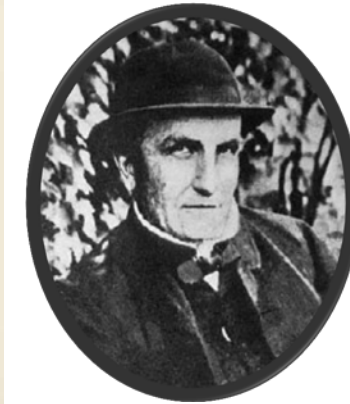
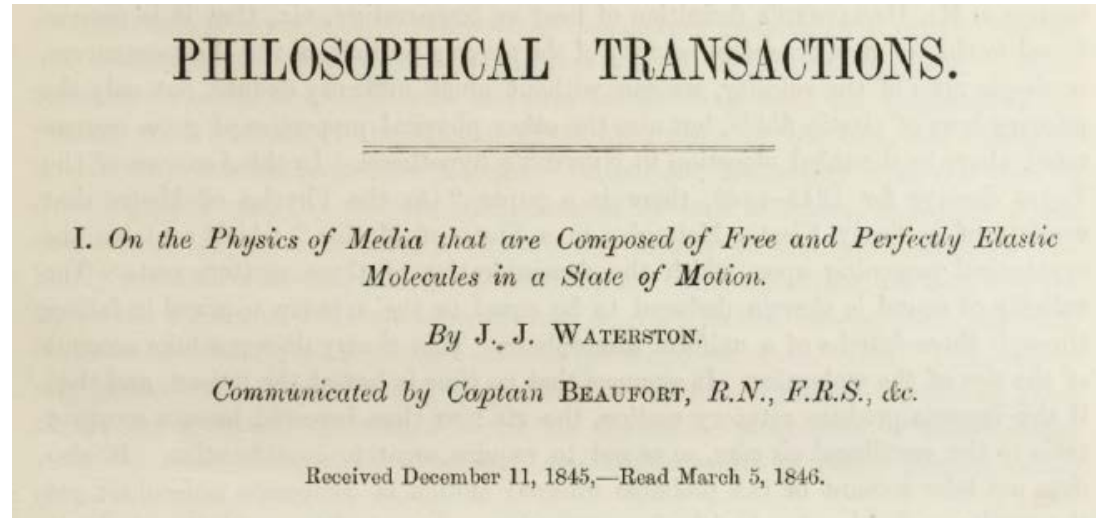


The redefinition of the kelvin

Christof Gaiser

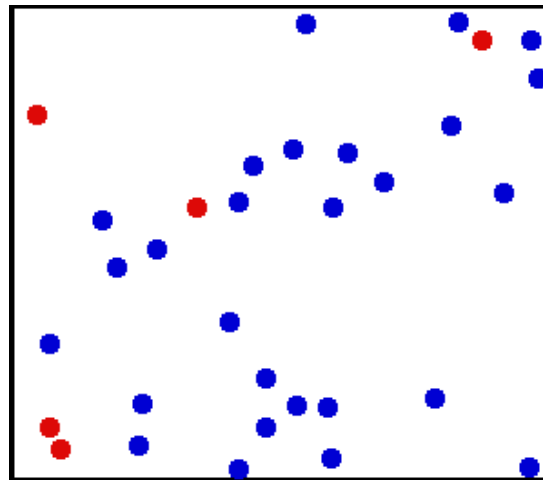
Physikalisch-Technische Bundesanstalt Berlin Germany



J.J. Waterston



L. Boltzmann



J.C. Maxwell



M. Planck, „Ueber irreversible Strahlungsvorgänge“,
Ann. Physik 1, 69 (1900)

Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhilfenahme der beiden in dem Ausdruck (41) der Strahlungsentropie auftretenden Constanten a und b die Möglichkeit gegeben ist, Einheiten für Länge, Masse, Zeit und Temperatur aufzustellen, welche, unabhängig von speciellen Körpern oder Substanzen, ihre Bedeutung für alle Zeiten und für alle, auch ausserirdische und aussermenschliche Culturen notwendig behalten und welche daher als „natürliche Maasseinheiten“ bezeichnet werden können.

...with the aid of... constants...establishing the **units** of length, mass, time and temperature, **independent of special artefacts or substances, keeping their relevance for all times** and all, including extraterrestrial and non-human cultures.

Why the community made no use of this idea for more than 100 years?

Not only because metrologists are highly conservative.

Mainly because the determination of thermodynamic temperature is far more difficult than comparing thermometers at fixed points.

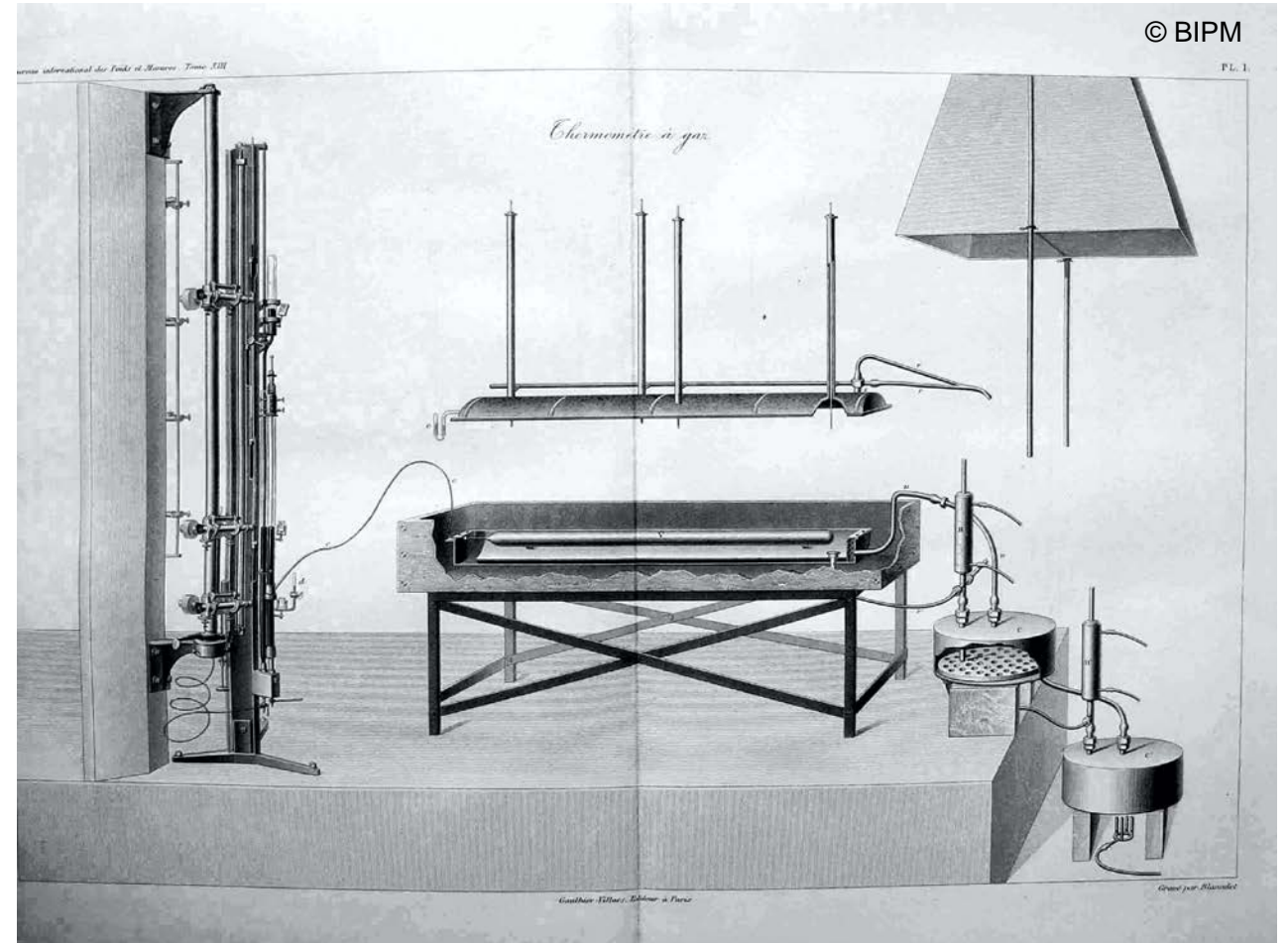
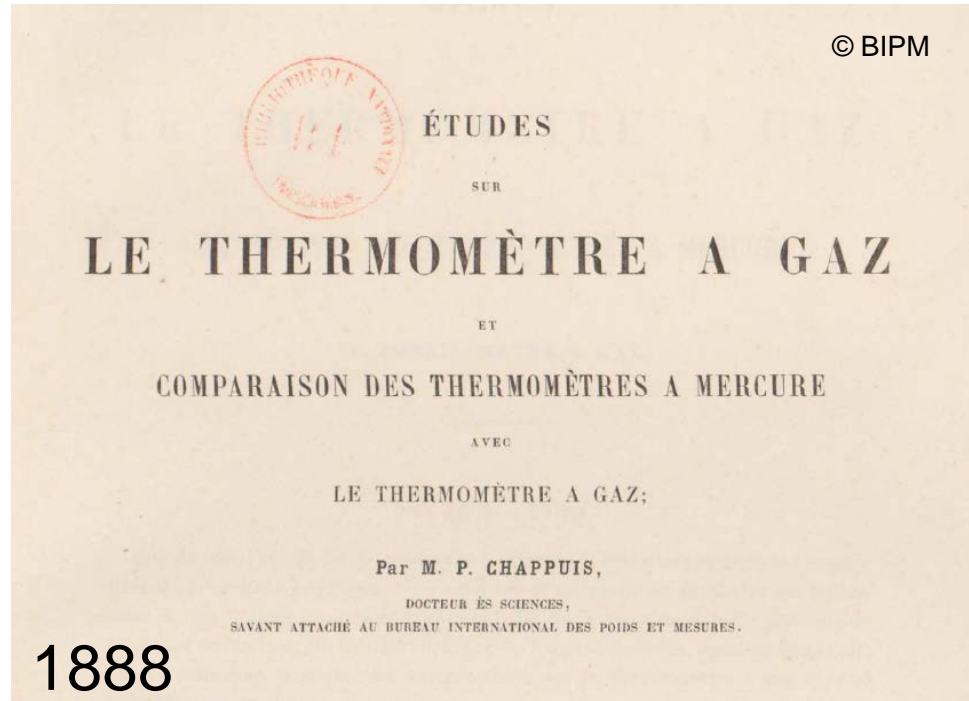
Chappuis's Gas thermometer

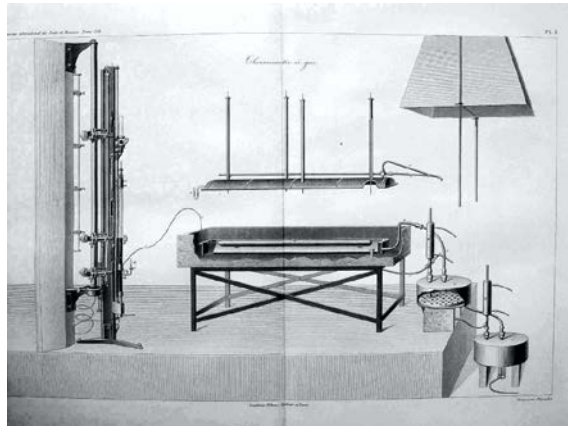
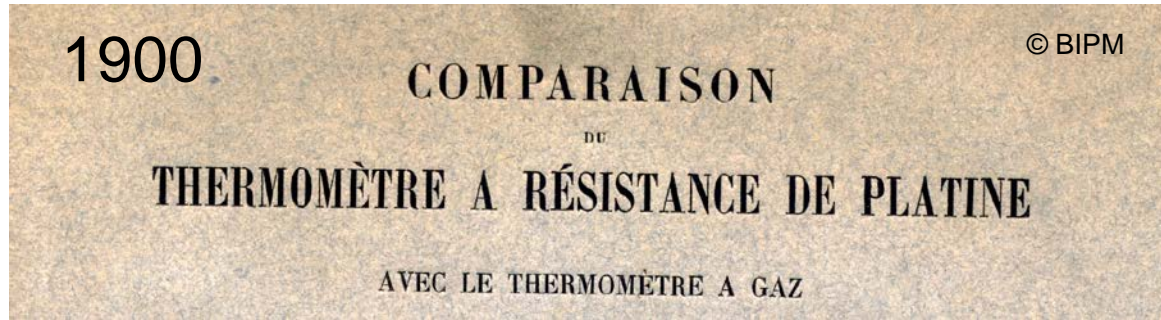


Pierre Chappuis
(1855-1916)

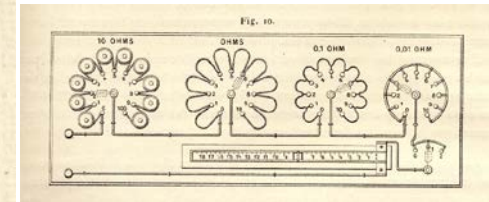
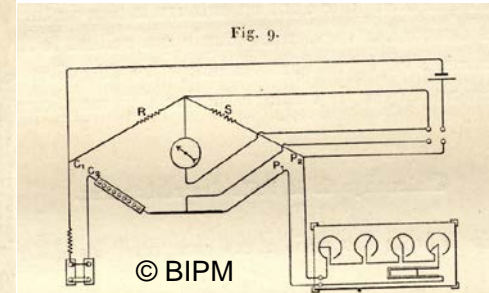
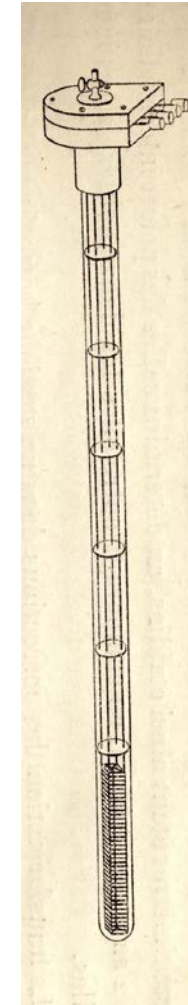
Science Museum, London
I. E. Cottingham
Platinum Metals Rev., 1987, 31, (4), 203

Not primary, but an example how difficult gas thermometry is!



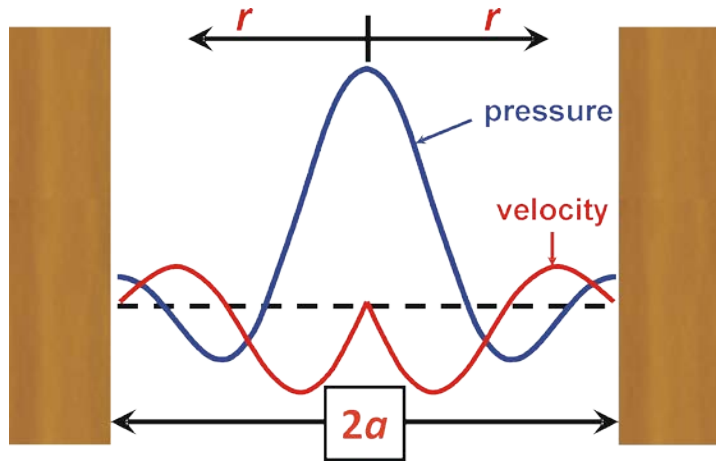


P. Chappuis & J. A. Harker



Absolute primary thermometry allows to measure thermodynamic temperature directly in terms of the definition of the base unit kelvin. No reference is made to any temperature fixed point and all other parameters specified in the equation of state are measured or otherwise determined.





*standing waves in
a resonator*

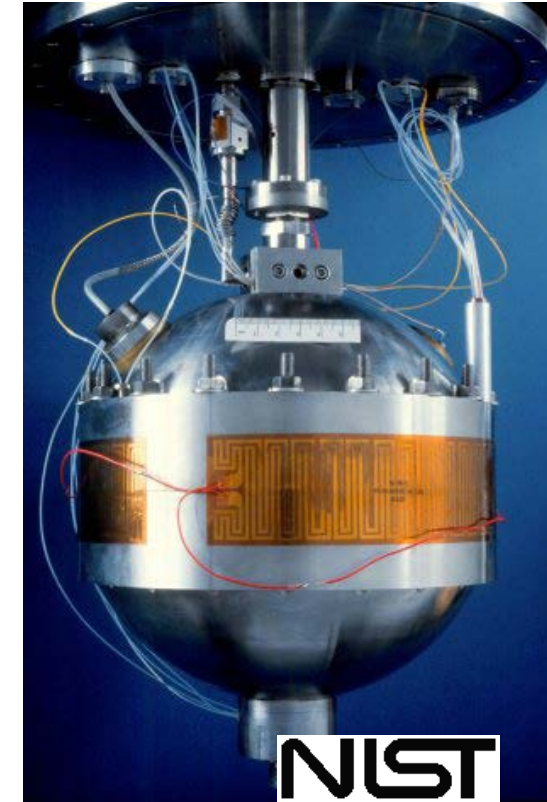
to be measured:

- ***frequency ν_a***
- ***resonator dimensions***

$$u_0^2 = \gamma_0 kT N_A / M$$

$$\gamma_0 = c_p / c_v$$

*M.R. Moldover et al.
J. Res. NBS 93(2), 85-144
(1988)*



CODATA 1998

$$k = 1.3806501 \times 10^{-23} \text{ J/K}$$

$$u_r = 1.8 \times 10^{-6} \quad (k=1)$$

Volume determination
by pycnometry

NIST 1988 with mercury

NPL  2012 with water
National Physical Laboratory

V=3 litre

**Boltzmann
Constant:**

$u(k)/k = 0.8 \text{ ppm}$

V=1 litre

**Boltzmann
Constant:**

$u(k)/k = 0.7 \text{ ppm}$



Microwaves in

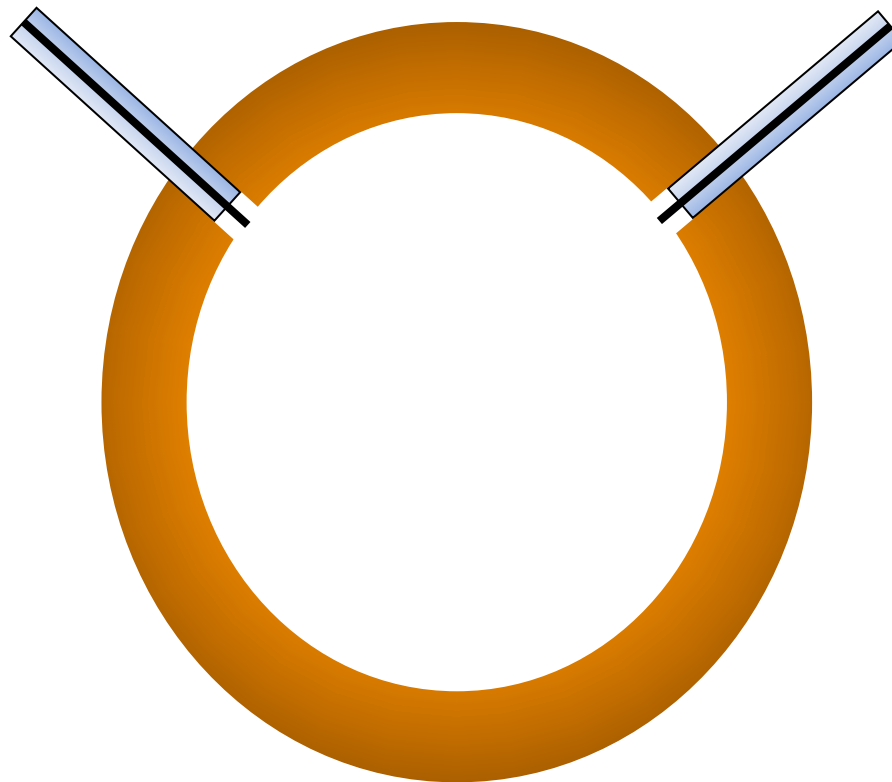
Microwaves out

Radius determination
with microwaves

$V=1$ litre

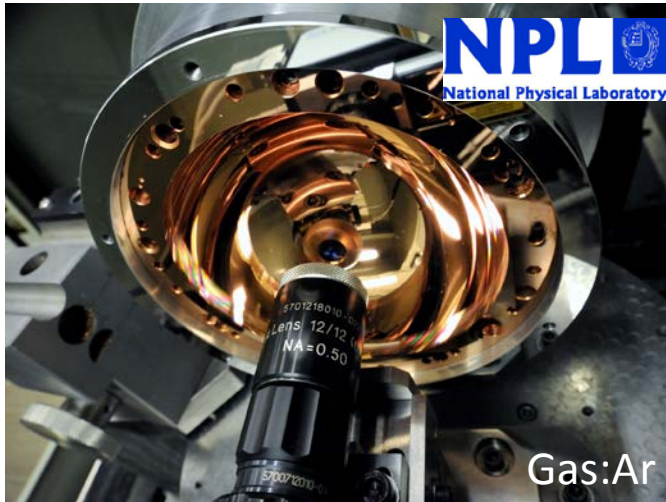
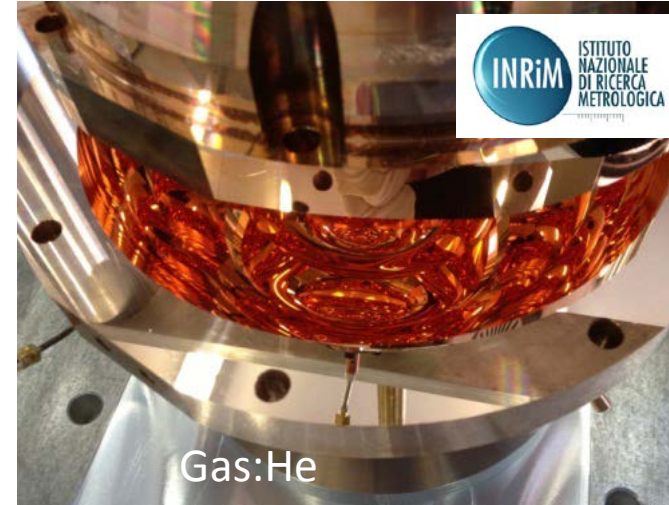
**Boltzmann
Constant:**

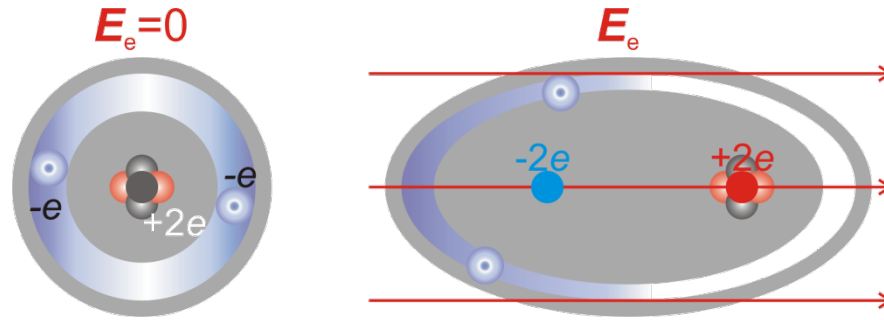
$u(k)/k = 0.4$ ppm



Quasi-sphere

The resonators of different institutes



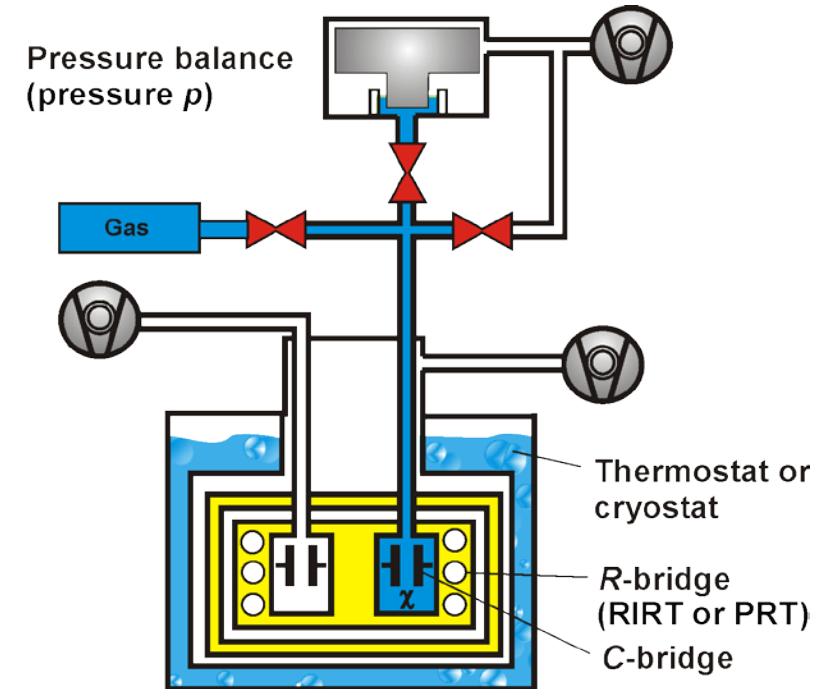


Clausius-Mossotti equation
combined with the ideal-gas law:

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{p}{kT} \frac{\alpha_0}{3\epsilon_0}$$

Measuring quantity :

$$\frac{C(p) - C(0)}{C(0)} = \epsilon_r - 1 + \epsilon_r \kappa_{\text{eff}} p$$



- ϵ_r dielectric constant
- ϵ_0 electric constant
- α_0 atomic polarizability
- κ_{eff} effective compressibility
- p pressure

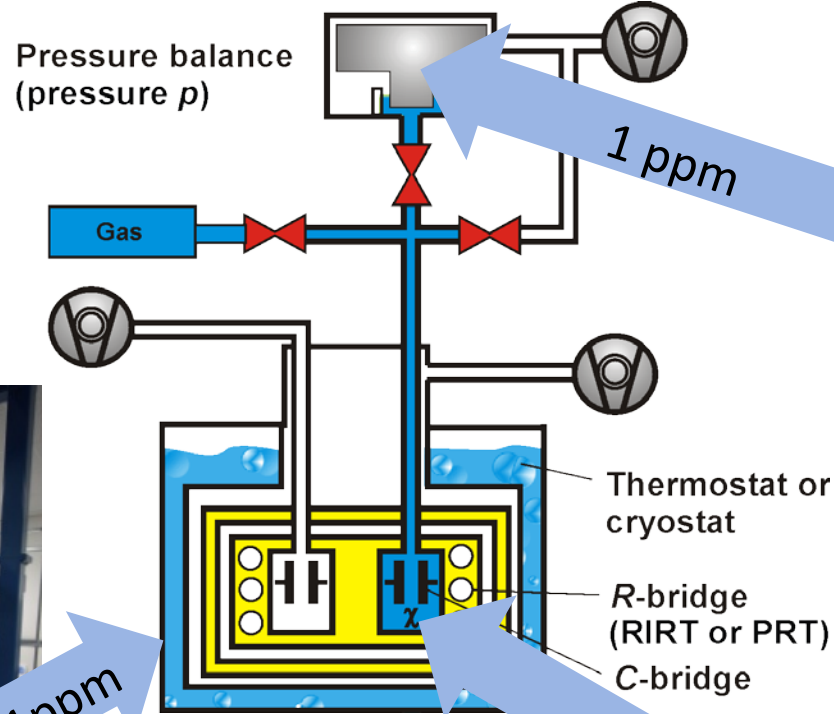
Determination of k with DCGT

α_0 atomic polarizability of Helium was needed on the level below 1 ppm. This subject was suggested to theorists by Mike Moldover in the early years 2000

No. CHE-0239611. We are grateful to Mike Moldover for suggesting the subject and to Krzysztof Pachucki for discussions.

$u_r(k) = 1.9 \text{ ppm}$

Temperature



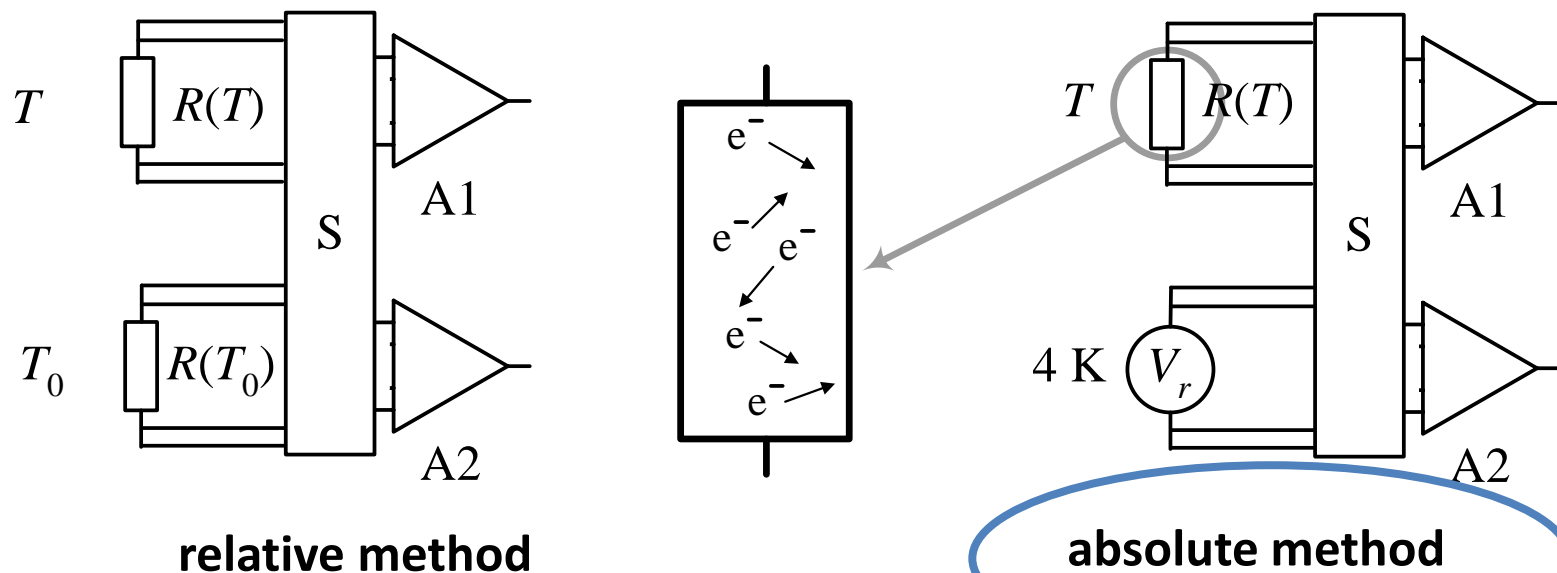
Pressure



Change of capacitance ratio



$$\langle V^2 \rangle = 4 k T R \Delta \nu$$



$\langle V^2 \rangle$	mean square noise voltage
R	resistance
$\Delta \nu$	bandwidth

- Calculable pseudo-noise waveform
 - Perfect linearity
- Absolute temperature calibration
 - MATCH V_Q to ANY sense T and R
 - Matched, uncorrelated resistors R', R''
 - Measure Sense and QVNS voltages

NIST



$$u_r(k) = 2.7 \text{ ppm}$$

- JNT is a **purely electronic approach** to temperature
- JNT with QVNS Links definition of kelvin with quantum electrical standards

Spectral density of voltage noise known :

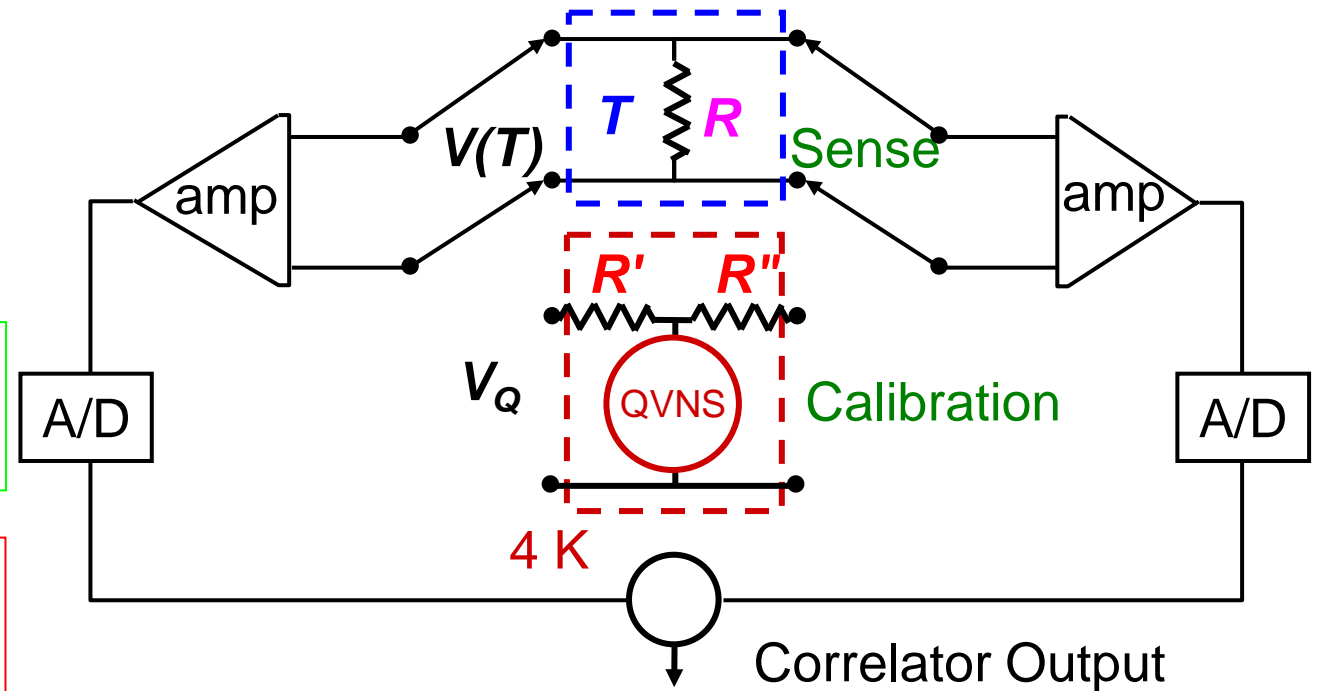
- **AC Josephson Voltage**

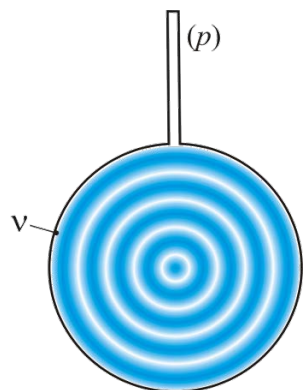
Spectral density of thermal noise known :

- Traceable to **Quantum-Hall Ohm**

$$K_J^2 = \frac{4e^2}{h^2}$$

$$R_K = \frac{h}{e^2}$$

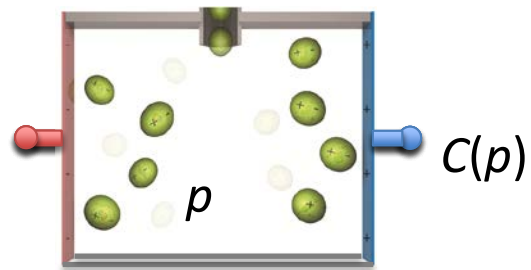




AGT

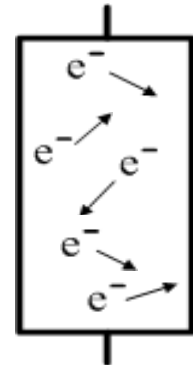
$$u_0^2 = \gamma_0 kT N_A / M$$

$$\gamma_0 = c_p / c_v$$



DCGT

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{p}{kT} \frac{\alpha_0}{3\epsilon_0}$$



JNT

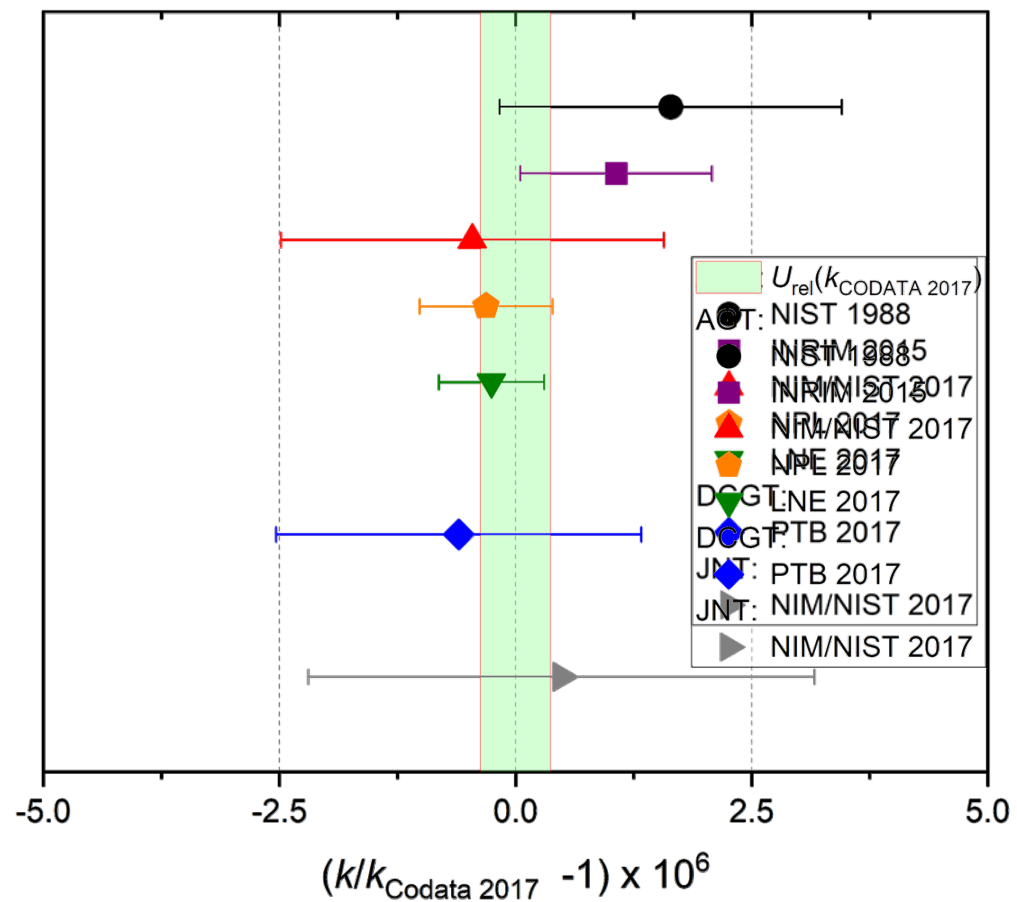
$$\langle V^2 \rangle = 4 kT R \Delta \nu$$

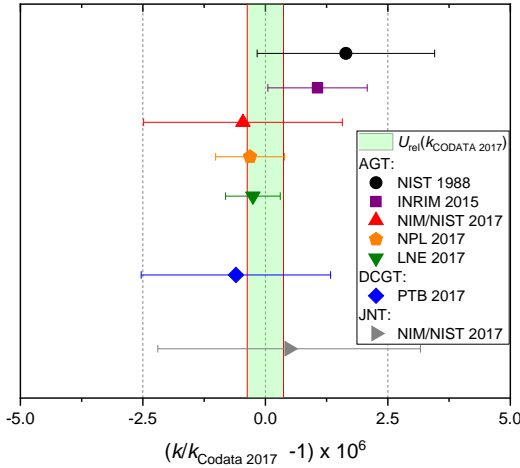
At this point we must admit:
Yes, partially it took so long for the kelvin to be redefined because metrologists are highly conservative.

But, on the other hand the conservative nature of metrologists led to highly improved and innovative techniques!

CCT recommendation T1 (2014)

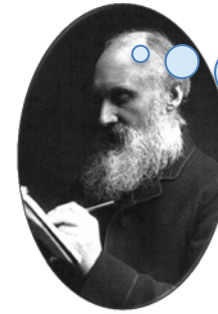
1. the relative standard uncertainty of the adjusted value of k is **less than 1×10^{-6}** ;
2. the determination of k is based on **at least two fundamentally different methods**, of which at least one result for each shall have a relative standard uncertainty **less than 3×10^{-6}** .





$$k \stackrel{\text{def}}{=} 1.380\,649 \times 10^{-23} \text{ J/K}$$

$$T_{\text{TPW}} \stackrel{\text{def}}{=} 273.1500(1) \text{ K}$$

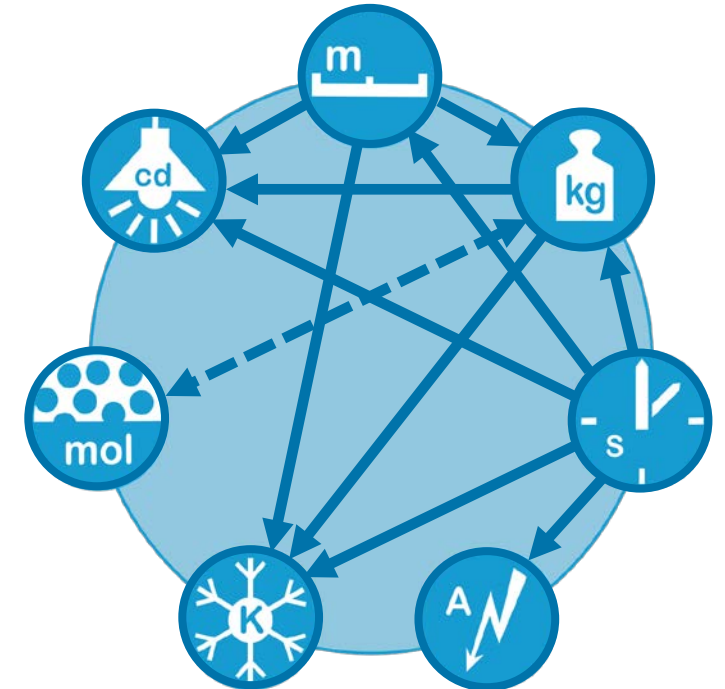


The unit kelvin is substance independent!
Absolute, based on fundamental units!

Resolution 1 of the 26th CGPM (2018):

decides that, effective from 20 May 2019, the International System of Units, the SI, is the system of units in which:

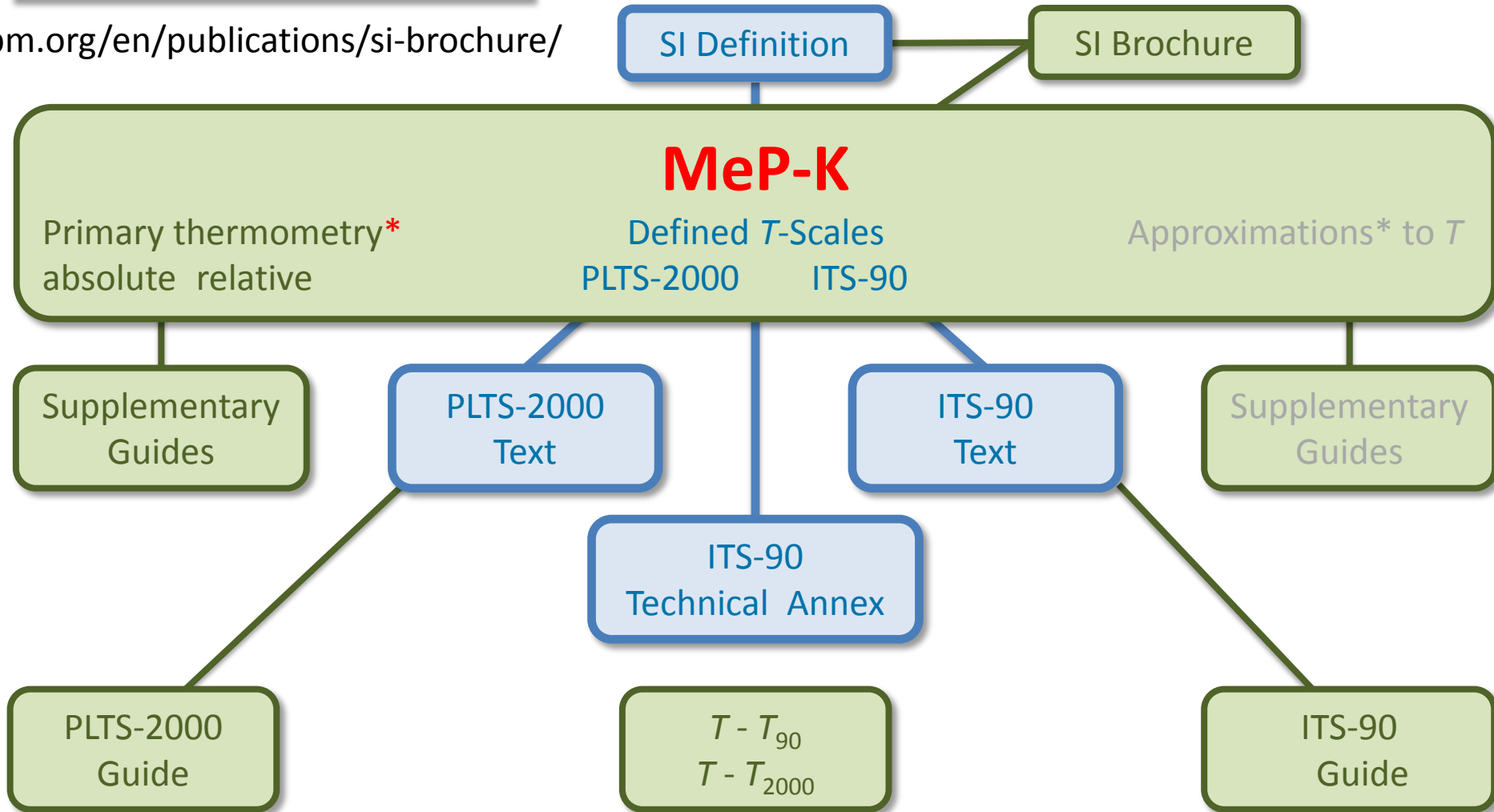
...
the Boltzmann constant k is $1.380\,649 \times 10^{-23} \text{ J/K}$



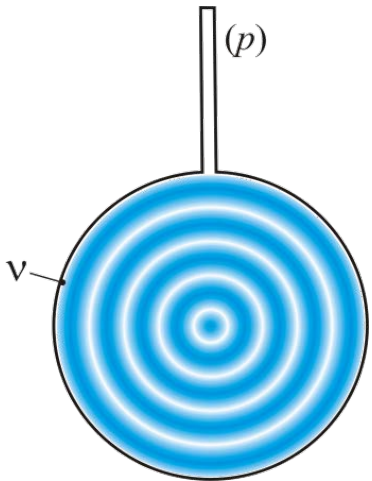
Blue – prescriptive documents
Green – non-prescriptive guidance

* Only state of the art methods

<https://www.bipm.org/en/publications/si-brochure/>



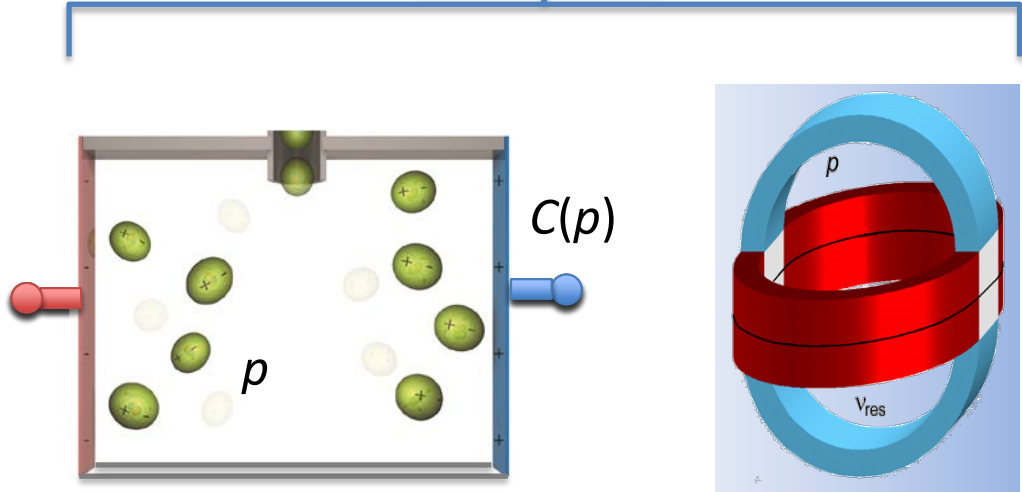
PGT



AGT

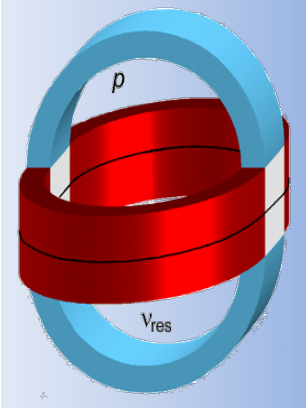
$$u_0^2 = \gamma_0 kT N_A / M$$

$$\gamma_0 = c_p / c_v$$



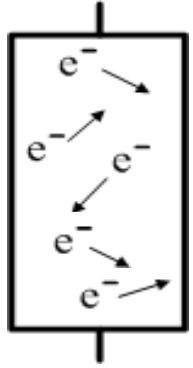
DCGT

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{p}{kT} \frac{\alpha_0}{3\epsilon_0}$$



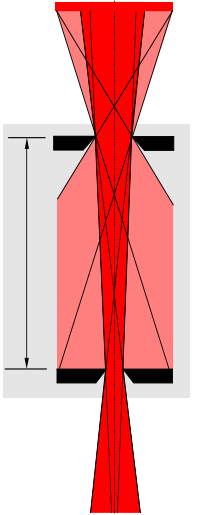
RIGT

$$\frac{n^2 - 1}{n^2 + 2} \approx \frac{p}{kT} \frac{\alpha_0}{3\epsilon_0}$$



JNT

$$\langle V^2 \rangle = 4 kT R \Delta\nu$$

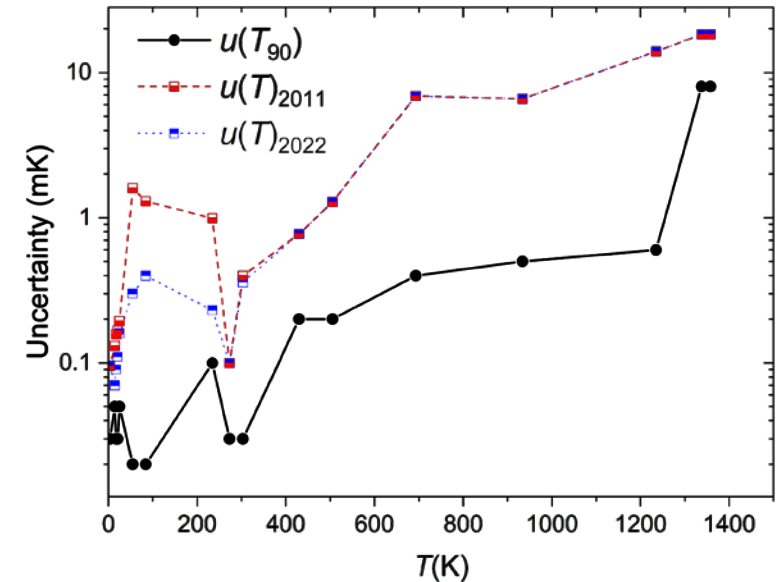
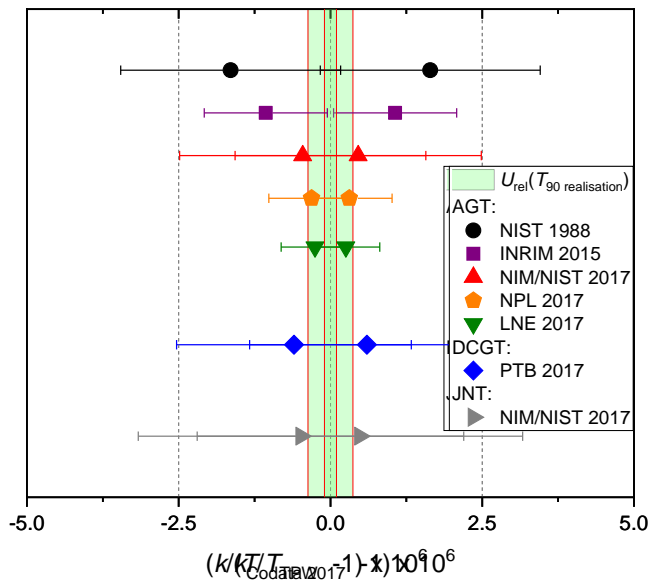


RT



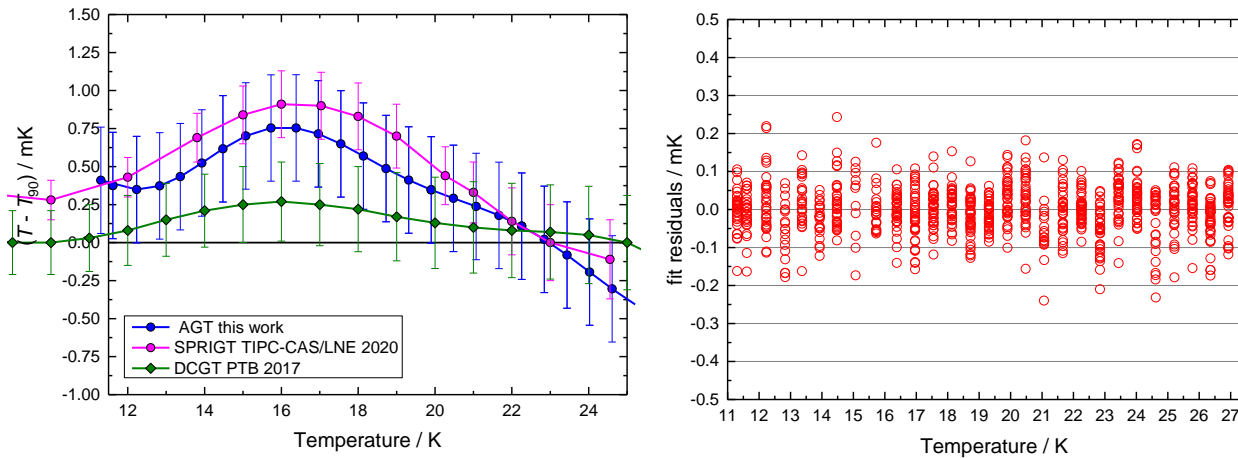
The “Boltzmann” experiments can be regarded as a high-level performance test of primary thermometry at the TPW.

General statement:
In largest part of the temperature range of contact thermometry still $u(T_{90}) < u(T)$



Direct calibration of resistance thermometers between 10 K and 25 K by absolute acoustic gas thermometry in helium

Dario Imbraguglio, Peter P. M. Steur and Roberto M. Gavioso



First „direct“ comparison of thermodynamic temperature measurements via 3 different primary thermometers!



DIREK-T

EUROPEAN PARTNERSHIP



Co-funded by the European Union

METROLOGY PARTNERSHIP



Int J Thermophys
DOI 10.1007/s10765-011-0922-1

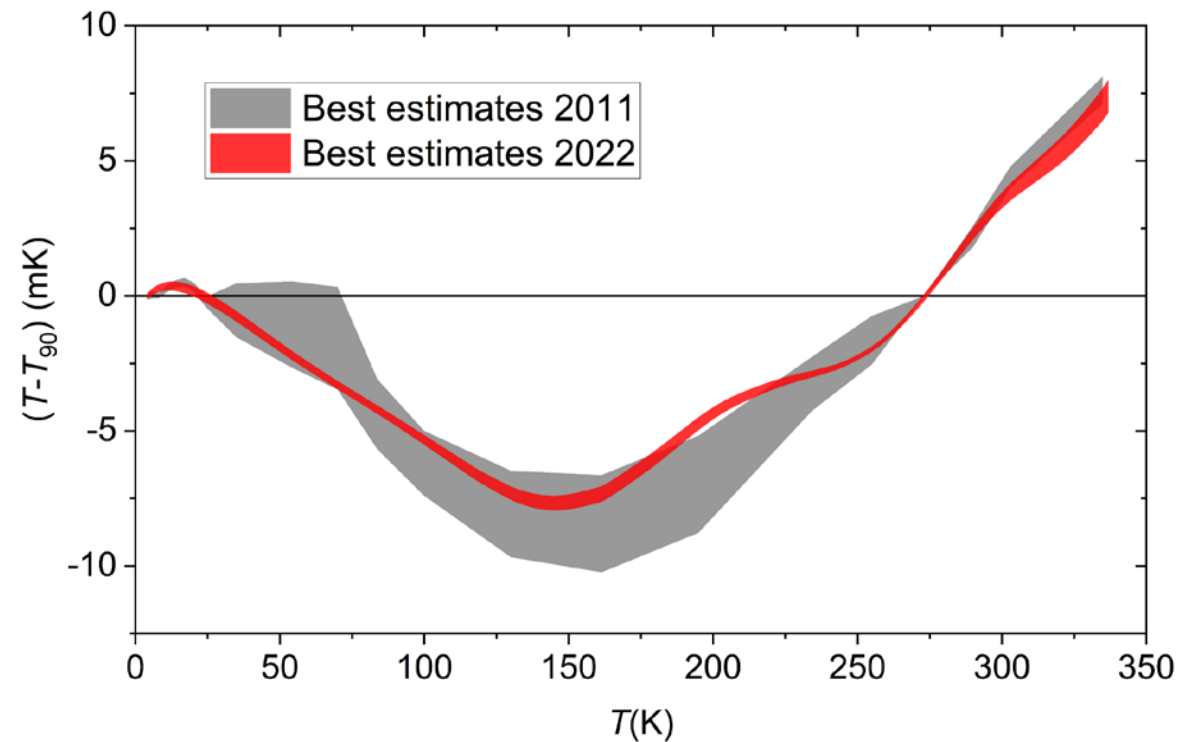
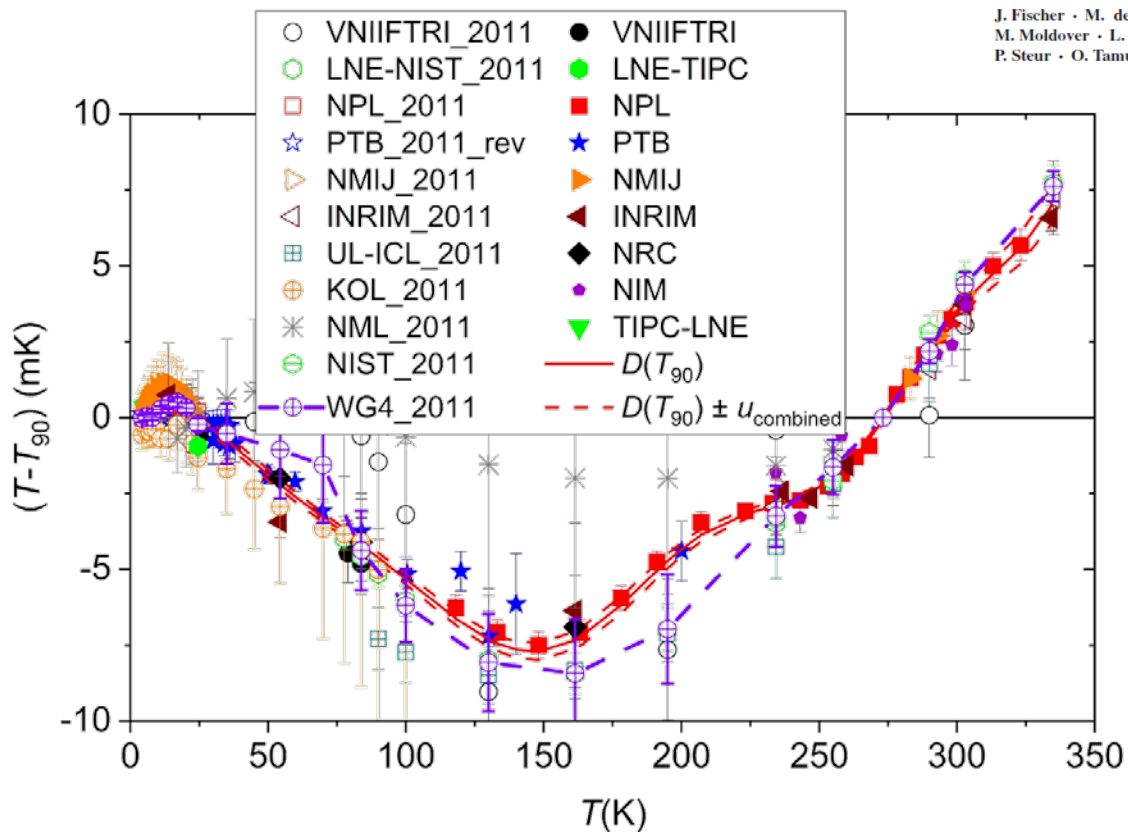
Present Estimates of the Differences Between
Thermodynamic Temperatures and the ITS-90

J. Fischer · M. de Podesta · K. D. Hill ·
M. Moldover · L. Pitre · R. Rusby ·
P. Steur · O. Tamura · R. White · L. Wolber

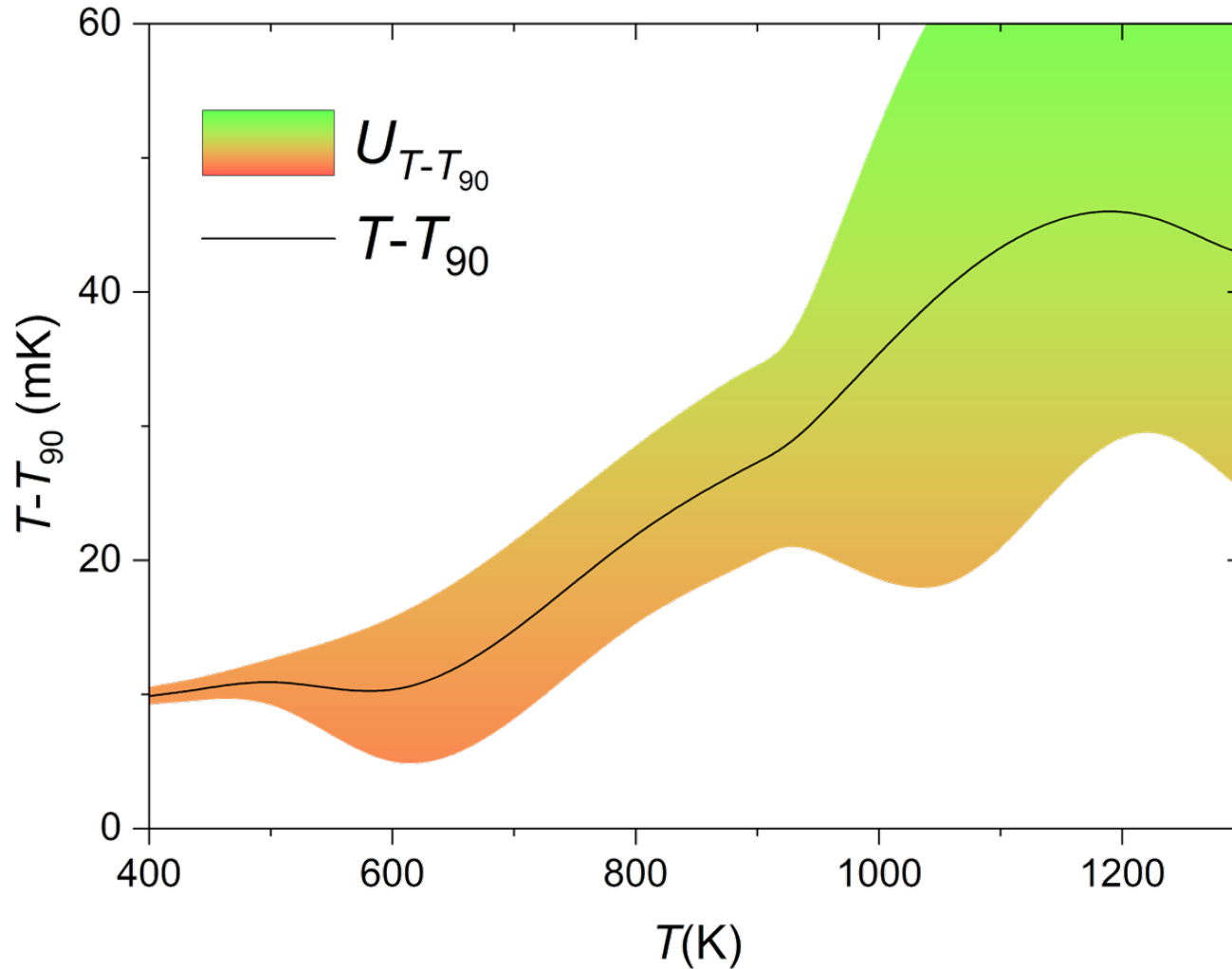
2022 Update for the Differences Between
Thermodynamic Temperature and ITS-90
Below 335 K

Cite as: J. Phys. Chem. Ref. Data 51, 043105 (2022); doi: 10.1063/5.0131026
Submitted: 17 October 2022 · Accepted: 23 November 2022 ·
Published Online: 27 December 2022

Christof Kaiser,^{1,2} Bernd Fellmuth,¹ Roberto M. Gavioso,³ Murat Kalemci,⁴ Vladimir Kytin,⁵
Tohru Nakano,⁶ Anatolii Pokhodun,⁷ Patrick M. C. Rourke,⁸ Richard Rusby,⁹ Fernando Sparasci,³
Peter P. M. Steur,¹⁰ Weston L. Tew,¹¹ Robin Underwood,¹ Rod White,^{11,12} Inseok Yang,¹³
and Jintao Zhang¹⁴



At present the best access to T for users via T_{90} realisation and $T-T_{90}$ estimates



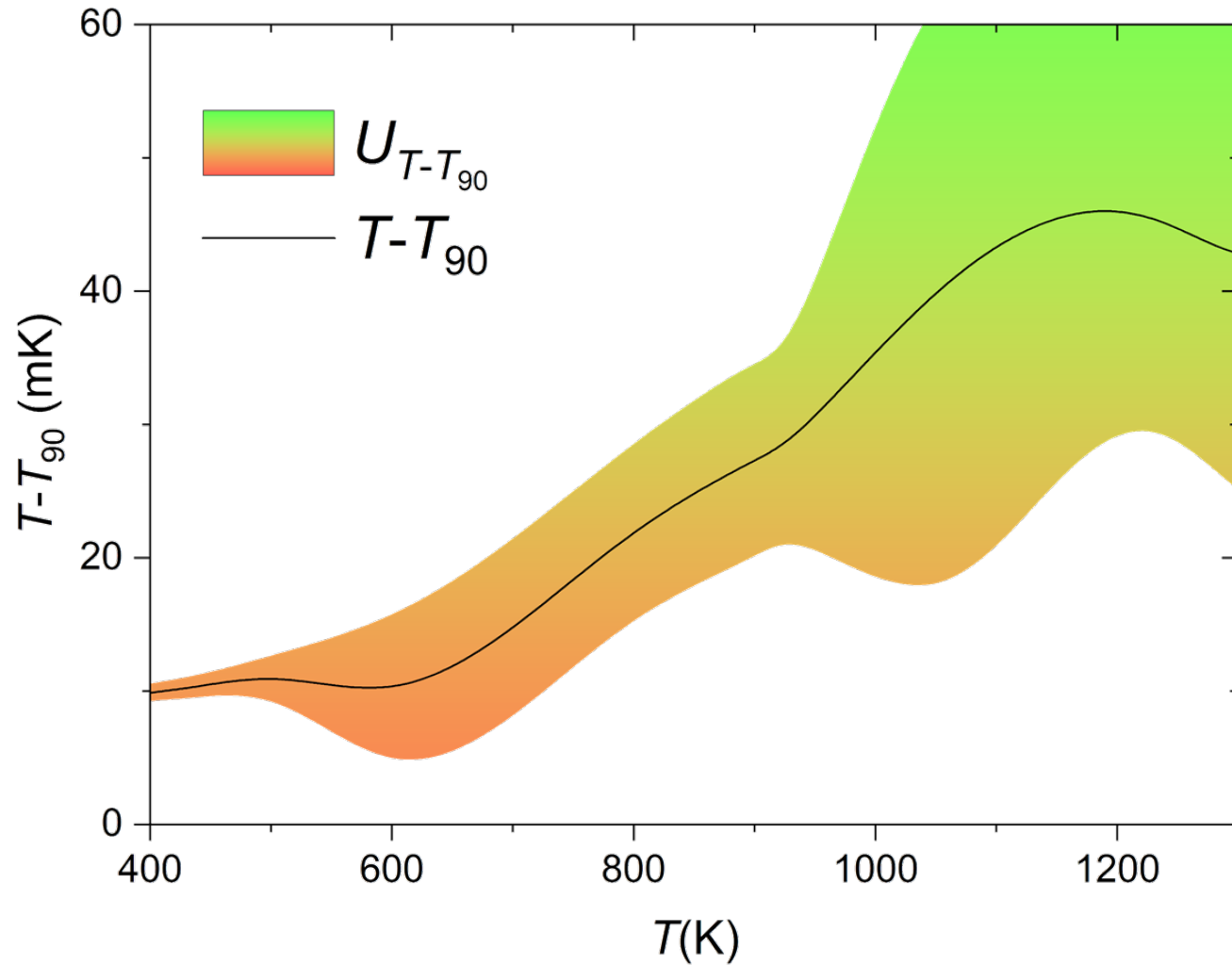
Recommendation 1 of the 29th CCT (2021)

Requirement for new determinations of thermodynamic temperature above 400 K

The Consultative Committee for Thermometry (CCT), at its 29th meeting in 2020/2021,

For next update on $T - T_{90}$, new data above 400 K is needed

Lack of data above 400 K is severe !



Method	Institute	T_{90} / K	$T-T_{90} / mK$	$u(T-T_{90}) / mK$	Weight in %	
CVGT	NIST	505.08	4.88	4.7	8	
		600.61	9.21	6.1	100	
		692.68	13.38	7.5	84	
		800.00	18.24	9.1	50	
		903.78	22.94	10.6	51	
		933.47	19.00	15.0	20	
AGT	INRIM	373.12	10.02	1.56	17	
	NIST1	373.12	9.68	0.70	83	
		429.75	10.64	0.97	71	
		505.08	12.35	1.52	73	
NIST2	429.75	8.800	1.50	29		
	505.08	10.800	3.00	19		
JNT	NIST	692.68	7.000	30.0	5	
SRT	PTB 1	933.47	31.400	9.3	51	
		1234.93	45.000	18.1	62	
		1337.33	56.30	22.4	78	
		PTB 2	692.68	20.659	21.0	11
			800.00	26.680	9.10	50
			903.78	32.502	10.8	49
	Various	933.47	34.168	13.8	23	
		1052.78	40.861	25.8	100	
		1150.00	46.315	20.2	100	
		1234.93	51.080	30.0	23	
		NPL	933.47	16.000	27.0	6
			1234.93	52.000	44.0	11
1337.33	-29.000		49.0	16		
NIST	1234.93	26	65.0	2		
	1337.33	14	80.0	1		
BIPM	1357.77	148.000	77.0	7		
Various	1357.77	45	21.0	5		

Challenges and major uncertainty components:

- For relative RT in the work of Fischer & Jung the main uncertainty component arises from the thermodynamic reference
- ...

Perspectives:

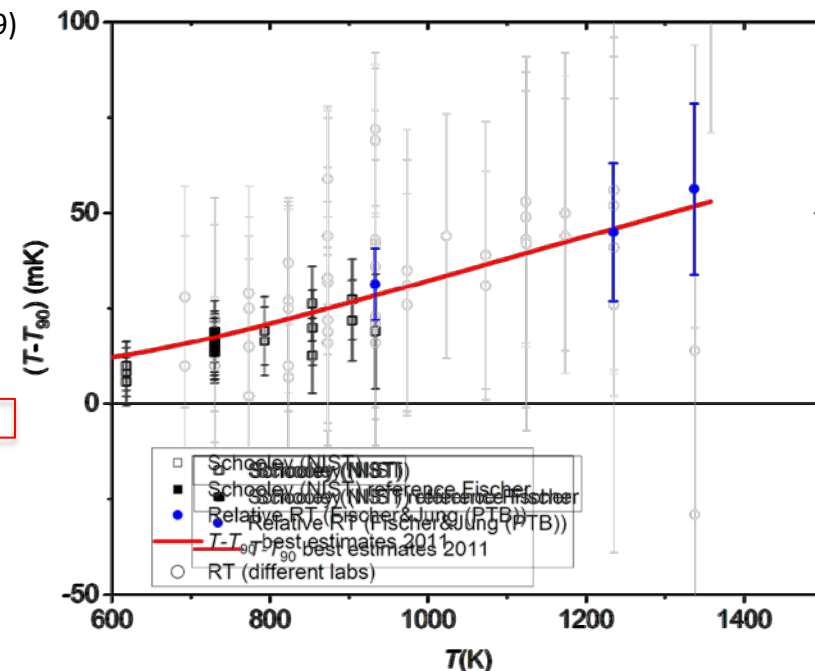
- The thermodynamic reference at temperatures around 700 K can be provided by AGT or JNT or PGT? Relative RT can provide small uncertainties from 700 K up to 1250 K and higher.
- ...

J. Fischer and H. J. Jung *Metrologia* **26** 245 (1989)

Table 4. Uncertainty contributions to T_{Ag} and T_{Au} at 68.3% confidence limits:

Source of uncertainty	ΔT_{Ag} mK	ΔT_{Au} mK
Spectral transmittance of interference filter	4.4	4.7
Relative spectral response of photodiode	2.3	3.3
Non-linearity of photodiode	3.4	4.3
Resistance ratio of feedback resistors used in current-to-voltage converter	4.0	7.0
Thermodynamic temperature of Al	16.3 ^a	19.1 ^a
Difference in size-of-source effects	1.0	1.0
Impurity of sample	3.0	6.0
Random uncertainty (15 determinations)	1.0	1.0
Addition in quadrature	18.1	22.4

^a Based on the uncertainty value 9.3 mK of the freezing point of Al [2] at the 1 σ level



Reference of Fischer & Jung was made to Constant Volume Gas Thermometry (CVGT) by Schooley at 730 K



Within the DireK-T project, for the first time AGT measurements up to 1300K have been performed!

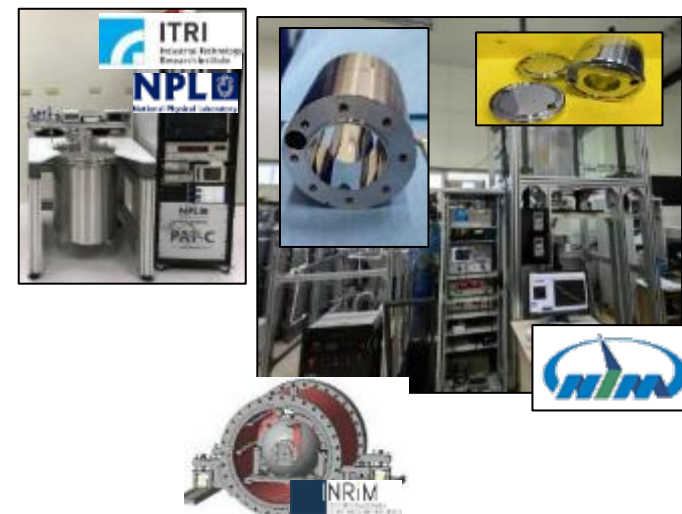
EUROPEAN
PARTNERSHIP



METROLOGY
PARTNERSHIP



DIREK-T



NIM is already working on a combination of cylindrical AGT and Radiometric thermometry from 400 K to 1300 K

Common challenges “Platinum thermometry”

In a very broad T range from 25 K up to 1235 K, platinum thermometers are today the only scale carrier we have for contact thermometry, with by far the smallest uncertainties. **This is the case for T as well as for T_{90}**

+

If treated well → extremely stable and suitable to carry the scale on the highest level

More than 100 years of experience

Full traceability to national standards

Easily applicable in accreditation labs and industry

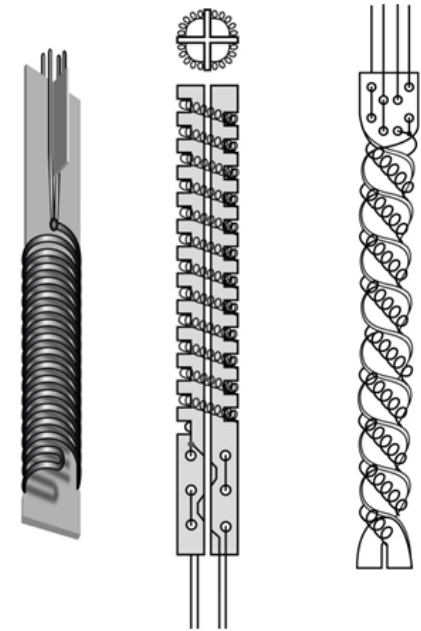
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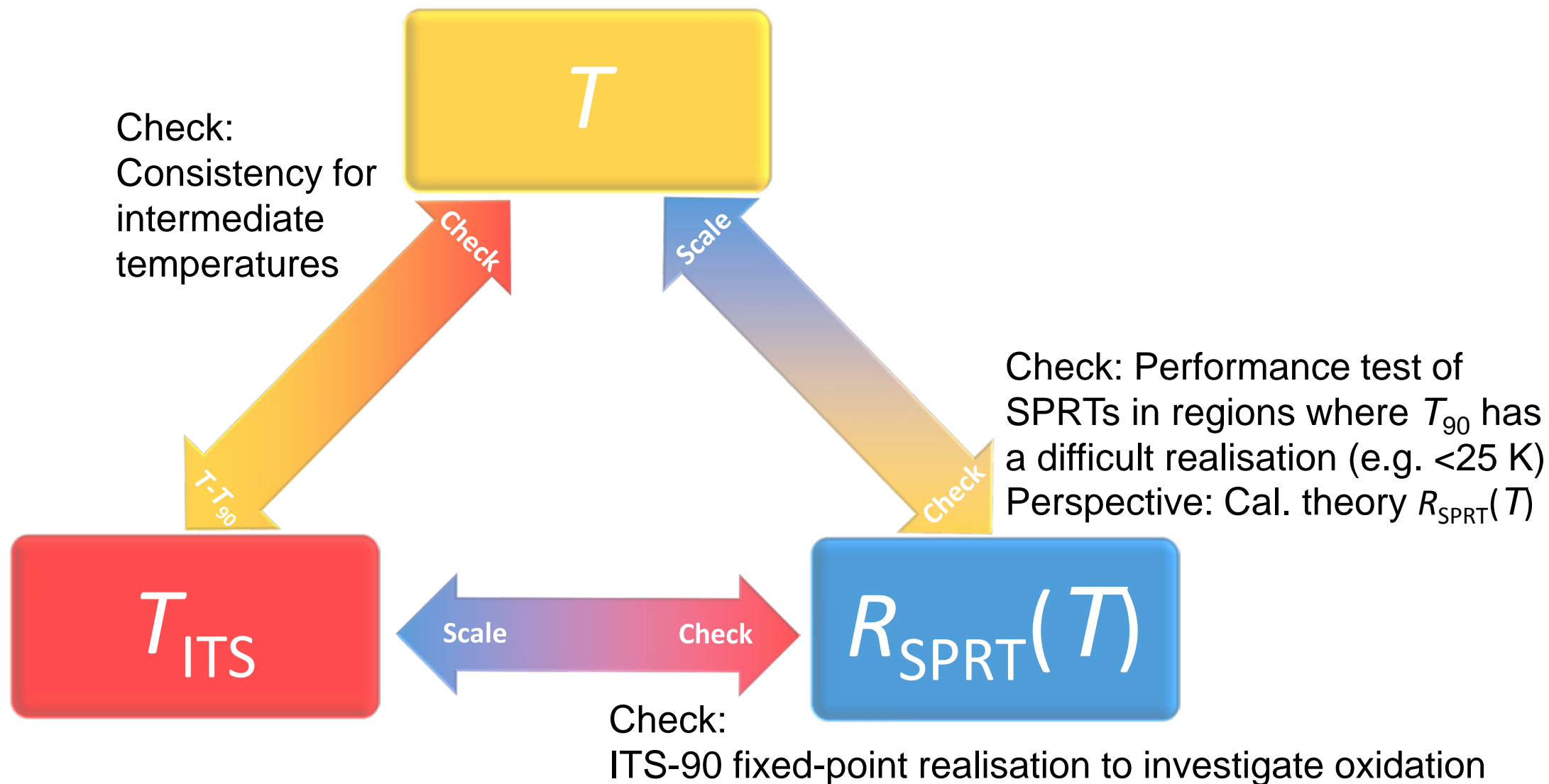
Production Problems

LSPRTs huge insulation problems above 900 K

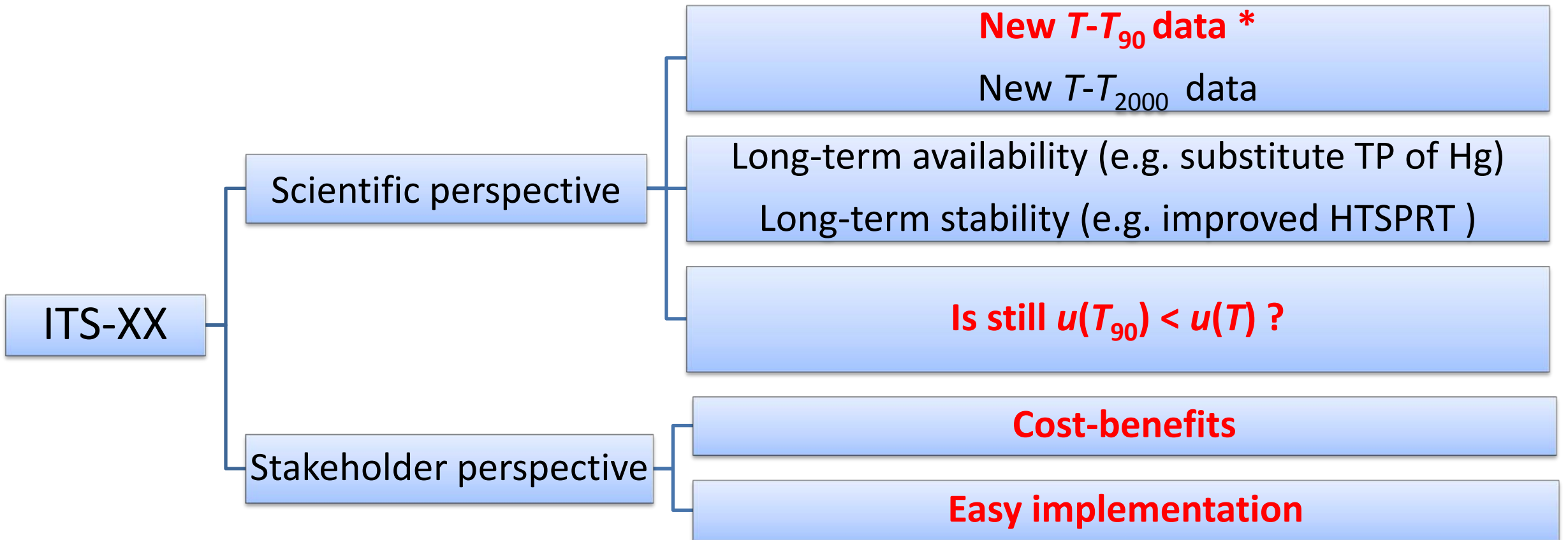
HTSPRTs stability problems and others like diffusion of Ag

Oxidation (especially important for T measurements above 500 K)





Do we need a new ITS-XX and what are the requirements:



* Recommendation similar to T1 in 2014

Criteria agreed in WG-CTh and WG-NCTh !

After decades of work, the kelvin was redefined and measurement of T is more and more competitive with T_{ITS} .

There is a lack of primary thermometry data between 400 K and 1235 K

The primary thermometers within the MeP-K have a huge potential to fill the gap.
Maybe a strong cooperation between contact and non-contact thermometry can help.

Resistance thermometry is a shared problem of T and T_{90} .
Alternatives would be welcome, but this is surely a long-term goal.

Before a new ITS-XX can be established, several problems have to be solved.