Atomic Frequency Standards

NICT Space-Time Standards Group

Tetsuya Ido

Clock using real Cs

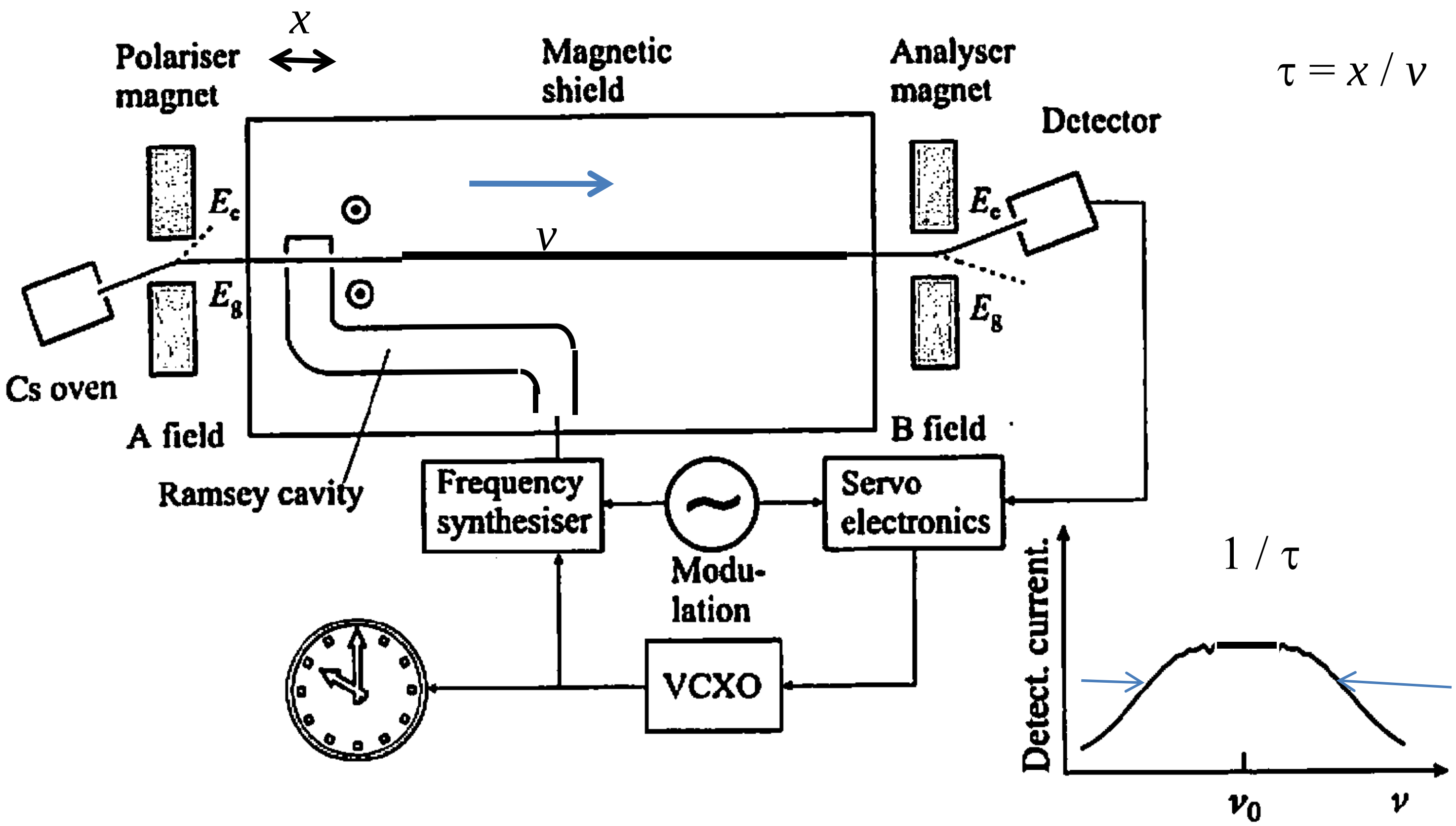


Figure 7.3: Schematic layout of a commercial Cs atomic clock. The magnetic quantisation field (C field) is perpendicular to the paper plain. The inset shows the detector current when the frequency of the synthesiser is tuned across the atomic resonance displaying the Ramsey resonance on the Rabi pedestal.

As longer time atom interacts with RF, the width will be narrower.

Cs beam clock

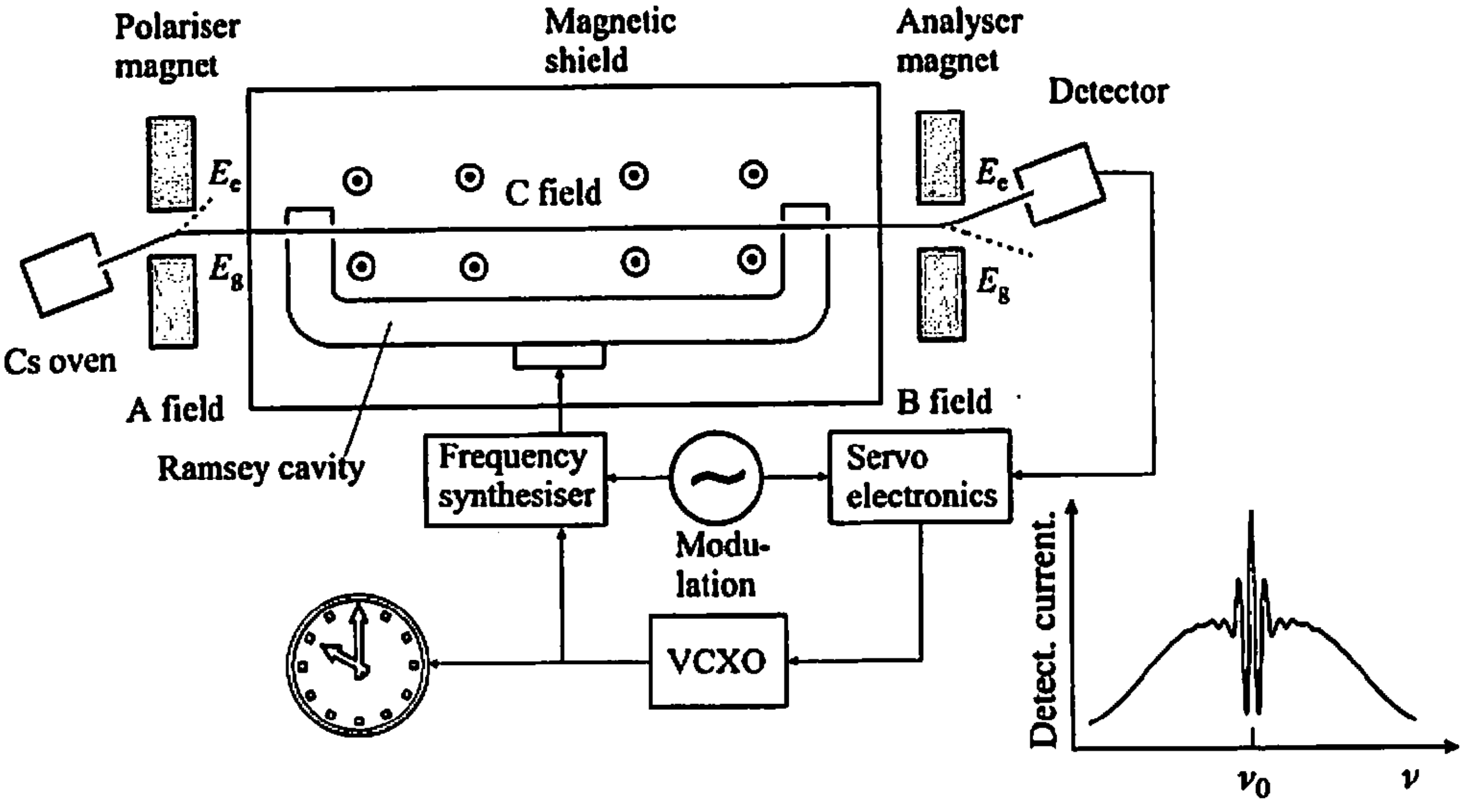


Figure 7.3: Schematic layout of a commercial Cs atomic clock. The magnetic quantisation field (C field) is perpendicular to the paper plain. The inset shows the detector current when the frequency of the synthesiser is tuned across the atomic resonance displaying the Ramsey resonance on the Rabi pedestal.

Optically-pumped Cesium Beam clock

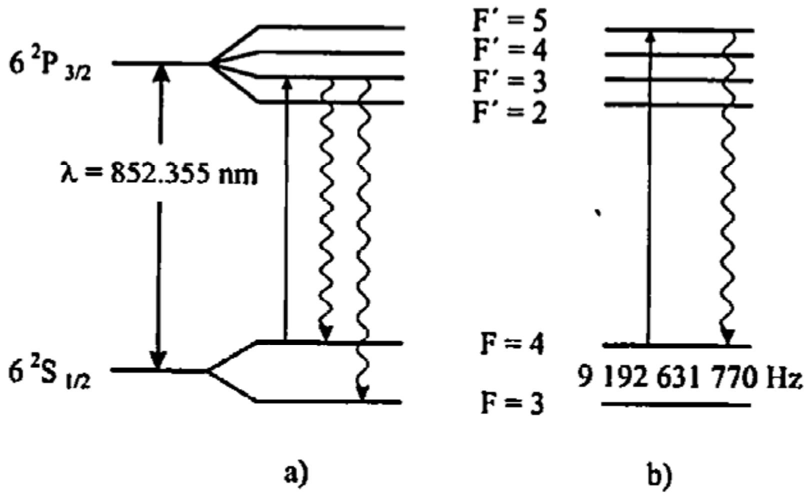


Figure 7.8: A simple version of optical pumping of a Cs atomic clock for state preparation.

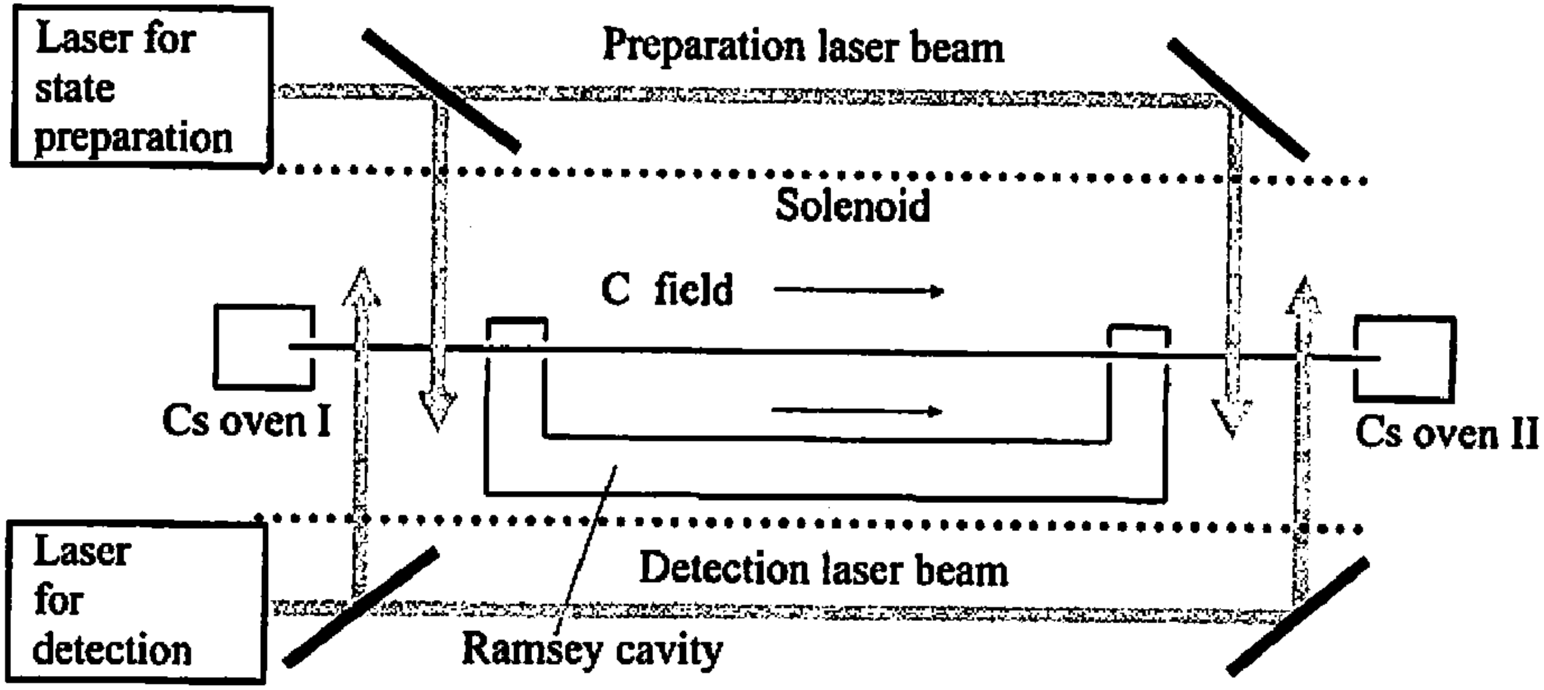


Figure 7.9: Simplified set-up of a Cs atomic clock with optical state selection and detection.

Cs fountain clock

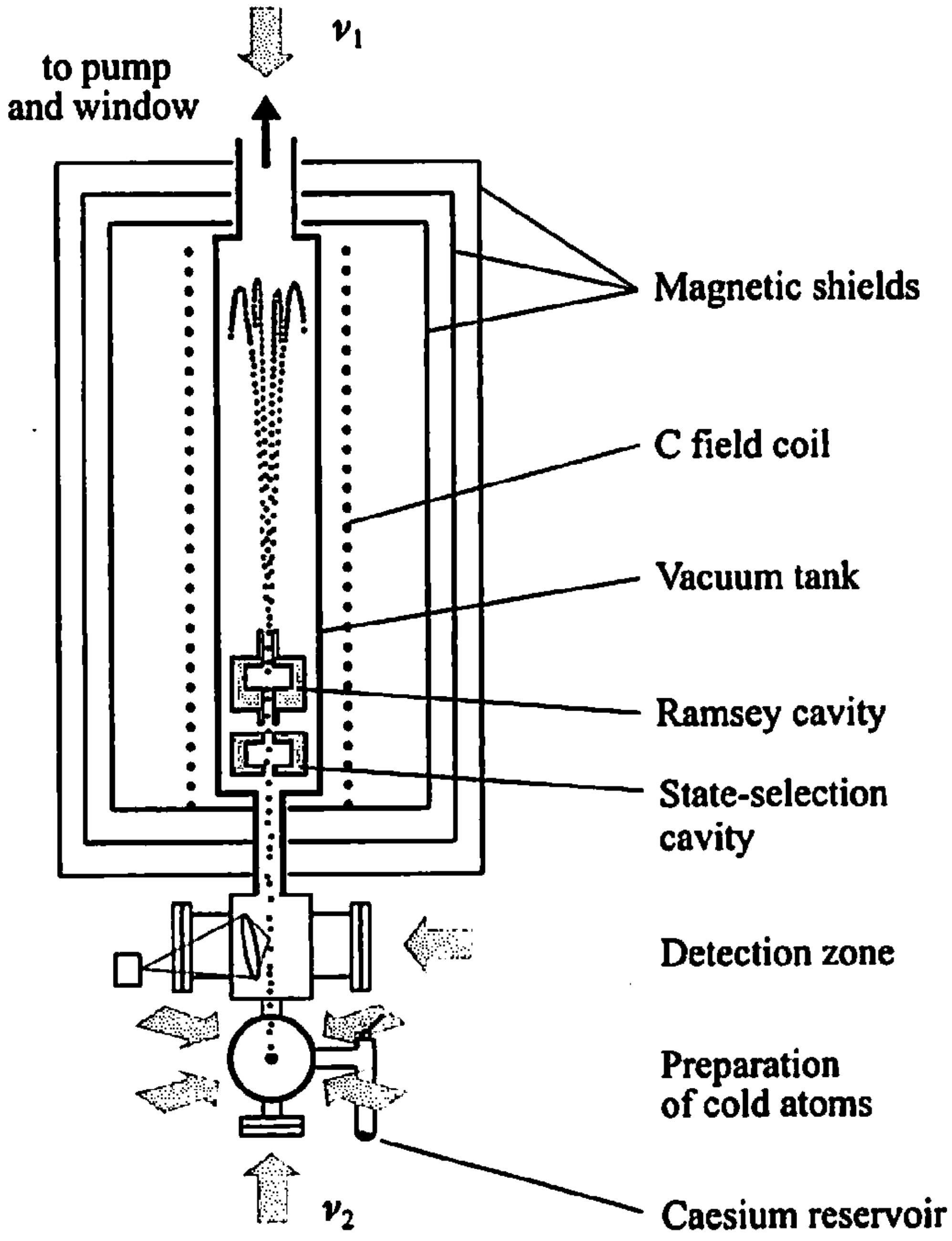
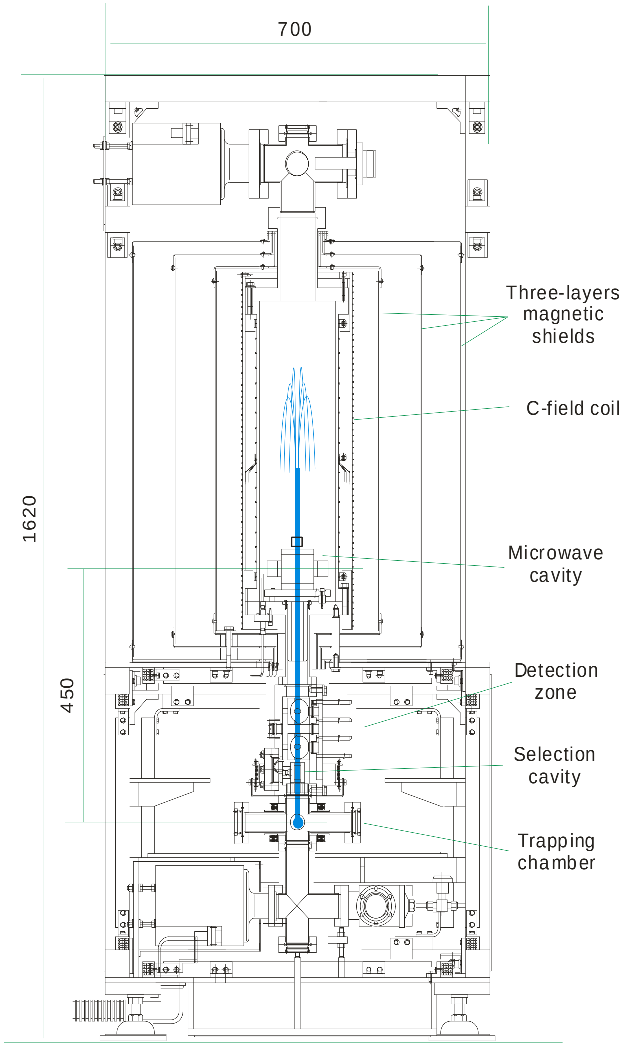


Figure 7.10: Set-up of an atomic fountain clock.

Cesium Atomic Fountain NICT-CsF1（2）



Captured by MOT in (0,0,1) cooling geometry

State-select just above laser cooling region

Rectangular cavity for state-selection

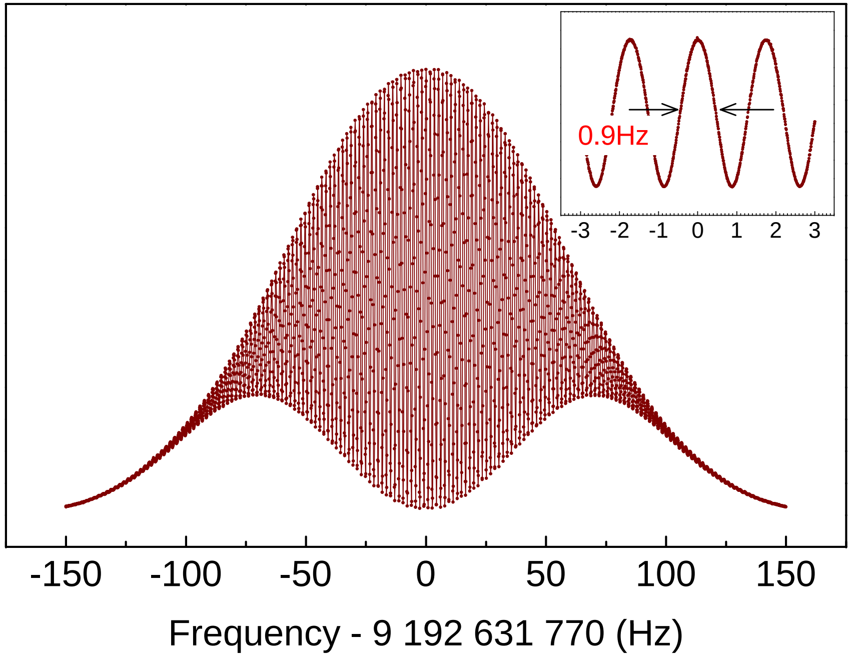
Cylindrical cavity for Ramsey resonance

Detection region above laser cooling region

Three-layers magnetic shield

Ultra high vacuum of less than 2×10^{-7}Pa

Frequency Stability of NICT-CsF1



冷却温度：1〜2μK

打上げ速度：4m/sec

打上げ高さ：82cm

ドリフト時間：570ms

↓

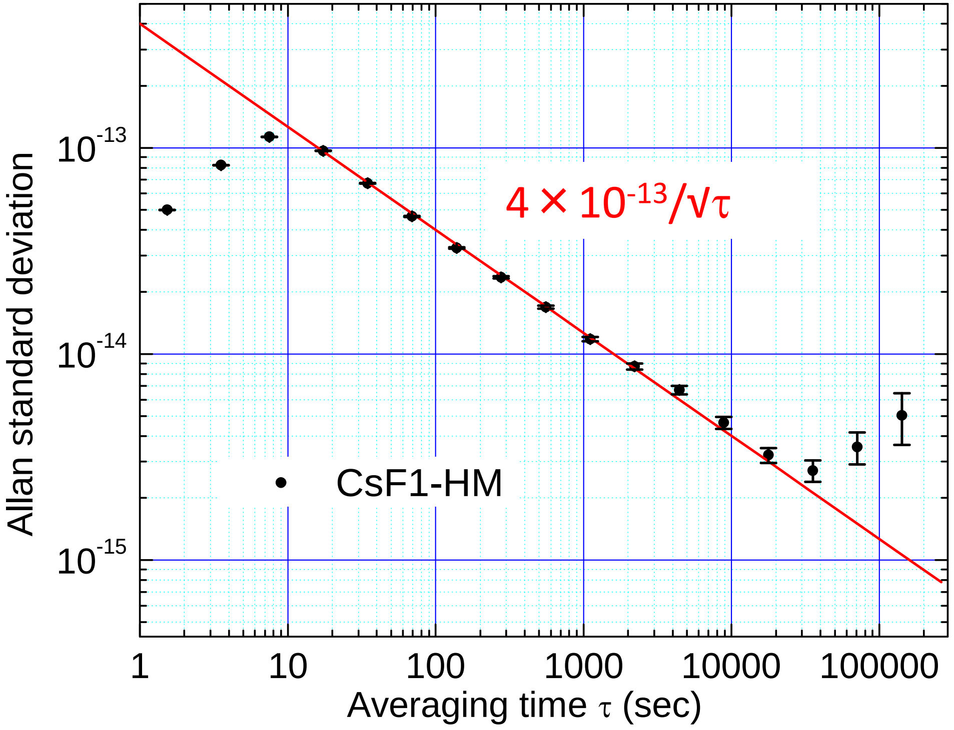
線幅：＜0.9Hz

4×10^{-13} @1秒

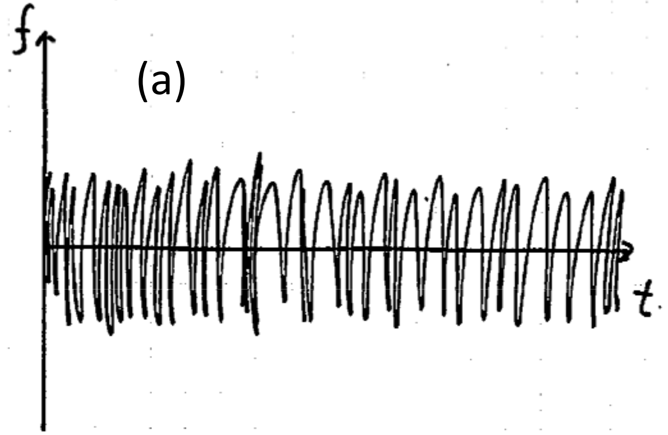
1.4×10^{-15} @1日

↓

1日前と1日後では1.4×10^{-15}
しか値はずれない

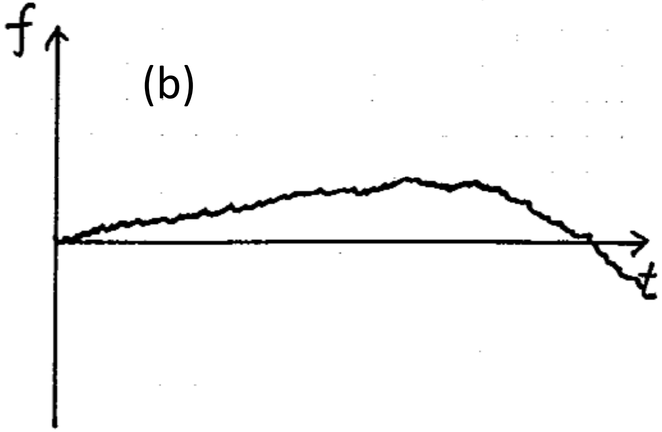


Which oscillator do you like?



(b) Is drifting, but (a) is not.
Then, obviously (a)?

Cs clock



But we often say (a) is noisy and (b) is smooth.

H-maser

Hydrogen maser

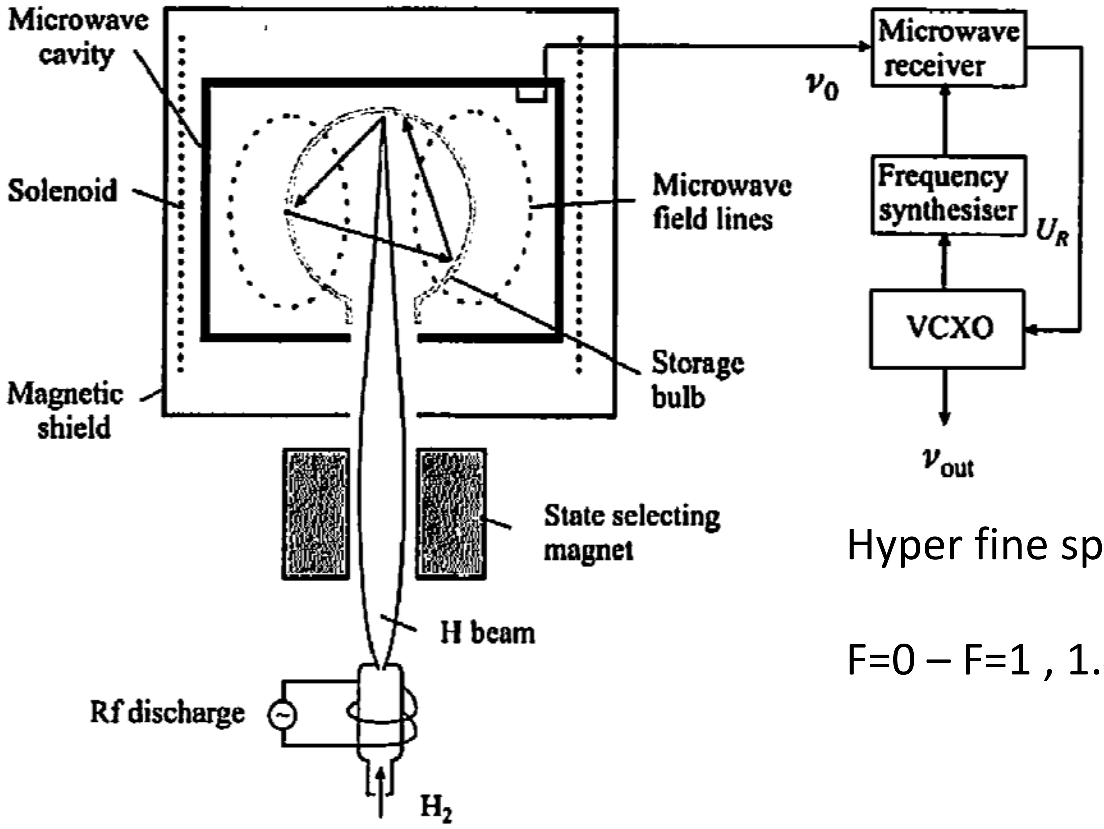


Figure 8.1: Schematic of an active hydrogen maser.

Hyper fine splitting of hydrogen

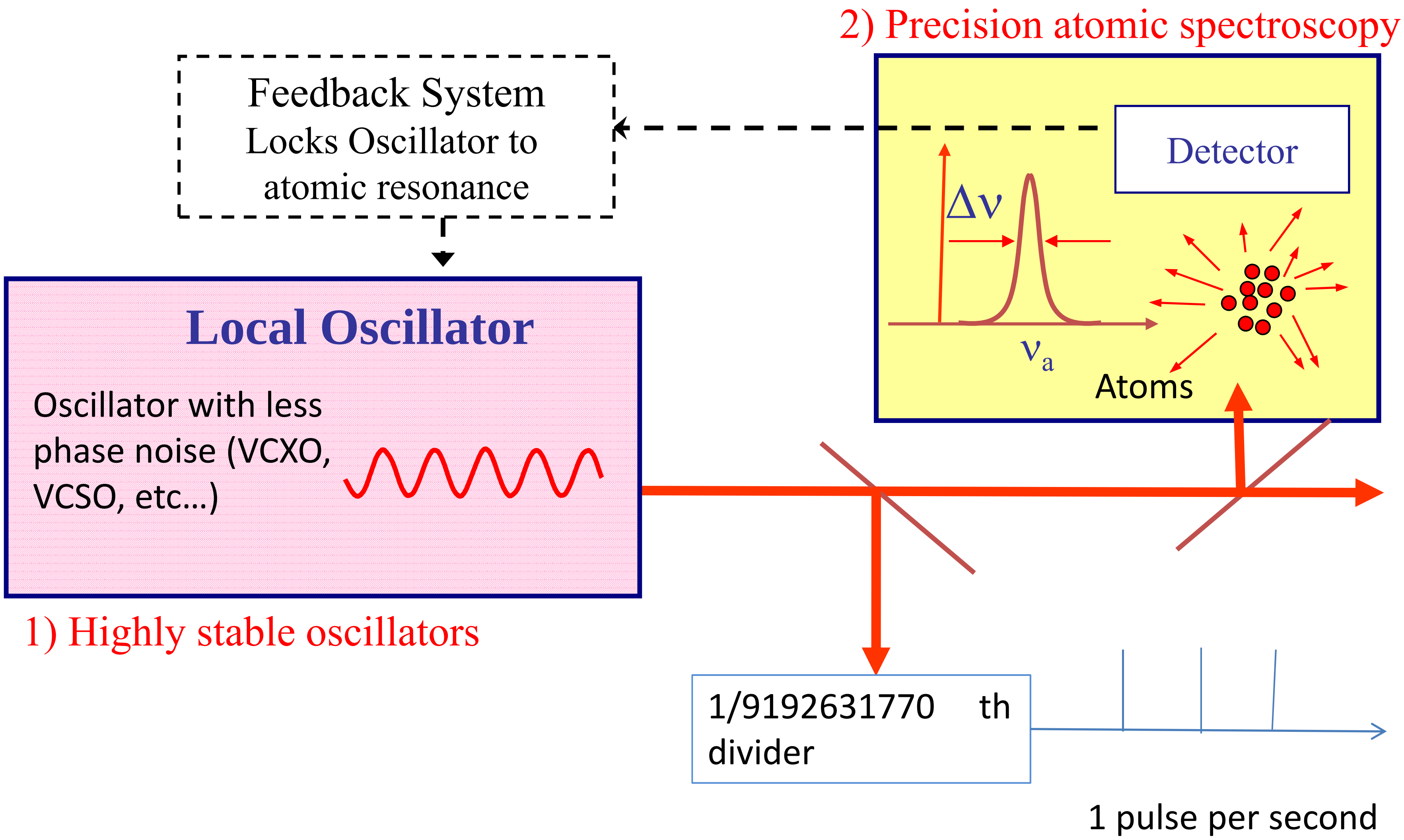
F=0 – F=1 , 1.42GHz

Active clock

Oscillator = standards

All Cs clock are passive. Source oscillator does not have Cs inside.

Components of passive clock



2) Precision atomic spectroscopy

Feedback System
Locks Oscillator to
atomic resonance

Detector

Local Oscillator

Oscillator with less phase noise (VCXO, VCSO, etc…)

1) Highly stable oscillators

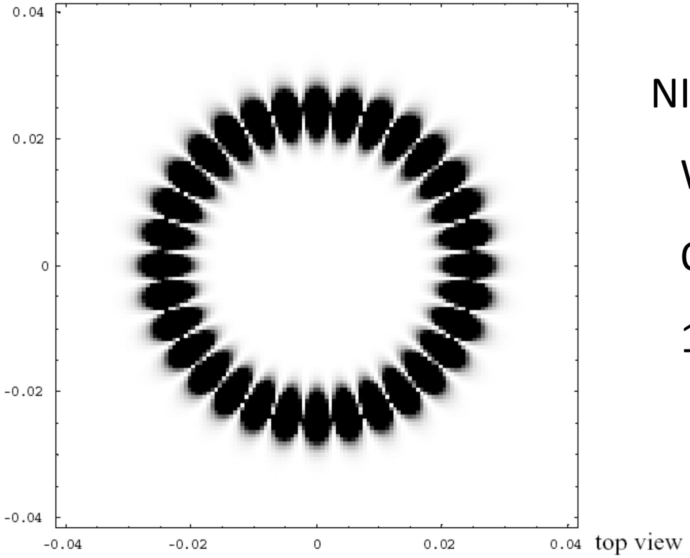
1/9192631770 th divider

1 pulse per second

Local oscillator for microwave clock

Cryogenic Sapphire Oscillator

- Sapphire crystal inside liquid helium
- Whispering Gallery Mode
- Q-value = 10^9
- Narrow BPF



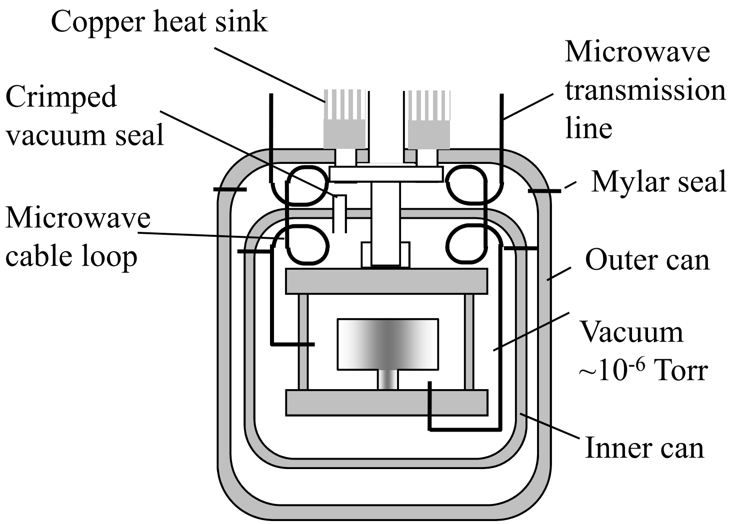
NICTのCSO

WGH$_{16,0,0}$

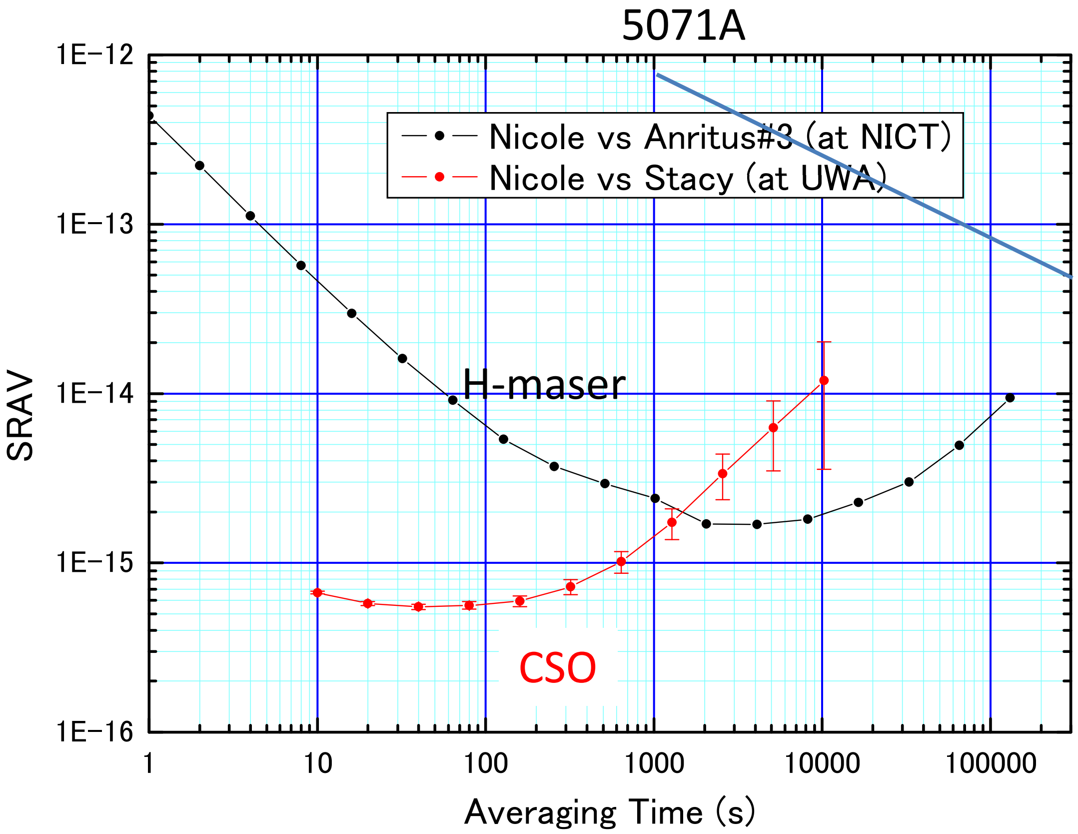
Q-value = 1.7×10^9

11.2005GHz@7K

NICT-CSO(1)

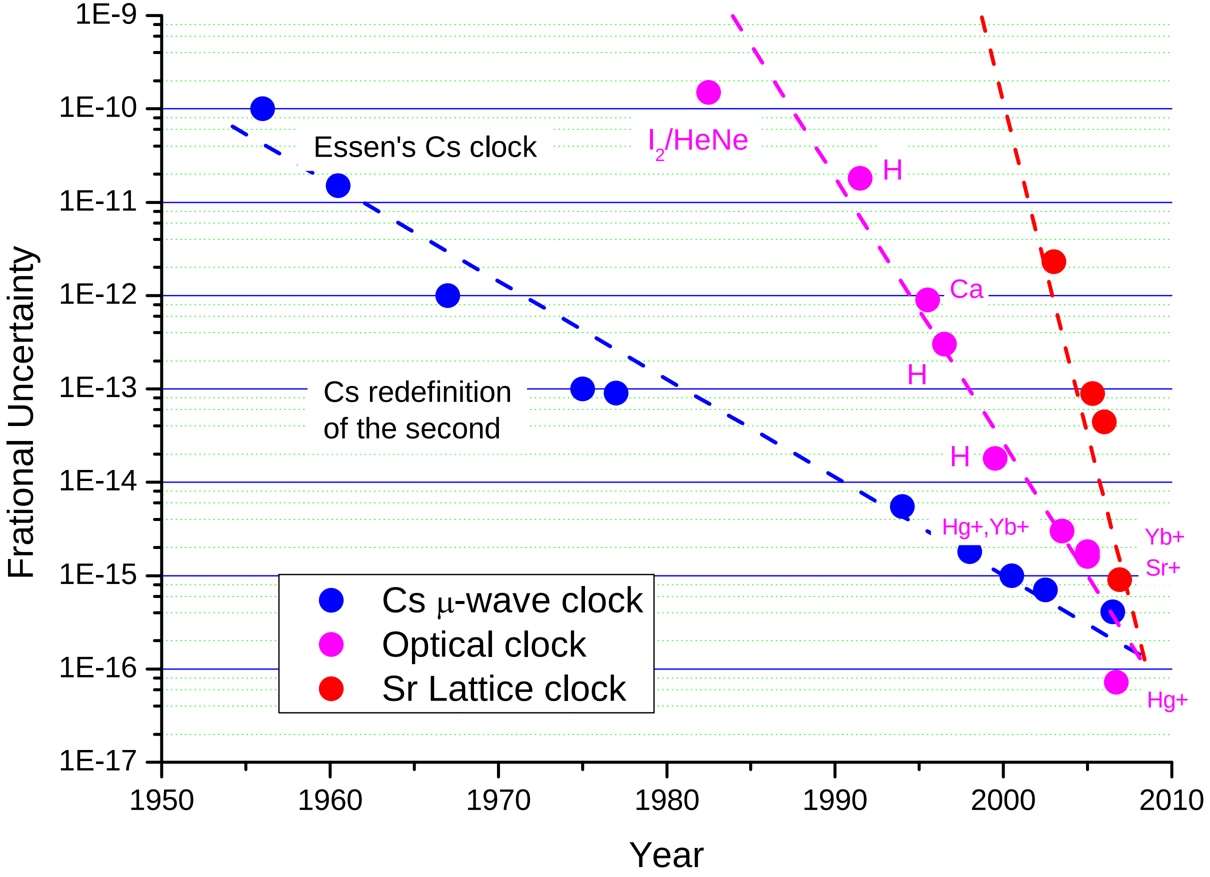

Copper heat sink
Crimped vacuum seal
Microwave transmission line
Mylar seal
Microwave cable loop
Outer can
Vacuum ~10^{-6} Torr
Inner can

NICT-CSO


5071A
Nicole vs Anritus#3 (at NICT)
Nicole vs Stacy (at UWA)
H-maser
CSO
SRAV
1E−12
1E−13
1E−14
1E−15
1E−16
1
10
100
1000
10000
100000
Averaging Time (s)

Optical Clocks

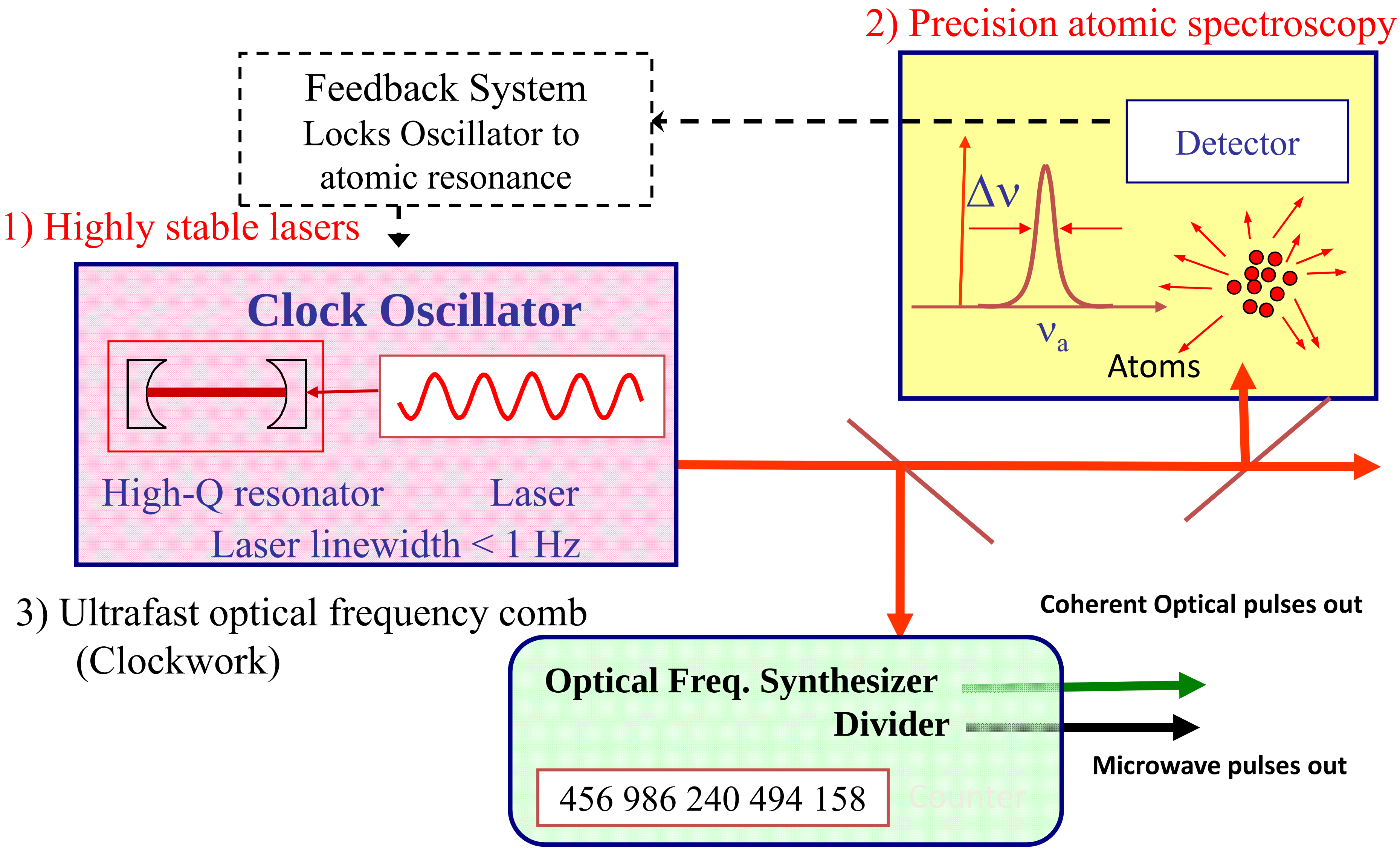
Accuracy: Optical clock now comparable or even better than Cs



- Now a Hg ion has better accuracy than Cs.
- Short time Instability: Cs > ions > lattice clock
- Are lattice clocks really promissing?

My talk could be biased to lattice clocks to introduce ideas and latest results

Optical Clock Components



2) Precision atomic spectroscopy

Detector

$\Delta\nu$

ν_a

Atoms

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)

Coherent Optical pulses out

Optical Freq. Synthesizer
Divider

456 986 240 494 158

Counter

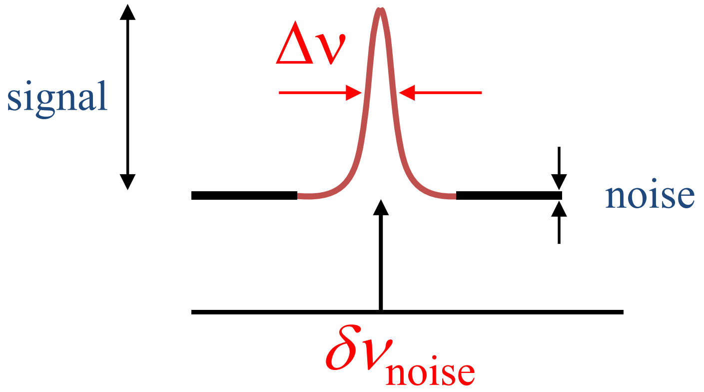
Microwave pulses out

Atomic References
Ion and neutral atoms

Optical Frequency Standards

sensitivity and resolution

High line Q & good signal-to-noise ratio (stability)



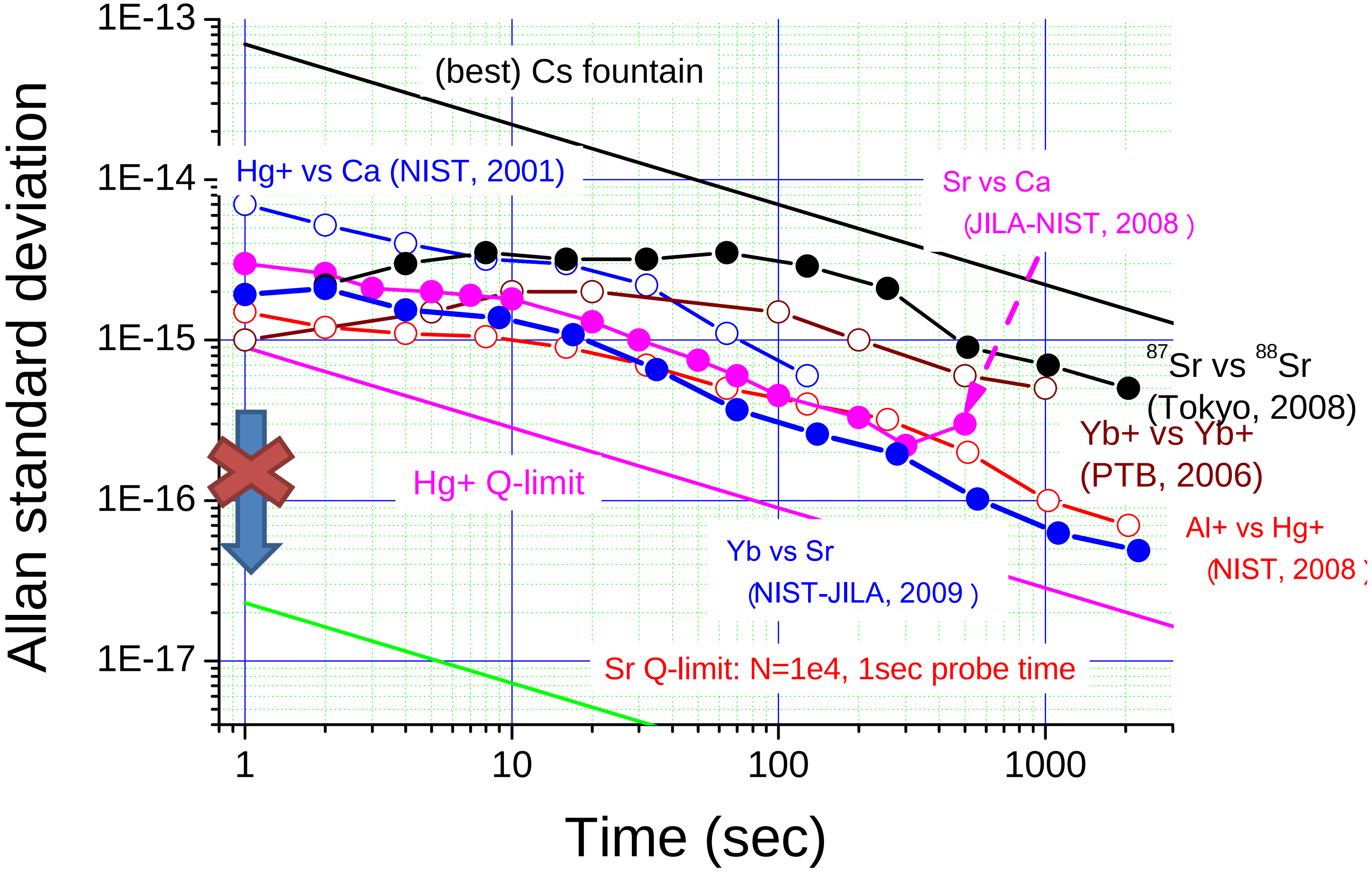
$$\delta\nu_{noise} \approx \frac{\Delta\nu\ (FWHM)}{\left(S/N\right)\big|_{\tau}} \longrightarrow \frac{\delta\nu_{noise}}{\nu_0} \approx \frac{1}{Q}\cdot\frac{1}{S/N}\cdot\frac{1}{\sqrt{\tau}}\ , \qquad Q \approx \nu_0 / \Delta\nu$$

Increase S/N, or Q, by 10, ⟶ decrease waiting time by 100

neutral vs. ion optical-standards *(before lattice clock)*

	neutral atom	**trapped ion**
	ENSEMBLE of atoms in free space	***SINGLE ion*** in ***Lamb-Dicke regime*** $E_R \ll \hbar\Omega, \quad (\gamma \ll \Omega)$ $\Rightarrow \Delta x \ll \lambda$
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 $S/N \sim (N_{atom})^{1/2}$	High line-Q (long $\tau_{int} \sim 1/\Delta\nu$) Shot noise; $N_{ion}=1$
Uncertainties & Improvements	**atom-atom interactions** **-cold-collision shifts**	trapping EM field →micromotion

Optical atomic clocks



- Comparison with other clocks is necessary to know the stability
- (Averaging time)$^{-1/2}$ dependece
- Short time stability limited by laser spectral width

Single ion Clocks

Single Ions in Paul Traps: state-of-the-art optical clocks

→ Very low uncertainty is possible (to 10^{-18})
proposed by Hans Dehmelt 1975

“Alkali-like” ions

S-D Q-pole trans.
Natural width: ~Hz…

Hg^+ (NIST)
Yb^+ (PTB, NPL)
Sr^+ (NPL, NRC)
Ca^+(Mars., Innsb., NICT)
Ba^+ (U Wash.)

- Quadrupole shift
- Broader natural linewidth (~Hz)

“Alkaline earth-like” ions

$^1S_0$-$^3P_0$ doubly forbidden
Natural width: ~mHz!!

In+ (NICT?,)
Al+ (NIST)

- Strong transitions from ground states locate in VUV region
→Schemes of cooling and detection needed

Recent progress of ion clocks

Alkaline earth-like ions

Al+: $^1S_0$-$^3P_0$
Natural linewidth: ~mHz
Insensitive to black body radiation

Spectroscopy Using Quantum Logic

P. O. Schmidt,*† T. Rosenband, C. Langer, W. M. Itano,
J. C. Bergquist, D. J. Wineland

Excited state population of Al+ was effectively copied to Be+ which has a good "detection" transition

P. Schmidt, Science **309** 749 (2005)

Ion clocks became available for intrinsically ultranarrow transitions, and currently NIST Al+ clock reaches 1e-17 level

*Rosenband, Science **319, 1808 (2008);***

Lattice Clocks

We can be picky!
That’s a lattice clock

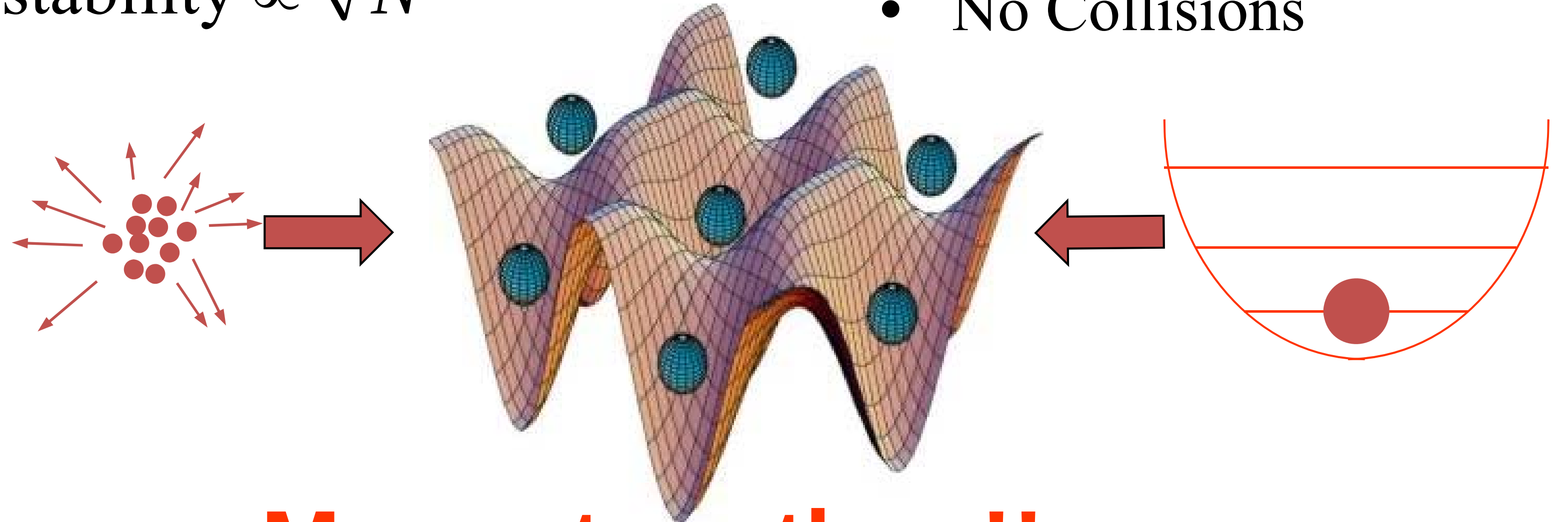
Free Neutral Atoms (Stability)

- Many Quantum Absorbers
  - Large N

$$\text{stability} \propto \sqrt{N}$$

Single Trapped Ion (Accuracy)

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



Merge together !!

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***.

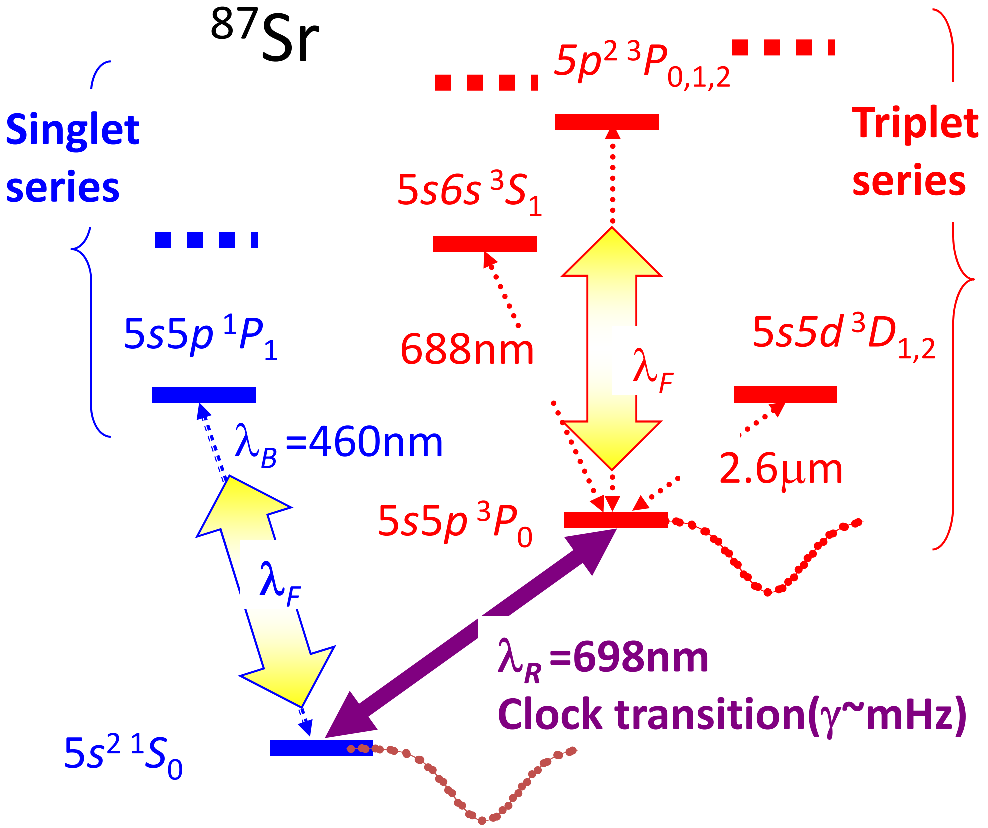
induced polarizability

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

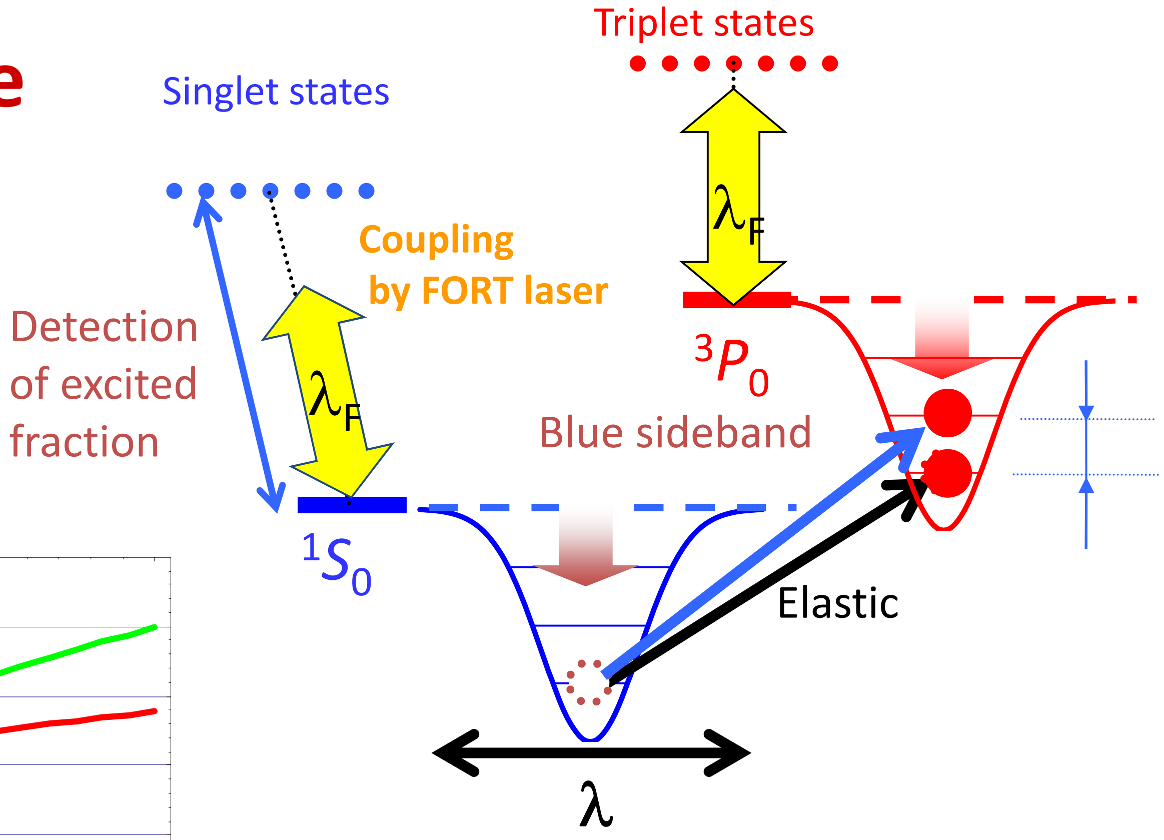
$$\hbar\omega_{nm} = E_n - E_m$$

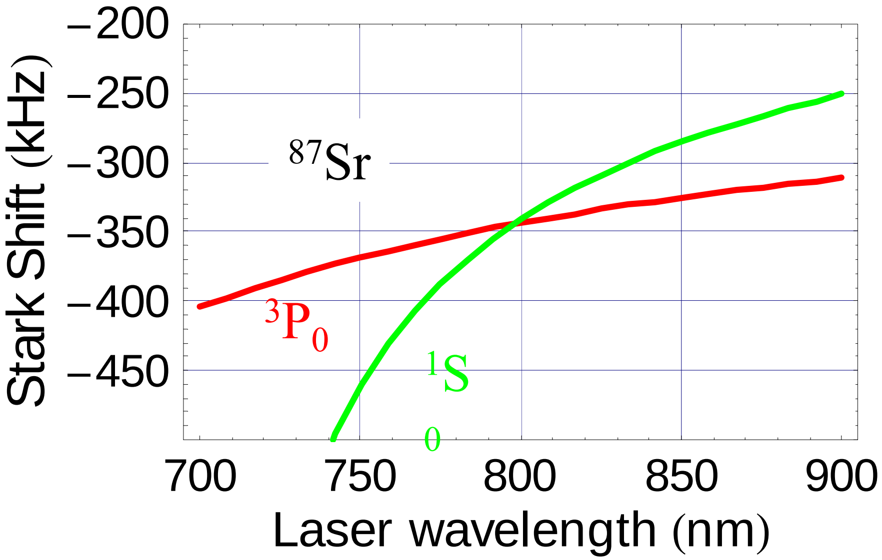
light shift potential

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



State insensitive optical lattice



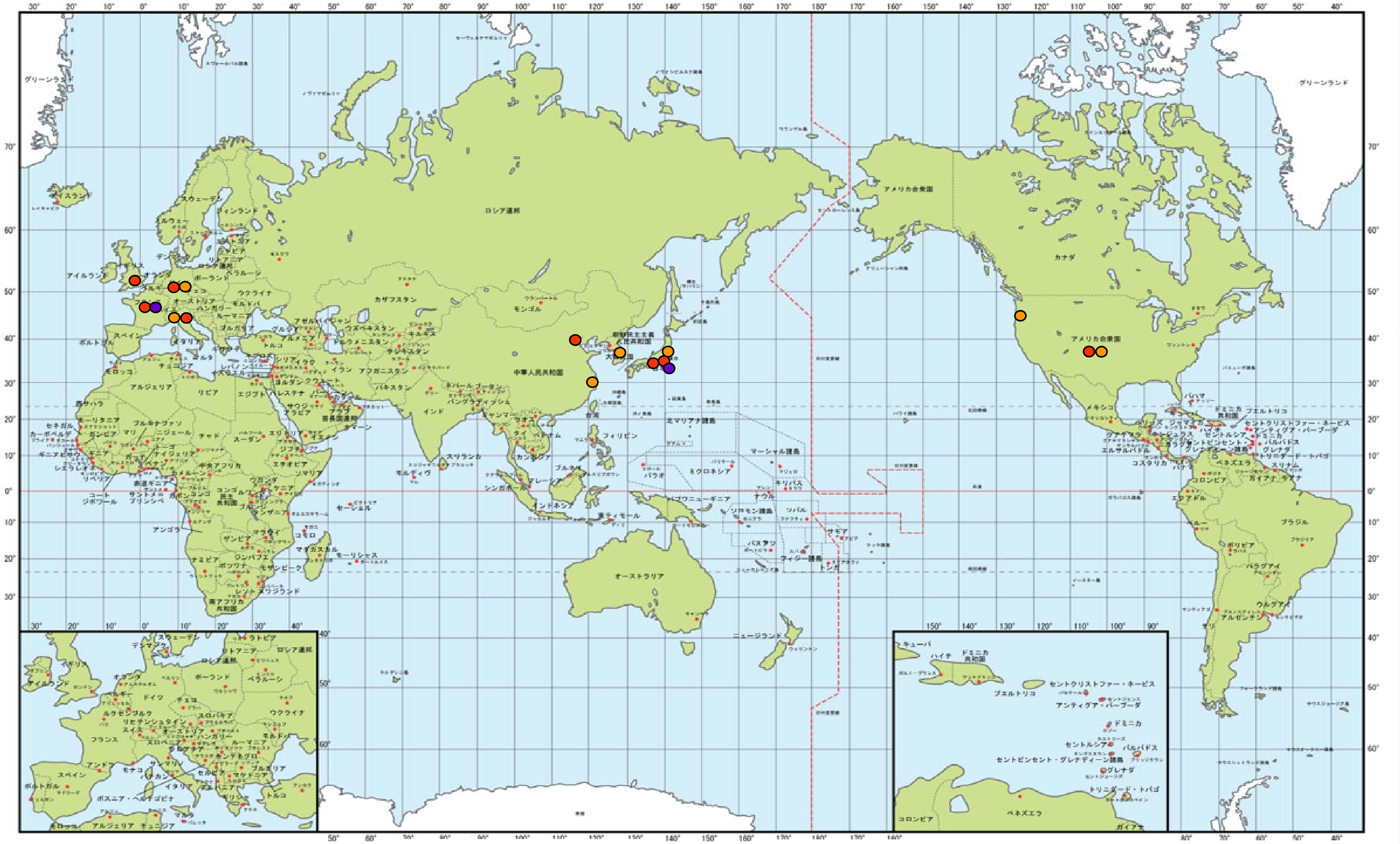


Katori *et al.*, Phys. Rev. Lett. 91, 173005 (2003).

		Magic λ	
Sr	$^1S_0$-$^3P_1$	914nm	JST, JILA
Sr	$^1S_0$-$^3P_0$	813nm	Tokyo, JILA, SYRTE, NICT
Yb	$^1S_0$-$^3P_1$	759nm	NIST, AIST
Hg	$^1S_0$-$^3P_0$	358nm	Tokyo, SYRTE

Optical lattice clock

Worldwide spread



● strontium ● ytterbium ● mercury

List of optical radiation to express meter

λ		frequency	uncertainty
237 nm	$^{115}In^+$, $5s^2\ ^1S_0$ - $5s5p\ ^3P_0$ transition	1267402452899.92 kHz	3.6×10^{-13}
243 nm	^1H, 1S - 2S, 2 photon transition	1233030706593.55 kHz	2.0×10^{-13}
282 nm	$^{199}Hg^+$, $5d^{10}6s\ ^2S_{1/2}$ (F=0) - $5d^96s^2\ ^2D_{5/2}$ (F=2) transition	1064721609899145 Hz	3×10^{-15}
436 nm	$^{171}Yb^+$, $6s^2S_{1/2}$ (F=0) - $5d^2D_{3/2}$ (F=2) transition	688358979309308 Hz	9×10^{-15}
467 nm	$^{171}Yb^+$, $^2S_{1/2}$ (F=0) - $^2F_{7/2}$ (F=3) transition	642121496772657 Hz	6×10^{-14}
532 nm	Nd:YAG laser, $^{127}I_2$, R(56)32-0:a_{10}	563260223513 kHz	8.9×10^{-12}
543 nm	He-Ne laser, $^{127}I_2$, R(106)28-8:b_{10}	551580162400 kHz	4.5×10^{-11}
578 nm	^{171}Yb, $6s^2\ ^1S_0$ (F=1/2) - $6s6p\ ^3P_0$ (F=1/2) transition	518295836590864 Hz	1.6×10^{-13}
633 nm	He-Ne laser, $^{127}I_2$, R(127)11-5:a_{16}	473612353604 kHz	2.1×10^{-11}
657 nm	^{40}Ca, $^1S_0$ - $^3P_1$, $\Delta m_J = 0$	455986240494140 Hz	1.8×10^{-14}
674 nm	$^{88}Sr^+$, $5^2S_{1/2}$ - $4^2D_{5/2}$	444779044095484 Hz	7×10^{-15}
698 nm	^{87}Sr, $5s^2\ ^1S_0$ - $5s5p\ ^3P_0$ transition	429228004229873.65 Hz	1×10^{-15}
698 nm	^{88}Sr, $5s^2\ ^1S_0$ - $5s5p\ ^3P_0$ transition	429228066418012 Hz	1×10^{-14}
729 nm	$^{40}Ca^+$, $4s\ ^2S_{1/2}$ – $3d\ ^2D_{5/2}$ transition	411042129776393 Hz	4×10^{-14}
778 nm	^{85}Rb, $5S_{1/2}$(F=3) - $5D_{5/2}$(F=5), 2 photon transition	385285142375 kHz	1.3×10^{-11}
1.5mm	$^{13}C_2H_2$, P(16)($\nu_1 + \nu_3$) transition	194369569384 kHz	2.6×10^{-11}
3.39mm	He-Ne laser, CH_4, n_3, P(7), $F_2^{(2)}$	88376181600.18 kHz	3×10^{-12}