Systèmes de Référence Temps-Espace

SYRTE

Progress in optical clocks
Optical clocks at SYRTE

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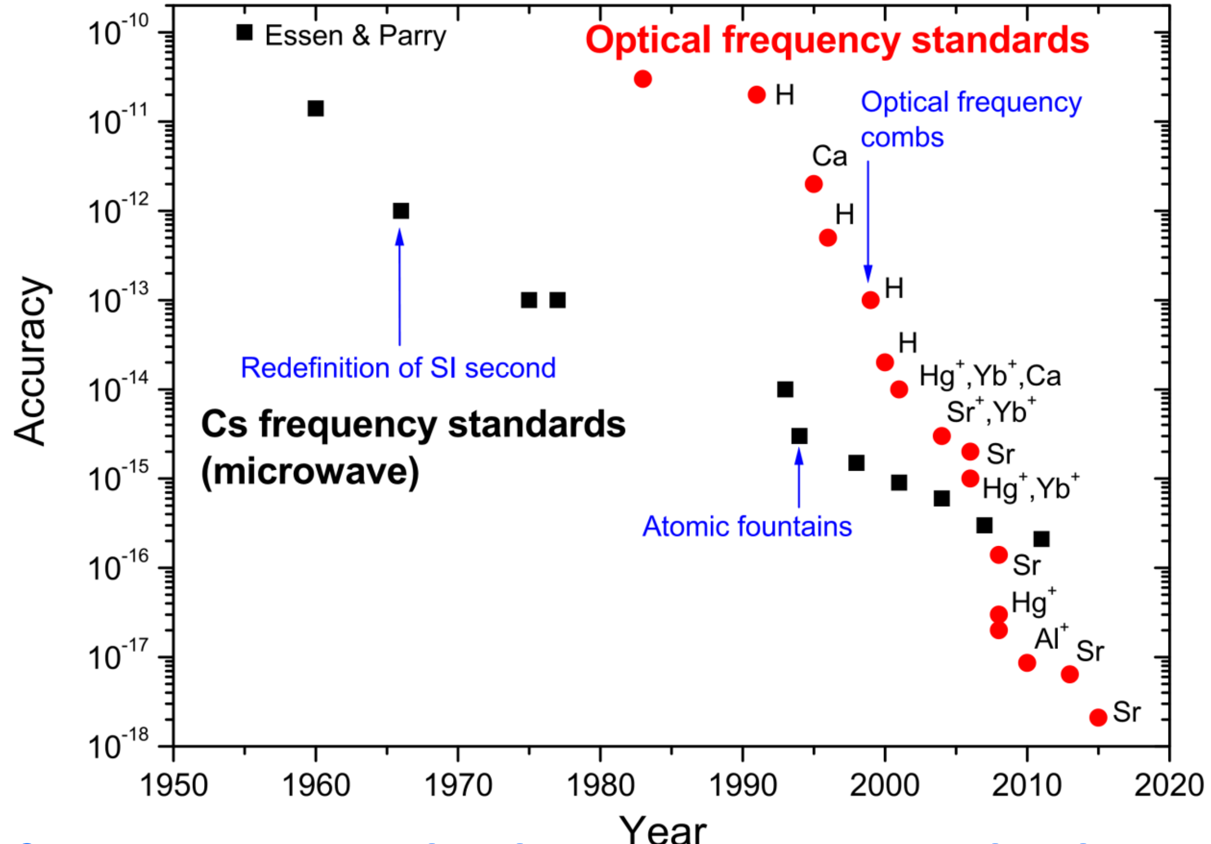
IAG Workshop on Relativistic Geodesy
October 10th 2018
BIPM, Sèvres, France

Progress of frequency standards over time

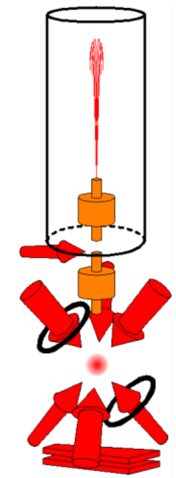


- **Optical frequency standards surpass Cs standards**
  - By up to 2 orders of magnitudes
- **Points toward a redefinition of the SI second**
  - Once readiness of optical frequency standards is proven
- **Status of optical frequency standards**
  - See e.g. Rev. Mod. Phys. 87, 637 (2015)

Optical frequency standards

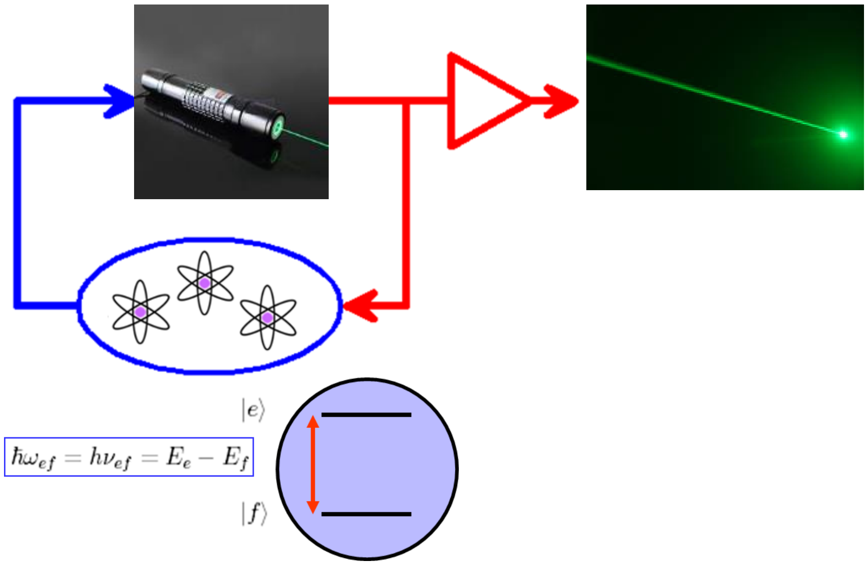
❑ Current primary frequency standards

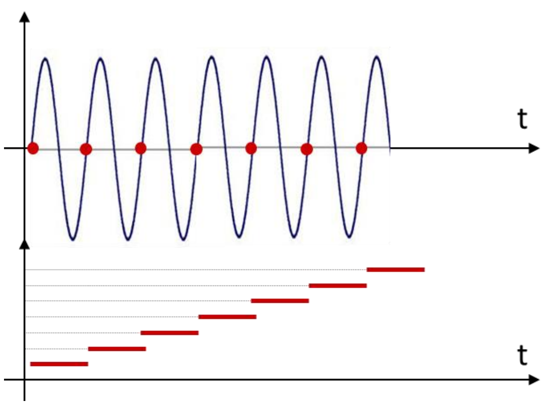
- Cs hyperfine transition in laser-cooled atomic fountains
- Accuracy: 2-3x10^{-16} , stability: <2x10^{-14} at 1s



❑ 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



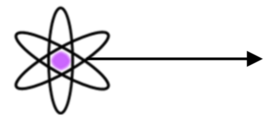


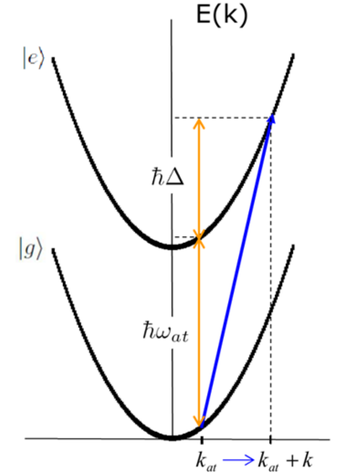
Lamb-Dicke spectroscopy

❑ 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} !

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

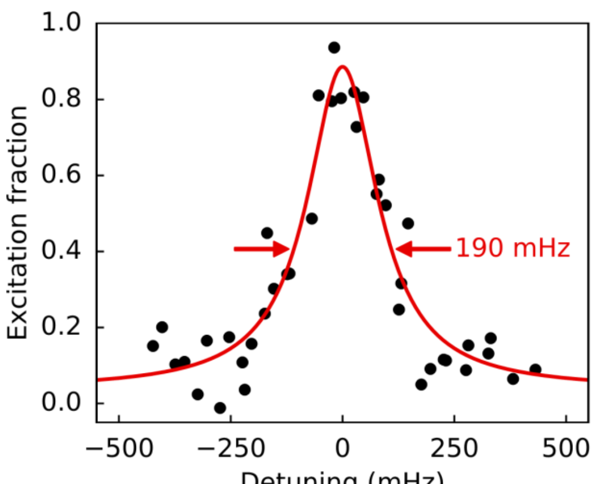




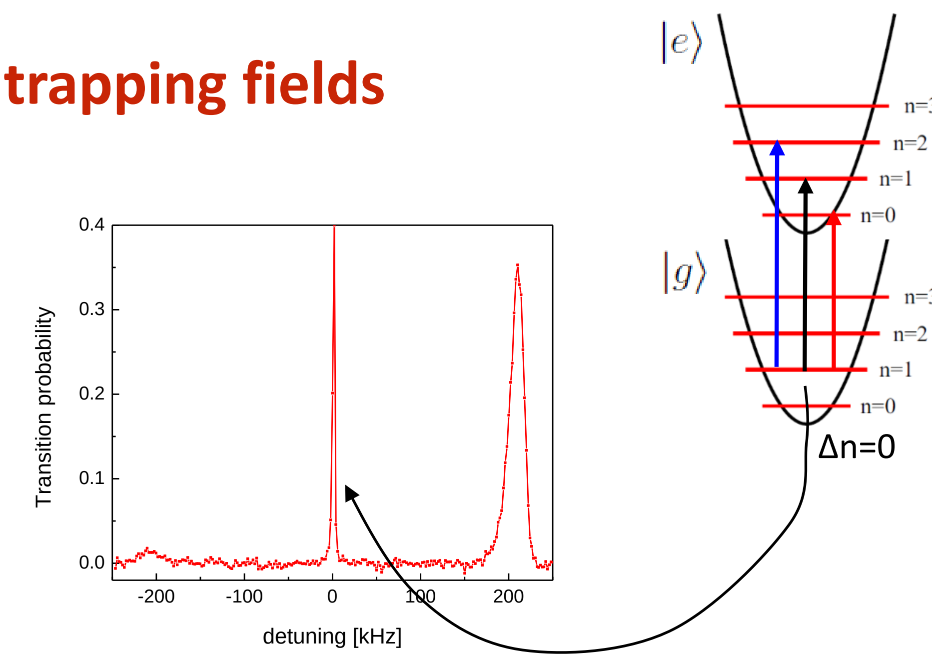
❑ Laser cooling & tight confinement

- 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

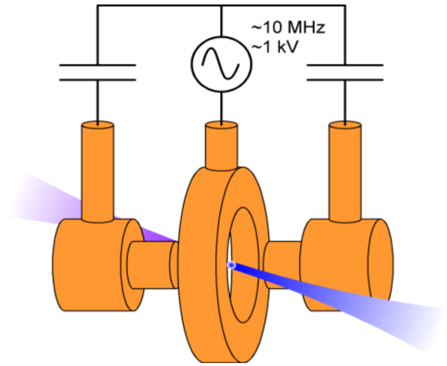


Campbell et al. Science 358, 90 (2017)

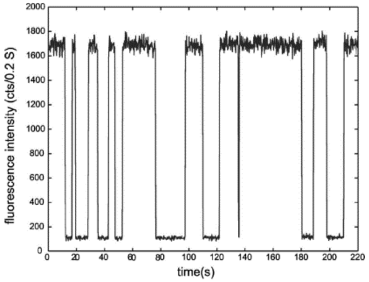


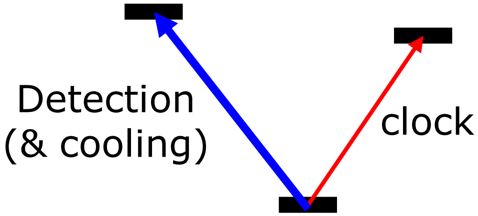
(Single) ion optical clocks

- **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





- **Disadvantage**
  - Low signal-to-noise (quantum projection noise for N=1)
- **Advantage**
  - Ion kept cycle-to-cycle
  - No collision shift

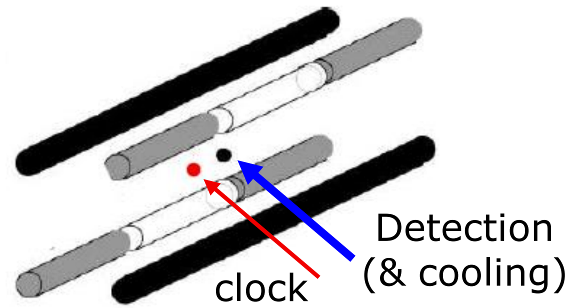
(Single) ion optical clocks

Candidates

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

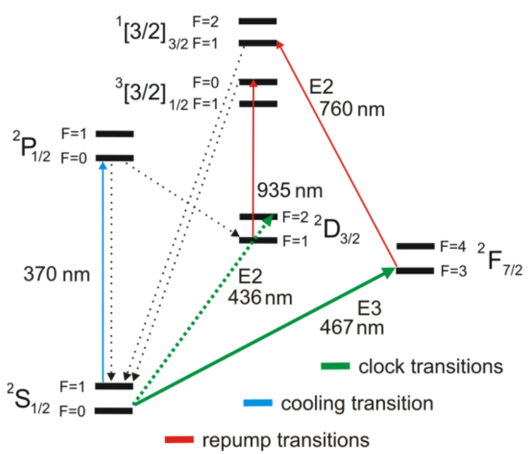
Quantum logic clocks

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



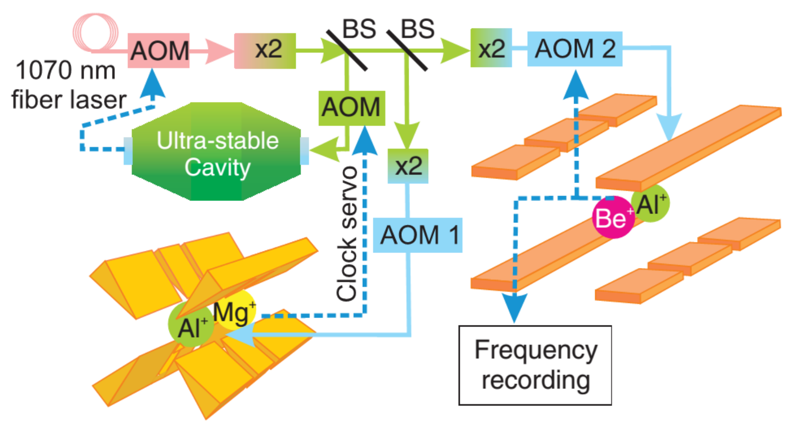
Examples

Yb+(E3) at PTB: 3.2×10^{-18}



Huntemann et al. PRL 116,063001 (2016)

Al+ at NIST: 8.6×10^{-18}

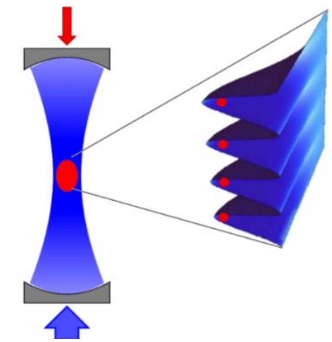


Chou et al. PRL104,070802 (2010)

Optical lattice clocks

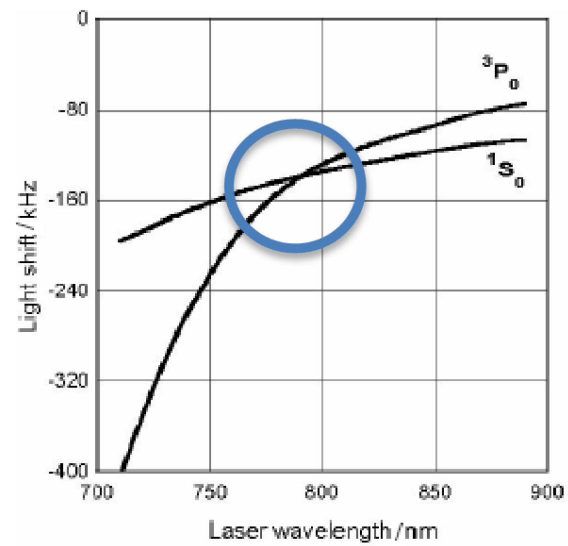
❑ Dipole lattice trap

- By an intense standing-wave laser field



❑ Mitigation of trapping effects

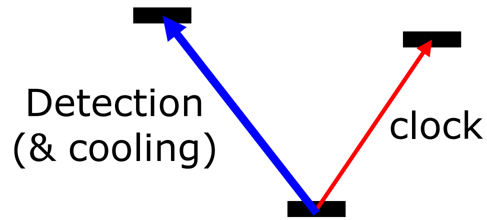
- Laser cooling
- Lattice trap at magic wavelength



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

❑ Detection

- Fluorescence



❑ 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)

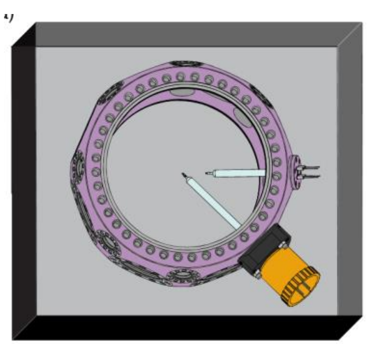
Optical lattice clocks

❑ Candidates

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

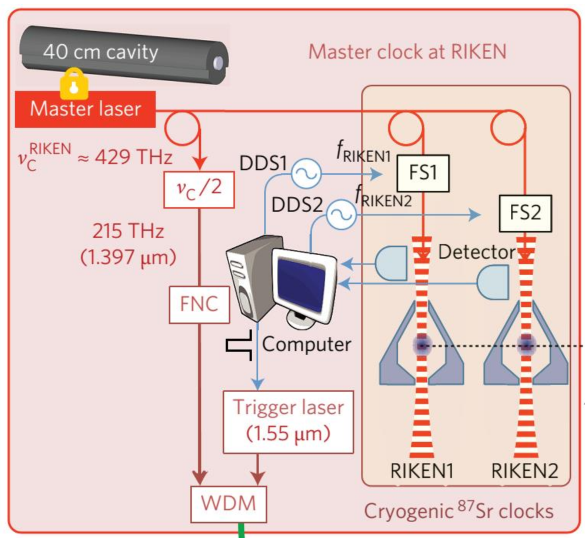
❑ Examples

Sr at JILA: 2.1×10^{-18}



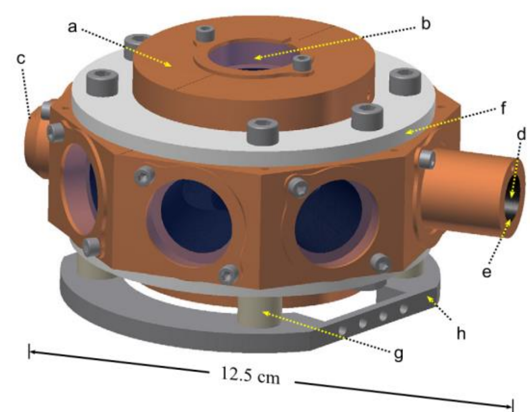
Nicholson et al., Nat. Com. 6, 6896 (2015)

Sr at UT/RIKEN: 4.8×10^{-18}



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

Yb at NIST: 1.4×10^{-18}



Beloy at al. EFTF 2018
PRL120, 183201 (2018)
PRL 119, 253001 (2017)

Assessing optical frequency standards

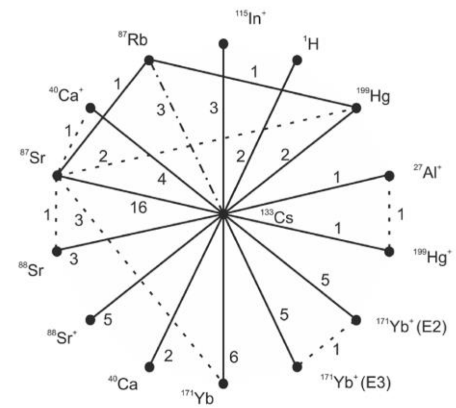
SYRTE

❑ Same frequency standard comparisons

- Chou et al., Al+ (2010), Le Targat et al. Sr (2013), Bloom et al., Sr (2013), Ushijima et al., Sr (2015), Beloy et al., Yb (EFTF 2018)
- Now down to the low 10^{-18}

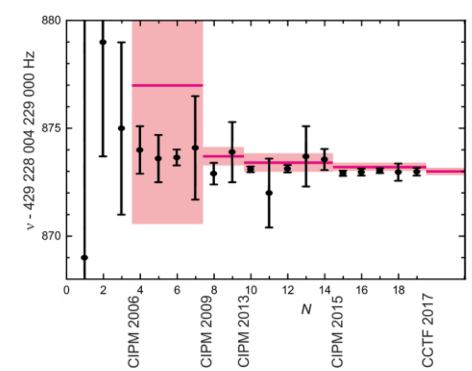
❑ Frequency ratios

- 13 optical transitions against Cs to $<10^{-14}$.
- 7 optical-to-optical ratios
  - Down to 4.6×10^{-17}
  - Sr/Yb & Sr/Hg measured in at least 2 places



❑ Monitored by CCTF & CCL

- CIPM CCL-CCTF WG FS
- In the view of a redefinition of the SI second
- →F. Riehle et al., Metrologia 55, 188 (2018)
- →BIPM website

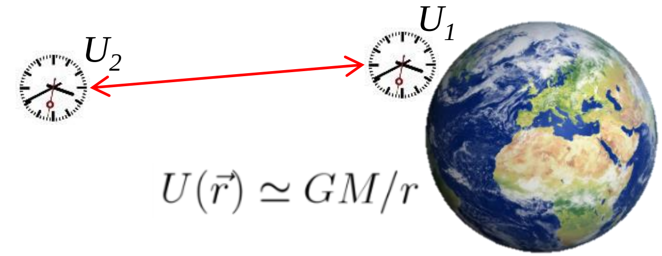


Ratio	Value	Fractional uncertainty	Reference
88Sr/87Sr	1,0000001448836827727	2.30E-17	Takamoto2017
Hg/Sr	2,62931420989890915	1.80E-16	Tyumenev2016
Hg/Sr	2,62931420989890960	8.40E-17	Yamanaka2015
Yb/Sr	1,207507039343337749	4.60E-17	Nemitz2016
Yb/Sr	1,20750703934333776	2.40E-16	Takamoto2015
Yb/Sr	1,2075070393433412	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

Chronometric geodesy: clocks for Earth science

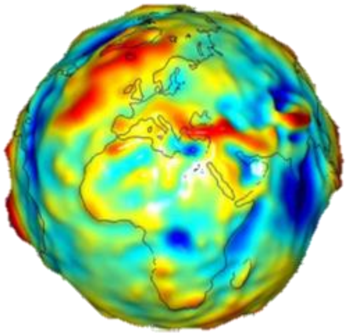
- Einstein's gravitational redshift

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

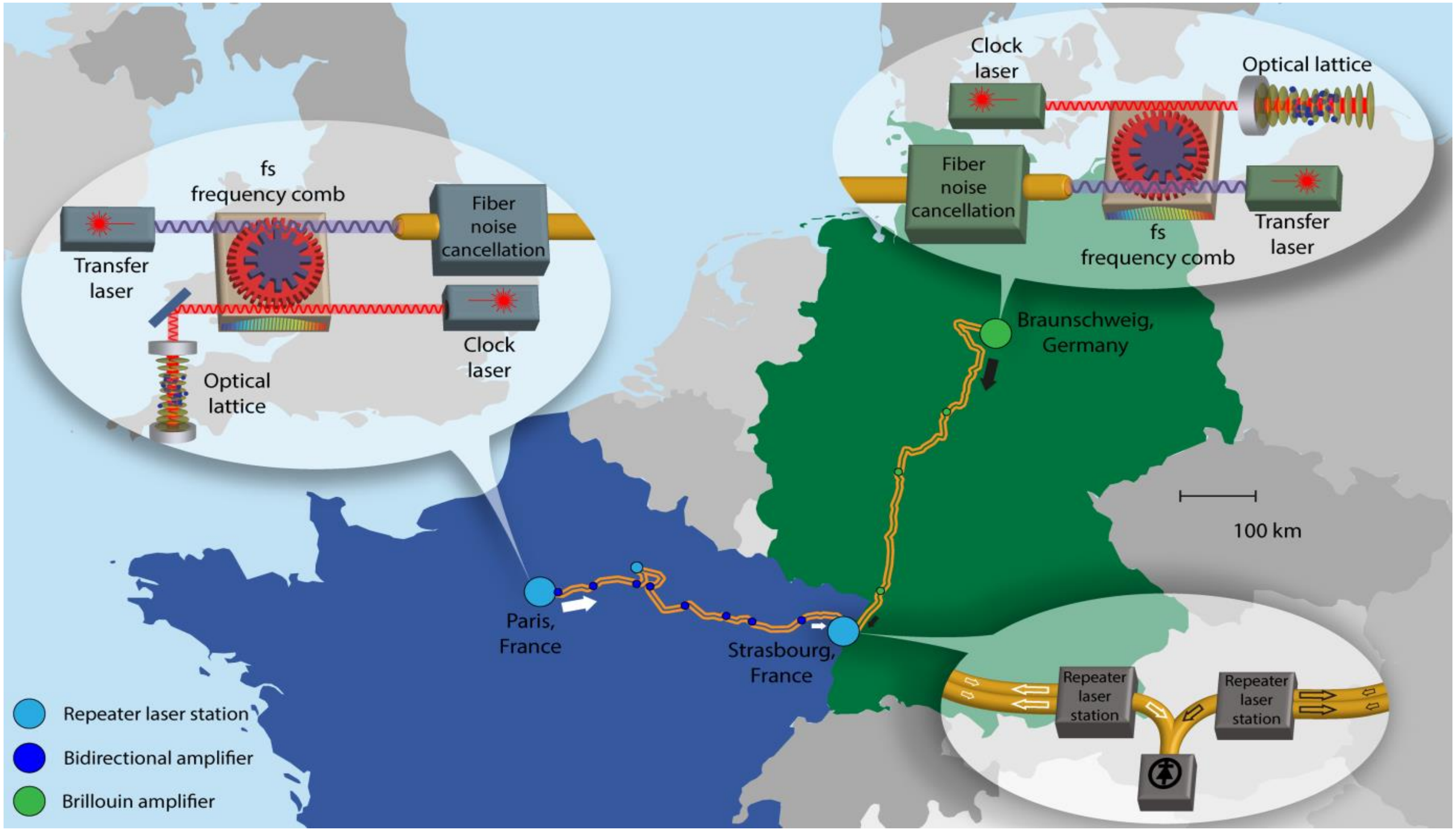


- The idea of "chronometric geodesy"
  - Remote clock comparisons to determine gravity potential differences
  - Sensitivity: 10^{-18} ⇔ 1 cm in height
  - Long-range sensitivity to source masses: $U(\vec{r}) \propto 1/r$

- What role for clocks in Earth Science?
  - Improve references: global/local geoid models, height of tide gauges, etc.
  - Sense geophysical phenomena

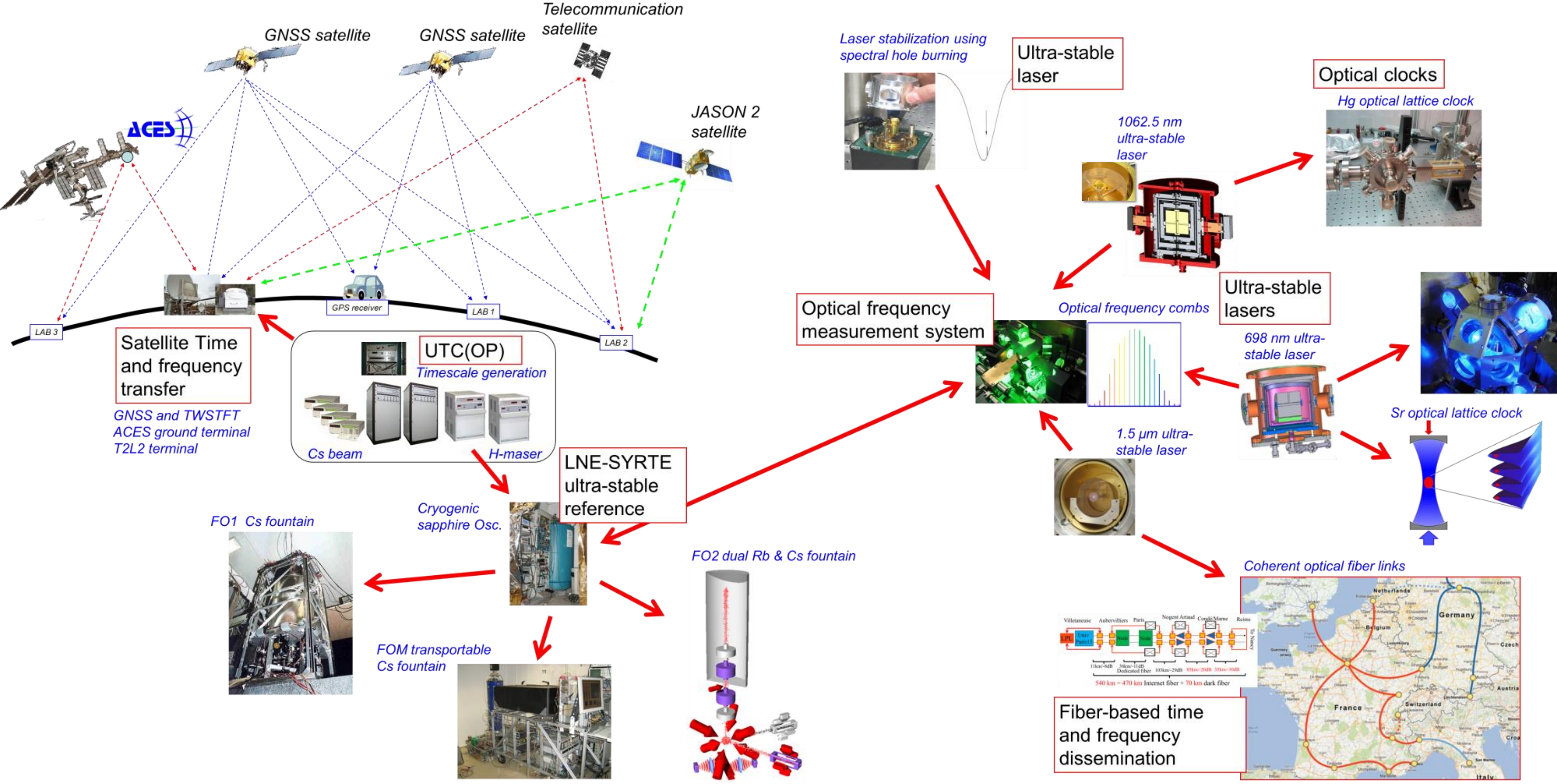


Optical clock comparisons



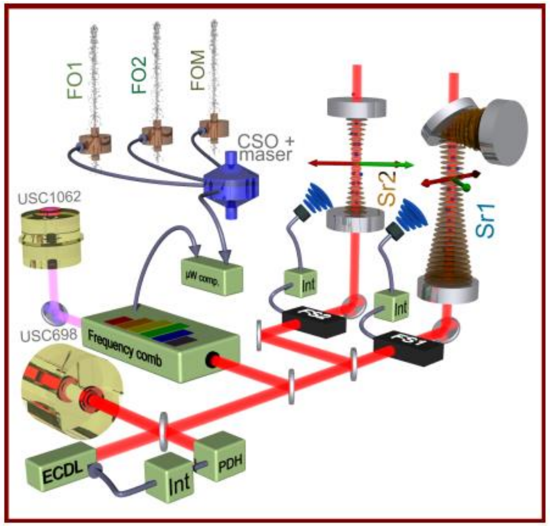
► An international comparison over continental distance: 1440 km

Optical clock developements at SYRTE

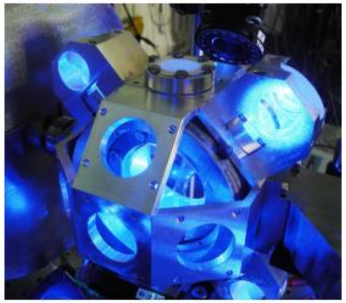


Strontium lattice clocks at SYRTE

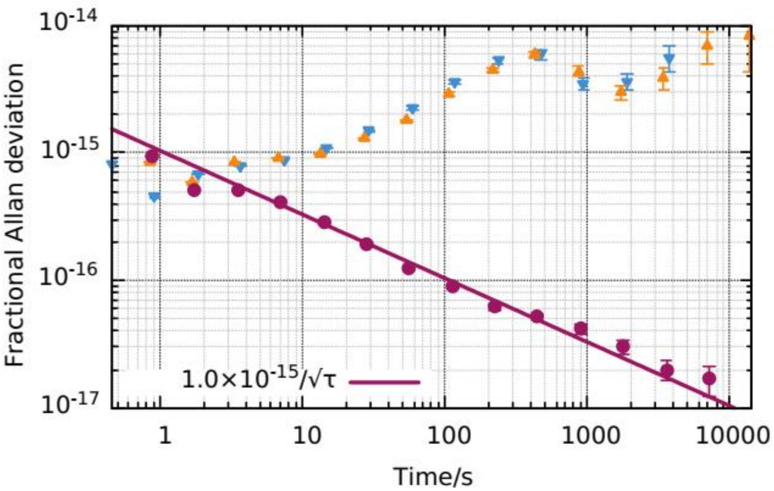
Sr1



Sr2



Stability



Accuracy (in 10^{-18})

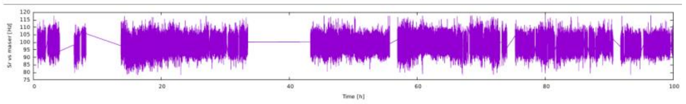
Effect	Uncertainty in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Lattice spectrum	1
Density shift	8
Line pulling	6
Background collisions	4
Static charges	1.5
Total	**17** $\times 10^{-18}$

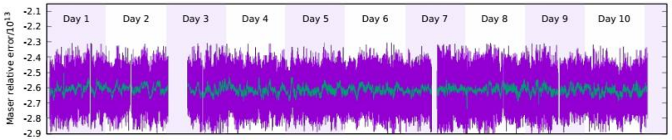
- **Recent studies**
  - Phase perturbations
  - Background gas collisions

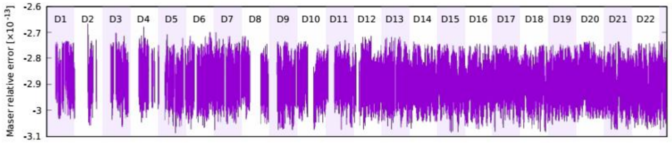
Strontium lattice clocks at SYRTE

SYRTE

- First agreement between two OLCs with an uncertainty beyond the accuracy of microwave clocks
- Record absolute frequency measurement by comparing with Cs and Rb microwave fountains
- Continuous operation of two Sr clocks over periods up to 3 weeks
- Optical to optical clocks comparison with a Hg OLC
- First international comparison between optical clocks $\longrightarrow$ all optical comparison with phase compensated fibre links
- Bounds on tests of Local Lorentz Invariance with remote clock comparisons (with LPL, PTB and NPL)
- First contribution to TAI with optical clocks







3 - Duration of the TAI scale interval d.

Table 1: Estimate of d by individual PSFS measurements and corresponding uncertainties.
All values are expressed in 10**-15 and are valid only for the stated period of estimation.

Standard	Period of Estimation	d	uA	uB	ul/Lab	ul/Tai	u	uSrep	Ref(uS)	Ref(uB)	uB(Ref)	Steer	Note
PTB-CS1	57784 57809	-18.71	6.00	8.00	0.00	0.15	10.00	PFS/NA		T148	8.	Y	(1)
PTB-CS2	57784 57809	-0.28	3.00	12.00	0.00	0.15	12.37	PFS/NA		T148	12.	Y	(1)
SYRTE-FO2	57784 57809	-1.30	0.40	0.32	0.11	0.32	0.61	PFS/NA		T301	0.23	Y	(2)
SYRTE-FORb	57784 57809	-0.91	0.20	0.29	0.11	0.32	0.49	0.7	[1]	T328	0.34	Y	(2)
SYRTE-SR2	56954 56964	0.81	0.20	0.04	0.10	0.53	0.57	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57179 57199	0.46	0.20	0.04	0.10	0.28	0.36	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57469 57479	-1.39	0.25	0.20	0.11	0.53	0.63	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57539 57554	-1.24	0.30	0.04	0.11	0.37	0.49	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SRB	57539 57554	-1.22	0.25	0.05	0.10	0.37	0.46	0.5	[1]	[2]	0.05	N	(3)
PTB-CSF2	57779 57809	-1.36	0.09	0.20	0.03	0.13	0.26	PFS/NA		T287	0.41	Y	(4)

Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report 03 MAR. 2017 by LNE-SYRTE
(3) Report 16 AUG. 2016 by LNE-SYRTE
(4) Report 02 MAR. 2017 by PTB
[1] CIPM Recommendation 2 (CI-2015) : Updates to the list of standard frequencies in Proces-Verbaux des Seances du Comite International des Poids et Mesures, 104th meeting (2015), 2016, 47 p.
[2] Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock. Lodewyck J., Bilicki S., Bookjans E., Robyr J.L., Shi C., Vallet G., Le Targat R., Nicolodi D., Le Coq Y., Guéna J., Abgrall M., Rosenbusch P. and Bize S.. Metrologia 53(4), 1123, 2016.

Included in Circular T 350 (Feb. 2017) as a non-steering contribution

P. Delva *et al.*, Phys. Rev. Lett. **118**, 221102 (2017)
J. Lodewyck *et al.*, Metrologia **53**, 1123 (2016)
R. Tyumenev *et al.*, New Journal of Physics, **18** 113002 (2016)
C. Lisdat *et al.*, Nat. Comm. **7** 12443 (2016)
R. Le Targat *et al.* Nat. Comm. **4** 2109 (2013)

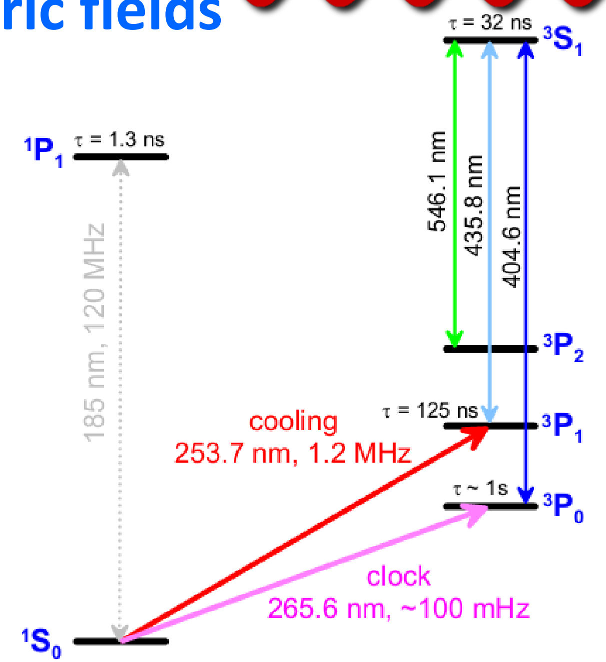
Optical lattice clock with Hg: motivations

- **Low sensitivity to blackbody radiation & electric fields**
  - At 300 K: -1.6×10^{-16} ; -2.1×10^{-18} K^{-1}. Sr/30, Yb/15.
- **7 isotopes, 6 with abundance >6%**
  - 2 fermions (17% & 13%), 5 bosons.
- **^{199}Hg is a fermion with nuclear spin 1/2**
  - Simpler level structure, no tensor light shift.
- **Magic wavelength**
  - Our 2011 measurement: 362.5697±0.0011 nm.
- **High sensitivity of to α variations**

$$\frac{\delta\nu}{\nu} = 0.81\frac{\delta\alpha}{\alpha}$$

*Phys. Rev. A **70**, 014102 (2004)*

- **High vapor pressure**
  - No oven, 2D-MOT possible.
- **Unexplored in the laser-cooled regime (2005)**
  - Still mostly the case.
- **Challenges & limits**
  - Need for deep UV lasers.
  - Comparatively high non-linear lattice light shifts (theory).



Hg, Z= 80

Measurements with the Hg optical lattice clock

❑ Uncertainty

- Limited by statistics
- Lattice light shift

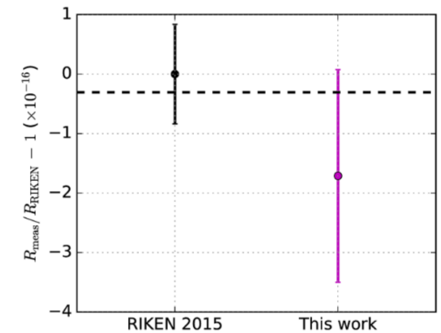
Effect	Correction	Uncertainty
2nd-order Zeeman	8.2	4.8
Atom density	5.2	6.4
Background gas	0	2
Lattice light shift linear	-4	13.8
Lattice light shift non-linear	6	4
Blackbody radiation	16.1	2.2
Probe light shift	0	0.1
AOM chirp	0.2	0.4
Total	31.7	16.7

in units of 10^{-17}

❑ Measurements

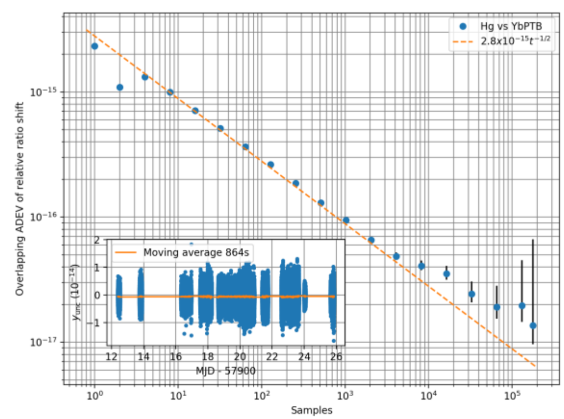
- State-of-the-art measurements against microwave standards (Cs & Rb)
- Hg/Sr optical-to-optical frequency ratio to 1.7×10^{-16}
- One of the very few measured independently in 2 places

  see Yamanaka et al., PRL 114, 230801 (2015)
- ^{199}Hg is a secondary representation of the second (2017)



❑ 2017 fiber link campaign

- Hg vs Yb+(E3) PTB: stability down to 2×10^{-17}

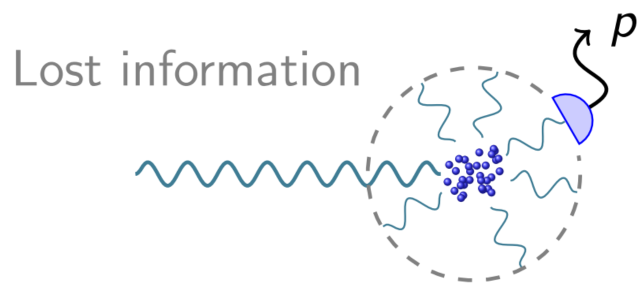


Non-destructive atomic detection

SYRTE

❑ Destruction of the atomic sample in conventional detection

- Atoms are scattered and lost
- Time spent making a new sample

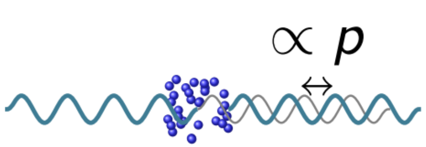


❑ Benefits of non-destructive detection

- Classical non-destructivity: Clock dead time reduced, probe time beyond probe laser coherence time
- Quantum non-destructivity: quantum state preserved after detection, creation of spin-squeezed atomic states, detection beyond the quantum projection noise limit

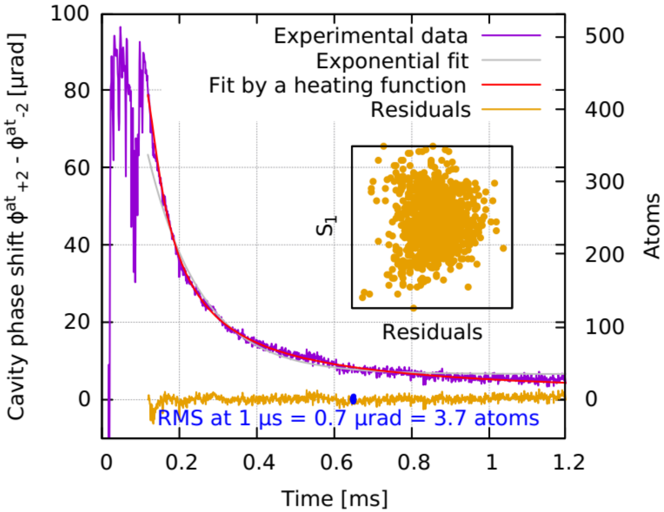
❑ Principle

- Dispersive phase shift induced by the atomic sample on detection light



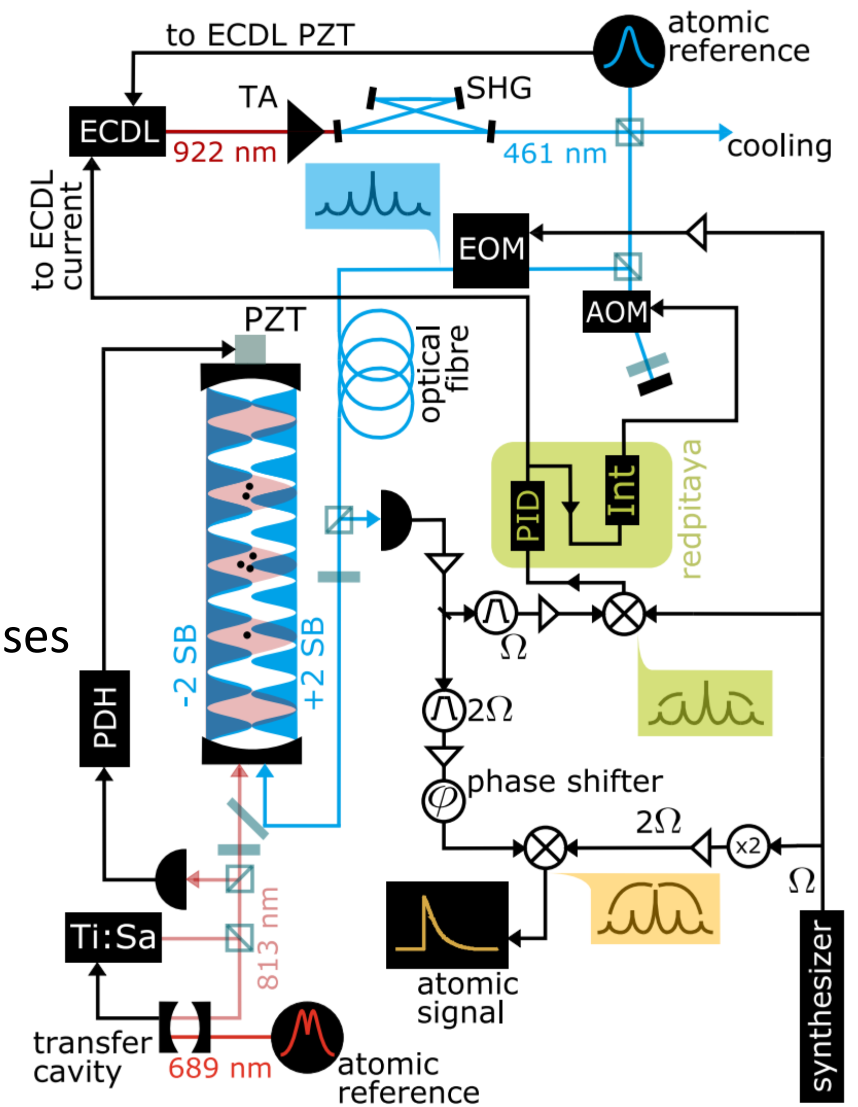
- Phase shift $\Rightarrow$ low power probe beam
- SNR fundamentally limited by the light shot noise

Non-destructive detection in a Sr lattice clock



J. Lodewyck *et al.* Phys. Rev. A **79** 061401(R) (2009)

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



❑ Last implementation

- Auto aligned dichroic FP cavity
- Finesse: 16000 at 461 nm
- Heterodyne scheme immune to tec. noises

Detection noise δN

- $\delta N = 23$ atoms$/\sqrt{n_\gamma}$
- Classical non-destructive regime
  ($n_\gamma < 40$ photons)
  $\Rightarrow$ high resolution: $\delta N < 3.7$
- Quantum non-destructive regime
  ($n_\gamma < 1$ photon)
  $\delta N > 23$ atoms