DRTBT2024

MÉTROLOGIE DES BASSES TEMPÉRATURES

Laurent Pitre

LNE–Cnam

Cnam

University established in 1794
Staff: 2,500; Students: 70,000
Store the metric standard since 1848

LNE

Providing calibration services since 1901
Staff: 1,500

Note that Bureau International des Poids et Mesures is a metrology international organism but not link to Cnam or LNE

LNE–Cnam

Thermometry
One part of
Photometry and
Radiometry

Cnam (93 Saint-Denis)

LNE (78 Trappes)

The other part of
Photometry and
Radiometry

LNE (75 Paris)

Length

Thermometry

We never measure the temperature directly; we measure an effect that depends on the temperature.

During this talk, I will present measurements on pressure, capacitance, resistance, magnetic susceptibility, acoustic resonance, microwave resonance, phase transition of pure substances, superconductor transition,noise and liquid dilation.

The very first thermometer

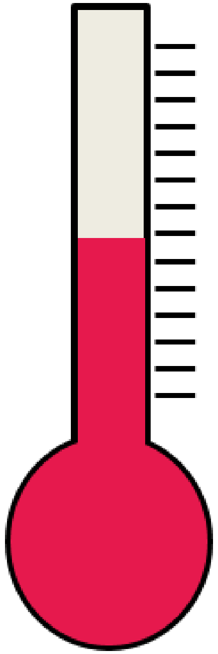
The first scale made by Torricelli, Ferdinand II de Medici and Galileo in 1650

from https://www.museogalileo.it//en

The very first thermometer

In 1650 -50 years before Fahrenheit and 100 years before Celsius

- A thermometer repeatable after 370 years!!!
- More than 300 thermometers were produced.
- Exchangeable thermometer.
- Use of freezing point of water as temperature reference in 1650 !!!!



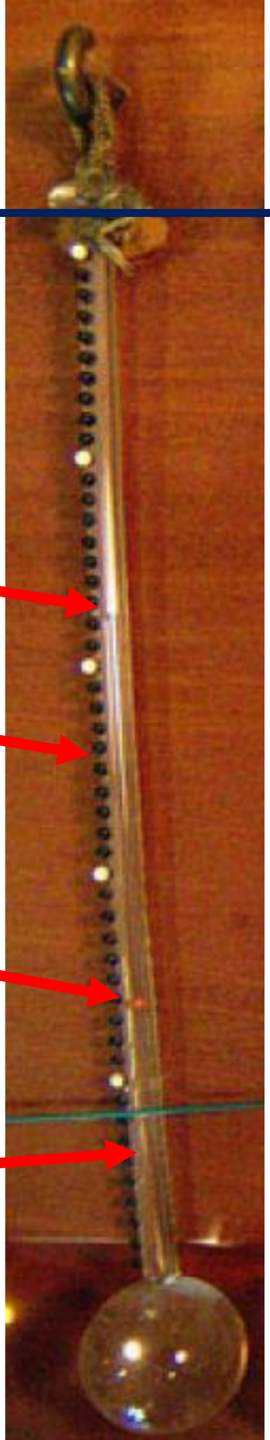
Camuffo D. and Bertolin C. “The earliest temperature observations in the world: the Medici Network (1654–1670)” Climatic Change (2012)

Alcohol 80 %

Spacement for the graduation 1,8 mm

freezing point of water!!! Used to seal thermometer

Internal diameter from 1,1 to 1,2 mm.

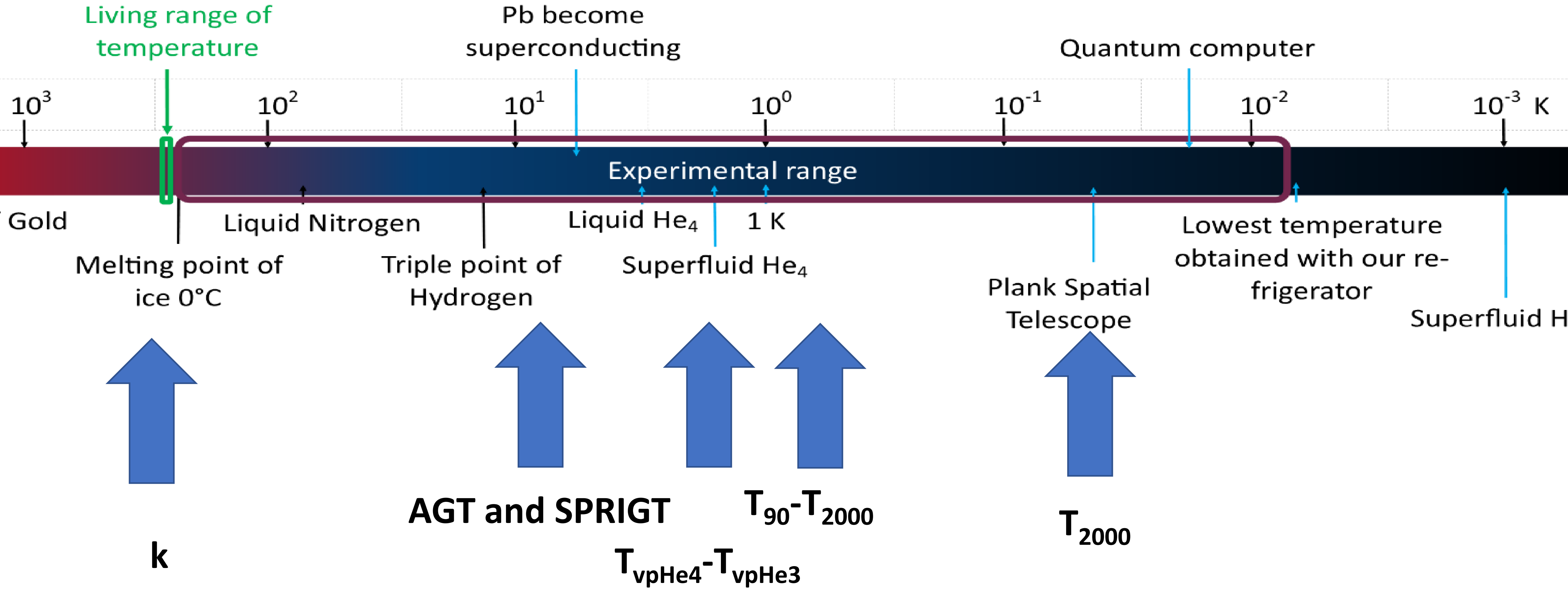


A good thermometer

- The relationship between what we measure and the temperature must be established by the laws of physics.
- The thermometer should be able to be used across a very wide range of temperatures.
- It should be precise and stable over time.
- It should be robust, easy to use, affordable and with very high resolution.
- It should be able to be used in environments inaccessible to humans: chemical, magnetic, nuclear, vacuum, etc

This thermometer don‘t exist

The Low temperature at LNE-Cnam



Living range of temperature

Pb become superconducting

Quantum computer

10^3

10^2

10^1

10^0

10^{-1}

10^{-2}

10^{-3} K

Experimental range

Gold

Liquid Nitrogen

Liquid He_4

1 K

Lowest temperature obtained with our re-frigerator

Melting point of ice 0°C

Triple point of Hydrogen

Superfluid He_4

Plank Spatial Telescope

Superfluid H

AGT and SPRIGT

T_{90}-T_{2000}

T_{2000}

k

T_{vpHe4}-T_{vpHe3}

Outline

- International System of Units
- Boltzmann constant determination
- Thermometry below 1K
    - PLTS2000
    - SDR1000
    - MFFT
    - Resitance measurement
- ITS90
    - 0.65K-5K vapor pressure of He_3 and He_4
    - Primary thermometer, SPRIGT and AGT
    - 24.5K-273K Fix point and CSPRT25
    - RdFe
- Conclusion and the search of metrological sensor

Why an International System of Units ?

In the past different country = different units
This harmed commerce and the spread of idea

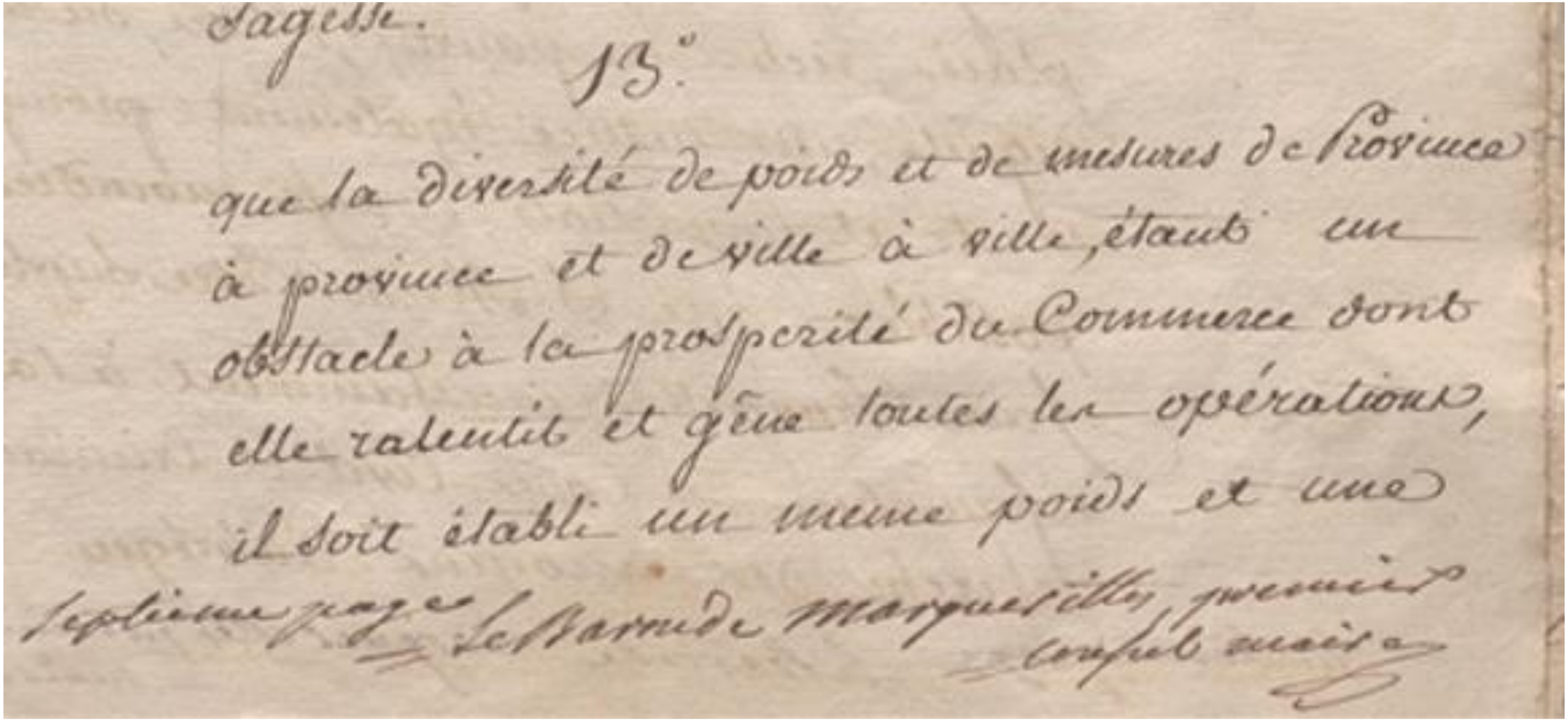
Over time many systems of units were used:

Sumerian Nippur cubit 4500 years old

Egypt cubit 3500 years old

China 尺 (chi) 3000 years old
France Lieue de Paris 1700
English British Imperial Unit 1825
France *mètre* and the metric system 1790

France 1789: register of grievances



sagesse.

13°.

que la diversité de poids et de mesures de Province
à province et de ville à ville, étant un
obstacle à la prospérité du Commerce dont
elle ralentit et gêne toutes les opérations,
il soit établi un même poids et une

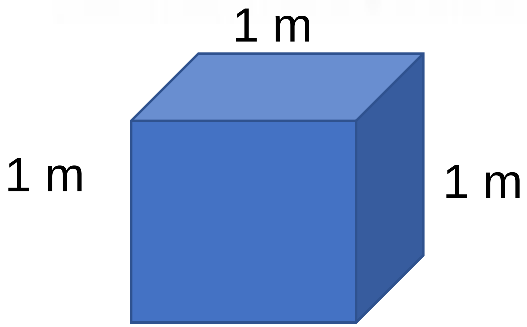
septième page Le Baron de Marguerittes premier
consul maire

Extrait du cahier de doléances de Nîmes (1789). Arch. dép. du Gard : C 1196.

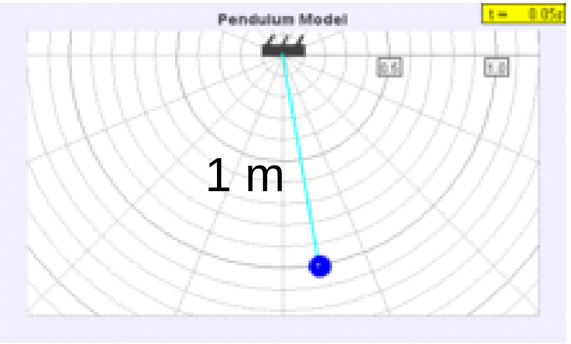
The historical metric system (1793)

Decimal unit

Divide by 10 000 000 any ¼ of meridian of Earth
and you have 1 metre



A cube of 1 m ×1 m × 1 m filled with water is 1000 kg



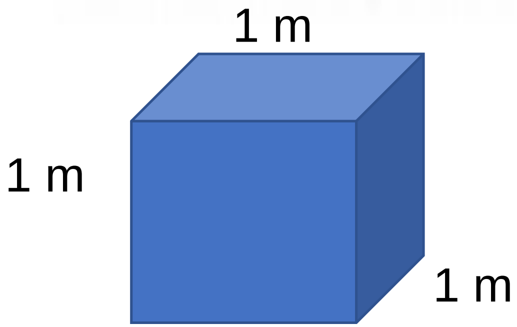
With a metre long pendulum you get 2 second

Can be realized anytime, anywhere

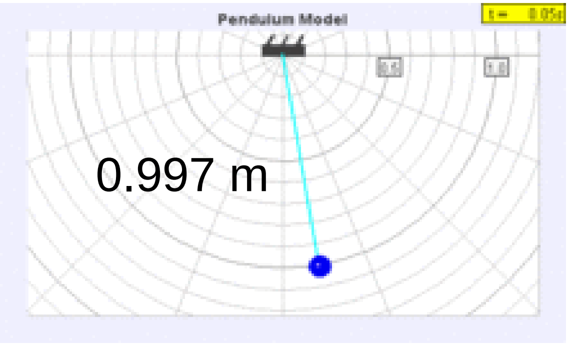
The historical metric system (1793)

Concept not easy to realize, not precise enough

7 years for two surveyors to measure 1000 km along a meridian and get 1 metre



Depending of the temperature of the water and its quality



Gravity is not constant on Earth. To get 2 s the pendulum length is actually 99.7 cm

Artefact is more stable and easy to use

Units defined by artefacts before 2019

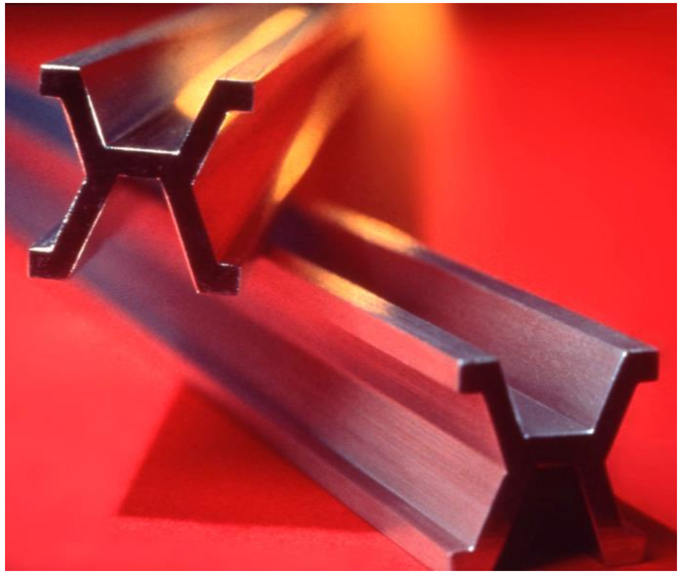
Mass

Credit: NIST

Kilogram

Platinum-iridium kilogram

Length

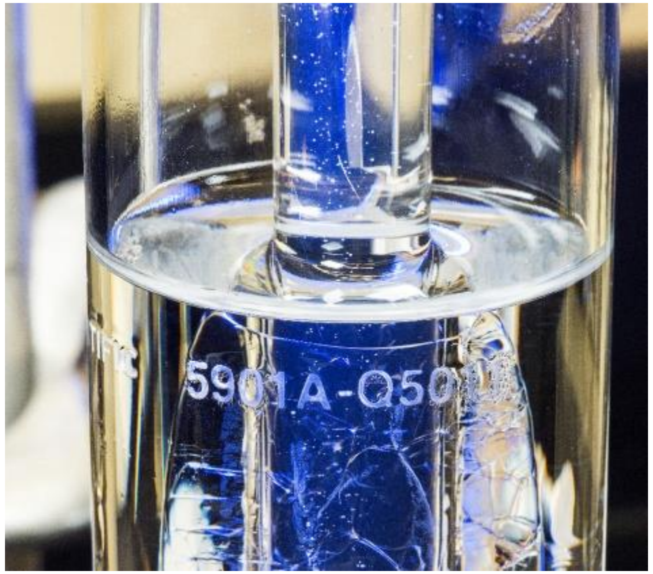


Credit: NIST

Meter

Platinum-iridium meter bar

Thermodynamic Temperature



Credit: NIST

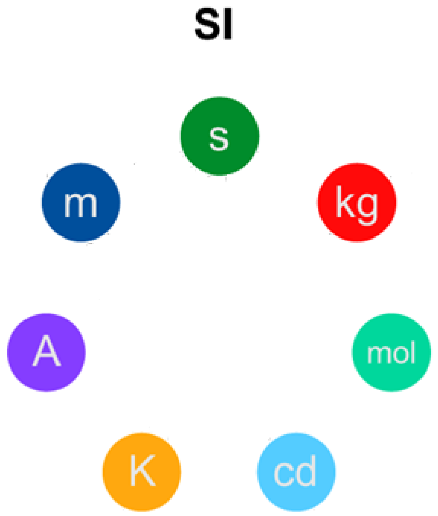
Kelvin

Triple-point of water cell

Artefacts are convenient to use and standardize but not stable for long term

The historical metric system (1793)

- 1799 metric system adopted by law of the french republic
- 1800-1810 Napoleon impose the metric system in all Europe except UK
- 1860 Maxwell and Lord Kelvin add electric units and make it coherent (CGS)
- 1870 Metre convention (17 countries) only for m and kg
- 1971 The *Système International* (SI) with 7 base units



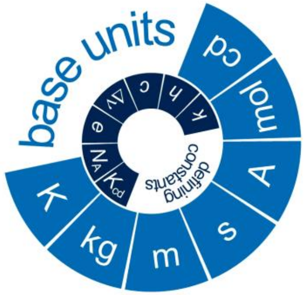
BUT all those units were linked to artefacts, and

- the artefacts are not stable over a long time period (100 years)
- the artefacts reduce the possibility of innovation

The new SI opens the way to new possibilities

Units redefined by universal constants

The 7 commandements



- **Time：** the caesium hyperfine frequency, $\Delta\nu_{Cs}$=9 192 631 770 Hz
- **Length：** the speed of light in vacuum, c=299 792 458 m/s
- **Mass:** the Planck constant, h=6.626 070 15×10^{-34} Js
- **Electric Current:** the elementary charge, e=1.602 176 634×10^{-19} C
- **Thermodynamic Temperature:** the Boltzmann constant, k=1.380 649×10^{-23} J/K
- **Amount of Substance:** the Avogadro constant, N_A=6.022 140 76×10^{23} mol^{-1}
- **Luminous Intensity:** the luminous efficacy of a defined visible radiation, K_{cd}= 683 lm/W

Consequence in temperature: the triple point of water loses its central role in temperature measurements

Boltzmann constant determination

LNE 2017 **Helium**

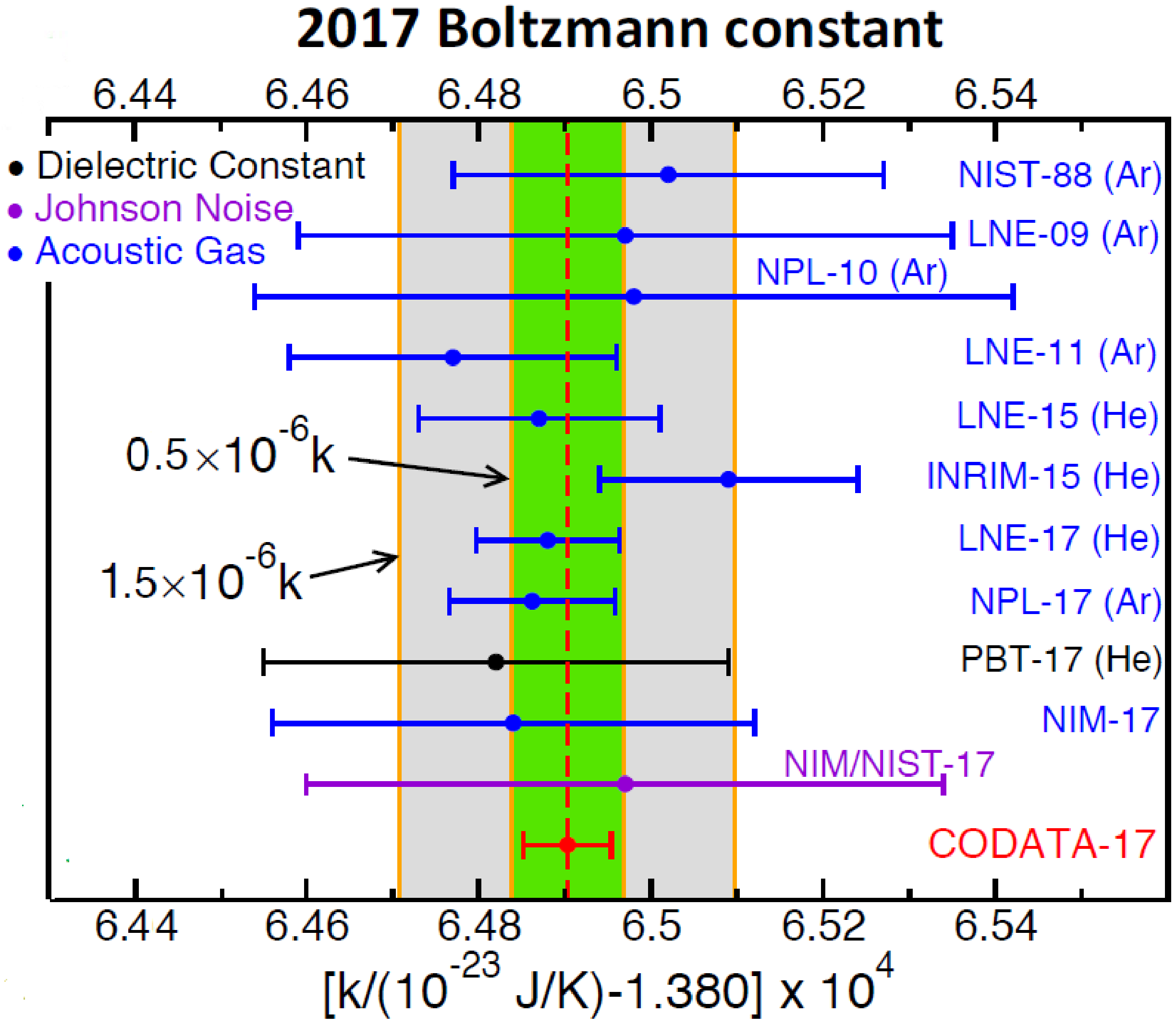
k=1.380 648 37(81) × 10^{-23}J/K

relative uncertainty

$u(k) / k = 0.60 \times 10^{-6}$

$k = 1.380649 \bullet 10^{-23}\ J \bullet K^{-1}$

Depuis 2019



Peter J Mohr *et al. Metrologia* 55 (2018) 125;
Laurent Pitre *et al. Metrologia* 54 (2017) 856

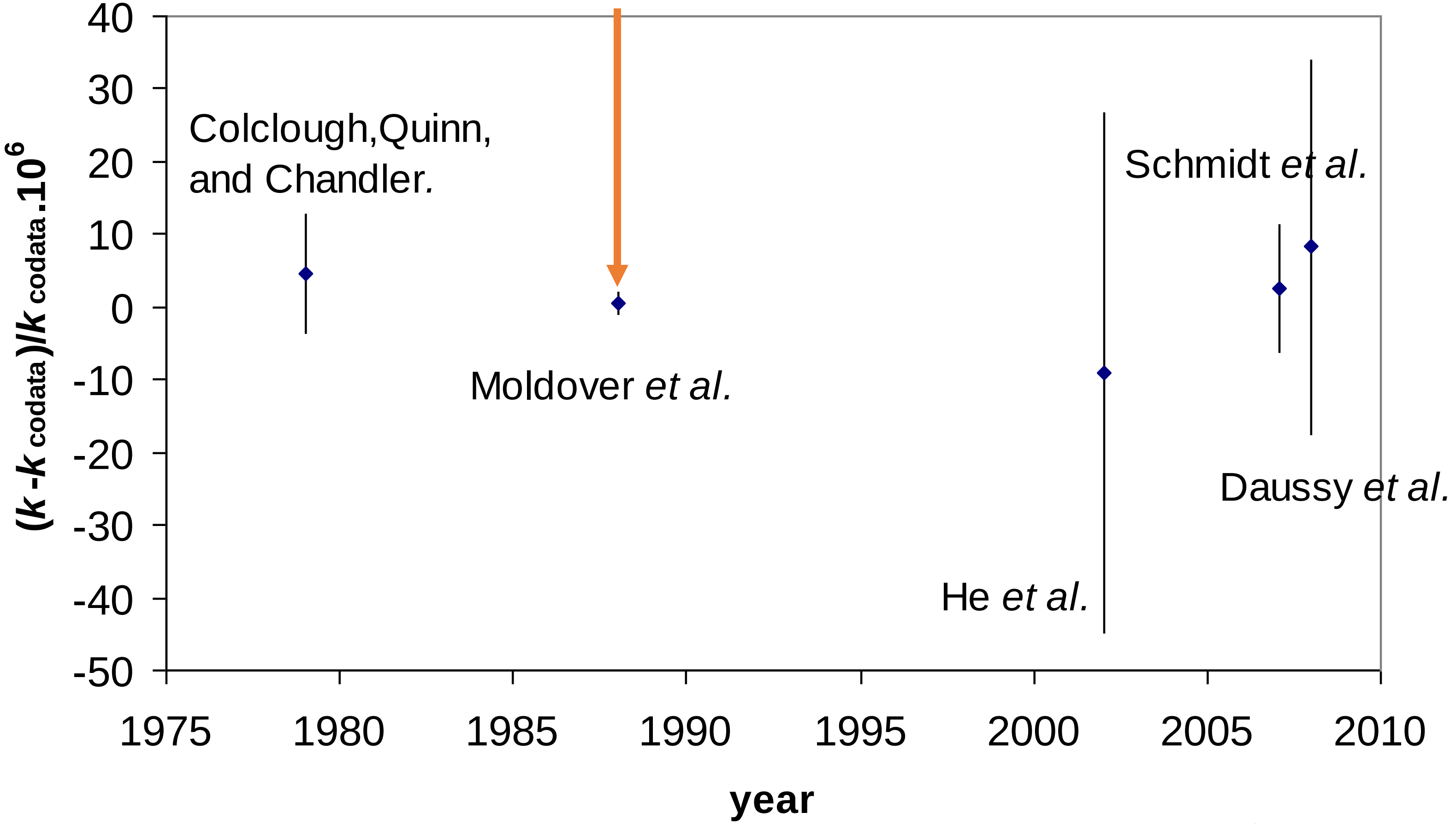
A Team

L.Pitre, F. Sparasci, L. Risegari, C. Guianvarc’h, C. Martin, M. E. Himbert, M. Plimmer, A. Allard, B. Marty, P. G. Albo, B. Gao, M. R. Moldover and J. B. Mehl

Boltzmann constant determination

The situation in 2008

Uncertainty is 7 times lower compared to the other results



if k=1, body temperature= 4.28222093840000000224 $*10^{-21}$K

If the numerical value of k is correct, no experiment should detect any change due to the redefinition of the unit

Acoustic Determination of the Boltzmann Constant

Principle of the experiment

Boltzmann constant

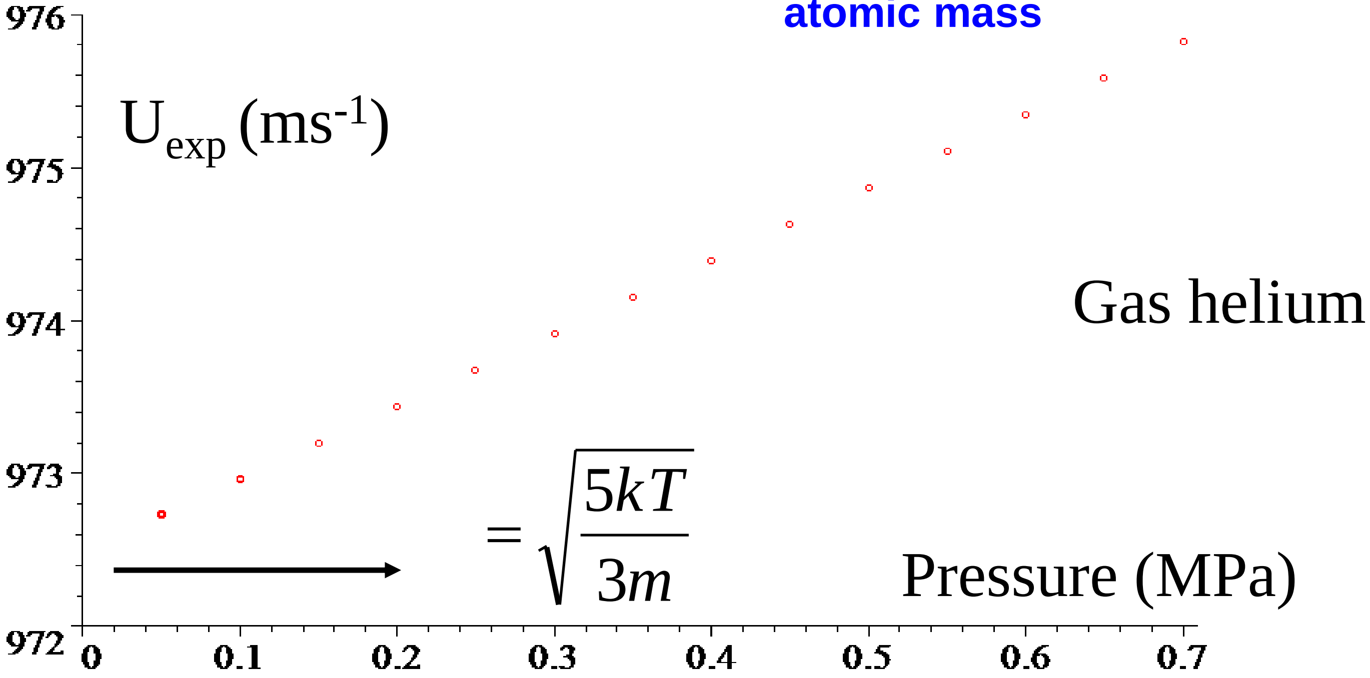
For real gas:

$$U_A^2 = \gamma_{pg} \frac{kT}{m} \left(1 + \beta_a(T)\, p + \ldots\right)$$

specific heats ratio

acoustic virial coefficient

atomic mass



Standing wave in a spherical cavity

Speed of sound

$$U_A = \frac{Radius}{Z_{nl}^{A}} 2\pi < f_{nl}^{A} + \Delta f_{nl}^{A} >$$

Eigenvalue

Resonance frequency

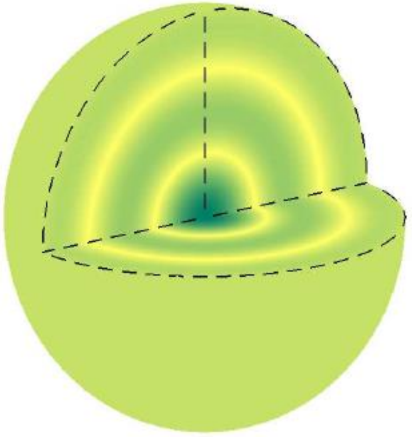
Boundary layer tube and microphone effect

Eigenvalue **Speed of light**

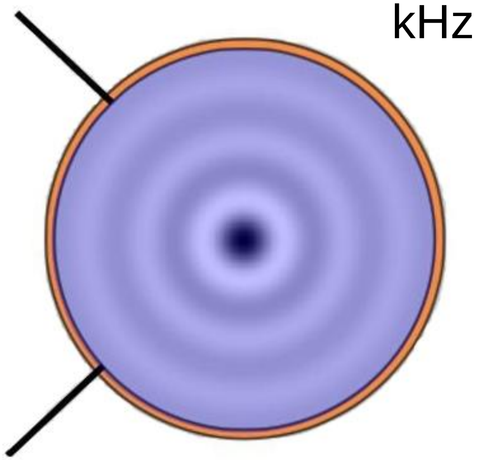
$$Radius = \frac{Z_{nl}^{EM} c}{2\pi < f_{nl}^{EM} + \Delta f_{nl}^{EM} >}$$

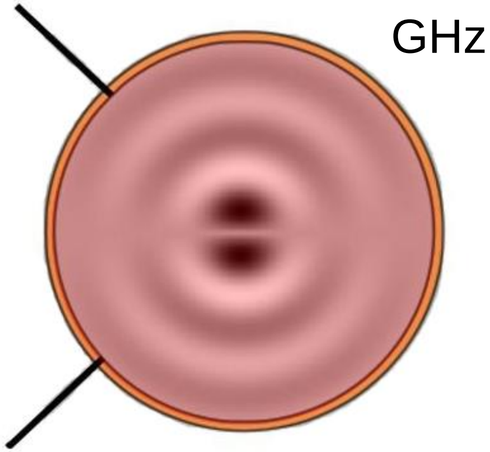
Resonance frequency

Skin depth Holes and Antennas effect



$l = 0, n = 3$





k determination with speed of sound measurement

Principle of the experiment

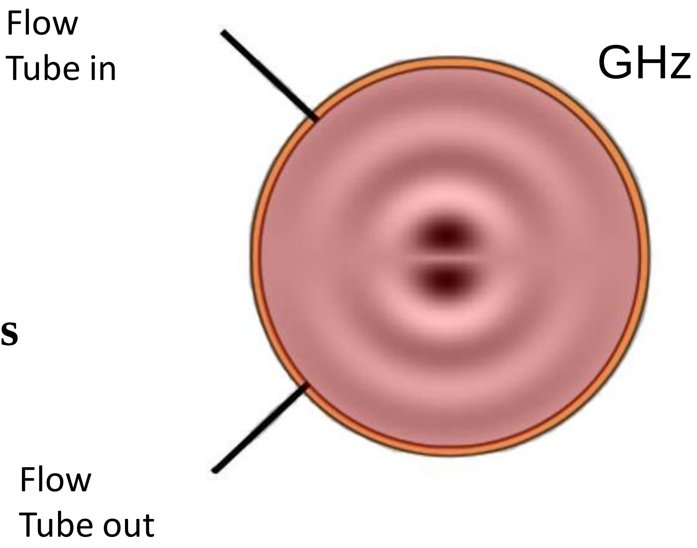
Simultaneous acoustic (u) and microwave (c) resonances in a cavity

Acoustic resonances measurement

⇒ Boltzmann constant but linked to a volume

Microwave resonances measurement

⇒ Volume measurement



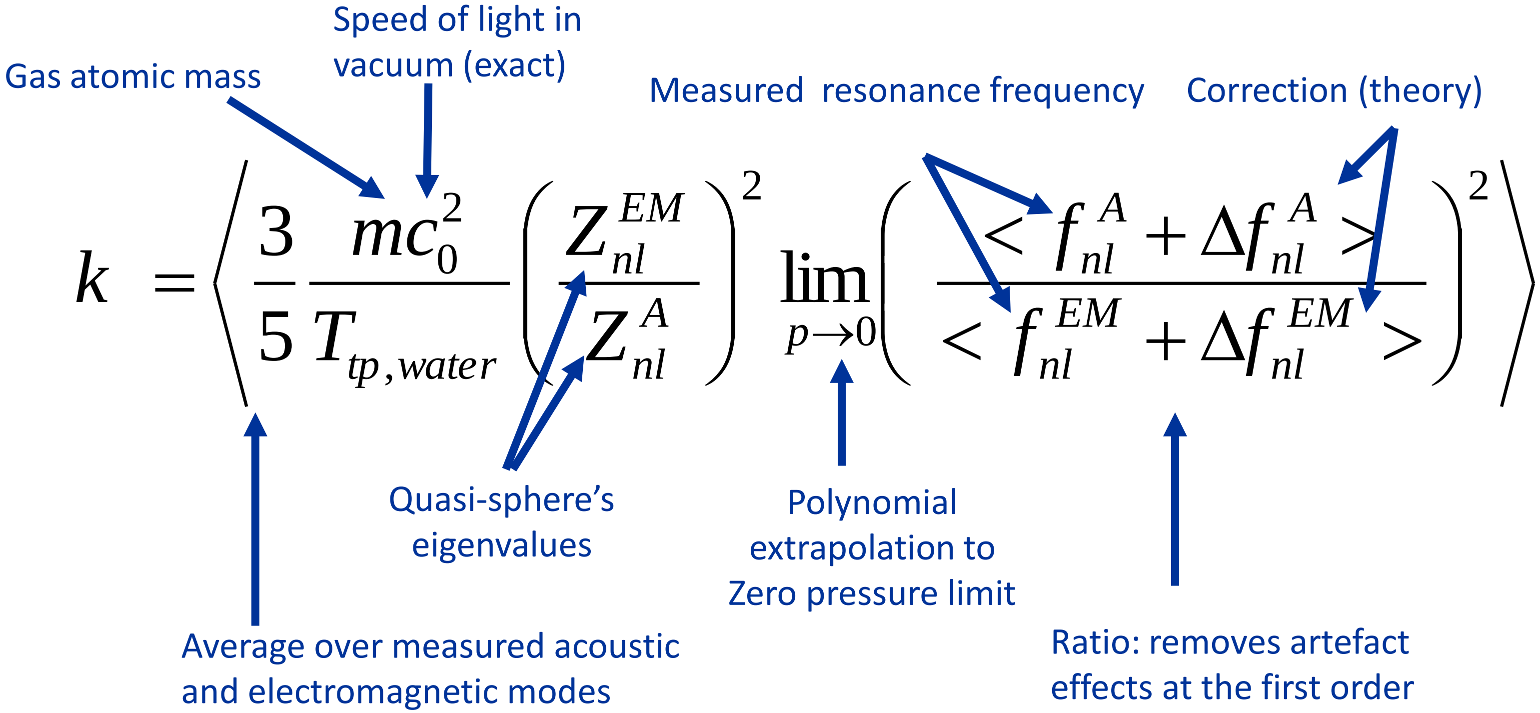
Gas flow minimizes the effects of impurities

Non-quite spherical simplify the microwave measurements

Acoustic Determination of the Boltzmann Constant

Relationship between the Boltzmann constant and acoustic/microwave measurements

With $U_A^2 = \gamma_{pg}\frac{kT}{m}\left(1+\beta_a(T)p+\ldots\right)$ $U_A = \frac{Radius}{Z_{nl}^A}2\pi < f_{nl}^A + \Delta f_{nl}^A >$ $Radius = \frac{Z_{nl}^{EM}c}{2\pi < f_{nl}^{EM} + \Delta f_{nl}^{EM} >}$



Gas atomic mass

Speed of light in vacuum (exact)

Measured resonance frequency

Correction (theory)

$$k = \left\langle \frac{3}{5}\frac{mc_0^2}{T_{tp,water}}\left(\frac{Z_{nl}^{EM}}{Z_{nl}^{A}}\right)^2 \lim_{p\to 0}\left(\frac{< f_{nl}^{A} + \Delta f_{nl}^{A} >}{< f_{nl}^{EM} + \Delta f_{nl}^{EM} >}\right)^2 \right\rangle$$

Quasi-sphere's eigenvalues

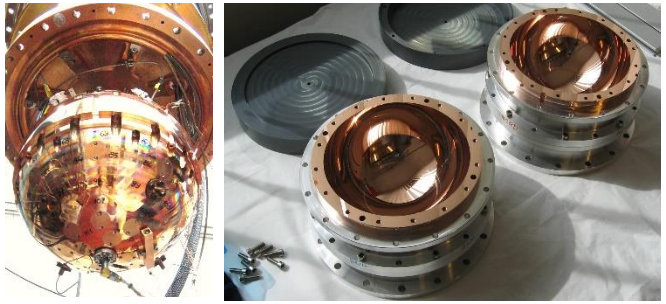
Polynomial extrapolation to Zero pressure limit

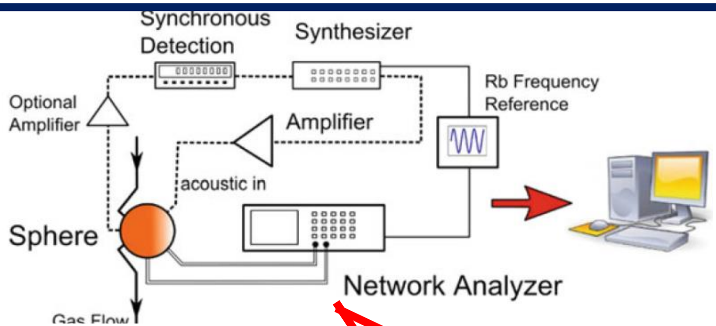
Average over measured acoustic and electromagnetic modes

Ratio: removes artefact effects at the first order

k determination with speed of sound measurement

A 3.1 liter sphere

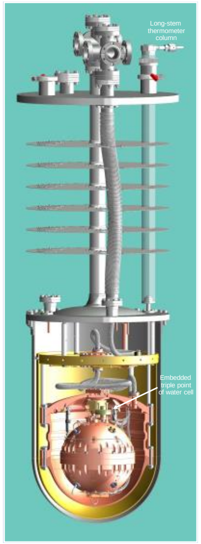




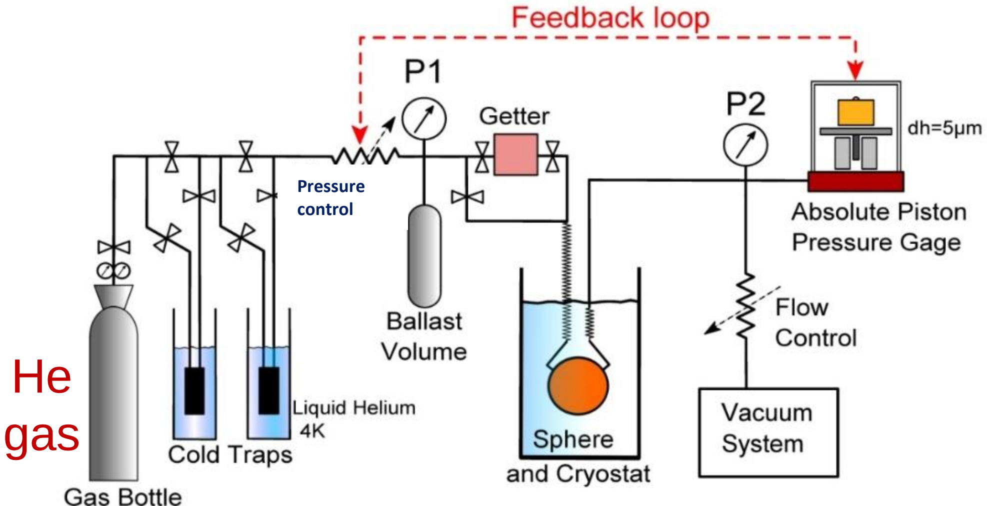
$$k = \left\langle \frac{3}{5}\frac{mc_0^2}{T_{tp,water}}\left(\frac{Z_{nl}^{EM}}{Z_{nl}^{A}}\right)^2 \lim_{p\to 0}\left(\frac{< f_{nl}^{A} + \Delta f_{nl}^{A} >}{< f_{nl}^{EM} + \Delta f_{nl}^{EM} >}\right)^2 \right\rangle$$

20 Instruments
used at the
state of the art

Adiabatic Cryostat
(weak link to the thermal bath)

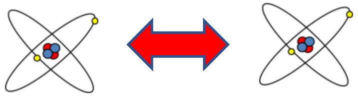


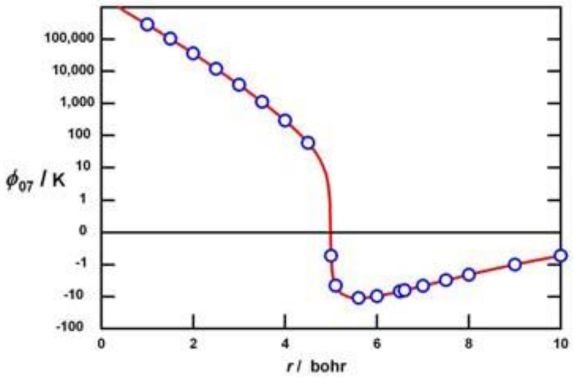
Ultra clean gas handling systems
With a piston gage as pressure measurement



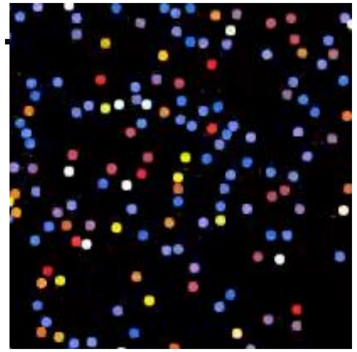
ab initio calculation for the thermo-physical propriety of Helium gas

Microscopic propriety

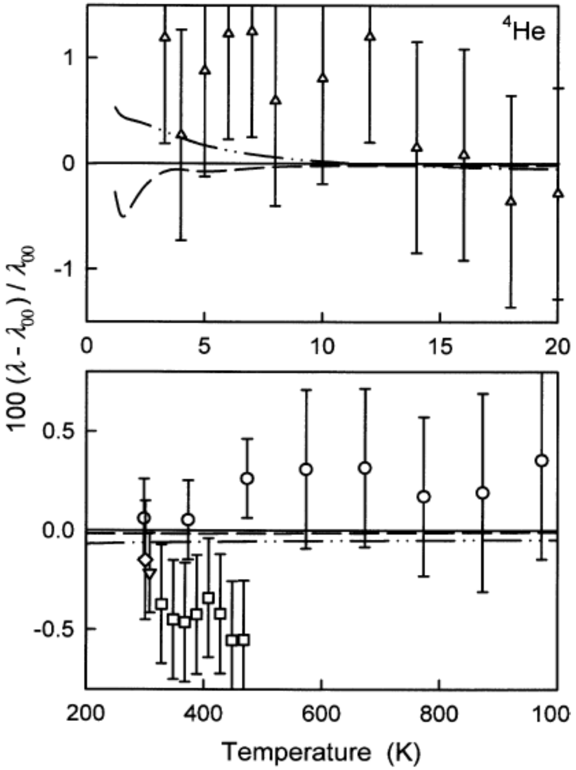




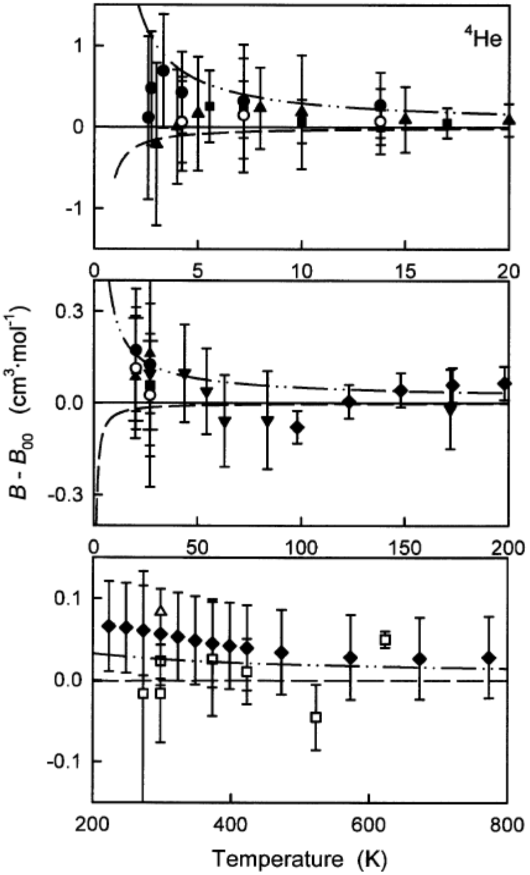
Simulation of many collisions with the helium interaction potential.



Macroscopic propriety



Conductivity of helium-4 gas

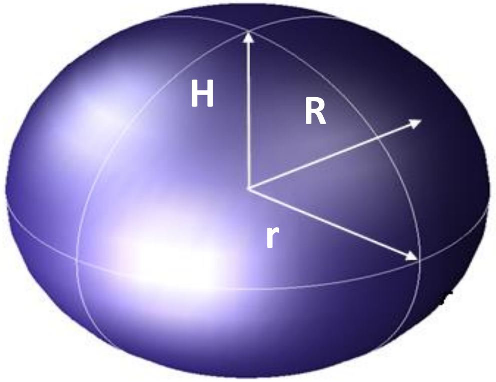


viscosity of helium-4 gas

Ab initio calculation of fluid properties for precision metrology
Giovanni Garberoglio, Christof Gaiser, Roberto M Gavioso, Allan H Harvey, Robert Hellmann, Bogumił Jeziorski, Karsten Meier, Michael R Moldover, Laurent Pitre, Krzysztof Szalewicz, Robin Underwood J. Phys. Chem. Ref. Data 52, 031502 (2023)

A Non-Quite Spherical Cavity

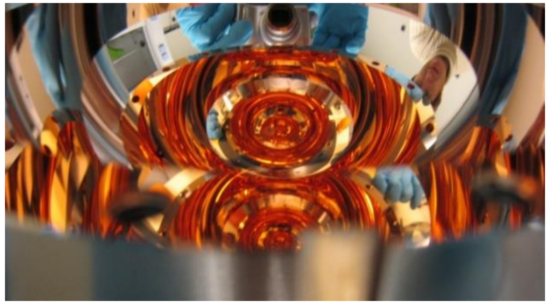
- The use of a slightly deformed spherical geometry, a triaxial ellipsoid, removes the degeneracy of resonator modes



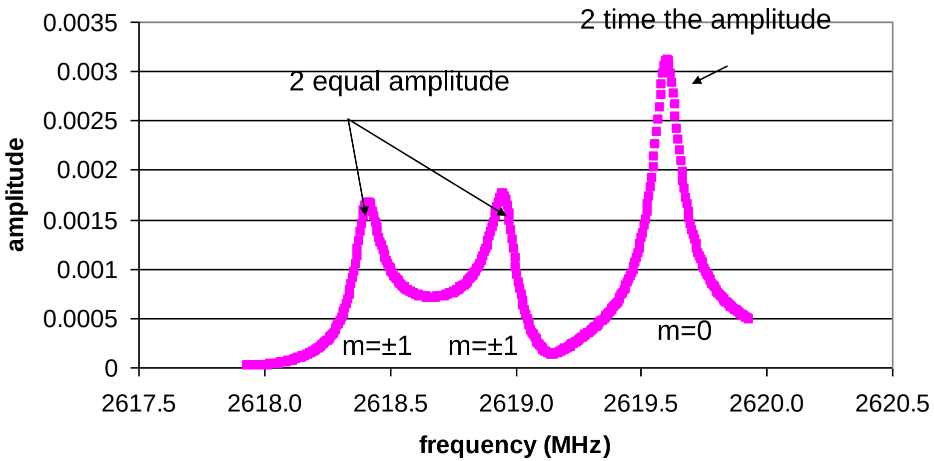
$$\frac{x^2}{(89.950)^2}+\frac{y^2}{(89.975)^2}+\frac{z^2}{(90.000)^2}=1$$

Inner shape: the difference between r, R and H is 0.025 mm:

H = 90.000 mm
R = 89.975 mm
r = 89.950 mm

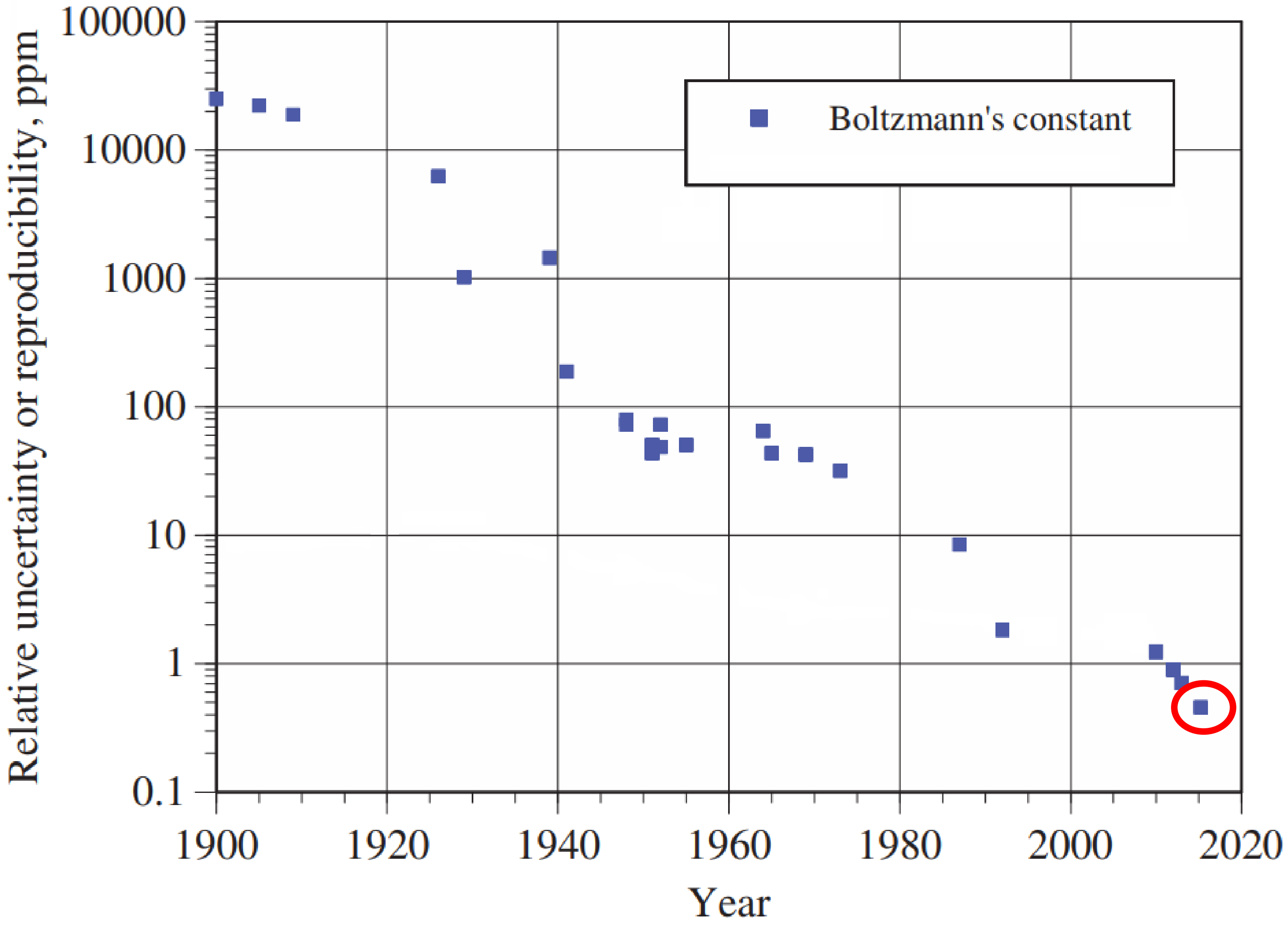


Electromagnetic measurements in very good agreement with the theoretical model



Uncertainty of the Boltzmann constant determination

Uncertainty of the Boltzmann constant determination in function of the time



LNE-Cnam

After 2017, the Boltzmann constant will no longer be measured because its value has been established by definition.

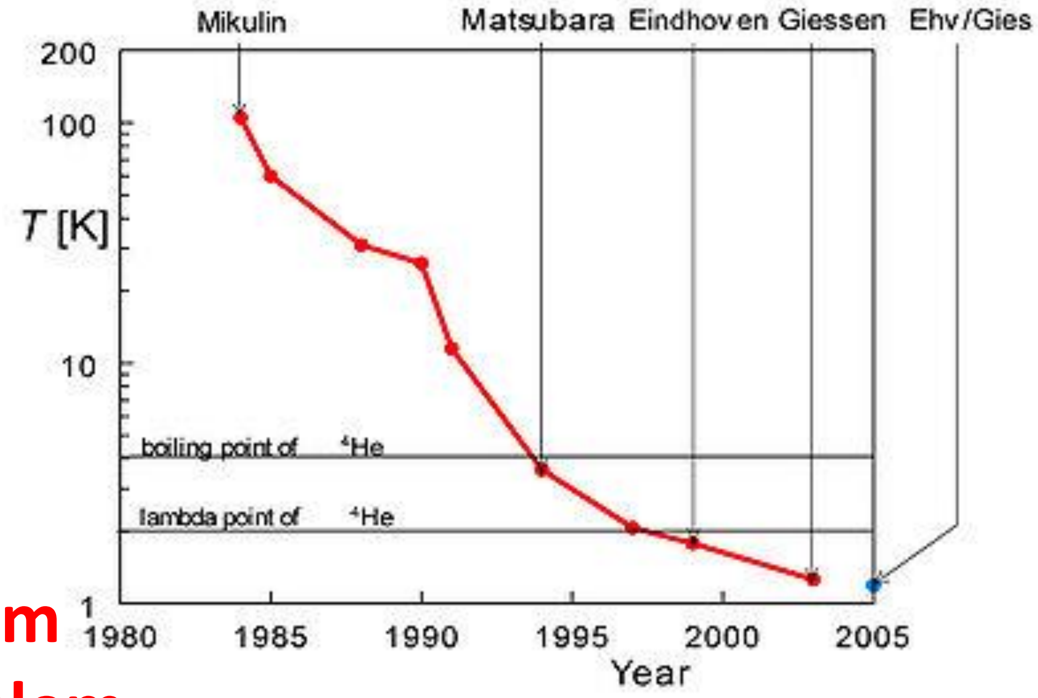
If you want more information about the changes to the SI (International System of Units)

Search on Google: 'YouTube LNE unité'
Find 7 talks about the 7 units (in French, one hour each, with hardly any equations)

Temperature measurement at low temperatures

The cryocooler revolution

4 K

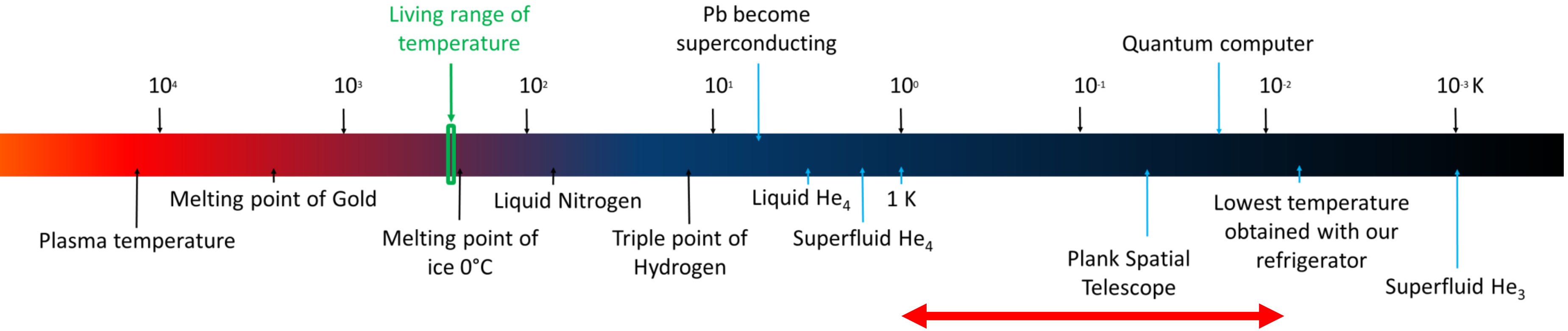


No need for liquid helium

Time is not more a problem

But also no more thermometry check at 4.2K

Thermometry below 1K at LNE–Cnam



Living range of temperature

Pb become superconducting

Quantum computer

10^4

10^3

10^2

10^1

10^0

10^{-1}

10^{-2}

10^{-3} K

Melting point of Gold

Plasma temperature

Melting point of ice 0°C

Liquid Nitrogen

Triple point of Hydrogen

Liquid He_4

1 K

Superfluid He_4

Plank Spatial Telescope

Lowest temperature obtained with our refrigerator

Superfluid He_3

- constructed a reference scale, PLTS-2000.
- calibrated this against a stable instrument, the SRD1000
- compared our PLTS2000 to a primary thermometer, the MFFT
- compared our scale to three resistively calibrated thermometers from three different companies.

PhD student Clément Tauzin

Provisional Low Temperature Scale 2000 or PLTS2000 or T_{2000}

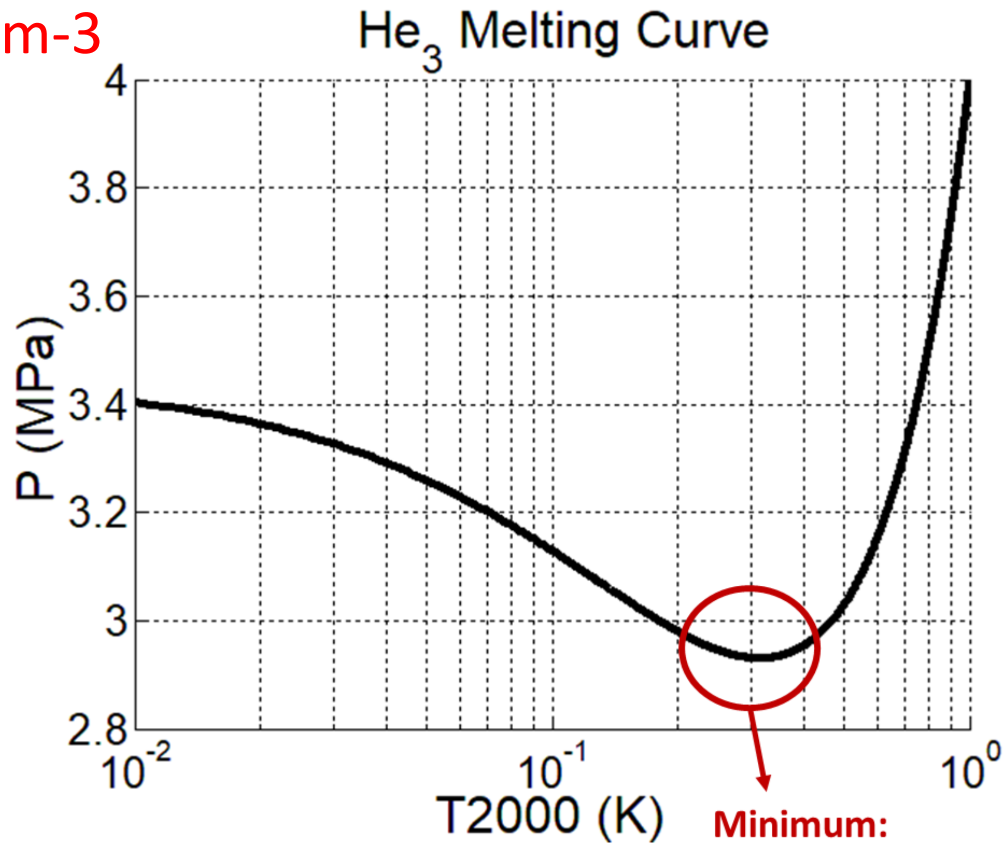
Base on the thermophysical melting curve of Helium-3

$$p_{\mathrm{m}}/\mathrm{MPa} = \sum_{i=-3}^{+9} a_i (T_{2000}/\mathrm{K})^i$$

with the following coefficients:

$$a_{-3} = -1.3855442 \cdot 10^{-12}, \qquad a_{-2} = 4.5557026 \cdot 10^{-9},$$
$$a_{-1} = -6.4430869 \cdot 10^{-6}, \qquad a_0 = 3.4467434 \cdot 10^{0},$$

$$a_1 = -4.4176438 \cdot 10^{0}, \qquad a_2 = 1.5417437 \cdot 10^{1},$$
$$a_3 = -3.5789853 \cdot 10^{1}, \qquad a_4 = 7.1499125 \cdot 10^{1},$$
$$a_5 = -1.0414379 \cdot 10^{2}, \qquad a_6 = 1.0518538 \cdot 10^{2},$$
$$a_7 = -6.9443767 \cdot 10^{1}, \qquad a_8 = 2.6833087 \cdot 10^{1},$$
$$a_9 = -4.5875709 \cdot 10^{0}.$$



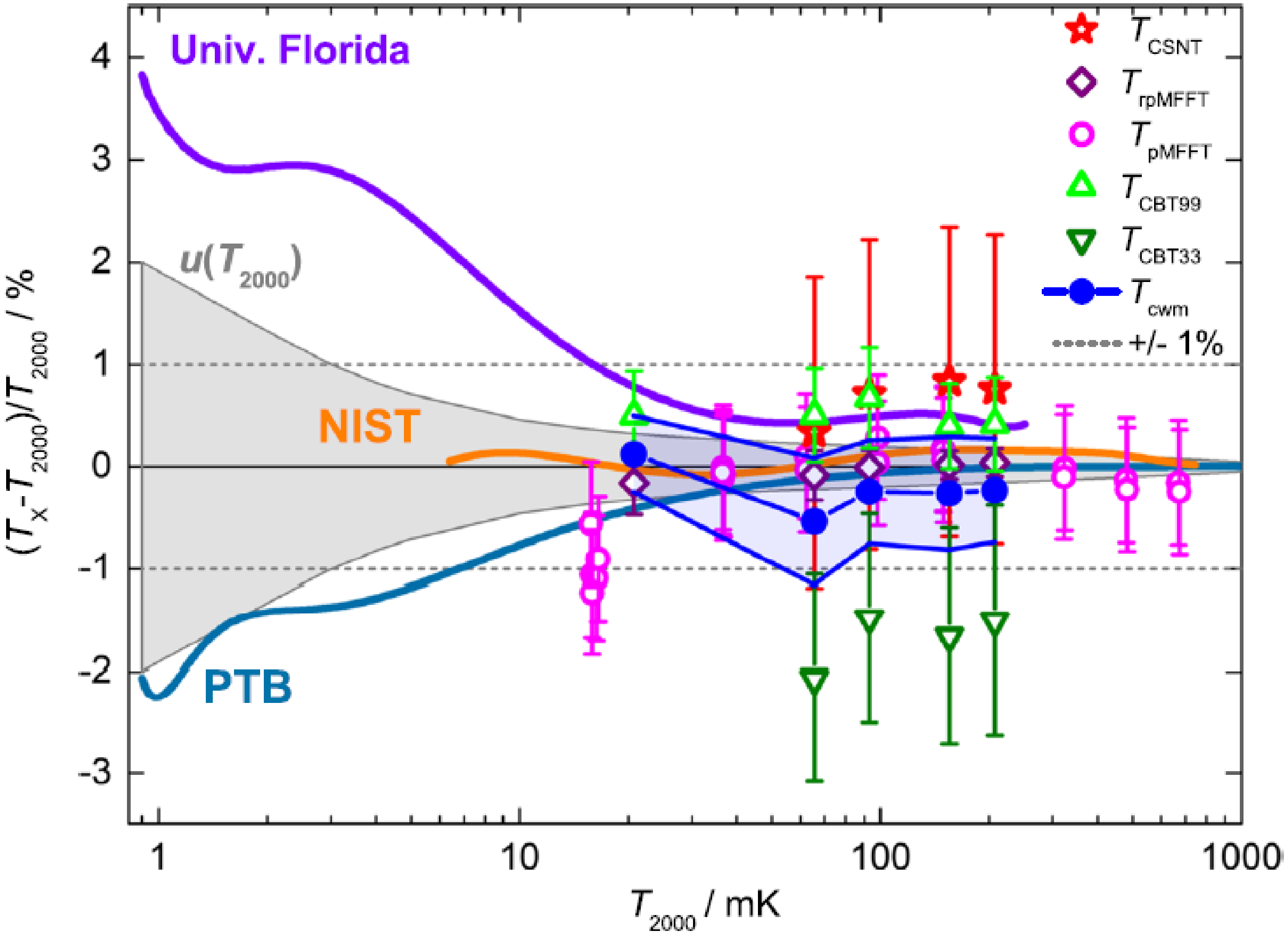
Minimum:
P=2.93113 Mpa
T_{2000}=315.25 mK

We measure P we deduceT_{2000}

The equation is valid from 0.9 mK to 1 K, covering more than three decades.

Why Provisional in PLTS2000 ?

Below 7 mK, T2000 is the average of the scales from PTB and the University of Florida. It is why the world provisional in PLTS2000



From New evaluation of T -T2000 from 0.02K to 1K by independent thermodynamic methods J. Engert *et al*. https://doi.org/10.1007/s10765-016-2123-4

Capacitance strain gauge

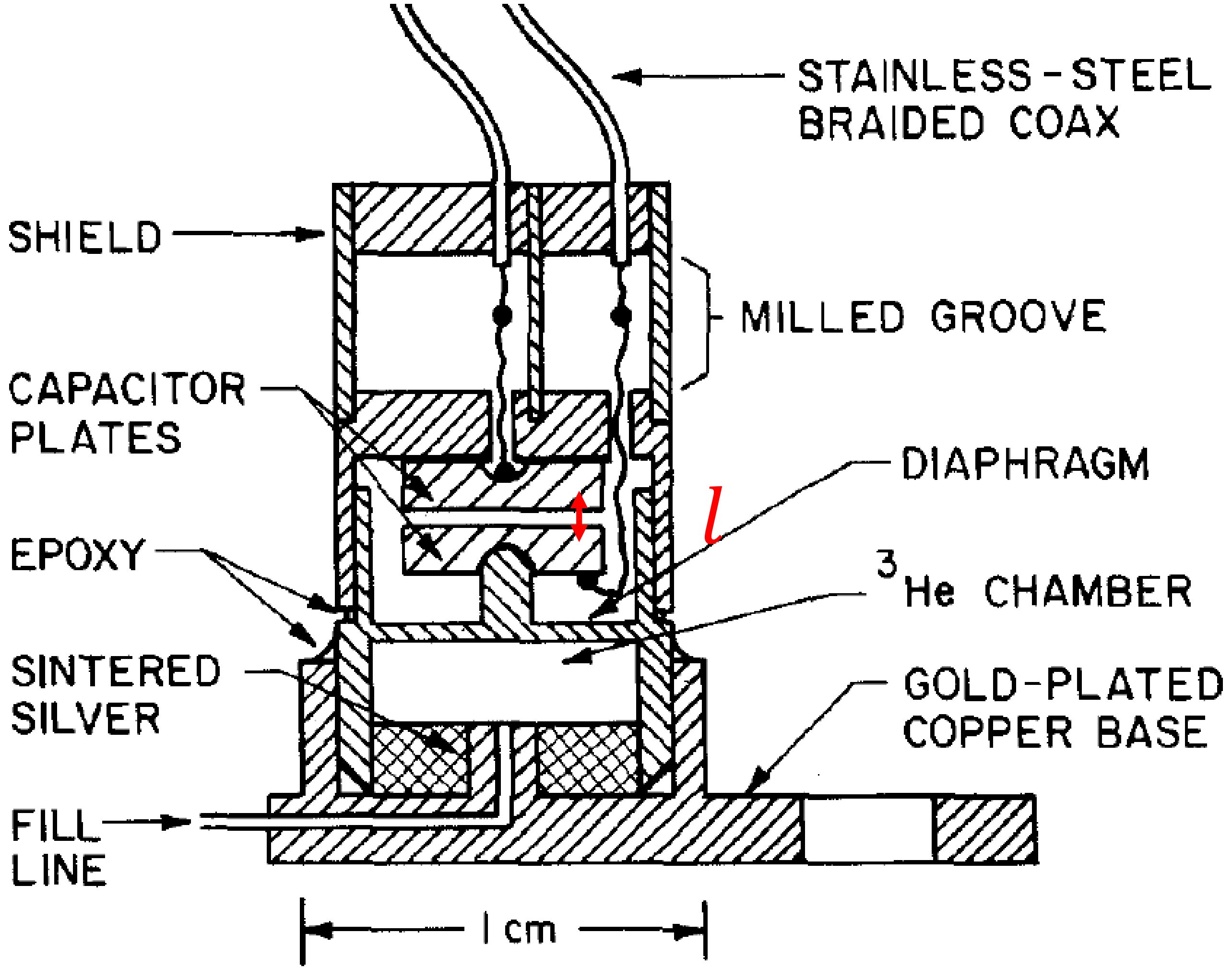
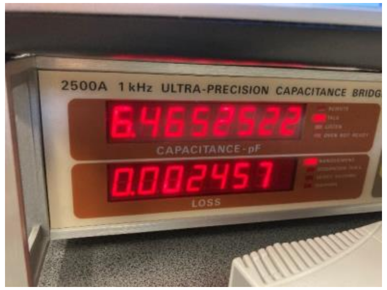


Fig. 1. Melting curve thermometer.

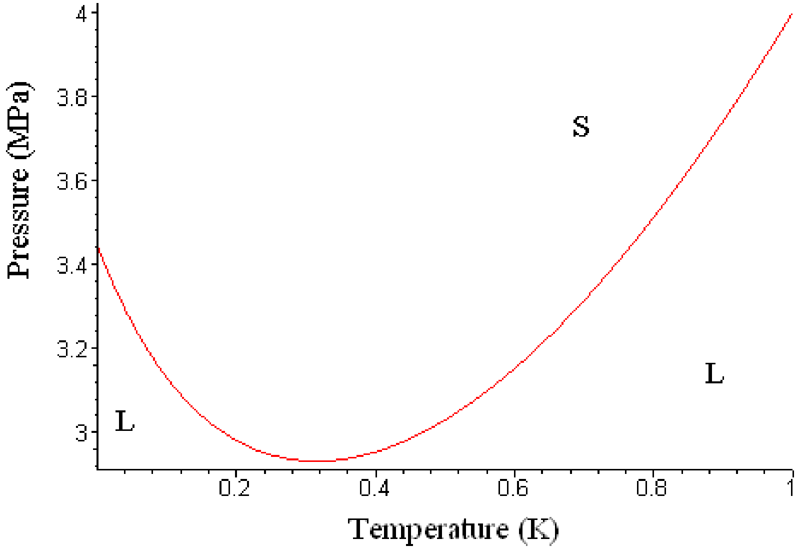
$$C = \frac{\epsilon A}{l}$$

$$\frac{dC}{C} = -\frac{dl}{l}$$



8 Digits instrument

Understand the Melting Curve oh Helium-3?

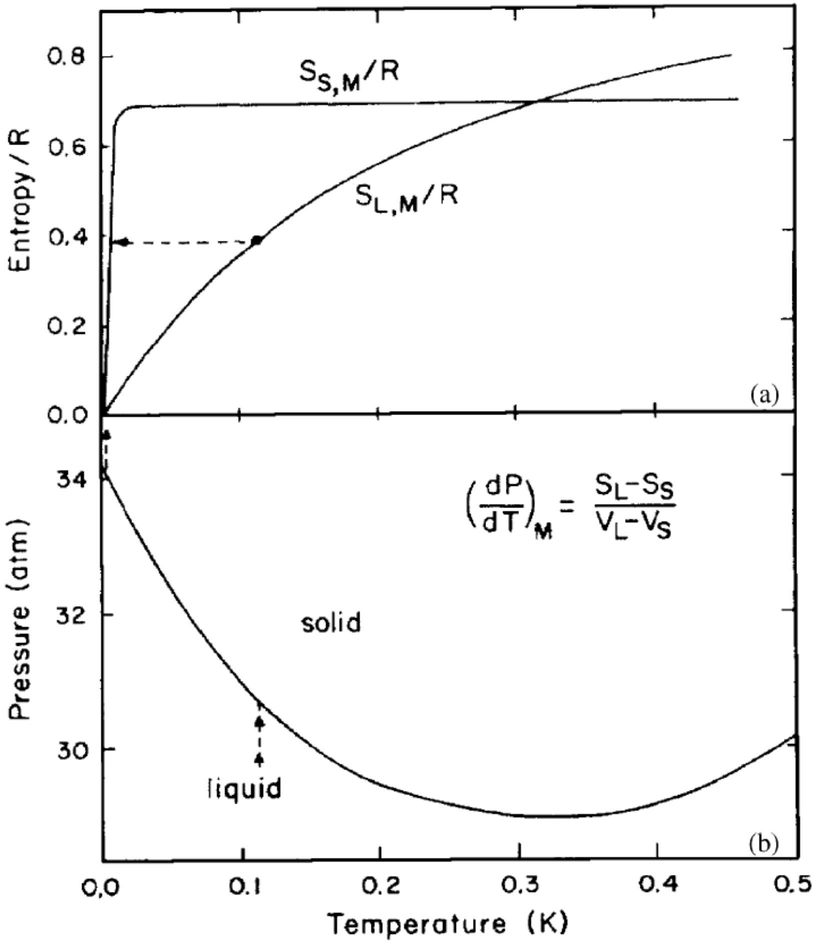


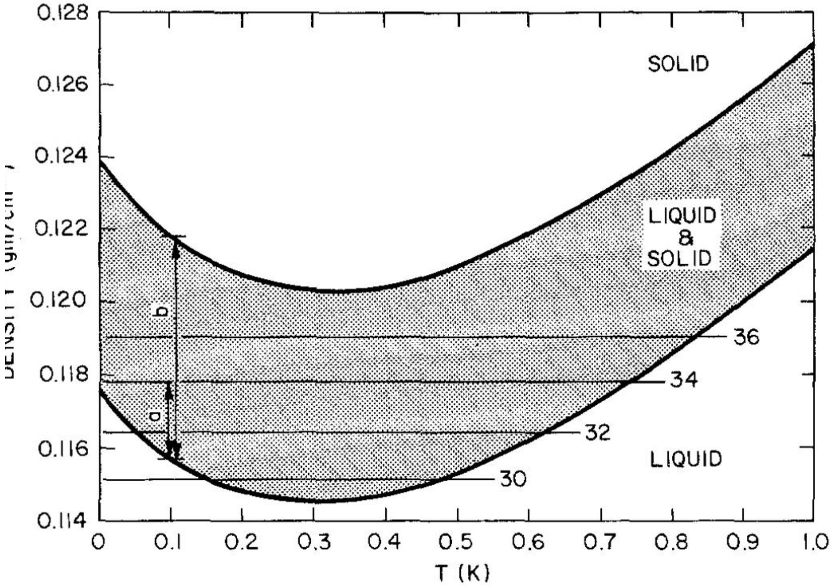
Clausius–Clapeyron equation

$$\left(\frac{\mathrm{d}P}{\mathrm{d}T}\right)_{\mathrm{m}} = \frac{S_{\mathrm{L}} - S_{\mathrm{S}}}{V_{\mathrm{L}} - V_{\mathrm{S}}}$$

VL=VS+1,314cm^3/mol

VL>VS



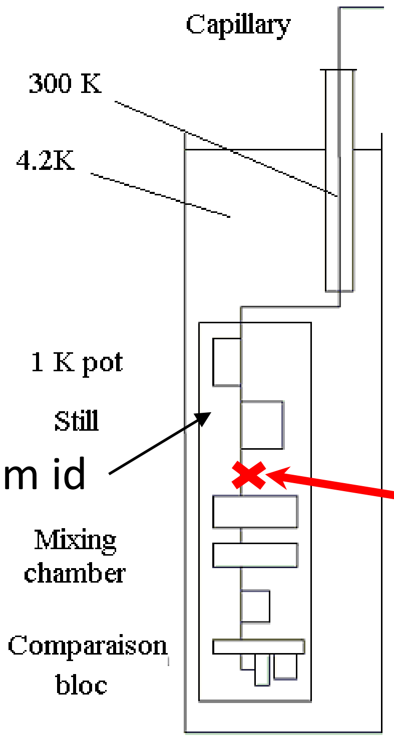


ig. 2. Density of liquid and solid ^{3}He along the melting curve plotted sing data from Refs. 3 and 4. Other details are given in the text.

From “THE 3HE MELTING CURVE AND MELTING PRESSURE THERMOMETRY » E. DWIGHT ADAMS,chapter 4; Progress in Low Temperature Physics

How to isolate the Melting Curve Thermometer?

Normal use of a DR

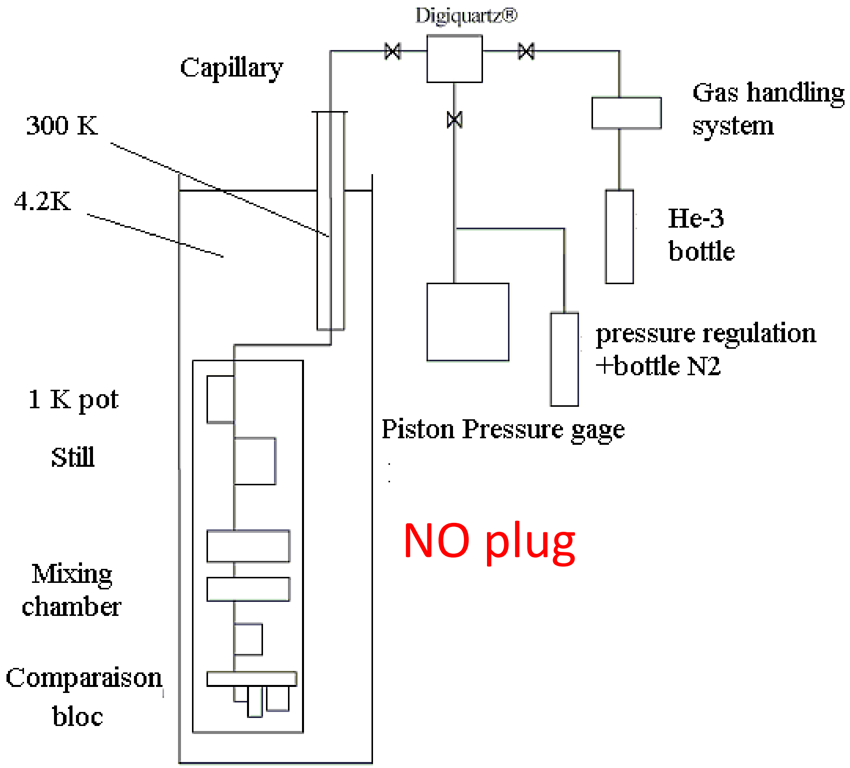


Small capillary
Less than 0,5mm id

He3 solid plug

MCT isolate and can be use as a thermometer

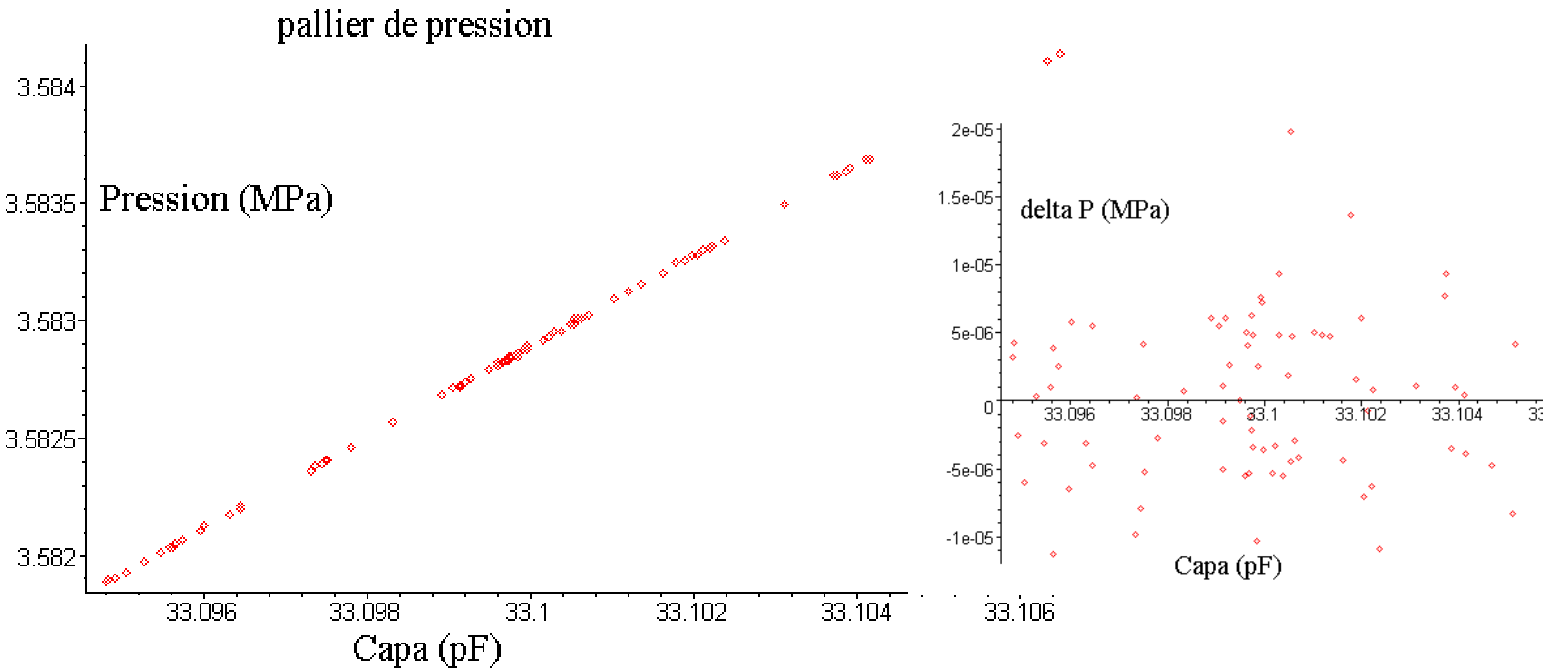
Every stage at 1.1K

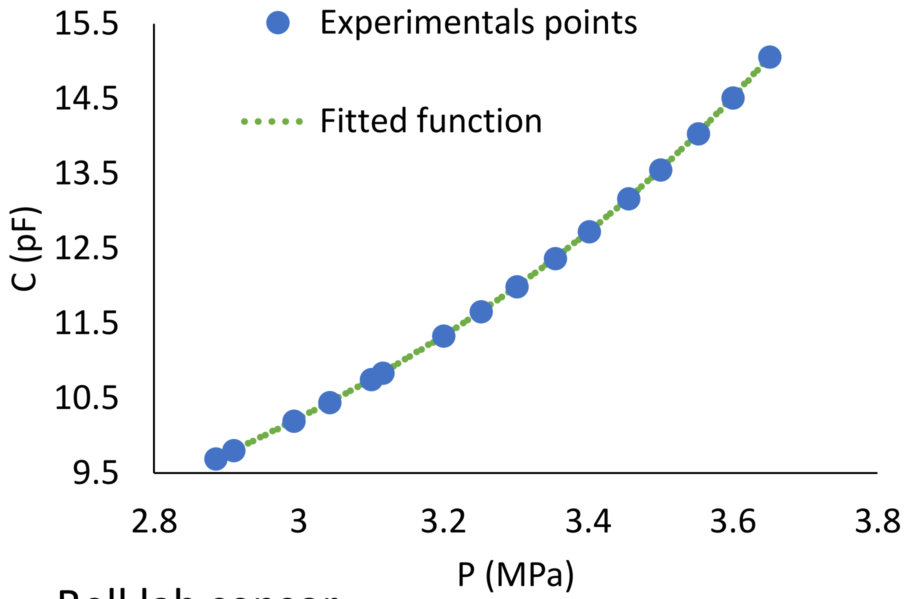


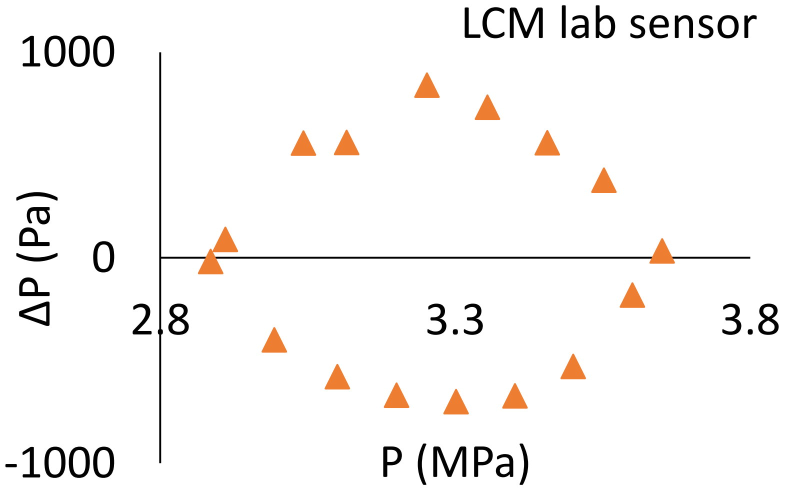
NO plug

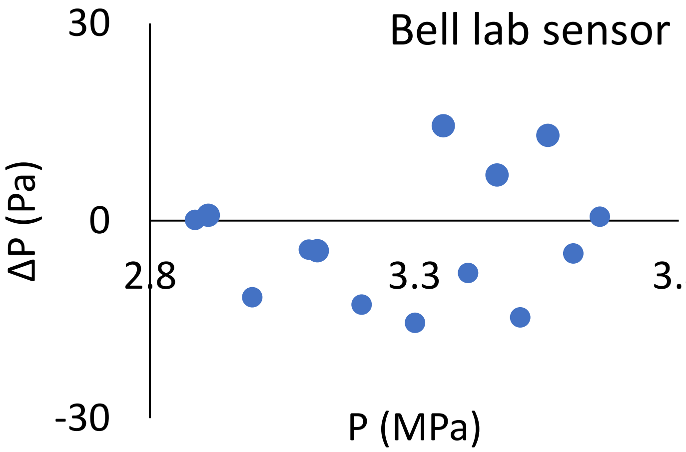
MCT can be calibrate with a secondary pressure sensor as Digitquartz

Calibration of the capacitance strain gauge



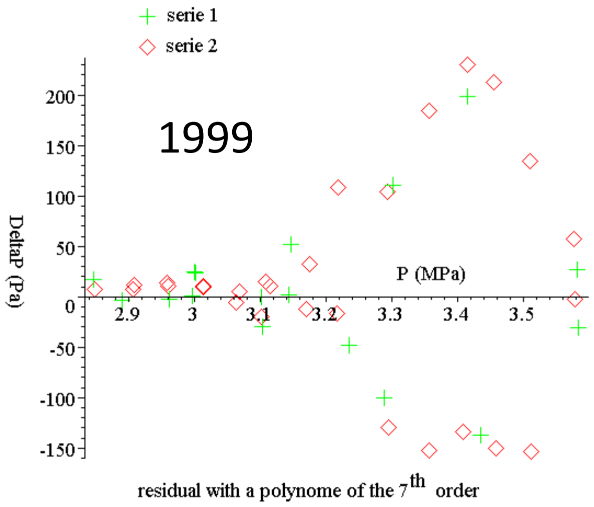


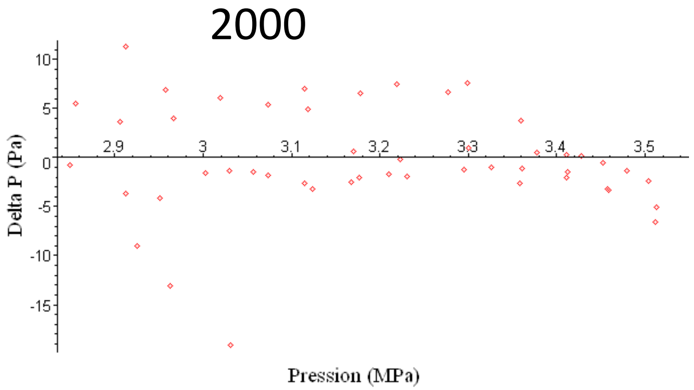


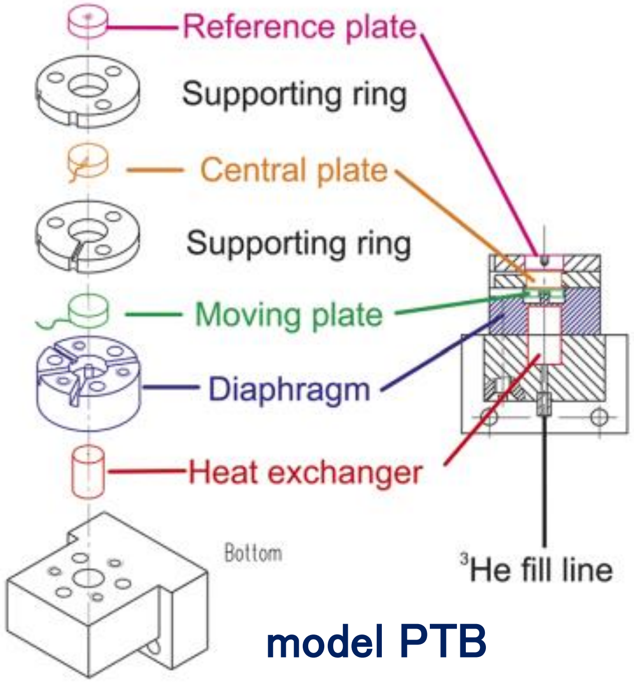


NO Hysterisys !

Hysterisys of the same capacitance strain gauge over time

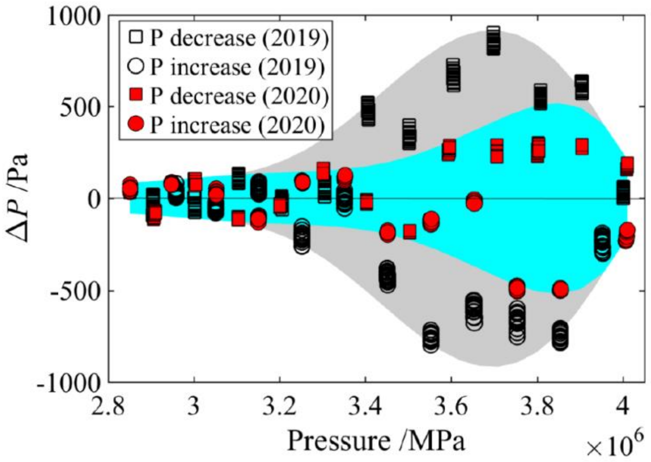






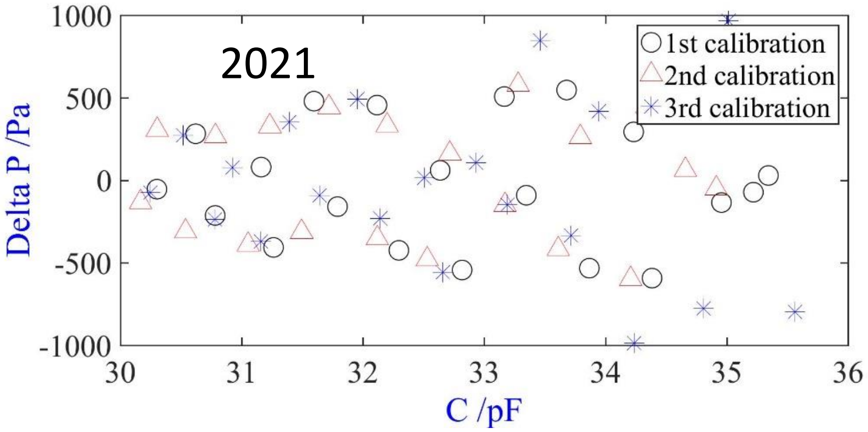
model PTB

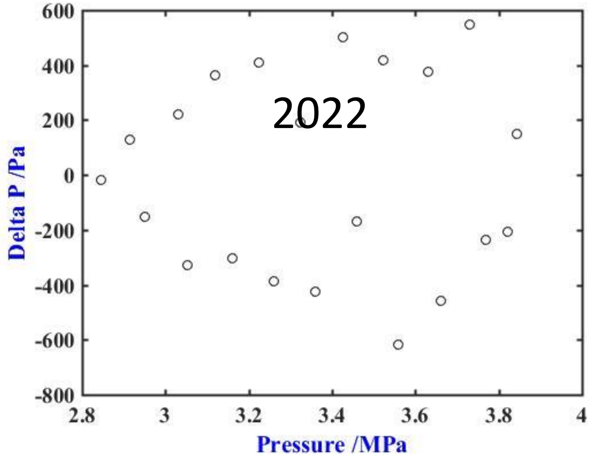
The bolt and the indium joint play a critical role in the mechanical behavior of the capacitance strain gauge.



2019

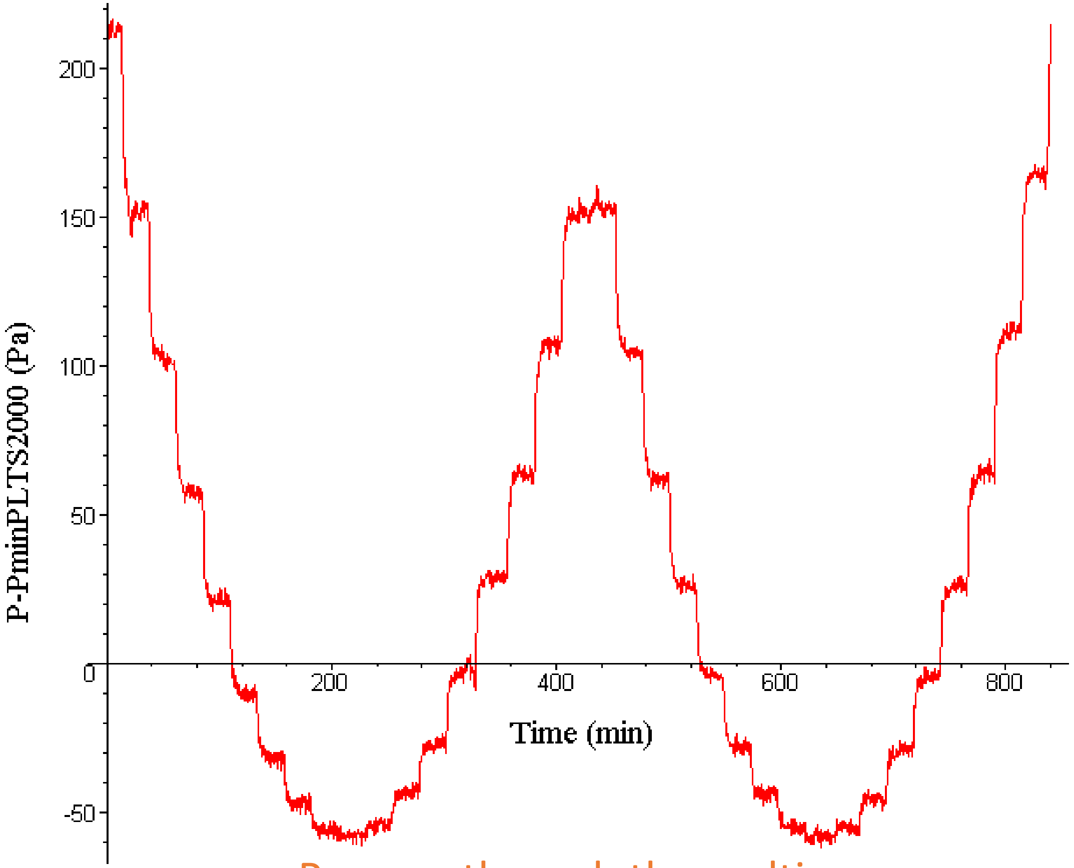
2020

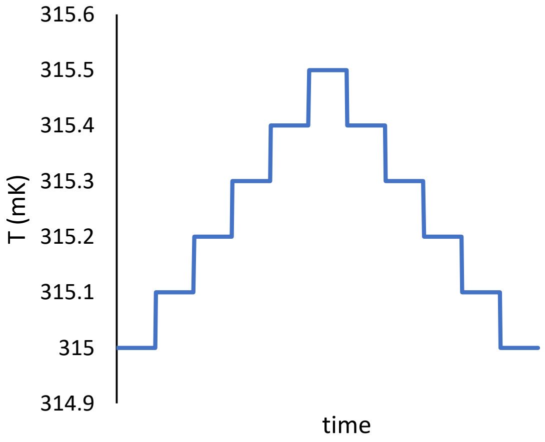




Very precise realization of the melting pressure minimum

Pmin =2931130Pa



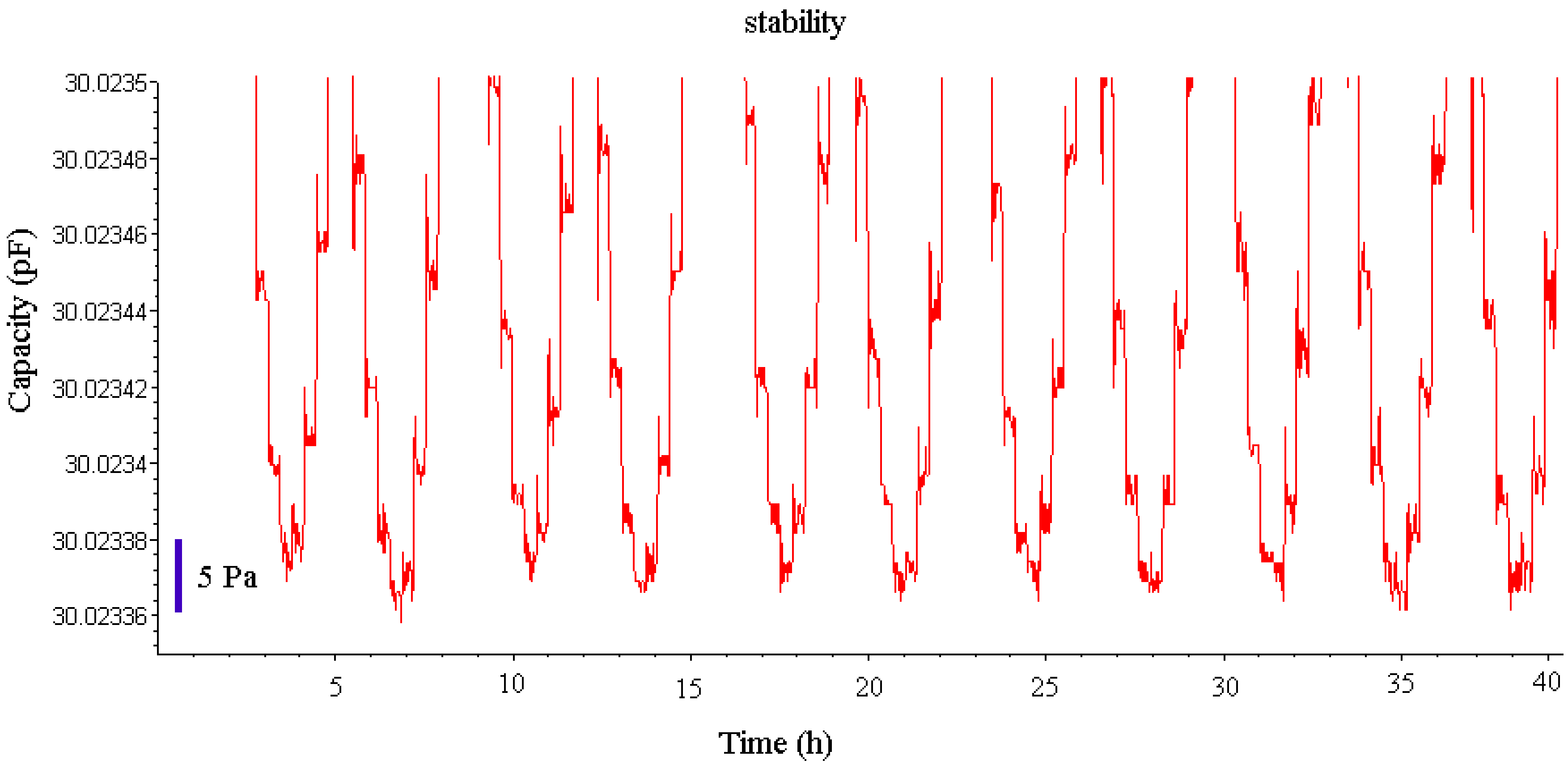


Passage through the melting pressure minimum in step of

1 mK with rising and falling temperature

Stability of the melting pressure minimum

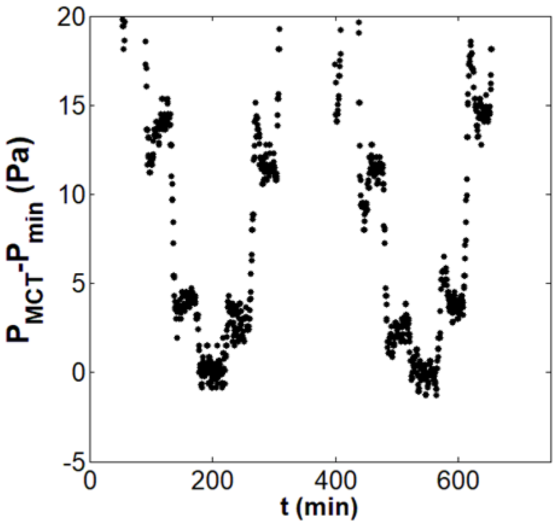
Pmin =2931130Pa

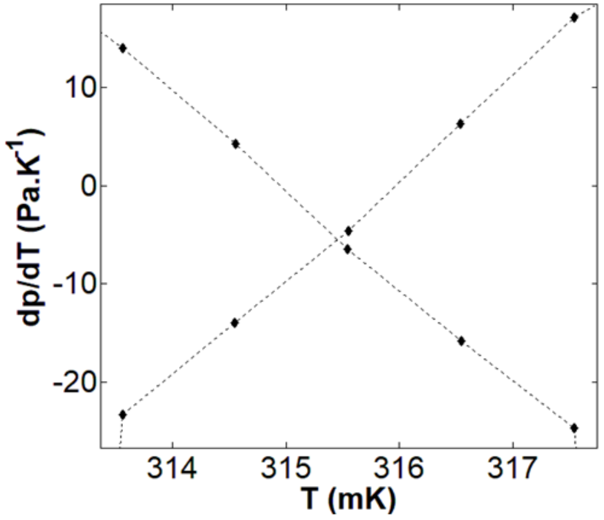


Because PLTS2000 give the pressure of the minimum
We can use the minimum to estimate the hydrostatic correction

Temperature of the melting pressure minimum

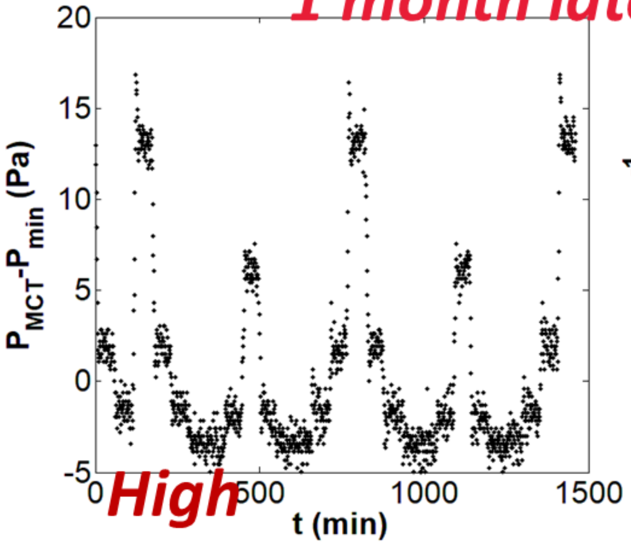
Pmin =2.931 130 MPa



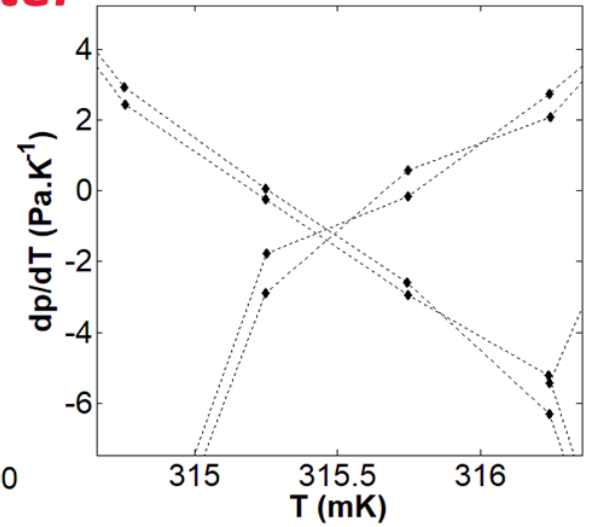


Tmin=315.24

1 month later



High stability



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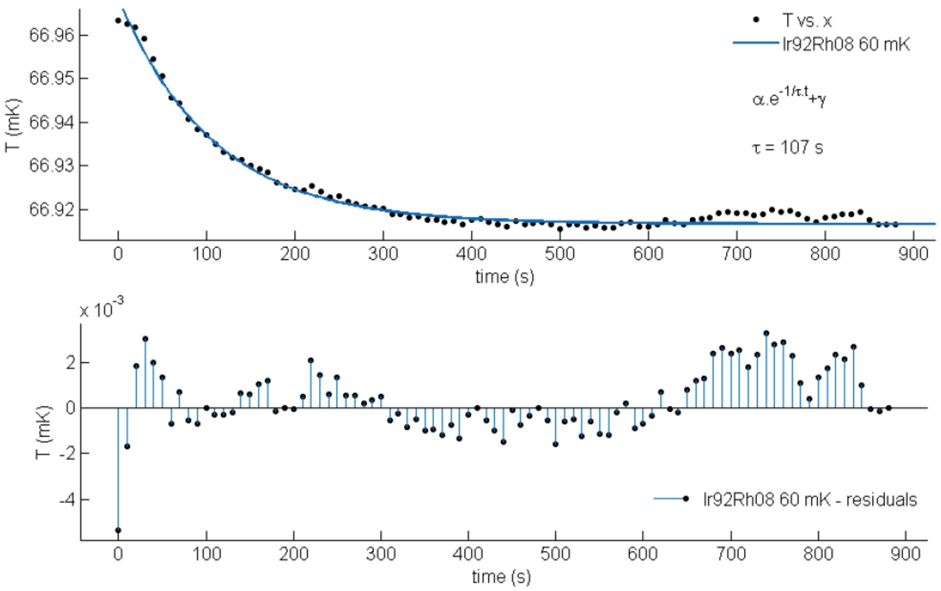
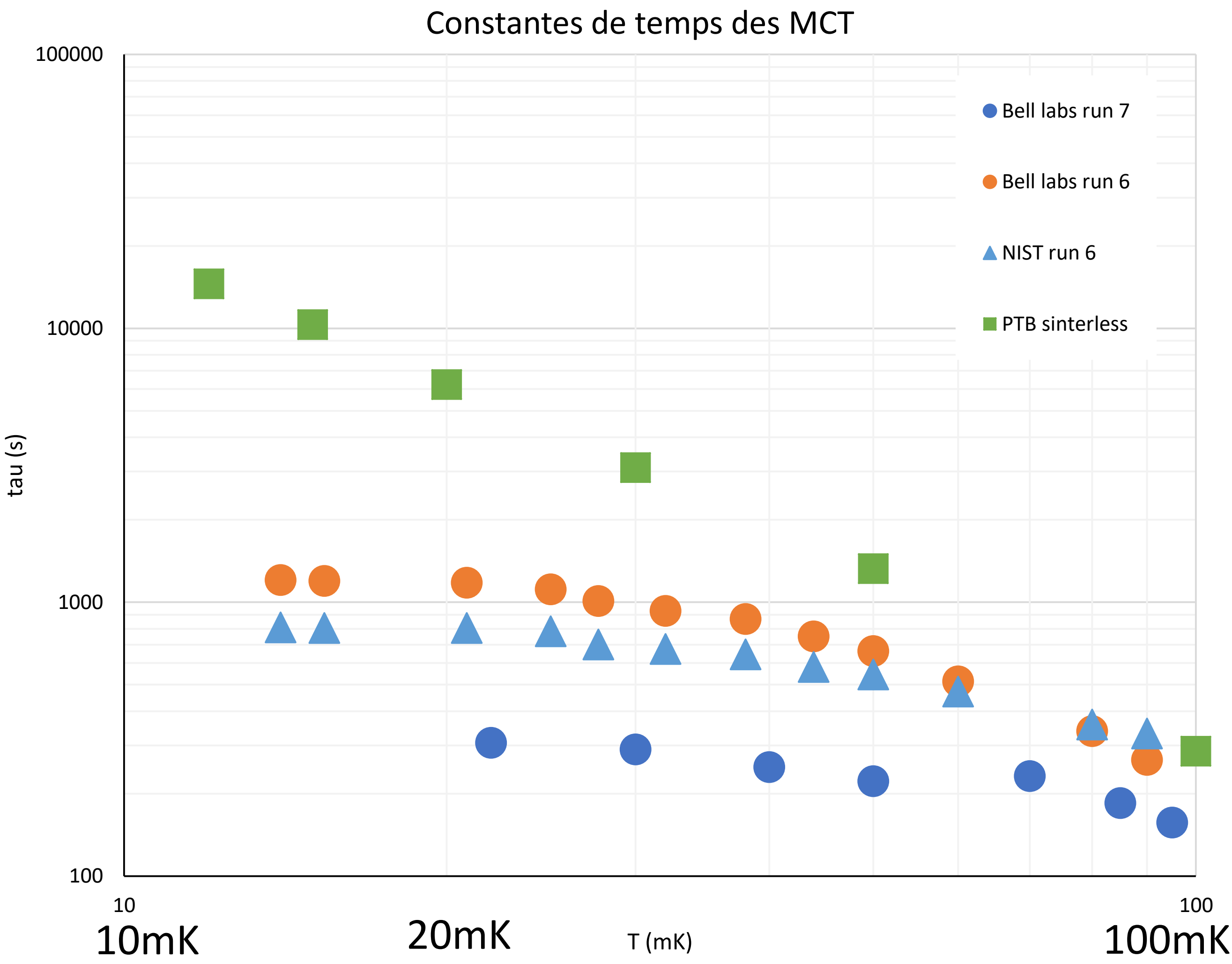
Time constant of the melting curve thermometer





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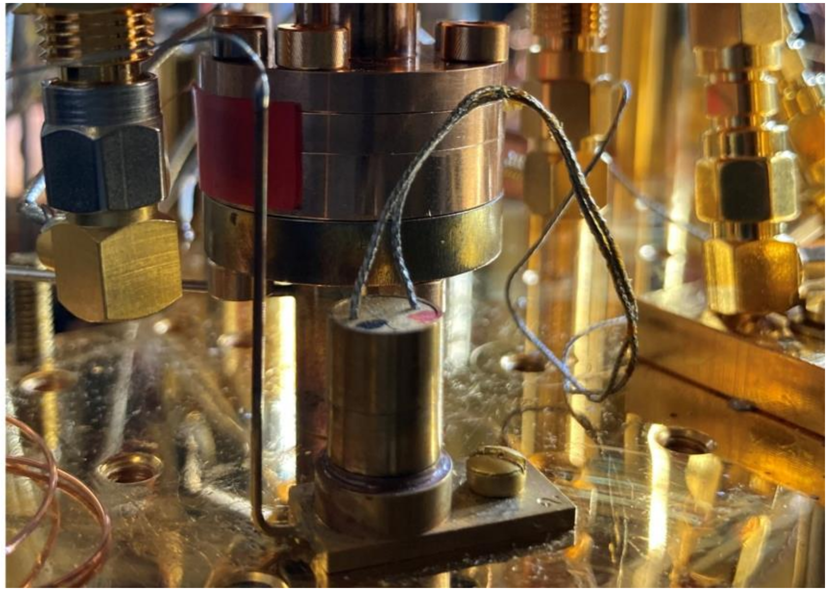
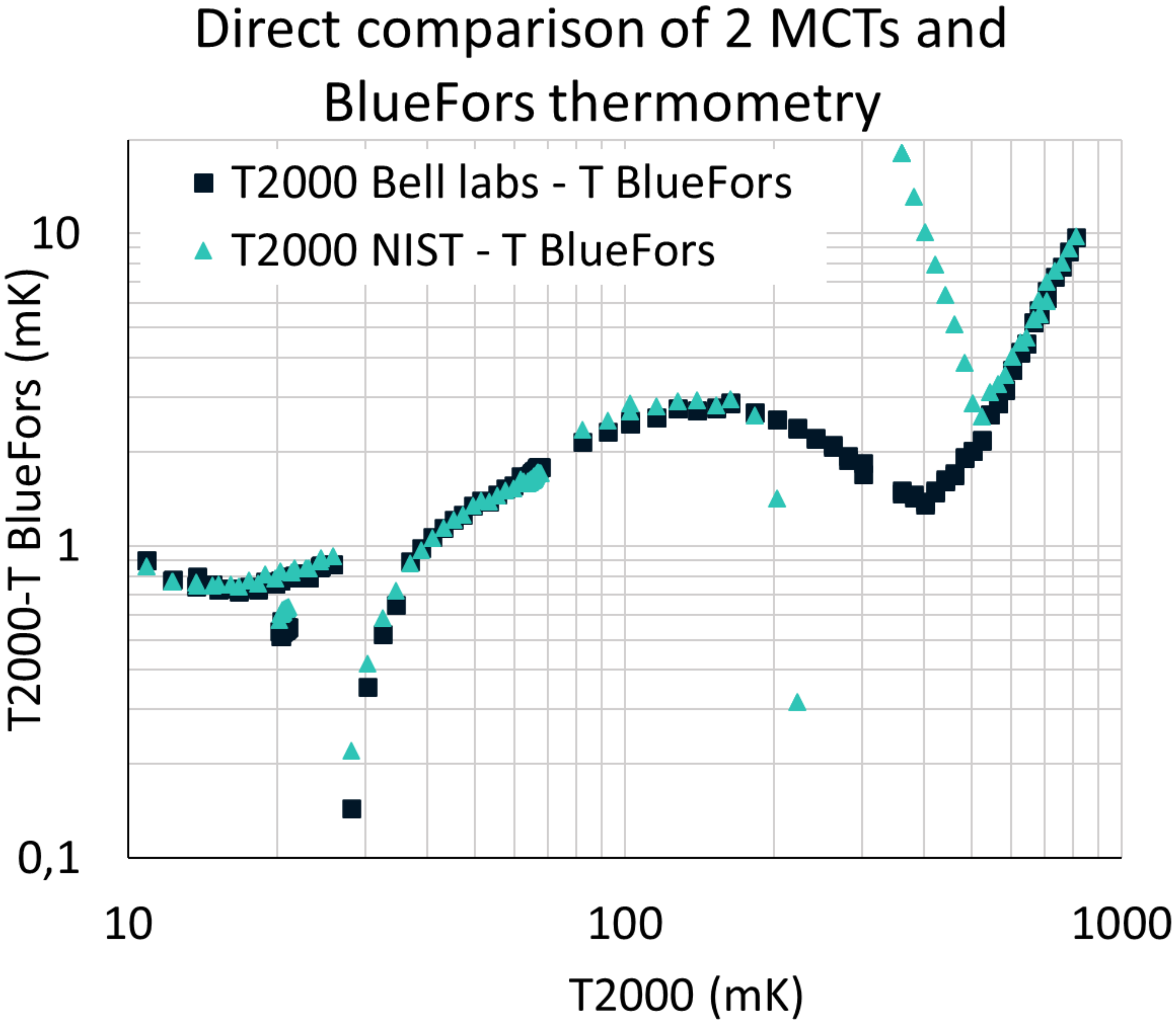
Comparison of Two Melting Curve Thermometers





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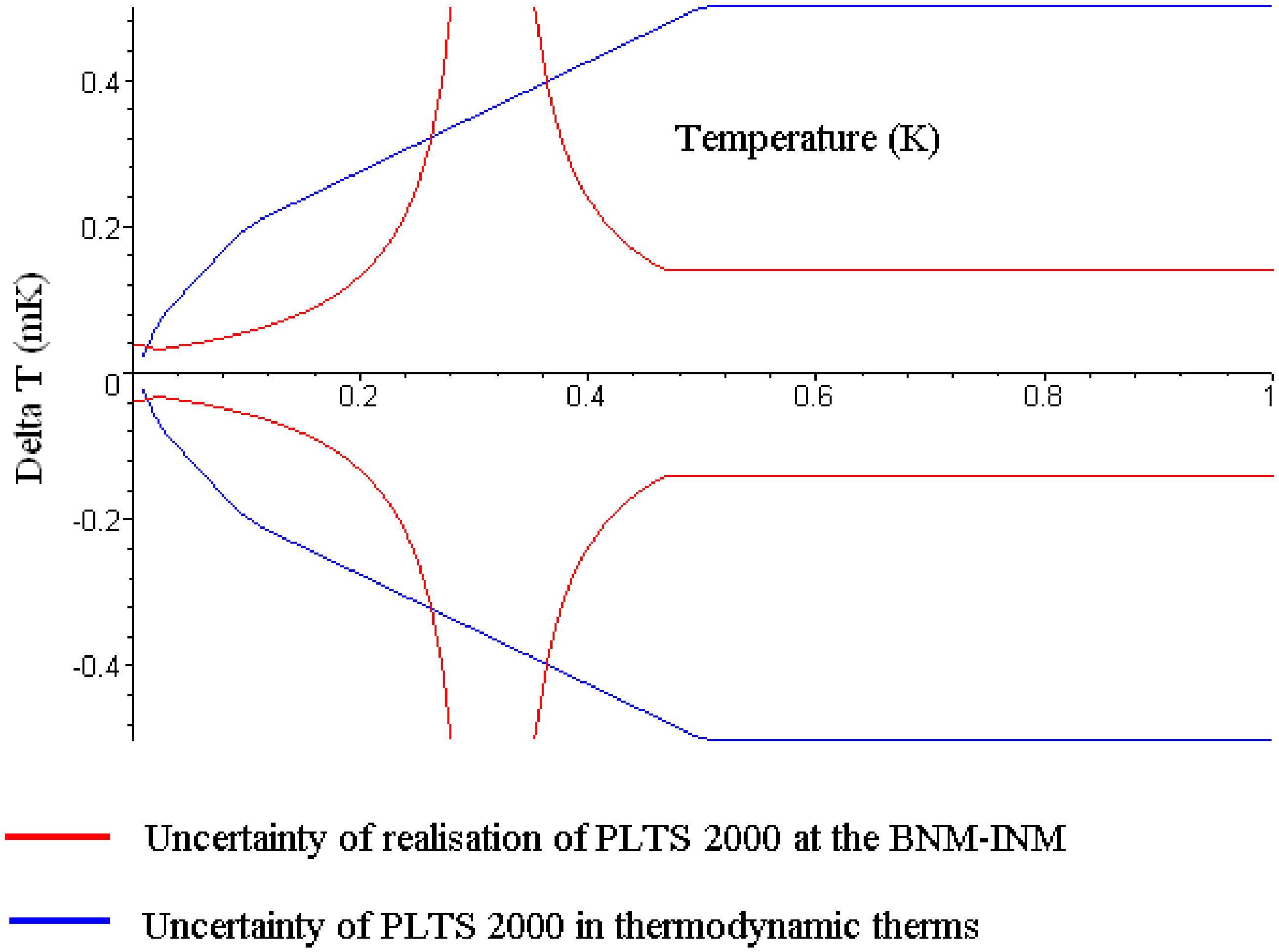
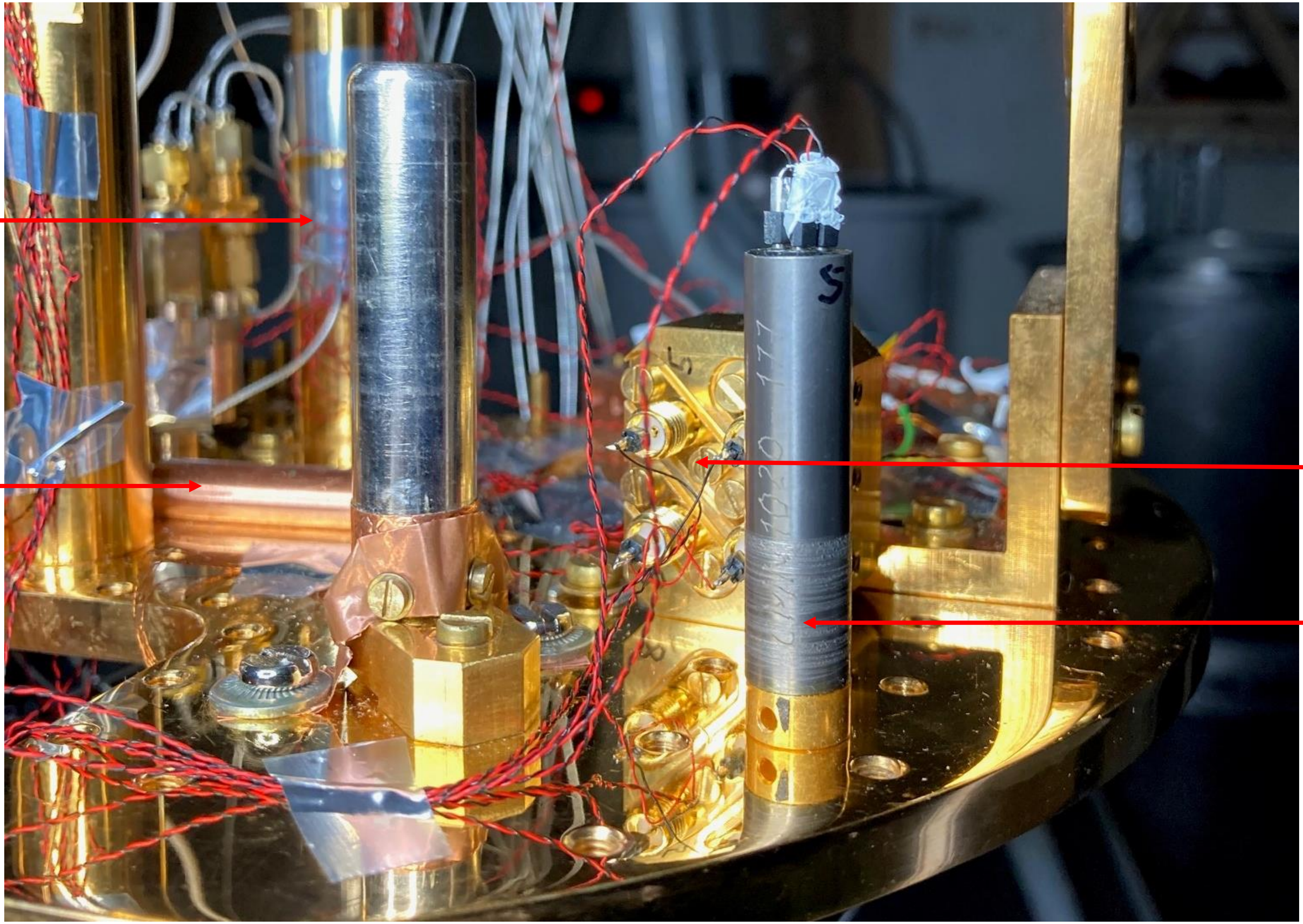
Uncertainty of PLTS2000 at LNE

The complete uncertainty budget 2024 is not finished, but it is expected to be better than, the one from 2002.



Low temperature thermometry compared to PLTS2000



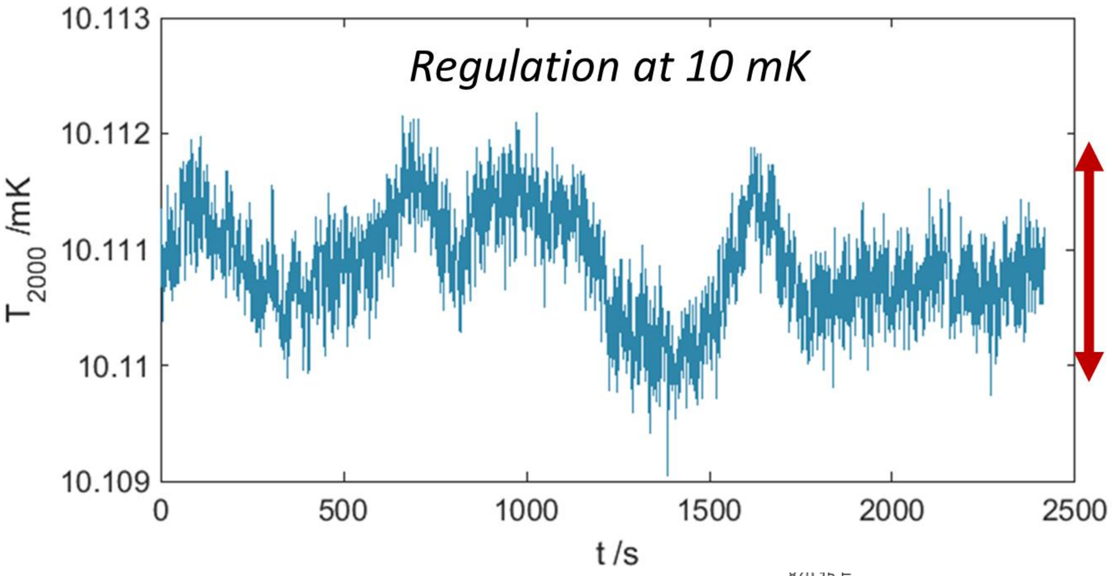
SRD1000

RdFe

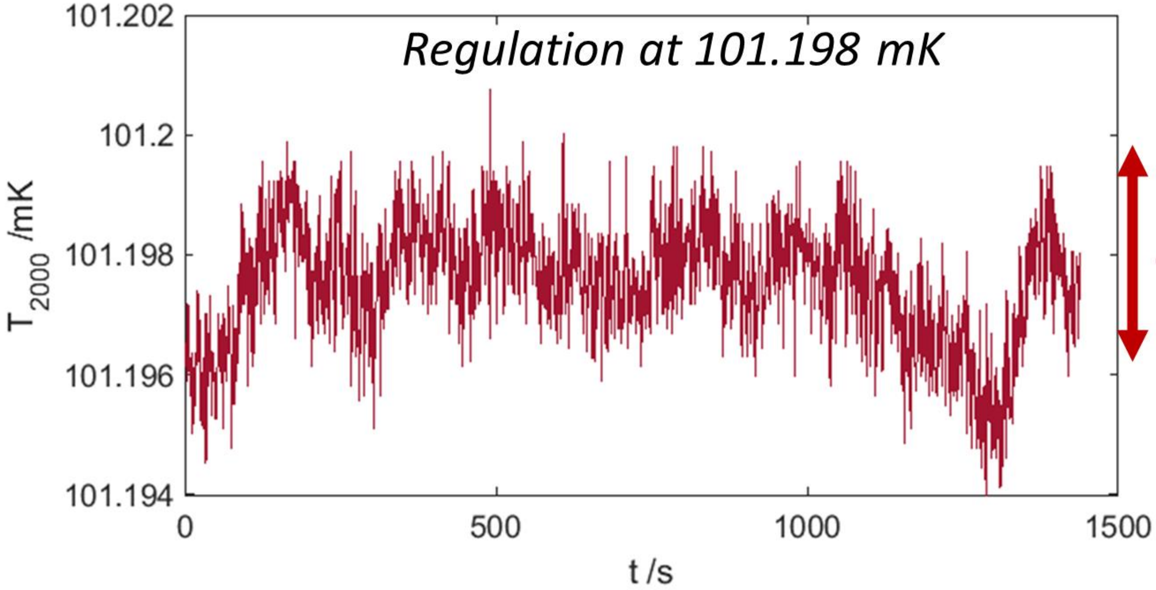
CBT

CMN

Low temperature thermometry regulation

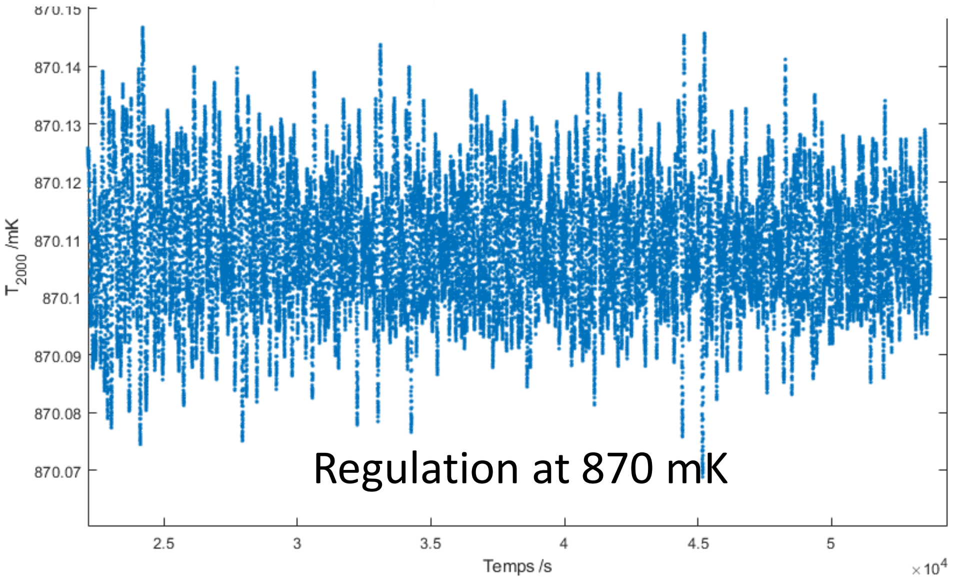


2 µK



4 µK

30µK



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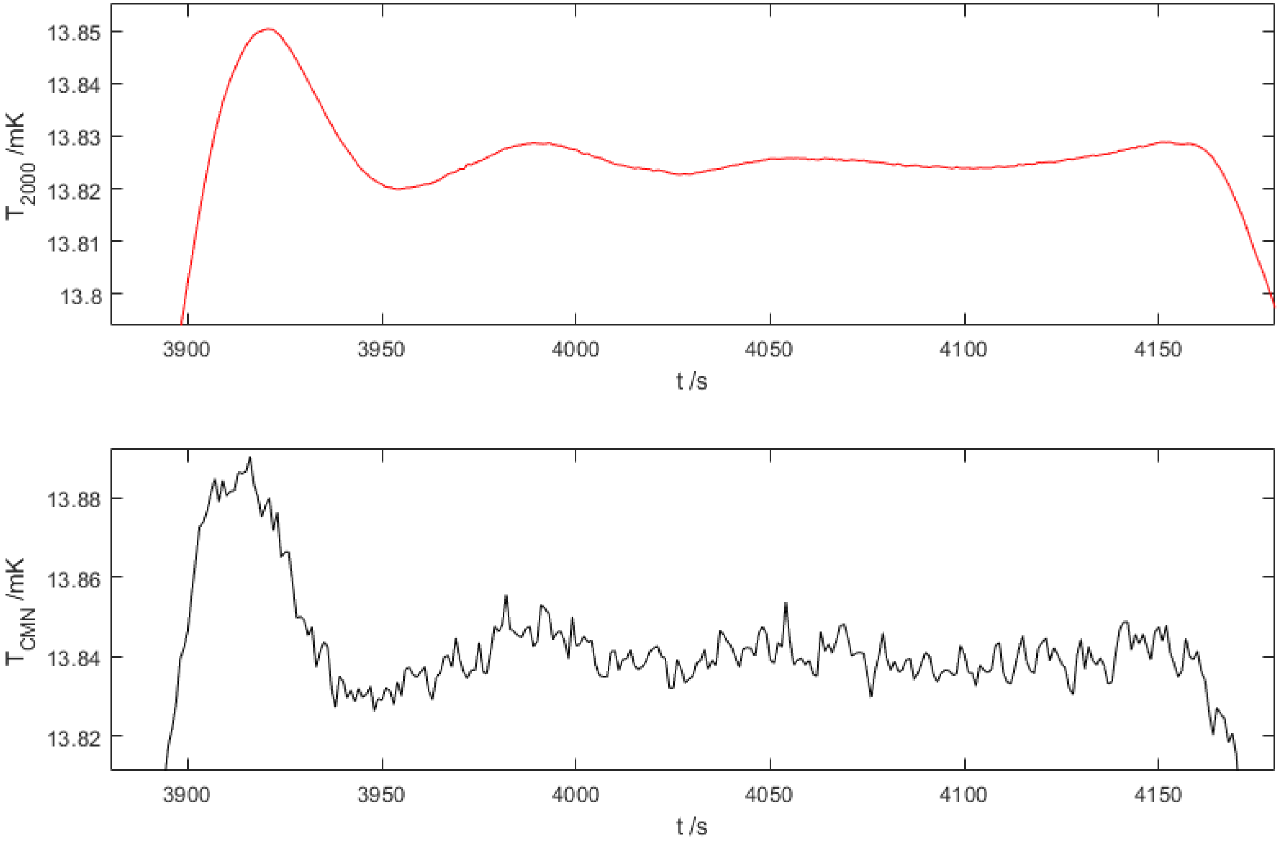
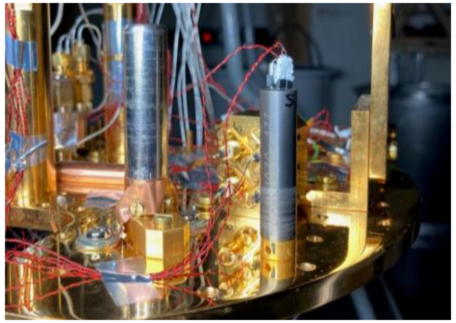
Low temperature thermometry regulation

@13,8mK

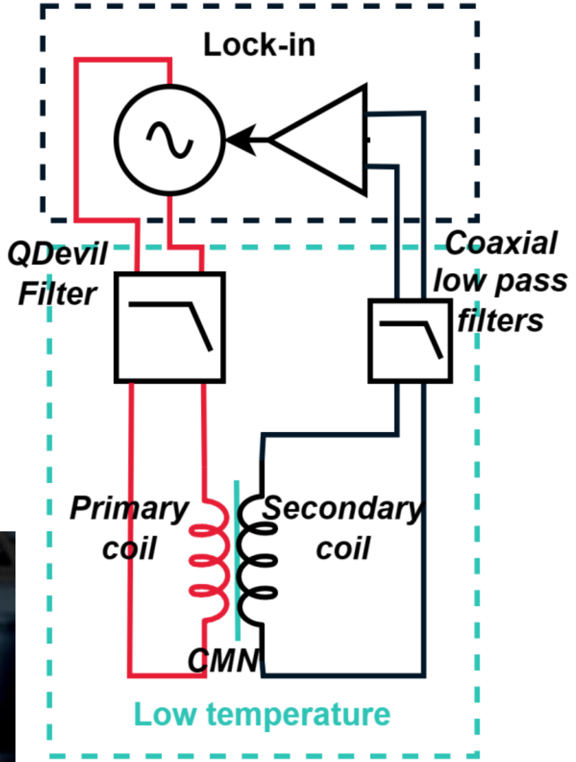


Curie weiss law

$$\chi = b + \frac{a}{T + \triangle}$$



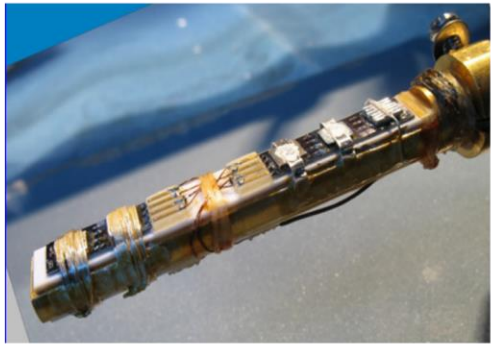
CMN



SRD1000 from HDL

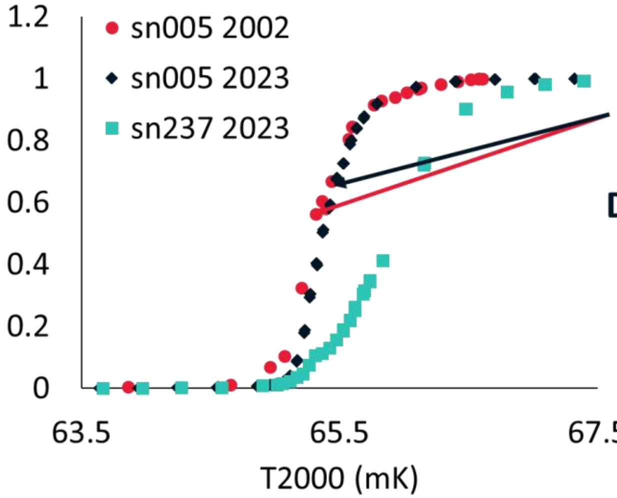
SRD1000 Superconducting transition

We obtain the transition temperatures of 13 superconducting elements by measuring their magnetic susceptibility.



Inside of an SRD1000

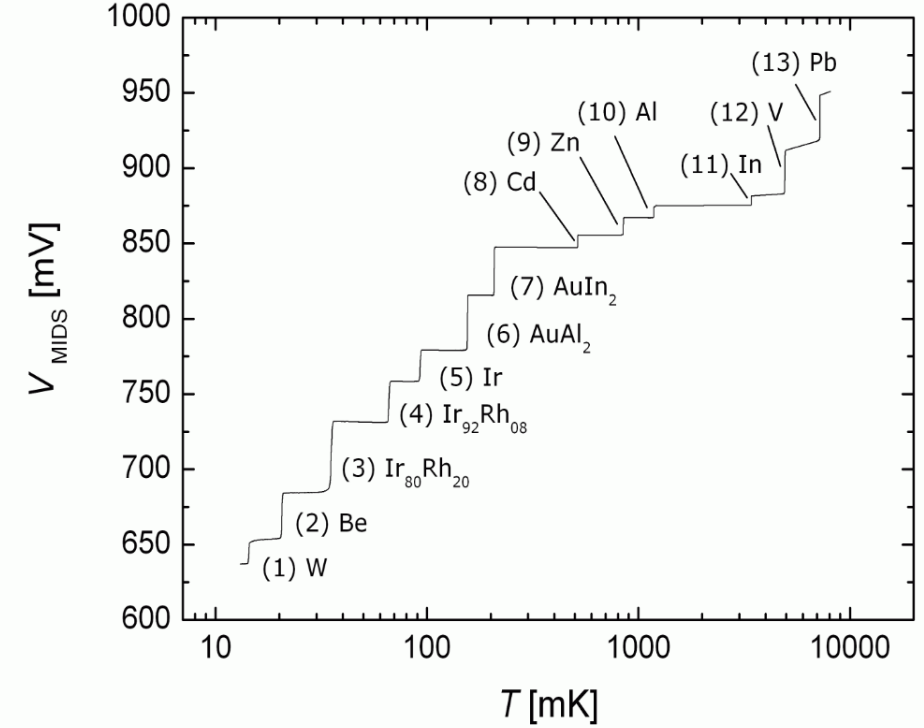
We compared 2 SRD1000, one (sn005) which shows the aging of the sensor over more than 20 years and the second, (sn237) bought in 2021 is tested in order to compare 2 same sensors.



Difference over 20 years in the $Ir_{92}Rh_8$ transition at 65 mK (0.11 mK)

Difference between sn005 and sn237 (0.51 mK)

Each sensor needs to be calibrated independently.



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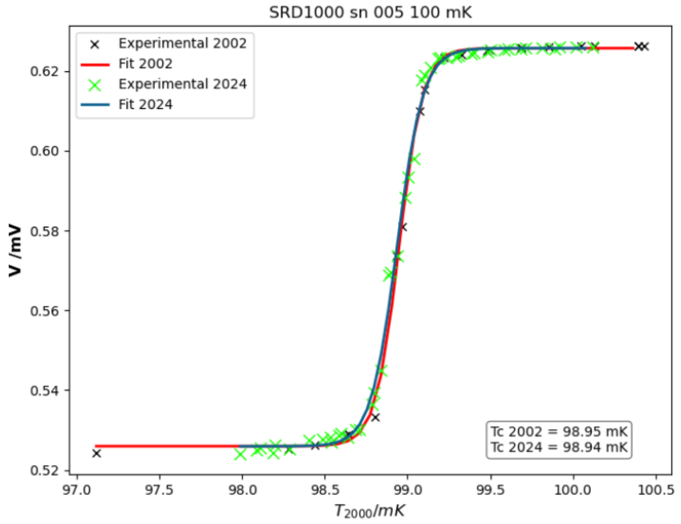
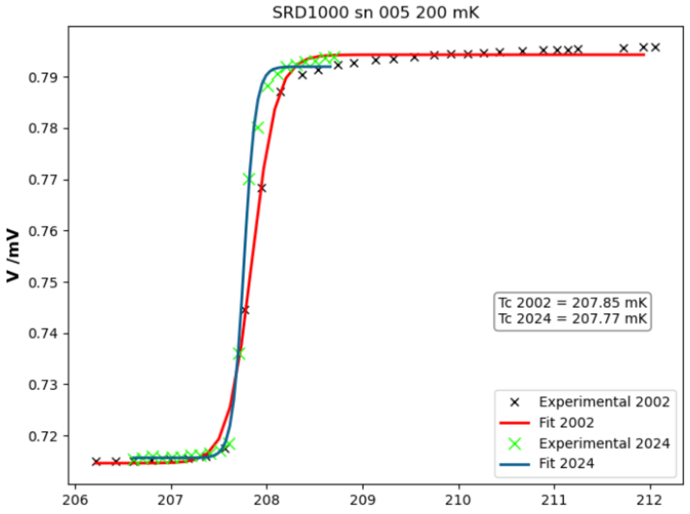
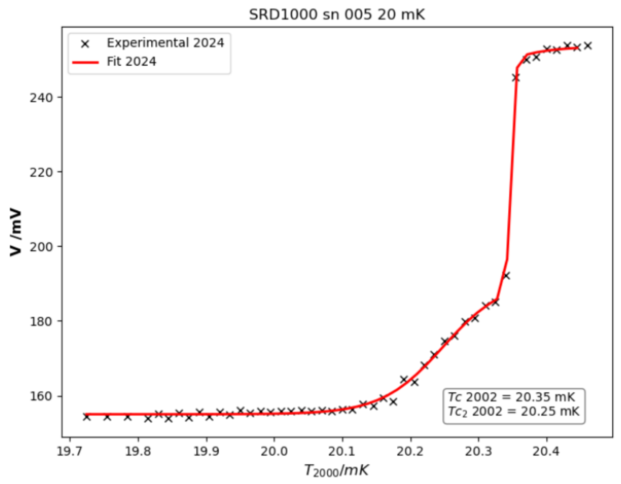
SRD1000 from HDL

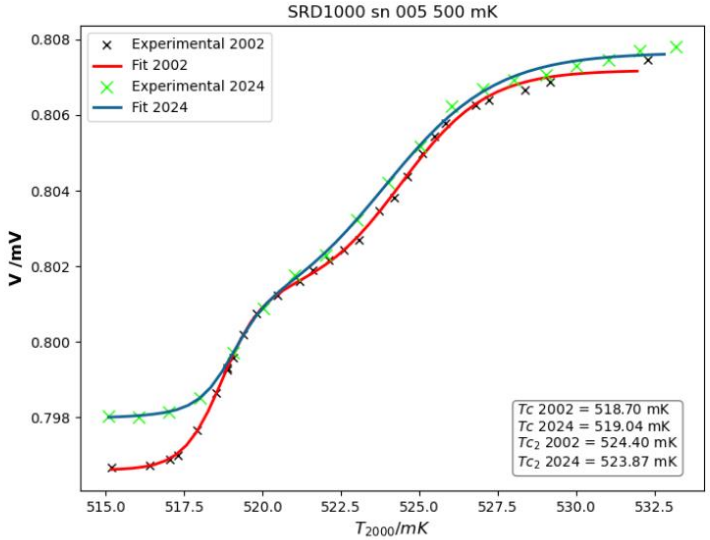
Use of **sigmoid function** models on the transitions (conducted in collaboration with Rod White (NZ)).





The data points represent the average of at least 15 minutes with very stable regulation, where half the points are taken during a rise in temperature and the other half during a decrease... showing no hysteresis.





Two sigmoid functions can accurately fit even a more complex transition.

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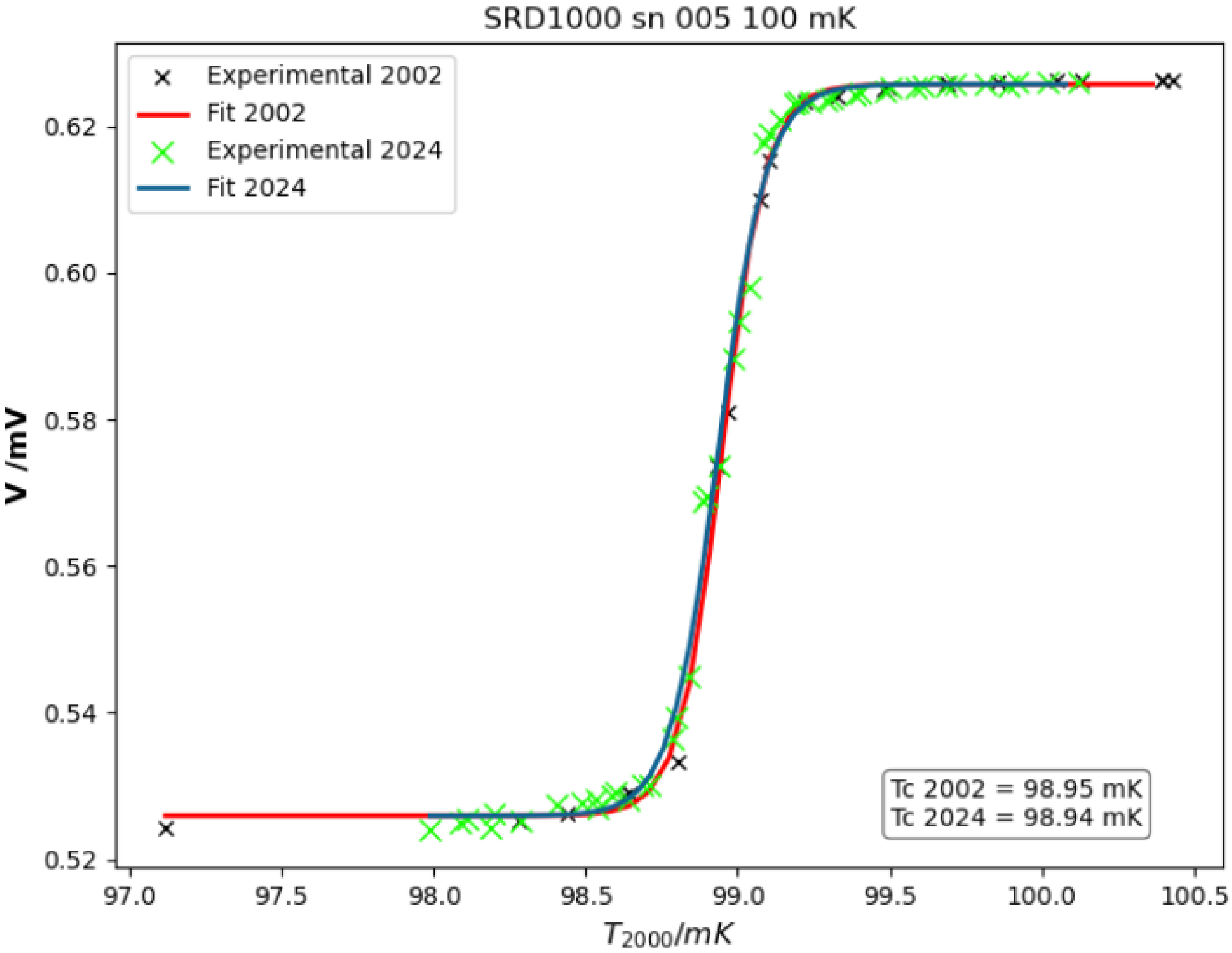
SRD1000 from HDL over 22 years



The SRD1000 from HDL is very stable; however, the shape of some transitions changes over the years. Uncertainty budget will come…

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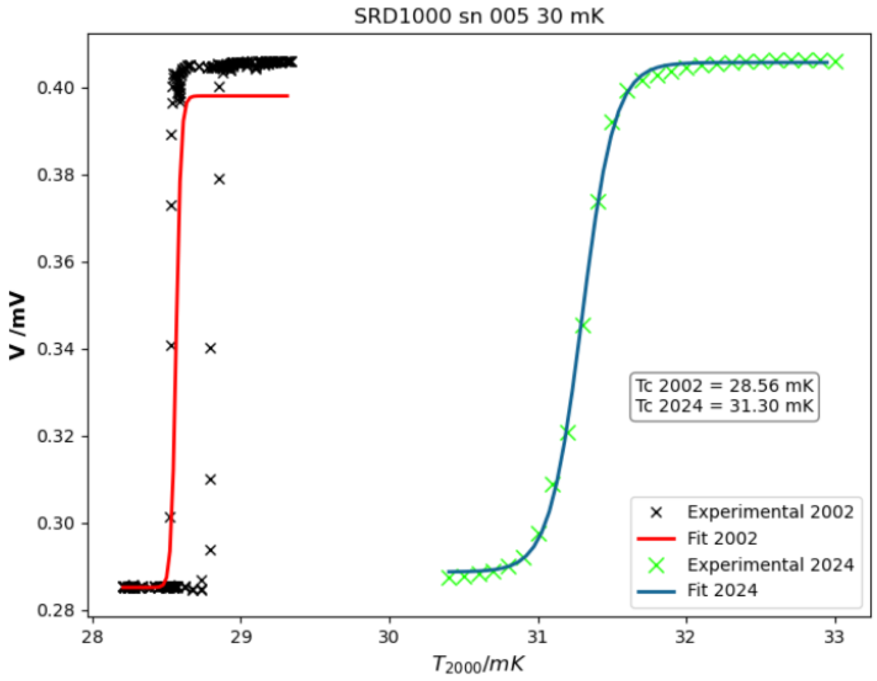
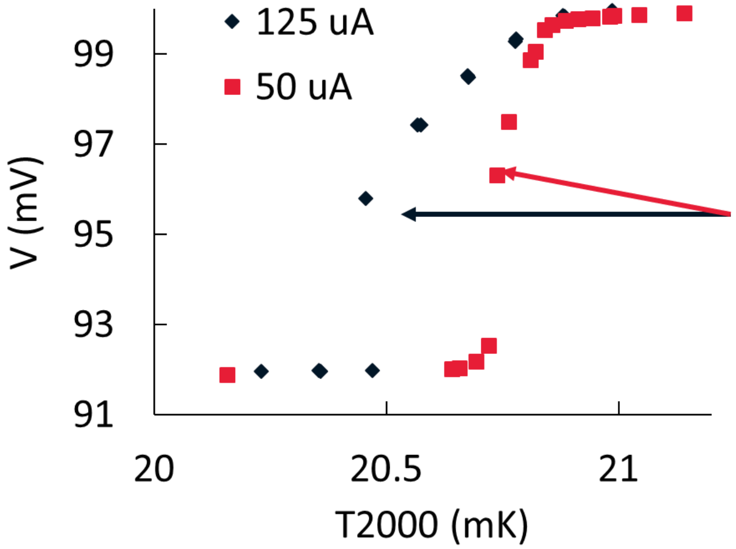
SRD1000 from HDL



Without microwave filter

With a filter



Influence of the excitation current in the Be transition at 20 mK with the sn237 (0.3 mK)

Even the shape of the transition has changed by reducing the current.

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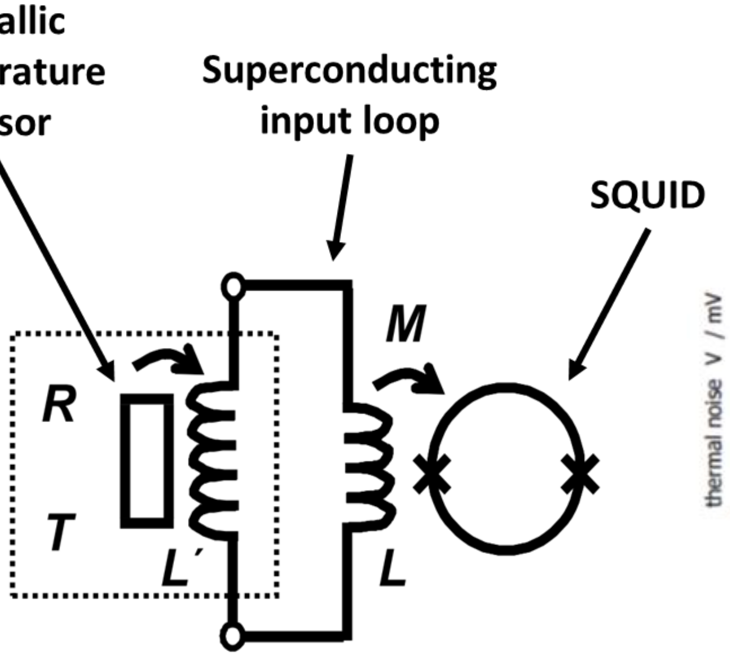
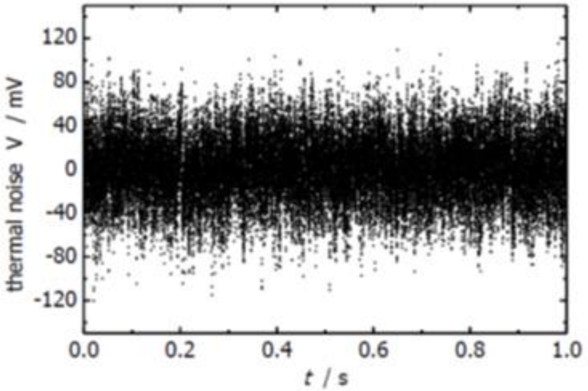
TMFFT from Magnicon

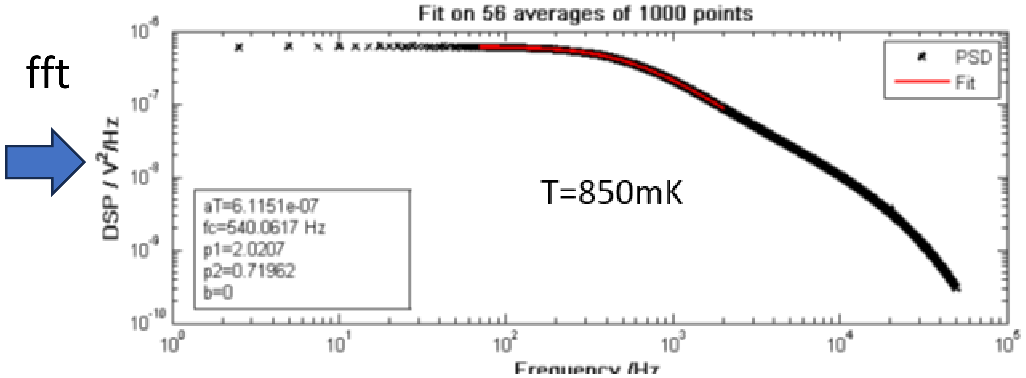

Metallic temperature sensor

Superconducting input loop

SQUID

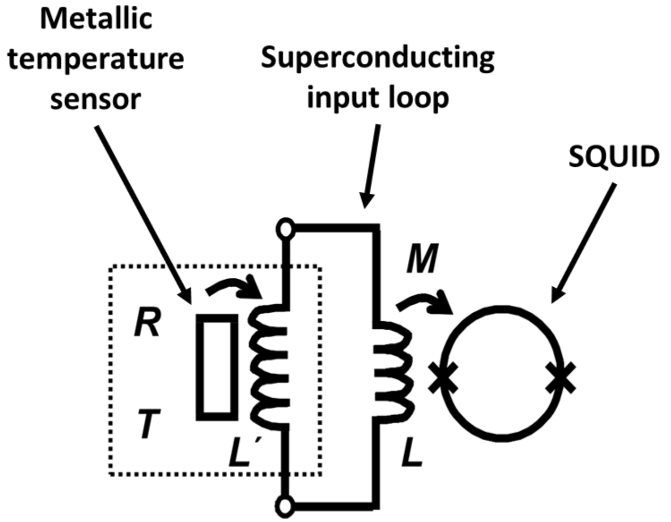


fft

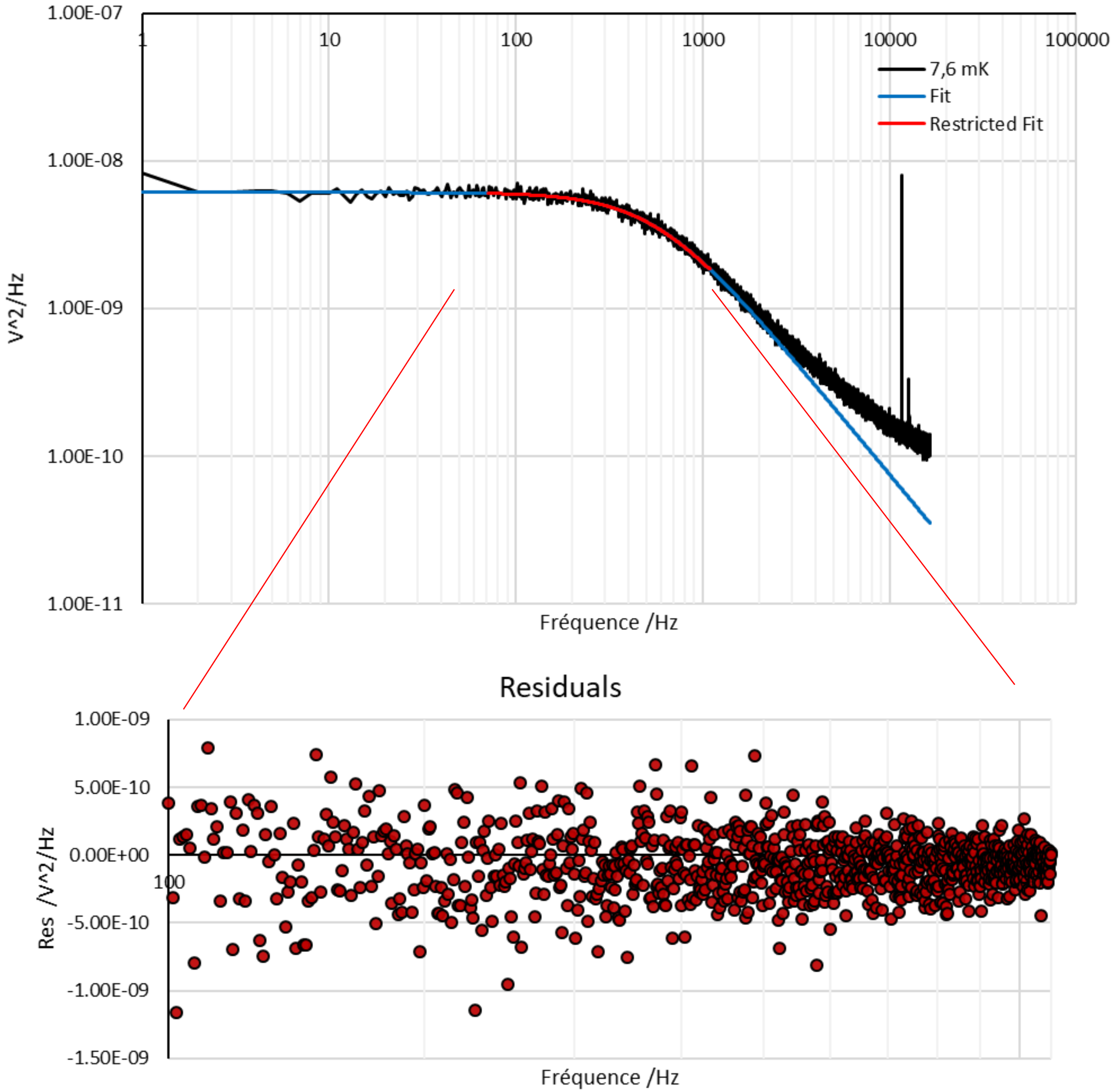


T=850mK

TMFFT from Magnicon



$$S_\Phi(f,T) = \frac{aT}{\left(1+\left(\frac{f}{f_c}\right)^{2p_1}\right)^{p_2}} + b$$



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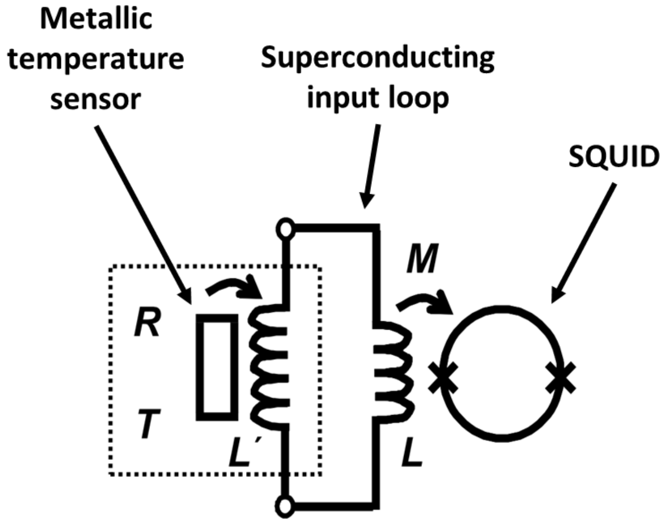
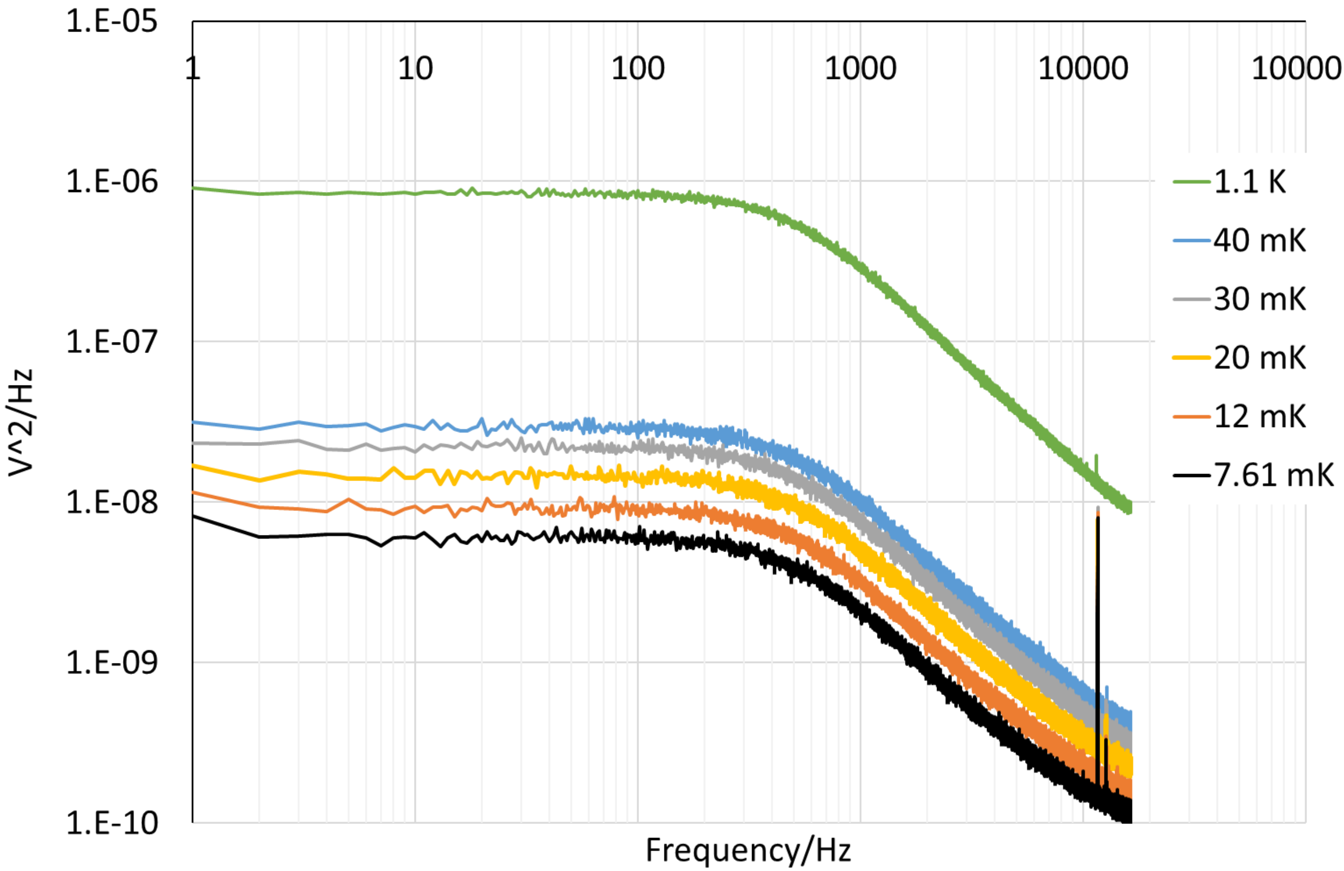
TMFFT from Magnicon



$$T = T_{ref}\frac{S_0(T)}{S_0(T_{ref})}$$



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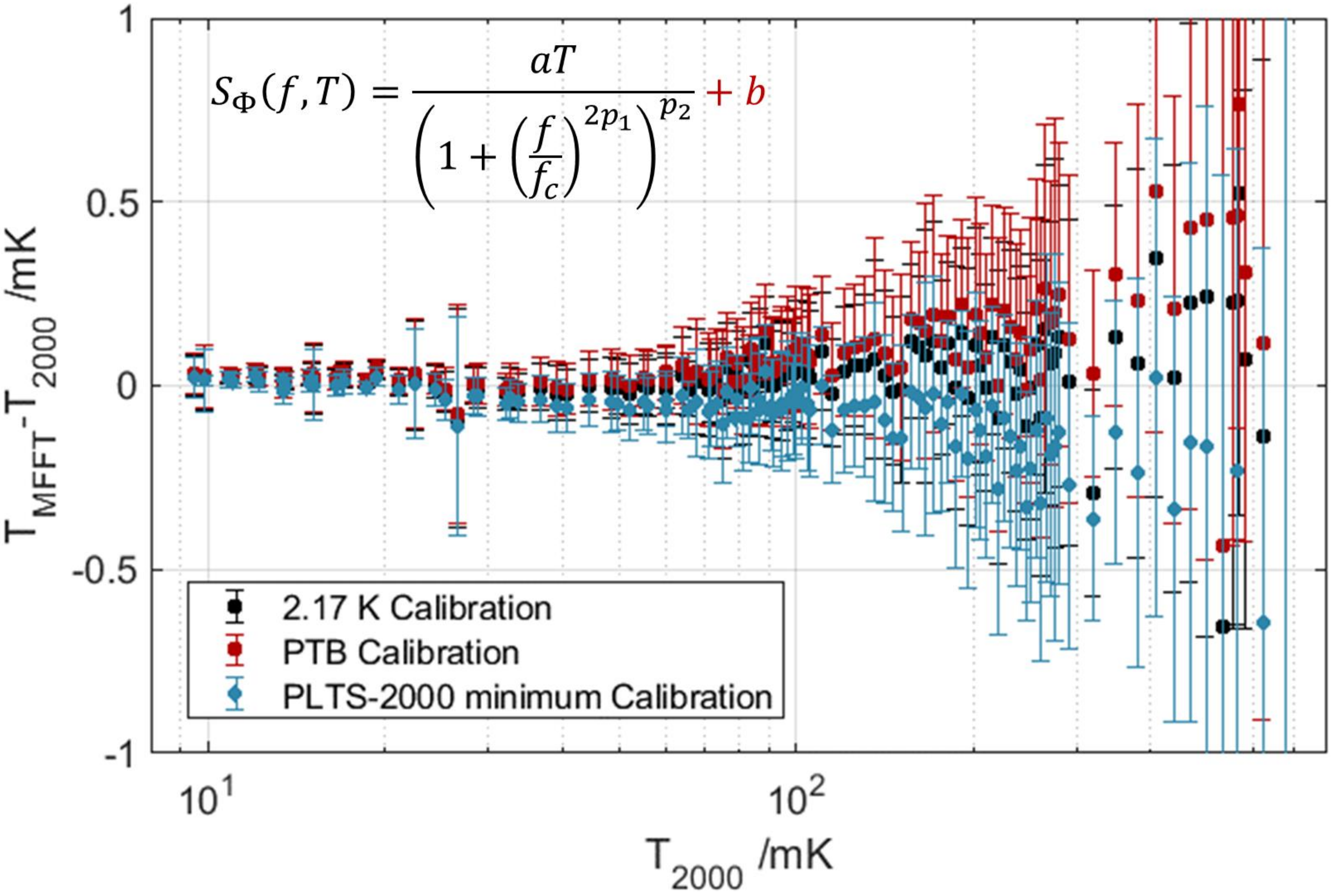
$T_{MFFT} - T_{2000}$ at LNE

120 temperature measurements
Preliminary results



$$S_\Phi(f,T) = \frac{aT}{\left(1+\left(\frac{f}{f_c}\right)^{2p_1}\right)^{p_2}} + b$$

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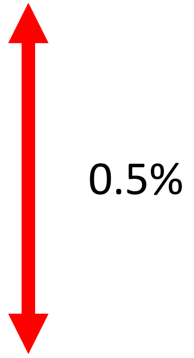
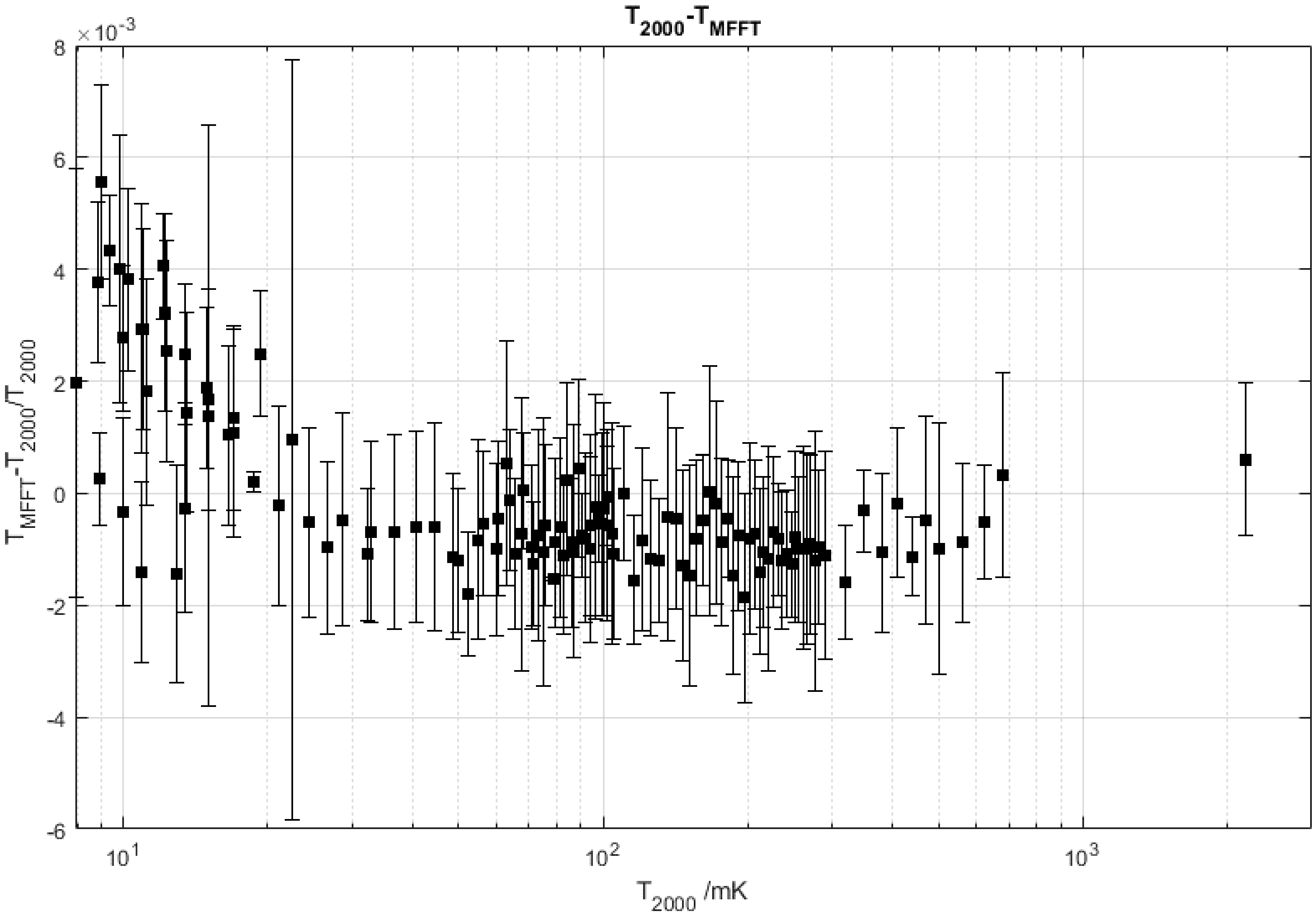
$T_{MFFT} - T_{2000}$ at LNE-Cnam





Preliminary results:
The uncertainty budget is not finished.
Soon, Clément Tauzin will defend his PhD.

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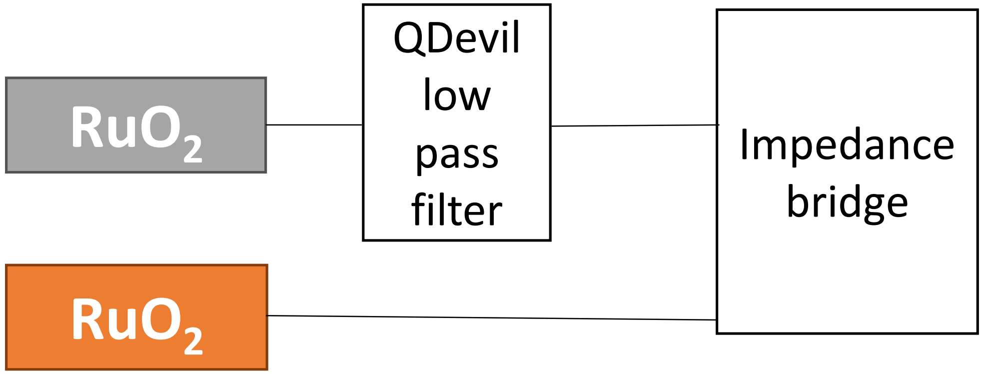
T_{MFFT} – T_{2000} at LNE

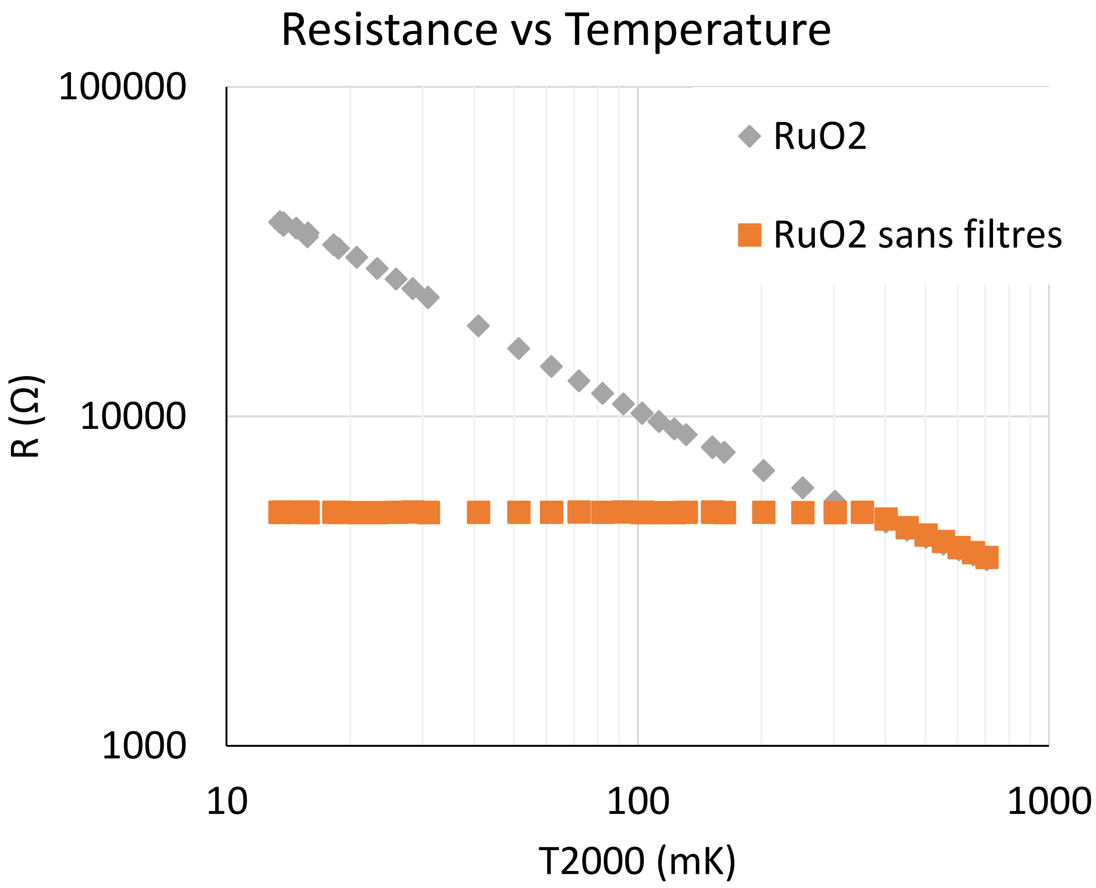
- Over three months of noise integration
- 120 temperature measurements
- Work in progress (uncertainty budget not yet complete), but results are very promising.

- Excellent linearity of PLTS-2000 as a function of temperature from 8 mK to 800 mK, even with a 12-parameter polynomial for PLTS-2000!
- Primary relative temperature measurements at 2.1768 K and 315.24 mK are equivalent.

Resistive Thermometer and T2000 at LNE-Cnam

Same bridge
Same position
Same excitation
Same sensor




Resistance vs Temperature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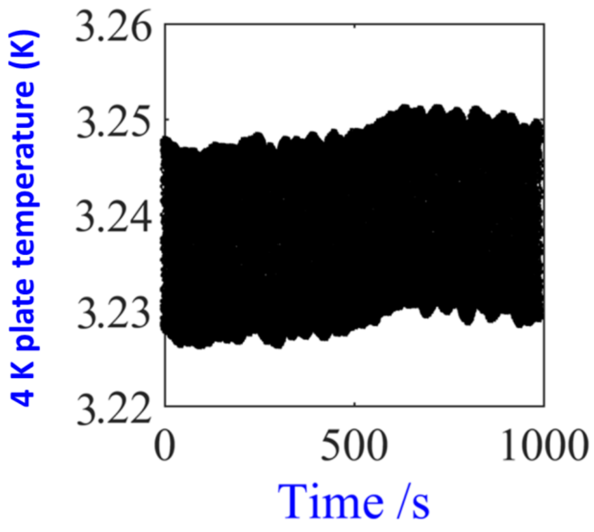
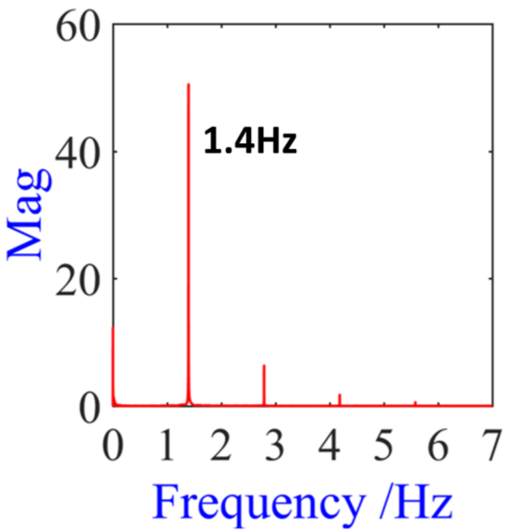
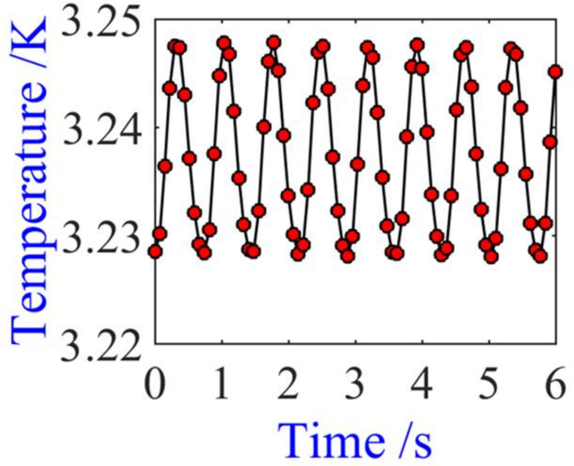
Resistive Thermometer and sampling

Temperature measurement performed at LNE-Cnam on the 4 K plate @ 10 Hz



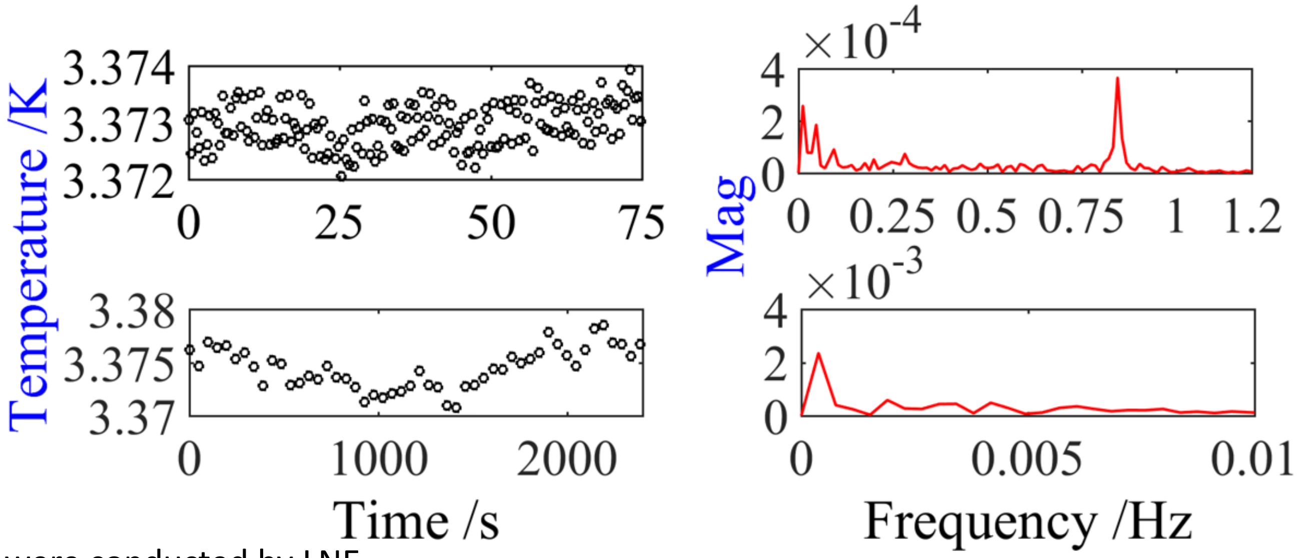
Frequency analysis





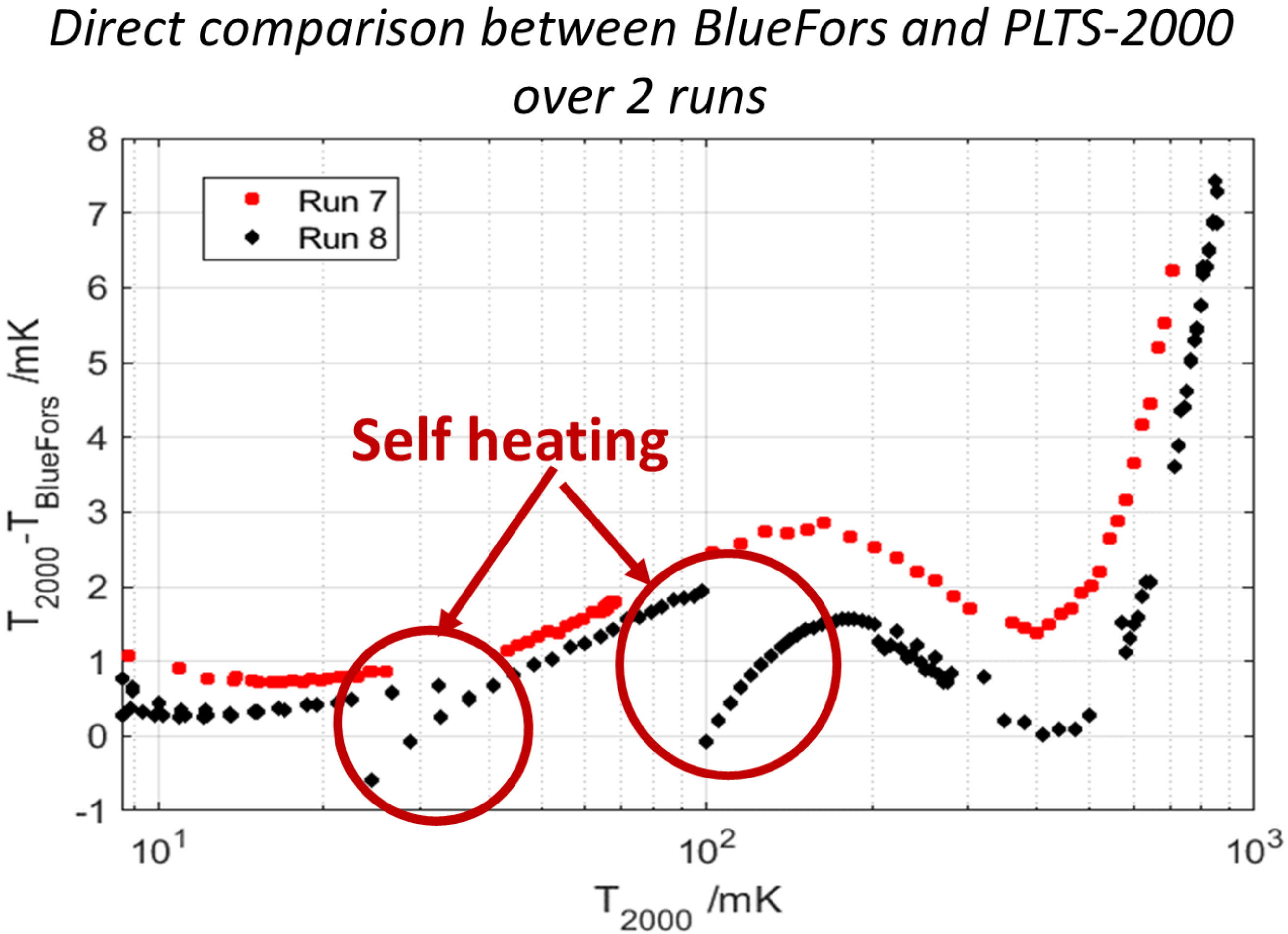
Temperature measurements were conducted by LNE-Cnam on the 4 K plate of a DR from BlueForth using a 10 Hz digital multimeter to measure a Cernox thermometer through a 4-wire resistance measurement method. sinusoidal temperature oscillations are well visible

But if we use only instruments and settings provided by Bluefors, we cannot observe any thermal oscillations because **the sampling rate is too low**



Resistive Thermometer and T2000 at LNE

Self heating and repeatablility over 2 cooldowns!!!



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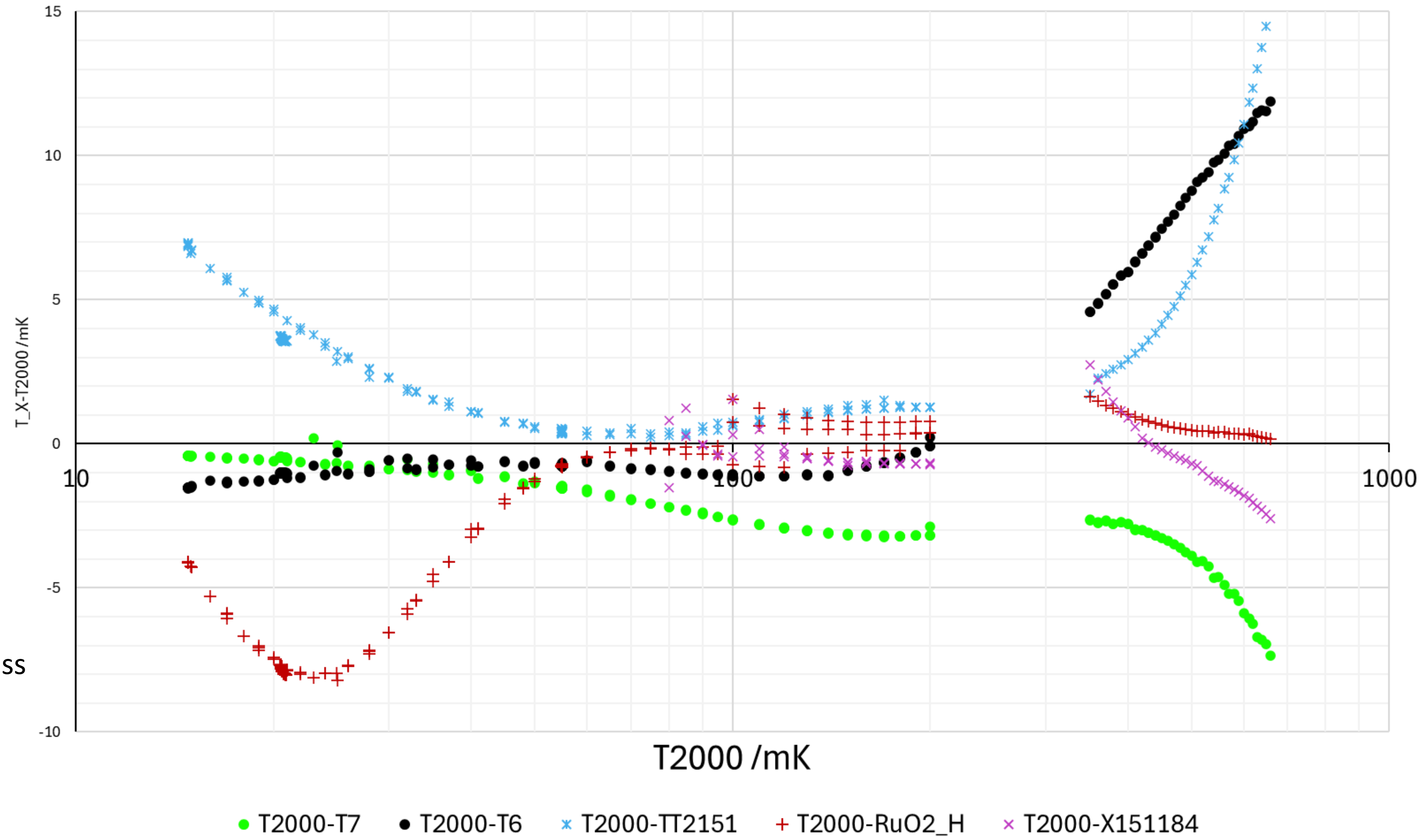
Doctorant

Resistive Thermometer and T2000 at LNE



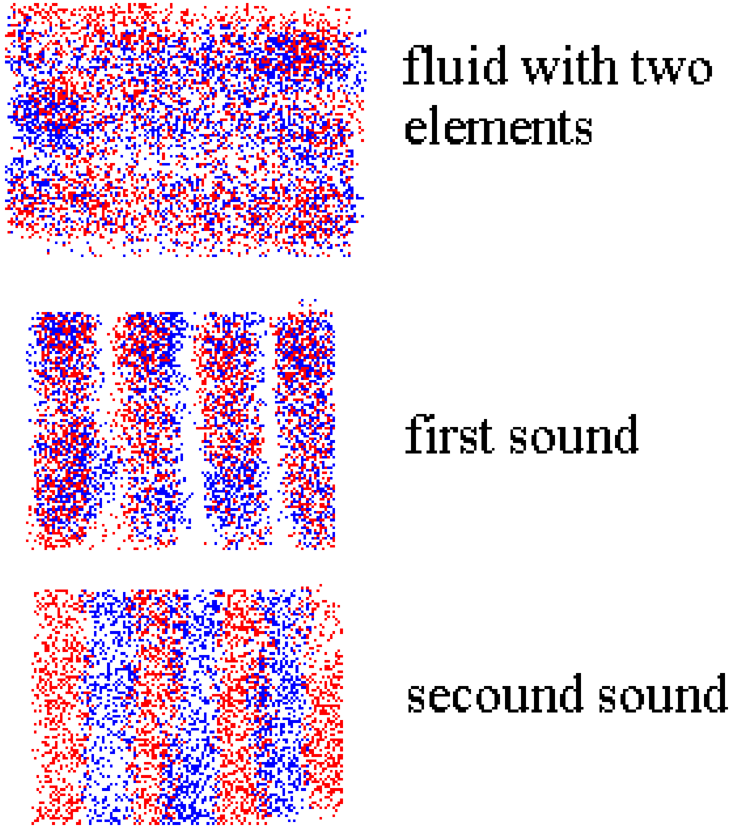
Work in progress

Clement Tauzin
Doctorant

Second Sound in the mixture of He^3–He^4

In superfluid helium, the normal component of the Helium-3/Helium-4 mixture can move frictionlessly through the superfluid Helium-4 component.

In **first** (normal) sound, acoustic waves propagate as compressions and rarefactions i.e. density varies spatially



In **second** sound the total density of the mixture remains constant

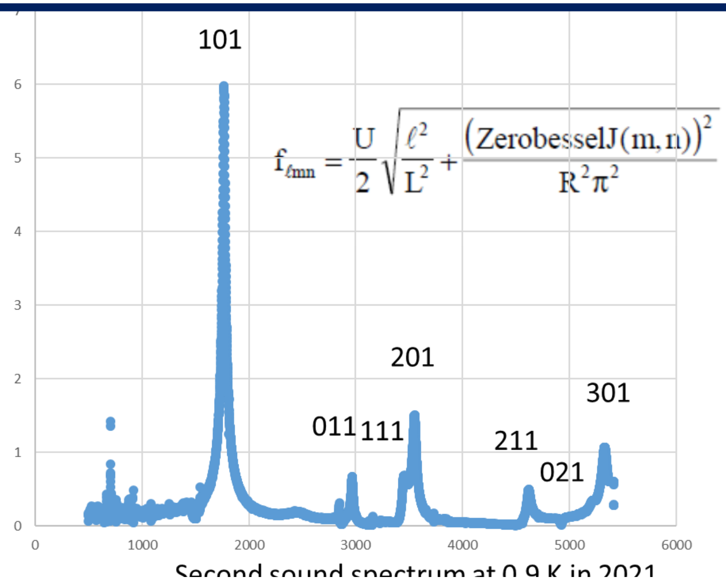
$$\rho_m = \rho_s + \rho_{4n} + \rho_3$$

Superfluid He^4

Normal He^4

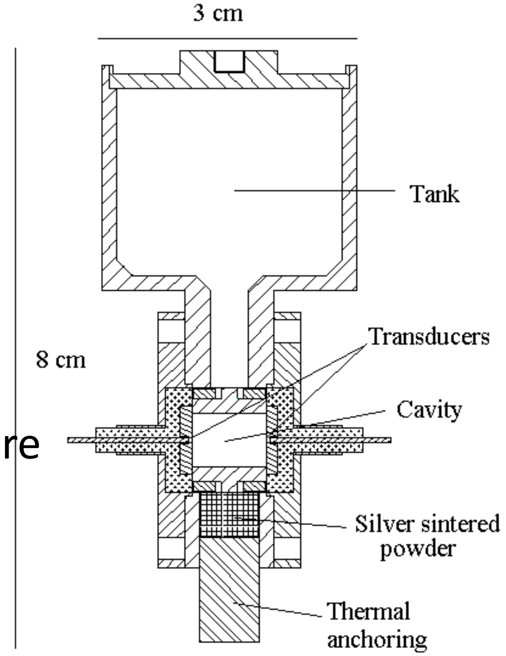
With a He^3 concentration around 1%, the liquid in a He^3-He^4 mixture exhibits the properties similar to a gas consisting of particles heavier than He^3 (approximately 2.3 times). It resembles a gas where 'pressure' is substituted by the He^3 concentration (determined by X), while the speed of sound varies with the square of temperature (T^2).

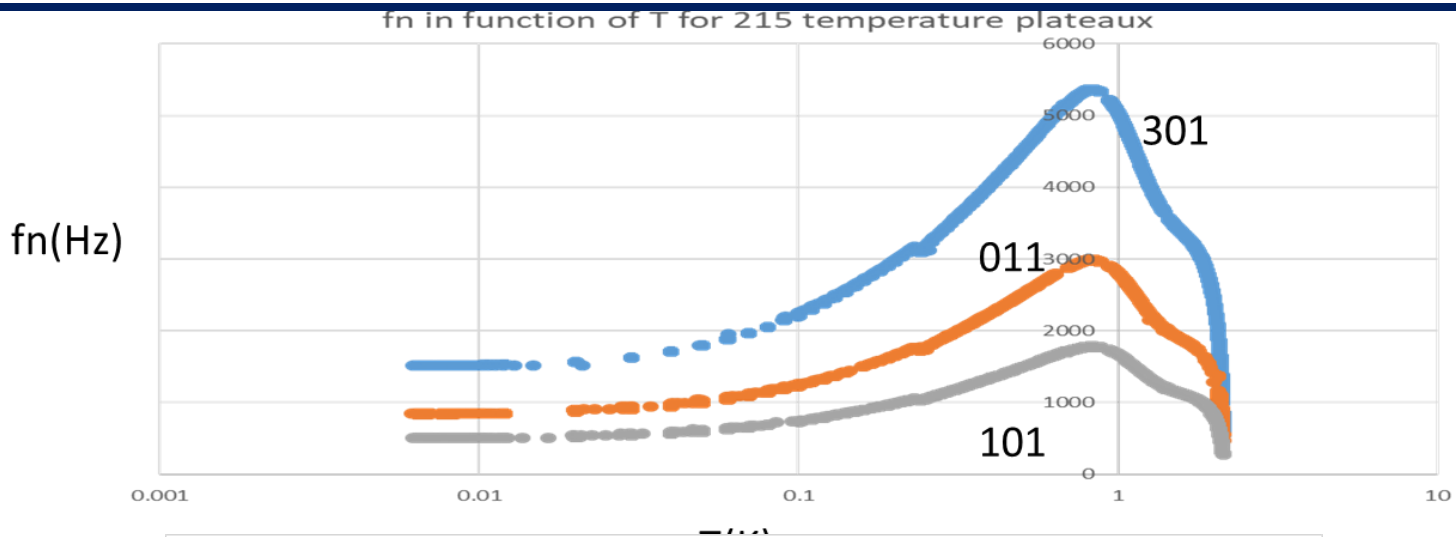
Second Sound Thermometer in the mixture of He^3–He^4

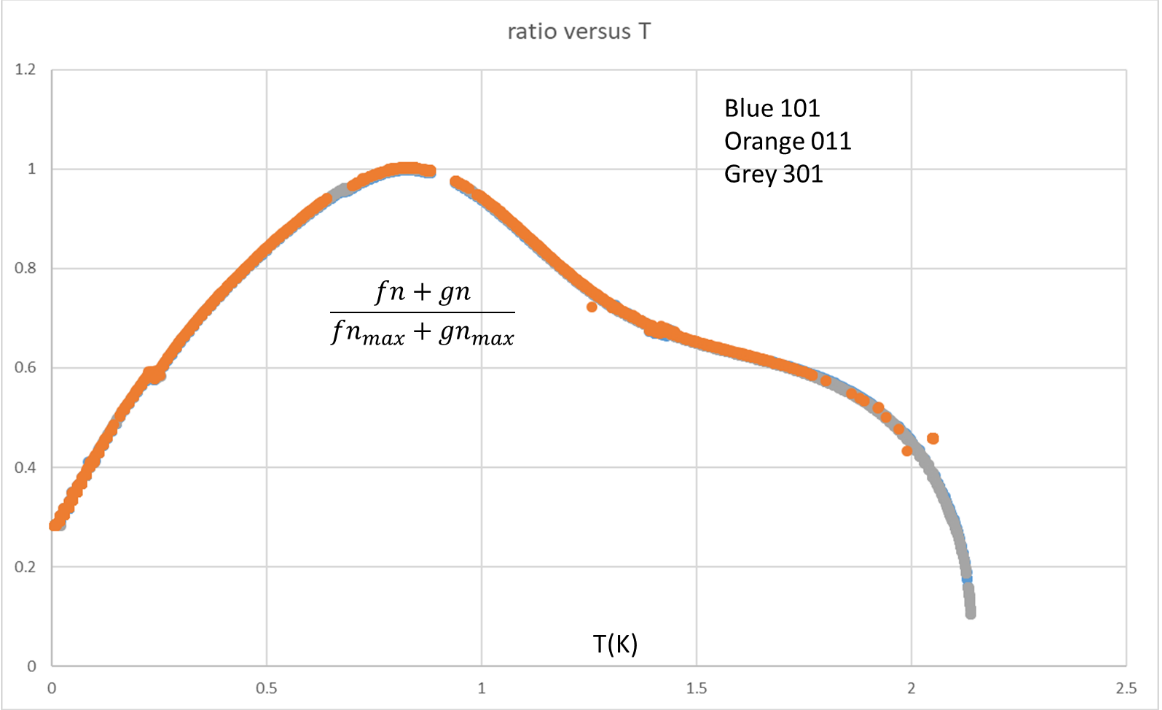


Second sound spectrum at 0.9 K in 2021

Sealed at room temperature

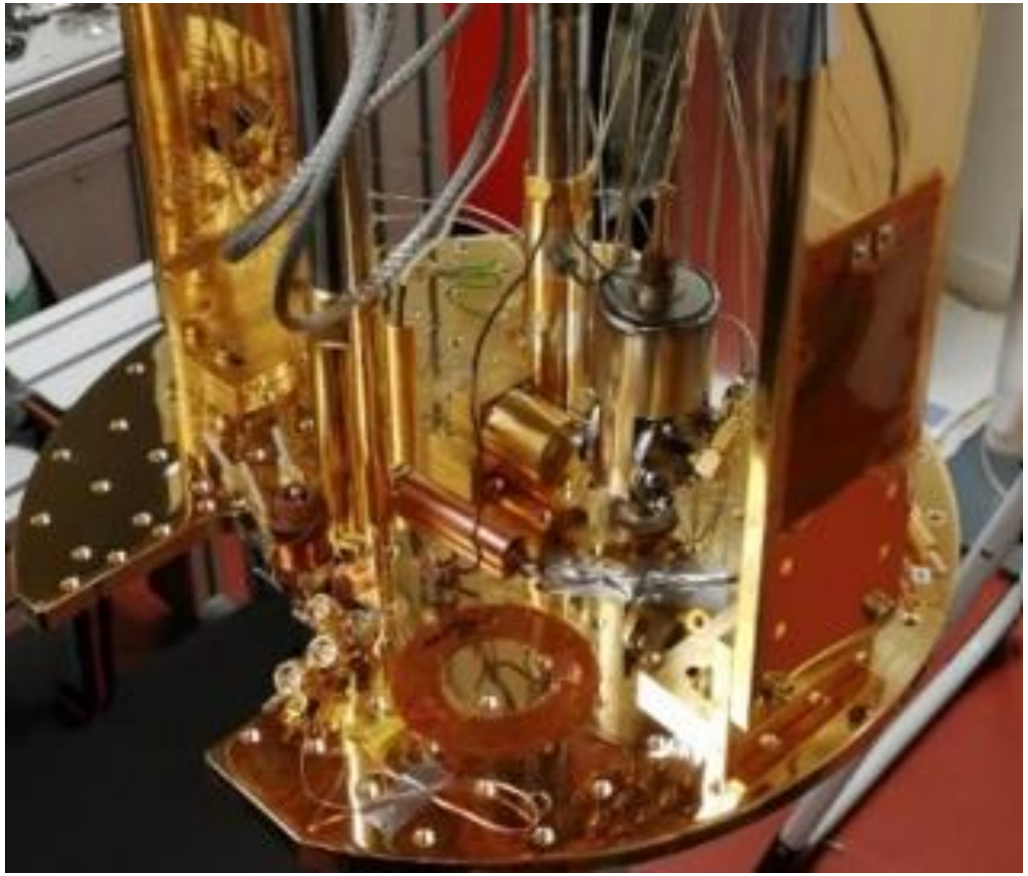



fn in function of T for 215 temperature plateaux


ratio versus T

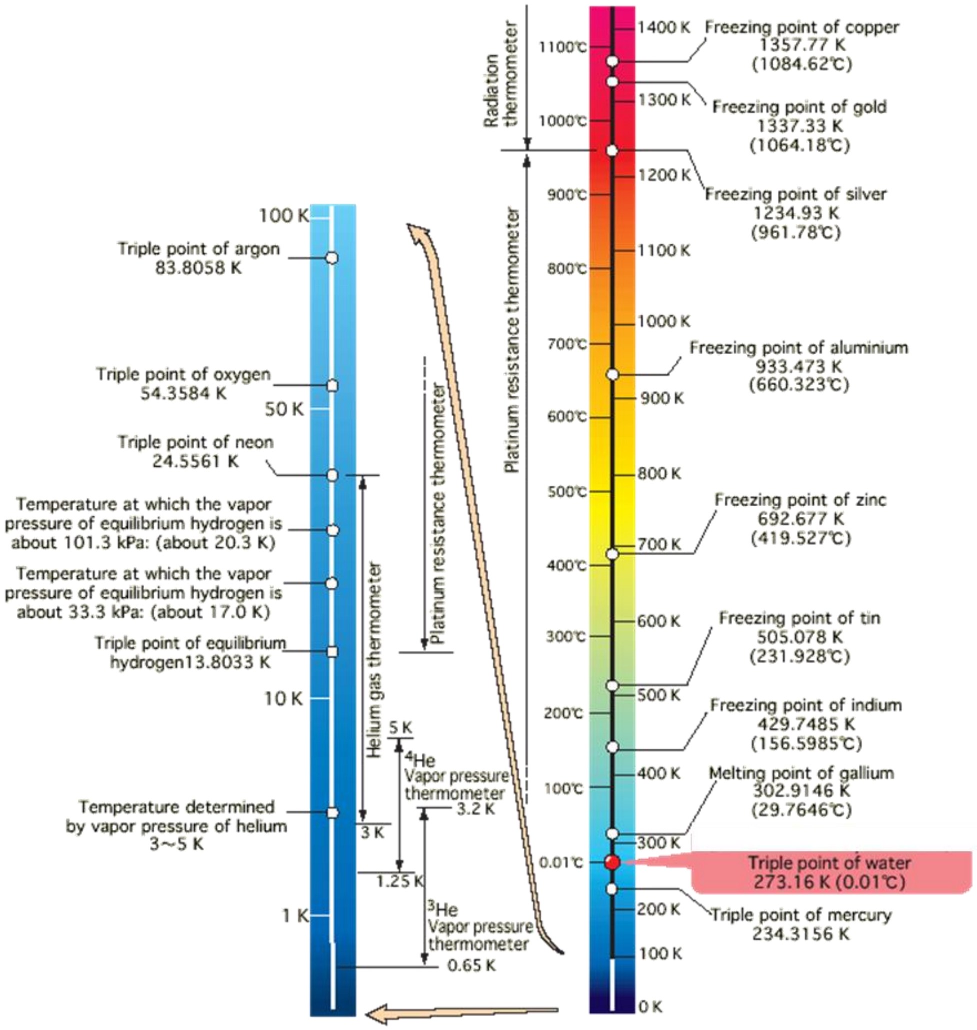
Second Sound Thermometer in the mixture of He^3–He^4

Measurement of the second sound in a ^{3}He- ^{4}He mixture with 3 acoustic modes from 8.3 mK to 2.15 K (factor 262 in T)



- Connected with thermophysical properties.
- Easy to measure and not dependent on cable impedance.
- Stable cell (over 20 years).
- Easy to install (no filling tube required).
- Redundancy in measurement (multiple modes).
- Potential for use as a primary thermometer.
- Wide range of applications.

International Temperature Scale 1990



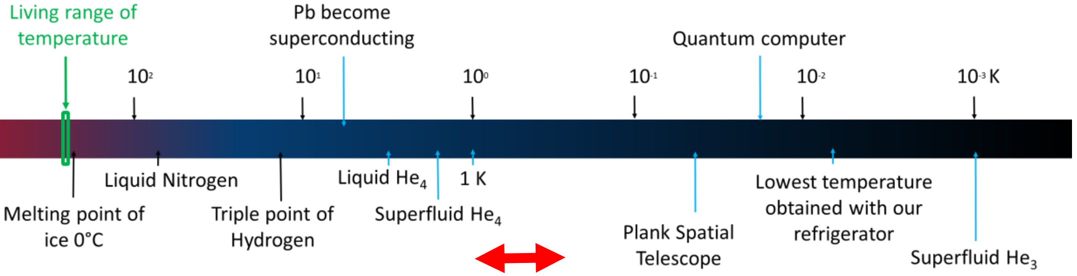
From www.NMiJ.jp

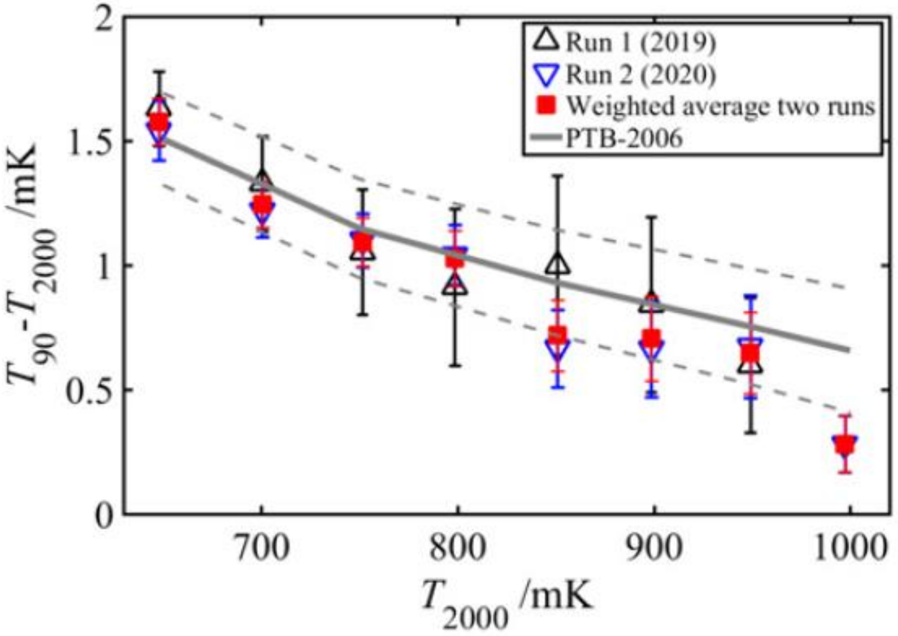
ITS90 is an approximation of the thermodynamic temperature

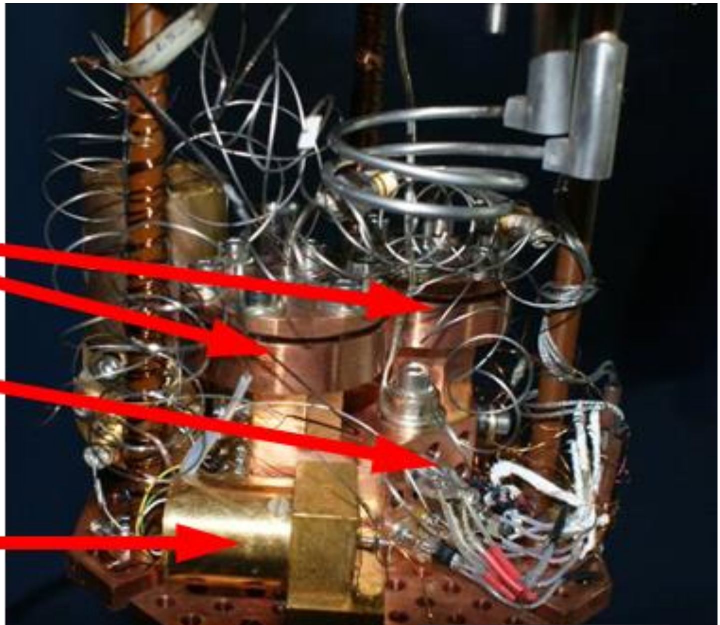
From **0,65K to 5K** ITS 90 give:

- A thermometer
- Interpolating equation

Mesurement with two scales between 0,65K and 1K T_{90}–T_{2000}







Vapor Pressure Chambers

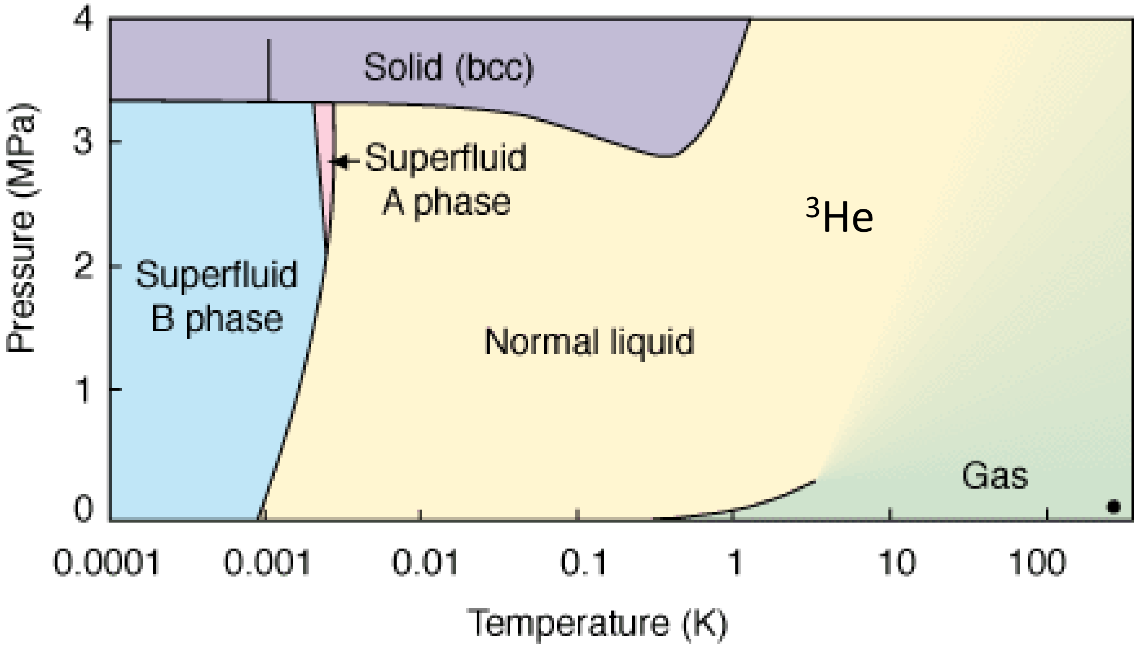
RhFe Thermometers

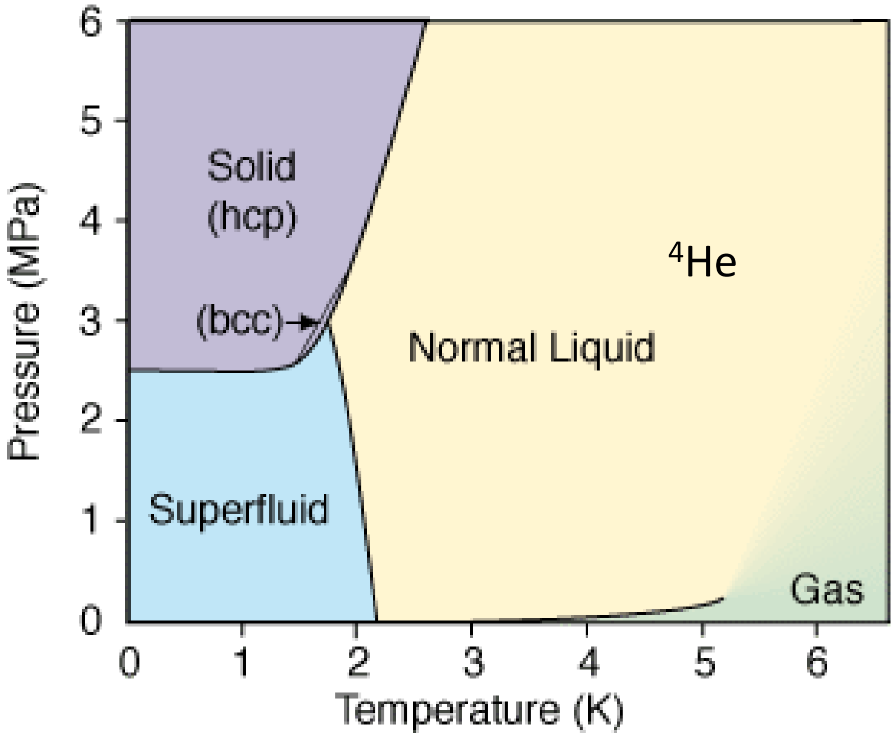
Melting-curve thermometer

Changzhao Pan

C Pan, FSparasci, M Plimmer, L Risegari, J-M Daugas, G Rouille, B Gao, L Pitre Direct comparison of ITS-90 and PLTS-2000 from 0.65 K to 1 K at LNE-CNAM Metrologia 58 (2), 025005 https://doi.org/10.1088/1681-7575/abd845

Helium-3 and Helium-4





http://ltl.tkk.fi/research/theory/helium.html

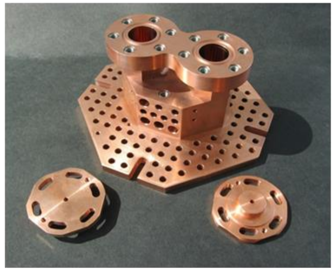
C Pan, H Zhang, G Rouillé, B Gao, L Pitre Journal of Physical and Chemical Reference Data 50 (4), Helmholtz Free Energy Equation of State for 3He–4He Mixtures at Temperatures Above 2.17 K 043102 https://doi.org/10.1063/5.0056087

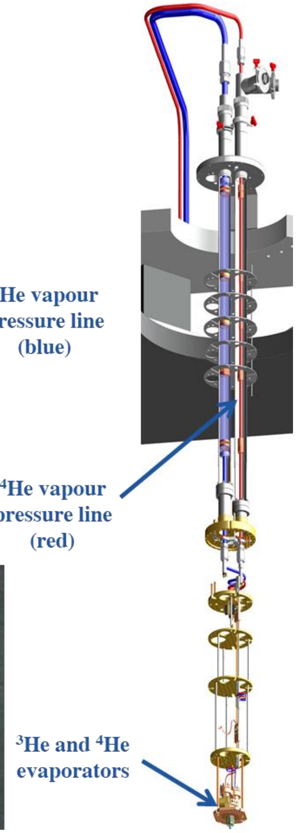
TVPHe4–TVPHe3 2.2K–3.2K

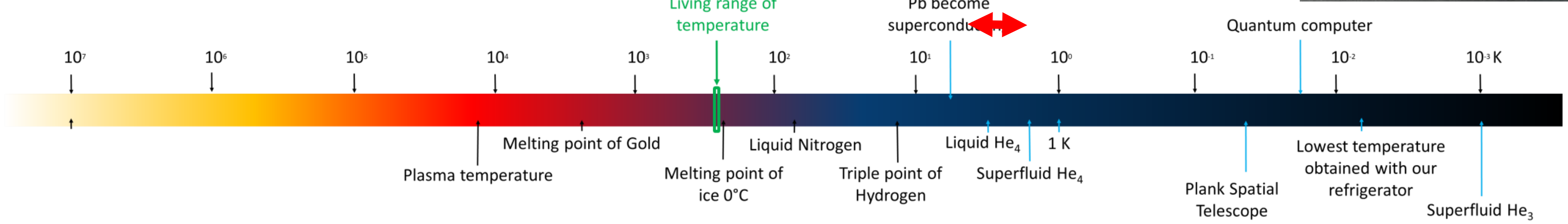
- ^{3}He–^{4}He vapour-pressure thermometer was installed in a commercial dilution refrigerator
- The system was made of one copper block:
  - two separate cylindrical vapour-pressure chambers, one for ^{3}He and the other for ^{4}He
  - Comparison block for 9 resistance thermometers

Collaboration with
INTiB (Poland)
TIPC-CAS (China)

Article at ITS10







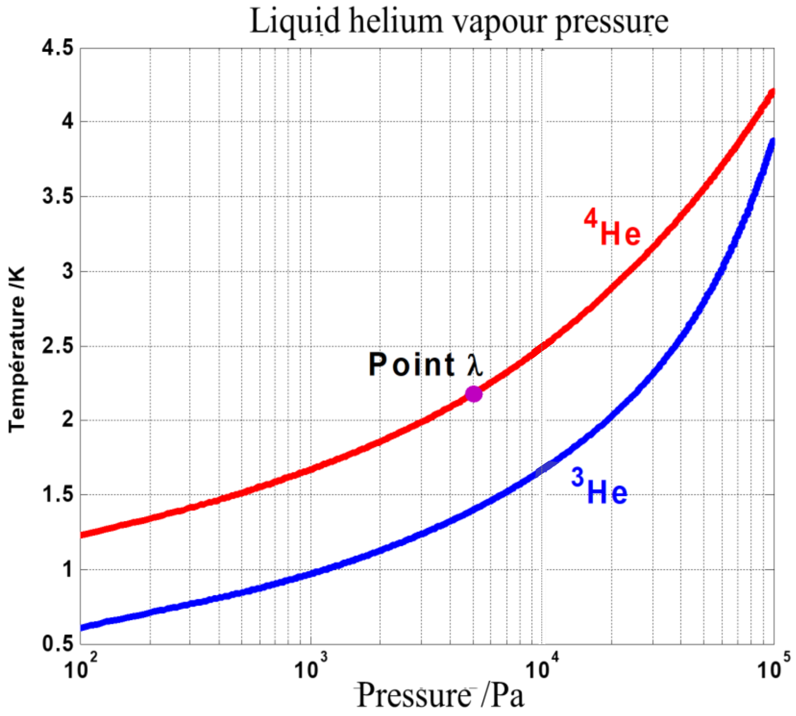

Fernando Sparasci


Aleksandra Kowal

From 0.65 K to 5.0 K helium vapour–pressure temperature equations

From ITS90

$$T_{90}, \mathrm{K} = A_0 + \sum_{i=1}^{9} A_i [(\ln(p, \mathrm{Pa}) - B)/C]^i$$



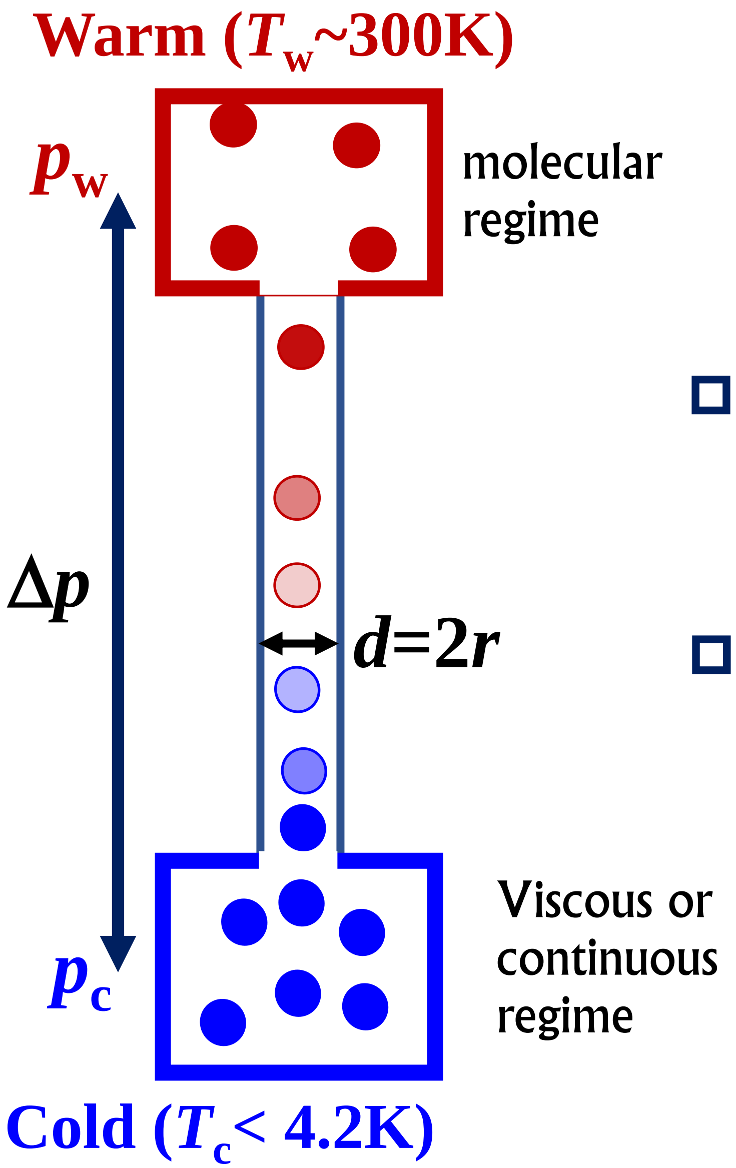
The values of the constants A_0, A_i B and C are given:

- for ^{3}He in the range 0.65 K to 3.2 K
- for ^{4}He in the range 1.25 K to 2.1768 K (the λ point) and 2.1768 K to 5.0 K.

Fernando Sparasci

Aleksandra Kowal

Thermomolecular pressure difference



A thermomolecular pressure difference appears at lower pressures when the gas mean free path is comparable to the tube diameter, and it plays an important role in vapor pressure thermometry.

☐ **Ideal case**

$$\frac{p_w}{p_c} = \left(\frac{T_w}{T_c}\right)^{1/2}$$

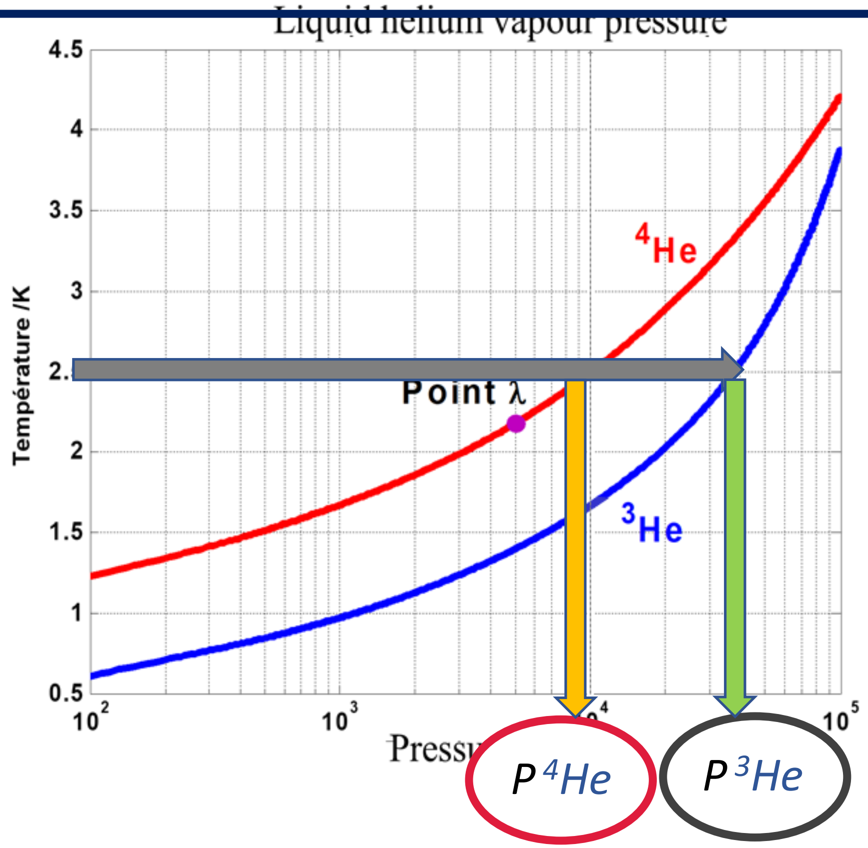
☐ **In practice**

complicated

$$\frac{\Delta p}{p_c} = \frac{p_w - p_c}{p_c} = \frac{2\times 10^{-9}}{\left(\dfrac{rp_c}{\mathrm{m}\cdot\mathrm{Pa}}\right)^{1.99}}\left[\left(\frac{T_w}{K}\right)^{2.27} - \left(\frac{T_c}{K}\right)^{2.27}\right]$$

No general theory is applicable in all possible experimental cases. More understanding is needed

3He - 4He vapour pressure thermometer at LNE-CNAM



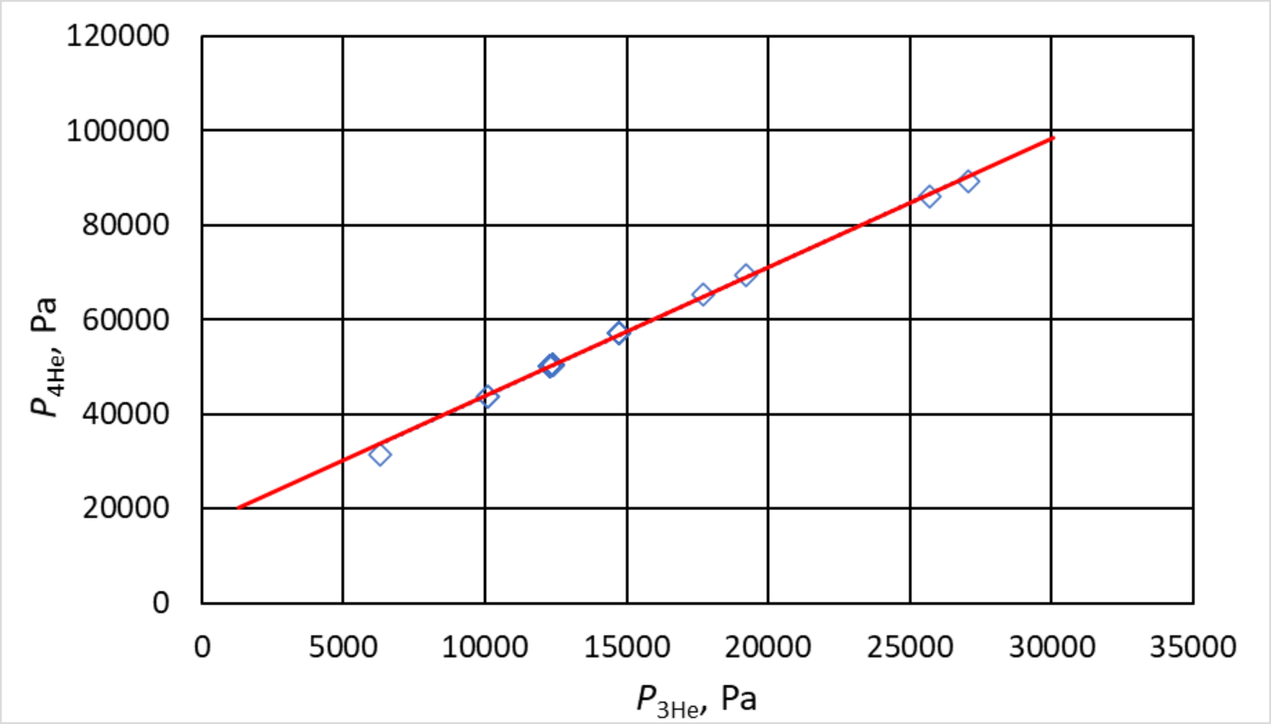
$$P\,{}^4He = P_{measured} + \Delta P_{calibration} + \Delta P_{hydrostatic} + \Delta P_{thermomolecular}$$

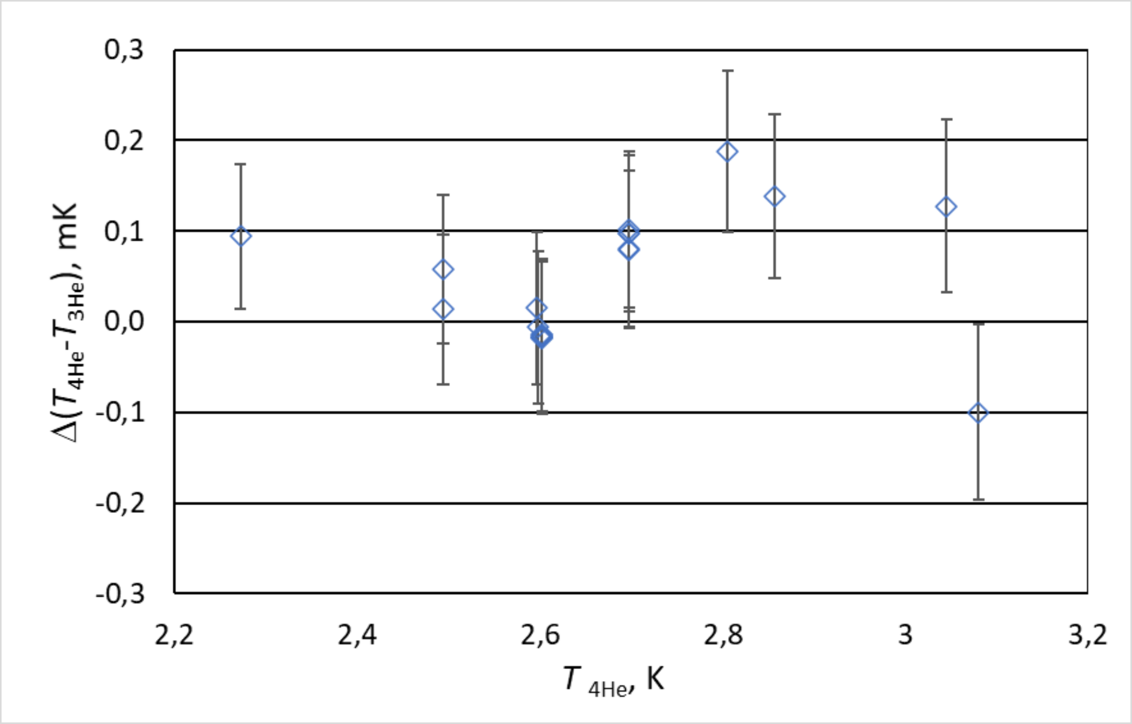
$$P\,{}^3He = P_{measured} + \Delta P_{calibration} + \Delta P_{hydrostatic} + \Delta P_{thermomolecular}$$


Fernando Sparasci


Aleksandra Kowal

TVPHe4–TVPHe3 2.2K–3.2K



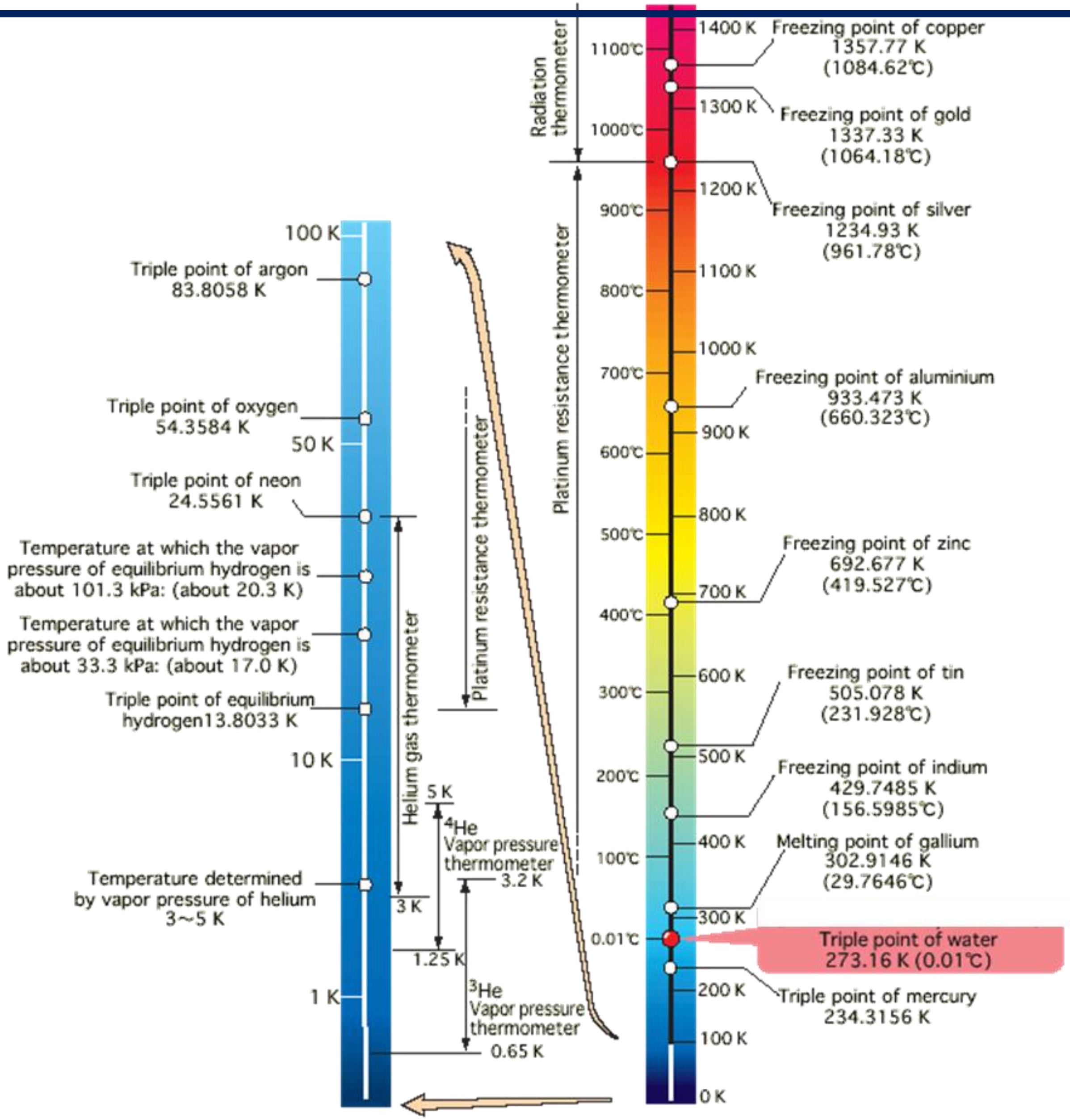


The Direct Comparison of 3He and 4He Vapor-Pressure Thermometers at LNE-Cnam within their Overlapping Temperature Range. A. Kowal, F. Sparasci *et al. Accepted for publication on the* ITS10 *symposium*


Fernando Sparasci


Aleksandra Kowal

International Temperature Scale 1990



ITS90 is an approximation of the thermodynamic temperature

From 3K to 24,5 K IST 90 give:

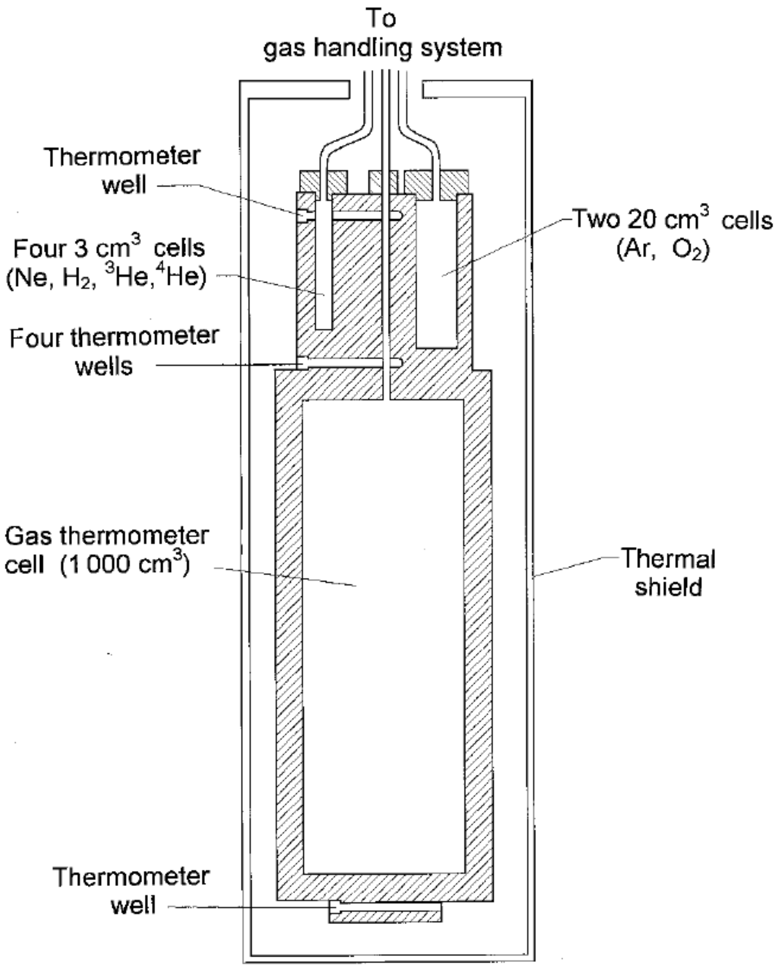
A thermometer

Fix point

And interpolating equation

From www.NMiJ.jp

But a very complex ITS90 scale below 25K



As far as I know, the most recent implementation of ITS90 for temperatures below 25K occurred in 1996 at NIST. Since then, the only method used worldwide has been the wire scale.
However, there is an issue with the wire scale in that it relies on a resistive thermometer that is no longer being manufactured.

Does the primary thermometry is the solution?

Pro

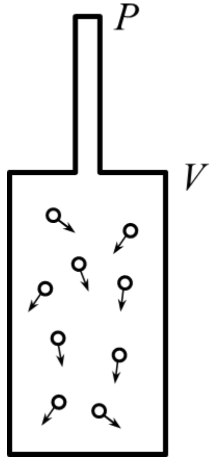
- Pollution has minimal effect at temperatures below 25K.
- Gases with higher density yield stronger signals.
- Progress has been made in ab initio calculations.
- There is a well-established model in place.
- Perturbations from the shell have been eliminated.

Con

- Hydrostatic correction must be determined.
- Multiple measurements are necessary at identical temperatures.
- Analysis is complex.
- Need to know the accommodation coeficiant

Typical primary thermometry in low temperature

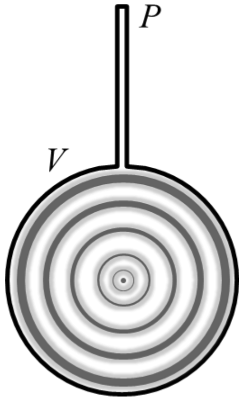
Constant Volume Gas Thermometry (CVGT)



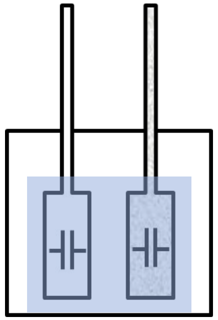
$$\frac{1}{k}\cdot\frac{pV}{n_m N_A}$$

Acoustic Gas Thermometry (AGT)

$$\frac{1}{k}\cdot\frac{u_0{}^2 M}{\gamma_0 N_A}$$



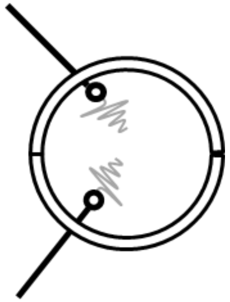
T



$$\frac{1}{k}\cdot\frac{p\alpha_0}{(\varepsilon-\varepsilon_0)}$$

Dielectric-constant gas thermometry (DCGT)

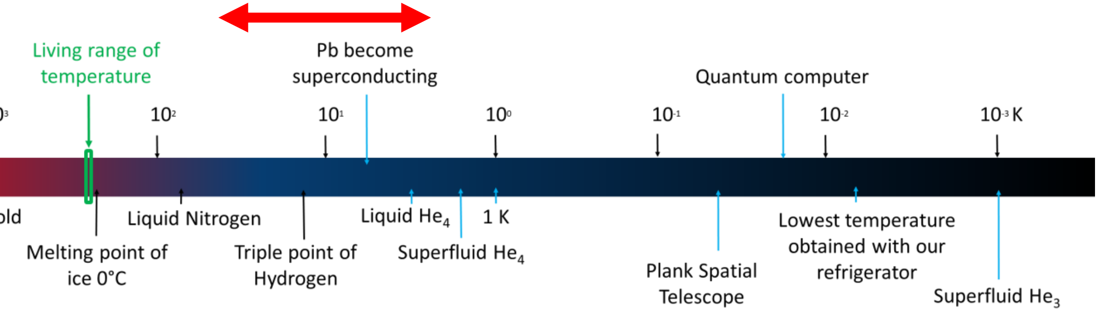
$$\frac{1}{k}\cdot\frac{p\alpha_0}{(n^2-1)\varepsilon_0}$$



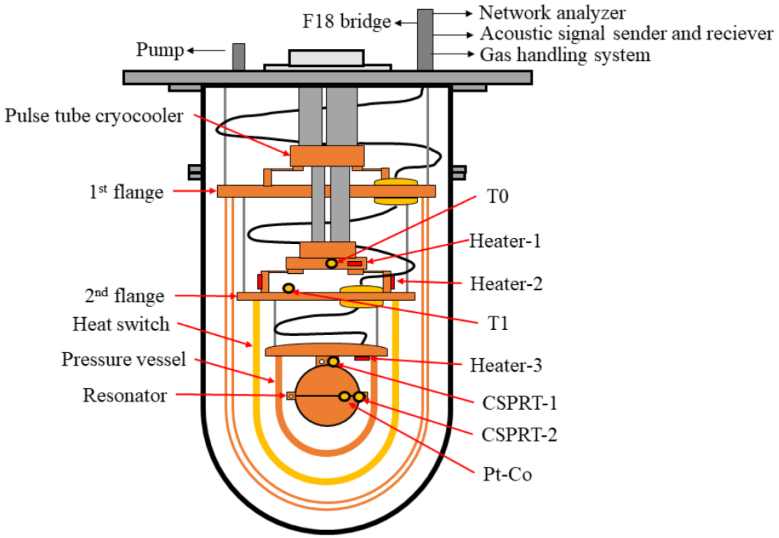
$$n\approx\frac{f_0}{f_p}$$

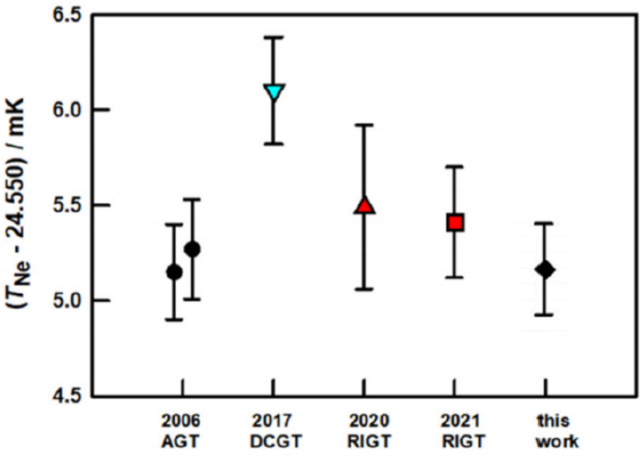
Refractive-index gas thermometry (RIGT)

AGT and the world's first primary thermometry calibration at Low temperature



We used a quasi-spherical AGT to calibrate the Pt–Co RS144.08 resistance thermometer with the result: (9.607 2558 ± 0.000 006 3) Ω at the thermodynamic temperature *T* =(24.55499 ± 0.000 16) K





Changzhao Pan, Fernando Sparasci, Haiyang Zhang, Pascal Gambette, Mark Plimmer, Dario Imbraguglio, Roberto Maria Maria Gavioso, Michael R Moldover, Bo Gao, Laurent Pitre "Acoustic measurement of the triple point of neon TNe and thermodynamic calibration of a transfer standard for accurate cryogenic thermometer" 2021 Metrologia 58 045006

Does the relative primary thermometry is the solution?

Pro

- Pollution has minimal effect at temperatures below 25K.
- Gases with higher density yield stronger signals.
- Progress has been made in ab initio calculations.
- There is a well-established model in place.
- Analysis is straightforward.
- Measurements can be taken quickly.
- Uncertainty is equivalent to that of the reference temperature.

Con

- Hydrostatic correction must be determined.
- Perturbations from the shell are possible.
- Need to know the accommodation coeficiant

Theory of SPRIGT

☐ Lorentz–Lorenz equation:

$$T \approx \frac{3A_\varepsilon p}{R[n^2(T,p)-1]}$$

☐ If *p* is fixed at 2 temperatures:

$$\frac{T}{T_\mathrm{ref}} \approx \frac{n^2(T_\mathrm{ref},p)-1}{n^2(T,p)-1}$$

☐ n^2 can be estimated by the ratio of resonance frequencies:

$$n^2(T,p) \approx \left(\frac{(f_\mathrm{m})_{T,0}}{(f_\mathrm{m})_{T,p}}\right)^2$$

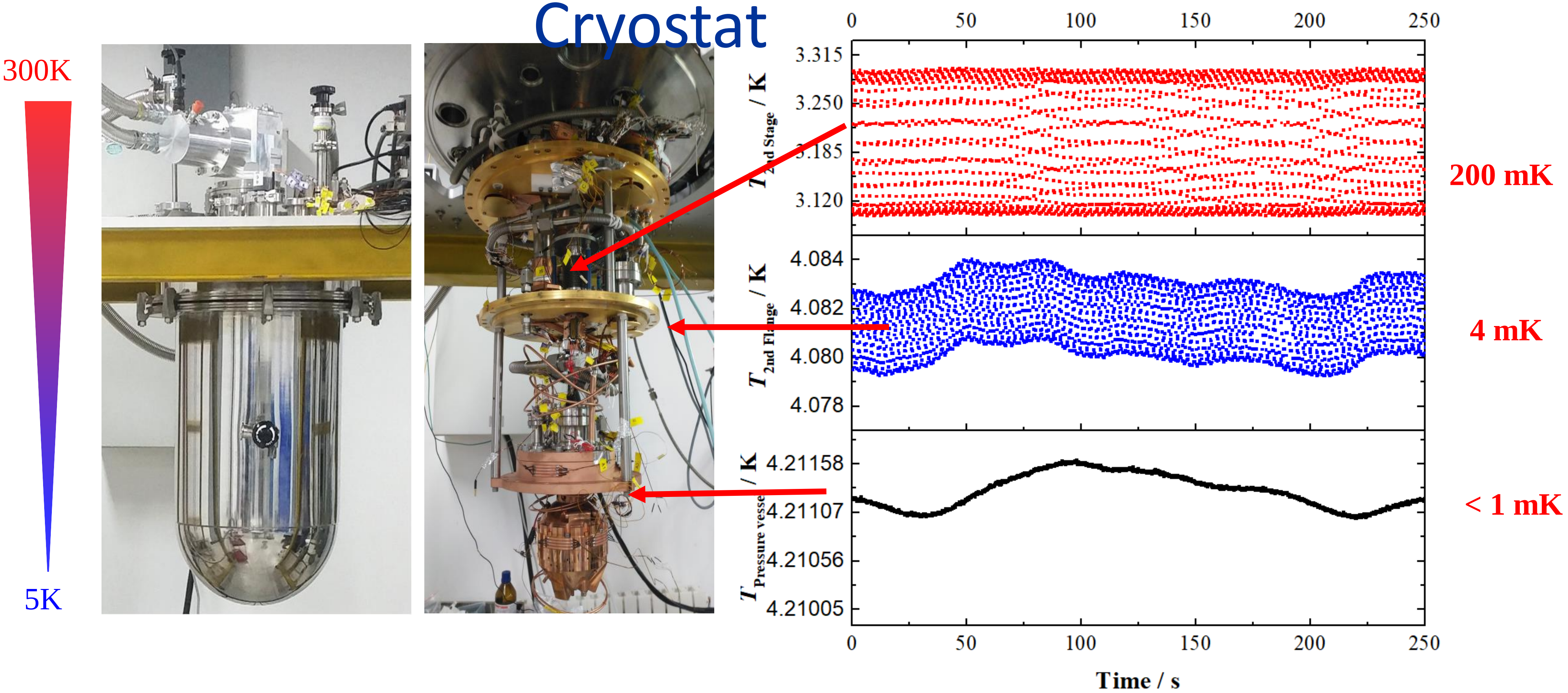
1. Ratio is used to reduce the absolute pressure effect
2. Advance of the "*ab initio*" calculation of gas thermal-properties
3. High accuracy of microwave resonances

We need stable *p, T* and good measurement of f_m

Bo Gao
(Bo)

Cryostat

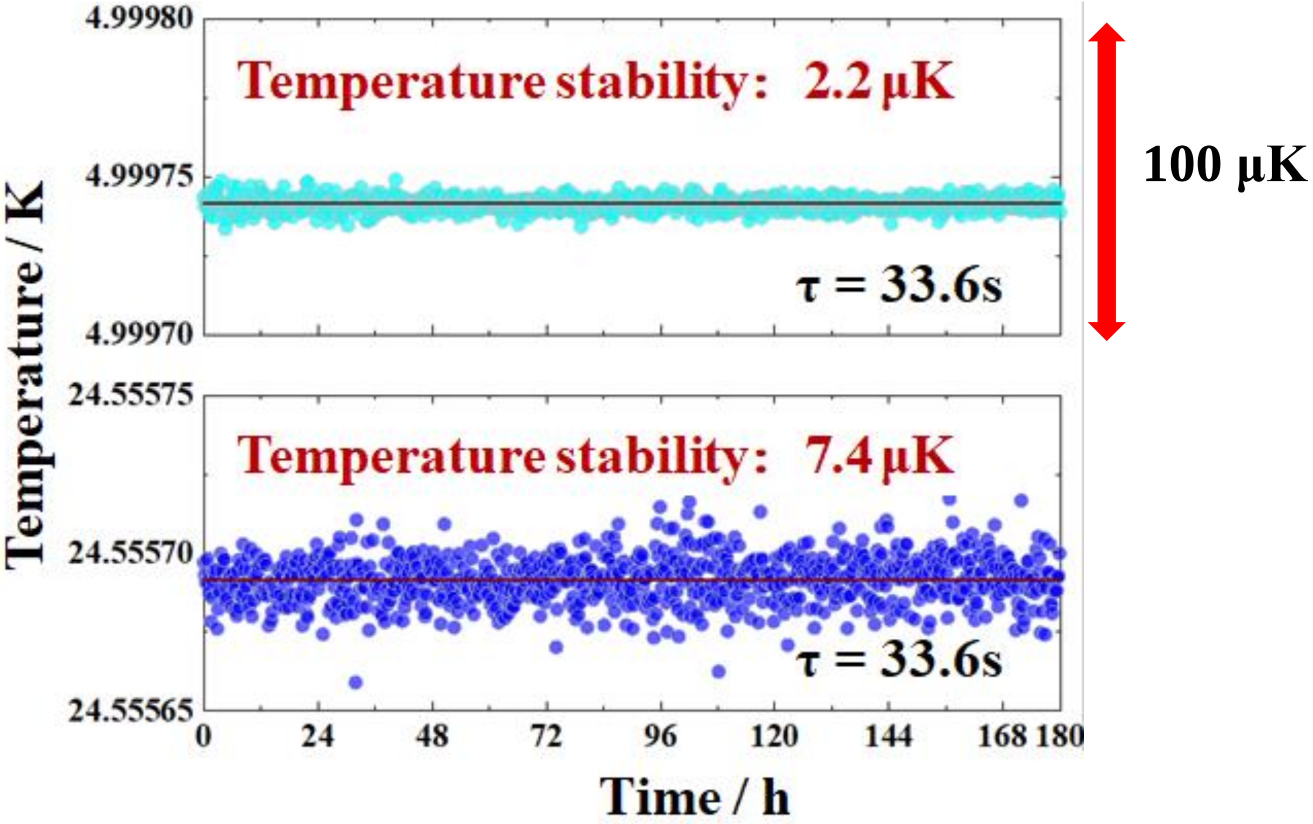
Cryostat



Temperature oscillation is reduced from 200 mK to < 1 mK with passive elements

Bo Gao
(Bo)

Temperature control in vacuum



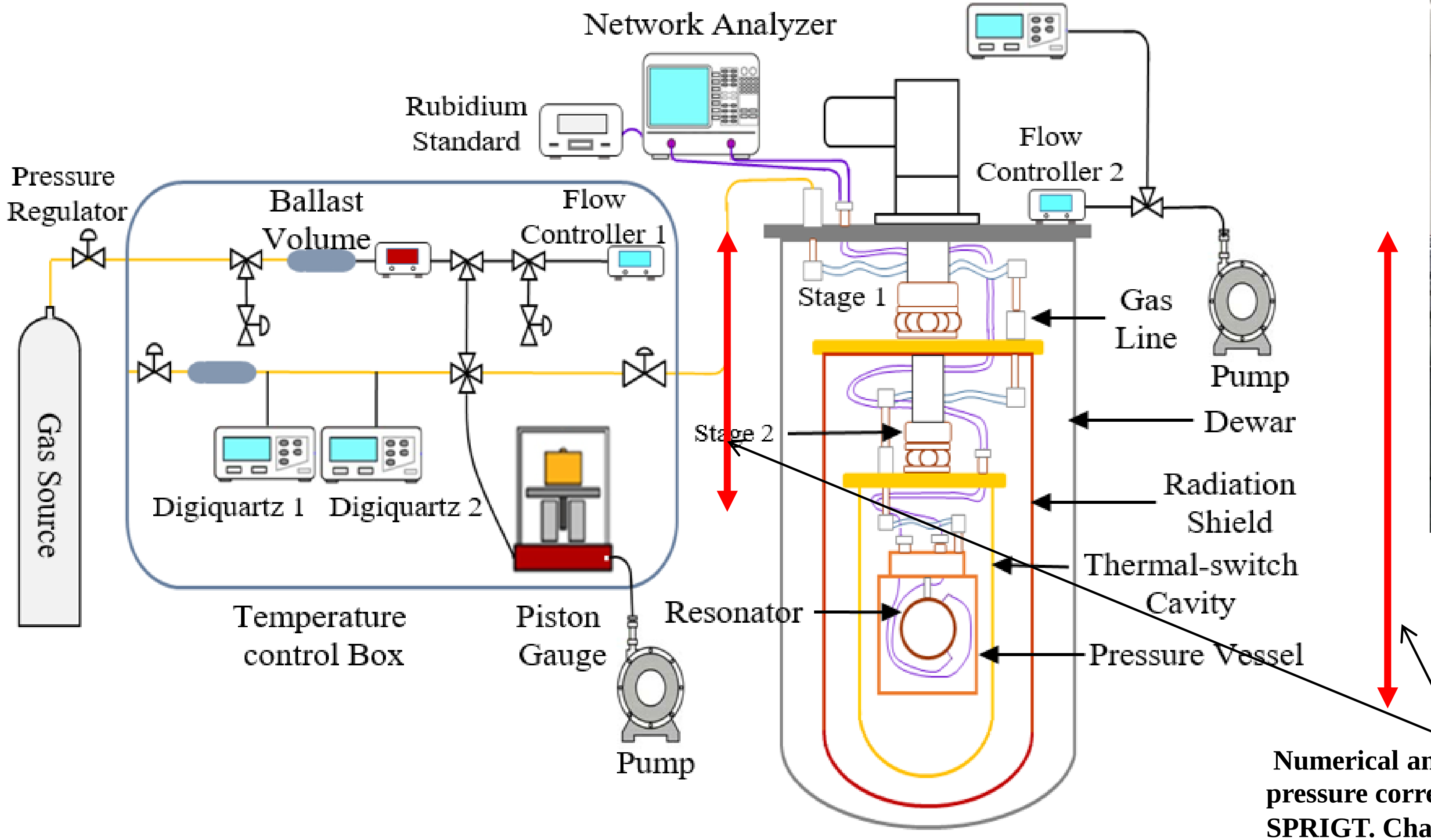
1. Chinese SPRIGT realizes high temperature stability in the range of 5–25 K. ***Science Bulletin***. 2018, 63(12), 733–734.
2. Realization of an ultra-high precision temperature control in a cryogen-free cryostat. ***Review of Scientific Instruments***, 2018, 89, 104901
3. Thermal response characteristics of a SPRIGT primary thermometry system. ***Cryogenics.*** 2019, 97, 1-6.

One-week stability is better than 8 μK in vacuum

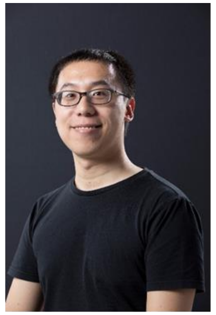
Bo Gao
(Bo)

SPRIGT system

Schematic diagram of SPRIGT



Numerical and experimental study of the hydrostatic pressure correction in 1 gas thermometry: A case in the SPRIGT. Changzhao Pan et al. International Journal of Thermophysics (2020) 41:108



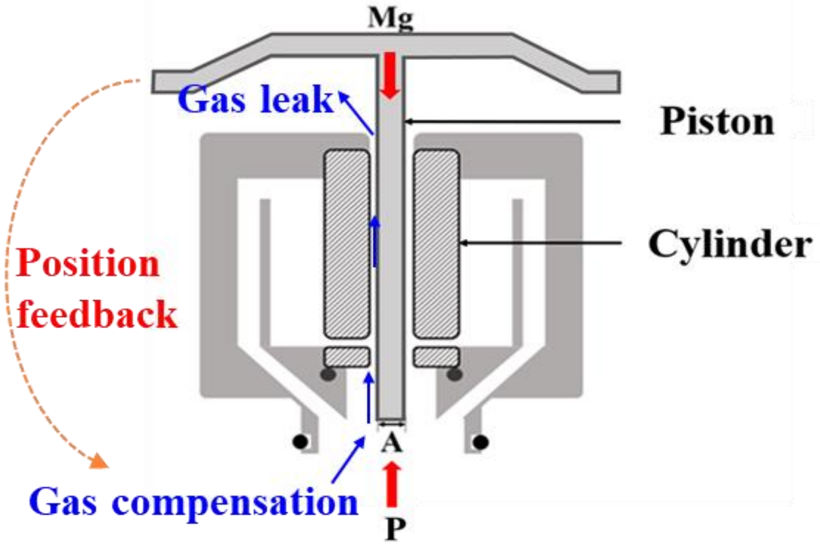
Changzhao Pan

Pressure control system

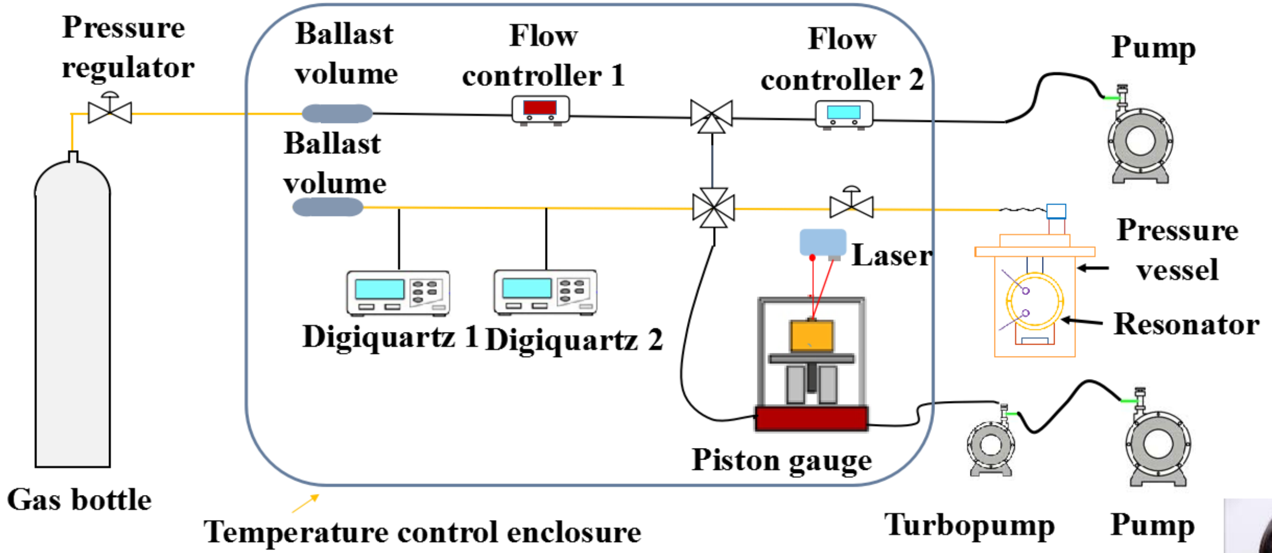
Challenge: The pressure cannot be controlled for a long time due to the piston falling caused by the unavoidable leak.

Solution: Gas compensation system

Piston gauge



Gas compensation system



1. Ultra-stable pressure is realized for Chinese Single Pressure Refractive Index Gas Thermometry in the range 30 kPa to 90 kPa. ***Science Bulletin***, 2018, 63:1601-1603.

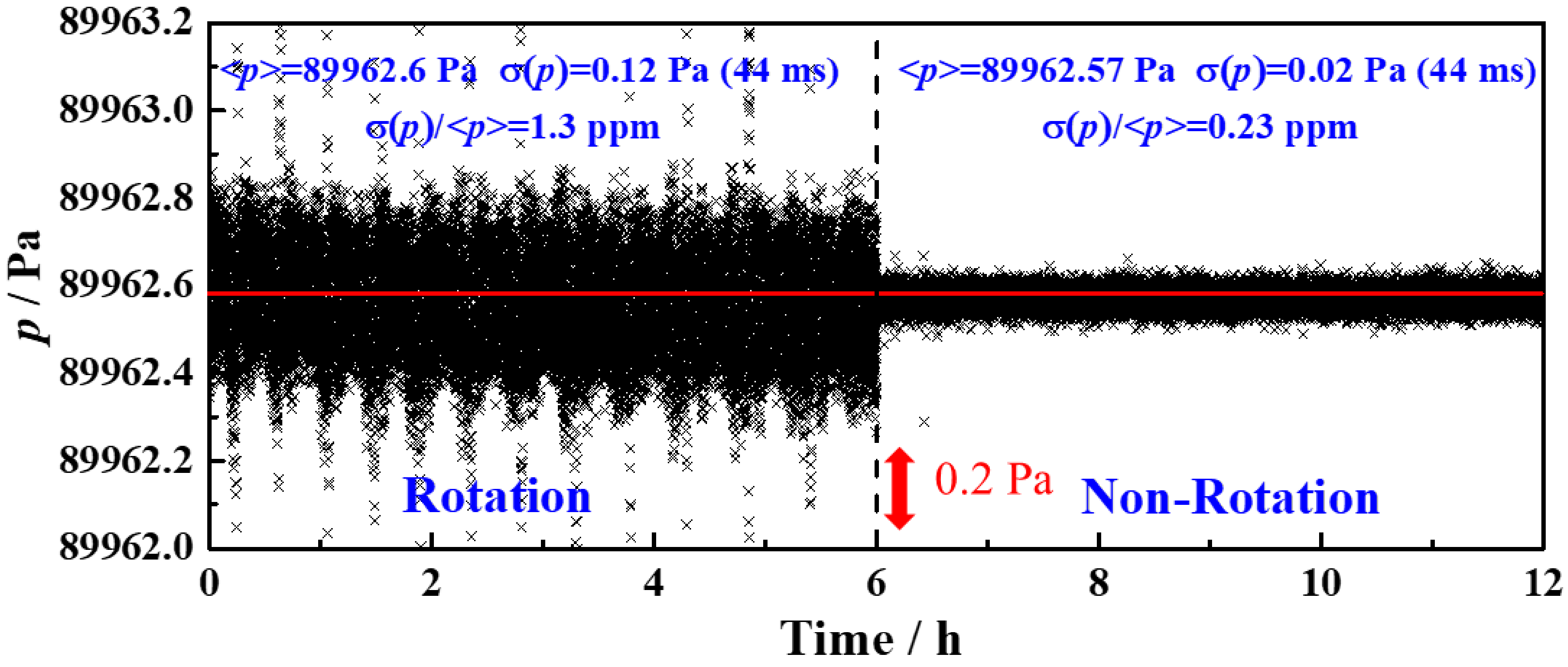
Bo Gao
(Bo)

This method can realize long term pressure stability

Piston rotation

Challenge: The rotation makes the piston swing. It's hard to control the piston position.

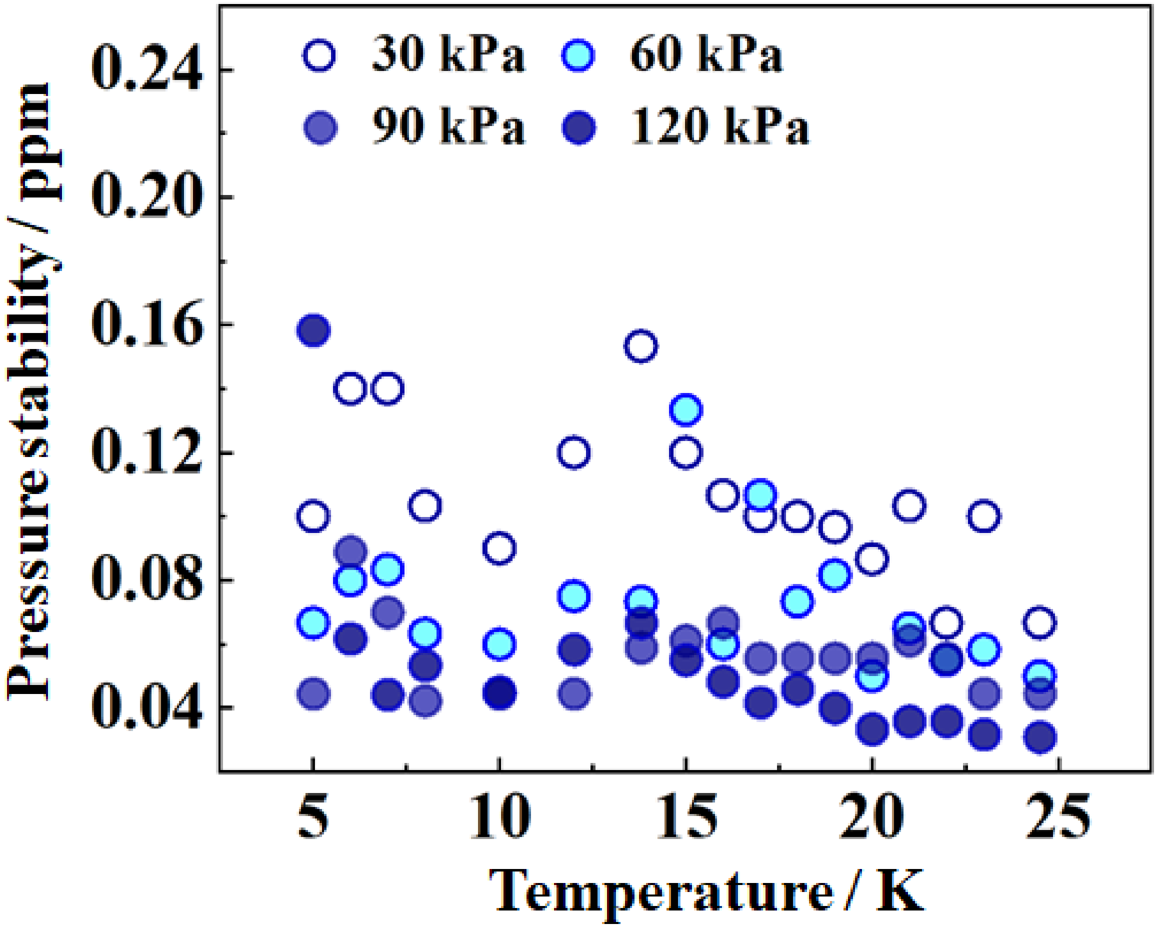
Solution: Non-rotation



The pressure stability is improved without changing the mean value

Bo Gao
(Bo)

Connection to cryostat

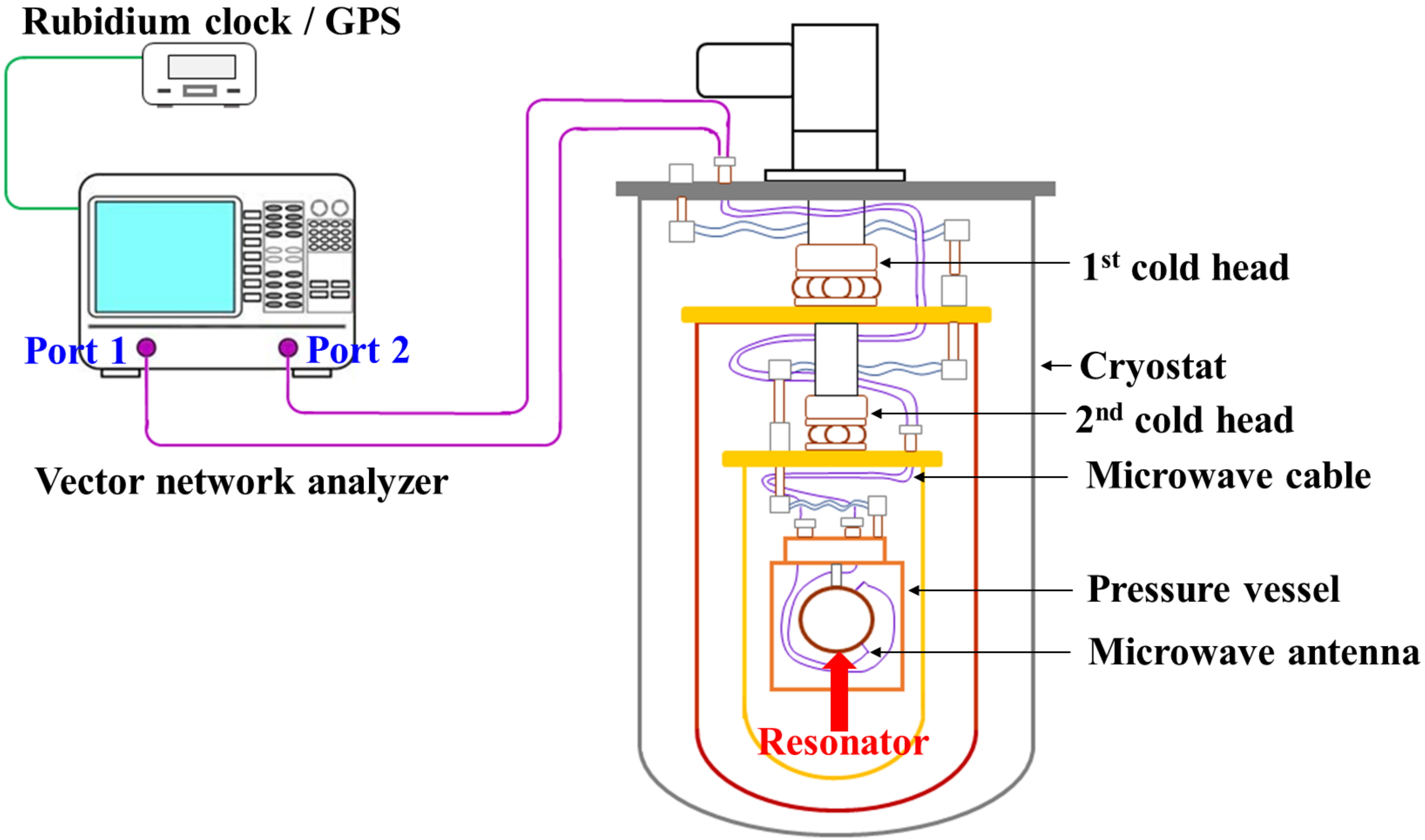


1. Realization of ppm level pressure stability for primary thermometry using a primary piston gauge, ***Measurement***, 2020, 160: 107807.

High stability pressure(< 0.16 ppm) is realized from 5 K – 24.5 K

Bo Gao
(Bo)

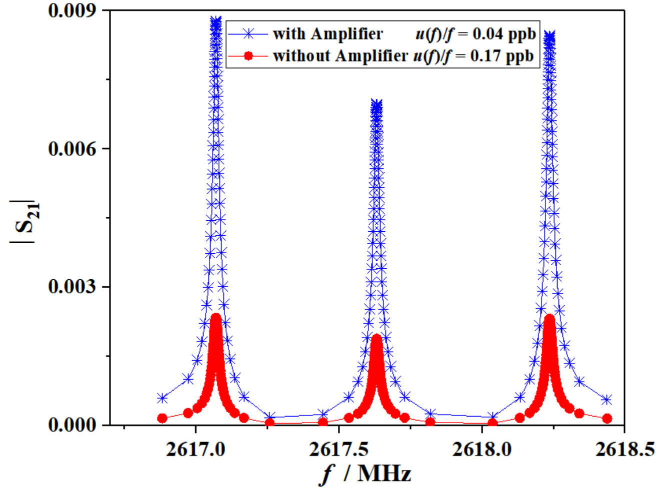
Microwave measurement system



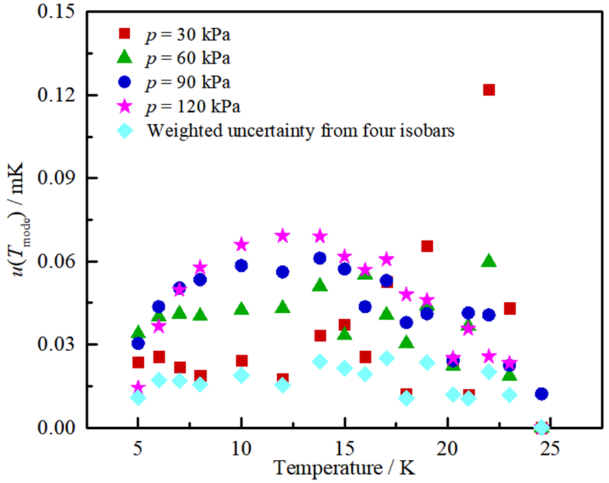
1. A high-stability quasi-spherical resonator in SPRIGT for microwave frequency measurements at low temperatures. ***Science Bulletin***, 2019, 64:286-288.
2. Resonance frequency measurement with accuracy and stability at the 10^{-12} level in a copper microwave cavity below 26 K by experimental optimization, ***Measurement Science and Technology***, 2020, 31: 075011.

Bo Gao
(Bo)

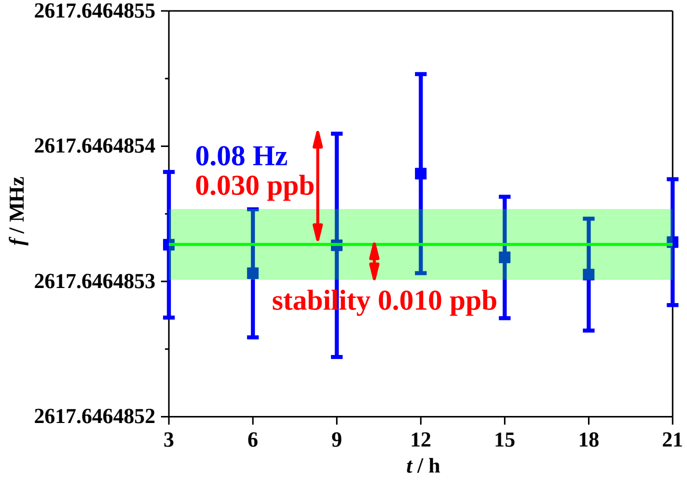
Experimental results



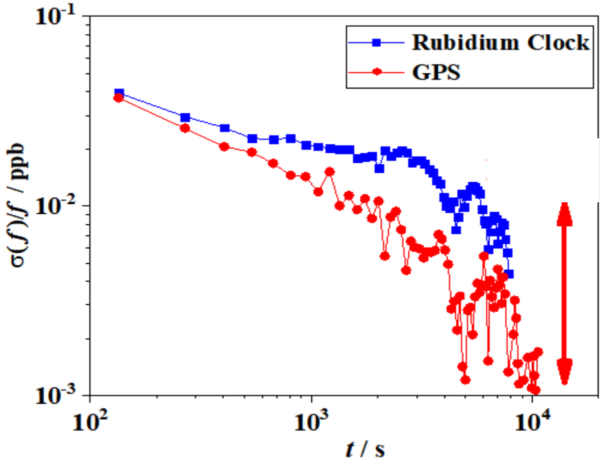
(a) S21 parameter of TM11 mode at 5 K with and without amplifier.



(b) Thermodynamic temperature difference from TM11, TE11 and TE13 modes at 30-120kPa.



(c) High-accuracy measurement on TM11 at 8 K under vacuum.



(d) Allen variance of TM11 mode at 5 K with FS725 and GPS.

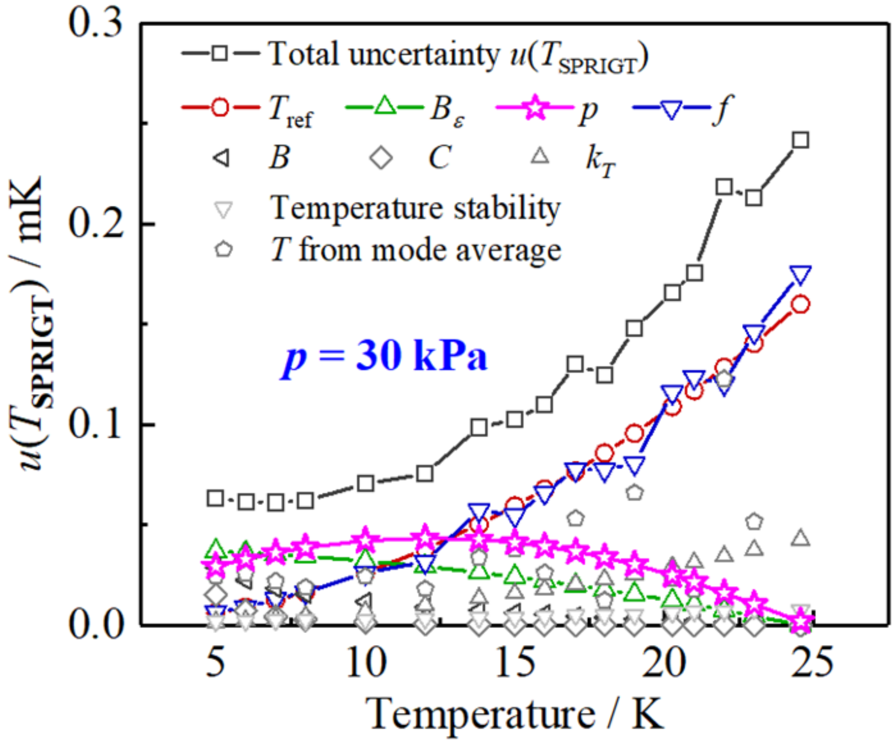
10ppt!!!

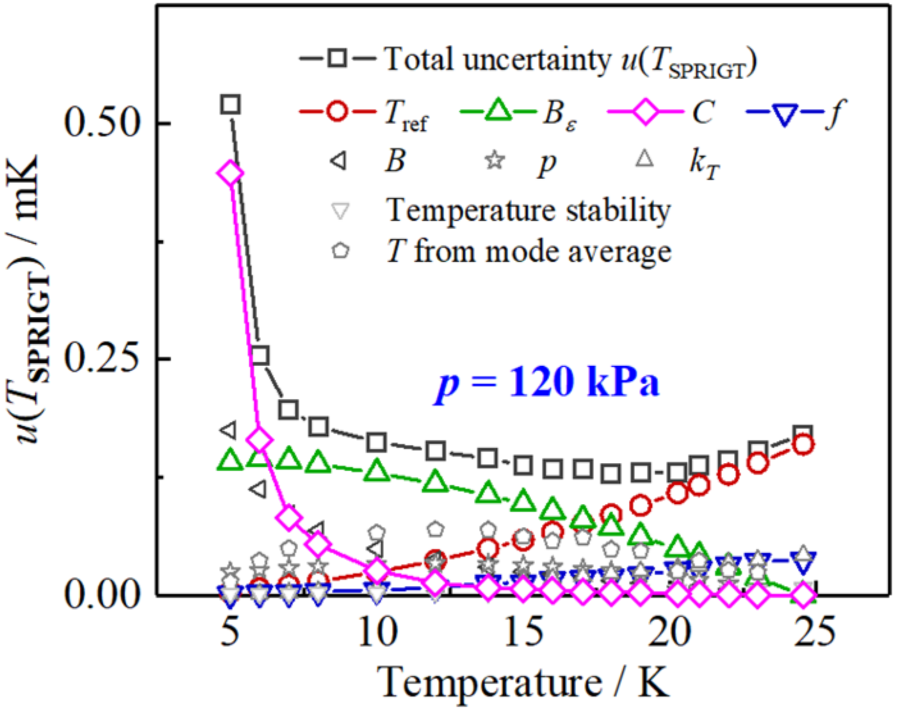
11 Digits

Bo Gao
(Bo)

in practice < 0.01 ppb, good mode consistency on T_{SPRIGT}

Uncertainty budget

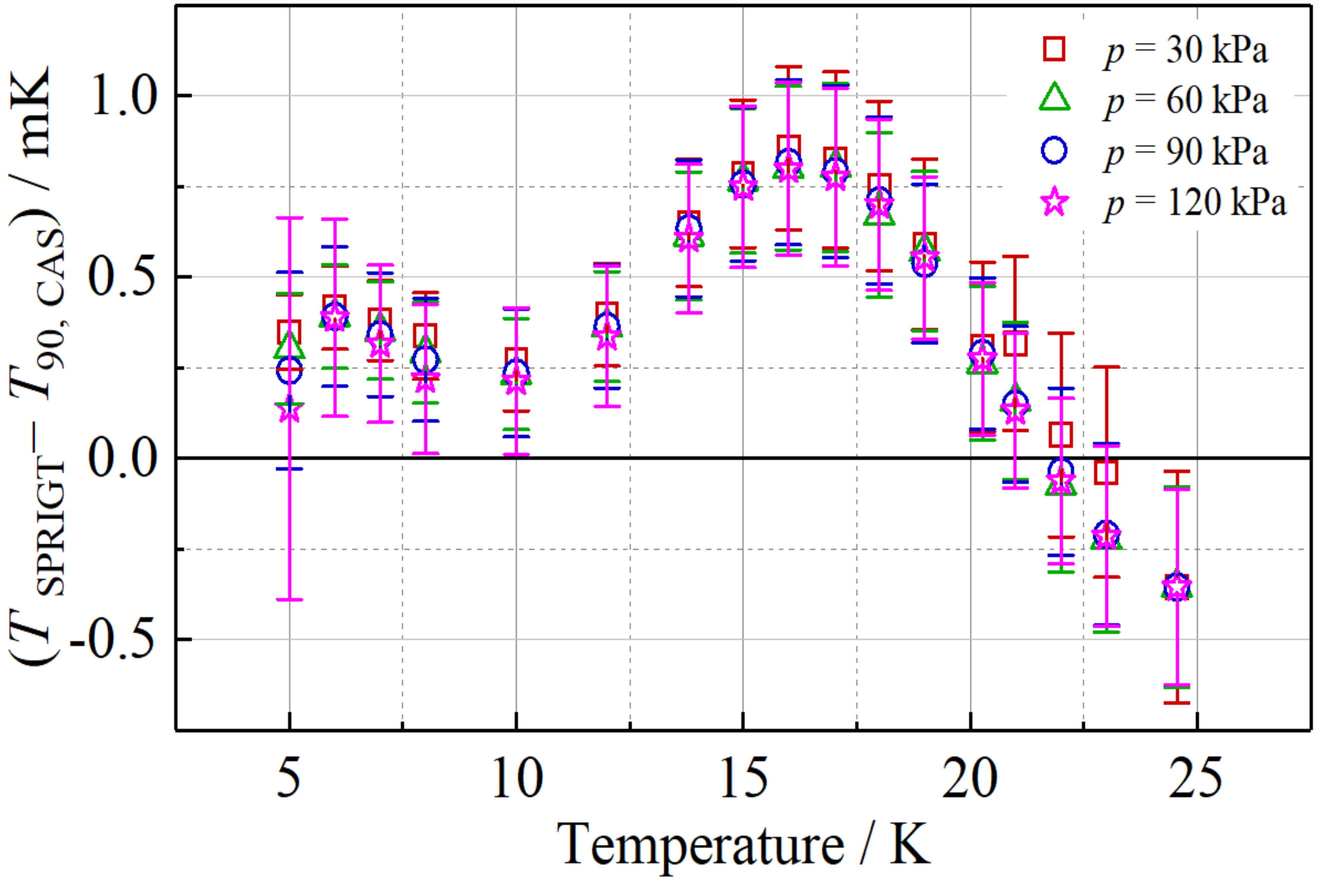




Main uncertainty components: T_{ref} and C

Bo Gao
(Bo)

T–T90 at 4 pressures



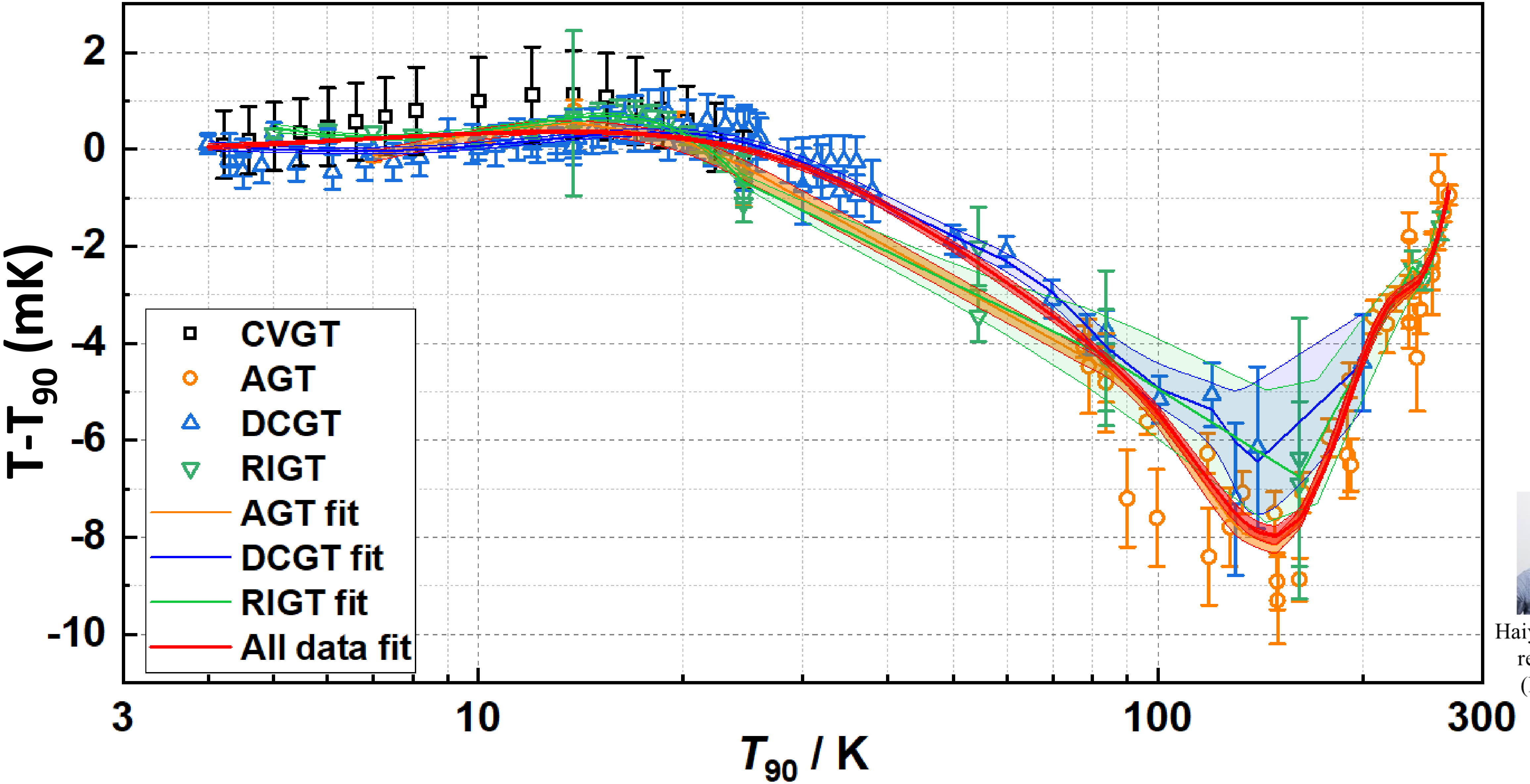
Different pressures give same T-T_{90}, Good repeatability and consistency

Gao B, Zhang H, Han D, Pan C, Chen H, Song Y, Liu W, Hu J, Kong X, Sparasci F, Plimmer M, Luo E, Pitre L “Measurement of thermodynamic temperature between 5 K and 24.5 K with single-pressure refractive-index gas thermometry” Metrologia 57 065006

33 pages

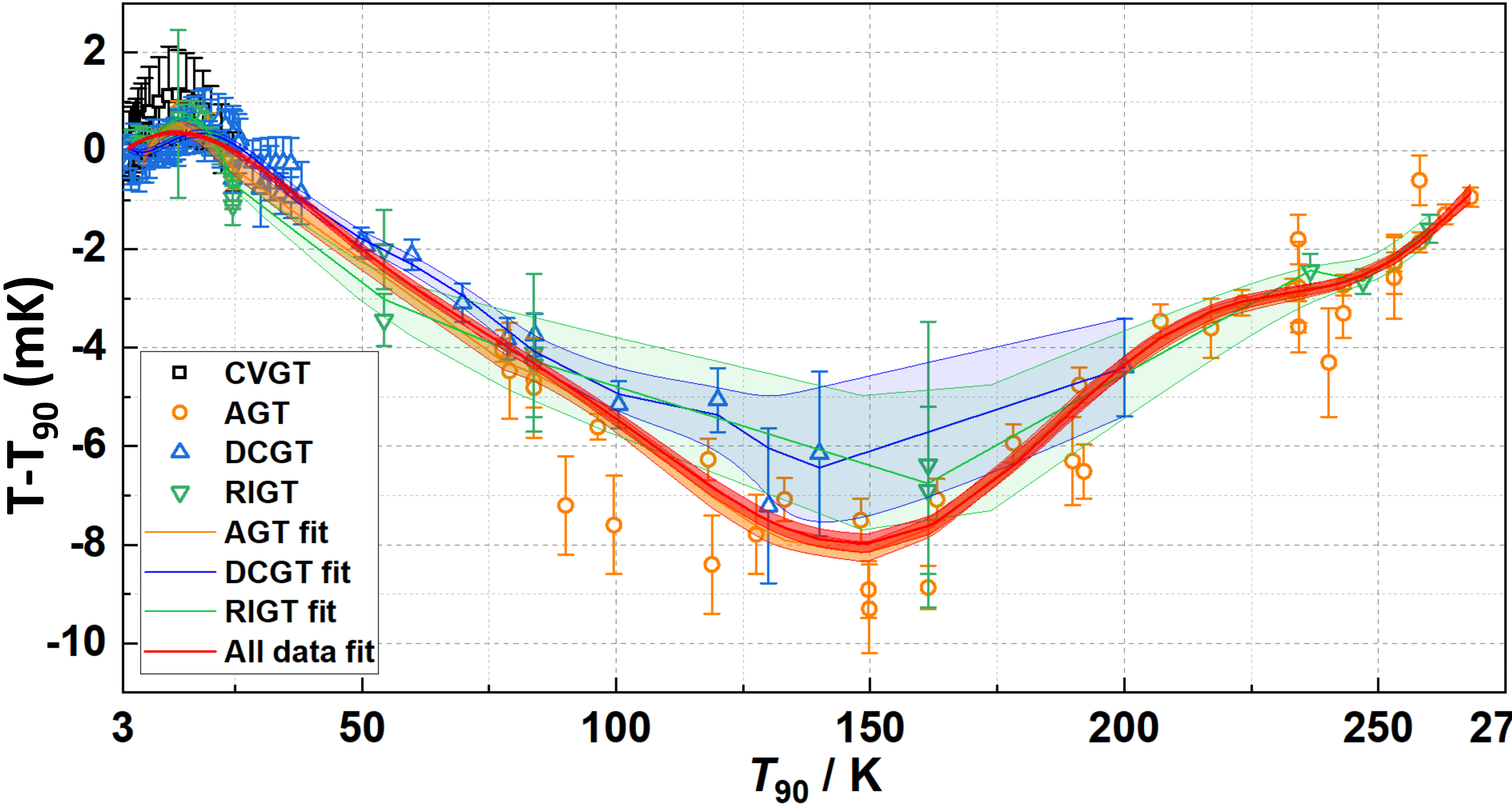
Bo Gao
(Bo)

The overall fit and separate fit of different primary thermometry



Haiyang Zhang
researcher
(Richard)

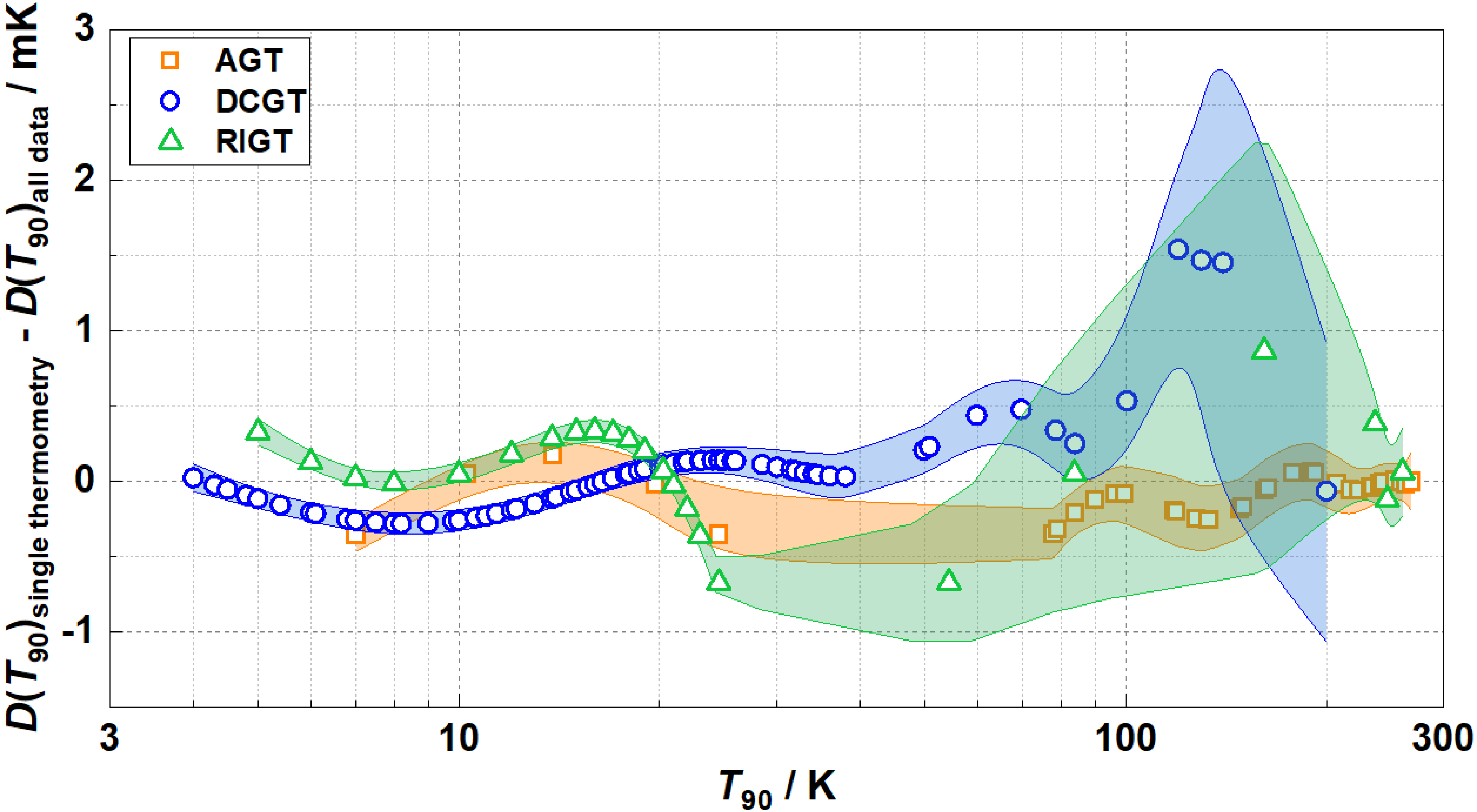
The overall fit and separate fit of different primary thermometry



Haiyang Zhang
researcher
(Richard)

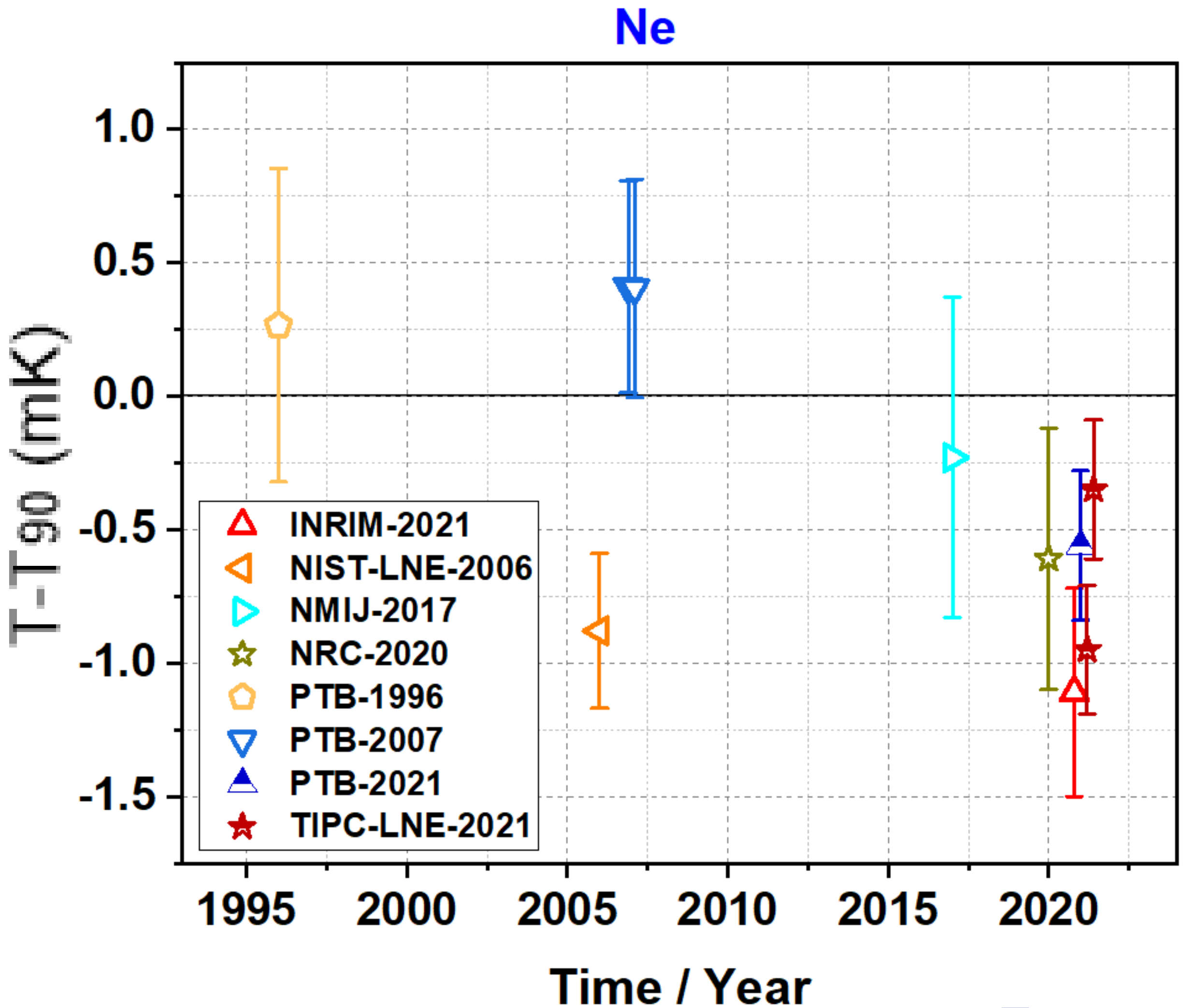
Does the primary thermometry give the same T? Yes

The overall fit and separate fit of different thermometry



Haiyang Zhang
researcher
(Richard)

Measurements at around Ne fixed point, chronologically



	T_{90} points
INRIM-2021	24.5561
NIST-LNE-2006	24.551
NMIJ-2017	24.5559
PTB-1996	24.6
PTB-2008	24, 25
PTB-2021	24.55518
TIPC-LNE-2021	24.5561, 24.55535
NRC-2020	24.5561

Europeen project: DireK-T

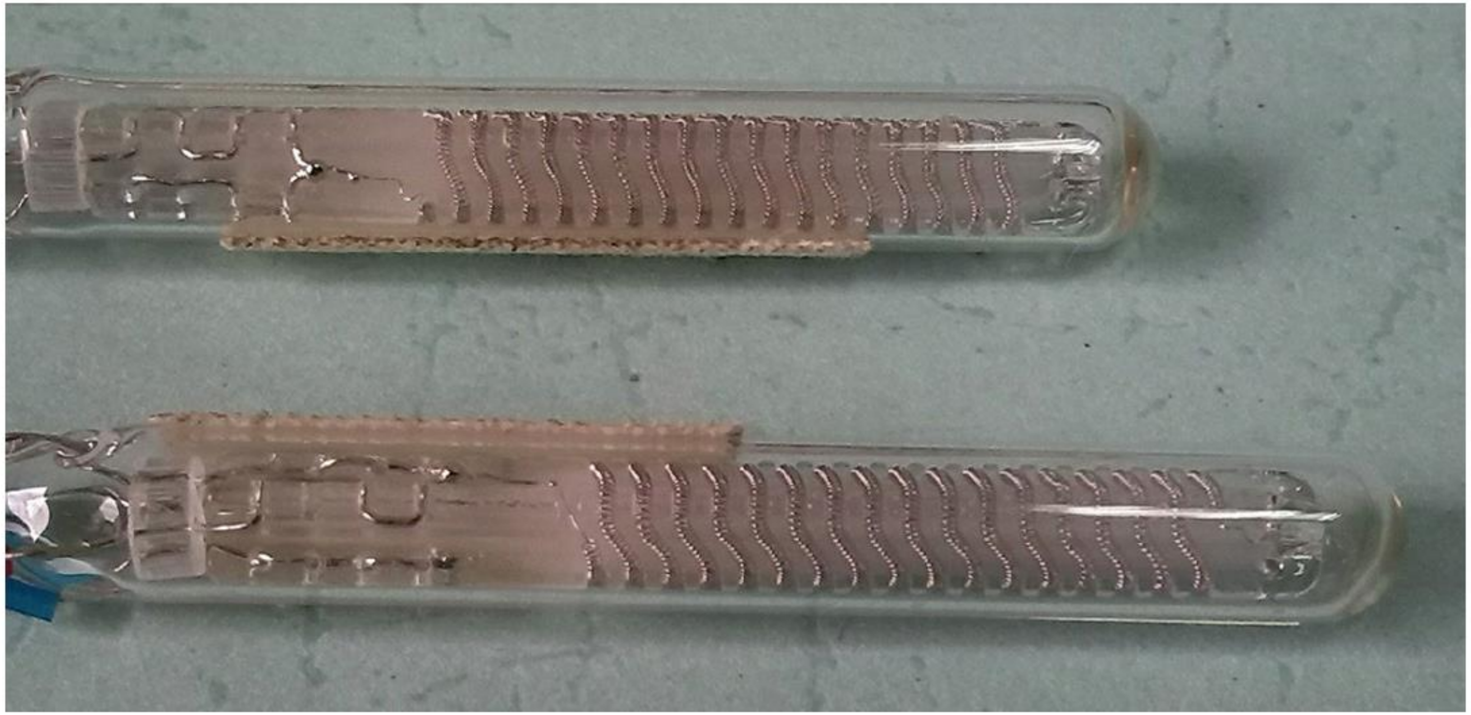
From T90, how to get T?

Visit the BIPM website and search for 'T-T90'; you'll find the last equation there.

Personally, I disagree with the 2022 equation (I believe tables one and two should not be averaged). I couldn't convince my colleagues, and I have requested that my name be removed from the paper.

RdFe thermometer from Yunnan Dafan Meter Industrial

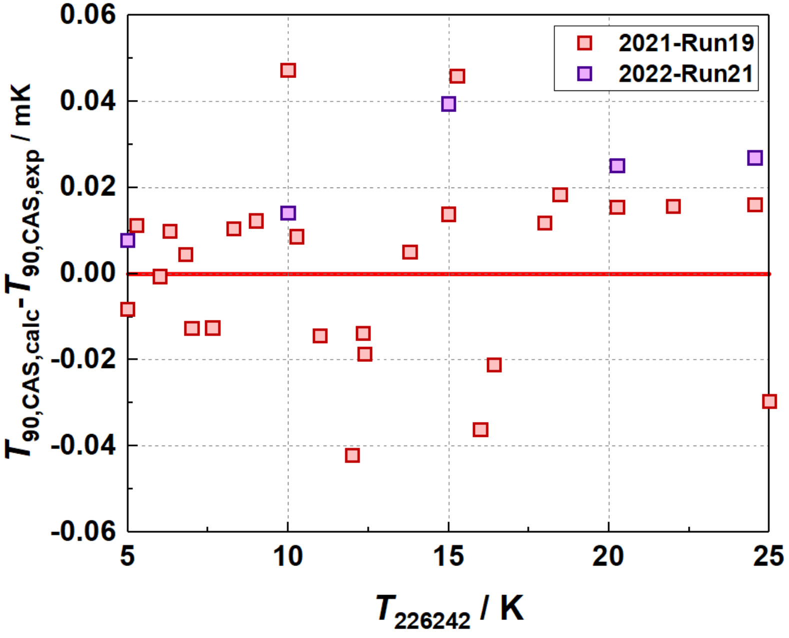
The reference standard for the range of 0.65 to 25 K. Only one company continues to produce reference standard RdFe



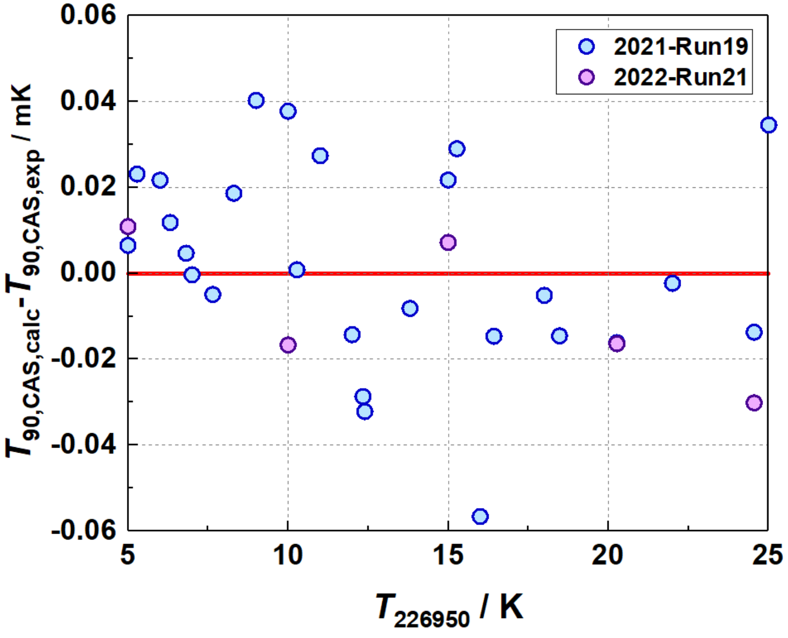
Maintaining T_{90} with RdFe

- Comparison of experimental T_{90}over a 2,5 years

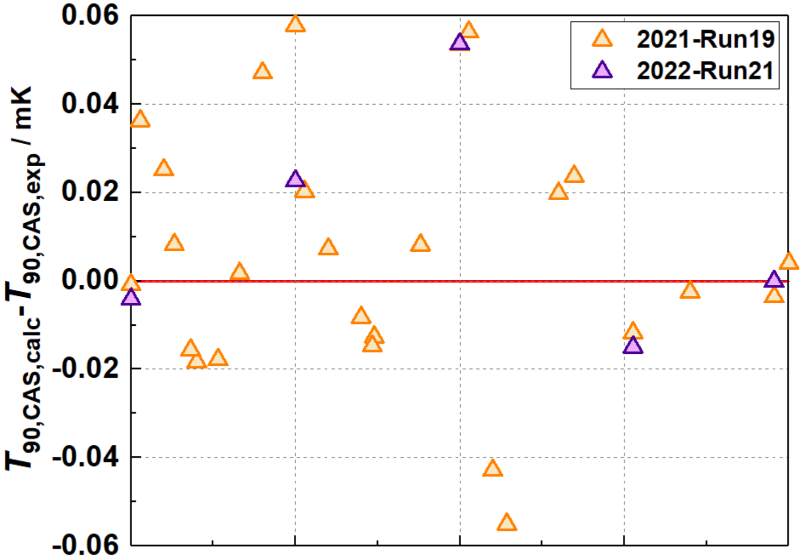
226242, ±0.042mK



226950，±0.056mK



20107，±0.058mK



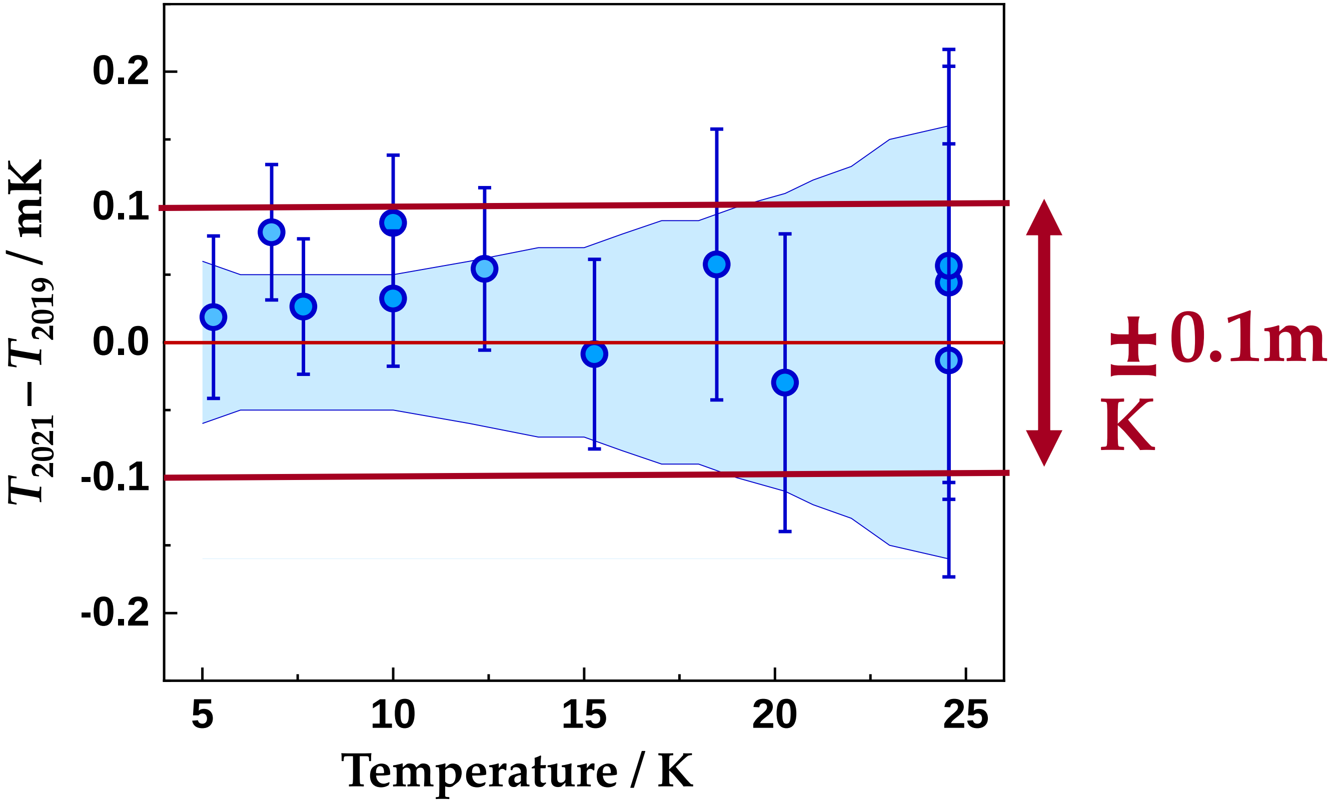
T_{90} reproducibility within ±0.058mK

Stability better than 0.028mK

Haiyang Zhang
researcher
(Richard)

Stability of SPRIGT

- ☐ After 2.5 years, the difference of *T* in the two rounds of experiments ($T_{2021} - T_{2019}$)

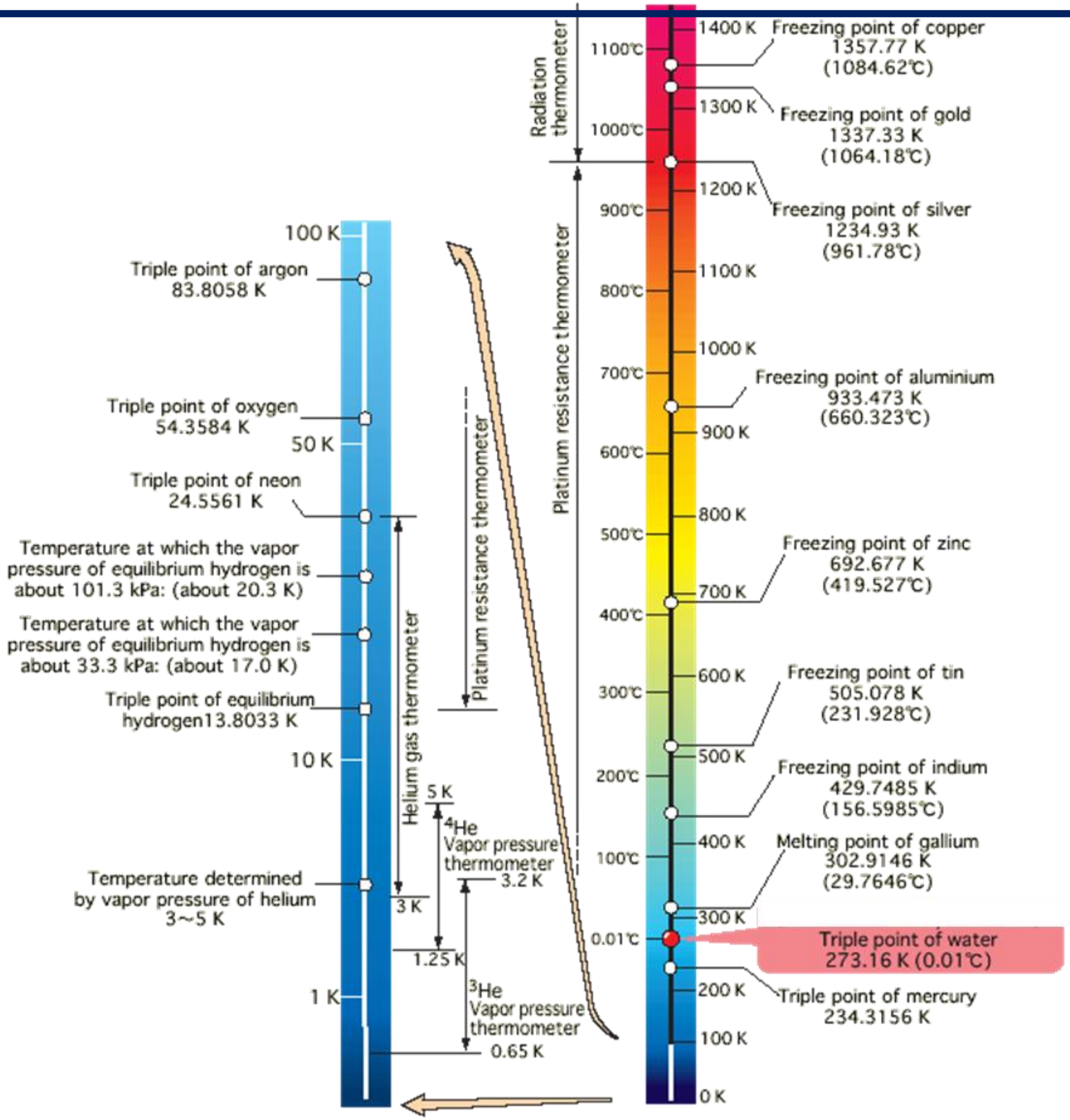


T_{SPRIGT} **has a stability better than 0.1mK**

Haiyang Zhang
researcher
(Richard)

Bo Gao *et al.* ***Metrologia*** 58 (2021) 071501; New data to be submitted.

International Temperature Scale 1990



ITS90 is an approximation of the thermodynamic temperature

From **13,8K to 273,16 K** IST 90 give:

A thermometer

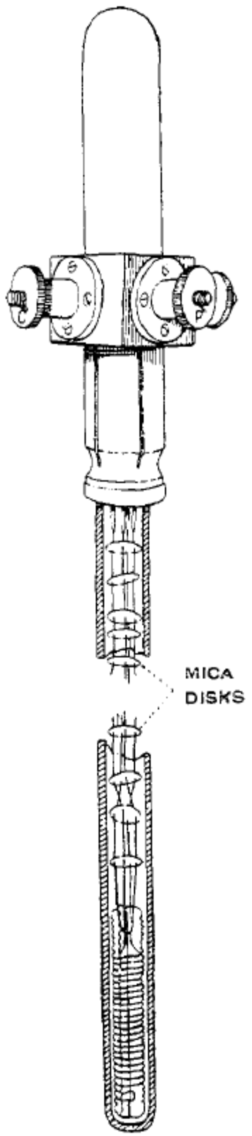
Fix point

And interpolating equation

From www.NMiJ.jp

The Pt thermometer is at its beginning

Platinum Resistive thermometer is since 1887 and in metrology 1923



4-wire resistance measurement method in 1887

Figure 2. Callendar's design of thermometer.

Concept by Siemens and Implementation by Callendar in 1887

Progress in platinum resistance thermometry

C R Barber[1] and J A Hall[1]

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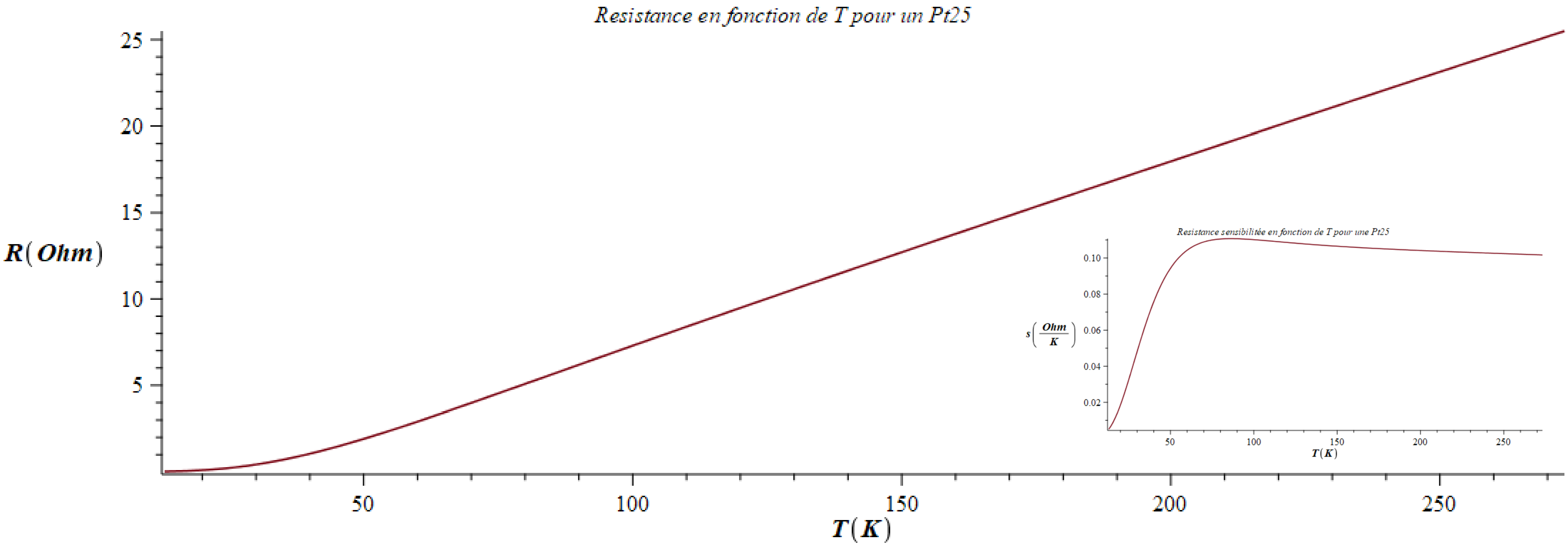
British Journal of Applied Physics, Volume 13, Number 4

From **A short history of temperature scales**

Terry Quinn*

“During these 1923 discussions the form of the future scale was agreed. It would comprise the platinum resistance thermometer from – 38.81 °C up to the freezing point of aluminium at 650 °C “

Pt25 thermometer curve

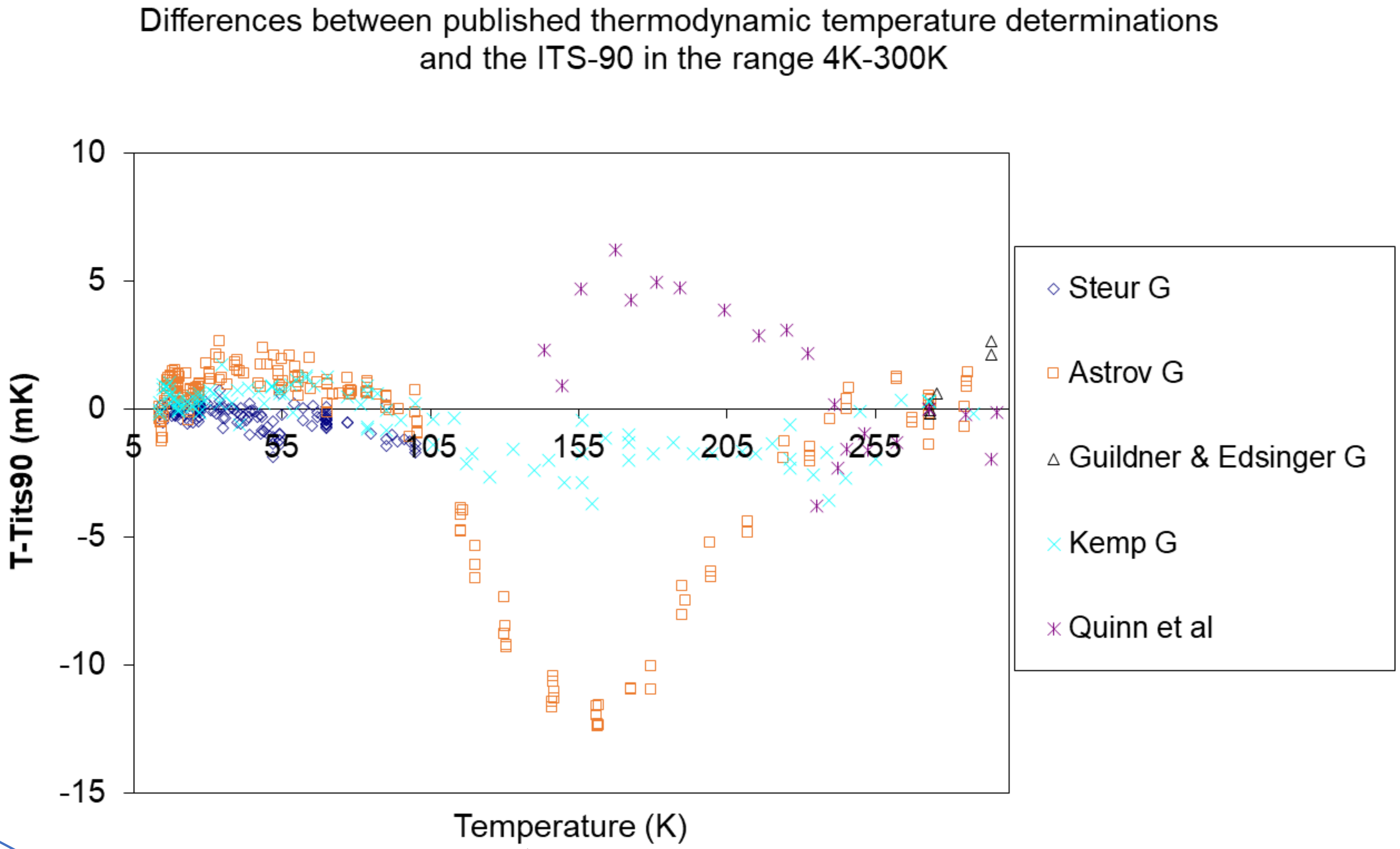


$$W = \frac{R(T)}{R(273.16)}$$

$$\ln[W_r(T_{90})] \equiv A_0 + \sum_{i=1}^{12} A_i \left[\frac{\ln(T_{90} / 273.16\ \mathrm{K}) + 1.5}{1.5} \right]^i \qquad 13.8033\ \mathrm{K} \leq T_{90} \leq 273.16\ \mathrm{K},$$

https://www.bipm.org/documents/20126/41791796/ITS-90.pdf/

Origine of the ITS90 reference function

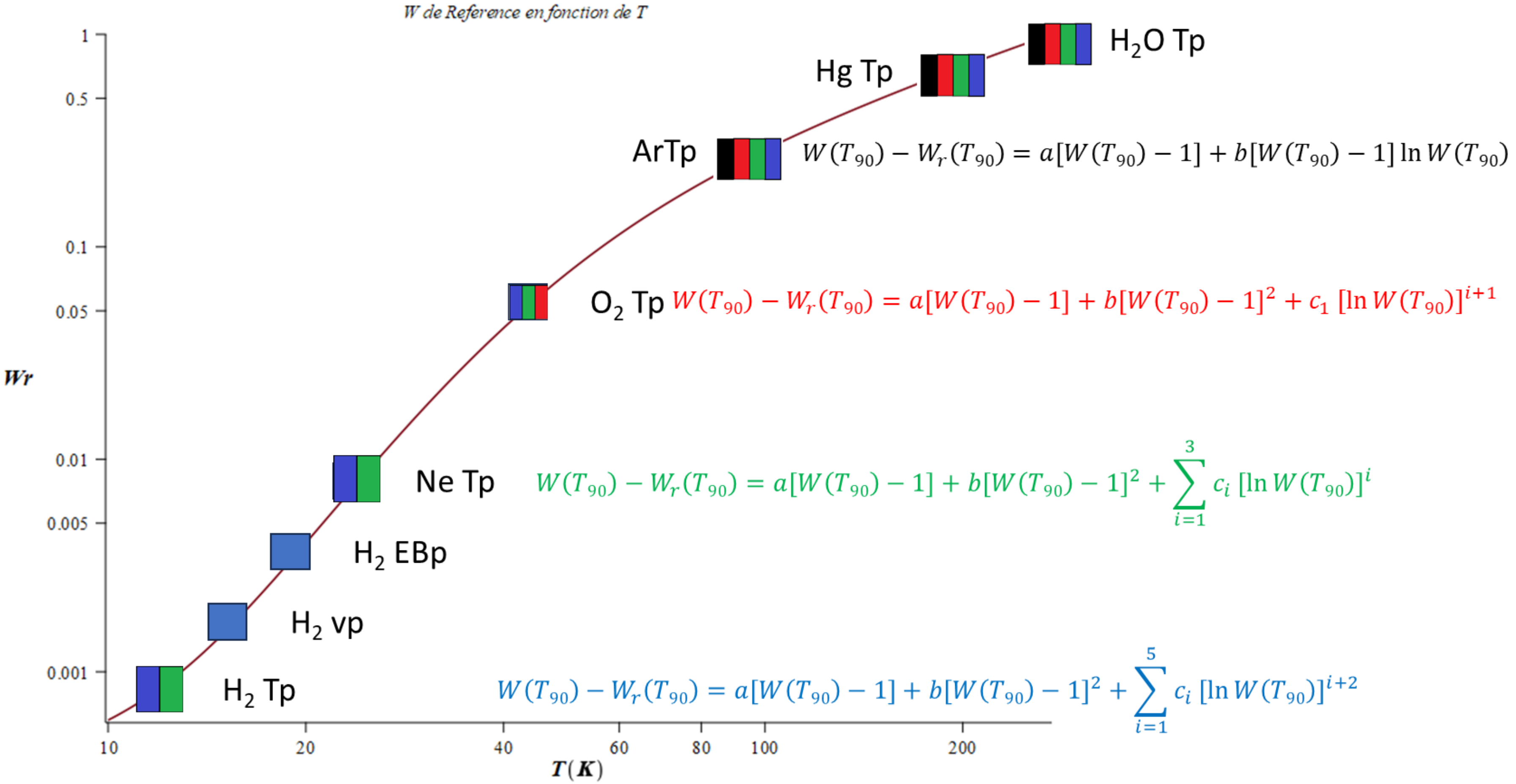


It is the result of a fit from the best known relationship at that time (before 1990) between some resistance of CSPRPT25 and the most accurate understanding of thermodynamic temperature.

$$\ln\left[W_{\mathrm{r}}\left(T_{90}\right)\right] \equiv A_0 + \sum_{i=1}^{12} A_i \left[\frac{\ln\left(T_{90} / 273.16\ \mathrm{K}\right) + 1.5}{1.5}\right]^i \qquad 13.8033\ \mathrm{K} \leq T_{90} \leq 273.16\ \mathrm{K},$$

ITS90 reference and deviation function

Every CSPRT25 must be calibrated using specific fixed points of the ITS-90. The number of fixed points and the equation for the deviation function depend on the temperature range in which the thermometer will be used.



$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]\ln W(T_{90})$$

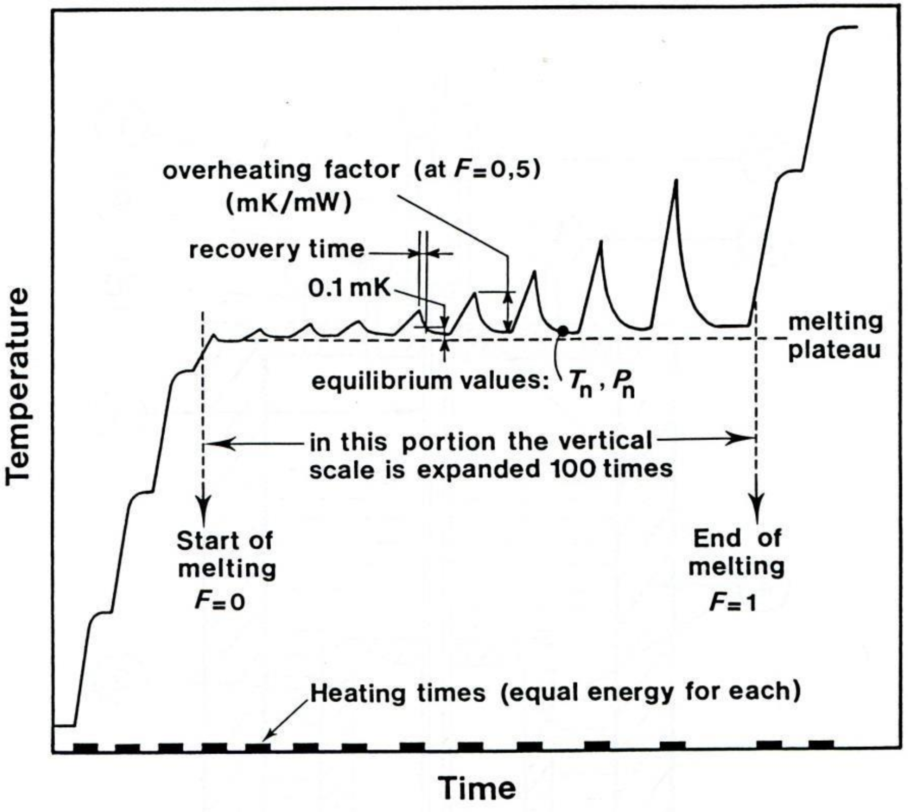
$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + c_1\,[\ln W(T_{90})]^{i+1}$$

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + \sum_{i=1}^{3} c_i\,[\ln W(T_{90})]^{i}$$

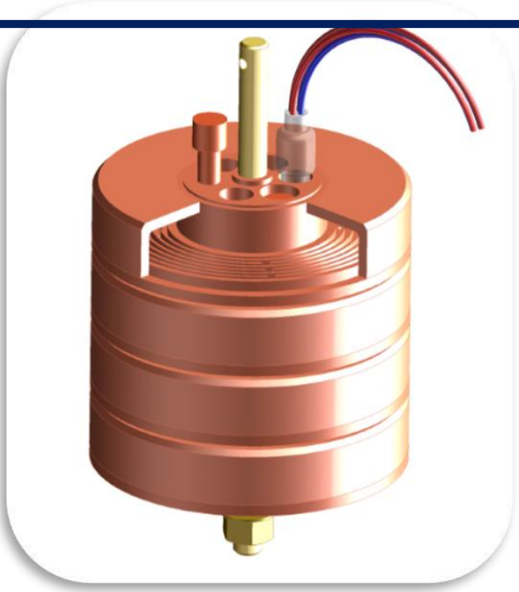
$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + \sum_{i=1}^{5} c_i\,[\ln W(T_{90})]^{i+2}$$

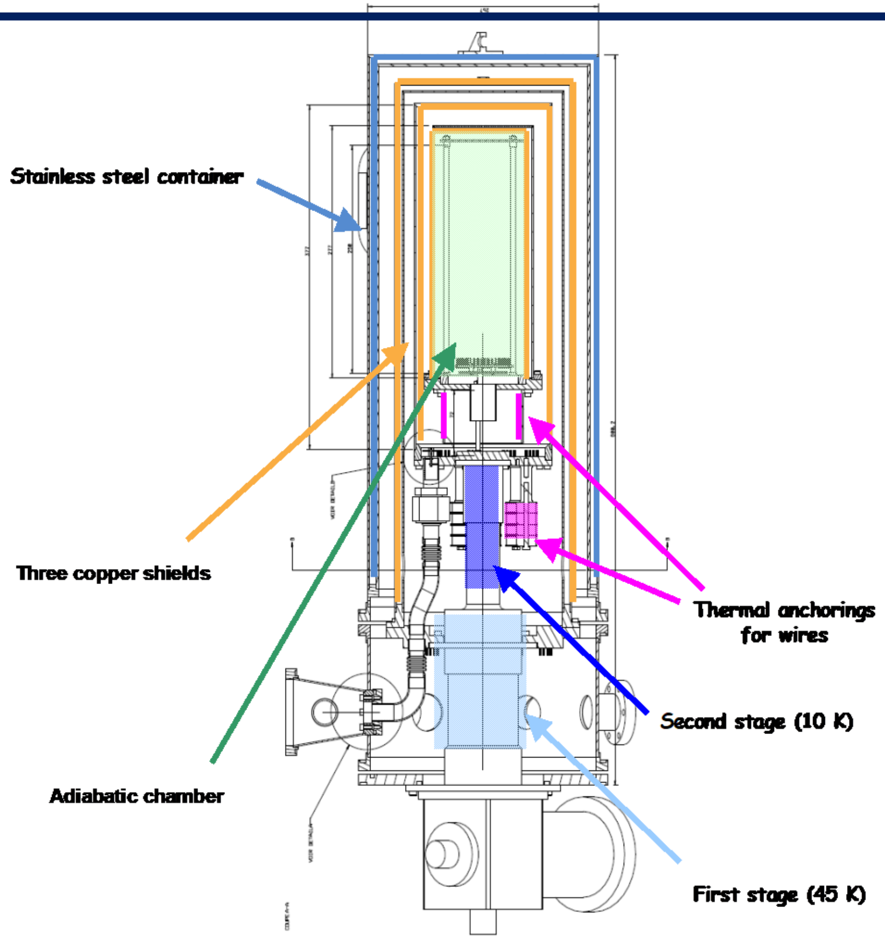
$$\ln\left[W_r\left(T_{90}\right)\right] \equiv A_0 + \sum_{i=1}^{12} A_i \left[\frac{\ln\left(T_{90}/273.16\ \mathrm{K}\right)+1.5}{1.5}\right]^i \qquad 13.8033\ \mathrm{K} \le T_{90} \le 273.16\ \mathrm{K},$$

Cryogenic fix point at LNE



Graph BIPM Guide to the Realization of the ITS90. Cryogenic Fixed Points

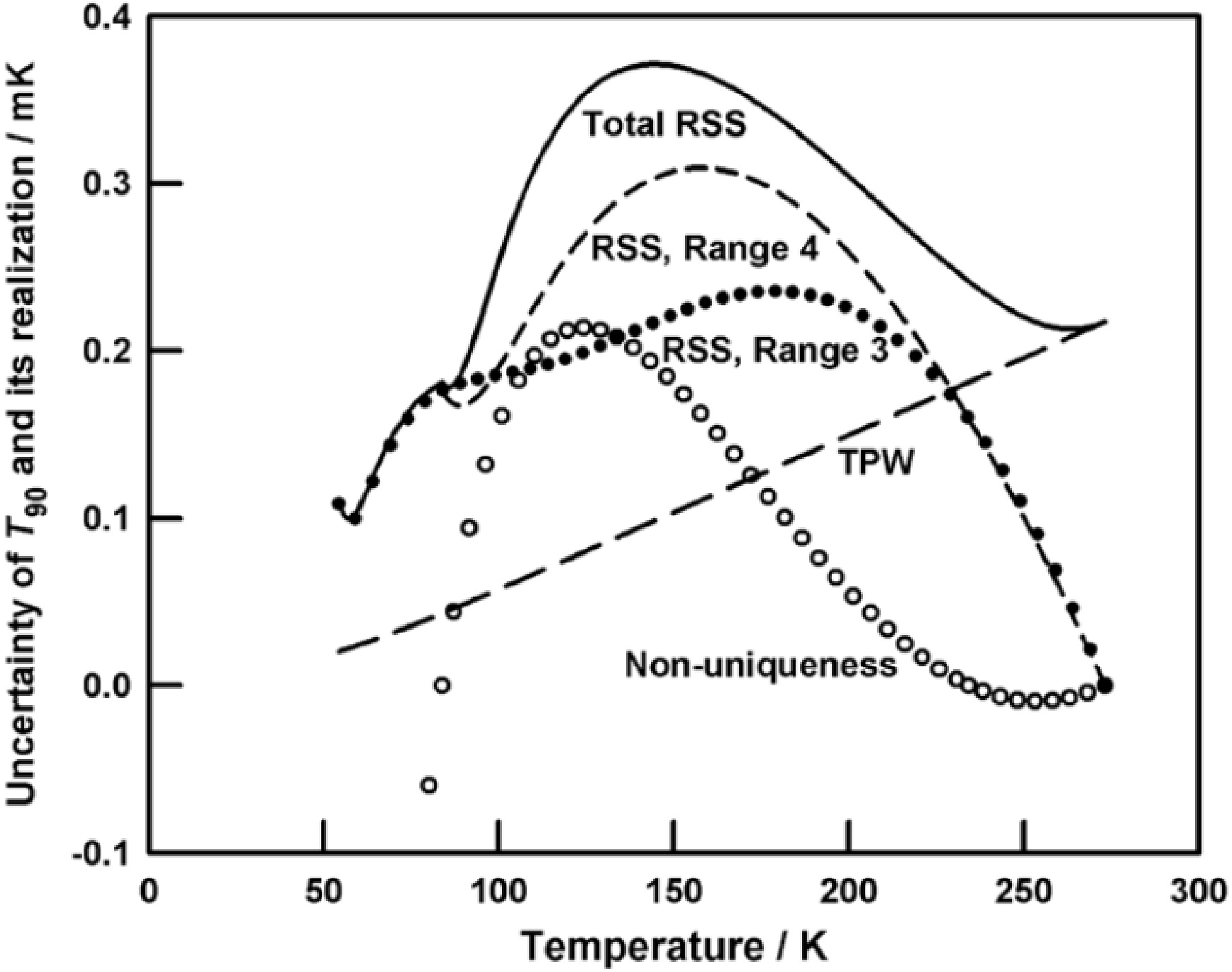




G. Bonnier

Y. Hermier

Example of the propagation of uncertainty with ITS90



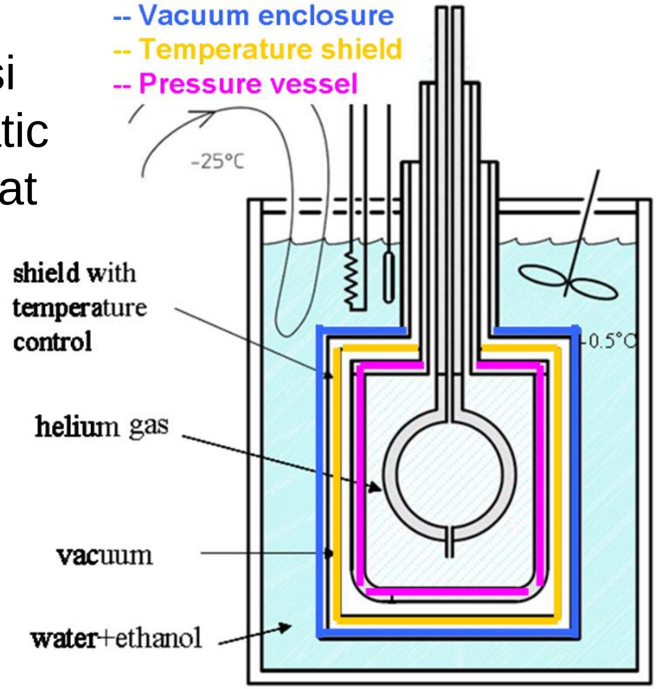
Acoustic thermometry: new results from273K to 77K and progress towards 4K, L Pitre, M R Moldover and W L Tew Metrologia **43** (2006) 142–162

Uncertainty of the Boltzmann constant determination

The most challenging use of the CSPRT Pt25 was in the project for determining the Boltzmann constant

Uncertainty of the Boltzmann constant determination

Quasi
adiabatic
cryostat



Thermal Cartography of the Resonator

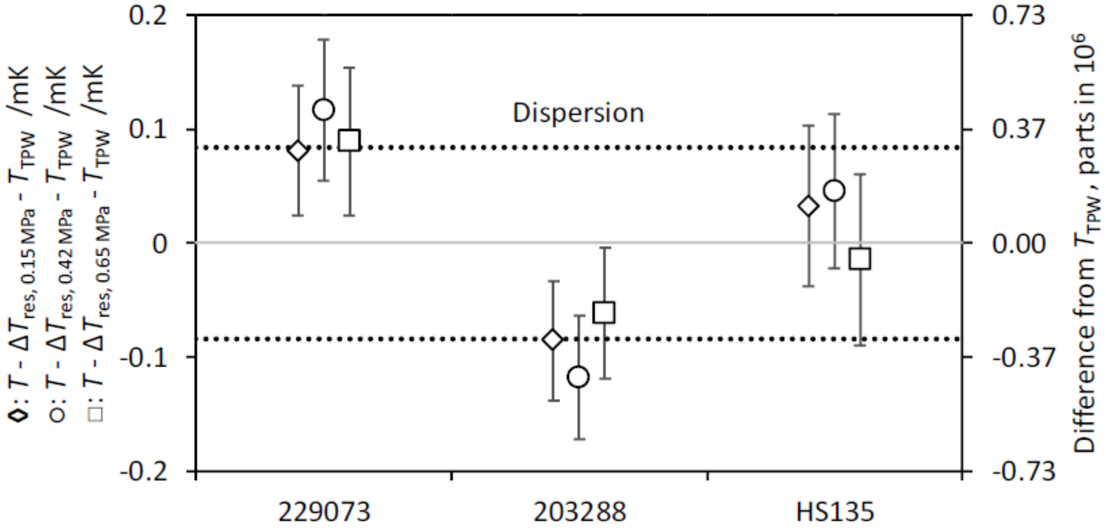
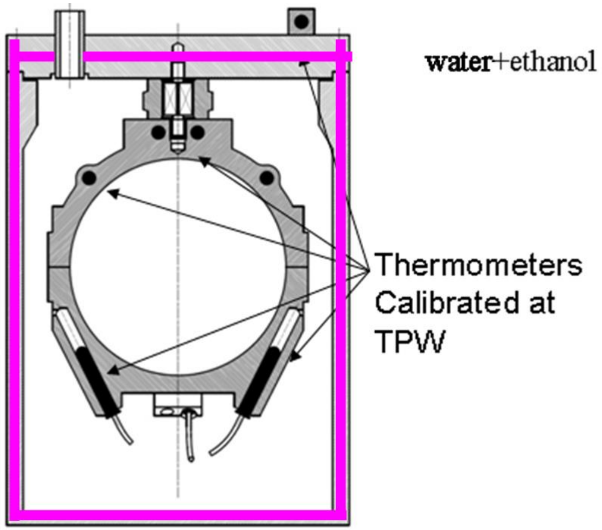
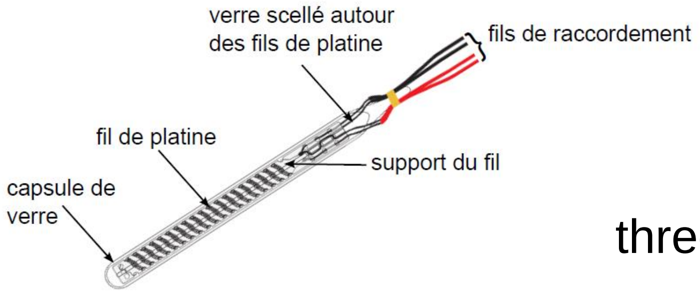


Figure 1. Temperature of the resonator measured using three different capsule-type standard platinum resistance thermometers, during three different runs at three different gas pressures. Values are expressed as differences with respect to T_{TPW}, both in millikelvin and in parts in 10^6. The dotted lines represent the uncertainty interval related to the dispersion of thermometer readings.



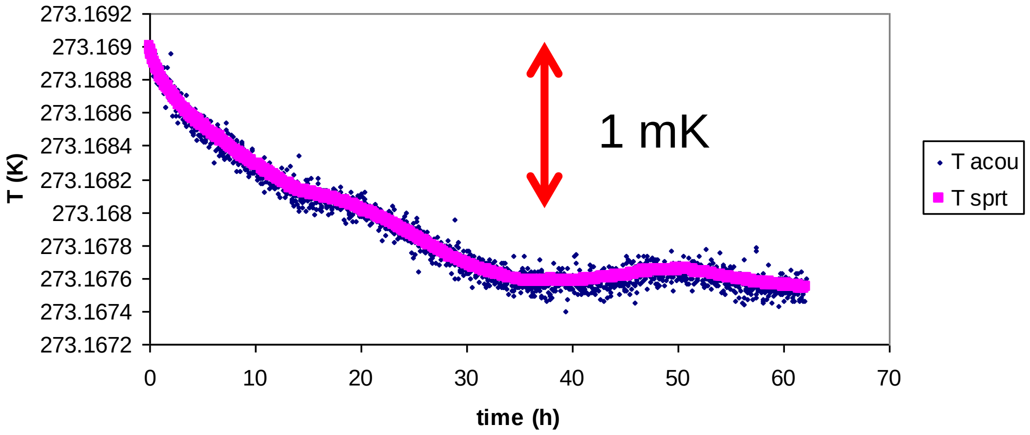


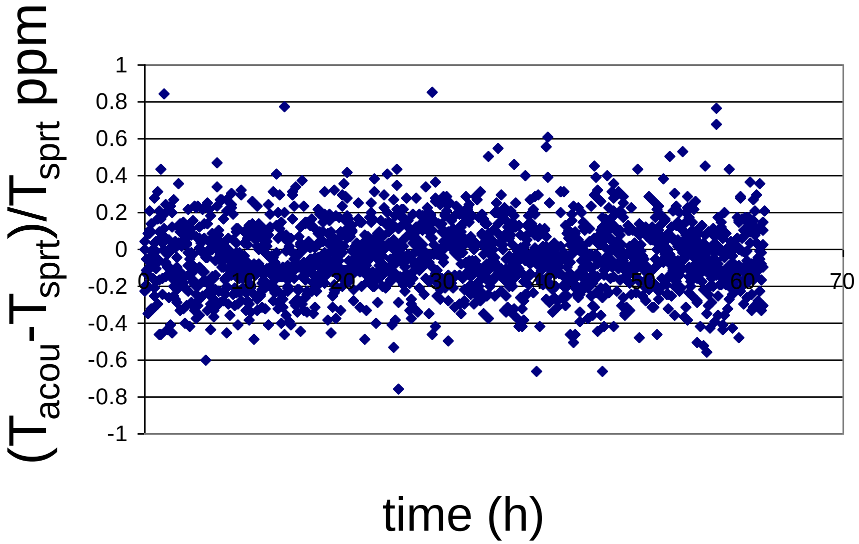
All of those manufacturer have stopped their production.

three capsule thermometers

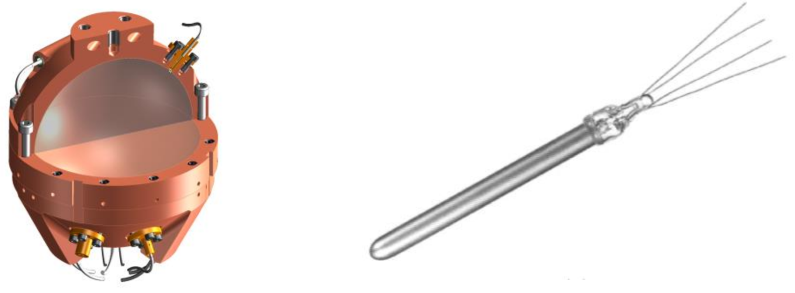
Uncertainty of the Boltzmann constant determination

Same Thermostat, Two Types of Thermometer





2 types of thermometer

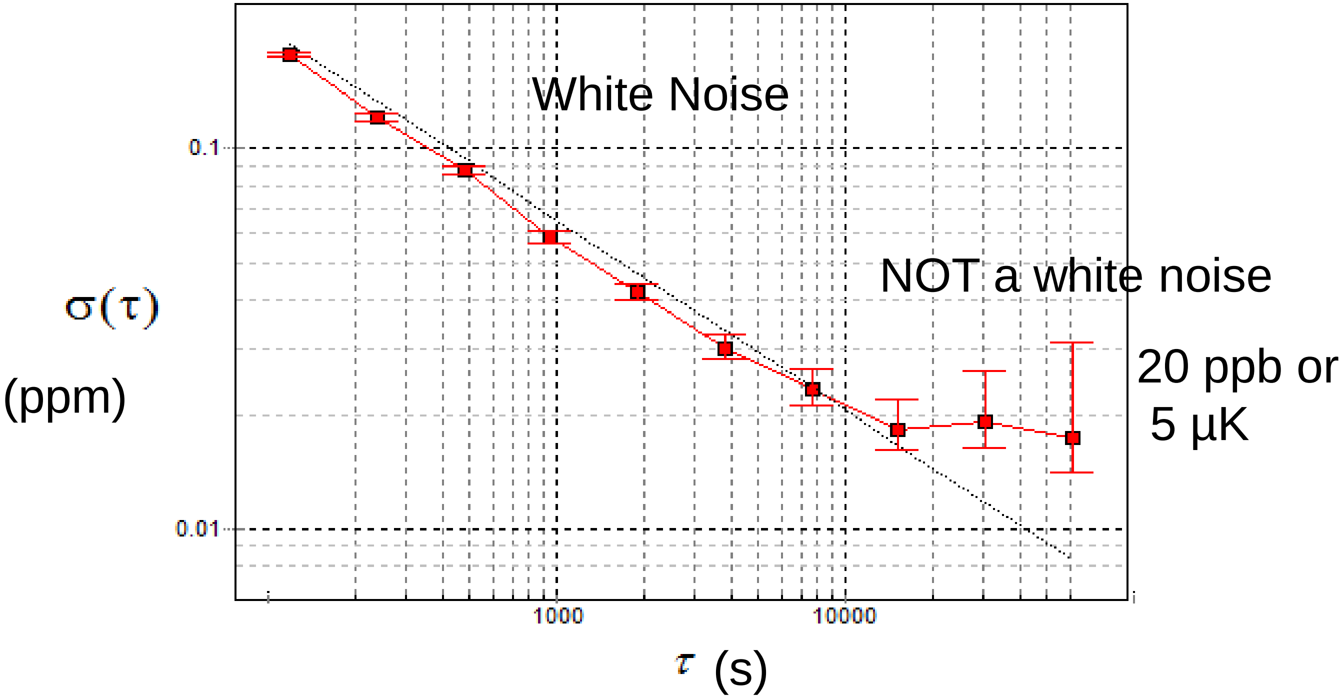


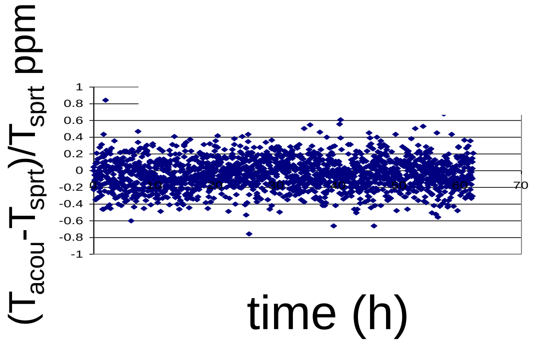
reference	10 MHz	25 Ohm
method	Sinus around the frequency fn	Resistance bridge

To study the noise, we remove the temperature dependence

Uncertainty of the Boltzmann constant determination

Analyze of the Allan Variance at 273.16K with 2 thermometers





Uncertainty of T_{TPW} for the Boltzmann constant determination

Thermal Cartography of the Resonator BCU4

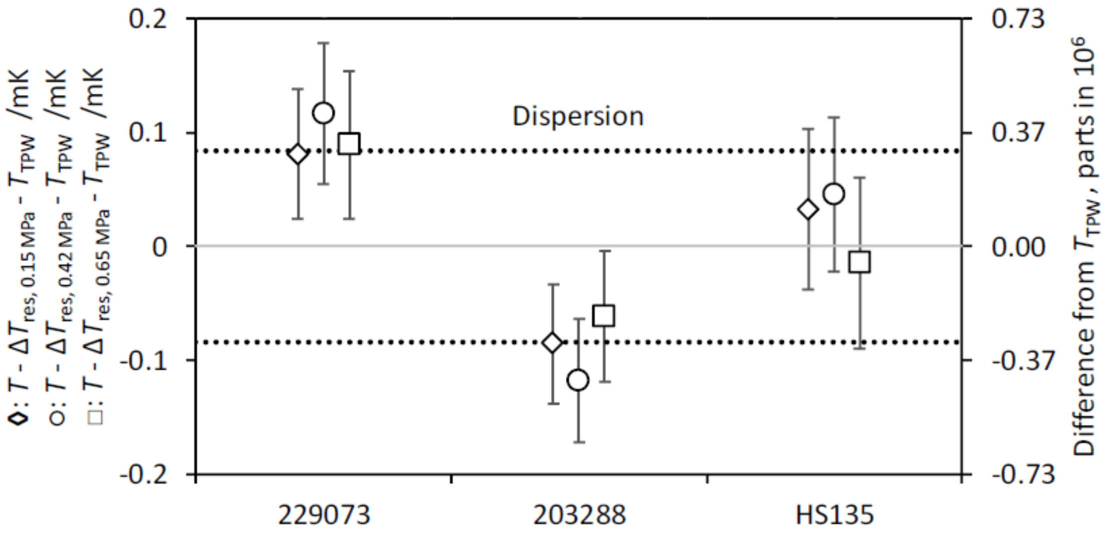


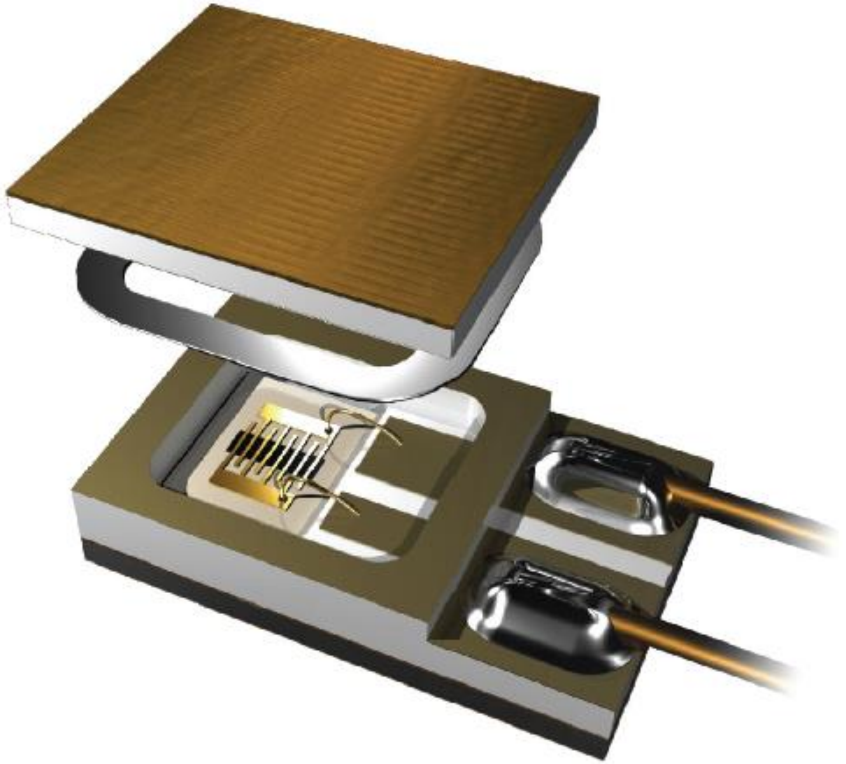
Figure 1. Temperature of the resonator measured using three different capsule-type standard platinum resistance thermometers, during three different runs at three different gas pressures. Values are expressed as differences with respect to T_{TPW}, both in millikelvin and in parts in 10^6. The dotted lines represent the uncertainty interval related to the dispersion of thermometer readings.

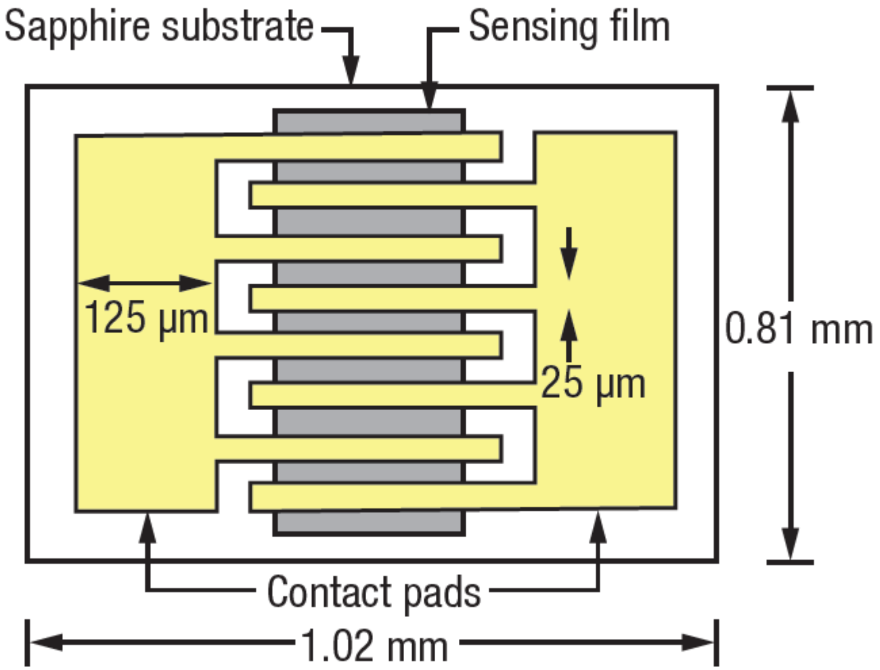
Term	Uncertainty in *k* (Parts in 10^6)	Note
Repeatability and self-heating	0.08	Evaluated with measurements performed on the resonator
Standard resistor stability	0.05	Temperature stability and time-drift of the standard resistor
Resistance bridge	0.04	Bridge linearity and bandwidth
Dispersion of thermometer readings	0.31	Standard deviation of the temperatures measured on the resonator (scaled to T_{TPW}), includes the contribution of the correction ΔT_{res}
TPW calibration	0.21	Calibration at the TPW, including TPW repeatability, isotopic effect, purity, hydrostatic head effect and heat fluxes
TOTAL	**0.39**	**Square root of the sum of squares**

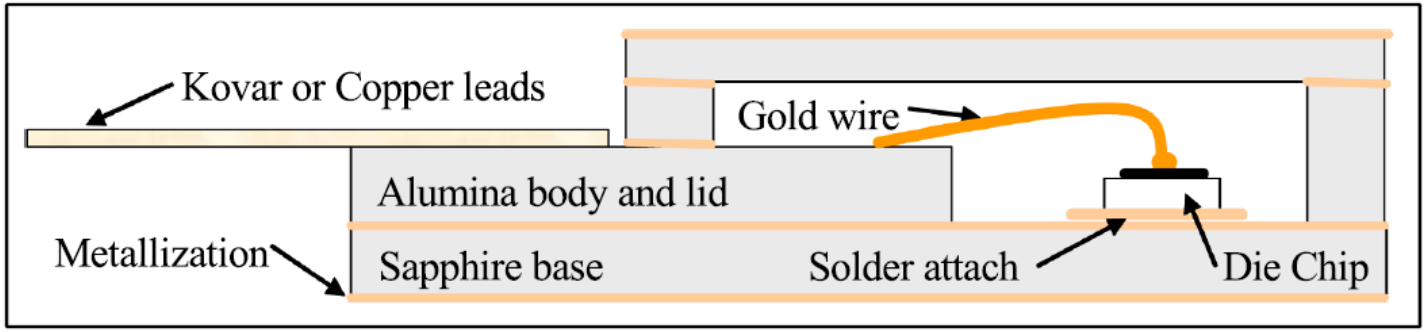
or 0.1 mK

CERNOX

Cernox from lakeshore







Cernox good against irradation

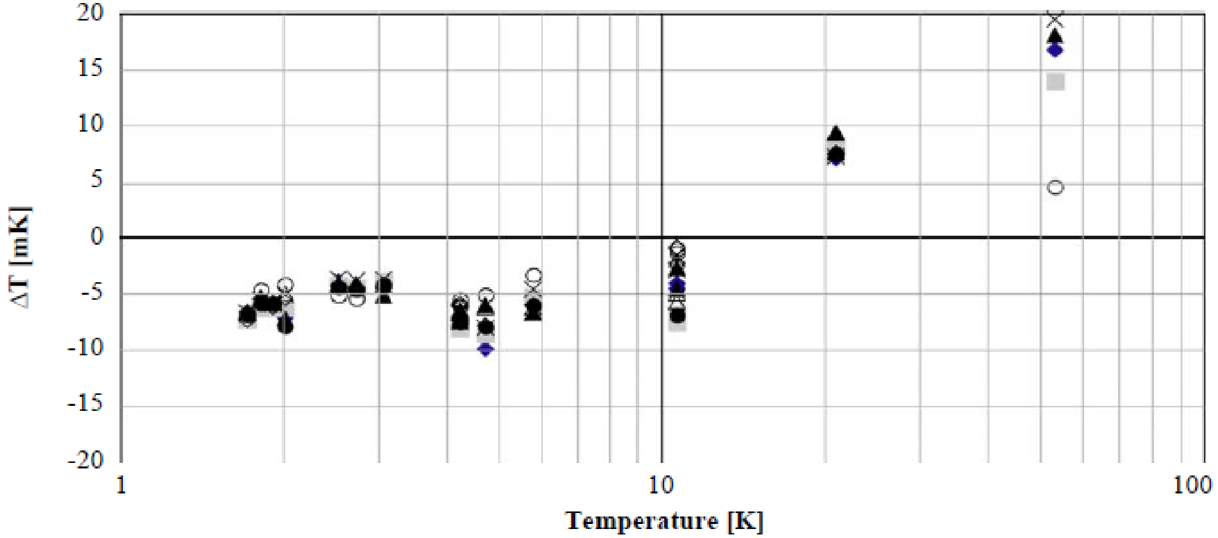
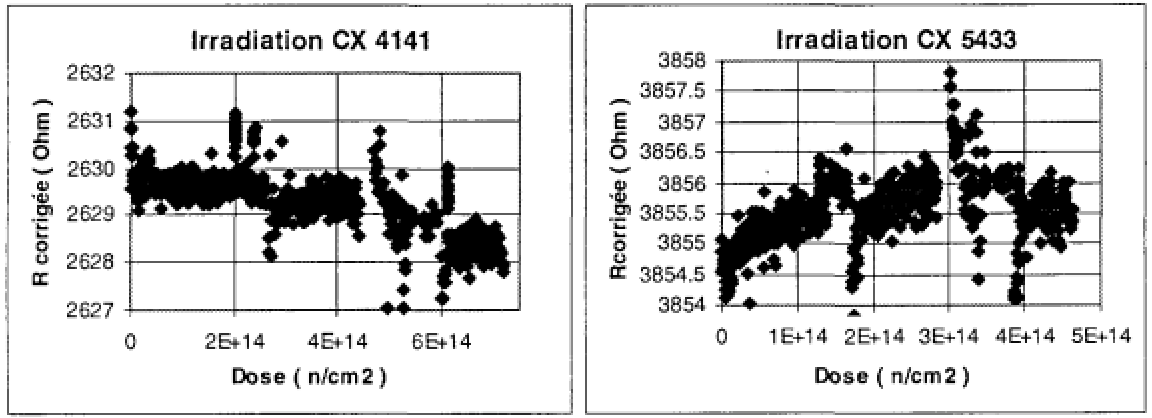


FIGURE 5. Crosscheck between IPN and CERN calibration. ($\Delta T = T_{CERN}(R) - T_{IPN}(R)$)

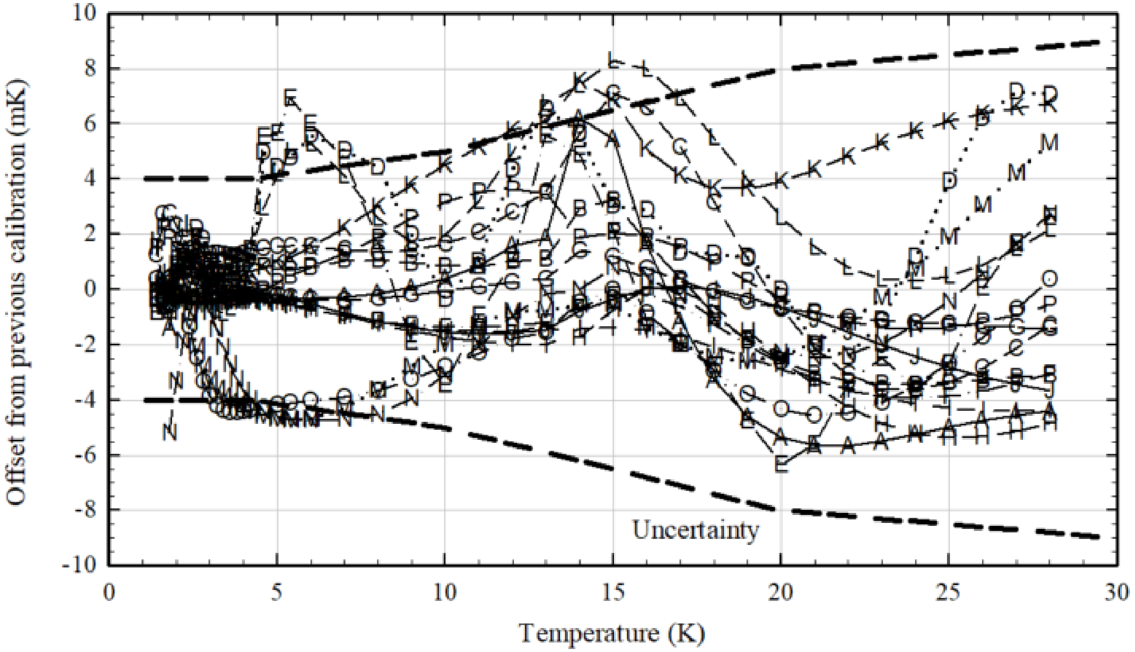


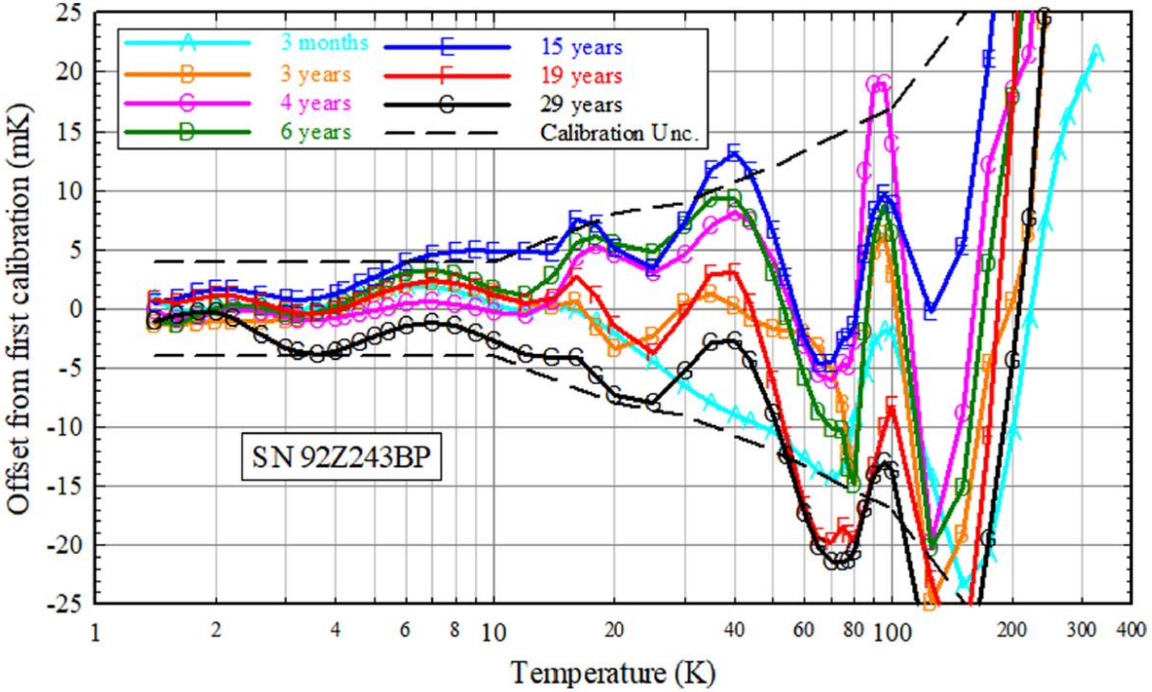
Figures 30 et 31

CALIBRATION OF CRYOGENIC THERMOMETERS FOR THE LHC. LHC Project Report 1077 Ch. Balle, J.Casas-Cubillos, N. Vauthier and J.P. Thermeau

Expériences d'irradiation à basse température des thermomètres du LHC J.F. AMAND, P. BUJARD, C. JOLY, T. JUNQUERA, J.P. THERMEAU

Stability of Cernox over time: ±5mK @ 4K





temperature offset from first calibration as a function of temperature cycling and elapsed storage time at room temperature

We have observed much worse than ±5 mK

We need better stability

In Conclusion

The international temperature measurement structure

The International Bureau of Weights and Measures (BIPM), through the Consultative Committee for Temperature (CCT), coordinates efforts to establish a consistent temperature scale worldwide.

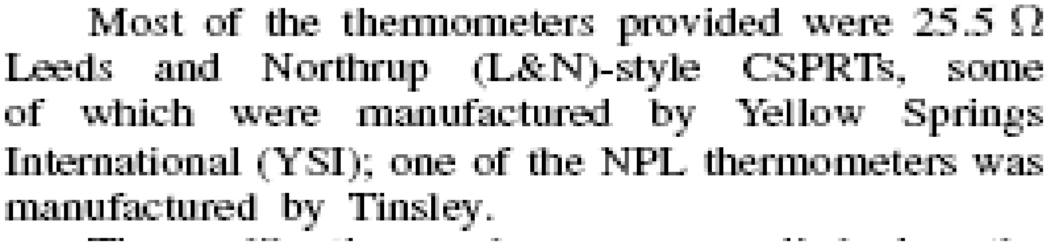
Whether you purchase a sensor from France, the USA, or Japan, there's no need to adjust your measurements based on the sensor's origin.

Periodically, the CCT conducts international comparisons, known as key comparisons. At the highest precision, the CCT employs resistance thermometers.

The need for a new metrological sensor for thermometry

Below 273K 2 type of resistive sensor have the metrological propriety
-CSPRT (Pt25)
-Rhodium Iron Capsule type thermometer

CCT K2 Key comparaison



Most of the thermometers provided were 25.5 Ω Leeds and Northrup (L&N)-style CSPRTs, some of which were manufactured by Yellow Springs International (YSI); one of the NPL thermometers was manufactured by Tinsley.

All of those manufacturer have stopped their production.

CCT K1 Key comparaison

-Rhodium Iron Capsule type thermometer from Tinsley

This manufacturer has stopped its production.

All the metrological institutes worldwide need to characterize new sensors for thermometry or new company production
At least 10 years of study are needed.

In Conclusion

- Need for a new metrological sensor for low-temperature thermometry... please help us.
- LNE-Cnam has developed a characterized platform for temperatures below 4K.
- Direct thermodynamic measurements will become increasingly common in the future.
- ITS-90 will remain in use for many more years due to company investments in quality systems.
- The T-T90 equation will be updated from time to time.

The need for a new metrological sensor for thermometry

If your lab has any of the following items and they are not being used:

- Rhodium Iron Capsule type thermometer from Tinsley
- Leeds and Northrup CSPRT 25
- SRD1000 from HDL

Please contact me, as my lab **could purchase** them.

Thank you

And see you at Tempmeko Oct 2025 in France

My Encouragement Stick

My new management method

Encouragement Stick (*Keisaku*)

Looking for a new PhD student
- 3 years
- Low temperature subject
- Location Paris with 2000 euro/month