Gravitational Wave Detection with Atom Interferometry

Surjeet Rajendran, MIT

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with

Savas Dimopoulos,
Peter Graham,
Jason Hogan,
Mark Kasevich

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arXiv:0806.2125

Gravity Waves: An Introduction

Gravity waves are to General Relativity what light is to electromagnetism.

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Many interesting astrophysical sources like black holes, neutron stars etc.

Probe the earliest epochs of the Universe.

Can see cosmic strings, phase transitions, radion fluctuations...

Outline

1. Gravitational Wave detection
2. Atom Interferometry
3. Terrestrial Experiment (1 Hz - 10 Hz)
4. Satellite Setup (10^{-2} Hz - 1 Hz)
5. Sensitivities

Gravity Wave Detection

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

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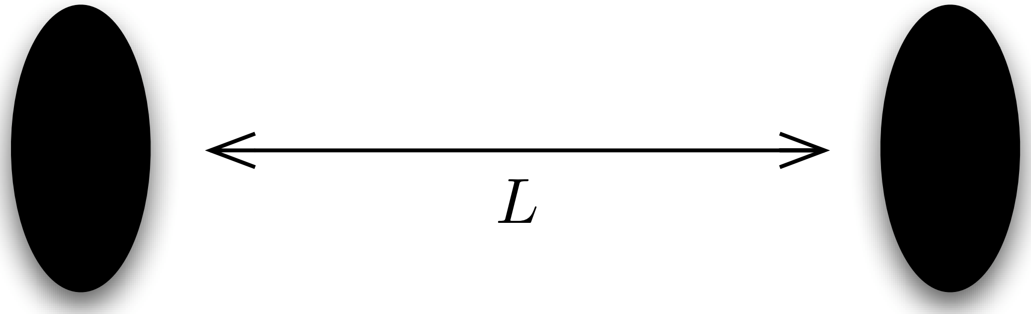
Consider two objects separated by L



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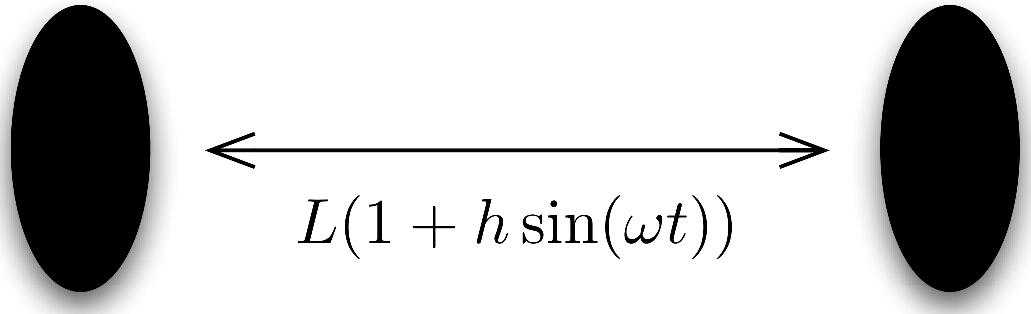

$L(1 + h\sin(\omega t))$

The distance between them oscillates with amplitude hL and frequency ω when $\omega L \ll 1$

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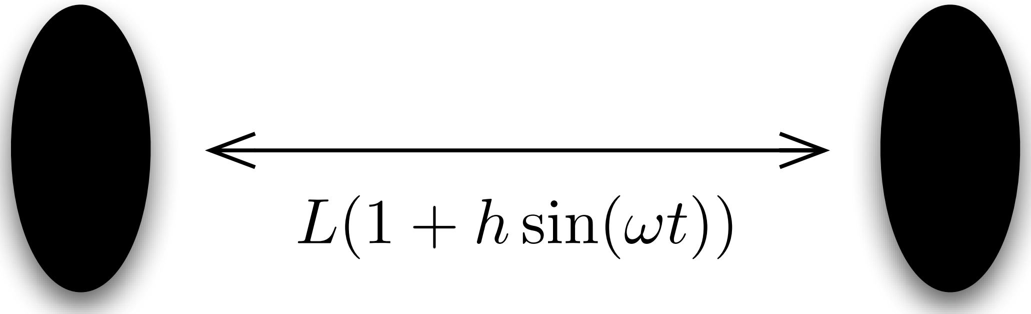

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The gravity wave can be detected if this oscillation is observed

The Technical Challenge

- Brightest source of gravity waves gives $h \sim 10^{-20}$
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- Brightest source of gravity waves gives $h \sim 10^{-20}$
- With L ~ 1 km, need to measure length changes $hL \sim 10^{-17}\mathrm{m}$
- Need to ensure that the distance between the objects changes only due to gravity wave i.e. vibrational noise needs to be smaller than hL in the frequency band of interest.

LIGO

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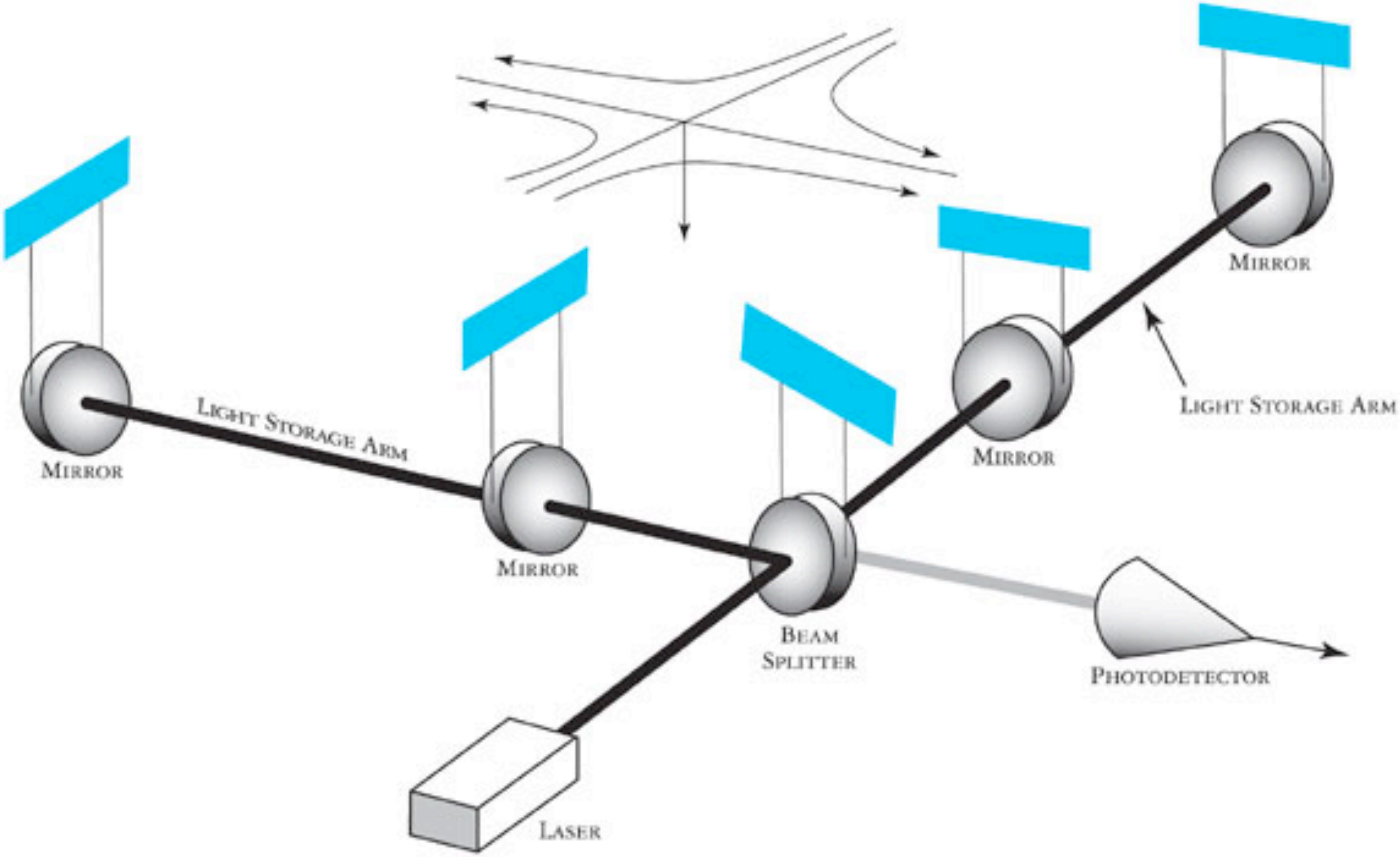
Mirror
Light Storage Arm
Mirror
Beam
Splitter
Mirror
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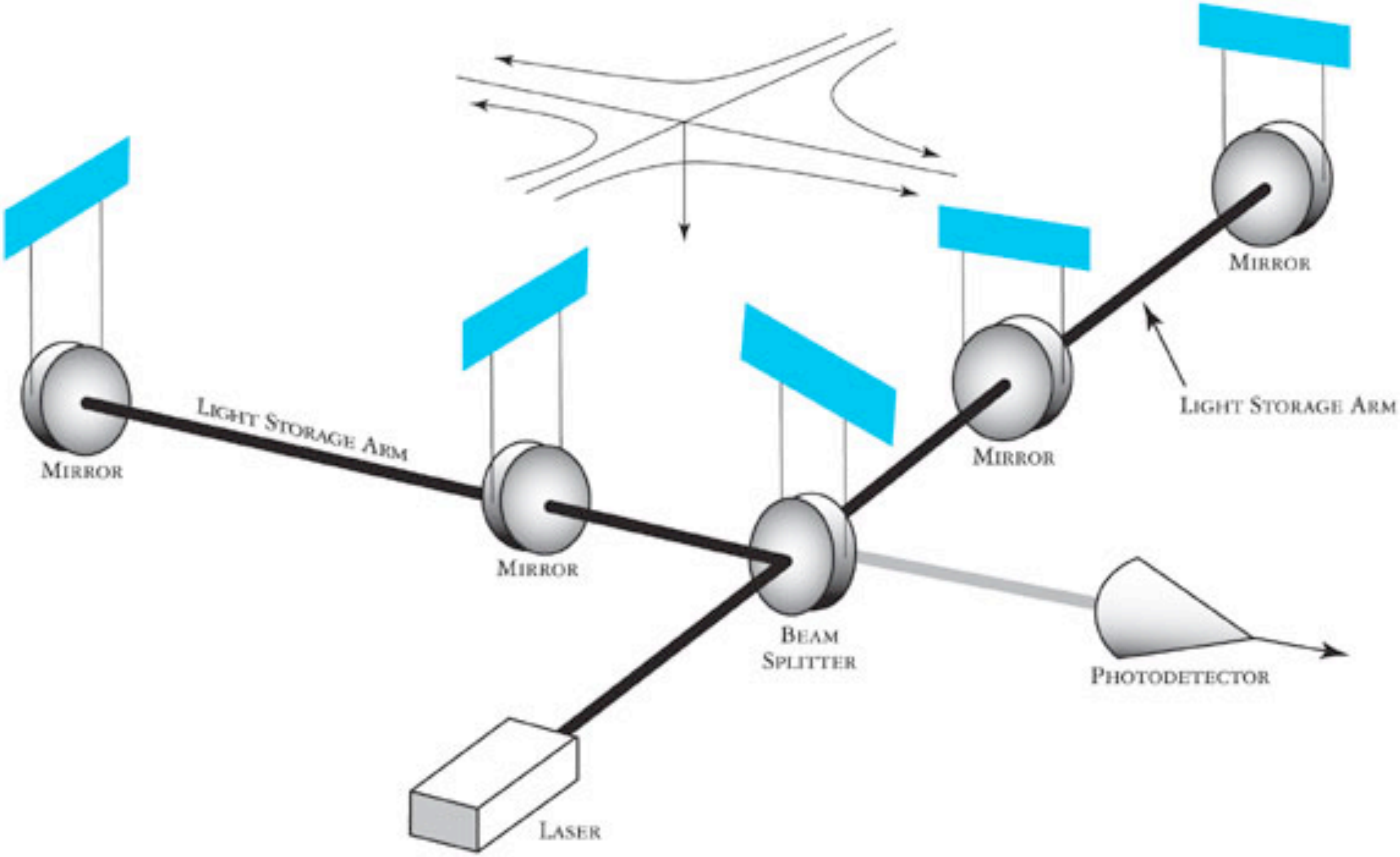
Photodetector
Laser

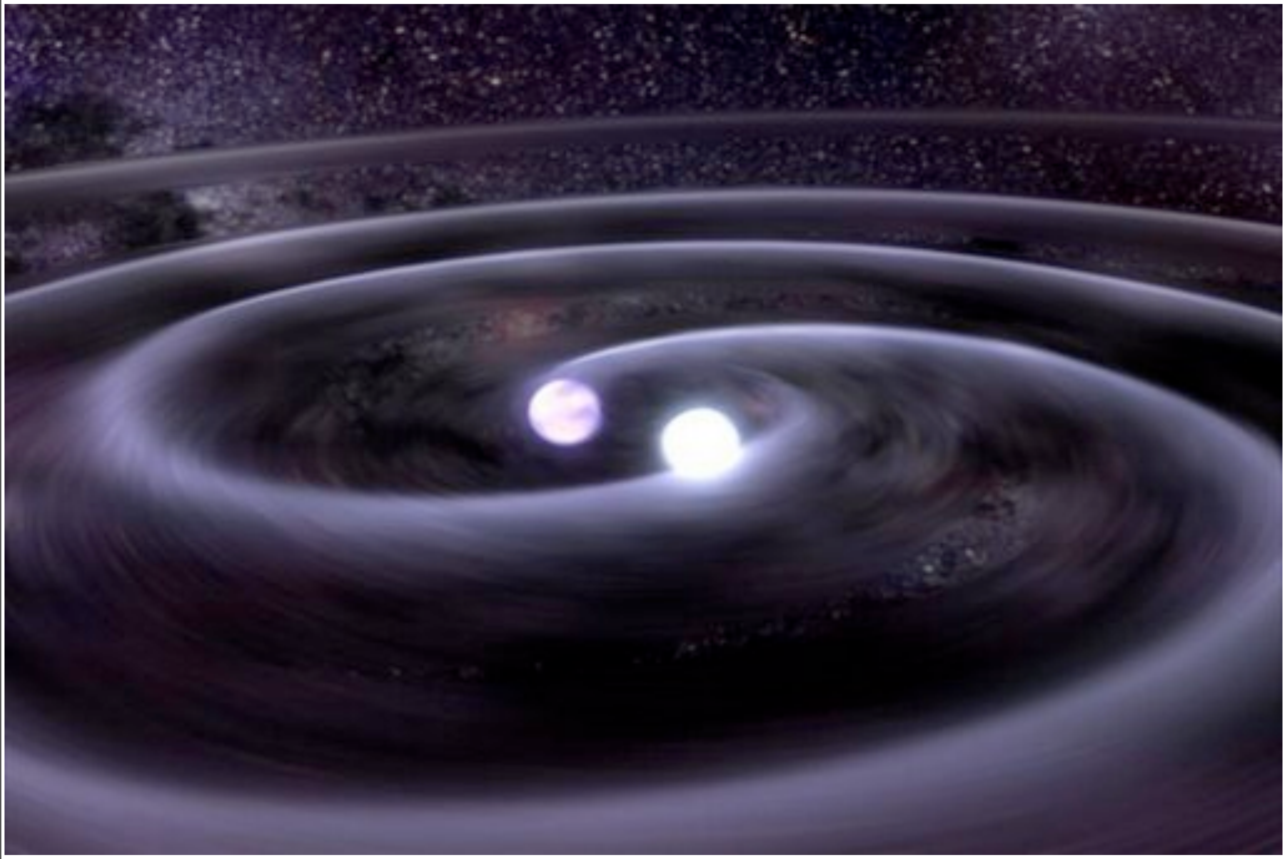
LIGO



Seismic vibrations rapidly cut off LIGO's sensitivity at frequencies below 40 Hz

Astrophysical Sources in the 10^{-2} Hz - 10 Hz band

Astrophysical sources spend long times (> 10^6 s) moving through this band, compared to ~ 5 s in LIGO's frequency band (40 Hz - 10 KHz).



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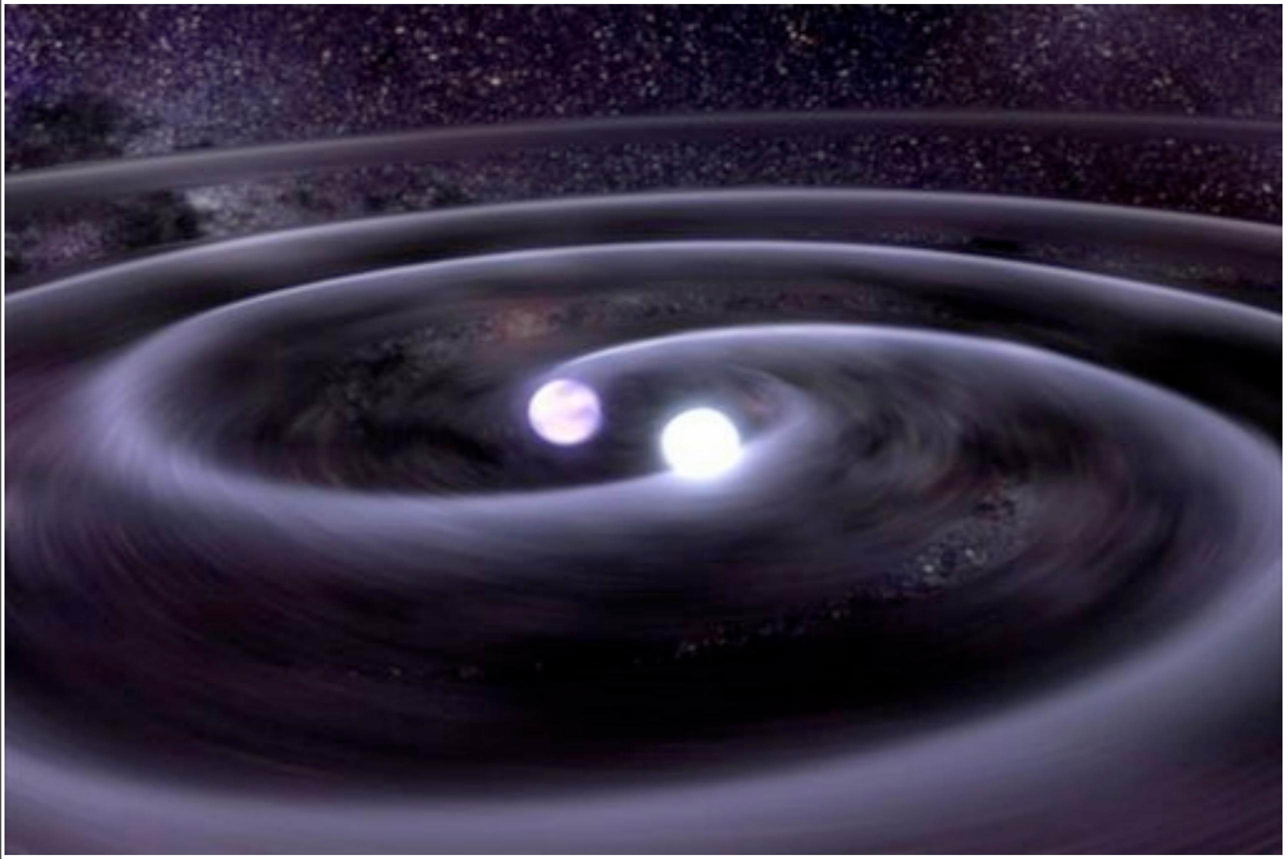

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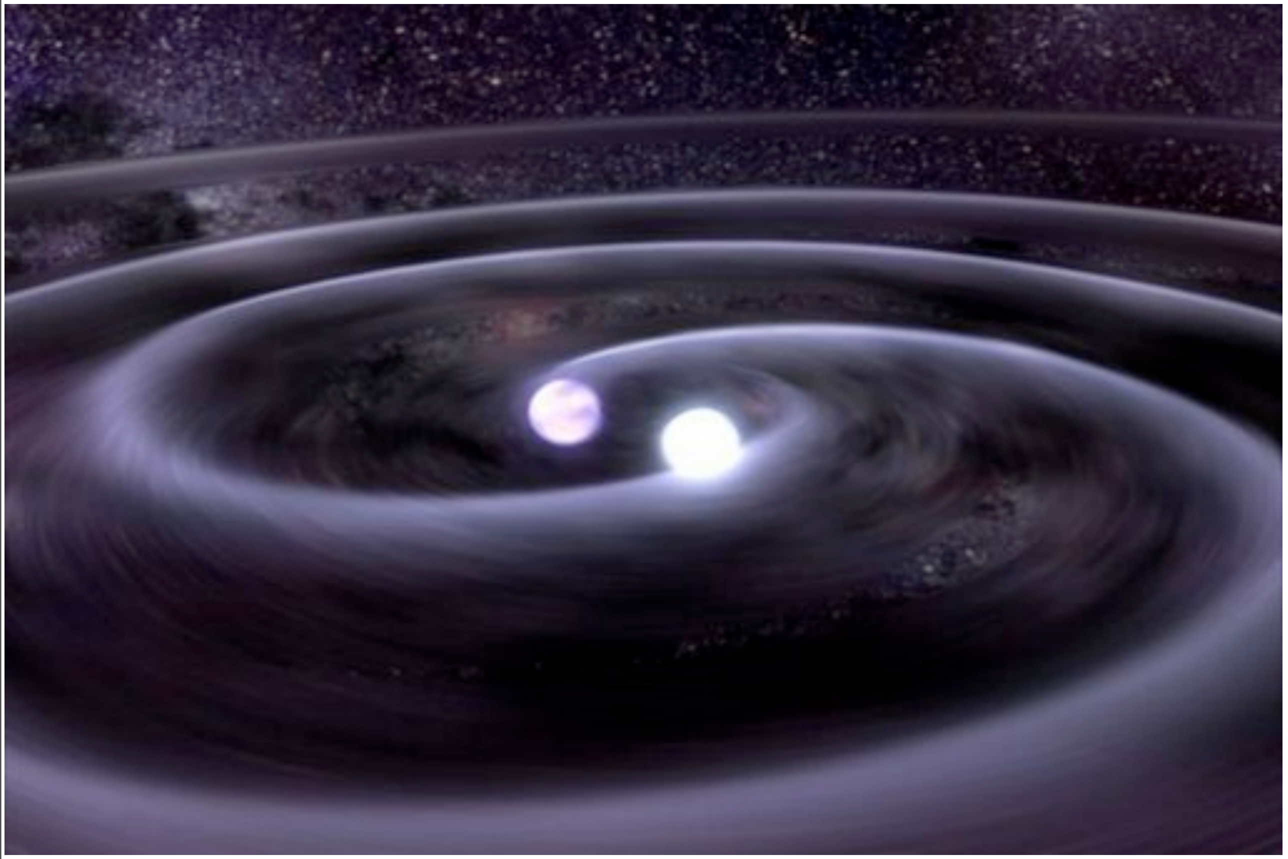

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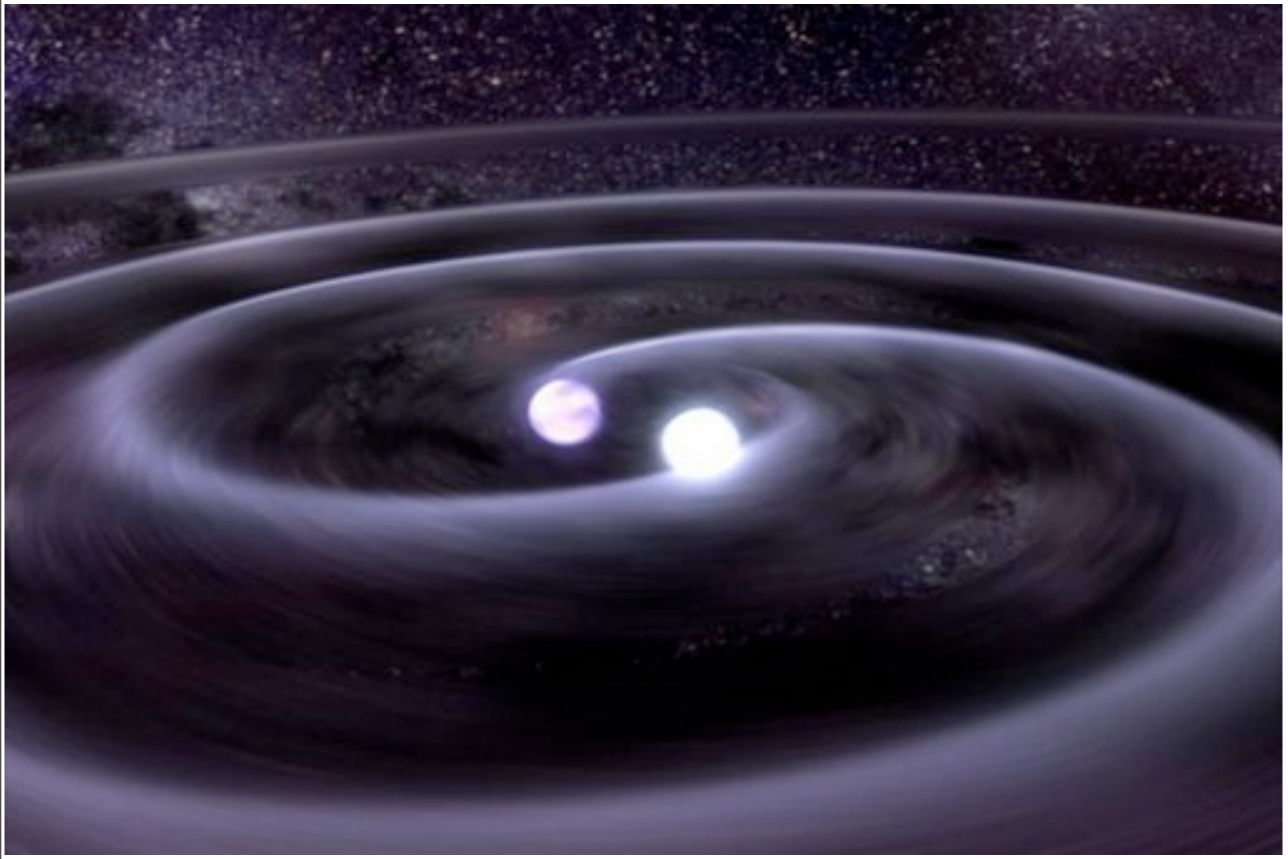

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Bright gravitational wave sources like mergers of white dwarves and massive black holes do not enter LIGO's band.

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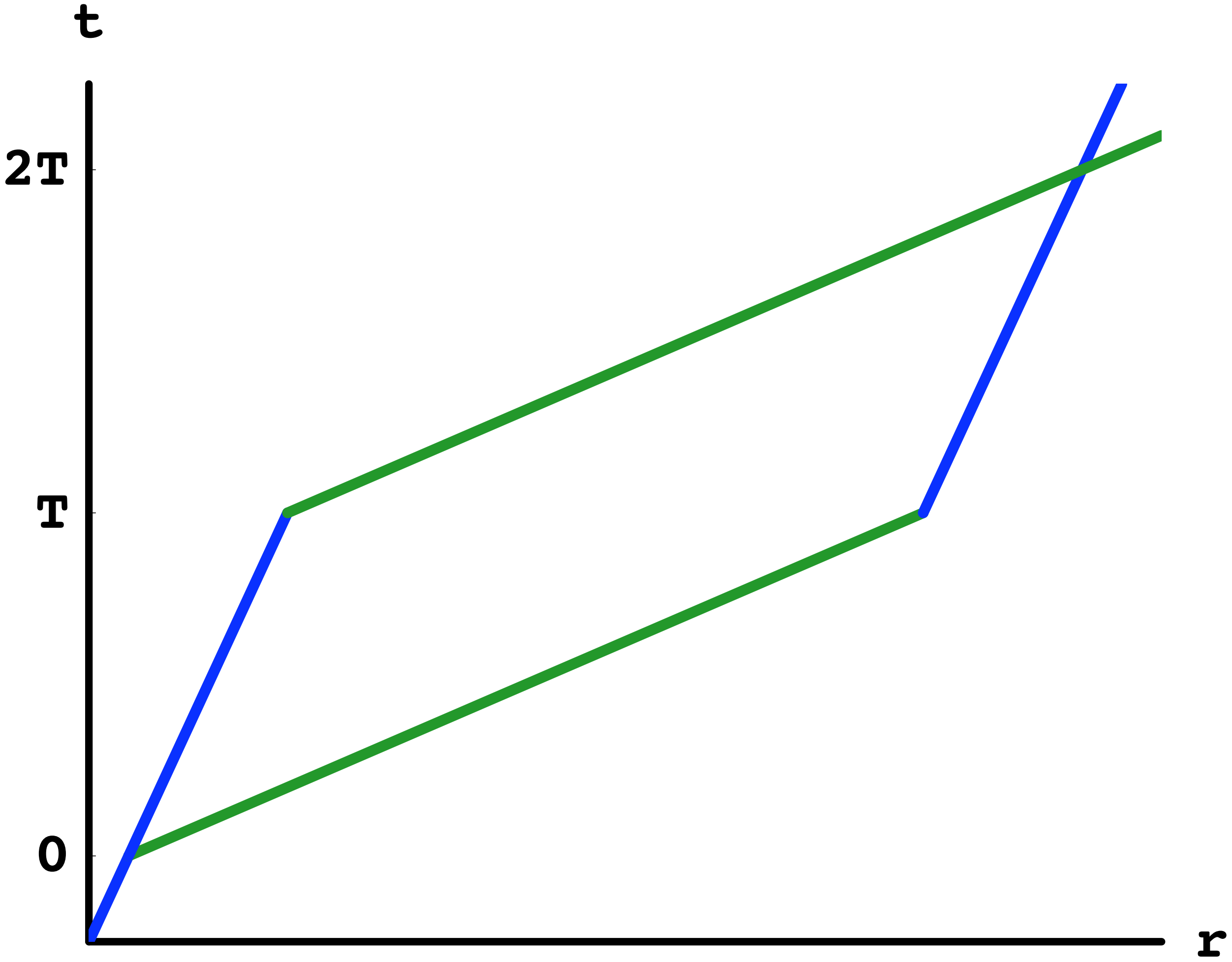
Source rich band probing a lot of interesting physics.

Atom Interferometry

- Established technology, successfully applied to many fields like precision navigation, gravity gradiometry etc.
- High precision sensors, e.g. 16 digit atomic clock synchronization, accelerometers with 12 digit sensitivity.
- Rapidly evolving field. Several future advances possible e.g. atom cooling techniques etc.

What is an atom interferometer?



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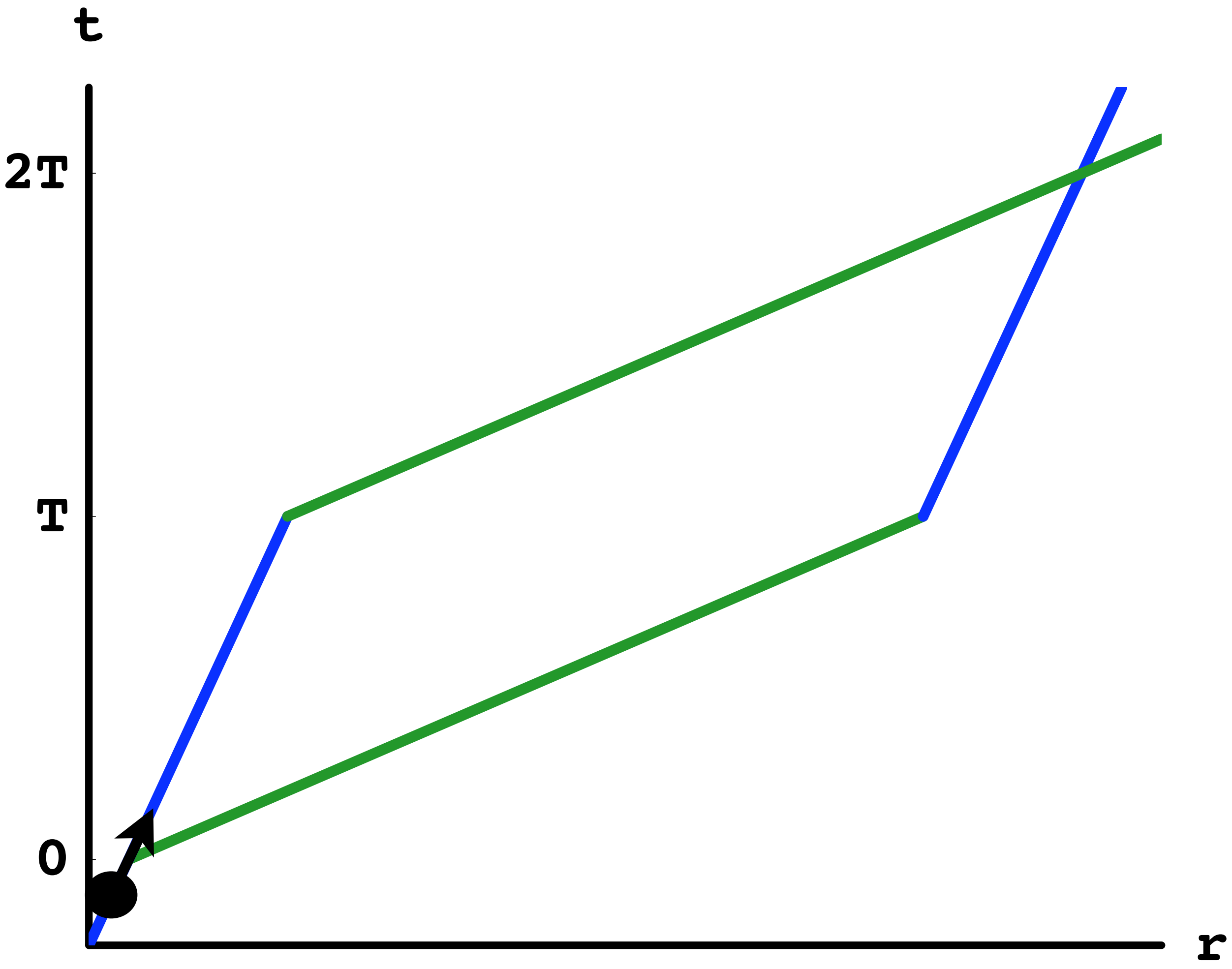

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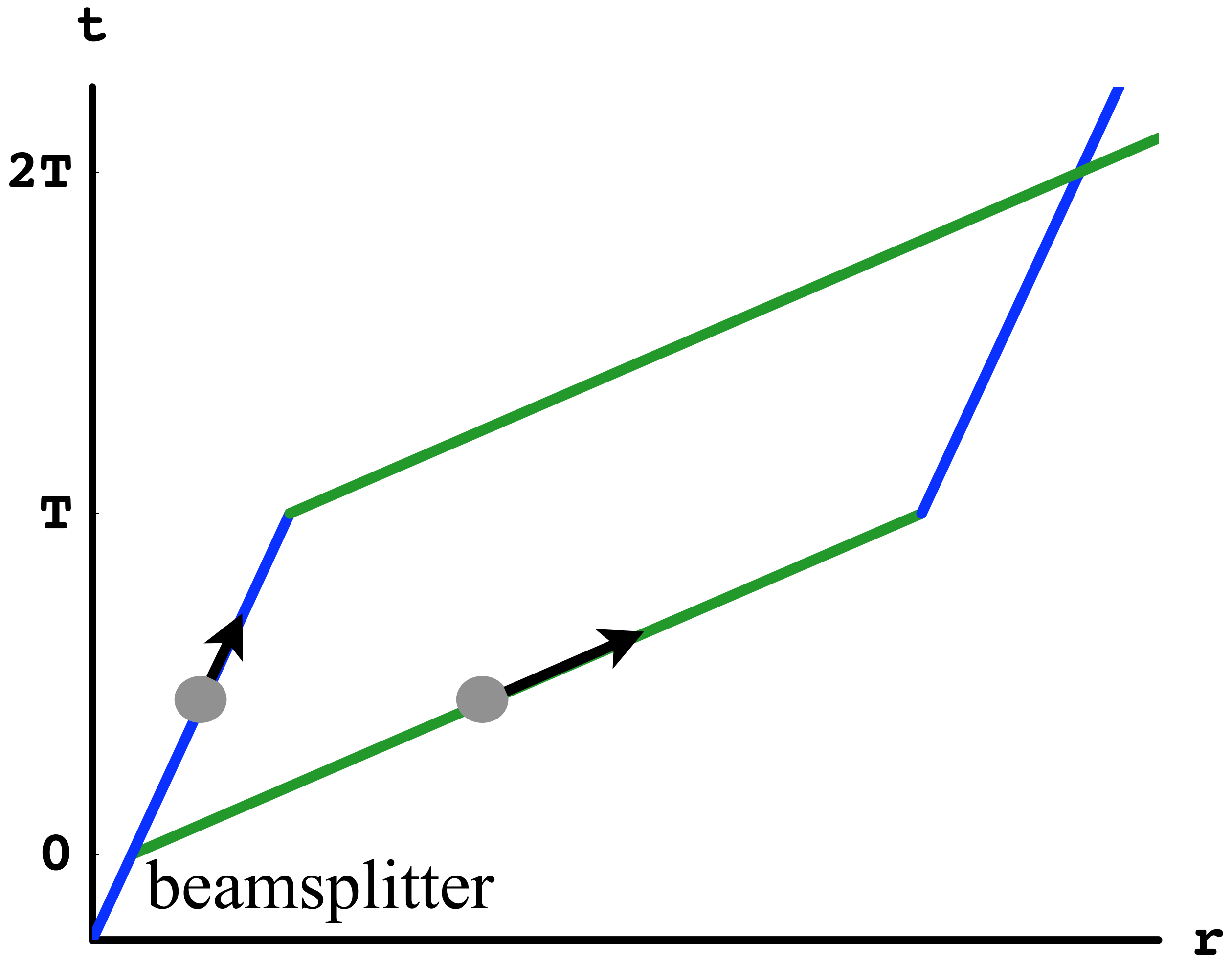

$$\frac{1}{\sqrt{2}}\left(|p\rangle + e^{i\Delta\phi}|p+k\rangle\right)$$

$$\uparrow$$

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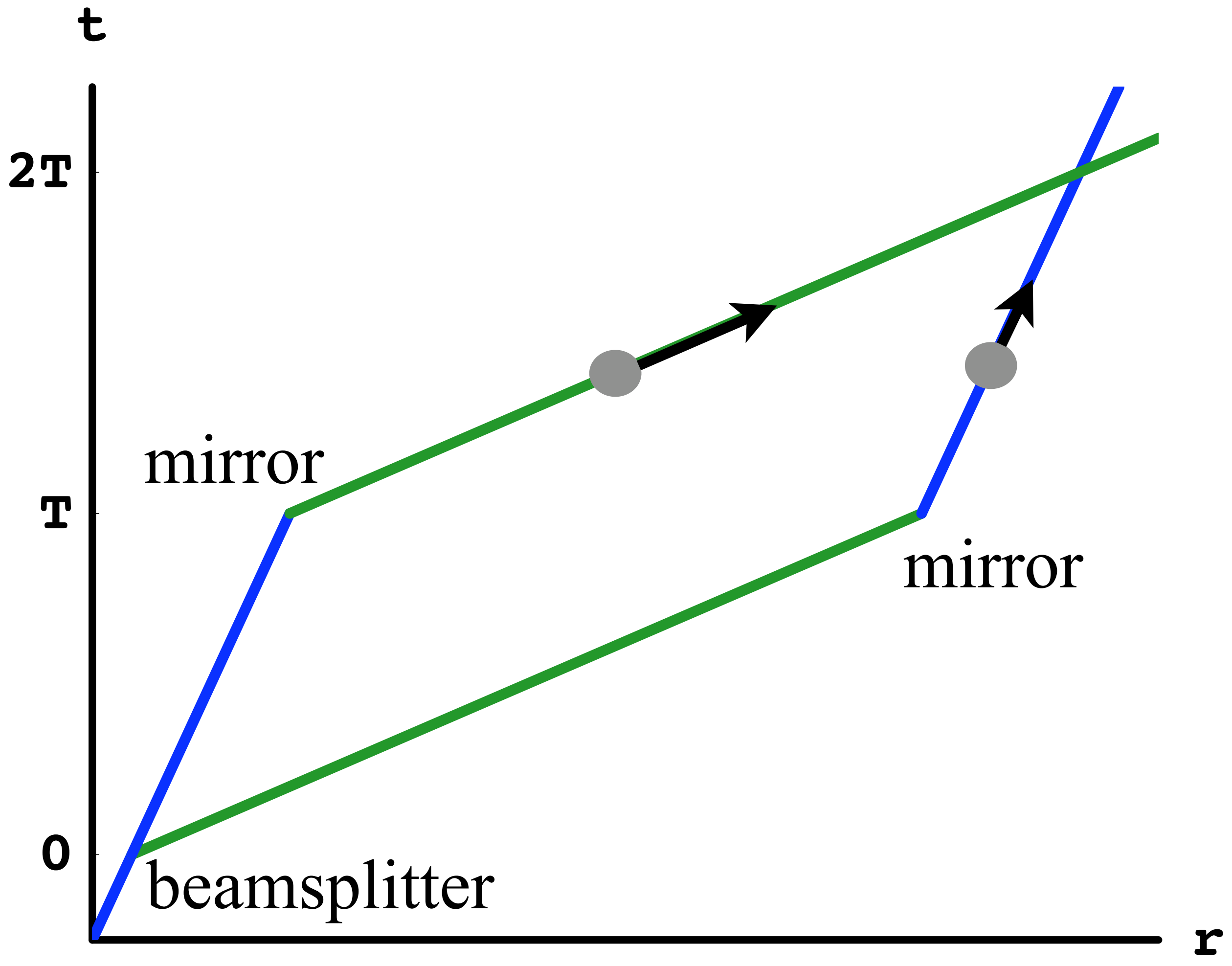

$$\begin{tikzcd}
\frac{1}{\sqrt{2}}\left(|p+k\rangle + e^{i\Delta\phi}|p\rangle\right) \\
\frac{1}{\sqrt{2}}\left(|p\rangle + e^{i\Delta\phi}|p+k\rangle\right) \arrow[u, two heads] \\
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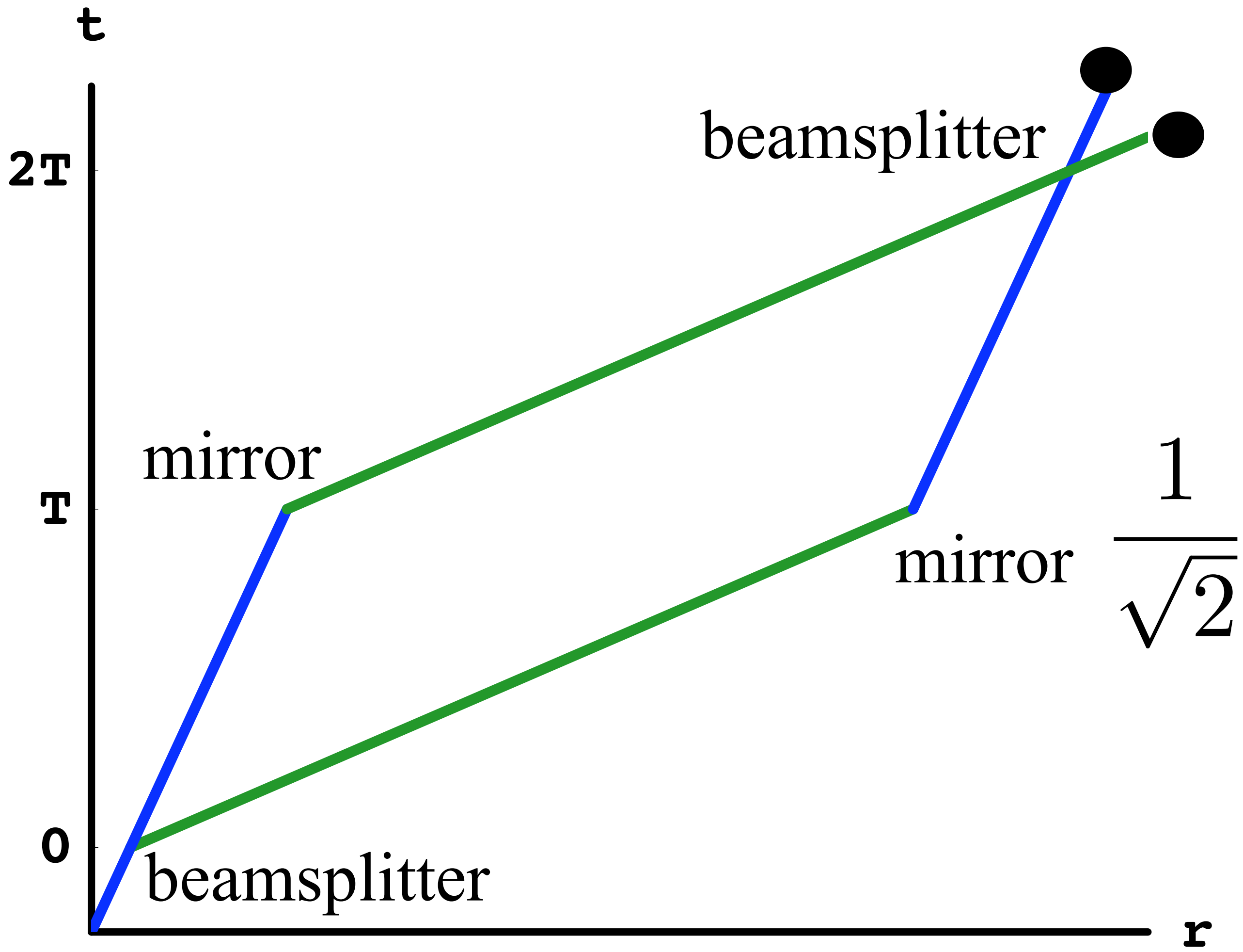
\end{tikzcd}$$

What is an atom interferometer?



$$\frac{1}{\sqrt{2}}(|p+k\rangle + e^{i\Delta\phi}|p\rangle)$$

$$\frac{1}{\sqrt{2}}(|p+k\rangle - |p\rangle) \qquad \frac{1}{\sqrt{2}}(|p\rangle + |p+k\rangle)$$

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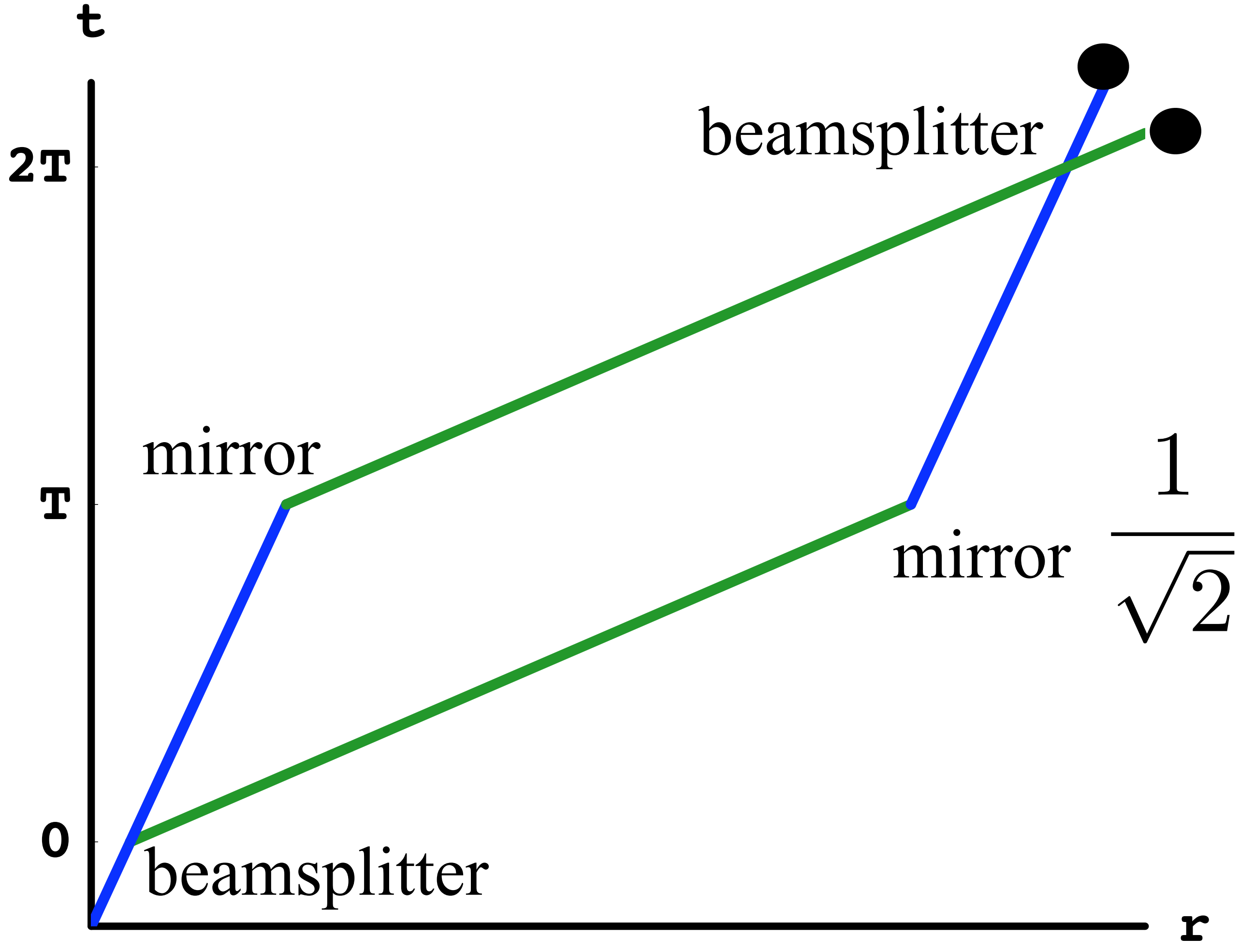

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Final State

$$\frac{1}{2}((1+e^{i\Delta\phi})|p\rangle + ((1-e^{i\Delta\phi}))|p+k\rangle)$$

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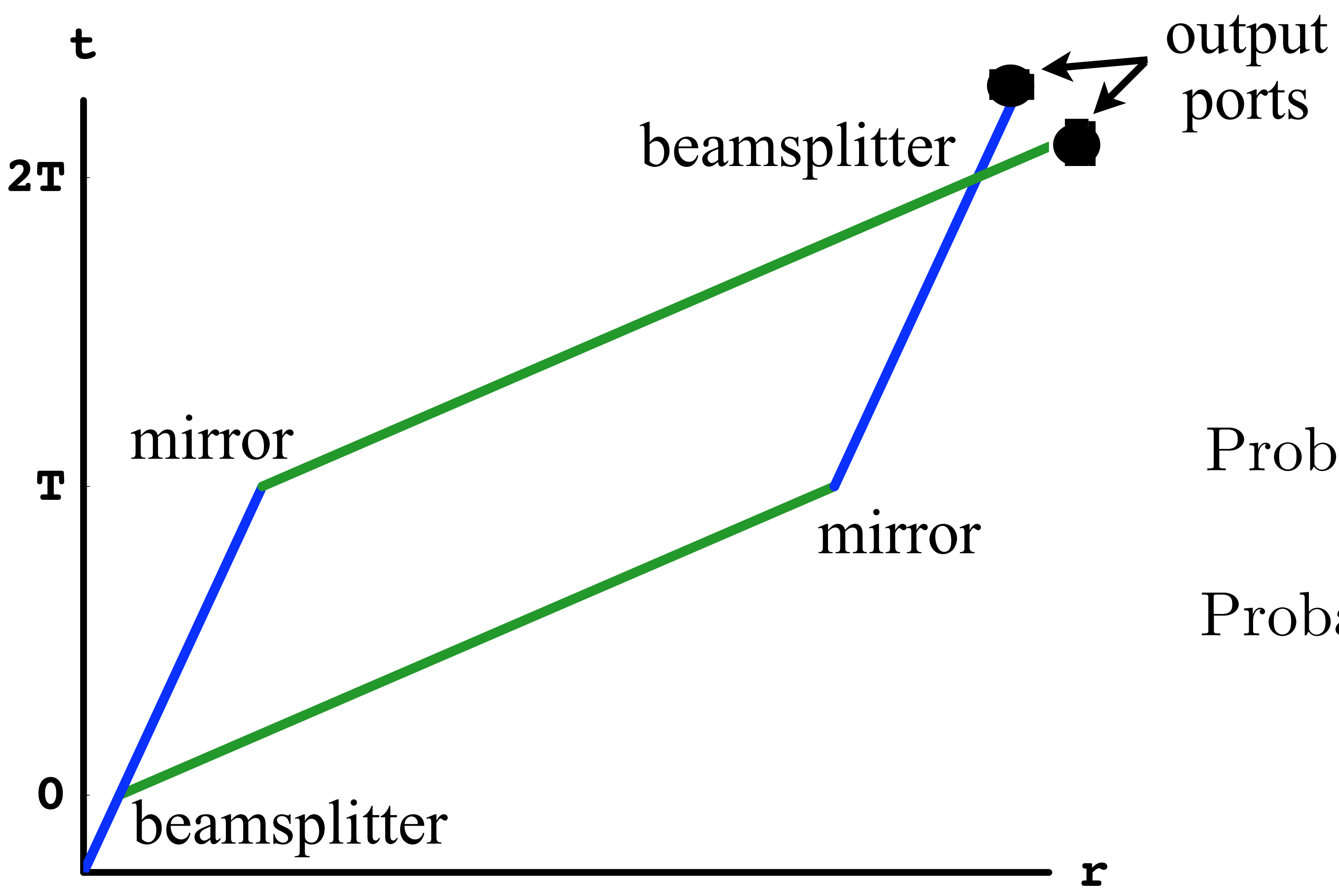

$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

$$\text{Probability in State } |p+k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

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Light Pulse Atom Interferometry

(Kasevich and Chu, 1991)

Beamsplitter and mirror must transfer momentum to the atom.

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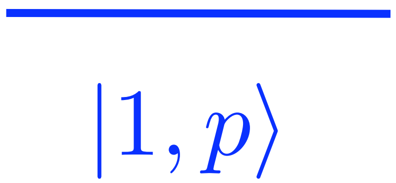

$|1, p\rangle$

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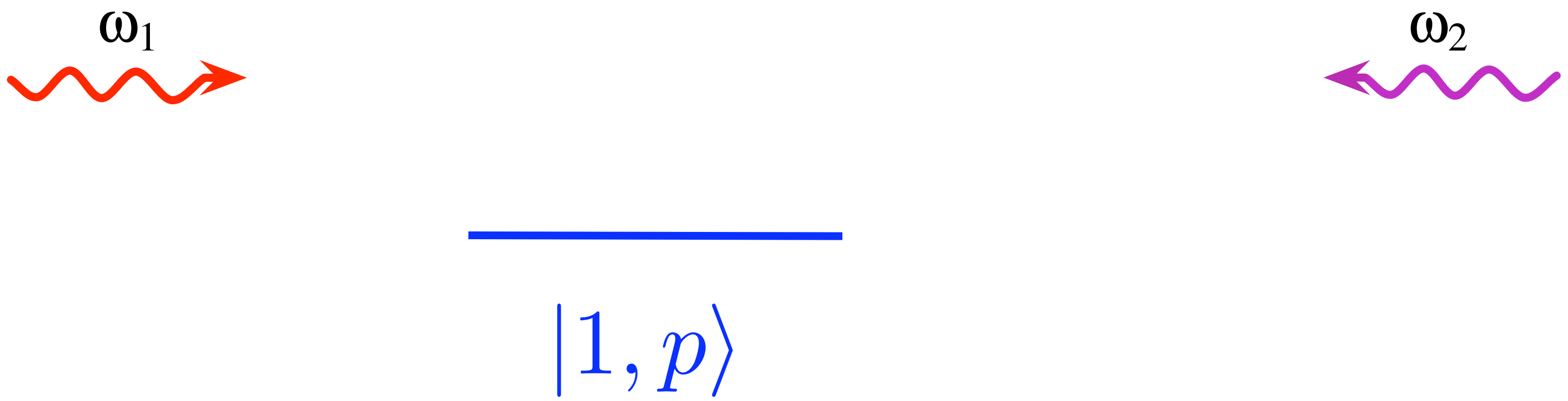

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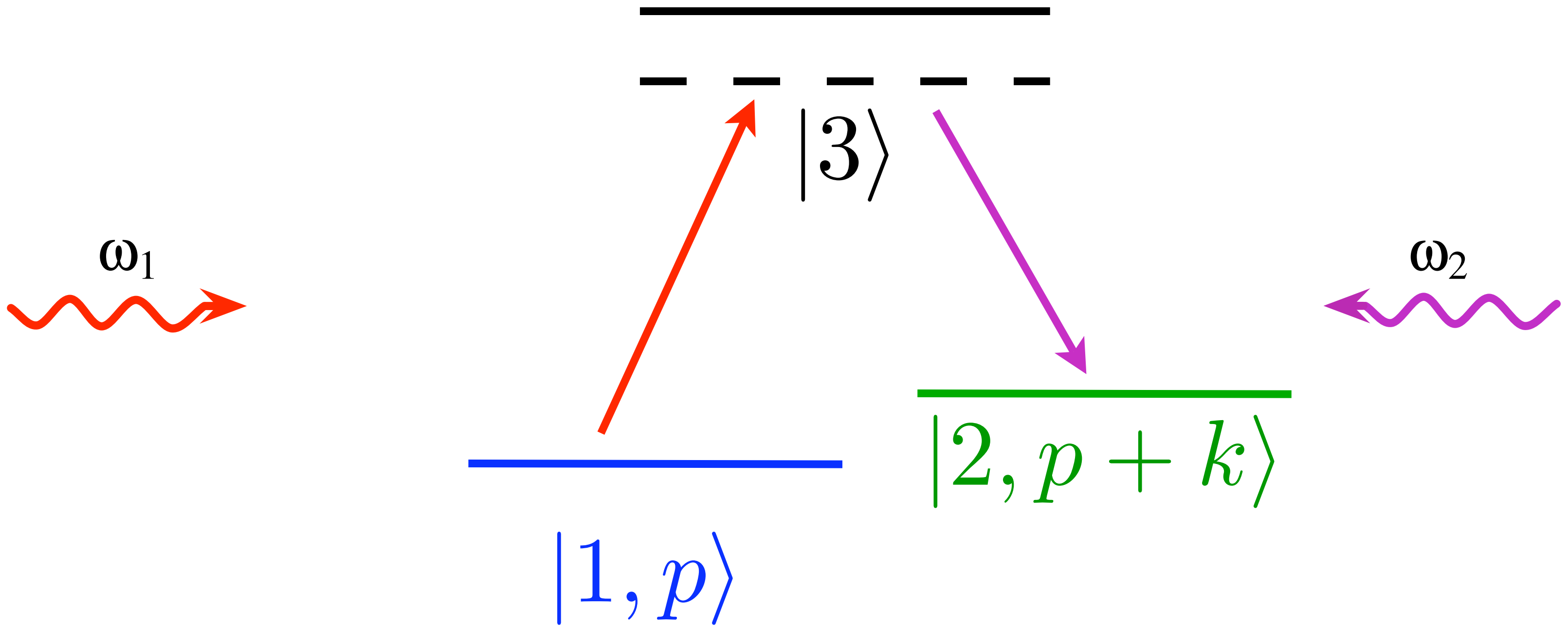

Atom undergoes coherent Raman Scattering with momentum transfer

$$k = \omega_1 - \omega_2 \approx 2\,\omega_1 \sim 1\mathrm{eV}$$

Light Pulse Atom Interferometry

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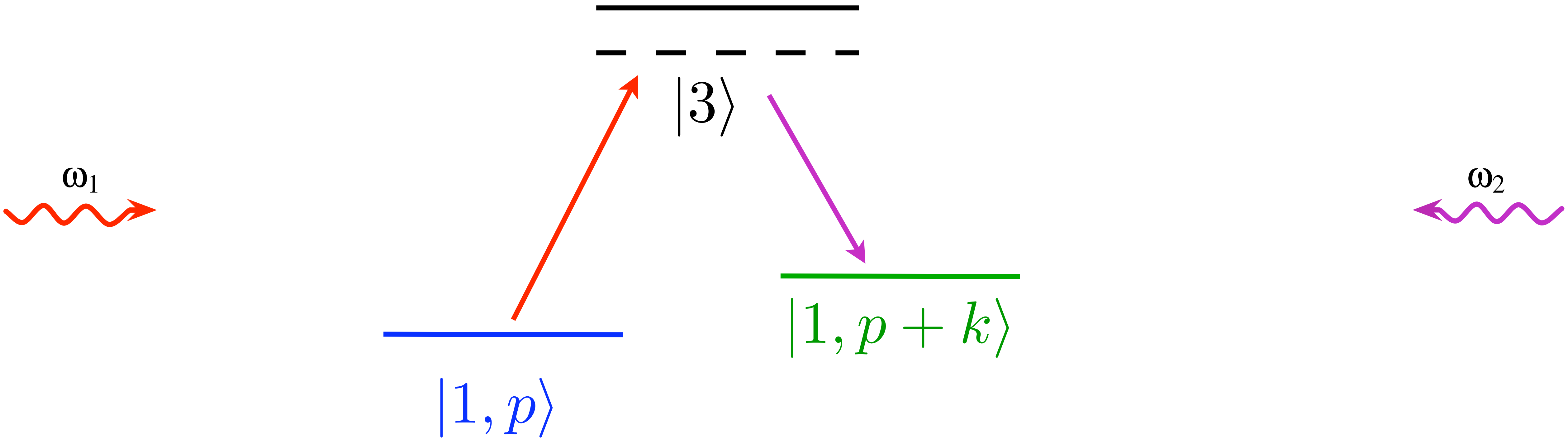
Atom can remain in the same internal level and receive momentum kick.



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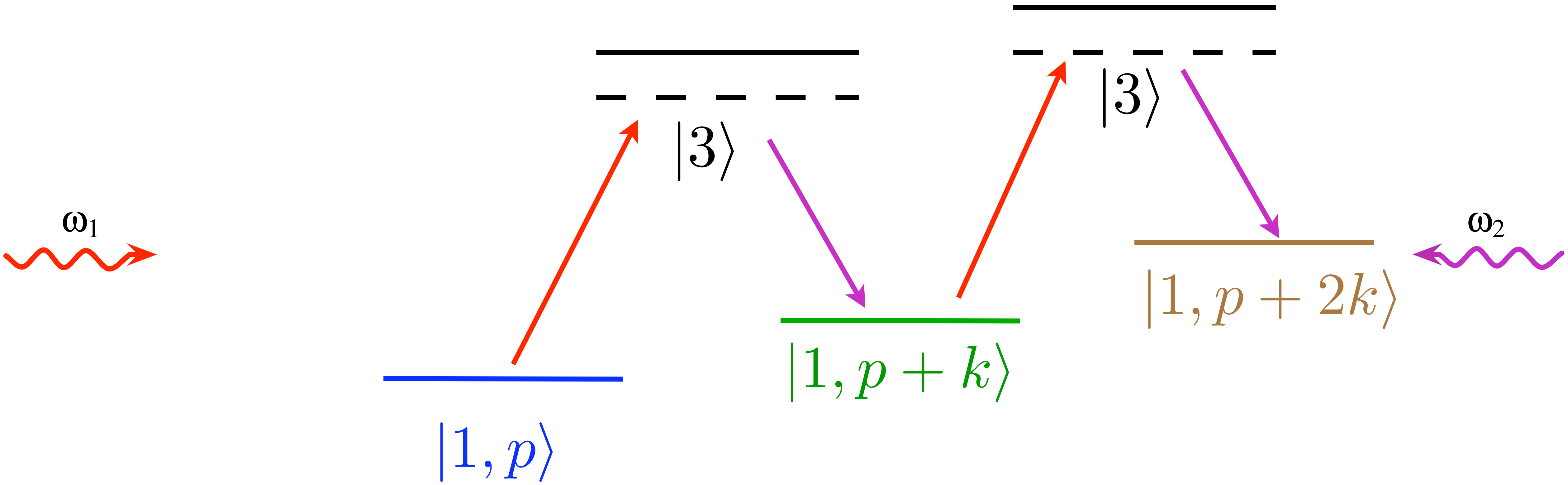


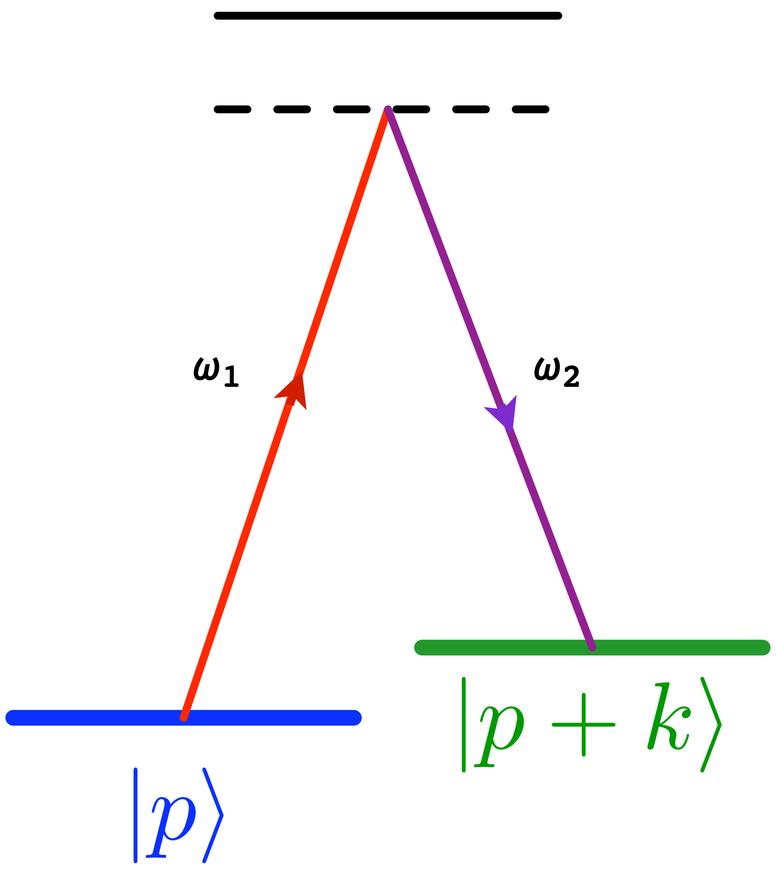
Large Momentum Transfer (LMT) beamsplitter

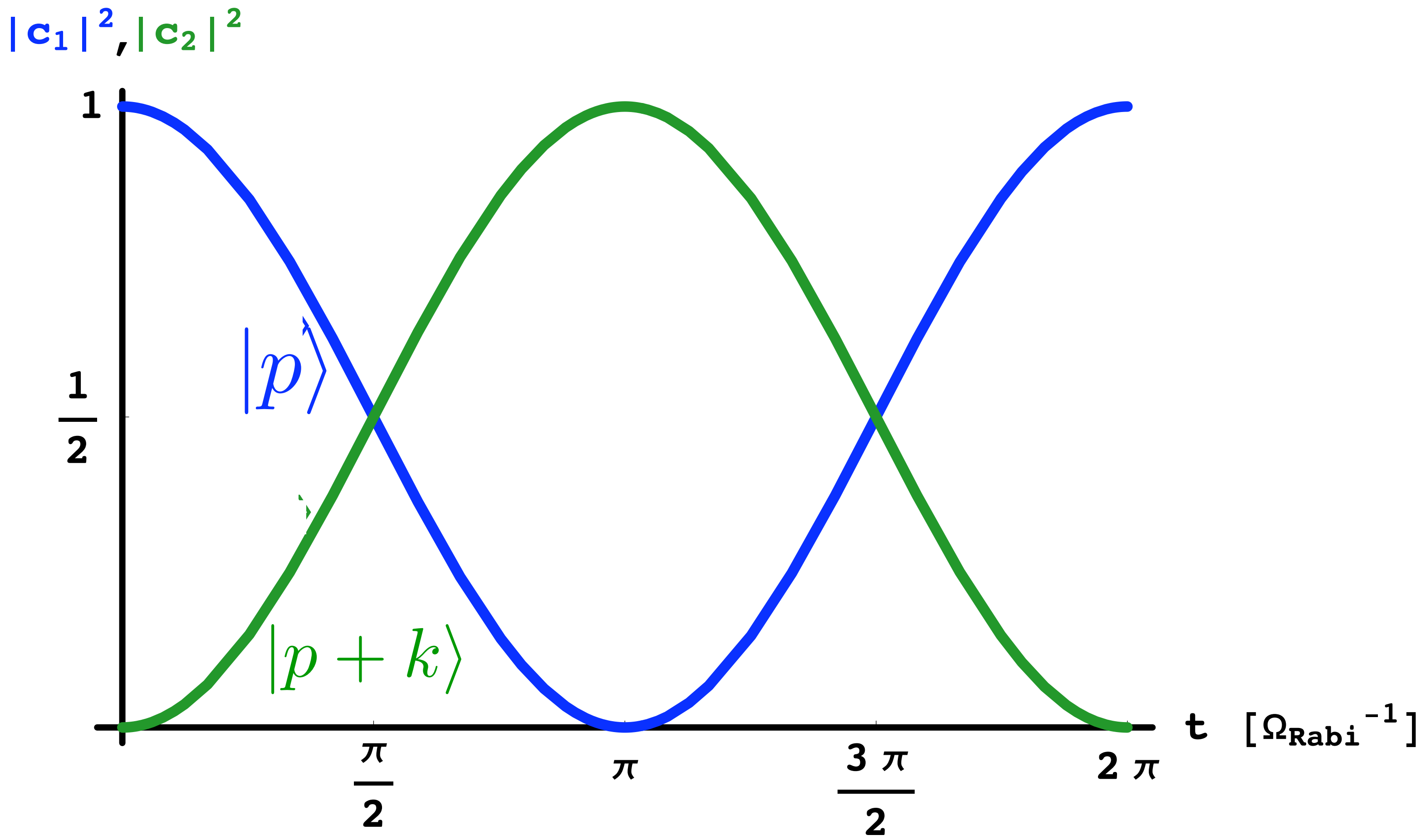
By driving the transition N times, large momenta can be transferred.

$$k_{\text{eff}} \sim N\omega_1$$

Beamsplitter and Mirror Pulses

$$\psi = c_1|p\rangle + c_2|p+k\rangle$$

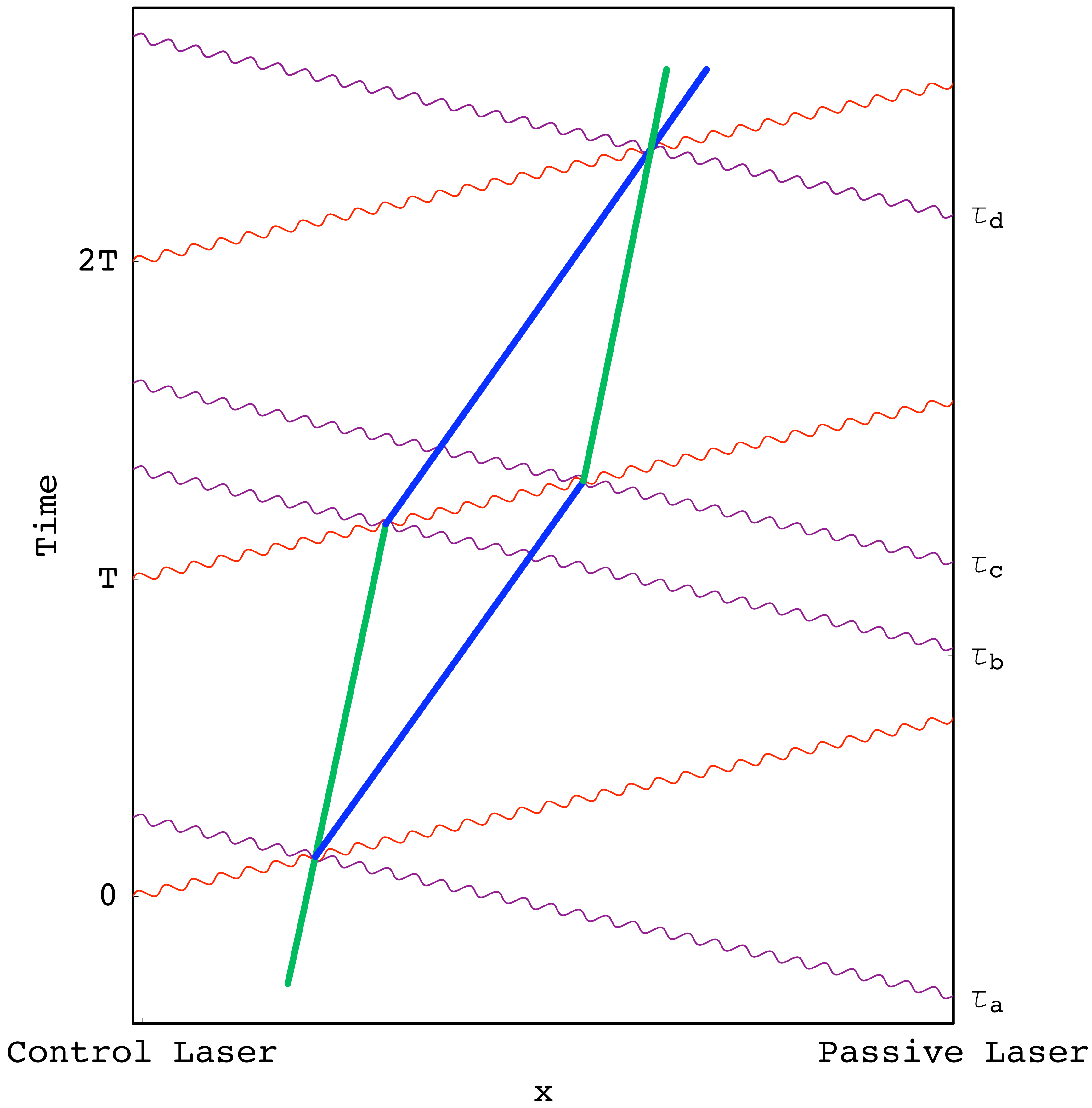




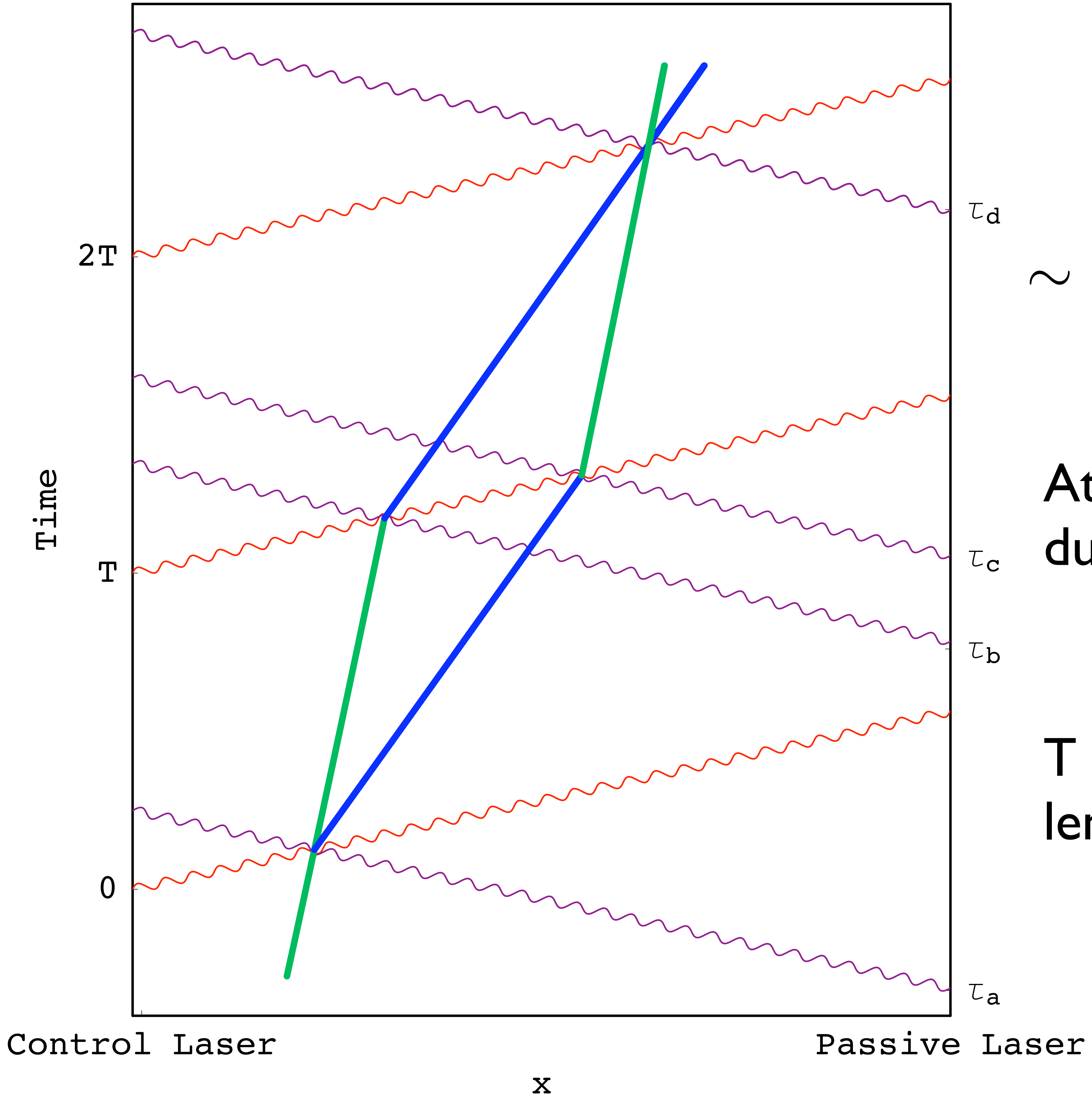
$\pi/2$ pulse is a beamsplitter

π pulse is a mirror

Spacetime Diagram of the Atom Interferometer



Spacetime Diagram of the Atom Interferometer



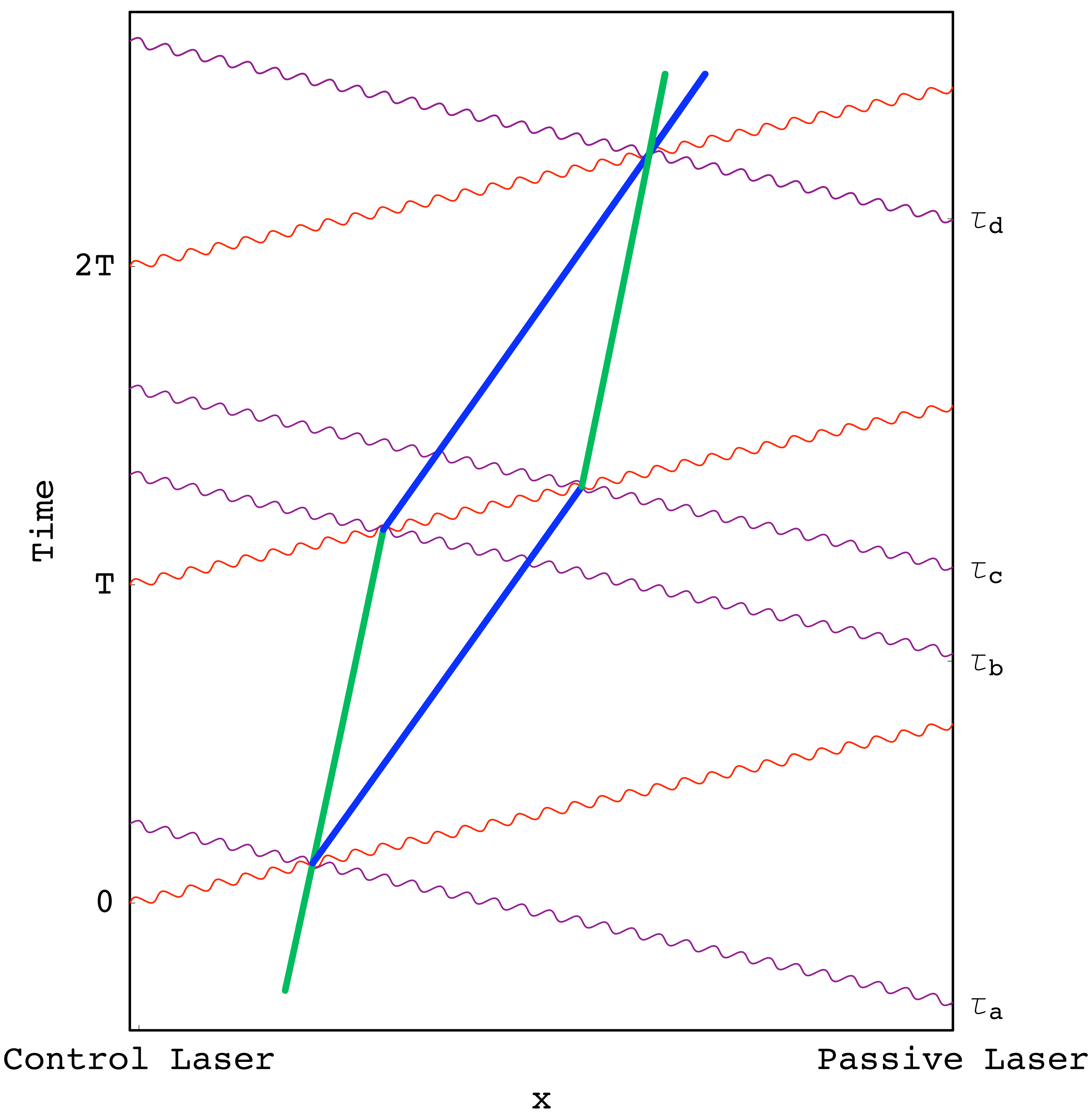
Typical Terrestrial Interferometer

$\sim 10^7$ atoms launched with velocities ~ 10 m/s

Atoms are in free fall during interferometer.

T ~ 1 s sets interferometer length to ~ 10 m.

Phase Shift in the Interferometer



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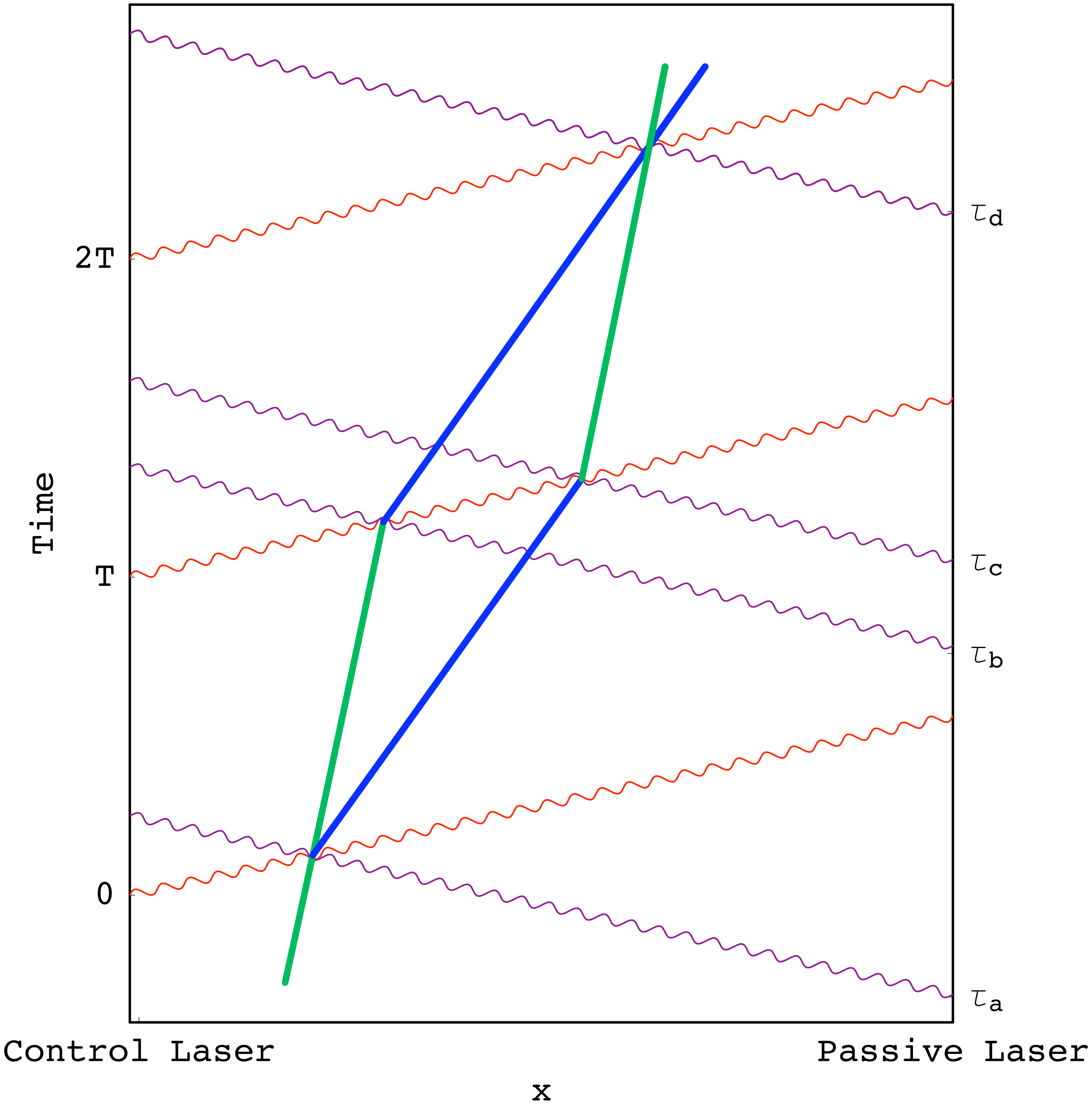

- Differences in the trajectories of the wavepackets.

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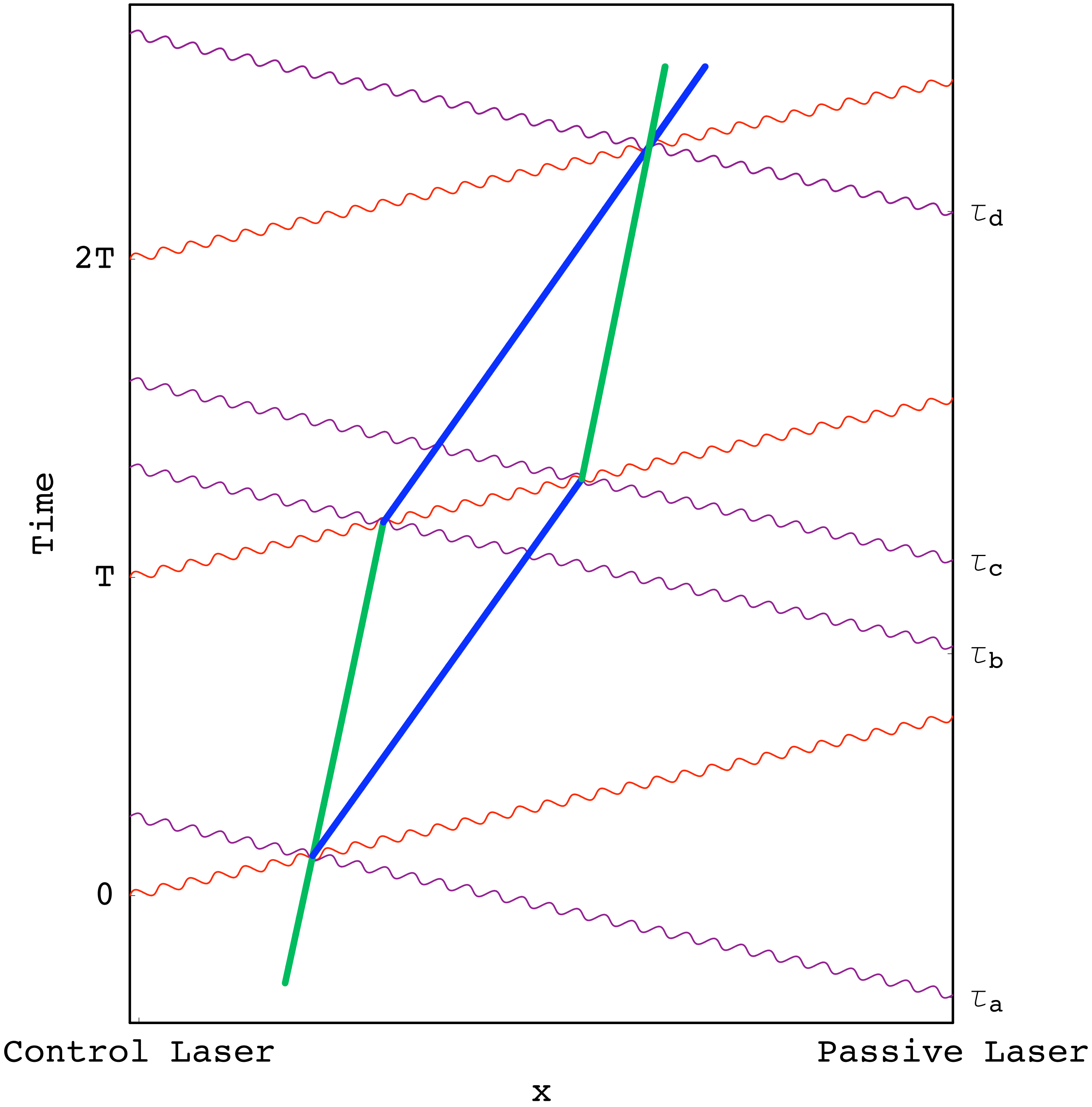
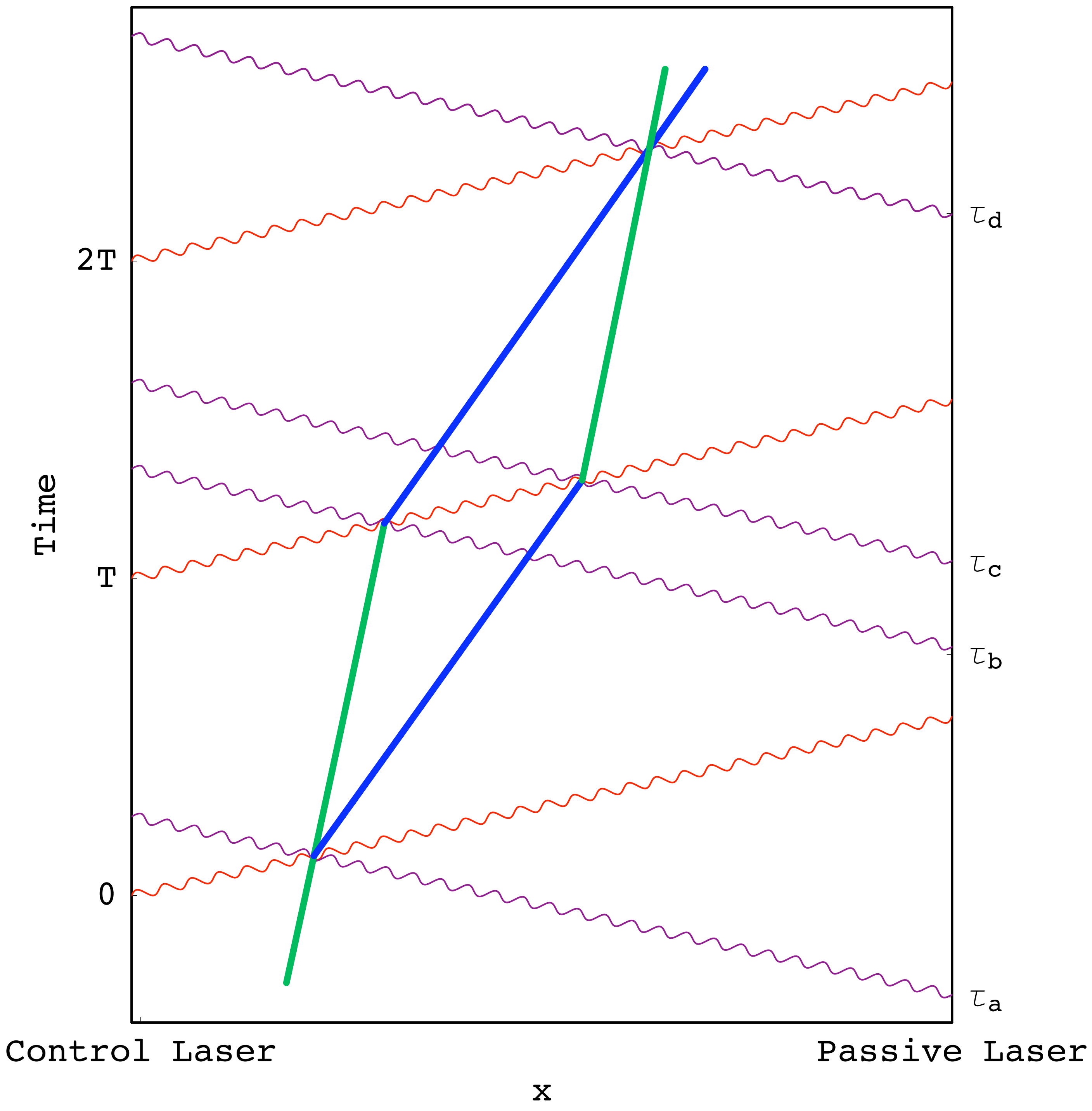


- Differences in the trajectories of the wavepackets.

- The laser phase imprinted on the atom during the atom laser interaction.

What can cause a phase shift?



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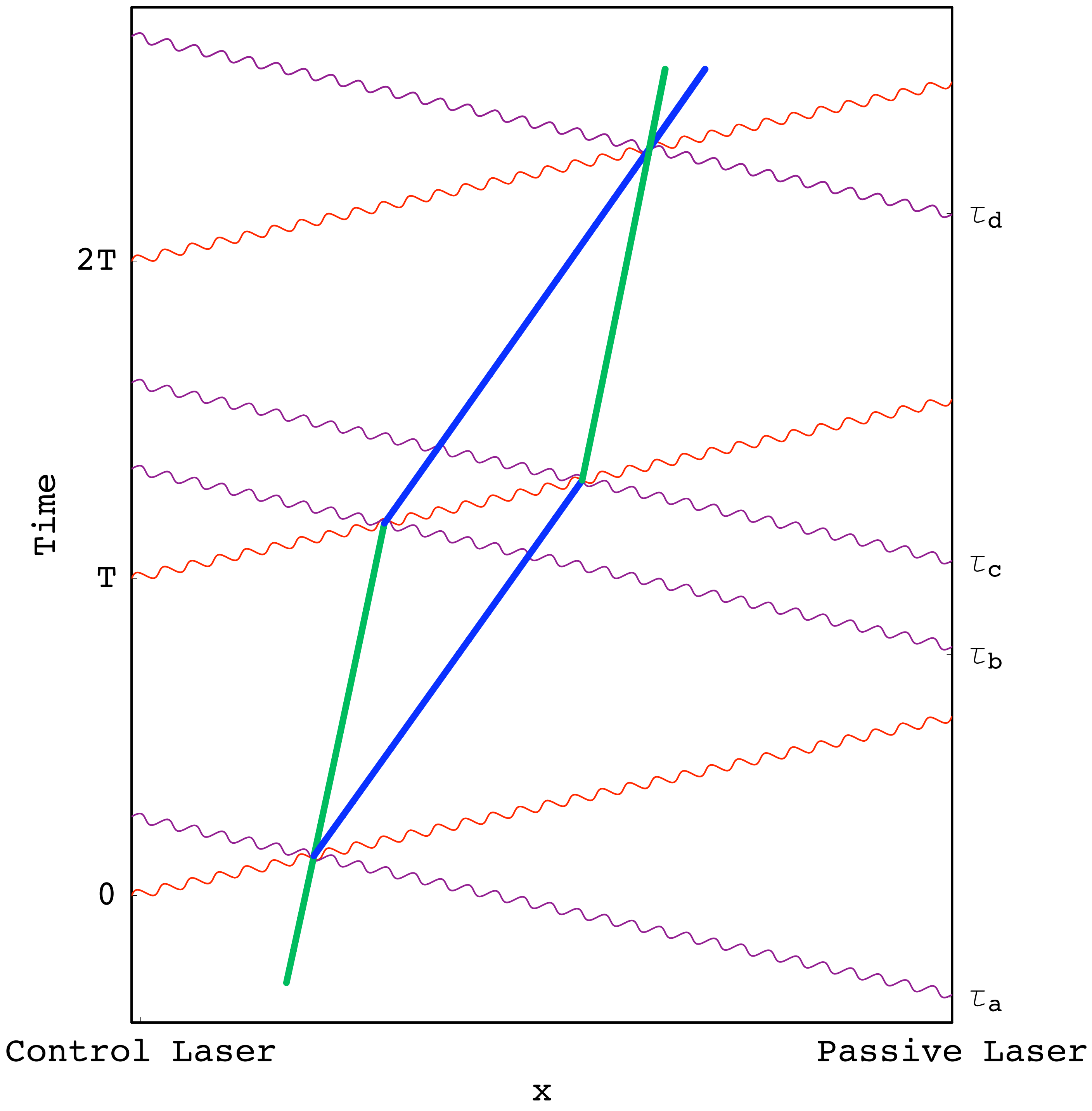

Interferometer symmetric about the mirror pulse at T.

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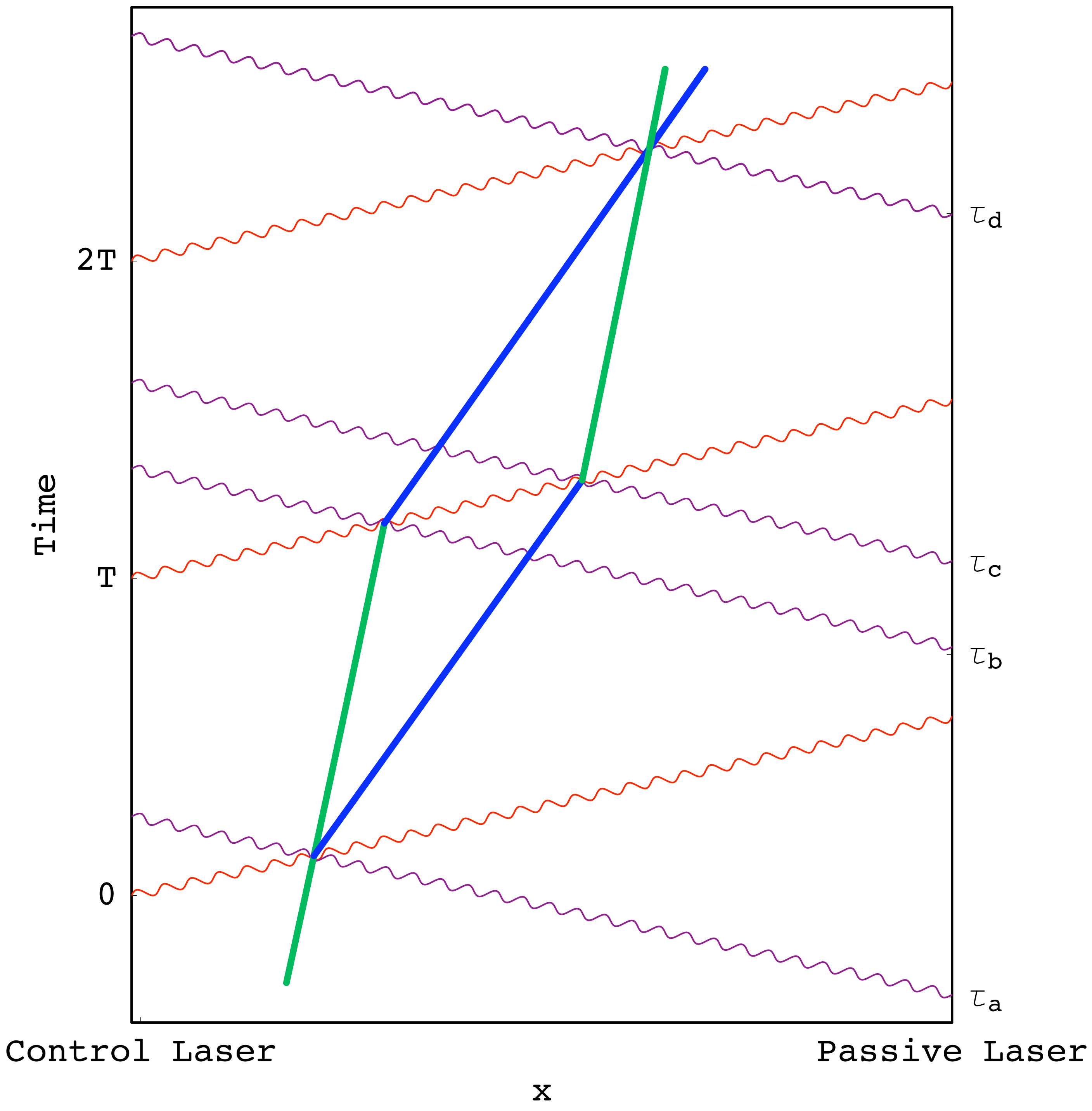

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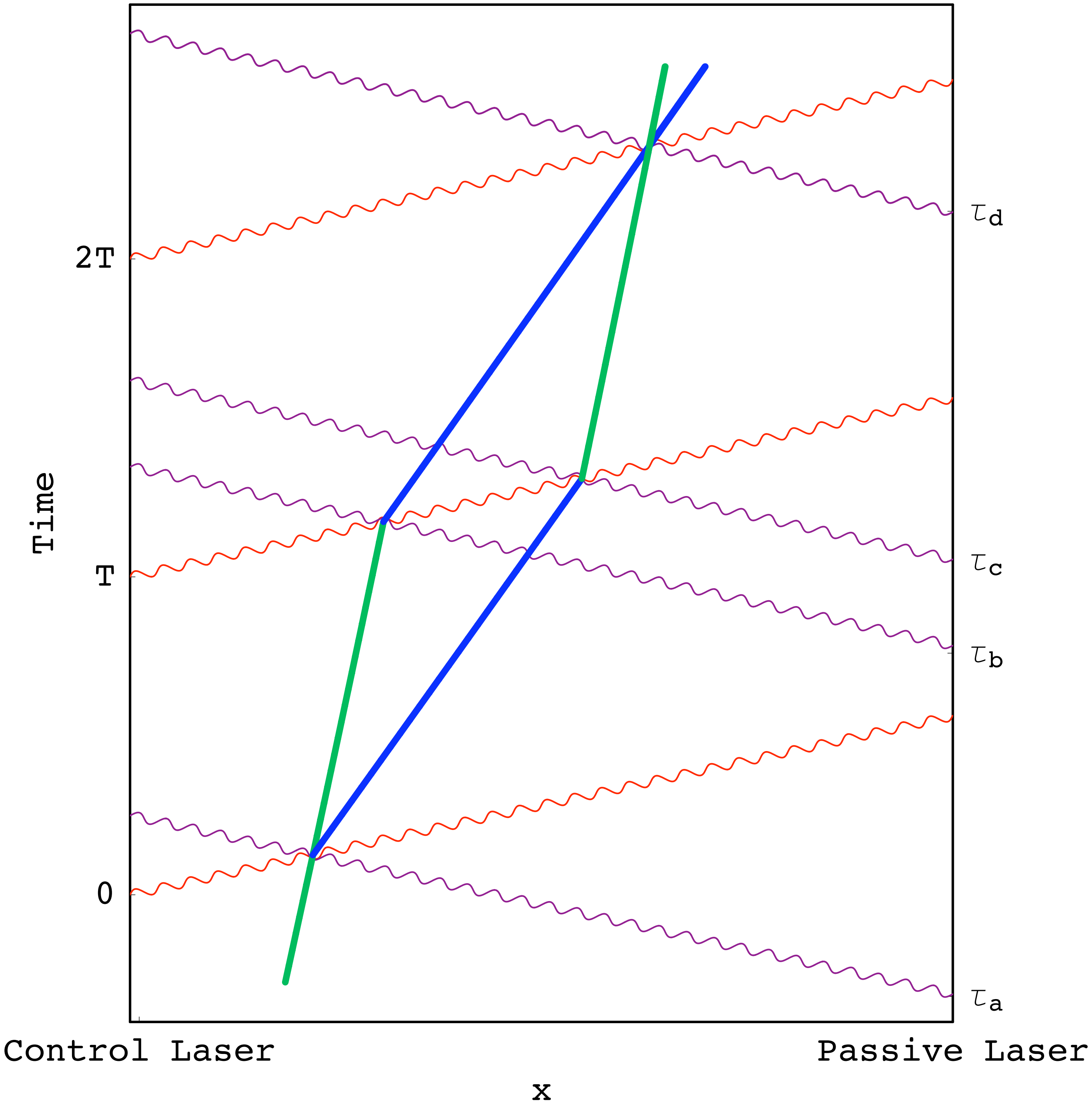

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Interferometer is an accelerometer.

The Gravitational Wave Signal in the Interferometer

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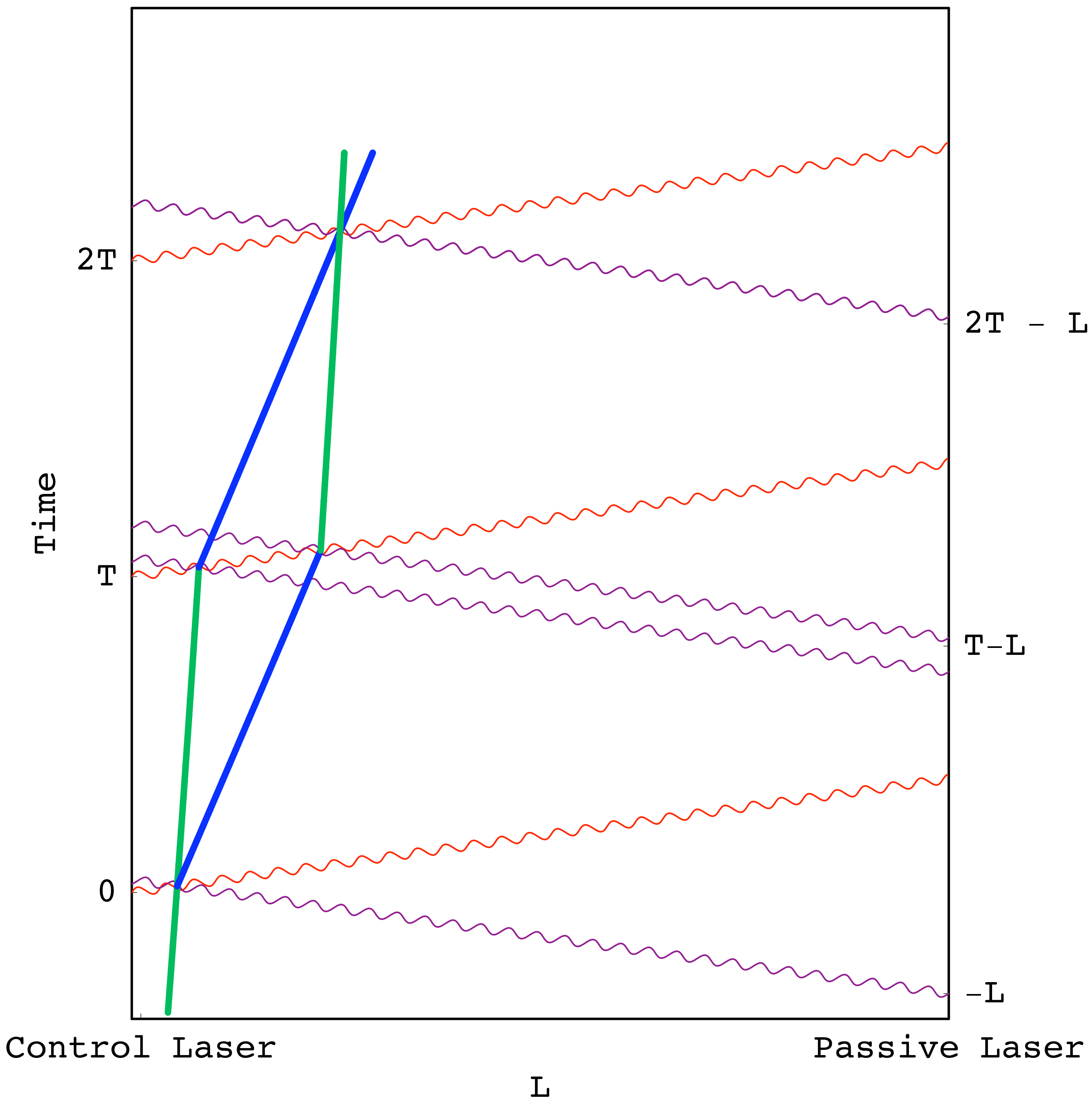

Pulse control laser at 0, T and 2 T.

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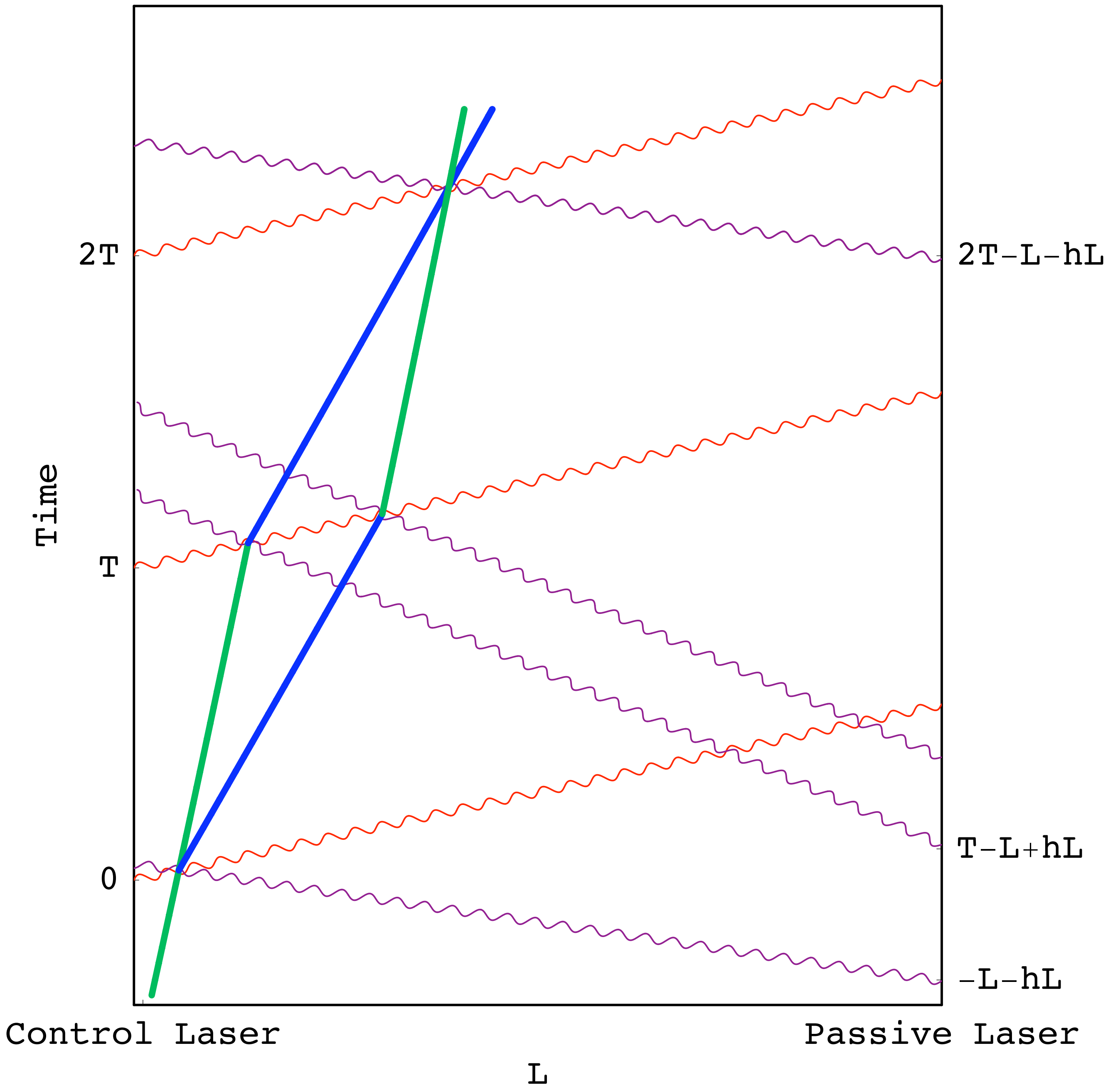

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Distance between passive laser and the atom altered by gravity wave.

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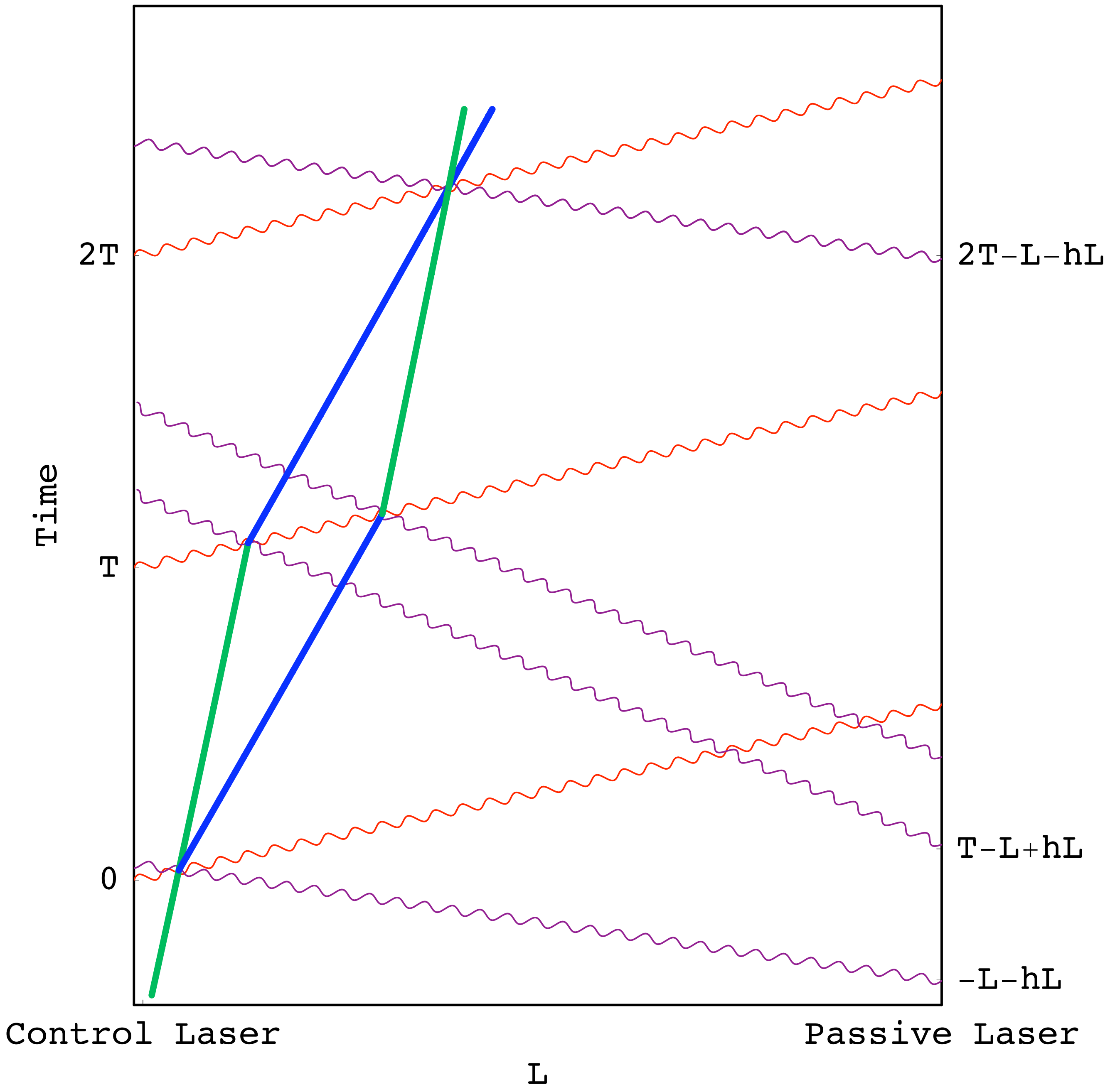

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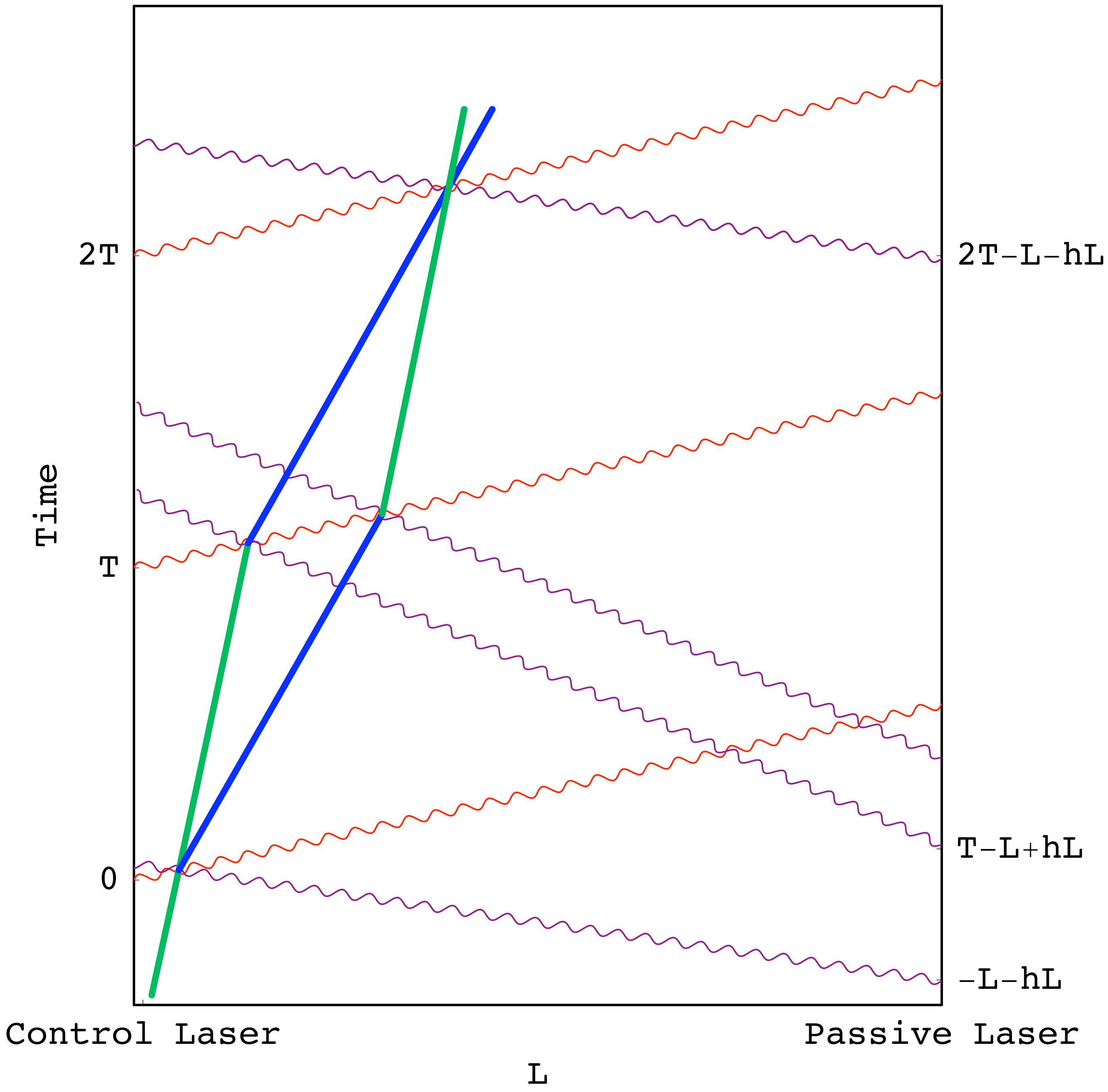

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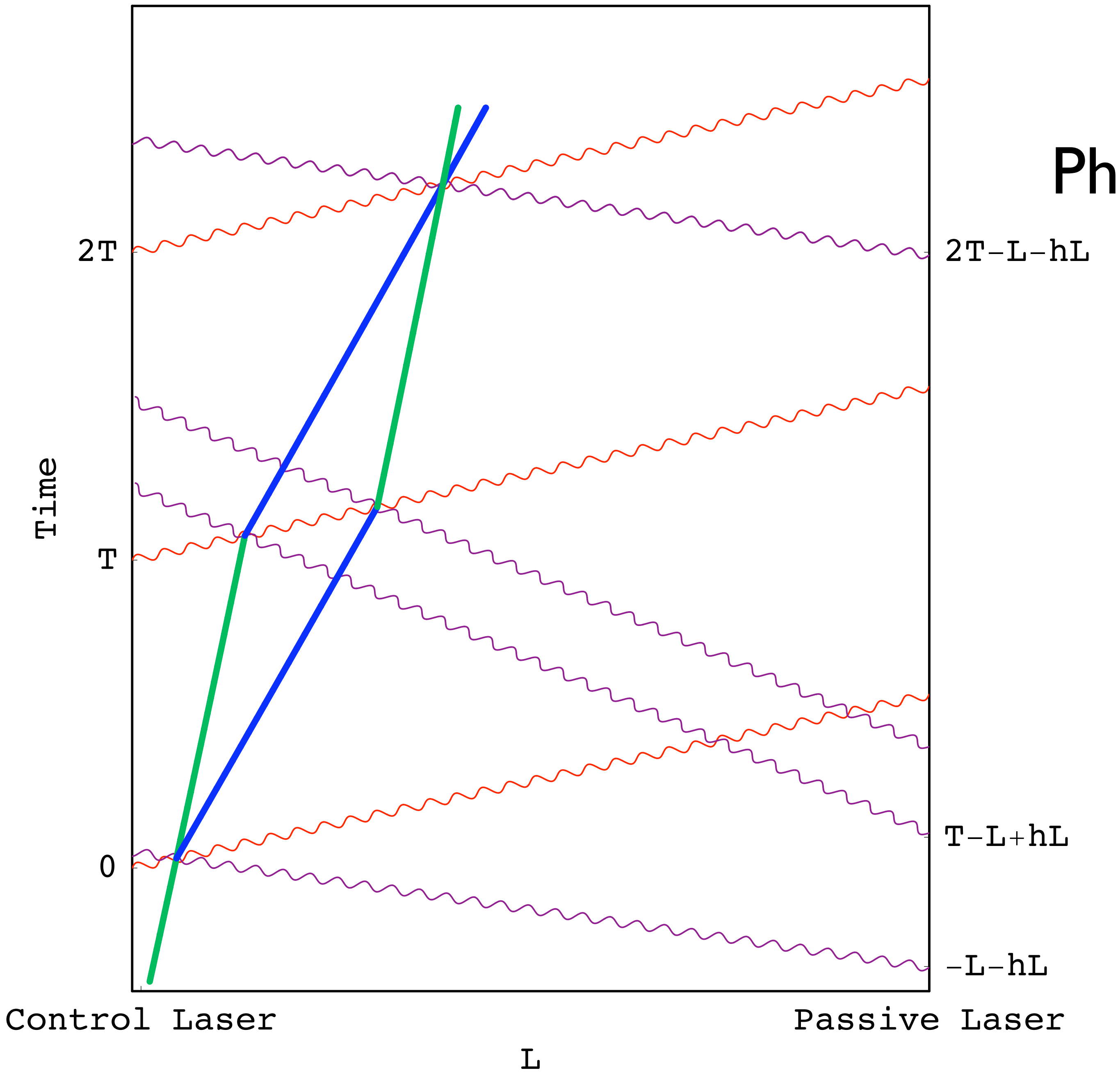

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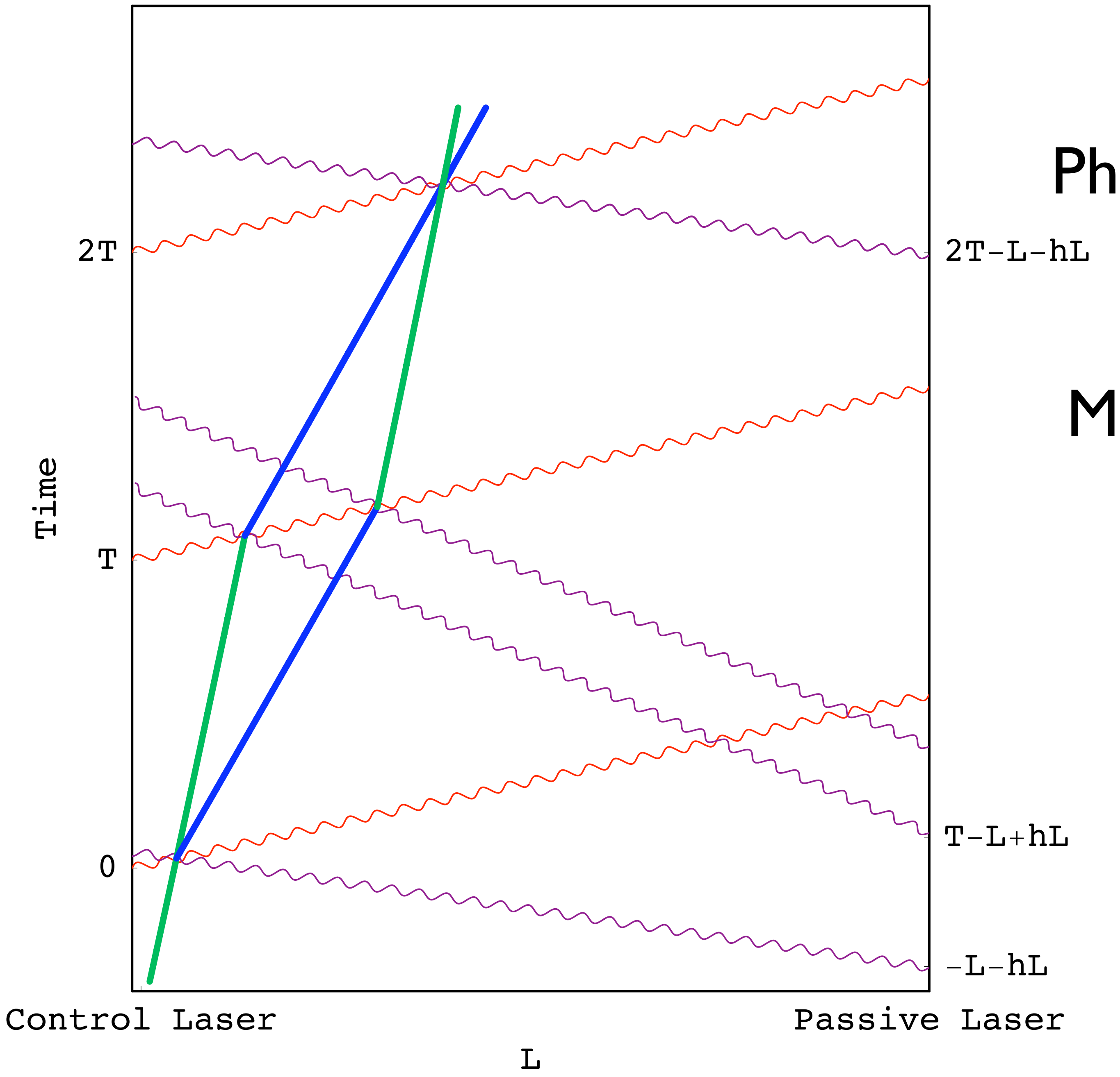

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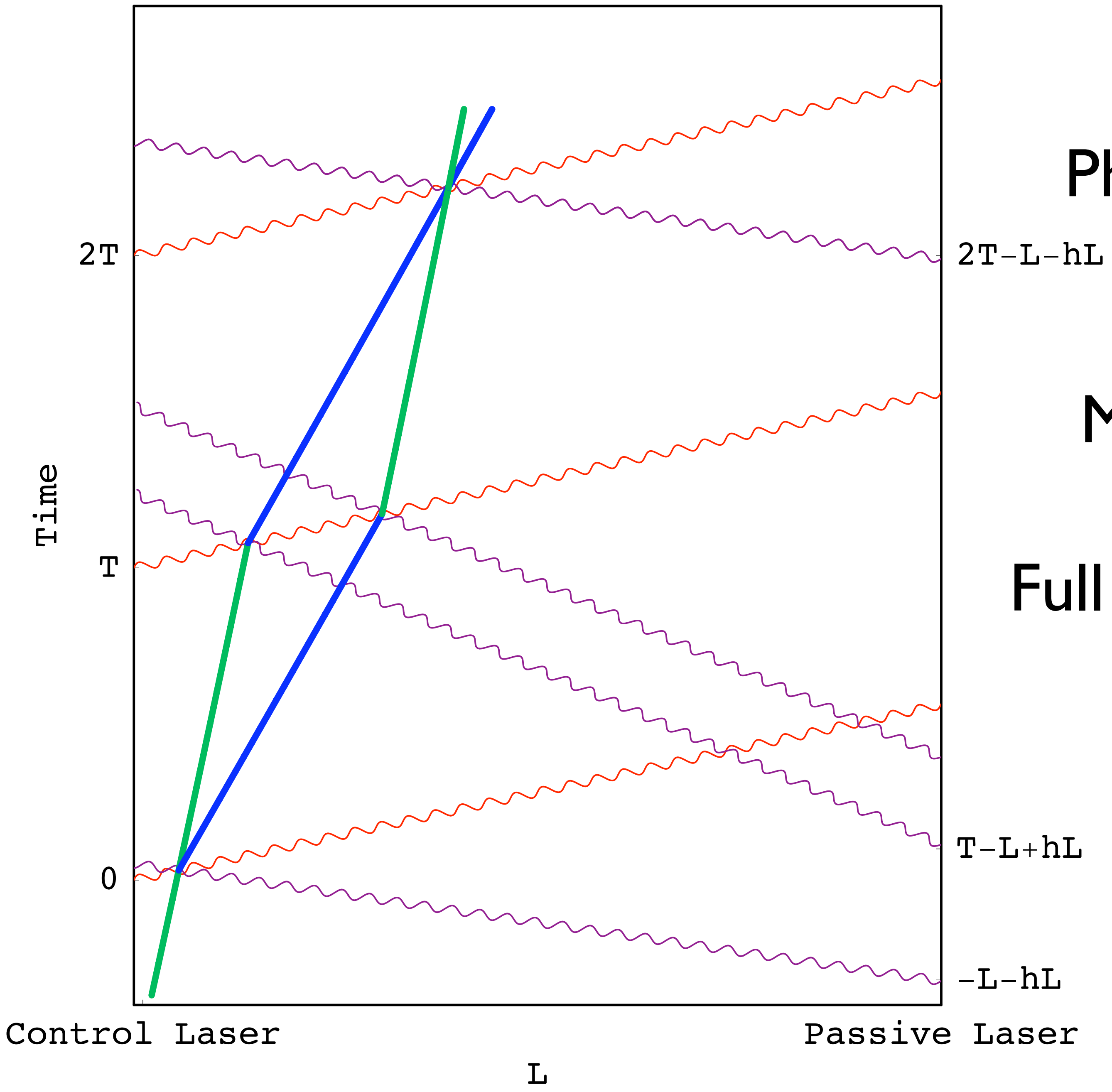

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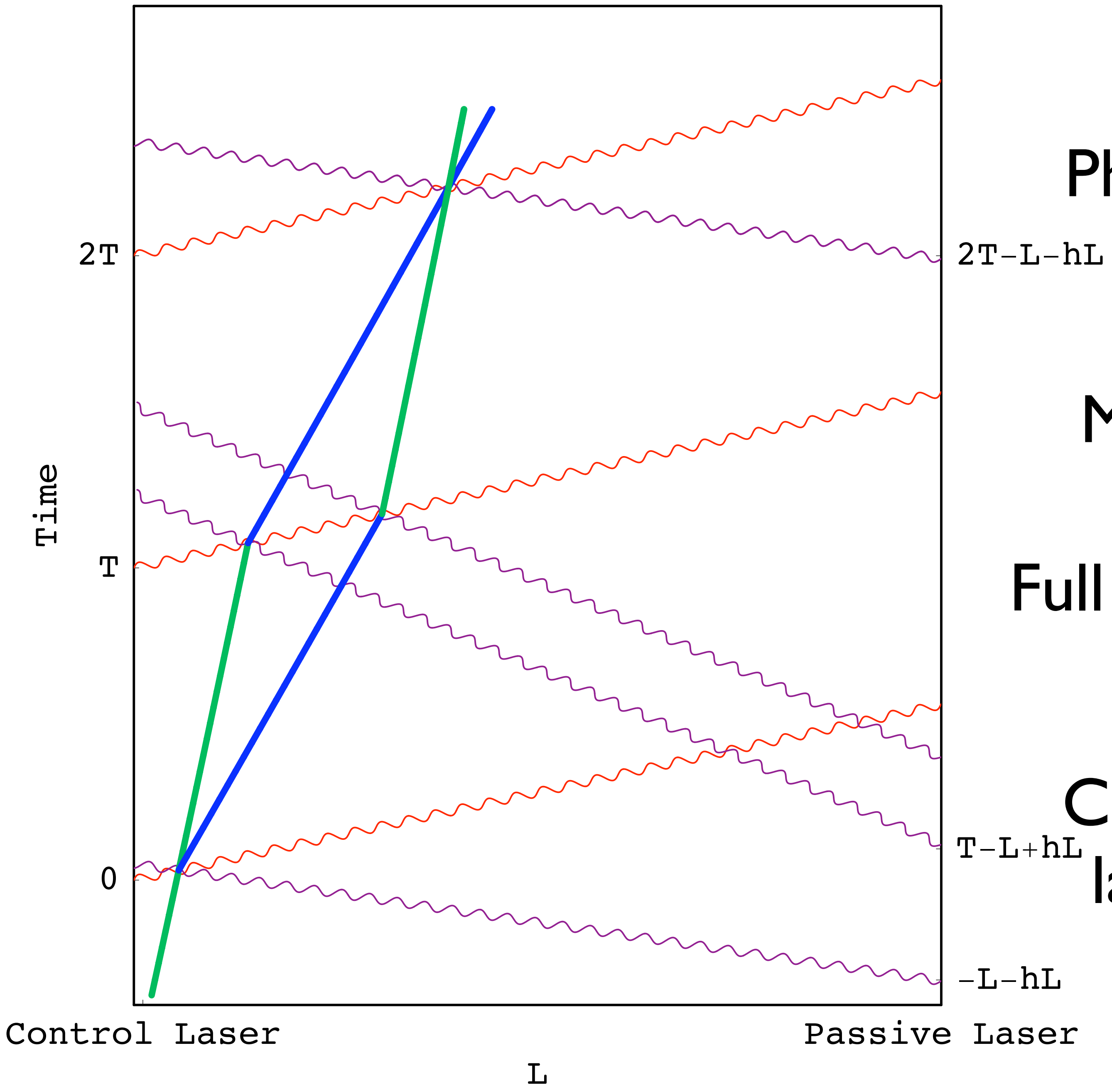

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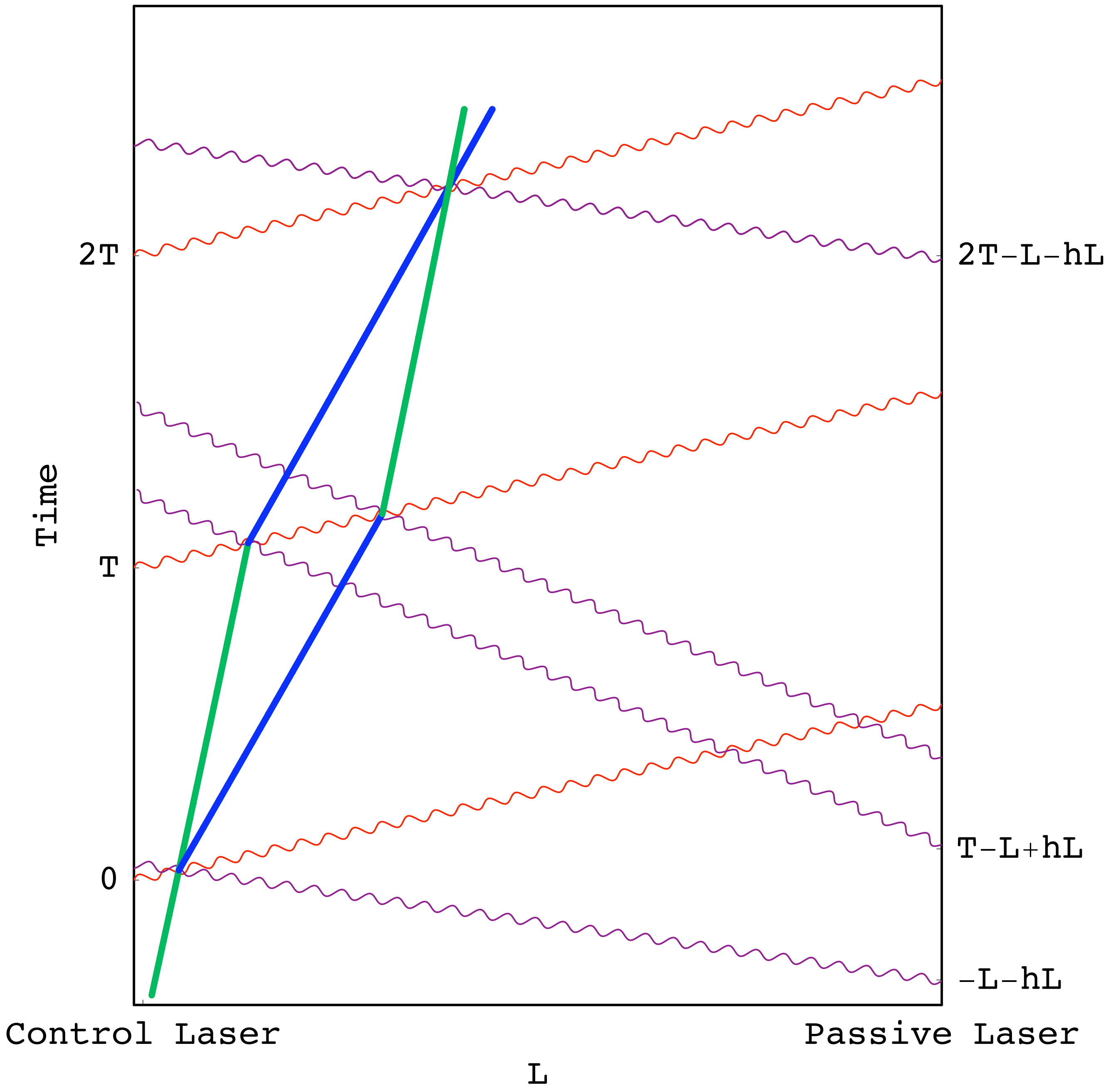
Comparison of two distant clocks (atom, laser) in the presence of a gravitational wave.

The Gravitational Wave Signal in the Interferometer

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



Measuring acceleration ~ h L between atom and laser due to gravitational wave.

What about vibrational noise?

The atoms are in free fall during the course of the interferometry.

Atoms coupled to vibrations only gravitationally. A *much* smaller effect!

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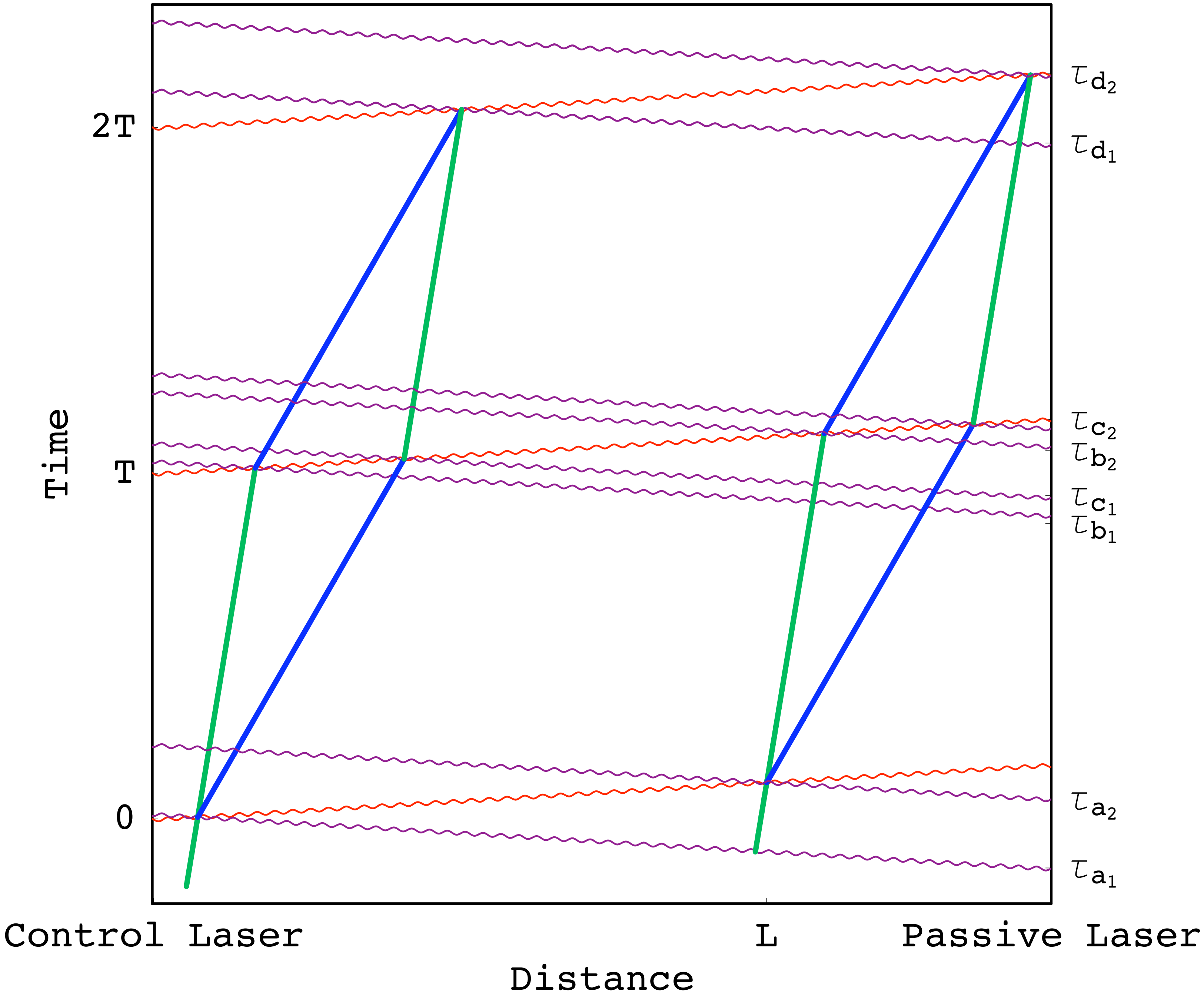
Laser phase noise?

Differential Measurement

Run two, widely separated atom interferometers using common lasers.



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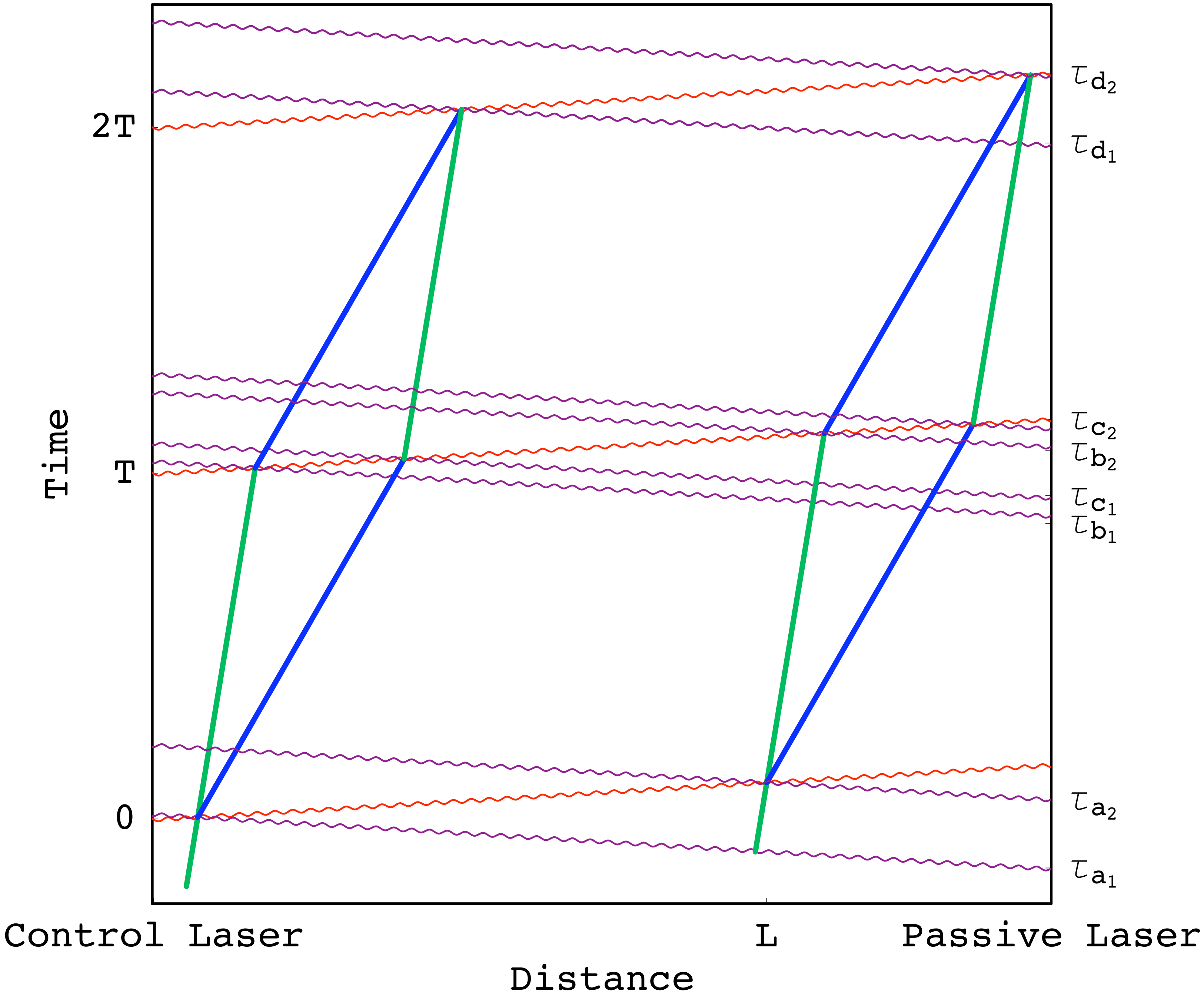

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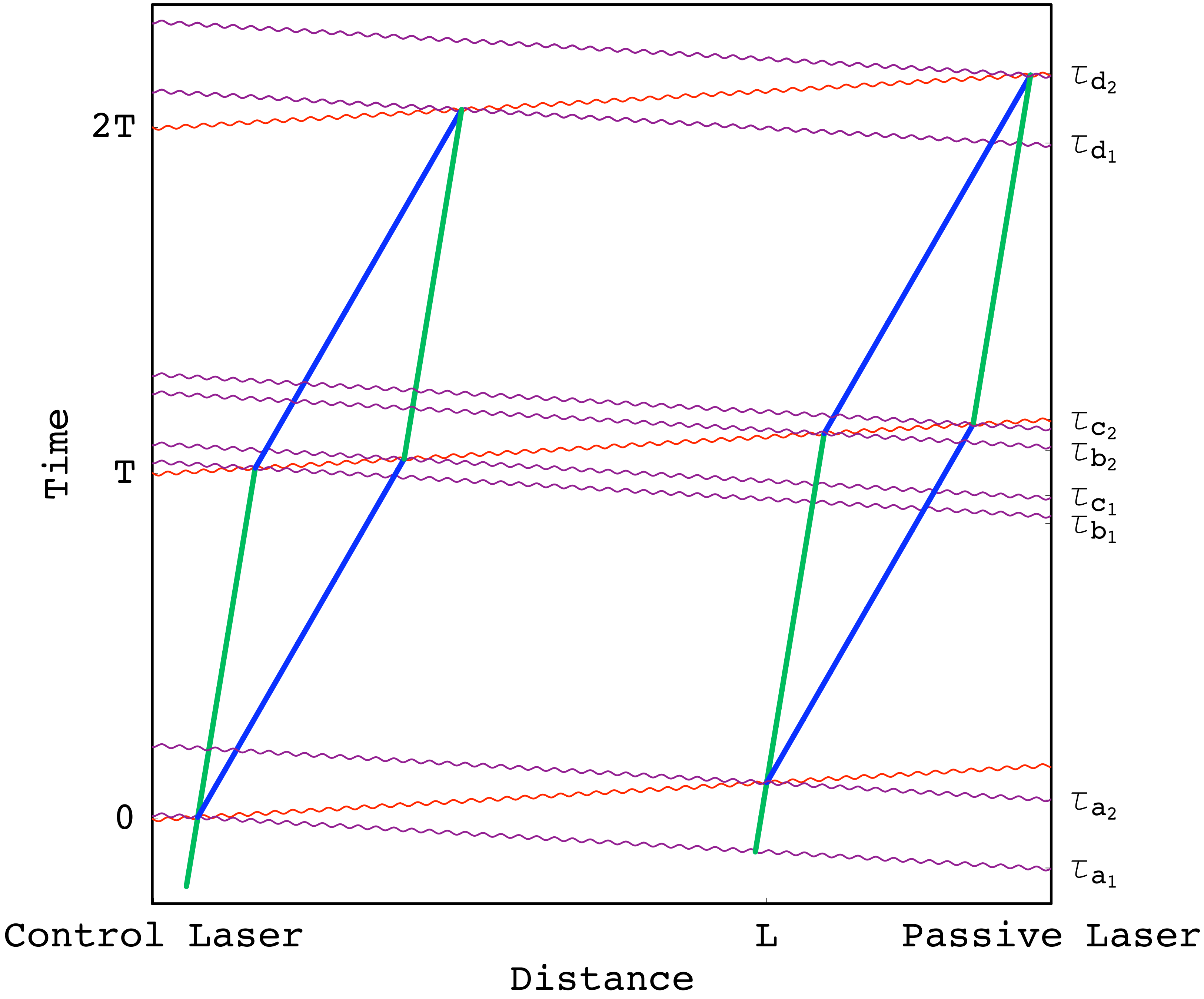

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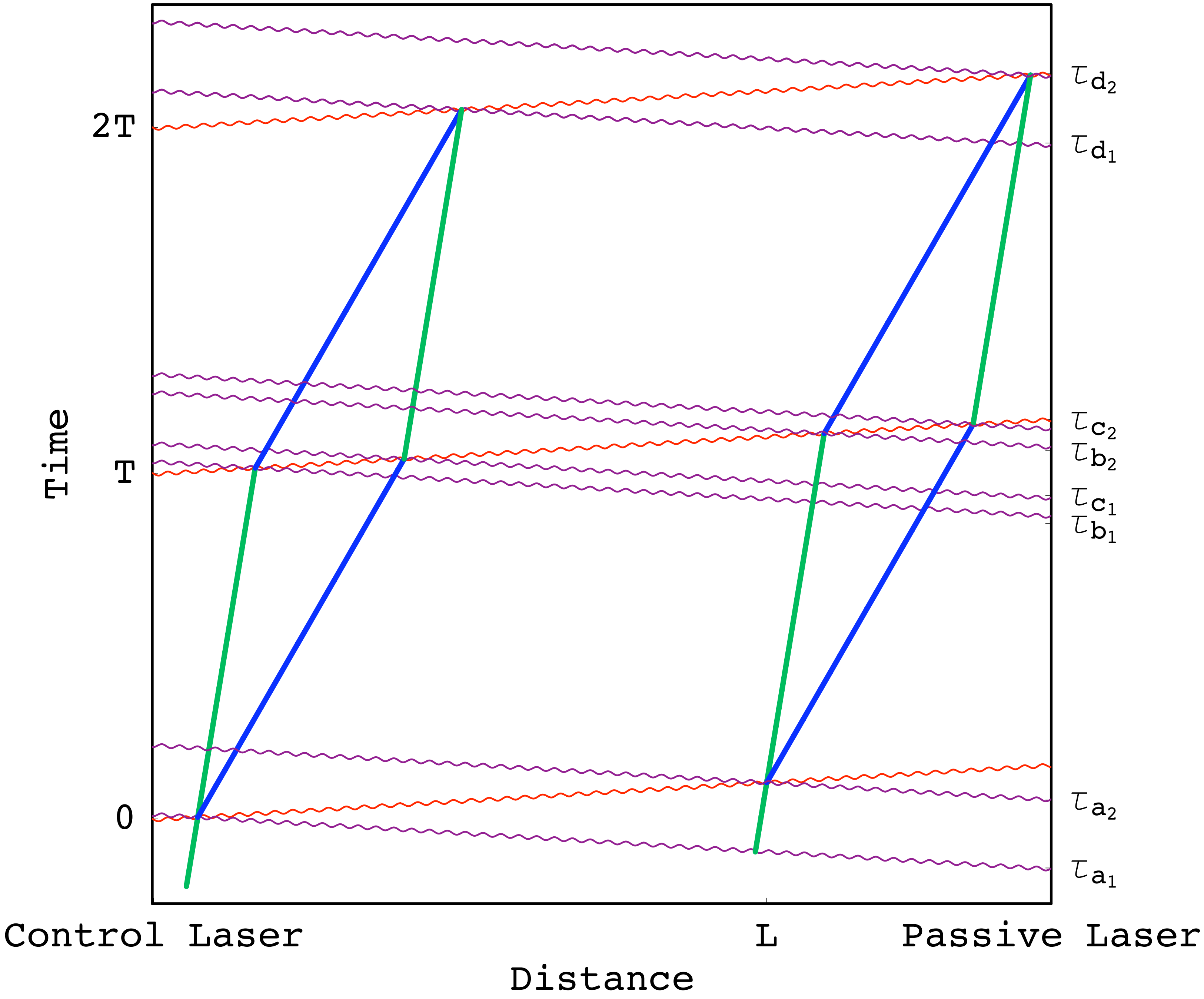

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Laser vibration and phase noise cancels (up to finite light travel time effects).

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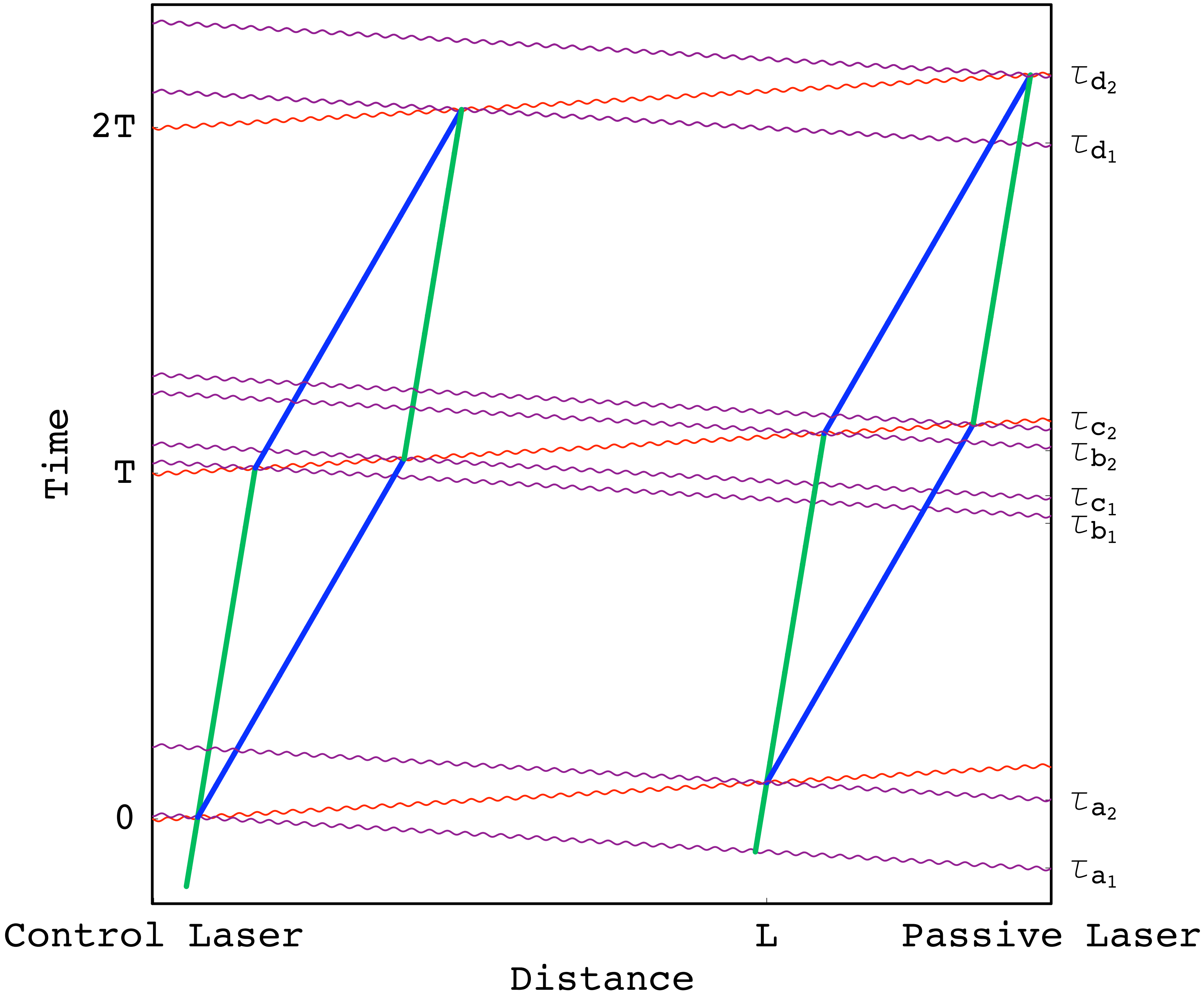

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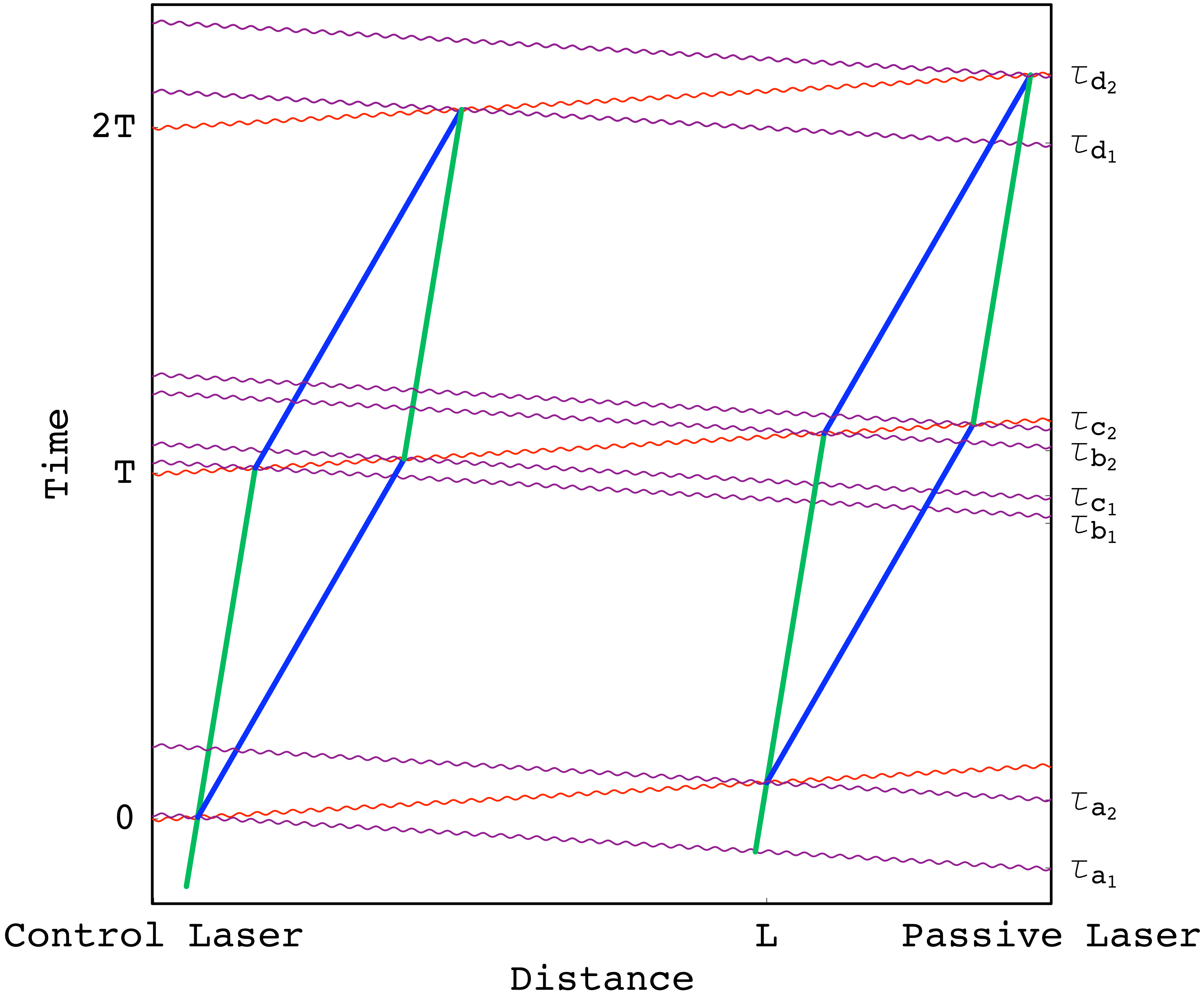

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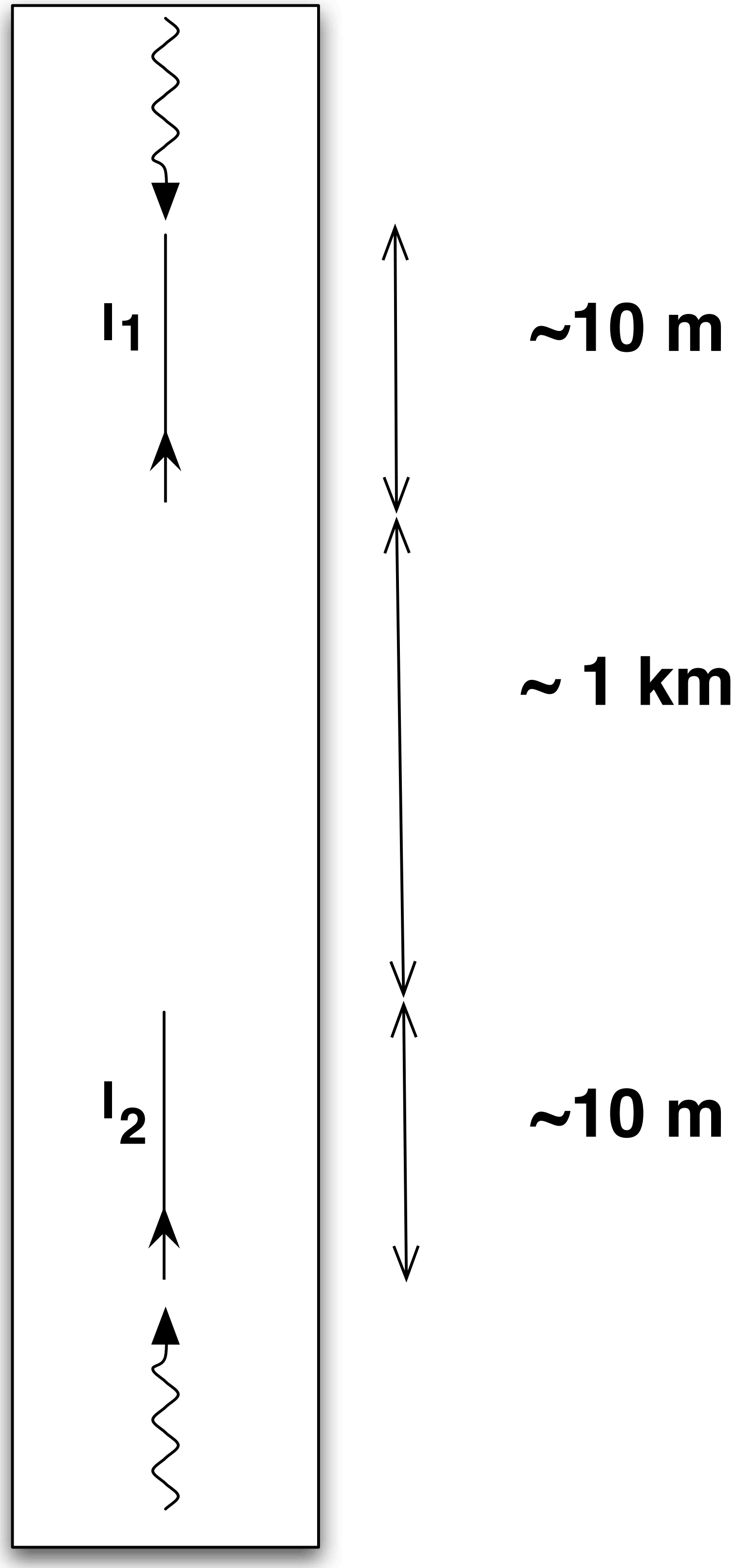
Atoms are LIGO's mirrors.

Role of laser similar to LIGO's laser.

Terrestrial Configuration

Two 10 m atom interferometers at either ends of a vertical mine shaft.

Both interferometers are operated by common lasers.



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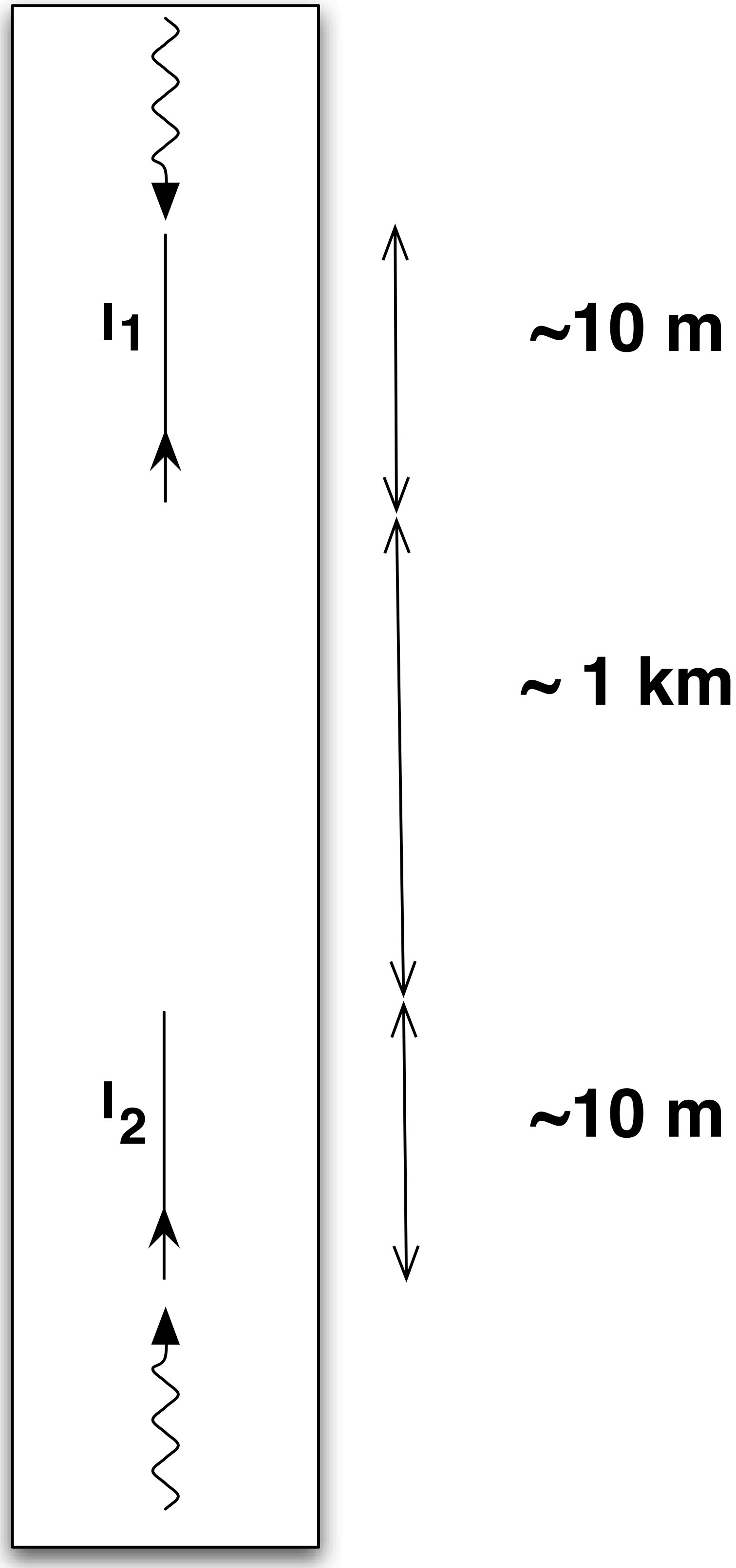

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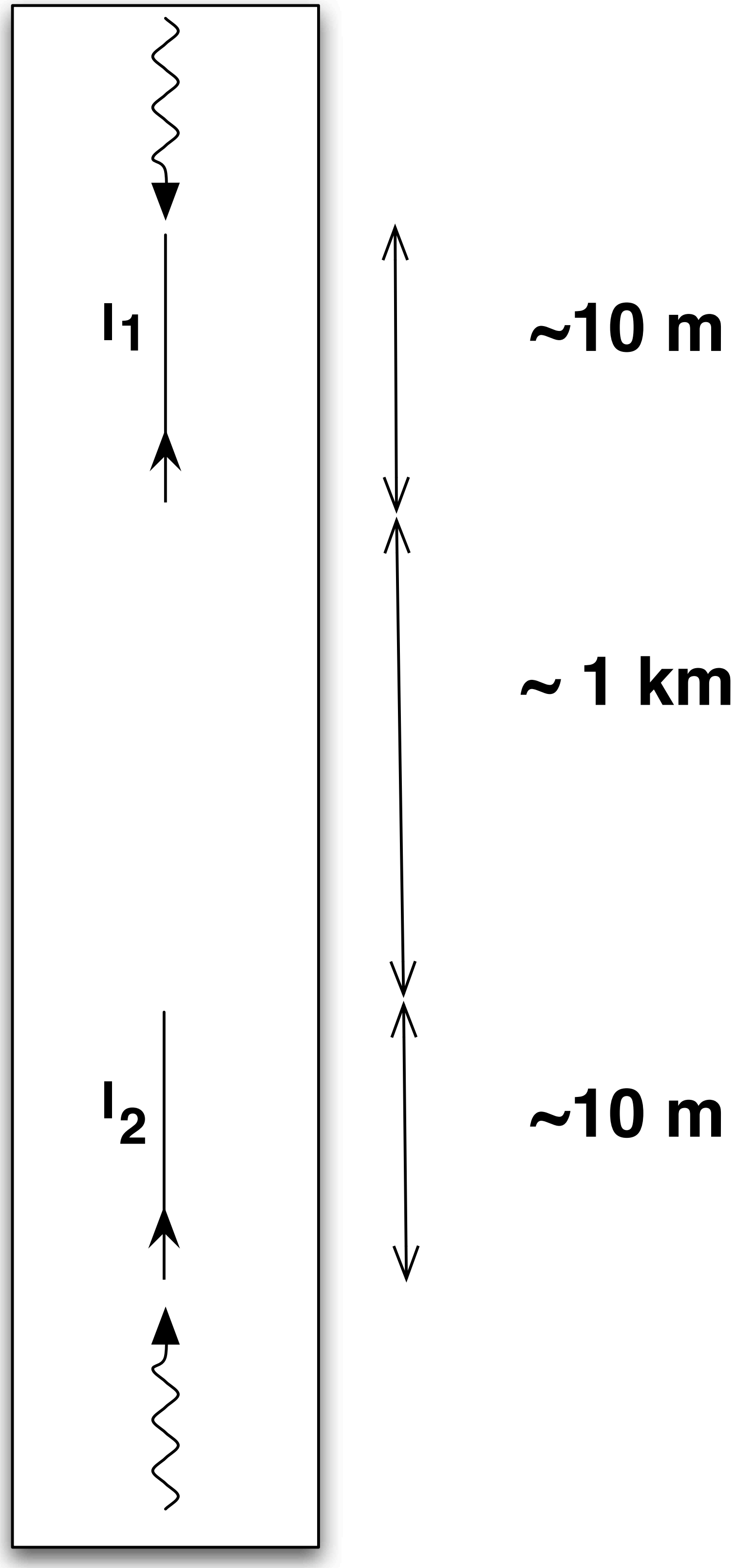

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One possible site: DUSEL Homestake Mine in South Dakota (longest shaft ~ 2.5 km).

Backgrounds

Systematics due to finite light travel time:

For L ~ 1 km, light travel time ~ $3 \times 10^{-6}\mathrm{s}$

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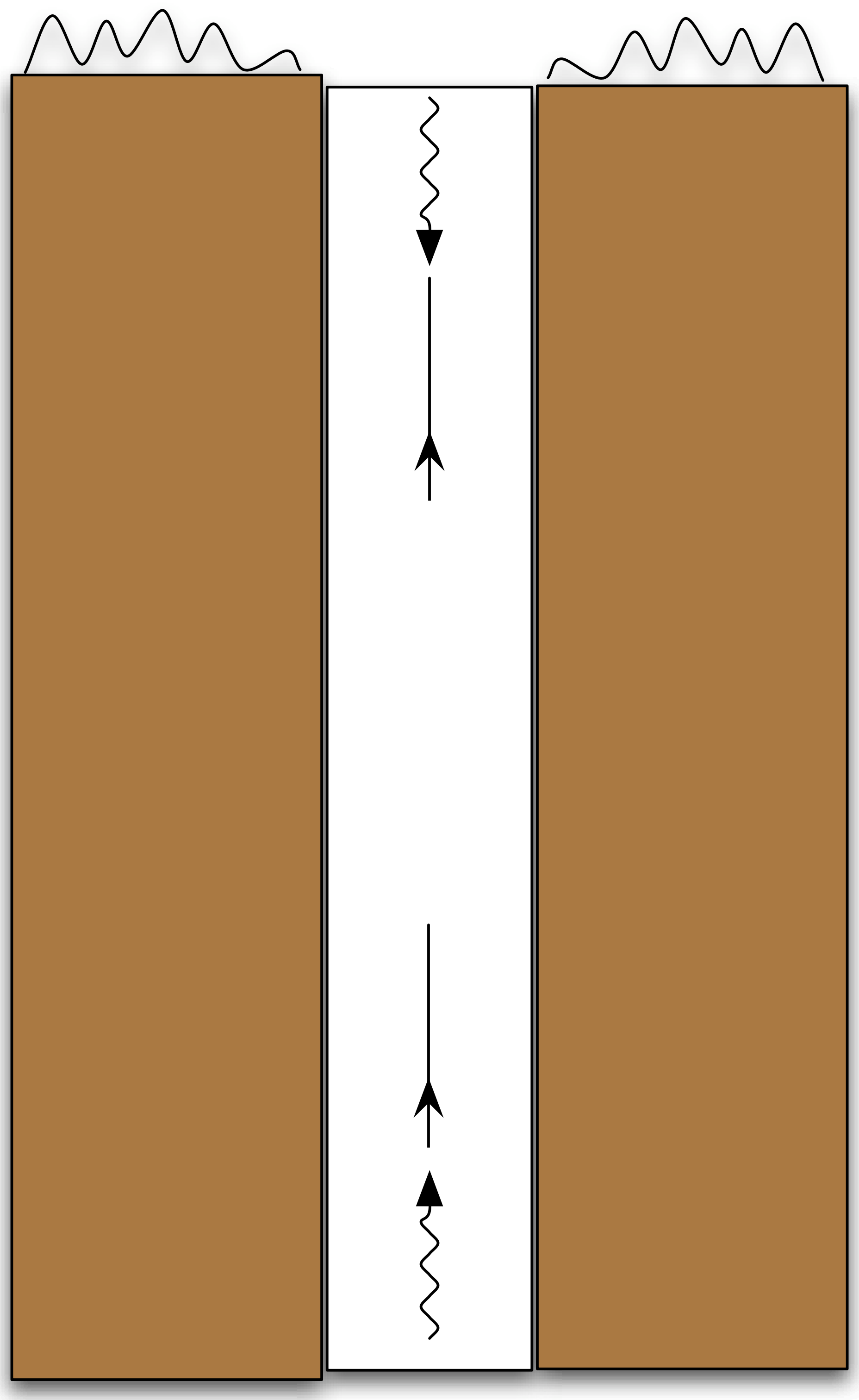
Ultimate Background for Terrestrial Gravitational Wave Detection



Seismic vibrations gravitationally couple to the free falling atoms.

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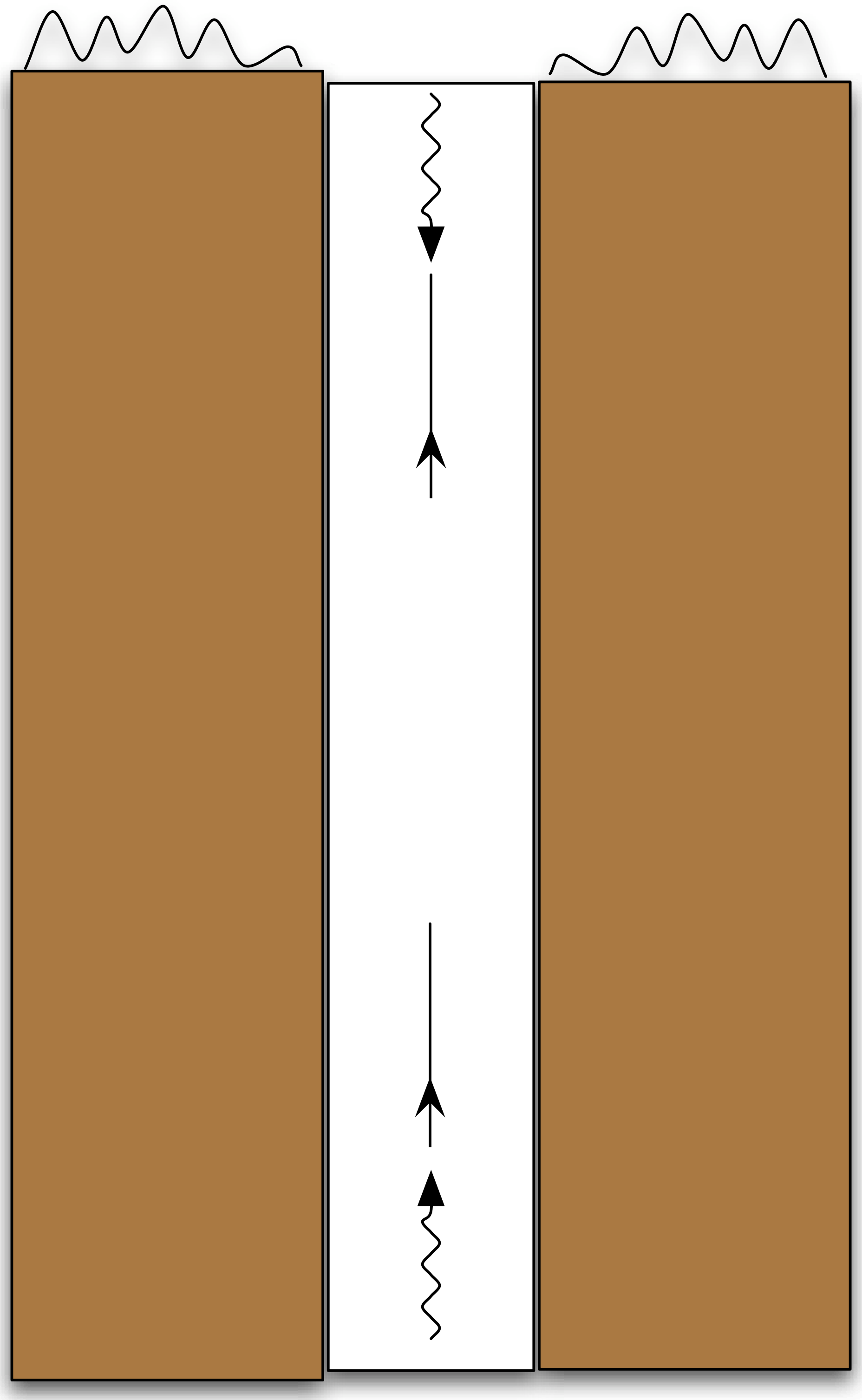

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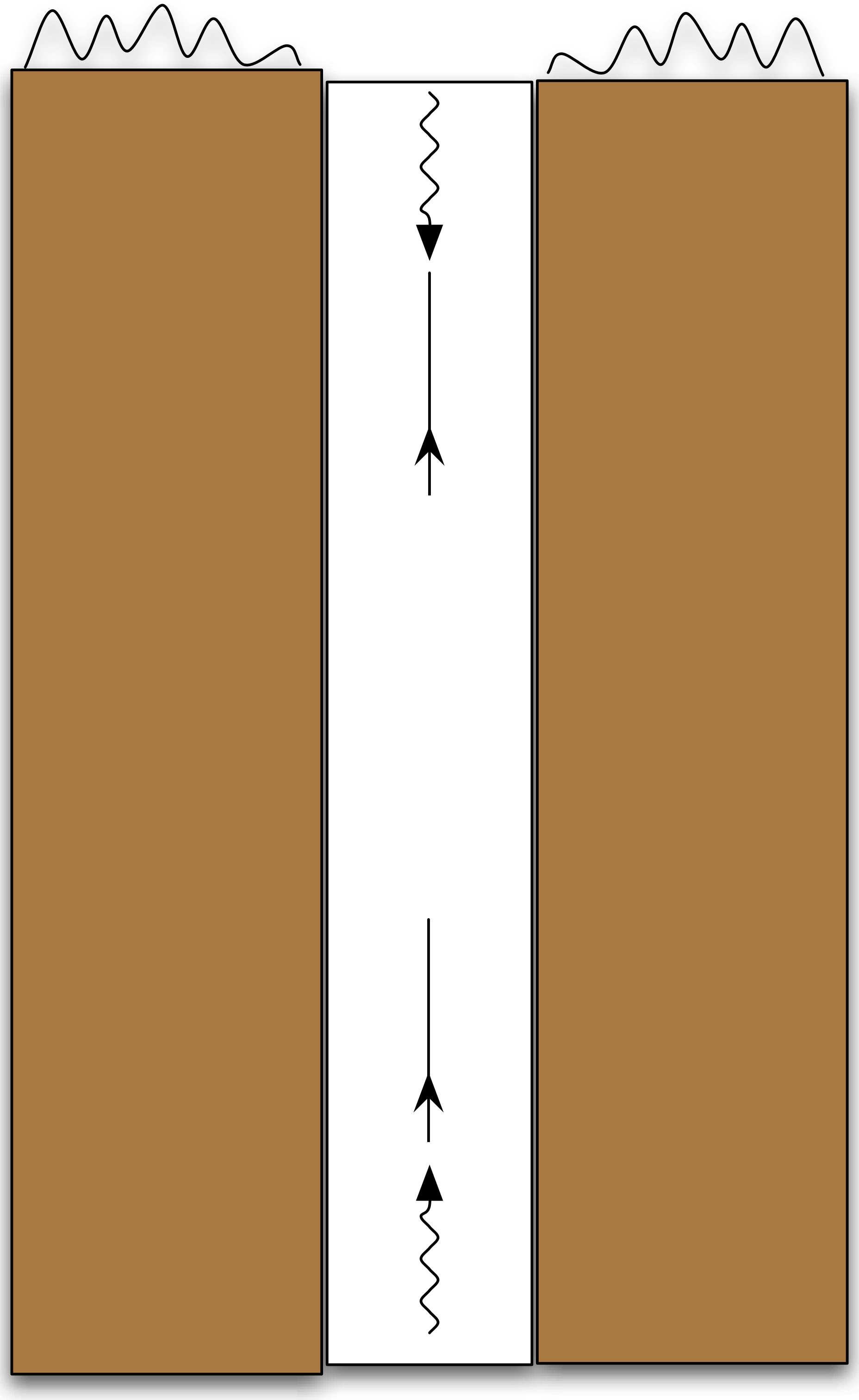

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Allows for gravitational wave detection down to

$$\omega \sim 0.3 \text{ Hz}$$

(Thorne and Hughes)

Satellite based Gravitational Wave Detection

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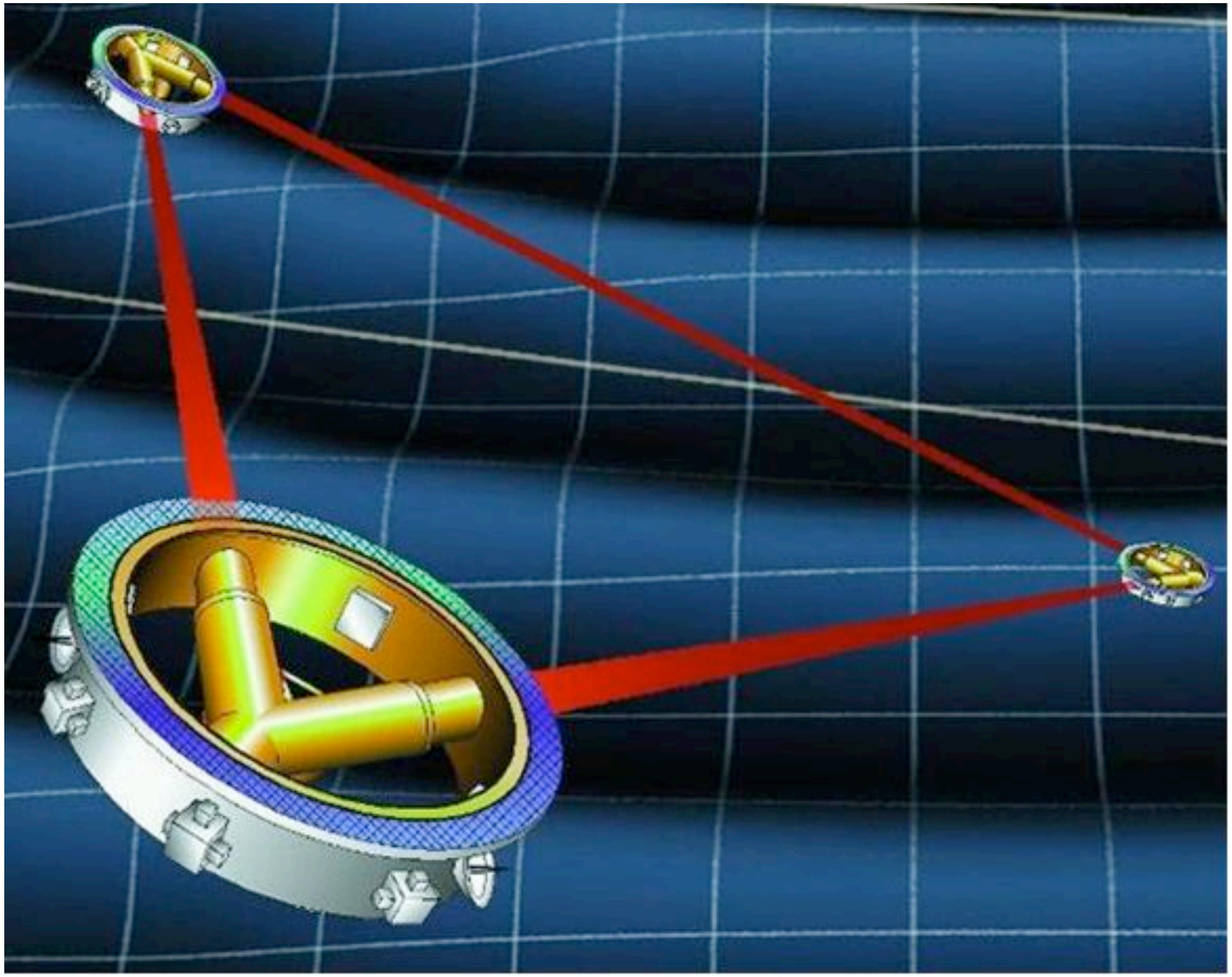
LISA



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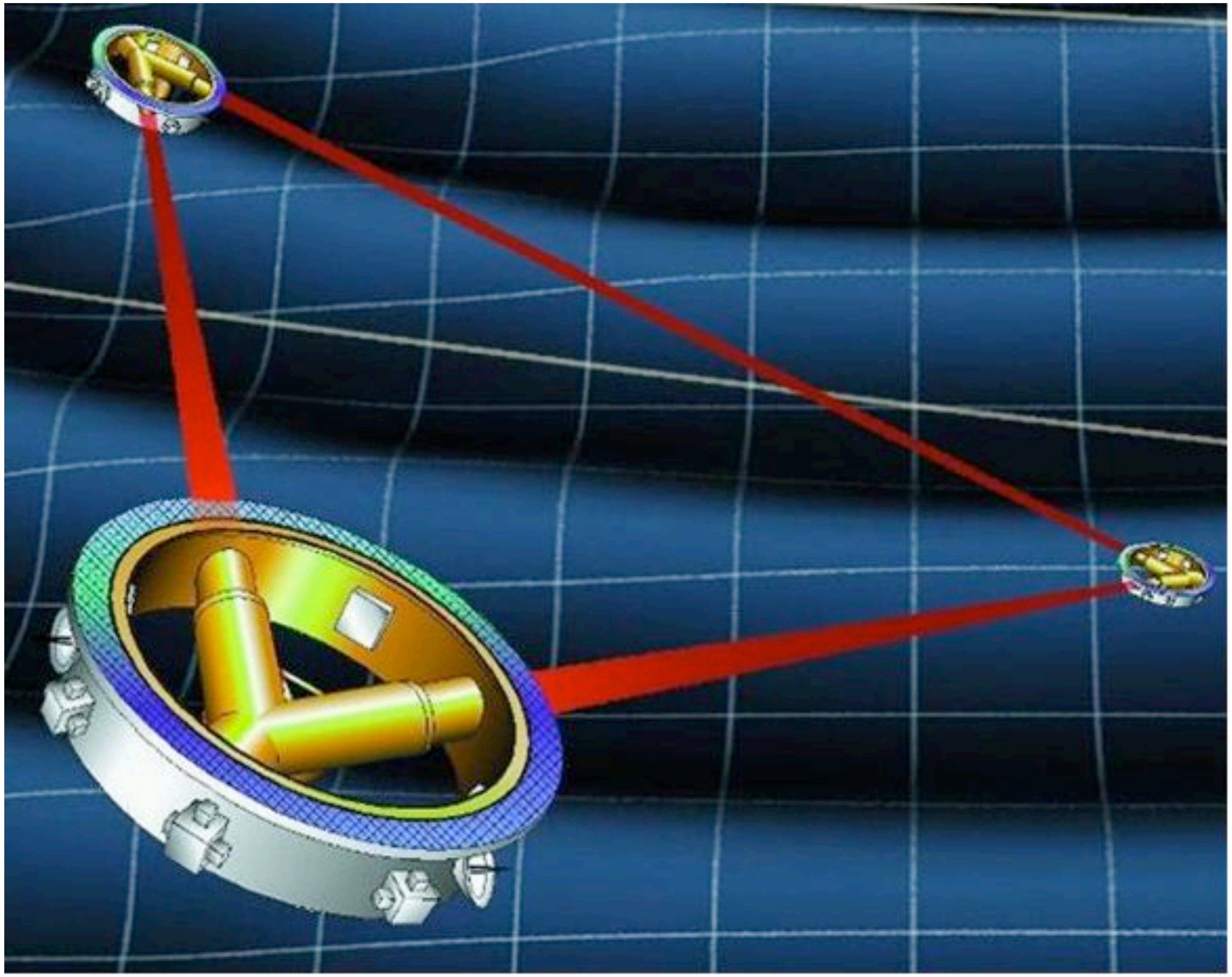

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Arm length L ~ 5 million km.

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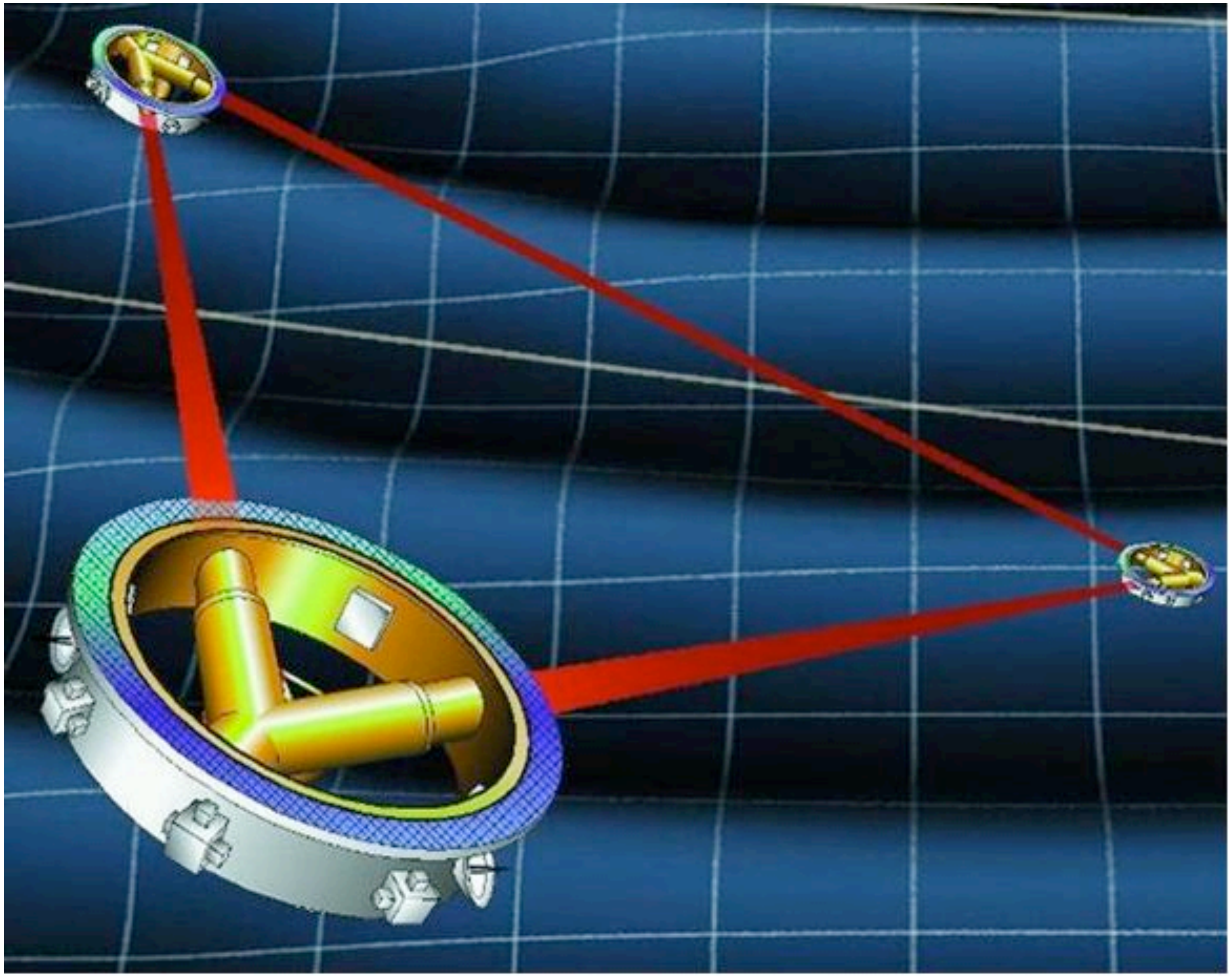

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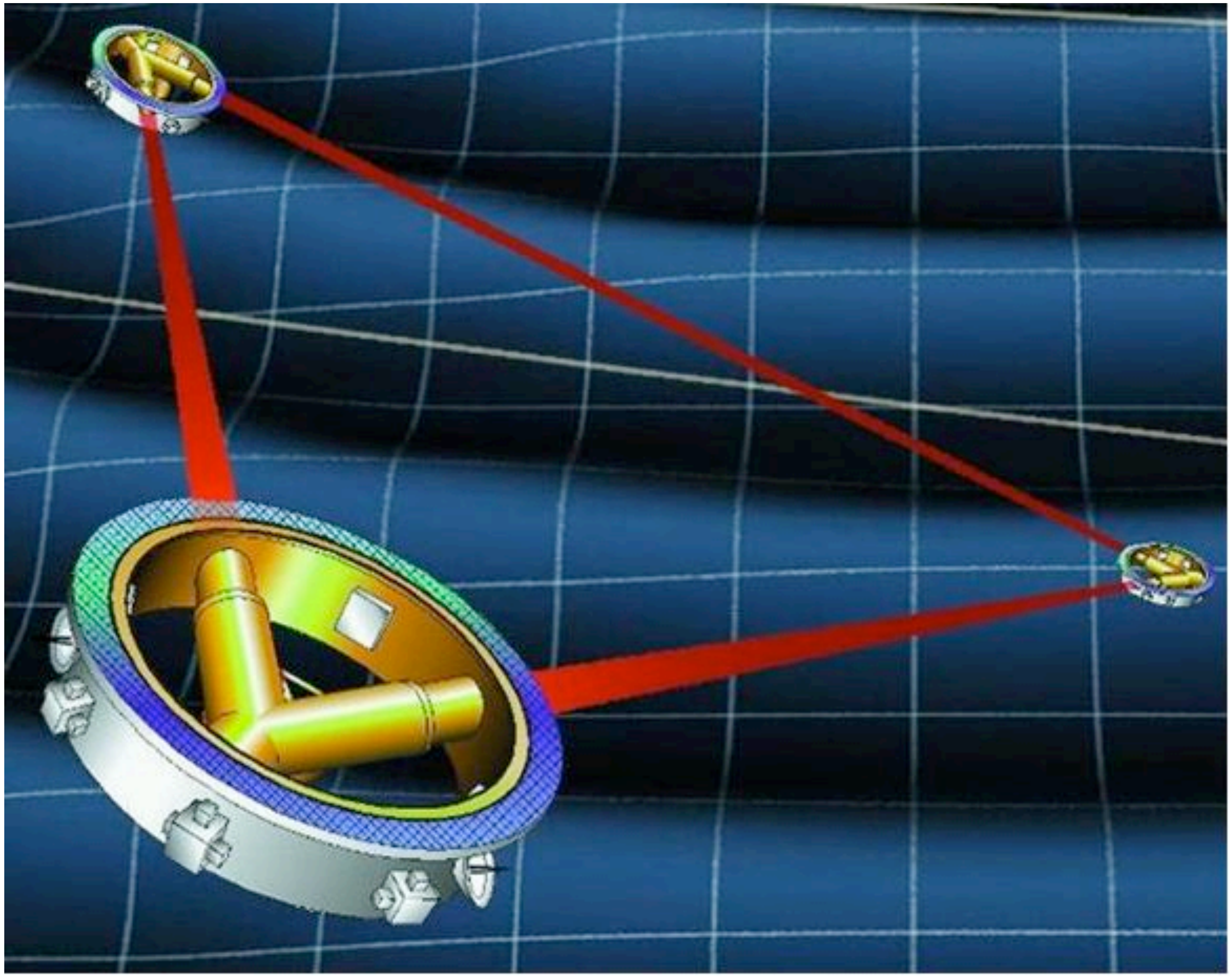

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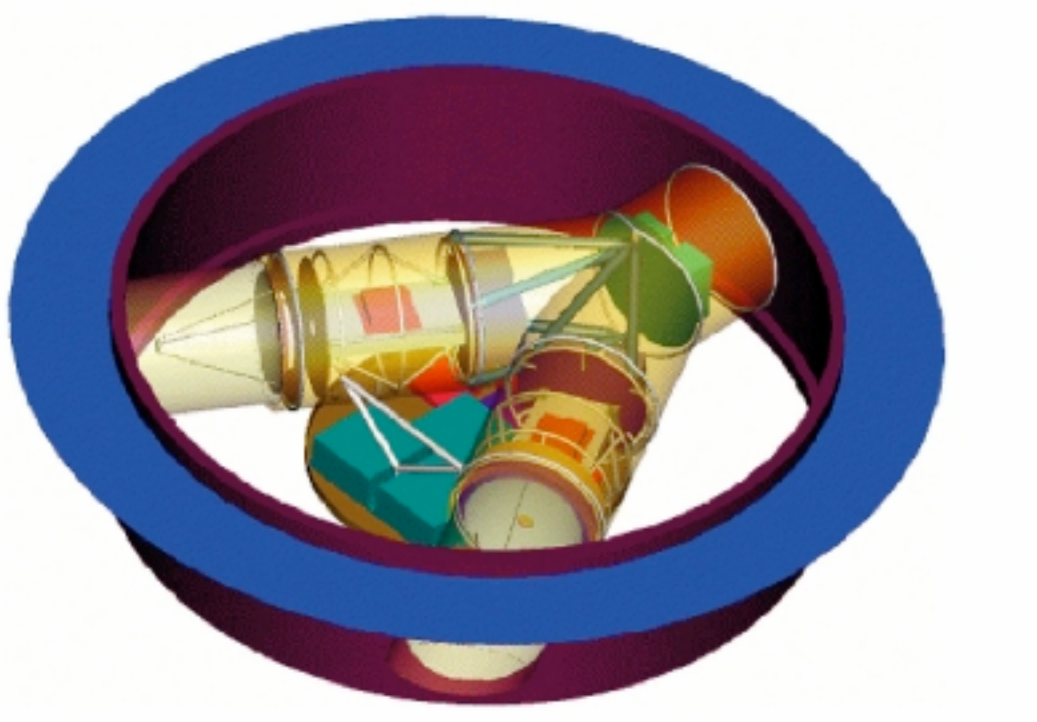
A gravity wave of amplitude $h \sim 10^{-20}$ causes a length change $hL \sim 10^{-10}$ m.

The LISA Challenge

LISA Satellite



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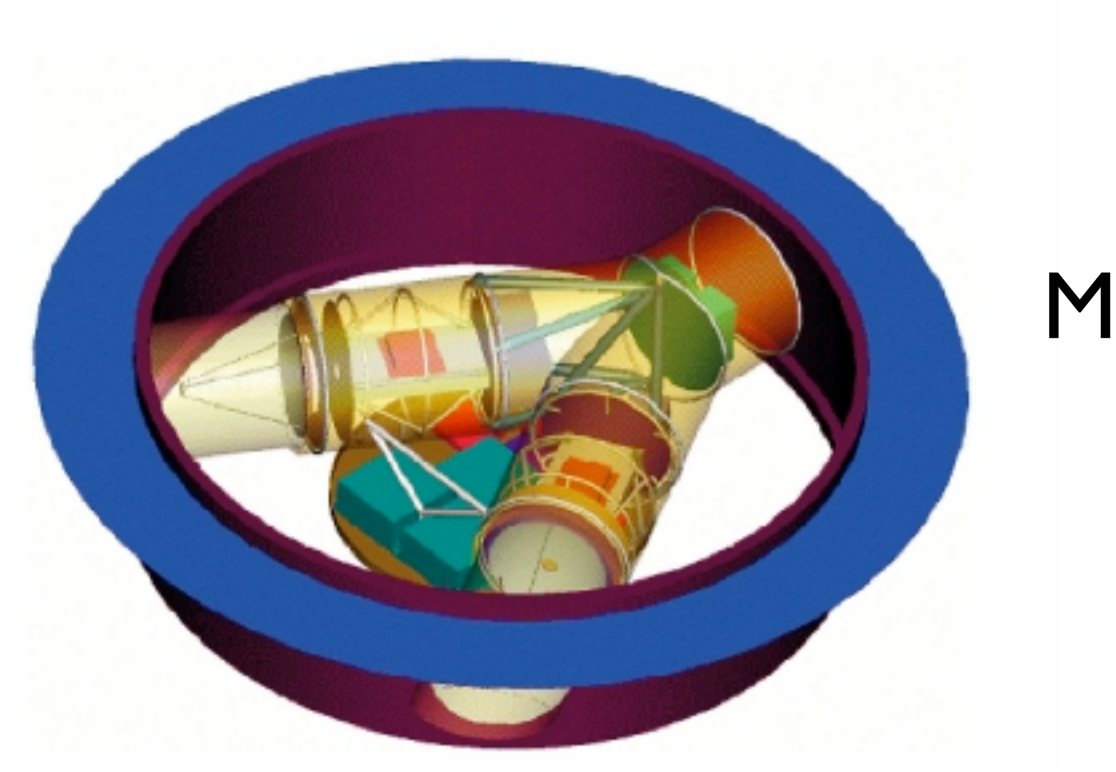

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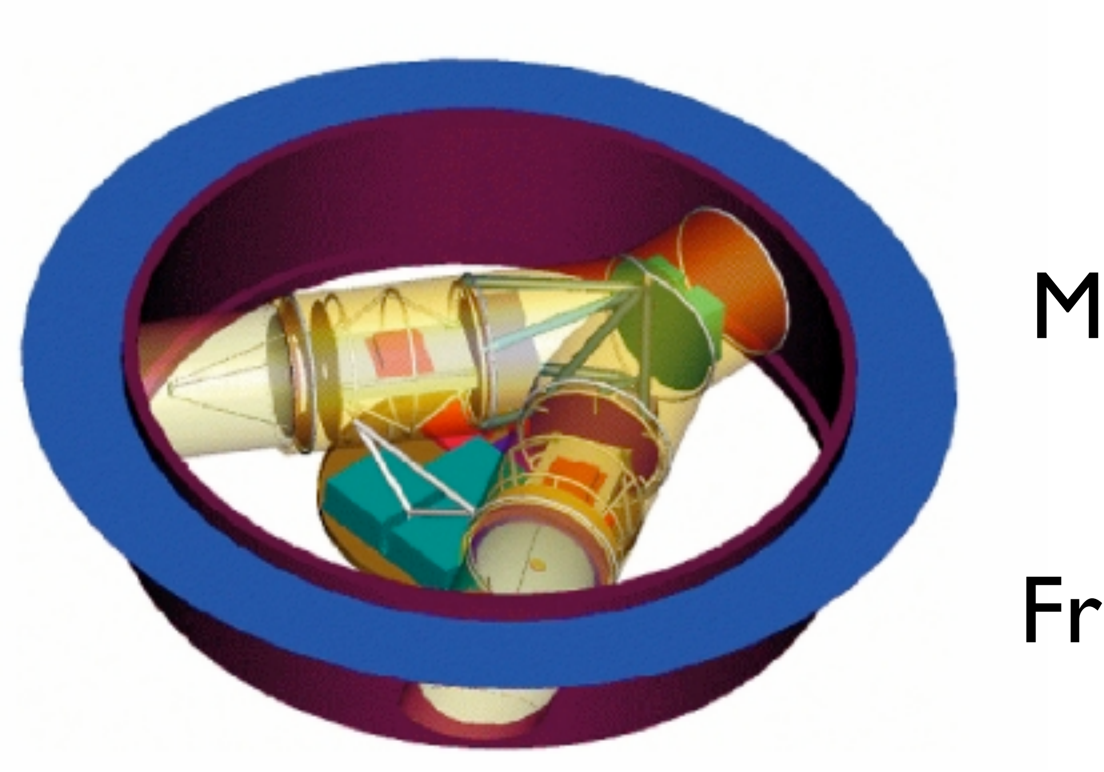

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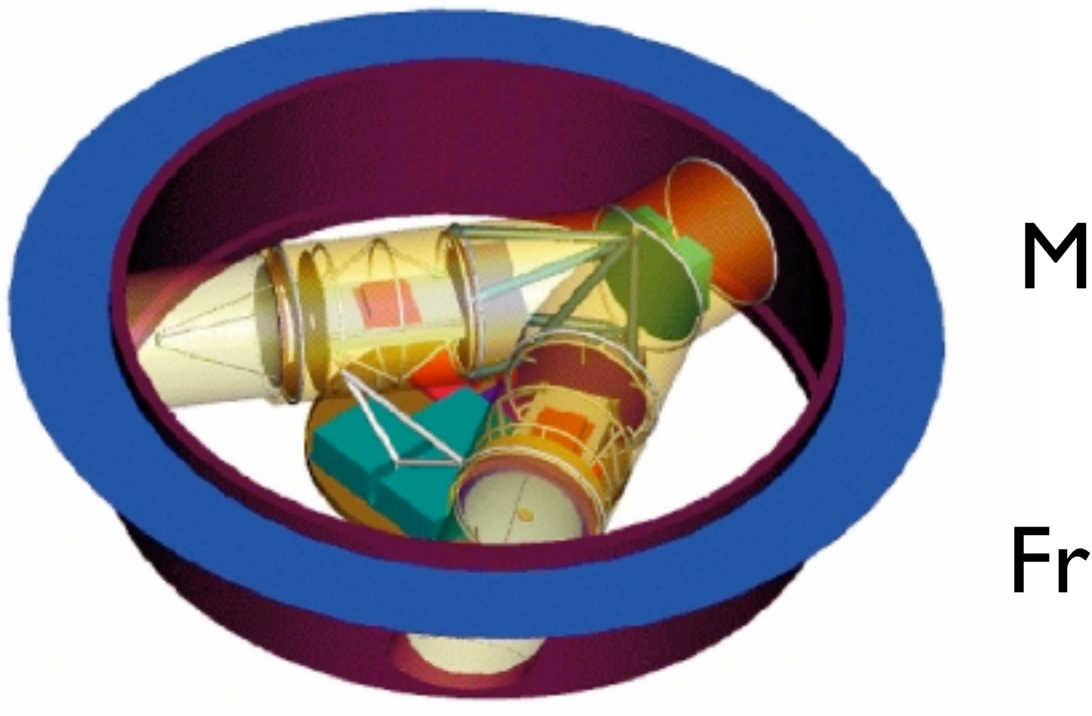

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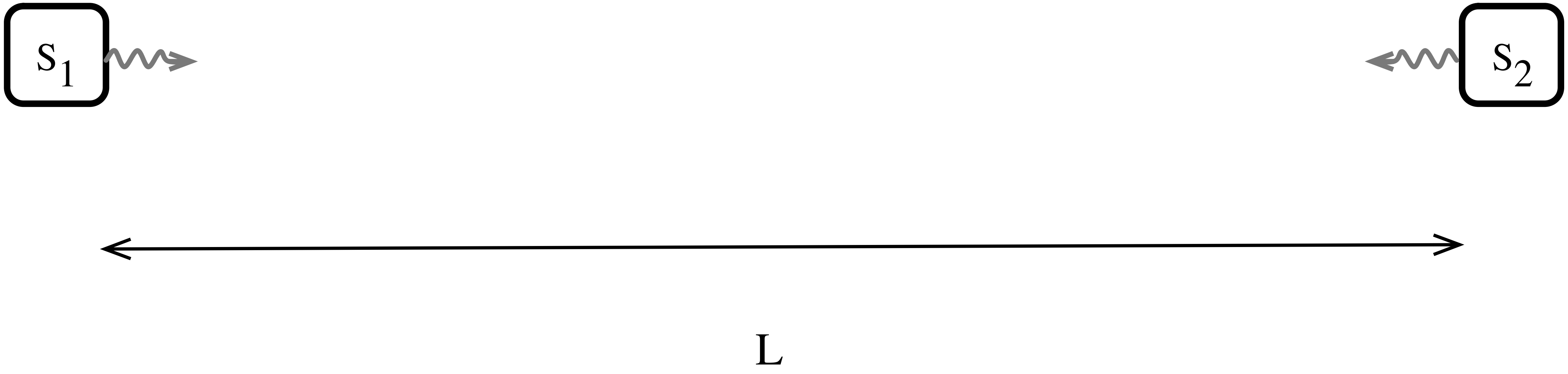
Major hurdle for LISA

Atom Interferometer Satellite Configuration



Two widely separated atom interferometers run by common lasers.

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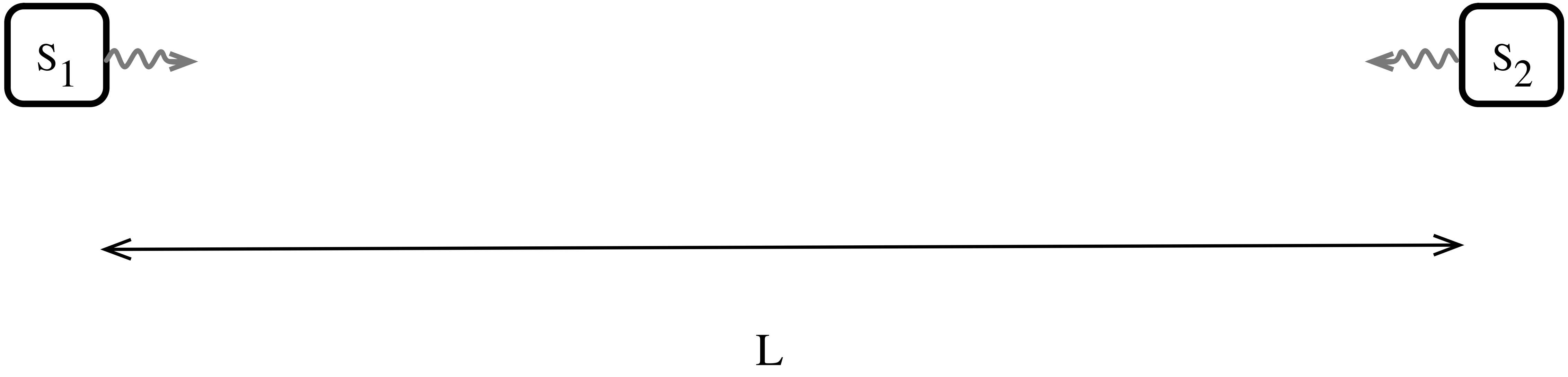

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Atom sources and lasers need to be housed in the satellite.

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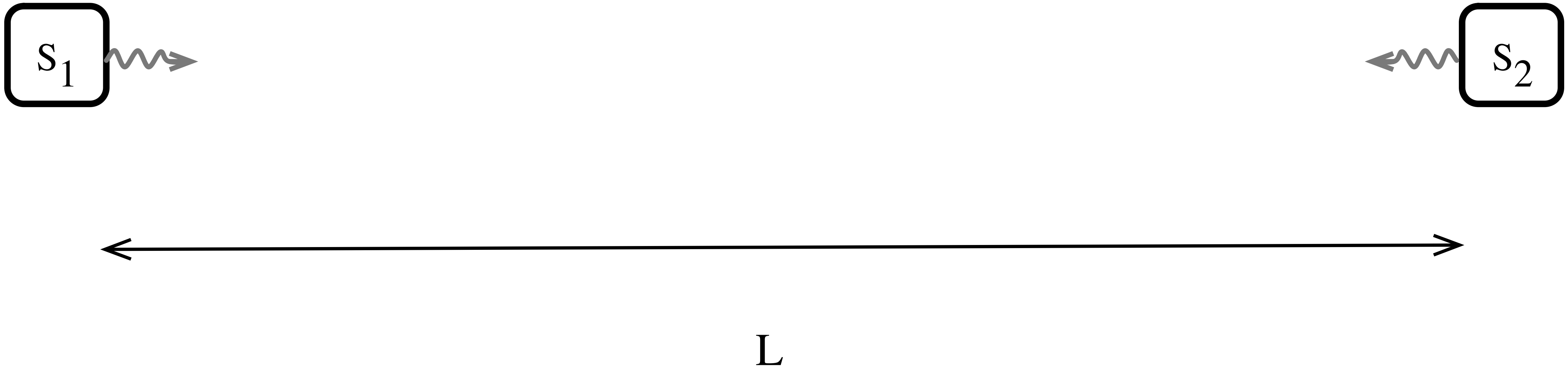

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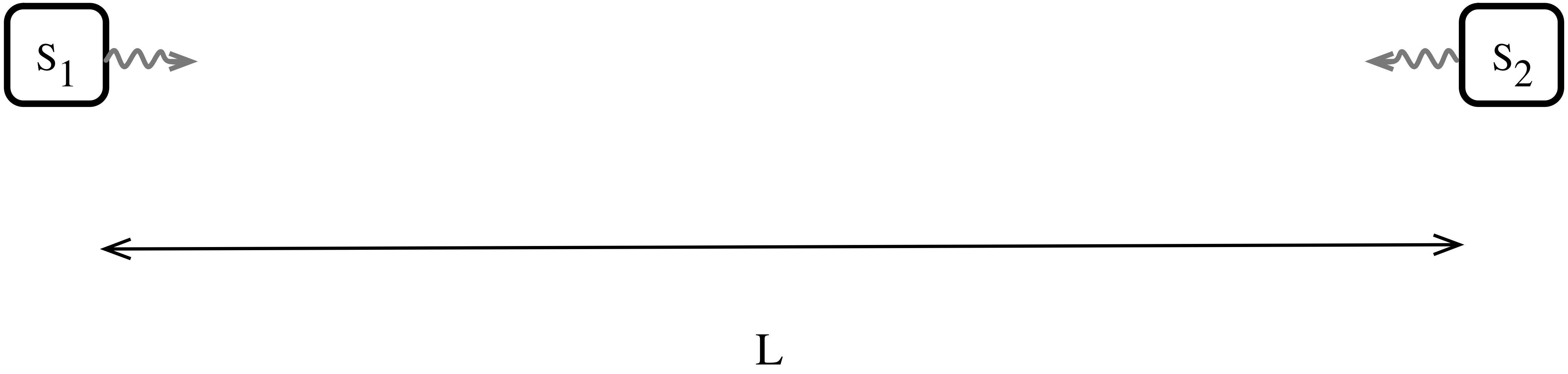

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Do the atom trajectories have to lie inside the satellite?

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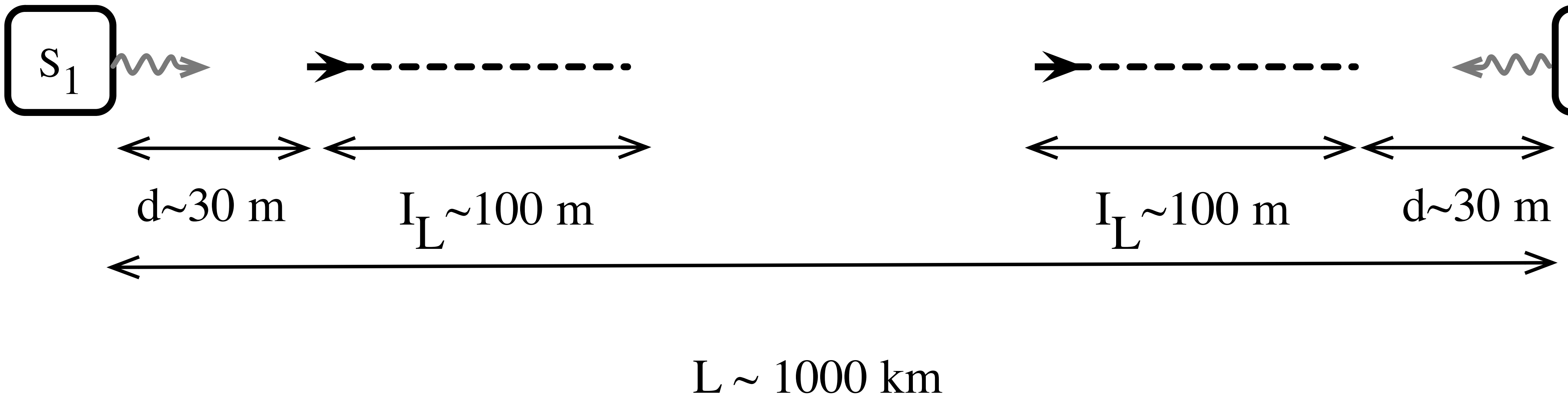
Interplanetary magnetic field at 1 AU ~ 5 nT. Permanent magnet can provide bias field ~ 20 - 100 nT over 100 m region from satellite.

Satellite Experiment Setup



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Run interferometer over region l_L ~ 100 m.

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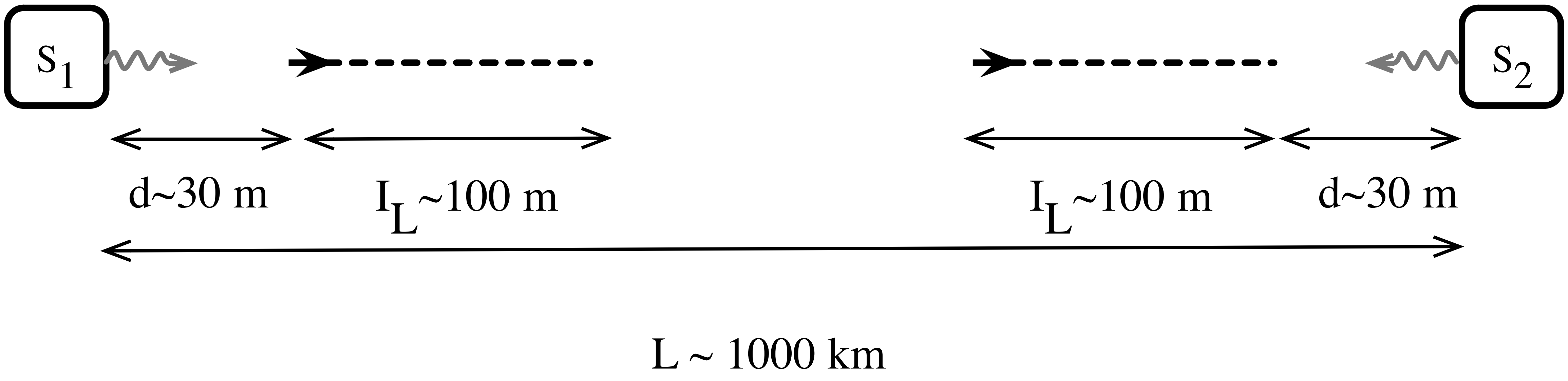

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Position fluctuation δr of the satellite causes an acceleration $\sim \left(\frac{GM_{\rm sat}}{d^2}\right)\left(\frac{\delta r}{d}\right)$

Effects of satellite position noise strongly suppressed with increasing d.

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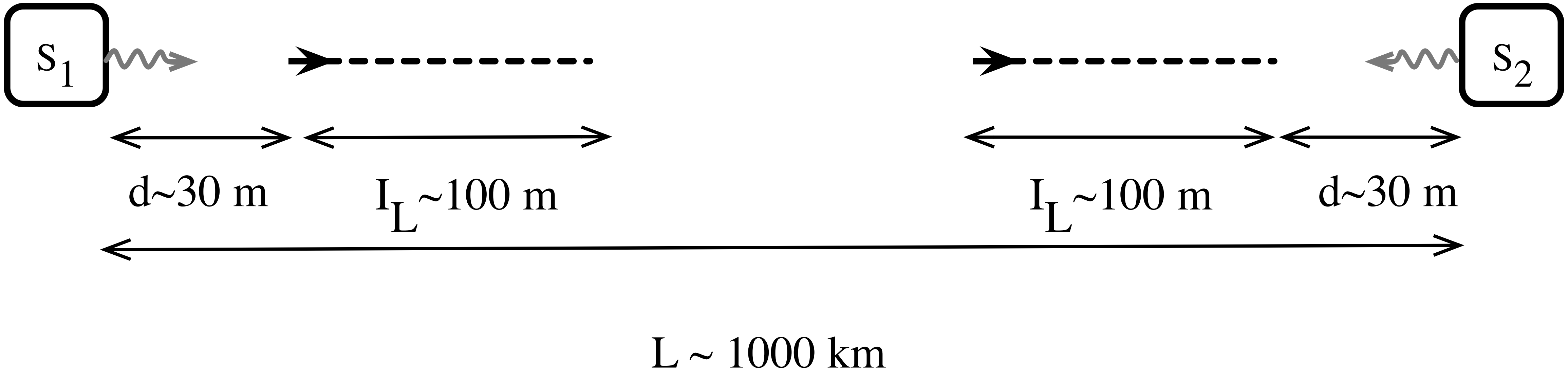

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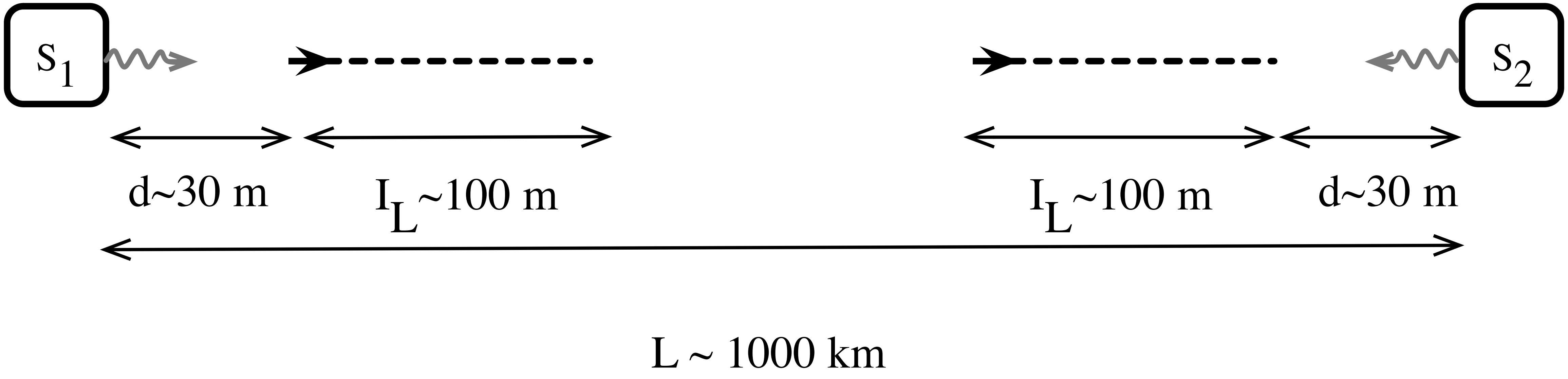

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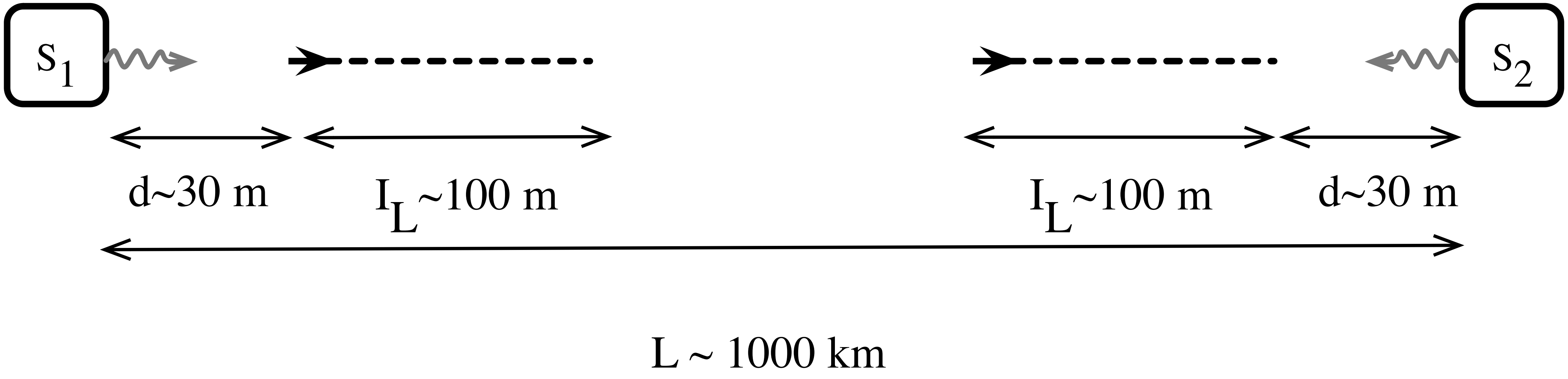

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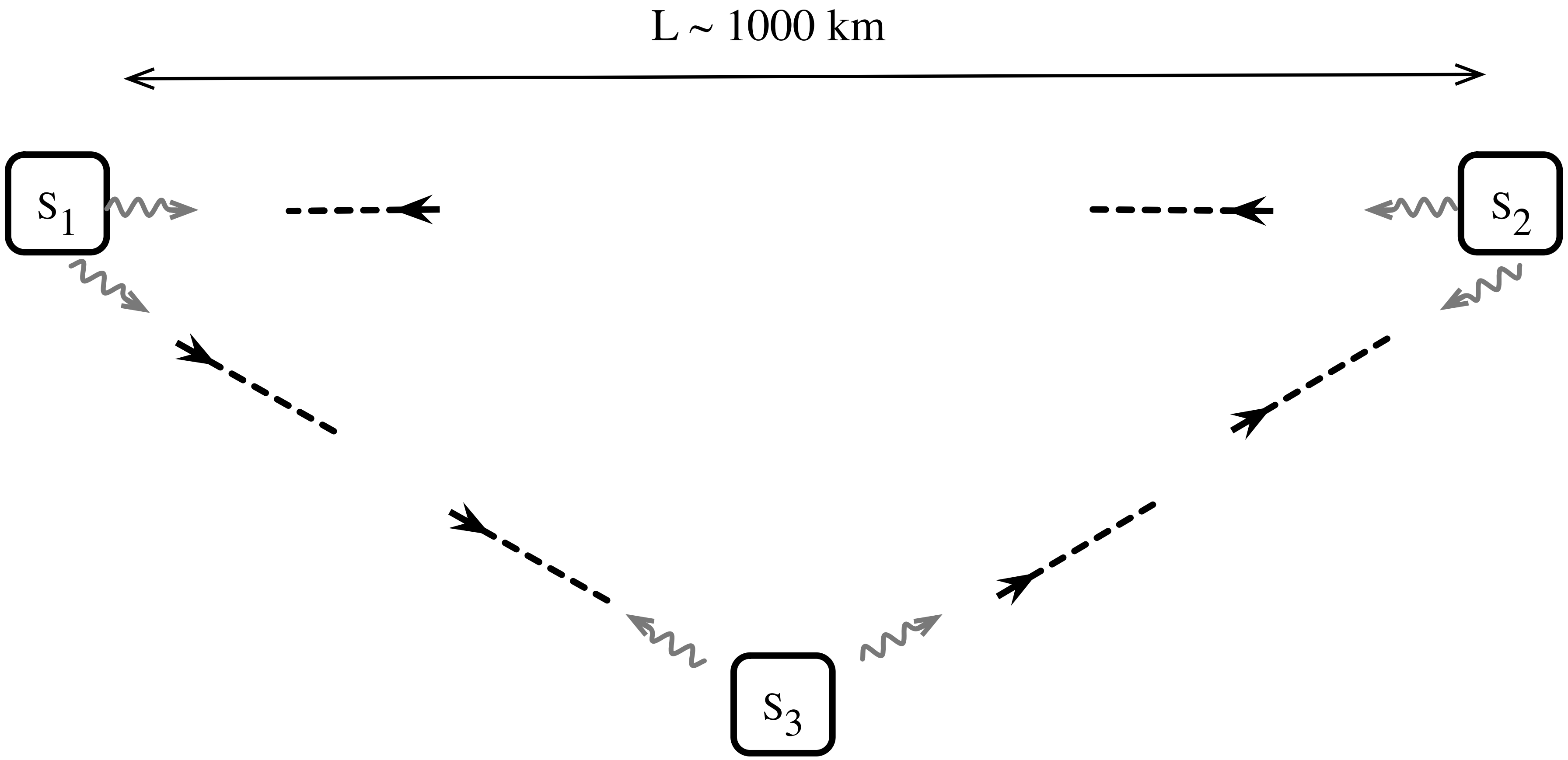
Signal again scales with the distance L between interferometers. Distance limited by laser power. With One Watt, L ~ 1000 km.

Ideally...



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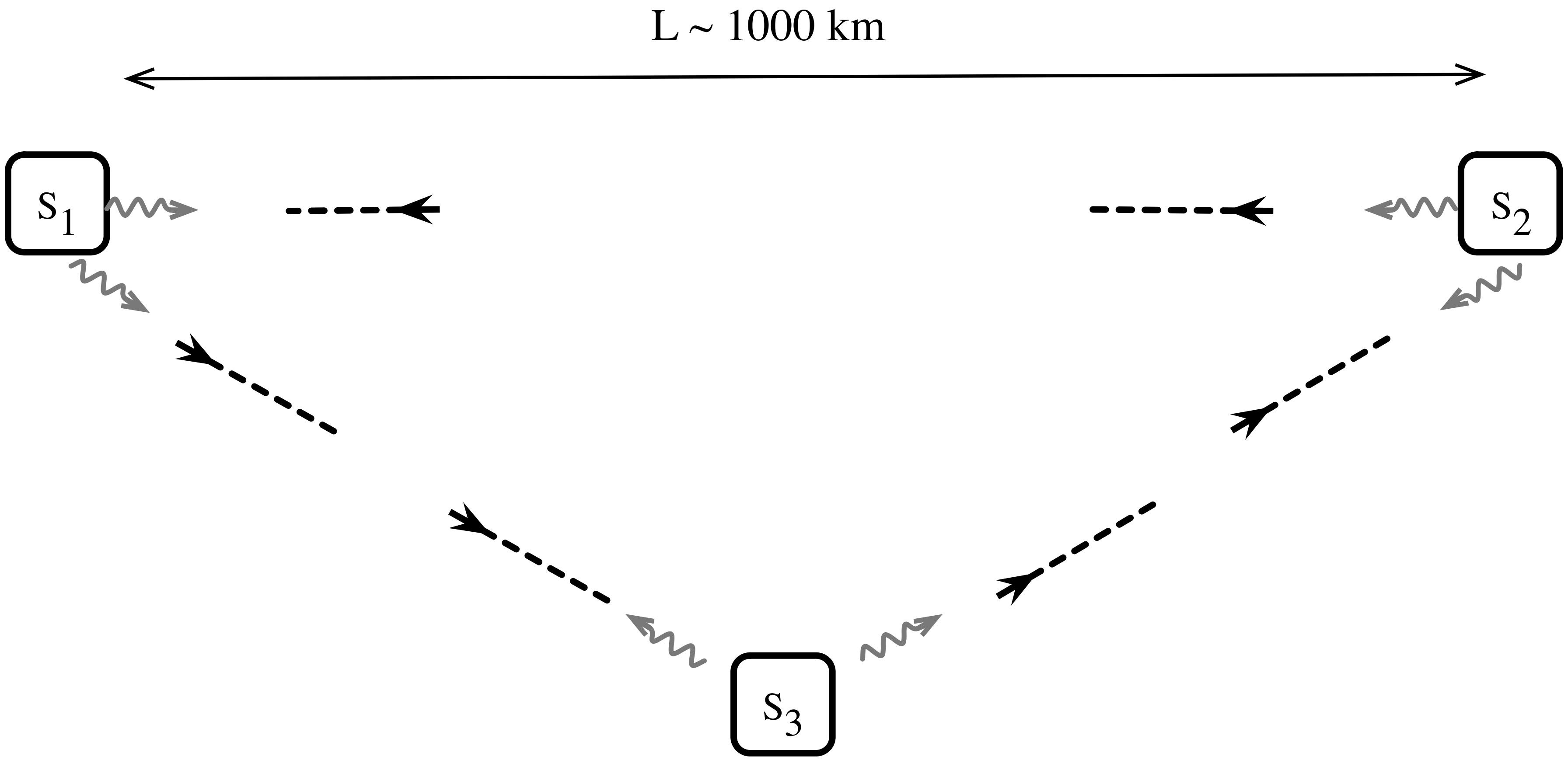

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Increases confidence in detection.

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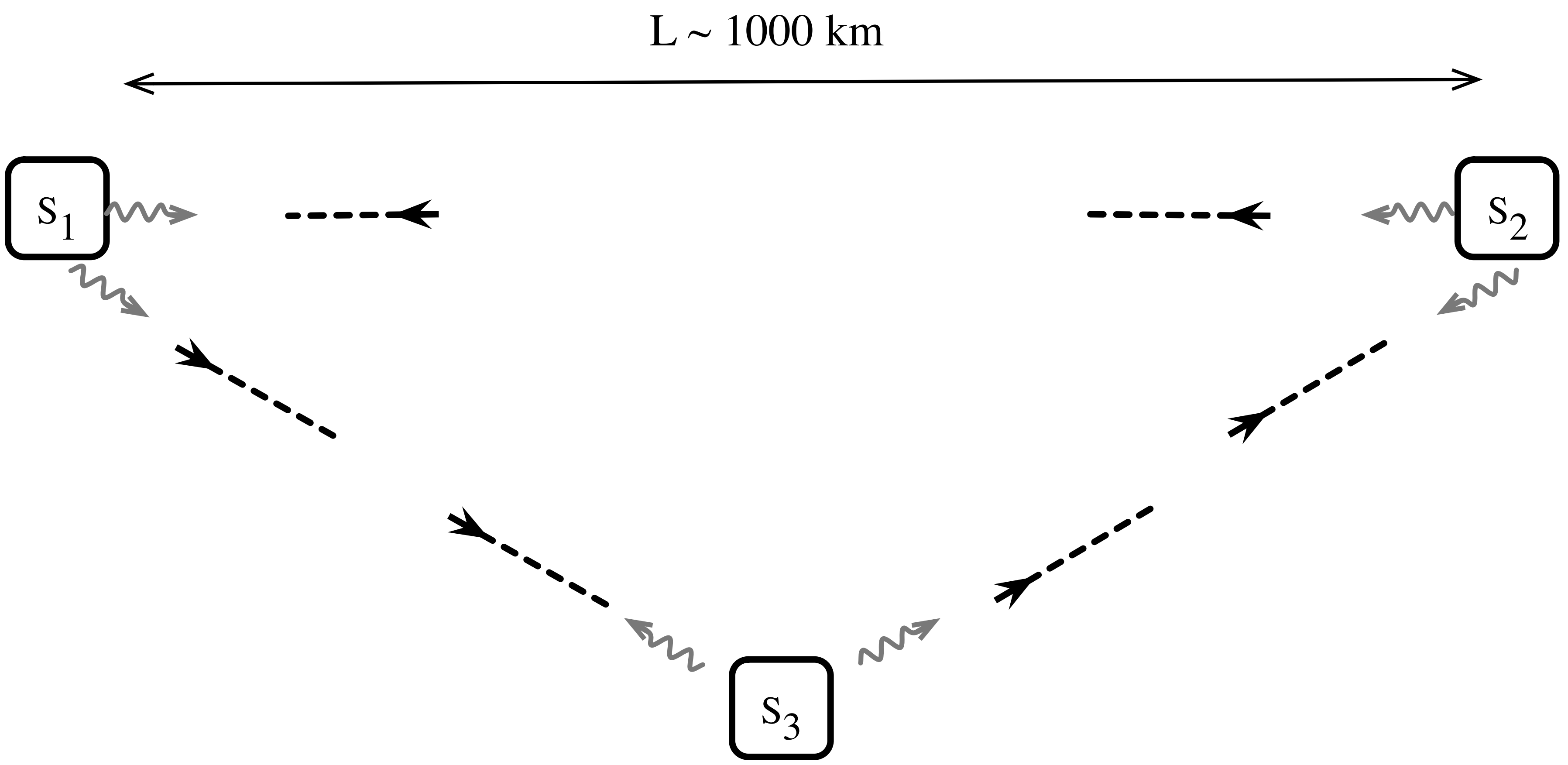

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Further suppresses laser phase noise.

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For gravitational wave sensitivity similar to LISA, the atom interferometer requires position control of the satellite at

$$\sim 10\,\frac{\mu\mathrm{m}}{\sqrt{\mathrm{Hz}}}\ \text{at}\ 10^{-2}\ \mathrm{Hz}\ \text{for}\ d \sim 30\ \mathrm{m}.$$

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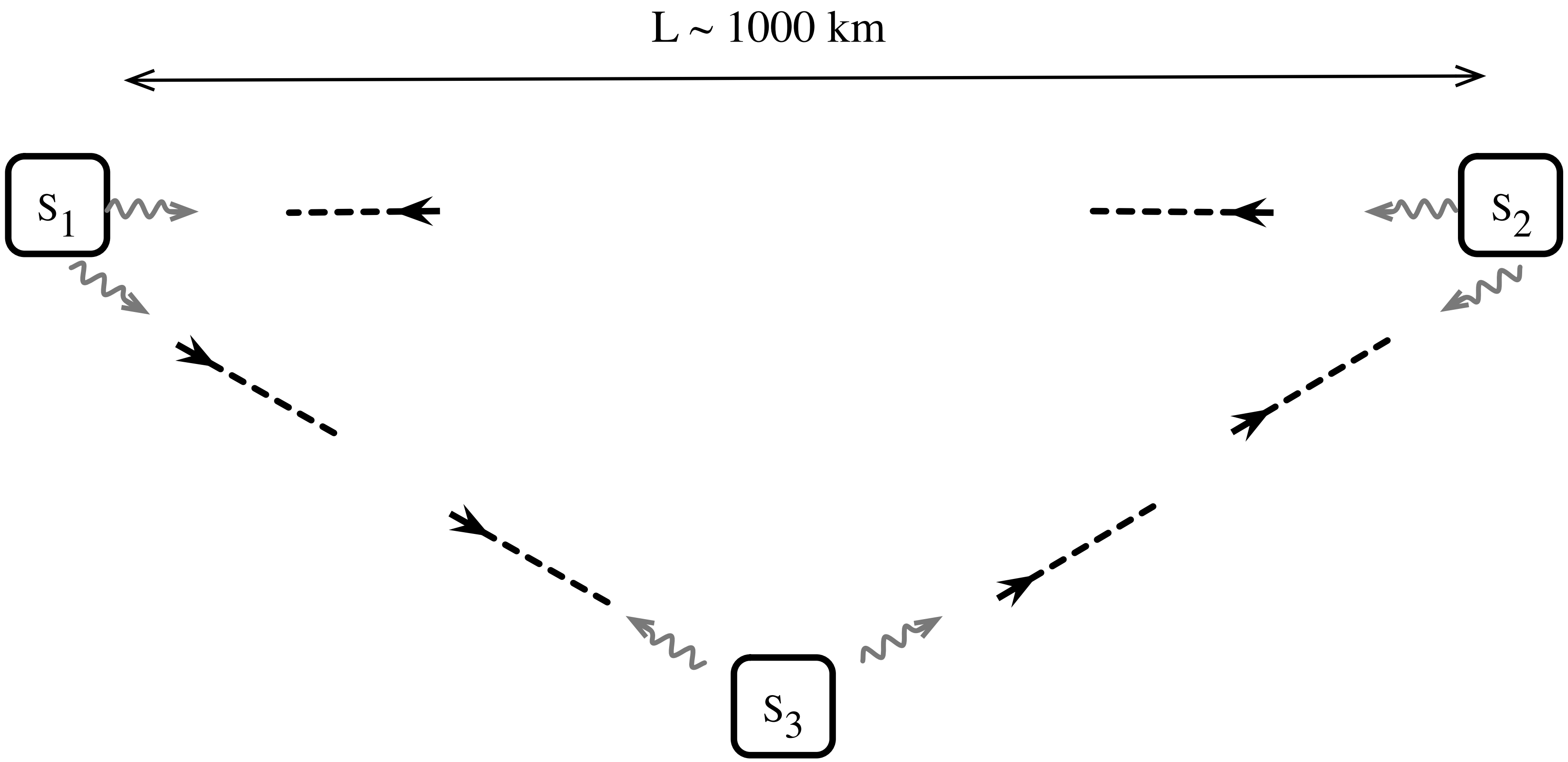

Phase noise cancellation up to knowledge of arm length.

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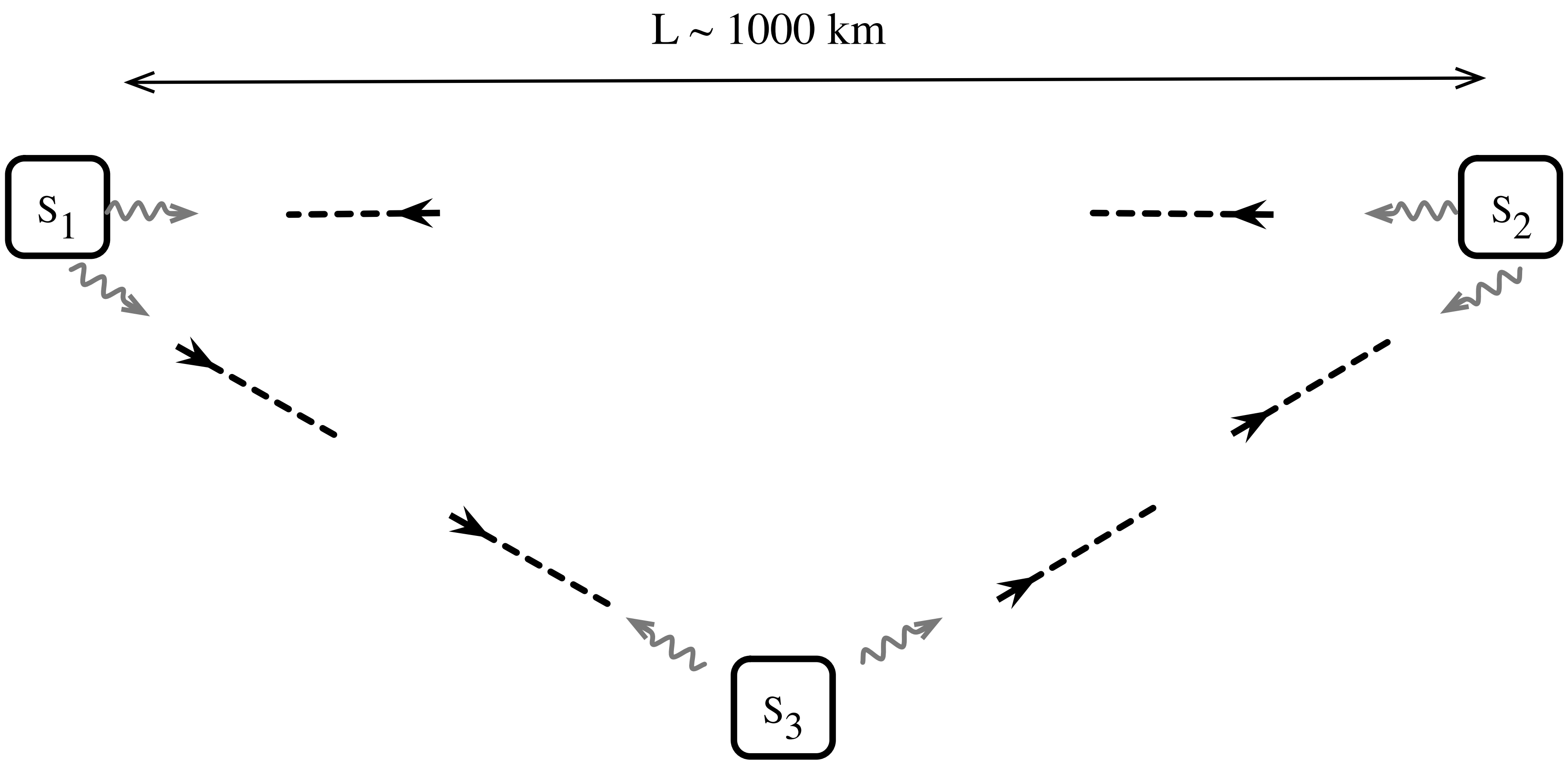

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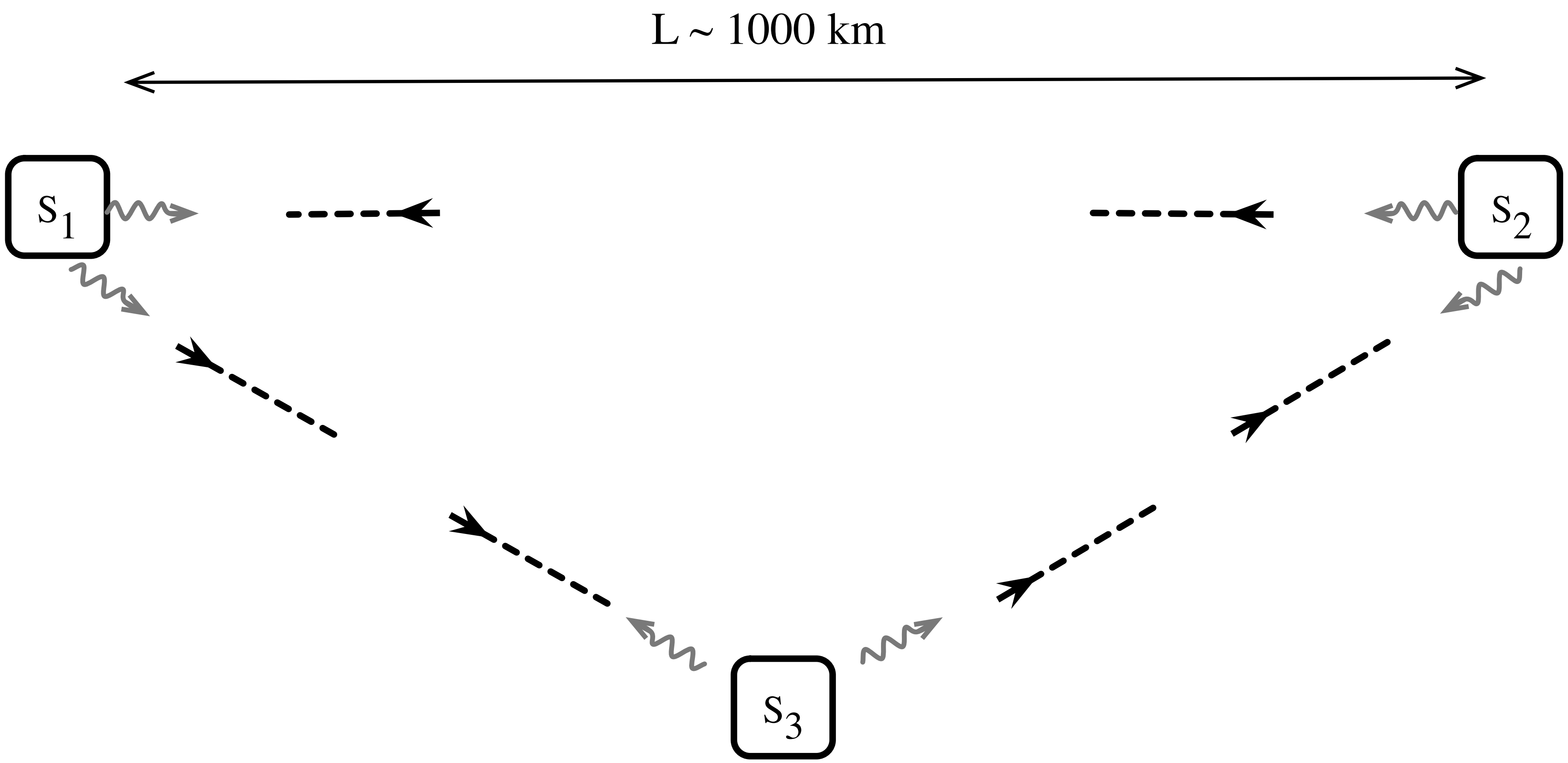

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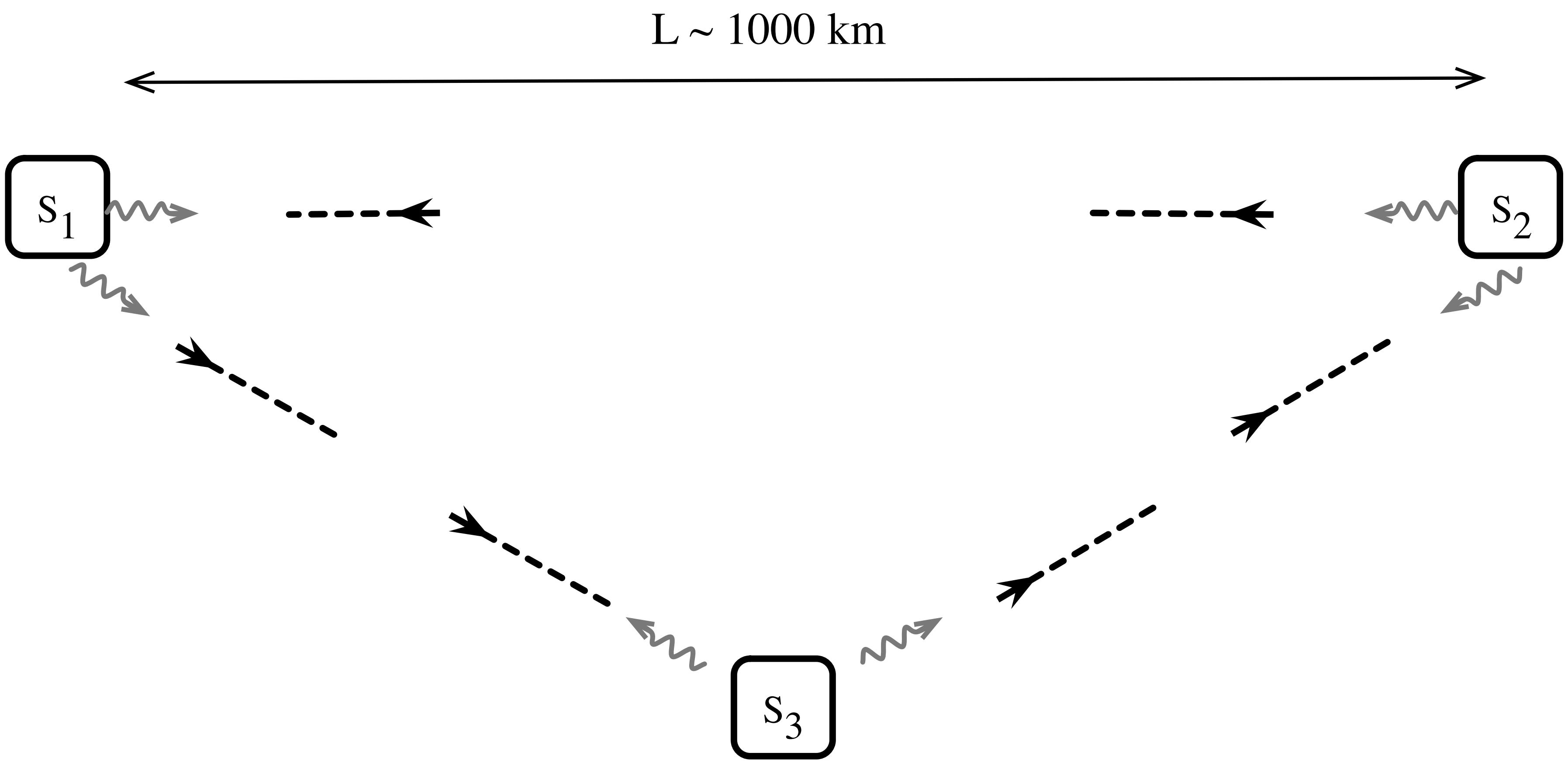

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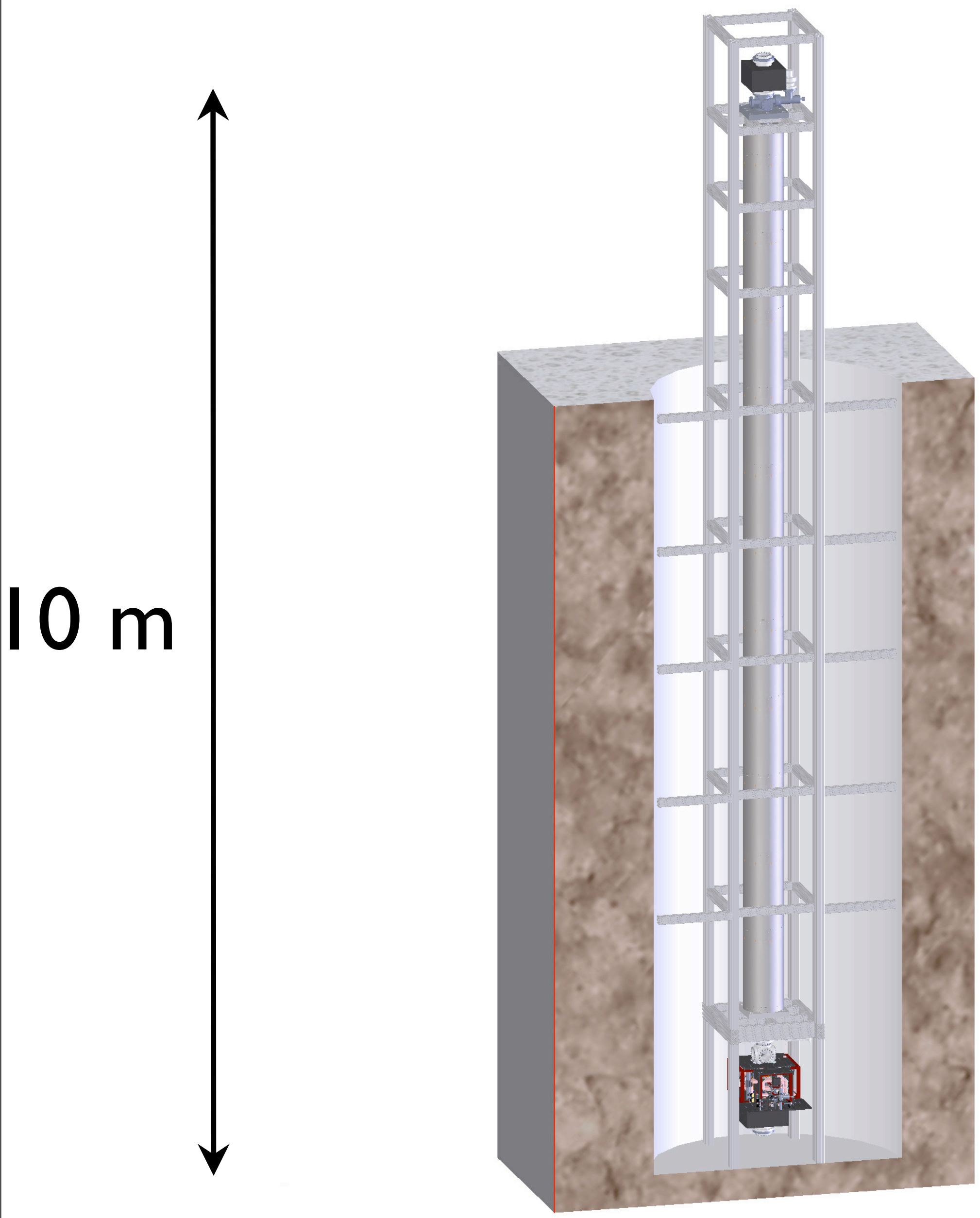
Status of the technology?

The Stanford 10 m Atom Interferometer

(Hogan, Johnson and Kasevich)

drop colocated ^{85}Rb and ^{87}Rb clouds to test Principle of Equivalence



The Stanford 10 m Atom Interferometer

(Hogan, Johnson and Kasevich)

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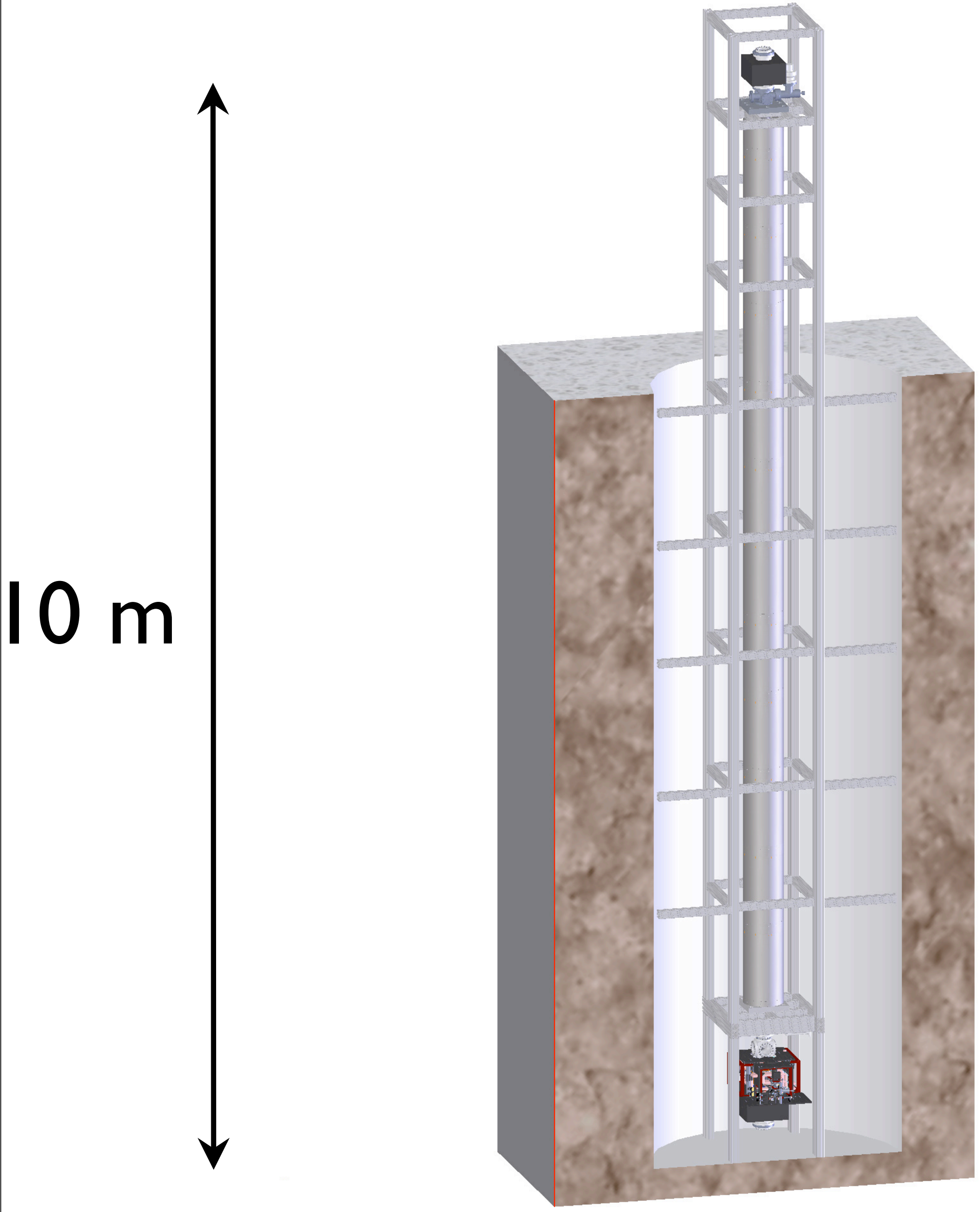

Goal

Test equivalence principle to 10^{-15} in controlled (lab) conditions. Improves current bounds by ~ 300.

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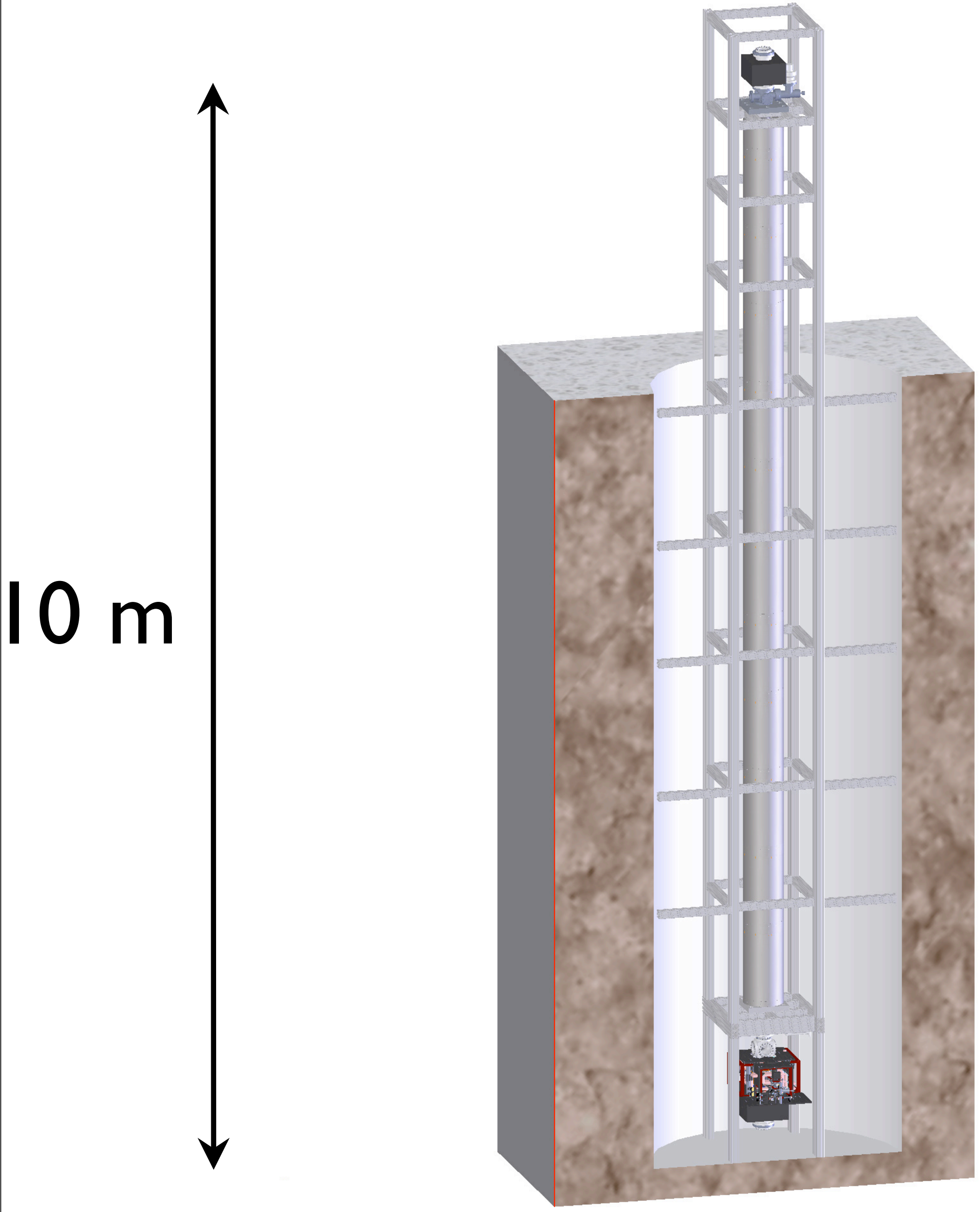

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Demonstrated $k_{\text{eff}} \sim 88\,k$

Might get up to $k_{\text{eff}} \sim 100\,k$

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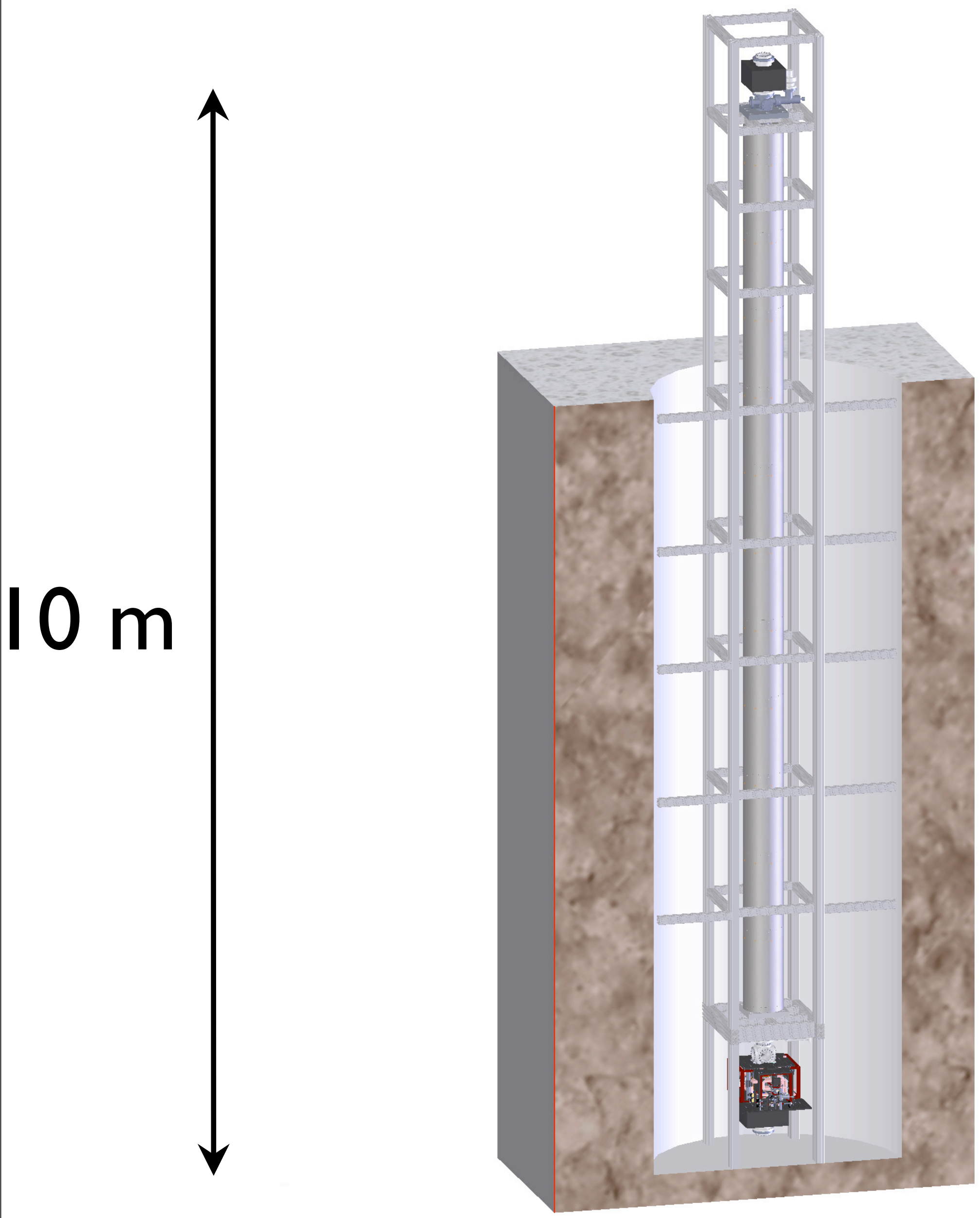

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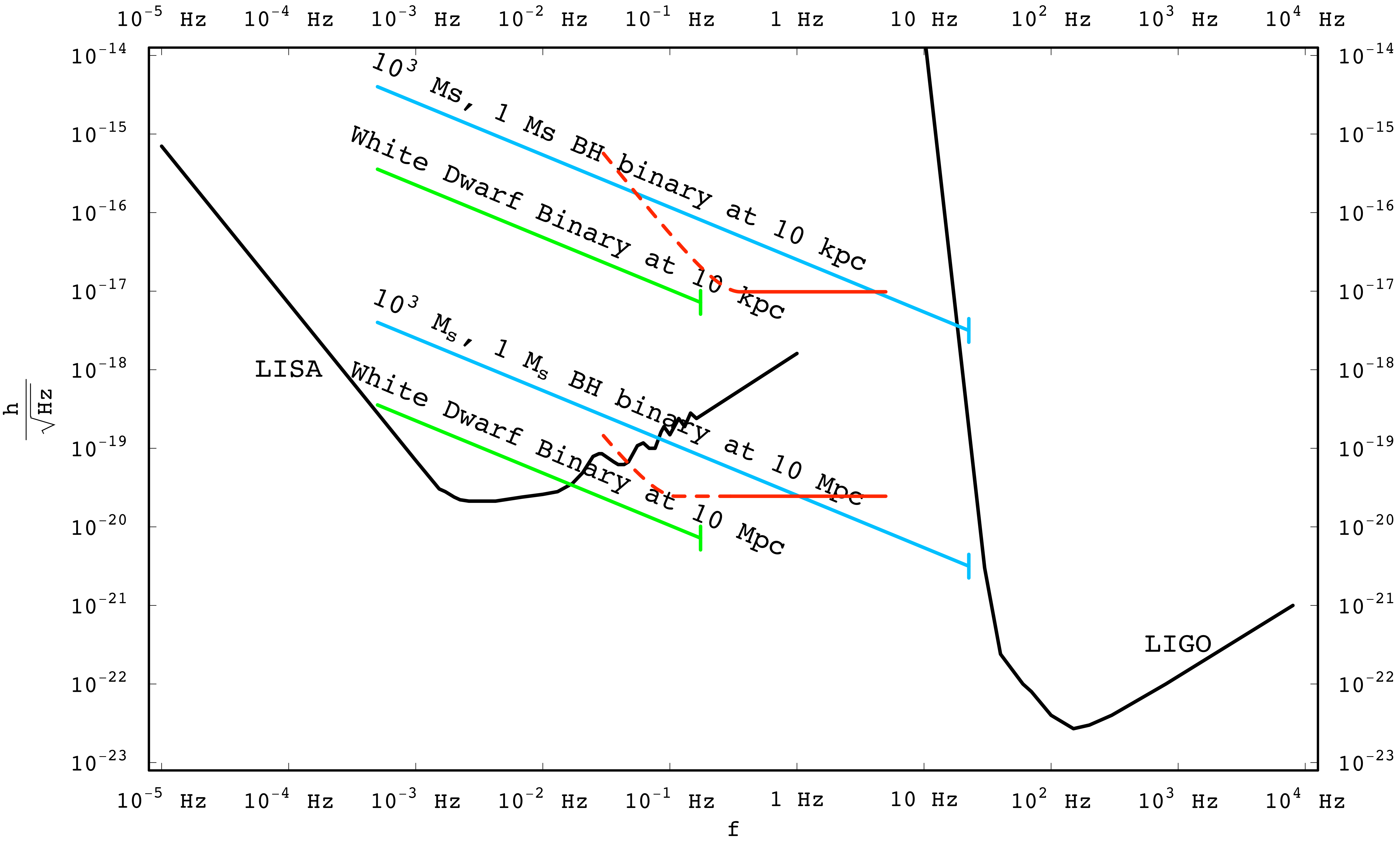
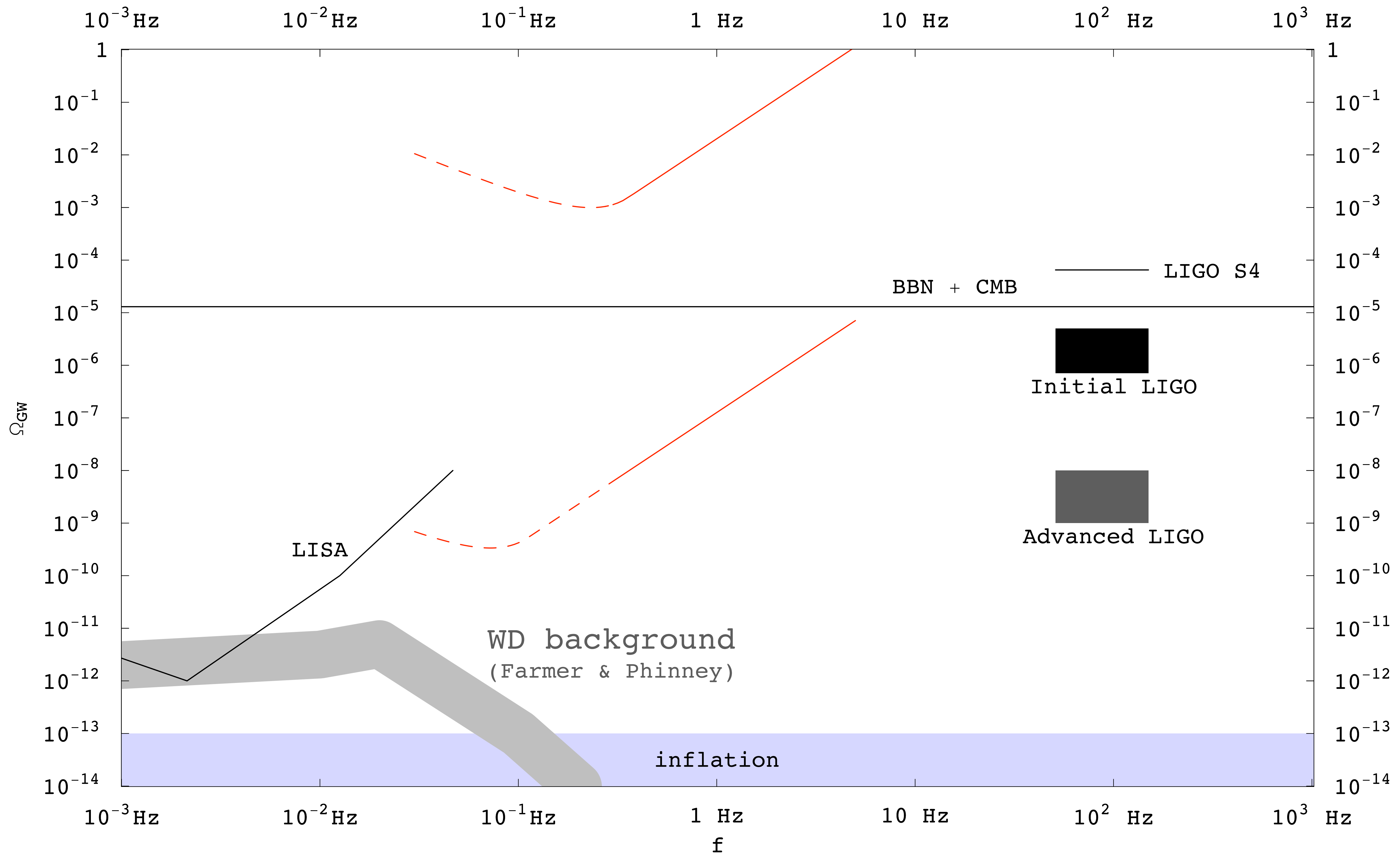
Results expected soon!

Projected Terrestrial Sensitivity

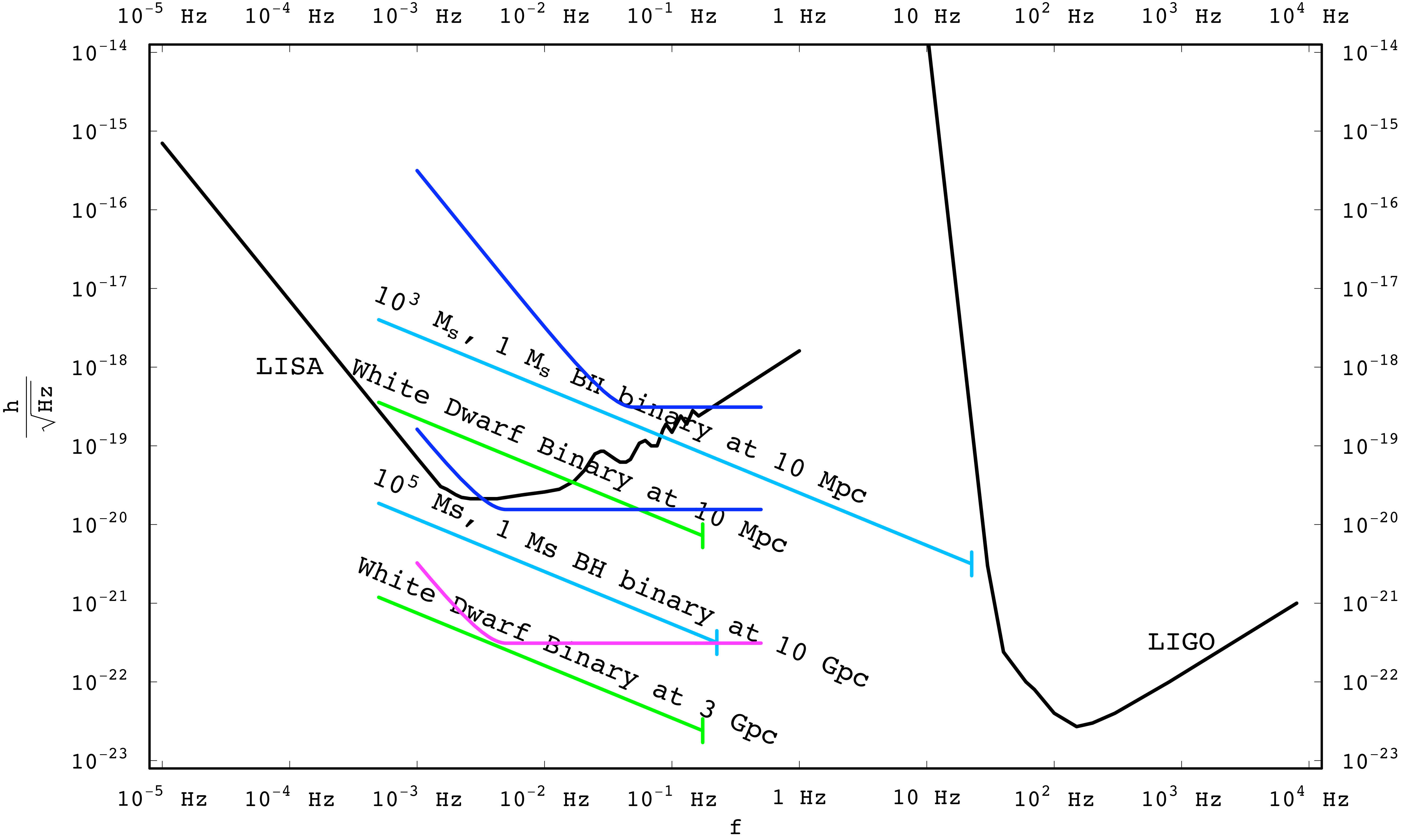


L= 1 km and 4 km

Terrestrial Stochastic Sensitivity

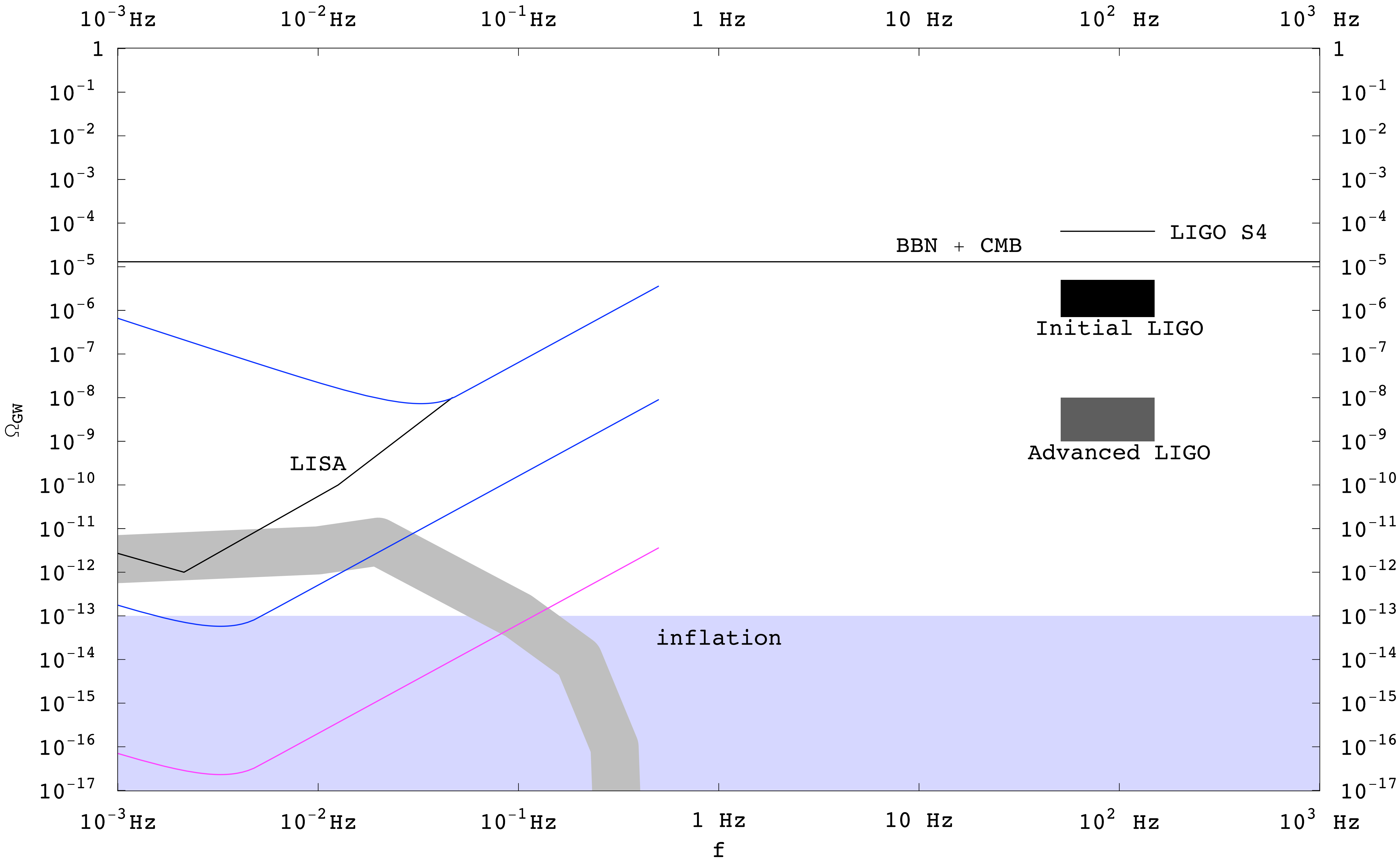


Projected Satellite Sensitivity



L= 100 km, 10^3 km, and 10^4 km

Satellite Stochastic Sensitivity



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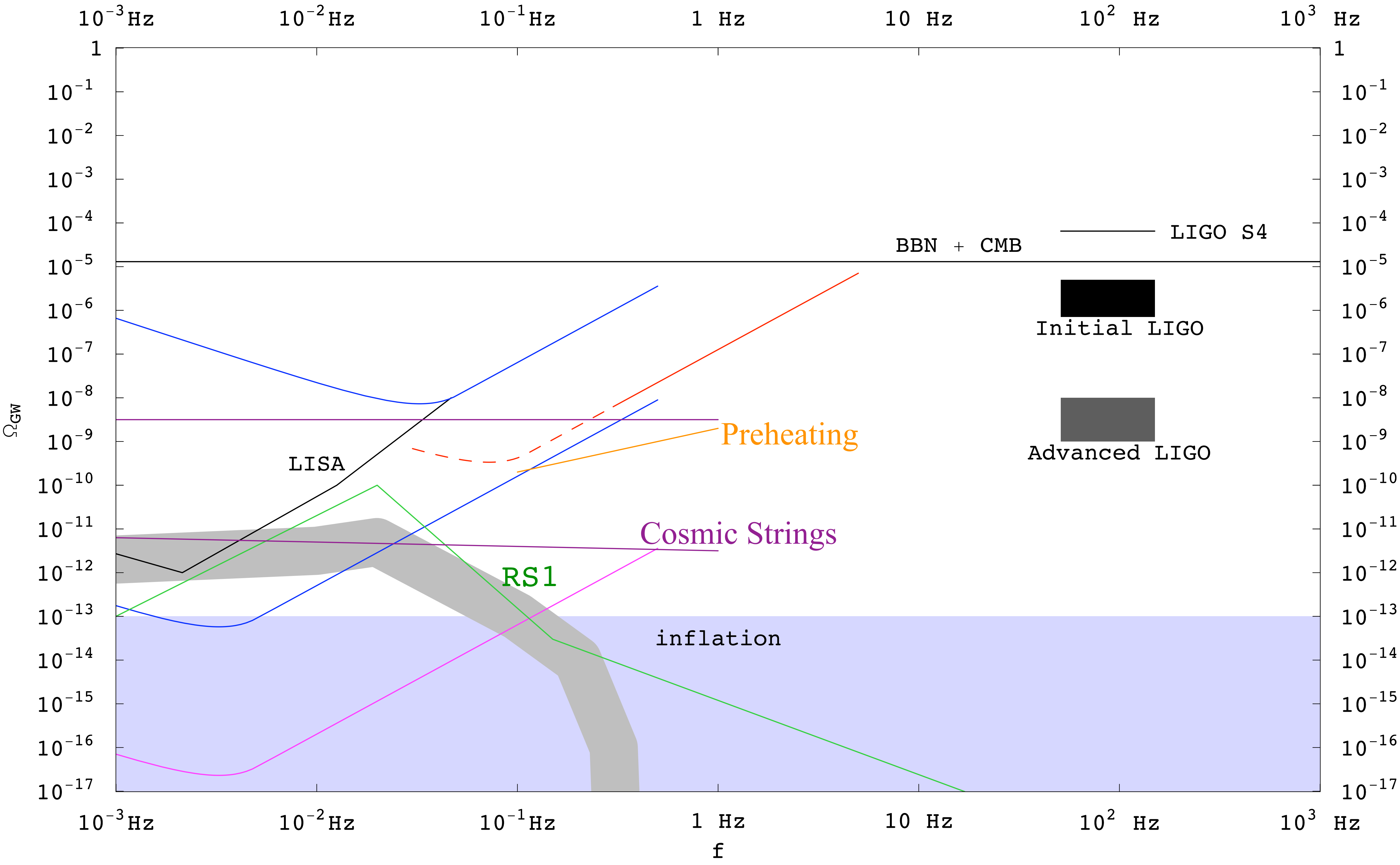

also get observable gravity waves from some SUSY models (NMSSM)

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Improved technology (e.g. more photon kicks, squeezed atom states etc.) imply direct sensitivity gain.

Conclusions

- The discovery of gravitational waves will open a new window into the Universe.
- The frequency band 10^{-2} Hz - 10 Hz is rich with a large number of expected astrophysical sources. It also probes the cosmology of the Universe during the electroweak transition.
- Frequency band complementary to LIGO.
- The atom interferometer configuration discussed in this talk allows for large signal enhancements while simultaneously suppressing backgrounds.
- Potentially easier systematics than conventional light interferometers.

Mock Sensitivity Plot

$$\delta\phi \sim k_{\mathrm{eff}} h L \sin^2\left(\frac{\omega T}{2}\right)$$