CGPM

Draft Resolution E

“On the future redefinition of the second”

Noël Dimarcq, CCTF President
Patrizia Tavella, BIPM Time Dept. Director

November 2022

CGPM

Projet de résolution E

« Sur la future redéfinition de la seconde »

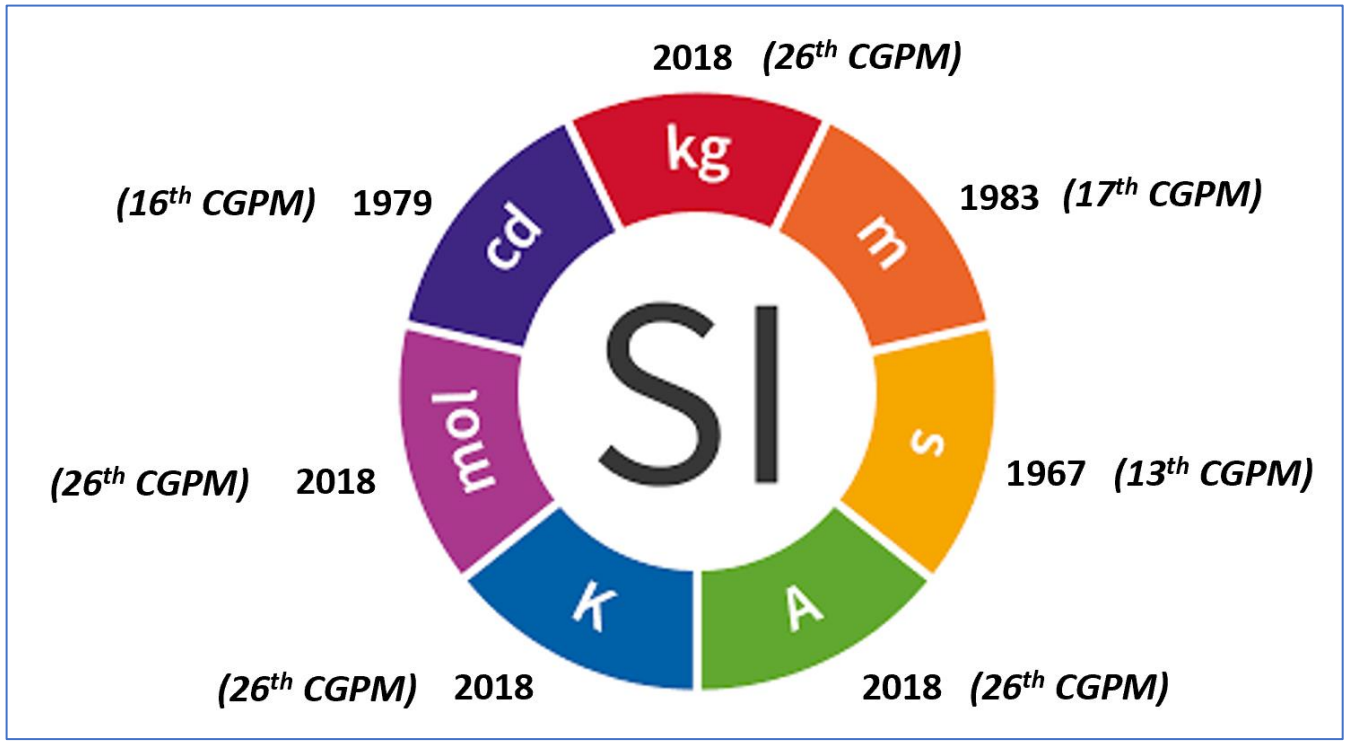
Noël Dimarcq, Président du CCTF
Patrizia Tavella, Directrice BIPM Time Dept

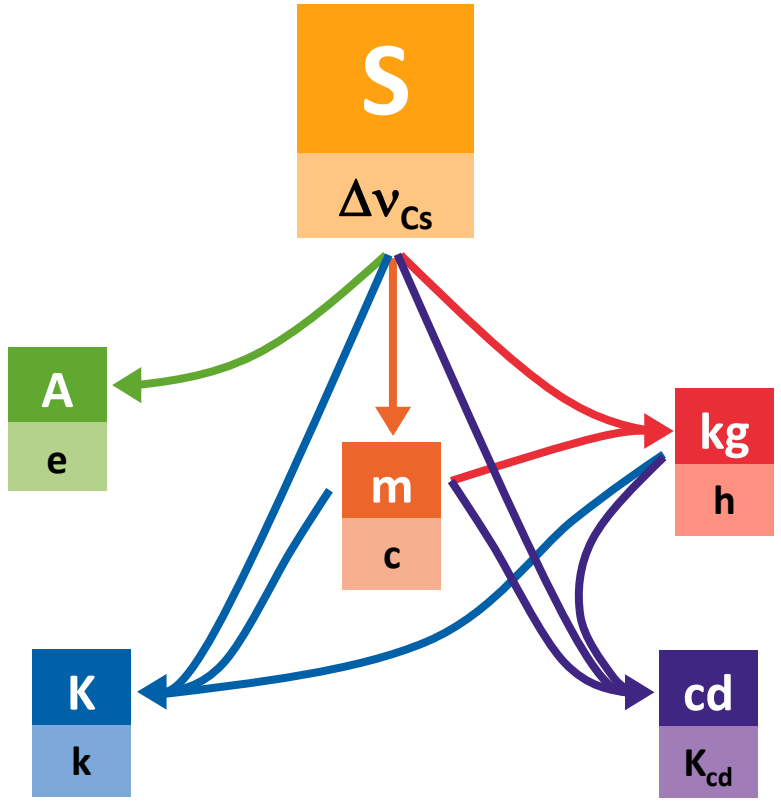
November 2022

27e réunion de la Conférence générale des poids et mesures

The International System of Units

At CGPM 2018, redefinition of 4 units (kg, A, K, mol) relying on fondamental constants (h, e, k, N_A) + fixing the value of $\Delta\nu_{Cs}$





Definitions of the SI unit of time

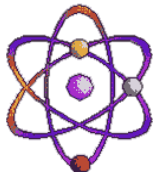
The SI unit of time – the second – is defined as:

Astronomy

→ **until 1956** : the fraction 1/86 400 of the mean solar day

→ **1956 to 1967** : the fraction 1/31,556,925.9747 of the tropical year 1900

Quantum physics

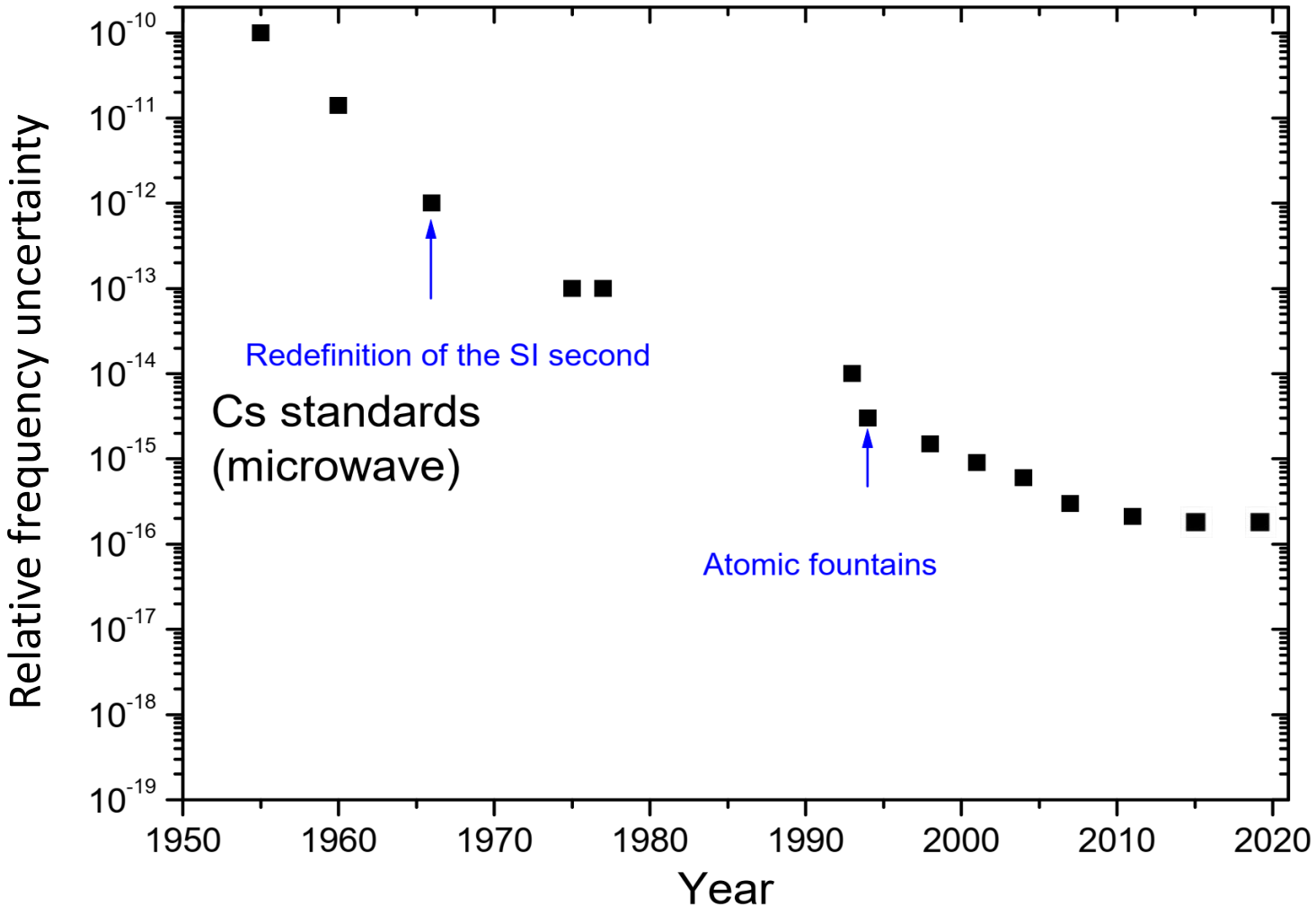


→ **1967** : the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom
Added in 1999: This definition refers to a cesium atom at rest at a temperature of 0 K

New formulation in 2018:

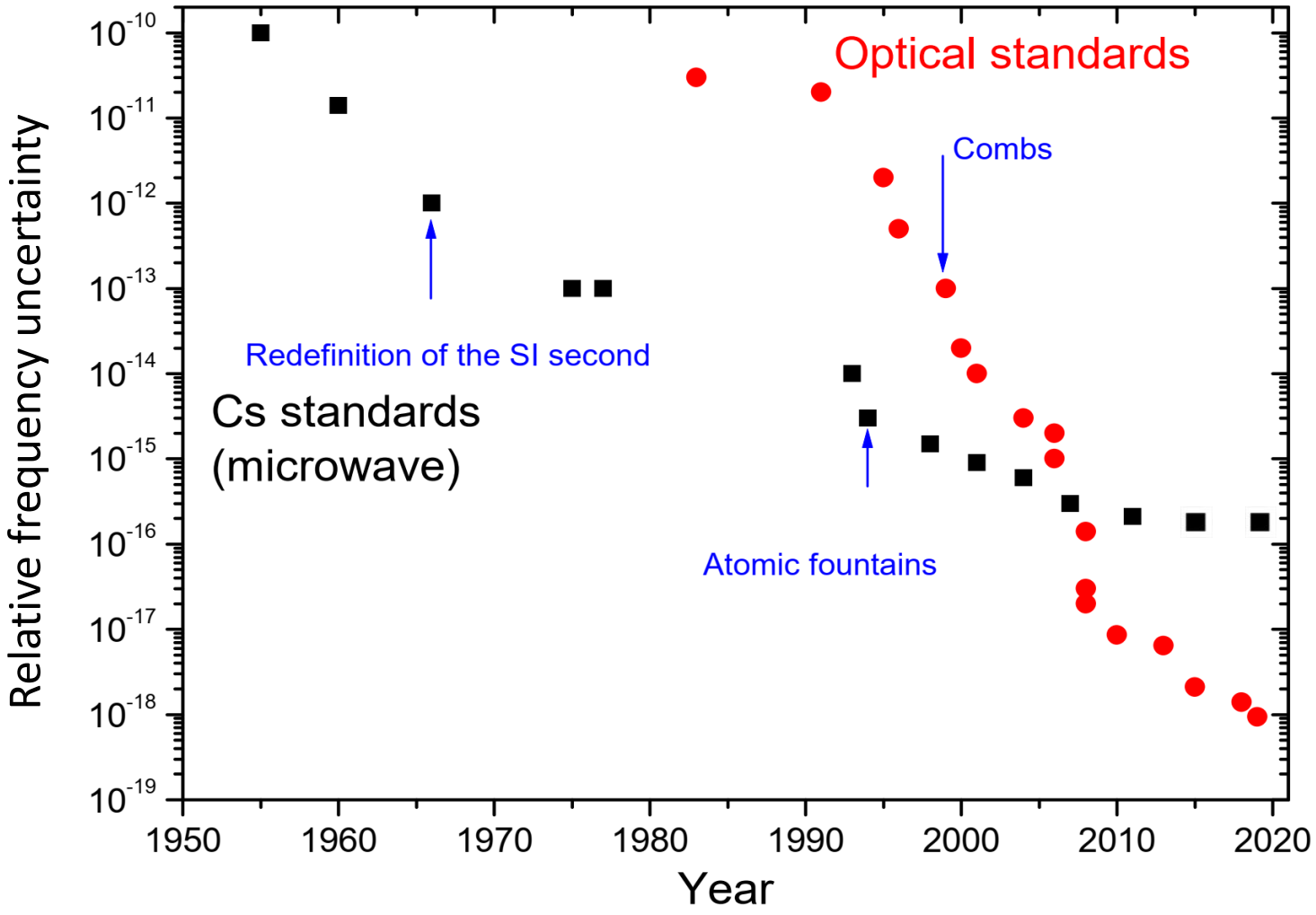
The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.

Realization of the SI second with primary Cs frequency standards



Cs fountain uncertainty floor ~ 10^{-16}

The era of Optical Frequency metrology



Optical Frequency Standards (Sr, Yb, Yb+, Al+, Ca+, …) uncertainty at 10^{-18} level

Goals for a new definition

→ **Offer an improvement** by 10 to 100 of the realization of the new definition on short term after the redefinition (reaching 10^{-17} to 10^{-18} relative frequency accuracy) and a larger improvement on longer term

→ **Ensure continuity with the current definition**

→ **Ensure continuity and sustainability of the availability of the new SI second** through the International Atomic Time (TAI), and a **significant improvement of the quality of TAI** as soon as the definition is changed (at least no degradation !)

→ **Enable the dissemination of the unit** towards wide categories of users

→ **Be acceptable** by all NMIs and stakeholders

Updated CCTF Roadmap towards the redefinition of the SI second

→**Dedicated CCTF Task Force** with 40 people in 4 specific Working Groups :

- Roadmap and mandatory criteria
- Request from user communities, NMIs and Liaisons
- Atomic frequency standards, and possible redefinition approaches
- Time & Frequency dissemination and time scales

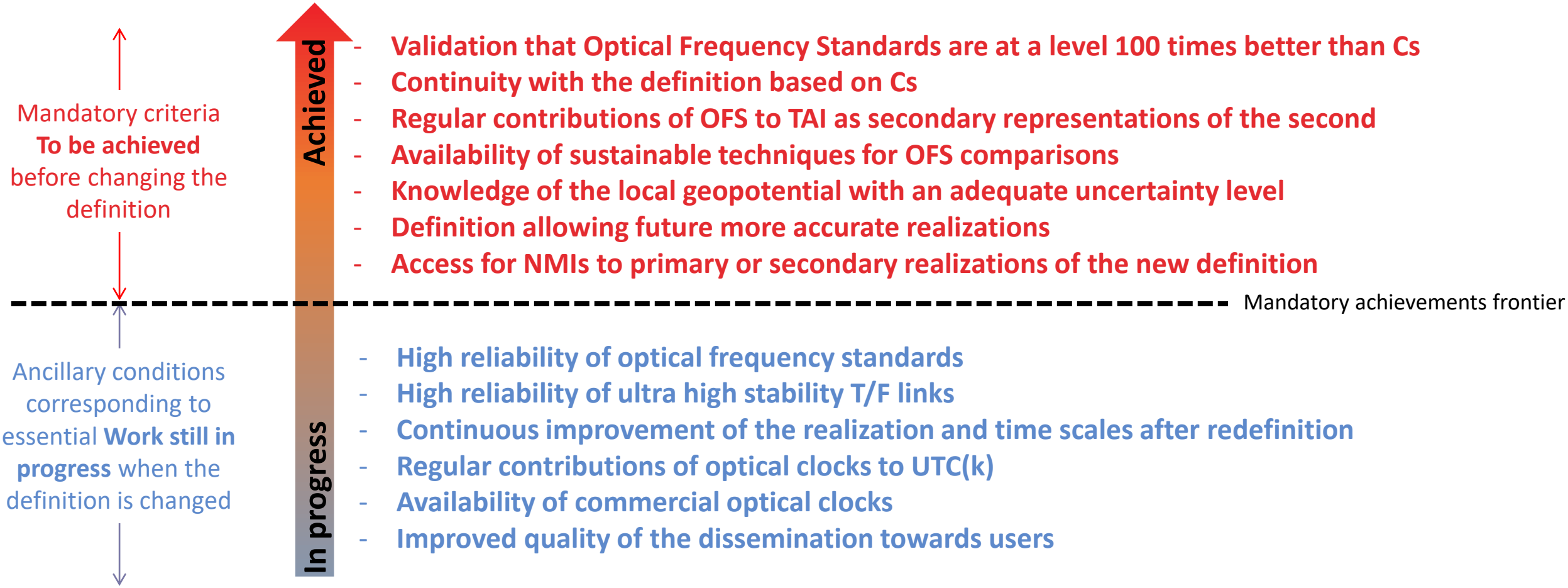
SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the possible options for the new definition:

Option 1: Single atomic transition
Option 2: Ensemble of atomic transitions
Option 3: Fixing the value of another fundamental constant

→**Definition of an ensemble of criteria** and conditions to change the definition, with associated indicators to evaluate **fulfilment levels**

→**Analyse of possible schedule scenarios** for the redefinition of the second

Criteria / conditions to change the definition



Criteria / conditions to change the definition

Frequency standards & contribution to atomic time scales

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

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

Achieved

- **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

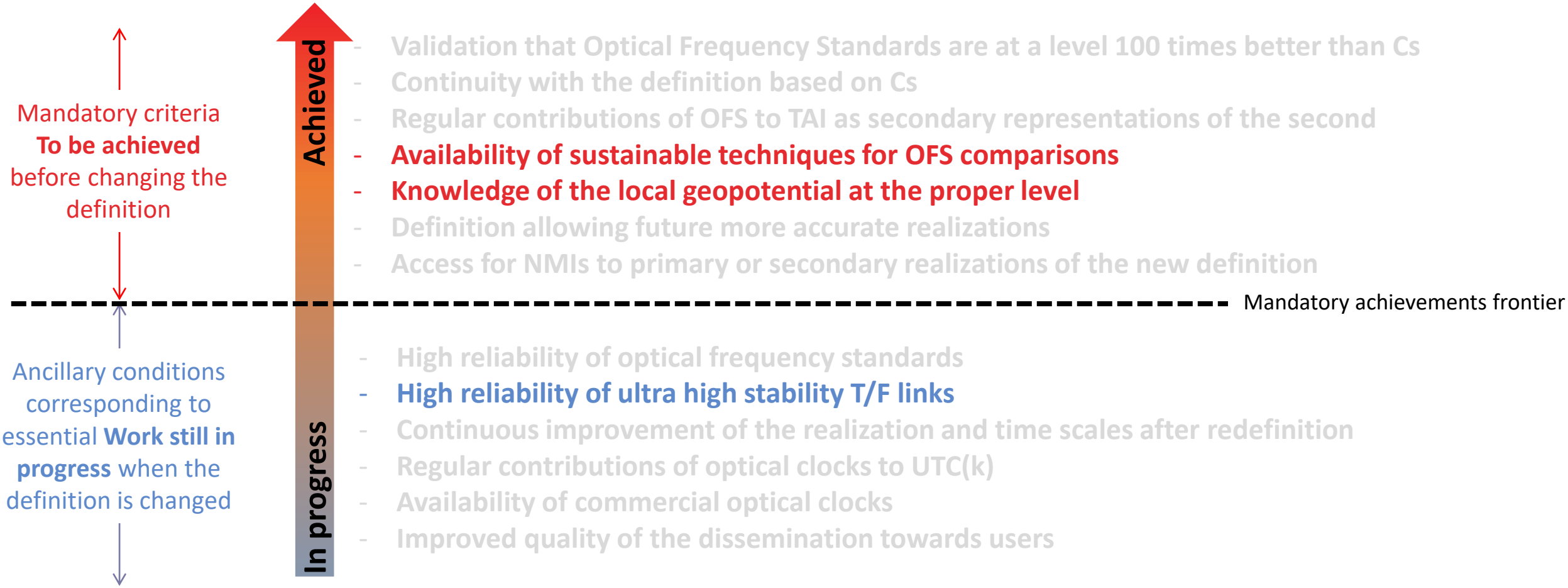
Mandatory achievements frontier

In progress

- **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 (III.4)
- Improved quality of the dissemination towards users (III.5)

Criteria / conditions to change the definition

TF comparison and dissemination



Criteria / conditions to change the definition

Acceptability of the new definition

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

Achieved

- 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**

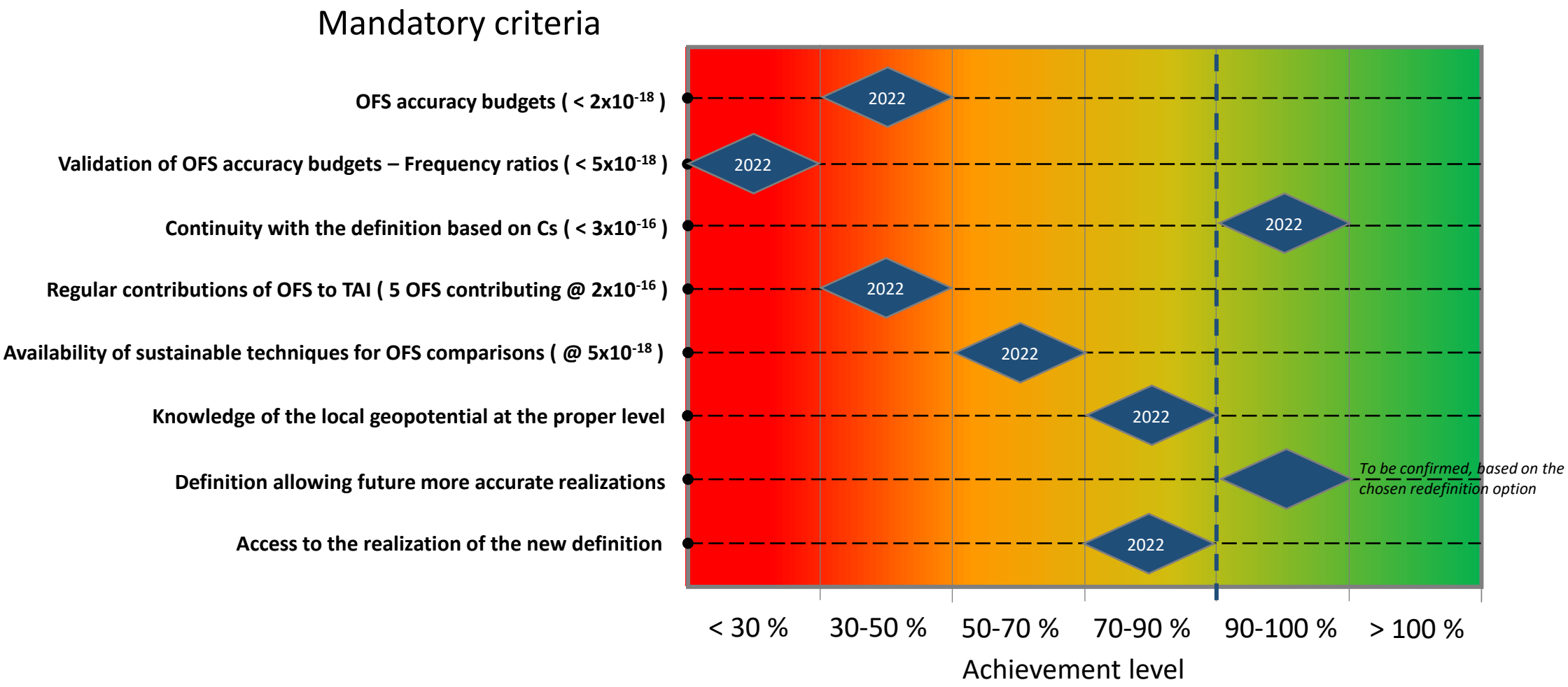
Mandatory achievements frontier

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

In progress

- 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**

Fulfilment level of mandatory criteria (2022)



Scenarios for the redefinition of the second

CGPM 2022 **2026** 2030 2034 ….

A redefinition at CGPM 2026 is unrealistic since today there is no consensus on the preferred option and still some important work to do to fulfil all mandatory criteria.

Scenarios for the redefinition of the second

CGPM 2022 2026 2030 2034 ….

A redefinition at CGPM 2026 is unrealistic since today there is no consensus on the preferred option and still some important work to do to fulfil all mandatory criteria.

CGPM 2026 could validate a roadmap towards a redefinition in 2030 if, in 2026, there is a consensus on the redefinition option to be chosen and if the work to fulfil mandatory criteria is likely to be achievable by 2030.

Scenarios for the redefinition of the second

CGPM 2022 2026 2030 2034 ….

A redefinition at CGPM 2026 is unrealistic since today there is no consensus on the preferred option and still some important work to do to fulfil all mandatory criteria.

CGPM 2026 could validate a roadmap towards a redefinition in 2030 if, in 2026, there is a consensus on the redefinition option to be chosen and if the work to fulfil mandatory criteria is likely to be achievable by 2030.

If it is not possible in 2030, the redefinition will have to be postponed, at CGPM 2034 or the following one… But it will require to maintain until the late 2030s the operation of Cs fountains primary frequency standards that have been built in the 1990s - 2000s.

Dratf Resolution E - On the future redefinition of the second

encourages the International Committee for Weights and Measures (CIPM)

- to promote the importance of achieving the objectives in the roadmap for the redefinition of the second,
- to bring proposals to the 28th meeting of the CGPM (2026) for the choice of the preferred species, or ensemble of species for a new definition of the second, and for the further steps that must be taken for a new definition to be adopted at the 29th meeting of the CGPM (2030),

and **invites** Member States to support research activities, and the development of national and international infrastructures, to allow progress towards the adoption of a new definition of the second.

CGPM

Special thanks to the CCTF WGs, the Task Force, external experts, the BIPM Time Department for fruitful discussions, support and contribution

Thanks for

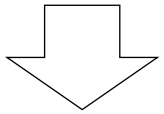
your attention

Extra slides

Options for the redefinition of the second

Option 1: Single atomic transition
Definition: fix the frequency of a single (optical) atomic transition

$$\Delta\nu_{\mathrm{Cs}} = 9\ 192\ 631\ 770\ \mathrm{Hz}$$



$$\Delta\nu_{\mathrm{Xy}} = 567\ 890\ 123\ 456\ 789.01\ \mathrm{Hz}$$

- Realization: with frequency standards based on Xy
- Continue to maintain and update a list of Second Representations of the Second (including Cs)
- To be redefined on the long term if major progress occurs in the uncertainty of frequency standards based on other transition(s)

→ **Classical approach similar to the current definition**

Options for the redefinition of the second

Option 2: Ensemble of transitions on an even basis

Definition: weighted geometric mean of an ensemble C of chosen transitions

Weight inversely proportional to the uncertainty of best standard using transition i

$$\Delta\nu_{\mathrm{Cs}} = 9\ 192\ 631\ 770\ \mathrm{Hz}$$

$$\nu = \frac{1}{N}\prod_{i\in C}\nu_i^{w_i}$$

- Realization: with frequency standards based on transitions part of C (representations of the second) using frequency ratio matrix updated by the CIPM
- A single frequency standard i part of C realizes the unit
- 133Cs can (should) be part of C
- Including transitions in ensemble C and transitions not yet part of C
- Can follow the progress of frequency standards by updating the ensemble and the weights
- Merges the concept and use of primary and secondary representations of the second

See J. Lodewyck, Metrologia 56, 055009 (2019)

→ **Novel approach providing a dynamic definition**

Options for the redefinition of the second

Option 3: Fixing the value of another fundamental constant
Definition: fix the value of one more fundamental constant

$$\Delta\nu_{\mathrm{Cs}}, c, h, e, k$$

$$X, c, h, e, k$$

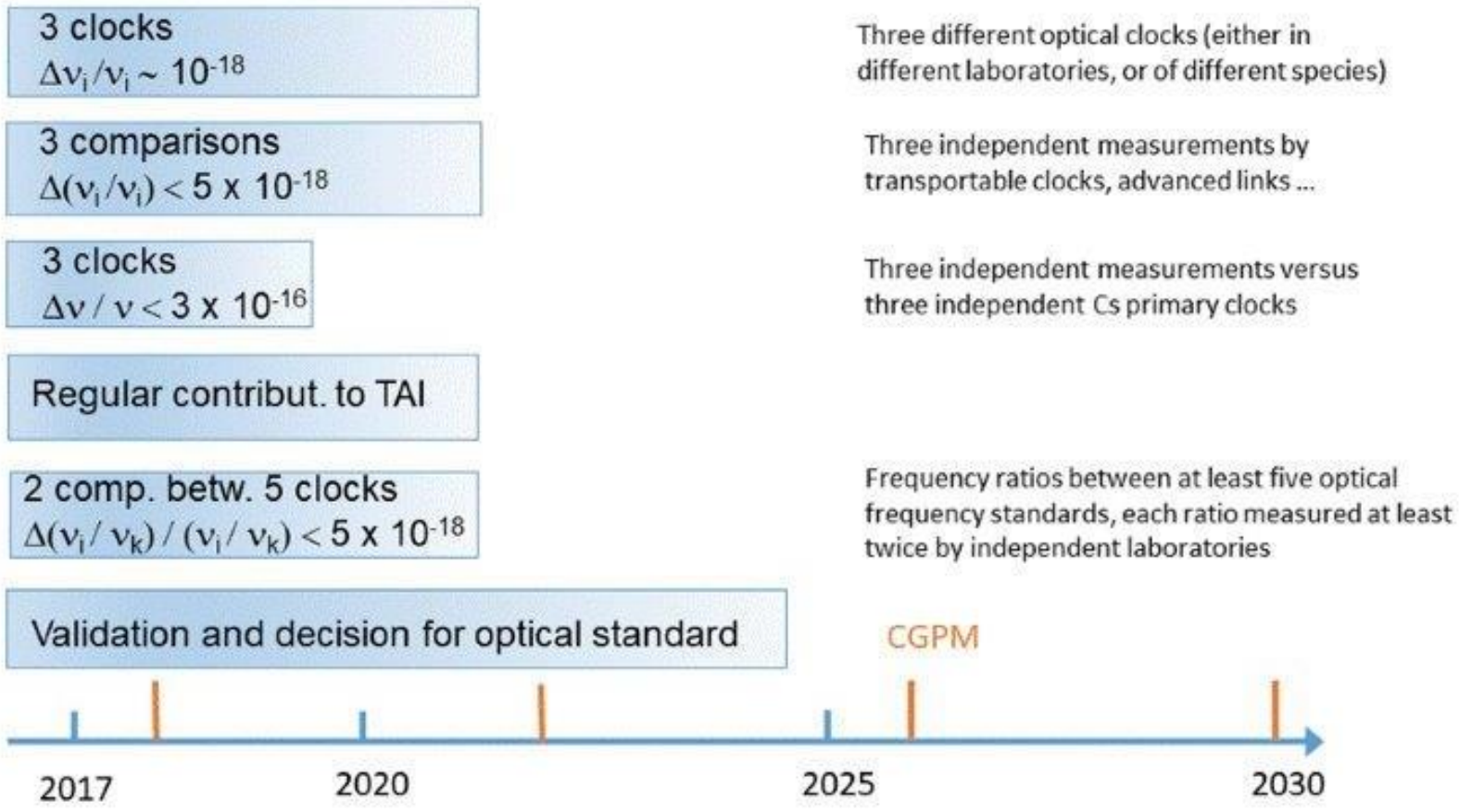
- Directly connected to the underlying fundamental framework: general relativity and the standard model of particle physics
- Realization: would be based on atomic transition(s) (one of 2 previously discussed options)

Constant	Frac. Unc.
G	2.2×10^{-5}
m_e	3.0×10^{-10}
R_∞	1.9×10^{-12}
$\mathrm{H(1S-2S)}$	4.5×10^{-15}

→ An ideal option that could complete the consistency of the SI system based on fundamental constants. But more futurist because to date, fundamental constants are known with a too large uncertainty

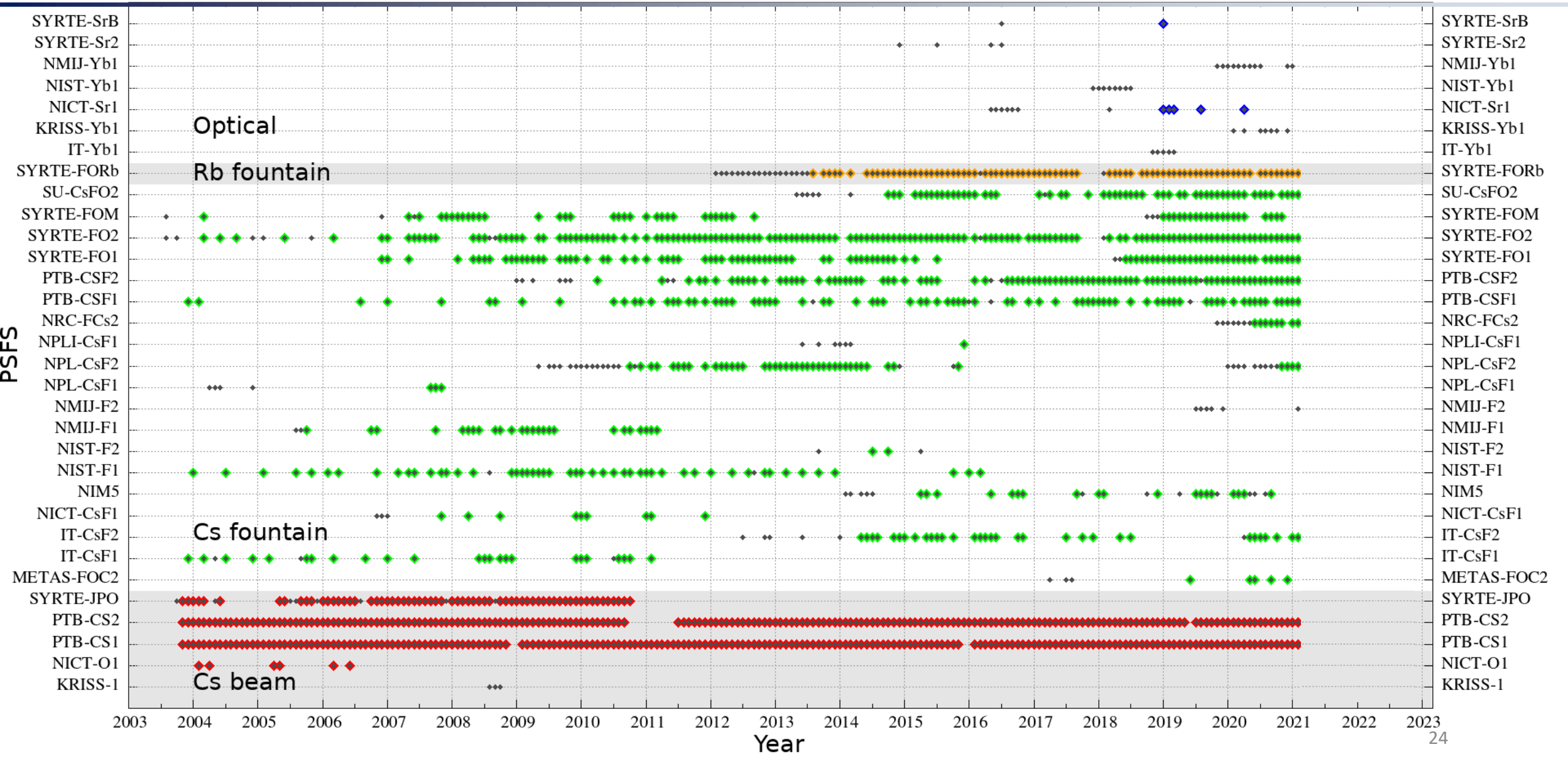
First ensemble of criteria fixed in 2016 for a change of the definition

Roadmap towards a redefinition of the SI second (CCTF 2016)

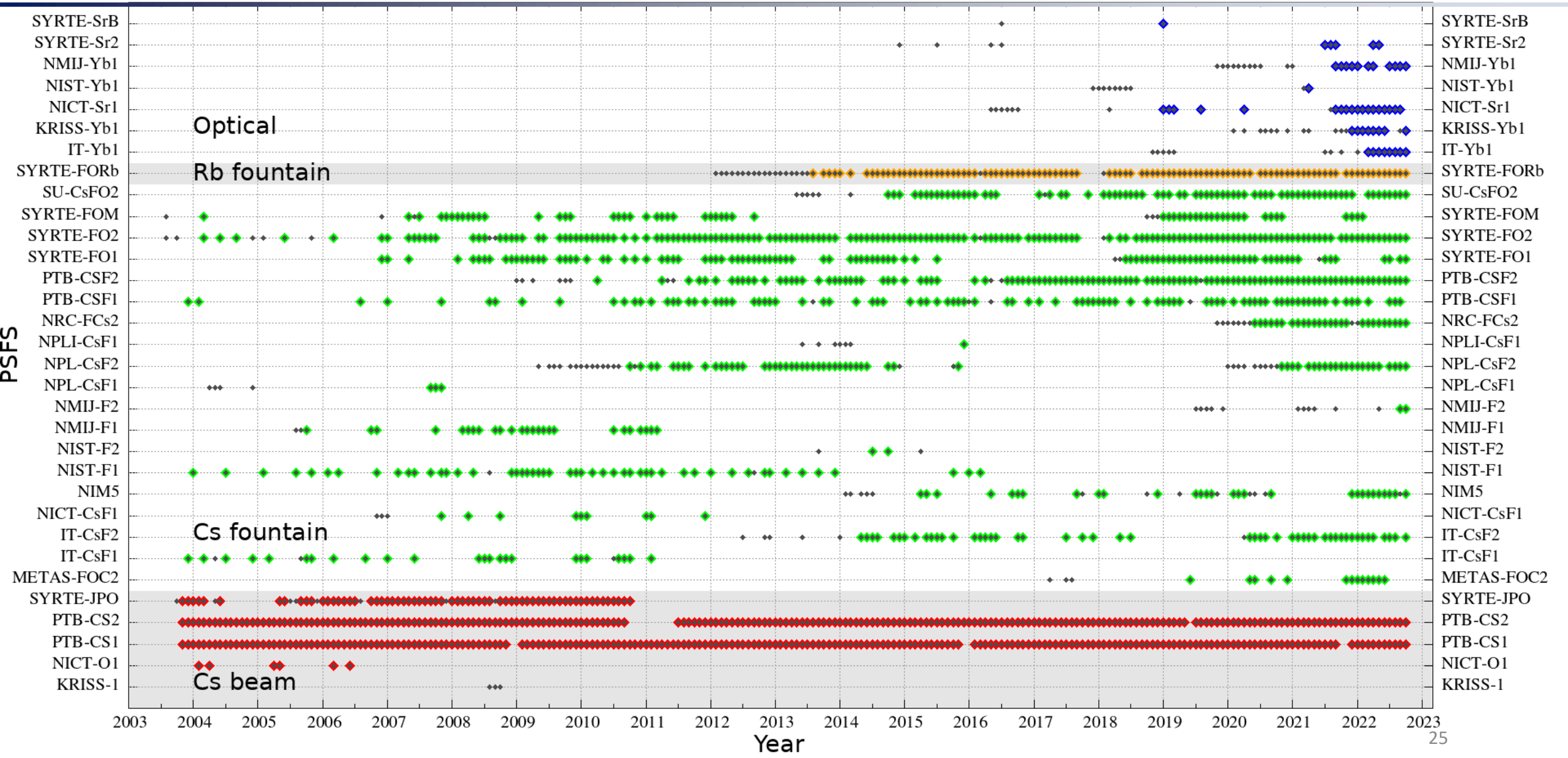


https://www.bipm.org/utils/en/pdf/CCTF-strategy-document.pdf

Contribution from Primary and Secondary Frequency Standards to TAI



Contribution from Primary and Secondary Frequency Standards to TAI



Record number of frequency standards contribute to International Atomic Time

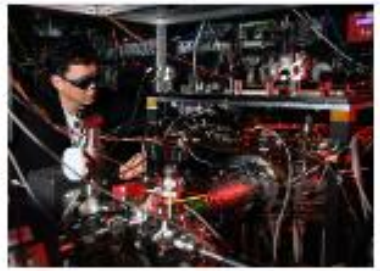
International Atomic Time (TAI) achieves its stability from more than 450 atomic clocks world-wide and its accuracy from a small number of primary and secondary frequency standards which aim at realizing the SI second with the smallest uncertainty. Each month the BIPM publishes, in section 3 of *Circular T* [1], an estimation of the TAI frequency accuracy as measured by those individual frequency standards, as well as an ensemble average computed by the BIPM. In November 2021, sixteen different frequency standards operated in eleven laboratories contributed to this estimation, including ten Cs fountains, one Rb fountain, one Sr optical lattice and two Yb optical lattice clocks, in addition to the two legacy Cs beams operated by the PTB. This constitutes a record level of participation, both in terms of the number of different standards and the number of different laboratories.

Optical clocks have reached a proven accuracy of order 10^{-18} in relative frequency, surpassing the present Cs fountains by two orders of magnitude and driving the Consultative Committee for Time and Frequency (CCTF) to initiate work towards a redefinition of the second [2]. The CCTF has set-up a wide-ranging task force of experts, which worked to define a number of mandatory criteria to be achieved before changing the definition. One of the mandatory criteria states that optical standards should regularly contribute to TAI, with a goal of at least three contributions per month, with a total uncertainty not larger than 2×10^{-16}. This criterion is intended to ensure that the accuracy of TAI is at least maintained and hopefully improved when the redefinition takes place and that it will be based on a robust set of optical frequency standards. Indeed after redefinition Cs fountains will become secondary standards with enlarged uncertainty while the uncertainty of optical standards will be reduced and it is important to ensure that the overall effect of the change is beneficial to TAI.

In 2021, 13 evaluations of optical frequency standards could be used to calibrate TAI, this is more than twice as many as the total number in the preceding three years (PSFS chart). Furthermore, two of them had a total uncertainty around 2.5×10^{-16}, which is close to the requirement set in the criterion for redefinition. While this is only a first step towards achieving one of the mandatory criteria, this shows the strong impetus from NMIs and DIs to operate optical frequency standards and move towards the redefinition. The results show significant progress in the operational capabilities, with optical clock uptime exceeding 90 % in some cases. This allows longer operating period and reduced frequency transfer uncertainty, key factors to achieve contributions of optical standards to TAI with a total uncertainty not larger than 2×10^{-16} as required. Looking at the past history of Cs fountain development (PSFS chart) we expect that a similar trend will occur for optical standards, so that the redefinition of the second could take place in 2030 as in the current CCTF plans.

Nov 2021

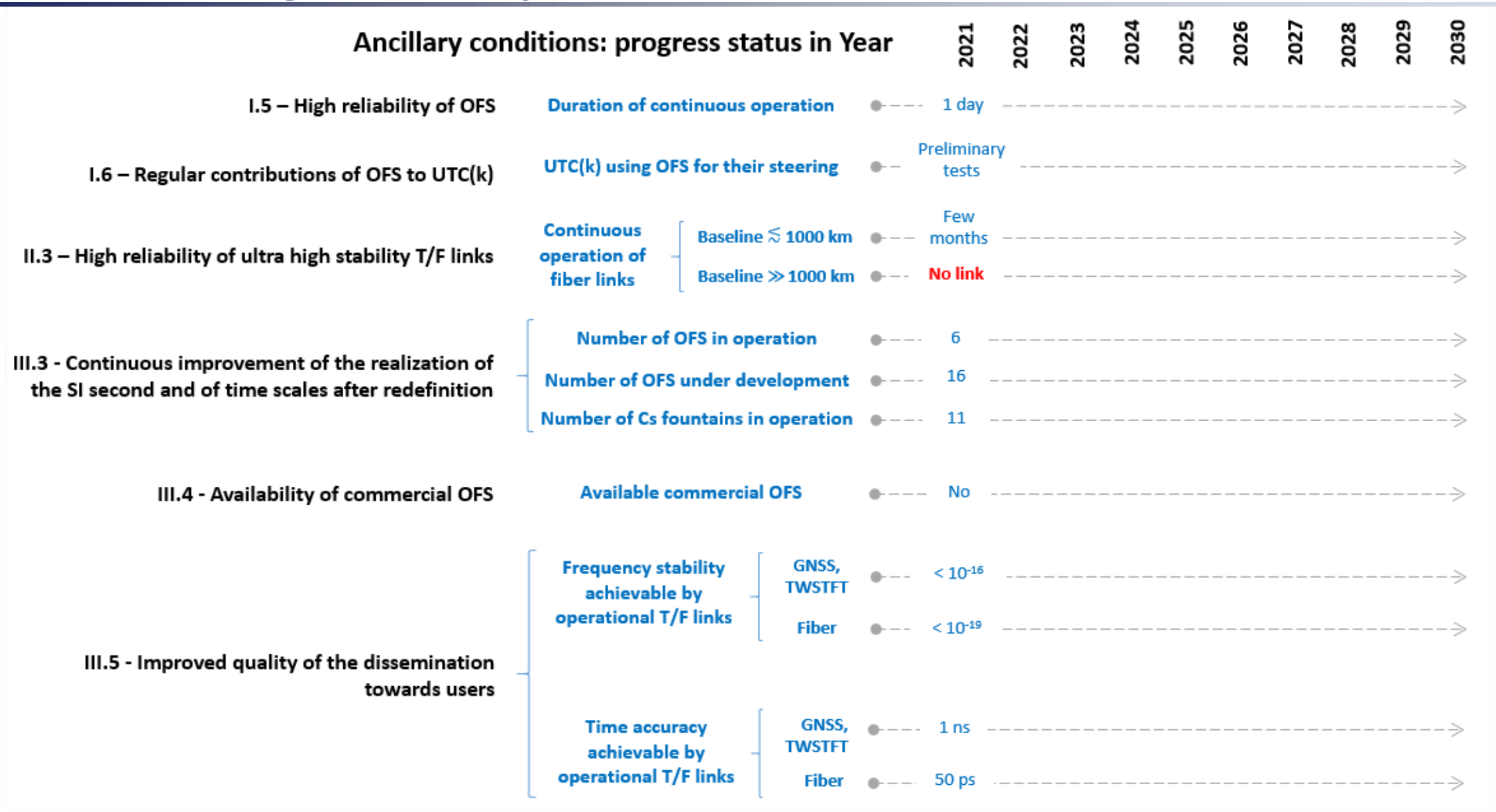
Sr optical lattice clock (image courtesy of NICT)



Yb optical lattice clock (image courtesy of KRISS)

Yb optical lattice clock (image courtesy of NMIJ)

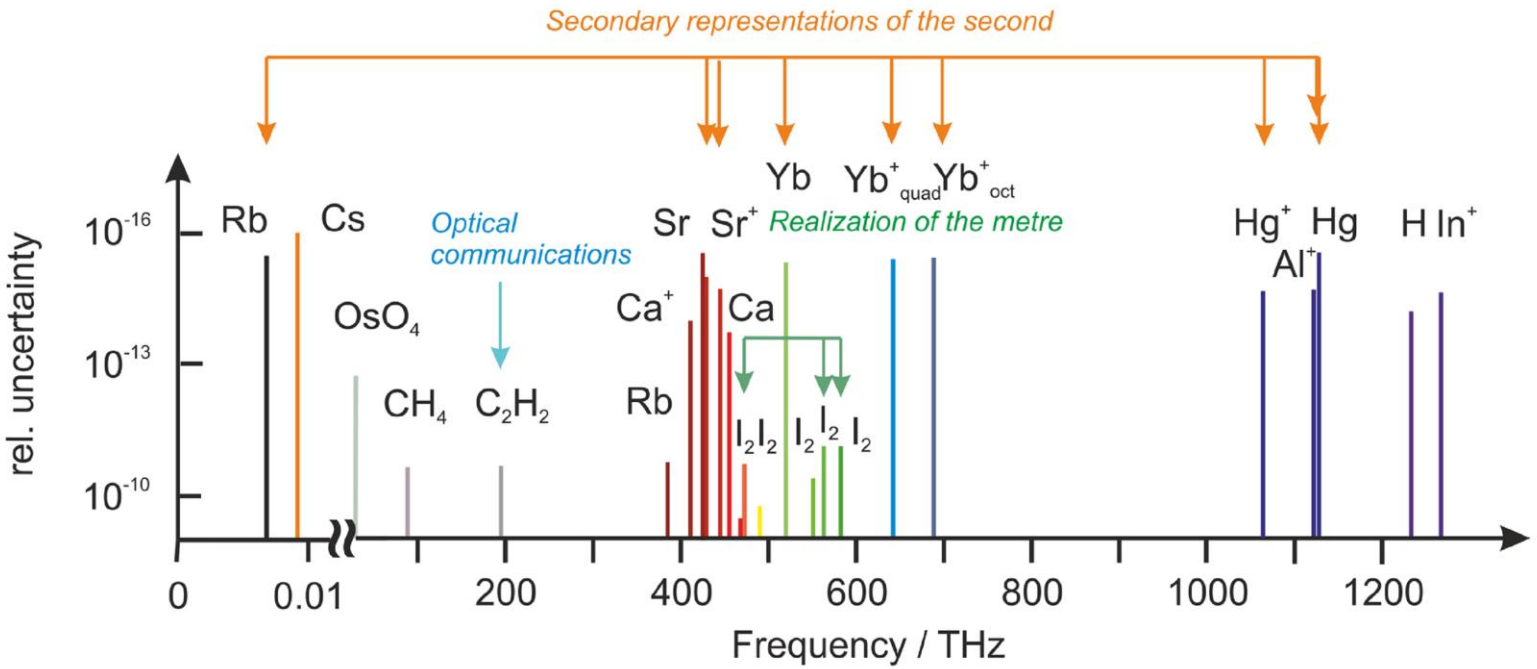
Progress level of ancillary conditions



Secondary representations of the second

https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies-info

List of recommended standard frequencies (validated by CIPM, published on the BIPM website) recommended for applications including the practical realization of the metre and secondary representations of the second



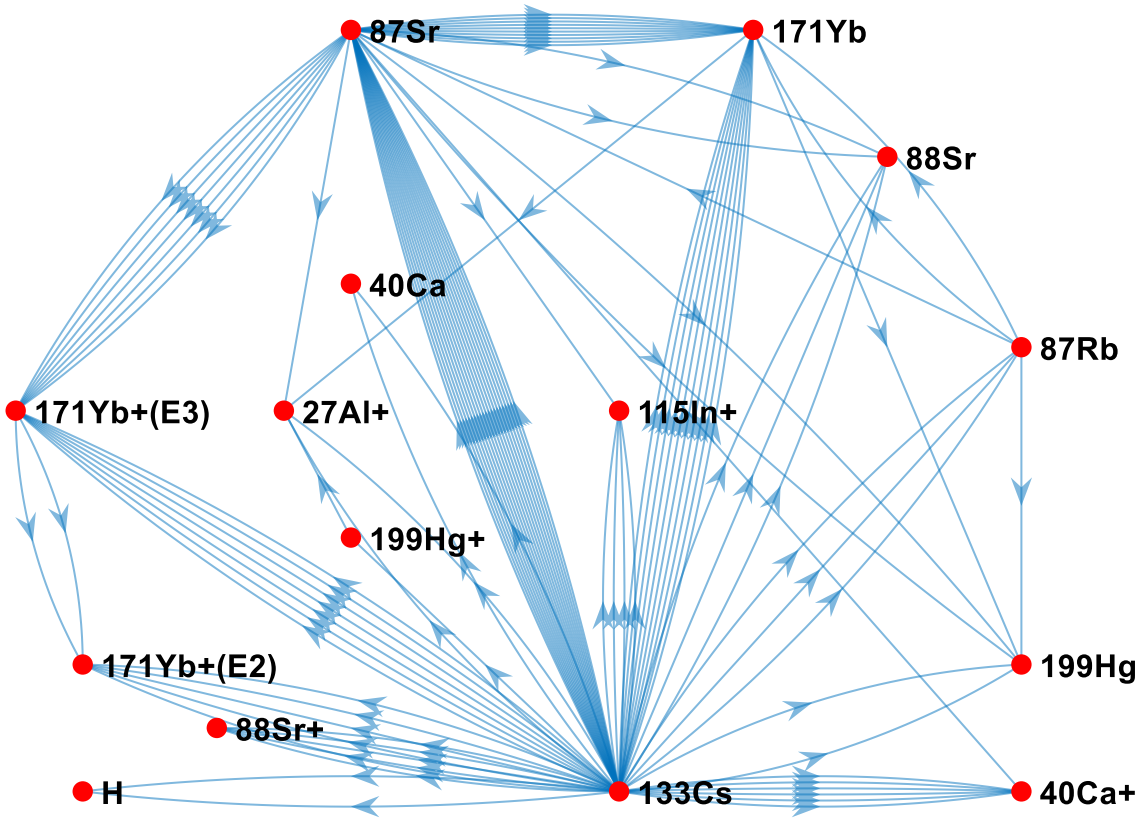
Uncertainty limited by the Cesium primary realization

	2020 rec value	2020 rec unc
115In+	1267402452901041.3	4.3E-15
1H	1233030706593514	9.0E-15
199Hg	1128575290808154.32	2.4E-16
27Al+	1121015393207859.16	1.9E-16
199Hg+	1064721609899146.96	2.2E-16
171Yb+(E2)	688358979309308.24	2.0E-16
171Yb+(E3)	642121496772645.12	1.9E-16
171Yb	518295836590863.63	1.9E-16
40Ca	455986240494140	1.8E-14
88Sr+	444779044095486.3	1.3E-15
88Sr	429228066418007.01	2.0E-16
87Sr	429228004229872.99	1.9E-16
40Ca+	411042129776400.4	1.8E-15
87Rb	6834682610.9043126	3.4E-16

Values of the secondary representations of the second from a multisystem of frequency ratio measures

Estimation by independent methods and software

Take into account the correlation between measurements (e.g. due to their comparison to the same Cs standards



All the estimates are interrelated

Joint CCL-CCTF WG (2020-21)

Graphical representation of 105 frequency measures (33 optical frequency ratios and 72 absolute frequency measures vs Cesium) used for the calculation of 14 frequency values.

The new computational mode has been able to take into account 483 correlations

Options for the redefinition of the second

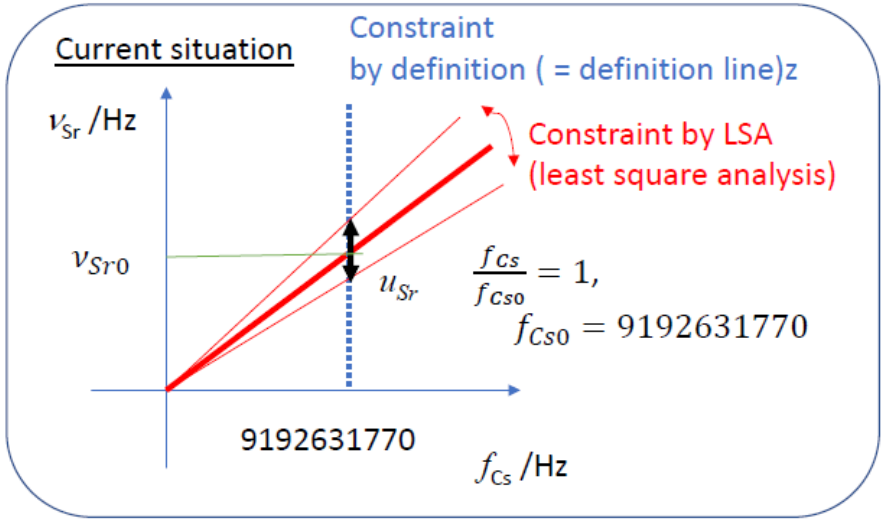
Option 1: Single atomic transition
Definition: fix the frequency of a single (optical) atomic transition

$$\Delta\nu_{\mathrm{Cs}} = 9\ 192\ 631\ 770\ \mathrm{Hz}$$

$$\Delta\nu_{\mathrm{Xy}} = 567\ 890\ 123\ 456\ 789.01\ \mathrm{Hz}$$

- Realization: with frequency standards based on Xy
- Continue to maintain and update a list of Second Representations of the Second (including Cs)
- To be redefined on the long term if major progress occurs in the uncertainty of frequency standards based on other transition(s)

→ **Classical approach similar to the current definition**
→ **Fix one frequency and measure all the others versus that one**
→ **Which one?** Currently, there are many promising transitions. The situation is highly dynamical, not settled. An obvious single best transition may or may not emerge



Courtesy of T. Ido, NICT

Options for the redefinition of the second

Option 2: Ensemble of transitions on an even basis
Definition: weighted geometric mean of an ensemble C of chosen transitions
Weight inversely proportional to the uncertainty of best standard using transition i

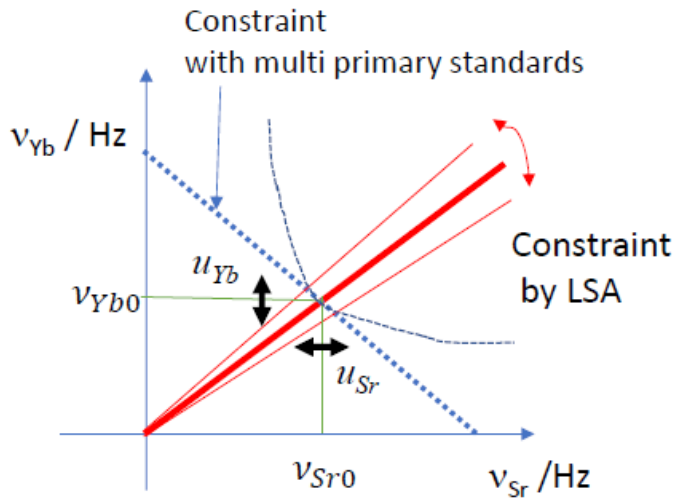
$$\Delta\nu_{\mathrm{Cs}} = 9\ 192\ 631\ 770\ \mathrm{Hz}$$

$$\nu = \frac{1}{N}\prod_{i\in C}\nu_i^{w_i}$$

See J. Lodewyck, Metrologia 56, 055009 (2019)

- Realization: with frequency standards based on transitions part of C (representations of the second) using frequency ratio matrix updated by the CIPM
- A single frequency standard i part of C realizes the unit
- 133Cs can (should) be part of C
- Including transitions in ensemble C and transitions not yet part of C
- Can follow the progress of frequency standards by updating the ensemble and the weights
- Merges the concept and use of primary and secondary representations of the second

→ **Fix a "mathematical constraint" and measure all frequencies versus that constraint**
→ **frequency values are already interrelated**
→ **weights and the constant N could be updated**



Courtesy of T. Ido, NICT

Options for the redefinition of the second

Option 3: Fixing the value of another fundamental constant *X*

$$\Delta\nu_{\mathrm{Cs}}, c, h, e, k$$

$$X, c, h, e, k$$

- Directly connected to the underlying fundamental framework of general relativity and the standard model of particle physics
- Realization: would be based on atomic transition(s) (one of 2 previously discussed options)

Constant	Frac. Unc.
G	2.2×10^{-5}
m_e	3.0×10^{-10}
R_∞	1.9×10^{-12}
$\mathrm{H(1S-2S)}$	4.5×10^{-15}

→ **An ideal option that could complete the consistency of the SI system based on fundamental constants. But more futurist because to date, fundamental constants are known with a too large uncertainty**

Strengths, Weaknesses, Opportunities and Threats

— Based on the many inputs from CCTF workshop participants

- A Git page is available
- One SWOT analysis for each option 1, 2 & 3.
- 3 discussion tracks: “understanding the options”, “Fundamental issues of the definition” and “Primary/secondary realizations”