Systèmes de Référence Temps-Espace

Atomic Clocks and Frequency Metrology

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Workshop on the 229m Thorium Nuclear Isomer Clock
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GSI, Darmstadt, Germany

Outline

- Atomic clocks
  - μW clocks (fountains)
  - Optical clocks
- Applications of clocks
  - Atomic physics, fundamental physics,…
  - SI second, international atomic time (TAI)
  - Frequency and time transfer methods
- Metrology in curved space-time
  - General relativity, gravitational redshift
  - Impact on clock comparisons: present and future
- Other examples
  - Ion clocks
  - Lattice clocks
  - Ultra-stable lasers

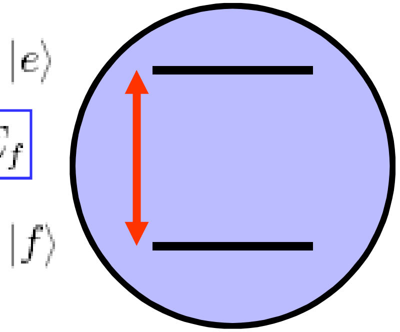
Atomic clocks

Principle of atomic clocks

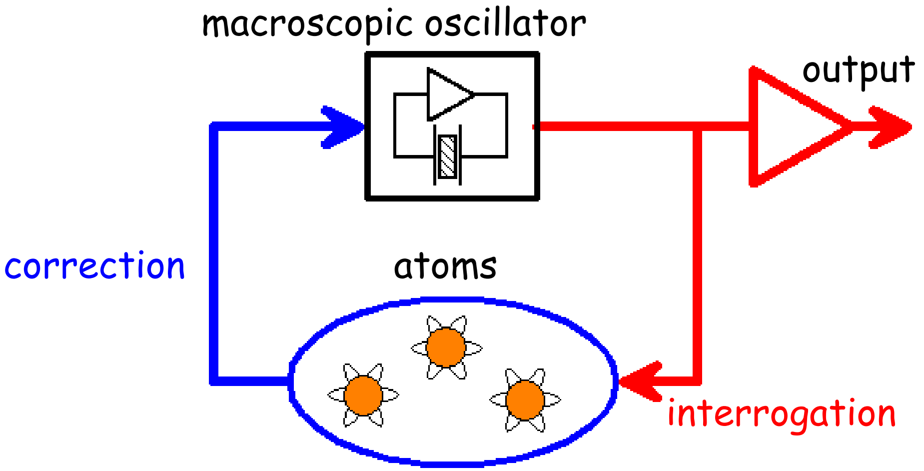
Goal: deliver a signal with stable and universal frequency

Bohr frequencies of unperturbed atoms are expected to be stable and universal

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



Building blocks of an atomic clock



$$\omega(t) = \omega_{ef} \times (1 + \varepsilon + y(t))$$

ε : fractional frequency offset

Accuracy: overall uncertainty on ε

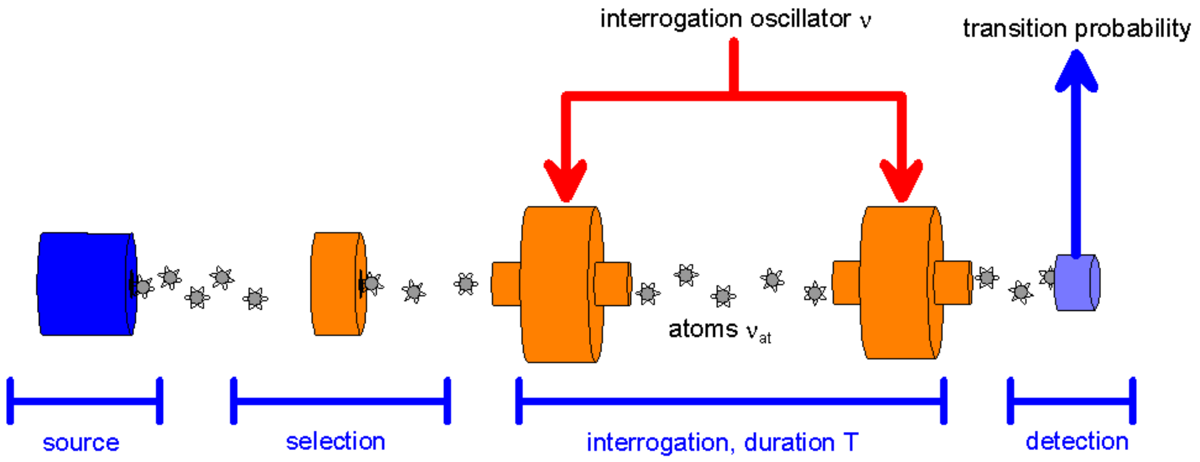
$y(t)$: fractional frequency fluctuations

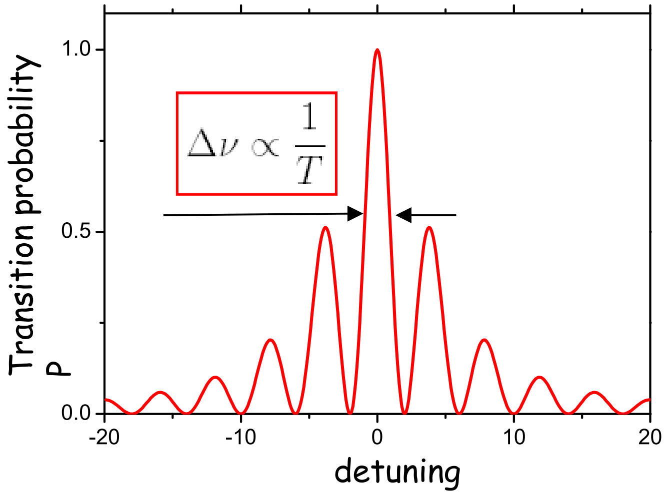
Stability: statistical properties of $y(t)$, characterized by the Allan variance $\sigma_y^2(\tau)$

Can be done with microwave or optical frequencies, with neutral atoms, ions or molecules

Principle of atomic clocks (2)

How to probe the atomic transition:





The two main parameters:

the atomic quality factor $\boxed{Q_{at} = \frac{\nu_{ef}}{\Delta\nu} \propto \nu_{ef} T}$

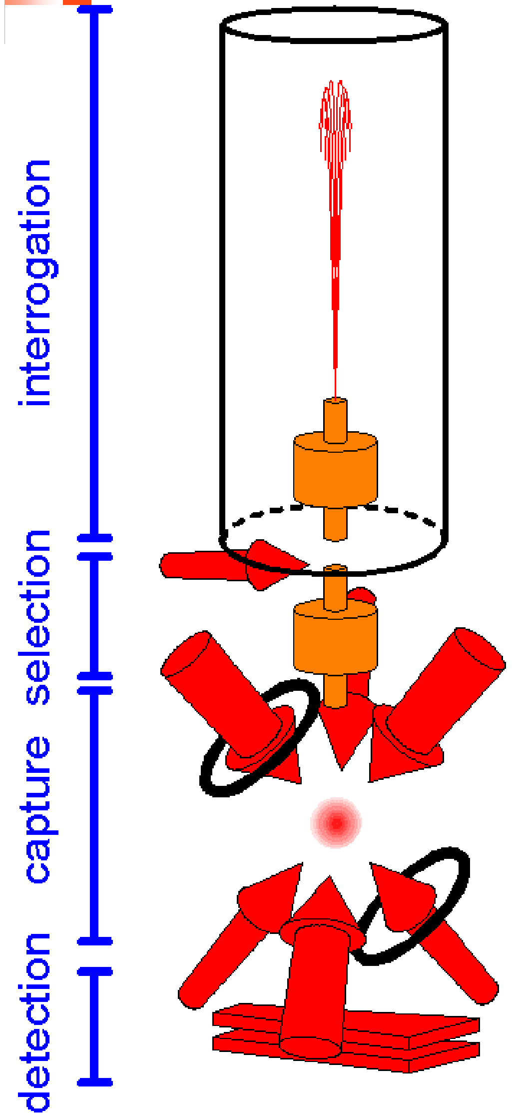
fluctuations of the measured transition probability for integration time T_c: $\boxed{\sigma_{\delta P}}$

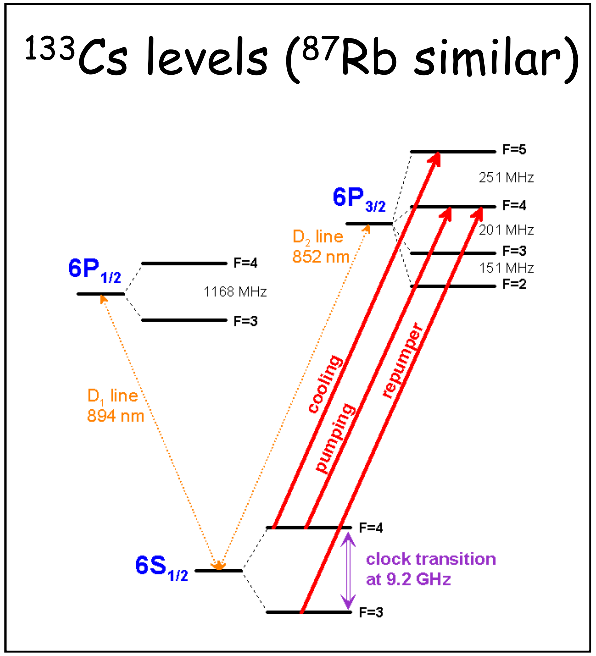
Scaling of the fractional frequency instability: $\boxed{\sigma_y(\tau) \propto \frac{\sigma_{\delta P}}{Q_{at}} \sqrt{\frac{T_c}{\tau}}}$

Example: optimized Ramsey interrogation $\sigma_y(\tau) = \frac{2}{\pi} \frac{\sigma_{\delta P}}{Q_{at}} \times \sqrt{\frac{T_c}{\tau}}.$

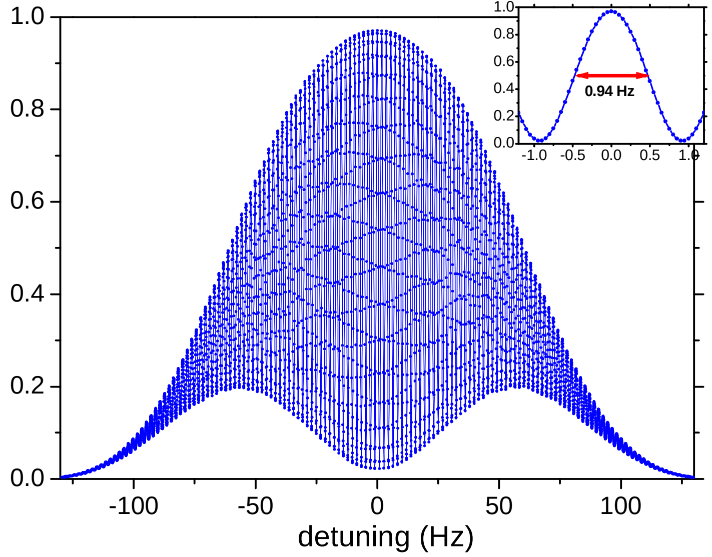
Atomic fountain clocks

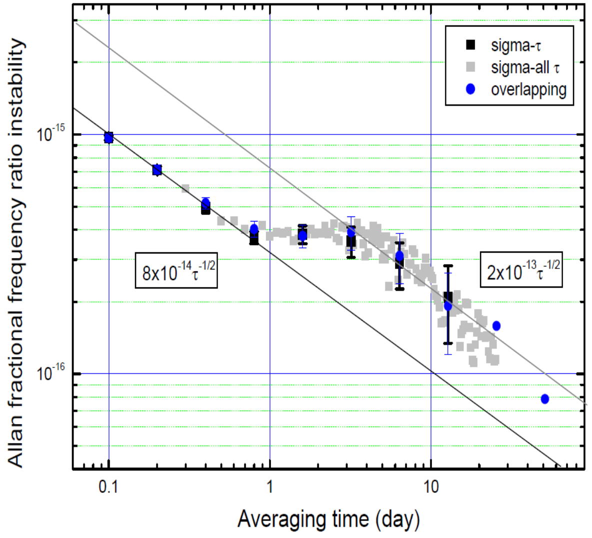
J. Guéna et al., IEEE TUFFC 59, 391 (2012)




^{133}Cs levels (^{87}Rb similar)

Ramsey fringes





Atomic quality factor:

$$Q_{at} = \nu_{ef}/\Delta\nu \simeq 9.8\times 10^{9}$$

Best frequency stability (Quantum Projection Noise limited): 1.6×10^{-14} @1s

Best accuracy: $(2\text{-}3)\times 10^{-16}$

Motivations for developing optical clocks

Quantum limited stability :

$$\boxed{\sigma_y(\tau) = \frac{1}{\pi Q_{at}} \times \frac{1}{\sqrt{N_{det}}} \times \sqrt{\frac{T_c}{\tau}}.}$$

$$\boxed{Q_{at} = \frac{\nu_{ef}}{\Delta\nu} \propto \nu_{ef} T}$$

Microwave transition : ν_{ef} ~ 10 GHz, optical transition : $\nu_{ef}=c/\lambda$ ~10^{14} Hz

Example #1: cycle T_C ~ 1s, linewidth ~1 Hz et $\sigma_{\delta p}$ ~ 10^{-4} :

Microwave : $\sigma_y = 10^{-14}$ @1s

Optical : $\sigma_y = 10^{-18}$ @1s

In practice, best reported stabilities σ_y= 5x10^{16} @1s

Example #2: cycle T_C ~ 1s, linewidth ~1 Hz et N_{det} ~ 1 (1 atom !):

Optical : $\sigma_y = 3\times10^{-15}$ @1s

➔Better stability implies better resolution to evaluate systematic shifts
➔Many systematic shifts are much smaller as compared to microwave clocks

➔ 10^{-17} or better is within reach provided a solution is found for the effects of external motion

$$\delta\omega_{Doppler} = \vec{k}.\vec{v} \sim \omega \times \frac{v}{c}$$

$$\boxed{\frac{\delta\omega_{Doppler}}{\omega} \sim \frac{v}{c}}$$

1 mm/s (~ 1 recoil) corresponds to a 3x10^{-12} fractional shift !

Motional effects on confined atoms: Lamb-Dicke regime

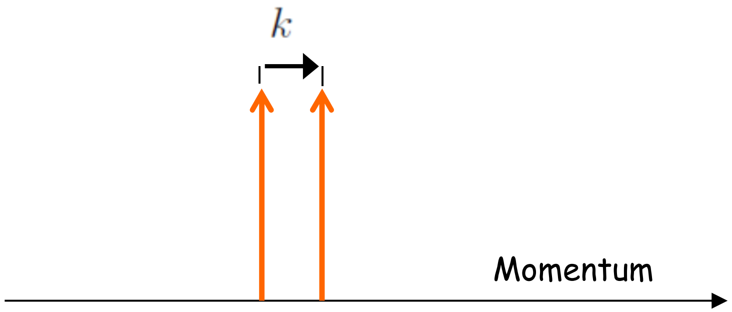
- Consider an atom spatially confined to much less than the wavelength of the incoming photon

$$\Delta x_{at} \ll \frac{\lambda}{4\pi}$$

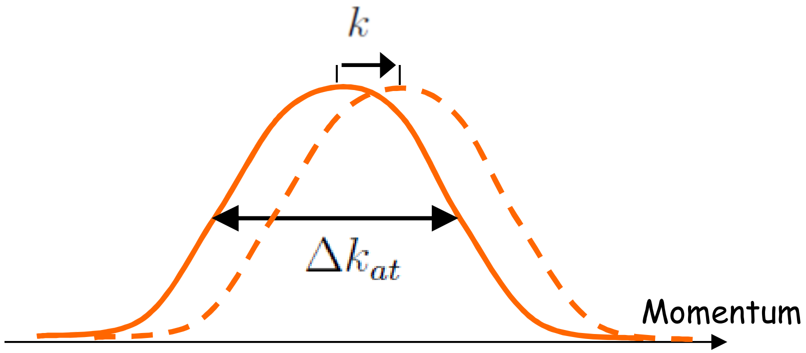
- In momentum space, the atomic wave-function is such that:

$$\Delta p_{at}.\Delta x_{at} > \hbar/2 \quad \text{or} \quad \Delta k_{at}.\Delta x_{at} > 1/2$$

- This implies that: $\Delta k_{at} > \frac{1}{2\Delta x_{at}} \gg \frac{2\pi}{\lambda} = k$ or $\boxed{\Delta k_{at} \gg k}$
  - ☐ ➔ the size of the wave-function in momentum space is large compared to the photon momentum
  - ☐ The shift in momentum space implied by momentum conservation induces a minor modification of the wave-packet
  - ☐ ➔ Small shift of the resonant frequency when the energy conservation is applied



Free space



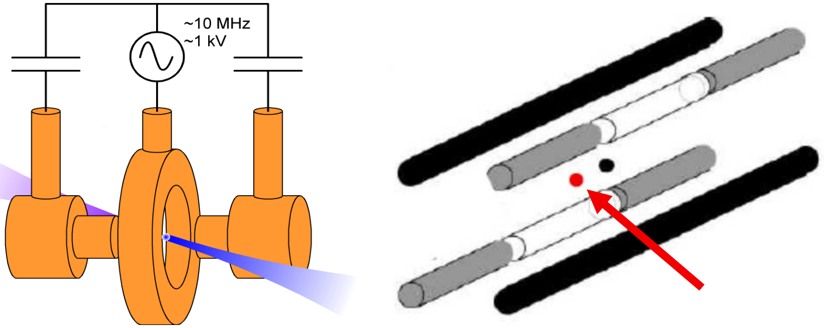
Lamb-Dicke regime

Optical clocks

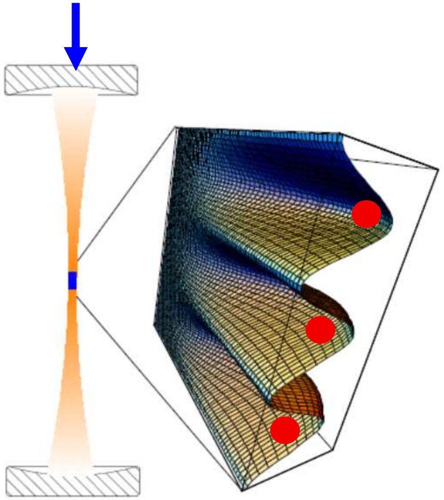
- The clock transition is in the optical domain allowing improved accuracy
- Confinement into the Lamb-Dicke regime is used to dramatically reduce the effects of external motion
  - ☐ Mandatory to gain over μWave clocks:

$$\delta\omega_{Doppler} = \vec{k}.\vec{v} \sim \omega \times \frac{v}{c} \Rightarrow \boxed{\frac{\delta\omega_{Doppler}}{\omega} \sim \frac{v}{c}}$$

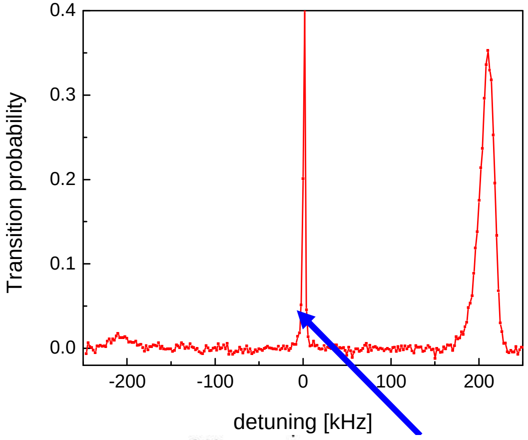
Trapped ion clocks

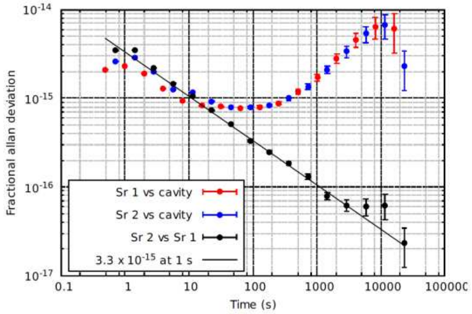


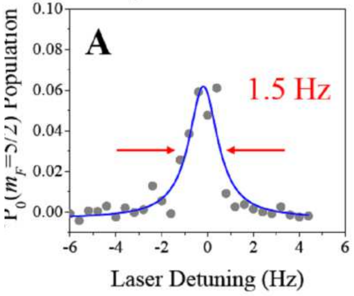
Lattice clocks



Spectroscopy in the Lamb-Dicke regime







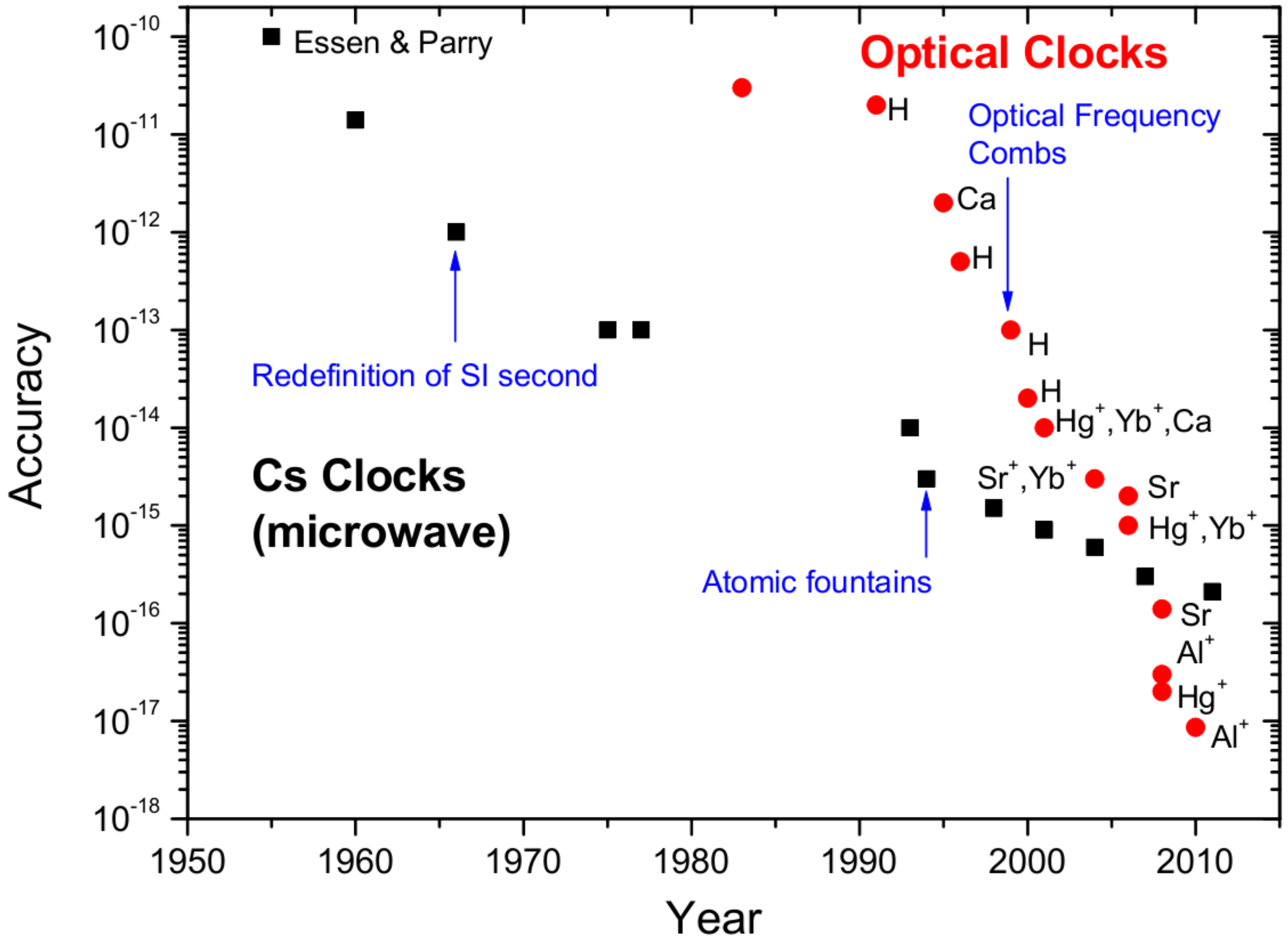
Research in optical clocks

- Best performance to date:
  - Accuracy: Al^+, 8.6×10^{-18} (NIST)
  - Stability: Yb & Sr, $(4\text{-}5) \times 10^{-16}$ @1s (PTB, NIST, JILA)

- Many aspects to this active research field
  - Physics of the clock
  - Use of quantum gates, quantum non-demolition measurements, spin-squeezing
  - Ultra-stable lasers
  - Optical frequency combs
  - Toward transportability and optical space clocks

- Many systems investigated
  - Hg^+, Al^+, Sr^+, Ca^+, Yb^+ (quad., octup.), In^+
  - Sr, Yb, Mg, Hg. Bosons and fermions
  - Nuclear transition in ^{229}Th

Improvement of clock accuracy with time



- Optical clocks are clearly surpassing microwave clocks in terms of accuracy and stability
- Optical clock development is an active, innovative and competitive field

LNE-SYRTE ATOMIC CLOCK ENSEMBLE

l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace

LNE Le progrès, une passion à partager

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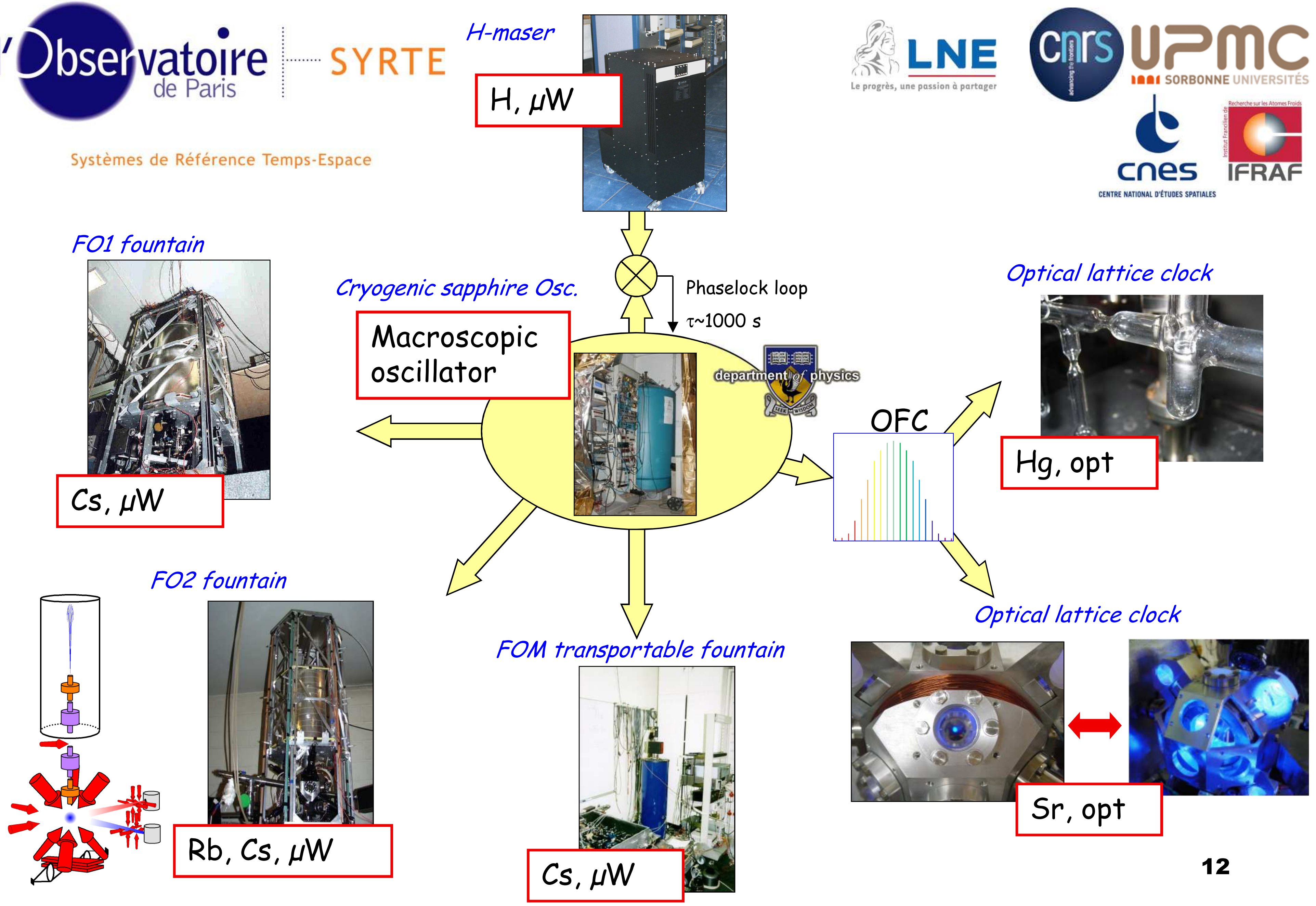
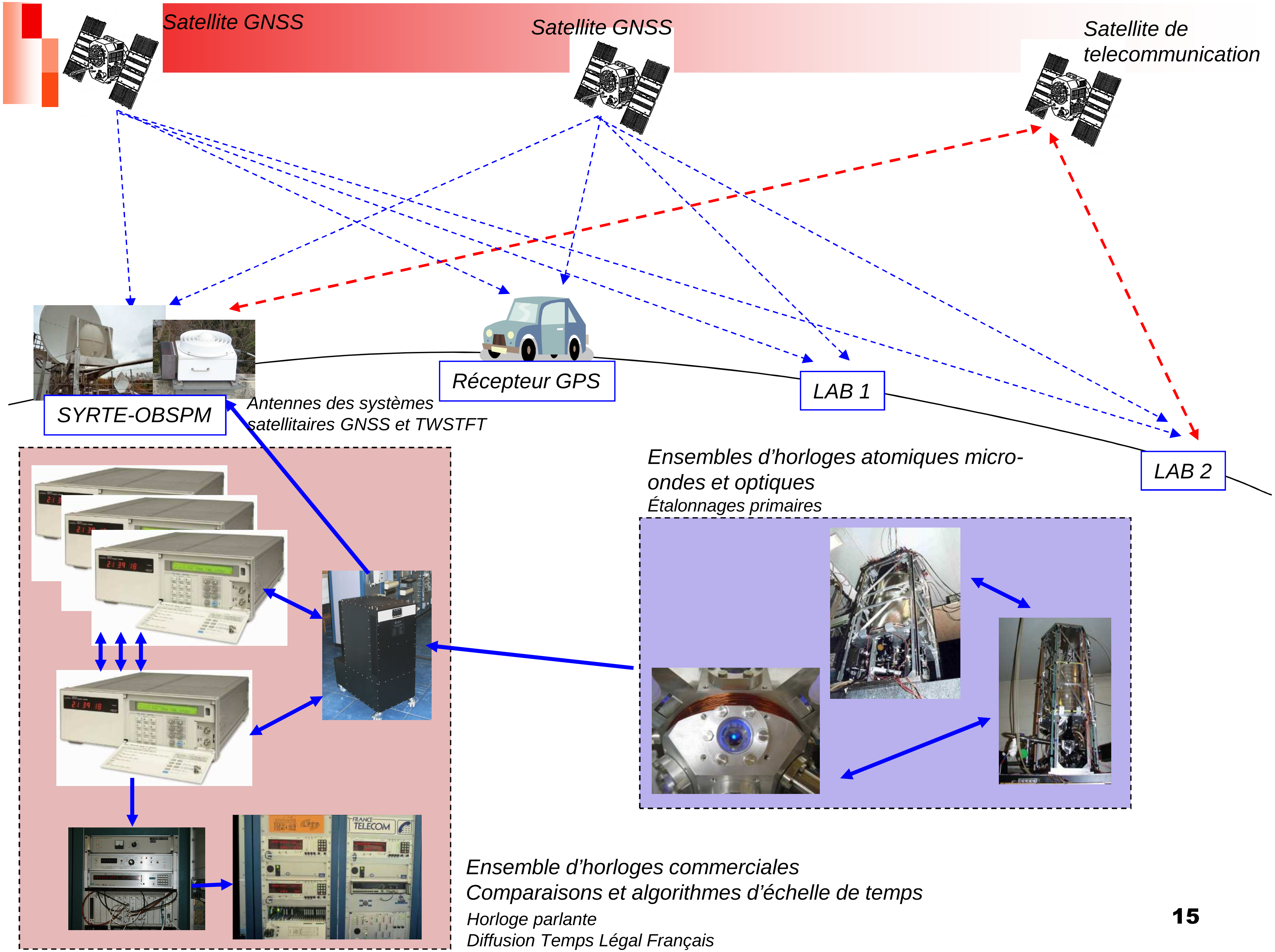


Applications of clocks

Applications of clock ensembles

- Atomic and quantum physics
  - Collisions, Feshbach resonances, collisions in relation with fermion/boson statistics in confined atoms
  - Distributed cavity phase shift, microwave lensing
  - High precision atomic properties: polarizabilities, hyperpolarizabilities, vector and tensor light shifts
- Time and frequency metrology
  - Realization of the SI second, of international atomic time (TAI)
  - High accuracy absolute frequency measurements (Rb, Sr, Hg, H, Ca^+,…), secondary representations, toward a new SI second
  - Determination of natural constants (R_y, α, m_e/m_p), radius charge of the proton
- Fundamental physics tests
  - Local Lorentz Invariance (photon sector, matter sector, MM, KT)
  - Local Position Invariance, Stability of natural constants, Isotropy of space
- Space clock missions (ACES) and projects (STE-QUEST,…)
  - Support to the development of PHARAO with ACES
  - Ground segment of ACES



Satellite GNSS

Satellite GNSS

Satellite de
telecommunication

SYRTE-OBSPM

Antennes des systèmes
satellitaires GNSS et TWSTFT

Récepteur GPS

LAB 1

LAB 2

Ensembles d'horloges atomiques micro-ondes et optiques

Étalonnages primaires

Ensemble d'horloges commerciales

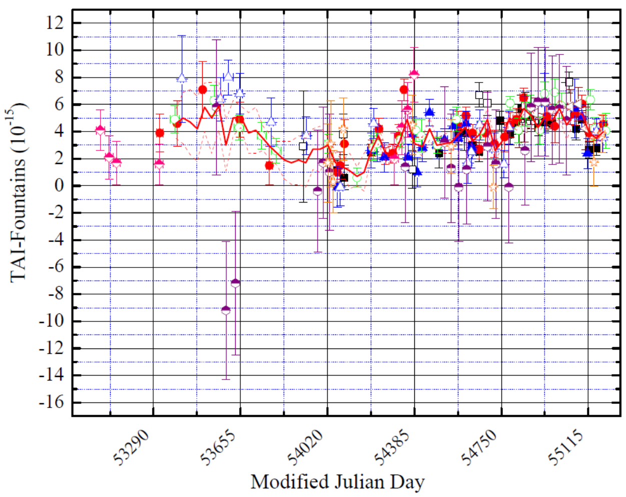
Comparaisons et algorithmes d'échelle de temps

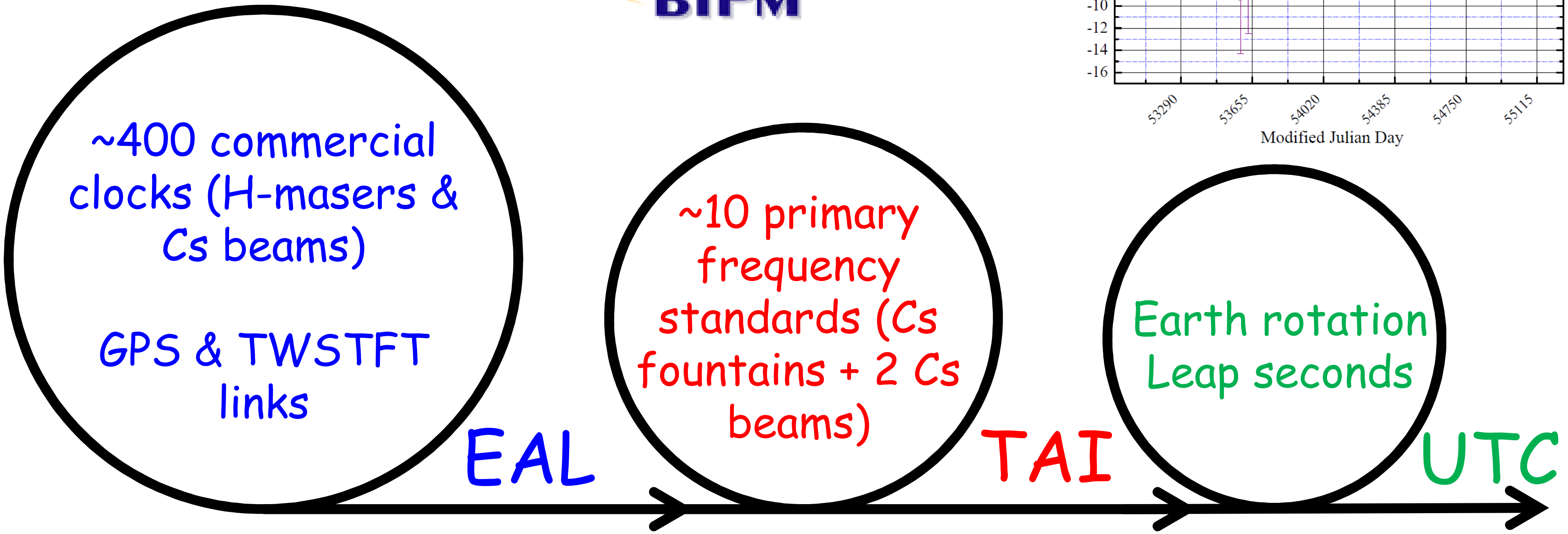
Horloge parlante

Diffusion Temps Légal Français

International Atomic Time (TAI)

Timescale elaborated by BIPM





~400 commercial clocks (H-masers & Cs beams)

GPS & TWSTFT links

EAL

~10 primary frequency standards (Cs fountains + 2 Cs beams)

TAI

Earth rotation
Leap seconds

UTC

- Stability of TAI (τ in days)

$$\sigma_y(\tau) = 20 \times 10^{-16}\, \tau^{-1/2}$$
$$\sigma_y(\tau) = 4 \times 10^{-16}$$
$$\sigma_y(\tau) = 1 \times 10^{-16}\, \tau^{-1/2},$$

- Several PFS reports/month. Accuracy of TAI-SI: mid-10^{-16}
- UTC-UTC(k): few 10 ns typical. Best, experimental: 1 ns

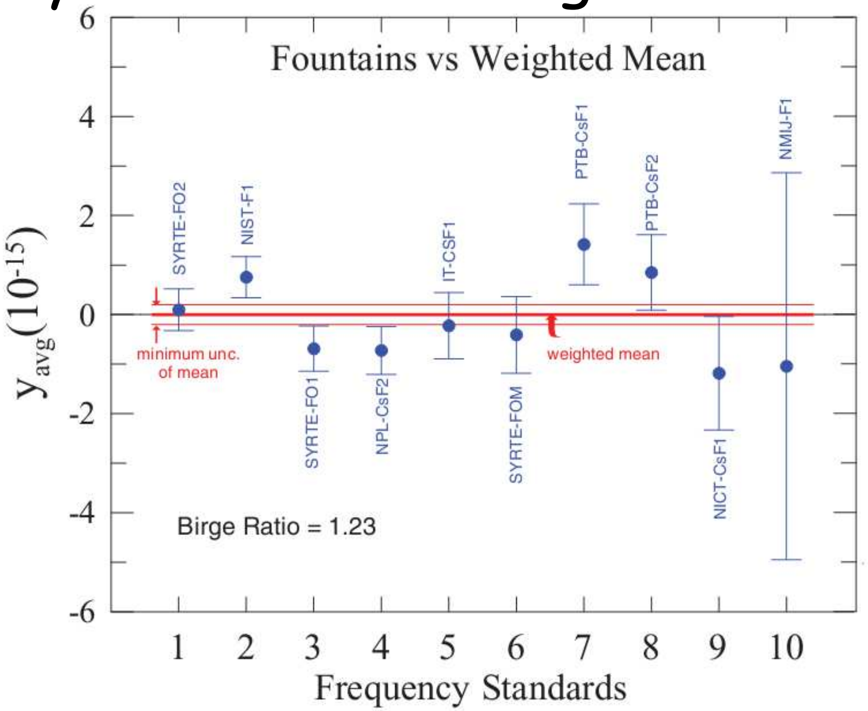
Example of applications

- Metrology: consistency of time and frequency references between NMIs
- Dissemination of accurate frequency and time to laboratories
- Synchronization of VLBI stations
- Study of Earth rotation
- Pulsar timing → astrophysics, tests of GR, evidence of gravitational waves,…
- …

Frequency comparisons through TAI

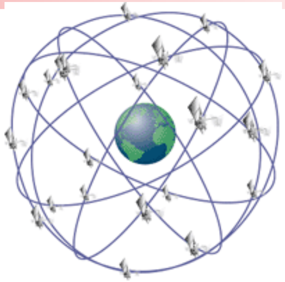
- Comparisons of Primary Frequency Standard through TAI

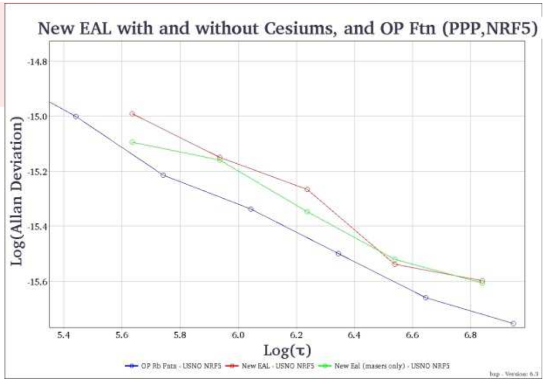
T. Parker, Rev. Sci. Instrum. 83 , 021102 (2012)
G. Petit et al., BIPM



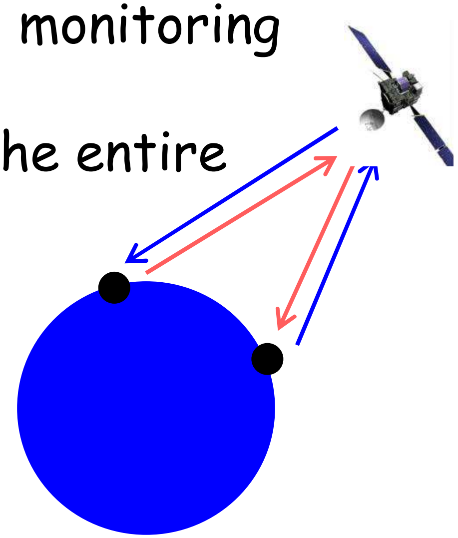
- A high accuracy measurement through TAI
  - >80 formal calibrations of TAI by LNE-SYRTE PFS since Jan. 2009
  - Calibrations by FO2-Rb used as a SFS submitted to BIPM in Jan. 2012 and evaluated by the WG PFS
  - FO2-Rb data now included in *Circular T*, but with no weight in TAI
  - 17 formal reports already, allowing FO2-Rb SFS to be directly linked to TAI to <3x10^{-16} [G. Petit, BIPM]

Long distance T&F transfer via satellite





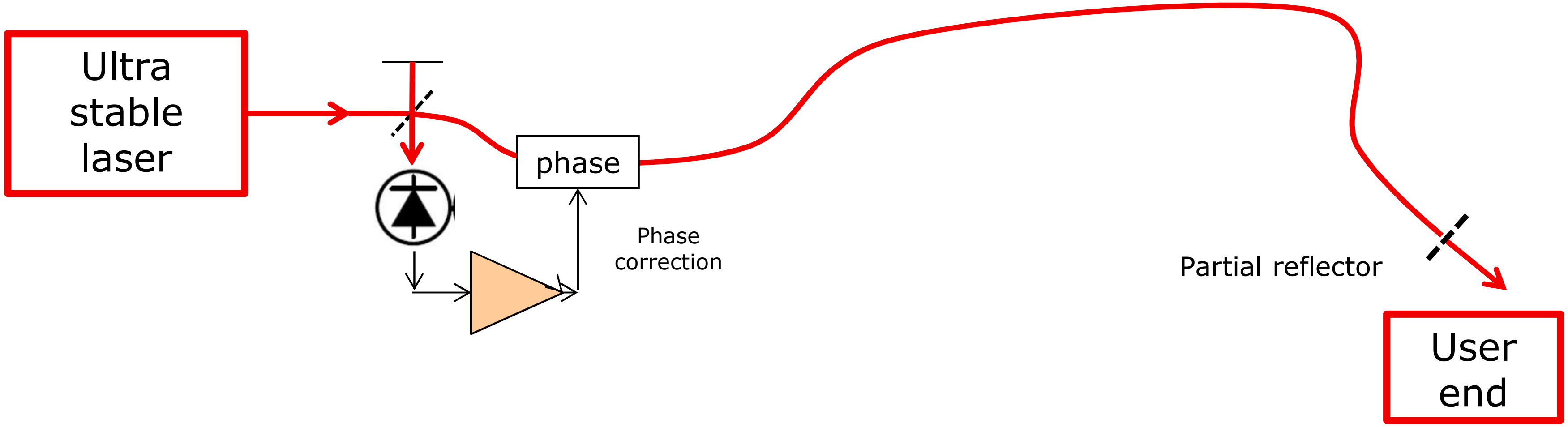
- GPS
  - Satellites broadcast several carriers modulated with PRN codes
  - Satellites orbits and clocks are known from ground monitoring stations and master clocks
  - “PPP” method: a global post-processed analysis of the entire constellation is made to make T&F transfer



- TWSTFT
  - Exchange of PRN coded signal through the same geostationary telecommunication satellite
- Typical performance
  - Stability: 10^{-15} @1d. Timing accuracy: 1 ns
  - NOT sufficient for present and future optical clocks

Long distance T&F transfer: advanced methods

- Coherent optical fiber link
  - Enabled by the "easy" manipulation/measurement of optical carrier signals (ultra-stable lasers, optical frequency combs)
  - Largely passes GPS PPP and TWSTFT
  - Adapted to the generation of optical clocks
  - Principle: heterodyne Michelson-like interferometer

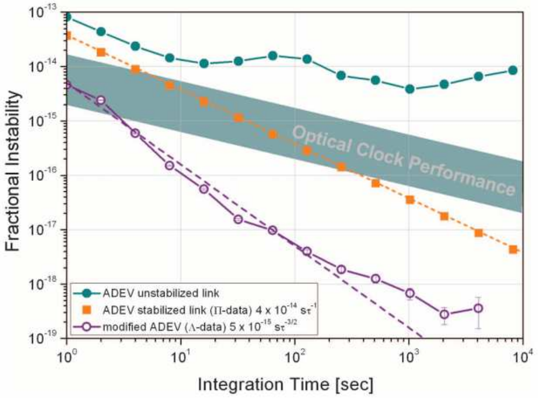


- Investigation of similar ground to space optical link
- ACES μW link: ~10^{-16} @1d

Coherent optical fiber links

- Feasibility well-established (years ago)
  - Demonstration of ultra stable optical carrier transfer in telecom fiber over ~100-200 km in several groups (PTB, JILA/NIST, SYRTE/LPL, NMIJ/Tokyo Univ.,…)
  - Over a single such segment stability is <10^{-19} @1d
- Long link demonstrated
  - PTB: 920 km in a dark fiber

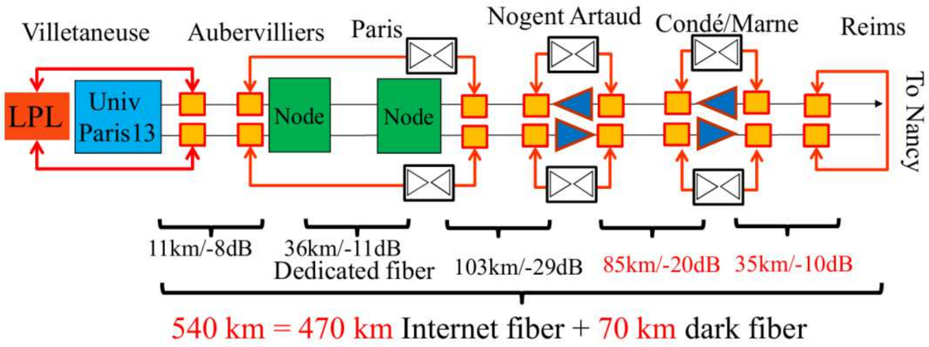
Science 336, 441 (2012)



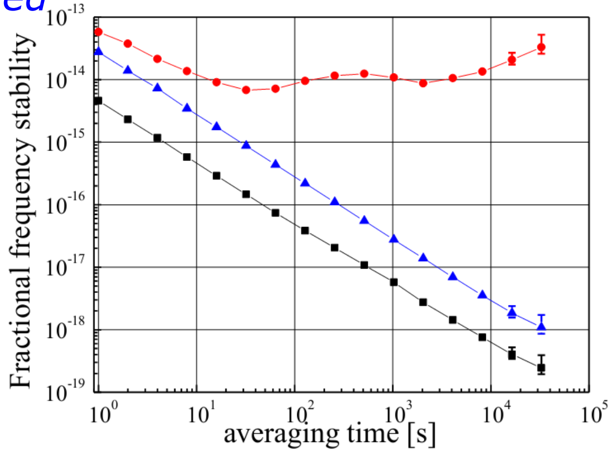
  - SYRTE/LPL: 540 km in a dark channel (fiber shared with internet)

Opt. Express 18, 16849 (2010)

Opt. Express submitted
arXiv:1206.5591



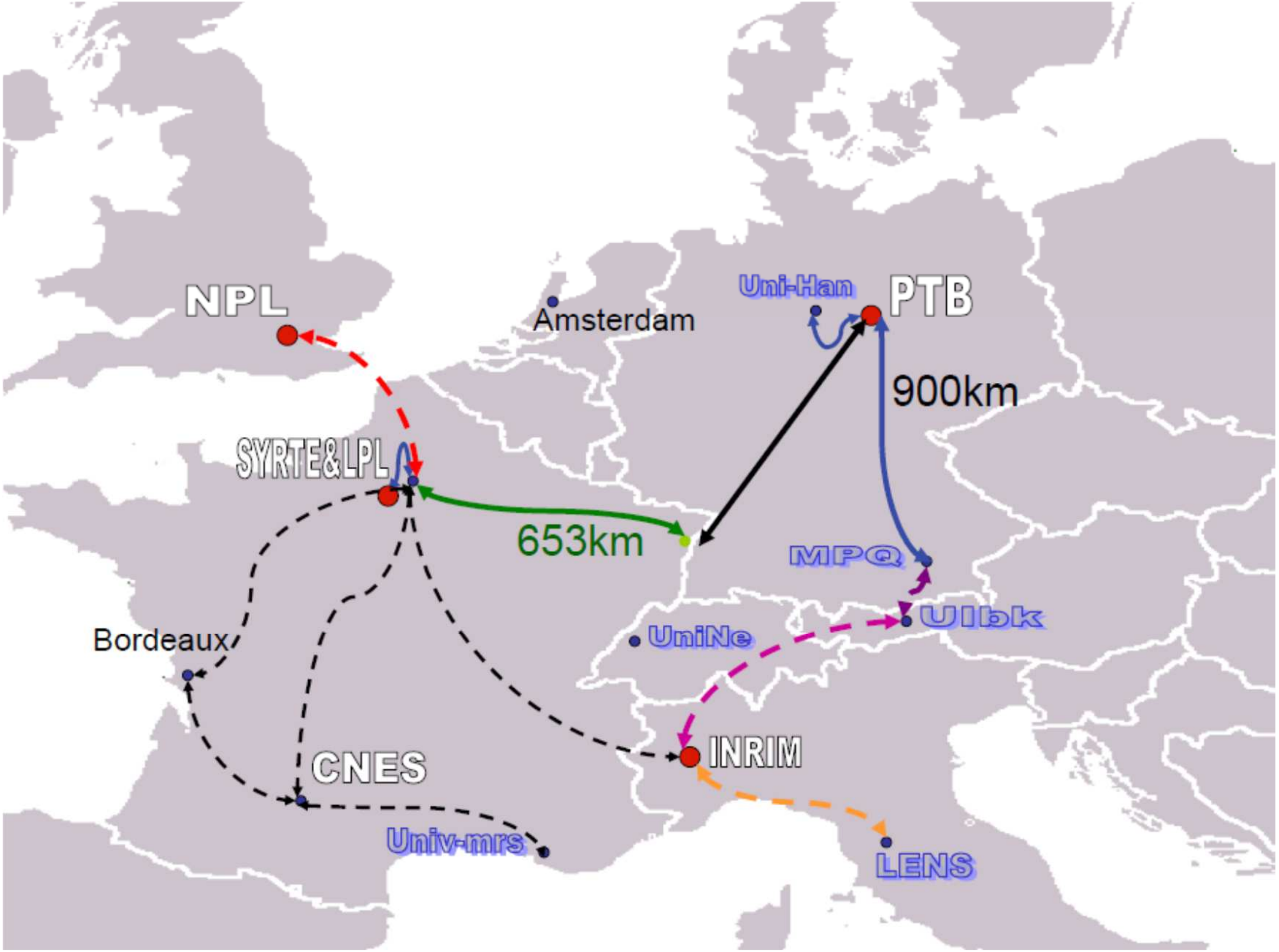
540 km = 470 km Internet fiber + 70 km dark fiber



In the future: a European network

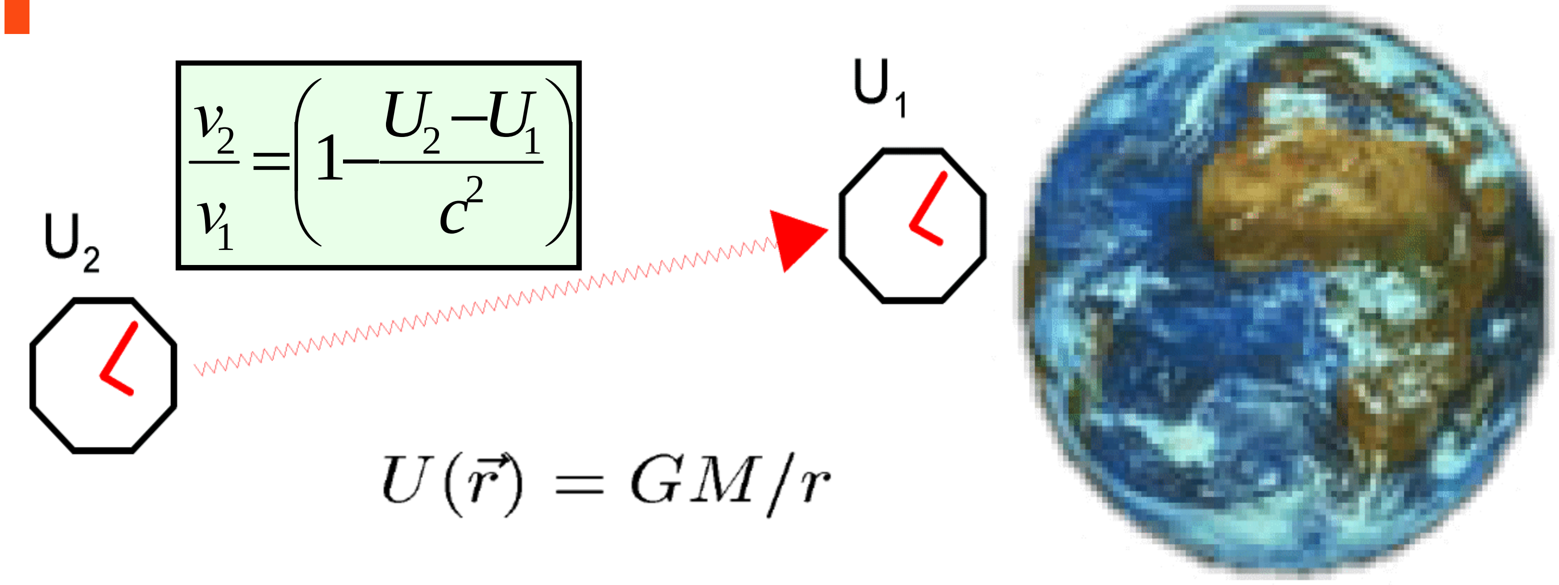
On-going now

- Deployment at national and international scales



Metrology in curved space-time

Einstein's Gravitational Redshift



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

$$U(\vec{r}) = GM/r$$

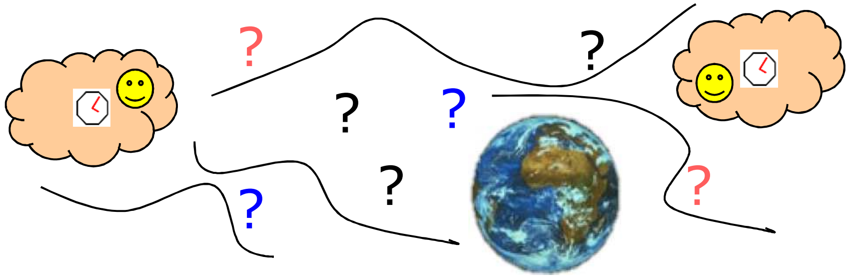
- Potential of the Earth at its surface: 7×10^{-10}
- Gradient at Earth surface: $\sim10^{-16}\ \mathrm{m}^{-1}$
- Surface to GNSS satellite (R=29600 km) difference: $\sim 5.5\times10^{-10}$

Redshift measurement with a 7×10^{-5} uncertainty: GPA, R. Vessot *et al.* (1976)
To be improved by ~30 by ACES

Frequency metrology and General Relativity

- A clock realizes its proper time
  - valid in a small volume where is the metric is ~flat

$$d\tau^2 = \left(1 - 2\frac{U(T,\vec{R})}{c^2}\right) dT^2 - \frac{1}{c^2} d\vec{R}^2 \qquad d\tau \simeq \left(1 - \frac{U(T,\vec{R})}{c^2} - \frac{1}{2}\frac{\vec{V}^2}{c^2}\right) dT$$



- Given present accuracies, remote clock comparisons in the vicinity of the Earth unavoidably amount to big General Relativity experiments
  - Need to define coordinate system
  - Need to taken into account for gravitation precisely
  - In this context, TAI is a realization the T coordinate of the chosen geocentric coordinate system

Impact of gravitation on TAI & clock comparisons

- A gravitational redshift correction must be included
- For TAI, the gravitational potential difference wrt the geoid is what matters
  - Ex: NIST Boulder: -1.7987×10^{-13} with a 3×10^{-17} unc. (⇔30 cm)
  - Significant impact of Rocky Mountains

Metrologia 40, 66 (2003)

  - In some places, 10^{-17} or slightly less
- Currently, temporal variations due to tides are not taken into account
- Clocks with accuracy of 10^{-17}-10^{-18} (will) exist shortly as well as the means of comparing them remotely at this level
- ➔ the current approach must be refined or modified
- ➔ possibility to use clock to learn about the gravitational potential: “relativistic geodesy”

Ion clocks examples

Doppler cooling and fluorescence detection

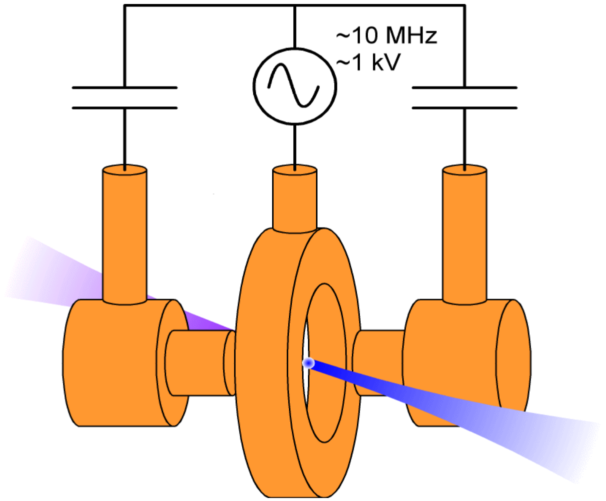
- Trap configuration

Ring inner diameter: 0.8 mm

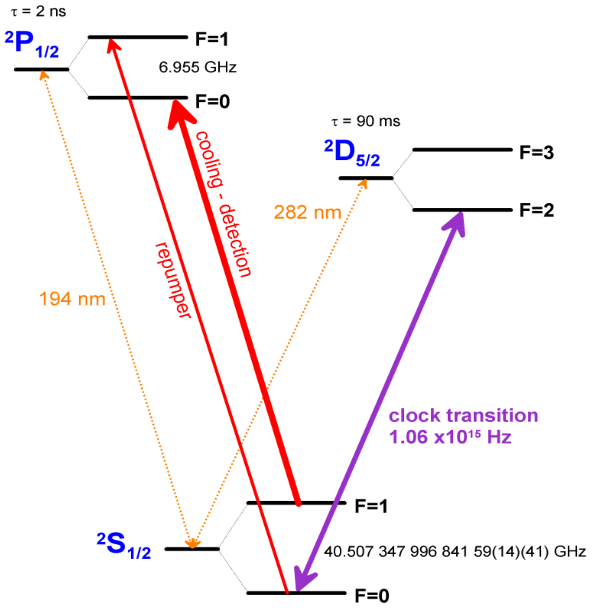
Drive frequency: 10 MHz

Drive amplitude: 1 kV

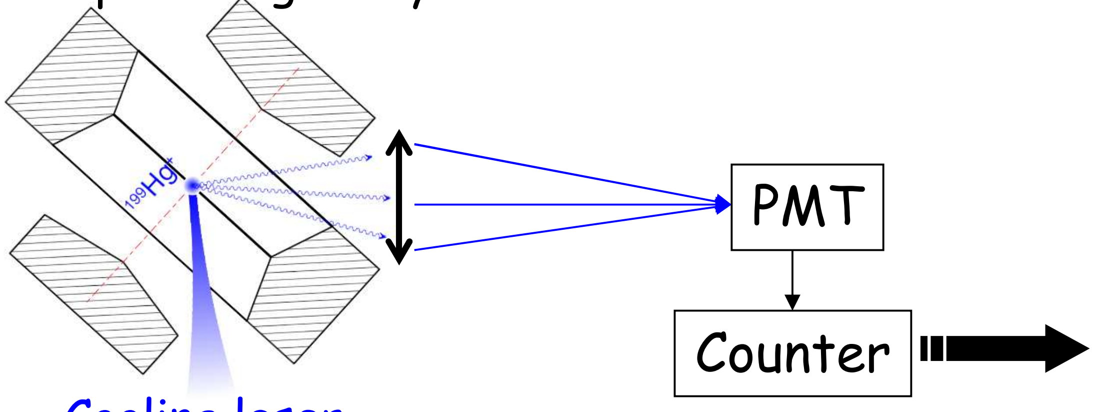
$\upsilon_x, \upsilon_y \sim 1$ MHz
$\upsilon_z \sim 2$ MHz



Hg+: cooling wavelength: 194 nm
$\Gamma=1/\tau$; $\tau \sim 2$ ns ➔ $T_{min} \sim 1.7$ mK

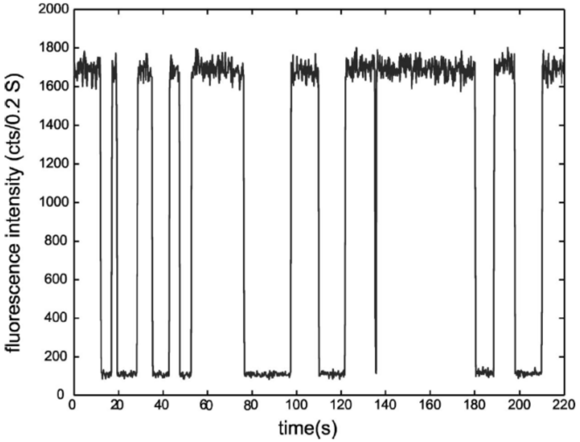


- Doppler cooling
  - ☐ Temperature: ~ few mK
  - ☐ Average vibrational quantum number: <ni> ~35
  - ☐ RMS size of motion: $\Delta z \sim 42$ nm
- Fluorescence detection
  - ☐ When cooling light is on, the ion is scattering photons
  - ☐ This is providing a way to detect the ion



Cooling laser

Quantum jumps in Ba⁺

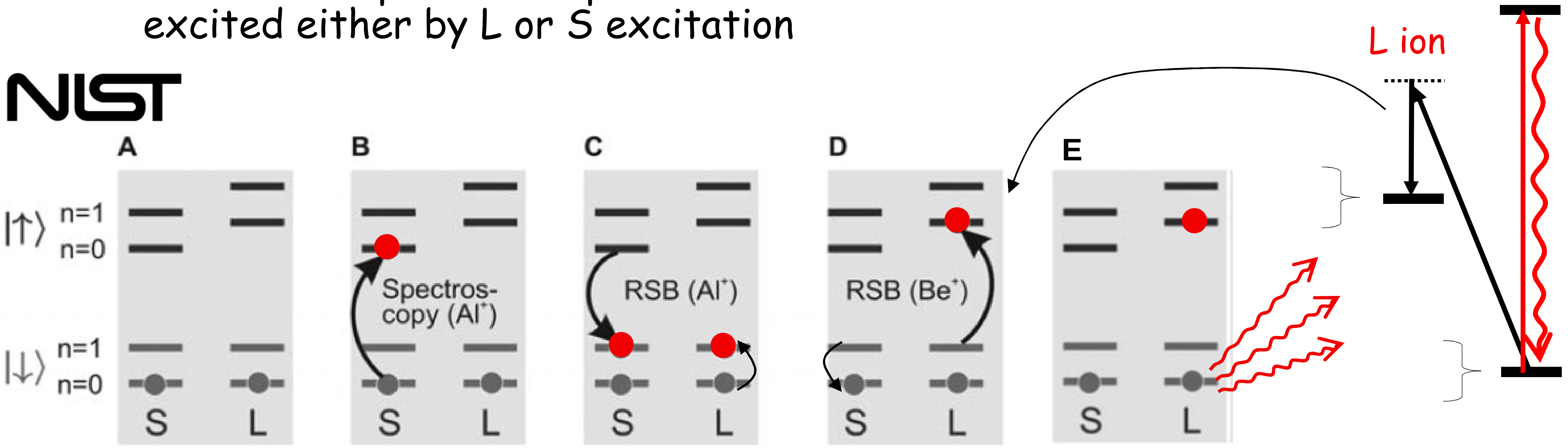


Detection and spectroscopy using quantum logic

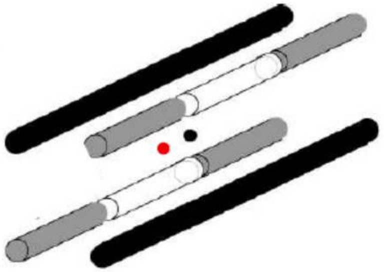
- Assume the following situation

  P. O. Schmidt et al.,Science 309, 749 (2005)

  - 2 ions in a linear trap: Spectroscopy (clock) ion (S: Al^+) + Logic ion (L: Be^+)
  - System cooled to the vibration ground state (sympathetic Raman sideband cooling with the logic ion)
  - Usual probe pulse on the clock transition of the S ion
- The scheme is a way to detect the out-coming state of the S ion using a quantum logic gate to transfer the information to the L ion
  - Vibrational spectrum is present on both L and S transitions and can be excited either by L or S excitation



State selective fluorescence detection of the L ion



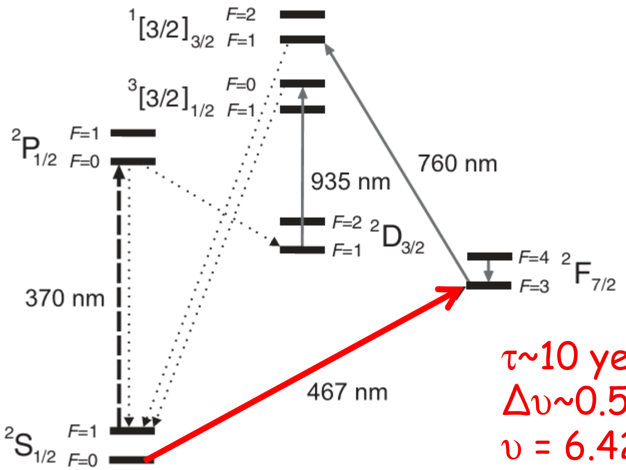
Fluorescence means “detection in the ground state of the S ion”

No Fluorescence means “detection in the excited state of the S ion”

Ion clock performance

- ^{171}Yb^{+} octupole clock (NPL, PTB)

Huntemann et al., Phys. Rev. Lett. 108, 090801 (2012)



τ~10 years !!!

Δυ~0.5 nHz

υ = 6.42x10^{14} Hz

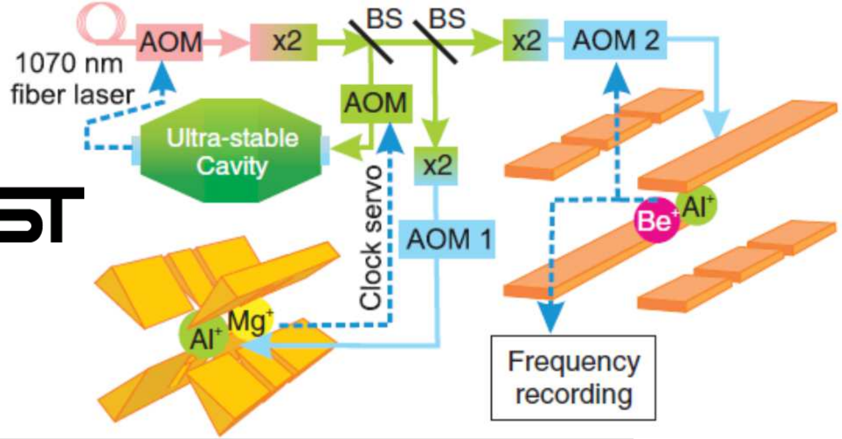
λ = 467 nm

Effect	$\delta\nu/\nu_0(10^{-18})$	$u/\nu_0(10^{-18})$
Blackbody radiation shift	−105	50
Light shift extrapolation	0	42
Quadrupole shift	0	22
Second-order Doppler shift	0	16
Quadratic dc Stark shift	0	4
Servo error	0	3
Second-order Zeeman shift	−36	1
Total	−141	71

- Al^{+} quantum logic clocks (NIST,…)

Effect	Shift (10^{-18})	Uncertainty (10^{-18})
Excess micromotion	−9	6
Secular motion	−16.3	5
Blackbody radiation shift	−9	3
Cooling laser Stark shift	−3.6	1.5
Quad. Zeeman shift	−1079.9	0.7
Linear Doppler shift	0	0.3
Clock laser Stark shift	0	0.2
Background-gas collisions	0	0.5
AOM freq. error	0	0.2
Total	−1117.8	8.6

Stability: ~2.8x10^{-15} @1s



Fractional frequency difference: $(\nu_{\mathrm{AlMg}} - \nu_{\mathrm{AlBe}})/\nu = (-1.8 \pm 0.7) \times 10^{-17}$

Total uncertainty: 2.5×10^{-17}

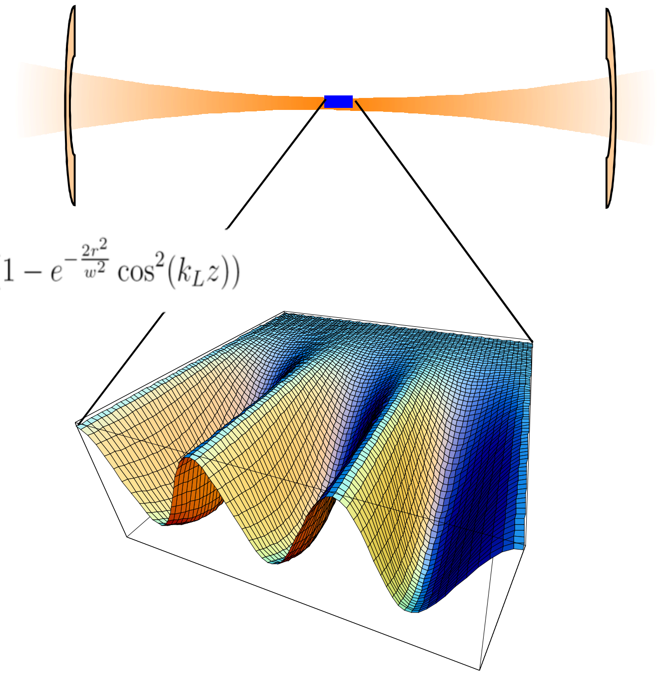
Chou et al., PRL 104, 070802 (2010)

Lattice clocks examples

"Non-perturbing" dipole lattice trap

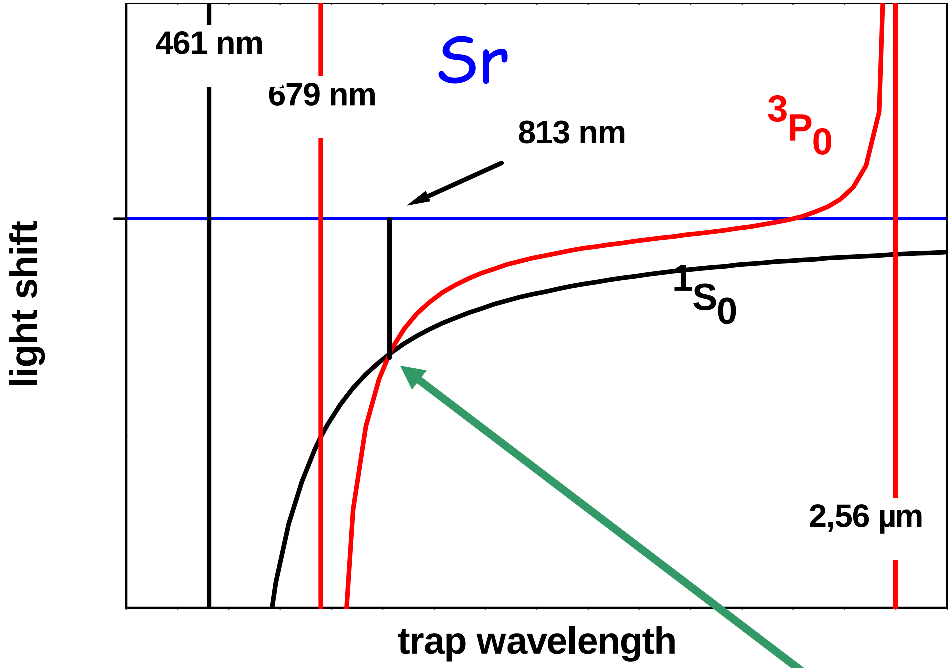
H. Katori et al., Phys. Rev. Lett. 91, 173005 (2003)

Typical max depth
~ 4 MHz
~ 200 μK



$$U(r,z) = U_0(1 - e^{-\frac{2r^2}{w^2}} \cos^2(k_L z))$$

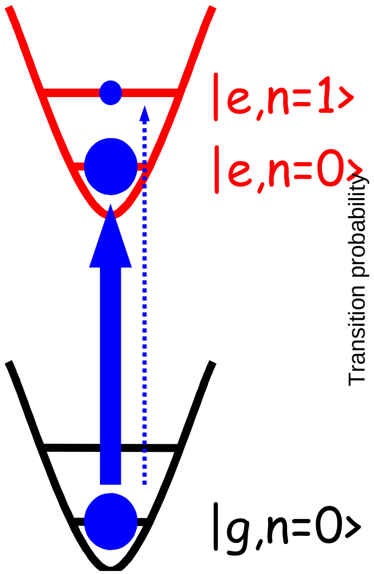
Light shift as a function of trap wavelength

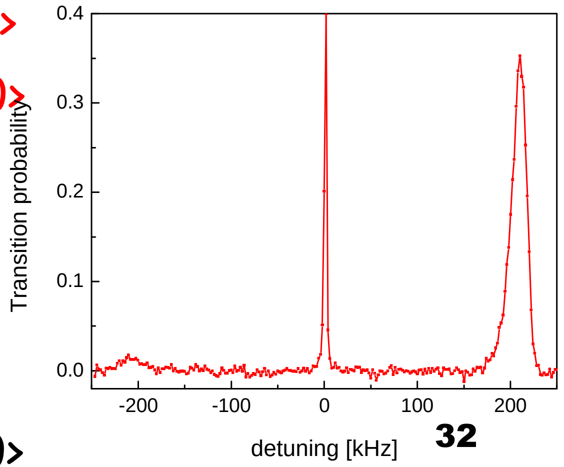


Magic wavelength : polarizabilities are equal for both clock states

Sensitivity under typical conditions : 10^{-15} /GHz

Combines the advantages of trapped ion and neutral atom: large atom number in the Lamb-Dicke regime



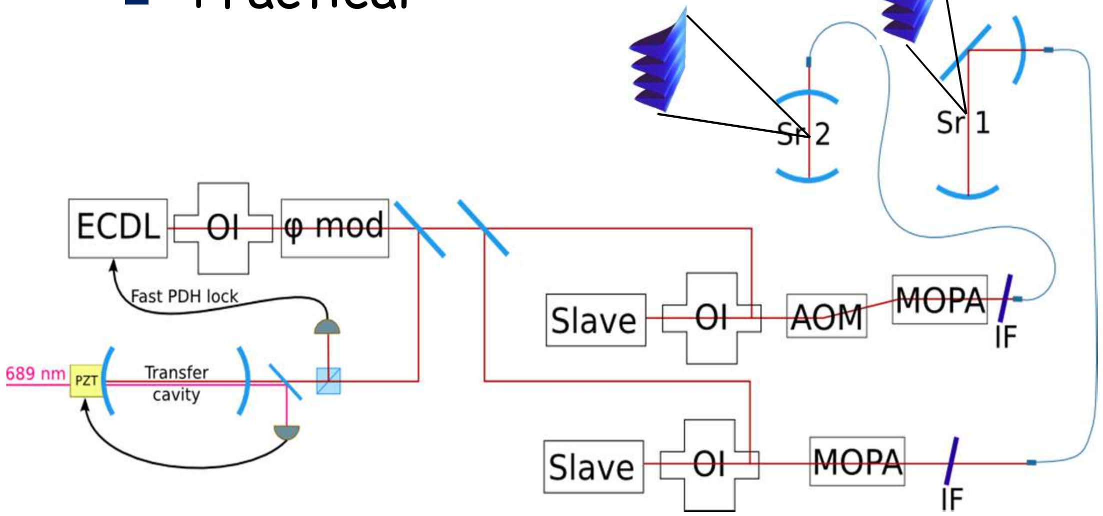


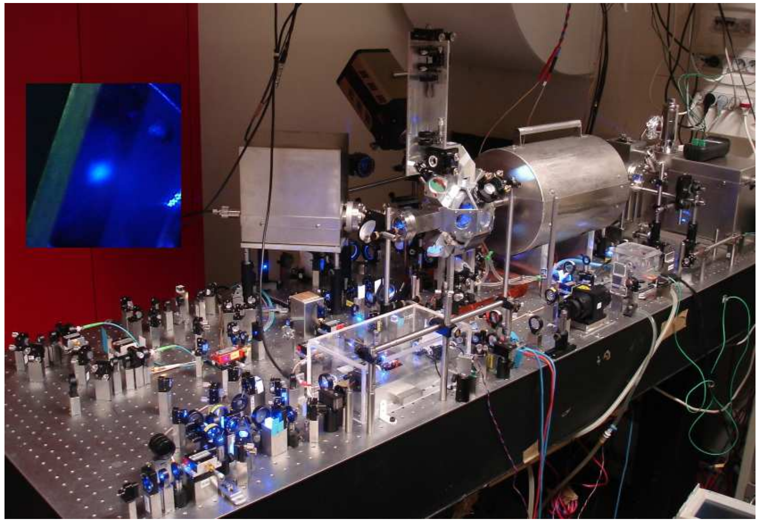
Sr lattice clocks at LNE-SYRTE

- 2 operating Sr optical lattice clocks
  - Ultra-stable laser (698 nm) with 10 cm FS mirror cavity
  - Lattice traps with build-up cavity: depth up to several 1000 E_R
  - Only semi-conductor lasers
- Recent studies of systematic shifts
  - Hyperpolarizability
  - Tensor lattice light shift

P. Westergaard et al., PRL 106, 210801 (2011)

- Non-destructive detection
  - High stability by reducing the Dick effect
  - Could generate non-classical states ➔ sub-QPN regime
  - Practical





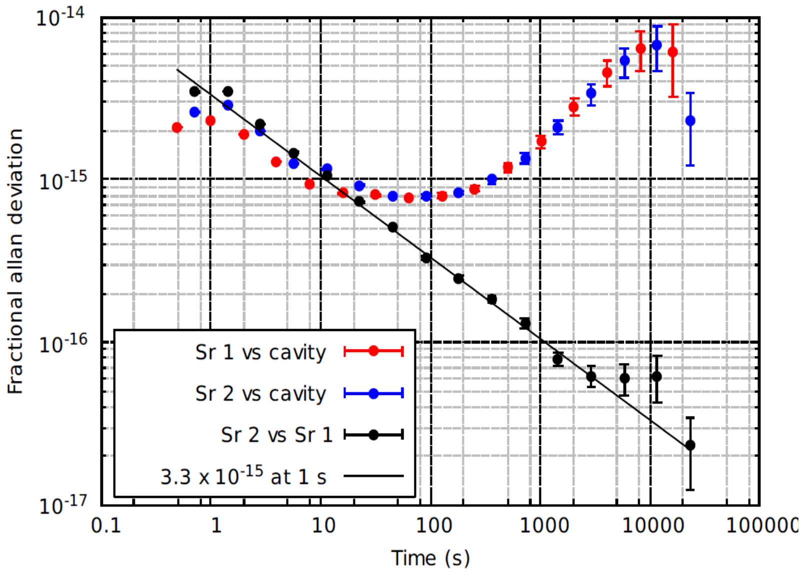
Accuracy of Sr clocks

Typical accuracy budget at 500 E_R trap depth

Effect	Correction	Uncertainty	
Quadratic zeeman	835 mHz	2 mHz	0.05×10^{-16}
Lattice (first order)	-84 mHz	20 mHz	0.5×10^{-16}
Lattice (second order)	-35 mHz	14 mHz	0.3×10^{-16}
Black body	2.376 Hz	45 mHz	1×10^{-16}
Density shift	-8 mHz	19 mHz	4.5×10^{-17}
Line pulling	0	20 mHz	0.5×10^{-16}
Lightshift probe	0	8 mHz	2×10^{-17}
Total	3.084 Hz	58 mHz	1.4×10^{-16}

- Note: see also JILA (Science 319, 1805 (2008)) and PTB (Metrologia 48, 399 (2011))

- Comparisons
  - Agreement to $<10^{-16}$…
  - … After fighting several unexpected "technical" shifts

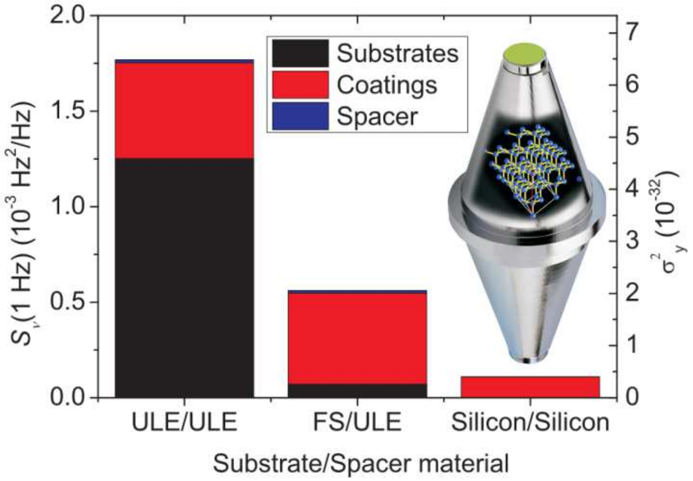


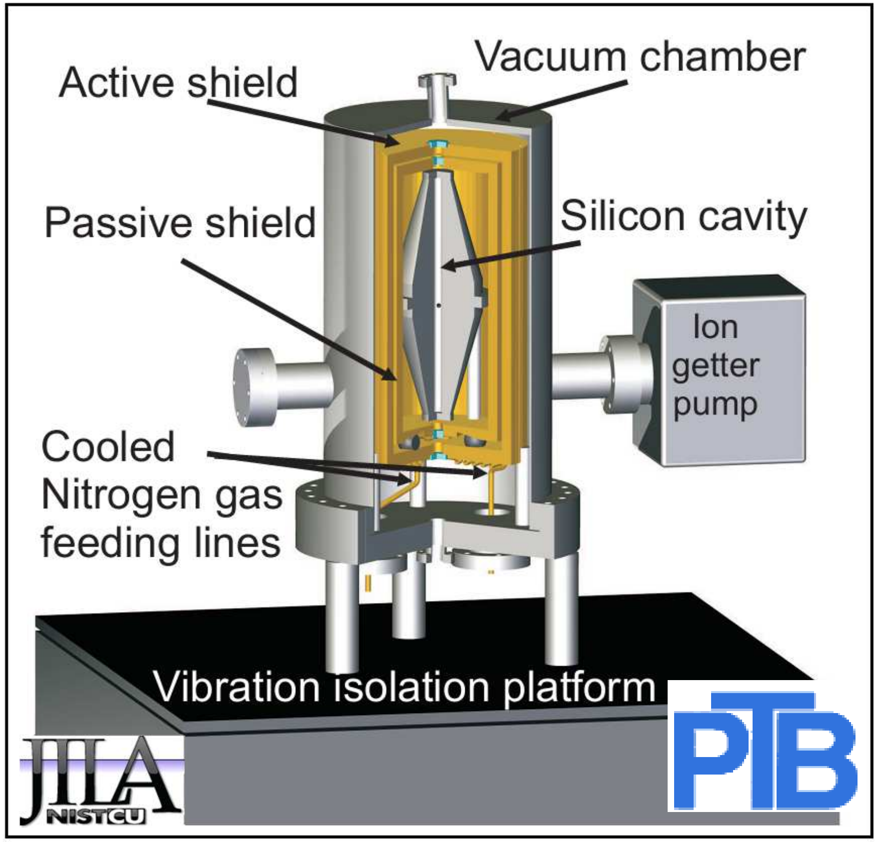
Ultra-stable lasers examples

Cryogenic silicon cavity

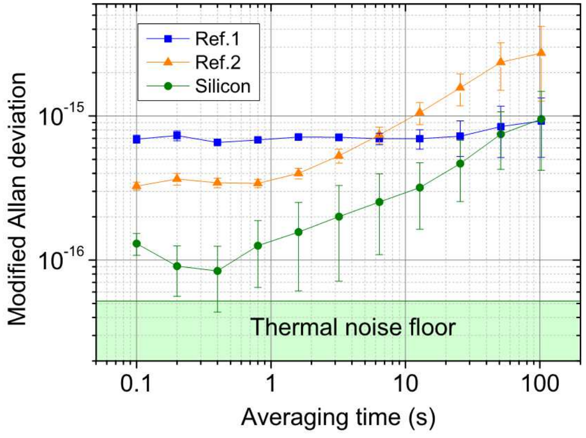
T. Kessler et al., Nat Photon (2012)

- Features of crystalline Si
  - ☐ Turning point in thermal expansion at 124 K
  - ☐ Higher mechanical Q than ULE or FS : Q >10^7
  - ☐ Transparent at 1.5 μm
  - ☐ High Young modulus: E=187.5 GPa (<111> axis)
  - ☐ High thermal conductivity: 500 W m^{-1} K^{-1}





➔ 1x10^{-16} at short times



Measured with three-cornered hat method

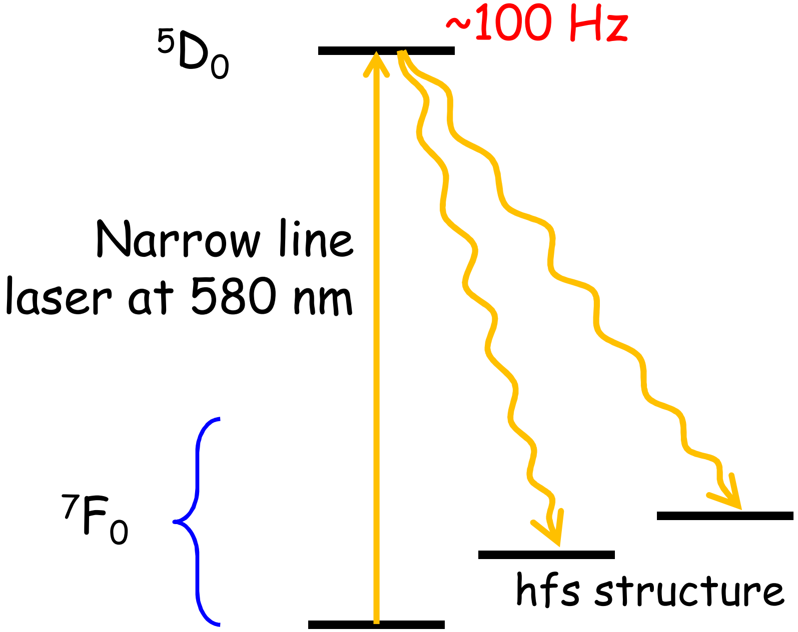
➔ 4.5x10^{-16} @1s with Sr lattice clock at PTB

Stabilization using spectral hole burning (1)

Rare-earth ions in crystal at 4 K

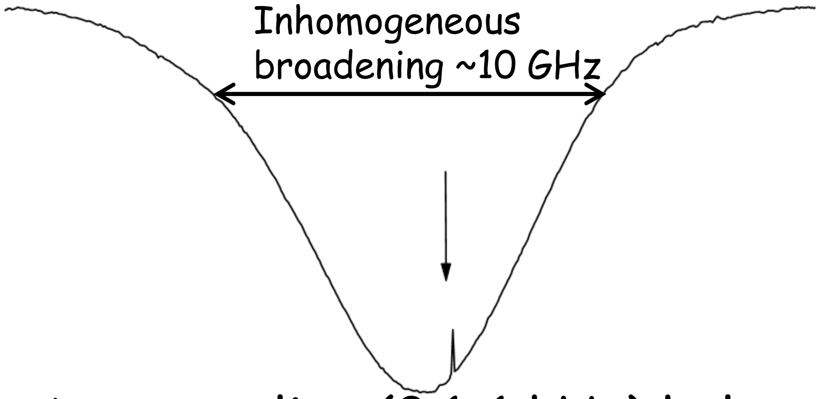
$Eu^{3+}:Y_2SiO_5$

Linewidth down to ~100 Hz



Lifetime of ground state populations at 4 K: 1 day !!!

Absorption spectrum

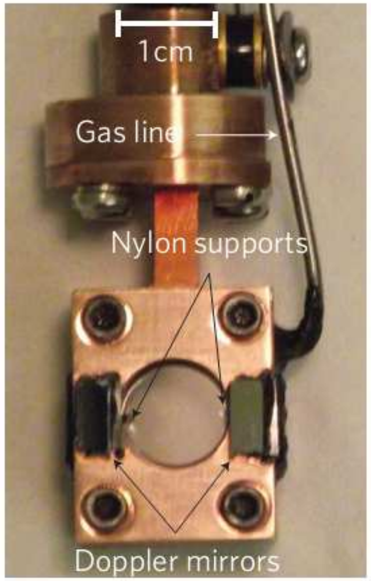


- A narrow line (0.1-1 kHz) hole can be burned in the absorption spectrum
- The same hole can be probed later to stabilized the laser frequency
- ➔ increases the autocorrelation of the laser in time
- ⇔ improving the laser stability

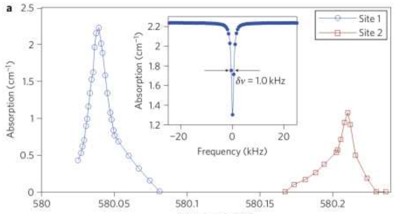
- Many absorbers ➔ low quantum limit
- Atomic system (+ well-chosen matrix) ➔ low thermal noise limit, low sensitivity to vibration,…
- $Eu^{3+:}Y_2SiO_5$ chosen for narrow line, long lifetime, low sensitivity to B,…

Stabilization using spectral hole burning (2)

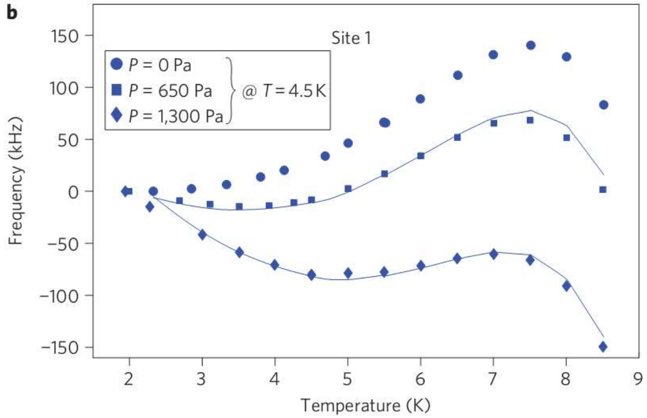
Thorpe et al., Nat. Photon. 5, 688 (2011)



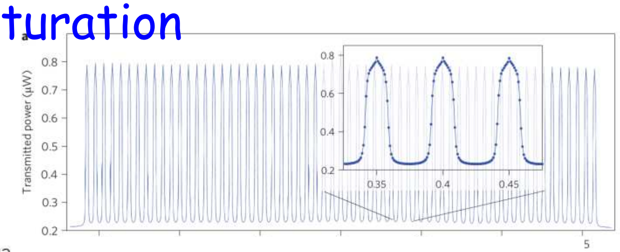
NIST

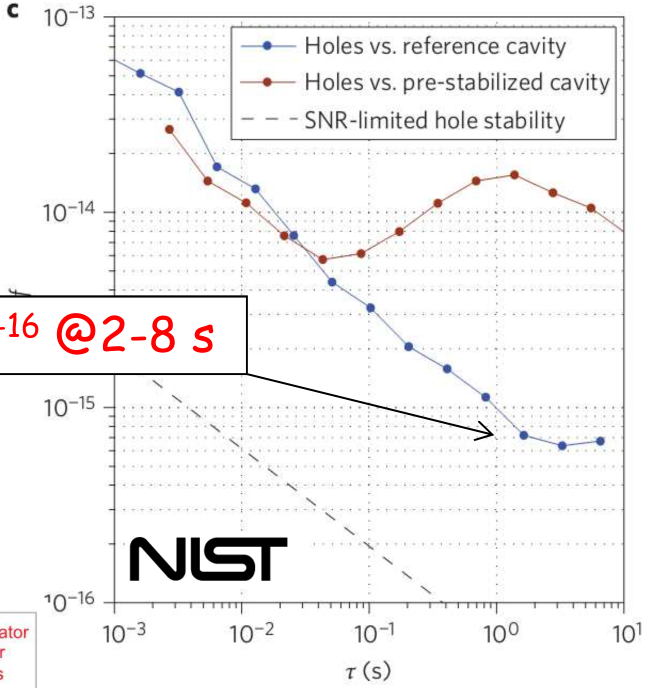


Cell with turning point in T°



Uses multiple holes to "save" them from fast saturation





6×10^{-16} @2-8 s

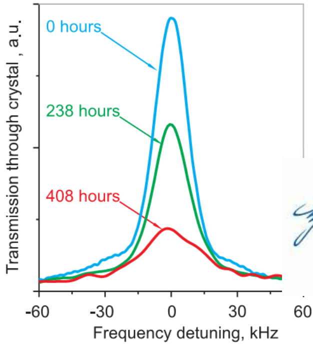
NIST

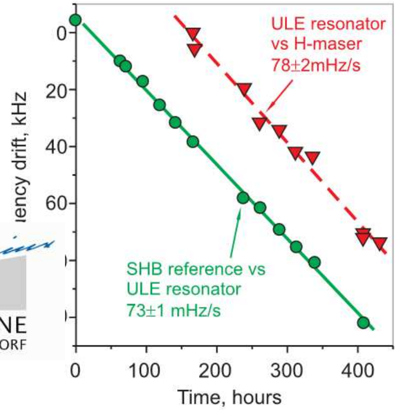
Chen et al., Phys. Rev. Lett.107, 223202 (2011)

➔Long term stability with a single hole

➔ 5 mHz/s drift rate

➔ 10^{-17}/s





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