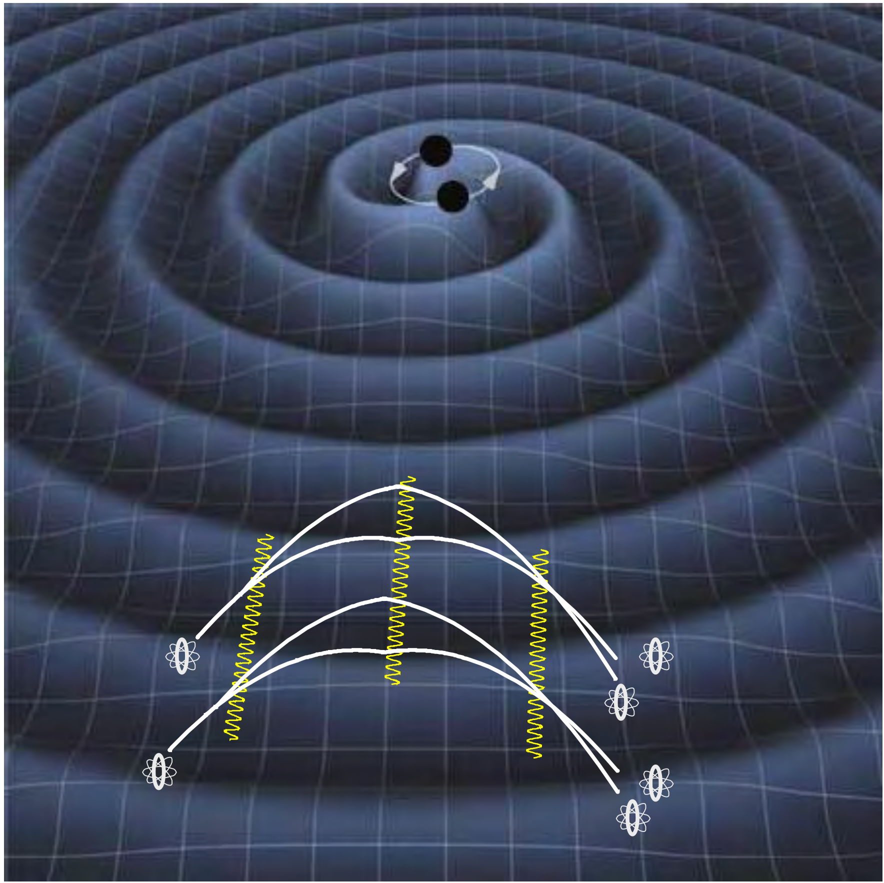
Gravitational wave detection with light and atom interferometry

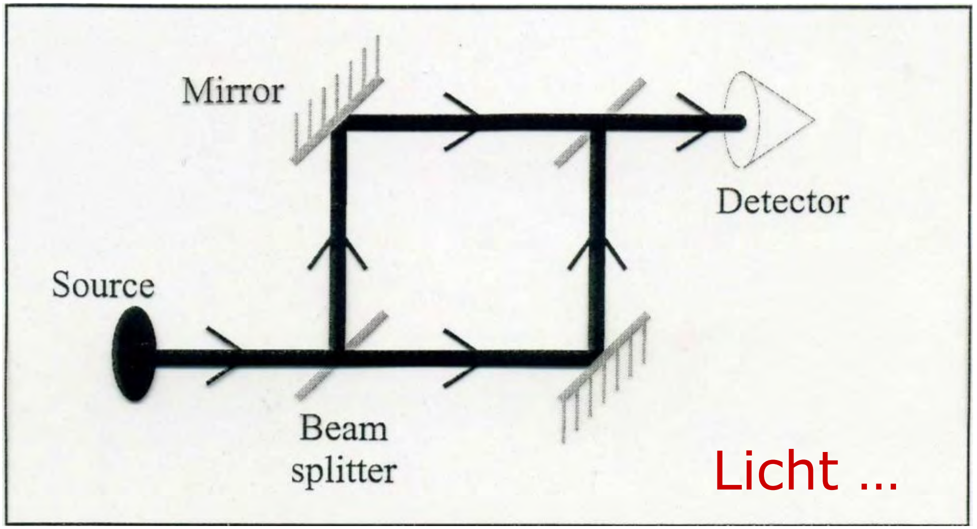
Holger Müller, UC Berkeley



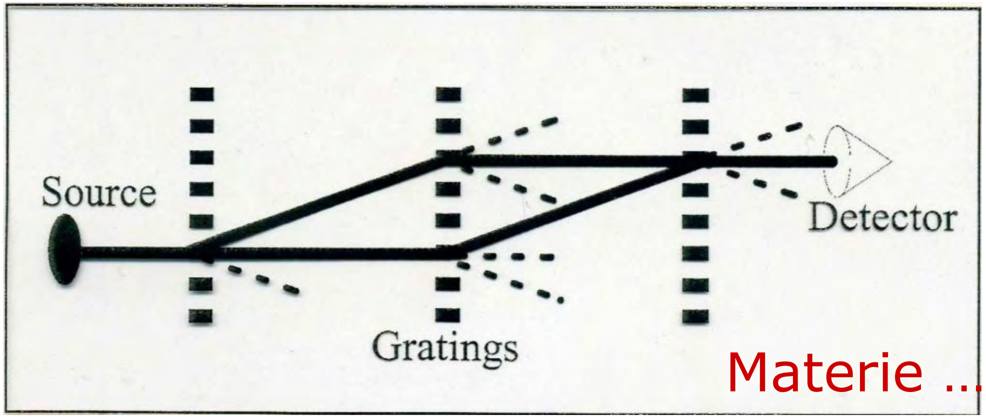
THE UNIVERSITY OF CALIFORNIA · BERKELEY · 1868

Atom interferometry

Interferometry



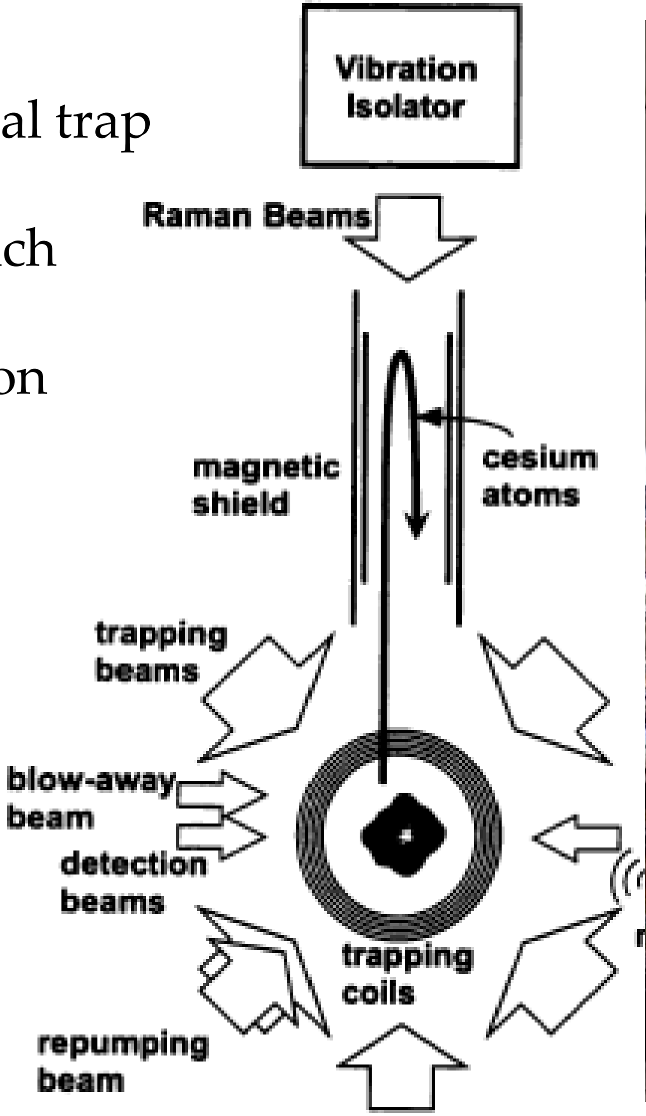
Licht …



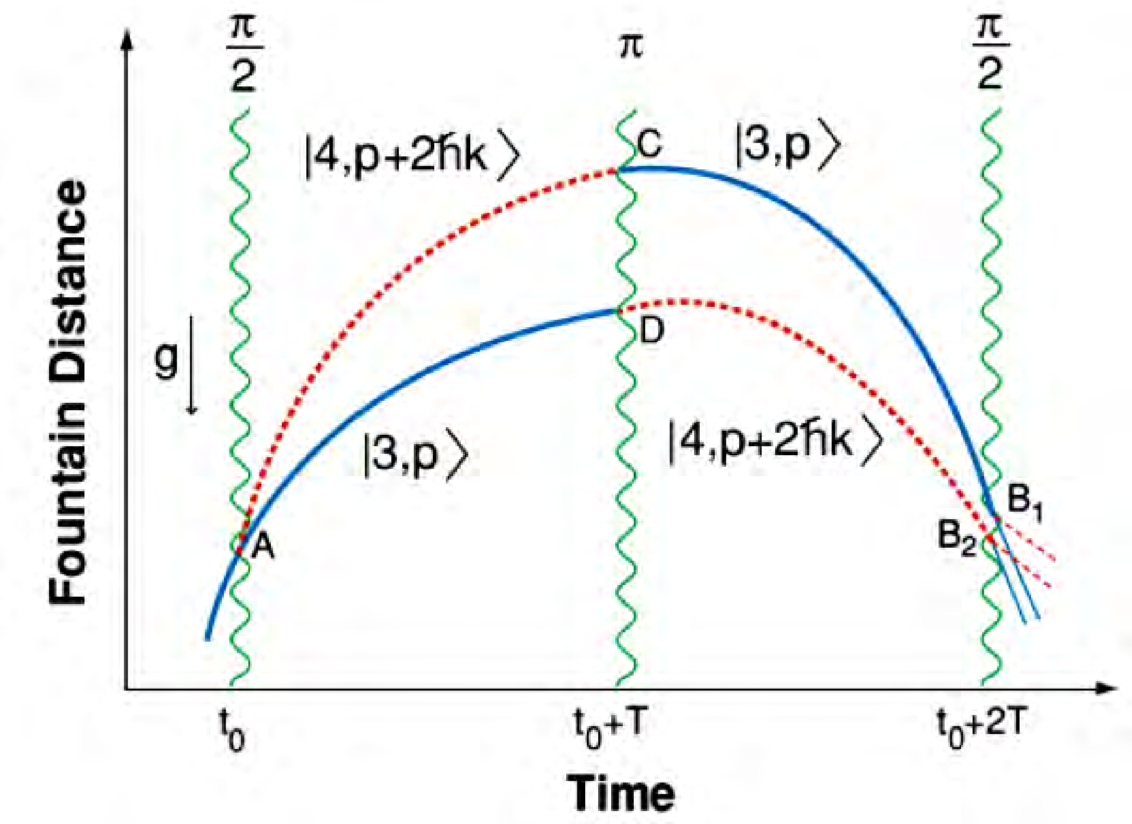
Materie …

Atomic fountain

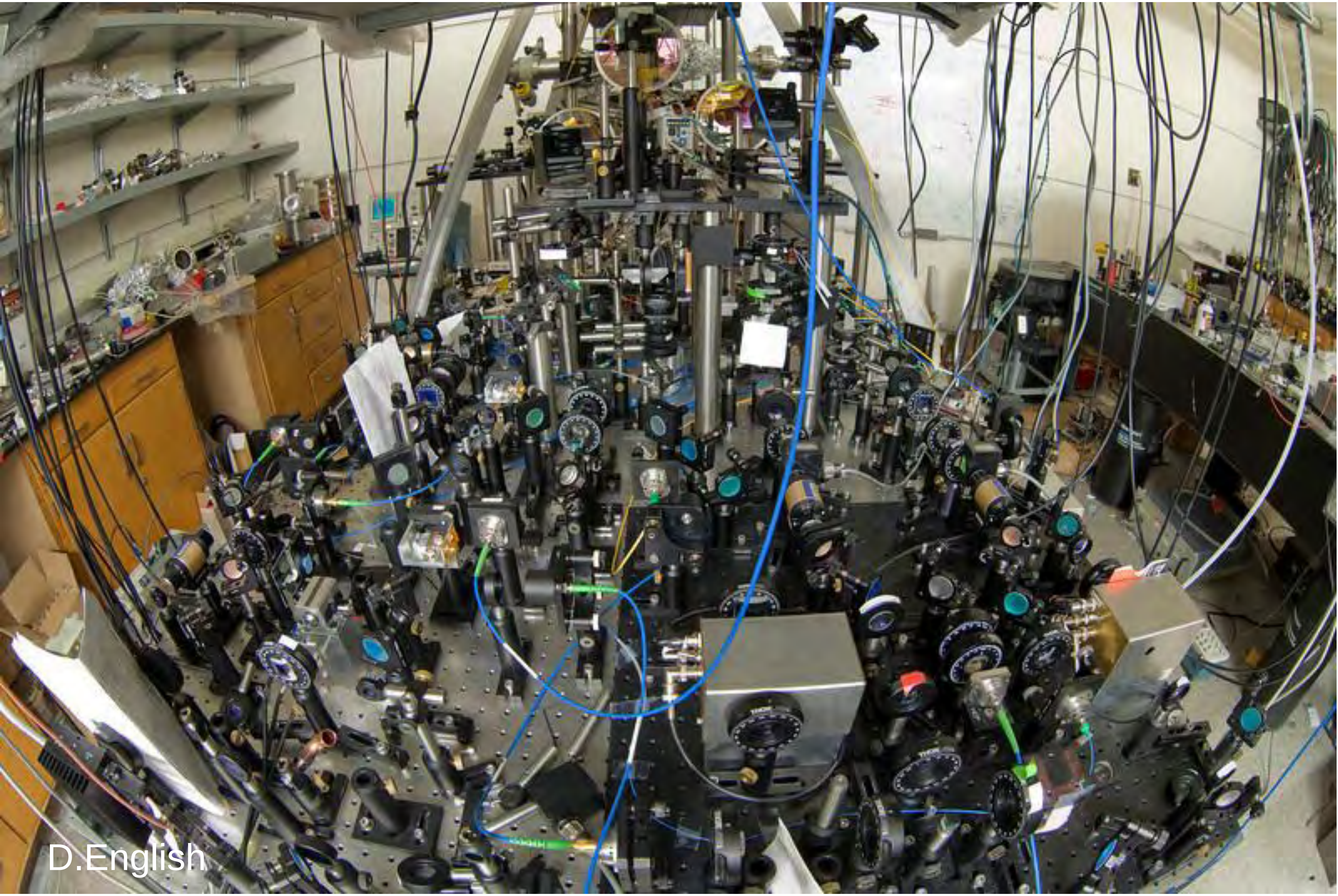
- Magneto-optical trap
- Cooling & launch
- State preparation
- Experiment



Mach-Zehnder Atom Interferometer

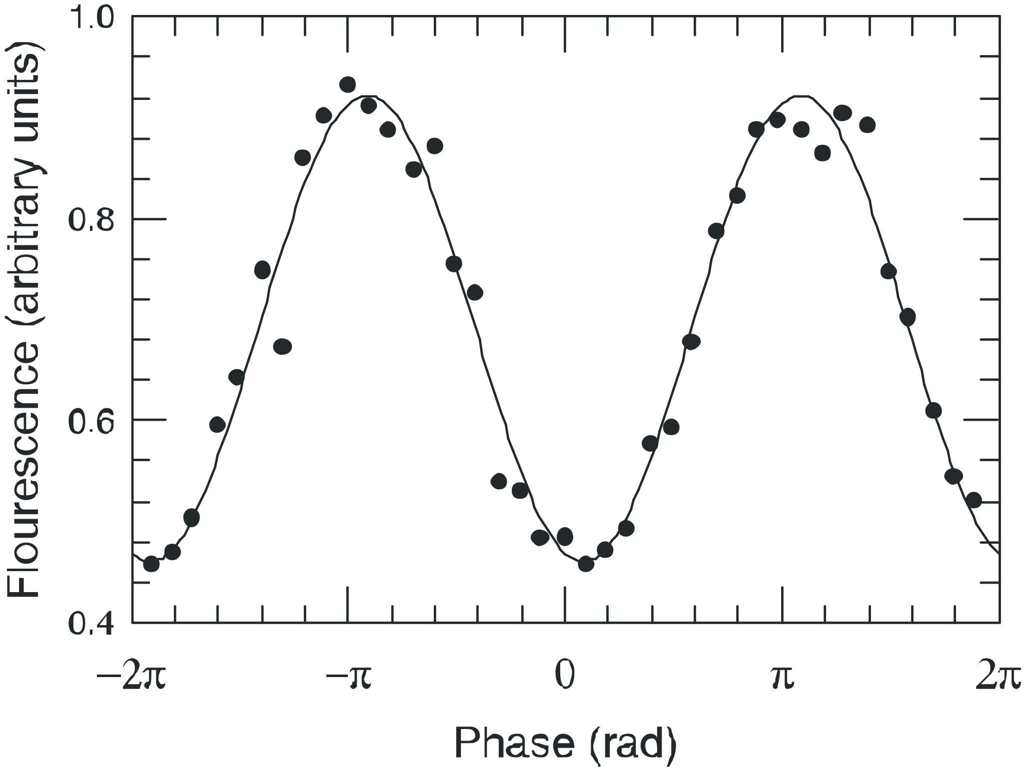


$$\Delta\varphi = \frac{mc^2}{\hbar}(\tau_1 - \tau_2) + \Delta\varphi_{\text{laser}}$$



D.English

Highest-precision conventional atom interferometer



Each data point is from a single launch

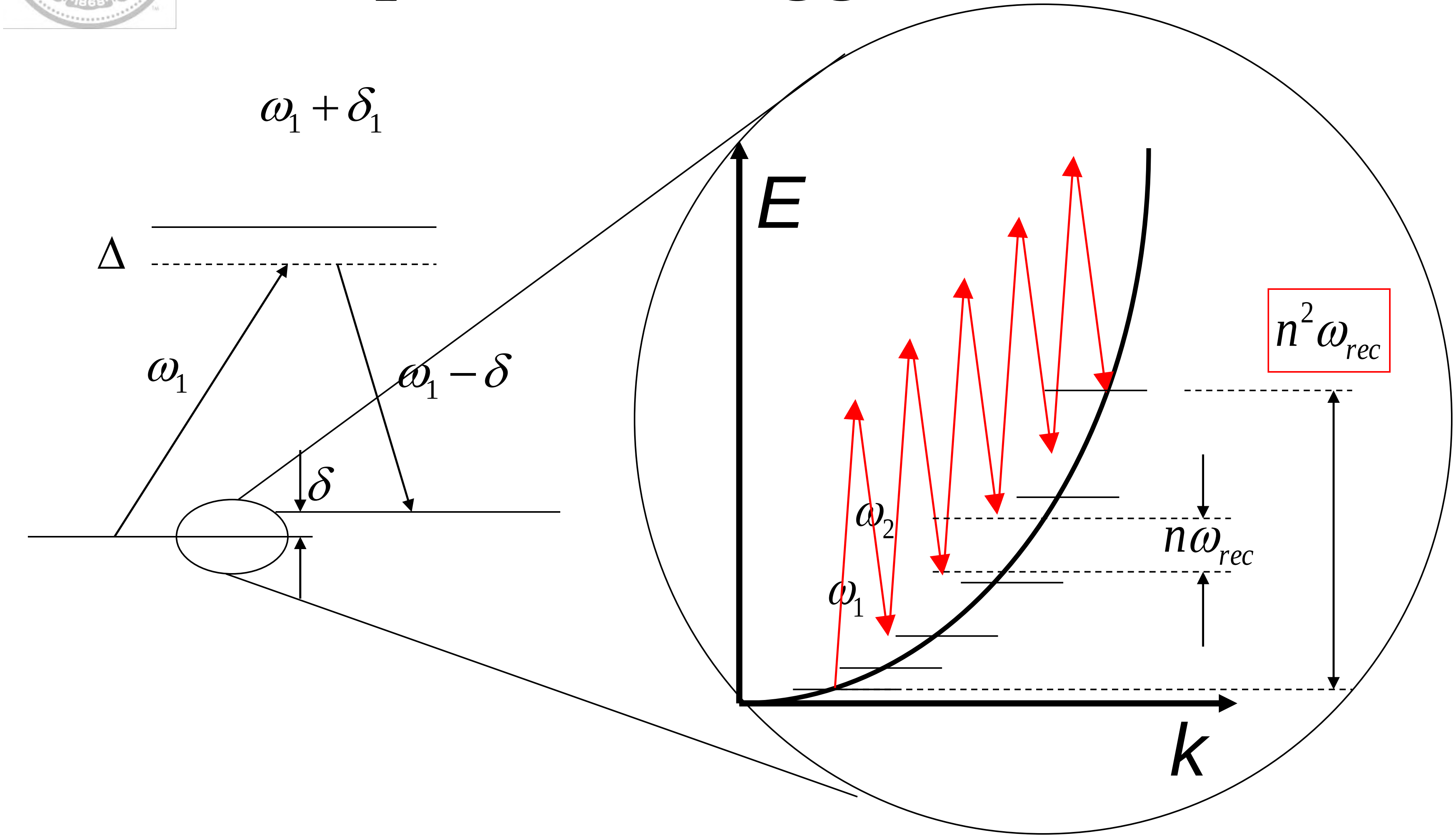
Fit error 0.031rad, determines g to 1.3ng

=>11ng/sqrt(Hz)

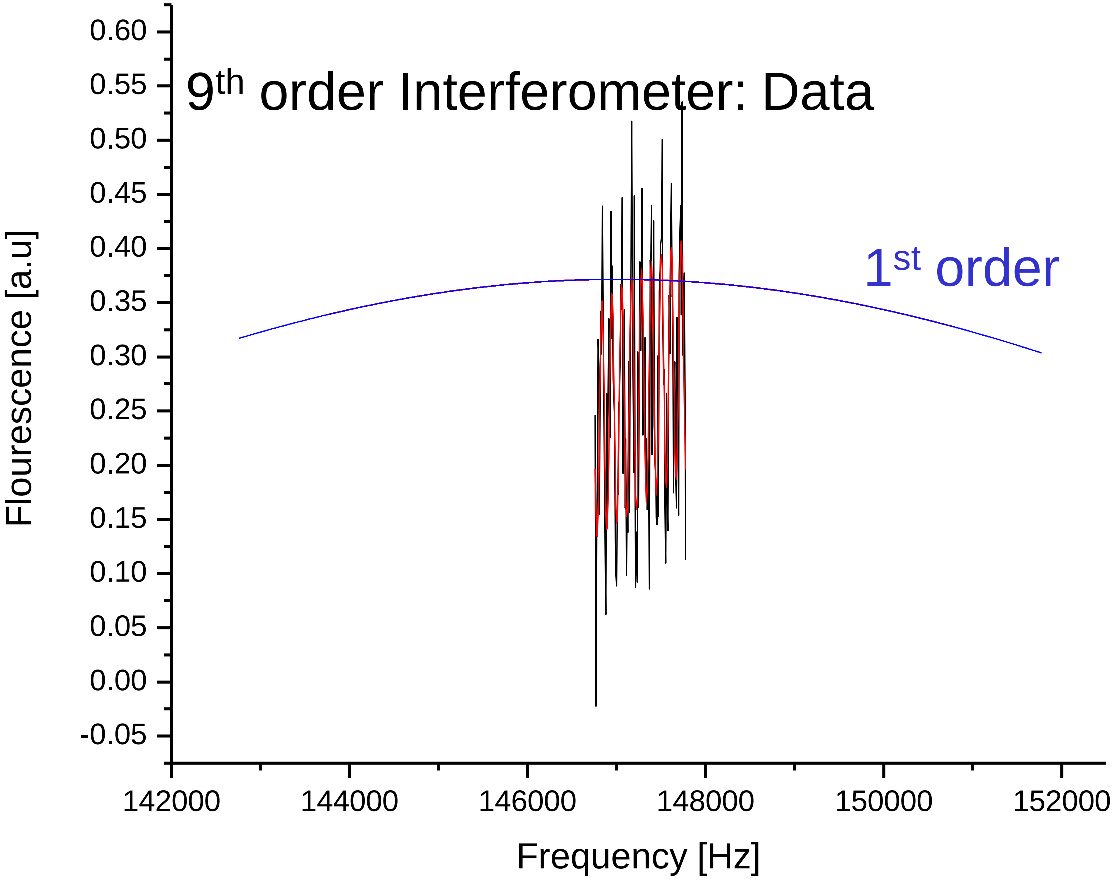
[H. M. *et al.*, PRL **100,** 031101 (2008), K.Y. Chung, PRD 2009]

Technology

Multiphoton Bragg diffraction

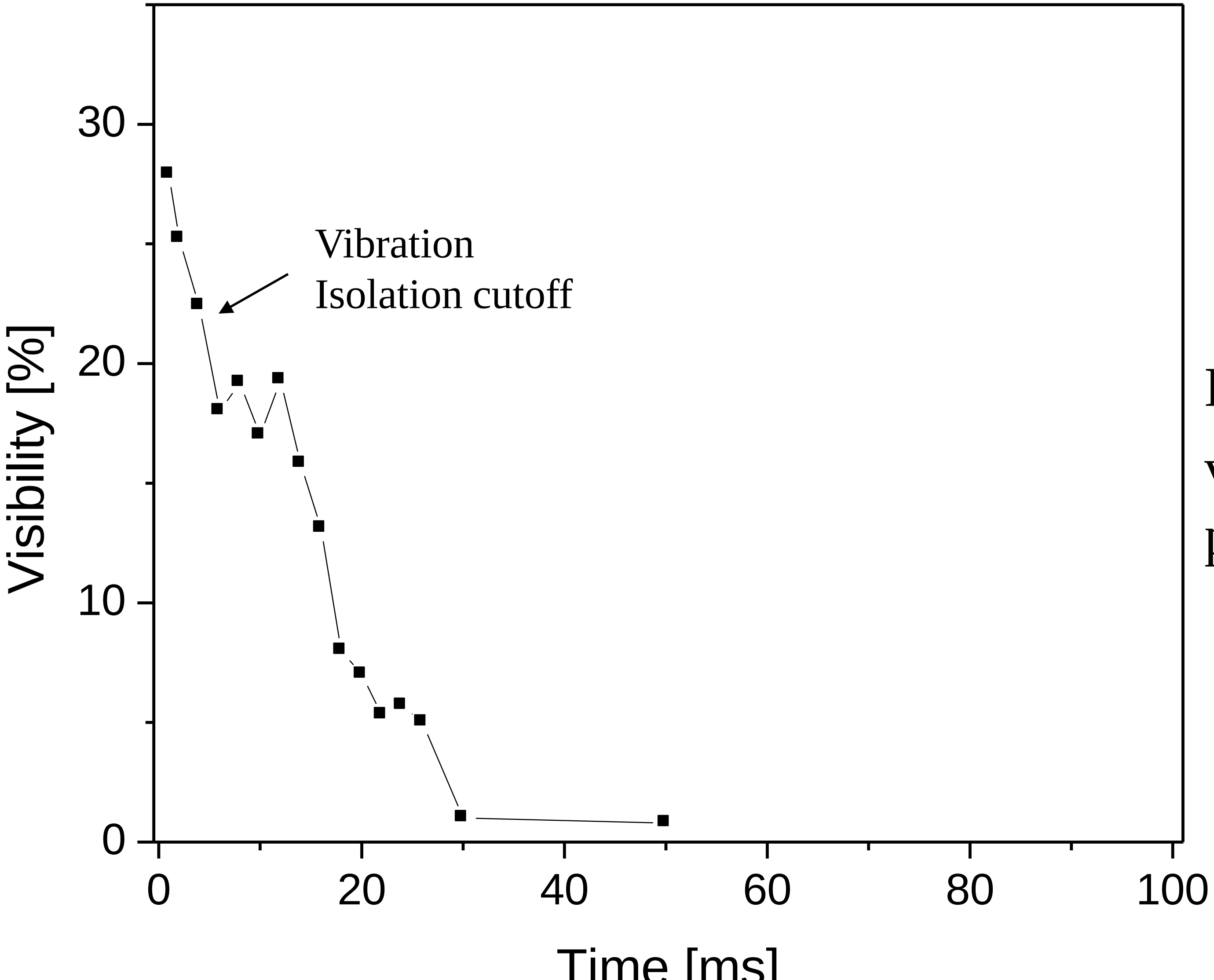


Large momentum transfer



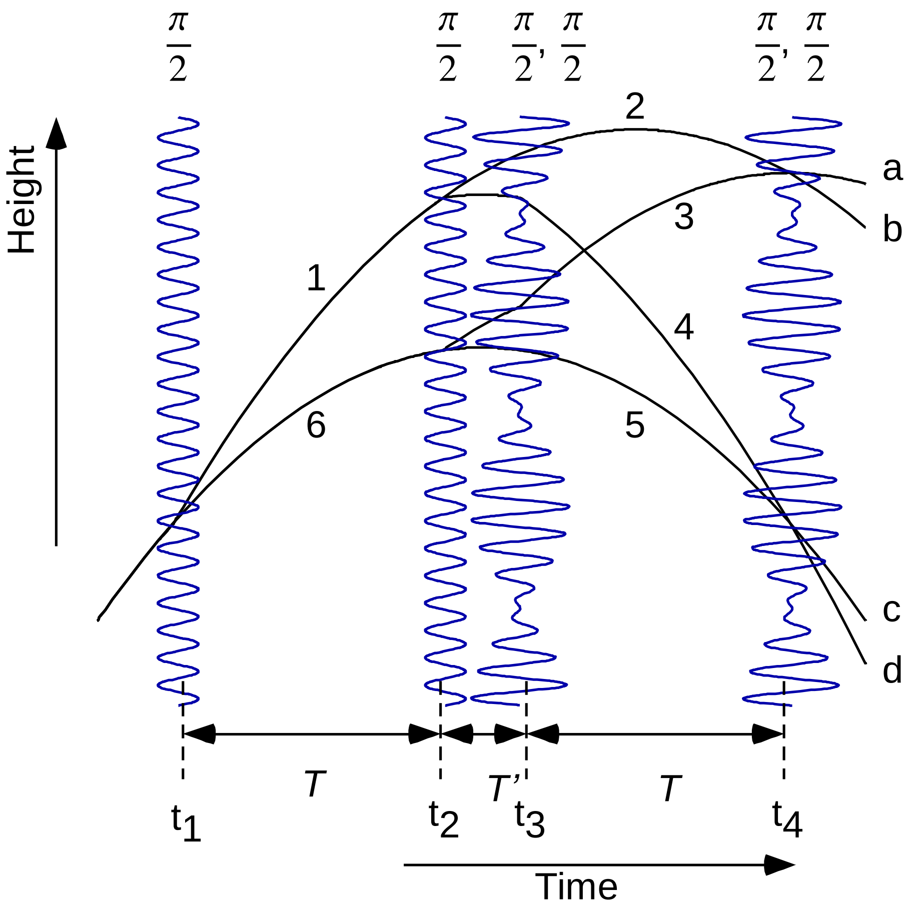
H. M. *et al.*, PRL 100 (2009): Chiow et al, PRL 2009

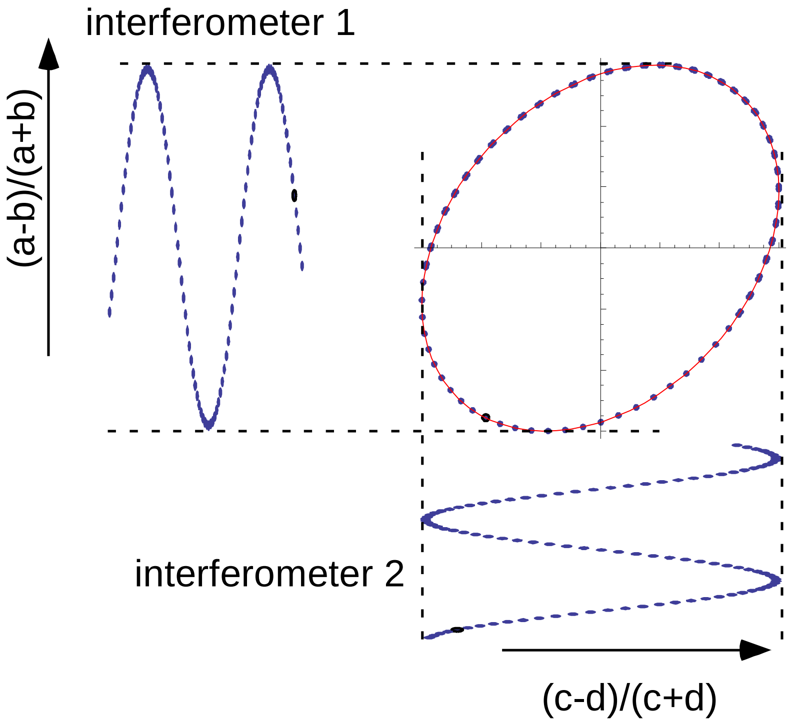
Problem: Contrast decay



Limitation:
vibrational
phase noise

Solution: Simultaneous conjugate Interferometers

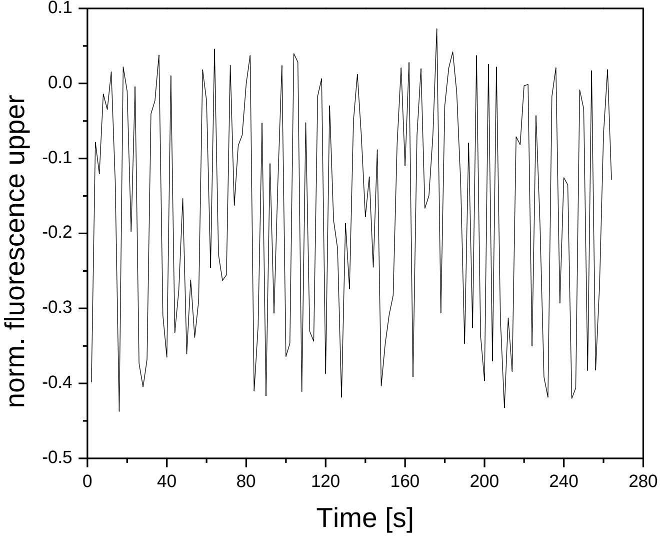


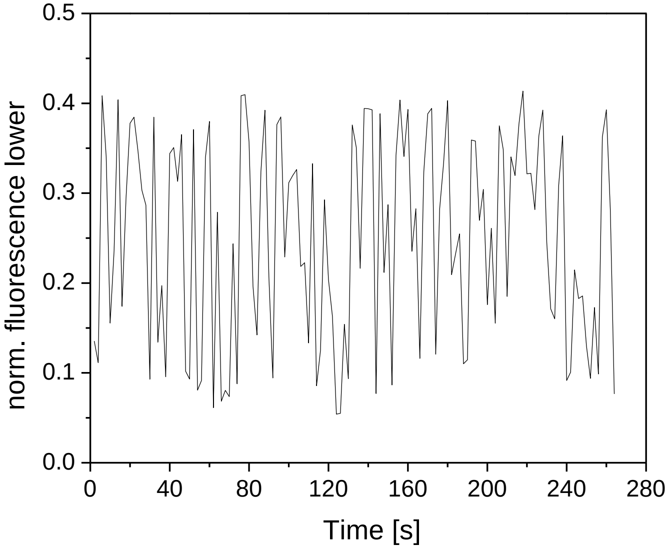


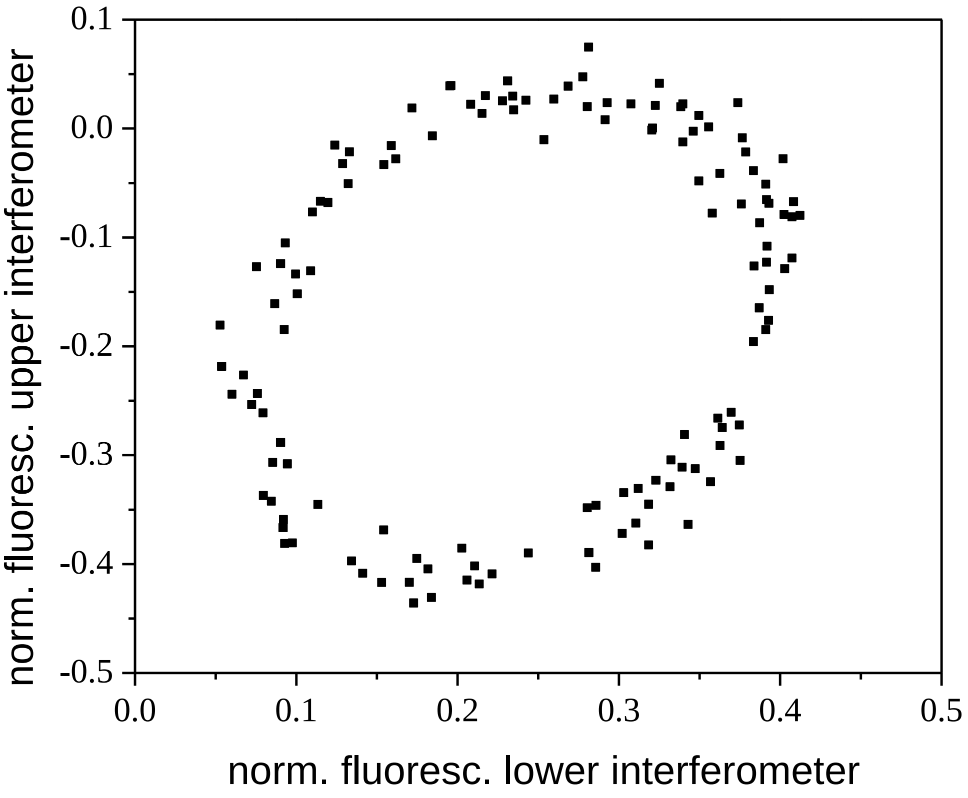
$$\Phi_1 - \Phi_2 = 4\frac{\Delta E_{kin}}{\hbar}T = 16n^2\frac{\hbar k^2}{2m}T$$

Results

6th order Bragg diffraction, T =1 ms



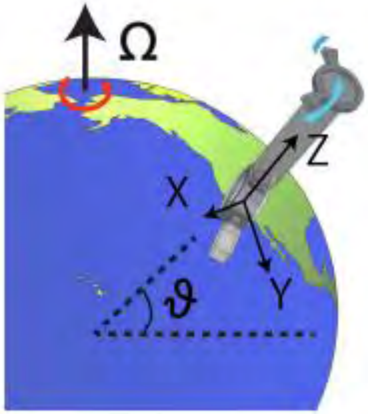


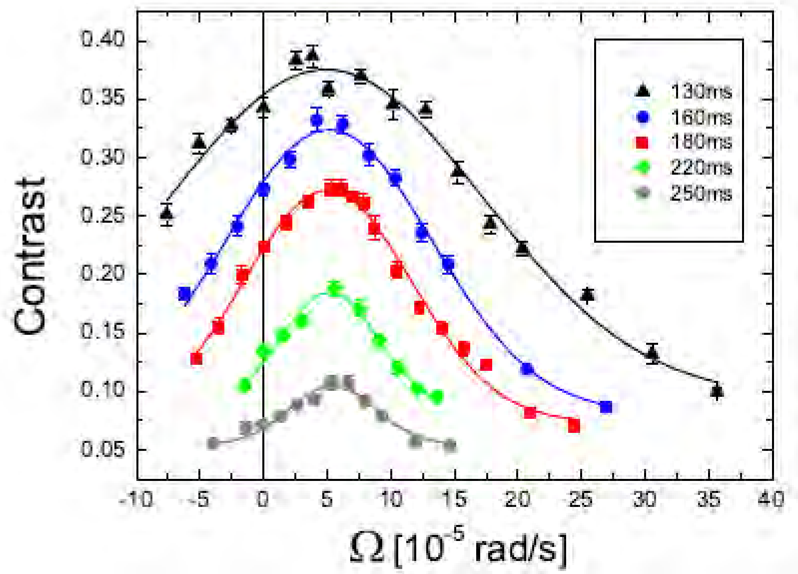


H. M. *et al.,* PRL 102, 240403 (2009)

Coriolis force

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

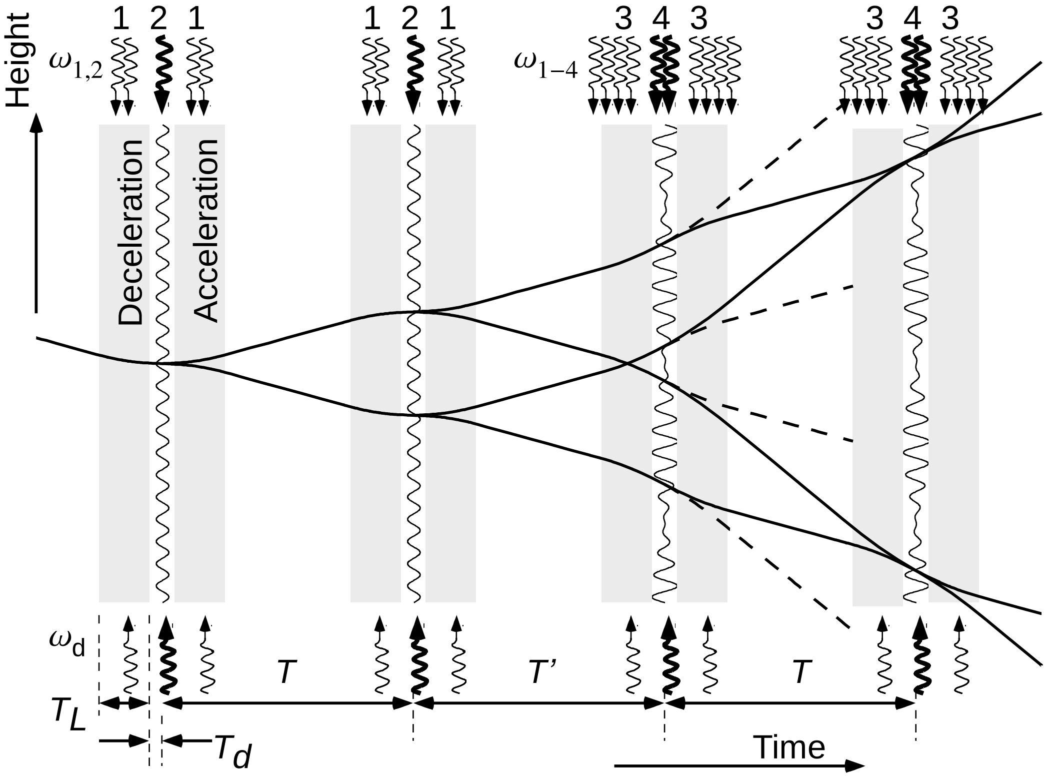


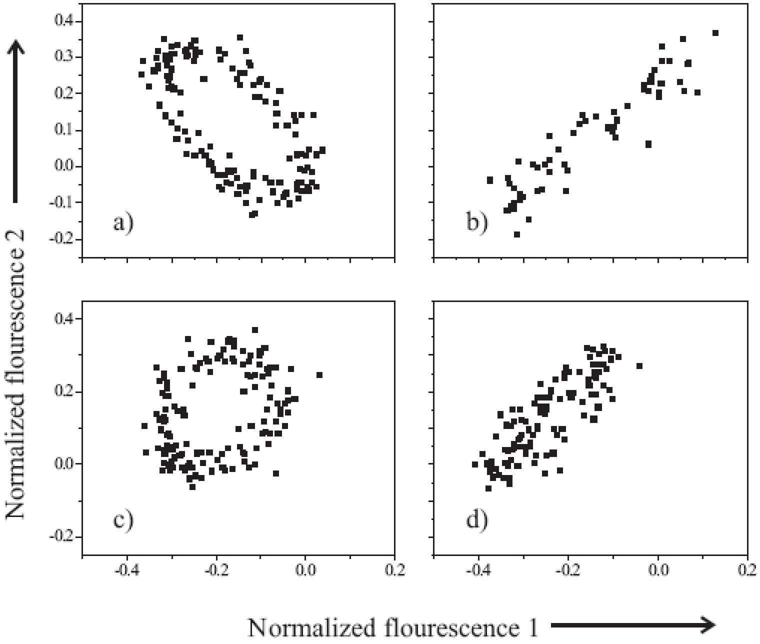


- Interferometer does not close
- Cancellation improves contrast (350%), T
- World’s most sensitive atom interferometer (10 ħk, 250 ms)

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

BBB interferometers



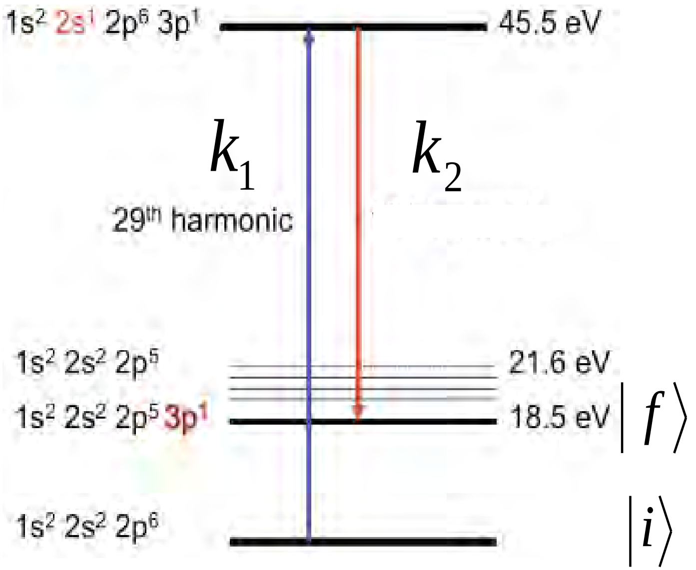


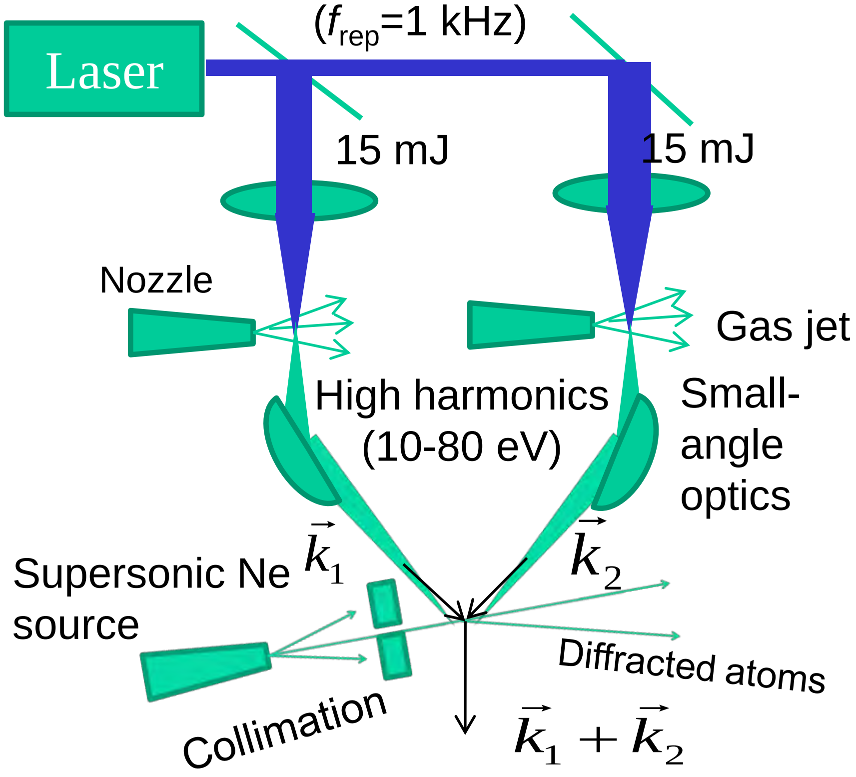
1: dual lattice (Matter wave accelerator)
2: single Bragg
3: quadruple lattice
4: dual Bragg

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

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

Coherent Electronic and Motional Effects of Ultra-fast X-rays (H.M., B. Whaley, A. Belkacem)





Laser

(f_{rep}=1 kHz)

15 mJ

15 mJ

Nozzle

Gas jet

High harmonics (10-80 eV)

Small-angle optics

Supersonic Ne source

$\vec{k}_1$

$\vec{k}_2$

Diffracted atoms

Collimation

$\vec{k}_1 + \vec{k}_2$

- Electron-nuclear coherences, localized excitations in molecules, CARS
- Based on existing 1 kHz, 80 mJ, 100 eV source in Belkacem lab
- Use Li or Ne, later C_{60}, NaH, LiH, CO, NO,…

DARPA RA-12-12: Quantum Science and Technology
Holger Müller, UC Berkeley

Cavity-based atomic rotation and acceleration sensor

Key insight / innovation

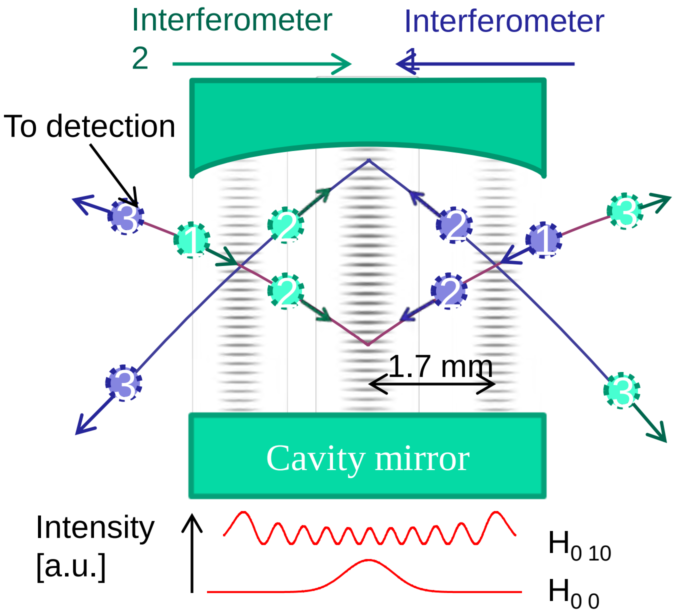
- **Cavity:** High intensity
- Very large momentum transfer
- Mode filtering
- **Compact**
- **Extremely precise**
- Fully coherent atom-optics
- Low power laser

Scientific/technical impact

- Operation independent of gravity
- Operates in any orientation
- **Tiny setup, full performance** comparable to best 1-m fountain
- High (10 Hz) data rate

Application

- Inertial navigation
- Low drift quantum sensor
- Field conditions of acceleration and rotation
- Full 6-axis inertial base



Size comparison (trajectories to scale, cavity length ~ 30 cm)

Applications

α from recoil measurements

$$\alpha^2 = \frac{c}{2} f_{rec} R_\infty \left(\frac{1}{f_{D2}^2} \right) \left(\frac{m_{Cs}}{m_u} \right) \left(\frac{m_u}{m_e} \right)$$

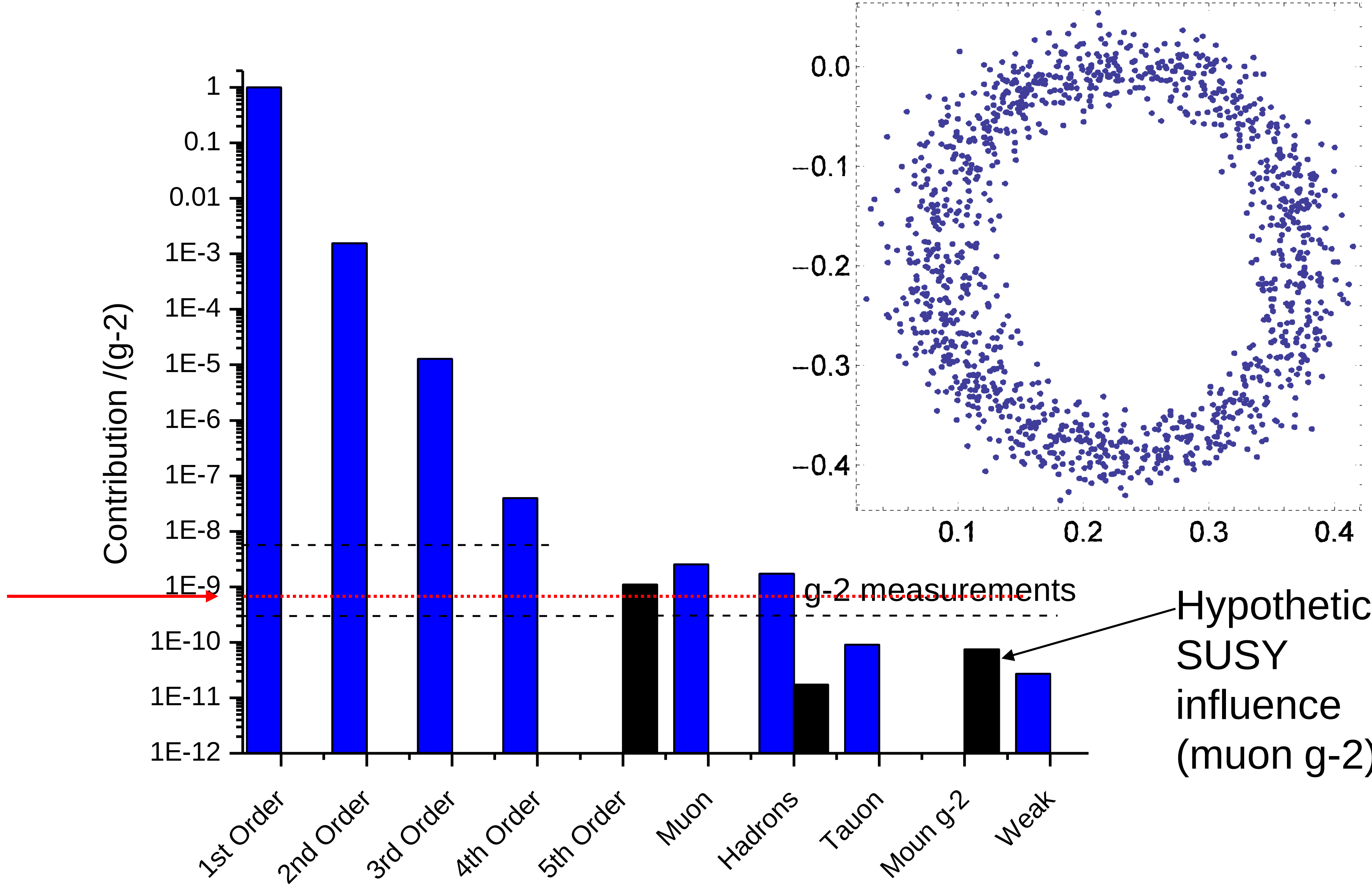
0.03ppb

0.44ppb

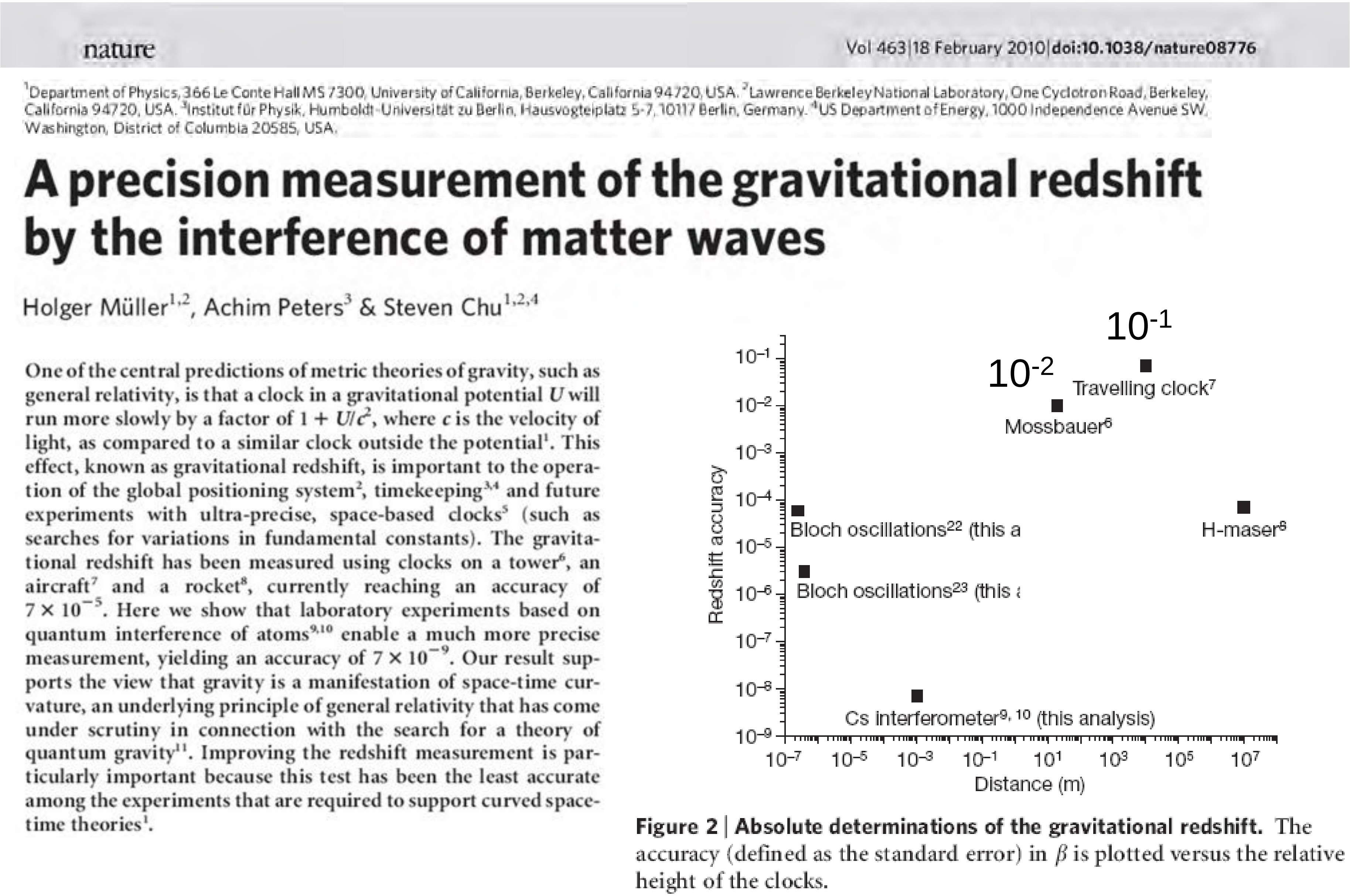
0.007ppb

0.20ppb

α from electron *g*-2



Hypothetical SUSY influence (muon g-2)



nature

Vol 463|18 February 2010|**doi:10.1038/nature08776**

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A precision measurement of the gravitational redshift by the interference of matter waves

Holger Müller[1,2], Achim Peters[3] & Steven Chu[1,2,4]

One of the central predictions of metric theories of gravity, such as general relativity, is that a clock in a gravitational potential U will run more slowly by a factor of $1 + U/c^2$, where c is the velocity of light, as compared to a similar clock outside the potential[1]. This effect, known as gravitational redshift, is important to the operation of the global positioning system[2], timekeeping[3,4] and future experiments with ultra-precise, space-based clocks[5] (such as searches for variations in fundamental constants). The gravitational redshift has been measured using clocks on a tower[6], an aircraft[7] and a rocket[8], currently reaching an accuracy of 7×10^{-5}. Here we show that laboratory experiments based on quantum interference of atoms[9,10] enable a much more precise measurement, yielding an accuracy of 7×10^{-9}. Our result supports the view that gravity is a manifestation of space-time curvature, an underlying principle of general relativity that has come under scrutiny in connection with the search for a theory of quantum gravity[11]. Improving the redshift measurement is particularly important because this test has been the least accurate among the experiments that are required to support curved space-time theories[1].

Figure 2 | Absolute determinations of the gravitational redshift. The accuracy (defined as the standard error) in β is plotted versus the relative height of the clocks.

H. M. *et al., Nature* 463 (2011)

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

Equivalence Principle and Gravitational Redshift

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(Received 17 February 2011; published 11 April 2011)

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

TABLE I. Sensitivity of redshift experiments. The EEP-violation signal for each experiment is given as a linear combination of SME parameters. The observable for the Pound-Rebka Mössbauer test, e.g., is $-1.1\ \mathrm{GeV}^{-1}\alpha(\bar{a}^n_{\mathrm{eff}})_0 - 1.1\ \mathrm{GeV}^{-1}\alpha(\bar{a}^{e+p}_{\mathrm{eff}})_0 + (-0.34 + [-0.66])(\bar{c}^n)_{00} + (-0.34 + [-0.006])(\bar{c}^p)_{00} + 0.0002(\bar{c}^e)_{00}$, with $\bar{a}^{e+p}_{\mathrm{eff}} = \bar{a}^p_{\mathrm{eff}} + \bar{a}^e_{\mathrm{eff}}$. The last column shows the measured value and 1σ uncertainty. Signals dependent on models for ξ are in square brackets. Curly brackets mark expected limits.

Method	$\alpha(\bar{a}^n_{\mathrm{eff}})_0$ GeV	$\alpha(\bar{a}^{e+p}_{\mathrm{eff}})_0$ GeV	$(\bar{c}^n)_{00}$	$(\bar{c}^p)_{00}$	$(\bar{c}^e)_{00}$	Limit ppm
Mössbauer effect [2]	−1.072	−1.072	0.3358 − [2/3]	−0.3353 − [0.006]	0.0001826	1000 ± 7600
H maser on rocket [3]	−1.072	−1.072	0.3358	0.3353 − [0.67]	0.0001826 − [1.3]	2.5 ± 70
Cs fountain (*proj.*) [16]	−1.072	−1.072	0.3358 + [0.40]	0.34 + [0.28]	0.0001826 − [1.3]	{2}
Bloch oscillations [4,17]	0.1632	−0.1580	−0.05112 − [0.0005]	0.04940 + [0.0010]	0.00002690	3 ± 1
Bloch oscillations [6]	0.1492	−0.1439	−0.04673 − [0.0006]	0.04500 + [0.0008]	0.00002451	0.16 ± 0.14
Cs interferometer [4]	0.1881	−0.1835	−0.05890 − [0.0004]	0.05739 + [0.001]	0.00003126	0.007 ± 0.007
Rb interferometer [18]	0.1632	−0.1580	−0.05112 − [0.0005]	0.04940 + [0.001]	0.00002690	−0.004 ± 0.007

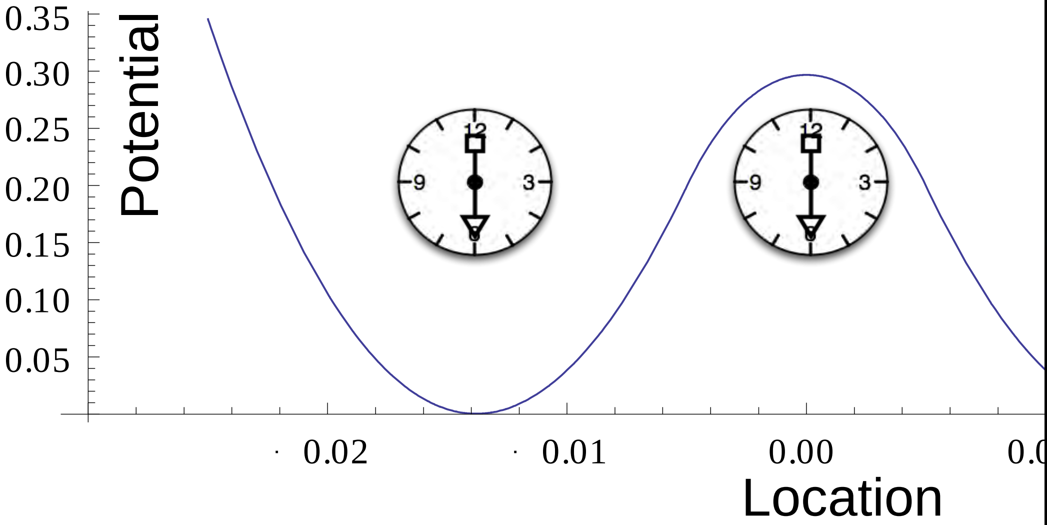
Bottom line

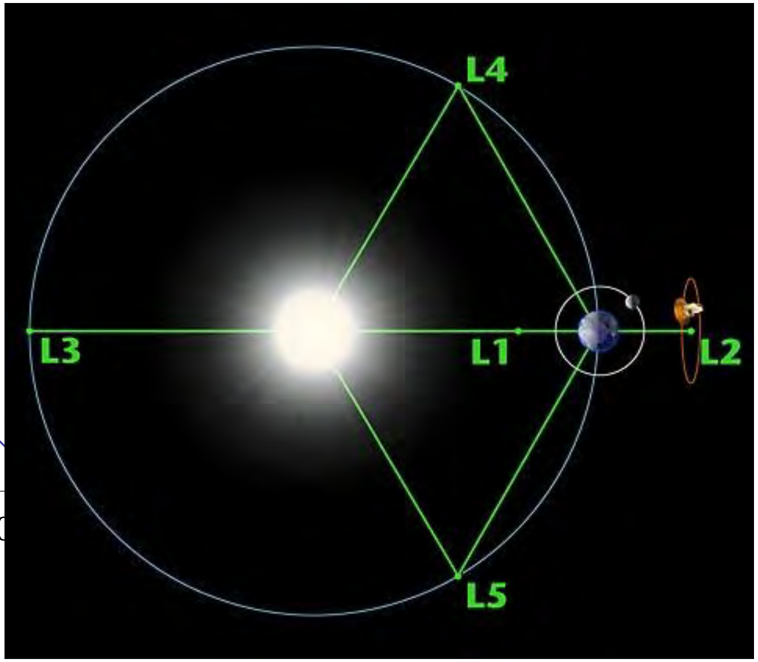
	$(a^{n}_{\mathrm{eff}})_0$	$(a^{p}_{\mathrm{eff}})_0 + (a^{n}_{\mathrm{eff}})_0$	$(c^{n}_{\mathrm{eff}})_{00}$	$(c^{p}_{\mathrm{eff}})_{00}$	$(c^{e}_{\mathrm{eff}})_{00}$
	GeV	GeV			
Clocks+UFF	-3±53	-1±11	-5±94	2.1±40	-1±40
	⇩ 14	⇩ 11	⇩ 14	⇩ 11	⇩ 9
AI+clocks+UFF	4.3±3.7	0.8±1.0	7.6±6.7	-3.3±3.5	4.6±4.6
					⇩ 3
+ future space clocks	-1.4±3.7	-0.3±1.0	-2.4±6.8	0.9±3.5	0.5±1.5

- The AI tests GR like conventional clocks
- improves overall bounds ~10-fold

Hohensee *et al.*, *PRL* **106,** 151102 (2011)

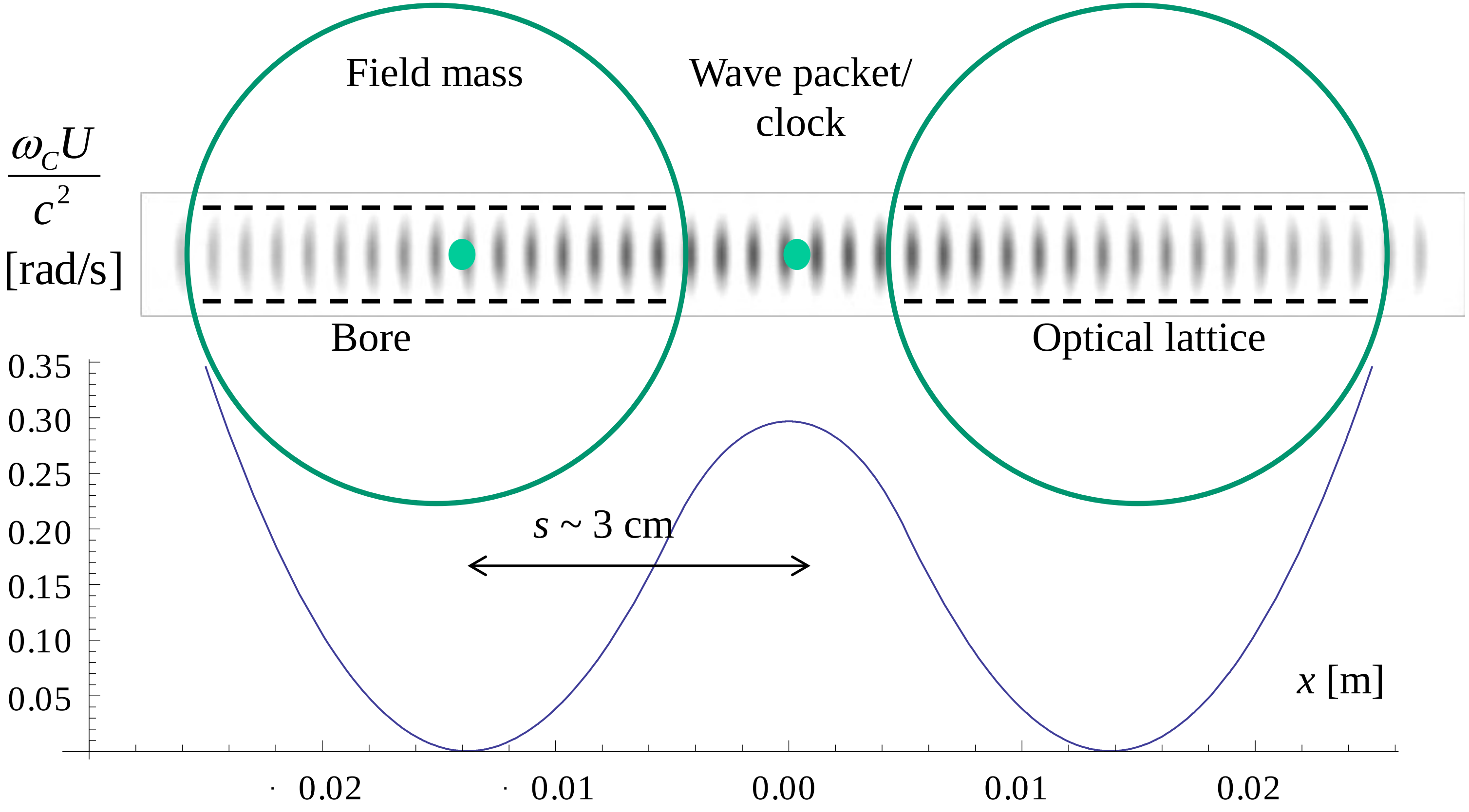
Gravity’s Aharonov-Bohm effect





- Terrestrial experiment: $\varrho=10\ \mathrm{g/cm^3}$, $R=10$ m: $\Delta\nu/\nu=5\mathrm{x}10^{-21}$
- Possible realization: Earth-moon Lagrange points

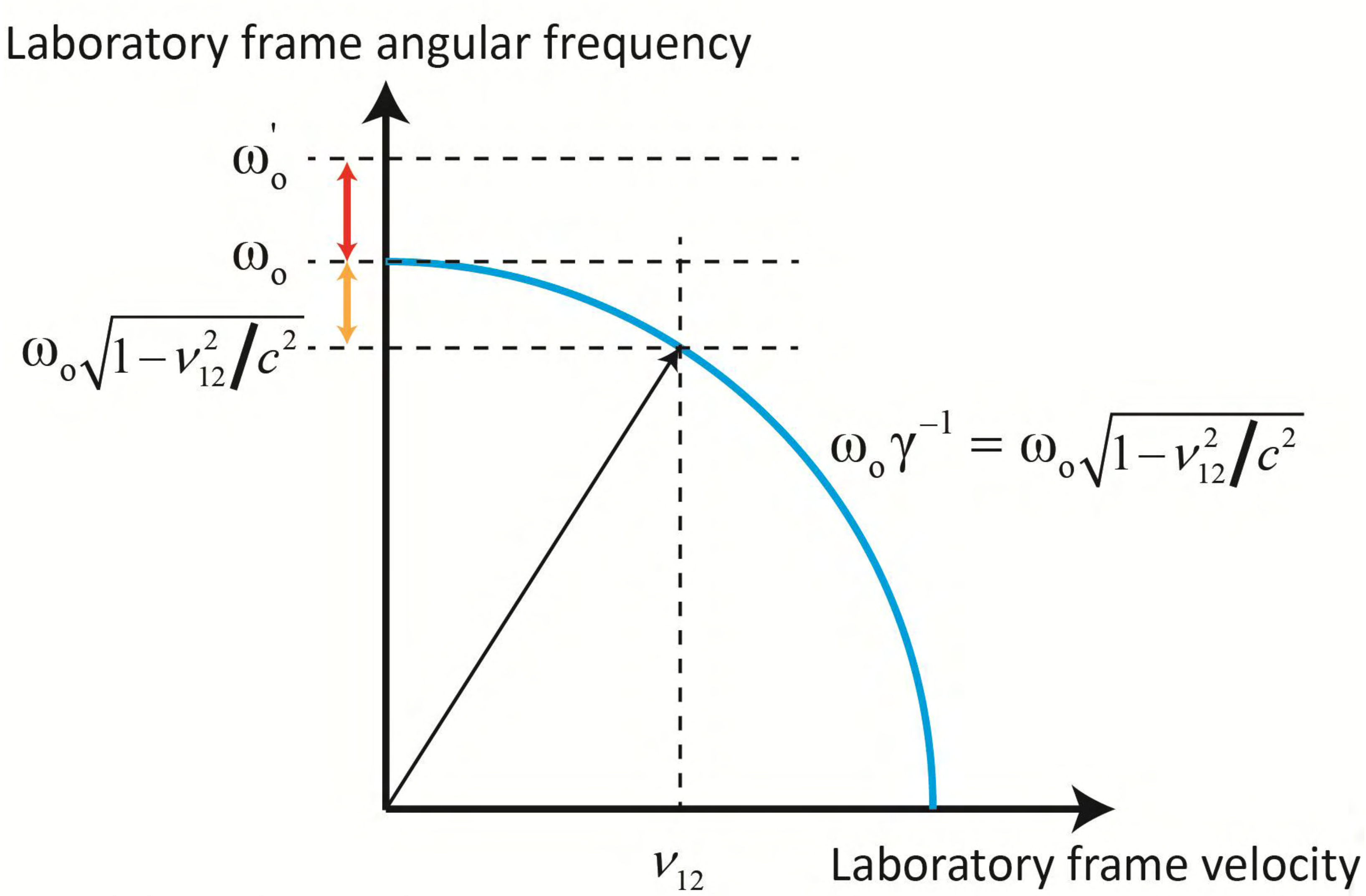
Realization with atom-clocks



$$\varphi = \omega_C \int \frac{\Delta U}{c^2} dt = 0.16 \left(\frac{s}{\text{cm}}\right)^2 \left(\frac{\rho}{10\,\text{g/cm}^3}\right) \left(\frac{m}{m_{Cs}}\right) \left(\frac{T}{\text{s}}\right)$$

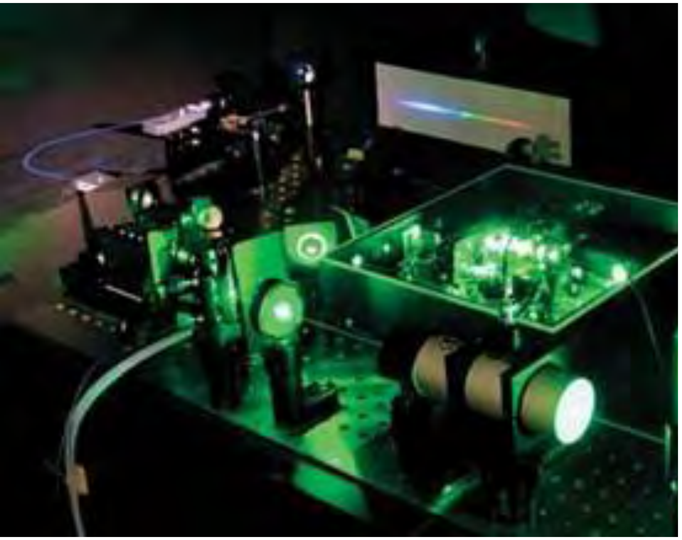
Nature’s elementary clock

Compton clock

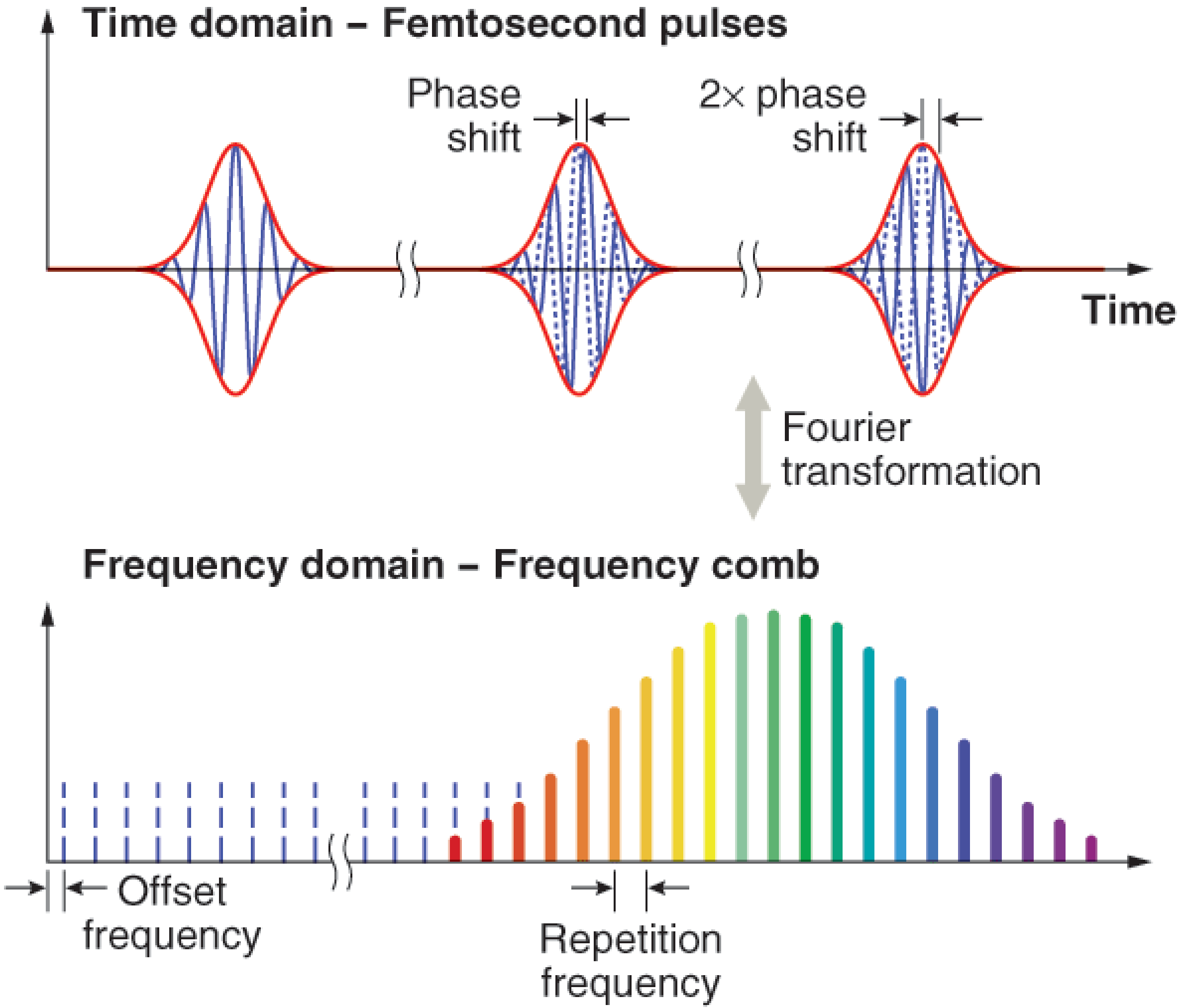


Clock based on entire rest mass

Frequency Comb

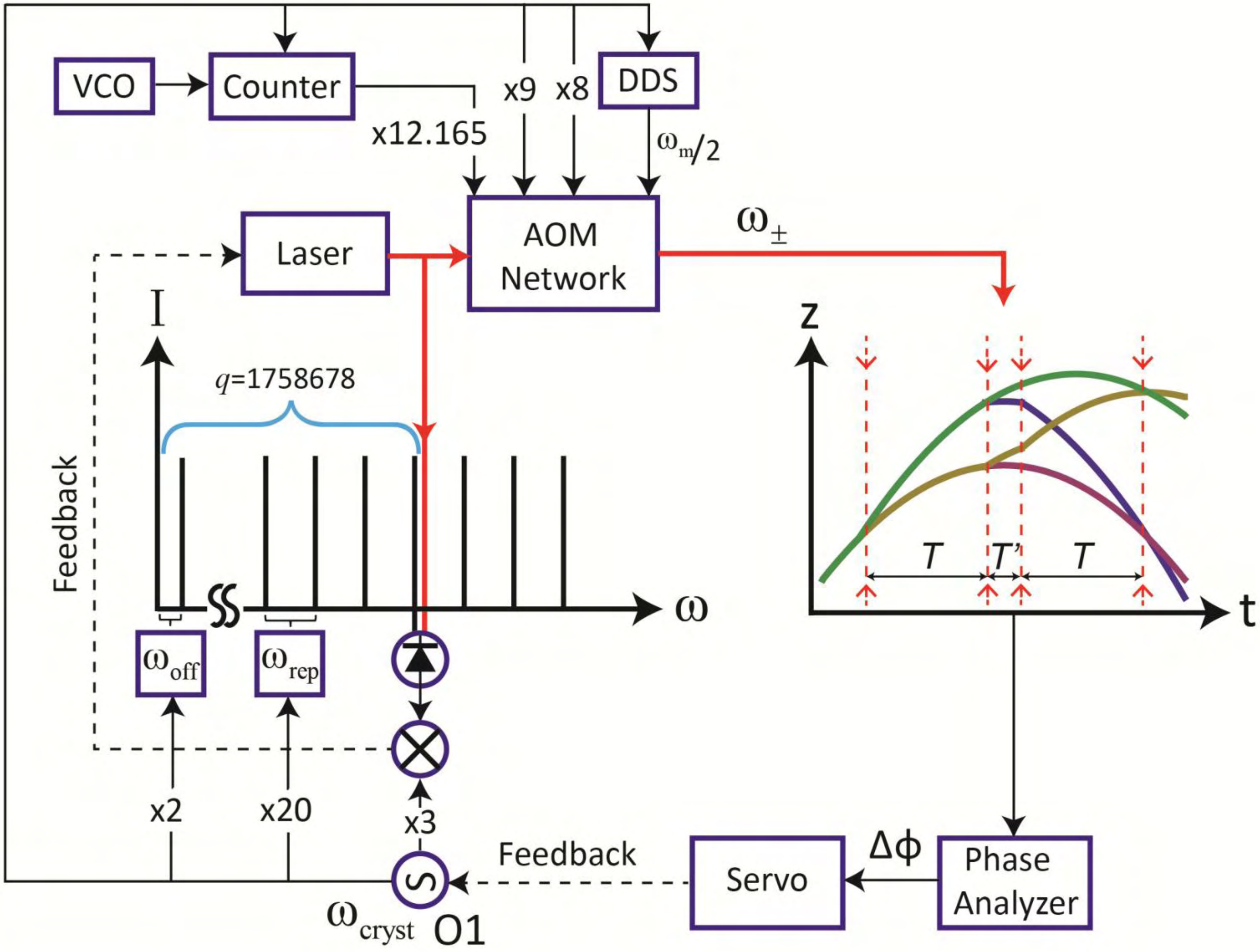


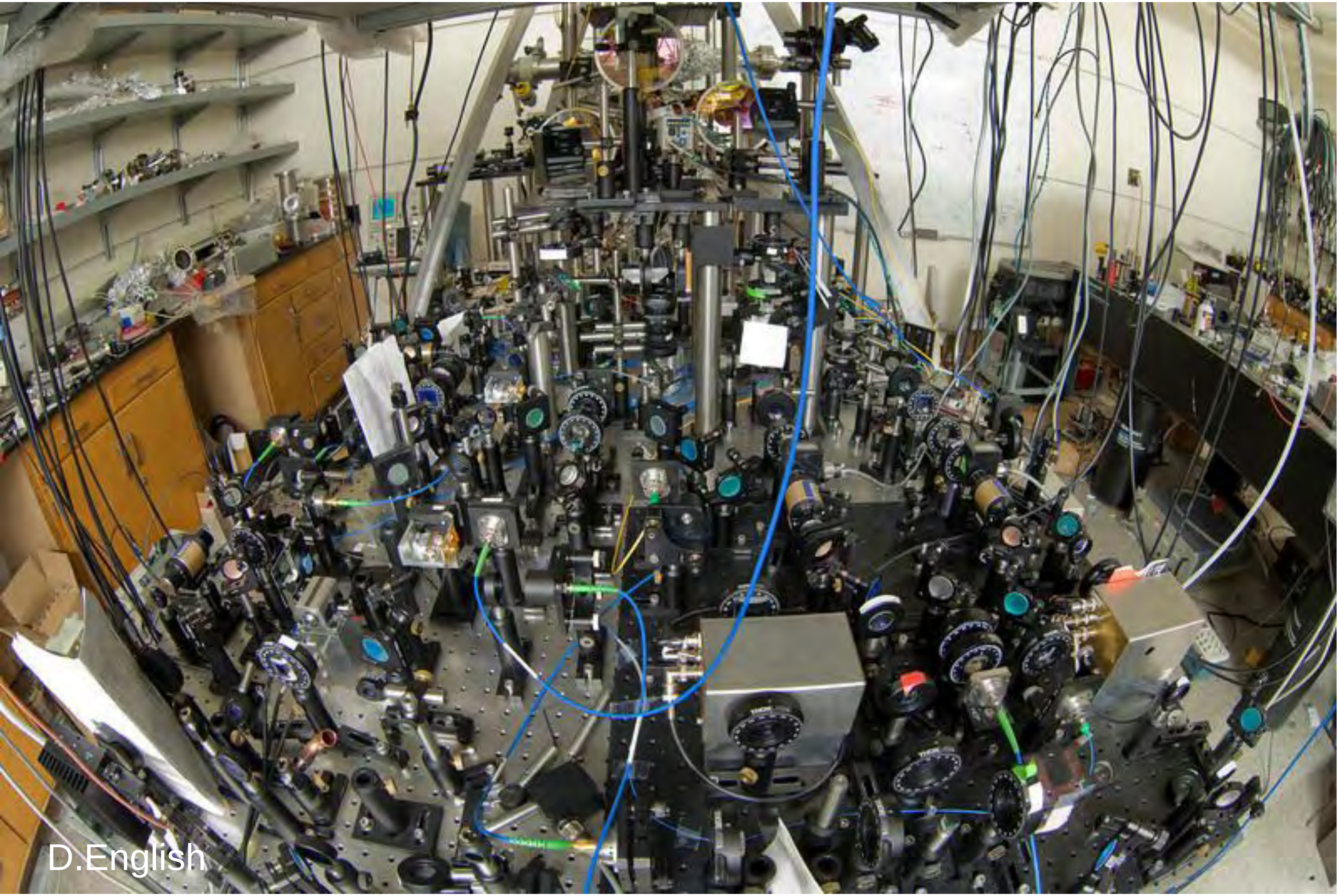
$$f_n = n f_r + f_{offset}$$



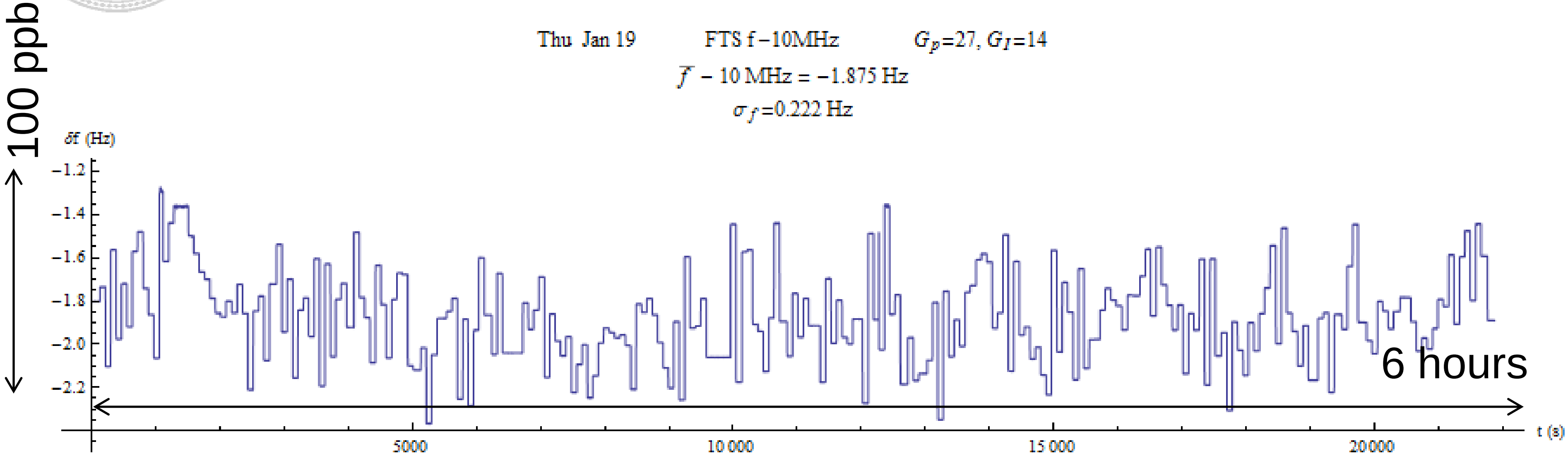
[1] Theodor Hänsch, Nobel Lecture, http://nobelprize.org/nobel_prizes/physics/laureates/2005/hansch-lecture.html
[2] J. Hall, Nobel Lecture, http://nobelprize.org/nobel_prizes/physics/laureates/2005/hall-lecture.html

Compton clock




D.English

Compton clock vs Rb



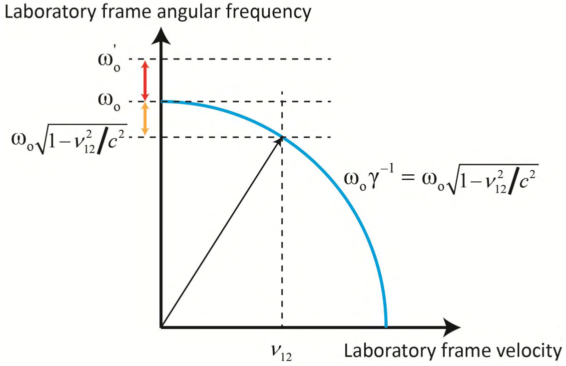
n	273
Average	-1.873 Hz
Standard error:	1.4 ppb
χ^2	1.7
Systematics	3.5 ppb
Total error	3.9 ppb

$$\omega_r = \omega_C / 2nN^2$$

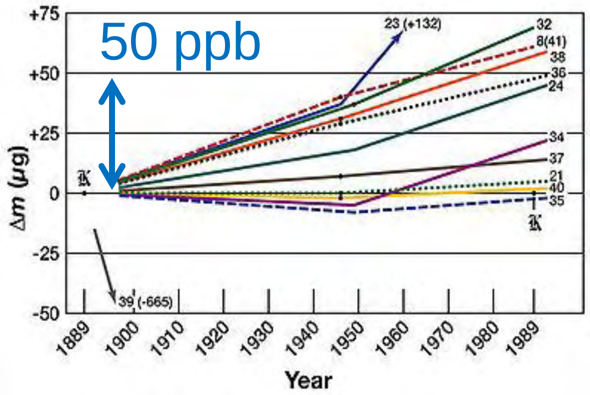
Confirmed to 4 ppb accuracy =>
Masses are fully practicable clocks

Timing Weight

=



+

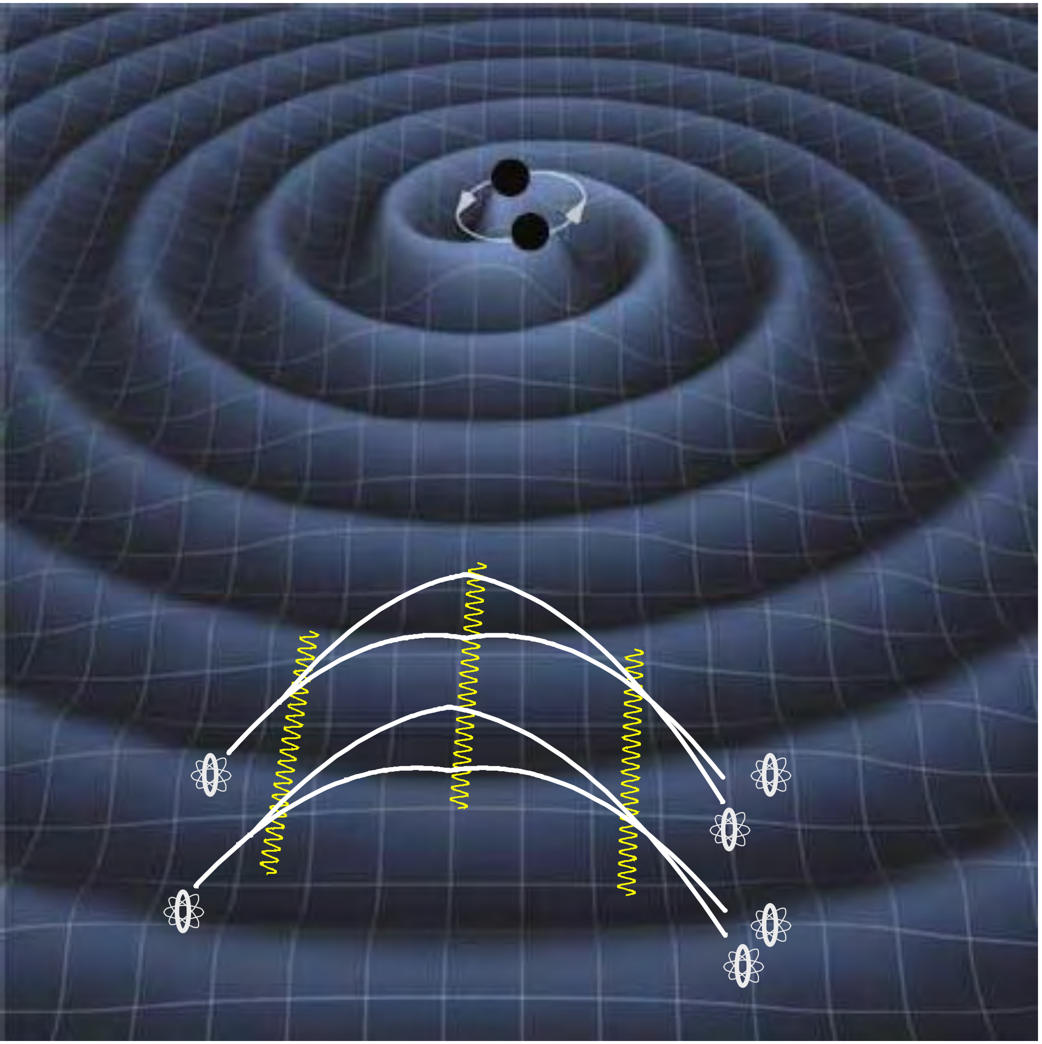


4 ppb

30 ppb

- Define *h* (GPMFC intended)
- kg: 31 ppb with present data
- AMU: 100-fold improvement compared to present Si

Atomic gravitational wave detection

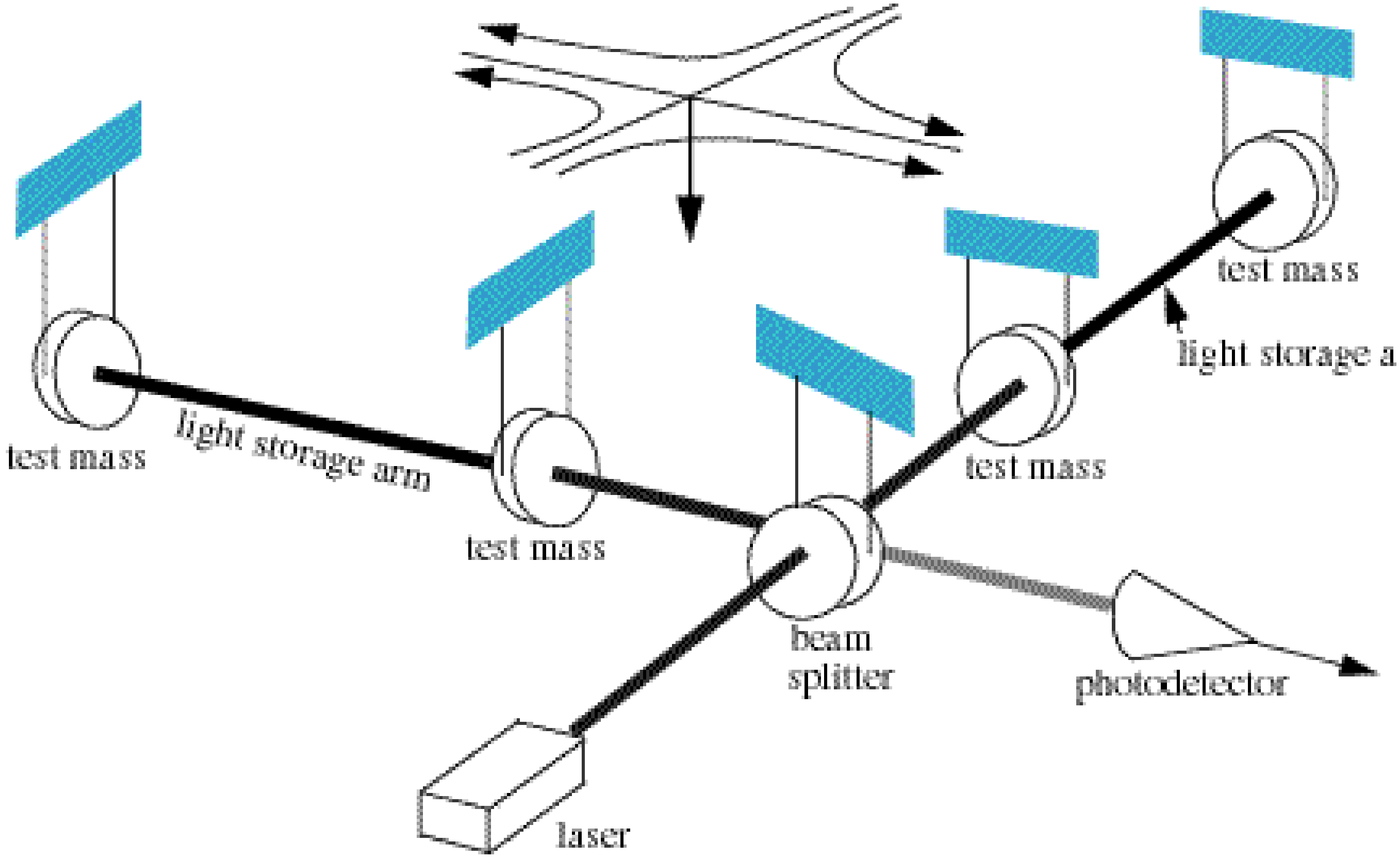


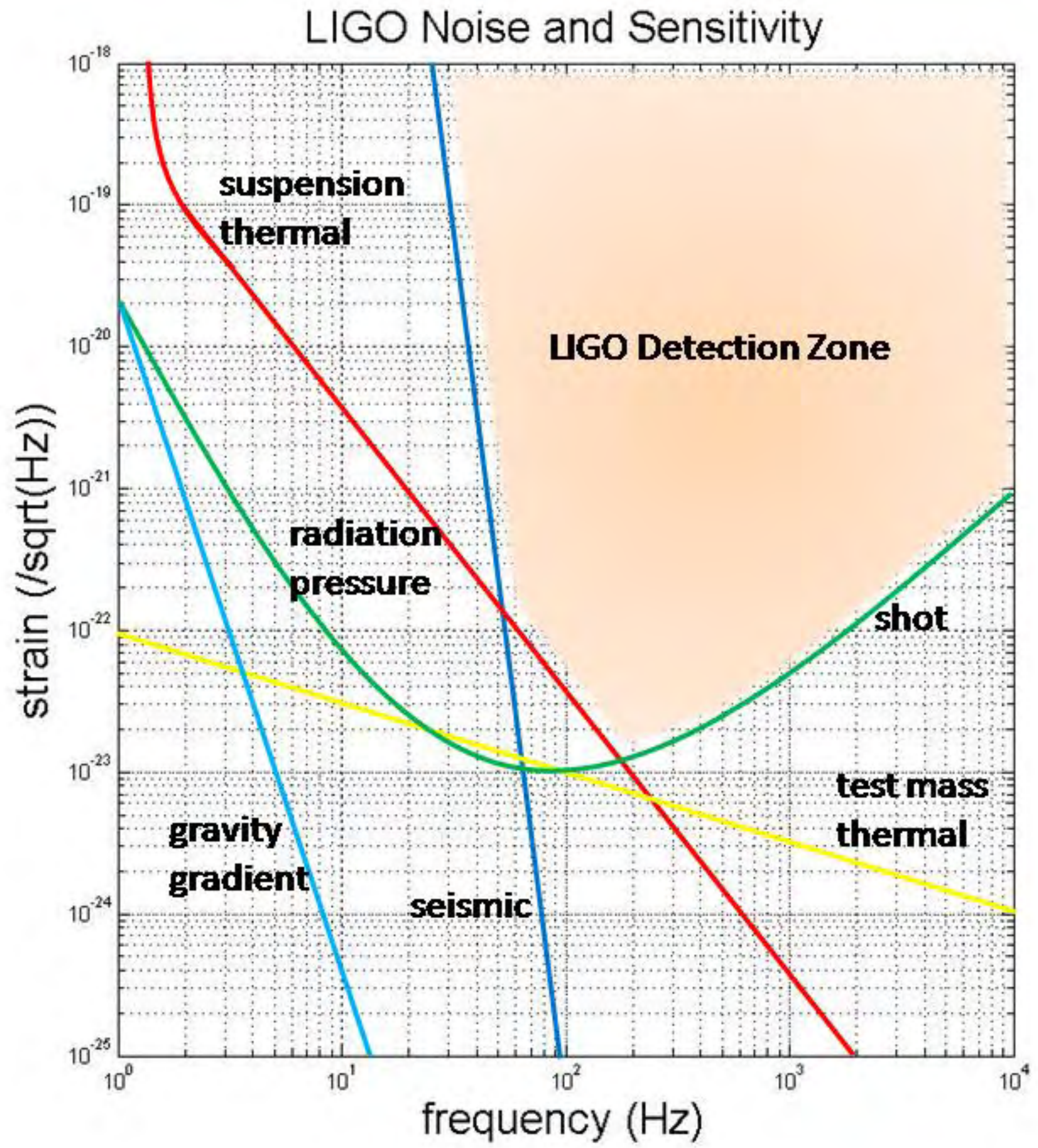
- “Mirrors” are atoms
- Have few degrees of freedom:
- no thermal noise,
- no radiation pressure noise
- no vibration isolation

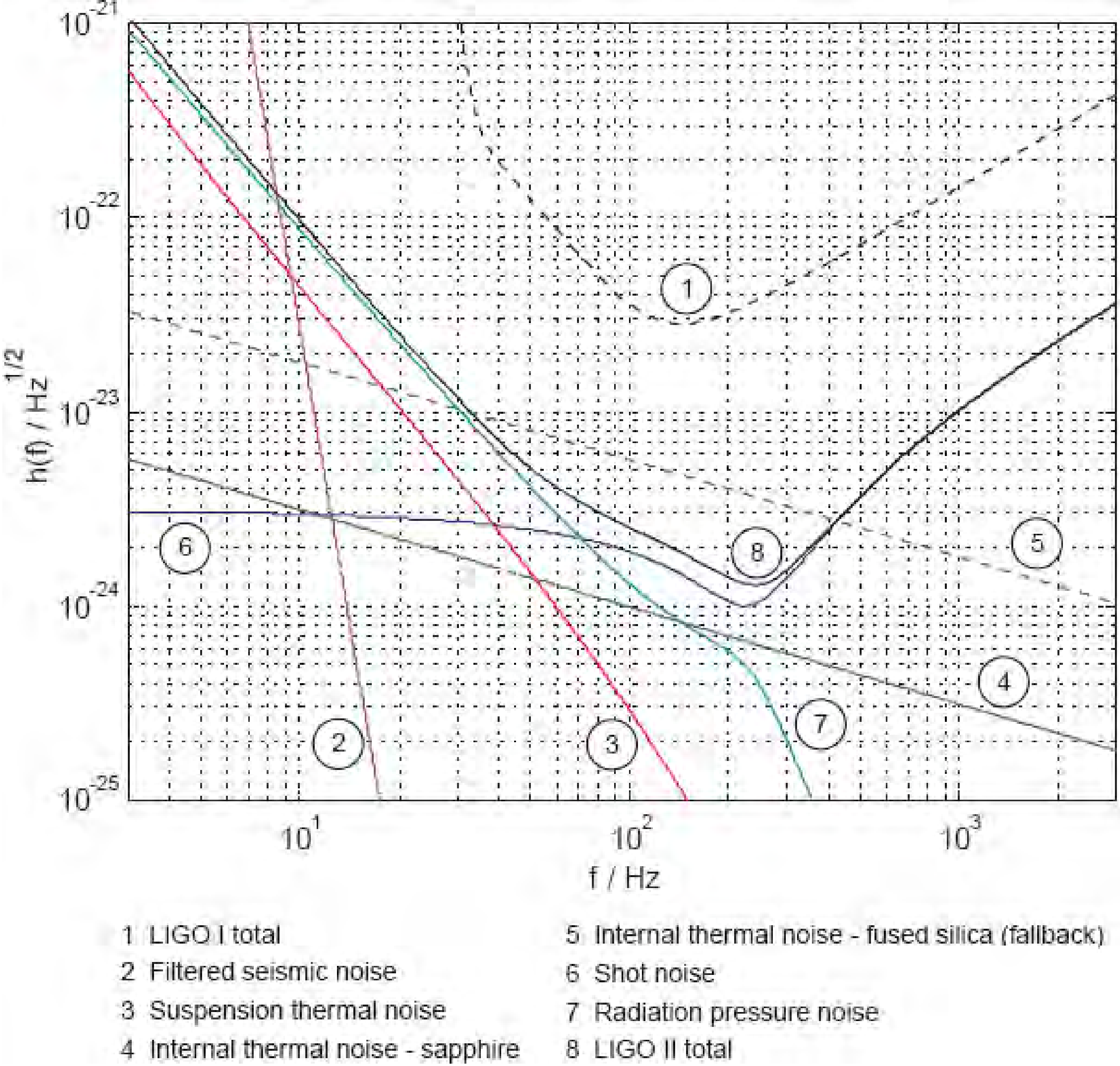
Contents

1. Basics: a. gravity wave detection
   b. Atom interferometers
2. Atomic gravitational wave interferometric sensor (AGIS)
3. Optimized AGIS
4. Sources
5. Challenges
6. Outlook

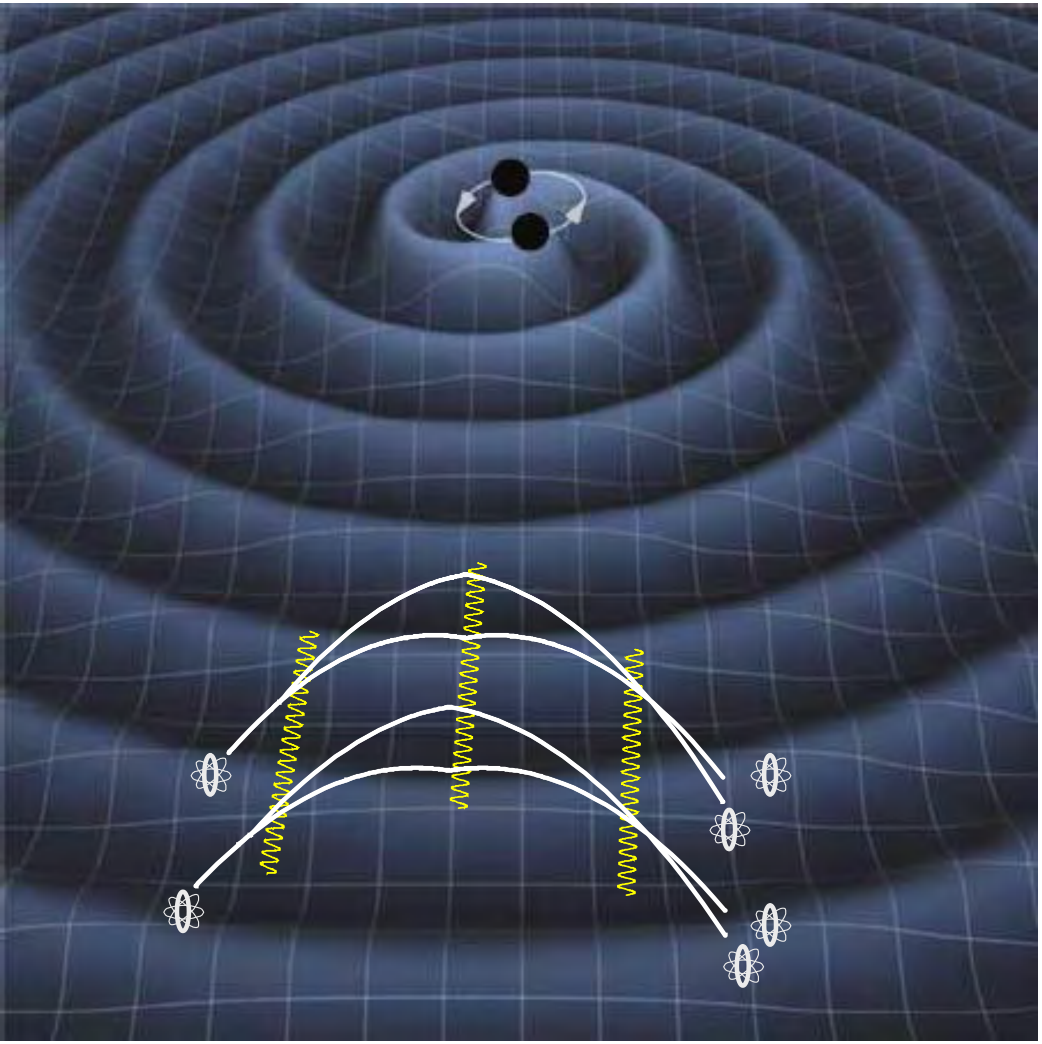
Principles of Operation


test mass
light storage arm
test mass
test mass
light storage arm
test mass
test mass
beam
splitter
photodetector
laser


LIGO Noise and Sensitivity
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}
suspension
thermal
LIGO Detection Zone
radiation
pressure
shot
test mass
thermal
gravity
gradient
seismic


10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
h(f) / Hz$^{1/2}$
10^{1}
10^{2}
10^{3}
f / Hz
1
2
3
4
5
6
7
8
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

Atomic gravitational wave interferometric sensor (AGIS)



- “Mirrors” are atoms

- Have few degrees of freedom:
no thermal noise,
no radiation pressure noise

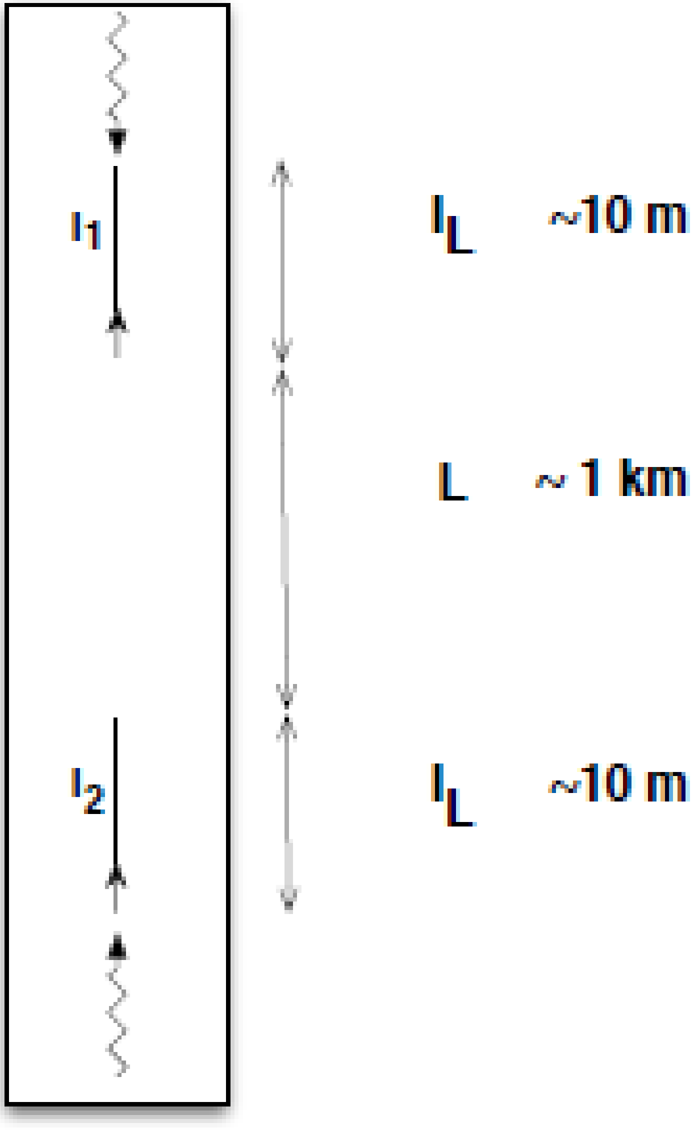
- Almost perfect free fall, no vibration isolation

- Distance measurement based on quantum mechanics

- Sensitivity below 1 Hz

- New technology, at the beginning of a development

AGIS: example



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

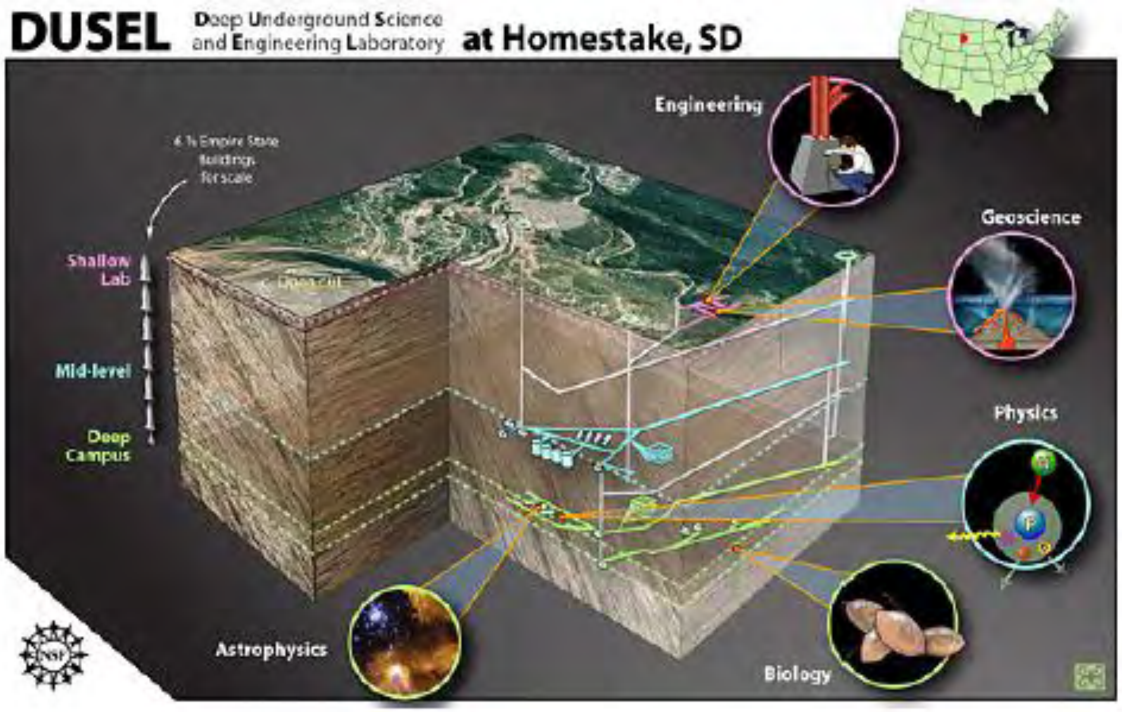
Examples:
$k=2\pi/1\mu$,
$h=10^{-17}$,
$\omega=2\pi*1\text{Hz}$

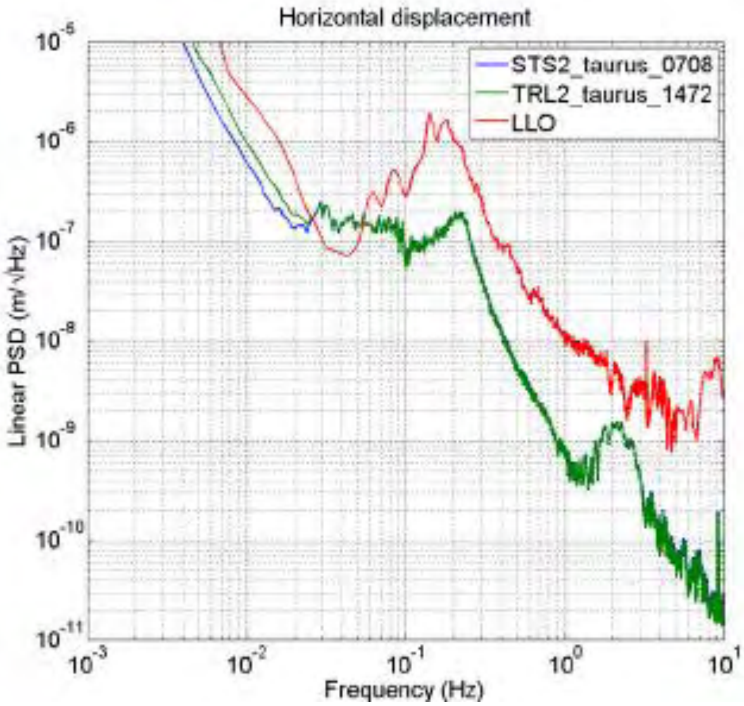
$\Rightarrow\Phi\sim3*10^{-7}$

$n=100$

$=>\Phi\sim3*10^{-5}$

Homestake gold mine: DUSEL





- Remote site, 3km deep. May be sufficiently low noise.
- Collaboration with Mark Kasevich to build demonstrator instrument

Optimization

Sensitivity

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

Low-frequency limit

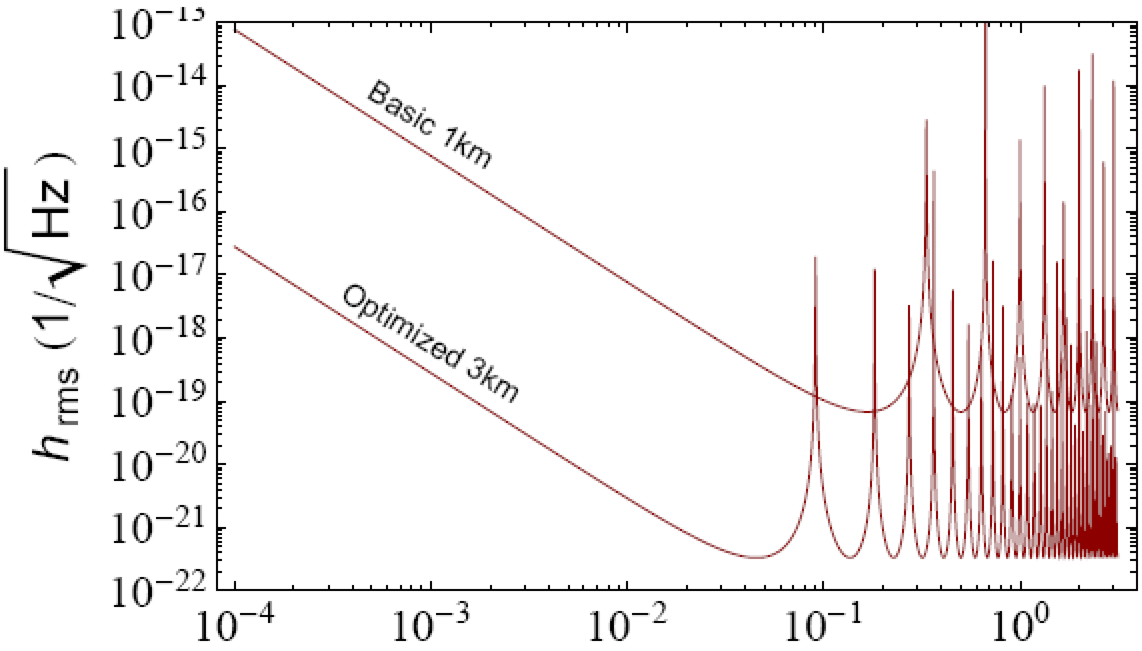
$$h_{\text{rms}}^{\text{LF}} = \frac{2}{nkL\omega^2 T^2\sqrt{\eta}}.$$

Optimizing T, n

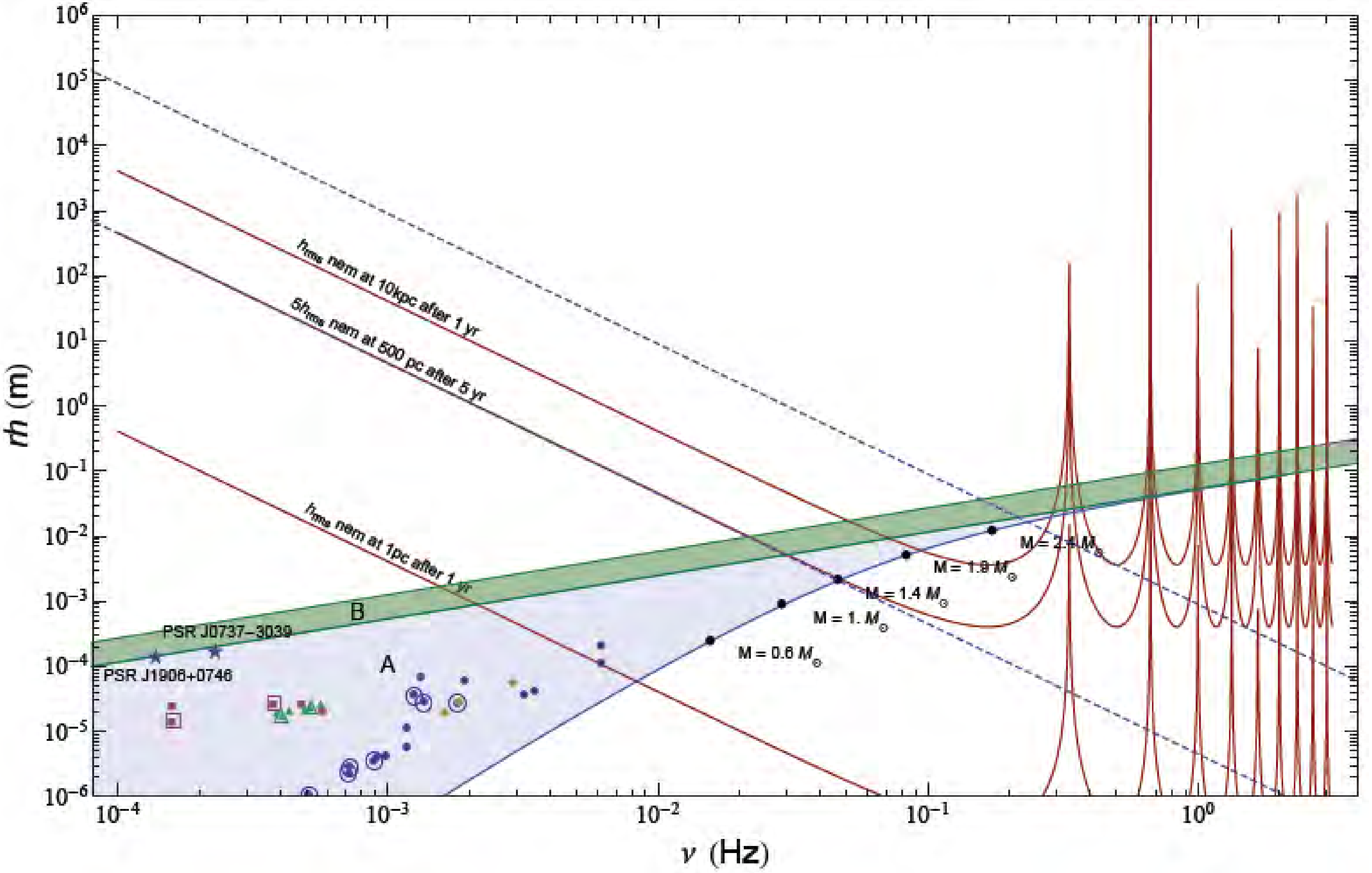
$$\begin{aligned} T_{\text{opt}} &= \sqrt{\frac{2L_{\text{Tube}}}{5g}}, \\ n_{\text{opt}} &= \frac{2L_{\text{Tube}} - gT^2}{4Tv_r}, \\ h_{\text{rms}}^{\text{LF,opt}} &= \frac{25v_r\sqrt{5g}}{2k\boxed{L_{\text{Tube}}^{5/2}}\omega^2\sqrt{2\eta}}. \end{aligned}$$

AGIS sensitivity

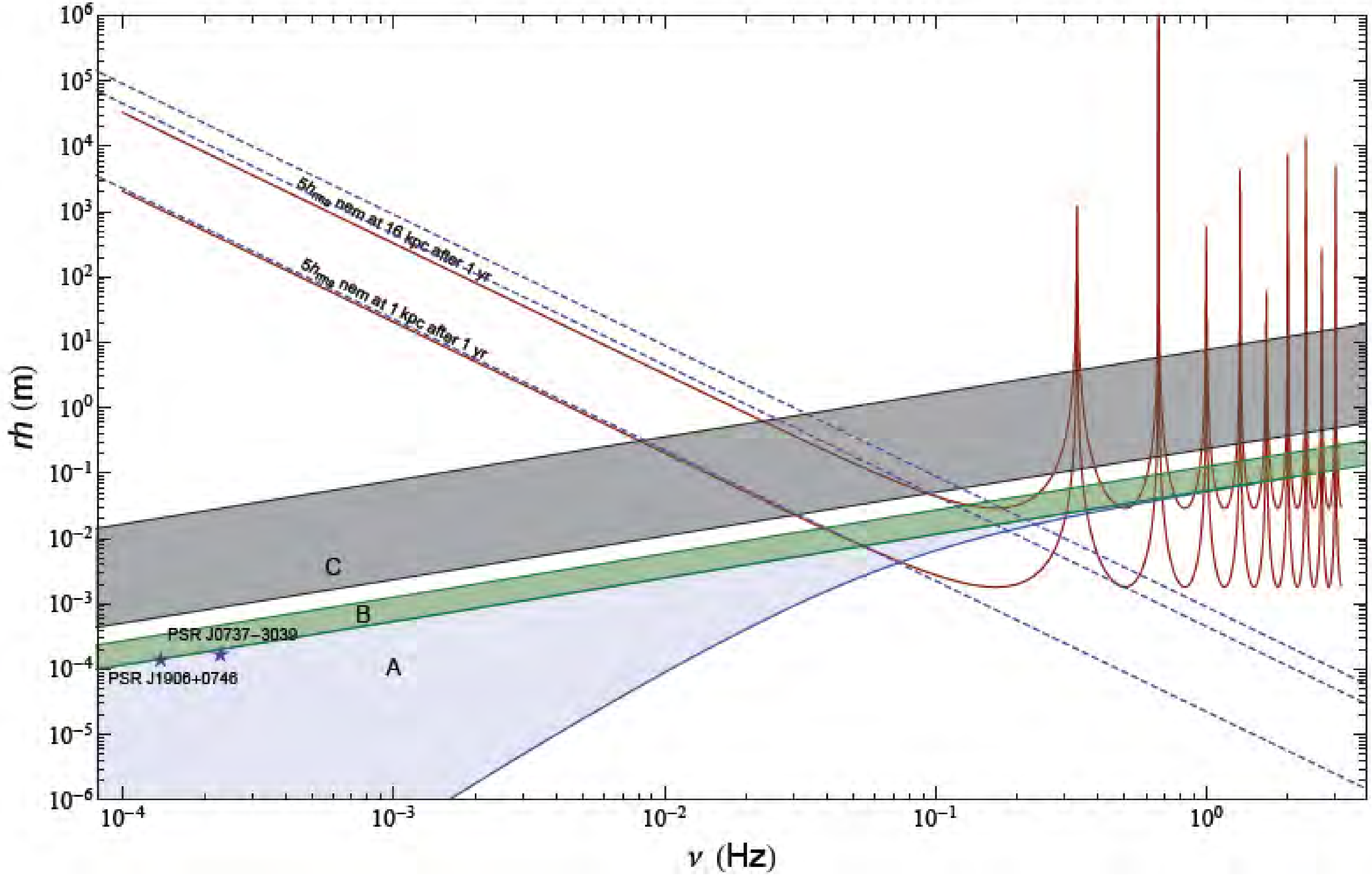
Parameter	Symbol	Basic	Optimized
Wavenumber	k	$2\pi/852\,\mathrm{nm}$	$2\pi/852\,\mathrm{nm}$
Momentum transfer/$(\hbar k)$	n	1,000	31,000
Pulse separation time	T	$3\,\mathrm{s}$	$11\,\mathrm{s}$
Tube length	L_{Tube}	$1{,}000\,\mathrm{m}$	$3{,}000\,\mathrm{m}$
Separation	L	$\approx L_{\mathrm{Tube}}$	$1{,}200\,\mathrm{m}$
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	$h_{\mathrm{rms}}^{\mathrm{LF,opt}}$	$3\times10^{-20}(\frac{\mathrm{Hz}}{\omega})^2\frac{1}{\sqrt{\mathrm{Hz}}}$	$1.1\times10^{-23}(\frac{\mathrm{Hz}}{\omega})^2\frac{1}{\sqrt{\mathrm{Hz}}}$



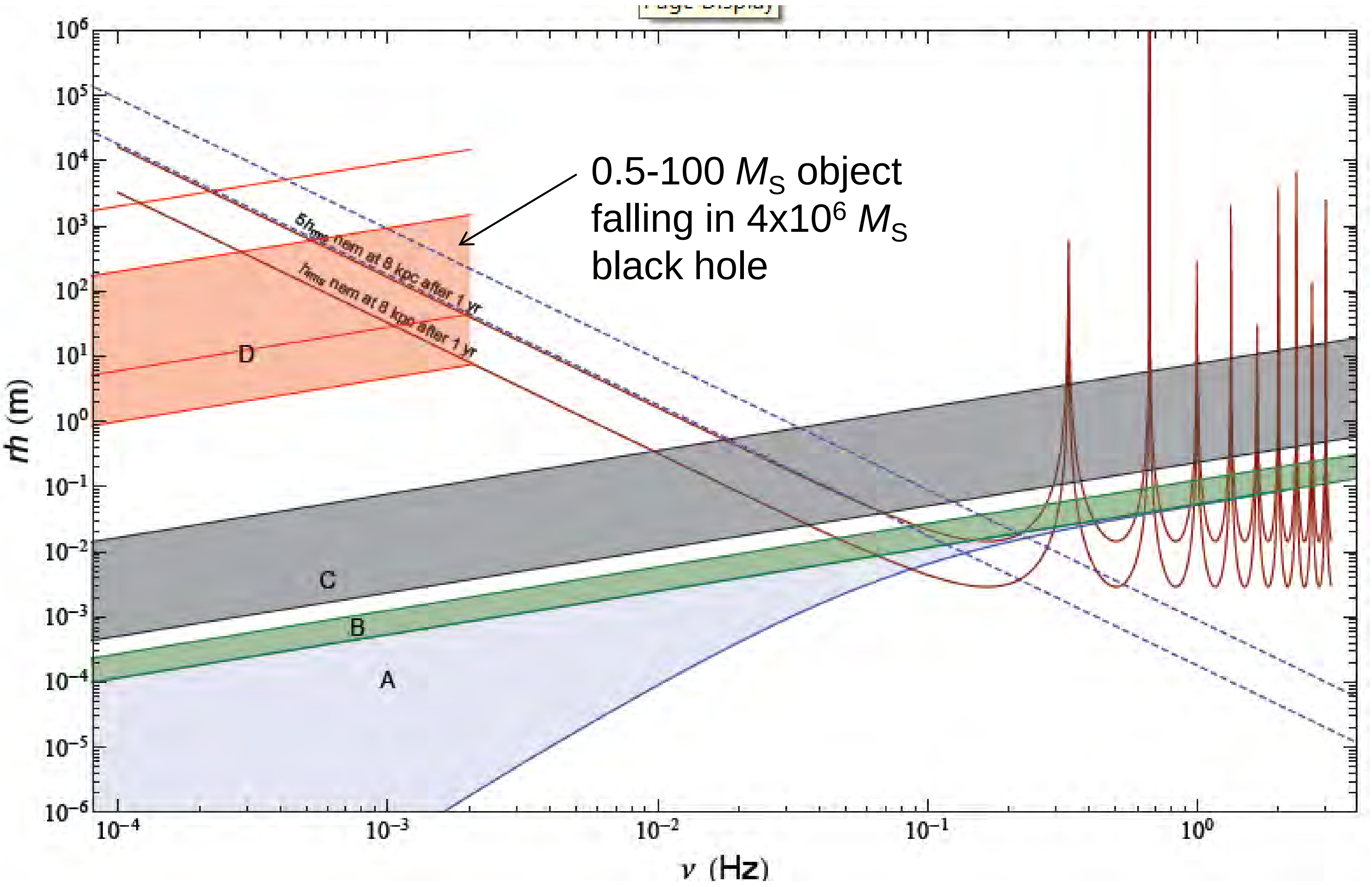
Galactic Binaries



Neutron Star Binaries

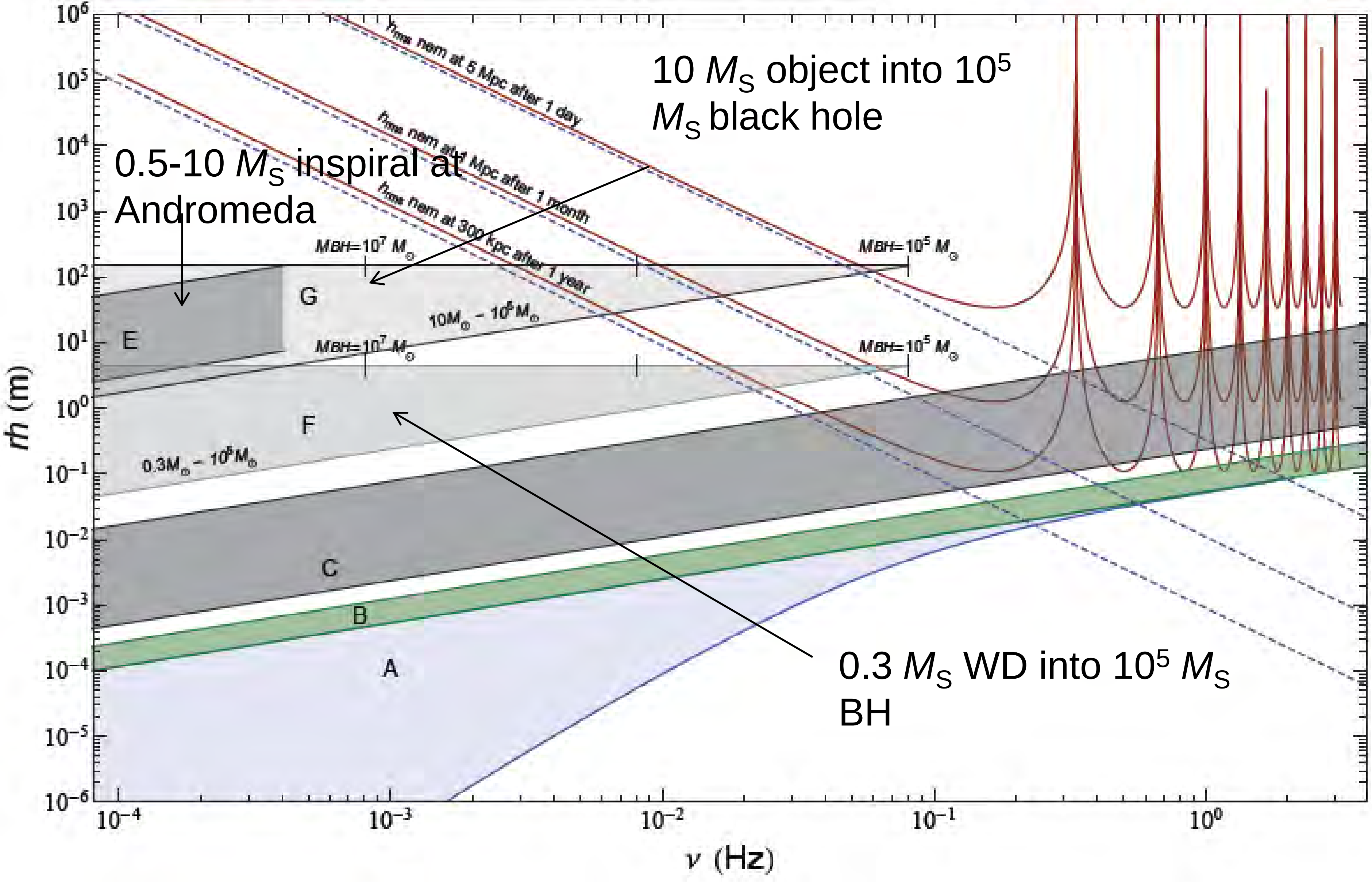


Galactic core sources



0.5-100 M_S object falling in 4x10^6 M_S black hole

Extragalactic sources

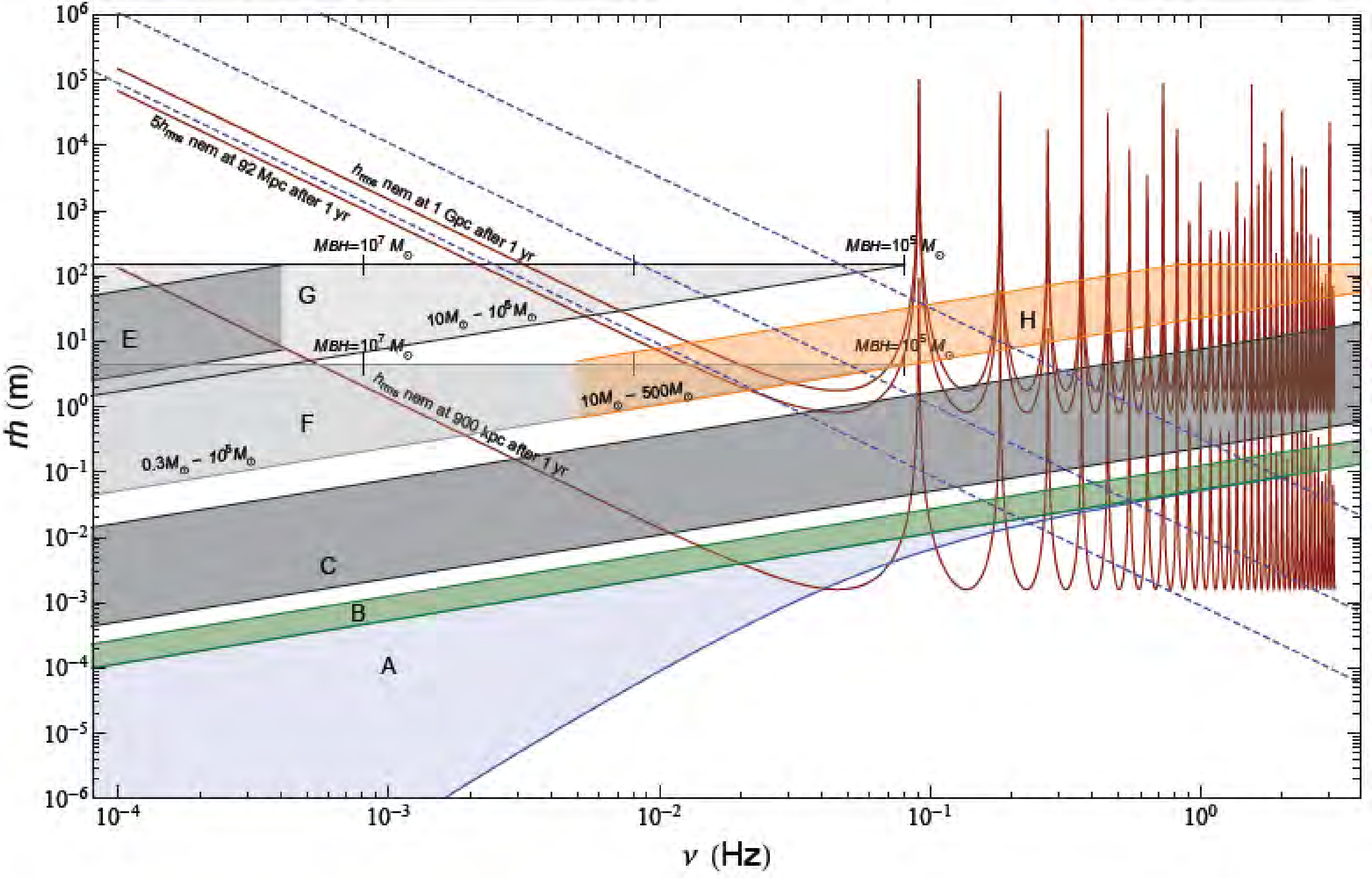


10 M_S object into 10^5 M_S black hole

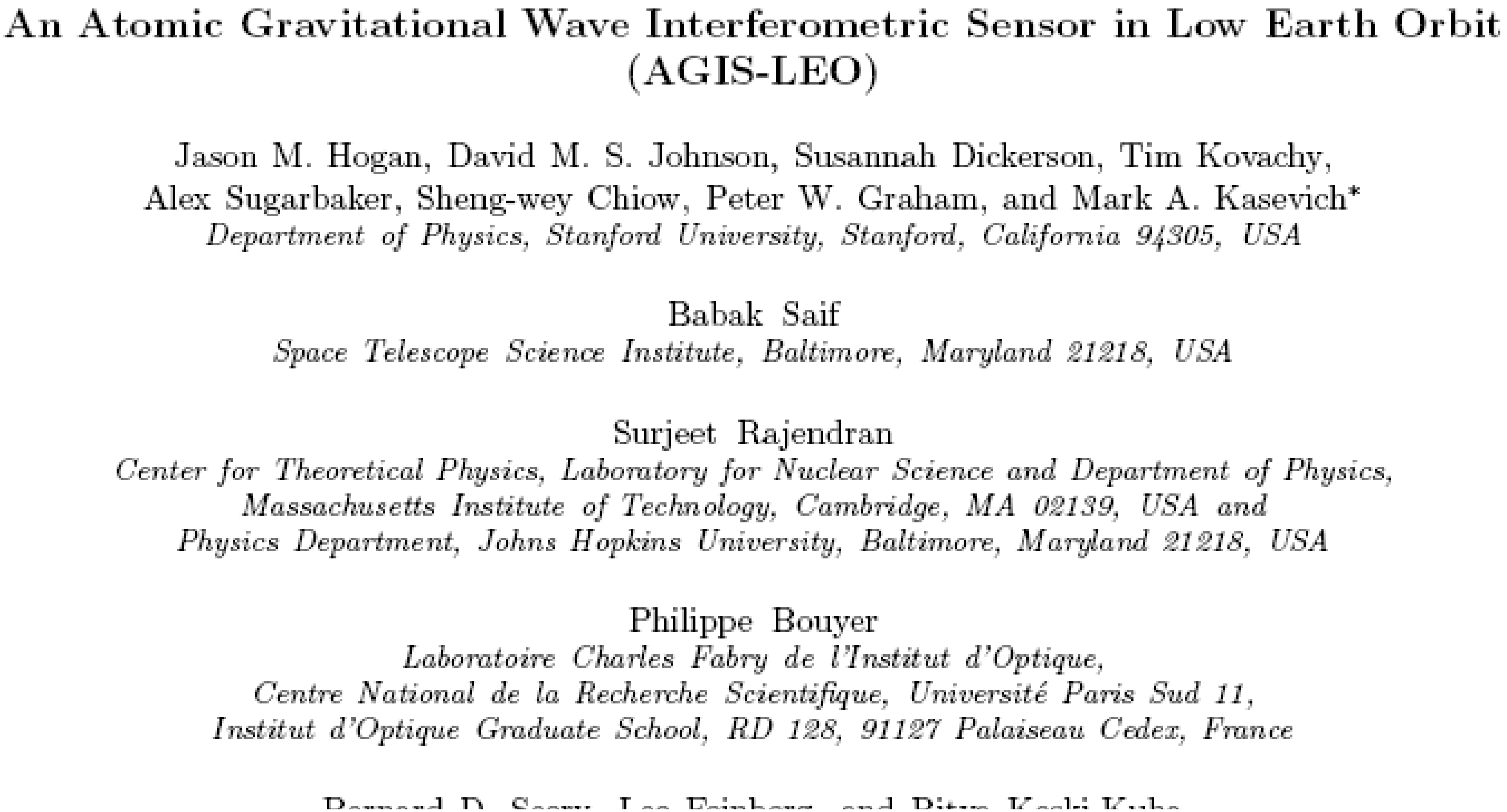
0.5-10 M_S inspiral at Andromeda

0.3 M_S WD into 10^5 M_S BH

Summary with optimized AGIS



Proposals



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

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Alex Sugarbaker, Sheng-wey Chiow, Peter W. Graham, and Mark A. Kasevich*
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Surjeet Rajendran
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics,
Massachusetts Institute of Technology, Cambridge, MA 02139, USA and
Physics Department, Johns Hopkins University, Baltimore, Maryland 21218, USA

Philippe Bouyer
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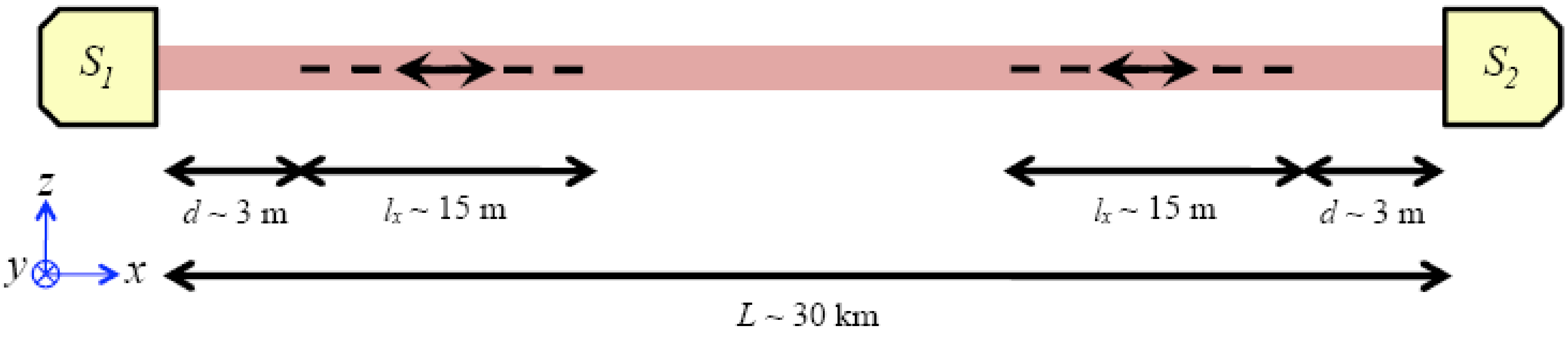
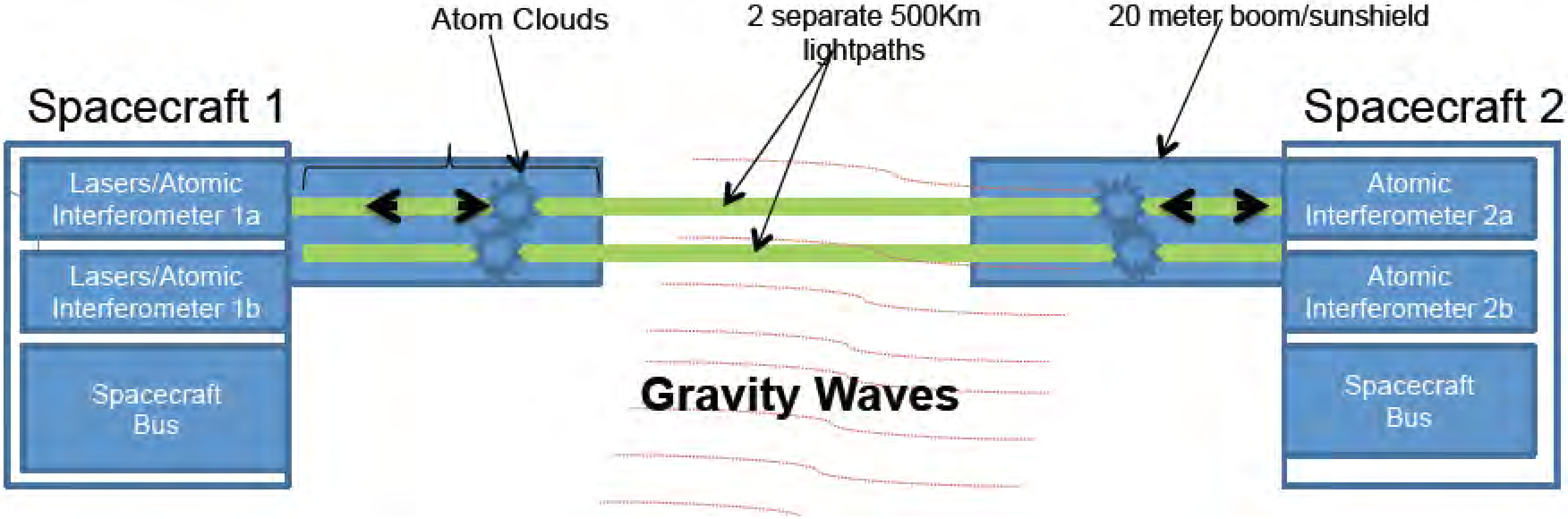
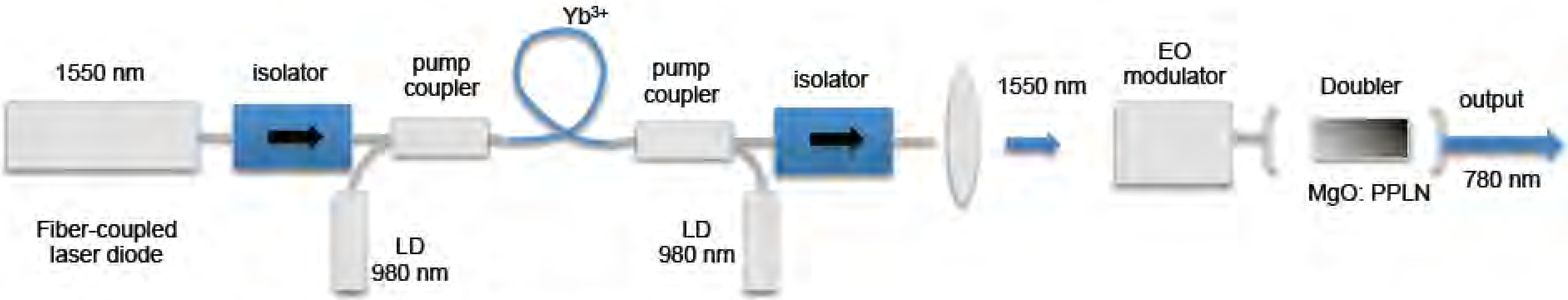
Centre National de la Recherche Scientifique, Université Paris Sud 11,
Institut d'Optique Graduate School, RD 128, 91127 Palaiseau Cedex, France

Bernard D. Seery, Lee Feinberg, and Ritva Keski-Kuha



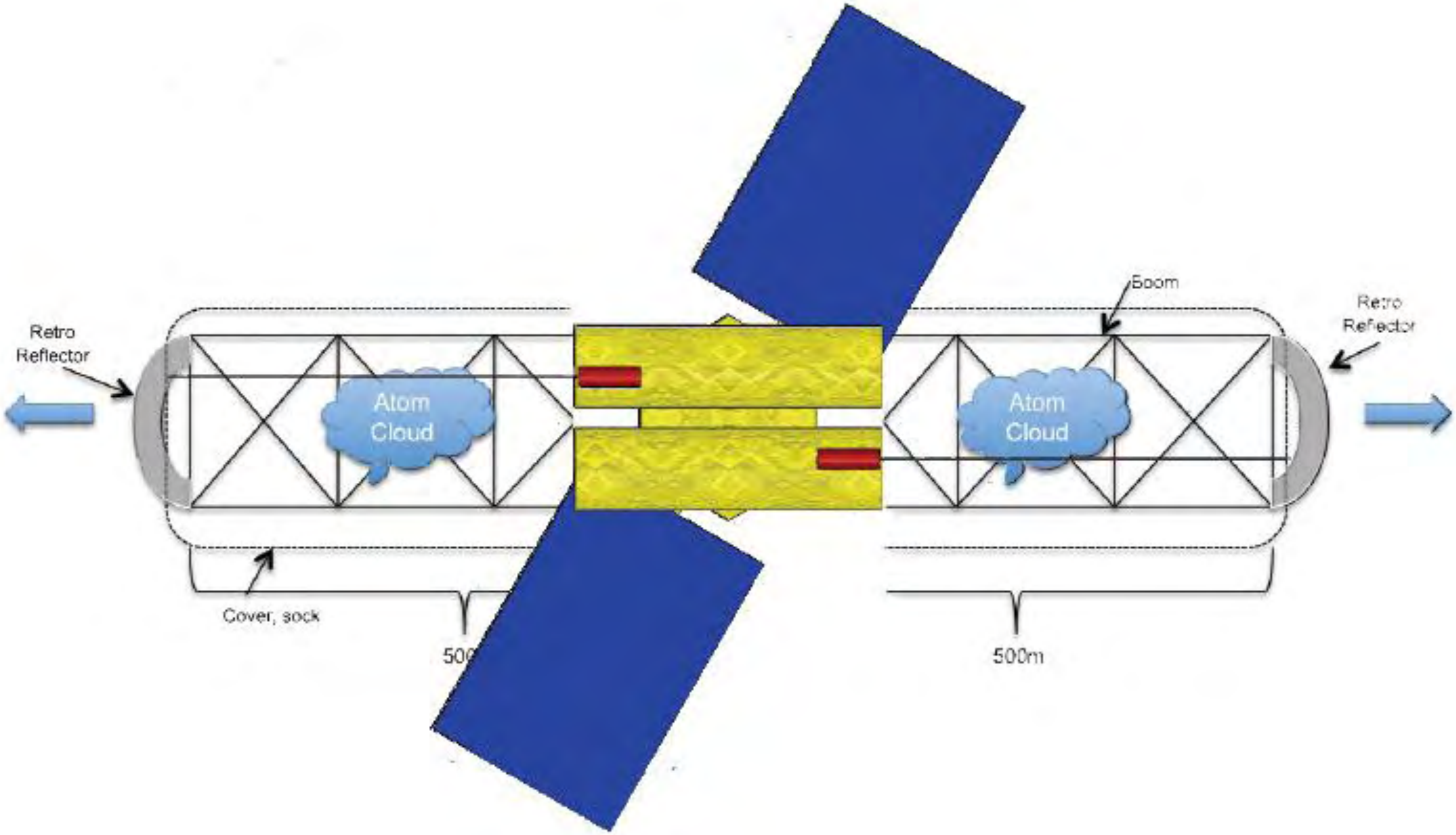
Interferometer in Space for Detecting Gravity Wave Radiation using Lasers (*InSpRL*)



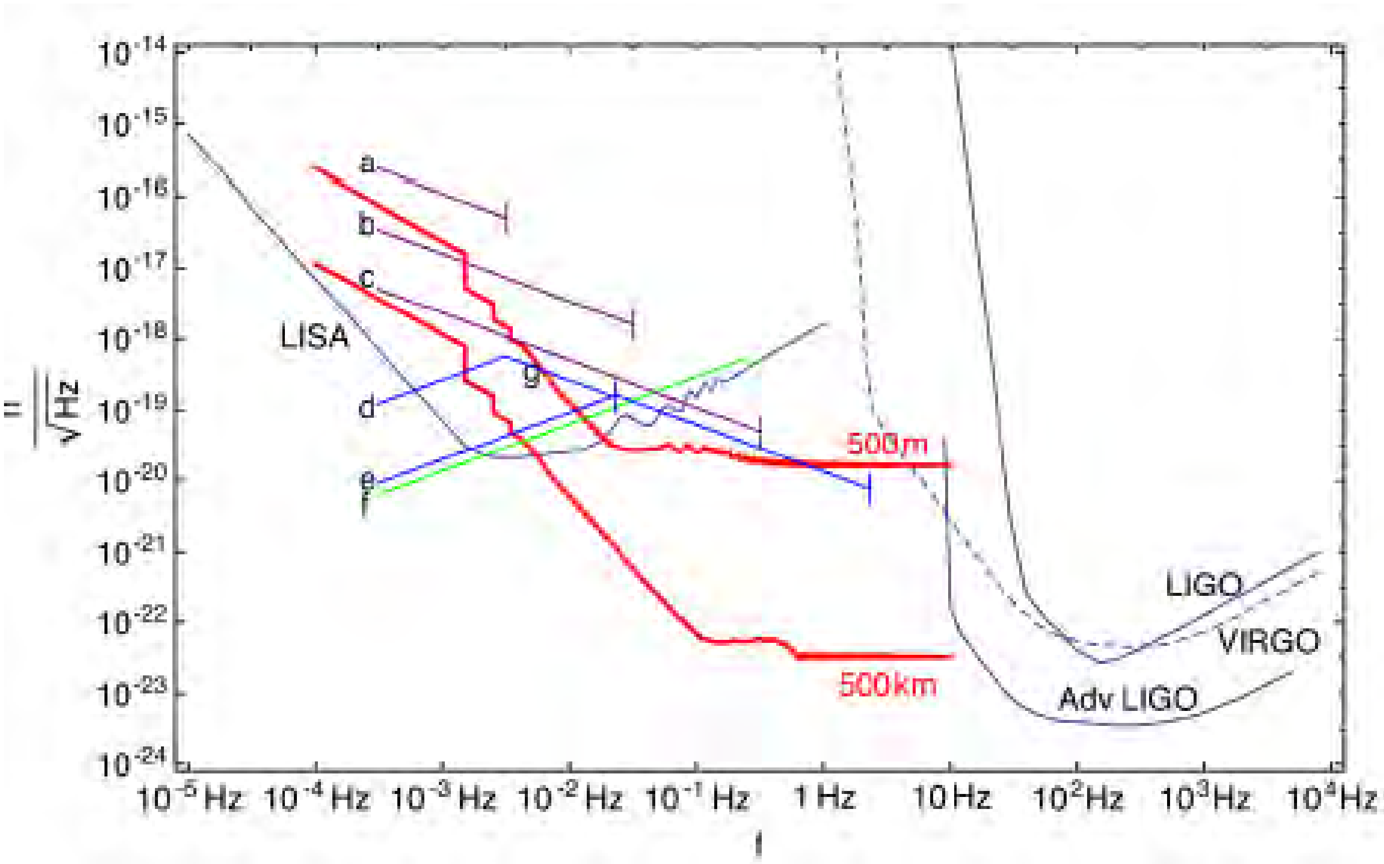


igure 4: Master Oscillator Fiber Laser for Atom Interferometry.

InSpRL boom concept

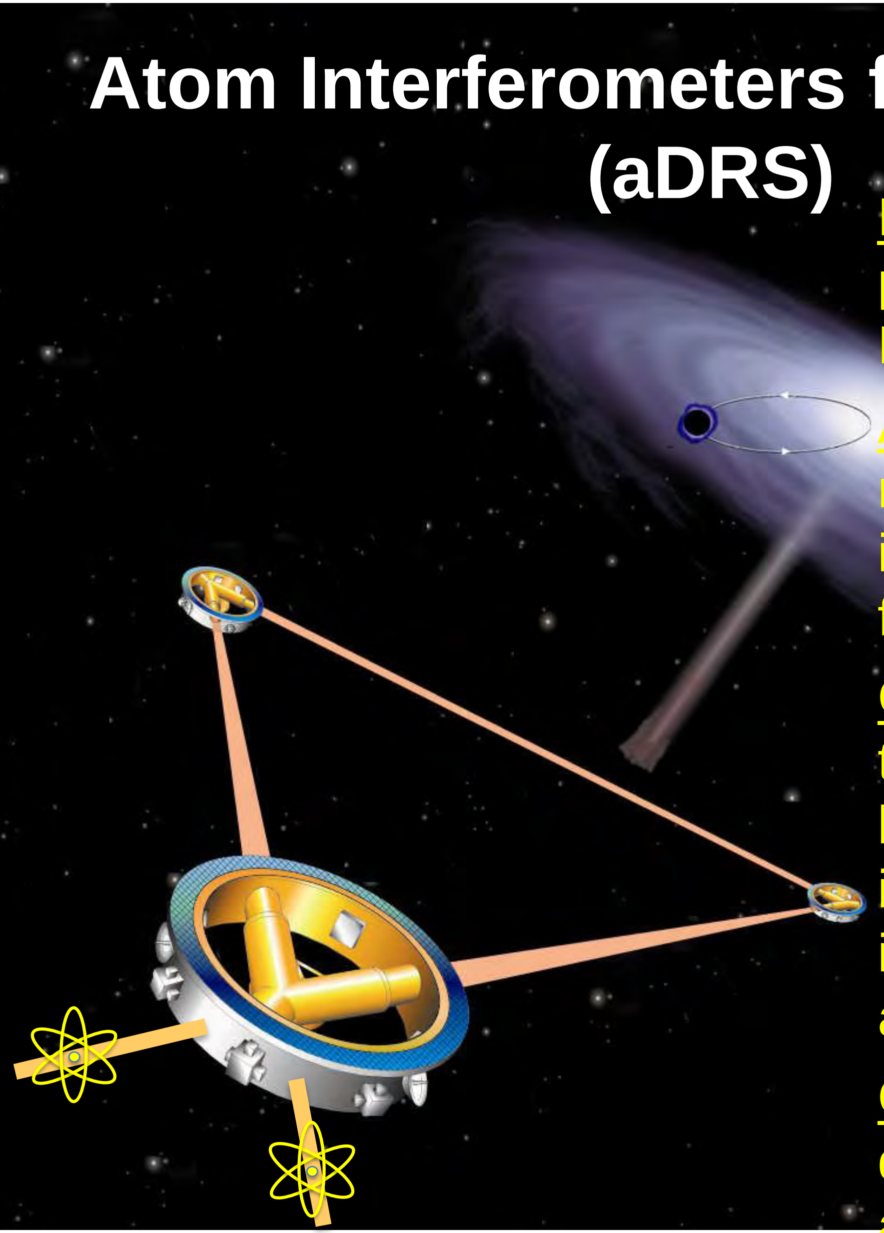


InSpRL sensitivity



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 based atom-wave interferometry using laser-cooled free fall atoms.

Concept: Use atomic inertial sensors to replace the LISA accelerometers by measuring relative acceleration-induced displacements between ideal drag-free atoms and spacecraft accelerometers.

Goal: Reduce/eliminate spacecraft drag-free requirement and the associated complexity, risk, and cost, while potentially increase

Challenges

Large momentum transfer: 1000’s of hk

High-frequency sensitivity

Atom sources

Most noise sources affect AI just as LIGO

Important exception: Mirror seismic noise

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

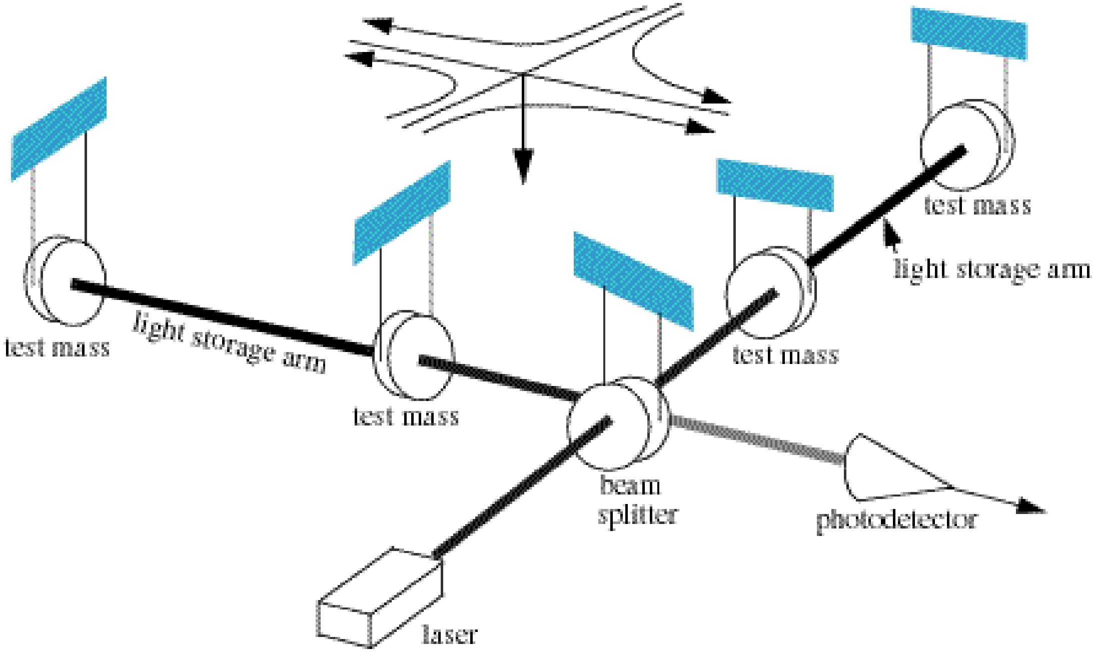
$$h = \frac{\rho G b}{2\omega c}$$

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

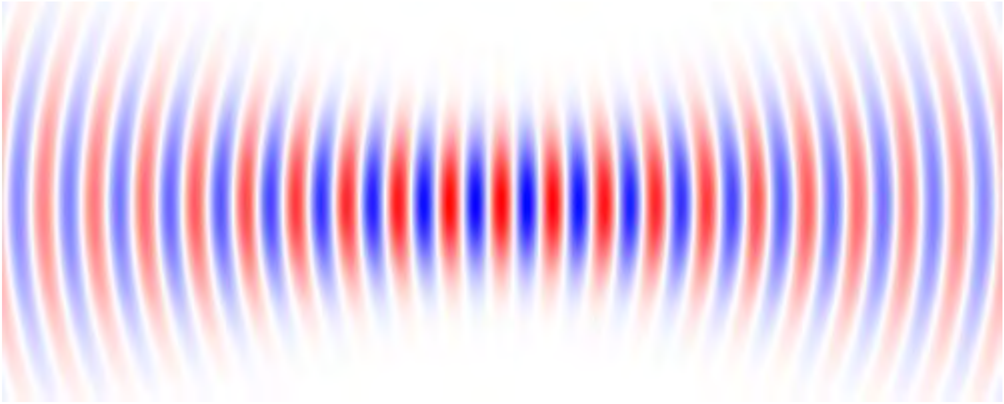
Mitigation
- monitoring?
- more than two clouds
- correlation

Laser noise / mirror motion

- Laser noise: nearly same influence as in LIGO
- Small differences due to aliasing favor LIGO
- AI is much less sensitive to mirror motion



Wavefront distortions



- Local phase variations picked up by atoms
- In LIGO, they tend to average out to higher degree
- Atom poistion changes aggravate this => need very cold atoms

Challenges

1. 1000 photon beam splitters
2. Common-mode rejection of vibrations
3. Atom sources
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

Conclusion

- LMT, Simultaneous, BBB, Coriolis compensation
- α, inertial sensors, tests of GR
- gravitational AB effect, Compton clock, Mass standard
- Basic GW sensor: principles, comparison to LIGO
- Proposals on Earth and in Space
- Challenges and possible solutions

Time is an illusion, lunchtime doubly so

Douglas Adams

$$\Psi = e^{i\frac{mc^2}{\hbar}t}\psi$$

A single massive particle is Nature's elementary clock

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

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