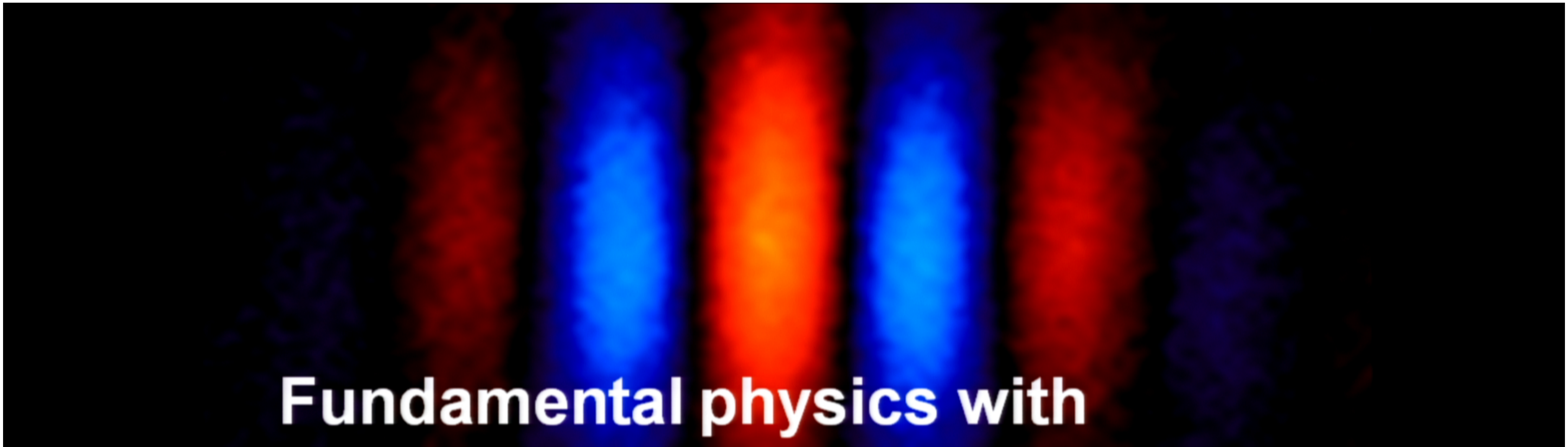
Title: Fundamental physics with atom interferometry

Date: Jun 17, 2014 11:00 AM

URL: http://pirsa.org/14060016

Abstract: Precision atom interferometry is poised to become a powerful tool for discovery in fundamental physics. Towards this end, I will describe recent, record-breaking atom interferometry experiments performed in a 10 meter drop tower that demonstrate long-lived quantum superposition states with macroscopic spatial separations. The potential of this type of sensor is only beginning to be realized, and the ongoing march toward higher sensitivity will enable a diverse science impact, including new limits on the equivalence principle, probes of quantum mechanics, and detection of gravitational waves. Gravitational wave astronomy is particularly compelling since it opens up a new window into the universe, collecting information about astrophysical systems and cosmology that is difficult or impossible to acquire by other methods. Atom interferometric gravitational wave detection offers a number of advantages over traditional approaches, including simplified detector geometries, access to conventionally inaccessible frequency ranges, and substantially reduced antenna baselines.



Fundamental physics with atom interferometry

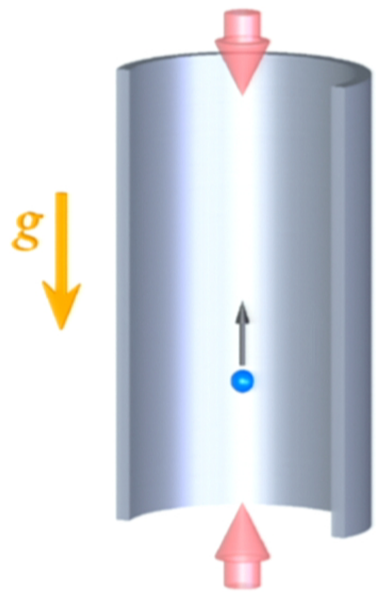
Perimeter Institute

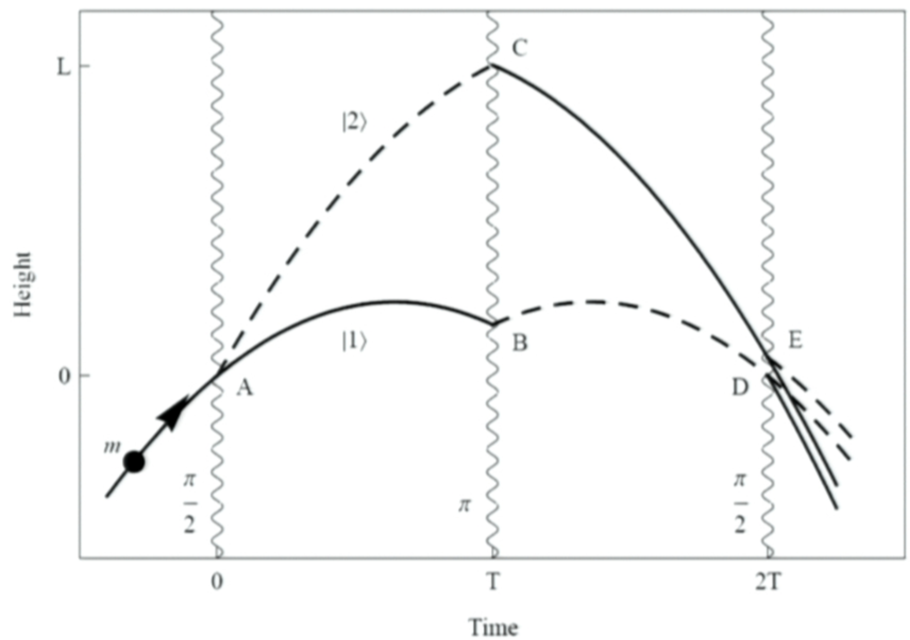
Jason Hogan

June 17, 2014

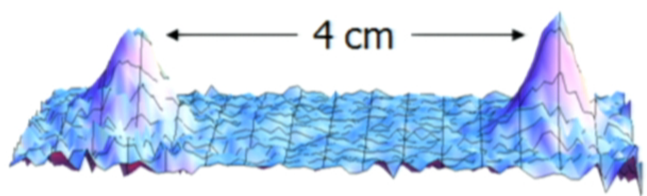
STANFORD UNIVERSITY

Light Pulse Atom Interferometry





- Long duration
- Large wavepacket separation



STANFORD UNIVERSITY

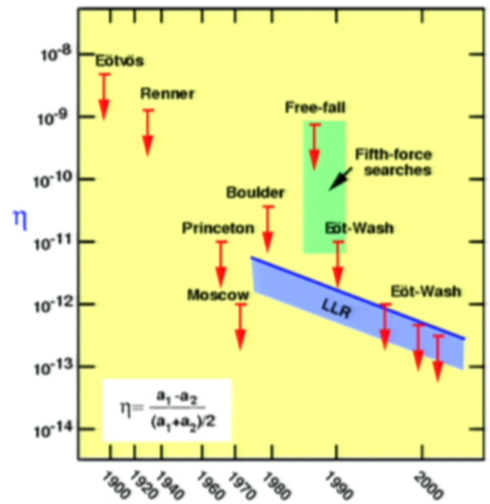
Equivalence Principle

Bodies fall at the same rate, independent of composition

$$\eta = \frac{\Delta a}{\bar{a}}$$

Why test the EP?

- Foundation of General Relativity
- Quantum theory of gravity (?)



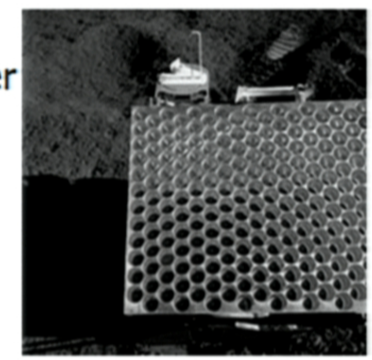
C. Will, *Living Reviews*

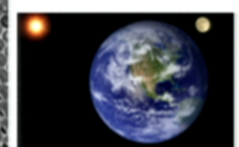
^{85}Rb vs ^{87}Rb

★ 10^{-15} (?)

Torsion balance (University of Washington)

Lunar Laser Ranging





STANFORD UNIVERSITY

Projected Sensitivity

$$\frac{\delta g}{g} \sim \frac{\delta\phi}{k_{\text{eff}} g T^2}$$

$$\Delta\phi = k_{\text{eff}} g T^2 \approx 3\times10^8 \text{ rad}$$

$(2T \sim 2$ s, $k_{\text{eff}} = 2k)$

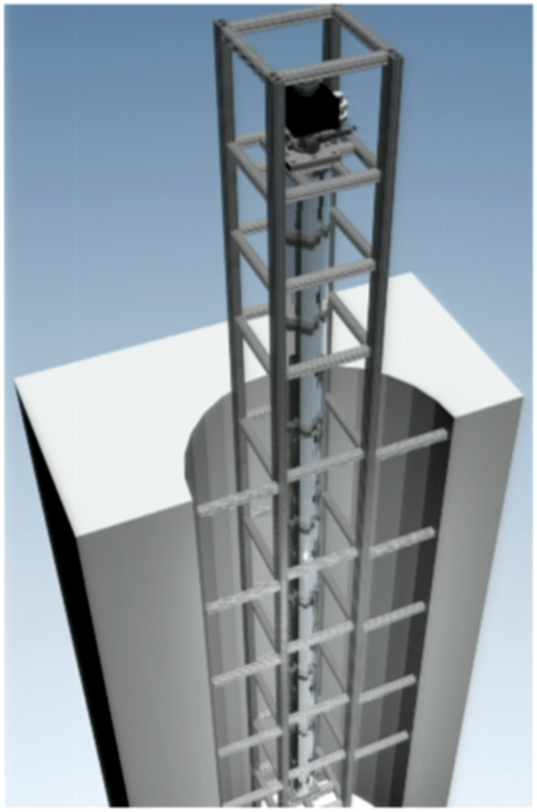
Shot noise limited detection @ 10^7 atoms per shot:

$$\delta\phi \sim \frac{1}{\sqrt{N}} \sim 3\times10^{-7} \text{ rad}$$

(~ 1 month)

$$\delta g < 10^{-15} g$$

10 m atom drop tower



Equivalence Principle Test

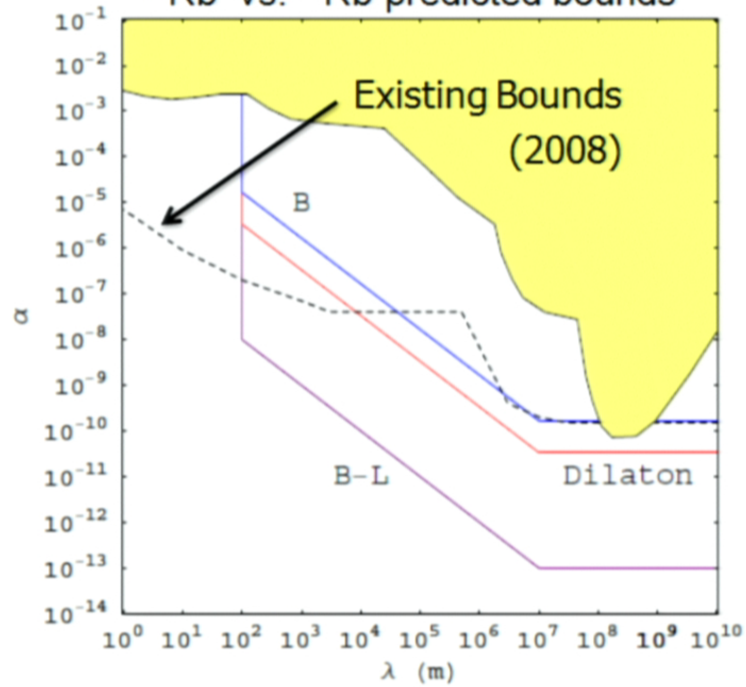
Violations of EP due to fifth forces

Yukawa type:

$$V(r) = -\frac{GM_1M_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

EP tests are sensitive to charge differences of new forces

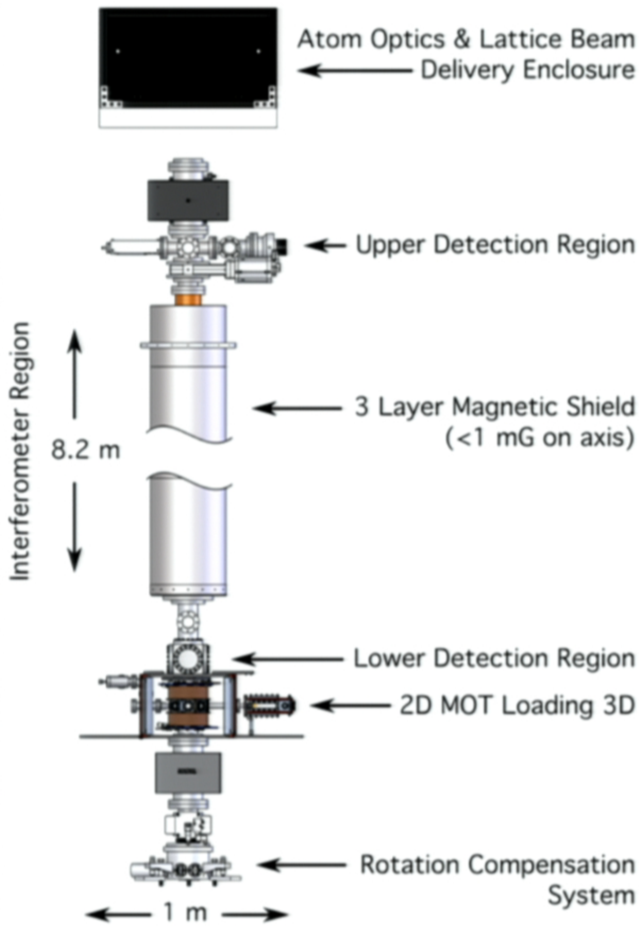
^{85}Rb vs. ^{87}Rb predicted bounds

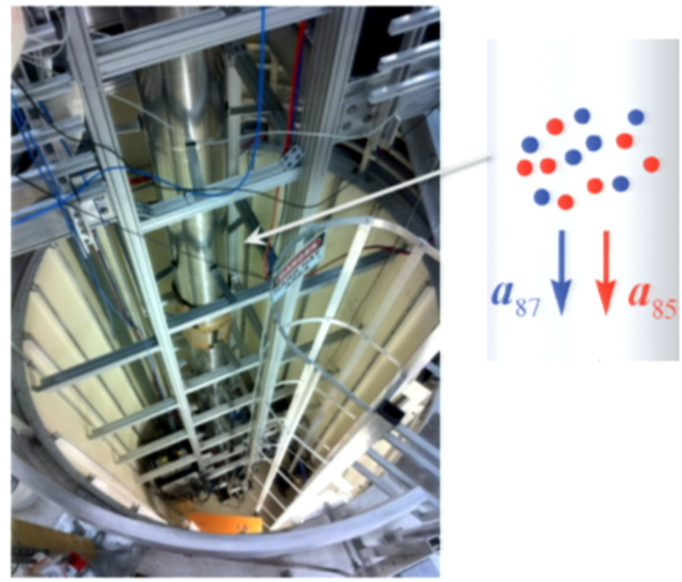


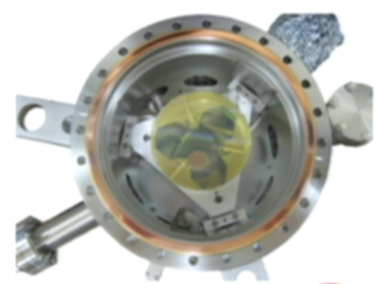
Analysis by P. Graham

STANFORD UNIVERSITY

Apparatus

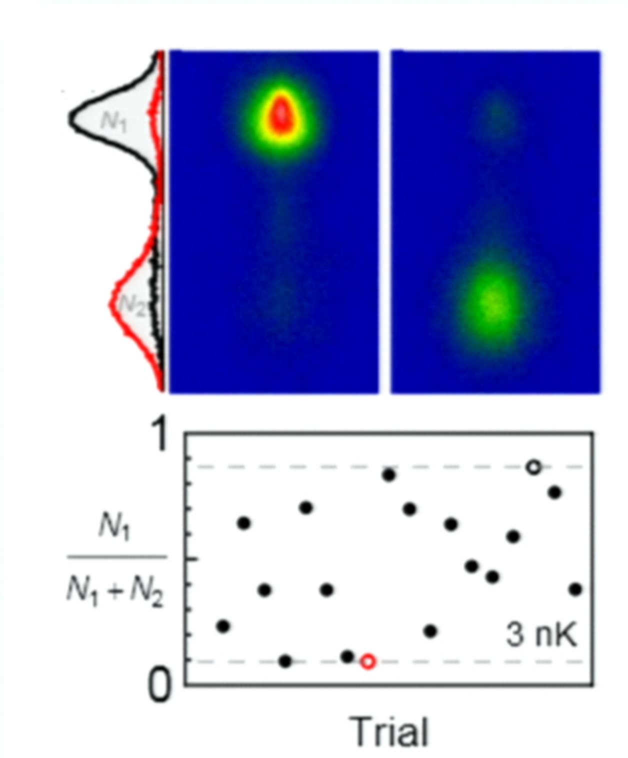




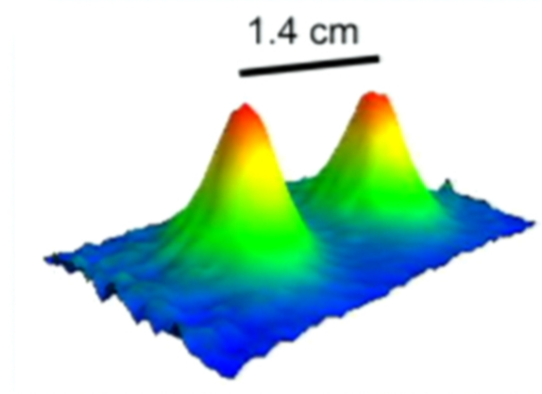


STANFORD UNIVERSITY

Interference at long interrogation time



Interference (3 nK cloud)



Wavepacket separation at apex (this data 50 nK)

2T = 2.3 sec
Near full contrast
6.7×10^{-12} g/shot (inferred)

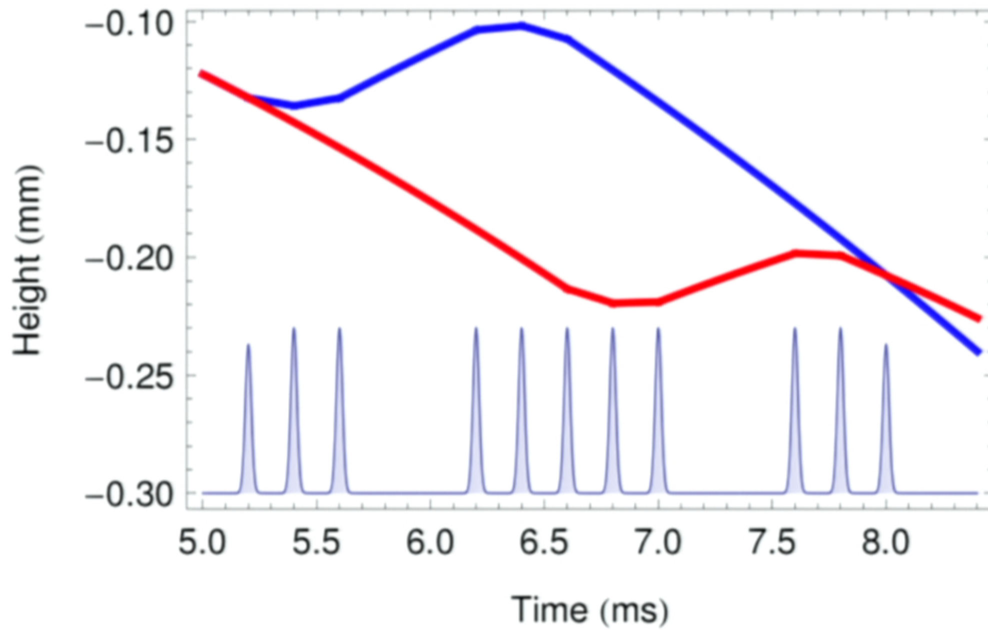
Demonstrated statistical resolution: $\sim 5\times10^{-13}\,g$ in 1 hr (^{87}Rb)

STANFORD UNIVERSITY

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

Large momentum transfer atom optics

Sequences of optical pulses can be used to realize large separations between interferometer arms.



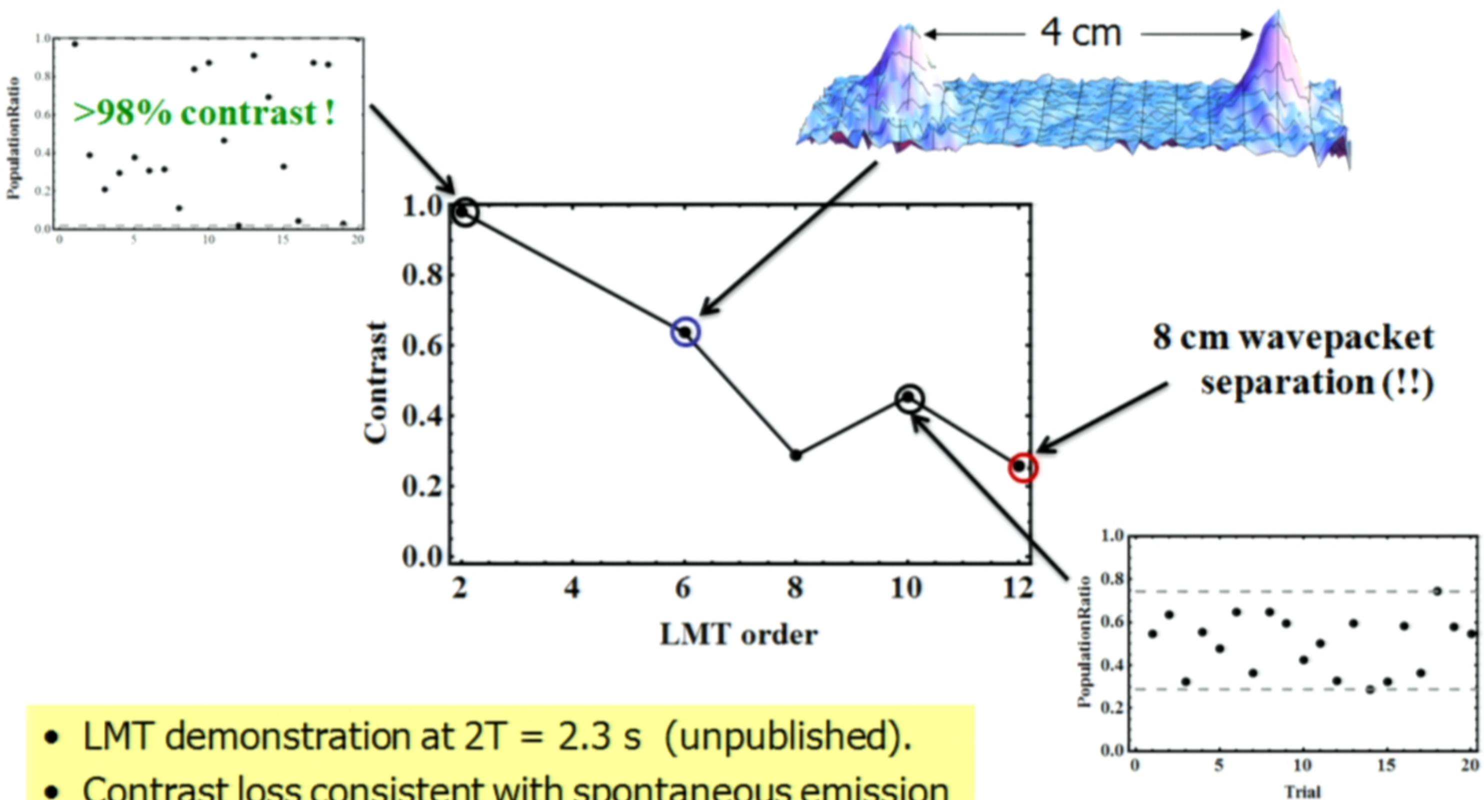
Example interferometer pulse sequence

Chiow, PRL, 2011

STANFORD UNIVERSITY

LMT in 10 m apparatus

LMT using **sequential Raman** transitions with long interrogation time.



- LMT demonstration at 2T = 2.3 s (unpublished).
- Contrast loss consistent with spontaneous emission

General Relativity Effects

Schwarzschild metric, PPN expansion:

$$ds^2 = (1 + 2\phi + 2\beta\phi^2)dt^2 - (1 - 2\gamma\phi)dr^2 - r^2 d\Omega^2$$

$$\frac{d\vec{v}}{dt} = -\vec{\nabla}[\phi + (\beta + \gamma)\phi^2] + \gamma[3(\vec{v}\cdot\hat{r})^2 - 2\vec{v}^2]\vec{\nabla}\phi + 2\vec{v}(\vec{v}\cdot\vec{\nabla}\phi).$$

Newtonian Gravity

Gravity Gravitates

Kinetic Energy Gravitates

Corresponding AI phase shifts:

	Phase Shift	Size (rad)	Interpretation
1.	$-k_{\text{eff}} g T^2$	3×10^8	gravity
2.	$-k_{\text{eff}}(\partial_r g) T^3 v_L$	-2×10^3	1st gradient
3.	$-3k_{\text{eff}} g T^2 v_L$	4×10^1	Doppler shift
4.	$(2-2\beta-\gamma)k_{\text{eff}} g\phi T^2$	2×10^{-1}	GR
5.	$-\frac{7}{12}k_{\text{eff}}(\partial_r^2 g)T^4 v_L^2$	8×10^{-3}	2nd gradient
6.	$-5k_{\text{eff}} g T^2 v_L^2$	3×10^{-6}	GR
7.	$(2-2\beta-\gamma)k_{\text{eff}}\partial_r(g\phi)T^3 v_L$	2×10^{-6}	GR 1st grad
8.	$-12k_{\text{eff}} g^2 T^3 v_L$	-6×10^{-7}	GR

Projected experimental limits:

Tested Effect	current limit	AI initial	AI upgrade	AI future	AI far future
PoE	3×10^{-13}	10^{-15}	10^{-16}	10^{-17}	10^{-19}
PPN (β, γ)	10^{-4}-10^{-5}	10^{-1}	10^{-2}	10^{-4}	10^{-6}

STANFORD UNIVERSITY

(Dimopoulos, *et al.*, PRL 2007; PRD 2008)

General Relativity Effects

Schwarzschild metric, PPN expansion:

$$ds^2 = (1 + 2\phi + 2\beta\phi^2)dt^2 - (1 - 2\gamma\phi)dr^2 - r^2 d\Omega^2$$

$$\frac{d\vec{v}}{dt} = -\vec{\nabla}[\phi + (\beta + \gamma)\phi^2] + \gamma[3(\vec{v}\cdot\hat{r})^2 - 2\vec{v}^2]\vec{\nabla}\phi + 2\vec{v}(\vec{v}\cdot\vec{\nabla}\phi).$$

Newtonian Gravity

Gravity Gravitates

Kinetic Energy Gravitates

Corresponding AI phase shifts:

	Phase Shift	Size (rad)	Interpretation
1.	$-k_{\text{eff}} g T^2$	3×10^8	gravity
2.	$-k_{\text{eff}}(\partial_r g)T^3 v_L$	-2×10^3	1st gradient
3.	$-3k_{\text{eff}} g T^2 v_L$	4×10^1	Doppler shift
4.	$(2-2\beta-\gamma)k_{\text{eff}} g \phi T^2$	2×10^{-1}	GR
5.	$-\frac{7}{12}k_{\text{eff}}(\partial_r^2 g)T^4 v_L^2$	8×10^{-3}	2nd gradient
6.	$-5k_{\text{eff}} g T^2 v_L^2$	3×10^{-6}	GR
7.	$(2-2\beta-\gamma)k_{\text{eff}}\partial_r(g\phi)T^3 v_L$	2×10^{-6}	GR 1st grad
8.	$-12k_{\text{eff}} g^2 T^3 v_L$	-6×10^{-7}	GR

Projected experimental limits:

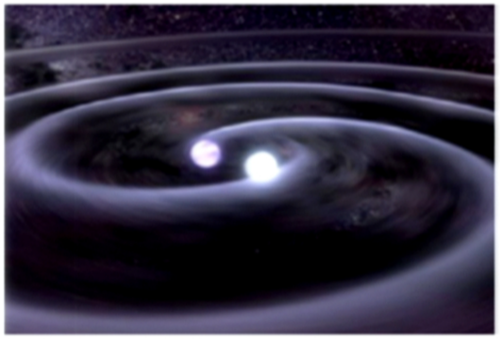
Tested Effect	current limit	AI initial	AI upgrade	AI future	AI far future
PoE	3×10^{-13}	10^{-15}	10^{-16}	10^{-17}	10^{-19}
PPN (β, γ)	10^{-4}-10^{-5}	10^{-1}	10^{-2}	10^{-4}	10^{-6}

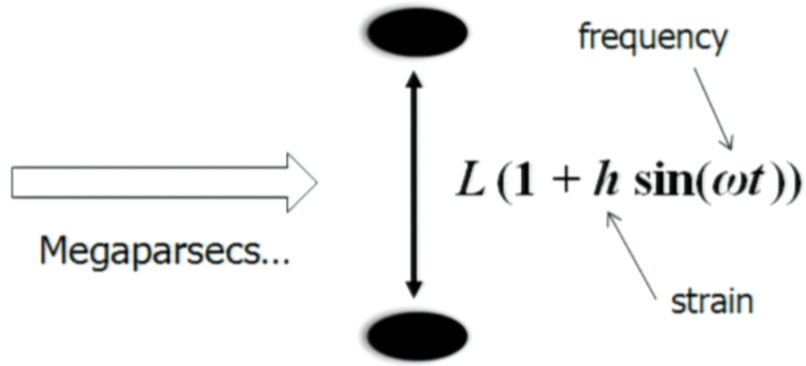
STANFORD UNIVERSITY

(Dimopoulos, *et al.*, PRL 2007; PRD 2008)

Gravitational Wave Detection

$$ds^2 = dt^2 - (1 + h\sin(\omega(t-z)))dx^2 - (1 - h\sin(\omega(t-z)))dy^2 - dz^2$$

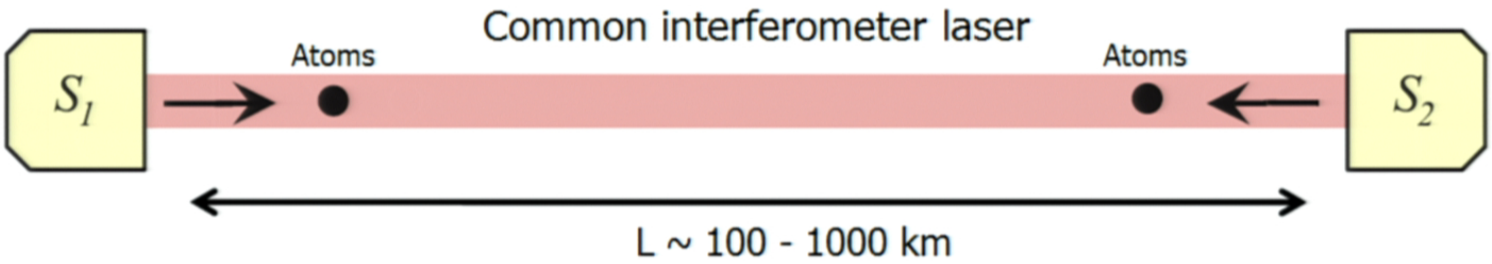


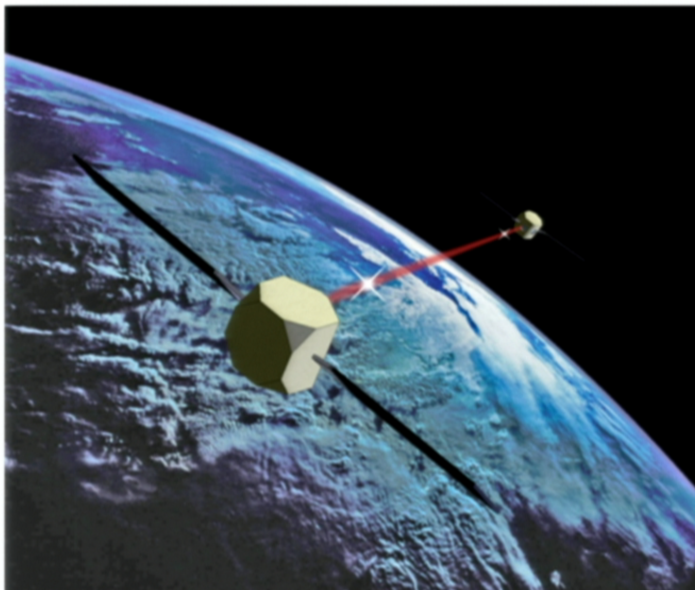


Why study gravitational waves?

- *New carrier for astronomy*: Generated by moving mass instead of electric charge
- *Tests of gravity*: Extreme systems (e.g., black hole binaries) test general relativity
- *Cosmology*: Can see to the earliest times in the universe

Satellite GW Antenna



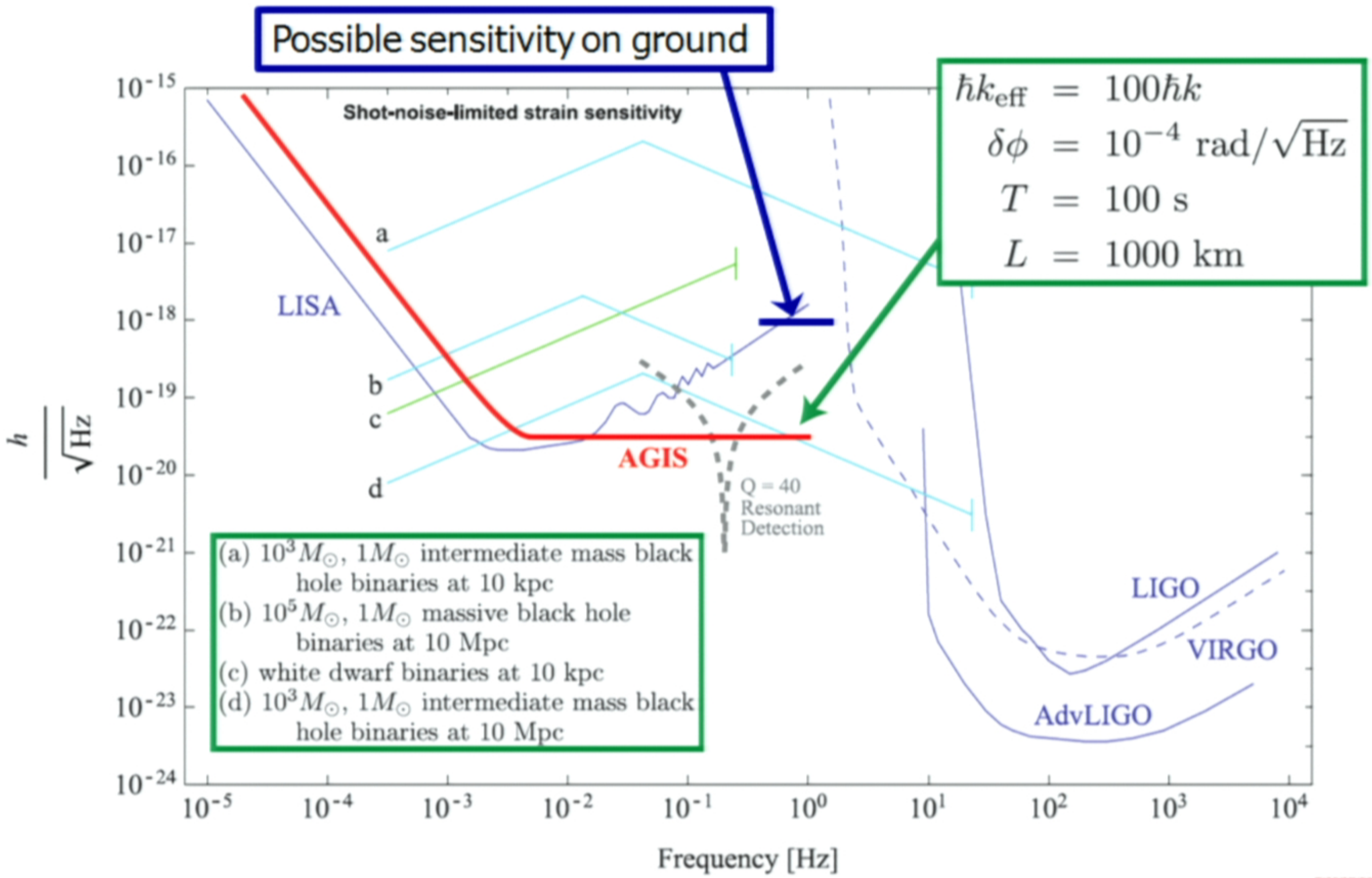


NASA Innovative Advanced Concepts

STANFORD UNIVERSITY


Satellite GW Antenna
Common interferometer laser
Atoms
Atoms
S_1
S_2
L ~ 100 - 1000 km
NIAC
NASA Innovative Advanced Concepts
NASA
STANFORD UNIVERSITY

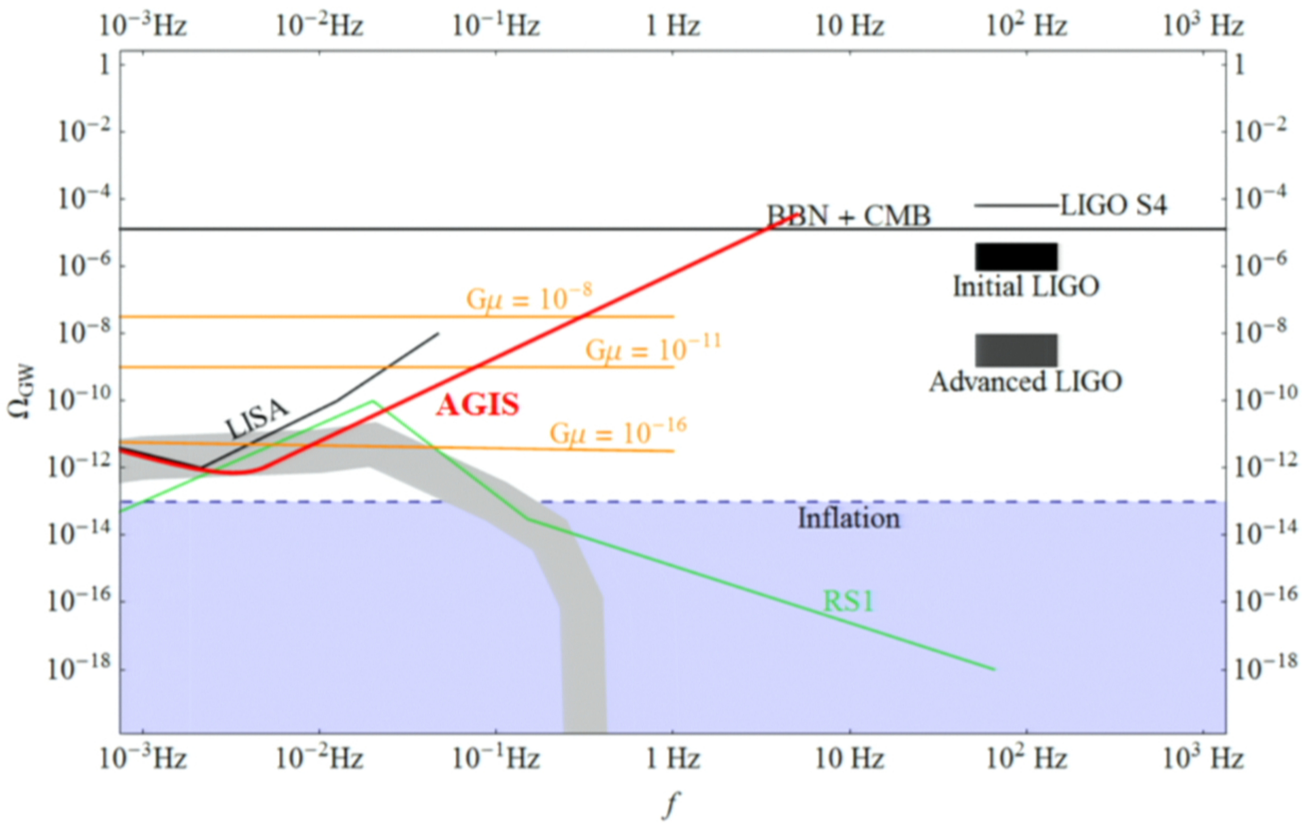
Potential Strain Sensitivity



STANFORD UNIVERSITY

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

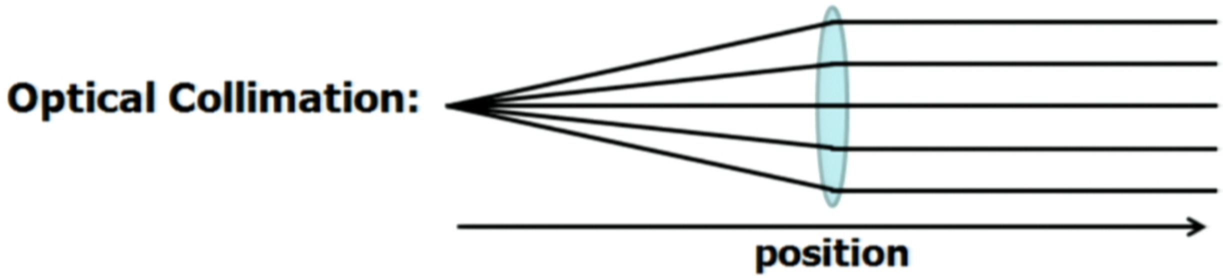
Stochastic GW Sensitivity

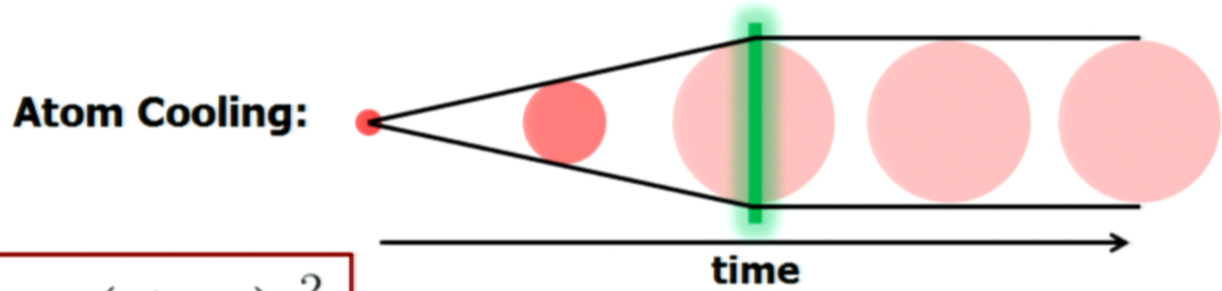


Requires correlation among multiple independent baselines

STANFORD UNIVERSITY

Atom Lens Cooling

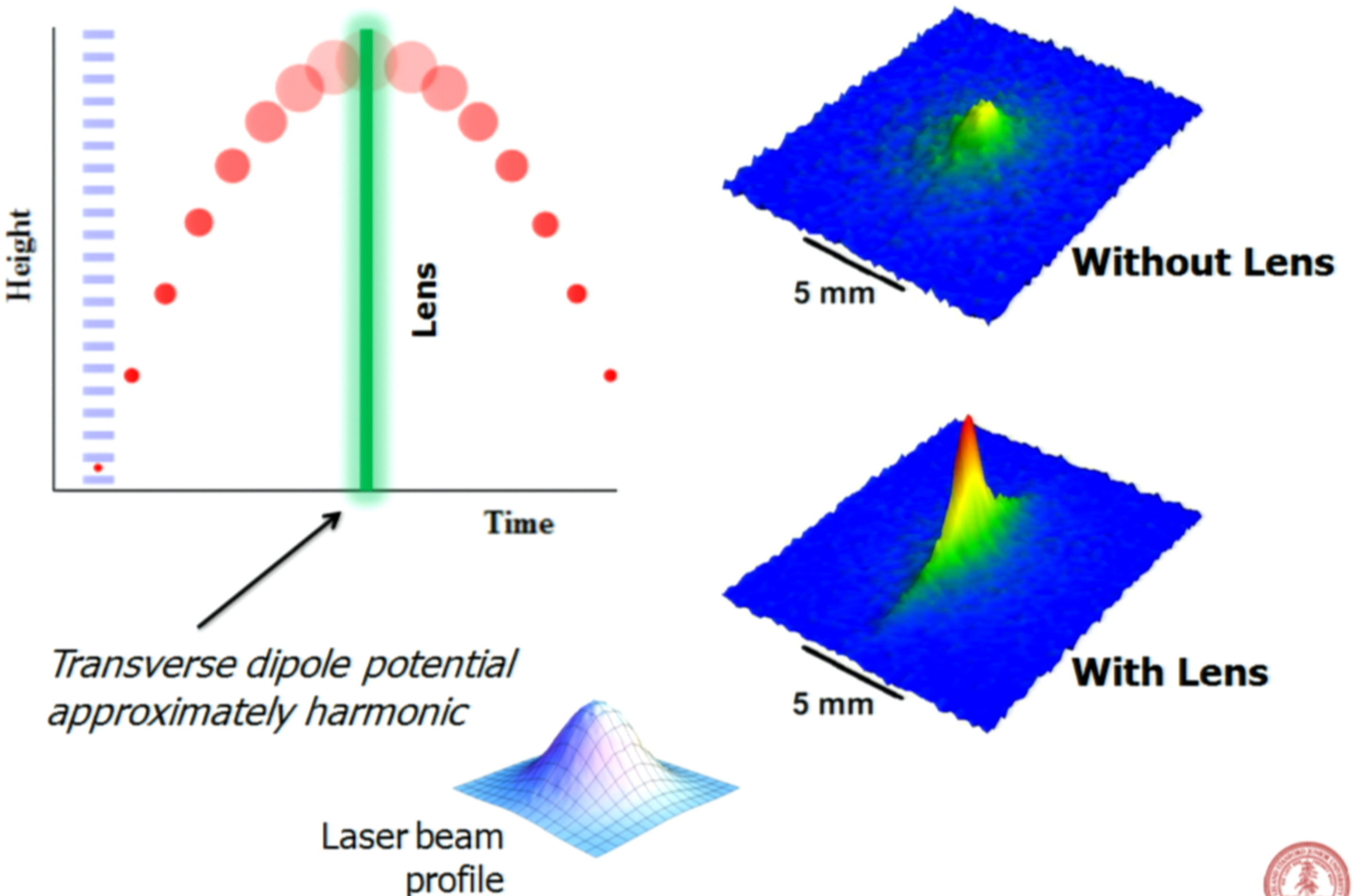




$$\frac{T_f}{T_i} = \left(\frac{\Delta x_i}{\Delta x_f}\right)^2$$

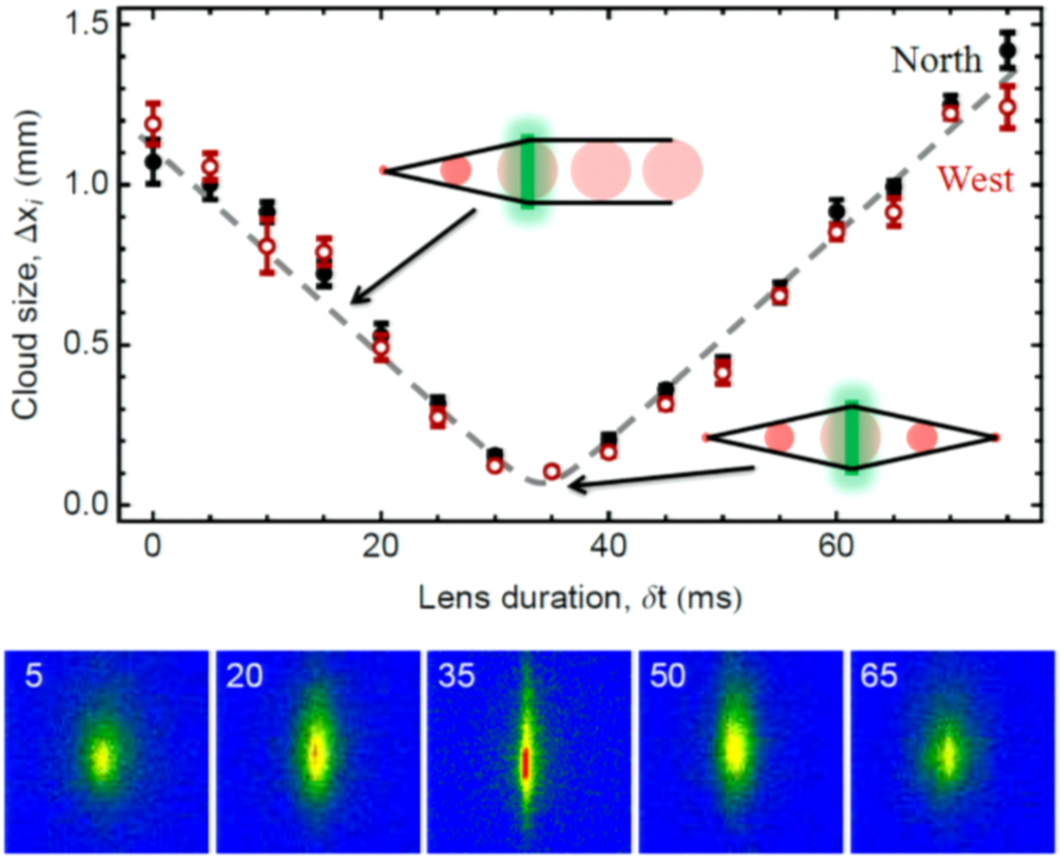
STANFORD UNIVERSITY

2D Atom Refocusing



STANFORD UNIVERSITY

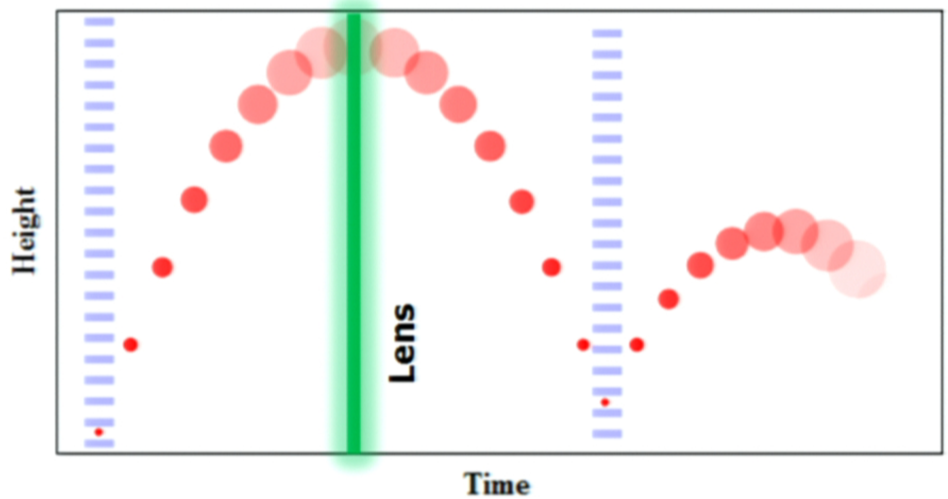
Vary Focal Length



STANFORD UNIVERSITY

Extended free-fall on Earth

Launch → Lens → Relaunch → Detect



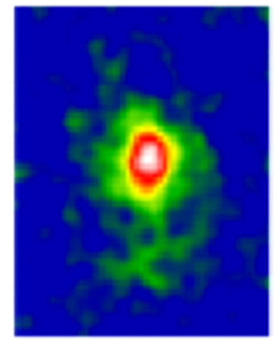
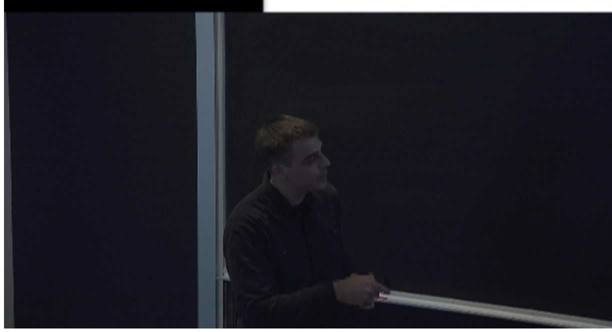


Image of cloud
after 5 seconds
total free-fall time



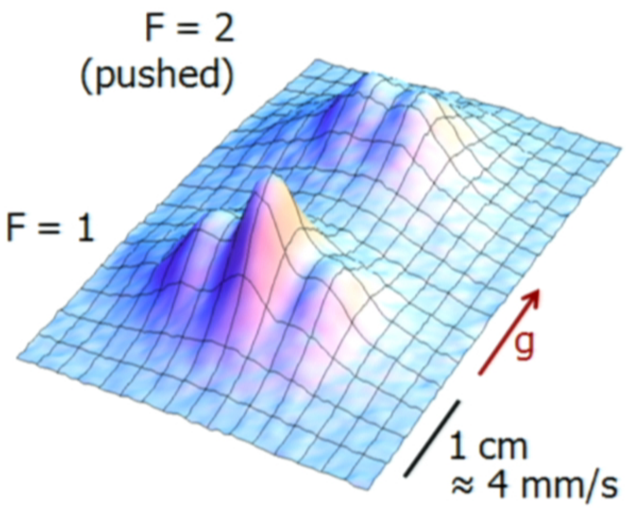
9.375 meters

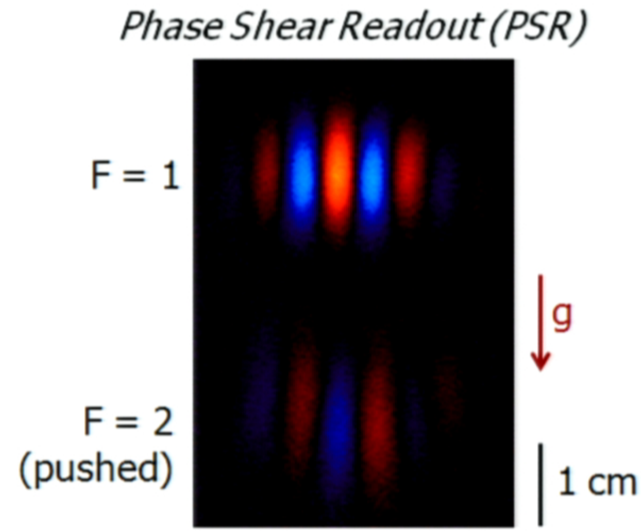
to 6 meters

Towards T > 10 s interferometry (?)

SITY

Phase shear readout





Mitigates noise sources:

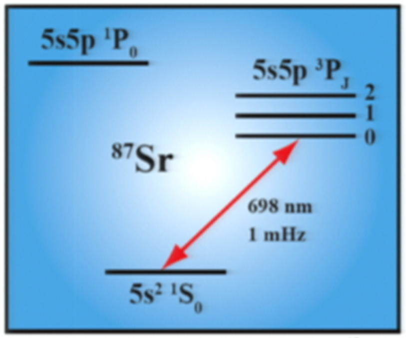
✓ Pointing jitter and residual rotation readout

✓ Laser wavefront aberration in situ characterization

Single-shot interferometer phase measurement

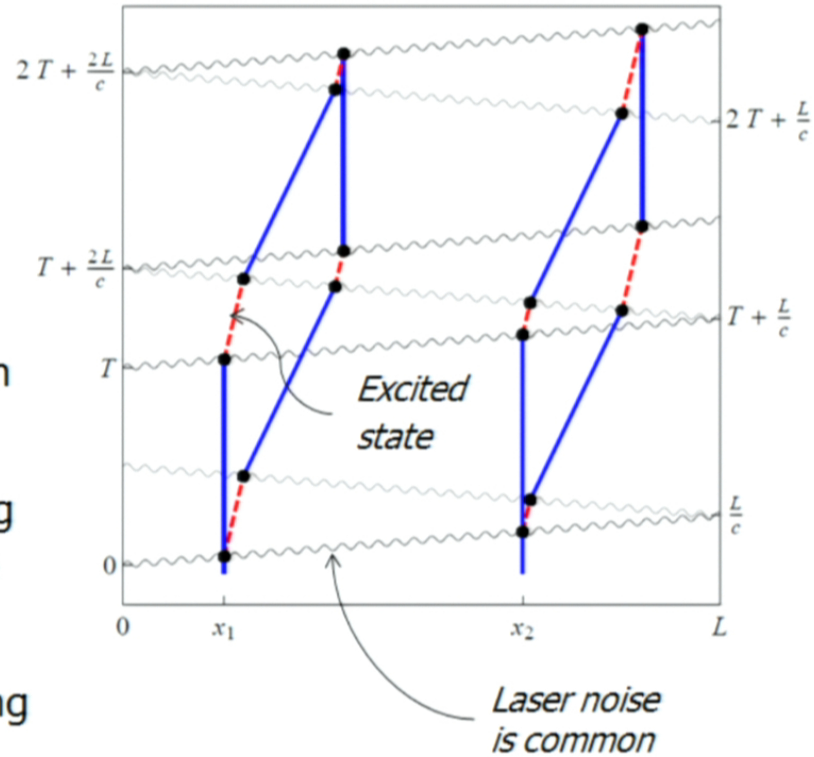
STANFORD UNIVERSITY

Laser frequency noise insensitive detector



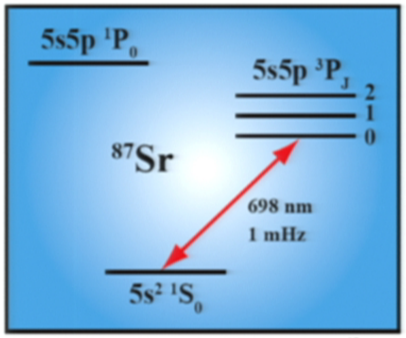
Clock transition in candidate atom ^{87}Sr

- 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.



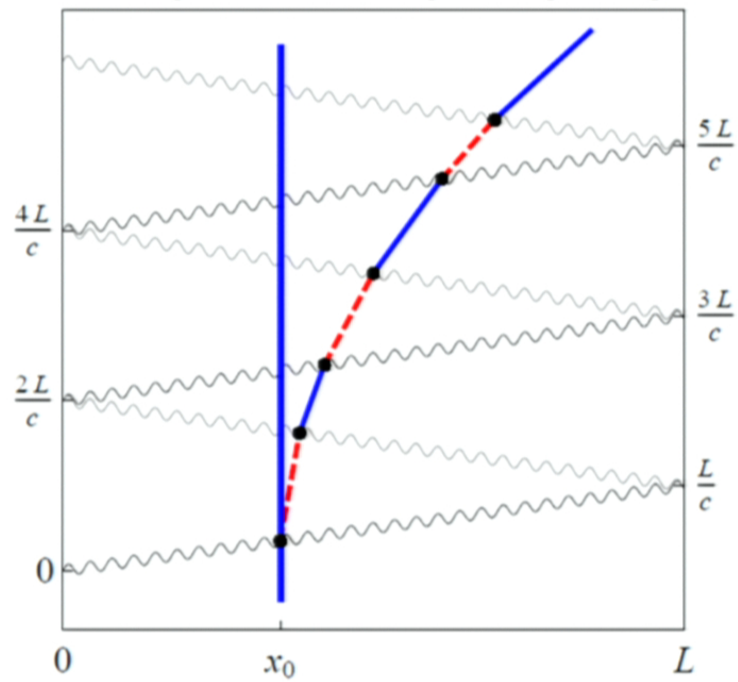
Graham, *et al.*, arXiv:1206.0818, PRL (2013)

Laser frequency noise insensitive detector



Clock transition in candidate atom ^{87}Sr

Example LMT beamsplitter (N = 3)



- 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.

STANFORD UNIVERSITY

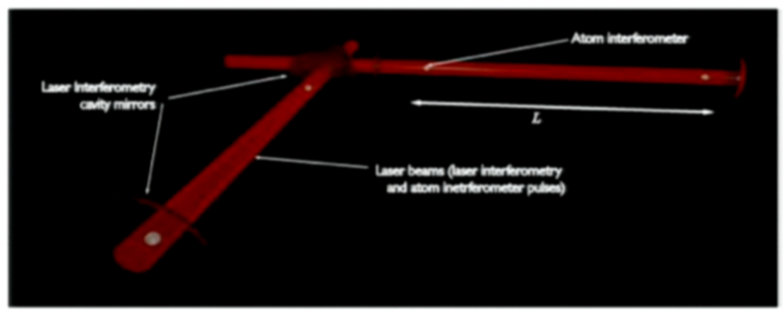
Graham, *et al.*, arXiv:1206.0818, PRL (2013)

Future GW work

Single photon AI gradiometer proof of concept

Ground based detector prototype work

10 m tower studies



MIGA; ~1 km baseline (Bouyer, France)

STANFORD UNIVERSITY

Collaborators

Stanford

Mark Kasevich (PI)
Susannah Dickerson
Alex Sugarbaker
Tim Kovachy
Christine Donnelly
Chris Overstreet

Theory:

Peter Graham
Savas Dimopoulos
Surjeet Rajendran

Former members:

David Johnson
Sheng-wey Chiow

Visitors:

Philippe Bouyer (CNRS)
Jan Rudolph (Hannover)

NASA GSFC

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

AOSense

Brent Young (CEO)

STANFORD UNIVERSITY