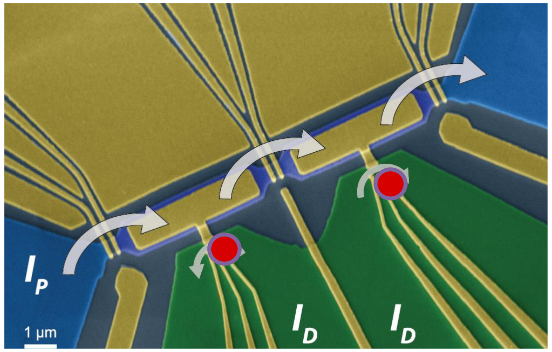
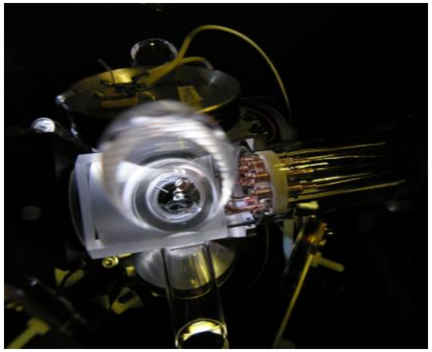
Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

The revised SI for innovation, science and the second quantum revolution





Prof Dr Joachim H. Ullrich

President of PTB, Physikalisch-Technische Bundesanstalt

President of the Consultative Committee of Units

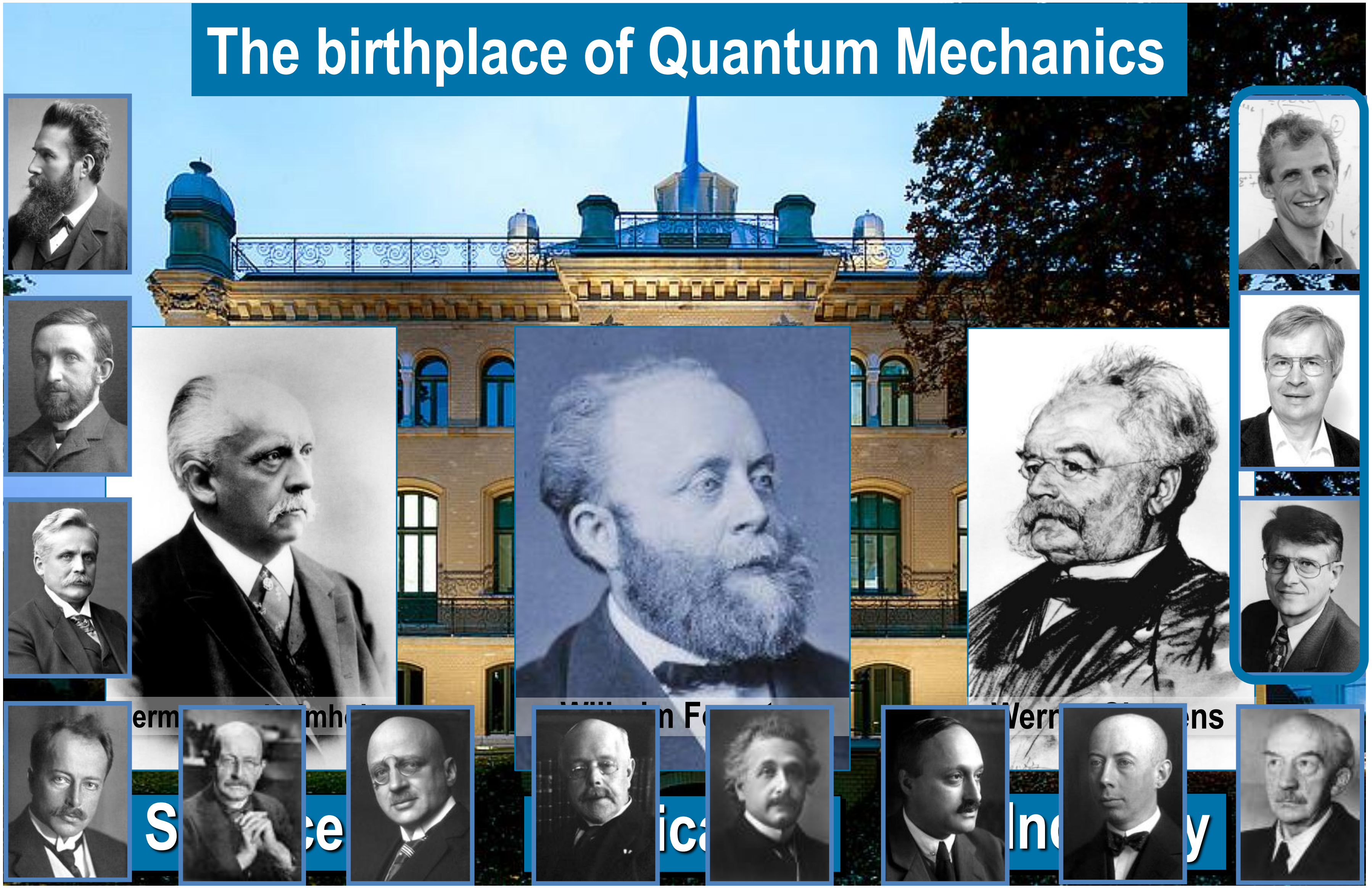
Vice President of the CIPM

International Symposium Tokyo, 21/02/2020

Physikalisch-Technische Reichsanstalt

PTB

The birthplace of Quantum Mechanics



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

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

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

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

von Max Planck.

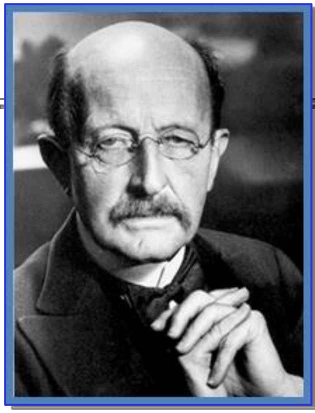
Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhülfenahme der beiden in dem Aus-

…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.



irrever… ungsvorgänge;
vor… k.

Dem gegenüber … ne Interesse sein zu bemerken, dass mit … beiden in dem Aus- druck (41) der Strahl…

…with the help of fu… tal 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…

…for all times and civilisations…

…throughout the Universe…

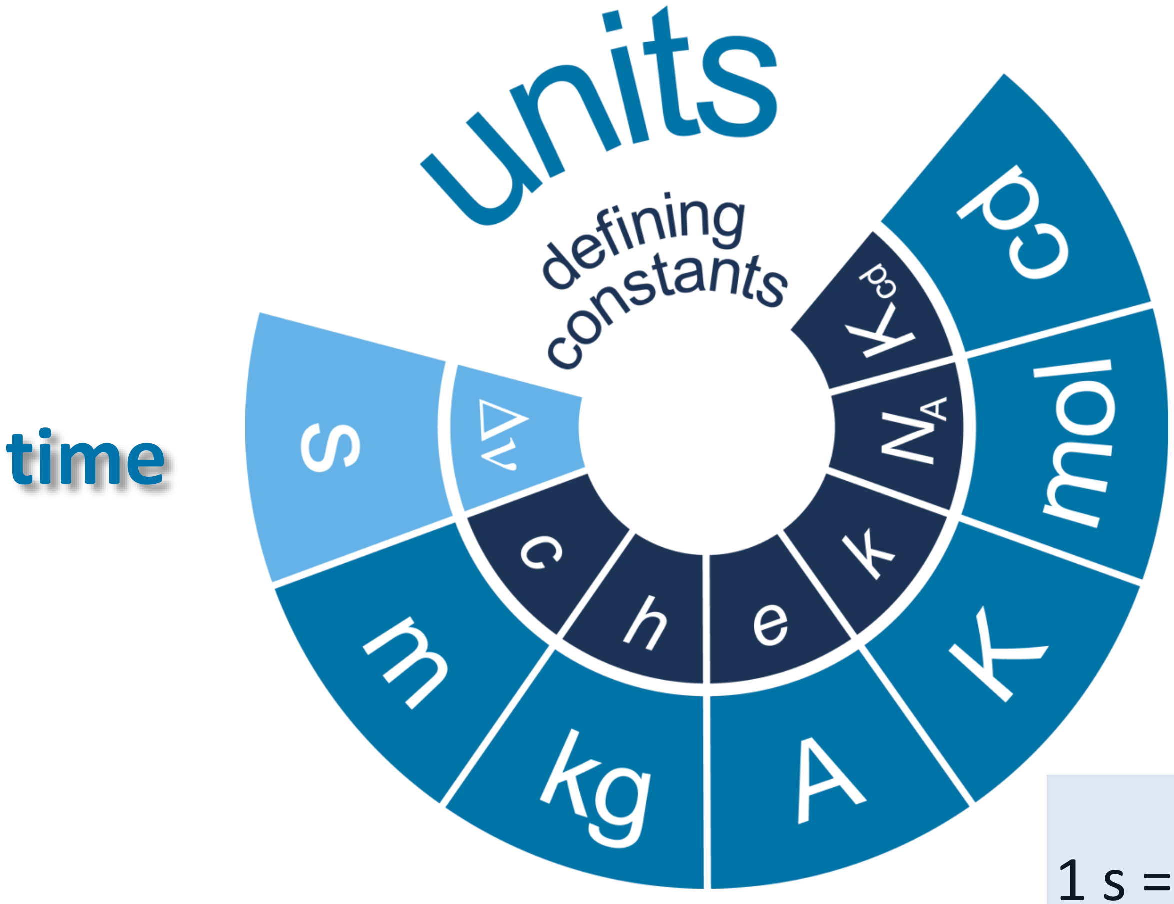
SI International System of Units

A consistent and coherent set:

based on our present understanding of nature

Revised International System of Units

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



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

Dissemination: Time/Frequency

PTB‘s Cesium Fountain Clock

Realization of SI second

- highest reliability
- small uncertainty: 2.0×10^{-16}

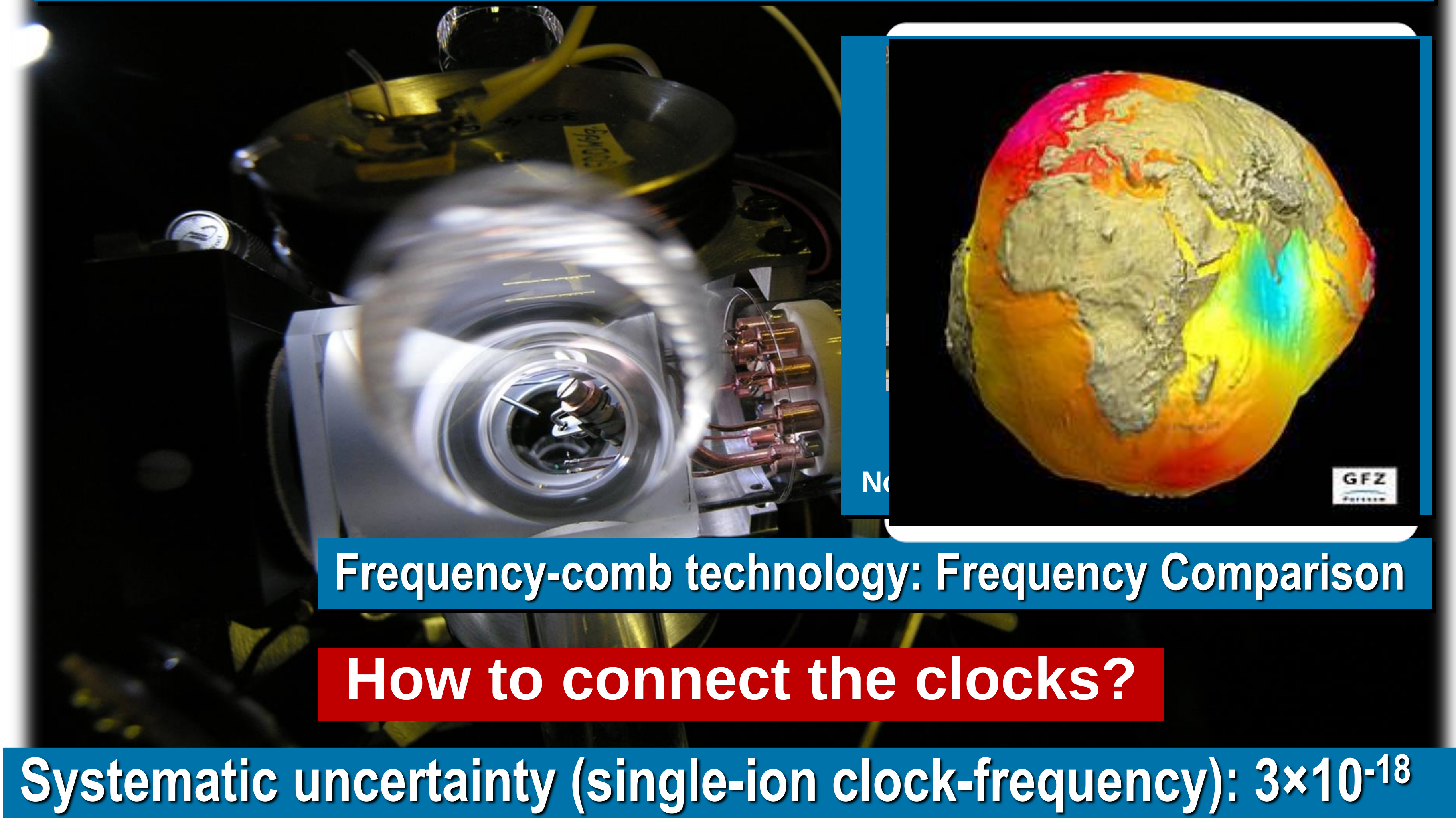
One of the most accurate realizations worldwide!

Impact: coordinated time for GALILEO, ACES

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

Innovation: Time/Frequency

The "optical pendulum" for next-generation atomic clocks



Frequency-comb technology: Frequency Comparison

How to connect the clocks?

Systematic uncertainty (single-ion clock-frequency): 3×10^{-18}

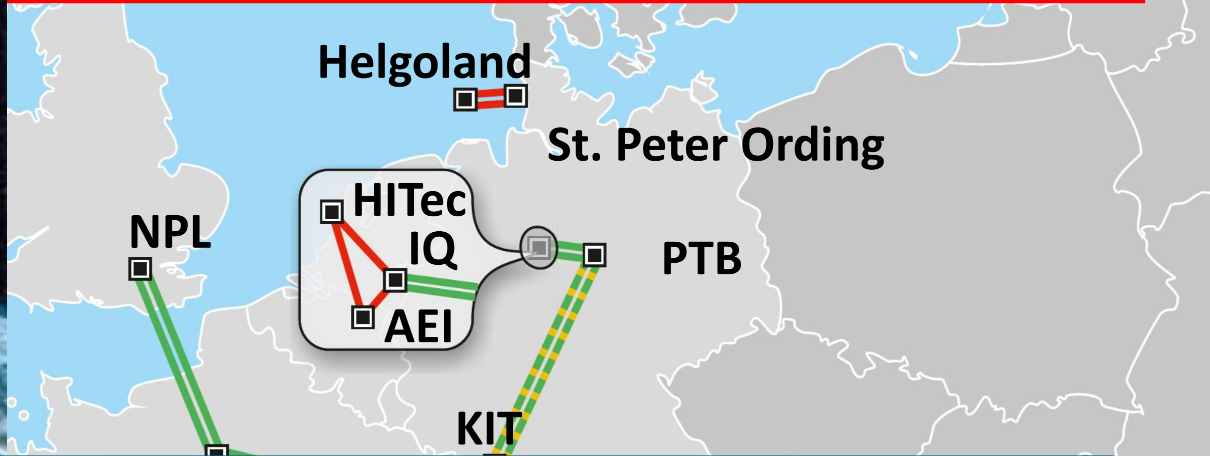
Innovation: Time/Frequency

rt. 1×10^{-20} accuracy in optical frequency transfer over
00 km of underground fibre

upach,[1,*] Andreas Koczwara,[1] and Gesine Grosche[1]

sanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany

(Dated: March 20, 2015)

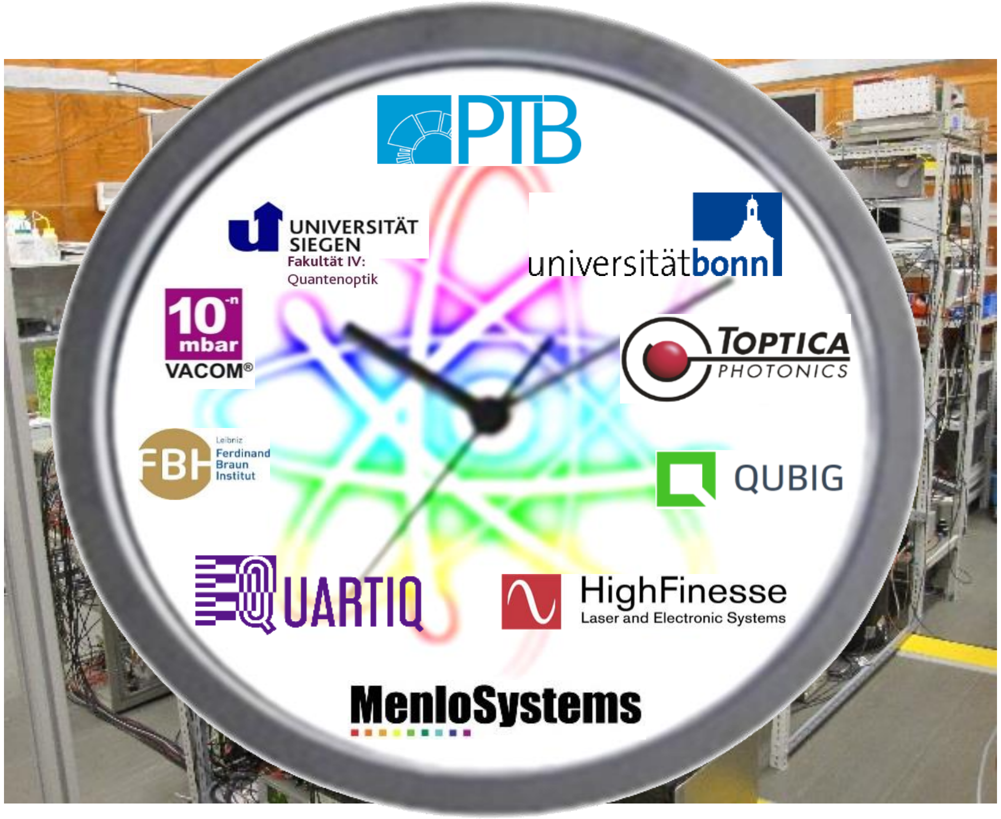


A European fiber network for

- high-precision frequency / time transmission
- quantum cryptography
- ultra-broadband information transmission

Innovation: Time/Frequency

Next-generation portable clocks: replace H-Maser



$<10^{-16}$ Uncertainty

- Data network synchronization
- Geoid surveying

~10^{-1} OptIClock Consortium
Optical Single Ion Clock
Clock

DLR-SI: QT for space

a. Satellite geodesy and geodetic modelling — Institute of Geodesy

b. Laser interferometric sensing — Institute of Gravitational Physics

c. Quantum sensing and quantum engineering — Institute of Quantum Optics

d. Optical clocks and frequency metrology — Physikalisch-Technische Bundesanstalt

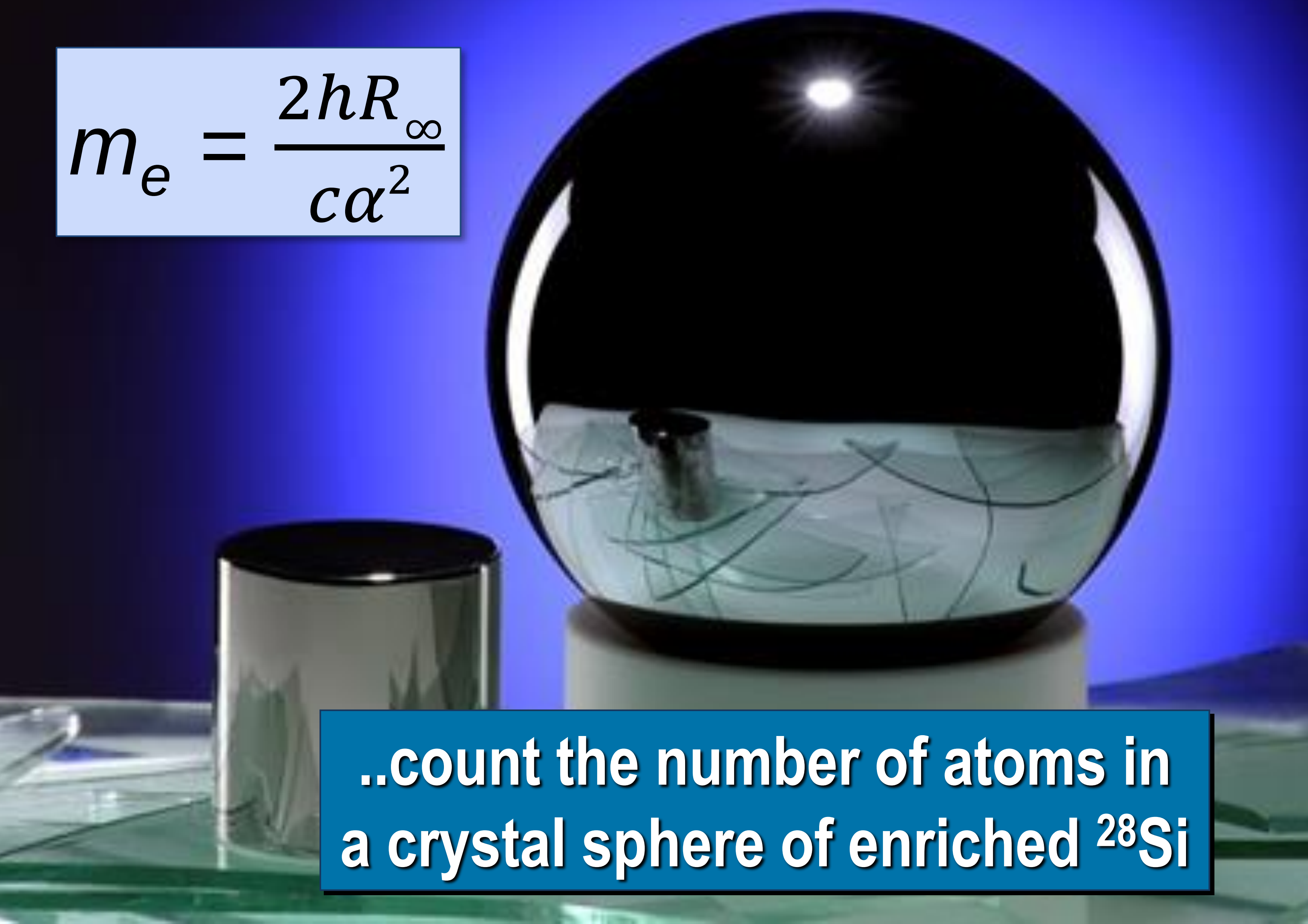
e. Tests and satellite modelling — Center of Applied Space Technology and Microgravity

PTB contributions

- Phase-stable laser systems for ground and space applications
- Integrated quantum sensors
- Optical atomic clocks for ground and space applications
- Phase-coherent optical time and frequency transfer

The Quantum Mechanics provides the mass scale via fundamental constants

$$m_e = \frac{2hR_\infty}{c\alpha^2}$$



..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

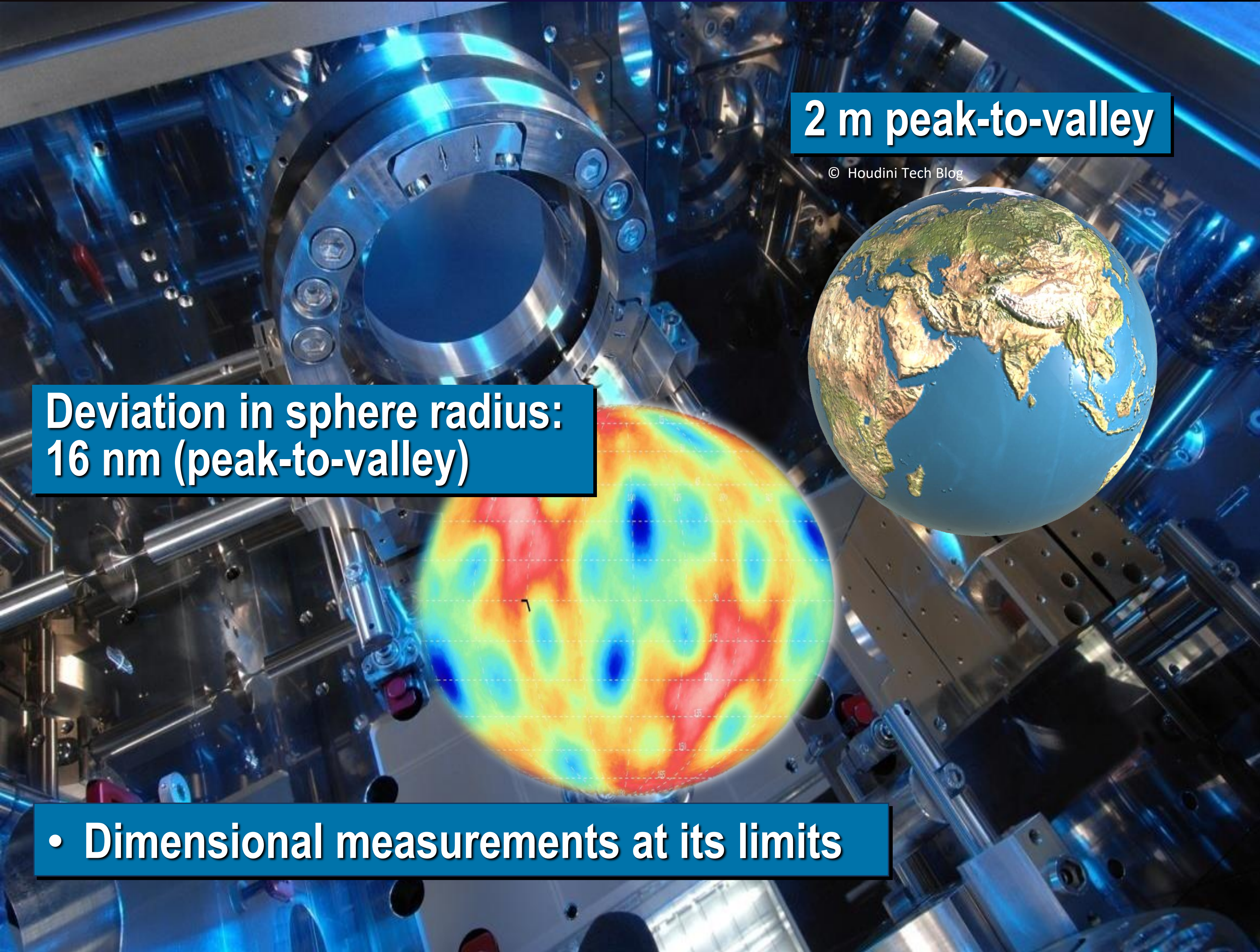
NIST

Australian Government National Measurement Institute

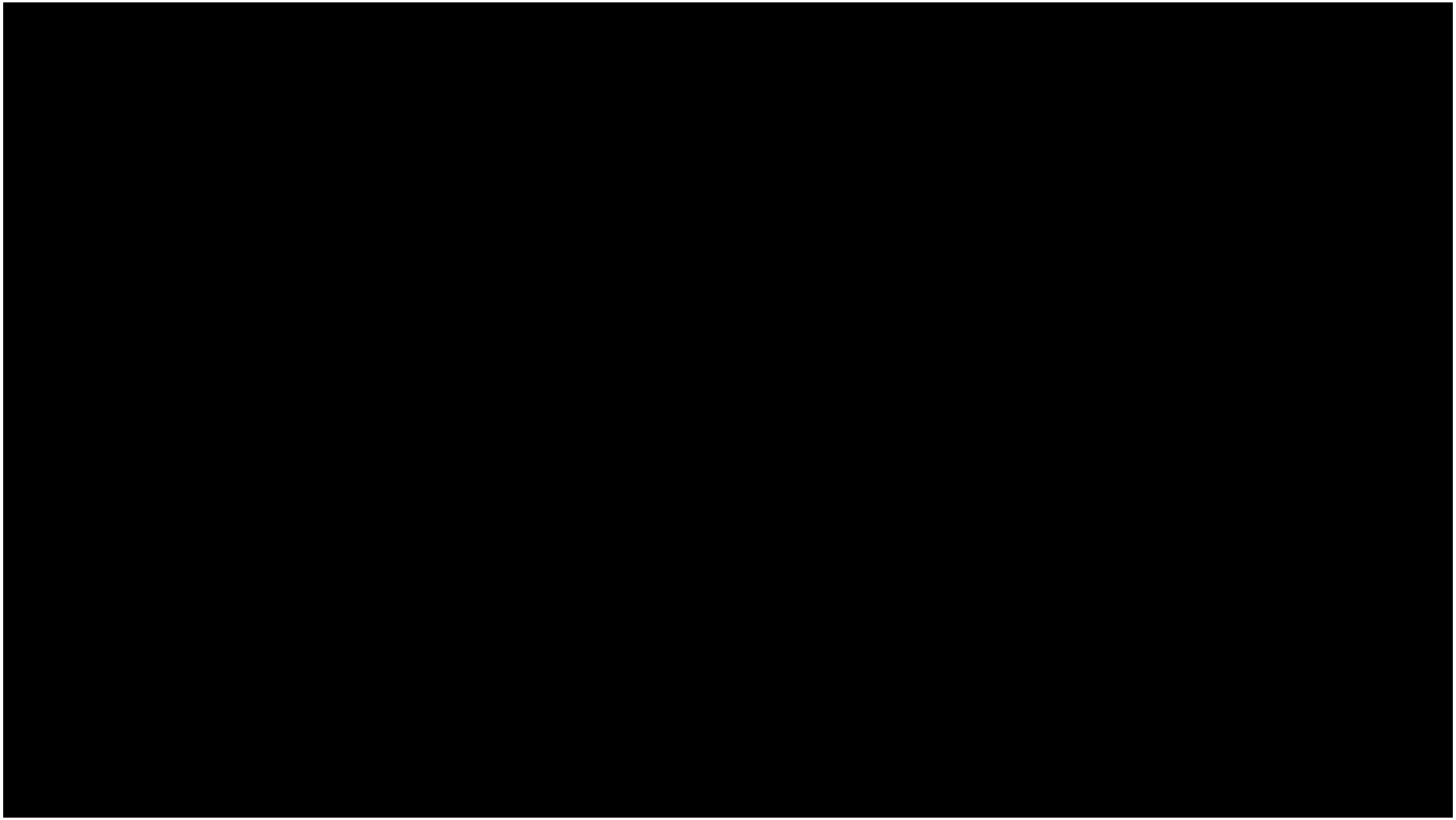
NMIJ

NPL National Physical Laboratory

PTB


2 m peak-to-valley
© Houdini Tech Blog
Deviation in sphere radius:
16 nm (peak-to-valley)
• Dimensional measurements at its limits

Si Spheres and Characterization



Innovation: Natural Silicon

Determination of ρ_{28} → Density transfer via hydrostatic comparison: ρ_{nat}

Determination of V_{nat}

→ $m_{qp} = \rho_{nat} V_{nat}$

“primary”

Mass determination by characterisation of the sphere parameters

“quasi-primary”

“potential” to become primary

“secondary”

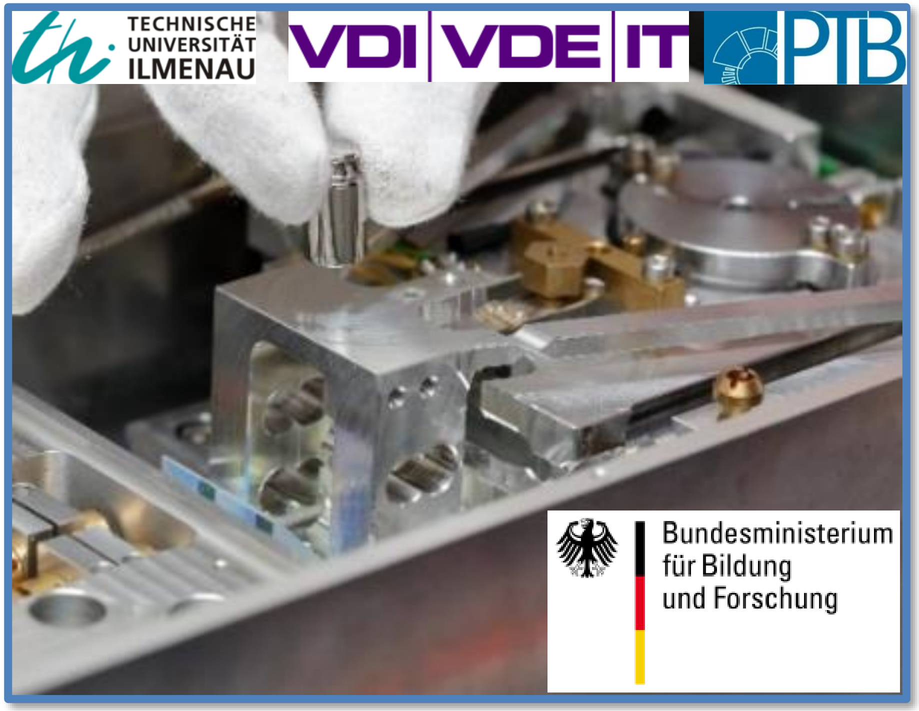
Mass determination via mass calibration

Relative uncertainty depends mainly on determination of molar mass of natural silicon – at present in the order of 10^{-6}

Innovation: Kibble Balance

Commercial Kibble Balances

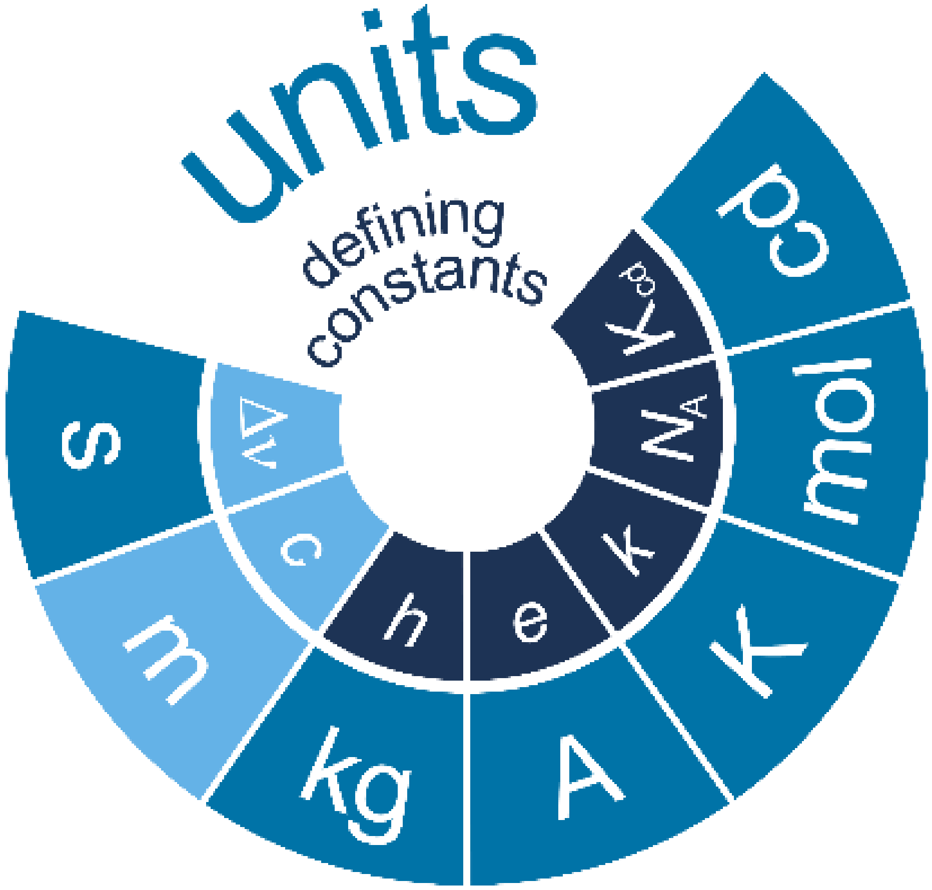
- "self-calibrating"
- high precision
- industrial application: E1, E2
- "off-the-shelve" components
- connected to the IoT



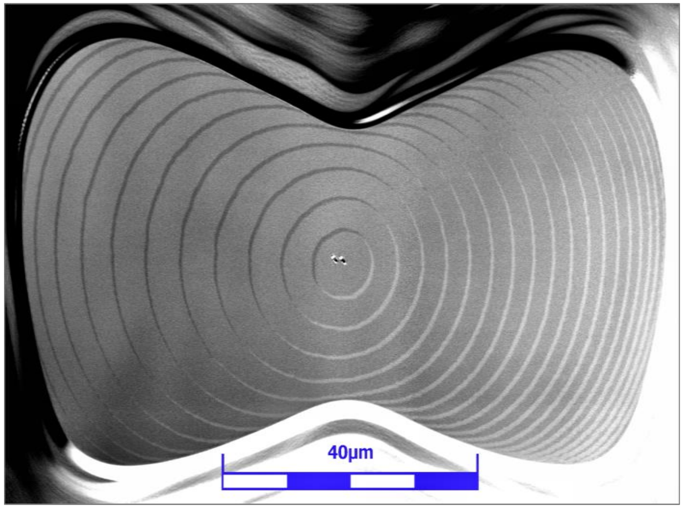
Version	Mass range	MPE OIML R111-1	$U_r \leq 1/3 \cdot$MPE k=2	Environment
PB 2 (E2)	1 mg…100 g	$16 \cdot 10^{-7}$	$5.3 \cdot 10^{-7}$	Air
PB 1 (E1)	1 mg…1 kg	$5 \cdot 10^{-7}$	$1.7 \cdot 10^{-7}$	High Vacuum

Innovation: Nanometrology

Single crystal silicon lattice structures for nanometrology



Surface metrology
based on monoatomic steps and atomically flat areas

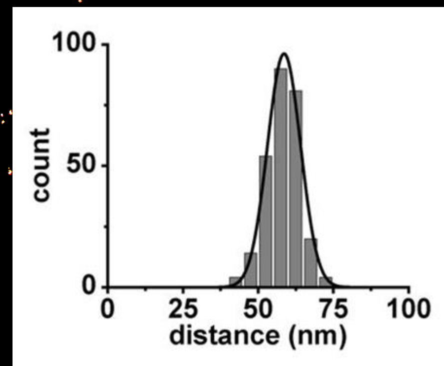


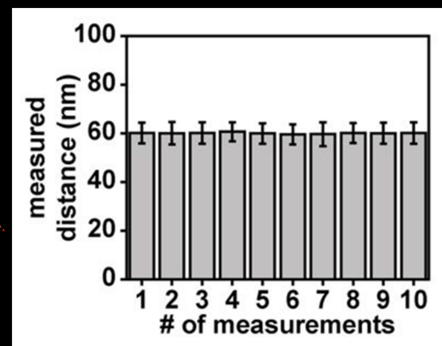
Innovation: DNA-Origami-Nanostructures

traceable length standard in the nanometre regime

Technology transfer award 2017
of the IHK Braunschweig

www.gattaquant.com



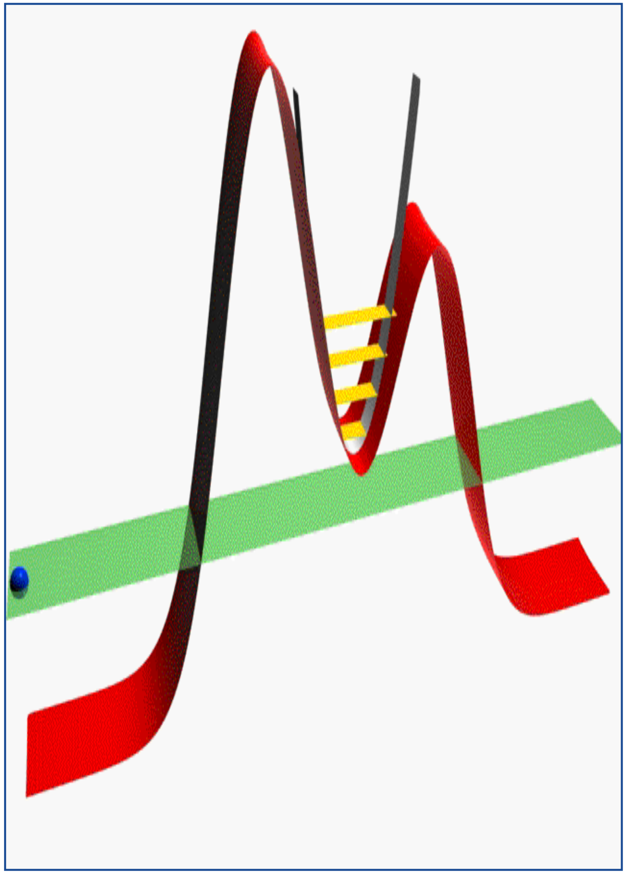


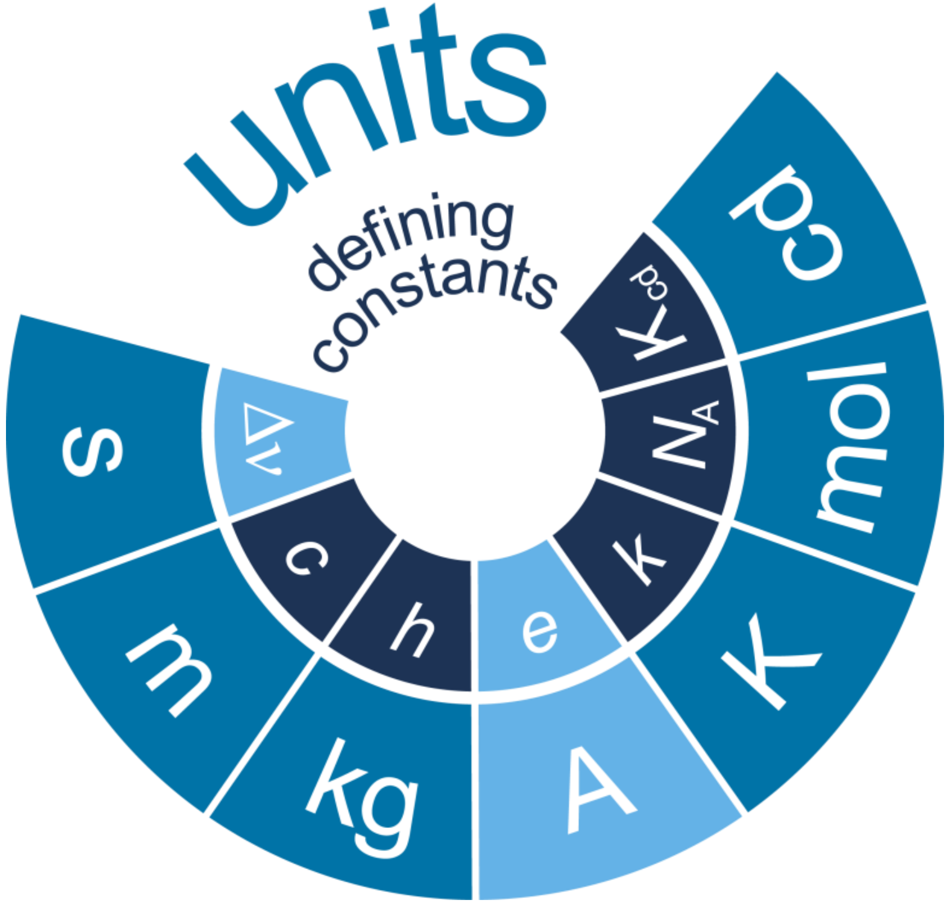
1 µm

→ quality assurance in bio-technology

- self-organized DNA
- **Support emerging German biotechnology industry**

Revised International System of Units



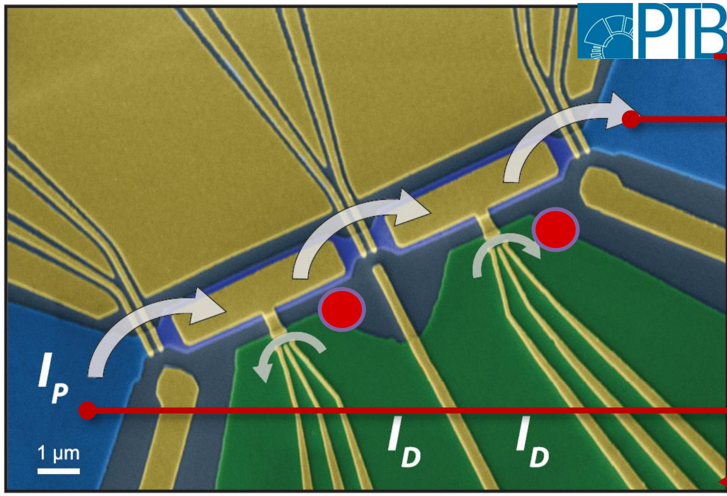


$$I = \langle n \rangle\, e\, f$$

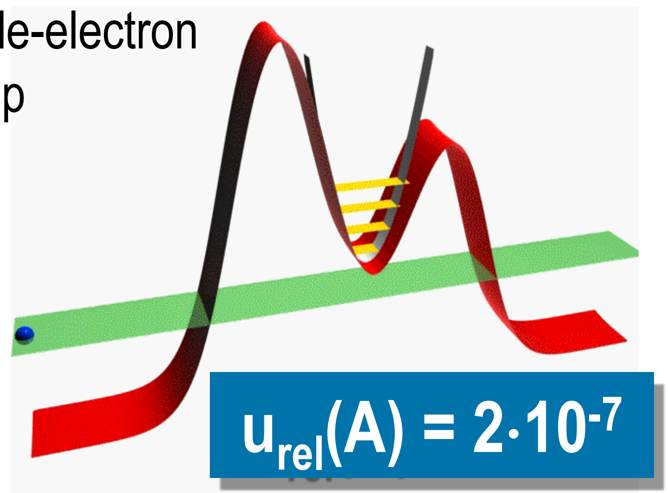
current

Innovation: Single Electron Tunneling Devices

Self-referenced noise-free electrical current



single-electron pump



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

Future applications

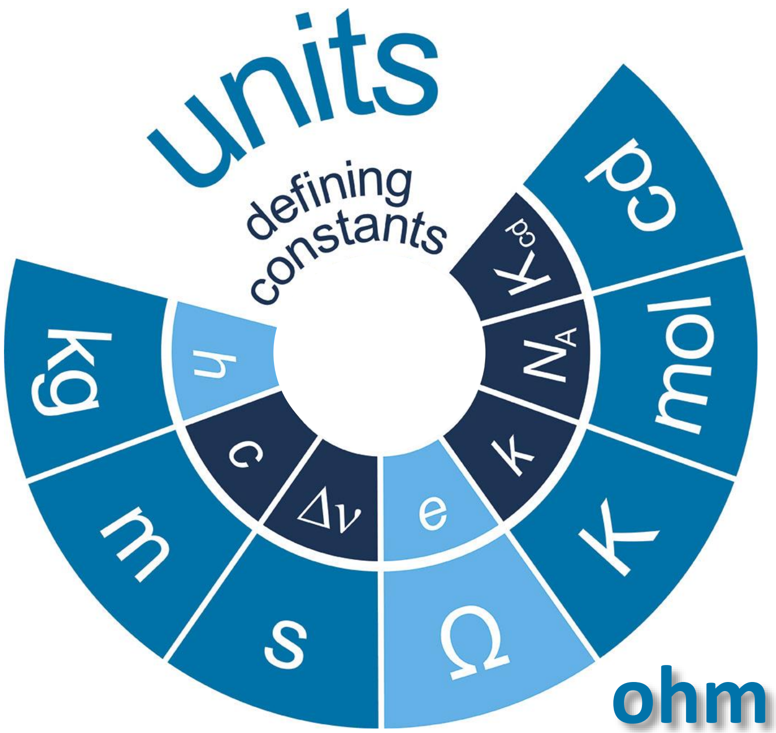
→ Shot-noise-free electronics

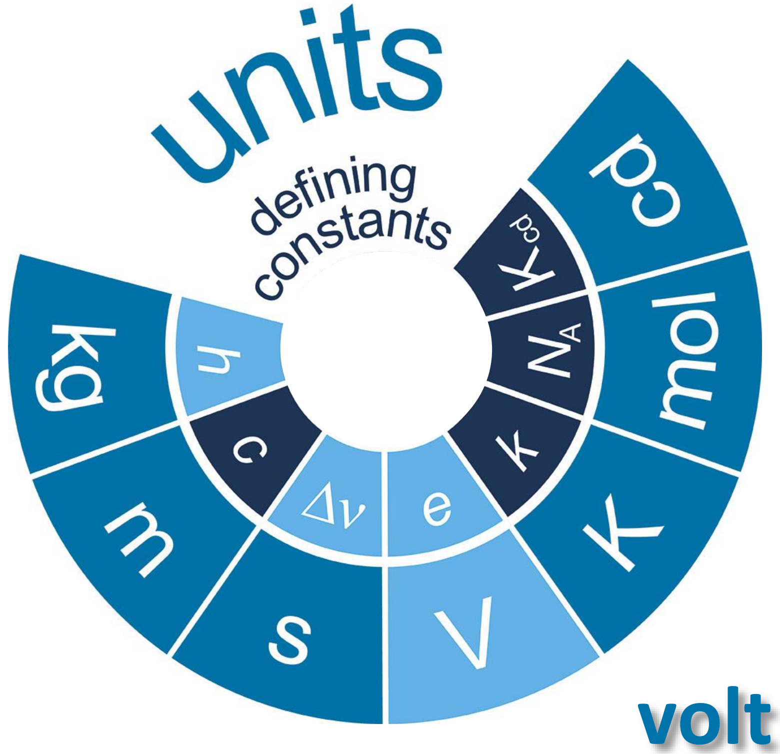
→ Quantum (spin)electronics

→ Photonic technologies

→ Quantum information

Revised International System of Units





$$R_K = h / e^2$$

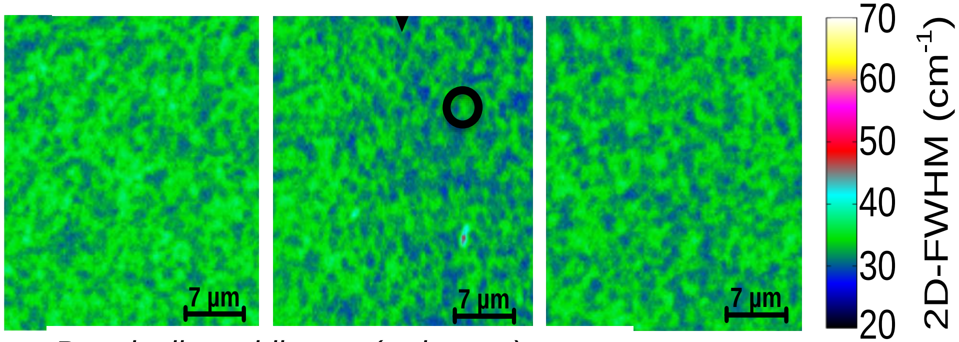
$$K_J = 2e / h$$

Innovation: Quantum Hall in Graphene

QHE Resistance: Graphene

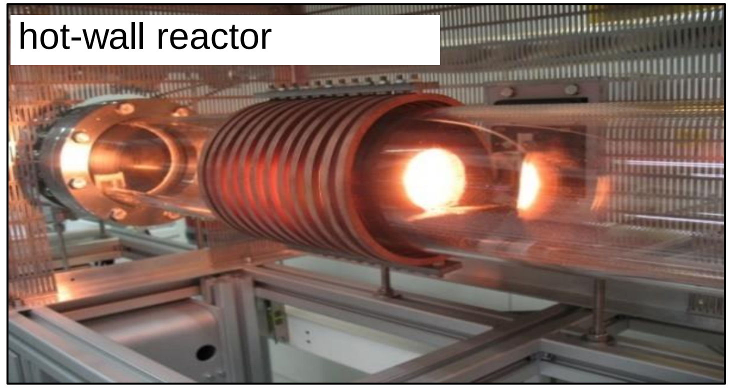
Goal: Operation at small B-field

- **Production of epitaxial graphene on SiC established at PTB**

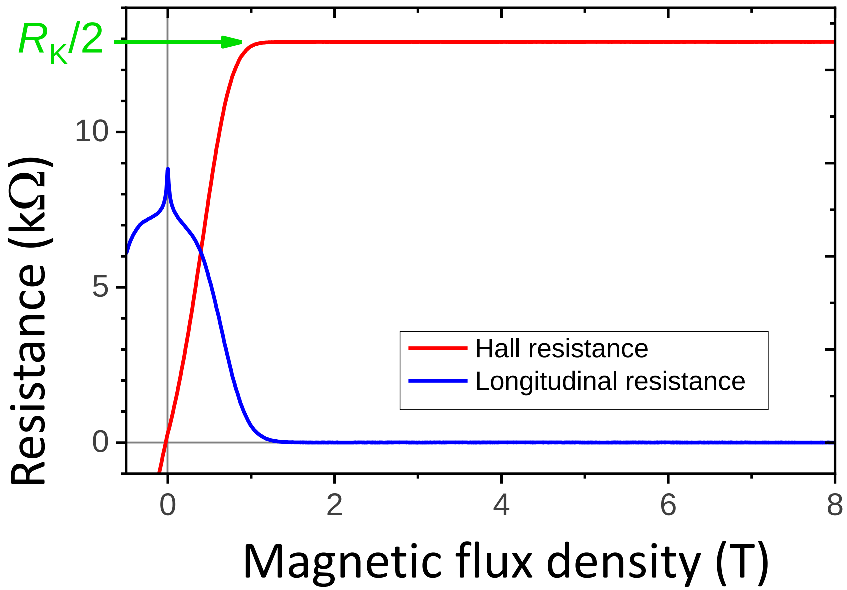


Practically no bilayers (red spots)

- **Excellent dc- and ac-QHE demonstrated**
- ***Yet to be optimized*: achieving stable and robust carrier concentration**

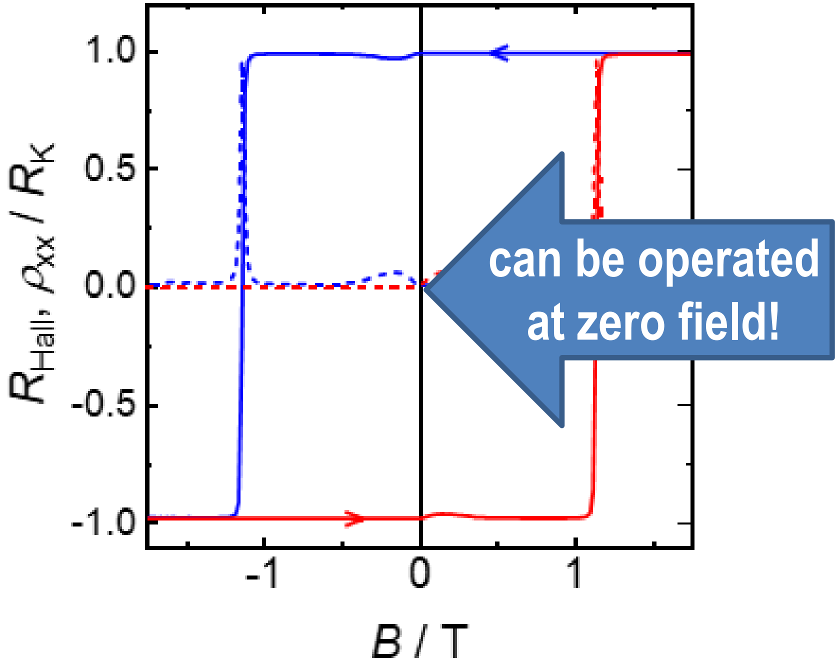


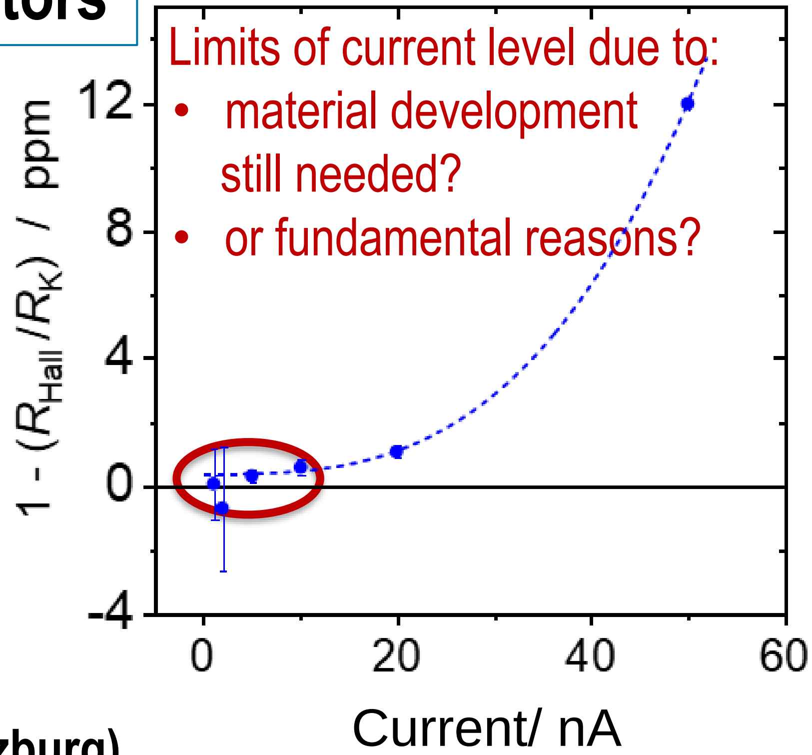
- **Patented growth method for single-layer graphene**



Innovation: Topological Insulators

QHE Resistance: Topological Insulators





Topological Insulators: W. Molenkamp (U. Würzburg)

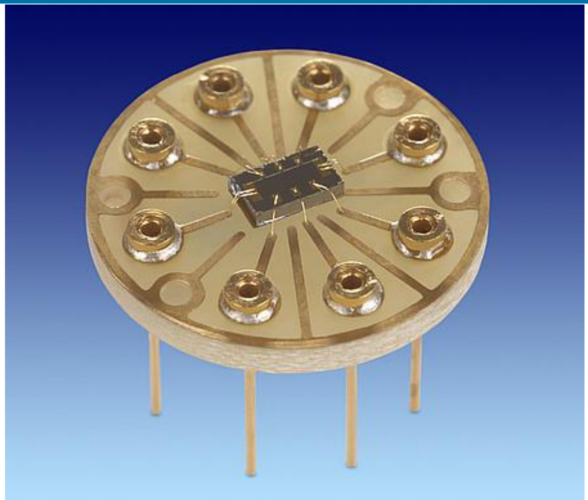
Proof of universality with 0.25 ppm measurement uncertainty at a few nA

Goal: increase operating currents and S/N by factor 1000

Innovation: Dream Team

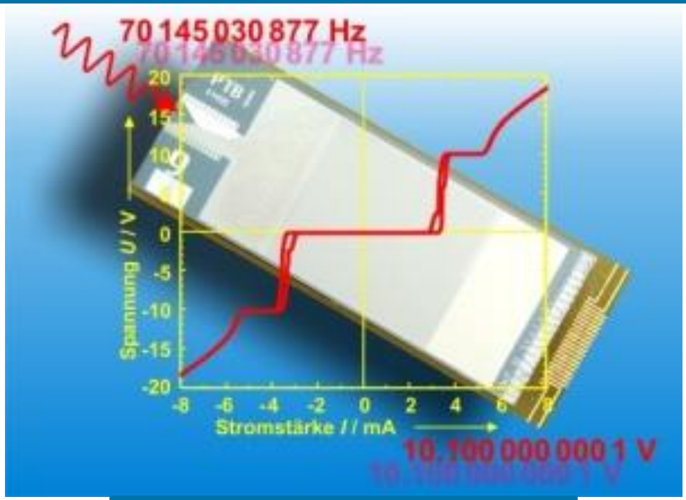
Combined Electrical Standard Device

Quantum Hall Resistor



Best operation:
1.5 K, 10 T

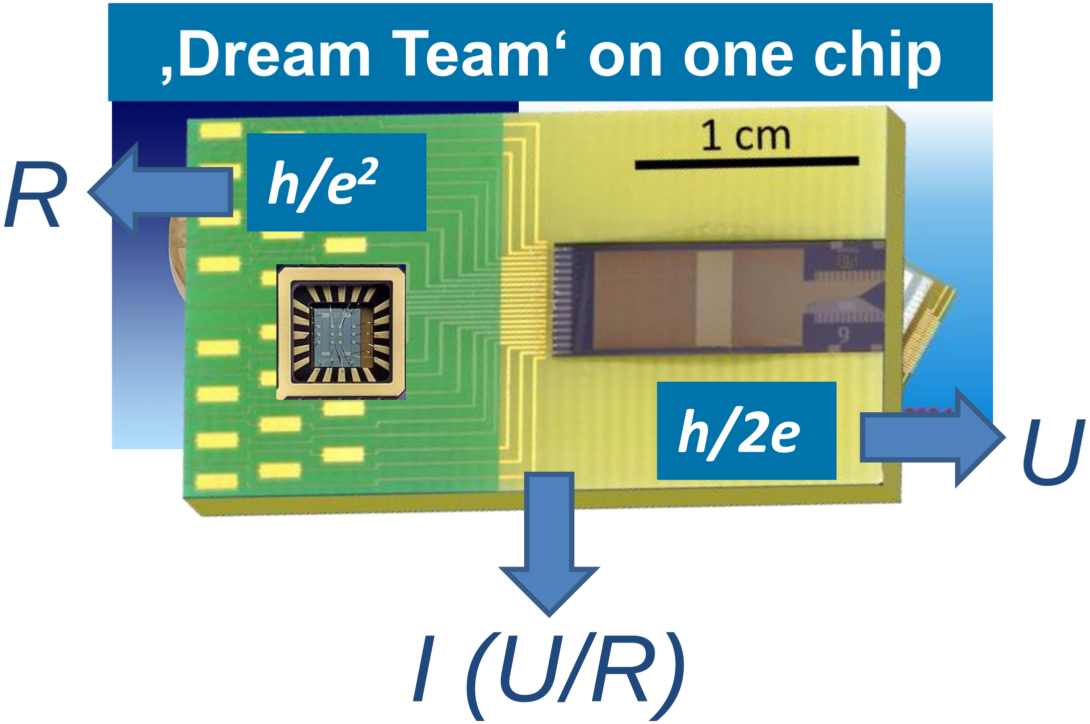
Josephson Voltage Standard



Best operation:
4 K, 0 T

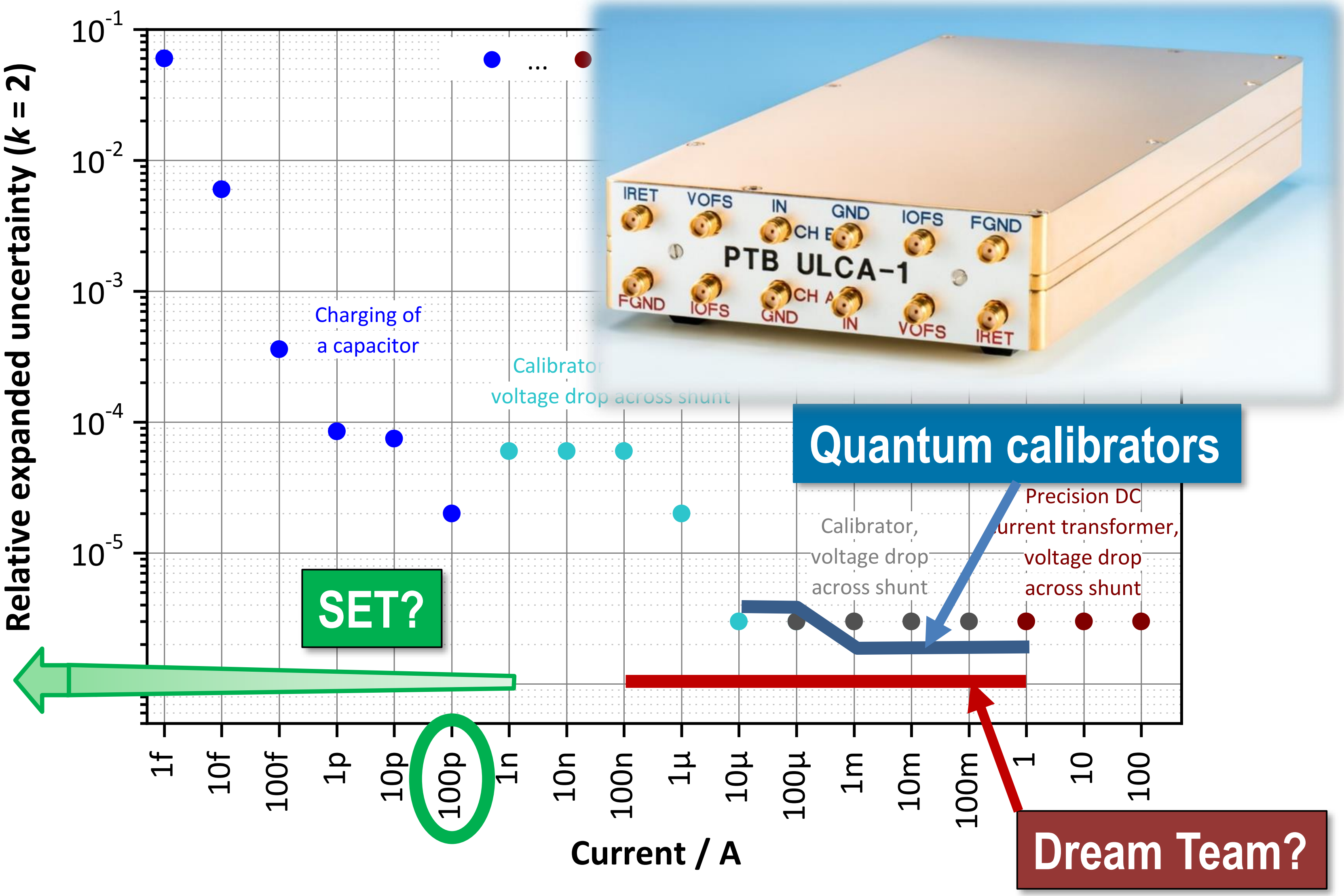
Innovation: Dream Team

Combined Electrical Standard Device

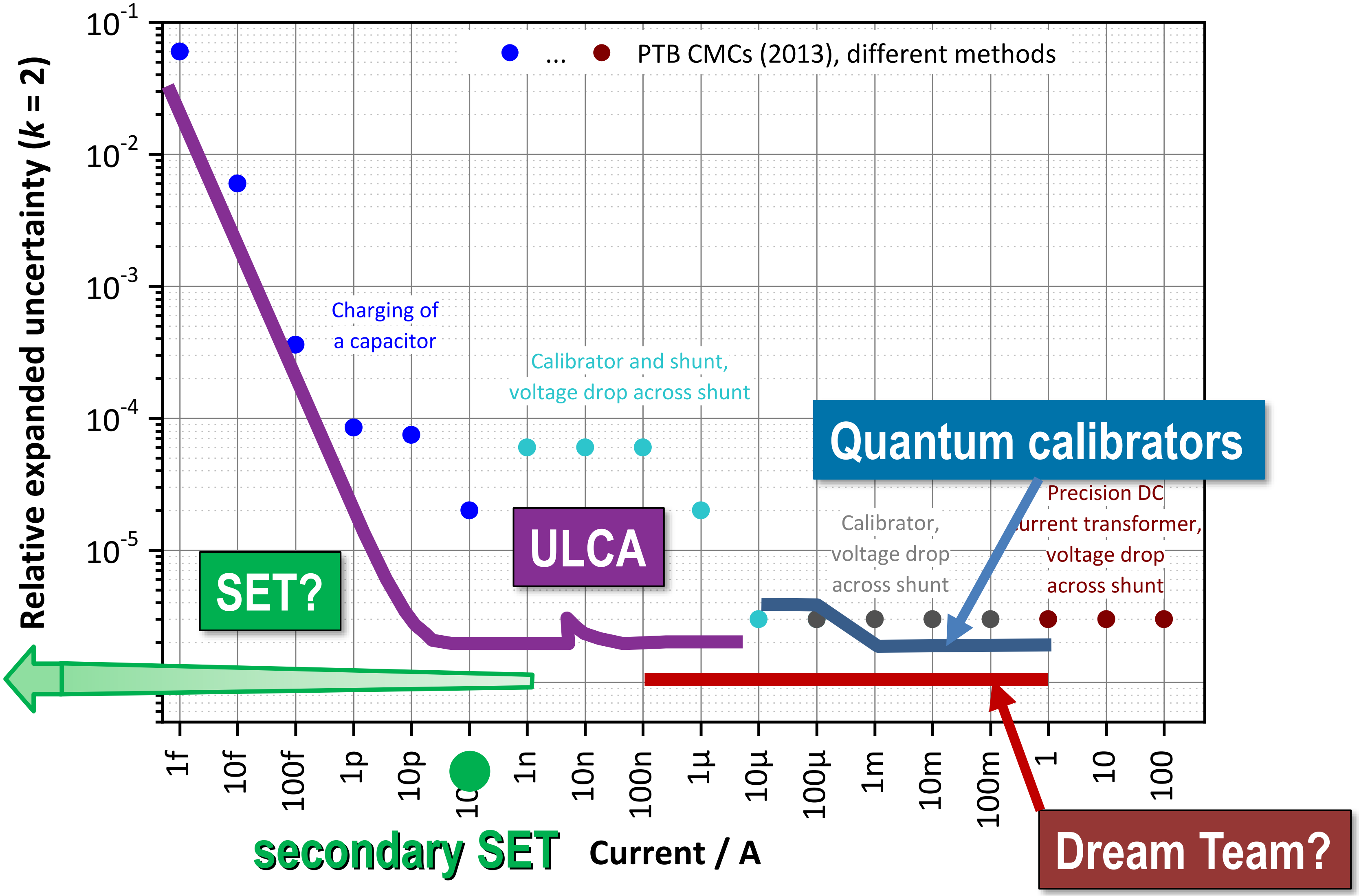


Operation at:
4 K, 0 T
A single cryostat
Cost: < 100 k€

DC Current Metrology: Present & Future



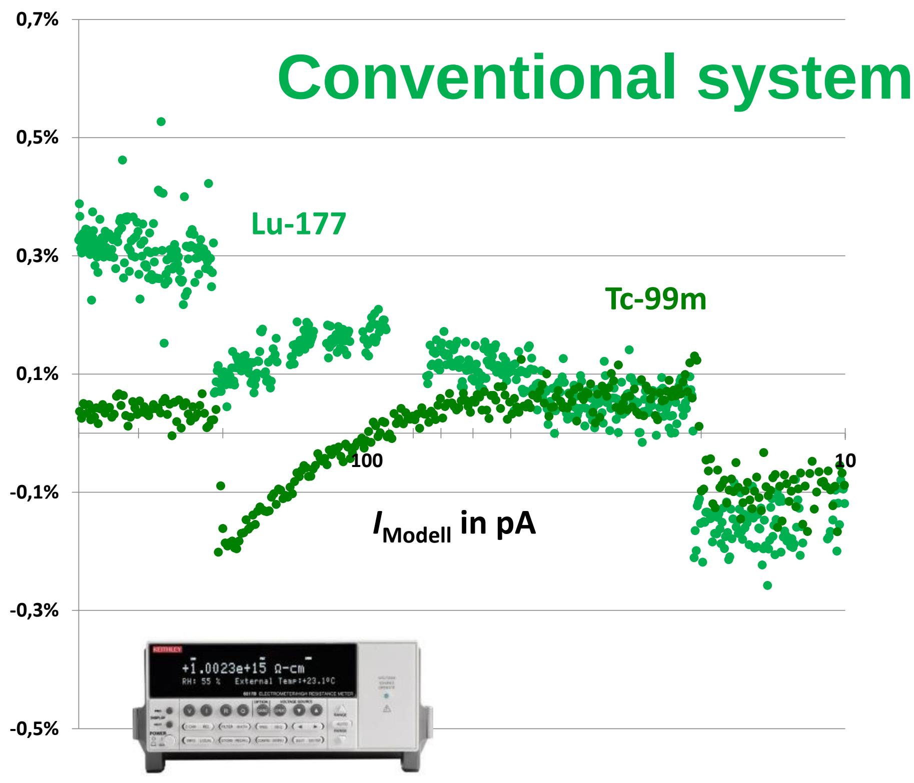
DC Current Metrology: Present & Future

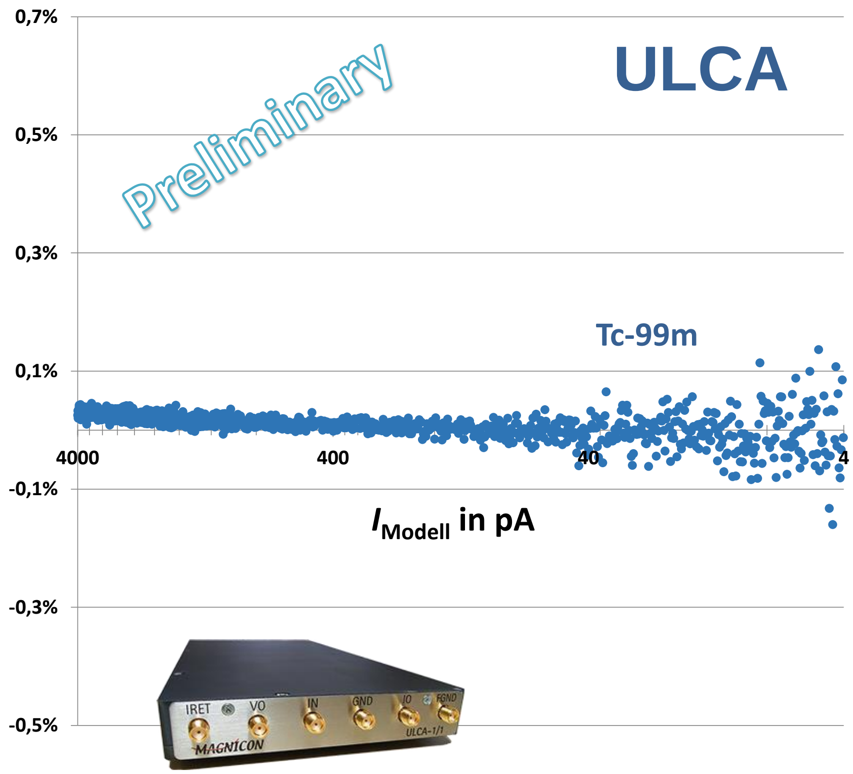


Innovation: ULCAs in Radiation Dosimetry

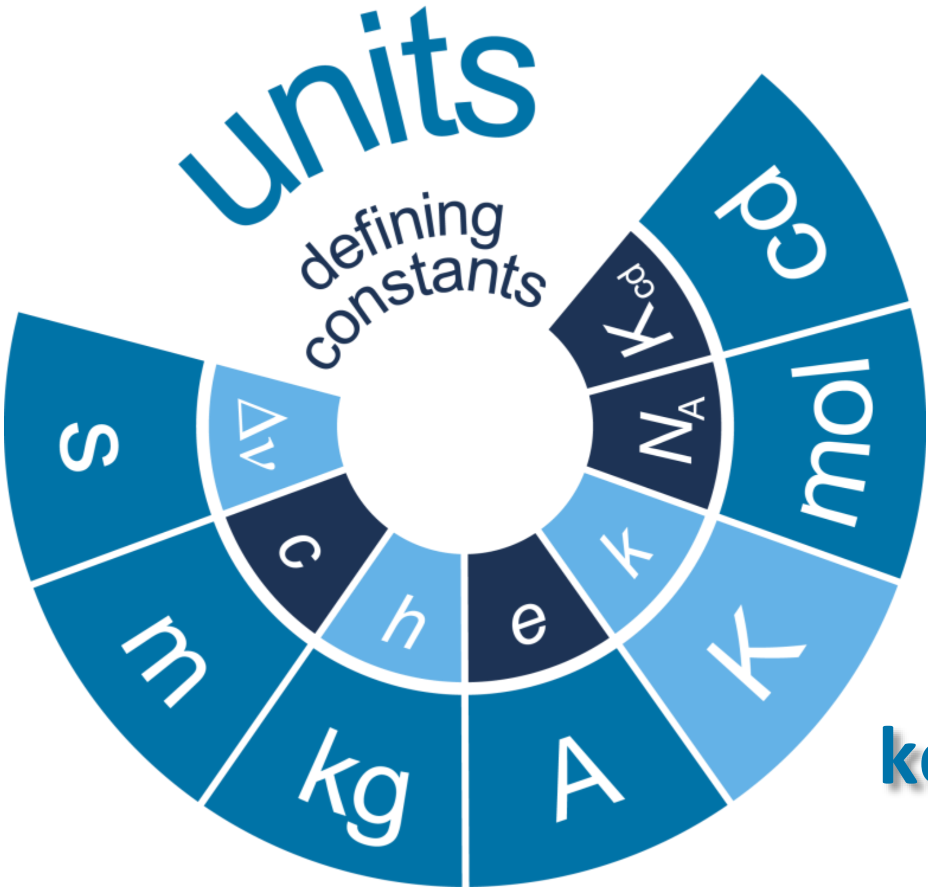
ULCAs at PTB Ionization Chamber

→ New: CCEM-CCRI task group on low current measurements





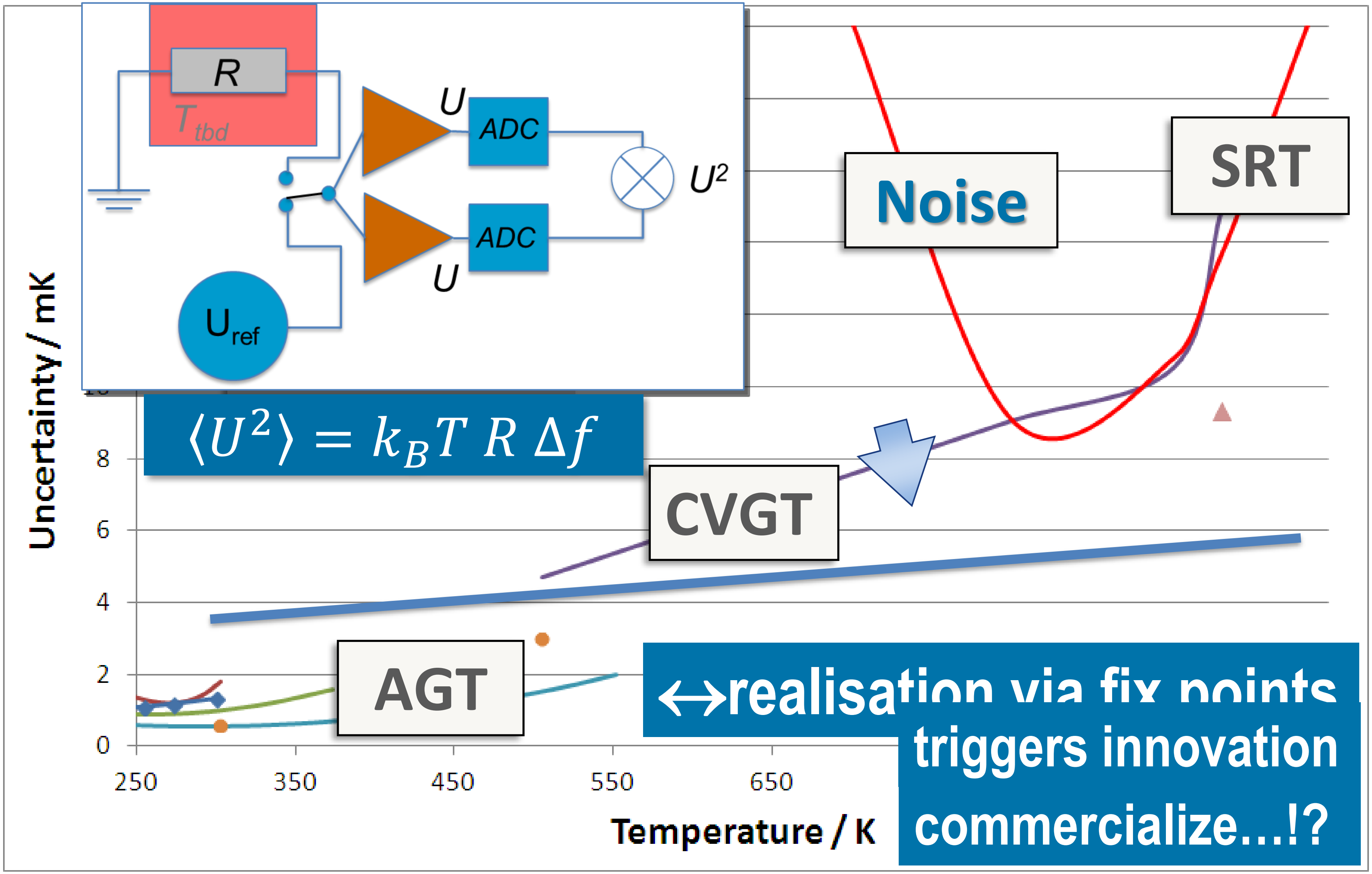
Revised International System of Units



kelvin

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

Innovation: Johnson Noise Thermometry



$$\langle U^2 \rangle = k_B T\, R\, \Delta f$$

↔realisation via fix points

triggers innovation

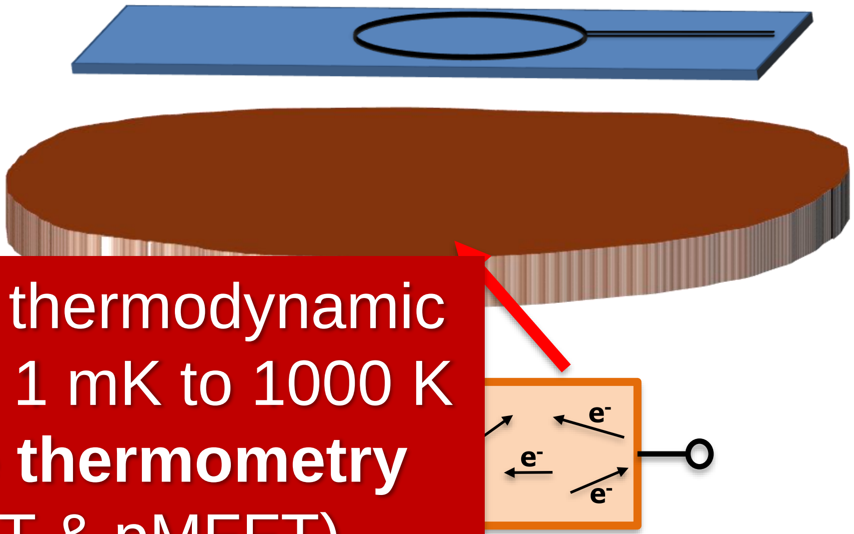
commercialize…!?

Innovation: Johnson Noise Thermometry

Primary Magnetic Field Fluctuation Thermometer (pMFFT)

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

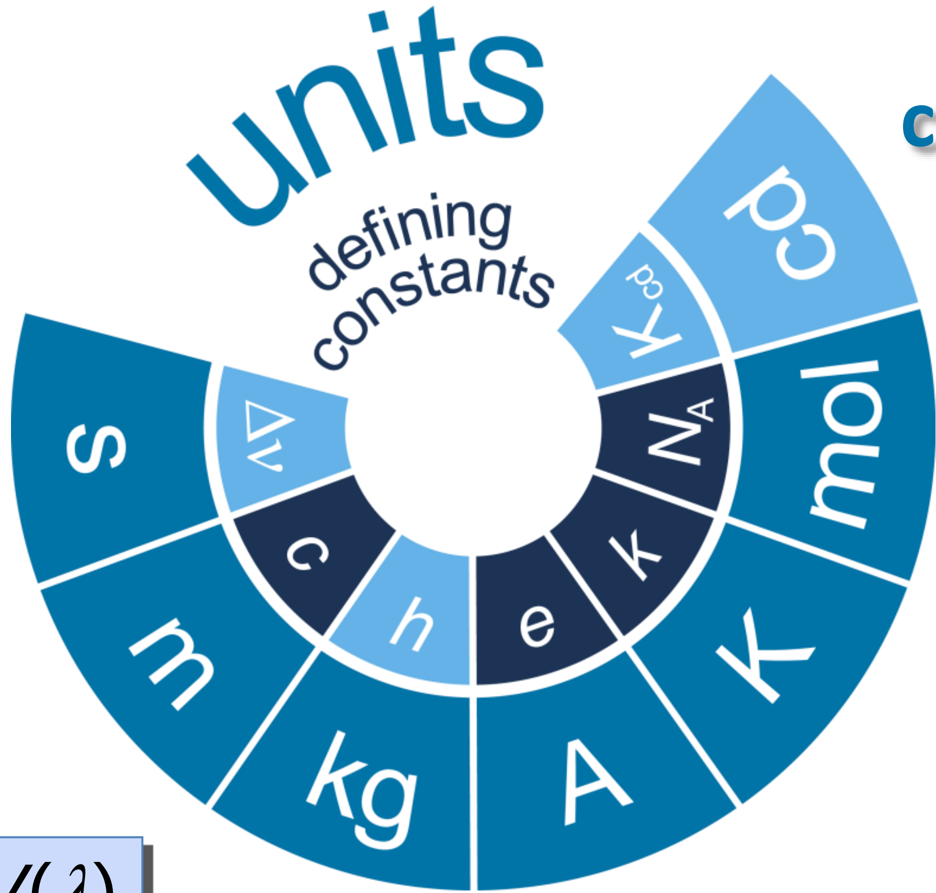
- SQUID based noise measurement
- Noise resistor made of high-purity copper
- Fully calculable thermometer
- Cross-correlation
- Relative combined
- Application range



Vision: measure thermodynamic temperature from 1 mK to 1000 K based on **noise thermometry** (new PTB-JNT & pMFFT)

$$S_\Phi(f,T) = \frac{4\,k\,T\,Re(Z(f))}{(\pi \cdot f)2}$$

Revised International System of Units



candela

$$K(\lambda) = K_{cd} \cdot V(\lambda)$$

Quantum-based definition of the candela

The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 x 10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr kg^{-1} m^{-2} s^3, where the kilogram, metre and second are defined in terms of h, c and $\Delta \nu_{Cs}$.

The "quantum candela"

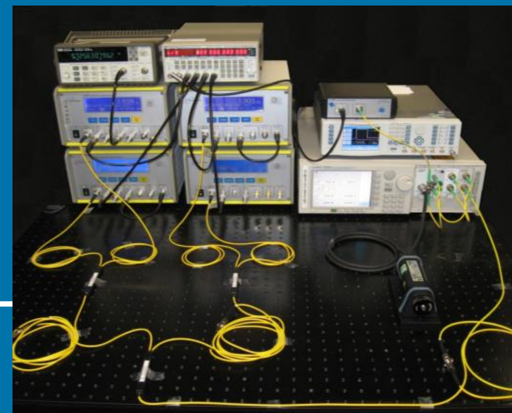
The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the „luminous photon rate" of monochromatic radiation of frequency 540 x 10^{12} Hz, N_{cd}, to be 4.0918… x 10^{15} when expressed in the unit lm s^{-1}, which is equal to cd sr s^{-1}, where the second is defined in terms of $\Delta \nu_{Cs}$.

$$1\ \mathrm{cd} = \left(\frac{N_{\mathrm{cd}}}{4.0918\ldots \times 10^{15}}\right) \mathrm{s\ sr^{-1}} = \frac{9192631770}{4.0918\ldots \times 10^{15}} \frac{N_{\mathrm{cd}}}{\Delta\nu_{\mathrm{Cs}}\ \mathrm{sr}} = 2.246\ldots \times 10^{-6} \frac{N_{\mathrm{cd}}}{\Delta\nu_{\mathrm{Cs}}\ \mathrm{sr}}$$

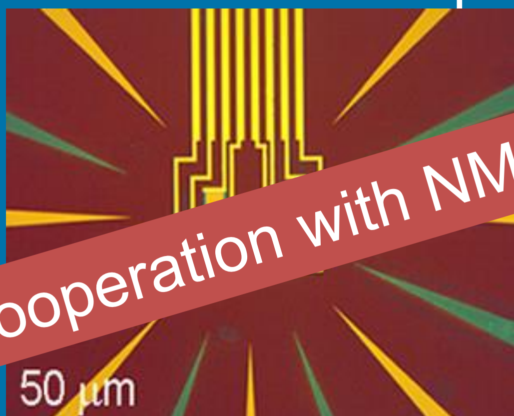
Innovation: Single Photon Detectors

SPAD

Detector Tree

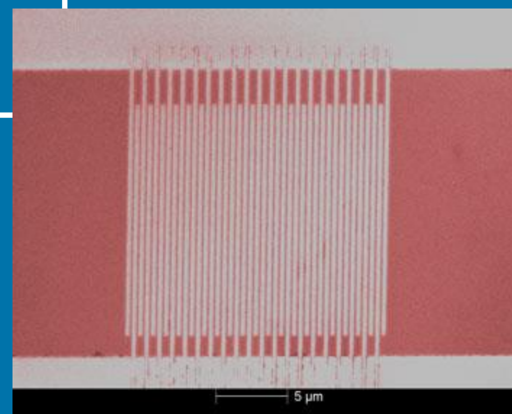


Single-photon detectors



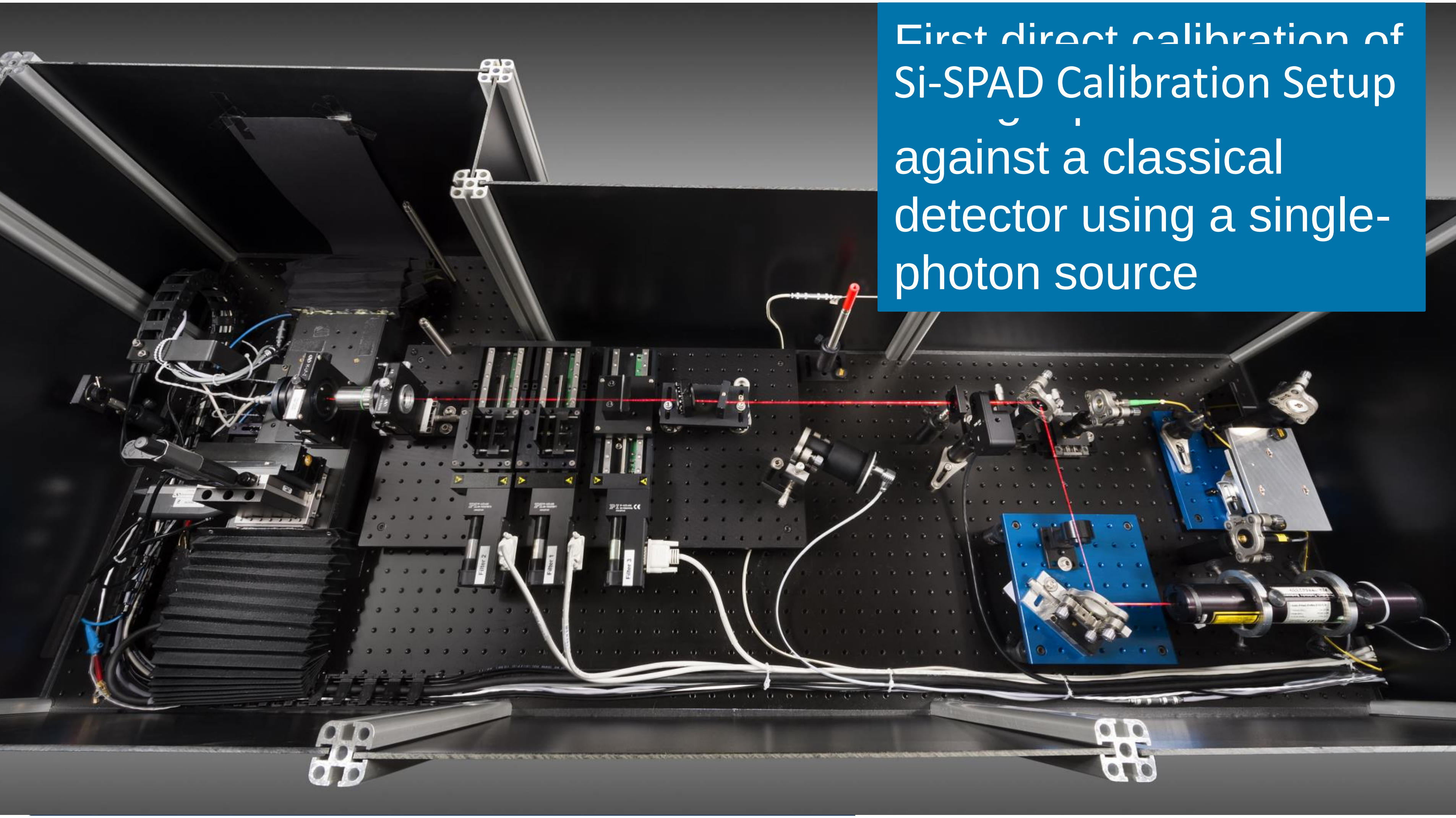
Cooperation with NMIJ

TES



SNSPD

Innovation: Si-SPAD calibration



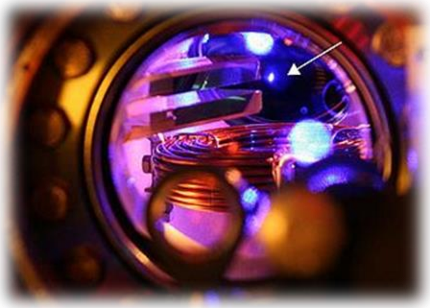
First direct calibration of
Si-SPAD Calibration Setup
against a classical detector using a single-photon source

© M. López, H. Hofer, S. Kück, "Detection efficiency calibration of single-photon silicon avalanche photodiodes traceable using double attenuator technique, Journal of Modern Optics 62, S21 – S27 (2015), http://dx.doi.org/10.1080/09500340.2015.1021724.

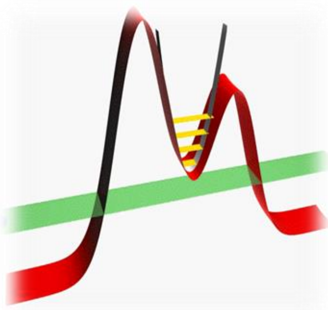
© Lombardi, P., et al., "A Molecule-Based Single-Photon Source Applied in Quantum Radiometry", Adv. Quantum Technol., doi:10.1002/qute.201900083 (2019)

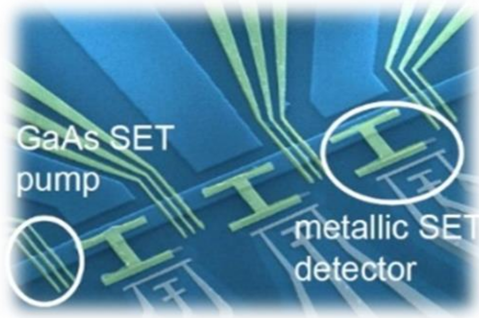
Research foci of QTZ

Time and frequency, quantum computing, quantum simulation

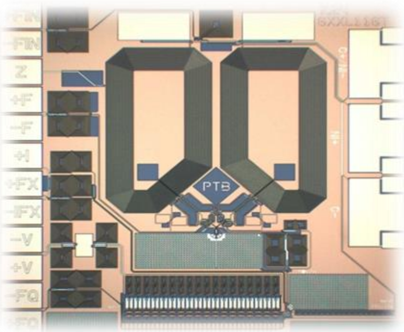


Electric quantum metrology

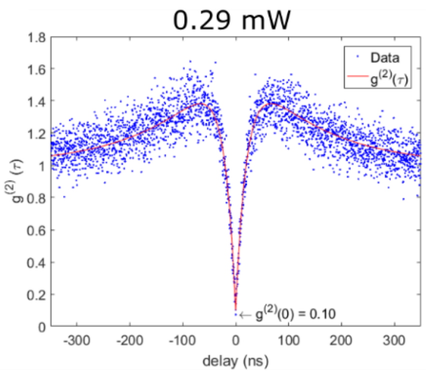




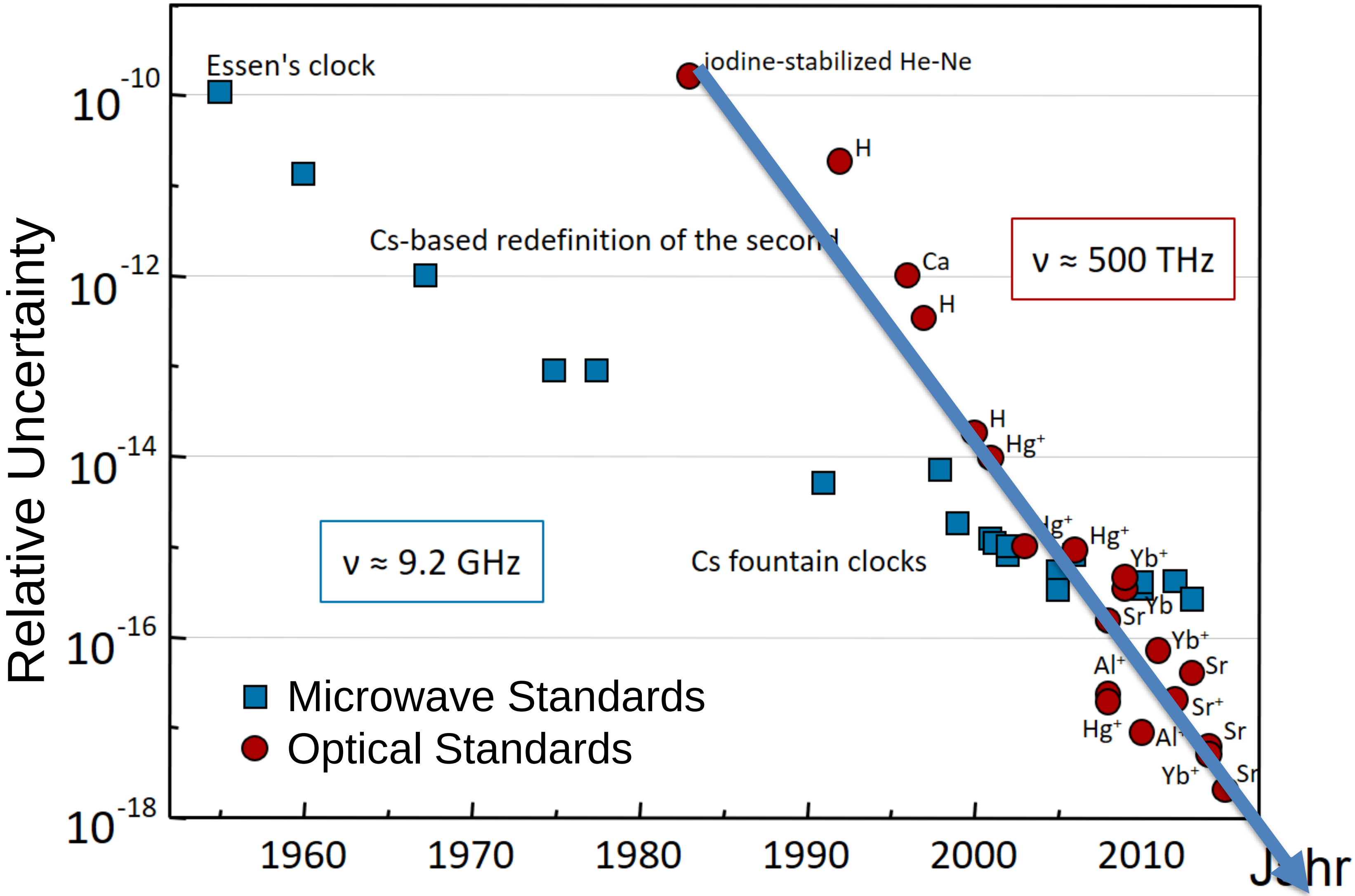
Quantum sensors for small magnetic fields



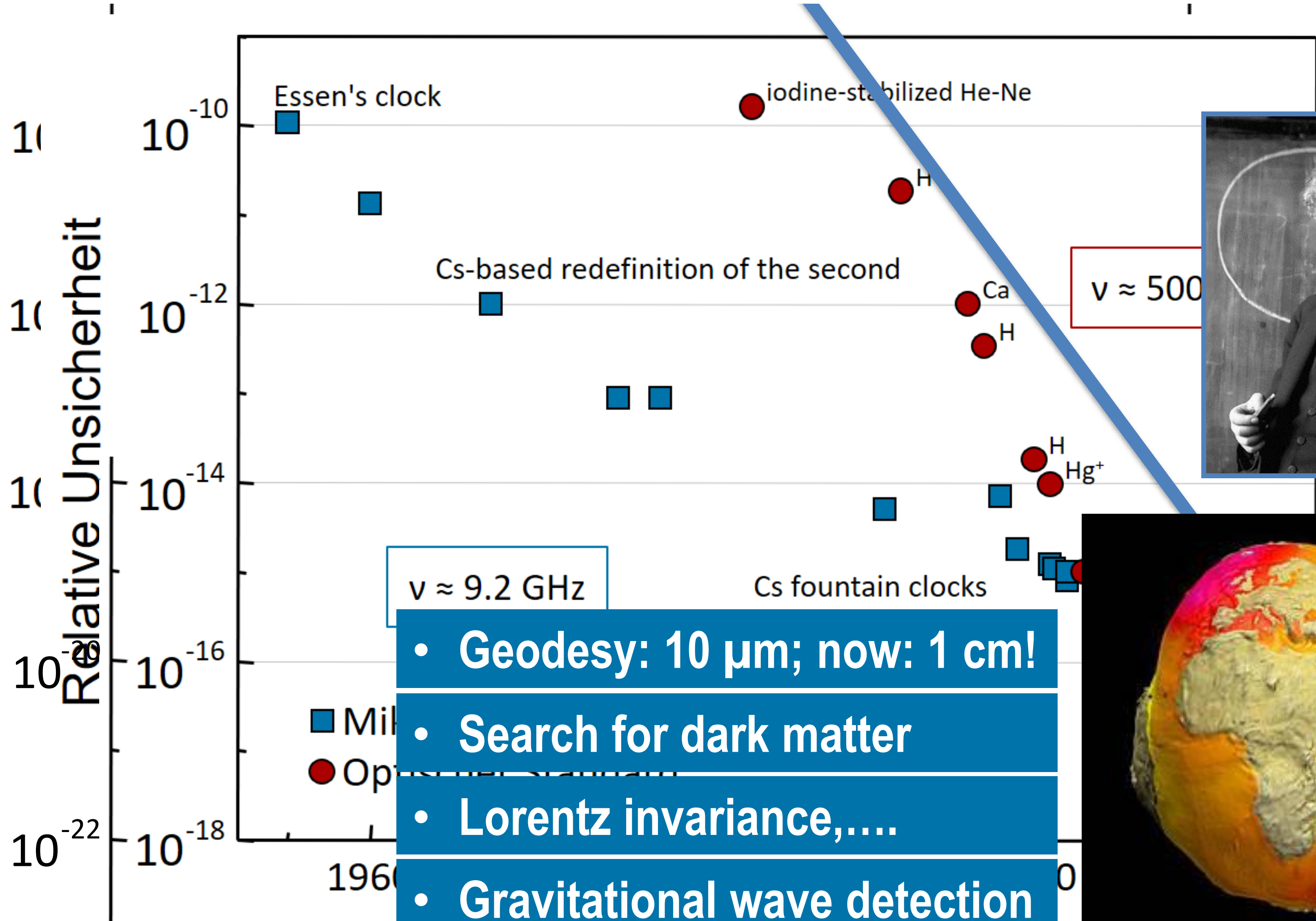
Quantum communication, quantum cryptography

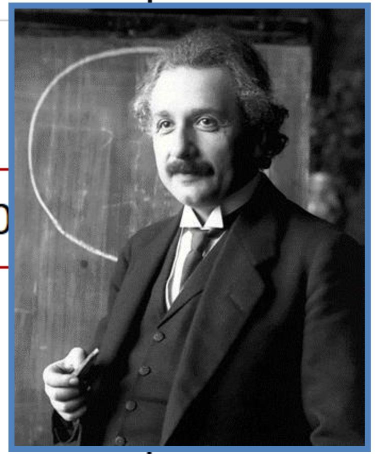


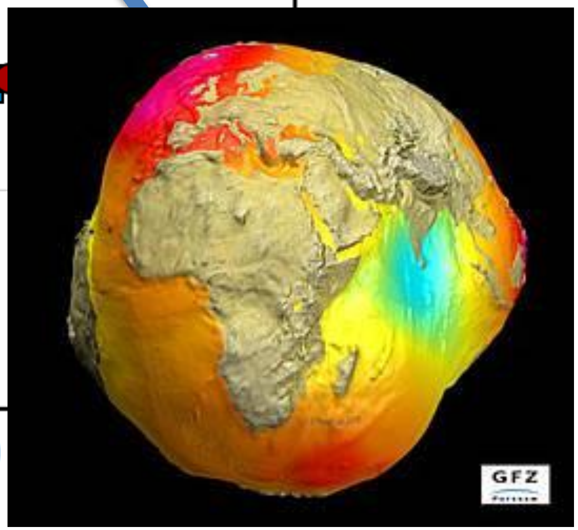
About the future of time



About the future of time



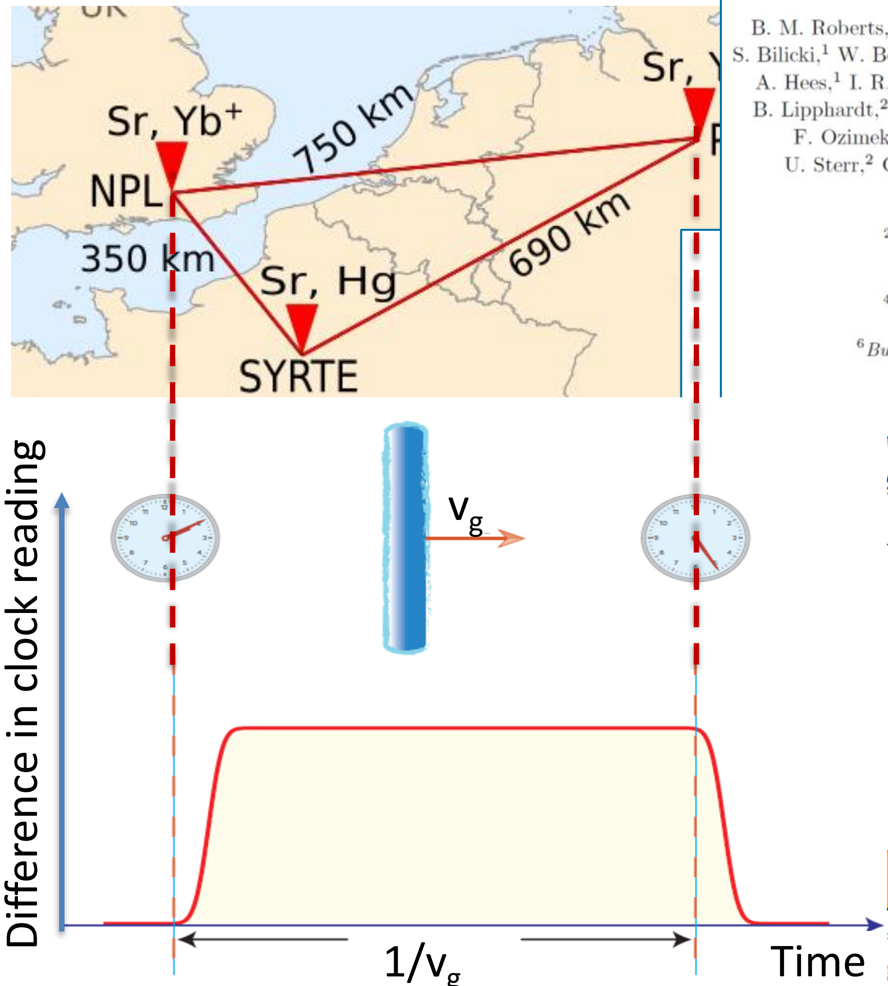




- Geodesy: 10 µm; now: 1 cm!
- Search for dark matter
- Lorentz invariance,….
- Gravitational wave detection

About the future of time

- **Search for dark matter**



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,‡]

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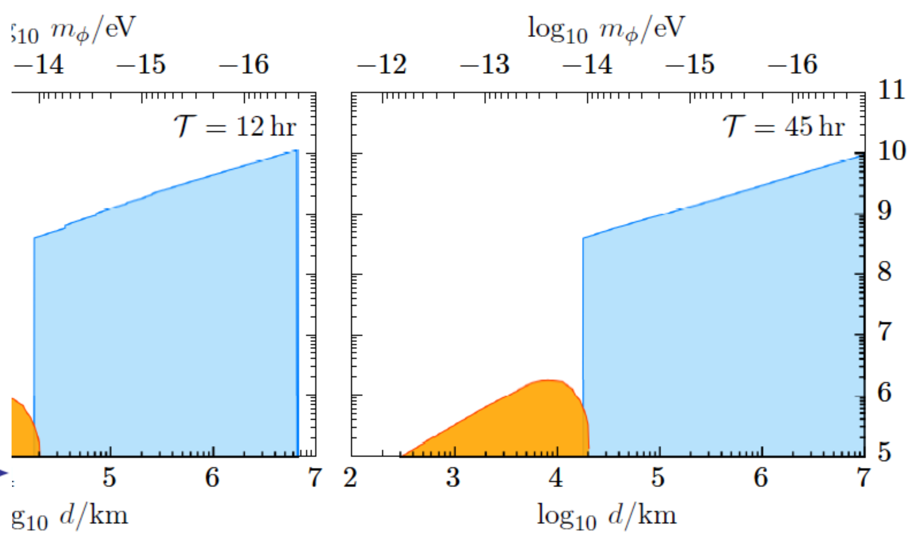
(Dated: May 21, 2019)

submitted to PRL



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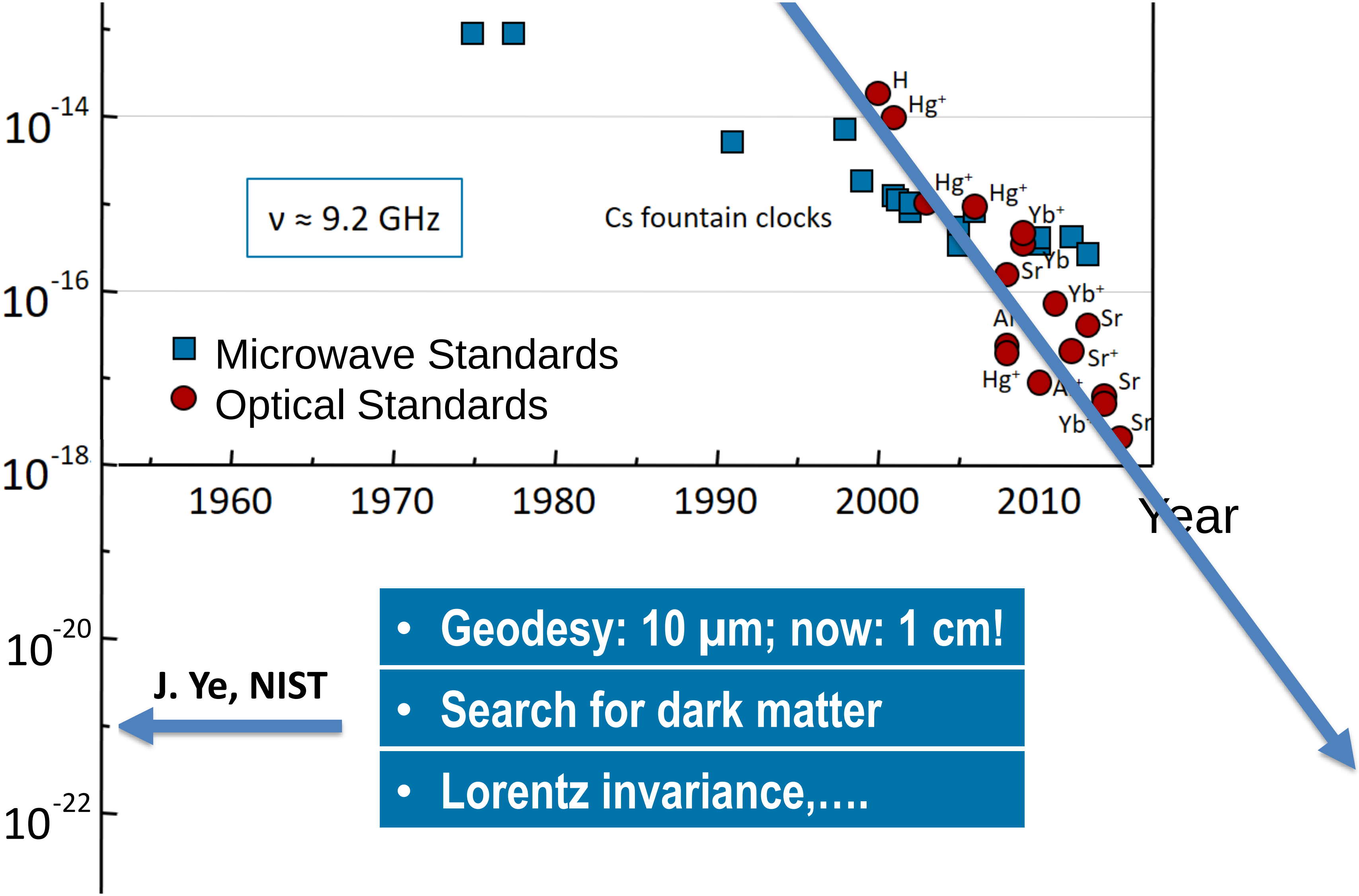
About the future of time



- Geodesy: 10 µm; now: 1 cm!
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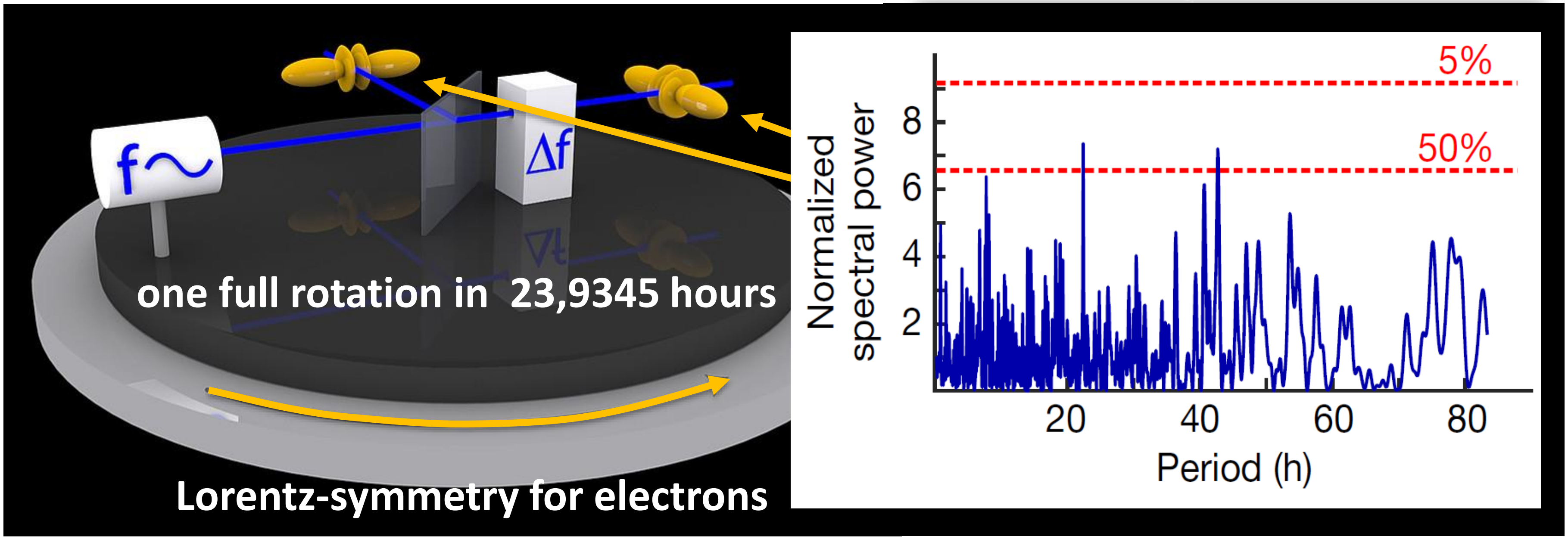
About the future of time

- **Lorentz invariance,….**

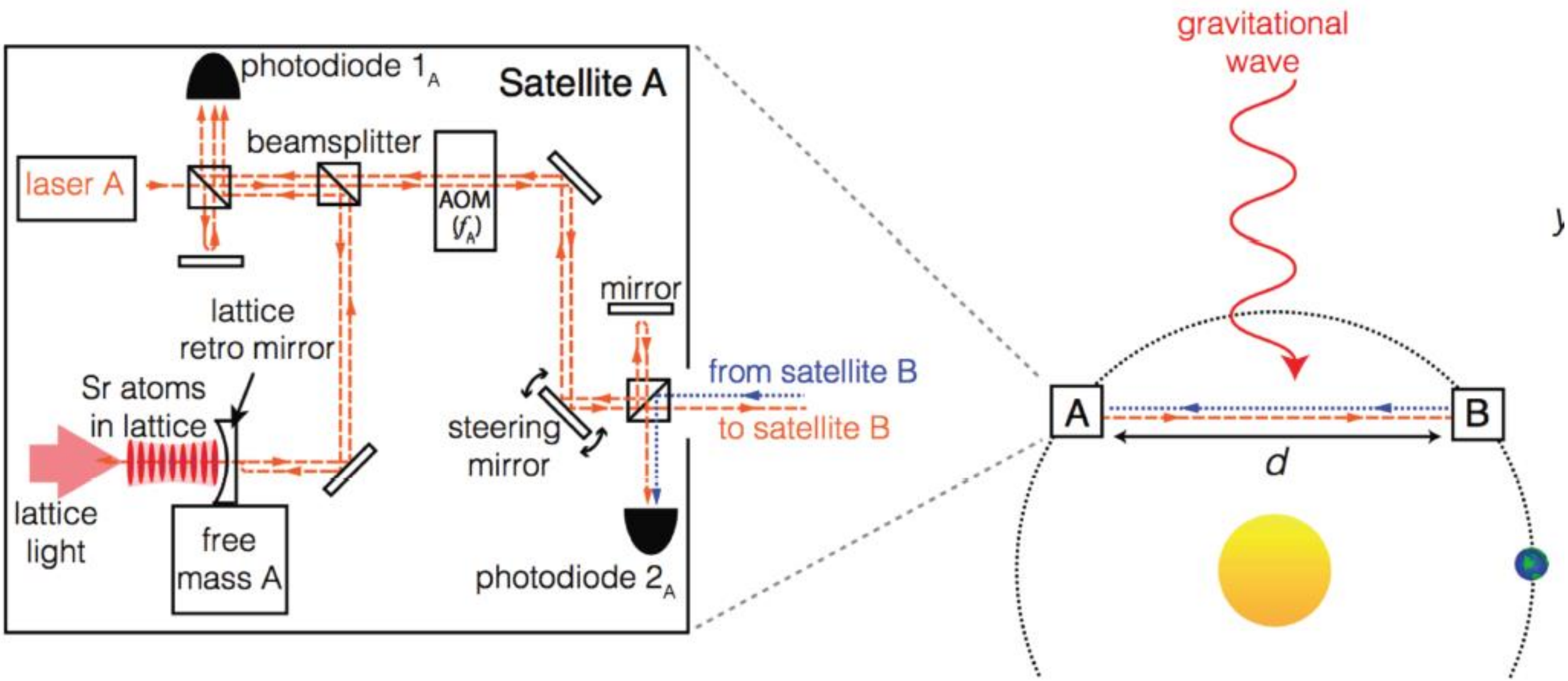


- Frequency comparison over more than 1000 h.
- No relative change for periods of few min - 80 h.

Ch. Sanner, N. Huntemann, R. Lange, Ch. Tamm, E. Peik, Marianna S. Safronova, S. G. Porsev
2 0 4 | N A T U R E | VO L 5 6 7 | 1 4 M A R C H 2 0 1 9

→ relative frequency deviation: < 3×10^{-18}

About the future of time

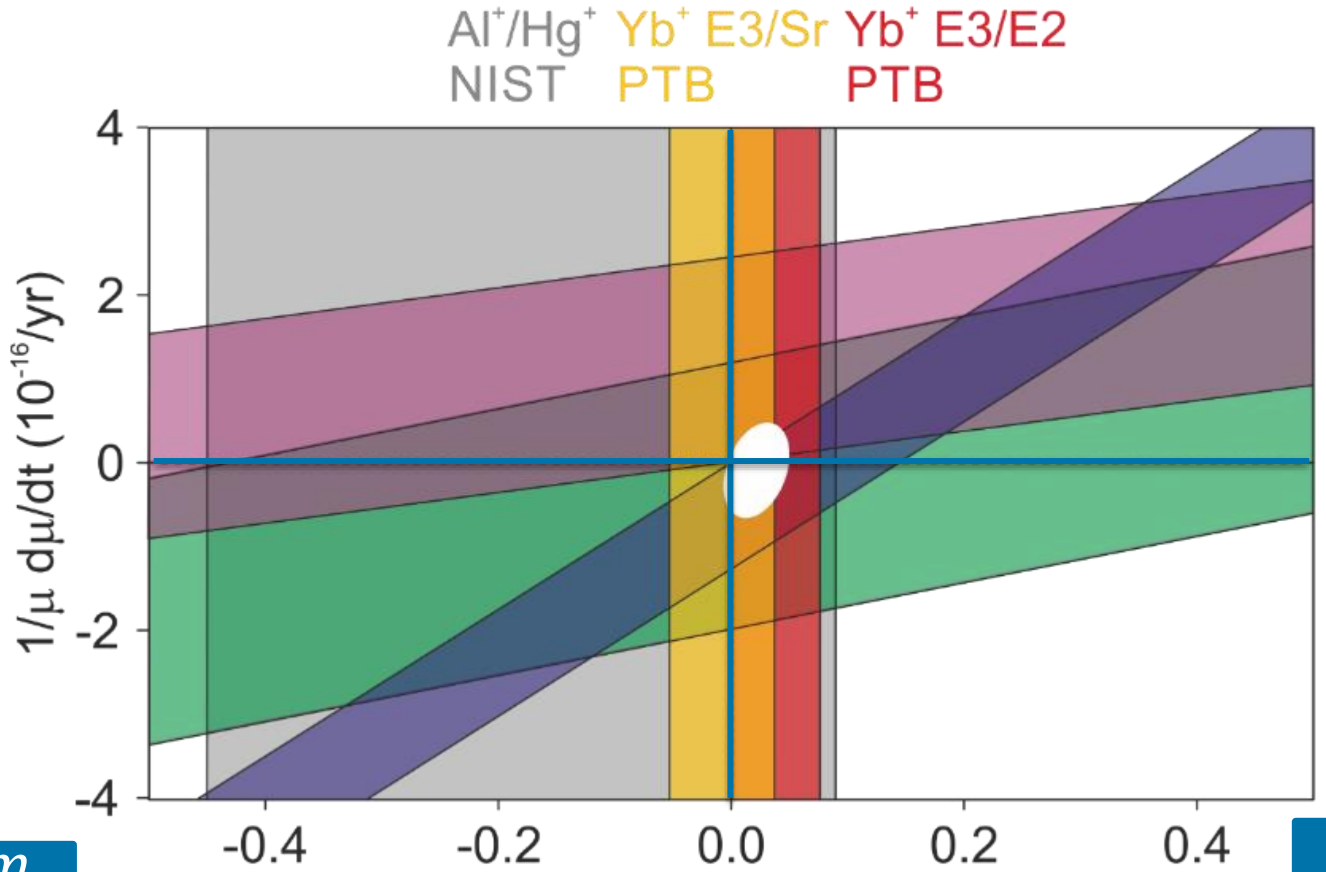


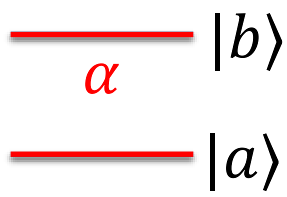
- Gravitational wave detection
- Are the constants constant?

Are the constants constant?

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

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





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

Can we do even better?

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

SI International System of Units

Metrology for the Digitalization

Quality in Cyberspace

~160 mio. instruments in legal metrology

strong measurement industry

smart cities

smart services

Quality Infrastructure in Cyberspace

Quality Infrastructure: Legal Metrology

Goal:

- **Protect**

  Consumer and user

- **Verify**

  Correct measurement

- **Create** **Mutual trust**

Europa:

- 2014/31/EU,
- 2014/32/EU
- Verordnung 765/2008
- Beschluss 768/2008/EG

National:

- Mess- und Eichgesetz
- Mess- und Eichverordnung

Quelle:
BMWi, Schlaglichter der Wirtschaftspolitik 11/2013

Impact:

- **~ 150 different types of instruments**
- **160 Mio. measurement instruments in Germany:**
  Electricity, Smart-Meter-Gateway, gas, heat flow, water, weighing instruments, mineral oil, transport goods, car exhaust, radioactivity,…
- **160 billio… ss national income**
- **53 % of the federal taxes** through verified measurement instruments (40 Mrd. €).

PTB: 600 certificates per year

40-50 % of World market

~ 30 % of World market

The revised SI for innovation, science and the second quantum revolution

END