Atom interferometry and application to fundamental physics

Quantum Sensors for Fundamental Physics

Oxford, UK

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• Equivalence principle tests

• Short distance gravity

• Dark sector physics

• QED tests (alpha measurements)

• Quantum mechanics at macroscopic scales

• Quantum entanglement for enhanced readout

• Gravitational wave detection, sky localization
Atom interference

Light interferometer

Atom interferometer

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

(1) Light absorption:

\[ \hbar k \]

\[ v = \hbar k/m \]

(2) Stimulated emission:

\[ \hbar k \]

Rabi oscillations

\[ |1,p\rangle \]

\[ |2,p+\hbar k\rangle \]

Time [\( \Omega_{\text{Rabi}}^{-1} \)]
Light Pulse Atom Interferometry

- Long duration
- Large wavepacket separation
10 meter scale atomic fountain

- Atom Optics & Lattice Beam
- Delivery Enclosure
- Upper Detection Region
- 3 Layer Magnetic Shield (<1 mG on axis)
- Lower Detection Region
- 2D MOT Loading 3D
- Rotation Compensation System

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Interference at long interrogation time

2T = 2.3 seconds
1.4 cm wavepacket separation

Interference (3 nK cloud)

Large space-time area atom interferometry

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

90 photons worth of momentum

World record wavepacket separation due to multiple laser pulses of momentum

Kovachy et al., Nature 2015
Gravity Gradiometer

Asenbaum et al., PRL 118, 183602 (2017)
Gradiometer Demonstration

Gradiometer response to 84 kg lead test mass

Detected the gravitational tidal force (spacetime curvature) across a single particle's wavefunction

GR: gravity = curvature
→ First true manifestation of gravitation in a quantum system

Asenbaum et al., PRL 118, 183602 (2017)
Equivalence Principle

Static EP tests
- Free-fall tests, torsion balance, Lunar Ranging
- Test foundation of General Relativity
- Search for new forces (e.g., Yukawa potential)

Time-varying EP tests
- New scalar (or vector) field that varies in space
- The field could be dark matter
- Force is oscillatory and EP violating:
  \[ F \propto g \sqrt{\rho_{DM}} \cos(m_{DM}t) \]

*Example: Coupling to electron mass*
Stanford 10-meter EP test

Simultaneous Dual Interferometer

Dual interferometer fringes

Sensitivity target for static EP: $< 10^{-14}$
Can also look for time-varying forces

Recent results: Suppressed GG sensitivity by x100
Overstreet et al., PRL 120, 183604 (2018)
There is a gap between the LIGO and LISA detectors (0.1 Hz – 10 Hz).

Moore et al., CQG 32, 015014 (2014)
Mid-band Science

**Mid-band discovery potential**
Historically every new band/modality has led to discovery
Observe LIGO sources when they are younger

**Excellent sky localization**
Predict *when* and *where* events will occur (before they reach LIGO)
Observe run-up using electromagnetic telescopes

**Cosmology and Astrophysics**
Black hole, neutron star, and white dwarf binaries
Parameter estimation (e.g., BH spin)
Ultralight scalar dark matter discovery potential
Early Universe stochastic sources (cosmic GW background)
Sky localization precision:

$$\sqrt{\Omega_s} \sim \left( \text{SNR} \cdot \frac{R}{\lambda} \right)^{-1}$$

**Mid-band advantages**
- Small wavelength $\lambda$
- Long source lifetime (~months) maximizes effective $R$

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$\sqrt{\Omega_s}$ [deg]</th>
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</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>0.16</td>
</tr>
<tr>
<td>GW151226</td>
<td>0.20</td>
</tr>
<tr>
<td>NS-NS (140 Mpc)</td>
<td>0.19</td>
</tr>
</tbody>
</table>
A different kind of atom interferometer

Hybrid “clock accelerometer”

Clock: measure light travel time → remove laser noise with *single baseline*

Accelerometer: atoms excellent inertial test masses

Simple Example: Two Atomic Clocks

\[ \begin{align*}
|g\rangle & + \frac{1}{\sqrt{2}} |e\rangle \ e^{-i\omega_\alpha T} \\
|e\rangle & + \frac{1}{\sqrt{2}} |g\rangle \ e^{-i\omega_\alpha T}
\end{align*} \]

Phase evolved by atom after time \( T \)
Simple Example: Two Atomic Clocks

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

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega T} \]

\[ \Delta T \sim \frac{hL}{c} \]

GW changes light travel time
Phase Noise from the Laser

The phase of the laser is imprinted onto the atom.

Laser phase noise, mechanical platform noise, etc.

\[
\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{i\phi_L}
\]

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

Excited state phase evolution:

$$\Delta \phi \sim \omega_A \left( \frac{2L}{c} \right)$$

Two ways for phase to vary:

- Dark matter: $\delta \omega_A$
- Gravitational wave: $\delta L = hL$

Each interferometer measures the change over time $T$

Laser noise is common-mode suppressed in the gradiometer

**Ultralight scalar dark matter**

**Ultralight dilaton DM** acts as a background field (e.g., mass $\sim 10^{-15}$ eV)

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

- DM scalar field
- DM mass density

$$\phi(t, \mathbf{x}) = \phi_0 \cos [m_{\phi}(t - \mathbf{v} \cdot \mathbf{x}) + \beta] + \mathcal{O} (|\mathbf{v}|^2)$$

DM coupling causes time-varying atomic energy levels:

- Dark matter coupling
- DM induced oscillation
Sequential single-photon transitions remain laser noise immune


GW Sensitivity for a Satellite Detector

Satellite detector concept
- Two spacecraft, MEO orbit
- Atom source in each
- Heterodyne laser link
- Resonant/LMT sequences

$L = 4 \times 10^7$ meters

$10^{-4} \text{ rad/}\sqrt{\text{Hz}}$

$\frac{n h k}{m} T < 1 \text{ m}$

$2TQ < 300 \text{ s}$

$n_p < 10^3$

Dots indicate remaining lifetimes of 10 years, 1 year and 0.1 years
Matter wave Atomic Gradiometer Interferometric Sensor

- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration
MAGIS-100 Design

System Components:
- ~90 meter vacuum tube (vertical)
- Atoms sources (three, attached to tube)
- Laser system for implementing atom interferometry (hutch at top)

Laser hutch location

CAD drawing of top of detector installation
MAGIS Estimated Sensitivity

DM sensitivity
(coupling to electron mass)

Full-scale instrument (km baseline)

GW strain sensitivity

Stanford MAGIS prototype

Sr gradiometer CAD
(atom source detail)

Two assembled Sr atom sources

Trapped Sr atom cloud
(Blue MOT)

Atom optics laser
(M Squared SolsTiS)
Collaborators

**Rb Atom Interferometry**
- Mark Kasevich
- Tim Kovachy
- Chris Overstreet
- Peter Asenbaum
- Remy Notermans

**Sr Atom Interferometry**
- Jan Rudolph
- TJ Wilkason
- Hunter Swan
- Yijun Jiang
- Connor Holland
- Ben Garber

**MAGIS-100:**
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- Swapan Chattopadhyay (Fermilab/NIU)
- Jeremiah Mitchell (Fermilab)
- Roni Harnik (Fermilab)
- Phil Adamson (Fermilab)
- Steve Geer (Fermilab)
- Jonathon Coleman (Liverpool)
- Tim Kovachy (Northwestern)

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- Babak Saif
- Bernard D. Seery
- Lee Feinberg
- Ritva Keski-Kuha

**Theory**
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- Roger Romani
- Savas Dimopoulos
- Surjeet Rajendran
- Asimina Arvanitaki
- Ken Van Tilburg
Atomic sensors for gravitational wave detection

Atomic clocks and atom interferometry offer the potential for gravitational wave detection in an unexplored frequency range ("mid-band")

Potential for single baseline detector (use atoms as phase reference/local clock)

Mid-band science
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multimessenger astronomy)
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, ...)

Satellite proposal using optical lattice clocks + drag free inertial reference (Kolkowitz et al., PRD 2016)

MAGIS: Atom interferometry with clock atoms serving as both inertial reference + phase reference (Hogan, Kasevich)

MIGA: Terrestrial detector using atom interferometer + optical cavity (Bouyer, France)
Lattice Clocks

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

## GW Detector Comparison

<table>
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<tr>
<th>Detector</th>
<th>Inertial reference</th>
<th>Laser phase reference</th>
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</thead>
<tbody>
<tr>
<td>LIGO</td>
<td>Suspended end mirrors</td>
<td>Second arm</td>
</tr>
<tr>
<td>LISA</td>
<td>Drag-free proof masses</td>
<td>Second baseline</td>
</tr>
<tr>
<td>MAGIS</td>
<td>Atom</td>
<td>Atom</td>
</tr>
<tr>
<td>Atomic clock</td>
<td>Drag-free proof mass</td>
<td>Atom</td>
</tr>
</tbody>
</table>
Compare to LISA

**LISA:**
- Measurement S/C to test mass

**Atom interferometer:**
- Measurement S/C to test mass

Second baseline needed for phase reference:

Atom test mass
- Records laser noise
- Acts as phase reference

(Figures adapted from LISA yellow book.)
Bounds on stochastic GW sources

Example resonant sequence

Narrow band sensitivity possible in 1 year