Optical lattice clocks
& time scale as an application

Tetsuya Ido

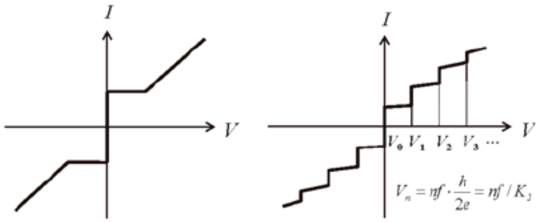
Space-Time Standards Laboratory
National Institute of Information and Communications Technology
Japan

NICT (Japan) : not an NMI, but generates, maintain, and disseminate Japan Standard Time

outline

- Dawn in optical lattice clocks
    - Laser cooling of alkaline earth atoms
    - Recoil-free spectroscopy of neutral atoms
- Japan Standard Time
- Absolute frequency measurement with respect to International atomic time (TAI)
- Time scale
- TAI evaluation using strontium

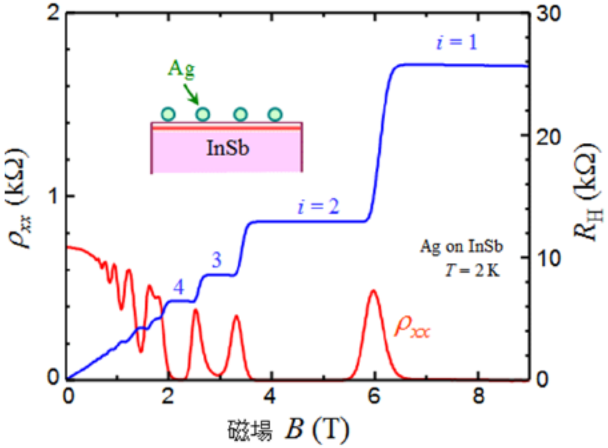
Quantum nature often helps metrologists



No microwave なし

With microwave
Shapiro step

Josephson junction



Quantum hall effect

Energy level of atoms are also discrete.

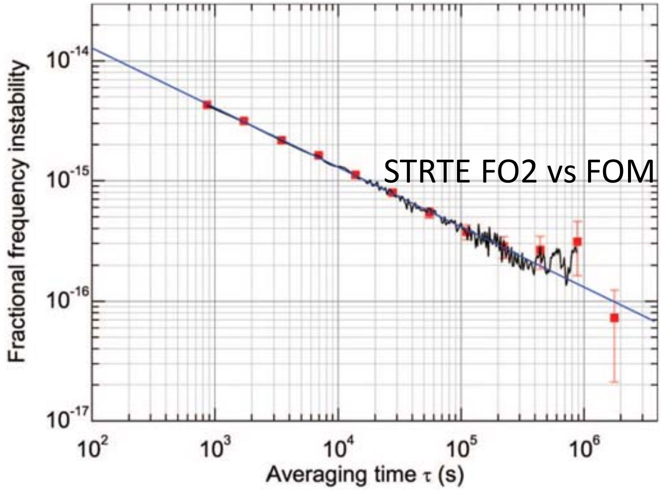
→ Atomic clock

Definition of the second

Cs hyper fine transition since 1967

Transfer from astronomy to atomic physics

Current SI second: Cs hyperfine transition



Guena et al., IEEE Trans. **59**, 391 (2012).

NICT-CsF1

- Accuracy limited around 2e-16 in recent 5 years
- 10 days averaging required to reach the accuracy of 2e-16

→ long operation hampers further improvement

Optical clocks are “in principle” much faster due to the high line-Q.
1e-15@1s or better should be possible.

But optical transition has…

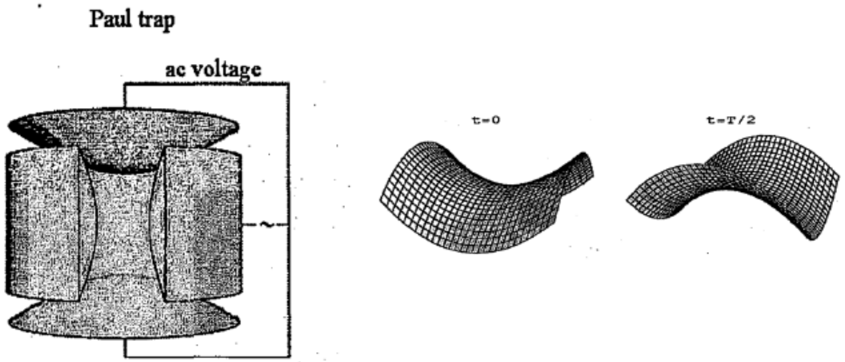
- Doppler broadening
  ~GHz(10^{-5}) at room temprature.
- 100kHz(10^{-9}) even laser-cooled sample

In other words, external degree is still classical

Quantization of external degree

Spatially confining atoms give rises discrete vibrational levels

Tight confinement to zero-perturbation point
→ ion trap using AC E-field



How about neutral atoms?

Alkaline earth has good ground state $^1S_0$

True resonance

One photon-recoil

Spectrum in free space

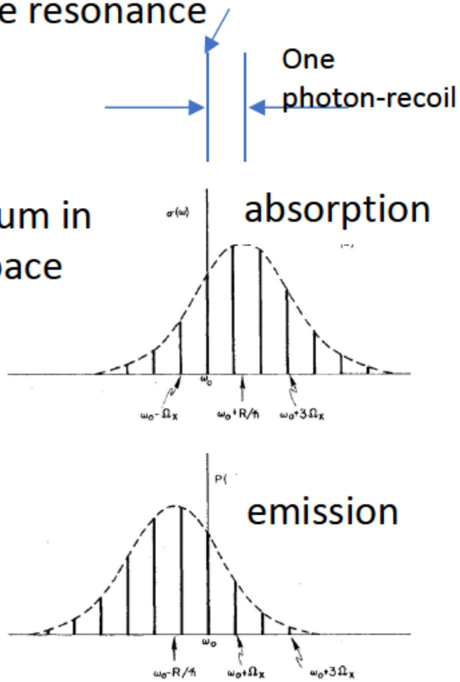
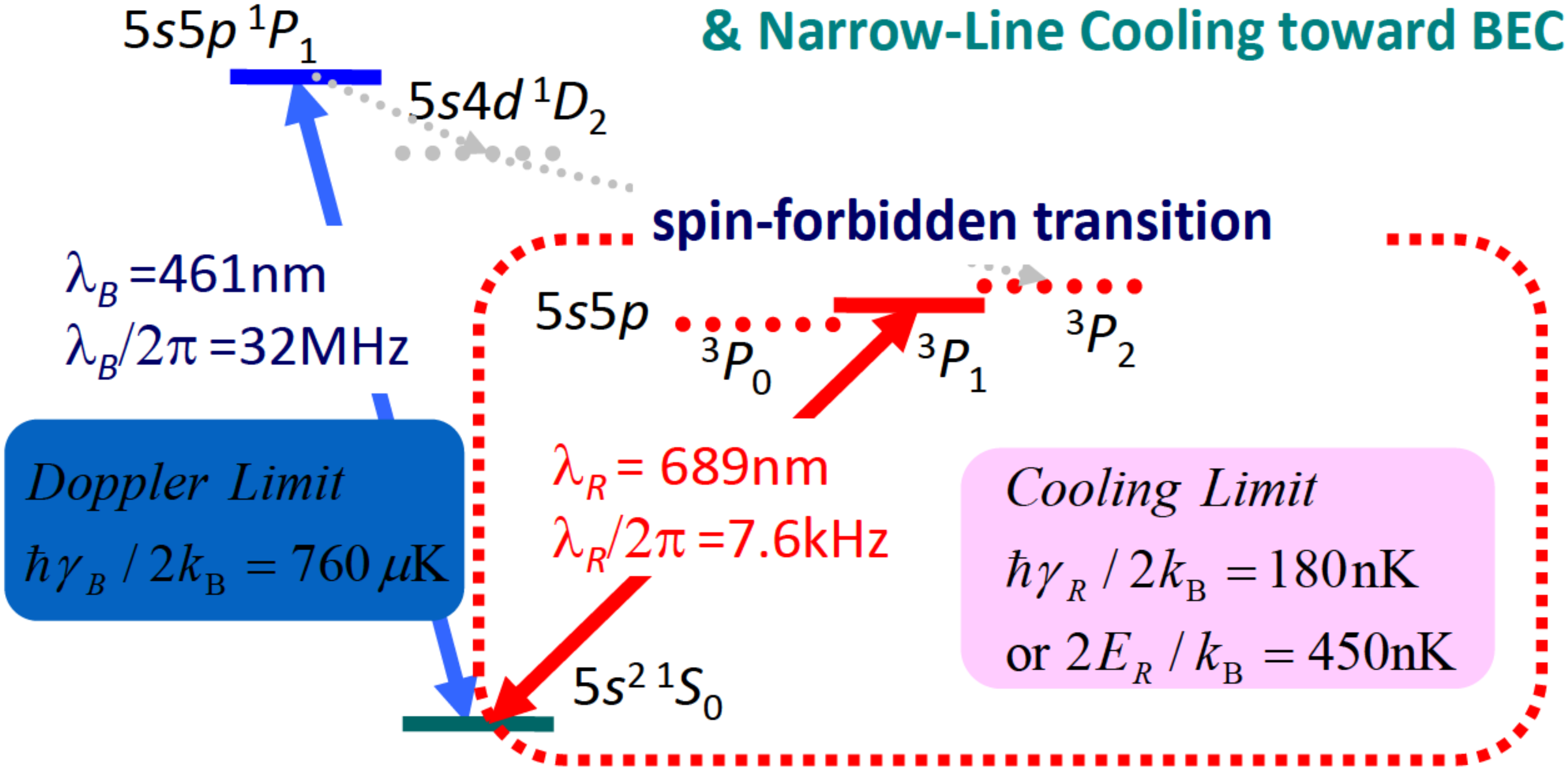


FIG. 7. Atomic spectra in classical limit ($\hbar\Omega_x \ll k_B T$) when $R \lesssim \hbar\omega_D$. Part (a) shows the absorption cross section for a laser directed along the x axis for the case when $\gamma \ll \Omega_x$ (giving the discrete lines) and when $\Omega_x \to 0$ (dashed curve) which is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

Optical dipole trap using interference fringe allows tight confinement.

But
Need to cool down to μK regime. No magnetic sublevel prohibits polarization gradient cooling
Intensity dependent systematic shift → non-sense for freq. standard..

Strontium Energy Levels & Narrow-Line Cooling toward BEC



$5s5p\ {}^1P_1$

$5s4d\ {}^1D_2$

$\lambda_B = 461\text{nm}$
$\lambda_B/2\pi = 32\text{MHz}$

spin-forbidden transition

$5s5p$ $^3P_0$ $^3P_1$ $^3P_2$

Doppler Limit
$\hbar\gamma_B / 2k_B = 760\,\mu\text{K}$

$\lambda_R = 689\text{nm}$
$\lambda_R/2\pi = 7.6\text{kHz}$

Cooling Limit
$\hbar\gamma_R / 2k_B = 180\text{nK}$
or $2E_R / k_B = 450\text{nK}$

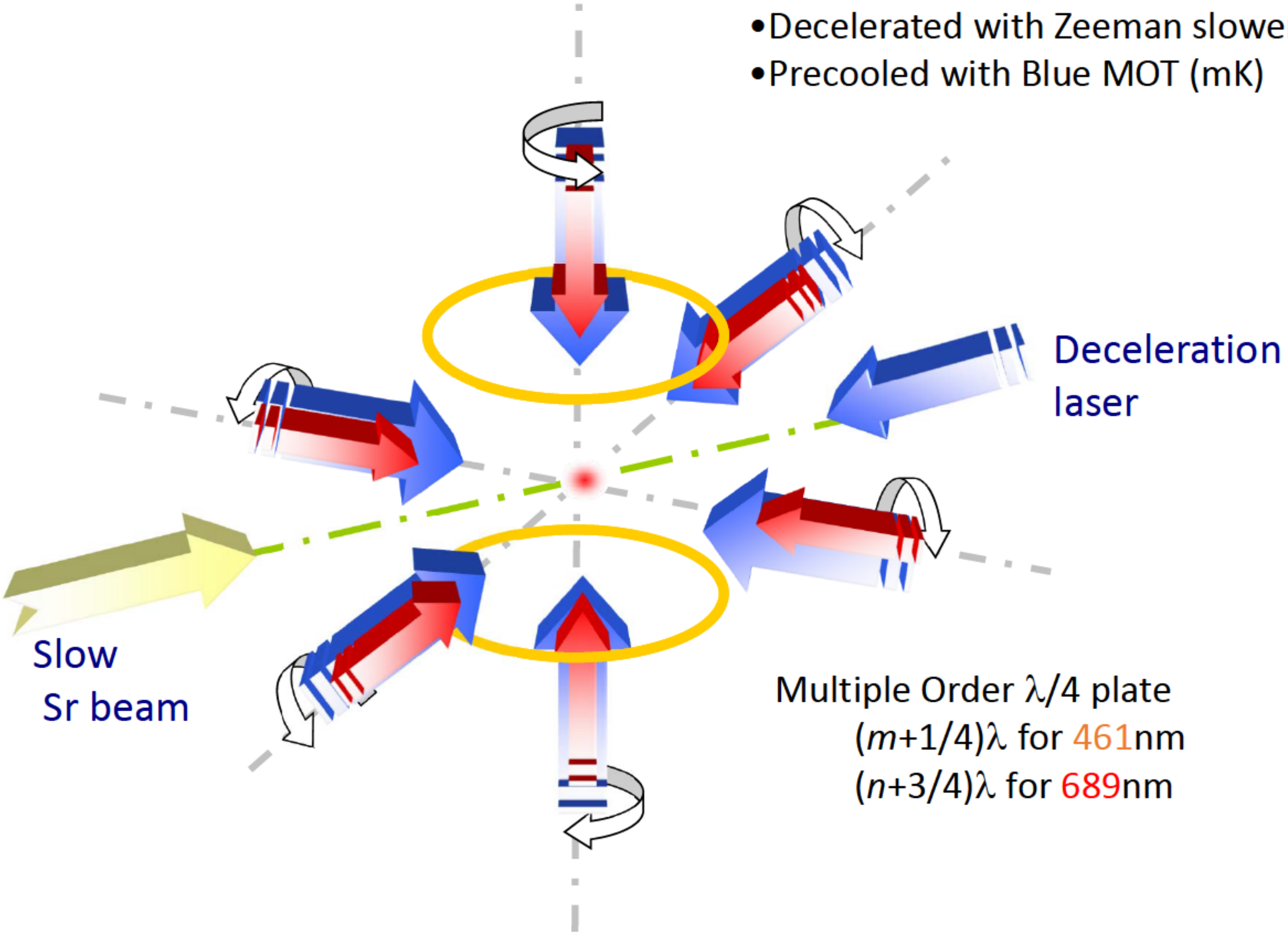
$5s^2\ {}^1S_0$

Features

- Suppression of radiation trapping; $\gamma < \hbar k^2/m$ (recoil shift; 9.4kHz)
- Recoil limited temperature
- Stable trapping under gravity; $a_{\max} = \hbar k\gamma/2m$ (155m/s^2)
- Two stage cooling

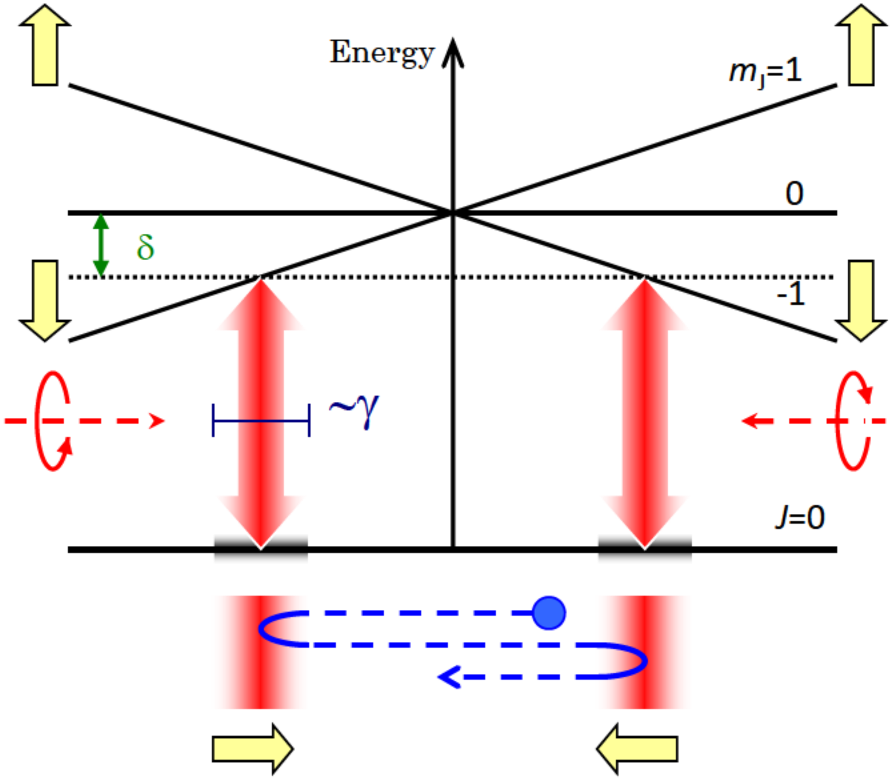
2-stage MOT for Strontium to reach μK regime

- Decelerated with Zeeman slower
- Precooled with Blue MOT (mK)



Multiple Order λ/4 plate
$(m+1/4)\lambda$ for 461nm
$(n+3/4)\lambda$ for 689nm

Narrow Line MOT
for High Phase Space Density



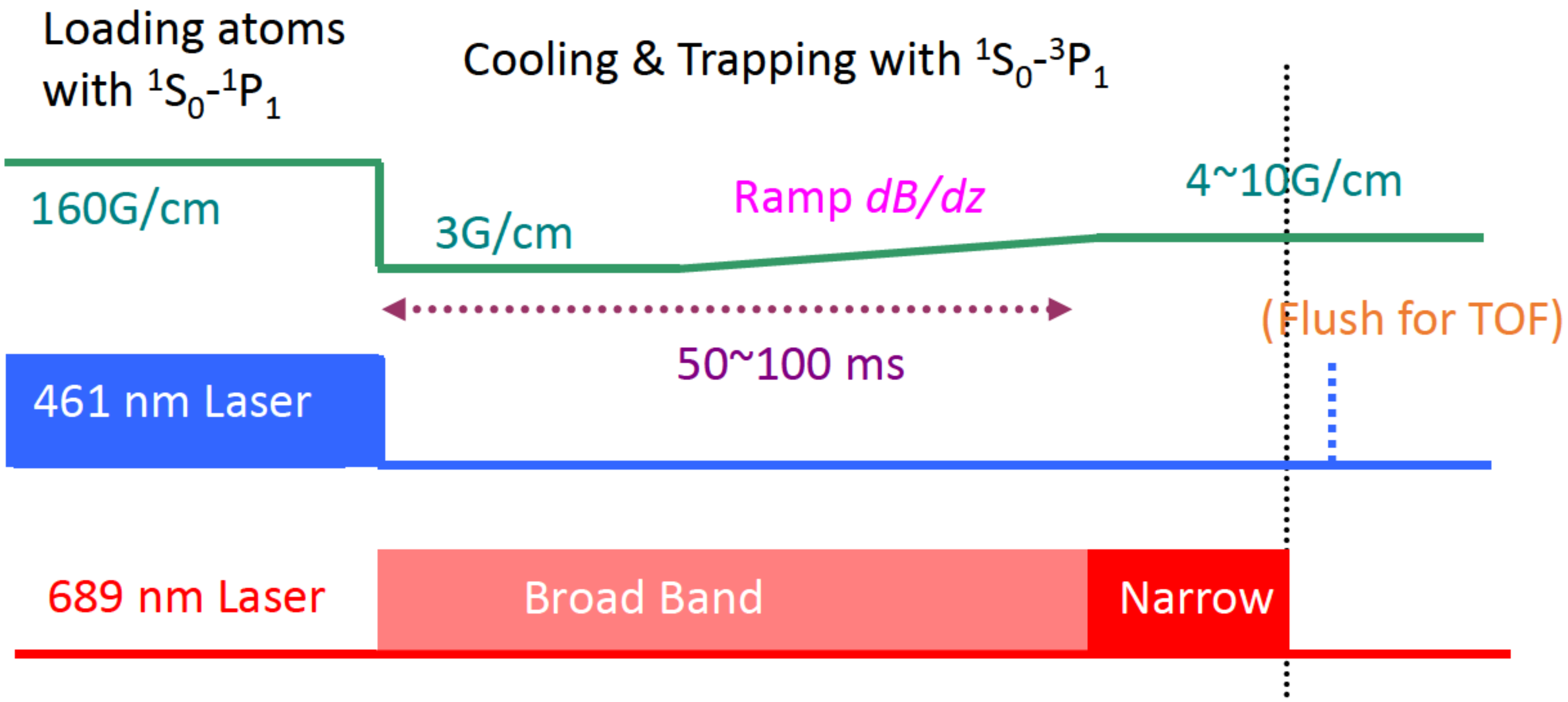
- Position dependant excitation.
- Less reabsorption of scattered photons

Accumulate atoms
with broad band laser in large
trap volume

Compress the atom cloud by increasing *dB/dz*

Decrease blue-detuned wing of the laser spectrum

Experimental Procedure



Loading atoms with $^1S_0$-$^1P_1$

Cooling & Trapping with $^1S_0$-$^3P_1$

160G/cm

3G/cm

Ramp dB/dz

4~10G/cm

50~100 ms

(Flush for TOF)

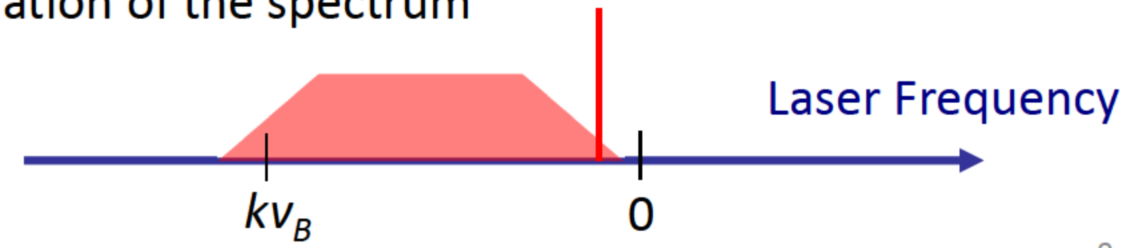
461 nm Laser

689 nm Laser

Broad Band

Narrow

Manipulation of the spectrum



Laser Frequency

kv_B

0

Experimetnal Parameter

Blue MOT

δ=70MHz, T_{blue} ~ mK, dB/dz = 160G/cm

Red MOT

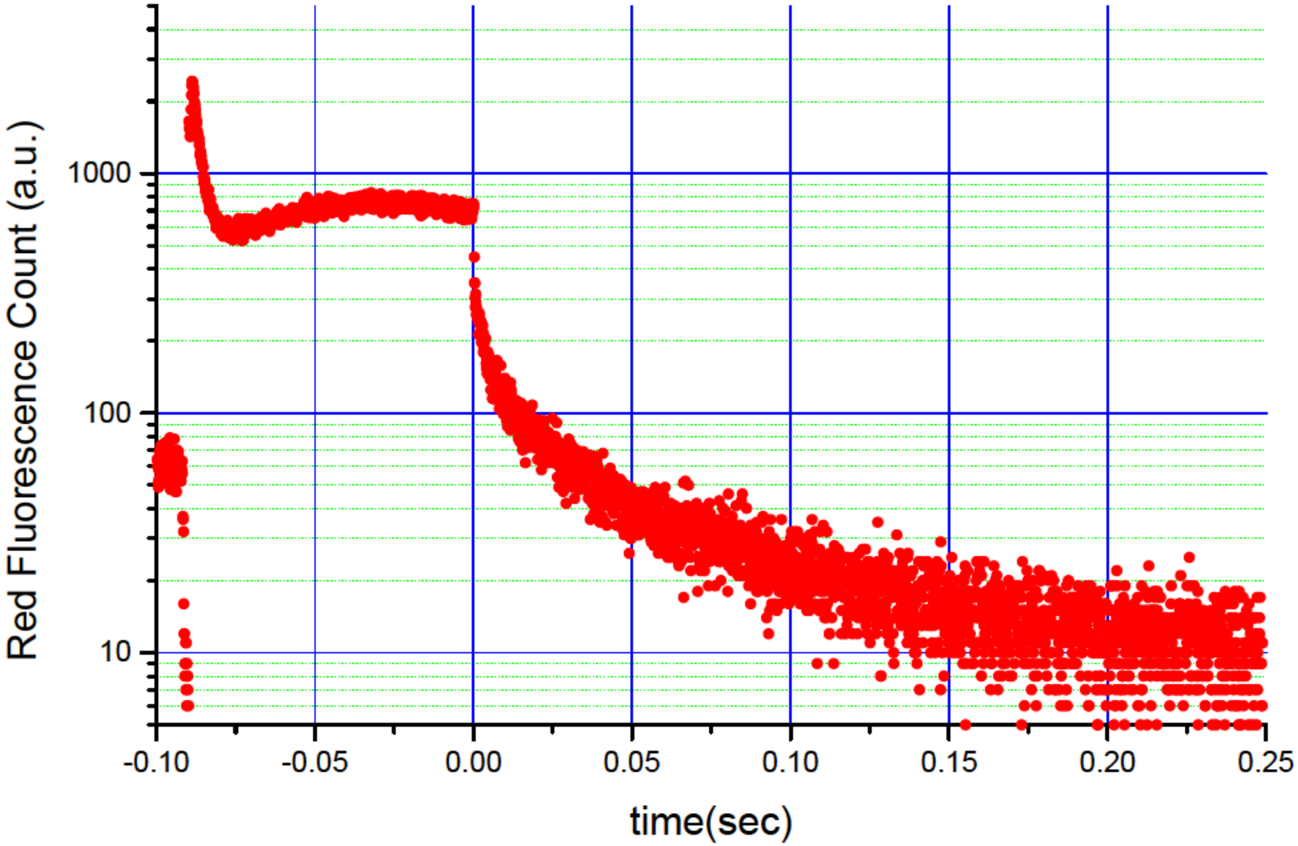
Broad spectrum :

Center Frequency:	-1.6MHz
Moduration Frequency:	50kHz
Bandwidth:	3MHz ($k_b v_b$~500kHz)
Duration:	50-100msec
dB/dz:	Ramped 3→4-10G/cm

Single frequency:

detuning:	δ = -50~-300kHz (γ = 8kHz)
Total power density:	I = 10μ~5mW/cm^2(I_{sat}=3μW/cm^2)
dB/dz:	4~10G/cm

Red MOT Fluorescence Decay



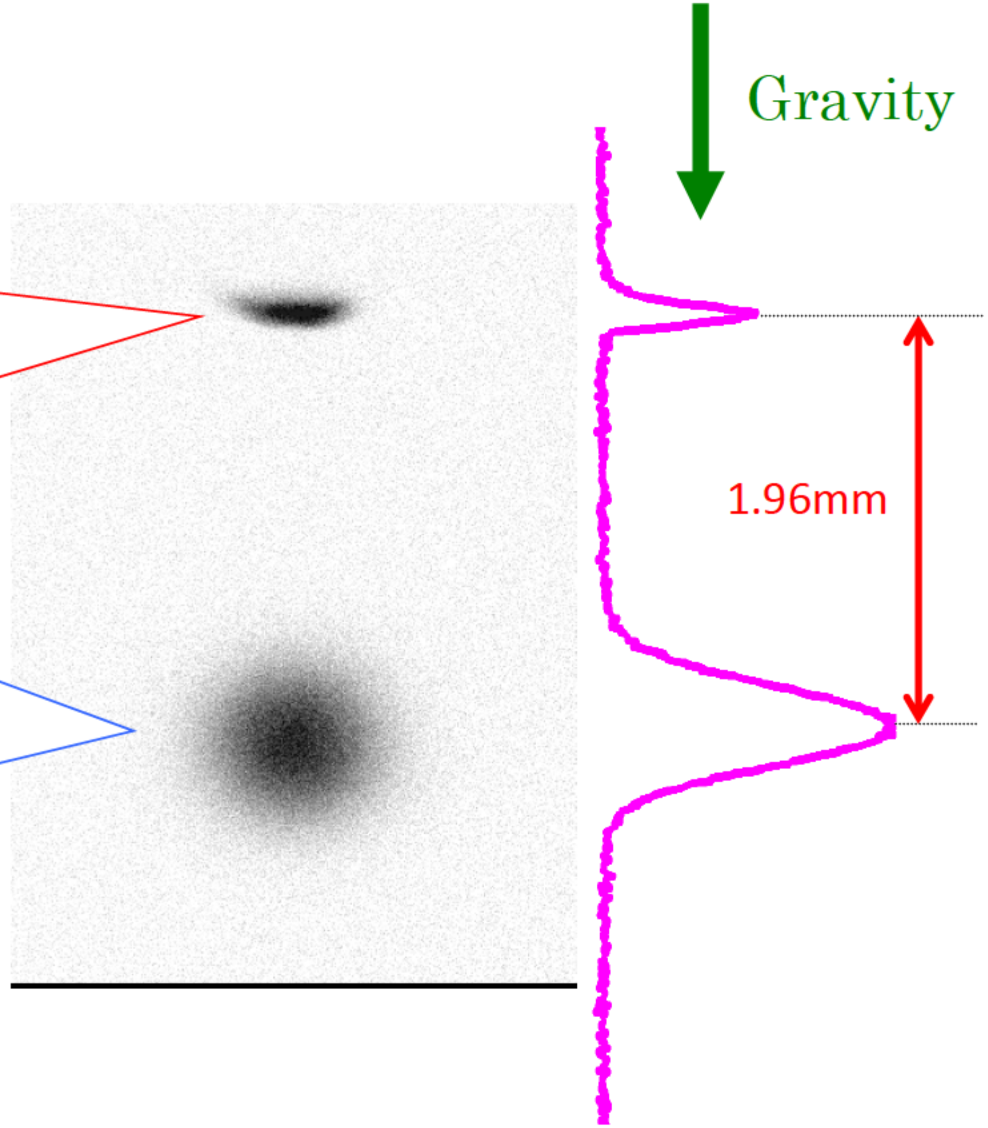
TOF Measurements for atoms in the MOT

RED MOT after compression:
Diameter: 50~500μm
depending on *dB/dz* and
laser detuning
Shape distorted by gravity

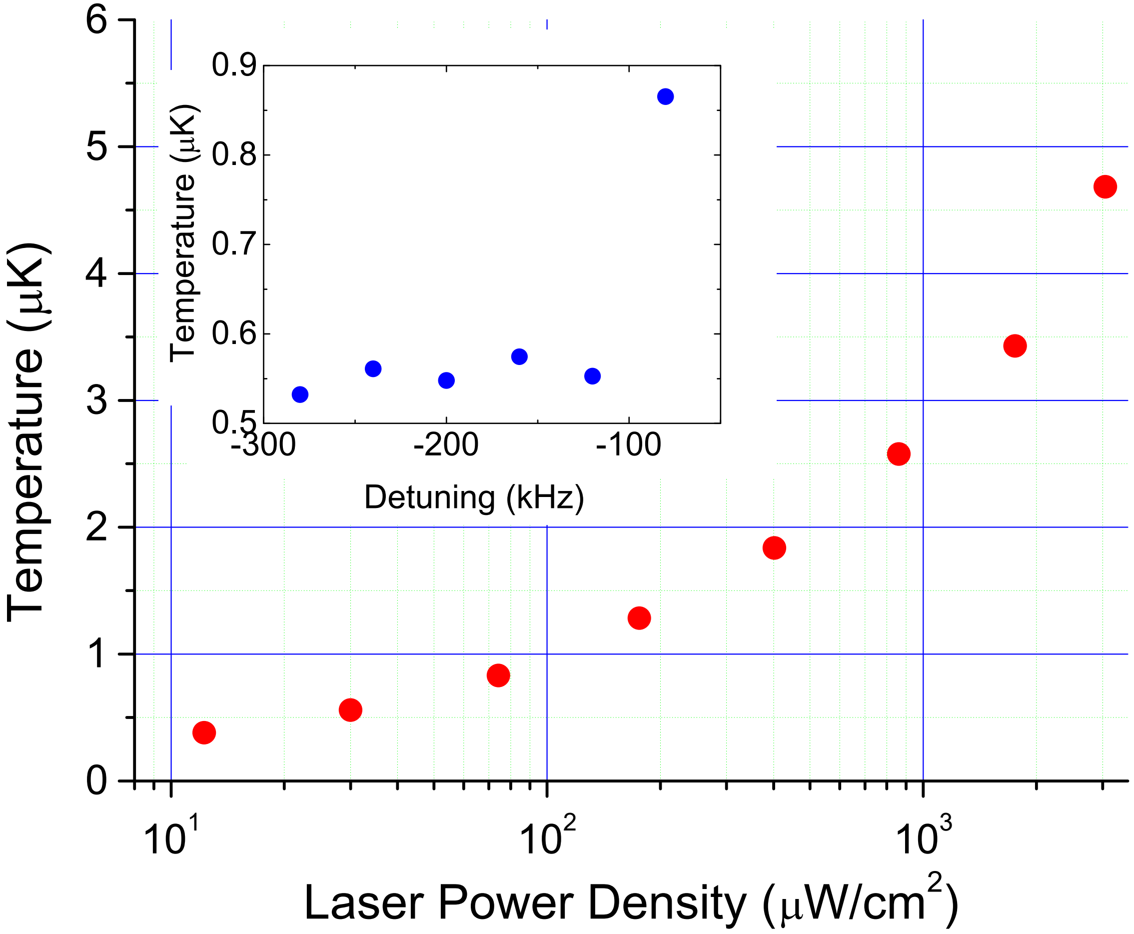
TOF Image by blue Flash:

Flight duration: 20msec
Flash duration: 50μsec

Temperature: 800nK
Number: $N=1.9\times10^7$



Temperature vs Laser Power Density



δ=120kHz

dB/dz =5G/cm

T_{min} =380nK

Temperature insensitive to detuning

Simultaneous control of induced dipole potentials for cooling transition

A strong laser light couples states ***connected by dipole transitions***.
Cooling ground & excited states can be controlled ***independently***.

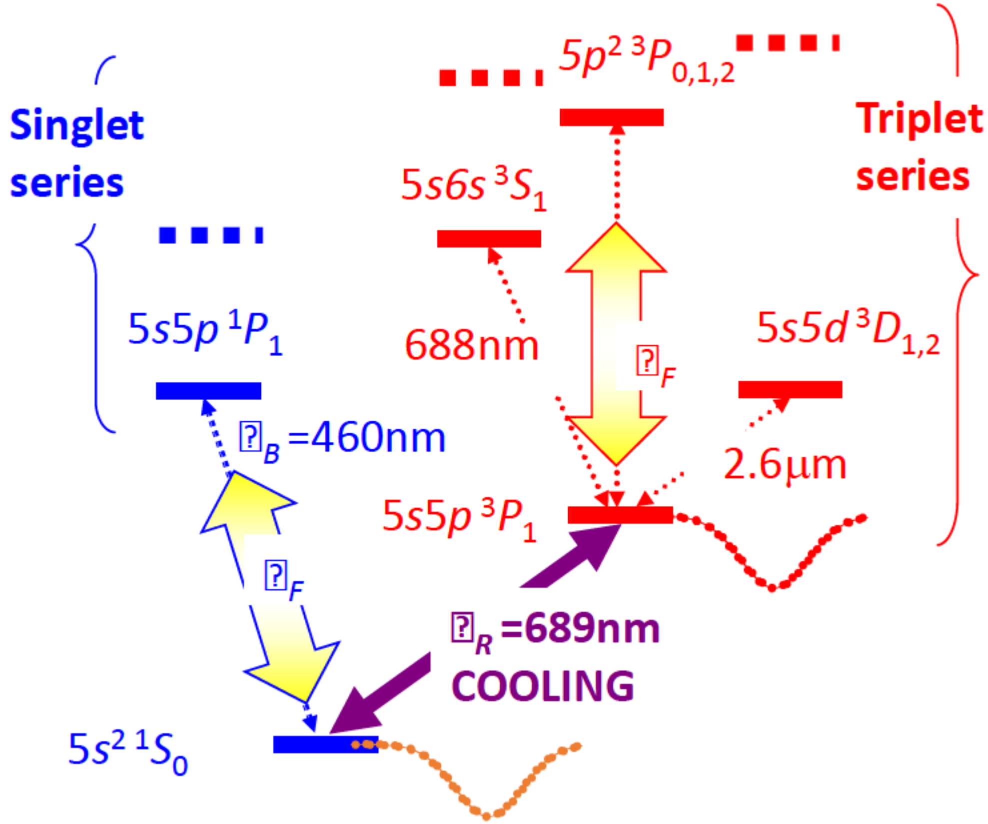
induced polarizability

$$\alpha_n(\omega) = -\frac{2}{\hbar}\sum_m \frac{\omega_{nm}\left|\mu_{nm}\right|^2}{\omega_{nm}^2-\omega^2}$$

$$\hbar\omega_{nm} = E_n - E_m$$

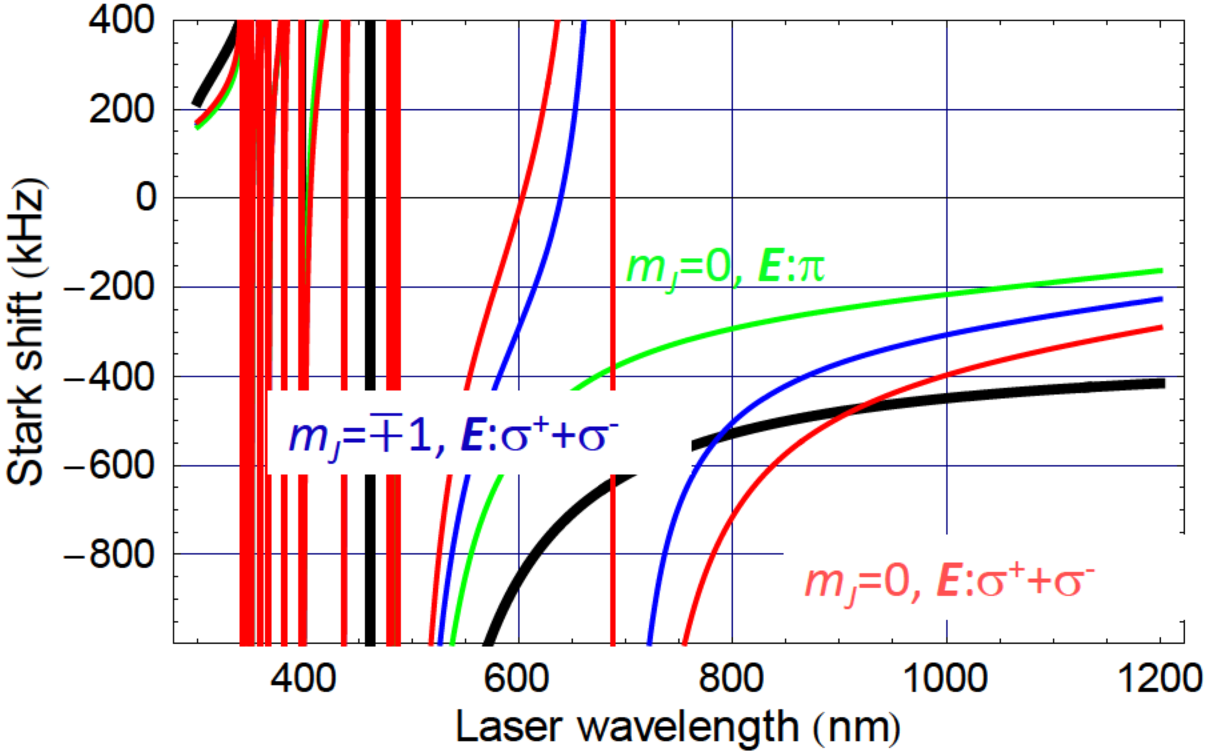
light shift potential

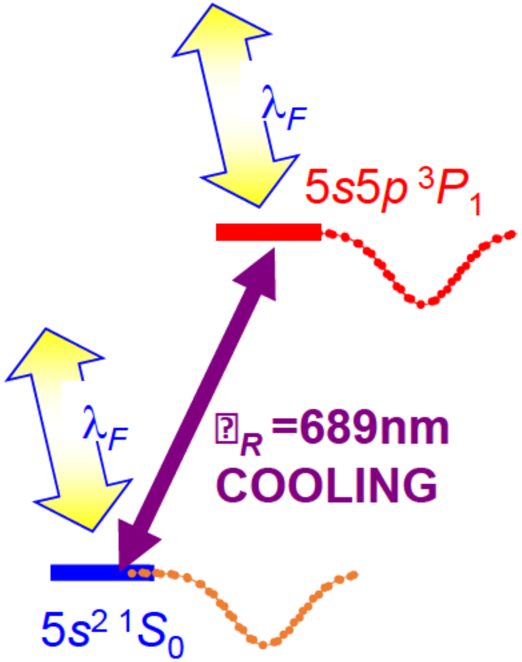
$$U_n(r,\omega) = -\frac{1}{4}\alpha_n(\omega)\left|E(r,\omega)\right|^2$$



Light shifts for $^1S_0$ & $^3P_1$ states

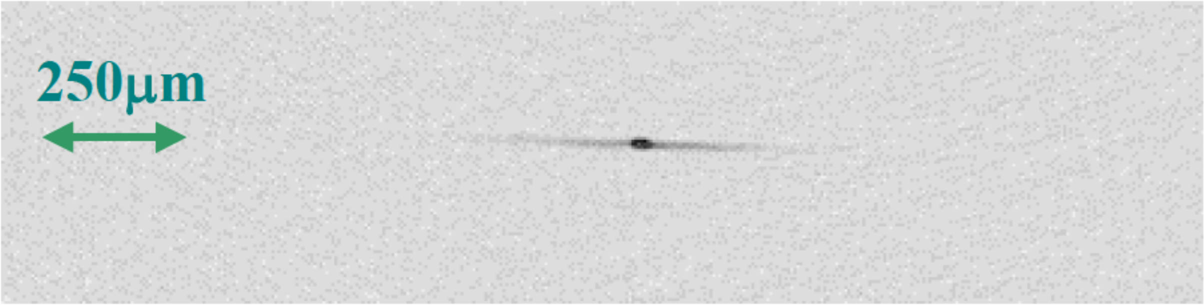
P = 2W / π(23μm)^2

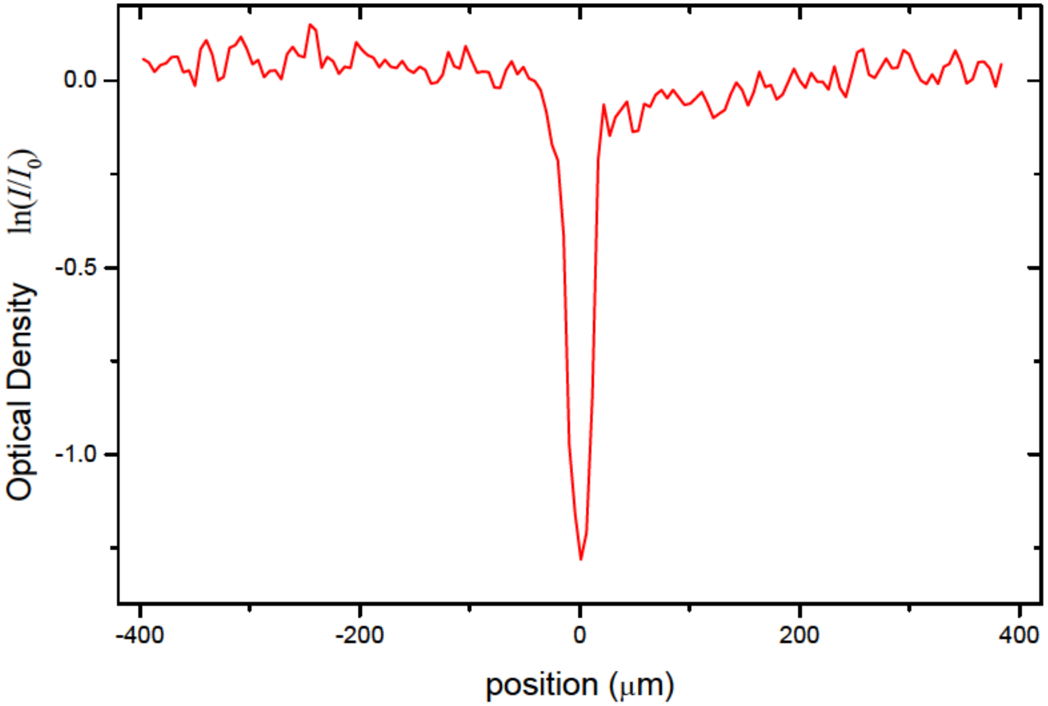




Equal light shifts at λ~800-900 nm
Far Off Resonant Trap

Absorption image of atoms in the FORT





A Half of trapped atoms in crossed region

Observed Size(1/*e* diameter)
Horizontal: 33μm
Vertical: 17μm

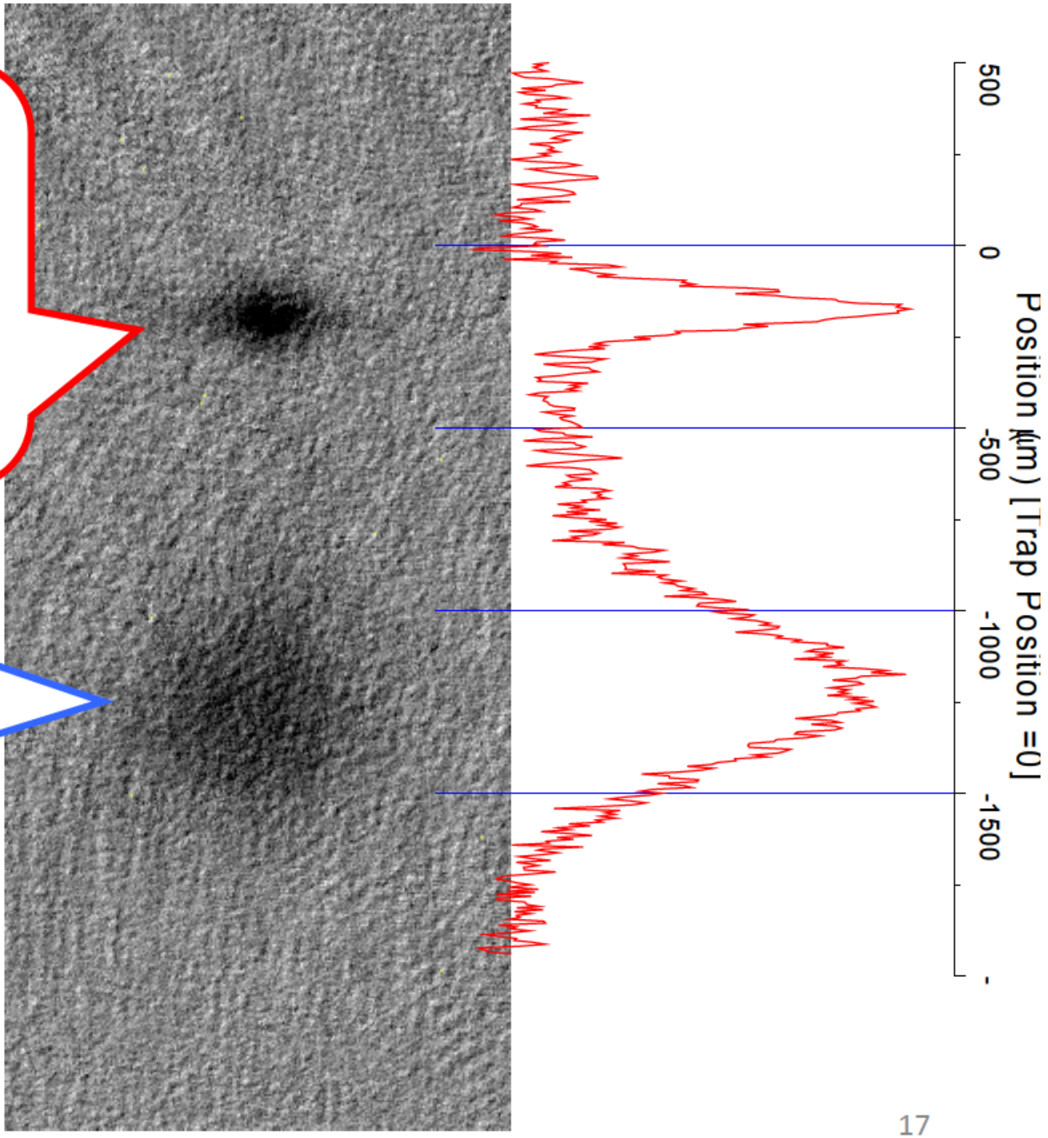
TOF Measurements

Expanded cloud of FORT Atoms

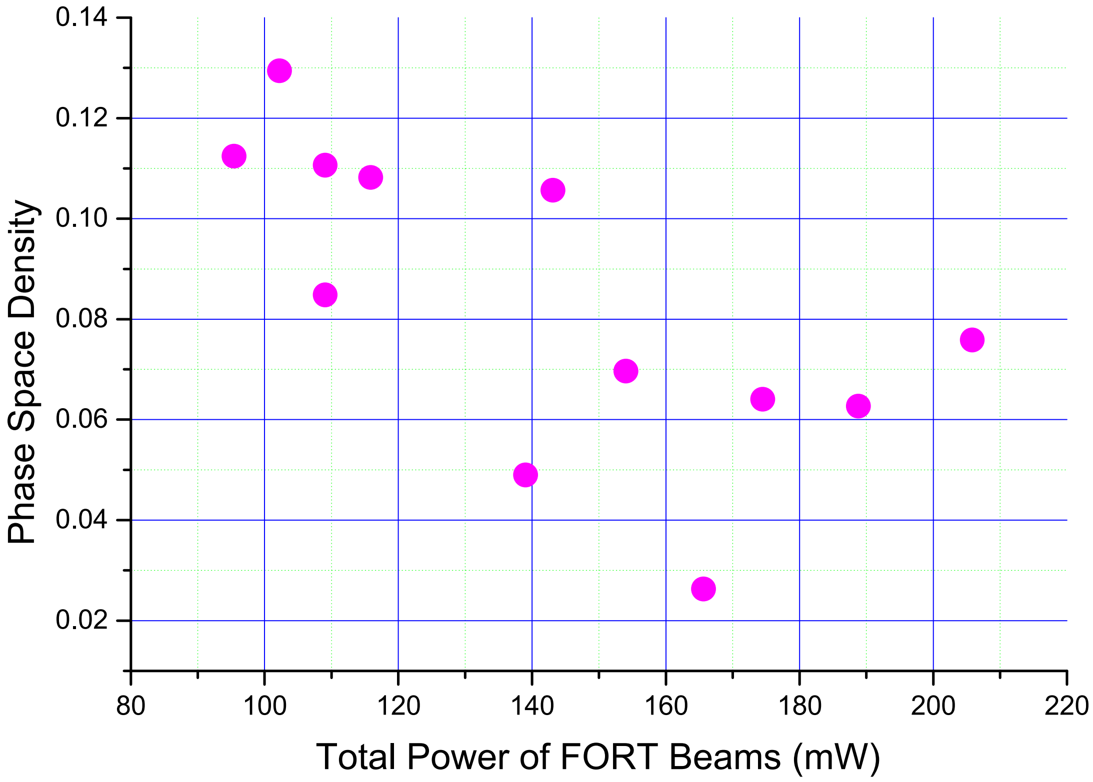
Flight Time: 6msec
Temperature: 750nK
Number: N=2.0 × 10^5

Leak atoms at the moment of switching off MOT laser

Temperature: 1.8μK
Number: N=7.9 × 10^5



Phase Space Density



Phase Space Density

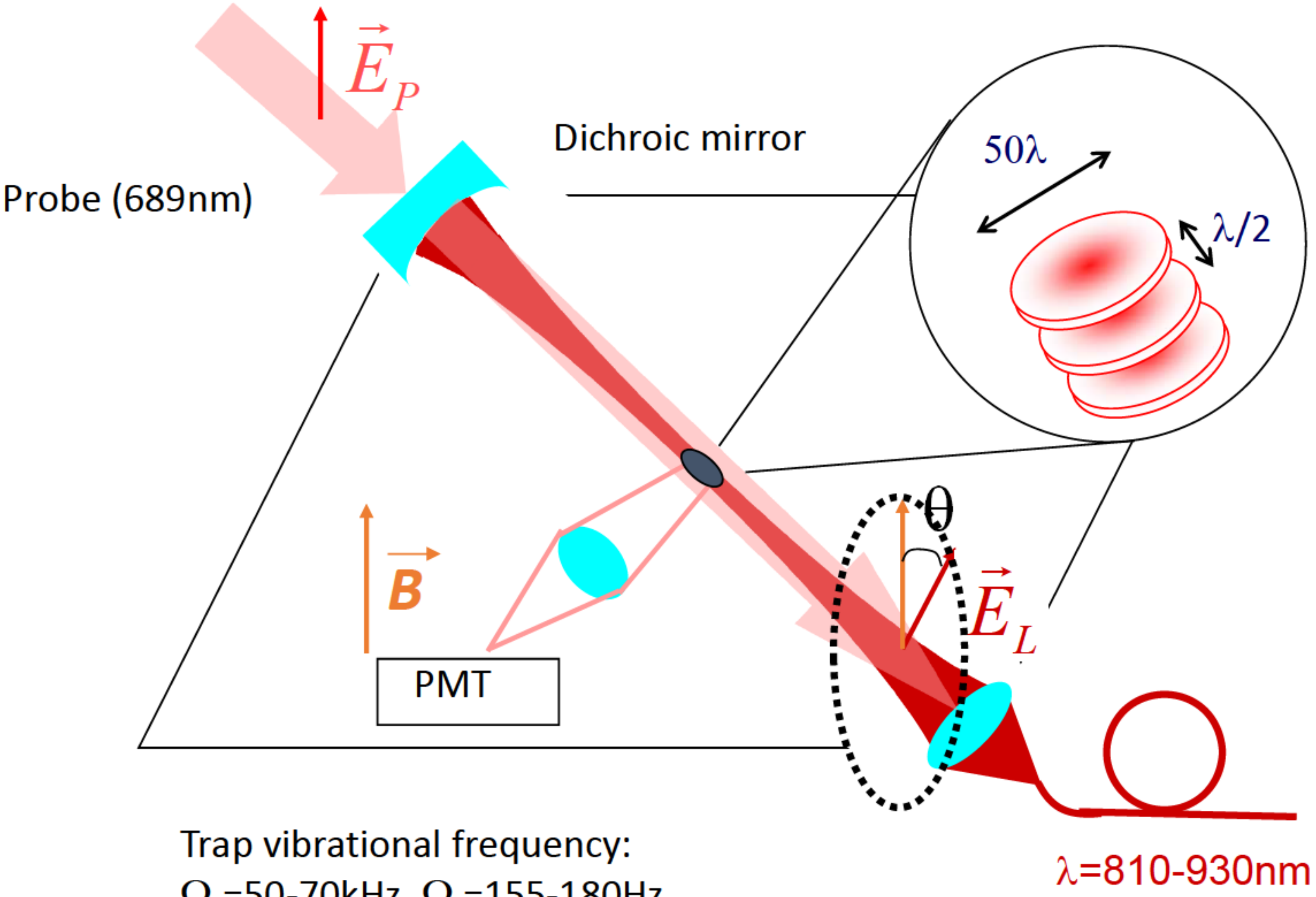
$$\rho = n\left(\frac{h}{\sqrt{2\pi m k_B T}}\right)^3$$

$$\rho_{\max} = 0.13$$

10 × improvement
over nallow-line MOT

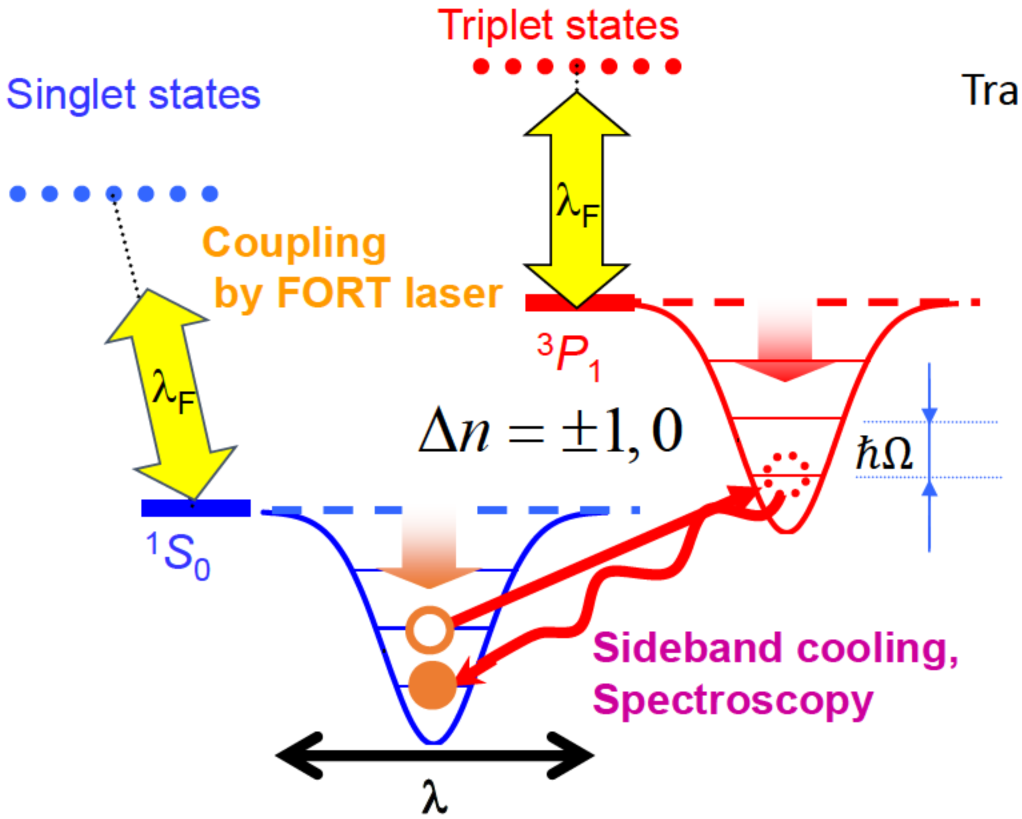
Did not reach BEC… Then, why not fermionic ^{87}Sr

Configuration for 1D Lamb-Dicke confinement



Trap vibrational frequency:
Ω_z=50-70kHz, Ω_r=155-180Hz

Cold Sr atoms in the Lamb-Dicke regime



Transition from n_i to n_f

$$\langle n_f | exp(ik_L x) | n_i \rangle$$

$$= \left\langle n_f \middle| 1 + ik_L x - \frac{(k_L x)^2}{2} \ldots \middle| n_i \right\rangle$$

$$= ik_L \langle n_f | x | n_i \rangle - \frac{k_L{}^2}{2} \langle n_f | x^2 | n_i \rangle$$

$$k_L \Delta x \ll 1$$

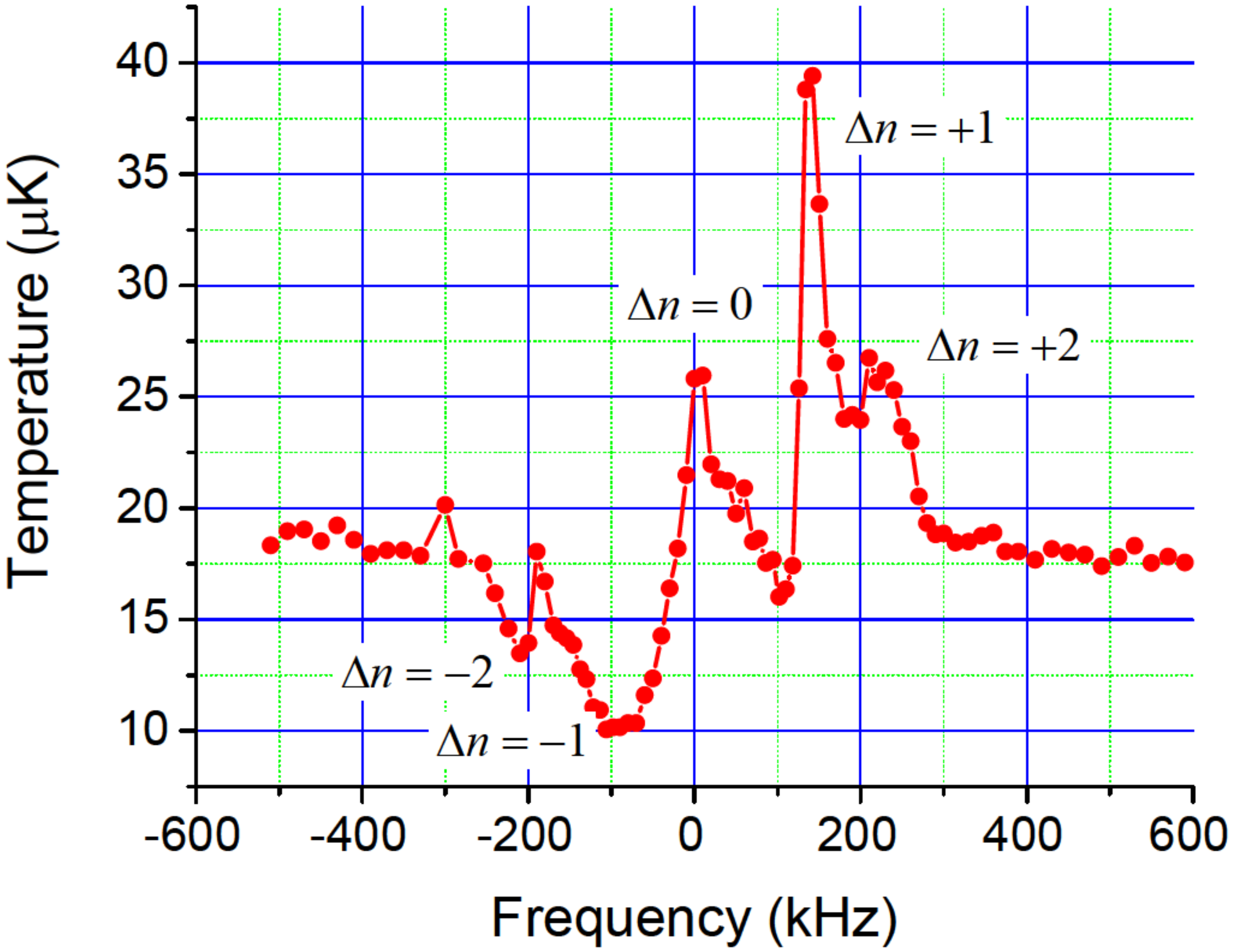
$$\rightarrow |\langle n_i | \exp(ik_L x) | n_i + 1 \rangle| \ll 1$$

Sideband transition rate small

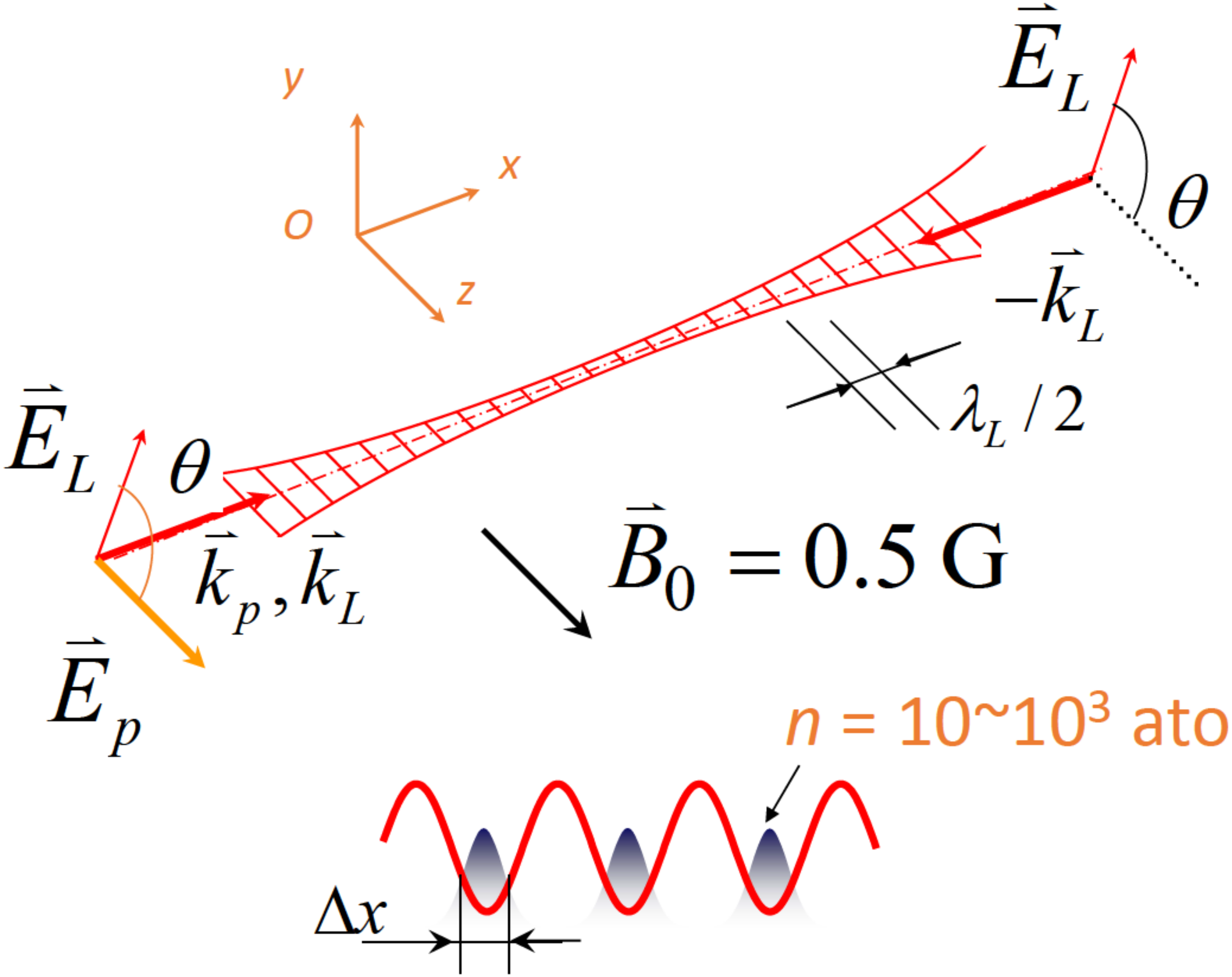
Only carrier i.e. recoil-free

- Optical dipole potential for $^1S_0$, $^3P_1$ states
- $\Omega \gg \gamma(2\pi \times 7.1\mathrm{kHz})$; resolved sideband
- $\Omega \gg E_R / \hbar (2\pi \times 10\mathrm{kHz})$; Lamb-Dicke condition
- $|^1S_0, n\rangle \Rightarrow |^3P_1, n-1\rangle$; excite lower sideband

Sideband cooling in an optical lattice



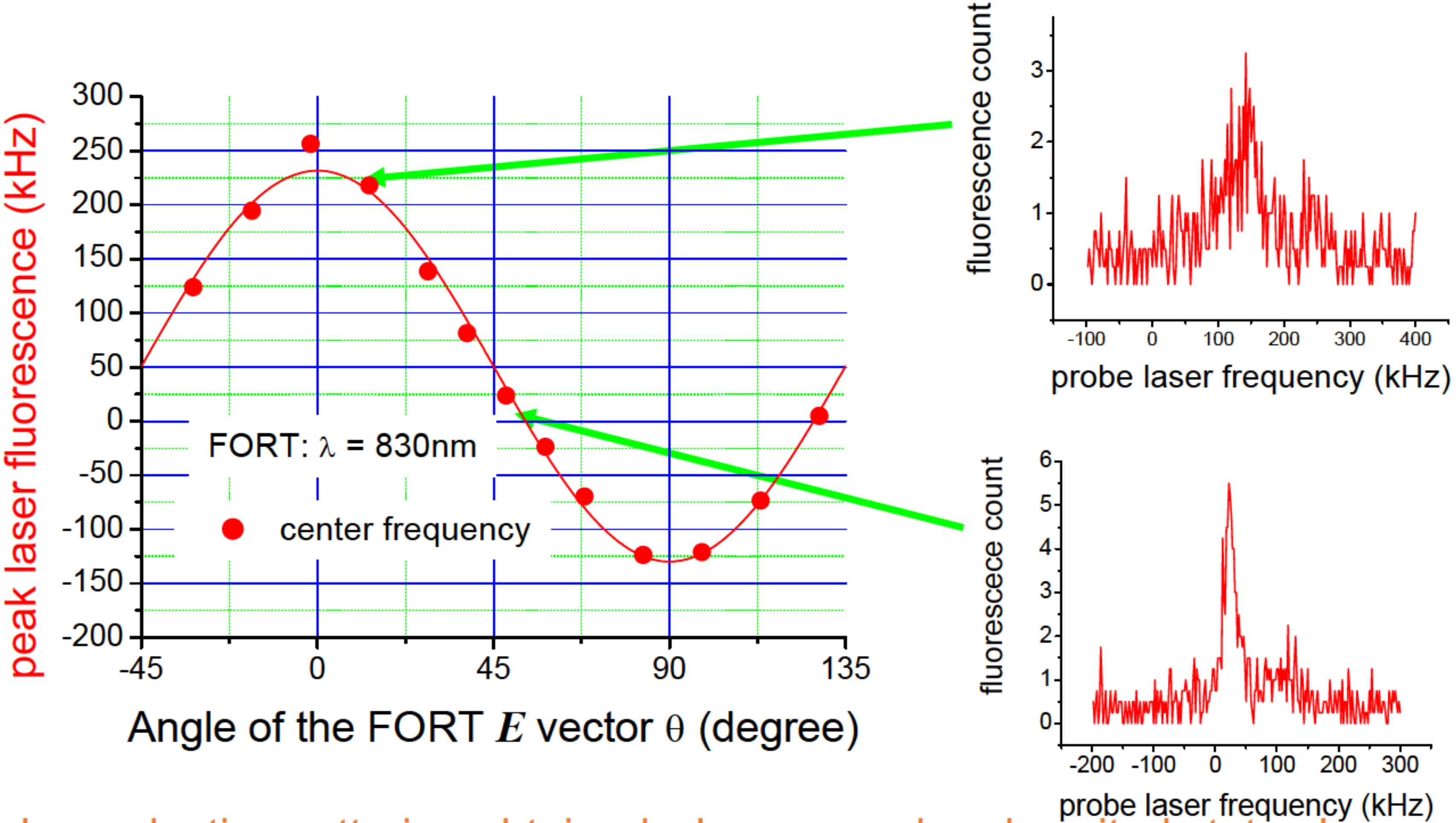
Experimental configuration: 1D FORL



n = 10~10^3 atoms/well

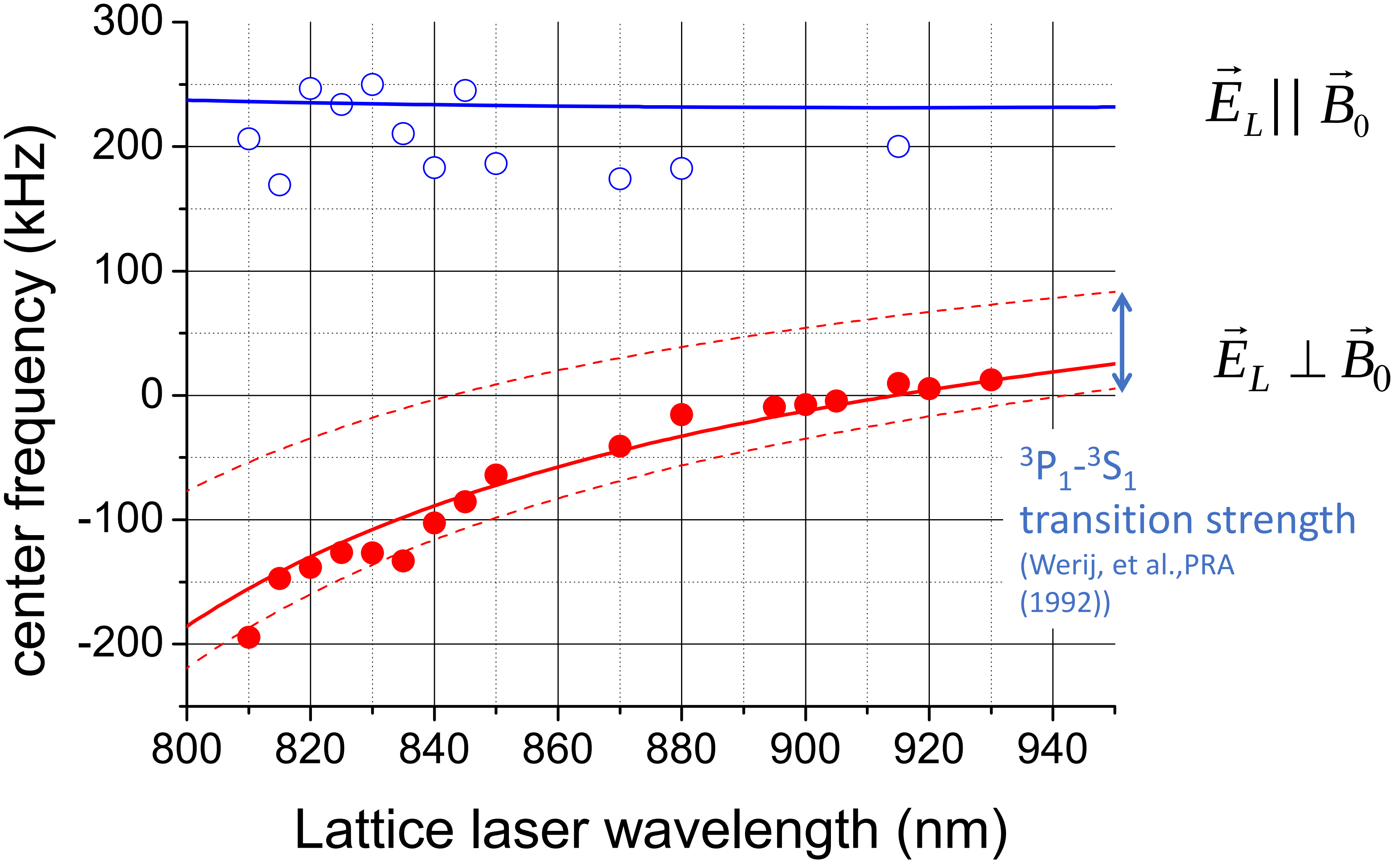
$k\Delta x < 1$: Lamb-Dicke condition is satisfied

Peak frequency vs lattice laser polarization



- sharp elastic scattering obtained when ground and excited states have same AC stark shift

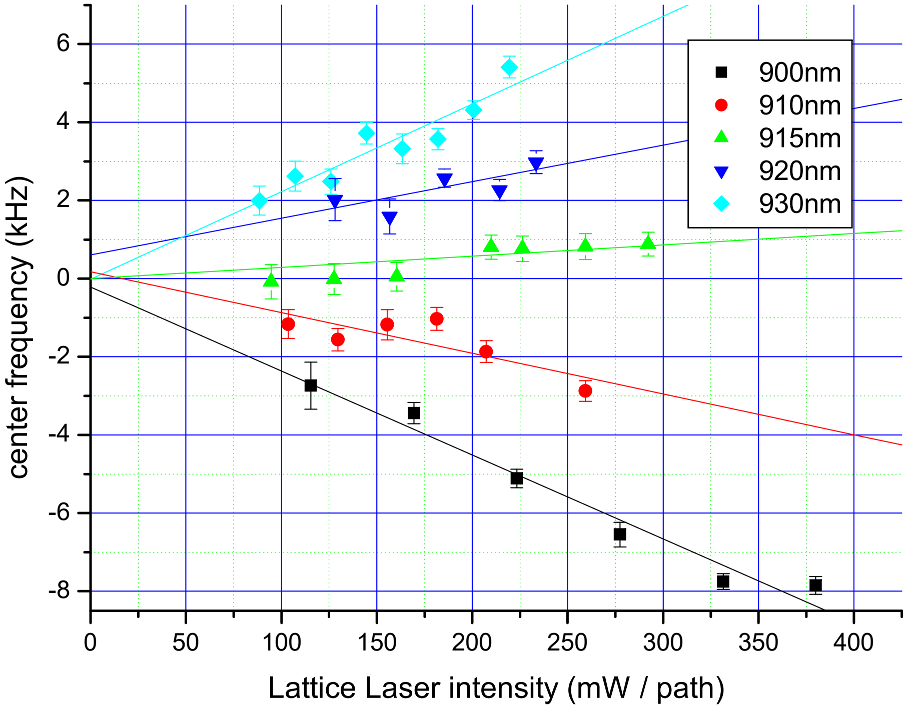
Wavelength dependence of stark shifts

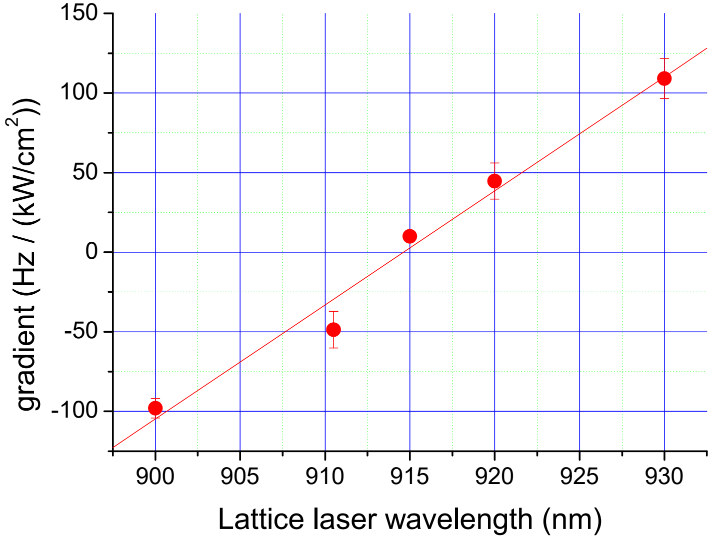


$^3P_1$-$^3S_1$ transition strength

(Werij, et al.,PRA (1992))

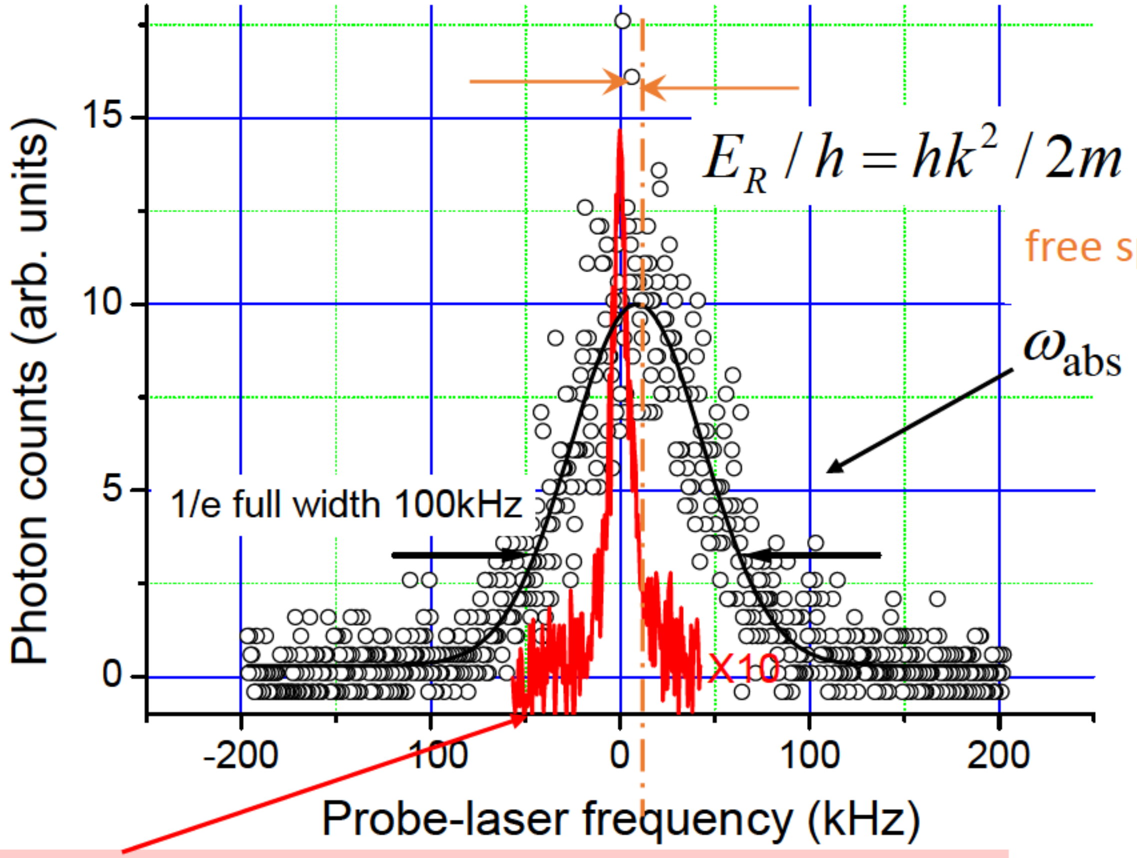
Center frequency v.s. Lattice laser intensity





- No evidence of higher-order stark shift
- Magic wavelength at 914nm

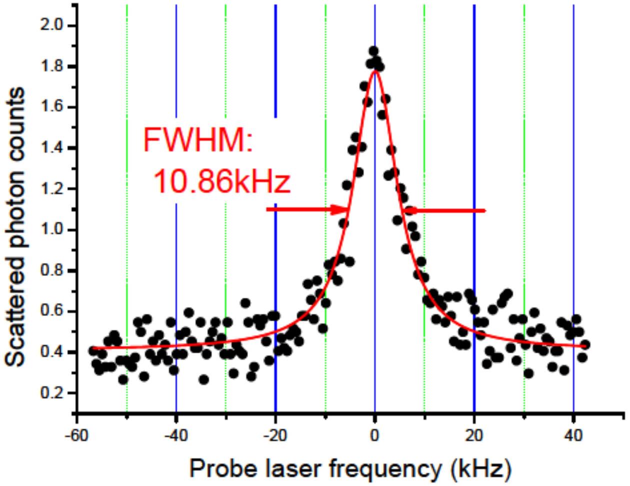
Suppression of photon-recoil shift in LDR



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

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: $I_{\pm 1} / I_0 << 1$

Probe intensity $I = I_{\text{sat}}$

$$\gamma \sqrt{1 + I / I_{sat}} = 10\text{kHz}$$

Ido and Katori, Physical Review Letters **91**, 053001 (2003).

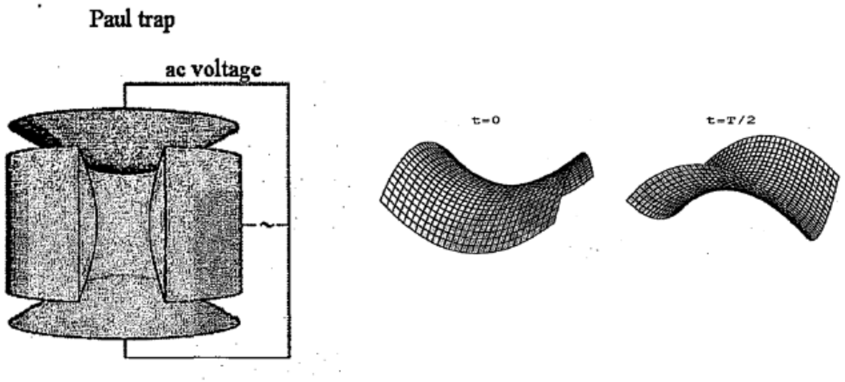
Quantization of external degree

Spatially confining atoms give rises discrete vibrational levels

True resonance

One photon-recoil

Tight confinement to zero-perturbation point
→ ion trap using AC E-field



Spectrum in free space

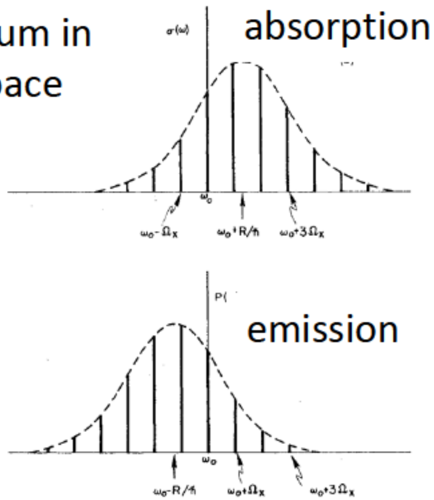


FIG. 7. Atomic spectra in classical limit ($\hbar\Omega_x \ll k_B T$) when $R \lesssim \hbar\omega_D$. Part (a) shows the absorption cross section for a laser directed along the x axis for the case when $\gamma \ll \Omega_x$ (giving the discrete lines) and when $\Omega_x \to 0$ (dashed curve) which is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

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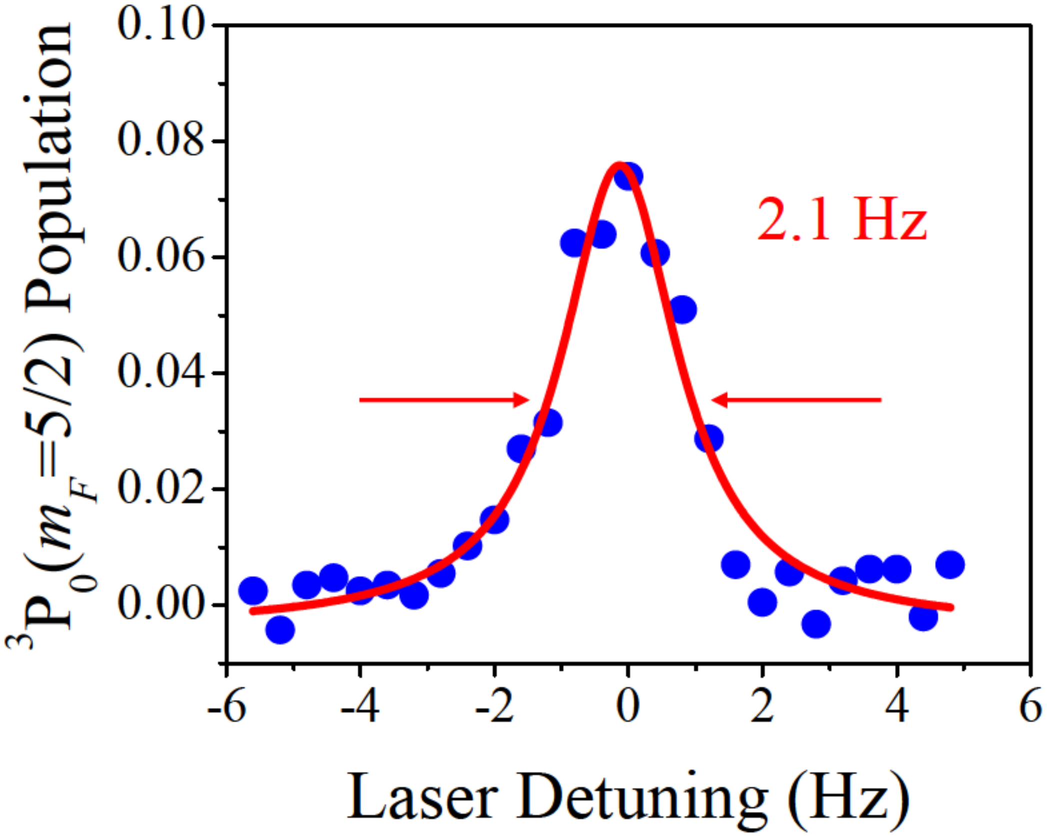
Optical dipole trap using interference fringe allows tight confinement.

But
Need to cool down to μK regime. No magnetic sublevel prohibits polarization gradient cooling
Intensity dependent systematic shift → non-sense for freq. standard..

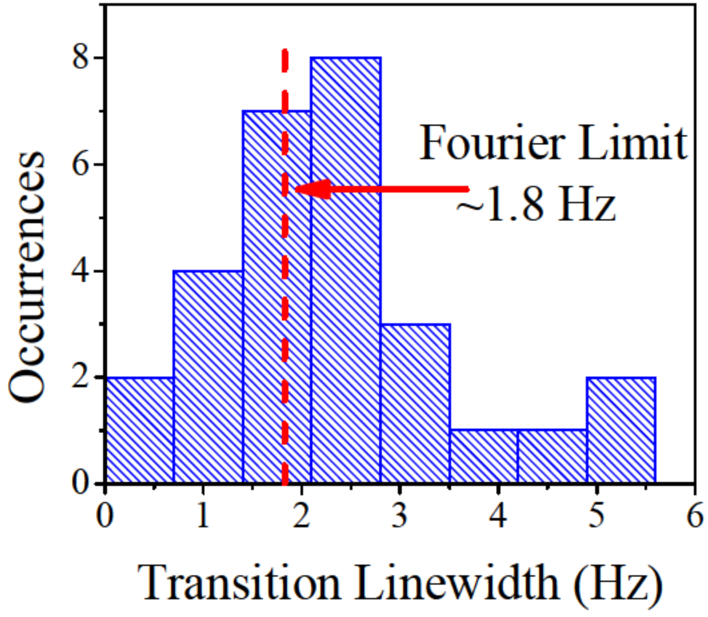
Coherent spectroscopy Q ~ 2.4x 10^{14}



Lifting the m_F degeneracy ,
Narrower spectra observed in a single $m_F=5/2$ transition

Probe-time limited
(=Probe time: 480ms)

Loading time dominant regime
→Probe time dominant



Longer probing time?
Spectrum width limited by nonlinear drift of the probe laser frequency

Secondary representation of the second (SRS)

Frequency combs proposed in late 90s easily provide coherent link of optical frequency to (microwave) SI second.

→ Optical clocks became SI traceable.

→ Transitions with uncertainty in same level as the best Cs recognized as SRS

Ion trap

	u_{SRS} (E-16)	u_{sys} (E-17)	# of labs
Al+	19	0.9	1
Hg+	19	1.9	1
Yb+(E3)	6	0.3	2
Yb+(E2)	6	3.2	2
Sr+	15	2.2	2

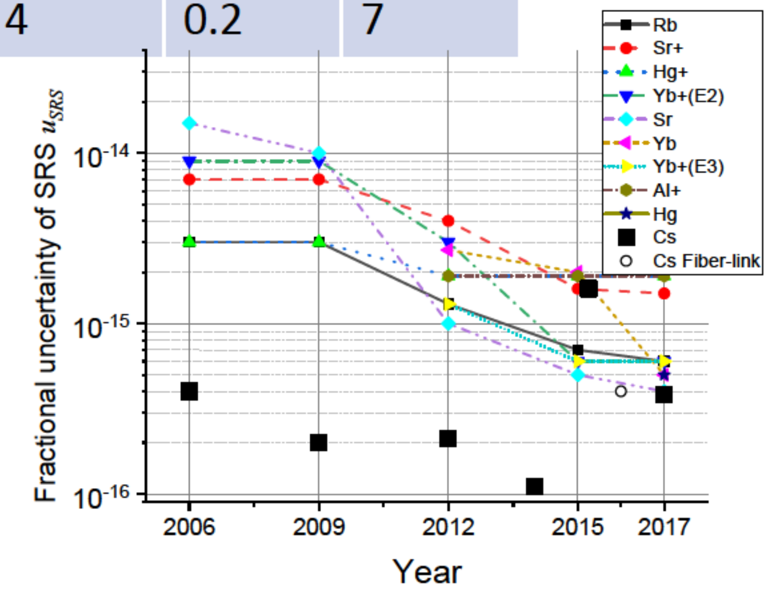
Lattice clock

	u_{SRS} (E-16)	u_{sys} (E-17)	# of labs
Hg	5	7.2	2
Yb	5	0.1	5
Sr	4	0.2	7

u_{SRS} : uncertainty as a substitute of Cs. Limited by Cs

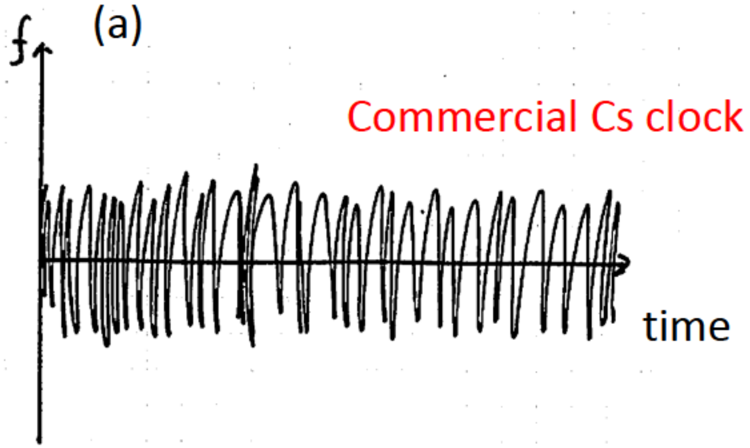
u_{sys}: uncertainty as an optical frequency standard

# of labs: # which reported frequency to CCTF.

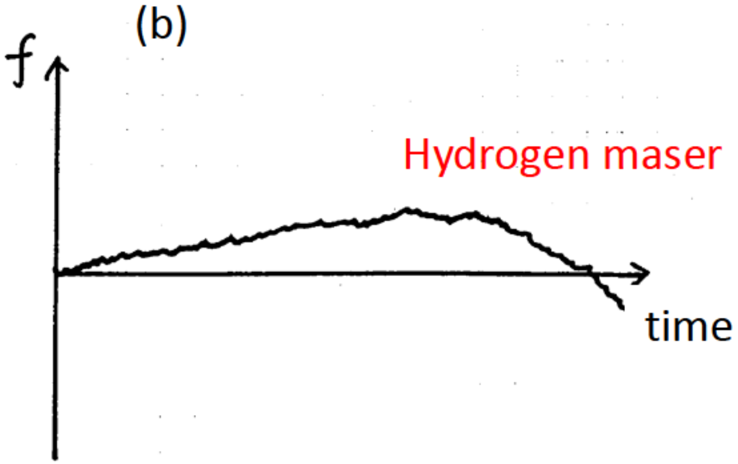


Japan Standard Time (JST)

Commercial Cs clock & H maser



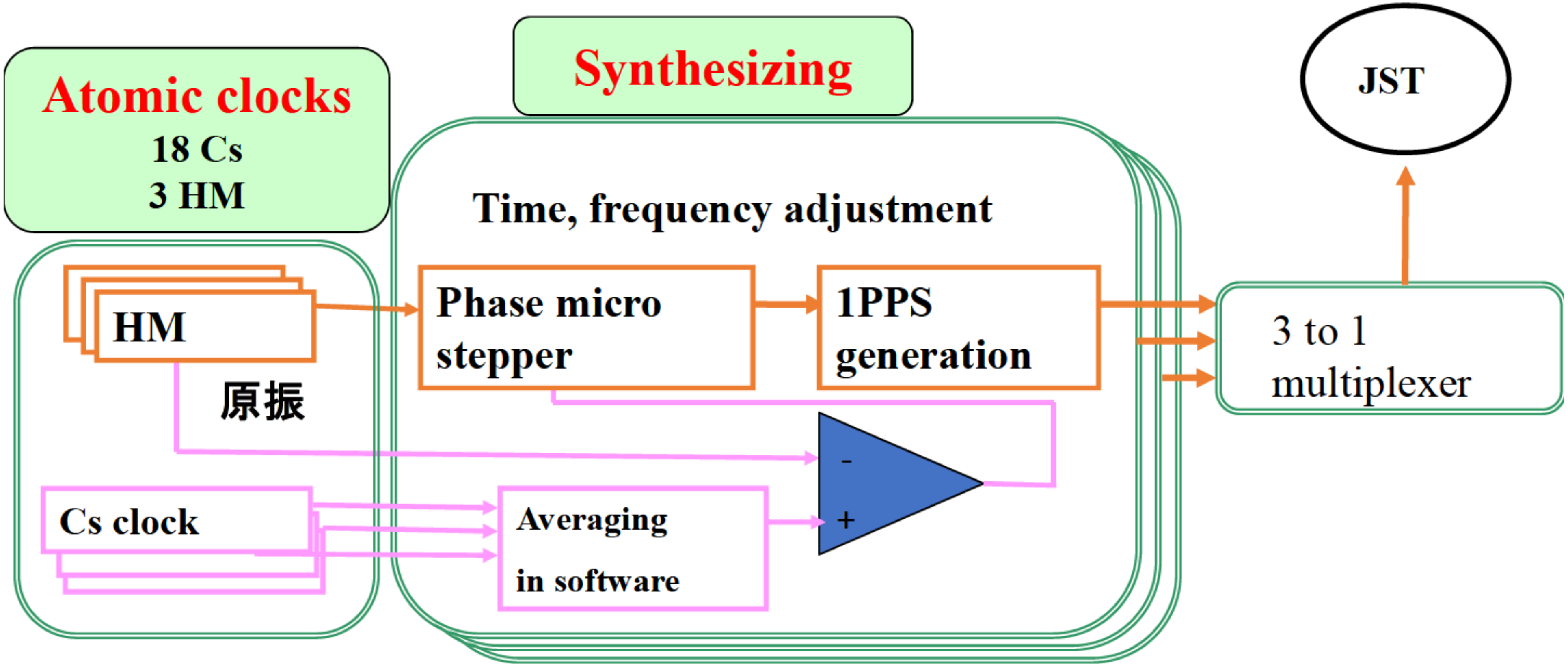
9.2GHz
Noisy, but no drift



1.42GHz
Less (short-time) noise, but drifty

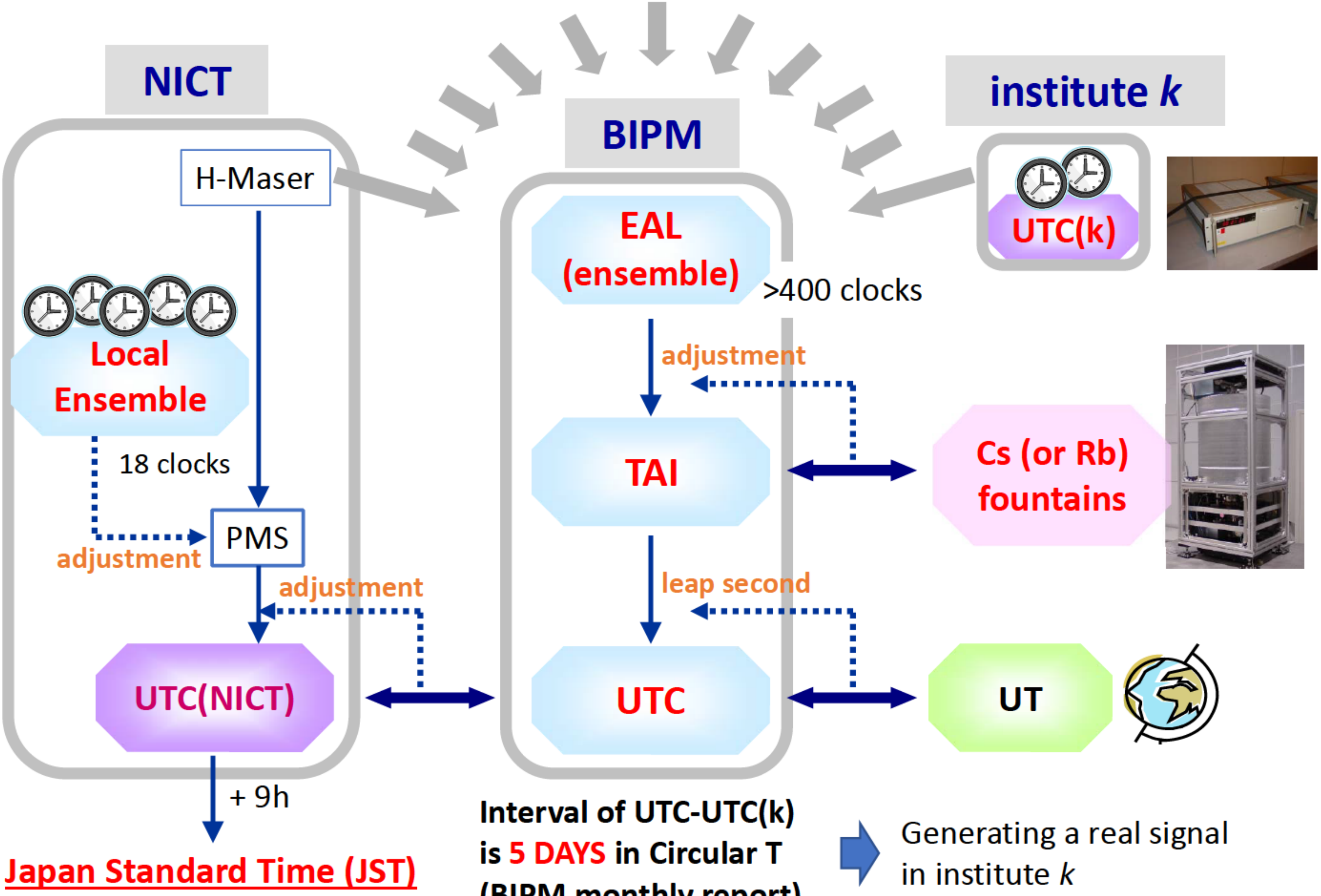
JST employed only Cs clocks before 2006. But since 2006, Cs and H-maser have been combined to get better stability in short term too.

JST generation



HM frequency was steered to ensemble of 18 Cs clock

Time scale



NICT

H-Maser

Local Ensemble

18 clocks

adjustment

PMS

adjustment

UTC(NICT)

+ 9h

Japan Standard Time (JST)

BIPM

EAL (ensemble)

>400 clocks

adjustment

TAI

leap second

UTC

institute *k*

UTC(k)

Cs (or Rb) fountains

UT

Interval of UTC-UTC(k)
is 5 DAYS in Circular T
(BIPM monthly report)

Generating a real signal
in institute *k*

JST : Time scale generation

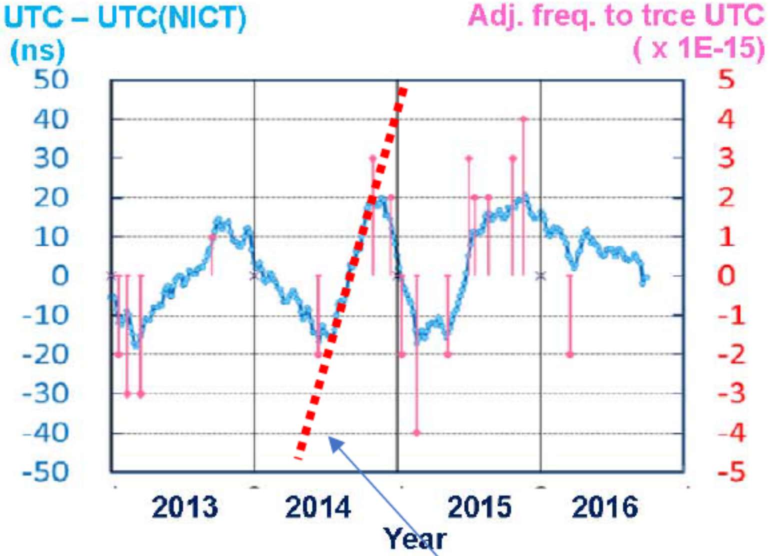
Timescale

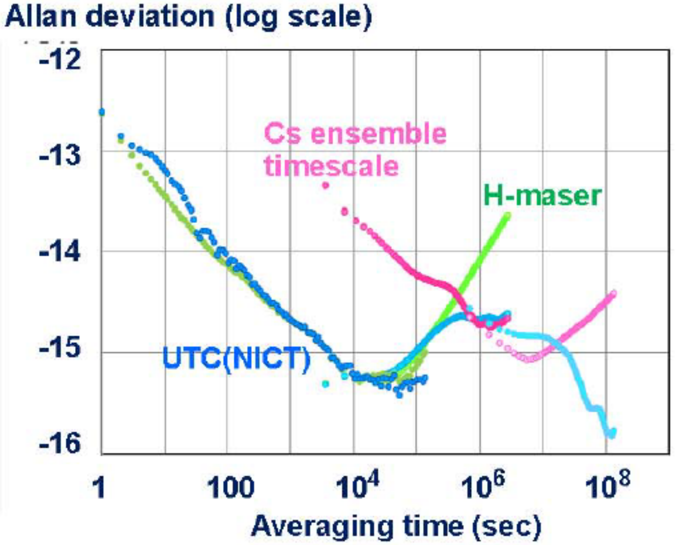
- **Clocks for generating UTC(NICT) :**

  Cs 5071A : 18 (ensemble timescale)
  Anritsu H-Masers : 1(source) + 2(backup)

- **The behavior of UTC(NICT) :**

  | UTC – UTC(NICT) | < 20 ns.
  stability ∼ $5\mathrm{x}10^{-16}$@1d, $2\mathrm{x}10^{-15}$@10~30d





80 ns / 0.6 year = 4 × 10^{-15}

JST : Time scale generation

Timescale

- **Clocks for generating UTC(NICT) :**

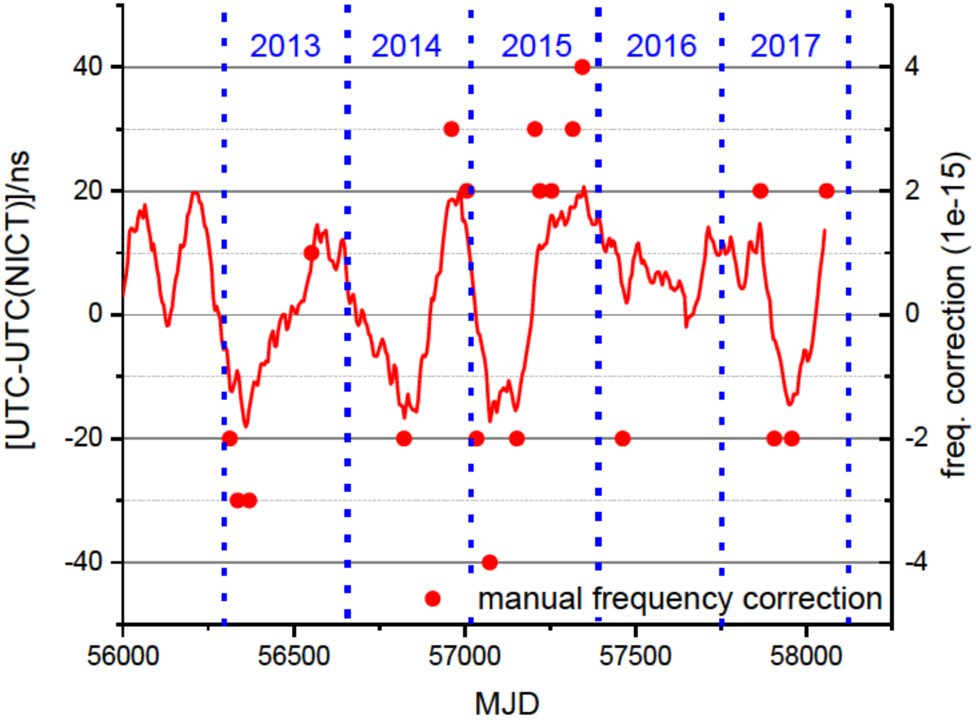
  Cs 5071A : 18 (ensemble timescale)
  Anritsu H-Masers : 1(source) + 2(backup)

- **The behavior of UTC(NICT) :**

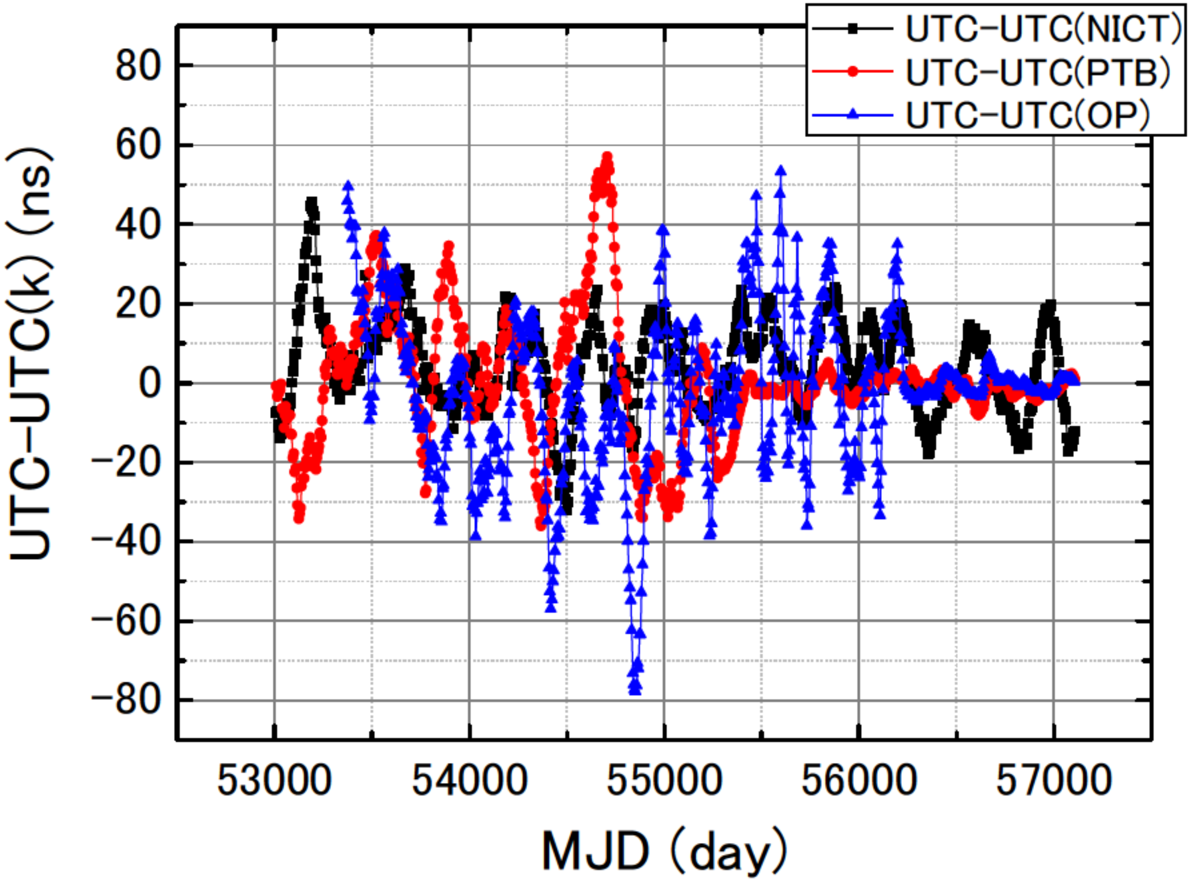
  | UTC – UTC(NICT) | < 20 ns.
  Stability ~ 2E-15 @ 10-30d.

Accuracy
conservative: 5e-14
(employed for calibration service)
Standard deviation: <4e-14

24hours, 7days a week



Current status of UTC(k)



UTC(PTB):
Metrologia 49, 180 (2012).

UTC(OP):
Metrologia 53, S81 (2016).

Reliable fountains enable real-time steering of UTC(k).

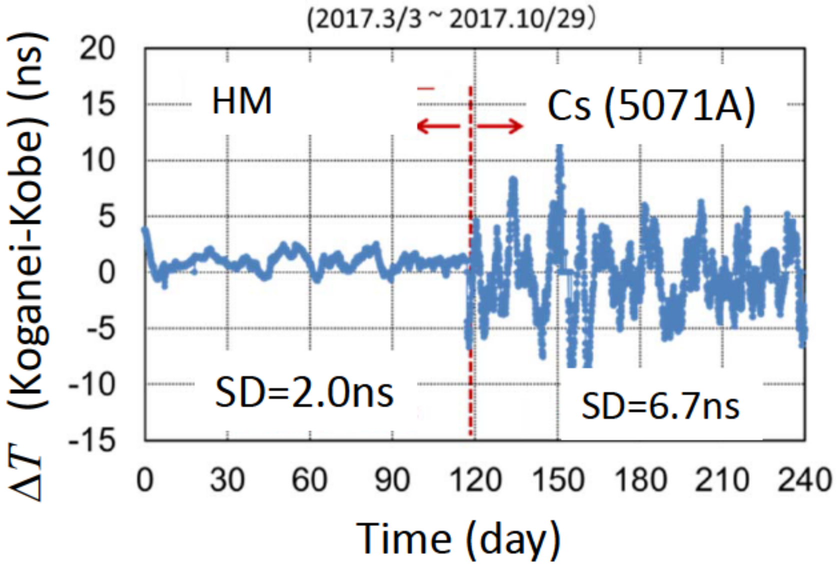
Why not optical clocks?
Particularly for emerging countries, getting difficult to assign young talents to fountains.

JST Kobe sub-station in becoming ready

Distributed generation of JST

- Kobe sub-station is scheduled to begin time-keeping in June 2018
- 2 H-maser & 5 Cs clocks
- Primary purpose is a backup of Koganei HQ against disasters

(JST has never stopped in more than 40 years)

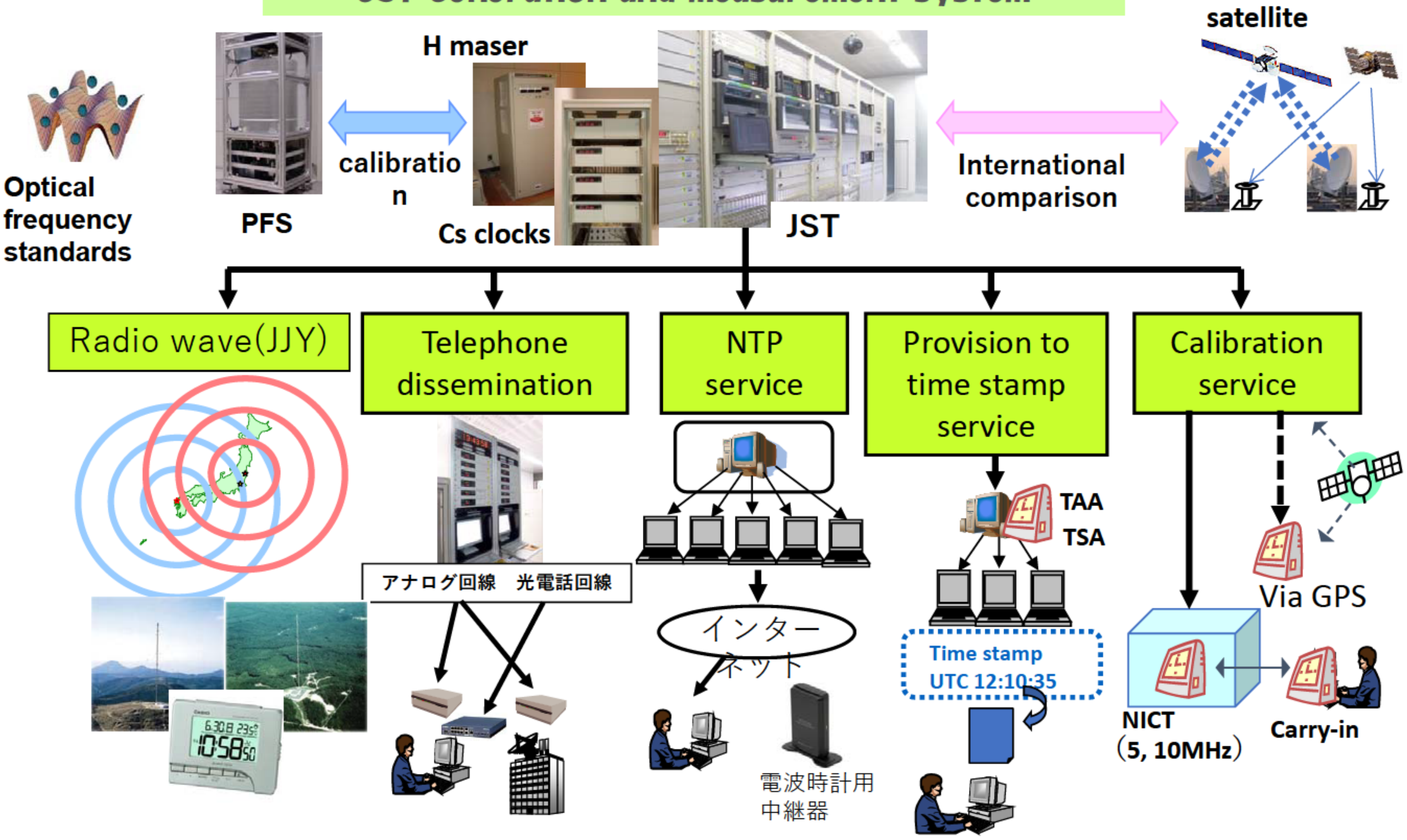


Operation mode:

1. Copy of Koganei HQ
2. Independent operation
3. JST as an ensemble of all clocks operated in 4 stations

Dissemination service of Japan Standard Time

JST Generation and measurement system



Optical frequency standards

PFS

calibration

H maser

Cs clocks

JST

International comparison

satellite

Radio wave(JJY)

Telephone dissemination

アナログ回線　光電話回線

NTP service

インターネット

電波時計用
中継器

Provision to time stamp service

TAA

TSA

Time stamp
UTC 12:10:35

Calibration service

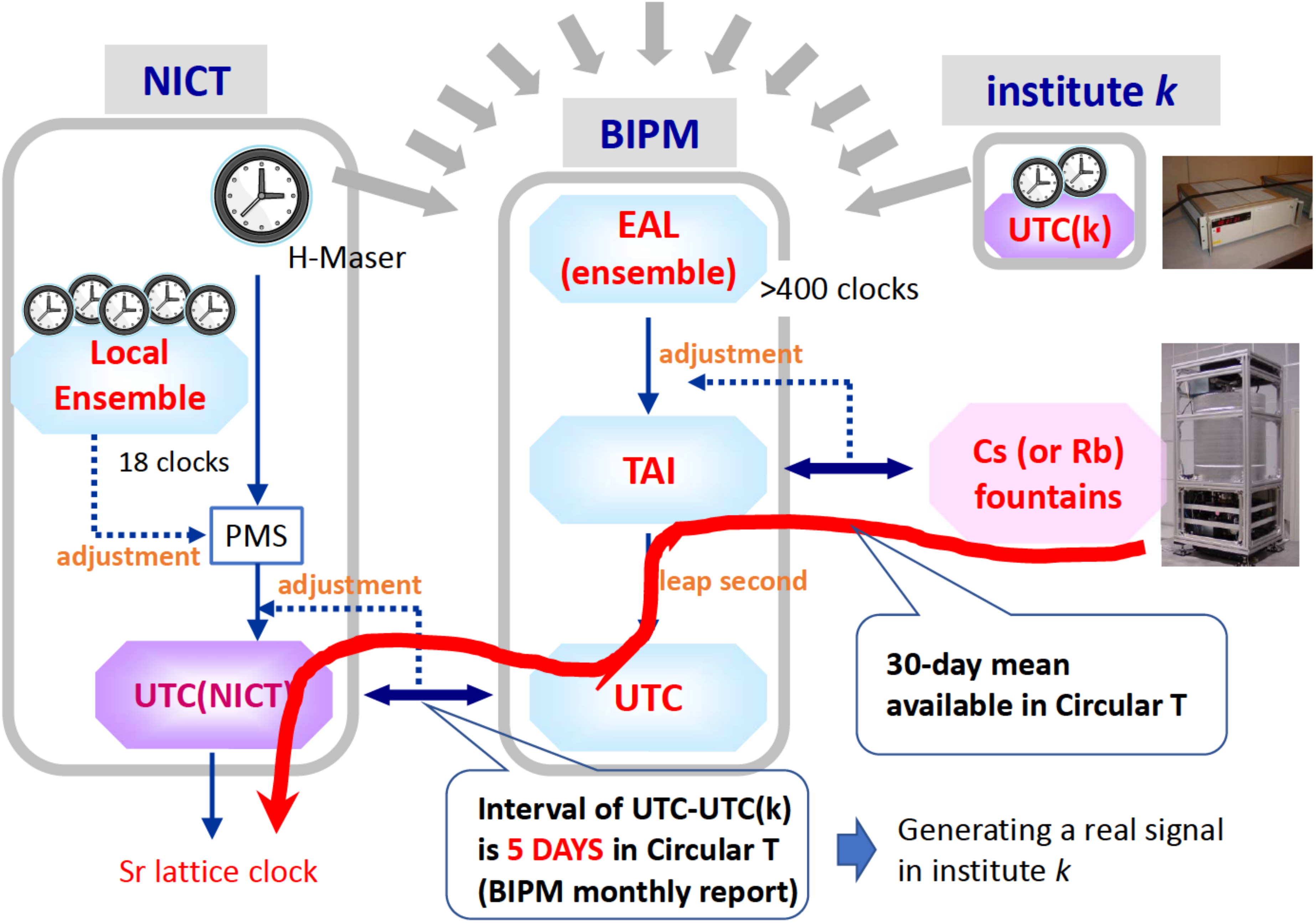
Via GPS

NICT
(5, 10MHz)

Carry-in

Absolute frequency measurement using International Atomic Time

Absolute frequency measurement using TAI



NICT

H-Maser

Local Ensemble

18 clocks

adjustment

PMS

adjustment

UTC(NICT)

Sr lattice clock

BIPM

EAL (ensemble)

>400 clocks

adjustment

TAI

leap second

UTC

institute *k*

UTC(k)

Cs (or Rb) fountains

30-day mean available in Circular T

Interval of UTC-UTC(k) is 5 DAYS in Circular T (BIPM monthly report)

Generating a real signal in institute *k*

Time = phase?

Atomic physicists, particularly in optical, always think frequency.
When they draw graph, optical phase never show as vertical axis.

Why? Probably, optical phase is fragile. Easily jump and so on (coherence)

On the other hand, those in timescale like phase.
Our phase always have the unit of “rad”. But their phase often has the unit of “s”. What’s happen?

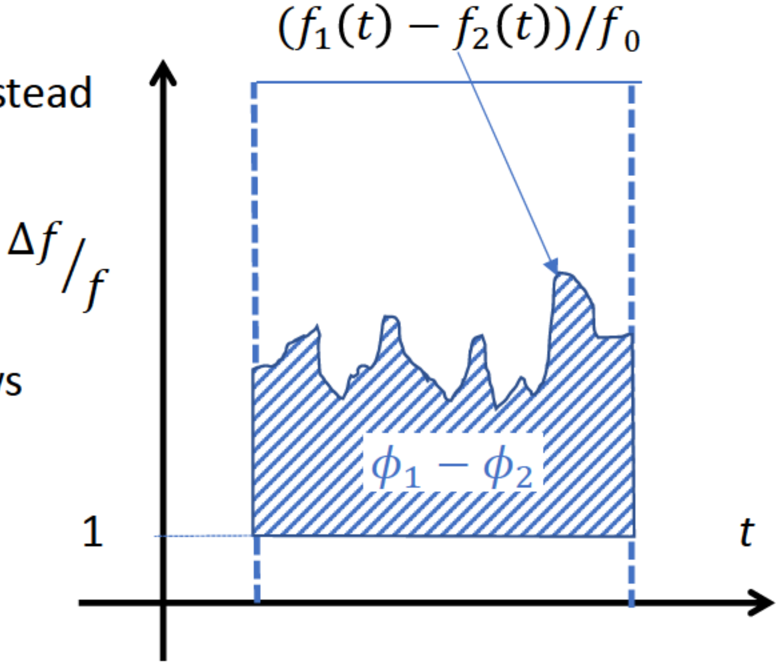
No absolute phase. Phase is always difference of two signals.

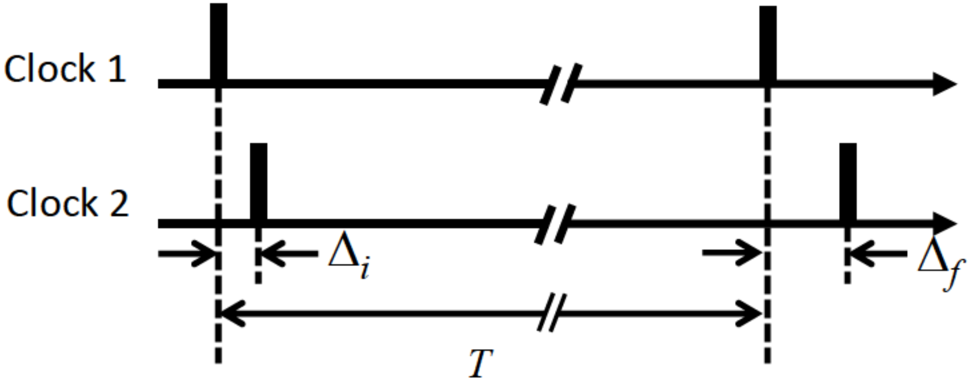
Why don't we think "fractional frequency difference" instead of absolute frequency when we compare two signals.

→

Time integration of fractional frequency difference shows relative phase in unit of second.

$$\phi_1 - \phi_2 = \Delta\phi = \int \frac{\Delta f}{f_0} dt = \int \frac{f_1 - f_2}{\bar{f}} dt$$





Time (phase) difference Δ_i and Δ_f at two instances which areseparated for T

$$(f_2 - f_1)/f_0 = -\frac{\Delta_f - \Delta_i}{T}$$

Circular T shows this Δ =UTC-UTC(k).

This formula lead fractional frequency difference between UTC & UTC(k)

TAI-based frequency measurement @ lab. “k”

Calibration of TAI
Reported from BIPM

$$\frac{\nu(Sr@k)}{\nu(SI)} = \frac{\nu(Sr@k)}{\nu(HM)}\frac{\nu(HM)}{\nu(UTC(k))}\frac{\nu(UTC(k))}{\nu(TAI)} \times \frac{\nu(TAI)}{\nu(SI)}$$

Suffers from link uncertainties
But not dependent on specific
Cs fountain

Goal is to get this ratio

What lab k measures or calculate.
In future, this process will calibrate the TAI using a lattice clock

	$\frac{\nu(Sr@k)}{\nu(HM)}$	$\frac{\nu(HM)}{\nu(UTC(k))}$	$\frac{\nu(UTC(k))}{\nu(TAI)}$	$\frac{\nu(TAI)}{\nu(SI\ )}$
Link uncertainty	negligible	2e-16	9.8e-16@5day (satellite link)	~ 2-5e-16 (Cs, satellite)
Minimum Averaging Time	1 second	1 second ➡	5 days ➡	1 month

➡ Suffers from dead time uncertainty

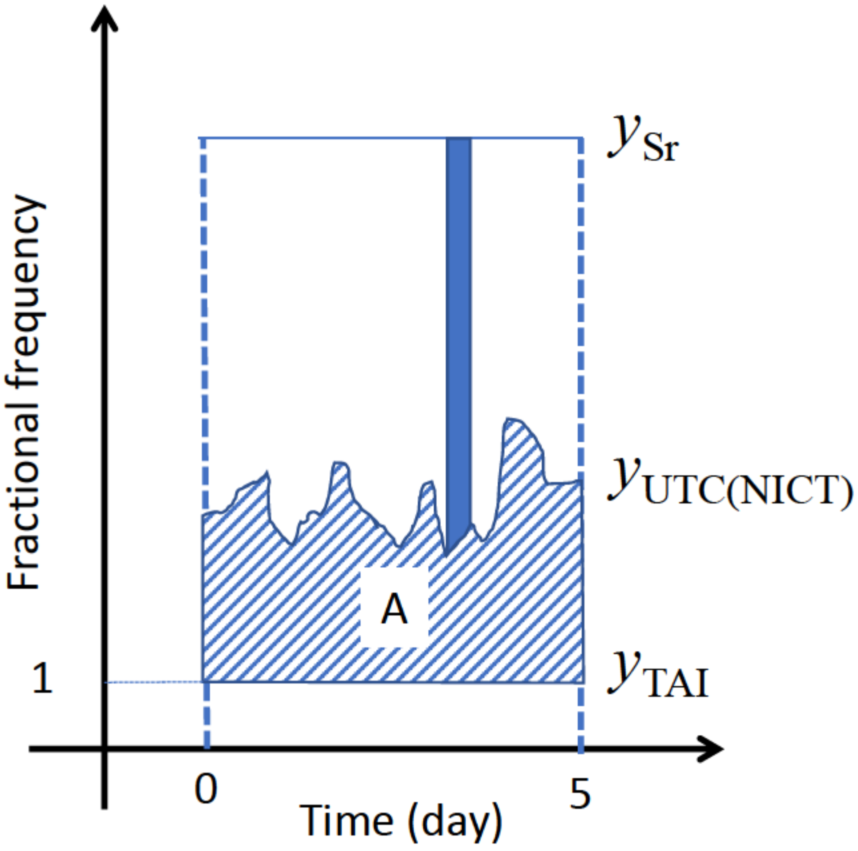
$$\overline{\nu(UTC(k))}_{10000s} \neq \overline{\nu(UTC(k))}_{5days}$$

$$\overline{\nu(TAI)}_{5days} \neq \overline{\nu(TAI)}_{1month}$$

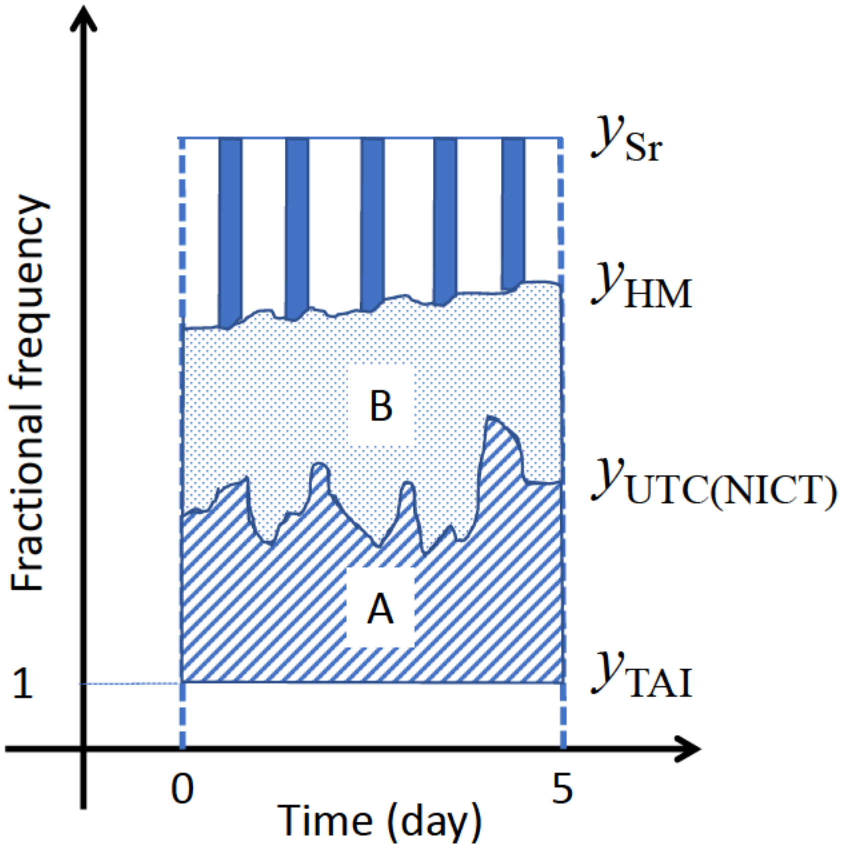
Link from Sr to TAI

$$A = \int_{Day0}^{Day5} \left(y_{UTC(k)} - 1\right) dt = [UTC(k) - UTC]_{Day5} - [UTC(k) - UTC]_{Day0}$$

Temporal average of frequency difference = <u>Variation of the time difference</u>

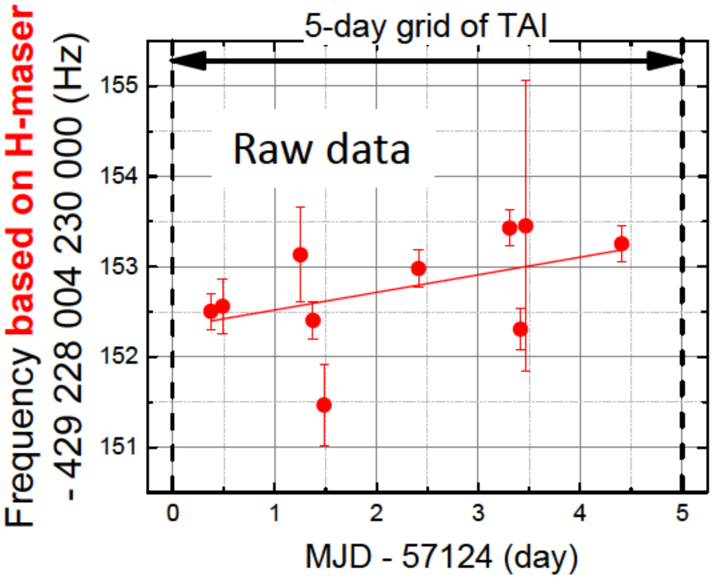


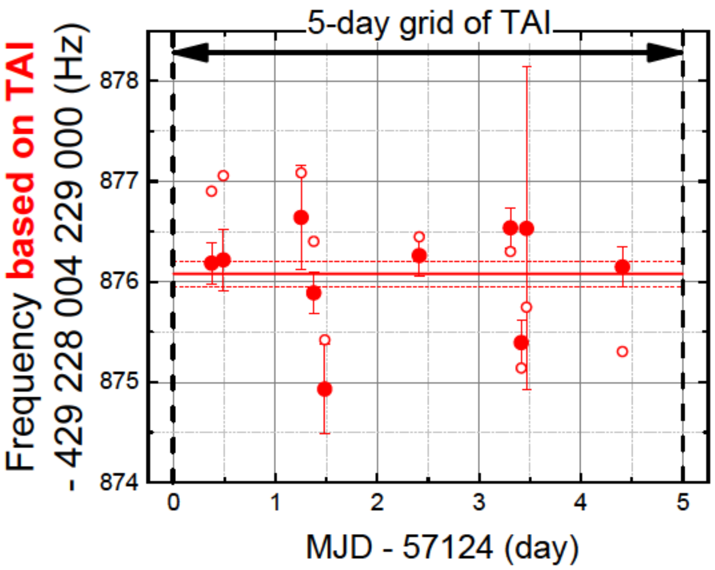
Previous measurement in 2012
Link uncertainty: 2.8e-15

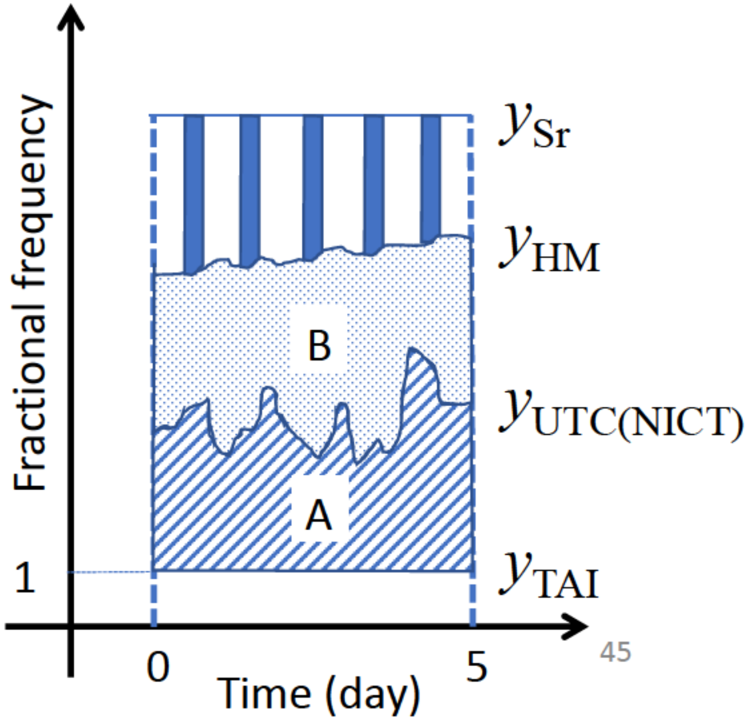


Measurement in 2015
Link uncertainty: 7.2e-16

Measurement







How much clocks deviate from linear drift?

Allan variance (= two sample variance) is insensitive to constant frequency difference.

↓

Raise the # of variance.
Three sample variance (Hadamard variance) is insensitive to constant difference of frequency drift rate.

3-sample variance　（Hadamard variance)

$$\begin{aligned}\frac{1}{6(M-2)}\sum_{i=1}^{M-2}[y(i+2)-2y(i+1)+y(i)]^2 = \frac{1}{6(N-3)\tau^2}\sum_{N=1}^{N-3}[x(i+3)-3x(i+2)\\ +3x(i+1)-x(i)]\end{aligned}$$

Dead time uncertainty

Hadamard deviation (effective deviation of de-drift signal) of our HMs has flicker floor up to one month

Deviation of phase was investigated in 1980s.

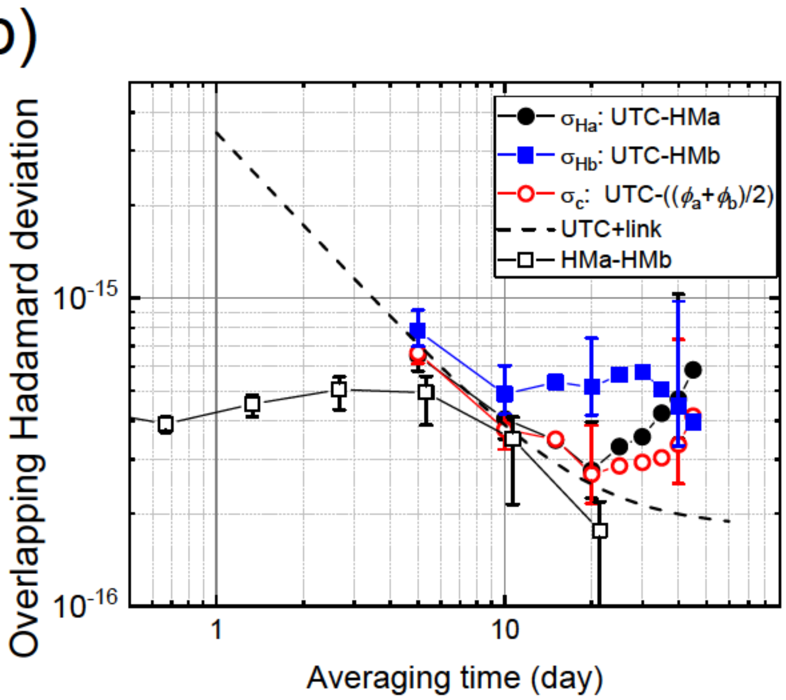


TABLE III

α	Typical Noise Types Name	Optimum Prediction $x(\tau_p)$ rms[a]	Time Error: Asymptotic Form
2	white-noise PM	$\tau_p \cdot \sigma_y(\tau_p)/\sqrt{3}$	constant
1	flicker-noise PM	$\sim \tau_p \cdot \sigma_y(\tau_p)\ \sqrt{\ln \tau_p / 2 \ln \tau_0}$	$\sqrt{\ln \tau_p}$
0	white-noise FM	$\tau_p \cdot \sigma_y(\tau_p)$	$\tau_p^{1/2}$
−1	flicker-noise FM	$\tau_p \cdot \sigma_y(\tau_p)/\sqrt{\ln 2}$	τ_p
−2	random-walk FM	$\tau_p \cdot \sigma_y(\tau_p)$	$\tau_p^{3/2}$

[a] τ_p is the prediction interval.

Ref. D. W. Allan, IEEE Trans. Ultrasonic, Ferro. Freq. Control UFFC-34, 647 (1987).

Phase noise during two operation separated τ : $\tau\sigma(\tau)/(\ln 2)^{1/2}$

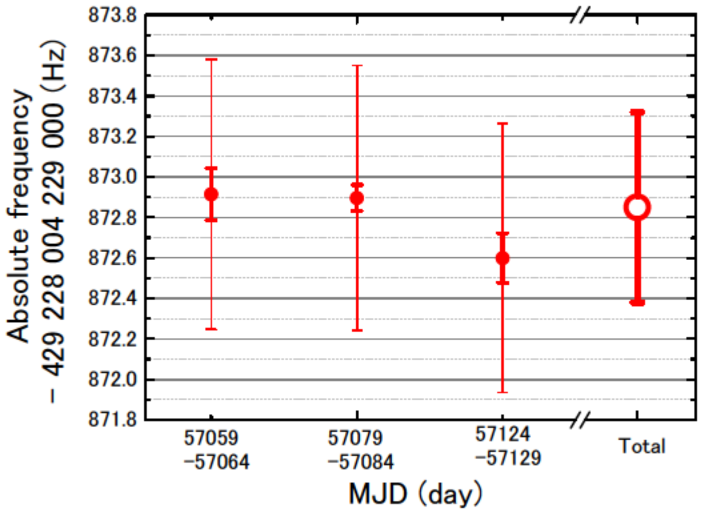
Link from TAI to SI second

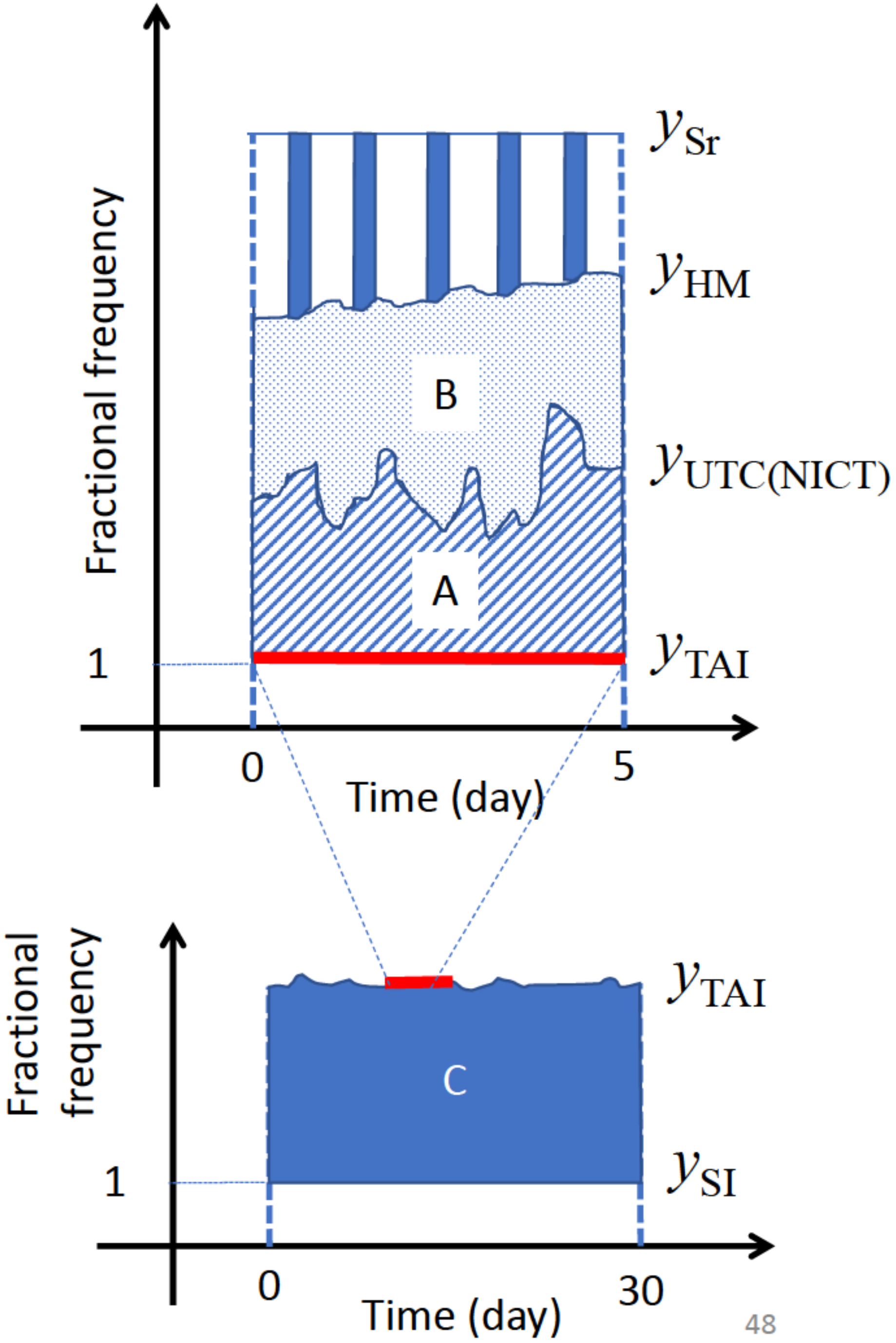
BIPM tells us the calibration of TAI
in 1-month average basis.
The TAI in previous slide is 5-day average.

$$C = \int_{Day0}^{Day30} \left(y_{TAI(k)} - 1\right) dt$$

$$\overline{\nu(TAI)}_{5days} \neq \overline{\nu(TAI)}_{1month}$$

Uncertainty of this deviation
7.6e-16



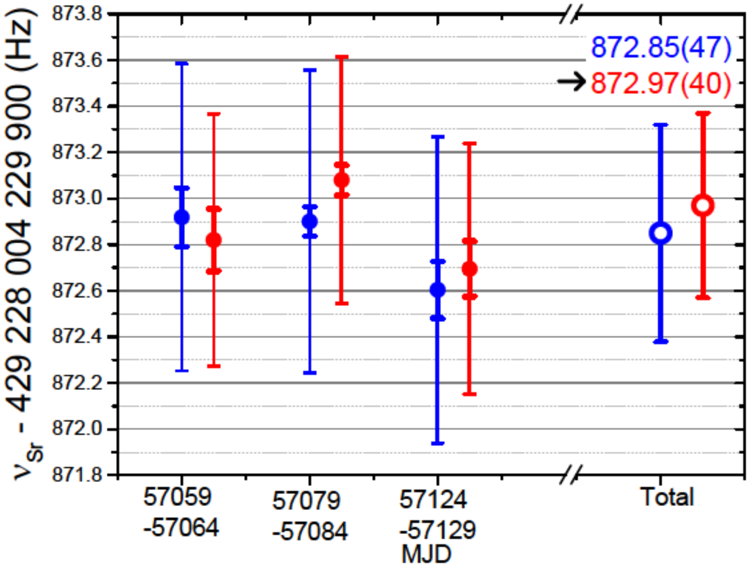


Evaluation using three 5-day campaigns

G. Petit at BIPM time department calculated the TAI calibration on three 5-day averages of our measurement campaigns

Day of average	campaign #1	campaign #2	campaign #3
30 (Cir. T)	-4.4 (2.6)	-2.7(2.5)	-2.3 (2.6)
5 (by Petit)	-2.5 (8.1)	-6.8 (8.2)	-4.5 (7.4)

(× 10^{-16})



	30day	5day
Statistical	10	
Sr systematic	9	
Gravity	8	
Dead time (HM-UTC(k))	19	
Satellite link	69	
Dead time(TAI-SI second)	76	0
TAI-SI second	25	57
Total	109	93

(× 10^{-17})

CIPM#(2017): … 873.0

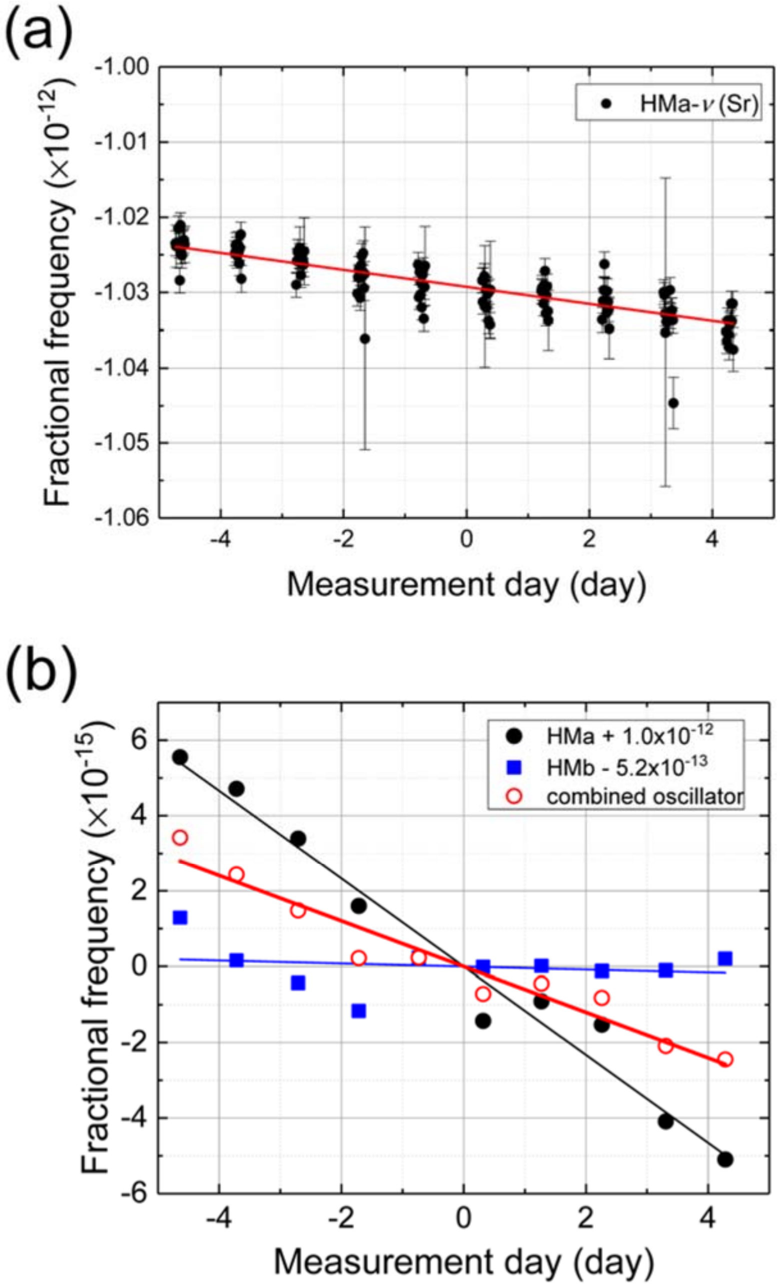
Appl. Phys. B **123**, 34 (2016).

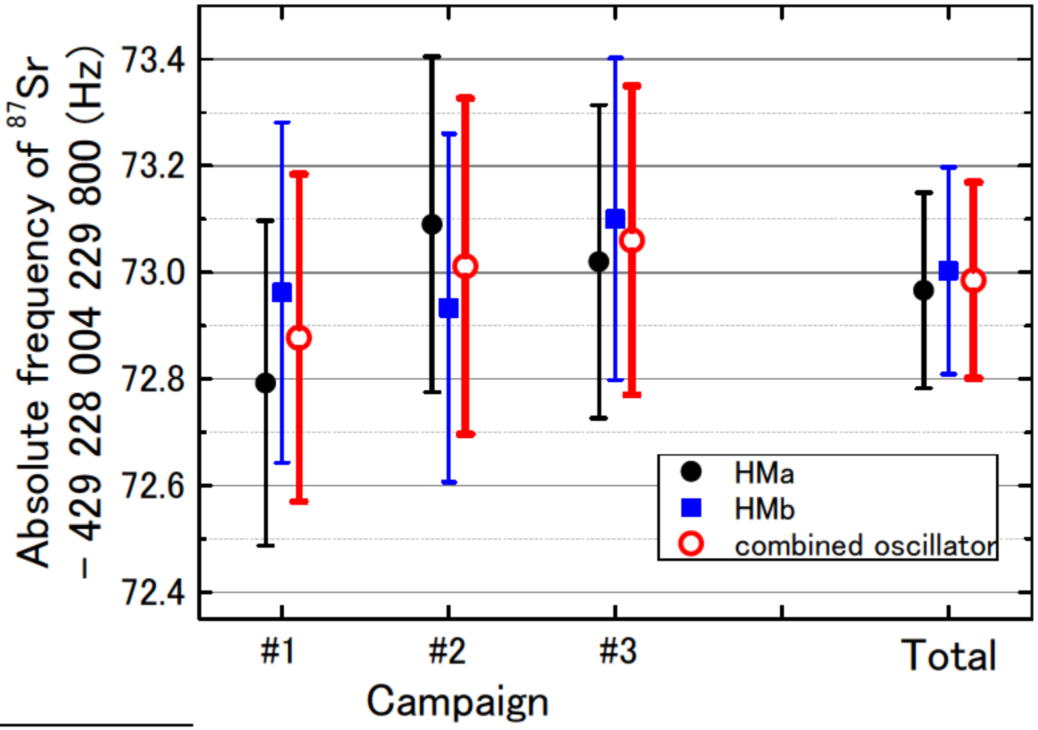
Furthermore… 10 day campaign X 3 + two HM ensemble

Benefit of 5-day →10-day

Fitting uncertainty ↓
UTC(NICT)-UTC error ↓

Ensemble of two HMs may mitigate sporadic phase excursion of one HM





	Campaign # 2 (10^{-17})	Total (10^{-17})
Strontium		
statistical	2	1
systematic	6	6
Gravity	2	2
Local flywheel oscillator		
deterministic	18	10
stochastic (dead time)	10	6
Link		
UTC-UTC(NICT) link	49	28
UTC- SI second	(50)	
systematic uncertainty	15	14
rest of random part	48	26
Total	73	43

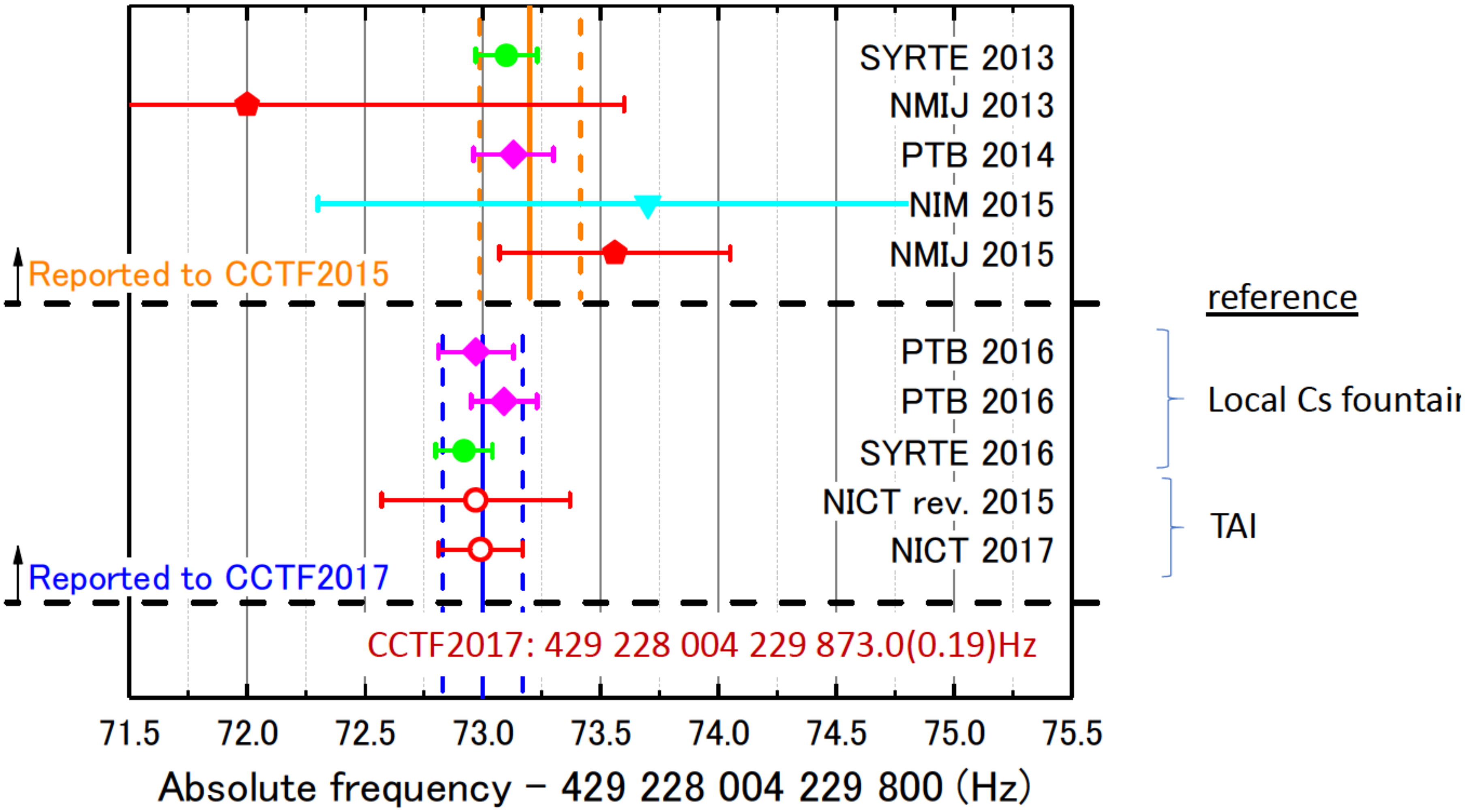
Due to the error in linear fitting

Due to the dead time error

These two uncertainty could be not independent.

< 5e-16

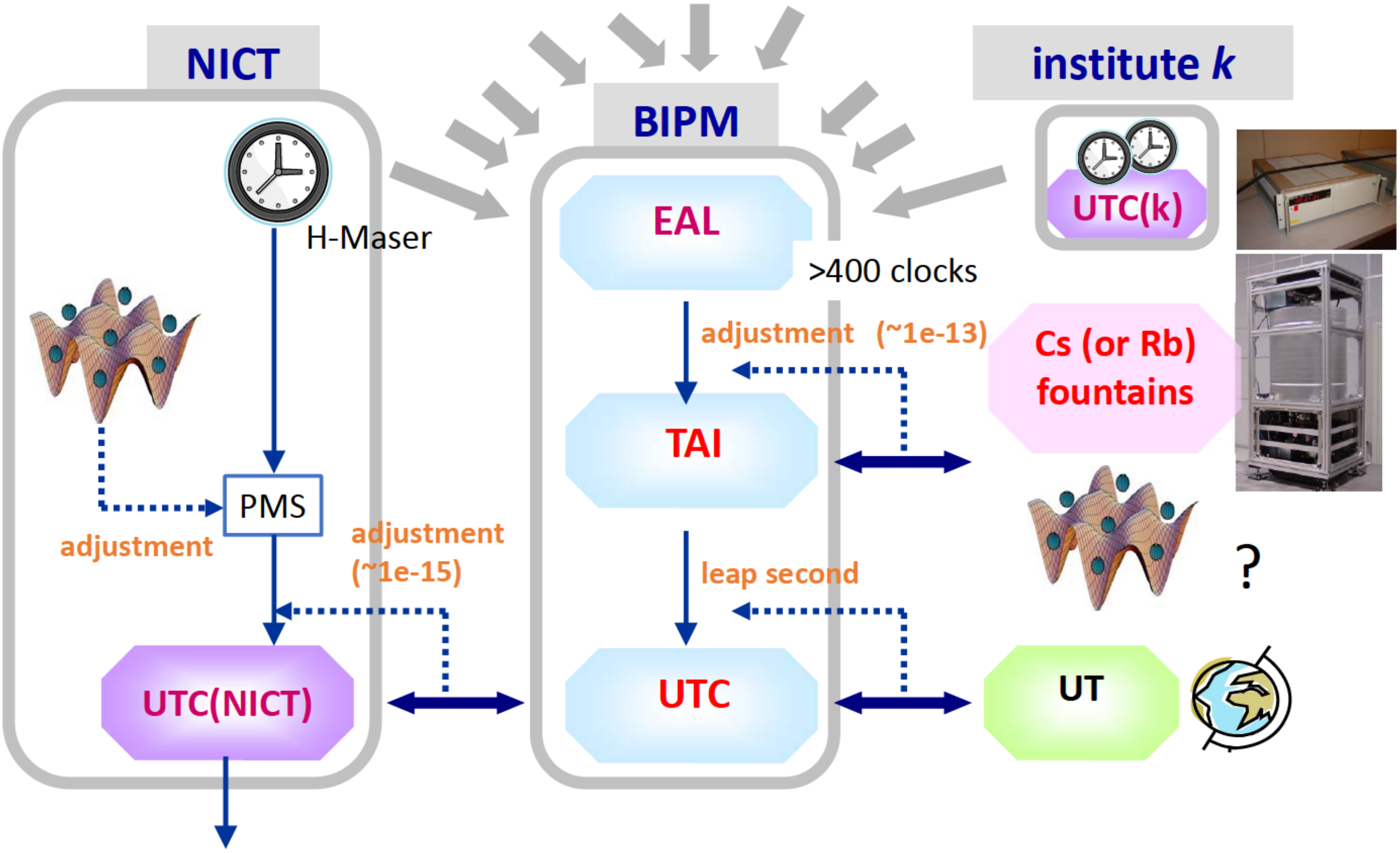
Continuity of the S second



Last 5 data: std. deviation 6e-17 < Cs type-B uncertainty
Will be no jump on the redefinition (Possible jump inside the current Cs ability of realization)
But contribution of more Cs clocks is expected.

Optical – microwave hybrid time scale using Sr lattice clock

Optical clocks utilized for time scale



NICT

H-Maser

adjustment

PMS

adjustment (~1e-15)

UTC(NICT)

BIPM

EAL

>400 clocks

adjustment (~1e-13)

TAI

leap second

UTC

institute *k*

UTC(k)

Cs (or Rb) fountains

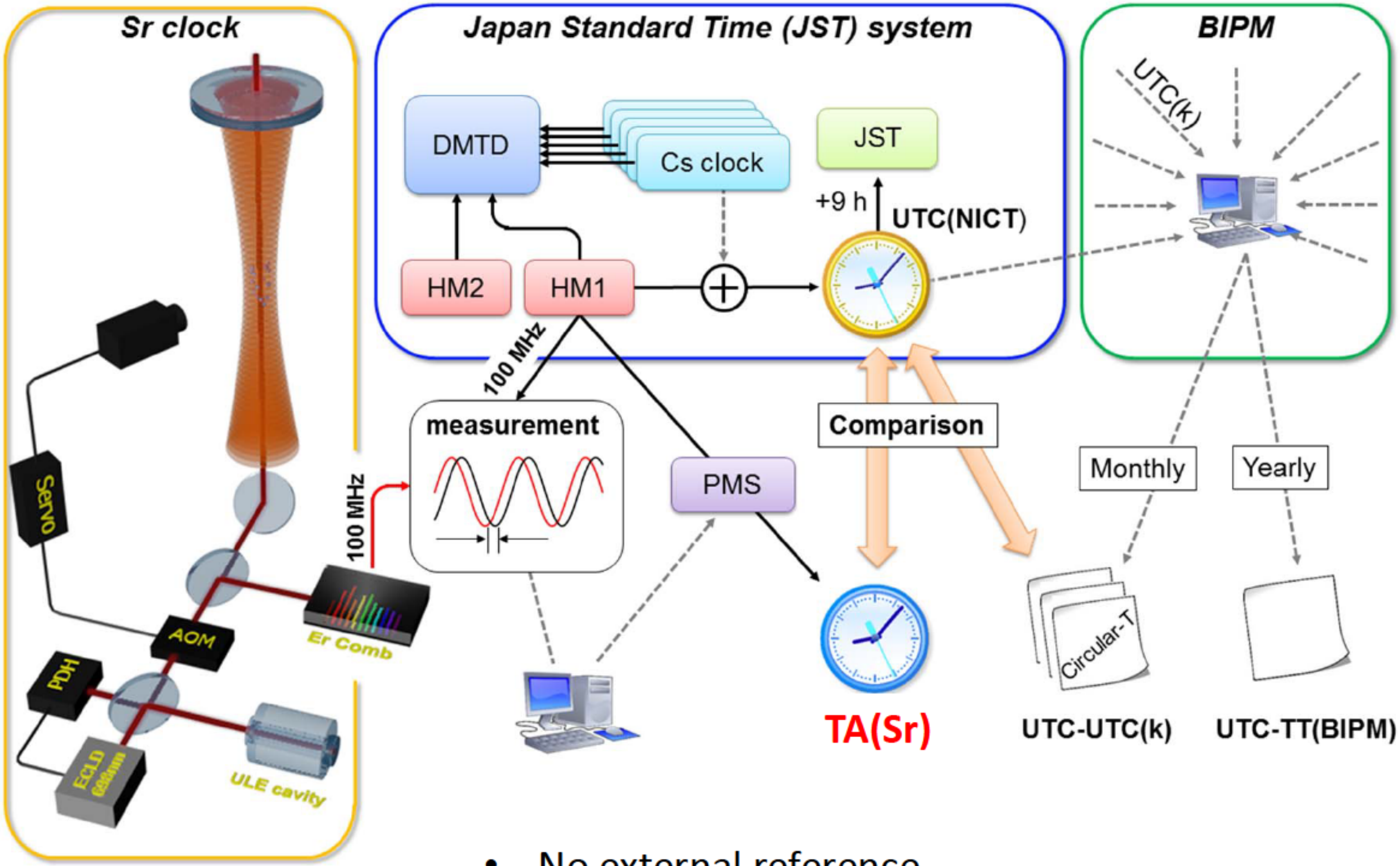
?

UT

Japan Standard Time (JST)

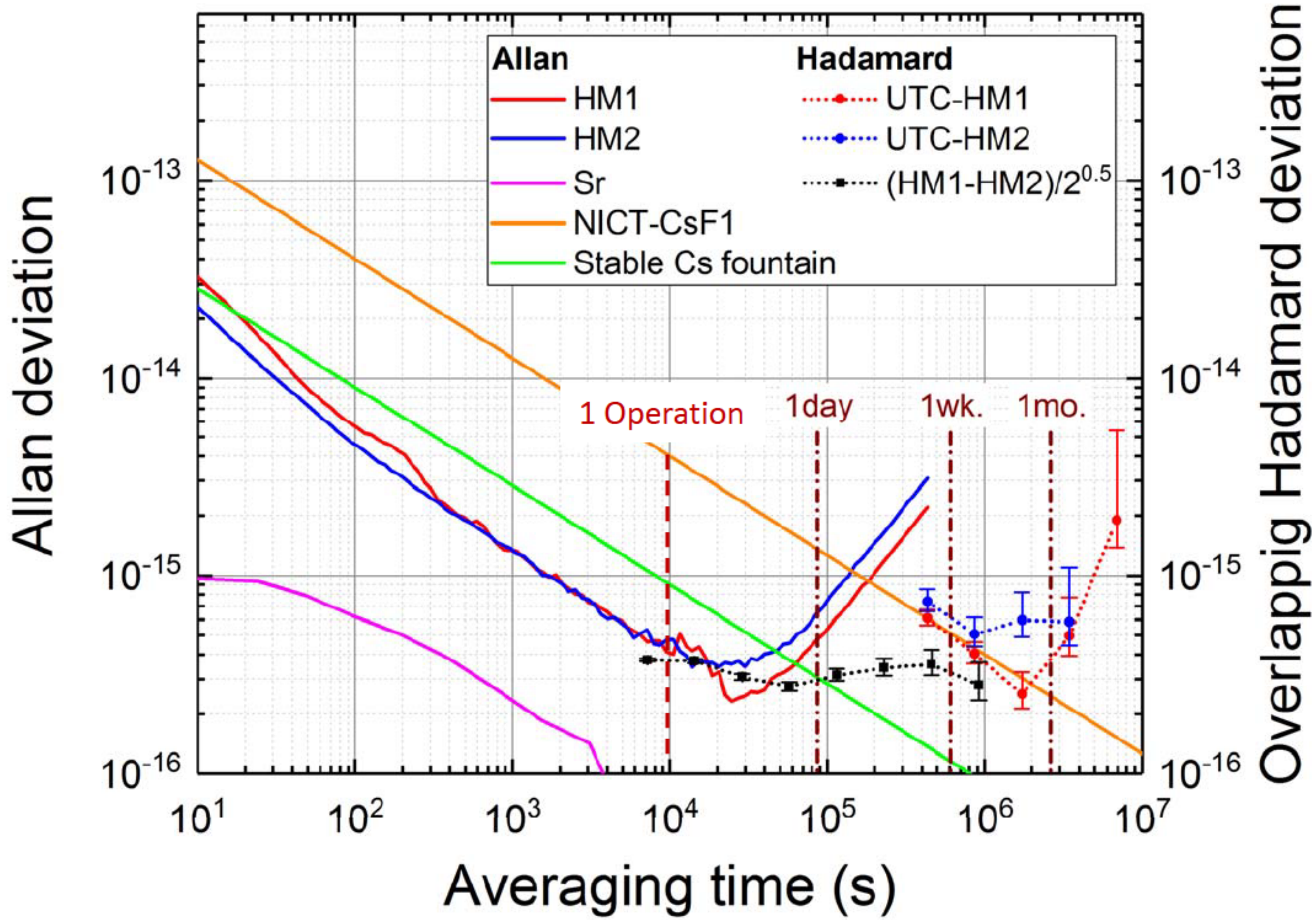
PMS: Phase micro stepper

Optically steered time scale



- No external reference
- Reference to compare with: UTC, TT(BIPM16)

Advantage of “optical” steering

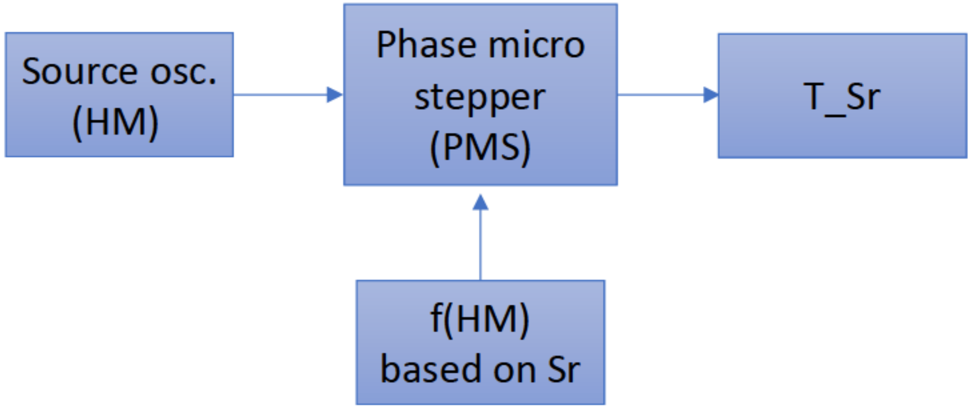


- 10^4 s of operation is sufficient to evaluate the scale unit of a HM at mid-10^{-16} level

- Short term fluctuation of HM may be compensated by an optical clock.
- Not necessary to operate all the time.

once in a week for 3 hours

Steering by intermittent operation of Sr lattice clock

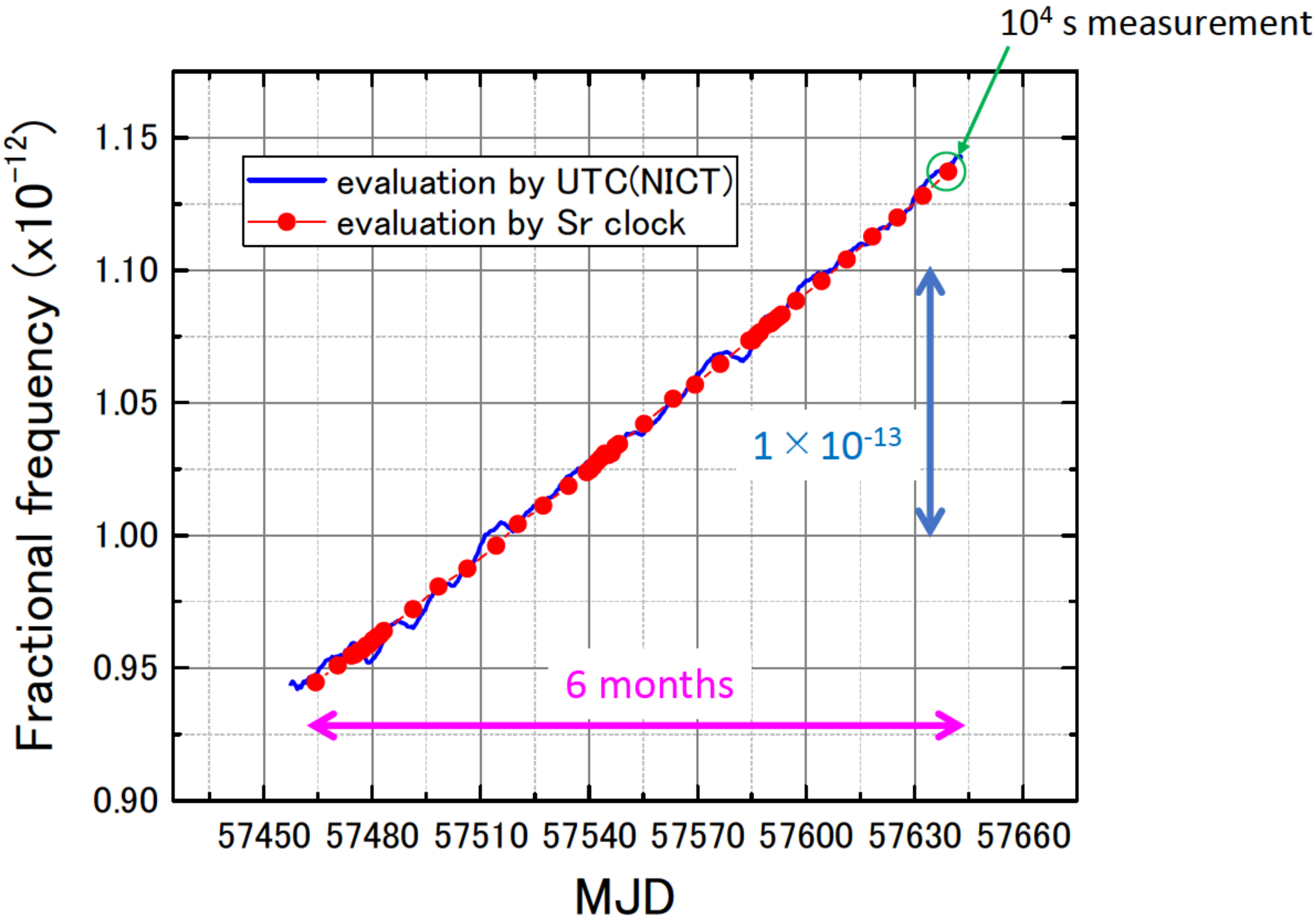


- HM frequency and drift rate calibrated by Sr
- Adjustment of PMS offset frequency every 4 hours
- No servo to reduce the time offset UTC-T_Sr
- Based on our frequency* obtained in 2015

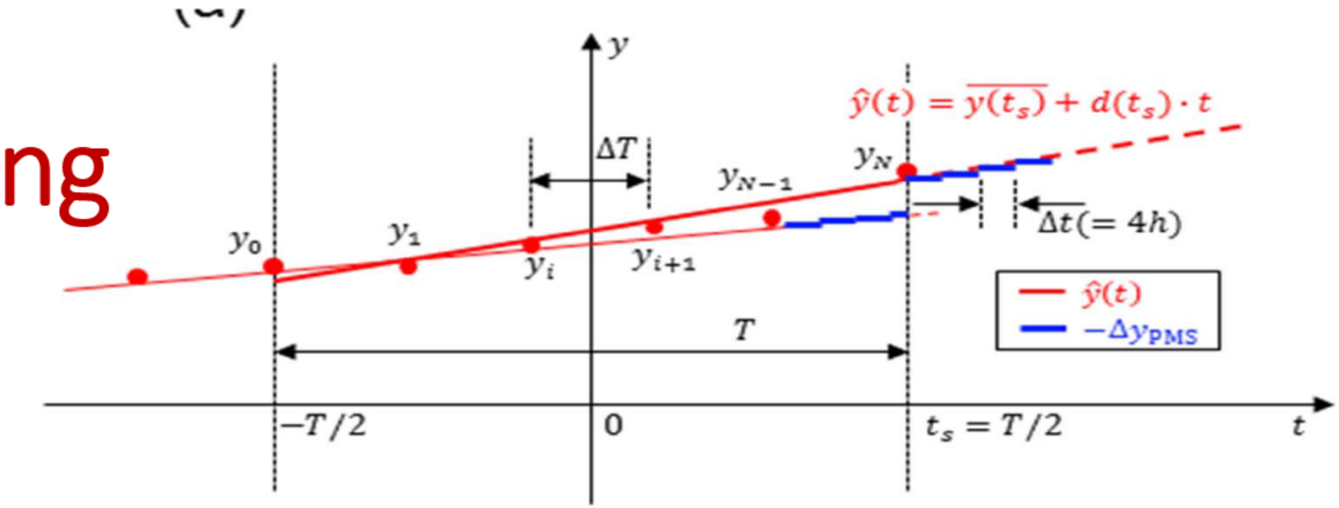
→ Intermittent operation more than once a week for 10^4 s continued

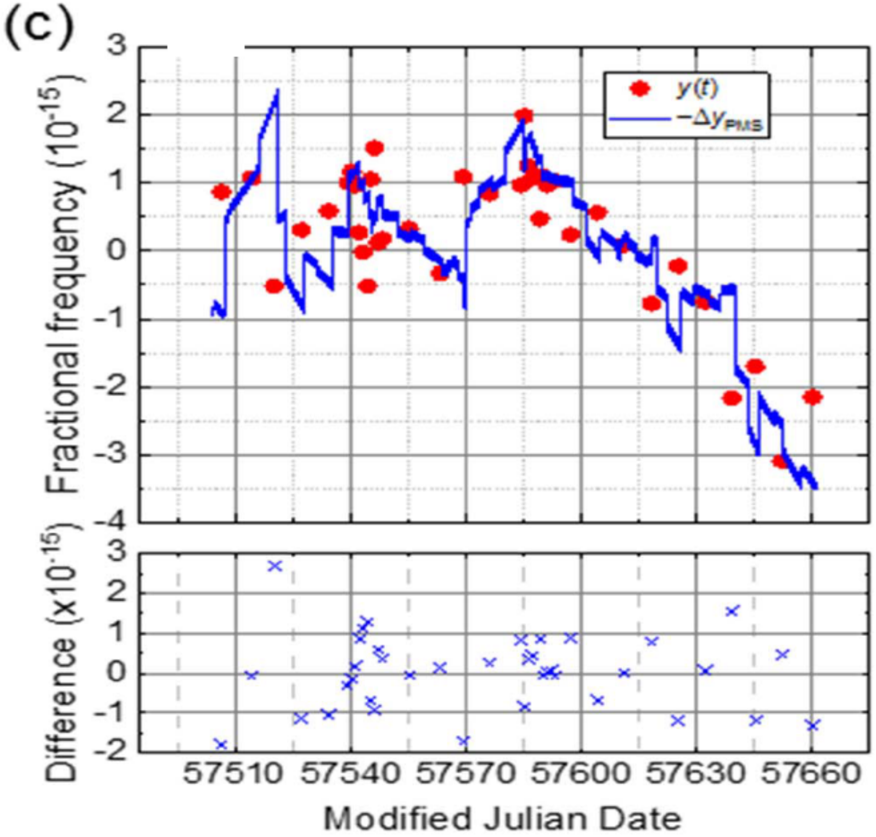
*429 228 004 229 872.97 Hz (Hachisu et al., Appl. Phys. B **34**, 123 (2017))
… 873.2 Hz (CIPM2015) → … 873.0 Hz (CCTF WGFS, Jun 2017)

INTERMITTENT Evaluation of a HM for 6 monthsby Sr and UTC(NICT)



Steering





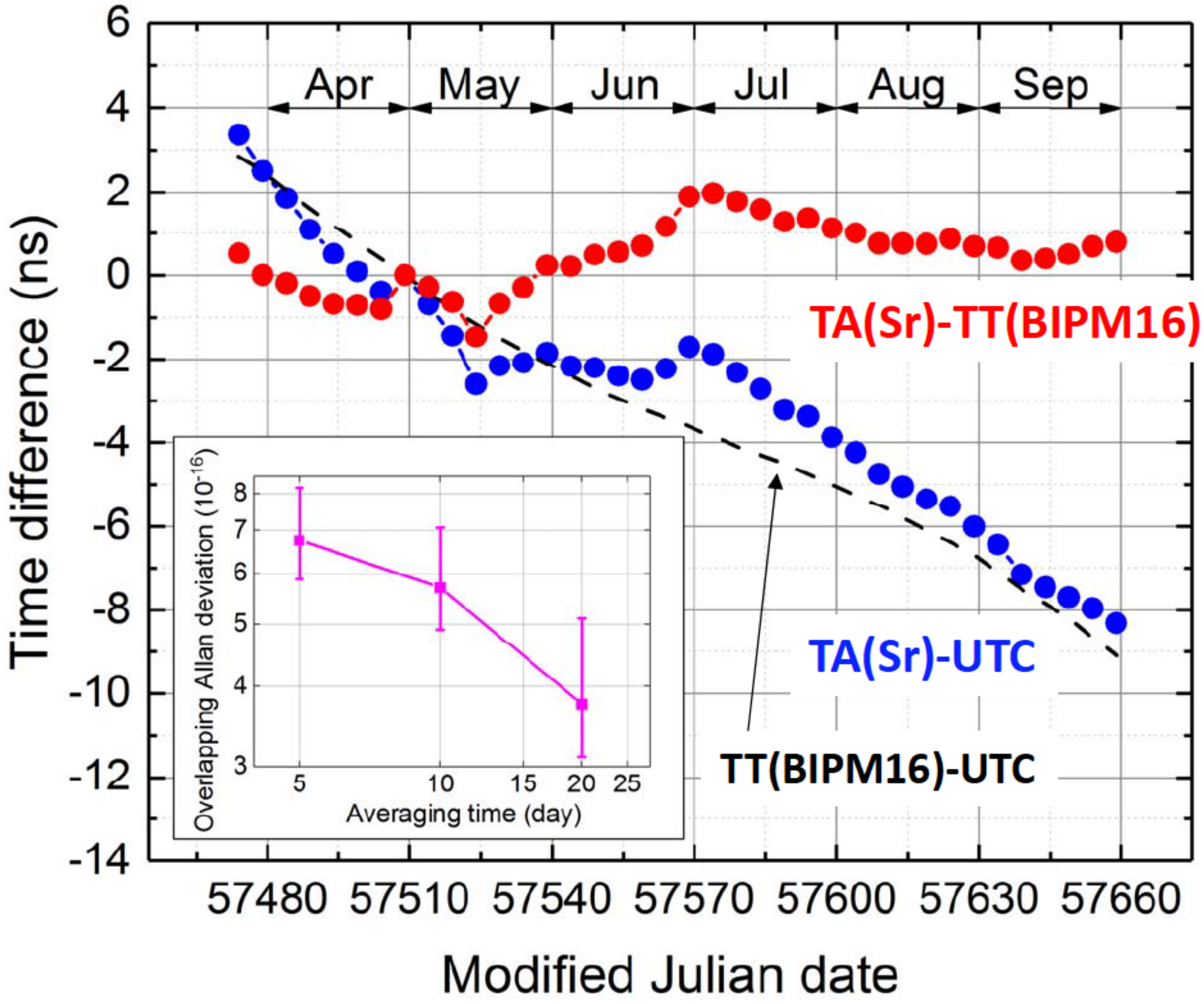
Linear drift estimation interval: T=25days

Number of OFS operation in T : N+1 >4
(once per week or more frequently)

One HM free evolution time: $\Delta T = T/N$

Comparison against UTC & TT(BIPM16)

- Clearly detect the frequency offset of UTC
- Phase difference against TT(BIPM16)
  < 1ns after 5months
- Stability 4e-16 @ 20 days

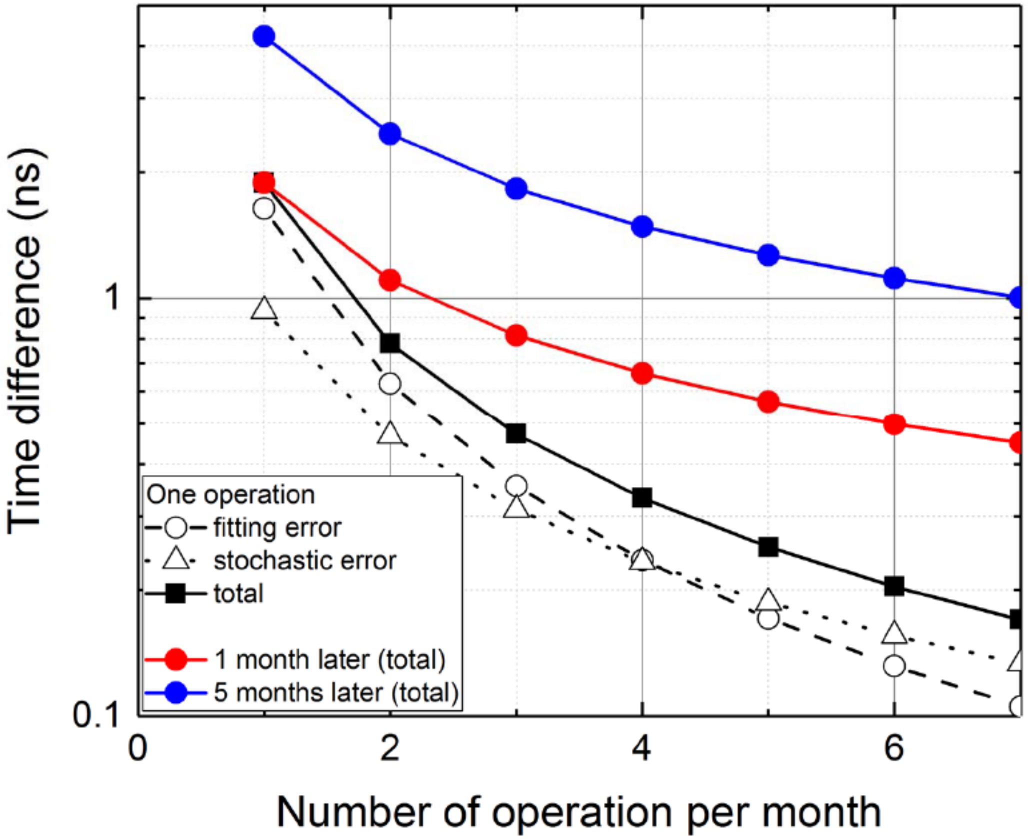


H. Hachisu et al., Sci. Rep. **8**, 4243 (2018)

equirement for HM nd OFS operation rate

$$E[|\Delta\phi|] = \left(\varepsilon_p^2 + \varepsilon_F^2\right)^{1/2}$$

$$= \frac{T}{N}\left[\underbrace{\frac{(2N+1)(2N+3)}{N(N+1)(N+2)}\sigma_p{}^2}_{\text{Linear drift estimation error (from LSF)}} + \underbrace{\frac{1}{\ln 2}\sigma_F{}^2}_{\text{Stochastic phase excursion in Flicker noise (*)}}\right]^{\frac{1}{2}}$$



$\sigma_p = 4E-16$

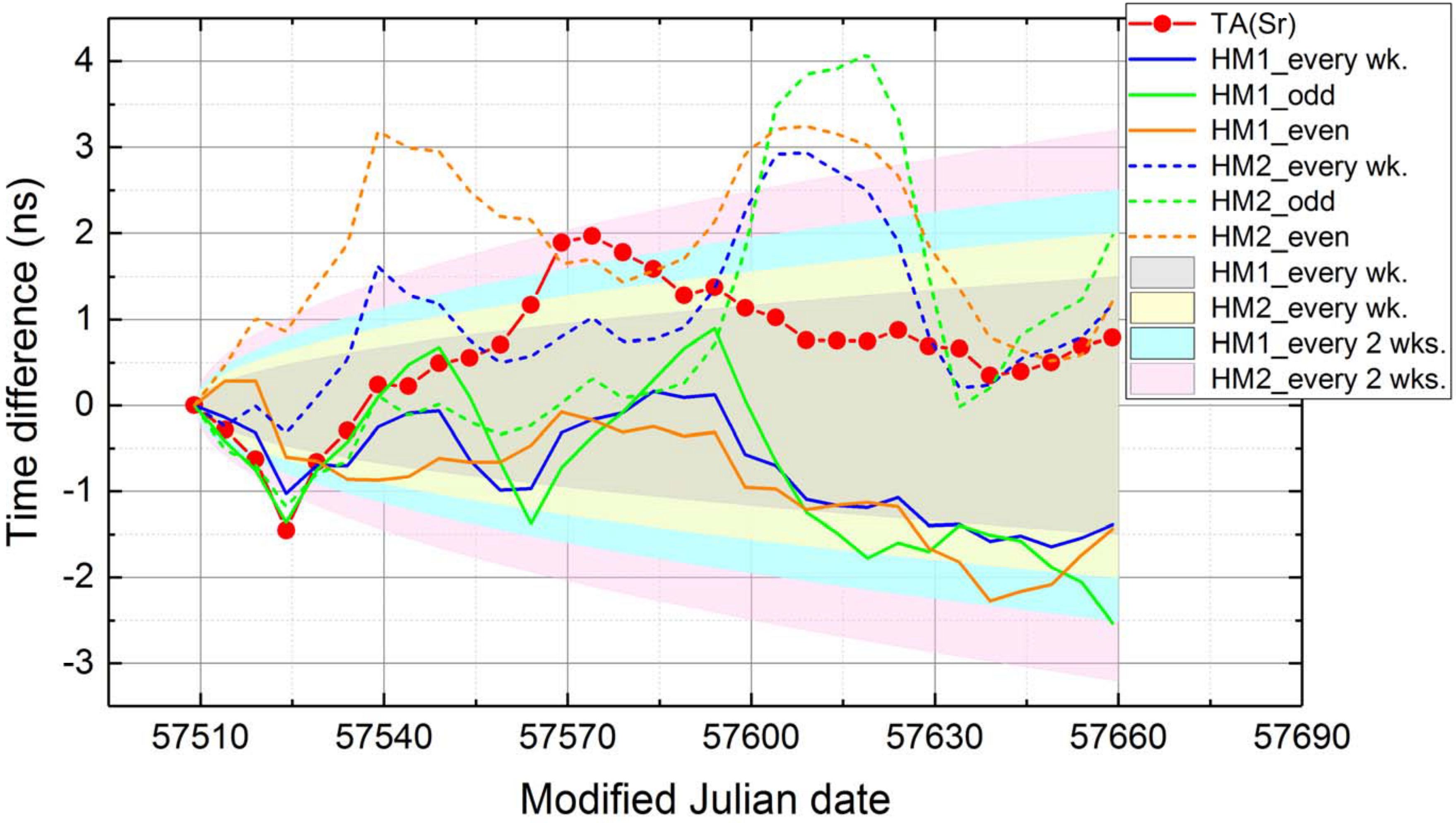
(stability @ 10^4 s)

$\sigma_F = 3E-16$

Flicker floor of Hadamard dev.

* D. Allan, IEEE Trans. Ultrasonic. Ferro. Freq. Cont., **34** 647 (1987)

Simulation in worse HM & infrequent OFS operation



HM2 (dash) noisier than HM1 (solid) (HM2 Flicker floor: 5e-16)

Blue: once per week, orange and green: once per two weeks (odd, even)

Evaluation of TAI scale interval

Strontium is not the definition of the second.

Does it calibrate TAI scale interval equivalently or even more accurately?

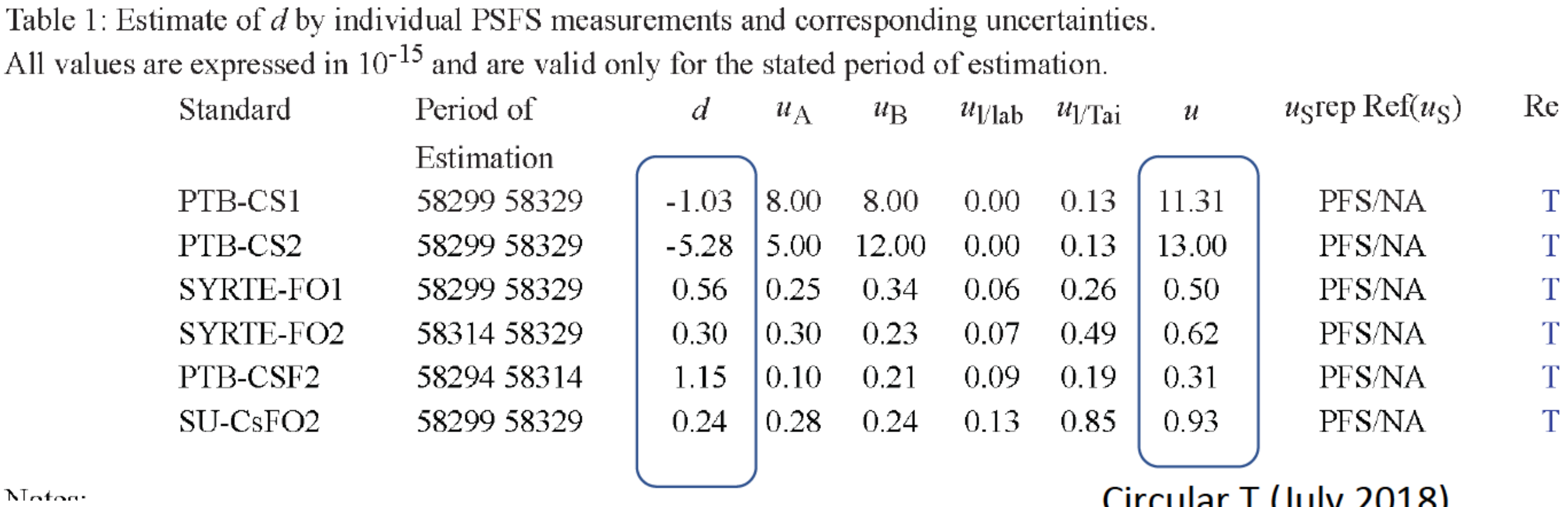


Table 1: Estimate of d by individual PSFS measurements and corresponding uncertainties.
All values are expressed in 10^{-15} and are valid only for the stated period of estimation.

Standard	Period of Estimation	d	u_A	u_B	$u_\mathrm{l/lab}$	$u_\mathrm{l/Tai}$	u	$u_\mathrm{S}$rep Ref(u_S)	Re
PTB-CS1	58299 58329	-1.03	8.00	8.00	0.00	0.13	11.31	PFS/NA	T
PTB-CS2	58299 58329	-5.28	5.00	12.00	0.00	0.13	13.00	PFS/NA	T
SYRTE-FO1	58299 58329	0.56	0.25	0.34	0.06	0.26	0.50	PFS/NA	T
SYRTE-FO2	58314 58329	0.30	0.30	0.23	0.07	0.49	0.62	PFS/NA	T
PTB-CSF2	58294 58314	1.15	0.10	0.21	0.09	0.19	0.31	PFS/NA	T
SU-CsFO2	58299 58329	0.24	0.28	0.24	0.13	0.85	0.93	PFS/NA	T

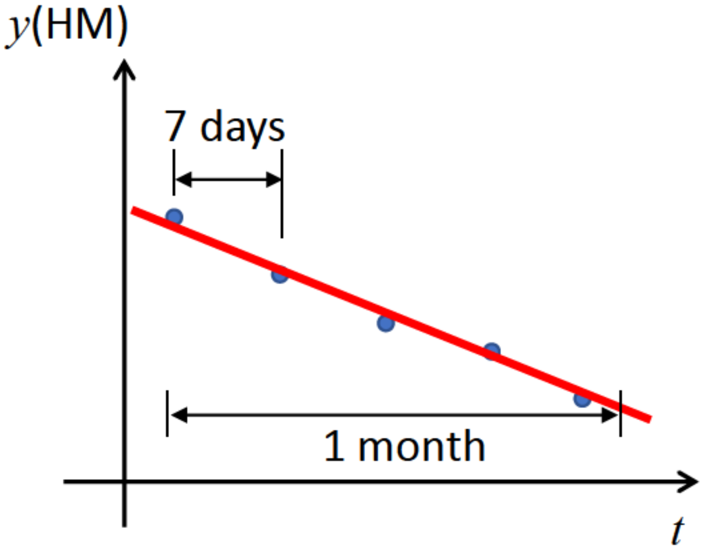
Notes:

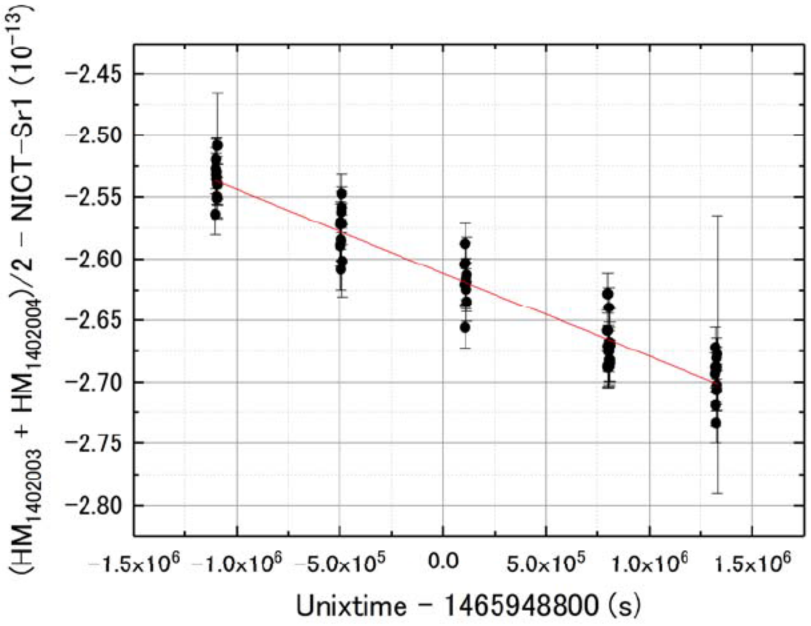
Circular T (July 2018)

SYRTE reported the calibration by Sr in 4 of (<20day) estimation period.
Longer estimation period is better owing to reduced $u_\mathrm{l/Tai}$
Secondary representation of the second suffers u_Srep of 0.40 (CIPM2017#), which is 0.17Hz.

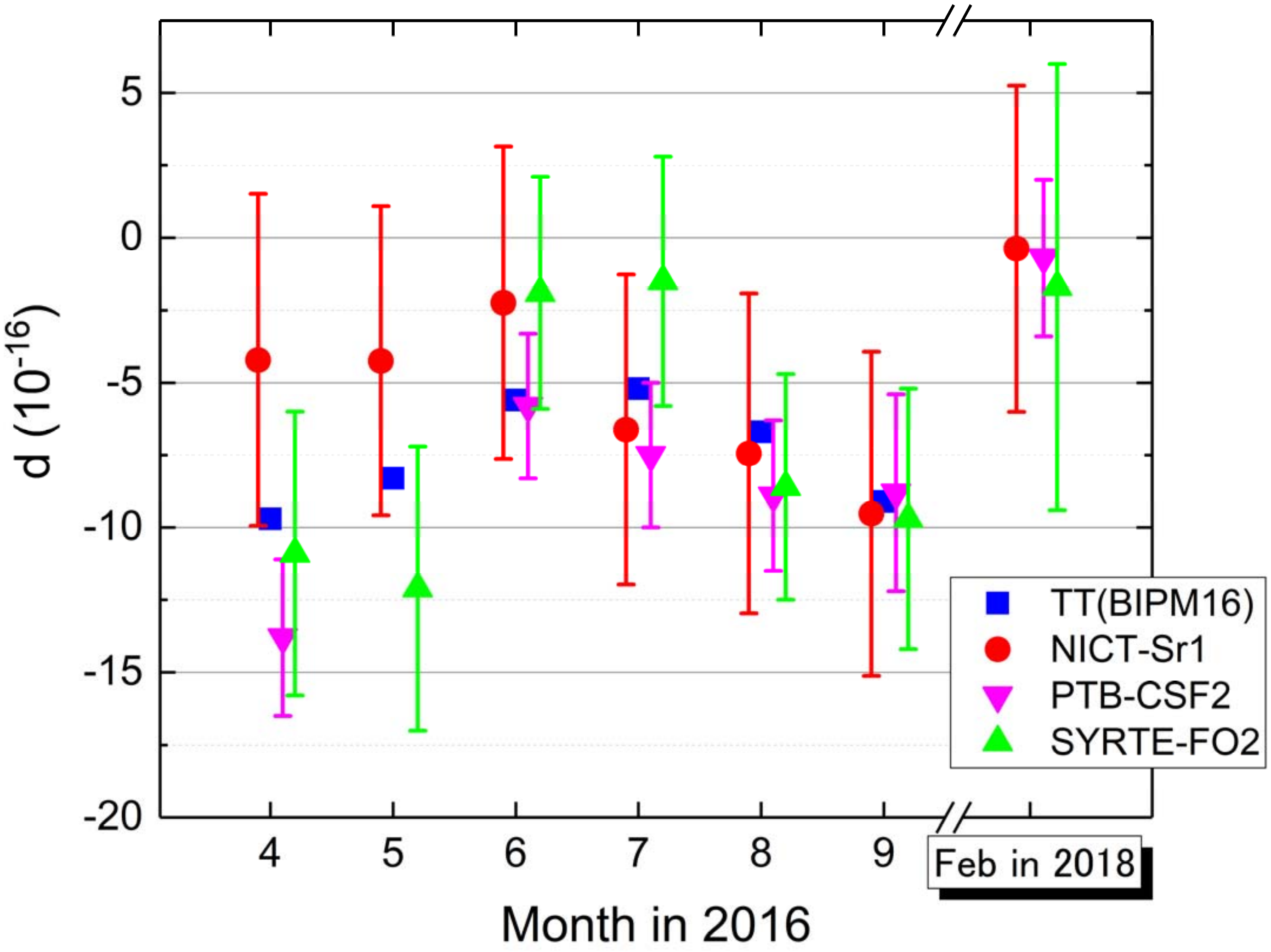
Evaluation of one-month mean TAI scale interval by Sr

Effects	Uncertainty (10^{-17})
Sr systematic	6
Gravity	2.2
Hydrogen maser	
deterministic	25
stochastic (dead time)	18
Phase measurement	5
UTC-UTC(NICT) link	26 (30 days average)
Sr frequency (uSrep)	40 (CIPM 2017)
Total	**57 (40 w/o uSrep)**





Result: Evaluation of TAI scale interval by Sr

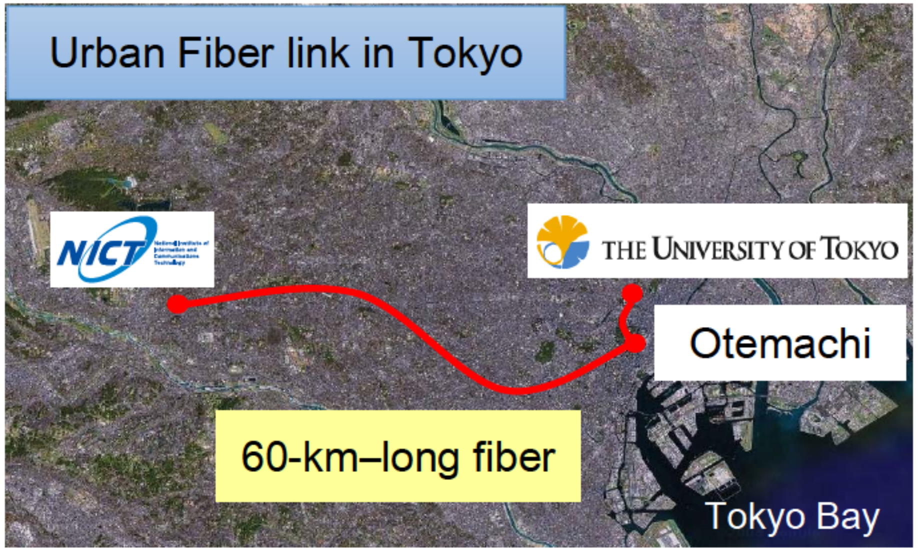


Sr standard frequency: 429 228 004 229 873.0 Hz
(2017 CIPM#)

Various link activities in NICT

- Fiber link to UT
- Two-way satellite link to PTB, KRISS
- VLBI (Very Long Baseline Interferometry) link to INRIM (ongoing)

Fiber link of clocks located at NICT and UT



Urban Fiber link in Tokyo

NICT

THE UNIVERSITY OF TOKYO

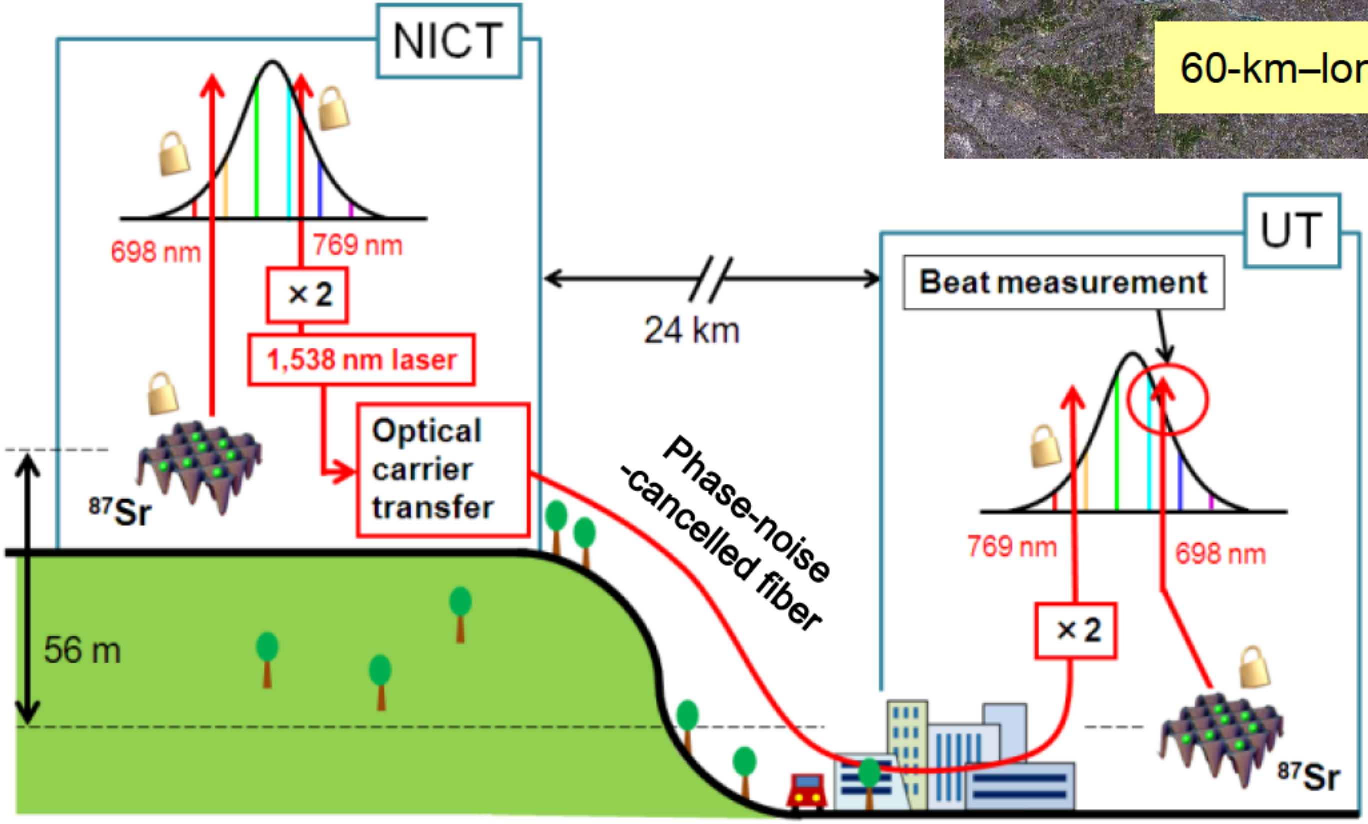
Otemachi

60-km–long fiber

Tokyo Bay

Google map

Schematics of the frequency comparison



NICT

698 nm

769 nm

×2

1,538 nm laser

Optical carrier transfer

^{87}Sr

56 m

24 km

Phase-noise -cancelled fiber

UT

Beat measurement

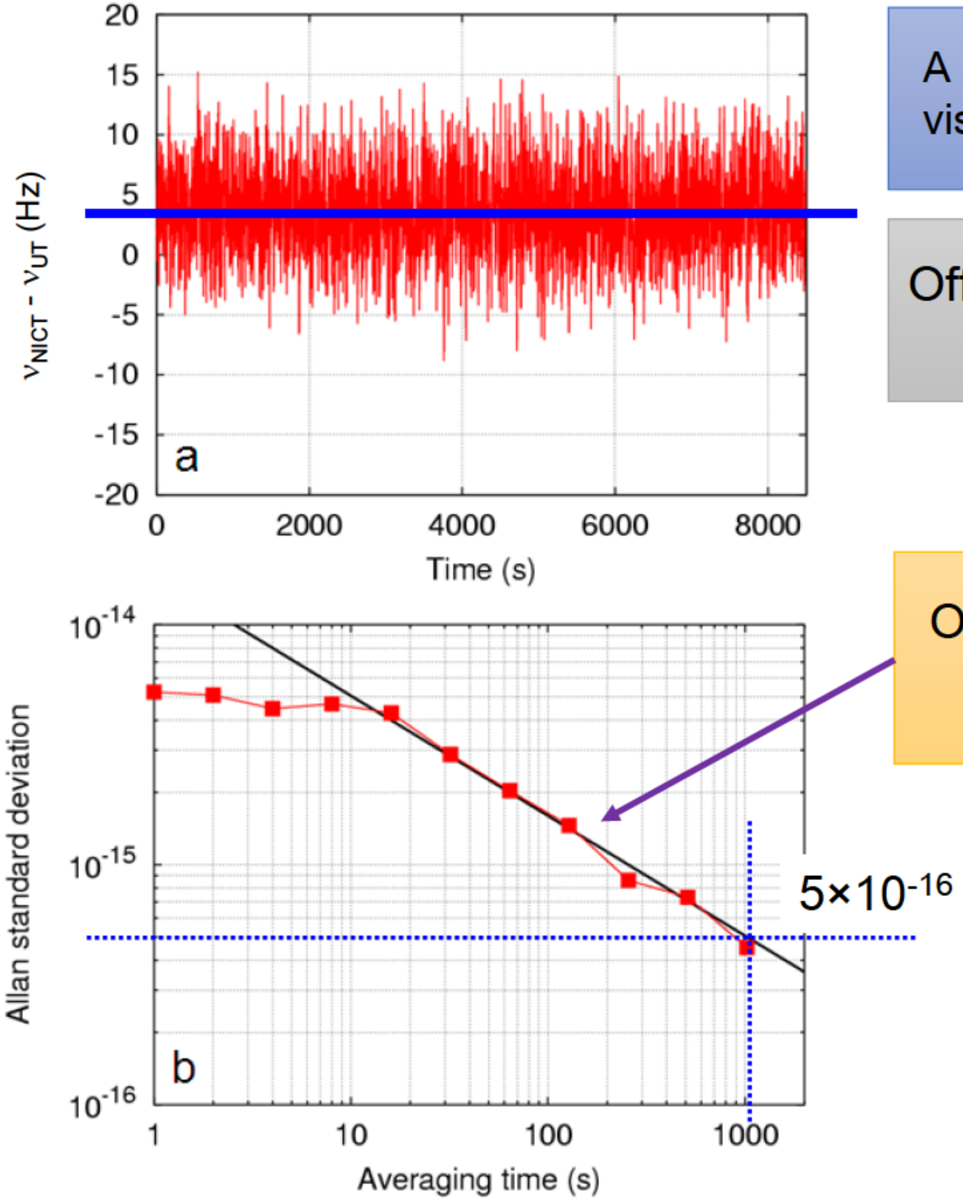
769 nm

698 nm

×2

^{87}Sr

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

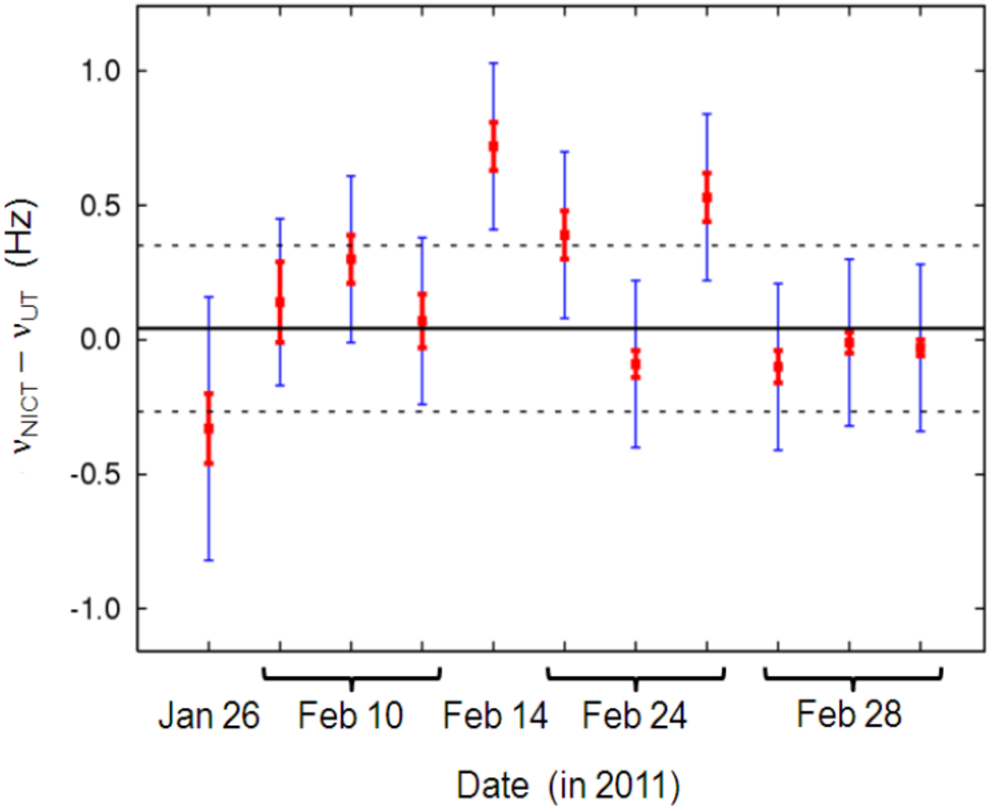
Dick-effect-limited instability

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

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

Frequency difference

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)

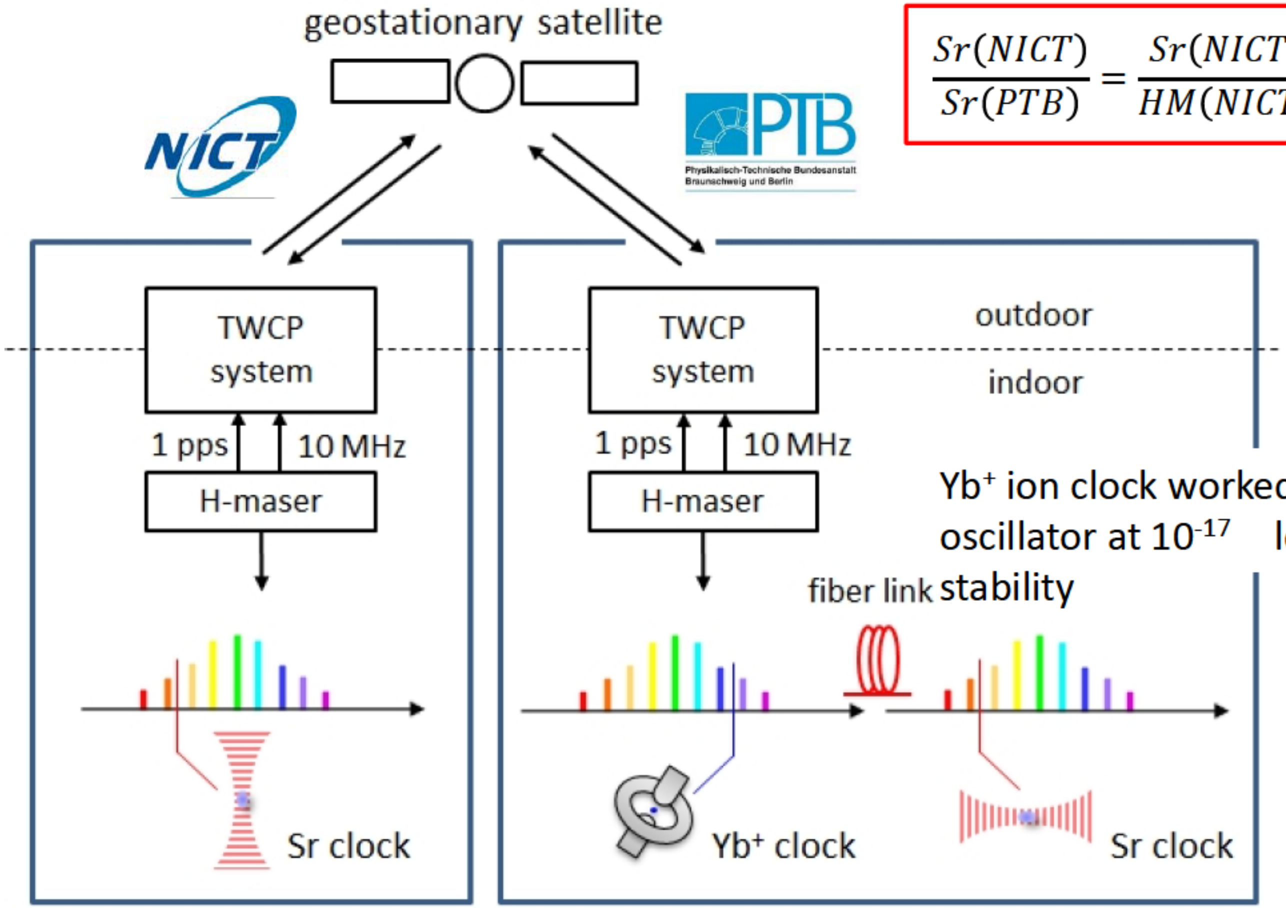
No limitation imposed by the fiber transfer

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

Atsushi Yamaguchi Appl. Phys. Express 4, 082203 (2011).

Schematic diagram of a direct frequency comparison using a geostationary satellite

$$\frac{Sr(NICT)}{Sr(PTB)} = \frac{Sr(NICT)}{HM(NICT)} \cdot \frac{HM(NICT)}{HM(PTB)} \cdot \frac{HM(PTB)}{Sr(PTB)}$$



Yb^+ ion clock worked as a transfer oscillator at 10^{-17} level of stability

Accuracy: 2×10^{-16} $< 10^{-17}$ [1,2] 4×10^{-17} [3]

[1] N. Huntemann *et al.*, PRL**108**, 090801(2012)
[2] N. Huntemann *et al.*, PRL**109**, 213002(2012)
[3] St. Falke *et al.*, arXiv:1312.3419(2013)

Uncertainty budget & result

	Uncertainty (10^{-16})
Systematics	
TWCP link	10 [*]
Sr clock @NICT	2
Sr clock @PTB	0.4
Gravitational red shift	1
Total systematics	**10**
Statistics	**12**
Total all	**16**

Average of fractional difference : 1.1×10^{-15}

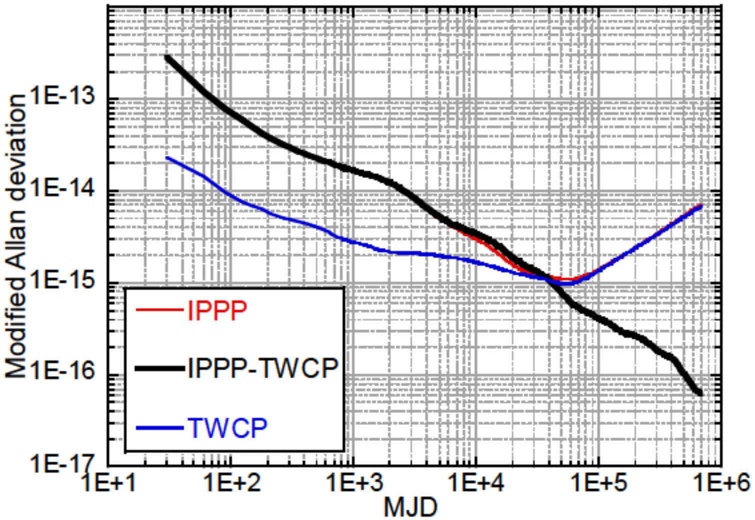
$$\frac{f(NICT)}{f(PTB)} - 1 = 1.1\,(1.6) \times 10^{-15}$$

[*] M. Fujieda *et al.*, Metrologia **51**, 253 (2014)

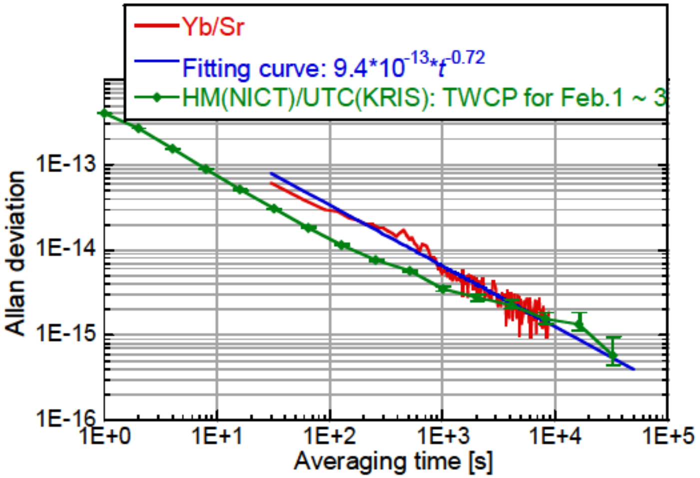
■ NICT-KRISS Yb/Sr measurement using TWCP

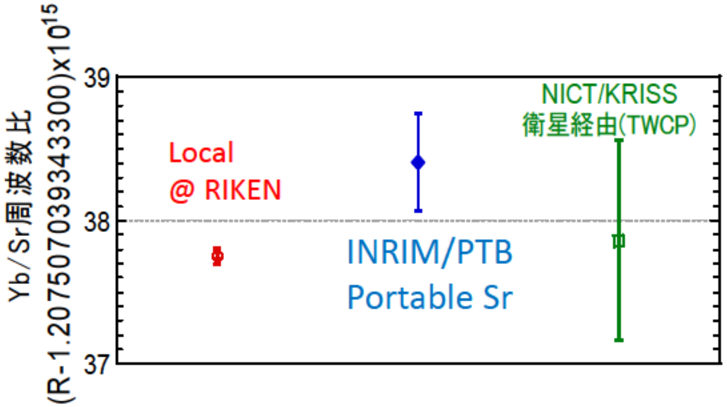
UTC(NICT)-UTC(KRISS) simultaneously measured using TWCP and IPPP technique.

They agreed in 10^{-17} level.



2) Yb/Sr ratio measurement using TWCP



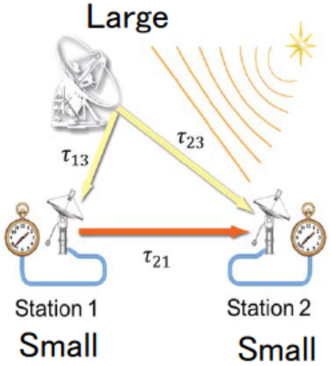


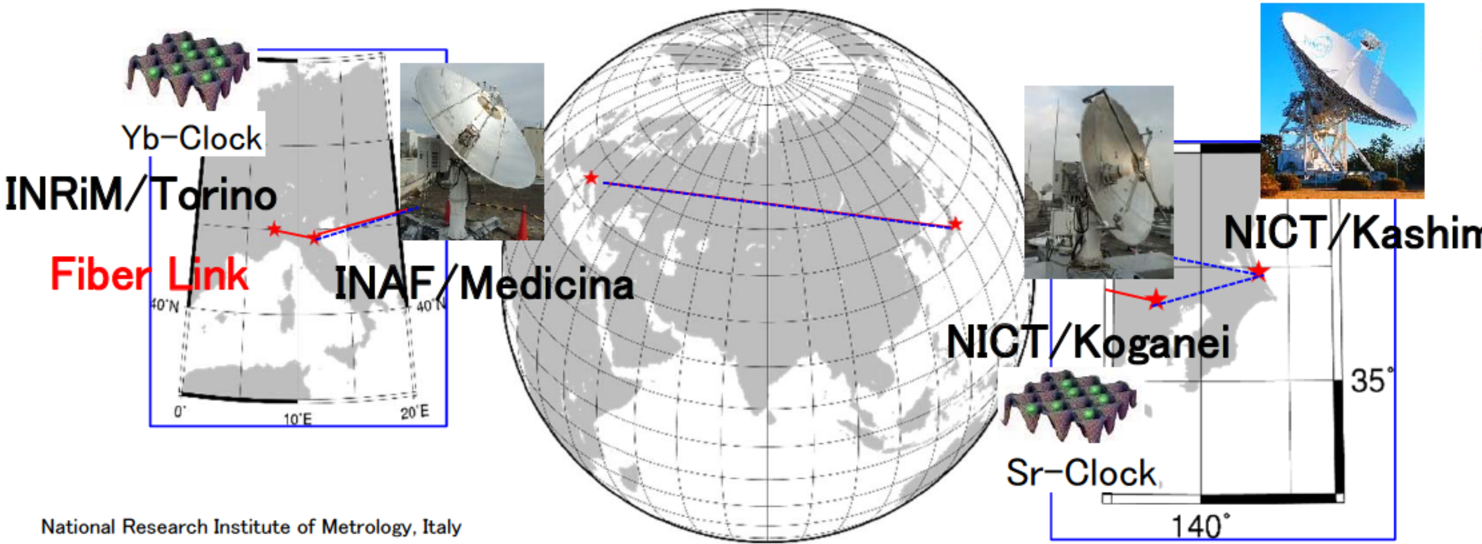
4h X 3 = 12h campaign.
Mid 10^{-16} level in one day.

Frequency Link INRiM–INAF/IRA–NICT by VLBI

Joint research for precise frequency comparison with VLBI among INRiM,INAF/IRA, and NICT since 2017.
Transportable small antenna(2.4m diameter) pair is used as nodes of comparison.
In 2018 July, one of the 2.4m antenna was installed at Medicina VLBI station of INAF/IRA.

Test VLBI experiment from this August. If there are no problem, the first clock comparison experiment in this fall.





$1\text{x}10^{-16}$
by 5 days
comparison

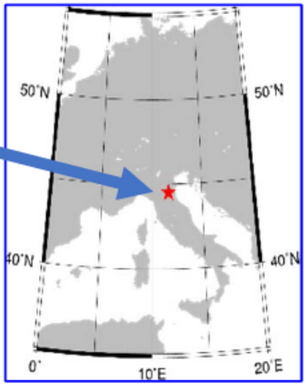
INRiM: National Research Institute of Metrology, Italy
INAF/IRA: National Institute for Astrophysics/Institute of Radio Astronomy, Italy
NICT: National Institute of Information and Communications Technology, Japan

Installation of 2.4m Broadband antenna to INAF/Medicina and the first VLBI on 14th Aug.

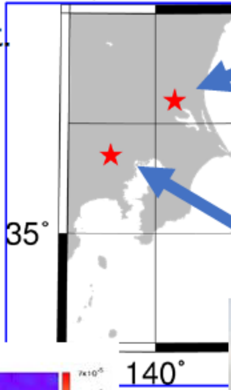
Broadband(3-14GHz) VLBI observation enables higher delay precision observation.

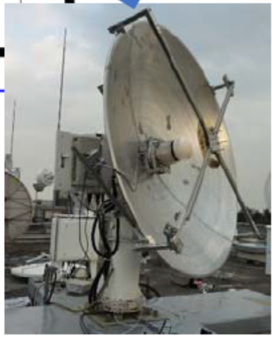
Since Kashima 34m is under maintenance in Aug., Ishioka13m VGOS Station/GSI is supporting our experiment.

INAF/Medicina 2.4m Broadband antenna



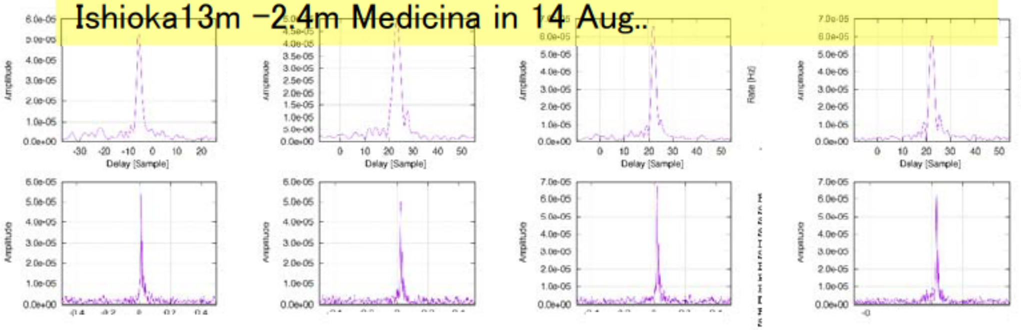
Ishioka 13m VGOS VLBI station/GSI Japan





NICT/Koganei 2.4m Broadband antenna

First Fringe detected for all four band(1GHz x 4) between Ishioka13m -2.4m Medicina in 14 Aug..

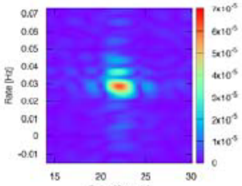


6.0GHz

8.5GHz

10GHz

11GHz



```
Epoch      : 2018/226 08:20:00
Station-1:             ISHIOKAH
Station-2:              MARBLE1
Source     :        OJ287[   D]
Length     :   180.000000[sec]
Sampling   :   2048000000[sps]
Frequency:+10488.000000[MHz]
Peak Amp   :     0.006271[ % ]
Peak Phs   :   -54.771271[deg]
Delay      :   +22.106781[spl]
Rate       :   +28.782315[mHz]
SNR        :    38.086637
```