the future is quantum

radu ionicioiu

roqnet

aims

- introducing basic notions of q.technologies, q.information
- understand fundamental concepts and protocols (superposition, entanglement, teleportation etc)
- familiarise with state-of-the-art devices used in q.communications, q.technologies

outline

- I. the future is quantum
  overview of quantum technologies
- II. quantum information: foundations and entanglement
  qubit, quantum gates, entanglement
- III. quantum mechanics: protocols and applications
  teleportation, entanglement swapping, quantum cryptography

bibliography

1. P.Kaye, R.Laflamme, M.Mosca, *An Introduction to Quantum Computing*, Oxford University Press, 2007

2. M.Nielsen, I.Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, 2000

3. V.Vedral, *Introduction to Quantum Information Science*, Oxford University Press, 2006

4. N.Yanofsky, M.Manucci, *Quantum Computing for Computer Scientists*, Cambridge University Press, 2008

5. J.Preskill, *Quantum Computation*, http://theory.caltech.edu/∼preskill/ph229/

6. M.Loceff, *A course in quantum computing*, pdf here

about myself

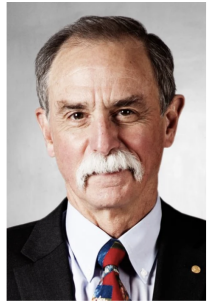
- theoretical physicist, 25+ yrs experience in q.info/q.tech, 4 QKD patents (HP Labs)
- senior researcher (CS I) at IFIN-HH
  https://web.theory.nipne.ro/index.php/rionicioiu-home
- founder of RoQnet, https://roqnet.ro
- member of Strategic Advisory Board, Quantum Flagship
- project director QUTECH-RO, QTSTRAT
- contact: r.ionicioiu@roqnet.ro

The Nobel Prize in Physics 2012

© The Nobel Foundation. Photo: U. Montan

Serge Haroche

Prize share: 1/2



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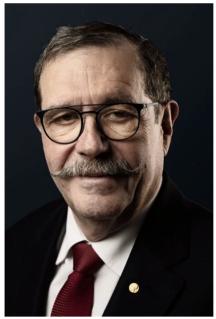
David J. Wineland

Prize share: 1/2

”for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems”

https://www.nobelprize.org/prizes/physics/2012/summary/

The Nobel Prize in Physics 2022



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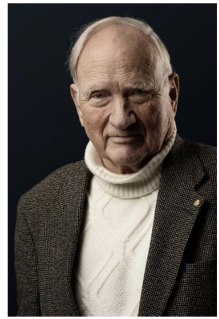
Alain Aspect

Prize share: 1/3



© Nobel Prize Outreach. Photo: Stefan Bladh

John F. Clauser

Prize share: 1/3

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Anton Zeilinger

Prize share: 1/3

”for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”

https://www.nobelprize.org/prizes/physics/2022/summary/

what are quantum technologies

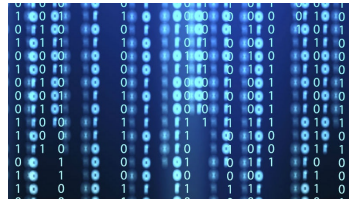
and

why you need them?

revolutions

a historical perspective

1.0: industrial	2.0: electronics	3.0: digital
work as a resource	electricity as a resource	information as a resource



two key points

KP 1: science drives technology

new science $\Rightarrow$ *new technologies*

KP 2: it's all about resources

harnessing resources is key

generate, transport, control, transform, use

quantum

the driving technology of the 21st century

the art of controlling

individual quantum systems

to perform useful tasks

quantum resources

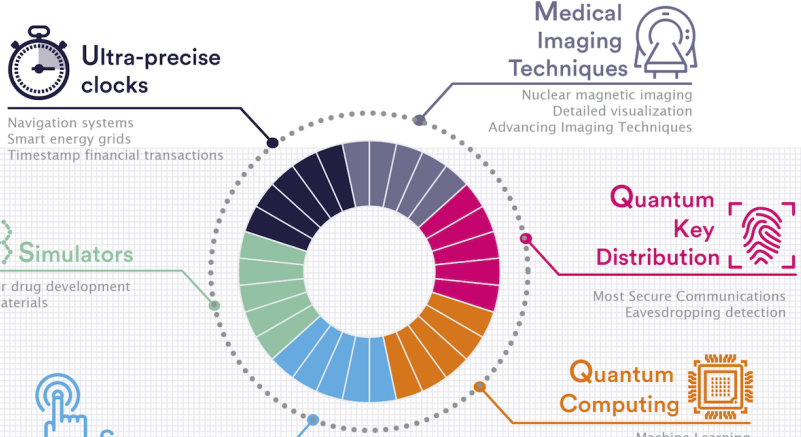
superposition, entanglement, nonlocality, duality

quantum features:

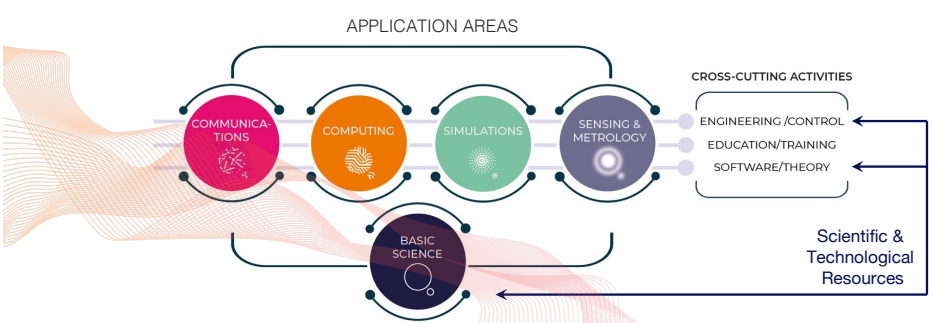
- cannot be explained classically
- essential for quantum technologies
- goal: harness quantum systems for useful tasks

generate, transport, control, transform, use

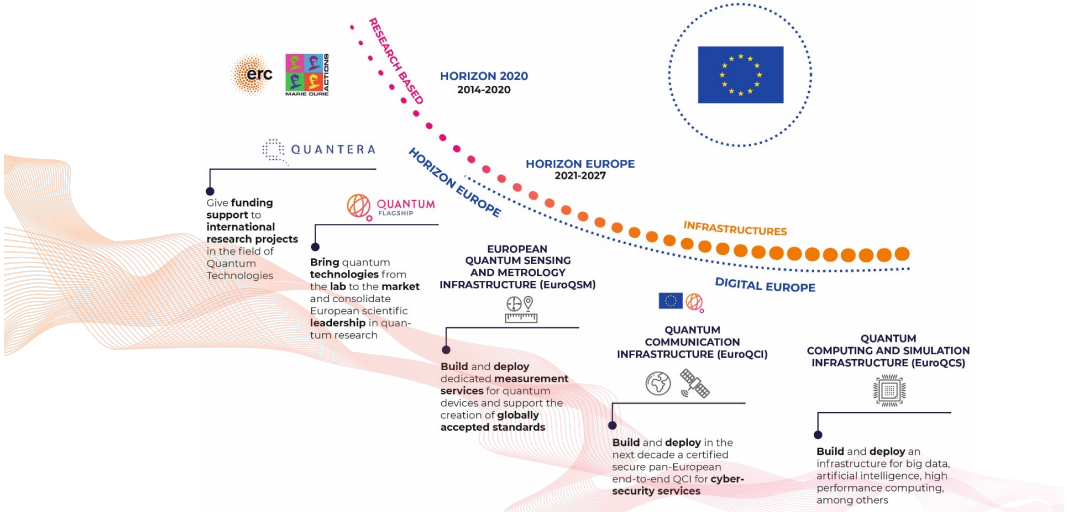
Quantum Technology Applications



The Quantum Flagship
Structuring activities & efforts

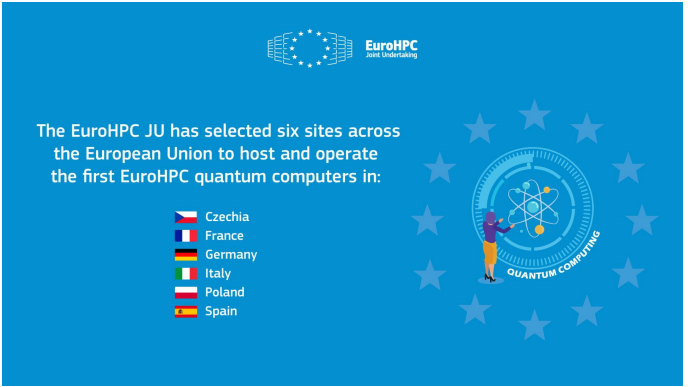


From Flagship to Fleet



EuroQCS

- 6 sites across EU
- applications
  - molecular simulations: new medicines
  - new materials: batteries
  - traffic optimisation: maps
  - logistics: eMAG
  - scheduling: Bolt Glovo
- R&D, industry need quantum computers



BASF We create chemistry · BMW GROUP · BOSCH · T · infineon · Lufthansa Industry Solutions · MERCK · SAP · SIEMENS · VOLKSWAGEN AKTIENGESELLSCHAFT

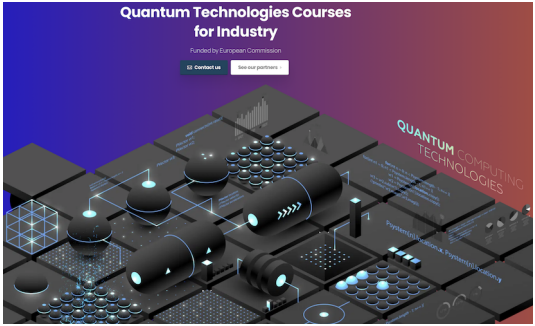
EU quantum ecosystem

QTEdu
QUANTUM TECHNOLOGY EDUCATION

https://qtedu.eu

EuroQuIC
European Quantum Industry Consortium

https://www.euroquic.org



https://qtindu.eu

QT1: quantum communications

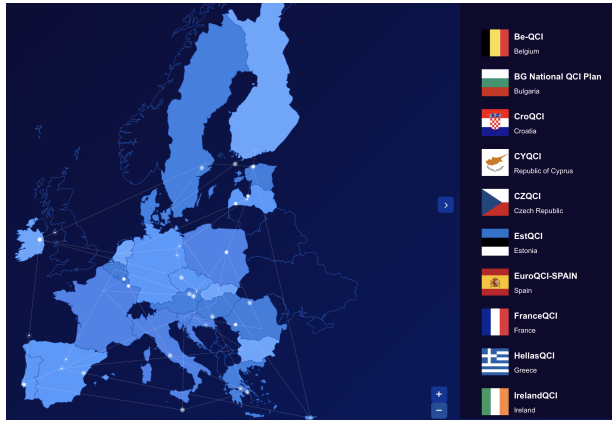
quantum computers will break internet security

- secure communications
- digital signatures
- mobile networks
  5G, 6G, ...
- financial transactions
  mobile banking, POS, e-commerce
- authentication
- critical infrastructure
- blockchain
  bitcoin, ethereum, ...
- software updating
  cars, computers

$\Rightarrow$ *need to avoid the quantum apocalypse (Q-Day)*

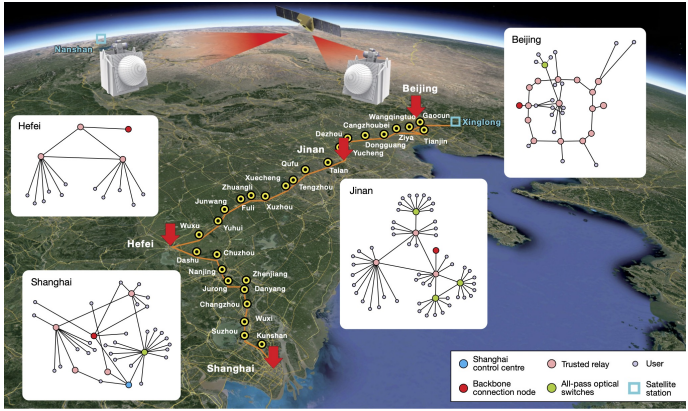
Petrus: building EuroQCI

- network of 27 national QCIs
- fiber + free-space links
- cross-border links



China

Beijing-Shanghai quantum backbone, 2000 km (≃ Bucharest-Brussels)



- Hefei: 46 nodes intra-city quantum network

(4th gen. crypto machine)

China

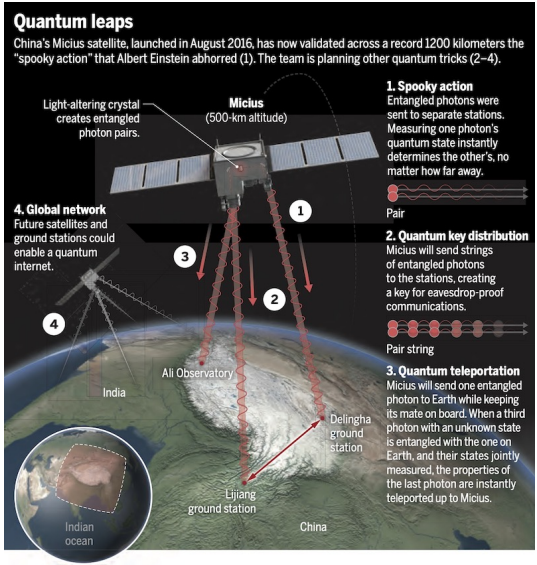
space

2016: Mozi/Micius satellite

- 635 kg, $100 Mil.
- QKD
- entanglement distribution
- teleportation

2022: Jinan-1 satellite

- < 100 kg
- key rate 10^2-$10^3\times$ Mozi



Science (16 June 2017)

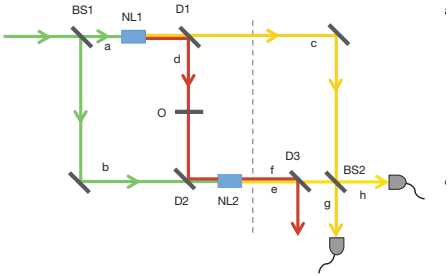
QT2: quantum imaging

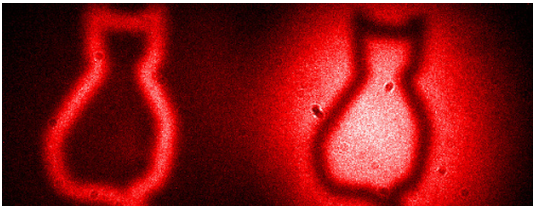
LETTER

doi:10.1038/nature13586

Quantum imaging with undetected photons

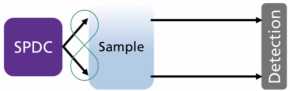
Gabriela Barreto Lemos[1,2], Victoria Borish[1,3], Garrett D. Cole[2,3], Sven Ramelow[1,3]†, Radek Lapkiewicz[1,3] & Anton Zeilinger[1,2,3]





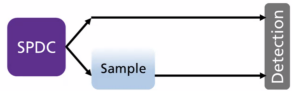
Nature **512**, 409 (2014)

quantum imaging: 3 ways



Entanglement based

- ETPA fluorescence microscopy
  - N00N state microscopy
- Low photo toxicity
  - More efficient fluorescence excitation



Correlation based

- Ghost imaging
  - Biphoton imaging
- Noise reduced imaging
  - Extend exploitable spectral range

Interference based

- Imaging with undetected light
- Sensing in exotic spectral ranges

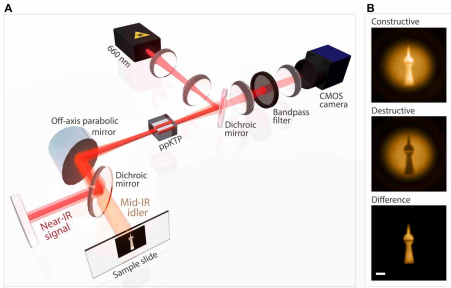
Gilaberte Basset *et al.*, https://doi.org/10.1002/lpor.201900097

IR microscopy with visible light

OPTICS

Microscopy with undetected photons in the mid-infrared

Inna Kviatkovsky[1]*, Helen M. Chrzanowski[1], Ellen G. Avery[2,3,4,5,6,7], Hendrik Bartolomaeus[2,3,4,5,6], Sven Ramelow[1,8]

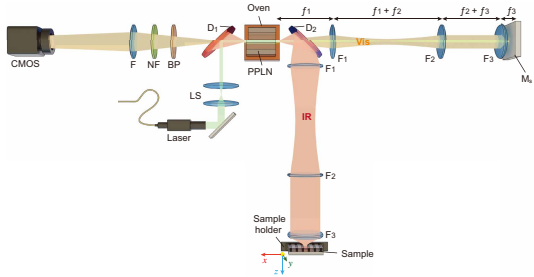


Sci.Adv. **6**, eabd0264 (2020)

OPTICS

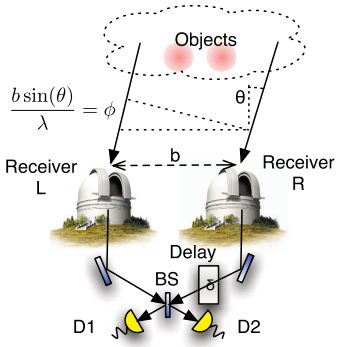
Hyperspectral infrared microscopy with visible light

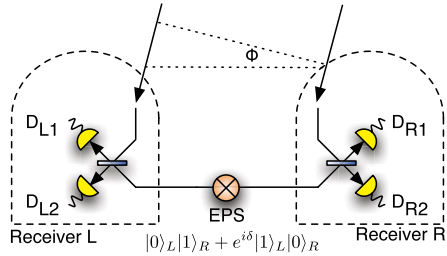
Anna V. Paterova[1], Sivakumar M. Maniam[2,3], Hongzhi Yang[1], Gianluca Grenci[2,4]*, Leonid A. Krivitsky[1]*



Sci.Adv. **6**, eabd0460 (2020)

quantum-enhanced VLBI





P. Riaud, Eur. Phys. J. D **66**, 8 (2012)

D. Gottesman *et al.*, PRL **109**, 070503 (2012)

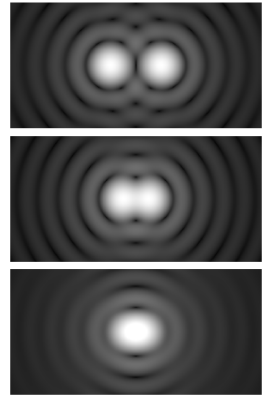
beating the Rayleigh curse

- Rayleigh criterion: artefact of the imaging system
- info is contained in the phase, but imaging is done in intensity
- parameter estimation: Cramér-Rao bound

$$MSE(\theta) \geqslant \frac{1}{F(\theta)}$$

MSE: mean-square error

F: Fisher information



Tsang *et al.*, PRX **6**, 031033 (2016); Bojer *et al.*, New J. Phys. **24**, 043026 (2022)

Nair & Tsang, PRL **117**, 190801 (2016); Lupo & Pirandola, PRL **117**, 190802 (2016)

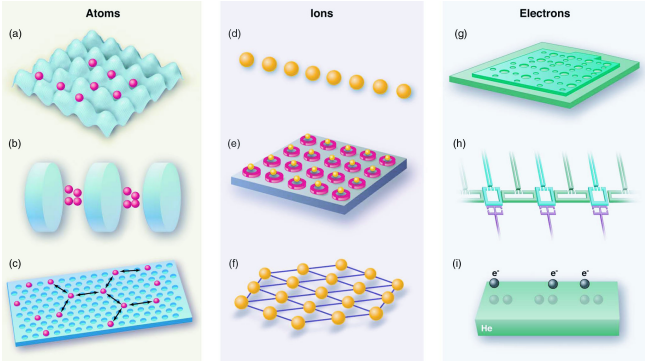
QT3: quantum simulation

Feynman

simulating quantum systems on classical computers is exponentially difficult

$2n$ *vs.* 2^n

- complex molecules
  ⇒ faster drug development
- new materials
- better bateries



Rev.Mod.Phys **86**, 153 (2014)

QT4: quantum computation

a $65 billion industry by 2030

how to build a quantum computer

DiVincenzo's criteria

five (not so easy) steps

1. qubits — well-defined, scalable
2. low decoherence
3. state preparation — input
4. quantum gates — computation
5. measurement — output

qubit

two-level quantum system

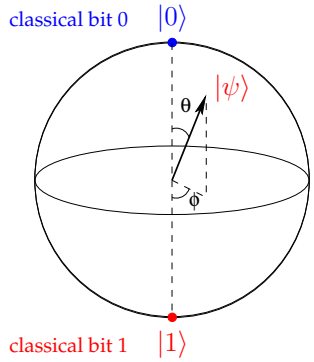
$$|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \alpha|0\rangle + \beta|1\rangle$$

$\alpha, \beta \in \mathbb{C}$

$$\begin{aligned} ||\psi||^2 &= \langle\psi|\psi\rangle = \begin{bmatrix} \overline{\alpha} & \overline{\beta} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \\ &= |\alpha|^2 + |\beta|^2 \\ &= 1 \end{aligned}$$

qubit states have norm 1

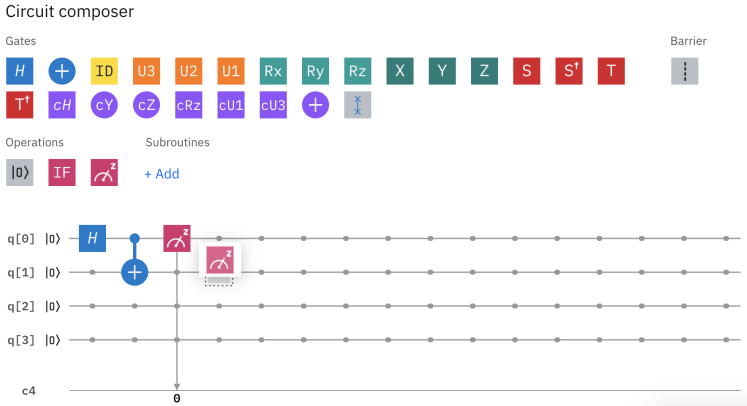
$|\psi\rangle \sim e^{i\alpha}|\psi\rangle$: *same state*



$$|\psi\rangle = \cos\tfrac{\theta}{2}|0\rangle + e^{i\phi}\sin\tfrac{\theta}{2}|1\rangle$$

quantum algorithms

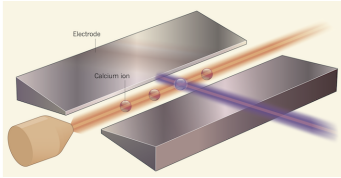
universal quantum gates: $\{H, T, CNOT\}$

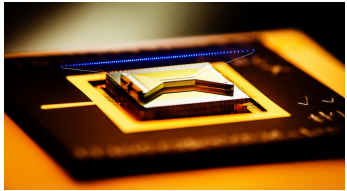


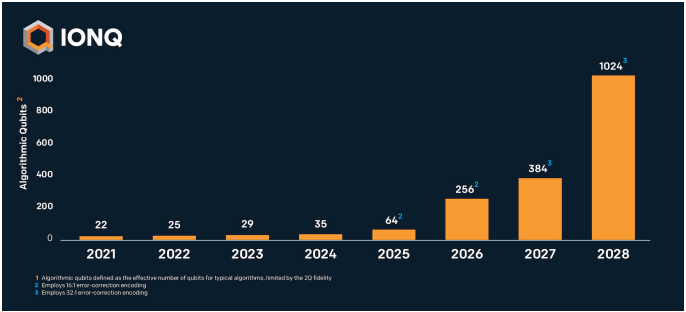
IBM Quantum Composer

qubits 1: ion traps

IonQ, AQT, Quantinuum







qubits 2: superconducting

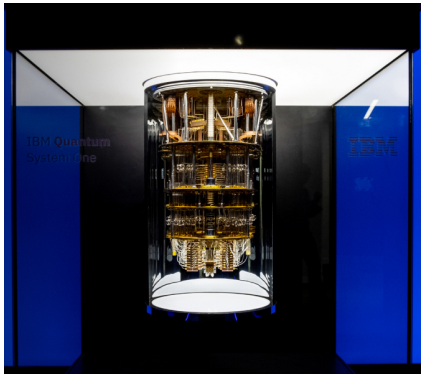
IBM Q System Two

www.ibm.com/quantum

2016: 5 qubits

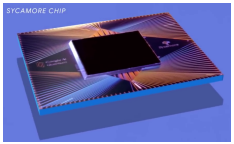
2017: 16 qubits

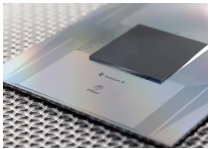
2022: $\sim$ 400 qubits



google

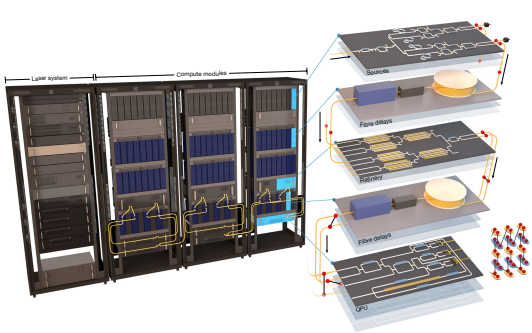
Willow: 105 qubits





qubits 3: integrated photonics

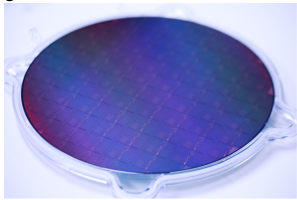
XANADU



- modular, 35 photonic chips
- 12 physical qubits

PsiQuantum

c



k

qubits 3: integrated photonics

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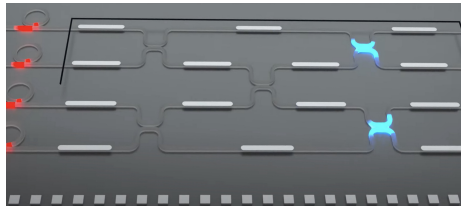
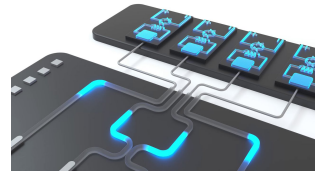
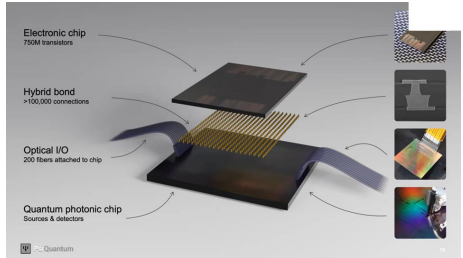
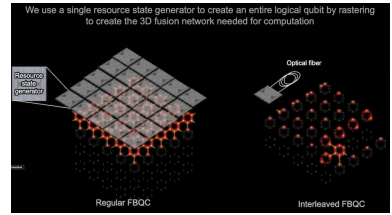




2022: Borealis 216 qubits

PsiQuantum

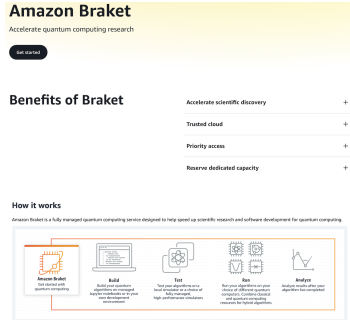




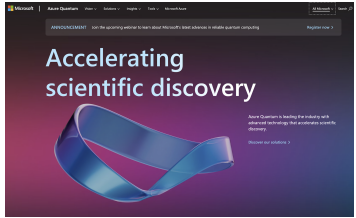
plan: 10^6 qubits

QC: cloud providers

- Amazon Braket
  - superconducting: IQM, Rigetti
  - ion traps: IonQ
  - neutral atoms: QuEra

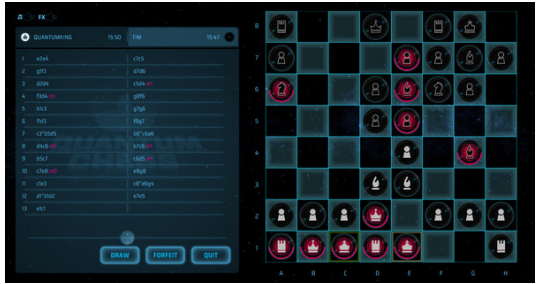


- Microsoft
  - Azure Quantum



quantum: fun and games

https://quantumchess.net



have fun with Q @youtube:

- *Anyone can Quantum* (Quantum chess): Keanu Reeves, Stephen Hawking, Paul Rudd
- *Quantum is Calling*: Zoe Saldana, Simon Pegg, Stephen Hawking

any sufficiently advanced technology is indistinguishable from magic

Arthur Clarke

quantum mechanics is magic

Daniel Greenberger

Thank you!