Fundamental Physics with Atomic Interferometry

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with

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PRL 98 (2007)
PRD 78 (2008)
PRD 78 (2008)
PLB 678 (2009)
arXiv:1009.2702
arXiv:1101.2691
1. Atomic Interferometry

2. Gravitational Wave Detection

3. Axion Dark Matter Detection
Atomic Interferometry
Atom Interferometry

- established technology

- rapidly advancing
  driven by progress in atom cooling (BEC), atomic clocks, ...
  1991 - Kasevich & Chu - $3 \times 10^{-6}$
  1998 - A. Peters - $10^{-10}$
  2011? - $10^{-15}$

- high precision
  already reached $10^{-11} \ g_{\text{earth}}$, 17 digit clock synchronization
  path to future improvements (increased atom flux, entangled atoms...)

  can test e.g. time variation of fundamental constants

There must be more fundamental physics to be done with it
Atomic Clock

\[ |\text{atom}\rangle = |1\rangle \]

\[ \begin{array}{c}
  2 \\
  1 \\
\end{array} \implies \Delta E \]
Atomic Clock

\[ |\text{atom}\rangle = |1\rangle \]

beamsplitter

\[
\frac{1}{\sqrt{2}} (|1\rangle + |2\rangle)
\]

\{ \Delta E \}
Atomic Clock

\[ |\text{atom}\rangle = |1\rangle \]

\[
\frac{1}{\sqrt{2}} \left( |1\rangle + |2\rangle \right)
\]

beamsplitter

wait time \( t \)

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

\[ 2 \]

\[ 1 \]

\[ \Delta E \]
Atomic Clock

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2

1

\[ \{ \Delta E \} \]

beamsplitter

\[ \frac{1}{2} \left[ \left( 1 - e^{i(\Delta E)t} \right) |1\rangle + \left( 1 + e^{i(\Delta E)t} \right) |2\rangle \right] \]
Atomic Clock

$$\left| \text{atom} \right\rangle = \left| 1 \right\rangle$$

beamsplitter

$$\frac{1}{\sqrt{2}} \left( \left| 1 \right\rangle + \left| 2 \right\rangle \right)$$

wait time $t$

$$\frac{1}{\sqrt{2}} \left( \left| 1 \right\rangle + e^{i(\Delta E)t} \left| 2 \right\rangle \right)$$

beamsplitter

$$\frac{1}{2} \left[ \left( 1 - e^{i(\Delta E)t} \right) \left| 1 \right\rangle + \left( 1 + e^{i(\Delta E)t} \right) \left| 2 \right\rangle \right]$$

output ports $N_1, N_2$

can measure times $t \sim \frac{1}{\Delta E} \sim 10^{-10}$ s
Raman Transition

\[
\psi = c_1 |1, p\rangle + c_2 |2, p+k\rangle
\]

\[
|c_1|^2, |c_2|^2
\]

\[
\pi/2 \text{ pulse is a beamsplitter}
\]

\[
\pi \text{ pulse is a mirror}
\]
Raman Transition

\[ k_{eff} = \omega_1 + \omega_2 \sim 1 \text{ eV} \]

\[ \omega_{eff} = \omega_1 - \omega_2 \sim 10^{-5} \text{ eV} \]
Light Pulse Atom Interferometry

\[ t \]

\[ r \]

\[ \frac{\pi}{2} \text{ beamsplitter} \]

\[ \pi \text{ mirror} \]

\[ \frac{\pi}{2} \text{ beamsplitter} \]
Light Pulse Atom Interferometry

A constant gravitational field produces a phase shift:

\[ \Delta \phi \sim mg(\Delta h)T \sim mg \left( \frac{k}{m} \right) T = kgT^2 \sim 10^8 \text{ rad} \]

\[ \text{sensitivity} \sim 10^{-7} \text{ rad} \]

The interferometer can be as long as \( T \sim 1 \text{ sec} \sim \text{earth-moon distance}! \)
colocated $^{85}$Rb and $^{87}$Rb clouds test Principle of Equivalence initially to $10^{-15}$ in controlled (lab) conditions
Atomic Gravitational Wave Interferometric Sensor (AGIS)
Motivation

Gravitational waves open a new window to the universe

- sourced by mass, not charge
- universe is transparent to gravity waves

- provide unique astrophysical information
  - compact object binaries
  - black holes, strong field GR tests

- Every new band opened has revealed unexpected discoveries
Cosmology

Gravitational waves open a new window to the universe
sourced by mass, not charge
universe is transparent to gravity waves

• rare opportunity to study cosmology before last scattering
  inflation and reheating
  early universe phase transitions
  cosmic strings ...

Galaxy formation
Epoch of gravitational collapse
Recombination
Re-emergence of CBR
Matter domination
Onset of gravitational instability
Nucleosynthesis
Light elements created - D, He, Li
Quark-hadron transition
Hadrons form - protons & neutrons
Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated
\[ SU(3) \times SU(2) \times U(1) \rightarrow SU(2) \times U(1) \]

Grand unification transition
\[ G 

The Planck epoch
The quantum gravity barrier
Gravitational Wave Signal

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

For GR calculation see PRD 78 (2008)

laser ranging an atom (or mirror) from a starting distance \( L \) sees a position:

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

and an acceleration \( a \sim hL\omega^2 \sin(\omega t) \)
Gravitational Wave Signal

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gives a phase shift \( \Delta \phi = kaT^2 \sim khL\omega^2 \sin(\omega t)T^2 \)

actual answer \( \Delta \phi_{tot} = 4\frac{hk}{\omega} \sin^2 \left( \frac{\omega T}{2} \right) \sin (\omega L) \sin (\omega t) \)
Experiment Design
Differential Measurement

similar to comparing two clocks separated by L
Terrestrial Backgrounds

• A differential measurement cancels vibrations and laser phase noise (at least to leading order)

• Time-varying gravity gradient noise due to nearby motions of earth

\[
\text{earth vibrations naturally } \lesssim 10^{-7} \frac{\text{m}}{\sqrt{\text{Hz}}} \text{ at 1 Hz}
\]

allows GW detection down to \( \omega \sim 0.3 \text{ Hz} \) (Hughes and Thorne ‘98)

possible site: DUSEL, Homestake mine (~ 2 km shaft)
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- All other backgrounds including timing errors, launch position uncertainty, Coriolis effects, and magnetic fields seem controllable to below shot noise

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

laser phase noise control: \(-140 \frac{\text{dBc}}{\text{Hz}} \) @ \( 3 \times 10^5 \text{Hz} \)

laser frequency stability: \( \frac{\delta f}{f} \sim 10^{-15} \) over time scales of 1 s
Possible Satellite Configuration

space allows a longer interferometer time and sensitivity to lower $\omega$

- ambient B-field ($\sim$ nT), vacuum, etc. in space sufficient for interferometer region
- laser power sufficient for atomic transitions
- the time-varying gravitational fields, vibrations, etc. naturally much smaller than for LISA
Atom Interferometry (AGIS)  
baseline $L \sim 10^3$ km  
requires satellite control (at $10^{-2}$ Hz) to $10 \frac{\mu m}{\sqrt{Hz}}$  
atoms provide inertial proof mass, neutral  
gas collisions remove atoms, not a noise source  

LISA  
baseline $L = 5 \times 10^6$ km  
satellite control to $1 \frac{nm}{\sqrt{Hz}}$  
large EM force on charged proof mass  
collisions with background gas are noise  

several backgrounds and technical requirements may be easier with AI  
motivates more careful consideration of engineering details
Projected Terrestrial Sensitivity

L = 1 km and 4 km

$10^{-5}$ Hz to $10^4$ Hz

LIGO

LISA

White Dwarf Binary at 10 kpc

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

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

White Dwarf Binary at 10 Mpc

LIGO
Projected Satellite Sensitivity

White Dwarf Binary at 10 kpc

10^3 M_☉, 1 M_☉ BH binary at 10 Mpc

10^5 M_☉, 1 M_☉ BH binary at 10 Gpc

LIGO

LISA

L = 100 km, 10^3 km, and 10^4 km
also get observable gravitational waves from some SUSY models (NMSSM)
Cosmic Strings

DePies & Hogan PRD 75 125006
AGIS-LEO

low Earth orbit may be simpler

White paper with detailed proposal, backgrounds, etc: arXiv:1009.2702

a: $10^3 M_\odot$ IMBH @ 10 kpc

b: $10^5 M_\odot$ BH @ 10 Mpc

c: WD binary @ 10 kpc

d: $10^3 M_\odot$ IMBH @ 10 Mpc
Axion Dark Matter Detection
Cosmic Axions

Strong CP problem:

\[ \mathcal{L} \supset \theta G\tilde{G} \] creates a nucleon EDM \[ d \sim 3 \times 10^{-16} \theta e \text{ cm} \]

measurements \( \Rightarrow \) \[ \theta \lesssim 3 \times 10^{-10} \]
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the axion is a simple solution:

\[ \mathcal{L} \supset \frac{a}{f_a} G\tilde{G} + m_a^2 a^2 \]  
with  
\[ m_a \sim \frac{(200 \text{ MeV})^2}{f_a} \sim \text{MHz} \left( \frac{10^{16} \text{ GeV}}{f_a} \right) \]
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\[ a(t) \sim a_0 \cos (m_a t) \]

cosmic expansion reduces amplitude \( a_0 \)
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this field has momentum = 0 \( \Rightarrow \) it is non-relativistic matter

the axion is a good cold dark matter candidate
Axions From High Energy Physics

Easy to generate axions from high energy theories have a global symmetry broken at a high scale $f_a$

string theory or extra dimensions naturally have axions from non-trivial topology

naturally gives large $f_a \sim$ GUT ($10^{16}$ GeV) or Planck ($10^{19}$ GeV) scales

Axions and WIMPs are the best motivated cold dark matter candidates
Constraints and Searches

$f_a$ (GeV)

$10^8$
$10^{10}$
$10^{12}$
$10^{14}$
$10^{16}$
$10^{18}$
Constraints and Searches

$f_a$ (GeV)

Axion dark matter
Constraints and Searches

\[ \mathcal{L} \supset \frac{a}{f_a} F \tilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B} \]

- Axion dark matter
- Microwave cavity (ADMX)

\[ f_a \text{ (GeV)} \]

- \[ 10^8 \]
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Constraints and Searches

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axion-photon conversion suppressed by \( f_a \)

size of cavity increases with \( f_a \)

signal \( \propto \frac{1}{f_a^4} \)
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How search for high $f_a$ axions?
Axion Dark Matter

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axion dark matter is the biggest BEC \( \rho_{\text{DM}} \sim m_a^2 a_0^2 \sim 0.3 \frac{\text{GeV}}{\text{cm}^3} \)

the axion gives all nucleons a rapidly oscillating EDM
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the axion gives all nucleons a rapidly oscillating EDM

thus all (free) nucleons radiate

Axion is more observable through its effects on atomic energy levels
(significantly different from standard EDM searches)
Atomic Axion Searches

Unlike a normal EDM search, can look directly for the axion, without external EM fields to modulate the signal

instead use internal fields, much larger: \( E_{\text{int}} \sim \frac{e}{A^2} \sim 10^{12} \text{ V/m} \)

induces a shift to the energy levels: \( \delta \omega \sim \vec{E}_{\text{int}} \cdot \vec{d}_n \sim 10^{-24} \text{ eV} \)
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if cool \( 10^8 \) atoms per sec, interferometer lasts \( \sim 1 \) sec, and take \( 10^6 \) trials then shot noise limit is \( \delta \omega \sim \left( \frac{1 \text{ s} \cdot \sqrt{10^{14} \text{ atoms}}}{10^8 \text{ atoms}} \right)^{-1} \sim 7 \times 10^{-23} \text{ eV} \)

There are two important caveats: Parity and Schiff’s Theorem
Parity Breaking

Axion breaks parity (CP)

Atomic states have very little parity breaking

thus \[ \vec{E}_{\text{int}} \cdot \vec{d}_n \approx 0 \]
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One possible solution:

molecules can naturally break parity at O(1), though more difficult to work with due to low-lying modes

Must control molecular rotation with applied E field (~ 10^6 V/m)

Use applied B field (< 0.1 T) to rotate nuclear spin with axion’s frequency (easily scanned)
Schiff’s Theorem

Schiff’s theorem: in electrostatic equilibrium the E field on any point charge is zero

thus $\vec{E}_{\text{int}} \cdot \vec{d}_n \approx 0$
Schiff’s Theorem

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higher moments take into account corrections to this (e.g. finite size of nucleus...)

Schiff moment: \( \delta \omega \sim E_{\text{int}} d_S \sim (10^{-9} Z^3) E_{\text{int}} d_n \)

often use Hg or Tl \( \delta \omega \sim 10^{-3} E_{\text{int}} d_n \sim 10^{-27} \text{ eV} \)
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<tr>
<td>(^{225}\text{Ra})</td>
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NIST cooled polar \(^{40}\text{K}^{87}\text{Rb}\) to < \(\mu\text{K}\)
Molecular Axion Searches

$f_a$ (GeV)

Planck

$10^{18}$

GUT

$10^{16}$

$10^{14}$

$10^{12}$

$10^{10}$

$10^8$

Axion dark matter

microwave cavity (ADMX)

astrophysical constraints
Molecular Axion Searches

$\alpha_f$ (GeV)

Planck

$10^{18}$

$10^{16}$

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molecular interferometry

Axion dark matter

microwave cavity (ADMX)

astrophysical constraints

can most easily search in kHz - MHz frequencies $\rightarrow$ high $\alpha_f$
Molecular Axion Searches

- microwave cavity (ADMX)
- Axion dark matter
- astrophysical constraints

Can most easily search in kHz - MHz frequencies $\rightarrow$ high $f_a$

difficult technological challenges, similar to early stages of WIMP detection

Axion dark matter is very well-motivated, no other way to search for at high $f_a$

Would be both the discovery of dark matter and a glimpse into physics at very high energies
1. Considered the use of molecular interferometry to detect Axion dark matter
   - Axion dark matter is well motivated
   - unlike WIMPs, currently no way to detect over most of parameter space

2. Proposed an Atomic Gravitational Wave Interferometric Sensor (AGIS)
   - both terrestrial and satellite versions
   - AGIS-LEO in low Earth orbit

3. Proposed laboratory tests of General Relativity
   - including test of Equivalence Principle to $10^{-15}$ under construction @ Stanford

4. New ideas?