Optical lattice clock

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National Institute of Information and Communications Technology (NICT)

Personal research background

- Ph. D thesis in ’98 in Tokyo (Prof. Shimizu)
  - Dynamics of cite-hopping processes of cold atoms in <u>optical lattices</u>
- Post doc. in Gonokami JST-ERATO project (98.4-02.9)
  - Cold Sr experiment from scratch with Katori
- Post doc. In Jun Ye’s group in JILA (’02.10-’06.6)
  - Built a Sr system, learn lots for precision spectroscopy
- JST-PRESTO (’05.10-’09.03)
  - HHG of NIR pulses to obtain coherent VUV pulses for a state-detection of Al+ or In+ ions (ongoing zt NICT)
- NICT Space-Time Standards section (’06.10 – ’12.10)
  - Sr lattice clock, fiber-transfer

(Temporarily (?) at Strategic Planning Section)

What's NICT?

Japanese national institute
responsible for frequency standards & Japan Standard Time (JST).

Activity on atomic frequency standards in NICT

Cs fountain primary frequency standard (NICT-CsF1)

$$|\delta f / f| = 1.4 \times 10^{-15}$$

(BIPM accepted this # in 2007)

The most accurate Cs fountain in Asia

Metrologia **45** 139 (2008)

^{87}Sr lattice clock optical standard

ν_{clock} = 429 228 004 229 873.9 (1.4) Hz
(Cs limit)

$|\delta \nu_{clock} / \nu_{clock}| = 5.1 \times 10^{-16}$

App. Phys. Express 5, 022701 (2012)

$^{40}Ca^{+}$ single-ion optical standard

ν_{clock} = 411 042 129 776 398.4 (1.2) Hz

$|\delta \nu_{clock} / \nu_{clock}| = 2.2 \times 10^{-15}$

Opt. Express , **20**, 22034 (2012)

New ion clock In+ project has started.

Measurement

Evaluation of the nature quantitatively

Result of the measurement (Normally expressed as a number)

$$= \frac{\text{Value to be measured}}{\text{Standard}}$$

Measurement consists of (i) ratio measurement and (ii) preparation of standards.

Uncertainty of measurement

$$= \sqrt{(Uncertainty\ of\ ratio)^2+(Uncertainty\ of standard\ you\ have)^2}$$

In case of
optical frequency, …

$<10^{-19}$ (frequency comb)

$\sim 10^{-17}$ (Al+, Yb+, Sr)

Invention of frequency combs has reduced 1st term in early 2000s.
Then, second term needs to be improved. → lattice clock & QIP clock proposed in 2001 by Wineland

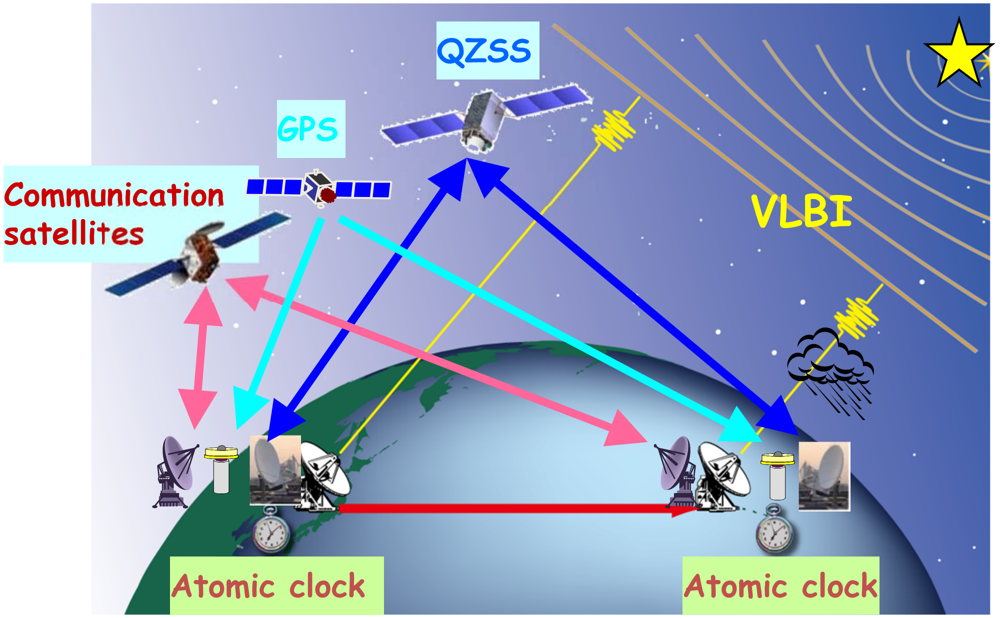
QIP: Quantum Information Processing

Are we ready to redefine the SI second ?

No.

Requirement

- Saturation of the progress in optical clocks
- Method to confirm the agreement of frequencies all over the world

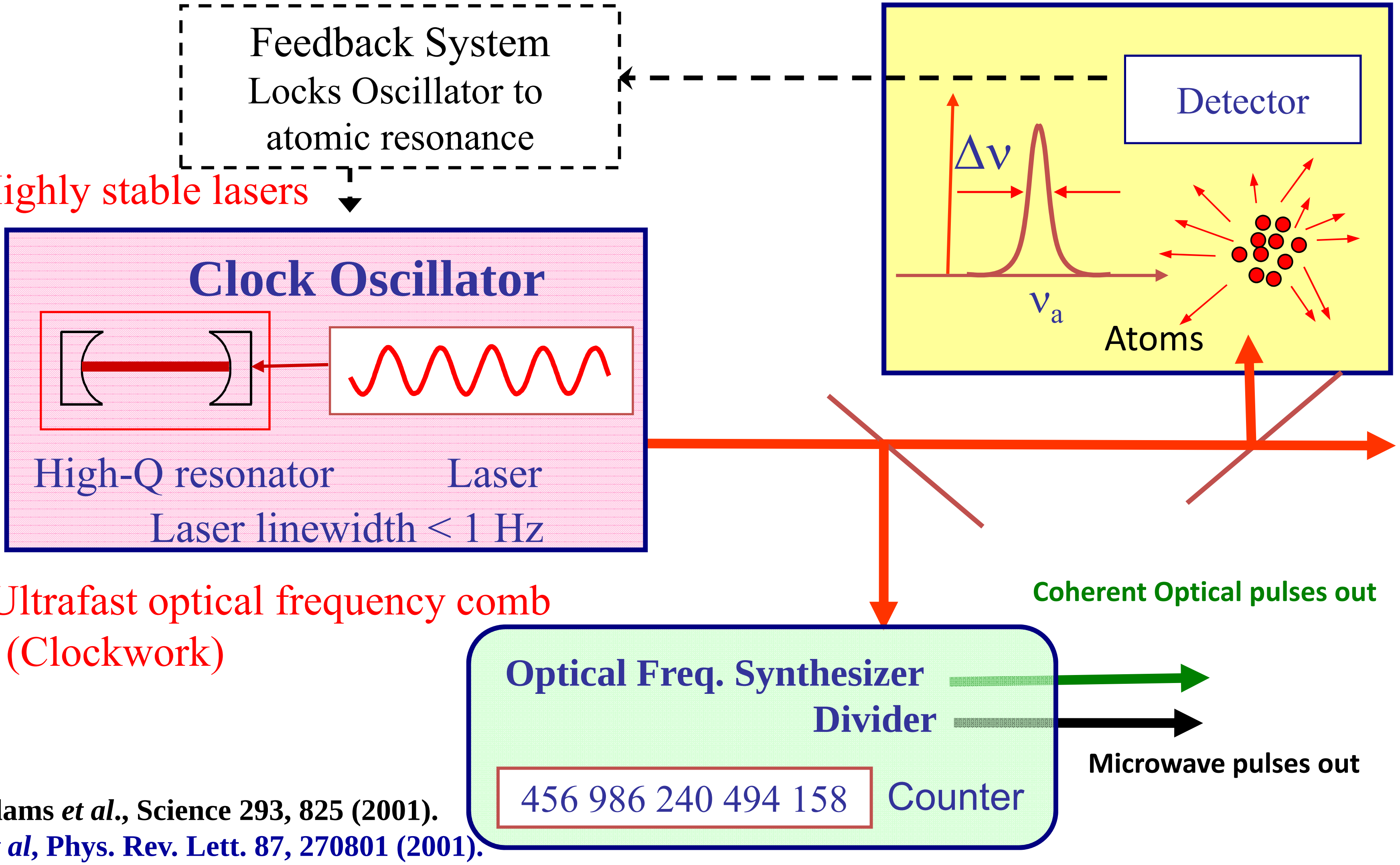


Ordinary time transfer using satellites

Currently 10^{-15} level

Uncertainty and stability incompatible with superb characteristics of optical standards

Optical Clock Components



2) Precision atomic spectroscopy

Detector

Feedback System
Locks Oscillator to
atomic resonance

1) Highly stable lasers

Clock Oscillator

High-Q resonator
Laser
Laser linewidth < 1 Hz

3) Ultrafast optical frequency comb
(Clockwork)

Optical Freq. Synthesizer
Divider

456 986 240 494 158
Counter

Coherent Optical pulses out

Microwave pulses out

Diddams *et al*., Science 293, 825 (2001).
Ye *et al*, Phys. Rev. Lett. 87, 270801 (2001).

Before the lattice clock

	neutral atom	trapped ion
	ENSEMBLE of atoms in ***free space***	***SINGLE ion*** in ***Lamb-Dicke regime*** $E_R << \hbar\Omega, \quad (\gamma << \Omega)$ $\Rightarrow \Delta x << \lambda$
Laser cooling & Spectroscopy	**Residual Doppler shifts** Doppler-free spectroscopy Saturated-absorption;Ramsey	***Sideband cooling*** enables Lamb-Dicke regime **Recoil & Doppler free spectrum**
Precision	$(Q \times S / N)^{-1}$; $\quad Q = \nu / \Delta\nu$ better ***S/N*** **~ (*N*$_{\text{atom}}$)$^{1/2}$**	High line-Q (long τ_{int}~$1/\Delta\nu$) Shot noise; $N_{\text{ion}}=1$
Uncertainties & Improvements	**atom-atom interactions** **-cold-collision shifts**	trapping EM field →micromotion

What lattice clocks aimed: equivalently lots of ion clocks at once

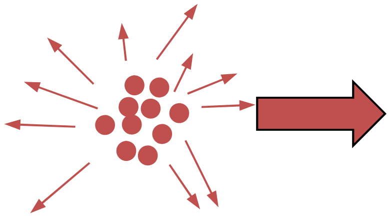
Free Neutral Atoms (Stability)

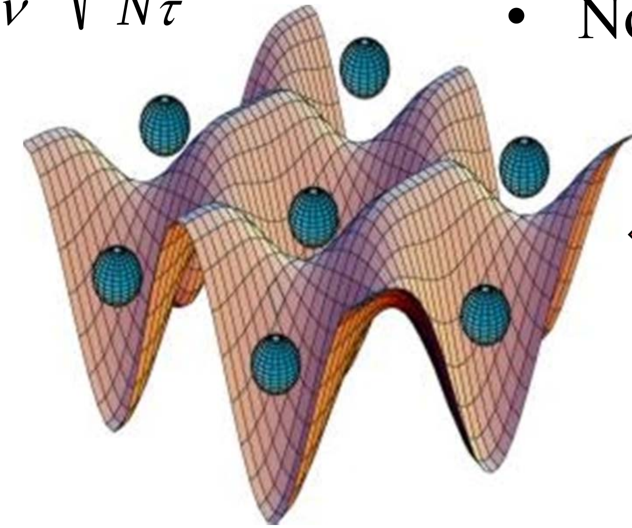
- Many Quantum Absorbers
  - Large N

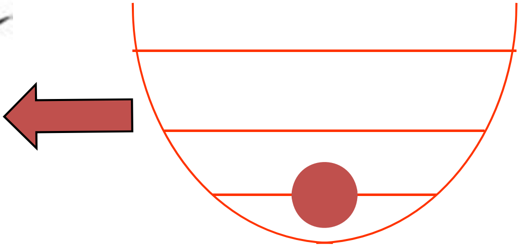
$$\frac{\delta\nu_{noise}}{\nu_0} \approx \frac{1}{Q}\cdot\frac{1}{S/N}\cdot\frac{1}{\sqrt{\tau}} = \frac{\Delta\nu}{\nu}\sqrt{\frac{T_{cycle}}{N\tau}}$$

Single Trapped Ion (Accuracy)

- Tight Confinement
  - No Doppler
  - Long Interrogation Times
- No Collisions



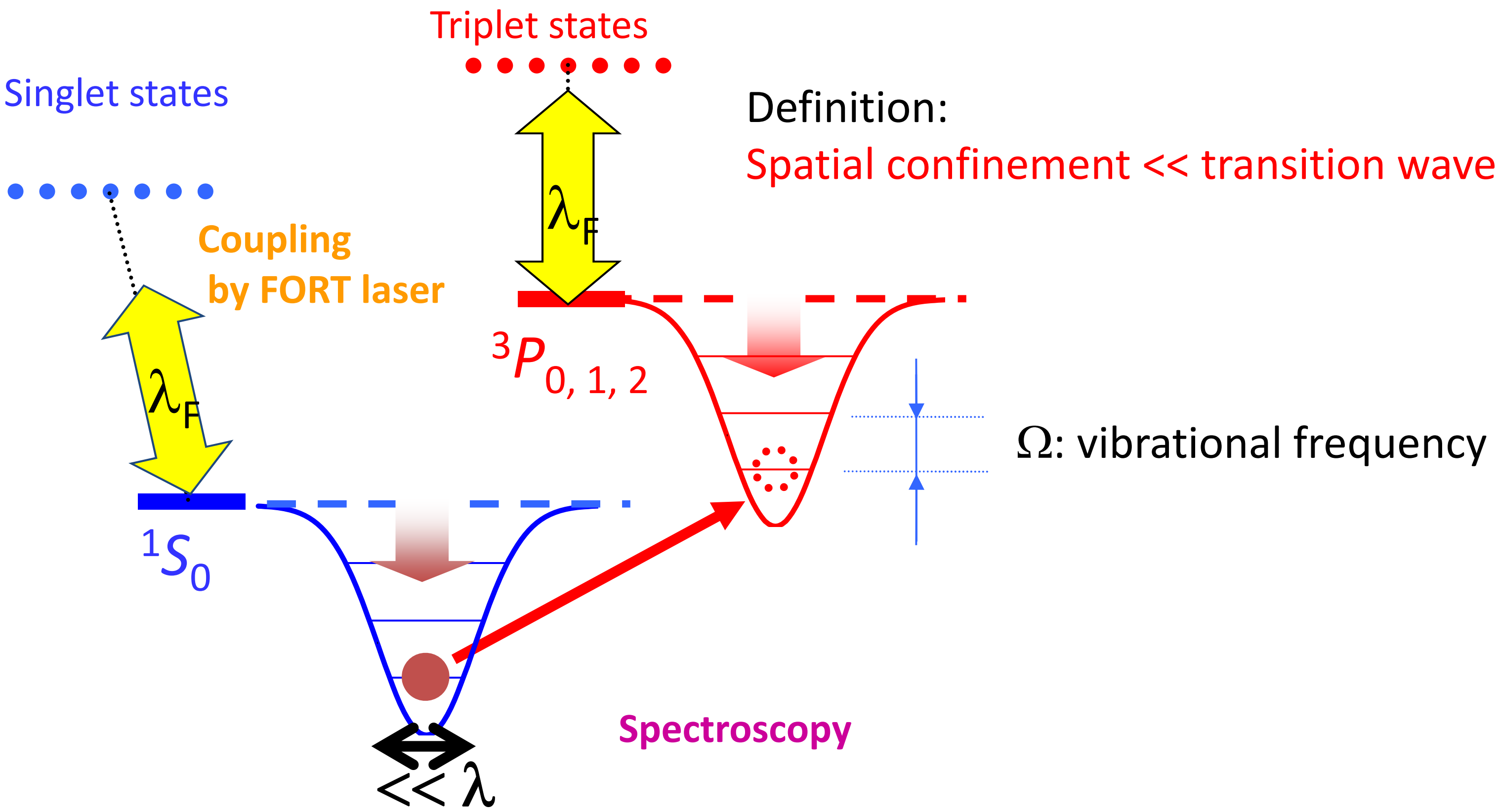




MERGE TOGETHER !!

Tight confinement of neutral atoms w/o perturbation to clock frequency

The Lamb-Dicke regime

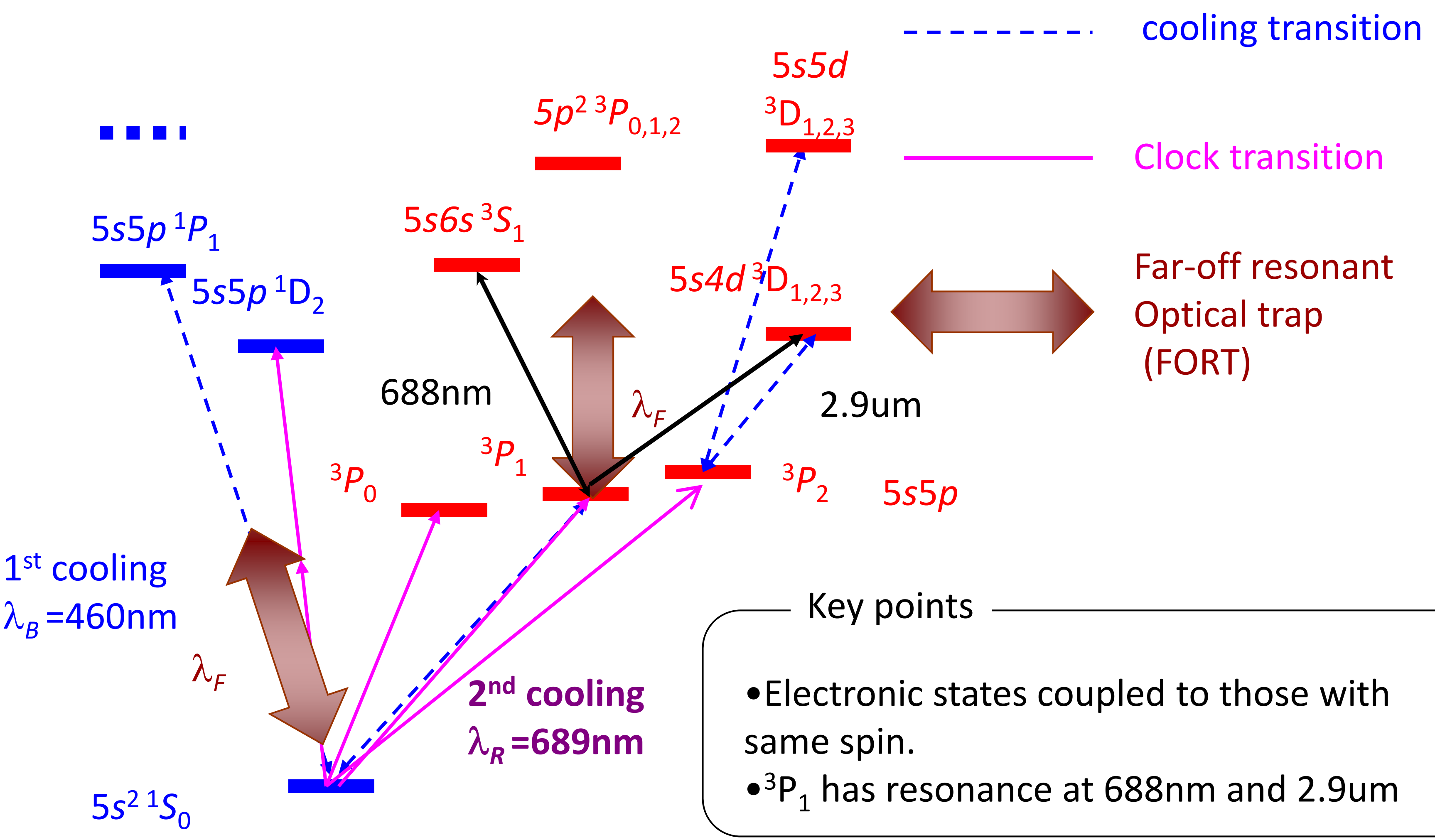


Definition:

Spatial confinement << transition wavelength

- Optical dipole potential for $^1S_0$, $^3P_1$ states
- $\Omega \gg \gamma\left(2\pi\times 7.1\mathrm{kHz}\right)$; resolved sideband
- Recoil frequency << Ω
- $\left|{}^1S_0, n\right\rangle \Rightarrow \left|{}^3P_1, n\right\rangle$; elastic scattering of photons

Optical dipole trap for alkaline earth atoms



Key points

- Electronic states coupled to those with same spin.
- $^3P_1$ has resonance at 688nm and 2.9um

Absorption
(from |g>)

Emission
(from |e>)

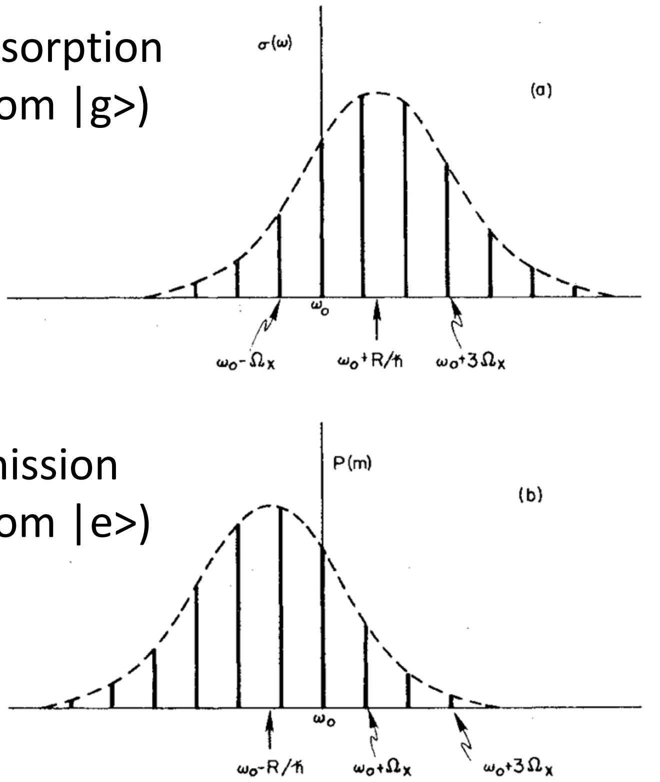


FIG. 7. Atomic spectra in classical limit ($\hbar\Omega_x \ll k_BT$) when $R \lesssim \hbar\omega_D$. Part (a) shows the absorption cross section for a laser directed along the x axis for the case when $\gamma \ll \Omega_x$ (giving the discrete lines) and when $\Omega_x \to 0$ (dashed curve) which is also the case for free atom. Part (b) shows the emission spectrum observed along the x direction for the same two cases.

D. Wineland and W. Itano,
"Laser cooling of atoms"
Phys. Rev. A, **20**, 1521 (1979)

ω_0: atomic (true) resonance
Ω_x: vibration frequency of confinment
R: photon recoil energy

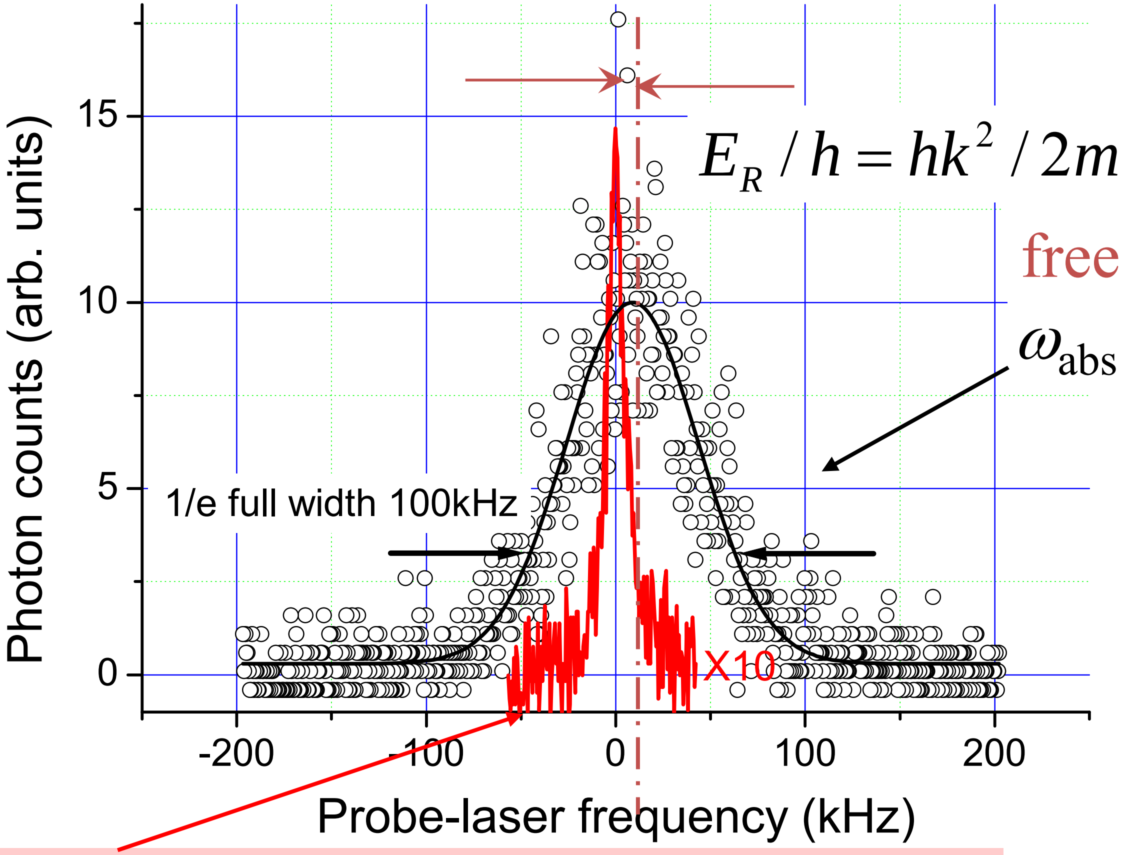
$$R = E_R = \frac{(\hbar k_L)^2}{2m}$$

------ Spectrum of free atoms with velocity distribution

Center shifts one recoil frequency from true resonance frequency

Confinements allows us to know where the resonance is.

Suppression of photon-recoil shift in Lamb-Dicke regime



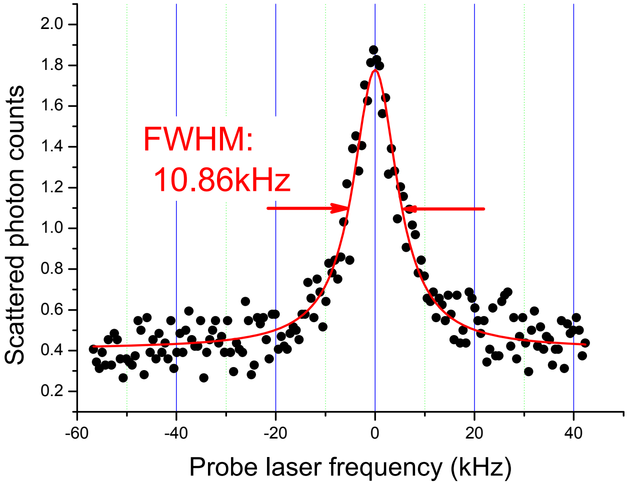
$E_R / h = hk^2 / 2m = 5\text{kHz}$

Doppler shift

Recoil shift

free space

$$\omega_{\text{abs}} = \omega_0 + \vec{k} \cdot \vec{v} + E_R / \hbar + O(v^2)$$



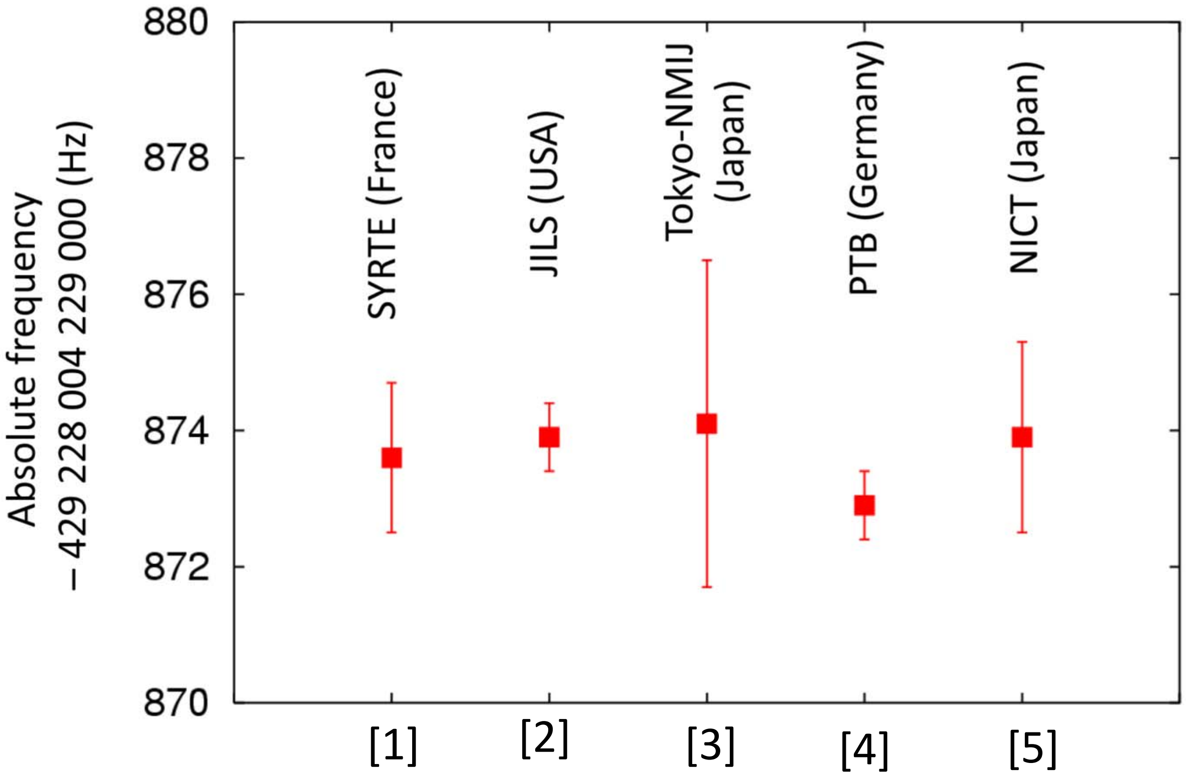
confined space: $\omega_{\text{abs}} = \omega_0 \pm n\Omega$

Lamb-Dicke regime: $I_{\pm 1} / I_0 << 1$

T. Ido and H. Katori, PRL **91** 053001 (2003).

Absolute frequency measured in NICT

429 228 004 229 873.9 (1.4) Hz (Cs limit)



[1] G. K. Campbell, *et al.*, Metrologia **45**, 539 (2008).
[2] X. Baillard, *et al.*, EPJD **48**, 11 (2008).
[3] F. L. Hong, *et al.*, Opt. Lett. **34**, 692 (2009).
[4] St. Falke, *et al.*, Metrologia, 48 399(2011)
[5] A. Yamaguchi, *et al.*, Appl. Phys. Express 5 022701 (2012)

Japanese Sr large uncertainty?

No. Basically due to the lack of stable Cs fountain clocks in Japan.
Both Japanese clocks rely on International Atomic Time

Goal:

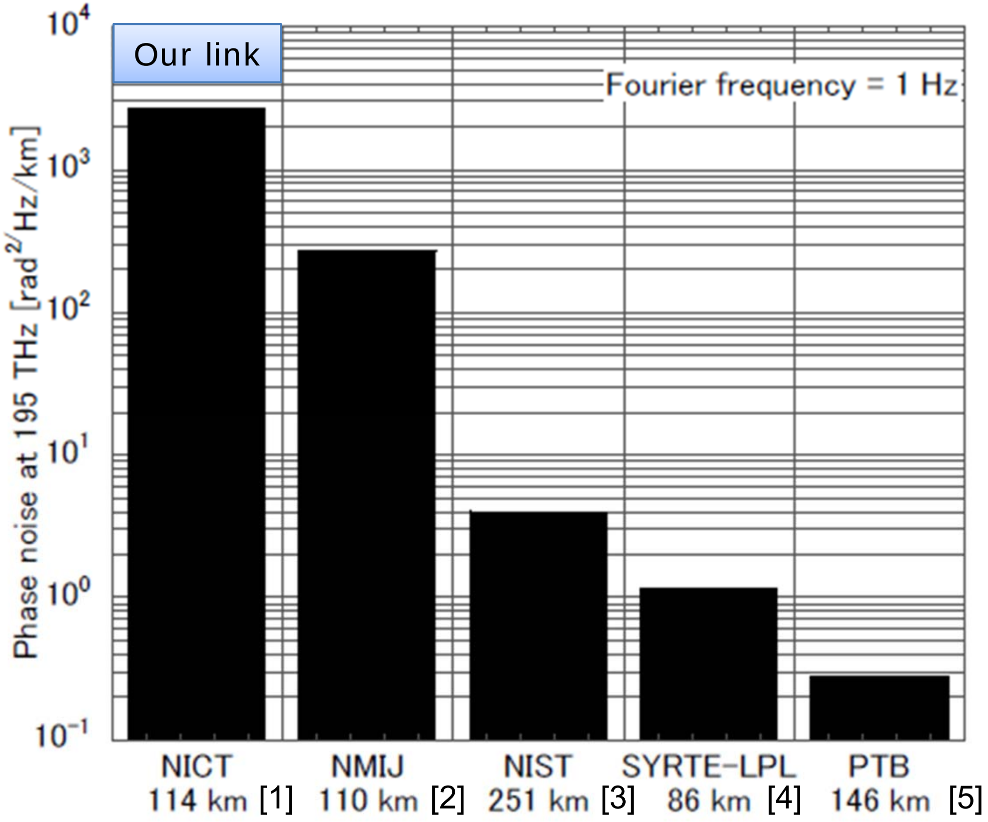
Confirmation of same frequency in ~10^{-16} between the clocks located at NICT and the Univ. of Tokyo by a fiber-link

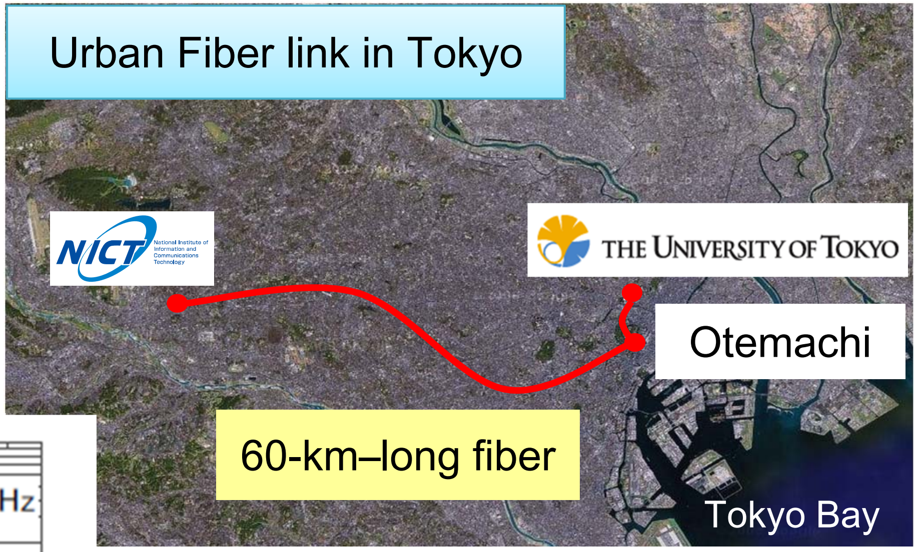
Tokyo is the only area that has two optical lattice clocks in distant laboratories.

Fiber link of clocks located at NICT and UT

[1] M. Kumagai *et al.*, Opt. Let. **34**, 19, 2949 (2009).
[2] M. Musha *et al.*, Opt. Exp. **16**, 21, 16459 (2008).
[3] N. Newbury *et al.*, Opt. Let. **32**, 21, 3056 (2007).
[4] H. Jiang *et al.*, J. Opt. Soc. Am. B **25**,12,2029 (2008).
[5] G. Grosche *et al.*, Opt. Lett. **34**, 2270 (2009).

Phase noise per km





Urban Fiber link in Tokyo

60-km–long fiber

Google map

Much larger amount of phase noise

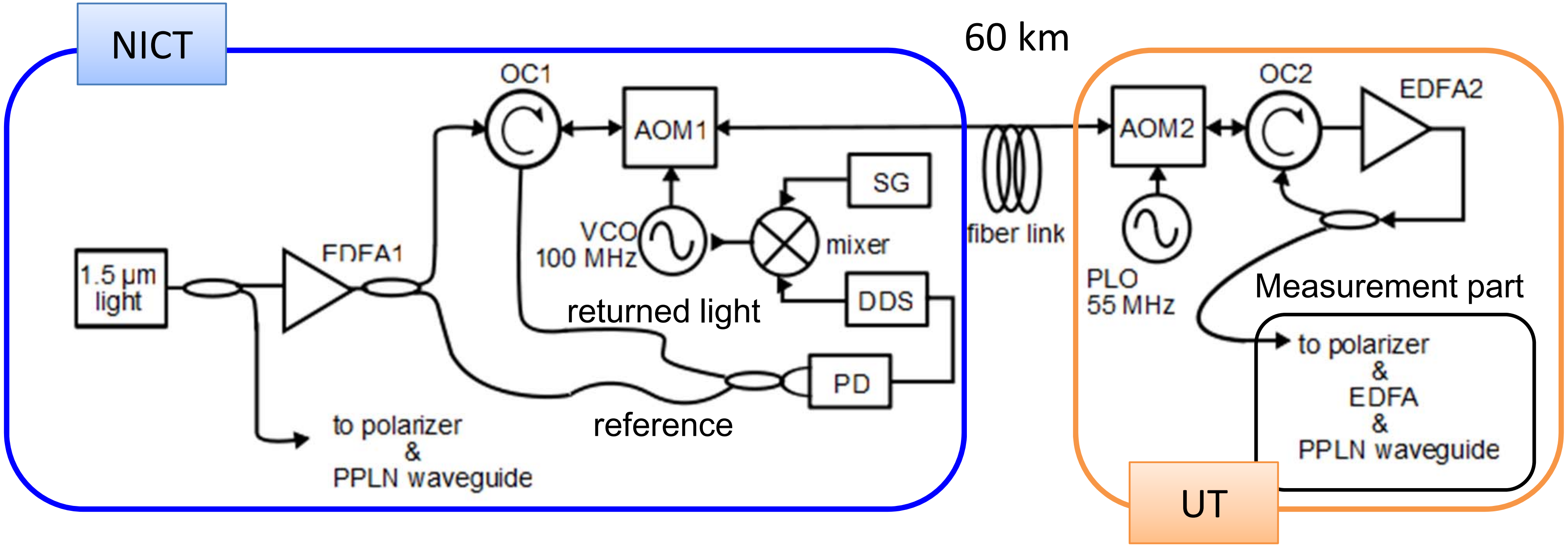
Probably due to

(1) Almost half of the link is buried along a subway line

(2) About one third of the link is wired in the air

Almost of the link noise comes from NICT-Otemachi part

Optical carrier transfer using a fiber link



Transfer system based on a fiber interferometer

- Double fiber noises, 2φ, canceled at the local site

  φ = 0 at the remote site

L. S. Ma *et al.*, Opt. Lett. **19**, 1777 (1994).

- EDFA is out of the phase-noise compensated path

⇨ Remaining half of the noise does not limit the performance of our system

By independent measurements

M. Fujieda *et al.*, Opt. Express. **19**, 16498 (2011).

Theoretical limit by round-trip cancellation

Round-trip signal delay ➡ limitation of loop bandwidth

Phase noise cancellation ratio:

$$\frac{S_{remote}(f)}{S_{fiber}(f)} = \frac{1}{3}(2\pi f\tau)^2$$

S_{remote}: phase noise at remote site
S_{fiber}: fiber induced phase noise

f: Fourier frequency
τ: One-way traveling time

Ref: Williams et al., JOSA B 25 8.

ex. In 90 km transfer, cancellation ratio = 56 dB at 1 Hz

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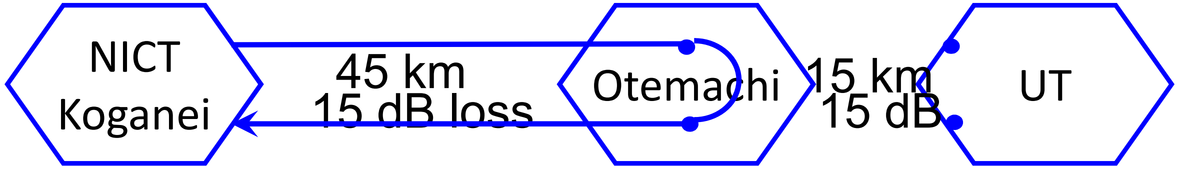
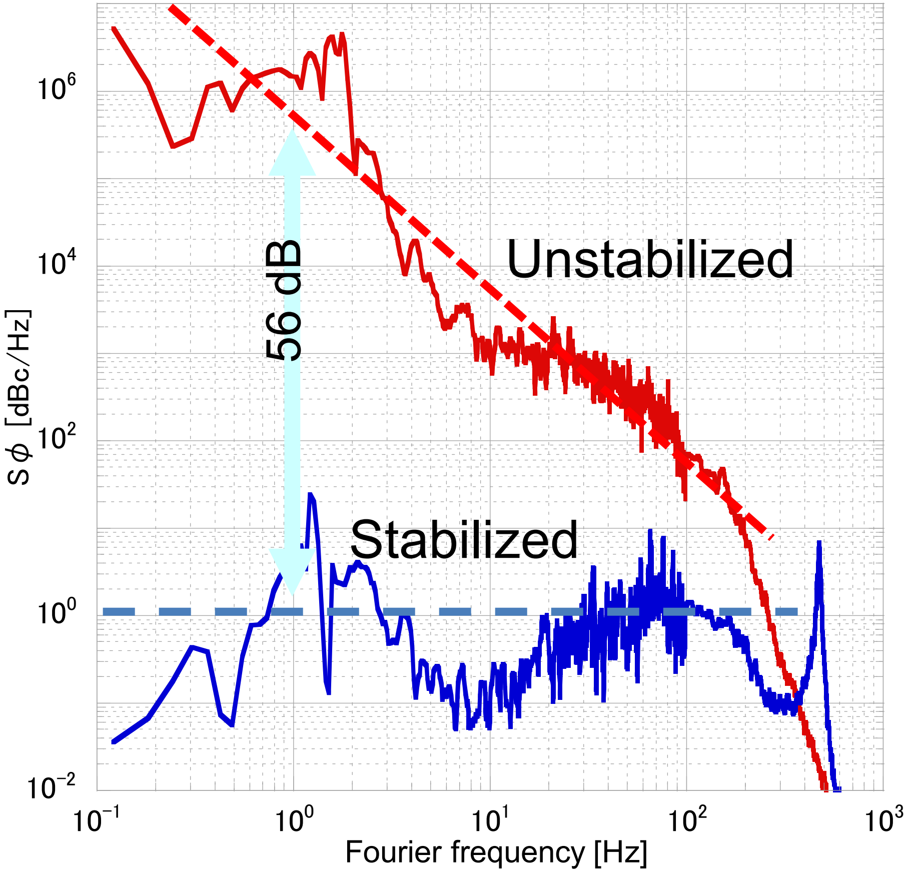
Evaluation of the fiber link

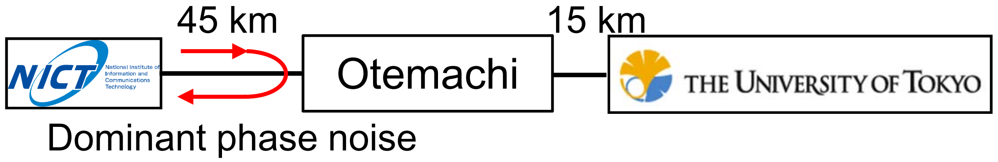


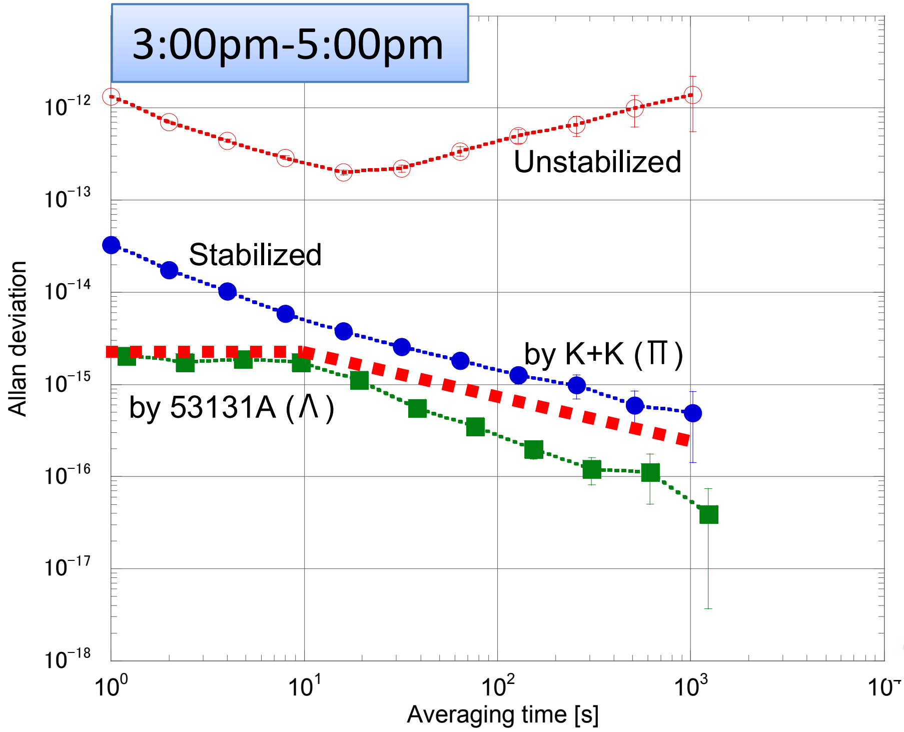
Total length: 90 km, optical loss: 30 dB

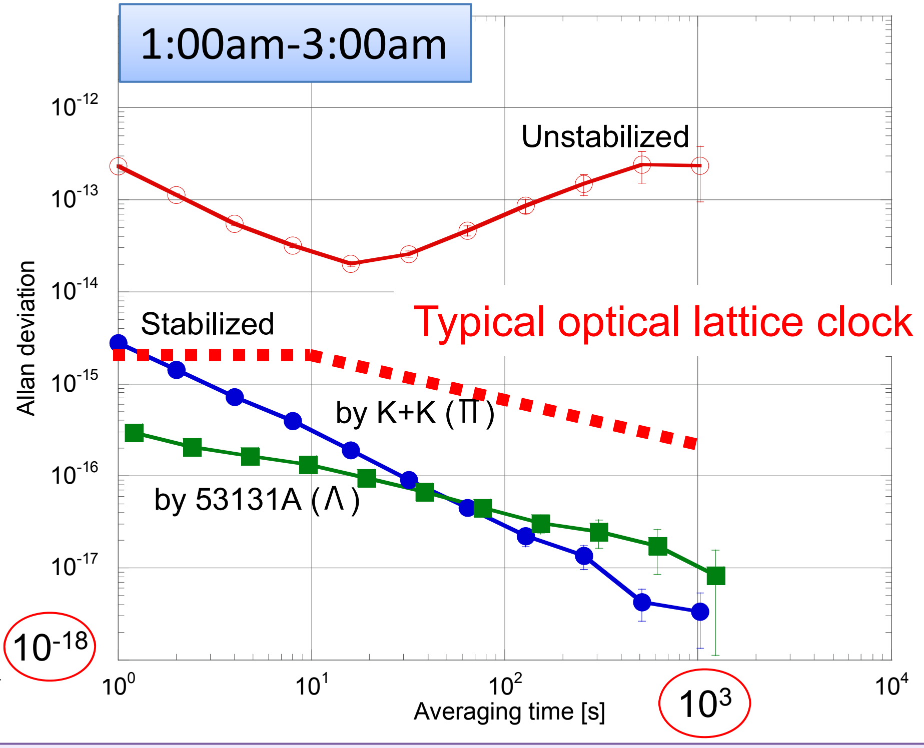


Instability of a fiber link: Day & Night

Transfer instability of out-of-loop beat
in NICT-Otemachi round-trip link





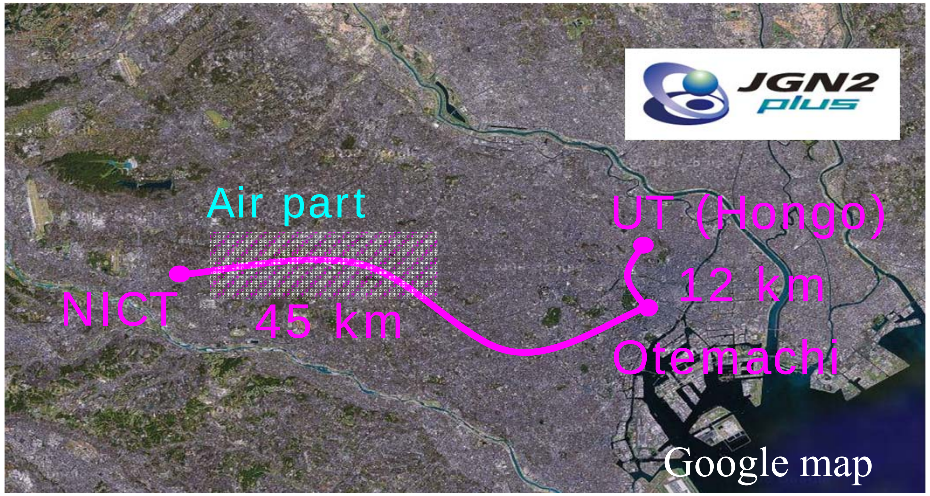


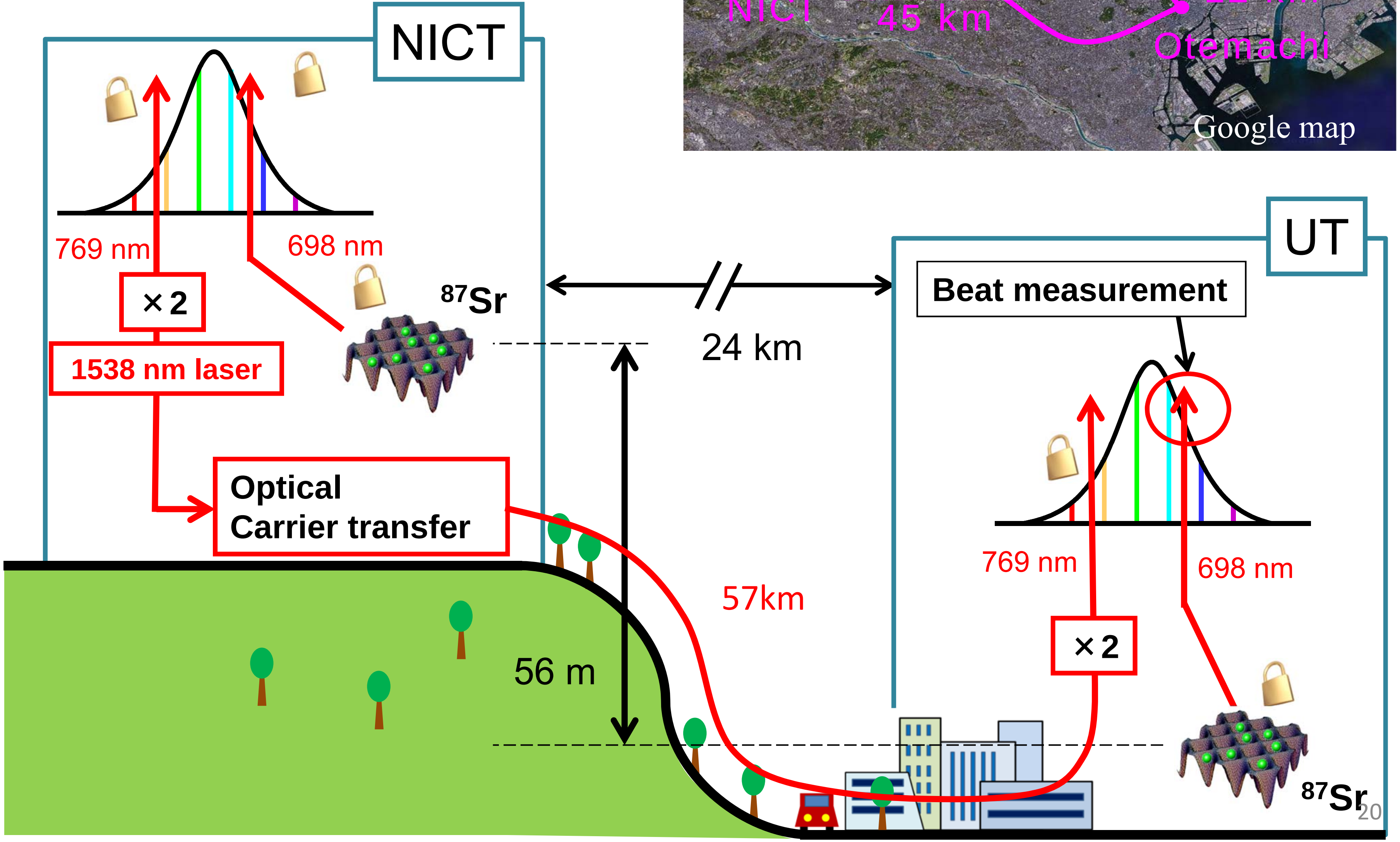
Overall system instability: 2×10^{-15} at 1s
7×10^{-17} at 1000s

Should be done
in midnight in current circumstances

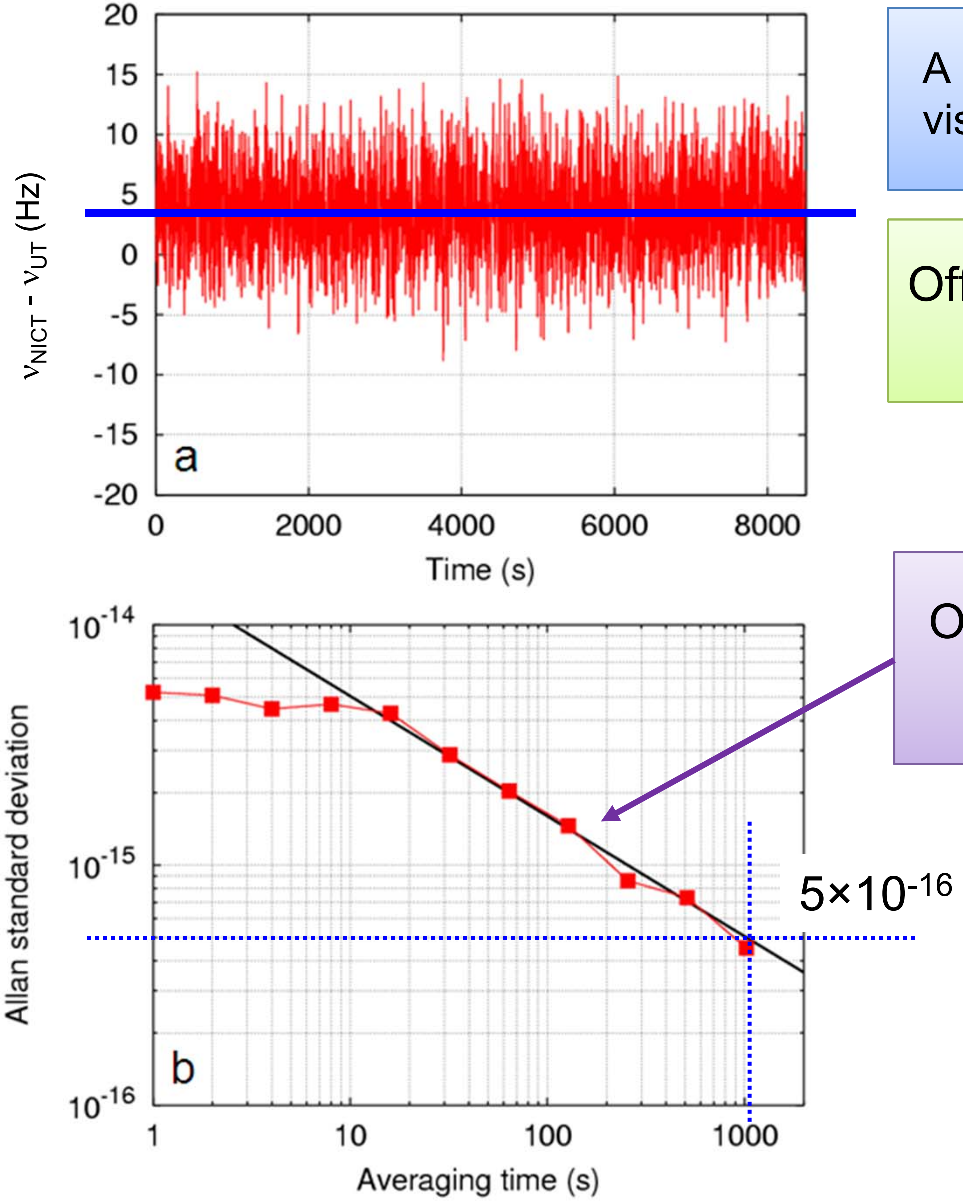
Including:
- EDFA
- waveguide PPLN
- frequency comb

All-optical direct comparison between NICT & UT clock





Frequency difference & stability between distant Sr clocks



A Hz-level frequency difference is clearly visible over the time scale of minutes

Offset: predominantly due to differential gravity shift

Obtained instability

$1.6\times10^{-14}/\sqrt{\tau}$

consistent

Dick-effect-limited instability

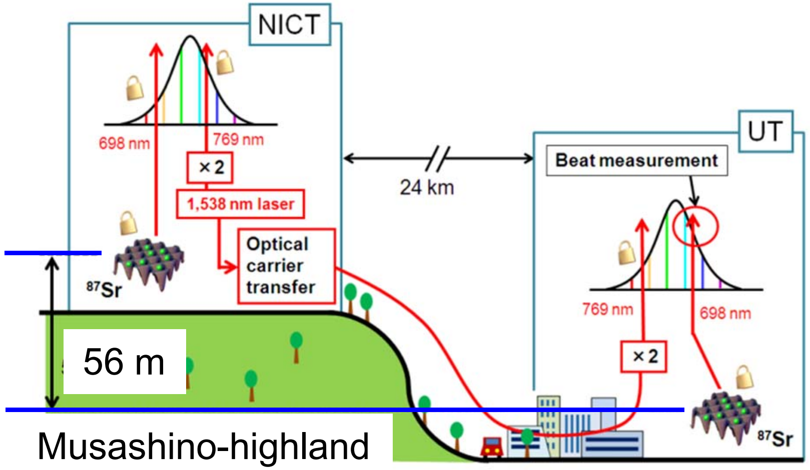
UT : $6.0\times10^{-15}/\sqrt{\tau}$

NICT : $1.5\times10^{-14}/\sqrt{\tau}$

Corrections and uncertainties at UT and NICT

	UT (Hz)		NICT (Hz)	
contributor	Correction	Uncertainty	Correction	Uncertainty
AC Stark –Lattice	0.19	0.10	0.10	0.10
AC Stark -Probe	0.00	0.00	0.01	0.01
BBR	2.1 7	0.10	2.26	0.10
2nd Zeeman	1.24	0.10	0.23	0.10
Gravitational shift	-0.95	0.09	-3.57	0.05
Collision	0.00	0.10	-0.04	0.12
Servo error	0.00	0.01	0.00	0.01
Total	2.65	0.22	-1.01	0.22

(Link uncertainty to SI second) (0.78)



Elevation of a lattice clock from Earth's geoid surface

UT: 20.37 ± 2 m

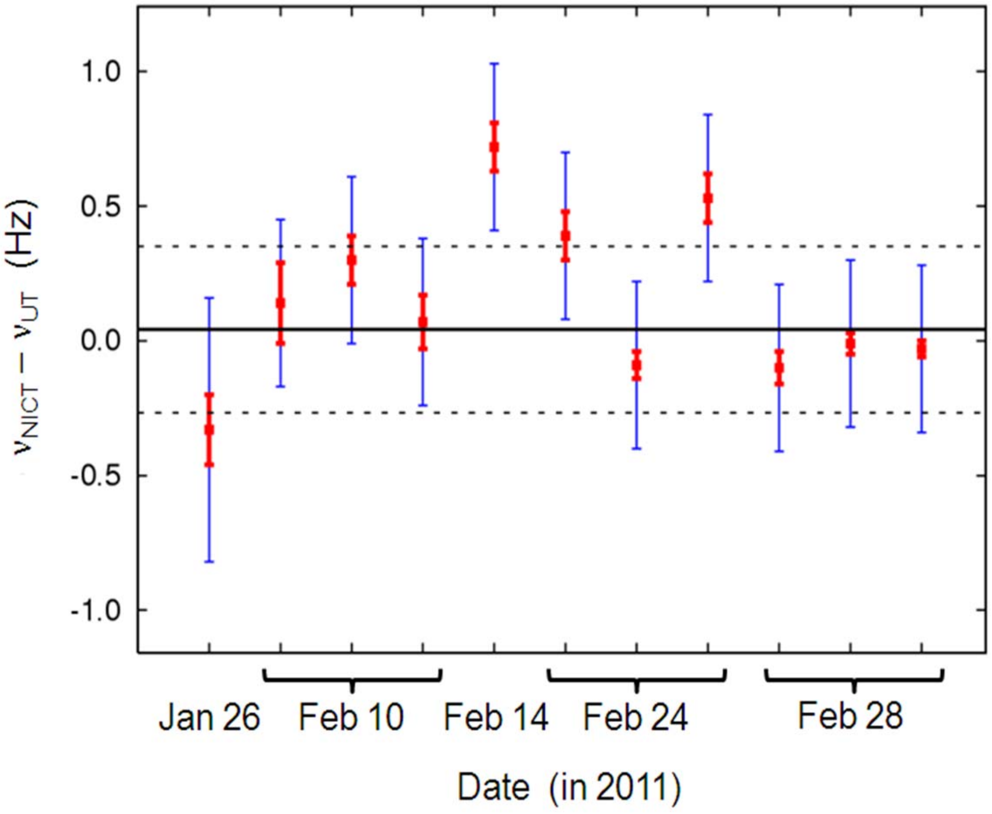
NICT: 76.33 ± 1 m

Systematic shift of Frequency difference

$\nu_{NICT} - \nu_{UT}$ = 3.66 (0.31)Hz

Frequency difference between two distant Sr clocks

Frequency difference after correcting systematic frequency shift



Total systematic uncertainty of two clocks (0.31Hz)

Measurement records in the range of 900-12000s

Weighted mean 0.04Hz (1.0×10^{-16}) < Total systematic uncertainty 0.31Hz (7.3×10^{-16})

(Solid black line in figure)

(dashed lines in figure)

No limitation imposed by the fiber transfer

Agreement between institutes for the 1st time in 10^{-16} level !

Atomic clocks: tools to measure gravity ?

Only for accurate measurement of Gravity force,
gravimeter is very accurate. The state-of-the-art uncertainty is 1×10^{-9}.

But only shows spatial gradient of the potential .

Clocks directly observe the potential.

Gravitational potential:
Just a concept in classical mechanics.
But accurate clocks changes it to a real object of observation.

How much does OUR time pass slowly due to the gravity?

$$\frac{GM_E}{r_E c^2} = \frac{6.67 \times 10^{-11} \times 6 \times 10^{24}}{6.4 \times 10^6 \times (3 \times 10^8)^2} = 6.9 \times 10^{-10}$$

$M_E = 6 \times 10^{24}$kg: mass of the earth

$r_E = 6400$ km: radius of the earth

earth

$$\frac{GM_S}{r_S c^2} = \frac{6.67 \times 10^{-11} \times 2 \times 10^{30}}{1.5 \times 10^{11} \times (3 \times 10^8)^2} = 9.9 \times 10^{-9}$$

$M_S = 2 \times 10^{30}$kg: mass of the sun

$r_E = 1.5 \times 10^8$ km: radius of the earth orbital

Sun

Ideal time would be defined by an atom in no gravity environment?
Impossible to realize it. → Current definition on the earth could be a compromise…

Our time ticks 1 × 10^{-8} slower than the ideal due to the gravity,
not from the earth but from the sun.

Another question: Are transition frequencies determined by electromagnetic interaction affected by gravitational field ?

Atomic clocks show that space and time is not independent (general relativity)

And… may show that transition frequency is affected by gravity thorough a coupling of α to gravity.

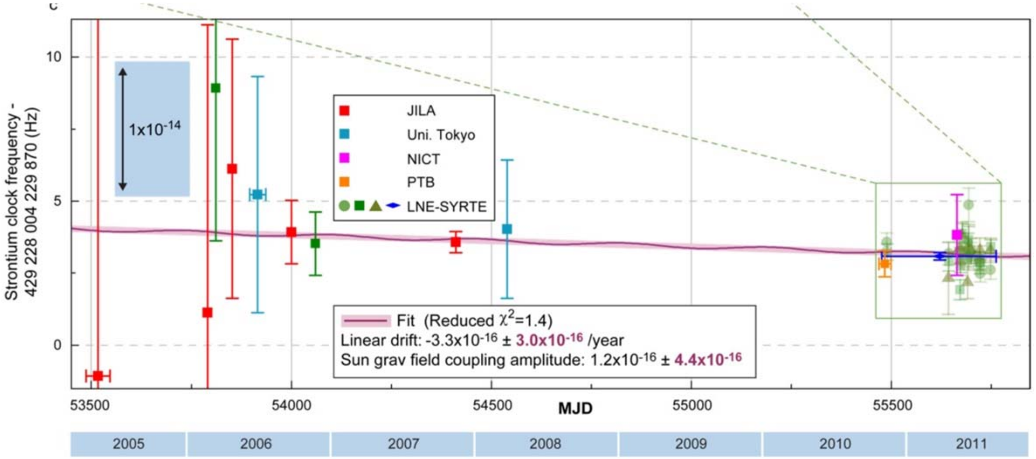
Gravity & EM force coupled → info to know correlation between gravity & others

Comparing transition frequency in summer and winter?
Snow can be kept until next summer. But frequency cannot.

All we can do is to make absolute frequency measurement in summer and winter…

If α is coupled to the gravity,
f(Sr)/f(Cs) may show annual oscillations.

The ratio between two optical transitions should be more sensitive to detect the coupling.

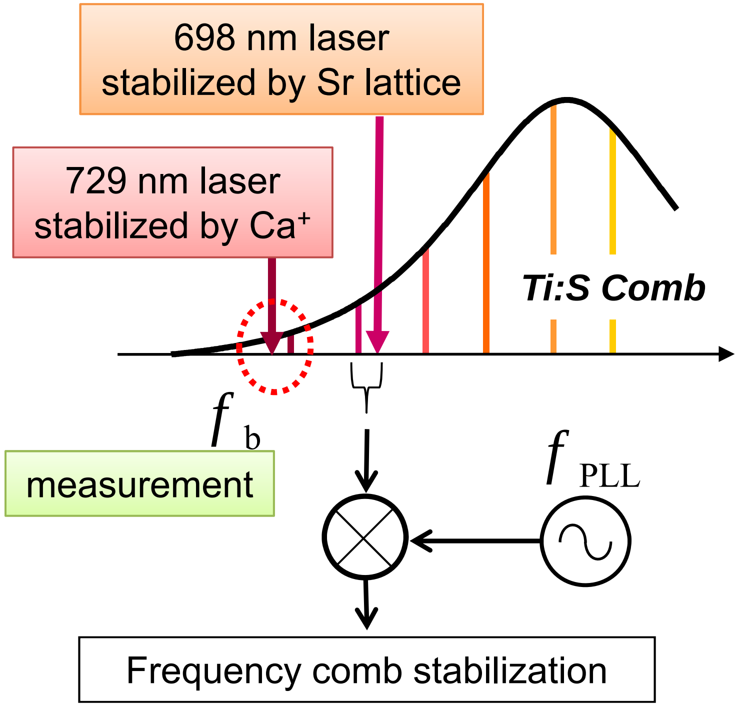


R. Le Targat et al., arxiv:1301.6046

AIST will join soon. The largest community!!

All optical measurement of frequency ratios : That's the measurements based on optical standard

Frequency bridge by optical frequency comb



Frequency ratio $\frac{\nu_{Ca}}{\nu_{Sr}}$

$$\frac{\nu_{Ca}}{\nu_{Sr}} = \underbrace{\boxed{\frac{N_2}{N_1}}}_{\sim 1} + \underbrace{\boxed{\frac{\overset{(\sim 10^{7}\text{ Hz})}{\boxed{\left(1-N_2/N_1\right) f_{ceo} - \left(N_2/N_1\right) f_{PLL} + f_b}}}{\nu_{Sr}\ (\sim 10^{14}\text{ Hz})}}}_{\sim 10^{-7}}$$

f_{CEO}, f_{b}, f_{PLL} : 10^{-10} fractional accuracy

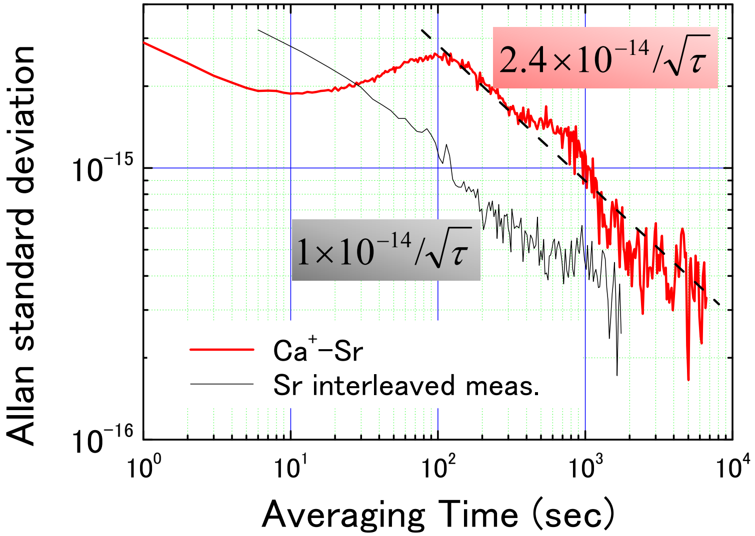
⇨ Sufficient for evaluation at the level of 10^{-16}

Stability and Frequency Ratio

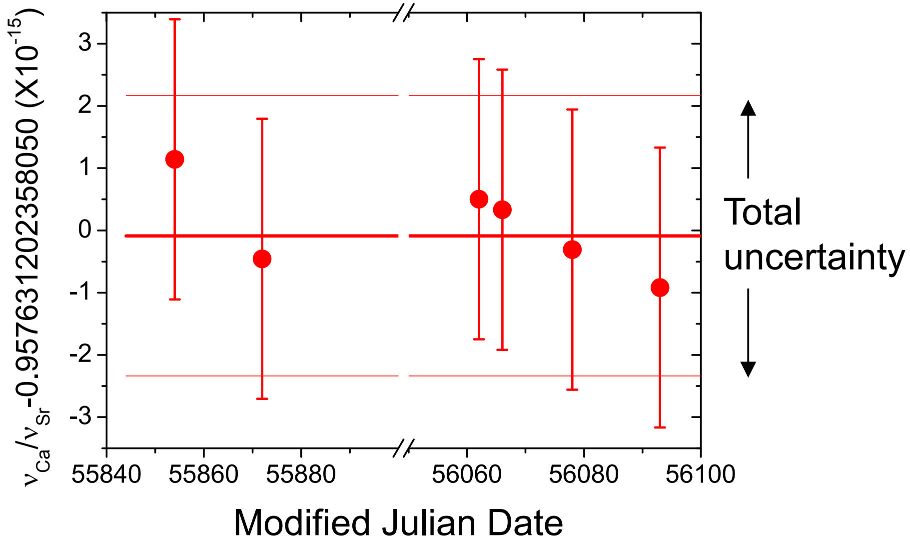
Frequency ratio

$$\frac{\nu_{Ca}}{\nu_{Sr}} = 0.957\ 631\ 202\ 358\ 049\ 9\ (2\ 3)$$

Instability at the ratio measurement



Ratios measured at each of 6 days



Reproducibility of <10^{-15} is consistent with the systematic uncertainties of two clocks

K. Matsubara *et al.*, Opt. Express, **20** 22034 (2012).

Sr and Ca+ : bridge between the most major lattice clocks & ion clocks

Sr:	5 in operation and others will soon follow
Ca+:	3 in operation

Ca+ clock will not be an ultimate.
But still there is reason for an accurate characterization.

1. test of the α-variation
using a sensitive neutral Hg clock & insensitive Al+ clock

$$\frac{\nu(Hg)}{\nu(Al+)} = \frac{\nu(Hg)}{\nu(Sr)} \times \frac{\nu(Sr)}{\nu(Ca+)} \times \frac{\nu(Ca+)}{\nu(Al+)}$$

Locally available
at U. Tokyo and SYRTE

QIP ion clock
Al+: spectroscopy
Ca+: logic (& spectroscopy)

2. Ca+ as a logic ion also works as a meter to probe the electromagnetic environment of the trap center.
→ Need the frequency as accurate as possible

Summary

Lattice clocks

- Lots of ion clocks equivalent
- Sr: the most popular second representation of the second
- Yb: NIST & AIST→ lately recognized as a second representation

Optical clocks will redefine the second after

- progress is slowed
- method to confirm the identical frequency across the sea is established

Ratio, ratio, ratio

measurement = evaluation of a ratio against a standard

NICT-UT link, α variation, α–gravity coupling, Ca+/Sr ratio, …

Absolute frequency based on Cs is no longer absolute at the ultimate of metrology. Ratio, in other words relative things are what we can trust.