Interferometer in Space for Detecting Gravity Wave Radiation using Lasers (InSpRL)

Dec-21-2011

Workshop on Gravity Wave Detection

Presenter: Babak . N . Saif

InSpRL Team

Gravitational-Wave Mission RFI

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Outline of the talk

- Why Atom Interferometry to detect Gravity Waves?
- Basics Of Atom Interferometer.
- Atom Gradiometer as a sensor for detection of Gravity Wave.
- Amplification of Gravity Wave Phase:

    1) Large Momentum Transfer (LMT)

    2) Resonance(Heterodyne) detection
- Laser Phase Noise Mitigation
- Proposed Configurations.
- Phase calculation.
- Existing Technologies and Technology Maturation

Atom Interferometer Contributions

Why Atom Interferometry for Gravity Wave Detection???

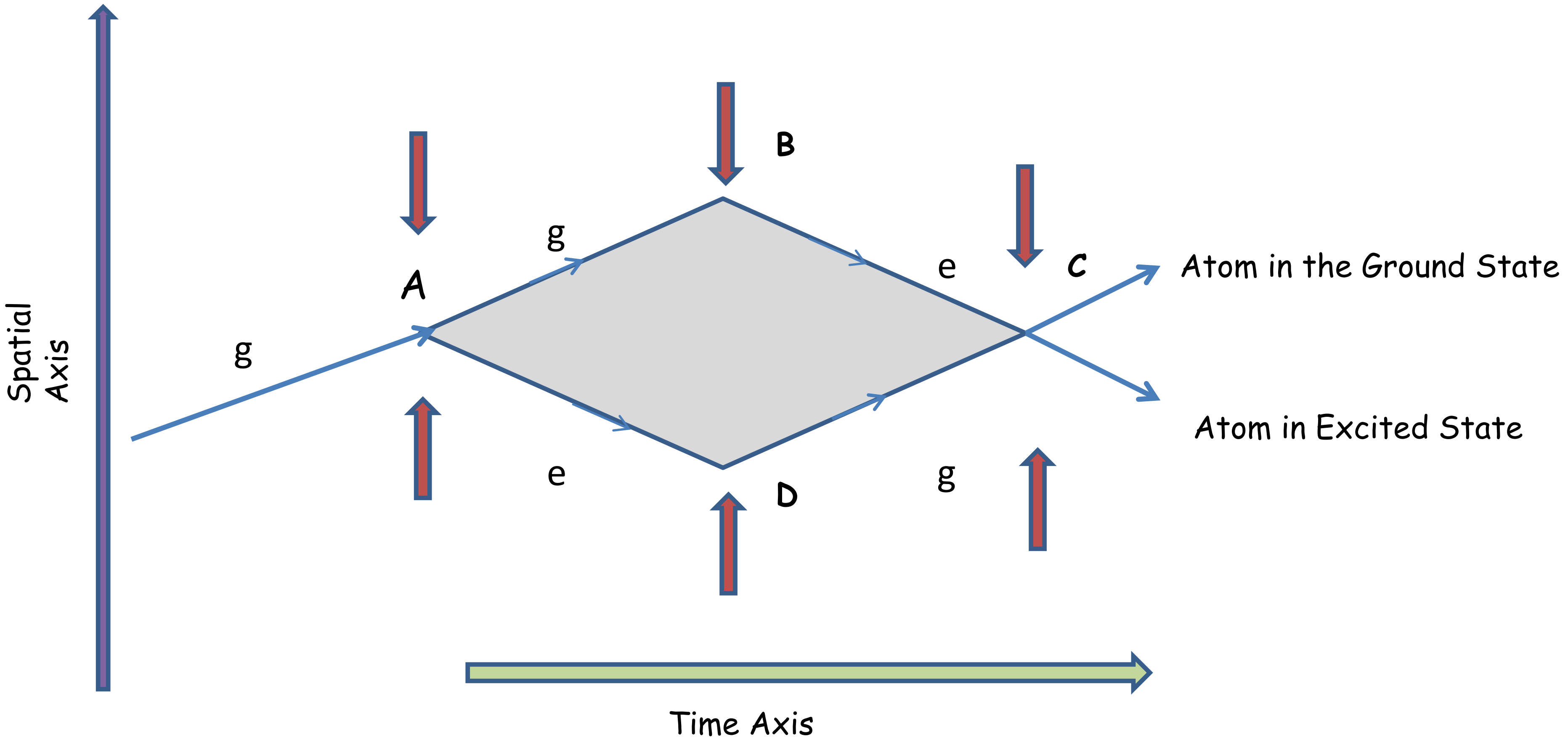
- A neutral atom is naturally decoupled from its environment. That makes atoms nearly ideal inertial test masses. This means they are ideally suited to measure Gravitational effects of all kinds including Gravity Wave.

- Amplification of the Gravity Wave OPD(phase) due to Coherent multiple interaction of light with the atom. AKA Large Momentum Beam Splitter. This is a noiseless quantum mechanical amplification of Phase.

- No Radiation Pressure Noise.

- Amplification of the Gravity Wave Phase due to Resonance(heterodyne) detections.

An Atom and a Set of Three Pulses Create a Mach-Zahnder interferometer



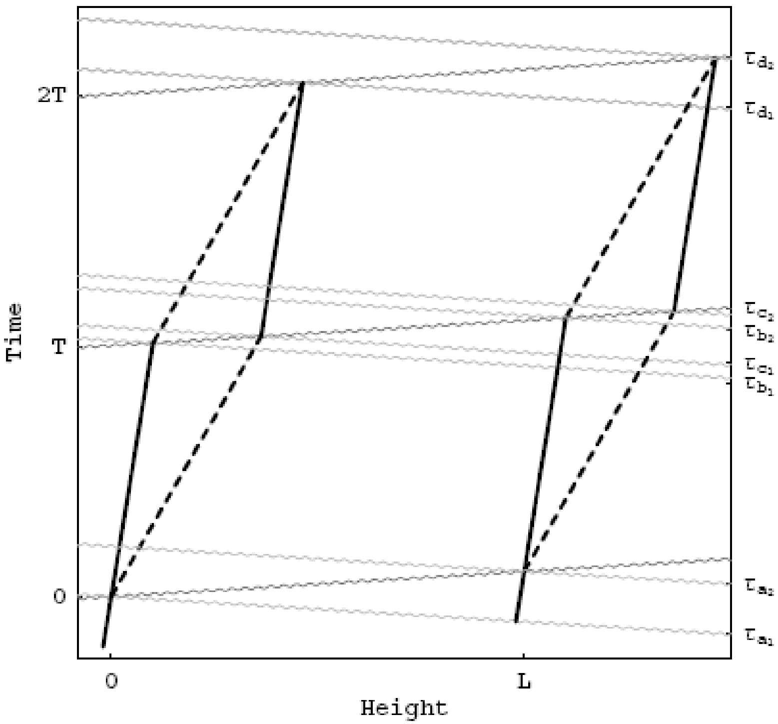
$$\varphi_{ABC} - \varphi_{ADC} = \Delta\varphi$$

$$\frac{1}{2}(1 - \cos\Delta\varphi) = \text{Probability } of\ finding\ Atom\ in\ e\ State$$

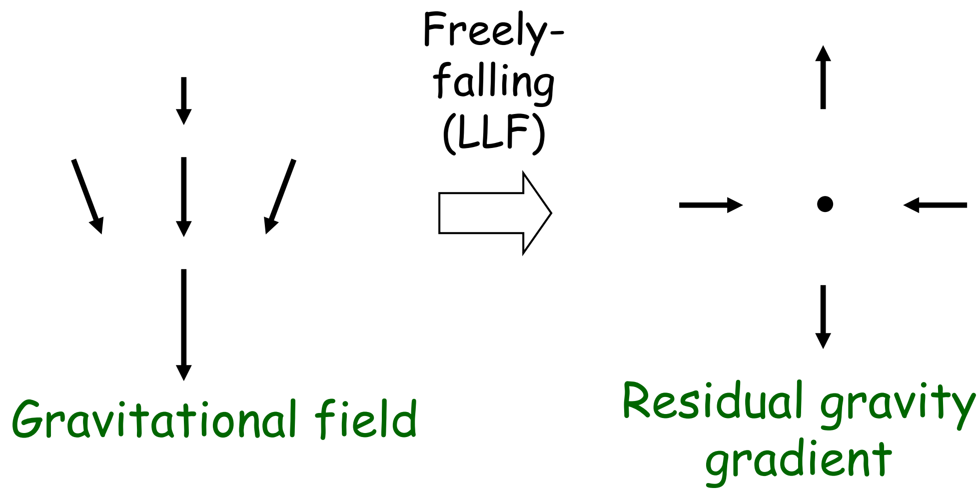
$$\frac{1}{2}(1 + \cos\Delta\varphi) = \text{Probability } of\ finding\ Atom\ in\ g\ State$$

GW as a Gravity Gradient

- We use a **differential** pair of atom interferometers to detect a GW
- Each measures the local acceleration, resulting in a gravity **gradiometer**



Gravity gradient is analogous to a GW:

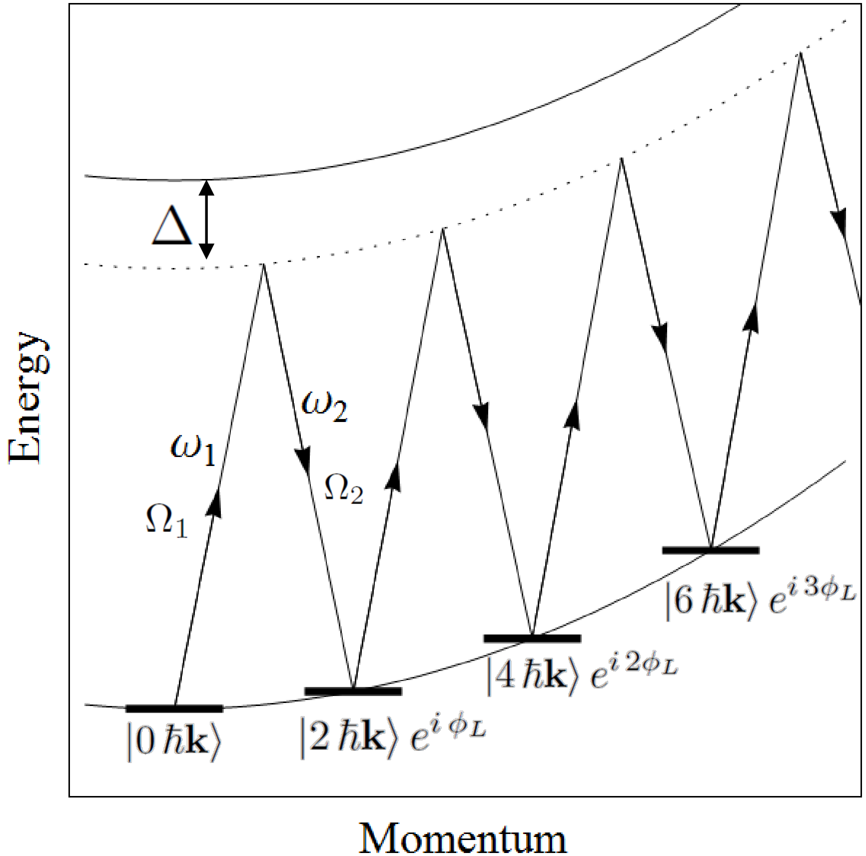


→ GW is like a (time dependent) gravity gradient
→ Geodesic deviation looks the same for GW and gravity gradient
→ Gravity gradiometer can detect GWs

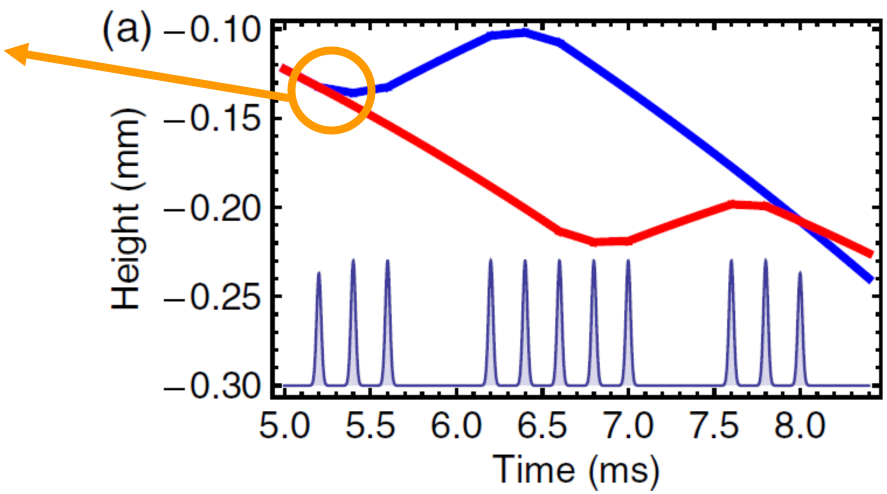
Coherent Phase Amplification

- Large momentum transfer (LMT) beamsplitters – multiple laser interactions
- Each laser interaction adds a **momentum recoil** and imprints the **laser's phase**

LMT energy level diagram



Example LMT interferometer



$$|0\,\hbar\mathbf{k}\rangle \xrightarrow{\text{LMT}} |2N\hbar\mathbf{k}\rangle\, e^{iN\phi_L}$$

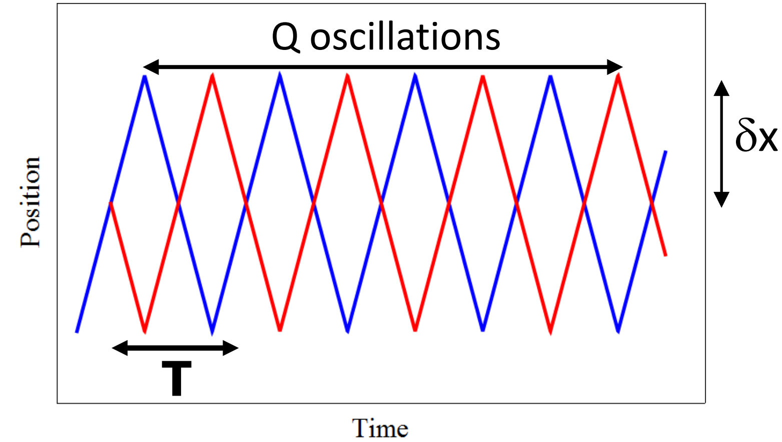
→ Phase amplification factor *N*

Resonant Detection

Additional phase amplification possible with **multiple loop** atom trajectory

Period **T** of atom oscillation matched to GW period, so each phase **adds constructively**.

→ Phase amplification factor Q



Constrained by ensemble lifetime and achievable atom kinematics:

$$T_{\mathrm{AI}} = QT < T_{\mathrm{max}}$$ (Vacuum)

$$4T_a Q < T_{\mathrm{sp}}$$ (Spontaneous emission)

$$\delta x < \delta x_{\mathrm{max}}$$ (Sunshield/boom length)

$$\ddot{x} < a_{\mathrm{max}}$$ (Rabi frequency)

(T_a is LMT pulse duration)

Phase Response Optimization

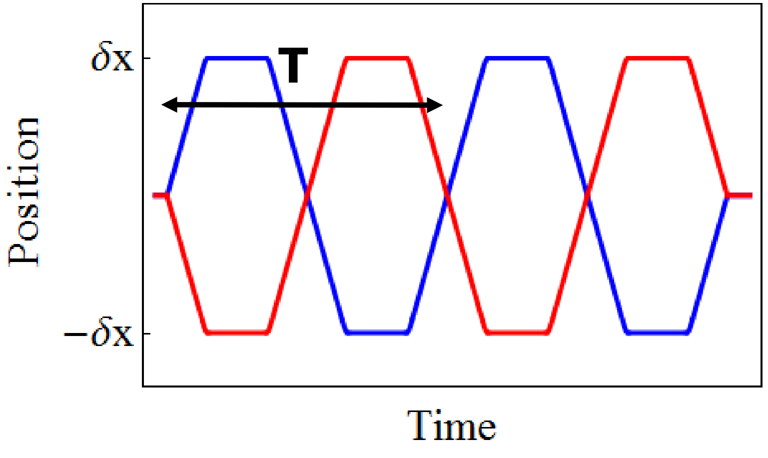
Constraints

Atom ensemble lifetime
- Total interferometer time < 1000 s (Vacuum)
- Acceleration time < 30 s (Spontaneous emission)

Kinematics
- Spatial extent < 250 m (Boom length)
- Max Acceleration < 300 m/s^2 (Rabi frequency)

Low frequency: f < 0.1 Hz

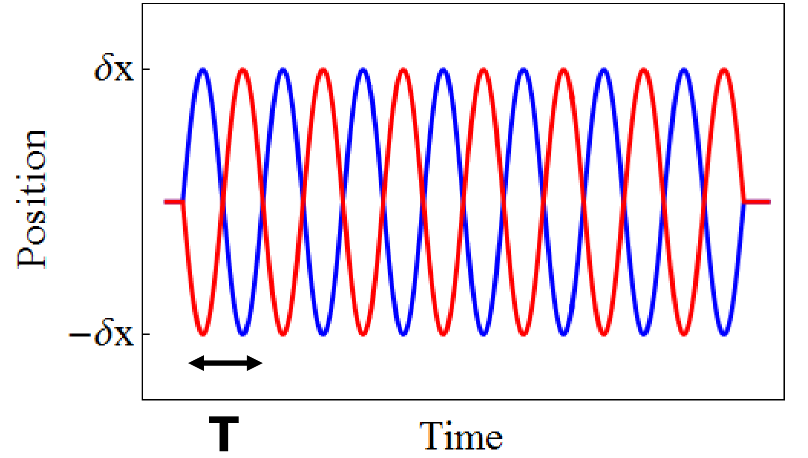
→ Drift and hold



Minimize spontaneous emission by limiting atom-light interaction time.

High frequency: f > 0.1 Hz

→ Continuous acceleration



Maximize spatial extent given maximum acceleration

Laser Phase Noise Mitigation

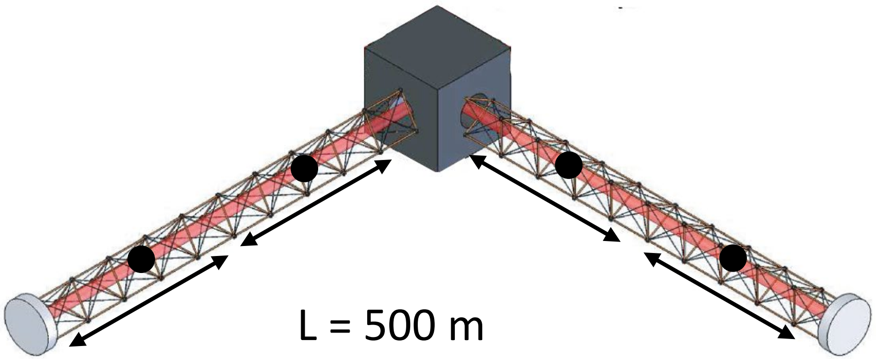
We have had discussions with members of CST and core team on laser phase noise mitigation for our single arm geometries.

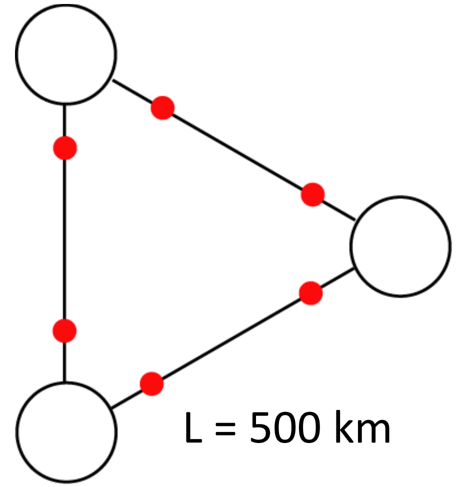
Our original RFI proposed method would require a stable laser oscillator.

While single arm configuration would be game changing, the above method needs further study and makes the comparison of our RFI response to others difficult.

Here we present two modified configurations to enable a direct comparison.

Two proposed short baseline configurations enabled by atom interferometry





Low	High	Low	High
f = 0.01 Hz N = 2100 Q = 9 (10 s drift time, 30 s hold)	f = 1 Hz N = 2000 Q =30 (sinusoidal)	f = 0.01 Hz N = 85 Q = 9 (10 s drift time, 30 second hold)	f = 1 Hz N = 2000 Q =30 (sinusoidal)

→ Scientifically interesting sensitivity possible with **short baseline** because of phase amplification factor of N*Q

Simple derivation of sensitivity curves

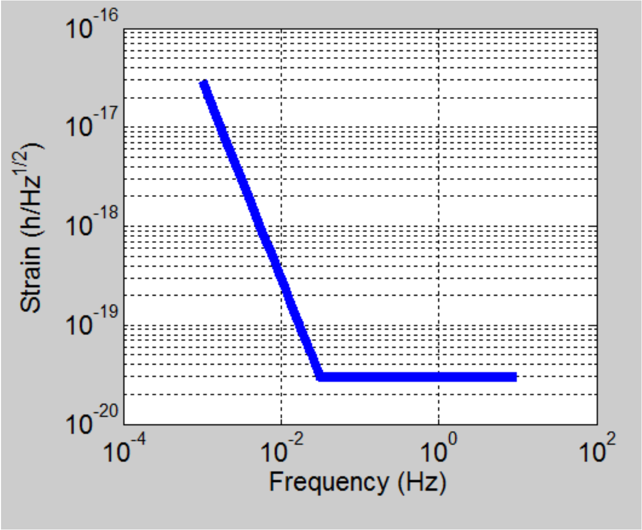
GW metric(LLF): $d\tau^2 = (1+2\Phi)dt^2 - dx^2$

GW potential: $\Phi = -\frac{1}{4}h\omega^2 x^2 \cos(\omega t)$ (like a gravity gradient potential)

Path integral phase shift: $\phi = \frac{1}{\hbar}\int_0^{QT} L\,dt \qquad L = -m\frac{d\tau}{dt}$

Differential phase between two interferometers separated by *L*, with arms oscillating sinusoidally with amplitude δx due to the atom optics sequence:

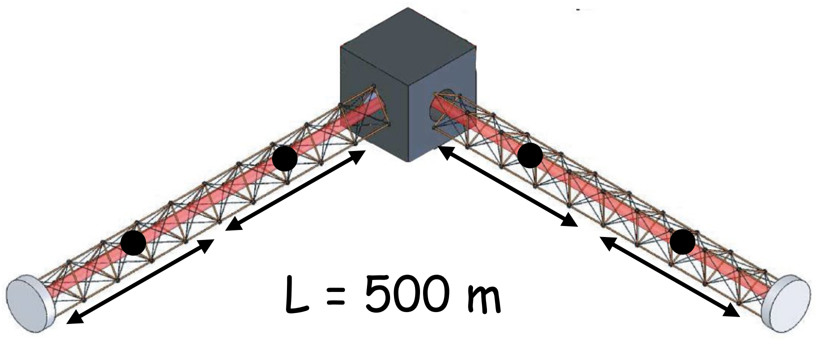
$$\Delta\phi = \pi h\, mL\, \delta x\, Q\, \omega/\hbar$$

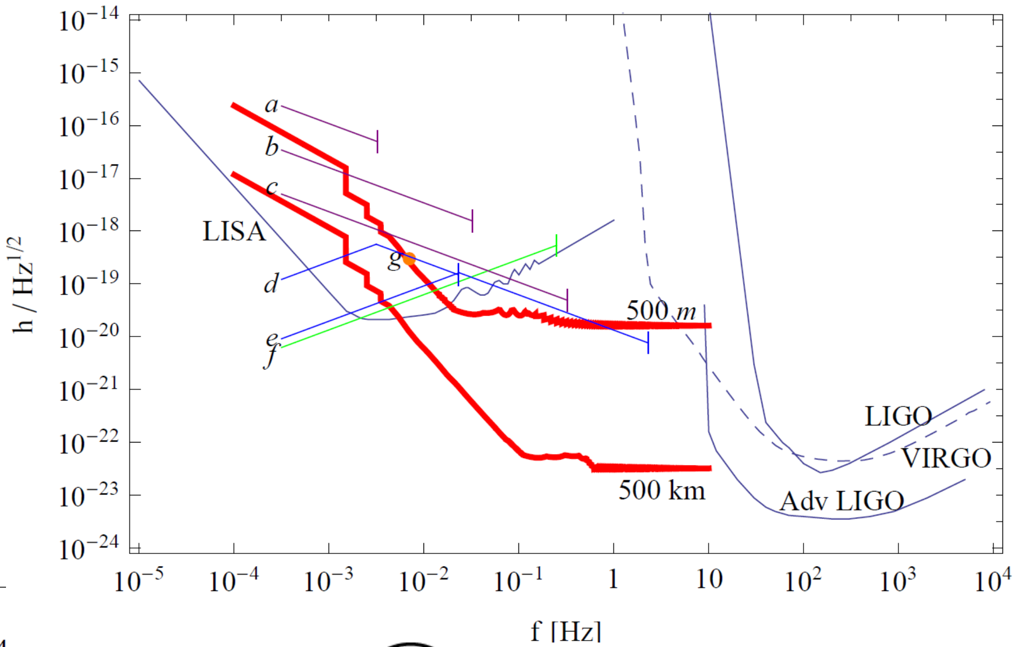


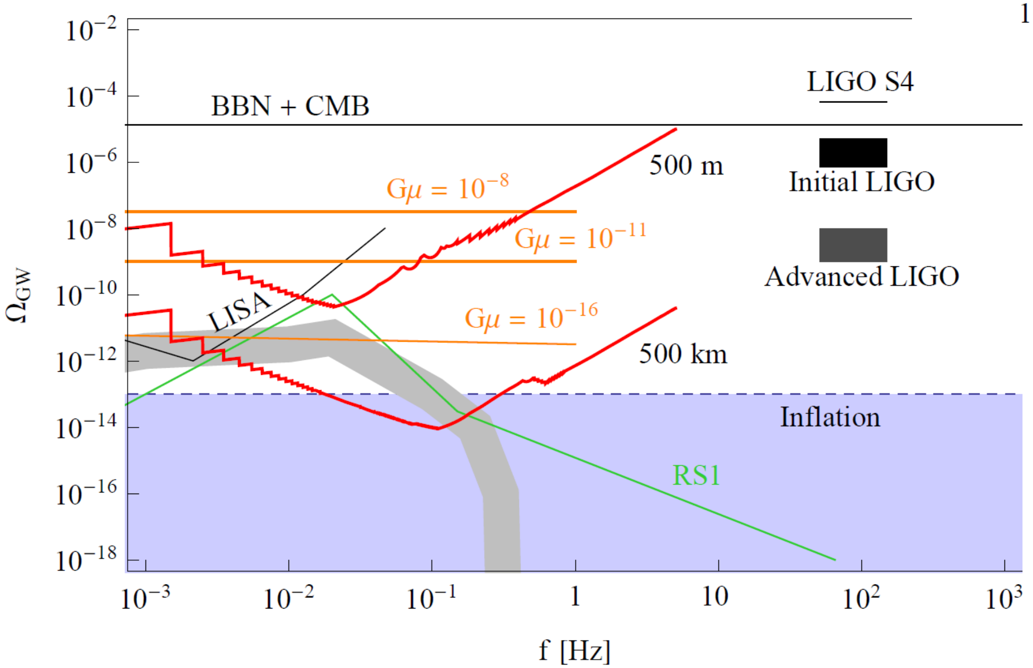
Example:
L = 500 m
δx = 250 m
Max. wavepacket acceleration: 1 *g*
QT = 1000 s
SNR: 10^4:1/Hz$^{1/2}$

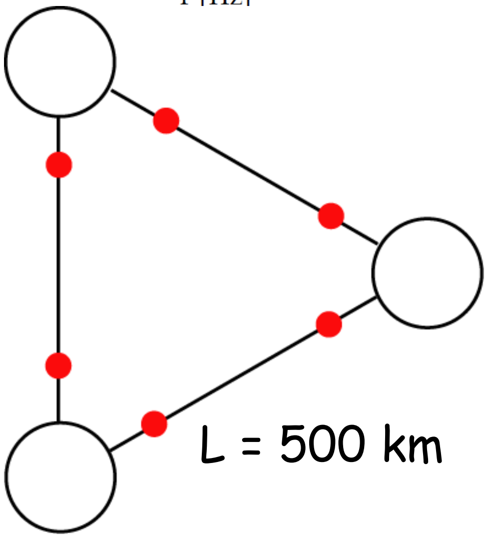
RFI response contains fully constrained optimization subject to spontaneous emission and lattice depth.

Strain Sensitivity

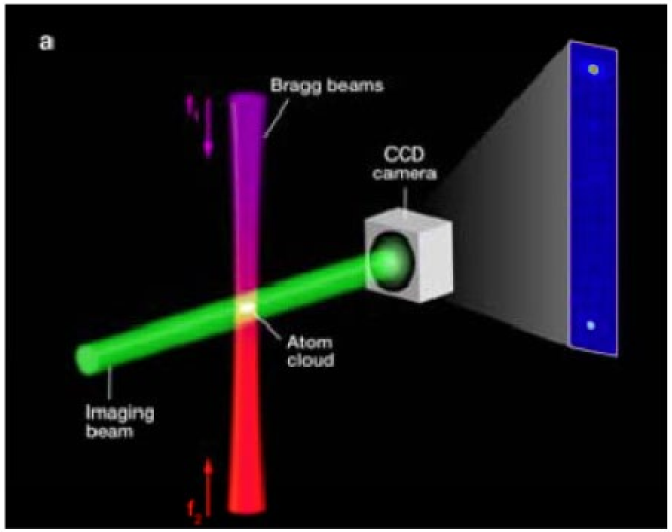








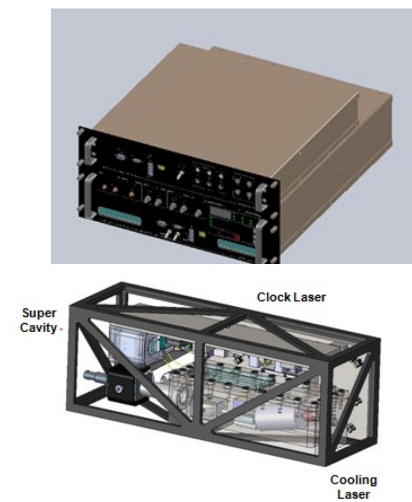
Existing Technology



$102\hbar k$ LMT atom optics demonstrated

10 m atom drop tower test facility

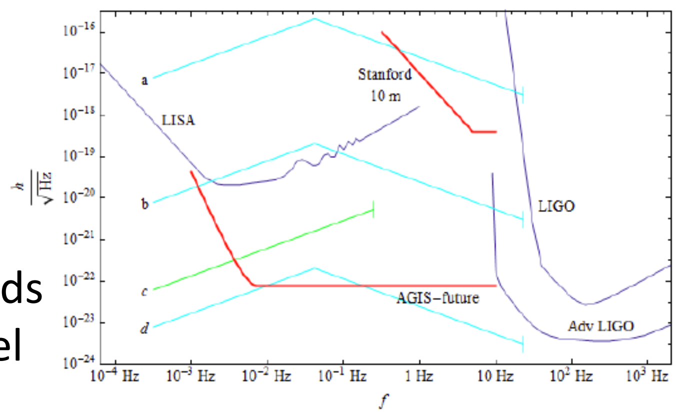
AOSense commercial AI gravimeter



AOSense commercial Sr clock

Use 10 m prototype to evaluate atom optics sequences.

Can demonstrate methods at the $h \sim 10^{-19}/\mathrm{Hz}^{1/2}$ level at 3 Hz (but blinded by seismic noise).



Collaboration with L. Hollberg for ultra-stable laser required for single-arm design.

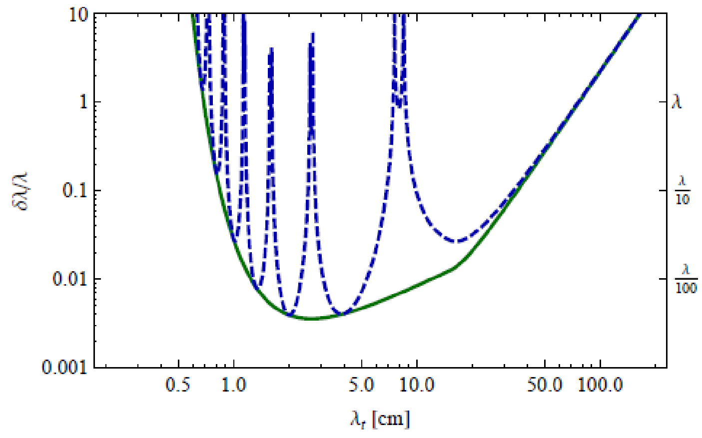
FY' 12/13 Technology Maturation Activities

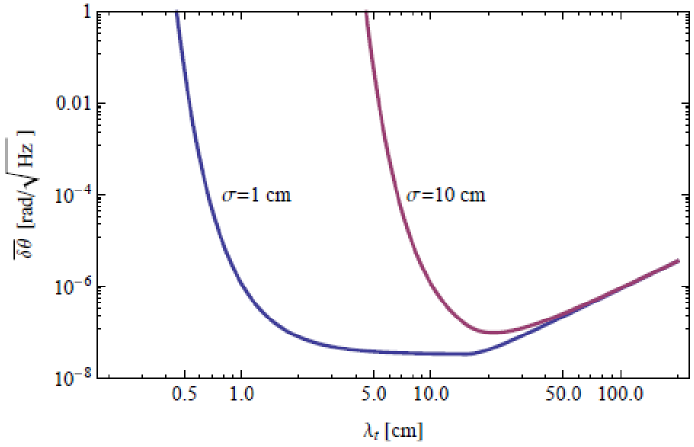
Technology	Descriptions	Lead Institution	TRL status	Facility
LMT	Higher Momentum Recoil	Stanford University	3	Stanford University 10 Meter Tower
WavePackets Coherence	Spatial Coherence over 10 meters	Stanford University		Stanford University 10 Meter Tower
Atom Source Engineering	Delta kick Cooling	Stanford University	3	Stanford University 10 Meter Tower
Laser	PSD Measurements of MOFA	GSFC	5	GSFC laser Lab
System Design	Over all System Design. Instruments, Orbit, Launch Vehicle,……	GSFC	N/A	GSFC IDC/MDL
Boom Stability	ATK Boom Stability and dynamics	ATK	4	ATK Test Facility

Backup Slides

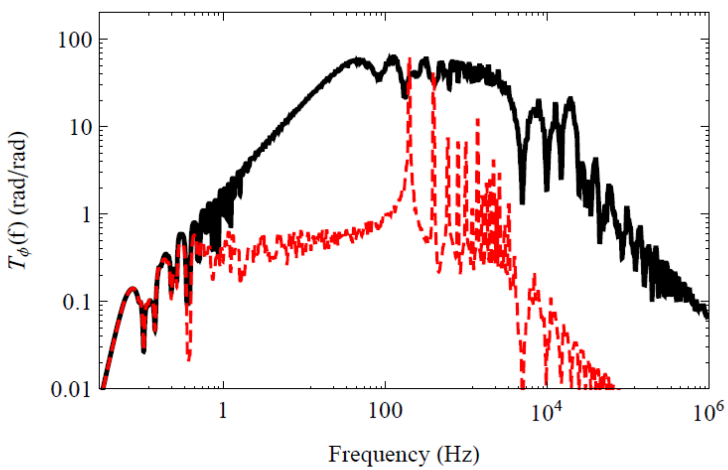
Example transfer functions

Spatial and temporal laser beam phase requirement vs. transverse spatial frequency.

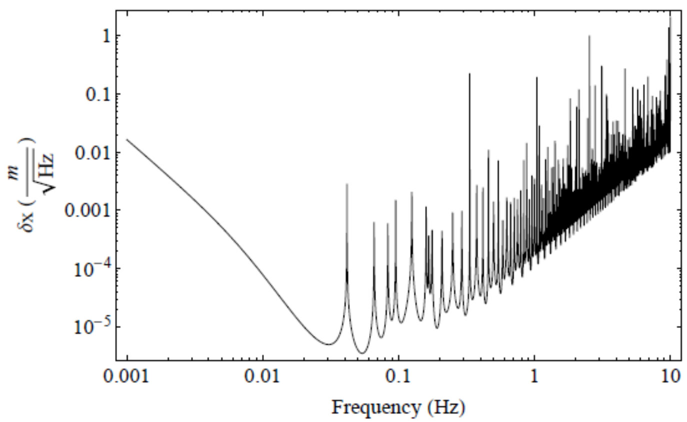




Laser phase noise transfer function



Satellite jitter



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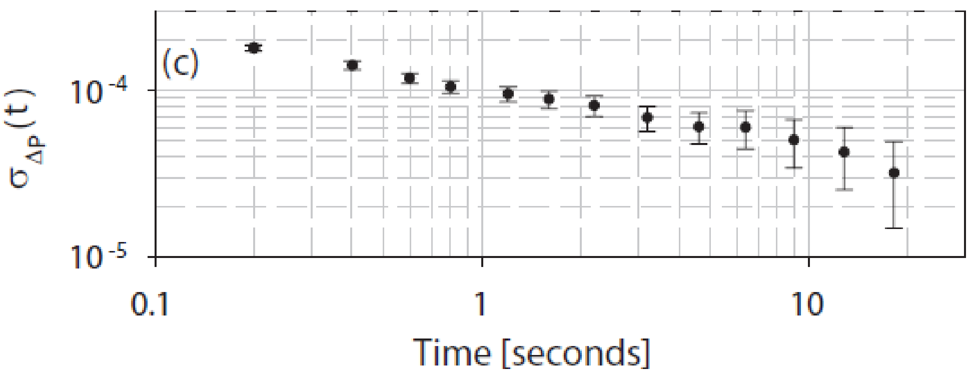
Example error model

	Differential phase shift	Size (rad)	Constraint
1	$\frac{15k_{\rm eff}^2\hbar}{Lm}T^4T_{\rm yz}\Omega_{\rm or}(\delta x_{\rm f}+\delta x_{\rm n})$	$(2.3\times10^{-3}\ {\rm m}^{-1})\,(\delta x_{\rm f}+\delta x_{\rm n})$	$(\delta x_{\rm f}+\delta x_{\rm n})<43$ mm
2	$\frac{15}{2}k_{\rm eff}T^4T_{\rm yy}^2(\delta y_{\rm n}-\delta y_{\rm f})$	$(5.6\ {\rm m}^{-1})\,(\delta y_{\rm n}-\delta y_{\rm f})$	$(\delta y_{\rm n}-\delta y_{\rm f})<18\ \mu$m
3	$\frac{45}{2}k_{\rm eff}T^4T_{\rm zz}\Phi\Omega_{\rm or}^2(\delta z_{\rm f}+\delta z_{\rm n})$	$(6.9\times10^{-2}\ {\rm m}^{-1})\,(\delta z_{\rm f}+\delta z_{\rm n})$	$(\delta z_{\rm f}+\delta z_{\rm n})<1.5$ mm
4	$15k_{\rm eff}T^4\Omega_{\rm or}\left(T_{\rm yz}+\Phi\left(T_{\rm yy}+T_{\rm xx}+2\Omega_{\rm or}^2\right)\right)(\delta v_{\rm xf}+\delta v_{\rm xn})$	$(140\ {\rm s/m})\,(\delta v_{\rm xf}+\delta v_{\rm xn})$	$(\delta v_{\rm xf}+\delta v_{\rm xn})<0.72\ \mu$m/s
5	$\frac{45}{2}k_{\rm eff}T^5T_{\rm yy}^2(\delta v_{\rm yf}-\delta v_{\rm yn})$	$(67\ {\rm s/m})\,(\delta v_{\rm yf}-\delta v_{\rm yn})$	$(\delta v_{\rm yf}-\delta v_{\rm yn})<1.5\ \mu$m/s
6	$\frac{135}{2}k_{\rm eff}T^5T_{\rm yz}\Omega_{\rm or}^2(\delta v_{\rm zf}+\delta v_{\rm zn})$	$(1.2\ {\rm s/m})\,(\delta v_{\rm zf}+\delta v_{\rm zn})$	$(\delta v_{\rm zf}+\delta v_{\rm zn})<81\ \mu$m/s
7	$30k_{\rm eff}T^4\left(T_{\rm zz}+3\Omega_{\rm or}^2\right)\delta\Omega\,\delta v_{\rm zn}$	$(1.7\times10^7\ {\rm s^2/m})\ \delta\Omega\,\delta v_{\rm zn}$	$\delta\Omega<6.0\ \mu$rad/s
8	$\frac{171k_{\rm eff}^3\hbar^2}{2L^2m^2}\Omega_{\rm or}T^4\delta\Omega\,\delta x_{\rm n}$	$(63\ {\rm s/m})\,\delta\Omega\,\delta x_{\rm n}$	$\delta\Omega<37\ \mu$rad/s
9	$30k_{\rm eff}T^4\Omega_{\rm or}^2\left(\frac{k_{\rm eff}\hbar}{Lm}+\frac{45}{4}T\Omega_{\rm or}^2\right)\delta\Omega\,\delta z_{\rm n}$	$(1.7\times10^3\ {\rm s/m})\,\delta\Omega\,\delta z_{\rm n}$	$\delta\Omega<40\ \mu$rad/s
10	$\frac{27k_{\rm eff}^3\hbar^2}{4L^2m^2}T^3\delta\Omega\,\delta z_{\rm f}$	$(1.1\times10^3\ {\rm s/m})\,\delta\Omega\,\delta z_{\rm f}$	$\delta\Omega<62\ \mu$rad/s
11	$\frac{225}{2}k_{\rm eff}RT^5\Omega_{\rm or}^2\left(T_{\rm zz}+3\Omega_{\rm or}^2\right)\varepsilon_g\delta\Omega$	$(2.4\times10^9\ {\rm s})\,\varepsilon_g\delta\Omega$	$\varepsilon_g<6.8\times10^{-9}$
12	$\frac{30k_{\rm eff}^2\hbar}{L^2m}T^4R\Omega_{\rm or}^3\varepsilon_g(\delta x_{\rm n}-\delta x_{\rm f})$	$(180\ {\rm m}^{-1})\,\varepsilon_g(\delta x_{\rm n}-\delta x_{\rm f})$	$\varepsilon_g<1.3\times10^{-5}$
13	$60k_{\rm eff}T^4\Omega_{\rm or}^3\varepsilon_{\rm xx}\delta\Omega\,\delta x_{\rm n}$	$(3.8\times10^4\ {\rm s/m})\,\varepsilon_{\rm xx}\delta\Omega\,\delta x_{\rm n}$	$\varepsilon_{\rm xx}<1.0\times10^{-2}$
14	$60k_{\rm eff}T^4\Omega_{\rm or}^2\left(\frac{k_{\rm eff}\hbar}{Lm}+\frac{15}{2}T\Omega_{\rm or}^2\right)\varepsilon_{\rm zz}\delta\Omega\,\delta z_{\rm n}$	$(2.6\times10^3\ {\rm s/m})\,\varepsilon_{\rm zz}\delta\Omega\,\delta z_{\rm n}$	$\varepsilon_{\rm zz}<4.2$
15	$9\sqrt{2}k_{\rm eff}y_n\frac{L}{R}\Omega_{\rm or}^2T^2\chi(\omega T)\overline{\delta\theta}$	$(1.4\times10^4\ {\rm m}^{-1})\,y_n\overline{\delta\theta}$	$\overline{\delta\theta}<0.71$ nrad
16	$4k_{\rm eff}\delta z_n(7+8\cos(\omega T))\sin^4\left(\frac{\omega T}{2}\right)\overline{\delta\theta}$	$(1.3\times10^{10}\ {\rm m}^{-1})\,\delta z_n\overline{\delta\theta}$	$\overline{\delta\theta}<0.77$ nrad

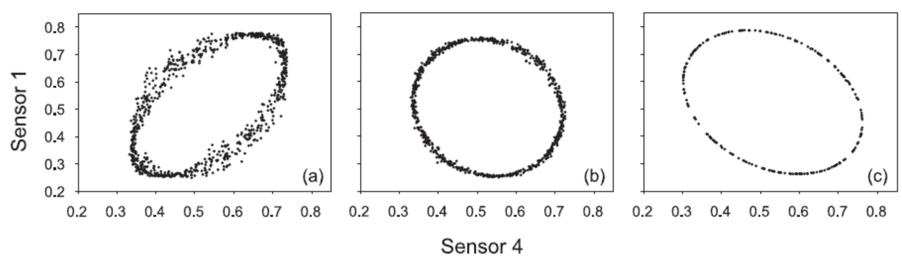
Requires specialization to the proposed antenna geometries.

SNR

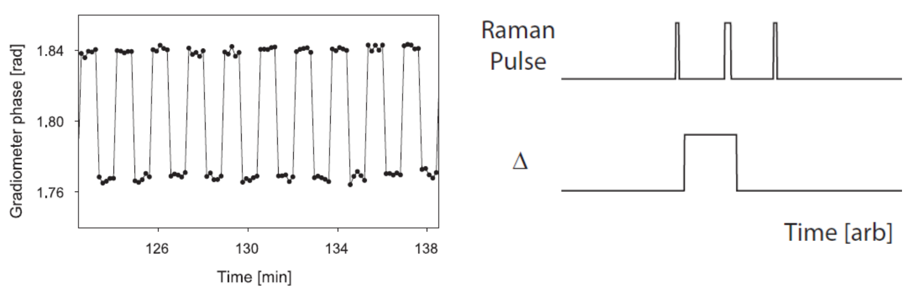
GW sensitivity curves derived assuming 10^4:1 in 1 second.



SNR of 1.4×10^4 in 1 second demonstrated on Cs clock transition (Biedermann PhD, also Opt. Lett).

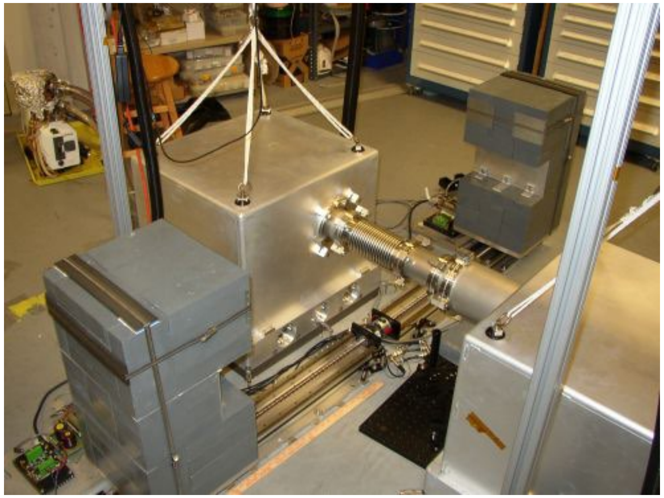


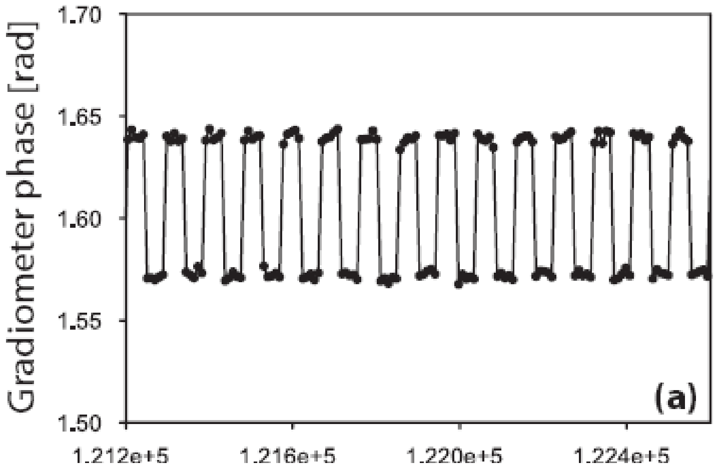
Gradiometer laser phase noise study (left to right: DBR, ECDL, cavity locked)

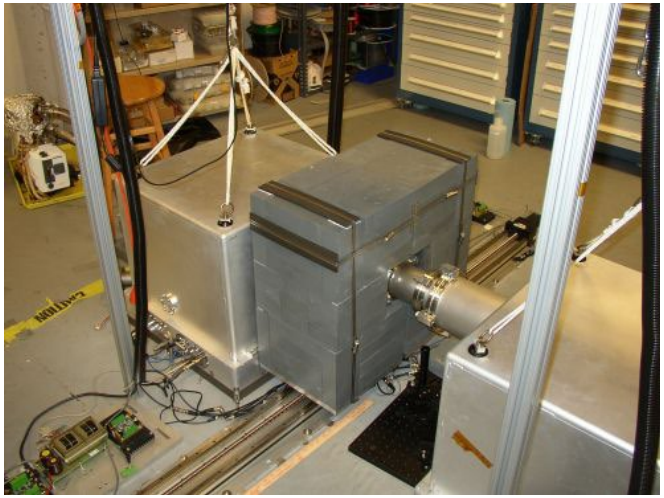


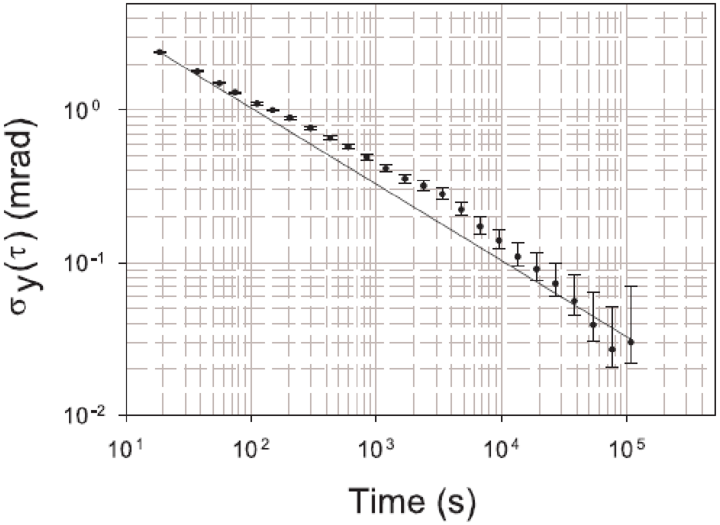
Phase shift as a function of applied frequency shift for middle interferometer pulse. Allows determination of baseline.

Gravity gradiometer









Demonstrated accelerometer resolution: ~10^{-11} g. Operated on a truck.

Optical Atomic "clock" serves as **Phase Reference** for Atom Interferometry

- Do not require absolute frequency accuracy nor even reproducibility
- Do not require operation as a "clock"
- Do not require continuous measurements
- Continuous operation could be benefit in some cases and is feasible
  - Very short "fountain 1.25 cm for T_{ramsey}= 100 ms; easy on ground
  - Interleaved clouds of atoms
  - Space operation even easier, atoms don't fall, near 100% recapture
- Do require outstanding frequency and phase stability
- Do want synchronization with Atom Interferometry pulses
  - Then laser frequency noise can be removed, dead time not an issue
  - Optical cavity thermal noise will not limit performance
-

Cold Atom Optical Clocks

$\sigma_y(\tau) = 1x10^{-19}\ \tau^{-1/2}$?

Atomic fractional frequency instability: (Allan deviation)

$$\sigma_y \approx \frac{Noise}{\pi Q * (Signal)} \approx \frac{\Delta\nu}{\nu_0} \frac{1}{\sqrt{N_{atoms}}} \sqrt{\frac{T_{cycle}}{2\tau}} \frac{1}{C}$$

T_{cycle} = time to measure both sides of atomic resonance
T_{Ramsey} = Ramsey interrogation time
Q = line quality factor = $\nu/\Delta\nu$
τ = averaging time

C = fringe contrast
N_{atom} = # of atoms detected in T_{cycle}

For example: atomic stability feasible w/ **Ytterbium (Sr, …)**

λ = 556 nm, 519 THz clock transition
$\Delta\nu = 1/(2T_{Ramsey})$ = 5 Hz , T_{Ramsey} =100 ms
C = 30 %
ν_0 = 519 THz
$N_A = 10^8$

$\sigma_y = 3x10^{-18}$ in 200 ms

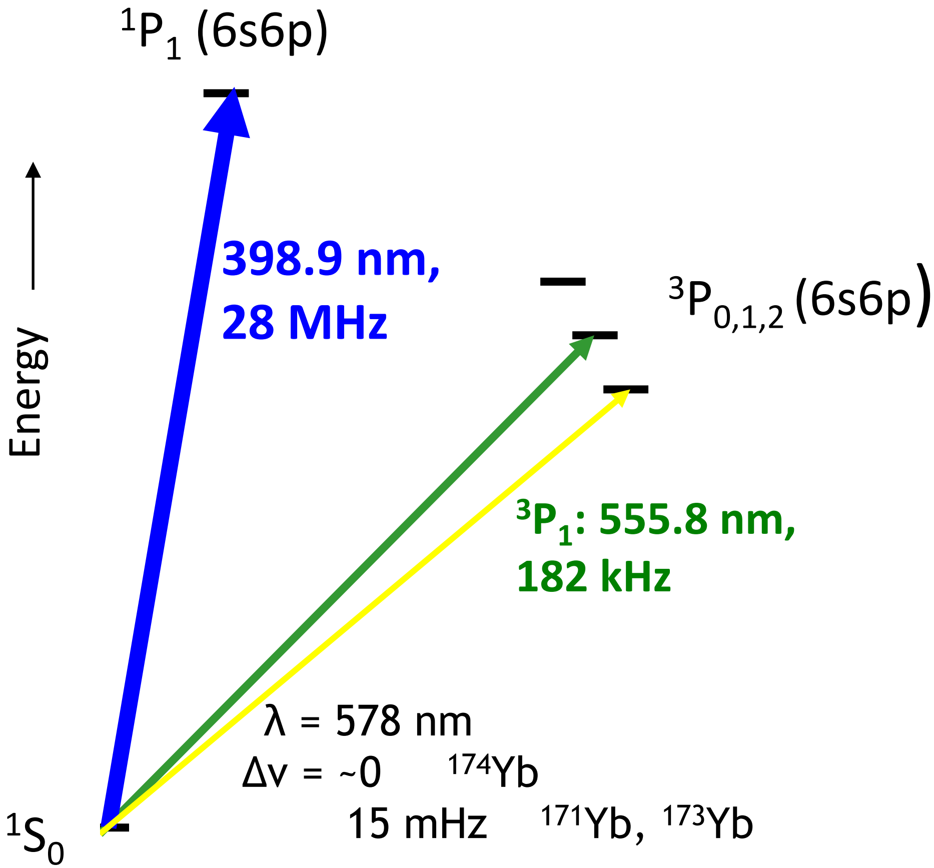
$\sigma_y(\tau) = 1x10^{-18}\ \tau^{-1/2}$

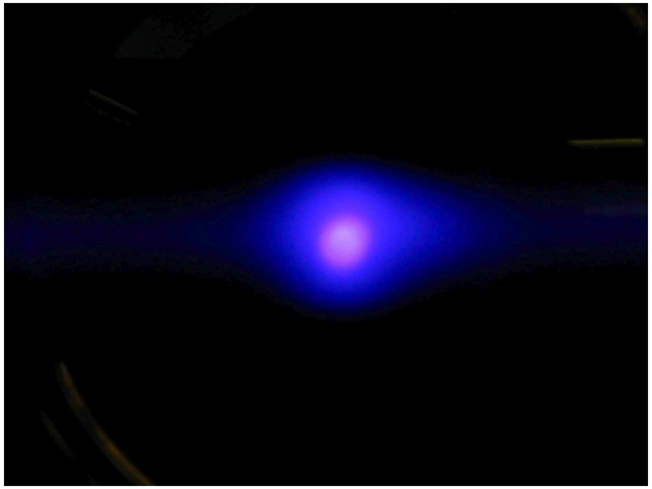
$T_{cycle} = 4\ T_{Ramsey}$

Hollberg et al. IEEE, JQE 37 (2001)

Ytterbium optical atomic clock

- Excellent prospects for high stability and small absolute uncertainty





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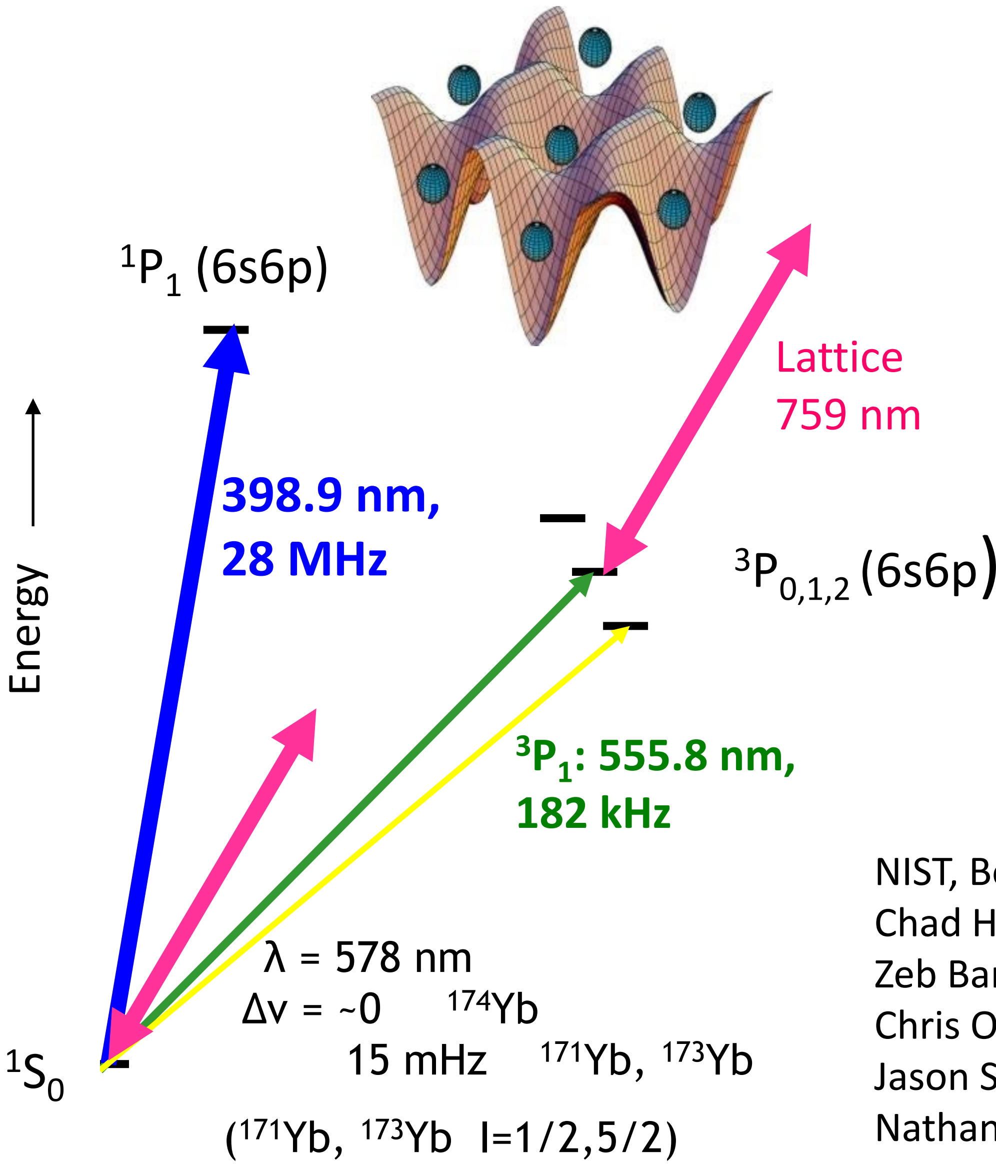

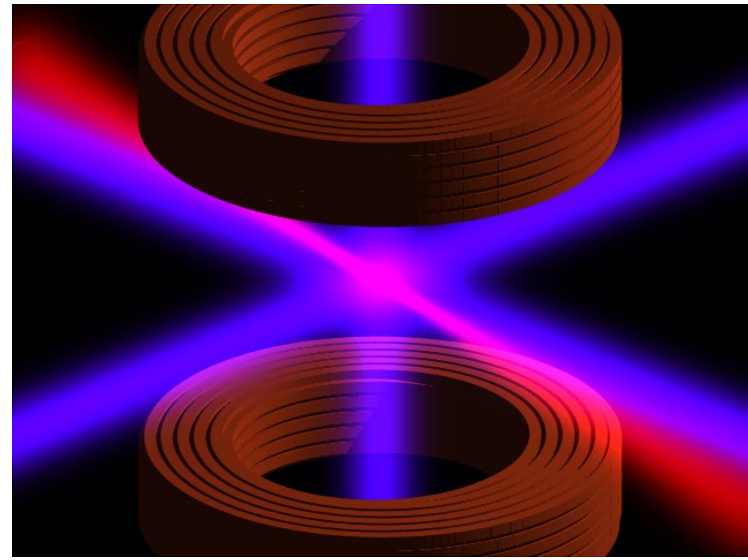

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