Gravitational Wave Detection with Atom Interferometry

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with

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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

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

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

Consider two objects separated by \( L \)
Gravity Wave Detection

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Consider two objects separated by \( L \)

The distance between them oscillates with amplitude \( hL \) and frequency \( \omega \) when \( \omega L \ll 1 \).
Gravity Wave Detection

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Consider two objects separated by \( L \)

\[ L(1 + h \sin(\omega t)) \]

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

The gravity wave can be detected if this oscillation is observed
The Technical Challenge

• Brightest source of gravity waves gives $h \sim 10^{-20}$

• With $L \sim 1$ km, need to measure length changes $hL \sim 10^{-17}$ m
The Technical Challenge

- Brightest source of gravity waves gives $h \sim 10^{-20}$

- With $L \sim 1 \text{ km}$, need to measure length changes $hL \sim 10^{-17} \text{ m}$

- 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
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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More sources in the sub-Hertz band than in the LIGO band.
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Bright gravitational wave sources like mergers of white dwarves and massive black holes do not enter LIGO’s band.
Cosmological Sources in the $10^{-2}$ Hz - 10 Hz band

Cosmological sources characterized by $\Omega_{GW}$
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Gravitational wave detectors respond to $h$. For fixed $\Omega_{GW}$,

$$h \propto \left(\frac{1}{\omega}\right)^{\frac{3}{2}}$$

These sources are brighter at lower frequencies.
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Gravitational radiation from TeV scale first order phase transitions are red shifted to $10^{-2}$ Hz.
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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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\[ |\text{atom}\rangle = |p\rangle \]
What is an atom interferometer?

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

|atom\rangle = |p\rangle
What is an atom interferometer?

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

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

\[
\frac{1}{\sqrt{2}}(|p + k\rangle - |p\rangle) = \frac{1}{\sqrt{2}}(|p\rangle + |p + k\rangle)
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What is an atom interferometer?

Final State

\[ \frac{1}{\sqrt{2}}(|p + k⟩ + e^{i\Delta \phi}|p⟩) \]

\[ \frac{1}{\sqrt{2}}(|p + k⟩ - |p⟩) \]

\[ \frac{1}{\sqrt{2}}(|p⟩ + |p + k⟩) \]

\[ \frac{1}{2}((1 + e^{i\Delta \phi})|p⟩ + ((1 - e^{i\Delta \phi}))|p + k⟩) \]
What is an atom interferometer?

Final State

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

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

Probability in State \( |p + k\rangle = \sin^2 \left( \frac{\Delta \phi}{2} \right) \)
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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\[ |1, p\rangle \]
Light Pulse Atom Interferometry
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Beamsplitter and mirror must transfer momentum to the atom.

Atom undergoes coherent Raman Scattering with momentum transfer

\[ k = \omega_1 - \omega_2 \approx 2\omega_1 \sim 1\text{eV} \]
Light Pulse Atom Interferometry
(Kasevich and Chu, 1991)

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

\[ |1, p\rangle \rightarrow |3\rangle \rightarrow |1, p + k\rangle \]
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\[ |1, p \rangle \quad |1, p + k \rangle \quad |3 \rangle \quad |3 \rangle \]

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

\( \pi \) pulse is a mirror
Spacetime Diagram of the Atom Interferometer

Typical Terrestrial Interferometer

\[ \sim 10^7 \text{ atoms launched with velocities } \sim 10 \text{ m/s} \]

Atoms are in free fall during interferometer.

\[ T \sim 1 \text{ s sets interferometer length to } \sim 10 \text{ m.} \]
Phase Shift in the Interferometer
Phase Shift in the Interferometer

- 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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Interferometer symmetric about the mirror pulse at \( T \).

Need to break symmetry to cause phase shift.
What can cause a phase shift?

Interferometer symmetric about the mirror pulse at $T$.

Need to break symmetry to cause phase shift.

Interferometer is an accelerometer.
The Gravitational Wave Signal in the Interferometer

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

Pulse control laser at 0, T and 2 T.
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Distance between passive laser and the atom altered by gravity wave.
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Phase difference maximal when \( T \sim \frac{1}{\omega} \)
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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

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Measuring acceleration \( \sim hL \) 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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The lasers are not in free fall.
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Laser phase noise?
Differential Measurement

Run two, widely separated atom interferometers using common lasers.
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Measure differential phase shift.
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Gravitational wave signal is retained \( \sim k_{\text{eff}} hL \)
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Measure differential phase shift.

Gravitational wave signal is retained $\sim k_{\text{eff}} h L$

Laser vibration and phase noise cancels (up to finite light travel time effects).
Take LIGO’s mirrors, drop them and measure relative acceleration during free fall.

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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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Signal scales with the length ~ 1 km between interferometers.

Allows free fall time ~ 1s. Maximally sensitive in the 1 Hz band.
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One possible site: DUSEL Homestake Mine in South Dakota (longest shaft ~ 2.5 km).
Systematics due to finite light travel time:

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

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Laser vibration control requirement: $10^{-7} \frac{m}{\sqrt{\text{Hz}}} \left( \frac{1 \text{ Hz}}{f} \right)^{3/2} \left( \frac{1 \text{ km}}{L} \right)$

(for frequencies $1 \text{ Hz} < f < 3 \times 10^5 \text{ Hz}$)
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Control over laser phase noise : 
\[ -140 \frac{\text{dBc}}{\text{Hz}} @ 3 \times 10^5 \text{Hz} \]

Fractional frequency stability : 
\[ \frac{\delta f}{f} \sim 10^{-15} \text{ over time scales of 1 s} \]

(demonstrated with lasers locked to high finesse cavities)
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A lot of other backgrounds. While non-trivial, they all seem controllable.
Ultimate Background for Terrestrial Gravitational Wave Detection

Seismic vibrations gravitationally couple to the free falling atoms.
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Seismic vibrations gravitationally couple to the free falling atoms.

Cannot be shielded.
Ultimate Background for Terrestrial Gravitational Wave Detection

Seismic vibrations gravitationally couple to the free falling atoms.

Cannot be shielded.

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
Satellite based Gravitational Wave Detection

LISA

Technical Details

Arm length $L \sim 5$ million km.
Satellite based Gravitational Wave Detection

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Technical Details

Arm length $L \sim 5$ million km.

Measure length changes between free floating mirrors due to gravitational wave.
Satellite based Gravitational Wave Detection

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Technical Details

Arm length $L \sim 5$ million km.

Measure length changes between free floating mirrors due to gravitational wave.

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

LISA Satellite Mirror Position should fluctuate by < 0.1 nm in the frequency band of interest.
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Mirror is inside a satellite of mass of a few hundred kg.
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Requires position control of the satellite $\sim 1 \frac{\text{nm}}{\sqrt{\text{Hz}}}$ at $10^{-2} \text{ Hz}$

(LISA Pre Phase A Report)
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(LISA Pre Phase A Report)

Major hurdle for LISA
Two widely separated atom interferometers run by common lasers.
Atom Interferometer Satellite Configuration

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

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BUT

Do the atom trajectories have to lie inside the satellite?
Atom Trajectory Environmental Requirements
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Mean collision time with background gas and photons must be larger than the interferometer operation time.
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Interplanetary gas at 1 AU has $n \sim 5$ particles/cm$^3$, moving at $v \sim 500$ km/s. Mean collision time $>> 1000$ s.
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Stable magnetic field direction required during the interferometer operation time to stabilize the atom’s quantization axis.
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Interplanetary magnetic field at 1 AU \( \sim 5 \text{ nT} \). Permanent magnet can provide bias field \( \sim 20 - 100 \text{ nT} \) over 100 m region from satellite.
Satellite Experiment Setup

Atoms brought $d \sim 30$ m from satellites through laser manipulations. Run interferometer over region $l_L \sim 100$ m.
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Atoms brought $d \sim 30$ m from satellites through laser manipulations. Run interferometer over region $l_I \sim 100$ m.

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

Effects of satellite position noise strongly suppressed with increasing $d$. 

$L \sim 1000$ km
Satellite Experiment Setup

Final phase shift can be read either by kicking the atoms back to the base satellite or by imaging the cloud using lasers from the opposite satellite.
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With $l_L \sim 100$ m, $T < 100$ s. Can probe gravitational waves with frequencies greater than $10^{-2}$ Hz.
Satellite Experiment Setup

Final phase shift can be read either by kicking the atoms back to the base satellite or by imaging the cloud using lasers from the opposite satellite.

With $l_L \sim 100$ m, $T < 100$ s. Can probe gravitational waves with frequencies greater than $10^{-2}$ Hz.

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

$L \sim 1000 \text{ km}$

$S_1 \quad \cdots \quad S_2$

$S_3$
Three independent channels with directional information.

Increases confidence in detection.

Enhances sensitivity to stochastic gravitational wave sources by cross-correlation.
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Three independent channels with directional information.

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Further suppresses laser phase noise.
Backgrounds

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

\[ \sim 10 \, \frac{\mu m}{\sqrt{Hz}} \] at \( 10^{-2} \, \text{Hz} \) for \( d \sim 30 \, \text{m} \).
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LISA Requirement: \[ 1 \frac{\text{nm}}{\sqrt{Hz}} \text{ at } 10^{-2} \text{ Hz} \]
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Collisions with background gas also a problem for LISA.
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Not a problem for atom interferometer.
Laser Requirements

Phase noise cancellation up to knowledge of arm length.
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Phase noise cancellation up to knowledge of arm length. 1 m arm length resolution, need laser frequency stability

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Laser Requirements

\[ L \sim 1000 \text{ km} \]

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LISA \sim 10 \frac{\text{Hz}}{\sqrt{\text{Hz}}} @ 10^{-2} \text{ Hz}
A lot of other backgrounds. While non-trivial, they all seem controllable.
Sensitivity of the Atom Interferometer

The phase shift in the interferometer is $\sim k_{\text{eff}} \hbar L \sin^2 \left( \frac{\omega T}{2} \right)$.
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The phase shift in the interferometer is \( \sim k_{\text{eff}} \hbar L \sin^2 \left( \frac{\omega T}{2} \right) \).

Ultimate sensitivity depends on the smallest detectable phase

\[ \delta \phi \sim \frac{1}{\sqrt{N_{\text{atoms}}}} \]

and the momentum \( k_{\text{eff}} \) transferred to the atom.
Sensitivity of the Atom Interferometer

The phase shift in the interferometer is $\sim k_{\text{eff}} h L \sin^2 \left( \frac{\omega T}{2} \right)$

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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
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Goal

Test equivalence principle to $10^{-15}$ in controlled (lab) conditions. Improves current bounds by ~ 300.
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Phase sensitivity $\delta \phi \sim 3 \times 10^{-4} \frac{\text{rad}}{\sqrt{\text{Hz}}}$

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

Might get up to $k_{\text{eff}} \sim 100 \text{ } k$
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Results expected soon!
Projected Terrestrial Sensitivity

$L=1$ km and 4 km

$LIGO$

$LISA$

White Dwarf Binary at 10 kpc

White Dwarf Binary at 10 Mpc

$10^3$ M$_s$, 1 Ms BH binary at 10 kpc

$10^3$ M$_s$, 1 Ms BH binary at 10 Mpc

LIGO

$L=1$ km and 4 km
Terrestrial Stochastic Sensitivity

- BBN + CMB
- LIGO S4
- Initial LIGO
- Advanced LIGO
- LISA
- WD background (Farmer & Phinney)
- inflation

Frequency range: $10^{-3} \text{Hz} - 10^3 \text{Hz}$
Projected Satellite Sensitivity

$L = 100 \text{ km}, \ 10^3 \text{ km}, \text{ and } 10^4 \text{ km}$

$LIGO \quad LISA$

$10^3 \text{ Ms}, \ 1 \text{ Ms} \ \text{BH binary at } 10 \text{ Mpc}$

$10^5 \text{ Ms}, \ 1 \text{ Ms} \ \text{BH binary at } 10 \text{ Gpc}$

$\text{White Dwarf Binary at } 10 \text{ Mpc}$

$\text{White Dwarf Binary at } 3 \text{ Gpc}$

$L = 100 \text{ km}, \ 10^3 \text{ km}, \text{ and } 10^4 \text{ km}$
Satellite Stochastic Sensitivity

The graph illustrates the sensitivity of different gravitational wave detectors across a range of frequencies, from $10^{-3}$ Hz to $10^3$ Hz.

Key features include:
- **BBN + CMB** and **LIGO S4**
- **Initial LIGO**
- **Advanced LIGO**
- **LISA**

The horizontal axis represents frequency $f$, while the vertical axis represents the gravitational wave frequency $\Omega_{GW}$.

Significant regions include:
- **Inflation**

The graph highlights the sensitivity improvements expected from advanced detector technologies and the impact of inflation on gravitational wave sensitivity.
also get observable gravity waves from some SUSY models (NMSSM)
Morals
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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.
\[ \delta \phi \sim k_{\text{eff}} h L \sin^2 \left( \frac{\omega T}{2} \right) \]