# Redéfinition de la seconde, pourquoi, comment et quand ?

ELISA FELICITAS ARIAS

SYRTE, OBSERVATOIRE DE PARIS, UNIVERSITÉ PSL, CNRS, SORBONNE UNIVERSITÉ, LNE

AVEC LA CONTRIBUTION DE PATRIZIA TAVELLA

BUREAU INTERNATIONAL DES POIDS ET MESURES

JOURNÉE SCIENTIFIQUE URSI FRANCE – 31 MARS 2021

# Outline

- The Metre Convention
  - Redefining units
- Case study: the unit of time
  - Evolution of its definition and accuracy
  - Continuity
- Primary frequency standards and secondary representations of the second
- Redefining the SI second
  - Motivations
  - Conditions
  - Timeline
- Information from the CCTF

# Redefining a SI unit

- MOTIVATION
- STRATEGY (CCX + CCU)
- ROADMAP (CCX + CCU)
- TECHNICAL WORK (NMIS, CCX, BIPM)
- RECOMMENDATIONS TO CIPM
  - from CCX
  - from CCU
- DRAFT RESOLUTION
  - from CIPM to CGPM
- CGPM APPROVAL OF RESOLUTION

# Reasons for redefining a unit

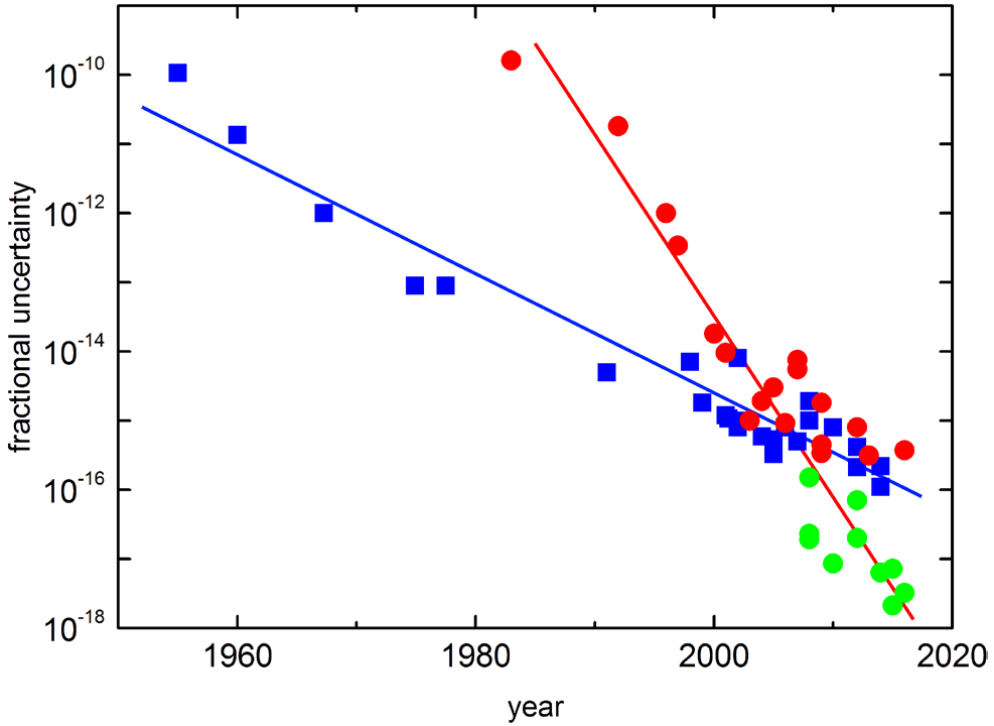
- Drawbacks of the current definition
  - metre and kilogram defined in the past by artifacts
  - process of realization does not guarantee uniformity and degrades accuracy; ex. second defined through Earth's rotation;
- Global SI consistency
  - units defined in terms of constants that describe the natural world, which represent the most stable references; ex. the Revised SI adopted at the 26th CGPM in 2018;
- Advancement in science and technology overcame the current definition
  - need of higher accuracy to support demanding applications; ex. optical clocks achieving accuracy to refine the Earth's model

# Why redefining the SI second? (1)

- Drawbacks of the current definition?

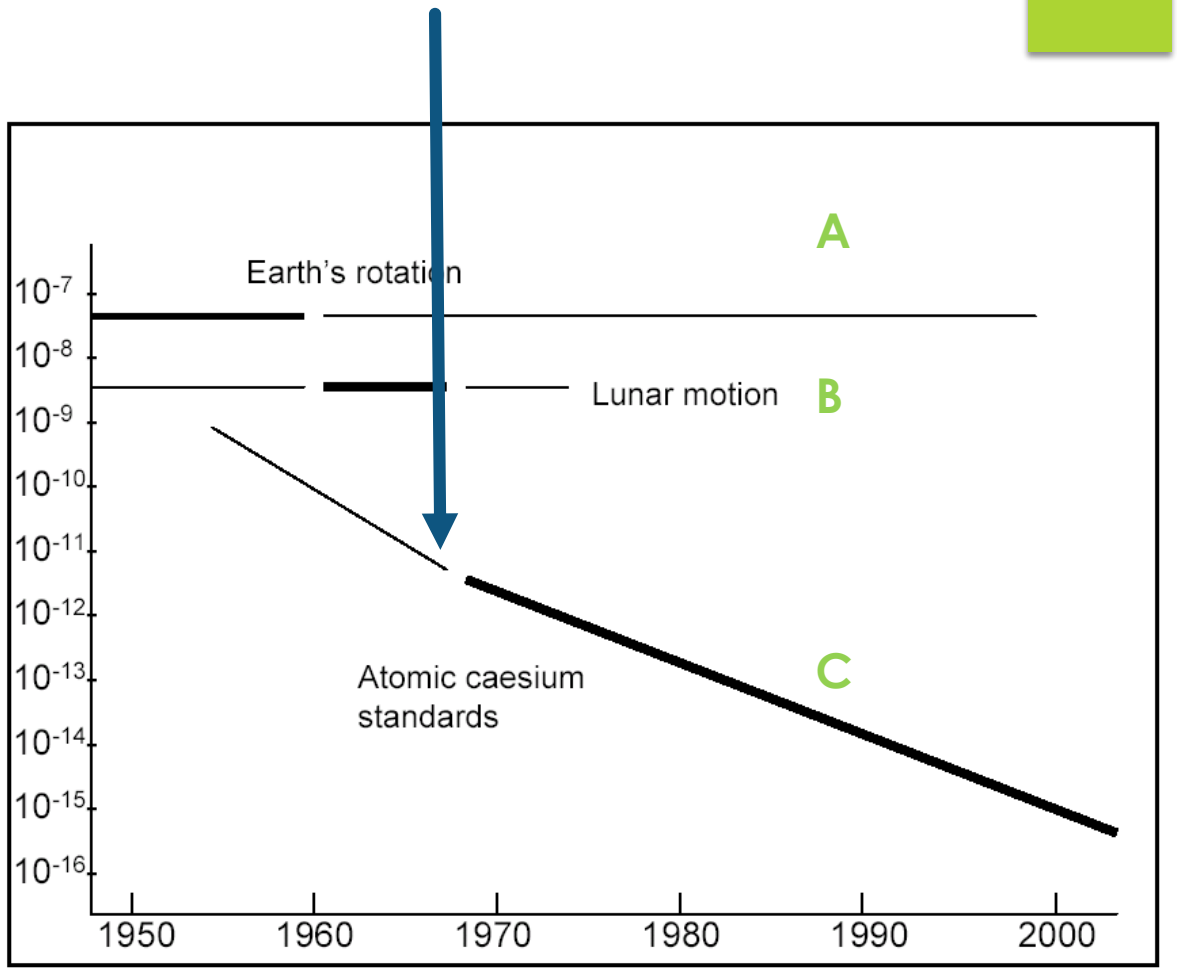
**The second** is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cæsium 133 atom. [(Res.1, 13th CGPM (1967/68)]

Current uncertainty few parts in $10^{16}$



# RELATIVE ACCURACY OF THE SUCCESSIVE DEFINITIONS OF THE SECOND

A. Rotational second
B. Ephemeris second
C. Atomic second



# Why redefining the SI second? (2)

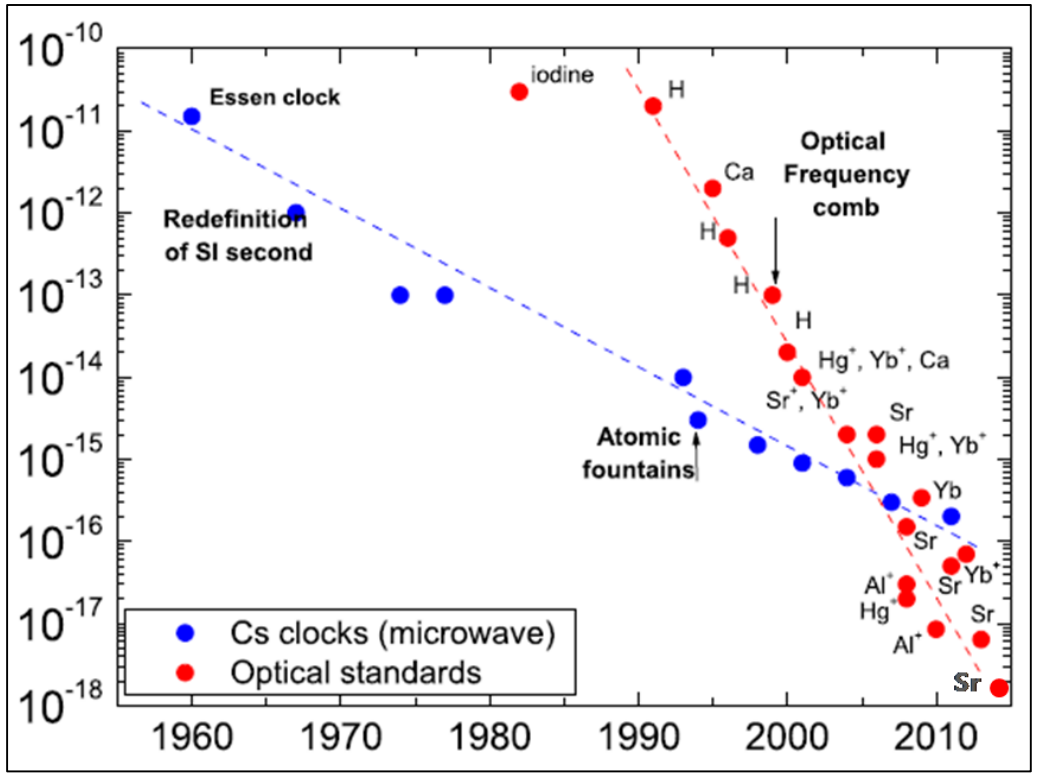
- Global SI consistency

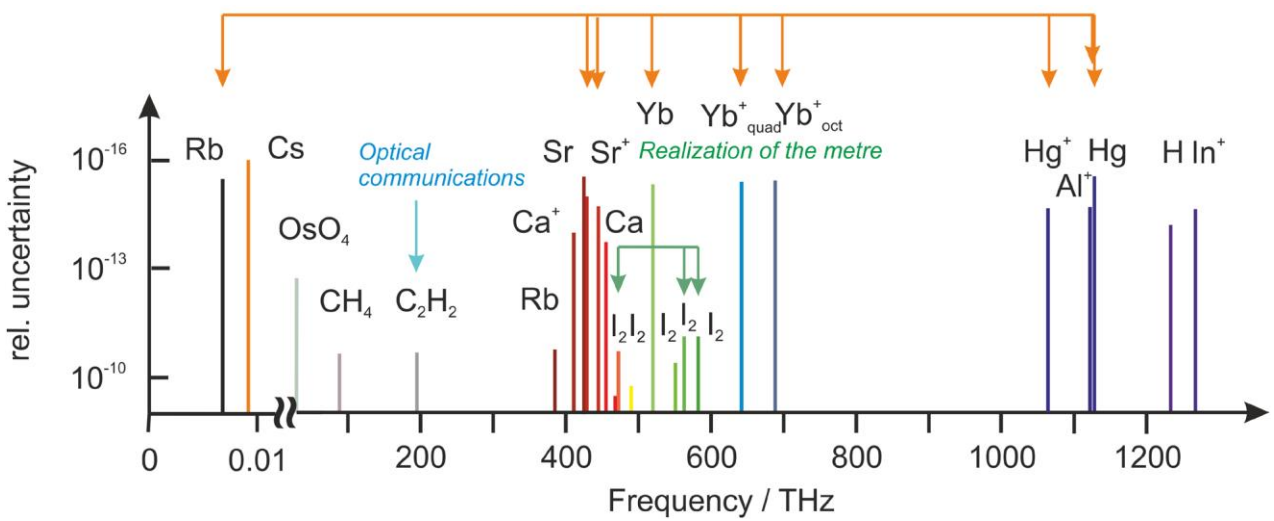
## THE SECOND

' ( ) *) +, - . / *01 2, 3*/ 4* 5( ) 678- 45, 9541 ) : 754*
. ) 94 ) . 20 5, <4 = 5( ) 94>) . - 81 ) ?4+; 3@ 3B) , 95( )
+; ) *481 9?) A8) - +0 $\Delta\nu_{Cs}$ / 5( ) 8- B) ?5B?2) .
=?, 8- . !*5, 5) ( 0B) ?94 ) 5?, - *464 - 9?) A8) - +0 , 95( )
+; ) *481 !" ## ; 5, 1 / 5, 2) &" &%C#" DDE F ( ) -
) >B?) **) . 4 5( ) 8- 45GH/ F ( 4+( 4* ) A8; 35, *!" :

# Why redefining the SI second? (3)

- Advancement in science and technology overcame the current definition



# Continuity: the requisit to redefine a unit

| | |
|---|---|
| 1832 Gauss | Metric system with the second defined by astronomy |
| 1874 BAAS | Coherent system of units (CGS system) |
| 1889 CGPM | MKS system, astronomical second is time unit |

CONTINUITY

The second is (1/86 400) of the mean solar day.

$$s_{Eph} = s_{MSD} - 1.4 \times 10^{-8}\ s$$

| | |
|---|---|
| 1960 CGPM | Ephemeris second |

The SI second is a fraction of a tropical year 1900 (1/ 31 556 925.9747)

# Continuity: the requisit to redefine a unit

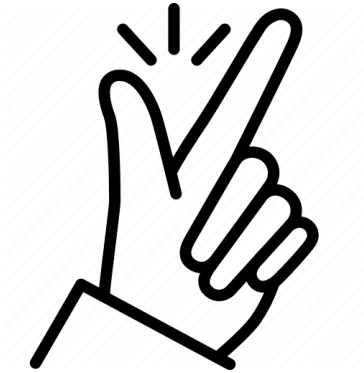
1960 CGPM

THEORY
OBSERVATION

Ephemeris second

1/ 31 556 925.9747 duration of tropical year 1900

CONTINUITY



1. Linking two (stable) clocks independently to a phenomenon;
2. Comparing their output frequencies

1. How stable clocks?
2. Frequency and time comparisons over the Atlantic Ocean

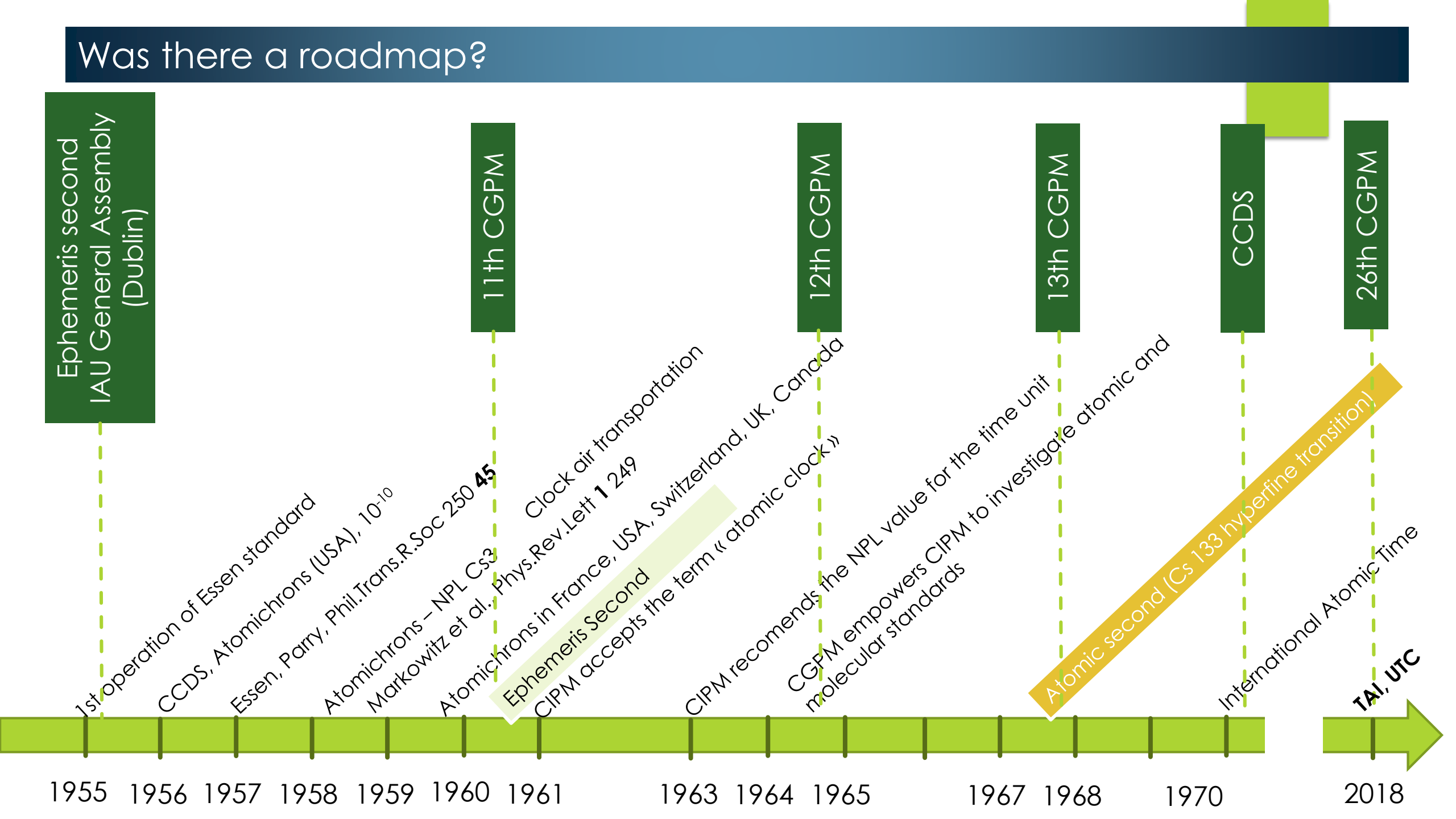
the duration of 9 192 631 770 periods of the radiation….

1967/68 CGPM

EXPERIMENTAL
PHYSICS

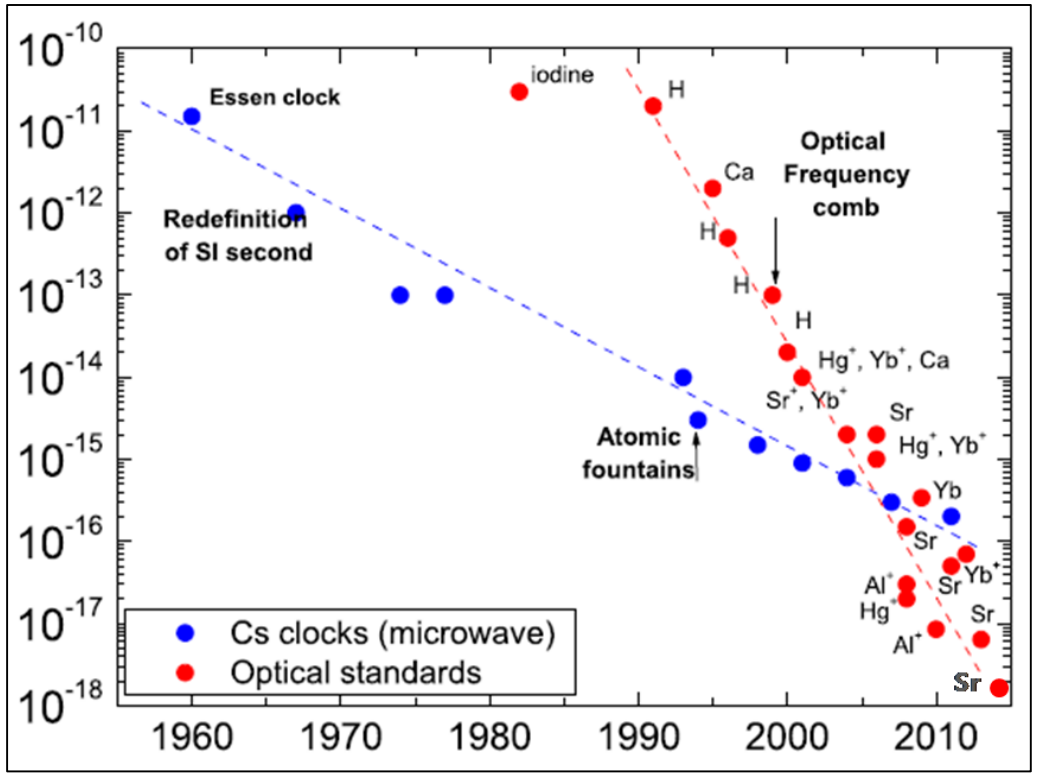
Atomic second (Cs 133 hyperfine transition)

# Was there a roadmap?

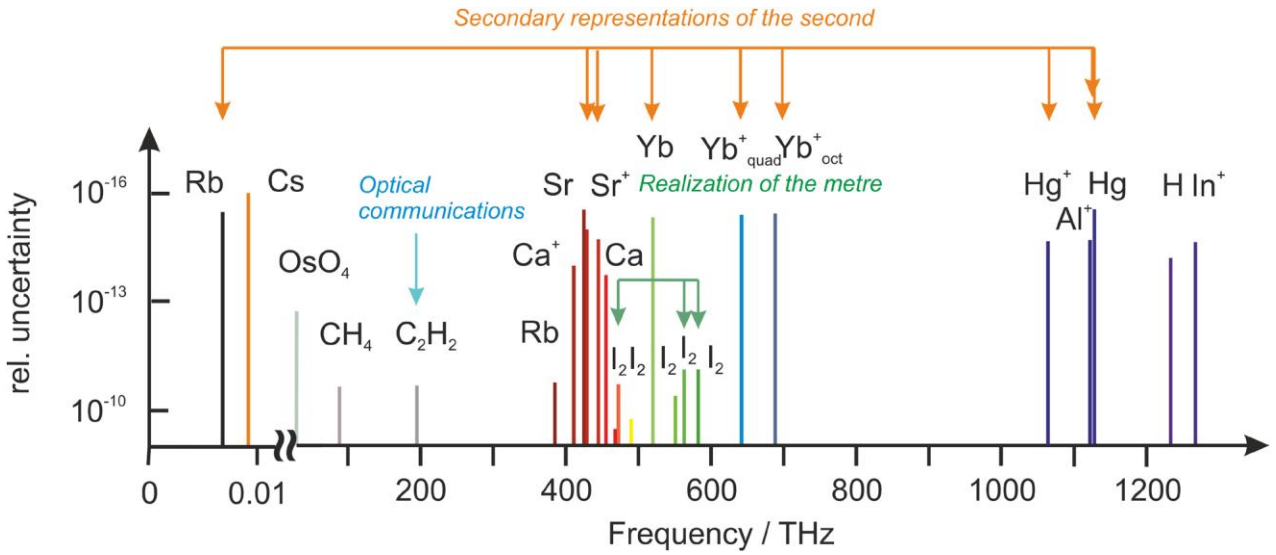


# How to redefine the SI second?

CIPM List of frequencies recommended as secondary representations of the second

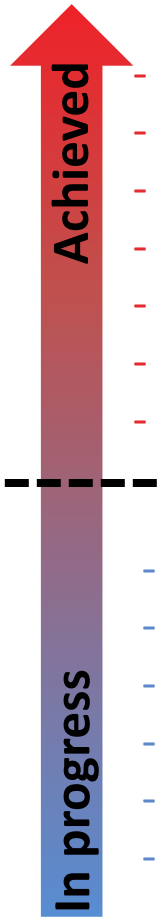



Metrologia **55** (2018) 188 F Riehle *et al*



# CCTF march 2021

## *Priority setting of criteria / conditions to change definition*




Mandatory criteria **To be achieved** before changing the definition

- **Validation that Optical Frequency Standards are at a level 100 times better than Cs**
- **Continuity with the definition based on Cs**
- **Regular contributions of OFS to TAI as secondary representations of the second**
- **Availability of sustainable techniques for OFS comparisons**
- **Knowledge of the local geopotential at the proper level**
- **Definition allowing future more accurate realizations**
- **Access for NMIs to primary or secondary realizations of the new definition**

Mandatory achievements frontier

Conditions corresponding to essential **Work still in progress** when the definition is changed

- **High reliability of optical frequency standards**
- **High reliability of ultra high stability T/F links**
- **Continuous improvement of the realization and time scales after redefinition**
- **Regular contributions of optical clocks to UTC(k)**
- **Availability of commercial optical clocks**
- **Improved quality of the dissemination towards users**

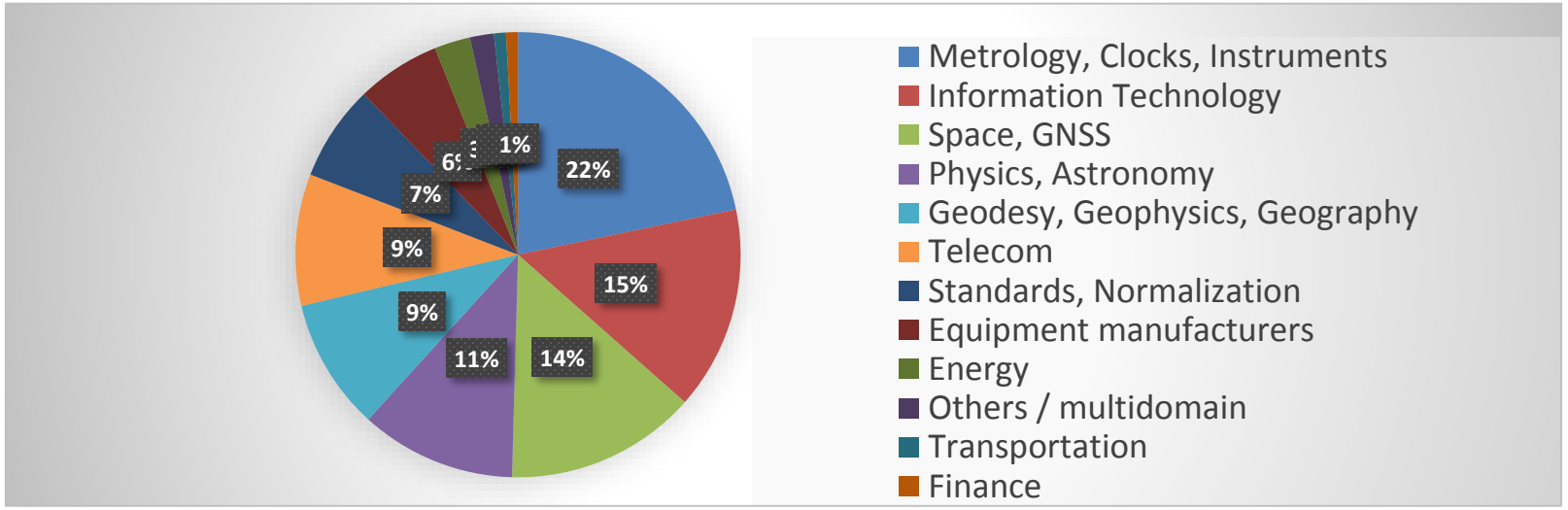
Bureau International des Poids et Mesures

The detailed specification of these criteria is in progress

# More than 200 answers to the CCTF questionnaire :

| Category | Number of answers |
|---|---|
| **CCTF Members, Observers, and UTC contributors** | 78 (among which 24 CCTF members, 53 UTC(k) representatives) |
| **NMIs not yet contributing to UTC** | 12 |
| **CCTF liaisons** | 4 |
| **Stakeholders** | 117 |

**Stakeholders**




Bureau International des Poids et Mesures

# Main outcome from the questionnaire

- There is high awareness on the possibility of the redefinition of the second and benefits are foreseen as:
  - Development of science, satellite navigation systems, deep space exploration, other space applications, fundamental physics, geodesy, SI system of units, fundamental constants
  - Redefinition will provided impetus for the development of fundamental research
  - Opportunities for new industrial developments
  - Opportunity for some institutes to reach state-of-the-art faster
- There is a strong interest in affordable commercial optical clocks. Their availability is essential to support the implementation of the redefinition of the second.
- Further information on an ongoing basis should be provided to all NMIs, DIs and Stakeholders as the redefinition work progresses

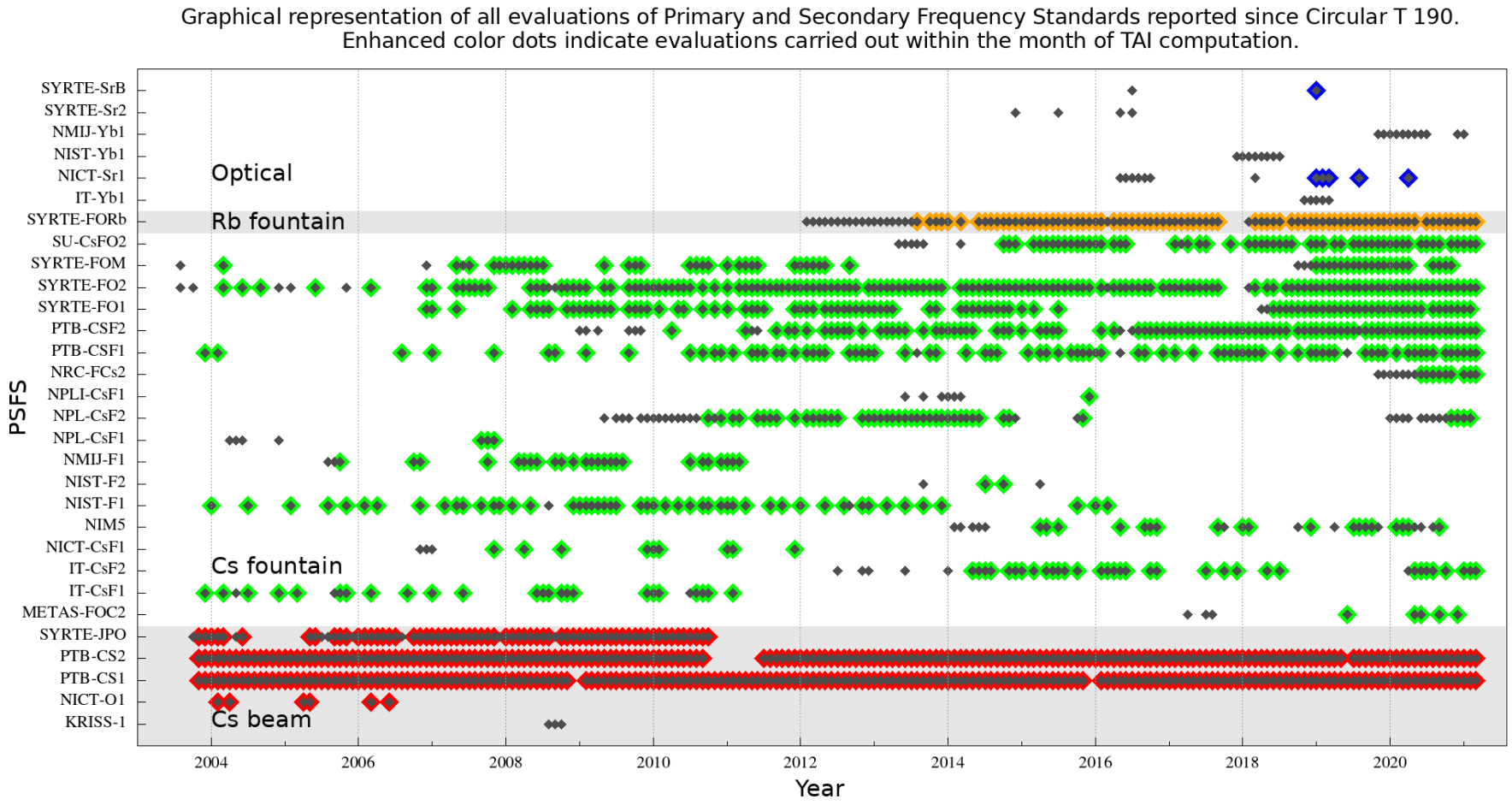
# Optical frequency standards

- Several time laboratories are working to develop and improve optical frequency standards

  - 37 new optical  frequency measurements were submitted  to the CCTF from 2017
  - 11 optical transitions are now recommended as secondary representation of the second (2 new in 2021)
  - The uncertainties improved significantly: 8 secondary representations of the second have an uncertainty around $2 \times 10^{-16}$

- 12 laboratories are working on optical transportable clocks

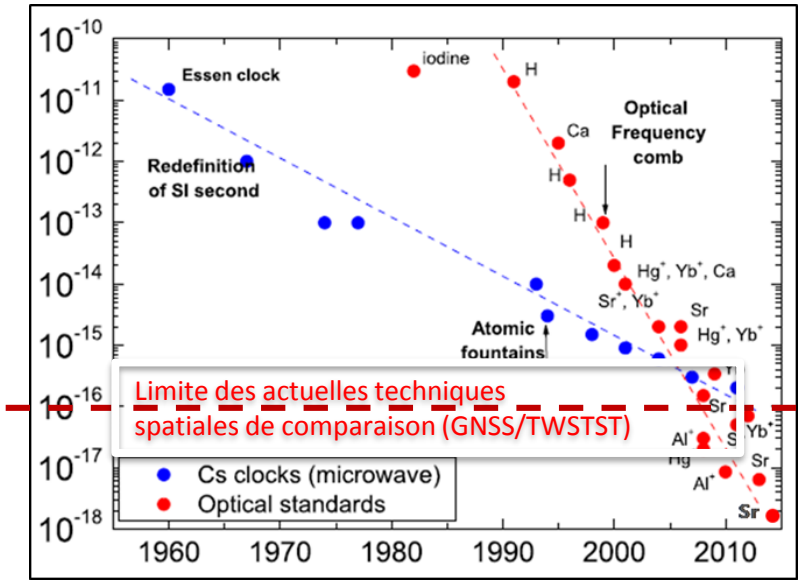
# The participation to TAI is still limited, it will grow




Bureau International des Poids et Mesures

# Time and frequency transfer capabilities

- Existing techniques: GNSS and TWSTFT
- Becoming popular: Precise Point Positioning with Integer Ambiguity Resolution (IPPP) with instability $10^{-16}$ @ a few days
- TW Carrier Phase : $10^{-17}$
- Existing fibre links:
  - NIST-JILA < $10^{-18}$
  - European links from $10^{-16}$ to <$10^{-18}$ in frequency, 2 ns to 2 ps in time
  - Tokyo 100 km $10^{-18}$
  - China 100km $10^{-18}$, 10 ps.
- Free-air optical link: NIST-JILA
- VLBI technique $10^{-16}$




The community should dedicate a large effort in building a solid comparison infrastructure.

We need regular comparison campaigns beyond GNSS performances;

-at the continental scale: we should have fibre comparisons on a regular basis;

-at the intercontinental scale: we should develop and consolidate comparisons using fibres, IPPP or new techniques, e.g. VLBI, optical satellite, TWCP.

Improving the geopotential measurement uncertainty at the clock sites is under way, all NMIs need to strengthen their relationship with geodesists

Bureau International des Poids et Mesures

# Work in progress

The CCTF and its Working Groups will still evaluate

- the status and development perspectives of optical frequency standards,
- the possibility to compare them at the requested level of uncertainty,
- their capacity to contribute to a time scale

and will prepare an updated roadmap to the redefinitiin of the second to the Conference General des Poids et Mesures 2022

Bureau International des Poids et Mesures

# CONCLUSIONS

- The accuracy of the realization of the second by cesium primary standards has increased 5 orders of magnitude in 50 years ($10^{-16}$ today);
- The relative frequency uncertainty of optical clocks has increased 7 orders of magnitude in 20 years ($10^{-18}$ today);
- Optical standards can be compared without losing accuracy with fibre optics;
- Work is ongoing for long-distance optical clock comparisons;
- Few optical transitions are reported to TAI more or less regularly;
- The CCU started discussions on the strategy for the redefinition;
- The CCTF took actions to update the roadmap for the redefinition of the SI second;
- If conditions are fulfilled, the CGPM could adopt a new definition by 2026-2030;

# *Concerning the CCTF work on Leap seconds in UTC and building a consensus for a continuous timescale*

*The survey has demonstrated that a high majority of users and NMIs would prefer the extension of the tolerance UT1-UTC now limited to 1 second.*

*For some applications as Industry 4.0 and the digital transformation, this modification and the interruption of leap second is highly recommended.*

*The CCTF is working on a recommendation to extend the tolerance UT1-UTC to be proposed to the CGPM in 2022*

*In the meantime the CCTF will work on:*

1. Support UT1-UTC dissemination service, with security, machine readable, trustable, authenticated signals.
2. Work in liaison with ITU-R to address the Radiocommunication needs and the definition of codes to properly disseminate UTC and the offset UT1-UTC
3. Support NMIs in the evaluation of changes with countries that use mean solar time as legal time
4. Work with other organizations as IAU, ITU, IUGG, URSI, IGS to fix the new tolerance
5. Support the astronomical community for the necessary upgrades and information

Bureau International des Poids et Mesures

URSI Commission A has proposed a recommendation to the be discussed at the newt URSI GASS 2021

# MERCI DE VOTRE ATTENTION