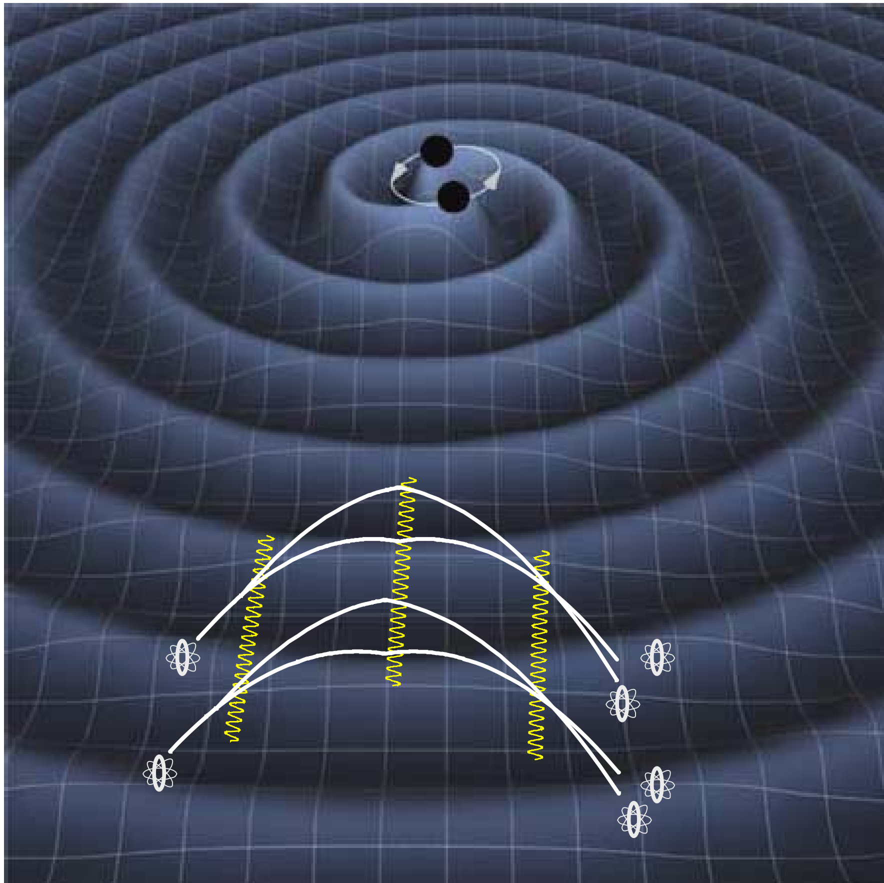
Gravitational wave detection with atom interferometry

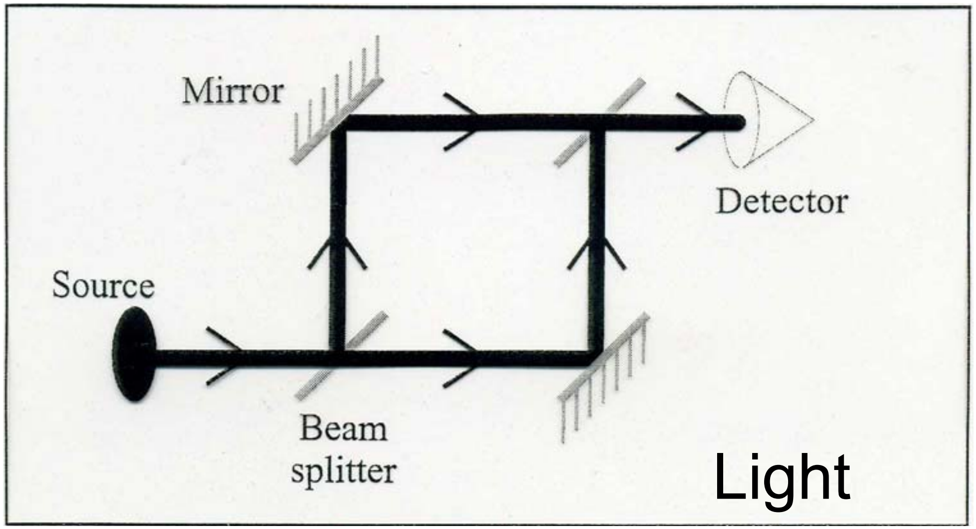
Holger Müller, UC Berkeley

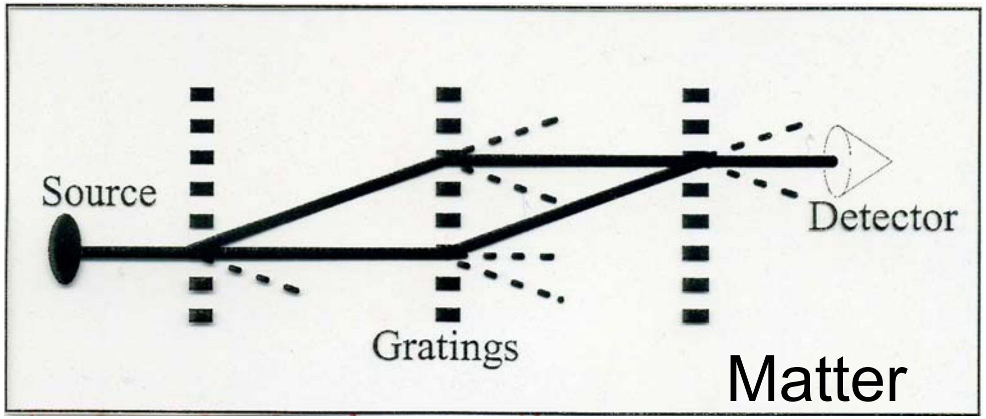


A question we answer…
and some we don't

1. How to best detect gravitational waves?
2. Are atom interferometers better than LIGO/LISA?
3. Should an atom interferometer gravitational wave detector be built?
4. What will be its limits?
5. Should we start a moderate research program, advancing AIs, answering 3) and 4)?

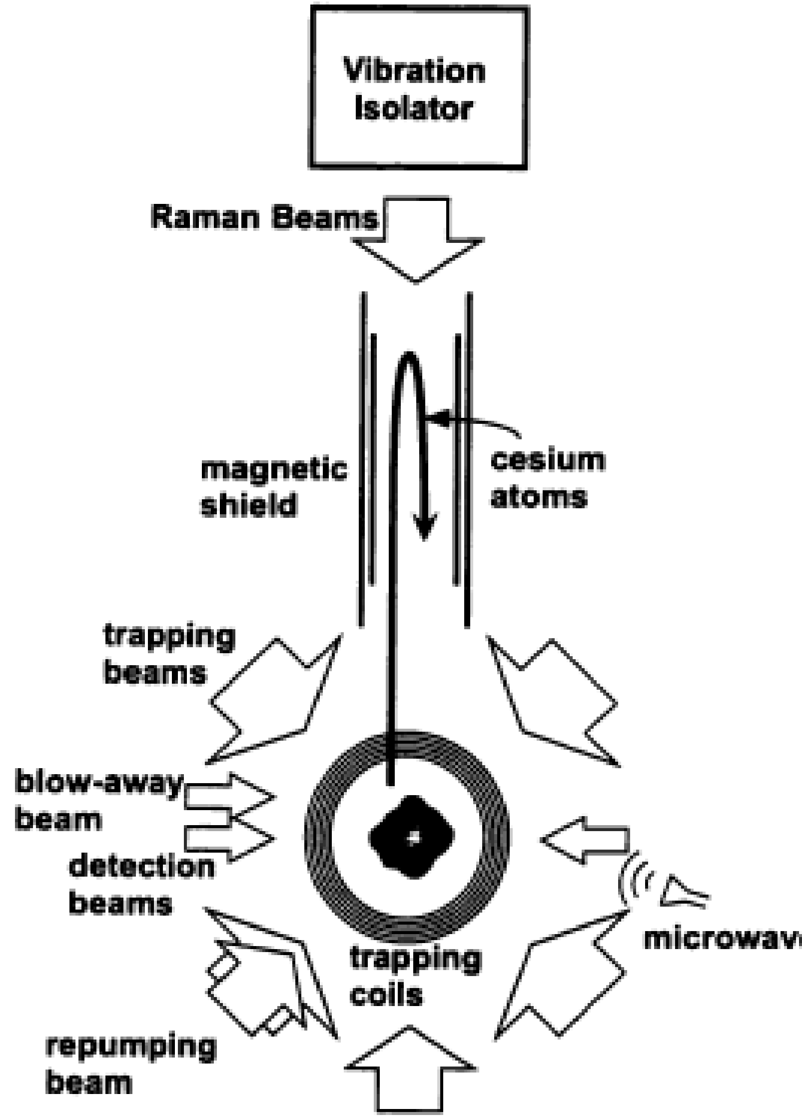
Interferometry





Atomic fountain

- Magneto-optical trap
- Cooling & launch
- State preparation
- Experiment



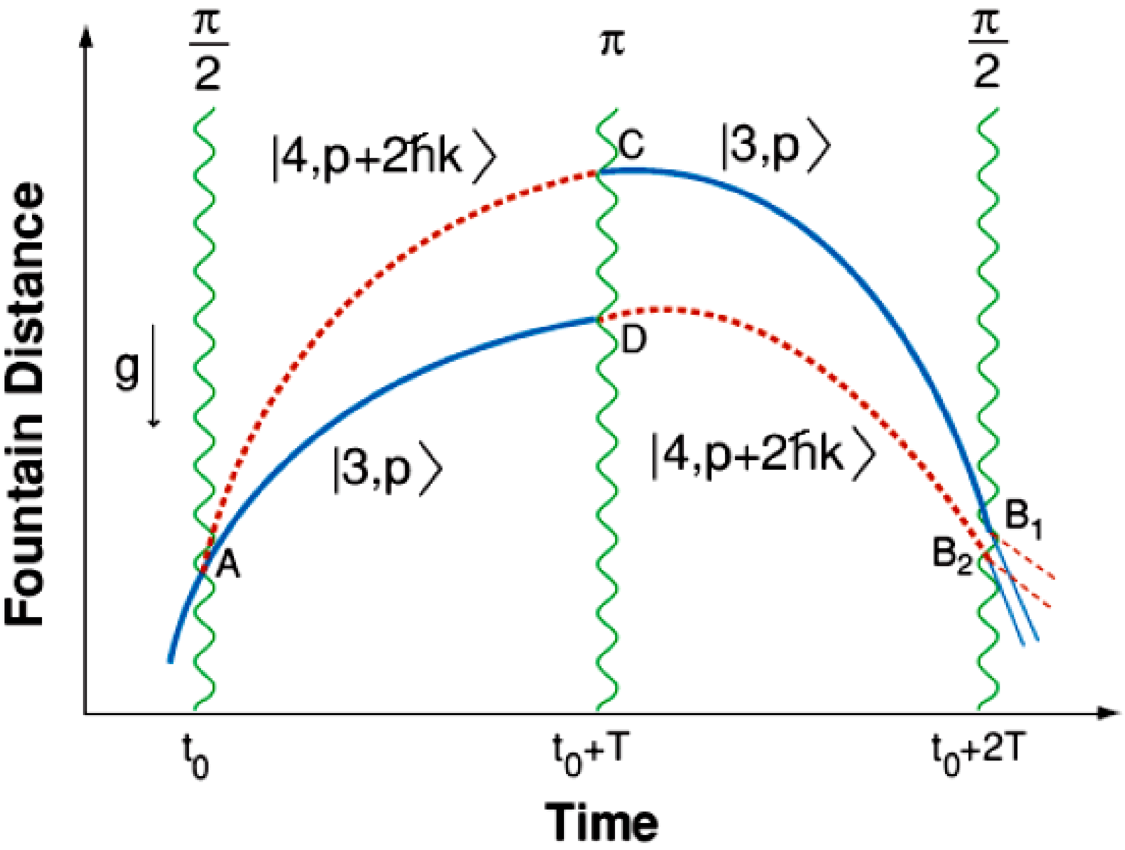
Mach-Zehnder Atom Interferometer

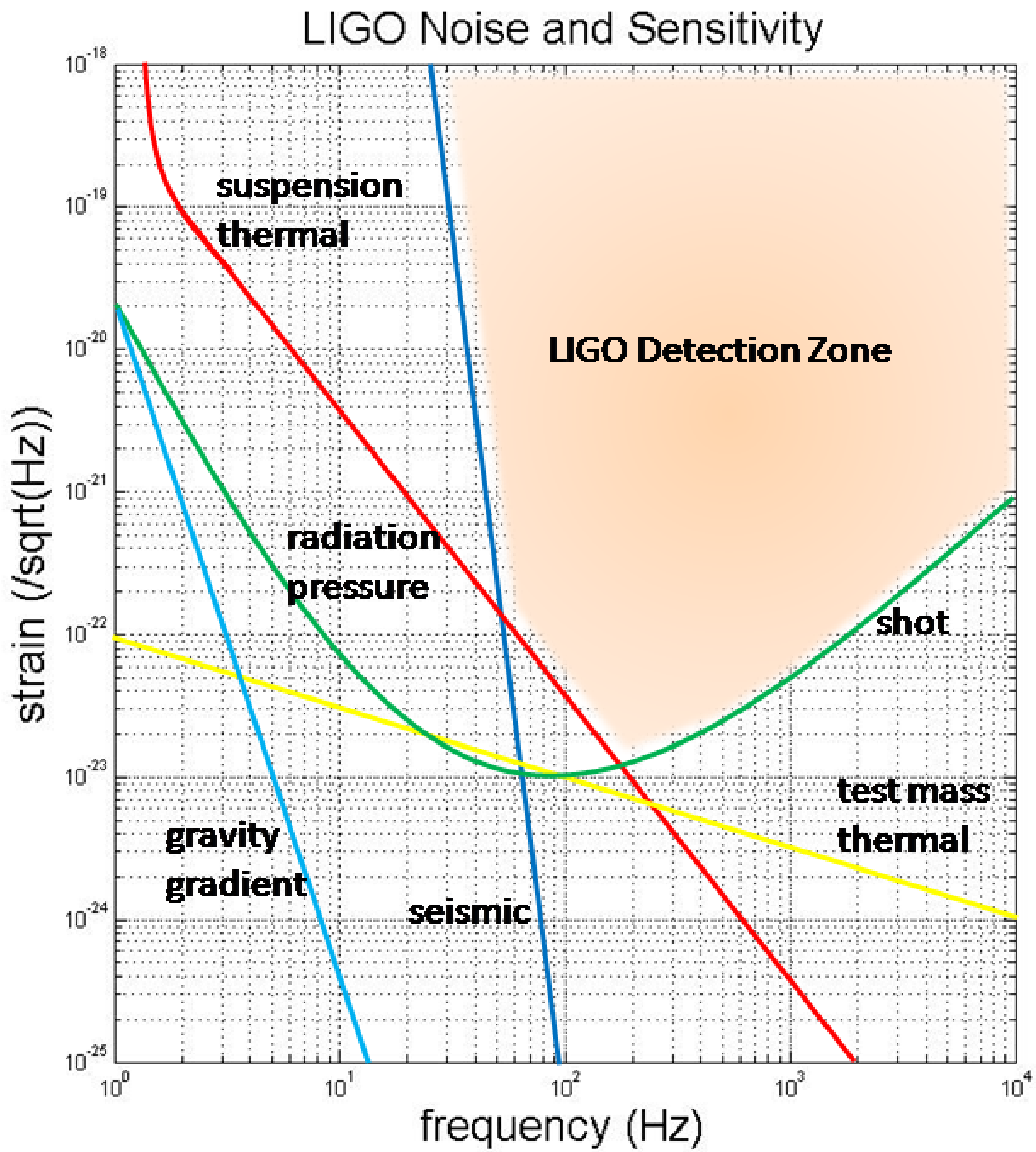
$$\varphi = \underbrace{\varphi_{\text{kin}} + \varphi_{\text{pot}}} + \varphi_{\text{interaction}}$$

$$\varphi_{\text{free}} = \frac{1}{\hbar}\int L dt$$

$$\varphi_{\text{int}} = -\varphi_{\text{kin}} = \varphi_{\text{pot}} = kgT^2$$

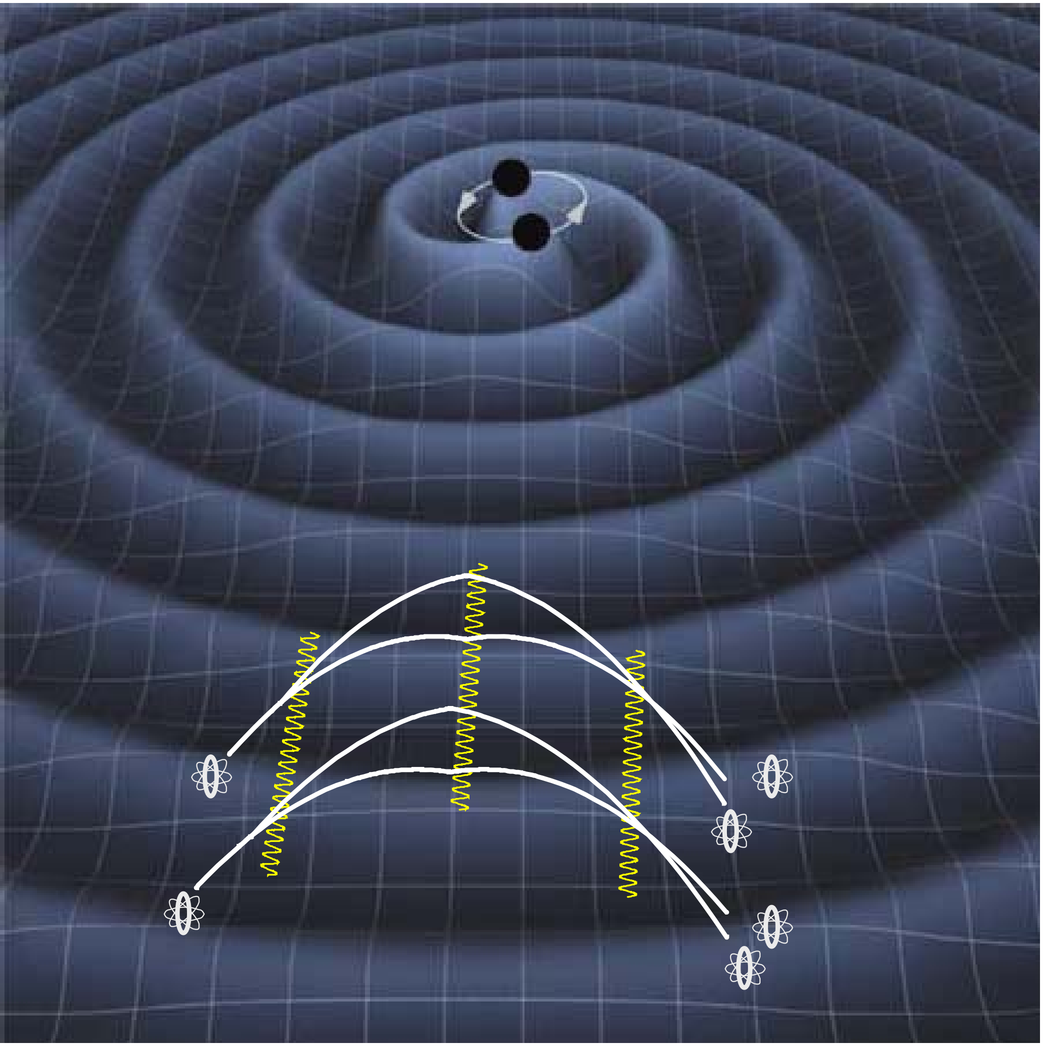
$$\varphi = kgT^2$$





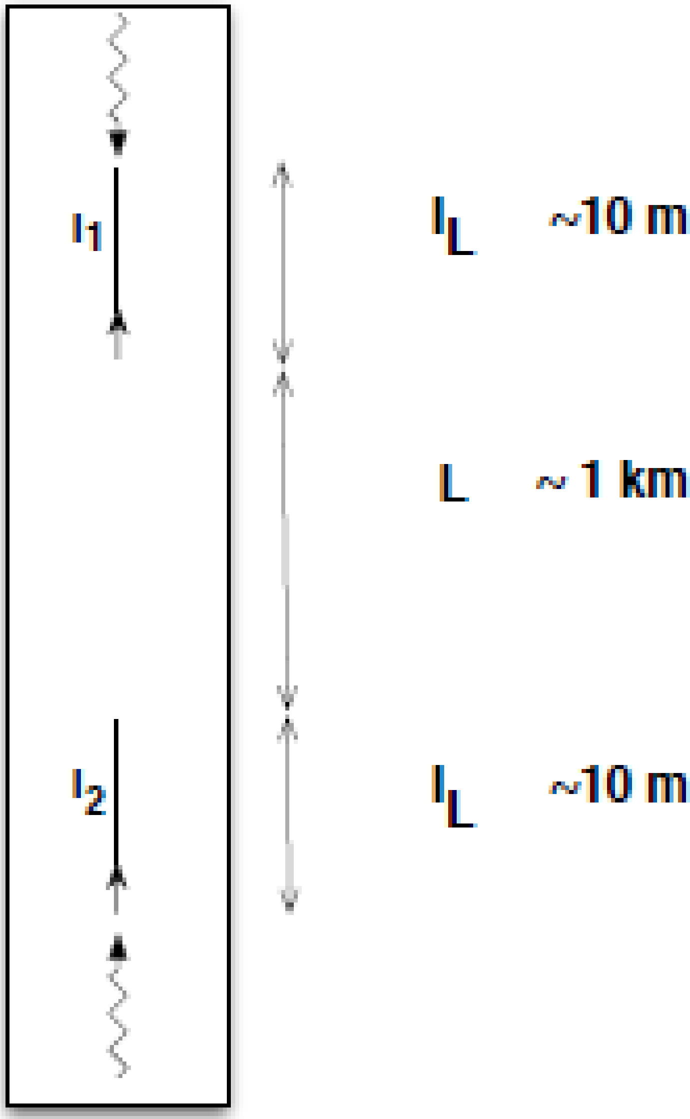
LIGO Noise and Sensitivity
suspension thermal
LIGO Detection Zone
radiation pressure
shot
test mass thermal
gravity gradient
seismic
strain (/sqrt(Hz))
frequency (Hz)
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

Atomic gravitational wave interferometric sensor (AGIS)



- “Mirrors” are atoms
- few degrees of freedom => no thermal noise, no radiation pressure noise
- Almost perfect free fall => no seismic insulation needed
- New technology, at the beginning of a development

AGIS: example



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

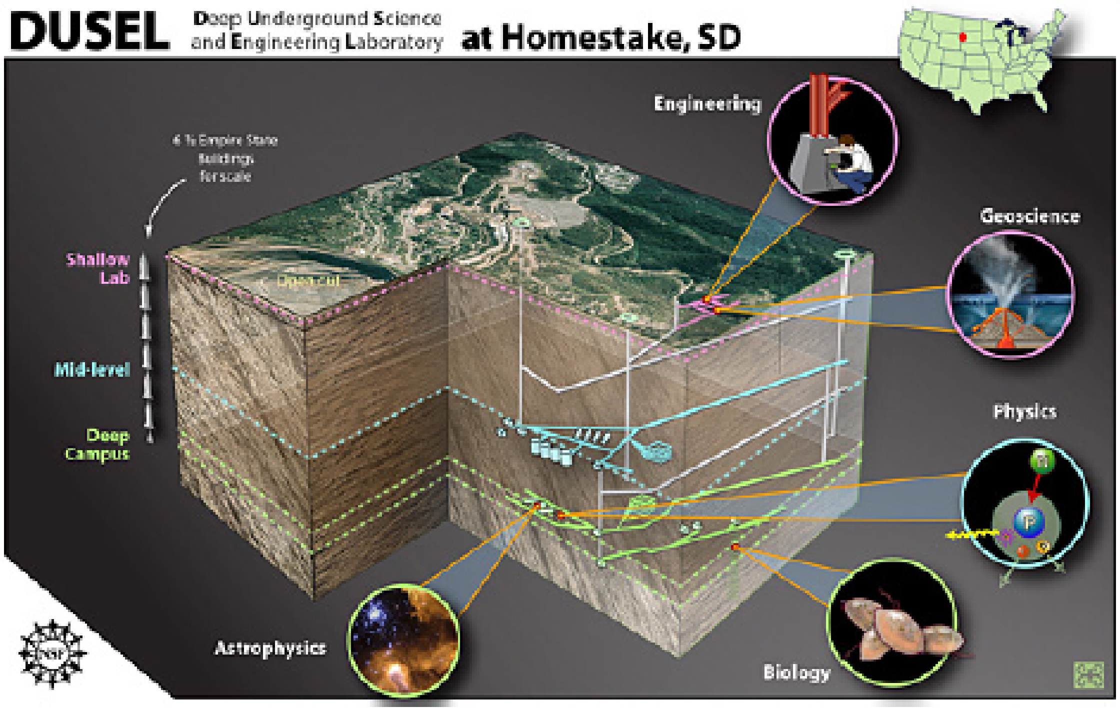
Examples:
k=2π/1μ,
h=10^{-17},
ω=2π*1Hz

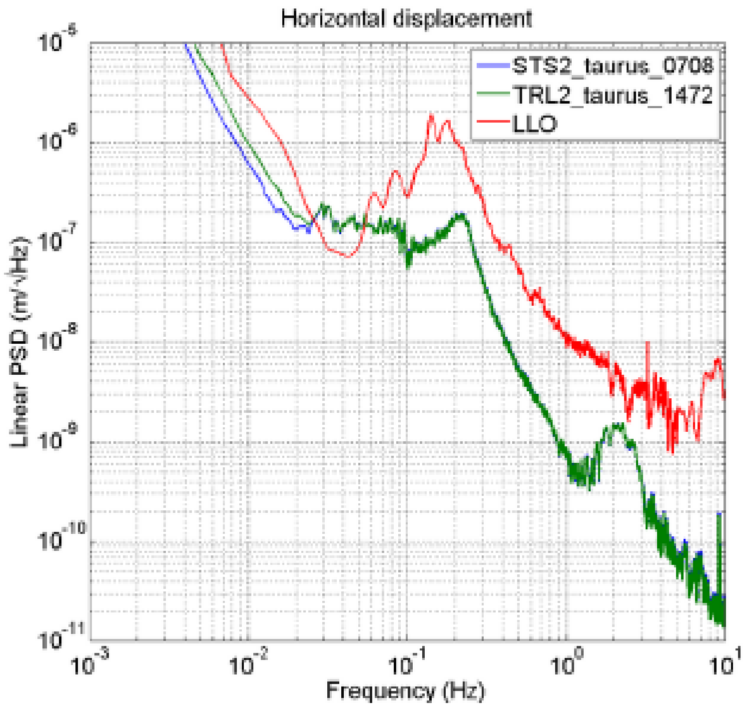
⇒Φ~3*10^{-7}

n=100

=>Φ~3*10^{-5}

Homestake gold mine: DUSEL





•Remote site, 3km deep. May be sufficiently low noise.

•Collaboration with Mark Kasevich to build demonstrator instrument

AGIS: challenges

1. 100-1000 photon beam splitters
2. Common-mode rejection of vibrations
3. Atom sources
4. Low-noise detection of atoms
5. (Squeezing)

Optimization

Sensitivity

$$h_{\mathrm{rms}} = \frac{1}{2nkL\sin^2(\omega T/2)\sqrt{\eta}},$$

Low-frequency limit

$$h_{\mathrm{rms}}^{\mathrm{LF}} = \frac{2}{nkL\omega^2 T^2\sqrt{\eta}}.$$

Optimizing T, n

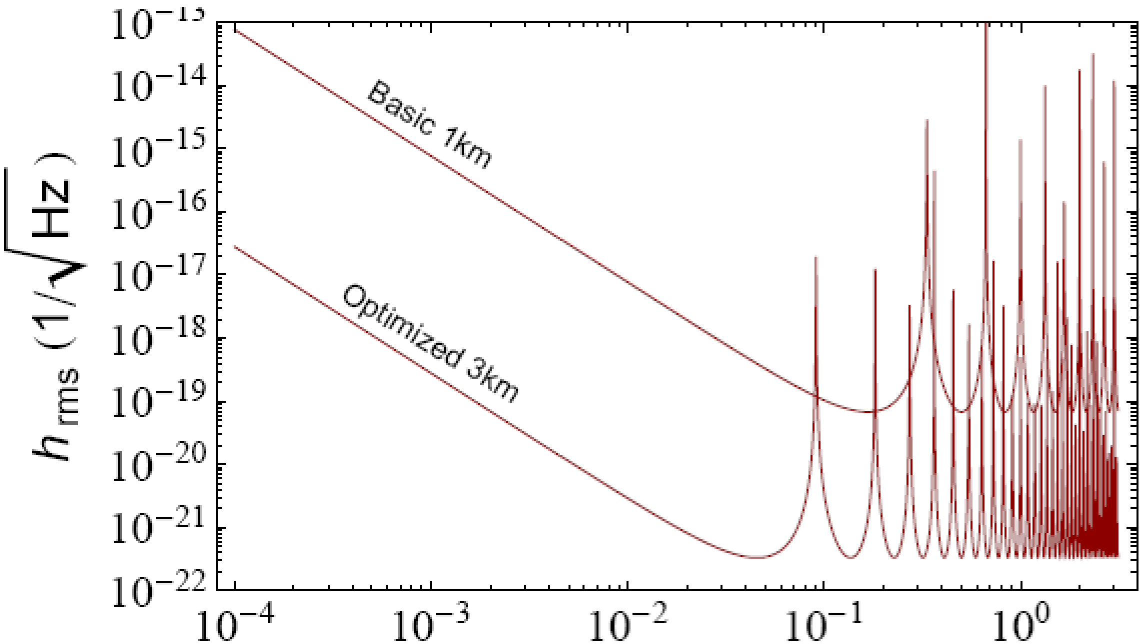
$$T_{\mathrm{opt}} = \sqrt{\frac{2L_{\mathrm{Tube}}}{5g}},$$

$$n_{\mathrm{opt}} = \frac{2L_{\mathrm{Tube}} - gT^2}{4Tv_r},$$

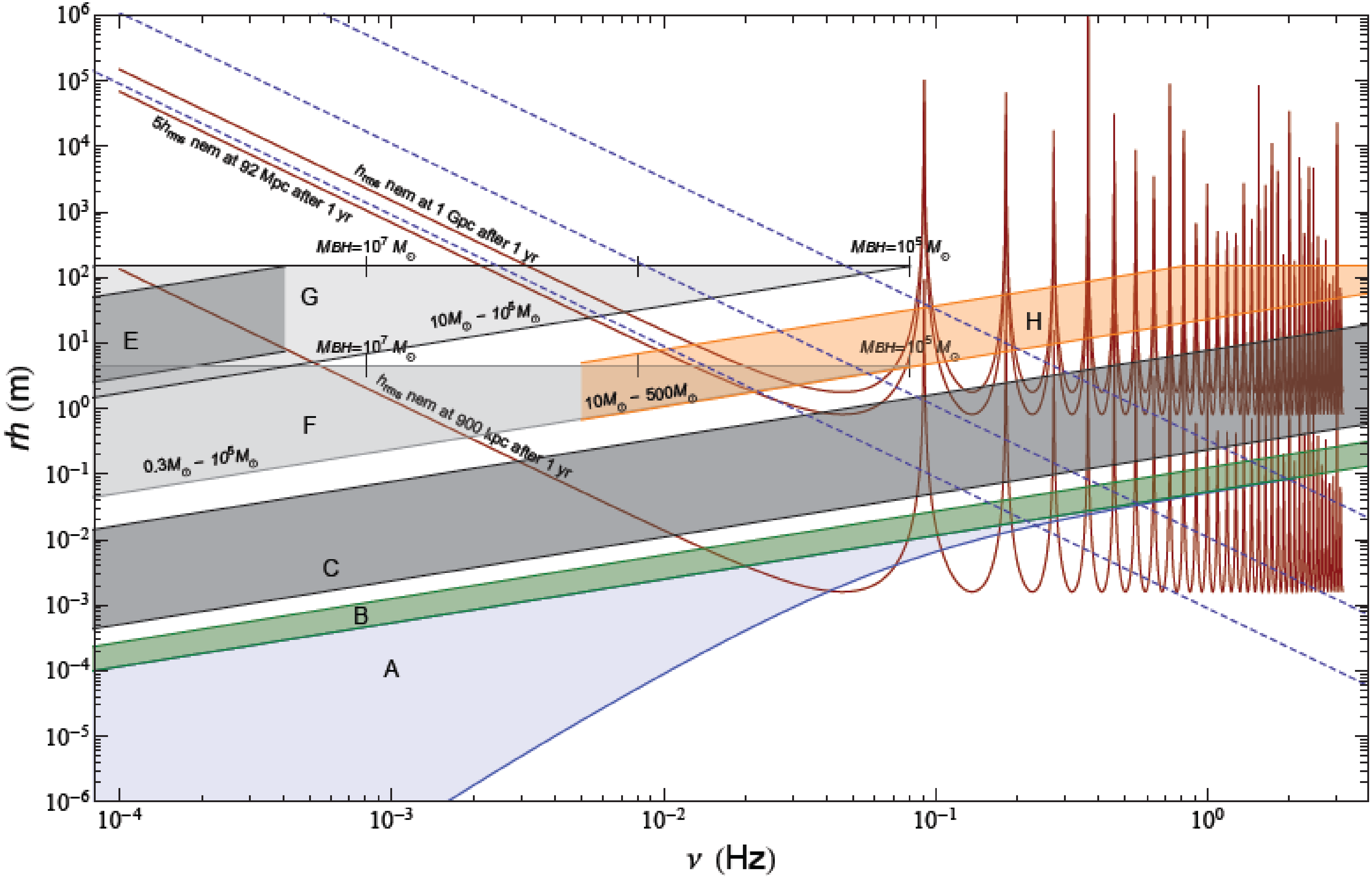
$$h_{\mathrm{rms}}^{\mathrm{LF,opt}} = \frac{25v_r\sqrt{5g}}{2kL_{\mathrm{Tube}}^{5/2}\omega^2\sqrt{2\eta}}.$$

AGIS sensitivity

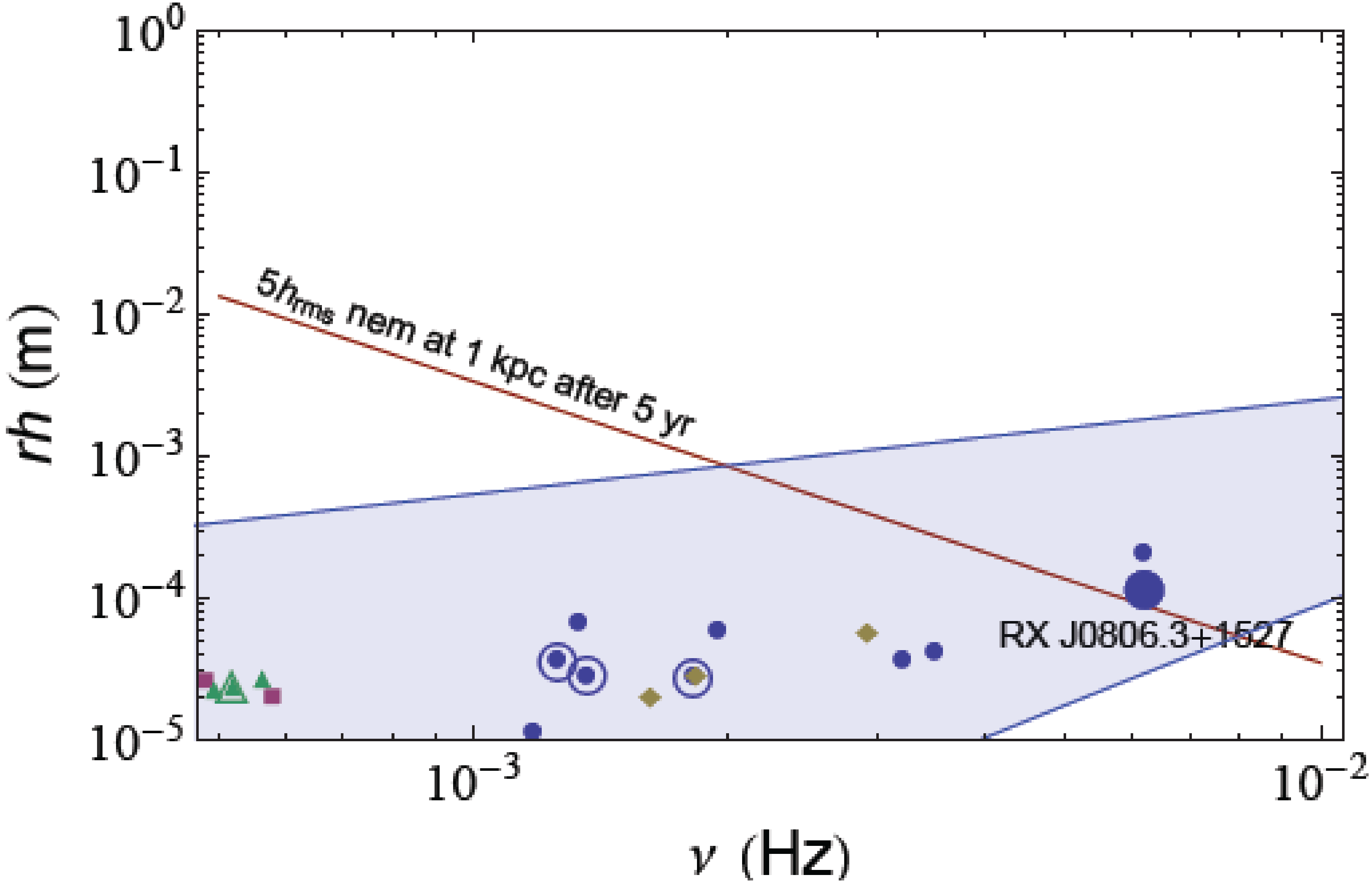
Parameter	Symbol	Basic	Optimized
Wavenumber	k	$2\pi/852\,\mathrm{nm}$	$2\pi/852\,\mathrm{nm}$
Momentum transfer/$(\hbar k)$	n	1,000	31,000
Pulse separation time	T	$3\,\mathrm{s}$	$11\,\mathrm{s}$
Tube length	L_{Tube}	$1{,}000\,\mathrm{m}$	$3{,}000\,\mathrm{m}$
Separation	L	$\approx L_{\mathrm{Tube}}$	$1{,}200\,\mathrm{m}$
Atom throughput	η	$10^{12}/\mathrm{s}$	$3\times10^{13}/\mathrm{s}$
Peak sensitivity	h_{rms}	$7\times10^{-20}/\sqrt{\mathrm{Hz}}$	$1.3\times10^{-22}/\sqrt{\mathrm{Hz}}$
Low freq. sensitivity	$h_{\mathrm{rms}}^{\mathrm{LF,opt}}$	$3\times10^{-20}(\frac{\mathrm{Hz}}{\omega})^2\frac{1}{\sqrt{\mathrm{Hz}}}$	$1.1\times10^{-23}(\frac{\mathrm{Hz}}{\omega})^2\frac{1}{\sqrt{\mathrm{Hz}}}$



Summary with optimized AGIS



Galactic Binaries



Challenge: gravity gradient noise

s=0.36

Rayleigh waves

$$u = C\left(-0.85e^{-qkz} + 1.5e^{-sk(x_3)}\cos k(ct - x)\right)$$

$$a_t - a_b = \pi\rho G b \frac{L}{\lambda}$$

Accelerations

Strain noise

$$h = \frac{\rho G b}{2\omega c}$$

2×10^{-14} / rt(Hz) at 10 mHz (14,000 times as large as AGIS noise),
2×10^{-16} /rt(Hz) at 100 mHz (1000 times as large)

Mitigation
- monitoring?
- more than two clouds
- correlation

An Atomic Gravitational Wave Interferometric Sensor in Low Earth Orbit (AGIS-LEO)

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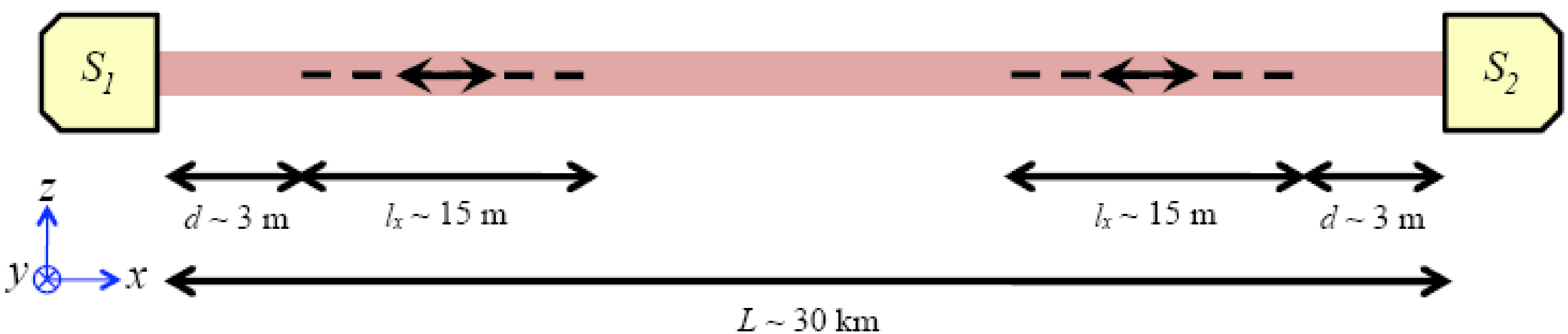
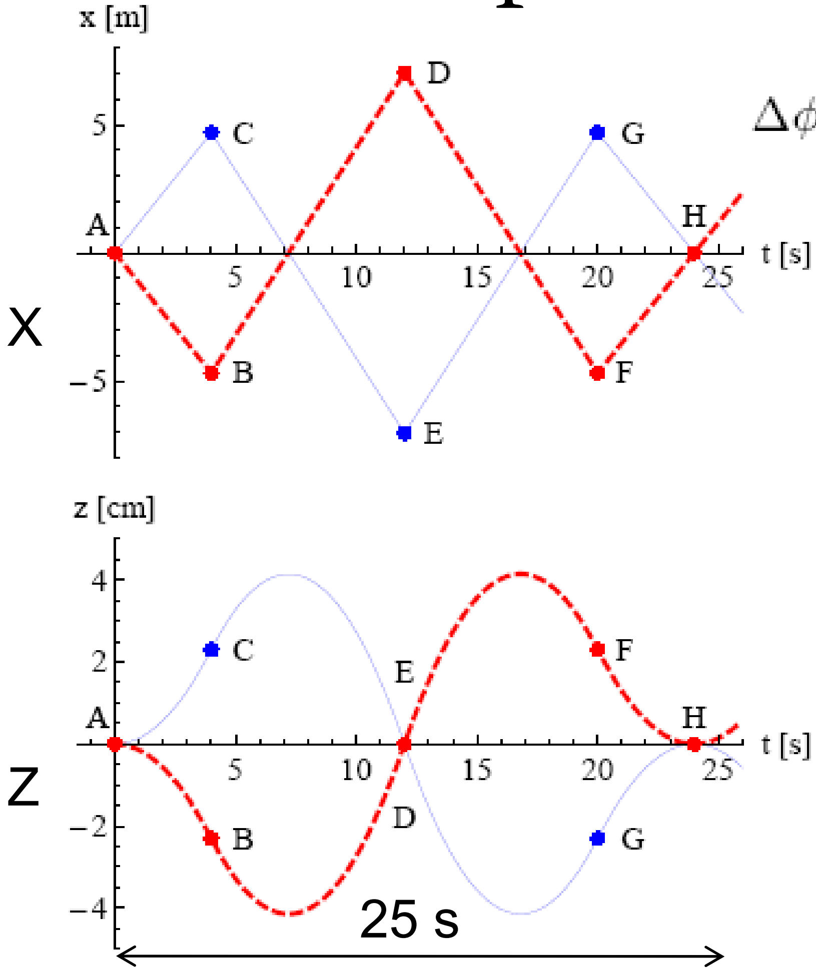
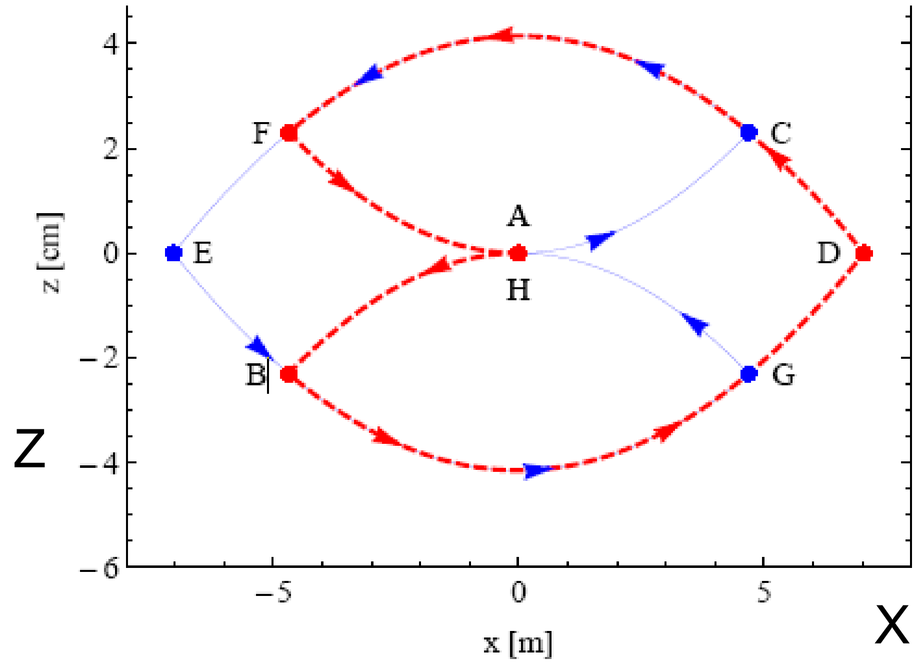
Laboratoire Charles Fabry de l'Institut d'Optique, Centre National de la Recherche Scientifique, Université Paris Sud 11, Institut d'Optique Graduate School, RD 128, 91127 Palaiseau Cedex, France



5-pulse Configuration



$$\Delta\phi_{GW} = 8k_{eff}hL\sin^4(\omega T/2)\left(\frac{7+8\cos\omega T}{2}\right)\sin\theta_{GW}$$



4 pulses needed because of Coriolis forces

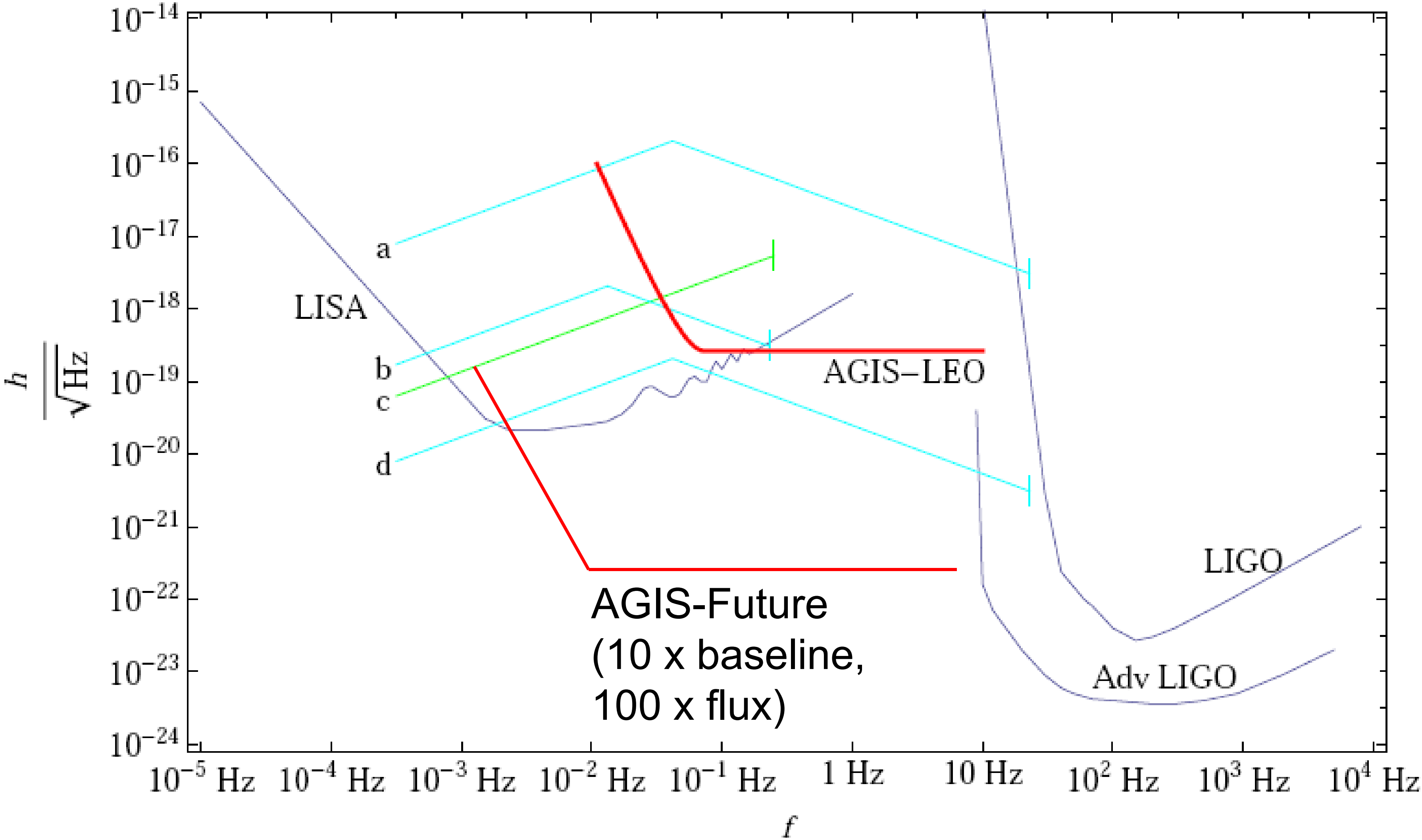
5 pulses cancel gravity gradients, wavefront distortions

Assumptions/requirements

Parameter	AGIS-LEO	LISA	DECIGO
Band / Hz	0.1-10	0.0001-1	0.1-10
Peak sensitivity	$3x10^{-19}$	$3x10^{-20}$	10^{-21}
Baseline	30 km	10^{6} km	10^{3}
Drag-free control	none		
Orbit	Earth	Sun	Sun
# satellites	2	3	6
Momentum transfer	200 ħk	-	-
Optical phase sens	10^{-6} rad	10^{-3} rad	10^{-8} rad (cavity)

Challenge: 1000 x the wavefront requirement of LISA, w/o cavity

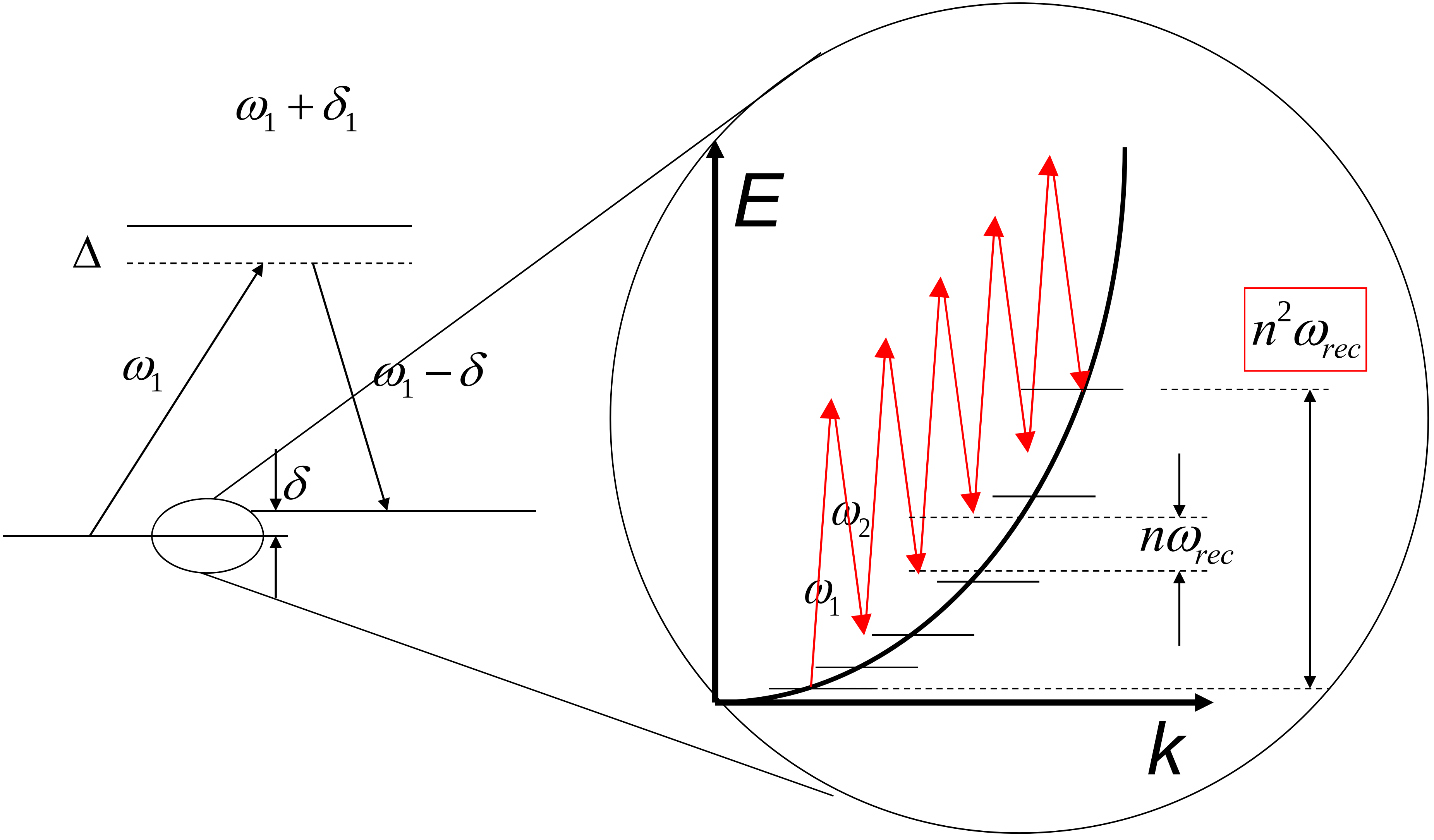
Shot noise-sensitivity



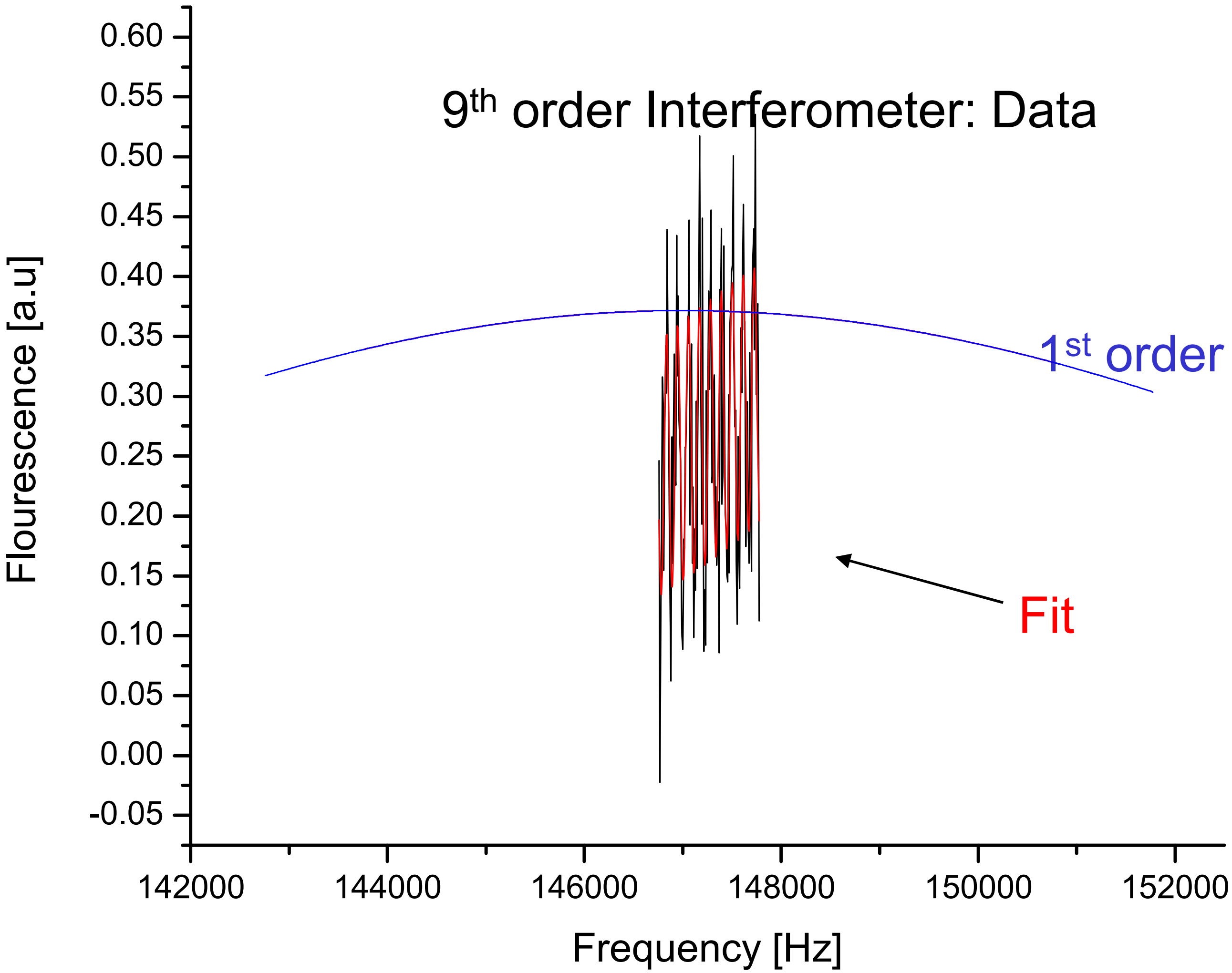
Not plotted: DECIGO

Real World: The development of LMT

Multiphoton Bragg diffraction



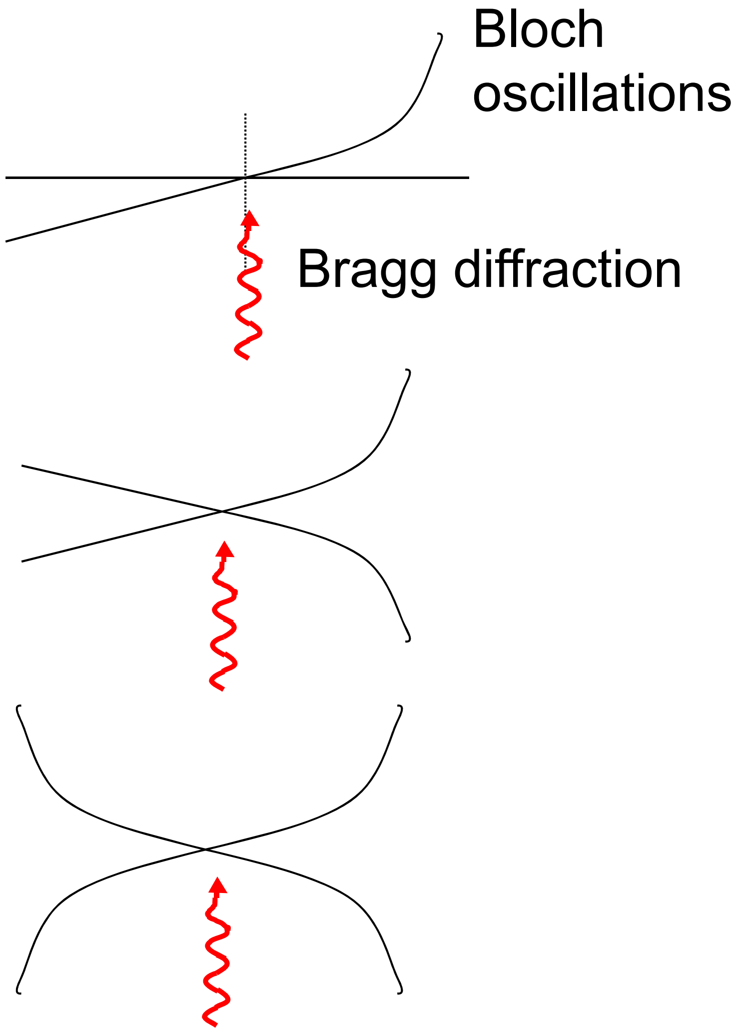
18 photon vs. 2 photon RB Interferometer



H.M. *et al.*, PRL 100, 180405 (2008)

Bloch-Bragg-Bloch (BBB) beam splitter

BBB splitter



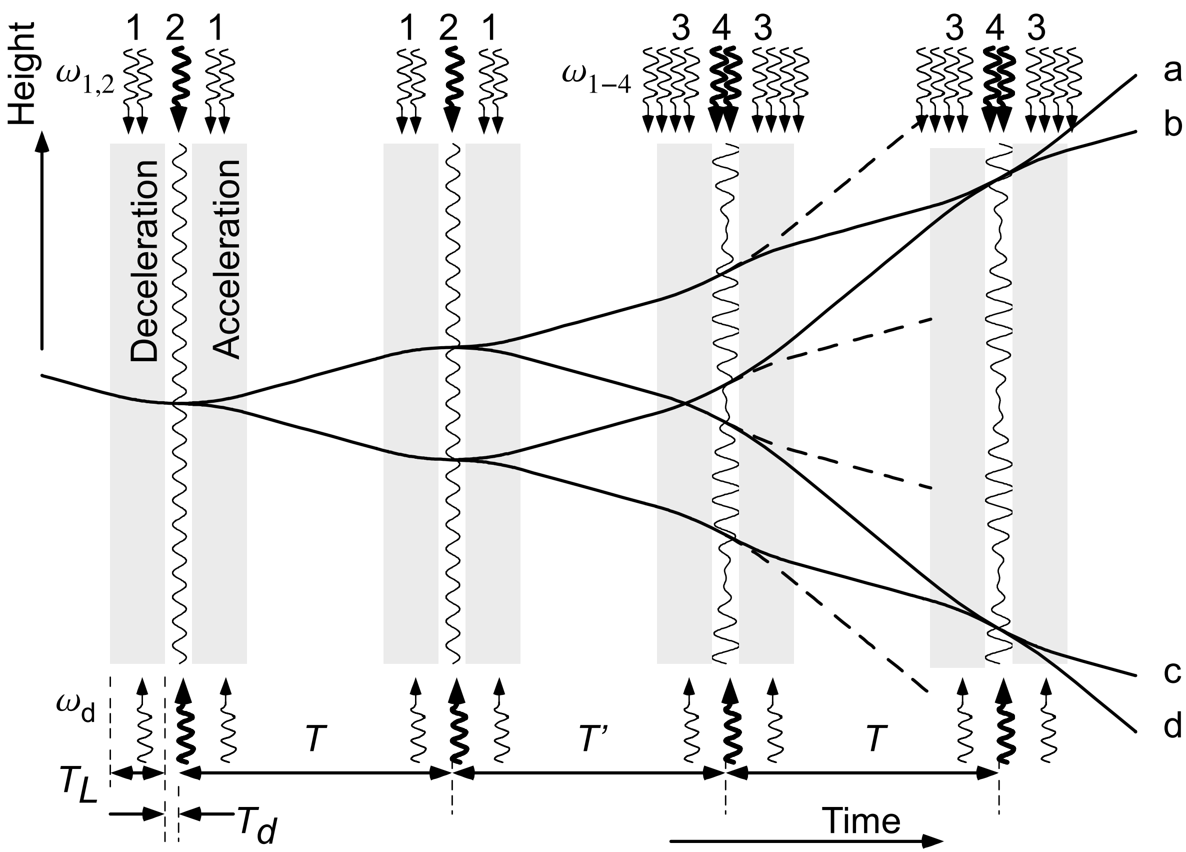
AC Stark effect not balanced

Assymetry input/output

That's it!

But: dual lattices,
lattice loaded twice,
and one Bragg diffraction.

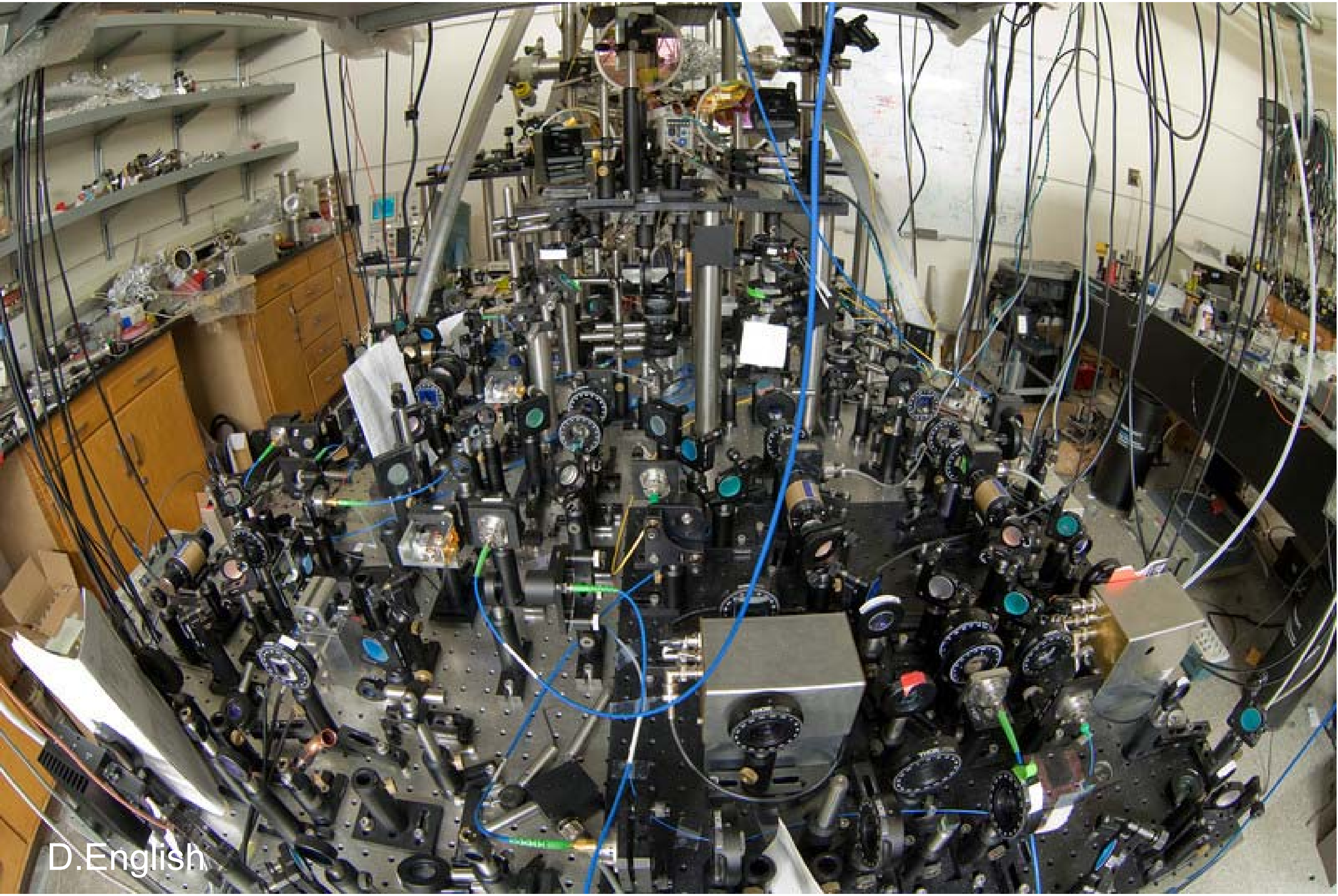
BBB interferometers



1: dual lattice
2: single Bragg
3: quadruple lattice
4: dual Bragg

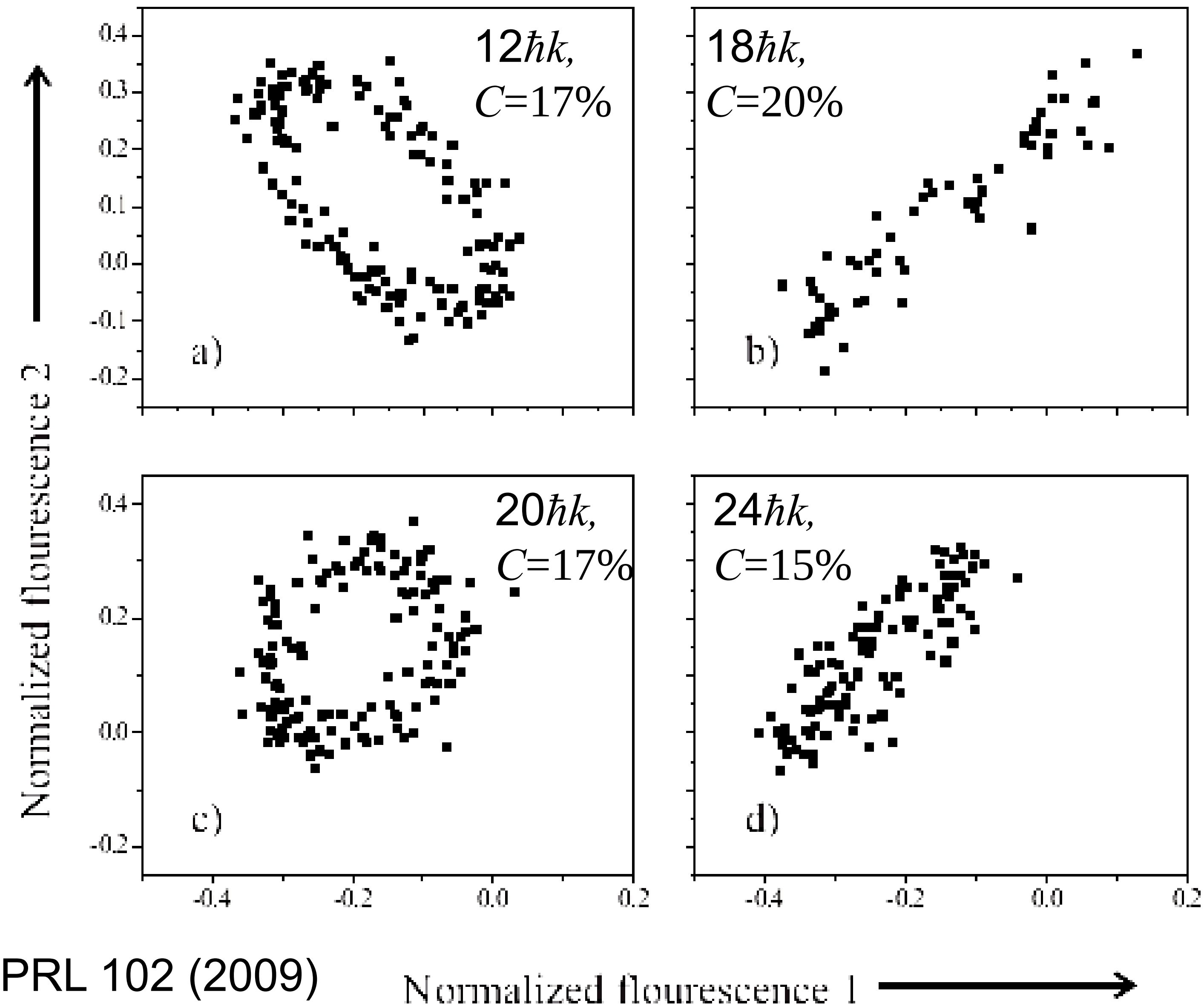
24 optical lattices:
4 dual
4 quadruple
6 Bragg diffractions:
2 single
2 dual.

Will it be coherent?


D.English

BBB interferometers

…yes! And might be scalable to 100s of $\hbar k$.



Mueller et al., PRL 102 (2009)

AGIS: challenges

1.	1000 photon beam splitters	in progress
2.	Common-mode rejection of vibrations	✓
3.	Atom sources	to be developed
4.	Low-noise detection of atoms	✓
5.	(Squeezing)	?
6.	Ultra low wavefront distortion optics	$
7.	High-power, ultra-low phase noise lasers	✓ ($)
8.	Large setup	$

To, for love of truth,
…
forward the search
Into the mysteries and marvelous simplicities
Of this strange and beautiful universe,
Our home.

John Archibald Wheeler, 1911-2008

A question we answer…
and some we don't

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2. Are atom interferometers better than LIGO/LISA?
3. Should an atom interferometer gravitational wave detector be built?
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5. Should we start a moderate research program, advancing AIs, answering 3) and 4)?

Answer…

Yes...

1. No thermal noise, no radiation pressure noise, no seismic insulation needed
2. But: shot noise, wavefront distortions (earth & space), gravity gardient mitigation (space)
3. LMT, squeezing, large atom sources: *recent* inventions => fast progress
4. Technology can be developed in table-top experiments, limits studied in Ph D theses

Two of our recent articles…

Gen Relativ Gravit
DOI 10.1007/s10714-010-1118-x

RESEARCH ARTICLE

Sources and technology for an atomic gravitational wave interferometric sensor

Michael Hohensee · Shau-Yu Lan · Rachel Houtz · Cheong Chan · Brian Estey · Geena Kim · Pei-Chen Kuan · Holger Müller

Received: 30 December 2009 / Accepted: 23 October 2010

Abstract We study the use of atom interferometers as detectors for gravitational waves in the mHz–Hz frequency band, which is complementary to planned optical interferometers, such as laser interferometer gravitational wave observatories (LIGOs) and the Laser Interferometer Space Antenna (LISA). We describe an optimized atomic gravitational wave interferometric sensor (AGIS), whose sensitivity is proportional to the baseline length to power of 5/2, as opposed to the linear scaling of a more conservative design. Technical challenges are briefly discussed, as is a table-top demonstrator AGIS that is presently under construction at Berkeley. We study a range of potential sources of gravitational waves visible to AGIS, including galactic and extra-galactic binaries. Based on the predicted shot noise limited performance, AGIS should be capable of detecting type Ia supernovae precursors within 500 pc, up to 200 years beforehand. An optimized detector may be capable of detecting waves from RX J0806.3+1527.

Keywords Gravitational waves · Atom interferometers · Binary systems

1 Introduction

The production and propagation of gravitational waves is a central prediction of the theory of General Relativity. Direct observation of such waves has been attempted using resonant bar detectors, which would be mechanically excited by passing gravitational

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Gen.Rel. Grav. online first
DOI 10.1007/s10714-010-1118-x

PRL 106, 151102 (2011) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2011

Equivalence Principle and Gravitational Redshift

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We investigate leading order deviations from general relativity that violate the Einstein equivalence principle in the gravitational standard model extension. We show that redshift experiments based on matter waves and clock comparisons are equivalent to one another. Consideration of torsion balance tests, along with matter-wave, microwave, optical, and Mössbauer clock tests, yields comprehensive limits on spin-independent Einstein equivalence principle-violating standard model extension terms at the 10^{-6} level.

DOI: 10.1103/PhysRevLett.106.151102 PACS numbers: 04.80.−y, 03.30.+p, 11.30.Cp, 12.60.−i

Gravity makes time flow differently in different places. This effect, known as the gravitational redshift, is the original test of the Einstein equivalence principle (EEP) [1] that underlies all of general relativity; its experimental verification [2–6] is fundamental to our confidence in the theory. Atom interferometer (AI) tests of the gravitational redshift [4,6] have a precision 10000 times better than tests based on traditional clocks [3], but their status as redshift tests has been controversial [7]. Here, we show that the phase accumulated between two atomic wave packets in any interferometer equals the phase between any two clocks running at the atom's Compton frequency following the same paths, proving that atoms are clocks. For a quantitative comparison between different redshift tests, we use the standard model extension (SME) [8–11], which provides the most general way to describe potential low energy Lorentz symmetry-violating (thus EEP-violating) signatures of new physics at high energy scales. We show that all EEP tests are sensitive to the same five terms in the minimal gravitational SME [9–11] and, for the first time, comprehensively rule out EEP violation in redshift tests greater than a few parts per million for neutral matter.

If two clocks are located at different points in spacetime, they can appear to tick at different frequencies, despite having the same proper frequency ω_0 in their local Lorentz frames. For clocks moving with nonrelativistic velocities $\vec{v}_1$ and $\vec{v}_2$ in a weak gravitational potential $\phi_i = -MG/|\vec{r}_i|$, the difference frequency is [12]

$$\frac{\delta\omega}{\omega_0} = \frac{\omega_1-\omega_2}{\omega_0} = \frac{\phi_1-\phi_2}{c^2} - \frac{v_1^2-v_2^2}{2c^2} + O(c^{-4}). \quad (1)$$

The first term is the gravitational redshift, originally measured [2] by Pound and Rebka in 1960, while the second term is the time dilation due to the clocks' relative motion. The redshift term can be isolated from the time dilation if the clocks' trajectories are known.

$$\delta\varphi_f = \omega_0 \int_0^T dt\left(\frac{\vec{r}_{12}\cdot\vec{g}}{c^2} - \frac{v_1^2-v_2^2}{2c^2}\right), \quad (2)$$

specializing to a homogenous gravitational field so that $\phi_1-\phi_2 = \vec{g}\cdot\vec{r}_{12}$, with $\vec{r}_{12}$ being the clocks' distance vector and $\vec{g}$ the local acceleration of free fall. If the clocks are freely falling, then their motion is an extremum of their respective actions [12] $S_i = \int mc^2 d\tau \approx \int m[c^2 + \phi_i - v_i^2/2]dt$. Thus $\delta\varphi_f$ is proportional to the difference $S_1 - S_2$ in their extremized actions.

To clarify the equivalence between matter-wave and clock comparison tests, consider two conventional clocks that follow the two piecewise freely falling trajectories indicated in Fig. 1. Initially, they are colocated and synchronized with zero phase difference. In a uniform gravitational field, it can be shown that the relative phase $\delta\varphi_f$ accumulated by the clocks in free fall vanishes, as the redshift and time dilation contributions in Eq. (2) are of the same magnitude $\omega_0 g v_r T^2/c^2$ but opposite sign [13]. Thus $\delta\varphi_f = 0$ is the measured phase difference at $t = 2T$, when they are again colocated and at rest relative to one another. The problem can also be solved from the viewpoint of the moving clocks rather than that of the stationary observer: $\delta\varphi_f$ vanishes because the time dilation term cancels the

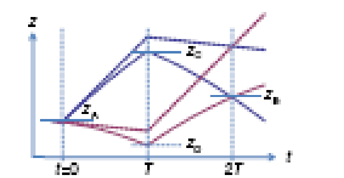

FIG. 1 (color online). Mach-Zehnder clock or atom interferometer. Two otherwise freely falling clocks (or halves of an atomic wave packet) receive momentum impulses that change their velocity by $\pm v_r$. The dashed lines indicate trajectories without gravity.

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106, 151102

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