A New Measure: The Revolutionary, Quantum Reform of the Metric System

IUPAP Centenary, ICTP, Trieste, 11 July 2022

William D. Phillips

Joint Quantum Institute

National Institute of Standards and Technology, Gaithersburg, MD
University of Maryland, College Park, MD

NIST Laser Cooling and Trapping Group:

Gretchen Campbell, Paul Lett, Trey Porto, Ian Spielman,
Eite Tiesinga, Charles Clark, Nicole Yunger Halpern

- 1931: IUPAP establishes the SUN commission (now C2-SUNAMCO: **S**ymbols, **U**nits, **N**omenclature, **A**tomic **M**asses, and fundamental **CO**nstants)

- 1931: IUPAP establishes the SUN commission (now C2-SUNAMCO: **S**ymbols, **U**nits, **N**omenclature, **A**tomic **M**asses, and fundamental **CO**nstants)

- 1948: The 9th CGPM, following an IUPAP recommendation, directs the establishment of an international system of units based on Meter, Kilogram, Second, and an absolute electrical unit.

IUPAP Centenary
YEARS 1922 - 2022

- 1931: IUPAP establishes the SUN commission (now C2-SUNAMCO: **S**ymbols, **U**nits, **N**omenclature, **A**tomic **M**asses, and fundamental **CO**nstants)

- 1948: The 9th CGPM, following an IUPAP recommendation, directs the establishment of an international system of units based on Meter, Kilogram, Second, and an absolute electrical unit.

- 1960: The 11th CGPM creates the International System of Units (the SI) that we all used today, and in whose development the IUPAP has continued to play a major role

Please think of questions.

There will be prizes for everyone who asks a question at the end!

A New Measure: The Revolutionary, Quantum Reform of the Metric System

IUPAP Centenary, ICTP, Trieste, 11 July 2022

William D. Phillips

Joint Quantum Institute

National Institute of Standards and Technology, Gaithersburg, MD
University of Maryland, College Park, MD

NIST Laser Cooling and Trapping Group:

<u>Gretchen Campbell</u>, Paul Lett, Trey Porto, Ian Spielman, Eite Tiesinga, Charles Clark, Nicole Yunger Halpern

The metric system came into being with the French Revolution, at the end of the 18th century.

20 May 2019 (World Metrology Day) experienced the greatest revolution in measurement since the French revolution.

The Metric System

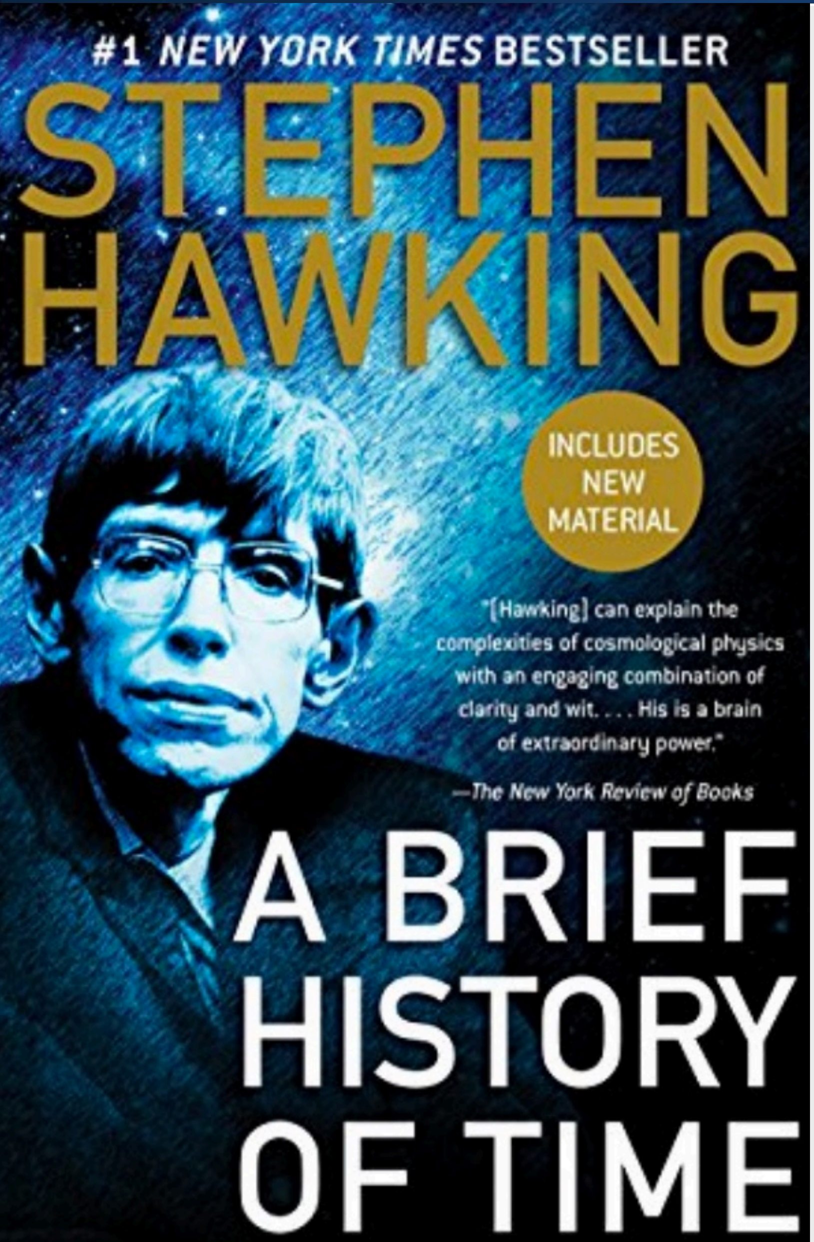
The International System of Units

Le Système Internationale d'Unités (SI)

expresses physical quantities in terms of seven base units.

The Metric System

The reform is that all of the base units of the International System of Units are now defined by fixing the values of constants of nature.



To see how this can be done, and how an earlier unit of measure (time) evolved over time and with apologies to Stephen Hawking,

I will attempt to bring you my version of "A Brief History of Time"

Conventionally, 1 second = 1day X (1/24x60x60)

= 1 day/86 400

But since about 1900, we have known that the day changes.

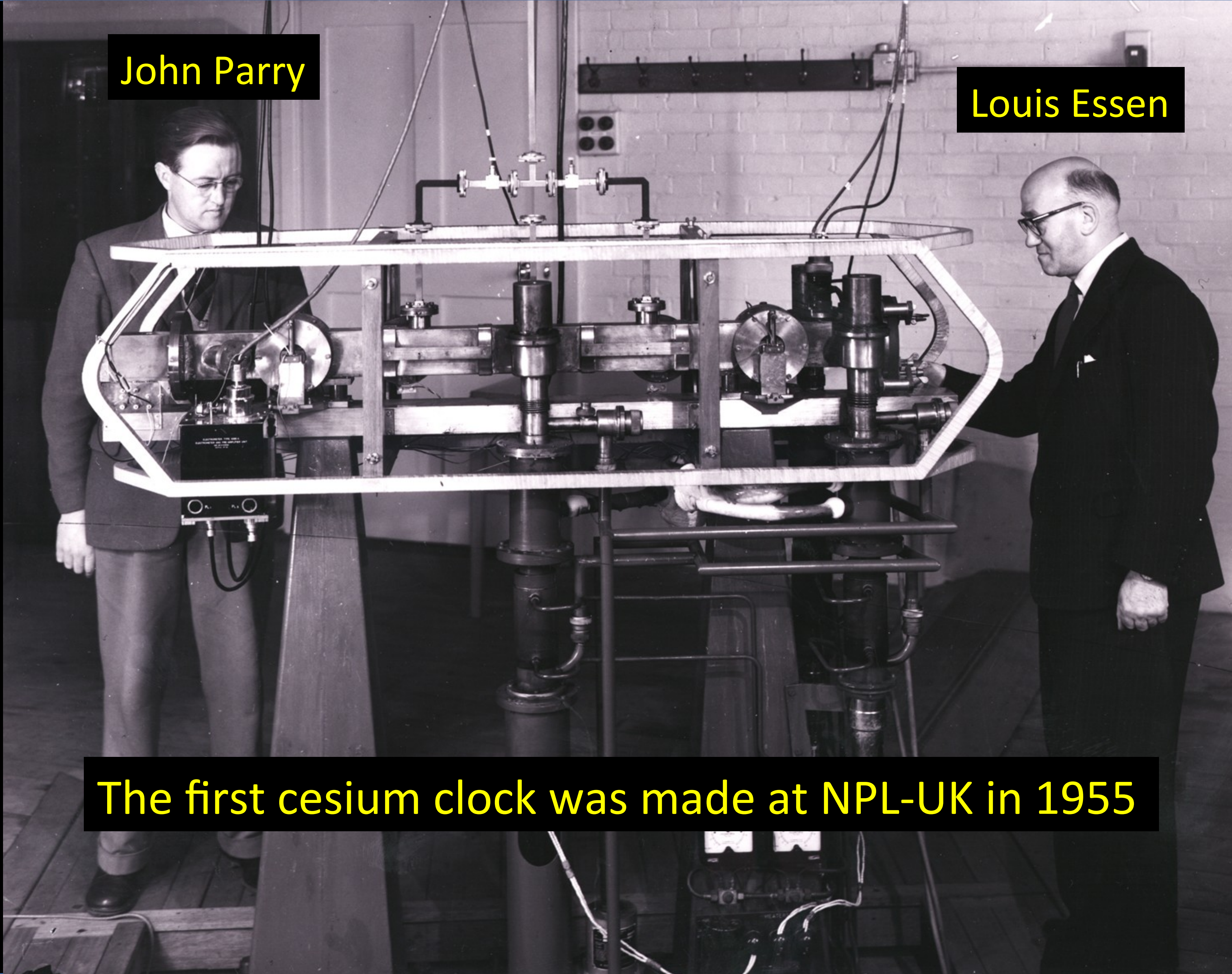
Photo: IEEE

Edward U. Condon [left], director of the National Bureau of Standards, with Harold Lyons, inventor of the ammonia absorption cell atomic clock [above].

Atomic Clocks

Better than the Earth:

The earth may change, but atoms (and molecules) do not—as far as we know. This ammonia molecule clock, built at the National Bureau of Standards (the ancestor of NIST), in 1949 was the first “atomic” clock.

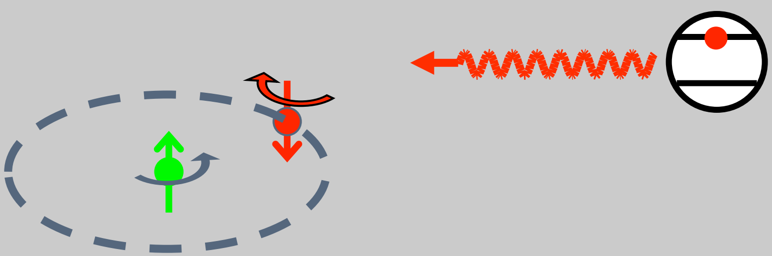


The first cesium clock was made at NPL-UK in 1955

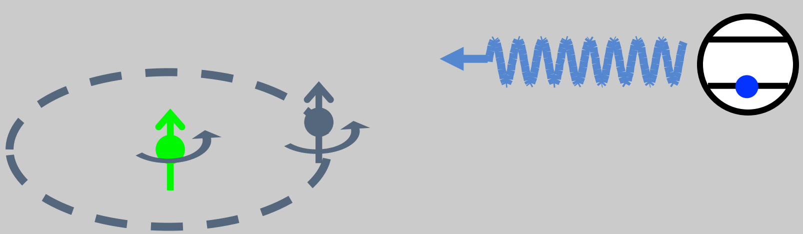
Atomic Clock Operation (over-simplified version)

(The truth is a bit (a lot) more complicated.)

Microwaves, about 9.192 631 770 GHz



When the frequency is "just right" the atom changes state: electron flips.

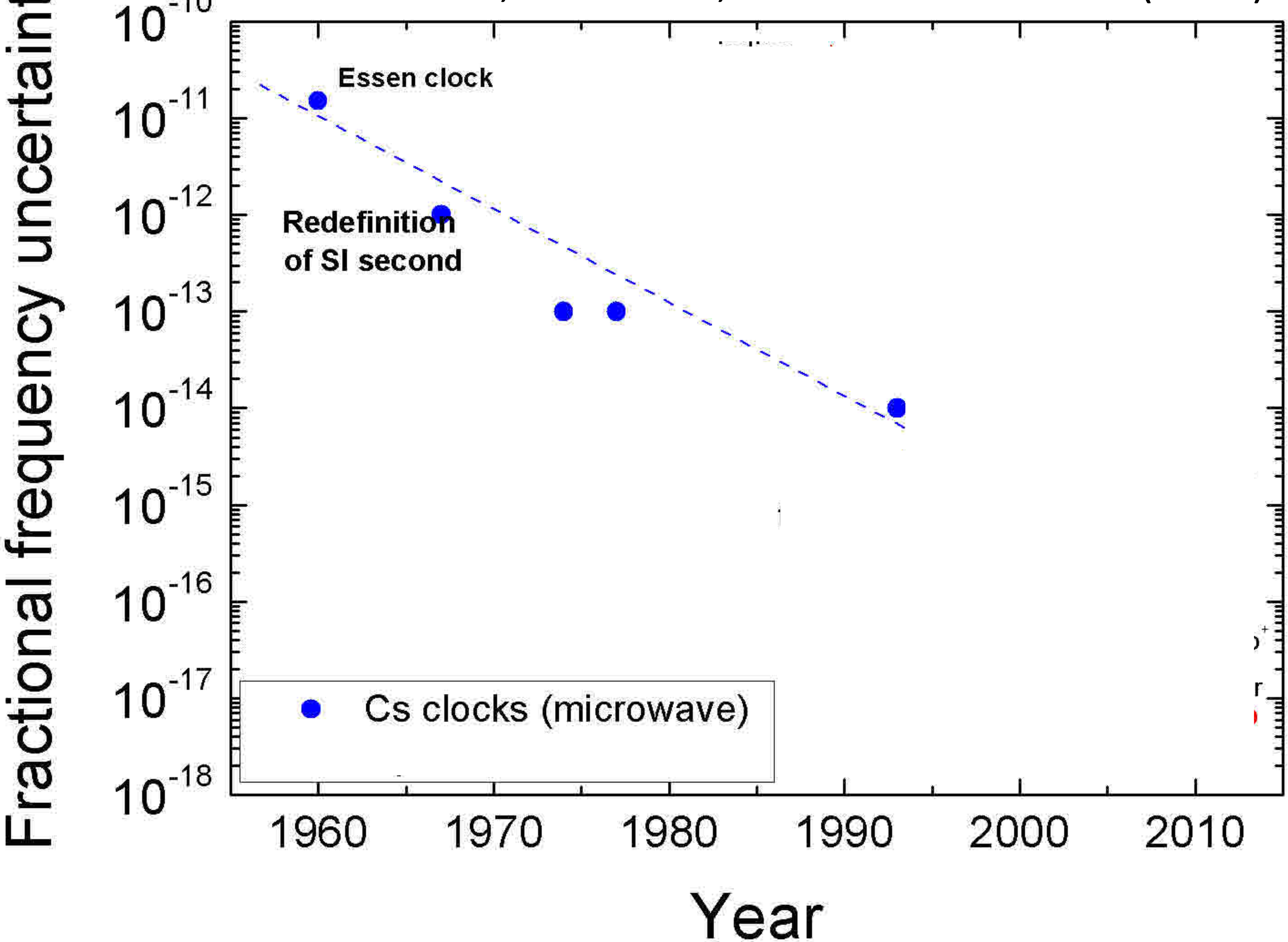


When the frequency is just a little off, the atom does not change state.

Atomic Time

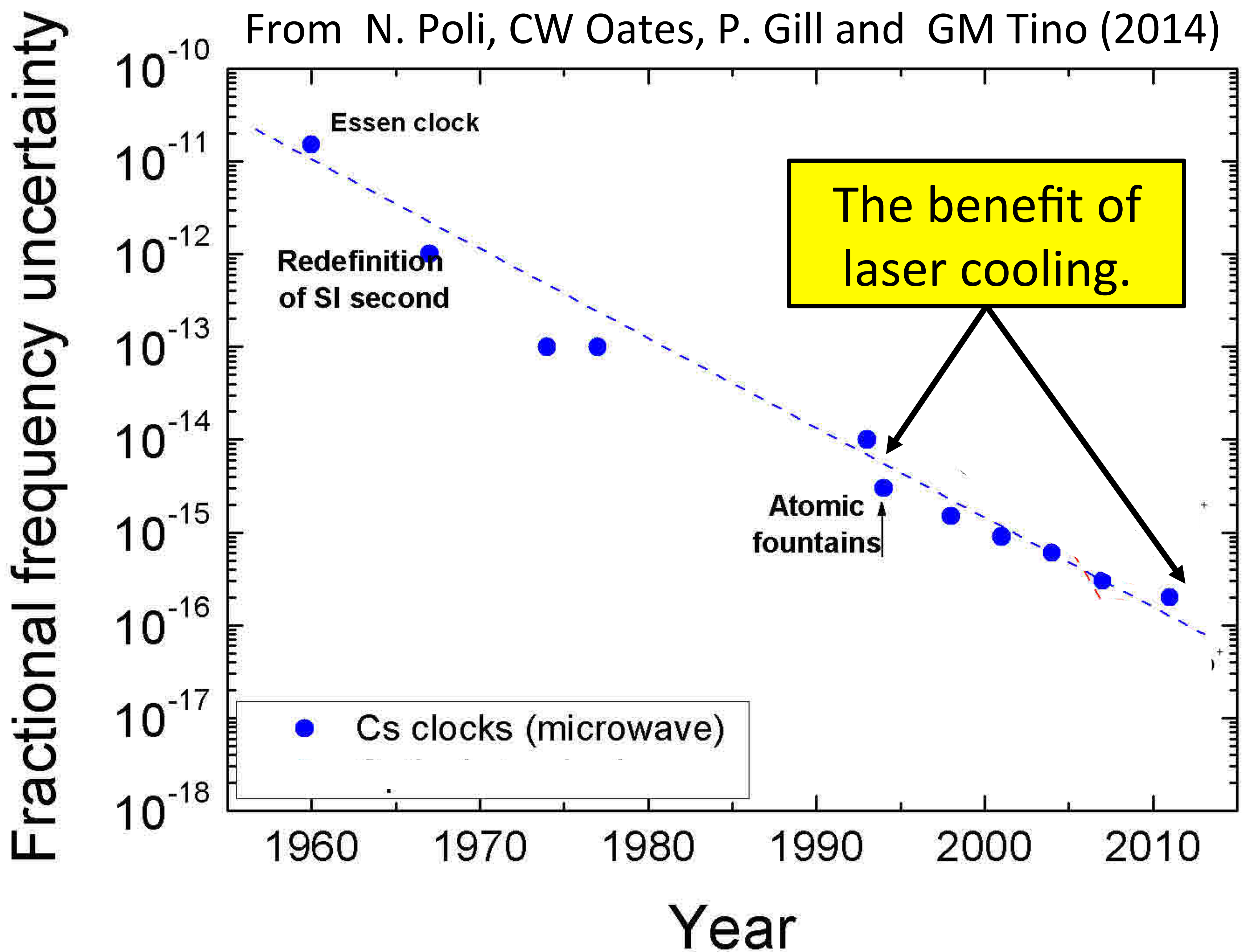
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom (13th CGPM 1967).

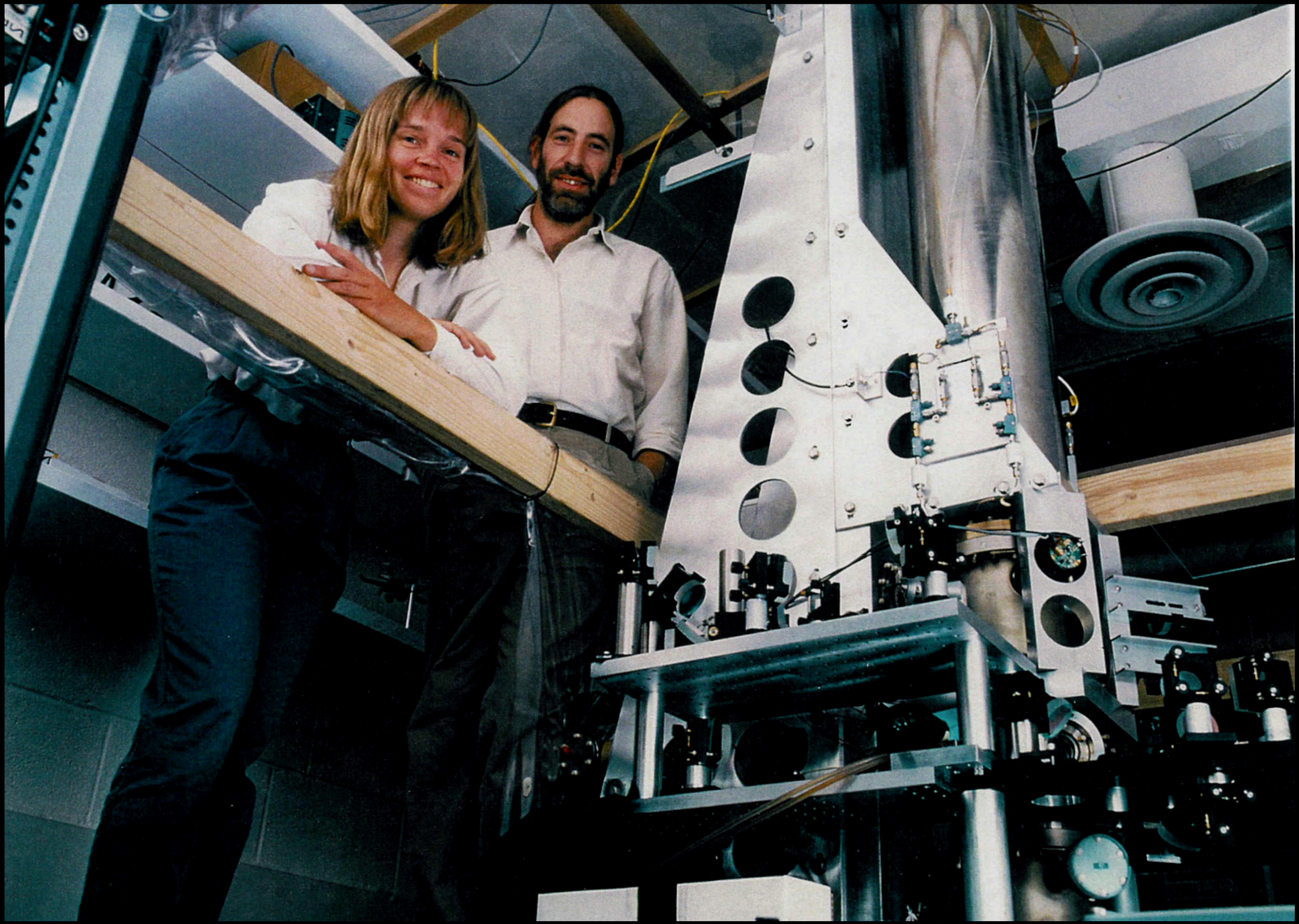
From N. Poli, CW Oates, P. Gill and GM Tino (2014)



The performance of Cs clocks stalled at a bit better than 10^{-14} because the Cs atoms move so fast (over 100 m/s). Laser cooling, many of the techniques of which were developed at NIST, addressed that and improved the performance to a few parts in 10^{16}.

From N. Poli, CW Oates, P. Gill and GM Tino (2014)





Cs fountain clocks like this, with atoms cooled below 1 μK (with techniques developed at NIST) keep time to a few parts in 10^{16}. This is the most accurately measured quantity in the SI.

The Key Concept

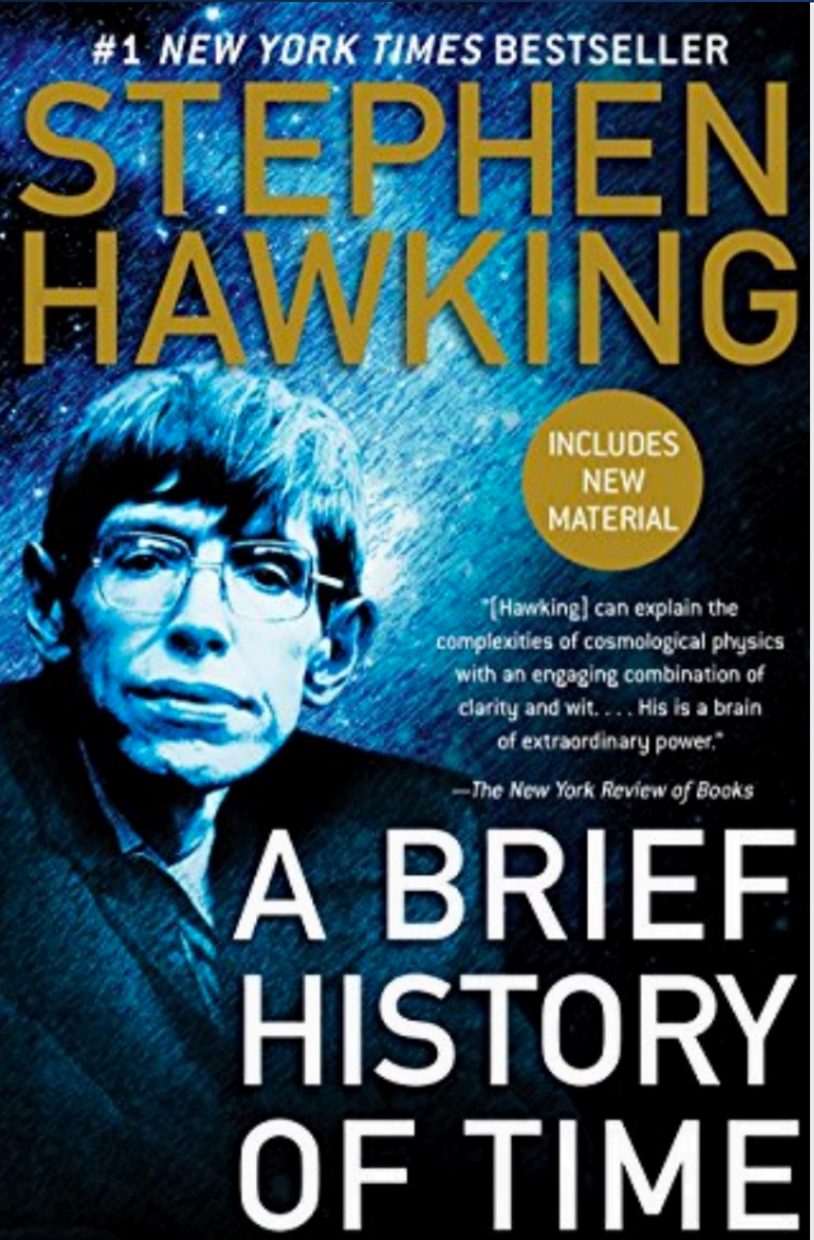
An arbitrary artifact, the rotating earth, whose rotation may change for any number of reasons, is replaced by a *constant of nature*—the frequency of a ***quantum*** transition in some atom.

Questions?

What about leap seconds?

How does general relativity affect the modern definition of the second?

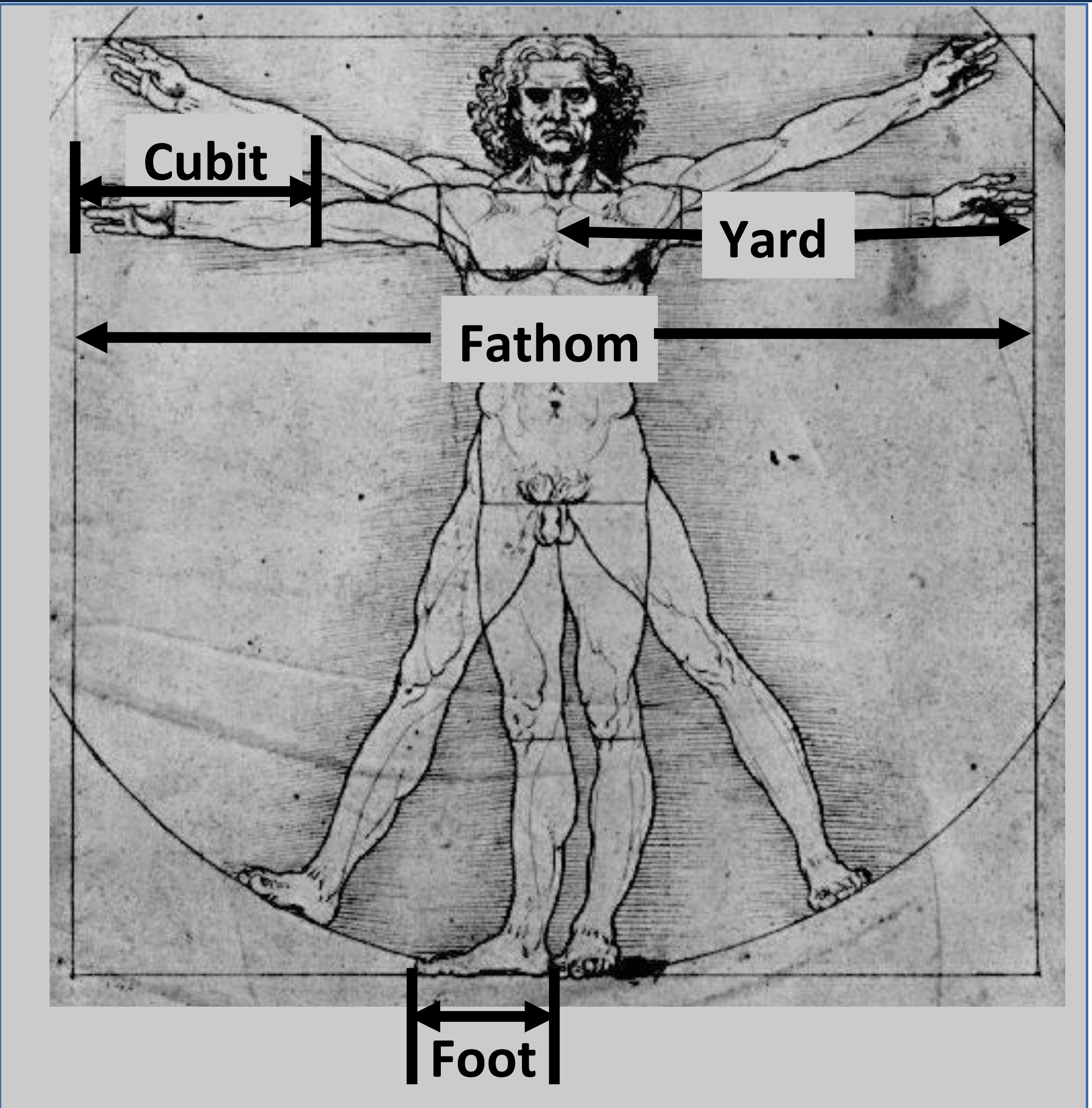
How does ambient blackbody radiation affect time?



Next, even better:
"A Short History of Length"

While time was important historically, length was REALLY important, because it involved commerce and construction.

Ancient length standards



The early approach to length used the human body as the standard.

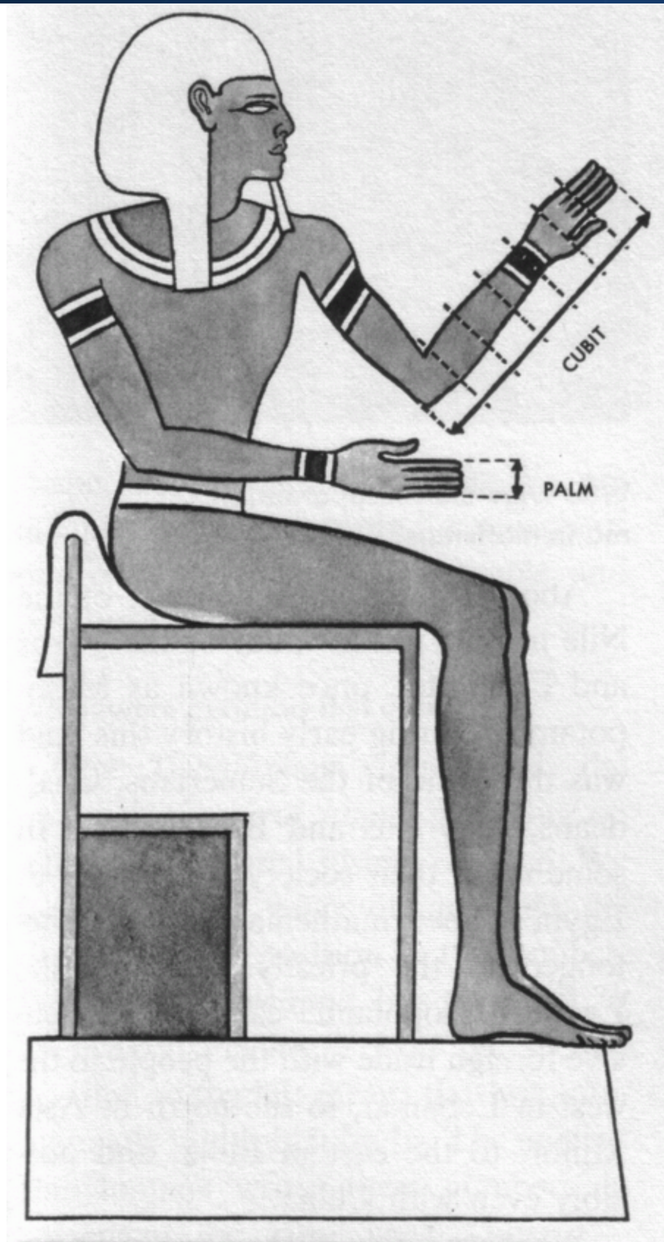
Ancient length standards

This was convenient, but not very consistent.

(A short fabric merchant might be selling you a smaller length of fabric than you had expected.)

Ancient length standards

NIST



One solution was to use a particular body—that of the king or pharaoh—as the standard.

Ancient Egyptian Approach

- Surprisingly modern
- Royal Egyptian cubit, based on the size of the Pharaoh’s forearm and hand, was embodied as an artifact.
- Primary cubit in granite
- Secondary cubits in wood
- Recalibration each month
- Death penalty for noncompliance


Photo:©Shutterstock

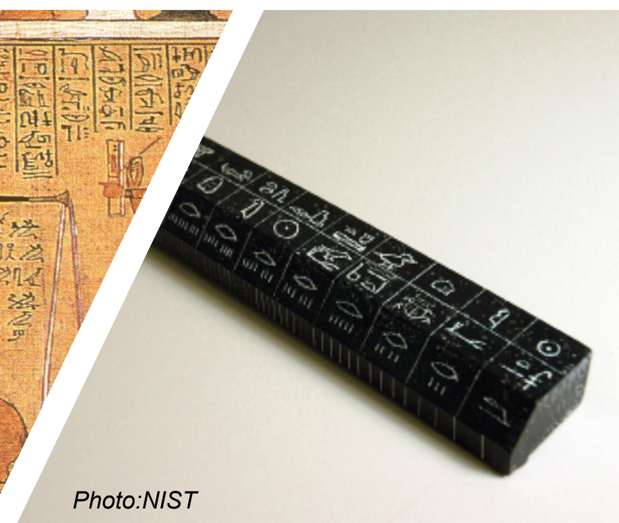


Photo:NIST

Ancient Egyptian Approach

NIST

- Surprisingly modern
- Royal Egyptian cubit, based on the size of the Pharaoh's forearm and hand, was embodied as an artifact.
- Primary cubit in gra
- Secondary cubits in
- Recalibration each month
- Death penalty for noncompliance

Base lines of pyramid consistent to 0.025%; square to 12 arcsec

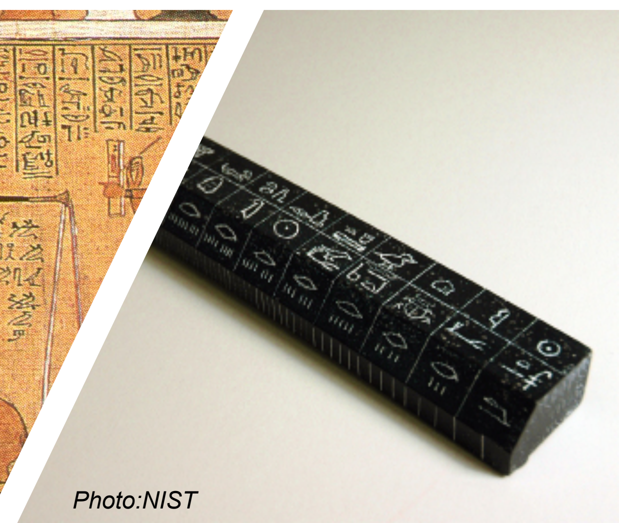


Photo:NIST

Antique length standards

Similar artifacts, sometimes varying from town to town, were common standards for length measurement in Europe.

Antique length standards

Photo:©Stephan Schlamminger, used by permission

- Standard fathom, foot and cubit fixed into the wall at the city hall of the city of Regensburg.

- These standards were different from those of surrounding Bavaria—a vexing, but common problem.

The revolutionary metre

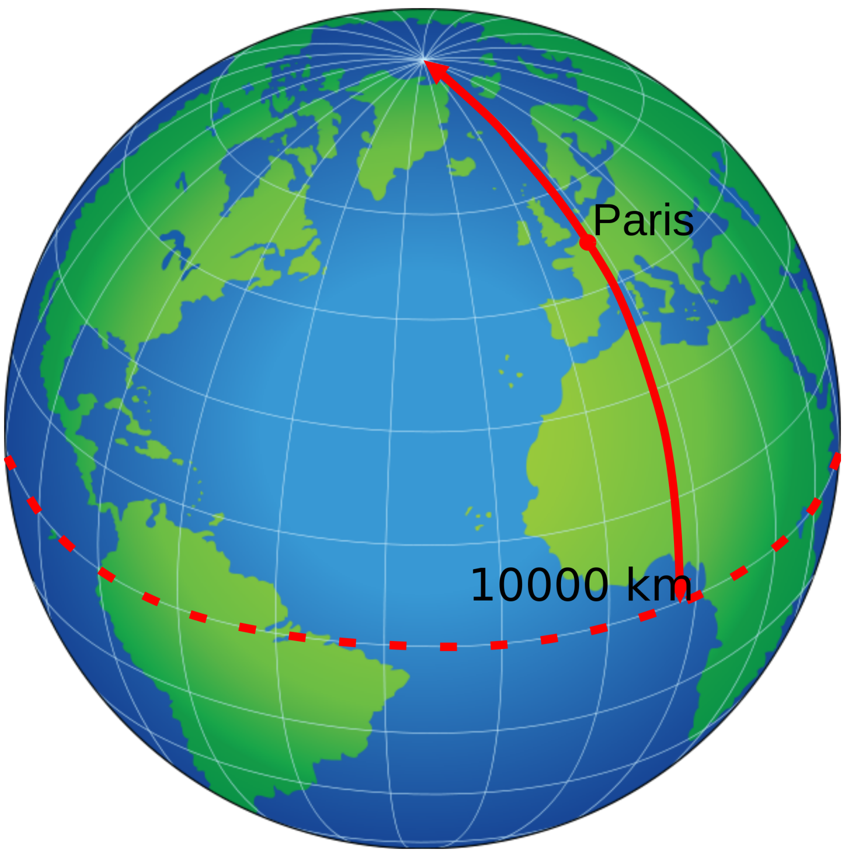


Image: U.S. Government

During the French Revolution (ca. 1791) the metric system came into being, based on the metre, and with a particular philosophy.

The metre was to be **"the measure of all things,"** and was (in the spirit of equality and fraternity) to be available to everyone.

The metre is **1/10 000 000 of the distance from the equator to the pole** along a meridian passing through Paris.

The Revolutionary Dream

À tous les temps,
à tous les peuples.

For all times, for all peoples.

Photo credit: http://monnaiesanciennes.free.fr/images_elsen_104/MED-000576-002dc.jpg

The Metre Archived

The earth as a definition of the metre was clear, and more stable (and global) than the Pharaoh's forearm, or a city-specific standard, but it was hardly more convenient.

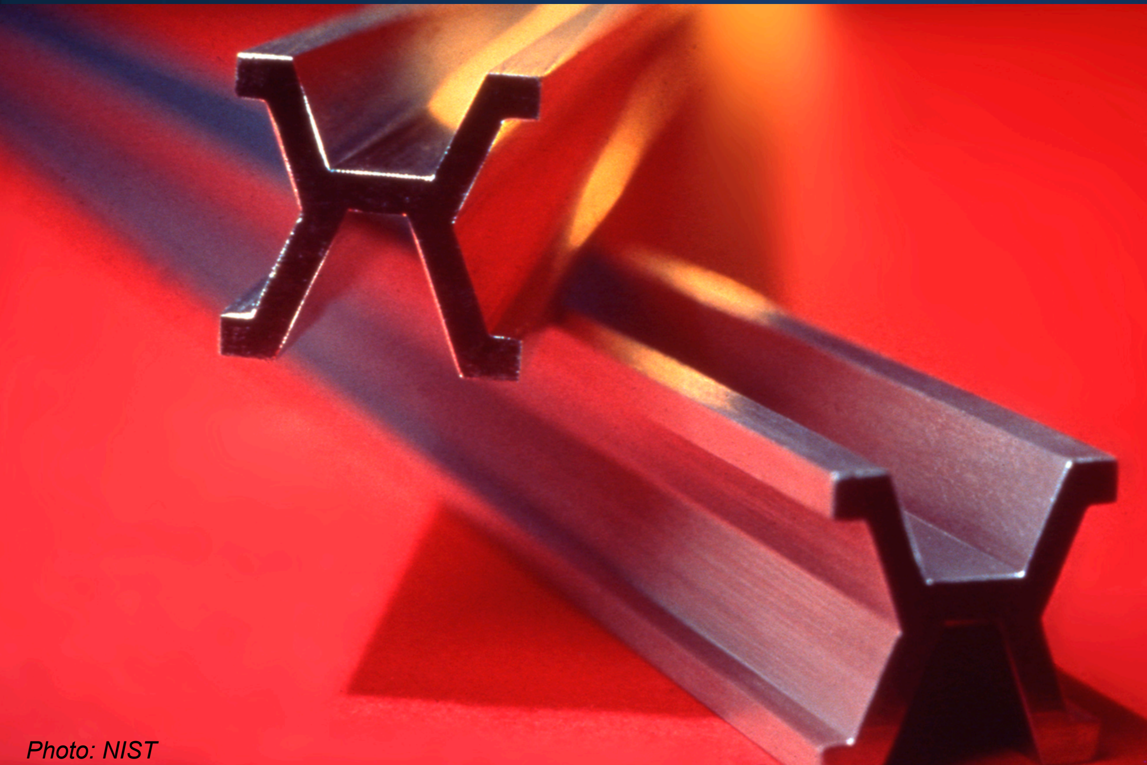
The meridian definition of the metre was used to create an artifact end-standard—the "metre of the archives."

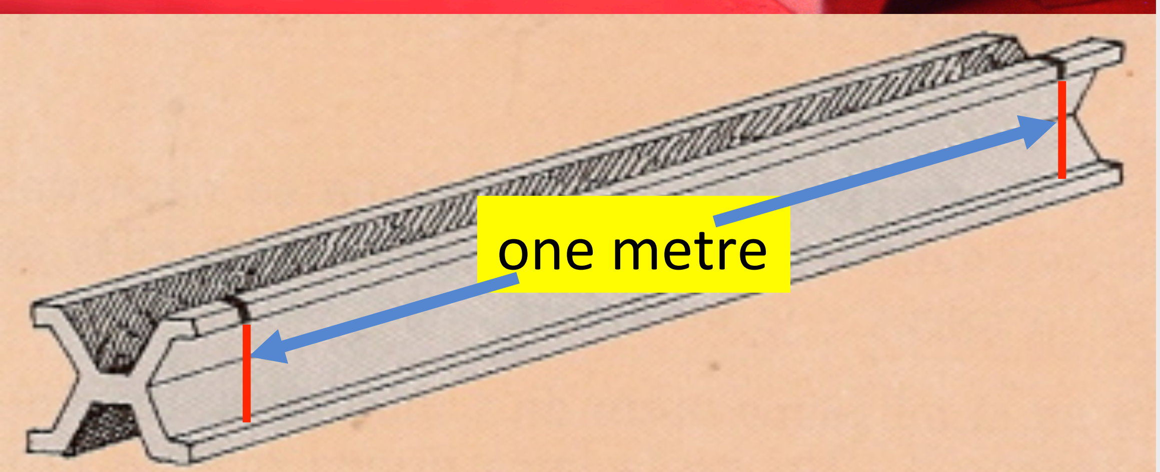
1799: Mètre des Archives (Platinum Bar)

Source: http://en.wikipedia.org/wiki/History_of_the_metre

This was very much in the spirit of the Egyptian cubit, where the definition of length was a primary-standard artifact, against which secondary, working standards were calibrated.

The New Metre

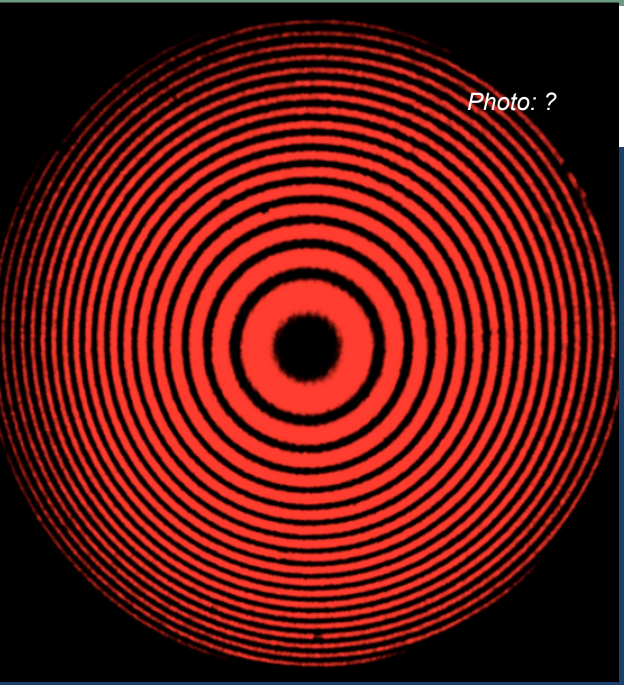


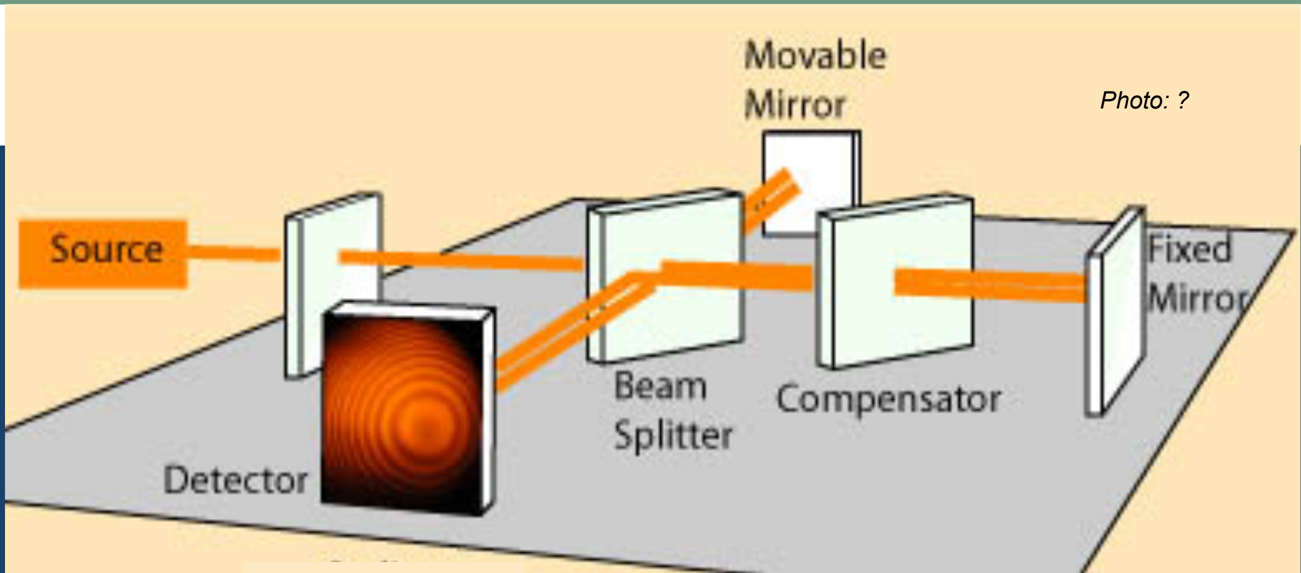


Following the famous **1875 Convention du Metre**, the metre of the archives was **replaced with a line standard**, the International Prototype of the Metre.

Light for Length

Soon, the distance between two scratches became inadequate as a standard, and people used the wavelength of light as a de facto standard.





Interference
Fringes

The Krypton Metre

So, in 1960 *(the year the laser was invented)*, the metre was re-defined as a certain number of wavelengths of light from a krypton lamp.

But soon, the purity of that light from krypton was found to be insufficient for the accuracy of measurements people were making with laser light

Laser-Light Length

Photo courtesy of Samuel M. Goldwasser, Sam's Laser FAQ

Laser light as a de facto length standard

By the 1970s, almost everyone was using an iodine-stabilized He-Ne laser as an ***unofficial*** standard of length. Such lengths were **NOT in SI metres**.

The metre needed to be re-defined.

The obvious choice:

Define the metre in terms of an I_2-stabilized He-Ne laser.

The metre needed to be re-defined.

The obvious choice:

Define the metre in terms of an I_2-stabilized He-Ne laser.

The brilliant choice:

Define the speed of light.

The Brilliant, BEAUTIFUL definition of the metre (17th CGPM, 1983)

The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 second.

This effectively **DEFINES** the speed of light, and given:

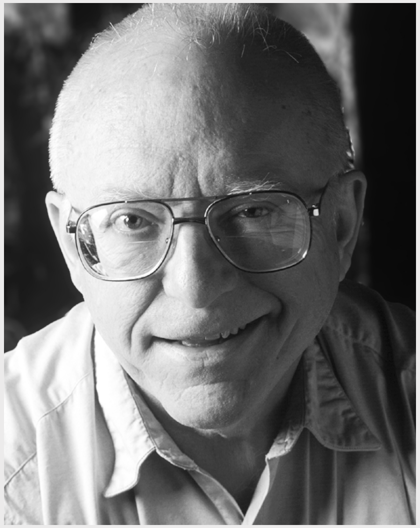
$$\lambda f = c$$

If we know the frequency ***f*** of any light, we know its wavelength ***λ***.

This definition incorporates improvements in lasers and frequency measurements.

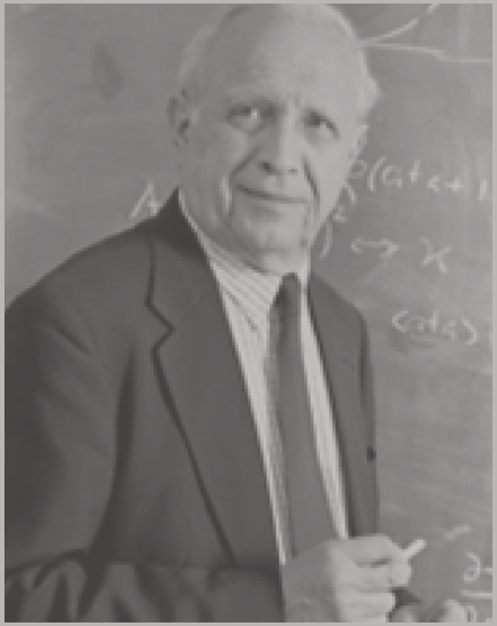
The 2005 Nobel Prize In Physics

The 2005 Nobel to Jan Hall and Ted Hänsch was for dramatic improvements in measuring the frequency of light.



John "Jan" Hall
Photo: NIST

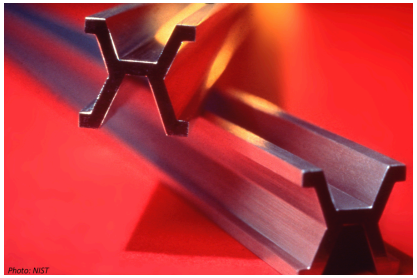
Theodor W. Hänsch
Photo: Courtesy Theodor Hänsch



Roy J. Glauber
Photo: J. Reed

The Key Concept

The meter went from an artifact to an atomic constant of nature to a *fundamental* constant of nature.

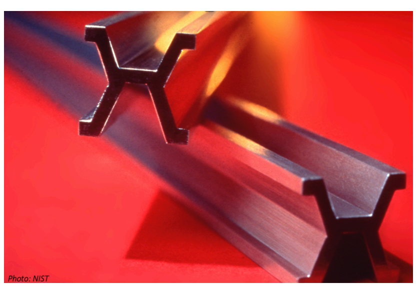


c

The Key Concept

The meter went from an artifact to an atomic constant of nature to a *fundamental* constant of nature.

No need ever to change again.



→

→

c

Beautiful definitions

NIST

The definition of the metre is both brilliant and beautiful—even more beautiful than the definition of the second.

On 20 May 2019, the international metrology community brought this beauty to the kilogram (and to the ampere, kelvin, and mole).

Why and How?

Questions?

How can we fix the value of *c*?
Isn't it fixed by Nature?

What limits our ability to measure length with the new, beautiful definition?

Beautiful definitions

NIST

The definition of the metre is both brilliant and beautiful—even more beautiful than the definition of the second.

On 20 May 2019, the international metrology community brought this beauty to the kilogram (and to the ampere, kelvin, and mole).

Why and How?

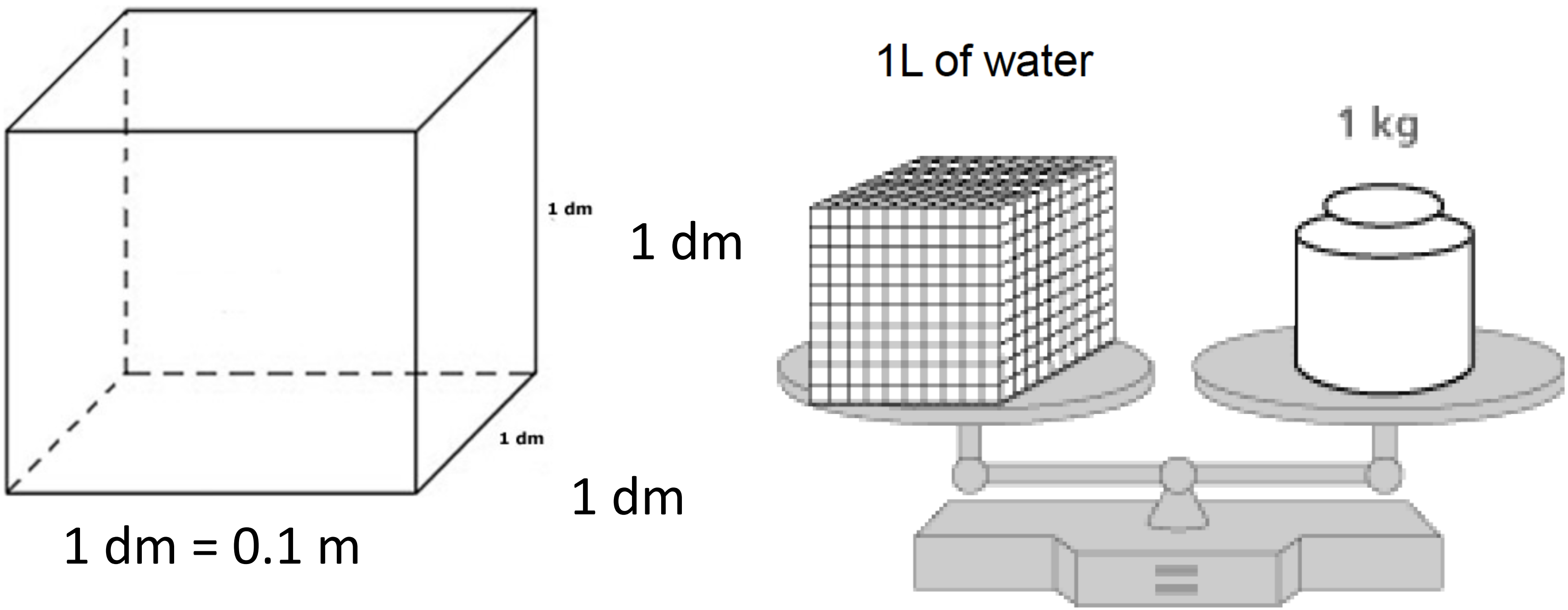
A Light History of Mass

Ancient mass standards

“Mesopotamian weights made from haematite” by geni is licensed under GFDL CC-BY-SA

In ancient Babylonia and elsewhere, manufactured objects were the mass standards.

Revolutionary mass standard



In the French metric revolution, ca. 1793, the kilogram was defined as the mass of a cubic decimetre (a litre) of water.

From Water to a New Artifact

The water definition of the kilogram was difficult to use. So, in 1799, a platinum artifact became the kilogram of the archives—a return to the ancient practice, just as with the metre.

IPK

After the 1875 *Convention du Mètre* (the International Treaty of the Metre), a new artifact kilogram (the International Prototype Kilogram–IPK) was made of Pt-Ir.

This was the <u>last</u> artifact.

The Old Definition

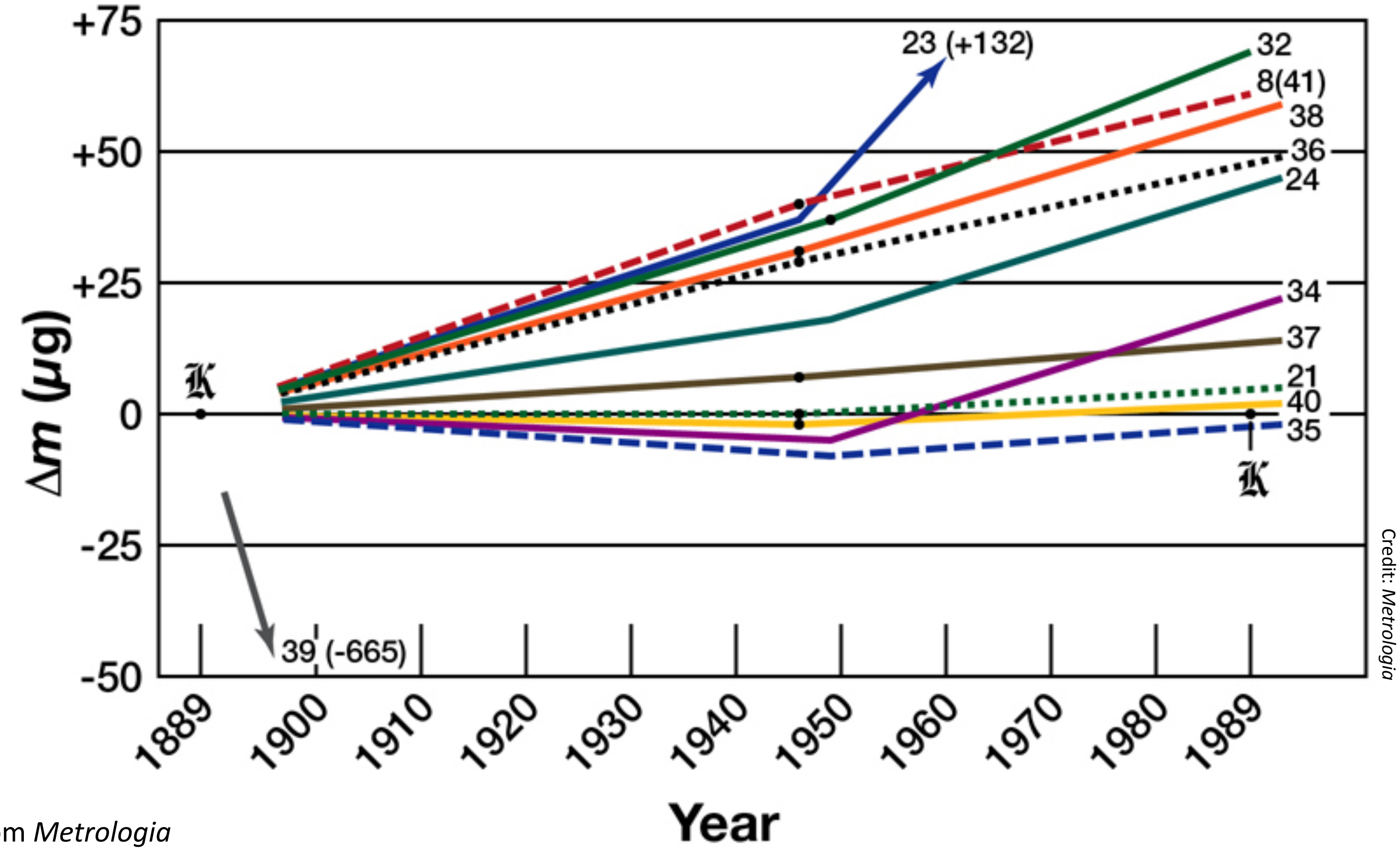
NIST

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

That in the 21st century, the unit of mass was an artifact, a piece of metal made in the 19th century, based on an object made in the 18th century, is a scandal. If someone left a fingerprint on the IPK, all of us would lose weight.

Nobody has left a fingerprint on the International Prototype Kilogram, but its mass is “changing” nevertheless.

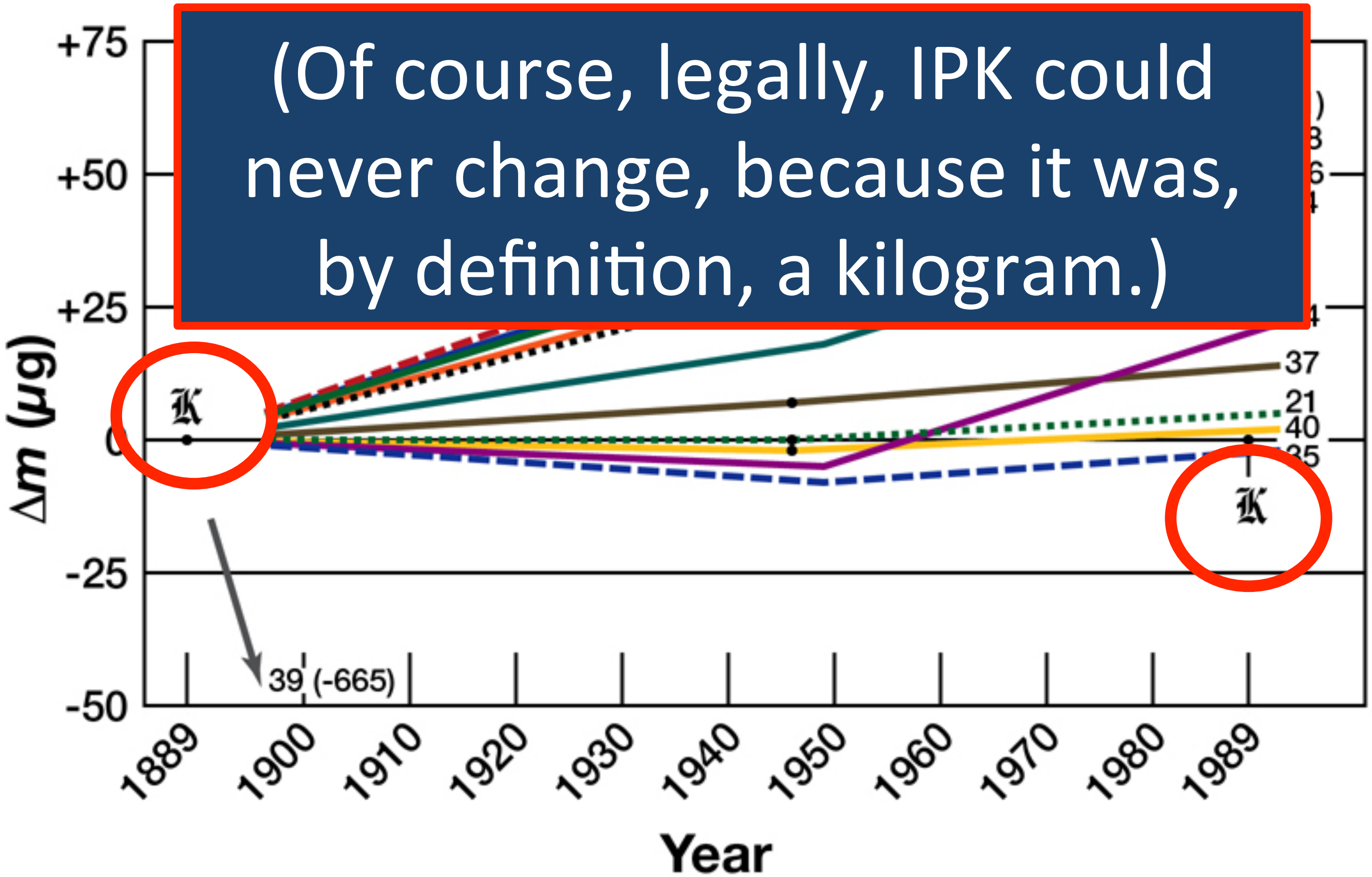
The International Prototype Kilogram appears to be changing!!



Credit: graph from *Metrologia*

The International Prototype Kilogram appears to be changing!!

(Of course, legally, IPK could never change, because it was, by definition, a kilogram.)



Credit: *Metrologia*

Fixing the Kilogram Problem

This scandalous situation had to be fixed. We wanted to use the beautiful approach used for the metre.

To define the metre, we defined the speed of light *c*.

What constant will we use for kg?

The most famous equation in history:

$$E = mc^2$$

Energy of an object at rest

Rest mass of the object

Speed of light

A slightly less famous equation:

$$E = hf$$

Energy of a photon (a particle of light)

Planck's constant

Frequency of the light

Defining Planck's constant *h* allows us to define mass.

$$E = mc^2 = hf = E$$

$$m = hf/c^2$$

The change in mass of a particle when it emits a photon of frequency *f*.

Bryan Kibble 1938-2016

We will not be weighing photons (we could, but not well enough). Instead, to use Planck's constant to define the kilogram, we turn to the electro-mechanical device known as a Kibble Balance or Watt Balance.

Operating Principles of the NIST-4 Watt Balance

NIST Physical Measurement Laboratory

Watt Balance

$$mgv = IV$$

mass (force) from weighing mode

velocity from velocity mode

current from weighing mode

voltage from velocity mode

Watt Balance

Mechanical Power = Electrical Power

$$mgv = IV$$

mass (force) from weighing mode

velocity from velocity mode

current from weighing mode

voltage from velocity mode

Watt Balance

$$m = IV/gv$$

From Watt to Planck

$$m = IV/gv$$

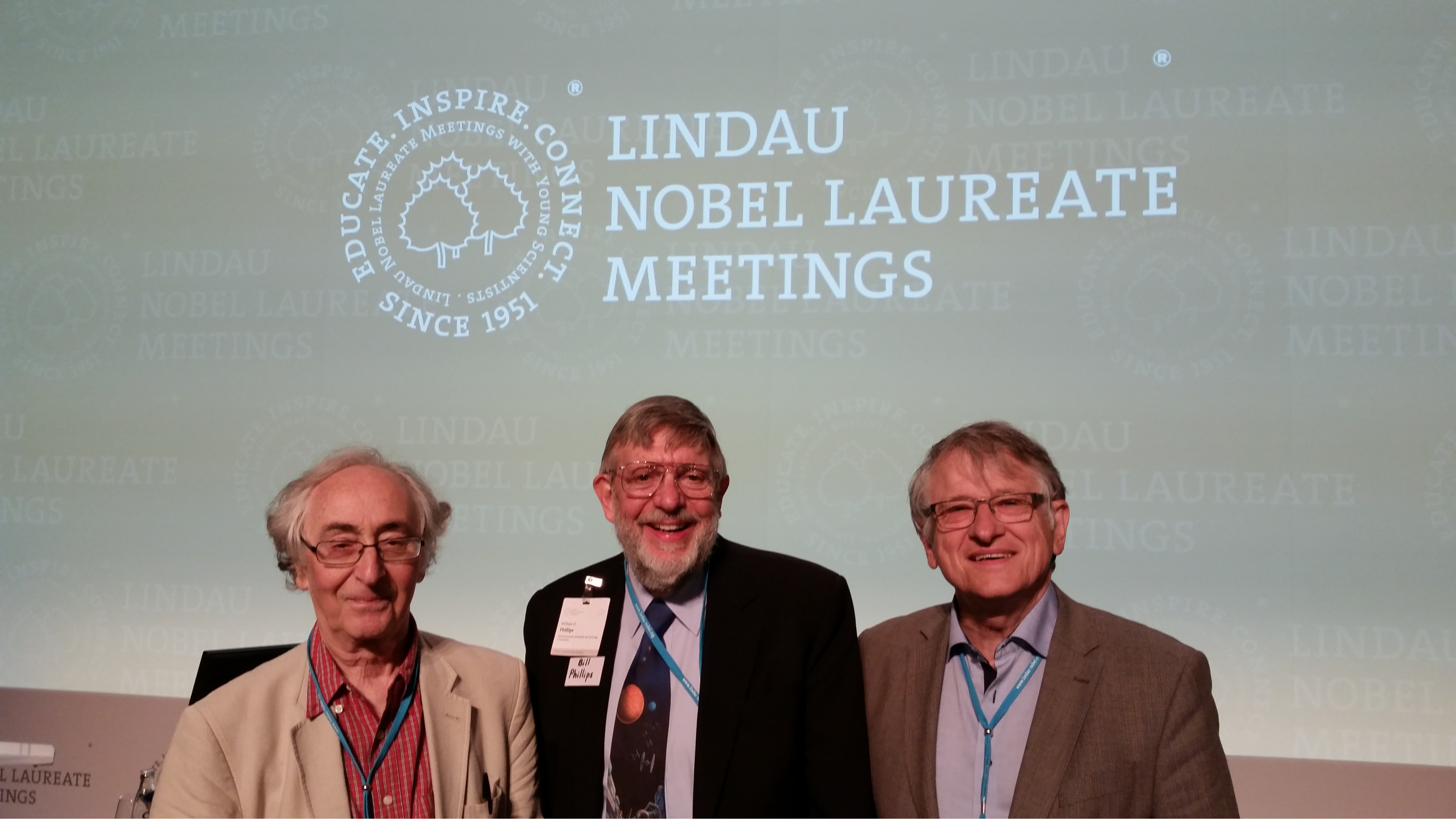
But—how does this relate to Planck's constant?

From Watt to Planck

$$m = IV/gv$$

But—how does this relate to Planck's constant?

<u>Answer</u>—the quantum way of doing electrical measurements: the quantum Hall effect (von Klitzing) and the Josephson effect.



Quantum Electrical Measurements

Brian Josephson

$K_J = 2e/h$ (Hz/volt)

Klaus von Klitzing

$R_K = h/e^2$ (ohms)

From Watt to Planck

$$m = IV/gv$$

Voltage is proportional to *h*/2*e* (because of Josephson)

From Watt to Planck

$$m = IV/gv$$

Voltage is proportional to $h/2e$ (because of Josephson)

Current is proportional to V/R, with $R \sim h/e^2$, and $V \sim h/2e$, so $I \sim e$

From Watt to Planck

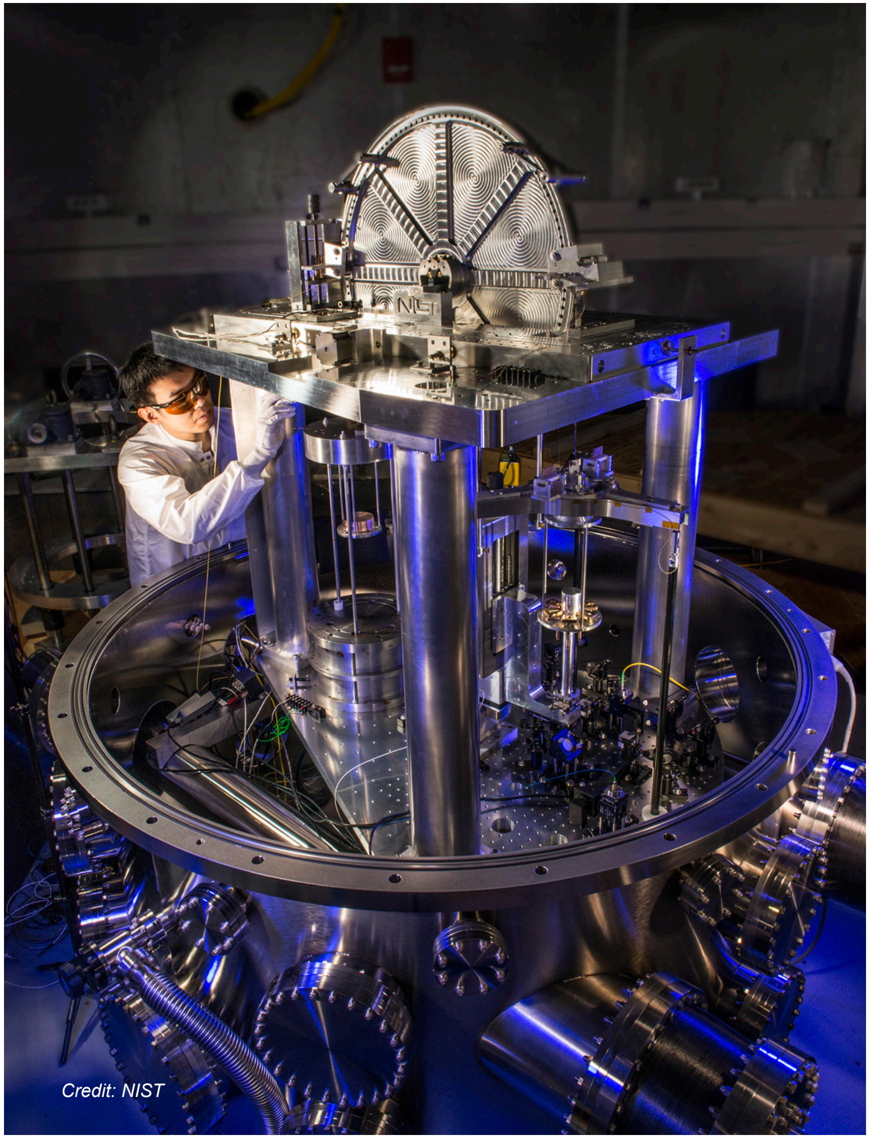
$$m = IV/gv$$

Voltage is proportional to $h/2e$ (because of Josephson)

Current is proportional to V/R, with $R \sim h/e^2$, and $V \sim h/2e$, so $I \sim e$

$$m \sim h$$

NIST Kibble Balance



Kibble balances can realize the kilogram to about 10^{-8}, which is better than the changes due to "dirt".

h = 6.626 070 15 × 10⁻³⁴ Js
A tous les temps, à tous les peuples.
A TOUS LES TEMPS A TOUS LES PEUPLES


h = 6.626 070 15 x 10-34 J Hz-1
e = 1.602 176 634 x 10-19 C
k = 1.380 649 x 10-23 J K-1
NA = 6.022 140 76 x 1023 mol-1
A TOUS LES TEMPS A TOUS LES PEUPLES
MAY 20, 2019

Questions?

You asserted that measured quantities from the weighing mode and the velocity mode, picked to have the units of mechanical and electrical power were equal, but you didn't show it. Besides, aren't there losses associated with electrical resistance and mechanical friction?

What about the acceleration of gravity?

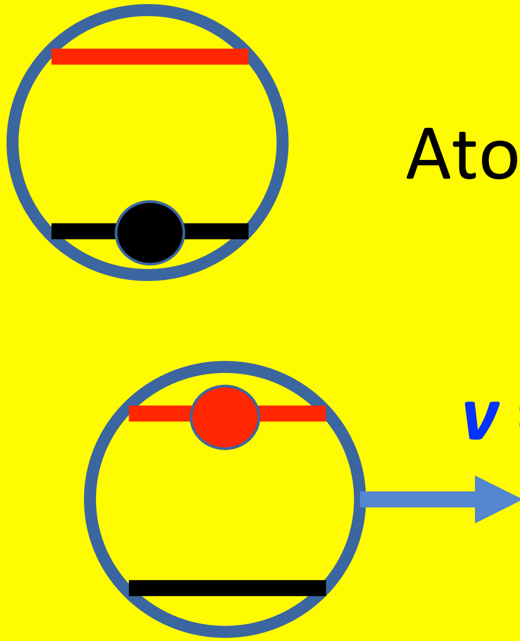
Why were you wearing a winter coat in the picture with the Kilogram of the Archives?

Mass from *h* another way

one photon

$E = hf$

$p = h/\lambda$



Atom at rest in ground state

$v = h/m\lambda$

Atom moving at $v = h/m\lambda$
in excited state

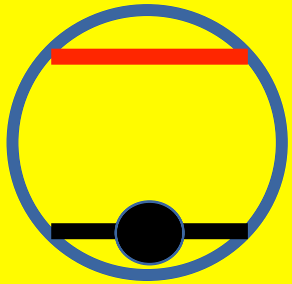
Atom interferometry measures the recoil velocity; λ is "easy", so fixing *h* gives the atomic mass *in kilograms*.

Mass from *h* the AMO way

one photon

$E = hf$

$p = h/\lambda$



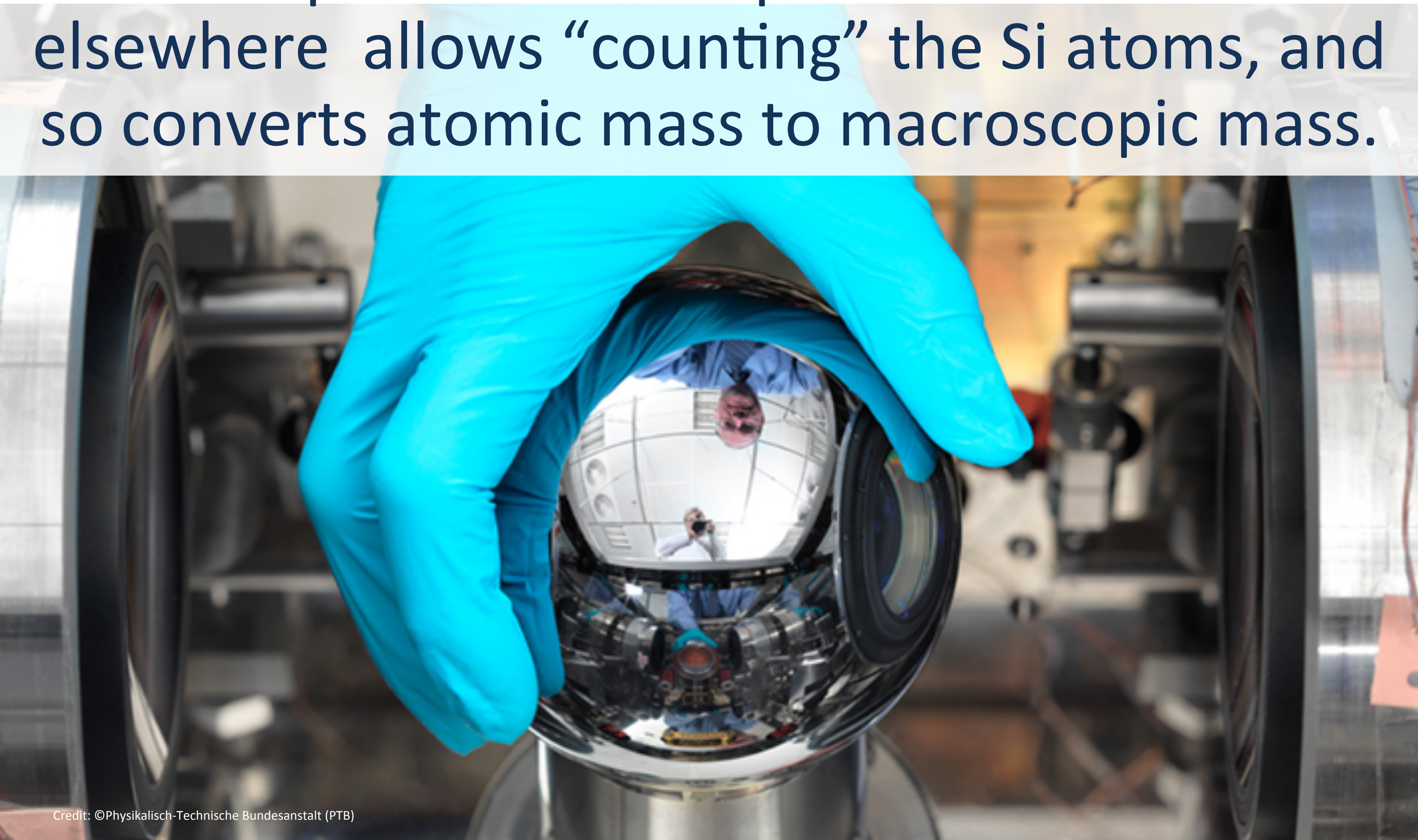
Atom at rest in ground state

The Early Career, Young Scientist Prize of IUPAP commission C2 was awarded to Pierre Cladé in 2012 for his measurements of this atomic recoil..

Another route to the kilogram via *h*

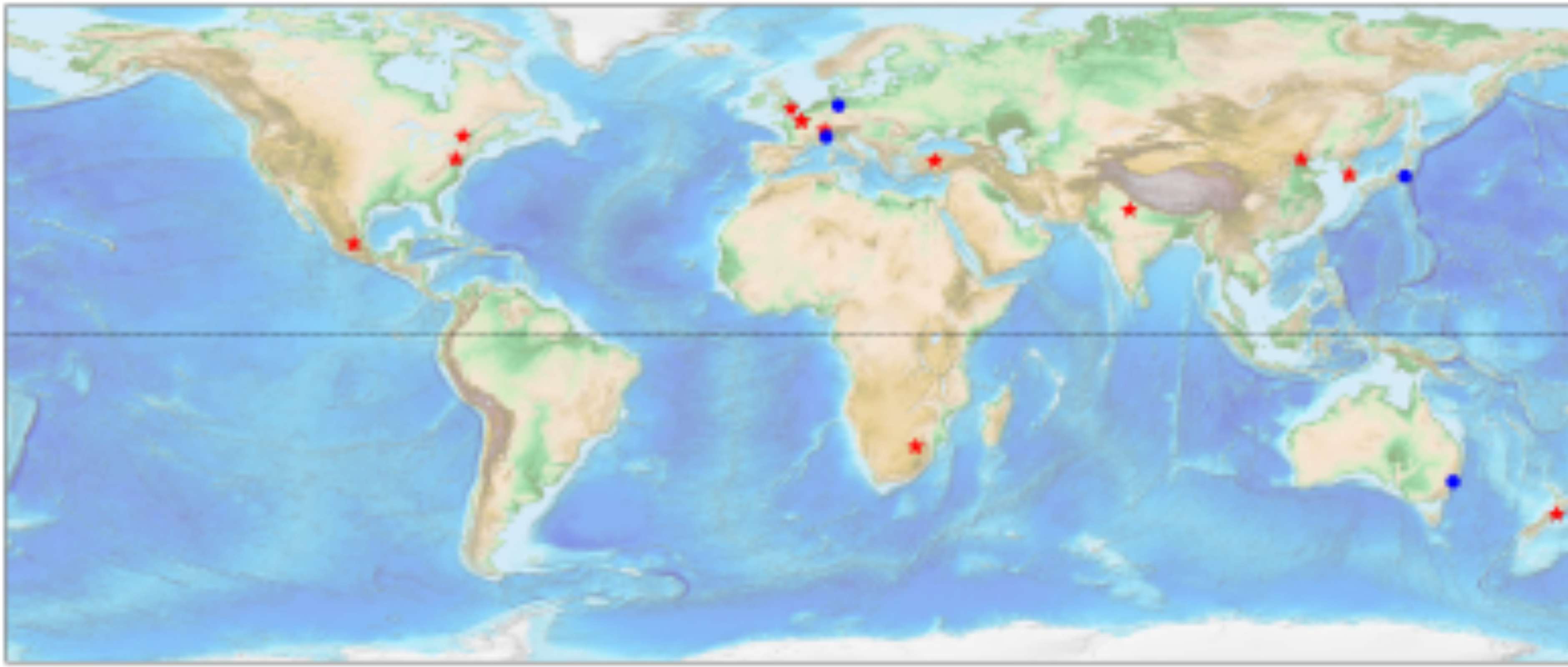
NIST

Near-perfect silicon spheres at PTB and elsewhere allows "counting" the Si atoms, and so converts atomic mass to macroscopic mass.



Credit: ©Physikalisch-Technische Bundesanstalt (PTB)

Other Kibble balance work: NPL (UK), Metas (Switzerland), LNE (France), NIM (China), BIPM (the World), NRC (Canada), UME (Turkey), NMISA (South Africa), and others



Silicon work: (PTB (Germany); INRIM (Italy); NMI (Australia); NMIJ (Japan); NIST (US), BIPM, NPL (UK) and others

26th General Conference of Weights and Measures

Redefinition of SI Adopted
Versailles, France 2018

A final part of the story: the ampere

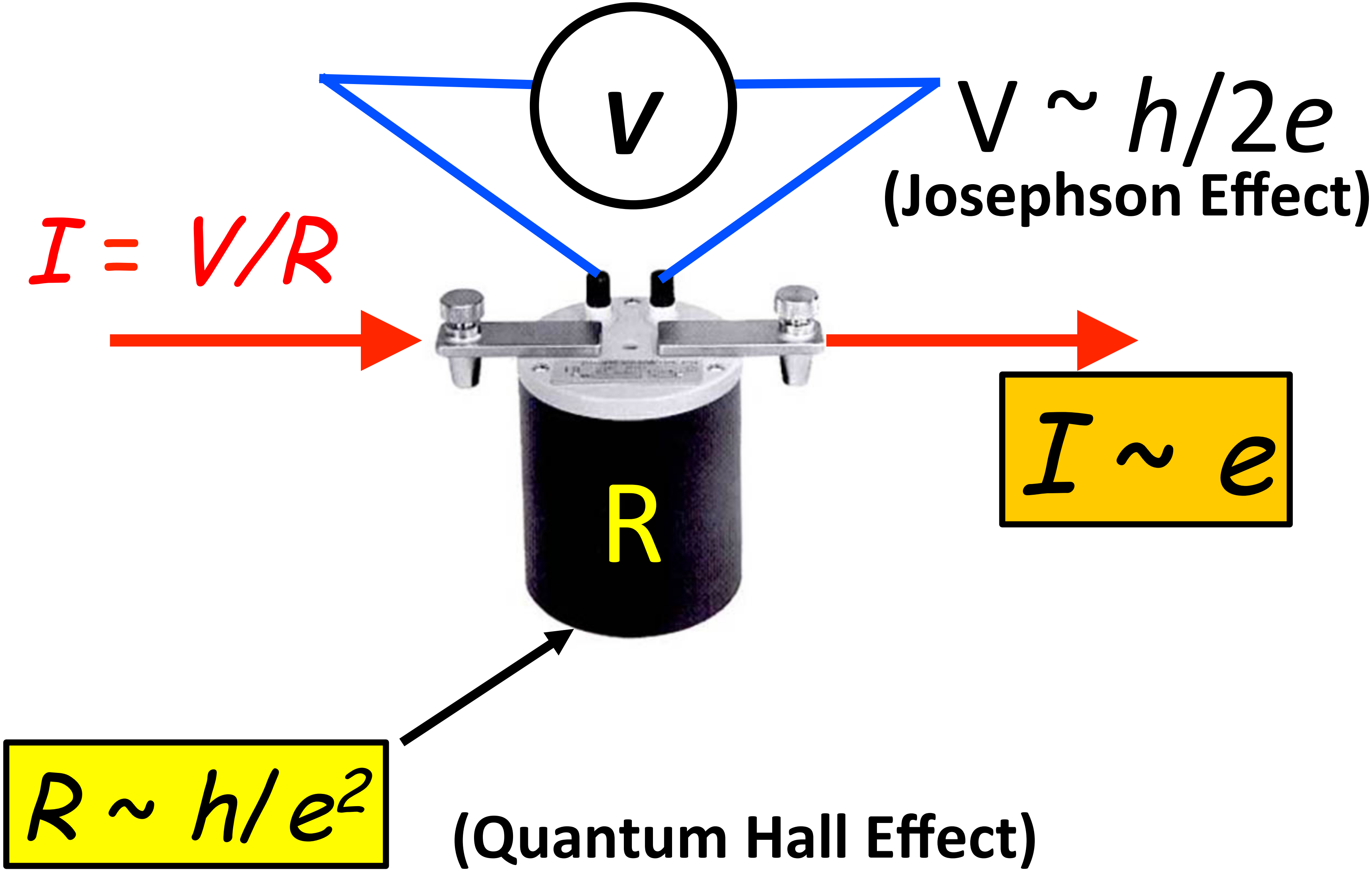
NIST

Before: "The ampere is that current…which…in two straight,..infinite [wires]…one metre apart in vacuum would produce…a force of 2×10^{-7} newtons per metre."

Now: Define the electron charge $e = 1.602\ 176\ 634 \times 10^{-19}$ C , so the ampere is a certain number of electrons per second.

With both e and h defined, $2e/h$ and h/e^2 are exact, and allow us to use the Josephson and Quantum Hall effects to measure all electrical quantities.

Unified Electrical Standards



A dirty little secret about electrical units

There have been two separate kinds of electrical units in use throughout the world:

SI units: based on the distance and force definition of the ampere, with the ohm and volt defined so that mechanical and electrical power are equal. They depended on the artifact kilogram.

LEGAL units: originally maintained using standard cells (batteries) and standard resistors.

These are artifacts.
They drift and fail.
Each nation was different.

Legal versus SI electrical units

Since 1990: Legal electrical units were defined by fixed, chosen values of $2e/h$ and h/e^2 , which were not the SI values.

Since early in the 20^{th} century, we had the concept of "absolute" electrical units defined by the mechanical definition of the ampere.

With both e and h defined in the SI, $2e/h$ and h/e^2. are both exact in the SI, so legal and SI electrical units are finally the same.

Two More units

The Mole: Formerly, the amount of substance with a number of entities equal to the number of ^{12}C atoms in a 12 grams of ^{12}C. Now, simply a number the Avogadro constant:

$$N_A = 6.022\ 140\ 76 \times 10^{23}\ \text{mol}^{-1}.$$

The Kelvin: formerly 1/273.16 of the triple point of water. Now, we specify the thermal energy per kelvin of the atomic constituents, i.e., we define the Boltzmann constant $k_B = 1.380\ 649 \times 10^{-23}$ J/K

The New SI

NIST

The French revolution brought us the metric system, with metres as the measure of length, and kilograms as the measure of mass.

The *Convention du Metre* brought us an international agreement about the units.

On 20 May 2019 (the anniversary of the signing of the 1875 Convention du Metre), we had the biggest revolution in measurement units since the French Revolution.

Liberty leading the people means we will finally be **free of artifact standards of measurement.**

And we will be **free of a double standard for electrical measurements.**

The New Système Internationale

All of the base units of the International System of Units are now defined by fixing the values of constants of nature.

Realizing the dream

À tous les temps,

à tous les peuples.

For all times, for all peoples.

Photo credit: http://monnaiesanciennes.free.fr/images_elsen_104/MED-000576-002dc.jpg

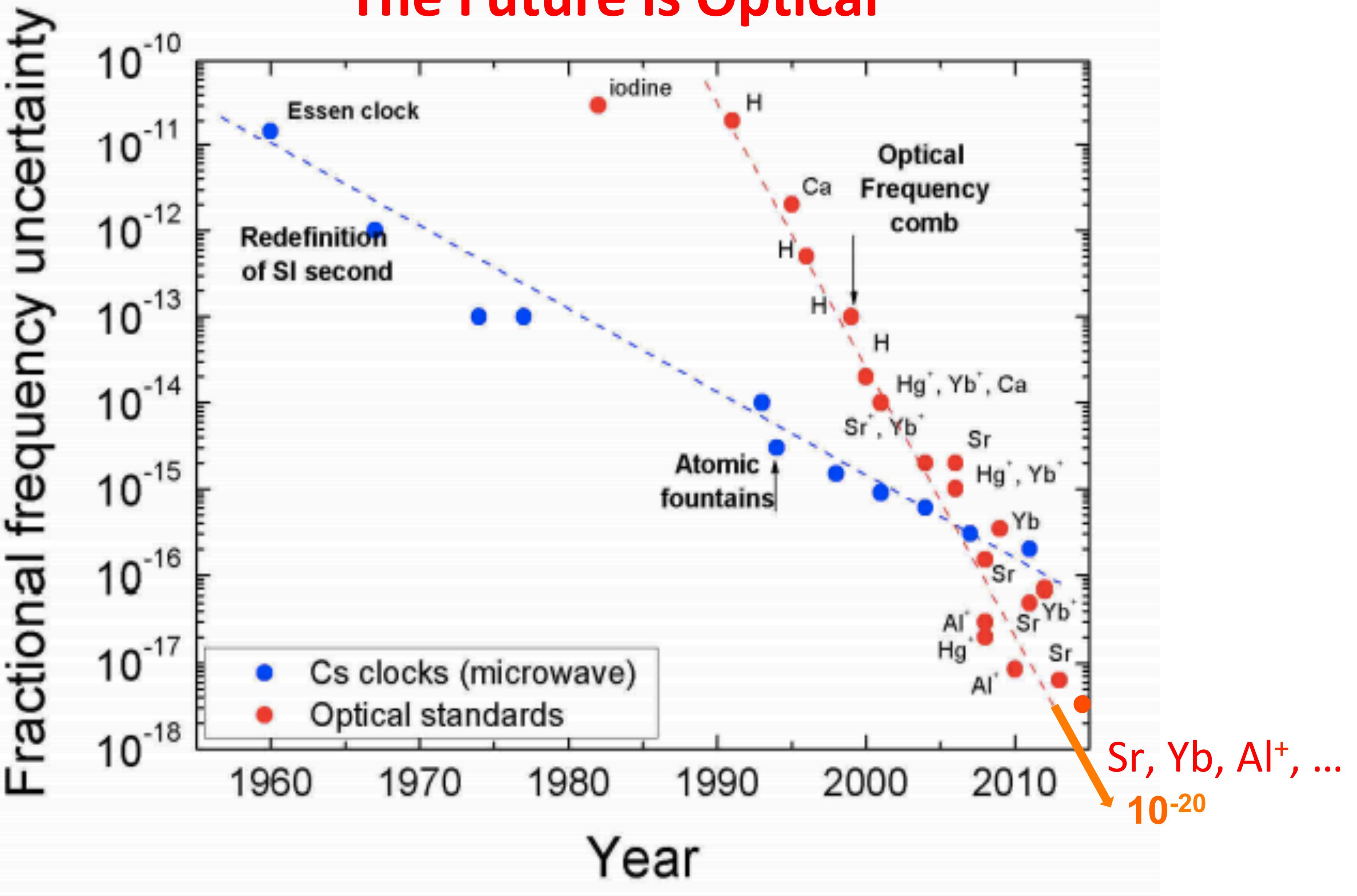
Except, it seems, for time itself, which is still tied to a *specific* atom (Cs) rather than to a *fundamental* constant.

THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	$m\ s^{-1}$
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	$J\ Hz^{-1}$
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	$J\ K^{-1}$
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	$lm\ W^{-1}$

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

The Future is Optical



Poli *et al.*, *La rivista del Nuovo Cimento*, **36** 555 (2013); Ludlow *et al*, RMP **87**, 637 (2015) (Thanks to Jun Ye for figure modifications)

As for the future
of time....
only time will tell.

The End