# Quantum Kelvin and its Application in Ocean

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# Outline

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2 Redefinition of kelvin

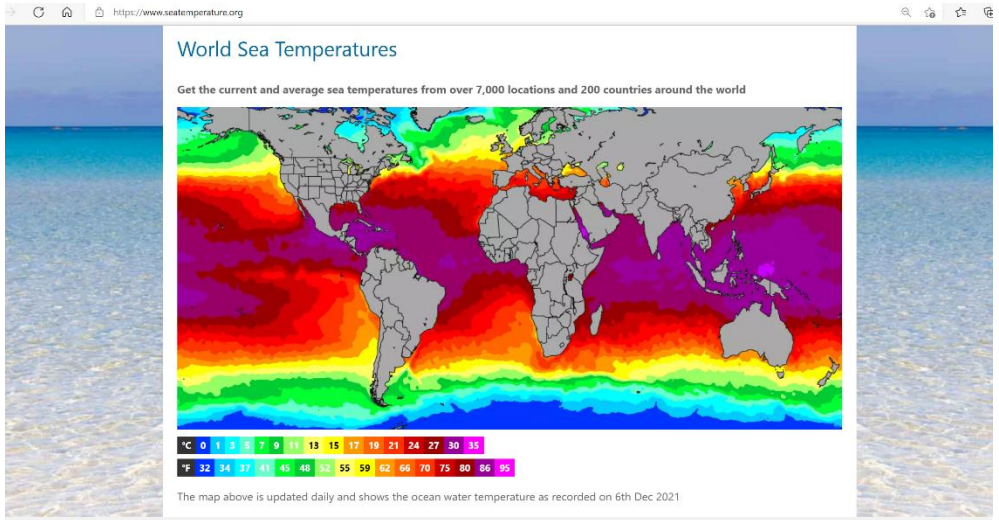
- the redefinition of kelvin and its influences
- thermodynamic temperature methods

3 Quantum temperature sensing

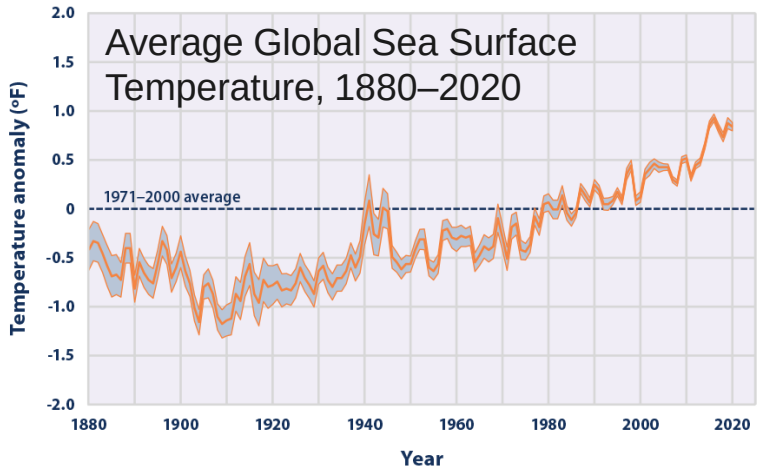
4 Summary

# Introduction

- **kelvin**
  - the unit of **thermodynamic temperature**
  - one of seven SI basic units
- **Temperature is one of the most important properties of ocean**
  - climate change indicator




https://www.seatemperature.com




**www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst.**

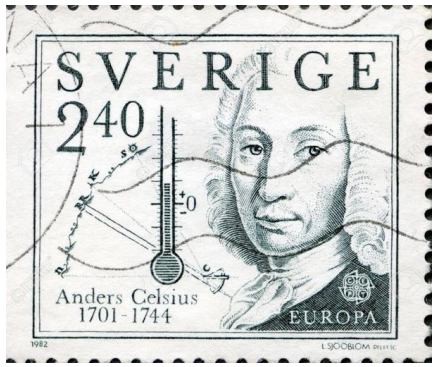
- **1880-2020**
- **2-3 K increasing**
- **change rainfall patterns around the globe**

# Introduction

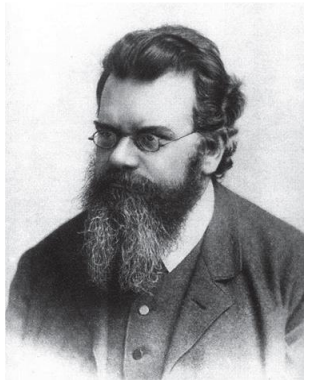
- **Measurements and fundamentals of temperature**

**Galileo Galilei**

**Anders Celsuis**




**Ludwig Boltzmann**



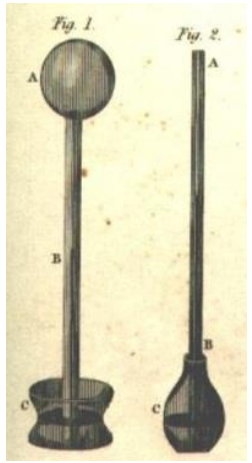
$$S(U) = k \ln \Omega(U)$$

**120 years later, the uncertainty of Boltzmann constant is small enough**

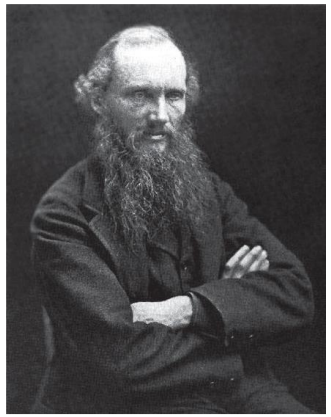
$k$

1592 — 1742 — 1848 — 1884 — 1967 — 2019

**The first thermometer** — **Freezing/boiling point of water**




$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$



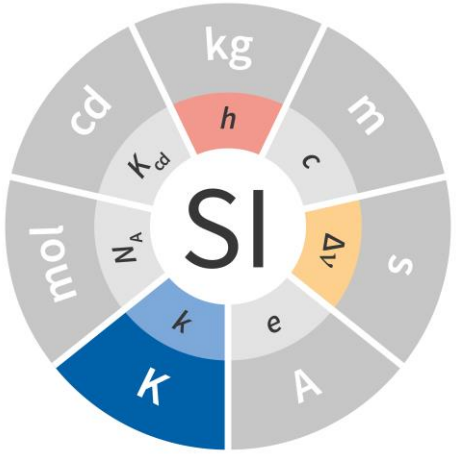
**William Thomson (Lord Kelvin)**

**13th CGPM**

**1K**

**1/273.16 of the thermodynamic temperature of triple point of water**

# Redefinition of kelvin




**"The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant *k* to be 1.380 649 × $10^{-23}$ when expressed in the unit J $K^{-1}$, which is equal to kg $m^2$ $s^{-2}$ $K^{-1}$, where the kilogram, metre and second are defined in terms of *h*, *c* and Δ*v*Cs."**

- **May 20th, 2019**
- **Fundamentally better**


- **has its statistical mechanics, thermodynamic temperature is a measure of the average thermal energy per degree of freedom in the system**
- **$u(T_{TPW})$=0.1 mK**


1. Mise en pratique for the definition of the kelvin in the SI. SI Brochure-9th edition (2019)-Appendix 2. CCT 2019.5.20

# Redefinition of kelvin

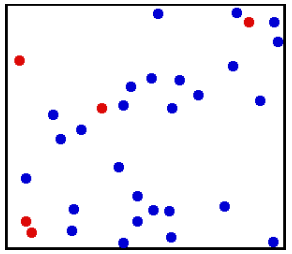
## Energy

$$S = k_B \ln\Omega$$

$k_B$

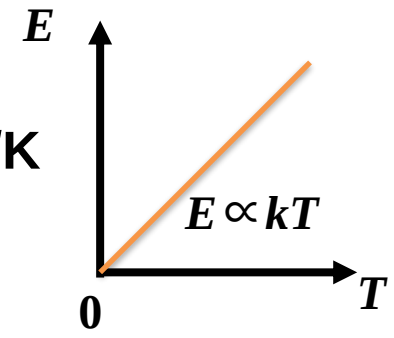
## Molecules' average energy

$$\frac{1}{2} m v_{RMS}^2 = \frac{3}{2} k_B T$$



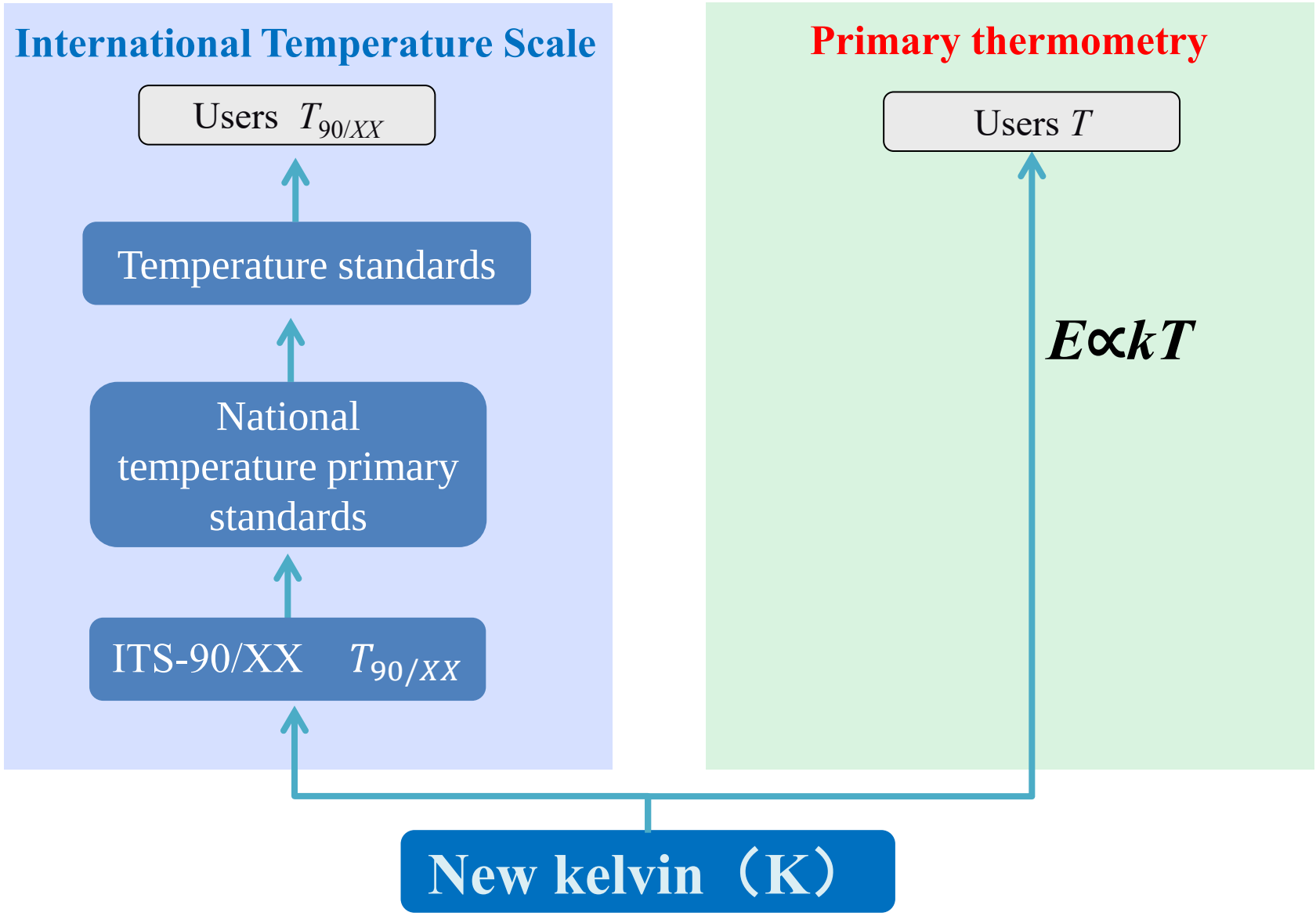
$$\frac{1}{T} = k \frac{d \ln \Omega(E)}{dE}$$

$k_B$ = 1.380 649 × $10^{-23}$ J/K




- Theoretically, we can measure temperature at the full range with the same level

# Redefinition of kelvin




- Has a very small effects on practical using
- CAN NOT feel the change
- ITS-90 will continue be used for quite a long time for its good consistence

- ITS-XX based on new ($T$-$T_{90}$) measurements

- For extreme temperature range/environment, special techniques could be developed

# Redefinition of kelvin

Acoustic gas thermometry

$$u^2 = \frac{\gamma kT}{m}$$

Radiometric thermometry

$$L(\lambda, T) = \left(\frac{2hc^2}{\lambda^5}\right)\frac{1}{e^{hc/\lambda kT} - 1}$$

Polarizing gas thermometry

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{A_\varepsilon p}{kN_A T}$$

$$\frac{n^2 - 1}{n^2 + 2} = \frac{\left(A_\varepsilon + A_\mu\right) p}{kN_A T}$$

Johnson noise thermometry

$$\left\langle V^2 \right\rangle = 4kT\ R\Delta f$$

SI Brochure – 9th edition (2019) – Appendix 2 20 May 2019

## *Mise en pratique* for the definition of the kelvin in the SI

**Consultative Committee for Thermometry**

**1. Introduction**

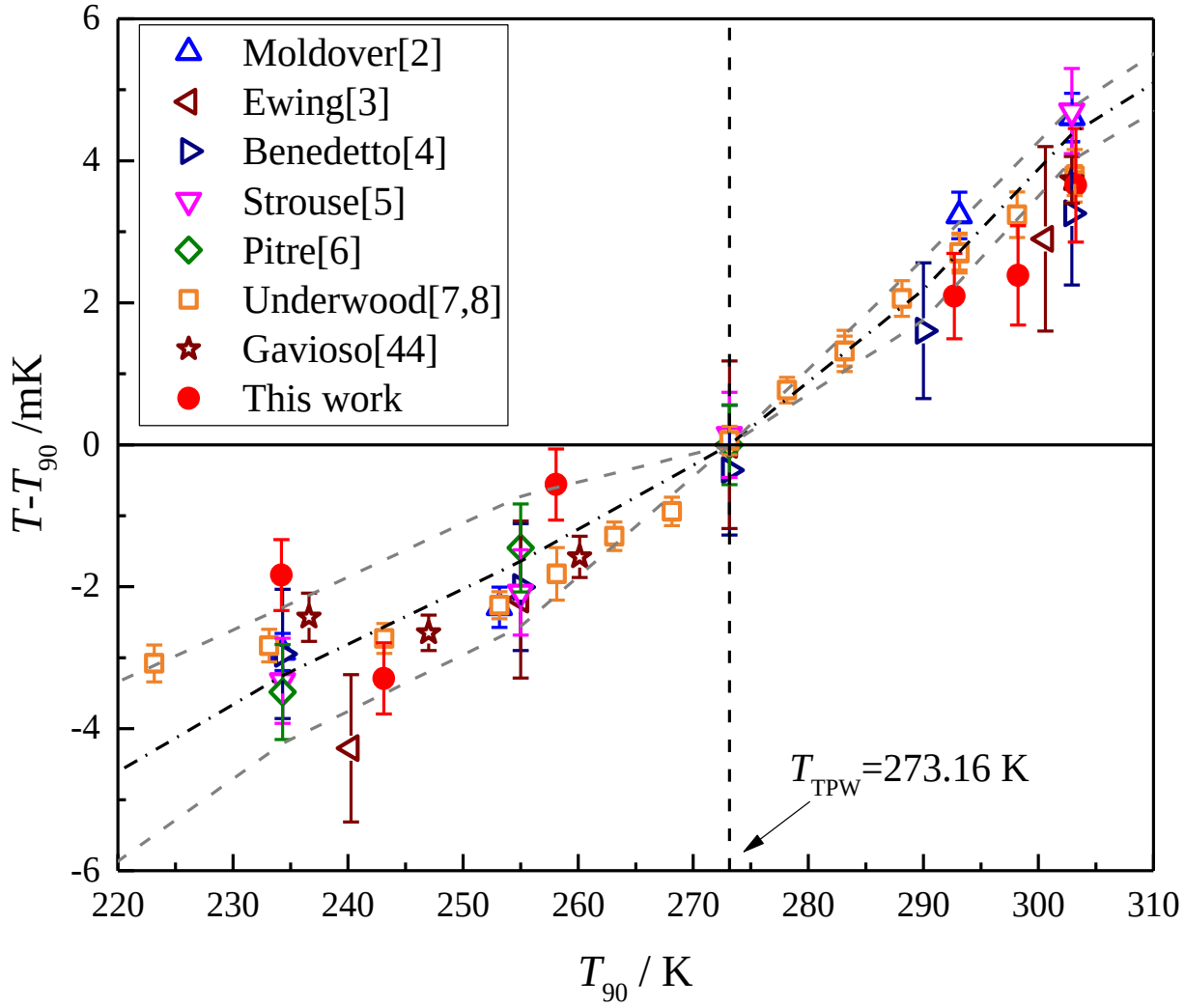
The purpose of this *mise en pratique*, prepared by the Consultative Committee for Thermometry (CCT) of the International Committee for Weights and Measures (CIPM), is to indicate how the definition of the SI base unit, the kelvin, symbol K, may be realized in practice.

1. **Mise en pratique for the definition of the kelvin in the SI. SI Brochure-9th edition (2019)-Appendix 2. CCT 2019.5.20**

# Redefinition of kelvin- applications in ocean

Indirectly

- The triple point of water has an uncertainty 0.1 mK
- In the future, ITS-XX will be more closer to the physical truth→ more reliable ocean temperature→ calibration of ocean thermometers





1. Zhang K, Feng X J, et al. Metrologia, 2020, 57: 024004

# Redefinition of kelvin- applications in ocean

Directly

- Practical on-site thermodynamic temperature measurements for ocean?
- Small size thermometers
- Large-scale temperature monitoring

**GAS**

- Speed of sound
- Refractive index
  Dielectric constant
- Doppler Broadening

…

✓ Stable

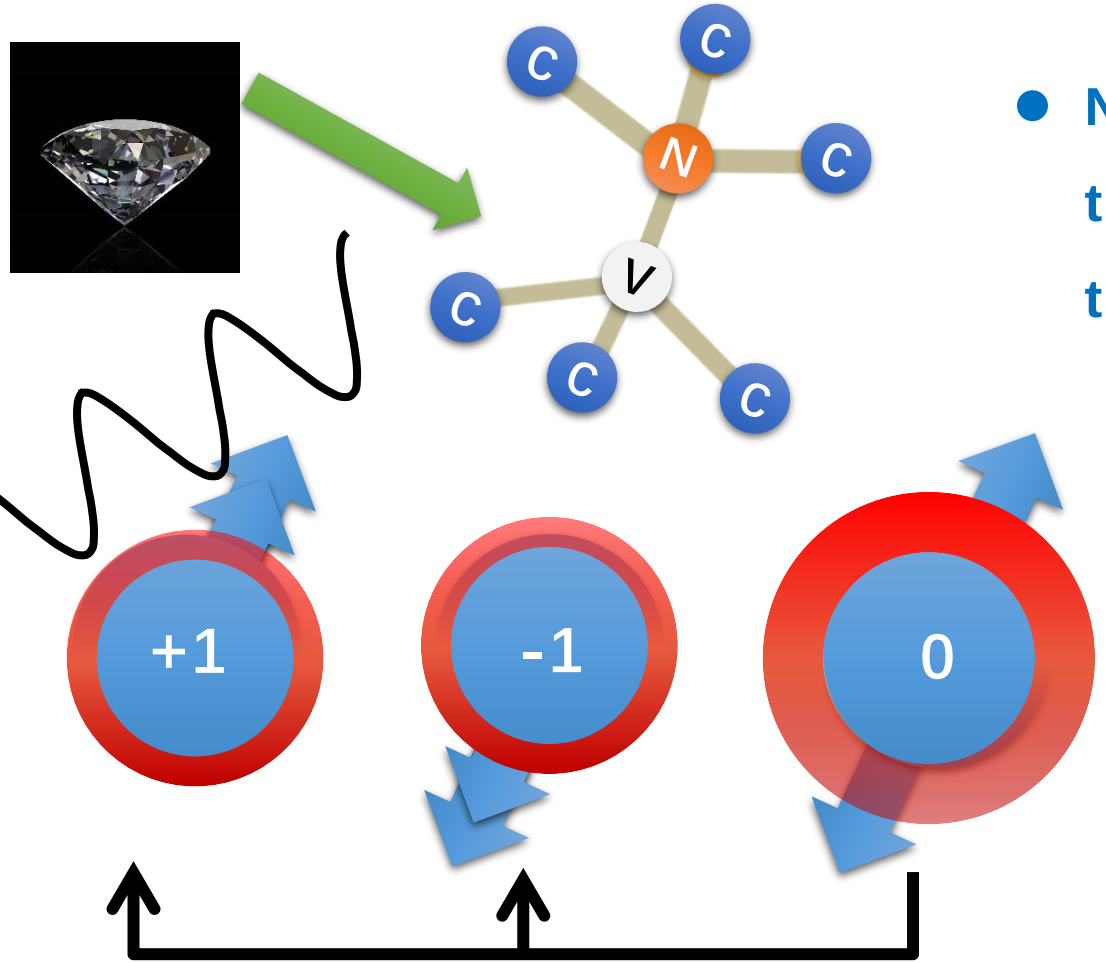
× Slow response

**Speed of sound in sea water**

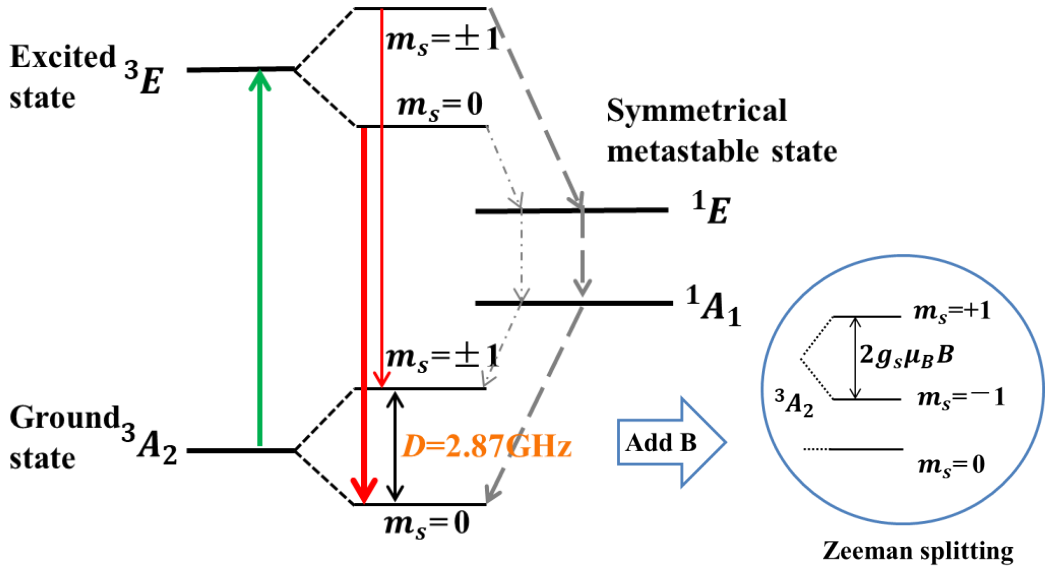
- Relative method

# Quantum temperature sensing

- Quantum effects usually occurs at low temperature
- In the ocean temperature range, one of the possible approaches is NV centers in diamond sensing




- NV, a carbon atom is replaced by a nitrogen atom in the diamond lattice, and a carbon atom is missing in the adjacent position, leaving a vacancy.




Energy level structure of NV center.

# Quantum temperature sensing

**The precise measurement physical quantity of NV center is determined by its Hamiltonian（*H*）：**

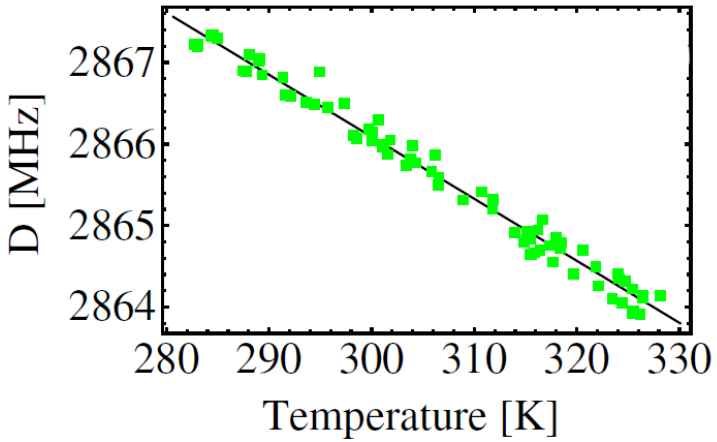
$$H = DS_z^{\,2} + E(S_x^{\,2} - S_y^{\,2}) + g_s\mu_B B \cdot S$$

| The spin - spin interaction between the unpaired electrons caused by the zero field splitting *D* | The influence of energy level change caused by stress (*E*) and electric field | The effect of external magnetic field (*B*) |
|---|---|---|
| **Temperature** | **Stress, electric field** | **Magnetic field** |

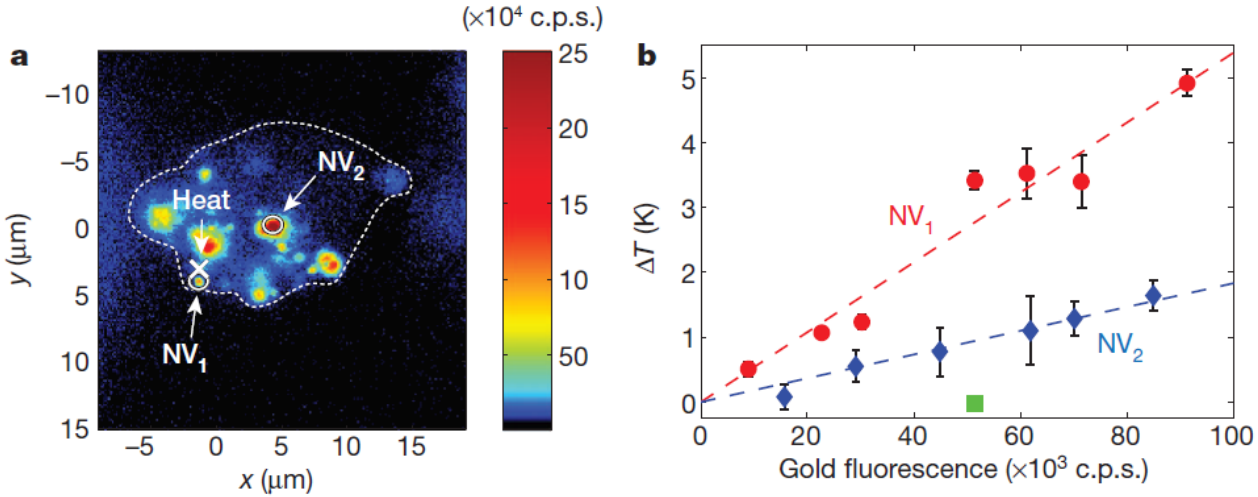
In 1997, Wrachtup's research group in Germany first used confocal system to study a single NV center of diamond, and obtained **optically detected magnetic resonance(ODMR)** signal of a single NV center **at room temperature**.

*S* is the spin angular momentum, $S_x$ ,$S_y$ ,$S_z$is its component in *x*, *y* and *z* axes. $g_s$ is the Lande factor, and $\mu_B$ is the Bohr magneton.

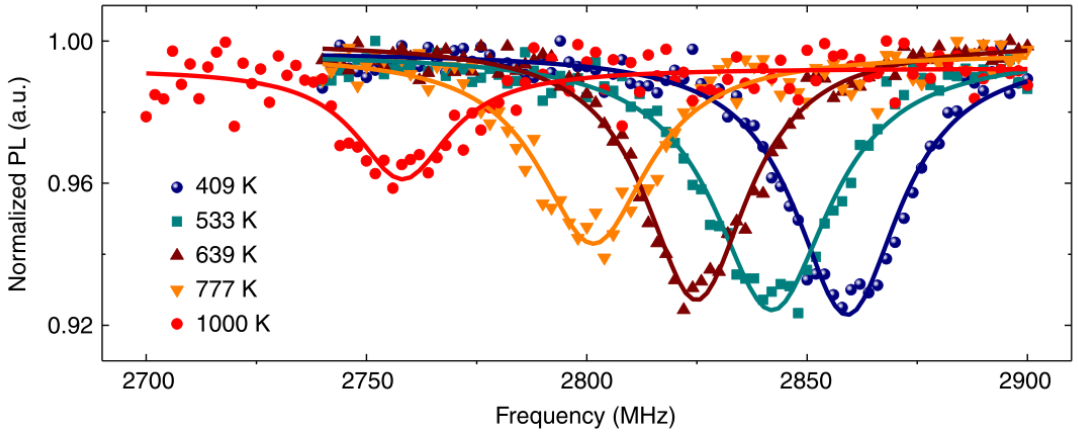
# Quantum temperature sensing




V, M, Acosta, et al. Temperature Dependence of the Nitrogen-Vacancy Magnetic Resonance in Diamond. Physical Review Letters, 2010.




Kucsko G , Maurer P C , Yao N Y , et al. Nanometre-scale thermometry in a living cell[J]. Nature, 2013, 500(7460):54-58.




Liu, G. Q. , et al. "Coherent quantum control of nitrogen-vacancy center spins near 1000 kelvin." Nature Communications 10.1(2019).

# Quantum temperature sensing

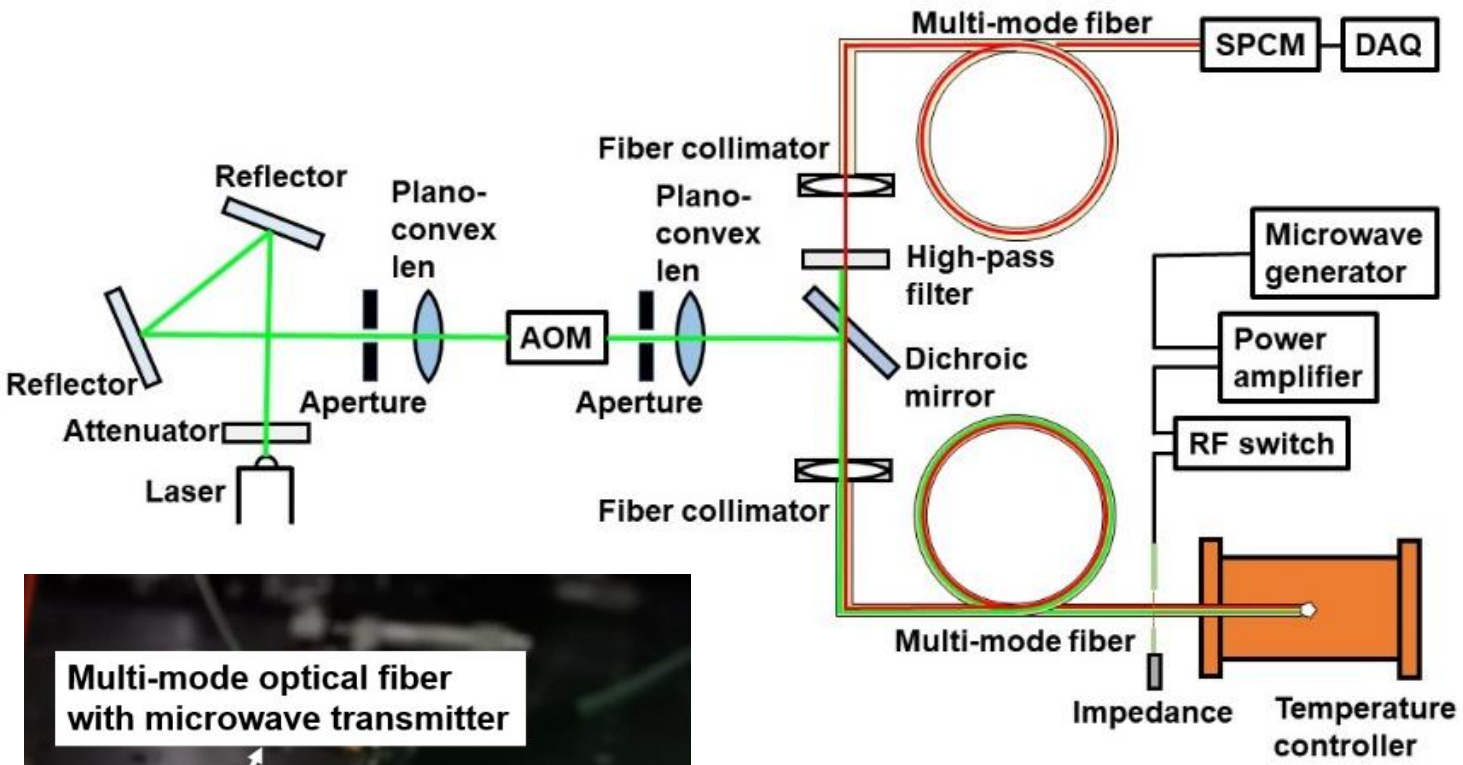
- **NV center is a new kind quantum sensing material for temperature, electric, magnetic and pressure measurement.**

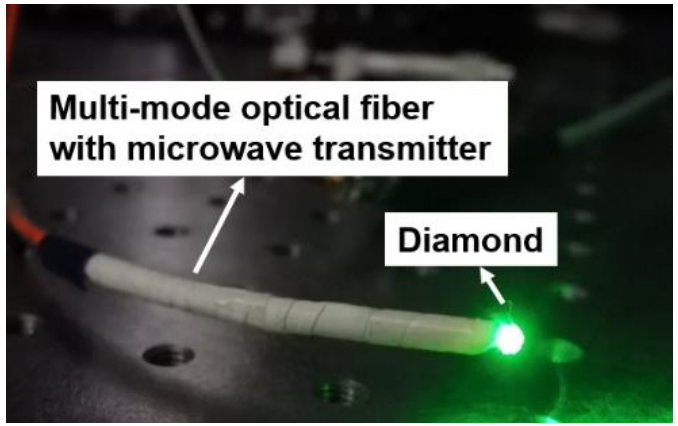
  - ✓ **Diamond: very stable**
  - ✓ **Multiple physical parameters sensing**
  - ✓ **Size: nm scale to mm scale (quick response)**
  - ✓ **Good S/N and sensitivity (mK)**
  - ✓ **Optical fiber probe coupled with NV centers makes it have the potential of integration**

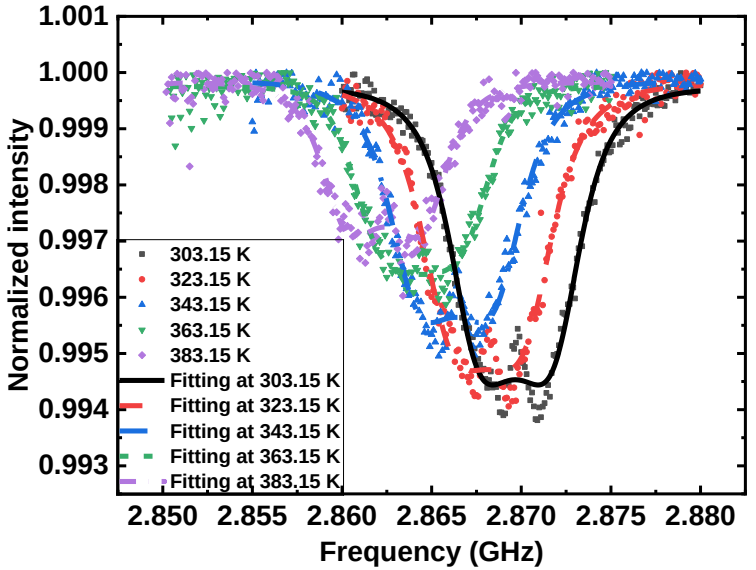
**Could be used in ocean temperature sensing in the future**

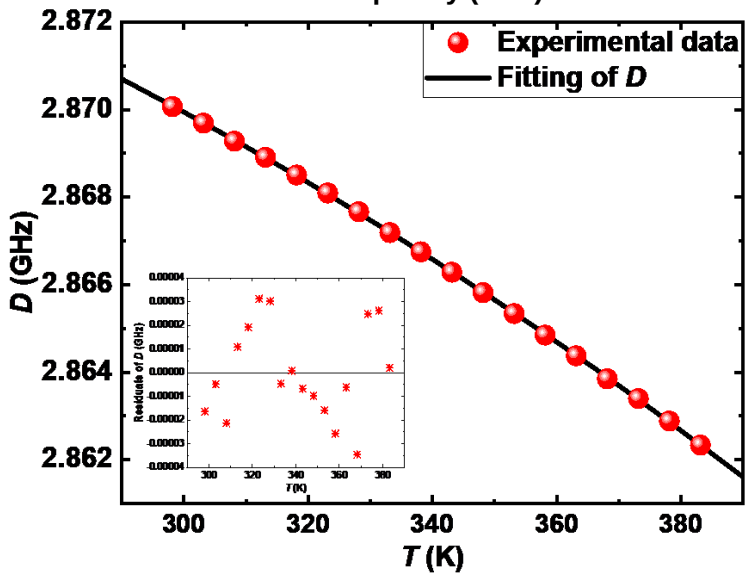
# Quantum temperature sensing

- Optically detected magnetic resonance (ODMR)




Temperature Dependence of Nitrogen-Vacancy Center Ensembles in Diamond Based on an Optical Fiber. OuYang K-C et al. (submitted to Optical Express)

# Summary

- The redefinition of kelvin DOES NOT have an obvious effect on practical temperature measurement of ocean
- In the future, the revision of ITS could lead a better understanding of practical temperature scale closer to physical truth
- Practical thermodynamic temperature measurement could provide a stable temperature (no calibration) as far as the techniques are developed
- New quantum sensing technology such as NV center in diamond could also be used in ocean in the future

# Thank you very much for your attention!

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