Title: Clock atom interferometry for gravitational wave detection and dark matter searches

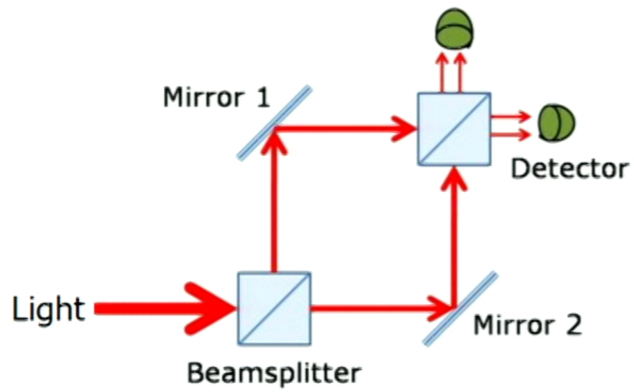
Date: Aug 22, 2017 02:00 PM

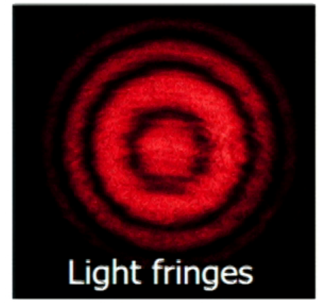
URL: http://pirsa.org/17080025

Abstract:

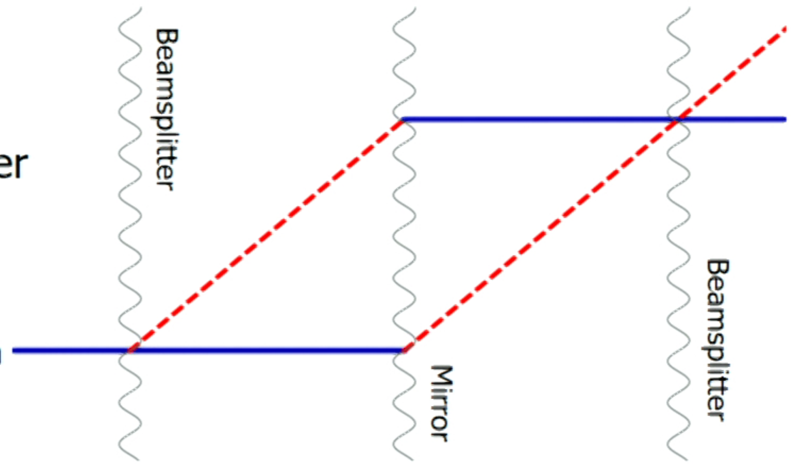
Atom interference

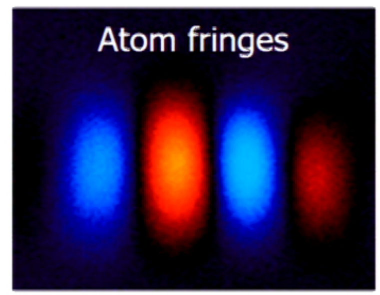
Light interferometer





Atom interferometer





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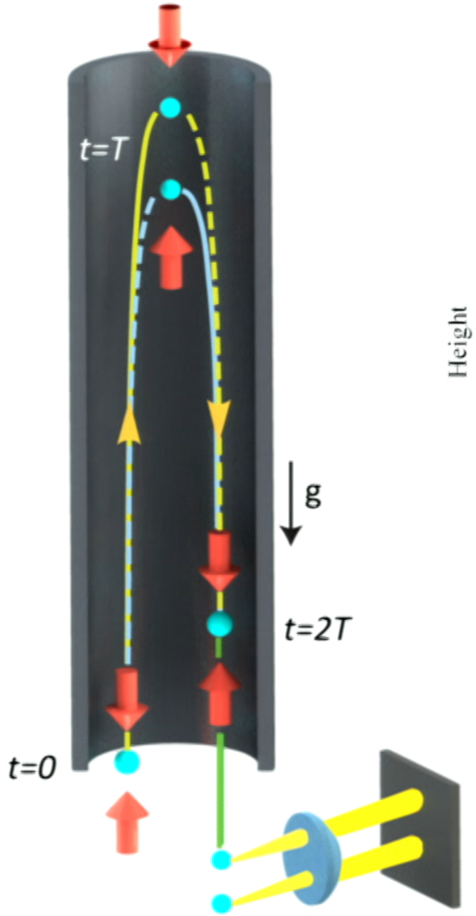
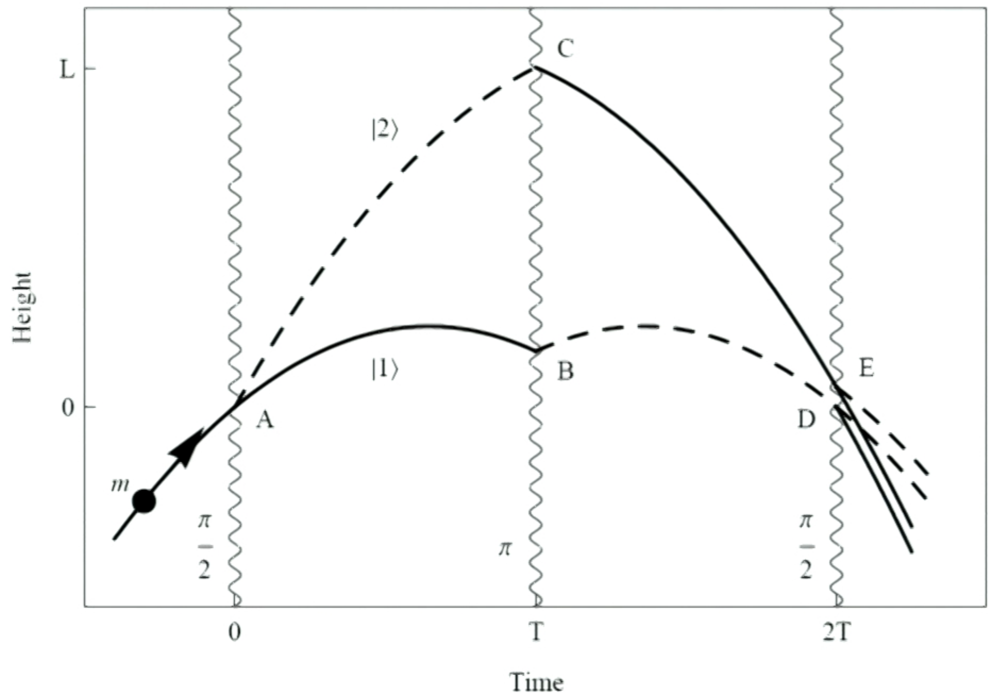
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Light Pulse Atom Interferometry





- Long duration
- Large wavepacket separation

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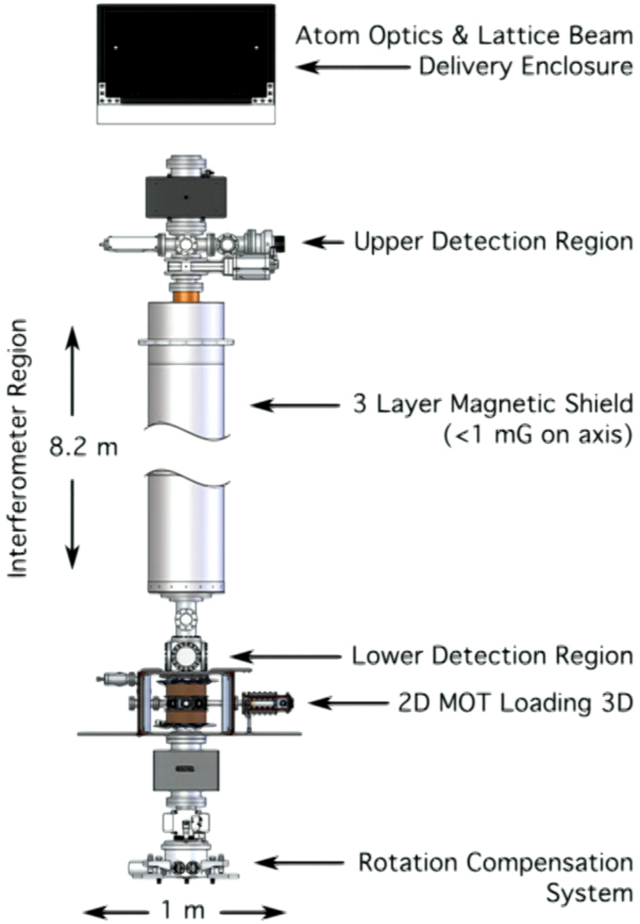
10 meter scale atomic fountain



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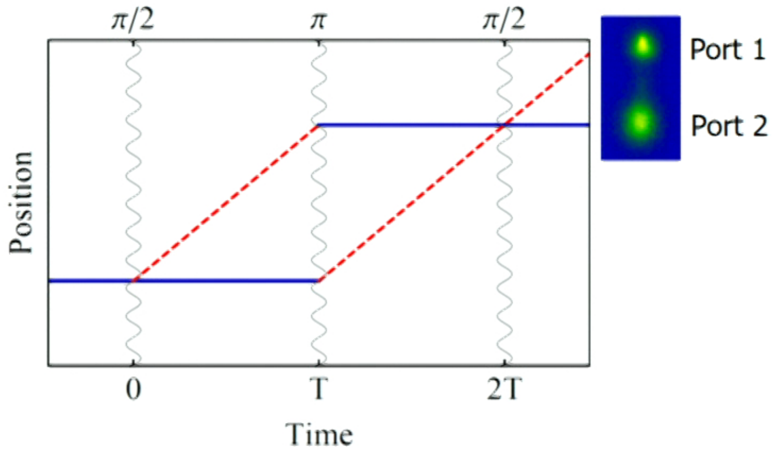
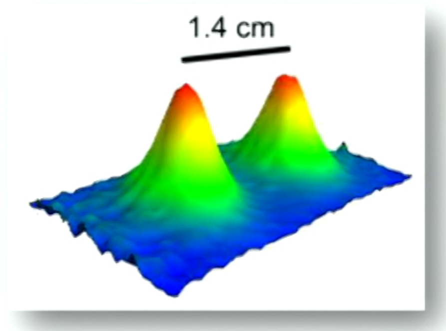
Interference at long interrogation time



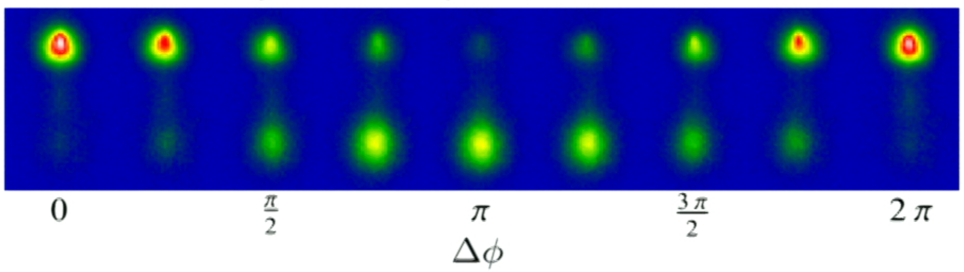
$2T = 2.3$ seconds

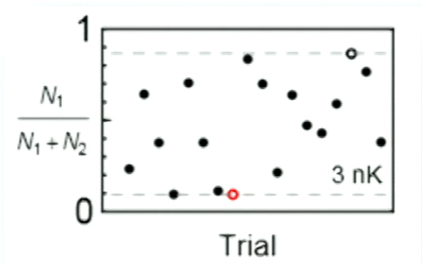
1.4 cm wavepacket separation



Wavepacket separation at apex (this data 50 nK)

Interference (3 nK cloud)





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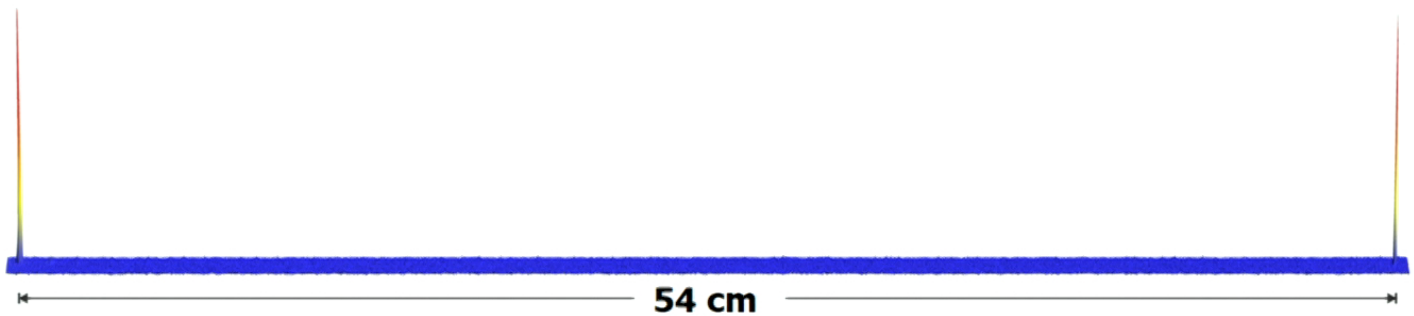
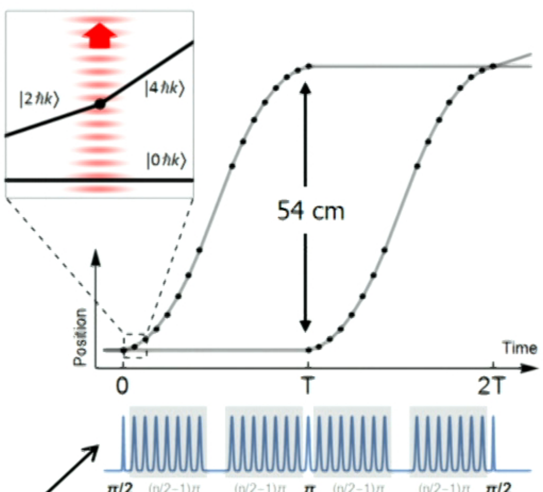
Dickerson, et al., PRL **111**, 083001 (2013).

Large space-time area atom interferometry

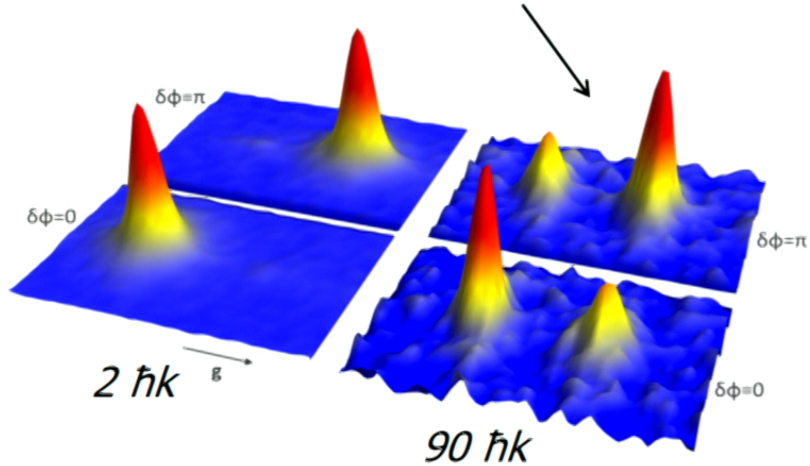
Long duration (2 seconds), large separation (>0.5 meter) matter wave interferometer





Sequential Bragg pulse sequence

Robust interference observed at macroscopic time and length scales



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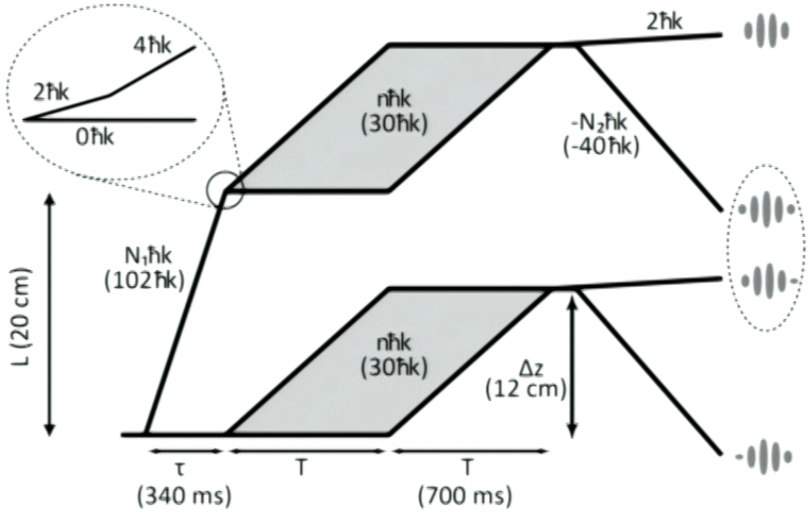
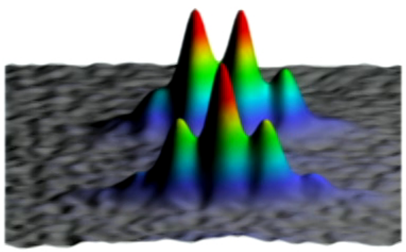
Kovachy et al., *Nature* 2015

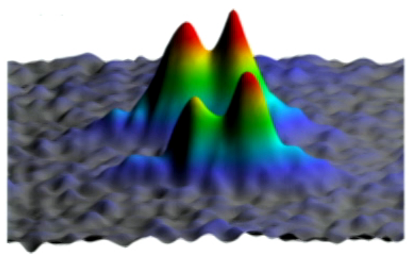
Gravity Gradiometer





$\Delta z = 4\,\text{cm}$

10 ħk



$\Delta z = 12\,\text{cm}$

30 ħk

Gradiometer baseline defined by atom recoil:

$$L = (N_1 \hbar k/m)\tau$$

(Insensitive to initial source position)

Gradiometer interference fringes

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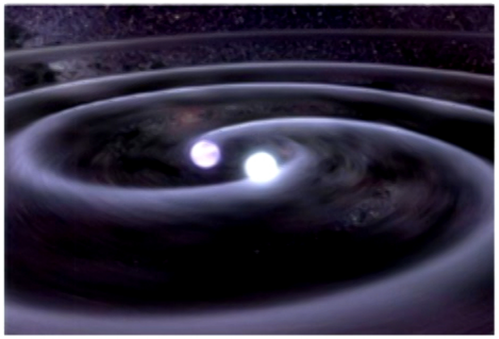
P. Asenbaum et al., PRL 2017.

Gravitational Wave Detection



Why study gravitational waves?

- New carrier for astronomy
- Extreme tests of gravity
- Early universe cosmology

Why consider atoms?

- Neutral atoms are excellent proof masses
- Atom interferometry to measure geodesic
- Atoms are excellent clocks

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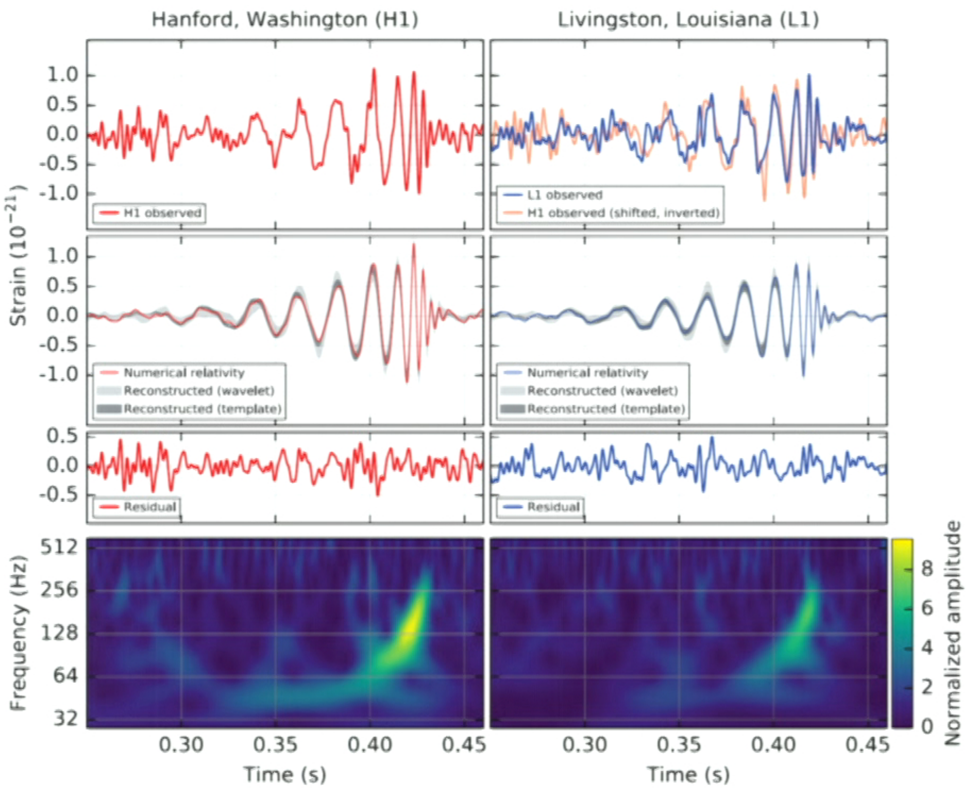
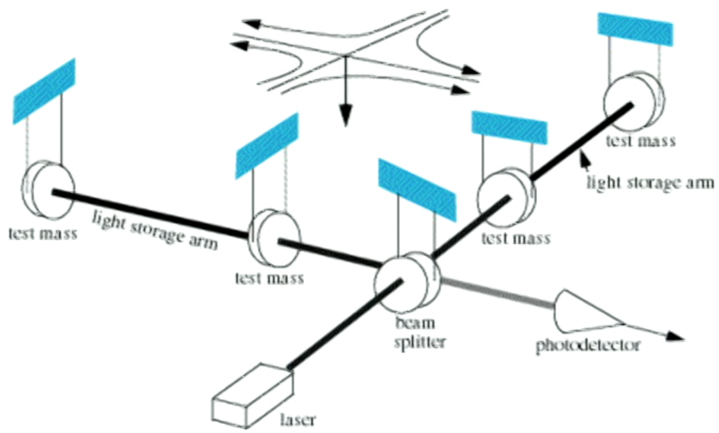
LIGO Detection



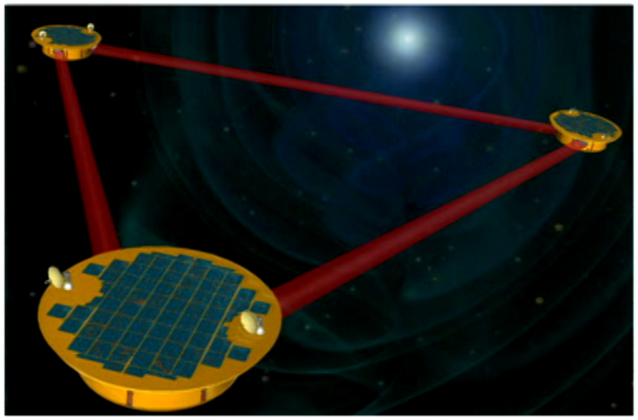
GW 150914

B. P. Abbott et al., PRL **116**, 061102 (2016)

Laser Interferometer Detectors



Ground-based detectors: LIGO, VIRGO, GEO (> 10 Hz)



Space-based detector concept: LISA (1 mHz – 100 mHz)

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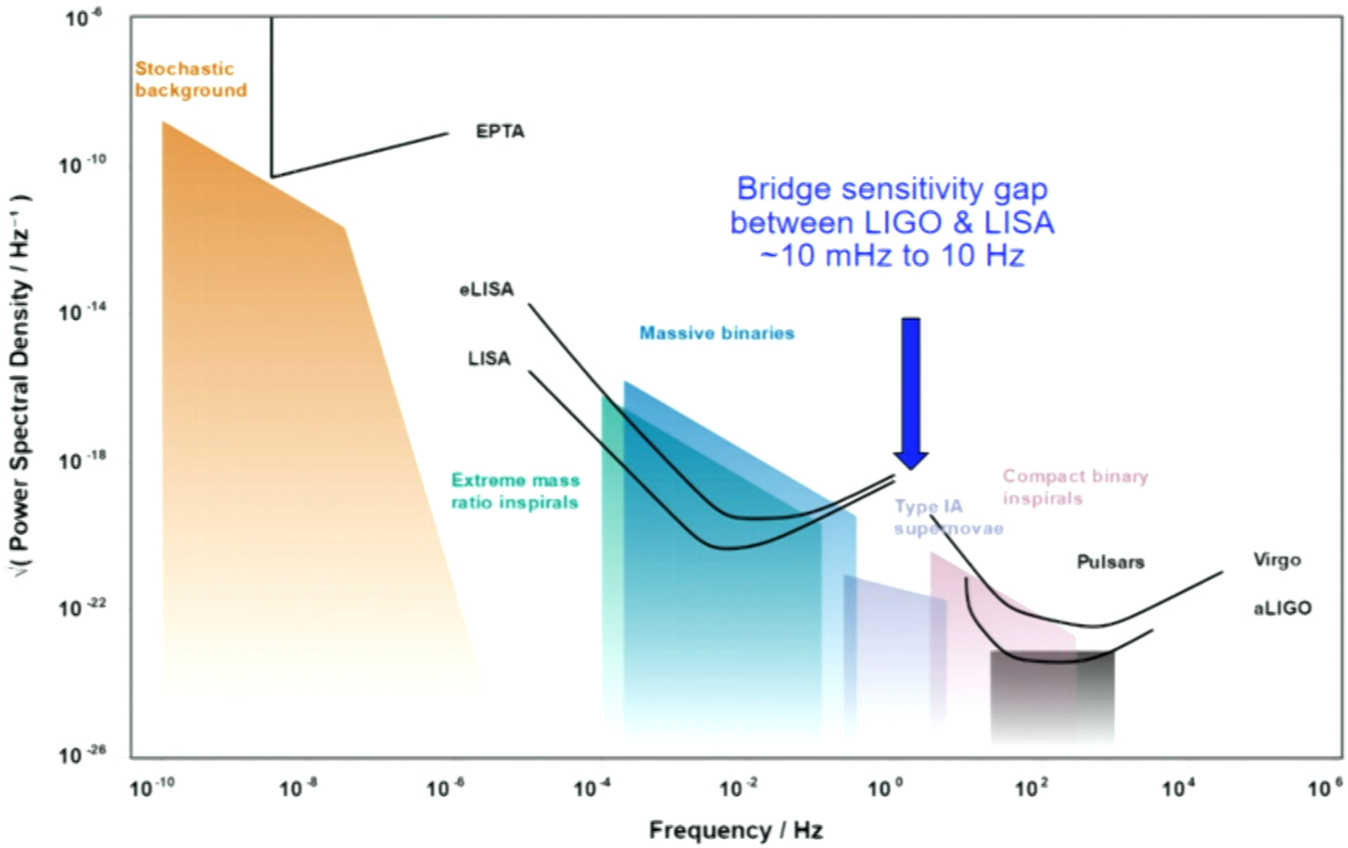
Mid-band Gravitational Wave Detection



STANFORD UNIVERSITY Figure: C. J. Moore et al., Class. Quantum Grav. **32**, 015014 (2015)

Mid-band Science

Discovery potential

- Historically every new band/modality has led to discovery

Frequency band 0.03 Hz to 3 Hz

LIGO/x-ray/gamma messenger for BH and NS binaries

- Sky localization
- Merge time
- BH spin determination

WD-WD binaries in isolation

- Avoids proliferation of source in LISA band
- Likely not visible in LIGO band
- Origin of Type 1A supernovae

Intermediate mass BH

- Outside LIGO band

Early Universe (pre-CMB)

- Inflation and reheating
- Cosmic strings
- Phase transition

Dark matter (AI and clocks) e.g., Arvanitaki *et al.*, arXiv:1606.04541 [hep-ph] (2016)

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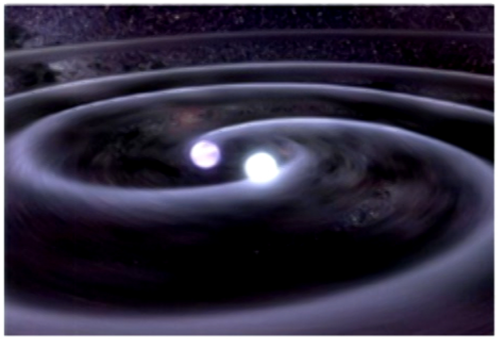
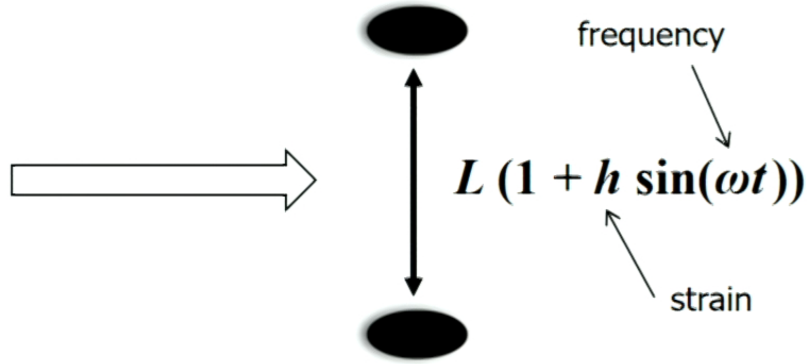
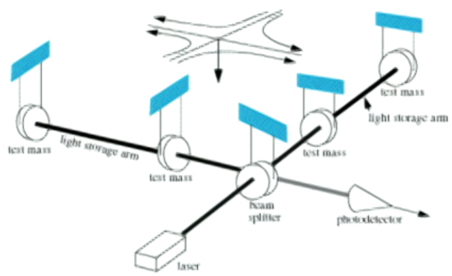
Gravitational Wave Detection







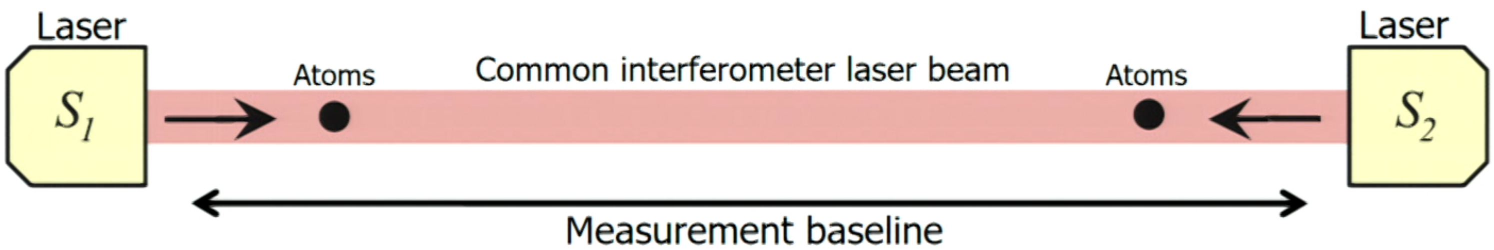
Laser interferometer GW detector

Laser interferometers suppress laser noise by comparing multiple baselines

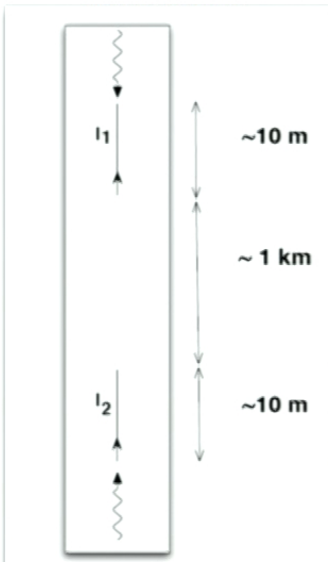
Atom interferometer only requires single baseline

Compare to LISA (2 vs. 3 spacecraft)

Gradiometer configuration

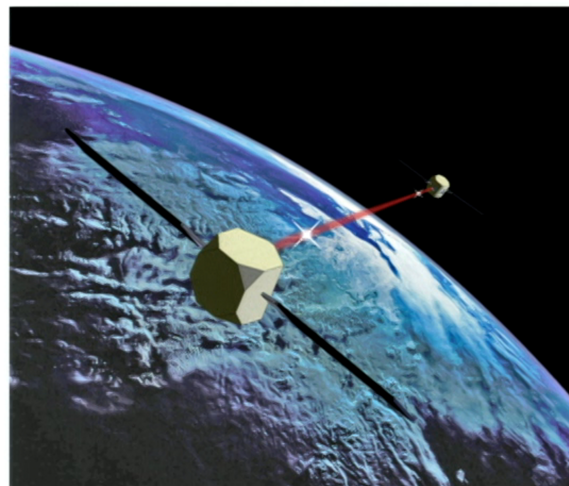


Terrestrial



(Vertical mine shaft)

Space



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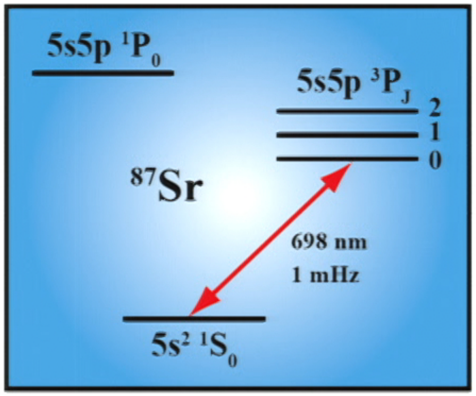
Clock gradiometer

- *Clock* - Single photon transitions in clock atoms (e.g., Sr)
- *Gradiometer* - Compare two separated clock atoms
- Inertially sensitive (accelerometer)
- Common laser phase noise



Measurement Concept

Essential Features

1. Light propagates across the baseline at a constant speed
2. Atoms are good clocks

$$L\,(1 + h\,\sin(\omega t))$$

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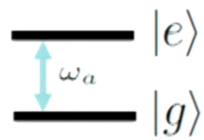
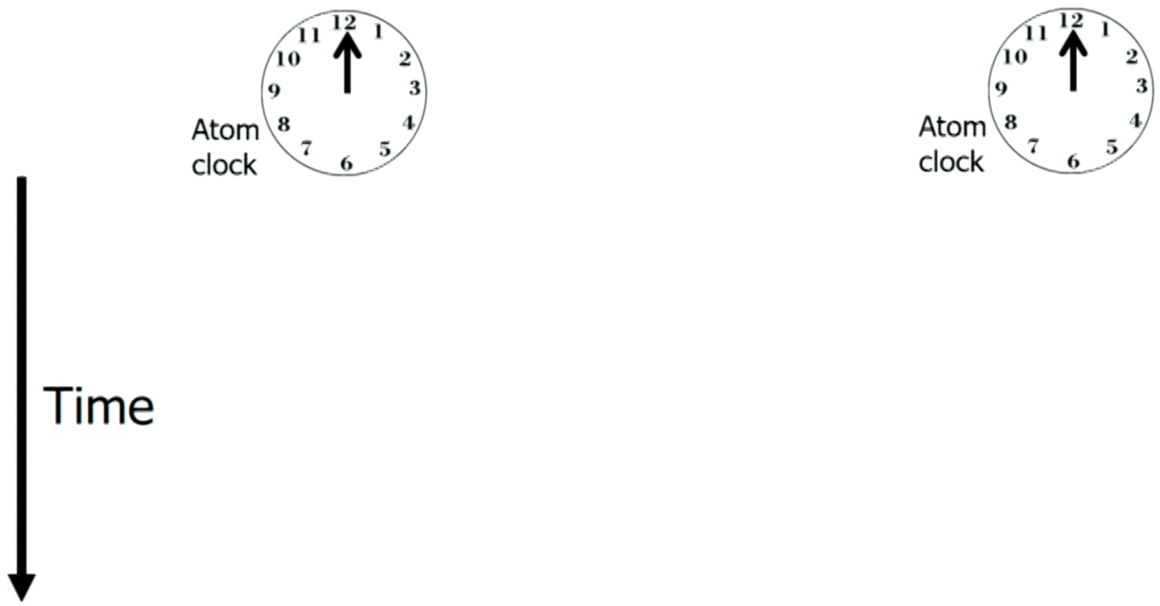
Simple Example: Two Atomic Clocks





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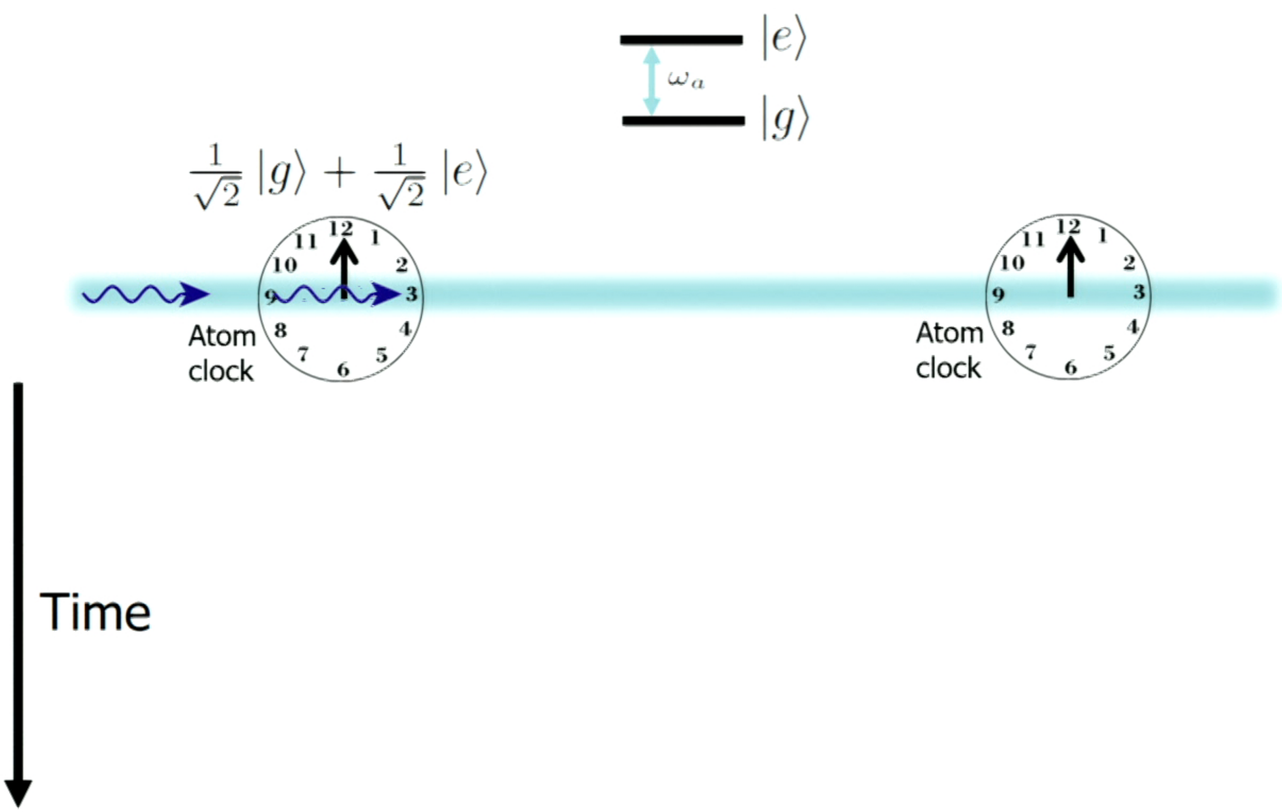

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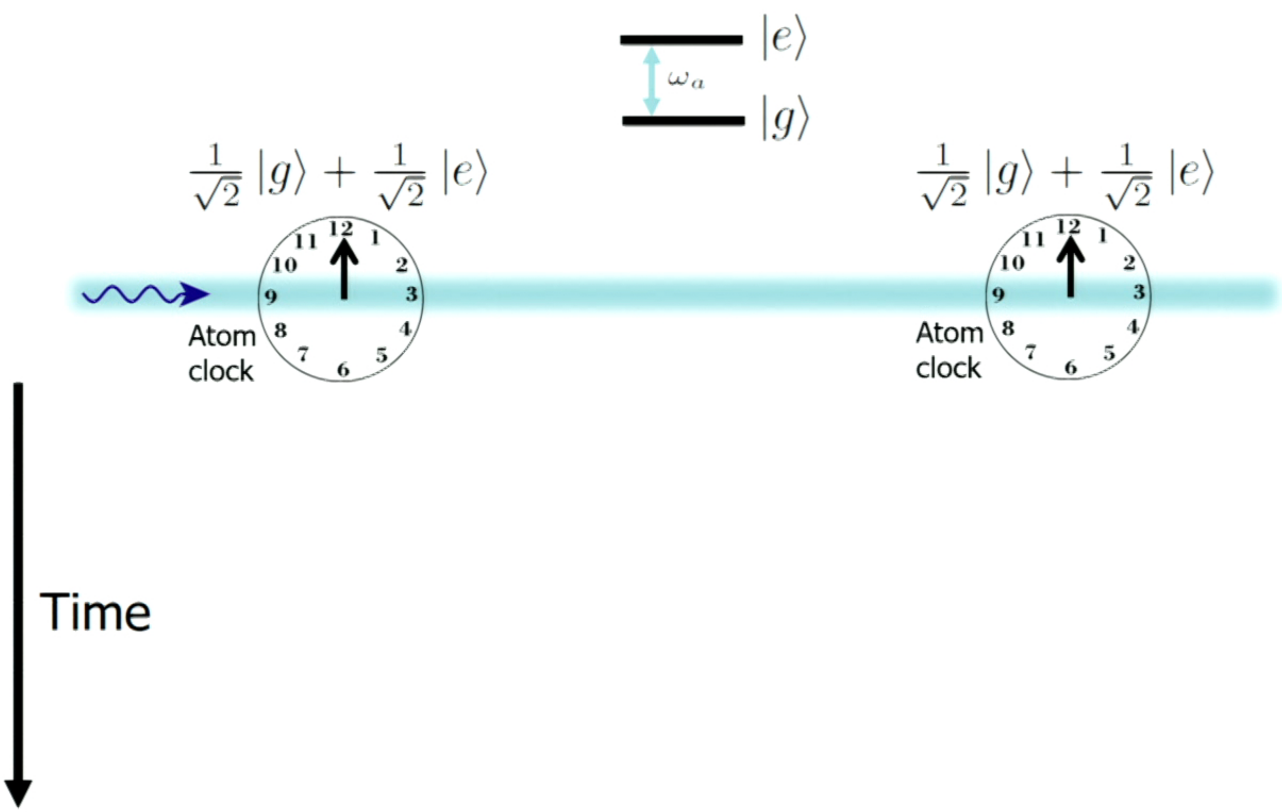

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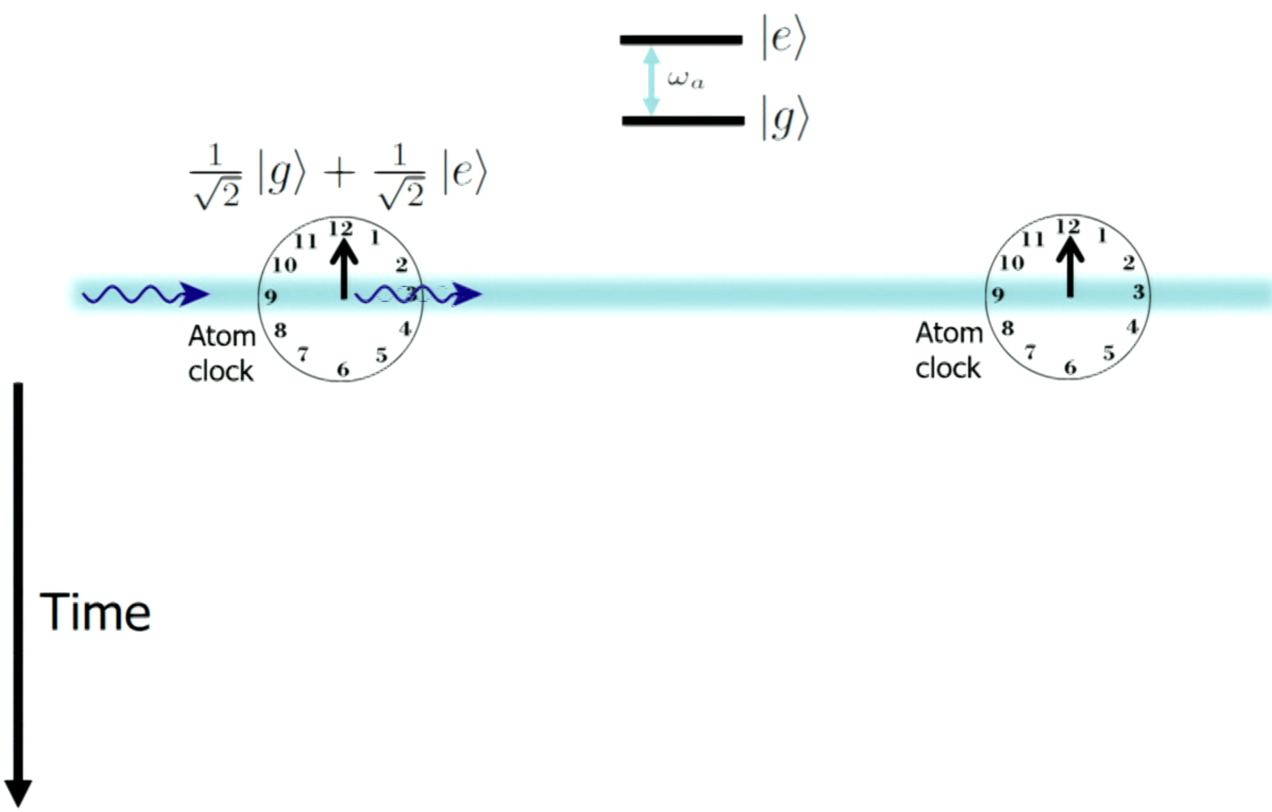

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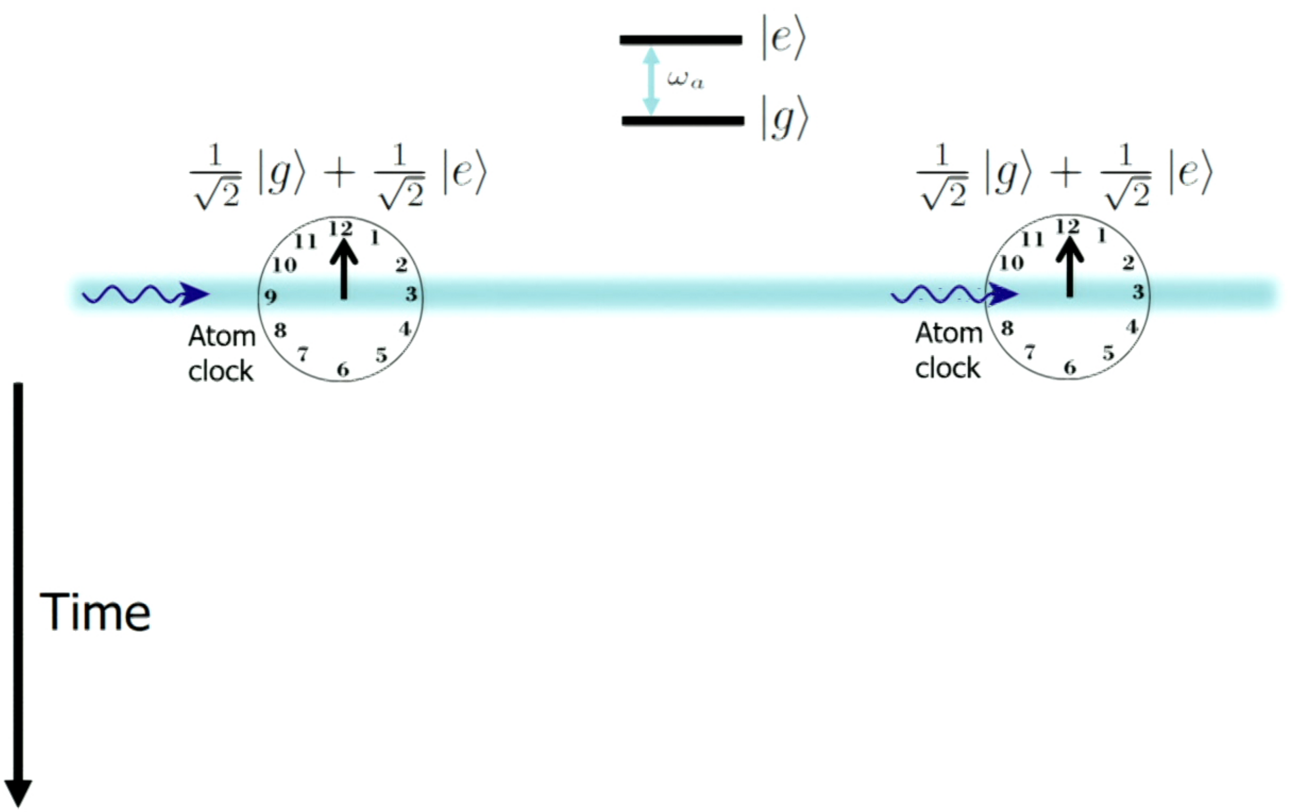

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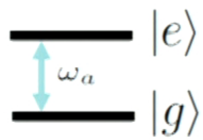
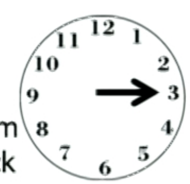


$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$ $\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

Time

Atom clock

Atom clock



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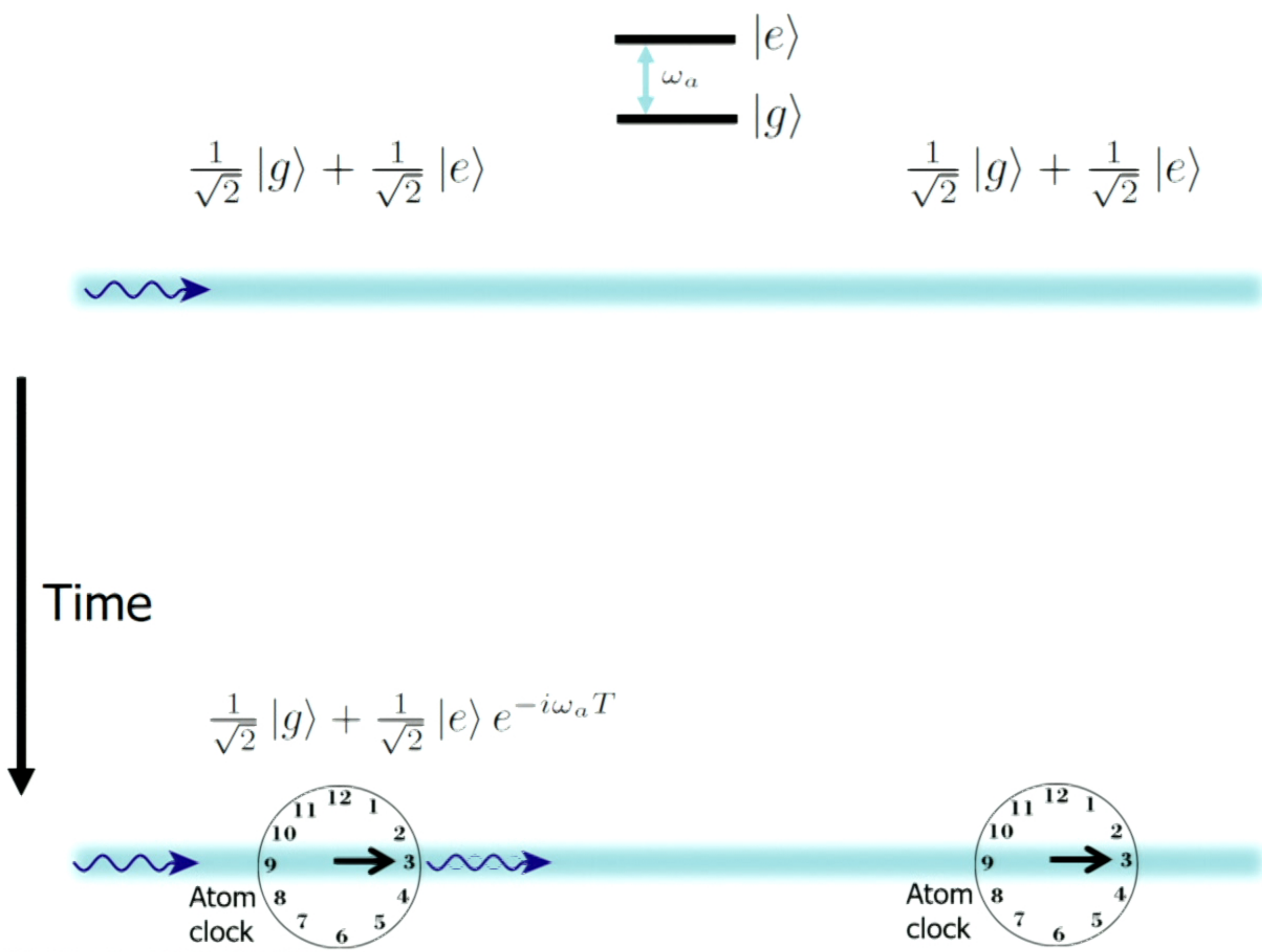

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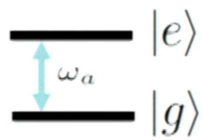

$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle \qquad\qquad \frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle$$

$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a T} \qquad\qquad \frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a T}$$

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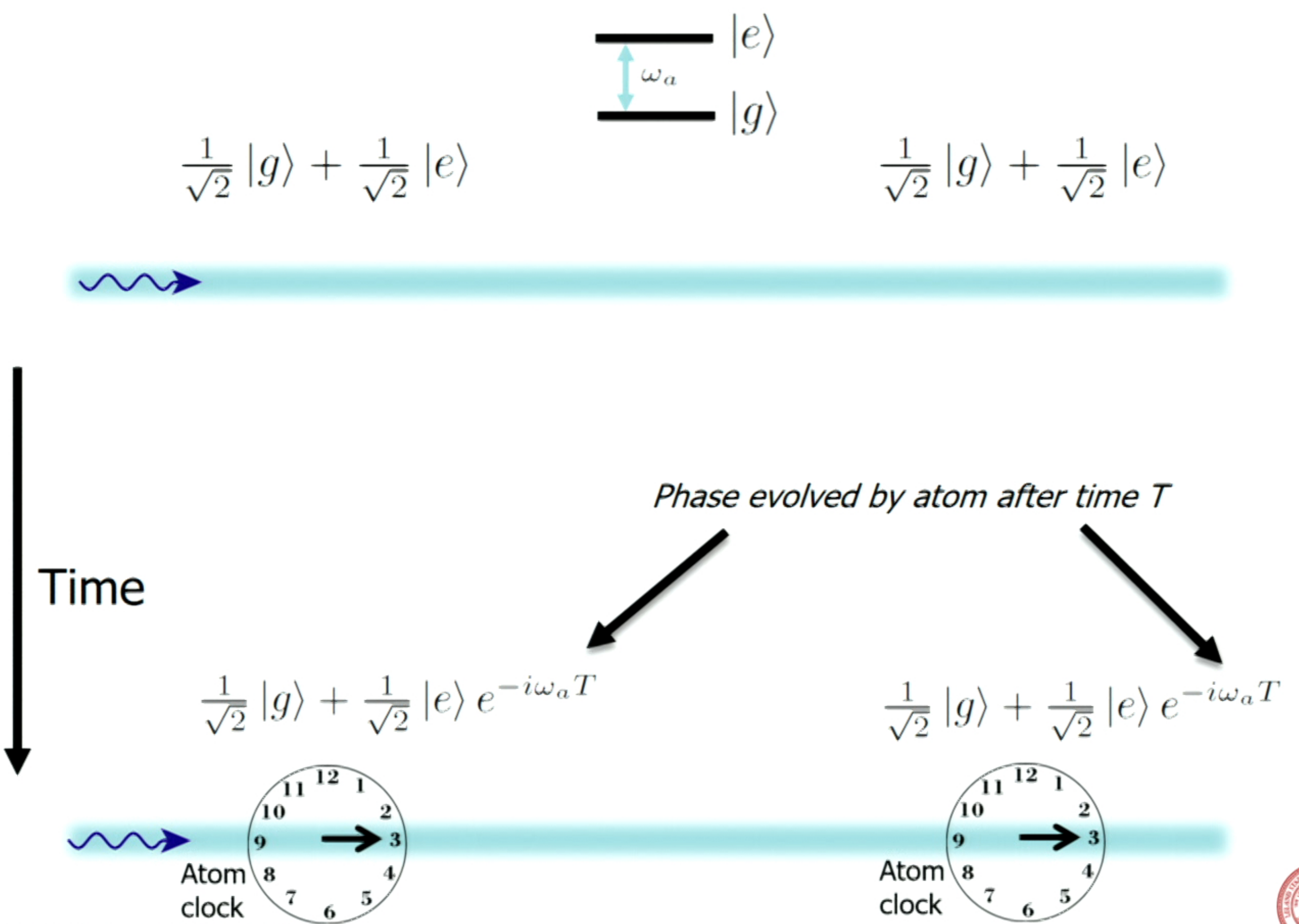
Simple Example: Two Atomic Clocks



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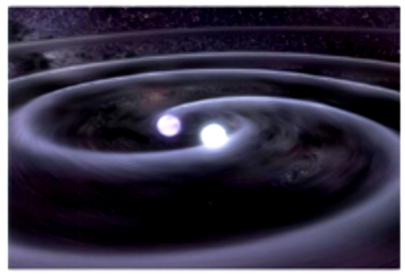
Simple Example: Two Atomic Clocks

$$|e\rangle$$
$$\omega_a$$
$$|g\rangle$$

$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle \qquad\qquad \frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle$$

Time



GW changes light travel time

$$\Delta T \sim hL/c$$

$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a T} \qquad\qquad \frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a (T+\Delta T)}$$

Atom clock

Atom clock

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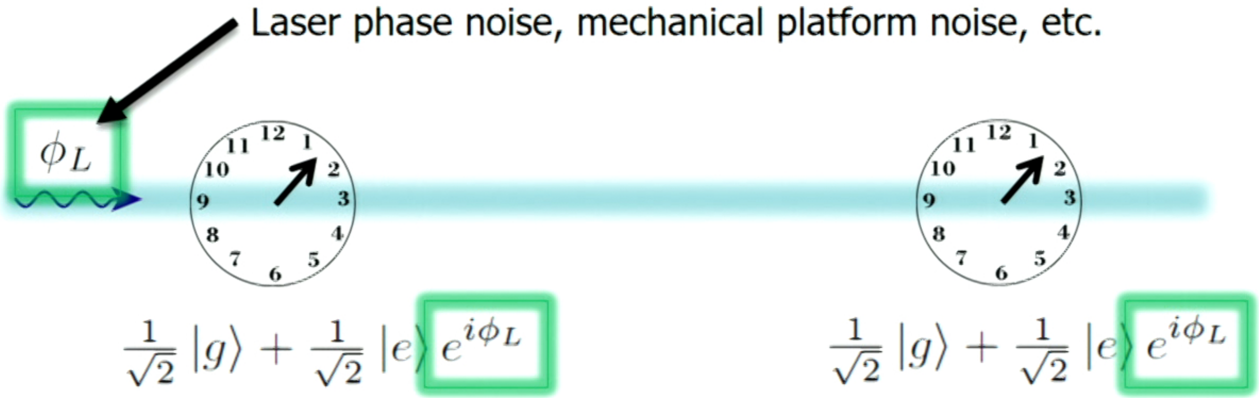
Phase Noise from the Laser

The phase of the laser is imprinted onto the atom.



*Laser phase is **common** to both atoms – rejected in a differential measurement.*

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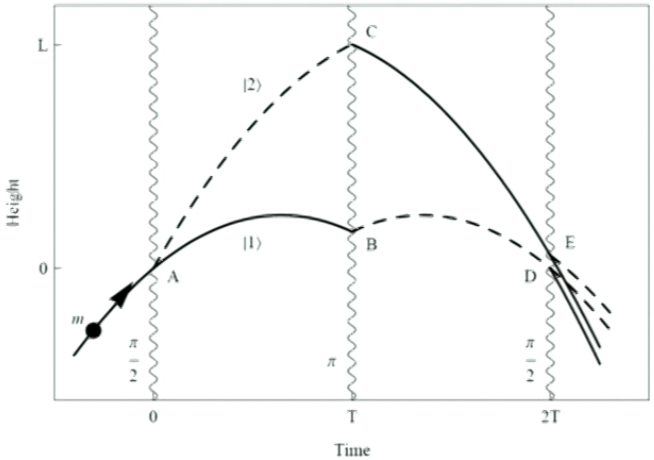
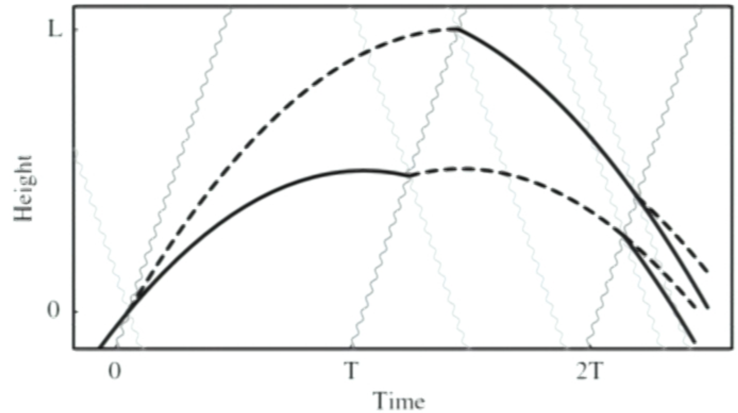
General relativistic analysis

Newtonian → GR

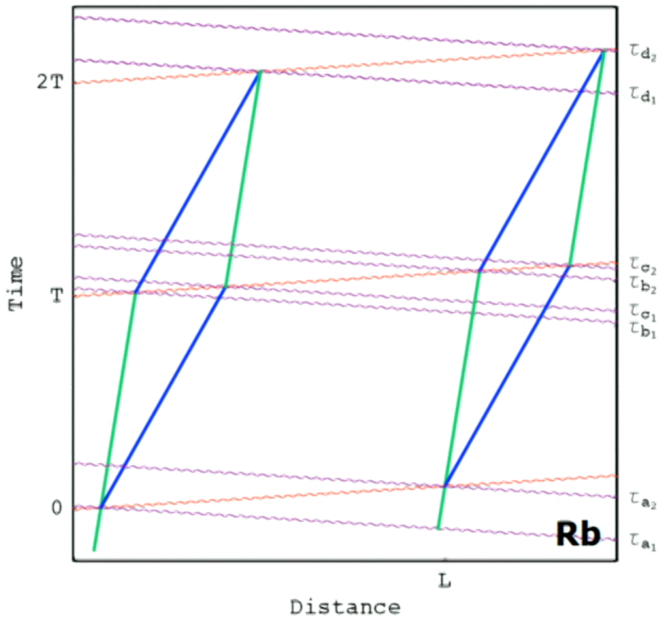




Finite speed of light!

Two-photon vs. single photon transitions

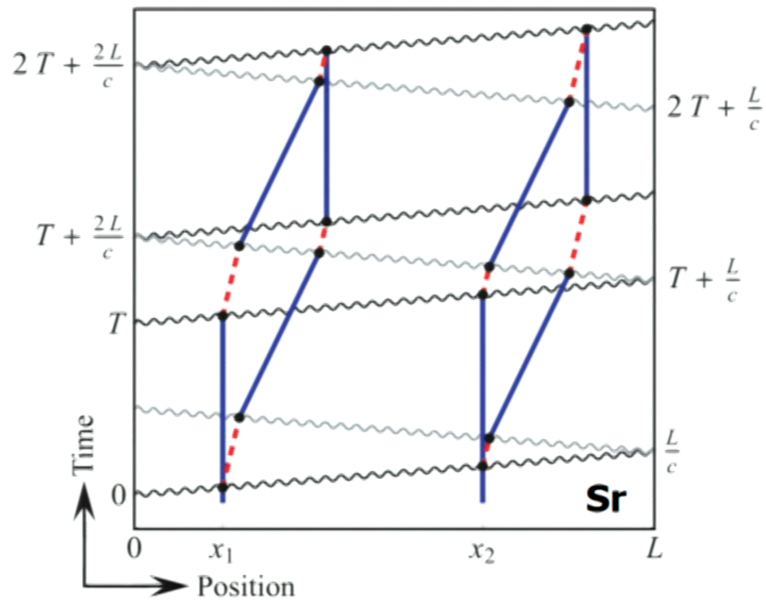
2-photon transitions



Signal from relative positions of atoms w.r.t. optical phase fronts.

$$\Delta\Phi = k_{\text{eff}} a T^2$$

1-photon transitions



Signal from light propagation time between atom ensembles.

$$\Delta\Phi = (\omega_A/c) a T^2$$

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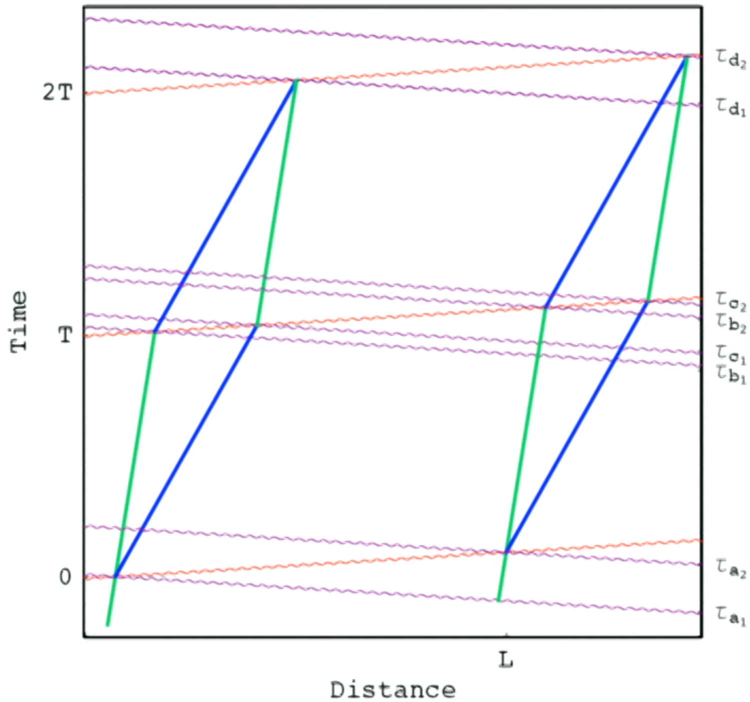
Graham et al., PRD 78, 042003, (2008).
Yu et al., GRG 43, 1943, (2011).

Two photon laser frequency noise



Consider a laser frequency error $\delta\omega$ that varies at the GW frequency

Phase error:

$$\delta\phi_L = \delta\omega\,\Delta t \sim \delta\omega\, L/c$$

GW Signal:

$$\Delta\Phi_{GW} \sim k\,\delta L \sim khL$$

$$\frac{\delta\omega}{\omega} \ll h \sim 10^{-20}$$

(and even harder with LMT)

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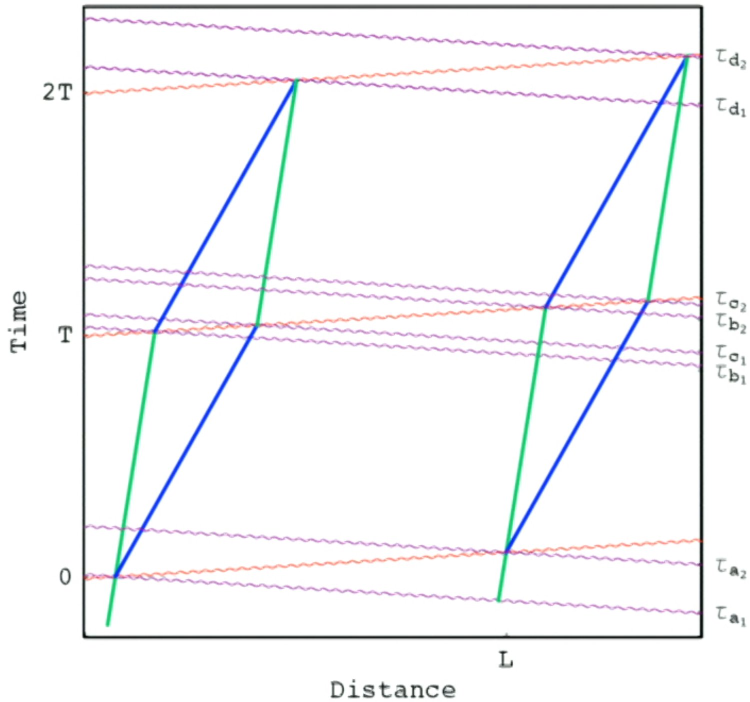
Two photon laser frequency noise



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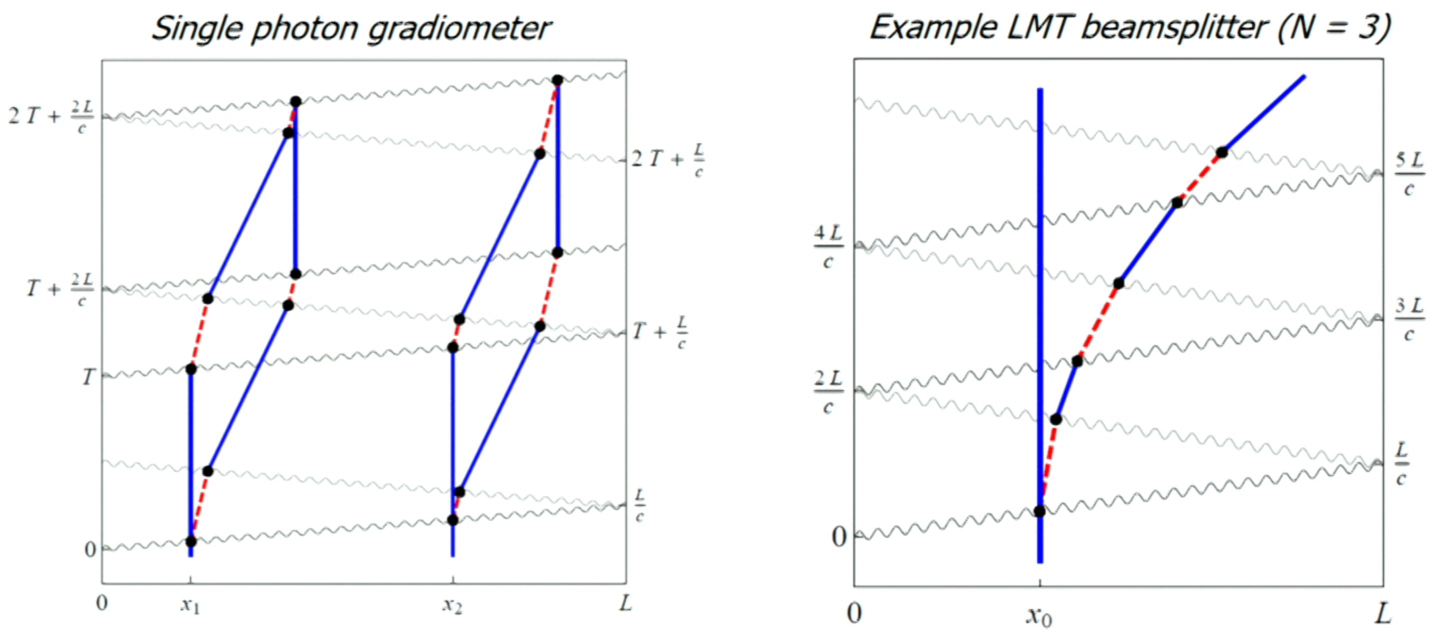
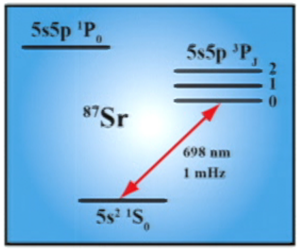
Clock gradiometer pulse sequence



AI with single photon transitions:

- Laser noise suppression using a single baseline
- LMT using pulses from alternating directions



Candidate transition

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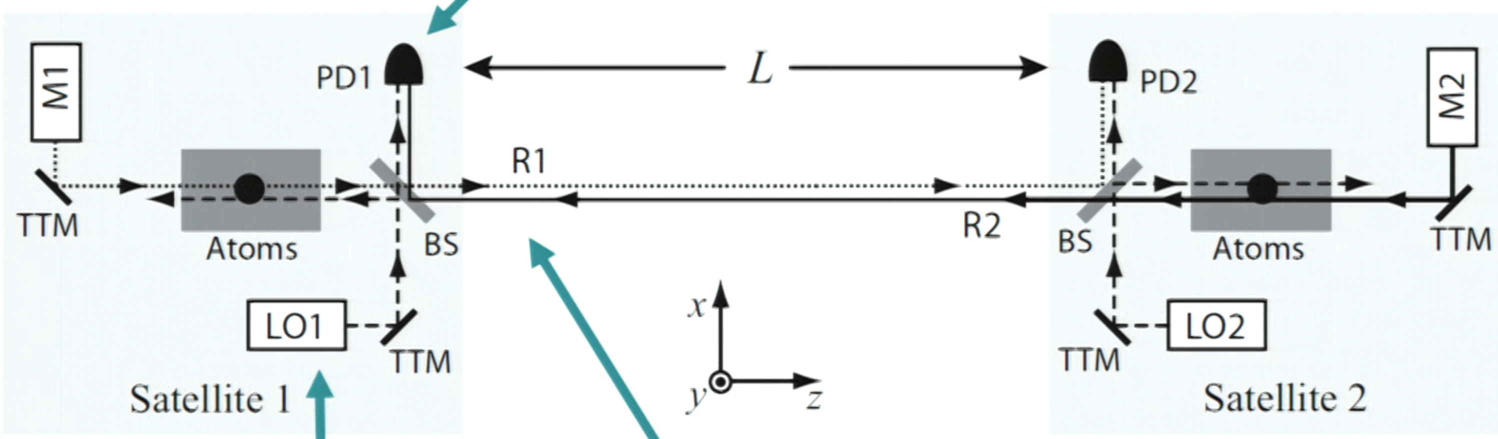
Heterodyne laser link for long baselines

Phase lock local laser to incoming reference



Reference laser can be weak (long baseline)

Strong local oscillator laser drives atomic transition

Maintains immunity to laser noise and spacecraft motion

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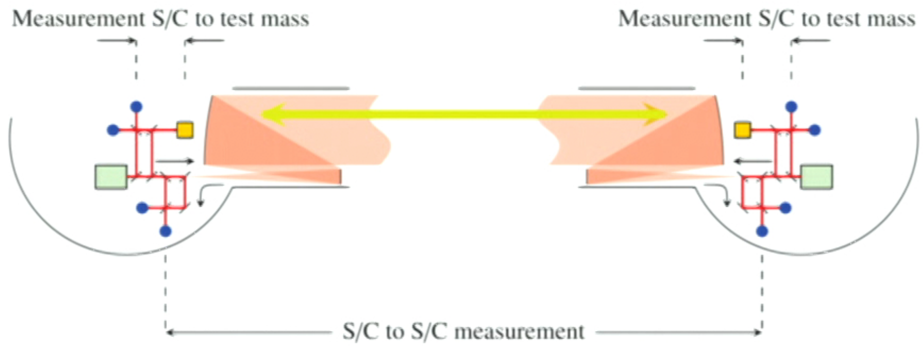
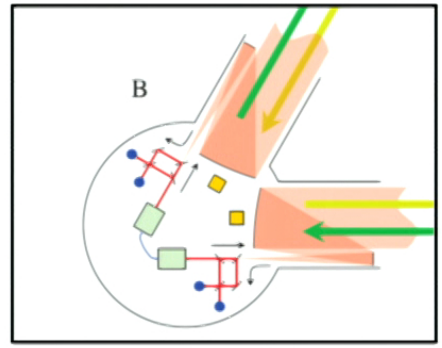
JH and M. Kasevich, PRA **94**, 033632 (2016)

Compare to LISA

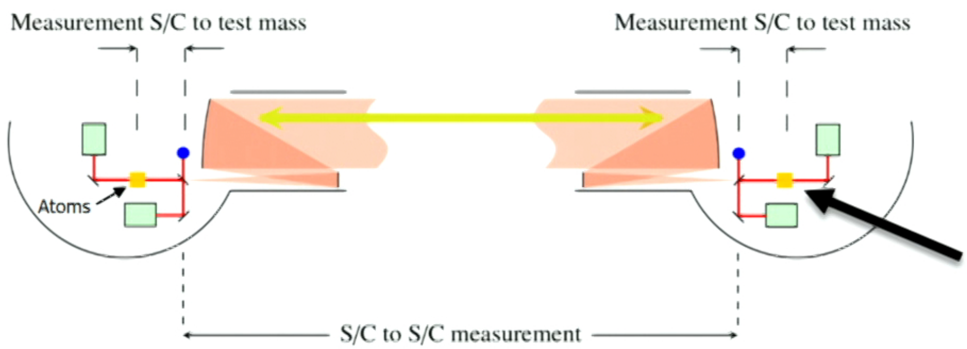
LISA:



Second baseline needed for phase reference:



Atom interferometer:



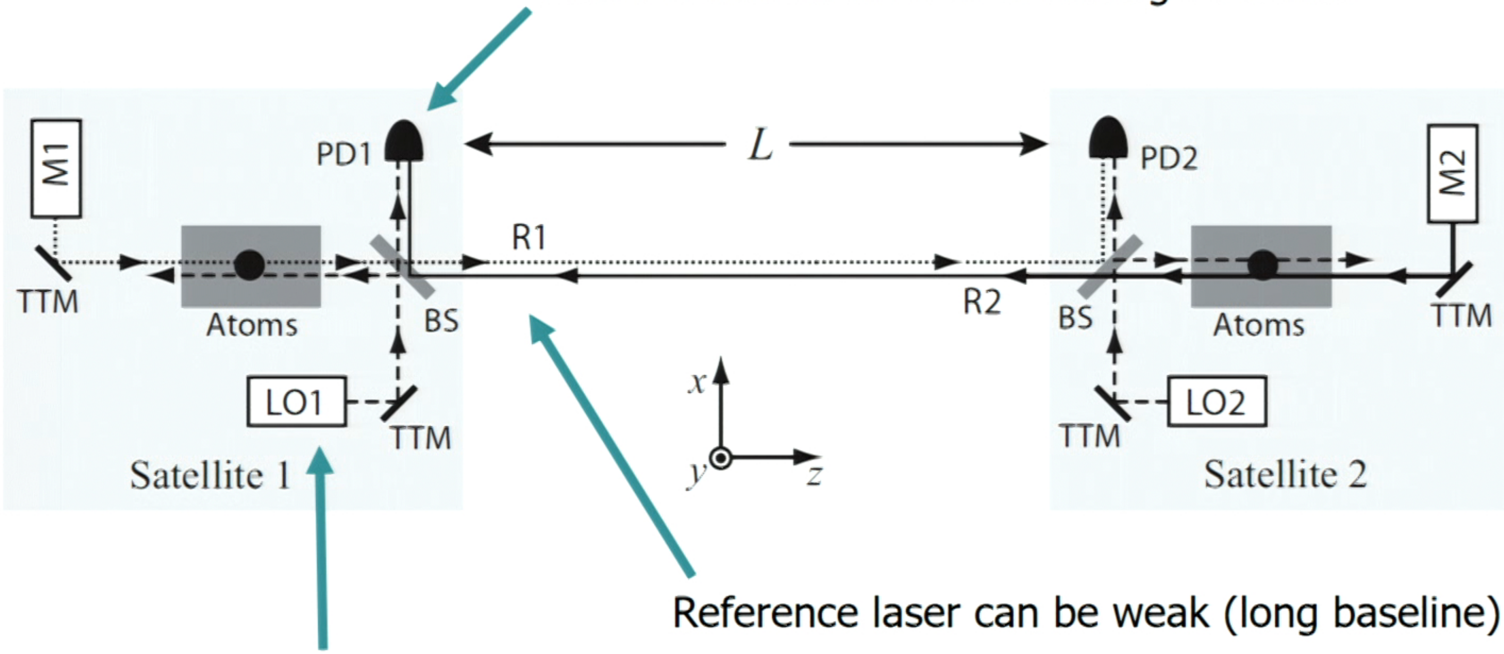
Atom test mass

- Records laser noise
- Acts as phase reference

(Figures adapted from LISA yellow book.)

Heterodyne laser link for long baselines

Phase lock local laser to incoming reference



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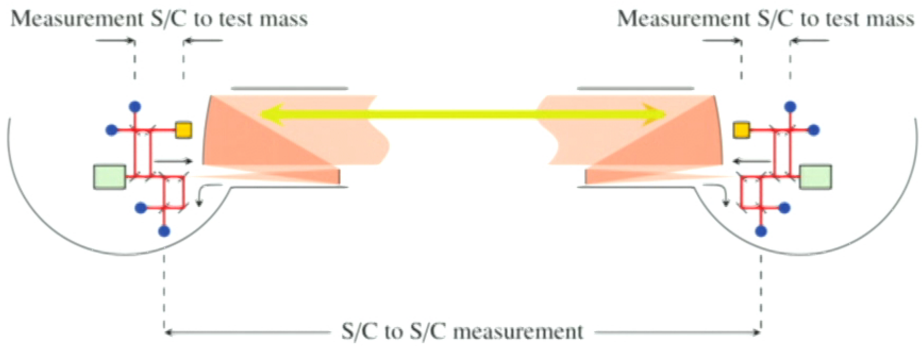
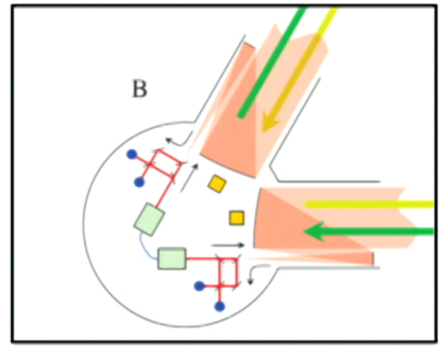
Compare to LISA

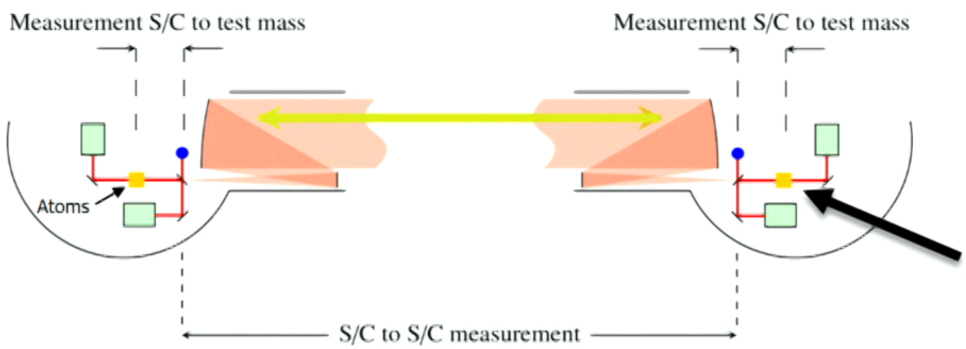
LISA:



Second baseline needed for phase reference:



Atom interferometer:



Atom test mass

- Records laser noise
- Acts as phase reference

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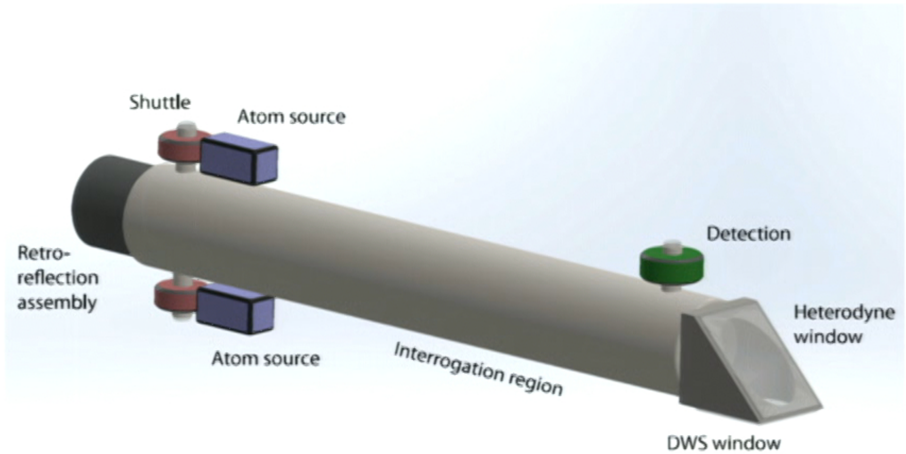
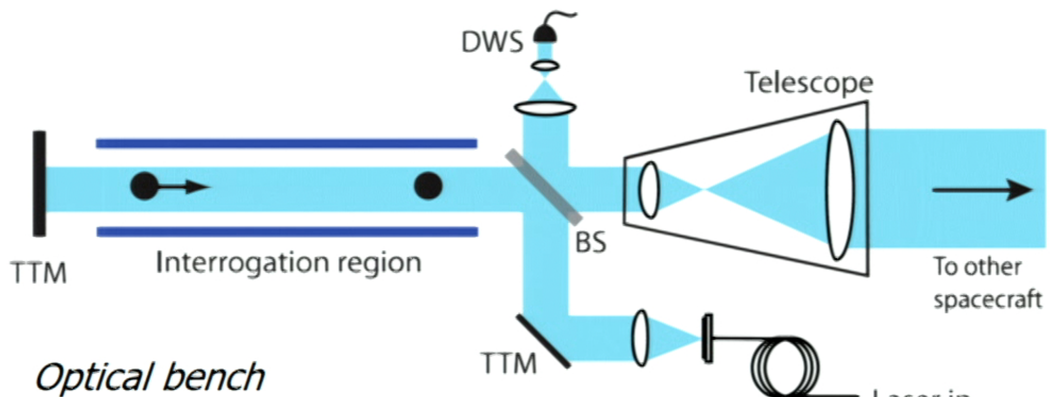
(Figures adapted from LISA yellow book.)

Conceptual Schematic of Instrument





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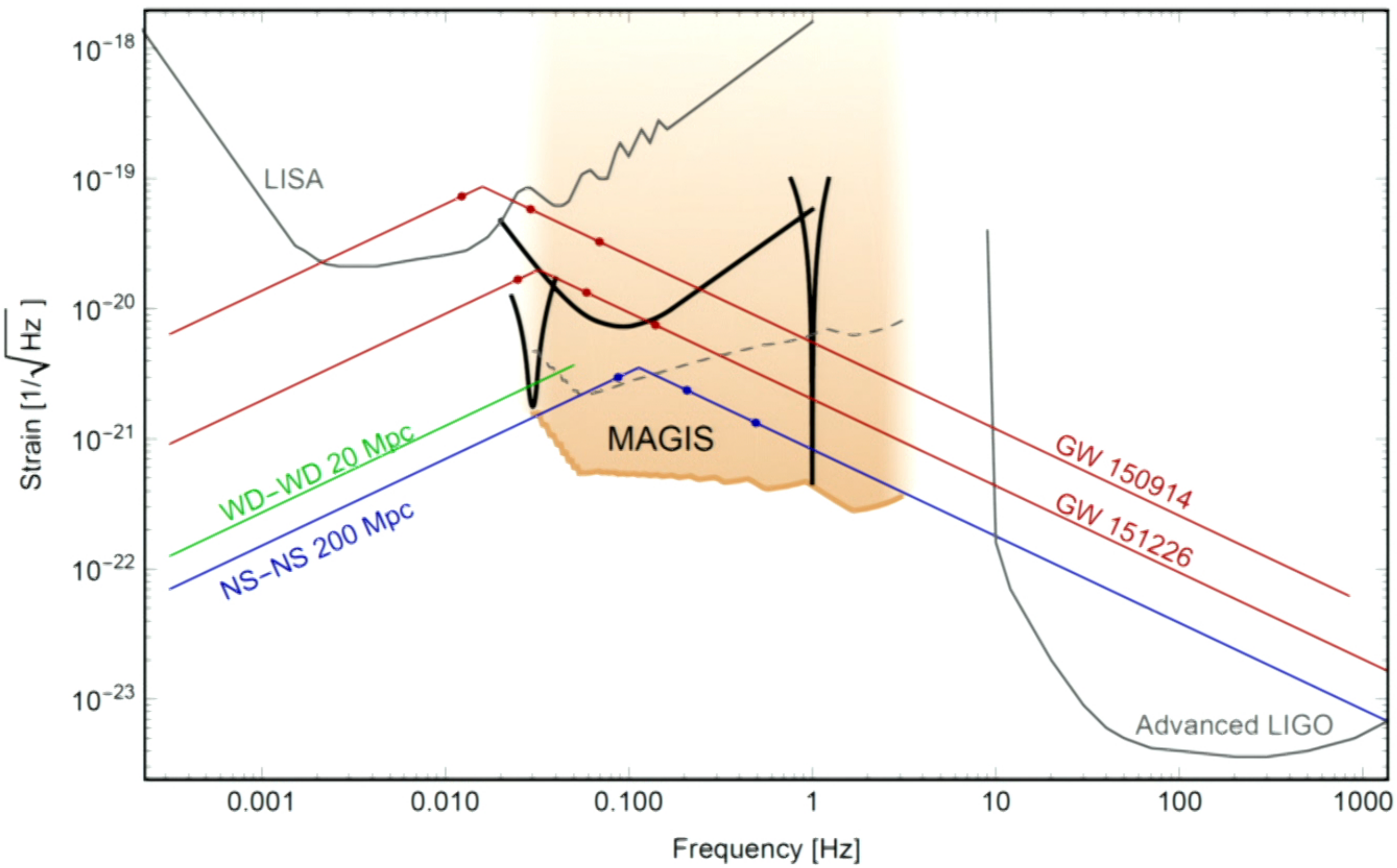
Proposed Atom GW Sensitivity



Dots indicate remaining lifetimes of 10 years, 1 year and 0.1 years

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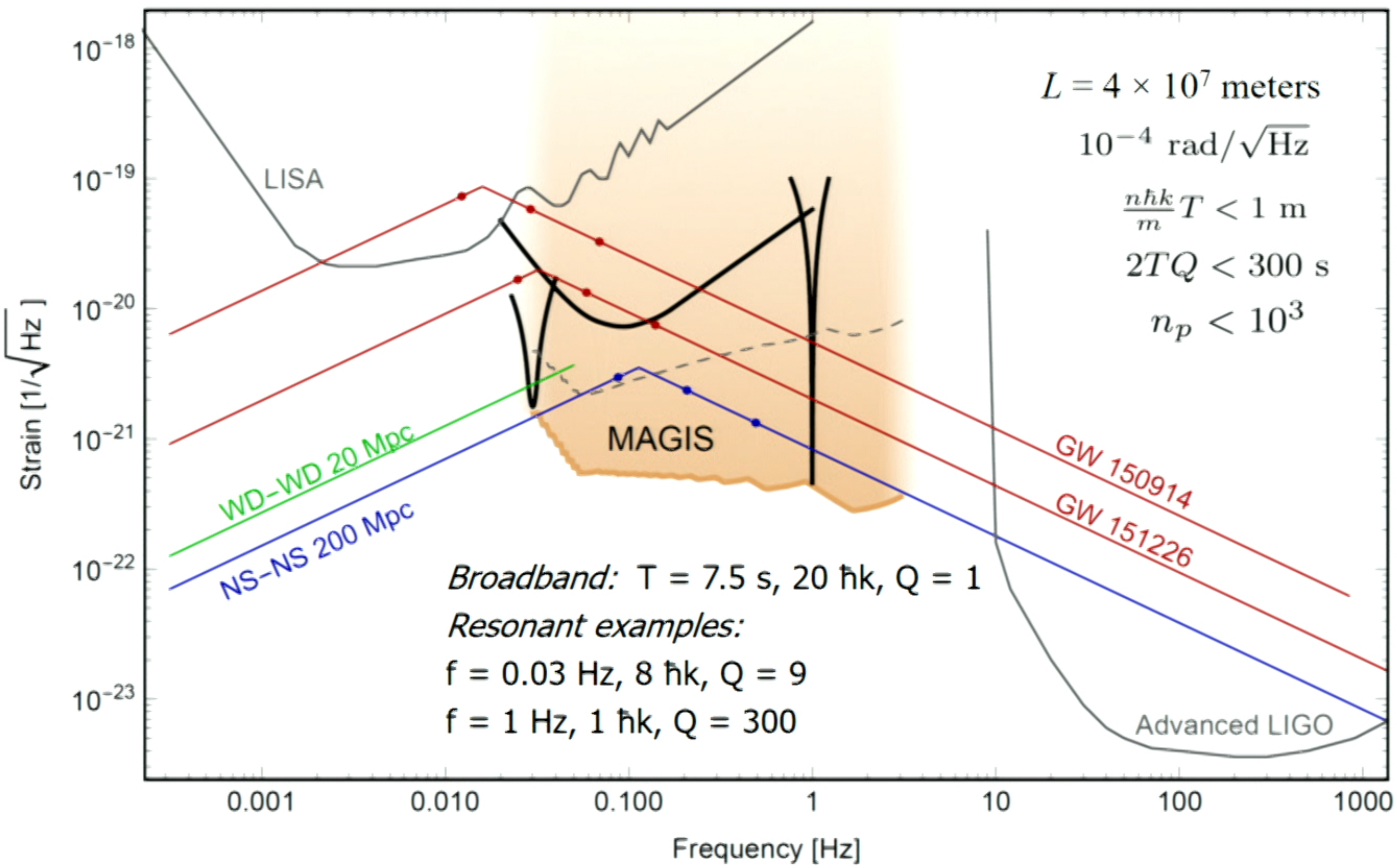
Proposed Atom GW Sensitivity



Dots indicate remaining lifetimes of 10 years, 1 year and 0.1 years

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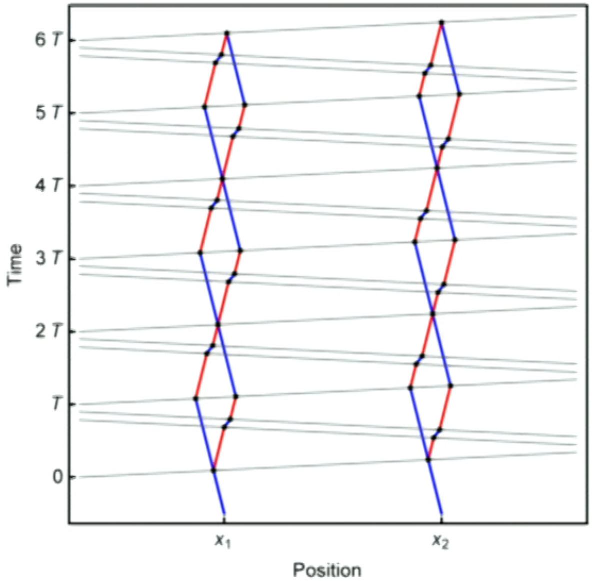
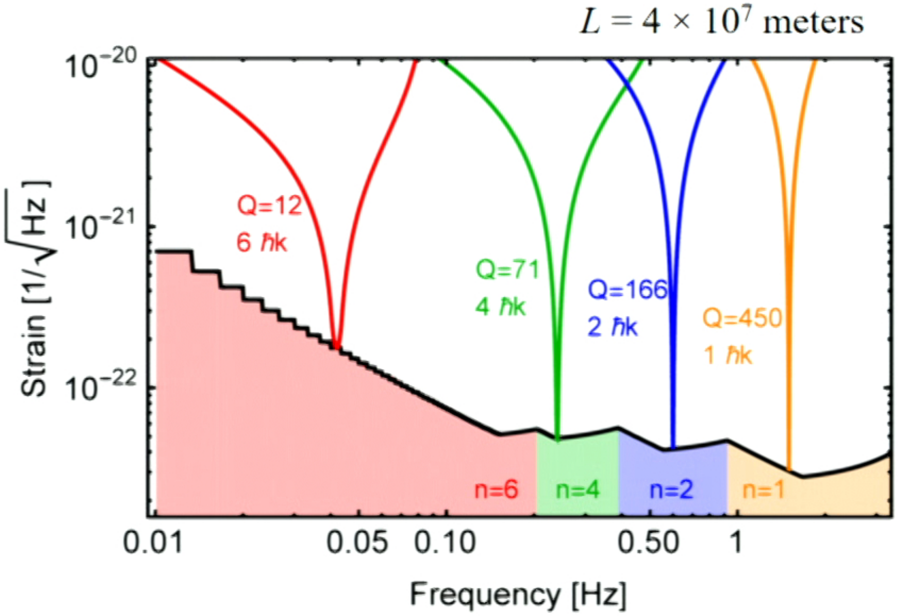
Resonant Detection Mode



Resonant interferometer sequences for enhanced, narrow band response



Optimized sensitivity near 1 Hz

Includes constraints on total pulses and source lifetime

Graham, *et al.*, PRD **94**, 104022 (2016)

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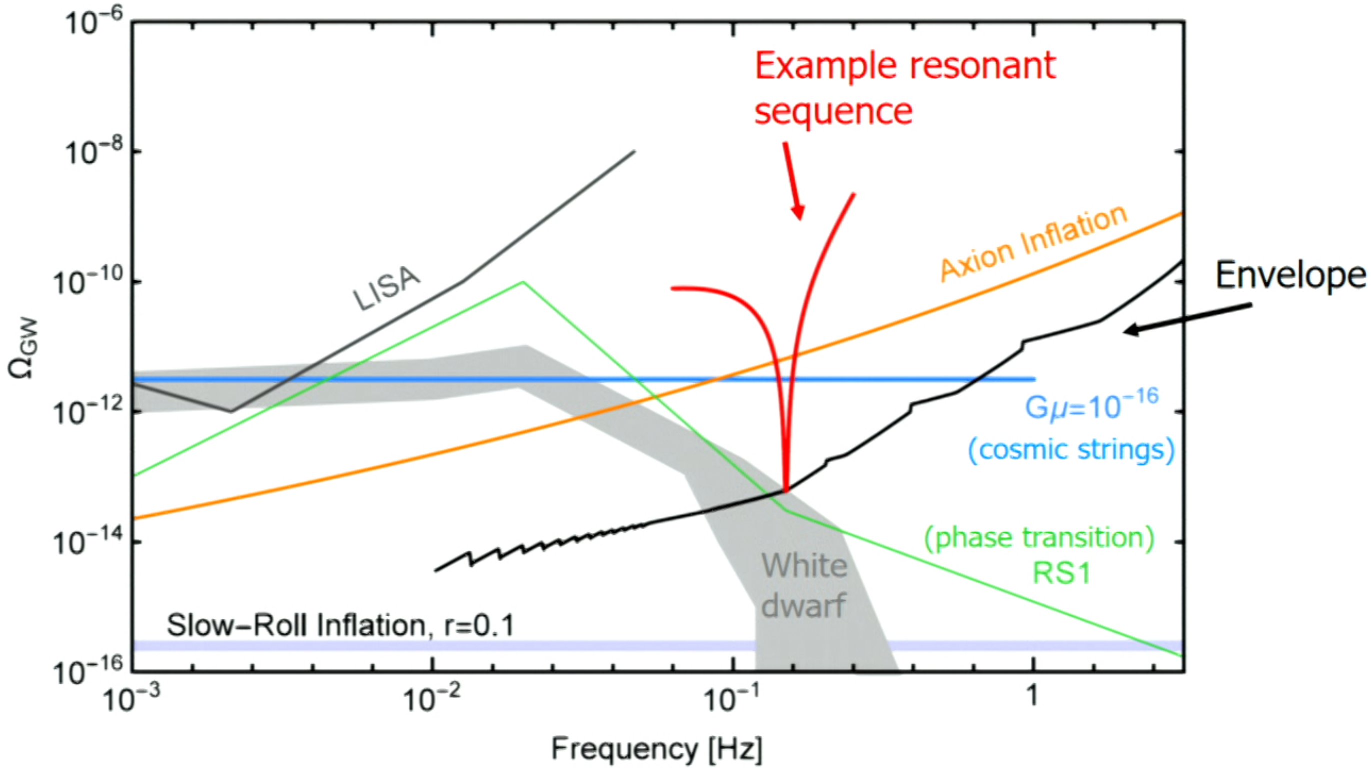
Bounds on stochastic GW sources



Narrow band sensitivity possible in 1 year

Graham, *et al.*, PRD **94**, 104022 (2016)

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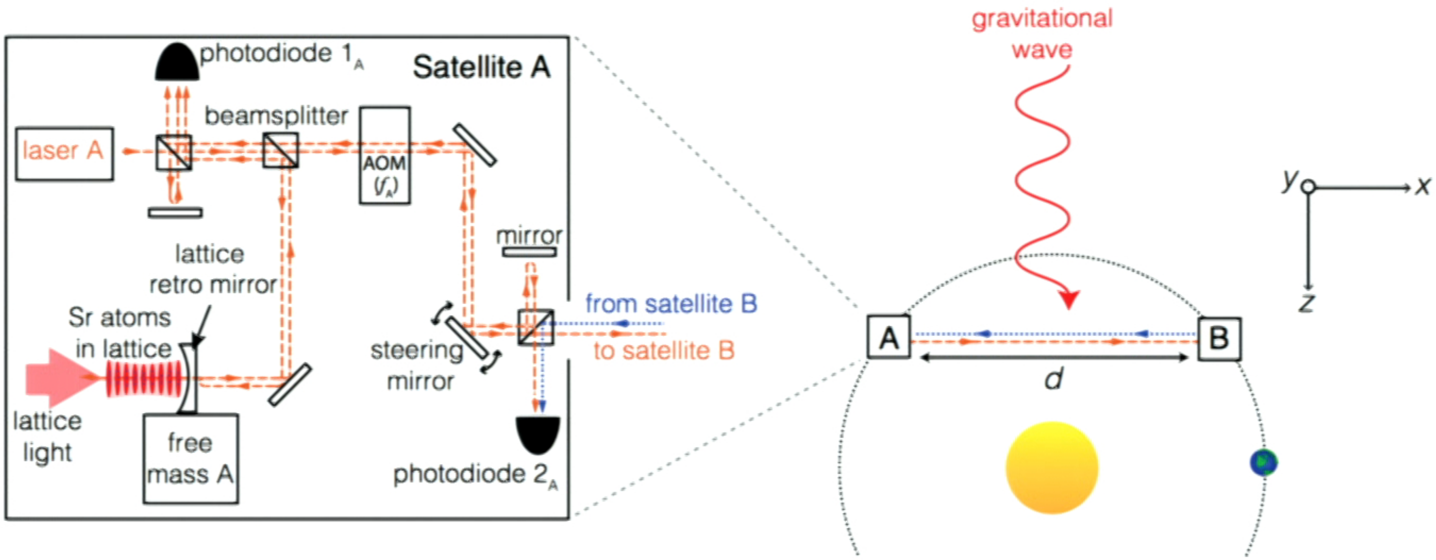
Lattice Clocks



- Optical lattice atomic clocks
- Resonant (dynamical decoupling)
- Drag-free satellites

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S. Kolkowitz, I. Pikovski, N. Langellier, M. D. Lukin, R. L. Walsworth, and J. Ye, Phys. Rev. D **94**, 124043 (2016)

Atomic clock vs Atom interferometer

Lattice clock

- Atoms rigidly confined in lattice
- No photon recoil, no wavepacket separation
- Requires separate inertial reference, drag free control

Atom interferometer

- Freely falling atoms provide inertial reference
- Reduced requirements on satellite drag control
- Recoil of atoms must be managed

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Single photon atom interferometry

Sr gradiometer demonstration experiment

Proof of concept experiment

- New tower with Sr atoms
- AI on the the clock transition
- Compare two Sr interferometers

Equivalent two-photon laser noise requirements:

$$\delta\phi_{\nu} = k_{\text{eff}} L \left(\delta\nu/\nu\right)$$

$$\delta\nu < 2\ \text{kHz}/\sqrt{\text{Hz}}$$

Target gravity gradiometer performance:

$$\delta T_{zz} = 0.1\ \text{E}/\sqrt{\text{Hz}}$$

$$L = 1\ \text{m}$$

$$T = 200\ \text{ms}$$

$$k_{\text{eff}} = 30k$$

$$\delta\phi = 1\ \text{mrad}/\sqrt{\text{Hz}}$$

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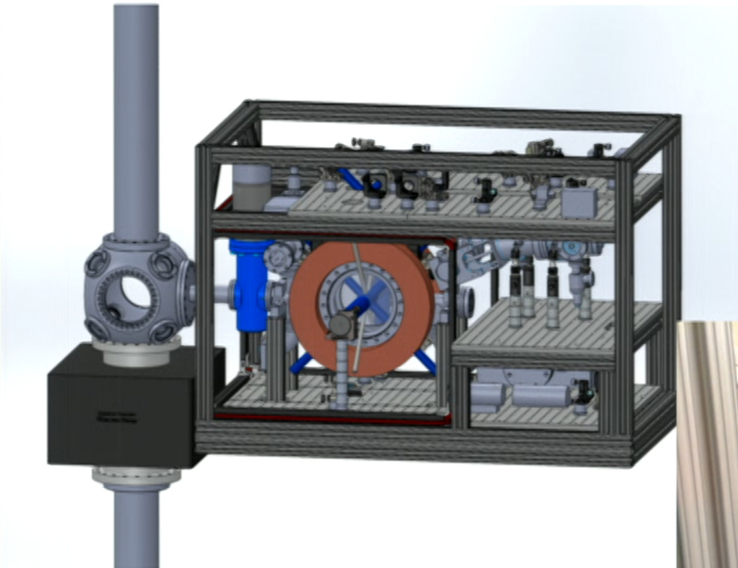
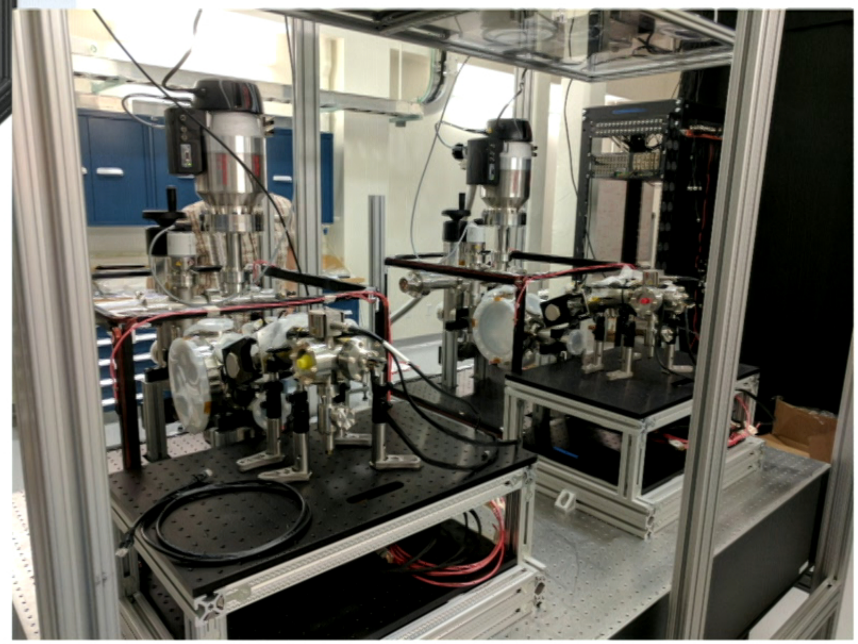
Sr gradiometer apparatus



Sr gradiometer CAD (atom source detail)

Two assembled Sr atom sources



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Ultralight scalar dark matter

- Ultralight dilaton DM acts as a background field (high occupation number)
- Can cause small (but coherent) oscillations in Standard Model parameters

$$\mathcal{L} = +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \sqrt{4\pi G_N}\phi\left[d_{m_e}m_e\bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right] + \ldots$$

DM scalar field

Electron coupling

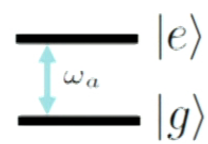
Photon coupling

e.g., QCD

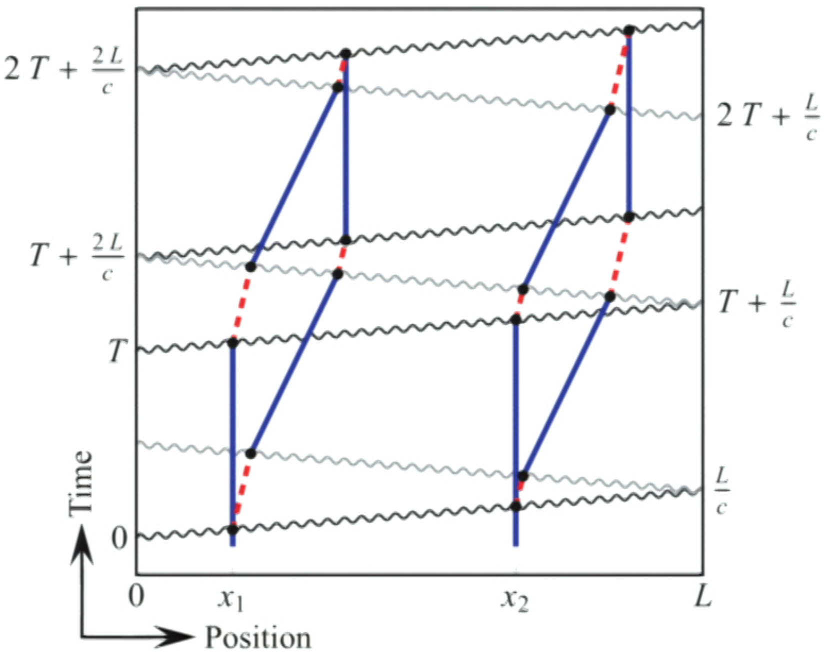
$$\phi\left(t,\mathbf{x}\right) = \phi_0\cos\left[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right) \qquad \phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$

DM coupling causes time-varying atomic energy levels:

$$\omega_{\mathrm{A}}(t) \simeq \omega_{\mathrm{A}} + \Delta\omega_{\mathrm{A}}\cos(m_\phi t);$$
$$\Delta\omega_{\mathrm{A}} \equiv \omega_{\mathrm{A}}\sqrt{4\pi G_N}\phi_0\left(d_{m_e} + \xi d_e\right)$$

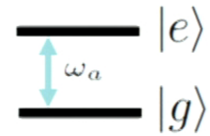


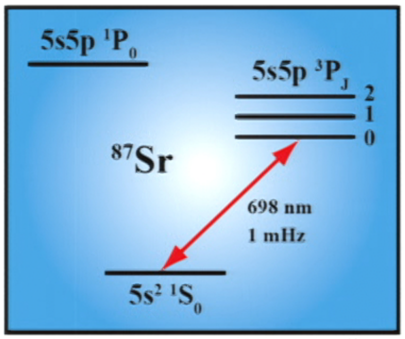
Differential atomic clock



Excited state phase evolution:

$$\Delta\phi \sim \omega_A \left(2L/c\right)$$





Clock transition in candidate atom ^{87}Sr

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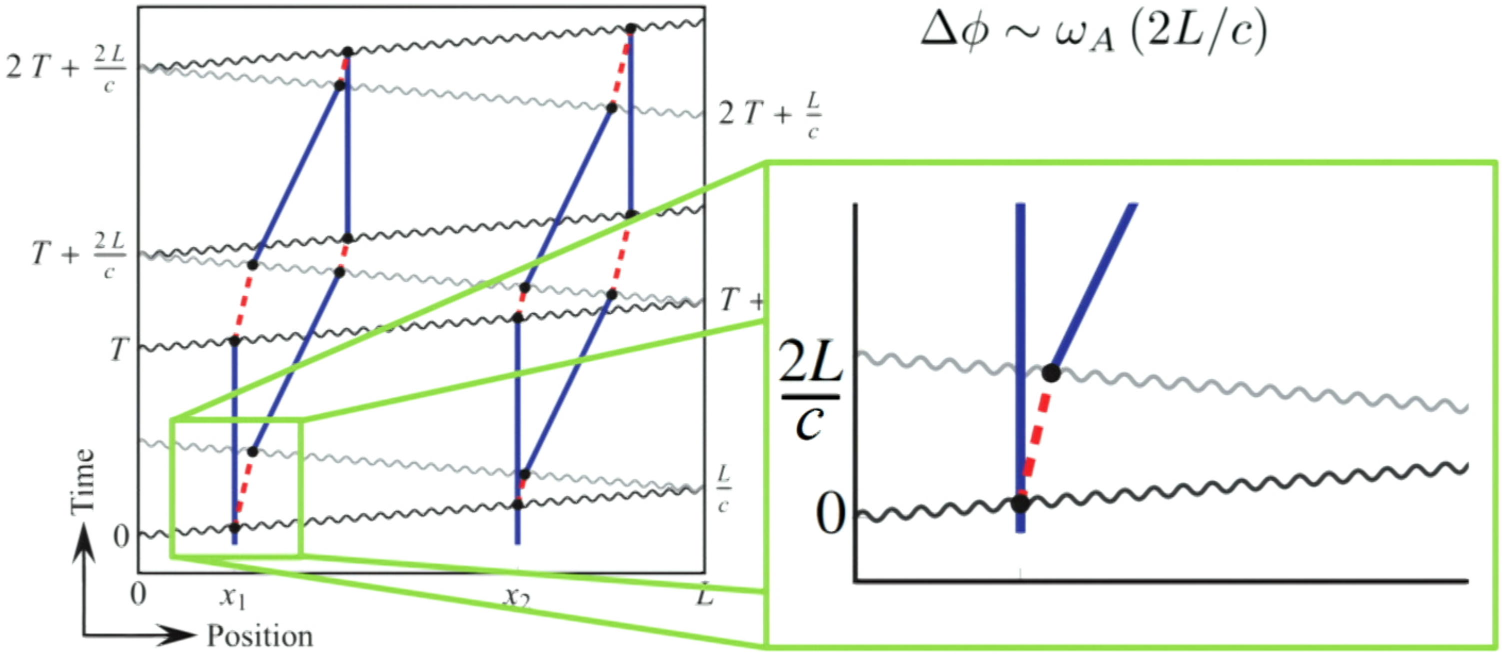
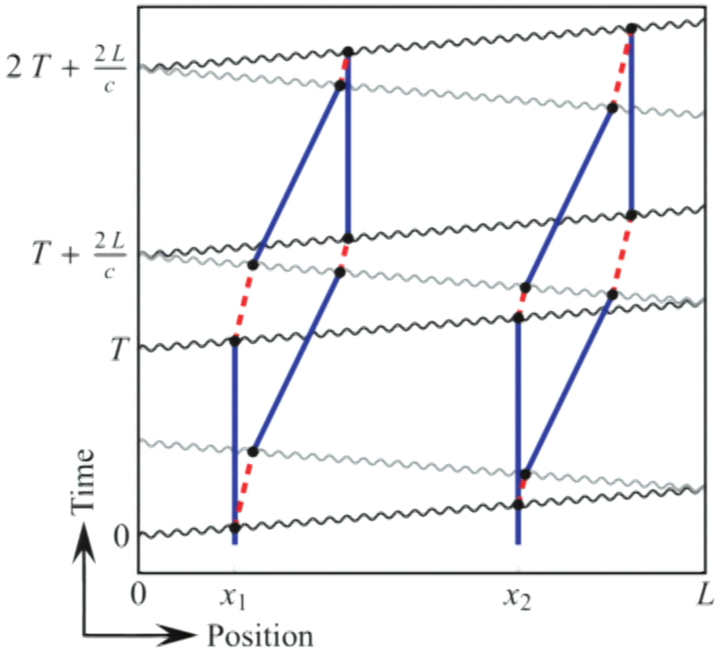
Differential atomic clock



Excited state phase evolution:

$$\Delta\phi \sim \omega_A\,(2L/c)$$

Differential atomic clock



Excited state phase evolution:

$$\Delta\phi \sim \omega_A \, (2L/c)$$

Two ways for phase to vary:

$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

Each interferometer measures the change over time T

Laser noise is common-mode suppressed in the gradiometer

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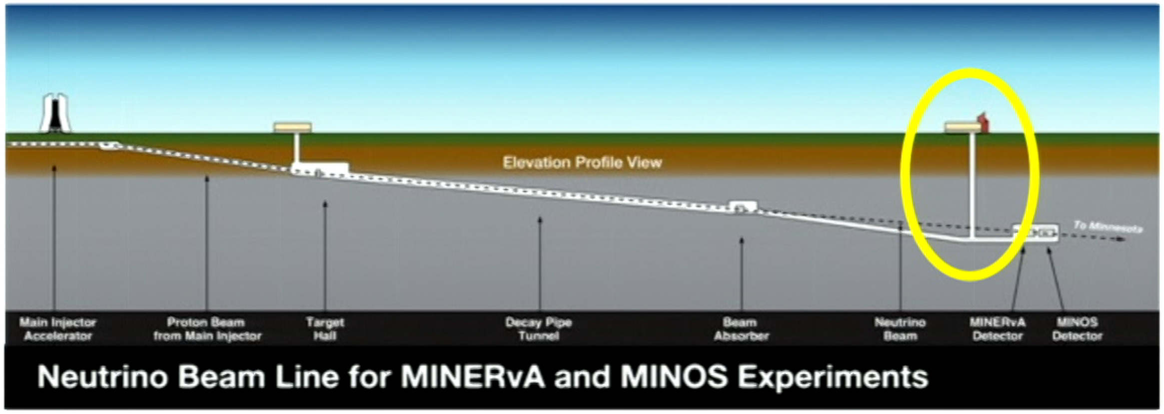
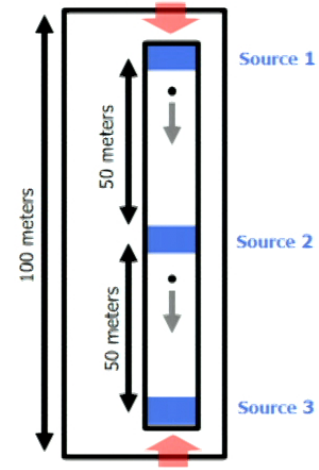
Proposal: MAGIS-100 detector at Fermilab





- MINOS, MINERvA and NOvA experiments use the NuMI beam
- 100 meter access shaft – 100 meter AI
- Intermediate step to full-scale detector for GWs

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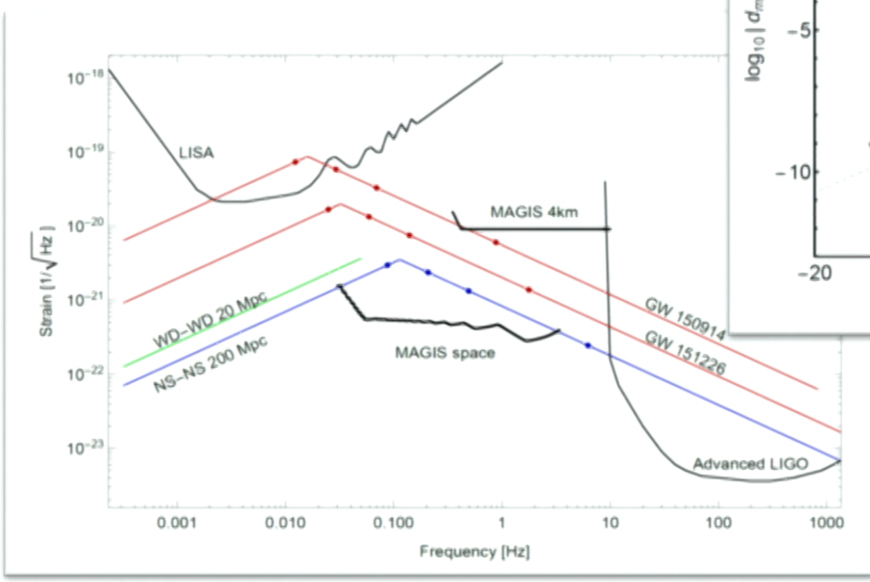
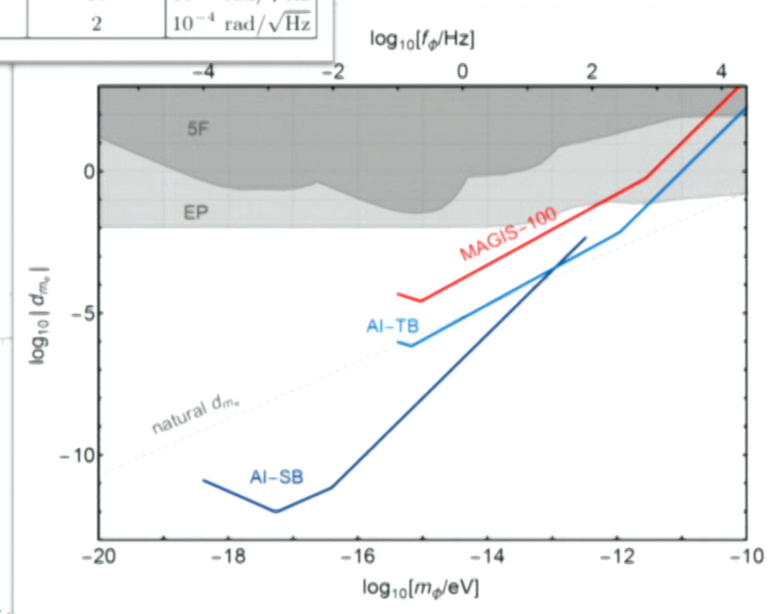
Estimated Sensitivity

Configuration	Proposed Site	Baseline L	LMT Atom optics N	Atom sources	Phase noise $\delta\phi$
MAGIS-100	FermiLab, NuMI shaft	100 m	10^2	3	10^{-4} rad/$\sqrt{\text{Hz}}$
Terrestrial	Homestake mine	$\approx$ 4 km	$\approx 10^4$	10	10^{-5} rad/$\sqrt{\text{Hz}}$
Satellite	Medium Earth orbit (MEO)	4×10^7 m	10^3	2	10^{-4} rad/$\sqrt{\text{Hz}}$

GW strain sensitivity





DM sensitivity (coupling to electron mass)

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Collaborators

Sr Atom Interferometry

TJ Wilkason
Hunter Swan
Jan Rudolph
Benjamin Spar
Connor Holland

Rb Atom Interferometry

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Tim Kovachy
Chris Overstreet
Peter Asenbaum
Daniel Brown

Theory:

Peter Graham
Savas Dimopoulos
Surjeet Rajendran
Asimina Arvanitaki
Ken Van Tilburg

Thanks to:

Joseph Lykken (Fermilab)
Swapan Chattopadhyay (Fermilab/NIU)
Jeremiah Mitchell (Fermilab)
Roni Harnik (Fermilab)
Robert Plunkett (Fermilab)
Juan Estrada (Fermilab)

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