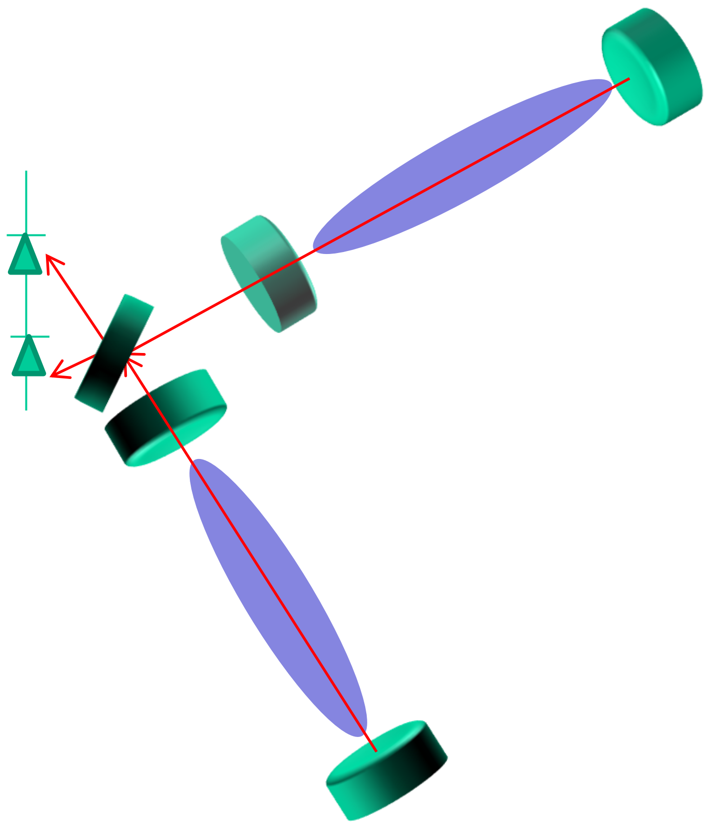
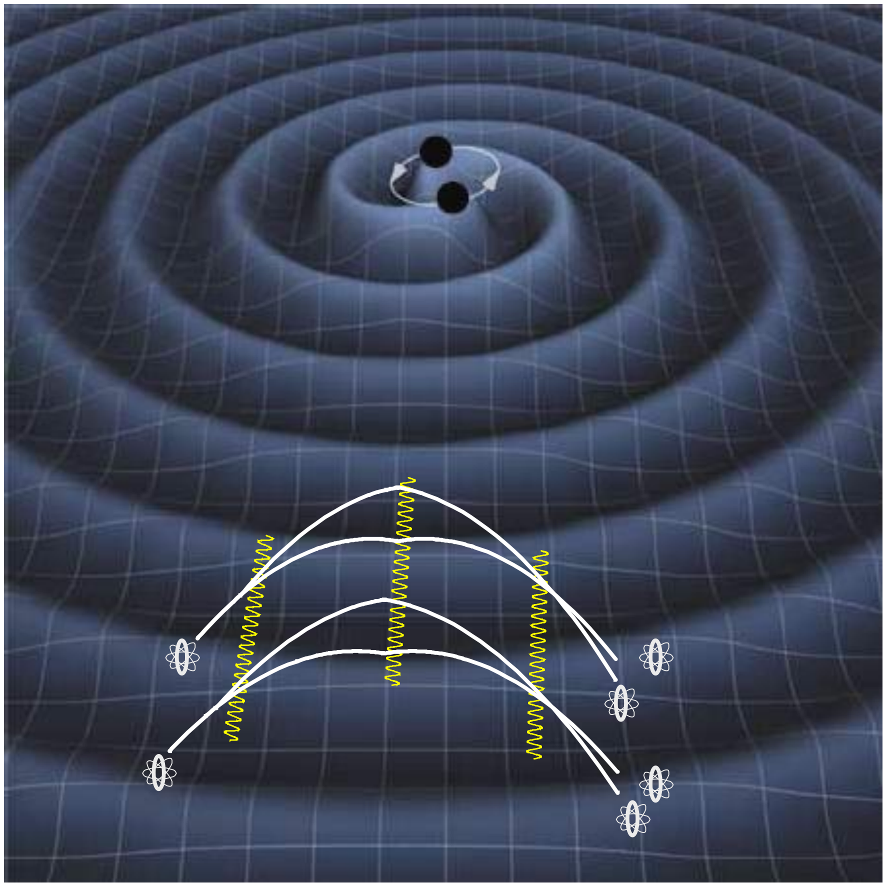
Gravitational wave detection with light and atoms

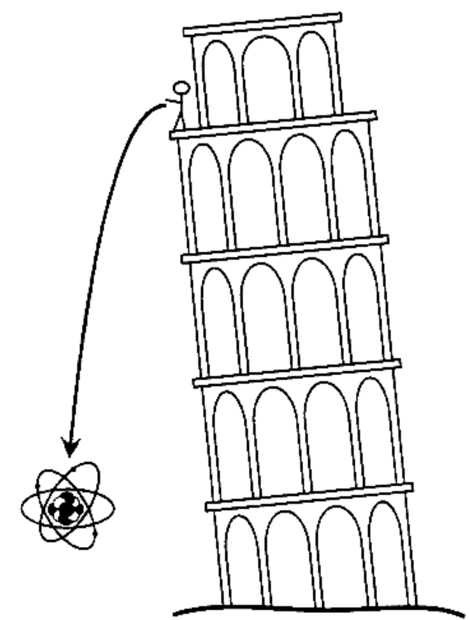




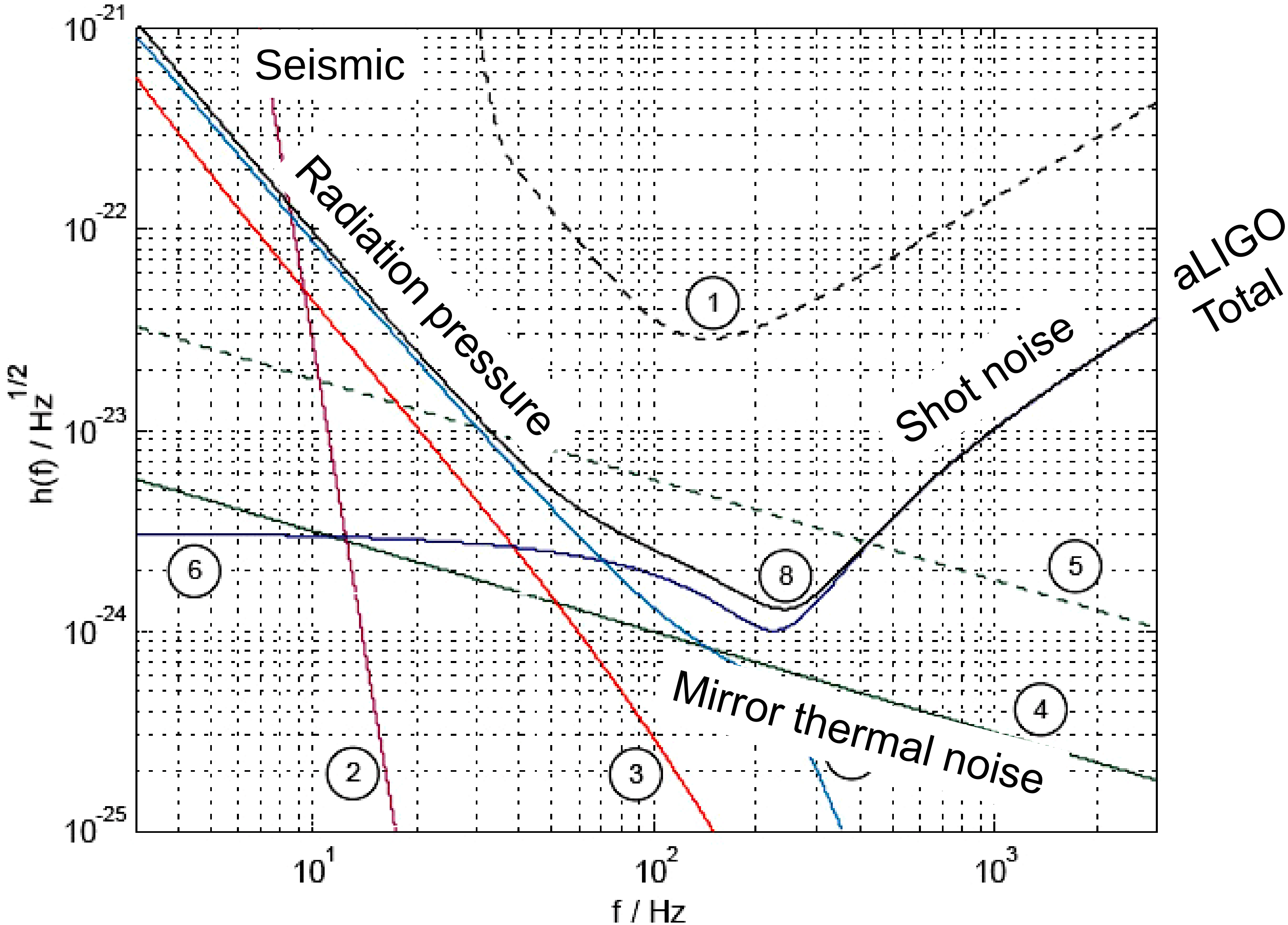
Holger Müller, UC Berkeley

Outline

1. Motivation
2. Atom interferometers
3. Sensitivity
4. Proposals for gravity wave detectors
5. Technical issues
6. Outlook



A. Peters



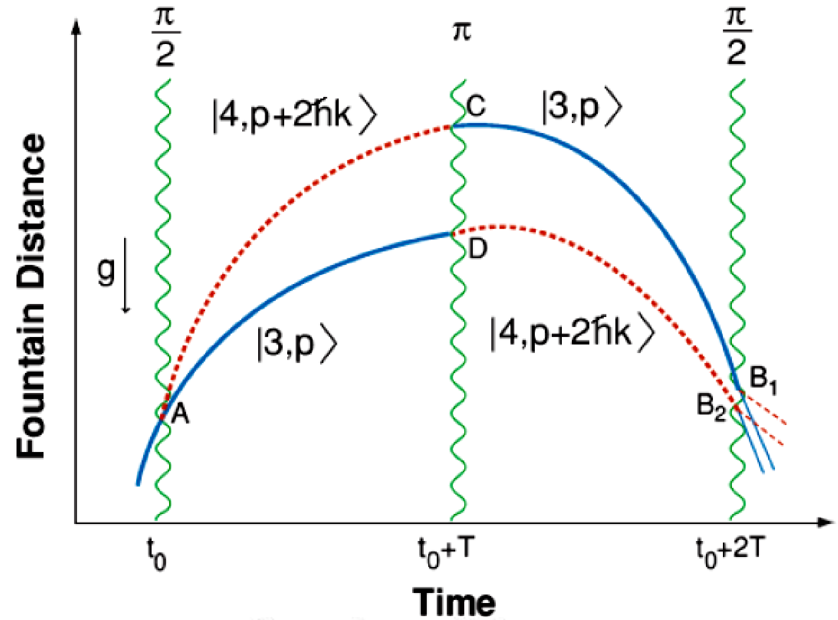
1 LIGO I total
2 Filtered seismic noise
3 Suspension thermal noise
4 Internal thermal noise - sapphire
5 Internal thermal noise - fused silica (fallback)
6 Shot noise
7 Radiation pressure noise
8 LIGO II total

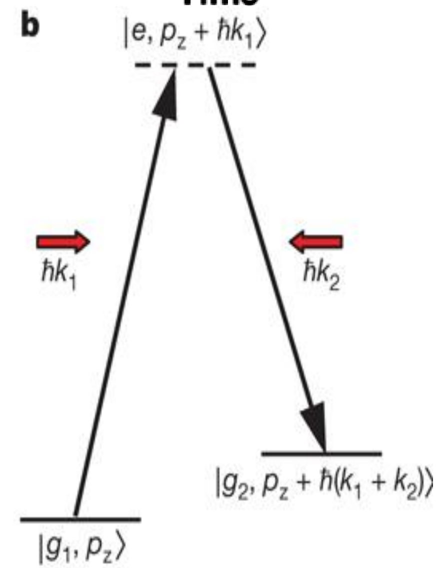
Principle

Light pulse atom interferometer

$$\Delta\varphi = -\frac{mc^2}{\hbar}\oint d\tau + \Delta\varphi_{\text{laser}} = kgT^2$$

- Independent of initial position and velocity
- No radiation pressure noise, as atoms interact with fixed number of photons
- No thermal noise, as parasitic transitions due to blackbody radiation are extremely rare
- We just drop the atoms => Near-perfect seismic isolation

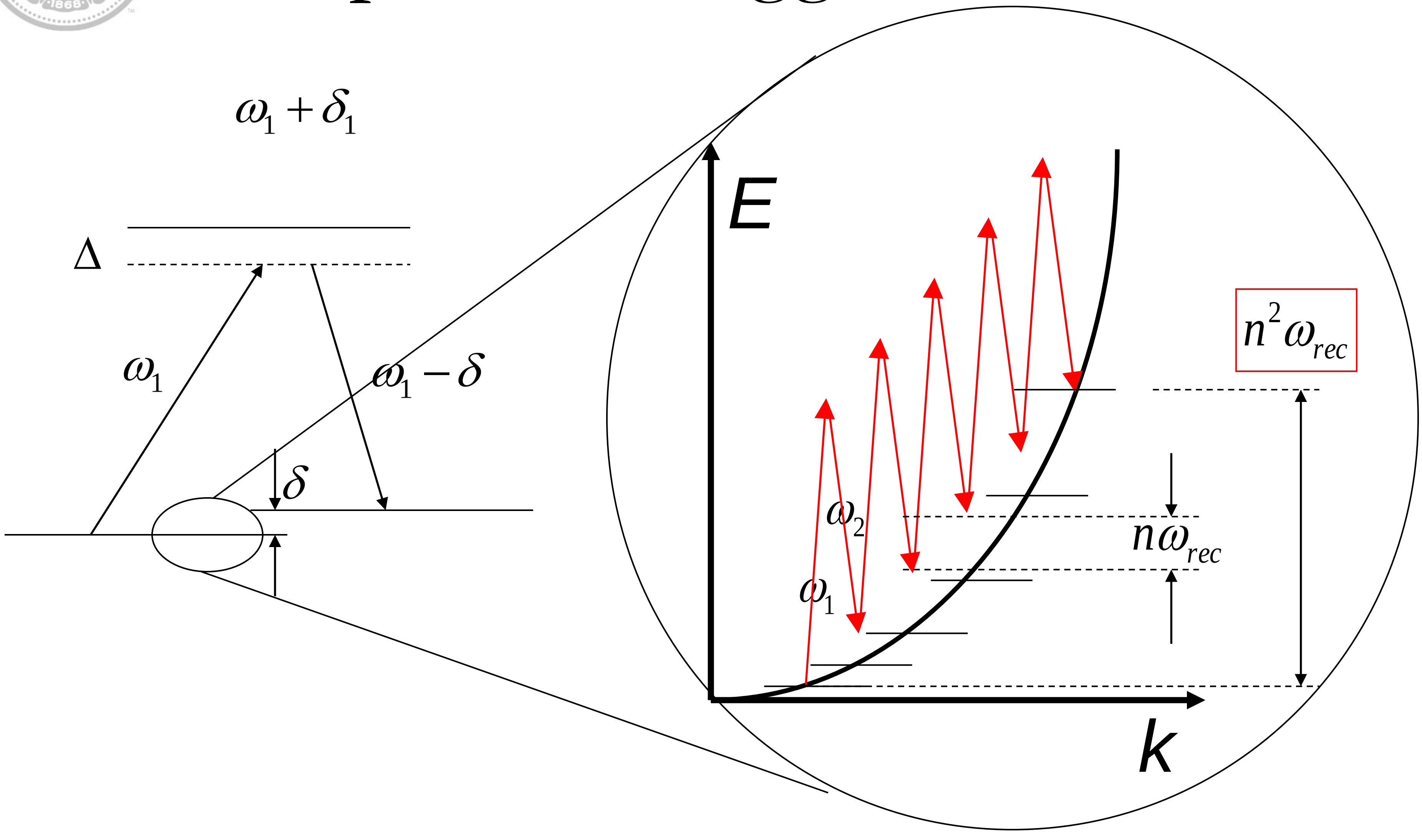




Technology

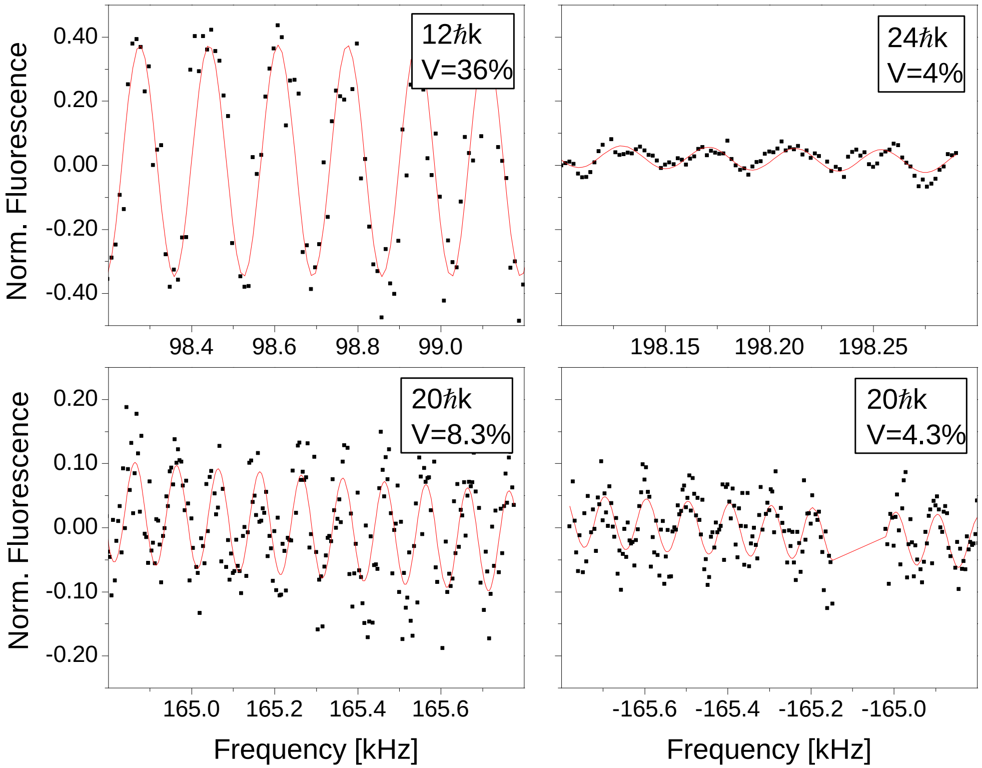
- Large momentum transfer , 100- 1000 ħk
- Parasitic phase shifts

Multiphoton Bragg diffraction

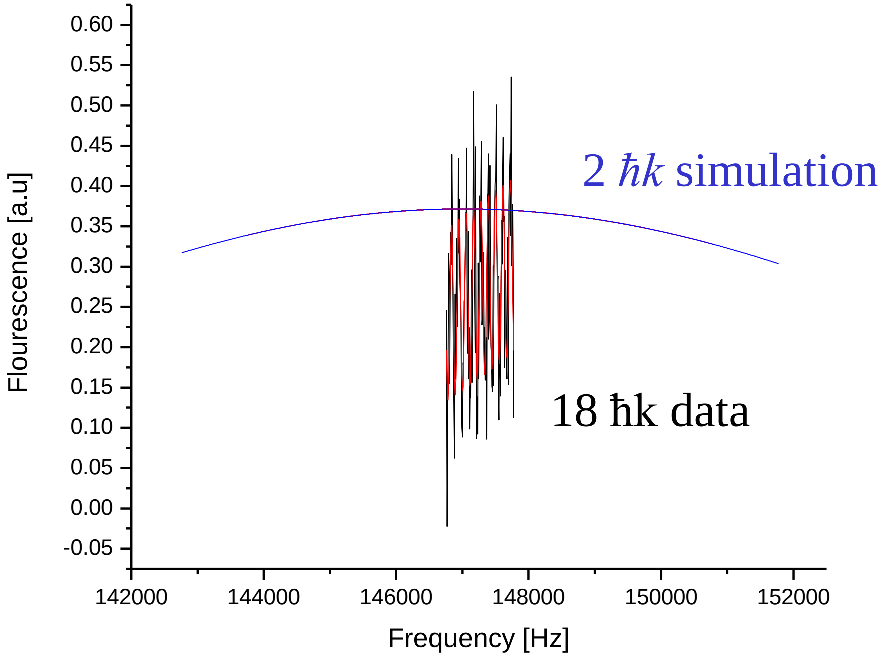


Large momentum transfer

12-24 $\hbar k$ interferometers



Comparison to 2 $\hbar k$

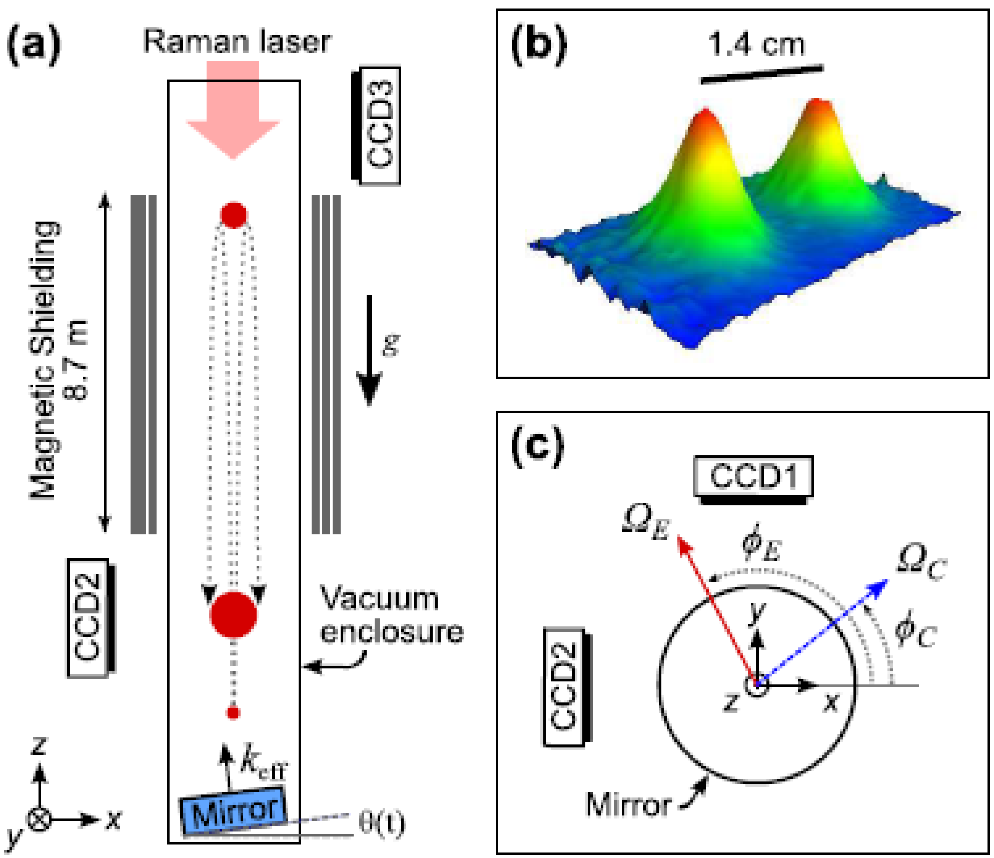


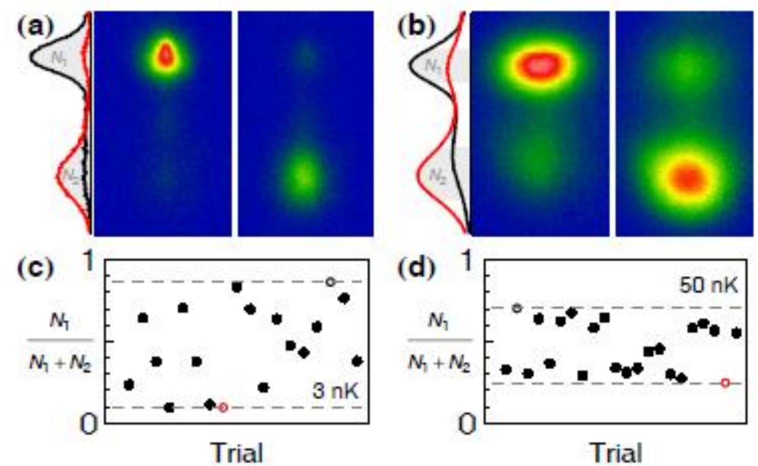
H. M. *et al.*, PRL 100 (2009): Chiow et al, PRL 2009

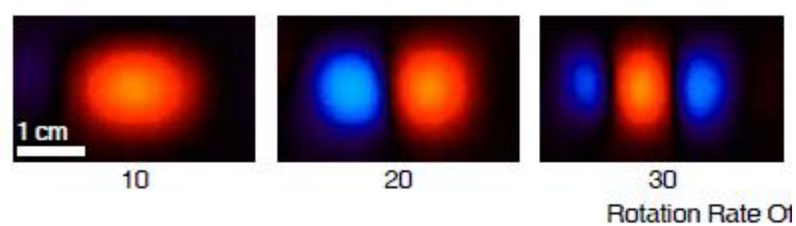
Selected for a Viewpoint in *Physics*
PRL 111, 083001 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Multiaxis Inertial Sensing with Long-Time Point Source Atom Interferometry

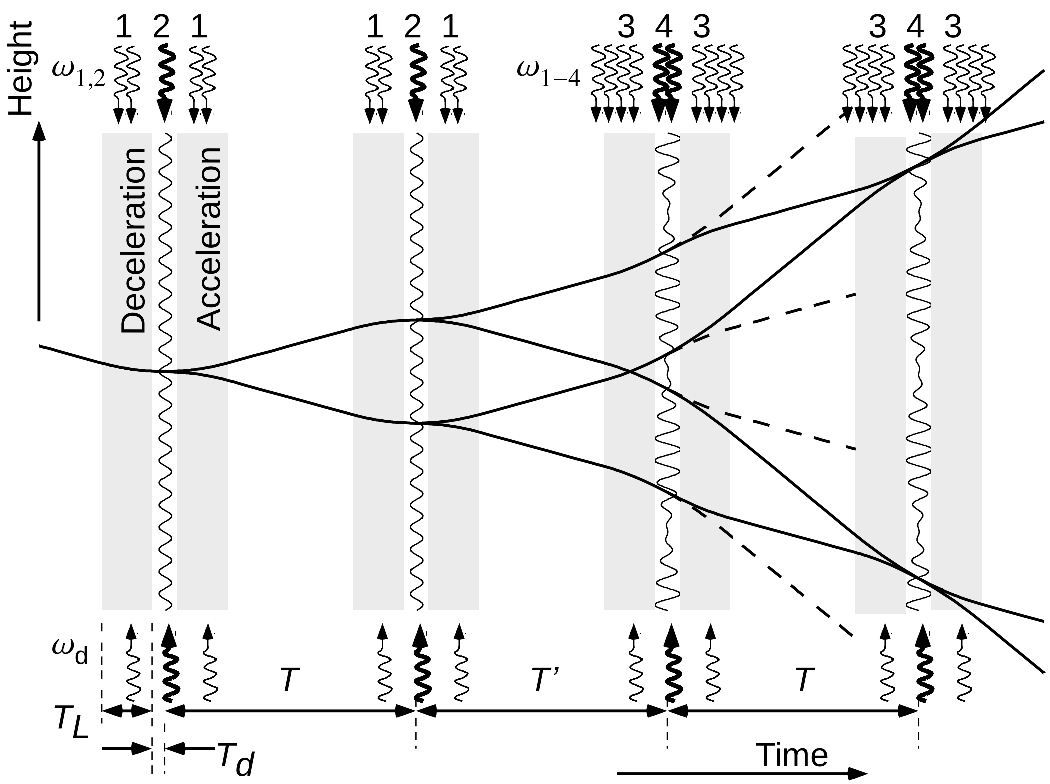
Susannah M. Dickerson, Jason M. Hogan, Alex Sugarbaker, David M. S. Johnson, and Mark A. Kasevich*
Department of Physics, Stanford University, Stanford, California 94305, USA
(Received 24 April 2013; published 19 August 2013)

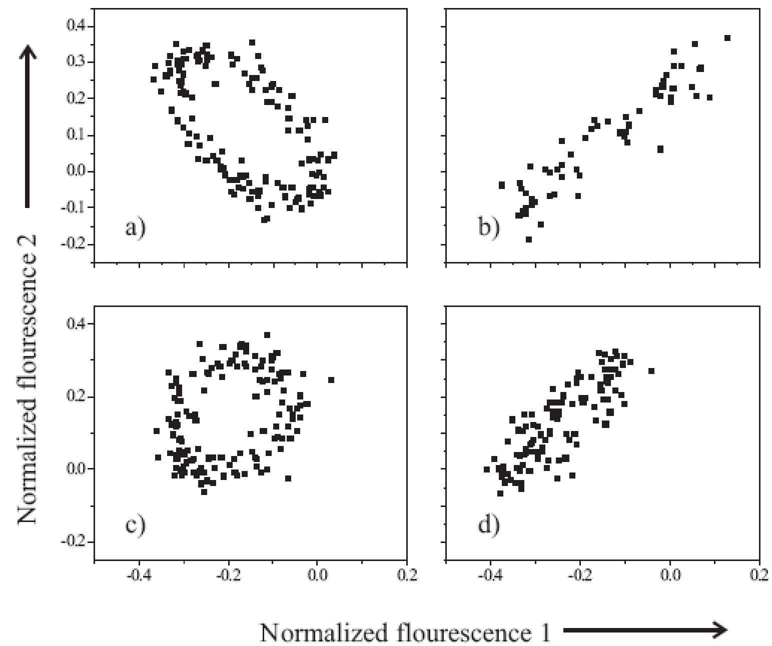






Scalable momentum transfer with Bloch oscillations





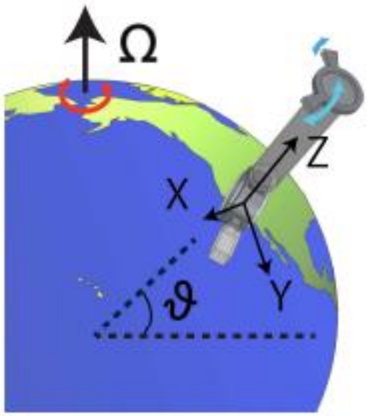
1: dual lattice (Matter wave accelerator)
2: single Bragg
3: quadruple lattice
4: dual Bragg

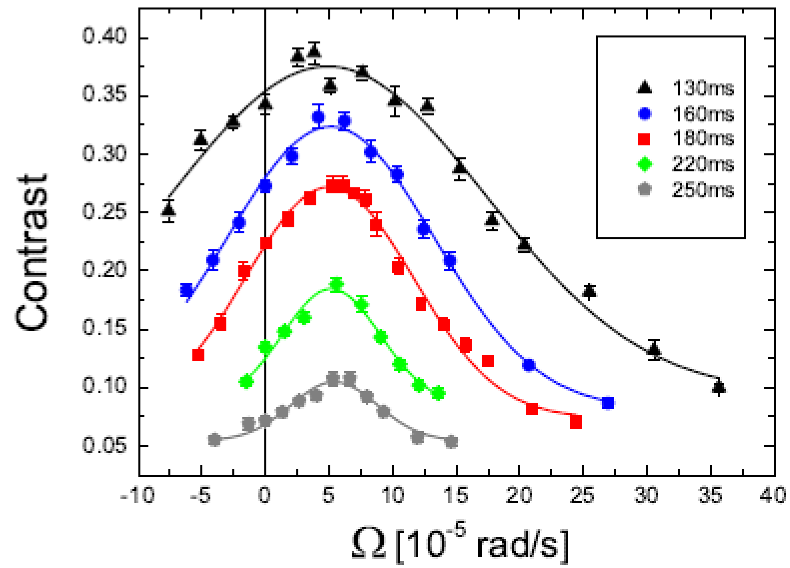
Large velocity difference can be used test PNO(4) while cancelling PNO(2)

H. M. *et al.*, PRL 100 (2009)

Coriolis force

$$\vec{\delta} = 4nv_r\Omega_{\oplus}T(T+T')\cos\vartheta(1,0,0).$$

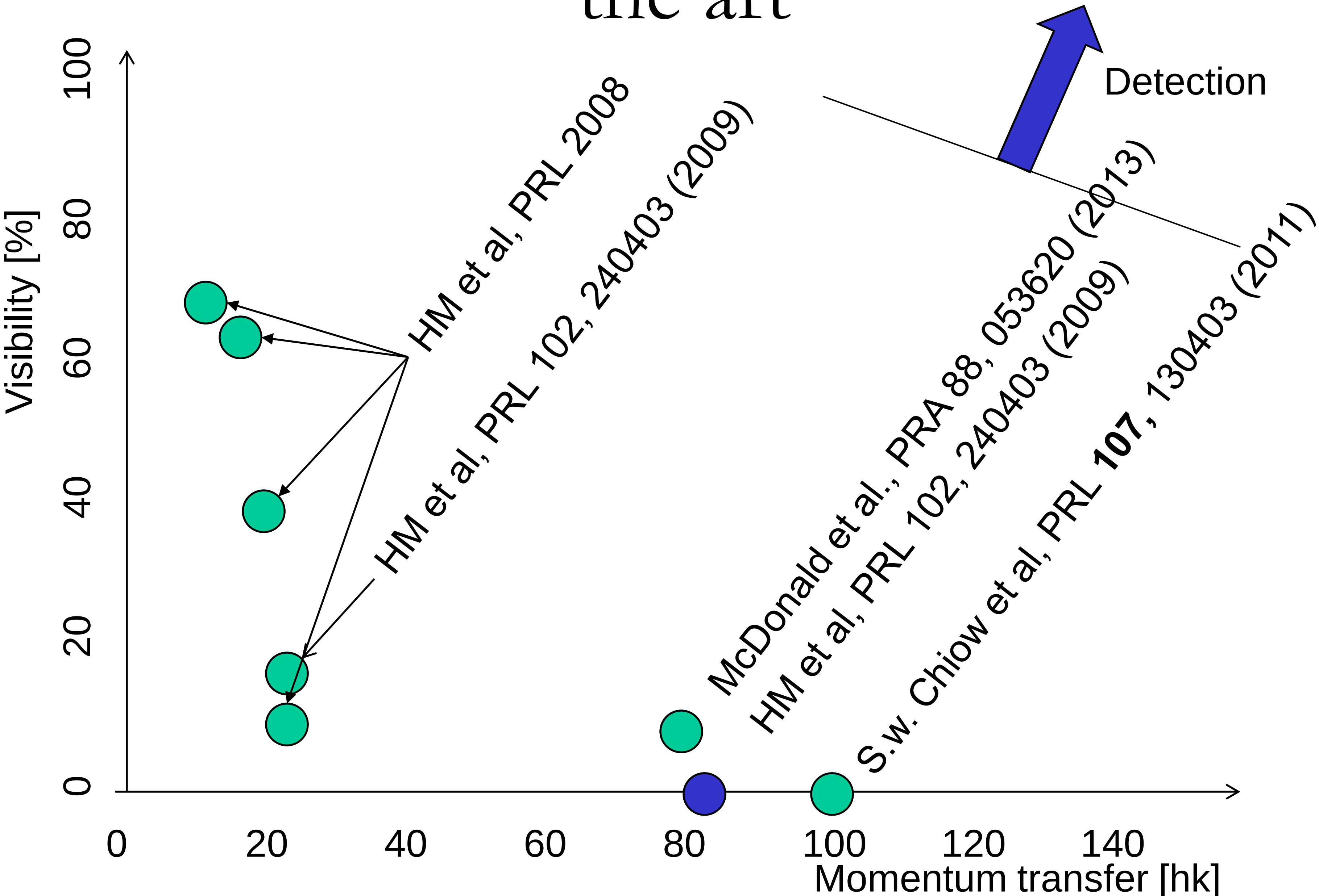




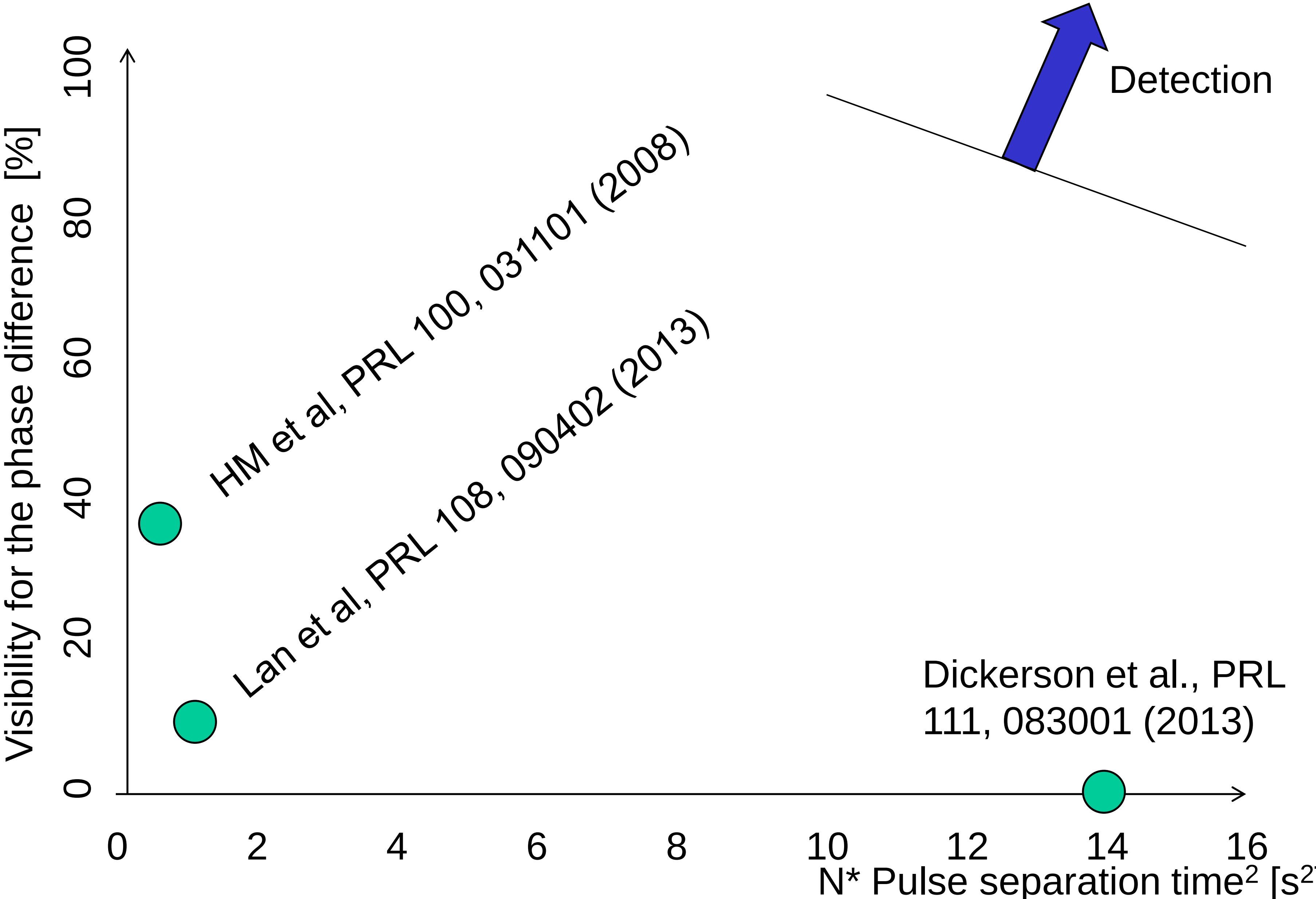
- Interferometer does not close
- Cancellation improves contrast (350%), T
- World's most sensitive atom interferometer (10 ħk, 250 ms)

Lan *et al., PRL* 108, 090402 (2012)

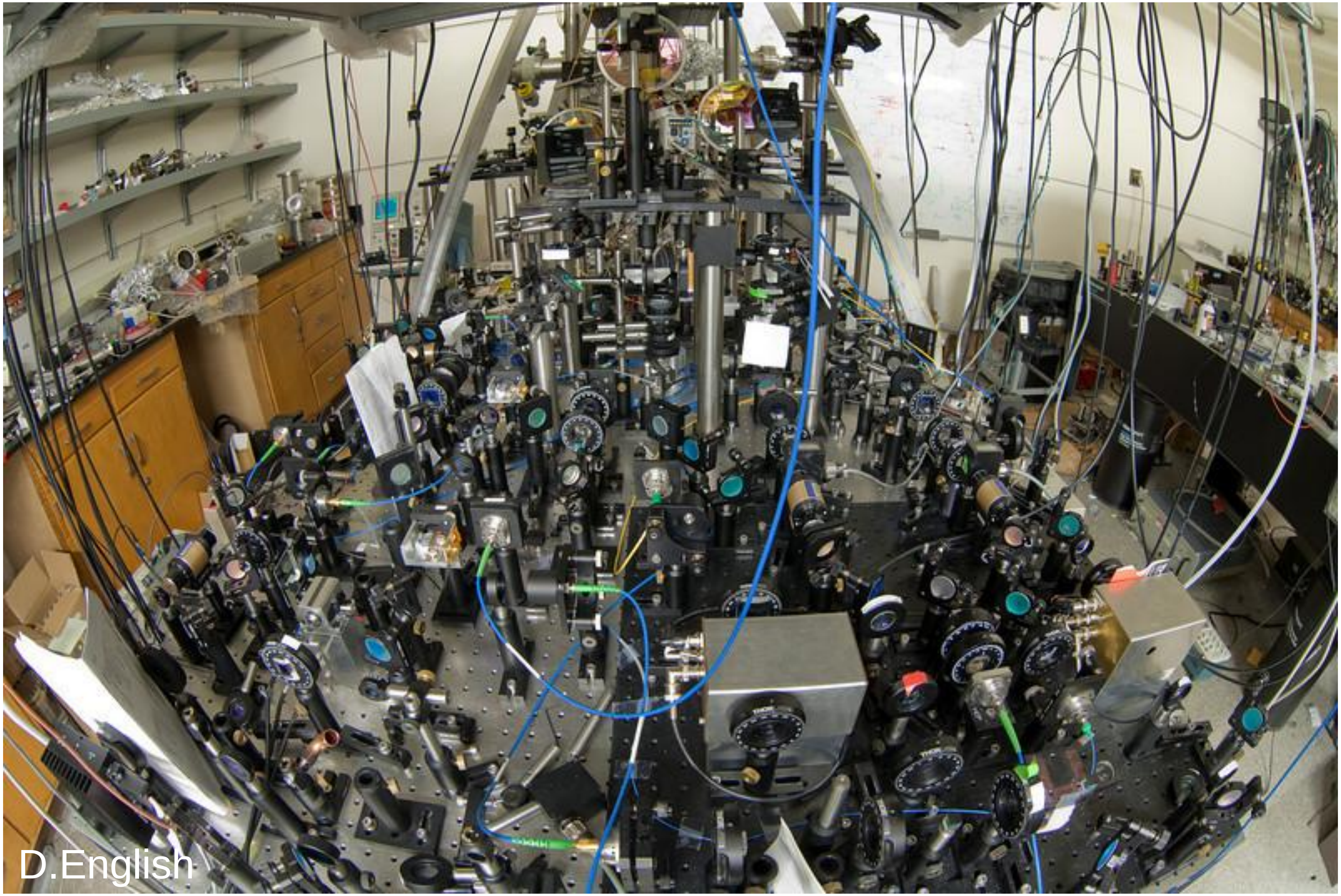
Large momentum transfer: state of the art



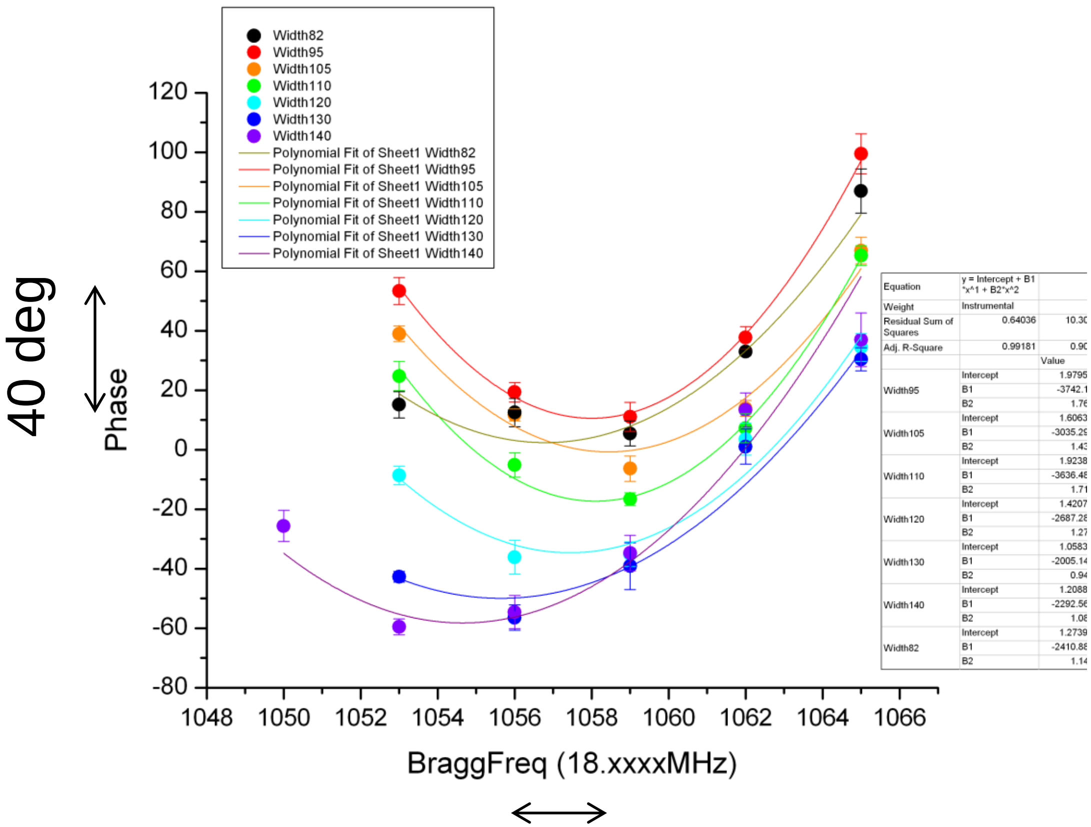
Enclosed area



This is how it looks like



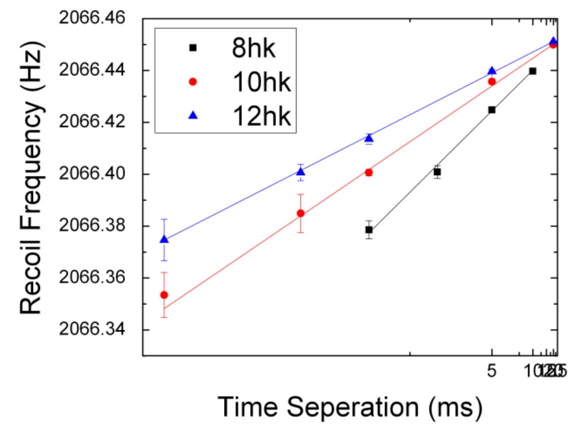
Parasitic phase shifts



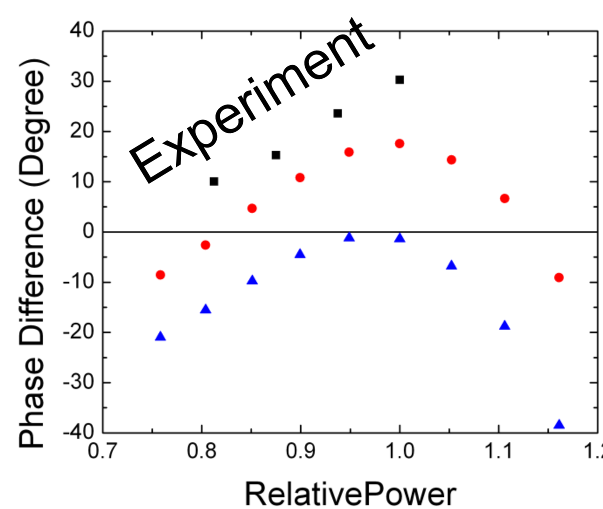
Equation	y = Intercept + B1 *x^1 + B2*x^2	
Weight	Instrumental	
Residual Sum of Squares	0.64036	10.30
Adj. R-Square	0.99181	0.90
		Value
Width95	Intercept	1.9795
	B1	-3742.1
	B2	1.76
Width105	Intercept	1.6063
	B1	-3035.29
	B2	1.43
Width110	Intercept	1.9238
	B1	-3636.48
	B2	1.71
Width120	Intercept	1.4207
	B1	-2687.28
	B2	1.27
Width130	Intercept	1.0583
	B1	-2005.14
	B2	0.94
Width140	Intercept	1.2088
	B1	-2292.56
	B2	1.08
Width82	Intercept	1.2739
	B1	-2410.88
	B2	1.14

2 kHz, 3.5 cm/s, ~0.5 μK

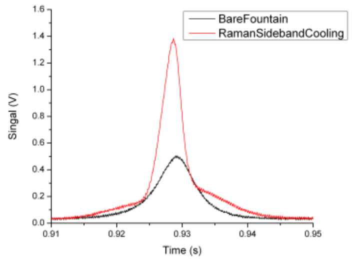
Smaller at higher Bragg order

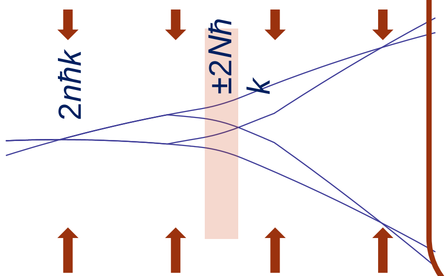


Incompletely understood



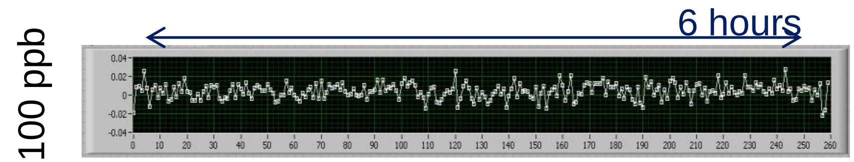
Technology: latest improvements





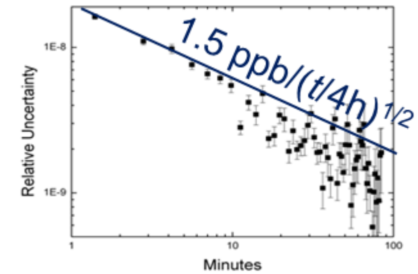
Method: Raman sideband cooling, Bloch oscillations

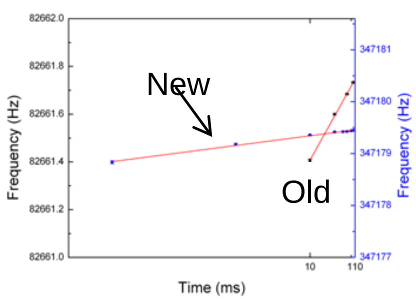
- Increases signal
- First use of Bloch oscillations in precision atom interferometers
- Important for compact atom interferometers



Results 1: Noise reduction

- Now 0.33 ppb/(6 hours)1/2 from 2 ppb/(6 hours)1/2
- No discernible drift, Allan variance keeps decreasing after 100 minutes



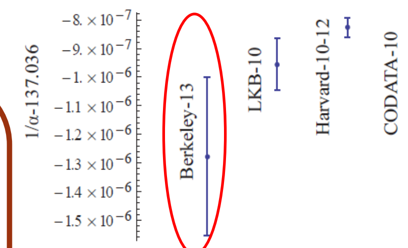


Results 2: 40-fold reduced systematics

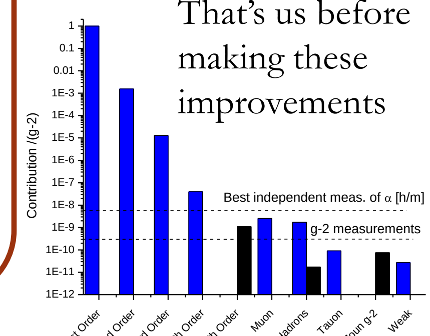
- Parsitic phase shift causes result to depend on pulse separation time
- Slope of the effect reduced to 1.5 ppb-seconds from 55 ppb-seconds

Application: Fine-stucture constant

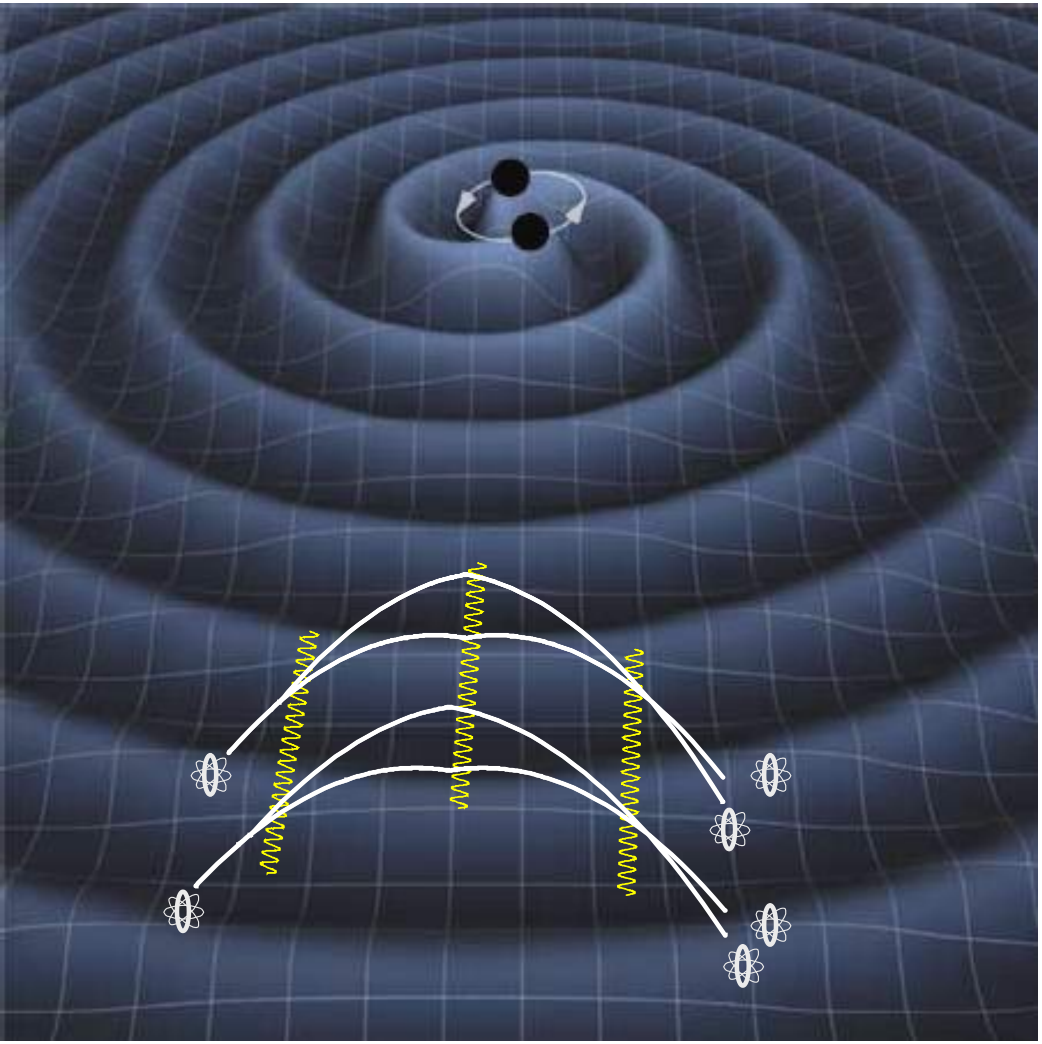
- Current most accurate measurement: Gabrielse 2012, 0.25 ppb
- We can beat that
- Most precise test of QED, supersymmetry,…



That's us before making these improvements



Atomic gravitational wave detection

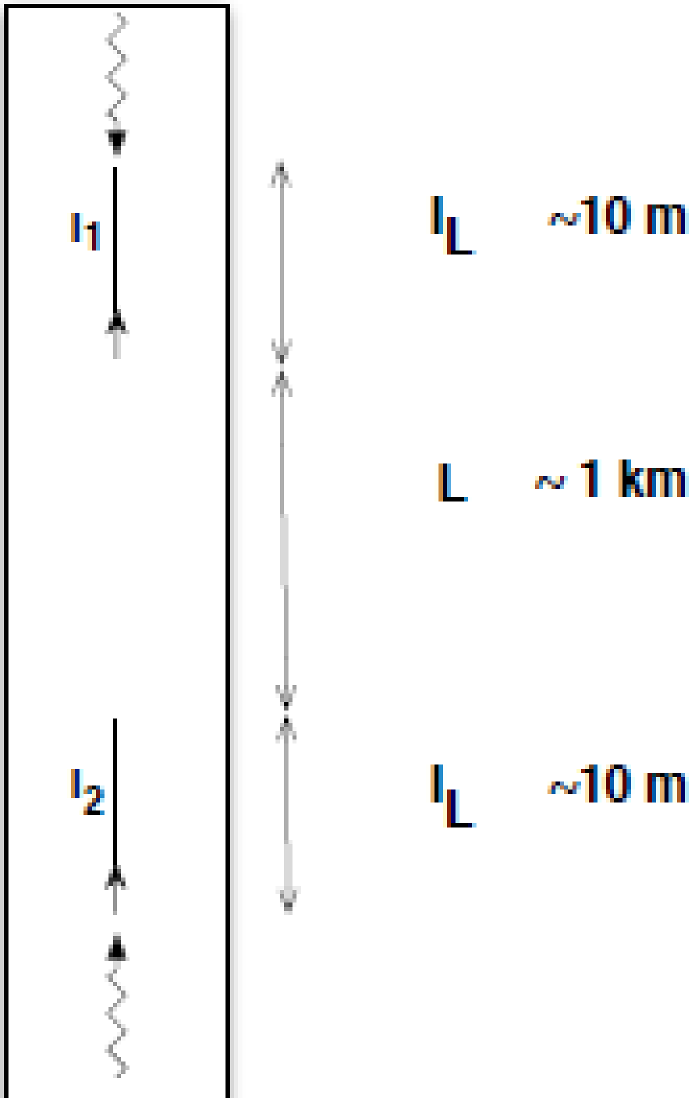


- “AGIS” Two interferometers in a line

- Atom interferometers as drag-free sensors in otherwise LISA-like mission setup

- Atoms as clocks

“Old” AGIS



$$\Phi_1 = 2nk_{eff}hL\sin^2\left(\frac{\omega T}{2}\right)\sin\varphi_0$$

Examples:
k=2π/1μ,
h=10^{-17},
ω=2π*1Hz

⇒Φ~3*10^{-7}

n=100

=>Φ~3*10^{-5}

Dimopoulos, Graham, Hogan, Kasevich & Rajendran, PR D **78,** 122002 (2008)

Comparison of Atom Interferometers and Light Interferometers as Space-Based Gravitational Wave Detectors

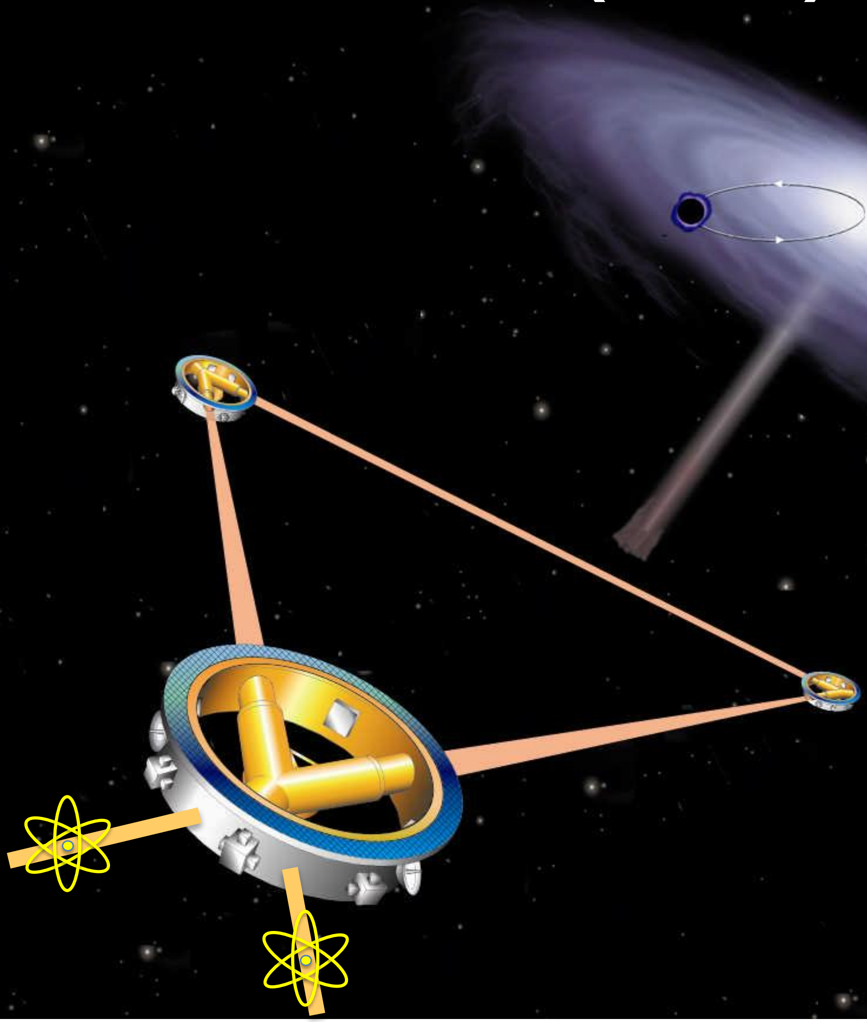
John G. Baker and J. I. Thorpe
Gravitational Astrophysics Laboratory, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, Maryland 20771, USA
(Received 26 January 2012; published 21 May 2012)

Laser noise doesn't cancel

It's essentially a measurement of the distance between the atoms, using the light as a ruler

Concept of Atomic Disturbance Reduction System

Atom Interferometers for LISA DRS (aDRS)



Big Idea: Truly drag-free atomic proof masses for LISA's Disturbance Reduction System (DRS).

Approach: Atomic acceleration reference

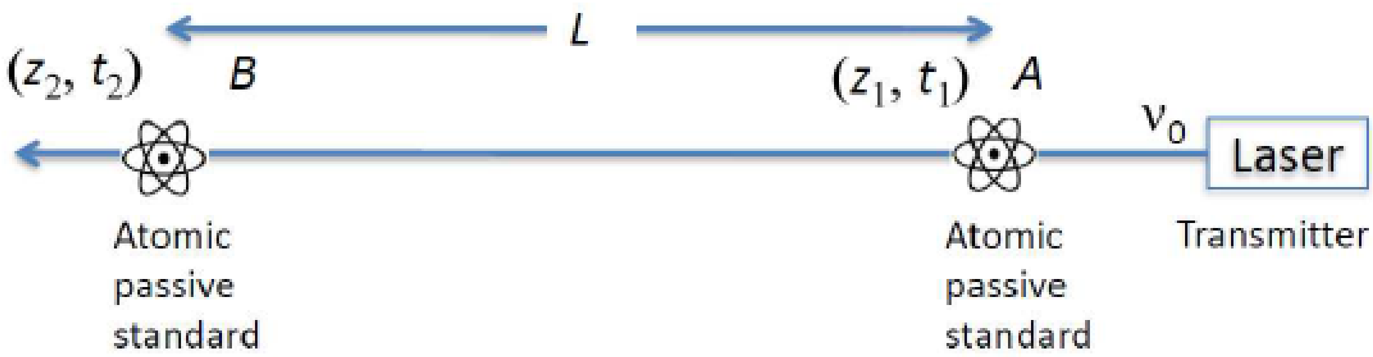
Concept: Use atomic inertial sensors to replace LISA accelerometers

Goal: Reduce/eliminate spacecraft drag-free requirement

Nan Ju, James Kohel, Massimo Tinto

Gravitational wave detection with single-laser atom interferometers

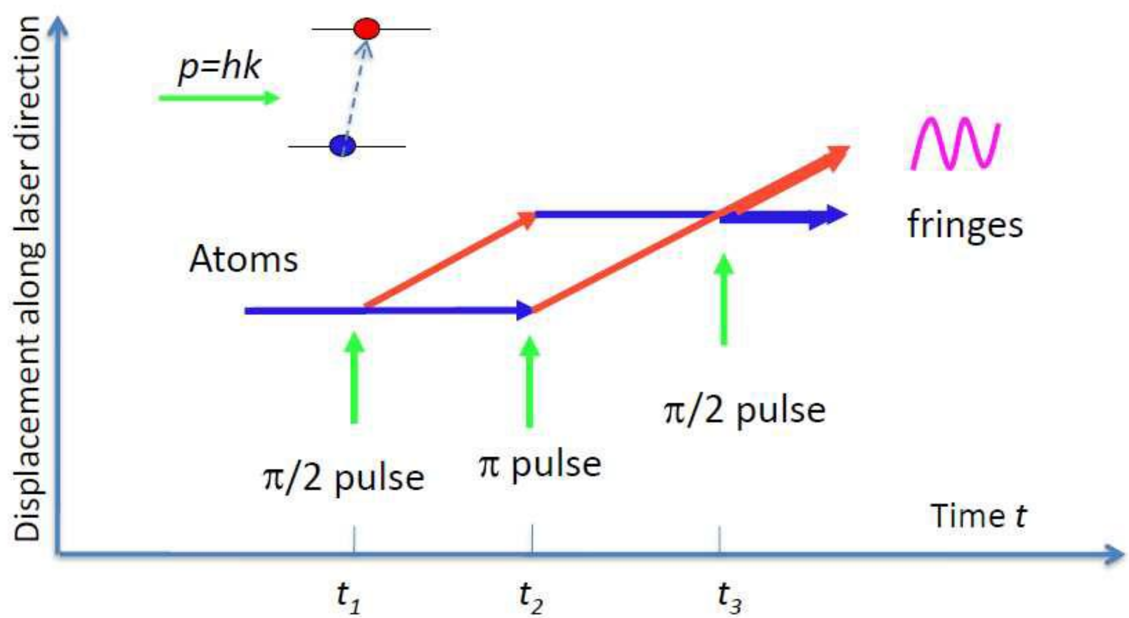
N. Yu and M. Tinto, GRG 43, 1943 (2011)



Measures GWs

Measures laser noise

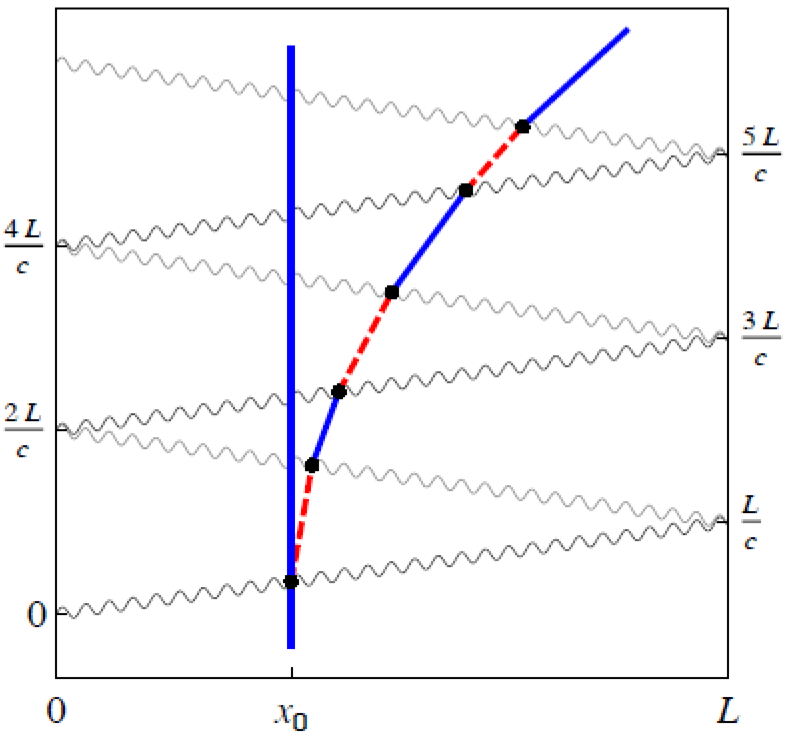
- Narrow-linewidth, optical atomic transitions
- Similar to comparison of two inertial clocks
- Suppresses laser noise, single-arm possible
- Subject to same bandwidth limitations, wavefont distortions, etc

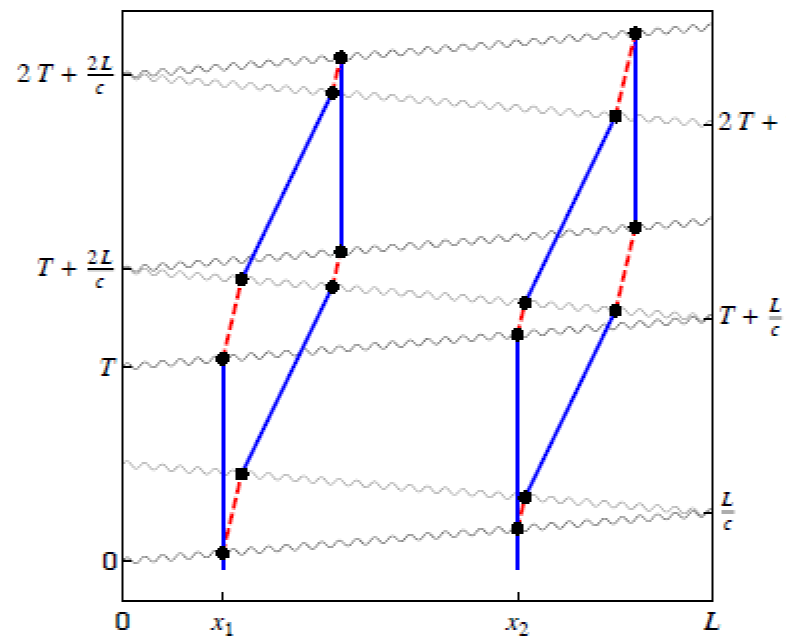


A New Method for Gravitational Wave Detection with Atomic Sensors

Peter W. Graham,[1] Jason M. Hogan,[2] Mark A. Kasevich,[2] and Surjeet Rajendran[1]
[1] Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305
[2] Department of Physics, Stanford University, Stanford, CA 94305

(Dated: April 30, 2013)





$$\varphi = \frac{4N\omega_a h}{c} L \sin^2\left(\frac{\omega T}{2}\right)\sin\left(\varphi_0 + \omega T\right)$$

Large momentum transfer reduces shot noise

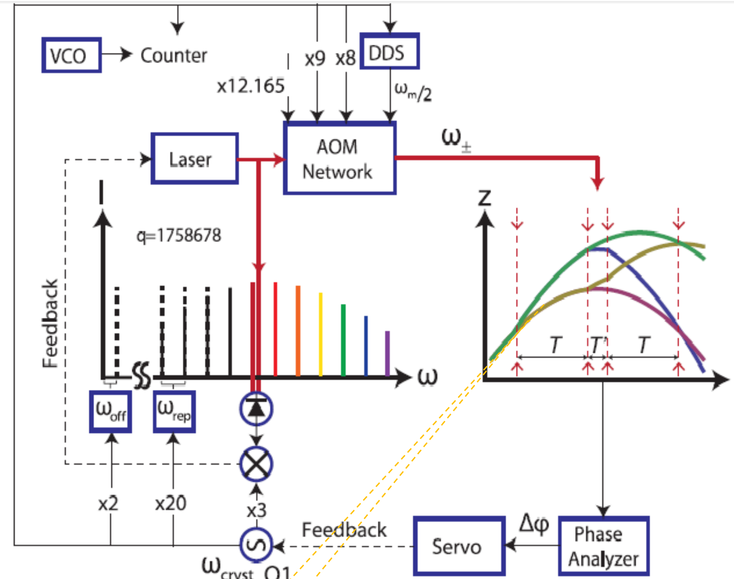
Phys. Rev. Lett.**110,** 171102 (2013)

Applications of atom interferometry

Science AAAS

A Clock Directly Linking Time to a Particle's Mass

Lan et al., Science **339,** 554 (2013)



$$\omega = \frac{1}{2nN^2}\frac{mc^2}{\hbar}$$

Key insight / innovation

- Feedback over atom interferometer using frequency comb
- Comb multiplies by N
- n-photon momentum transfer
- Clock frequency ~100 kHz= $(mc^2/\hbar)/(2nN^2)$, exactly

Technology impact

- A single particle is useful as a time/frequency reference
- Cesium atom used as approximation of a point mass
- 4 ppb accuracy demonstrated, < 1 ppb feasible

Application

- Mass standard in new SI where h and c are defined, kg measured
- With elementary (anti-) particles => equivalence principle with antimatter
- Light nanomechanical objects => mesoscopic mass standard

Watt balance

- 33 ppb for amu
- 33 ppb for kg
- Moving parts, gravity, standard resistors…
- Americans and Europeans disagree

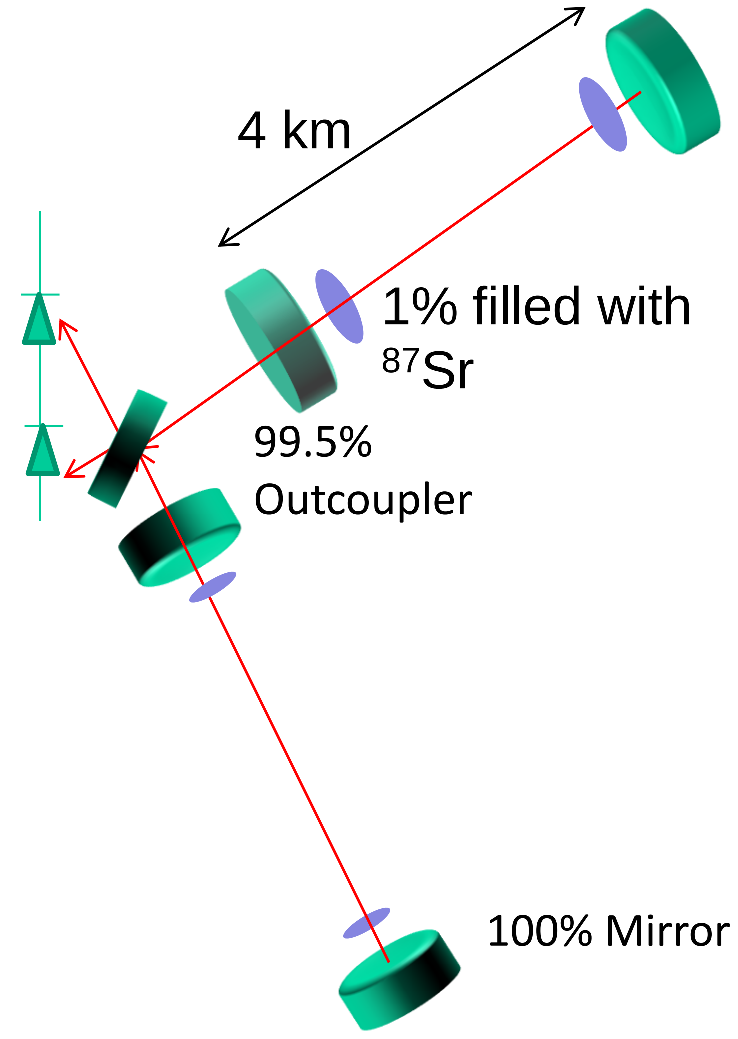
Atom interferometer+counting

- 4 ppb for amu
- 30 ppb for kg
- No moving parts, gravity, standard resistors…
- Agrees with European versions
- <1 ppb in the future

Independent methods realize the same definition ☺

A scenario

Quantity	
Cavity linewidth	30 Hz
Natural linewidth	1 mHz
Decoherence rate	10/s
Coupling	$5x10^{-6}$ Hz
Collective coupling	$3x10^{4}$
Atomic density	$10^{8}/cm^{3}$
Cavity Pulling	0.1
Atom Doppler linewidth	50 Hz
Photons/second	$3x10^{6}$
Sensitivity	$2x10^{-21}[f_{GW}/10$ mHz$]$



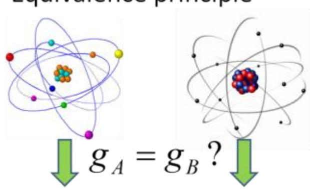
Atom interferometers in space: science

Key innovations vs other space projects and ground

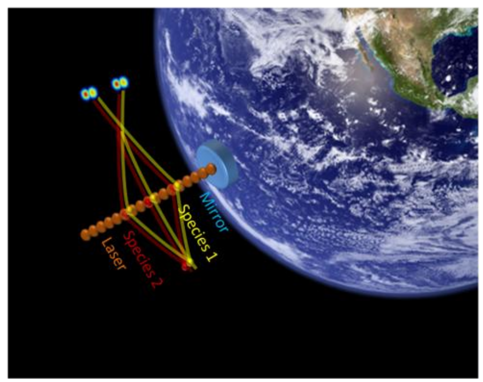
•Gimbal mount suppresses gravity gradient, atom overlap, atom thermal velocity
•Only possible in space
•Bragg atom optics, magic wavelength
•Controlled AC Stark effect for additional suppression
•*F*=1 and *F*=2 states to suppress quadratic Zeeman shift

- 10^{-15} accuracy
- 100x improved
- Combination K/Rb or ^{85}Rb/^{87}Rb: high impact of fundamental theories

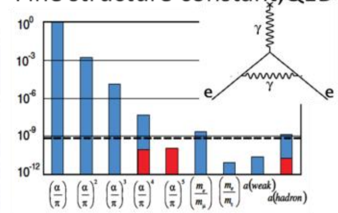
Equivalence principle



Light pulse atom interferometer in space



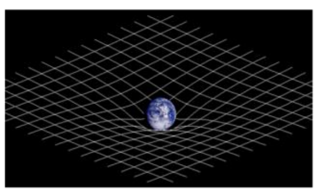
Fine structure constant,QED



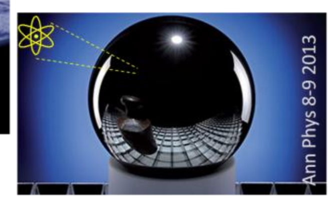
- 10-11 target accuracy
- Measuring α,
- Testing QED
- Searching for physics beyond the standard model

- Velocity of orbit increases effects $\sim(g/c^2)(v^2/c^2)$
- Is the equivalence principle valid for objects moving at high velocity?

Post-Newtonian gravity



Quantum mass standard



- Atomic balance
- Space program to provide best known mass standard in the new SI
- 10^{-11} target accuracy

Impact on society/space program

- Mass important in everyday life and commerce
- Spinoffs for inertial sensing in defense, geophysics, mineral exploration
- Technology for future gravitational wave detection
- Drag-free sensing

PRL 112, 121102 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Antimatter Interferometry for Gravity Measurements

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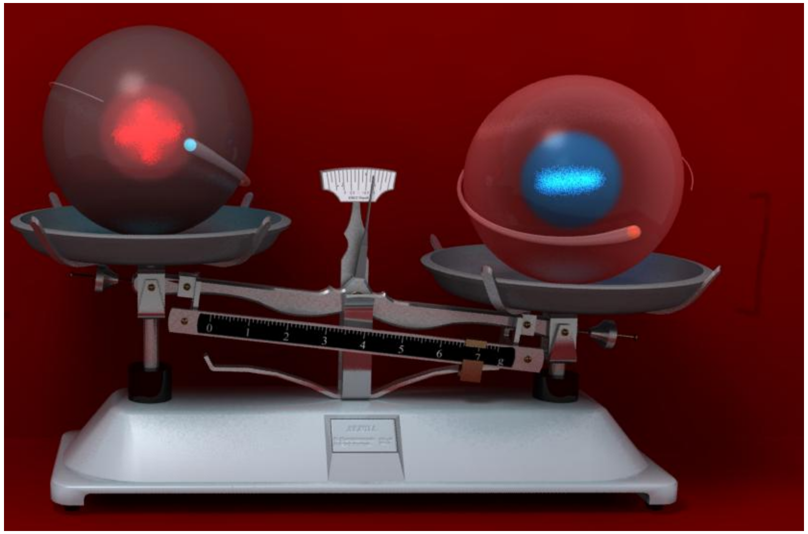
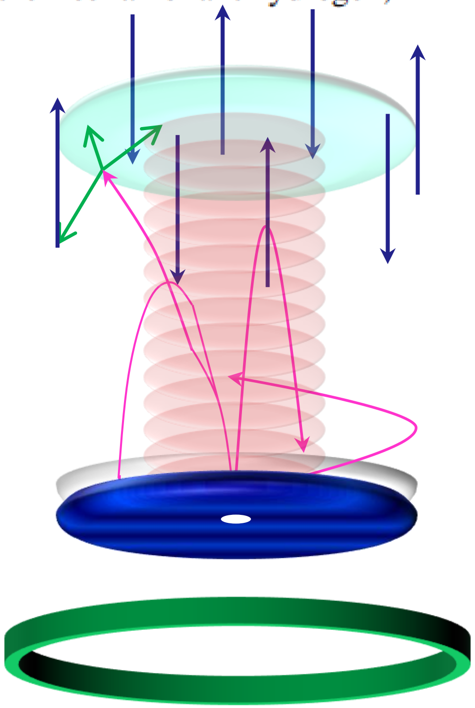
Jonathan S. Wurtele,[1,†] and Holger Müller[1,*,†]
[1]*Physics Department, University of California, Berkeley, California 94720, USA*
[2]*Department of Physics, Auburn University, Auburn, Alabama 36849, USA*
(Received 12 August 2013; published 25 March 2014)

We describe a light-pulse atom interferometer that is suitable for any species of atom and even for electrons and protons as well as their antiparticles, in particular, for testing the Einstein equivalence principle with antihydrogen. The design obviates the need for resonant lasers through far-off resonant Bragg beam splitters and makes efficient use of scarce atoms by magnetic confinement and atom recycling. We expect to reach an initial accuracy of better than 1% for the acceleration of the free fall of antihydrogen, which can be improved to the part-per million level.





Photons versus Atoms

Atom interferometers versus lasers (oversimplified)

LIGO	n=10^3, 10 km, 10^{10} atoms/s
Radiation pressure noise 10^{-22} at 10 Hz	No radiation pressure noise
Mirror thermal noise10^{-23} at 100 Hz	No mirror thermal noise
Photon shot noise 10^{-23} at 1 kHz	Atom shot noise $4x10^{-20}$
Demonstrated	Basic technology demonstrated, but parameters futuristic
Two arms required	Single-arm designs studied
Broadband	Narrow-band
Well understood	Needs study

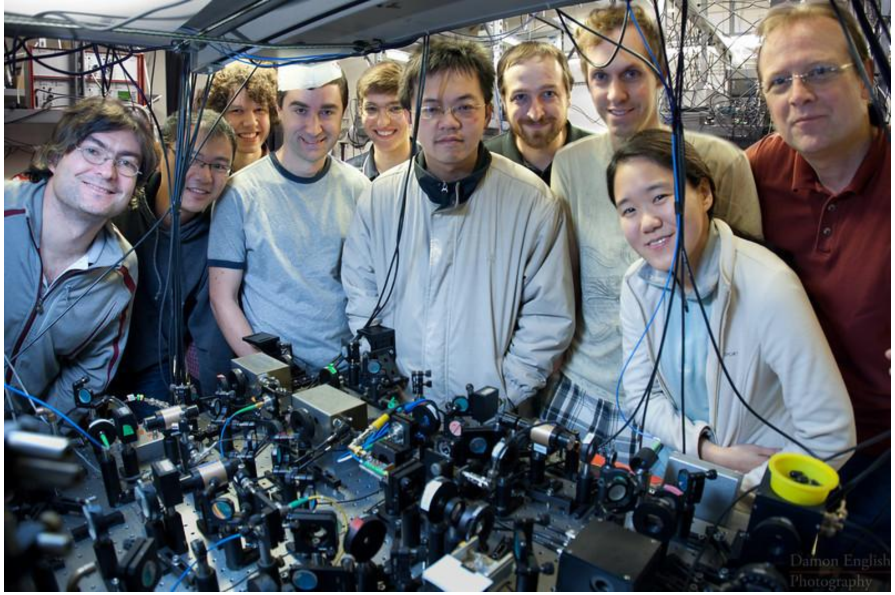
Compton clock
Postdocs: S.-y. Lan,
M. Hohensee,
D. English
Grad students:
P.-C. Kuan, B. Estey,

EEP
Postdocs: P. Hamilton
Grad student: G. Kim,

Lorentz invariance
Postodc: M. Hohensee
Grad student: F. Monsalve

Phase contrast TEM
Postdoc: M. Xu
Grad Student: E. Sohr

Cavity, AB effect
Postdoc :J. M. Brown
Grad student: B. Estey



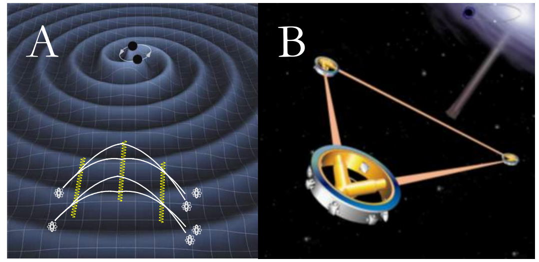
XUV atom interferometer
Postdoc :Paul Hamilton

the David & Lucile Packard FOUNDATION
NATIONAL SCIENCE FOUNDATION NSF
NIST
ALFRED P. SLOAN FOUNDATION 1934
NASA

Atomic gravitational wave detection

Approaches

A. "AGIS," atoms as poof-masses.
B. Light interferometry using atoms as drag-free proof masses
C. Single-laser interferometer using atoms as clocks



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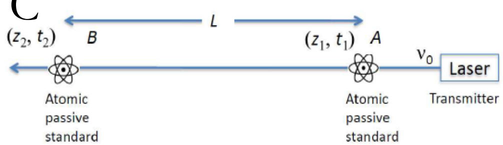
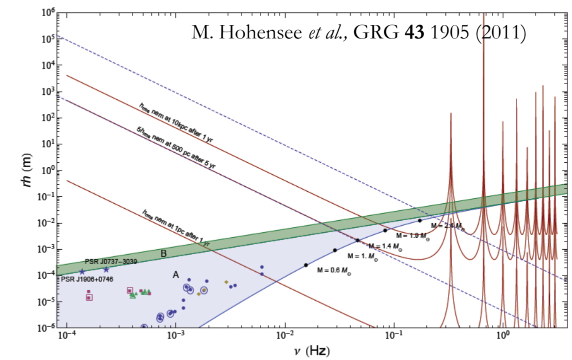




Key challenges

- Low atom number, high shot noise => Not competitive at high frequencies
- Atom temperature
- Technology maturity
- Novelty means that best approach may be unknown as yet

Key advantages

- No macroscopic proof masses
- No vibration isolation required
- Atoms have few internal degrees of freedom

⇒No thermal noise
⇒No radiation pressure noise

Current research

- Very large momentum transfer (Bloch oscillations)
- Noise sources, optimization
- Alternative schemes, e.g., superradiance
- Technology maturation
- Atom interferometers vs. other approaches

J. Harms, B.J.J. Slagmolen, R.X. Adhikari, M.C. Miller, M. Evans, Y. Chen, H. Müller, M. Ando, Phys. Rev. D **88,** 122003 (2013).
[M. Hohensee, S.-Y. Lan, R. Houtz, C. Chan, B. Estey, G. Kim, P.-C. Kuan, and H. Müller. Gen. Relativity Gravitat. **43,** 1905 (2013).

Summary

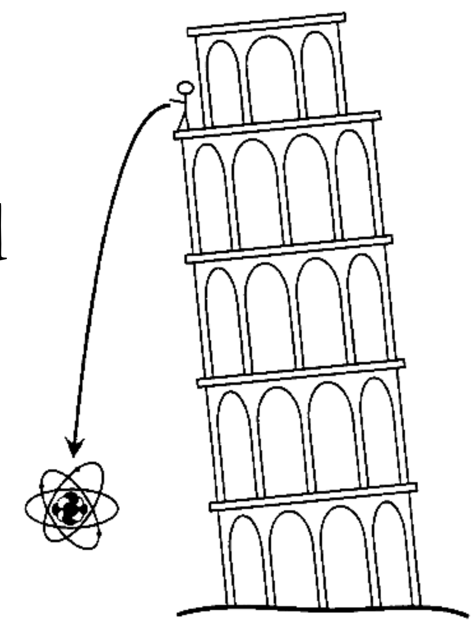
No radiation pressure noise, thermal noise, and seismic insulation issues

Possibly single-arm operation

Large influence of atom shot noise, wavefront distortions, narrowband operation

Sweet spot probably low frequencies, mHz (space) to 10 Hz (ground)

Technology not mature yet



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