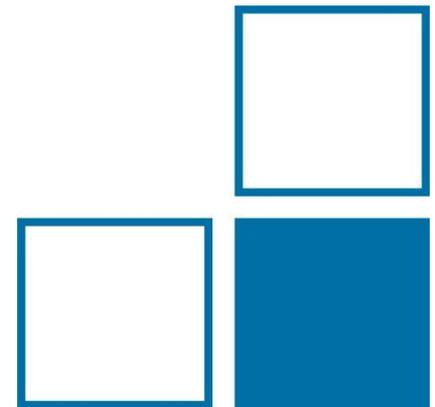


# The New Kilogram in the Revised International System of Units

*Roman Schwartz*



Physikalisch-Technische Bundesanstalt  
Braunschweig und Berlin  
Nationales Metrologieinstitut



# Overview

- 1. Motivation for the revision of the SI and the redefinition of the kilogram**
- 2. Status of current experiments to redefine the kilogram**
- 3. Realization and dissemination of the kilogram after its redefinition**
- 4. Consequences for derived or related SI units**

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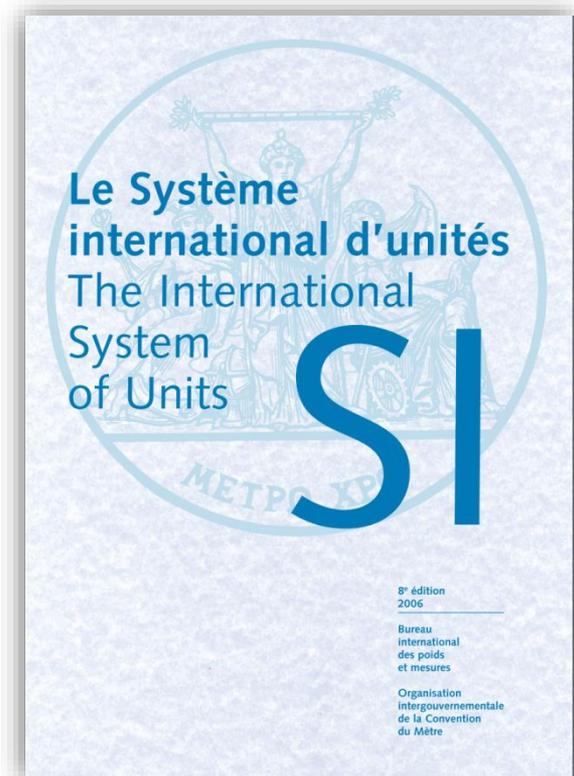
# The international System of Units

**Up to now different types of definitions are used for the base units:**

- artefact (kilogram)
- material properties (kelvin, mole)
- idealized experimental prescriptions (ampere)
- constants of nature (metre, second)

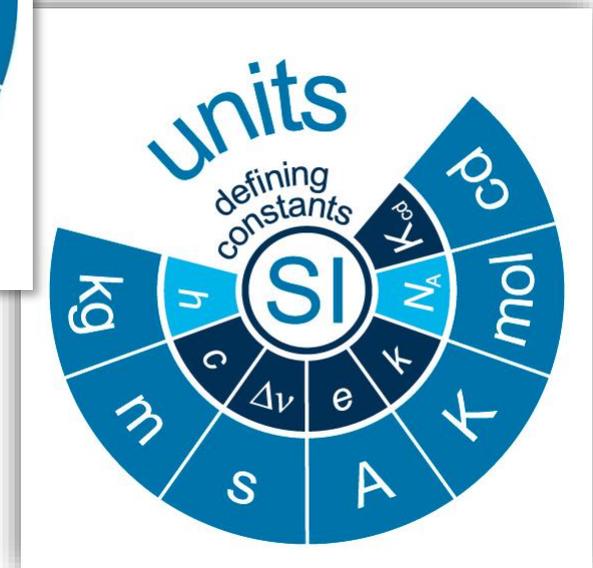
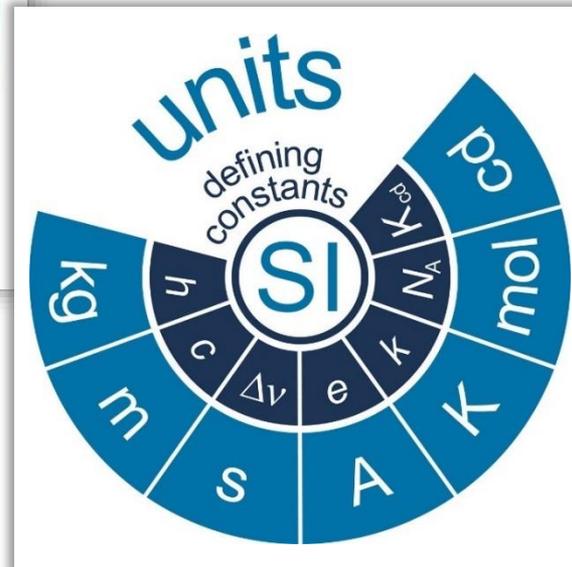
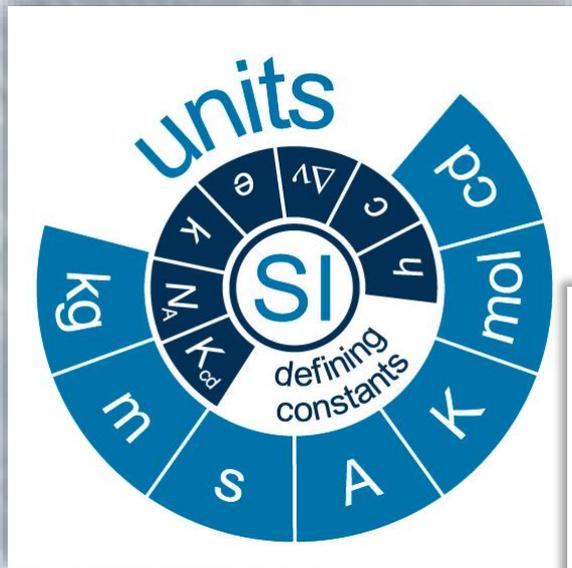
**Disadvantages:**

- artefacts involve the risk of change, damage or loss
- definitions are not independent (e.g. the unit of ampere involves the kilogram)
- conventional defined values for the von Klitzing and the Josephson constants are not identical to their corresponding SI values

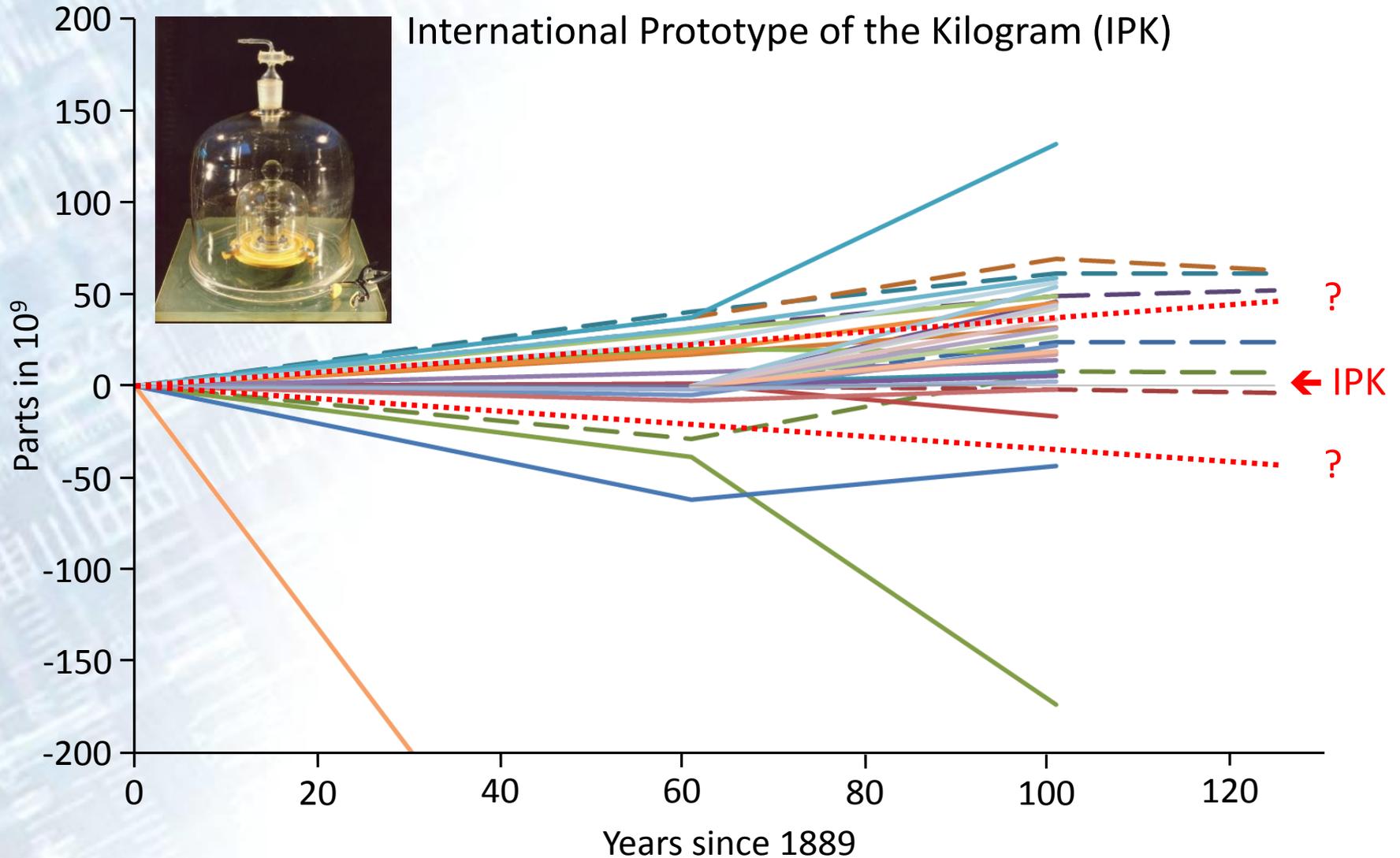




# Units and defining constants



# Possible change of the IPK



# CGPM Resolutions 2011 and 2014

## *The General Conference on Weights and Measures (CGPM)*

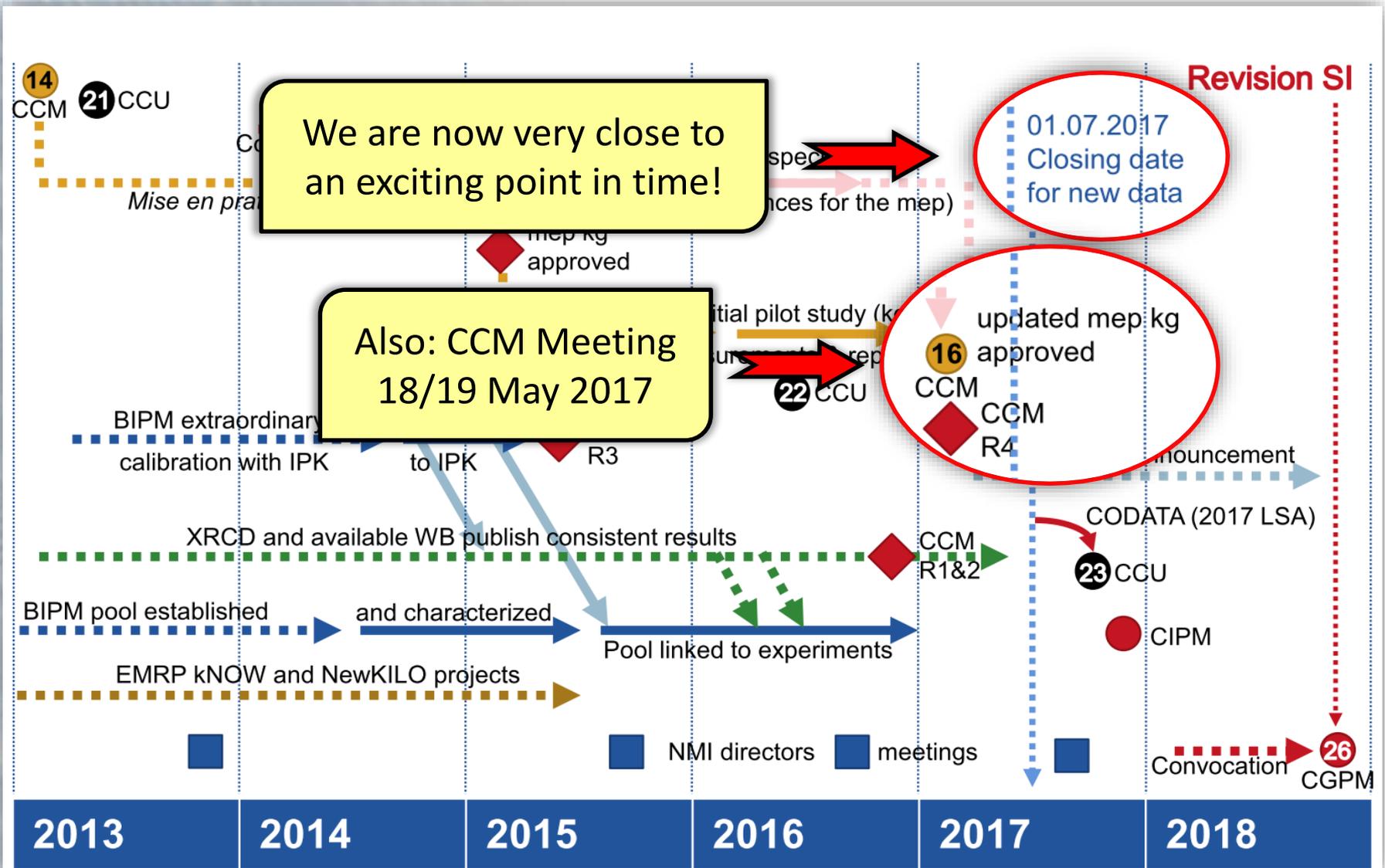
### considering

- that ... the IPK ... has a number of important limitations, one of the most significant being that its **mass is not explicitly linked to an invariant of nature and in consequence long-term stability is not assured,**

### encourages

- continued effort in the NMIs, the BIPM, and academic institutions to obtain **data relevant to the determination of  $h$ ,  $e$ ,  $k$ , and  $N_A$  with the requisite uncertainties,**
- continued effort by the CIPM, together with its Consultative Committees, the NMIs, the BIPM, and other organizations such as the International Organization of Legal Metrology (OIML), **to complete all work necessary for the CGPM at its 26<sup>th</sup> meeting (2018) to adopt a resolution that would replace the current SI with the revised SI, provided the amount of data, their uncertainties, and level of consistency are deemed satisfactory.**

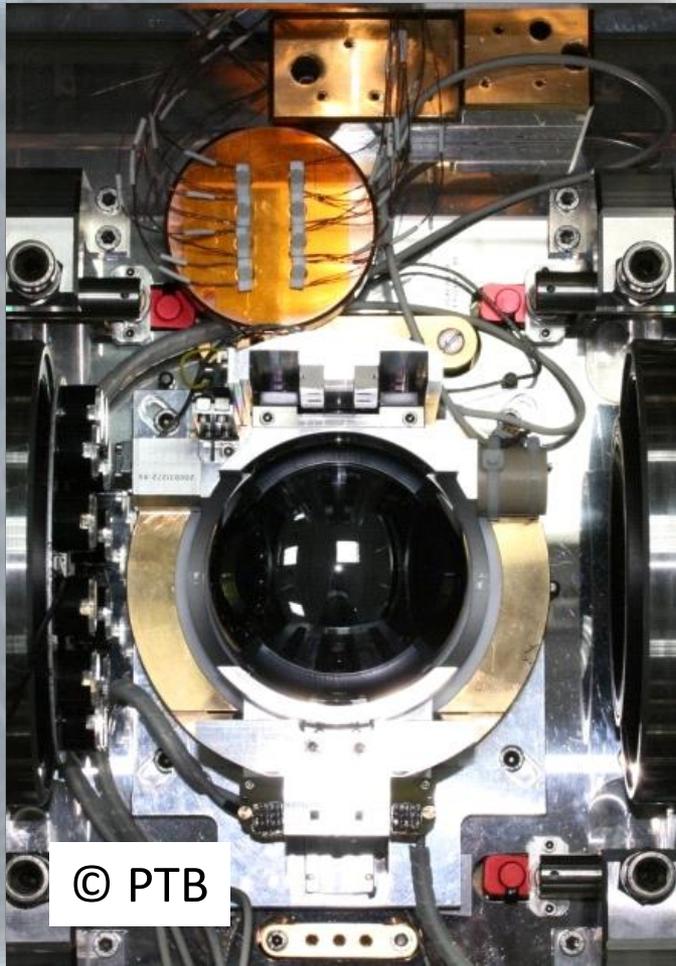
# Joint CCM-CCU roadmap for the new SI



# Overview

1. Motivation for the revision of the SI and the redefinition of the kilogram
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# Current experiments



© PTB

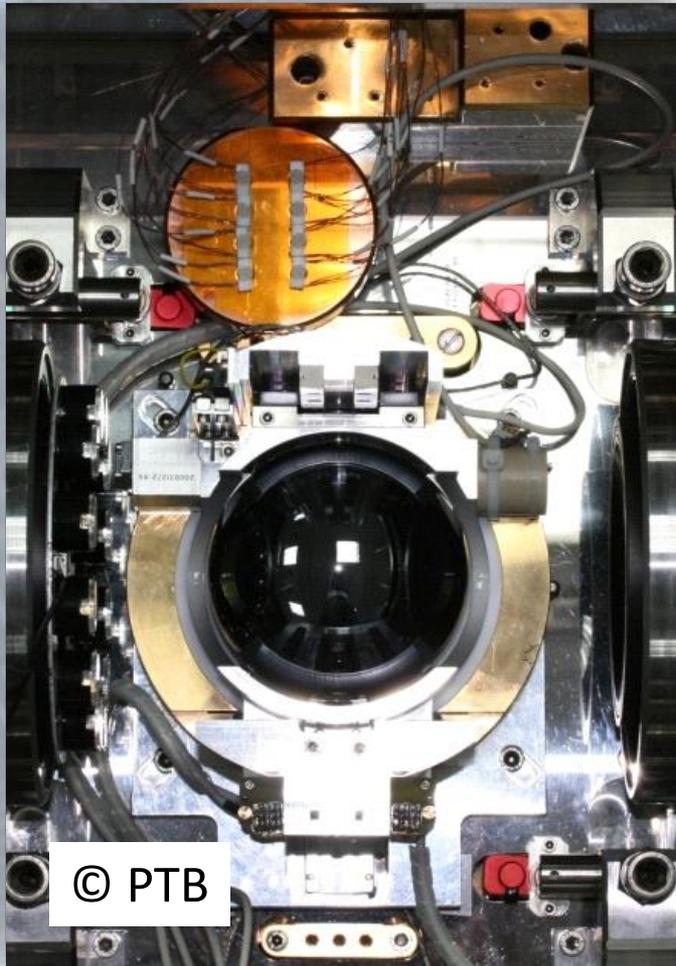
Avogadro Experiment  
("Si-28 or XRCD Method")



© BIPM

Watt Balance  
("Kibble Balance")

# Principle of the Avogadro Method



“Counting” atoms in a “perfect” silicon-28 sphere:

$$N_A = \frac{n V}{a^3} \cdot \frac{M_{\text{Si}}}{m}$$

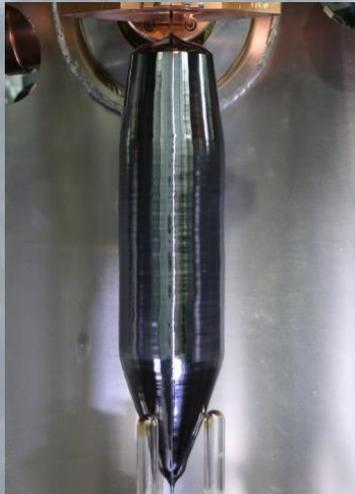
- $n$  number of atoms per unit cell ( $n=8$ )
- $V$  volume of the sphere
- $M_{\text{Si}}$  molar mass of the silicon used
- $a^3$  volume of the unit cell
- $m$  mass of the sphere

Relation between  $N_A$  und  $h$ :  
**molar Planck constant  $N_A \cdot h$**

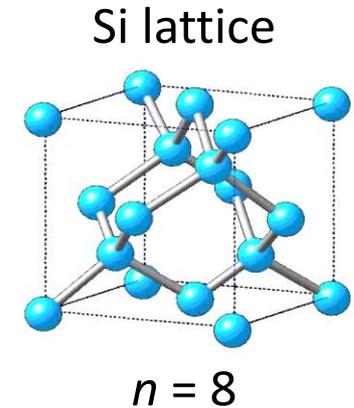
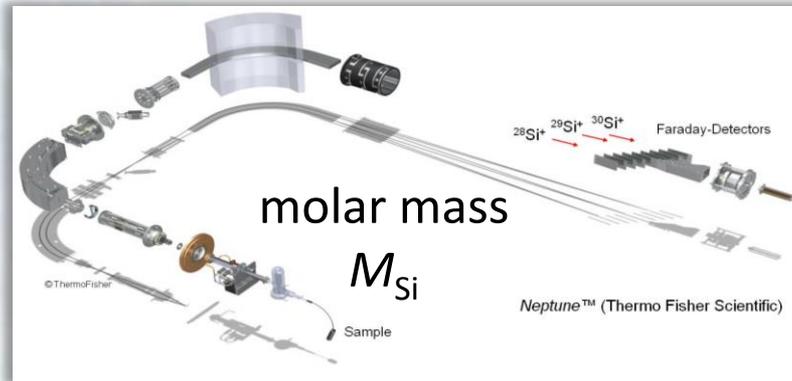
$$N_A \cdot h = 3.9903127110(18) \cdot 10^{-10} \text{ J s mol}^{-1}$$

$$u_{\text{rel}}(N_A \cdot h) = 4.5 \cdot 10^{-10} \quad (\text{CODATA 2014})$$

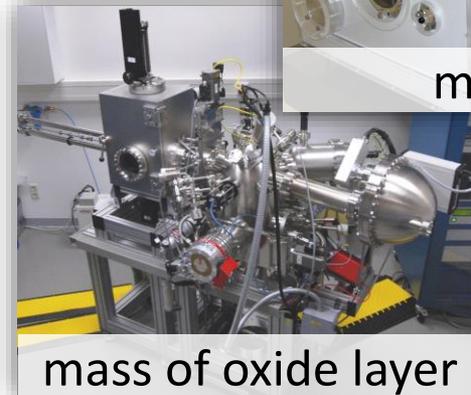
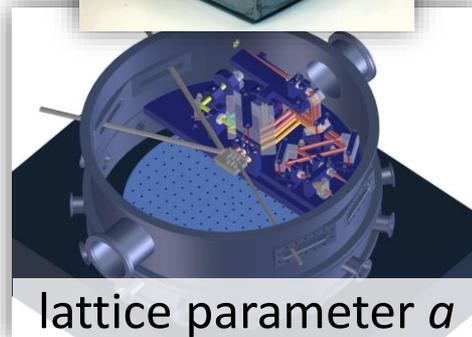
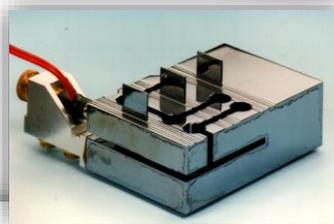
# Principle of the Avogadro Method



Si crystal  
(99.9995 %  $^{28}\text{Si}$ )

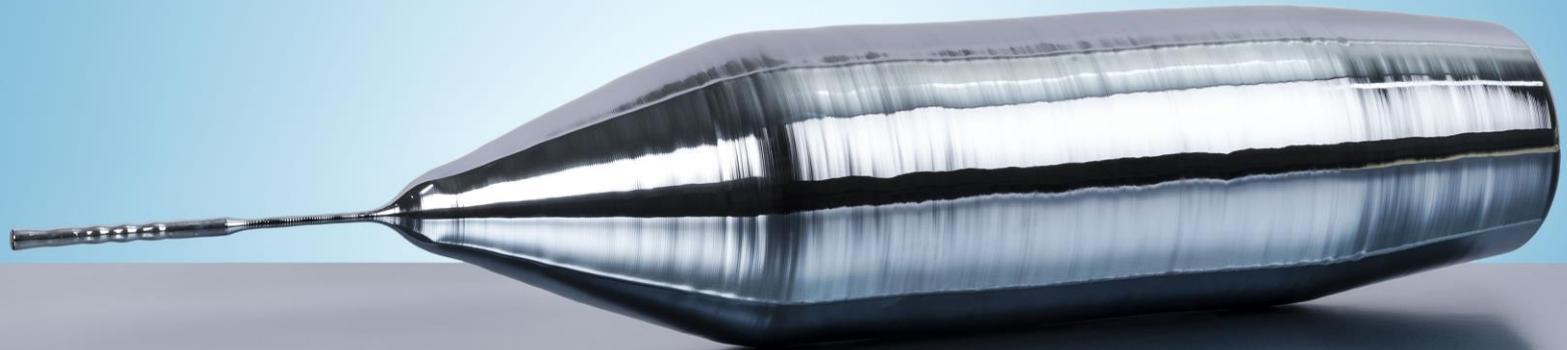
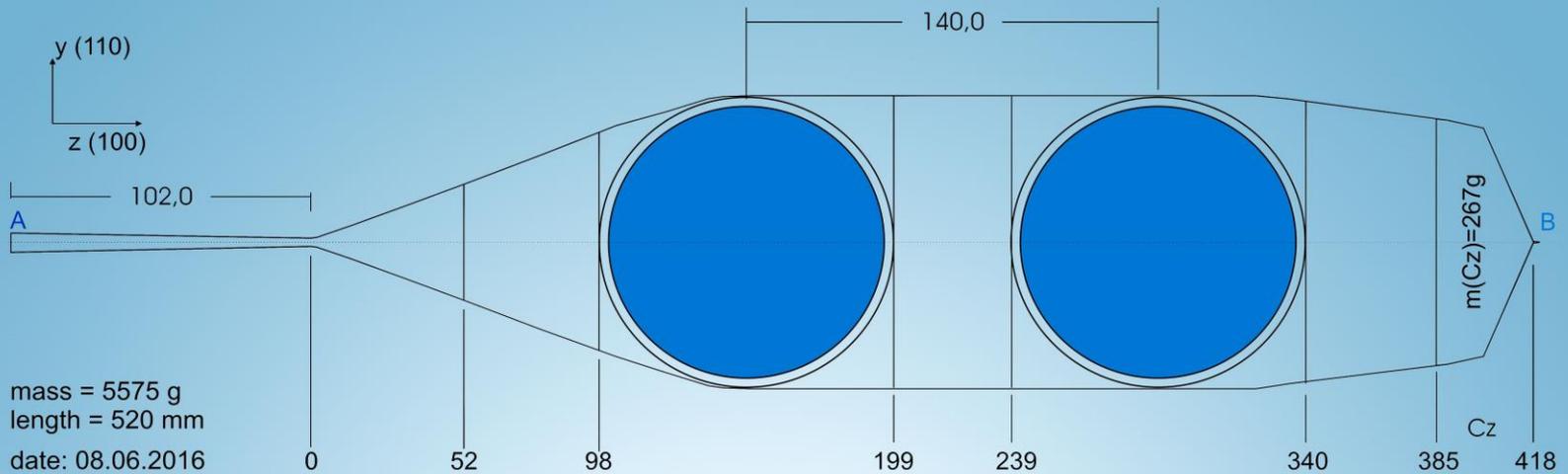


$$N_A = \frac{n V}{a^3} \cdot \frac{M_{\text{Si}}}{m}$$



# Silicon-28 Crystal

## Cutting plan of crystal Si28-24Pr11



# International Avogadro Cooperation



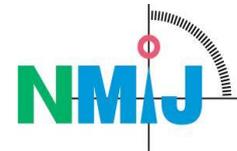
Bureau  
International des  
Poids et  
Mesures



NIST



Australian Government  
National Measurement  
Institute



NPL  
National Physical Laboratory



# International Avogadro Cooperation

Partners		Lattice parameter		Sphere volume	Sphere mass	Molar mass	Crystal perf.	Surface	Sphere fabr.
		Abs.	Rel.						
	BIPM				X			H <sub>2</sub> O	
	INRIM	X				<sup>30</sup> Si	X		
	METAS							XPS	
	NIM			2017	X	X		2017	
	NIST		X			X			
	NMI-A								X
	NMIJ		X	X	X	X	X	XPS, XRF, Ellips.	
	NRC					X			
	PTB	2018		X	X	X	X	XPS, XRF, Ellips.	X

# Current status of the Avogadro Project

## Surface layers:

- NMIJ: new XPS analyser for 1 kg Si spheres
- PTB: new XPS/XRF analyser in Braunschweig:
  - now near the vacuum balance / mass comparator of the mass lab
  - vacuum transfer of Si spheres is now possible and tested
- uncertainty of the mass of the surface layer (SL):  $u(m_{SL}) = 8.8 \mu\text{g}$



# Current status of the Avogadro Project

## Molar mass (PTB, NMIJ):

new  $^{28}\text{Si}$  crystal measured

- $u(M) = 1.4 \cdot 10^{-9} M$

## Volume (PTB):

new spheres polished and measured

- $u(V) = 7.1 \cdot 10^{-9} V$

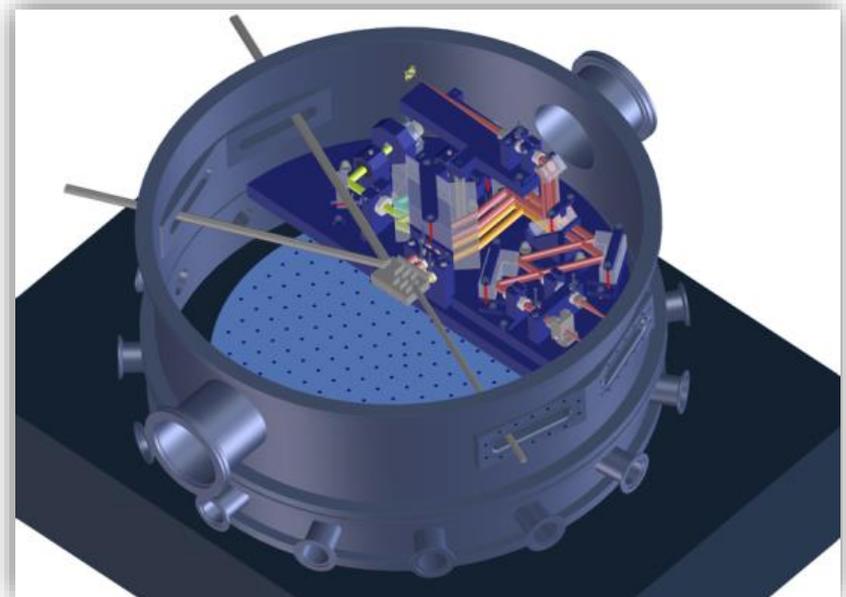
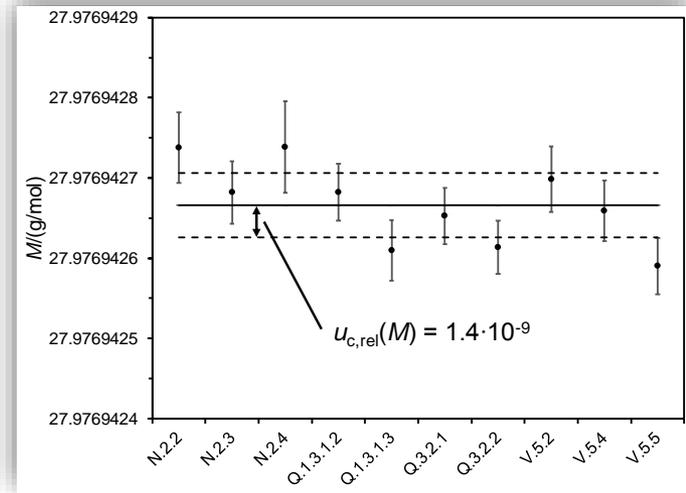
## Temperature (between different labs):

- $\Delta t < 0.1 \text{ mK} \leftrightarrow \Delta V < 10^{-9} V$

## Lattice parameter (INRIM):

- $u(a) = 1.7 \cdot 10^{-9} a$

- new set-up at PTB is now operational and under test

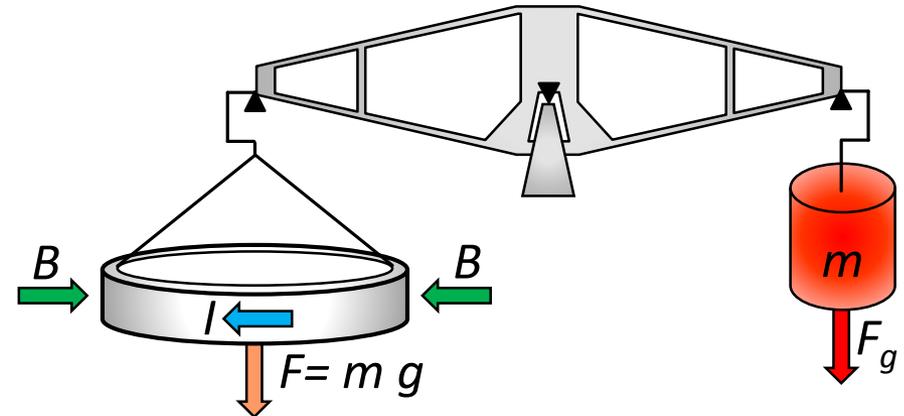


# Uncertainty budget / Avogadro Experiment

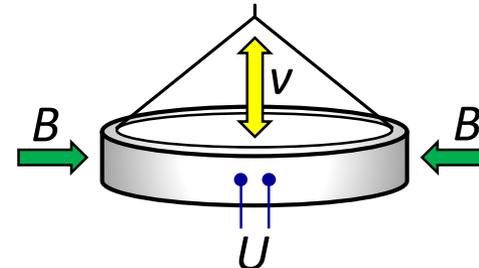
Quantity	Relative uncertainty $10^{-9}$
molar mass	1.4
sphere mass	6.1
surface layer mass	8.8
sphere volume	7.1
lattice parameter*	5.0
point defects	4.5
<b>total</b>	<b>14.6</b>

\* INRIM

# Principle of the Kibble Balance



a) "force mode" (static)



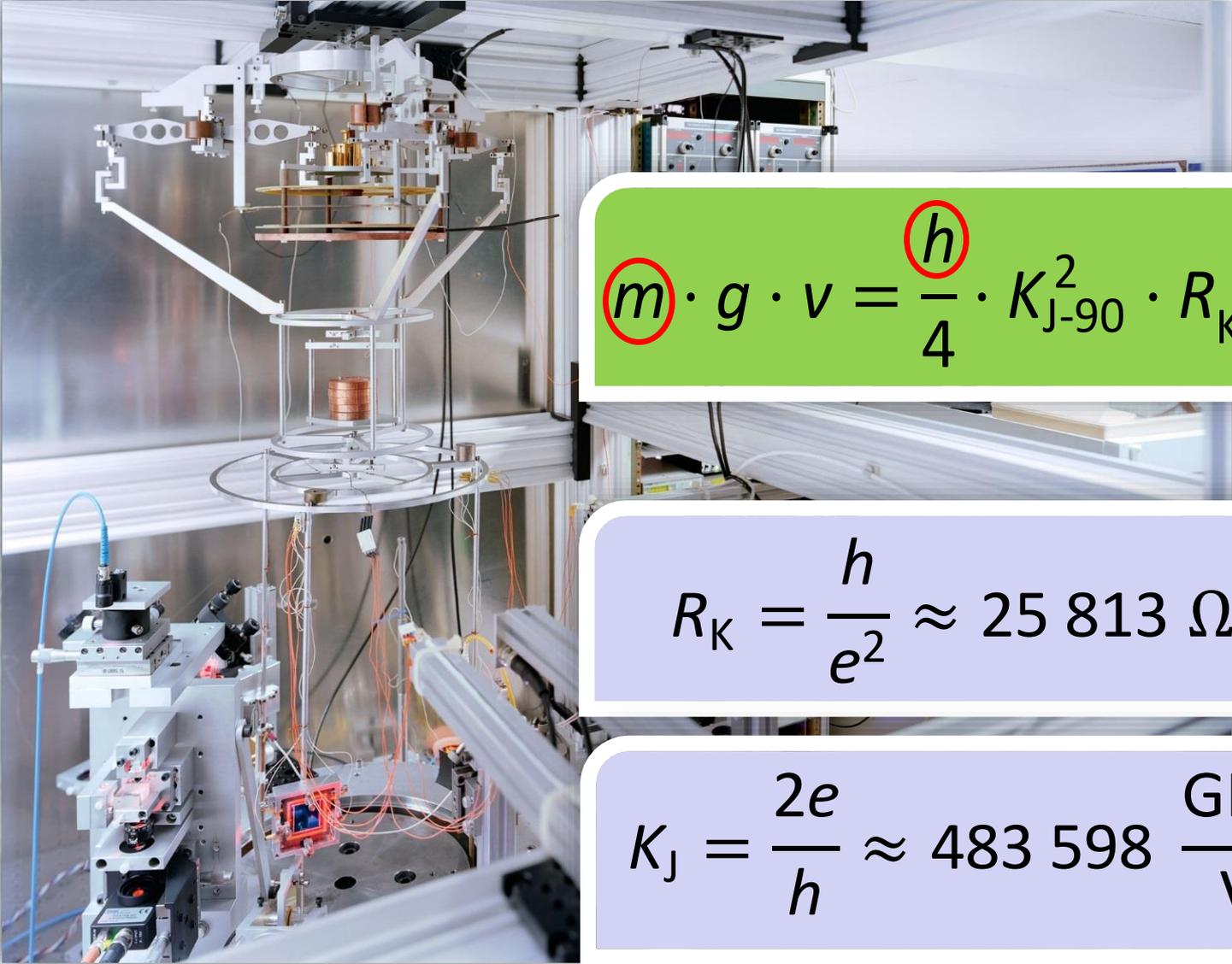
b) "velocity mode" (dynamic)

a) + b)

$$UI = mgv \sim h$$

electrical power = mechanical power

# Principle of the Kibble Balance


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

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

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

# Current status of advanced Kibble Balances

<i>Year</i>	NIST	NRC	METAS	LNE	BIPM	NIM	KRISS
2013	<b>7.3</b>	<b>6.5</b>	new set-up		1000	2500	set-up
2014	<b>4.5</b> <b>5.7</b>	<b>1.9</b> <b>1.8</b>	new set-up	<b>31</b>		<b>890</b>	set-up
2015						<b>260</b>	first tests
2016	<b>3.4</b>	1.5	tests	<b>14</b>	300		
2017	1.5	<b>0.9</b>	5?	6	10?	50?	10?

relative standard uncertainties in  $10^{-8}$

red: published values

# Relevant CCM conditions for the redefinition (CCM-Rec. G1, 2010/2013)

## 1. Uncertainty

At least three independent experiments (Avogadro/Si-28, Kibble balances) yield consistent values of  $h$  (or  $N_A$ ) with  $u_{\text{rel}} \leq 5 \cdot 10^{-8}$ ; at least one of these results with  $u_{\text{rel}} \leq 2 \cdot 10^{-8}$ .

## 2. Consistency

For each of the relevant constants, values provided by the different experiments are consistent at the 95 % level of confidence (G1, 2010).

## 3. Continuity

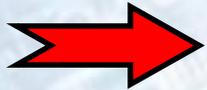
The BIPM prototypes, the BIPM ensemble of reference mass standards, and the mass standards used in the Avogadro/Si-28 experiment and Kibble balances are compared as directly as possible with the International Prototype of the Kilogram.

The procedures for the future realization and dissemination of the kilogram, as described in the ***mise en pratique***, have been validated in accordance with the principles of the CIPM-MRA.

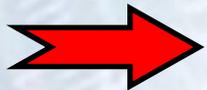
# Continuity of the new and current definition of the kilogram

## “Extraordinary use” of the IPK at the BIPM:

- calibration of all mass standards used for the experimental determination of the Planck / Avogadro constant, and
- calibration of the BIPM ensemble of reference mass standards



Just after the redefinition the mass of the IPK will be still 1 kg, but with an uncertainty!



All mass values traceable to the IPK will be unchanged after the redefinition, but all associated uncertainties will be increased by a certain component, equal to the relative uncertainty of the IPK just after the redefinition.

# CCM Pilot Study CCM.R-kg-P1

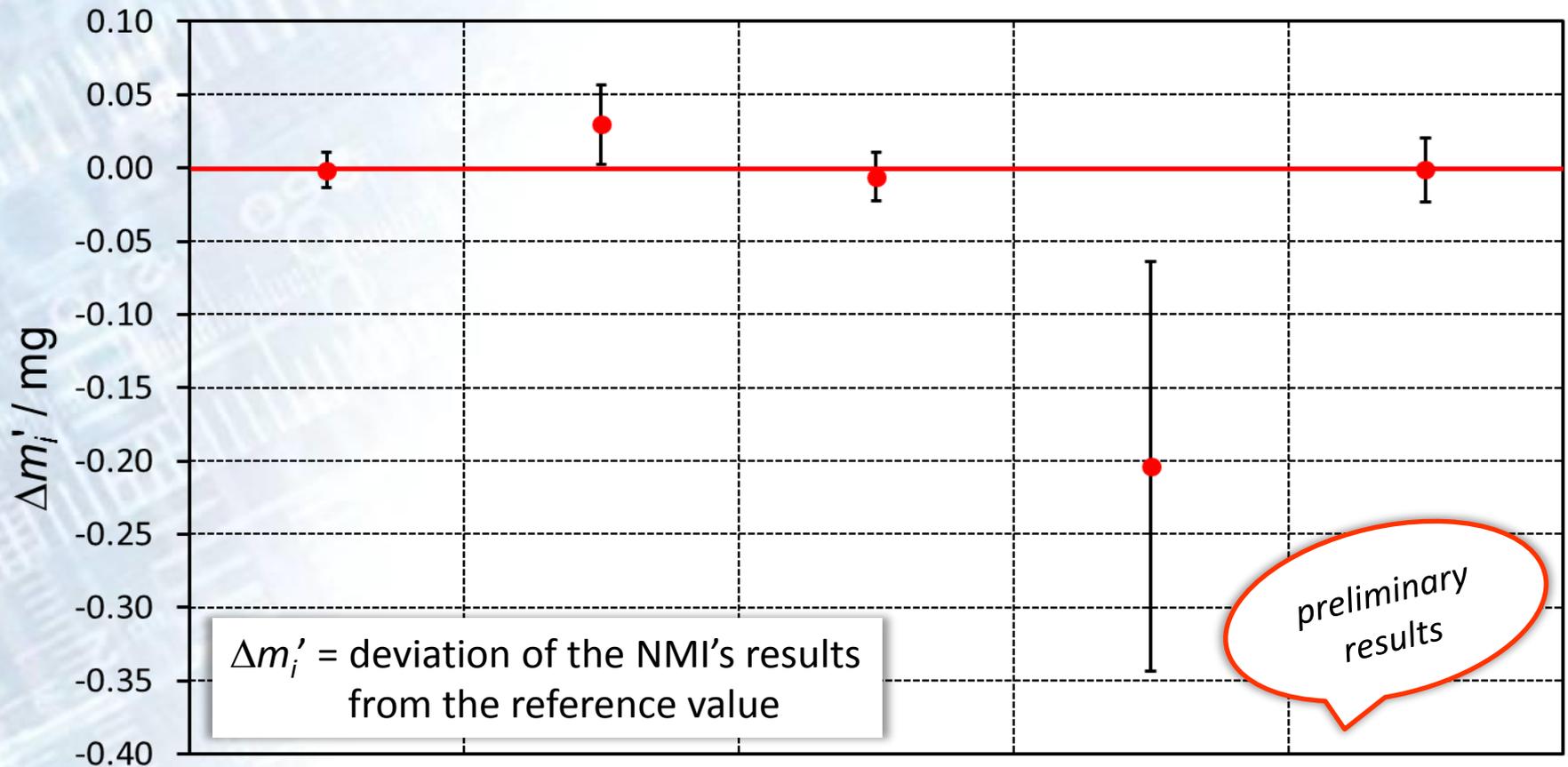
**Pilot study** including all experiments capable of determining the Planck or Avogadro constant with high accuracy.

= **First key comparison** for the new kilogram with the assumption of a **fixed value for the Planck constant  $h$** ; here  $h = 6.626\,070\,040 \cdot 10^{-34} \text{ J s}$

- time period: 01/2014 – 06/2017
- five participants (LNE, NIST, NMIJ, NRC, PTB) + pilot laboratory (BIPM)
- two sets of 1 kg travelling standards per participant:
  - one 1 kg Pt-Ir standard and optionally one 1 kg standard of the participant's choice, to be calibrated as directly as possible with the realization experiment (under vacuum if possible)
  - two 1 kg stainless steel standards, to be calibrated in air, traceable to the realization experiment

# CCM Pilot Study CCM.R-kg-P1

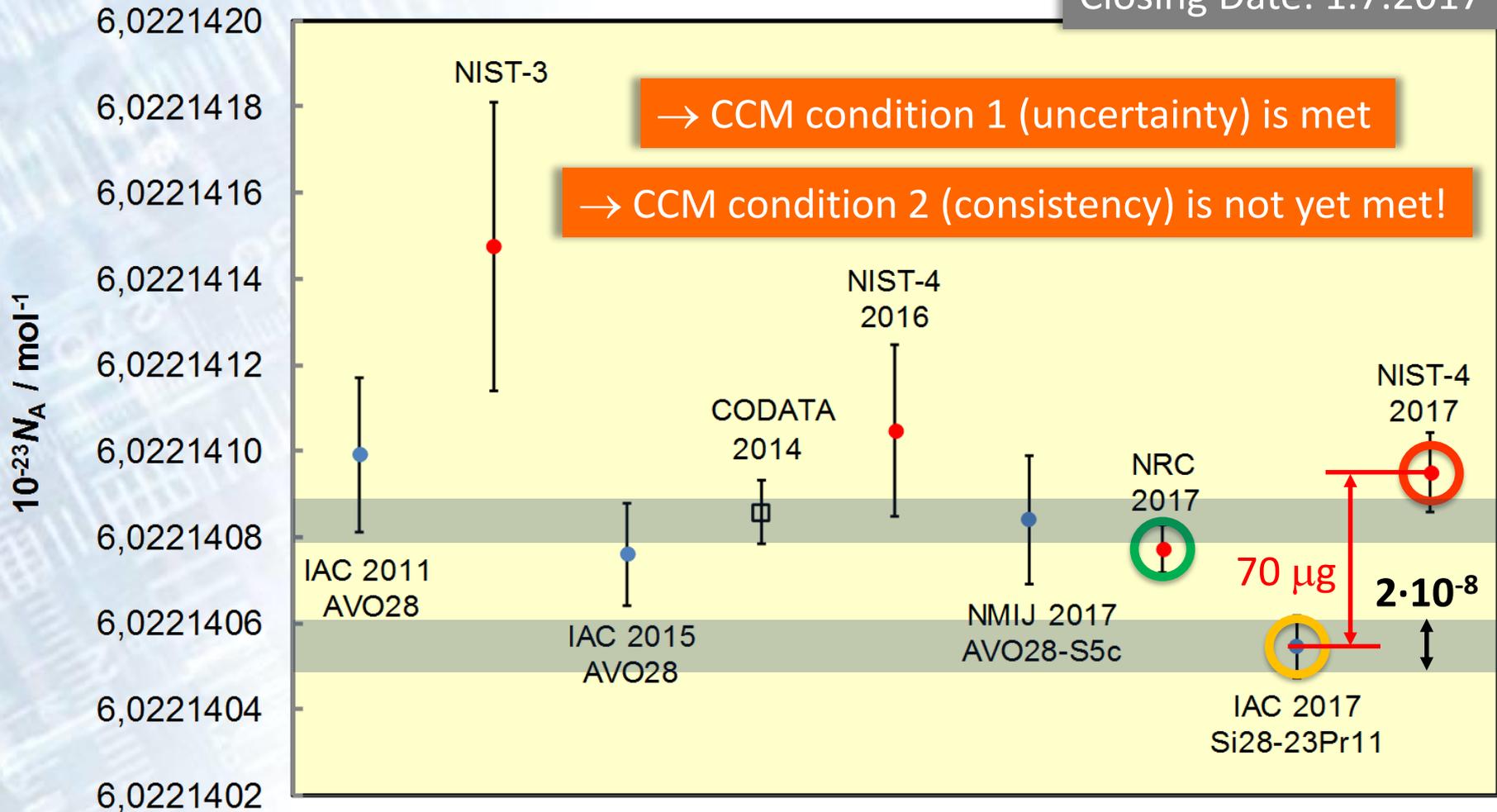
## Results (Draft A):



→ CCM condition 3 (continuity) is met

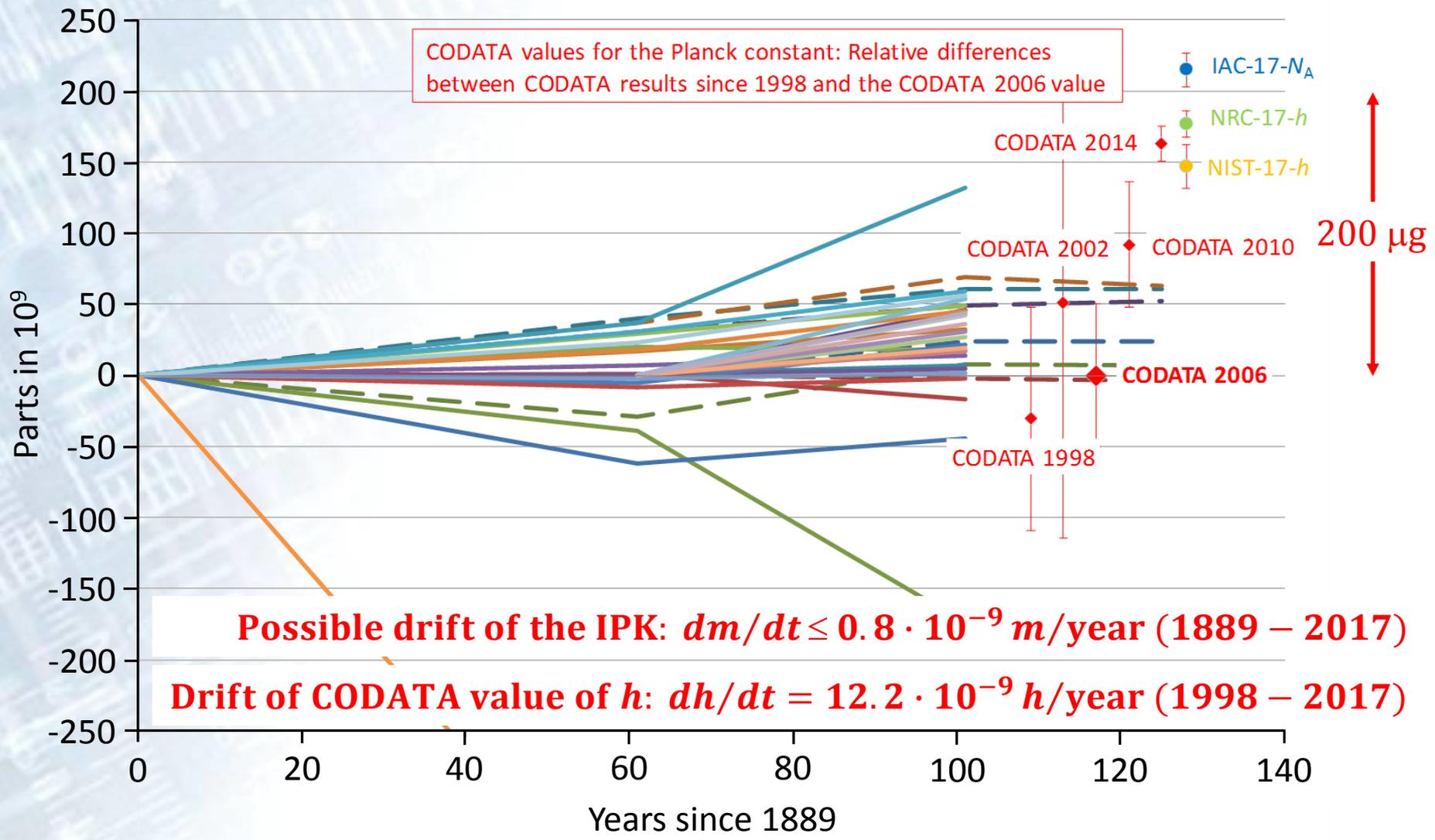
# Status of current experiments

Closing Date: 1.7.2017



published submitted / to be submitted for publication

# Stability of kilogram prototypes and CODATA recommended values of $h$



# 16<sup>th</sup> CCM meeting 18/19 May 2017

## CCM RECOMMENDATION G 1 (2017):

For a new definition of the kilogram in 2018, the CCM ...

...

### noting

- that the CCM will conduct an **on-going key comparison of primary realizations of the kilogram** that will capture and maintain a table of the experimental degrees of equivalence, which can be used to create a formal procedure for applying **corrections relative to the consensus value**,

### encourages

- all **National Metrology Institutes to continue research and further improve experiments** in support of primary realizations of the SI unit of mass at appropriate levels of precision and at different mass values appropriate for current and anticipated applications,

...

# CCM RECOMMENDATION G 1 (2017)

...

## requests

- those **National Metrology Institutes having a realization** of the kilogram to avail themselves of the **consensus value** (as determined from the **ongoing comparison**) when disseminating the unit of mass according to the new definition until the dispersion in values becomes compatible with the individual realization uncertainties, thus **preserving the international equivalence of calibration certificates and in accordance with the principles and agreed protocols of the CIPM Mutual Recognition Arrangement**,

## reminds

- members of the CCM that all Member States **not having realizations of the new definition of the kilogram** will have direct access to **traceability to the same consensus value** as determined by the ongoing comparison through the calibration services of the BIPM,

...

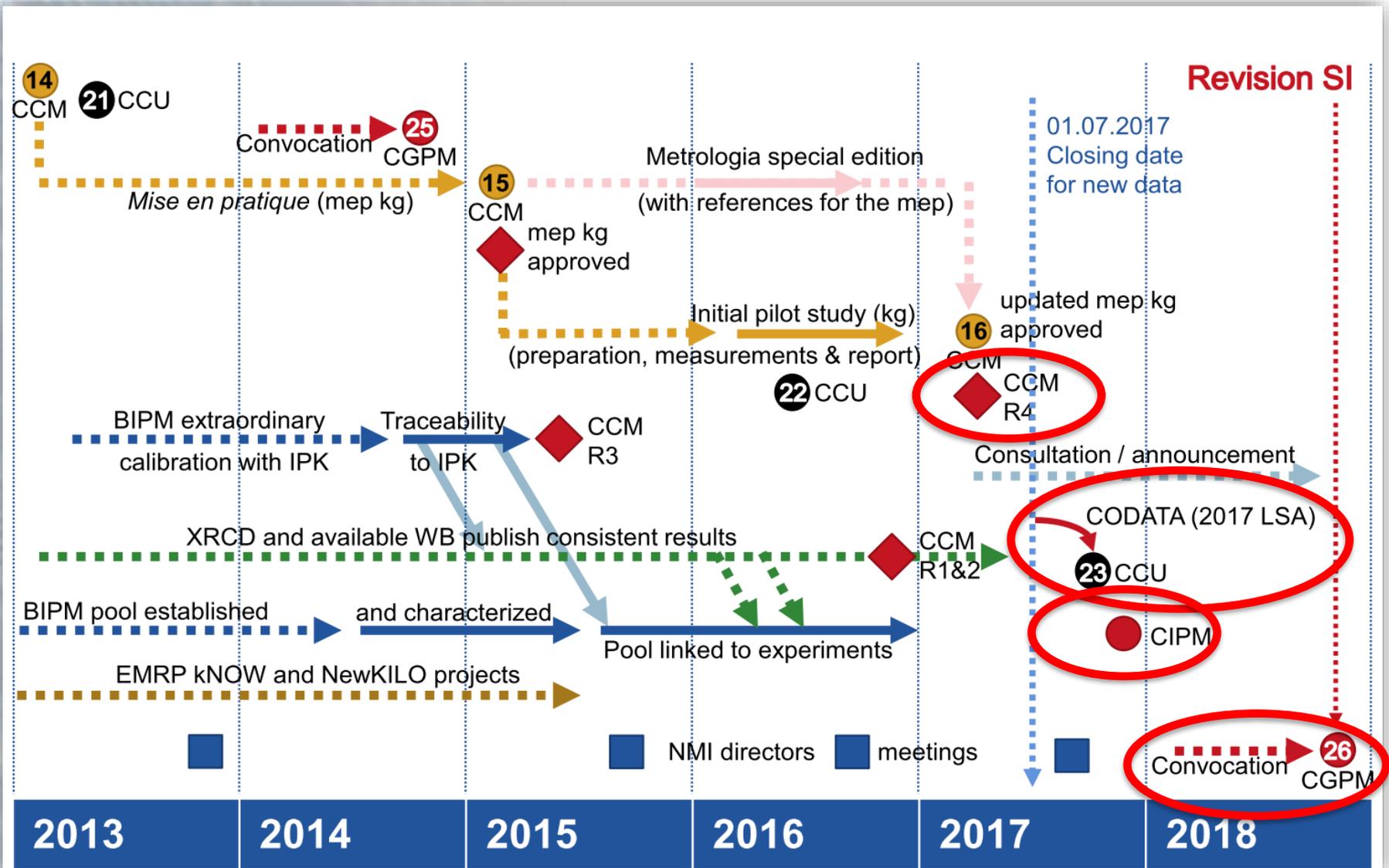
# CCM RECOMMENDATION G 1 (2017)

...

**recommends**

- that the **CIPM undertakes the necessary steps to proceed with the planned redefinition of the SI at the next meeting of the CGPM, acknowledging the measures to be taken by the CCM to ensure integrity and continuity in the dissemination of the kilogram.**

# Joint CCM-CCU roadmap for the new SI



# Overview

1. Motivation for the revision of the SI and the redefinition of the kilogram
2. Status of current experiments to redefine the kilogram
- 3. Realization and dissemination of the kilogram after its redefinition**
4. Consequences for derived or related SI units

# Current definition of the unit of mass

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

(1<sup>st</sup> CGPM 1889 and 3<sup>rd</sup> CGPM 1901)



➤  $m_{\text{IPK}} = 1 \text{ kg}$  (exactly)

# Proposed wording of the new definition of the kilogram<sup>1)</sup>

“The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant  $h$  to be  $6.626\,070\,040^{2)} \cdot 10^{-34}$  when expressed in the unit  $\text{J s}$ , which is equal to  $\text{kg m}^2 \text{s}^{-1}$ , where the metre and the second are defined in terms of  $c$  and  $\Delta\nu_{\text{Cs}}$ .”



<sup>1)</sup> see Draft 9<sup>th</sup> edition of the SI brochure → <http://www.bipm.org/utils/common/pdf/si-brochure-draft-2016b.pdf>

<sup>2)</sup> The exact value will be fixed after the final CODATA adjustment of relevant constants.

# Mise en Pratique (MeP) for the realization of the new kilogram<sup>1)</sup>

## 2. Primary methods to realize the definition of the kilogram

There are currently two independent primary methods that are capable of realizing the definition of the kilogram with relative uncertainties within a few parts in  $10^8$ . The first of these relies on determining the unknown mass using an electromechanical balance specially designed for the purpose. The second method compares the unknown mass to the mass of a single atom of a specified isotope, where the latter is well-known in terms of  $h$ .

### 2.1 Realization by comparing electrical power to mechanical power

Accurate instruments that function in a way that electrical and mechanical power can be equated are known as watt balances. Watt balances can be designed with different geometries and experimental protocols. The following schematic description serves to demonstrate that any of these watt-balance configurations has the potential to be a primary method to realize the definition of the kilogram.

The determination of the unknown mass  $m_x$  of an artefact  $x$  is carried out in two modes: the weighing mode and the moving mode. They may occur successively or simultaneously. In the weighing mode, the weight<sup>1</sup>  $m_x g$  of the artefact is balanced by the electromagnetic force produced, for example, on a circular coil of wire-length  $l$  immersed in a radial magnetic field of flux density  $B$  when a current  $I_1$  flows through the coil. The magnet and coil geometries are designed to produce a force that is parallel to the local gravitational acceleration. The acceleration of gravity  $g$  acting on the mass, and the current  $I_1$  flowing in the coil are measured simultaneously so that

$$m_x g = I_1 B l. \quad (2.1)$$

In the moving mode the voltage  $U_2$ , which is induced across the terminals of the same coil moving vertically at a velocity  $v$  through the same magnetic flux density, is measured so that

$$U_2 = v B l. \quad (2.2)$$

The equations describing the two modes are combined by eliminating  $B l$ :

...

### 2.2 Realization by the X-ray-crystal-density method

The concept of the X-ray-crystal-density (XRCD) method comes from a classical idea where the mass of a pure substance can be expressed in terms of the number of elementary entities in the substance<sup>2</sup>. Such a number can be measured by the XRCD method in which the volumes of the unit cell and of a nearly perfect crystal are determined, e. g. by measuring the lattice parameter  $a$  and the mean diameter of a spherical sample. Single crystals of silicon are most often used in this method because large crystals can be obtained having high chemical purity and no dislocations. This is achieved using the crystal growth technologies developed for semiconductor industry. The macroscopic volume  $V_s$  of a crystal is equal to the mean microscopic volume per atom in the unit cell multiplied by the number of atoms in the crystal. For the following, assume that the crystal contains only the isotope  $^{28}\text{Si}$ . The number  $N$  of atoms in the macroscopic crystal is therefore given by

$$N = 8 V_s / a(^{28}\text{Si})^3, \quad (2.5)$$

where 8 is the number of atoms per unit cell of crystalline silicon and  $a(^{28}\text{Si})^3$  is the volume of the unit cell, which is a cube; i.e.,  $V_s / a(^{28}\text{Si})^3$  is the number of unit cells in the crystal and each unit cell contains eight silicon-28 atoms. Since the volume of any solid is a function of temperature and, to a lesser extent, hydrostatic pressure,  $V_s$  and  $a(^{28}\text{Si})^3$  are referred to the same reference conditions. For practical reasons, the crystal is fashioned into a sphere having a mass of approximately 1 kg.

To realize the definition of the kilogram, the mass  $m_s$  of the sphere is first expressed in terms of the mass of a single atom, using the XRCD method<sup>3</sup>:

$$m_s = N m(^{28}\text{Si}), \quad (2.6)$$

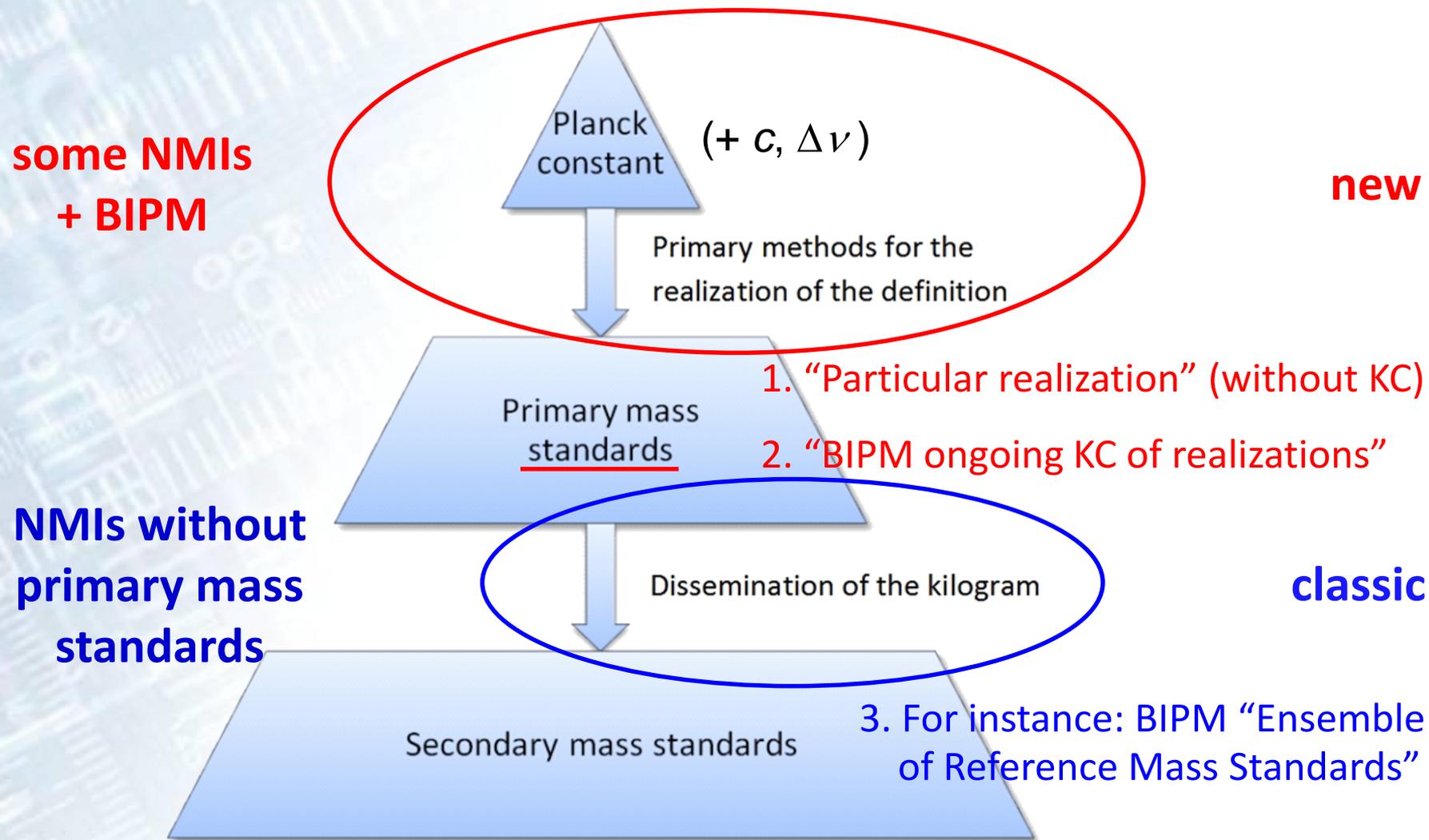
Since the experimental value of the physical constant  $h/m(^{28}\text{Si})$  is known to high accuracy [2.4], one can rewrite (2.6) as

$$m_s = h N \left( \frac{m(^{28}\text{Si})}{h} \right). \quad (2.7)$$

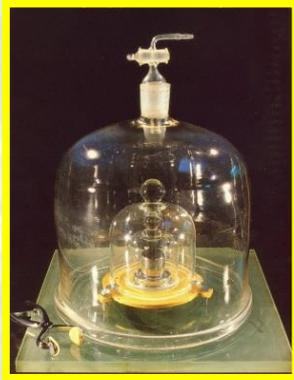
...

<sup>1)</sup> see BIPM website: [http://www.bipm.org/cc/CCM/Allowed/15/02A\\_MeP\\_kg\\_141022\\_v-9.0\\_clean.pdf](http://www.bipm.org/cc/CCM/Allowed/15/02A_MeP_kg_141022_v-9.0_clean.pdf)

# Future realization and dissemination of the kilogram



# Classic (current) realization and dissemination

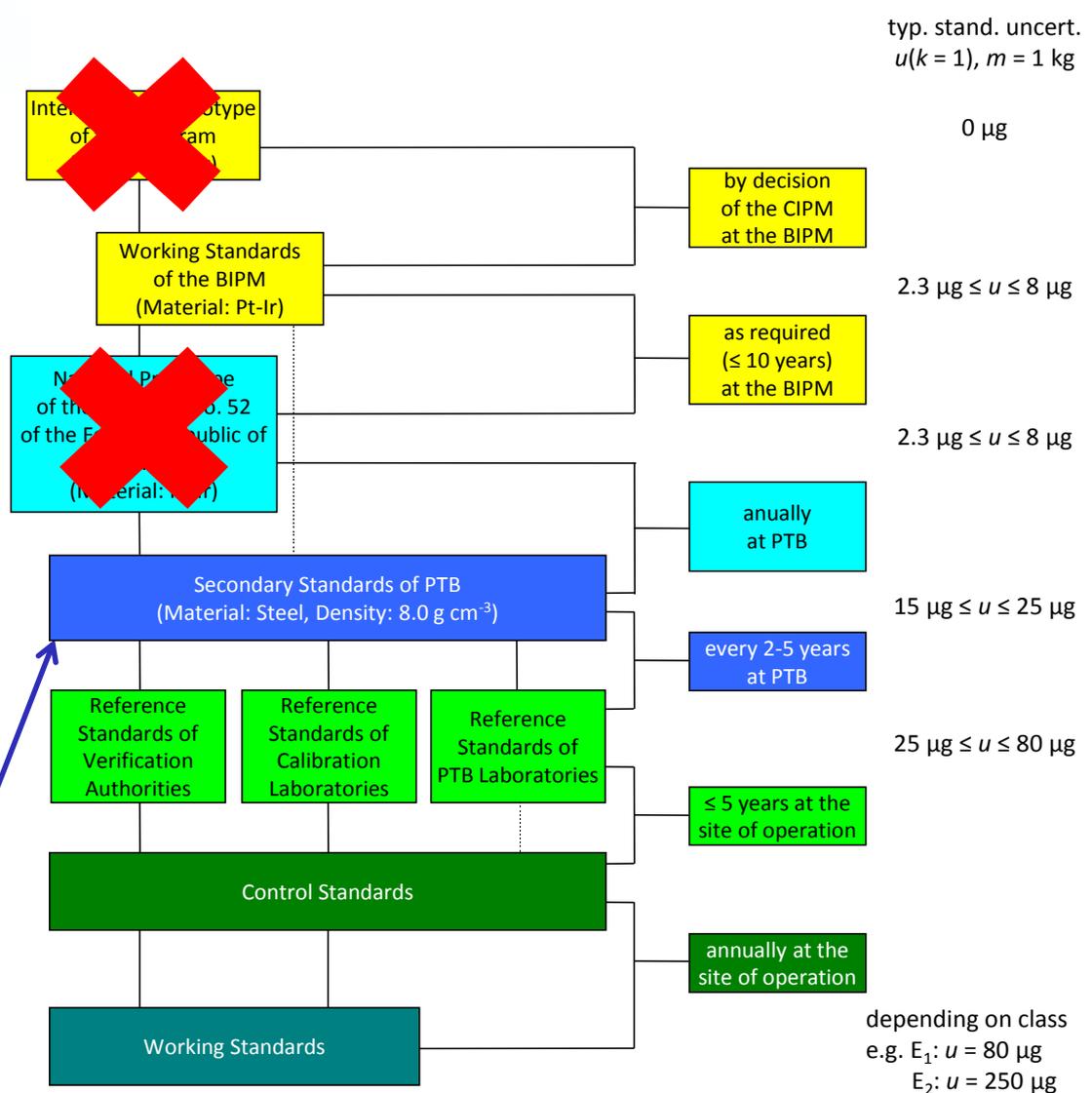


$m = 1 \text{ kg} + 0.261 \text{ mg}$   
 $u = 0.003 \text{ mg}$   
 (11.2009, Amendment to BIPM-certificate No. 21)  
**drift: +0.0008 mg/a**  
 $u(\text{drift}) = 0.0011 \text{ mg/a}$   
 other kilogram prototypes:  
 Nr. 55, 70, (15, 22, 109)



**Mass scale**  
**1 mg – 5 t**

$u_{\text{rel}} \geq 1 \cdot 10^{-8}$



# Future realization and dissemination according to the *Mise en Pratique* (Dec. 2014)

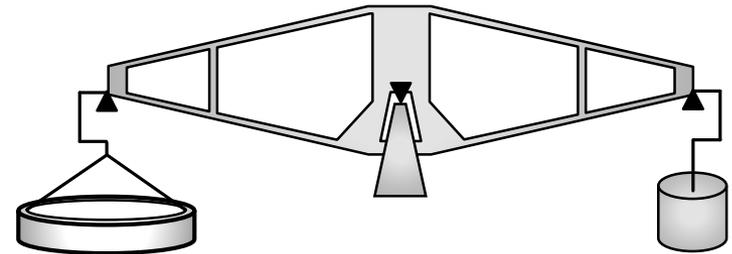
## 1. "Particular realization" by a NMI:

Primary realization: Si-28 (in vacuum)

Primary standards:



alternatively/additionally:



Secondary standards of a NMI



# Primary realization with Si-28

Mass of the sphere including surface layers:

$$m_{\text{sphere}} = \frac{2hR_{\infty}}{c\alpha^2} \frac{\sum_i x(^i\text{Si}) A_r(^i\text{Si})}{A_r(\text{e})} \frac{8V_{\text{core}}}{a^3} - m_{\text{deficit}} + m_{\text{SL}}$$



$h$  Planck constant

$R_{\infty}$  Rydberg constant

$c$  speed of light in vacuum

$\alpha$  fine-structure constant

$x(^i\text{Si})$  amount-of-substance ratio of  $^i\text{Si}$  in the sphere ( $i = 28, 29, 30$ )

$A_r$  relative atomic mass

$e$  electron

$V_{\text{core}}$  volume of the Si-28 sphere without surface layers

$a$  lattice parameter

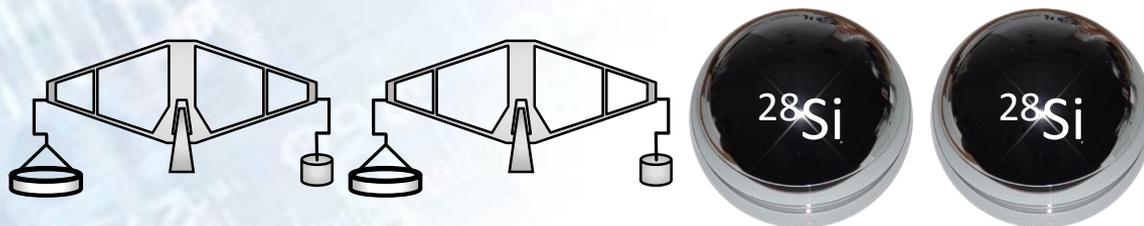
$m_{\text{deficit}}$  correction for impurities and vacancies in the sphere

$m_{\text{SL}}$  mass of surface layers

# Future realization and dissemination according to the *Mise en Pratique* (Dec. 2014)

## 2. “BIPM (ongoing) KC of realizations”:

Primary standards (several NMIs + BIPM):



→ KCRV  
(possible in air)



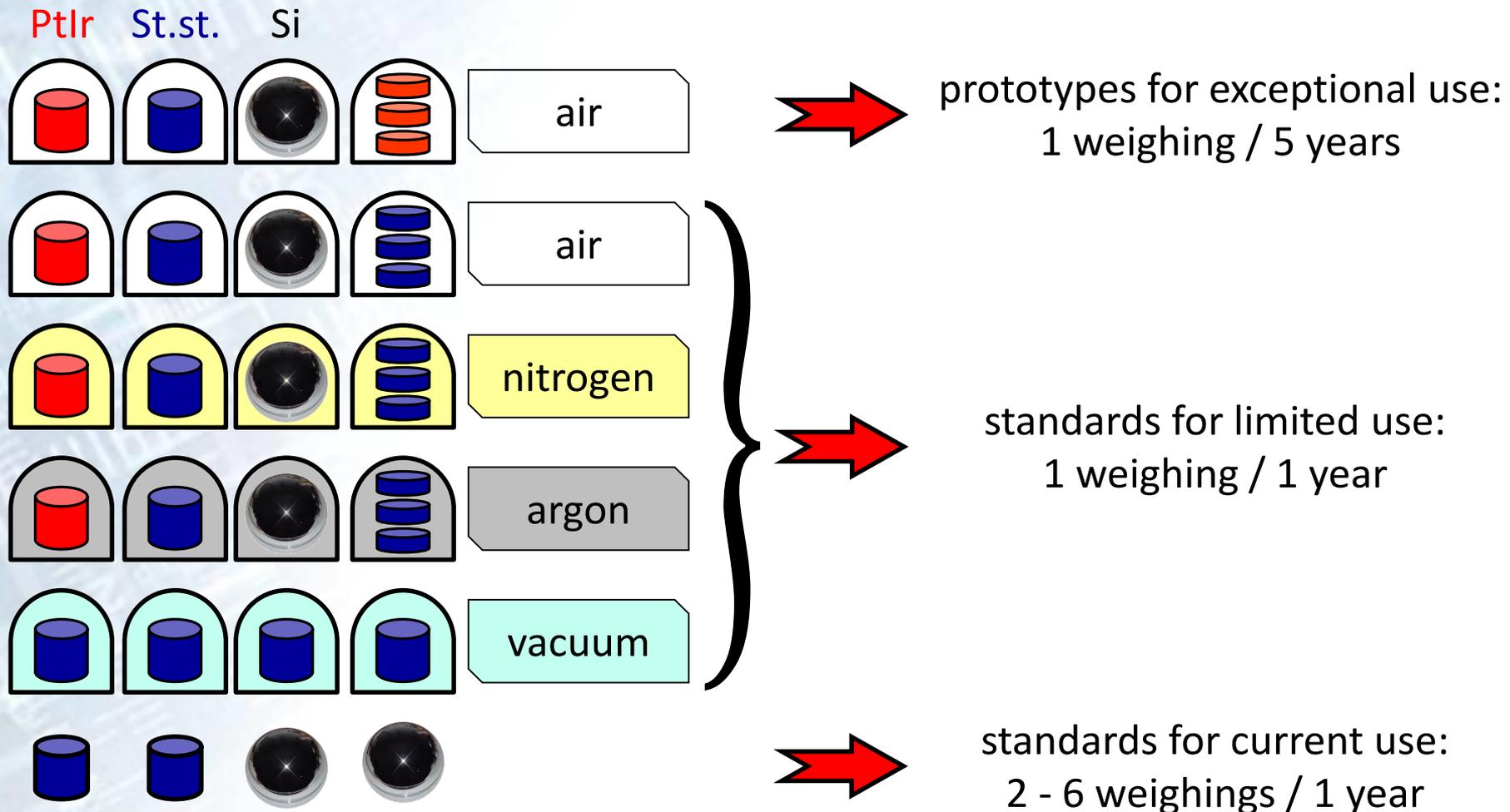
Secondary standards (of a NMI / the BIPM)



*Correction of mass values  
of all national / BIPM  
primary mass standards  
to a computed  
“consensus value” !*

# Future realization and dissemination according to the *Mise en Pratique* (Dec. 2014)

## 3. BIPM "Ensemble of Reference Mass Standards (ERMS)":



# Future realization and dissemination according to the *Mise en Pratique* (Dec. 2014)

## 3. BIPM “Ensemble of Reference Mass Standards (ERMS)”:

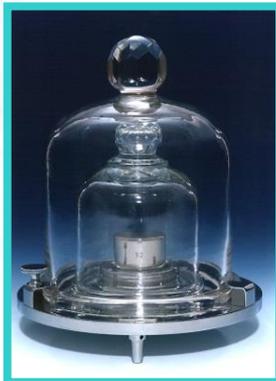
KCRV →

ERMS = secondary standards of the BIPM

ERMS  
(standards for current use)



Secondary standards of a NMI  
without own primary standard



# PTB activities towards the future realization of the kilogram

## Round and ready

dissemination of the kg via Si spheres



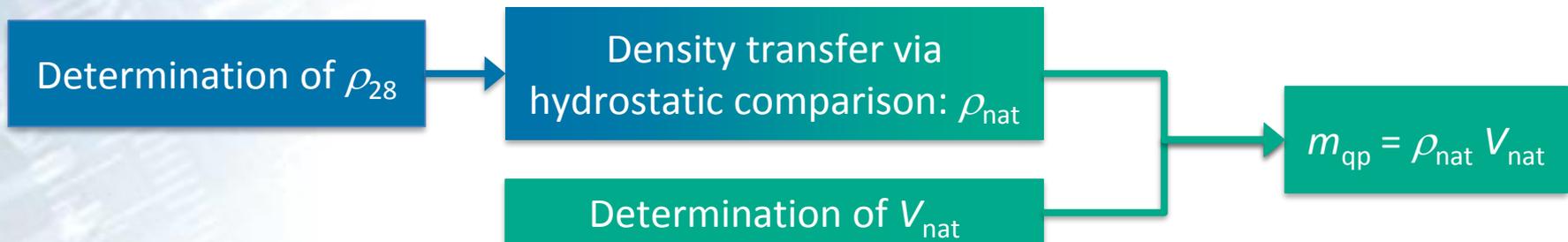
Dissemination of the unit kilogram by monocrystalline spheres made of natural silicon. Available types:

- **quasi primary realization** ( $^{\text{nat}}\text{Si}_{\text{qp}}$ ); density comparison, magnetic flotation
- **secondary materialization** ( $^{\text{nat}}\text{Si}_{\text{sc}}$ ); comparator principle

Specification	$^{\text{nat}}\text{Si}_{\text{qp}}$	$^{\text{nat}}\text{Si}_{\text{sc}}$
RONt	< 20 nm	< 80 nm
Ra	< 0.1 nm	< 1 nm
Price	100 000 €	10 000 €

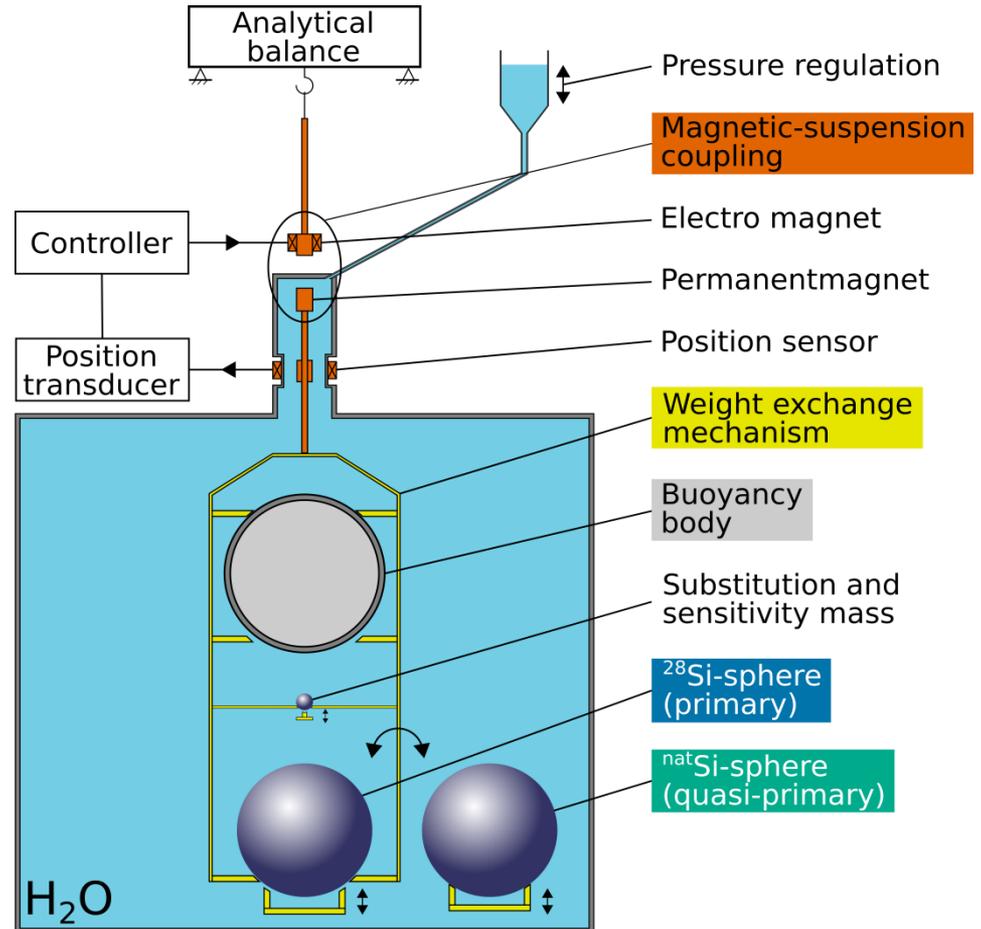
# <sup>nat</sup>Si-spheres as quasi-primary realization of the kilogram

- Spheres made of **natural silicon (<sup>nat</sup>Si)** represent a rather "inexpensive" alternative to spheres of isotopically enriched silicon.
  - The molar mass of <sup>nat</sup>Si cannot be measured accurately enough to be used as a primary realization of the new 'kg'.
- However, by means of a **hydrostatic comparison** the well-known density of <sup>28</sup>Si can be transferred to a <sup>nat</sup>Si-sphere.
  - Only the **density** of the <sup>28</sup>Si-sphere needs to be known.
  - **Volume and mass** of the <sup>28</sup>Si-sphere need **not** be known.
- After an accurate determination of its volume the **<sup>nat</sup>Si-sphere** can act as a **quasi-primary realisation** of the new 'kg'.
- Advantages: price; relative uncertainty  $\approx 3 \cdot 10^{-8}$



# Design of the magnetic flotation apparatus

- measurements only at 20 °C
- commercial analytical balance with capacity of 200 g
- magnetic-suspension coupling
- liquid: distilled water
- a buoyancy body reduces the load to a few grams
- constant load conditions guarantee high reproducibility when the two spheres are exchanged



# Joint PTB / TU Ilmenau research project to develop a new Planck Balance (PB)

A self-calibrating precision balance for industrial applications:

- **Project runtime:**  
→ Jan 2017 – Dec 2019
- **Project management:**  
→ VDI/VDE Innovation + Technik GmbH
- **Funding:**  
→ German Federal Ministry of Education and Research
- **Mass ranges and relative uncertainties aimed at:**

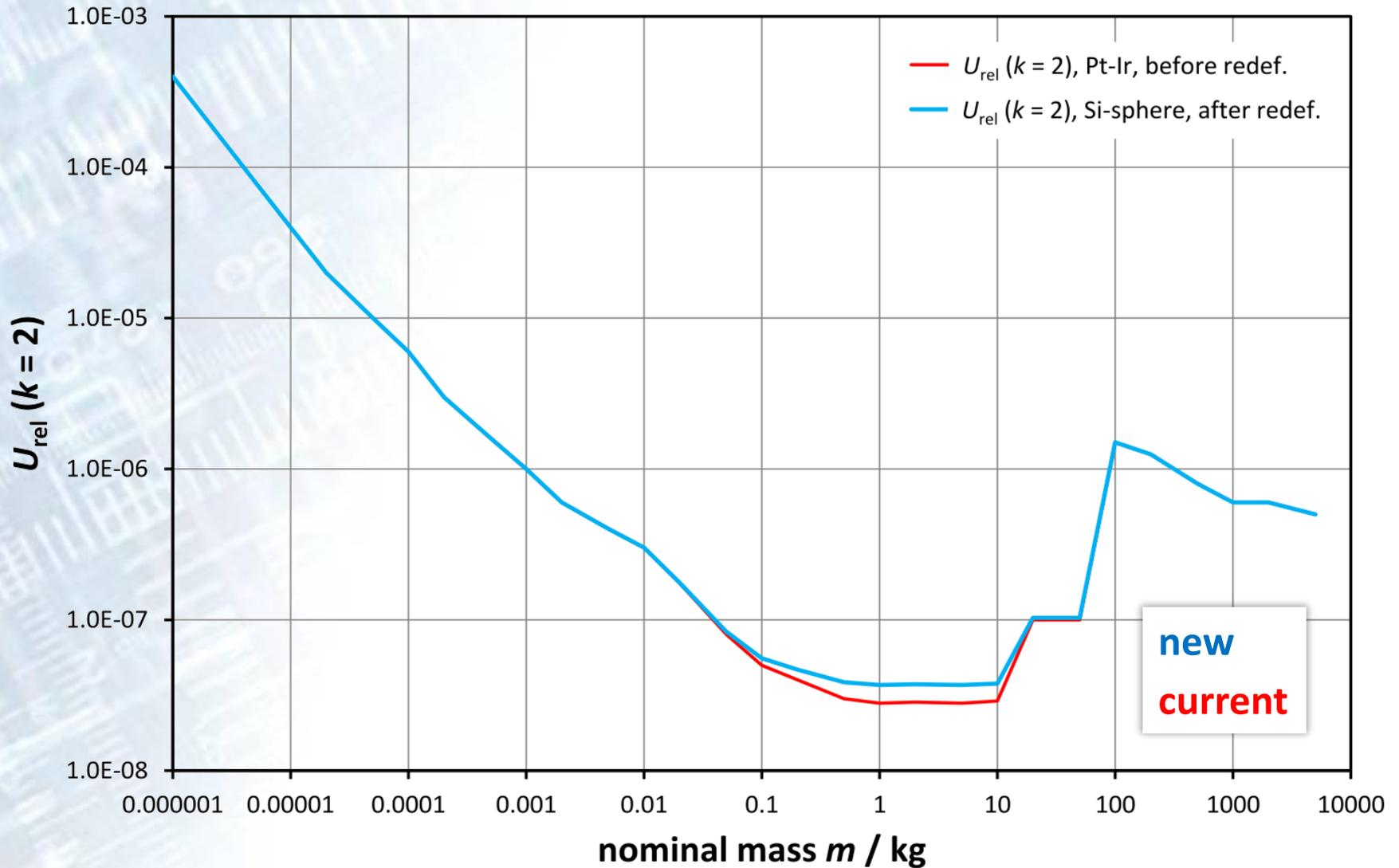


Version	Mass range	MPE OIML R111-1	$U_r \leq 1/3 \cdot \text{MPE}$ $k=2$	Environment
<b>PB 2</b>	1 mg...100 g	$16 \cdot 10^{-7}$	$5.3 \cdot 10^{-7}$	Air
<b>PB 1</b>	1 mg...100 g	$5 \cdot 10^{-7}$	$1.7 \cdot 10^{-7}$	High Vacuum
<b>PB 0</b>	1 kg	$1.5 \cdot 10^{-7}$	$0.5 \cdot 10^{-7}$	High Vacuum

# Overview

1. Motivation for the revision of the SI and the redefinition of the kilogram
2. Status of current experiments to redefine the kilogram
3. Realization and dissemination of the kilogram after its redefinition
- 4. Consequences for derived or related SI units**

# Expected consequences for a typical mass scale



# Expected consequences for other SI units

Derived quantity	Unit, symbol	CCM WG	Requirements of mass determination $u_{rel}$	Consequences of the redefinition
<b>Force</b>	Newton, N (kg m s <sup>-2</sup> )	Force	$\geq 1 \cdot 10^{-6}$	none
<b>Torque</b>	N m	Force	$\geq 1 \cdot 10^{-6}$	none
<b>Density</b>	kg m <sup>-3</sup>	Density and Viscosity	$\geq 4 \cdot 10^{-8}$	With <sup>28</sup> Si spheres the unit of density can be realized with smaller uncertainty than the unit of mass! (No uncertainty contribution from volume measurement)
<b>Pressure</b>	Pascal, Pa (N m <sup>-2</sup> )	Pressure	$\geq 1 \cdot 10^{-6}$	none
<b>Flow</b>	kg s <sup>-1</sup>	Flow	$> 1 \cdot 10^{-5}$	none
<b>Dyn. viscosity</b>	Pa s	Density and Viscosity	$> 1 \cdot 10^{-6}$	none
<b>Amount of substance</b>	mol	CCQM		<ul style="list-style-type: none"> <li>The molar mass constant will no longer be fixed.</li> <li>The unit mole will become independent of the unit of mass.</li> </ul>

# Summary

- The uncertainties achieved with current experiments meet the CCM conditions for a redefinition of the kilogram in 2018.
- The results of current experiments are not yet consistent.
- The CODATA values for  $h$  have drifted by about 200  $\mu\text{g}$  since 1998.
- The CCM recommends that the CIPM proceeds with the redefinition in 2018; corrections based on a computed "consensus value" will preserve international equivalence of calibration certificates and ensure integrity and continuity in the dissemination of the kilogram.
- The redefinition of the kilogram will have no practical consequences on derived or related SI units.

**Thank you  
for your attention!**

