Sievert Lecture Series: The Rise of Quantum Machines

Lecture III: Creation of Quantum Systems by Design

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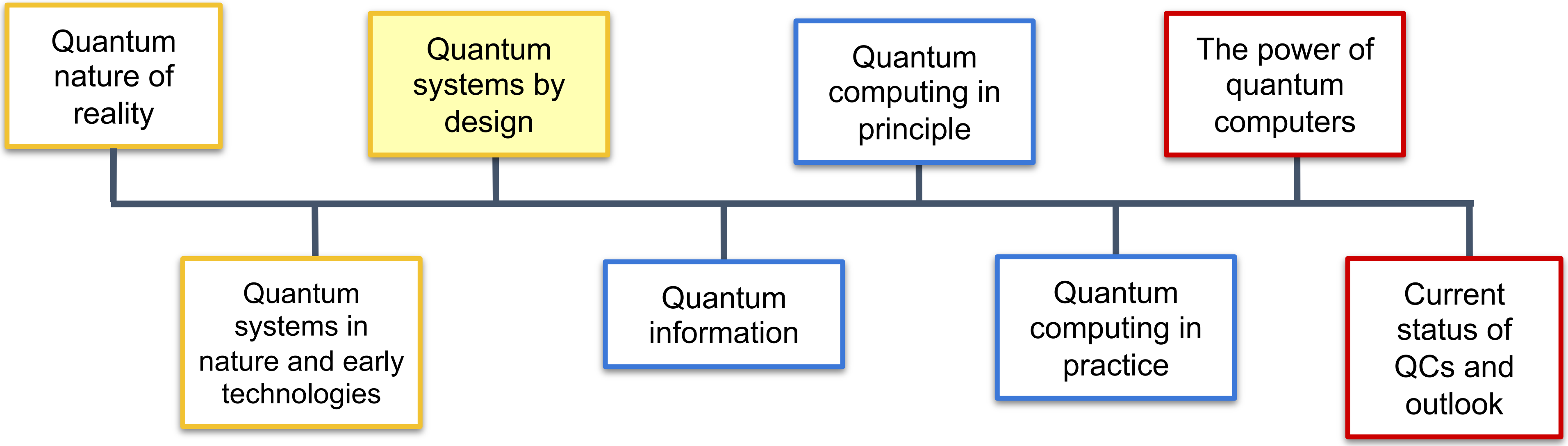
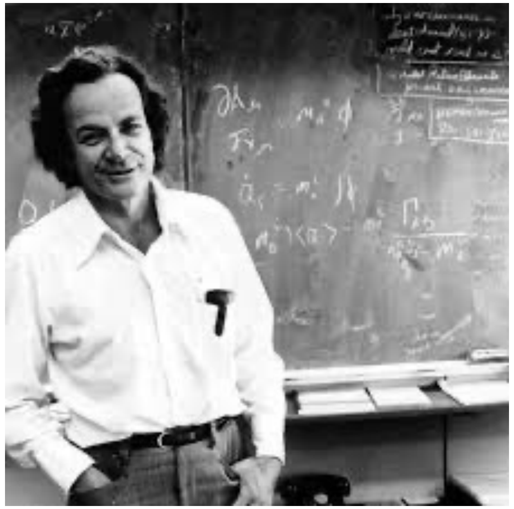
Sievert Lecture Series: The Rise of Quantum Machines

Roadmap



From 1st to 2nd quantum revolutions

- First quantum revolution
  - Make use of systems with quantum properties
  - Examples: laser and transistor
- Second quantum revolution
  - Design and manipulate individual quantum systems
- Goals
  - Understand and test quantum theories
  - Explore new quantum phenomena
  - Develop novel technologies



"… nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

— R. P. Feynman (1982)

Creation of quantum systems by design

- Matter
  - Bose—Einstein condensate (Nobel Prize 2001)
- Matter + Light
  - Cavity QED (Nobel Prize 2012)
  - Circuit QED (Nobel Prize ?)

The fifth state of matter

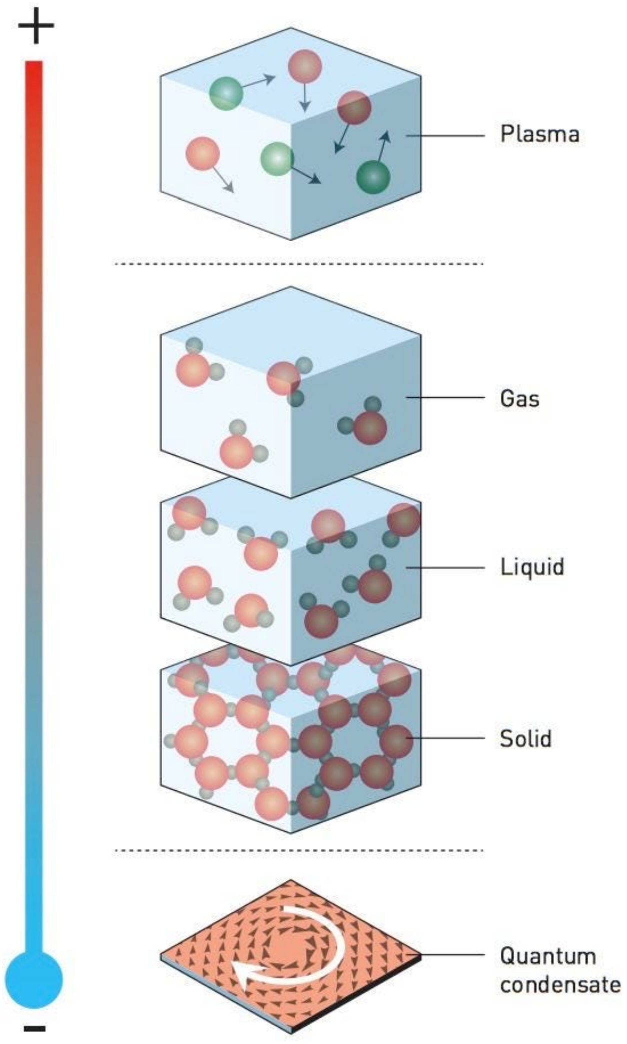


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

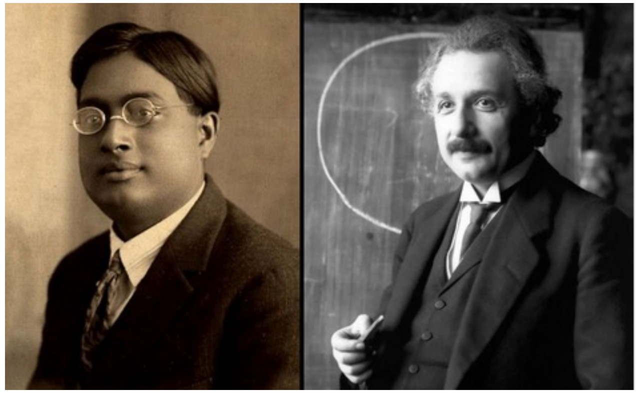
Three states of matter in daily life:

- Gas
- Liquid
- Solid

Ultra hot state: Plasma

Ultra cold state: Bose—Einstein condensate (BEC)

Prediction of Bose—Einstein condensate (1924)

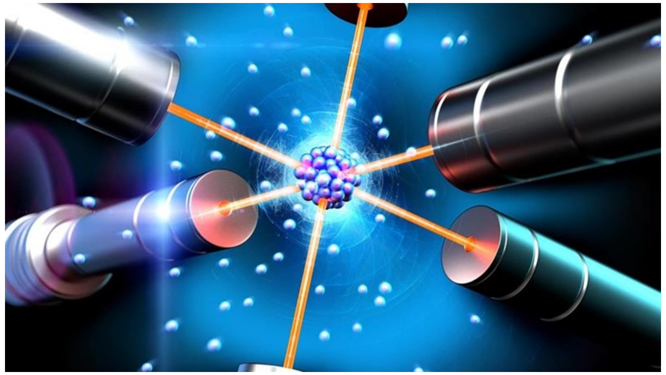


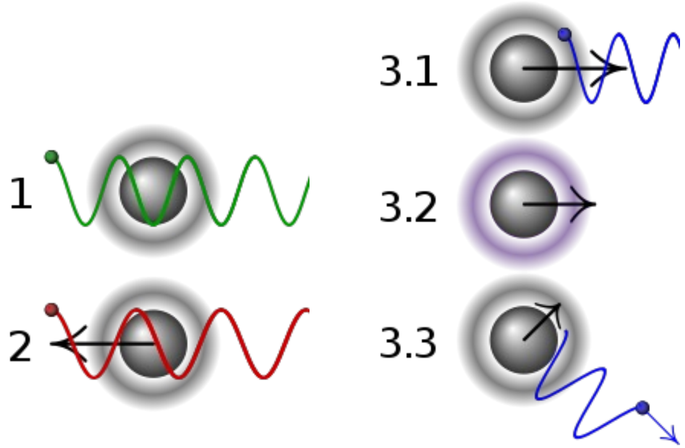
- Longer wavelength at lower temperature
- Below critical temperature (nanokelvin), particles start to overlap and behave as one single entity

How to reach the coldest place in the universe?

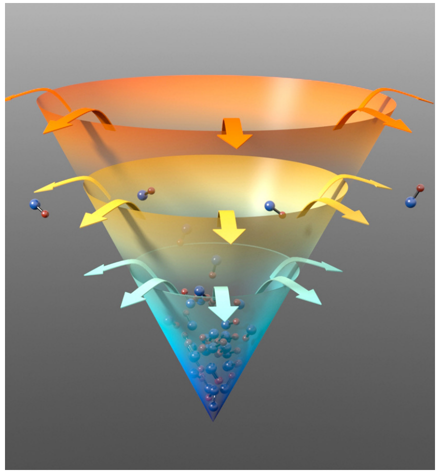
- Prepare lots of identical atoms, e.g., sodium, rubidium

- Laser cooling to millikelvin





- Evaporate cooling further to nanokelvin



Experimental realization of Bose—Einstein condensate (1995)

The Nobel Prize in Physics 2001

Photo from the Nobel Foundation archive.
Eric A. Cornell

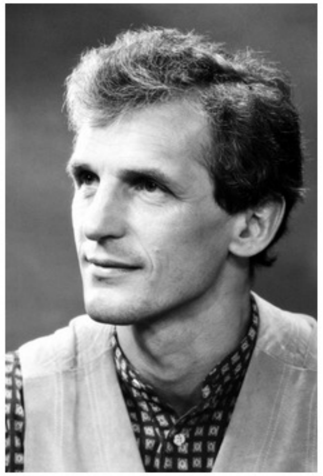
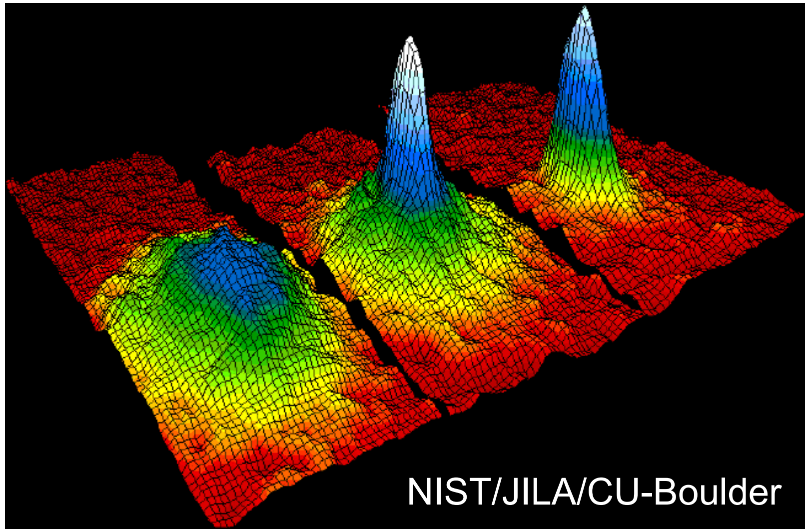


Photo from the Nobel Foundation archive.
Wolfgang Ketterle

Photo from the Nobel Foundation archive.
Carl E. Wieman

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"



Velocity distribution of rubidium atoms

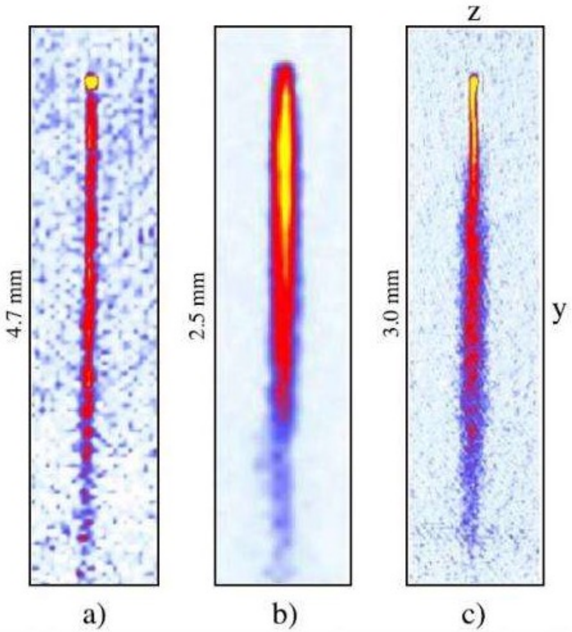
Zero gravity BEC experiments

Observation of Bose–Einstein condensates in an Earth-orbiting research lab

David C. Aveline, Jason R. Williams, Ethan R. Elliott, Chelsea Dutenhoffer, James R. Kellogg, James M. Kohel, Norman E. Lay, Kamal Oudrhiri, Robert F. Shotwell, Nan Yu & Robert J. Thompson

Applications of BEC

Atomic laser



V. Bolpasi, *et al*., New J. Phys. **16**, 033036 (2014)

Like laser, with photons replaced by atoms

Atomic clock

Better accuracy as all atoms behave collectively

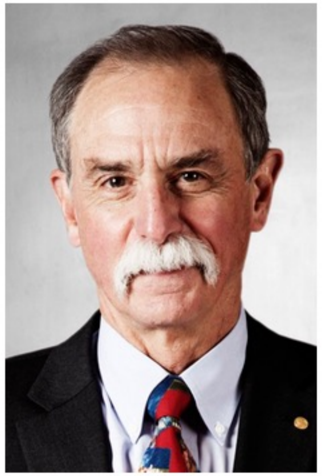
Cavity QED: light—matter interaction

The Nobel Prize in Physics 2012

Serge Haroche

Haroche: trap photons and then probe with atoms

Wineland: trap atoms and then probe with photons

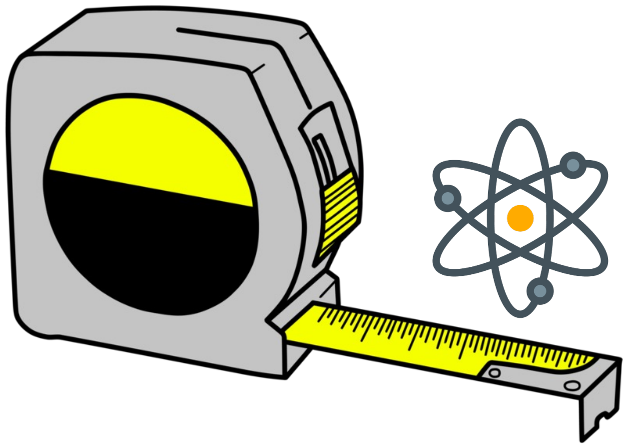


David J. Wineland

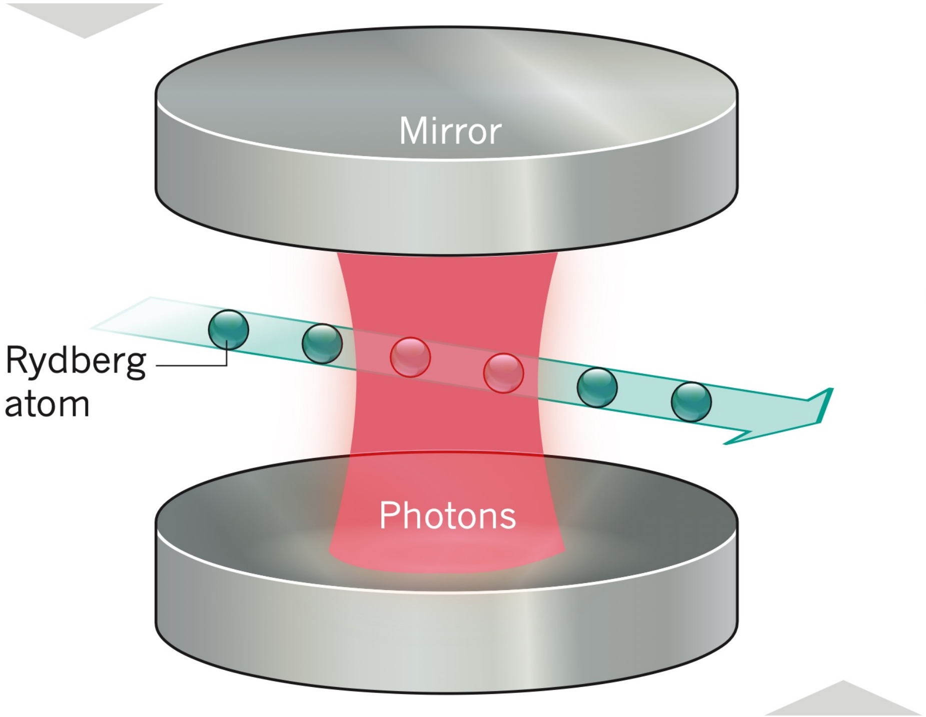
Main challenges

- How to trap photons/atoms?

- How to measure photons/atoms without destroying them?



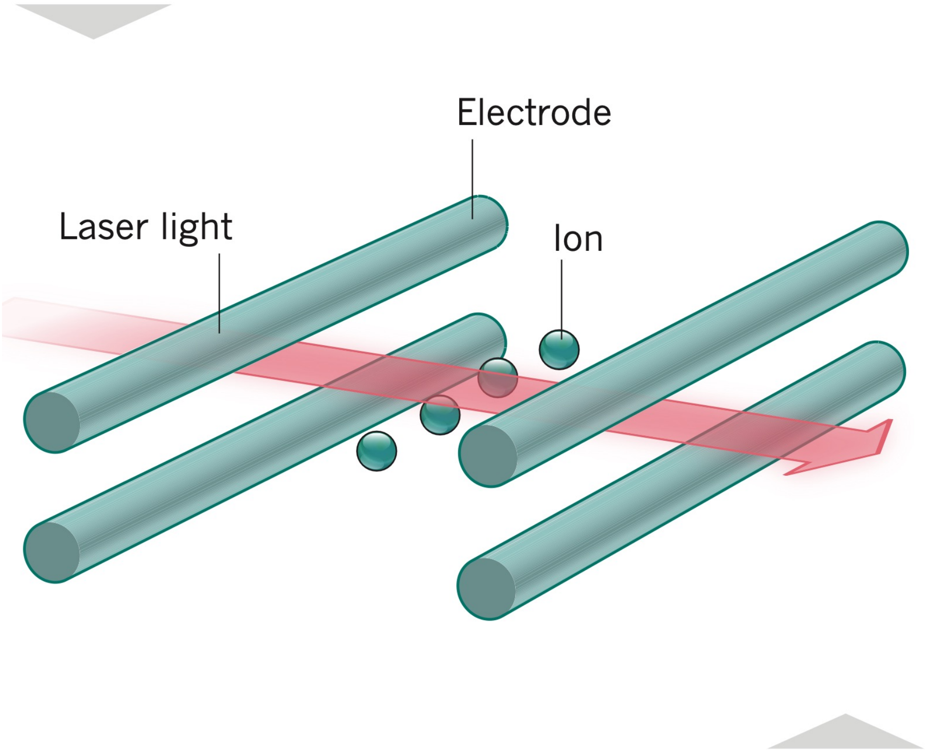
Haroche's approach



E. Hinds and R. Blatt, Nature **492**, 55 (2012)

- Photons are trapped in a two-mirror cavity
- Frequency of atom is shifted by light
- The photons survived after the measurement

Wineland’s approach

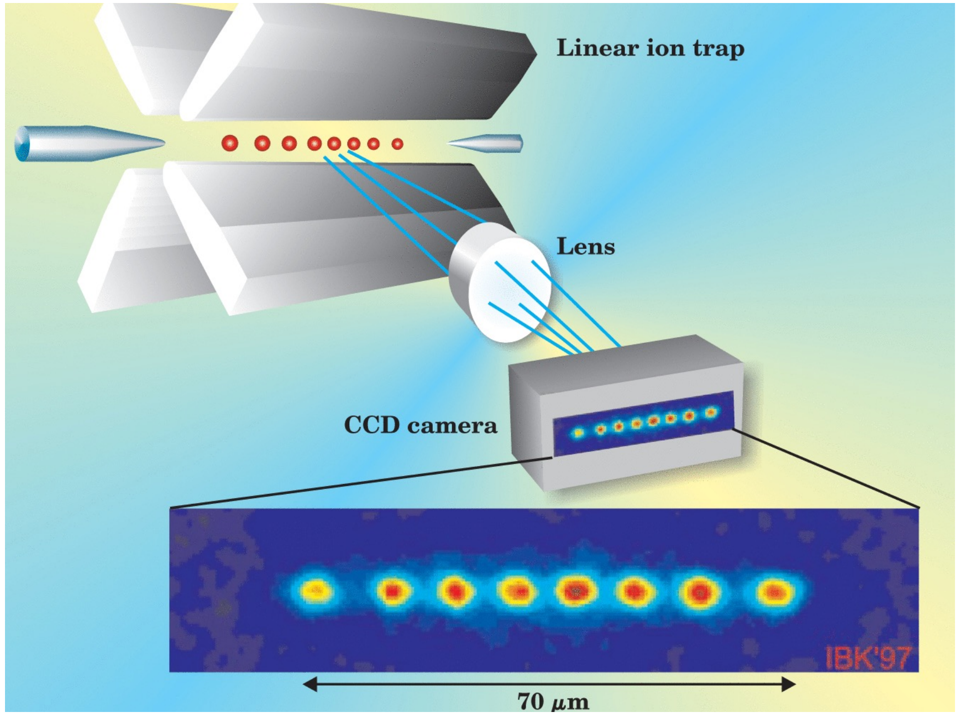


E. Hinds and R. Blatt, Nature **492**, 55 (2012)

- Charged atoms are trapped with electric fields
- Spectral information of the target ion is transferred via shared motion to a readout ion
- The target ion is intact after the measurement

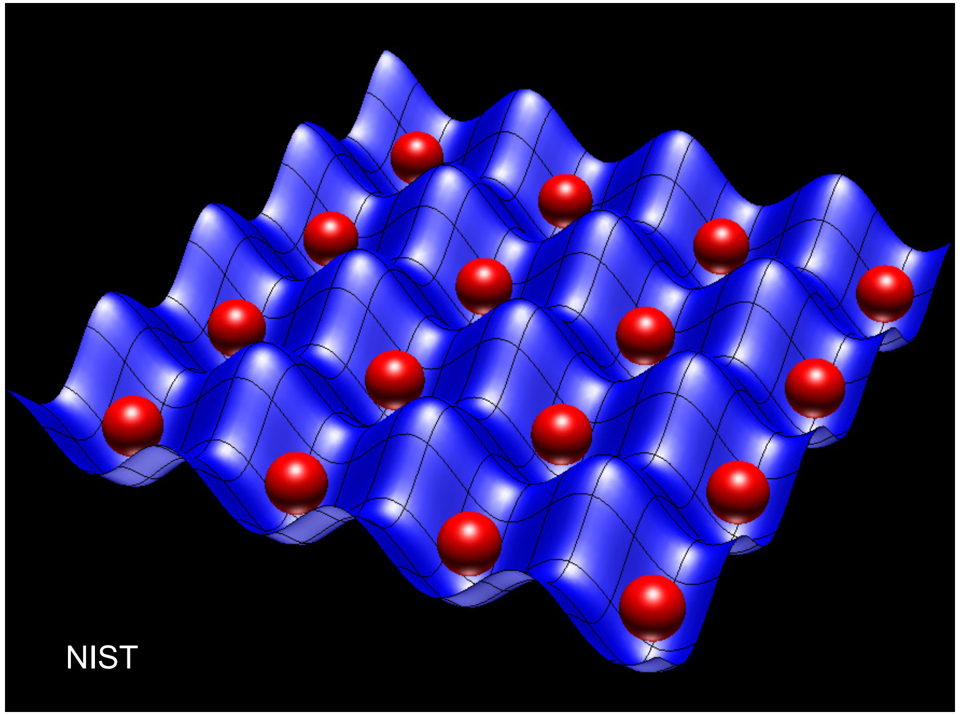
Applications: quantum computing based on natural atoms

Trapped ion quantum computing

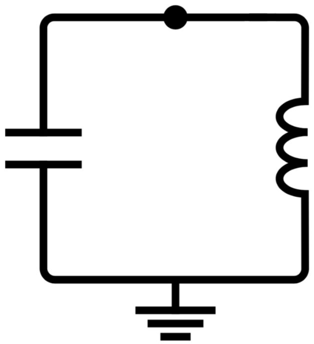


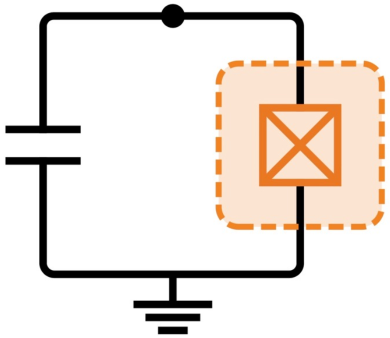
J. I. Cirac and P. Zoller, Phys. Today **57**, 38 (2004)

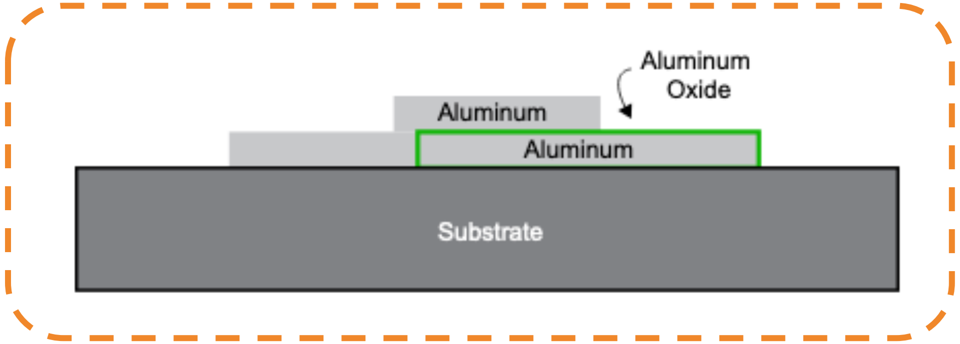
Neutral atom quantum computing

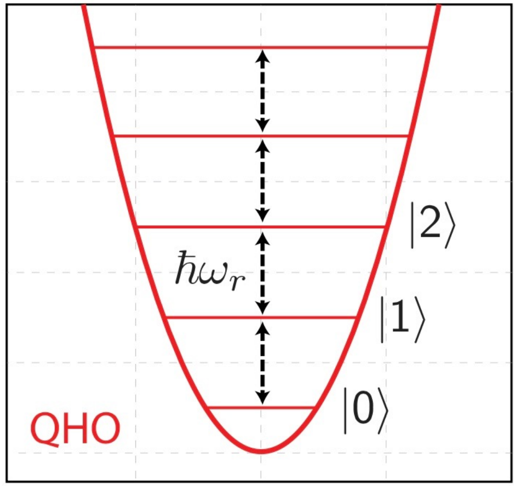


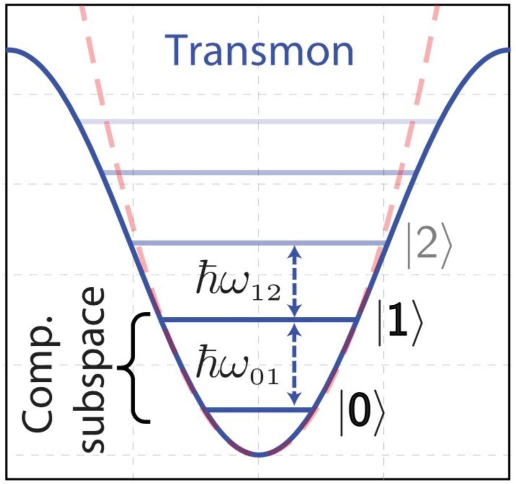
Basic elements of superconducting circuits







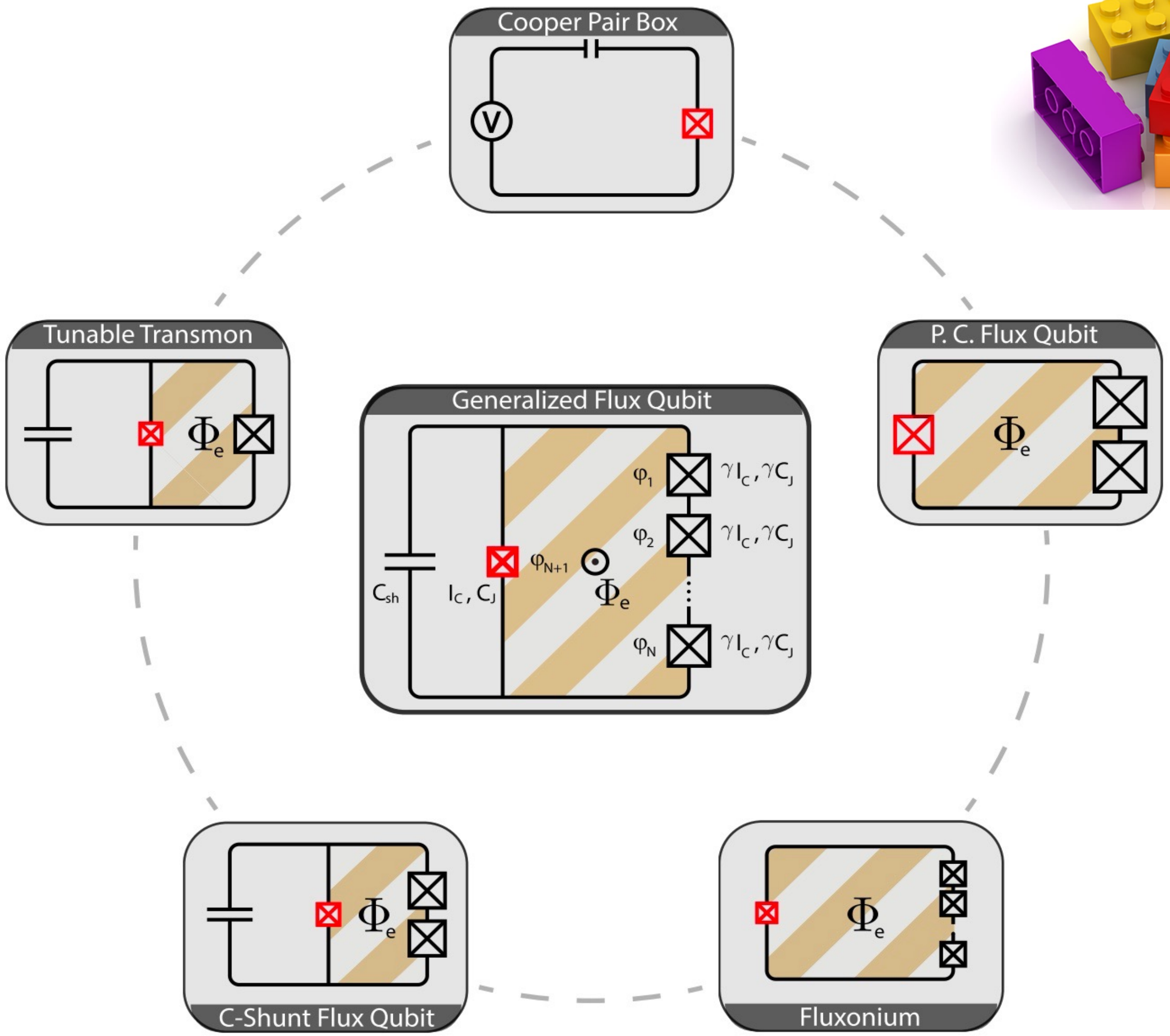




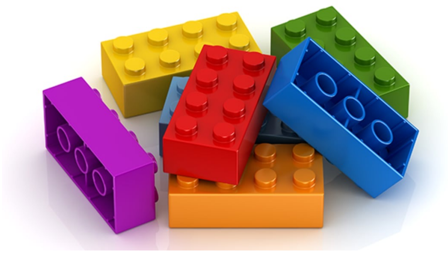
M. Kjaergaard, *et al.*, Annu. Rev. Condens. Matter Phys. **11**, 369 (2020)

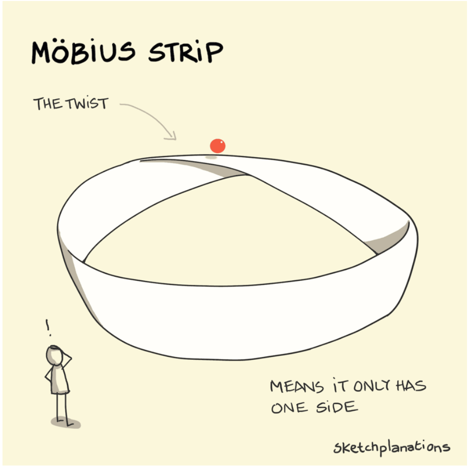
- No dissipation due to superconductivity
- Linear elements: capacitor, inductor
- Nonlinear element: Josephson junction

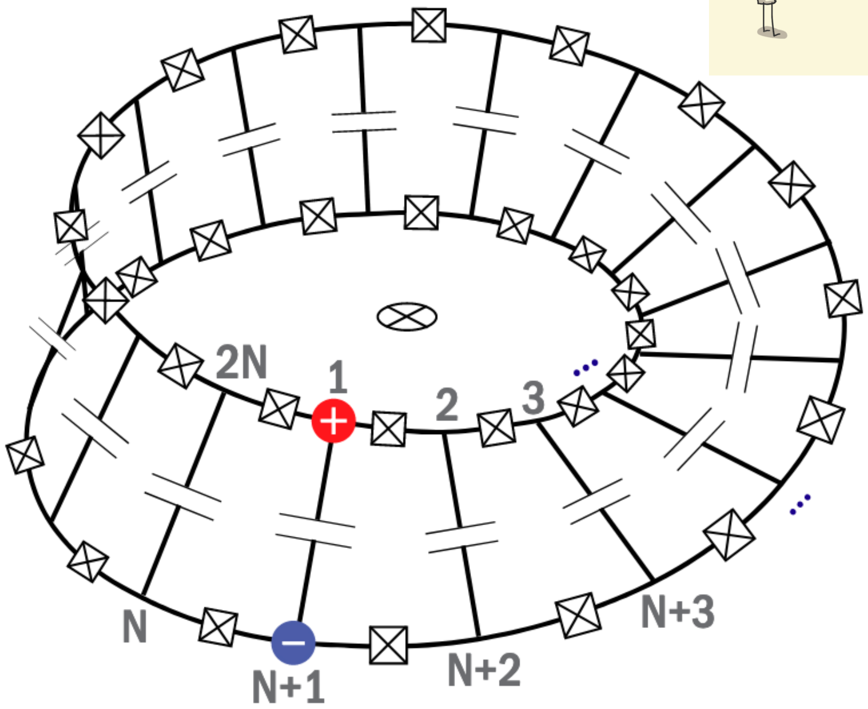
Zoo of superconducting circuits



F. Yan, *et al.*, arXiv:2006.04130 (2020)

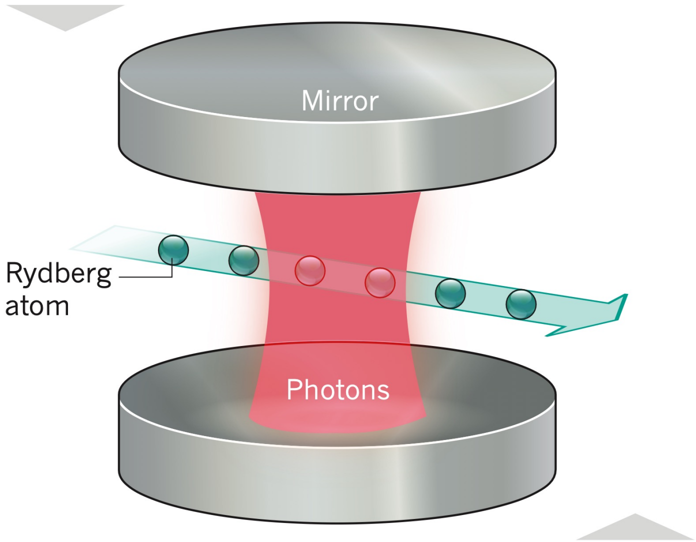






D. K. Weiss, *et al.*, Phys. Rev. B **100**, 224507 (2020)

From cavity QED to circuit QED



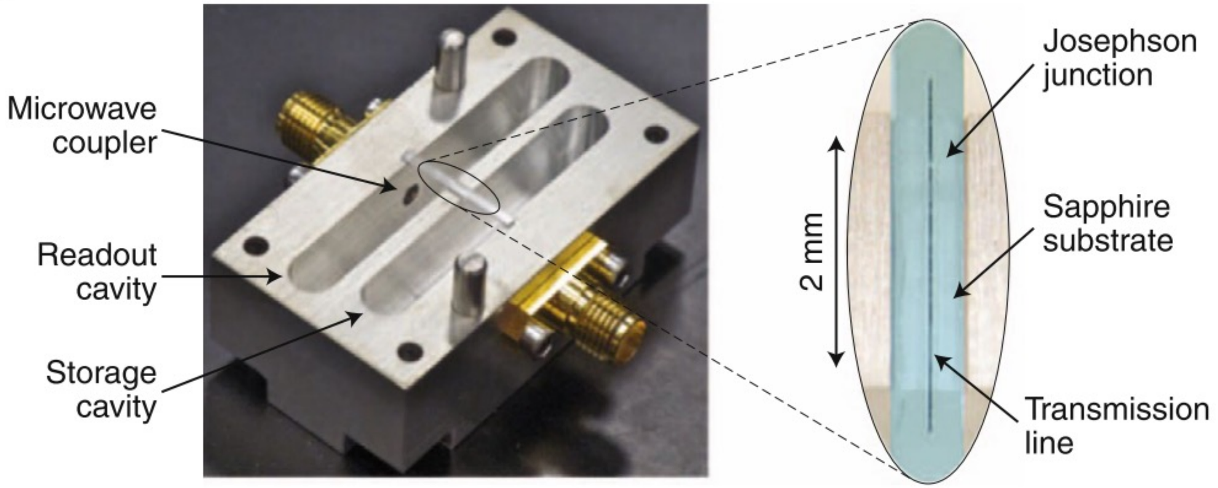
E. Hinds and R. Blatt, Nature **492**, 55 (2012)

Cavity QED

- Natural atoms interacting with EM field in cavity
- Long lifetime but small interaction

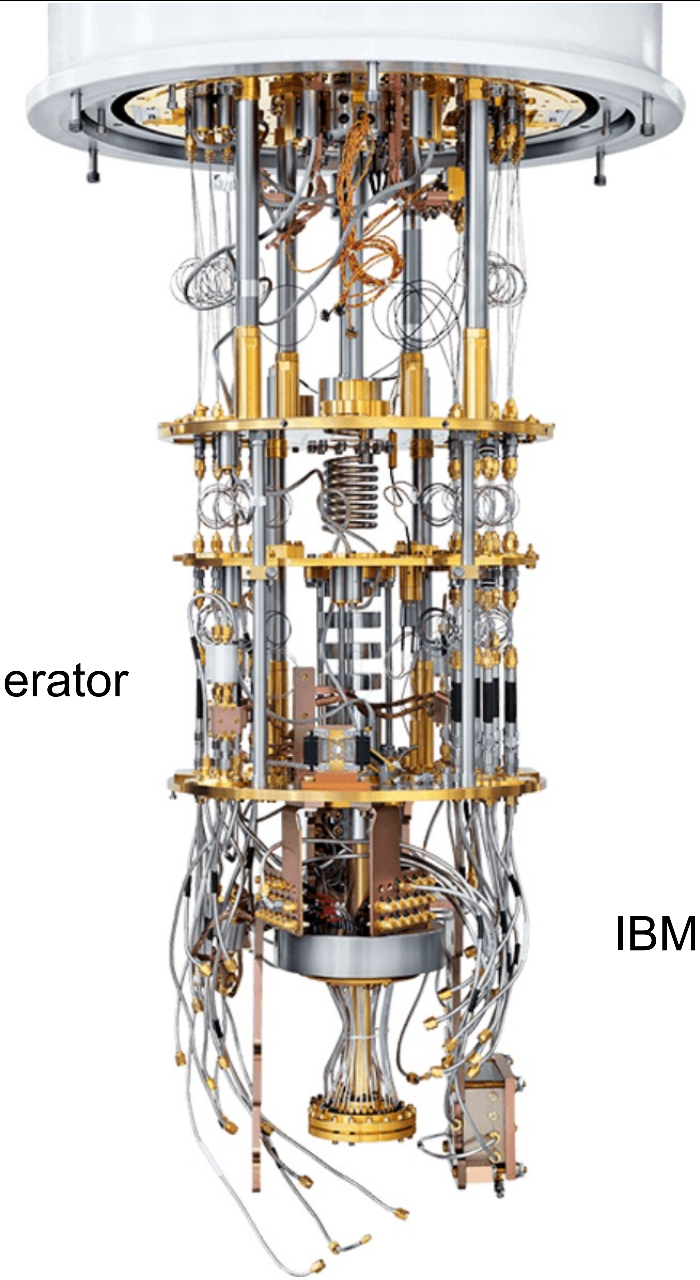
Circuit QED

- Artificial atoms interacting with EM field in resonator
- Short lifetime but large interaction

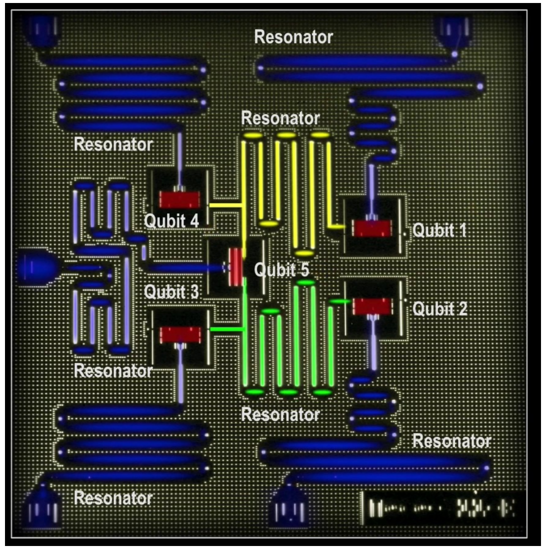


S. Haroche, *et al.*, Nat. Phys. **16**, 243 (2020)

Applications: quantum computing based on artificial atoms

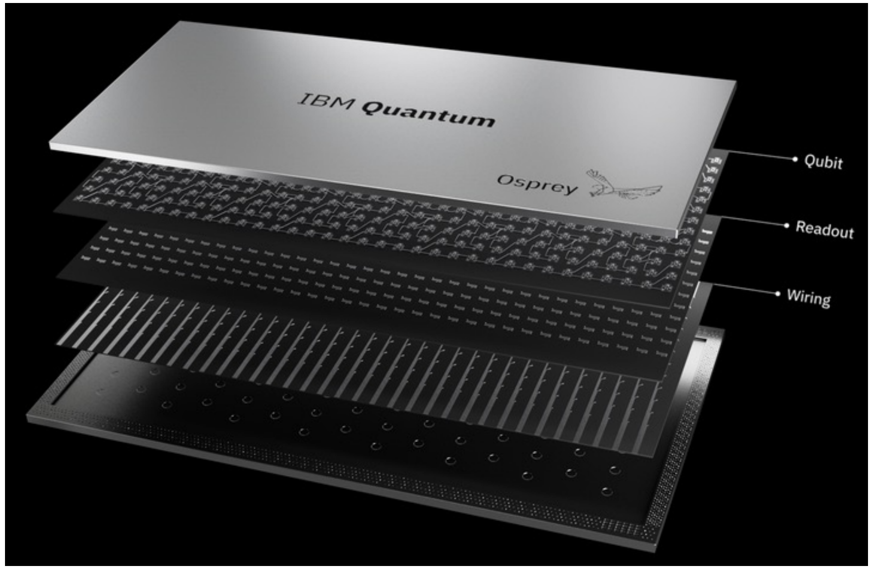


Rigetti
dilution refrigerator



IBM 5-qubit processor (2015)

IBM Ospery 433 qubits (2022)



Lecture III: Creation of quantum systems by design

- Creation of Bose—Einstein condensate
- Manipulate light interaction with natural and artificial atoms