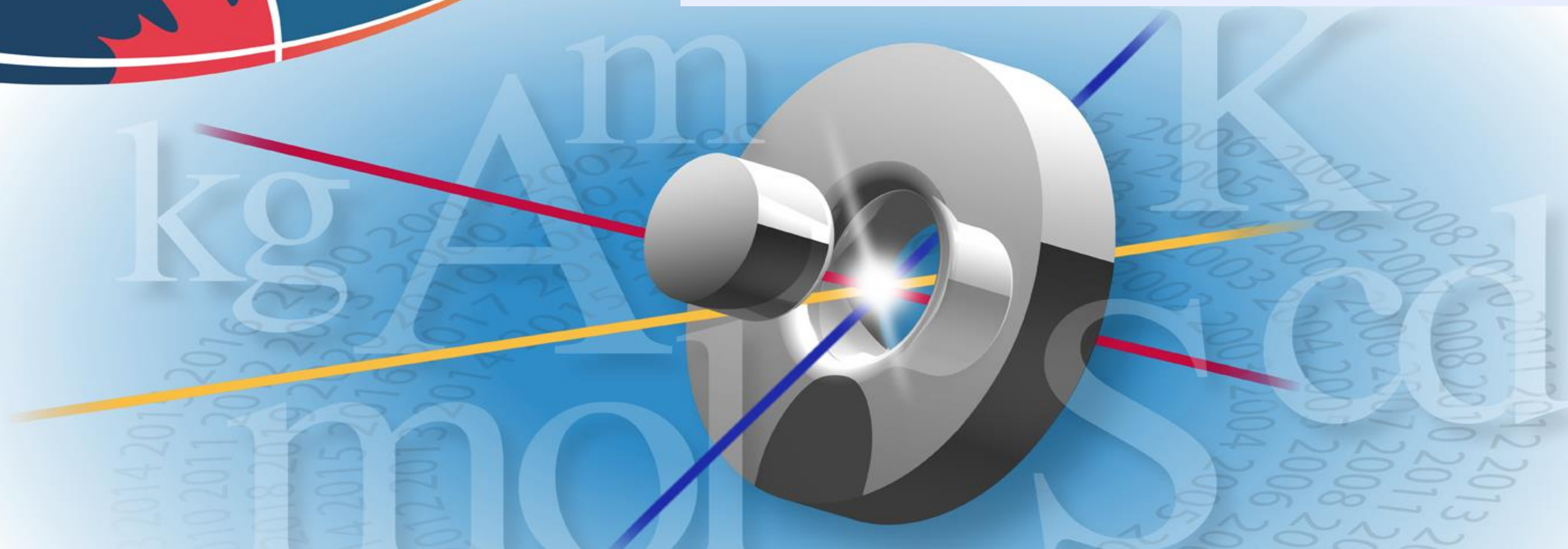


Moving Beyond the Current Limits of Time: Single Ion Optical Atomic Clocks and the Quest for the Ultimate Isolated Quantum System

Alan A. Madej , Pierre Dubé, Maria Tibbo, and John E. Bernard

U of T Physics Colloquium , Nov. 7, 2013

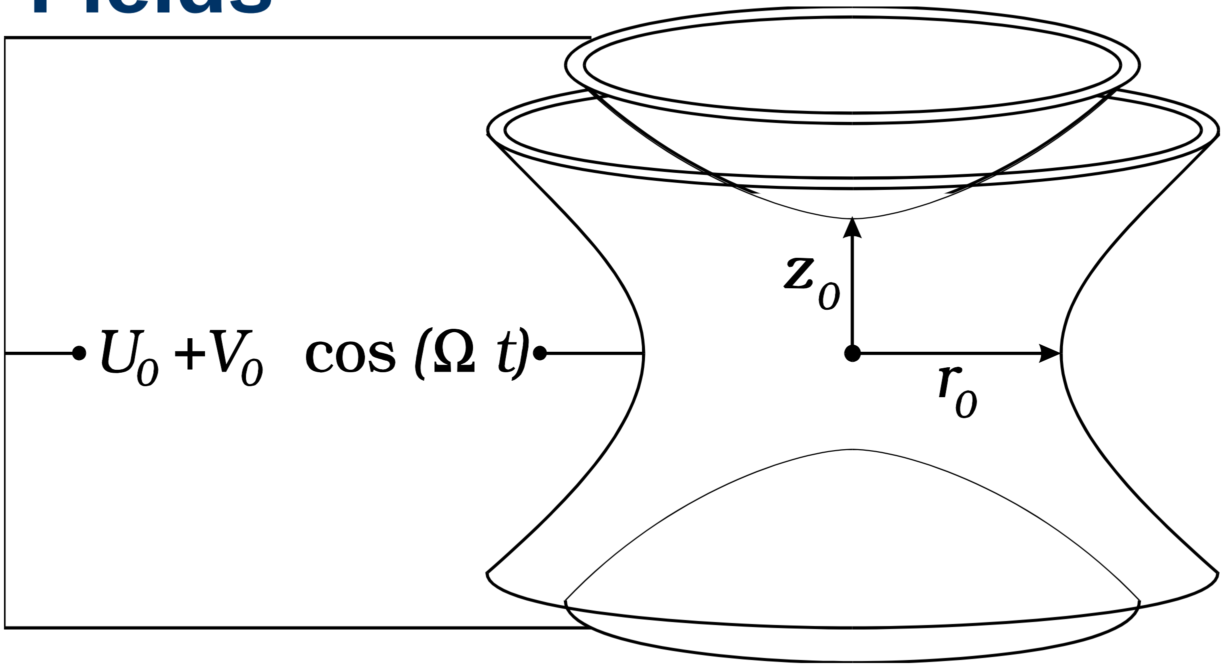
Frequency Standards and Atomic Clocks

Oscillator + Counter = Clock

A stable, periodic source: Pure Electromagnetic (E.M.) Radiation oscillates with an extremely regular frequency. Atoms or molecules absorb discrete energies or frequencies when the E.M. radiation matches the system's natural energy levels.

A way of reading out the number of periods of Time: Using electronic devices to count the cycles of the E.M. radiation allows us to count time intervals. By defining time in terms of the number of periods of E.M. radiation which is stabilized to the atomic standard's 'natural' frequency, we can create an atomic time standard.

Holding Single Ions With Time Varying Fields



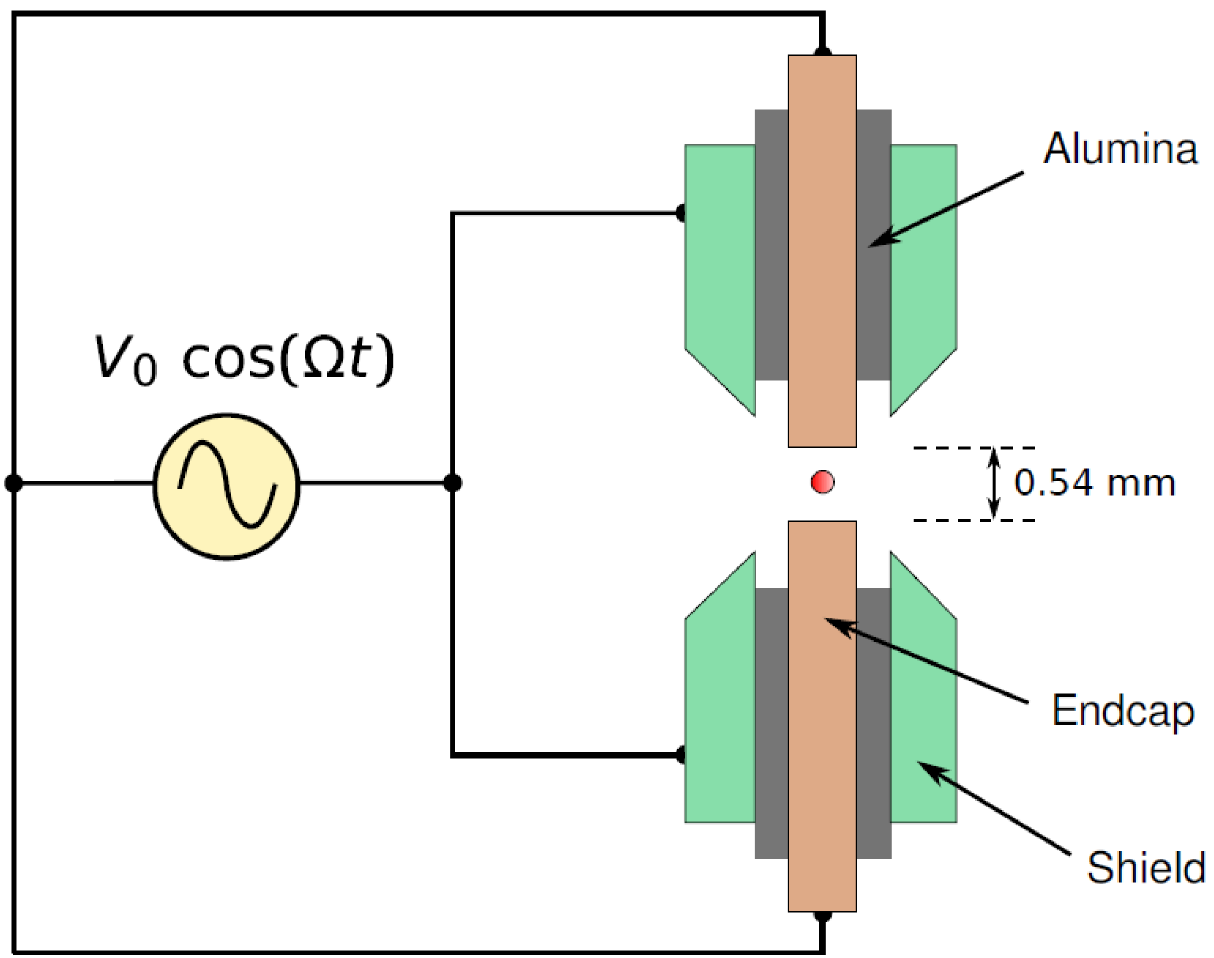
2-D Simulation Of Trapping fields and ion motion (courtesy U. of Washington)

Rf Trap: Axial (z) and Radial(r) confinement is provided by a

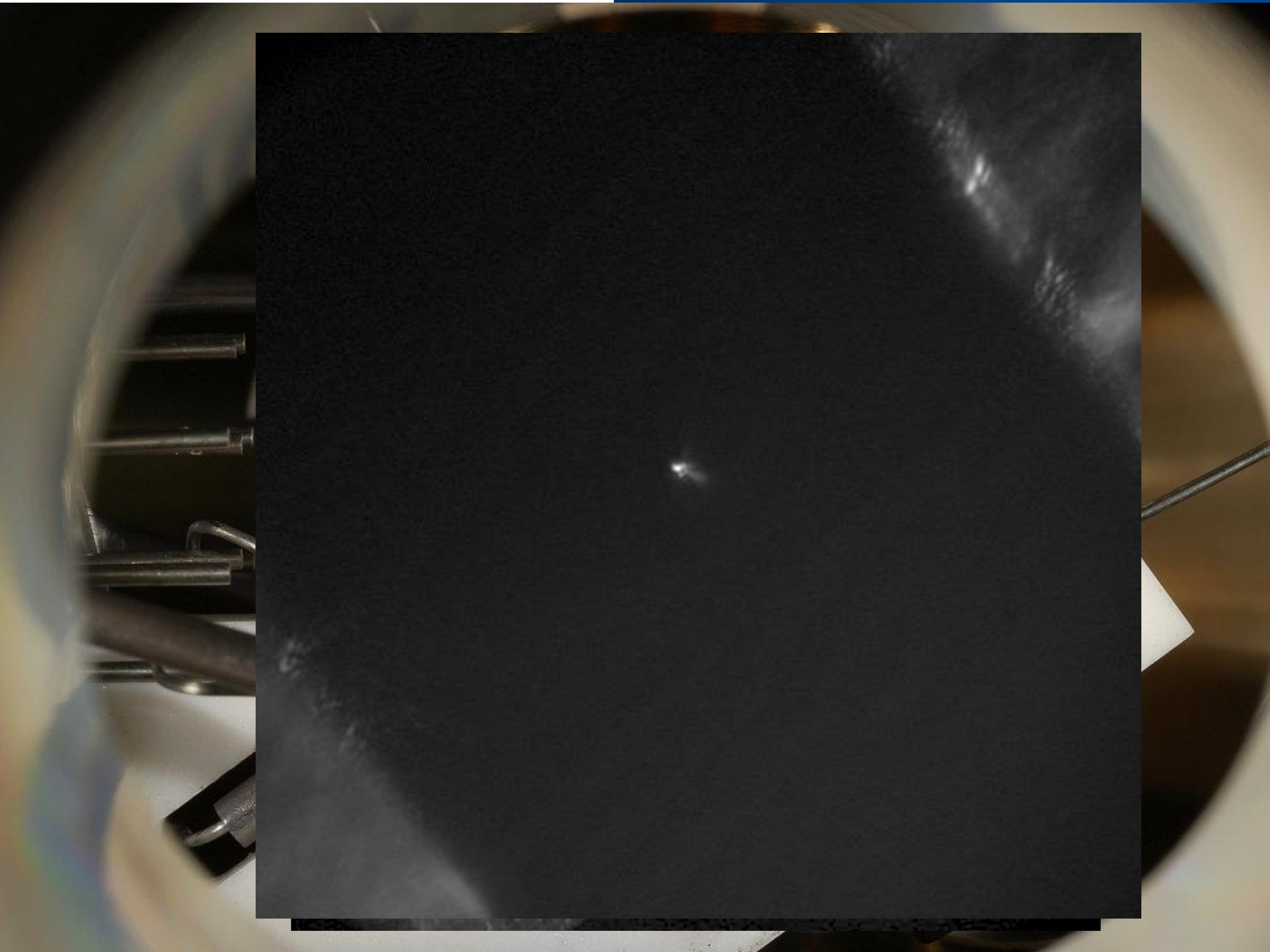
Secular motion:	ion temperature	1.2 MHz
Micromotion:	trap $\vec{E}$ fields	$\Omega/2\pi \simeq 14$ MHz

trap centre.

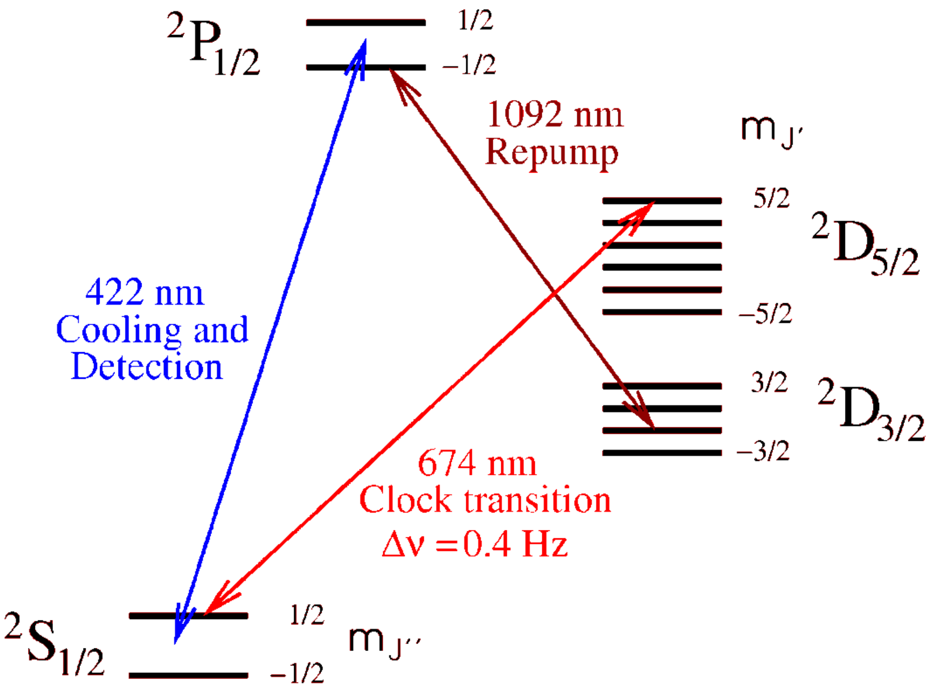
NRC Endcap Trap Configuration

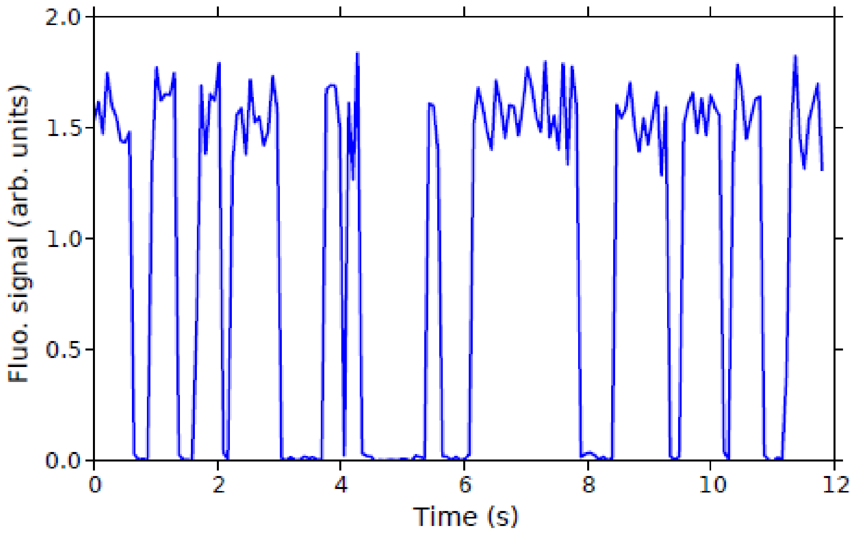


The new NRC single ion trap uses a endcap trap configuration where the ring electrode is replaced by shield electrodes located around the main RF drive electrodes.



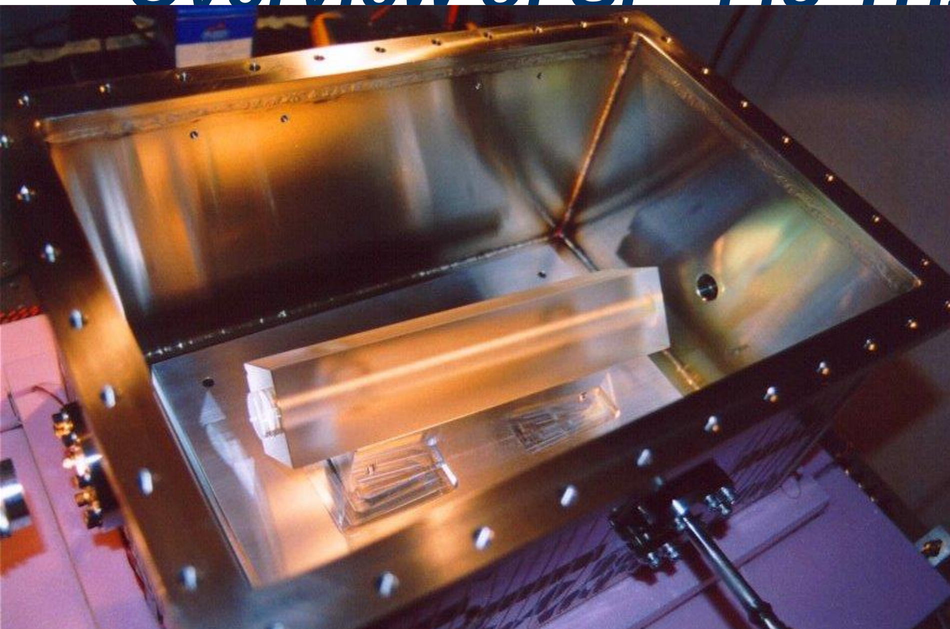
Single, Laser Cooled Sr^+ Optical Frequency Standard

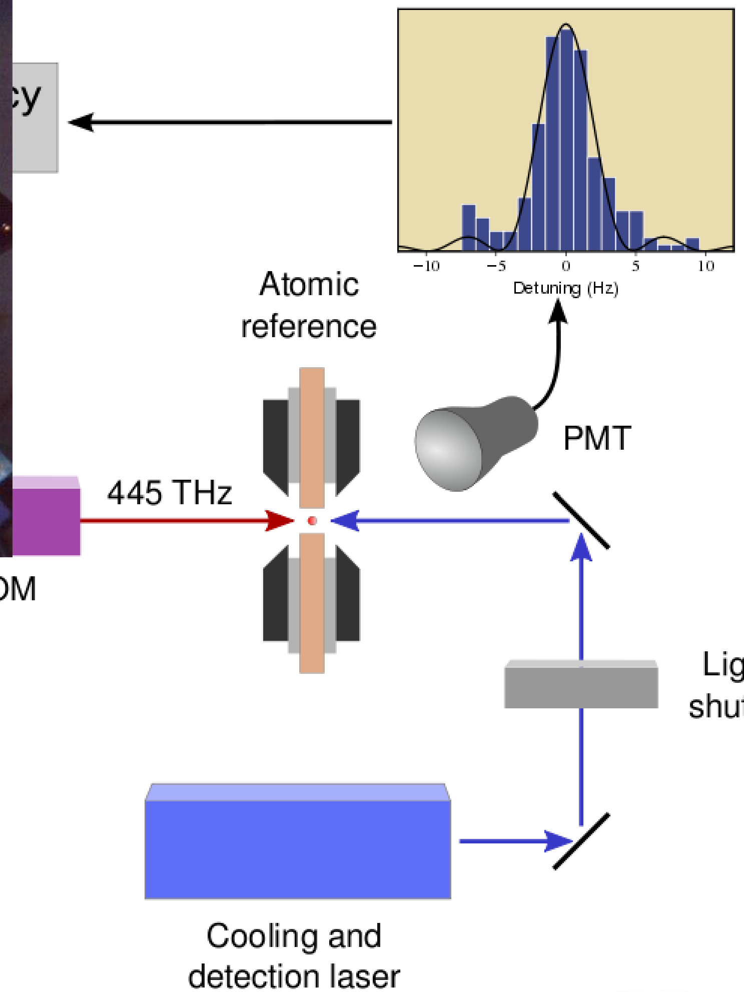




- Single Sr^+ Ion held in an Endcap Trap of 0.52mm electrode spacing and cooled to 1.8 mK.
- Probing on S-D quadrupole transition (0.4 Hz) using ULE cavity stabilized diode laser.

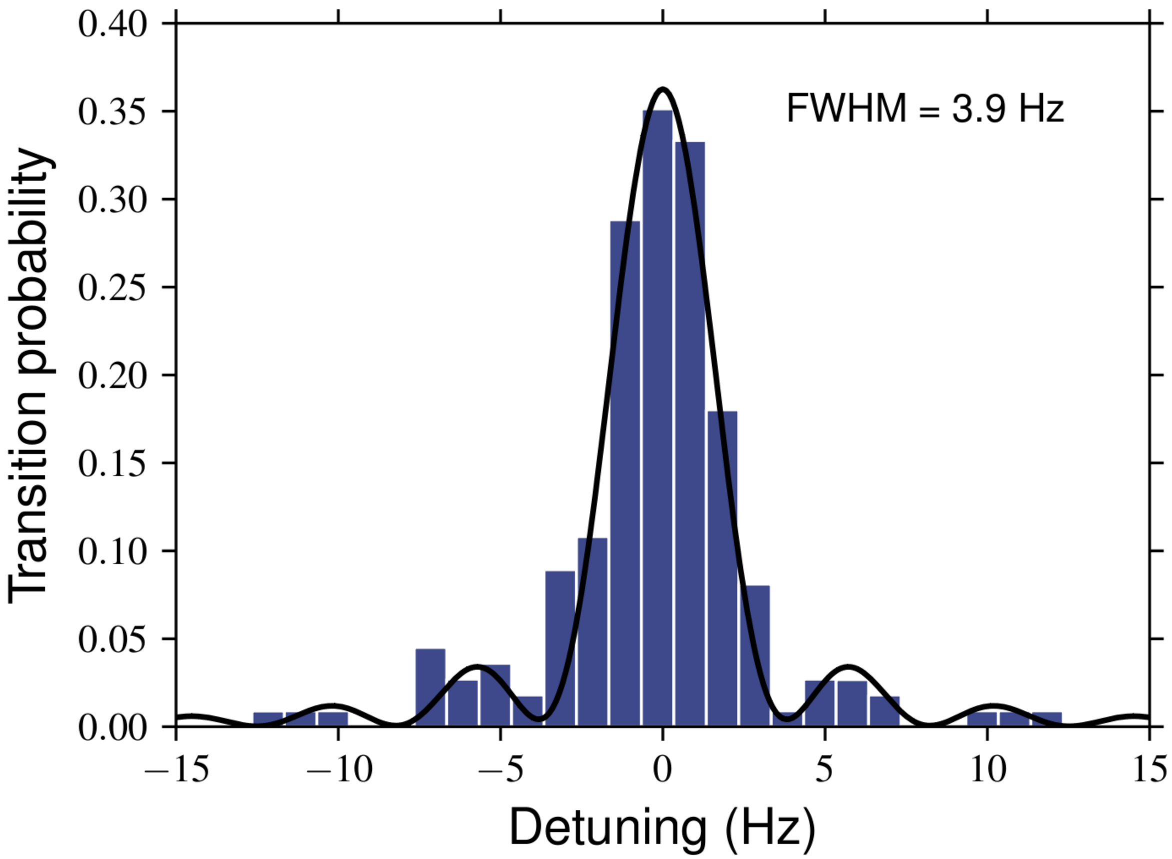
Overview of Sr^+ 445-THz Single Ion Experiment





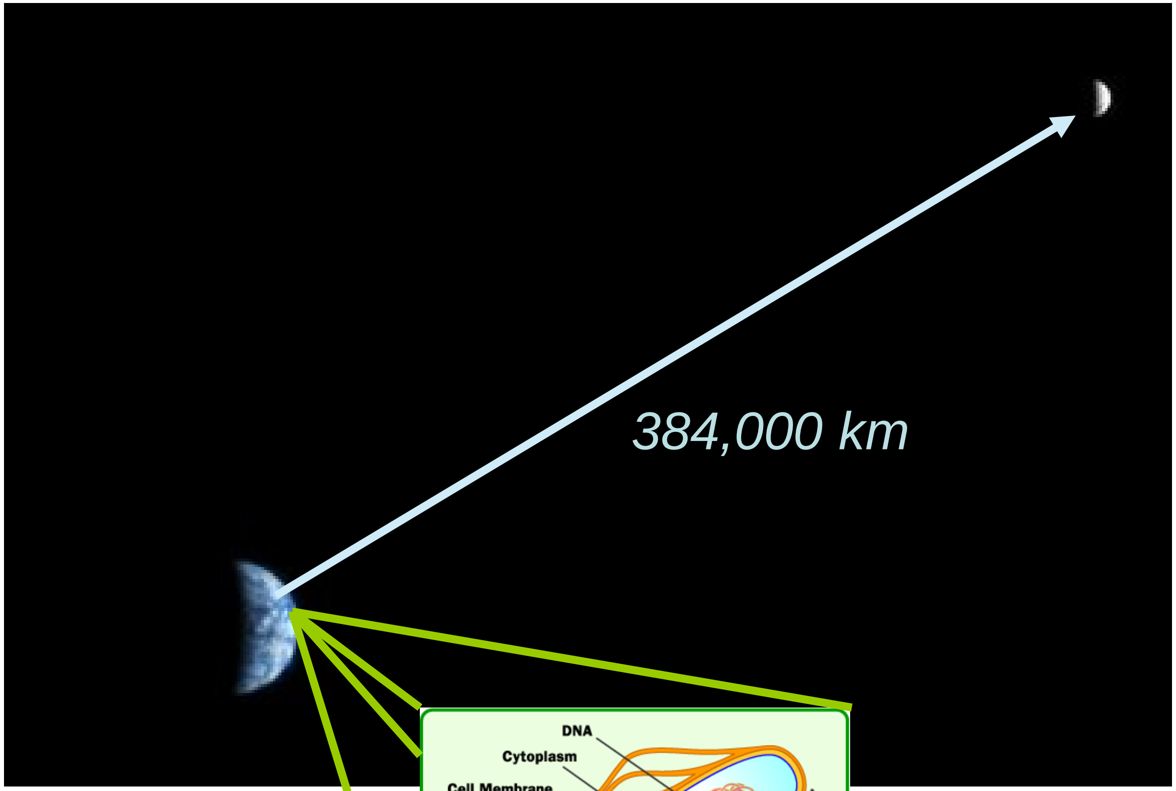
Spectral Scans On New Ion Trap

Observed Zeeman Spectrum of Single Ion in Endcap Trap System

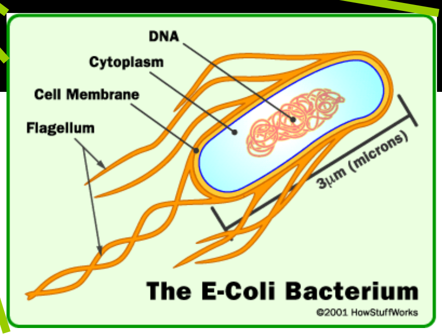


Spectra of the S-D transition with magnetic shielding in the single ion system with the new trap have been obtained. Good resolution of Zeeman spectra were seen and feature sizes of 4 Hz width seen limited by the probe laser system.

Relative Scale of Current Spectral Resolution



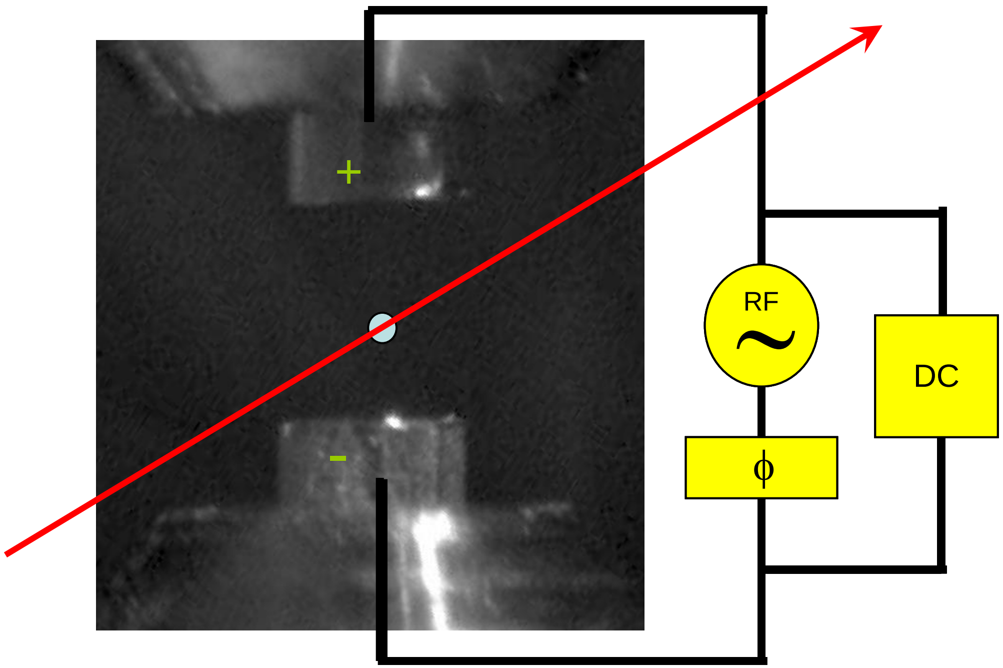
(courtesy NASA)

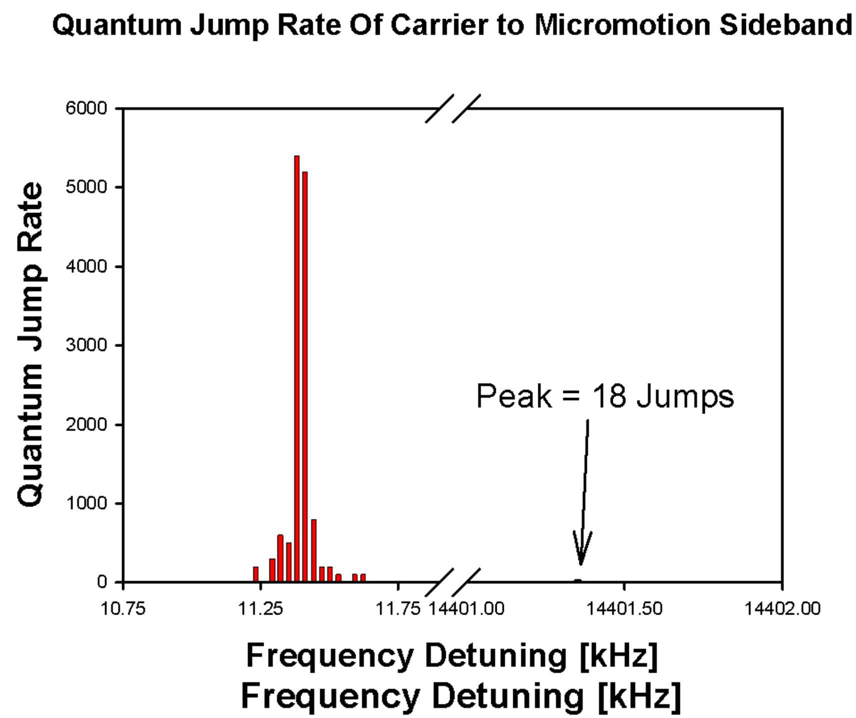


The current spectral resolution obtained of 1×10^{-14} is equivalent to resolving the earth moon distance to the size of an E-coli Bacterium!

- ***Accuracy Evaluation of The Single Ion***

Controlling the Micromotion Limit





shift level

Combined Time Dilation and Stark Shifts: The Magic Trap Frequency

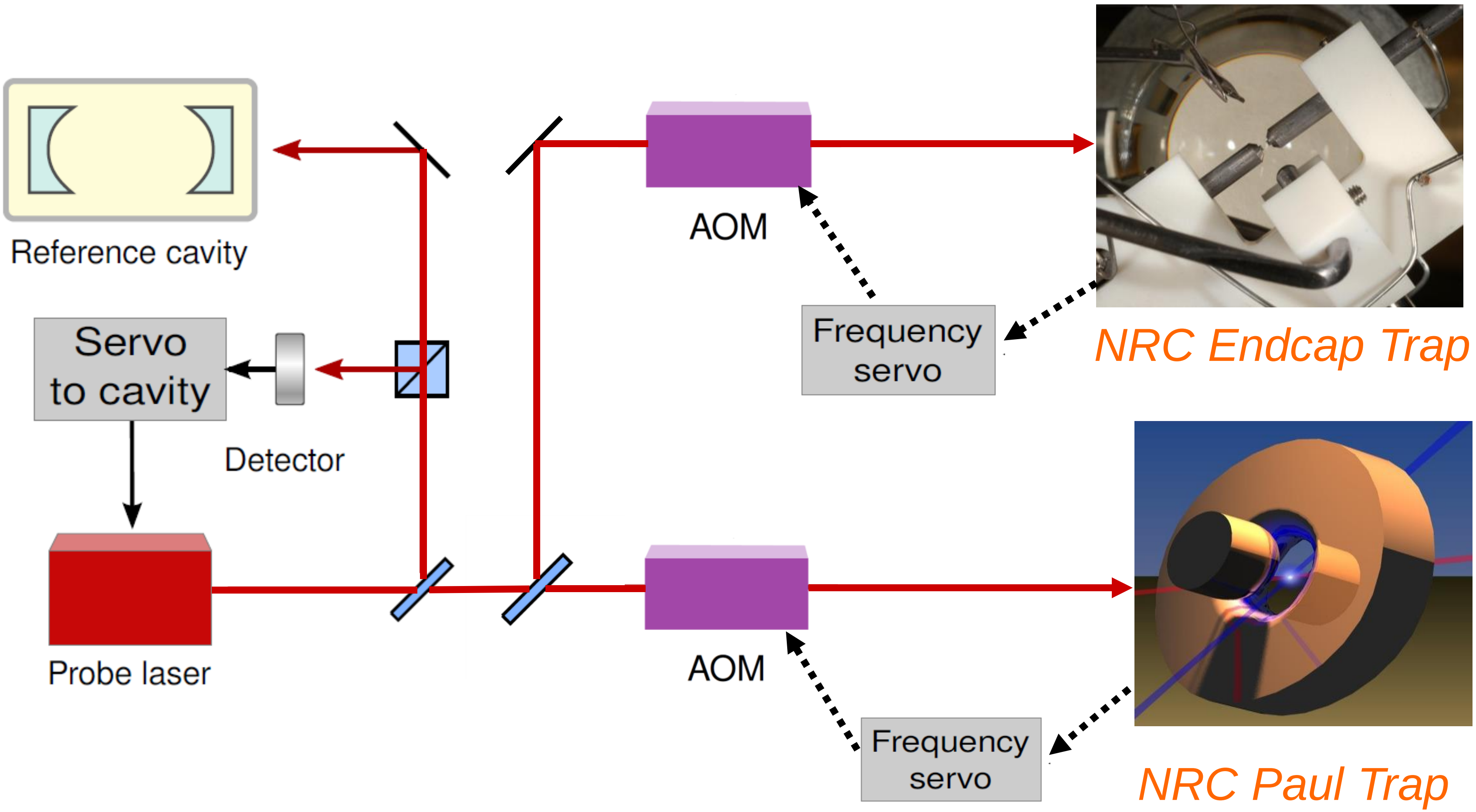
$$\frac{\Delta\nu_\mu}{\nu_o} = -\frac{\langle E^2(t)\rangle}{2}\left[\left(\frac{e}{m\Omega c}\right)^2 + \frac{\Delta\alpha_o}{h\nu_o}\right]$$

For $^{88}Sr^+$, $\Delta\nu_\mu = \Delta\nu_{\mathrm{Stark}} + \Delta\nu_{\mathrm{TD}} = 0$ if:

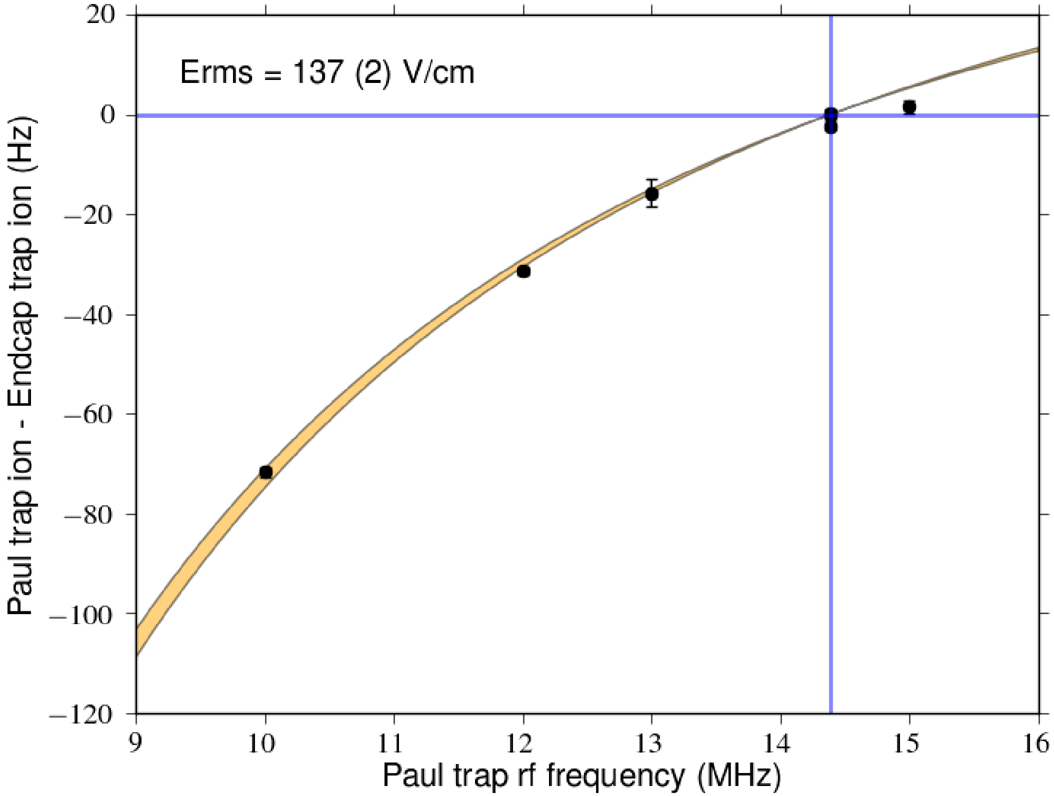
$$\Omega = \frac{e}{mc}\sqrt{-\frac{\hbar\,\omega_0}{\Delta\alpha_0}} = 2\pi \times 14.39\ \mathrm{MHz}$$

- $\Delta\alpha_0$ known with uncertainty of 3.5%
- Cancellation by factor of 28
- $\frac{\Delta\nu_\mu}{\nu_0}$ uncertainty $= \frac{2.2 \times 10^{-17}}{28} \lesssim 1 \times 10^{-18}$

Comparison of Reference Frequency With Different Generation NRC Trap Systems



Comparison of Traps : Tuning to the Magic Frequency



As a confirmation of the strong cancellation of the residual micromotion, the trap Frequency was tuned in the Paul trap showing a dramatic change in offset.

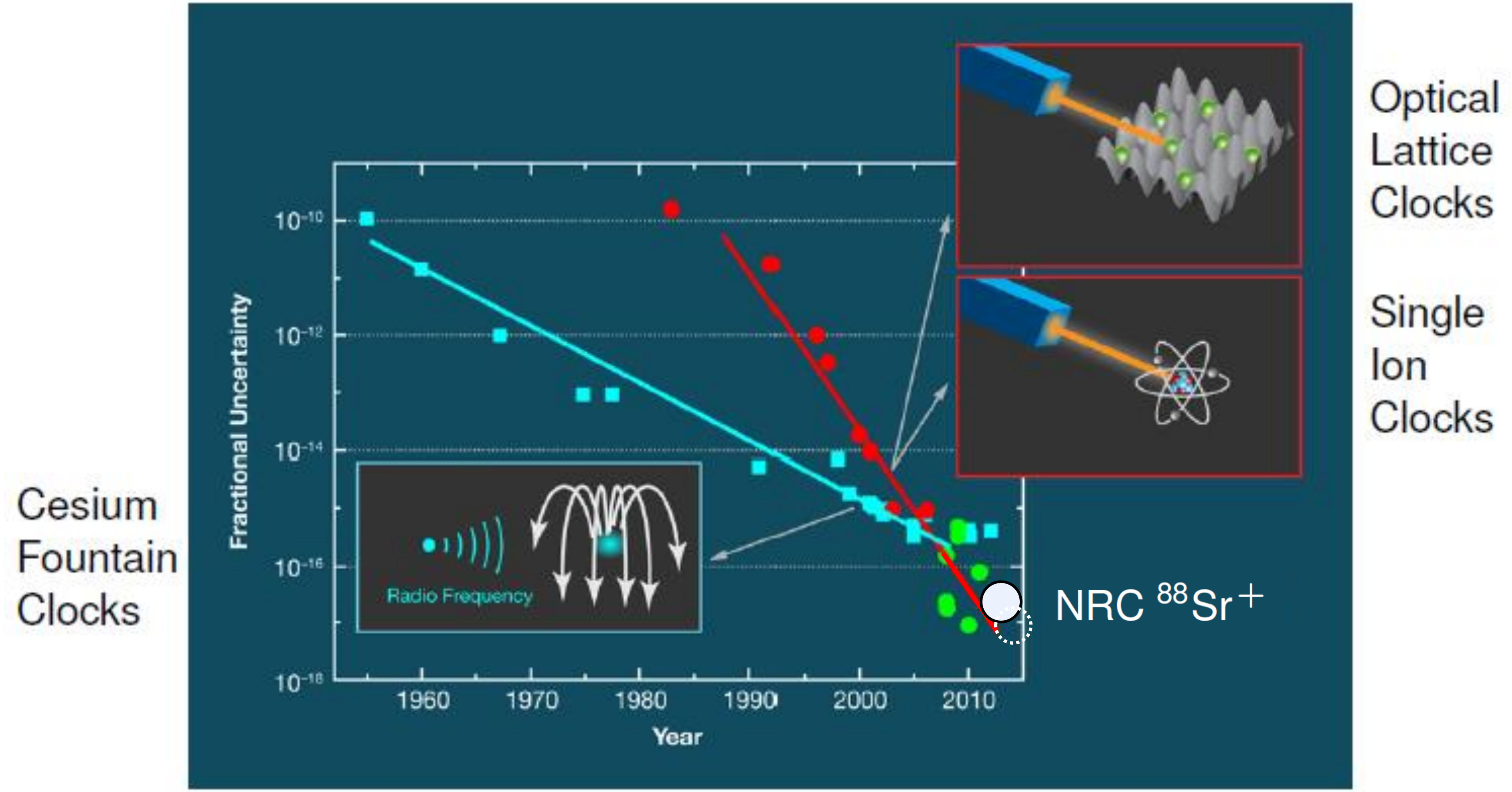
$$\frac{\Delta\nu_\mu}{\nu_o} = -\frac{\langle E^2(t)\rangle}{2}\left[\left(\frac{e}{m\Omega c}\right)^2 + \frac{\Delta\alpha_o}{h\nu_o}\right]$$

Summary of Potential Systematic Shifts for Sr^+ Next Generation Trap

Source	Shift [Hz]	Uncertainty [Hz]	Fractional Uncertainty
Micromotion ($\Delta\nu_{\text{Time Dilation}} + \Delta\nu_{\text{Stark Effect}}$)	0	0.0005	1×10^{-18}
AC Stark Shift from 1092 nm repump	-0.002	0.001	2×10^{-18}
Blackbody AC Stark Shift	0.250	0.010	2×10^{-17}
Collisions	0	0.001	2×10^{-18}
2nd Order Doppler shift (Thermal motion)	-0.0013	0.0005	1×10^{-18}
Electric Quadrupole Shift of $^2D_{5/2}$ level	0	0.00014	$< 3 \times 10^{-19}$
AC Stark Shift from Probe Laser	0.000016	0.000009	2×10^{-20}
Quadratic Zeeman shift (bias B field)	0.00004	0.000001	2×10^{-21}
Total	0.247	0.010	2.3×10^{-17}

P. Dube, A.A. Madej, Z. Zhou and J.E. Bernard, Phys. Rev. A , 87, 023806 (2013).

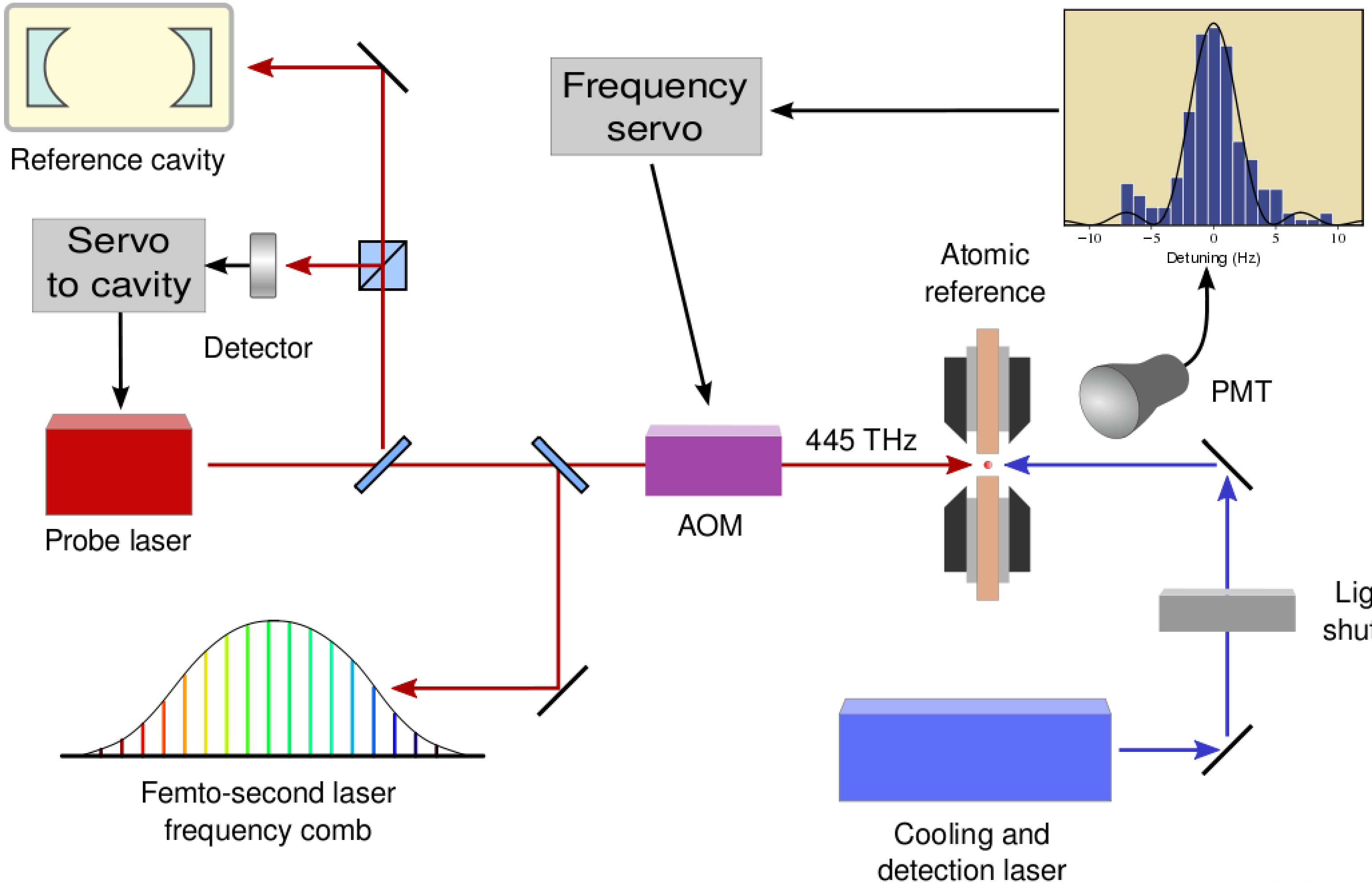
Sr^+ moves beyond the SI second



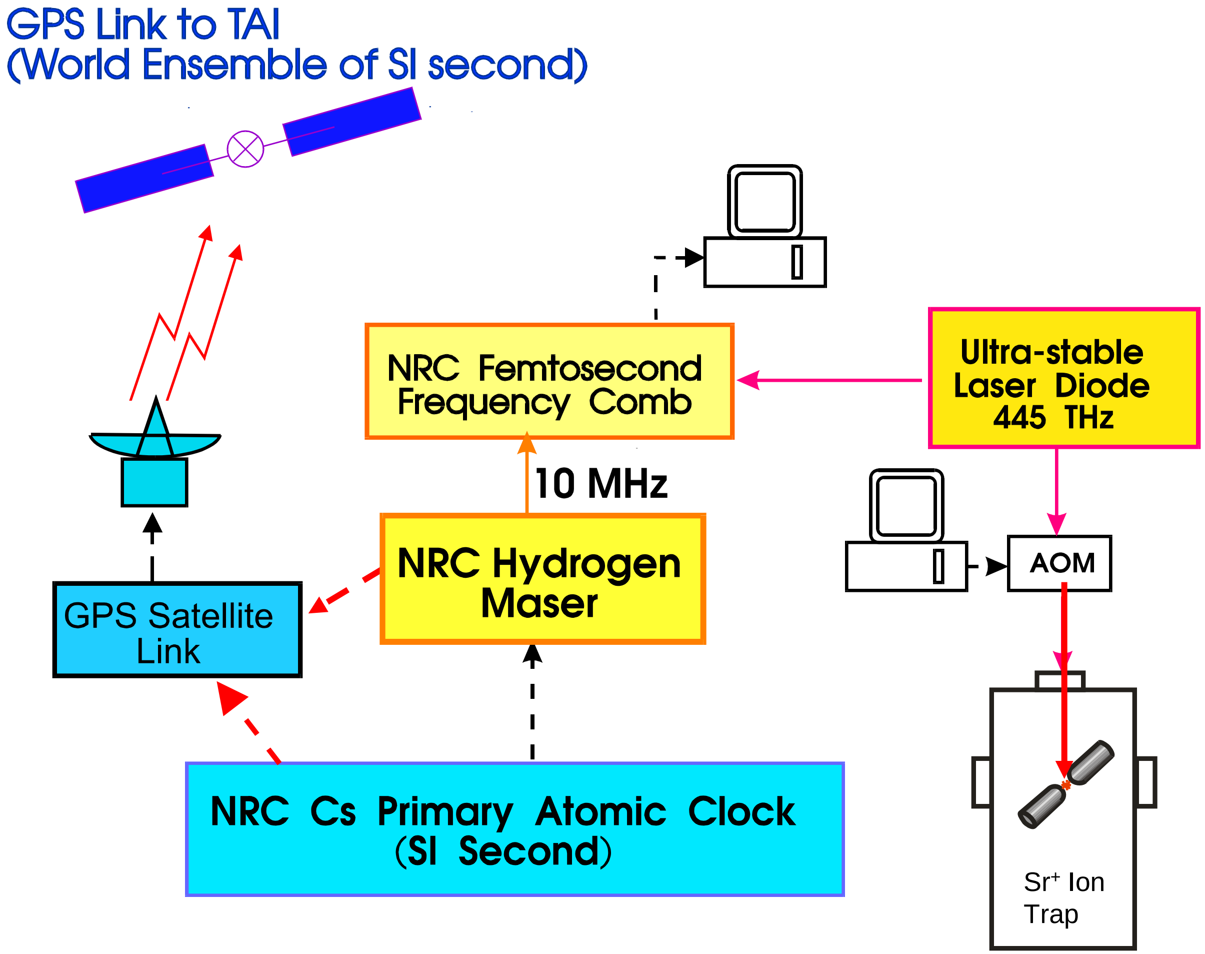
Adapted from: Physics Viewpoint, Fritz Riehle, Physics **5**, 126 (2012)

- ***Absolute Frequency measurement via Linkage to SI second using a Fiber based Frequency Comb System***

Overview of Sr^+ 445-THz Single Ion Experiment

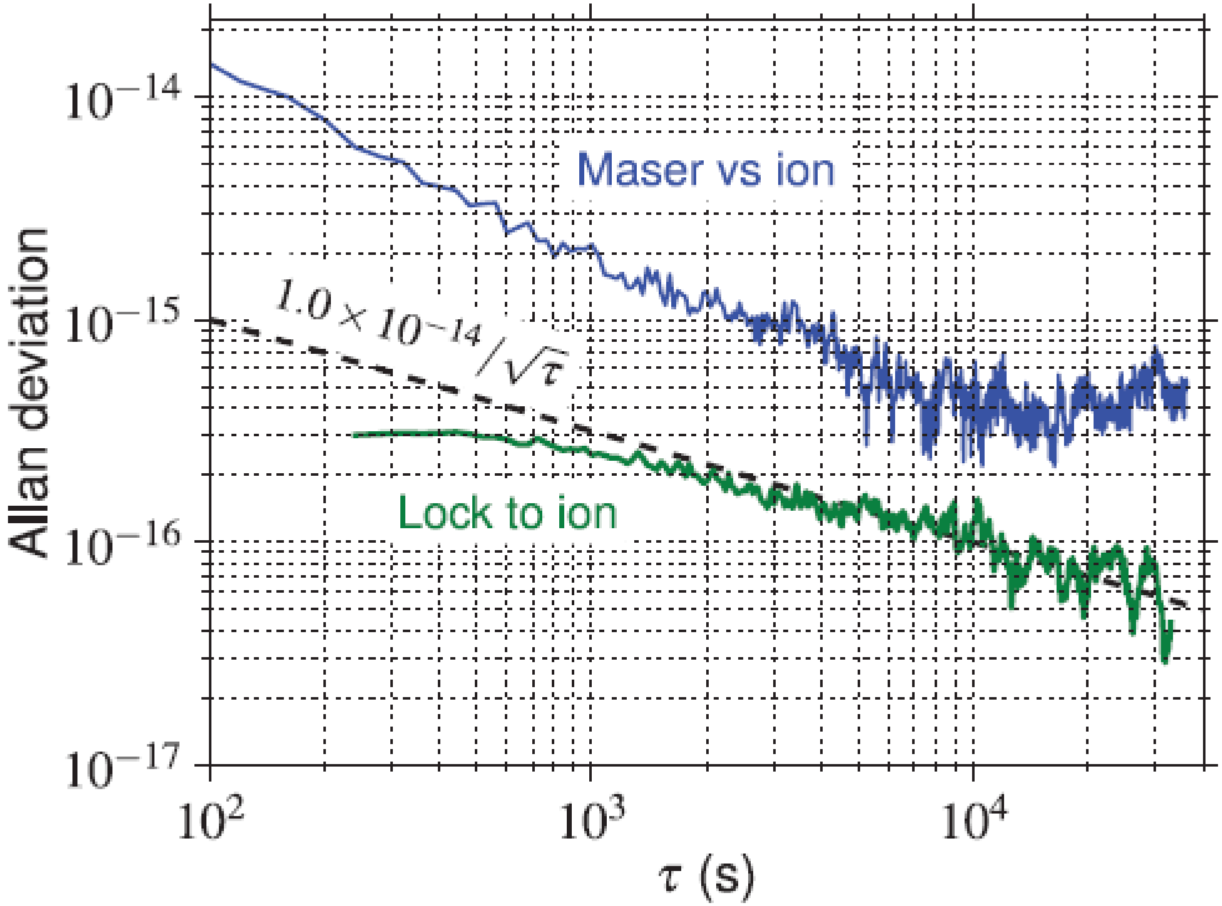


Absolute Frequency Measurement of the Sr^+ Transition vs. the SI Second



Measurements of the probe laser stabilized on the centre of the Ion Reference Frequency at 445 THz were obtained using a fiber based optical frequency comb. This was referenced to the NRC ensemble of Rf Time standards including H masers. Correction to International Atomic Time (TAI) was obtained by GPS satellite time transfer.

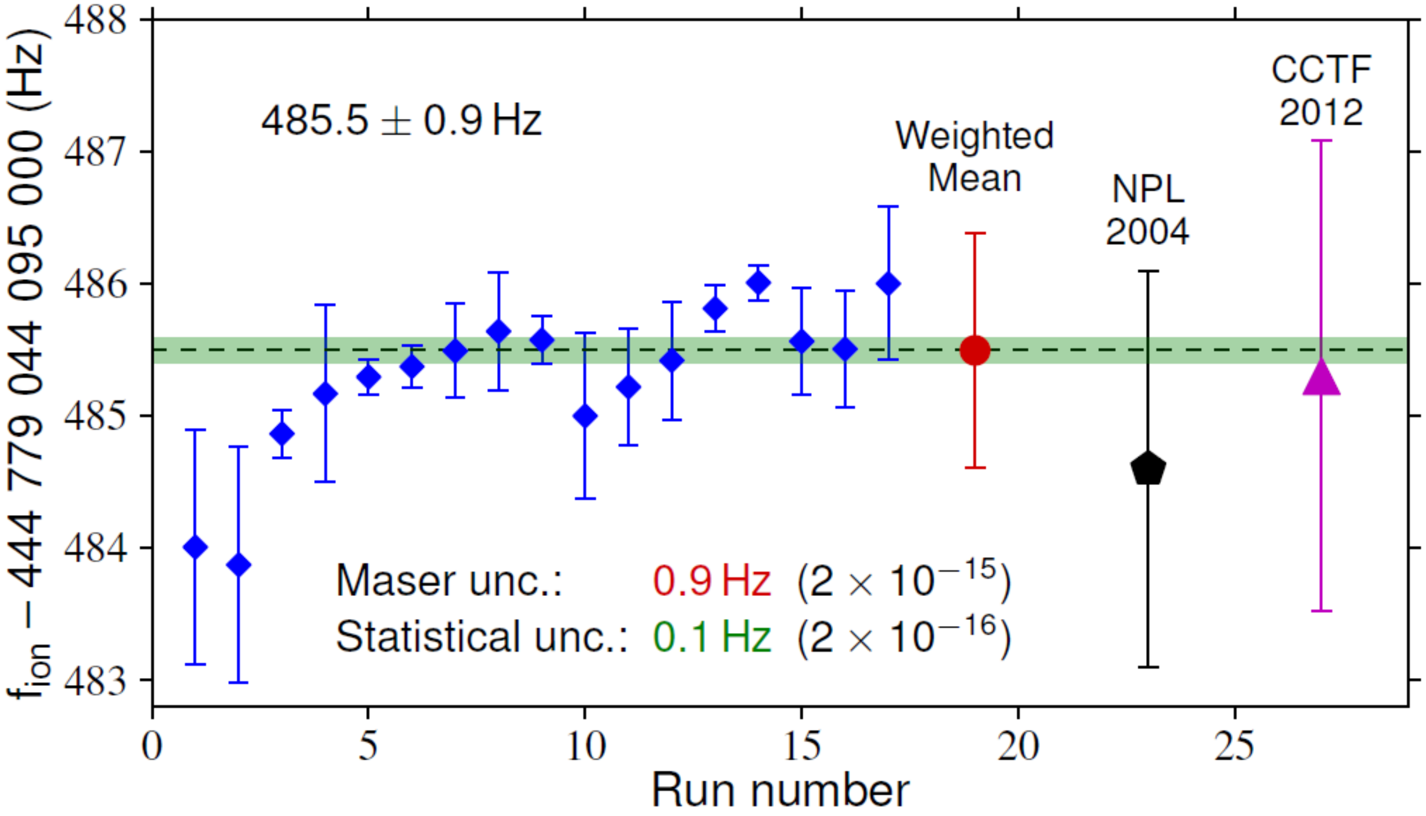
Results of NRC-UBC comb connection to 445-THz



Measurements of the probe frequency showed a drift of the 445-THz radiation at a rate of 10 mHz/s in agreement with previous long term measurements.

The observed stabilities versus the maser match that of the reference NRC H4 maser.

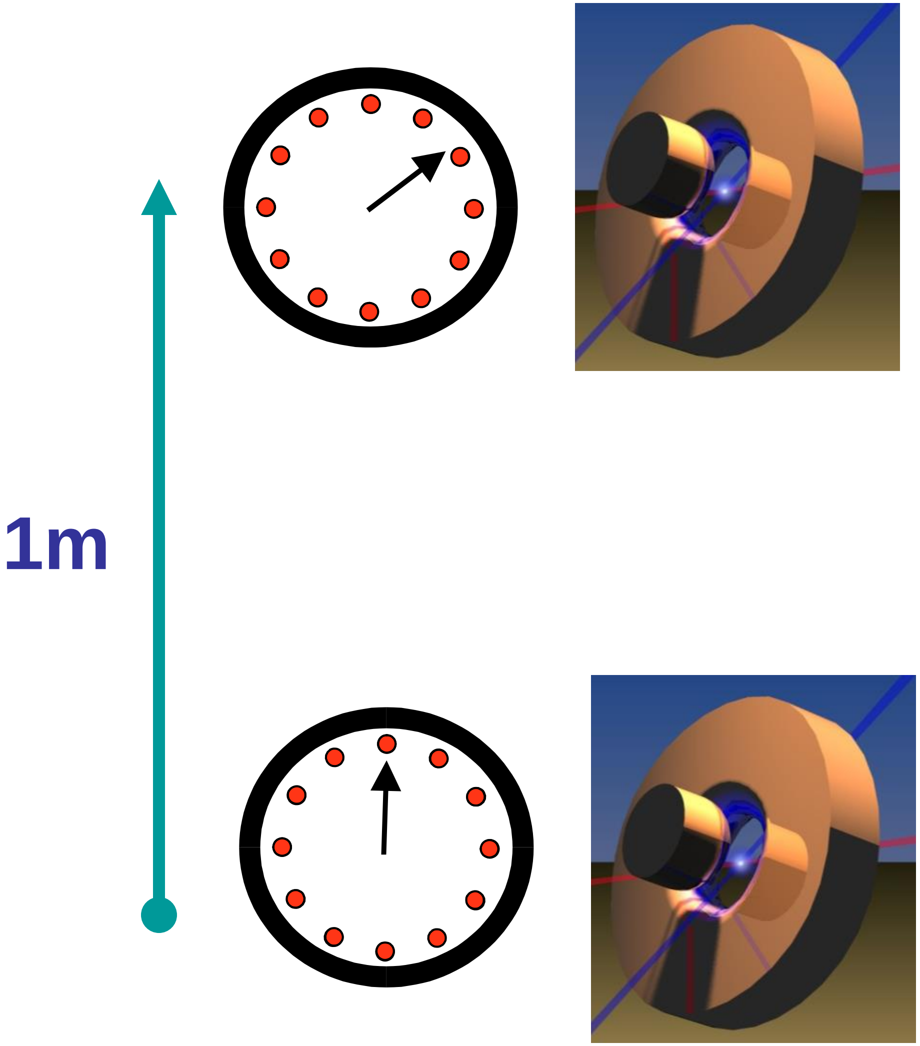
Summary of Recent Absolute Frequency Measurements of Sr^+ Line Centre Relative to SI second



A.A. Madej et al. Phys. Rev. Lett. 109, 203002 (2012)).

- ***Precision Measurements and Relativity***

Sensitive Measurements of General Relativity



- Following the Theory of General Relativity, relative Time as measured by Clocks progress slower in a stronger gravitational potential. The new generation of optical clocks will be able to sense the change in local time change in the Earth's field of 10^{-16} m^{-1}. This will enable sensitive tests of the theory and push the limits of time metrology as "Gravity" becomes a significant player in characterizing the clock's environment.

The End of Time ?(in the Laboratory)

If that wasn't bad enough, effects such as tidal forces, glacial

Geophysical Journal International

Geophys. J. Int. (2012) 191, 78–82 doi: 10.1111/j.1365-246X.2012.05636.x

EXPRESS LETTER

Geophysical applicability of atomic clocks: direct continental geoid mapping

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Use of Sr^+ Ion Clock as a Test Of Gravity and Physics in Space

Image Courtesy of P. Wolf (Observatoire de Paris)

- *A proposal has been made to ESA to use a space borne atom interferometer and optical atomic clock to search for non-Newtonian Gravity, Relativity tests, and search for Kuiper Belt mass distributions, and upper limit searches for Gravitational Waves of low frequency*
- *One proposed system would incorporate a Sr^+ ion trap optical clock and a 674 nm laser as the up down link.*

Conclusions

•Probing of the clock transition at below 5 Hz Level (1×10^{-14}) Stability of Probe drift vs. Ion averages down to 10^{-16} level. Probing of single ion transition performed for period exceeding 33 hrs. Storage Times now exceeding 7 days.

• Continuous Measurements of Probe frequency achieved for periods exceeding 30-hrs at stability of reference H maser. Absolute frequency relative to the SI second at 2×10^{-15} .

•Improvement using the new NRC ion trap system has lead to a greater quantification of the micromotion induced shifts and accuracies at the 2×10^{-17} have been achieved with this system.

- *Interesting Science and Metrology at the limits of Measurement.*

Discussion