Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

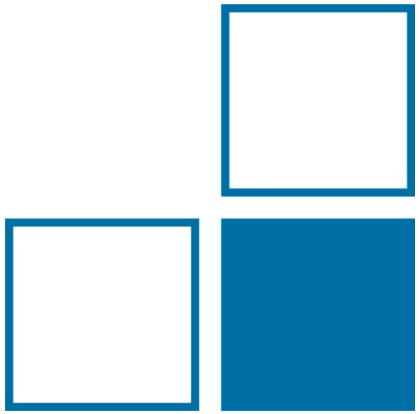
Linking the International System of Units to Fundamental Constants

Prof Dr Joachim H. Ullrich

President of the Consultative Committee of Units

Vice President of the CIPM

President of PTB, Physikalisch-Technische Bundesanstalt



Physikalisches Kolloquium Heidelberg, 31/01/2020

Properties of

- artefacts
- substances
- and phenomena

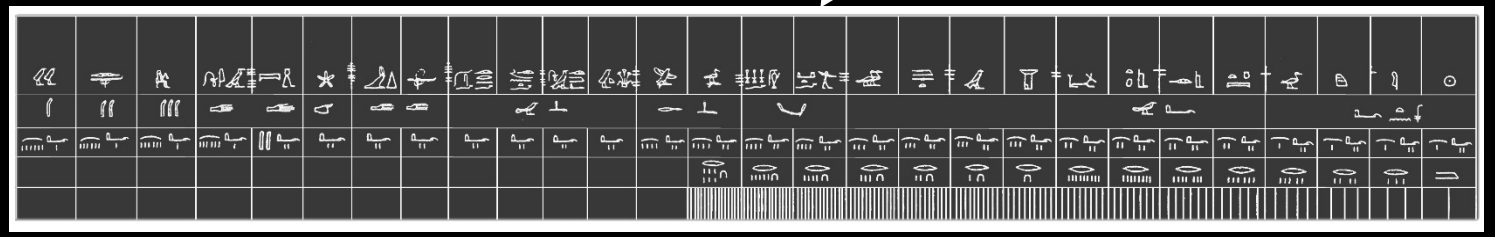
can be measured

Great Pyramid of Chephren
(built ~4600 years ago)

ancient Chinese volume units

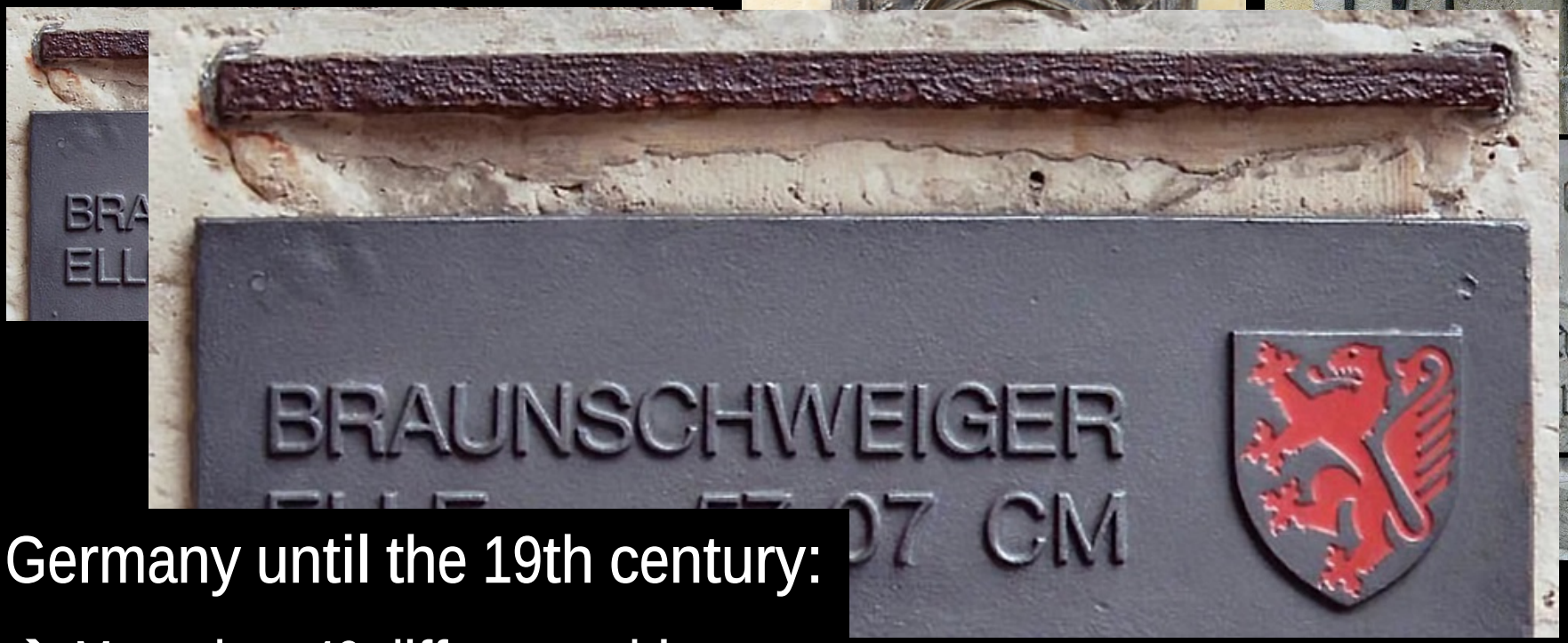
quantity = value · unit

artefact



ancient Egyptian royal cubit

Same quantity – different units



Germany until the 19th century:

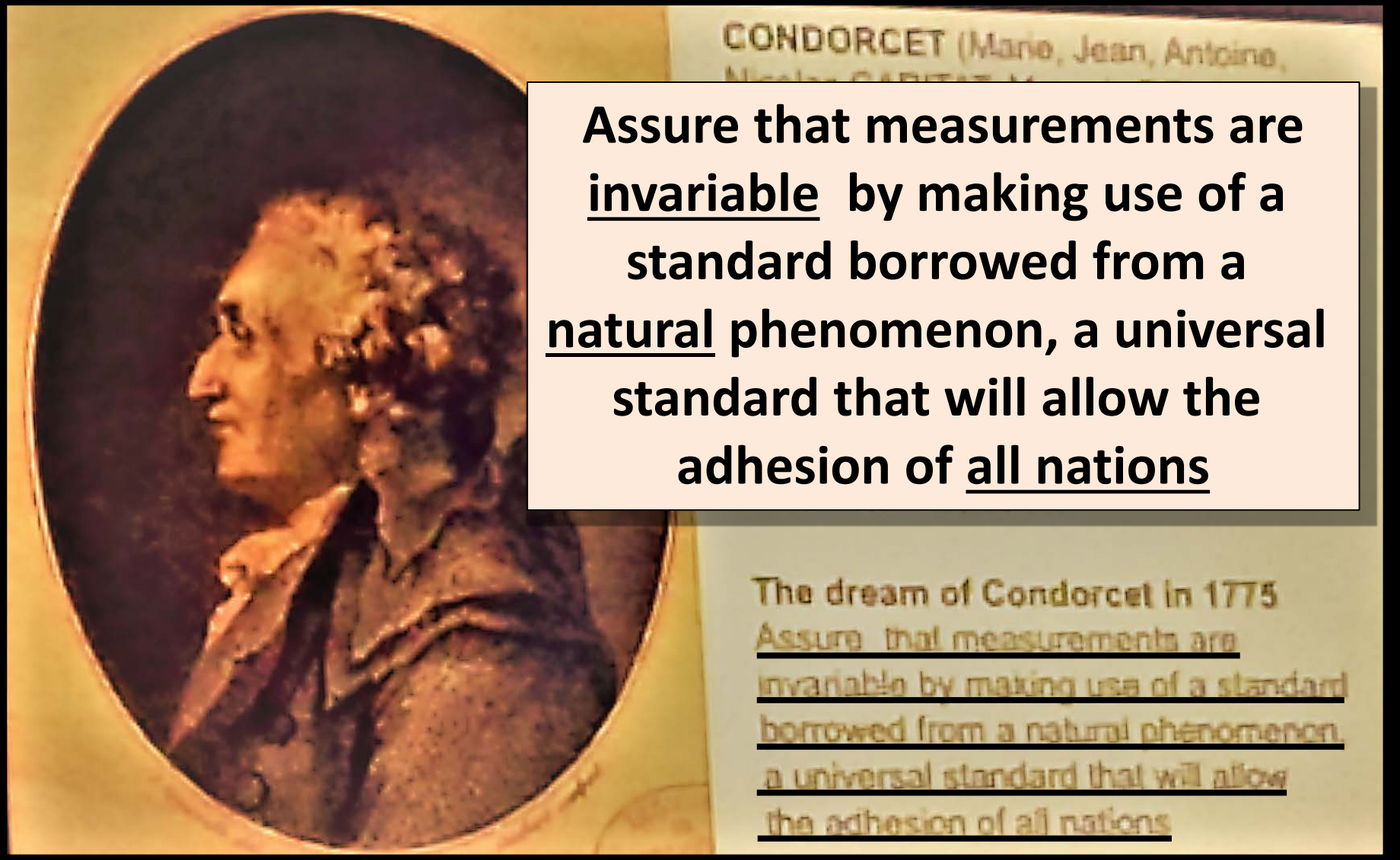
→ More than 40 different cubits

57.07 cm (Braunschweig) and 81 cm (Regensburg)

„technical obstacle“ for trade and manufacturing

Same unit –
different value

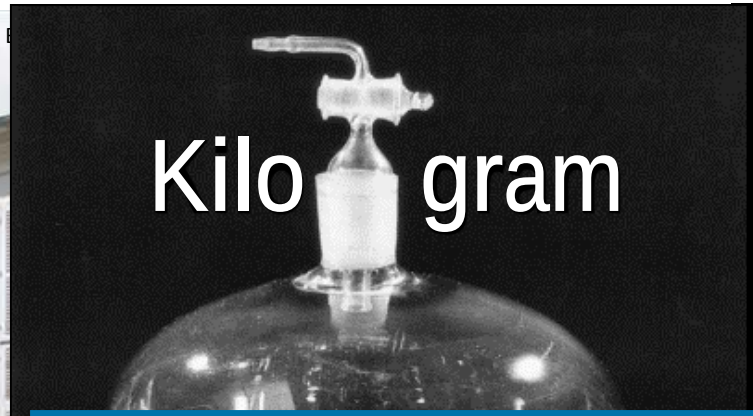
In France



Assure that measurements are <u>invariable</u> by making use of a standard borrowed from a <u>natural</u> phenomenon, a universal standard that will allow the adhesion of <u>all nations</u>

The French revolution, 1789

The Metre Convention 1875

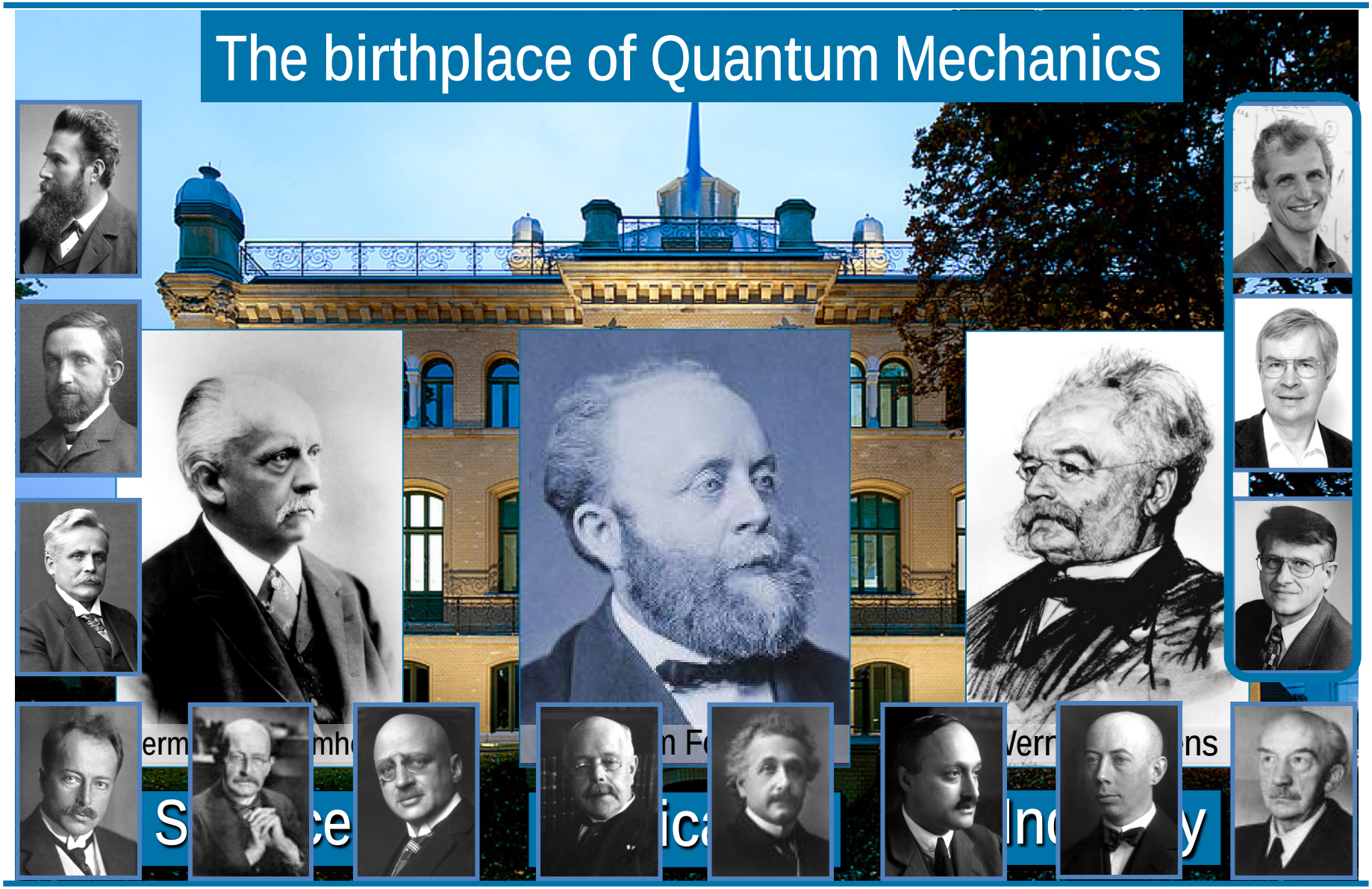


James Clark Maxwell (1870):

Definitions of the units are no true invariants since “….the properties of our planet can change and it would still be our planet, but if the properties of an atom were to change it would no longer be the same atom”

Understand “atoms” → Quantum Mechanics!

Physikalisch-Technische Reichsanstalt



The discovery of quantum mechanics

Physikalisches Kolloquium Heidelberg, 31/01/2020

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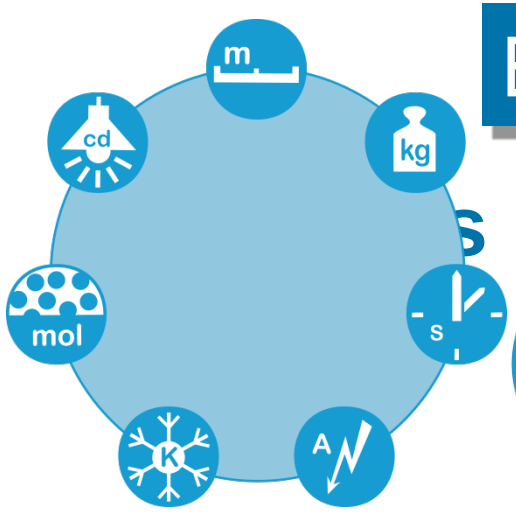
Linking the International System of Units to Fundamental Constants

1. The international system of units: SI
2. Defining constants for the revised SI
3. About the future of time

The International System of Units: SI

Established in 1960: CGPM



Name	Symbol	Name
length		metre
		second
		ampere
		kelvin
		mole
		candela

Le Système international d'unités
The International System of Units
SI

mass

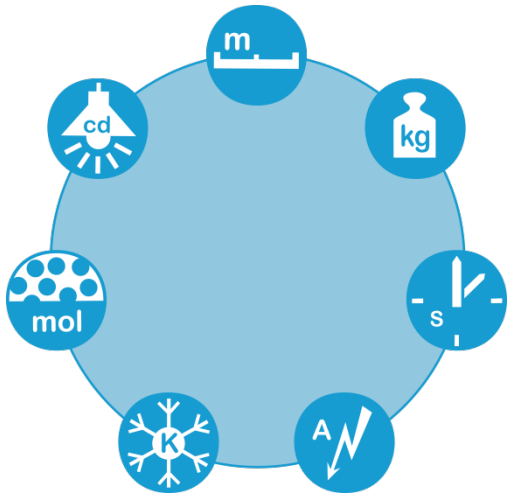
amount of substance

time

temperature

electric current

The International System of Units: SI



Base units

Derived units with special names

Dimensions of quantities

→ A set of coherent SI units

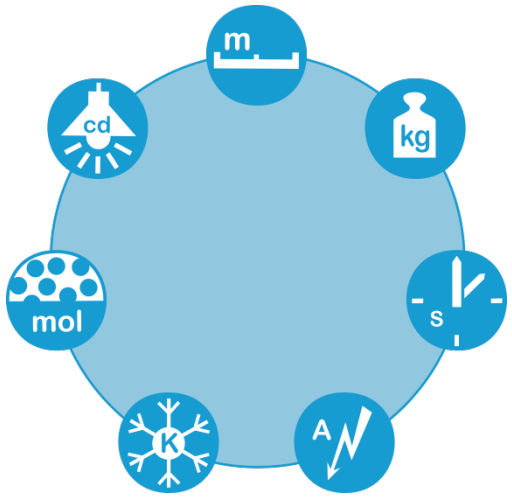
Derived units

$[v] = \mathrm{m\,s^{-1}}$

$[c] = \mathrm{mol\,m^{-3}}$

				SI base unit
			Expressed in terms of other SI units	Expressed in terms of SI base units
			1 (b)	m/m
			1 (b)	m^2/m^2
				s^{-1}
force	newton	N		$m\,kg\,s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1}\,kg\,s^{-2}$
energy, work, amount of heat	joule	J	N m	$m^2\,kg\,s^{-2}$
power, radiant flux	watt	W	J/s	$m^2\,kg\,s^{-3}$
electric charge, amount of electricity	coulomb	C		s A
electric potential difference, electromotive force	volt	V	W/A	$m^2\,kg\,s^{-3}\,A^{-1}$
capacitance	farad	F	C/V	$m^{-2}\,kg^{-1}\,s^4\,A^2$
electric resistance	ohm	Ω	V/A	$m^2\,kg\,s^{-3}\,A^{-2}$
frequency	hertz (d)	Hz		s^{-1}
force	newton	N		$m\,kg\,s^{-2}$
inductance	henry	H	Wb/A	$m^2\,kg\,s^{-2}\,A^{-2}$

The International System of Units: SI



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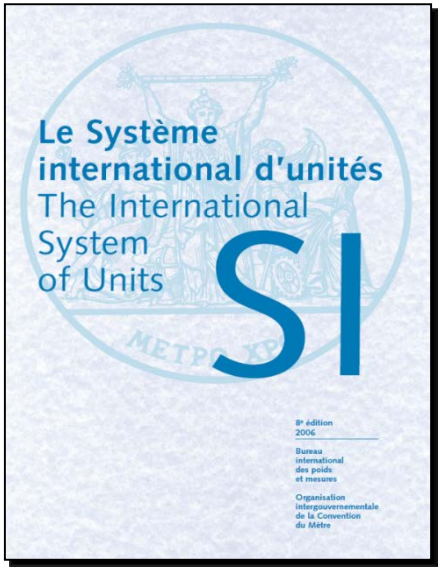
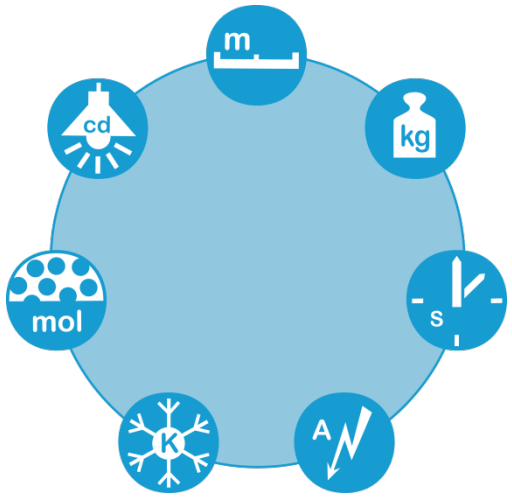
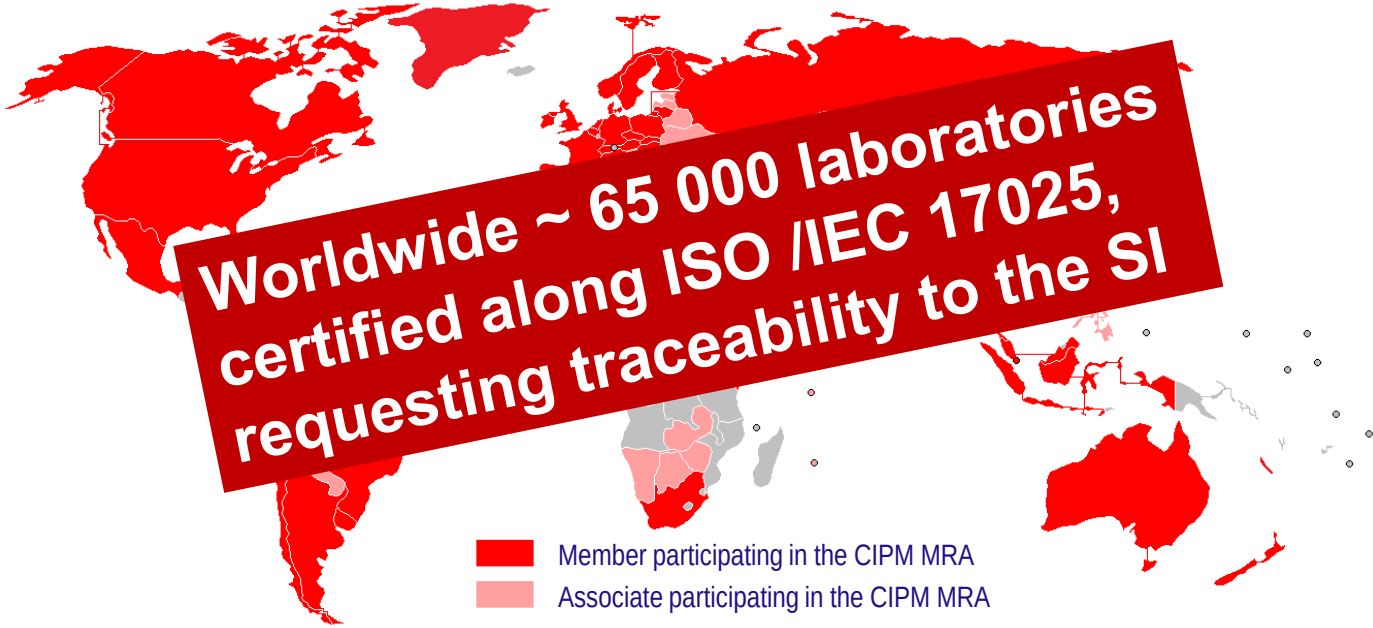
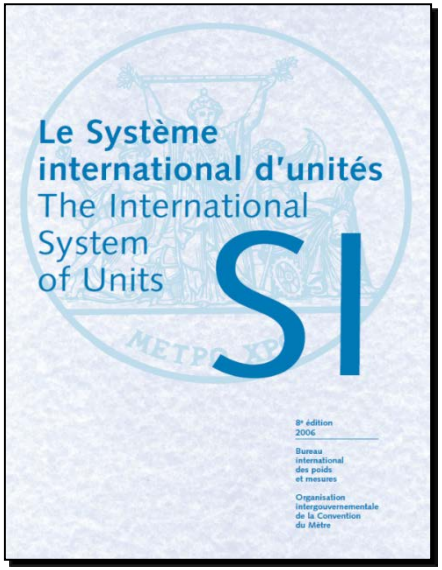


- A global measurement infrastructure
- Validity of light
  - Intensity of light from an LED
  - CO_2 concentration in the air
  - Creatinine concentration in blood serum
  - Dose equivalent outside nuclear reactors
  - ....

The International System of Units: SI







- A global measurement infrastructure
- Valid world wide: CIPM-MRA signed by
  - → 97.6 % of the world economy
  - → The cornerstone of international quality infrastructure (QI)

Quantities and measurement units

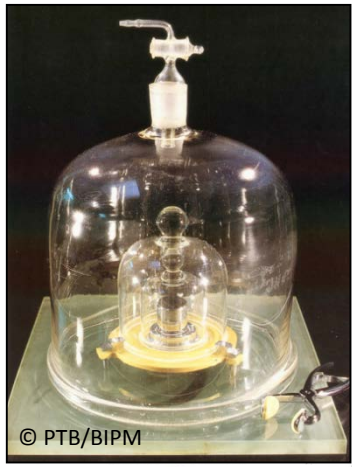
number

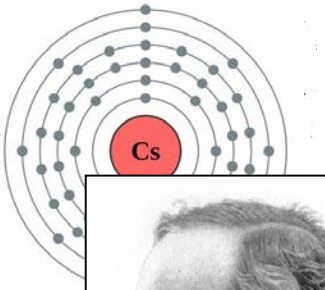
Value of a quantity → $Q = \{Q\}\ [Q]$ ← unit

artefact

$m = 10.1(2)\,\mathrm{kg}$

$t = 55.4(1)\,\mathrm{s}$





$\Delta\nu\,(^{133}\mathrm{Cs})_{\mathrm{hfs}} = 9\,192\,631\,770\ \mathrm{s}^{-1}$

Constant of nature

$$1\ \mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu\,(^{133}\mathrm{Cs})_{\mathrm{hfs}}}$$

"Take properties of atoms, not those of the Earth"

Define a unit by fixing the numerical value of a constant of nature

$$l_P = \sqrt{\frac{\hbar G}{c^3}} = 1.61 \cdot 10^{-31} m$$

$$m_P = \sqrt{\frac{\hbar c}{G}} = 2.17 \cdot 10^{-8} kg$$

$$t_P = \frac{l_P}{c} = 5.39 \cdot 10^{-44} s$$

$$T_P = \frac{m_P c^2}{k} = 1.41 \cdot 10^{32} K$$

von Max Planck.

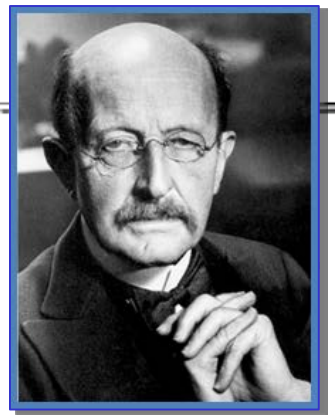
Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhülfenahme der beiden in dem Aus-

…with the help of fundamental constants we have the possibility of establishing units of length, time, mass, and temperature, which necessarily retain their validity for all times and civilisations, even extraterrestrial and nonhuman…

. 1900. № 1.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 1.



irreve[illegible]lungsvorgänge;

vo[illegible]c.

Dem gegenüber [illegible]ne Interesse sein zu bemerken, dass mit [illegible] beiden in dem Aus-

…with the help of fu[illegible]al constants we have the possibility of establishing units of length, time, mass, and temperature, which necessarily retain their validity for all times and civilisations,

…for all times and civilisations…

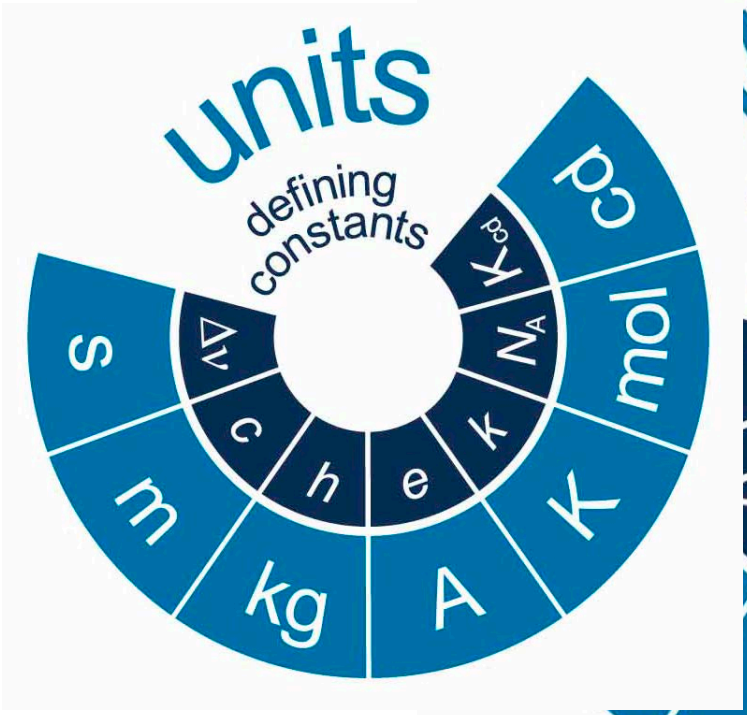
…throughout the Universe…

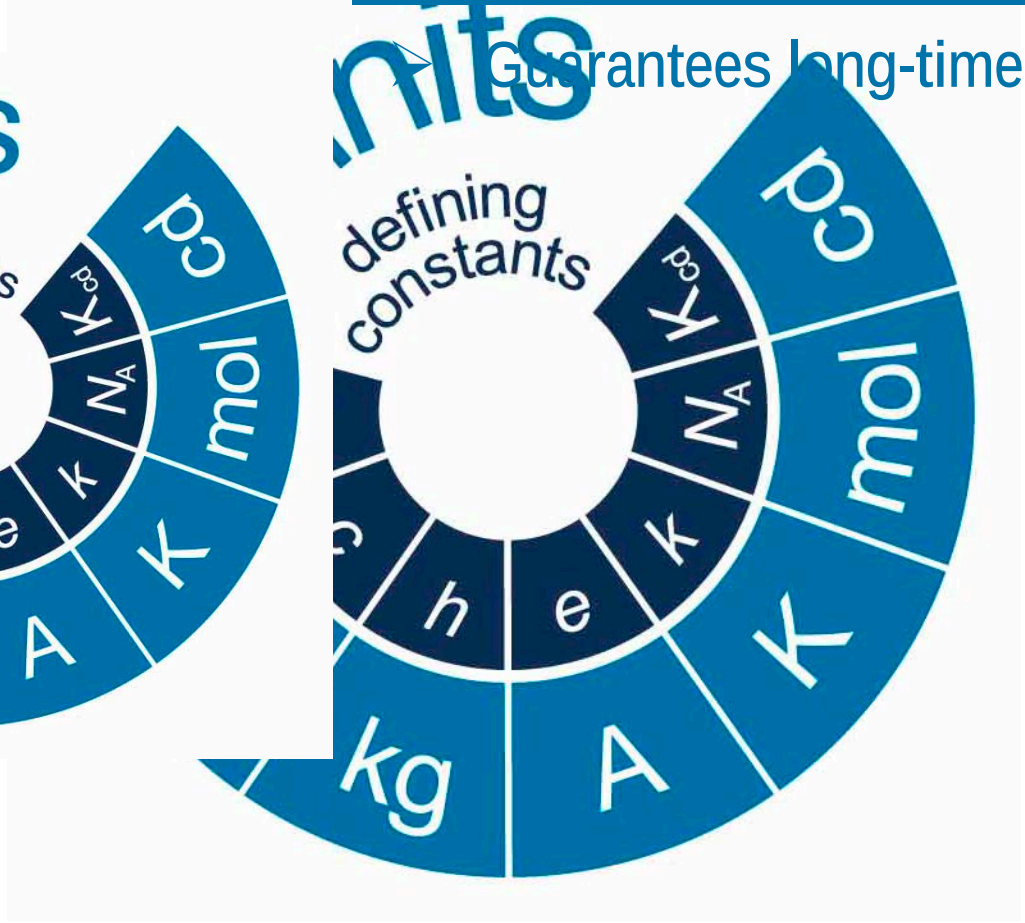
SI International System of Units

A consistent and coherent set:

based on our present understanding of nature

Revised International System of Units

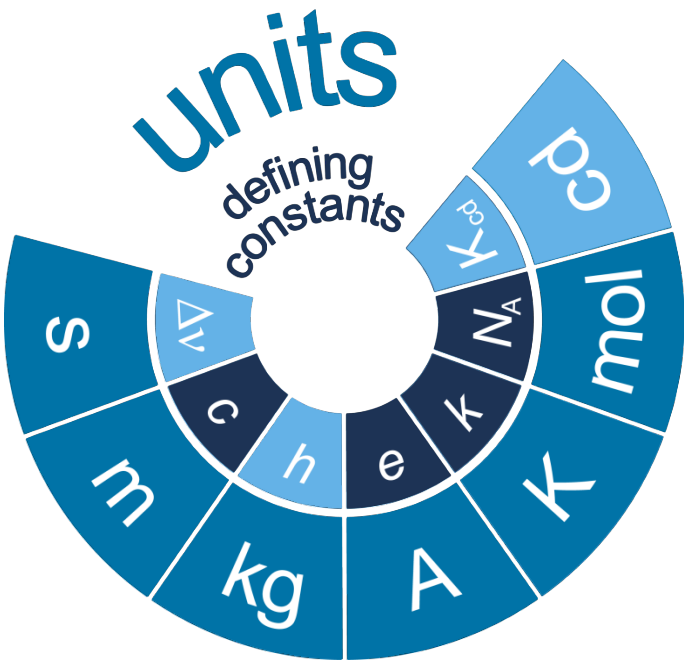




A concept improved fundamentally!

→ Guarantees long-time stability

Revised International System of Units

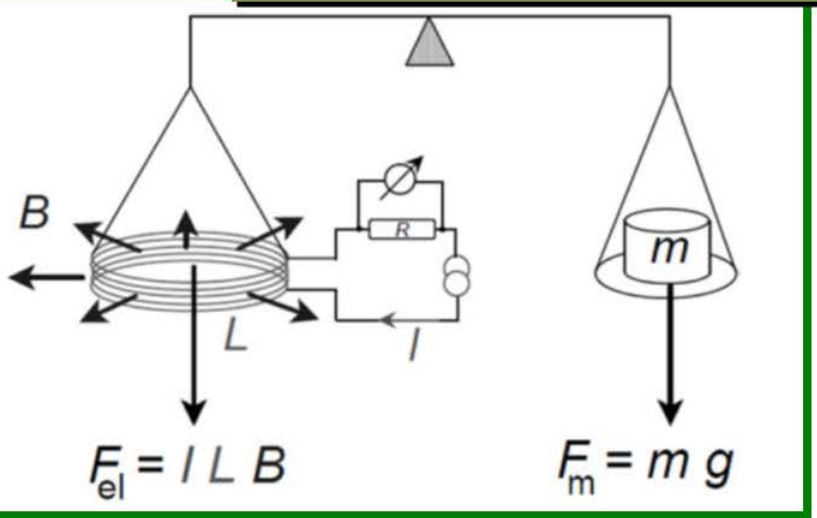


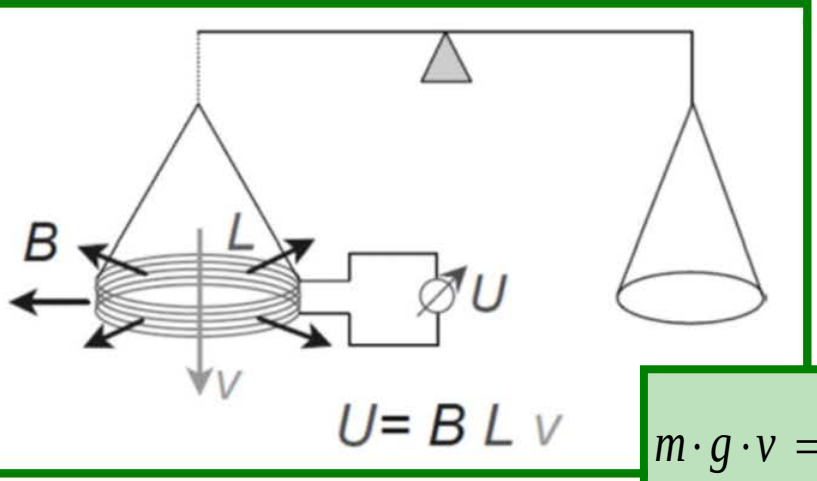
A concept improved fundamentally!

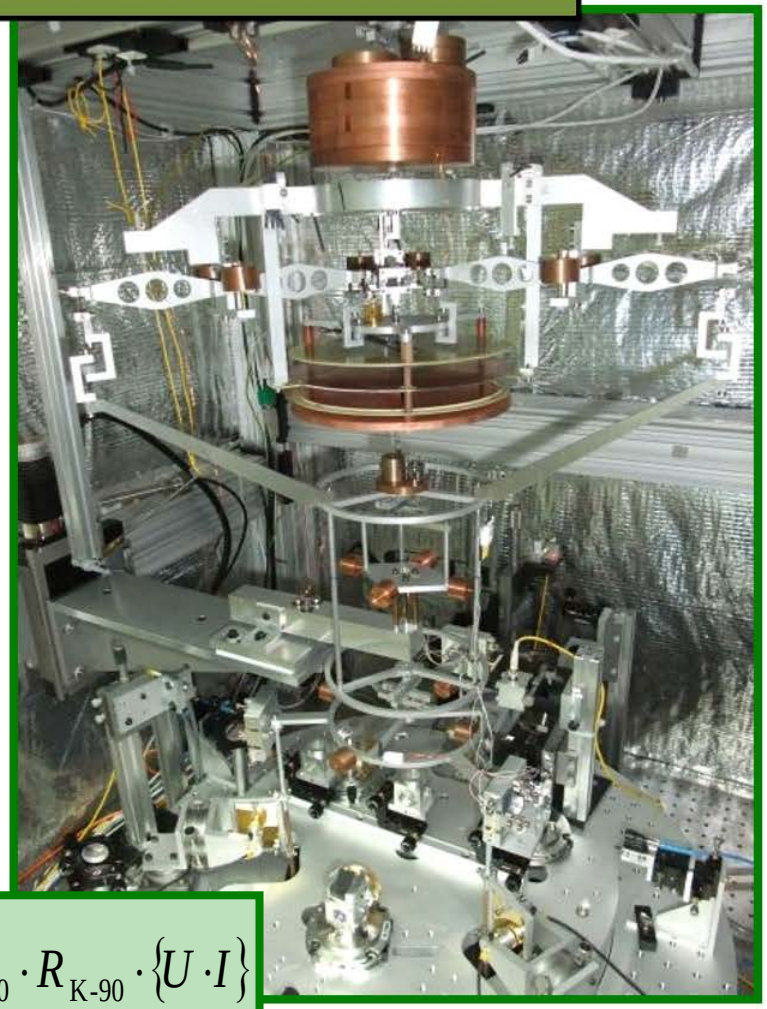
- Guarantees long-time stability
- A set of “defining constants” establish the units in general

Revised International System of Units

Watt balance or “Kibble” balance

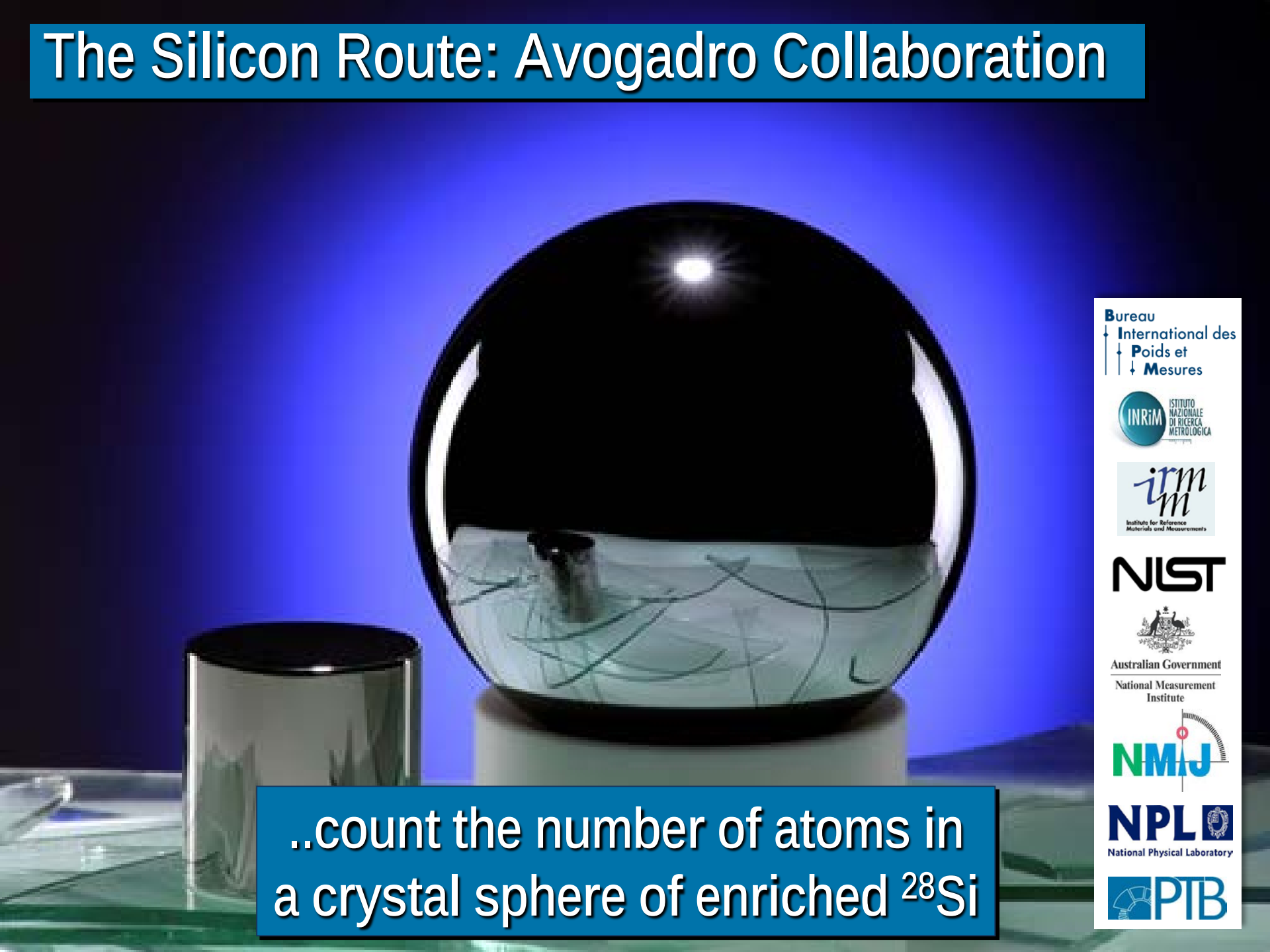






$$m \cdot g \cdot v = \frac{h}{4} K_{\text{J-90}}^2 \cdot R_{\text{K-90}} \cdot \{U \cdot I\}$$

The Silicon Route: Avogadro Collaboration



..count the number of atoms in a crystal sphere of enriched ^{28}Si

Bureau International des Poids et Mesures

INRiM Istituto Nazionale di Ricerca Metrologica

irmm Institute for Reference Materials and Measurements

NIST

Australian Government National Measurement Institute

NMIJ

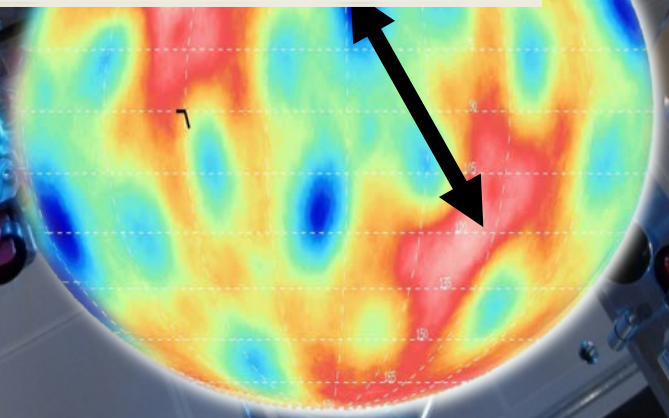
NPL National Physical Laboratory

PTB

The Silicon Route

2 m peak-to-valley

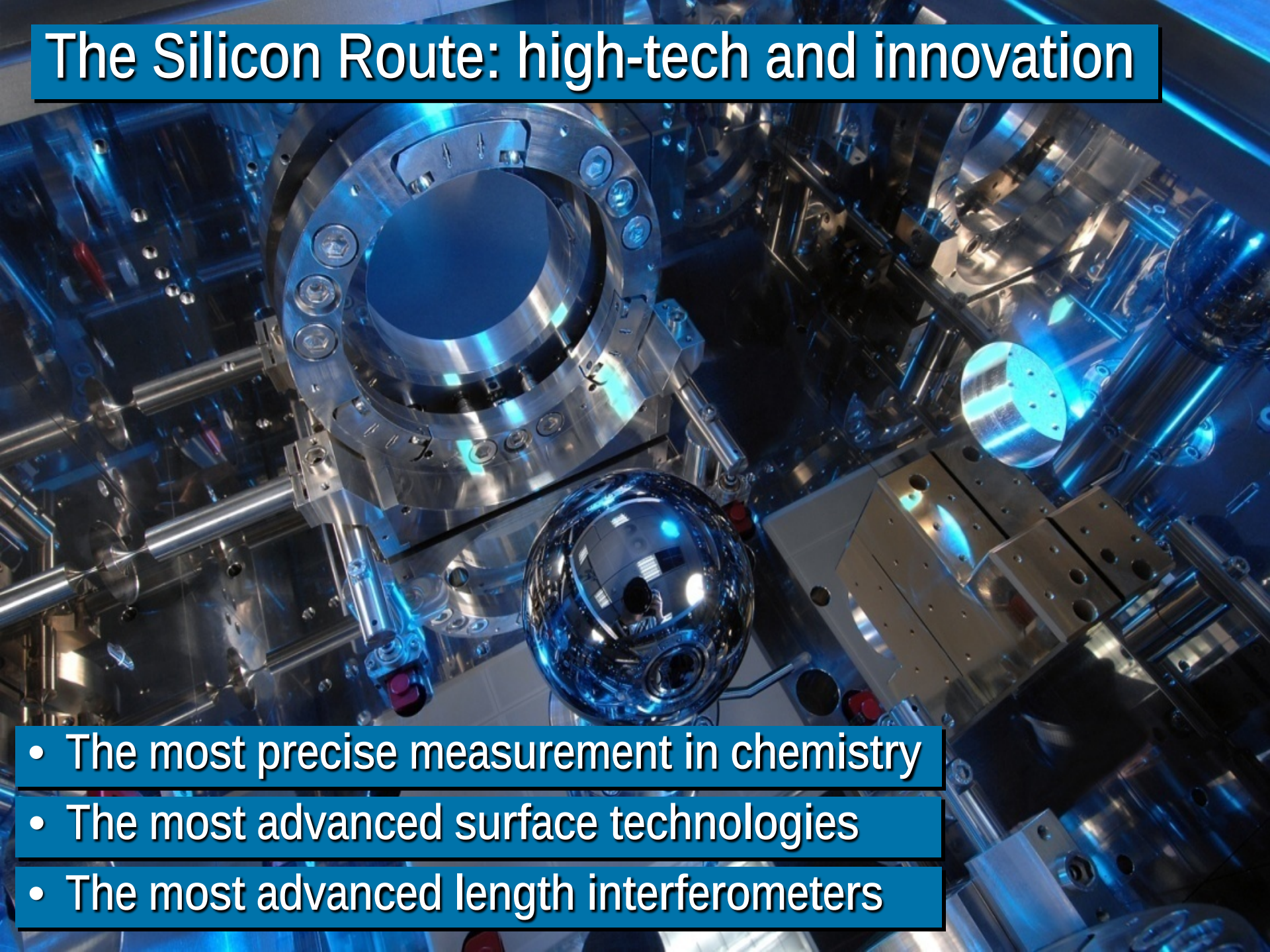
quantum theory of the hydrogen atom



≅ 6000 km

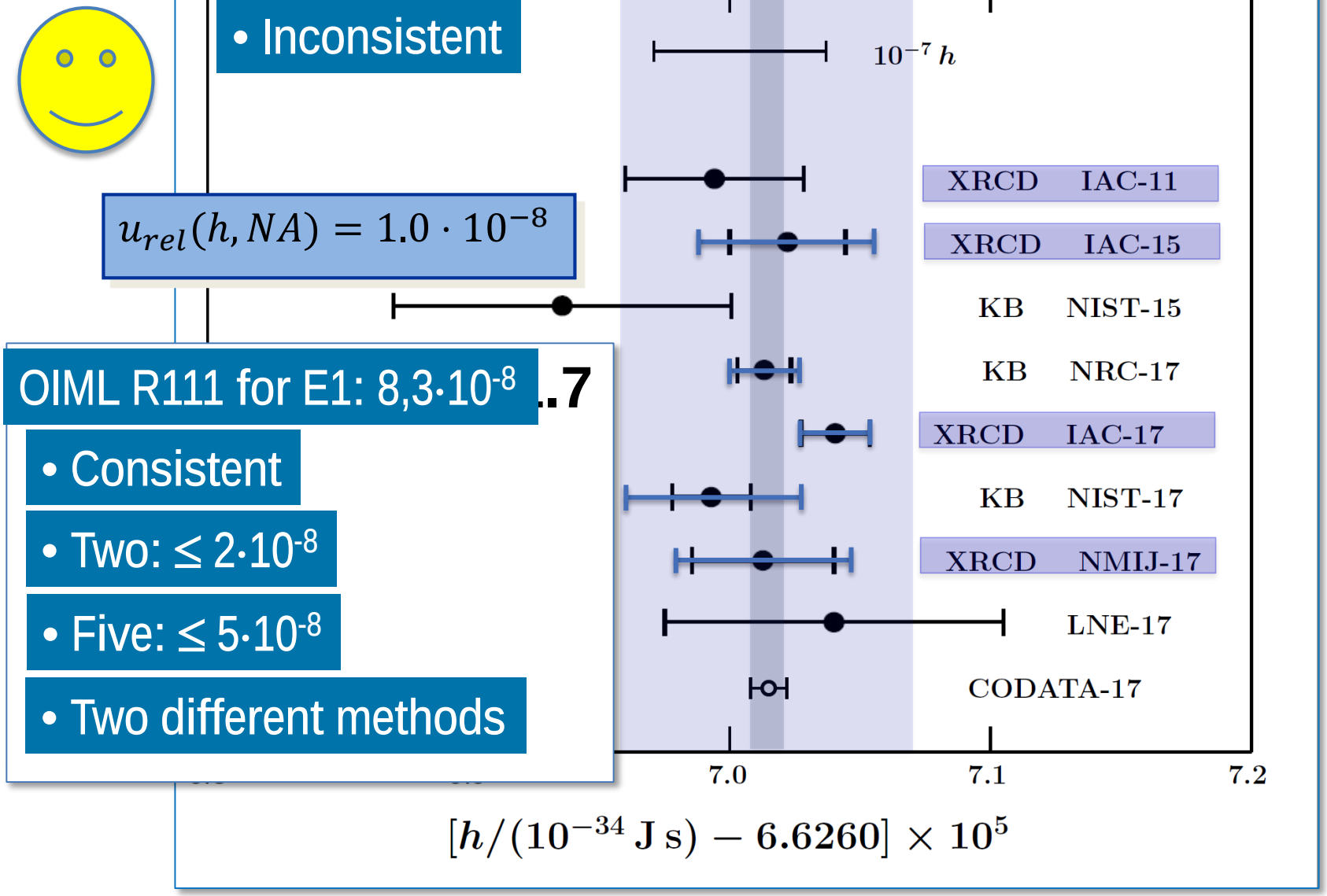
Deviation in sphere radius: 16 nm (peak-to-valley)

The Silicon Route: high-tech and innovation



- The most precise measurement in chemistry
- The most advanced surface technologies
- The most advanced length interferometers

Revised International System of Units



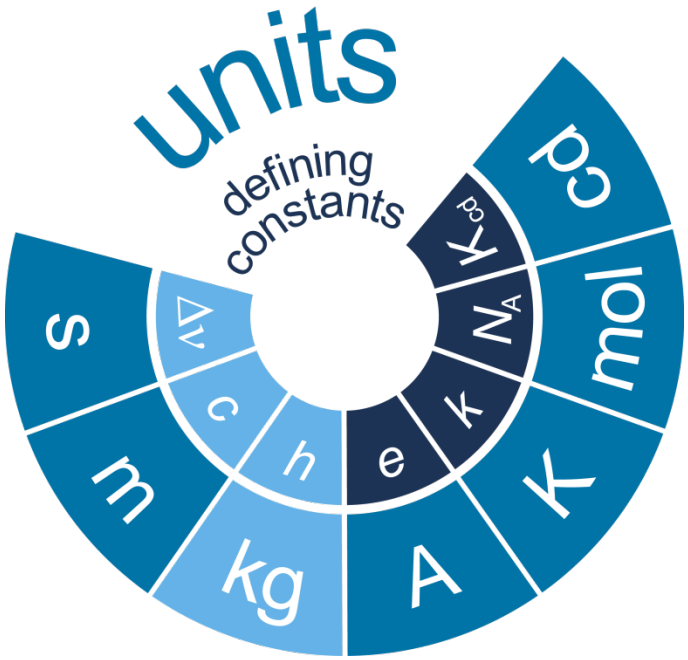
- Inconsistent

$u_{rel}(h, NA) = 1.0 \cdot 10^{-8}$

OIML R111 for E1: 8,3·10^{-8}

- Consistent
- Two: ≤ 2·10^{-8}
- Five: ≤ 5·10^{-8}
- Two different methods

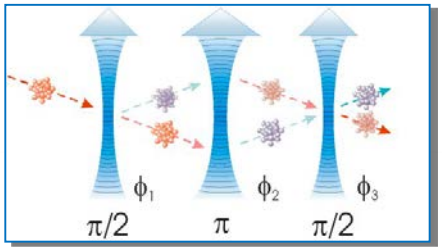
Revised International System of Units



A concept improved fundamentally!

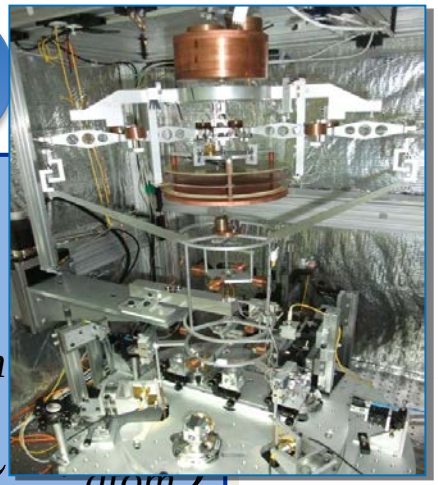
- Guarantees long-time stability
- A set of “defining constants” establish the units in general
- Different realisations
  - Key comparisons: safer, less correlation
- Realisation everywhere (Universe…)
  - Atomic masses

“De Broglie”



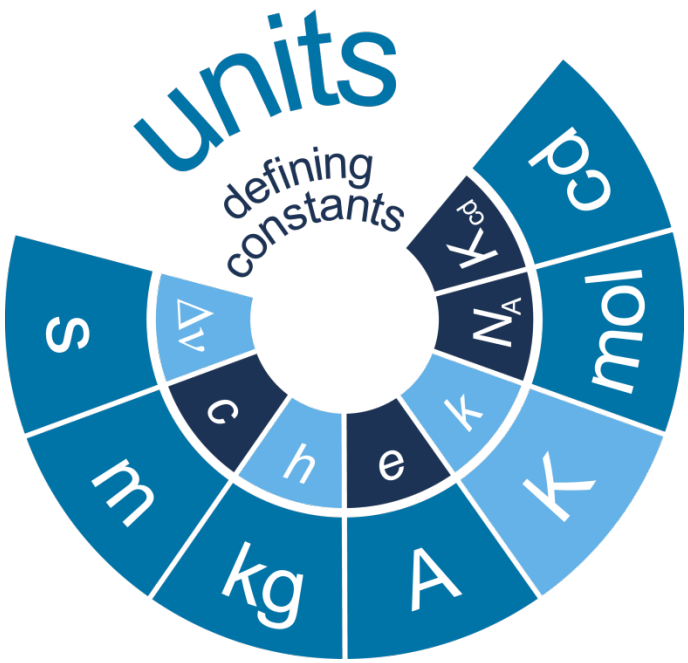
“Photon recoil”

“Silicon crystal”



“Watt balance”

Revised International System of Units



$$E = \frac{1}{2} k\ T$$

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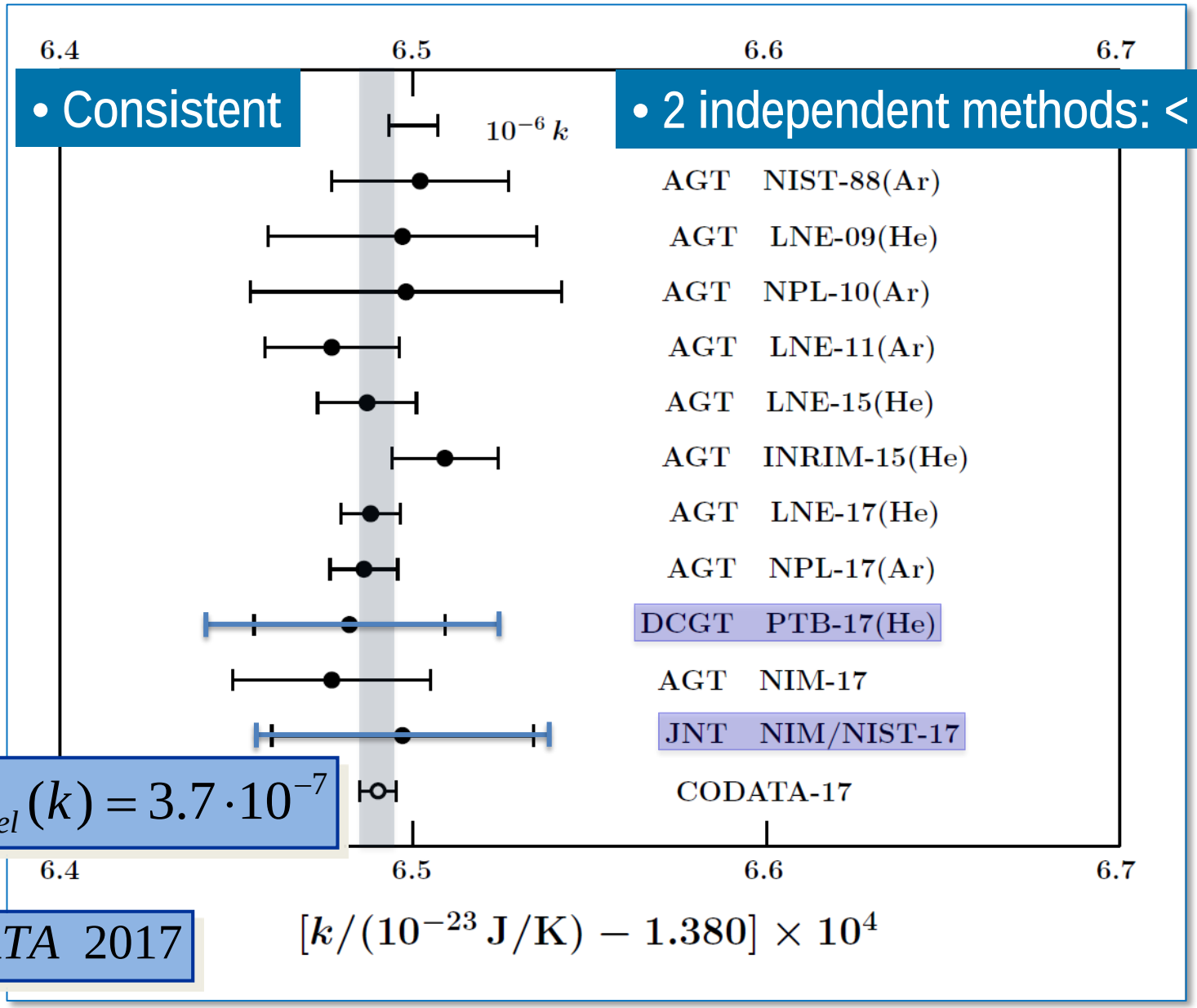
- Realisation everywhere (Universe…)
- Throughout the entire scale
  - Acoustic gas thermometry
  - Dielectric constant gas thermometry
  - Doppler thermometry
  - Noise thermometry
  - Radiation thermometry

Revised International System of Units

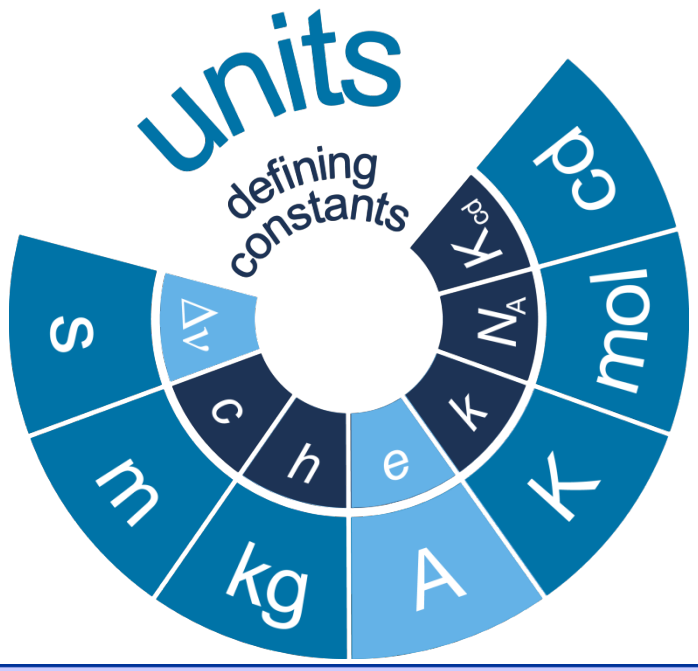


- Consistent
- 2 independent methods: < $3 \cdot 10^{-6}$

$u_{rel}(k) = 3.7 \cdot 10^{-7}$

CODATA 2017

Revised International System of Units



$$R_K = \frac{h}{e^2} \approx 25\,813\ \Omega \Leftrightarrow \cancel{R_{K-90}}$$

$$K_J = \frac{2e}{h} \approx 483\,598\ GHz/V \Leftrightarrow \cancel{K_{J-90}}$$

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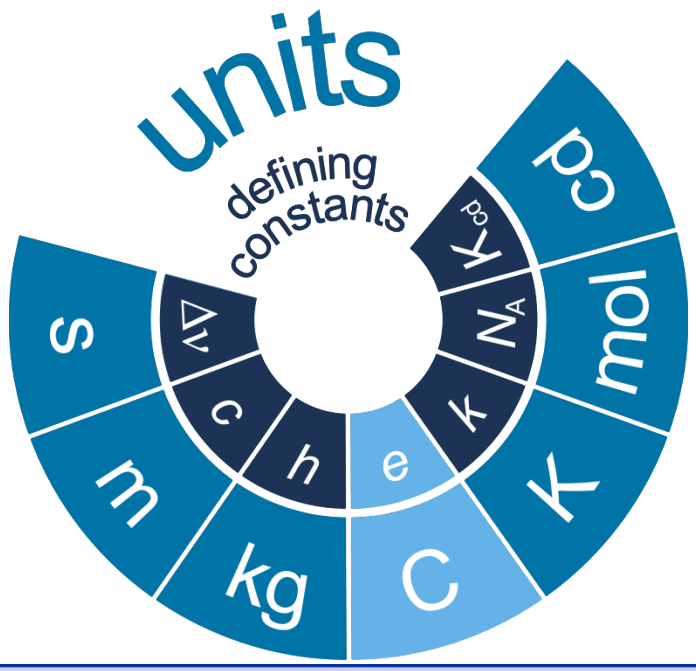
- Electrical units are back in the SI

Revised International System of Units



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- Base units are only a convention
- Innovation: research & industry

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$K_J = \frac{2e}{h} \approx 483\,598\,GHz/V \Leftrightarrow K_{J-90}$

- Commercial Watt balance
- Johnson noise thermometry
- Single Electron Tunneling devices
- QH in graphene, QHE in topological insulators

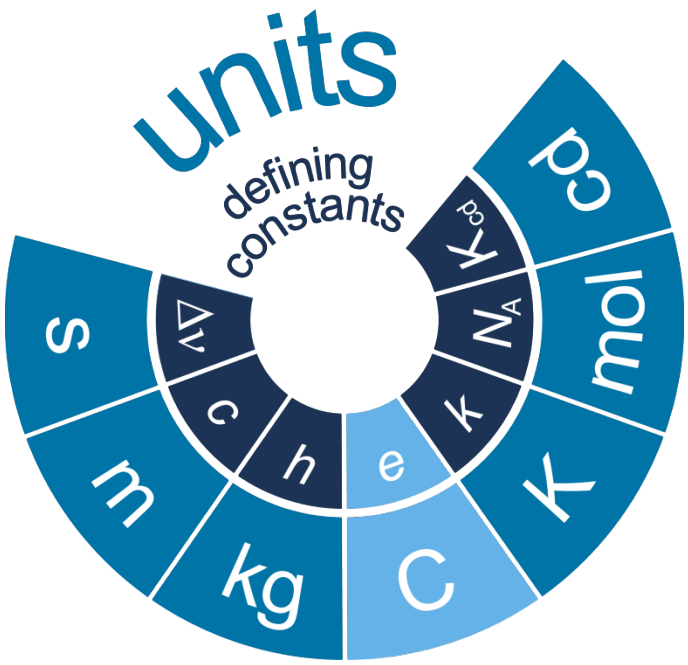
Commercial Watt balance: Planck Balance

Commercial Kibble Balances

- “self-calibrating”
- high precision
- industrial application: E1, E2
- “off-the-shelve” components
- connected to the IoT

Version	Mass range	MPE OIML R111-1	$U_r \leq 1/3 \cdot MPE$ $k=2$	Environment
PB 2 (E2)	1 mg…100 g	$16 \cdot 10^{-7}$	$5.3 \cdot 10^{-7}$	Air
PB 1 (E1)	1 mg…1 kg	$5 \cdot 10^{-7}$	$1.7 \cdot 10^{-7}$	High Vacuum

Revised International System of Units



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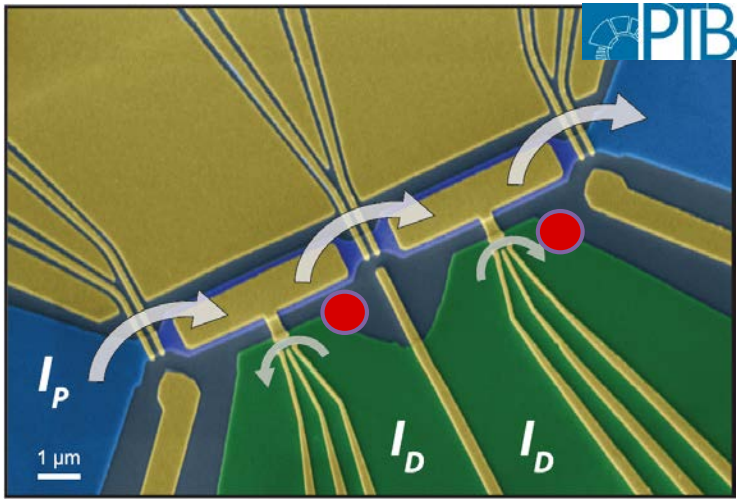
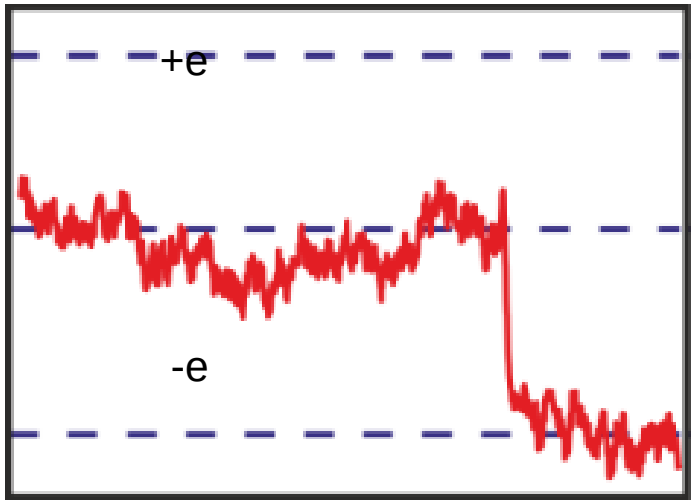
Single Electron Tunneling devices

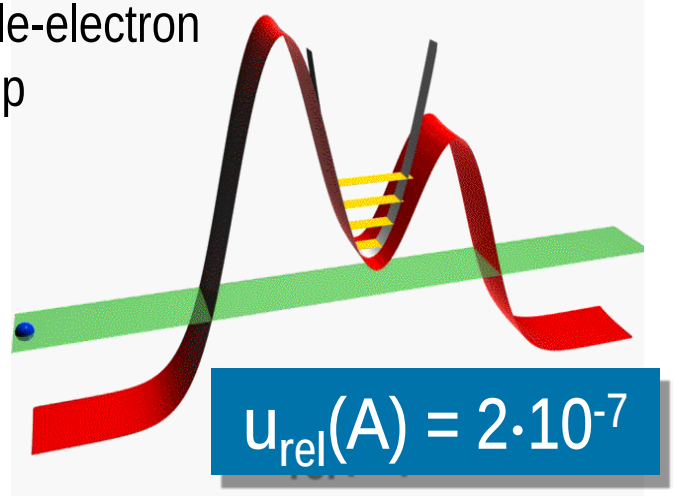
Self-referenced noise-free electrical current





single-electron detection

single-electron pump



$u_{rel}(A) = 2 \cdot 10^{-7}$

Future applications

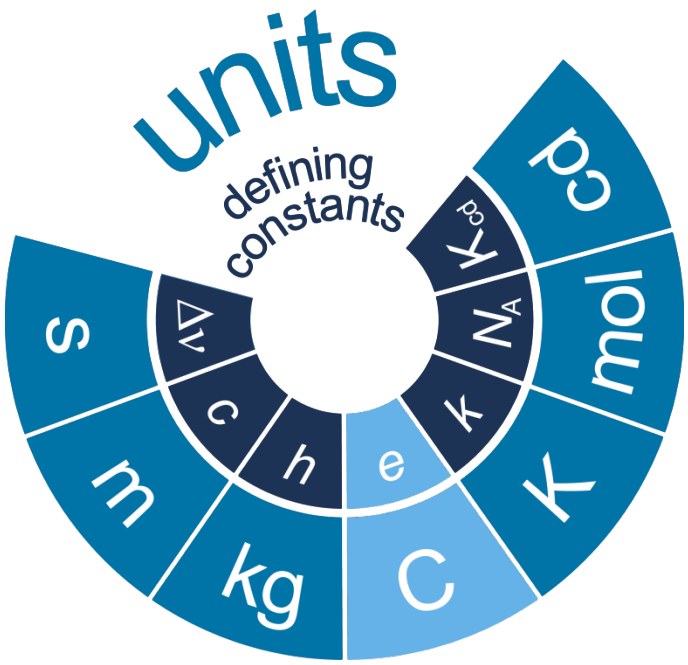
→ Shot-noise-free electronics

→ Quantum (spin)electronics

→ Photonic technologies

→ Quantum information

Revised International System of Units



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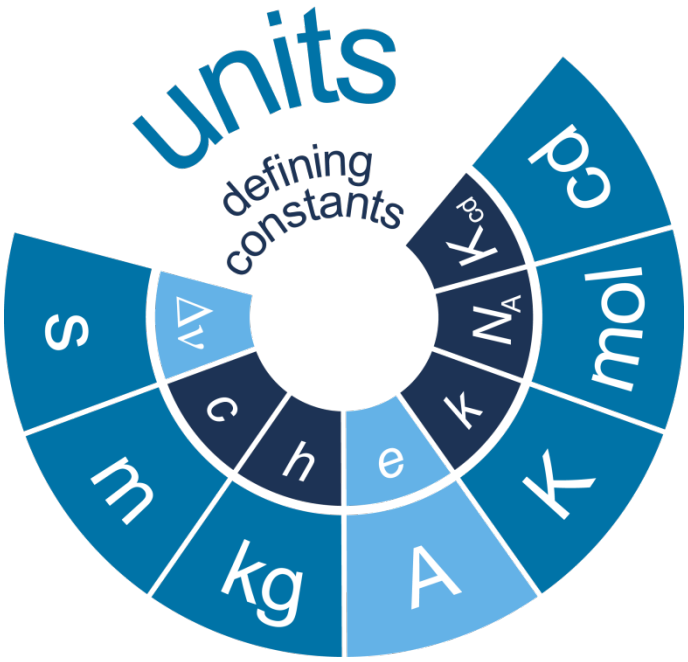
Revised International System of Units

Tremendous benefits:



a “huge” change…
but “no” change!

A concept improved fundamentally!

- Guarantees long-time stability
- A set of “defining constants” establish the units in general
- Different realisations
- Realisation everywhere (Universe…)
- Throughout the entire scale
- Electrical units are back in the SI
- Base units are only a convention
- Innovation: research & industry
- Better experiment → better realization

Ensure continuity, harmonization, stability

SI International System of Units

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.

26th CGPM Meeting, Versailles, 16.11.18

A historic event!

World metrology day celebration

Deutsches Museum

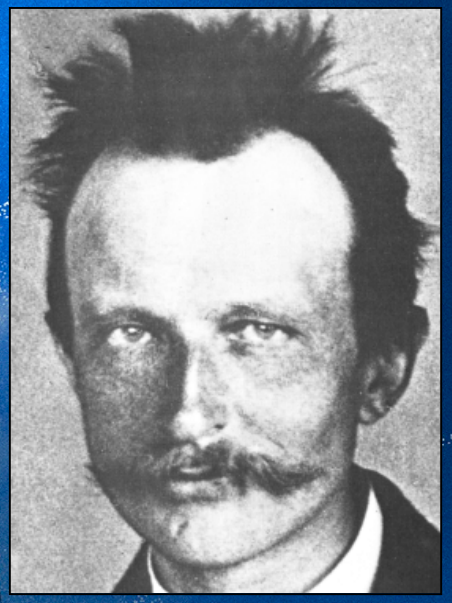
PTB

In force since: World Metrology Day 2019

SI International System of Units

…approaching the most abstract definition of units...

SI International System of Units

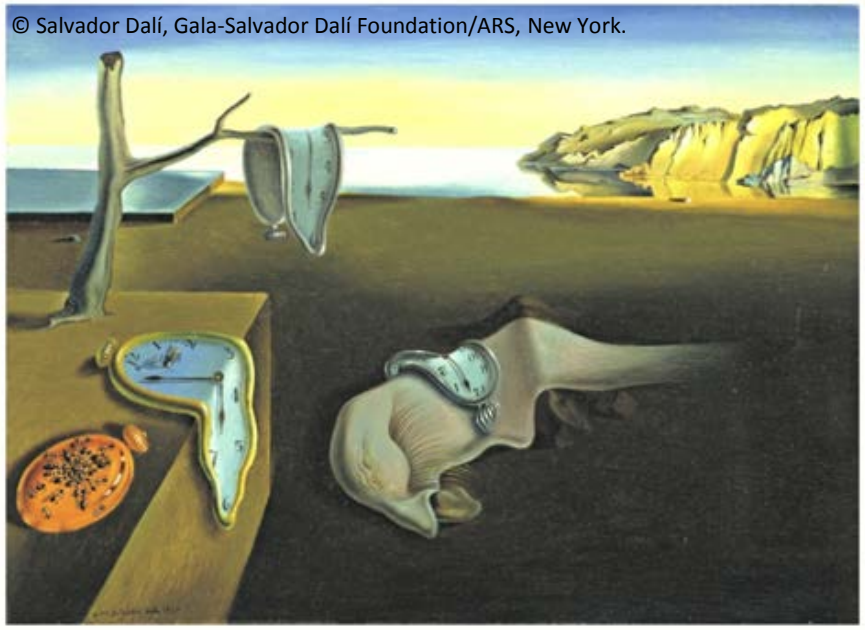


And what about the second?

For all times and cultures

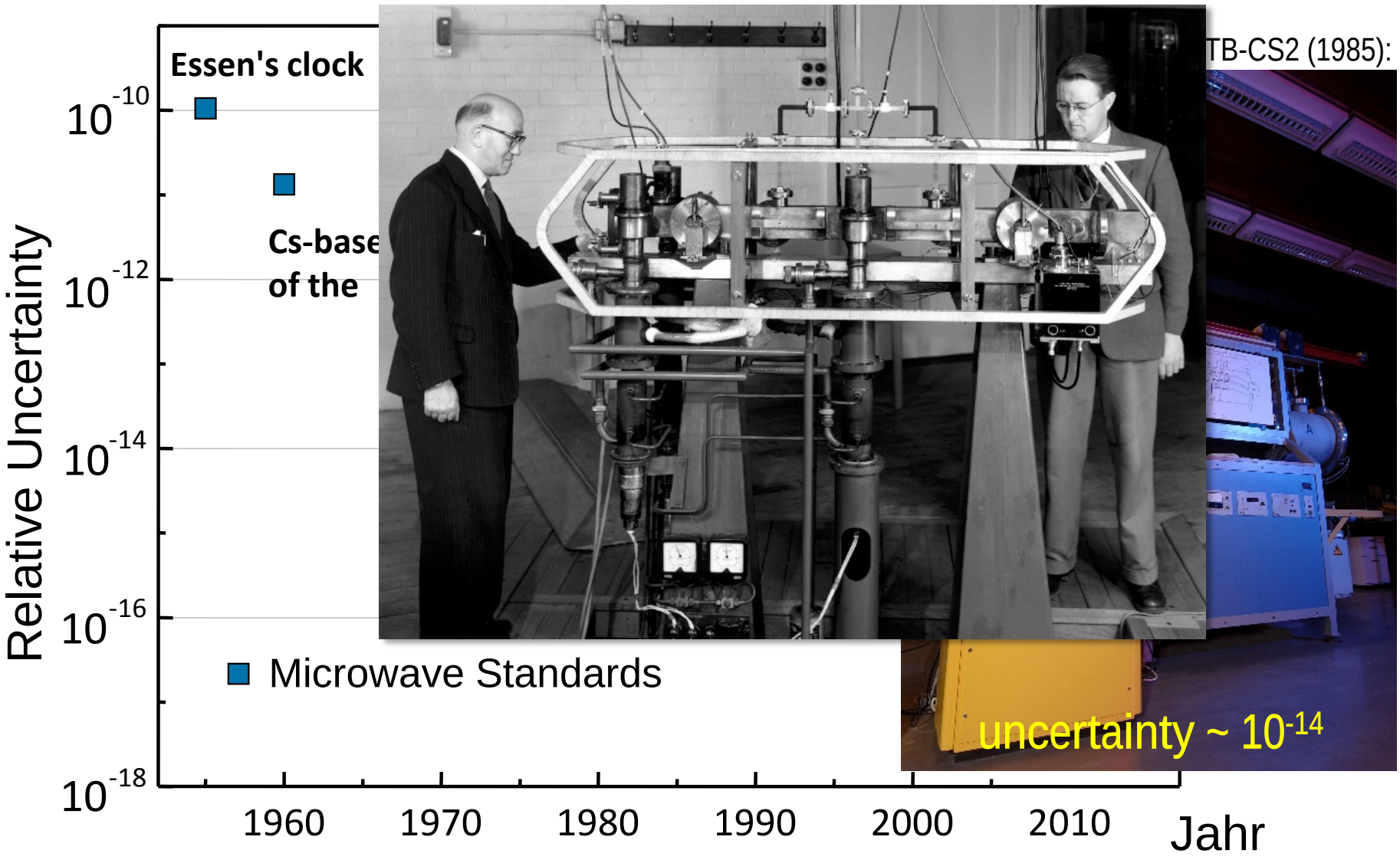
Throughout the Universe….

Linking the International System of Units to Fundamental Constants



1. The int its: SI
2. Definir sed SI
3. About

About the future of time



The Magneto-Optical Trap (MOT)

→ 3D trapping and cooling

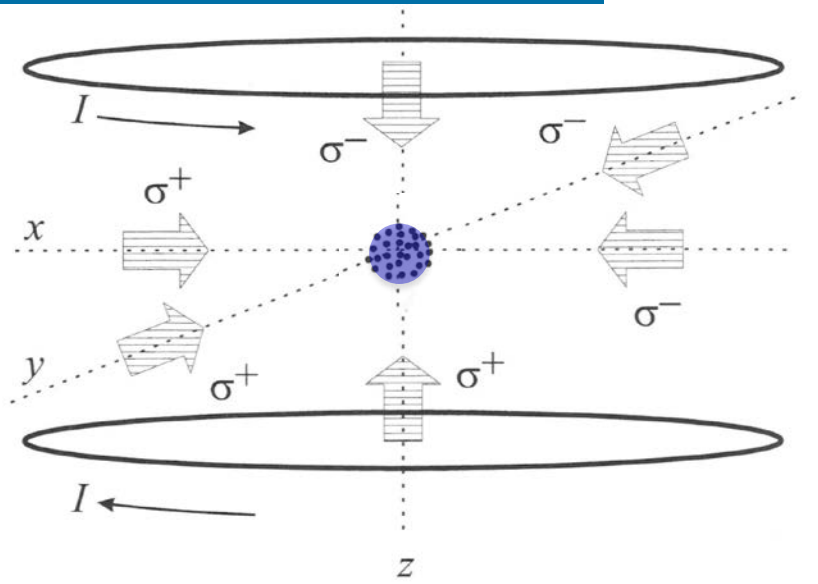


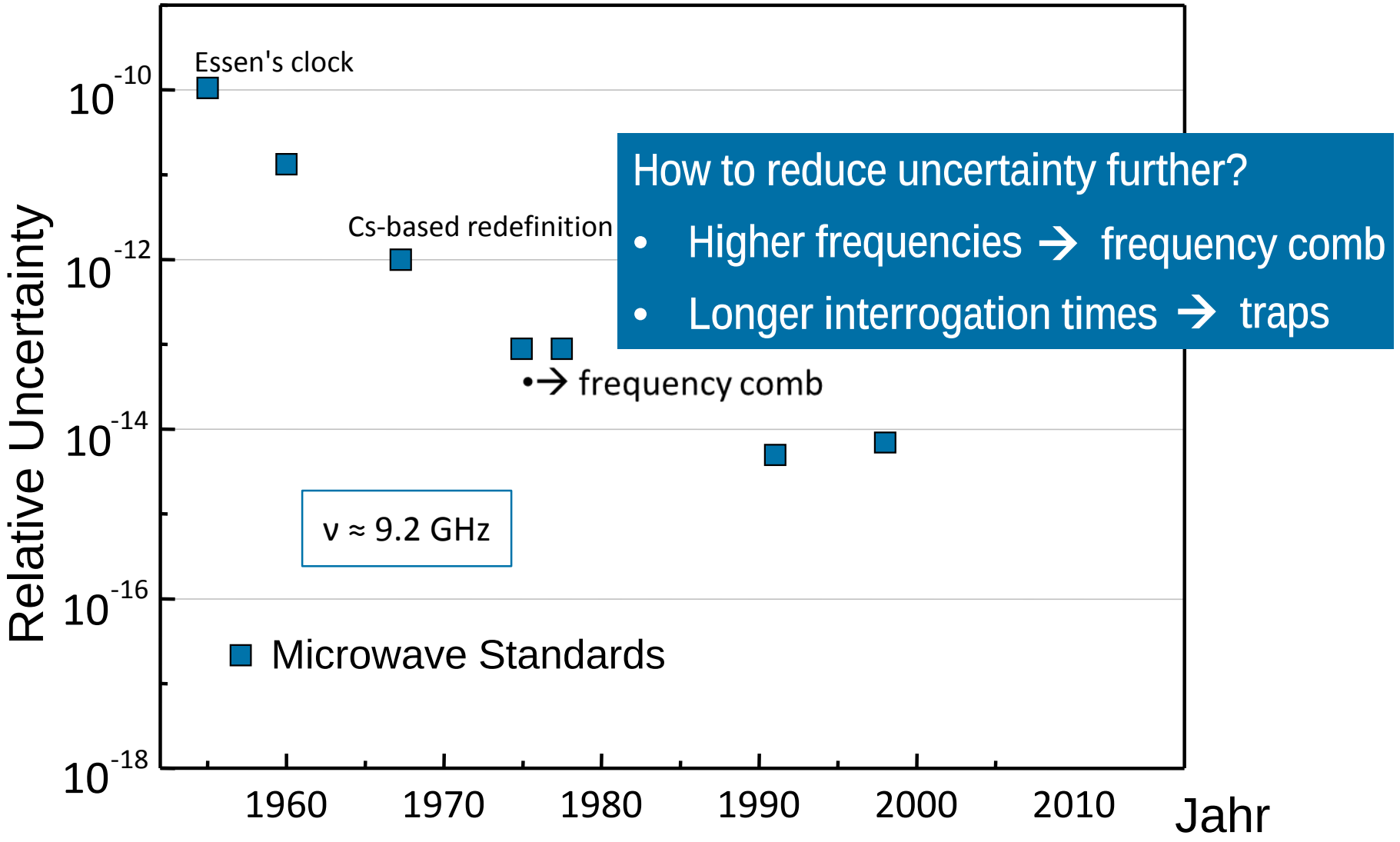
figure from F. Riehle,
Frequency Standards, Wiley-VCH

- 3 orthogonal pairs of counter-propagating laser beams
- a spherical quadrupole magnetic field (pair of anti-Helmholtz coils)

→ harmonic potential for trapping the atoms

→ Atomic fountain clock

About the future of time



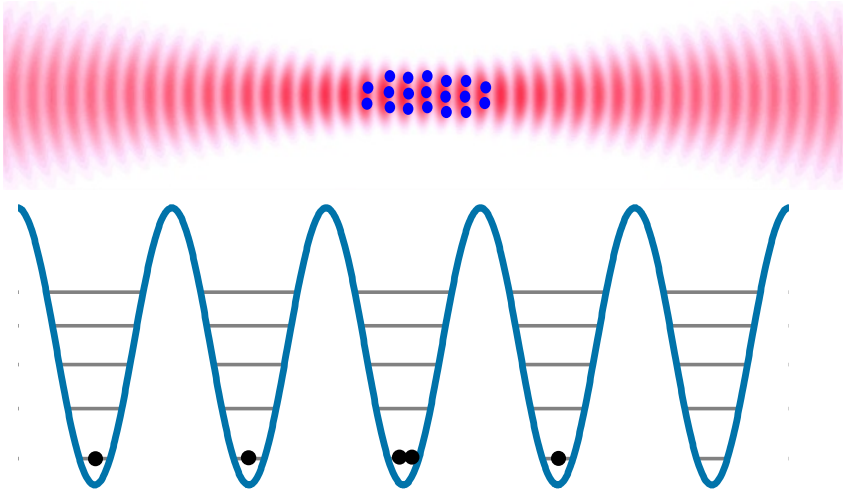
How to reduce uncertainty further?

- Higher frequencies → frequency comb
- Longer interrogation times → traps

Traps for clocks

Atom traps

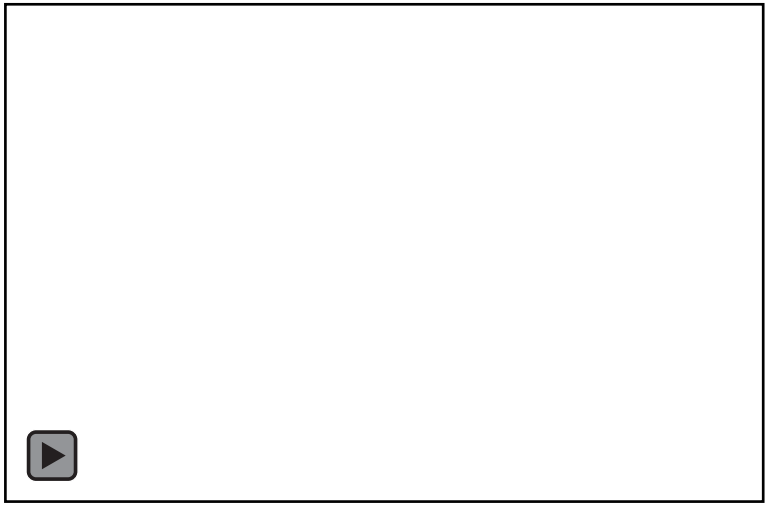
- Large number of atoms (n ~ 10^3 - 10^5)
  → High stability
- Optical lattice → Strong confinement
- "Magic" Wavelength
  → Suppress frequency shift of clock transition



Ion traps

- Uses RF-quadrupole-fields
- trap with electric fields
  → Charged particles interact strongly with environment
- large trap depth:
  → storage times: days/months

Wolfgang Paul
1913 – 1993
Nobel prize 1989



Ponderomotive Potential

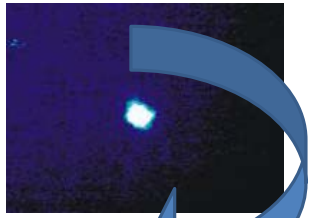
Traps for clocks

Atom traps

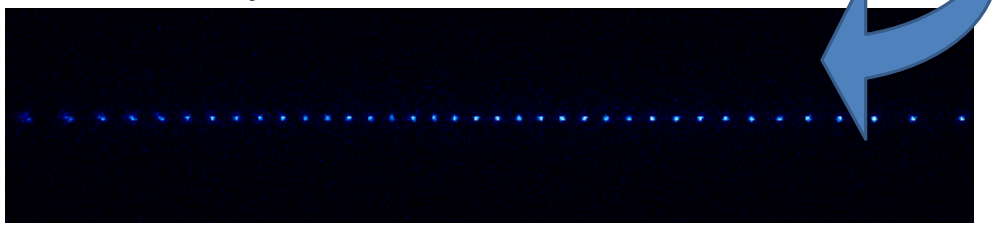
- Large number of atoms (n ~ 10^3 - 10^5)
  → High stability
- Optical lattice → Strong confinement
- "Magic" Wavelength
  → Suppress frequency shift of clock transition

Multi-ion traps

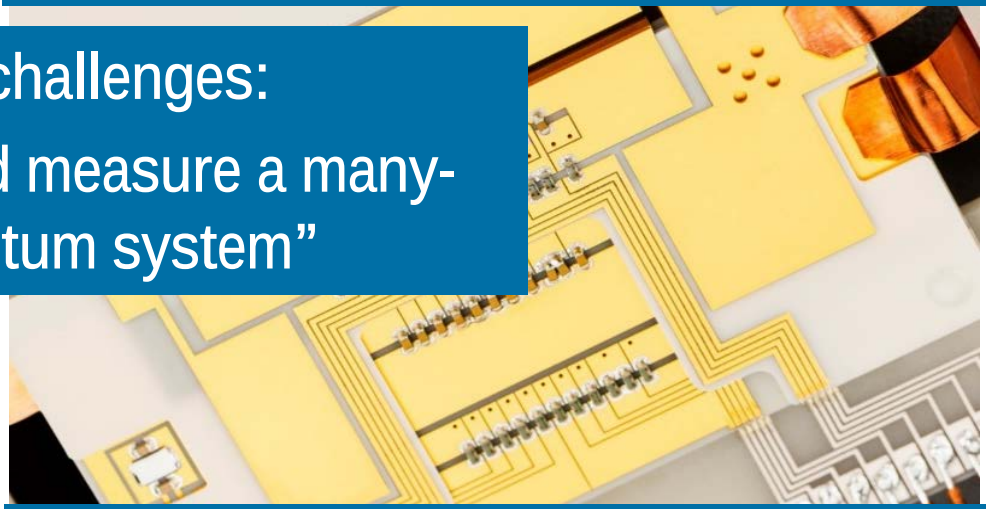
1 Yb^+ ion



Coulomb crystal of 37 Yb^+ ions

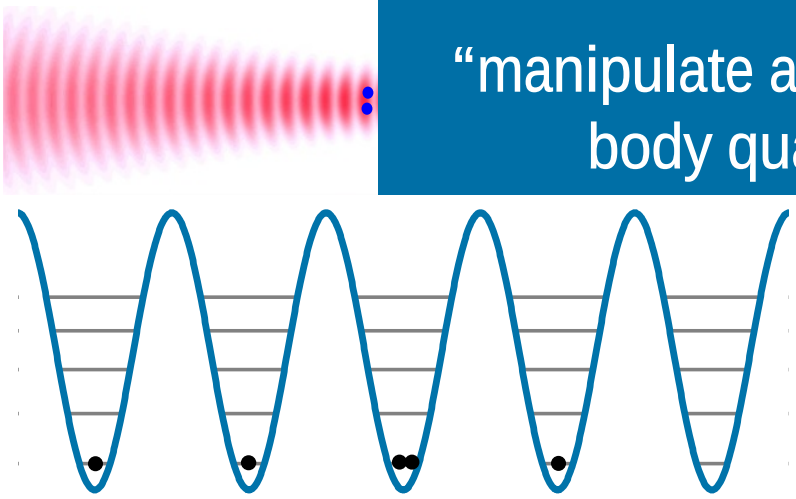


Segmented multi-ion traps: >100 ions



Further challenges:

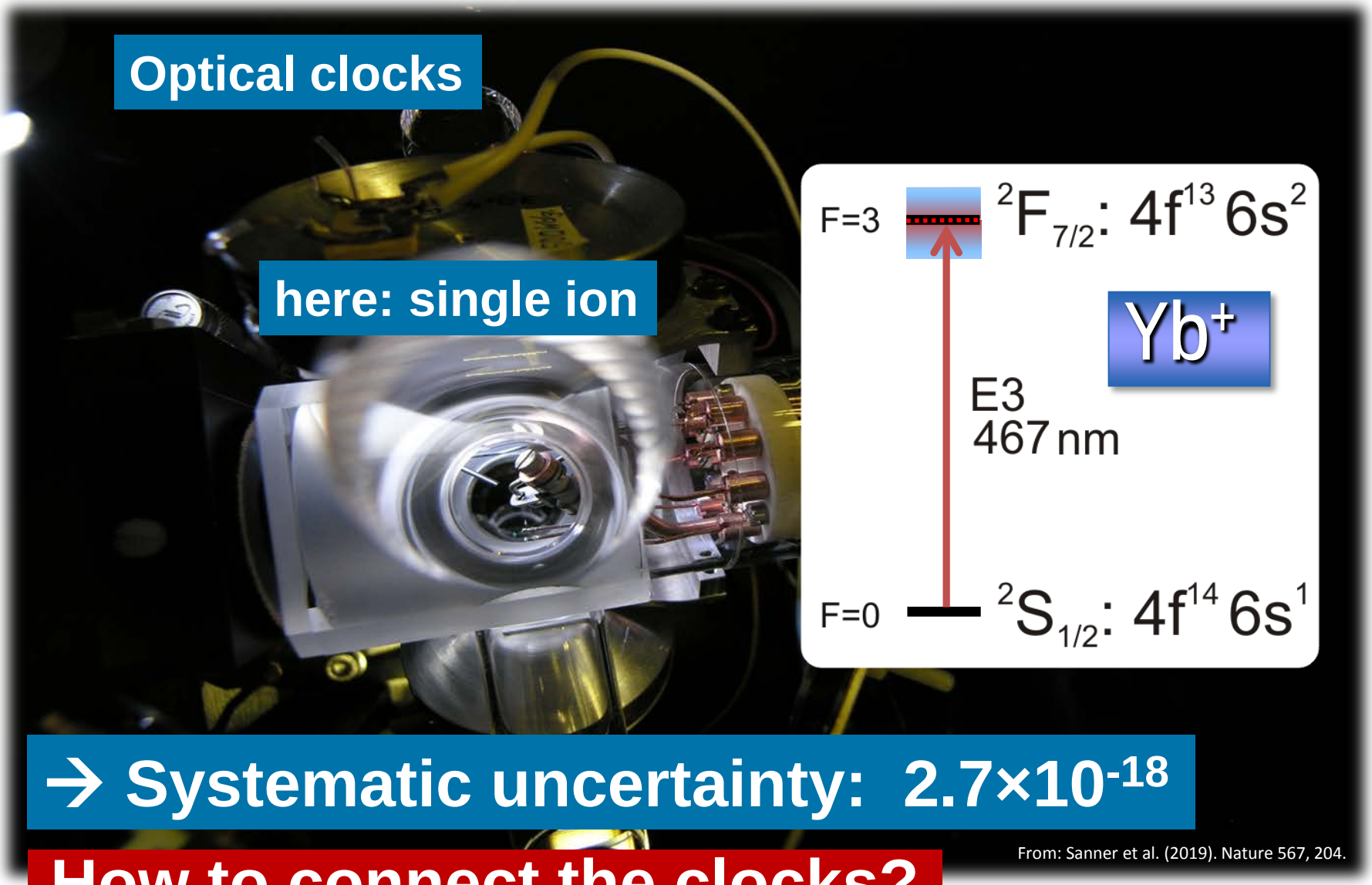
"manipulate and measure a many-body quantum system"



→ Entangled ions in multi-ion traps…

level in linear Coulomb crystals") Keller et al., PRA 99, 1 (2019)

About the future of time at PTB



→ Systematic uncertainty: 2.7×10^{-18}

From: Sanner et al. (2019). Nature 567, 204.

How to connect the clocks?

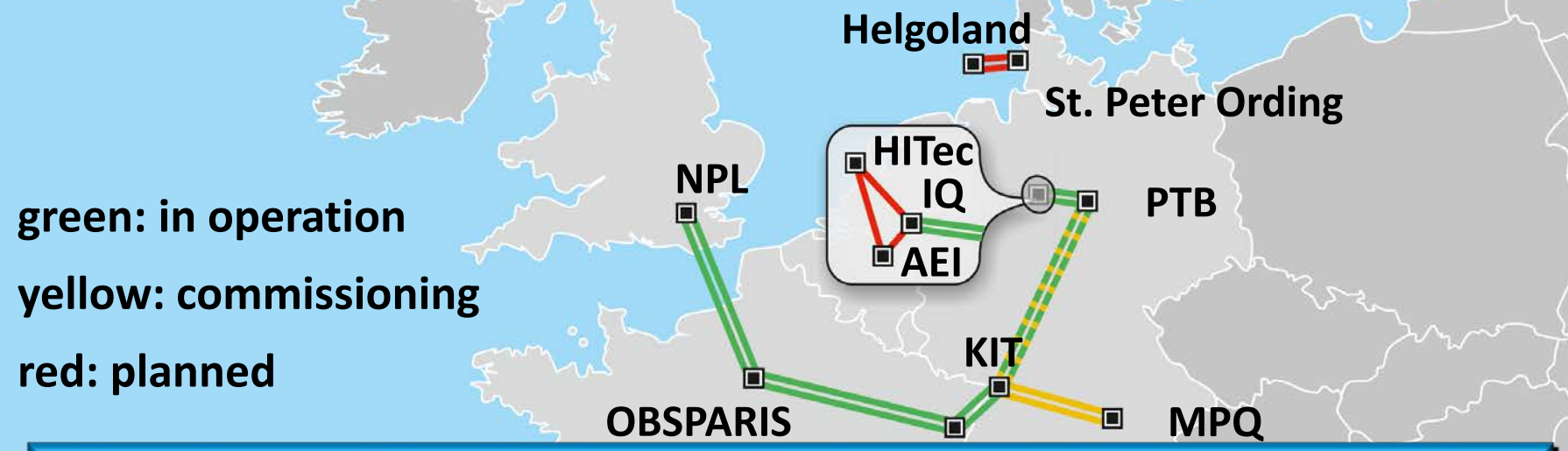
About the future of time

Brillouin amplification supports 1×10^{-20} accuracy in optical frequency transfer over 1400 km of underground fibre

Sebastian M. F. Raupach,[1,*] Andreas Koczwara,[1] and Gesine Grosche[1]

[1] *Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany*

(Dated: March 20, 2015)



green: in operation

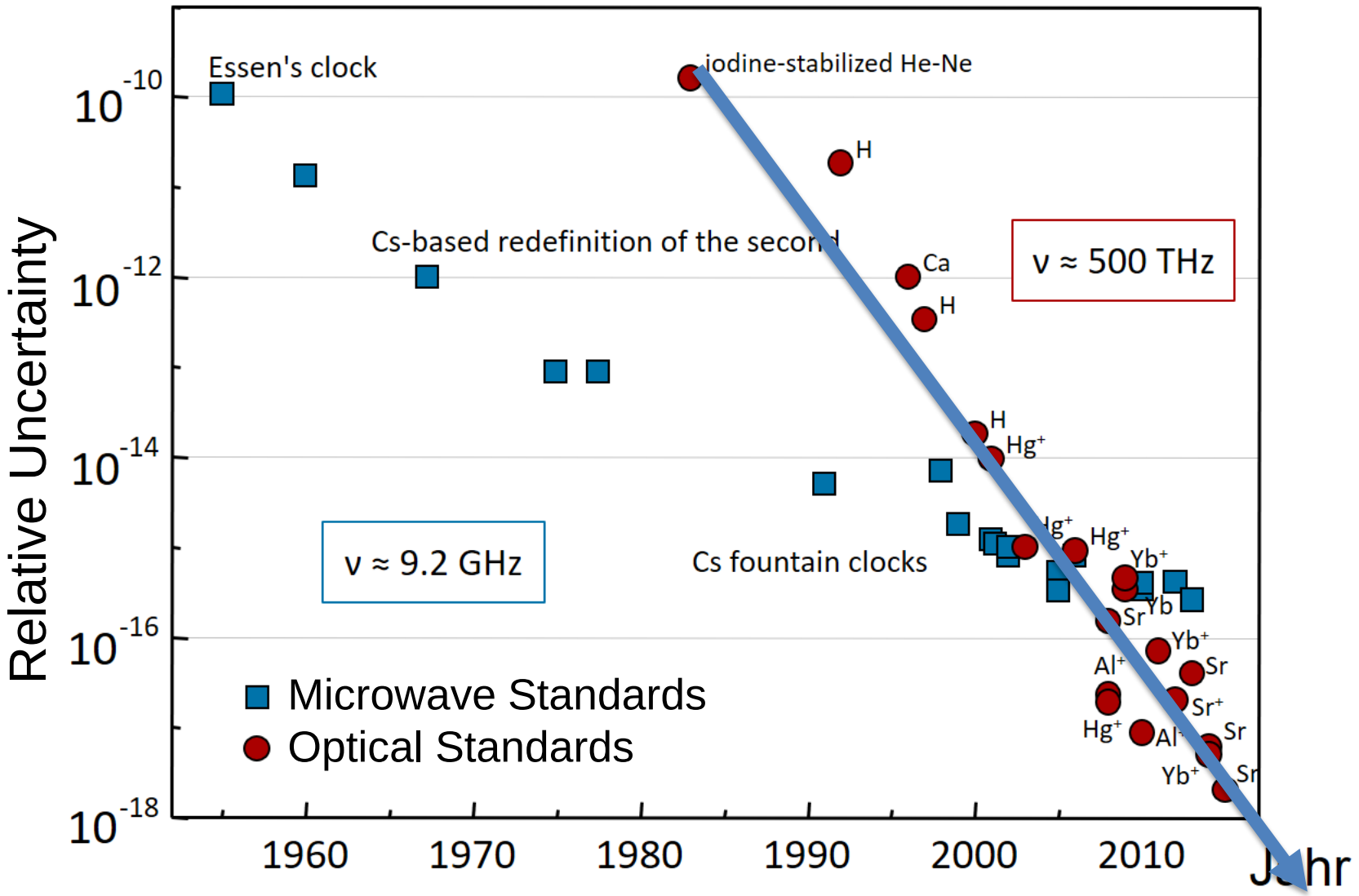
yellow: commissioning

red: planned

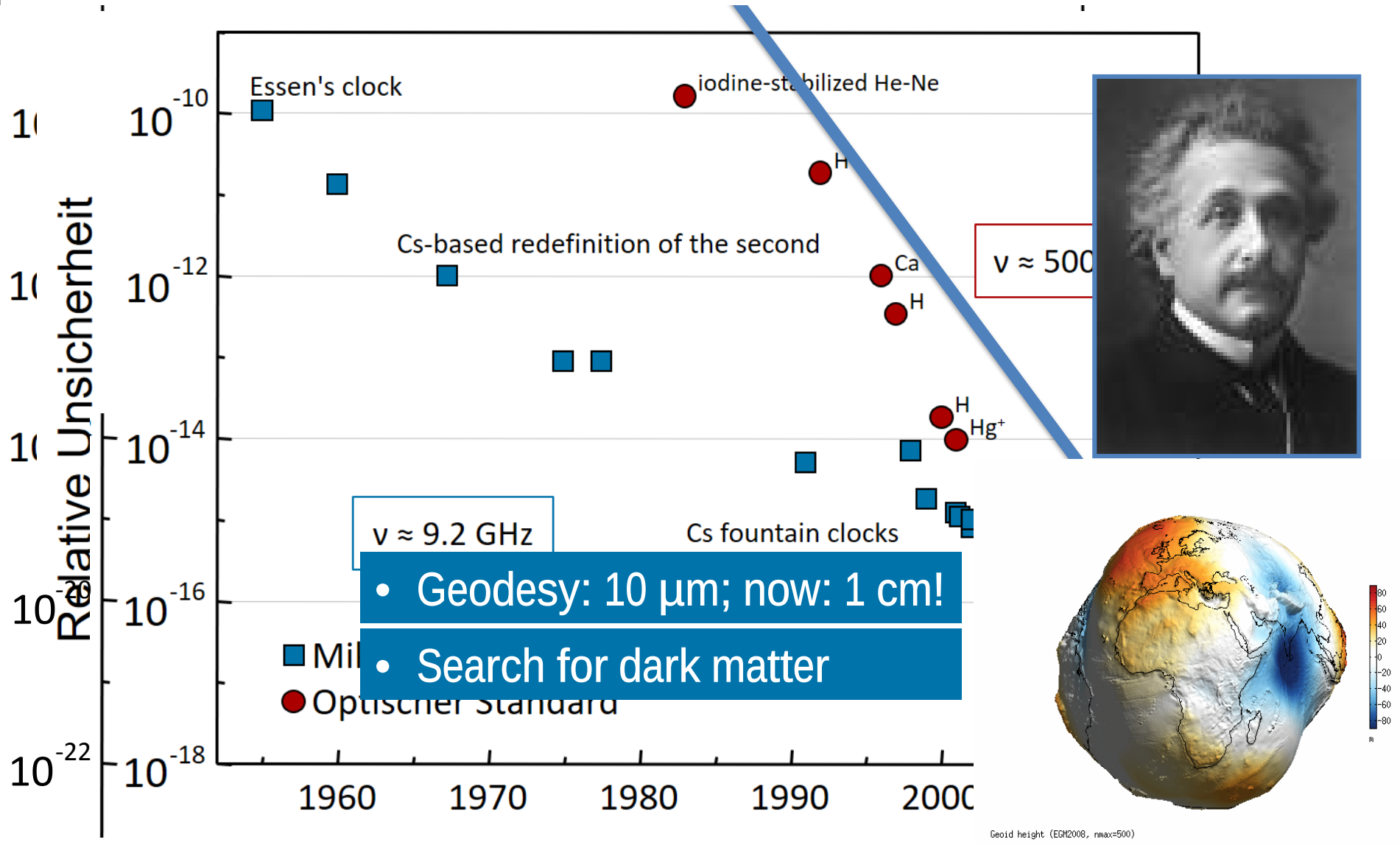
NIST (J. Ye): first laser air link: ~10^{-18} demonstrated!

First agreement of two very distant clocks with $4.7 \cdot 10^{-17}$! → world record!

About the future of time

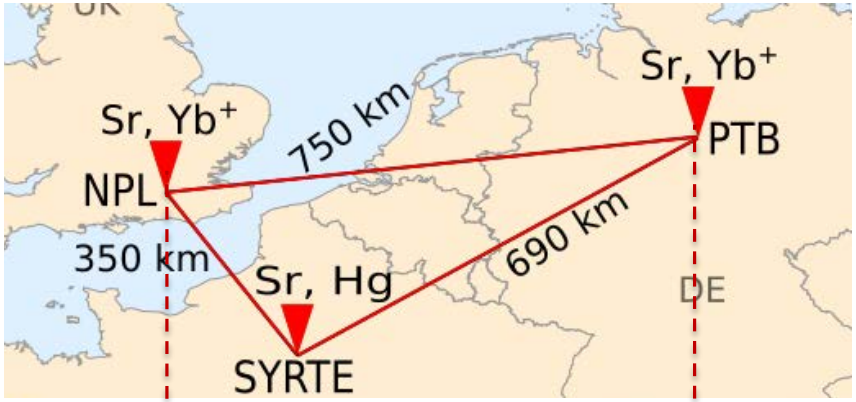


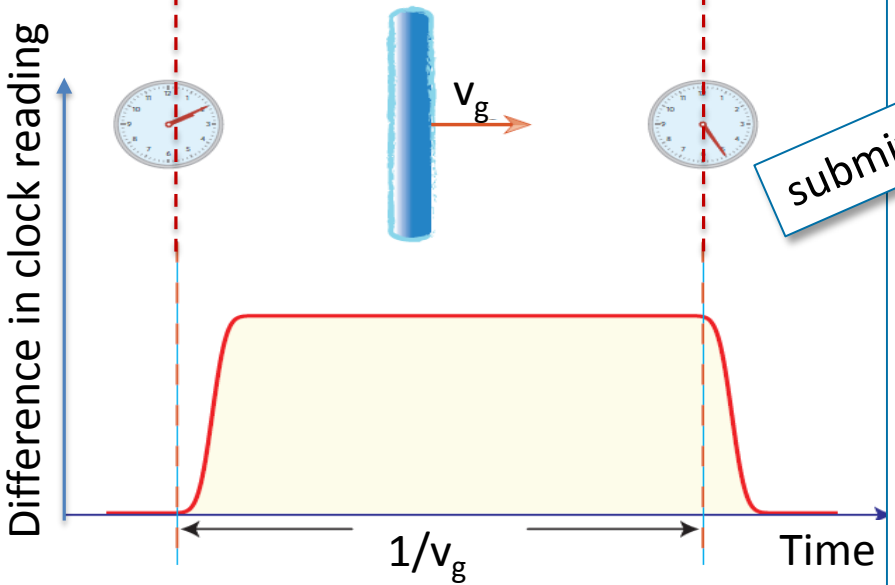
About the future of time



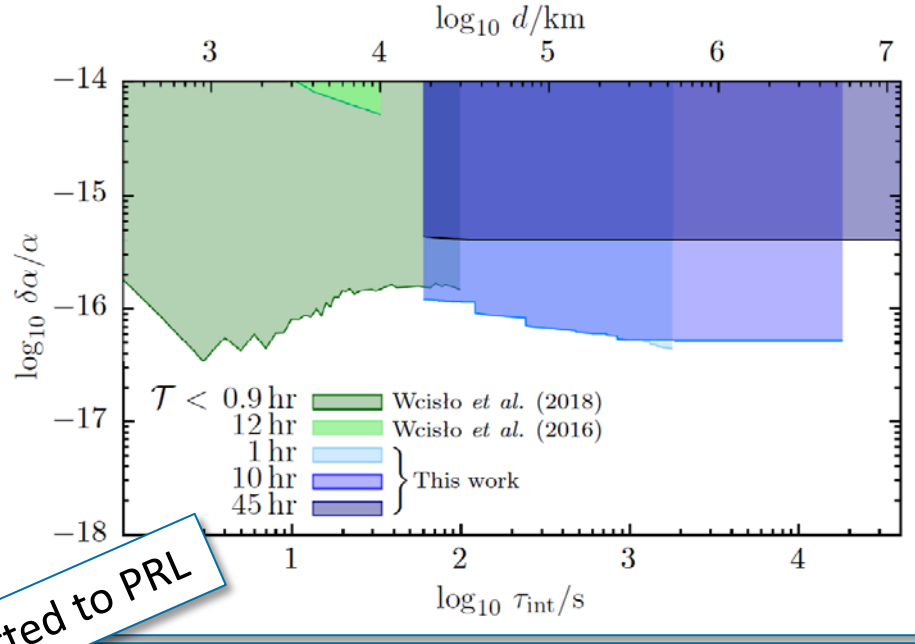
About the future of time

- Search for dark matter





© Derevianko *et al.* (2014). Nature Physics 10, 933-936.



submitted to PRL

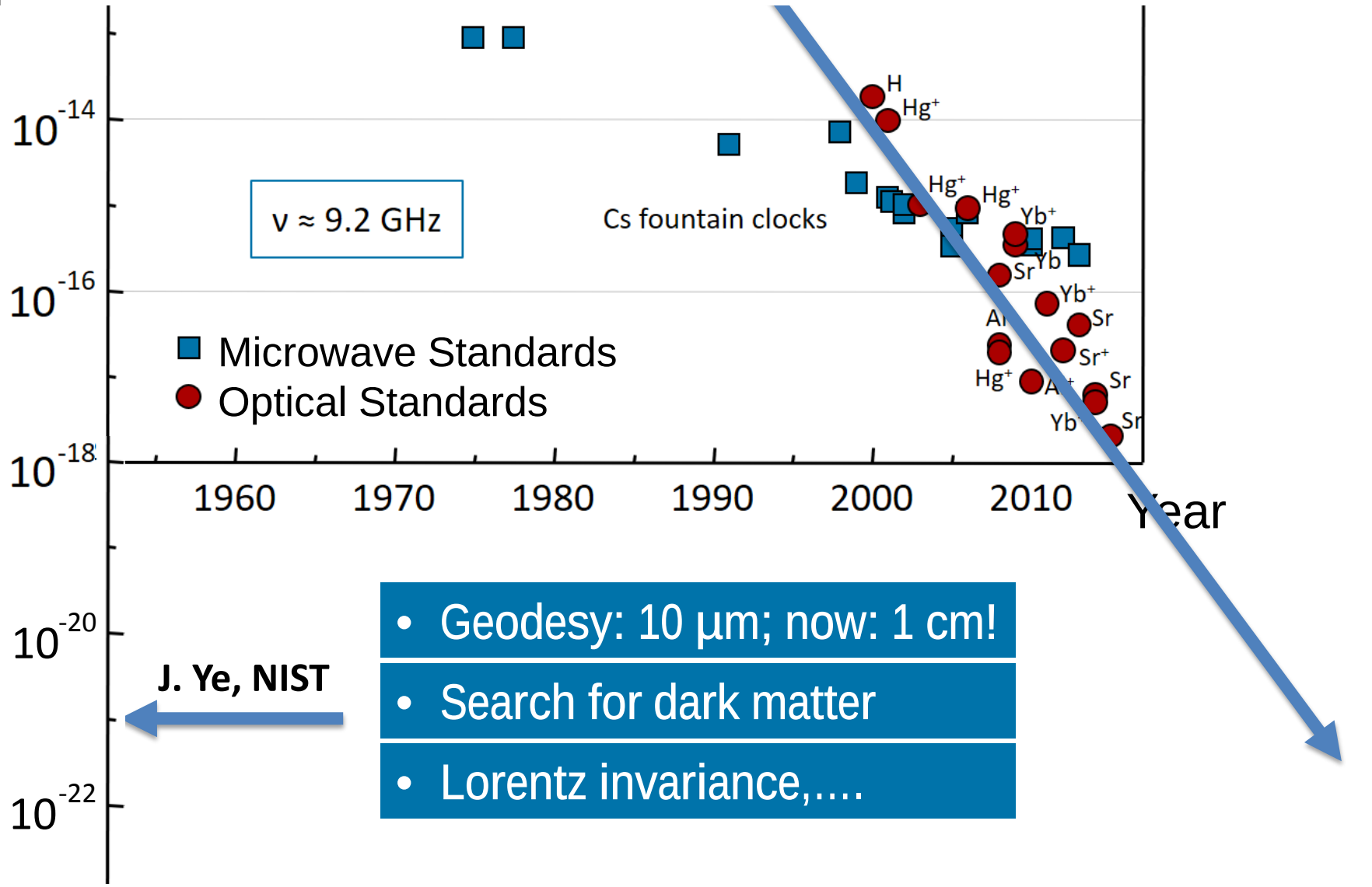
Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks

B. M. Roberts,[1,*] P. Delva,[1] A. Al-Masoudi,[2] A. Amy-Klein,[3] C. Bærentsen,[1] C. F. A. Baynham,[4] E. Benkler,[2] S. Bilicki,[1] W. Bowden,[4] E. Cantin,[1,3] E. A. Curtis,[4] S. Dörscher,[2] F. Frank,[1] P. Gill,[4] R. M. Godun,[4] G. Grosche,[2] A. Hees,[1] I. R. Hill,[4] R. Hobson,[4] N. Huntemann,[2] J. Kronjaeger,[4] S. Koke,[2] A. Kuhl,[2] R. Lange,[2] T. Legero,[2] B. Lipphardt,[2] C. Lisdat,[2] J. Lodewyck,[1] O. Lopez,[3] H. S. Margolis,[4] H. Álvarez-Martínez,[1,5] F. Meynadier,[1,6] F. Ozimek,[4] E. Peik,[2] P.-E. Pottie,[1] N. Quintin,[7] R. Schwarz,[2] C. Sanner,[2,†] M. Schioppo,[4] A. Silva,[4] U. Sterr,[2] Chr. Tamm,[2] R. Le Targat,[1] P. Tuckey,[1] G. Vallet,[1] T. Waterholter,[2] D. Xu,[1] and P. Wolf[1,‡]

[1] *SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France*
[2] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[3] *Laboratoire de Physique des Lasers, Université Paris 13, Sorbonne Paris Cité, CNRS, 99 Avenue Jean-Baptiste Clément, 93430 Villetaneuse, France*
[4] *National Physical Laboratory, Hampton Road, Teddington TW11 0LW, United Kingdom*
[5] *Sección de Hora, Real Instituto y Observatorio de la Armada, San Fernando, Spain*
[6] *Bureau International des Poids et Mesures, BIPM, Pavillon de Breteuil, 92312 Sèvres, France*
[7] *Réseau National de télécommunications pour la Technologie, l'Enseignement et la Recherche, 23–25 Rue Daviel, 75013 Paris, France*

(Dated: May 21, 2019)

About the future of time

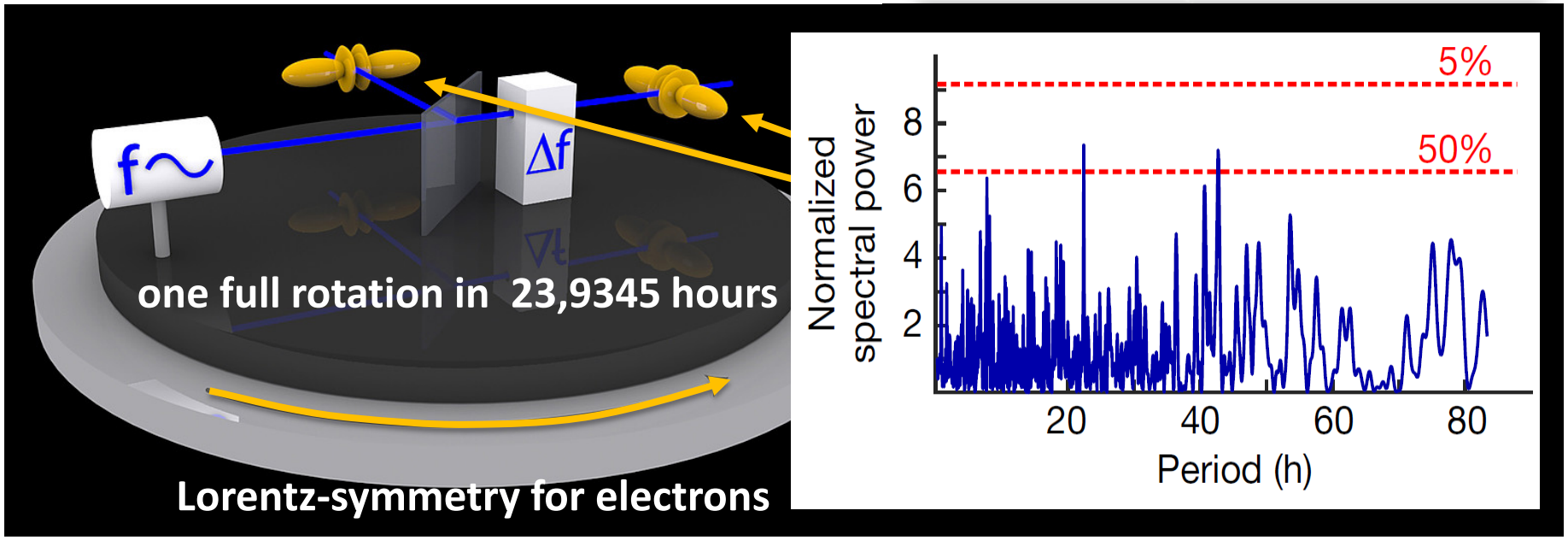


J. Ye, NIST

- Geodesy: 10 µm; now: 1 cm!
- Search for dark matter
- Lorentz invariance,….

About the future of time

- Lorentz invariance,….



- Frequency comparison over more than 1000 h.
- No relative change for periods of few min - 80 h.

→ relative frequency deviation: $< 3 \times 10^{-18}$

Ch. Sanner, N. Huntemann, R. Lange, Ch. Tamm, E. Peik, Marianna S. Safronova, S. G. Porsev
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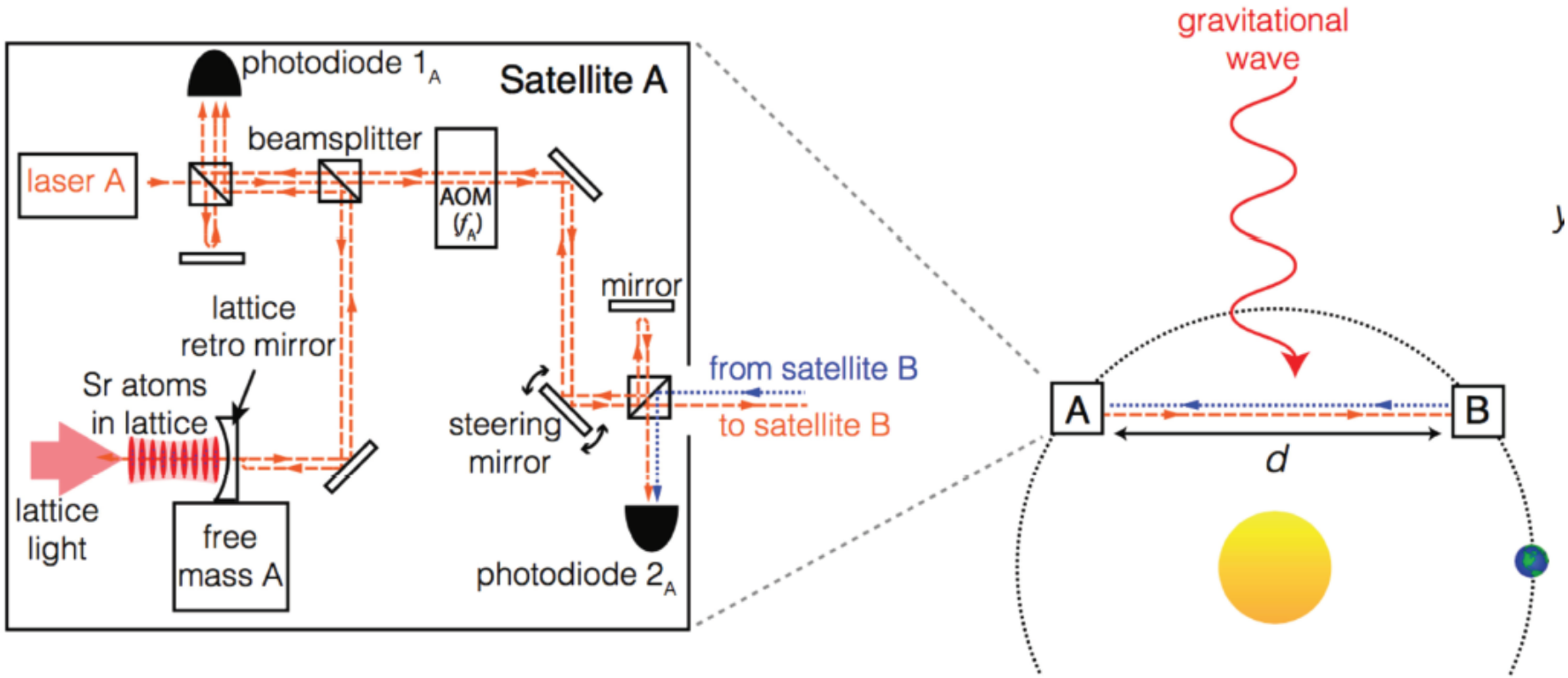
About the future of time

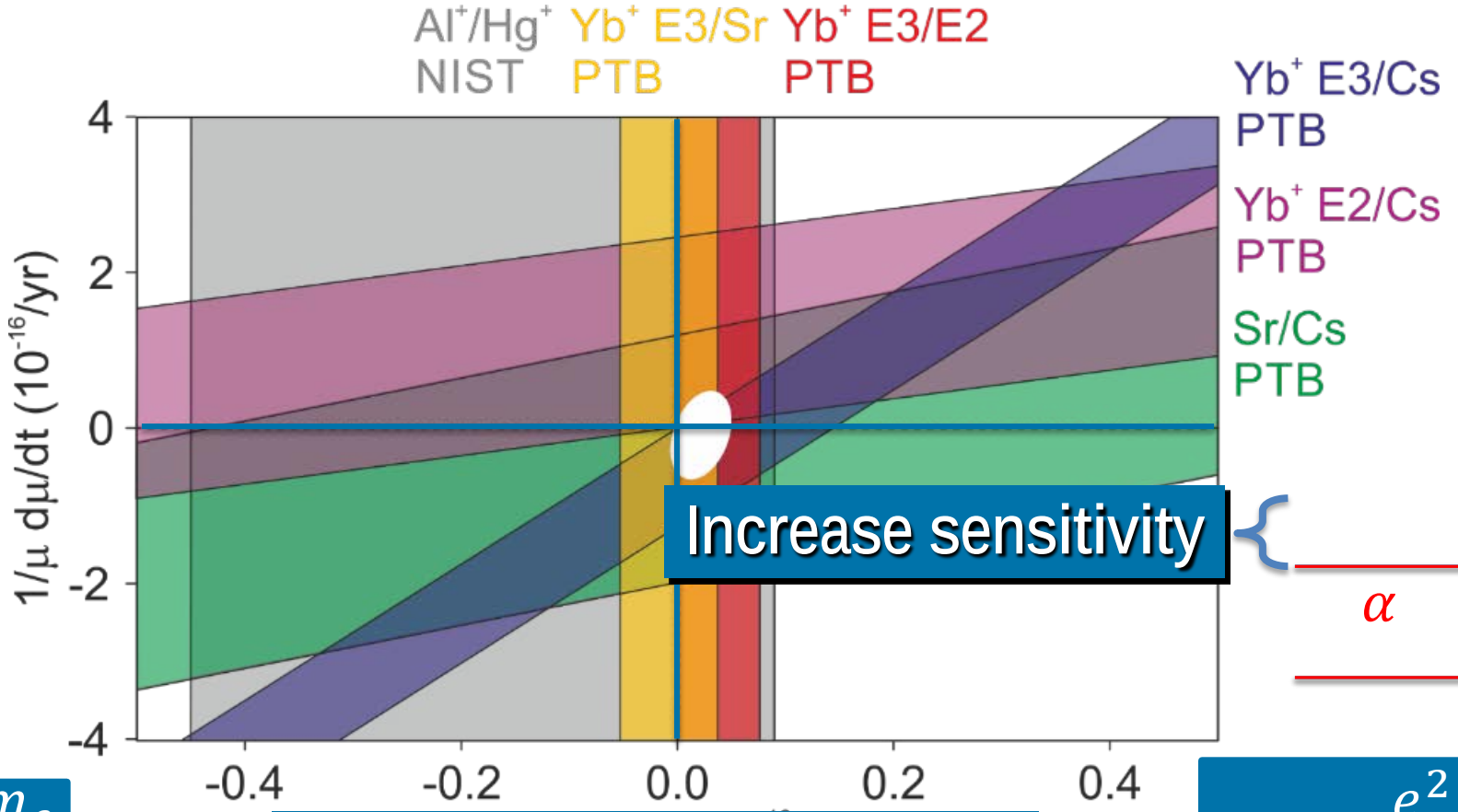


- Gravitational wave detection
- Are the constants constant?

Are the constants constant?

→ $\frac{1}{\mu}\frac{d\mu}{dt} = -1.2(5.8) \times 10^{-17}/\mathrm{yr}$

→ $\frac{1}{\alpha}\frac{d\alpha}{dt} = 2.3(2.8) \times 10^{-18}/\mathrm{yr}$



Increase sensitivity

$|b\rangle$

α

$|a\rangle$

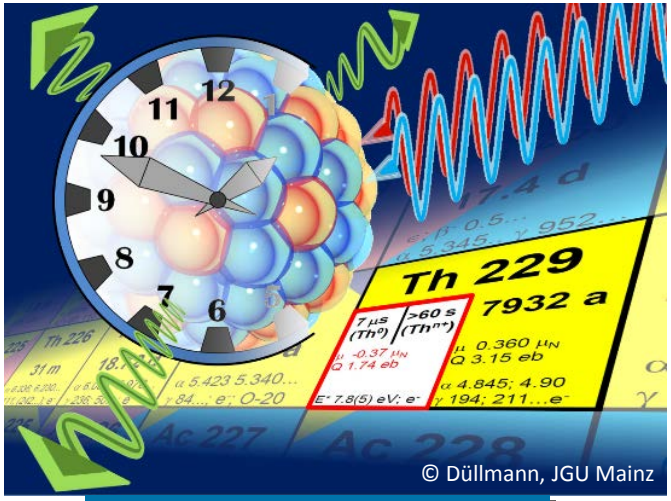
$\mu = \frac{m_e}{m_P}$

Can we do even better?

$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c}$

Are the constants constant?

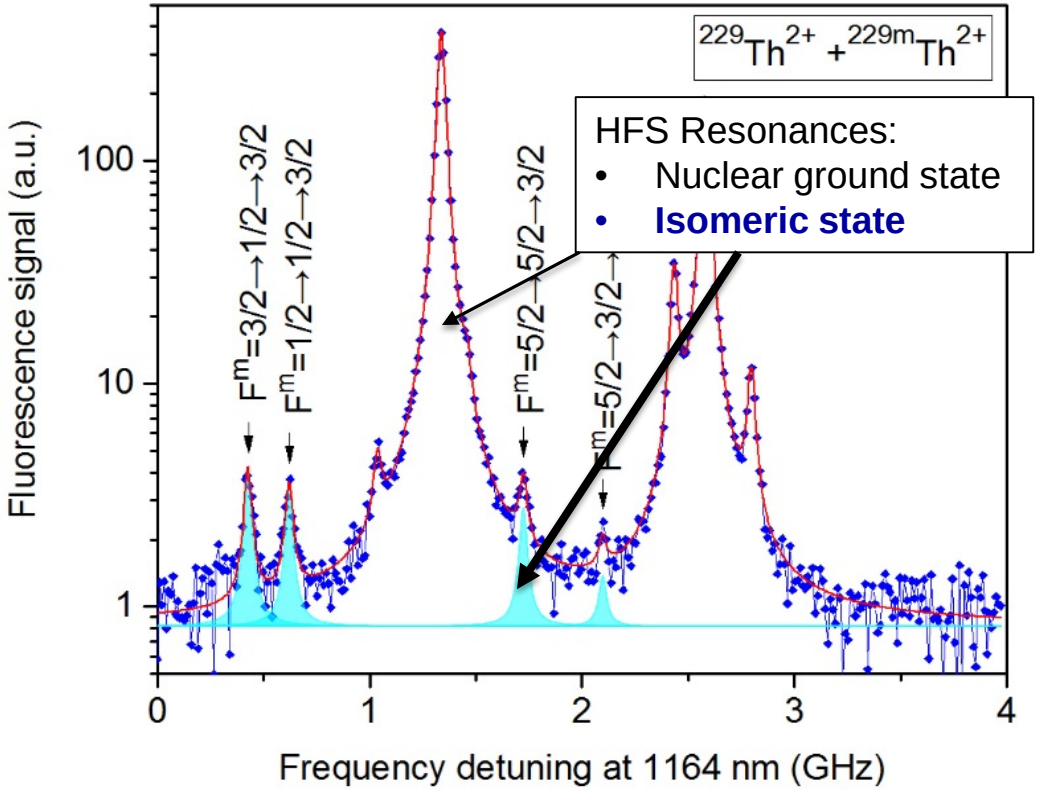
Nuclear Transition



$\Delta f/f \sim 10^{-19}$

$\Delta\alpha/\alpha < 10^{-20}$ /a

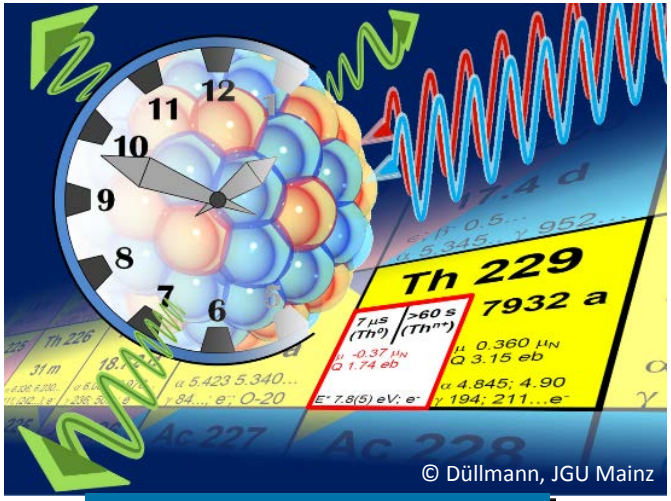
Enhancement: 0…10 000



- First optical detection of the isomer
- Nuclear moments of the isomer
- Charge radius of the isomer

Are the constants constant?

Nuclear Transition

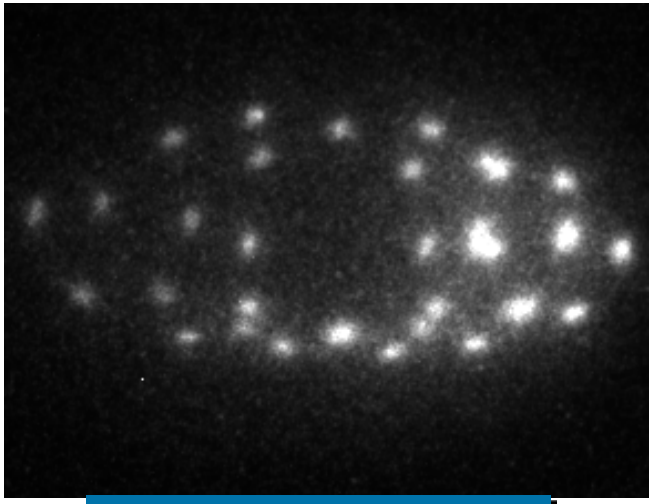


$\Delta f/f \sim 10^{-19}$

$\Delta\alpha/\alpha < 10^{-20}$ /a

Enhancement: 0…10 000

Highly Charged Ions



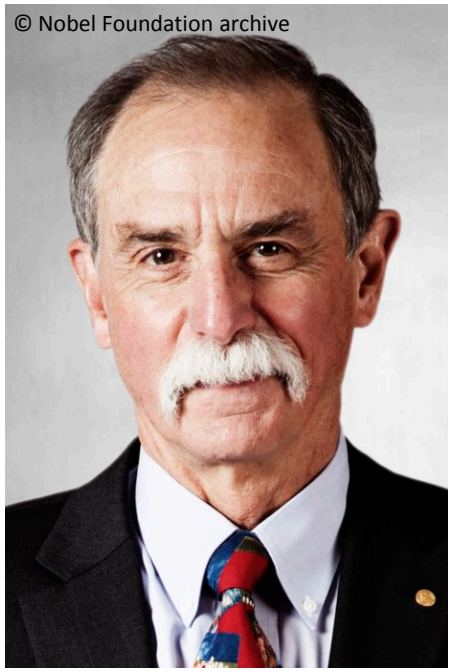
$\Delta f/f \sim 10^{-19}$

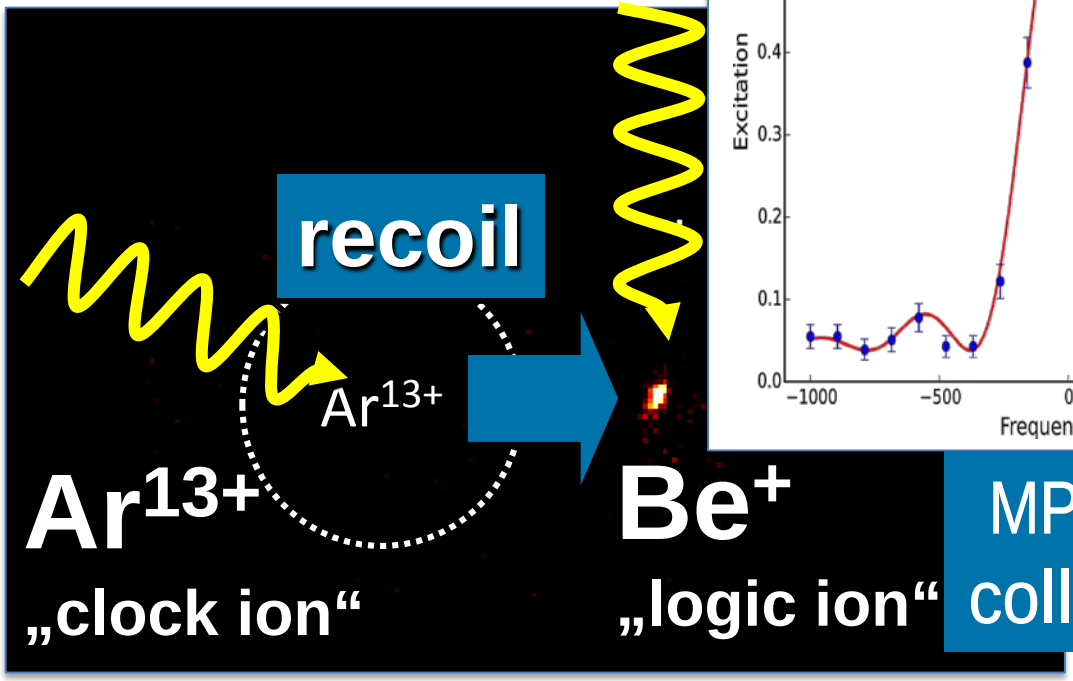
$\Delta\alpha/\alpha < 10^{-20}$ /a

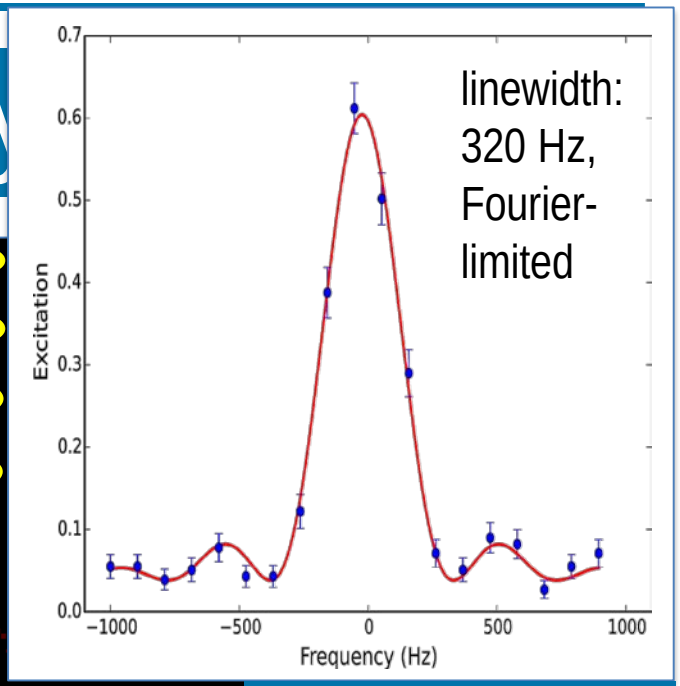
Enhancement: ~< 100

Highly Charged Ions: Optical Transitions

Quantum logic spectroscopy





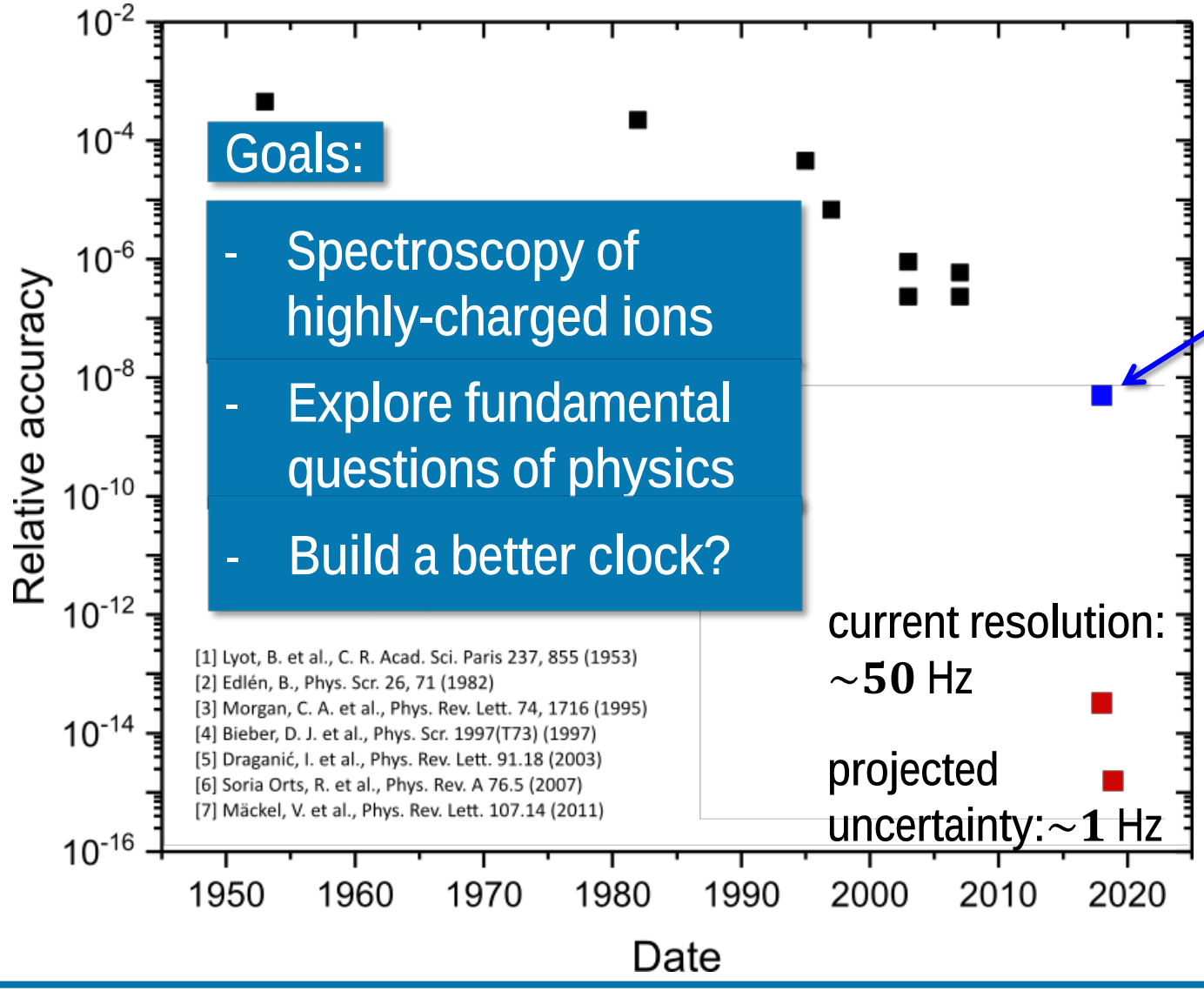


MPIK – PTB collaboration

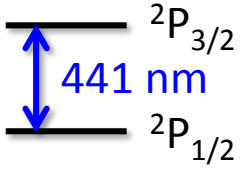
Nobel Price 2012: Dave Wineland & Serge Haroche

“for ground-breaking experimental methods to manipulate and investigate individual quantum systems”

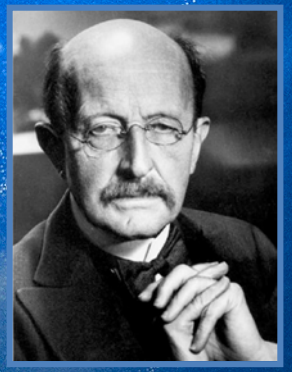
History of Ar^{13+} Frequency Measurements

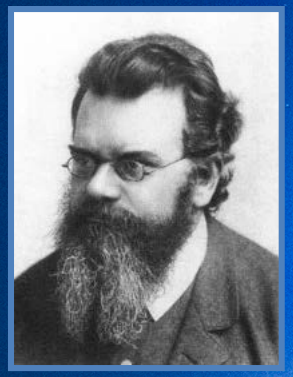


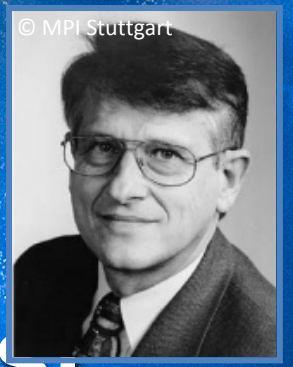
new Penning trap measurement [S. Sturm *et al.* (MPIK), to be published]



SI International System of Units







…approaching the most abstract definition of units...

End