

Physical Units based on Fundamental Constants – Changing with Time?

Prof Dr Joachim H. Ullrich

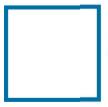
President of PTB, Physikalisch-Technische Bundesanstalt

Vice President of the CIPM

President of the Consultative Committee of Units

Vice President of DIN, the German Standardisation Organisation







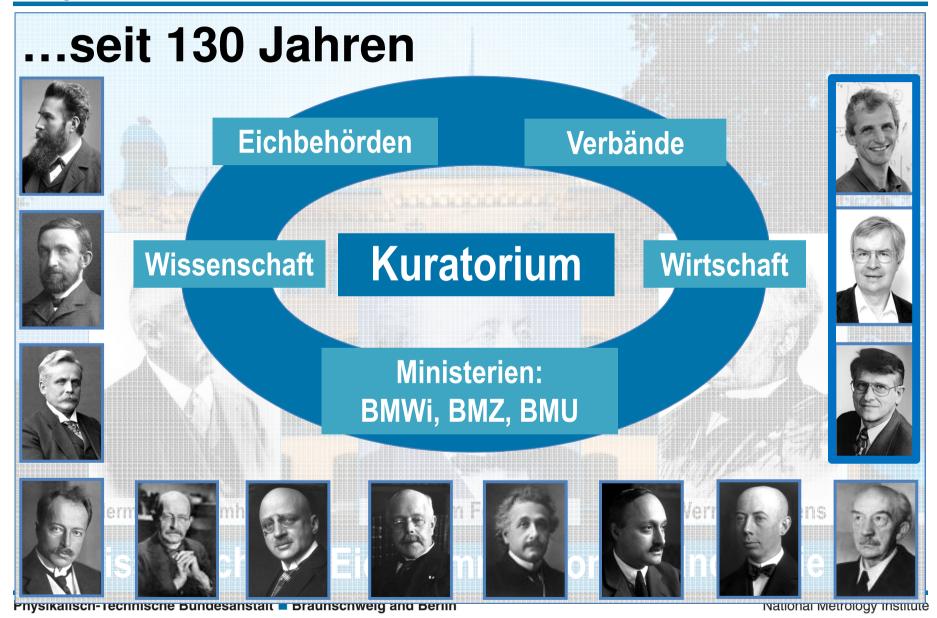
Physikalisch-Technische Bundesanstalt





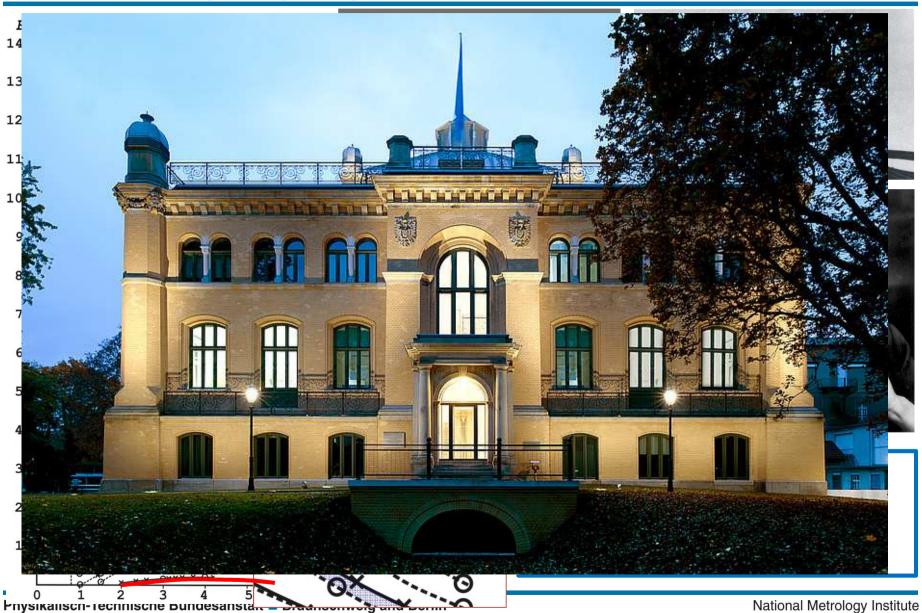
Physikalisch-Technische Bundesanstalt





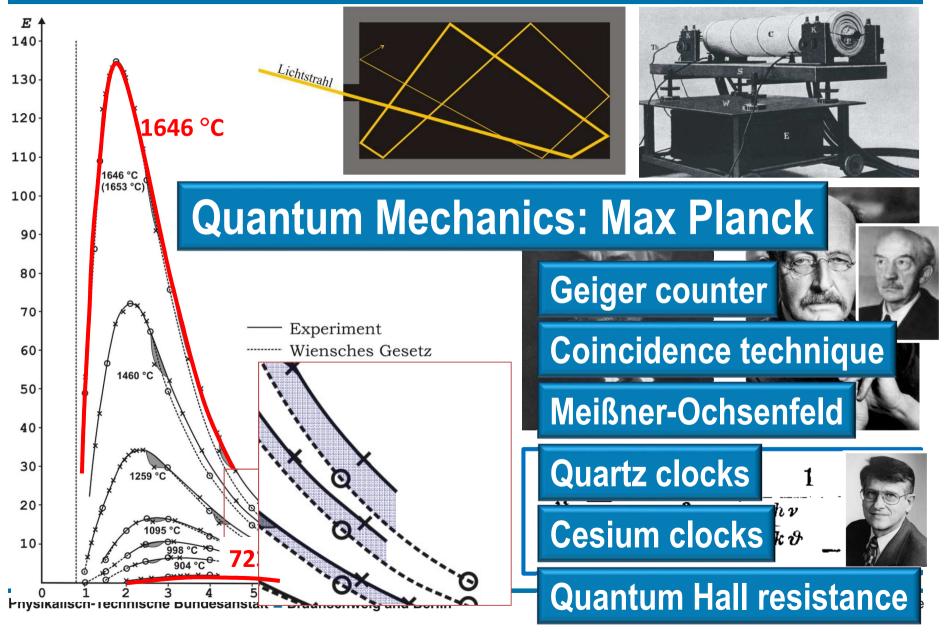
Some early highlights





Some early highlights





The Metre Convention





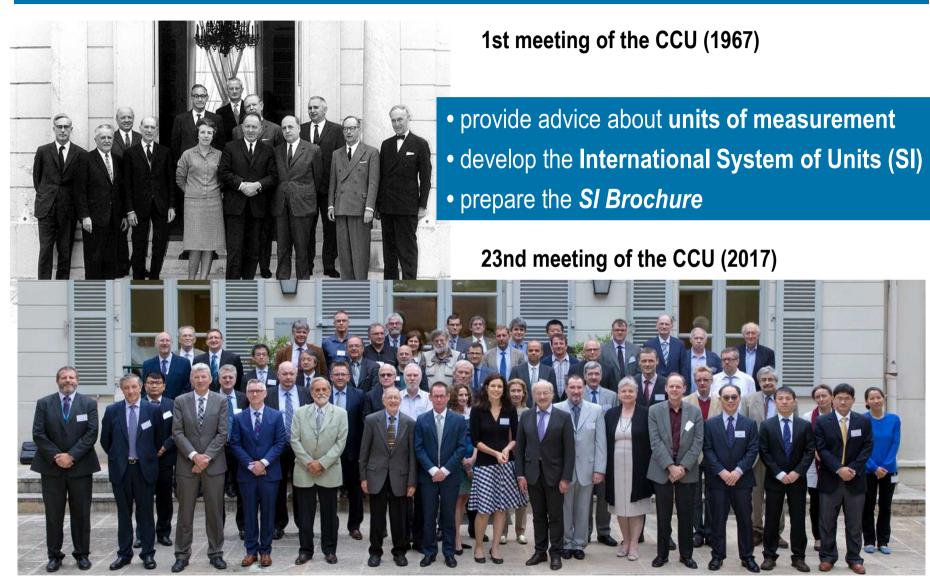
The Metre Convention



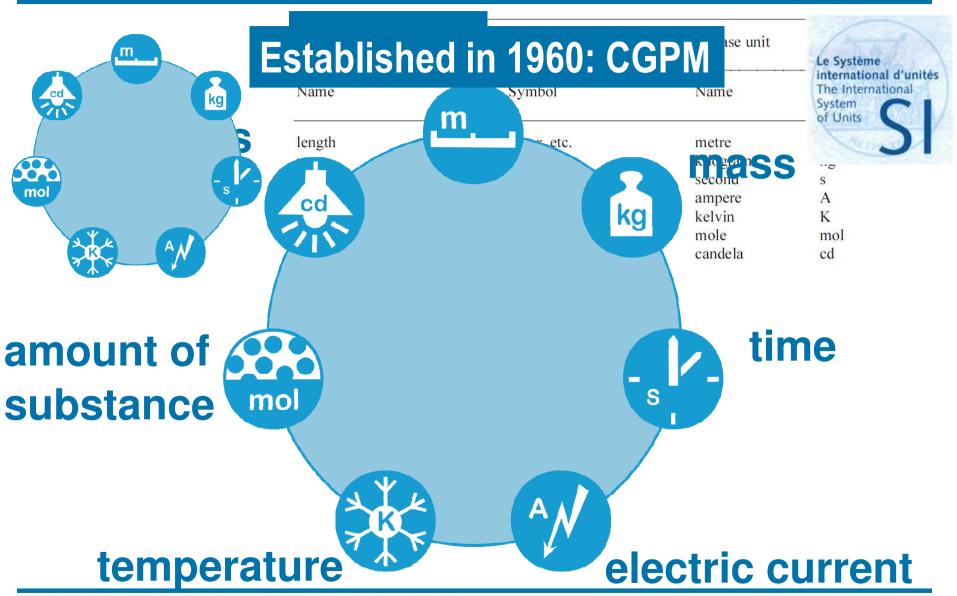


CCU: Consultative Committee for Units







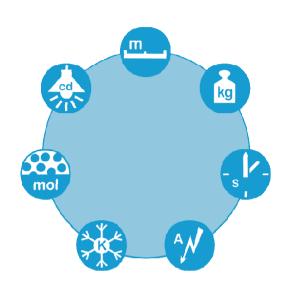




Symbol

m/m

 m^2/m^2



Base units

SI base unit

Derived units with special names

Dimensions of quantities of

Expressed Expressed in terms of other SI units SI base units

→ A set of coherent SI units

				S
force	newton	N		m kg s ⁻²
pressure, stress	pascal	Pa	N/m^2	$\mathrm{m}^{-1}\mathrm{kg}\mathrm{s}^{-2}$
energy, work,	joule	J	Nm	$m^2 kg s^{-2}$
amount of heat				
power, radiant flux	watt	W	J/s	$m^2 kg s^{-3}$
electric charge,	coulomb	C		s A
amount of electricity				
electric potential difference,	volt	V	W/A	$m^2 kg s^{-3} A^{-1}$
electromotive force				300
capacitance	farad	F	C/V	$m^{-2} kg^{-1} s^4 A^2$
electric resistance	ohm	Ω	V/A	$m^2 \text{ kg s}^{-3} \text{ A}^{-2}$
hertz (d)	Hz			s^{-1}
	-			2
newton	N			m kg s ~
inductance	henry	H	Wb/A	m kg s A

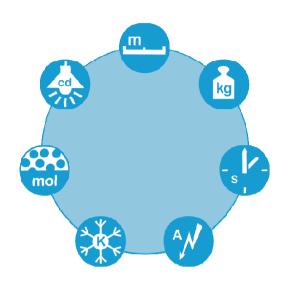
Derived units

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

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

frequenc	У
force	



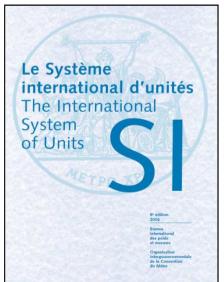


Base units

Derived units

Dimensions of quantities

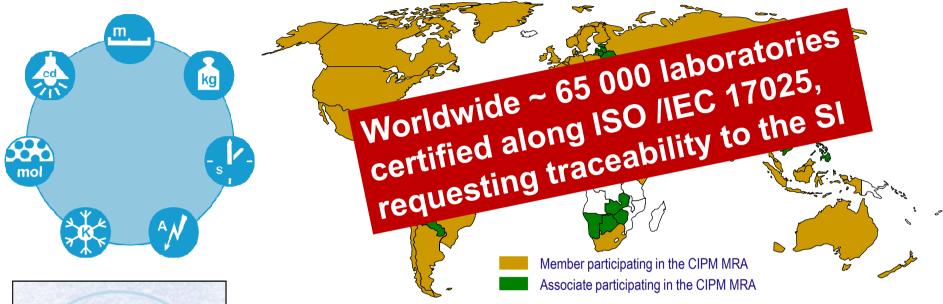
→ A set of coherent SI units



- > A global measurement infrastructure
- > Valtensity lof wighte from an LED
 - CO₂ concentration in the air
 - Creatinine concentration in blood serum
 - Dose equivalent outside nuclear reactors

•





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

 Pédio

 Burus de merces

 Generaled de Mêtre de Mêtre
- ➤ A global measurement infrastructure
- > Valid world wide: CIPM-MRA signed by
 - . -> 97.6 % of the world economy
 - -> The comerstone of international
 - quality infrastructure (QI)



Physical Units based on Fundamental Constants – Changing with Time?

- 1. Metre Convention: Cornerstone of global Ql
- 2. Motivation for revision of the SI
- 3. Linking the SI to defining constants
- 4. Are the constants constant?







Quantities and Measurement Units



Measurement units

number

quantity \longrightarrow Q

$$\longrightarrow$$
 Q = {Q} [Q]

$$m = 10.1 (2) \text{kg}$$

$$t = 55.4(1)s$$

unit

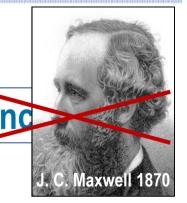
artefact

measurem. prescription defining constant

 $\Delta \nu (133 \text{Cs})_{\text{hfs}} = 9 192 631 770.5 (6) \text{s}^{-1}$

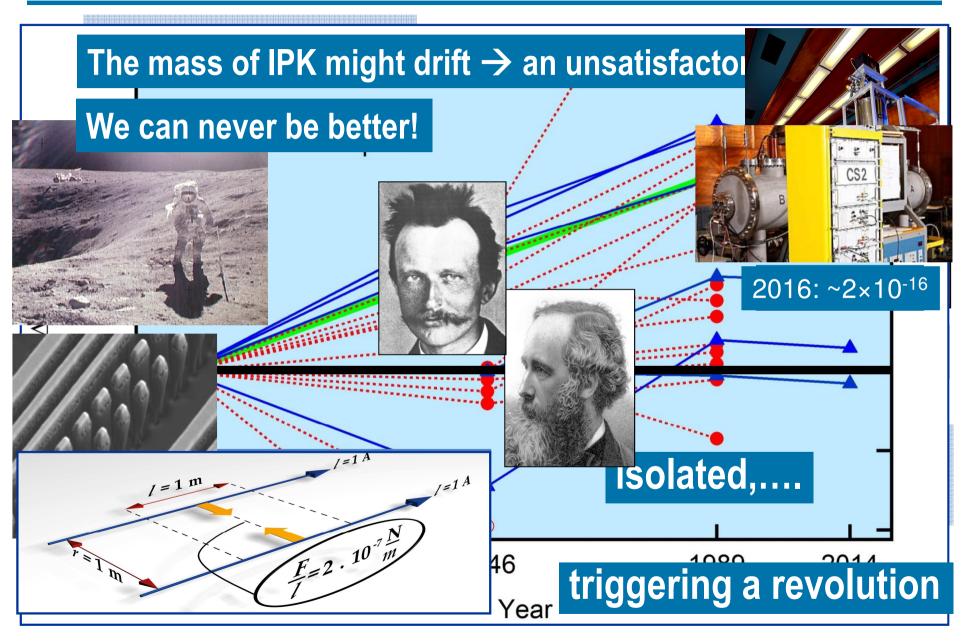
constant of nature

1 s =
$$\frac{9.192.631.770}{\Delta \nu \, (^{133}\text{Cs})_{\text{hfs}}}$$

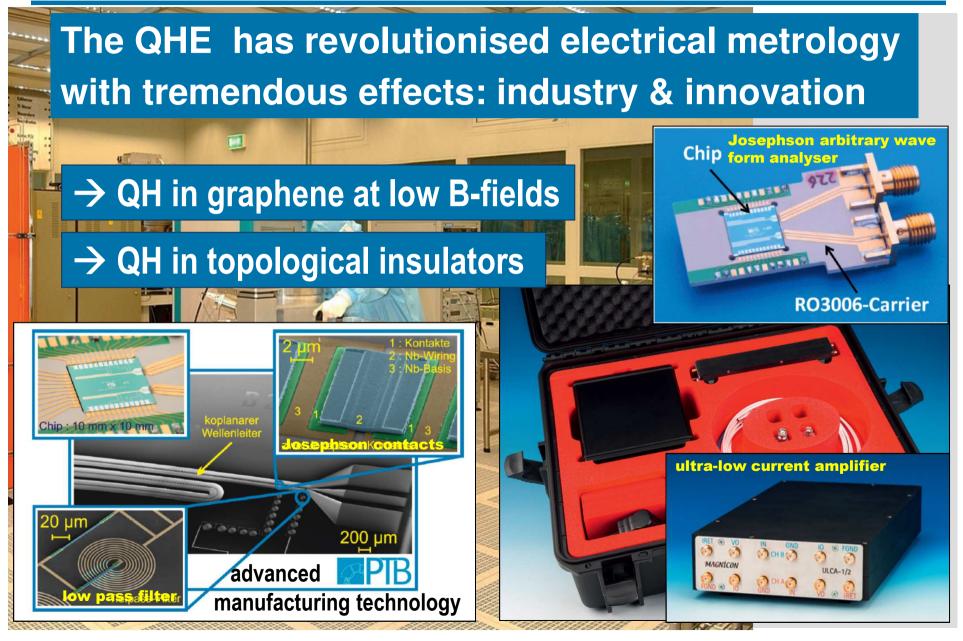


Define a unit by fixing the numerical value of a constant of nature

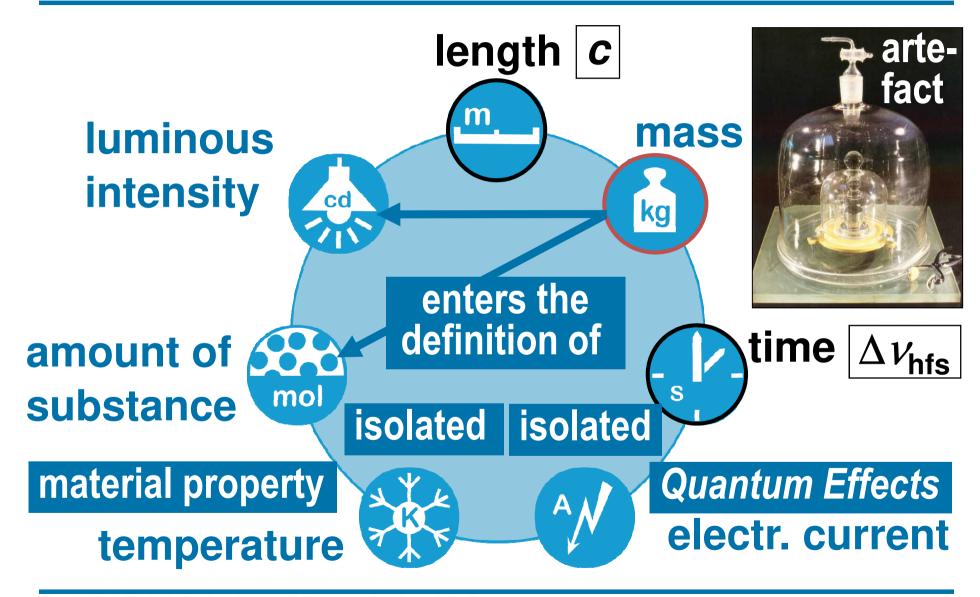




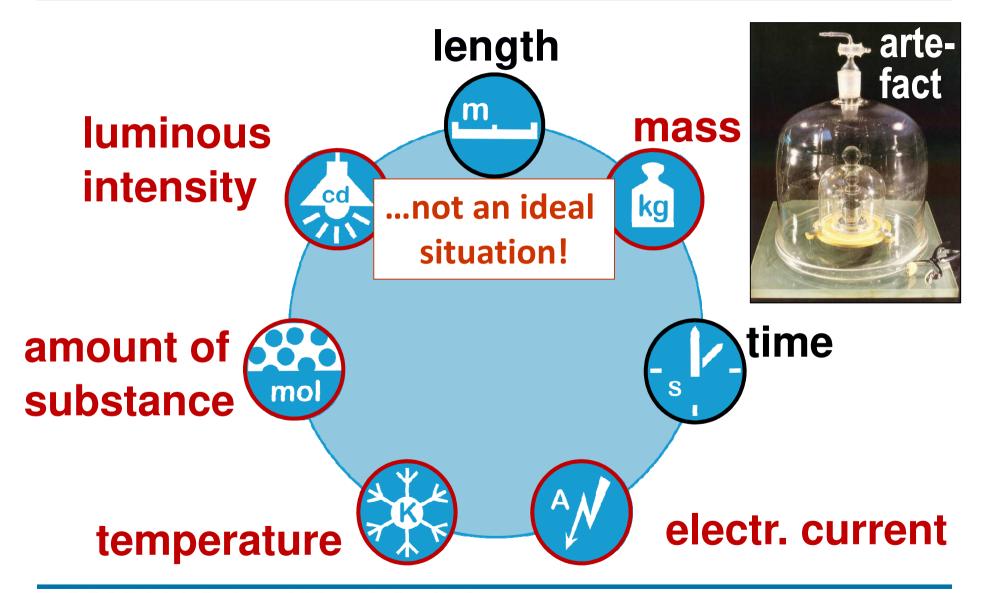




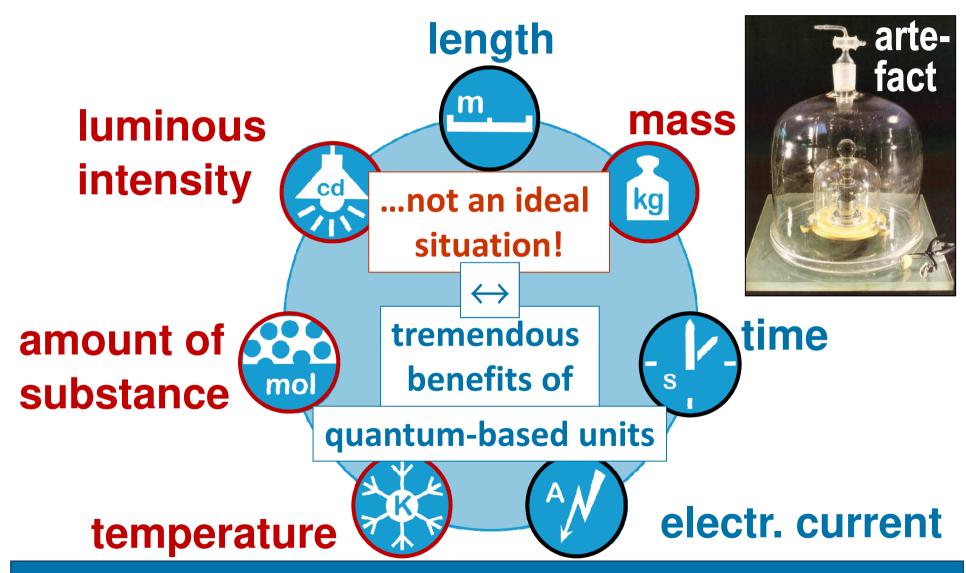












Built a coherent and consistent quantum-based system of units

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 1.

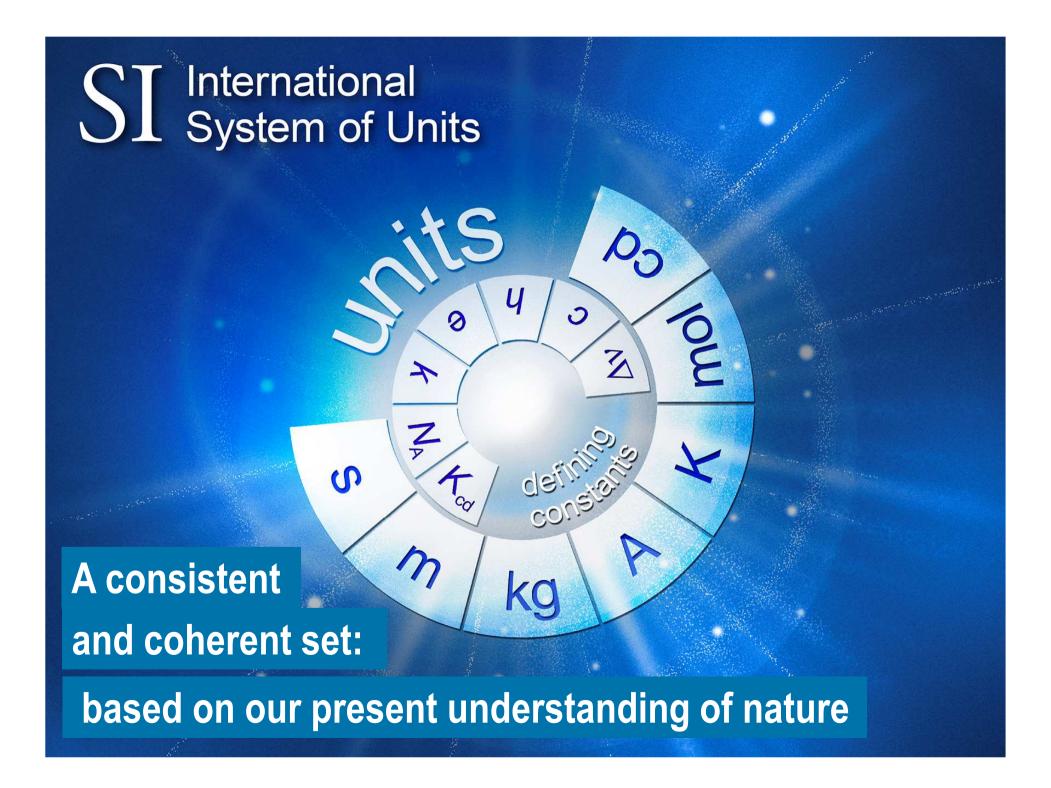
irreversible Strahlungsvorgänge; von Max Planck.

Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhülfenahme der beiden in dem Ausdrach (41) den Strahlungsantrania auftratenden Constants we have un ...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...

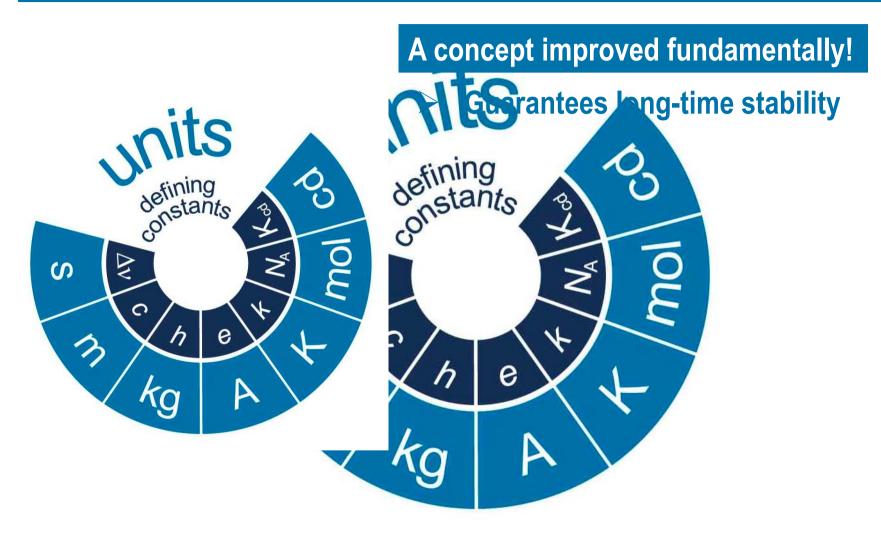
ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 1.

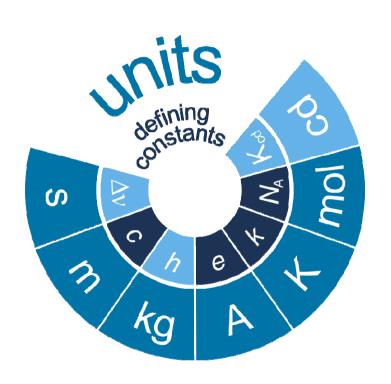
Tous Lungsvorgänge; irrever von von gegenüber ne Interesse sein zu beiden in dem Ausbemerken, dass mit estandan Constantan a a constants we have ...with the help of Zethe possibility of establishing units of length, sp Ze Cu time, mass, and temperature, which necessarily retain their variaity for all times and civilisations, rowg mouttremal whimeuse...









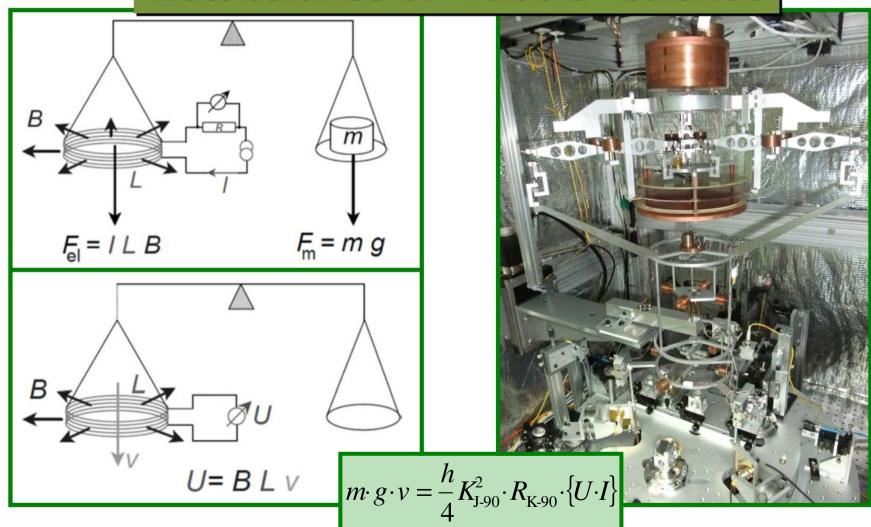


A concept improved fundamentally!

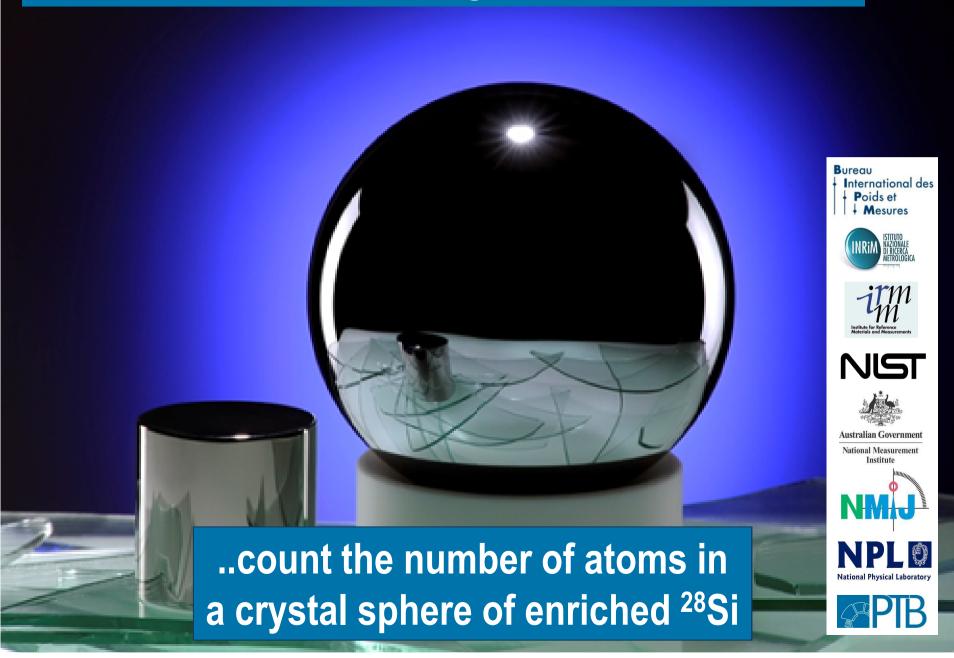
- Guarantees long-time stability
- A set of "defining constants" establish the units in general

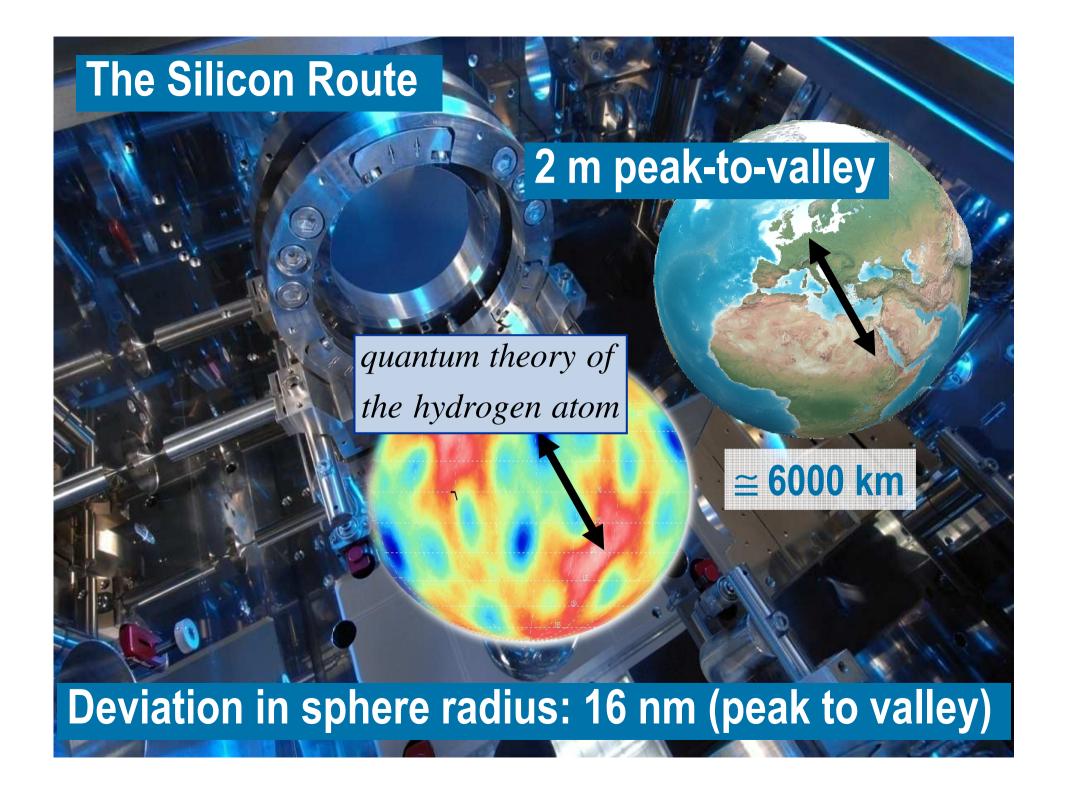


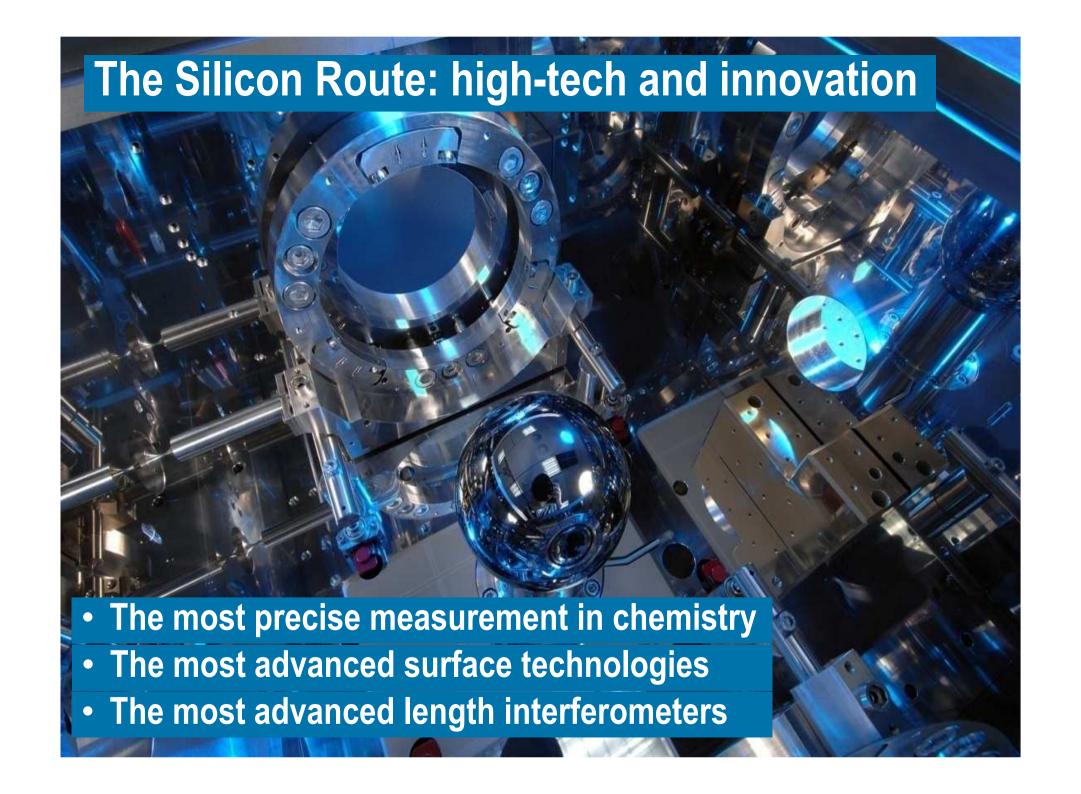
Watt balance or "Kibble" balance



The Silicon Route: Avogadro Collaboration







The Silicon Route: high-tech and innovation

Commercial Kibble Balances

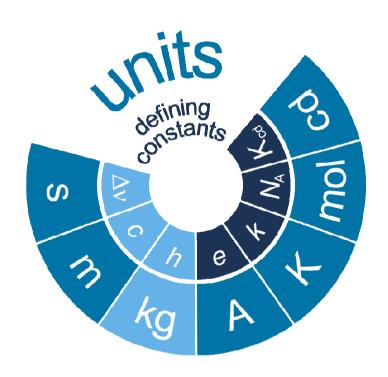
- "self-calibrating"
- high precision
- industrial application: E1, E2
- "off-the-shelve" components
- connected to the IoT



Version	Mass range	MPE OIML R111-1	U _r ≤ 1/3·MPE <i>k</i> =2	Environment
PB 2 (E2)	1 mg100 g	16·10 ⁻⁷	5.3·10 ⁻⁷	Air
PB 1 (E1)	1 mg1 kg	5·10 ⁻⁷	1.7·10 ⁻⁷	High Vacuum

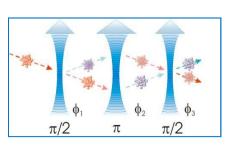
- The most precise measurement in chemistry
- The most advanced surface technologies
- The most advanced length interferometers







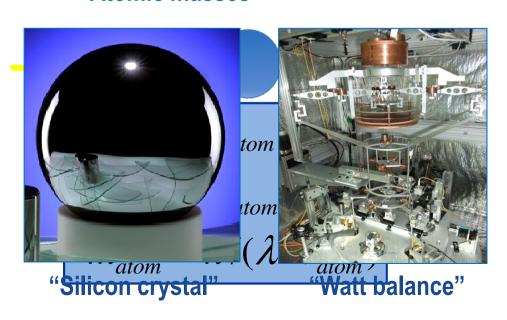
"De Broglie"



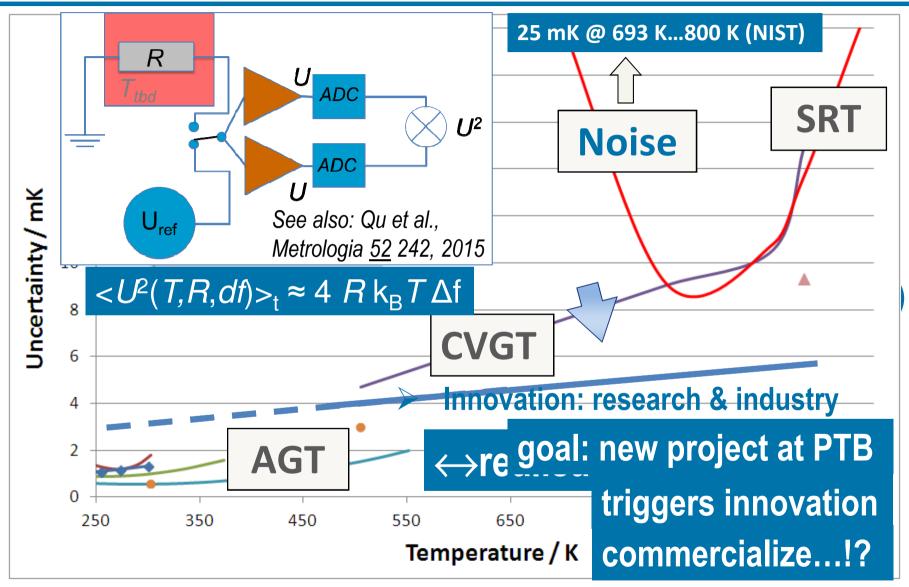
"Photon recoil"

A concept improved fundamentally!

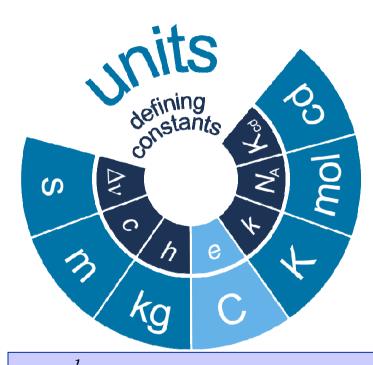
- Guarantees long-time stability
- A set of "defining constants" establish the units in general
- > Different realisations
- > Realisation reviews here, (Universition
 - Atomic masses











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

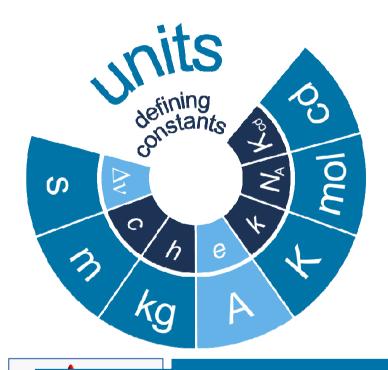
$$K_J = \frac{2e}{h} \approx 483 \ 598 \ GHz/V \iff K_{J-90}$$

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
- Innovation: research & industry
- Base units are only a convention
- Electric units are "back in the SI"
 - connected by the
 - equations of physics,



Tremendous benefits:



a "huge" change... but "no" change!

detector

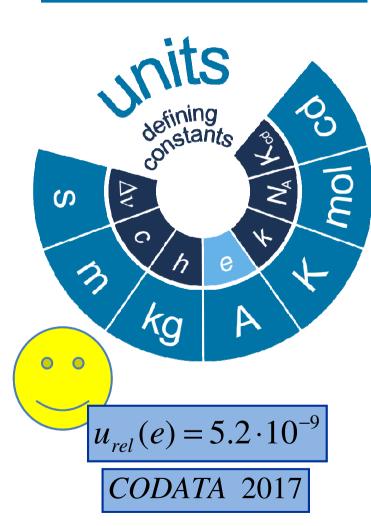
A concept improved fundamentally!

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

E ...towards quantum electronics!!! y



Establish the constants



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
- Innovation: research & industry
- Base units are only a convention
- Electric units are "back in the SI"
- ➤ Better experiment → better realization

Ensure continuity, harmonization, stability

The Boltzmann Project at PTB



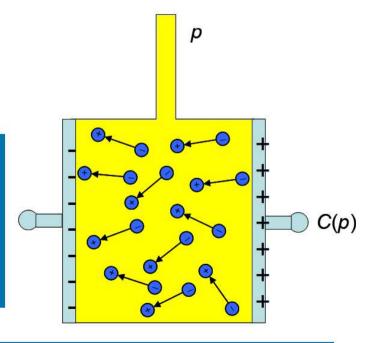


Goal:

Measure the Boltzmannconstant k with an uncertainty u(k) < 3 ppm

Experiment:

Determination of the Boltzmann-constant by measuring **pressure**, **temperature** and change of electric **capacity**



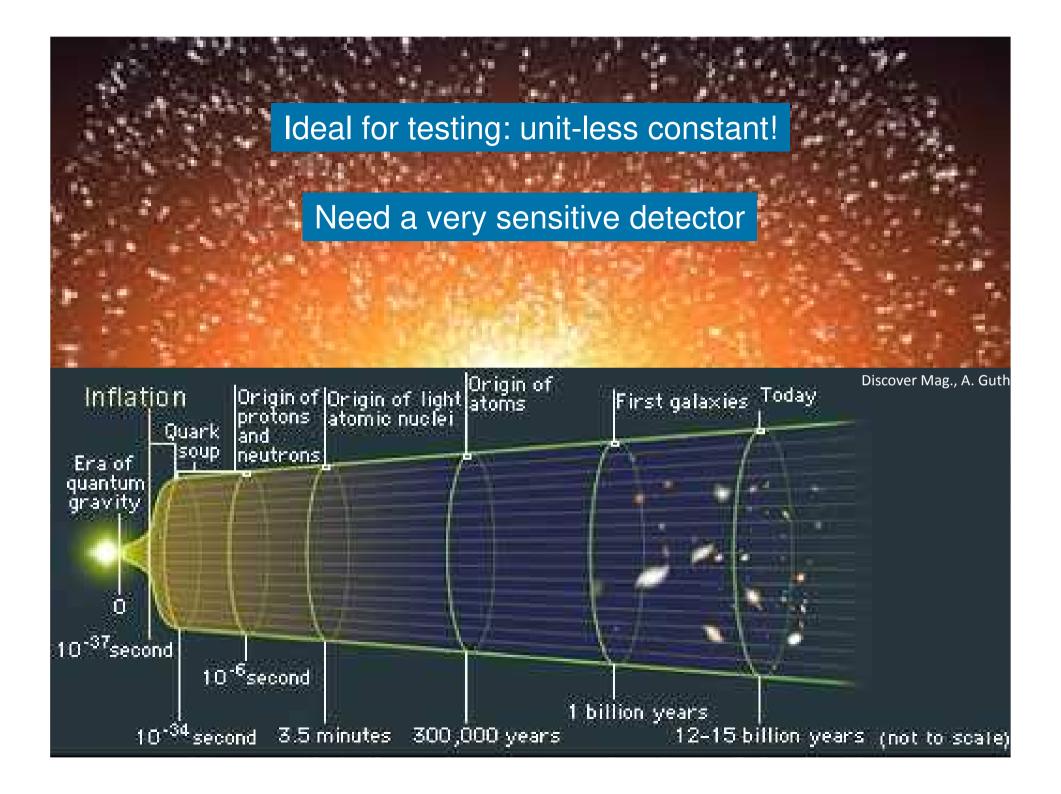
SI International System of Units

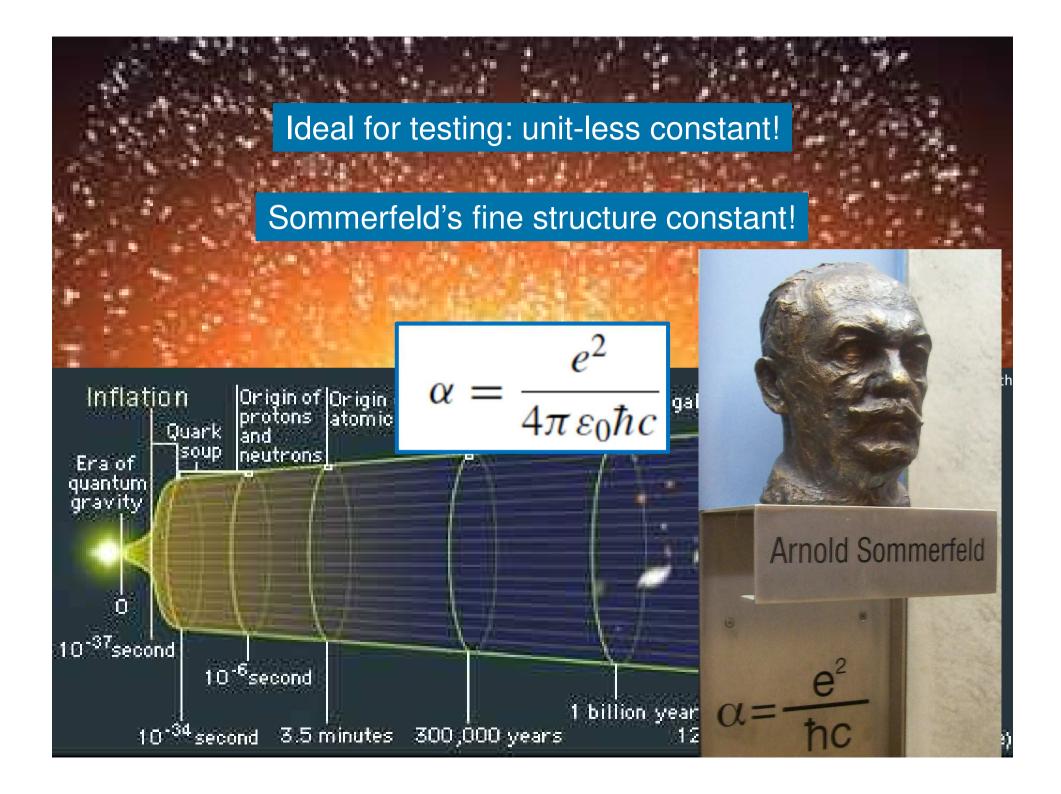
THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

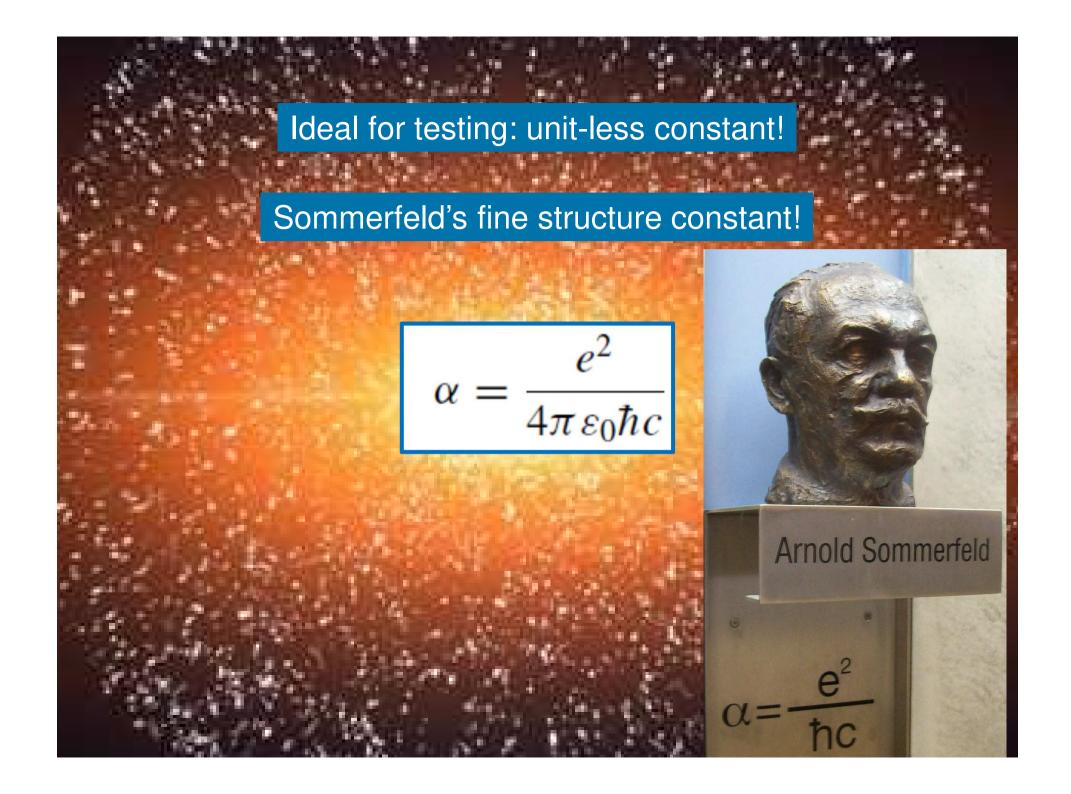
Defining constant	Symbol	Numerical value	Unit	
hyperfine transition				
frequency of Cs	$\Delta u_{ m Cs}$	9 192 631 770	Hz	
speed of light in vacuum	c	299 792 458	$m s^{-1}$	
Planck constant*	h	$6.62607015 imes10^{-34}$	$J Hz^{-1}$	
elementary charge*	e	$1.602176634 imes10^{-19}$	C	
Boltzmann constant*	k	$1.380649 imes10^{-23}$	$J K^{-1}$	
Avogadro constant*	N_{A}	$6.02214076 imes10^{23}$	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.













fine-structure constant (cgs)



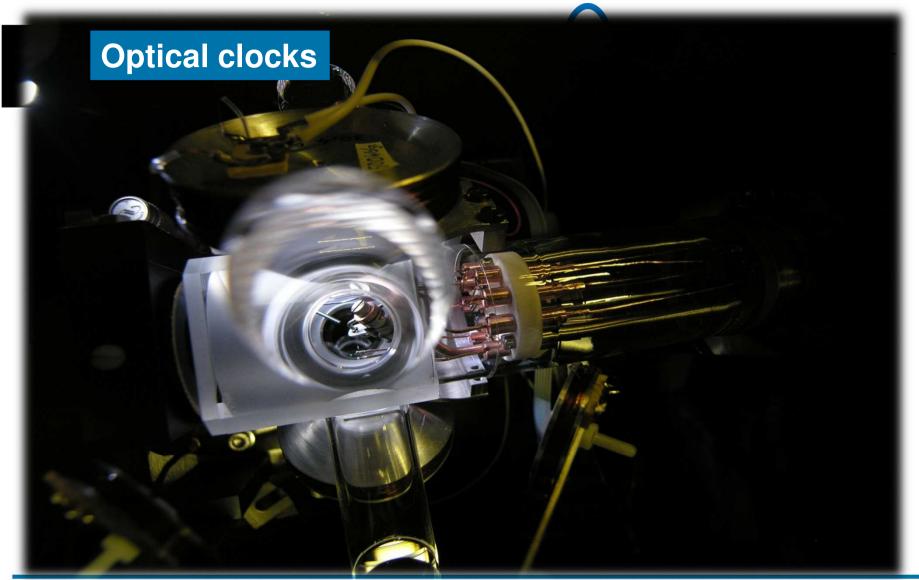


Arnold Sommerfeld

energy levels in hydrogen

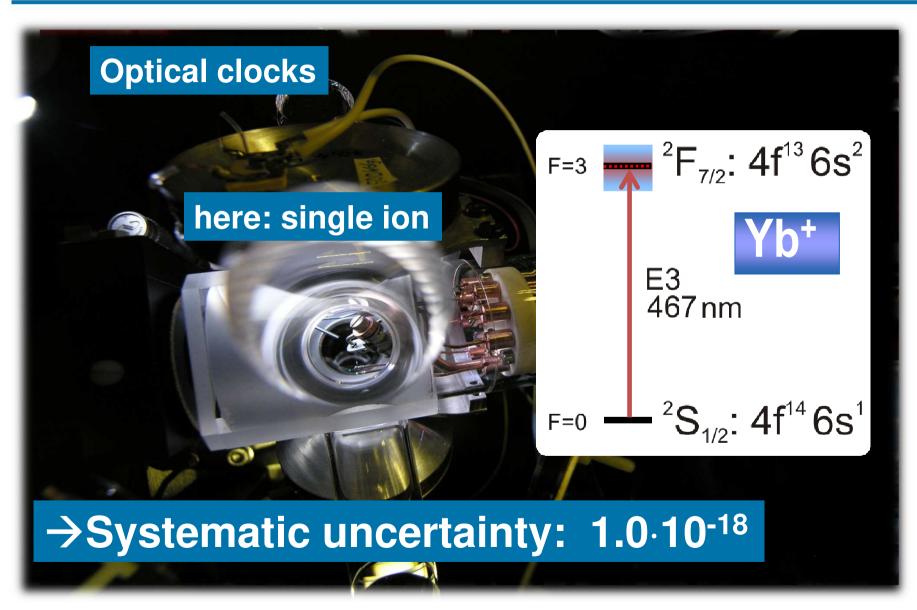
(21)
$$W = -\frac{Nh}{(n+n')^2} \left(\frac{E}{e}\right)^2 \left[1 + \frac{\alpha^2}{(n+n')^2} \left(\frac{E}{e}\right)^2 \left\{\frac{1}{4} + \frac{n'}{n}\right\}\right].$$





Physikalisch-Technische Bundesanstalt ■ Braunschweig and Berlin







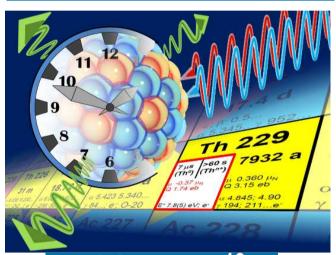








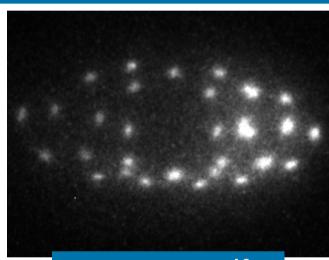
Nuclear Transition



 $\Delta f/f \sim 10^{-19}$ $\Delta \alpha/\alpha < 10^{-20} /a$

Enhancement: 0...10 000

Highly Charged Ions



 $\Delta f/f \sim 10^{-19}$ $\Delta \alpha/\alpha < 10^{-20} /a$

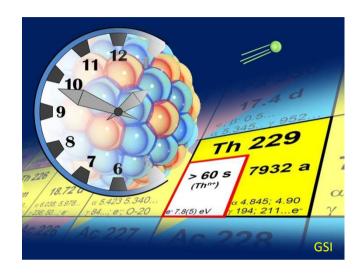
Enhancement: ~< 100

²²⁹Th: Nuclear clock & fundamental tests



Th-229 has an isomeric state at about 8 eV Excitation energy.

- Bridge between atomic and nuclear physics
- Reference for an ultra-precise optical clock
- Unique properties for fundamental tests with clocks (Standard Model, strong interaction)

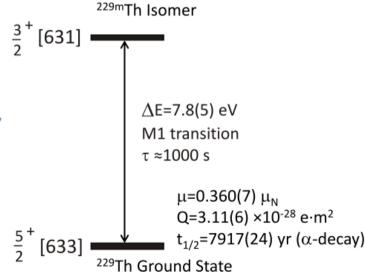


Laser spectroscopic characterization of the nuclear-clock isomer ^{229m}Th

Johannes Thielking, Maxim V. Okhapkin, Przemysław Głowacki, David M. Meier, Lars von der Wense, Benedict Seiferle, Christoph E. Düllmann, Peter G. Thirolf & Ekkehard Peik [™]

Nature 556, 321–325 (2018) doi:10.1038/s41586-018-0011-8 Download Citation

Received: 15 September 2017 Accepted: 13 February 2018 Published online: 18 April 2018



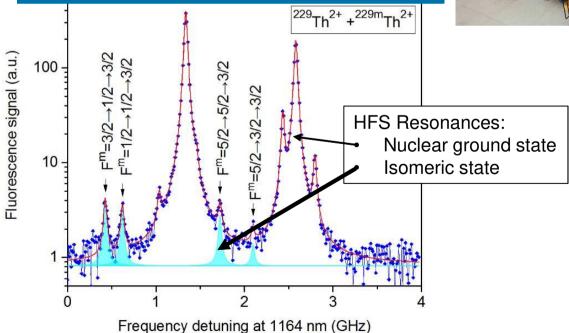
²²⁹Th: Nuclear clock & fundamental tests

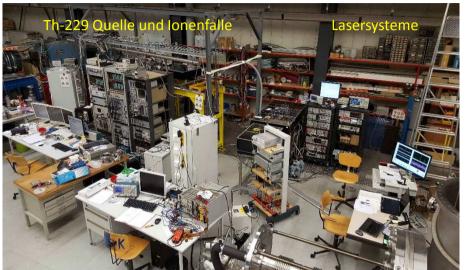


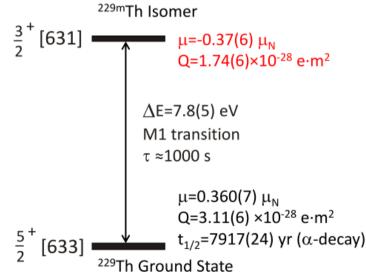
Cooperation between PTB, LMU München, Uni Mainz und GSI:

Laser hyperfine spectroscopy of trapped $^{229}\text{Th}^{2+}$ recoil ions from the α -decay of ^{233}U .

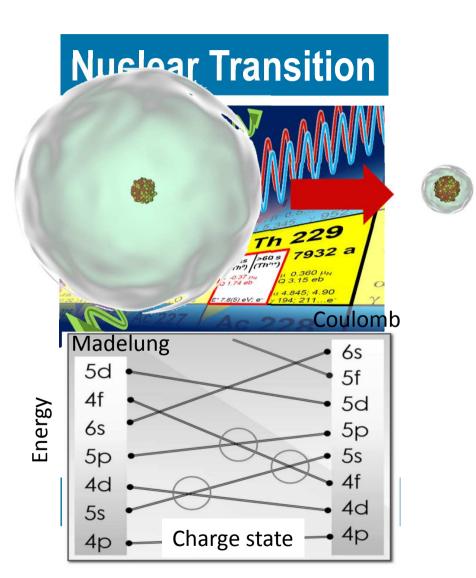
- First optical detection of the isomer
- Nuclear moments of the isomer
- Charge radius of the isomer



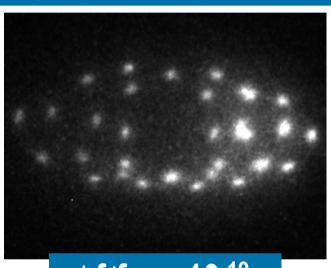








Highly Charged Ions



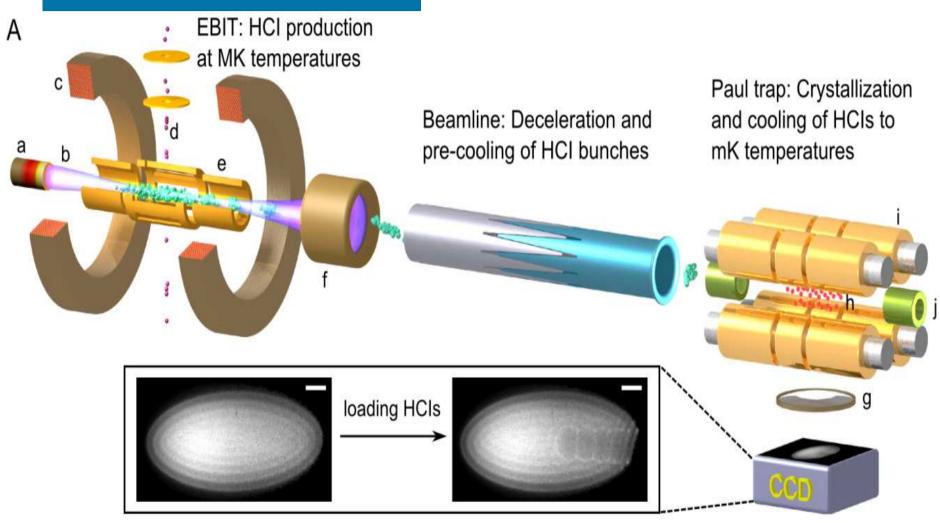
 $\Delta f/f \sim 10^{-19}$ $\Delta \alpha/\alpha < 10^{-20} /a$

Enhancement: ~< 100

Highly charged ions: Optical transitions



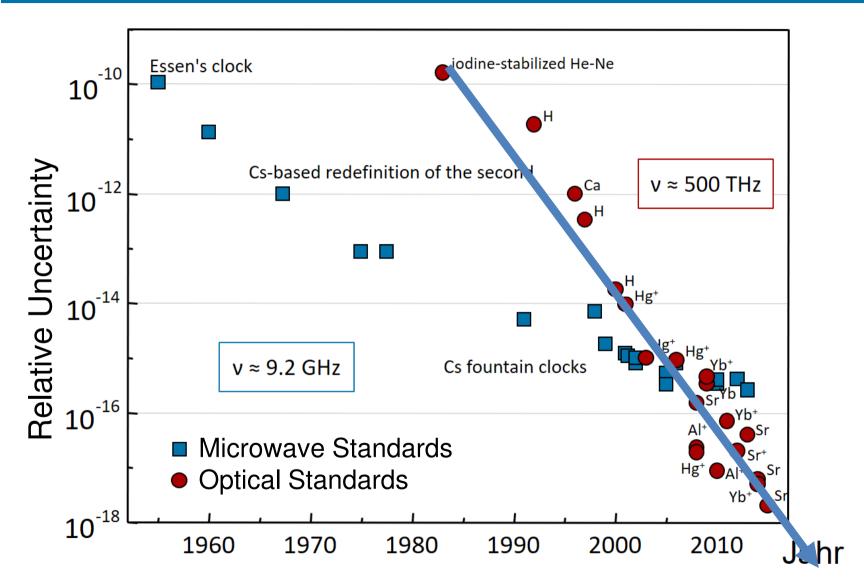
MPIK-PTB-Collaboration





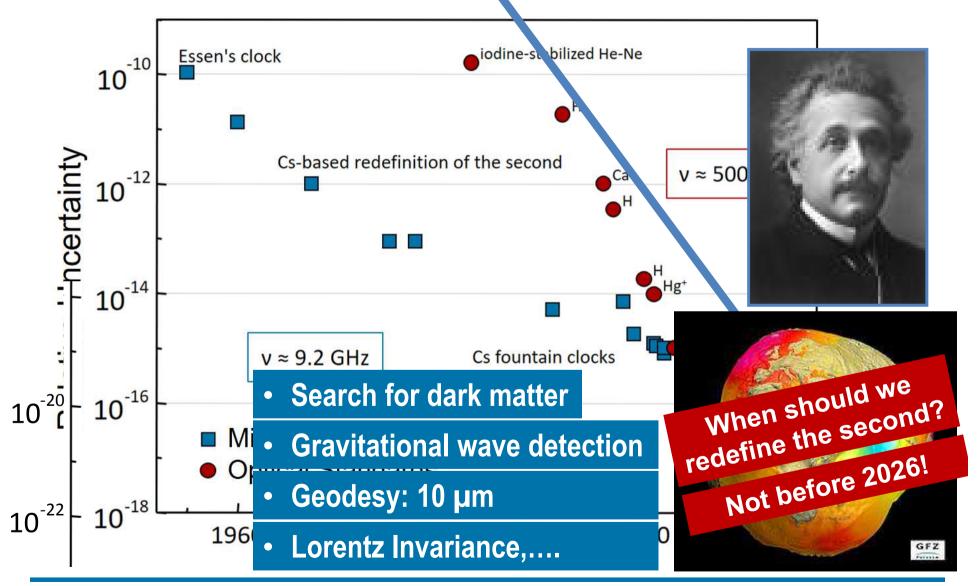
The Future of the Second



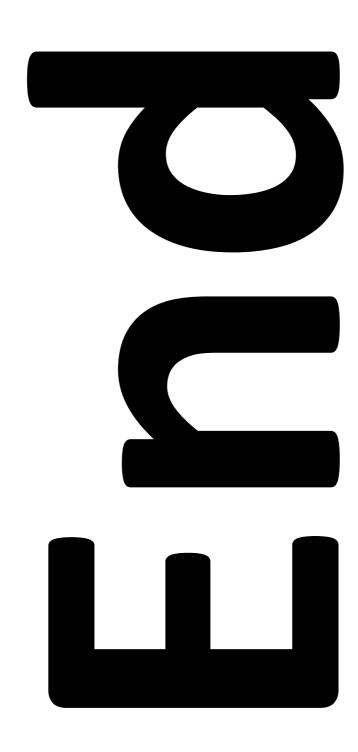


The Future of the Second



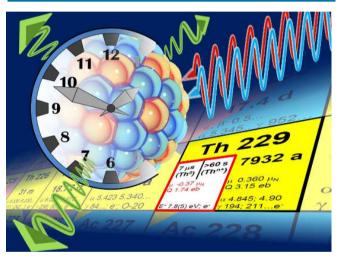








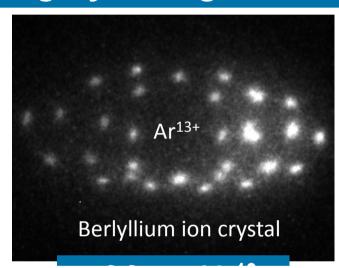
Nuclear Transition



Laser spectroscopic characterization of the nuclear-clock isomer ^{229m}Th

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

Highly Charged Ions



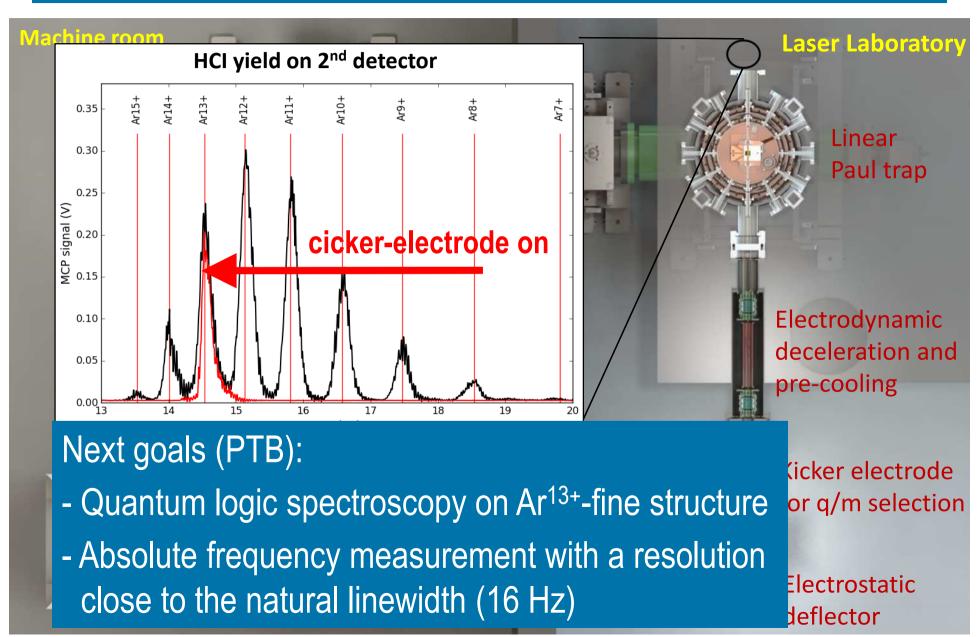
Coulomb crystallization of highly charged ions

Next goals:

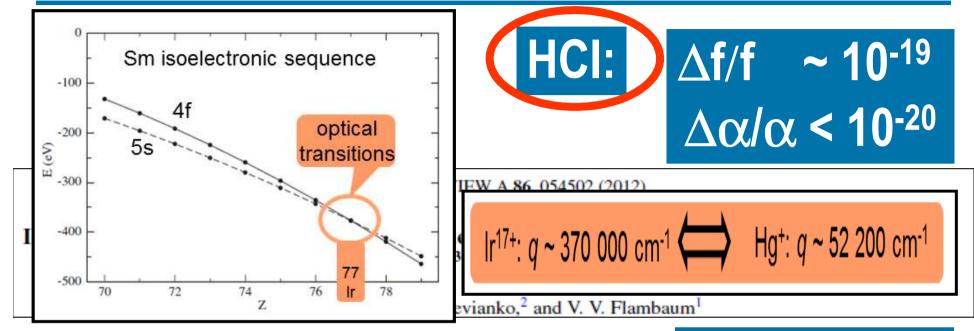
- Quantum logic spectroscopy: Ar¹³⁺
- Absolute frequency at a resolution close to the natural linewidth (16 Hz)

Highly charged ions: Optical transitions









ARTICLE

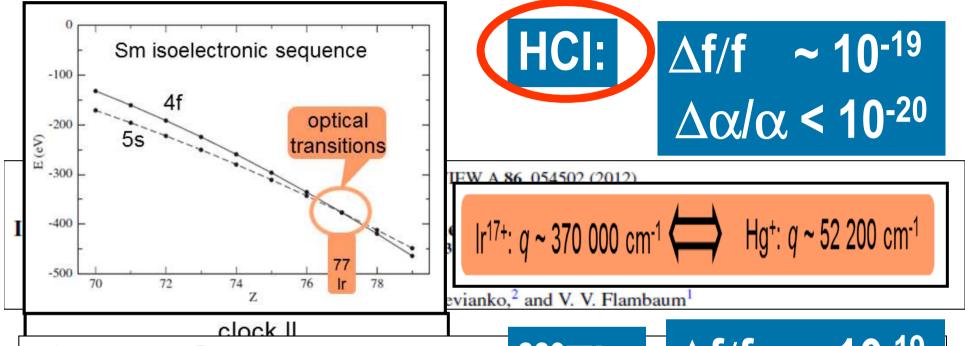
²²⁹Th:

 $\Delta f/f \sim 10^{-19}$ $\Delta \alpha/\alpha < 10^{-20}$

Direct detection of the ²²⁹Th nuclear clock transition

Lars von der Wense¹, Benedict Seiferle¹, Mustapha Laatiaoui^{2,3}, Jürgen B. Neumayr¹, Hans-Jörg Maier¹, Hans-Friedrich Wirth¹, Christoph Mokry^{3,4}, Jörg Runke^{2,4}, Klaus Eberhardt^{3,4}, Christoph E. Düllmann^{2,3,4}, Norbert G. Trautmann⁴ & Peter G. Thirolf¹





ARTICLE

²²⁹Th:

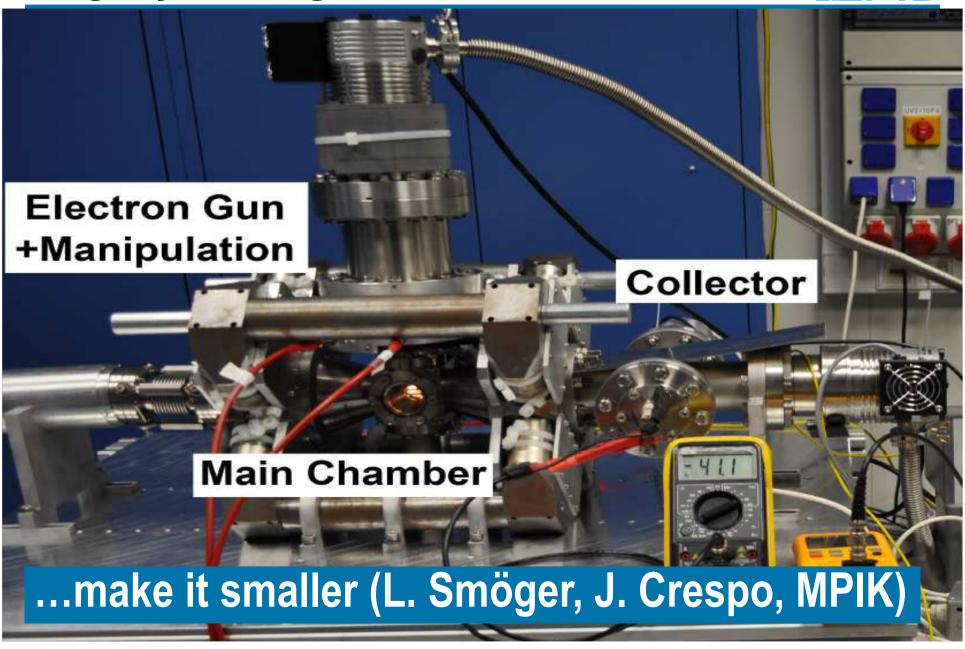
 $\Delta f/f \sim 10^{-19}$ $\Delta \alpha/\alpha < 10^{-20}$

Direct detection of the ²²⁹Th nuclear clock transition

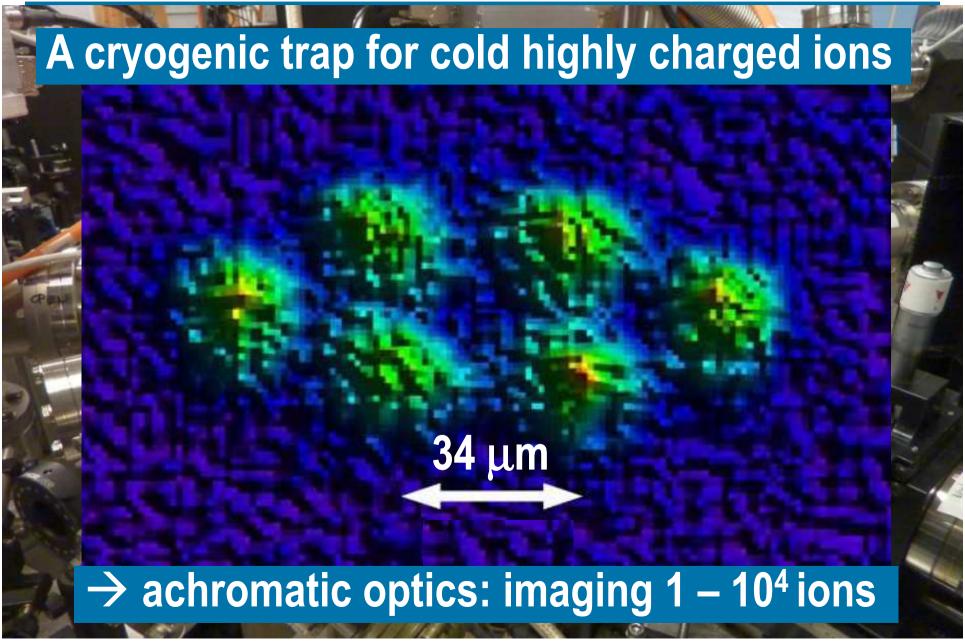
Lars von der Wense¹, Benedict Seiferle¹, Mustapha Laatiaoui^{2,3}, Jürgen B. Neumayr¹, Hans-Jörg Maier¹, Hans-Friedrich Wirth¹, Christoph Mokry^{3,4}, Jörg Runke^{2,4}, Klaus Eberhardt^{3,4}, Christoph E. Düllmann^{2,3,4}, Norbert G. Trautmann⁴ & Peter G. Thirolf¹

Highly Charged Ions



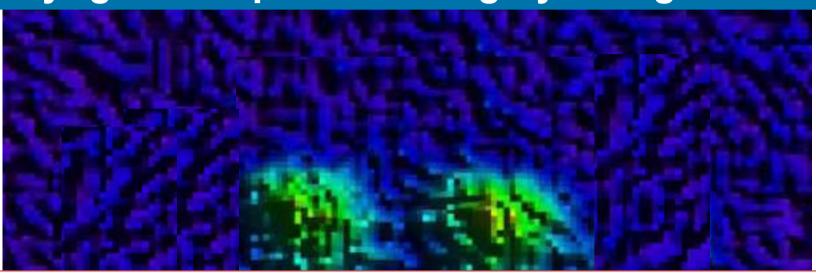








A cryogenic trap for cold highly charged ions



REVIEW OF SCIENTIFIC INSTRUMENTS 83, 083115 (2012)

Cryogenic linear Paul trap for cold highly charged ion experiments

M. Schwarz,^{1,3} O. O. Versolato,^{1,2} A. Windberger,¹ F. R. Brunner,¹ T. Ballance,¹ S. N. Eberle,¹ J. Ullrich,^{1,3} P. O. Schmidt,^{3,4} A. K. Hansen,⁵ A. D. Gingell,⁵ M. Drewsen,⁵ and J. R. Crespo López-Urrutia¹

¹Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

²University of Groningen, Kernfysisch Versneller Instituut, NL-9747 AA Groningen, The Netherlands

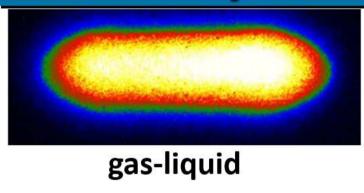
³Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

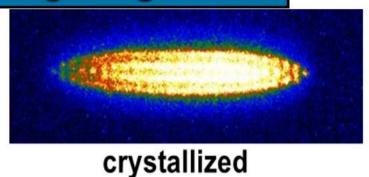
⁴Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

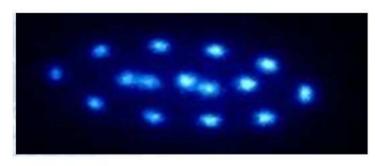
⁵Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark



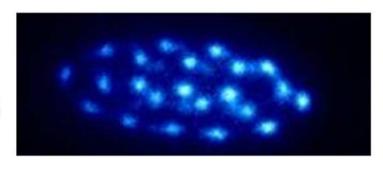
Coulomb crystals of Be cooling / logic ion

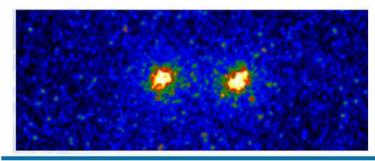




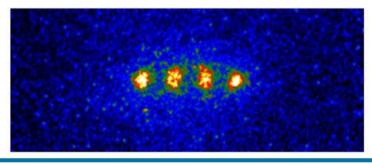


small ensembles

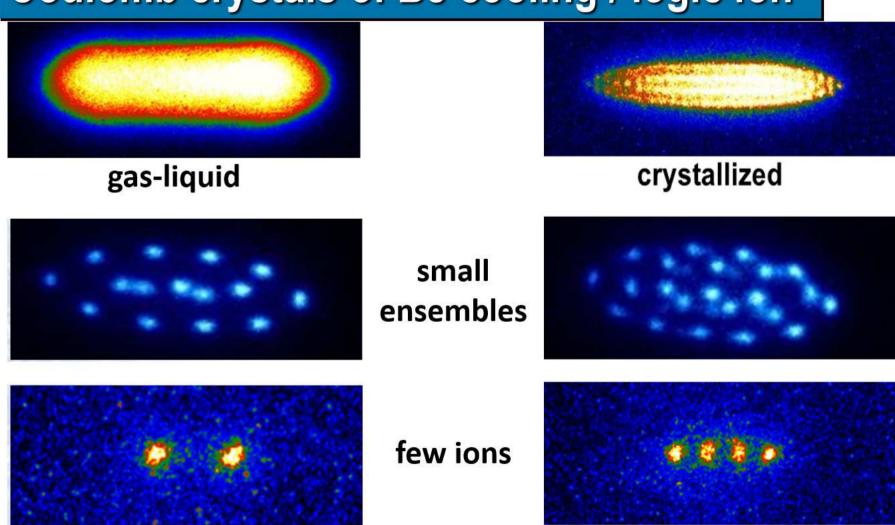




few ions

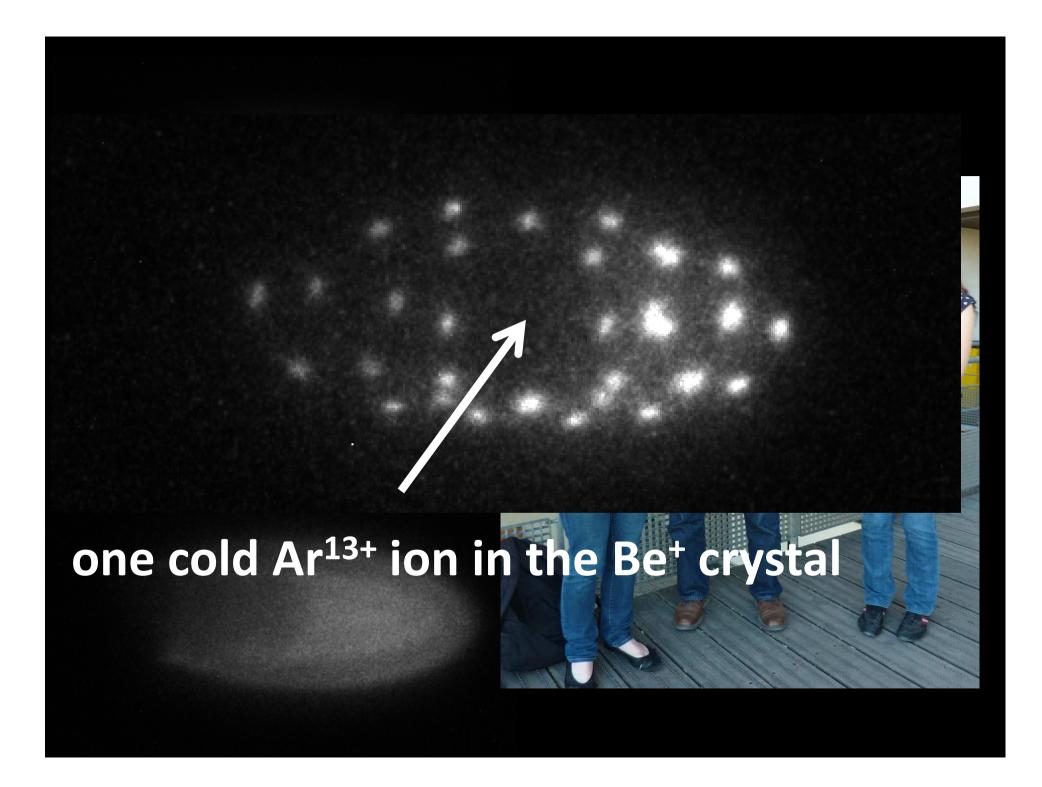


Coulomb crystals of Be cooling / logic ion



Physikalisch-Technische Bundesanstalt ■ Braunschweig and Berlin

National Metrology Institute





The Future of the Second



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

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

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

(Dated: March 20, 2015)

green: in operation
yellow: commissioning
red: planned

OBSPARIS

Helgoland
St. Peter Ording

NPL
IQ
PTB

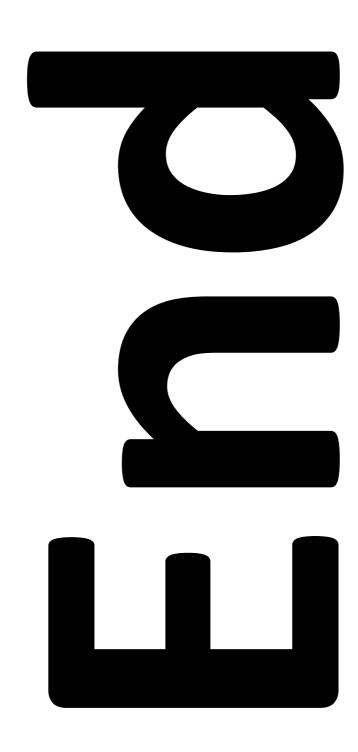
KIT
OBSPARIS

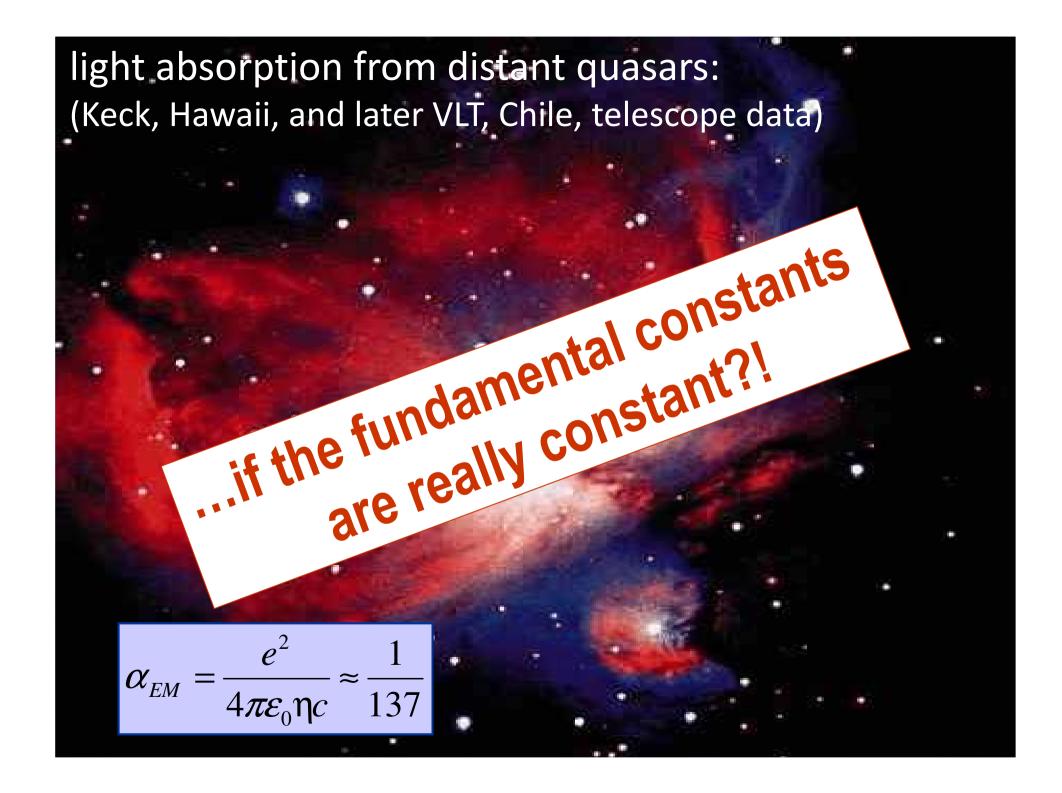
MPQ

NIST (J.Ye): first laser air link: ~10⁻¹⁸ demonstrated!

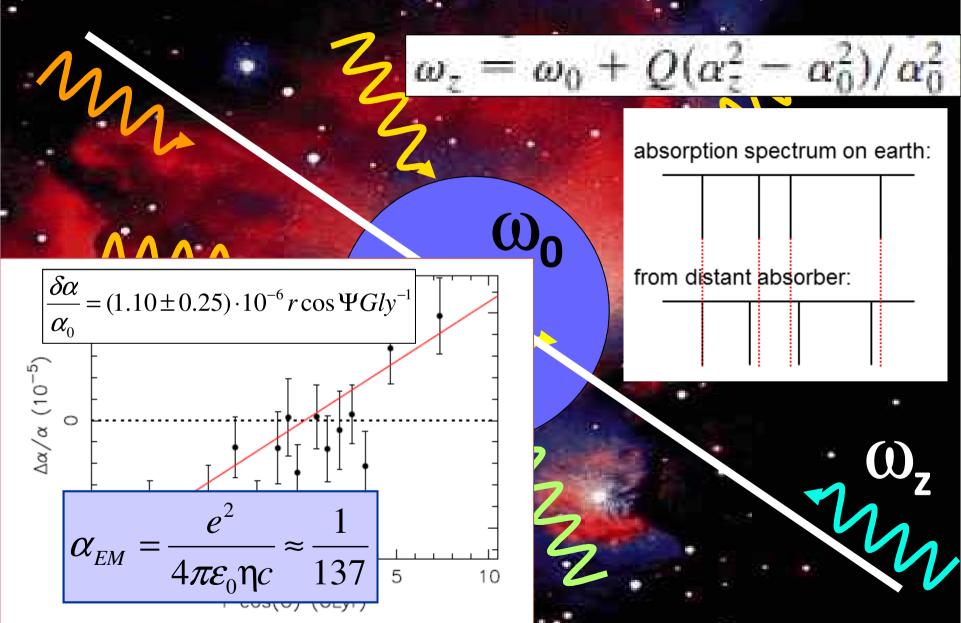
First agreement of two very distant clocks with 4.7·10⁻¹⁷! → world record!







light absorption from distant quasars: (Keck, Hawaii, and later VLT, Chile, telescope data)



Are the FCs changing with time?



Triggered quite some theory...

Berengut and Flambaum EPL **97** (2012) 2006

$$\dot{\alpha}/\alpha|_{\rm lab} = 1.35 \times 10^{-18} \cos \psi \, {\rm y}^{-1},$$

$$\cos \psi \sim 0.07$$
,

$$\frac{\delta\alpha}{\alpha} = 1.4 \times 10^{-20} \, \cos\omega t$$

Yearly variation

$$\frac{d \ln \alpha}{dt} = (-7.3 \pm 4.5) \cdot 10^{-18} \text{ yr}^{-1}$$

A DOTTOT TO

Yb⁺ E3/Cs

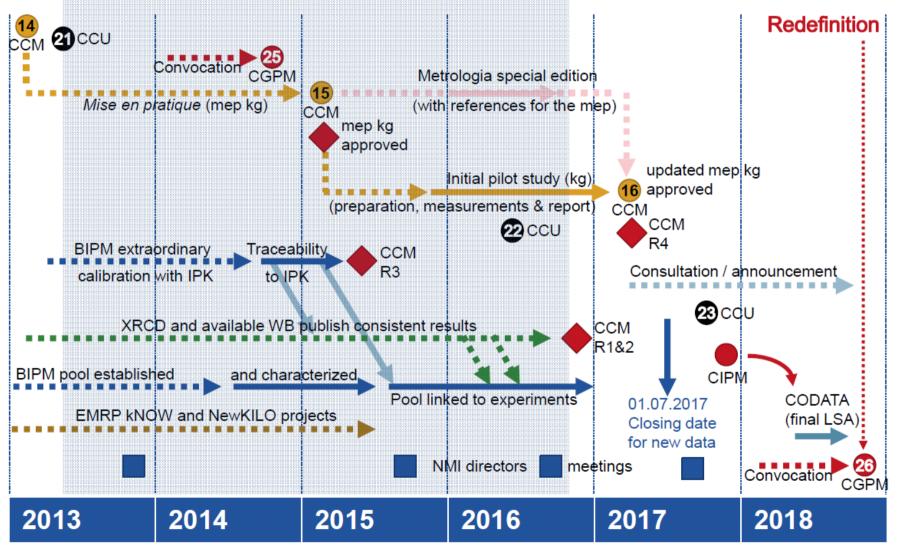
ARTICLE

doi:10.1038/nature17669

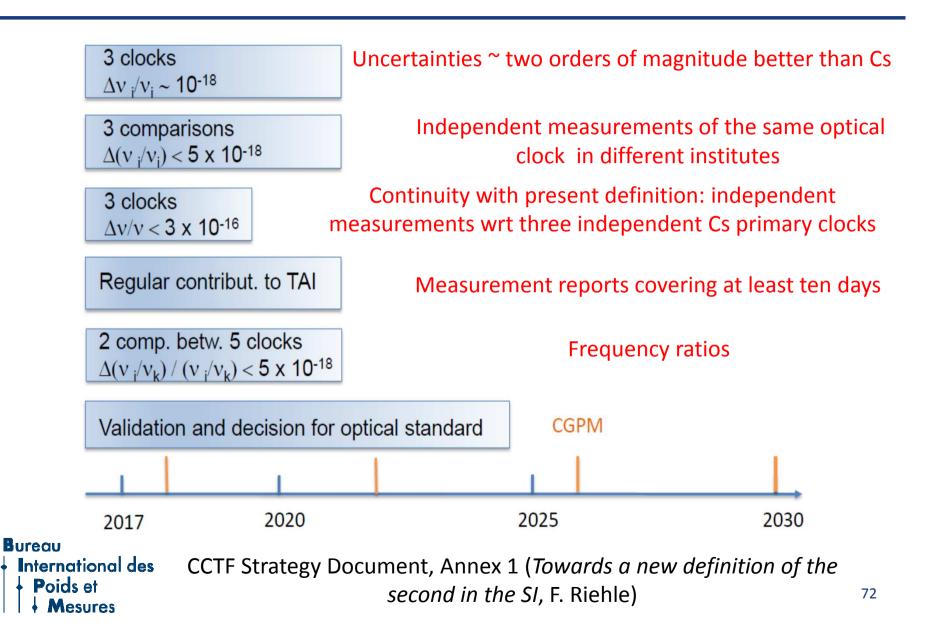
Direct detection of the ²²⁹Th nuclear clock transition

Lars von der Wense¹, Benedict Seiferle¹, Mustapha Laatiaoui^{2,3}, Jürgen B. Neumayr¹, Hans-Jörg Maier¹, Hans-Friedrich Wirth¹, Christoph Mokry^{3,4}, Jörg Runke^{2,4}, Klaus Eberhardt^{3,4}, Christoph E. Düllmann^{2,3,4}, Norbert G. Trautmann⁴ & Peter G. Thirolf¹

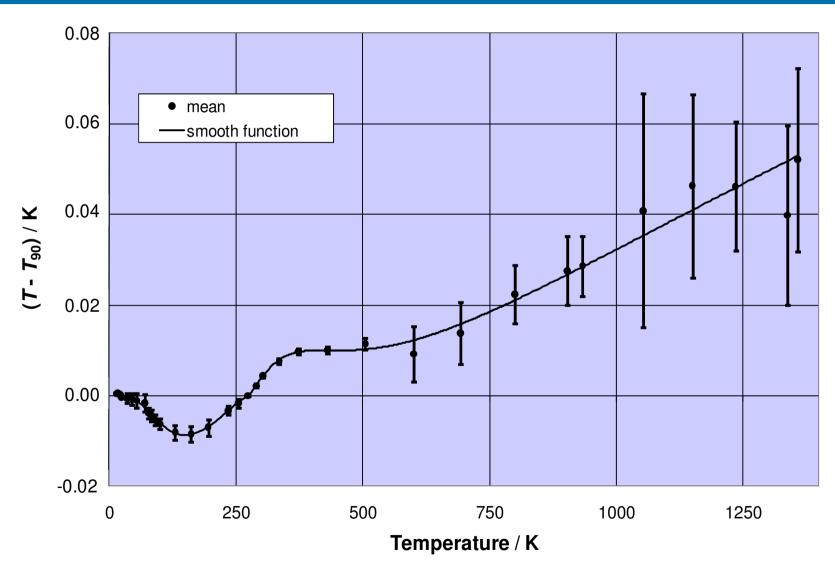
Joint CCM & CCU roadmap to 2018



« Prediction » of the timeline for redefinition











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

1988 Guarantees $u_r(k) \approx 2 \text{ ppm}$ A set of "dest Spee Diff a Realisation Throughout"

Throughout

ncer $c_0 \approx (\gamma k_B T / m)^{1/2}$ tally!

Guarantees long-time stability

A set of "defining constants"

Speed of sound in

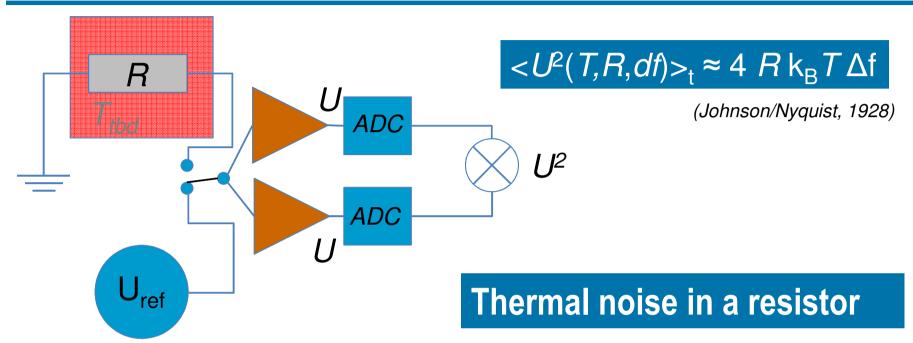
Difi a resonator

Realisation everywhere (Universe...)

Throughout the entire scale

- Acoustic gas thermometry
- Dielectric constant gas thermometry
- Doppler thermometry
- Noise thermometry
- Radiation thermometry





Johnson Voltage Standard

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

- Acoustic gas thermometry
- Dielectric constant gas thermometry
- Doppler thermometry
- Noise thermometry
- Radiation thermometry





See also: Qu et al., Metrologia <u>52</u> 242 (2015)

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

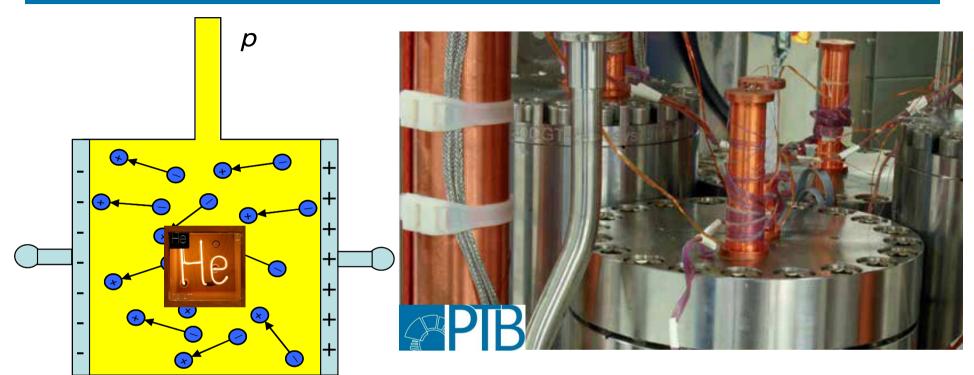
$< U^2(T,R,df)>_t \approx 4 R k_B T \Delta f$

(Johnson/Nyquist, 1928)

Thermal noise in a resistor

- Acoustic gas thermometry
- Dielectric constant gas thermometry
- Doppler thermometry
- Noise thermometry
- Radiation thermometry



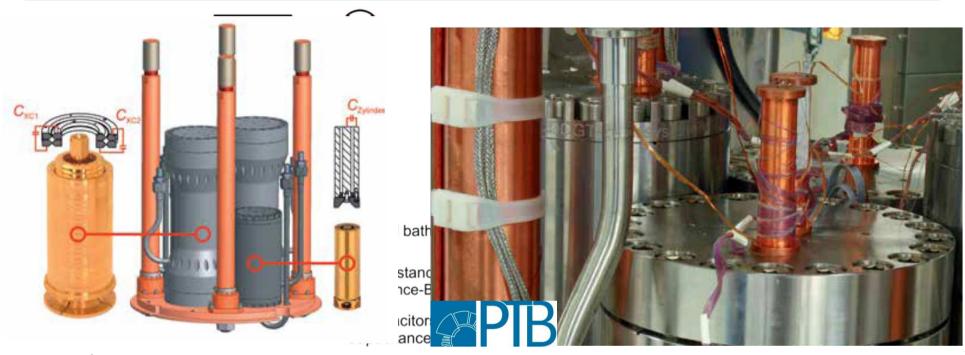


See also: Gaiser et al., Metrologia <u>52</u> 217 (2015)

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

- Acoustic gas thermometry
- Dielectric constant gas thermometry
- Doppler thermometry
- Noise thermometry
- Radiation thermometry





See also:

Gaiser et al., Metrologia <u>52</u> 217 (2015)

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

- Acoustic gas thermometry
- Dielectric constant gas thermometry
- Doppler thermometry
- Noise thermometry
- Radiation thermometry

Present SI (D. Newell)





Present SI "defining constants" that will be experimentally determined in new SI

International prototype of the kilogram:

$$m(\mathcal{K}) = 1 \text{ kg}$$

Permeability of vacuum:

$$\mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1}$$

Triple point of water:

$$T_{\rm TPW} = 273.16 \; {\rm K}$$

Molar mass of the carbon 12 atom:

$$M(^{12}C) = 0.012 \text{ kg mol}^{-1}$$

Future SI (D. Newell)





Appendix 3, 26th CGPM Draft Resolution A (document CCU/16-03)

Status of constants previously used in the former definitions:

- the mass of the international prototype of the kilogram m(X)
 will be 1 kg but within a relative uncertainty equal to that
 of the recommended value of h at the time this Resolution
 was adopted, namely xxxx, and that in the future its value will
 be determined experimentally,
- $\mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1}$, within $u_r(\alpha)$. . .
- $T_{\text{TPW}} = 273.16 \text{ K}$, (closely) within $u_{\text{r}}(k) \dots$
- $M(^{12}C) = 0.012 \text{ kg mol}^{-1}$, within $u_r(N_A h) \dots$

Future SI (D. Newell)





Number of digits and consistency factors from CODATA 2014 for three cases

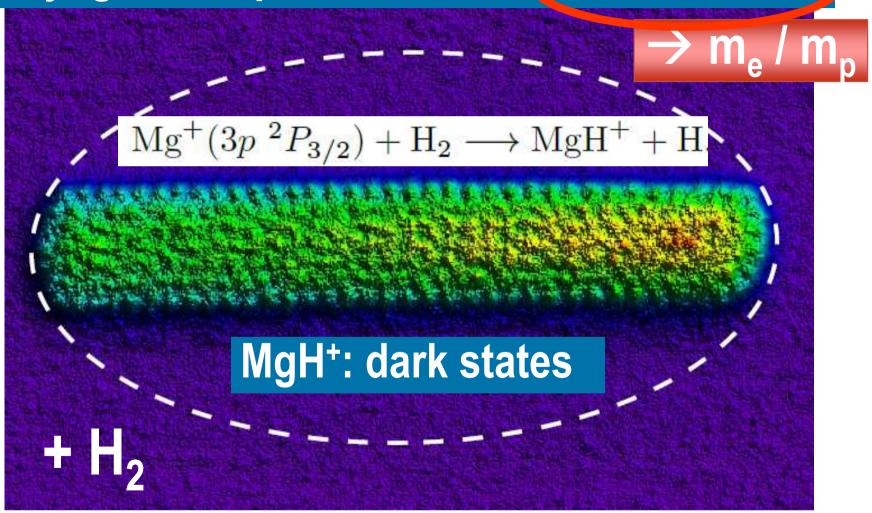
Constant	Case I; digits	Case II; digits	Case III; digits
h	6.626 070 039 6×10 ⁻³⁴ ; 11	6.626 070 04×10 ⁻³⁴ ; 9	6.626 070 04×10 ⁻³⁴ ; 9
e	1.602 176 620 77×10 ⁻¹⁹ ; 12	1.602 176 620 8×10 ⁻¹⁹ ; 11	1.602 176 621×10 ⁻¹⁹ : 10
k	1.380 648 52×10 ⁻²³ ; 9	1.380 648 52×10 ⁻²³ ; 9	1.380 649×10 ⁻²³ ; 7
$N_{\mathtt{A}}$	6.022 140 857 46×10 ²³ ; 12	6.022 140 857×10 ²³ ; 10	6.022 140 857×10 ²³ ; 10

"New" SI to "old" SI	Case I	Case II	Case III
consistency factor			
<i>m(K)</i> /kg	1.000 000 000(12)	1.000 000 000(12)	1.000 000 000(12)
$\mu_0/(4\pi \times 10^{-7} \text{ H m}^{-1})$	1.000 000 000 00(23)	1.000 000 000 02(23)	0.999 999 999 77(23)
$T_{\rm TPW}/(273.16~{\rm K})$	1.000 000 00(57)	1.000 000 00(57)	0.999 999 65(57)
$M(^{12}C)/(0.012 \text{ kg/mol})$	1.000 000 000 00(45)	0.999 999 999 98(45)	0.999 999 999 98(45)

Are the FCs changing with time?

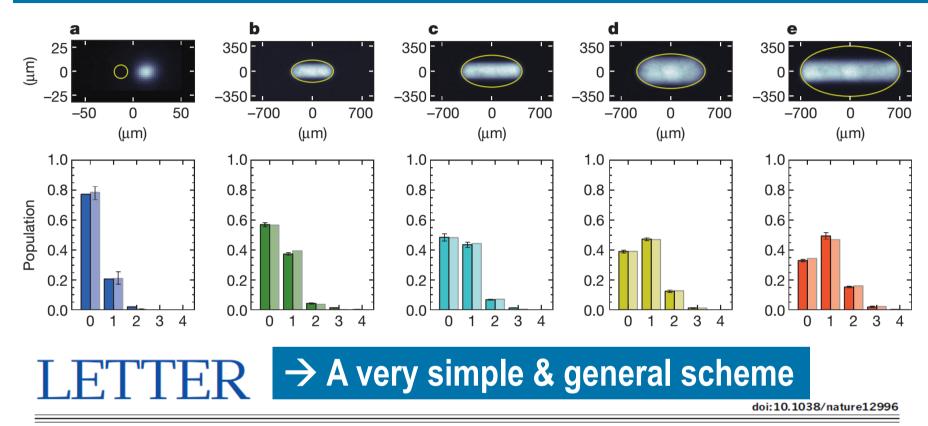


A cryogenic trap for cold HCI (molecular ions)



Are the FCs changing with time?



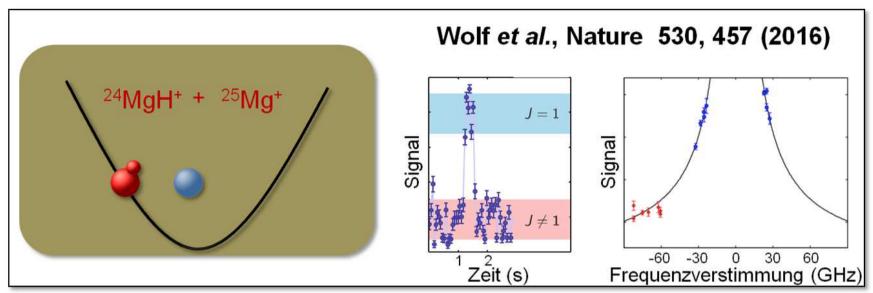


Efficient rotational cooling of Coulomb-crystallized molecular ions by a helium buffer gas

A. K. Hansen¹, O. O. Versolato², Ł. Klosowski³, S. B. Kristensen¹, A. Gingell¹, M. Schwarz², A. Windberger², J. Ullrich^{2,4}, J. R. Crespo López-Urrutia² & M. Drewsen¹

Are the FCs changing with time?





Quantum-logic with molecules

