Progress in Atomic Clocks and Tests of Fundamental Laws

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Basis of atomic Clocks

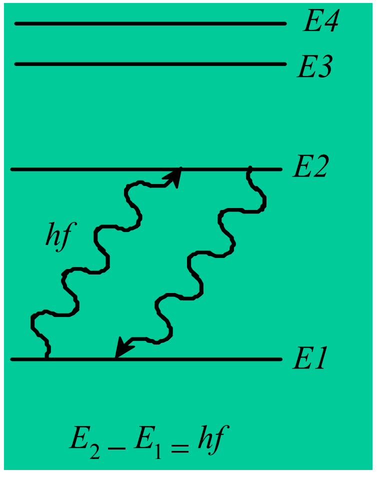
Identical atoms located in *identical environments* have identical energy level structures

<u>Recipe:</u>

Select the species

Select the transition

Realize clock by stabilizing a local oscillator

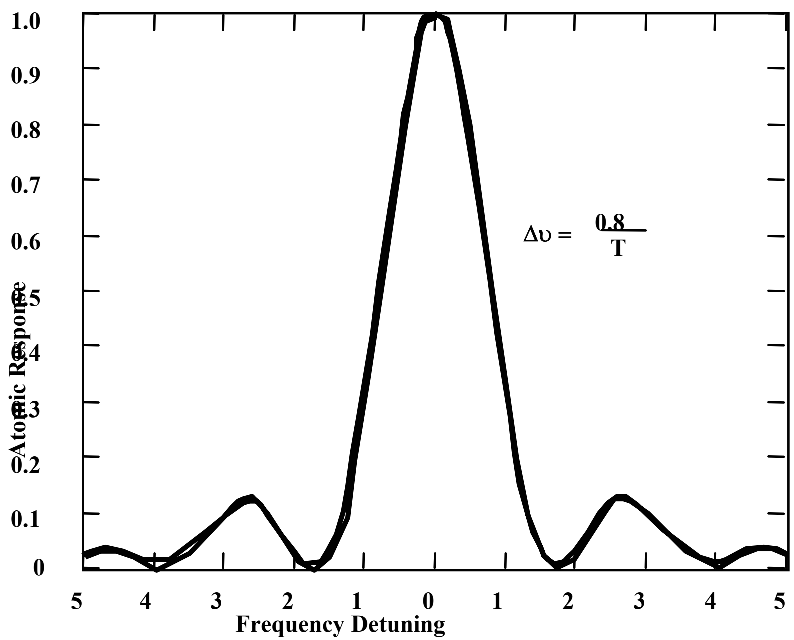


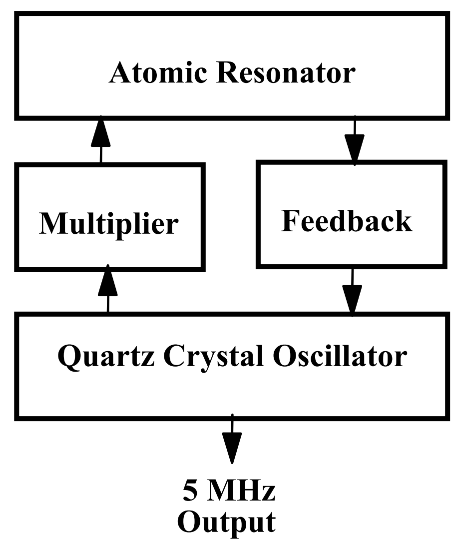
Steps for the realization of the atomic clock

1. Prepare atoms in the desired state
   - Magnetic field slection
   - Optical pumping
2. Allow interaction of atoms with applied radiation from a local oscillator (LO)
3. Determine if LO frequency at atomic resonance (atomic interrogation)
4. Apply correction to LO frequency at output

Block Diagram of an Atomic Clock

The atomic resonance transition, represented by the resonance line in the diagram below, is the basis for realizing an atomic clock. The realization of the clock is depicted as a block diagram.





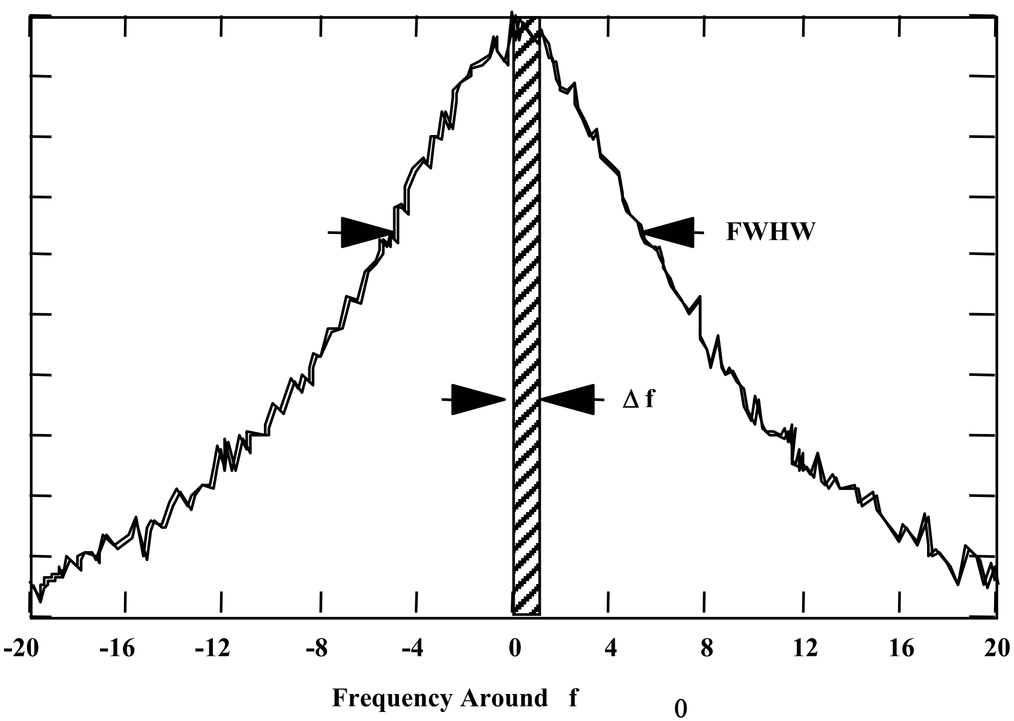
A voltage controlled crystal oscillator (VCXO) is locked to the atomic resonator, a highly stable frequency reference generated from an atomic transition. Of the many atomic transitions available, the ones selected are from those which are least sensitive to environmental effects and which can be conviently locked to the vcxo. The long term stability is determined by the atomic resonator, the short term stability, by the crystal oscillator.

The Importance of Q and SNR

$$\sigma_y \approx \frac{\Delta f}{f_0} = \left(\frac{FWHM}{f_0}\right)\left(\frac{\Delta f}{FWHM}\right) \alpha \frac{1}{Q} \frac{1}{SNR}$$

SNR = Signal-to-noise ratio of detected atomic transition

Q = Quality factor of resonance



Examples	Q	Best σ_y	No. of atoms
Rb	5×10^{7}	10^{-13}	5×10^{11}
Cs	$10^{7} - 5 \times 10^{9}$	10^{-14}	
H-Master	2×10^{9}	7×10^{-16}	10^{16}
Hg^{+}	2×10^{12}	$\sim 10^{-15}$	$10^{6} - 10^{7}$

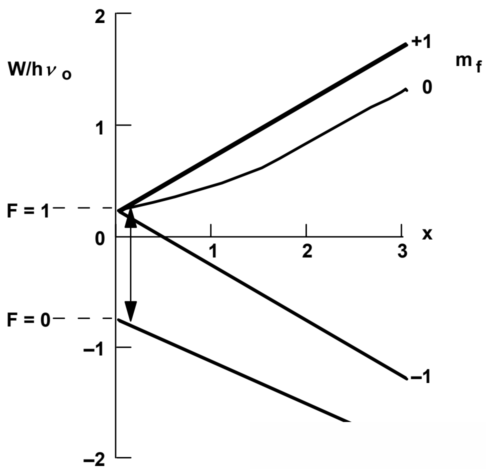
Desired Characteristics of Atoms for Frequency Standards Applications

- Simple atomic level structure scheme
- A transition involving two narrow levels (i.e., long lifetime)
- Transitions with large line Q, $Q_l = F_0 / \Delta F$
- Levels with small sensitivity to external perturbations
- Transitions with "accessible" frequency: multiply and divide with ease
- Solutions: use hyperfine transitions in alkali atoms and alkali-like atoms; Optical transitions are now accessible!

Major sources perturbing atomic energy levels

- First order Doppler effect
- Colloisional effects (with other atoms and the "container")
- Ambient fields
- Intensity dependent shifts
- Second order Doppler effect
- The blackbody shift
- Photon recoil

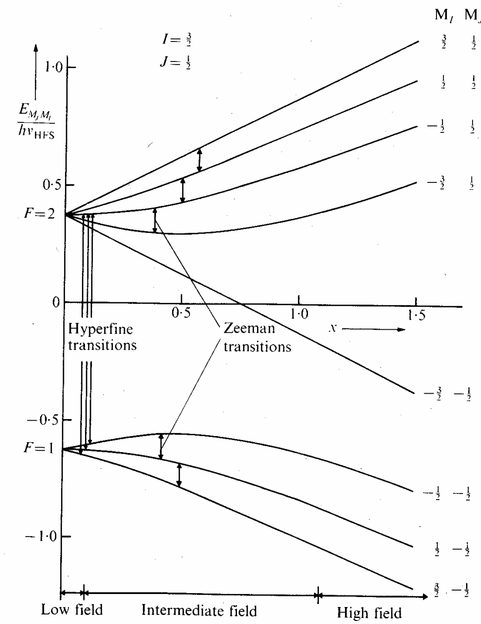
Hyperfine Structure of Atoms Commonly Used in Clocks



I = 1/2

^{1}H x = 1.97 x 10^{-3} Ho

^{199}Hg^{+} x = 3.72 x 10^{-4} Ho

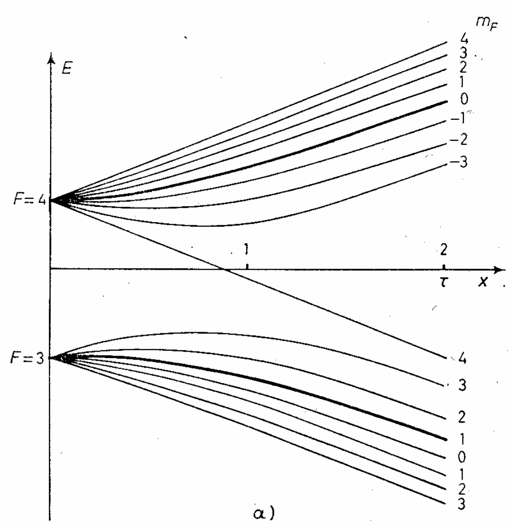


^{87}Rb

I = 3/2

^{133}Cs

I = 7/2



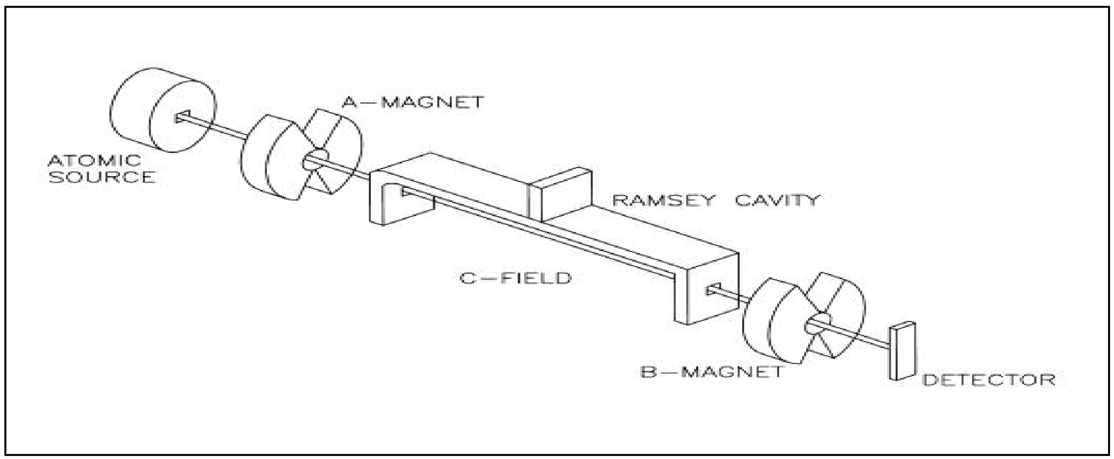
These diagrams depict the hyperfine structure and magnetic sub-levels of H, Hg, Rb, and Cs. Details of each structure is determined by the nuclear spin I, as determined by the specific isotope, and the hyperfine quantum number F. The magnetic field increases in the positive x-direction.

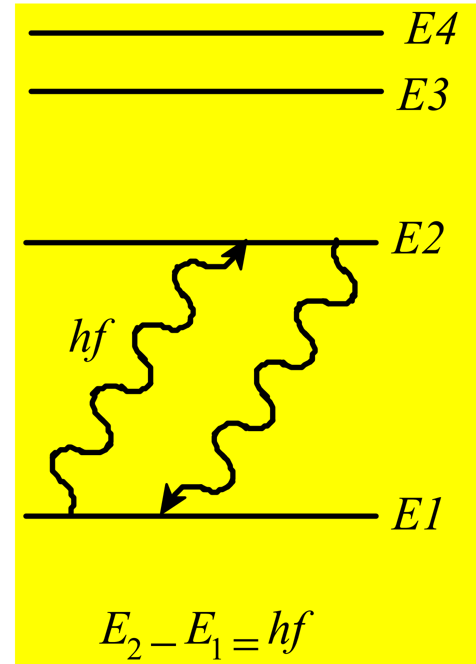
Elements of the Clock

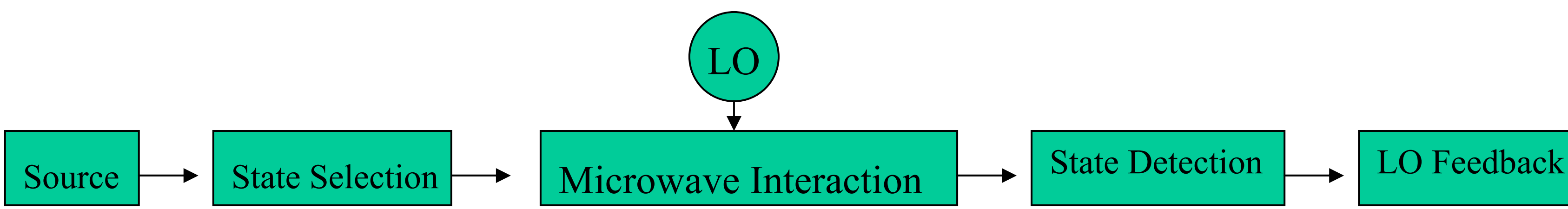
- **Source of atoms:** Vapor, beam, **cell**
- **State selection:** Magnets, **lasers**, lamps
- **Microwave interrogation:** Cavities, horns
- **State detection:** Magnets + particle detectors, (**lasers**, lamps) + **photodetectors**
- **Feedback:** Electronics and LO

Physical Basis of Passive Atomic Clocks

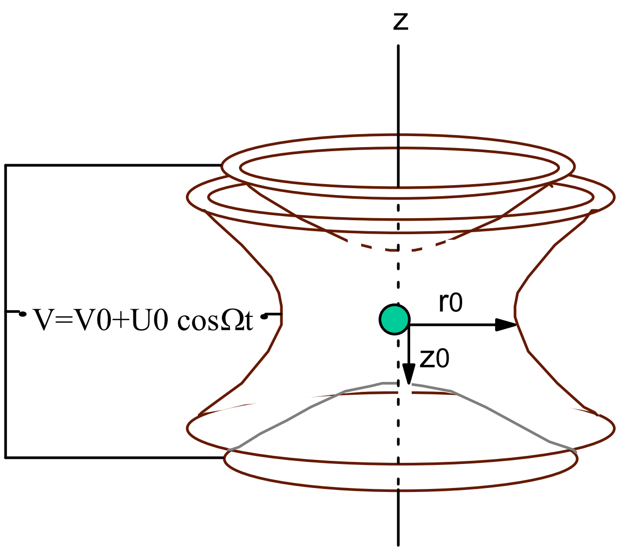
$$\Psi = \frac{\langle E_1 | - e^{i(2\pi f t + \phi(t))} | E_2 \rangle}{\sqrt{2}}$$





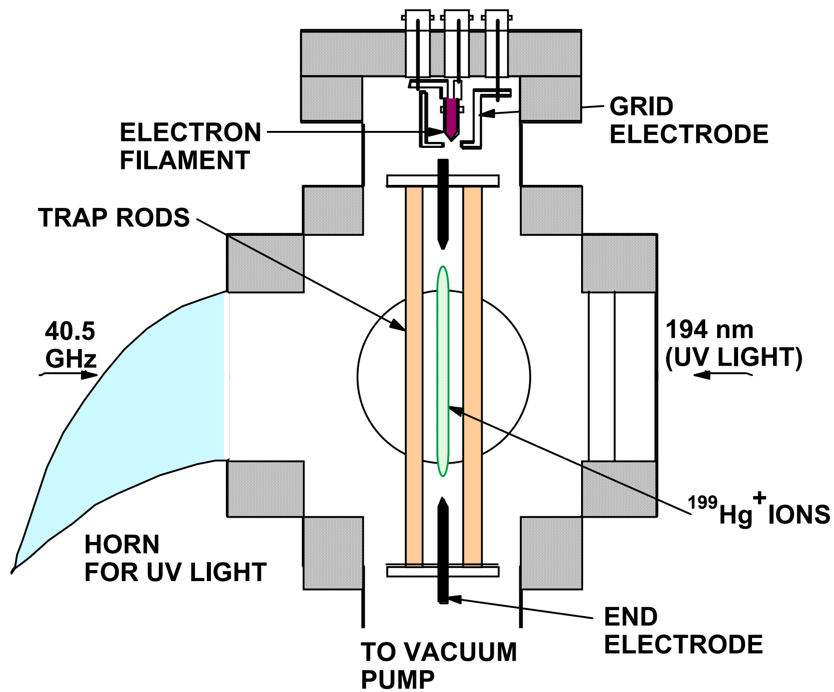


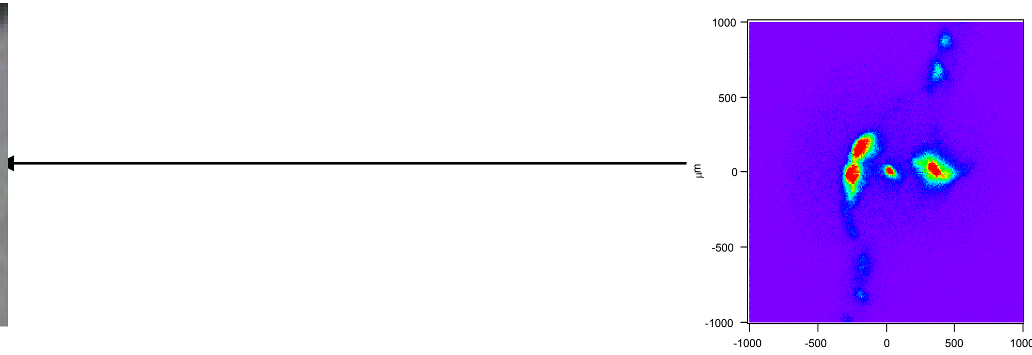
Trapped Ion Standard



Hyperbolic Ion Trap

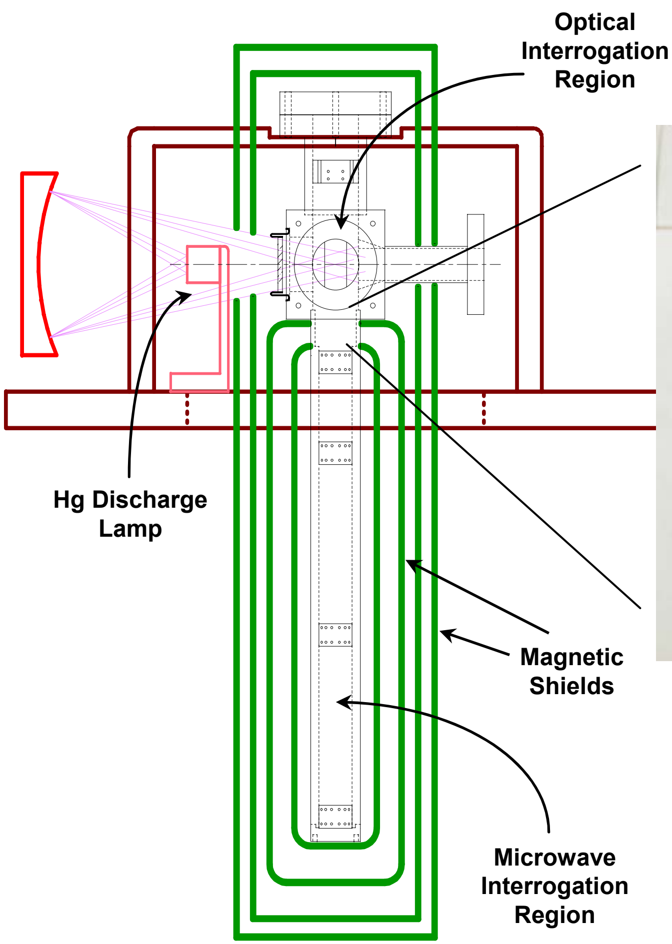
Schematic Diagram of the Linear Trap and the Vacuum Cube in JPL's LITS





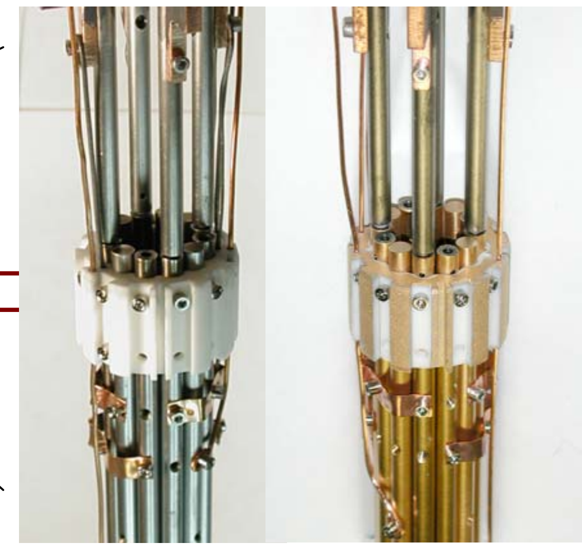
•**Shuttle Trap geometry reuces size and mass**

•**Multi-pole trap configuration reduces sensitivity to second order Doppler effect, for improved performance**



Hg Ion Frequency Standard

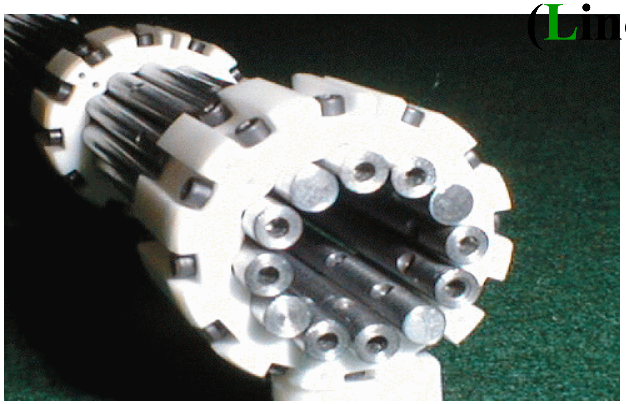
4-pole to 12-pole junction



Un-plated ceramic | **Gold Plated Ceramic**

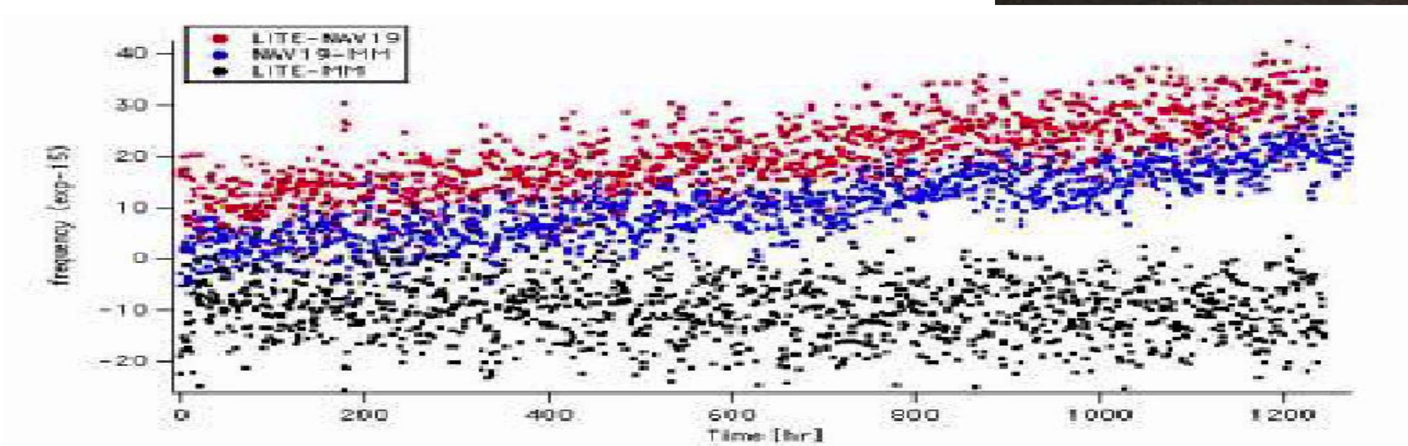
JPL Mercury LITS at the USNO

(Linear Ion Trap Standard)



Operational Configuration at the USNO

- Installed and operating since July 20, 2002
- Local Oscillator : H-maser NAV-19
- SNR set for stability of 1.7 x 10^{-13} / root tau
- Compare long term stability to USNO Maser Ensemble
- Plan for GPS comparison to second LITS at JPL

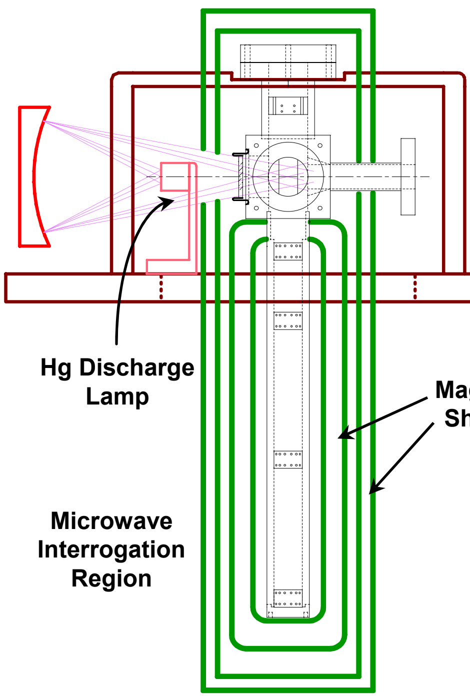


Relative drift between LITS and USNO Ensemble Maser Mean

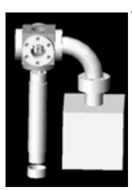
< 5 x 10^{-17} / day

Small Ion Clock (~ 1 liter) for 1-way Navigation

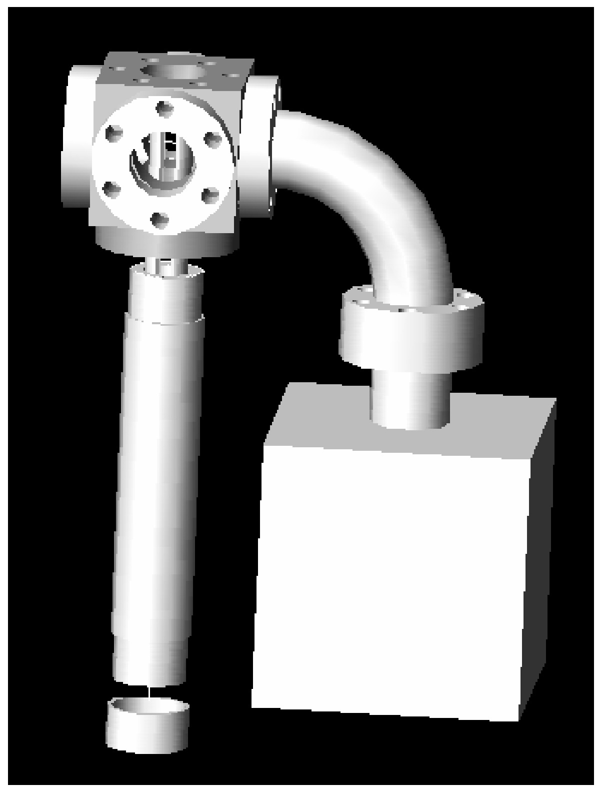
Laboratory Clock and Small Ion Clock Size Comparison (to scale, ~1 liter)



Laboratory Hg Ion Clock



1-way Nav clock



- Designed small prototype clock around COTS vacuum parts and custom ceramic tube

- !2-pole trap from circular Alumina ceramic with plated and brazed electrodes

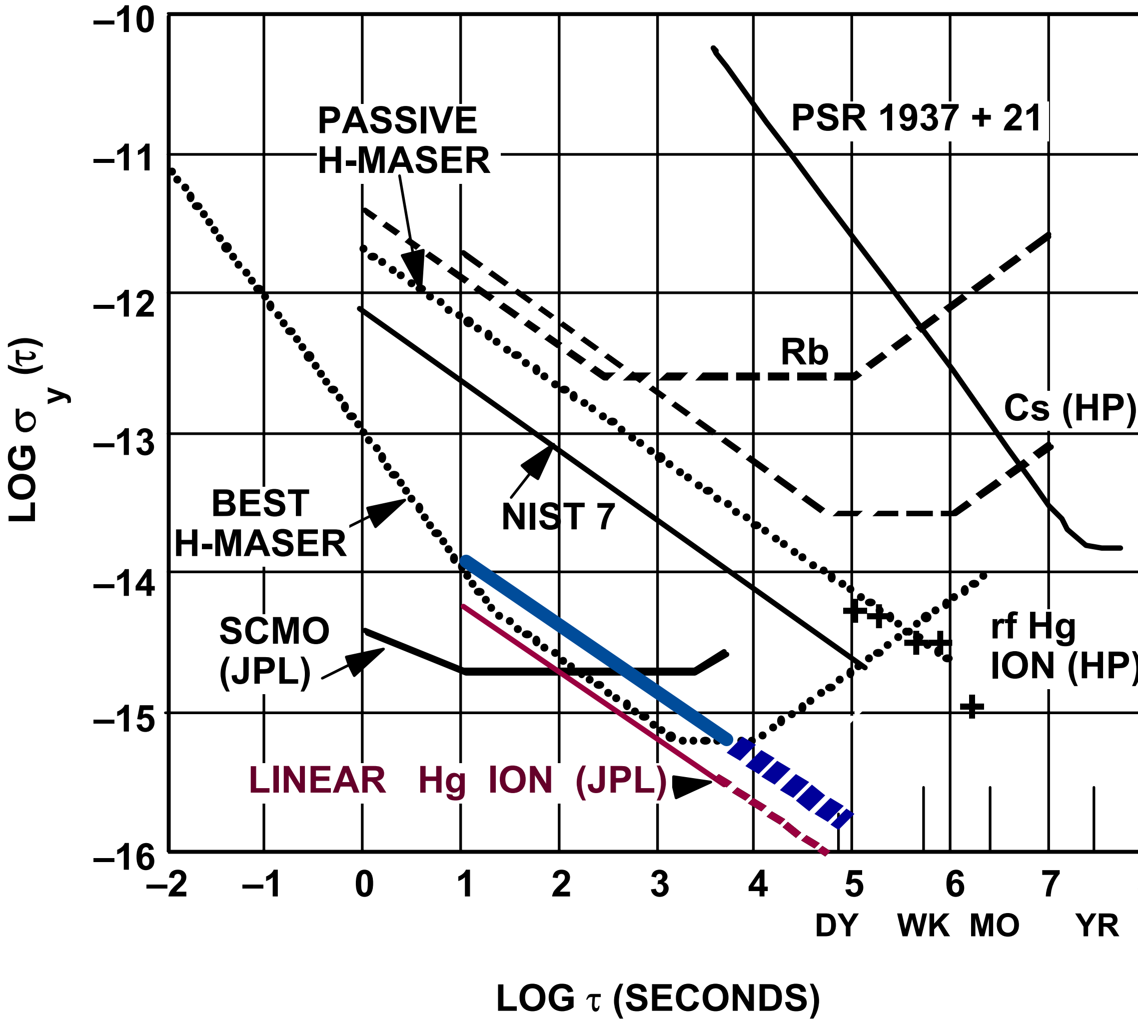
- RF/DC Feedthrus brazed into ceramic, ceramic is transparent to 40 GHz

- UV Optical system will be ‘collimation-based’ with no imaging
- Low profile Package
- 70 db Isolation between input light and collection channel required.

- Fabrication techniques and materials have all been employed successfully in ground based model.

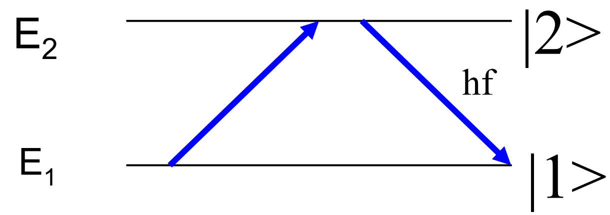
Linear Ion Trap Standard (LITS)

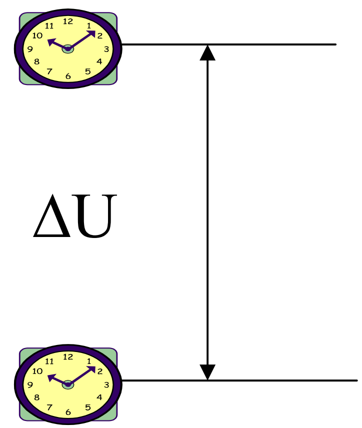
Fractional Frequency Stability



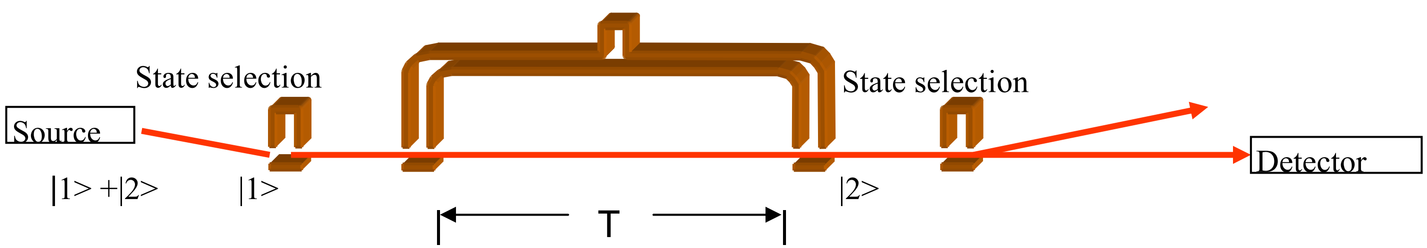
Clocks and Tests of GR

- -- Test of Redshift
  - -- Absolute and relative tests
- -- Variation of fine structure constant
- -- Tests of LLI





$$\frac{\delta f}{f} = (1+\alpha)\frac{\Delta U}{c^2}$$



Beyond the Standard Model

- The Standard Model leaves some fundamental questions unanswered:
  - How to unify gravity with quantum mechanics
  - Why do constants of nature have their current values (fine-tuning):

"Are the constants of nature uniquely determined by the physical law? Or,are they frozen accidents imprinted at the Big Bang?"

- These may be answered by String (M) theories
  - Nearly all require a scalar field (quintessence) in addition to the tensor field of gravity.

$g_s = e^{\phi}$, basic string coupling constant that (with moduli) determine the low-energy world's coupling constants.

Gravity and Time Variation of α

If the clock rate depends on location in space (and time) due to the change of a parameter of the physical law, α:

$$\delta f = \frac{1}{2\pi\hbar}\frac{\partial(E_i - E_j)}{\partial \ln\alpha}\frac{\delta\alpha}{\alpha}$$

$$\frac{\delta f_A}{f_A} - \frac{\delta f_B}{f_B} = \frac{\partial \ln E_{ij}(A)/E_{ij}(B)}{\partial \ln\alpha}\frac{\delta\alpha}{\alpha}$$

For clocks based on hyperfine transitions:

$$f = \alpha^4 \frac{m}{M}\frac{mc^2}{\hbar}F(Z\alpha)$$

$$\alpha = \frac{e^2}{\hbar c}$$

$$\frac{\delta f_A}{f_A} - \frac{\delta f_B}{f_B} = \frac{\partial \ln F(Z_A\alpha)/F(Z_B\alpha)}{\partial \ln\alpha}\frac{\delta\alpha}{\alpha}$$

If there is a dynamical scalar field ϕ:

$$\frac{\delta\alpha}{\alpha} = \frac{\partial \ln\alpha}{\partial\phi}\delta\phi$$

$$\delta\phi = f_s \frac{GM_s}{c^2 R}e^{-\mu R}$$

Hyperfine Transitions

For alkali atoms and alkali-like ions:

$$A_s = \frac{8}{3}\alpha^2 g_I Z \frac{z^2}{n*^3}(1 - \frac{d\Delta_n}{dn}) F_{rel}(\alpha Z)(1-\delta)(1-\varepsilon)\frac{m_e}{m_p} R_{\infty c}$$

With f as the frequency of transition:

$$f = \alpha^4 \frac{m}{M}\frac{mc^2}{\hbar} F(\alpha Z)$$

	H	Rb	Cs	Hg+
H	0	0.3	0.74	2.2
Rb	-0.3	0	0.45	1.9
Cs	-0.74	-0.45	0	1.4
Hg+	-2.2	-1.9	-1.4	0

Prestage, Tjoelker, Maleki
PRL, 74, 3511(1995)

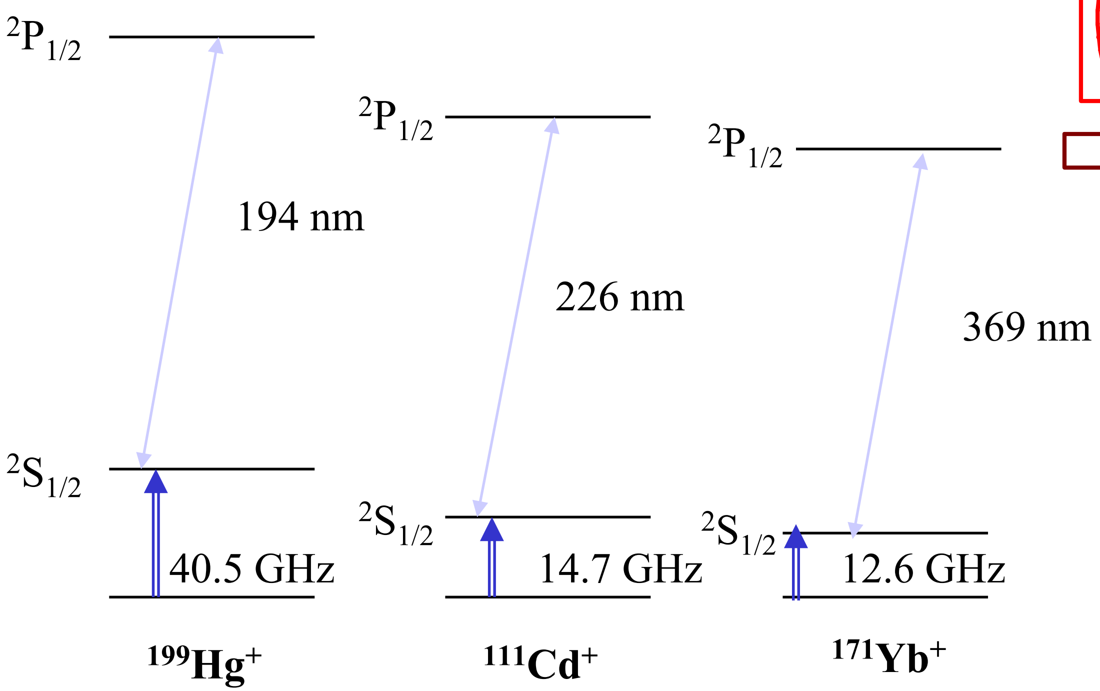
The Linear Trapped Ion Standard (LITS)

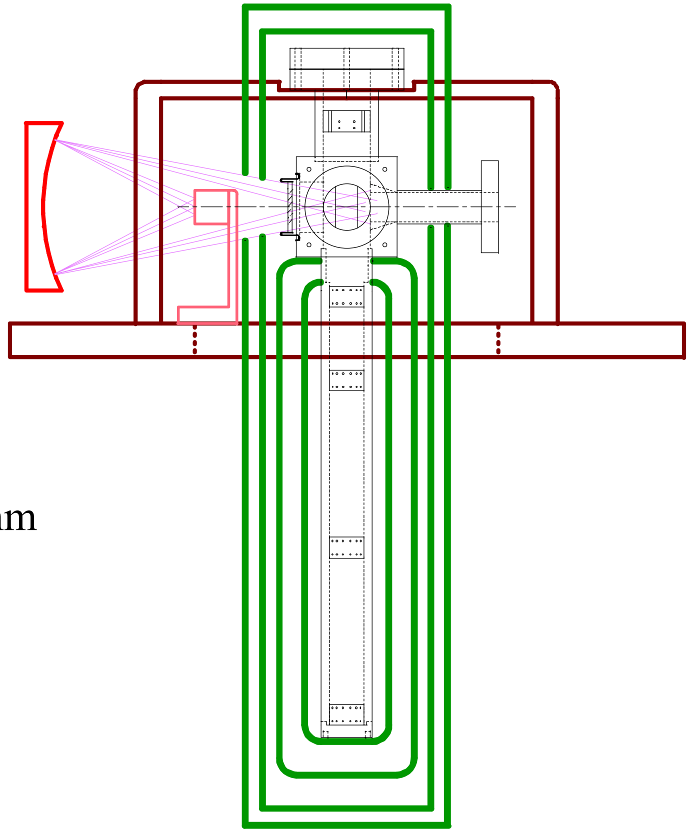
JPL LITS is presently world's best frequency standard for measuring times of hours to weeks

Simple design for reduced cost, increased reliability

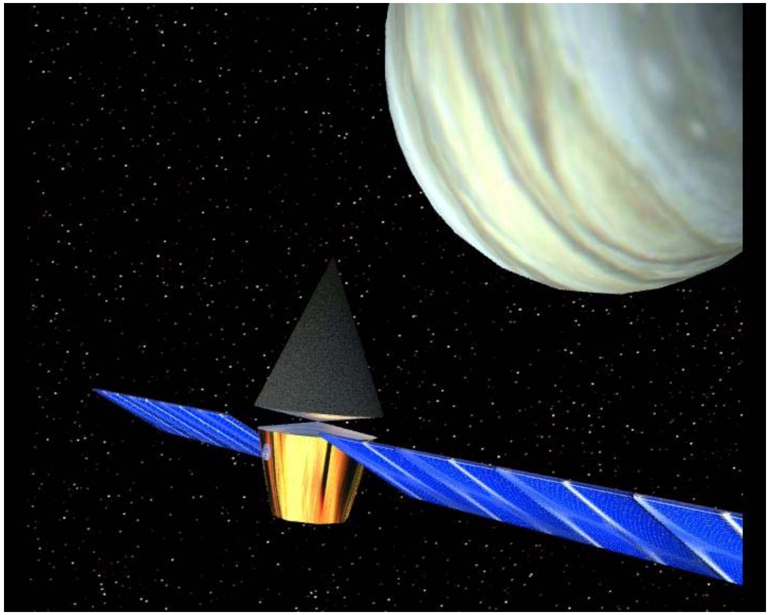
Presently being implemented in the DSN

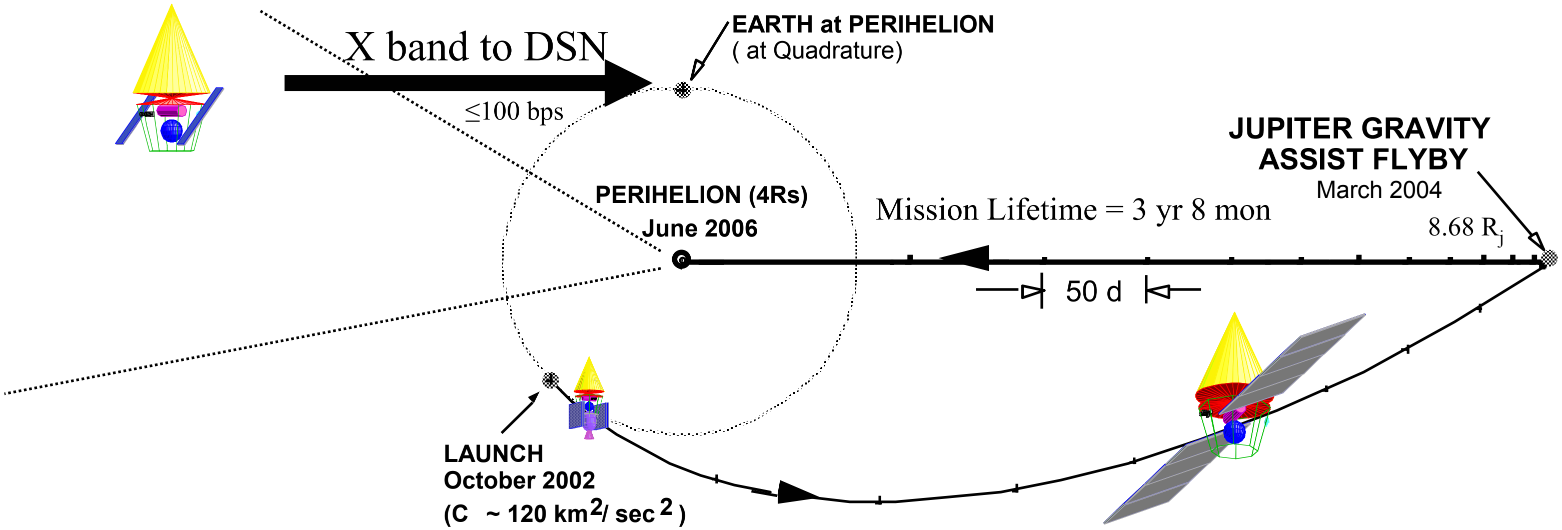
- **Four units complete, 3 installed, 2 in shake-down**
- **Unit also built for US Naval Observatory (USNO)**





Proposed SpaceTime Mission



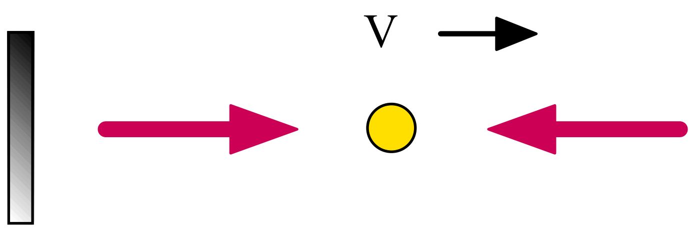


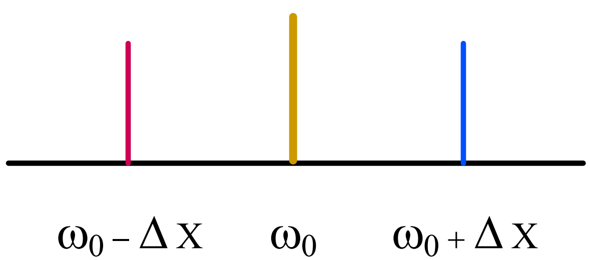
Comparison of SpaceTime and Observational Astronomy

$$\frac{\dot{\alpha}}{\alpha} \approx 10^{-16} \text{ /year}$$ From observational astronomy

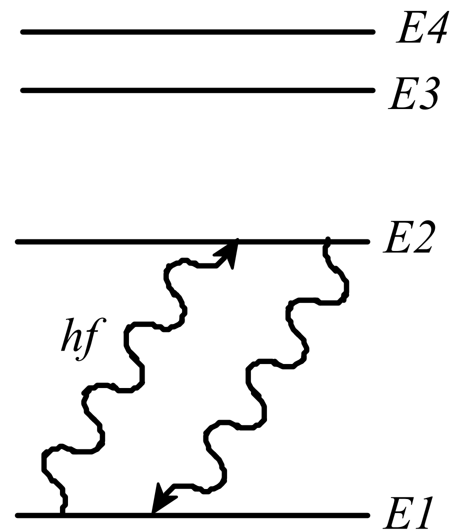
$$\frac{\dot{\alpha}}{\alpha} \approx 10^{-20} \text{ /year}$$ From SpaceTime experiment

Laser Cooling of Atoms



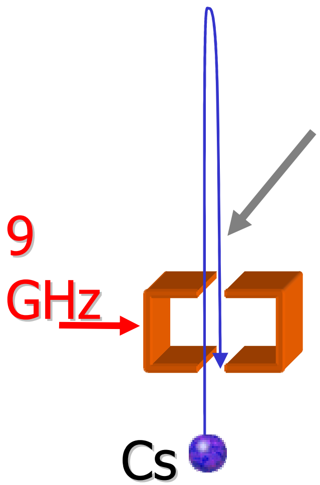


$$\mathbf{f} = \mathbf{f_0}(\mathbf{1} \pm \frac{\mathbf{v}}{\mathbf{c}})$$

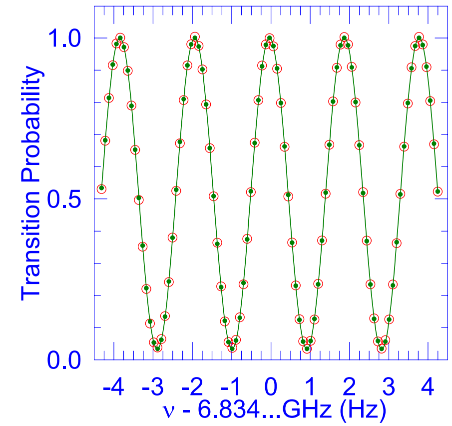


$$E_2 - E_1 = hf$$

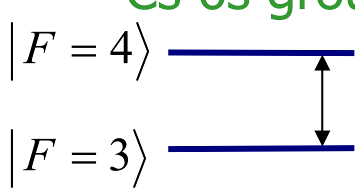
Physical Basis for the Fountain Clock



$$\Psi = \frac{|3\rangle + e^{i2\pi(9GHz)t + i\varphi_c}|4\rangle}{\sqrt{2}}$$



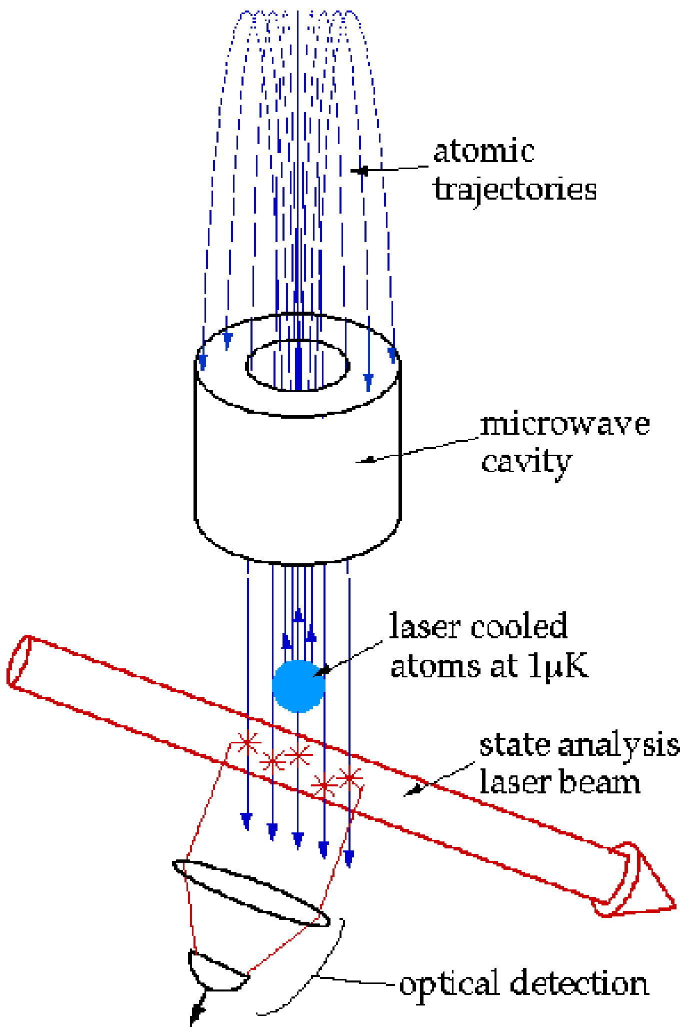
Cs 6s ground state

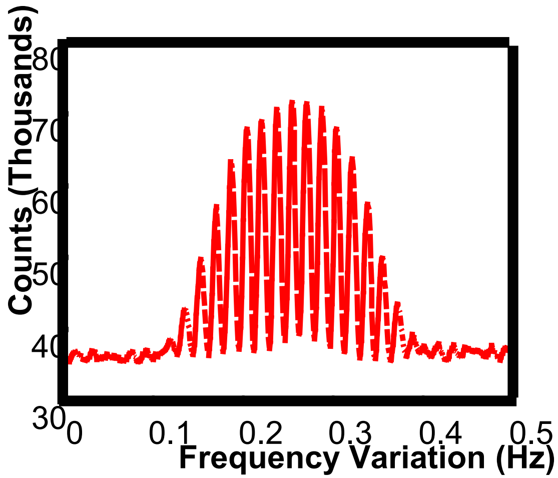


ν≡9,192,631,77<u>0</u> Hz

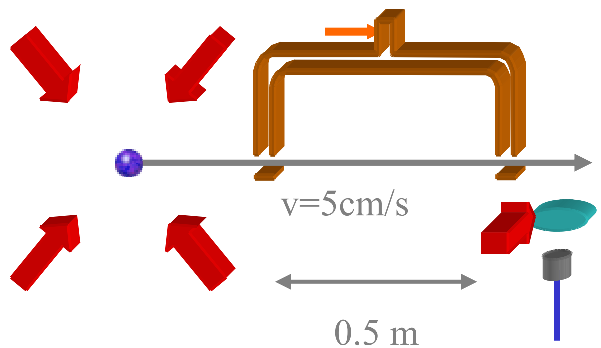
Accuracy of room temperature clocks < 10^{-14}
Potential accuracy of cold clocks: 10^{-16} to 10^{-17}
Cold collisions a fundamental limitation:
- Cs cold collision shift = 10^{-12} at n= 10^{9} cm^{3}

Atomic Clocks: Temporal Interferometers





Space Laser Cooled Clocks



Repeat every 10 s →

$$\sigma_y(\tau) = \frac{\Delta \upsilon}{\pi \upsilon \, \mathrm{S/N}} \sqrt{\frac{T}{\tau}} = 7.3 \times 10^{-15} \Big/ \sqrt{\tau}$$

Scaling of $\sigma_y(\tau=1\mathrm{s})$ with T

$$N \propto 1 / T^2$$

$$S / N = \sqrt{N} \propto 1/T$$

$$\Delta \nu = 1 / 2T$$

$$\sigma_y(\tau) = \frac{\Delta \upsilon}{\pi \upsilon \; S/N} \sqrt{\frac{T}{\tau}} \propto \sqrt{T}$$

ISS Clock Tests

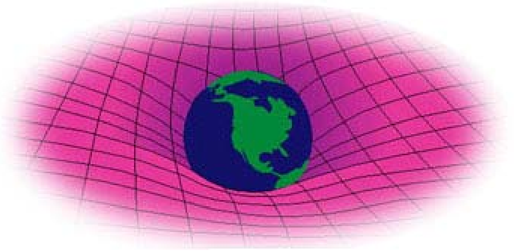
- Test of "preferred frame"
  - Speed of light depends on the velocity or the orientation of a moving frame with respect to a "preferred rest frame"
  - Michelson-Morely experiment
  - Kennedy-Thorndike experiment

$$\frac{c(\theta)}{c} = 1 + (\frac{1}{2} - \beta + \delta)\frac{v^2 \sin^2(\theta)}{c^2} + (\beta - \alpha - 1)\frac{v^2}{c^2}$$

v- the relative velocity of moving frame,

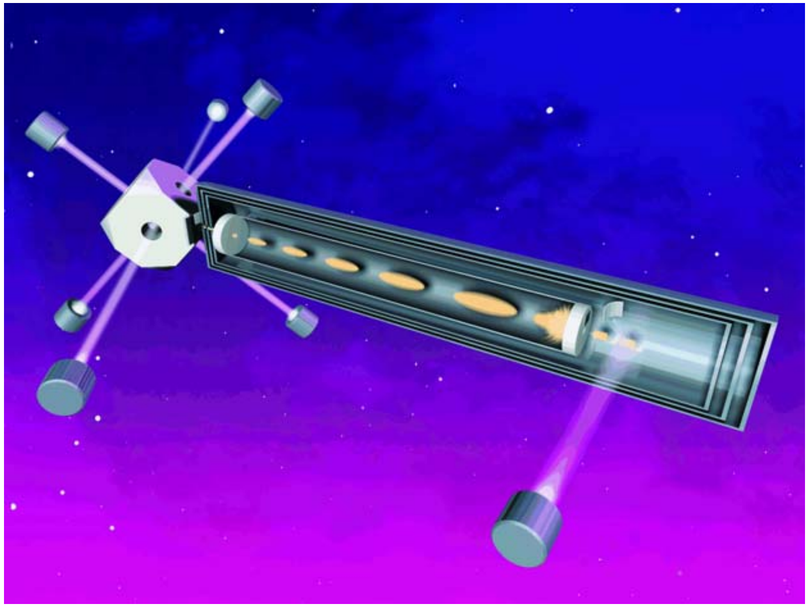
Θ - the angle relative to **v**

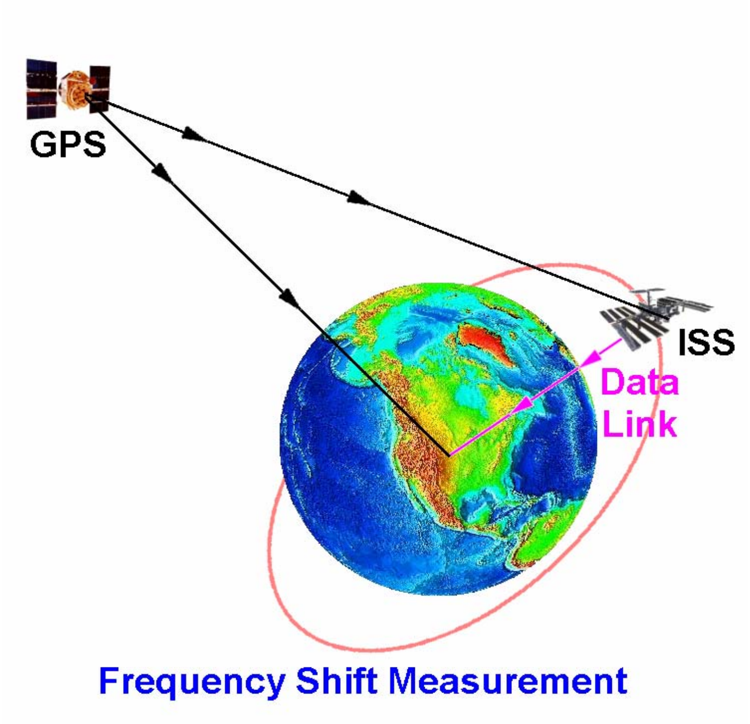
α,β,δ – parameters to test a theory (equal to zero in GR)



NASA Fundamental Physics Flight experiments

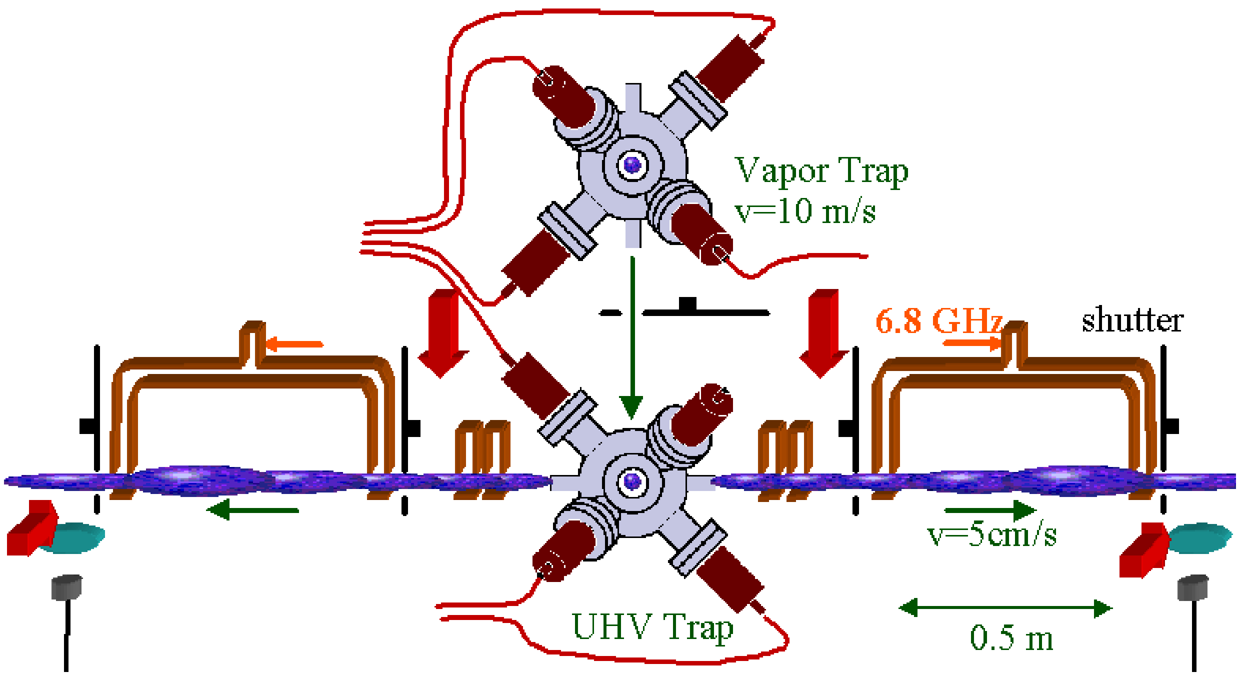
PARCS -- PI: D. Sullivan, NIST: Cs clock





NASA Fundamental Physics Flight experiments

RACE -- PI: Kurt Gibble, Penn State : Rb clock



Clock Comparision

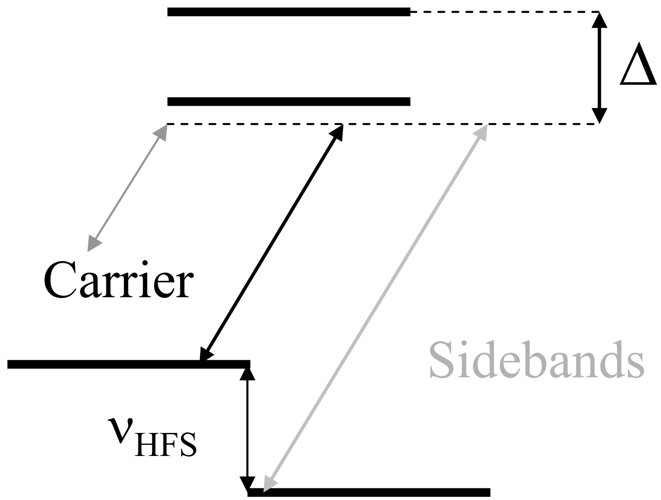
Earth-based Clocks: Space Clocks:

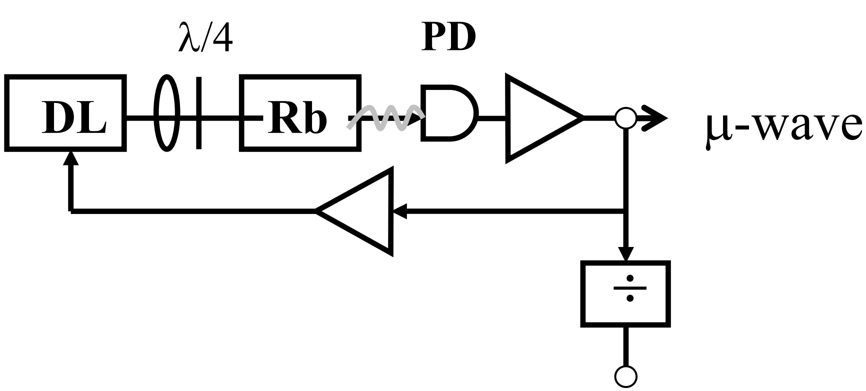
	NIST-7	Cs Fountain Clock	JPL Linear Ion Trap	PARCS	RACE
Accuracy (realization of the second)	5×10^{-15}	1.4×10^{-15}	–	1×10^{-16}	1×10^{-17}
Stability	$4 \times 10^{-13}/\tau^{1/2}$	$1.5 \times 10^{-13}/\tau^{1/2}$	$3 \times 10^{-14}/\tau^{1/2}$	$3 \times 10^{-14}/\tau^{1/2}$	$5 \times 10^{-16}/\tau^{1/2}$

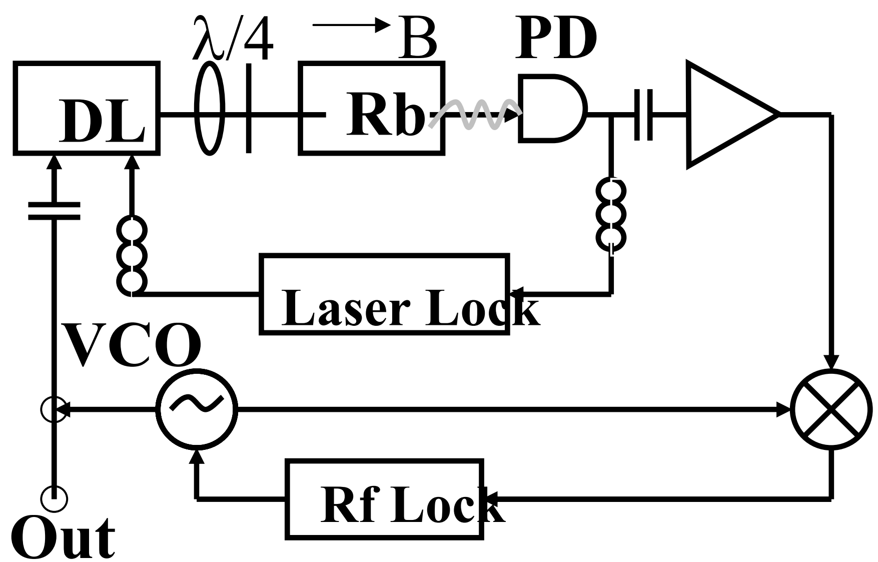
Raman/CPT Clocks

•Raman clocks offer prospects for a small, low power package with moderate (10^{-11}) performance

•Suitable for "backpack" application

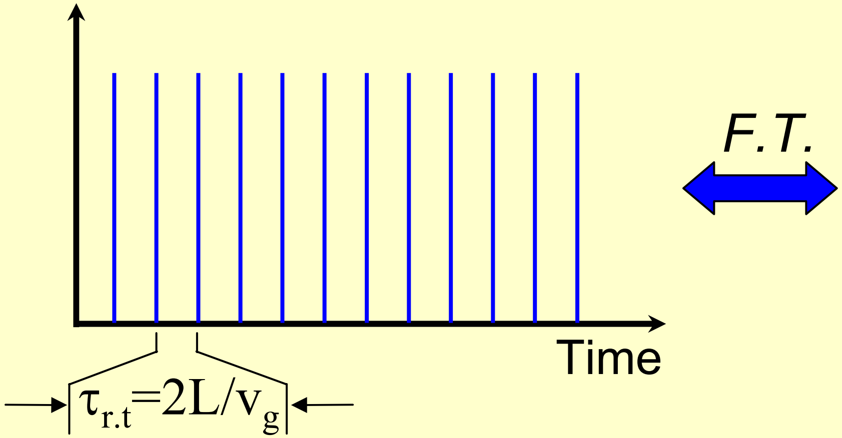


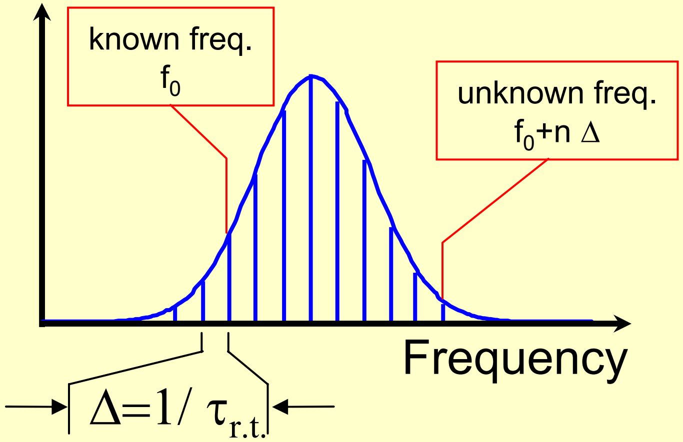




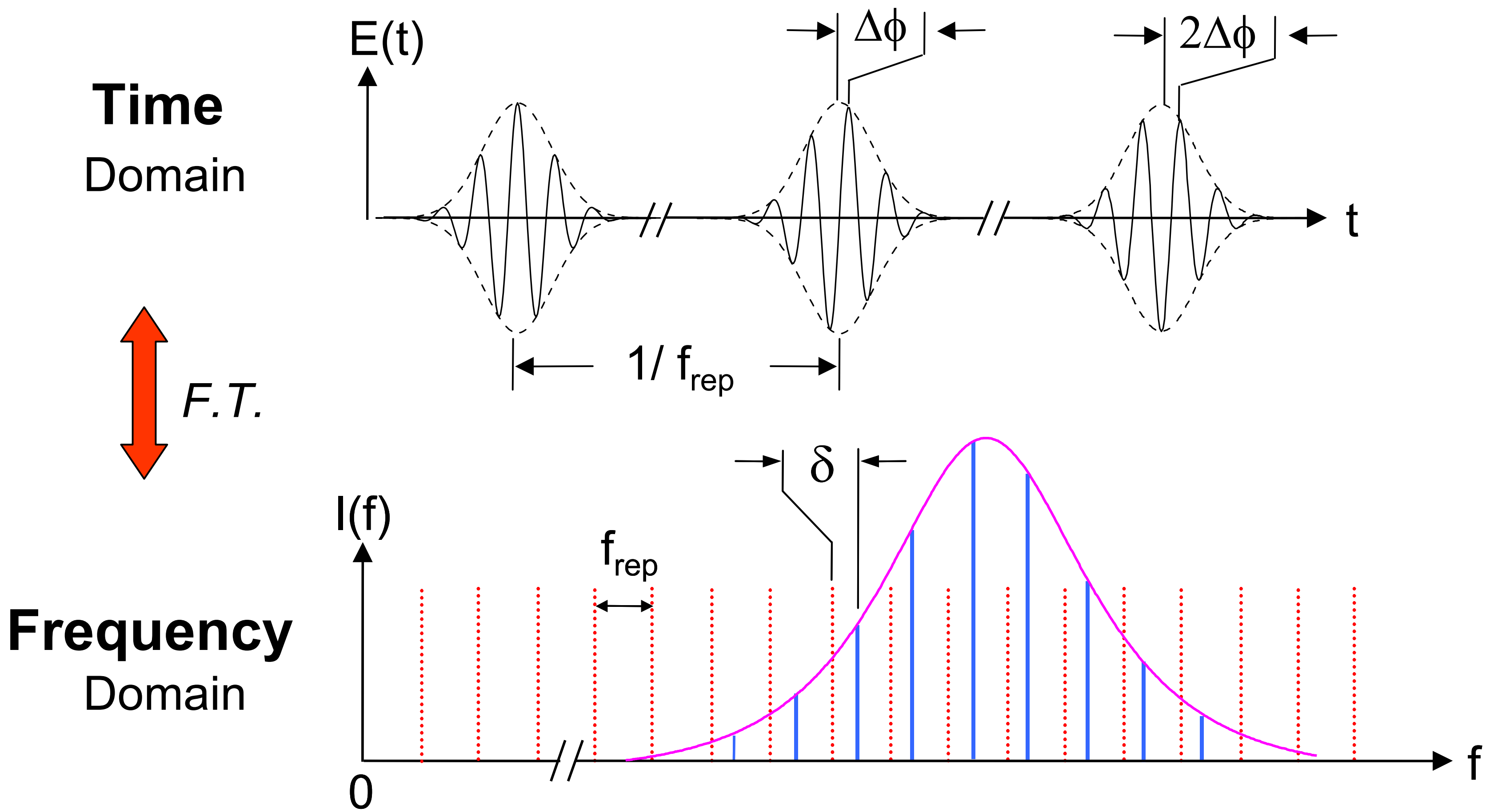
The Optical Comb Generator

- Periodicity in Time ⇔ Periodicity in Frequency





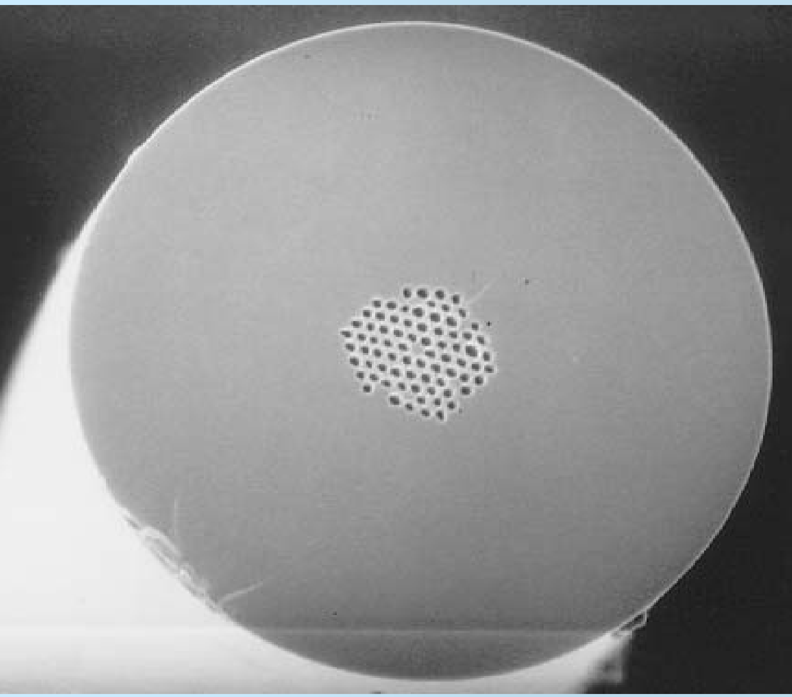
Time Domain ⟷ Frequency Domain

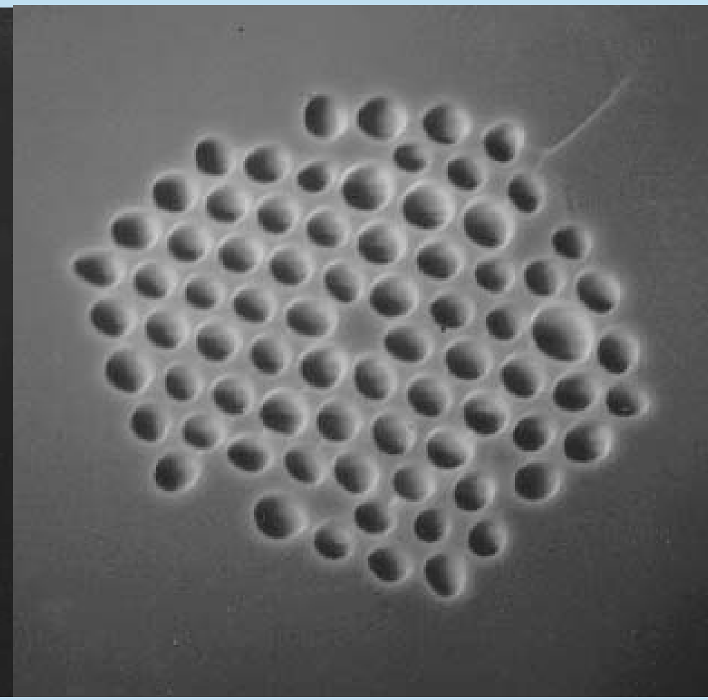


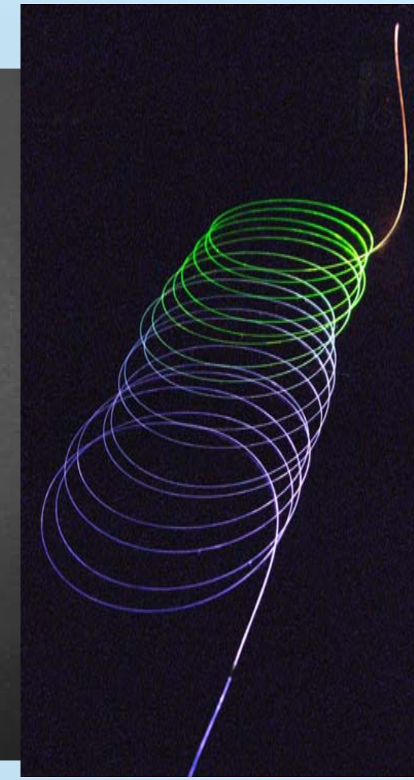
•Frequency modes of the fs pulse are offset from $f_{n=0}=0$ by δ

$$2\pi\delta = \Delta\phi \; f_{rep}$$

Honeycomb Microstructure Optical Fiber





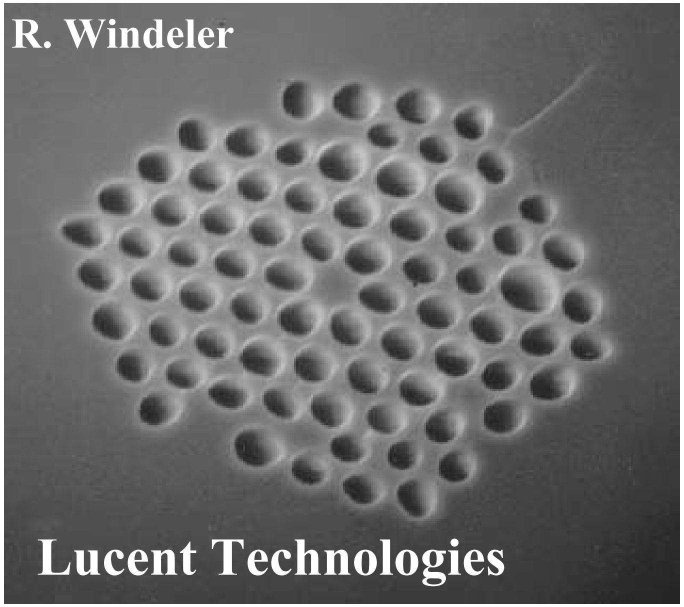


courtesy of Jinendra Ranka

Lucent Technologies
Bell Labs Innovations

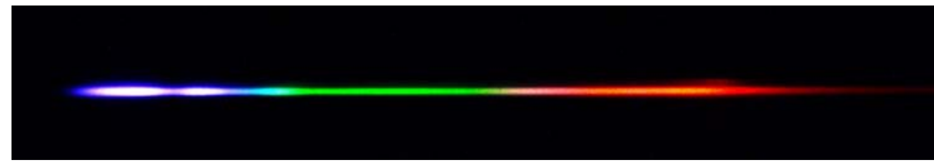
May, 1999

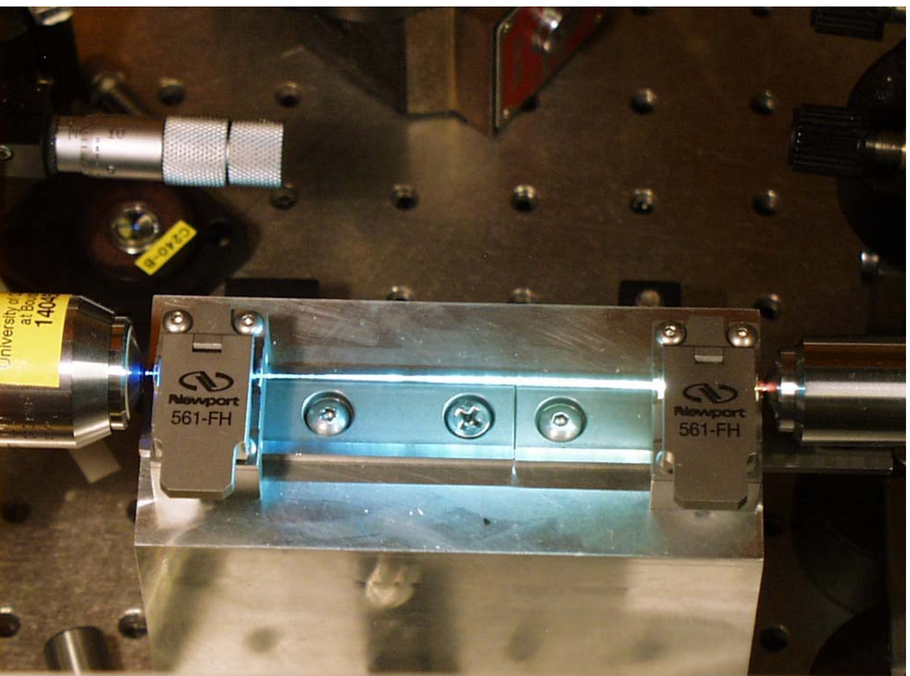
J.K Ranka, R. S. Windeler, A. Stenz, Opt. Lett. ***25****, 25 (Jan. 2000)*

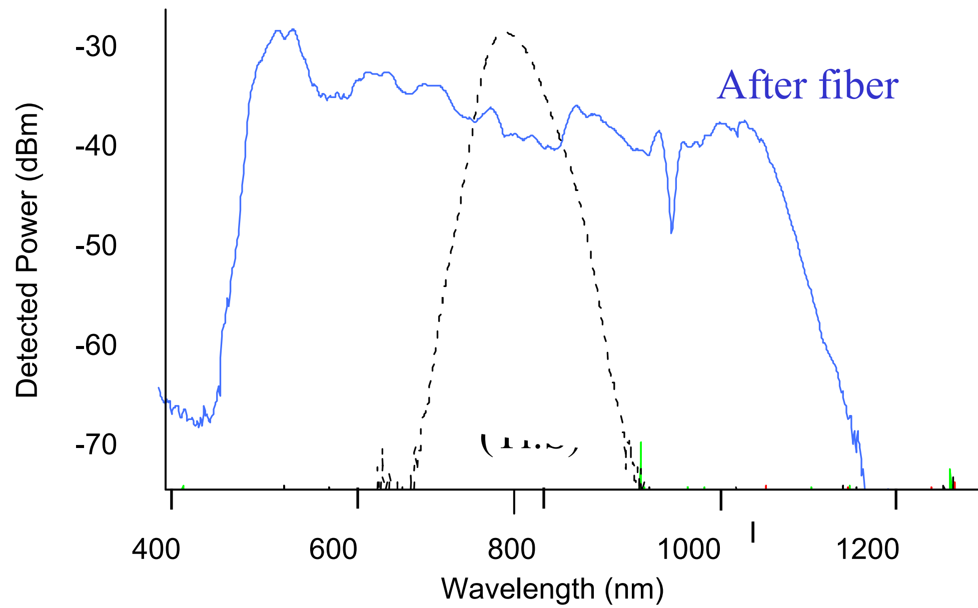


Microstructured fiber

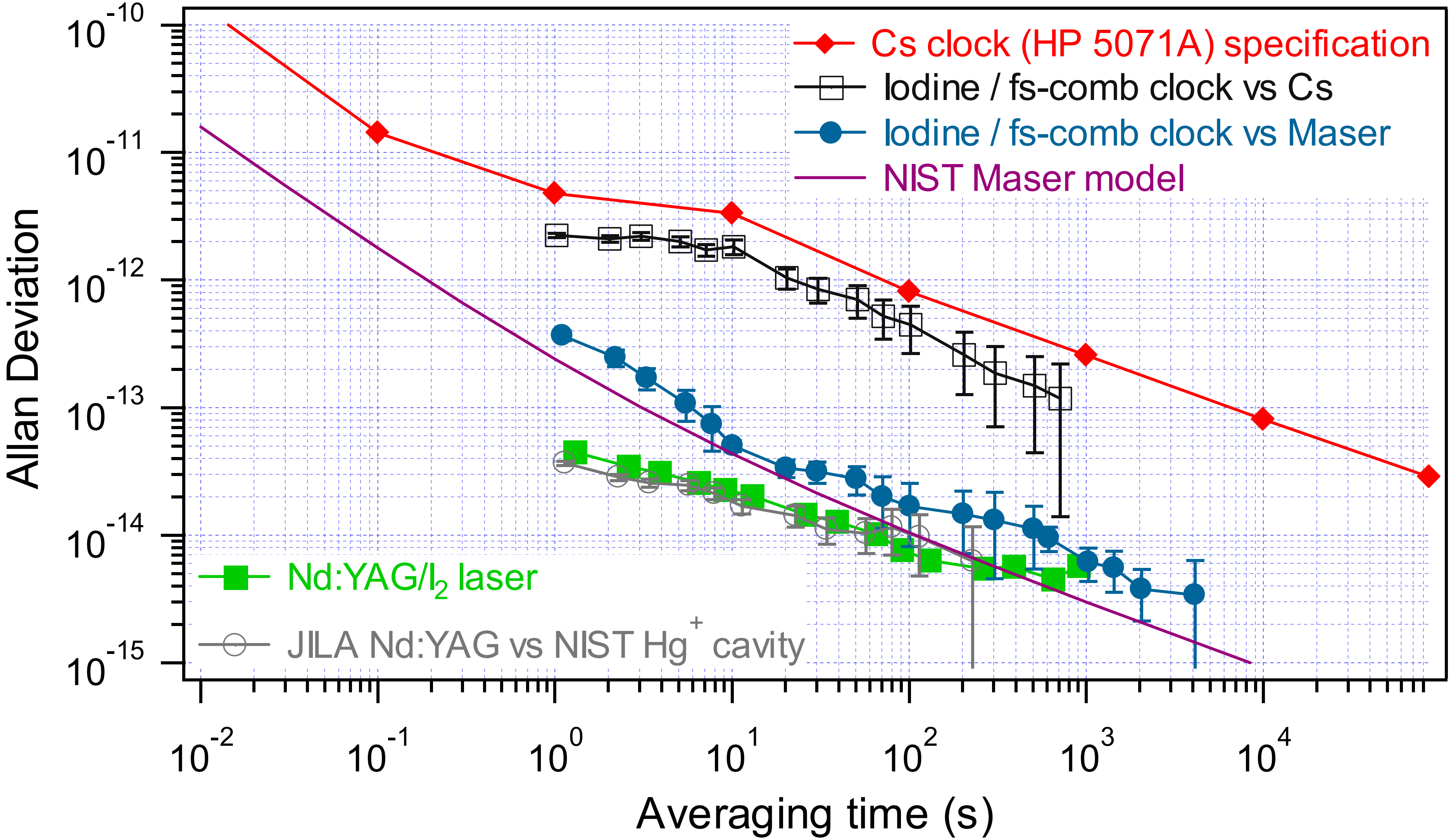
- dispersion zero at ~800 nm
- pulses do not spread
- continuum generation via self-phase modulation







NIST Optical Clock Performance



Summary

- Recent advances in ion traps, laser cooling and optical comb generation provide new opportunities for application of clocks to new tests of fundamental physics, on the ground and in space.

Acknowlegements

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