Ultralight Dark Matter & Gravitational Waves with Atom Interferometers

Atom interferometry
AION project
AION-100 @ CERN?
Examples of science studies
Search for Ultralight Dark Matter

**Known particle masses:**
- Neutrino
- Electron
- Proton
- Higgs

**Ultralight Dark Matter**
- QCD Axion
- Pre-Inflationary Axion
- Post-Inflationary Axion

**Massive dark matter**
- WIMPs
- Hidden Sector Dark Matter
- Hidden Thermal Relics / WIMPless DM
- Asymmetric DM
- Freeze-In DM
- SIMPs / ELDERS

**Ultra-Light dark matter**
- 'Ultra-Light' dark matter
- 'Massive' dark matter

---

**AION/AEDGE/STE-QUEST**
Ultralight Dark Matter

A scalar ULDM $\phi(x, t)$ field would be present throughout the Solar System.

The wavelength depends on the ULDM mass: $\lambda \sim 10^8 \text{ km} \left( \frac{10^{-15} \text{ eV}}{m_\phi} \right)$
Gravitational Waves

• General relativity proposed by Einstein 1915
• He predicted gravitational waves in 1916
• Tried to retract prediction in 1936!
Indirect Detection

- Binary pulsar discovered 1974 (Hulse & Taylor)
- Emits gravitational waves
- Change in orbit measured for years
- Perfect agreement with Einstein
- Nobel Prize 1993
Direct Discovery of Gravitational Waves

- Measured by the LIGO experiment in 2 locations

State of Washington

State of Louisiana
Principle of Laser Interferometer

- Interference between 2 laser beams measures the expansion and contraction of space
Direct Discovery of Gravitational Waves

• Very similar signals in the 2 detectors

In agreement with gravitational-wave predictions
Fusion of two massive black holes

• Einstein was right the first time!

• A new way to study the Universe
Observations of Neutron Star Merger

LIGO/Virgo/Fermi/INTEGRAL

Lightcurve from Fermi/GBM (10 – 50 keV)

Lightcurve from Fermi/GBM (50 – 300 keV)

Lightcurve from INTEGRAL/SPI-ACS (> 100 keV)

Velocity of gravity ~ light

LIGO/Virgo+70

10
GW190521 – a Bang not a Chirp

Triple measurement of merger of heaviest black holes seen so far
Masses of Black Holes Deduced from Measured Mergers

LIGO-Virgo Black Hole & Neutron Star Masses

Intermediate-Mass black holes

Low-mass gap between neutron stars and black holes?

Masses of Black Holes Deduced from Measured Mergers

LIGO-Virgo-KAGRA Black Hole & Neutron Stars

LIGO-Virgo-KAGRA Black Holes  LIGO-Virgo-KAGRA Neutron Stars  EM Black Holes  EM Neutron Stars

Solar Masses

“The Stellar Graveyard”
Ground-Based GW Detectors
Gravitational Wave Spectrum

A new type of astronomy

Cosmology

Astrophysics

Lasers + Atoms
Supermassive Black Holes in Active Galactic Nuclei: Image of M87

Mass $\sim 6.5 \times 10^9$ solar masses
Future Step: Interferometer in Space

LISA (+ Taiji, TianQin)
NANOGRav has observed 47 pulsars over 12.5 yrs

Gravitational Wave Spectrum

- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Supernovae? Phase transitions? ...
  - [Gap between LISA & pulsar timing arrays (PTAs)]
Principle of Atom Interferometry

Light interferometer

Mirror 1

Detector

Mirror 2

Beamsplitter

Light fringes

Atom interferometer

Beamsplitter

Mirror

Atom

Beamsplitter

Laser pulses act as beamsplitters and mirrors
Effect of Dark Matter on Atom Interferometer

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

DM cloud changes atom frequency

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i(\omega_a + \Delta \omega_{DM}) T} \]

DM coupling causes time-varying atomic energy levels.

\( \rho_{\text{DM}} = 0.4 \text{ GeV/cm}^3 \)

\( v_{\text{DM}} \sim 300 \text{ km/s} \)

Sun, bulge, disk, Milky Way

\( \Delta \omega_{DM} \)
Effect of Gravitational Wave on Atom Interferometer

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

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

GW changes light travel time

\[ \Delta T \sim \hbar L/c \]

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

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a (T+\Delta T)} \]
Atomic Multi-Gradiometer

Multiple atomic interferometers in the same vertical shaft, manipulated with same laser beam. Eliminate laser noise, minimize gravity gradient noise.
Network with MAGIS project in US


AION Collaboration


1Kings College London, 2STFC Rutherford Appleton Laboratory, 3University of Oxford, 4University of Birmingham, 5University of Liverpool, 6Imperial College London, 7University of Cambridge
AION – Staged Programme

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation for 100m baseline

- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning

- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond

- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

Initial funding from UK STFC

Workshop @ CERN, March 13/14, 2023

AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755
Planned Location of AlON-10m

- New purpose-built building (£50M facility)
- AlON-10 on basement level with 14.7m headroom (stable concrete construction)
- World-class infrastructure
- Experienced Project Manager:
- Engineering support from RAL (Oxfordshire)

Laser lab for AlON vibration criterion, VC-G = 10nm@10Hz. Temperature (22±0.1)° C
Planned Location of AION-10m
Strontium Atom Laboratories
Possible CERN Location of AION-100m

Supported by CERN PBC Team
(Gianluigi Arduini, Sergio Calatroni ...)
on feasibility study:
  - Seismology
  - Temperature
  - Ventilation
  - Radiation protection
  - Electromagnetic interference
  - Access & safety

Also studying possible site at STFC Boulby Laboratory in UK
AEDGE:
Atomic Experiment for Dark Matter and Gravity
Exploration in Space

Beyond LISA

White paper submitted to ESA Voyage 2050 Call
Ultralight Dark Matter

Interactions with the ULDM field lead to oscillations in fundamental 'constants'

Time-dependent electron mass:

$$m_e(t, x) = m_e \left[ 1 + \frac{d_{me} \phi(t, x)}{M_{Pl}} \right]$$

Time-dependent electromagnetic fine structure constant:

$$\alpha(t, x) = \alpha \left[ 1 + \frac{d_e \phi(t, x)}{M_{Pl}} \right]$$

Tiny oscillations induced in transition energies:

$$\frac{\delta \omega_{Sr}}{\omega_{Sr}} = \sqrt{2 \rho_{DM}} \frac{(d_{me} + \xi d_e)}{m_{DM} M_{Pl}} \cos(m_{DM} t)$$
Searches for Light Dark Matter

Linear couplings to gauge fields and matter fermions

\[ \mathcal{L}_{\text{int} \phi} = \kappa \phi \left[ + \frac{d_e}{4e^2} F_{\mu \nu} F^{\mu \nu} - \frac{d_g \beta_3}{2g_3} F_{\mu \nu} A^{\mu \nu} - \sum_{i=e,u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right] \]

Clocks

MICROSCOPE

AURIGA

Orders of magnitude improvement over current sensitivities

Gravity Gradient Noise

- **Rayleigh waves** propagating across the surface induce density variations underground.

- The density variations give rise to a phase shift:

\[ \Phi^{(i)}_{\text{GGN},m} = \sum_a \xi_a \left[ A_a \exp \left( -q \frac{\omega_a z_i}{c_H} \right) + B_a \exp \left( -\frac{\omega_a z_i}{c_H} \right) \right] \cos \phi_{a,m} \]

- Two key parameters:
  1. \( \xi_a \): surface displacement
  2. \( \lambda_{\text{GGN}} = \frac{c_H}{\omega_a} \): decay length with depth

Key quantity: velocity \( c_H \), depends on type of rock

Badurina, Gibson, McCabe & Mitchell, arXiv:2211.01854
How to Observe Mergers of Intermediate Mass BHs?

Volonteri, Habouzit & Colpi, arXiv:2110.10175
How to Make a Supermassive BH?

SMBHs from mergers of intermediate-mass BHs (IMBHs)?
Intermediate Mass Black Holes Identified as Low-Luminosity Active Galactic Nuclei

Chilingarian et al., arXiv:1805.01467
Gravitational Waves from IMBH Mergers

Probe formation of SMBHs
Synergies with other GW experiments (LIGO, LISA), test GR

GWs from IMBH Mergers: SNR = 8

AION complementary to LIGO, Einstein Telescope (ET) Operation before LISA
Gravitational Waves from IMBHs

Detect mergers of $\sim 10^4$ solar-mass BHs
with SNR 1000 out to $z \sim 10$,
Mergers of $\sim 10^3$ solar-mass BHs
with SNR 100 out to $z \sim 100$

Lighter shades: inspiral
Darker shades: merger + ringdown
Complementarity + synergy

Pulsar Timing Arrays

NANOGRav report of possible GW signal

PTA Measurements

“Common-spectrum process” (CP) measured by NANOGrav & other Pulsar Timing Arrays (PTAs)
Similar strengths
Spectral index compatible with mergers of SMBHs
Hellings-Downs (HD) angular dependence prediction of GWs unproven

Masses and Redshifts of BH Mergers

Using Extended Press-Schechter formalism for BH mergers following halo mergers

\[ \frac{R_{\text{BH}}}{p_{\text{BH}}} [\text{Gpc}^{-3} \text{year}^{-1}] \]

\[ 10^3 M_\odot < M < 10^6 M_\odot \]
\[ 10^6 M_\odot < M < 10^9 M_\odot \]
\[ M > 10^9 M_\odot \]
Stochastic GW Background from BH Mergers

Black dashed line is maximum possible $\Omega_{GW}$, i.e., $p_{BH} = 1$
Measuring IMBH Inspiralals

Inspiral events measured during last year before merger

AEDGE would observe mergers of these binaries observed by LISA during infall

Measuring IMBH Mergers

LISA and AEDGE would observe similar numbers of IMBH mergers. AEDGE mergers would have been observed by LISA during infall. Opportunities to test GR, multi messenger astronomy.
Probing Extensions of the Standard Model
GWs from a First-Order Phase Transition

• Transition by percolation of bubbles of new vacuum
• Bubbles grow and collide
• Possible sources of GWs:
  – Bubble collisions
  – Turbulence and sound waves in plasma
• Models studied:
  – Standard Model + $H^6/\Lambda^2$ interaction
  – Standard Model + $U(1)_{B-L} Z'$
• These also have prospective collider signatures
Gravitational Waves from $U(1)_{B-L}$ Phase Transition

---

Total  Bubble collisions  Sound waves  Turbulence

---

$T_* = \text{percolation temperature when transition completes}$

---


---

Probing Cosmic Strings
Hint from the NANOGrav pulsar timing array?

GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group
Cosmic String Interpretation of NANOGrav

Cosmic string prediction can be tested in several upcoming experiments (not LIGO).

See also: Blasi, Vrdar & Schmitz: arXiv:2009.06607v2
Summary

• Experience with electromagnetic waves shows the advantages of making astronomical observations in a range of different frequencies, and the same is expected to hold in the era of gravitational astronomy
• Gravitational waves from merging black holes observed
• Many opportunities to search for new fundamental physics: ultralight bosonic dark matter, phase transitions, cosmic strings, ...
• AION offers a programme for exploring deci-Hz GW and ULDM based on atom interferometry
• AEDGE is a concept for a space mission that would complement, and have synergies with, other future GW experiments
• Other possible opportunities in fundamental physics, astrophysics and cosmology have been identified, but not yet explored in detail
• Unique interdisciplinary science!
Was that you I heard chirp just now, or was it two black holes colliding?