Atom Interferometry for Detection of Gravitational Waves

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Atom-based Gravitational Wave Detection

Why consider atoms?

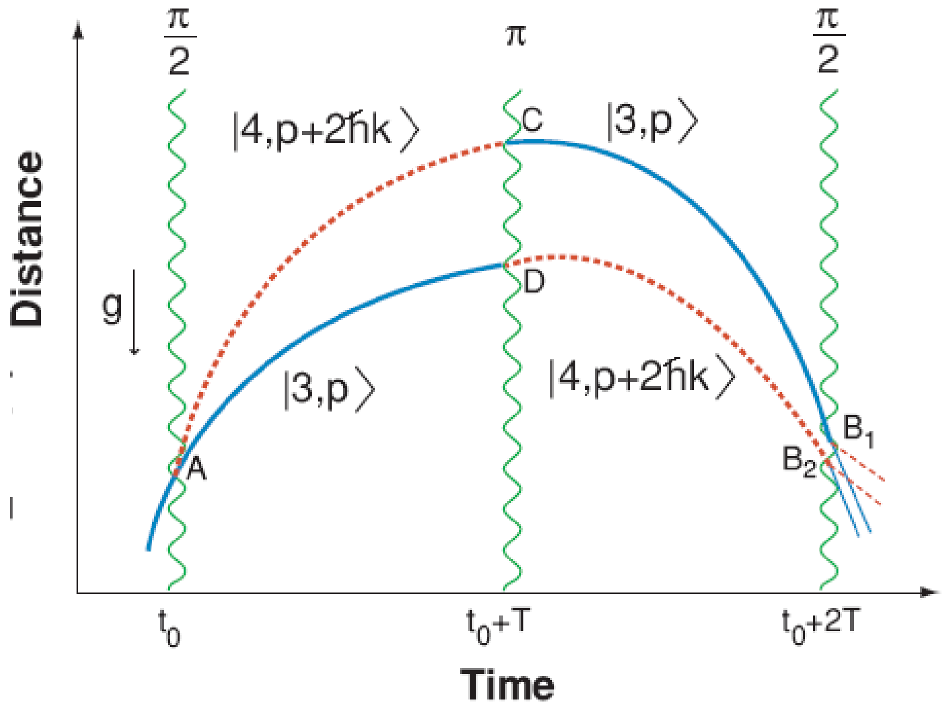
1) Neutral atoms are excellent proof masses
   - atom interferometry

2) Atoms are excellent clocks
   - optical frequency standards

Literature: B. Lamine, et al., Eur. Phys. J. D **20**, (2002); R. Chiao, et al., J. Mod. Opt. **51**, (2004); S. Foffa, et al., Phys. Rev. D **73**, (2006); A. Roura, et al., Phys. Rev. D **73**, (2006); P. Delva, Phys. Lett. A **357** (2006); G. Tino, et al., Class. Quant. Grav. **24** (2007), Dimopoulos, et al., PRD (2008), Graham, et al., PRL (2013).

Light-pulse atom interferometry

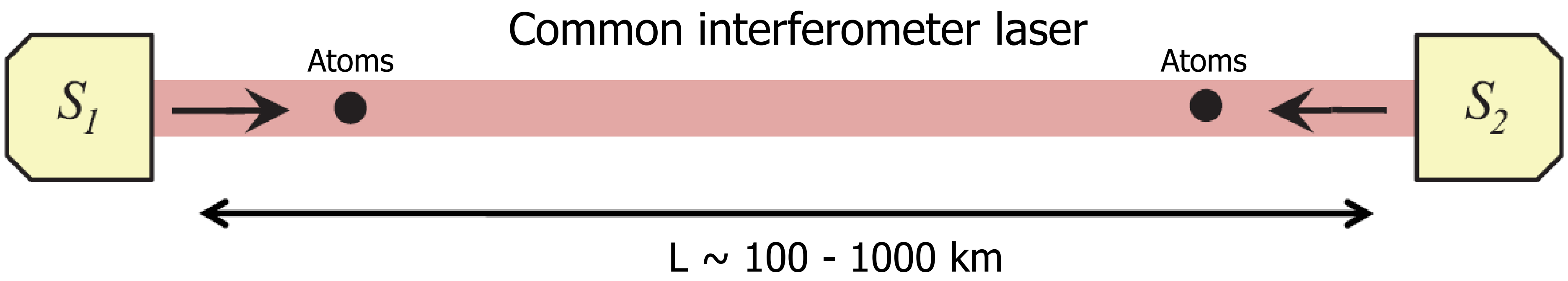
Pulses of light are used to coherently manipulate atom de Broglie waves:

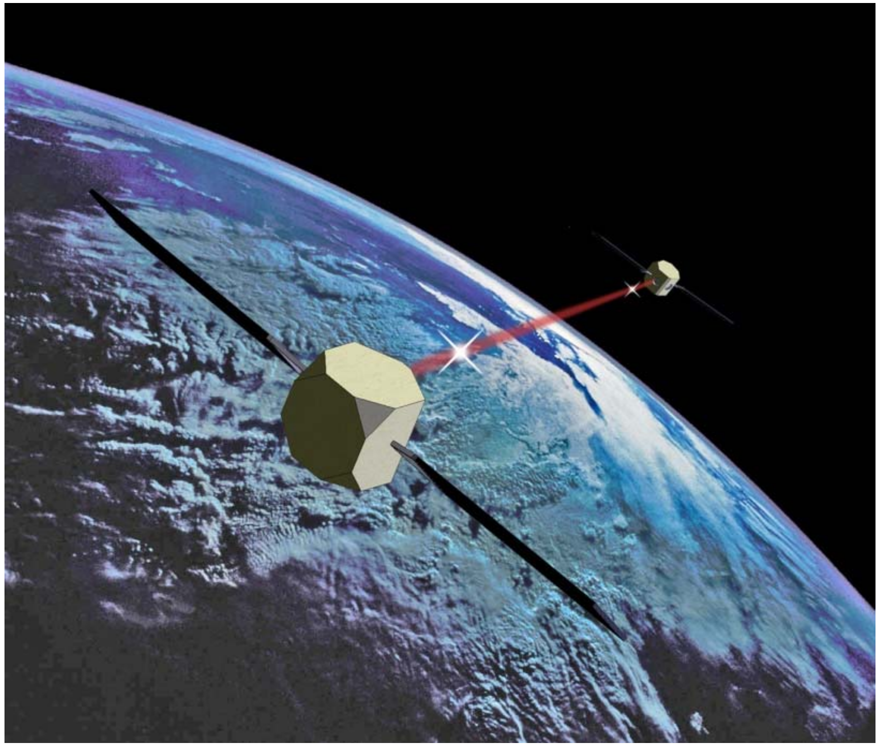


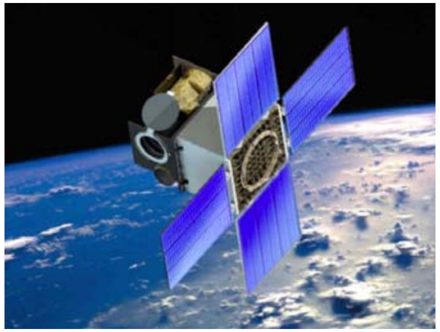
Phase shift read-out by counting atoms at each output port.

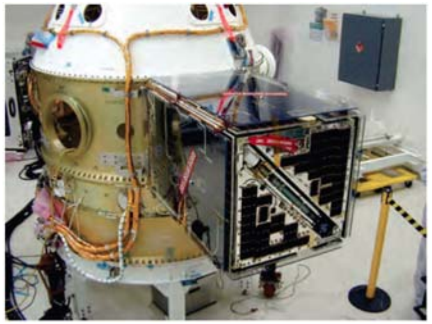
Kasevich and Chu, PRL, 1991

Satellite GW Antenna



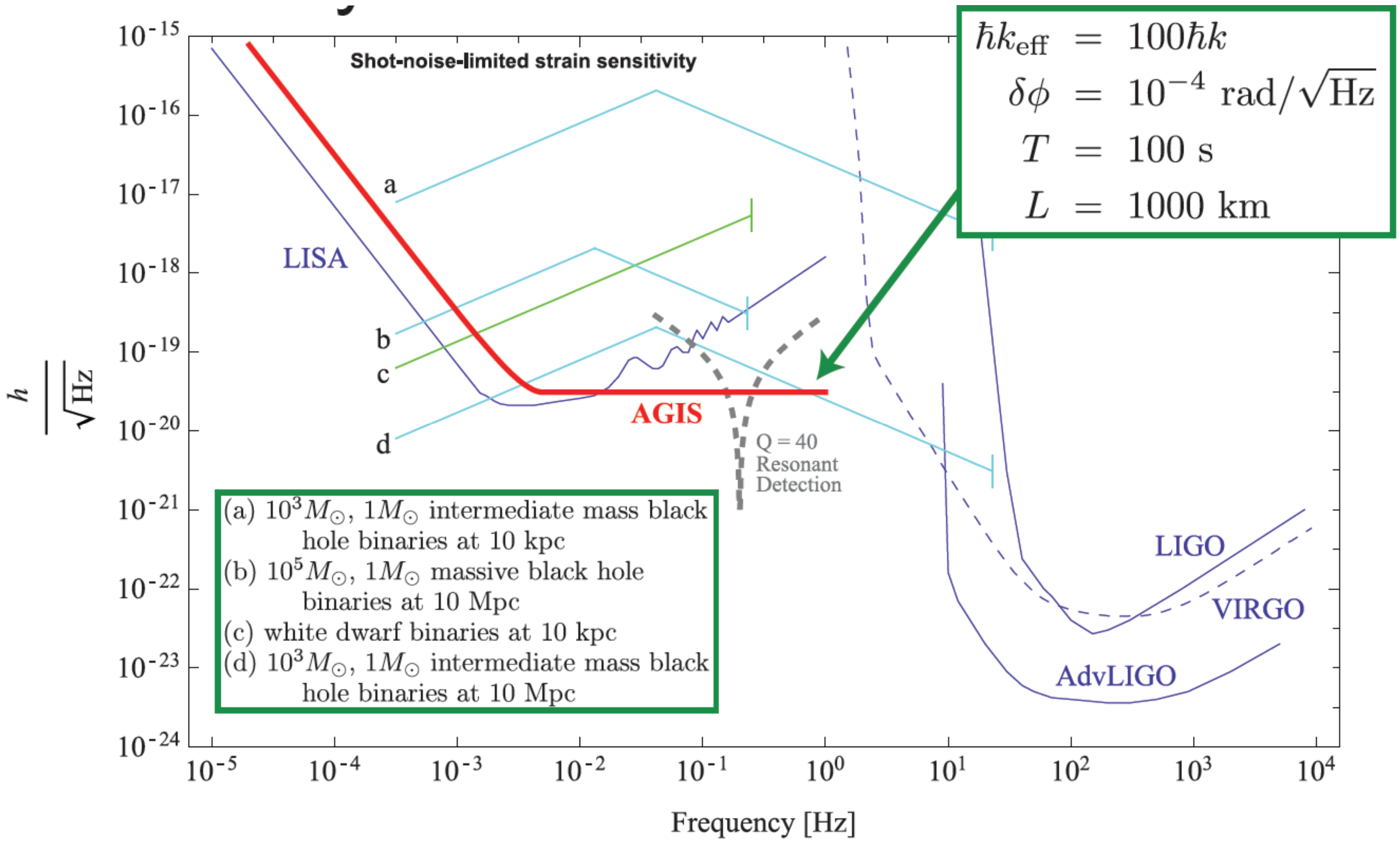






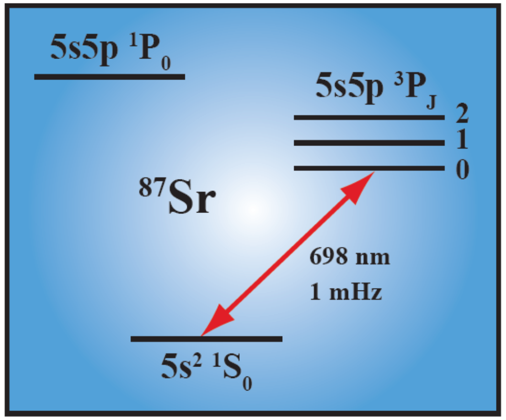
JMAPS bus/ESPA deployed

Potential Strain Sensitivity



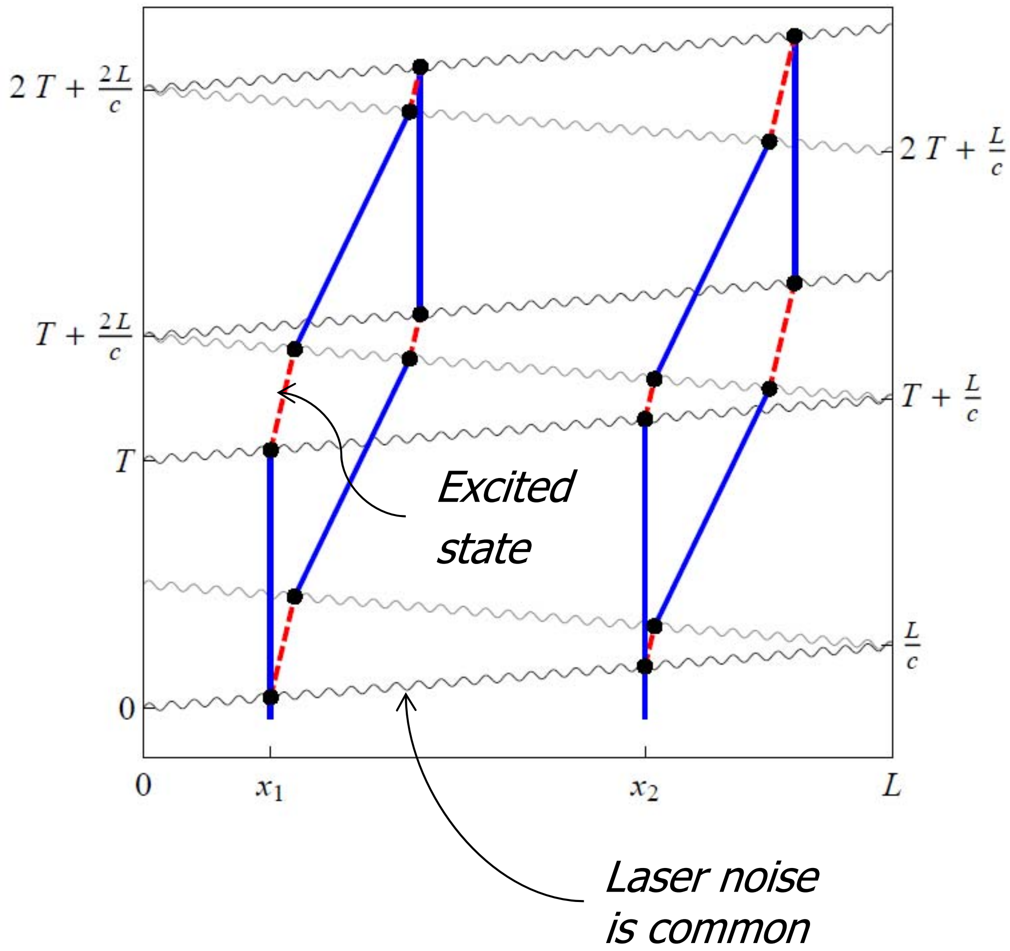
J. Hogan, et al., GRG **43**, 7 (2011).

Laser frequency noise insensitive detector



Clock transition in candidate atom ^{87}Sr

- Long-lived single photon transitions (e.g. clock transition in Sr, Ca, Yb, Hg, etc.).
- Atoms act as clocks, measuring the light travel time across the baseline.
- GWs modulate the laser ranging distance.



Graham, *et al.*, arXiv:1206.0818, PRL (2013)

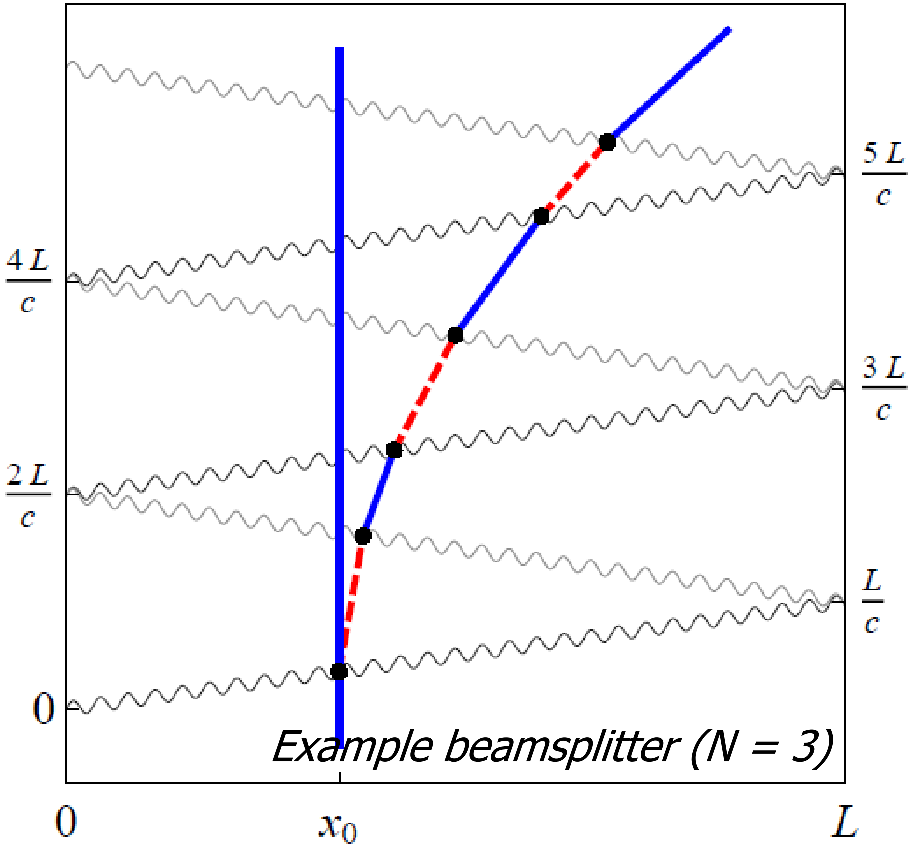
Atom optics with single photon transitions

$$\Delta\phi = \frac{4N\omega_a h}{c}(x_1 - x_2)\sin^2\left(\frac{\omega T}{2}\right)\sin\left(\phi_0 + \omega T\right)$$

GW phase shift for interferometer sequence

Atomic transition freq.

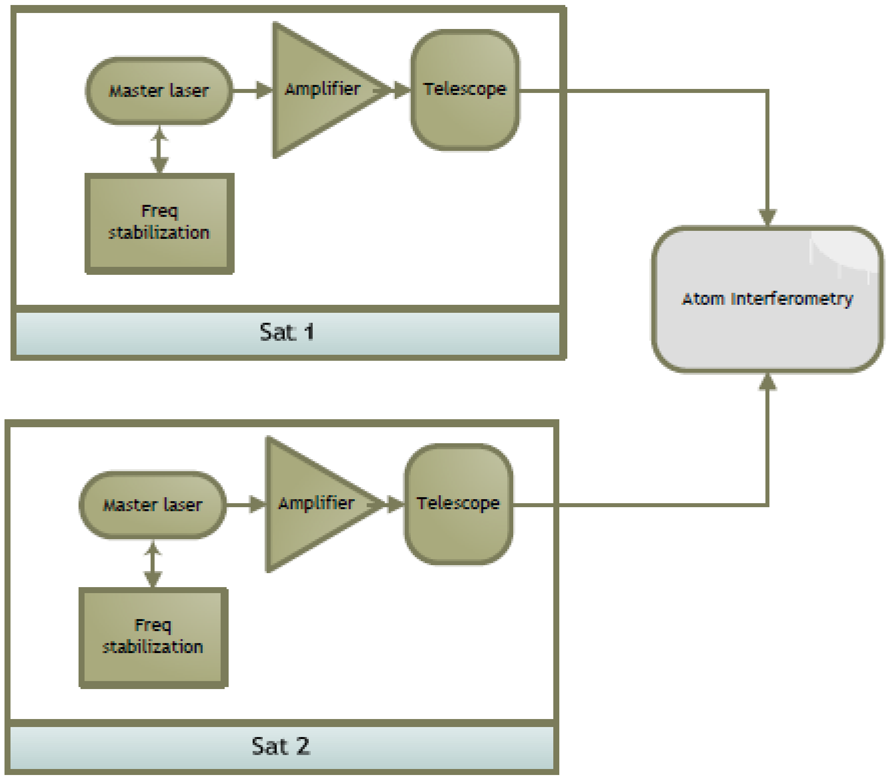
GW phase

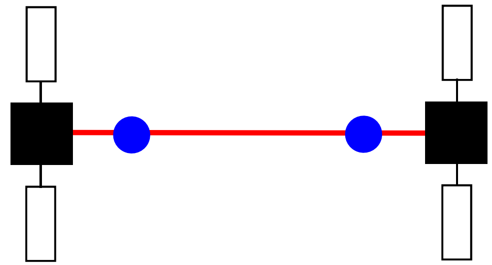


Example beamsplitter (N = 3)

- Large N realized by sequential pulses from alternating directions.
- Selectively accelerate one arm with a series of pulses

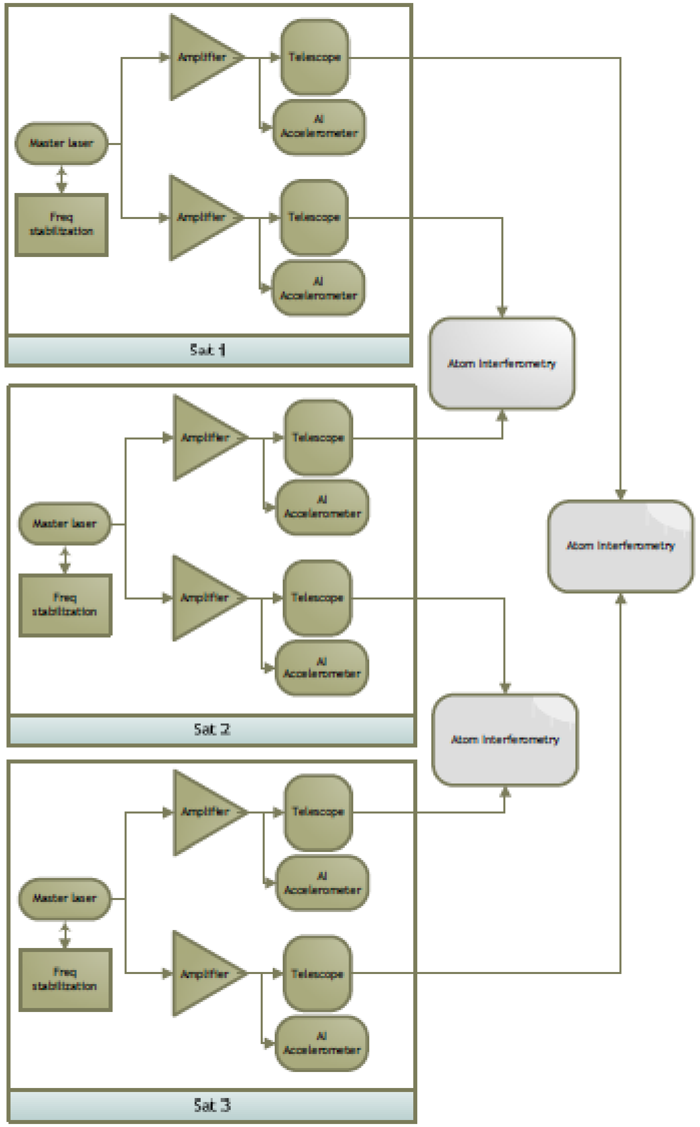
2 Satellite Sr Single Photon

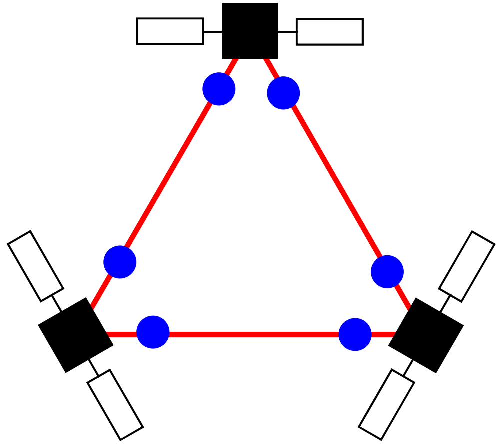




- Single baseline (two satellites)
- Single photon atom optics (e.g., Sr) for laser and satellite acceleration noise immunity
- Atoms act as clocks, measuring the light travel time across the baseline

3 Satellite Rb

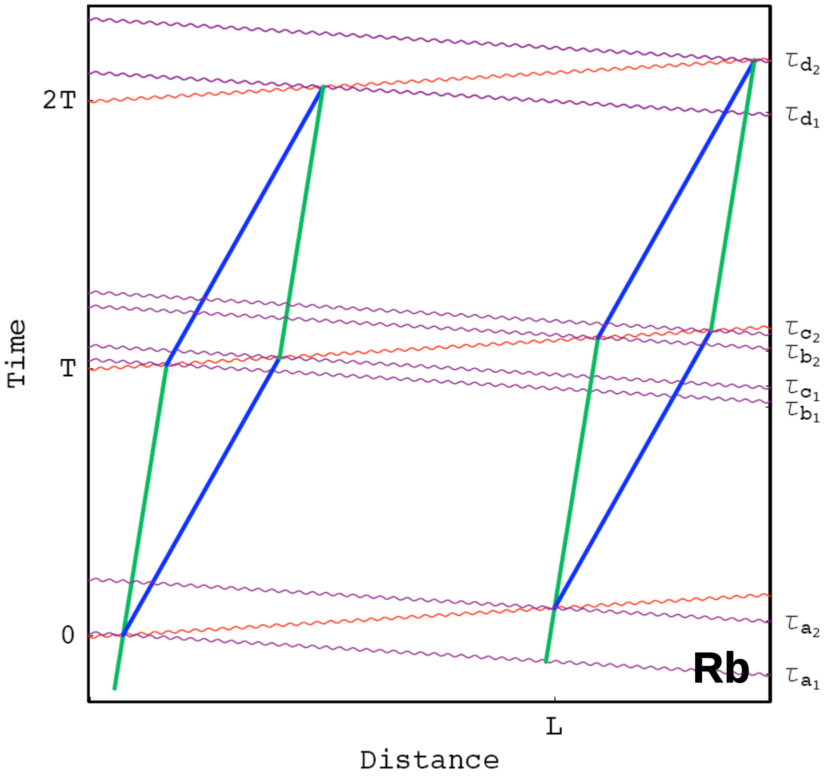




- Conventional, proven atom optics (Rb atom)
- Three satellites allow TDI for compensation of laser frequency noise.
- AI accelerometers to measure satellite vibration noise, which leads to laser frequency noise due to the Doppler effect.

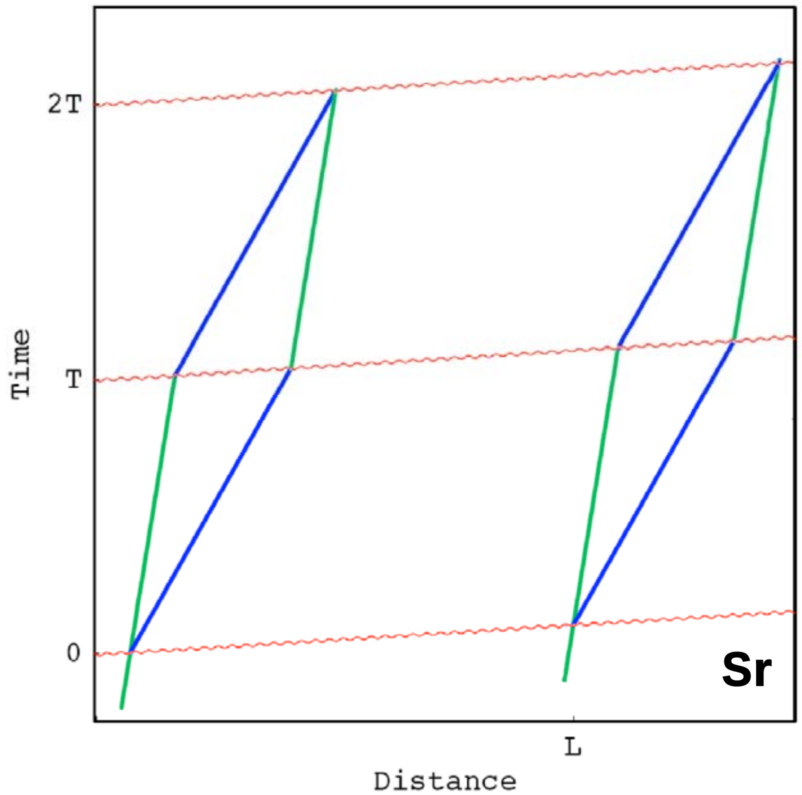
Two-photon vs. Single photon configurations

2-photon transitions



GW signal from relative positions of atom ensembles with respect to optical phase fronts.

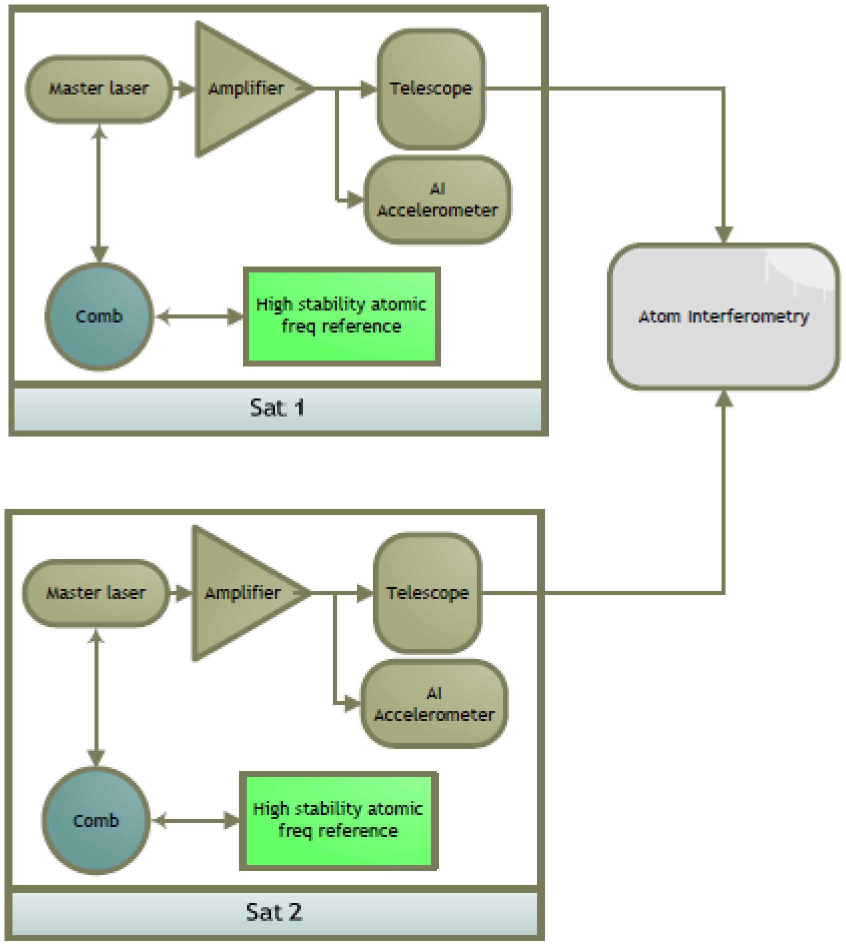
1 photon transitions

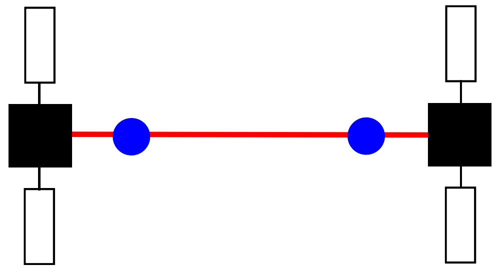


GW signal from light propagation time between atom ensembles.

Dimopoulos, et al., PRD (2008)

2 Satellite Rb + Atomic Reference





- Conventional, proven atom optics (Rb atom)
- Single baseline (two satellites)
- Atomic frequency reference (e.g., Sr) for laser noise tracking
- AI accelerometers to measure satellite vibration noise

Requirements for h = $1e\text{-}20/Hz^{1/2}$

Attribute	Req.
Sat. acceleration noise (longitudinal)	10^{-8} g/$Hz^{1/2}$
Transverse position jitter	10 nm/$Hz^{1/2}$
Spatial wavefront	$\lambda/100$
Atom cloud temperature	1 pK
Pointing stability	0.1 μrad
Magnetic fields	4 nT/$Hz^{1/2}$
Laser phase noise	10 Hz linewidth; 100 kHz/$Hz^{1/2}$
Atom optics	100 ħk
Formation flying	2 satellites
Atom source	10^8/s Sr

Risk

Noise source	Risk
Magnetic Fields	Low
AC Stark	Low
Laser intensity jitter	Low
Atom source velocity jitter	Mid
Laser pointing jitter	Mid
Solar radiation	Low
Blackbody	Low
Atom flux	Low
Laser wavefront noise	High?
Atom detection noise	High?
Gravity gradient	Mid

See analysis in Graham, *et al.*, arXiv:1206.0818, PRL (2013)
(and references therein).

Error Model

Analysis to determine requirements on satellite jitter, laser pointing stability, atomic source stability, and orbit gravity gradients.

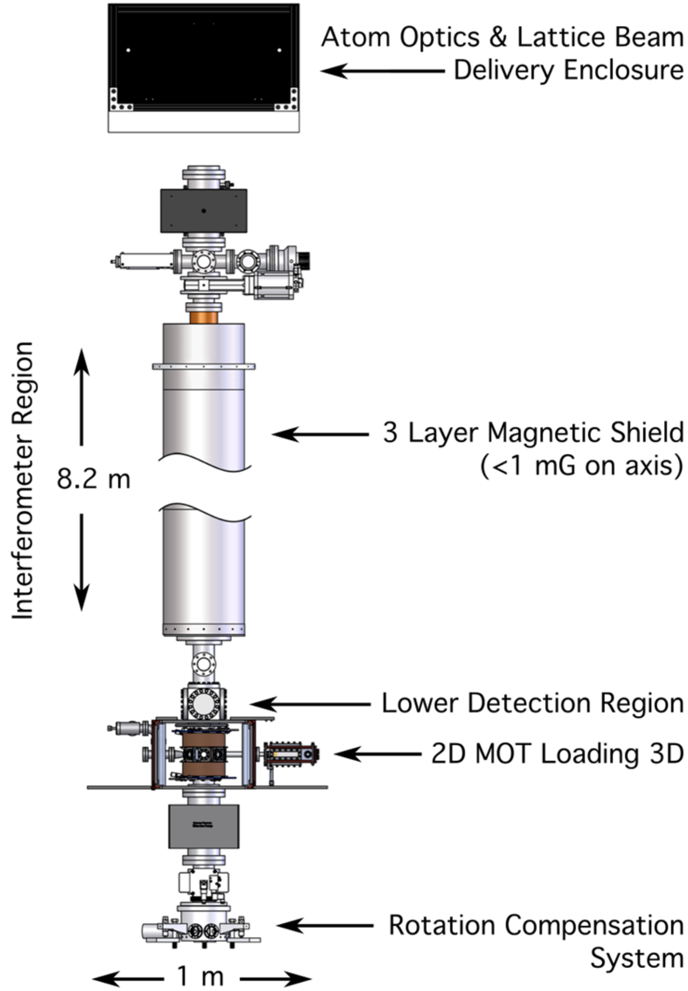
	Differential phase shift	Size (rad)	Constraint
1	$\frac{1485 k_{\text{eff}}^3 \hbar^2}{4 L m^2} T^6 T_{\text{xx}} \Omega_{\text{or}} \delta\Omega$	$(180\text{ s})\delta\Omega$	$\delta\Omega < 0.57\ \mu\text{rad/s}$
2	$\frac{1485 k_{\text{eff}}^3 \hbar^2}{2 L m^2} T^6 \Omega_{\text{or}}^3 \varepsilon_{zz} \delta\Omega$	$(350\text{ s})\varepsilon_{zz}\delta\Omega$	$\varepsilon_{zz} < 0.50$
3	$\frac{15}{2} k_{\text{eff}} T^4 R \Omega_{\text{or}}^2 \left(15T\left(T_{zz} + 3\Omega_{\text{or}}^2\right) + 8\Phi\Omega_{\text{or}}\right)\varepsilon_g \delta\Omega$	$(3\times 10^9\text{ s})\,\varepsilon_g \delta\Omega$	$\varepsilon_g < 5.8\times 10^{-8}$
4	$30 k_{\text{eff}} T^4 \Omega_{\text{or}}^4 \varepsilon_{\text{xx}} (\delta x_{\text{n}} - \delta x_{\text{f}})$	$(22\text{ m}^{-1})\varepsilon_{\text{xx}}(\delta x_{\text{n}} - \delta x_{\text{f}})$	$(\delta x_{\text{n}} - \delta x_{\text{f}})\varepsilon_{\text{xx}} < 4.5\ \mu\text{m}$
5	$15 k_{\text{eff}} T^4 T_{\text{xx}} \Omega_{\text{or}} \left(\frac{k_{\text{eff}}\hbar}{Lm} + 9T\Omega_{\text{or}}^2\right)(\delta z_{\text{f}} - \delta z_{\text{n}})$	$(0.84\text{ m}^{-1})(\delta z_{\text{f}} - \delta z_{\text{n}})$	$(\delta z_{\text{f}} - \delta z_{\text{n}}) < 120\ \mu\text{m}$
6	$30 k_{\text{eff}} T^4 \Omega_{\text{or}}^3 \left(\frac{k_{\text{eff}}\hbar}{Lm} + 9T\Omega_{\text{or}}^2\right)\varepsilon_{zz}(\delta z_{\text{f}} - \delta z_{\text{n}})$	$(1.7\text{ m}^{-1})\varepsilon_{zz}(\delta z_{\text{f}} - \delta z_{\text{n}})$	$\varepsilon_{zz} < 0.49$
7	$\frac{45}{2} k_{\text{eff}} T^5 \left(T_{\text{xx}}^2 + 6T_{\text{xx}}\Omega_{\text{or}}^2 + 4T_{zz}\Omega_{\text{or}}^2 + 5\Omega_{\text{or}}^4\right)\Delta v_x$	$(270\text{ s/m})\Delta v_x$	$\Delta v_x < 370\text{ nm/s}$
8	$3 k_{\text{eff}} T^4 \Omega_{\text{or}} \left(\frac{9 k_{\text{eff}}^2 \hbar^2}{L^2 m^2} - 5T_{\text{xx}}\right)\Delta v_z$	$(9.6\times 10^3\text{ s/m})\,\Delta v_z$	$\Delta v_z < 10\text{ nm/s}$
9	$30 k_{\text{eff}} T^4 \varepsilon_{zz} \Omega_{\text{or}}^3 \Delta v_z$	$(1.9\times 10^4\text{ s/m})\,\varepsilon_{zz}\Delta v_z$	$\varepsilon_{zz} < 0.52$
10	$60 \frac{\hbar k_{\text{eff}}^2}{L^2 m} T^4 T_{\text{yy}} \delta v_{\text{yn}} \delta y_{\text{n}}$	$(4.3\times 10^{-2}\text{ s/m}^2)\,\delta v_{\text{yn}}\delta y_{\text{n}}$	$\delta v_{\text{yn}}\delta y_{\text{n}} < 23\text{ cm}^2/\text{s}$
11	$36 k_{\text{eff}}^3 \frac{\hbar^2}{Lm^2} \Omega_{\text{or}} T^3 (7 + 8\cos(\omega T))\sin^4\left(\frac{\omega T}{2}\right)\overline{\delta\theta}$	$(3.9\times 10^5)\,\overline{\delta\theta}$	$\overline{\delta\theta} < 0.26\text{ nrad}$
12	$4 k_{\text{eff}} \delta z_n (7 + 8\cos(\omega T))\sin^4\left(\frac{\omega T}{2}\right)\overline{\delta\theta}$	$(1.3\times 10^{10}\text{ m}^{-1})\,\delta z_n \overline{\delta\theta}$	$\overline{\delta\theta} < 0.77\text{ nrad}$
13	$\frac{27\sqrt{2}}{4} k_{\text{eff}} x_n \frac{L}{R} \Omega_{\text{or}}^2 T^2 \chi(\omega T)\overline{\delta\theta}$	$(1.1\times 10^4)\,x_n \overline{\delta\theta}$	$\overline{\delta\theta} < 0.91\text{ nrad}$

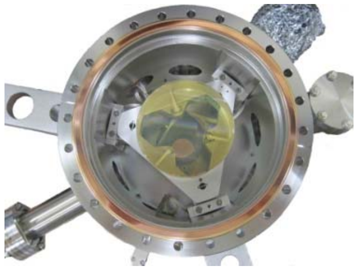
J. Hogan et al., GRG **43**, 7 (2011).

Atom technology roadmap

1) Large wavepacket separation
2) Ultracold atom temperatures
3) Optical wavefront noise characterization and mitigation
4) Phase readout
5) Satellite rotation jitter mitigation
6) Strontium atom interferometry development

Demonstration apparatus





Ultracold atom source

- $>10^6$ at 50 nK

Optical Lattice Launch

- 13.1 m/s with 2372 photon recoils to 9 m

Atom Interferometry

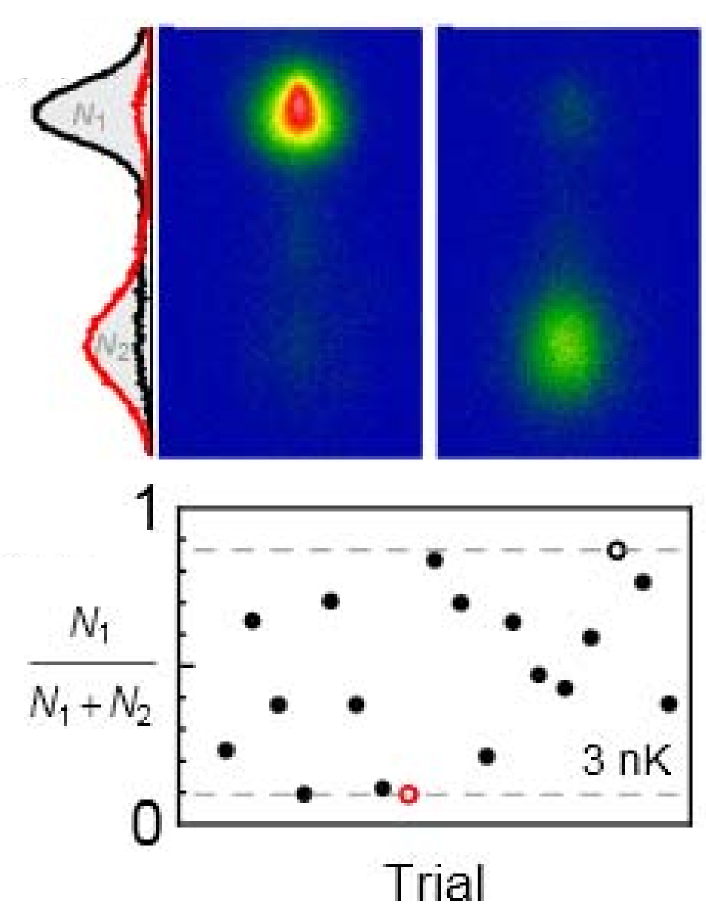
- 2 cm $1/e^2$ radial waist
- 500 mW total power
- Dyanmic nrad control of laser angle with precision piezo-actuated stage

Detection

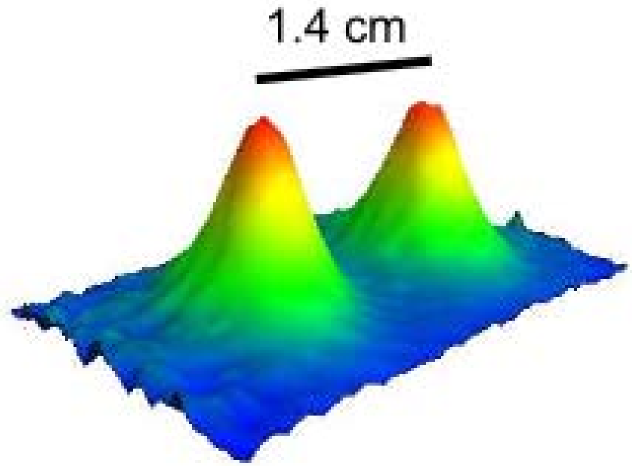
- Spatially-resolved fluorescence imaging
- Two CCD cameras on perpendicular lines of sight

Might achieve h ~ 3e-19/$Hz^{1/2}$ resolution on ground near 1 Hz

Interference at long interogation time



Interference



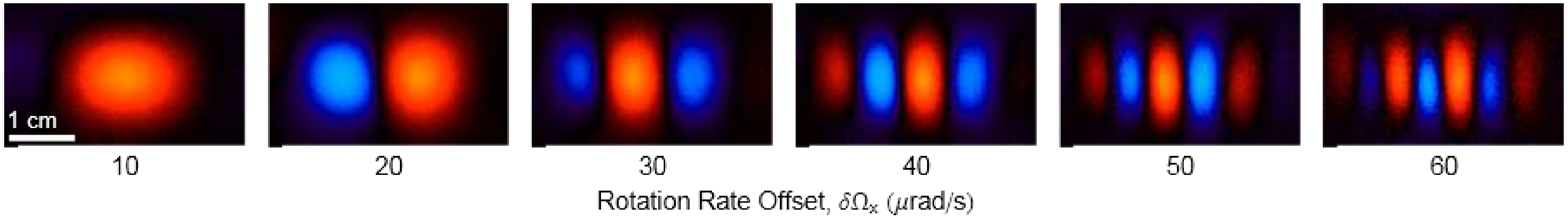
Wavepacket separation at apex

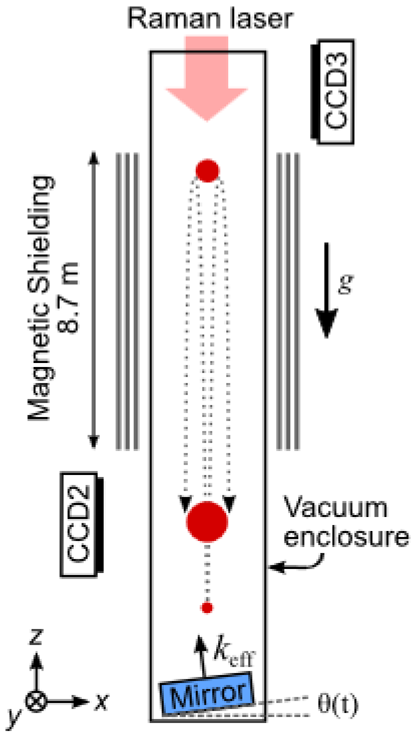
2T = 2.3 sec
Near full contrast
3 nK
6.7e-12 g/shot

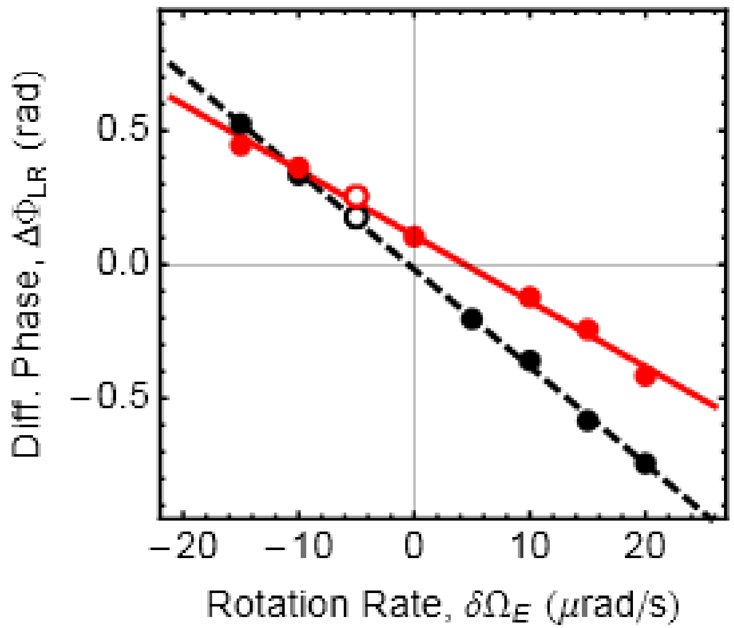
Dickerson, et al., arXiv:1305.1700 (2013)

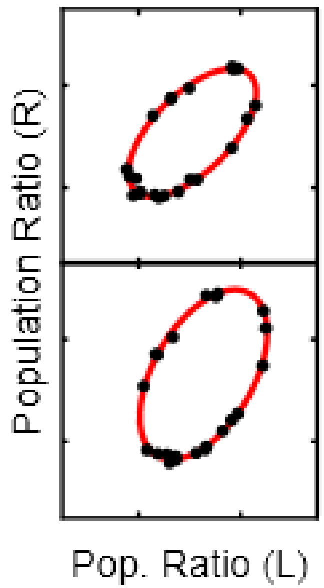
2-axis rotation measurement

Interference patterns for rotating platform:







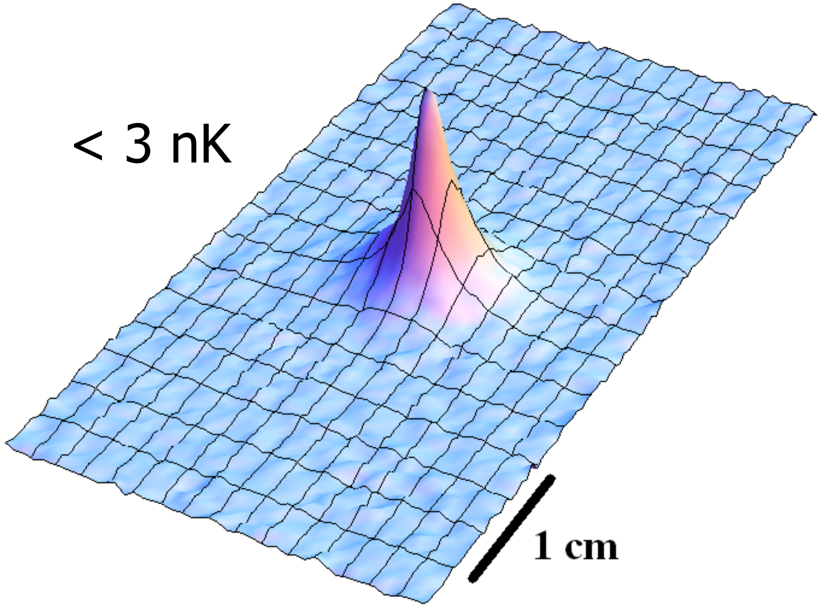


Measurement of rotation rate near null rotation operating point. Other form factors possible!

Dickerson, et al., arXiv:1305.1700 (2013)

Magnetic lens cooling

Cold atom temperatures are required for efficient excitation sequences.

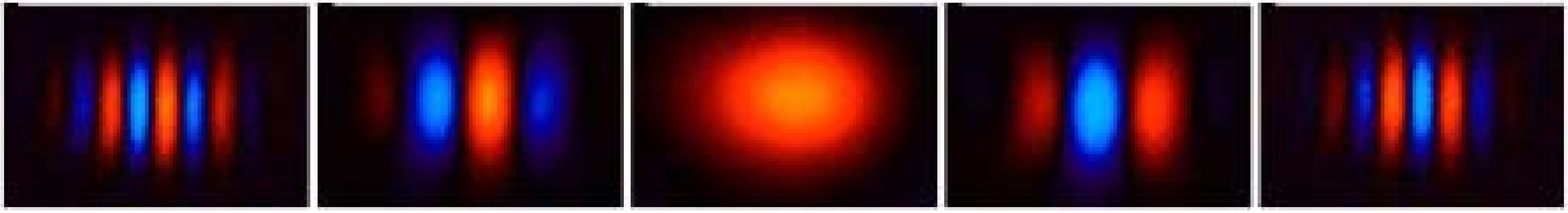


Atom cloud imaged after 2.6 seconds free-fall

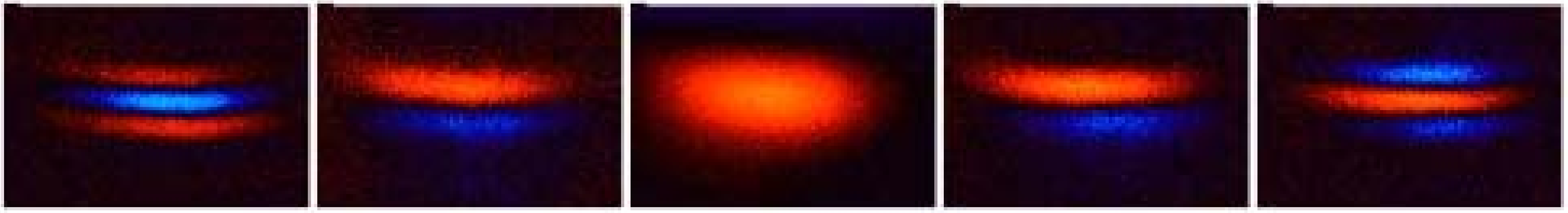
Cooling performance limited by Earth gravity.

Extrapolated microgravity performance: 1e-12 K.

Phase shear readout



Shear via laser beam tilt

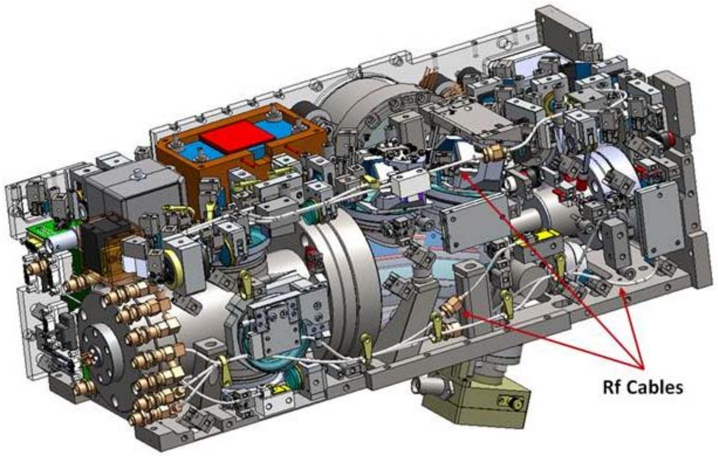


Shear via interferometer timing asymmetry

Enables simultaneous read-out of contrast and phase

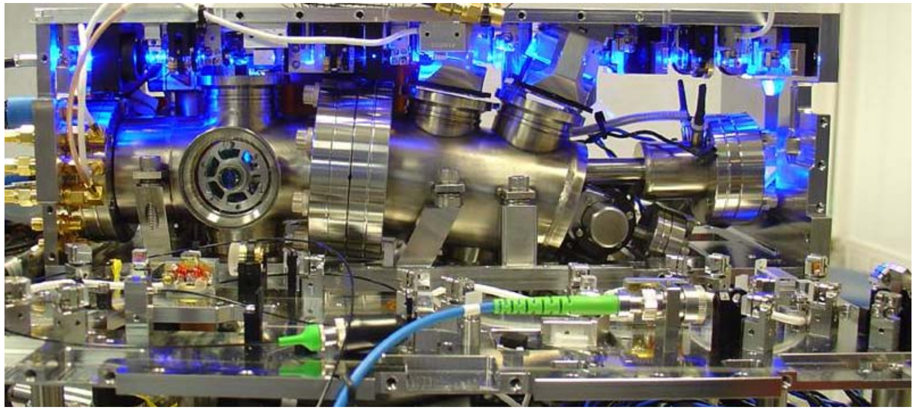
Sugarbaker, et al., arXiv:1305.3298 (2013).

DARPA QuASAR SBOC-1/Optical clock



6 liter physics package.

Contains all lasers, Sr source, 2D MOT, Zeeman slower, spectrometer, pumps, and 3 W Sr oven; 4e10 cold a/sec.



As built view with front panel removed in order to view interior.

AOSense

408-735-9500
AOSense.com
Sunnyvale, CA

Collaborators

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Also
Philippe Bouyer (CNRS)

NASA Goddard Space Flight Center

Babak Saif
Bernard D. Seery
Lee Feinberg
Ritva Keski-Kuha

AOSense

Kinematic Noise Sensitivity

Laser noise cancels. What are the remaining sources of noise?

Relative velocity Δv between the interferometers changes the time spent in the excited state, leading to a differential phase shift.

Leading order kinematic noise sources:

	Phase Shift	Control Required
1.	$N\frac{\Delta v}{c}\frac{\omega_a}{c}T^2\delta a$	$\delta a \lesssim 10^{-8} g/\sqrt{\text{Hz}}$
2.	$N\frac{\Delta v}{c}\omega_a\delta T$	$\delta T \lesssim 10^{-12}\ \text{s}$
3.	$N\Delta v\,\delta k\,\Delta\tau$	$c\delta k/2\pi \lesssim 10^2\ \text{kHz}/\sqrt{\text{Hz}}$
4.	$N^2\frac{\Delta v}{c}\frac{\hbar}{m}\frac{\omega_a}{c}T\delta k$	$c\delta k/2\pi \lesssim \text{GHz}/\sqrt{\text{Hz}}$

1. Platform acceleration noise δa

2. Pulse timing jitter δT

3. Finite duration $\Delta\tau$ of laser pulses

4. Laser frequency jitter δk

Most severe constraint on laser frequency noise is that laser needs to be resonant with the transition
(linewidth < transition Rabi freq.)

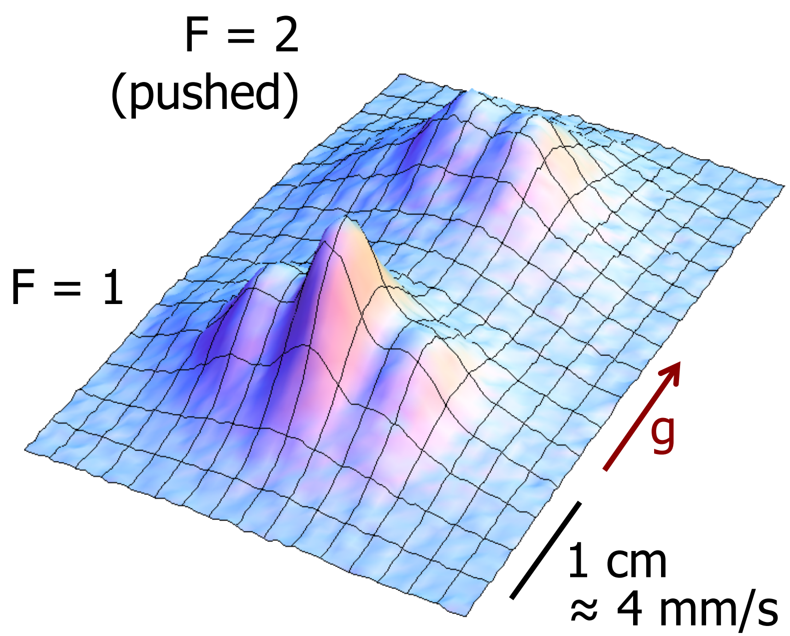
System architectures under study

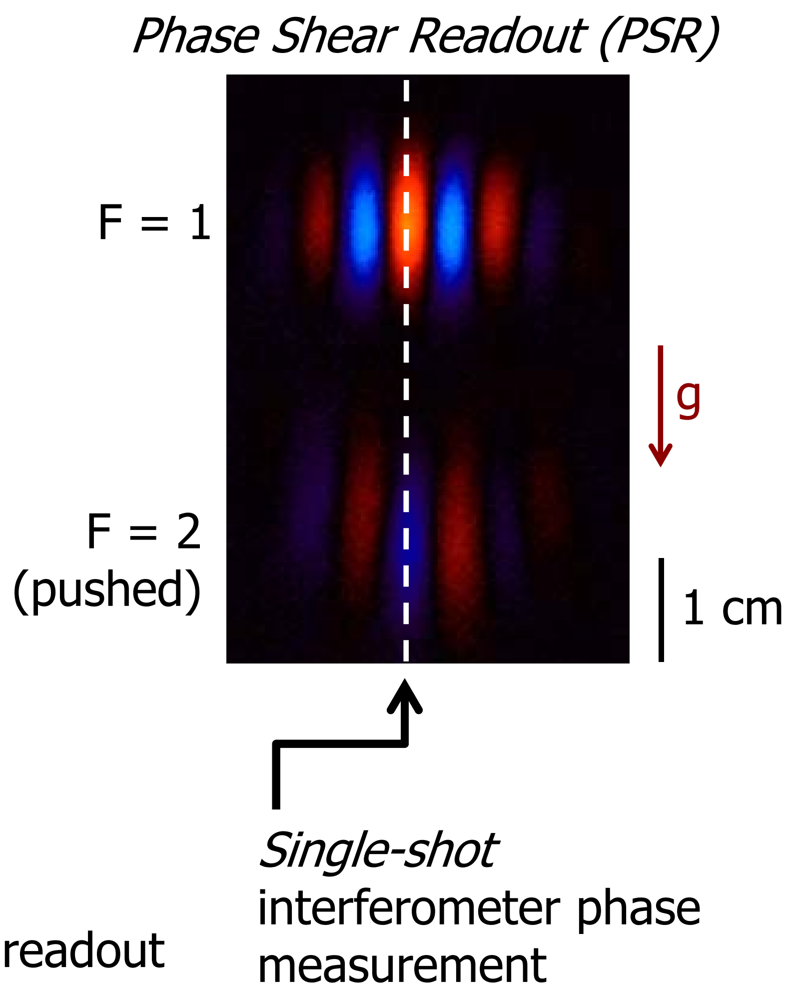
Currently evaluating several architectures:

1) Three satellite, Rb
2) Two satellite, Rb + atomic phase reference
3) Two satellite, Sr, single photon transition

Top level trade space is driven by strategy employed to mitigate laser frequency noise, which, if uncontrolled, will mask GW signatures.

Phase shear readout



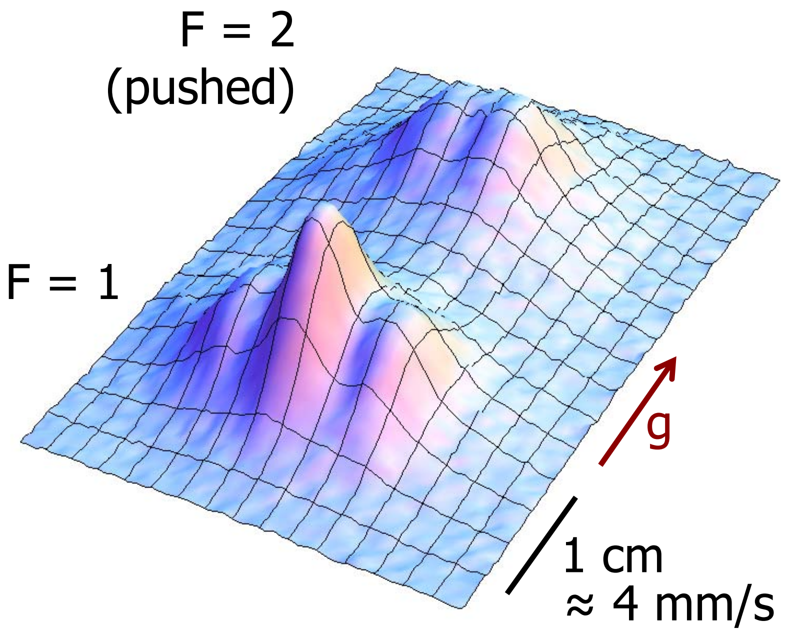


Mitigates noise sources:

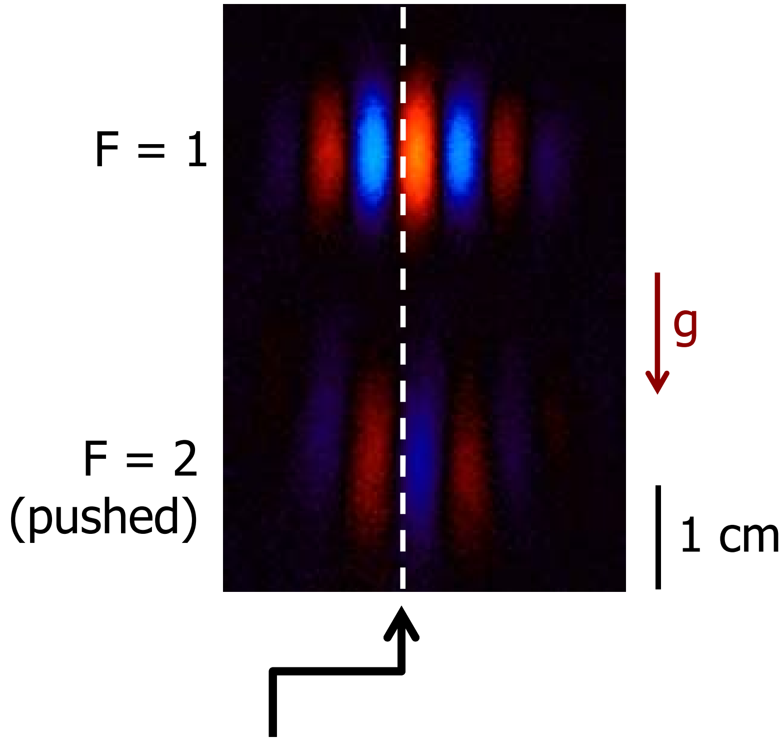
✓ Satellite pointing jitter and residual rotation readout

✓ Laser wavefront aberration in situ characterization

Phase Shear Readout



Phase Shear Readout (PSR)

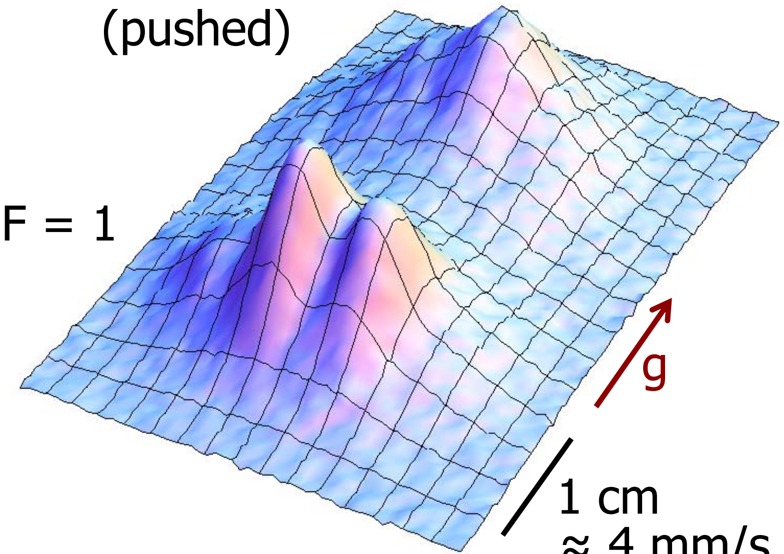


Single-shot interferometer phase measurement

Mitigates noise sources:

- ✓ Satellite pointing jitter and residual rotation readout
- ✓ Laser wavefront aberration in situ characterization

Phase Shear Readout



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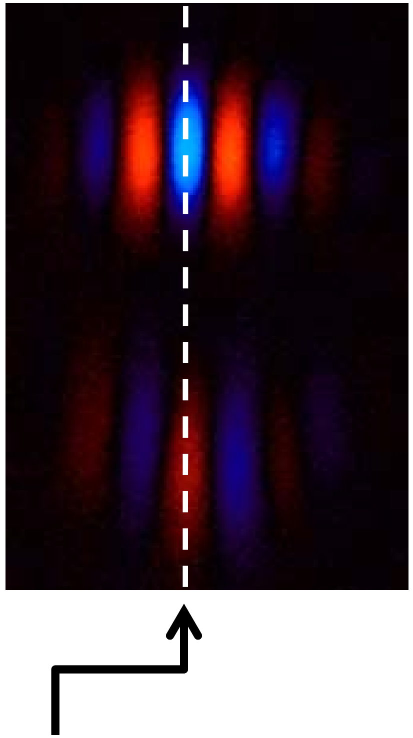

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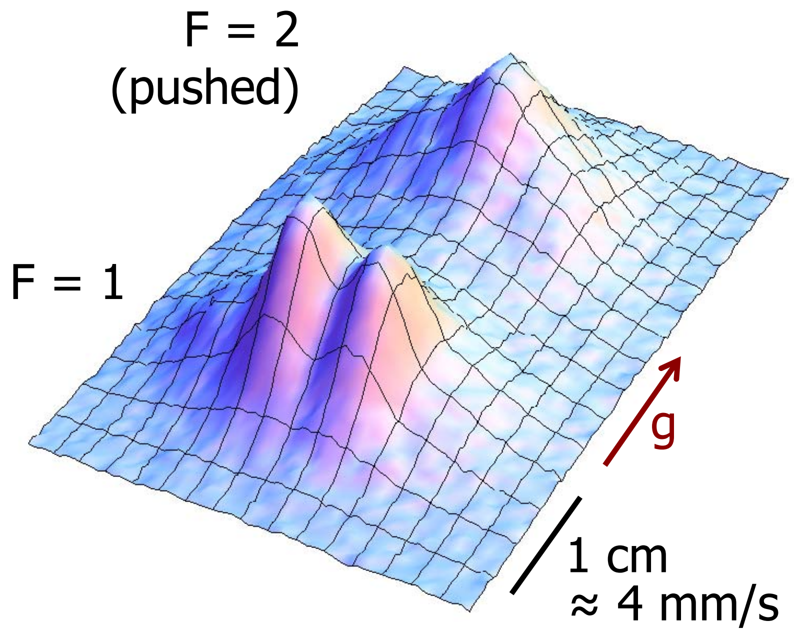
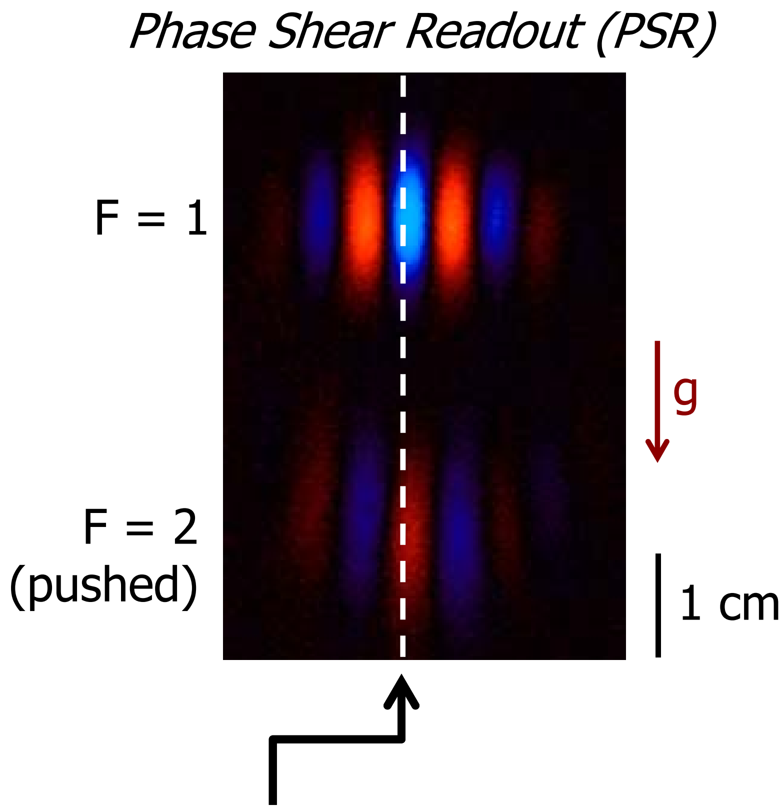
Phase Shear Readout





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