Towards Mapping Gravity and High-order Derivatives with a Compact Atom Interferometer

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Introduction

Current applications

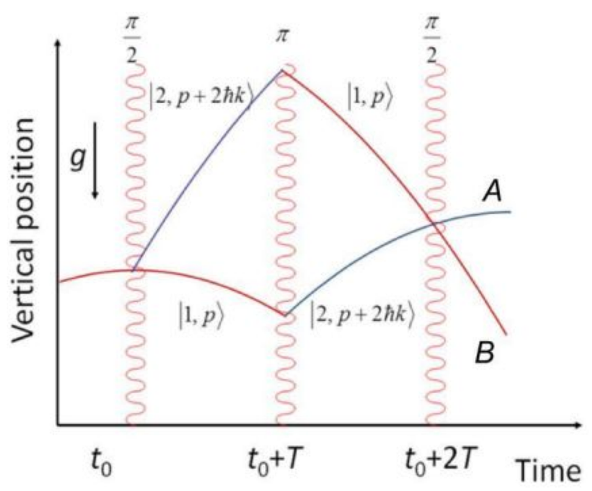
- ★ Inertial navigation
- ★ Hydrological studies
- ★ Hazard monitoring
- ★ Seismology
- ★ Geoid refinement
- ★ Resource exploration
- ★ Dark matter/energy searches

Quantum supremacy

- ★ Simultaneous vertical gravity, gravity gradient, and gravity curvature measurements
- ★ High precision and sensitivity
- ★ Compact and mobile
- ★ Driftless long-term signals

Atom Interferometry

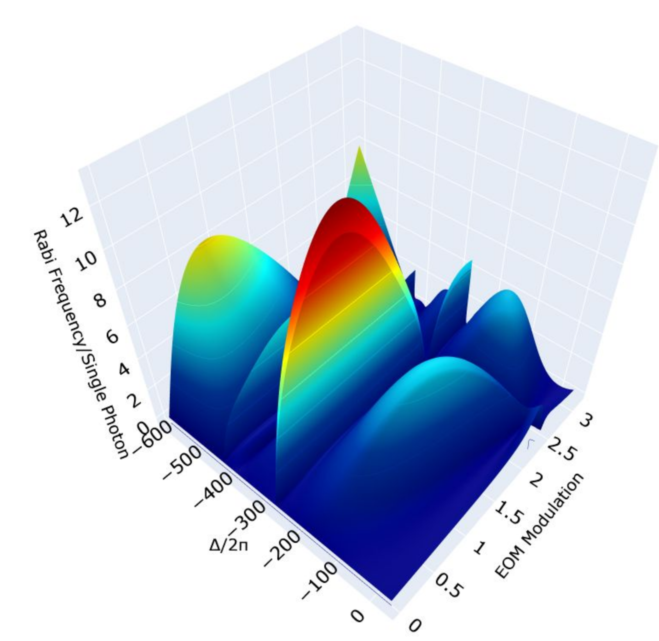
- Cold atoms act like waves; their waves can interfere
- Momentum from laser pulses can transfer to the atoms to split, reflect, and recombine atoms
- The phase difference (ϕ) and atom populations (P) measures gravity.
- Simultaneously occurs at three locations in our vacuum chamber allowing us to measure gravity gradient and curvature

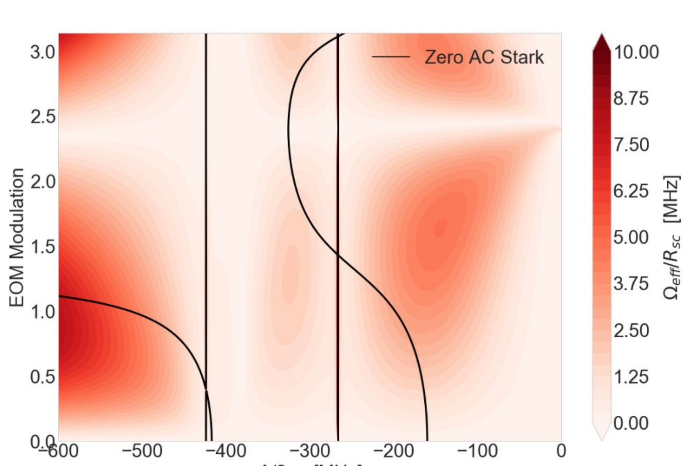


$$P(\phi) = P_0 - \frac{C}{2}\cos(\phi)$$

$$\Delta\phi = k_{\mathrm{eff}} g T^2$$

Raman Transitions





- Stimulated Raman transitions transfer momentum to atoms
- Controlled by the electro-optic modulator (EOM) strength and frequency detuning
- Maximize the Rabi frequency:

$$\Omega_{\mathrm{Rabi}} = \sum_{F'=0}^{3} \sum_{n=-\infty}^{\infty} \frac{M_{1,0}^{F',-} A_n M_{2,0}^{F',+} A_{n+1}}{2\Delta_1}$$

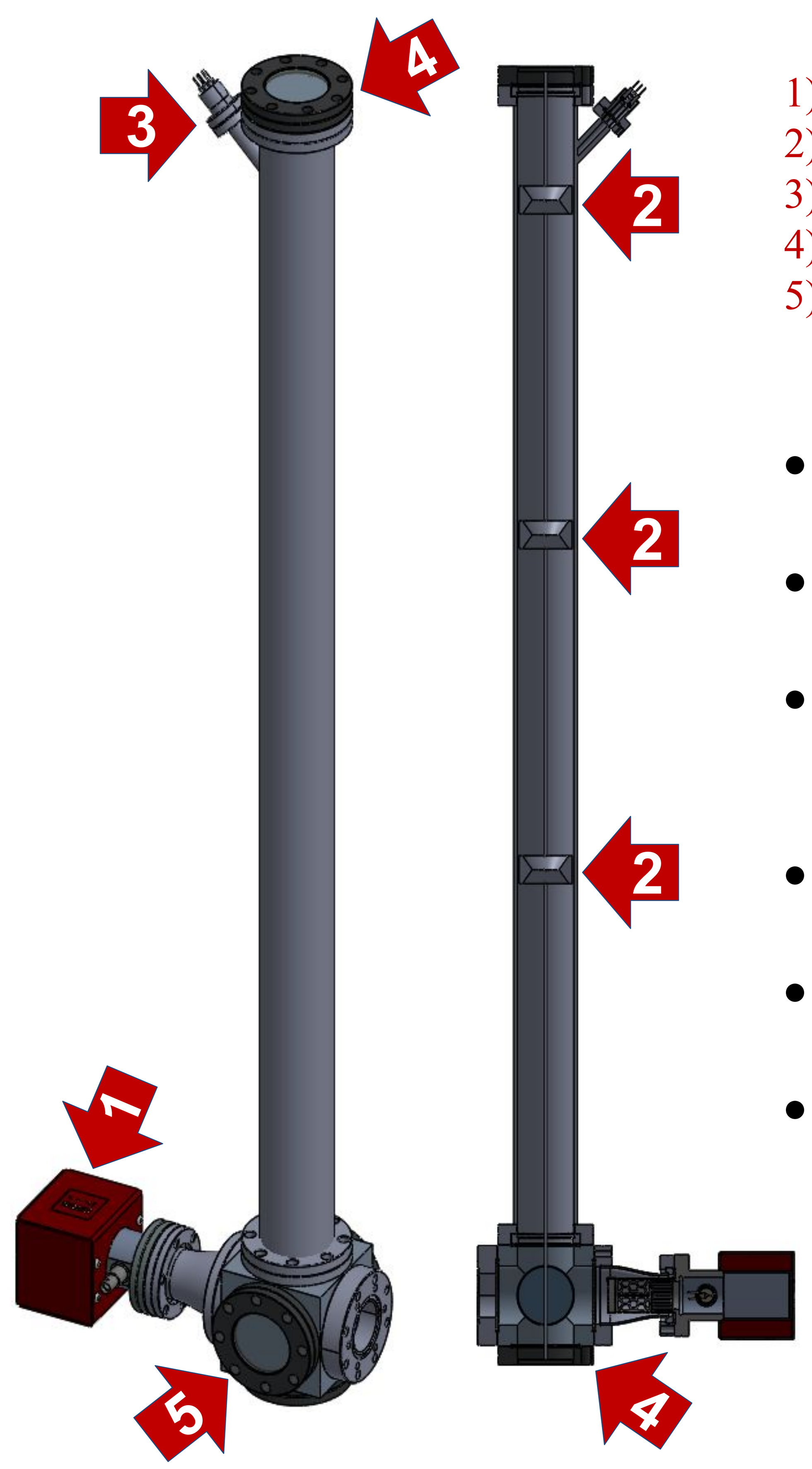
- Minimize the the single photon scattering:

$$R_{sc}^{F} = \sum_{F',n} \frac{\Gamma (M_{F,0}^{F',-} A_n)^2}{\Gamma^2 + 2(M_{F,0}^{F',-} A_n)^2 + 4(\Delta_F)^2}$$

- Zero out the AC Stark shift:

$$\Omega_{AC} = \sum_{F',n} \left(\frac{\left|M_{1,0}^{F',-} A_n\right|^2}{4\Delta_1} - \frac{\left|M_{2,0}^{F',+} A_n\right|^2}{4\Delta_2} \right)$$

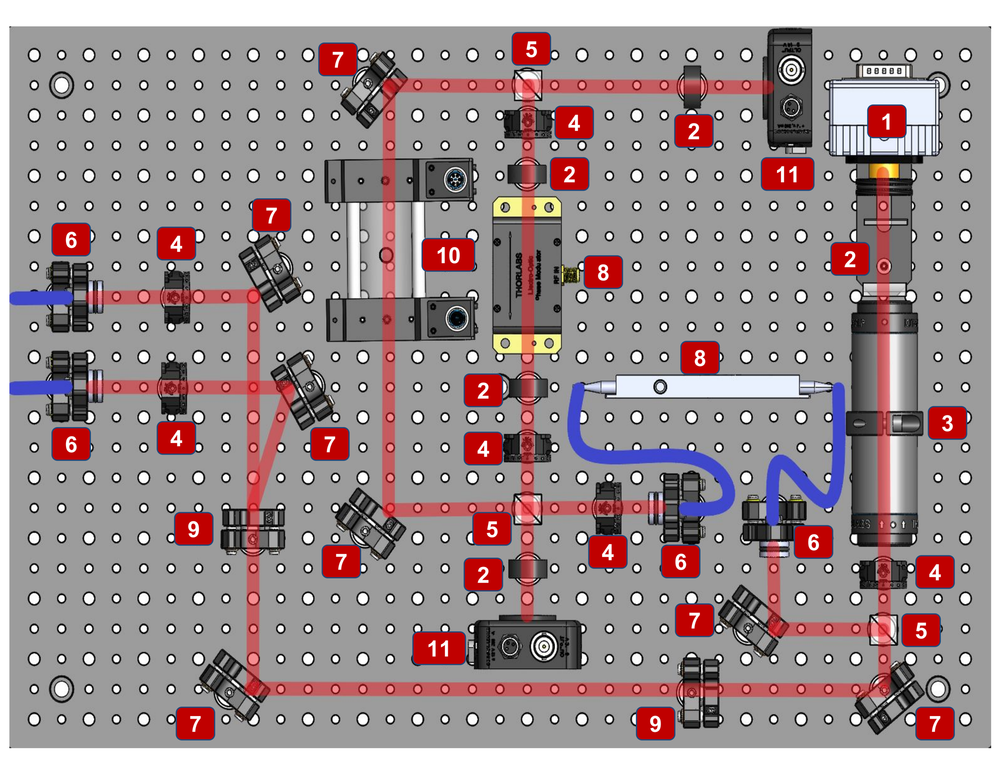
Vacuum Chamber



1) Ion Pump
2) MOT Mirrors
3) Rb Dispenser
4) Laser windows
5) Detection window

- The physics happens in here!
- ~1-meter tall aluminum chamber
- Mirrors separated ~0.3 m relative to each other
- Vacuum pressure of ~10^{-9} torr
- Minimum free-fall time of 120 ms
- Gravity sensitivity of ~300 nm/s^2/√Hz

Laser System



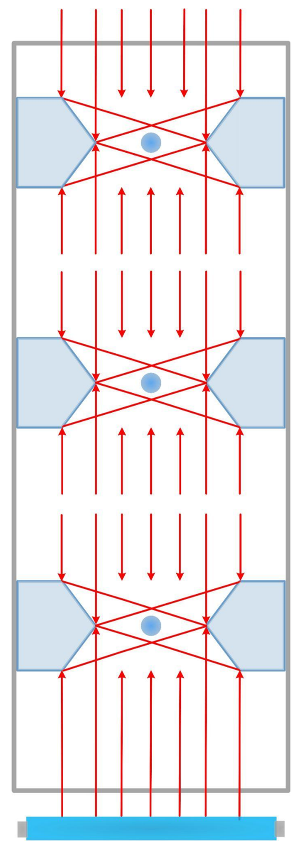
1) Laser Source
2) Lens
3) Isolator
4) Waveplates
5) Beam Splitters
6) Fiber Couplers
7) Mirror
8) EOM
9) AOM
10) Rb Vapor Cell
11) Detector

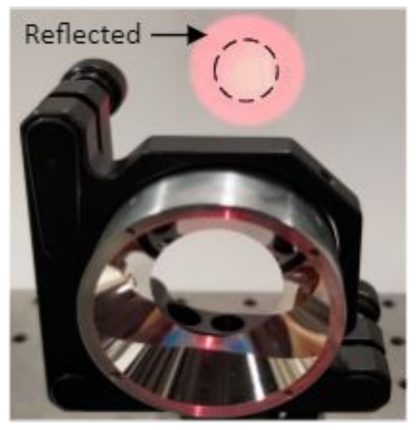
- Compact laser system, 0.5 m x 0.3 m
- Modulation transfer spectroscopy for laser frequency locking
- Generates laser frequencies for: Raman beam, pump beam, MOT beam, and detection beam

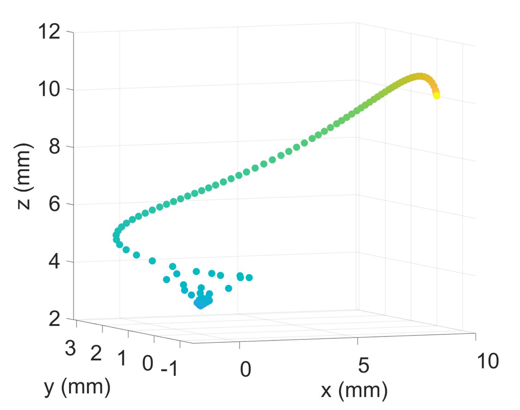
MOT Mirror Design

- Magneto-optical trap (MOT) is used to cool the Rb atoms
- Special mirror angle allows for use of 1 laser beam, instead of the typical 6
- Millions of atoms trapped to ~2 μK
- Maintains laser wavefront passing through the mirror to form 3 MOTs
- Atom trajectories subjected to the laser field are simulated using Runge-Kutta method to time evolve the atom's equations of motion:

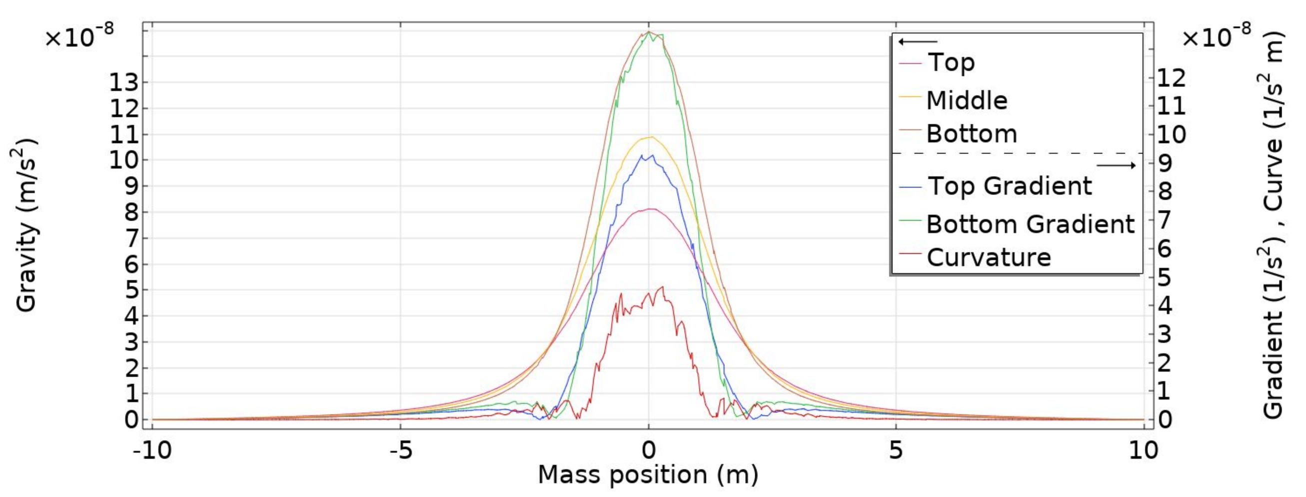
$$\mathrm{m}\ddot{\vec{x}} = \frac{\hbar \vec{k}_{+} s_0 \gamma/2}{1+s_0+(2\delta_{+}/\gamma)^2} + \frac{\hbar \vec{k}_{-} s_0 \gamma/2}{1+s_0+(2\delta_{-}/\gamma)^2}$$







Gravity Simulation



- Gravity of each drop, gradient between drops, and curvature is simulated by solving the Poisson equation:

$$\nabla^2 U = 4\pi G \rho \qquad g = -\nabla U$$

- Simulates a signal for a 2 m x 2 m x 1 m rectangular block of water 1 m underground
- Curvature has the advantage of localizing the mass's position
- Curvature has stronger sensitivity to near-surface signals

References

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