Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

# The future of contact-thermometry after the redefined kelvin

Christof Gaiser

Chairman of the CCT working group for contact thermometry CCT-CTh

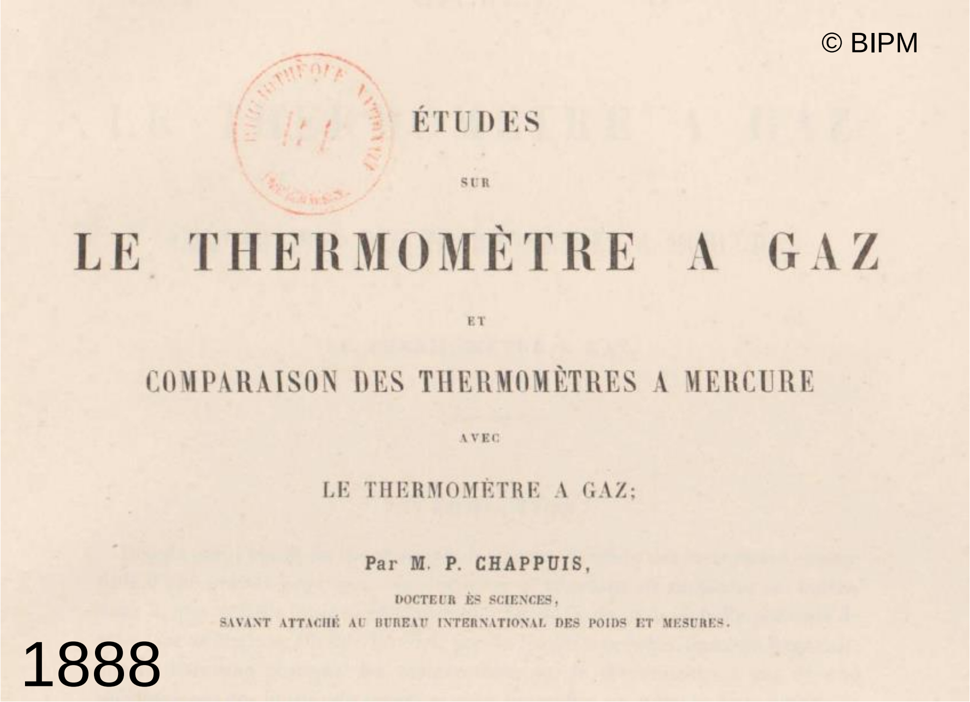
## Contents:

- Historical notes
- The way to the redefined kelvin
- Actual status
- Next steps
- Perspective

# Historical notes “Gas thermometry”

Pierre Chappuis
(1855-1916)

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





ÉTUDES

SUR

LE THERMOMÈTRE A GAZ

ET

COMPARAISON DES THERMOMÈTRES A MERCURE

AVEC

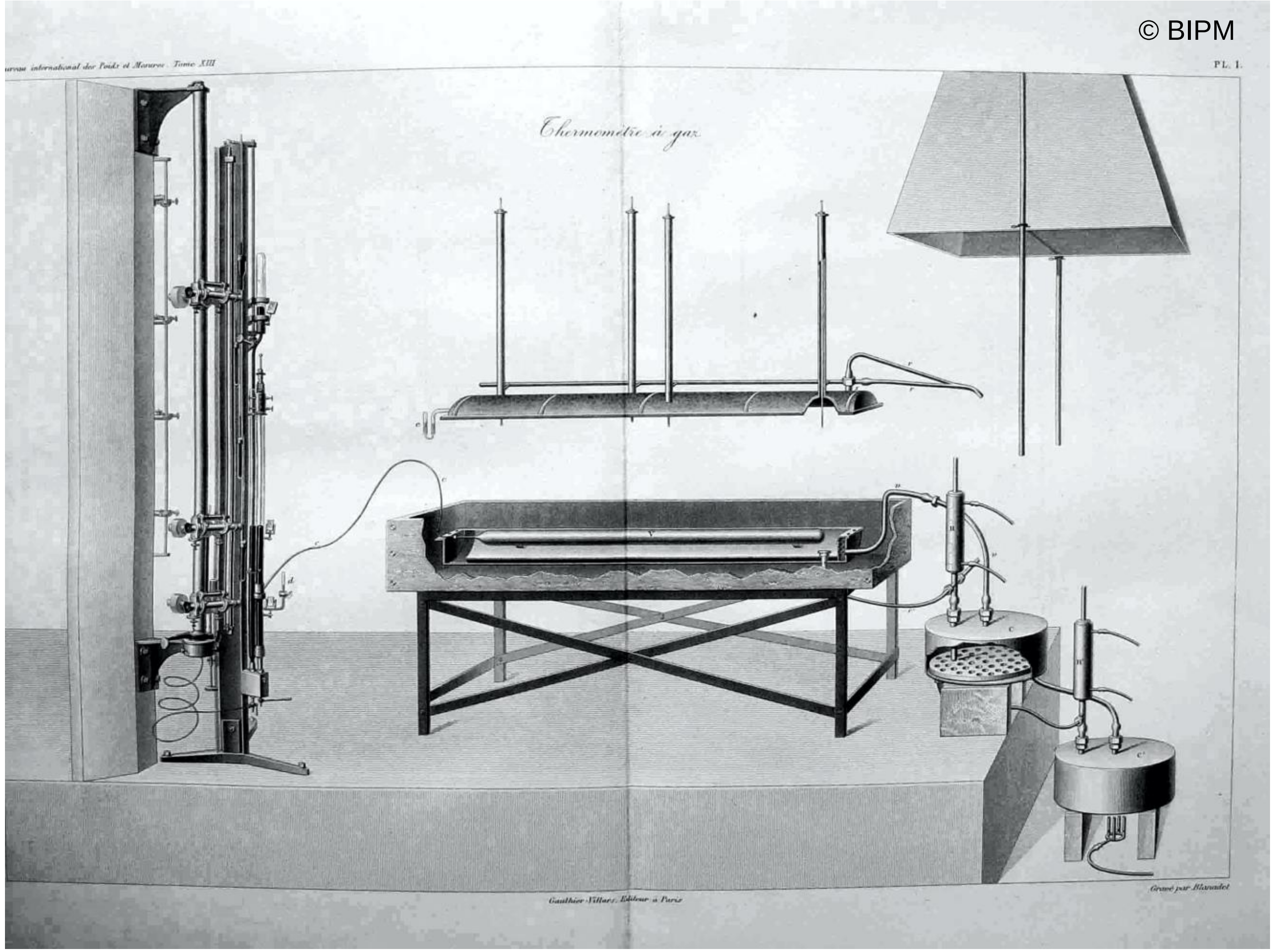
LE THERMOMÈTRE A GAZ;

Par M. P. CHAPPUIS,

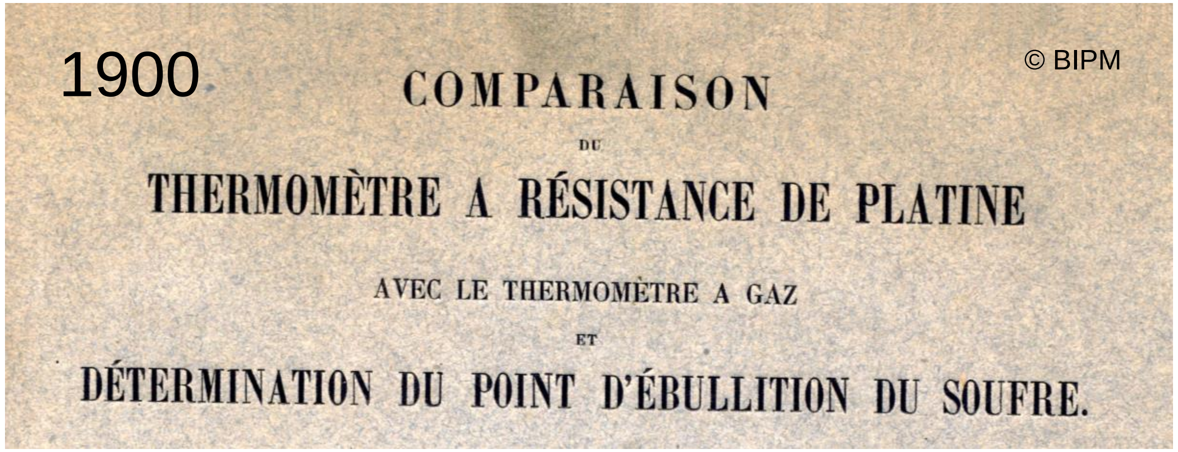
DOCTEUR ÈS SCIENCES,

SAVANT ATTACHÉ AU BUREAU INTERNATIONAL DES POIDS ET MESURES.

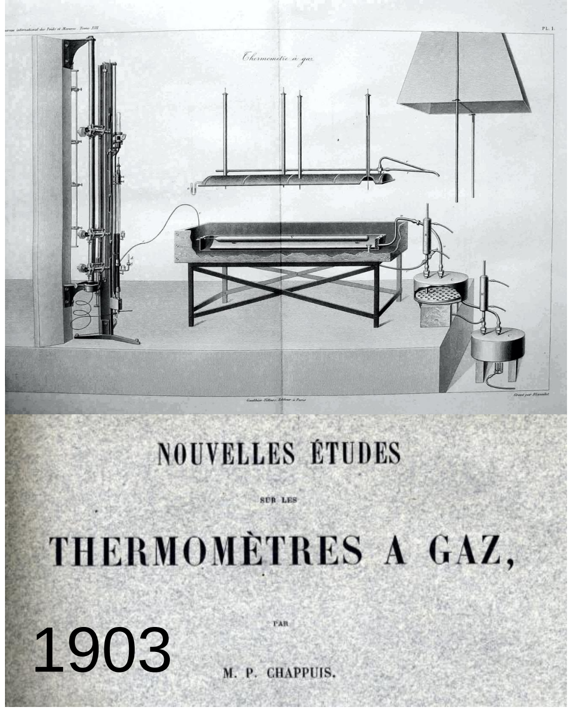
1888



# “ Gas- versus Platinum resistance thermometry”

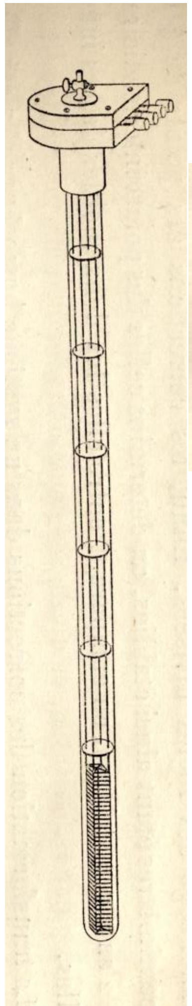

1900
© BIPM

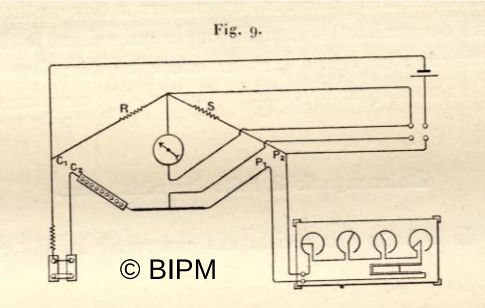
COMPARAISON
DU
THERMOMÈTRE A RÉSISTANCE DE PLATINE
AVEC LE THERMOMÈTRE A GAZ
ET
DÉTERMINATION DU POINT D'ÉBULLITION DU SOUFRE.


NOUVELLES ÉTUDES
SUR LES
THERMOMÈTRES A GAZ,
PAR
M. P. CHAPPUIS.

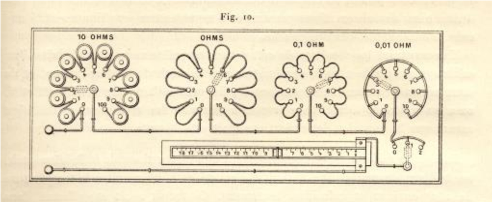
1903

P. Chappuis & J. A. Harker







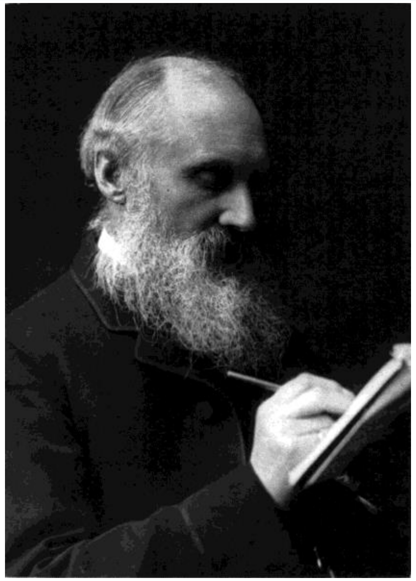



# The normal hydrogen scale: A check at $t = 50°C$

**Chapeau Chappuis!**
**Well done!**

- $T_{H2}$ – 1889 „Normal hydrogen scale“
- ITS-27 – $(T_{27} - T_{H2})_{50°C} = 0$ mK
- ITS 48 – $(T_{48} - T_{H2})_{50°C} = 0$ mK
- ITS-68 – $(T_{68} - T_{H2})_{50°C} = -10$ mK
- ITS-90 – $(T_{90} - T_{H2})_{50°C} = -23$ mK
- $T$ – $(T - T_{H2})_{50°C} =$ **-16 mK**

# The time was not yet ripe for a new definition

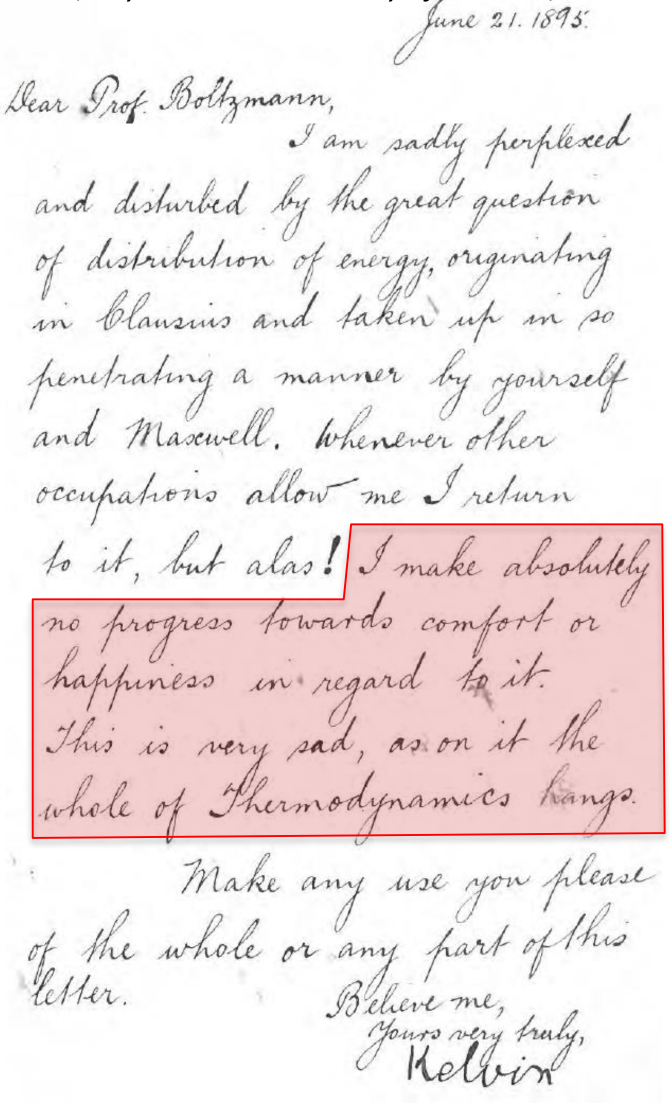


W. Thomson
(now Lord Kelvin)
at the age of 71

L. Boltzmann
at the age of 51

I make absolutely no progress towards comfort or happiness in regard to it (Maxwell-Boltzmann distribution). This is very sad, as on it the whole of thermodynamics hangs.

*Svante Arrhenius archives, Royal Swedish Academy of Sciences, Stockholm*



June 21. 1895.

Dear Prof. Boltzmann,

I am sadly perplexed and disturbed by the great question of distribution of energy, originating in Clausius and taken up in so penetrating a manner by yourself and Maxwell. Whenever other occupations allow me I return to it, but alas! I make absolutely no progress towards comfort or happiness in regard to it. This is very sad, as on it the whole of Thermodynamics hangs.

Make any use you please of the whole or any part of this letter.

Believe me,
Yours very truly,
Kelvin

## Contents:

- Historical notes
- **The way to the redefined kelvin**
- Actual status
- Next steps
- Perspective

# Triple point of water and the kelvin

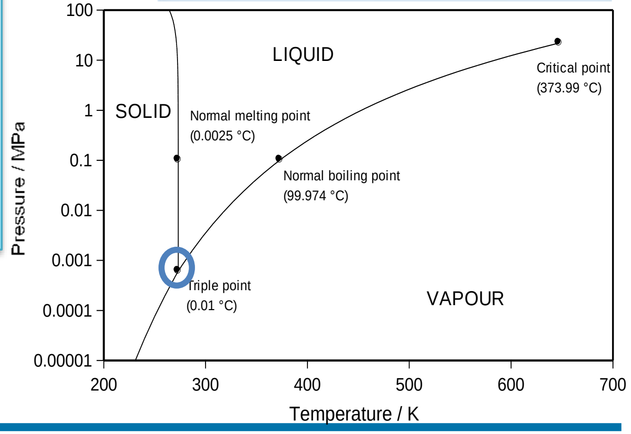
*J. P. Joule and W. Thomson Phil. Trans. June. 1854*

To fix on a unit or degree for the numerical measurement of temperature, we may either call some definite temperature, such as that of melting ice, unity, or any number we please; or we may

- Sealed glass cell containing the three phases
- Thermometer well surrounded by ice/water interface
- Corrections:
    - Head correction about 0.2 mK
    - Isotopic correction about 0.15 mK
- Typical uncertainty of the realisation **30 μK ($u_r \approx 1 \cdot 10^{-7}$)**

Variation of samples:

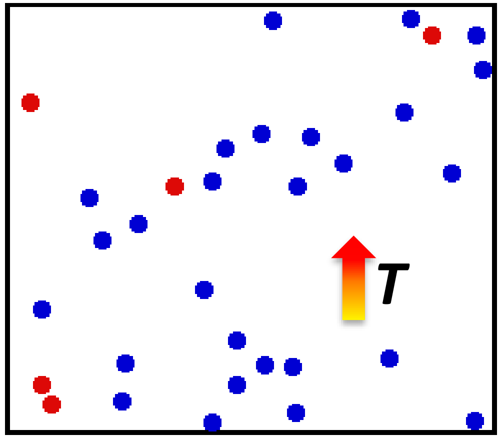
- isotope effects
- impurities



# The Boltzmann Constant $k$ and the kelvin

The ideal gas

$\langle E_{kin} \rangle = E_{Therm}$



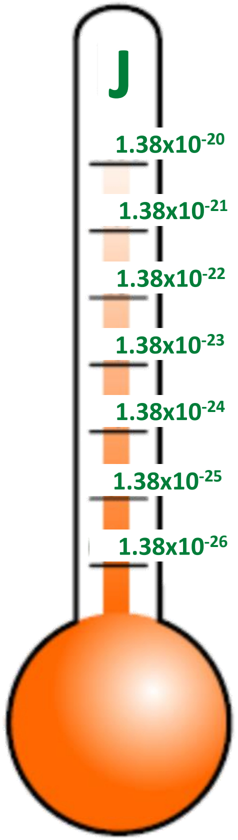

$\frac{1}{3} m \langle v^2 \rangle = T$

*measured in joule*

**thermodynamic temperature**

*measured in kelvin*

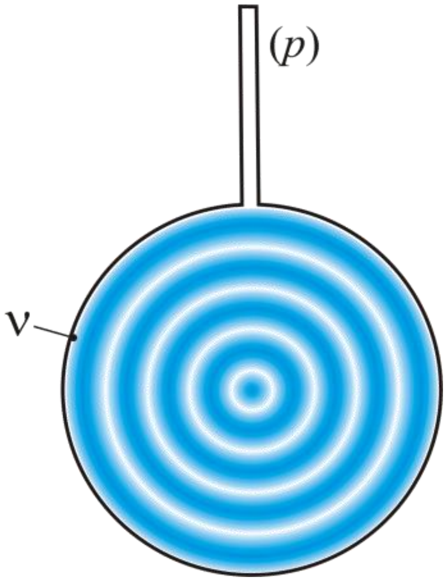
$\frac{1}{3} m \langle v^2 \rangle = kT$




**$k$ = conversion factor between energy and temperature**

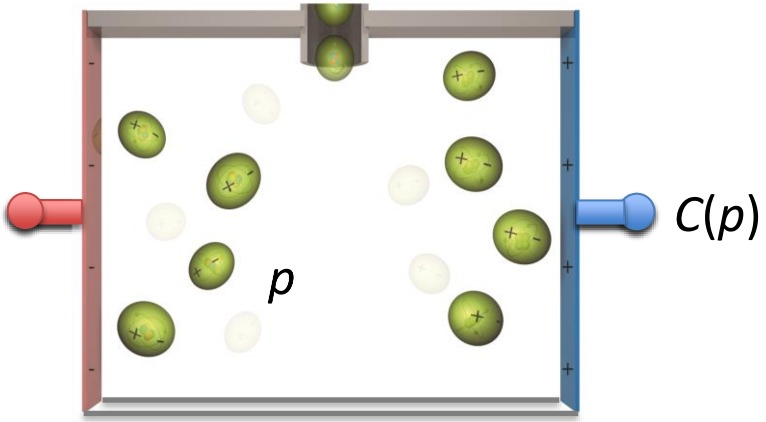
**fixing the value of $k$ fixes the temperature unit**

# Primary thermometers for the determination of *k*



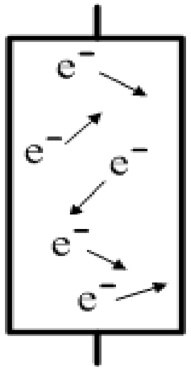

**AGT**

$$u_0^2 = \gamma_0 \, kT \, N_A / M$$
$$\gamma_0 = c_p / c_V$$




**DCGT**

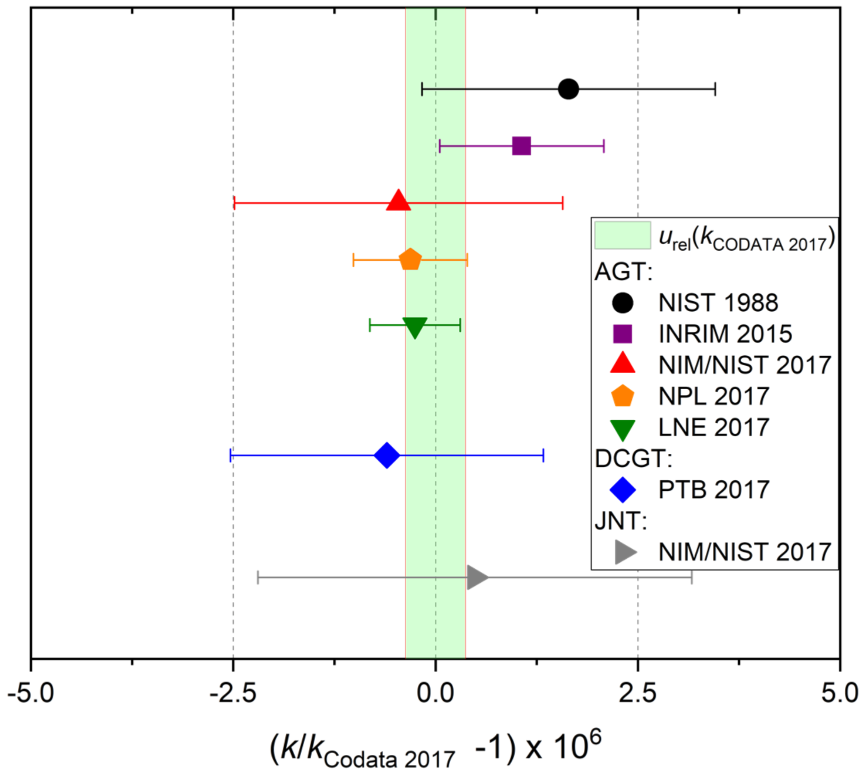
$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{p}{kT} \frac{\alpha_0}{3\varepsilon_0}$$




**JNT**

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

# *k*-Project: The final score




## *CCT recommendation T1 (2014)*

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 $1\times10^{-6}$**;
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 $3\times10^{-6}$**.

# The redefinition of the kelvin

$$k \overset{\text{def}}{=} 1.380649 \times 10^{-23}\ \text{J/K}$$

$$T_{\text{TPW}} = 273.1600(1)\ \text{K}$$


Redefined SI
came into force on
$20^{\text{th}}$ of May 2019

*Explicit-constant definition*

*The **kelvin**, K, is the unit of thermodynamic temperature; its magnitude is set by fixing the numerical value of the **Boltzmann** constant to be equal to exactly* $1.380649 \times 10^{-23}$ J/K.

# Contents:

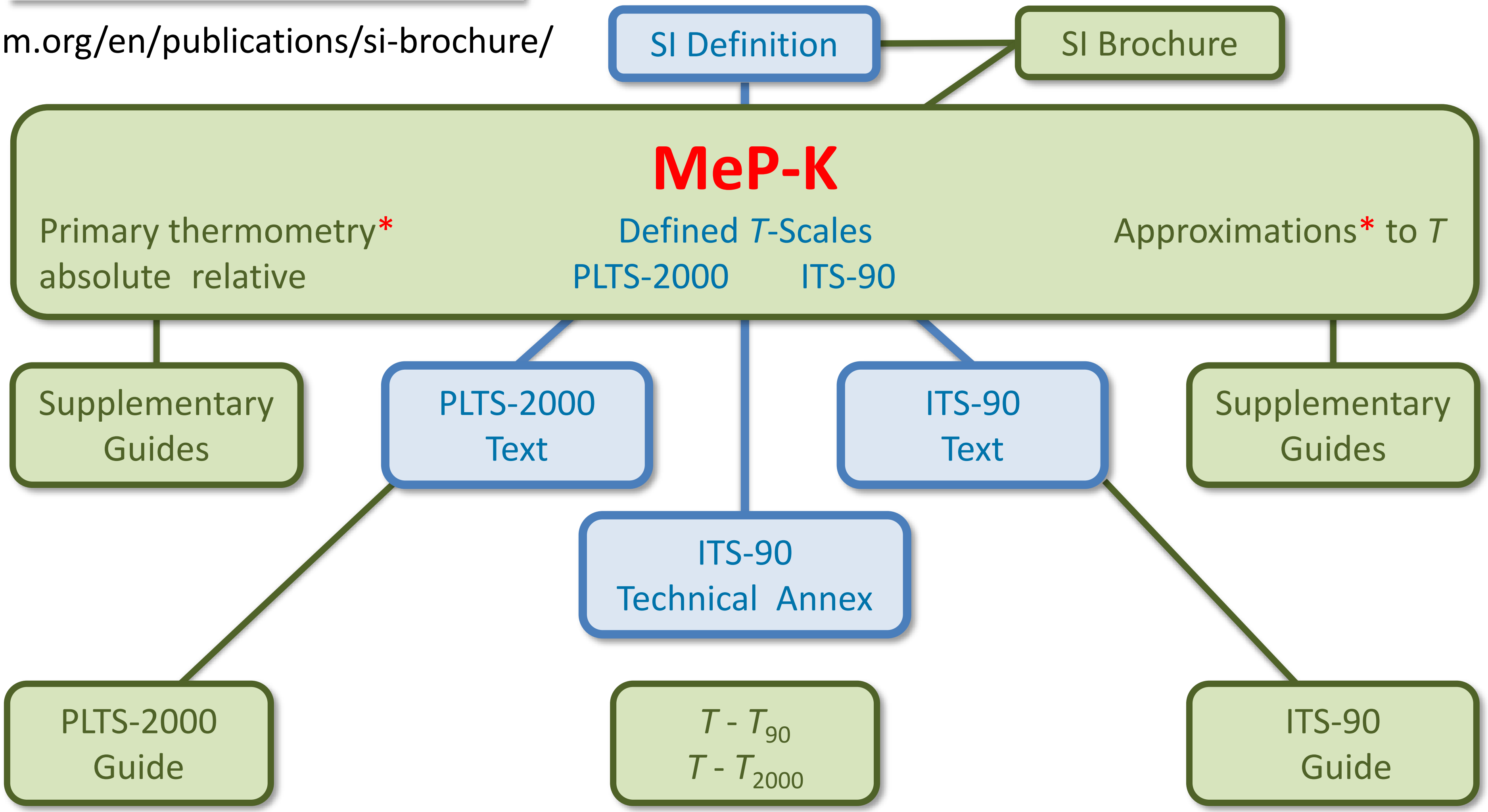
- Historical notes
- The way to the redefined kelvin
- Actual status
- Next steps
- Perspective

# Mise en Pratique for the kelvin (MeP-K)

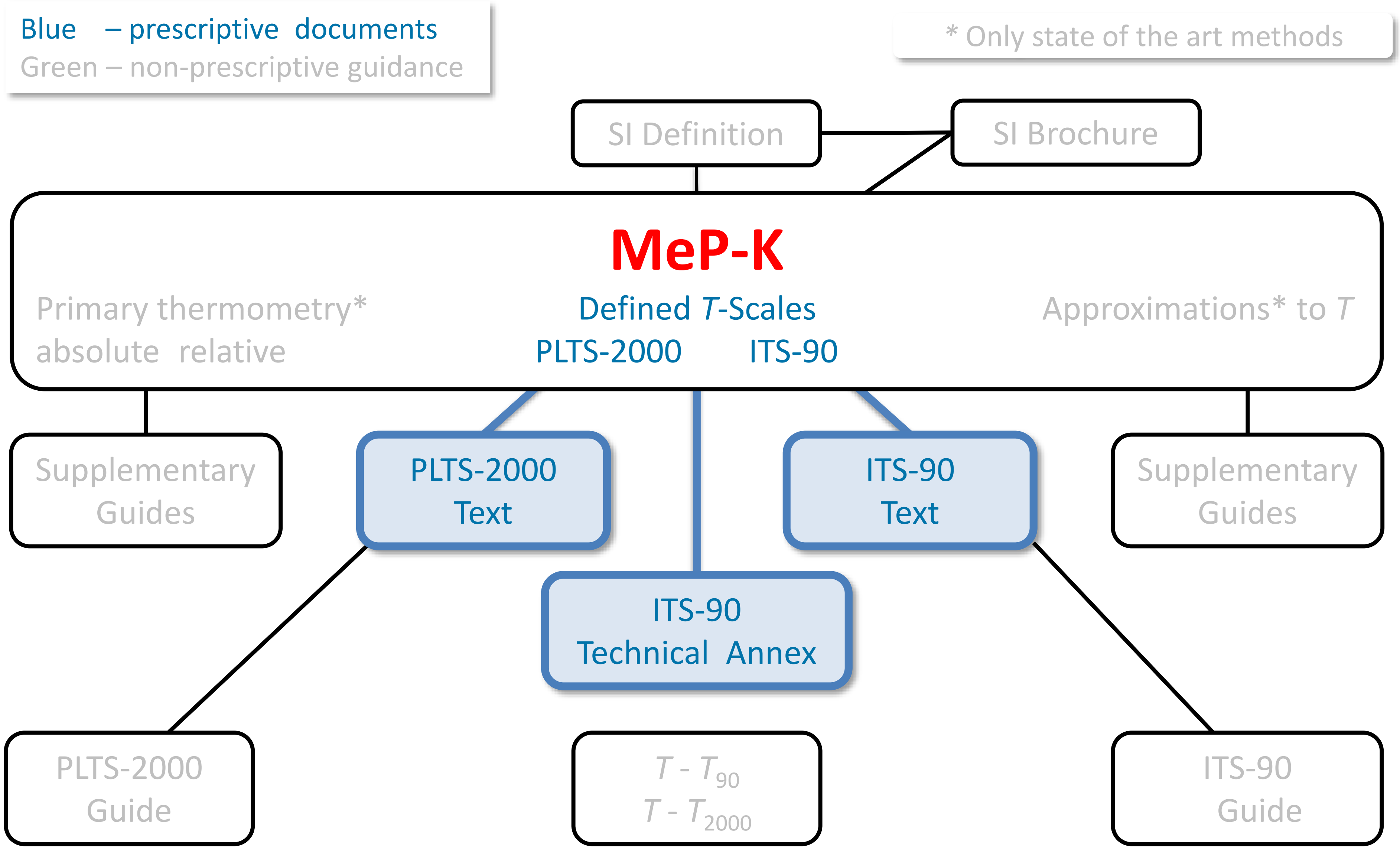
Blue – prescriptive documents
Green – non-prescriptive guidance

* Only state of the art methods

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

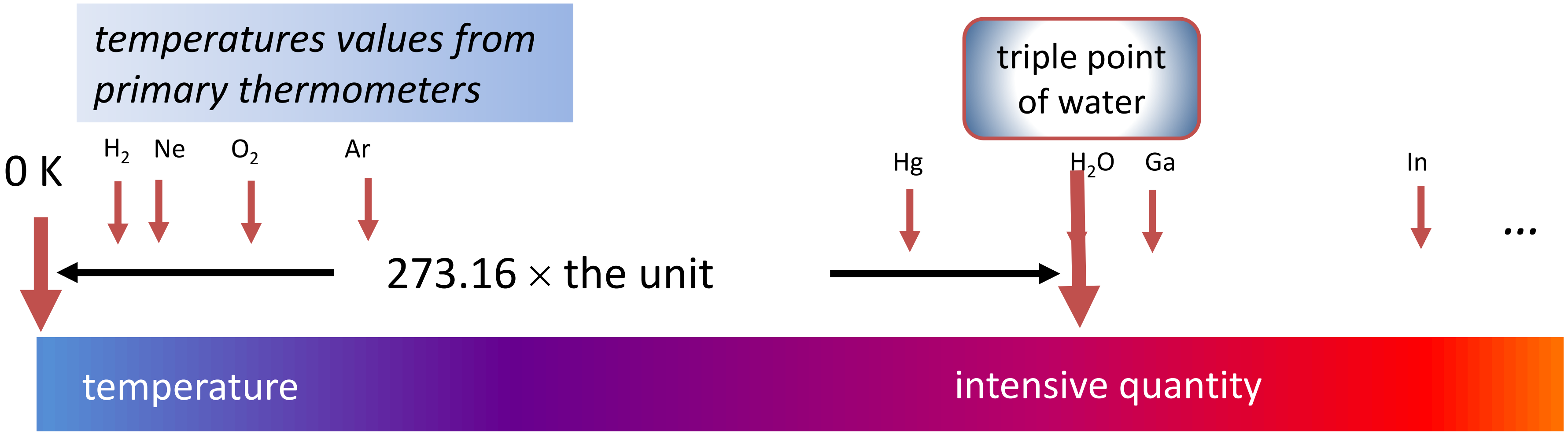


# Mise en Pratique for the kelvin (MeP-K)



# ITS-90 and the status after the redefinition

**The International Temperature Scale of 1990 (ITS-90): additional fixed points**

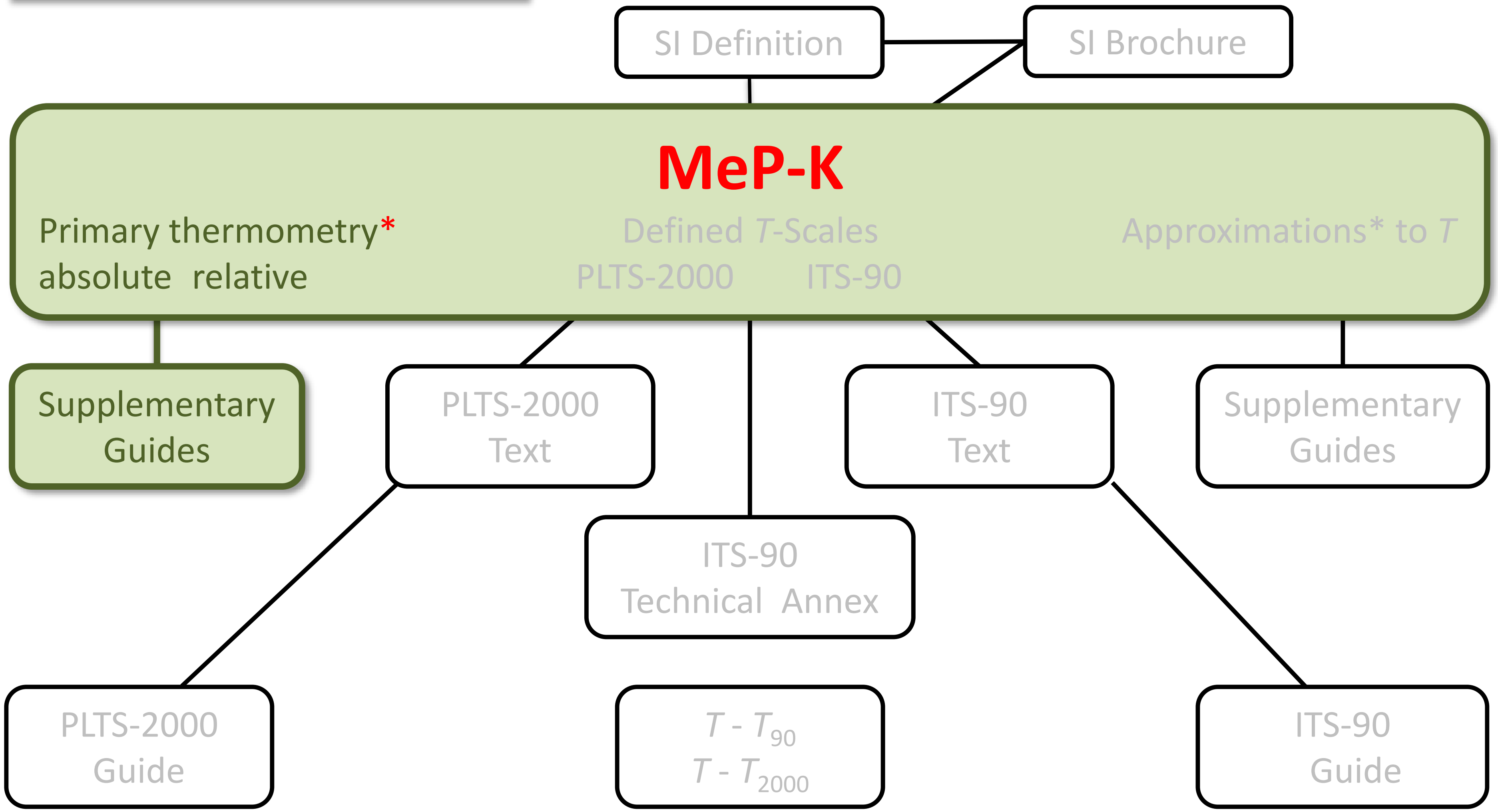



**Most important: The status of the ITS-90 is unchanged !**

**The fixed-point temperatures assigned in an International Temperature Scale are exact with respect to the respective scale temperature (there is no assigned uncertainty) and fixed (the value remains unchanged throughout the life of the scale).**

Blue – prescriptive documents
Green – non-prescriptive guidance

* Only state of the art methods



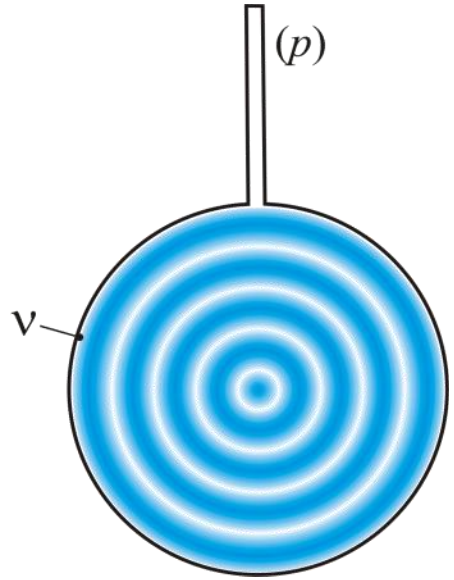
# Inclusion criteria for primary thermometers

**Primary Thermometers: based on well-understood physical systems, for which the equation of state describing the relation between *T* and other independent quantities can be written down explicitly without unknown constants**

- Primary thermometry: Well derived equation of state
- Complete uncertainty budget must be approved by CCT
- Uncertainty acceptable small
- At least two independent realisations
- Comparison with the results of already accepted methods
- Applicable over acceptable temperature ranges
- Detailed documentation in the open literature

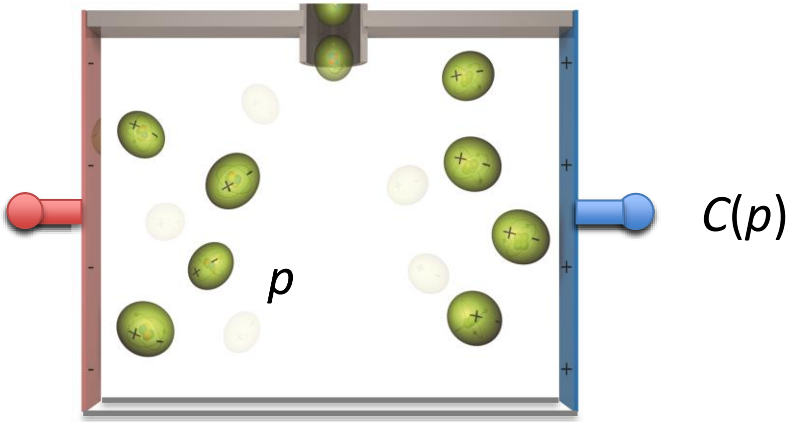
# Primary contact thermometers in MeP-K

## PGT



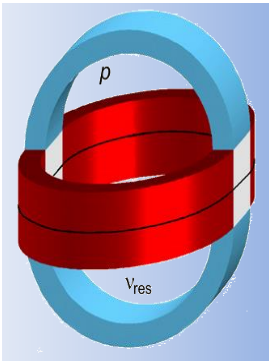

## AGT

$$u_0^2 = \gamma_0 \, kT \, N_A / M$$
$$\gamma_0 = c_p / c_V$$



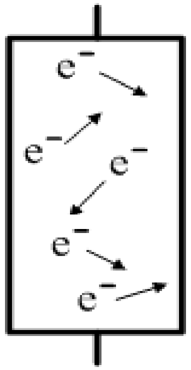

## DCGT

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{p}{kT} \frac{\alpha_0}{3\varepsilon_0}$$




## RIGT

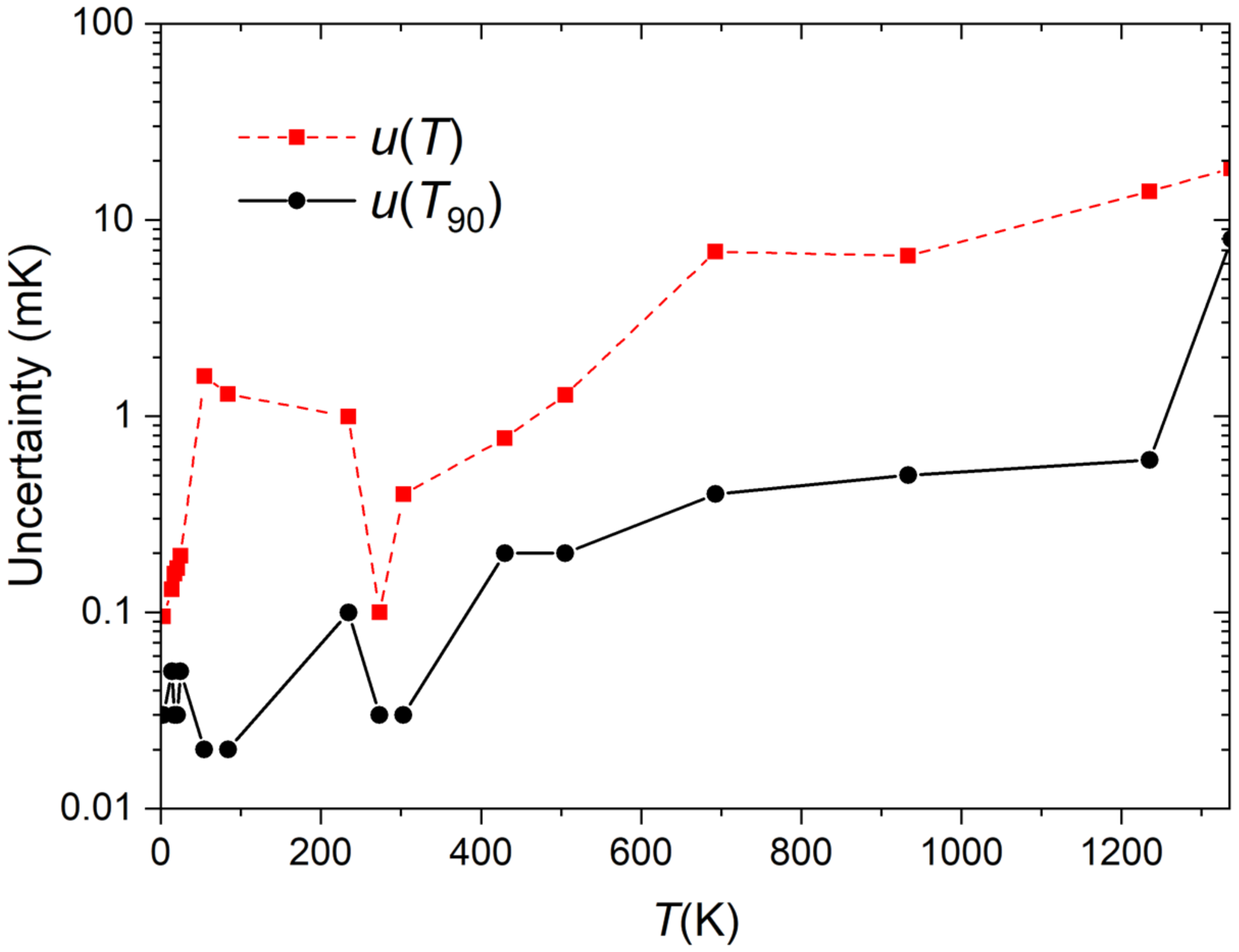
$$\frac{n^2 - 1}{n^2 + 2} \approx \frac{p}{kT} \frac{\alpha_0}{3\varepsilon_0}$$




## JNT

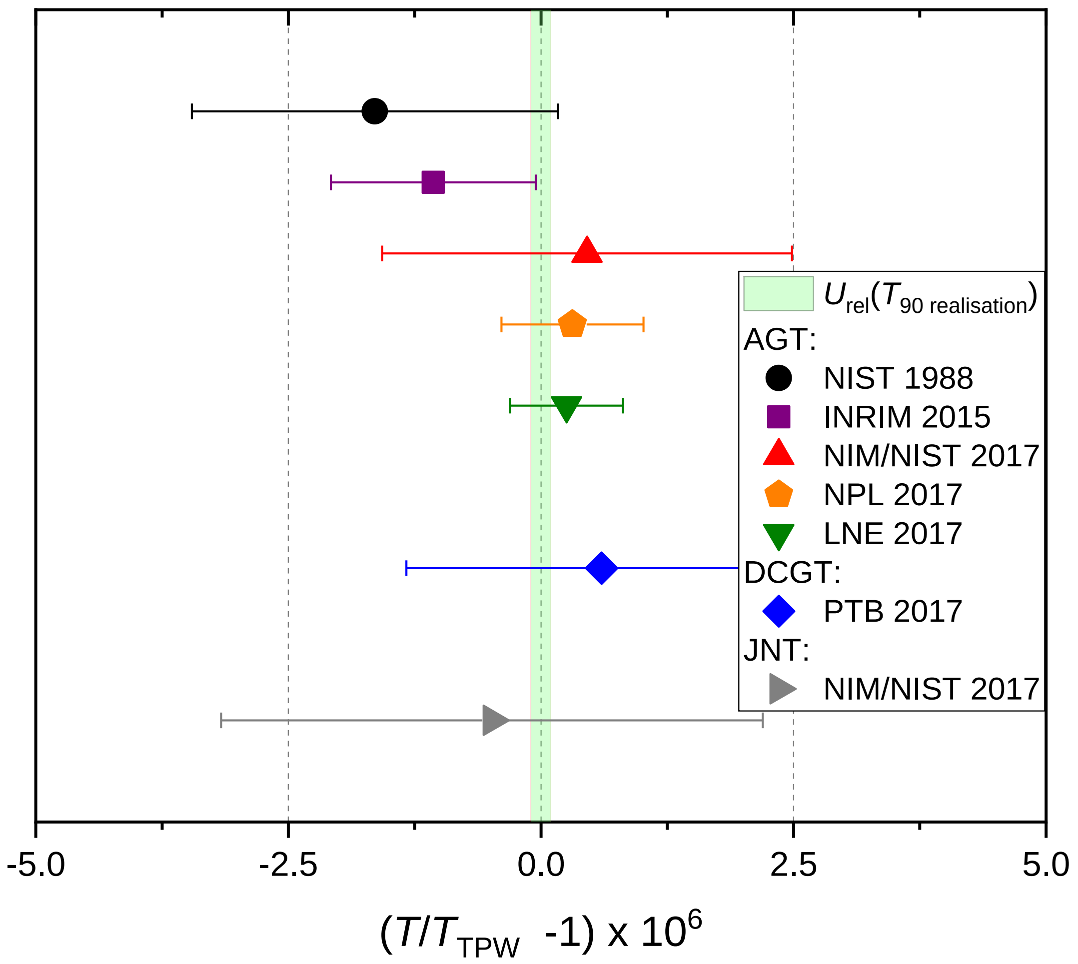
$$\langle V^2 \rangle = 4 \, kT \, R \, \Delta\nu$$

# Realisation of ITS-90 versus primary thermometry

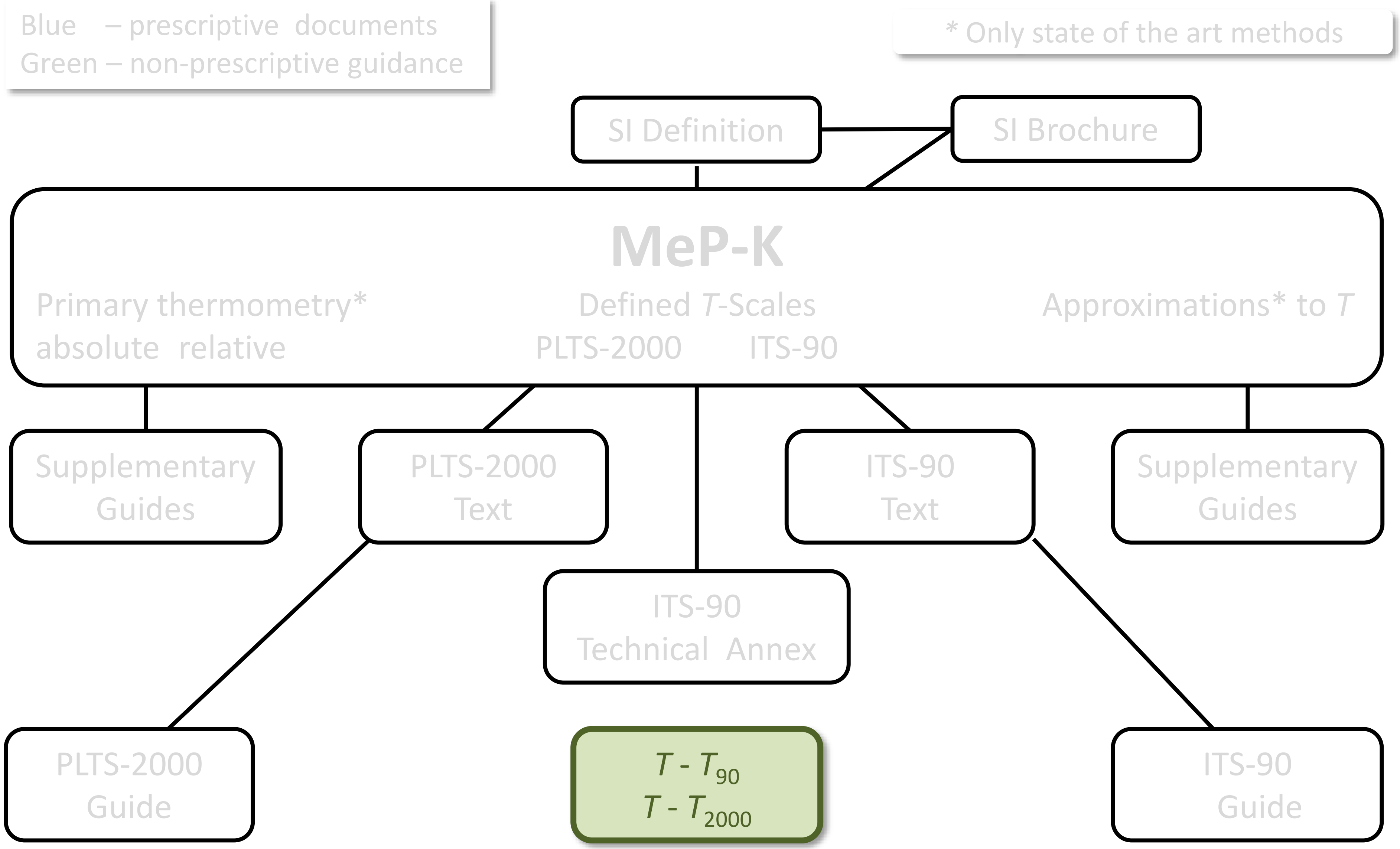


# $T_{90}$ versus $T$: A high level performance Test

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

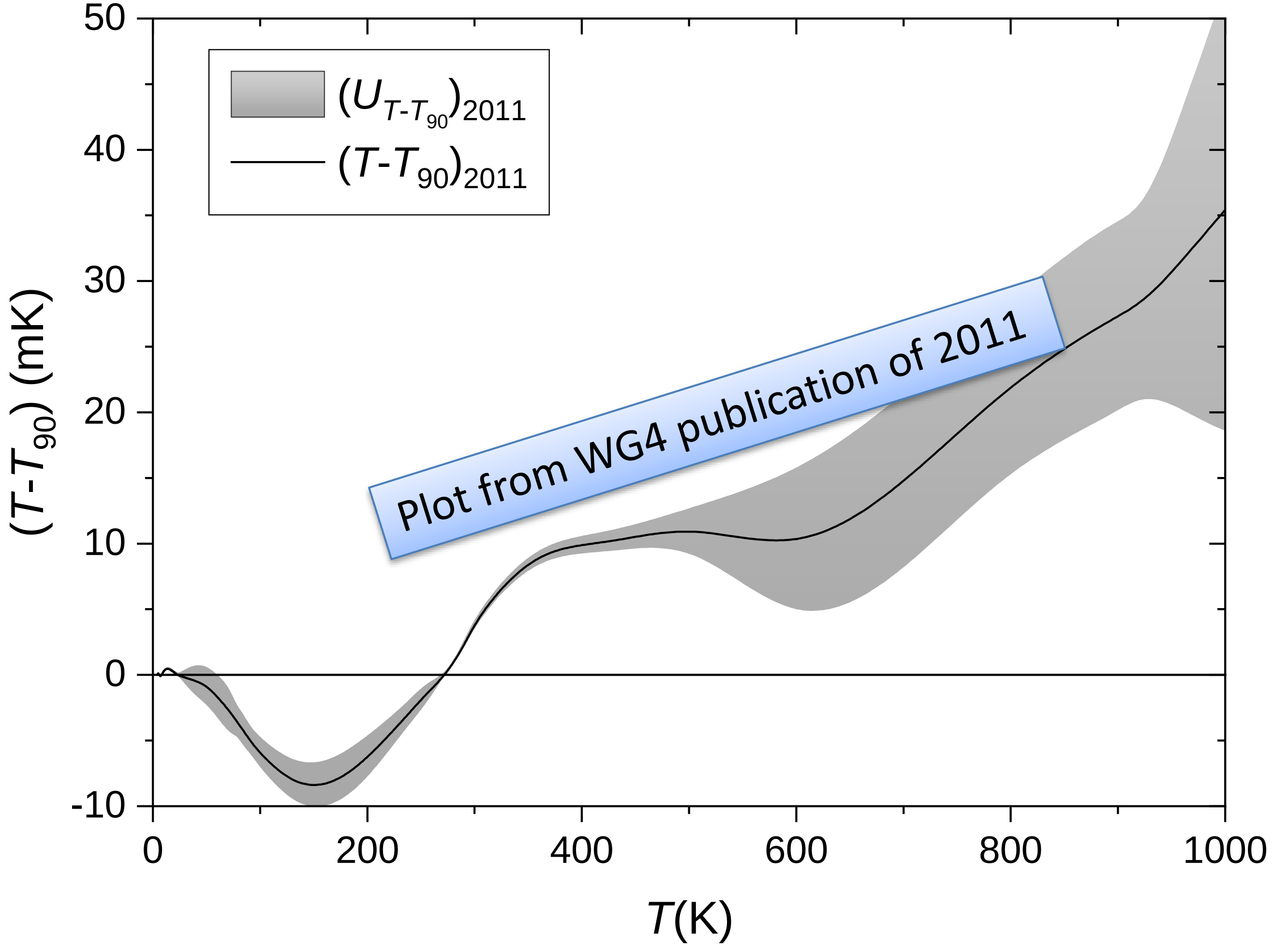


# $T$-$T_{90}$ gains importance

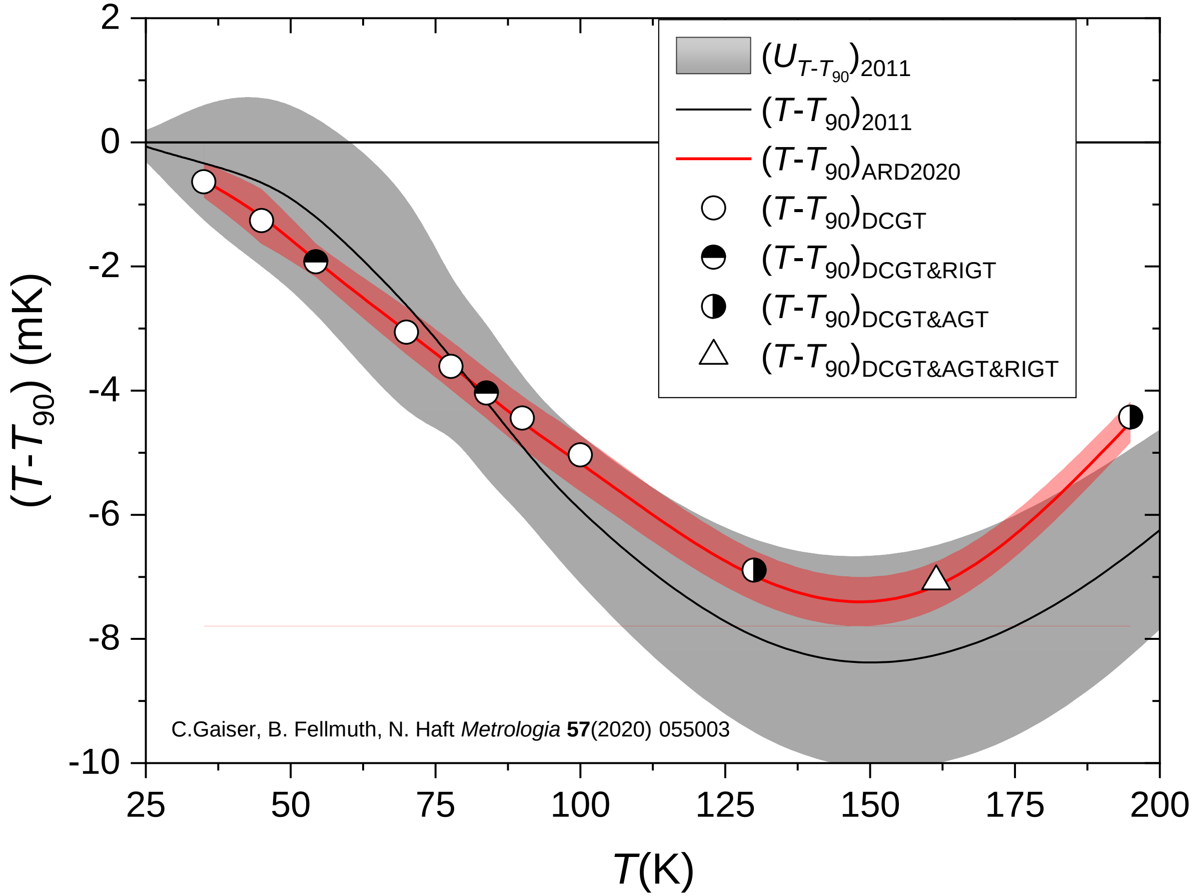


## Contents:

# Improvement in $T$ → better estimates of $T$-$T_{90}$



# Latest improvement in *T* between 30 K and 200 K




## AGT

Estimates of the difference between thermodynamic temperature and the ITS-90 in the range 118 K to 303 K

R Underwood[1], M de Podesta[1], G Sutton[1], L Stanger[1], R Rusby[1], P Harris[1], P Morantz[2], G Machin[1].


## RIGT

**Thermodynamic temperature of the triple point of xenon measured by refractive index gas thermometry**

P M C Rourke

## DCGT

**Thermodynamic-temperature data from 30 K to 200 K**

Christof Gaiser, Bernd Fellmuth and Norbert Haft

# Further new $T$-$T_{90}$ data from AGT

Metrologia 56 (2019) 045006 (25pp)
https://doi.org/10.1088/1681-7575/ab29a2

## Determination of the thermodynamic temperature between 236 K and 430 K from speed of sound measurements in helium

R M Gavioso, D Madonna Ripa, P P M Steur, R Dematteis and D Imbraguglio

## Deviation of Temperature Determined by ITS-90 Temperature Scale from Thermodynamic Temperature Measured by Acoustic Gas Thermometry at 79.0000 K and at 83.8058 K

V. G. Kytin[1,2] · G. A. Kytin[1] · M. Yu. Ghavalyan[1] · B. G. Potapov[1] · E. G. Aslanyan[1] · A. N. Schipunov[1]

## Determination of $T$–$T_{90}$ from 234 K to 303 K by acoustic thermometry with a cylindrical resonator

K Zhang[1,2], X J Feng[1], J T Zhang[1], Y Y Duan[2], H Lin[1] and Y N Duan[1]

[1] National Institute of Metrology, Beijing 100029, People's Republic of China
[2] Tsinghua University, Beijing 100084, People's Republic of China

## Thermodynamic Temperature Measurements from the Triple Point of Water up to the Melting Point of Gallium

J. V. Widiatmo[1] · T. Misawa[1] · T. Nakano[1] · I. Saito[1]

# Further new $T$-$T_{90}$ data from PGT

## Accepted manuscript in Metrologia:

**Measurement of thermodynamic temperature between 5 K and 24.5 K with Single-Pressure Refractive-Index Gas Thermometry**

Bo Gao[1,2*], Haiyang Zhang[1,2], Dongxu Han[3,1], Changzhao Pan[4,1], Hui Chen[5,1], Yaonan Song[1,2,6], Wenjing Liu[1,2,6], Jiangfeng Hu[1,2,6], Xiangjie Kong[1,2,6], Fernando Sparasci[4], Mark Plimmer[4], Ercang Luo[2,1,6*], Laurent Pitre[4,1*]



## Manuscript to be submitted to Metrologia:

Refractive index gas thermometry between 13.8 K and 161.4 K

D. Madonna Ripa[1], D. Imbraguglio[1], C. Gaiser[2], P. P. M. Steur[1], D. Giraudi[1], M. Fogliati[1], M. Bertinetti[1], G. Lopardo[1], R. Dematteis[1], R. M. Gavioso[1]

# New consensus values from 4K to 303K

## PGT

**Thermodynamic temperature of the triple point of xenon measured by refractive index gas thermometry**

P M C Rourke

**Thermodynamic-temperature data from 30 K to 200 K**

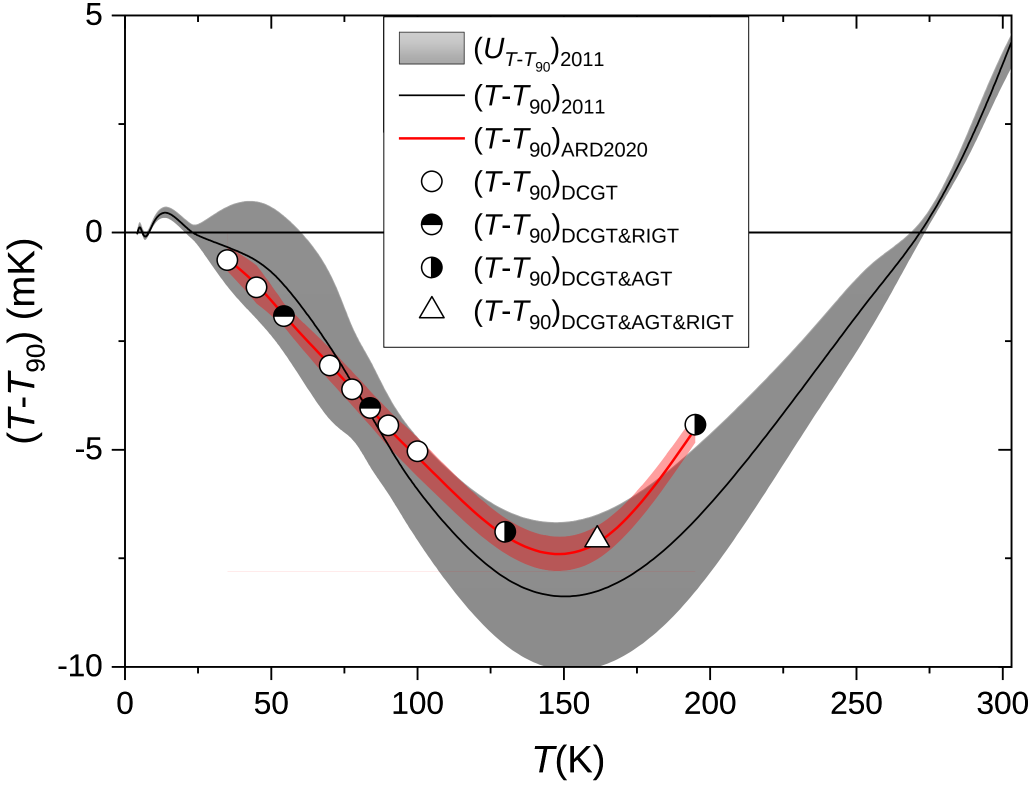
Christof Gaiser, Bernd Fellmuth and Norbert Haft

Refractive index gas thermometry between 13.8 K and 161.4 K

D. Madonna Ripa[1], D. Imbraguglio[1], C. Gaiser[2], P. P. M. Steur[1], D. Giraudi[1], M. Fogliati[1], M. Bertinetti[1], G. Lopardo[1], R. Dematteis[1], R. M. Gavioso[1]

**Measurement of thermodynamic temperature between 5 K and 24.5 K with Single-Pressure Refractive-Index Gas Thermometry**

Bo Gao[1,2*], Haiyang Zhang[1,2], Dongxu Han[3,1], Changzhao Pan[4,1], Hui Chen[5,1], Yaonan Song[1,2,6], Wenjing Liu[1,2,6], Jiangfeng Hu[1,2,6], Xiangjie Kong[1,2,6], Fernando Sparasci[4], Mark Plimmer[4], Ercang Luo[2,1,6*], Laurent Pitre[4,1*]




## AGT

Estimates of the difference between thermodynamic temperature and the ITS-90 in the range 118 K to 303 K

R Underwood[1], M de Podesta[1], G Sutton[1], L Stanger[1], R Rusby[1], P Harris[1], P Morantz[2], G Machin[1].

**Determination of the thermodynamic temperature between 236 K and 430 K from speed of sound measurements in helium**

R M Gavioso, D Madonna Ripa, P P M Steur, R Dematteis and D Imbraguglio

Thermodynamic Temperature Measurements from the Triple Point of Water up to the Melting Point of Gallium

J. V. Widiatmo[1] · T. Misawa[1] · T. Nakano[1] · I. Saito[1]

**Determination of $T\text{–}T_{90}$ from 234 K to 303 K by acoustic thermometry with a cylindrical resonator**

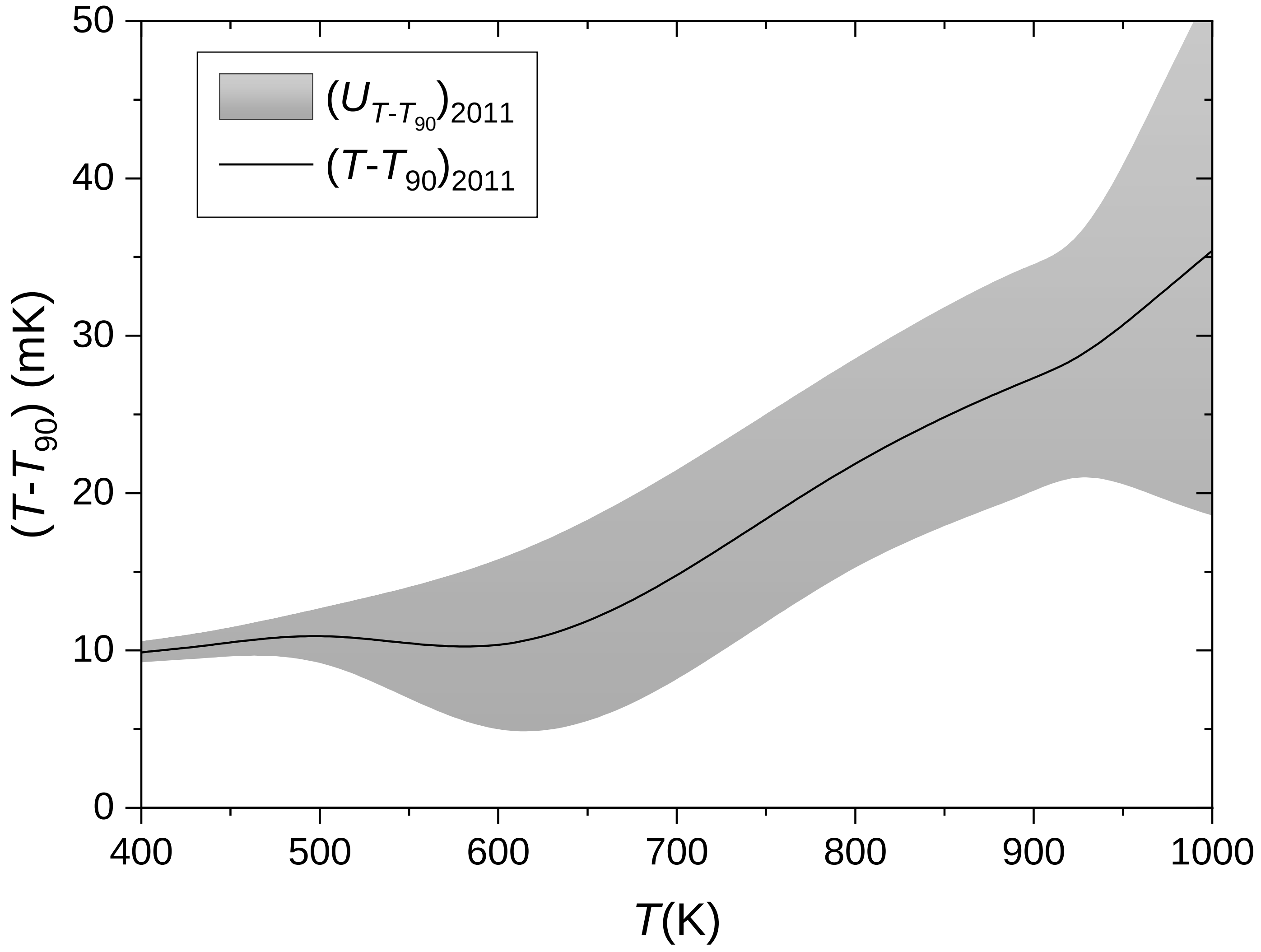
K Zhang[1,2], X J Feng[1], J T Zhang[1], Y Y Duan[2], H Lin[1] and Y N Duan[1]

Deviation of Temperature Determined by ITS-90 Temperature Scale from Thermodynamic Temperature Measured by Acoustic Gas Thermometry at 79.0000 K and at 83.8058 K

V. G. Kytin[1,2] · G. A. Kytin[1] · M. Yu. Ghavalyan[1] · B. G. Potapov[1] · E. G. Aslanyan[1] · A. N. Schipunov[1]

## Contents:

# New data $T\text{-}T_{90}$ above 400 K urgently needed!




## Suggestion for discussion:

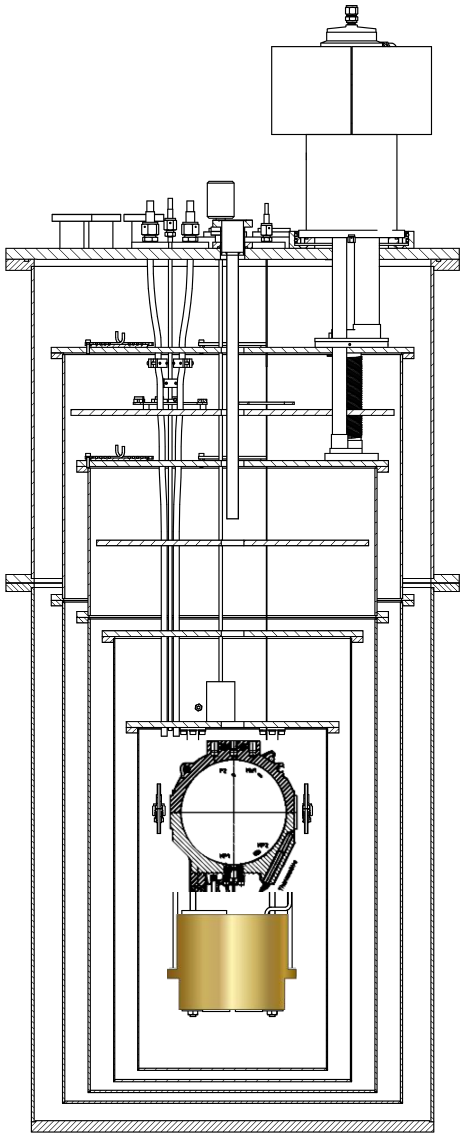
**RECOMMENDATIONS OF THE**
**CONSULTATIVE COMMITTEE FOR THERMOMETRY**
**SUBMITTED TO THE INTERNATIONAL COMMITTEE FOR WEIGHTS AND MEASURES**

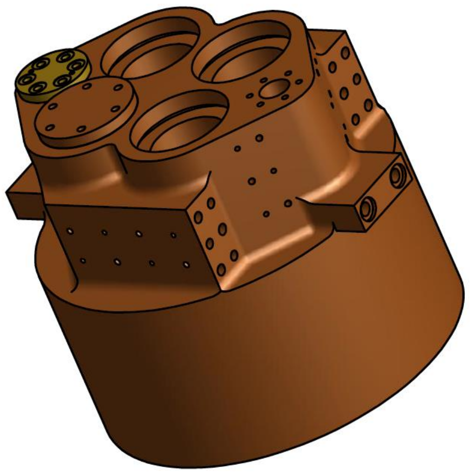
**RECOMMENDATION ??? (2020)**

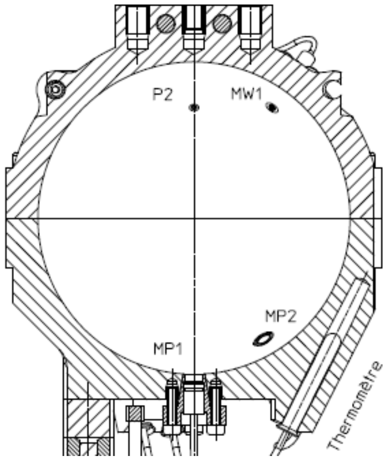
**Requirement for new determinations of thermodynamic temperature above 400 K**

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

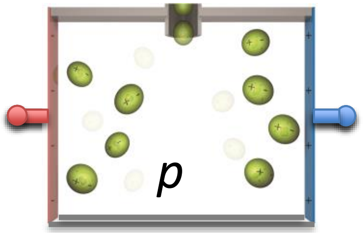
# Direct comparison of primary thermometers at $T \neq T_{TPW}$



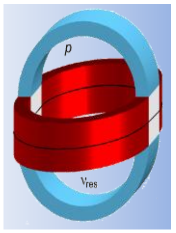




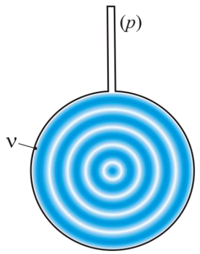

DCGT




RIGT

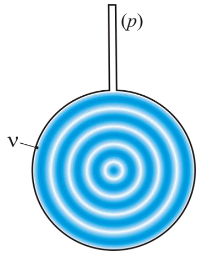



AGT

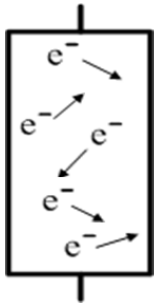



Below $T_{TPW}$

AGT




JNT




Above $T_{TPW}$

# Inclusion of new primary thermometers in the MeP-K

**Bureau International des Poids et Mesures**

– the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards.

Search

| Sit

ABOUT US | WORLDWIDE METROLOGY | INTERNATIONAL EQUIVALENCE | SI UNITS | SERVICES | PU

> You are here: worldwide metrology: committee structure > Consultative Committees > CCT > CCT-TG-CTH-ET

## CCT Task Group for Emerging Technologies (CCT-TG-CTh-ET)

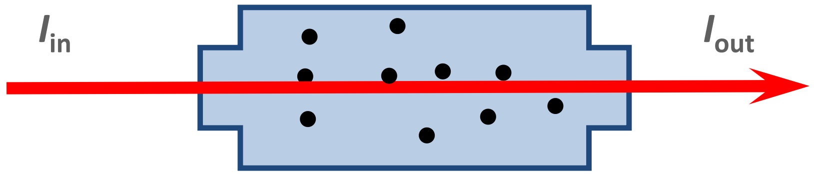
Mission | Members | Forum Workspace | CCT

### → Terms of reference and tasks

The terms of reference of the CCT TG-CTh-ET are to identify, study and advise the CCT on matters related to the areas of emerging technologies.

### → Tasks

- Review the field and report to the CCT on various emergent technologies for contact thermometry devices and measurement techniques;
- Review and report on published data from various emergent technologies including a comparative study of the advantages, limitations, materials, and temperature ranges;
- Review and report on the potential of some of these emergent technologies for primary thermometry.



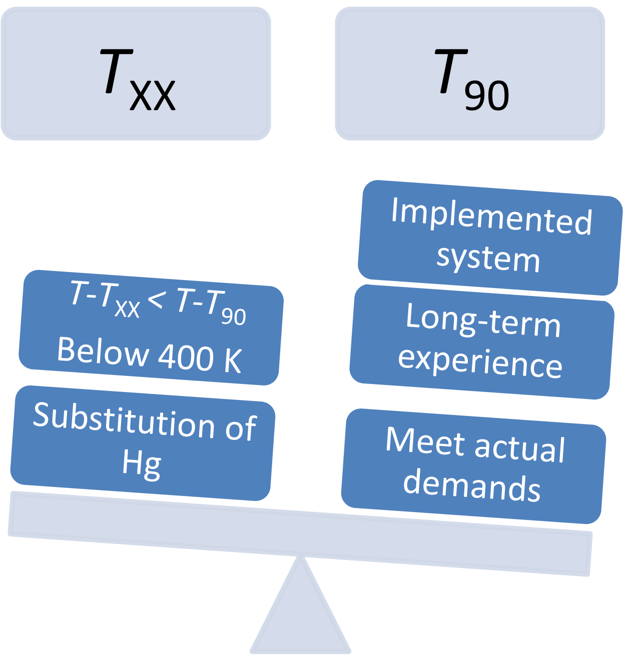

$$\Delta\nu_D = [2\,kT/(mc_0^2)]^{1/2}\cdot\nu_0$$

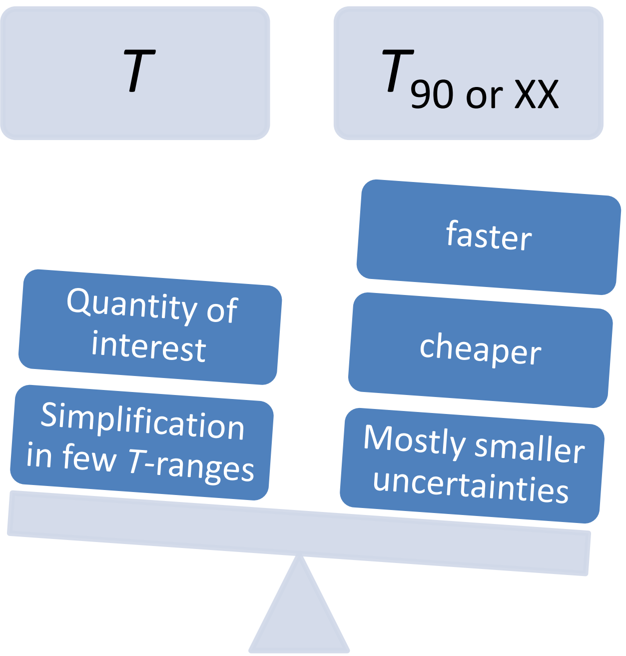
**DBT**

Candidate for an inclusion in the MeP-K, but still open questions:

- Temperature range of applicability
- Mathematical descriptions of the profile
- …

# New ITS and/or transition to direct *T* realisation




## Mid-term perspective:

Criteria for a new ITS:

- $T\text{-}T_{90}$ measurements with small uncertainties in the complete range of contact thermometry
- New demands not fulfilled by ITS-90
- $u(T_{XX}) < u(T_{90})$
- Bann of mercury (minor problem, solvable via an amendment)
- …

## Long-term perspective:

Criteria for a transition from $T_{XX}$ to $T$:

- Reliable primary thermometers in contact thermometry for the range 400 K < $T$ < 1000 K
- Primary thermometry realisable not only by NMIs
- Uncertainties $u(T)$ comparable with $u(T_{90})$
- Primary-thermometry effort comparable to ITS calibration
- Primary-thermometry price comparably to ITS calibration
- ….

# Summary

Redefinition has no immediate impact on the status of ITS-90

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

→ New consensus values between 4K and 303K

→ New data $T$ data above 400 K is urgently needed!

Direct realisation by primary thermometry without reference to TPW

→ In contact thermometry benefits in the near future only below ≈ 2 K and possibly below 20K

Innovation is possible with further development of primary thermometry

The urge for innovation ($T_{XX}$ or direct realisation of $T$) must include a view for the incredibly quality of the existing ITS and the outstanding scientific work behind it and its forerunners