Atom Interferometry Experiments for Precision Measurement of Fundamental Physics

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Contents

- Principle of Light-Pulse Atom Interferometer
- Fine Structure Constant
- Large Momentum Transfer
- Systematic Effects
- Matter Wave Source- Cold Atomic Fountain
- Outlook

Optical Interferometry

19th Century : Young's Experiment

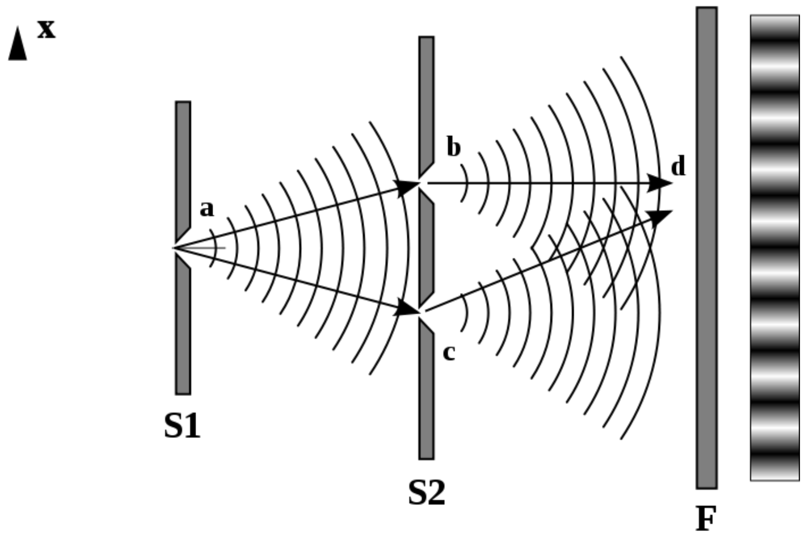
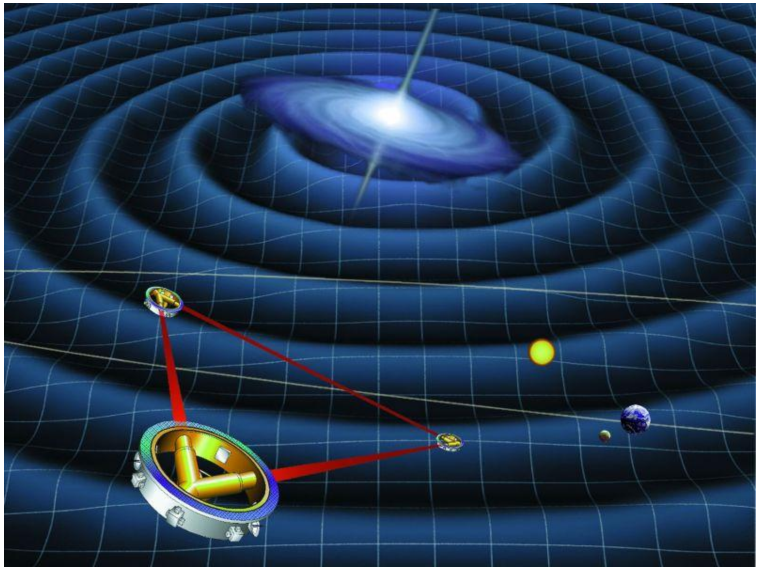


Image from Wikipedia

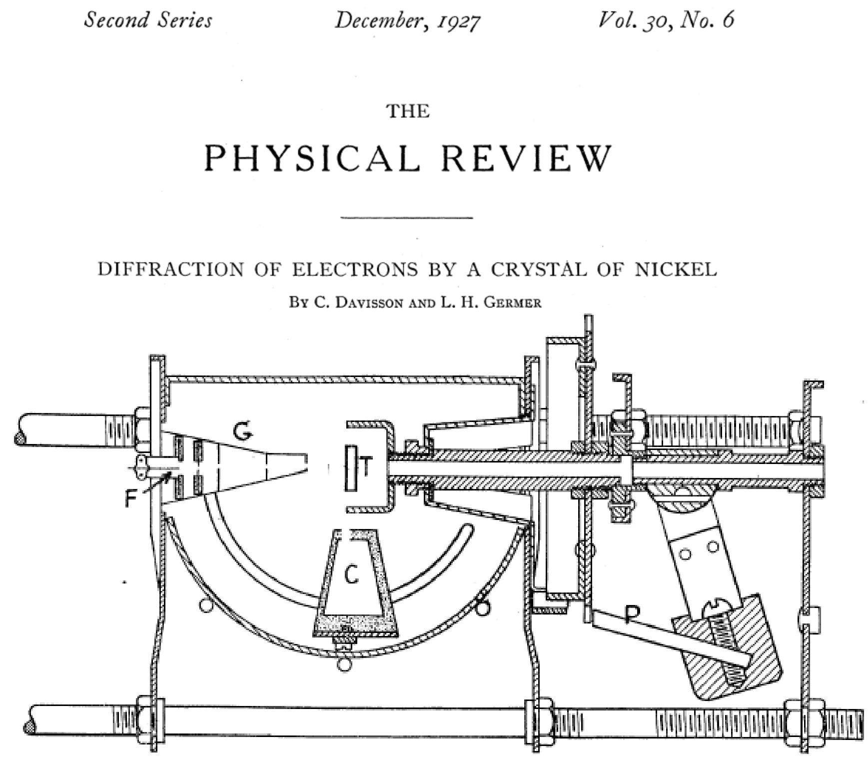
21st Century : Large Interferometry Space Antenna (LISA)



Matter Wave

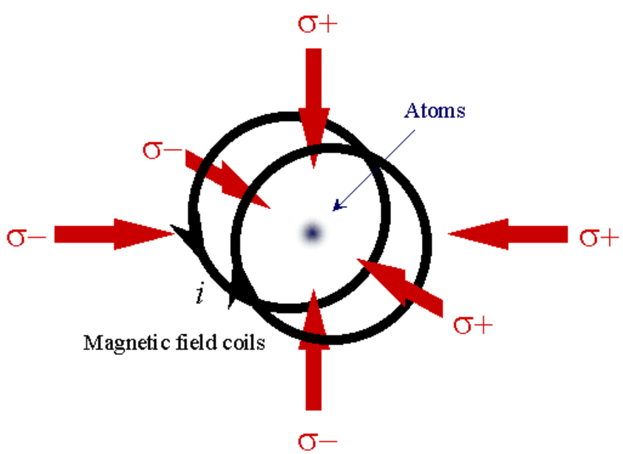
Louis de Broglie
1924

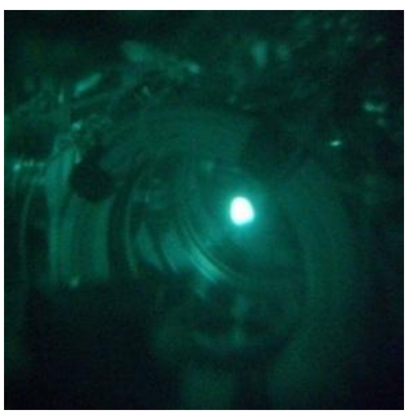
$$\lambda = \frac{h}{mv}$$

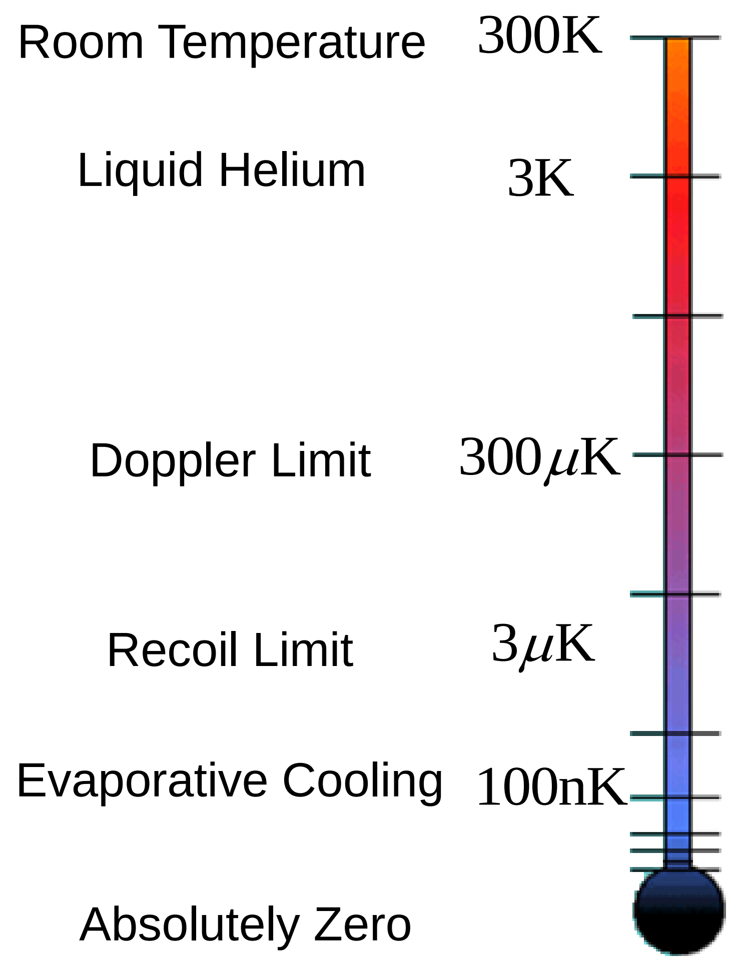


C. Davisson and L. H. Germer
1927

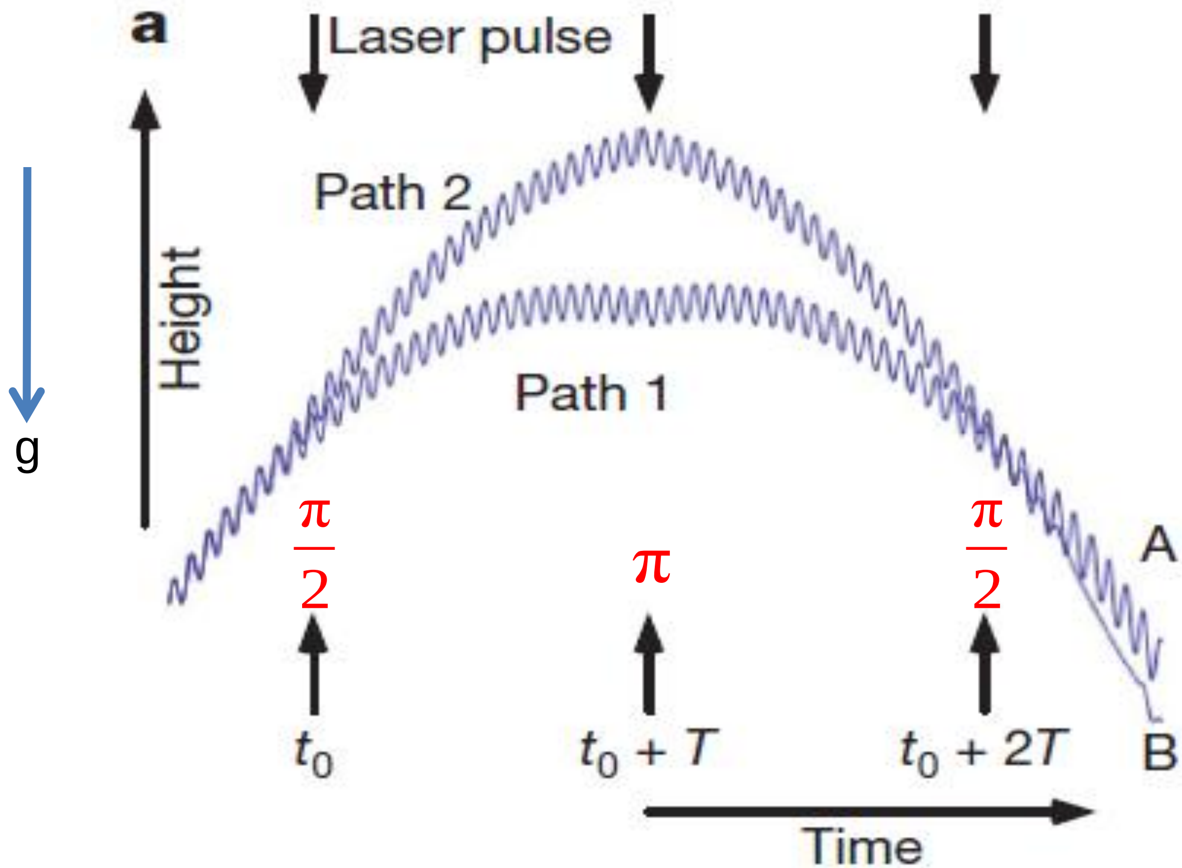
Laser cooling and trapping







Light-Pulse Atom Interferometer



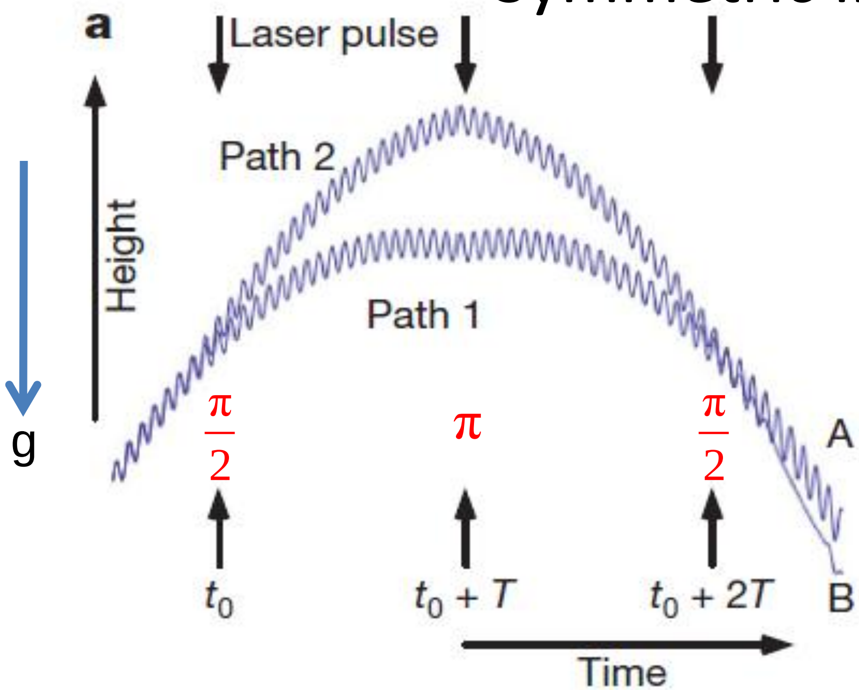
$$\Delta\Phi = \Delta\Phi_{free} + \Delta\Phi_{laser} \qquad \Delta\Phi_{free} = \frac{1}{\hbar}\int_{classical} L(\dot{z}(t), z(t))dt \qquad L = \frac{m\dot{z}^2}{2} - V(z)$$

Interferometer in time domain

Light-Pulse Atom Interferometer

Mach Zehnder interferometer

Symmetric interferometer



$$\Delta\Phi_{MZ} = \Delta\Phi_{free} + \Delta\Phi_{laser}$$

$$\Delta\Phi_{free} = 0$$

$$\Delta\Phi_{MZ} = \Delta\Phi_{laser} = n(kgT^2 - \phi_L)$$

$$\phi_L = \phi(t_0) - 2\phi(t_0 + T) + \phi(t_0 + 2T)$$

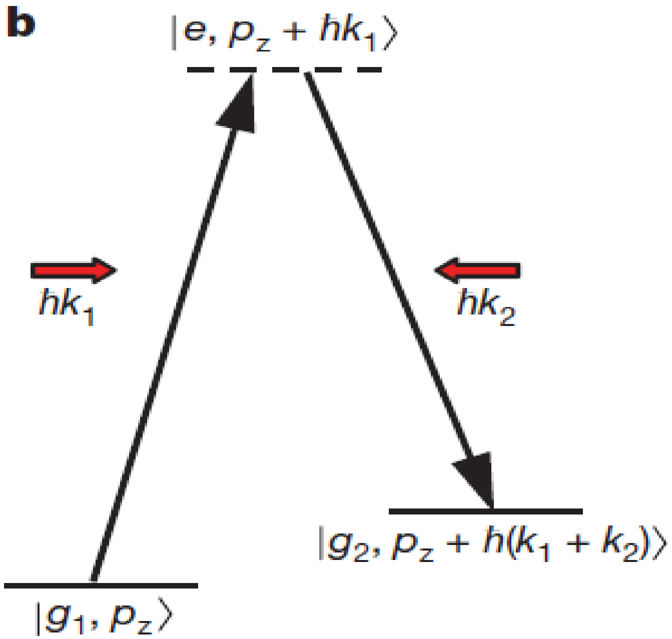
k is the wavenumber and n is the number of photons.

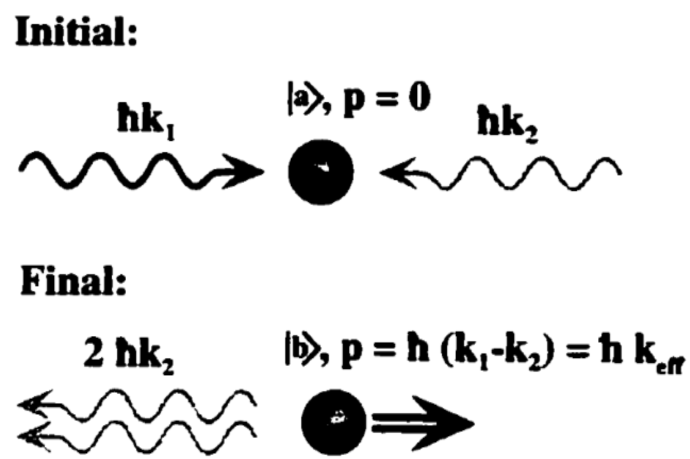
The sensitivity scales with the interferometer enclosed area

de Broglie Wave Beam Splitter

Off Resonant Two Photon Transition

Coherent Control of Atomic State





Effective Two Photon Rabi Frequency

$$\Omega_{eff} = \frac{\Omega_{g_1 e}\Omega_{g_2 e}}{\Delta_{g_1 g_2}}$$

Measurements Using Light-Pulse AI

Gravity g : 3×10^{-9}g   A. Peters *et al.* Nature **400**, 849–852 (1999).

Gravity gradient : $4\times10^{-9}\,\mathrm{g}/\sqrt{\mathrm{Hz}}$ J. B. Fixler et al, Science **315**, 74 (2007).

α : 4.6 ppb   M. Cadoret et al., Phys. Rev. Lett. 101, 230801 (2008).

Newton's constant G : 4 ppt   J. B. Fixler et al, Science **315**, 74 (2007).

UFF : 1.2×10^{-7} S. Fray, and M. Weitz - Space Science Reviews, 2009 – Springer

Gravitational redshift : 7×10^{-9} H. Mueller *et al.* Nature **463,** 926 (2010)

Sagnac effect : $6\times10^{-10}\,\mathrm{rad/sec}/\sqrt{\mathrm{Hz}}$ T. L. Gustavson *et al.* Class. Quantum Grav. **17 (2000) 2385–2398**

Fine Structure Constant

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} = \frac{1}{137.035999679(94)}$$ 2006 CODATA

Current Status of α

Electron's magnetic moment anomaly g-2 : 0.37 ppb

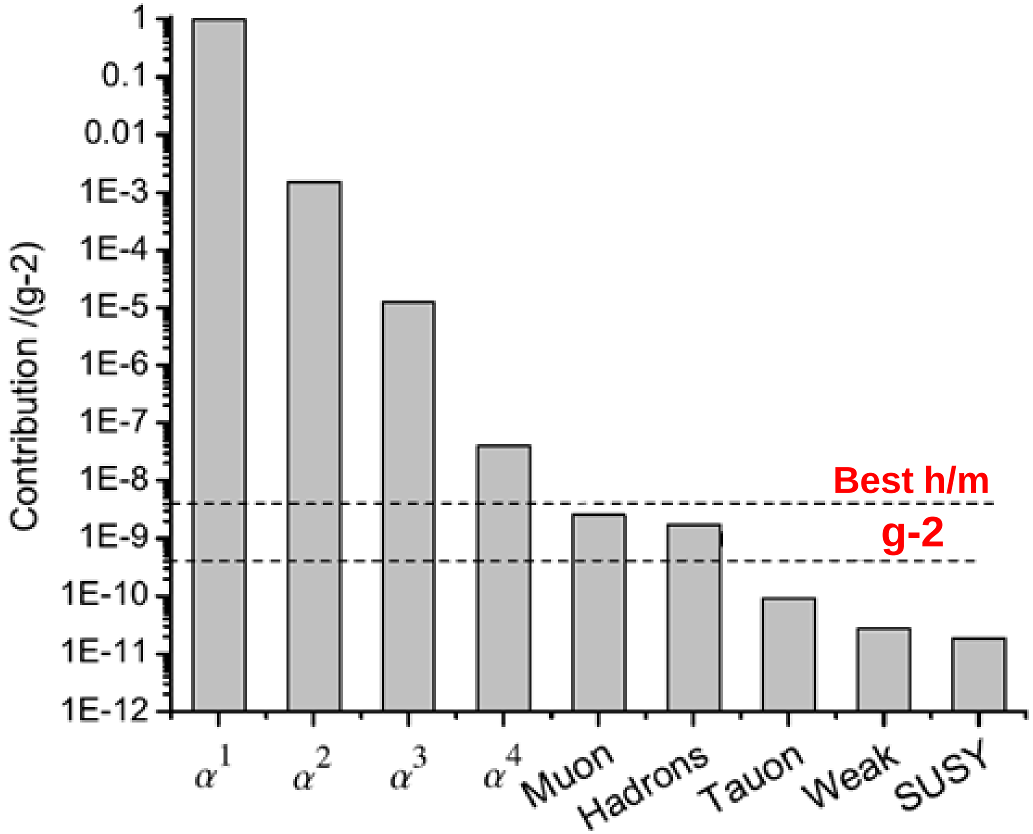
D. Hanneke *et al.* PRL **100**, 120801 (2008)

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots + a_{\mu,\tau} + a_{\text{hadronic}} + a_{\text{weak}}$$

Photon Recoil Measurement (Rb) : 4.6 ppb M. Cadoret *et al*. PRL **101**, 230801 (2008)

Photon Recoil Measurement(Cs) : 7.4 ppb A. Wicht *et al.*, Phys. Scr. T **102**, 82 (2002).

Contributions to g-2



Alpha in Atom Recoil Frequency

$$\alpha = \left[\frac{2R_\infty}{c} \frac{u}{m_e} \frac{M}{u} \frac{h}{M} \right]^{1/2}$$

Rydberg Constant
0.007 ppb P. J. Mohr *et al.*, Rev. Mod. Phys. **80**, 633 (2008).

Cs mass in u
0.43ppb M. P. Bradley *et al.*, Phys. Rev. Lett. **83**, 4510 (1999).

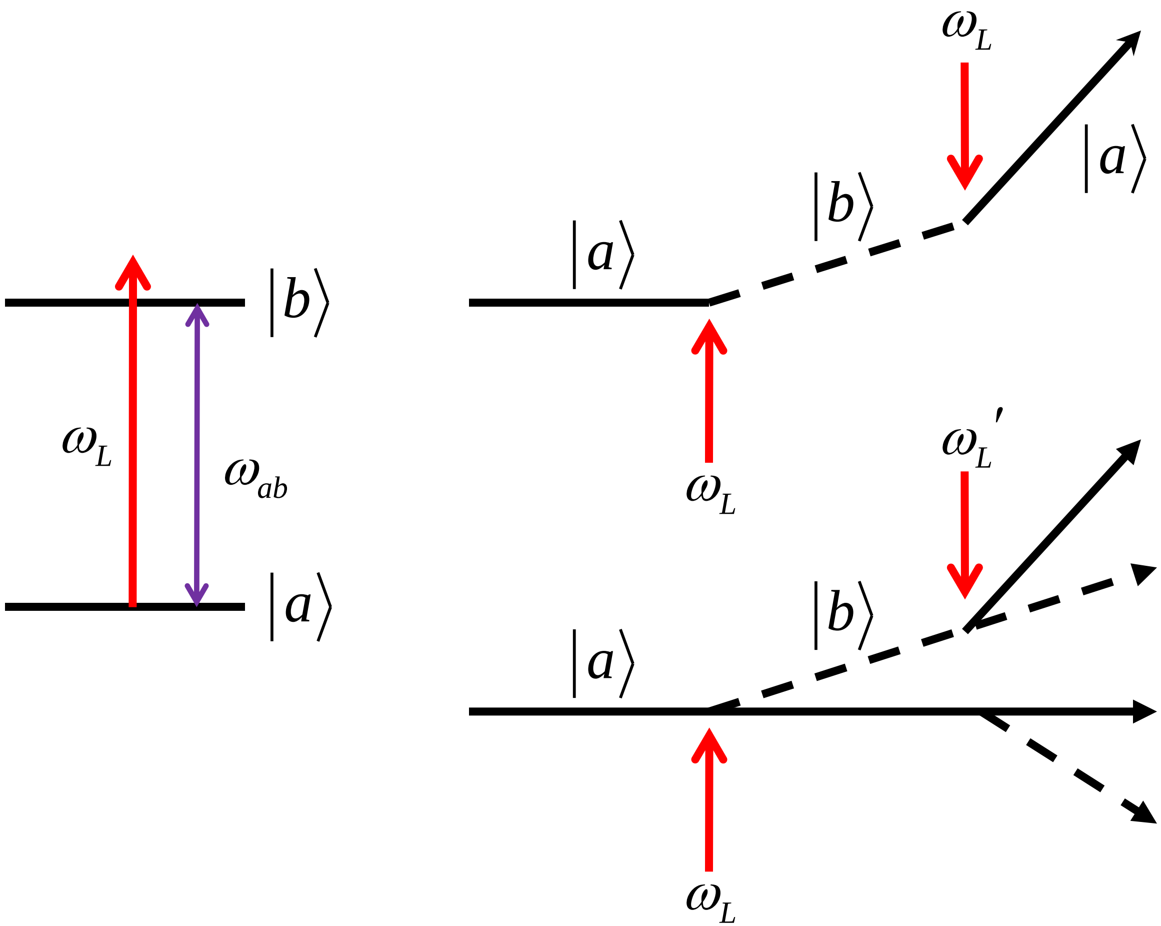
Electron mass in atomic mass units u
0.18 ppb P. J. Mohr *et al.*, Rev. Mod. Phys. **80**, 633 (2008).

Determined by the atom recoil frequency

$$\frac{h}{M} = \frac{4\pi c^2 \omega_r}{\omega^2}$$

Lowest : 0.23ppb

Photon Recoil Measurement

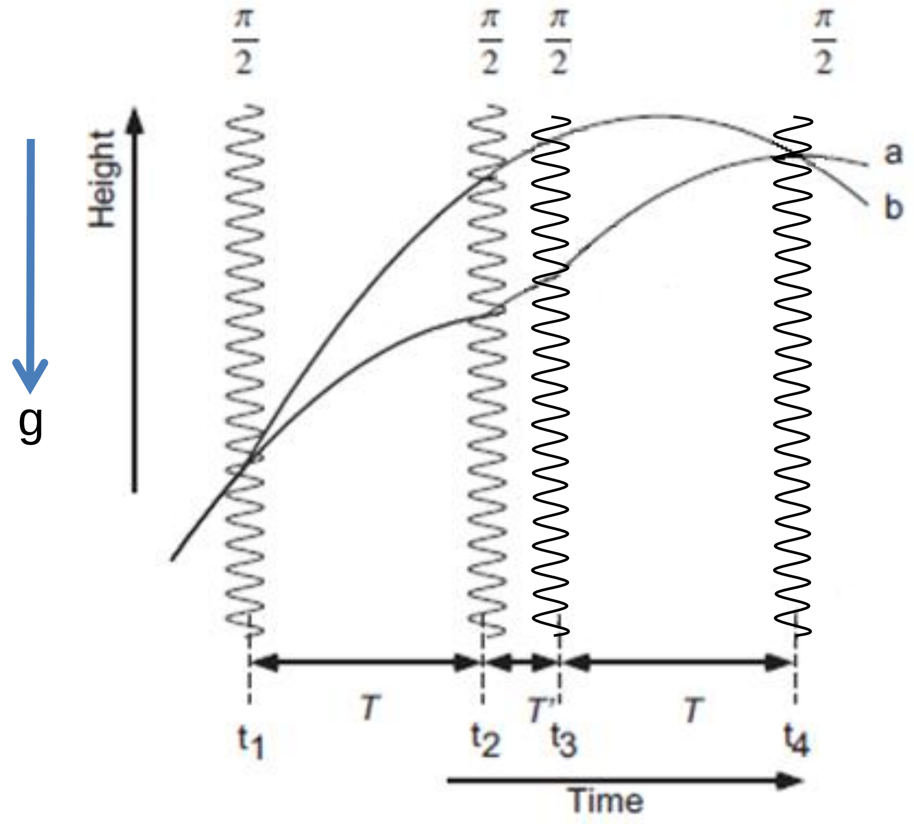


$$\omega_L - \omega_{ab} = \vec{v}_i \cdot \vec{k} \pm \frac{1}{2}\omega_{rec}$$

$$\omega_L'(|a\rangle) - \omega_L'(|b\rangle) = 2\omega_{rec}$$

For Cs D1 recoil frequency $\omega_{rec} = 2\mathrm{kHz}$, accuracy in part per billion need to pinpoint the resonance to $\mu\mathrm{Hz}$ range !!!

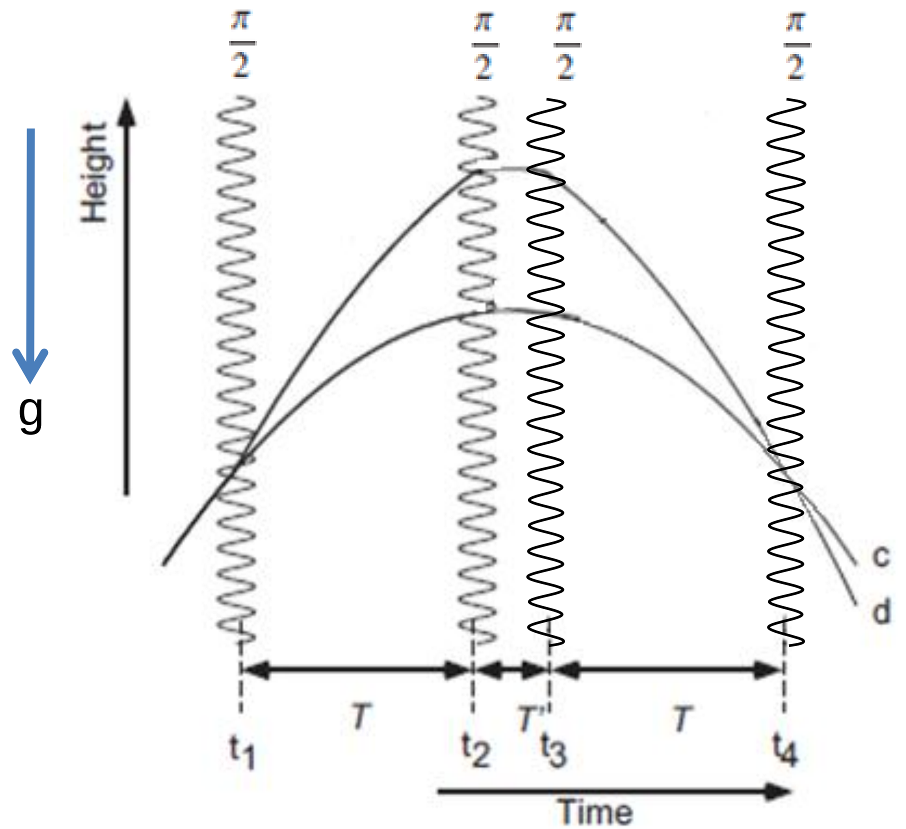
Ramsey Borde Interferometer



$$\Delta\Phi^{+}_{RB} = 8n^2\omega_r \mathrm{T} + 2nkg(\mathrm{T}+\mathrm{T}')\mathrm{T} + n\Phi^{+}_{\text{beamsplitter}}$$

$$\Phi^{+}_{\text{beamsplitter}} = (\Phi_2 - \Phi_1) - (\Phi^{+}_4 - \Phi^{+}_3)$$

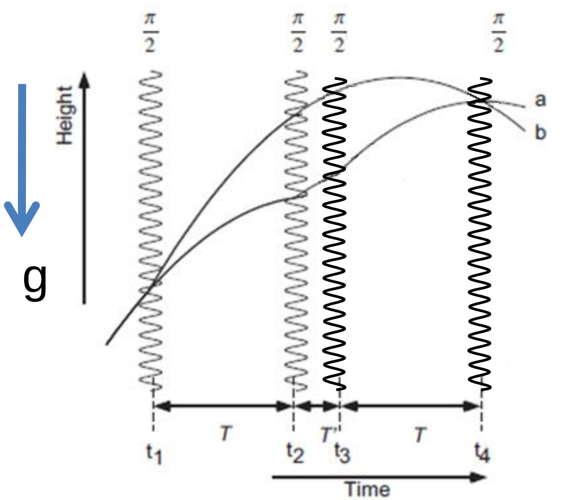
Ramsey Borde Interferometer



$$\Delta\Phi^{-}_{RB} = -8n^2\omega_r \mathrm{T} + 2nkg(\mathrm{T}+\mathrm{T}')\mathrm{T} + n\Phi^{-}_{\text{beamsplitter}}$$

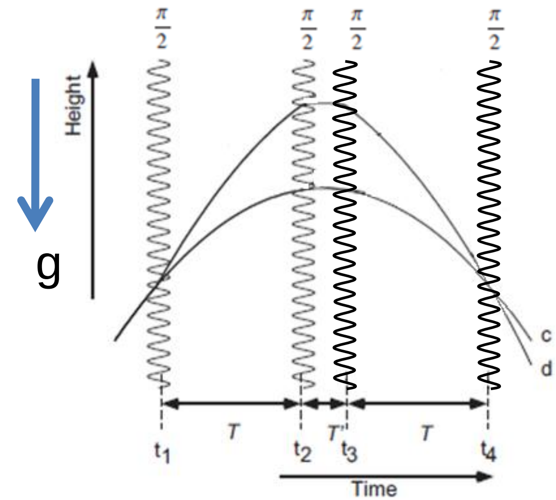
$$\Phi^{-}_{\text{beamsplitter}} = (\Phi_2 - \Phi_1) - (\Phi^{-}_4 - \Phi^{-}_3)$$

Conjugate Interferometer



$$\Delta\Phi^{+}_{RB} = 8n^2\omega_r \mathrm{T} + 2nkg(\mathrm{T}+\mathrm{T}')\mathrm{T} + n\Phi^{+}_{\text{beamsplitter}}$$

$$\Phi^{+}_{\text{beamsplitter}} = \Phi_2 - \Phi_1 - \Phi^{+}_4 + \Phi^{+}_3$$



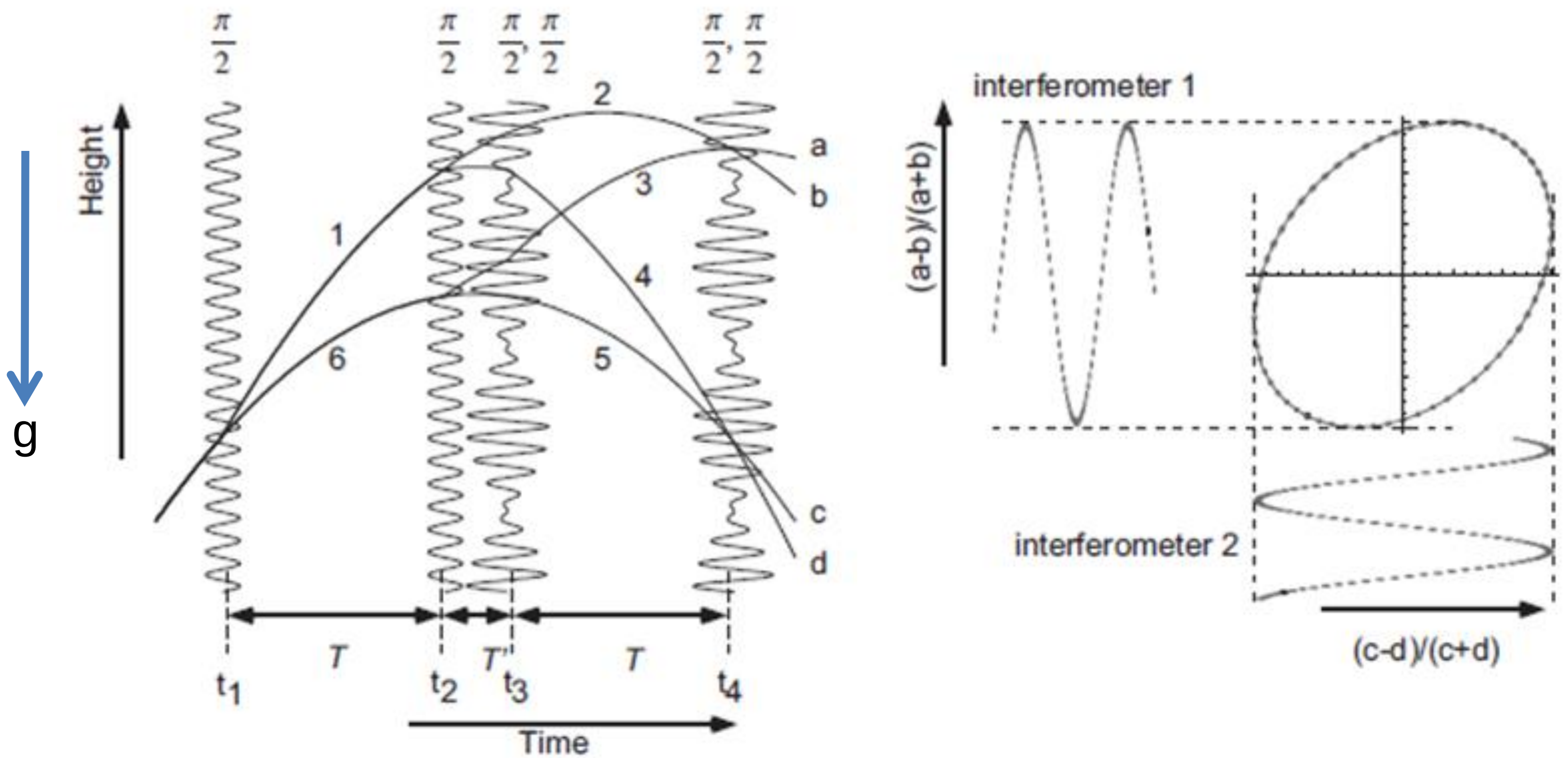
$$\Delta\Phi^{-}_{RB} = -8n^2\omega_r \mathrm{T} + 2nkg(\mathrm{T}+\mathrm{T}')\mathrm{T} + n\Phi^{-}_{\text{beamsplitter}}$$

$$\Phi^{-}_{\text{beamsplitter}} = \Phi_2 - \Phi_1 - \Phi^{-}_4 + \Phi^{-}_3$$

$$\Delta\Phi = \Delta\Phi^{+} - \Delta\Phi^{-} = 16n^2\omega_r \mathrm{T} + n\Phi_{beamsplitter}$$

$$\Phi_{\text{beamsplitter}} = (\Phi^{+}_3 - \Phi^{-}_3) + (\Phi^{-}_4 - \Phi^{+}_4)$$

Simultaneous Conjugate Interferometer



$$\Delta\Phi = \Delta\Phi^{+} - \Delta\Phi^{-} = 16n^2\omega_r \mathrm{T} + n\Phi_{beamsplitter}$$

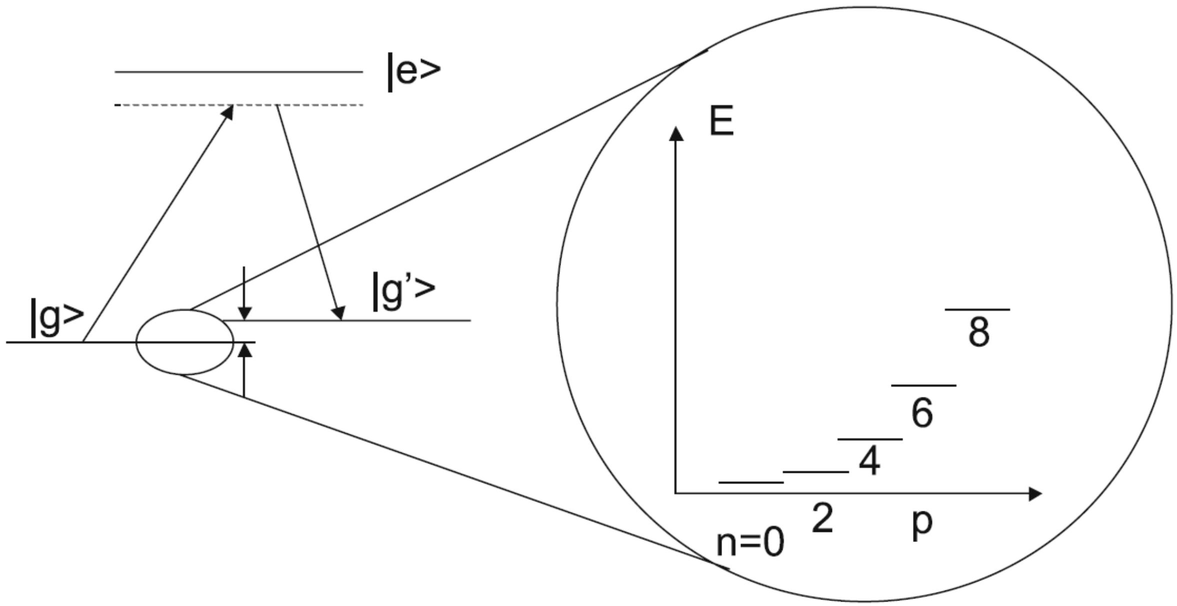
$$\Phi_{\mathrm{beamsplitter}} = (\Phi_3^{+} - \Phi_3^{-}) + (\Phi_4^{-} - \Phi_4^{+})$$

Common Mode Rejection

S.-w. Chiow *et al. Phys. Rev. Lett.* **103,** 050402 (2009)

Large Momentum Transfer

Multi-photon Bragg Diffraction



- $\left|g, p = p_0\right\rangle \rightarrow \left|g, p = n\hbar k_{eff}\right\rangle$

$\Rightarrow$ external field insensitive

- Energy Conservation: $4n^2\hbar\omega_r = n\hbar(\omega_1 - \omega_2)$

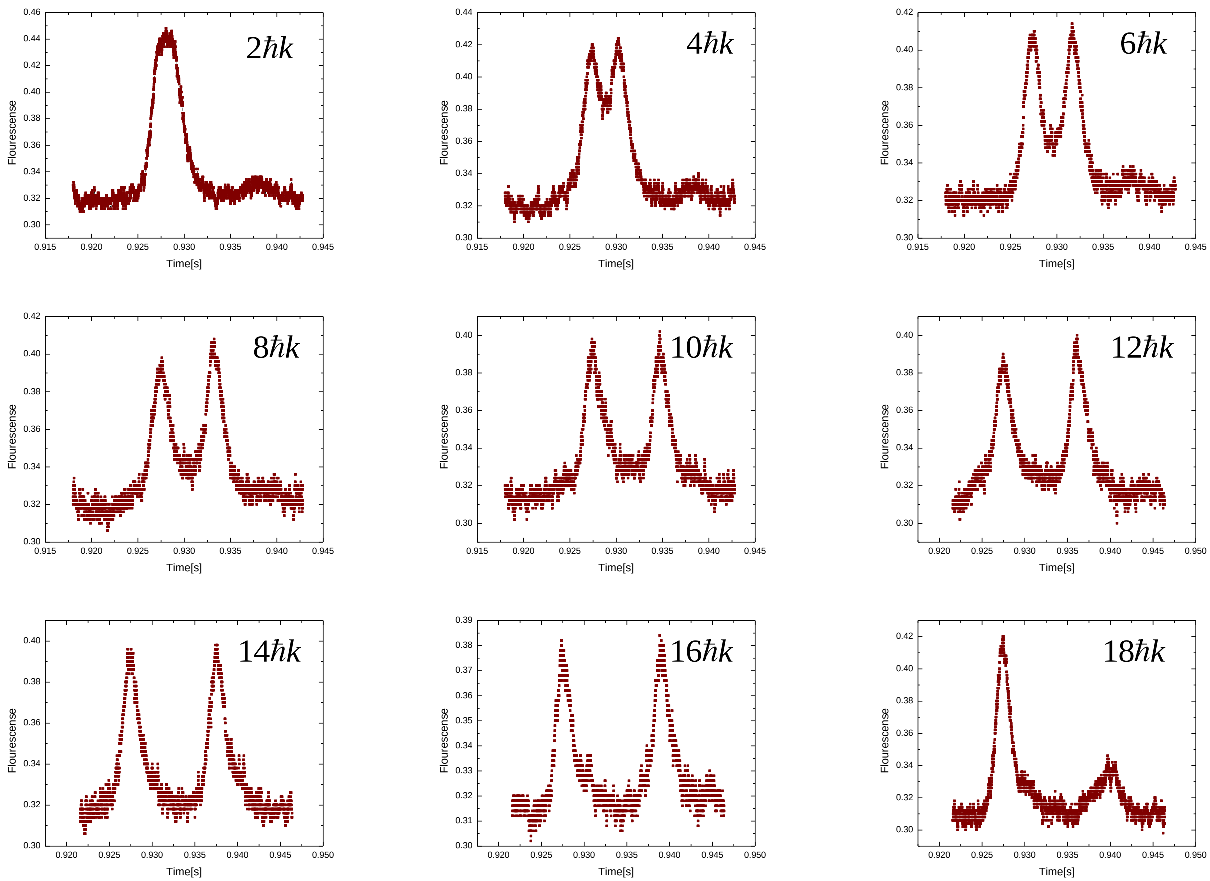
Effective Rabi Frequency

$$\Omega_n \simeq \frac{\Omega_{eff}^n}{8^{n-1}(n-1)!^2\,\omega_r^{n-1}}$$

$$\Omega_{eff} = \frac{\Omega_1\Omega_2}{2\Delta}$$

H. Mueller *et al. Phys. Rev. Lett.* **100,** 180405 (2008)

Multi-Photon Bragg Diffraction Beam Splitter

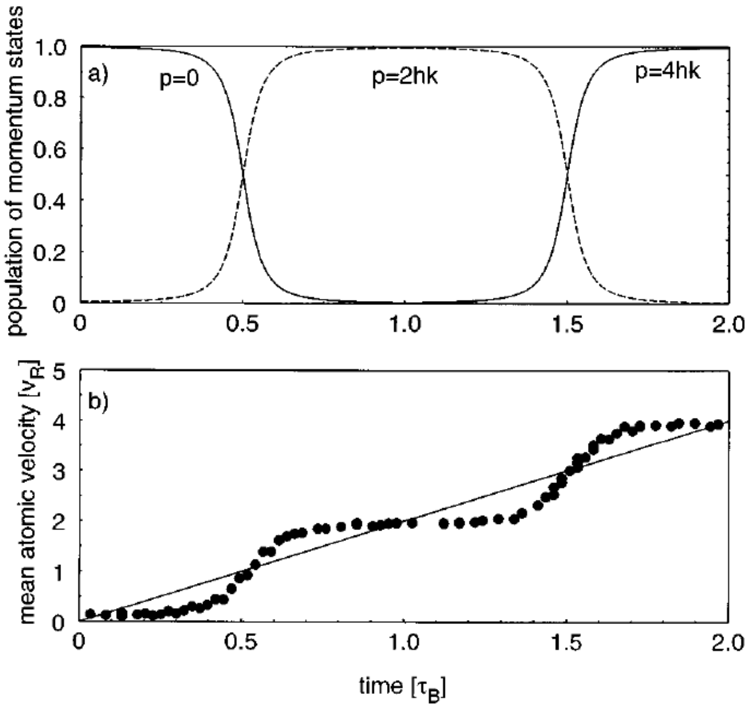


Required power for Cs $|3,0\rangle$: $I \simeq 5n^2\ \mathrm{mW/cm^2}$ with 5GHz detuning

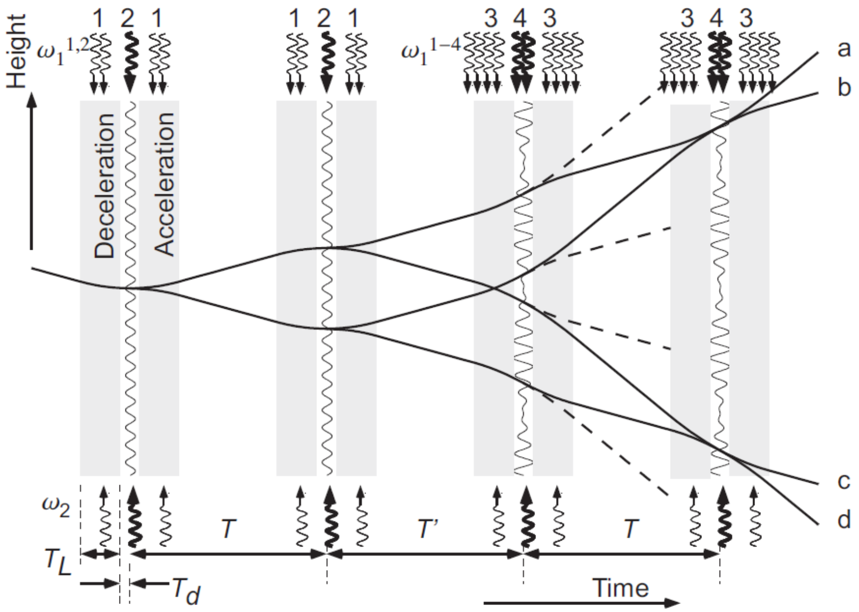
5GHz one photon detuning, 1.5cm diameter beam

Bloch Oscillation

Matter Wave Accelerator



E. Peik *et al*., Phys. Rev. A **55**, 2989 (1997).



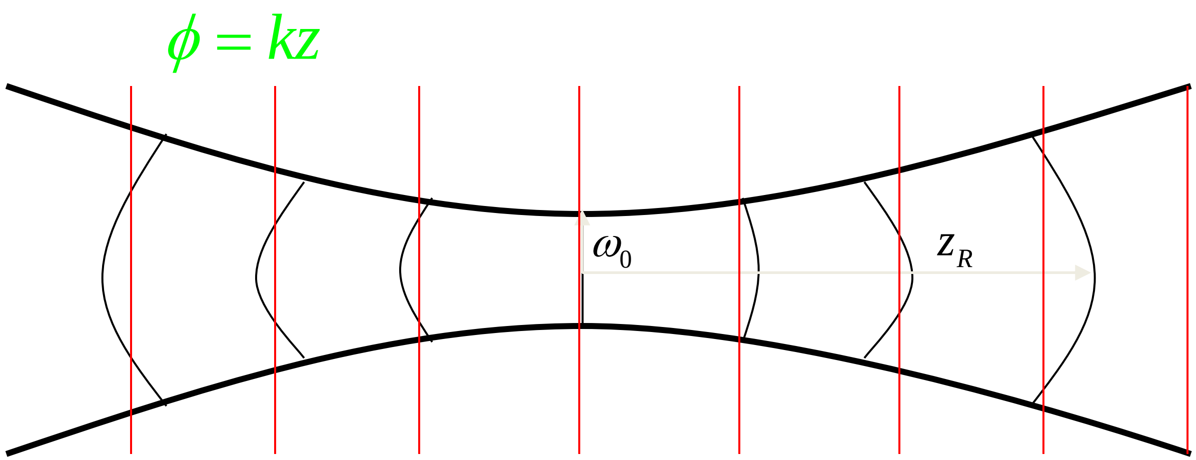
H. Mueller *et al*. Phys. Rev. Lett. **102,** 240403 (2009)

$$\omega_1 - \omega_2 = \dot{\omega} t$$

$$\text{Bloch Period } \tau_B = 8\omega_r / \dot{\omega}$$

Systematic Effects

Guoy Phase



$$\Phi(z) = \tan^{-1}\left(\frac{\lambda z}{\pi \omega_0^2}\right)$$

$$\frac{\Delta k}{k} = -\left.\frac{\partial \Phi}{\partial z}\right|_{z=0} \left(\frac{1}{k}\right) = \frac{-\lambda^2}{2\pi^2 \omega_0^2}$$

For λ=852nm and ω_0=1cm, $\frac{\Delta k}{k} = 0.15$ppb

Larger Beam Waist

Systematic Effects

Zeeman Effect

- No linear Zeeman Shift
- Quadratic Zeeman Shift for m_F=0

$$\Delta f \simeq \frac{(g_J + g_I)^2 \mu_B^2}{2f} B^2 \simeq (430\mathrm{Hz/G}^2) B^2$$

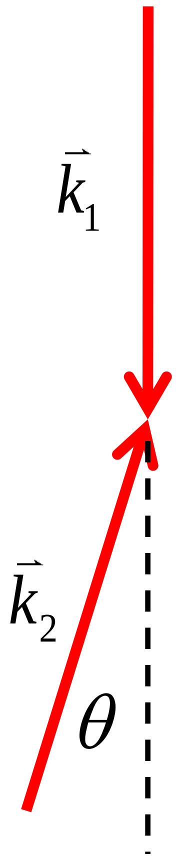
•Magnetic field gradient gives the shift

$$B(z)^2 = (B_0 + \frac{\partial B}{\partial z}\Delta z + \cdots)^2 \cong B_0^2 + 2B_0 \frac{\partial B}{\partial z}\Delta z$$

•Assume T=500ms, n=10 and $\frac{\partial B}{\partial z} \simeq 15\mathrm{mG}$ give error 0.14ppb

Systematic Effects

Beam Misalignment



$$\vec{k}_{eff} = \vec{k}_1 - \vec{k}_2$$

$$\left|\vec{k}_{eff}\right|^2 = (2k)^2(1 - \frac{\theta^2}{4})$$

Active stabilization can be done to $\theta \leq 5.1\mu\text{rad}$ which corresponds to 0.03ppb

Systematic Effects

AC Stark Shift

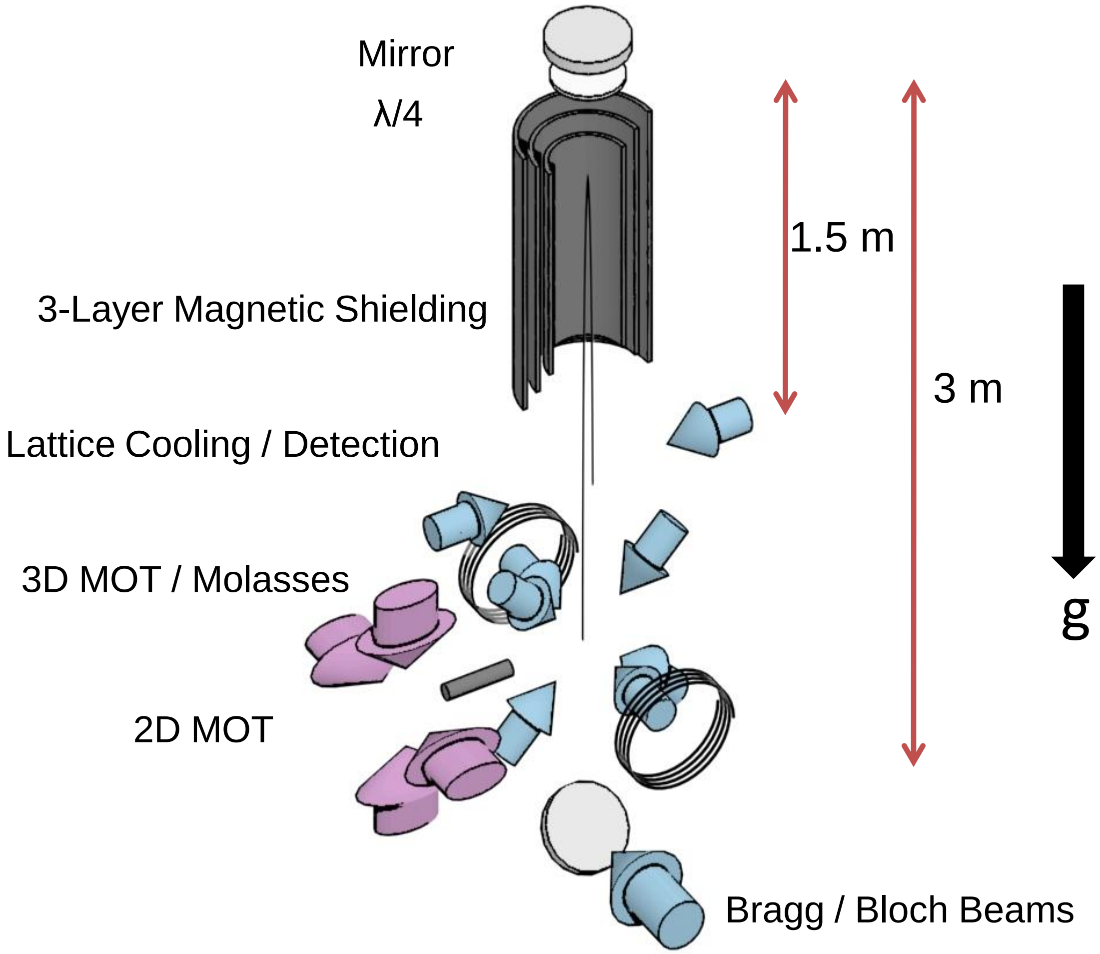
- Same internal state, differential Shift is negligible
- The laser frequencies used for addressing the upper interferometer may cause an AC Stark shift in the lower one
- Adding extra frequencies to the laser beam with the appropriate detuning to cancel the effect

More Systematic Effects

- Wavefronts
- Sagnac Effect
- Speckle
- Clipping
- Mean Field Shift
- Missed Recoils
- Gravity Gradient
-
-
-

Experimental Setup

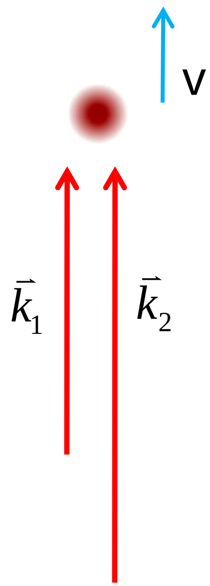
Atomic Fountain : Cs de Broglie Wave Source

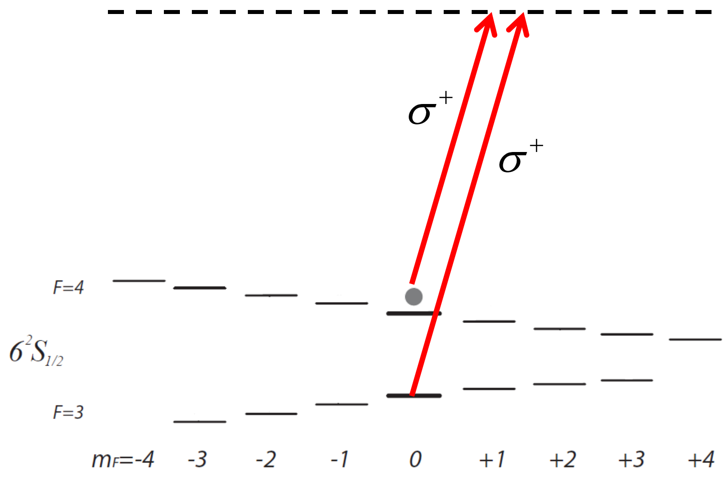


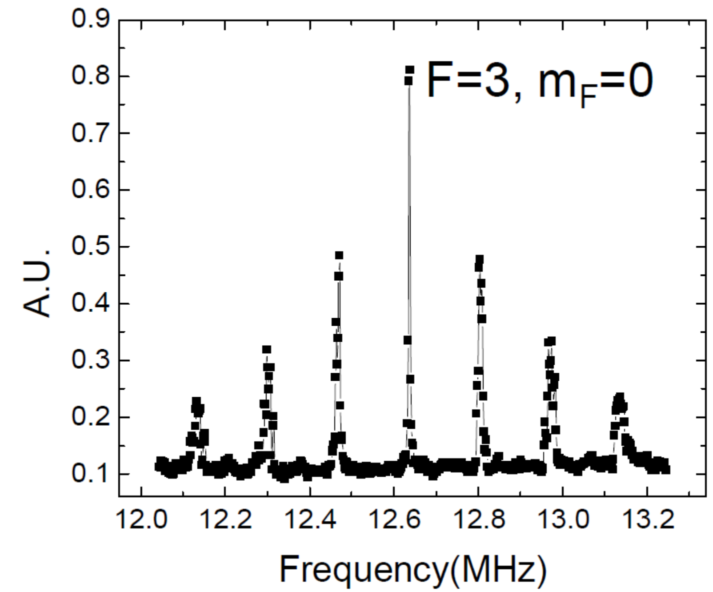
- molesses cooling~ 2 ms
- adiabatic cooling~ 0.5 ms
- T~2 μK

Experimental sequence

State selection using Doppler insensitive Raman transition

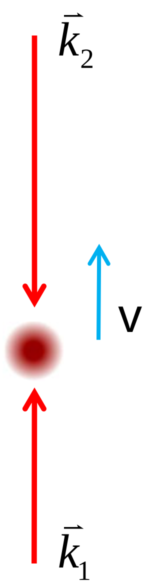






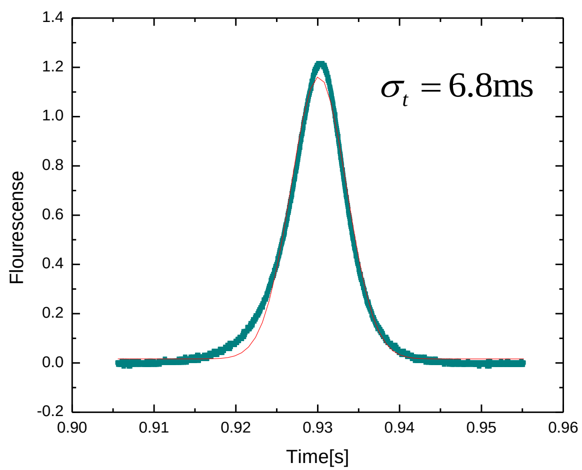
Experimental sequence

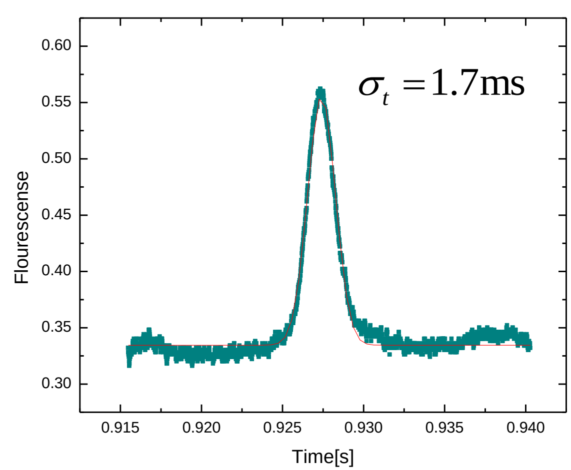
Velocity selection using Doppler sensitive Raman transition



- $2\mu\mathrm{K}$ of atoms has velocity spread $\sigma_\mathrm{v} \simeq 2\mathrm{cm/s}$
  After 1s of time of flight, atoms will drift out of interferometer beams

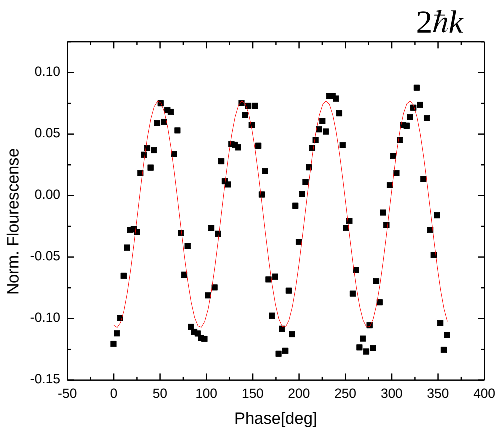
- 100 $\mu\mathrm{S}$ selection pulse selects about 1/10 of atoms in hundreds of nK

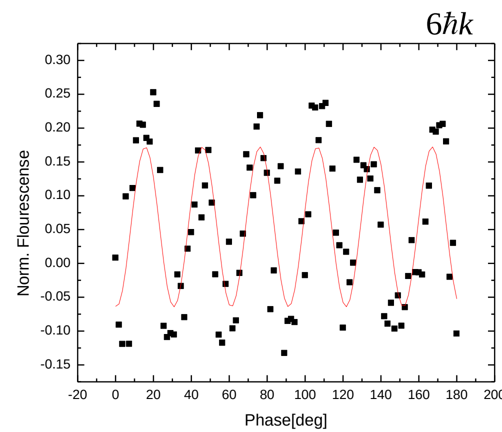


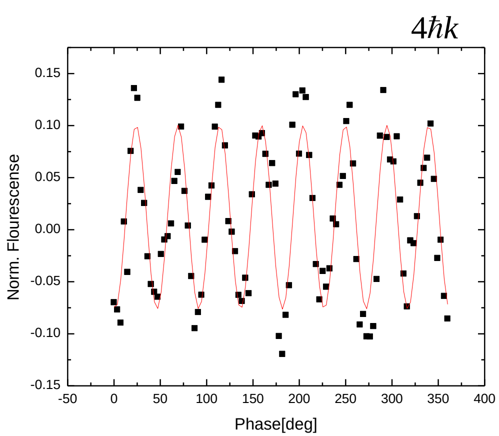


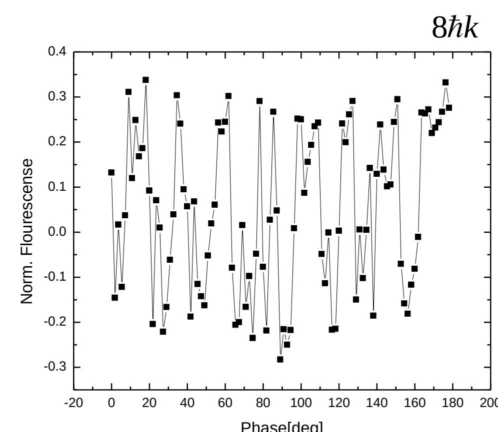
Mach Zehnder Interferometer fringe

First atomic inertia sensor in Berkeley





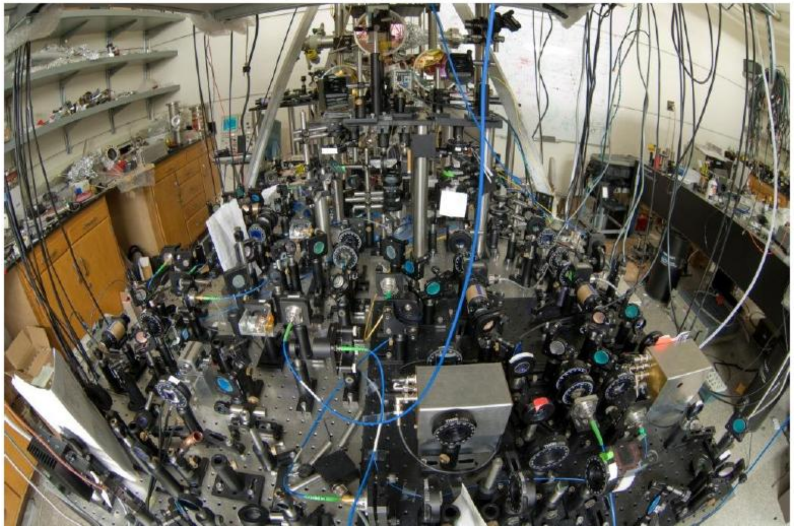


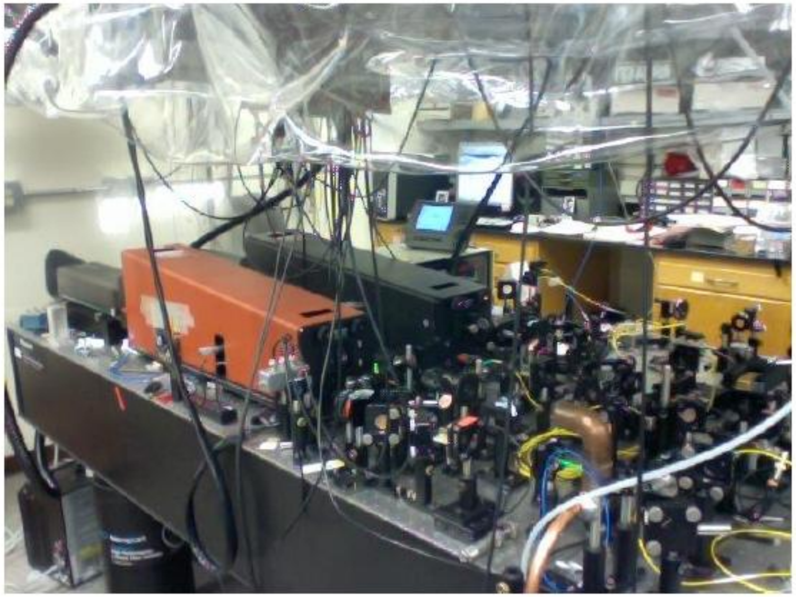


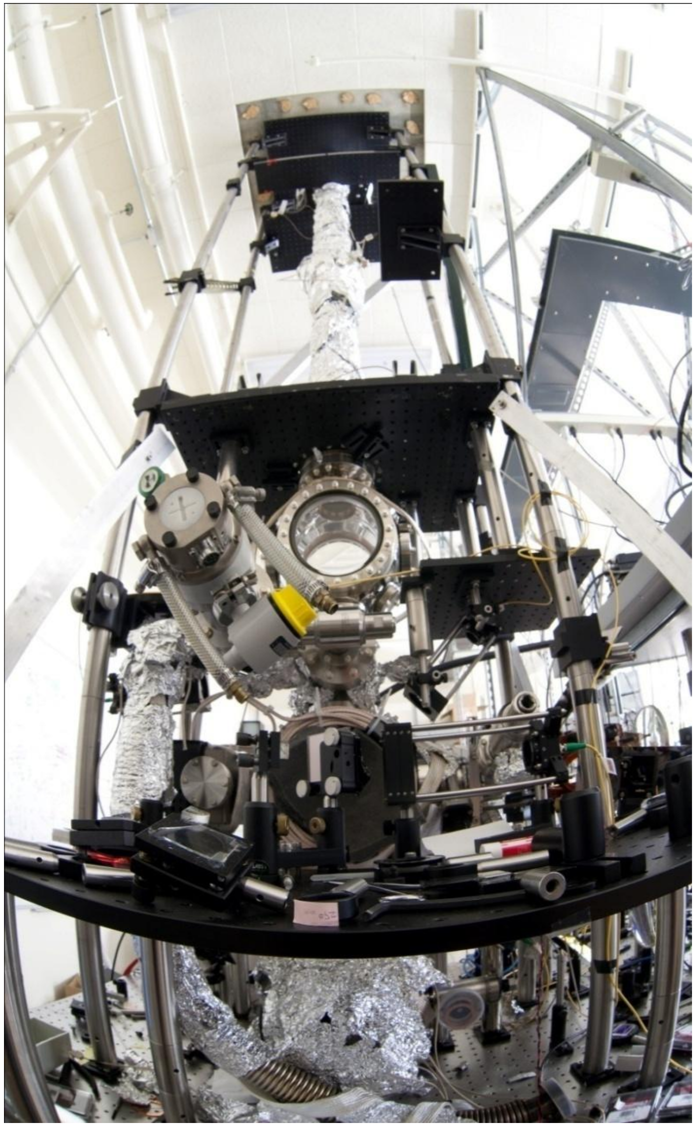
Period=360°/4n

Single shot, T=1ms, no vibration isolation

Cold Atomic Fountain







Outlook

- Implementing Raman sideband cooling to further increase signal by an order of magnitude
- Working on large momentum transfer to further boost the sensitivity
- Expecting the uncertainty of fine structure constant to be less than 1 ppb in 10 mins with T=500 ms and $\Delta p=20\hbar k$

Our Team

Principal Investigator:
Holger Mueller

Postdocs:
Shau-Yu Lan
Michael Hohensee
Paul Hamilton

Graduate Students:
Pei-Chen Kuan
Brian Estey
Geena Kim
Francisco J. Monsalve

Undergrads:
Cheong Chan