Boltzmann Project

2002:

Study on *k* determination with DCGT $u_r(k) \approx 2$ ppm

2004:

TEMPMEKO: Lecture with first idea for new definition

2005:

1st Boltzmann workshop with international experts at PTB

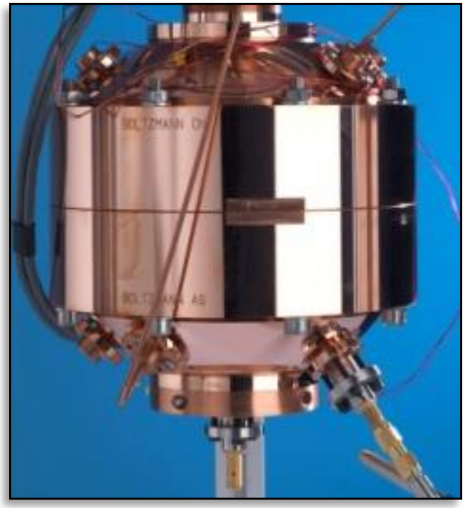
2006:

EURAMET-Project 885: „Determinations of the Boltzmann Constant“; CCT task group on the SI; 2nd Boltzmann workshop at PTB

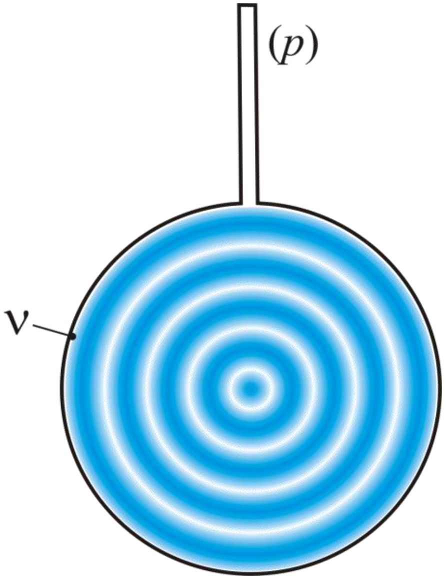
2008:

iMera+ Project coordinated by PTB

Determination of k and redefinition

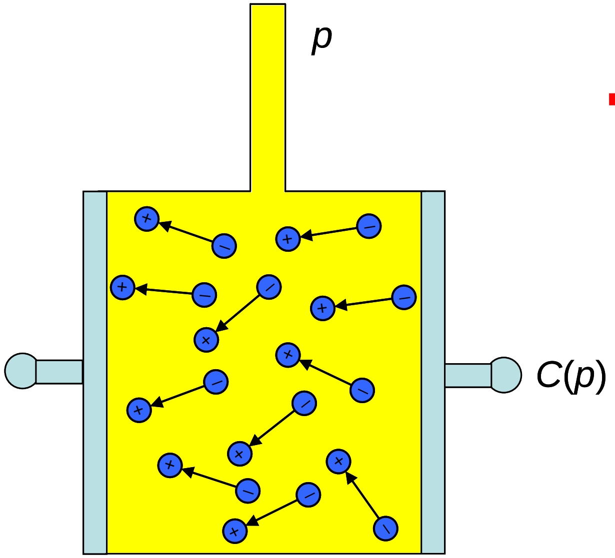


Determination of *k*



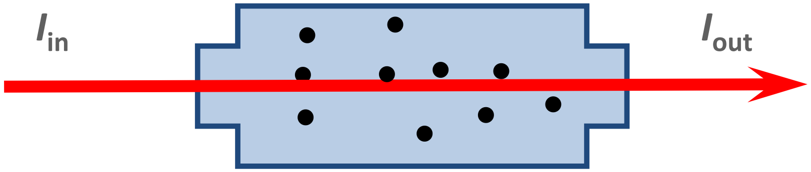
AGT

$$u_0^2 = \gamma\, kT / m$$
$$\gamma = c_p / c_V$$



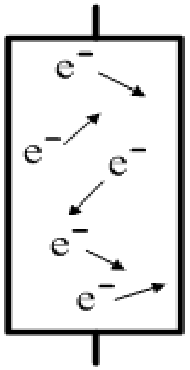
DCGT

$$p = kT\, \varepsilon_0 (\varepsilon_r - 1)/\alpha_0$$



$$\Delta \nu_D = [2\, kT/(mc_0^2)]^{1/2} \cdot \nu_0$$

DBT



JNT

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

LNE AGT results: 2011 Argon 2015 Helium

Uncertainty contributions

radius 50 mm

Term	Relative uncertainty (10^{-6})	
Gas	Ar	He
Acoustic frequency	0.80	0.62
Resonator volume	0.57	0.57
Molar mass and gas purity	0.60	0.53
Thermometry	0.3	0.3
Total (square root of quadratic sum)	1.24	1.02

Upper part of spherical resonator

L. Pitre, F. Sparasci, D. Truong,
A. Guillou, L. Risegari, M. E. Himbert
Int. J. Thermophys. **32** 1825-86 (2011)
$u(k)/k$ = 1.24 ppm

L. Pitre, L. Risegari, F. Sparasci, M.D. Plimmer, M. E. Himbert
Metrologia **52** S263-73 (2015)
$u(k)/k$ = 1.02 ppm

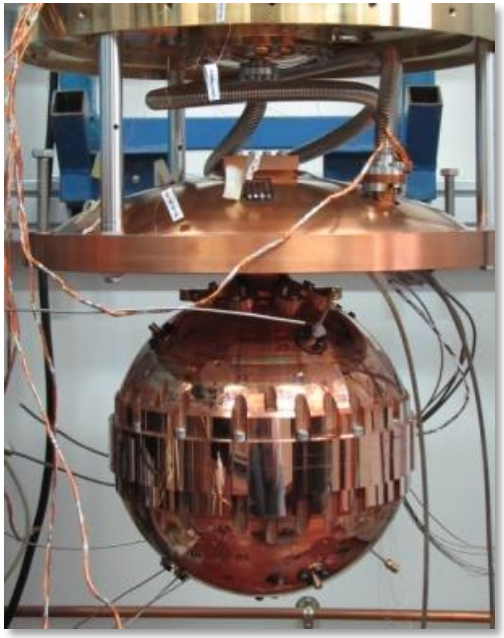
LNE AGT results: 2017 Helium

L. Pitre, F. Sparasci, L. Risegari, C. Guianvarc'h, C. Martin, M.E. Himbert, M.D Plimmer, A. Allard, B. Marty , P.A. Giuliano Albo, B. Gao, M.R. Moldover, and J.B. Mehl
Metrologia **54** submitted (2017)
$u(k)/k = 0.60$ ppm

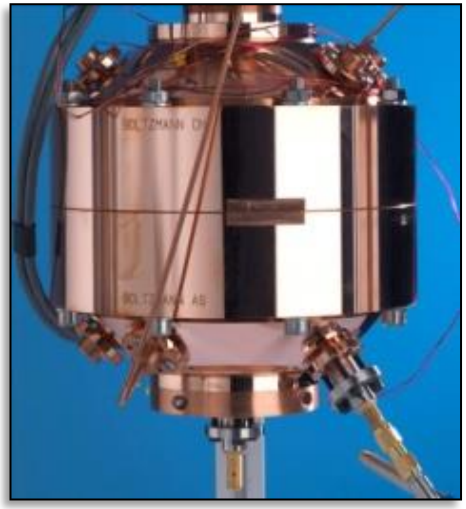
Uncertainty contributions

Term	**Effect on *k* (Parts in 10^6)**
Temperature measurements	0.39
Molar mass and gas purity	0.09
Volume measurements	0.20
Acoustic measurements	0.40
Total	**0.60**

3.1-litre copper triaxial ellipsoid, filled with helium



2013/2017: AGT with Argon at NPL



radius 62 mm, filled with Argon

Uncertainty contributions

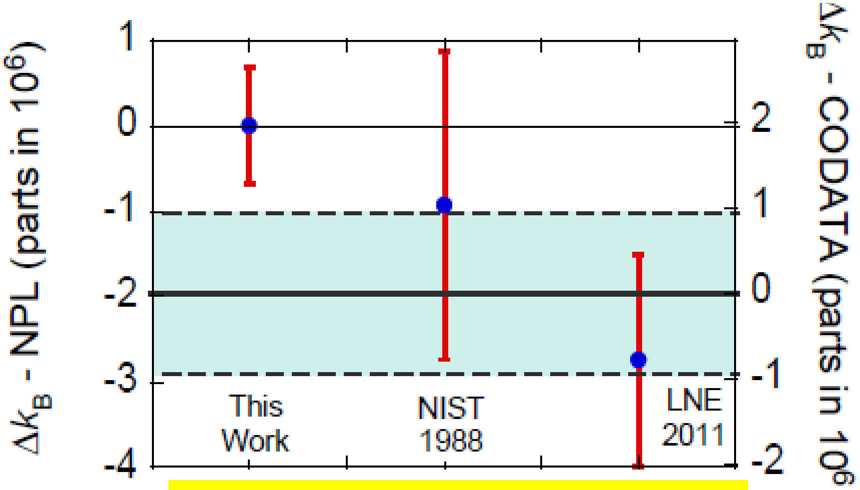
			Estimate	$u_R/10^{-6}$	Weight
molar mass	M	g mol^{-1}	39.947 727(19)	0.373	28.3%
temperature	T	K	273.160 000(99)	0.364	26.8%
speed of sound	c_0^2	m^2 s^{-2}	94756.245(45)	0.470	44.9%
	R	J K^{-1} mol^{-1}	8.314 460 3 (58)	0.702	
	N_A	mol^{-1}	6.022 140 857 (74) ×10^{23}	0.012	0.0%
	k_B	J K^{-1}	1.380 648 60 (97) ×10^{-23}	0.702	

Contamination of gas by atmospheric air during sampling

M. de Podesta, D.F. Mark, R.C. Dymock, R. Underwood, T. Bacquart, G. Sutton, S. Davidson, G. Machin

Metrologia **54** submitted (2017)

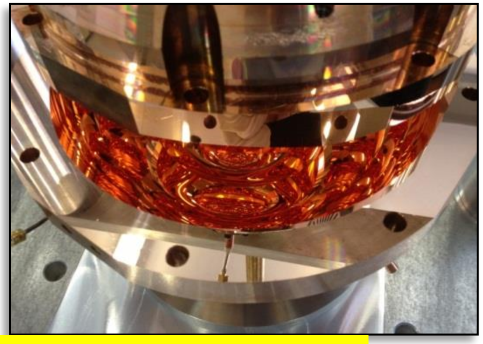
M
G
D.F. Mark, F.M. Stuart, G. Vargha, G. Machin
Metrologia **50** 354-376 (2013)



Δk = 2.8 ppm ± 1.4 ppm

2015: AGT with Helium at INRiM

New 3-litre volume diamond turned copper spherical resonator



apparatus

R. M. Gavioso, D. Madonna Ripa, P. P. M. Steur, C. Gaiser, D. Truong, C. Guianvarc'h, P. Tarizzo, F. M. Stuart, R. Dematteis
Metrologia **52** S274-S304 (2015)

Uncertainty contributions

	Quantity	Estimate	ppm
speed of sound	u_0^2	$(945\,710.45 \pm 0.85)\ \mathrm{m^{-2}s^{-2}}$	0.90
molar mass	M	$(4.002\,6032 \pm 0.000\,0015) \times 10^{-3}\ \mathrm{kg\,mol^{-1}}$	0.37
temperature	T	$(273.160\,05 \pm 0.000\,12)\ \mathrm{K}$	0.42
	R	$(8.314\,4743 \pm 0.000\,0088)\ \mathrm{J\,mol^{-1}\,K^{-1}}$	**1.06**
	$k = R\,/N_A$	$(1.380\,6508 \pm 0.000\,0015) \times 10^{-23}\ \mathrm{J\,K^{-1}}$	**1.06**

2011 - 2017 NIM – NIST:
AGT with cylindrical resonators

single cylinder arrangement

J.T. Zhang, H. Lin, X.J. Feng, J.P. Sun, K. A. Gillis, M.R. Moldover, Y.Y. Duan
Int. J. Thermophys. **32** 1297–1329 (2011)
$u(k)/k = 7.9$ ppm

H. Lin, X.J. Feng, K.A. Gillis, M.R. Moldover, J.T. Zhang, J.P. Sun, Y.Y. Duan
Metrologia **50** 417-432 (2013)
$u(k)/k = 3.7$ ppm

X.J. Feng, J.T. Zhang, H. Lin, K.A. Gillis, J.B. Mehl, M.R. Moldover, K. Zhang, , Y.N. Duan
Metrologia **54** submitted (2017)
$u(k)/k = 2.0$ ppm

two cylinder arrangement
with lengths 2 l and l

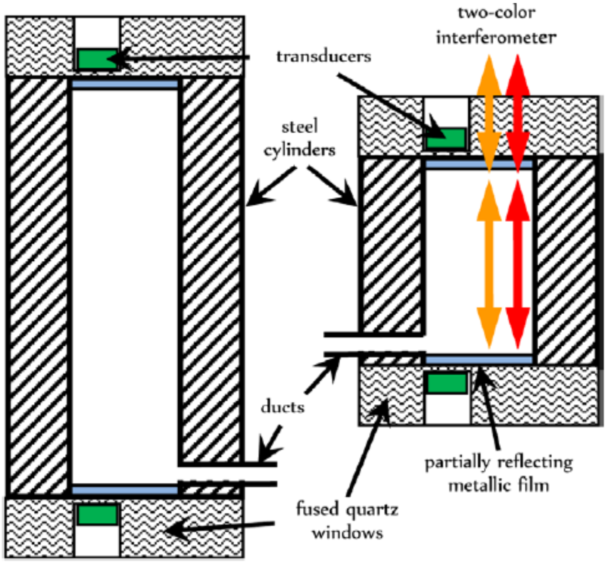


Figure 1. Schematic diagram of two resonators used to make a virtual resonator.

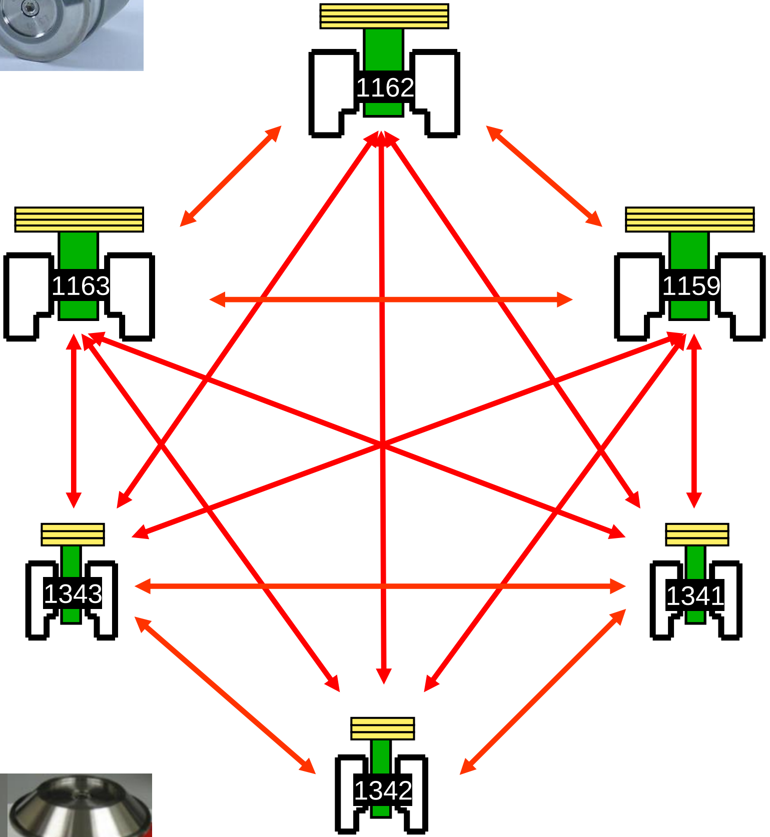
X.J. Feng, H. Lin, K.A. Gillis, M.R. Moldover, J.T. Zhang
Metrologia **52** S343-S352 (2015)

Measurements free from corrections of perturbations of end plates, transducer, gas duct

DCGT at PTB 2017: pressure with 1 ppm

C. Gaiser, B. Fellmuth,
N. Haft, A. Kuhn, B. Thiele-Krivoi, T. Zandt, J. Fischer
Metrologia **54**
280-289 (2017)
$u(k)/k = 1.9$ ppm

20 cm^2 – Systems
0.7 MPa

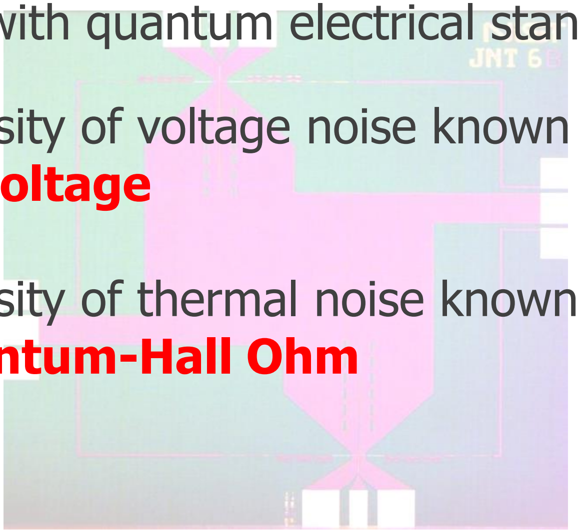


T. Zandt, W. Sabuga, C. Gaiser, B. Fellmuth
Metrologia **52**
S305-S313 (2015)
$u(p)/p = 1.0$ ppm

2 cm^2 – Systems
7 MPa

Noise thermometry at NIST

- Provides a new path to fundamental physical constants via quantum-based voltage sources
  - JNT is a **purely electronic approach** to temperature
  - Links definition of kelvin with quantum electrical standards



Spectral power density of voltage noise known :

- **AC Josephson Voltage**

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

Spectral power density of thermal noise known :

- Traceable to **Quantum-Hall Ohm**

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

S.P. Benz, A. Pollarolo, J. Qu, H. Rogalla, C. Urano, W.L. Tew, P.D. Dresselhaus, D.R. White
Metrologia **48** (2011) 142-153
$u(k)/k = 12.1$ ppm

Noise thermometry at NIM/NIST

se

w

ne

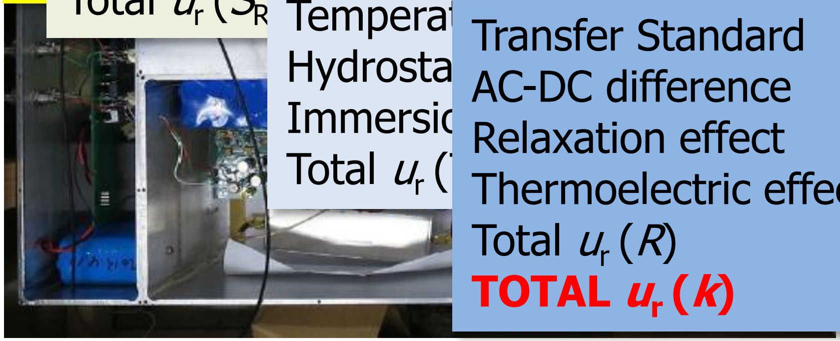
f ratio

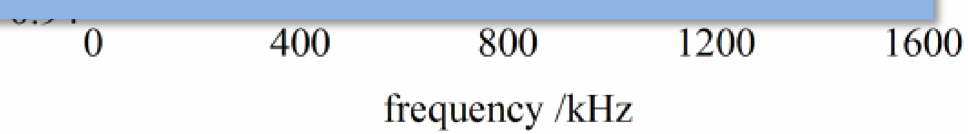
Component Term	Relative uncertainty	Correlation
Ratio of t		
Statistical		
Model Amb		
Bandwidth		
Dielectric l		
EMI		
Non-lineari		
Total $u_r\,(S_R$		

Component Term	Relative uncertainty	Correlation
QVNS w		
Frequenc		
Quantiza		
Total $u_r\,($		
TPW ter		
Referenc		
Temperat		
Hydrosta		
Immersio		
Total $u_r\,($		

Component Term	Relative uncertainty 2015	Relative uncertainty 2017	Correlation
Total $u_r\,(S_R/S_Q)$	**3.8**	**2.68**	
Total $u_r\,(S_Q)$	**0.11**	**0.11**	
Total $u_r\,(\mathrm{TPW})$	**0.35**	**0.35**	
Resistance *R*			
Ratio measurement	0.05	0.05	0
Transfer Standard	0.1	0.1	1
AC-DC difference	0.1	0.1	1
Relaxation effect	0.5	0.1	1
Thermoelectric effect	0.1	0.1	1
Total $u_r\,(R)$	**0.53**	**0.21**	
TOTAL $u_r\,(k)$	**3.9**	**2.7**	

J.
W
M
u

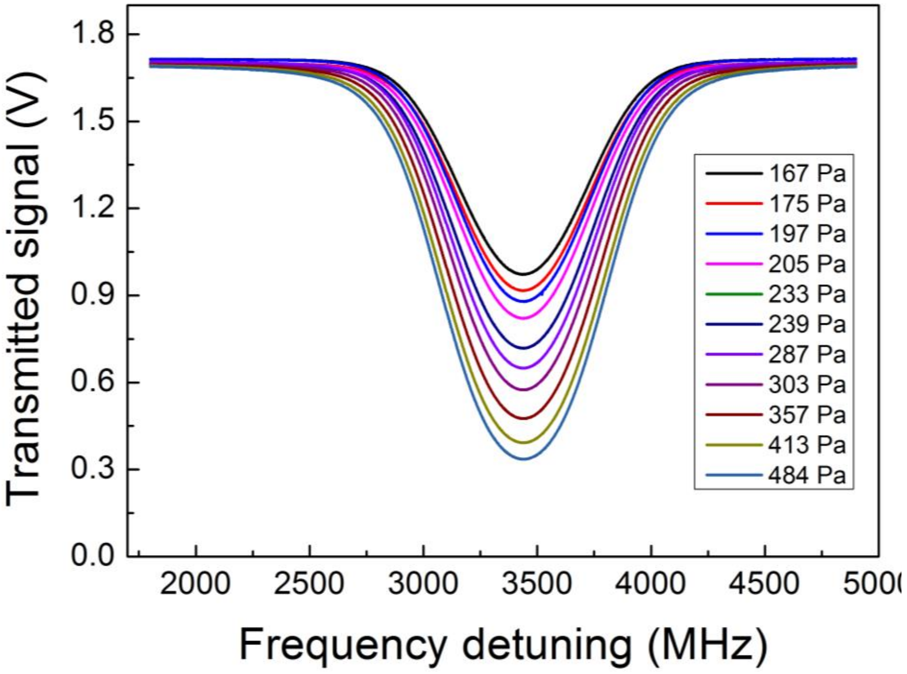


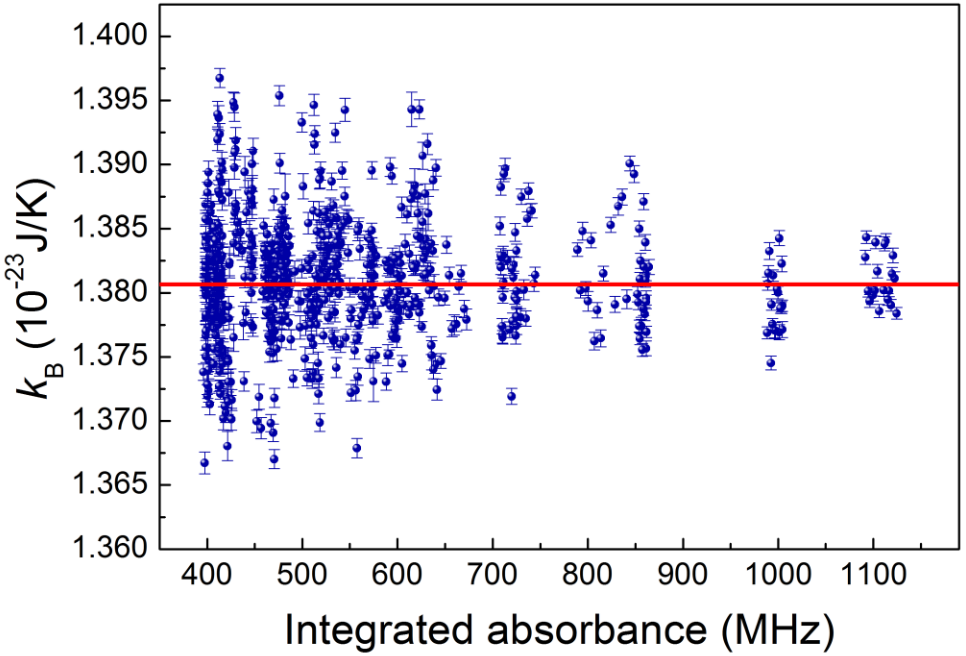


J. Qu, S.P. Benz, K. Coakley, H. Rogalla,
W.L. Tew, D.R. White, K. Zhou, Z. Zhou
Metrologia **54** submitted (2017)
$u(k)/k = 2.7$ ppm

2013: DBT result at Uni Naples

$H_2{}^{18}O$ spectra





L. Moretti, A. Castrillo, E. Fasci, M. D. De Vizia, G. Casa, G. Galzerano, A. Merlone, P. Laporta, L. Gianfrani
PRL **111**, 060803 (2013) $u(k)/k$ = 24 ppm

Uncertainties $u(k)/k$ of methods, history

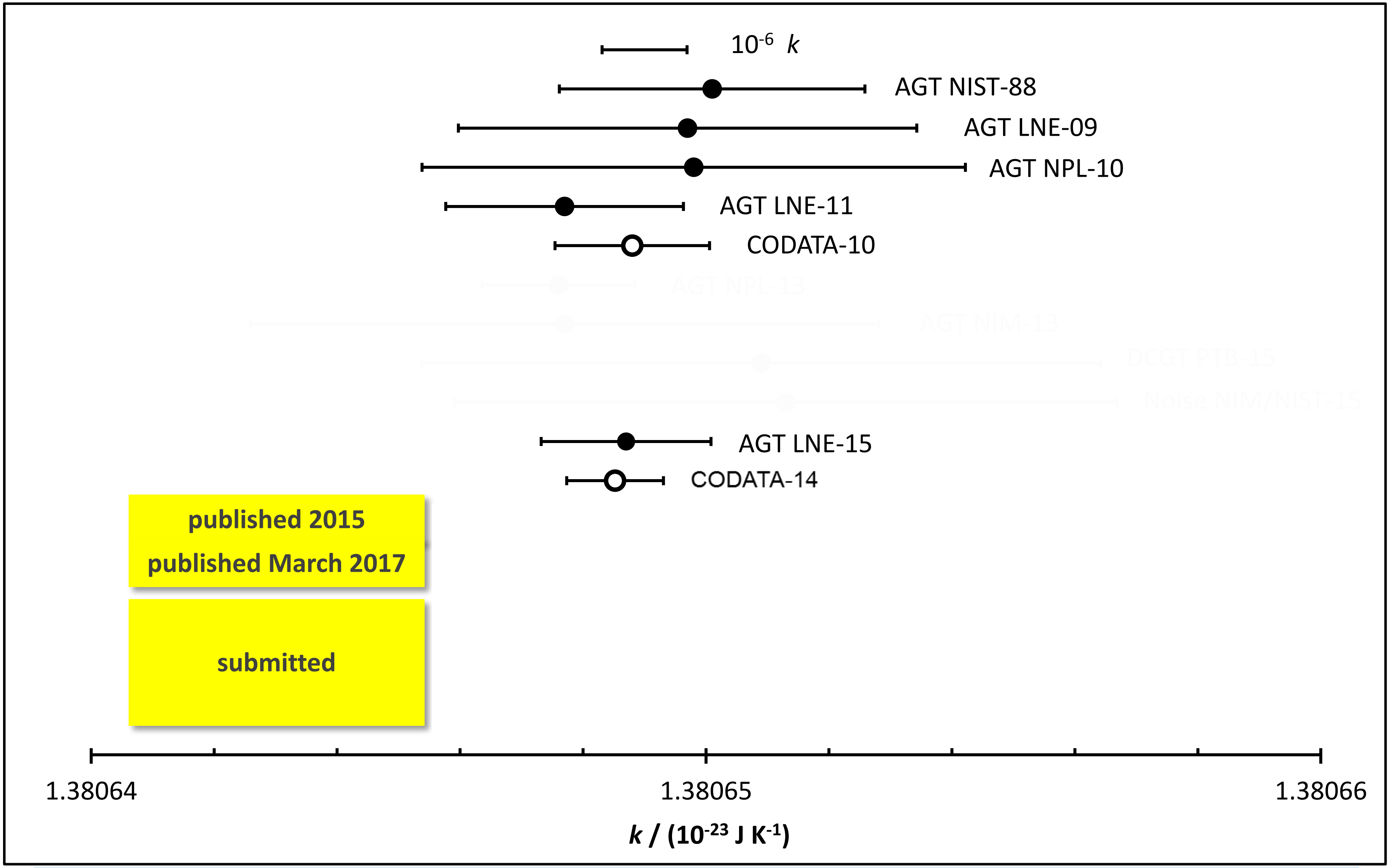
relative standard uncertainties in ppm

Method	gas	up to 2011	2013	2015	2017	institute
AGT	Ar	1.8	-	-	-	NIST
AGT	He	7.5	-	1.1	-	INRiM
AGT	He	2.7	-	1.0	0.6*	LNE-CNAM
AGT	Ar	1.4	-	-	-	LNE-CNAM
AGT	Ar	3.2	0.9	-	0.7*	NPL
AGT	Ar	-	-	20	7.5	UniVal+CEM
c-AGT	Ar	7.9	3.7	-	2.0	NIM/NIST
DCGT	He	7.9	4.3	4.0	1.9	PTB
JNT	-	-	-	3.9	2.7	NIM/NIST
JNT	-	12	-	-	< 3 ?	NIST
DBT	NH_3	50	-	-	-	LPL+LNE-CNAM
DBT	CO_2, H_2O	160	24	-	10 ?	UniNA+INRiM

new data since CODATA 2014

u with ?: estimate of CCT task group SI

Values to be considered by CODATA 2017

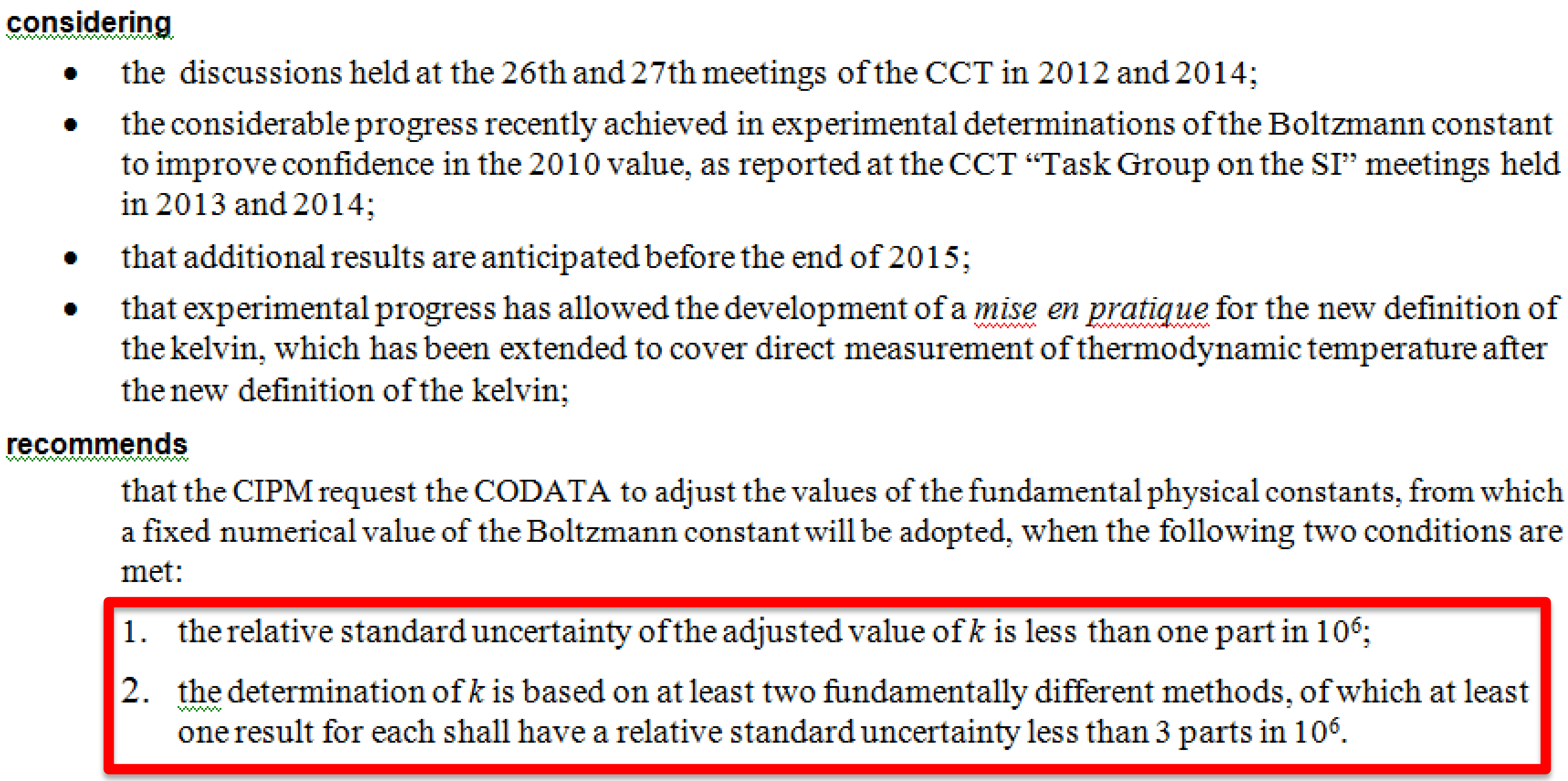


published 2015

published March 2017

submitted

CCT Recommendation T1 (2014)



considering

- the discussions held at the 26th and 27th meetings of the CCT in 2012 and 2014;
- the considerable progress recently achieved in experimental determinations of the Boltzmann constant to improve confidence in the 2010 value, as reported at the CCT “Task Group on the SI” meetings held in 2013 and 2014;
- that additional results are anticipated before the end of 2015;
- that experimental progress has allowed the development of a *mise en pratique* for the new definition of the kelvin, which has been extended to cover direct measurement of thermodynamic temperature after the new definition of the kelvin;

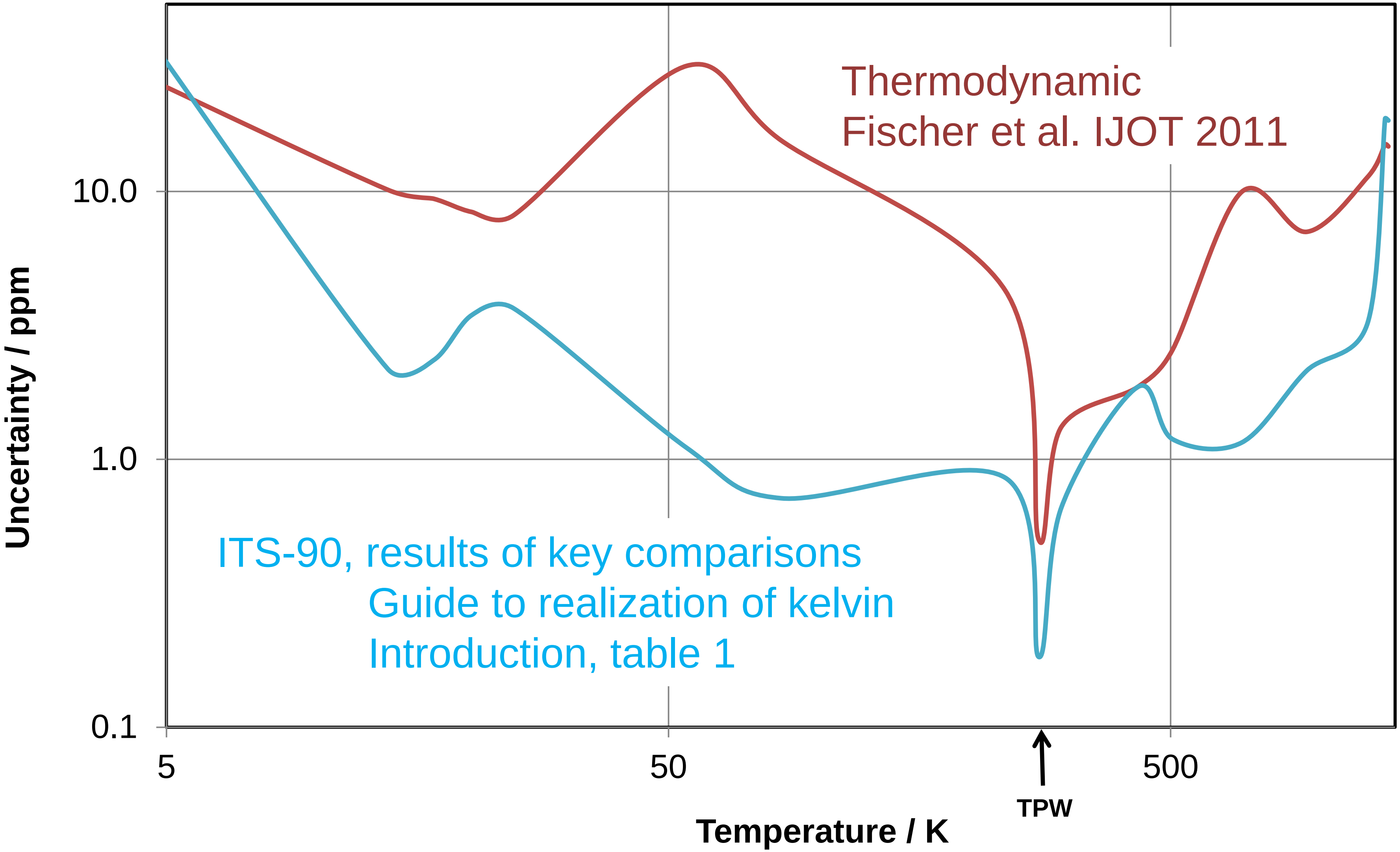
recommends

that the CIPM request the CODATA to adjust the values of the fundamental physical constants, from which a fixed numerical value of the Boltzmann constant will be adopted, when the following two conditions are met:

1. the relative standard uncertainty of the adjusted value of k is less than one part in 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 parts in 10^6.

second condition fulfilled by DCGT in March 2017

Uncertainties of fixed points: T vs. T_{90}



Status of ITS-90

For the foreseeable future :

Most temperature measurements in core temperature range (~ - 200 °C … 960 °C) with SPRTs calibrated accord. to ITS-90

ITS-90 will remain intact, with defined values of T_{90} for all of the fixed points, including the TPW

Uncertainties in T_{90} will not change

Dominated by uncertainties in the fixed-point realizations,

and the non-uniqueness of SPRTs, typically totalling < 1 mK

Uncertainties in thermodynamic temperature

2017 CODATA recommended value of k taken to be exact and used to define the kelvin :

Uncertainty of k transferred to the value of T_{TPW}

Best estimate of the value of T_{TPW} still 273.16 K,

but instead of being exact as result of definition of the kelvin :

Uncertainty associated with estimate would become today :

$u_{\mathrm{r}}(T_{\mathrm{TPW}}) = 5.7 \times 10^{-7}$, corresponds to 0.16 mK

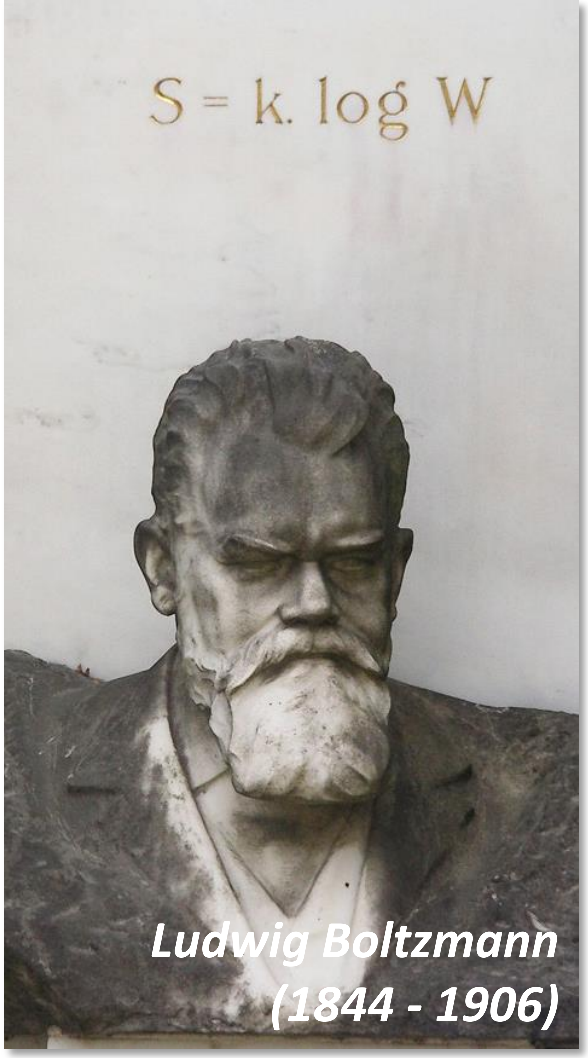
The impact of a new definition of the kelvin

Short term:

- the kelvin definition is independent of any material
- no favoured fixed point
- no favoured measurement method
- no error propagation from TPW
- thermodynamic measurements and ITS-90 are coexisting
- < 20 K and > 1300 K thermodynamics are superior

Long term:

- With improvement of primary thermometry thermodynamic measurements may replace ITS-90



Ludwig Boltzmann
(1844 - 1906)

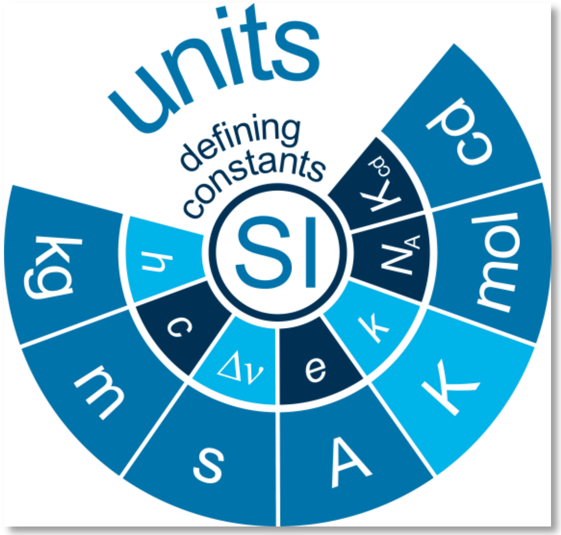
Text for the new definition of the kelvin

The kelvin, symbol K, is the SI unit of thermodynamic temperature; its magnitude is set by fixing the numerical value of the Boltzmann constant to be equal to exactly 1.380 65X × 10^{-23} when it is expressed in the SI unit s^{-2} m^2 kg K^{-1}, which is equal to J K^{-1}.

k = 1.380 65X × 10^{-23} J/K

with J/K = kg m^2 s^{-2} K^{-1}

where kg, m, s
are definded by h, c and $\Delta\nu_{Cs}$



CCU: Information for users on the proposed redefinition of the SI

- ***The kelvin*** will be redefined with no immediate effect on temperature measurement practice or on the traceability of temperature measurements, and for most users, it will pass un-noticed. The redefinition lays the **foundation for future improvements**. A definition free of material and technological constraints enables the development of new and more accurate techniques for making temperature measurements traceable to the SI, **especially at extremes of temperature**. After the redefinition, the guidance on the practical realization of the kelvin will support its world-wide dissemination by describing **primary methods for measurement of thermodynamic temperature and equally through the defined scales ITS-90 and PLTS-2000**.