

Atomtronics



A Very Short Introduction

Charles W. Clark
Joint Quantum Institute

Atomtronics



Internet electronics and photonics

Quantum computers and atomic clocks

Atomtronic concepts and devices

Internet



Is it just a flash in the pan . . .

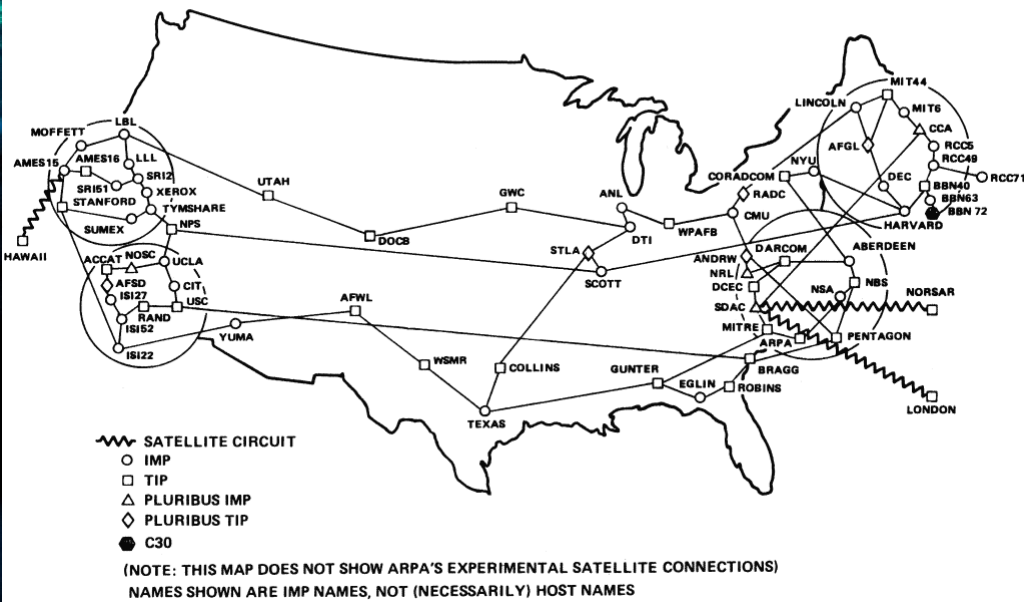
. . .or could it be REALLY BIG, someday?

Internet

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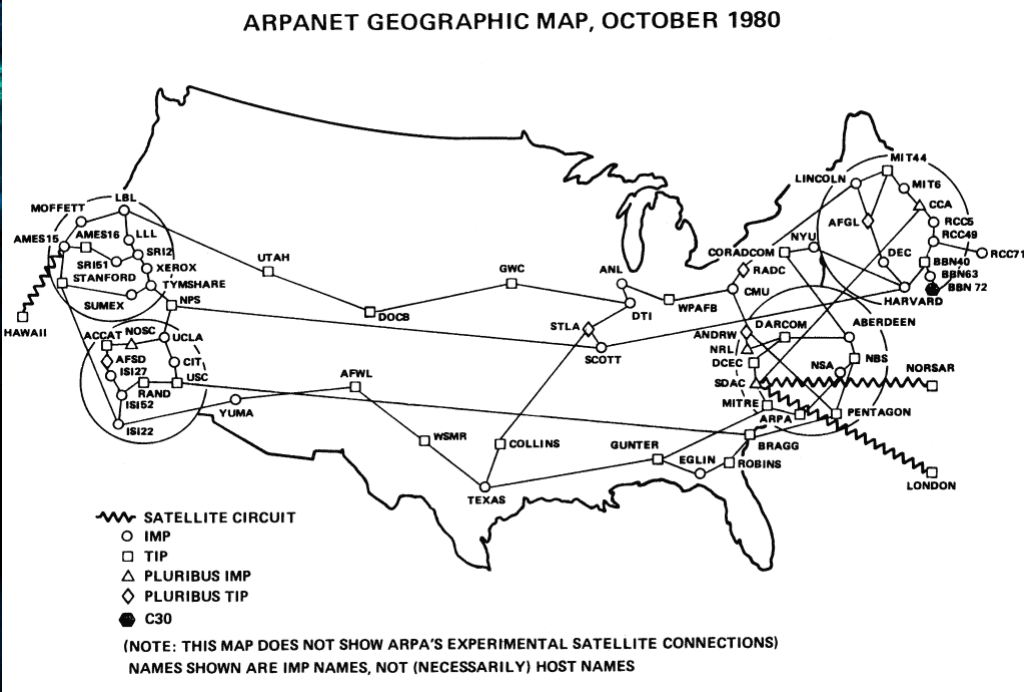
ARPANET GEOGRAPHIC MAP, OCTOBER 1980



ARPANET 1980
Computers connected by telephone lines and satellite links

Internet

Is it just a flash in the pan . . .
. . .or could it be REALLY BIG, someday?



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ARPANET DIRECTORY



NOVEMBER 1980

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A printed directory
of the 4,000 users



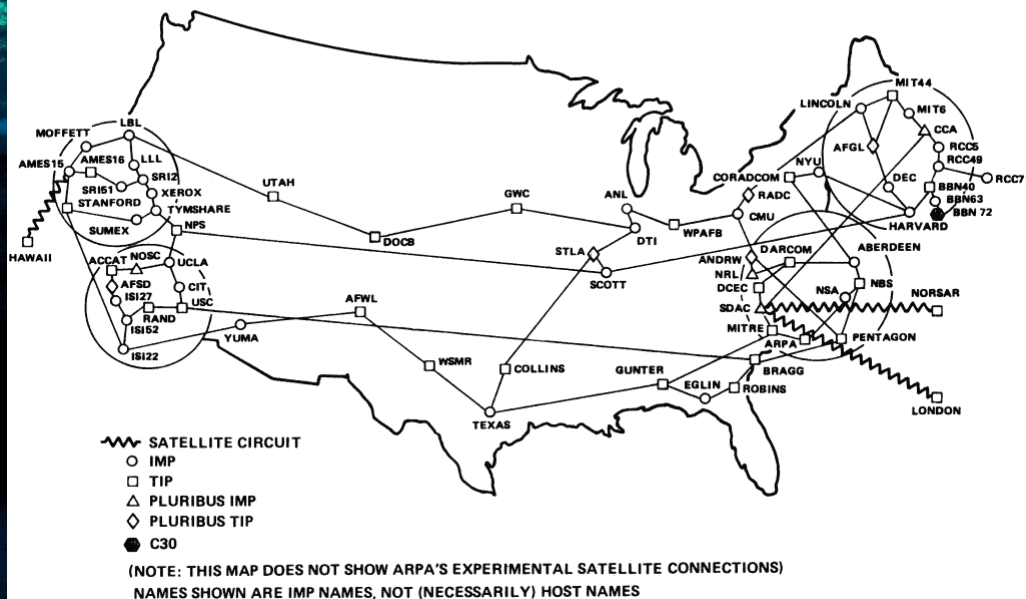
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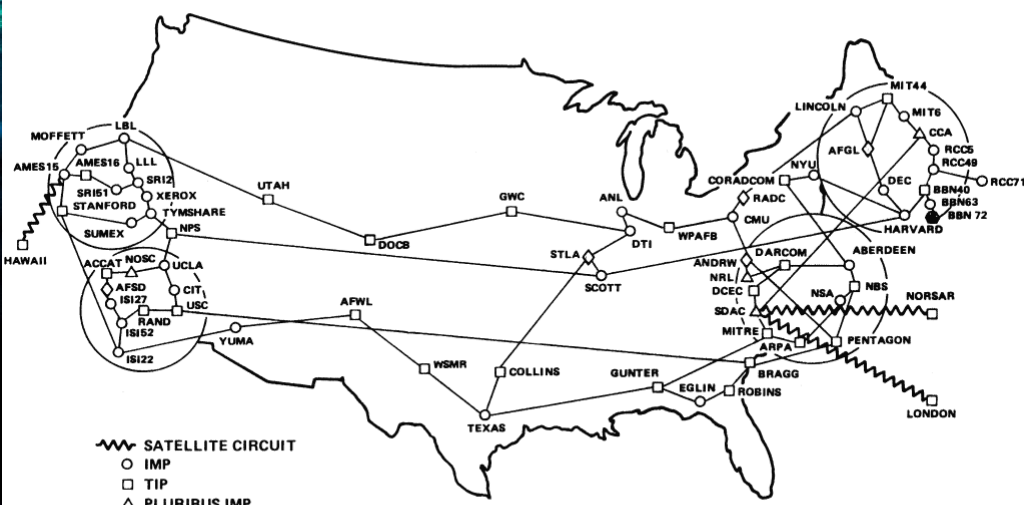
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(NOTE: THIS MAP DOES NOT SHOW ARPA'S EXPERIMENTAL SATELLITE CONNECTIONS)
NAMES SHOWN ARE IMP NAMES, NOT (NECESSARILY) HOST NAMES

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ARPANET DIRECTORY

The Electronic Age

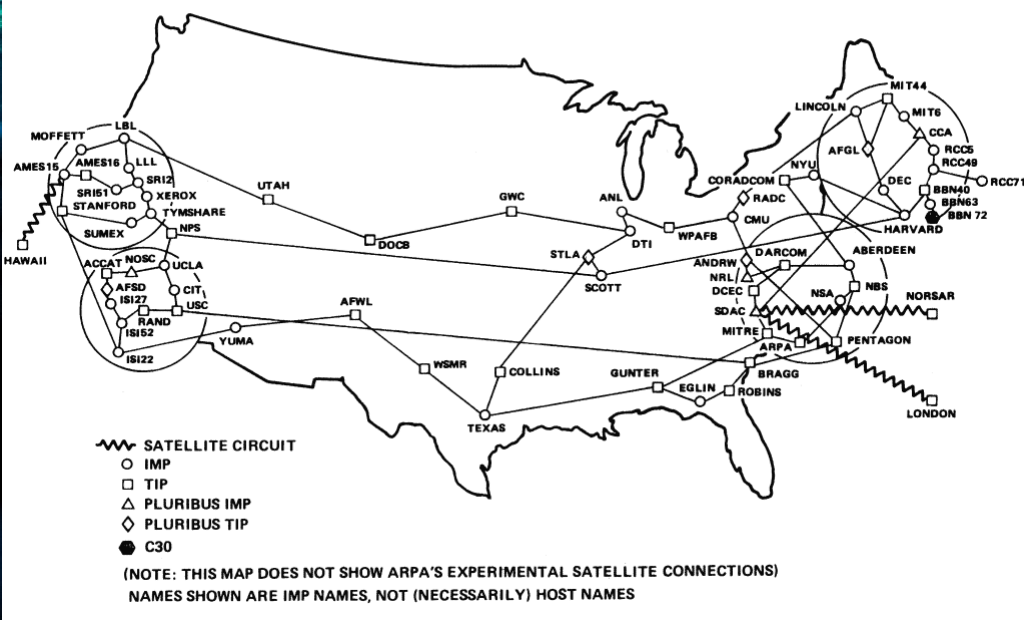


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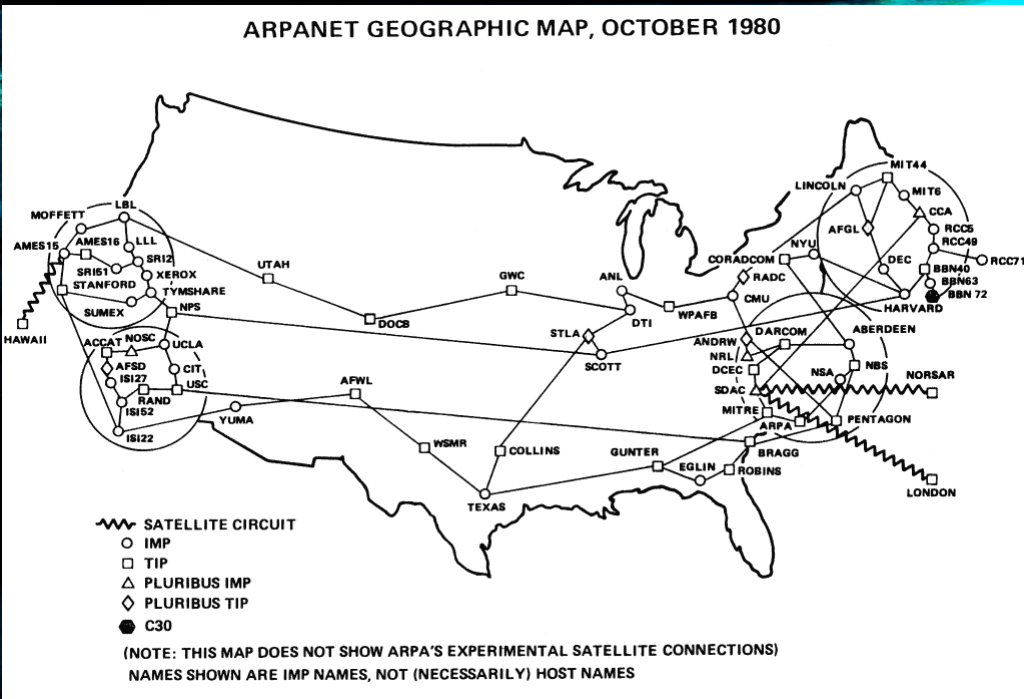
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The Electronic Age



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10 cm

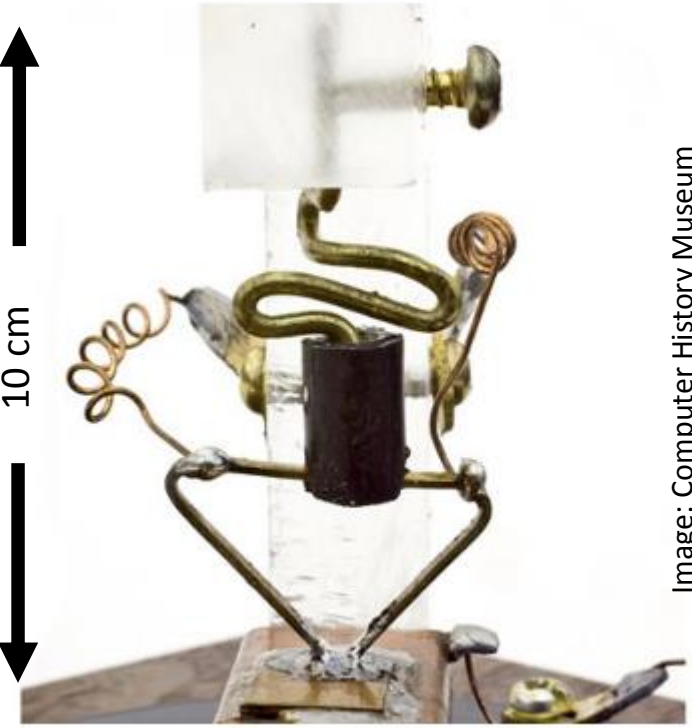


Image: Computer History Museum

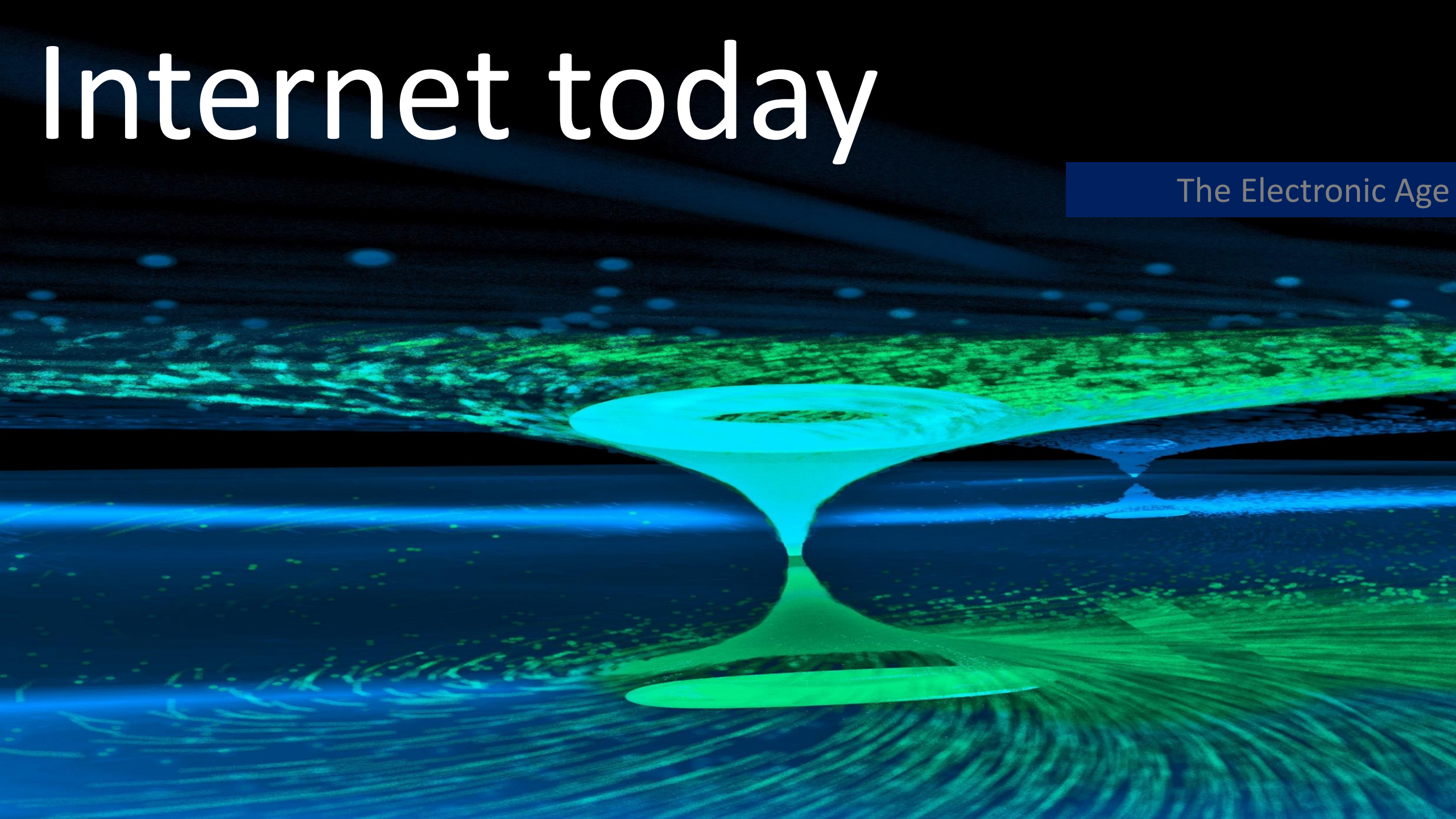
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Enabling technology of electronics:
The Transistor
Bell Laboratories 1947

Internet today

The Electronic Age



Internet today

2 billion smartphones worldwide; *each contains ~ 1 billion transistors = 10^{18}*

The Electronic Age

Vast global flow of data requires high-speed optical communication:

Photonics

Global reach requires precise network synchronization:

Atomic clocks

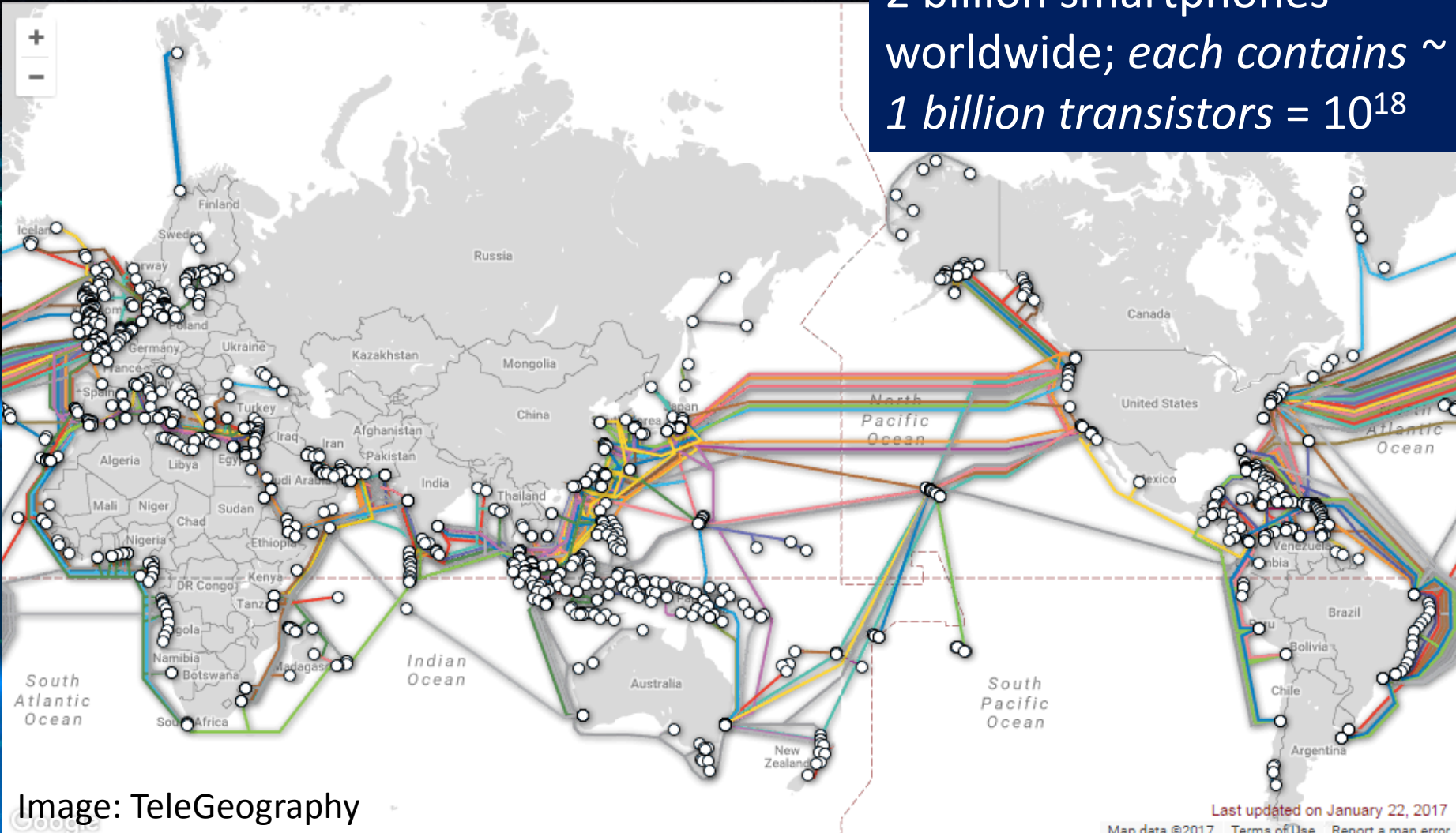


Image: TeleGeography

Internet today

1.3 million kilometers of submarine fibre-optic cables

2 billion smartphones worldwide; *each contains ~ 1 billion transistors = 10^{18}*

The Electronic Age

Vast global flow of data requires high-speed optical communication:

Photonics

Global reach requires precise network synchronization:

Atomic clocks

Atomic clock timing

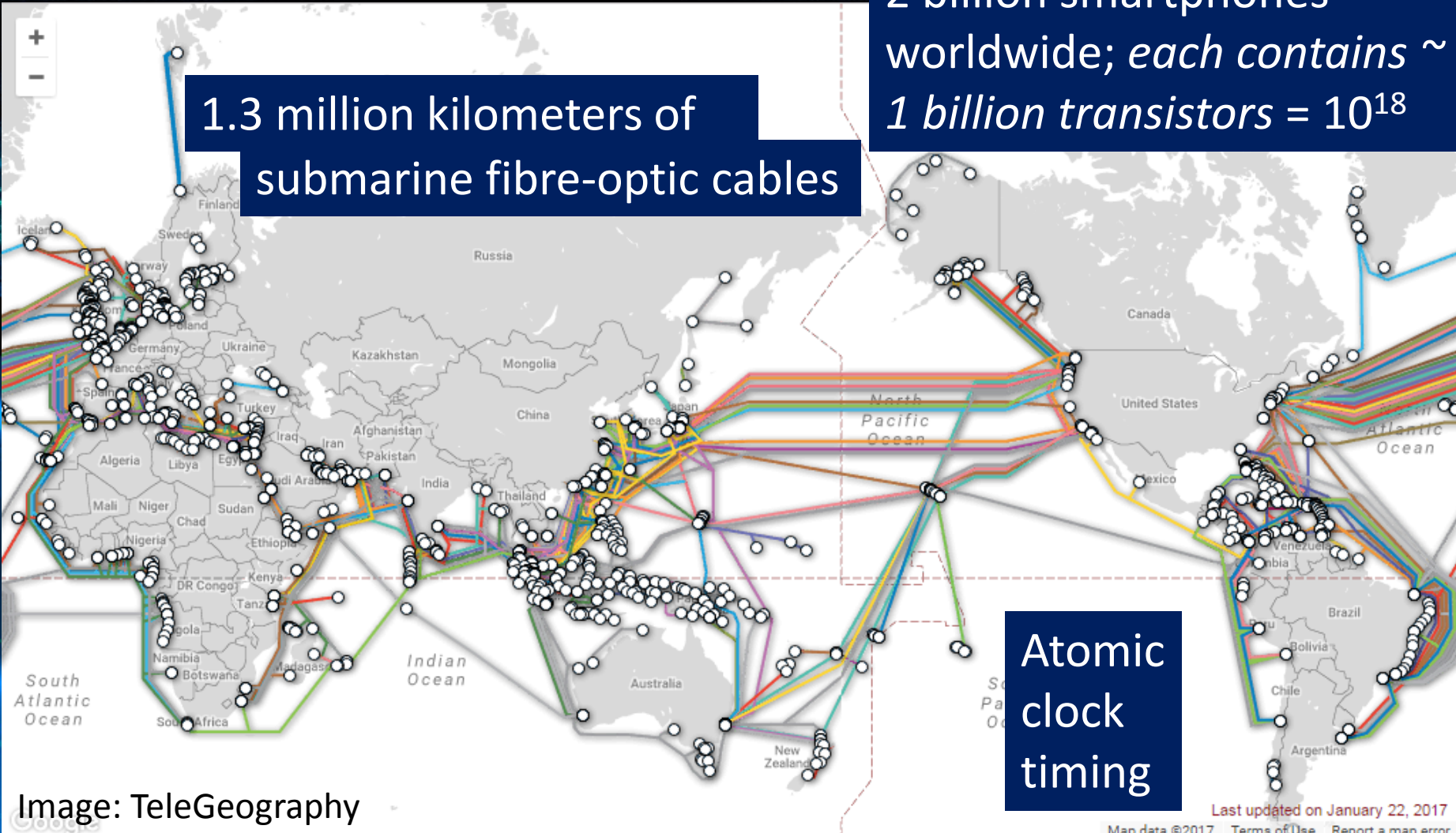


Image: TeleGeography

Atomic Clocks



The Electronic Age

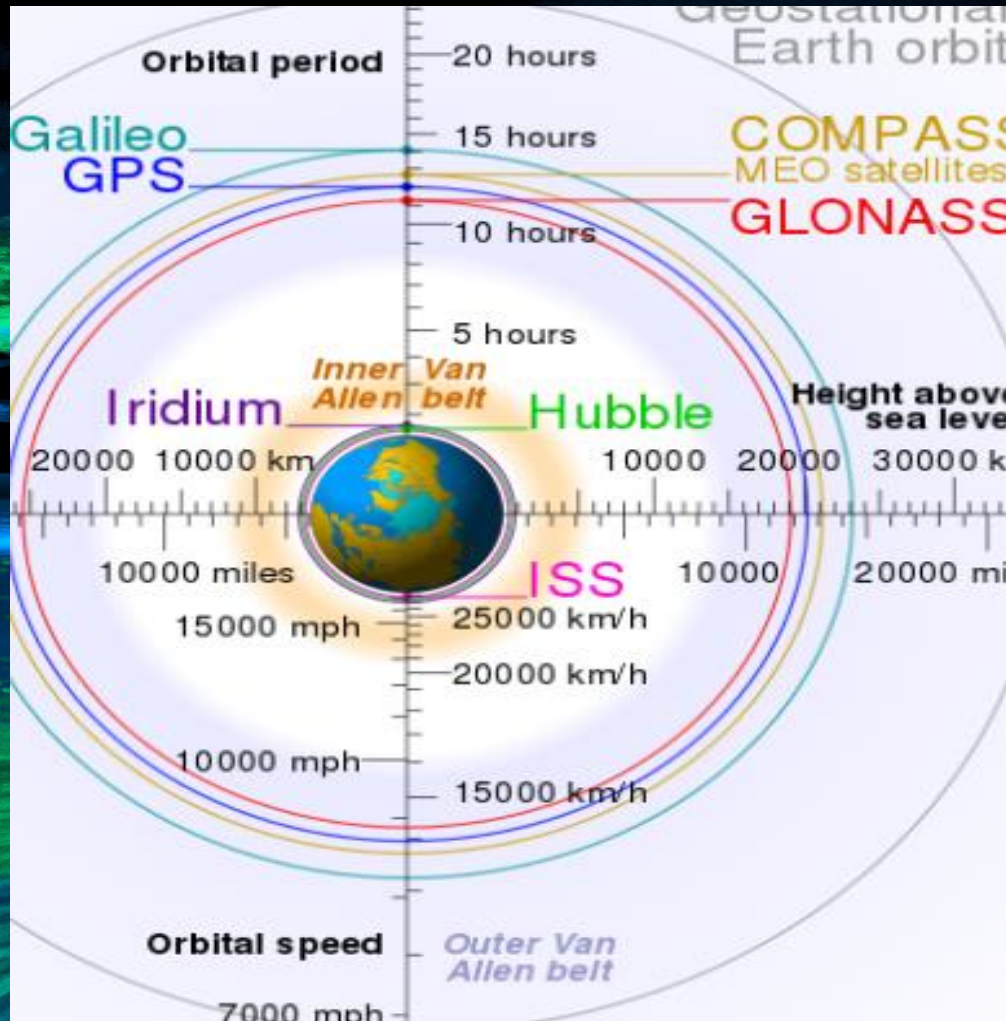
Vast global flow of data
requires high-speed
optical communication:

Photonics

Global reach requires
precise network
synchronization:

Atomic clocks

Atomic Clocks



Constellations of Atomic Clocks Aboard Earth Satellites

Global Navigation Satellite Systems (GNSS):

- Global Positioning System GPS (USA)
- GLONASS (Russia)
- Galileo (Europe)

Regional coverage:

- BeiDou (China)
- NAVIC (India)

The Electronic Age

Vast global flow of data requires high-speed optical communication:

Photonics

Global reach requires precise network synchronization:

Atomic clocks

Atomic Clocks

The original atomtronic devices

Atom – most precise oscillator
– sets the standard of time

Global reach requires
precise network
synchronization:
Atomic clocks

The clock in the control
room of the Laser
Interferometer
Gravitational-Wave
Observatory at Hanford,
WA, displays **PST** and
GPS Time (in seconds).
Shown on a GPS-enabled
smartphone.



Image: C. Suplee, NIST

Atomic Clocks


The original atomtronic devices

Global reach requires
precise network
synchronization:
Atomic clocks

Get your own atomic
clock on eBay for about a
hundred bucks
(plus shipping)

All Listings Auction Buy It Now Sort: Best Match View: [Grid Icon]


45 results for rubidium frequency... [+ Follow this search](#)




A photograph of a Symmetricom SA.22c 10MHz 1pps Rubidium Oscillator Frequency Standard Reference. The device is a small, rectangular metal box with a label on top. A wooden ruler is placed below it for scale, showing the device is approximately 4 inches long. The ruler has 'RDR ELECTRONICS' printed on it.

Symmetricom SA.22c 10MHz 1pps Rubidium Oscillator Frequency Standard Reference

\$120.00
Buy It Now

 Top Rated Plus

[See more like this](#)



A photograph of a Lucent rfg-m-rb 10 MHz and 15 MHz rubidium frequency standard. The device is a larger, rectangular metal box with a front panel featuring several indicator lights and a label. It is resting on a textured surface.

Lucent rfg-m-rb 10 MHz and 15 MHz rubidium frequency standard NICE !

\$575.00
or Best Offer
Free shipping

Image: eBay

Quantum Computers and Atomic Clocks

QUANTUM COMPUTERS AND ATOMIC CLOCKS

D. J. WINELAND, J. C. BERGQUIST, J. J. BOLLINGER,
R. E. DRULLINGER, AND W. M. ITANO

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Recent developments in quantum information processing may be applicable to future atomic clocks. In this paper we discuss two potential applications to trapped-ion frequency standards. In the first, quantum-mechanical entanglement can provide a resource for increased measurement precision in spectroscopy. In the second, we indicate how a simultaneously trapped auxiliary ion species can be used to provide cooling and as a quantum measuring device; this could be used to increase the number of ion species than can be used as frequency standards.

1 Introduction

The subject of quantum information processing (QIP) has recently received attention because quantum computers could provide a substantial speedup in factoring numbers¹ and in searching databases.² In spite of considerable interest in these goals, it is generally agreed that a quantum computer capable of useful factorization or searching (beyond what is possible with classical computers) will, at best, be extremely difficult to achieve in any currently proposed implementation.^{3,4} Nevertheless, it is highly likely that other, more tractable applications of QIP will be found and implemented. This paper cites two possible applications of QIP to frequency standards based on trapped atomic ions. Although the basic ideas for these applications emerged before the tidal wave of interest in QIP appeared (ca. 1995), these ideas have matured more rapidly due to advances in QIP. The first application, which we only summarize here, is to use entanglement to reduce frequency instability $\sigma_y(\tau)$ to the minimum level allowed by quantum mechanics. The second application uses the ideas of QIP to remove the functions of cooling and detection from the ion that is used for the frequency standard and place these functions on a second, simultaneously trapped ion species.

Image: NIST

<http://bit.ly/AtomQC>

Only have time to read
just one atomic physics
paper in your life?

← Try this.

David J. Wineland
2012 Nobel Prize in Physics

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



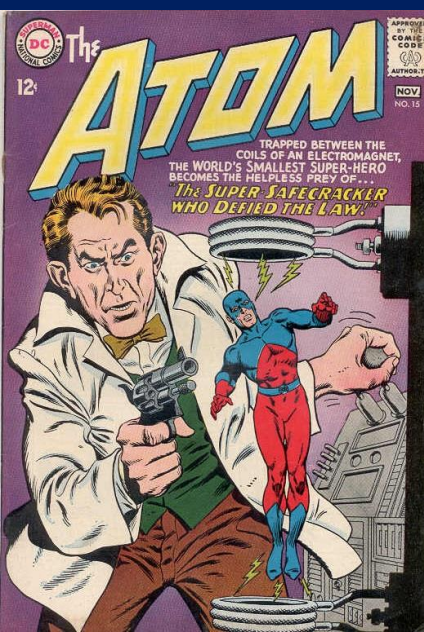
DAVID J.
WINELAND

The Nobel Prize in Physics 2012/USA

Image: Nobel Foundation

Atoms

- Identical
- Stable
- Quantum
- Diverse



Images: DC Comics

PERIODIC TABLE
Atomic Properties of the Elements

FREQUENTLY USED FUNDAMENTAL PHYSICAL CONSTANTS[§]

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum *c* 299 792 458 m s⁻¹ (exact)
 Planck constant *h* 6.626 070 × 10⁻³⁴ J s (*h* = *h*/2*π*)
 elementary charge *e* 1.602 177 × 10⁻¹⁹ C
 electron mass *m_e* 9.109 384 × 10⁻³¹ kg
m_ec² 0.510 999 MeV
 proton mass *m_p* 1.672 622 × 10⁻²⁷ kg
 fine-structure constant *α* 1/137.035 999
 Rydberg constant *R_∞* 10 973 731.569 m⁻¹
R_∞hc 3.289 841 960 × 10¹⁵ Hz
R_∞hc 13.605 693 eV
 eV 1.602 176 6 × 10⁻¹⁹ J
 electron volt *k* 1.380 65 × 10⁻²³ J K⁻¹
 Boltzmann constant *R* 8.314 5 J mol⁻¹ K⁻¹
 molar gas constant

[§] For the most accurate values of these and other constants, visit pml.nist.gov/constants

Legend:
■ Solids
■ Liquids
■ Gases
■ Artificially Prepared

| Group | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | |
|-------|---|--|---|---|---|--|--|--|---|---|--|--|---|---|--|---|--|--|---|
| | IA | IIA | IIIB | IVB | VB | VIB | VIIB | VIII | | | IB | IIB | IIIA | IVA | VA | VIA | VIIA | VIIIA | |
| 1 | 1 ² S _{1/2} H Hydrogen 1.008* 1s 13.5984 | | | | | | | | | | | | | | | | | 2 ¹ S ₀ He Helium 4.002602 1s ² 24.587 | |
| 2 | 3 ² S _{1/2} Li Lithium 6.94* 1s ² 2s 5.3917 | 4 ¹ S ₀ Be Beryllium 9.0121831 1s ² 2s ² 9.3227 | | | | | | | | | | | | 5 ² P _{1/2} B Boron 10.81* 1s ² 2s ² 2p 8.2980 | 6 ³ P ₀ C Carbon 12.011* 1s ² 2s ² 2p ² 11.2603 | 7 ⁴ S _{3/2} N Nitrogen 14.007* 1s ² 2s ² 2p ³ 14.5341 | 8 ³ P ₂ O Oxygen 15.999* 1s ² 2s ² 2p ⁴ 13.6181 | 9 ² P _{3/2} F Fluorine 18.99840316* 1s ² 2s ² 2p ⁵ 17.4228 | 10 ¹ S ₀ Ne Neon 20.1797 1s ² 2s ² 2p ⁶ 21.5645 |
| 3 | 11 ² S _{1/2} Na Sodium 22.98976928 [Ne]3s 5.1391 | 12 ¹ S ₀ Mg Magnesium 24.305* [Ne]3s ² 7.6462 | | | | | | | | | | | | 13 ² P _{3/2} Al Aluminum 26.9815385 [Ne]3s ² 3p 5.9858 | 14 ³ P ₀ Si Silicon 28.085* [Ne]3s ² 3p ² 8.1517 | 15 ⁴ S _{3/2} P Phosphorus 30.97376199* [Ne]3s ² 3p ³ 10.4867 | 16 ³ P ₂ S Sulfur 32.06* [Ne]3s ² 3p ⁴ 10.3600 | 17 ² P _{3/2} Cl Chlorine 35.45* [Ne]3s ² 3p ⁵ 12.9676 | 18 ¹ S ₀ Ar Argon 39.948 [Ne]3s ² 3p ⁶ 15.7596 |
| 4 | 19 ⁴ S _{1/2} K Potassium 39.0983 [Ar]4s 4.3407 | 20 ¹ S ₀ Ca Calcium 40.078 [Ar]4s ² 6.1132 | 21 ² D _{3/2} Sc Scandium 44.955908 [Ar]3d ¹ 4s ² 6.5615 | 22 ³ F ₂ Ti Titanium 47.887 [Ar]3d ² 4s ² 6.8281 | 23 ⁴ F _{3/2} V Vanadium 50.9415 [Ar]3d ³ 4s ² 6.7462 | 24 ⁵ S _{3/2} Cr Chromium 51.9961 [Ar]3d ⁵ 4s 6.7665 | 25 ⁶ S _{5/2} Mn Manganese 54.938044 [Ar]3d ⁵ 4s ² 7.4340 | 26 ⁶ D _{5/2} Fe Iron 55.845 [Ar]3d ⁶ 4s ² 7.9025 | 27 ⁴ F _{9/2} Co Cobalt 58.933194 [Ar]3d ⁷ 4s ² 7.8810 | 28 ³ F ₄ Ni Nickel 58.6934 [Ar]3d ⁸ 4s ² 7.6399 | 29 ² S _{1/2} Cu Copper 63.546 [Ar]3d ¹⁰ 4s 7.7264 | 30 ¹ S ₀ Zn Zinc 65.38 [Ar]3d ¹⁰ 4s ² 9.3942 | 31 ² P _{3/2} Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p 5.9993 | 32 ³ P ₀ Ge Germanium 72.630 [Ar]3d ¹⁰ 4s ² 4p ² 7.8994 | 33 ⁴ S _{3/2} As Arsenic 74.921595 [Ar]3d ¹⁰ 4s ² 4p ³ 9.7886 | 34 ³ P ₂ Se Selenium 78.971 [Ar]3d ¹⁰ 4s ² 4p ⁴ 9.7524 | 35 ² P _{3/2} Br Bromine 79.904* [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138 | 36 ¹ S ₀ Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶ 13.9996 | |
| 5 | 37 ⁴ S _{1/2} Rb Rubidium 85.4678 [Kr]5s 4.1771 | 38 ¹ S ₀ Sr Strontium 87.62 [Kr]5s ² 5.6949 | 39 ² D _{3/2} Y Yttrium 88.90584 [Kr]4d ⁵ 5s 6.2173 | 40 ³ F ₂ Zr Zirconium 91.224 [Kr]4d ⁵ 5s ² 6.6339 | 41 ⁴ D _{1/2} Nb Niobium 92.90637 [Kr]4d ⁴ 5s 6.7589 | 42 ⁵ S _{3/2} Mo Molybdenum 95.95 [Kr]4d ⁵ 5s 7.0924 | 43 ⁶ S _{5/2} Tc Technetium (98) [Kr]4d ⁵ 5s ² 7.1194 | 44 ⁵ F ₅ Ru Ruthenium 101.07 [Kr]4d ⁸ 5s 7.3605 | 45 ⁴ F _{9/2} Rh Rhodium 102.90550 [Kr]4d ⁹ 5s 7.4589 | 46 ¹ S ₀ Pd Palladium 106.42 [Kr]4d ¹⁰ 5s 8.3369 | 47 ² S _{1/2} Ag Silver 107.8682 [Kr]4d ¹⁰ 5s 7.5762 | 48 ¹ S ₀ Cd Cadmium 112.414 [Kr]4d ¹⁰ 5s ² 8.9938 | 49 ² P _{3/2} In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p 5.7864 | 50 ³ P ₀ Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 5p ² 7.3439 | 51 ⁴ S _{3/2} Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³ 6.6084 | 52 ³ P ₂ Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴ 9.0097 | 53 ² P _{3/2} I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 5p ⁵ 10.4513 | 54 ¹ S ₀ Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶ 12.1298 | |
| 6 | 55 ² S _{1/2} Cs Cesium 132.9054520* [Xe]6s 3.8939 | 56 ¹ S ₀ Ba Barium 137.327 [Xe]6s ² 5.2117 | | 72 ³ F ₂ Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ⁴ 6s ² 6.8251 | 73 ⁴ F _{3/2} Ta Tantalum 180.94788 [Xe]4f ¹⁴ 5d ³ 6s ² 7.5496 | 74 ⁵ D ₀ W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ² 7.8640 | 75 ⁶ S _{5/2} Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ² 7.8335 | 76 ⁵ D ₄ Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ² 8.4382 | 77 ⁴ F _{9/2} Ir Iridium 192.22 [Xe]4f ¹⁴ 5d ⁷ 6s ² 8.9670 | 78 ³ D ₅ Pt Platinum 195.084 [Xe]4f ¹⁴ 5d ⁹ 6s 8.9588 | 79 ² S _{1/2} Au Gold 196.966569 [Xe]4f ¹⁴ 5d ¹⁰ 6s 9.2256 | 80 ¹ S ₀ Hg Mercury 200.592 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375 | 81 ² P _{3/2} Tl Thallium 204.38 [Hg]6p ² 6.1083 | 82 ³ P ₀ Pb Lead 207.2 [Hg]6p ³ 7.4167 | 83 ⁴ S _{3/2} Bi Bismuth 208.98040 [Hg]6p ³ 7.2855 | 84 ³ P ₂ Po Polonium (209) [Hg]6p ⁴ 8.414 | 85 ² P _{3/2} At Astatine (210) [Hg]6p ⁵ 9.3175 | 86 ¹ S ₀ Rn Radon (222) [Hg]6p ⁶ 10.7485 | |
| 7 | 87 ² S _{1/2} Fr Francium (223) [Rn]7s 4.0727 | 88 ¹ S ₀ Ra Radium (226) [Rn]7s ² 5.2784 | | 104 ³ F ₂ Rf Rutherfordium (267) [Rn]5f ¹⁴ 6d ² 7s ² 6.01 | 105 ⁴ F _{3/2} Db Dubnium (268) [Rn]5f ¹⁴ 6d ³ 7s ² 6.8 | 106 ⁵ D ₀ Sg Seaborgium (271) [Rn]5f ¹⁴ 6d ⁴ 7s ² 7.8 | 107 ⁶ S _{5/2} Bh Bohrium (270) [Rn]5f ¹⁴ 6d ⁵ 7s ² 7.7 | 108 ⁴ F _{9/2} Hs Hassium (269) [Rn]5f ¹⁴ 6d ⁶ 7s ² 7.6 | 109 ⁵ D ₄ Mt Meitnerium (278) | 110 ³ D ₅ Ds Darmstadtium (281) | 111 ² S _{1/2} Rg Roentgenium (282) | 112 ¹ S ₀ Cn Copernicium (285) | 113 ² P _{3/2} Nh Nihonium (286) | 114 ³ P ₀ Fl Flerovium (289) | 115 ⁴ S _{3/2} Mc Moscovium (289) | 116 ³ P ₂ Lv Livermorium (293) | 117 ² P _{3/2} Ts Tennessine (294) | 118 ¹ S ₀ Og Oganesson (294) | |
| | | | 57 ² D _{3/2} La Lanthanum 138.90547 [Xe]5d ¹ 6s ² 5.5769 | 58 ¹ G ₄ Ce Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ² 5.5386 | 59 ⁴ I _{9/2} Pr Praseodymium 140.90766 [Xe]4f ² 6s ² 5.473 | 60 ⁵ I ₄ Nd Neodymium 144.242 [Xe]4f ³ 6s ² 5.5250 | 61 ⁶ H _{5/2} Pm Promethium (145) [Xe]4f ⁴ 6s ² 5.582 | 62 ⁷ F ₀ Sm Samarium 150.36 [Xe]4f ⁶ 6s ² 5.6437 | 63 ⁸ S _{7/2} Eu Europium 151.964 [Xe]4f ⁷ 6s ² 5.6704 | 64 ⁹ D ₂ Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ² 6.1498 | 65 ⁶ H _{5/2} Tb Terbium 158.92535 [Xe]4f ⁹ 6s ² 5.8638 | 66 ⁵ I ₈ Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ² 5.9391 | 67 ⁴ I _{15/2} Ho Holmium 164.93033 [Xe]4f ¹¹ 6s ² 6.0215 | 68 ³ H ₆ Er Erbium 167.259 [Xe]4f ¹² 6s ² 6.1077 | 69 ² F _{7/2} Tm Thulium 168.93422 [Xe]4f ¹³ 6s ² 6.1843 | 70 ¹ S ₀ Yb Ytterbium 173.045 [Xe]4f ¹⁴ 6s ² 6.2542 | 71 ² D _{3/2} Lu Lutetium 174.9668 [Xe]4f ¹⁴ 5d ¹ 6s ² 5.4259 | | |
| | | | 89 ² D _{3/2} Ac Actinium (227) [Rn]6d ¹ 7s ² 5.3802 | 90 ³ F ₂ Th Thorium 232.0377 [Rn]6d ² 7s ² 6.3067 | 91 ⁴ K _{11/2} Pa Protactinium 231.03688 [Rn]5f ² 6d ¹ 7s ² 5.89 | 92 ⁵ L ₆ U Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ² 6.1941 | 93 ⁶ L _{11/2} Np Neptunium (237) [Rn]5f ⁴ 6d ¹ 7s ² 6.2655 | 94 ⁷ F ₀ Pu Plutonium (244) [Rn]5f ⁶ 7s ² 6.0258 | 95 ⁸ S _{7/2} Am Americium (243) [Rn]5f ⁷ 7s ² 5.9738 | 96 ⁹ D ₂ Cm Curium (247) [Rn]5f ⁸ 6d ¹ 7s ² 5.9914 | 97 ⁶ H _{5/2} Bk Berkelium (247) [Rn]5f ⁹ 7s ² 6.1978 | 98 ⁵ I ₈ Cf Californium (251) [Rn]5f ¹⁰ 7s ² 6.2817 | 99 ⁴ I _{15/2} Es Einsteinium (252) [Rn]5f ¹¹ 7s ² 6.3576 | 100 ³ H ₆ Fm Fermium (257) [Rn]5f ¹² 7s ² 6.50 | 101 ² F _{7/2} Md Mendelevium (258) [Rn]5f ¹³ 7s ² 6.58 | 102 ¹ S ₀ No Nobelium (259) [Rn]5f ¹⁴ 7s ² 6.65 | 103 ² P _{1/2} Lr Lawrencium (266) [Rn]5f ¹⁴ 7s ² 7p 4.96 | | |

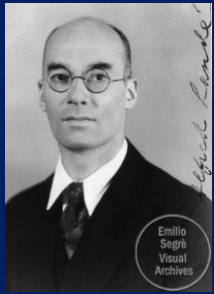
[†]Based upon ¹²C. () indicates the mass number of the longest-lived isotope.

[§]For the most accurate value, visit ciaaw.org.

For a description of the data, visit pml.nist.gov/data
NIST SP 966 (January 2017)

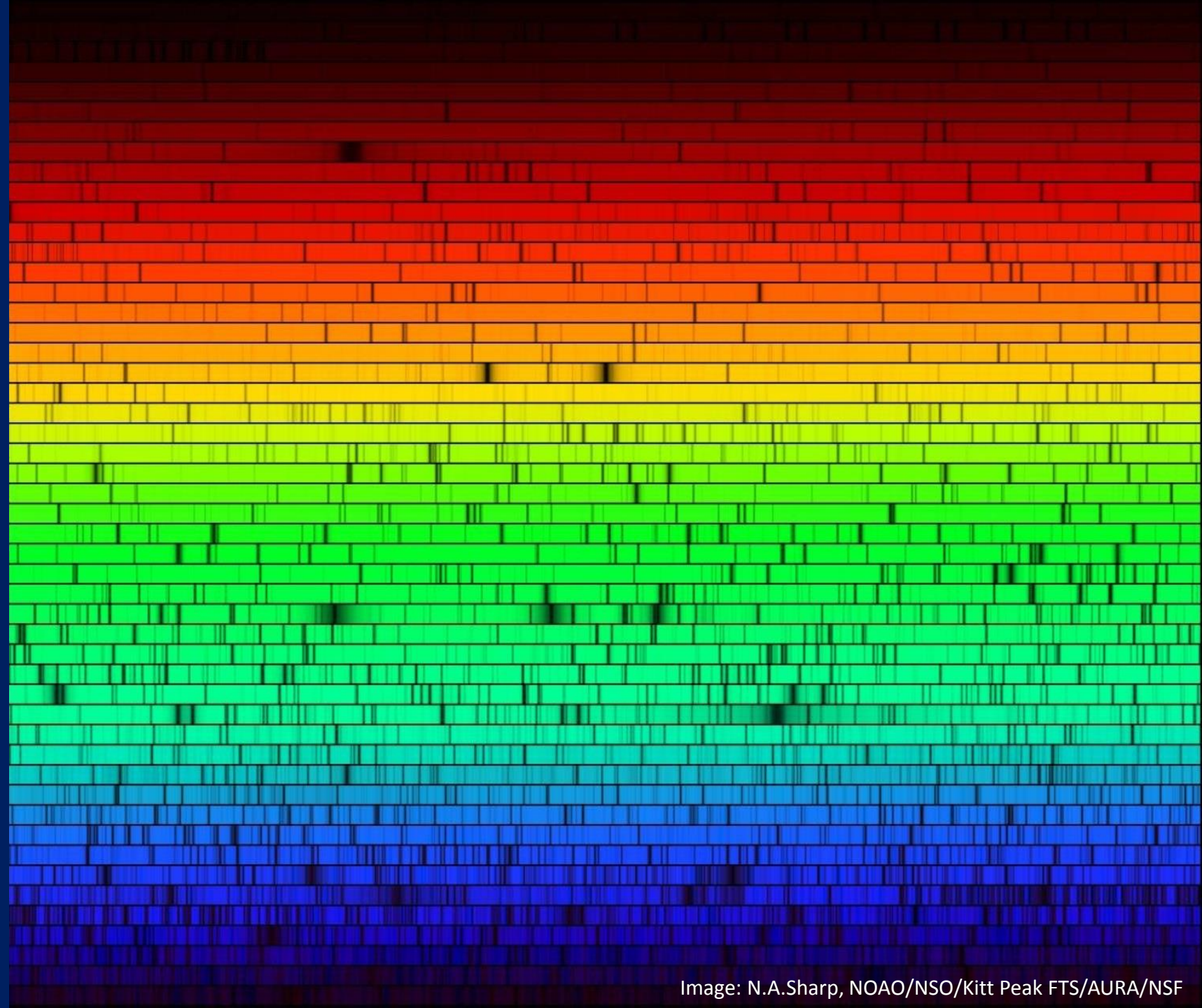
Atoms

- Identical
- Stable
- Quantum
- Diverse
- Electronic “vibrations”
- Light excitations

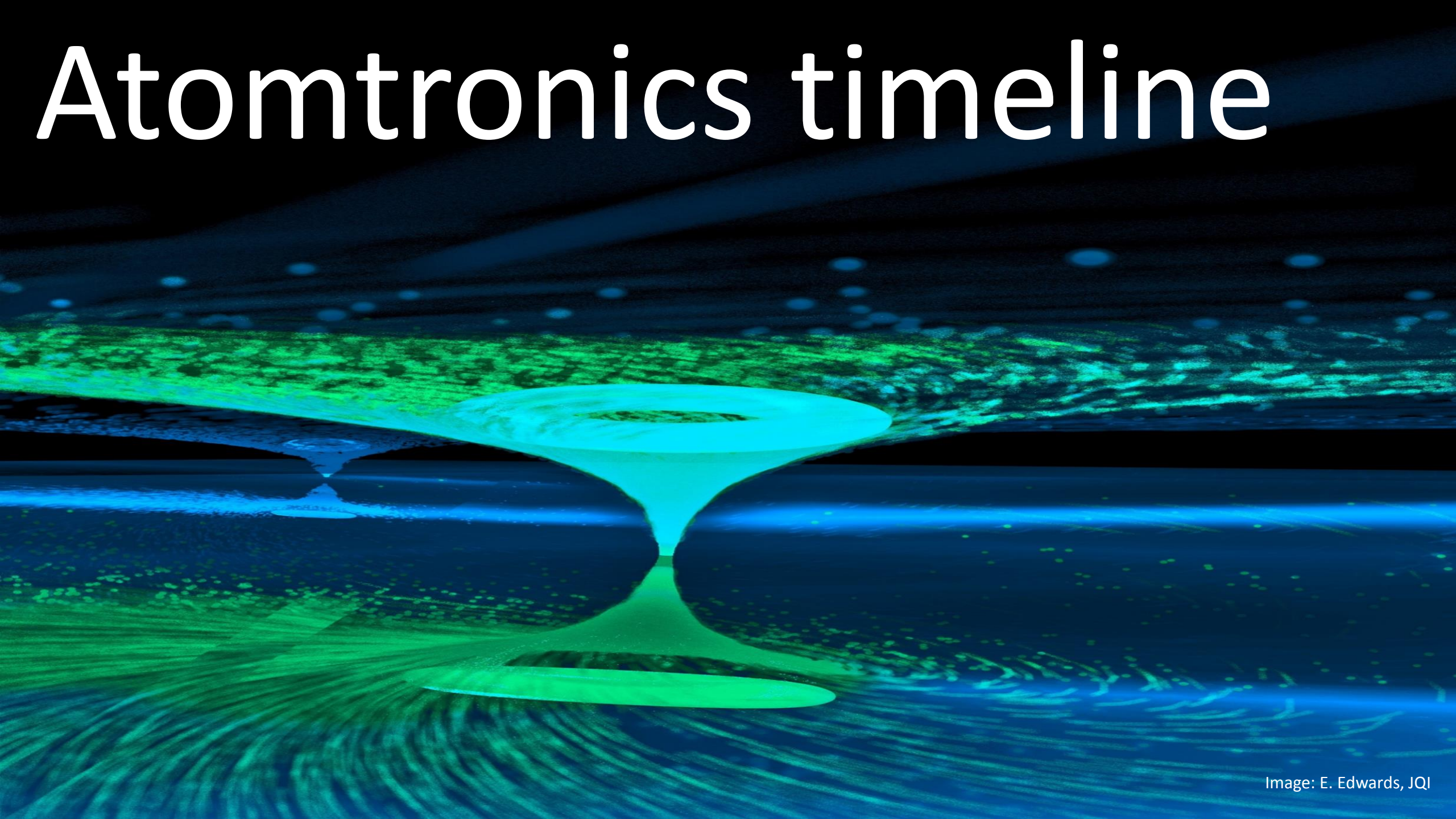


Alfred Landé
1888-1976

The “virtual orchestra” of atomic oscillators in the Sun’s atmosphere.



Atomtronics timeline



Atomtronics timeline



— Ion cooling and trapping —

— Cooling /trapping of neutral atoms —

— Optical lattices —

— Shor's algorithm —

— Experimental quantum logic —

— Bose-Einstein condensation —

— Atom laser —

— Commercial products —

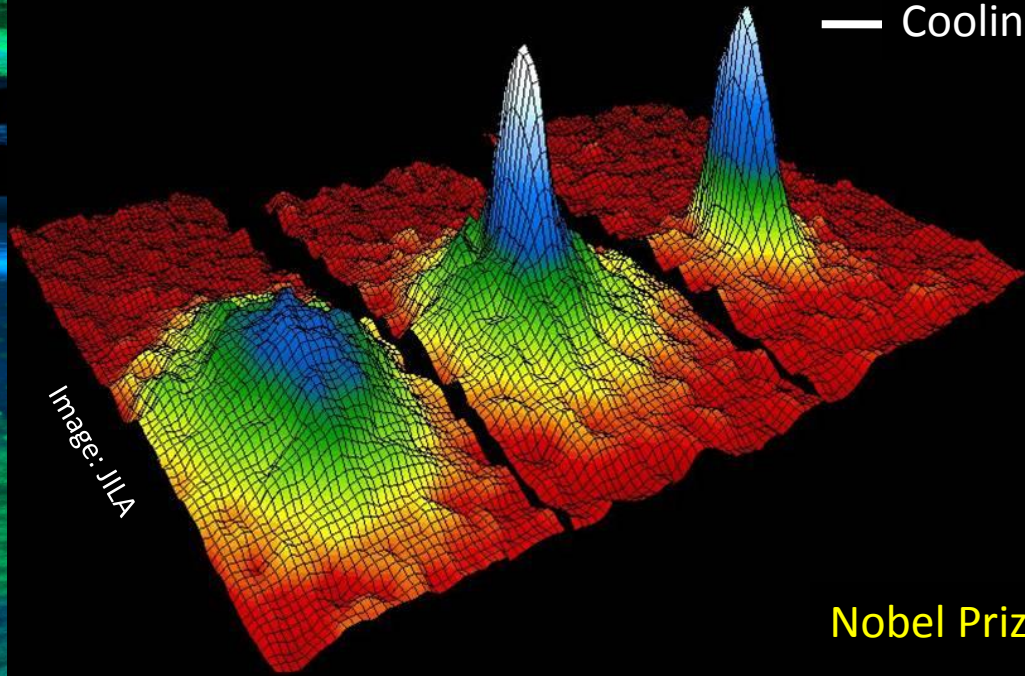


Image: JILA

Nobel Prizes in Physics

★★
★

★★
★

★★
★

★
★

Atomtronic applications

New Journal of Physics Focus on Atomtronic-enabled Quantum Technologies

<http://j.mp/At0mtr0nics>

Precision measurement – quantum-enhanced clocks, matter-wave interferometry

Sensing: magnetometry, gravity/gradiometry, rotation, acceleration

Novel scanning probe microscopy

Novel superconductivity and superfluidity

Experimental quantum logic

Novel magnetism and synthetic magnetic fields

Simulating complex quantum systems

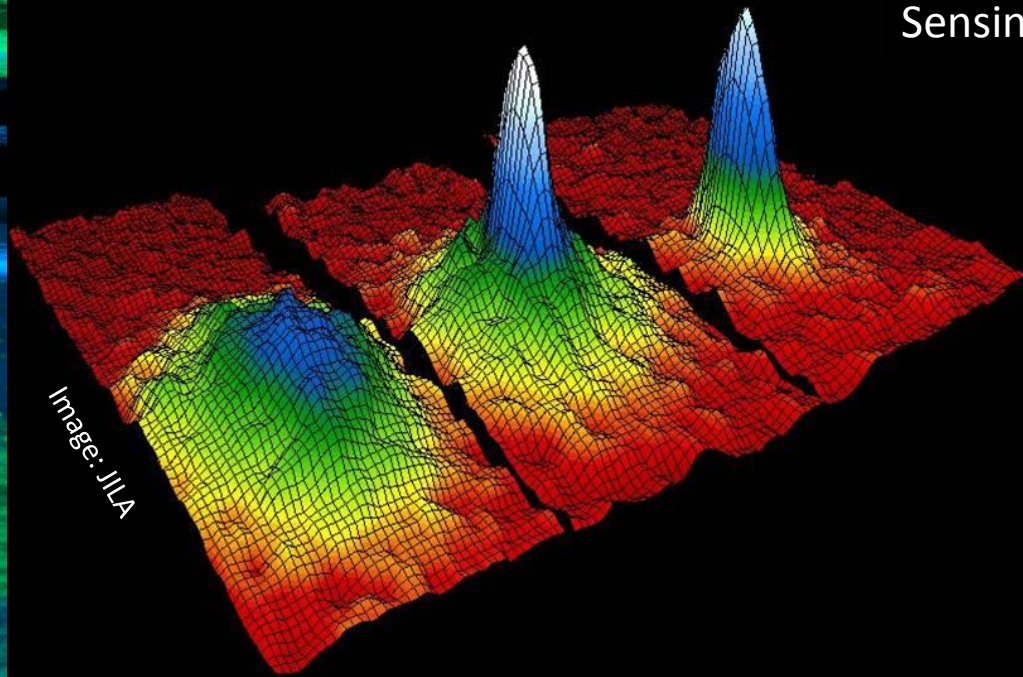


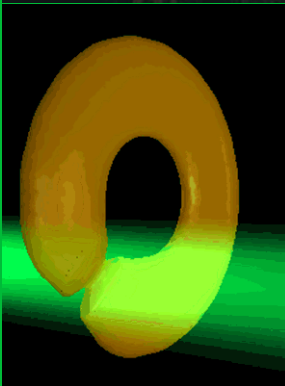
Image: JILA

Recent atomtronic devices

Portable
BEC
chamber
(2014)



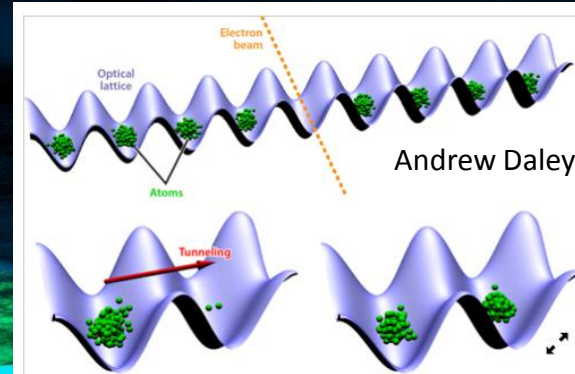
ColdQuanta



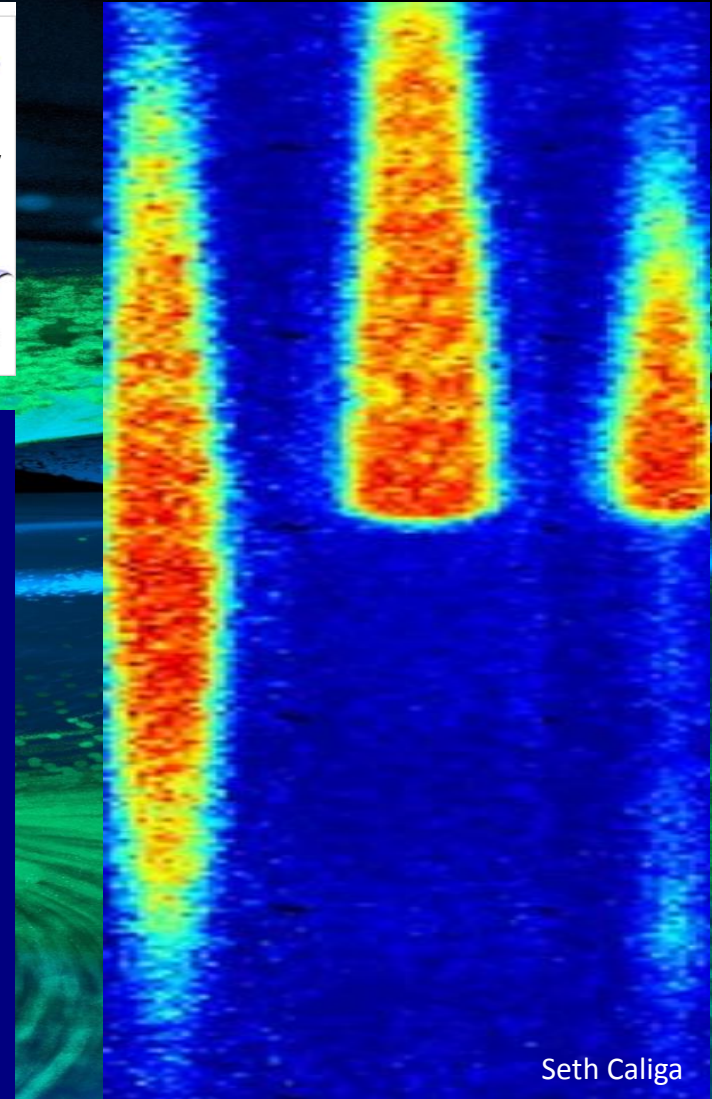
Atom
SQUID
(2014)

NIST

Diode (2015)

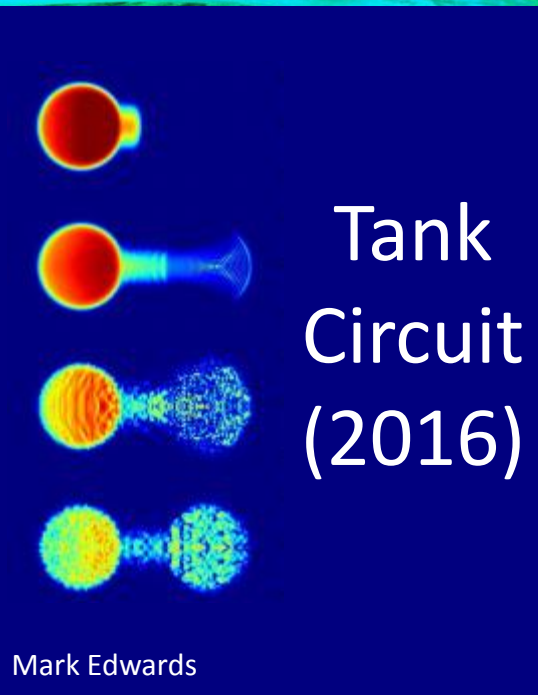


Battery (2017)



Seth Caliga

Tank
Circuit
(2016)



Mark Edwards

Atomtronics today

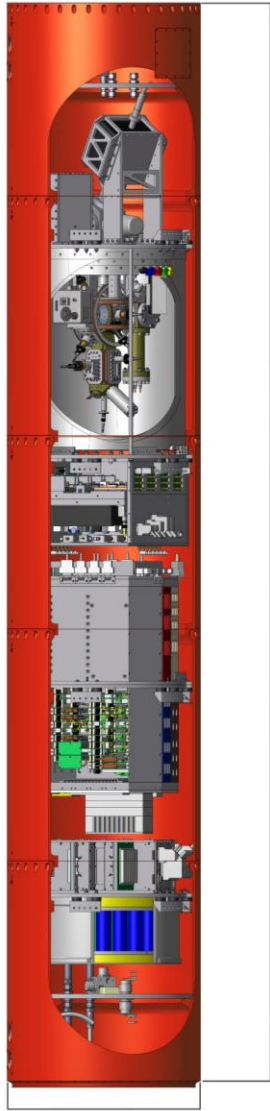


First Bose-Einstein condensate in space



11.9 m

1 m



0.5 m

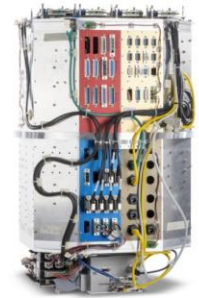
2.8 m



Atom-chip
Apparatur



Dioden-
lasersystem



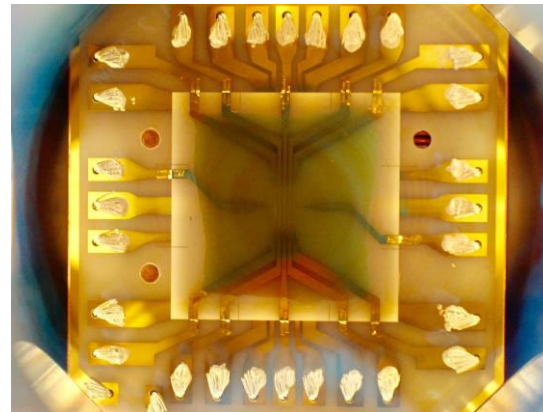
Elektronik



Batterien

MAIUS 1 Sounding Rocket Mission

- MAIUS: Matter-Wave Interferometry in Microgravity
- Launched 23 January 2017 in northern Sweden
- Produced Bose-Einstein condensate on board
- Performed 100 experiments in matter-wave interferometry



Images: DLR