9th Symposium on Frequency Standards and Metrology 2023
Kingscliff, NSW, Australia
16–20 October 2023
The Symposia on Frequency Standards and Metrology

Roadmap towards a redefinition of the SI second

Noel Dimarcq ***CIPM Member, CCTF President***
Patrizia Tavella ***BIPM, CCTF Executive secretary***

with the
CCTF Strategic WG extended to co-chairs of dedicated CCTF task groups
CCTF Task Force on the Roadmap towards the redefinition of the second

Bureau International des Poids et Mesures

CCTF

Definitions of the SI unit of time

Astronomy
(from the configurations of a dynamical system)

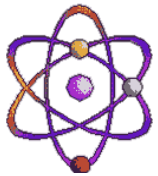
The SI unit of time – the second – is defined as:

→ **until 1960** : the fraction 1/86 400 of the mean (any) solar day

→ **1960 to 1967** : the fraction 1/31,556,925.9747 of the tropical year 1900 (This specific one)

1 tropical year = 365,2422 solar days = 366,2422 sideral days

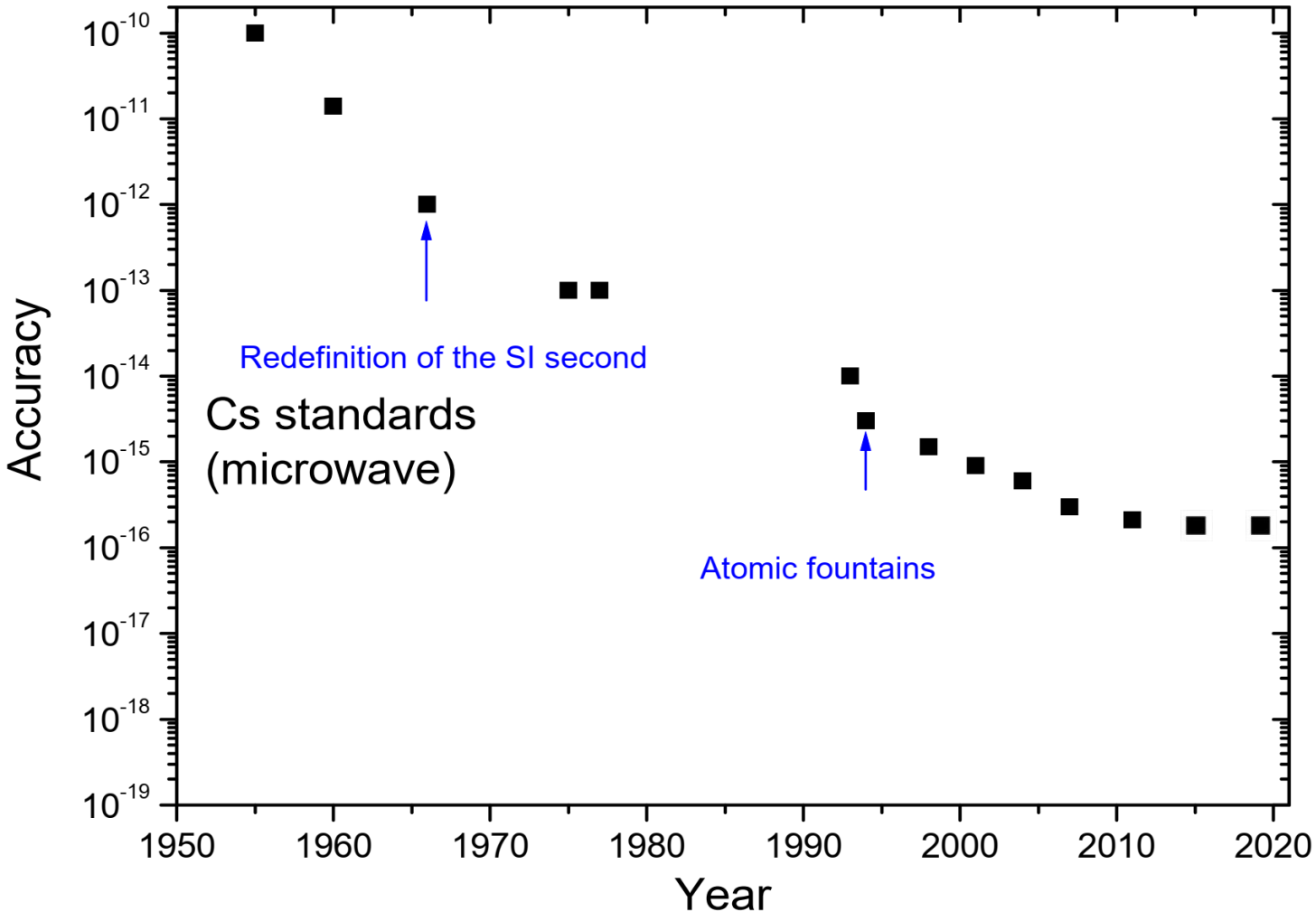
Quantum physics
(frequency of a periodic process)



→ **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 accuracy
$\sim 10^{-16}$

13th General Conference on Weights and Measures CGPM (1967)

Resolution 1

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 caesium 133 atom.

Resolution 2

Considering that the cesium frequency standard is still perfectible and current experiments allow the hope of producing other standards with even better qualities to define the second,

invites …. laboratories in the field of atomic frequency standards to actively pursue their studies.

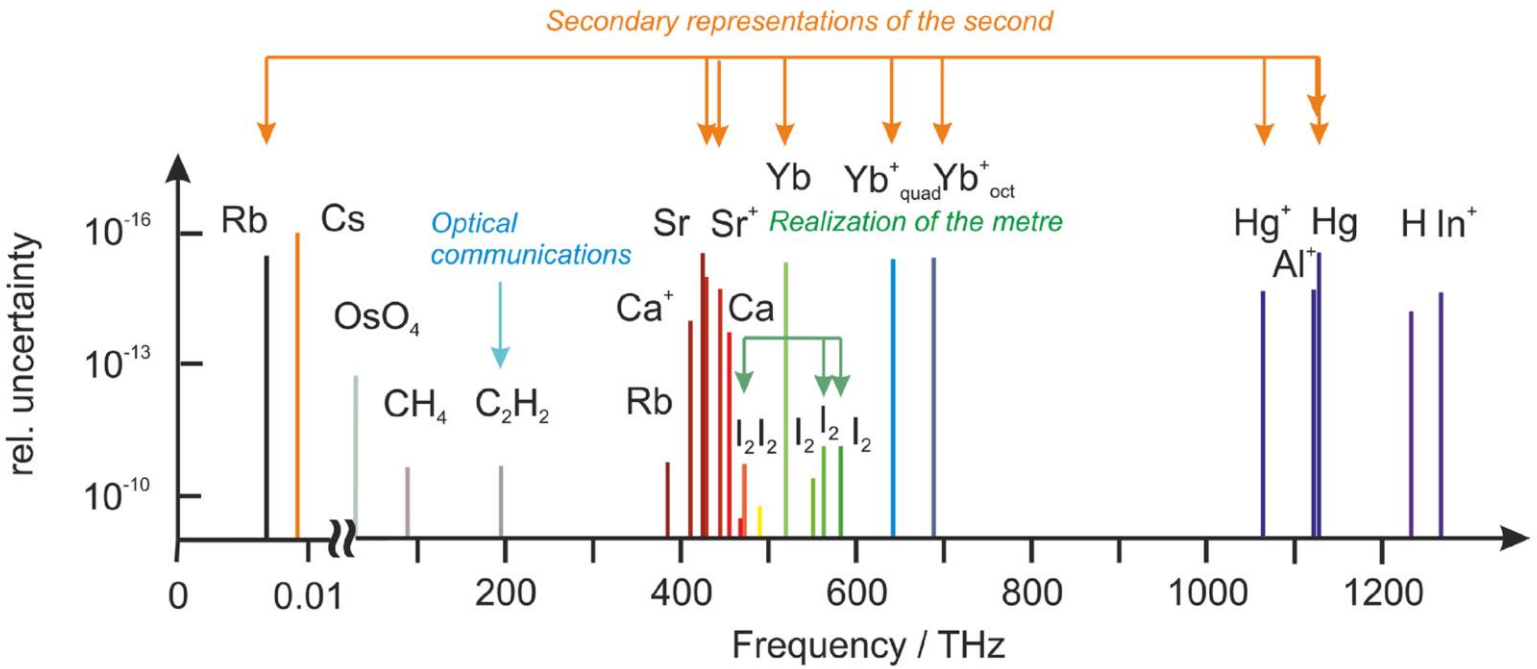
Since 2001 CCL-CCTF working group on Frequency Standards:

produces and maintains a single list of *Recommended frequency standard values for applications including the practical realization of the metre and* ***secondary representations of the second***.

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



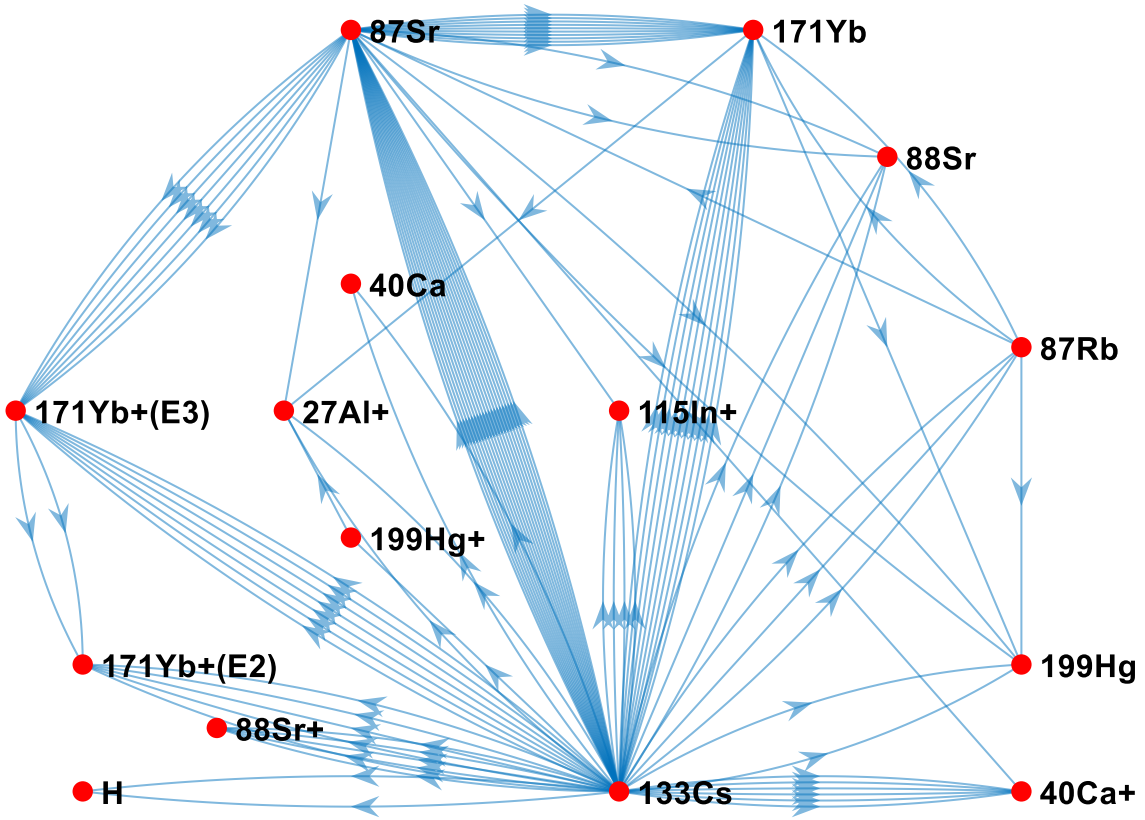
Uncertainty limited by the Cesium primary realization

	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 3 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)

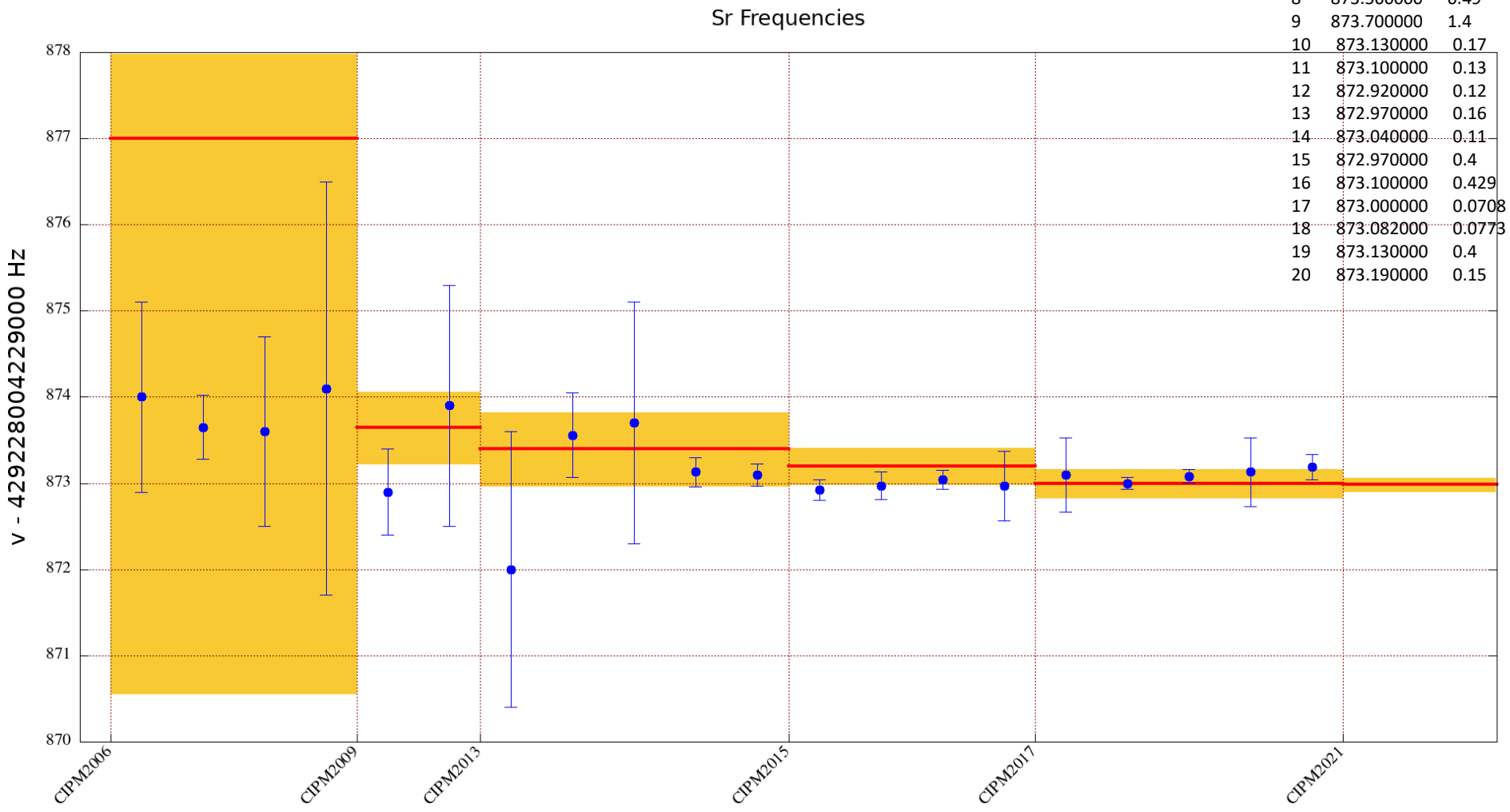
Graphical representation of 105 frequency measures (33 optical frequency ratios and 72 absolute frequency measures vs Cesium) used for the calculation of 14 frequency values.

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

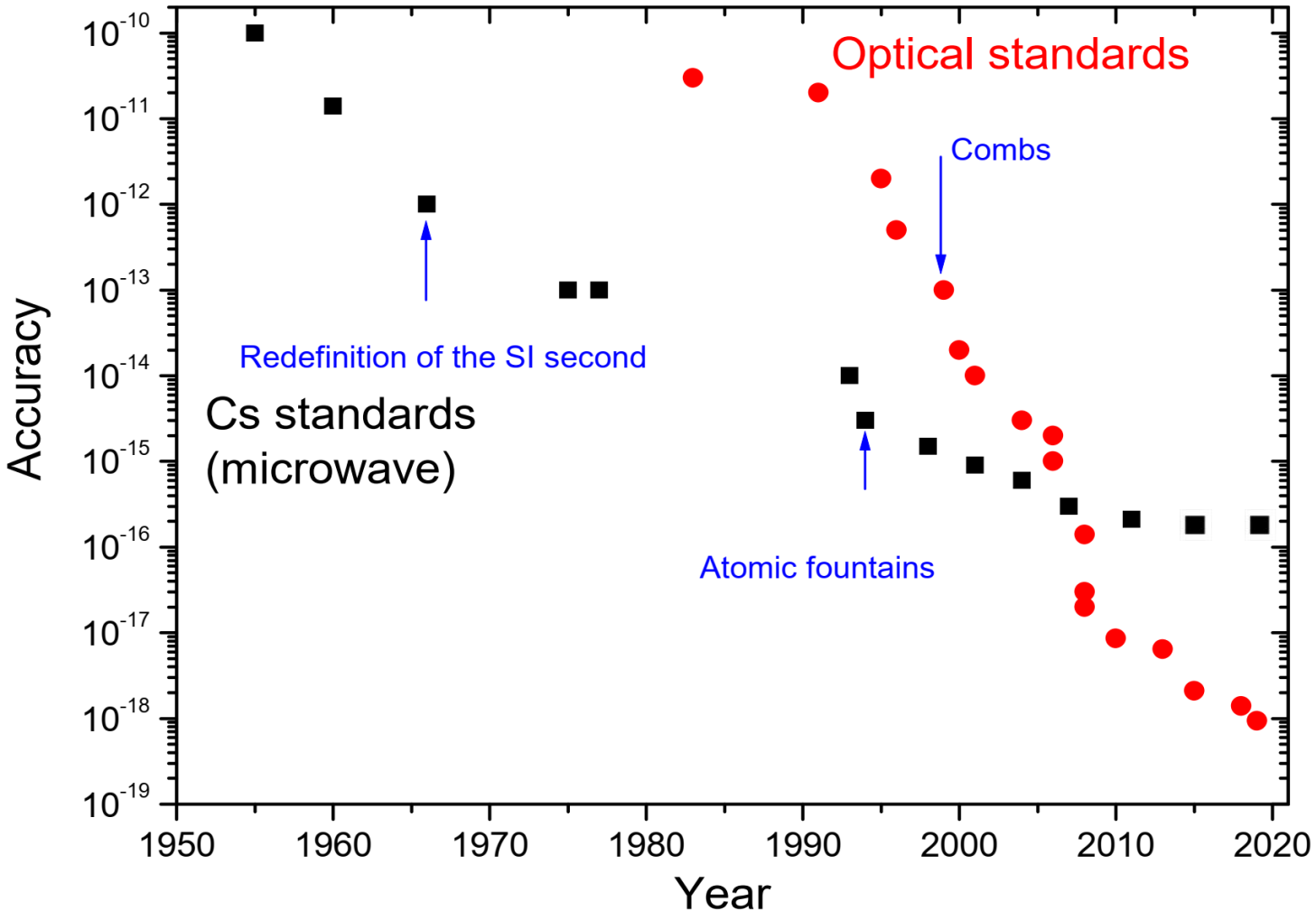
Metrologia paper in progress

87Sr	429228004229872.99	1.9 E-16

1	874.000000	1.1	[Boyd2007]
2	873.650000	0.37	[Campbell2008]
3	873.600000	1.1	[Baillard2008]
4	874.100000	2.4	[Hong2009]
5	872.900000	0.5	[Falke2011]
6	873.900000	1.4	[Yamaguchi2012]
7	872.000000	1.6	[Akamatsu2014b]
8	873.560000	0.49	[Tanabe2015]
9	873.700000	1.4	[Lin2015]
10	873.130000	0.17	[Falke2014]
11	873.100000	0.13	[LeTargat2013]
12	872.920000	0.12	[Lodewyck2016]
13	872.970000	0.16	[Grebing2016(Oct14)]
14	873.040000	0.11	[Grebing2016(Jun15)]
15	872.970000	0.4	[Hachisu2017]
16	873.100000	0.429	[Hobson2020]
17	873.000000	0.0708	[Schwarz2020]
18	873.082000	0.0773	[Nemitz2020]
19	873.130000	0.4	[Grotti2018]
20	873.190000	0.15	[Leopardi2020]



The era of optical frequency metrology



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

→ Time to change the definition?

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**

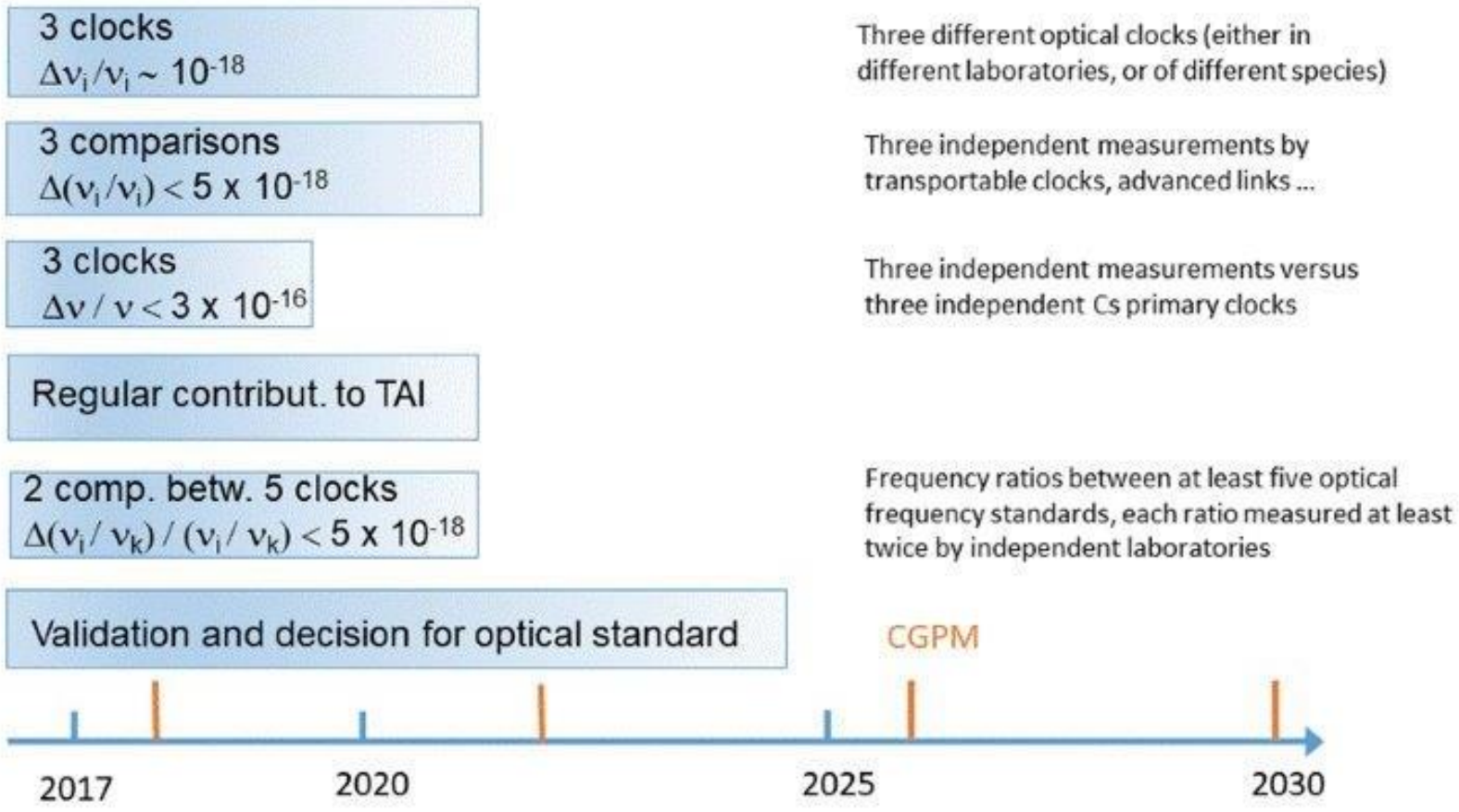
→ **Ensure continuity and sustainability of the availability of the new SI second** through TAI, and a **significant improvement of the quality of TAI** as soon as the definition is changed (at least no degradation !)

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

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

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

CCTF Task Force
Updating the roadmap towards the redefinition of the SI second

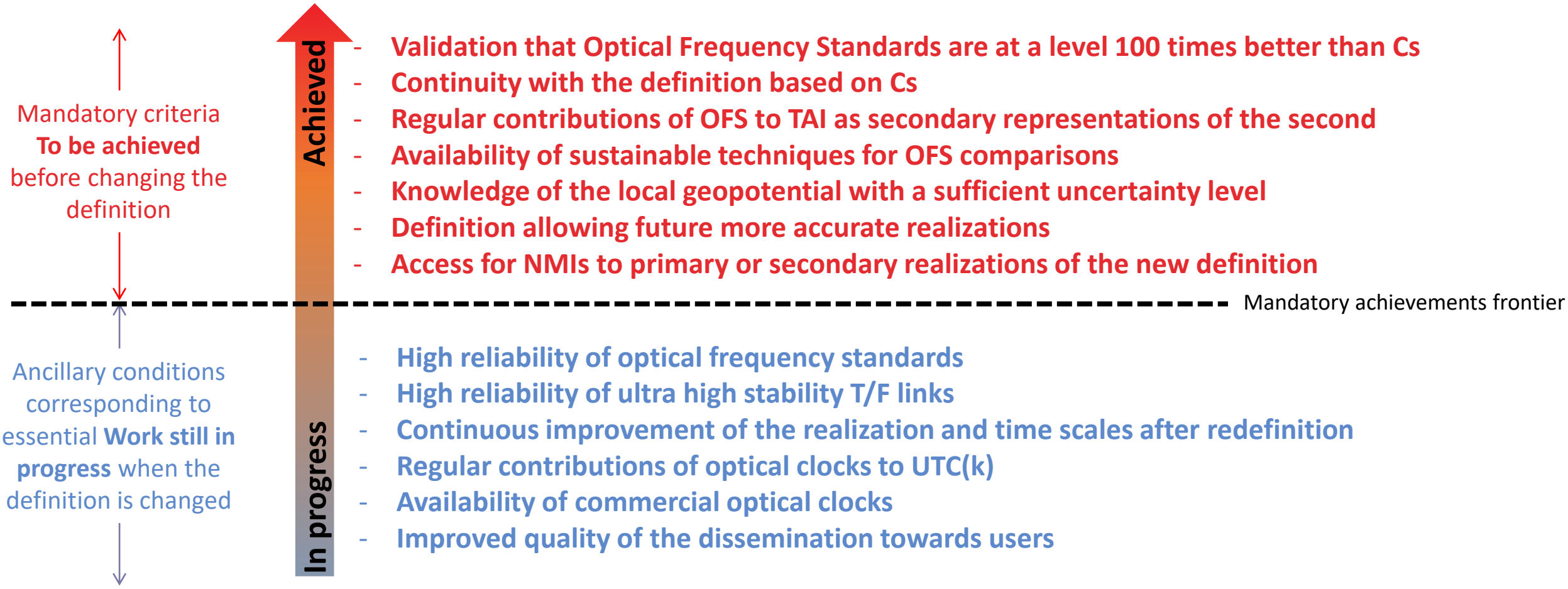
Roadmap and mandatory criteria		(N. Dimarcq CIPM, P. Tavella BIPM)
A.	*Request from user communities, NMIs and Liaisons*	(M. Gertsvolf, NRC; G. Mileti, Uni Neuchatel)
B.	*Atomic frequency standards, and redefinition approaches*	(S. Bize, SYRTE; E. Peik, PTB; C. Oates, NIST)
C.	*TF Dissemination and time scales*	(D Calonico, INRIM; T. Ido NICT)

More than 40 people from all the RMOs, all CCTF members at work

=> Started in 2020, presented the objectives to the CCTF 22-1 in October 2020, updates on the work to the CCTF 22-2 in March 2021, and CCTF 23rd in June 2022,

- Launched a questionnaire online and stimulated > 200 answers
- Defined the mandatory criteria and the ancillary conditions for the redefinition readiness
- Evaluated the status of criteria fulfilment in 2021 and 2022
- Evaluated the impact on the user communities
- Proposed 3 possible options for the redefinitions and organized two related workshops online
- Published a Metrologia paper (accepted, under revision, http://arxiv.org/abs/2307.14141), and several posters/papers in international fora

Priority setting of criteria / conditions to change definition



Priority setting of criteria / conditions to change definition

Frequency standards & contribution to atomic time scales

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

Priority setting of criteria / conditions to change definition

TF comparison and dissemination

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
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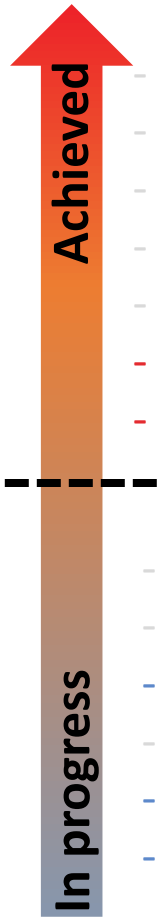
Priority setting of criteria / conditions to change definition

Acceptability of the new definition



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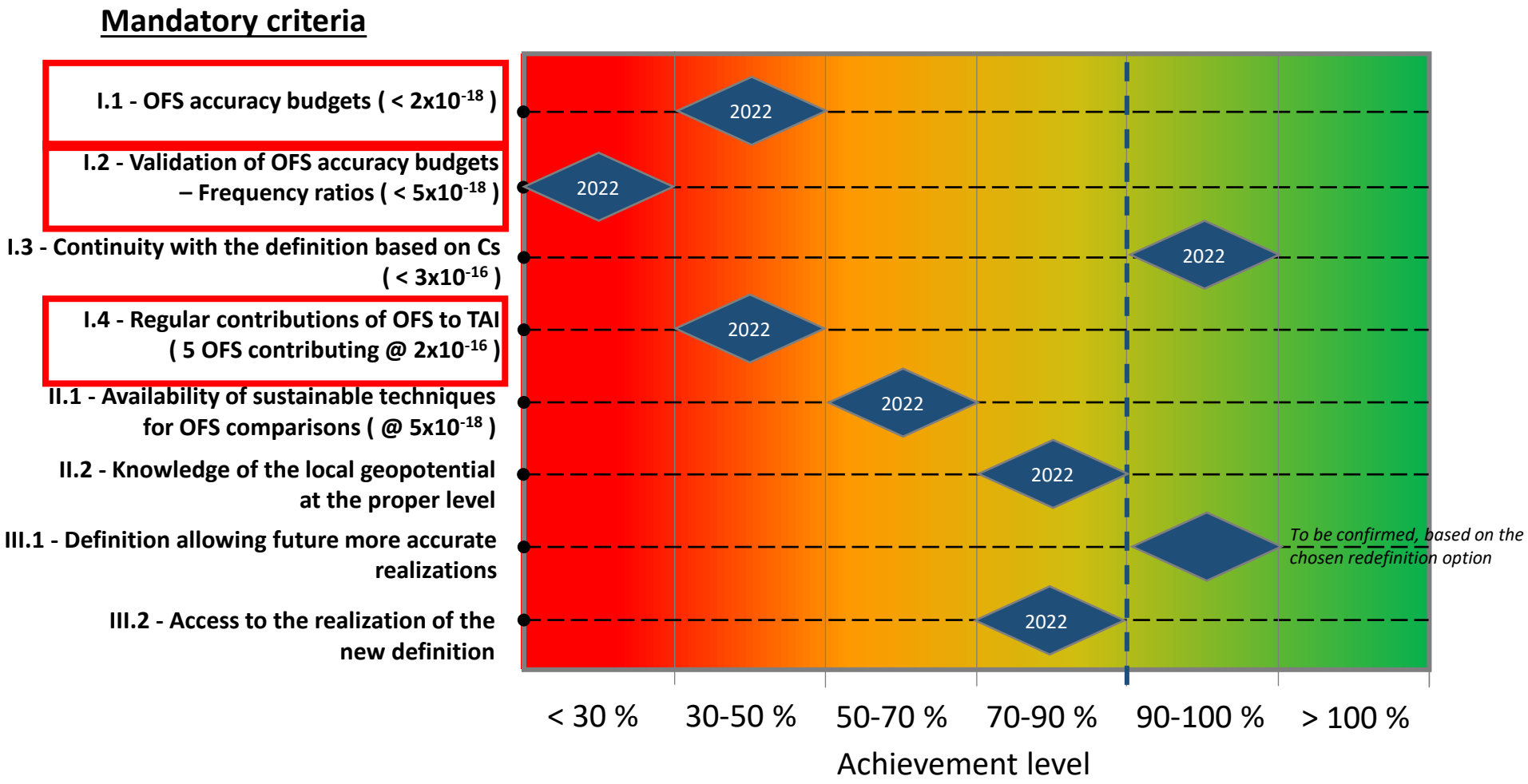
Fulfilment level of mandatory criteria (2022)



Criteria and conditions related to frequency standards and their contribution to time scales

To be achieved for redefinition

Criterion I.4 - Regular contributions of optical frequency standards to TAI (as secondary representations of the second)

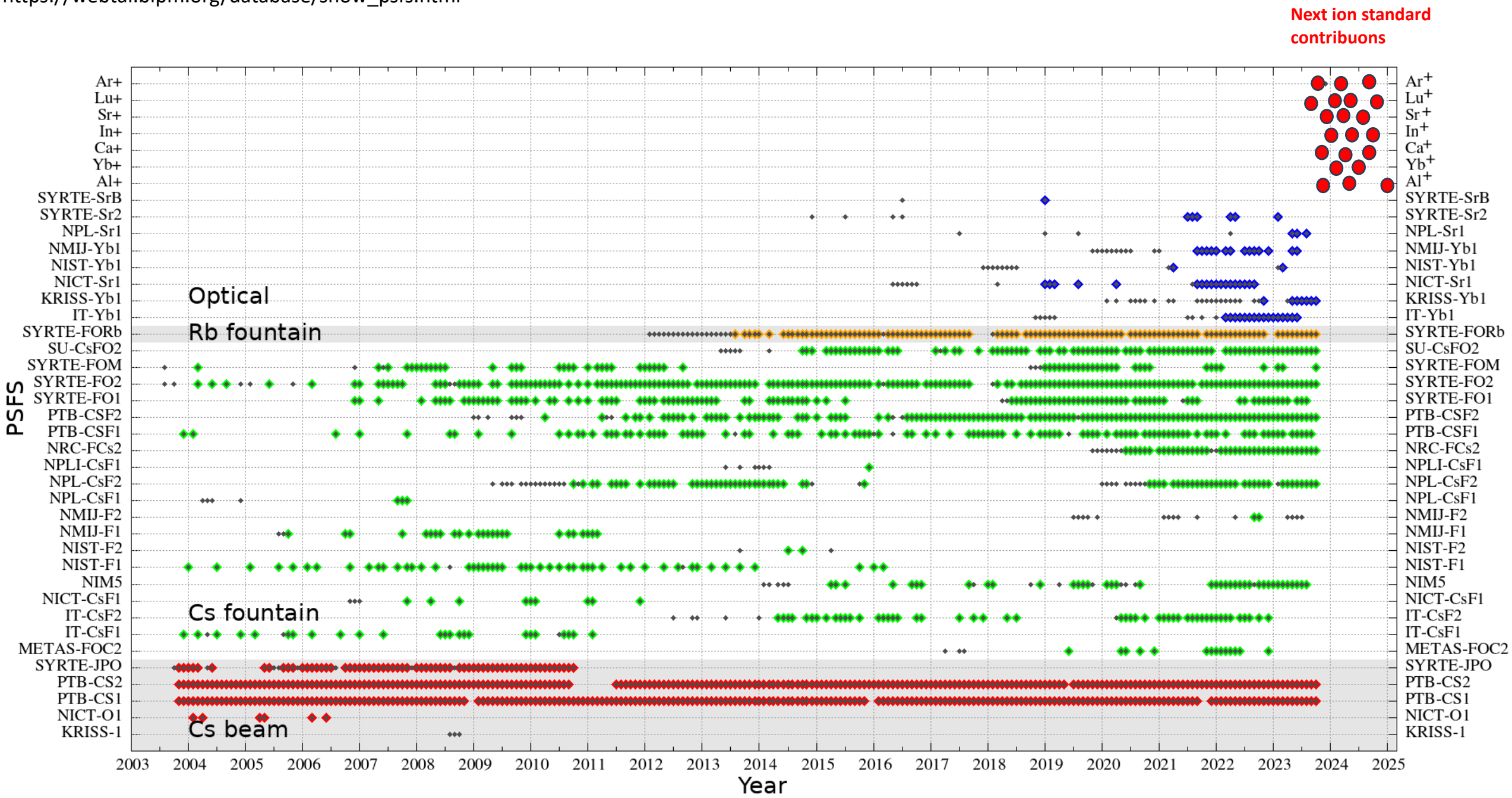
At least 3 state-of-art calibrations of TAI (uncertainty $\lesssim 2\times10^{-16}$ without counting the recommended uncertainty of the secondary representation of the second u_rep) each month from a set of at least 5 Optical Frequency Standards for at least 1 year. Check that there is no degradation of TAI if its calibrations were done by OFS considered as primary standards and Cs frequency standards considered as secondary standards.

Fulfilment Index:

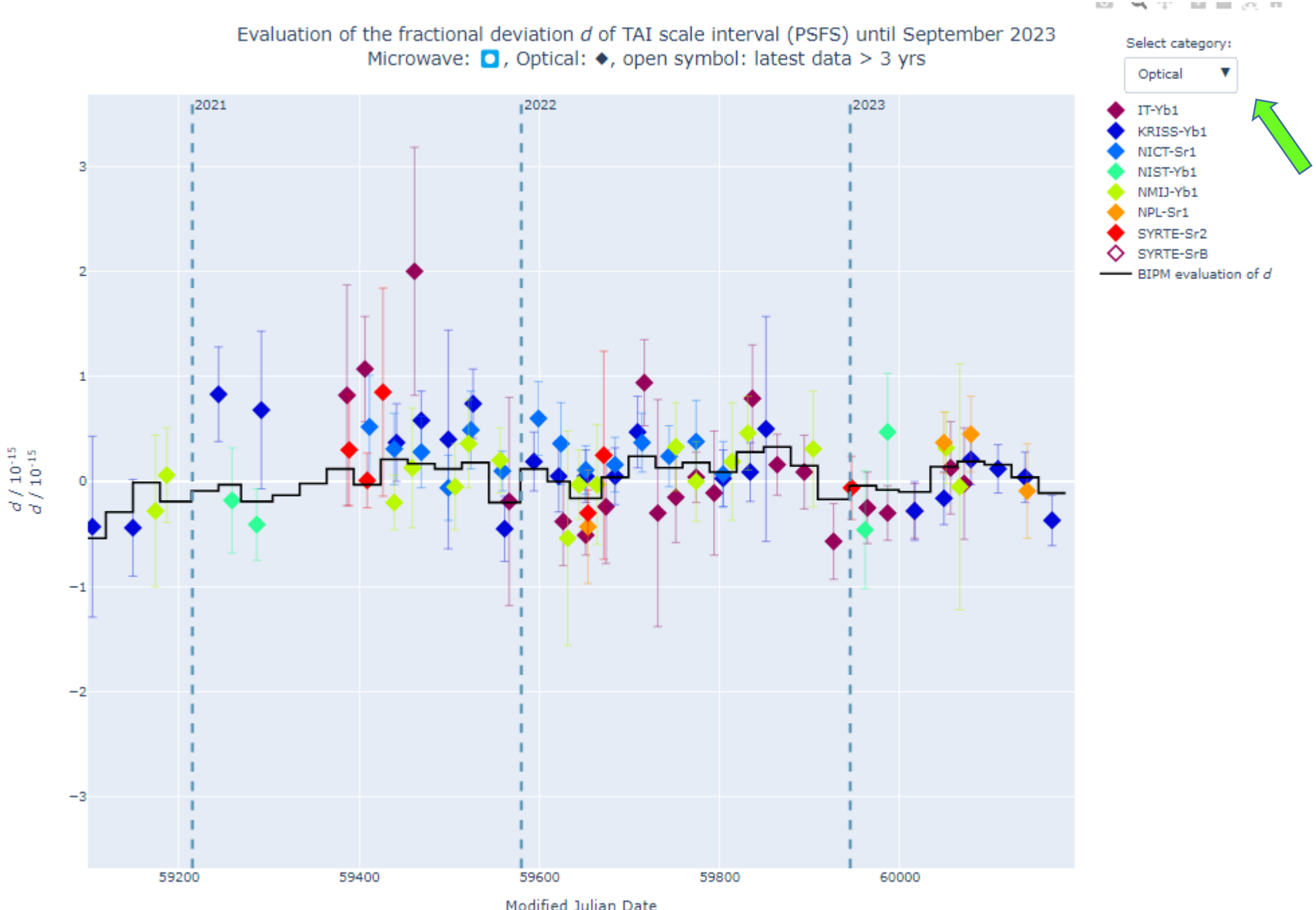
- Number of calibrations of TAI each month from a set of at least 5 Optical Frequency Standards for at least 1 year

Contribution from Primary and Secondary Frequency Standards to UTC

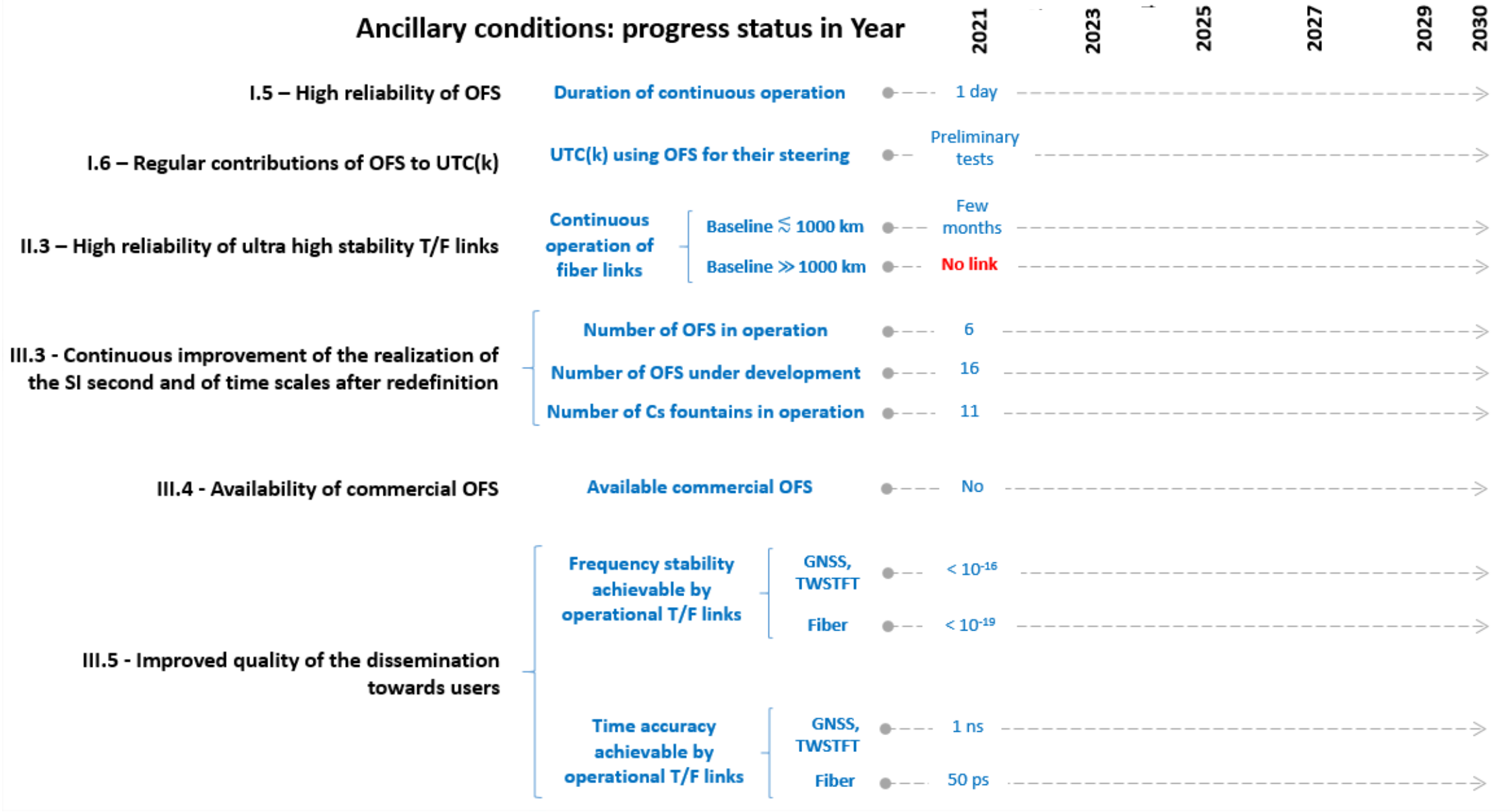
https://webtai.bipm.org/database/show_psfs.html



https://webtai.bipm.org/database/d_plot.html



Progress level of ancillary conditions



Summary of options for the redefinition

— Option 1:

$$\nu_{\mathrm{Xy}} = N\ \mathrm{Hz}, c, h, e, k$$

- Example

$$\nu_{^{87}\mathrm{Sr}} = 429\ 228\ 004\ 229\ 872.99\ \mathrm{Hz}, c, h, e, k$$

— Option 2.1:

$$\prod_i \nu_i^{w_i} = N\ \mathrm{Hz}, c, h, e, k \quad (\text{with} \sum_i w_i = 1)$$

static definition

- Example

$$(\nu_{^{87}\mathrm{Sr}})^{0.25} (\nu_{^{171}\mathrm{Yb}})^{0.25} (\nu_{^{171}\mathrm{Yb}^+(\mathrm{E3})})^{0.2} (\nu_{^{27}\mathrm{Al}^+})^{0.3} = 650\ 464\ 137\ 090\ 812.53\ \mathrm{Hz}, c, h, e, k$$

— Option 2.2:

$$\prod_i \nu_i^{w_i} = N\ \mathrm{Hz}, c, h, e, k \quad (\text{with} \sum_i w_i = 1)$$

dynamic definition

CIPM can update w_i, N and the ensemble of chosen transitions following a set of predefined rules

Opt 2.2 is initially identical to opt 2.1, and include opt 1 as special case

— Option 3:

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

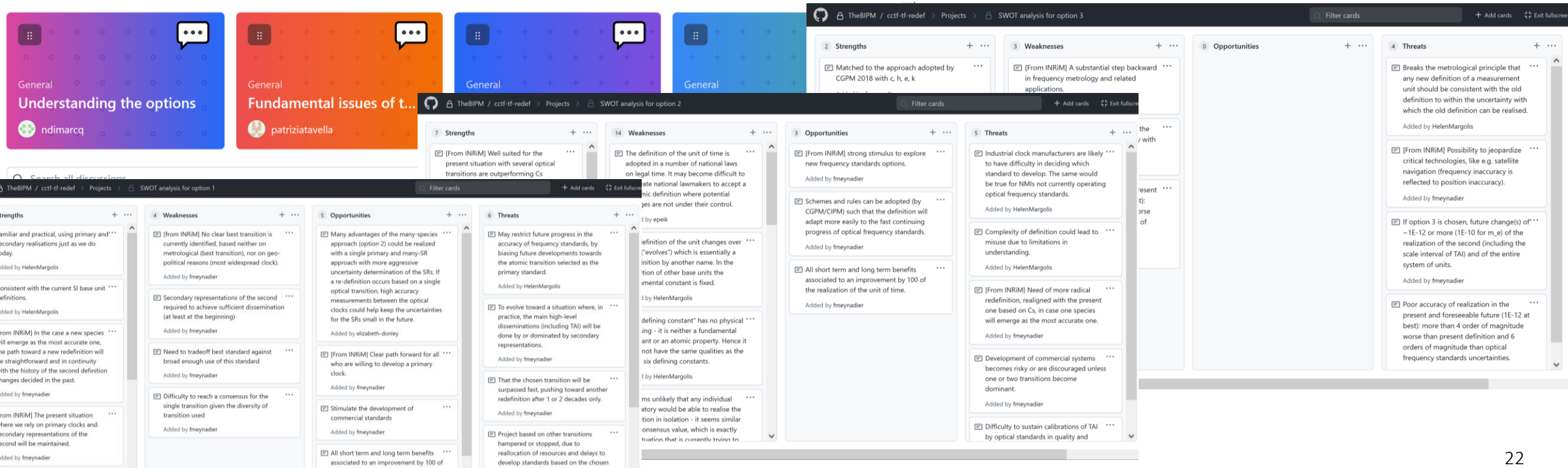
- Example:

$$m_e = 9.1093837015 \times 10^{-31}\ \mathrm{kg}, c, h, e, k$$

Strengths, Weaknesses, Opportunities and Threats

— Based on the many inputs from CCTF workshop participants

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



see presentation by Jerome Lodewyck

Scenarios for the redefinition of the second

CGPM	2022	2026	2030	2034	….

A redefinition at CGPM 2026 is unrealistic since in 2022 there was no consensus on the preferred option and still some important work 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 in 2022 there was no consensus on the preferred option and still some important work 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 in 2022 there was no consensus on the preferred option and still some important work 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 be postponed, to CGPM 2034 or the following one… But what about maintaining until 2040 and later the operation of Cs fountains that have been built in the 1990s - 2000s?

CGPM 2022 Resolution 5 - 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.

Working towards CGPM 2026

in preparation to CGPM 2026, we need a consensus on

1. **which definition option, which radiation(s) (or a few possibilities)**
2. **have a good confidence in the capacity to fulfil the mandatory criteria before 2030**

Re-organization of the Task Force for the redefinition of the second

Coordination: Dimarcq, Tavella

SG 1 - Redef options (Bize, Peik, Fang, Panfilo with members to ensure an international/all countries point of view)
Provide analysis of concrete proposals focused on options 1 and 2

SG 2 - Criteria (Calonico, Ido, Weyers, Tagliaferro with Chairs CCTF WG FS, PSFS, ATFT, TAI, ALGO, GNSS, TWSTFT)
Monitor fulfilment index and promotion of progress and achievements

SG 3 - Education (Gertsvolf and Mileti, Meynadier with dedicated members)
Educational activities and communication

TF Actions and deliverables

		KO all TF members Sept 26, 2023	CCTF Information meeting, Nov 16, 2023	24th CCTF Session 1 Nov 2024	24th CCTF Session 2 Sept. 2025	CGPM 2026
TF	Action Plan	Almost finalized	Finalized			
	Updated roadmap towards the redefinition of the second, criteria, conditions, and Indicators to discriminate among redef possibilities			Draft Preliminary redef possibilities	Updated roadmap with chosen redefinition option and species (or a few possibilities) and planned fulfilment of mandatory criteria by 2029	
	Draft resolution to the CGPM			draft	Submitted to CGPM	
SG1	Option documents 1. Description of options describing opt 1, opt 2 (a and b), (opt 3), 2. practical implementation of opt 1 and 2 (comparative table?) 3. Pros/cons	ToC and draft version	First version	Final version		
	Factsheets on most promising atomic species	Template/ Preliminary version	First version	Updated version - Categorize candidates (mostly ready, intermediate, not ready)	Final version	
SG2	Factsheet for each criterion fulfilment status	Template/ Preliminary version	First version	Updated version – Pointing out criticalities and achievements	Updated version	
	On CCTF web page: criteria fulfilment presentation	Announce	2023 version	2024 version	2025 version	2026 version
	Ideas for recognition of the activities in NMIs and for valorisation of achievements and progress. Monitor projects and possible delay in achievements with the Sg3 and all sg Chairs	Preliminary list of ideas	Proposed list of ideas	Updated status	Updated status	
SG3	Shared repository for educational, reference and supporting material (including attribution and copyright rules)	Announce	Draft plan	Updated status	Updated status	
	FAQ page on the CCTF web page (with possibility to raise additional questions)	Announce	Template	First update	Updated status	
	Develop tools for recognizing and acknowledging achievements at NMIs and progress status of the criteria fulfilment (with SG2)	Announce	Draft plan	Updated status	Updated status	
	Develop long-term plan for education and communication to wider audience (with SG1 and SG2)	Announce	Draft plan	Updated status	Updated status	

Discussion on the redefinition of the second at Consultative Committee for the Definition of the Second (now CCTF) (1963)

R. Essen, "The birth of atomic time", Upfront Publishing, 2015

Topics discussed:
- **Conditions for a change of the definition**
- **Choice of the atom (Cs, H) or molecule ?**
- **Radio techniques for comparisons**

RECOMMANDATIONS

1) the SI second be defined as the duration of a specified number of periods of a specified transition between two energy levels of an atom or a molecule

2) the definition of the second (when it will be time to choose the transition) be in accordance with the value of 9 192 631 770 Hz attributed to the radiation corresponding to the transition between the two hyperfine levels of the unperturbed ground state of the ^{133}Cs atom.

To review the long process to measure the Cs frequency in terms of Ephemerids second see Metrologia 42 (2005) S10–S19 "The definition of the 'atomic' second" by S. Leschiutta

CCTF

Thanks to CCTF, its WGs, the Task Force for the “roadmap to redefinition of the second”, National Metrology Institutes, academic experts, and concerned bodies for their constructive contribution and dedication

Thanks for your attention