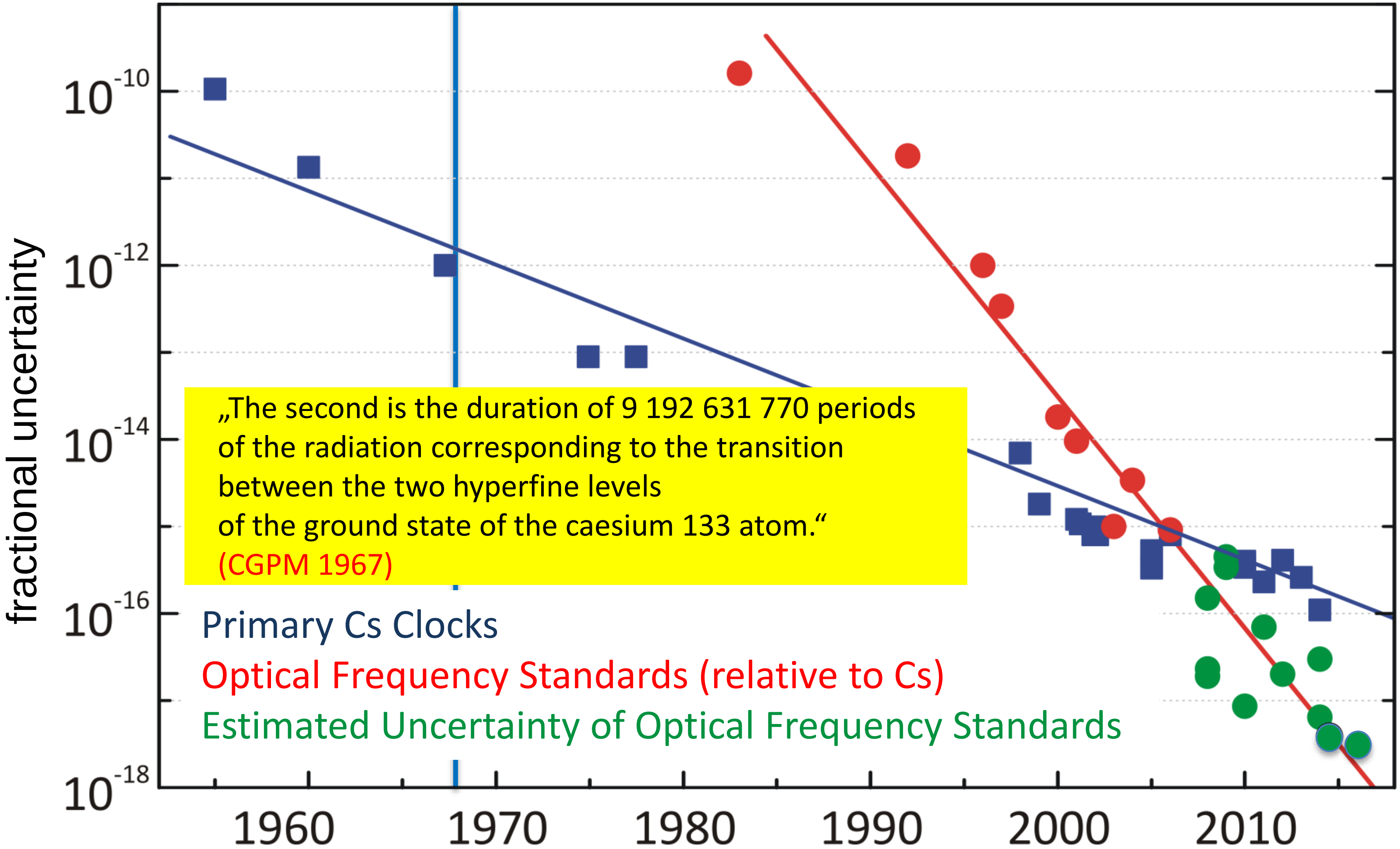
Towards a redefinition of the SI second by optical clocks: Achievements and challenges

- Status of Optical Atomic Clocks
  - Single Ion Clocks (Yb^+ Octupole Transition Clock)
  - Neutral Atom Clocks (Sr Lattice Clock)
- How to Assess and Validate Optical Clocks
  - Process of Validation by the CCTF
- Novel Opportunities by Optical Clocks
- Towards a New Definition
  - Procedures
  - Milestones
  - Tentative Roadmap


Caesium Clocks and Optical Atomic Clocks

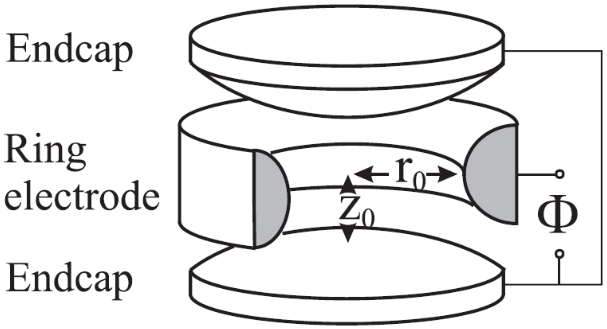


Future new definition of the second by optical clocks

Different technologies

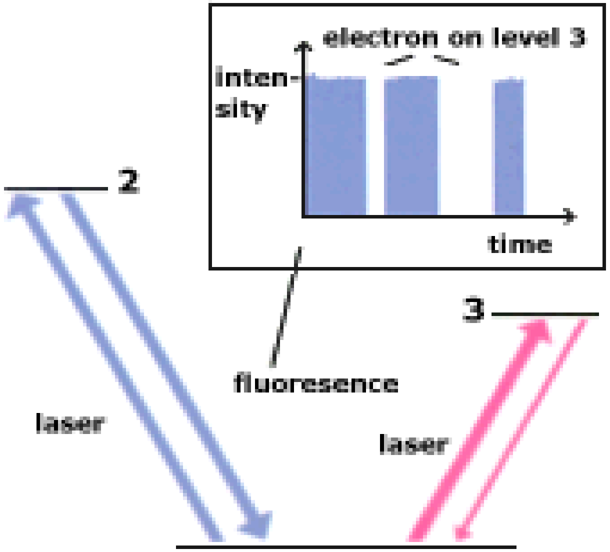
Single Ion Optical Clocks

Single ion clock



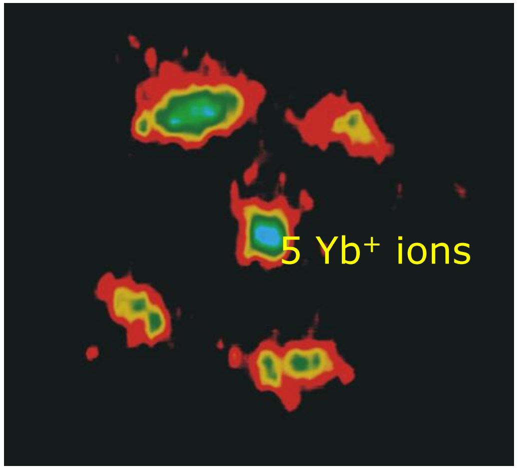
Electrodynamic (Paul) trap

Quantum jumps
for detection

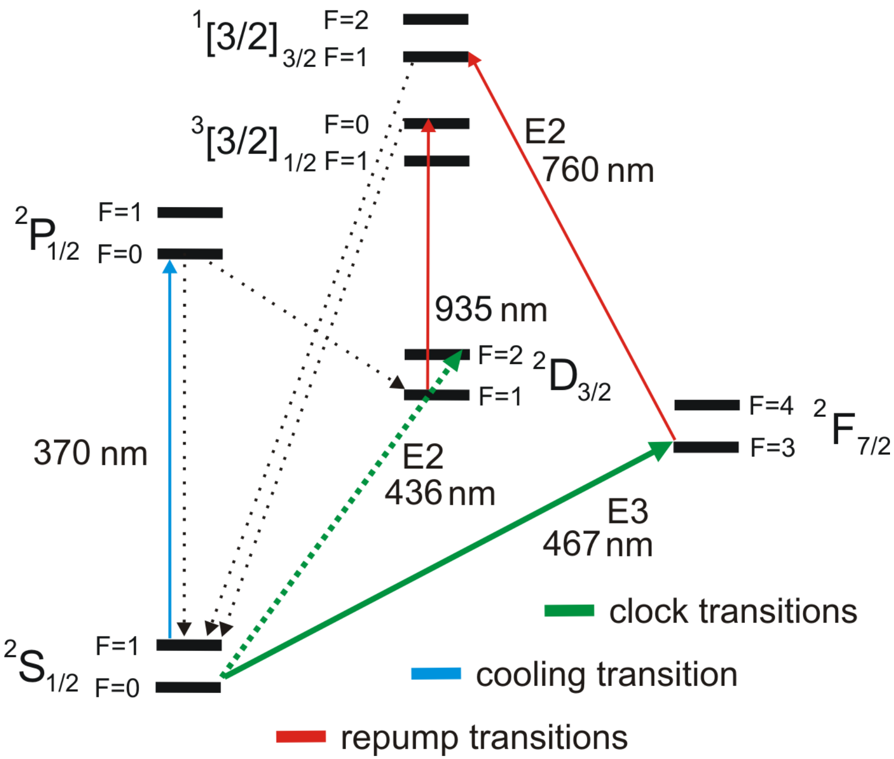


Plenty of excellent candidates
for frequency standards

Disadvantage: low S/N



PTB's Yb^+ Single Ion clock



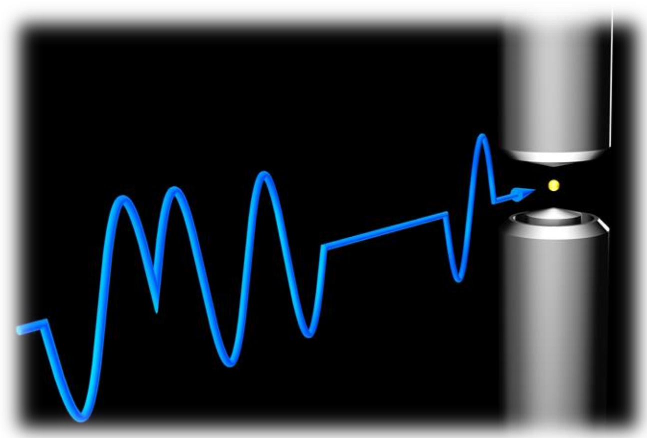
- E3: insensitive wrt external fields
- E3: extremely long natural lifetime
  - → potentially high stability
  - → large light shift

  (can be suppressed by a special Hyper - Ramsey – Technique)

V. Yudin *et al.*, Phys. Rev. A **82** 011804(R) (2010)
ILP (Russia), NIST and PTB

E2: Chr. Tamm *et al.*, Phys. Rev. A **89**, 023820 (2014)

E3: N. Huntemann *et al.*, Phys. Rev. Lett. **108**, 090801 (2012)

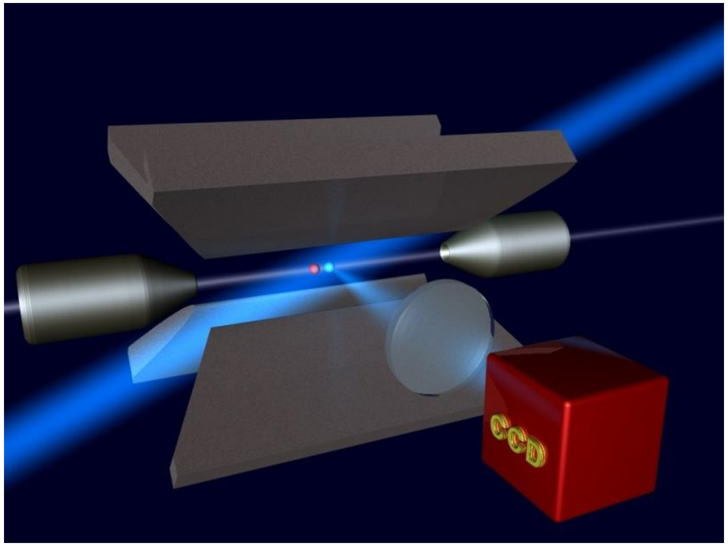


Uncertainty budget for PTB's Yb^+ E3 optical clock

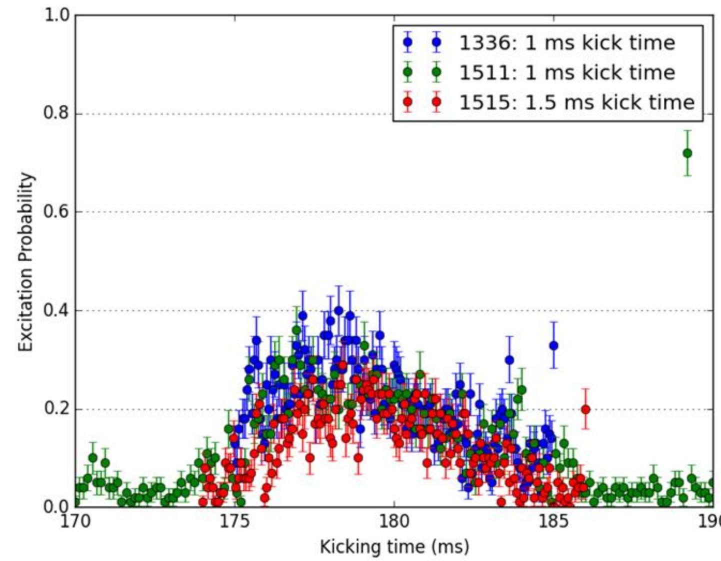
Effect	$\delta\nu/\nu_0$ (10^{-18})	u/ν_0 (10^{-18})
Second-order Doppler shift	−3.7	2.1
Blackbody radiation shift	−70.5	1.8
Probe light related shift	0	1.1
Second-order Zeeman shift	−40.4	0.6
Quadratic dc Stark shift	−1.2	0.6
Background gas collisions	0	0.5
Servo error	0	0.5
Quadrupole shift	0	0.3
Total	−115.8	3.2

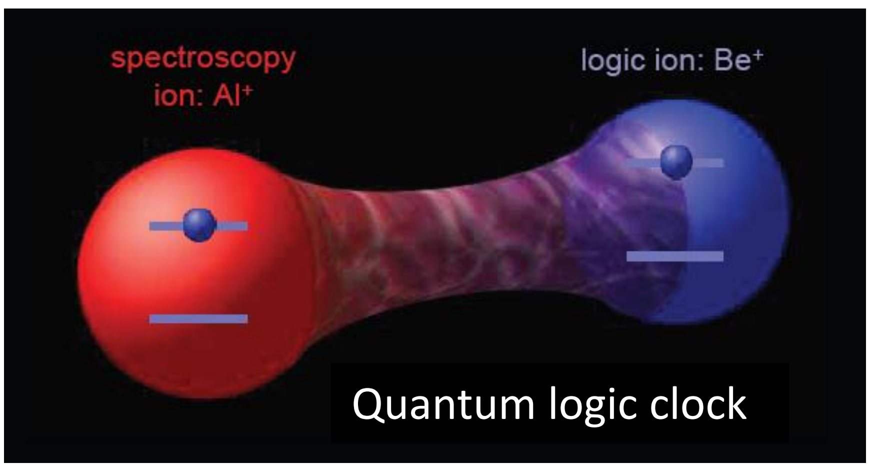
N. Huntemann, C. Sanner, B. Lipphardt, Chr. Tamm, E. Peik, Single-Ion Atomic Clock with 3 $\times 10^{-18}$ Systematic Uncertainty; Phys. Rev. Lett. **116**, 063001 (2016)

Al^+ Quantum Logic Clock



First signal of the $^1S_0$ -> $^3P_1$ logic transition in Al^+

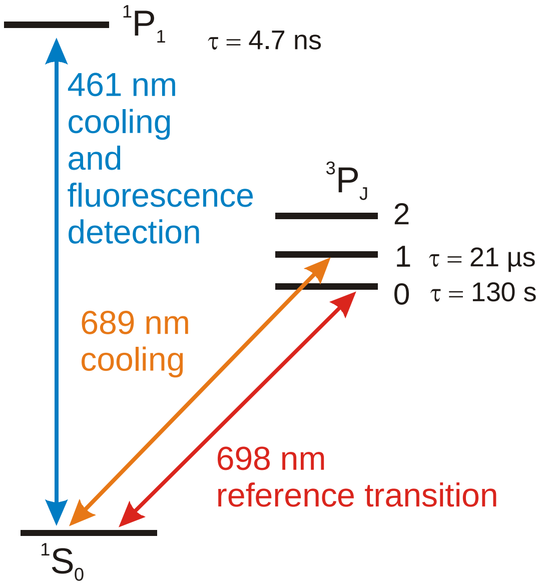




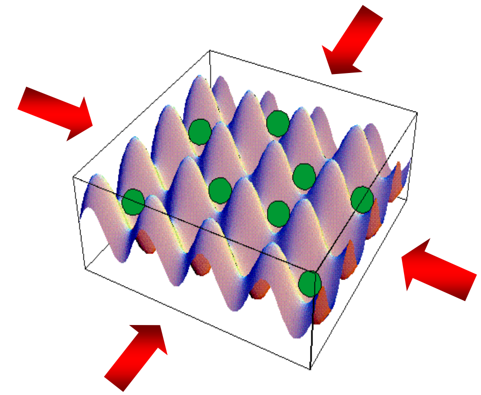
- Excitation of the Al^+ ion
- Transfer of internal state to Be^+, Ca^+ or Mg^+ logic ion
- Detection in the Be^+, Ca^+ or Mg^+ ion

NIST (Boulder), PTB / QUEST and others

Lattice Clock



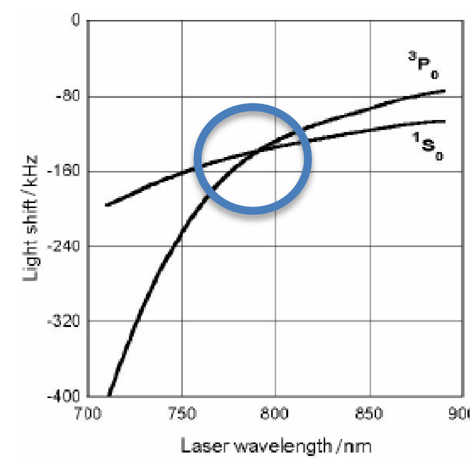
Neutral atom lattice clock



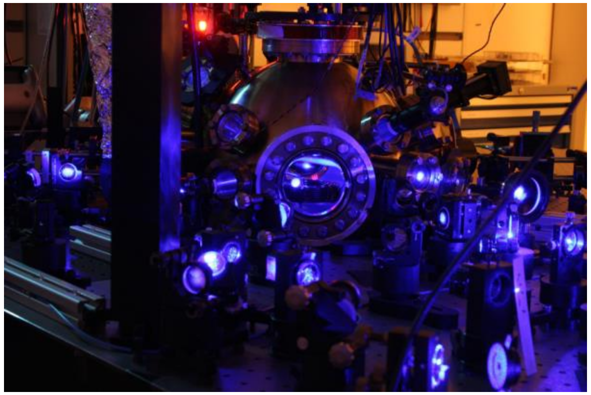
- $10^4 - 10^6$ atoms can be interrogated
- High S/N; high frequency stability

H. Katori: Spectroscopy of Strontium Atoms in the Lamb-Dicke Confinement. In: Proc. of 6th Symp. on Frequency Standards and Metrology, (P. Gill ed., World Scientific), p. 323 - 330, (2002).

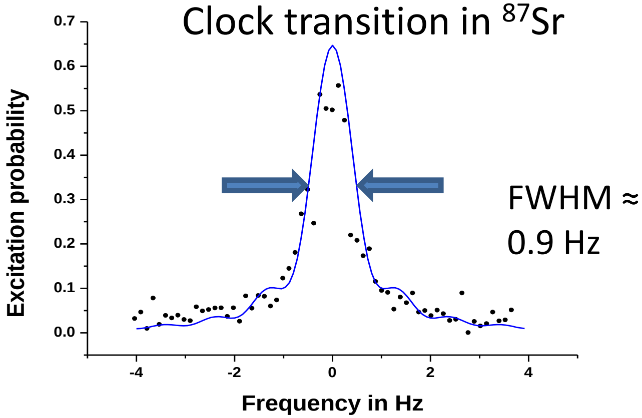
Operation at the „magic“ wavelength

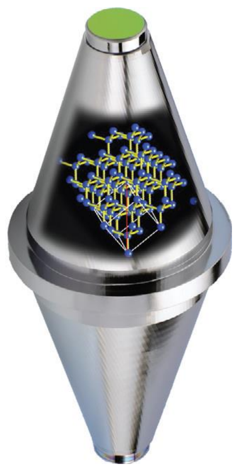


Optical Sr Lattice Clocks of PTB



Stationary
Sr lattice clock



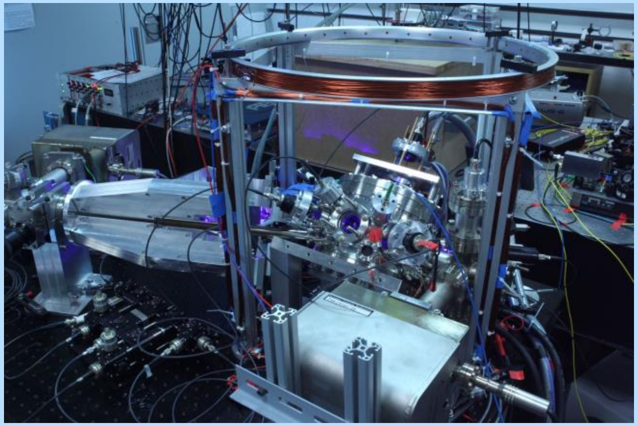


Cooperation with Jun Ye, JILA

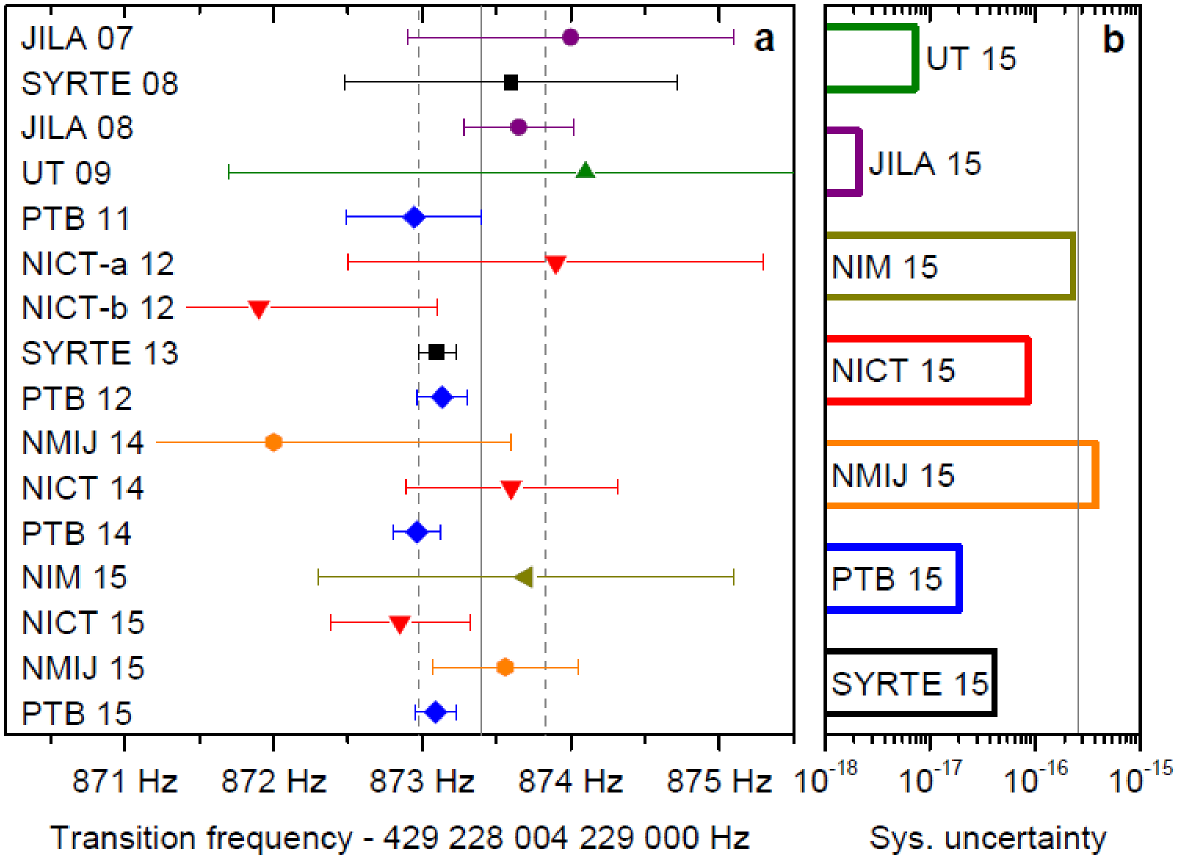
T. Kessler et al: A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity, Nat. Phot. **6** (2012) 687

S. Häfner et al: 8×10^{-17} fractional laser frequency instability with a long room-temperature cavity, Opt. Lett. **40** (2015) 2112

Transportable Sr lattice clock



Frequency Measurements of the Sr Clocks vs Cs



from: Ch. Grebing et al. **2015**
arXiv:1511.03888v2 [physics.optics]
22 Feb 2016

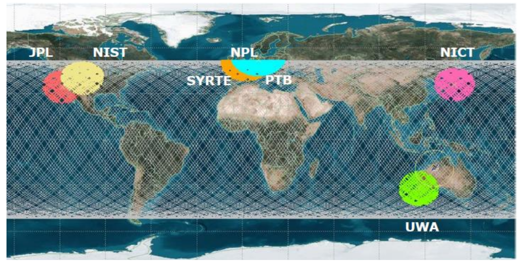
How to compare the different clocks all over the world?

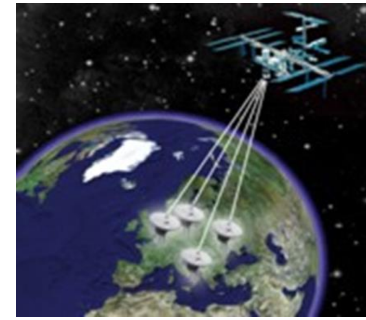
- Frequency measurements agree well
- Frequency values are going to be limited by the accuracy of the Cs clocks
- Validated and recommended values (CIPM 2012 and 2015/2016)

Direct Comparison of Remote Optical Clocks

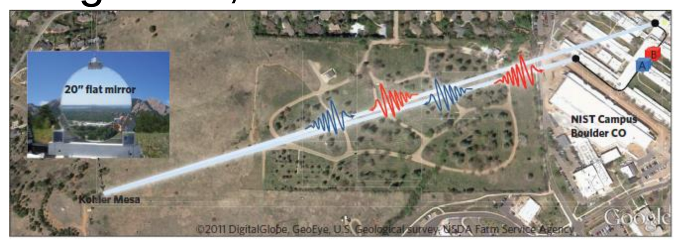
- 2-way satellite frequency transfer (10^{-15} per day)

- ACES on ISS
  (targeting < 10^{-16})
  µwave link ground terminals at 7 labs



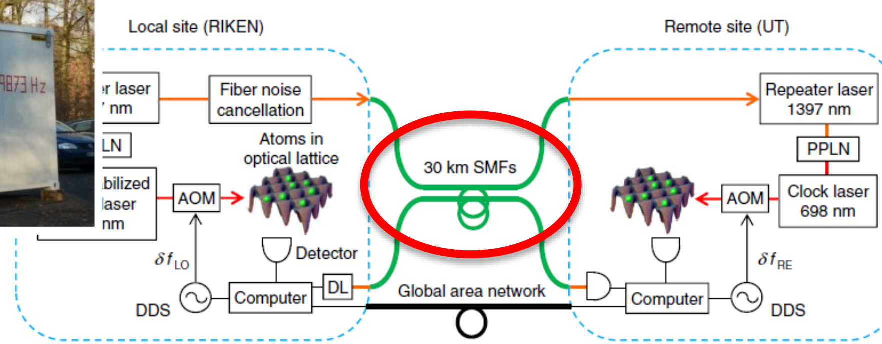


- Optical free-space links (ground – ground; satellite – satellite; ground → satellite;
  up to now proofs of principle; targetting 10^{-16} per day



- Transportable clocks going for accuracy; neglecting compactness

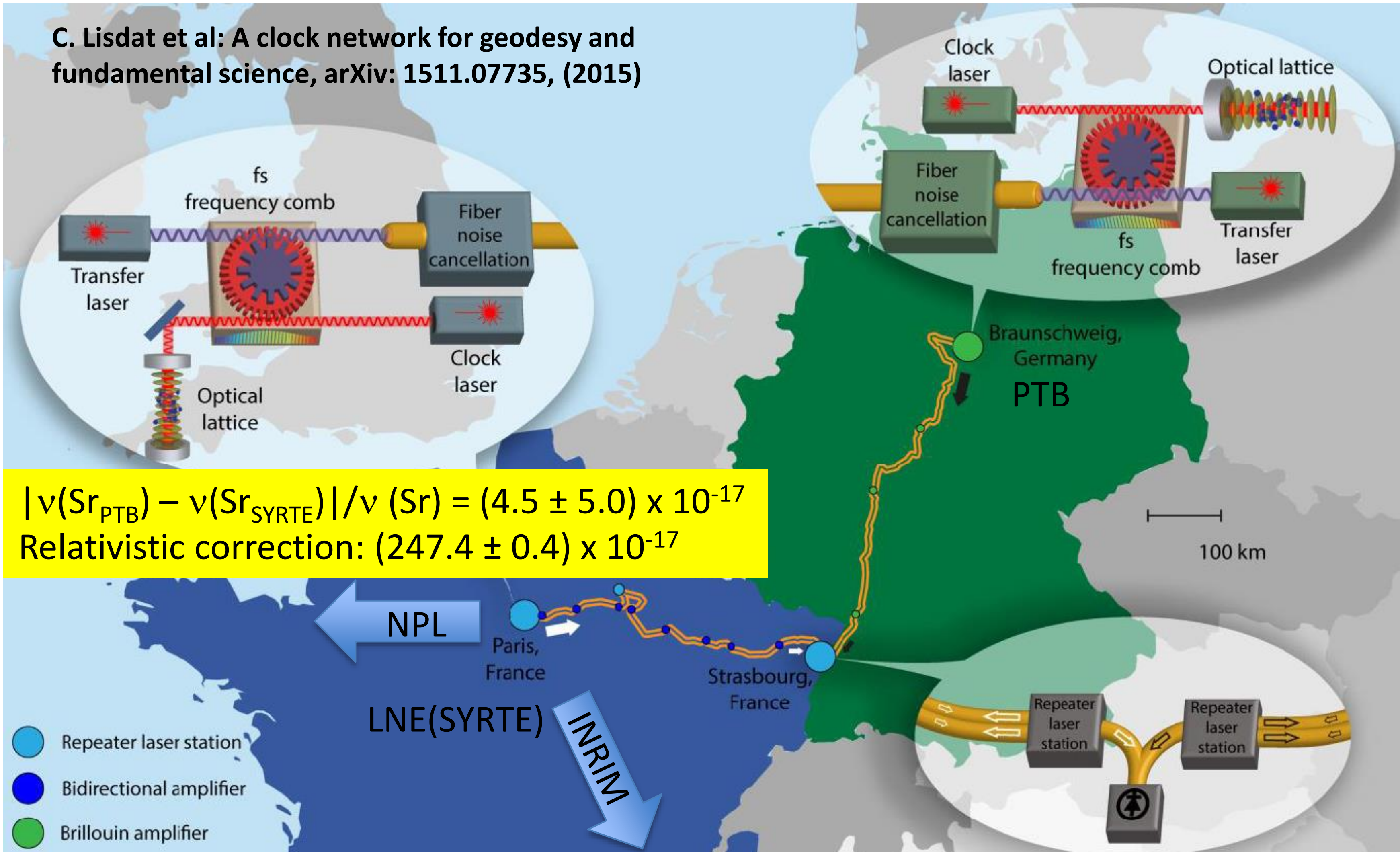
- Optical frequency transfer by fiber



T. Akatsuka et al: Jap. J. Appl. Phys. 53, 032801 (2014)

Sr Clock Comparison Paris - Braunschweig

C. Lisdat et al: A clock network for geodesy and fundamental science, arXiv: 1511.07735, (2015)



$|\nu(Sr_{PTB}) - \nu(Sr_{SYRTE})|/\nu\ (Sr) = (4.5 \pm 5.0) \times 10^{-17}$

Relativistic correction: $(247.4 \pm 0.4) \times 10^{-17}$

Direct Measurements of Optical Frequency Ratios

Reference	Absorber	Value	Relative uncertainty
Takamoto et al (2015)	f_{Yb}/f_{Sr}	1.207 507 039 343 337 76	2.4×10^{-16}
Yamanaka et al (2015)	f_{Hg}/f_{Sr}	2.629 314 209 898 909 60	8.4×10^{-17}
Takamoto et al (2015)	f_{Hg}/f_{Yb}	2.177 473 194 134 565 07	2.5×10^{-16}
Ushijima et al (2014)	$f_{Sr(1)}/f_{Sr(2)}$	1.0	1.6×10^{-18}
Bloom et al (2013)	$f_{Sr(1)}/f_{Sr(2)}$	1.0	5.3×10^{-17}
Chou et al (2010)	$f_{Al+(1)}/f_{Al+(2)}$	1.0	2.5×10^{-17}
Rosenband et al (2008)	f_{Hg+}/f_{Al+}	1/1.052871833148990438(55)	5.3×10^{-17}

Opportunity to compare frequencies without direct comparison

$\frac{f_A}{f_B}$ $\frac{f_B}{f_C}$ $\frac{f_A}{f_C}$

$$\frac{f_A}{f_B} \cdot \frac{f_B}{f_C} \cdot \frac{f_C}{f_A} = 1 + \Delta$$

Is Δ consistent with the claimed uncertainties of the clocks A, B, C ?

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Secondary Representations of the Second

CCTF 2001

- Optical and other micowave standards were expected to demonstrate reproducibility and stability approaching that of primary caesium

- Such systems could be used to realise the second, provided their accuracy was close to that of caesium

- Adoption as such secondary representations would help with detailed evaluation of reproducibility of these standards at the highest level

- Their uncertainty could obviously be no better than the caesium uncertainty

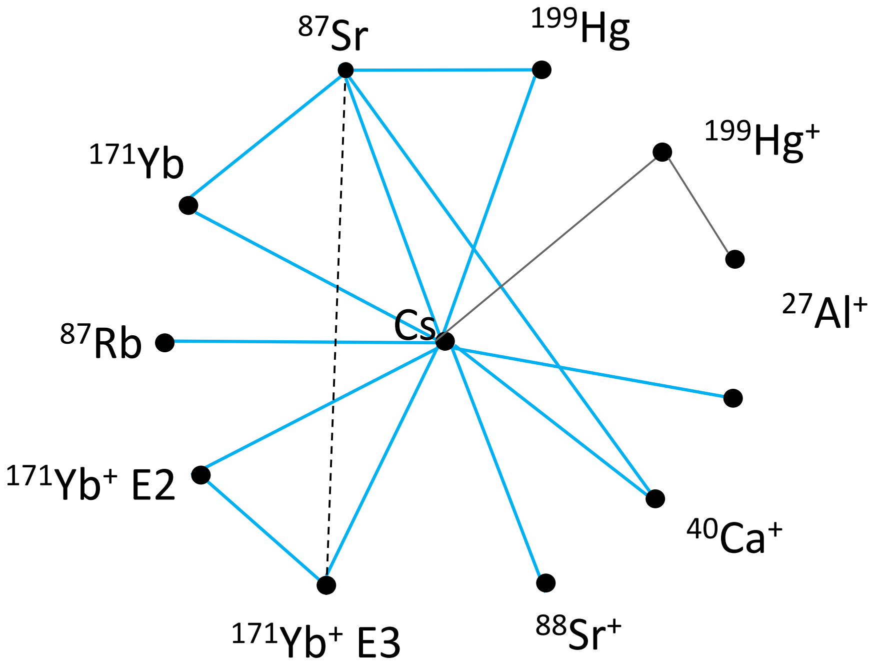
- This activity was likely to significantly aid the process of evaluation of different standards in preparation for a possible future redefinition of the second

Frequency Ratios Considered by CCTF

Several absolute measurements relative to Cs

Five direct optical frequency ratio measurements

Over-determined data set



September 2015

Applied procedure

- All measurements expressed in a frequency ratio matrix
- Least-squares adjustment

H. S. Margolis and P. Gill, Metrologia **52**, 628–634 (2015)

Updates of Frequency Values (CCTF ☞ CIPM)

Recommended value:
f **(^{87}Sr) = 429 228 004 229 873.4 Hz (1 x 10^{-15}) (CIPM2013)**

f **(^{87}Sr) = 429 228 004 229 873.2 Hz (5 x 10^{-16}) (CCTF 2015 ☞ CIPM approved);**
uncertainty limited essentially by Cs clock comparison)

Atom / Ion	Clock ν [THz]	Clock λ [nm]	CCTF fractional uncertainty
^{87}Sr	429	698	5 x10^{-16}
^{171}Yb^{+}	642	467	6 x10^{-16}
^{199}Hg	1129	266	6 x10^{-16}
^{171}Yb^{+}	688	435	6 x10^{-16}
^{88}Sr^{+}	445	674	1.6 x10^{-15}
^{171}Yb	518	578	2 x10^{-15}
^{1}H	1233	243	9 x10^{-15}
^{40}Ca^{+}	411	729	1.2 x10^{-14}
^{87}Rb	6.8 GHz		7 x10^{-16}

Some of these optical clocks are secondary representations of the second
i.e. they can be used with the attributed uncertainty to contribute to TAI and UTC.

Highly Accurate and Stable Optical Clocks

Atom / ion	Clock type	Clock ν THz	Clock λ nm	Lowest published clock systematic uncertainty	Uncertainty of CIPM ν value
^{87}Sr	Lattice	429	698	2.1×10^{-18}	5×10^{-16}
$^{171}Yb^{+}$	Ion octopole	642	467	3.2×10^{-18}	6×10^{-16}
$^{27}Al^{+}$	Ion, quantum logic	1121	267	8.6×10^{-18}	1.9×10^{-15}
$^{88}Sr^{+}$	Ion quadrupole	445	674	1.2×10^{-17}	1.6×10^{-15}
$^{199}Hg^{+}$	Ion quadrupole	1065	282	1.9×10^{-17}	1.9×10^{-15}
$^{40}Ca^{+}$	Ion quadrupole	411	729	3.4×10^{-17}	1.2×10^{-14}
^{199}Hg	Lattice	1129	266	7.2×10^{-17}	6×10^{-16}
$^{171}Yb^{+}$	Ion quadrupole	688	436	1.1×10^{-16}	6×10^{-16}
^{171}Yb	Lattice	518	578	3.4×10^{-16}	2×10^{-15}
^{1}H	Cryogenic beam	1233	243	4.2×10^{-15}	9×10^{-15}

From P. Gill, to be published

Conclusion:

- Rapid progress on a variety of optical clocks
  (atoms in optical lattice, ions in rf trap,
  different species and types of transition)
- Currently unclear which is the best candidate for a future re-definition
- Novel methods of direct comparisons of remote clocks are needed

Review on Optical Clocks:
A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, P. O. Schmidt; Rev. Mod. Phys. **87**, 637 (2015)

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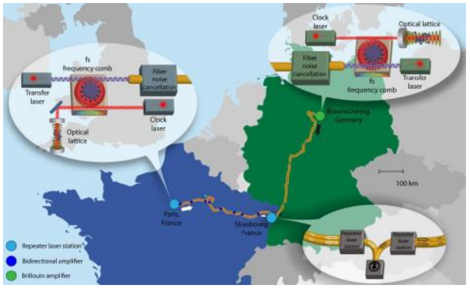
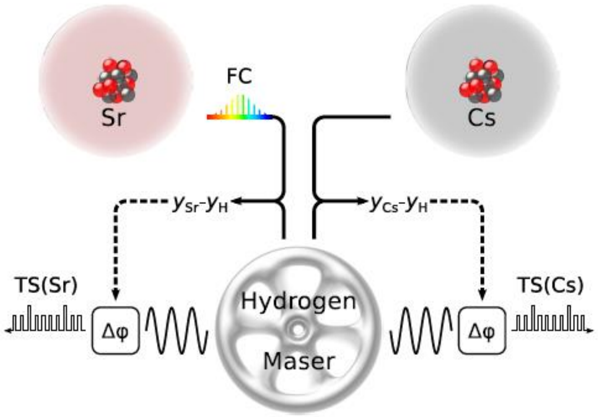
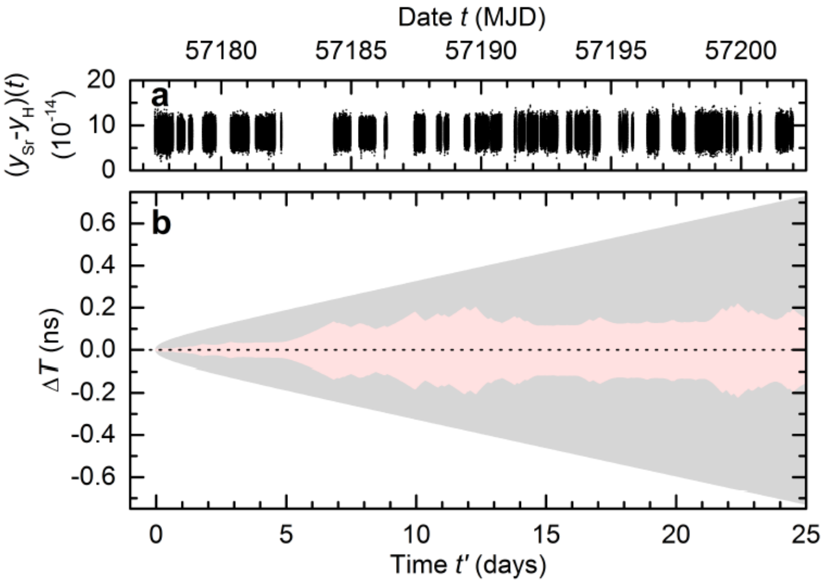
Novel Opportunities

- Time and Frequency Metrology
  - **Better Time Scales (more stable and more accurate)**
  - **Synchronization of clocks over large distances**
  - **Access to ultra precise reference frequencies for remote users**

    (novel services)







Realization of a timescale with an accurate optical lattice clock
Ch. Grebing, A. Al-Massoudi, S. Dörscher, S. Häfner, V. Gerginov, S. Weyers, B. Lipphardt, F. Riehle, U. Sterr, Ch. Lisdat
Optica (2016), submitted

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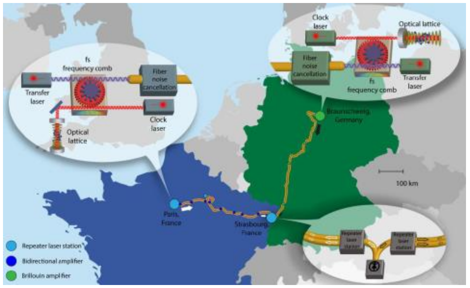
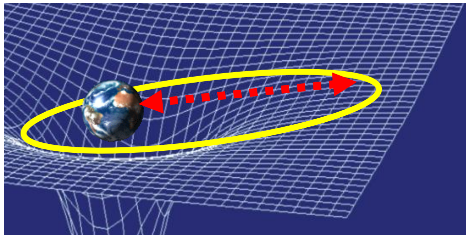
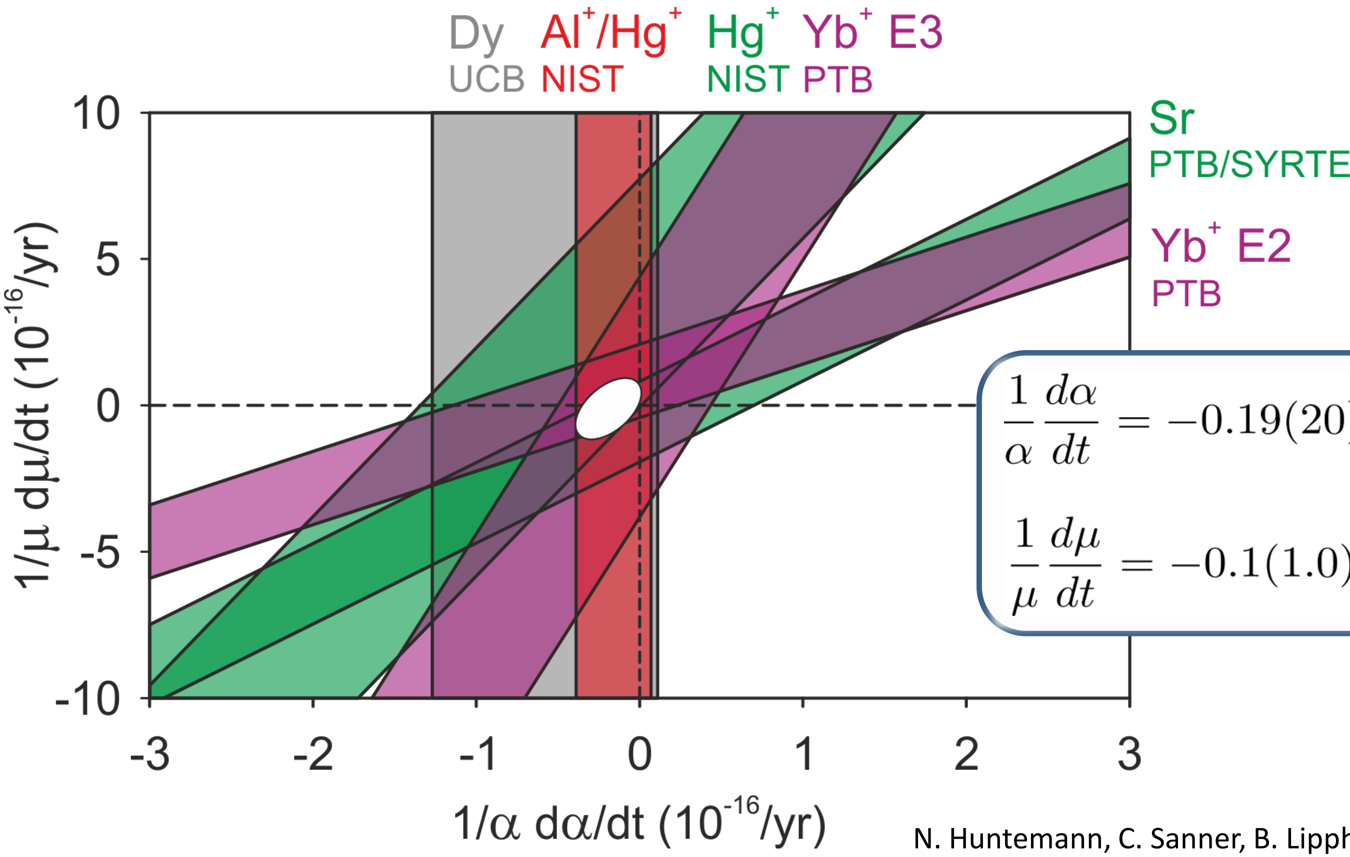


- Test of fundamental theories
  - Special and general theory of relativity, QED
  - Measurement of fundamental constants
  - How constant are the fundamental constants?

    (new science)



Limits for Temporal Variations of α and μ = m_p/m_e



$$\frac{1}{\alpha}\frac{d\alpha}{dt} = -0.19(20) \times 10^{-16}/\mathrm{yr}$$

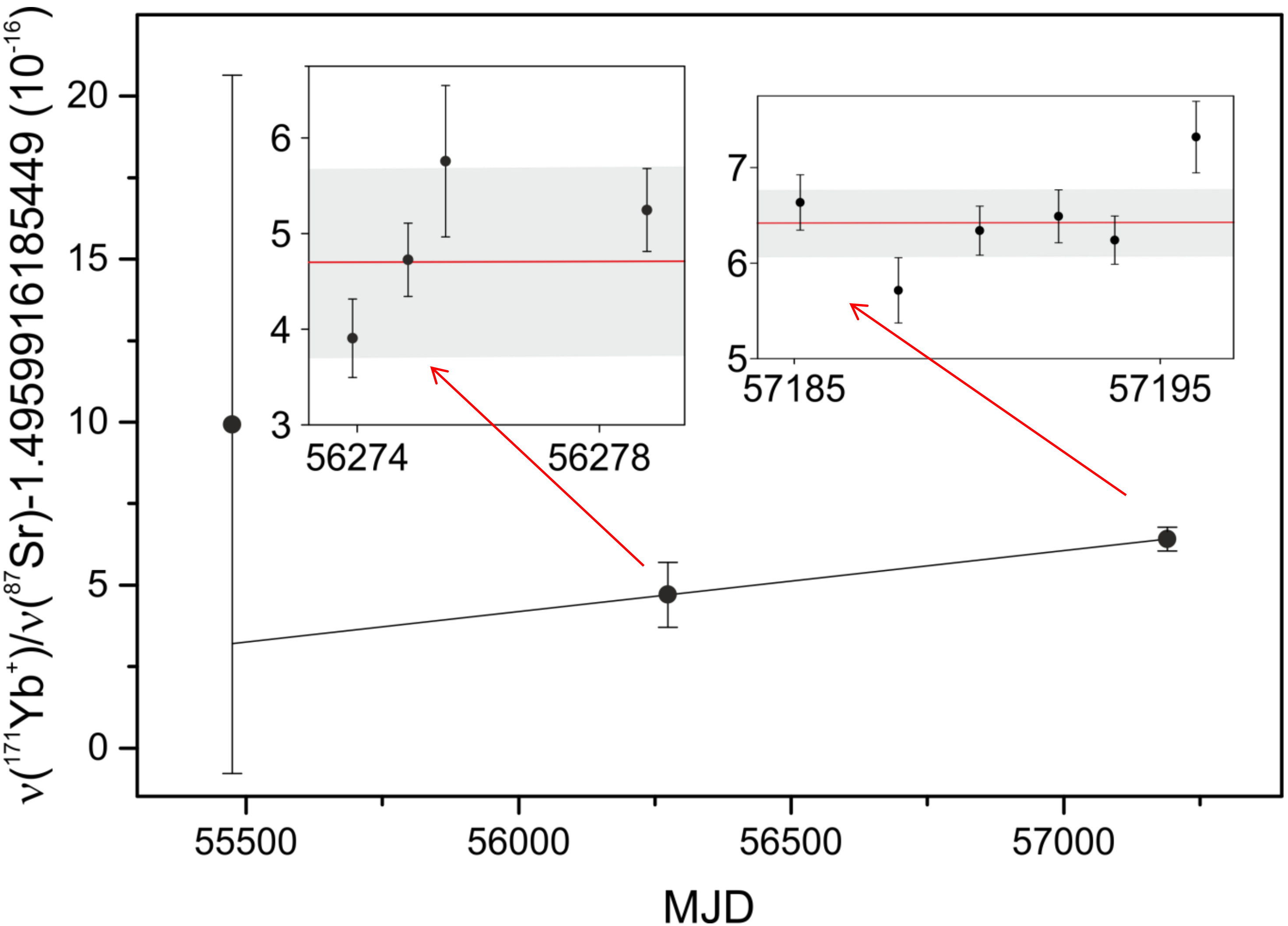
$$\frac{1}{\mu}\frac{d\mu}{dt} = -0.1(1.0) \times 10^{-16}/\mathrm{yr}$$

N. Huntemann, C. Sanner, B. Lipphardt, Chr. Tamm, E. Peik, Phys. Rev. Lett. (in print)

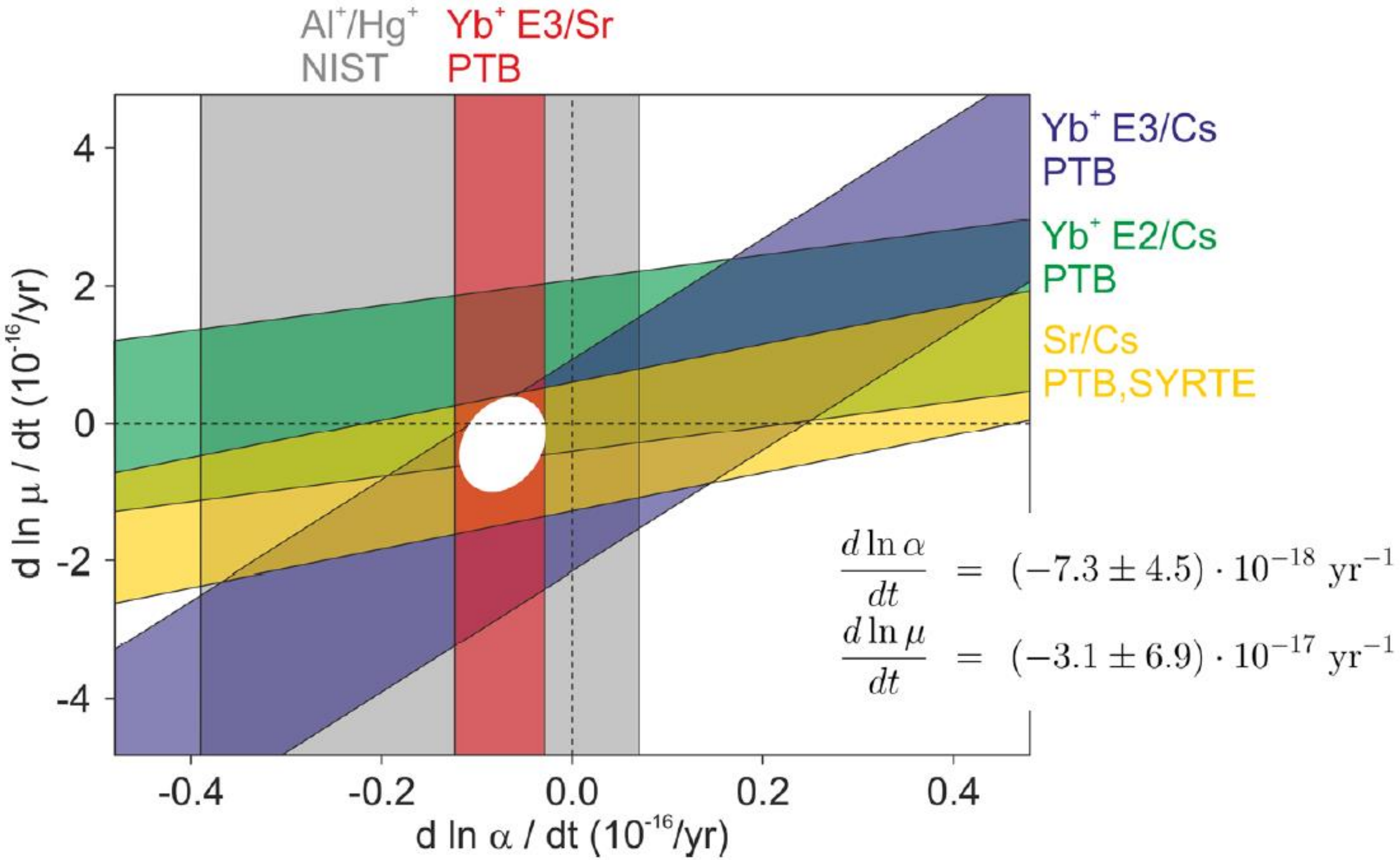
- Consistent with constancy of constants (in the present epoch)
- Most stringent laboratory limit on dμ/dt

Earlier versions:
R.M. Godun et al. (NPL), PRL **113**, 210801 (2014)
N. Huntemann et al. (PTB), PRL **113**, 210802 (2014)

Frequency ratio Yb^+(E3) / Sr



Reduced limits for dα/dt from ν(Yb⁺(E3)) / ν(Sr)



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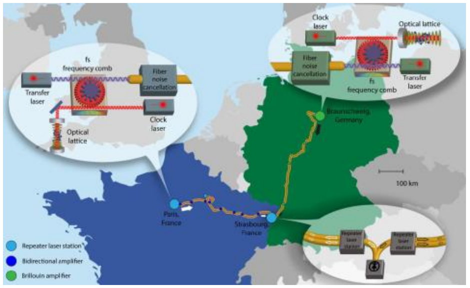
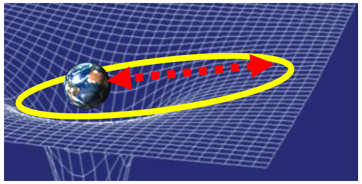
  (novel services)



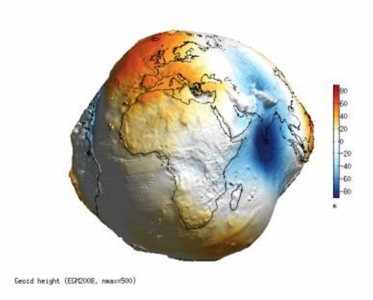
- Test of fundamental theories
  - **Special and general theory of relativity, QED**
  - **Measurement of fundamental constants**
  - **How constant are the fundamental constants?**

  (new science)



- Geodesy / Earth Science
  - **Earth's gravitational potential determination**

  (new products e.g. improved WGS)

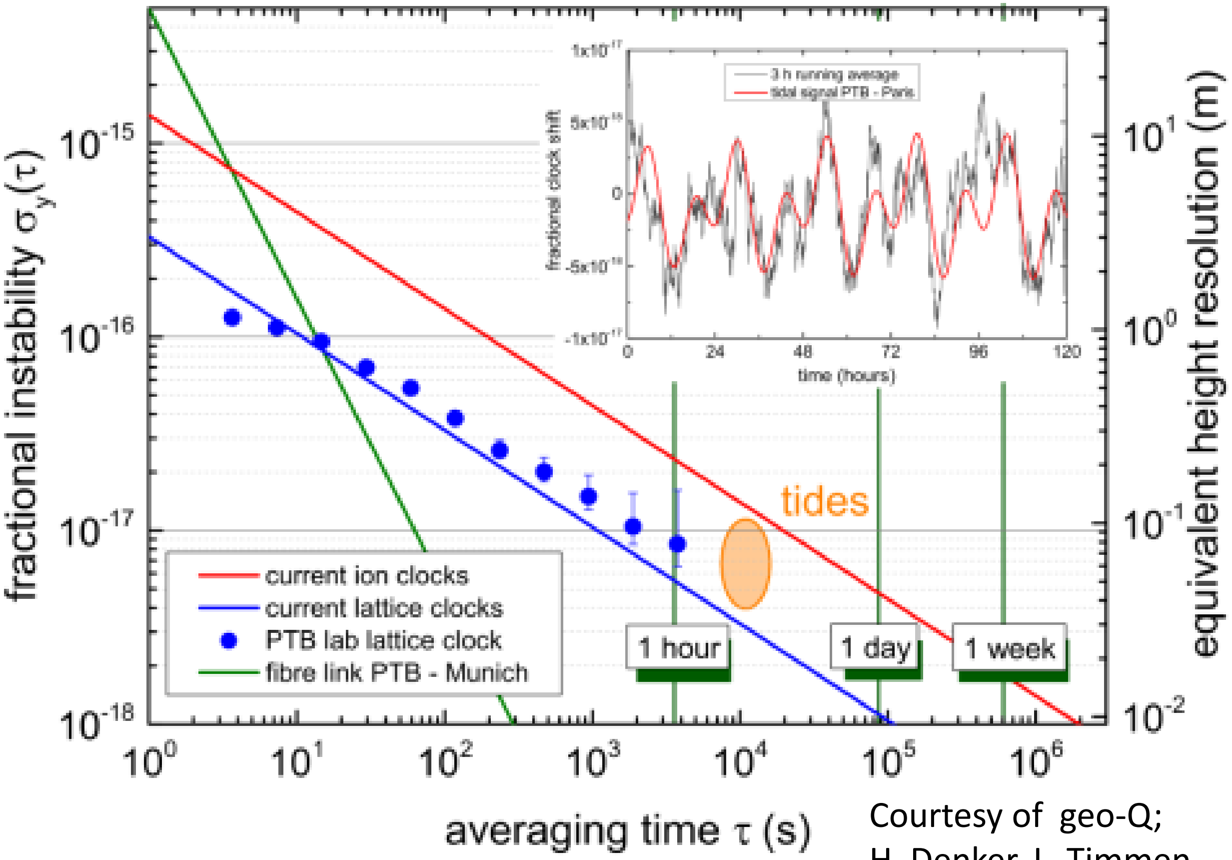


Prospects for a Relativistic Geodesy

- Chronometric levelling <10 cm resolution (PTB/Paris)
- Contributions of dynamic tides in the signal
- Improvement of geodetic modelling

Red shift on ground :

$$\frac{\Delta \nu}{\nu} \approx 10^{-16} \frac{\Delta h}{\mathrm{m}}$$



Courtesy of geo-Q;
H. Denker, L. Timmen

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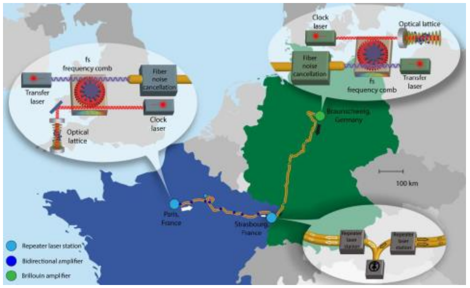
    (novel services)



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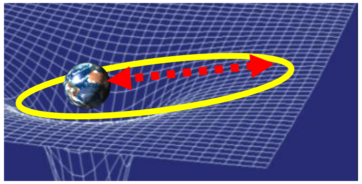
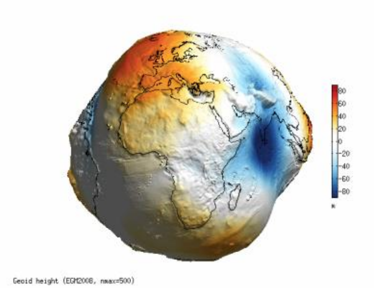


- Geodesy / Earth Science
  - Earth's gravitational potential determination
    (new products e.g. improved WGS)



- Astronomy / Space
  - Ultra precise tracking of space crafts
  - Better reference system for VLBI

    (next generation of space clocks; future market)

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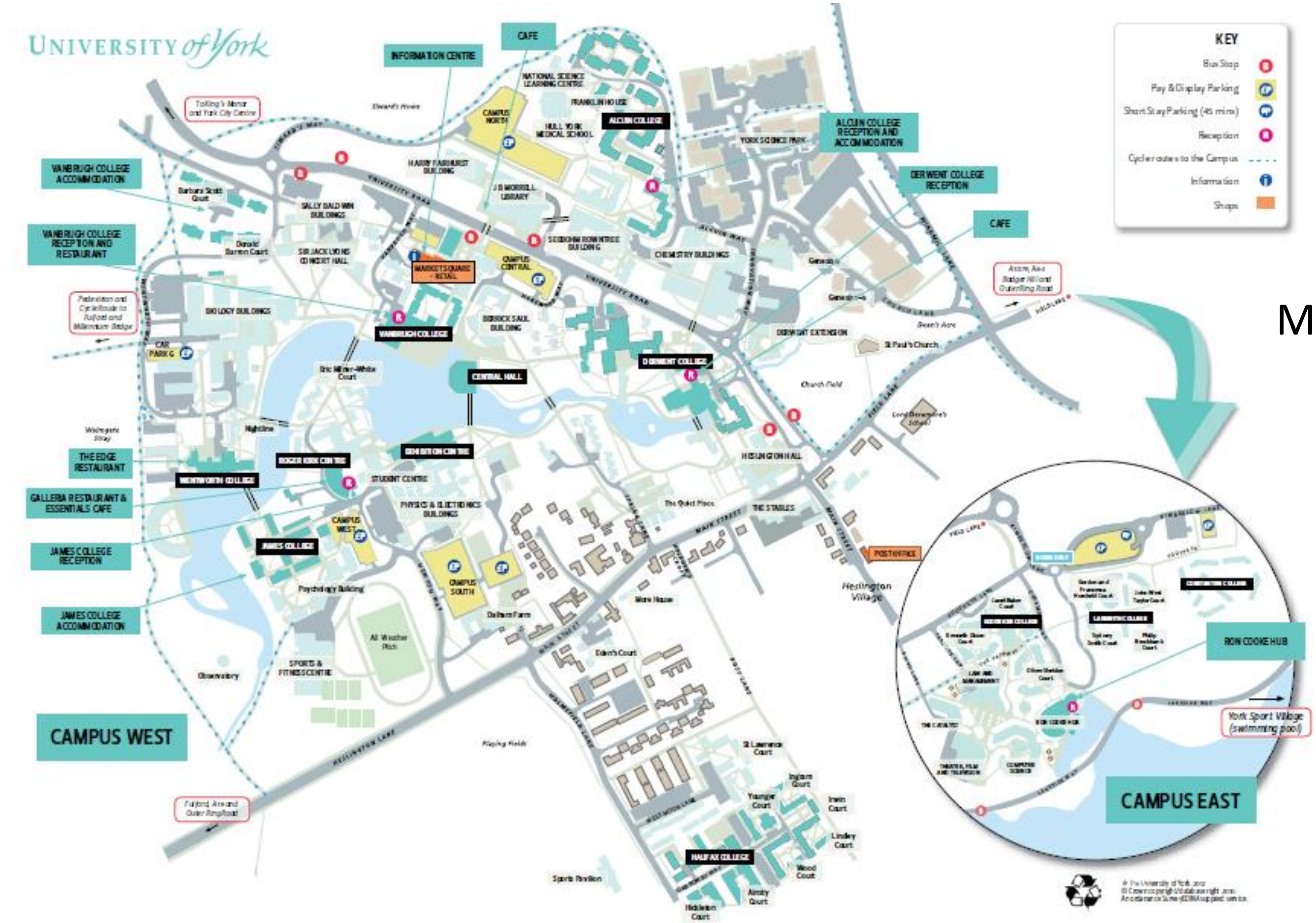
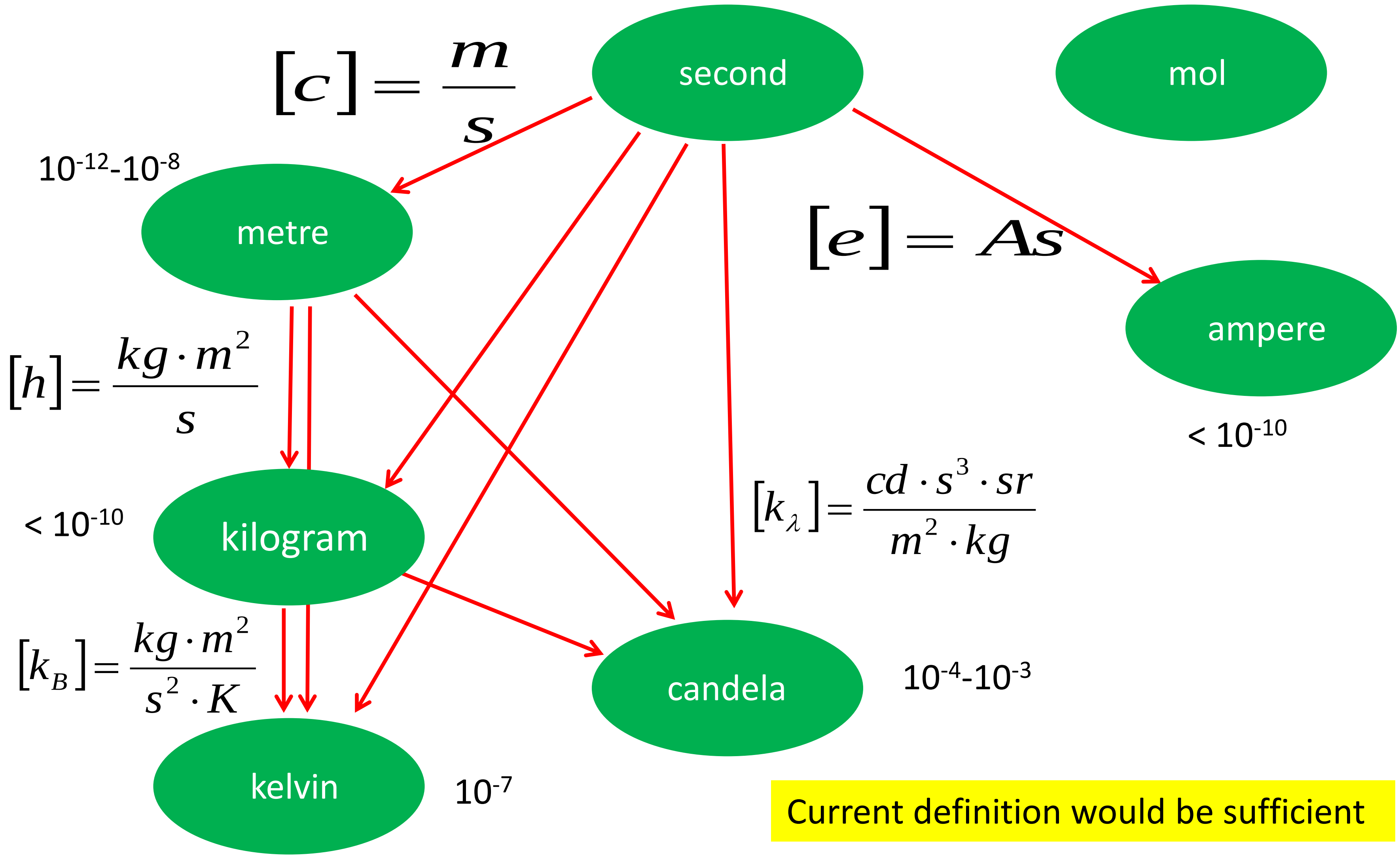
Towards a Roadmap for a New Definition

WG on Strategic Planning of the CCTF is preparing a roadmap



Milestones are needed

Will the new SI Need a Re-definition of the Second?



Current definition would be sufficient

On the Way to a New Definition – When?

- Cs definition serves for some time industry's needs

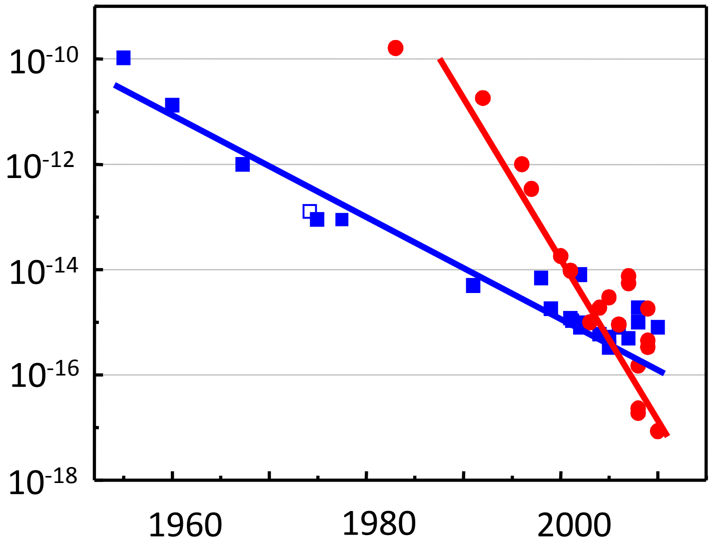
- Secondary Representations serve Science's needs

- There is currently no definite argument for decision between atom and ion

  - Work has to continue for a consensus

- Time will be right when

  - Progress with optical standards slows down
  - Transfer problem will be solved



Possible Milestones Towards a New Definition

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. $\Delta\nu/\nu < 5 \times 10^{-18}$)
  (To allow closures and links between the different optical standards)

Possible Roadmap

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

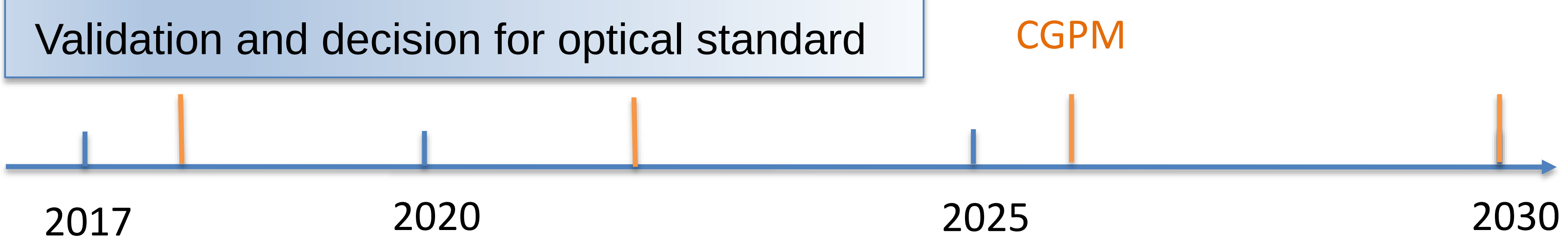
3 comparisons
$\Delta(\nu_i/\nu_j) < 5 \times 10^{-18}$

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

Regular contribut. to TAI

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

Validation and decision for optical standard



After a New Definition …

- Cs will be a secondary standard with the same well defined frequency as before (9 192 631 770 Hz)
- No change will be necessary for the established system of TAI, circular T, … at no additional cost
- If the Cs standards will be further developed to realize the unperturbed line center with smaller uncertainty, new measurement will lead to a new Cs frequency possibly deviating from 9 192 631 770 Hz
- More and more optical clocks are expected to contribute to TAI, Circular T, leading to a more stable time system
- Improvements of clock comparisons (either by TWSTF, fiber links, transportable clocks, …) will directly lead to improvements of the time scales.

Conclusion

At present no negative effects of a new definition of the second are seen.

No additional cost will be necessary to keep the status quo.

But the limitations of the current microwave technology need no longer limit the development of better time scales.

The new definition of the second should take place

as early as possible

as late as necessary.

Thanks to the People Who Did the Work at PTB

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Sr standard
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