Systèmes de Référence Temps-Espace

SYRTE

Toward a redefinition of the SI second with optical clocks: an overview of recent progress

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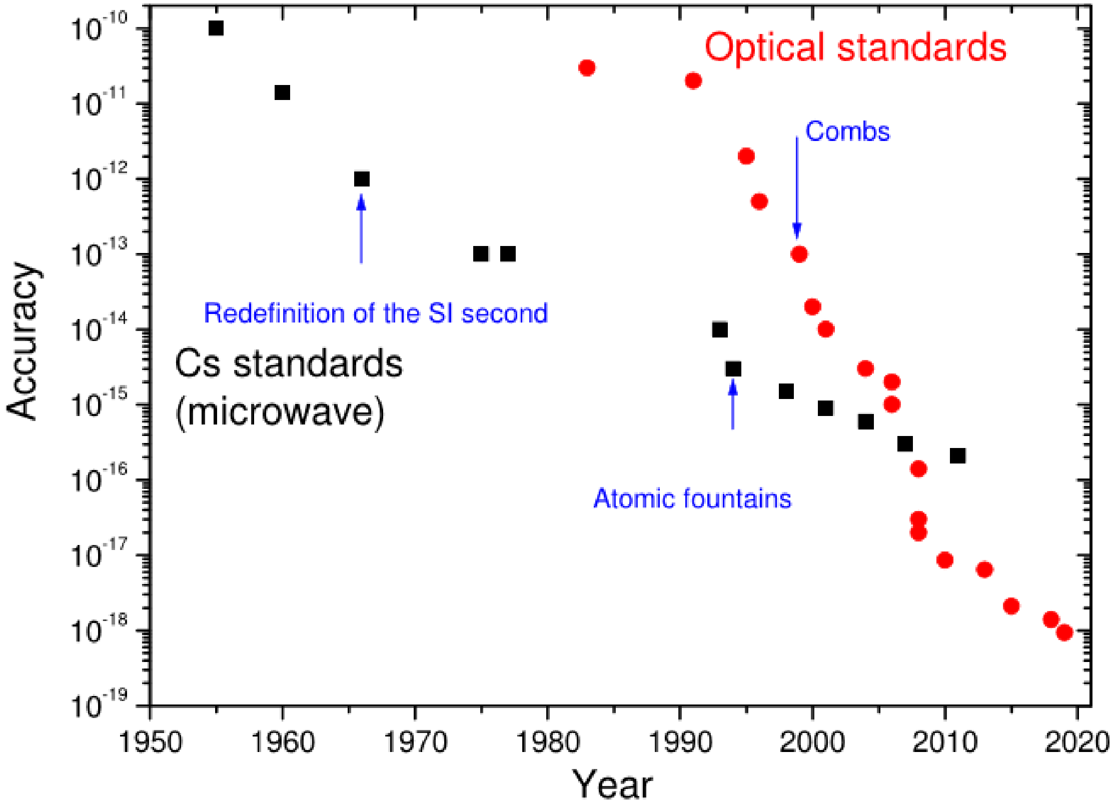
Consultative Committee on Units
October 09th 2019
BIPM, Sèvres, France

Overview

- Introduction
- Status of optical frequency standards
- Assessing optical frequency standards
- Work of the CIPM/CCTF
- Toward a redefinition of the SI second
- Conclusions

Progress of frequency standards over time

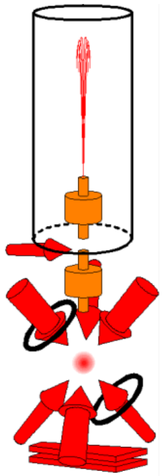


- **Optical frequency standards surpass Cs standards**
  - By more than 2 orders of magnitudes
- **Points toward a redefinition of the SI second**
  - Once readiness of optical frequency standards is proven
- **Status of optical frequency standards**
  - See e.g. Rev. Mod. Phys. 87, 637 (2015) & C.R. Physique 20, 153 (2019)

Optical frequency standards

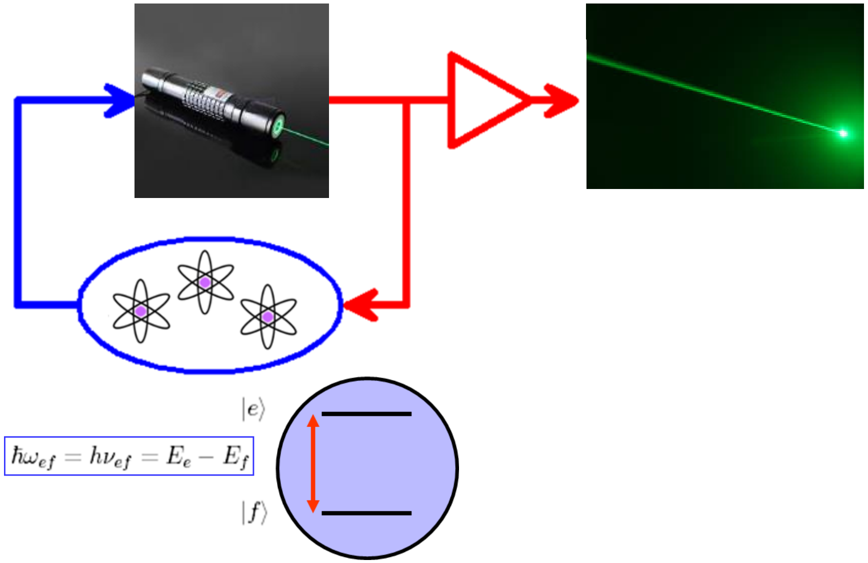
❑ Current primary frequency standards

- Cs hyperfine transition in laser-cooled atomic fountains
- Accuracy: 2-3x10^{-16} , stability: <2x10^{-14} at 1s

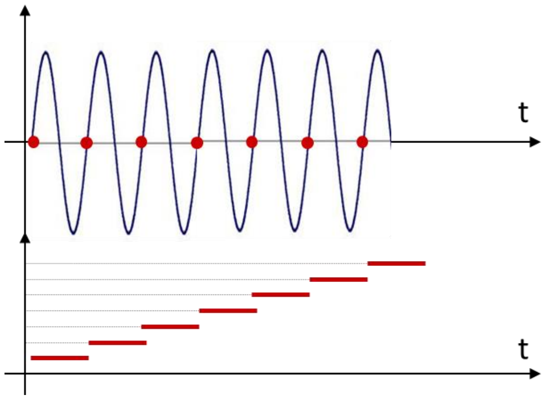


❑ Optical frequency standards

- Atomic transition frequency near 10^{15} Hz
- The fundamental output is the ultra-stable oscillation of electromagnetic fields of laser light
- Importance of ultra-stable lasers



$\hbar\omega_{ef} = h\nu_{ef} = E_e - E_f$

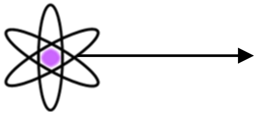


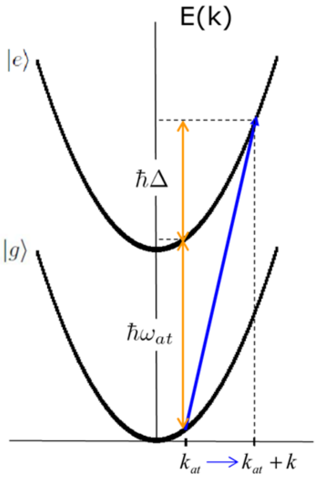
Lamb-Dicke spectroscopy

❑ Need to deal with the effect of external motion

- Limitation of probe time, Doppler shift, recoil shift, relativistic time dilation
- Laser-cooled atoms: v~1 cm/s, v/c ~3x10^{-11} !

$$E_{\text{kin}} = \frac{1}{2} m_{at} v^2$$

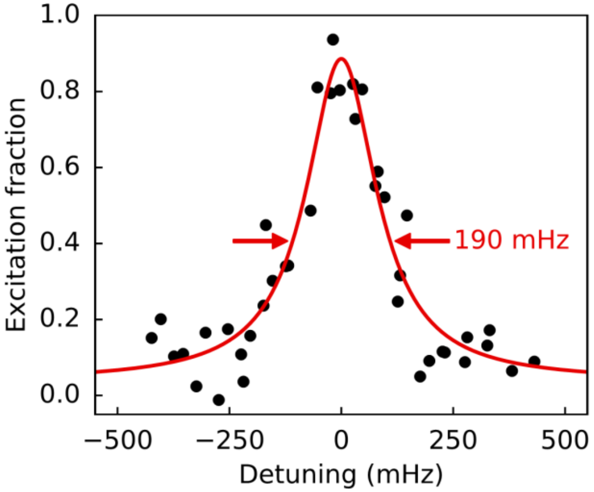




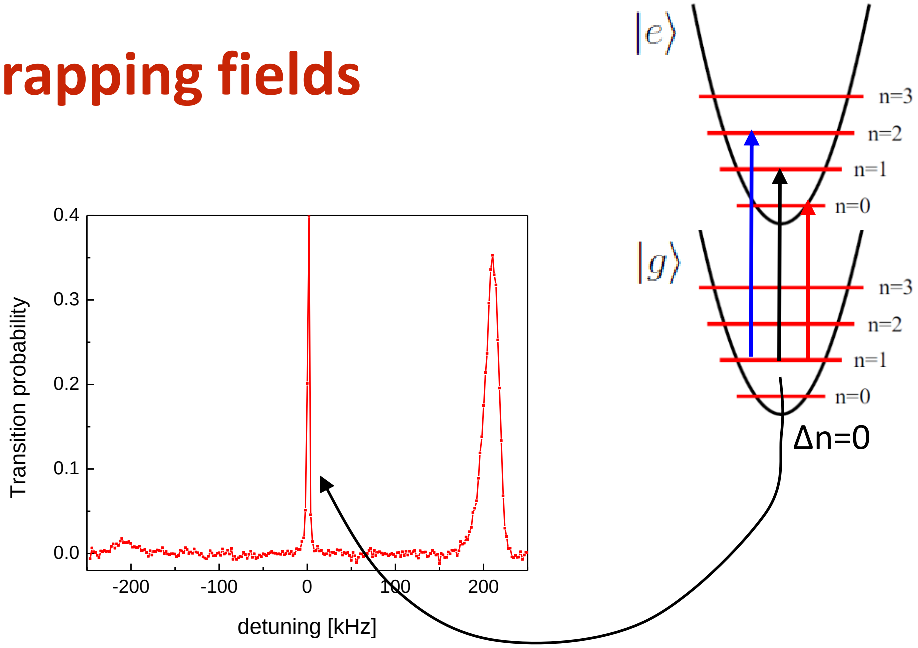
❑ Laser cooling & tight confinement

- Quantized states of motion
- Lamb-Dicke / resolved sideband regime
- Effects of motion in sidebands. Carrier essentially unaffected.

❑ Need to care for effects of trapping fields



Campbell et al. Science 358, 90 (2017)



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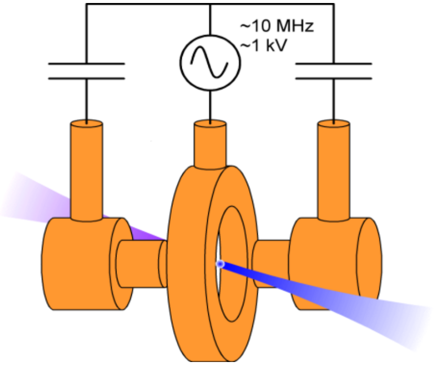
(Single) ion optical clocks



❑ Paul trap

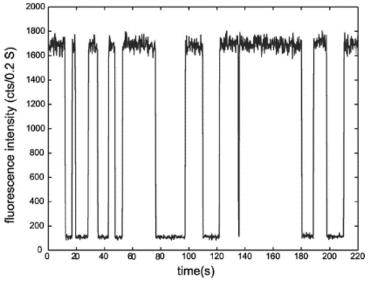
- Electric field acting on ion charge

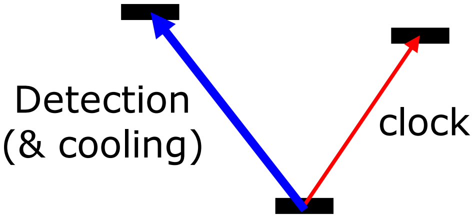
❑ Mitigation of trapping effects

- Laser-cooling
- Single ion at trap center where <E> = 0

❑ Detection by electron shelving

- Observation of quantum jumps





Detection
(& cooling)

clock

❑ Disadvantage

- Low signal-to-noise (quantum projection noise for N=1)

❑ Advantage

- Ion kept cycle-to-cycle
- No collision shift

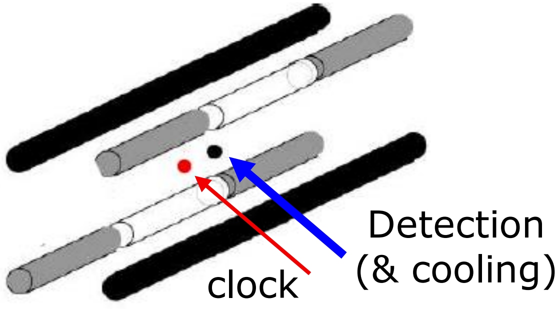
(Single) ion optical clocks

Candidates

- Hg+, Ca+, Sr+, Yb+(E2), Yb+(E3), In+, etc.

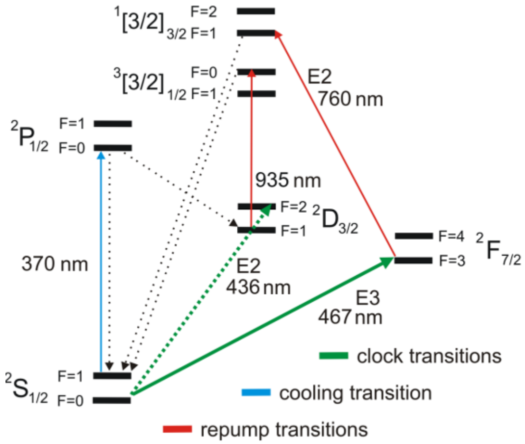
Quantum logic clocks

- Al+, assisted by Be+, Mg+, Ca+



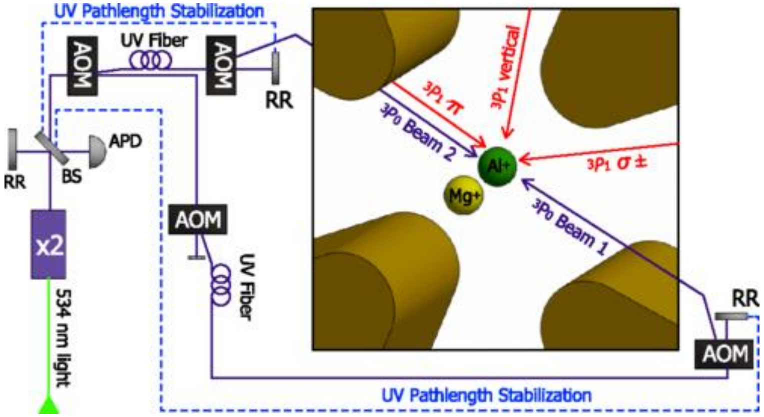
Examples

Yb+(E3) at PTB: 3.2x10^{-18}



Huntemann et al. PRL 116,063001 (2016)

Al+ at NIST: 9.4x10^{-19}

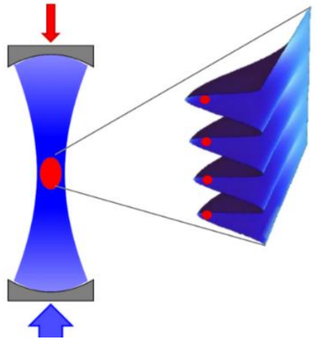


Brewer et al., Phys. Rev. Lett. 123, 033201 (2019)

Optical lattice clocks

❑ Dipole lattice trap

- By an intense standing-wave laser field

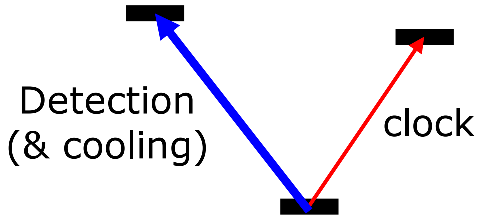


❑ Mitigation of trapping effects

- Laser cooling
- Lattice trap at magic wavelength

❑ Detection

- Fluorescence



Detection
(& cooling)

clock

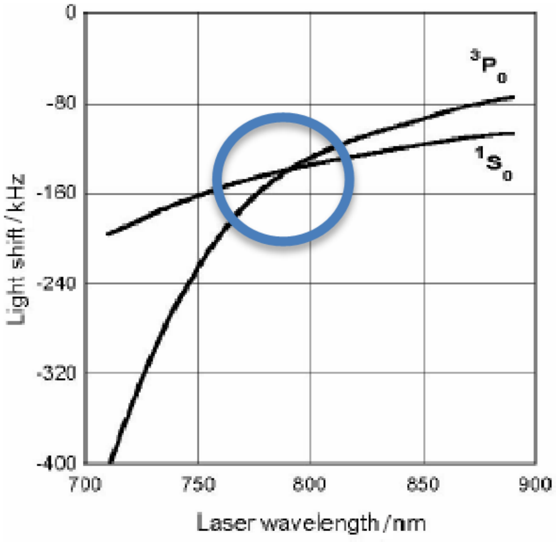
❑ Disadvantage

- Atom-atom interactions

❑ Advantage

- High signal-to-noise: N=10^4-10^5
- Possibility of non-destructive detection

Vallet et al., New J. Phys. 19 083002 (2017)



Katori, Proc. SFSM (2001)
& PRL (2003)

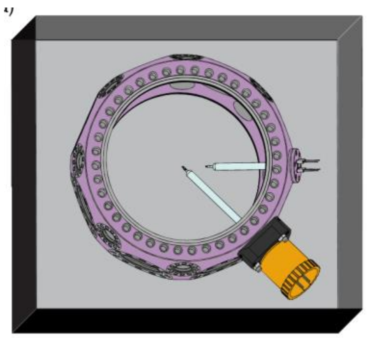
Optical lattice clocks

Candidates

- ^{87}Sr, ^{88}Sr, Yb, Hg, Mg, Cd, etc.

Examples

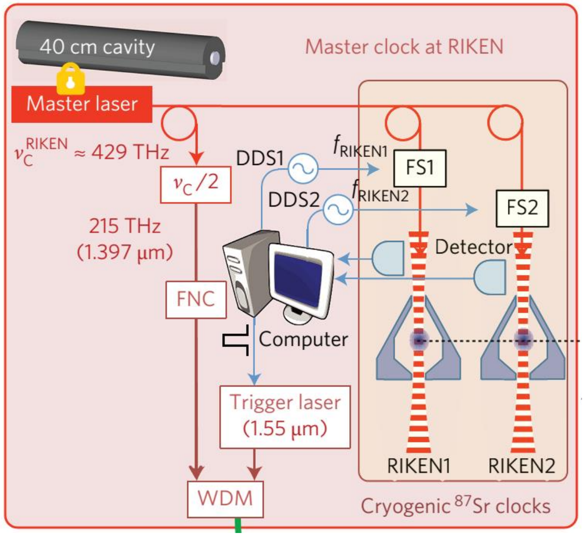
Sr at JILA: 2.0x10^{-18}



Nicholson et al., Nat. Com. 6, 6896 (2015)

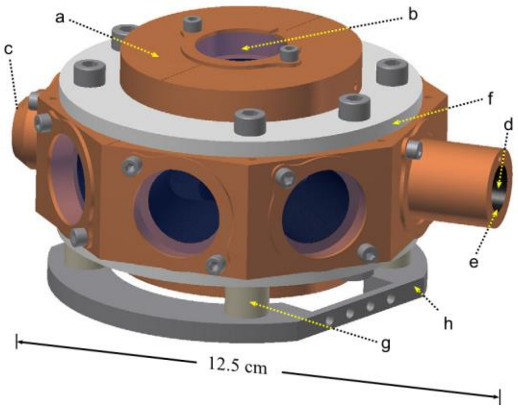
Bothwell et al (2019) Metrologia in press

Sr at UT/RIKEN: 4.8x10^{-18}



Ushijima et al. Nat. Phot. 10, 665 (2016)

Yb at NIST: 1.4x10^{-18}



McGrew et al., Nature 564, 87 (2018)

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How to assess optical frequency standards ?

- ❑ **Operate with all systematic shifts controlled at the same time**
  - Required but not enough

- ❑ **Comparisons of standards based on the same atom/ion**
  - Built a second system and check the agreement between them
  - ν_A/ν'_A should 1 within stated uncertainties

- ❑ **Frequency ratios**
  - Ratios of atomic frequencies are dimensionless quantities given by nature
  - Independent measurements in different places can be compared
  - A particular case corresponds to absolute frequency measurements
    - i.e. ratio to the Cs hfs
    - Limited by the accuracy of Cs standard

- ❑ **Closure based on multiple frequency ratios**
  - Closure within stated uncertainties can be verified

$$\frac{\nu_A}{\nu_B} \times \frac{\nu_B}{\nu_C} \times \frac{\nu_C}{\nu_A} = 1 + \Delta$$

Same standard comparisons

❑ Same clock comparisons

- Chou et al. Al+ (2010)
- Le Targat et al., Sr (2013)
- Bloom et al., Sr (2013)
- Ushijima et al., Sr (2015)
- McGrew et al., Yb (2018)

  $(-7\pm(5)_{stat}\pm(8)_{sys})\times10^{-19}$

❑ Example

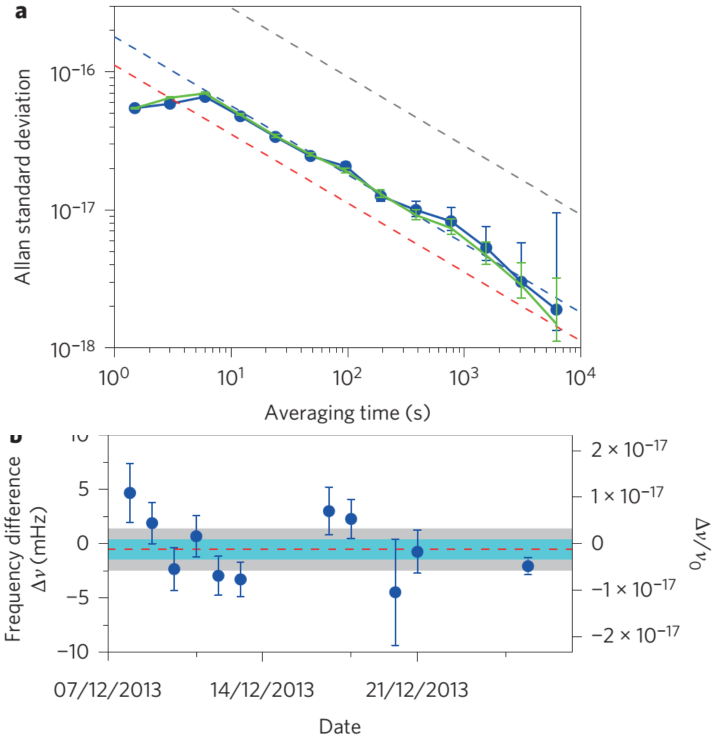
- Comparison of 2 cryogenic Sr clocks at RIKEN

  Ushijima et al., Nat. Photon. 9, 185 (2015)

- Uncertainty: 4.4×10^{-18}
- Note: a synchronized comparison

❑ Some terms can be common mode

- And therefore not well tested in comparisons
- e.g. atomic coefficient if fields are similar



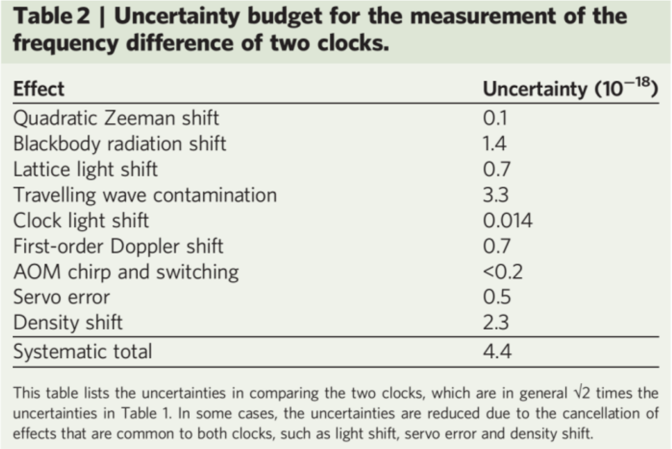


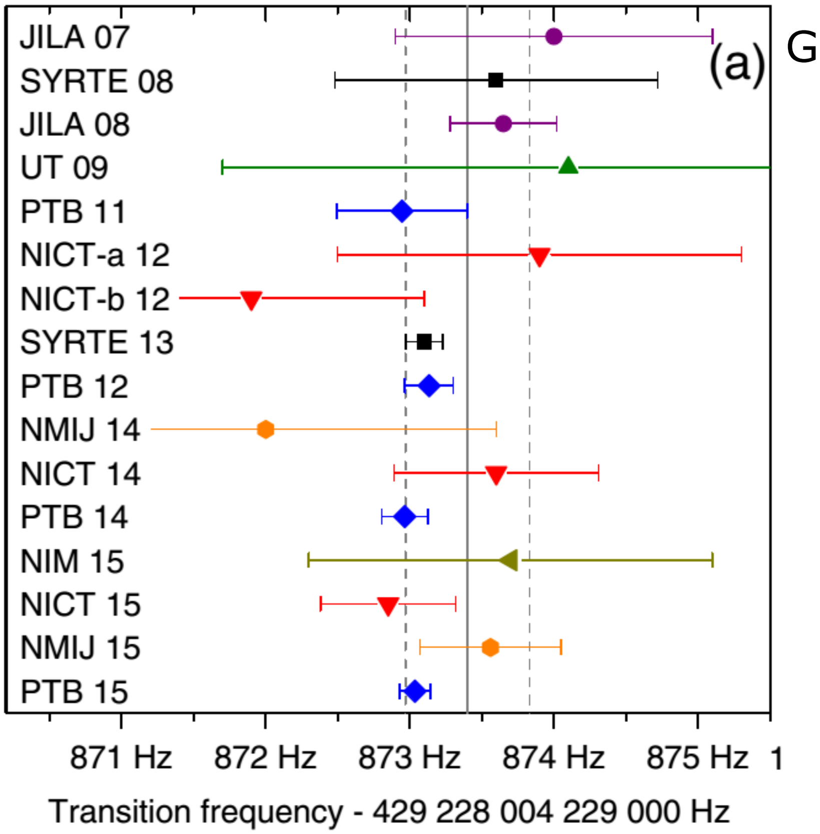
Table 2 | Uncertainty budget for the measurement of the frequency difference of two clocks.

Effect	Uncertainty (10^{-18})
Quadratic Zeeman shift	0.1
Blackbody radiation shift	1.4
Lattice light shift	0.7
Travelling wave contamination	3.3
Clock light shift	0.014
First-order Doppler shift	0.7
AOM chirp and switching	<0.2
Servo error	0.5
Density shift	2.3
Systematic total	4.4

This table lists the uncertainties in comparing the two clocks, which are in general √2 times the uncertainties in Table 1. In some cases, the uncertainties are reduced due to the cancellation of effects that are common to both clocks, such as light shift, servo error and density shift.

Absolute frequency measurements

- CCTF 2017: 13 optical transitions measured with uncertainties <10^{-14}
- ^{87}Sr 1S0-3P0 at 698 nm by far the most frequently measured (16x)



Grebing et al. Optica 3, 563 (2016)

Lodewyck et al. Metrologia 53, 1123 (2016)

Hachisu et al., Opt. Express 25, 8511 (2017)

Lowest uncertainty of
individual measurement:
2.6×10^{-16}

- Agreement. Limited by the accuracy of Cs fountain
- Measurements since CCTF 2017

Yb via TAI, 2.1E-16, NIST, McGrew et al., Optica 6, 448 (2019)

Optical frequency ratios (CCTF 2017)

- **7 optical ratios measured**
  - lowest uncertainty: 4.6x10^{-17}
  - 2.3x10^{-17} for ^{87}Sr/^{88}Sr in the same setup
- **Only 2 ratios measured independently in 2 institutes**
  - Sr/Yb, Sr/Hg

Ratio	Value	Fractional uncertainty	Reference
88Sr/87Sr	1,0000001448836827727	2.30E-17	Takamoto2017
Hg/Sr	2,62931420989890915	1.80E-16	Tyumenev2016
Hg/Sr	2,62931420989890960	8.40E-17	Yamanaka2015
Yb/Sr	1,20750703934337749	4.60E-17	Nemitz2016
Yb/Sr	1,20750703934333776	2.40E-16	Takamoto2015
Yb/Sr	1,207507039343412	1.40E-15	Akamatsu2014
Hg/Yb	2,17747319413456507	2.50E-16	Takamoto2015
Yb(E2)/Yb(E3)	1,07200737363420630	3.40E-16	Godun2014
Sr/Ca+	1,0442433345296416	2.40E-15	Matsubara2012
Al+/Hg+	1,052871833148990438	5.30E-17	Rosenband2008

- **Since CCTF 2017: 2 new measurements**
  - ^{87}Sr/^{88}Sr, 3E-17, independent apparatus, Phys. Rev. A 98, 053443 (2018)
  - ^{171}Yb/^{87}Sr, 2.8E-16, Nat. Phys. 14, 437 (2018)

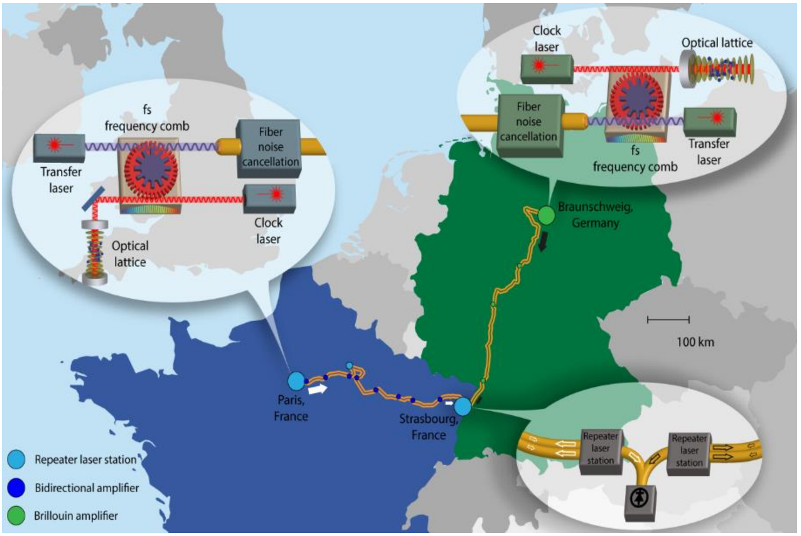
Remote optical clock comparisons

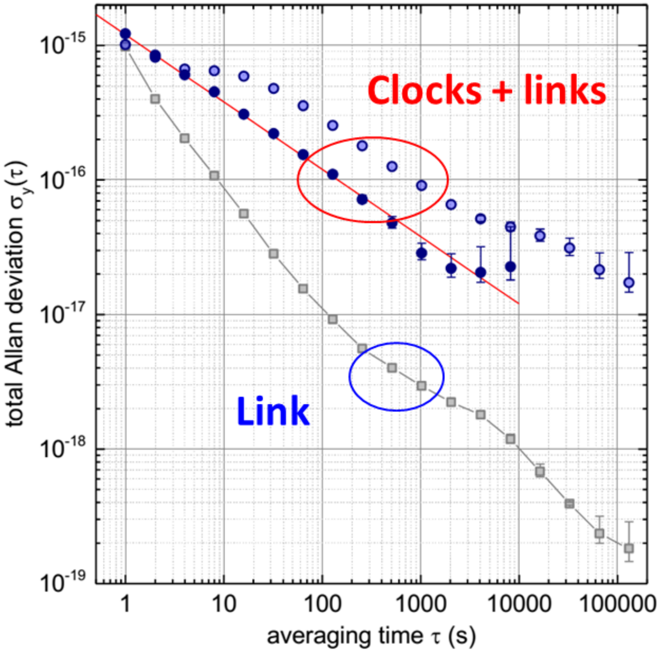
With optical frequency transfer by fiber

- Akatsuka et al., Jap. J. Appl. Phys. 53, 032801 (2014)
- Takano et al., Nat. Photon. 10, 662 (2016)

International comparison over 1450 km

- Lisdat et al., Nat. Commun. 7, 12443 (2016)
- Sr(SYRTE)/Sr(PTB) comparison: $(4\pm5)\times10^{-17}$
- Link compatible with 10^{-18} comparison at 10^{4} s





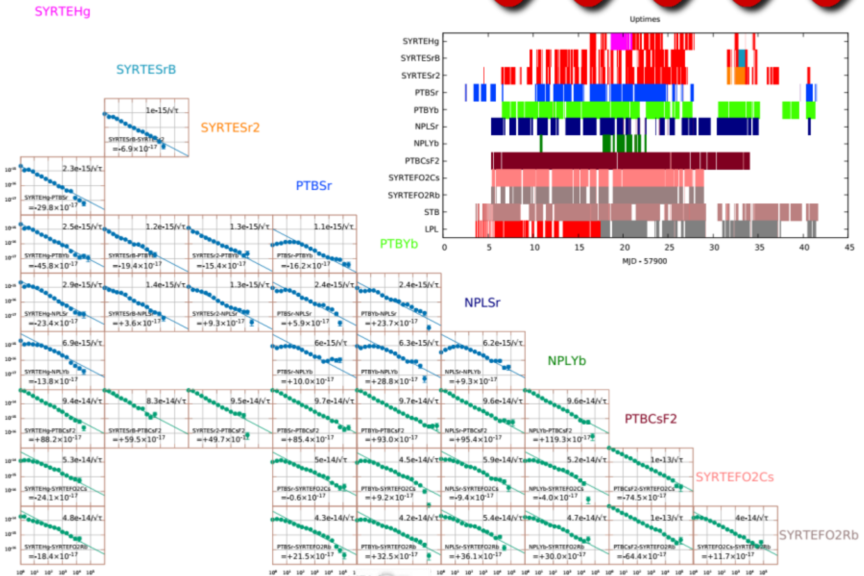
Transportable optical frequency standards

- Koller et al. Phys. Rev. Lett. 118, 073601 (2017): 7×10^{-17}

Development of optical fiber links

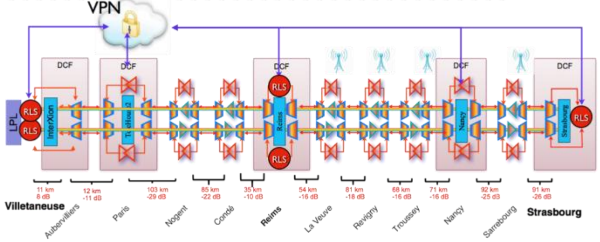
❑ A few more comparison campaigns

- ~ 1 month long, with holes
- LNE-SYRTE, PTB, NPL



❑ Maturity of coherent optical fiber links

- New 680 km cascaded link deployed by industry
- State-of-the-art performance



Appl. Opt. 57, 7203 (2018)

❑ Other cases, methods and applications

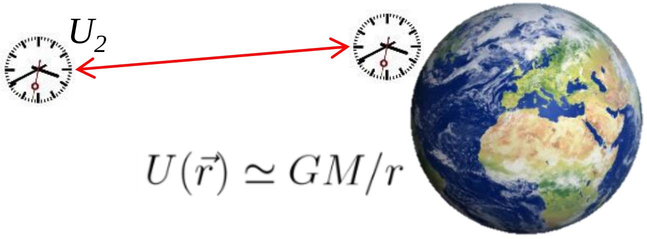
- e.g. INRIM: link to VLBI & laser ranging stations
- → WG ATFT workshop tomorrow

Chronometric geodesy

❑ Einstein’s gravitational redshift

- Space-time is modified in the vicinity of masses

$$\boxed{\frac{\nu_2}{\nu_1} = \left(1 - \frac{U_2 - U_1}{c^2}\right)}$$



- Magnitude near the surface of the Earth
  - 10^{-16} m^{-1} → 10^{-18} ⇔ 1 cm

❑ Chronometric geodesy

- Remote frequency standard comparisons to measure gravity potential differences

Delva P., Denker H., Lion G. arXiv:1804.09506

Müller J. et al., Space Sci. Rev. 214, 5 (2018)

❑ Present and future impact on TAI

- General relativity already taken into account in definition and elaboration of TAI. See Resolution 2 of the 2018 CGPM on the definition of timescale.
- Irregularities and variations may limit time coordinate with frequency standards on the Earth surface to few 10^{-18}.
- Tides amount to up to 10^{-16} (1 m).
- Started to be considered by IAG/IUGG, by the BIPM time department, etc.

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Toward a redefinition: work of the CIPM/CCTF

Bureau
International des
Poids et
Mesures

CIPM/CCTF 2001

- Expected optical and other microwave standards to surpass primary Cs standards in reproducibility, stability and uncertainty
- Such systems could be used to realize the second provided their accuracy is close to that of Cs standards
- Adoption of such **secondary representations of the second** (SRS) would help assessing these standards at the highest level
- This activity is likely to aid the process of evaluating standards in preparation for a possible redefinition of second

CIPM/CCTF documents

- Several recommendations
- CCTF strategic plan
- Work of several working groups and of the time department of the BIPM

Toward a redefinition: work of the CCTF & CCL

CCL-CCTF frequency standard working group

- Terms of reference - The objectives of the CCL-CCTF WGFS are:
  - *To make recommendations to the CCL for radiations to be used for the realization of the definition of the metre and to make recommendations to the CCTF for radiations to be used as secondary representations of the second;*
  - *To maintain, together with the BIPM, the list of recommended frequency standard values and wavelength values for applications including the practical realization of the definition of the metre and secondary representations of the second;*
  - *To take responsibility for key comparisons of standard frequencies such as CCL-K11;*
  - *To respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities.*

CCL-CCTF WGFS in particular and practically:

- Monitors the status of optical and microwave standards based on existing peer-reviewed publications
- Proposes updates to the CIPM *List of recommended standard frequencies (LoF) recommended for applications including the practical realization of the metre (MeP) and secondary representations of the second (SRS)*.

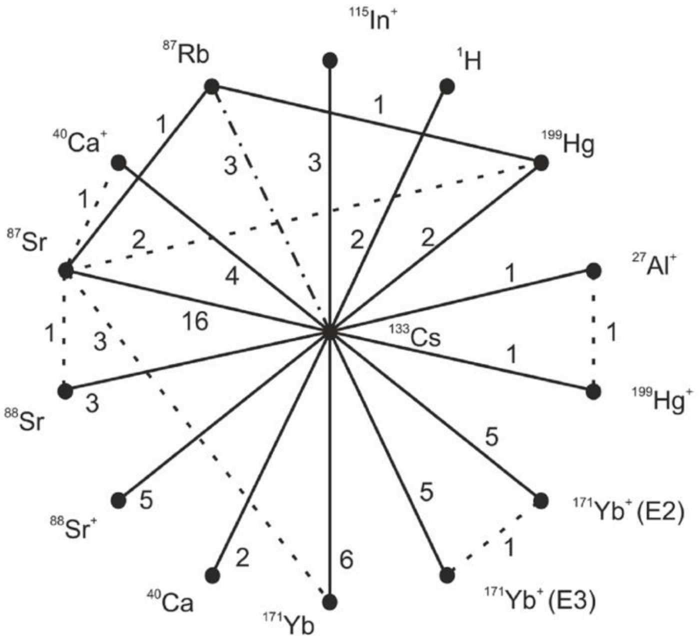
Recent description CCL-CCTF WGFS activity in Metrologia

- F. Riehle, P. Gill, F. Arias & L. Robertsson, Metrologia 55, 188 (2018)

Frequency ratios considered by the CCTF 2017

❑ Overview of measurements

- About 70 measurements
- 6 optical frequency ratios
- An over-determined dataset



❑ Procedure for consistency check

- Measurements expressed in a matrix of frequency ratios
- Least-square adjustment
- See H.S. Margolis & P. Gill, Metrologia 52, 628 (2015), L. Robertsson, Metrologia 53, 1272 (2016)
- 3 independent implementations by H. Margolis, L. Robertsson, C. Oates

❑ For the LoF, the CCL-CCTF WGFS takes into account

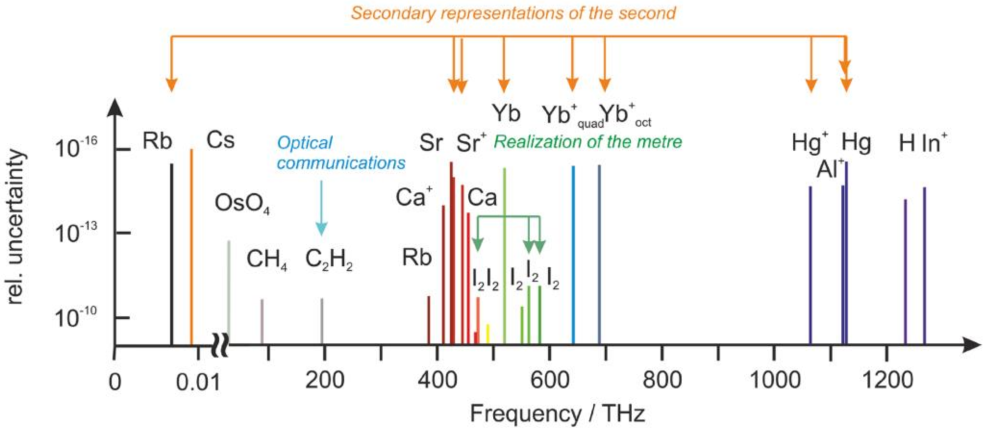
- Inconsistencies, scarcity of measurements, etc.

Overview of the 2017 LoF

❑ References

- F. Riehle, P. Gill, F. Arias & L. Robertsson, Metrologia 55, 188 (2018)
- LoF on BIPM website

❑ List of recommended standard frequencies (CCTF 2017)

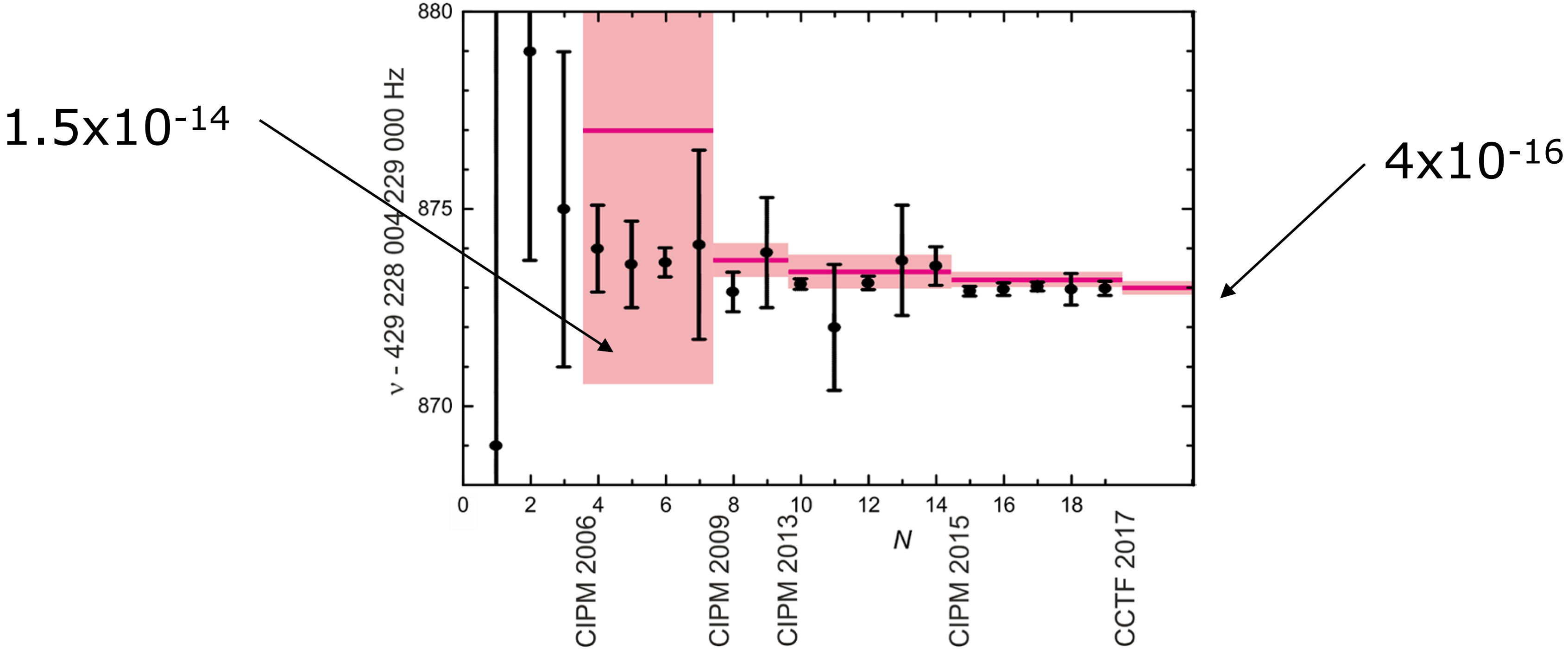


❑ List of SRS (CCTF 2017)

Frequency (Hz)	Fractional uncertainty	Transition
6 834 682 610.904 3126	6×10^{-16}	^{87}Rb ground state hfs
429 228 004 229 873.0	4×10^{-16}	^{87}Sr neutral atom, $5s^2\ ^1S_0$–$5s5p\ ^3P_0$
444 779 044 095 486.5	1.5×10^{-15}	$^{88}Sr^+$ ion, $5s\ ^2S_{1/2}$–$4d\ ^2D_{5/2}$
518 295 836 590 863.6	5×10^{-16}	^{171}Yb neutral atom, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$
642 121 496 772 645.0	6×10^{-16}	$^{171}Yb^+$ ion, $^2S_{1/2}$–$^2F_{7/2}$
688 358 979 309 308.3	6×10^{-16}	$^{171}Yb^+$ ion, $6s\ ^2S_{1/2}$–$5d\ ^2D_{3/2}$
1 064 721 609 899 145.3	1.9×10^{-15}	$^{199}Hg^+$ ion, $5d^{10}6s\ ^2S_{1/2}$–$5d^96s^2\ ^2D_{5/2}$
1 121 015 393 207 857.3	1.9×10^{-15}	$^{27}Al^+$ ion, $3s^2\ ^1S_0$–$3s3p\ ^3P_0$
1 128 575 290 808 154.4	5×10^{-16}	^{199}Hg neutral atom, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$

A dynamical process

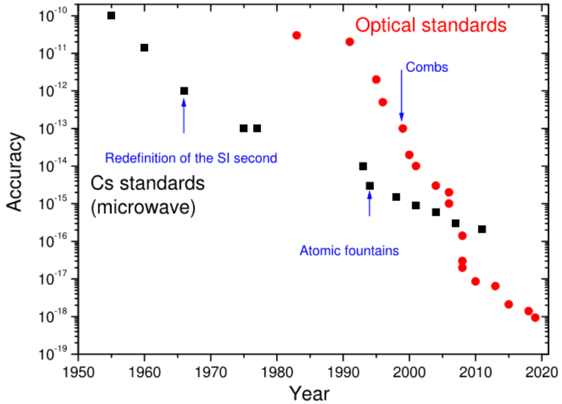
- Successive recommended values and uncertainty for ^{87}Sr



1.5×10^{-14}

4×10^{-16}

- Normal given the fast evolution of optical frequency metrology



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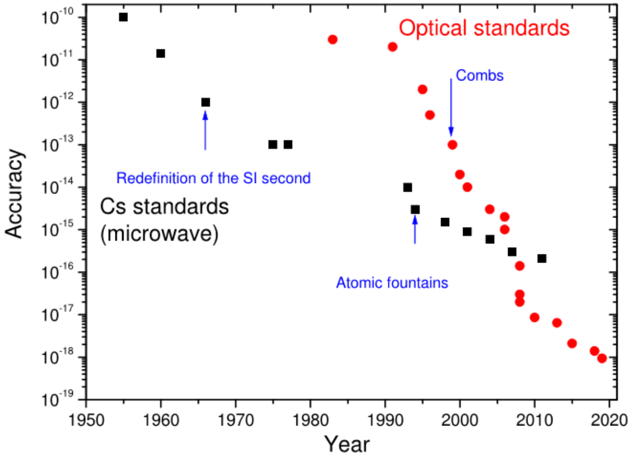
Impact of precise time and frequency references

- **Cs definition serves well industry’s needs**
- **Precise time is important in global scale applications & services**
  - Elaboration/dissemination of TAI/UTC
  - Determination of Earth orientation parameters
  - Global navigation satellite systems
  - Networks (telecommunication, transport, electrical power, etc.)
- **Precise, consistent time and frequency references are important for science**
  - VLBI, deep space navigation, pulsar timing, test of fundamental theories, fundamental constants, etc.
- **Progress of optical frequency standards continues**
  - No definite argument for a given atom or ion



Important considerations for a redefinition

- **New definition must last long**

- **Continuity between old and new definition must be ensured**

- **Effectiveness of dissemination must be guarantied**
  - In particular in the elaboration of TAI

- **Optical frequency standards must have validated uncertainties**
  - At a level much better than Cs standards (e.g. 2 orders of magnitudes)

Possible milestones towards a new definition

See CCTF strategy document and Metrologia 55, 188 (2018)

❑ New definition should not take place before…

- … the progress with the different optical frequency standards slows down
  Alternatively: .. when at least three different (either in different laboratories, or of different species) optical clocks have validated uncertainties two orders of magnitude better than the best Cs atomic clocks.
  (To increase the probability that the new definition will last long)

- … there are three independent measurements of the optical frequency standards listed in item 1 limited essentially by the uncertainty of the best Cs fountain clocks (e.g. $\Delta\nu/\nu < 3 \times 10^{-16}$).
  (To allow for continuity between the old and new definition)

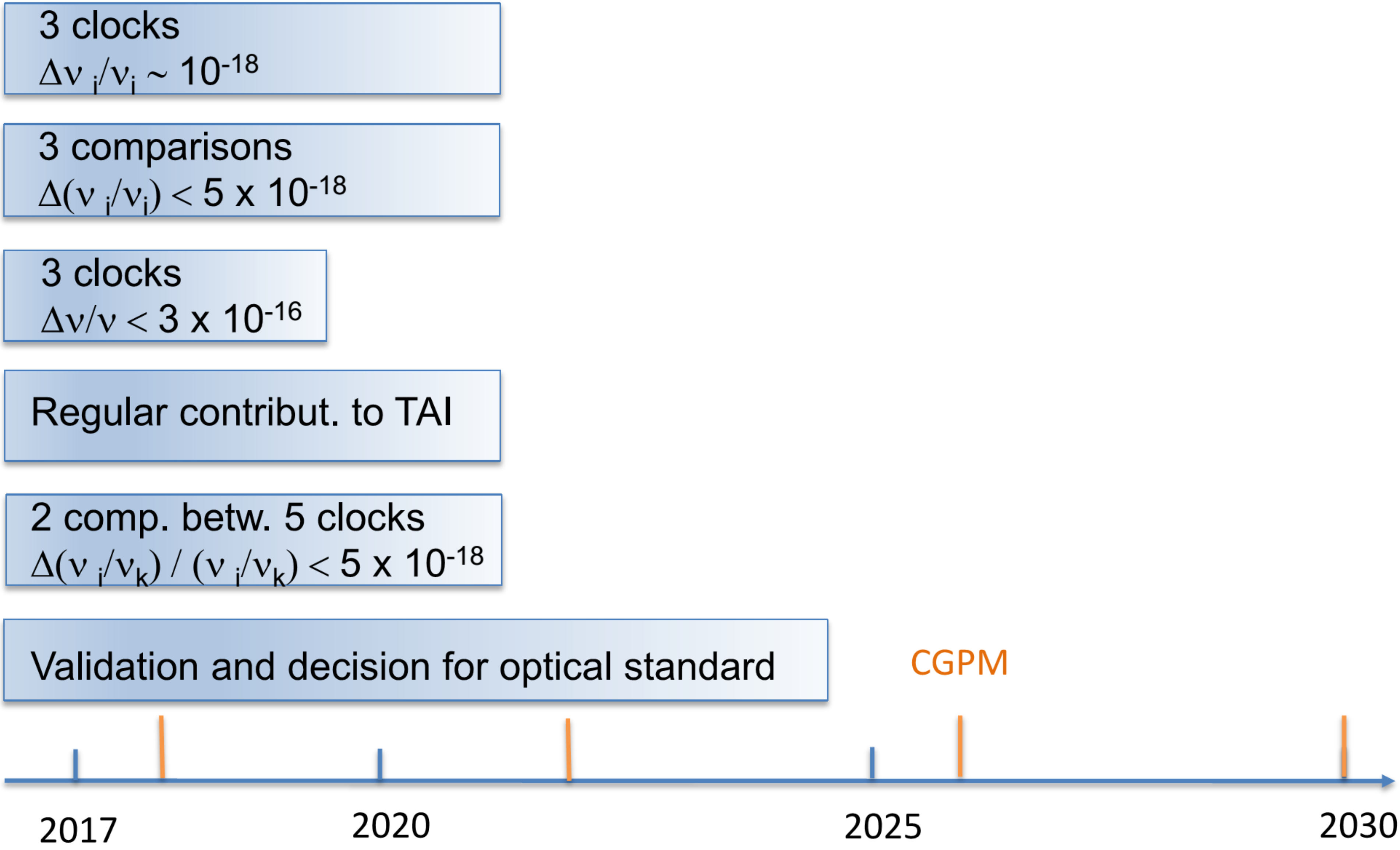
- … three or more optical clocks with the same atomic species were compared in different institutes (e.g. $\Delta\nu/\nu < 5 \times 10^{-18}$) (either by transportable clocks, fiber links, or frequency ratio closure)
  (To validate item 1)

- … optical clocks (secondary representations of the second) contribute regularly to TAI

- … optical frequency ratios between a few (at least 5) other optical frequency standards have been performed; each ratio measured at least twice by independent labs and agreeement (with e.g. $\Delta\nu/\nu < 5\times10^{-18}$)
  (To allow closures and links between the different optical standards)

Possible roadmap

See CCTF strategy document and Metrologia 55, 188 (2018)



3 clocks
$\Delta\nu_i/\nu_i \sim 10^{-18}$

3 comparisons
$\Delta(\nu_i/\nu_i) < 5 \times 10^{-18}$

3 clocks
$\Delta\nu/\nu < 3 \times 10^{-16}$

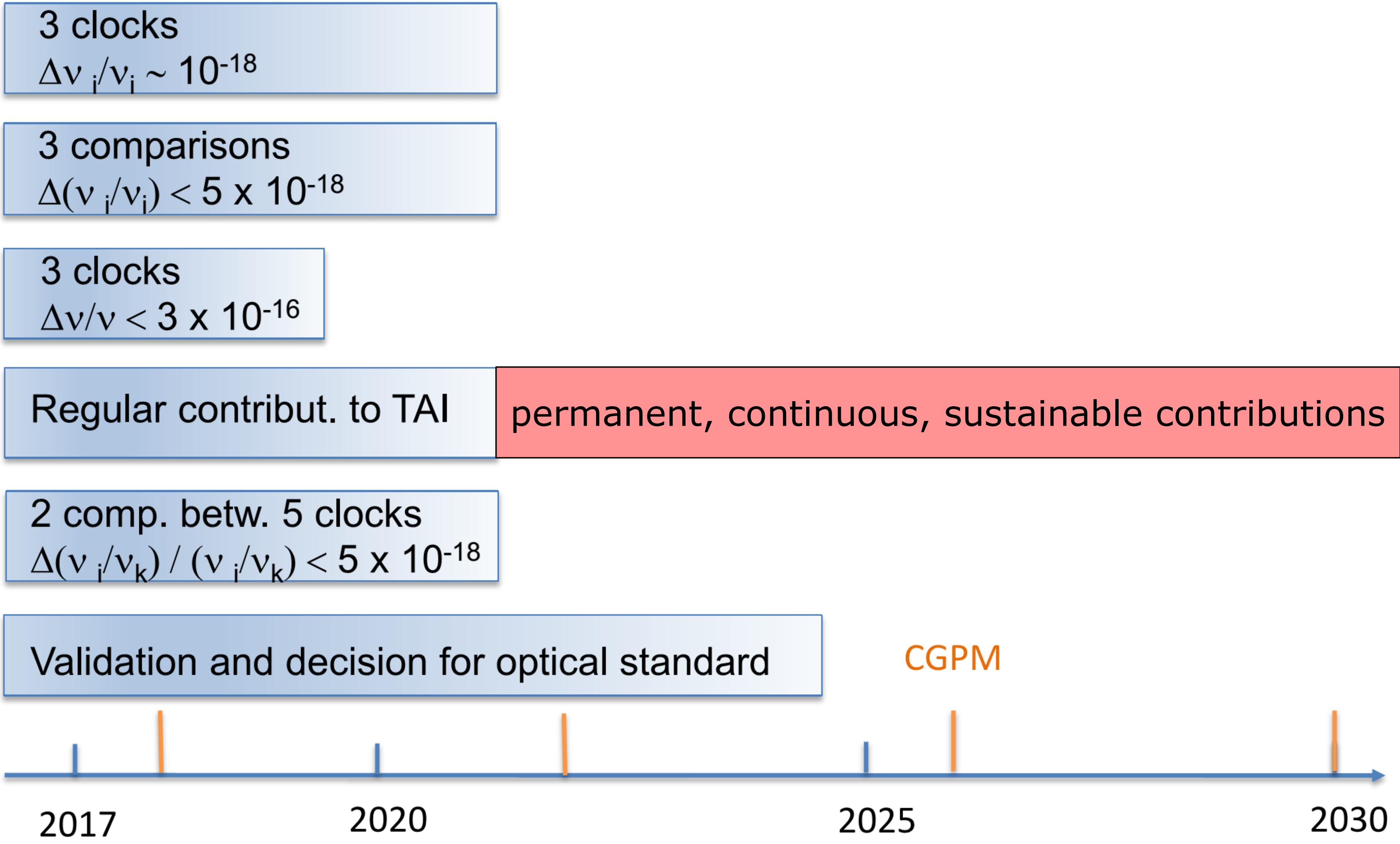
Regular contribut. to TAI

2 comp. betw. 5 clocks
$\Delta(\nu_i/\nu_k) / (\nu_i/\nu_k) < 5 \times 10^{-18}$

Validation and decision for optical standard

CGPM

Possible roadmap completed



3 clocks
$\Delta\nu_i/\nu_i \sim 10^{-18}$

3 comparisons
$\Delta(\nu_i/\nu_j) < 5 \times 10^{-18}$

3 clocks
$\Delta\nu/\nu < 3 \times 10^{-16}$

Regular contribut. to TAI

permanent, continuous, sustainable contributions

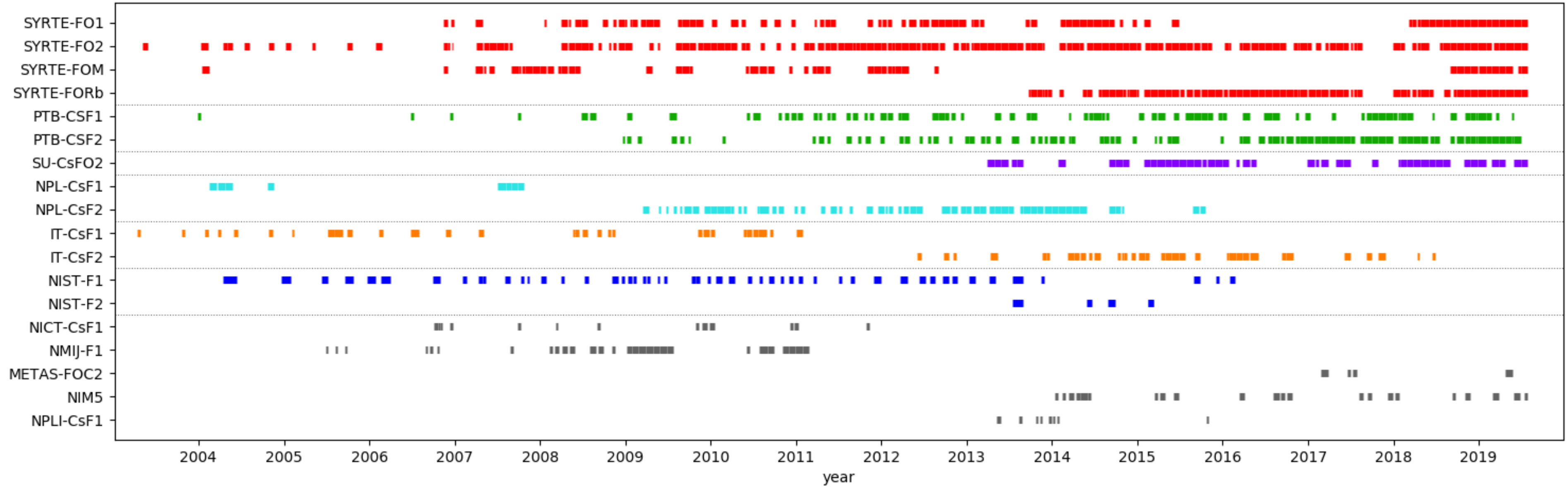
2 comp. betw. 5 clocks
$\Delta(\nu_i/\nu_k) / (\nu_i/\nu_k) < 5 \times 10^{-18}$

Validation and decision for optical standard

CGPM

Sustainable contribution to TAI

❑ Calibration with fountains



- See Circular T. Note: Cs beams not shown.

❑ So far, very few contributions from optical frequency standards

- LNE-SYRTE (Sr), NICT (Sr), NIST (Yb). Only 2 or 3 given in “real-time”.
- Note: comb generate a microwave frequency tied to the optical transition that readily connect to existing architectures.

❑ Need of strong commitment from NMIs

❑ Suggest to update strategy document accordingly

- And (stronger) recommendation at the 2020 CCTF

Options for a redefinition of the SI second

- Choose a single atomic transition similarly to what is currently done
    - And make use of secondary representations of the second
    - Change again once major progress is observed
- Adopt a definition using several transitions at the same time
    - See J. Lodewyck, Metrologia 56, 055009 (2019)
    - Realization using frequency ratio matrix from CIPM
    - Update the ensemble and weights, with rules yet to be agreed upon

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

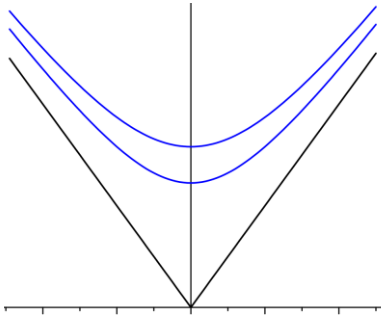
- Fix the value of the electron’s mass
    - Which fixes the value of the De Broglie-Compton frequency of the electron

$$\boxed{\nu_e = \frac{m_e c^2}{h}}$$

$$\nu_e \sim 10^{20}\ \mathrm{Hz}$$

C. Bordé, C. R. Physique 20, 22 (2019)

$$E(p) = \sqrt{m^2c^4 + p^2c^2}$$



    - And use one of the above as *mise en pratique*
    - Note: CODATA 2018: u(m_e)=3.0x10^{-10}, u(cR_∞)=1.9x10^{-12}
    - While: u(H(1S-2S))=4.5x10^{-15} (proton size)
- Fix the value of *G* which fixes Planck’s mass

$$m_P = \sqrt{\frac{\hbar c}{G}}$$

After a new definition

❑ Cs will be a secondary representation of the second

- with first the same frequency as before: 9 192 631 770 Hz
- If Cs standard improve and new measurements are made, a new recommended values be defined which will deviate from 9 192 631 770 Hz

❑ Processes for the elaboration of TAI will remain the same

- Cs (and other SRS) can and will continue to calibrate TAI (probably for quite some time)
- More and more optical frequency standards are accepted to contribute to TAI, gradually leading to improvement of the timescale

❑ Deeper impact of optical frequency standards on timekeeping

- With improved remote time and frequency comparisons
- With improved (optical) local oscillators

❑ Impact of the redefinition on other units

- Insignificant because of the gap in uncertainties