Experimental quantum computing with superconducting qubits

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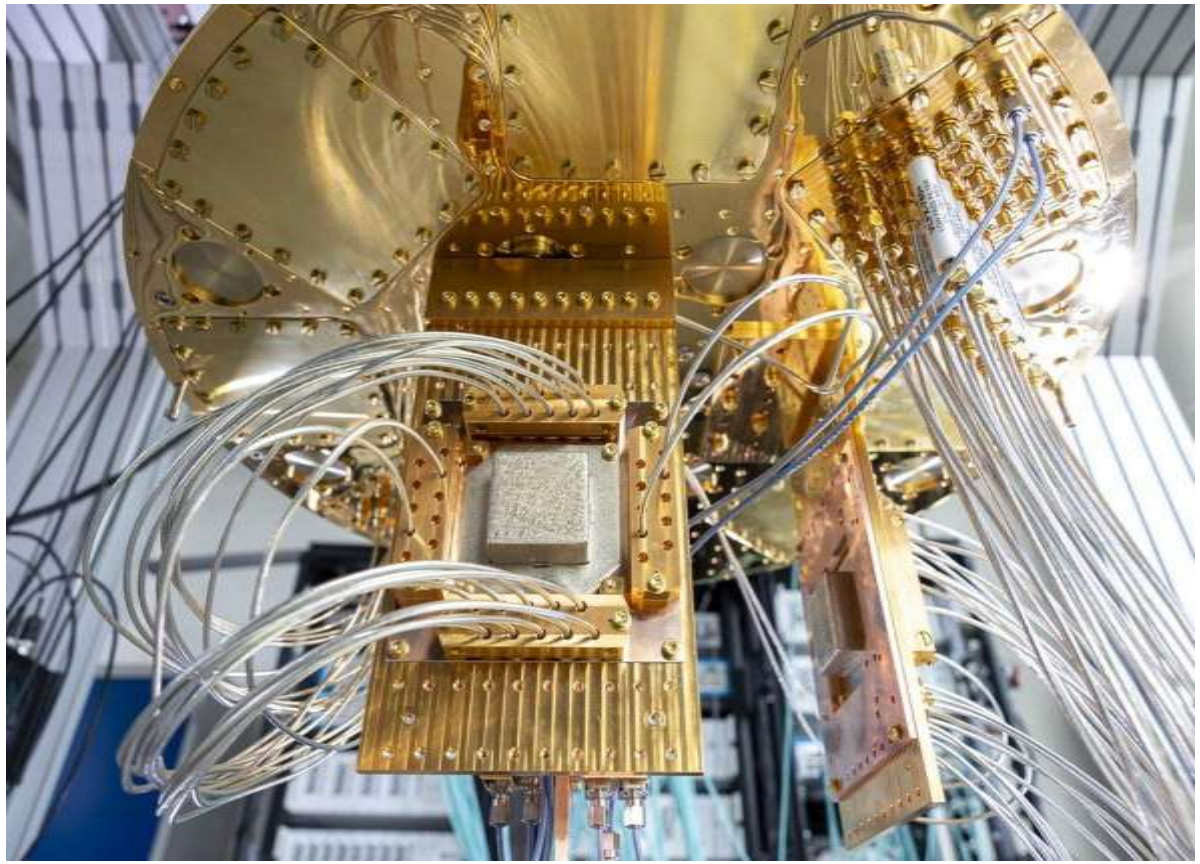
funqs.de

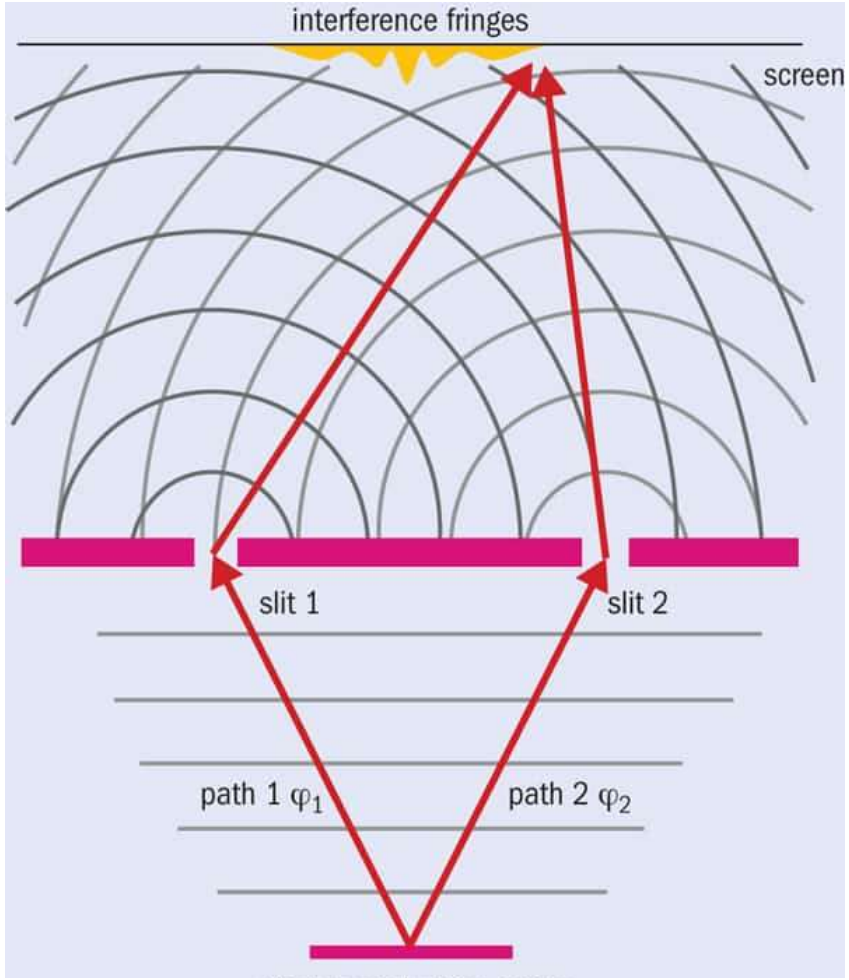


Outline

- Superposition & Entanglement
  - self-interference
  - correlation
- Quantum computing
  - Applications
- Hardware platform
  - Quantum objects
  - Superconducting qubits
  - Beyond-classical computing
- Course layout
  - Grading & Homework
  - Related courses
  - Lectures overview

Superposition & Entanglement refresh

Interference of *light*



Light source

Young's double slit experiment shows interfering paths:
Light is a wave, and has a phase

But: no individual photons

Further reading:
A. Murray, Double slits with single atoms, Physics Today, 2020

Interference of *matter*

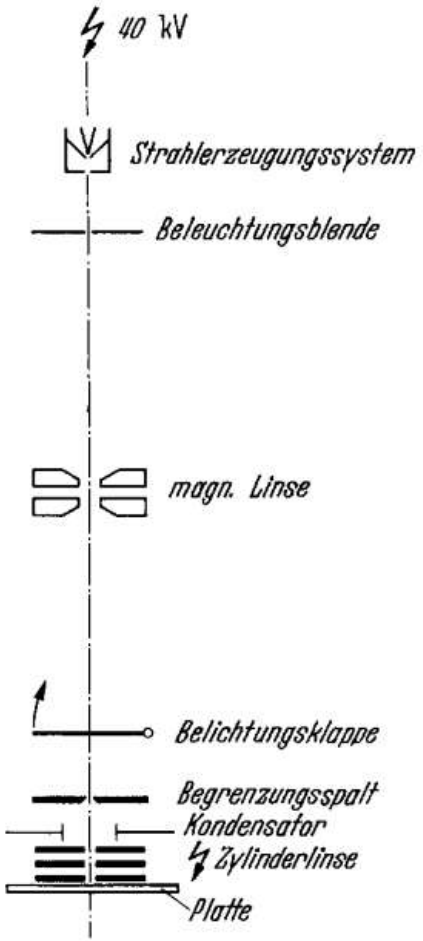
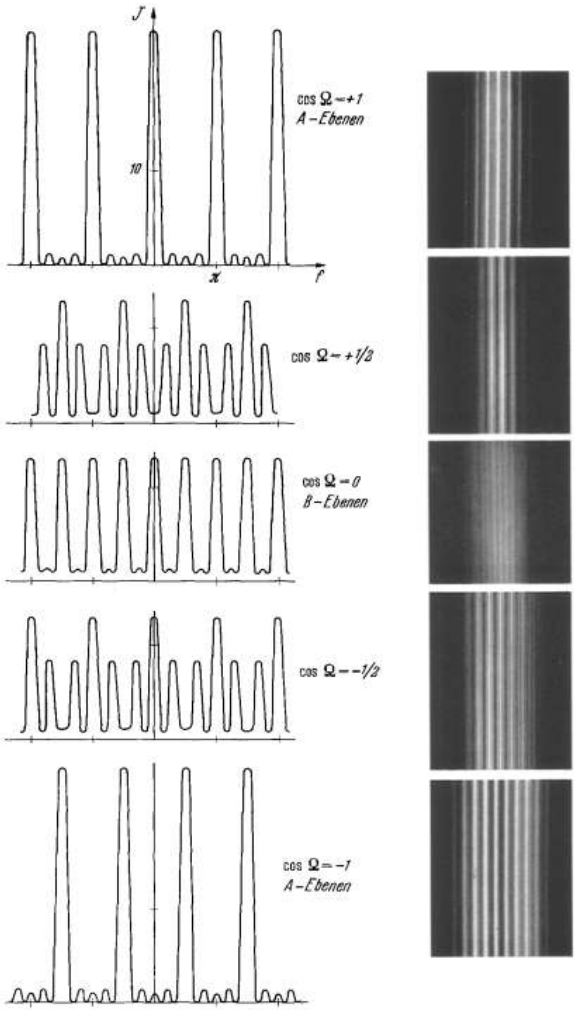


Fig. 2. Schema der Anlage zum Drucken von Polymerisatstreifen mit einer Elektronensonde



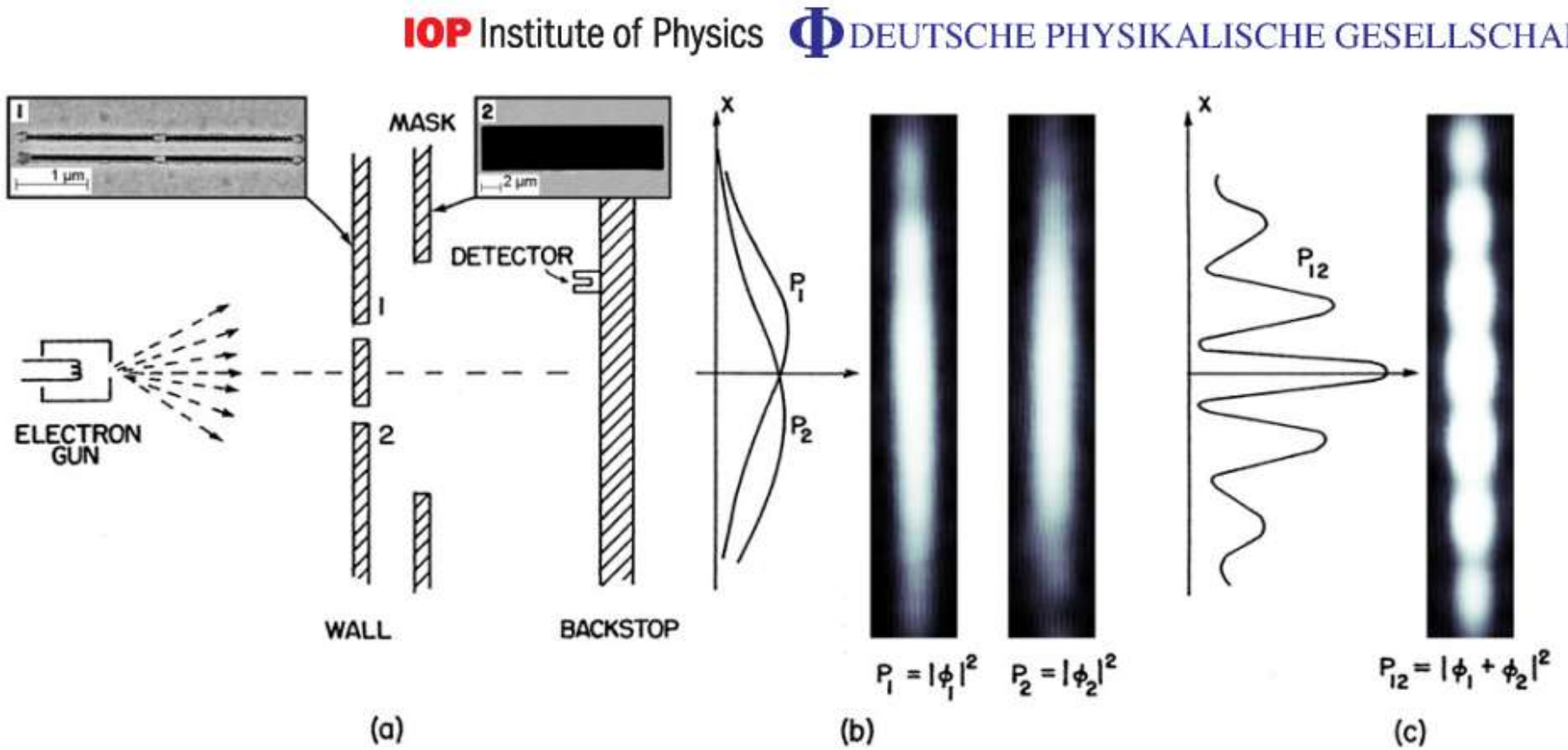
Interfering paths:
Electron beam is a wave and has a phase

But: no individual electrons

Sie stimmt mit der für die ψ-Wellen überein, womit hier für die ψ-Wellen der Anschluß an die bekannten Formeln und Ergebnisse der Lichtoptik gewonnen ist. Da in der Lichtoptik die Intensitätsverteilung der Interferenzerscheinungen durch $\mathfrak{A}\mathfrak{A}^*$ wiedergegeben wird, beschreibt insbesondere auch hier die Norm $\psi\psi^*$ die Intensitätsverteilung bei Elektroneninterferenzen.

Joensson, Zeitschrift fuer Physik 161, 454--474 (1961)

Interference of *matter*

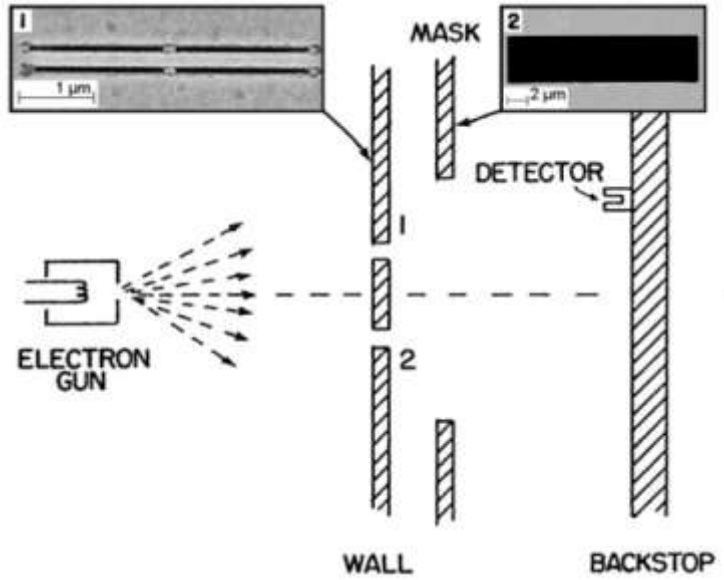


Then they decreased the power...

Bach et al 2013 New J. Phys. 15 033018 (2013)

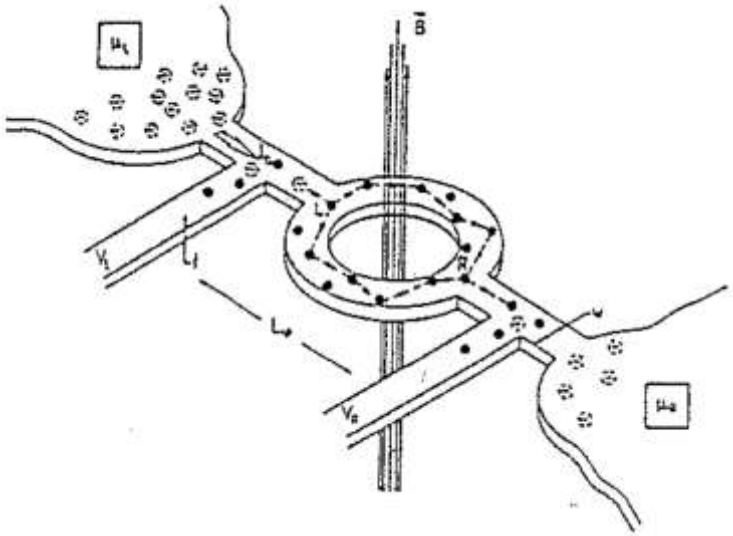
Interference of single particles of *matter*

single electron every 1.2 sec, 2 hour timelapse



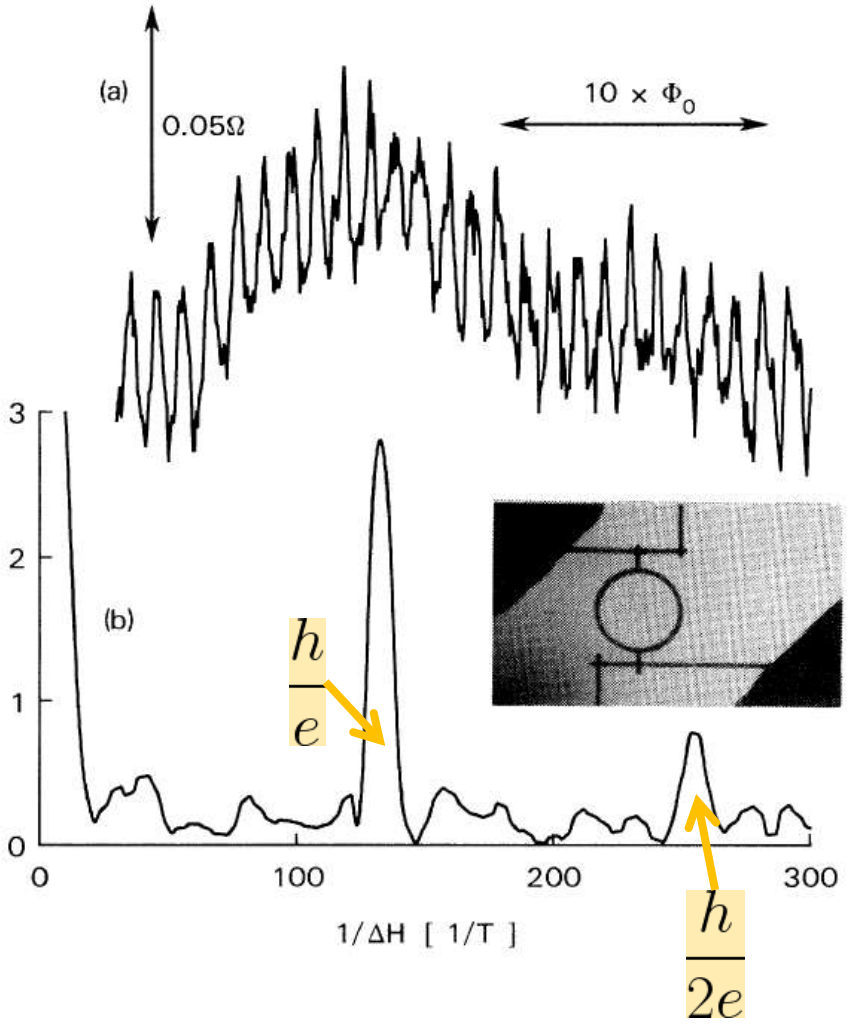
Bach et al 2013 New J. Phys. 15 033018 (2013)

Aharonov-Bohm oscillations
Electron interference in a solid state system



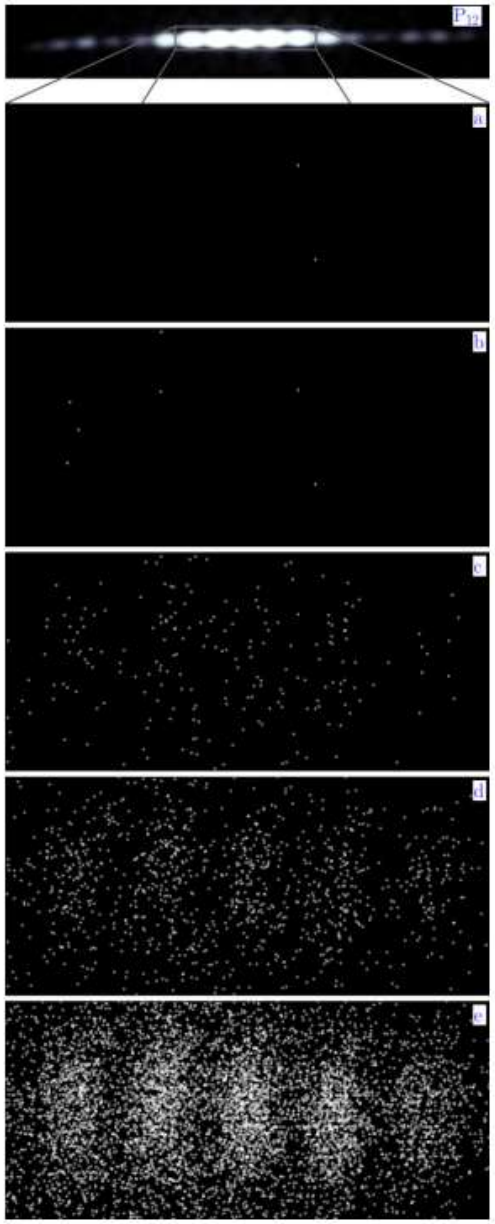
$$\Delta\phi = \frac{e}{\hbar}\iint BdA = 2\pi\frac{\Phi}{\Phi_0}$$

Mesoscopic physics:
Microscopic effects govern the behavior of *macroscopic* objects

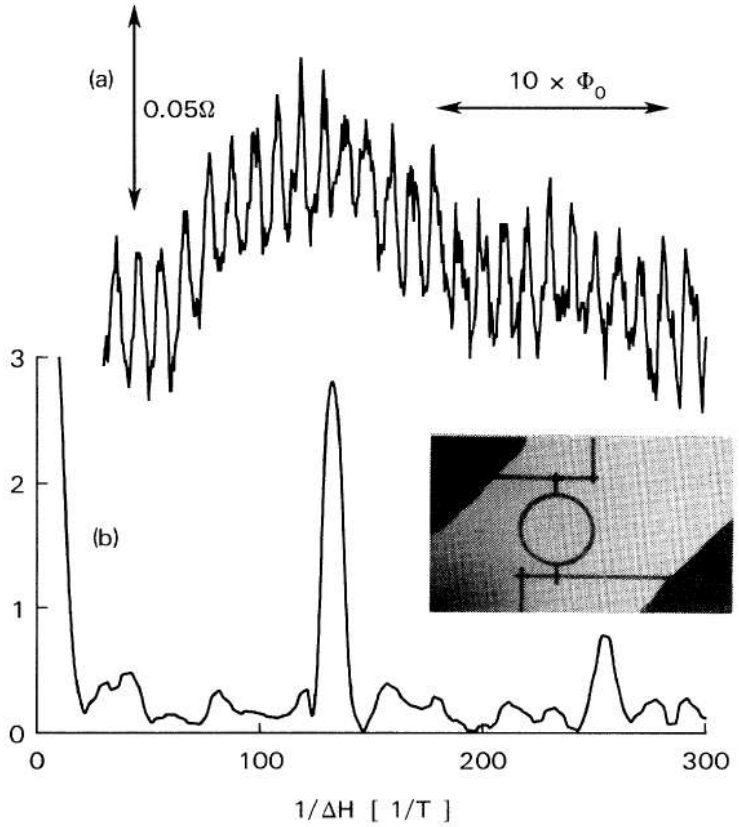


Webb et al., Phys. Rev. Lett. 54, 2696 (1985)

Self-interference



Electrons in vacuum



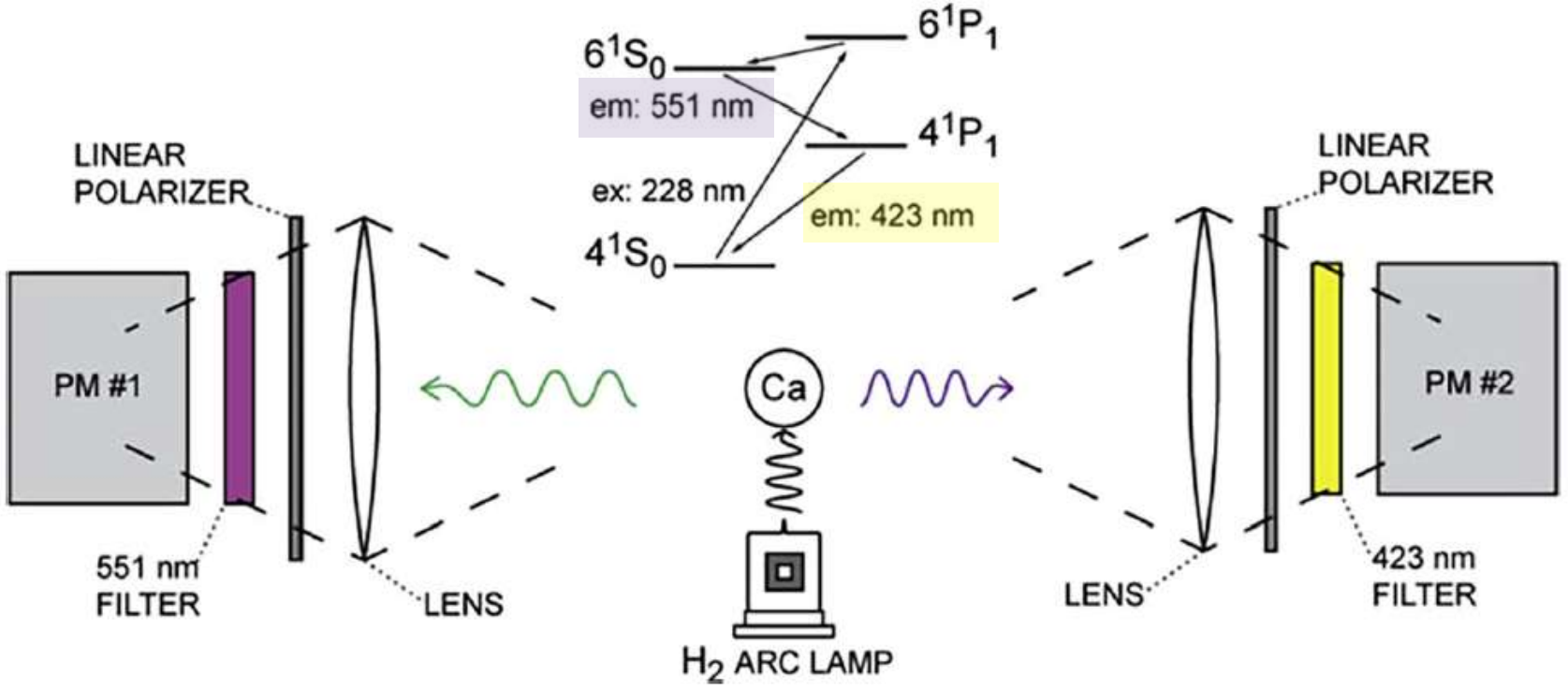
Electrons in the solid state

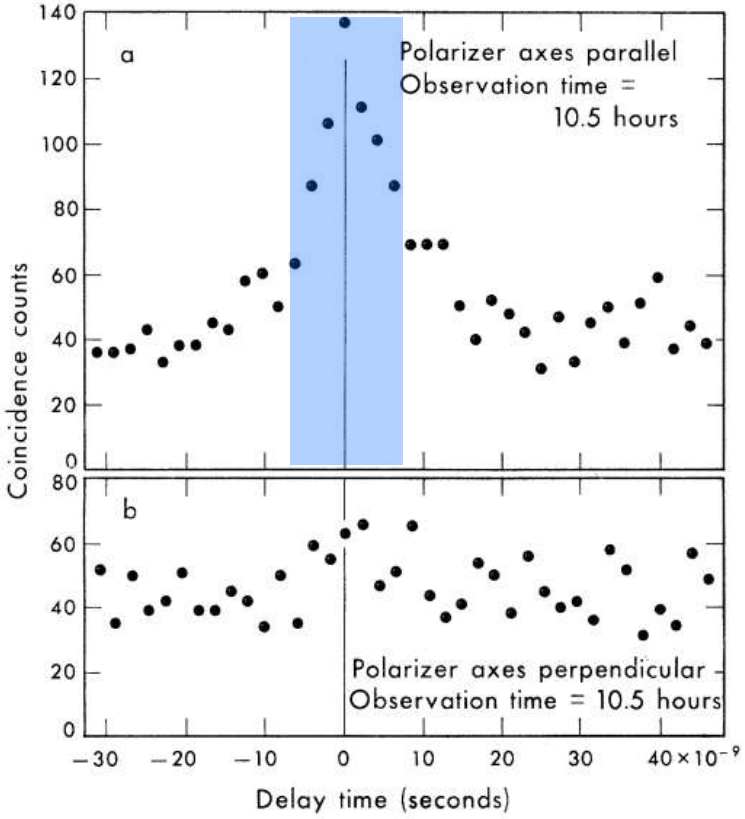
Light & matter display

self - interference

superposition phase → wave

Generation of correlated photons





Polarizer-dependent time coincidence

- Calcium decay: two correlated photons
- Measure simultaneous arrival with polarized detectors

First demonstration of entangled photon generation:
Kocher & Commins, Phys. Rev. Lett. 18, 575 (1967)
Review: Nordén, Chemical Physics 507, 28 (2018)

Demonstrating entanglement

$R(\varphi)$, the coincidence rate for two-photon detection, as a function of the angle φ between the planes of linear polarization defined by the orientation of the inserted polarizers; R_1, the coincidence rate with polarizer 2 removed; R_2, the coincidence rate with polarizer 1 removed[4]; R_0, the coincidence rate with both polarizers removed. Quantum mechanics predicts that $R(\varphi)$ and R_0 are related as follows[3,5]:

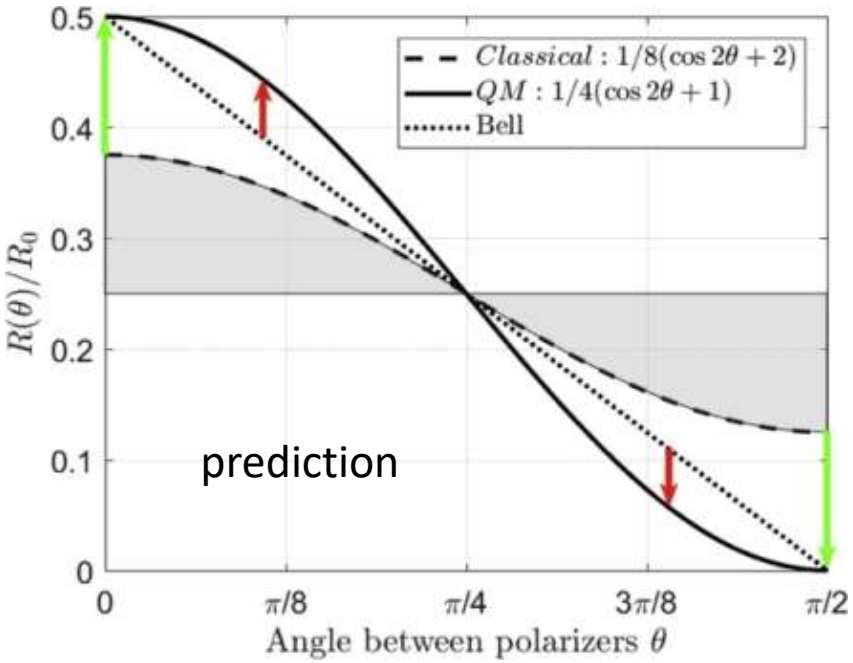
$$R(\varphi)/R_0 = \tfrac{1}{4}(\epsilon_M^{\,1} + \epsilon_m^{\,1})(\epsilon_M^{\,2} + \epsilon_m^{\,2}) + \tfrac{1}{4}(\epsilon_M^{\,1} - \epsilon_m^{\,1}) \times (\epsilon_M^{\,2} - \epsilon_m^{\,2}) F_1(\theta) \cos 2\varphi, \quad (1a)$$

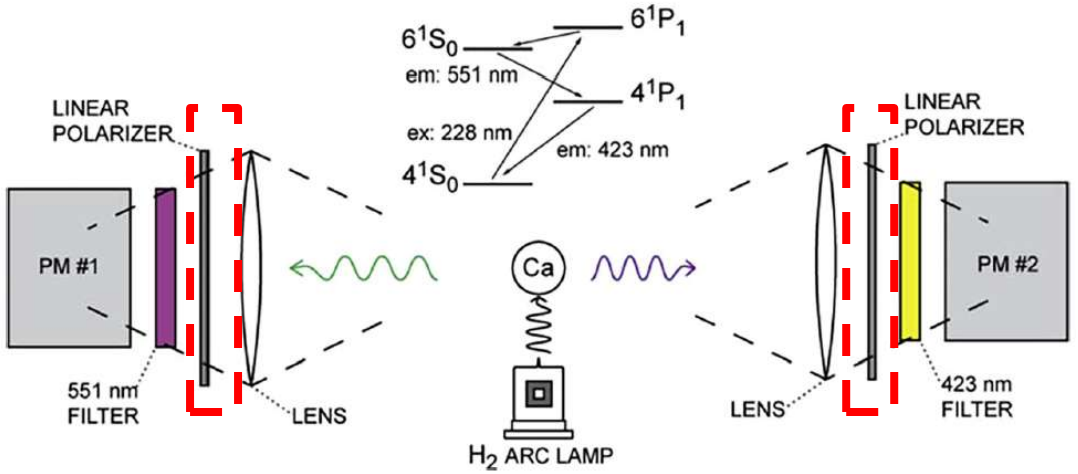
while

$$R_1/R_0 = \tfrac{1}{2}(\epsilon_M^{\,1} + \epsilon_m^{\,1}), \quad (1b)$$

and

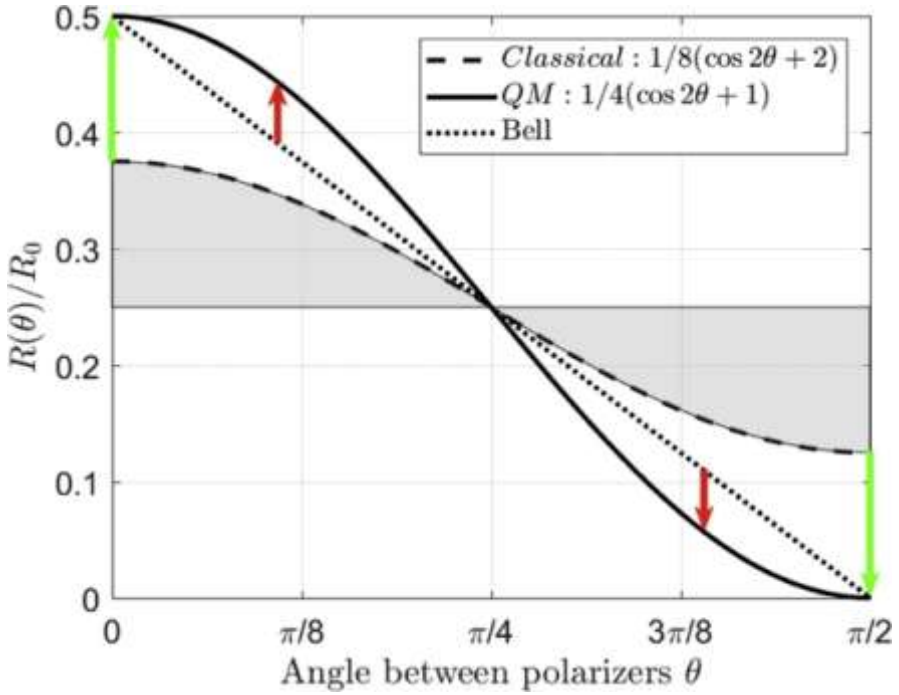
$$R_2/R_0 = \tfrac{1}{2}(\epsilon_M^{\,2} + \epsilon_m^{\,2}). \quad (1c)$$



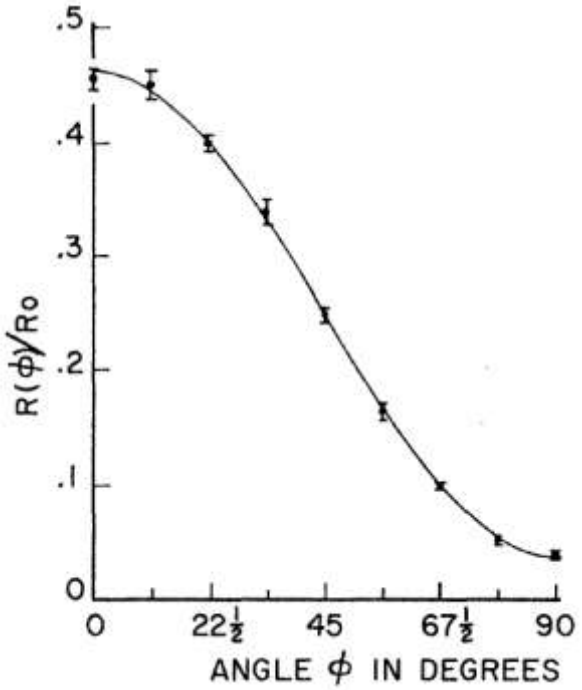


Freedman & Clauser, Phys. Rev. Lett. 28, 938 (1972)
Clauser, Horne, Shimony, Holt, Phys. Rev. Lett., 23, 880 (1969)

Demonstrating entanglement



Observation can tell apart classical from quantum



Demonstrating quantum entanglement

Freedman & Clauser, Phys. Rev. Lett. 28, 938 (1972)
Clauser; Horne; Shimony, Holt, Phys. Rev. Lett., 23, 880 (1969)

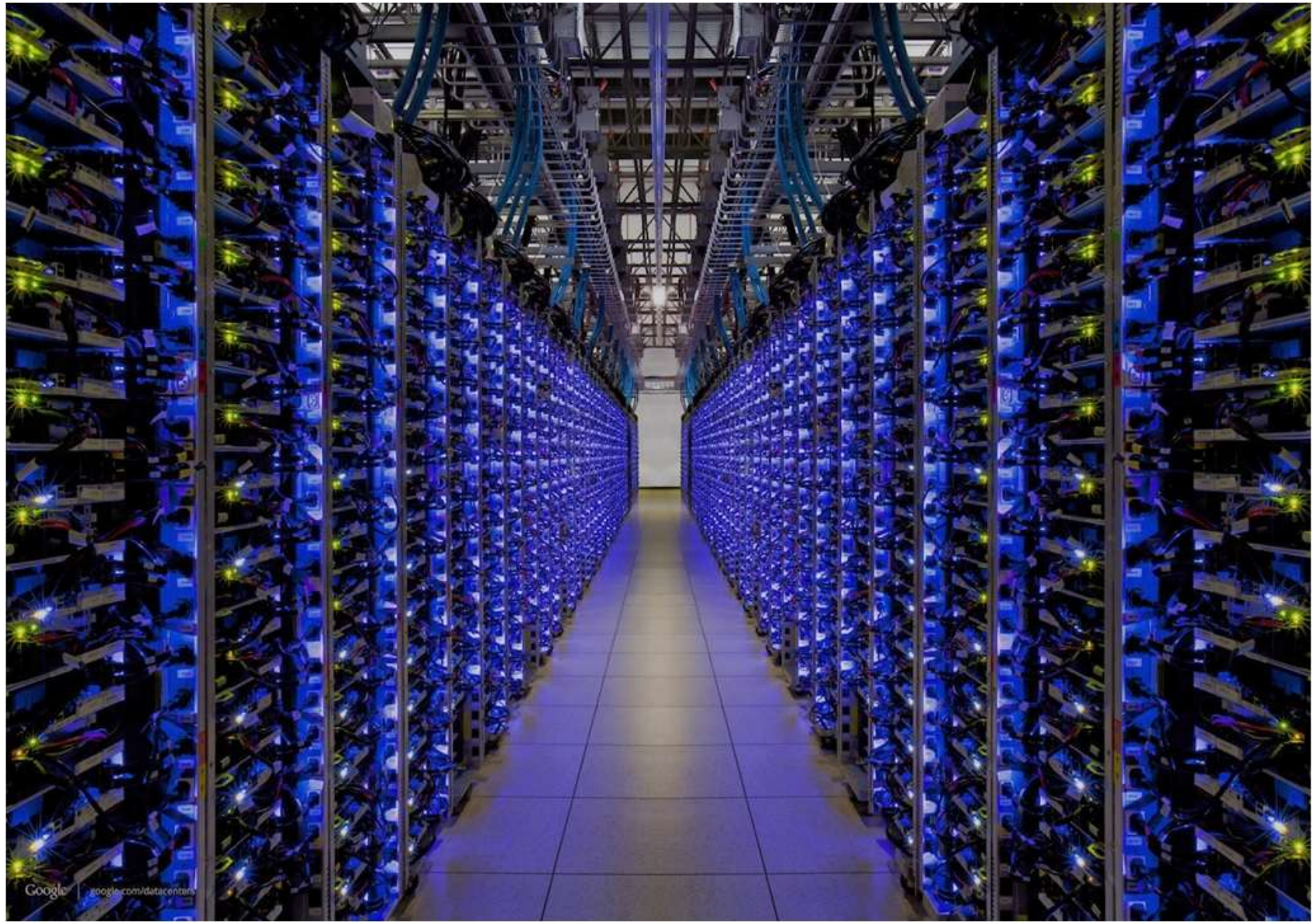
Quantum computing

Exponential possibilities

Grains of rice:

$2^{64}-1$

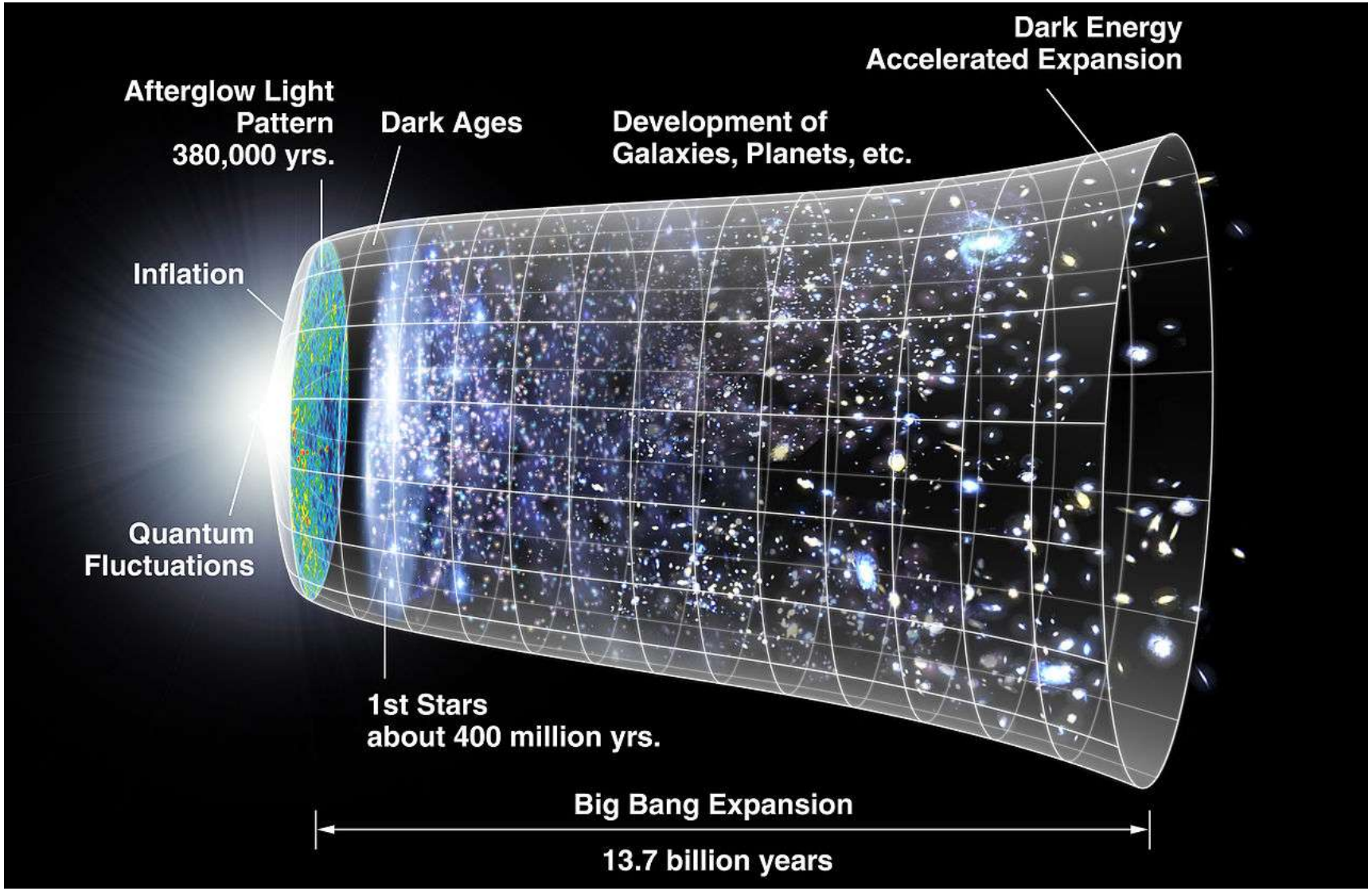
Exponential possibilities



Cloud storage space:

~2^{60}

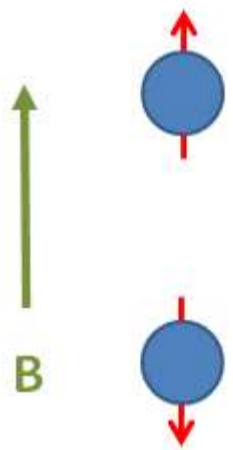
Exponential possibilities



Atoms in the universe:

$2^{260} \sim 2^{270}$

Quantum bit: spin in magnetic field



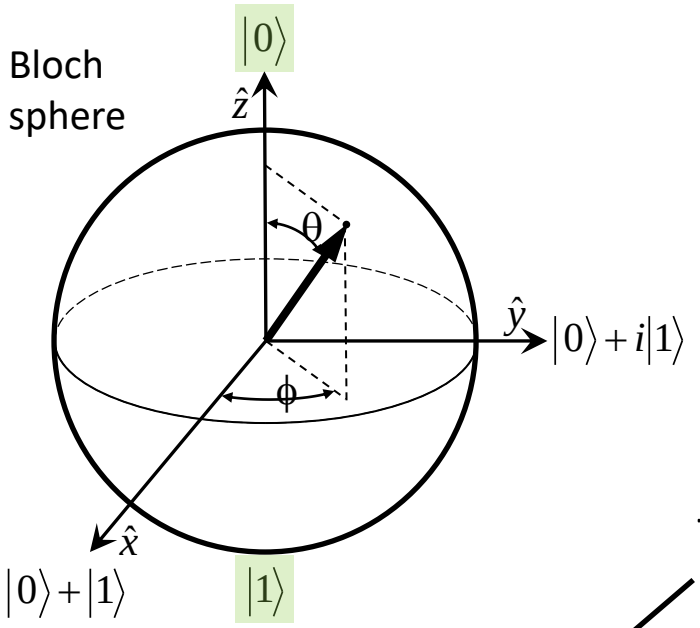
Low energy

High energy

$$H = -\frac{\mu_B}{2}\vec{\sigma}\bullet\vec{B}$$

$$= -\frac{\mu_B}{2}\left[\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}B_x + \begin{pmatrix}0 & -i\\ i & 0\end{pmatrix}B_y + \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}B_z\right]$$

σ_x σ_y σ_z



Larmor frequency: $\omega = \mu_B B/\hbar$

$$\Psi = \cos\frac{\theta}{2}|0\rangle + \sin\frac{\theta}{2}e^{i\phi}e^{-iE_{10}t/\hbar}|1\rangle$$

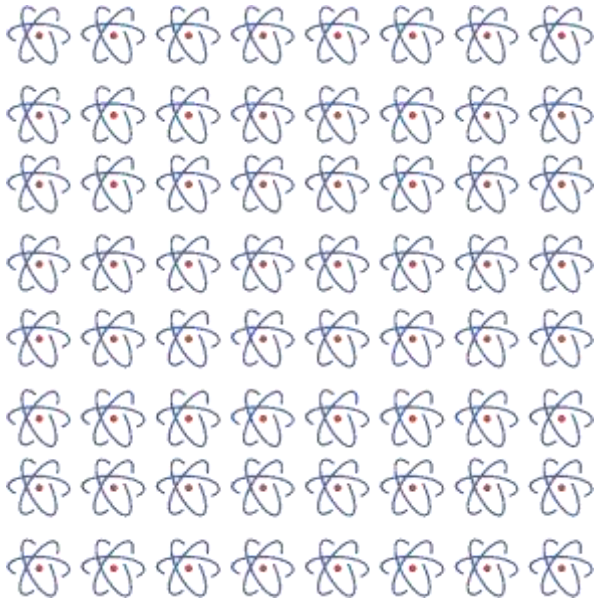
rotating frame with $B_z = 0$ $\rightarrow |1\rangle'$

Quantum state - vector on sphere
Quantum operations – rotations

Quantum data

$|0\rangle+|1\rangle$

$(|0\rangle+|1\rangle)^2=$
$|00\rangle+|01\rangle+|10\rangle+|11\rangle$

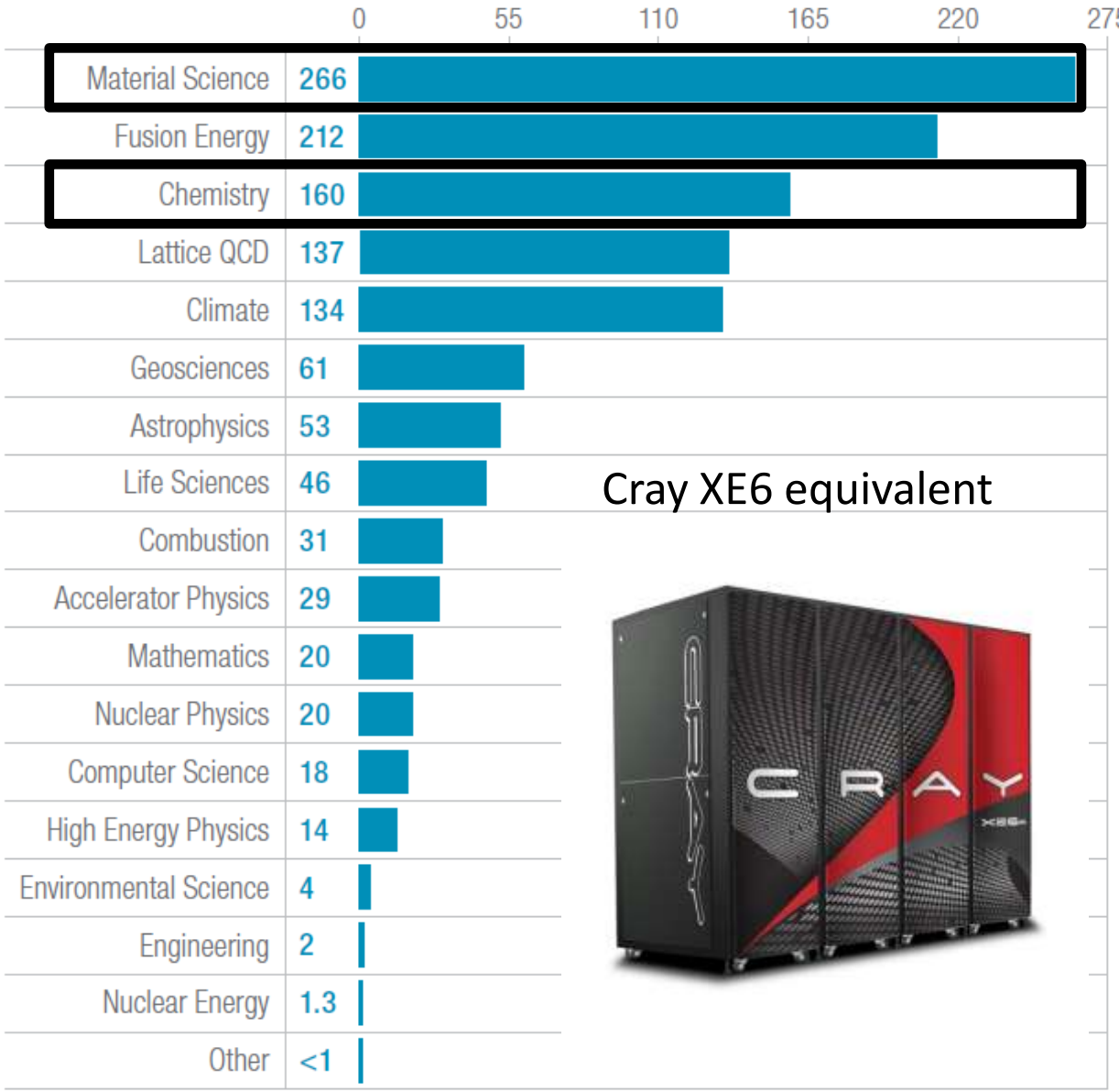


2^{64} $(1.8\bullet10^{19})$ states
more than cloud

Quantum measurement

- Measurement returns a classical “answer”
- A good algorithm uses the quantum space

Supercomputer usage



Cray XE6 equivalent

35 % of supercomputer usage:
materials & quantum chemistry

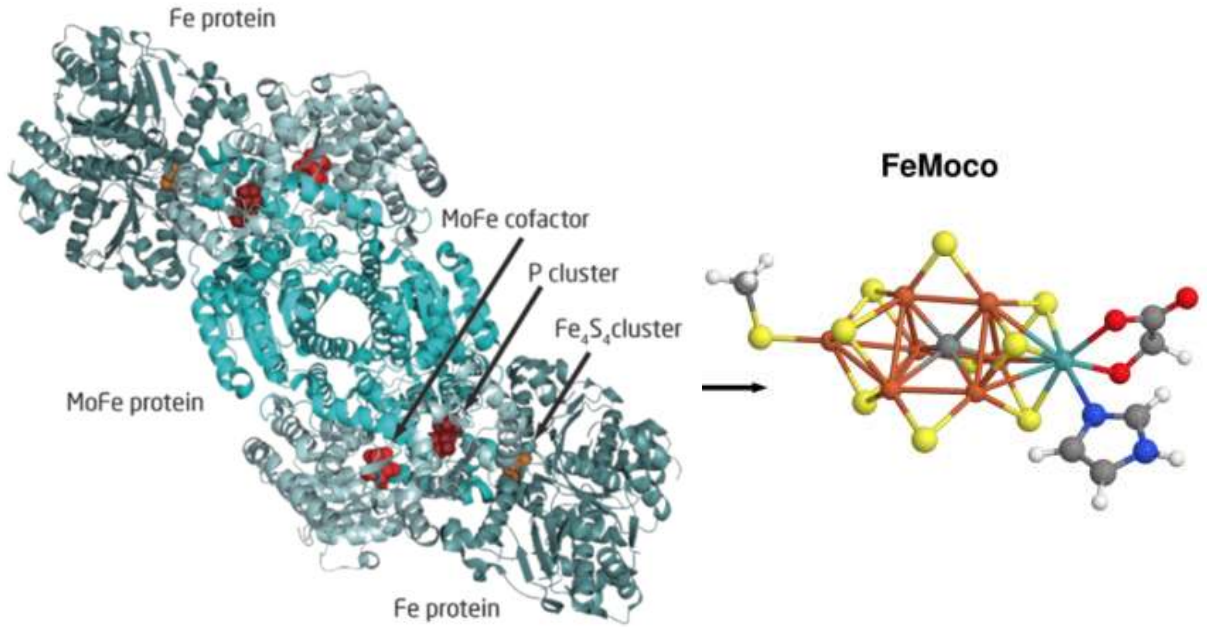
National Energy Research Scientific Computing Center annual report (2013)

Chemistry: Nitrogen fixation

Mankind
Haber-Bosch process:
$N_2 + 3H_2 \rightarrow 2NH_3$, 500 ^oC, 20 MPa

- 50% of N in your body
- Consumes 2% of world energy

Nature
Nitrogenase:
$N_2 + 3H_2 \rightarrow 2NH_3$, 20 ^oC, 0.1 MPa



MoFe cofactor
- Breaks N_2 triple bond
- Simulation: 111 qubits

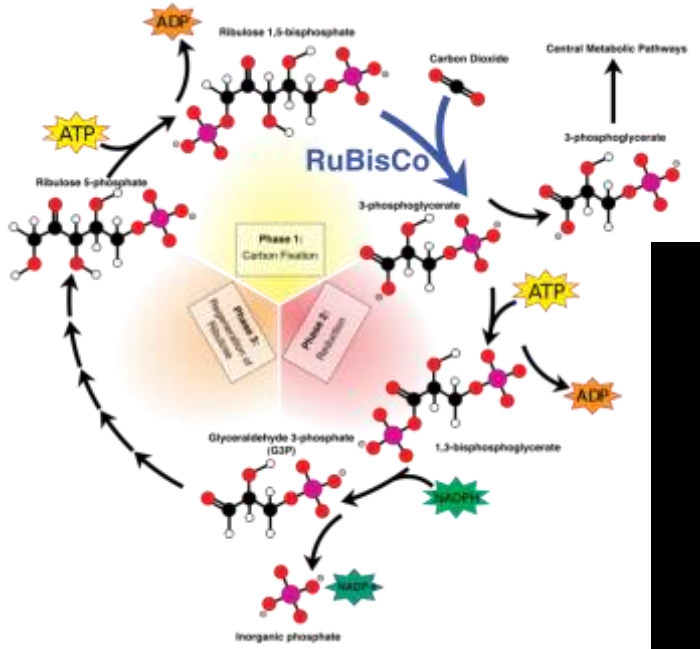
M. Reihera et al., PNAS 2017

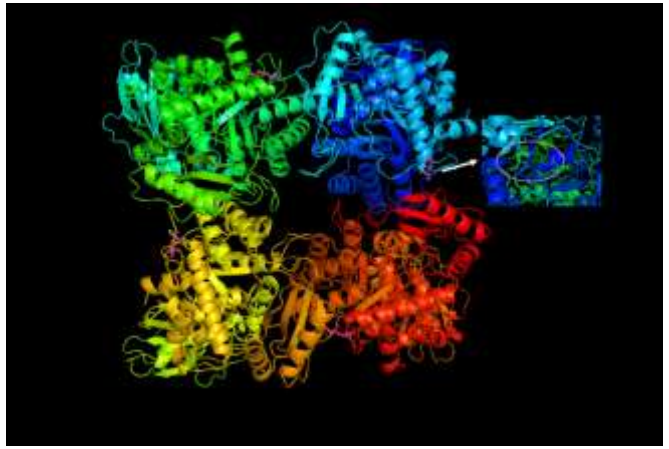
Chemistry: Carbon fixation

Mankind
Carbon capture

- Total carbon capture: 9000 tonnes / year
- Total CO_2 emissions (2020): 34 billion tonnes

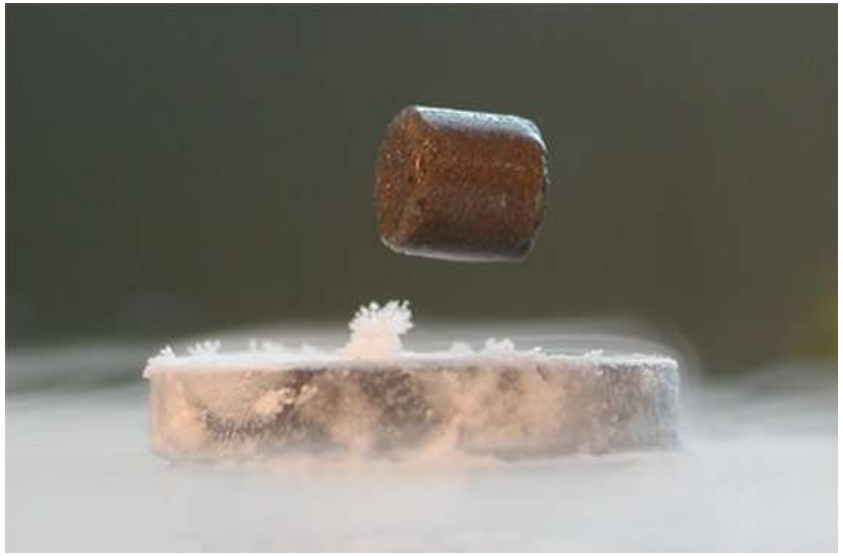
Nature
RuBisCO
(Photosynthesis)

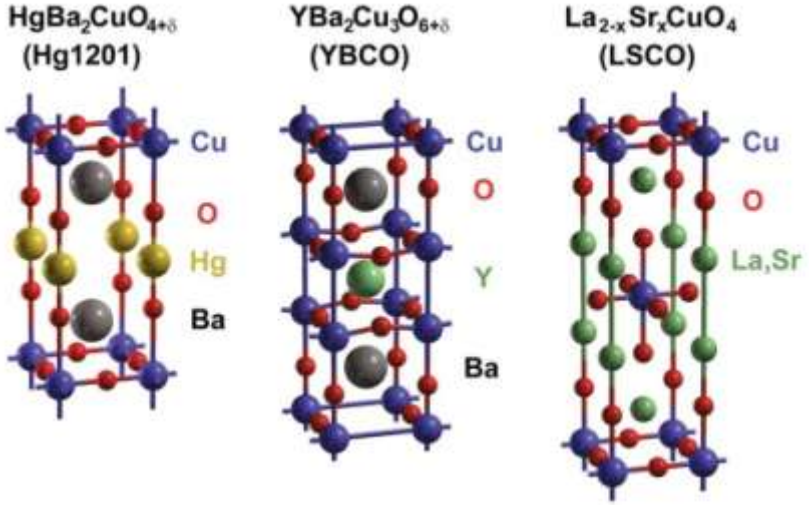


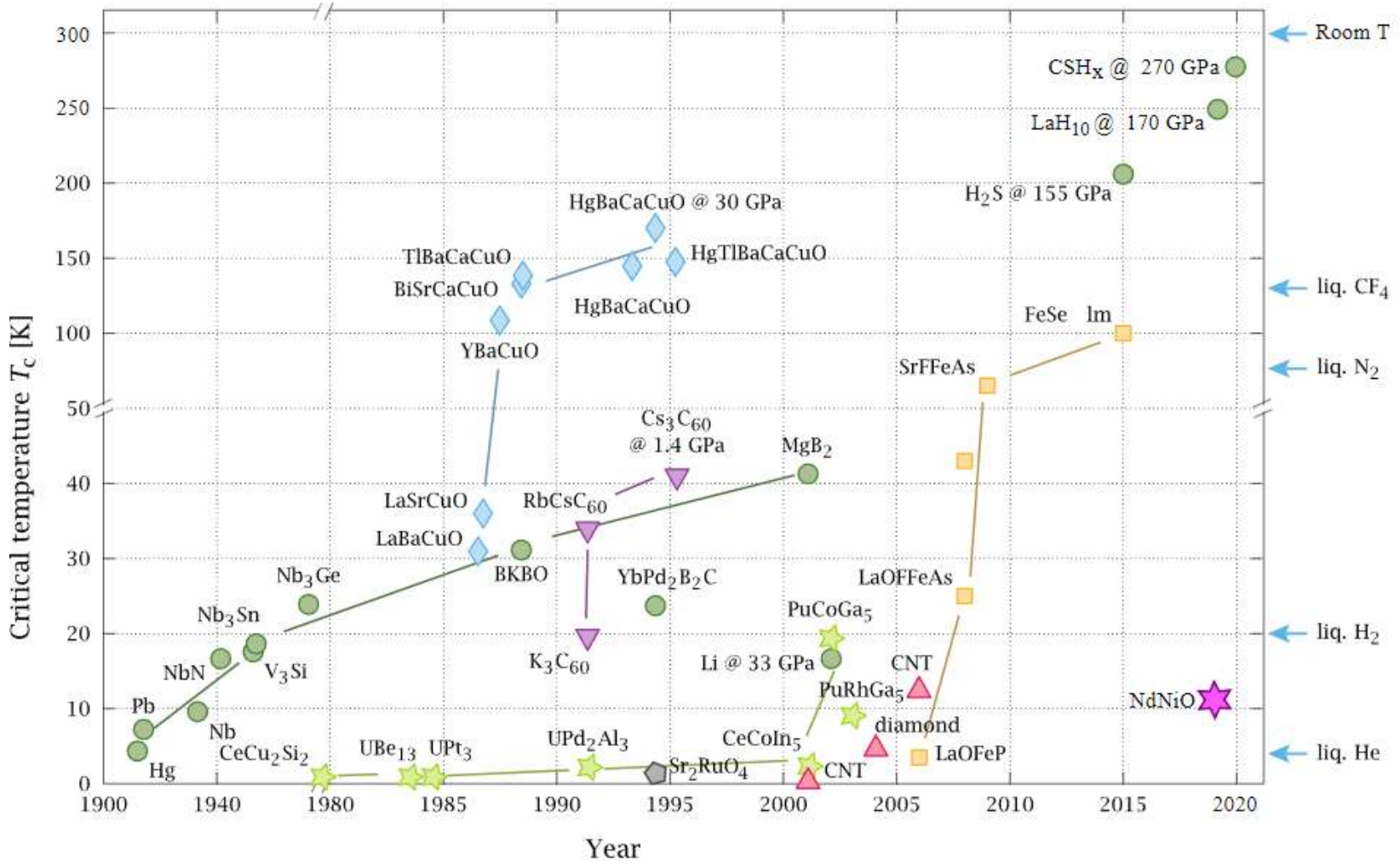


- Mg: binds CO_2 to amino acid
- Most abundant enzyme
- Carbon capture: 750 billion tonnes / year
- (Net capture: 19 billion tonnes / year)

Materials

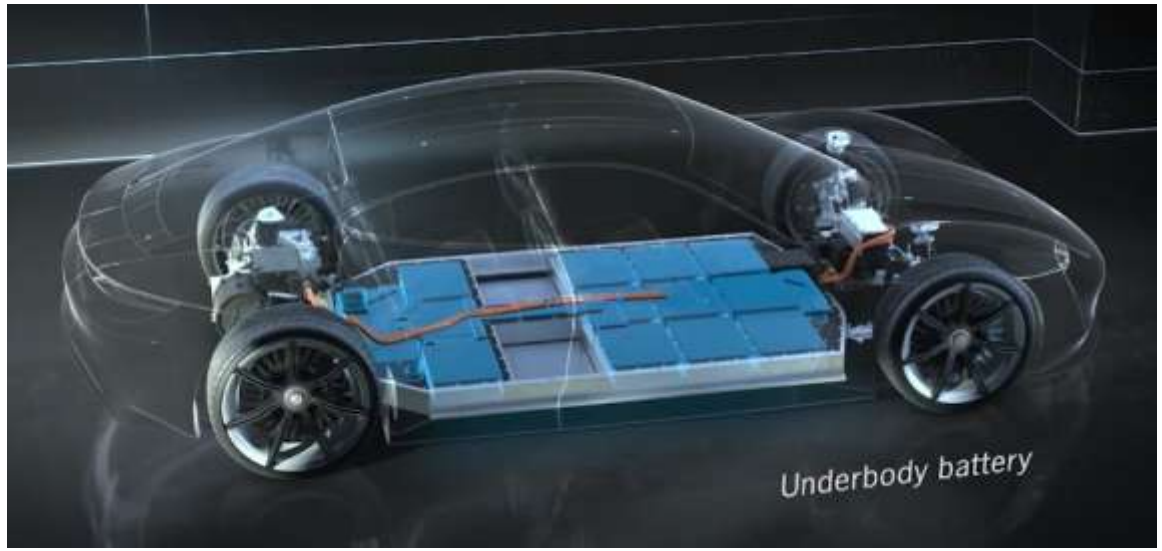






High T_c superconductivity

Materials



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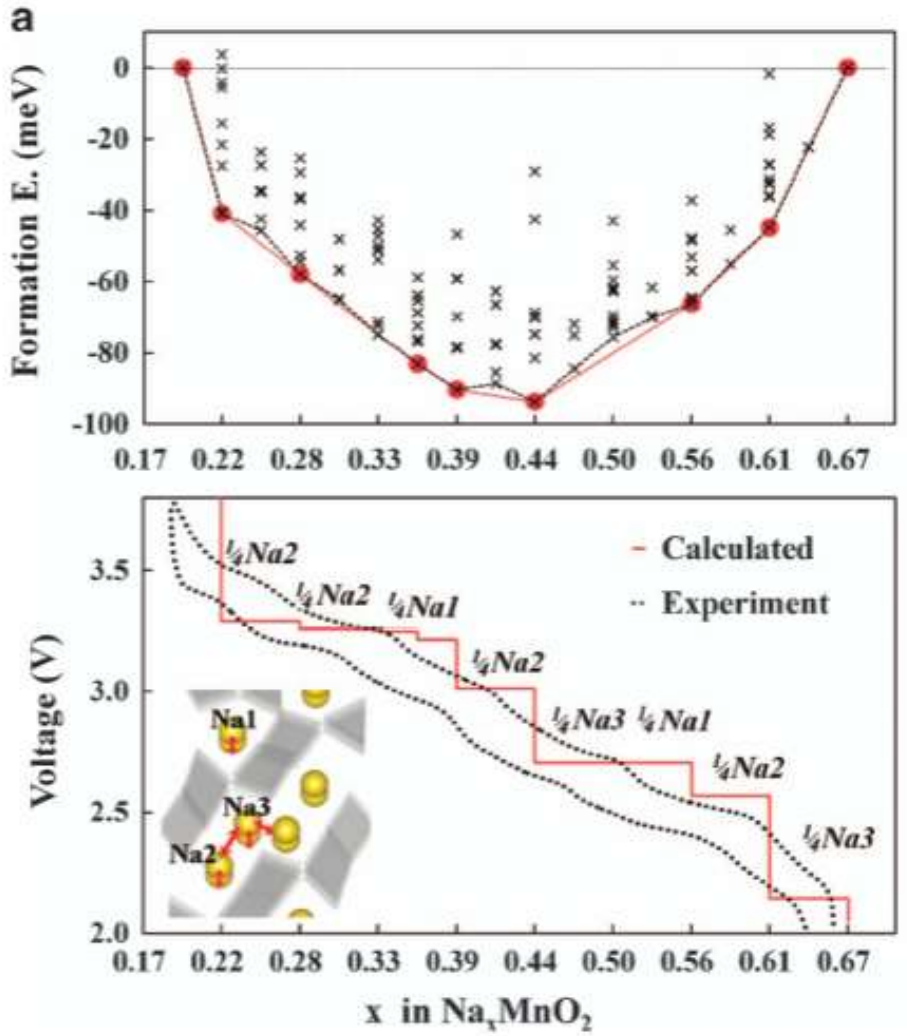
Articles | 14 December 2023 | 6 min read

Can sodium-ion batteries replace lithium-ion ones?

Ewa Manthey
Commodities Strategist

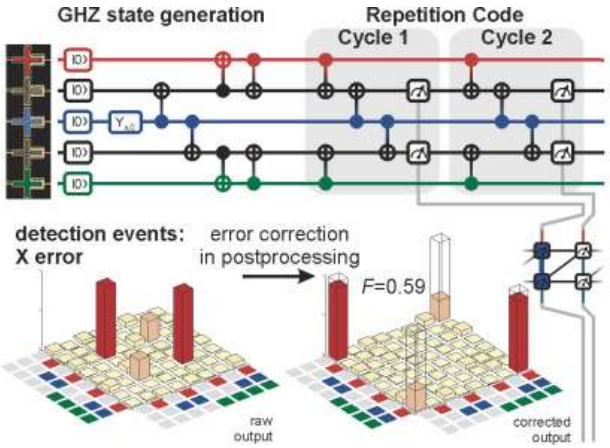
Sweden's Northvolt has developed an energy storage technology that has no lithium, cobalt, graphite or nickel. This could help to minimise green energy transition dependence on China



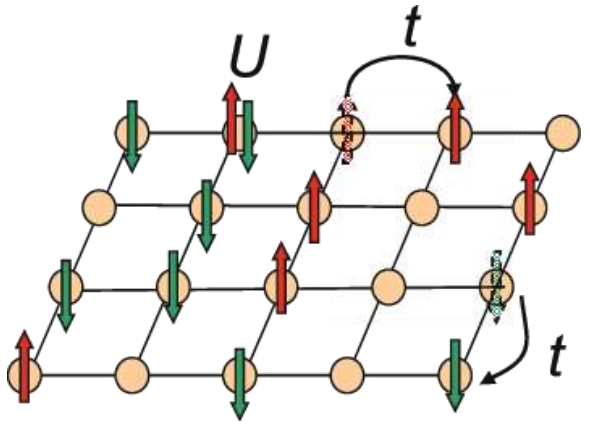
Competing phases in battery materials

Urban et al., npj comp. mat. 2016

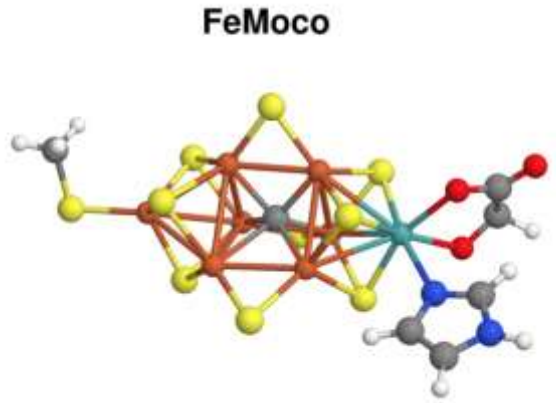
Applications



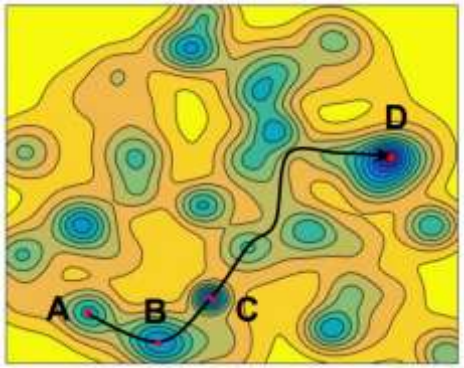
Error correction



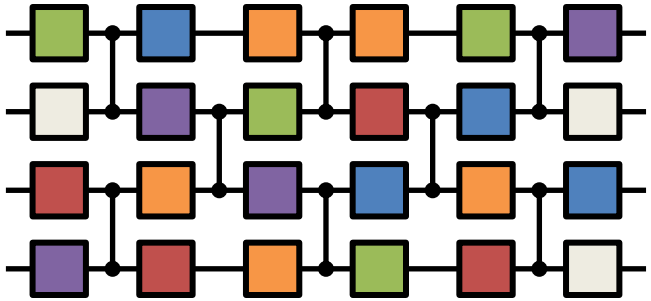
Simulation



Chemistry



Optimization



Validation

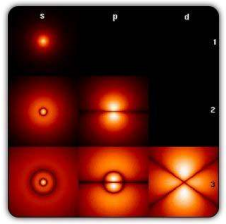
```
0100...001
0101...111
1101...101
1001...001
0101...111
1111...001
1000...110
```

Encryption

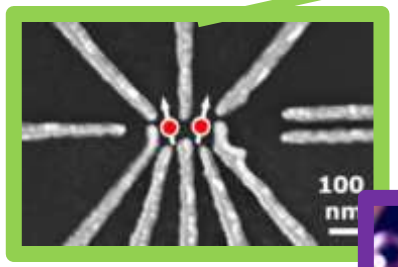
Hardware platform

Quantum objects

10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 m

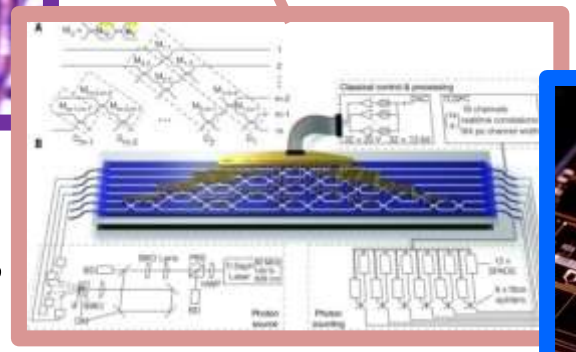


H atom

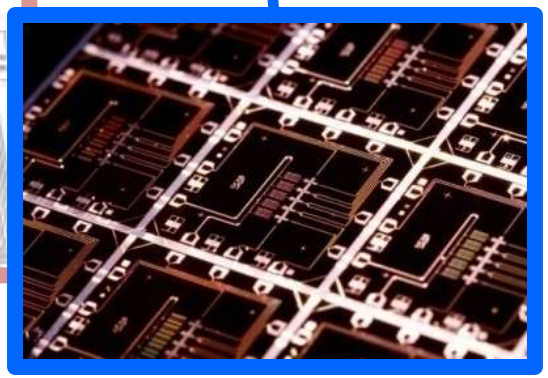


Spin qubits

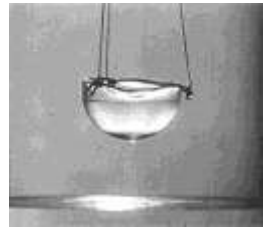
Ions &
Rydberg atoms



Linear optics



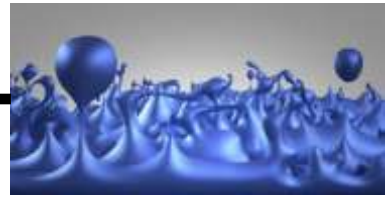
Superconducting



He superfluid

Electron

Neutron star



Planck length

Black hole

Quantum objects

10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 m

H atom

Spin qubits

The Quantum Physics of Neutron Stars

Cole Meldorf

March 18, 2021

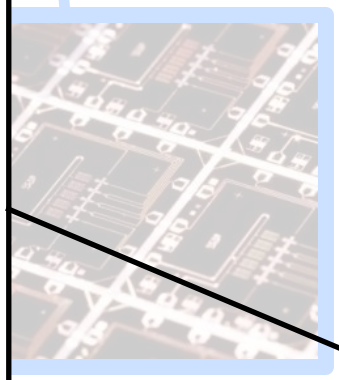
He superfluid

Electron

Black holes as mirrors: quantum information in random subsystems

Patrick Hayden
School of Computer Science, McGill University, Montreal, Quebec, H3A 2A7, Canada

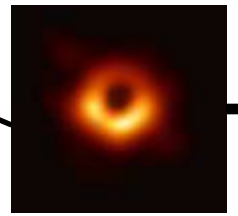
John Preskill
Institute for Quantum Information, California Institute of Technology, Pasadena CA 91125, USA



Superconducting

Neutron star

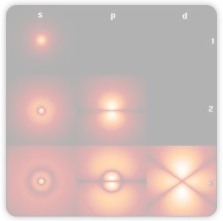
Planck length



Black hole

Quantum objects

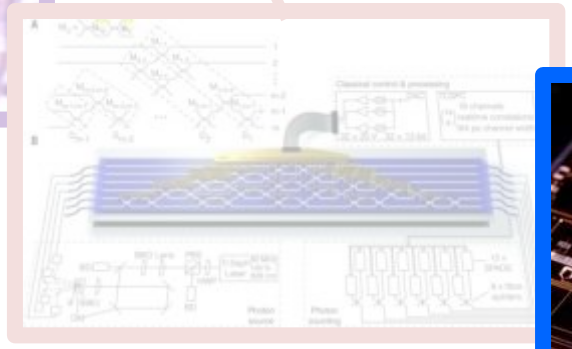
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 m



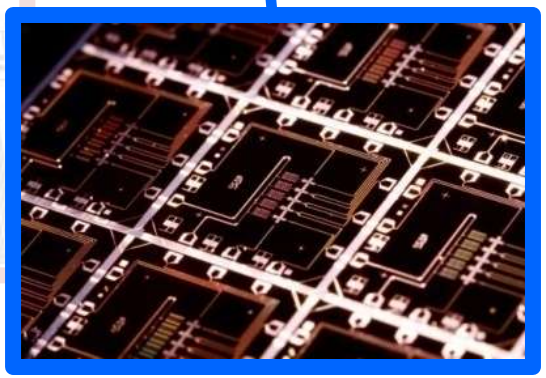
H atom

Spin qubits

Ions &
Rydberg atoms

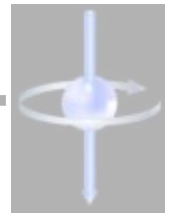


Linear optics



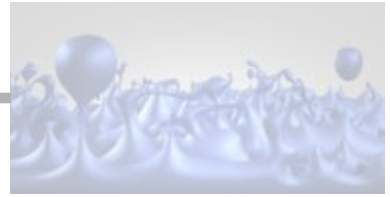
Superconducting

He superfluid



Electron

Neutron star



Planck length

Black hole

Superconductivity as you know it

MRI

CERN

Frog @ 16T

Magnetic Levitation

First superconducting quantum systems

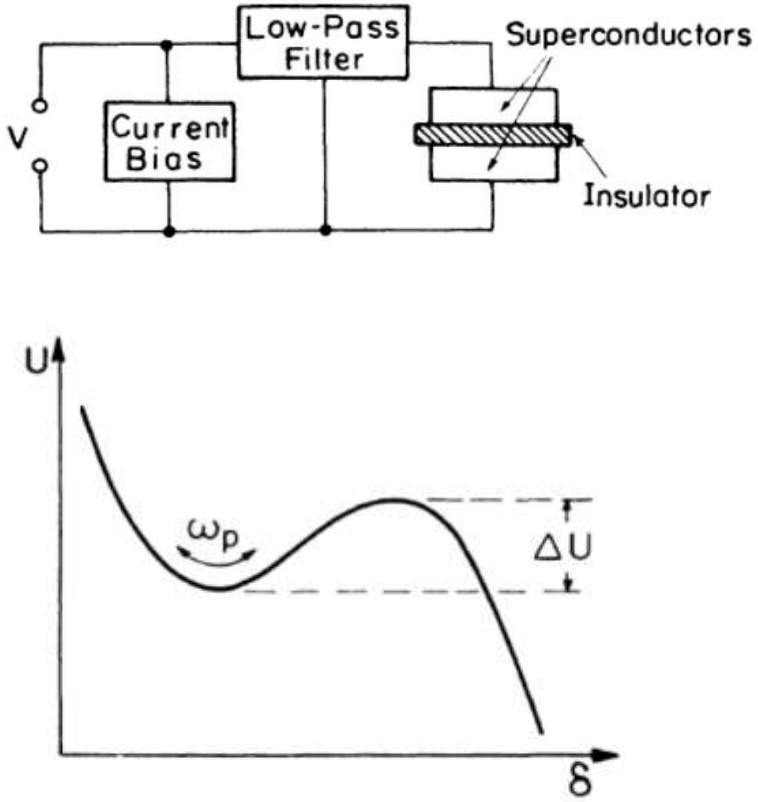
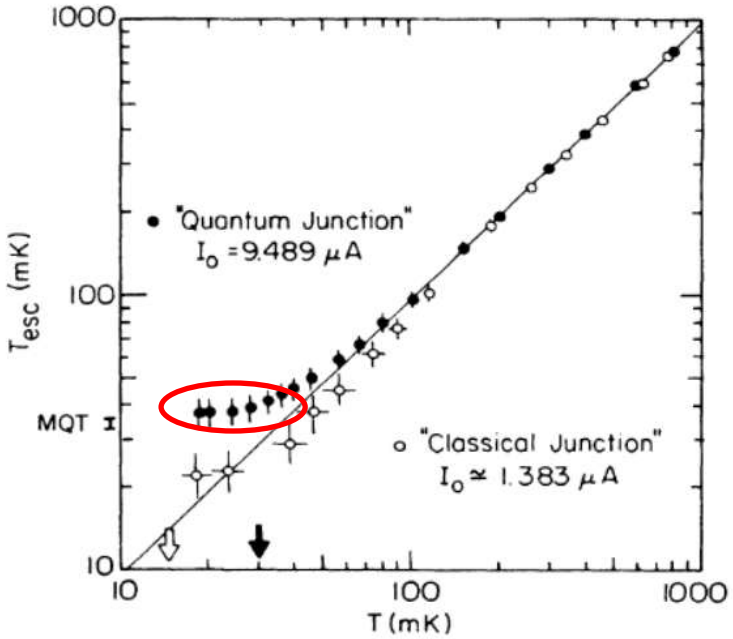
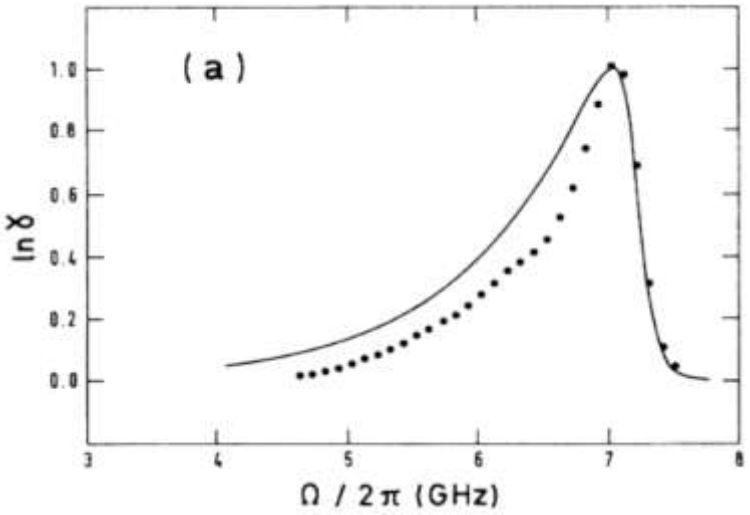


FIG. 2. Potential well from which particle escapes.



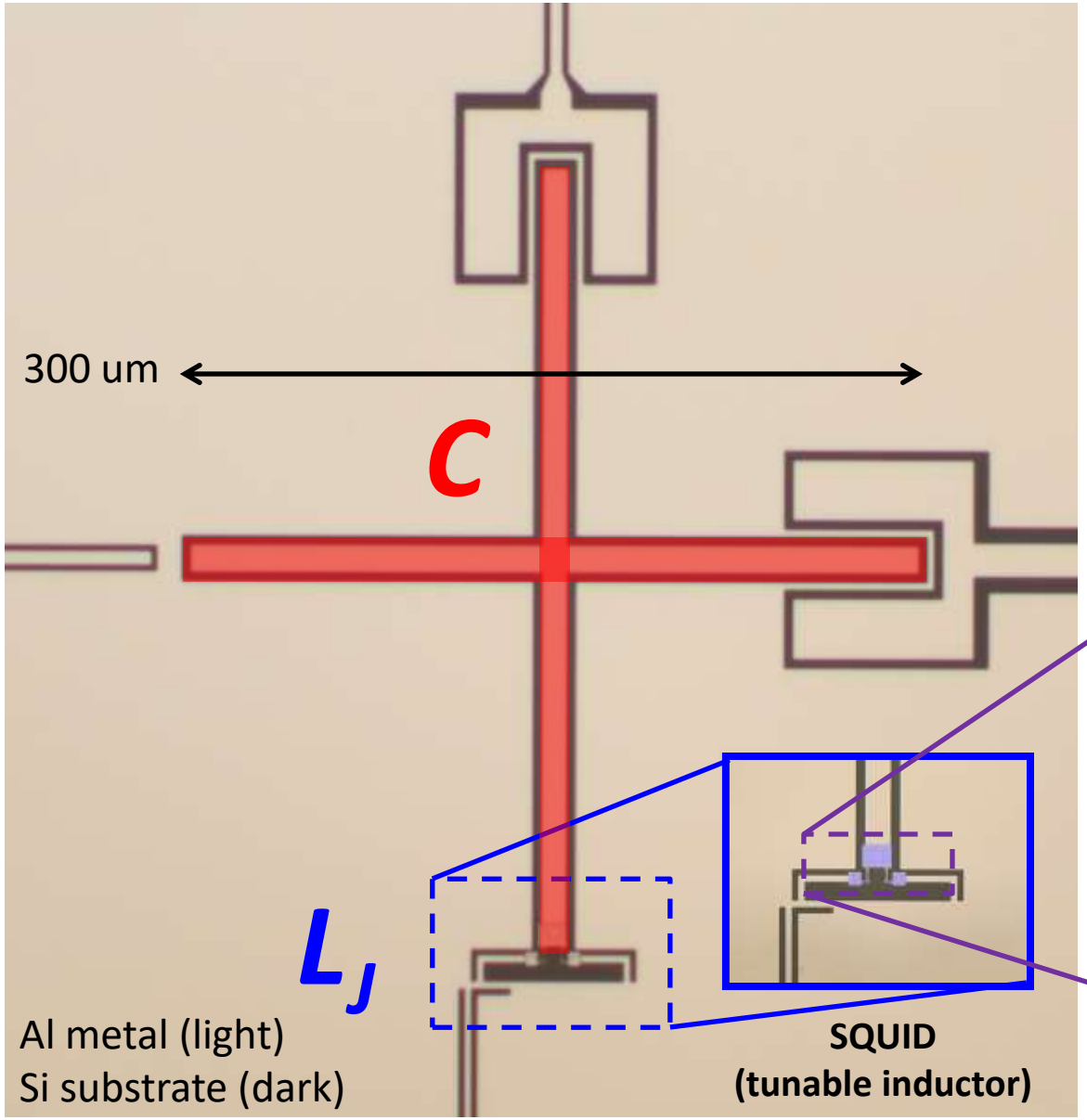
Macroscopic Quantum Tunneling

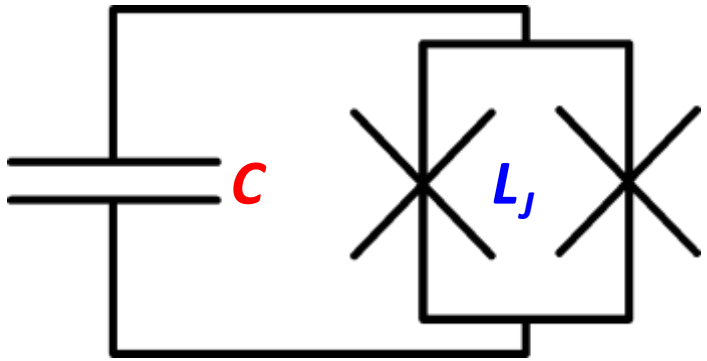


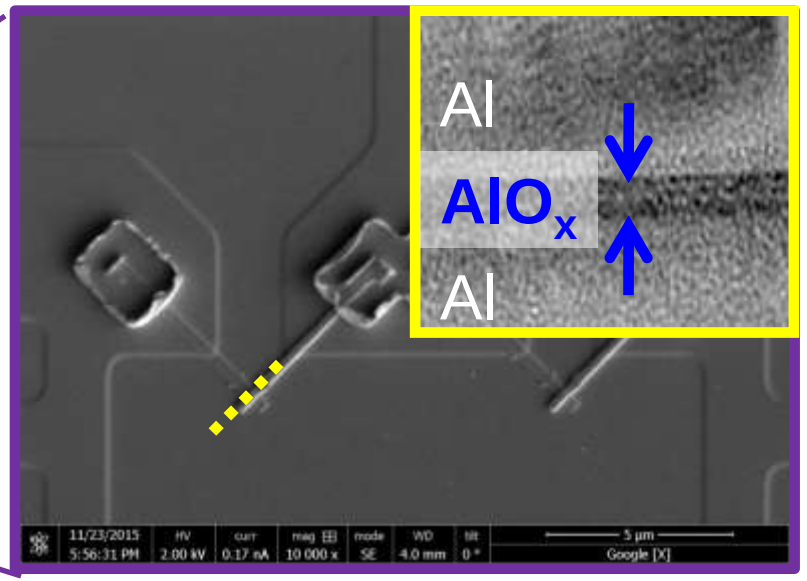
Resonant driving

Martinis, Devoret, Clarke, PRB 1987
Devoret, Esteve, Martinis, Cleland, Clarke, PRB 1987

Superconducting quantum bit

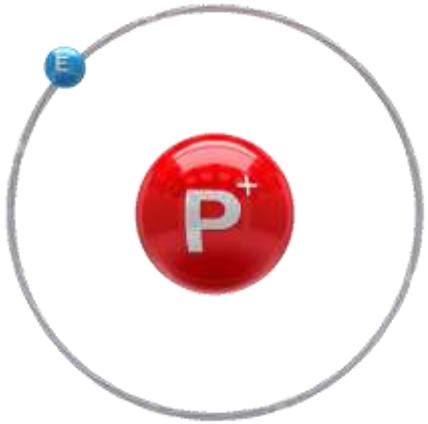


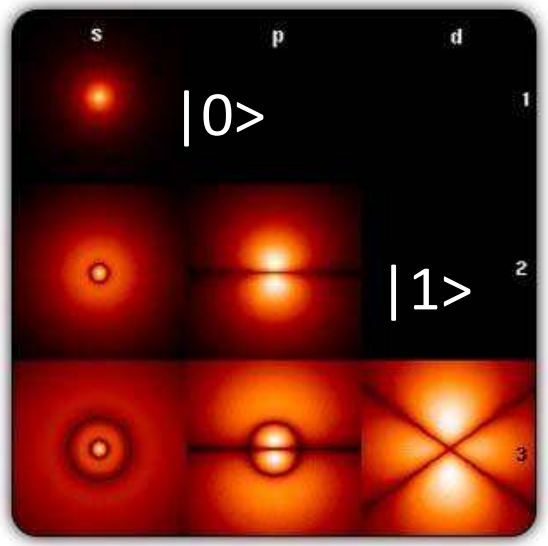




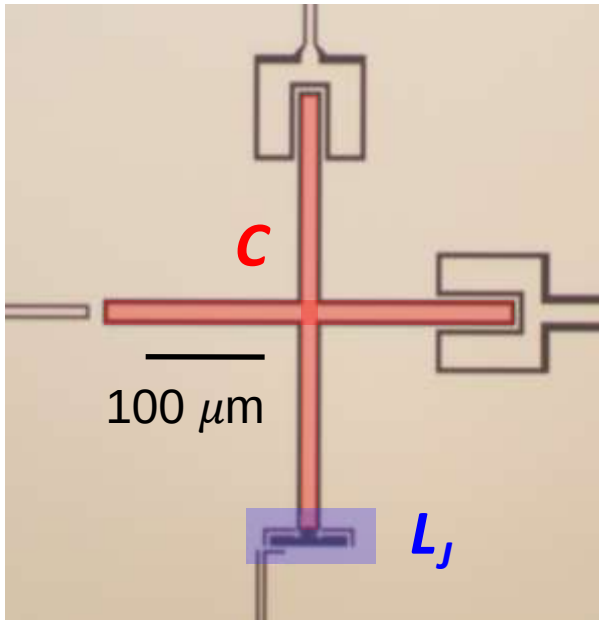
Barends, et al., Phys. Rev. Lett. 111, 080502 (2013)

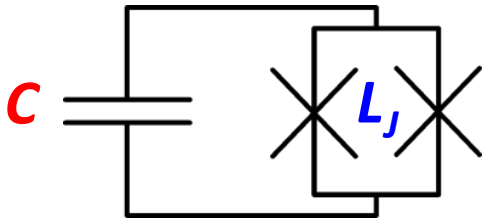
Circuit as artificial atom

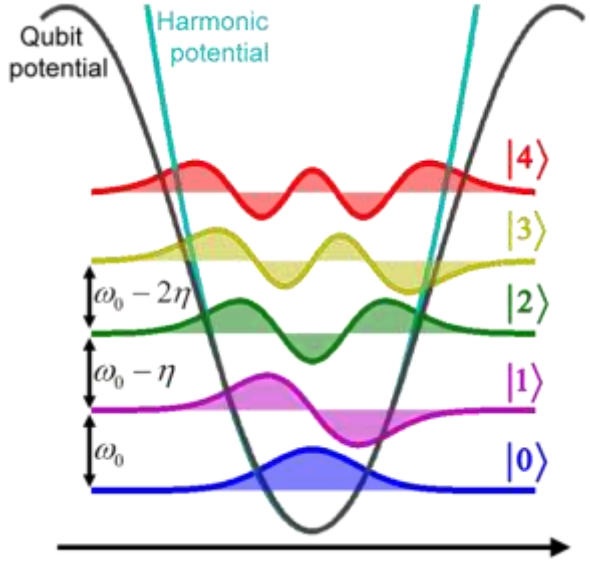




Hydrogen atom



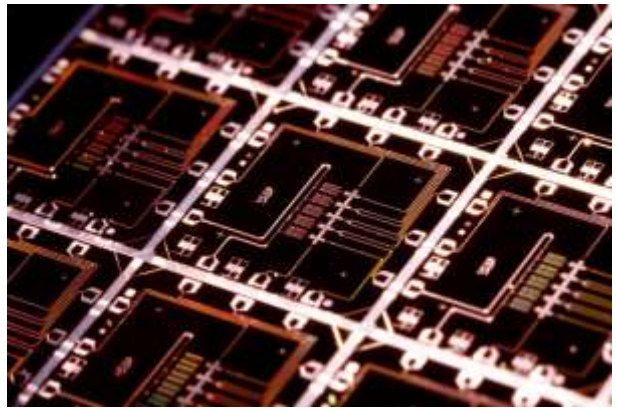


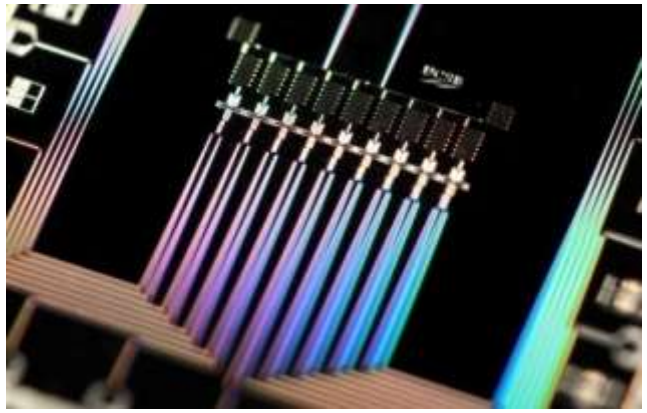


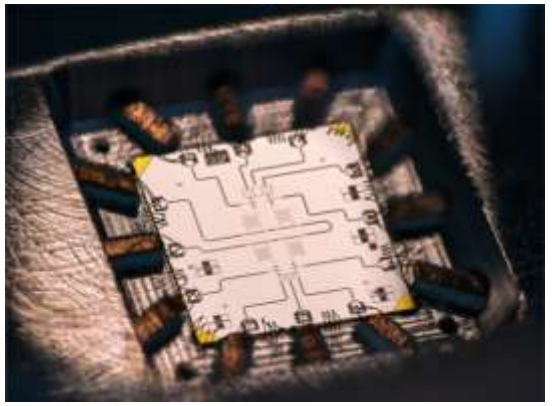
Superconducting quantum circuit

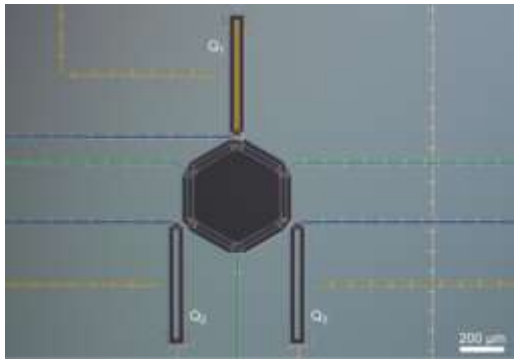
Quantum state controlled by voltages & currents

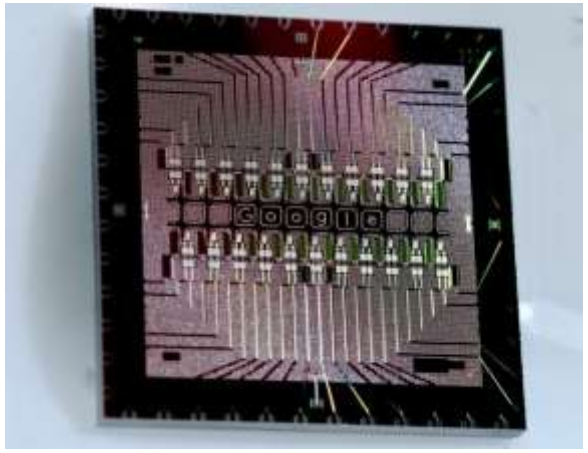
Large circuits

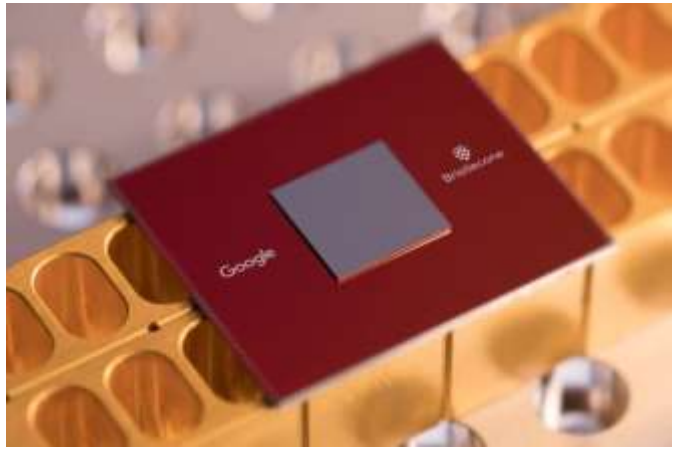


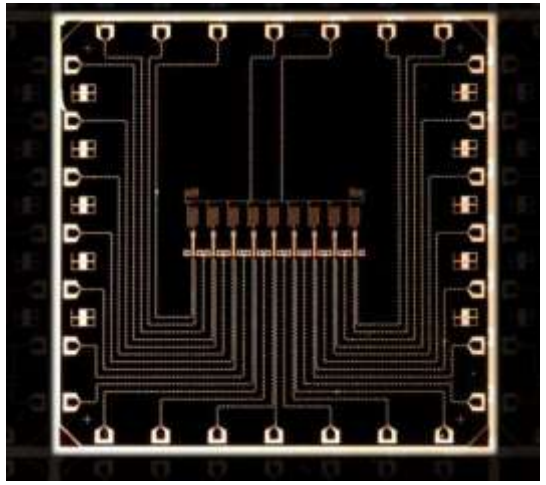


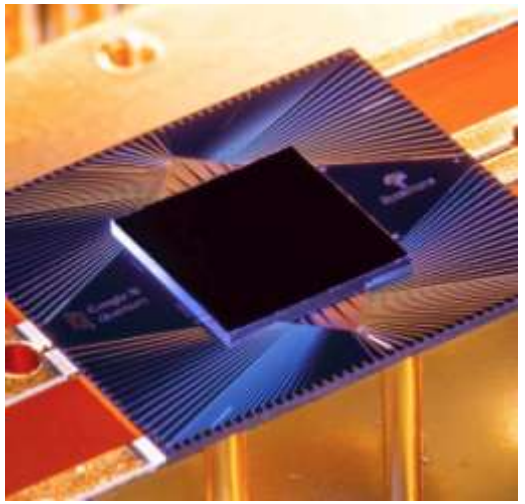












Article

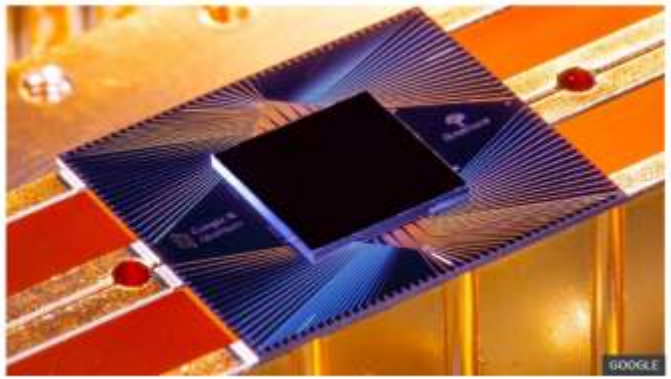
Quantum supremacy using a programmable superconducting processor

BBC NEWS

Home | Coronavirus | Climate | Video | World | UK | Business | Tech | Science | Stories | Entertainment & Art

Science

Google claims 'quantum supremacy' for computer



Quanta magazine

Physics Mathematics Biology Computer Science Topics

Quantum Supremacy Is Coming: Here's What You Should Know

Researchers are getting close to building a quantum computer that can perform tasks a classical computer can't. Here's what the milestone will mean.

Google claims it has achieved 'quantum supremacy' – but IBM disagrees

Task that would take most powerful supercomputer 10,000 years 'completed by quantum machine in minutes'

NEWS | 23 October 2019

Hello quantum world! Google publishes landmark quantum supremacy claim

The company says that its quantum computer is the first to perform a calculation that would be practically impossible for a classical machine.

Ivanka Trump @IvankaTrump · 7h

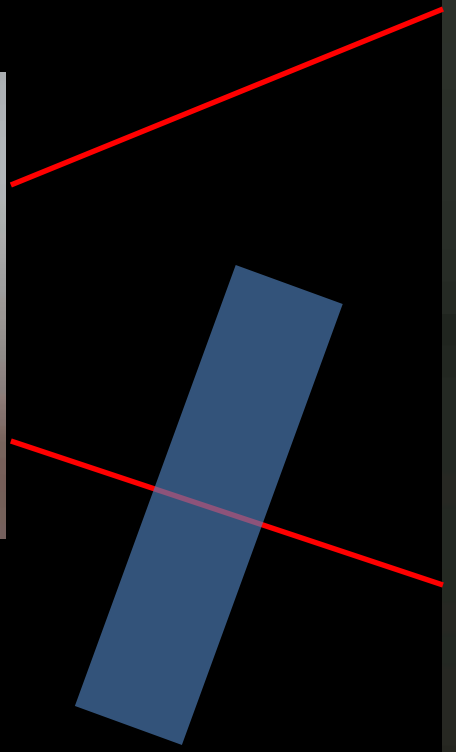
It's official! The US has achieved quantum supremacy!
In a collaboration between the Trump Admin, @Google and UC Santa Barbara, quantum computer Sycamore has completed a calculation in 3 min 20 sec that would take about 10,000 years for a classical comp.

571 1.1K 4.7K

Show this thread

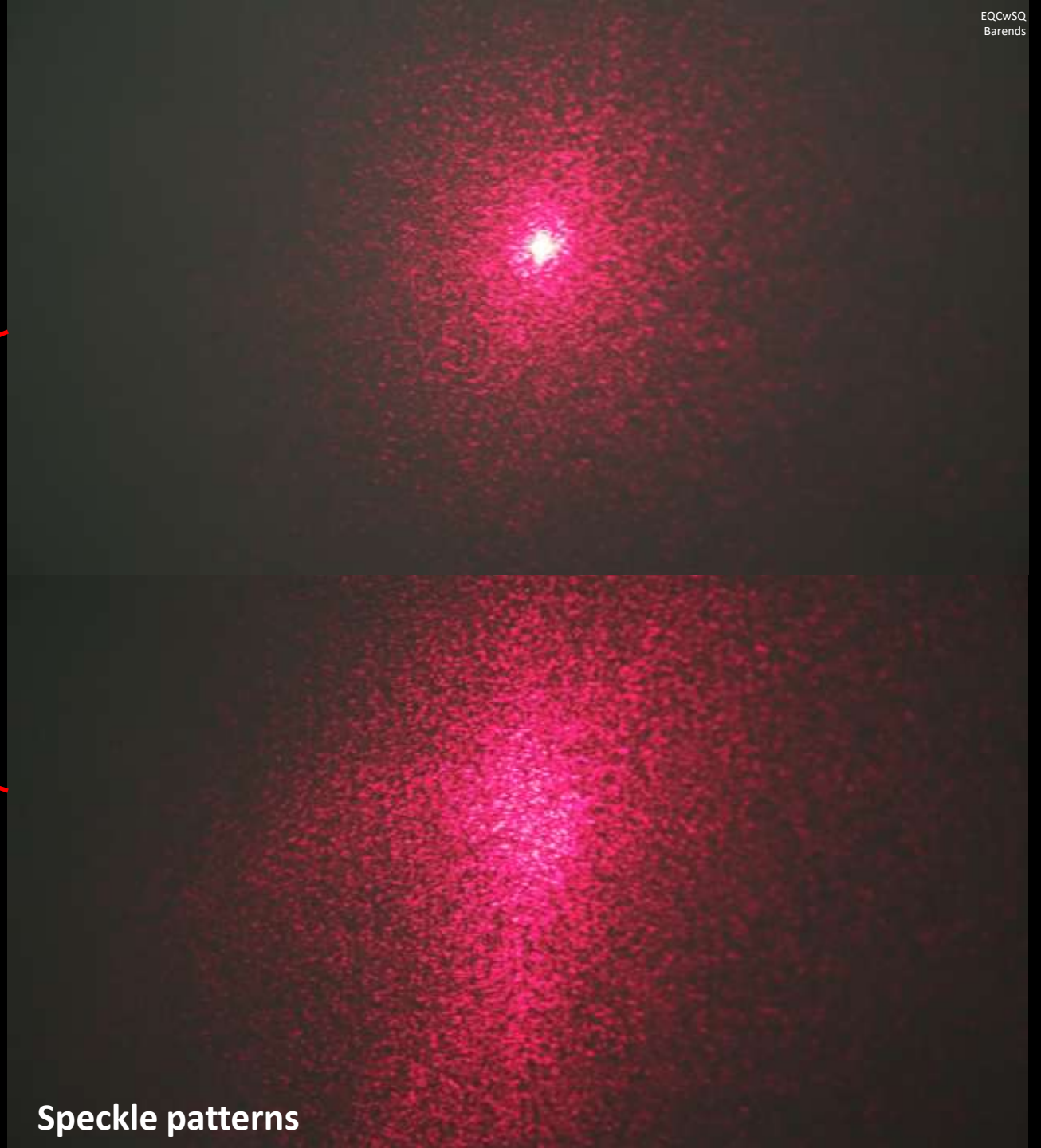
Arute et al., Nature 2019

Coherent source



Medium with scatterers

Randomized pathway

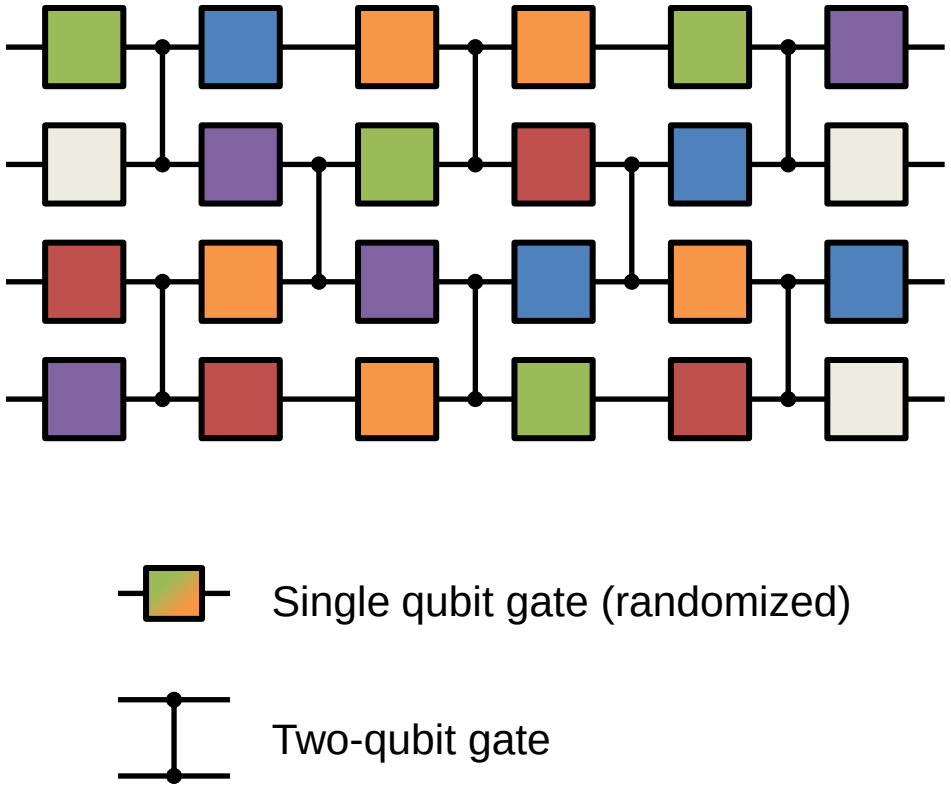


Speckle patterns

Random circuit

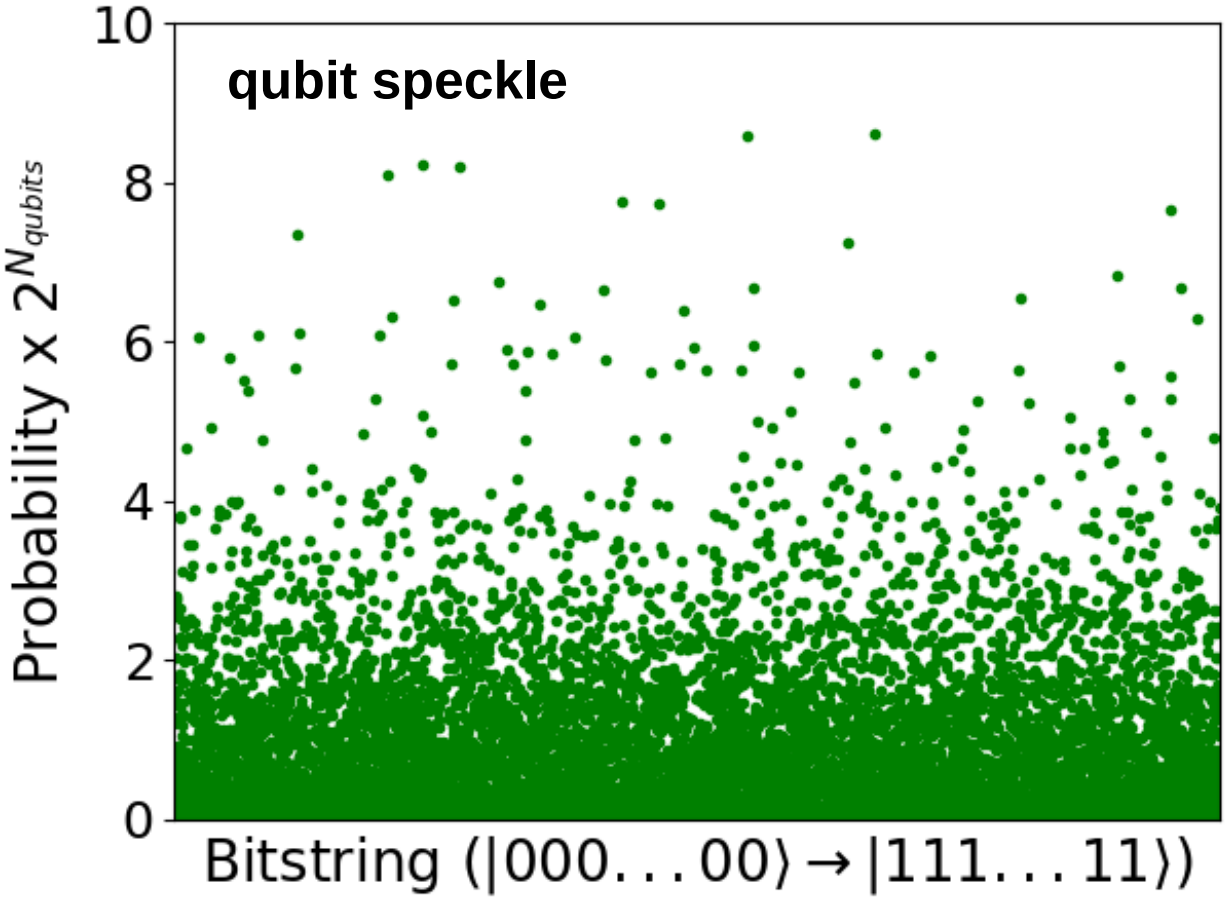
- Random circuit (U)
- Test ~10^6 runs, bitstrings x_i with probility p_i
- Classical, random guess: $p_{cl} \sim 1/2^N$
- QM: measure p_U, not uniform
- Fidelity: $F = 2^N \langle p_i(x_i) \rangle - 1$
  - F=0: incoherent
  - F=1: coherent

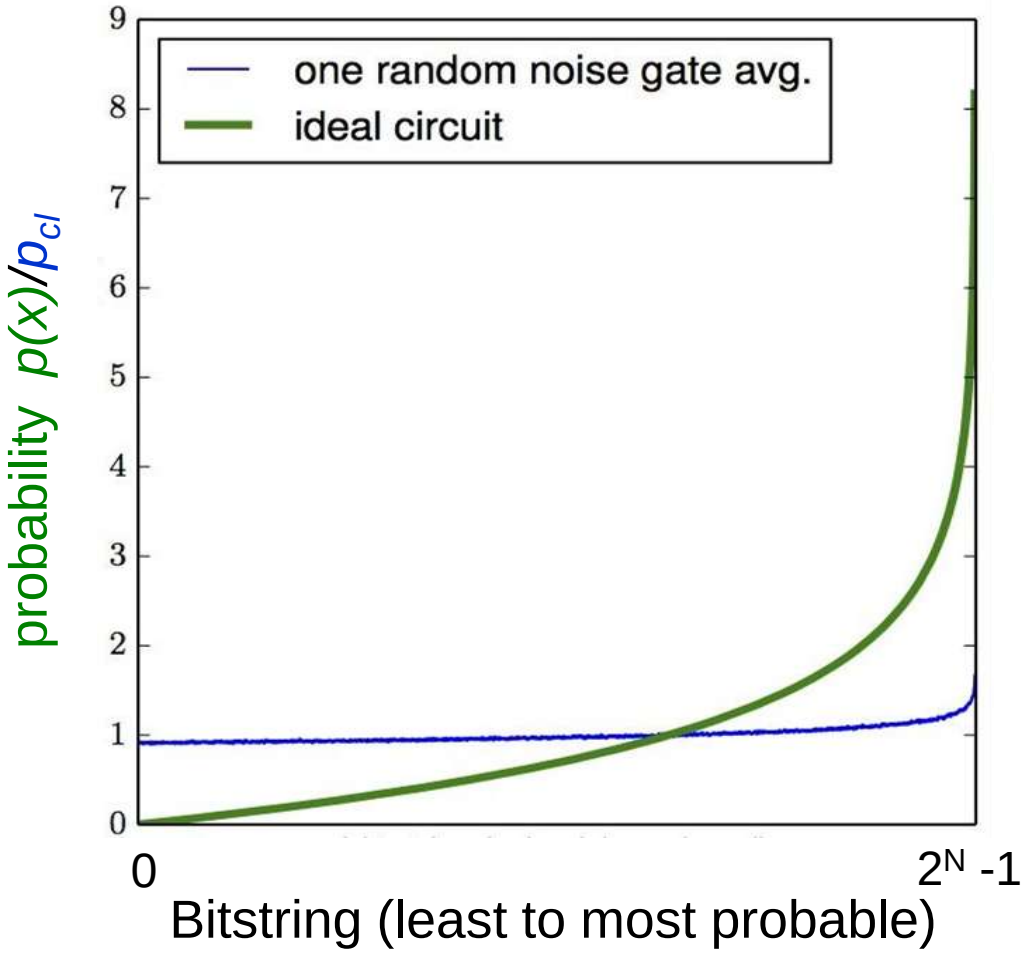
Random quantum circuits



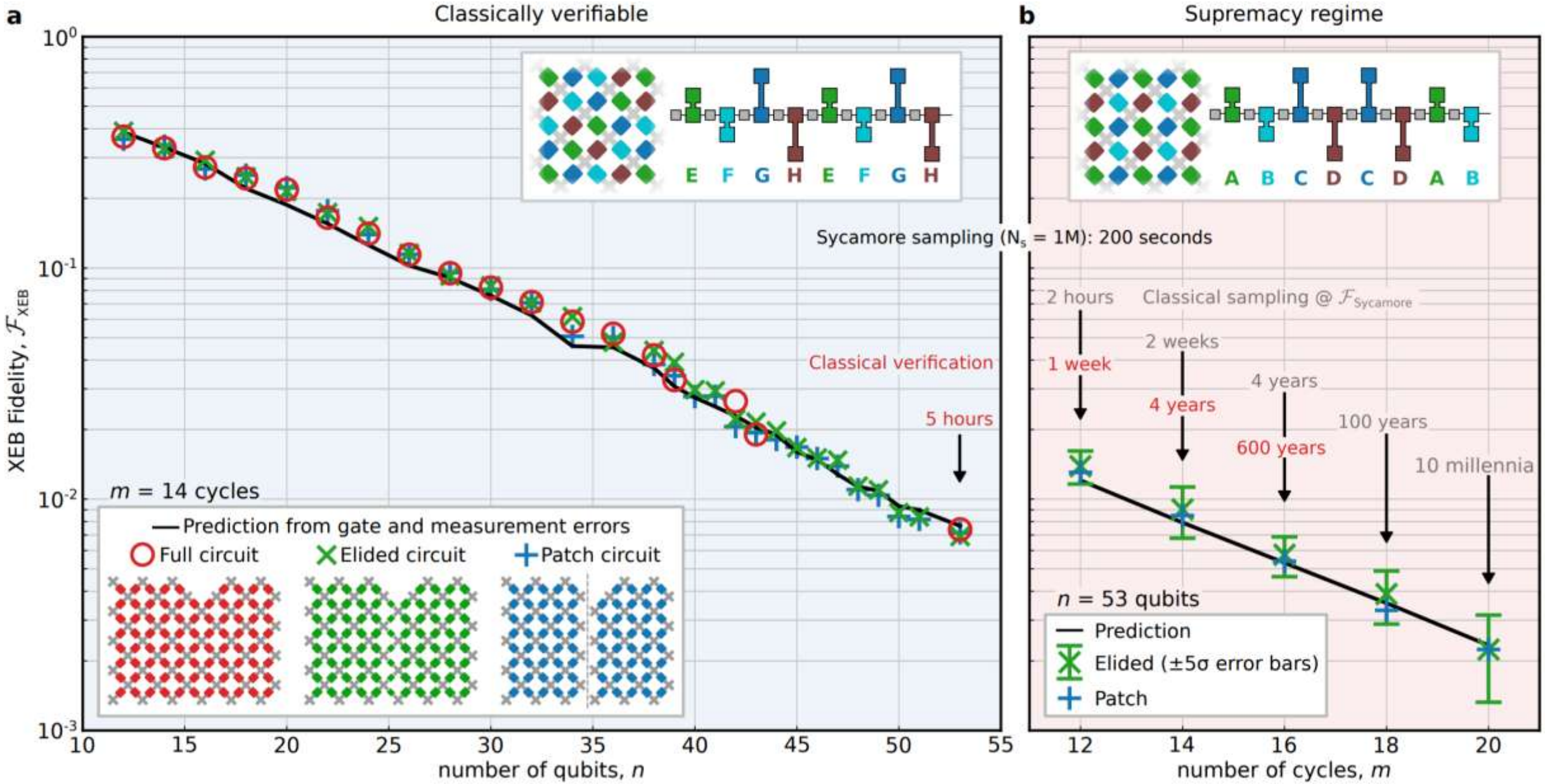
Boixo et al., Nat. Phys. 2018

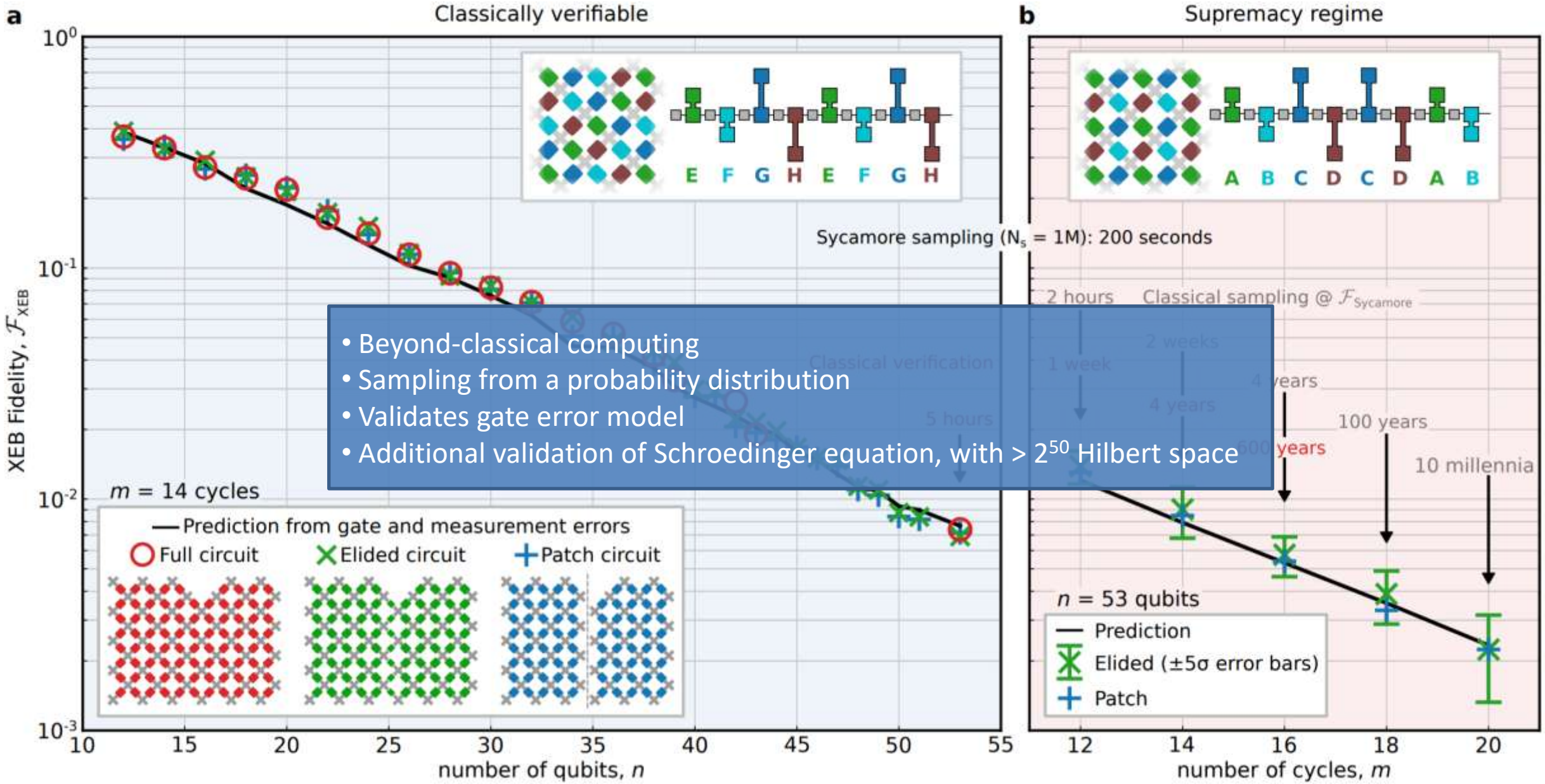
Random circuit





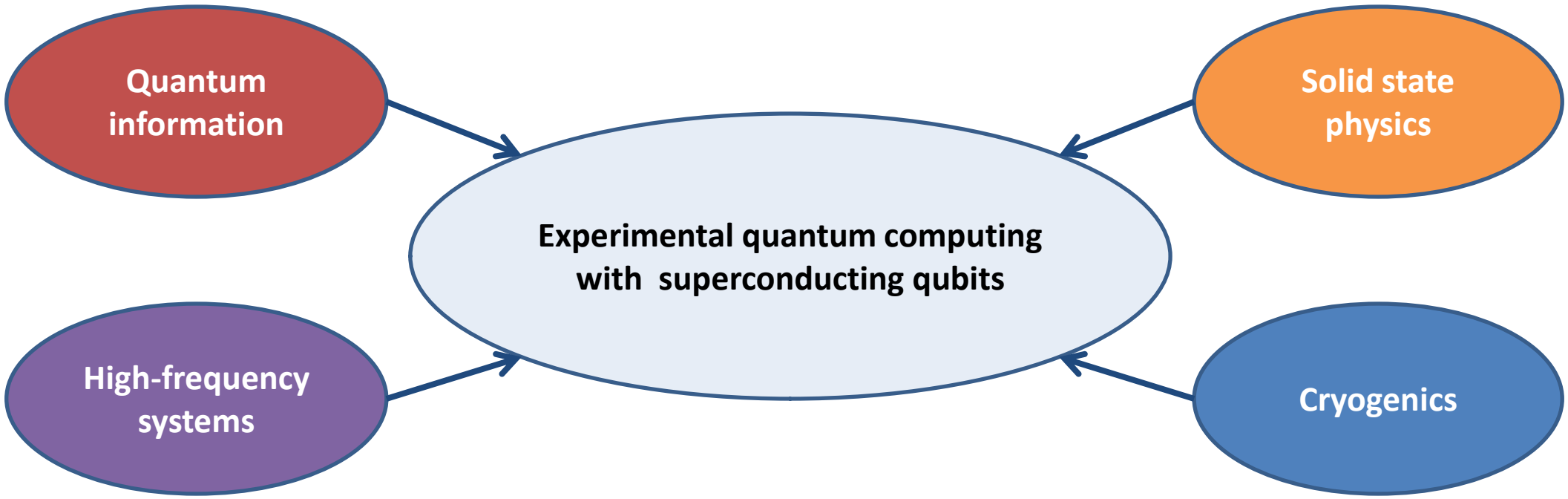
Explore enough Hilbert space:
Porter-Thomas distribution


a
Classically verifiable
b
Supremacy regime
XEB Fidelity, $\mathcal{F}_{XEB}$
number of qubits, n
number of cycles, m
E F G H E F G H
A B C D C D A B
Sycamore sampling (N_s = 1M): 200 seconds
Classical verification
5 hours
m = 14 cycles
Prediction from gate and measurement errors
Full circuit
Elided circuit
Patch circuit
2 hours
Classical sampling @ $\mathcal{F}_{Sycamore}$
1 week
2 weeks
4 years
4 years
600 years
100 years
10 millennia
n = 53 qubits
Prediction
Elided (±5σ error bars)
Patch


a
Classically verifiable
b
Supremacy regime
XEB Fidelity, $\mathcal{F}_{XEB}$
10^0
10^{-1}
10^{-2}
10^{-3}
E F G H E F G H
A B C D C D A B
Sycamore sampling (N_s = 1M): 200 seconds
2 hours
Classical sampling @ $\mathcal{F}_{Sycamore}$
Classical verification
1 week
2 weeks
5 hours
4 years
100 years
10 millennia
• Beyond-classical computing
• Sampling from a probability distribution
• Validates gate error model
• Additional validation of Schroedinger equation, with > 2^{50} Hilbert space
m = 14 cycles
Prediction from gate and measurement errors
Full circuit
Elided circuit
Patch circuit
n = 53 qubits
Prediction
Elided (±5σ error bars)
Patch
10 15 20 25 30 35 40 45 50 55
number of qubits, n
12 14 16 18 20
number of cycles, m

Course layout

Interdisciplinary system engineering



Experimental quantum computing happens at the crossroads of disciplines

Suggested literature for reference

Quantum information **High-frequency systems** **Solid state physics** **Cryogenics**

Tinkham, Introduction to superconductivity, 1996				
Ashcroft & Mermin, Solid State Physics, 1976				
Ketterson & Song, Superconductivity, Cambridge University Press, 1999				
Enss & Hunklinger, Low Temperature Physics, Springer, 2005				
Lounasmaa, Experimental Principles and Methods Below 1 K, Academic Press, 1976				
Cyrot & Pavuna, Introduction to Superconductivity and High-Tc Materials, World Scientific, 1992				
Pozar, Microwave engineering, Wiley & Sons, 2012				
Collins, Foundations for Microwave Engineering, McGraw Hill, 1992				
Martinis & Osborne, Superconducting Qubits and the Physics of Josephson Junctions, arXiv:cond-mat/0402415				
Wendin, Quantum information processing with superconducting circuits: a review, Rep. Prog. Phys. 80, 106001 (2017)				
Devoret, Wallraff & Martinis, Superconducting Qubits: A Short Review, arXiv:cond-mat/0411174				

Don’t try to read all this now. For reference.

Grading & homework

- Grading
  - Oral exam
  - entrance: presentation + mandatory coding homework
  - exam can cover any discussed topic, higher chance on blue topics

- Presentations
  - Mandatory
  - Relevant papers to the topic
  - Not graded

- Homework
  - Math – Optional, Discussed in-class next session
  - Python coding – Mandatory
  - Figure produced, tests need to pass
  - **Can work together!**

Grading & homework

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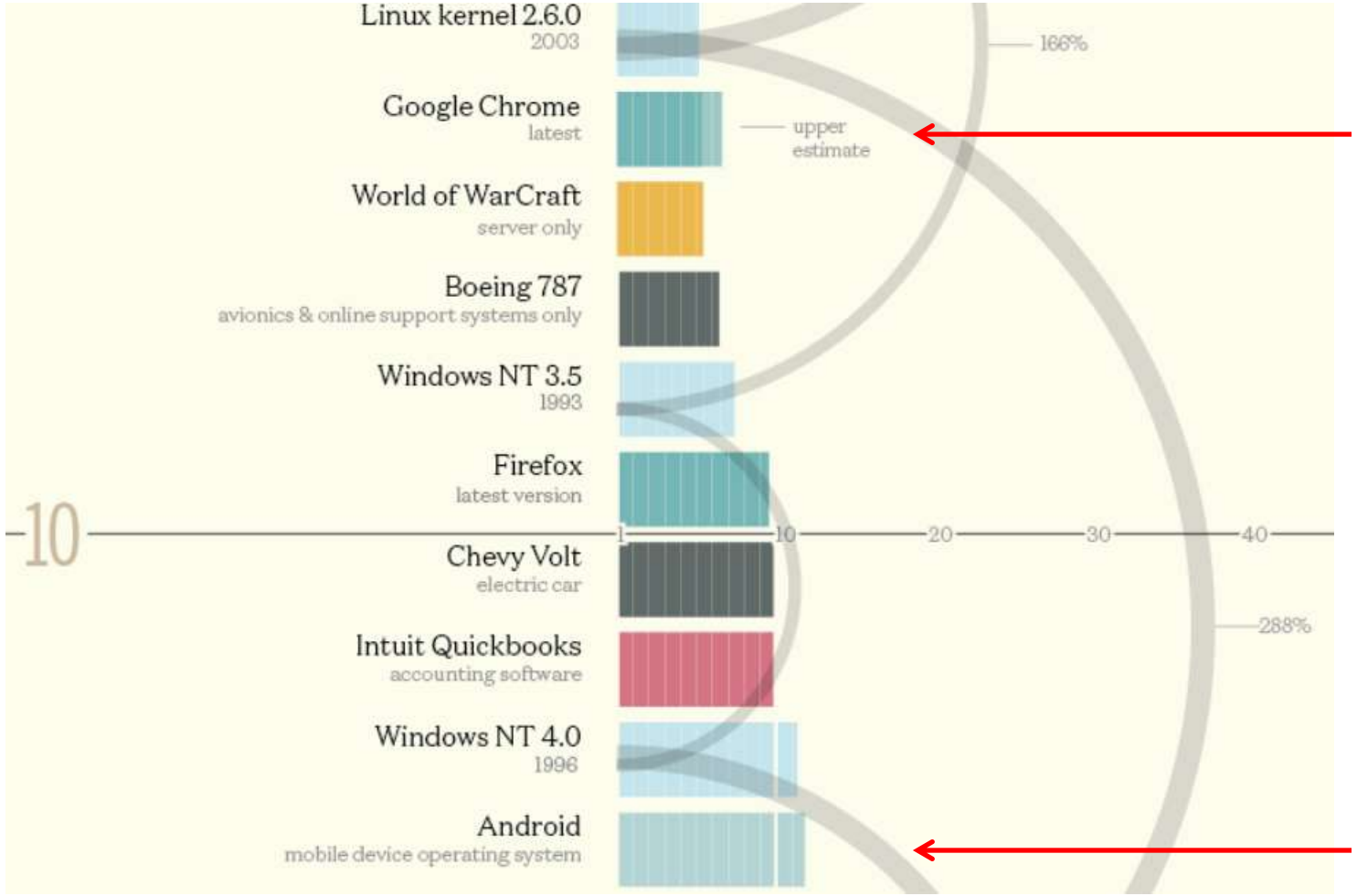
How many lines of code?
- You take your phone
- Snap a pic
- Upload to whatsapp/twitter etc

Needed:
- ❑ OS, camera driver, image processing, comm.
- ❑ Web browser

Code



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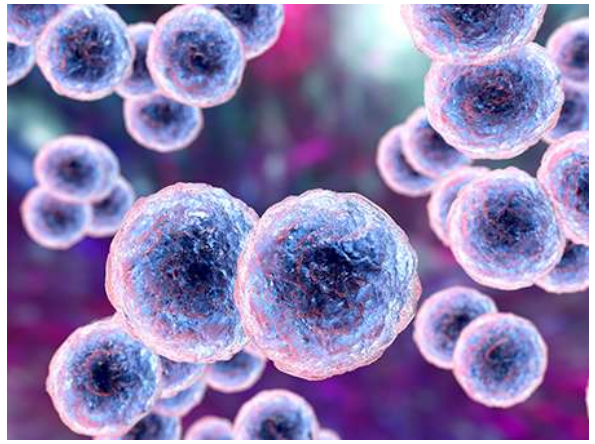
- ❑ Web browser

~20 million lines of code

https://www.visualcapitalist.com/millions-lines-of-code/

Code



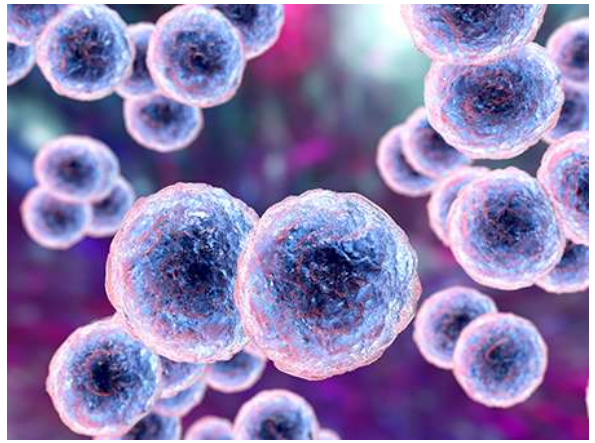
bacteria

F22 fighter

game engine

How many lines of code?

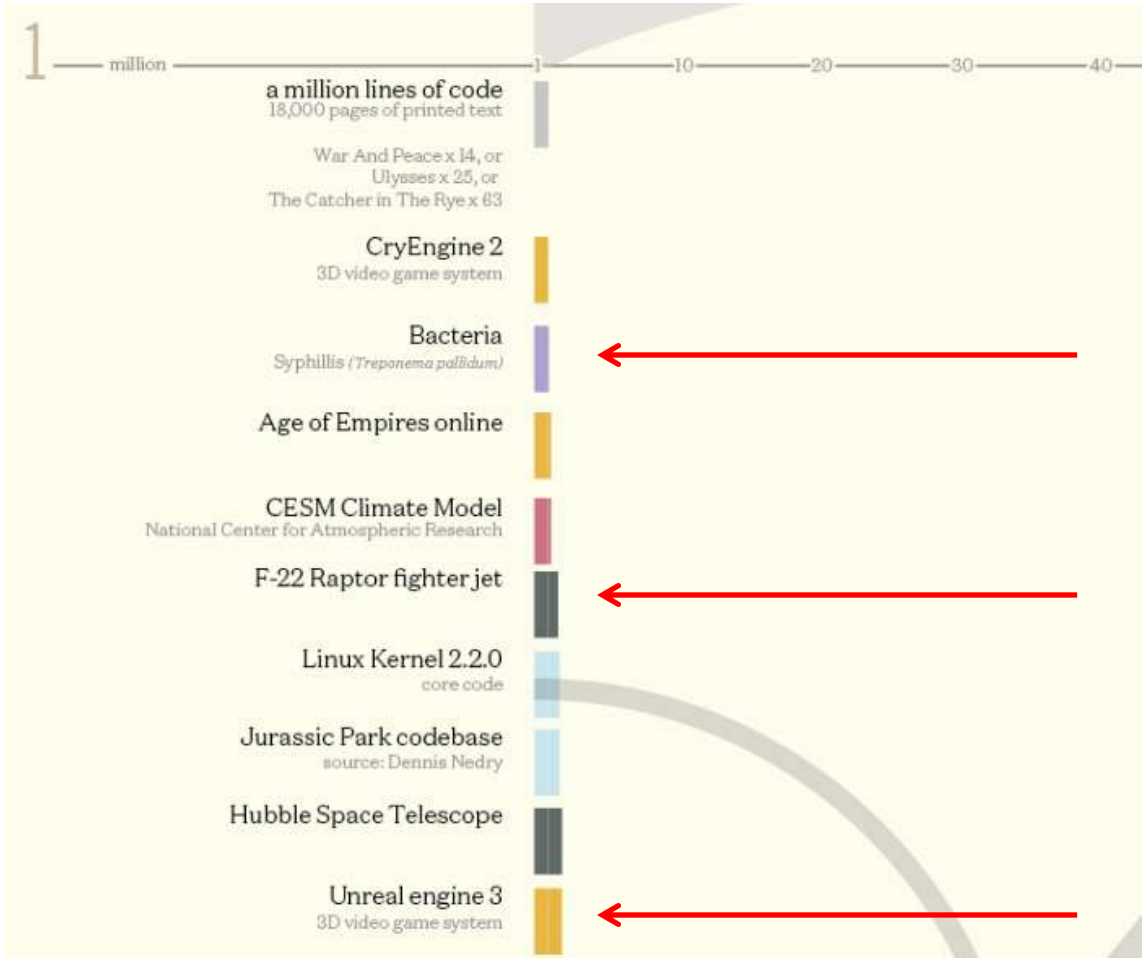
Code



bacteria

F22 fighter

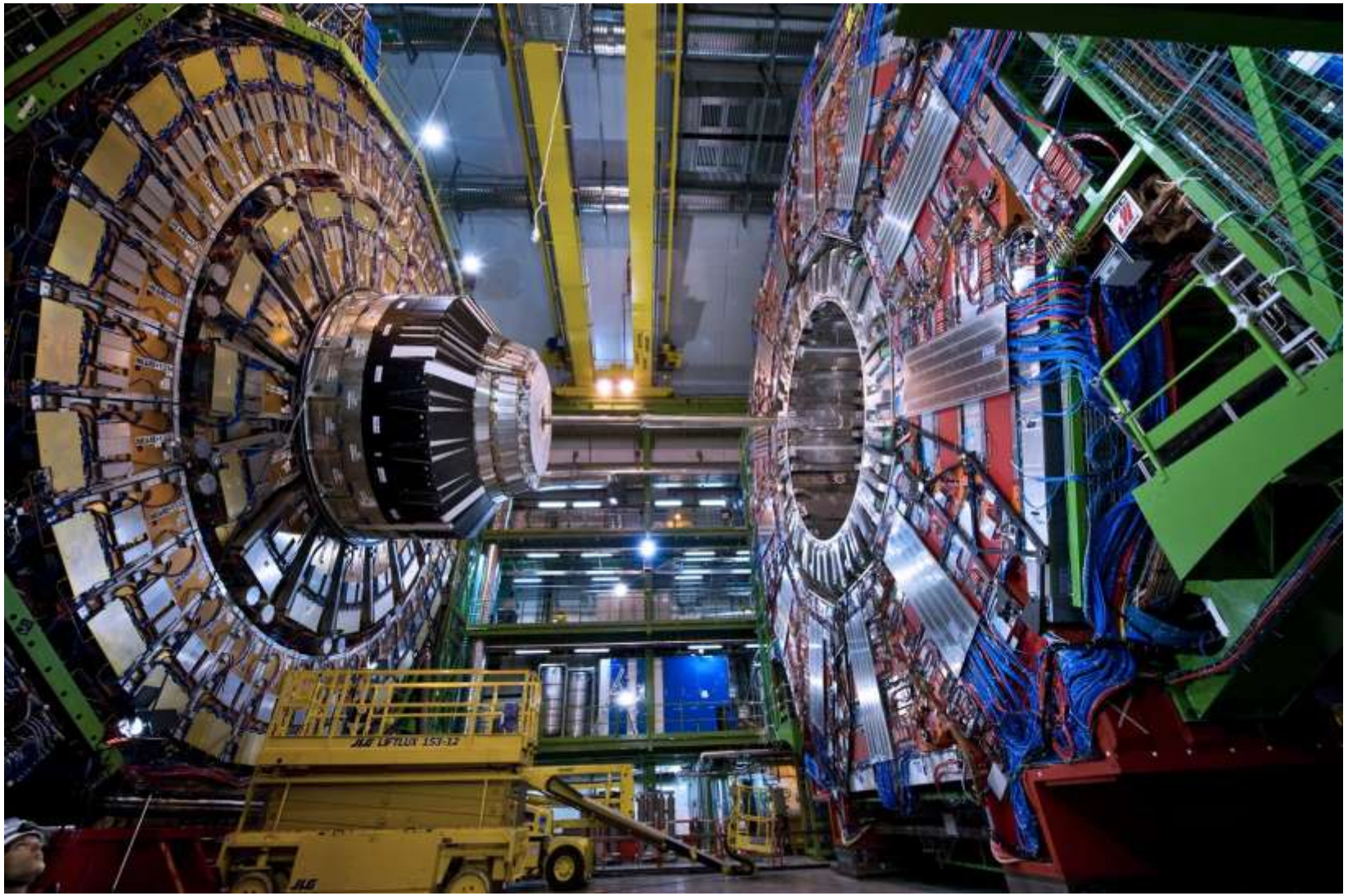
game engine



~1-2 million lines of code

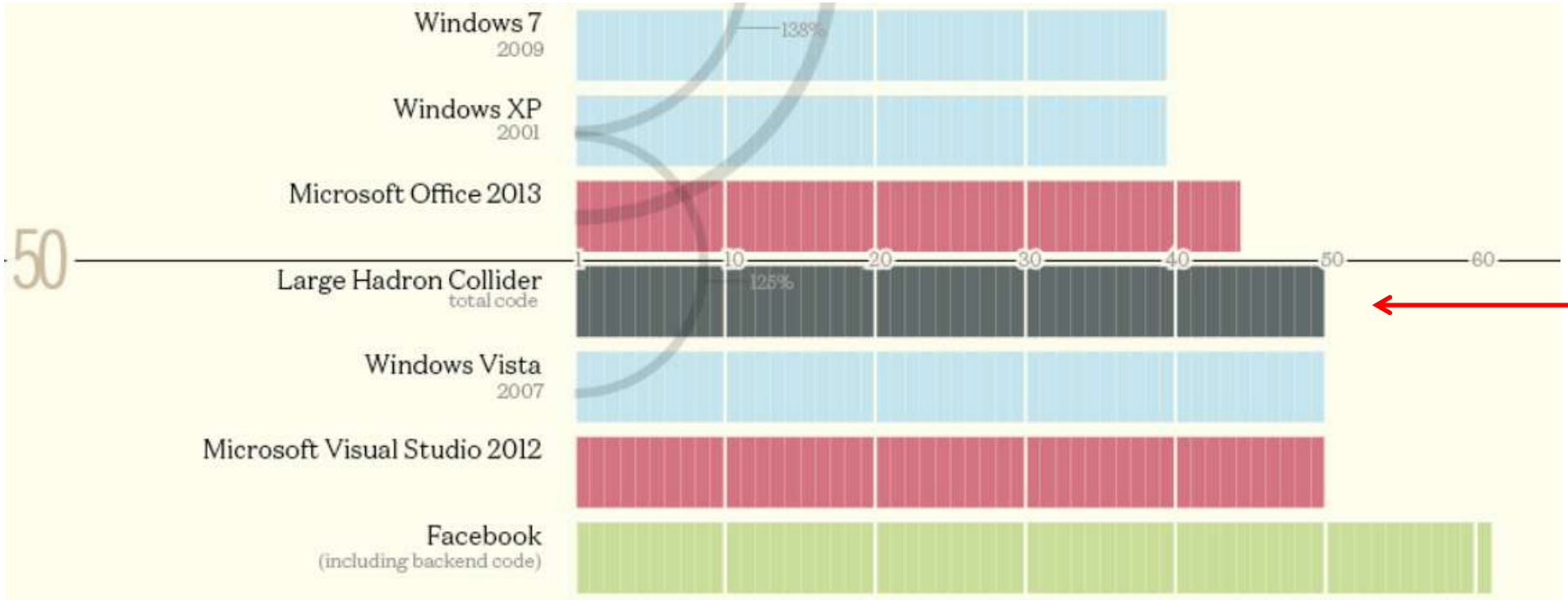
https://www.visualcapitalist.com/millions-lines-of-code/

Code



A big physics experiment: Large hadron collider

Code



Science at scale:

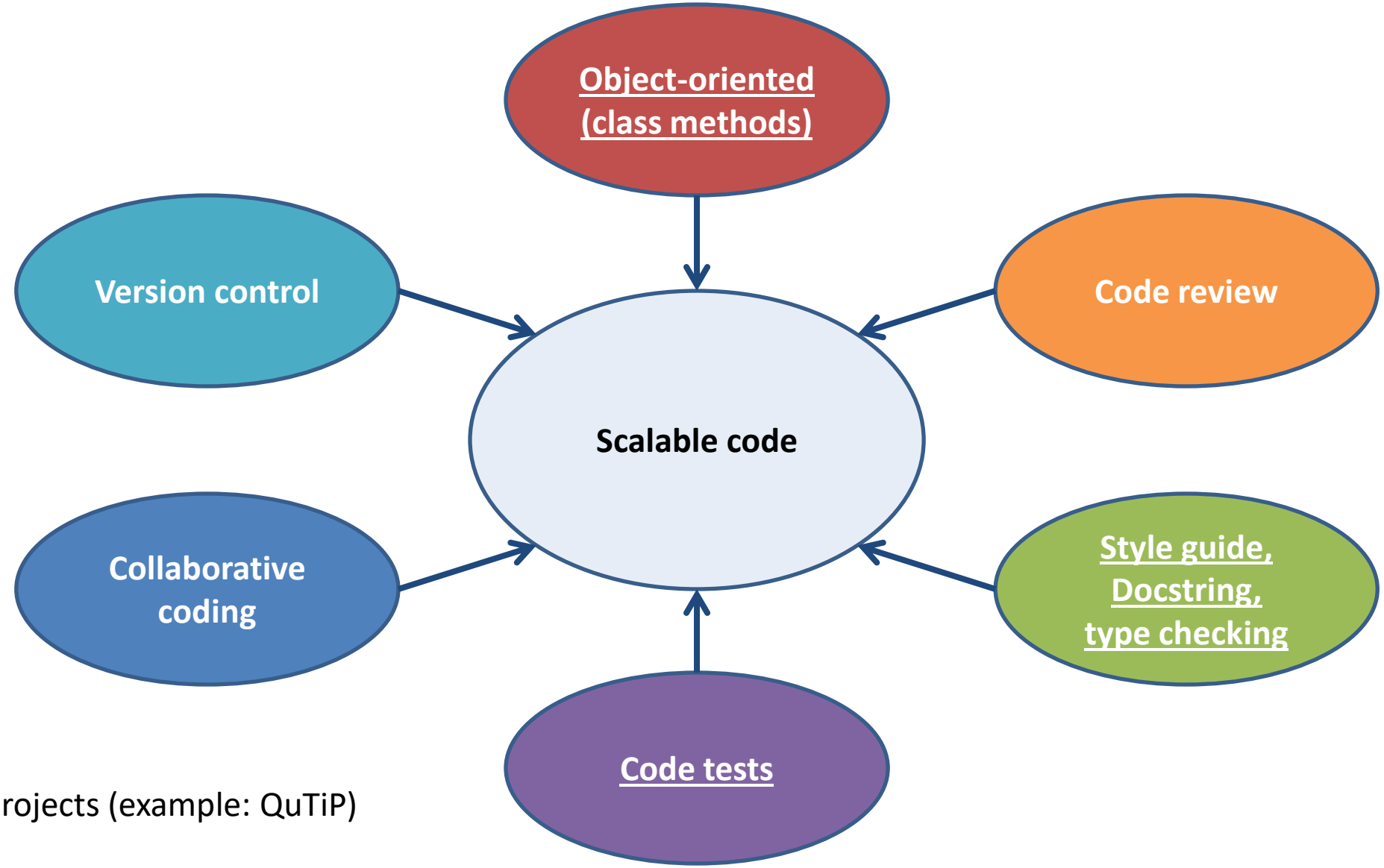
Running a large physics experiment requires as much code as modern computer OS and internet company systems

Even for individuals, coding is a key element of modern physics

- Simulation
- Data processing
- Hardware-interface programming

https://www.visualcapitalist.com/millions-lines-of-code/

Coding skills



Exposure:
Contribute to open-source projects (example: QuTiP)

Full list on:
https://qosf.org/project_list/

Whiteboard use

Two coupled two-level systems: Energy picture

$$H = -\frac{\sigma_{z,1}}{2}\omega_1 - \frac{\sigma_{z,2}}{2}\omega_2 + g\sigma_{x,2}\sigma_{x,1}$$

$$H = \begin{pmatrix} 0 & 0 & 0 & g \\ 0 & \omega_1 & g & 0 \\ 0 & g & \omega_2 & 0 \\ g & 0 & 0 & \omega_1 + \omega_2 \end{pmatrix}$$

blackboard

Apply rotation matrix

$$H_R = RHR^+ + i\hbar\dot{R}R^+$$

$$R = \sum e^{in_k\omega_d t}|k><k|$$

Two coupled two-level systems: Energy picture

$$H = -\frac{\sigma_{z,1}}{2}\omega_1 - \frac{\sigma_{z,2}}{2}\omega_2 + g\sigma_{x,2}\sigma_{x,1}$$

$$H = \begin{pmatrix} 0 & 0 & 0 & g \\ 0 & \omega_1 & g & 0 \\ 0 & g & \omega_2 & 0 \\ g & 0 & 0 & \omega_1 + \omega_2 \end{pmatrix} \rightarrow H_R = \begin{pmatrix} 0 & 0 & 0 & ge^{-2i\omega t} \\ 0 & 0 & g & 0 \\ 0 & g & \Delta & 0 \\ ge^{2i\omega t} & 0 & 0 & \Delta \end{pmatrix}$$

Apply rotation matrix

$$H_R = RHR^+ + i\hbar\dot{R}R^+$$

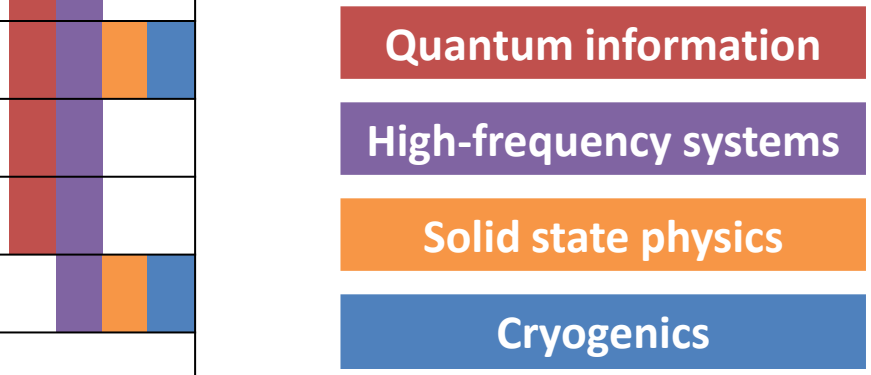
$$R = \sum e^{in_k\omega_d t}|k><k|$$

"blackboard" slide

Next slide shows final answer
(sometimes with derivation)

Lecture overview

Topic	Date	HW
Intro	0411	
Superconductivity and Josephson junctions	0418	Y
Qubits, measurement, and coherent & incoherent driving	0425	Y
From qubit design to quantum data (special guests: Yebin Liu & Asier Galicia)	0502	
Quantum phase coherence (code HW1 due)	0516	Y
Coupling in quantum systems	0606	Y
Quantum gate design & benchmarking (code HW2 due)	0613	Y
Physics of coherence (short) + Paper presentations	0620	Y*
Paper presentations	0627	
System engineering: building for scale (short) & Lab visit (code HW3 due)	0704	
Cryogenic engineering (special guest: Pavel Bushev)	0711	
Implementing algorithms	0718	



*Can't be done w/o in-class lecture notes