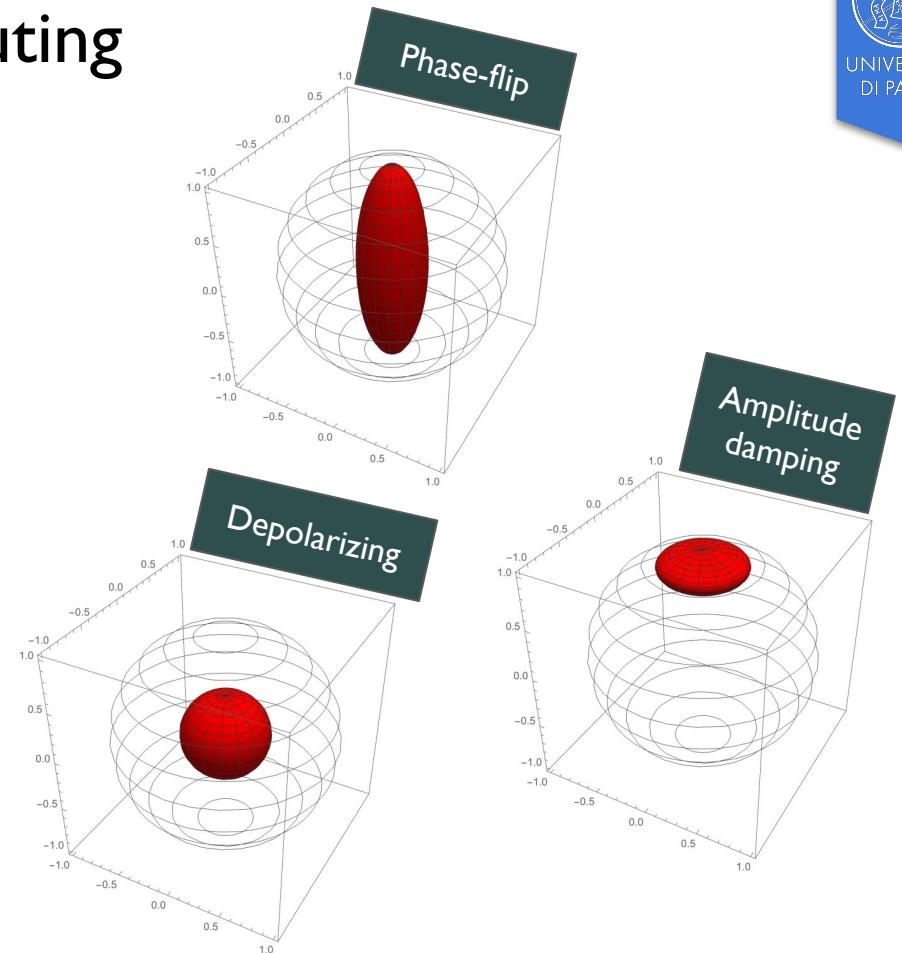
Rumore nel quantum computing



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Stato invertito con una
certa probabilità





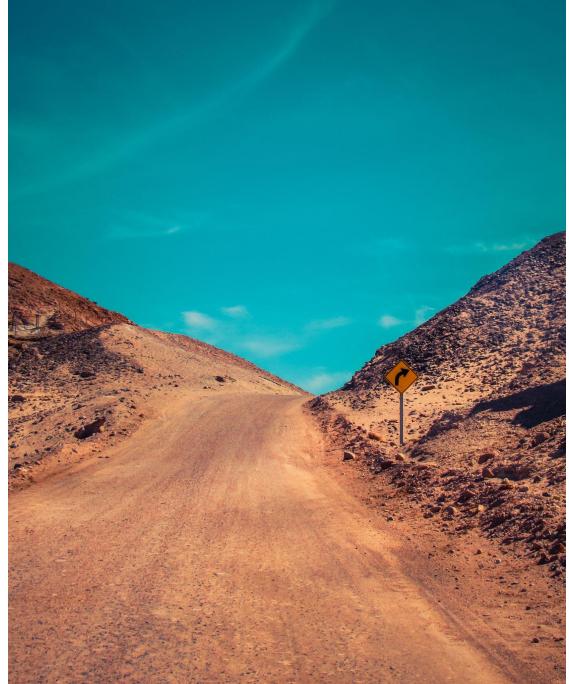
Noisy Intermediate-Scale Quantum Era (NISQ)



Expectation



Error-tolerant quantum
advantage

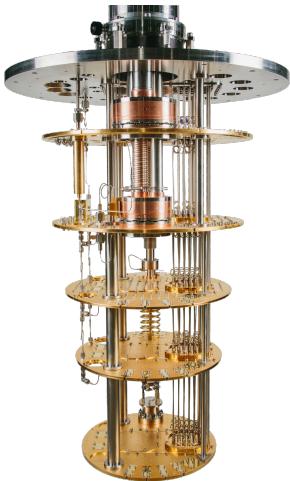
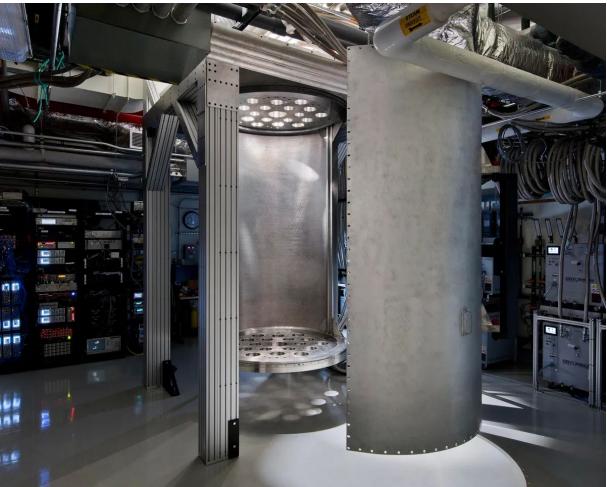


Reality



Come ridurre il rumore?

Hardware



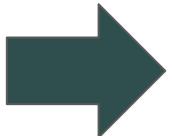


Come ridurre il rumore?

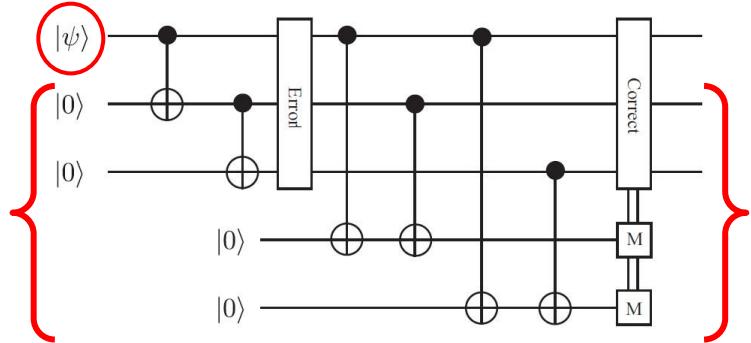
Software



Fare un backup
dello stato?



Quantum Error
Correction



Correzione “al volo”



Il numero di qubit aumenta



Come ridurre il rumore?

Software



Noise
Deconvolution



Riduzione
post-processing del
rumore

$$\langle O \rangle_{\mathcal{N}(\rho)} = \rho \xrightarrow{\mathcal{N}_{\text{Pauli}}} \xrightarrow{O} \quad (a)$$

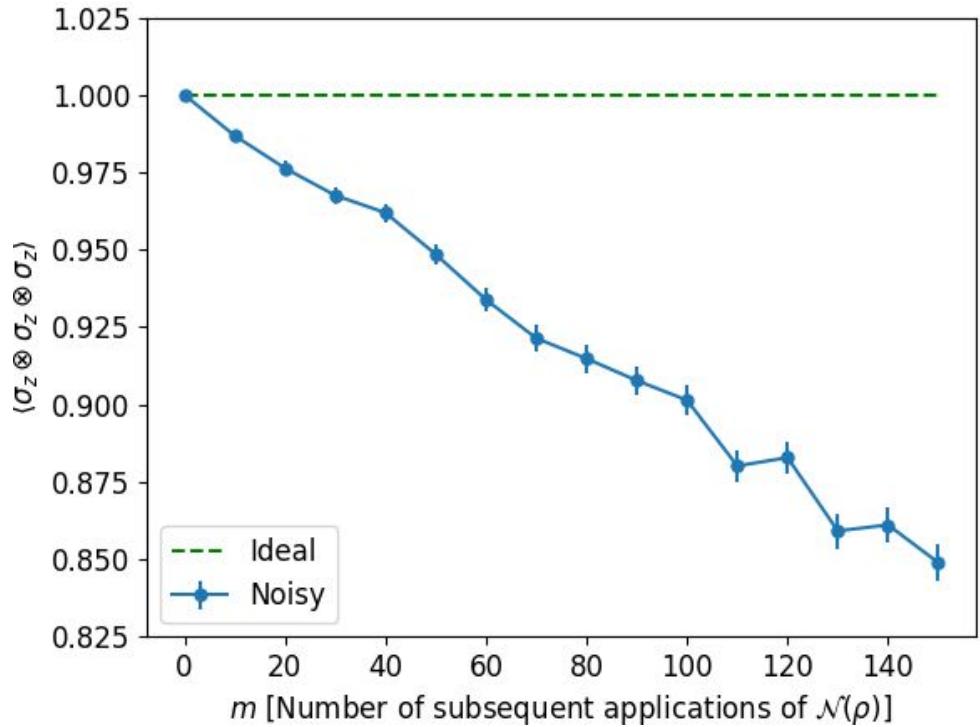
$$\langle O \rangle_{\rho} = \sum_{k=0}^{d^2-1} \frac{O_k}{\Gamma_{kk}} \times \rho \xrightarrow{\mathcal{N}_{\text{Pauli}}} \xrightarrow{\mathcal{P}_k} \quad (b)$$

🎯 Correzione all'analisi dei dati

✓ Il numero di qubit **NON** aumenta

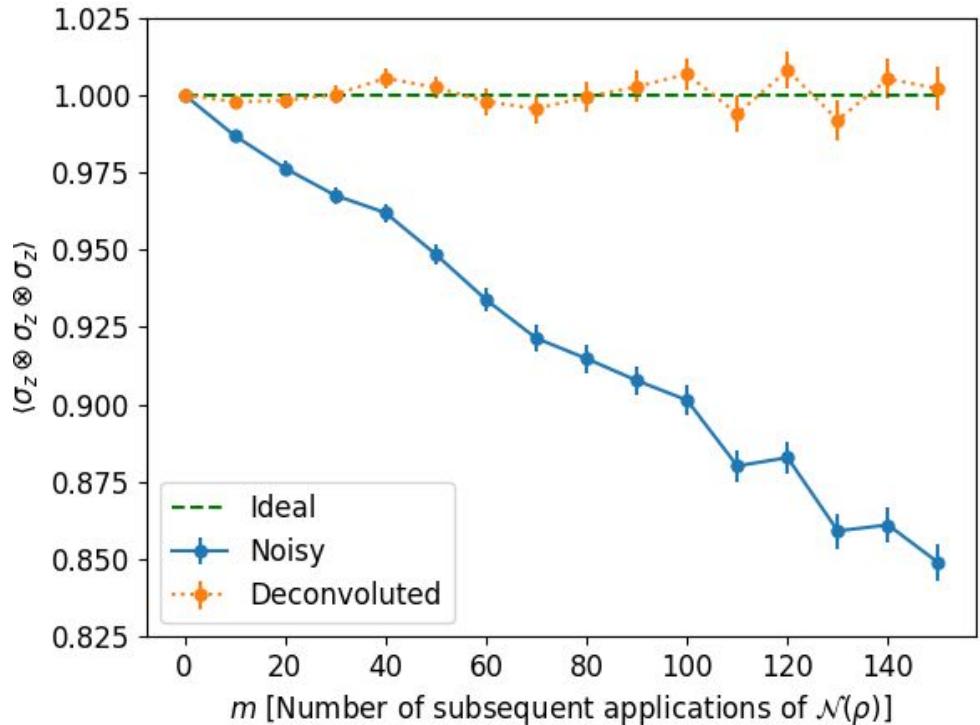


Noise Deconvolution





Noise Deconvolution

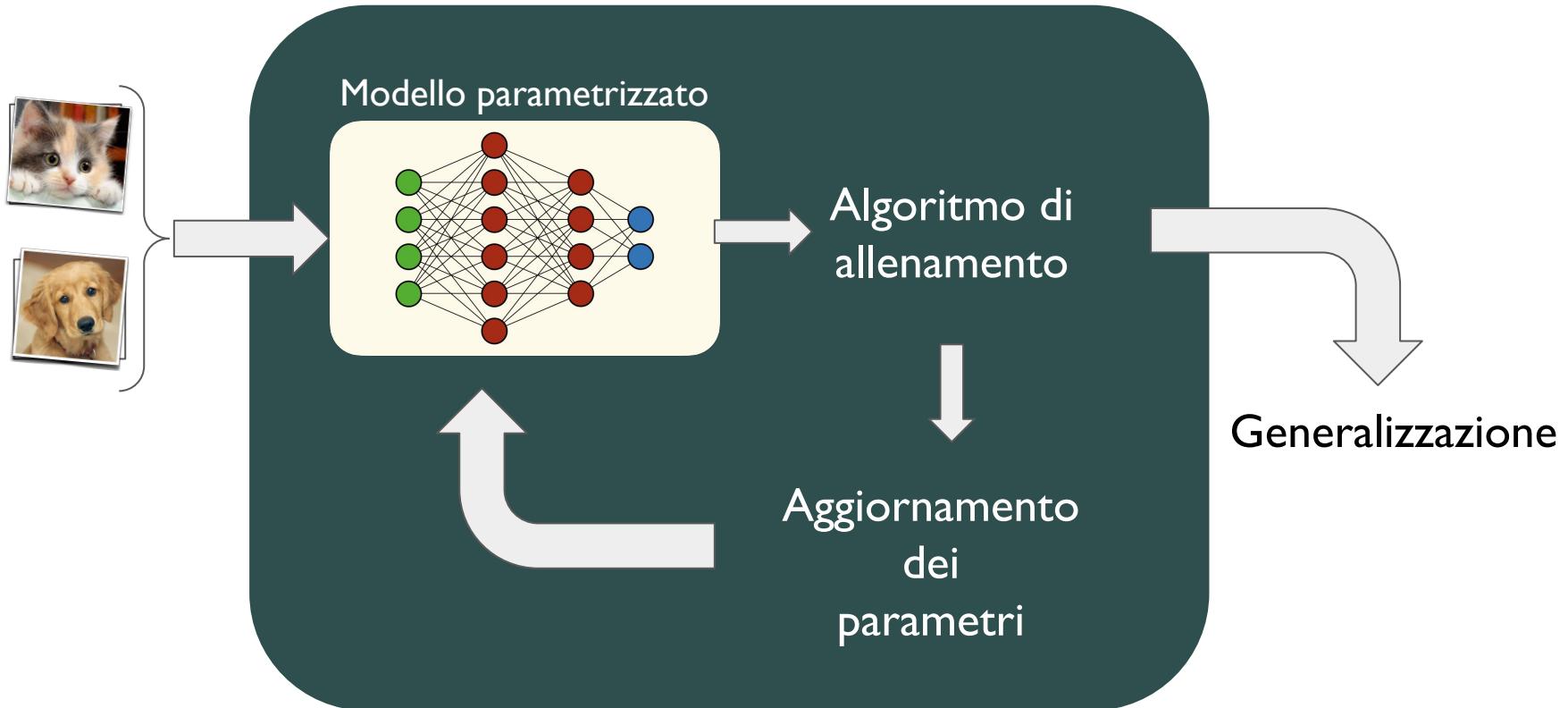


Machine Learning



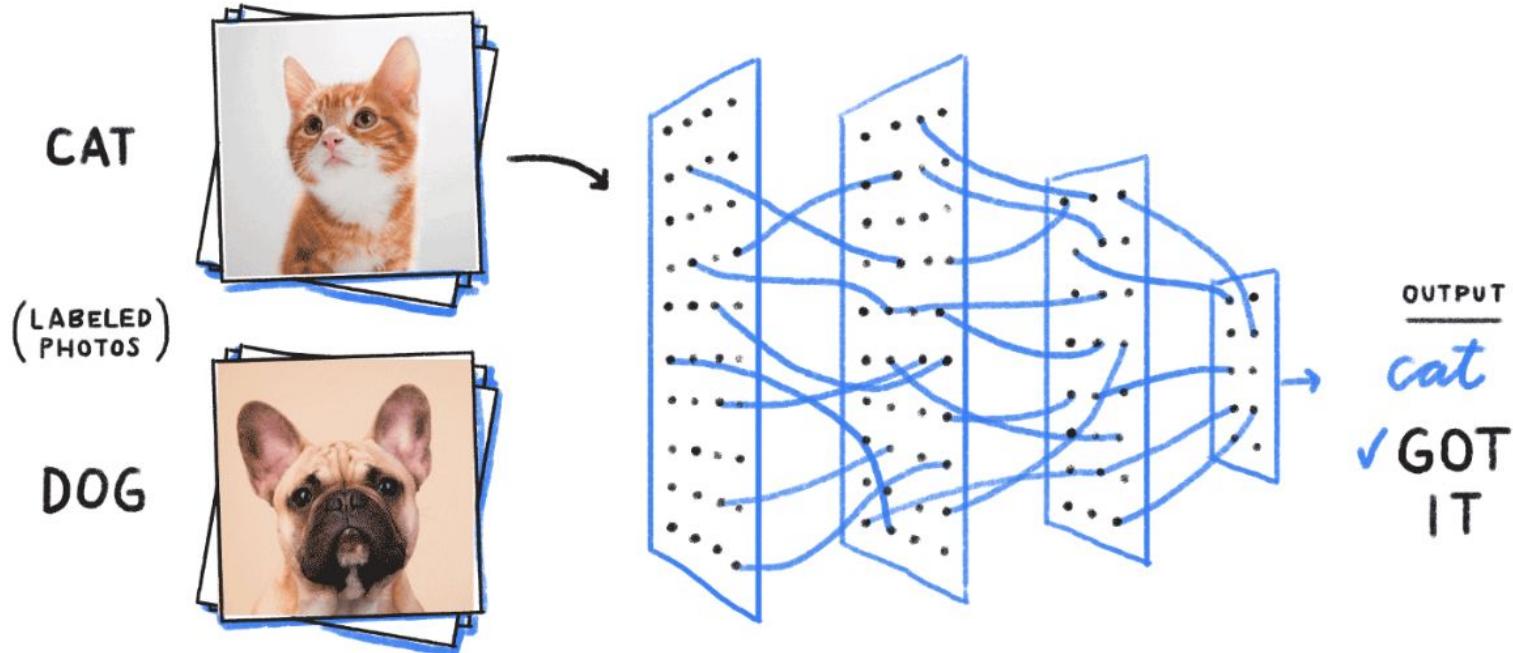


Schema generale





Generalizzazione



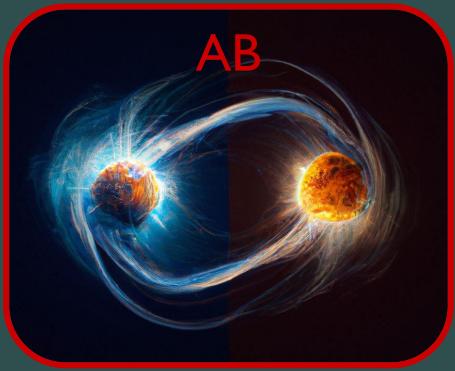


Entanglement

STATI ENTANGLED



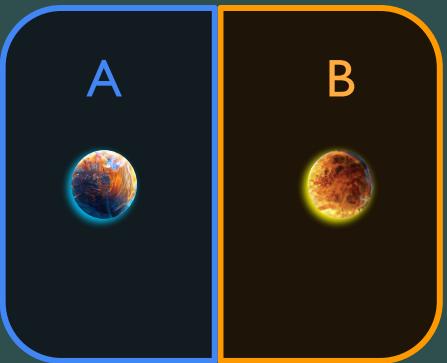
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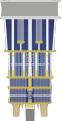


STATI SEPARABILI



I sistemi possono essere descritti da
funzioni d'onda separate distinte





Computer quantistico per analisi di stati quantistici



"La natura non è classica, e se vuoi fare una simulazione della natura, faresti meglio a renderla quantistica... è un problema meraviglioso, perché non sembra così facile."

Richard Feynman



QUANTUM COMPUTING

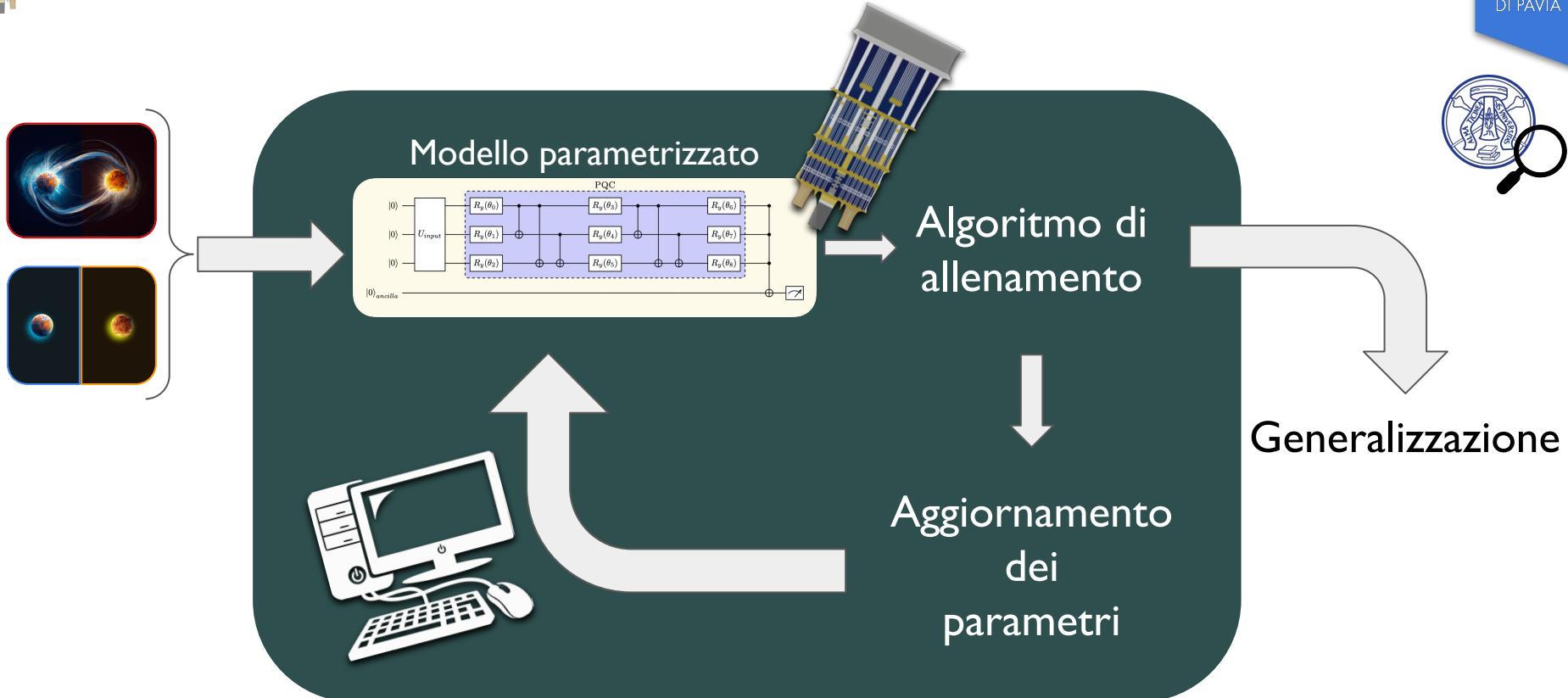
MACHINE LEARNING



QUANTUM MACHINE LEARNING



Distinguere stati quantistici





Take home message



- Si può sfruttare la meccanica quantistica per fare **computazione**
- L'obiettivo è ottenere **QUANTUM ADVANTAGE**
- Gli attuali hardware sono **RUMOROSI**
- Ci sono **tecniche** sia sperimentali che teoriche **per ridurre il rumore**
- Si possono combinare Quantum Computing e Machine Learning (**QML**)
- Un'ottima applicazione del QML può essere l'**analisi di stati quantistici**



Contatti

Quantum ML
e Photonics



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Quantum Noise -
Quantum Information e
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Risorse utili



UNIVERSITÀ
DI PAVIA

APPRENDIMENTO



Qiskit



Qiskit | Quantum Explorers



**XANADU QUANTUM
CODEBOOK**



ALTRO



Unitary Fund



Quantum Computing Report
Where Qubits Entangle with Commerce



Link alla presentazione



<https://github.com/fran-scala/Quantum-computing-slides>