Cryogenic Optical Clock with Trapped $^{88}Sr^{+}$

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Introduction

- The best atomic clocks achieve fractional uncertainties below 10^{-18}
- $^{88}Sr^{+}$ is a good candidate due to its narrow clock transition at 674 nm and convenient cooling and repump transitions in the visible spectrum
- Operating at cryogenic temperatures suppresses blackbody radiation and background gas collisions

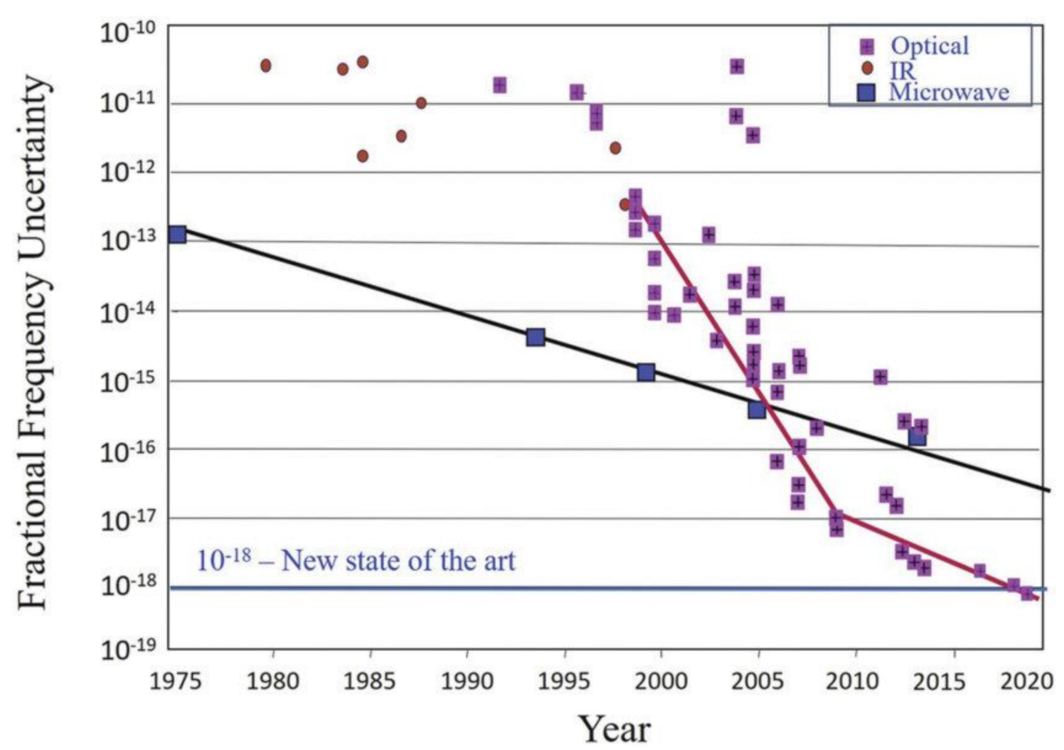


Figure 1: Fractional uncertainties of atomic clocks throughout history

Why Cryogenic Conditions?

Reduce Blackbody Radiation Shift

- An AC Stark shift is induced by the interaction of $^{88}Sr^{+}$ with the electromagnetic radiation from blackbody sources [1]

$$\Delta\nu_{\mathrm{BBR}} = \frac{-1}{2h}\langle E_T^2\rangle \Delta\alpha_0(1+\eta) \approx 0.248\left(\frac{T}{300\ \mathrm{K}}\right)^4\ \mathrm{Hz}$$

- Operating the clock a factor of 100 below room temperature reduces uncertainty by a factor of 10^8

Reduce Collisional Frequency Shift

- Background gas molecules interact with the trapped ion through collisions perturbing the ion's energy levels and causing frequency shifts that scale linearly with pressure
- The cryogenic chamber walls absorb background gas molecules

	Fractional Shift $\Delta\nu/\nu_0$ $[\times 10^{-18}]$	
Source	Room Temperature clock	Estimates for Cryoclock
Collisional	2.6	0.0001
Blackbody Radiation	12	0.00002
Electric Quadrupole	0.03	0.03
Micromotion	0.2	0.2
Thermal Motion	0.8	0.8
Other	0.4	0.4
Total	11.14	0.86

Figure 2: Projected systematic uncertainty contribution at room temperature and under cryogenic conditions [2]

Ionizing Sr and Trapping Sr^{+}

Ablation and Ionization

- Pulsed 532 nm laser ablates a $SrTiO_3$ crystal creating a vapor of neutral strontium

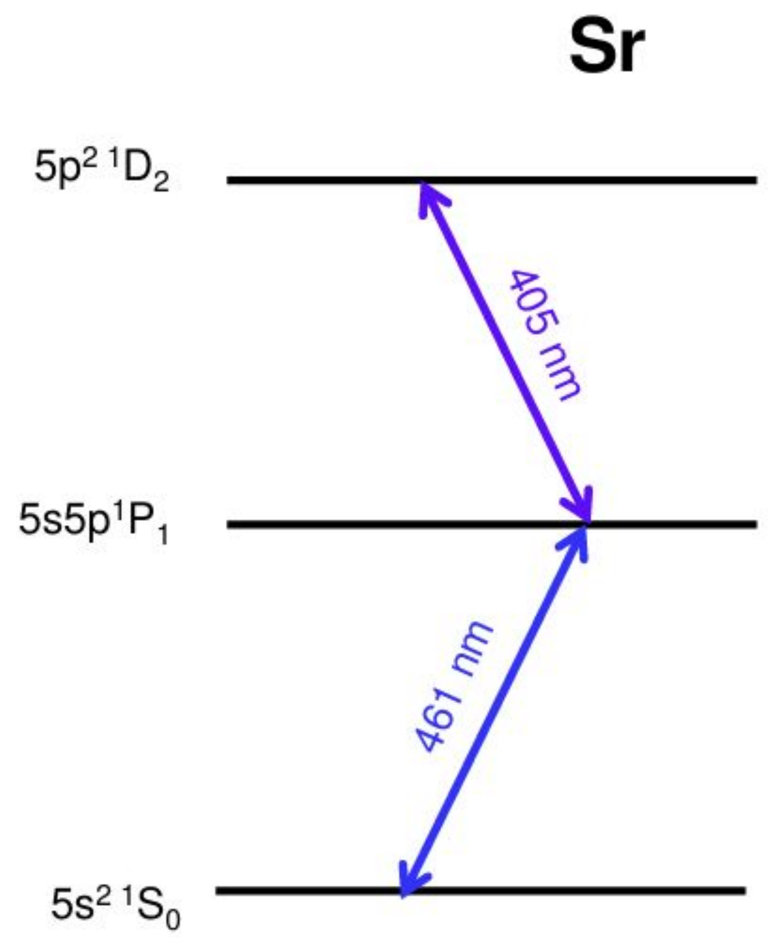


Figure 3: Two step ionization pathway of ^{88}Sr [3]

Operating the Clock

- 422 nm laser cools kinetic motion
- 1092 nm re-pump laser contains $^{88}Sr^{+}$ to S-P cooling branch
- 674 nm laser to address clock transition
- 1033 nm laser to quickly return ion to ground state after exciting to long lived $^2D_{5/2}$ state

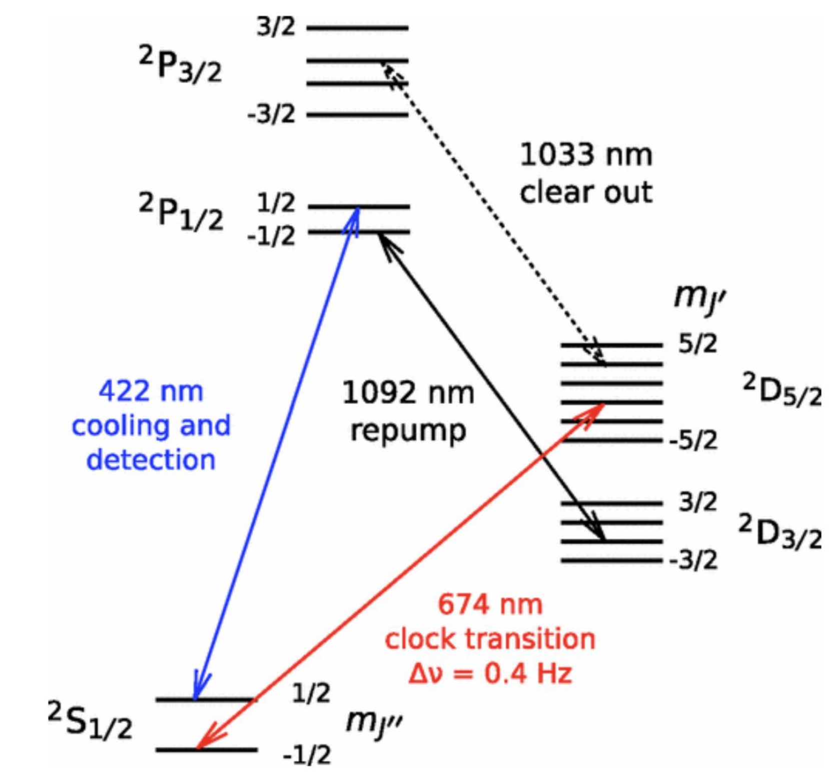


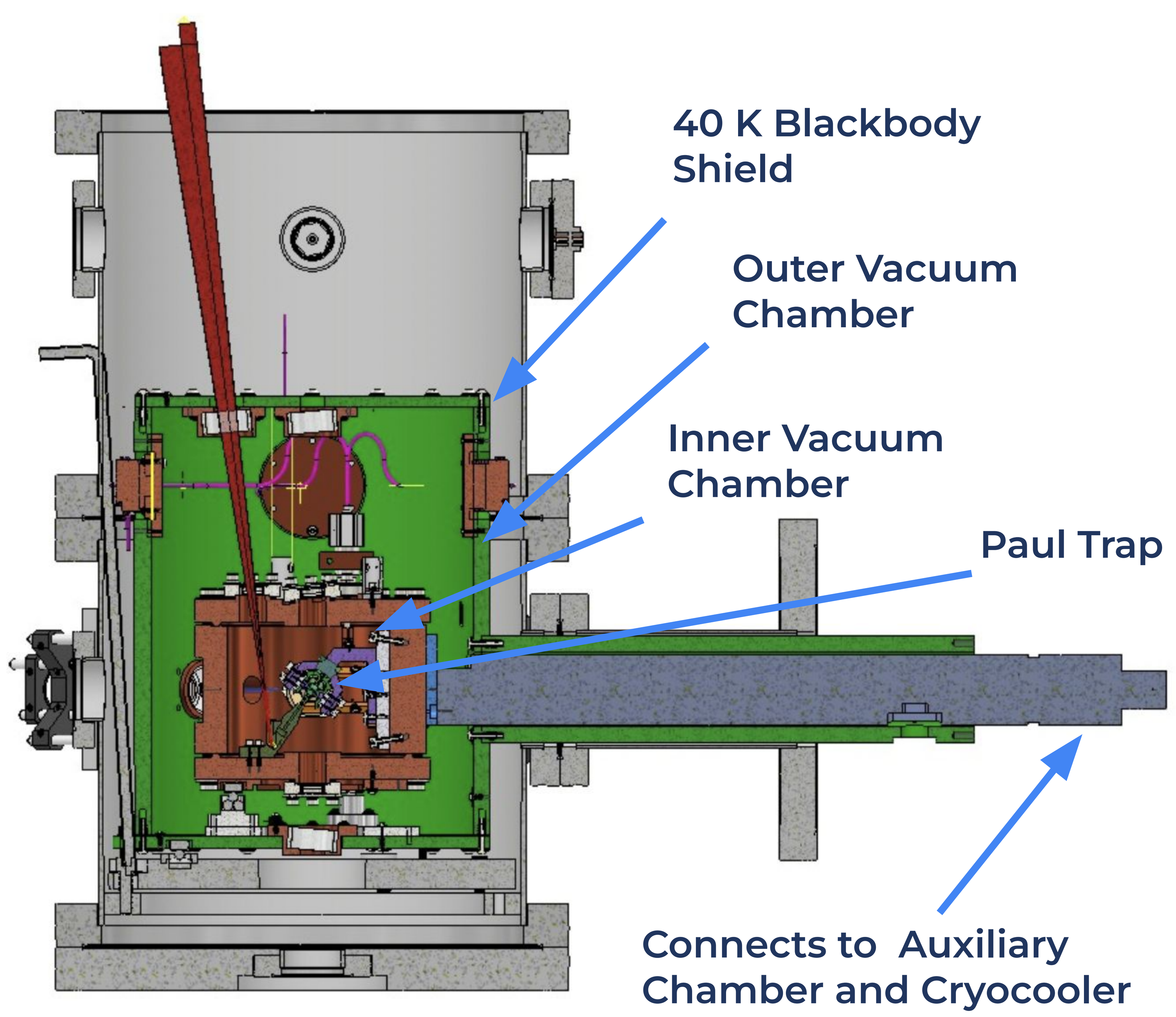
Figure 4: Partial energy level diagram of $^{88}Sr^{+}$ [3]

Trapping

- Trap driven at 14.4 MHz to cancel the electric quadrupole and second order Doppler shifts [4]
- Helmholtz coils for magnetic field control and suppression of magnetic field noise

Figure 5: Camera image of Paul trap, used for ion detection

Design Highlights



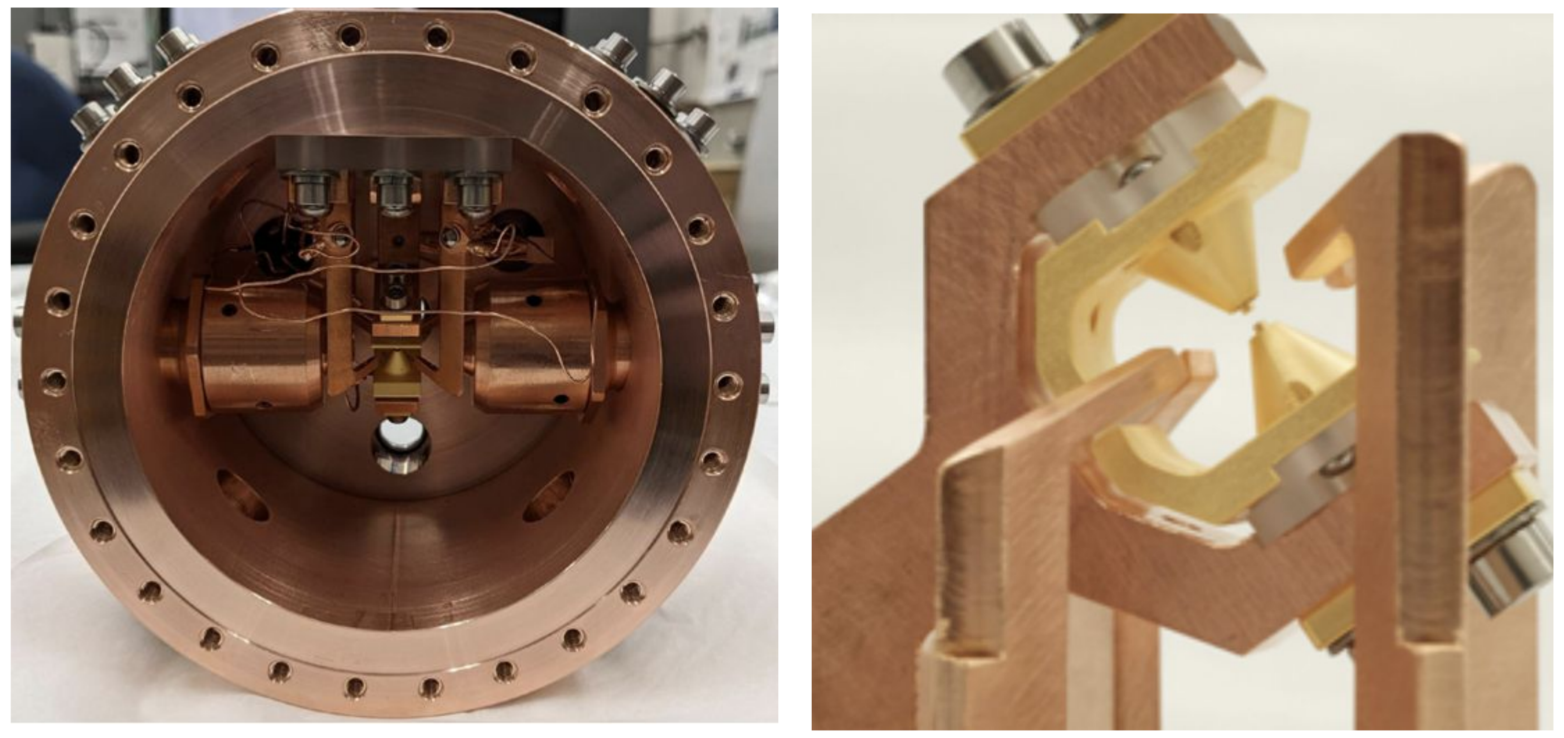


FIgure 6: Interior of the inner vacuum chamber (left) and enlarged view of Paul trap (right)

- 40 K blackbody radiation shield thermally isolates $^{88}Sr^{+}$ from 300 K environment
- Inner vacuum chamber maintains temperatures below 5 K and pressure $<10^{-15}$ Torr

[1] D. Jiang, B. Arora, M. S. Safronova, and C. W. Clark, "Blackbody-radiation shift in a $^{88}Sr^{+}$ ion optical frequency standard," *Journal of Physics B: Atomic, Molecular and Optical Physics*, vol. 42, no. 15, p. 154020, Jul. 2009.
[2] B. Jian, J. Bernard, M. Gertsvolf, and P. Dubé, "Improved absolute frequency measurement of the strontium ion clock using a GPS link to the SI second," *Metrologia*, vol. 60, no. 1, p. 015007, Dec. 2022.
[3] P. Dubé, A. A. Madej, Z. Zhou, and J. E. Bernard, "Evaluation of systematic shifts of the $^{88}Sr^{+}$ single-ion optical frequency standard at the 10^{-17} level," *Physical Review A*, vol. 87, no. 2, Feb. 2013.
[4] P. Dubé, A. A. Madej, M. Tibbo, and J. E. Bernard, "Control of the systematic shifts of the strontium ion optical frequency standard at the 10 mHz level," *Measurement Science and Technology*, vol. 29, no. 8, p. 085011, Aug. 2018.