MAGIS-100 at Fermilab:

A Matter-wave Atomic Gradiometer with Sensitivities to Dark Matter

Sam Hindley, University of Liverpool
on behalf of the MAGIS Collaboration

Fermilab
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STANFORD
UNIVERSITY OF CAMBRIDGE
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NORTHWESTERN UNIVERSITY 1851
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NIU Northern Illinois University

Overview

- Science goals
- MAGIS-100 & AION experiments
- Scalar dark matter detection
- UK involvement
- Future development plans

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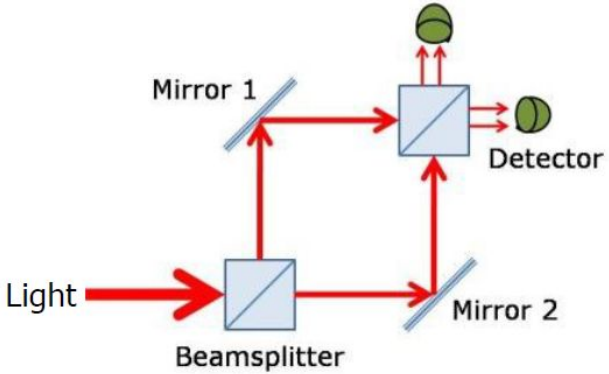
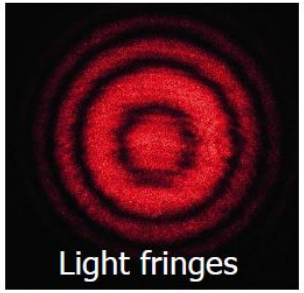
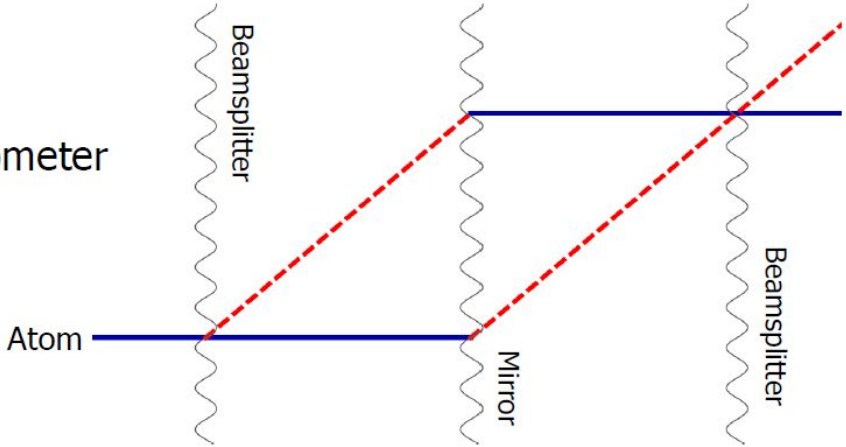
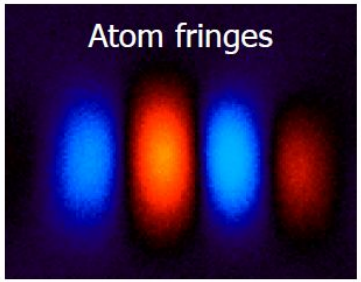
Light interferometer





Atom interferometer





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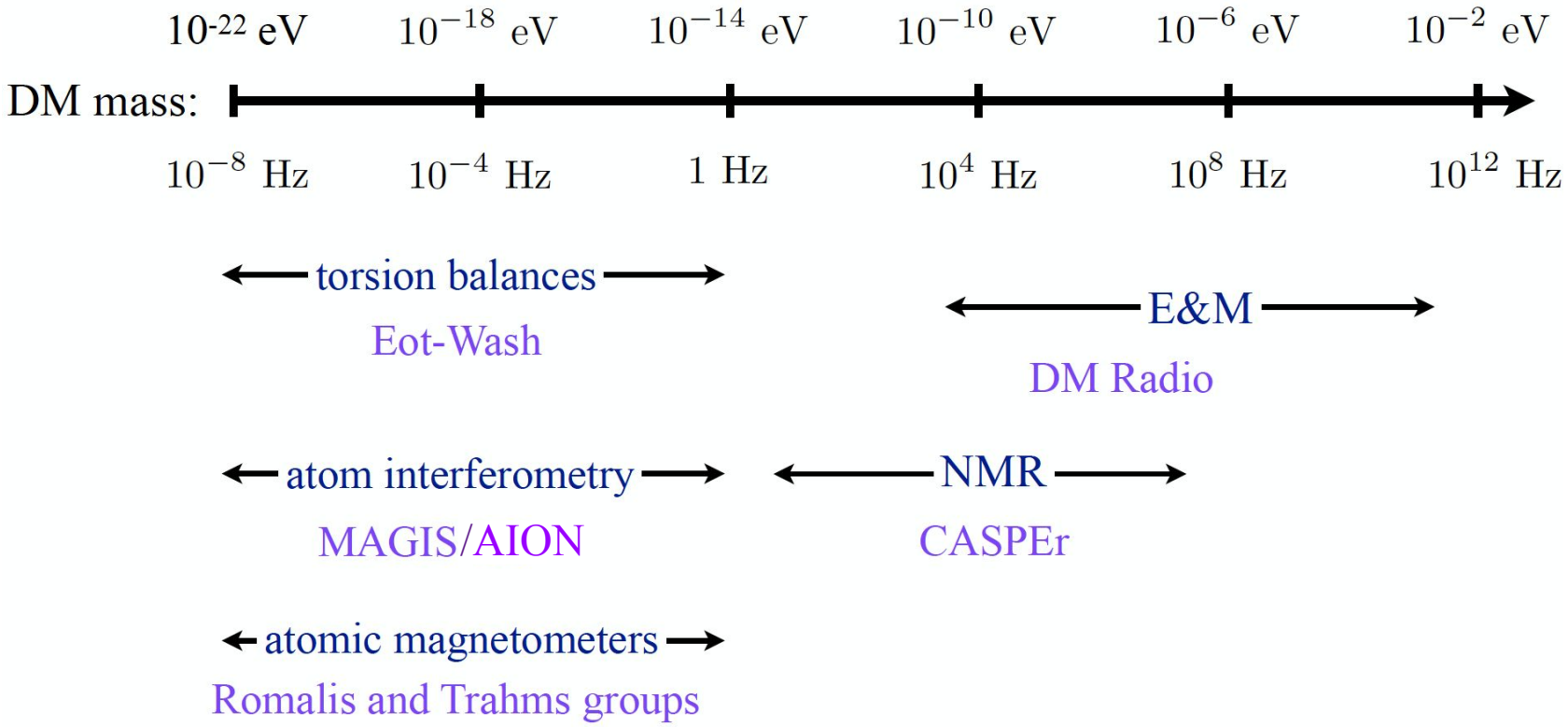
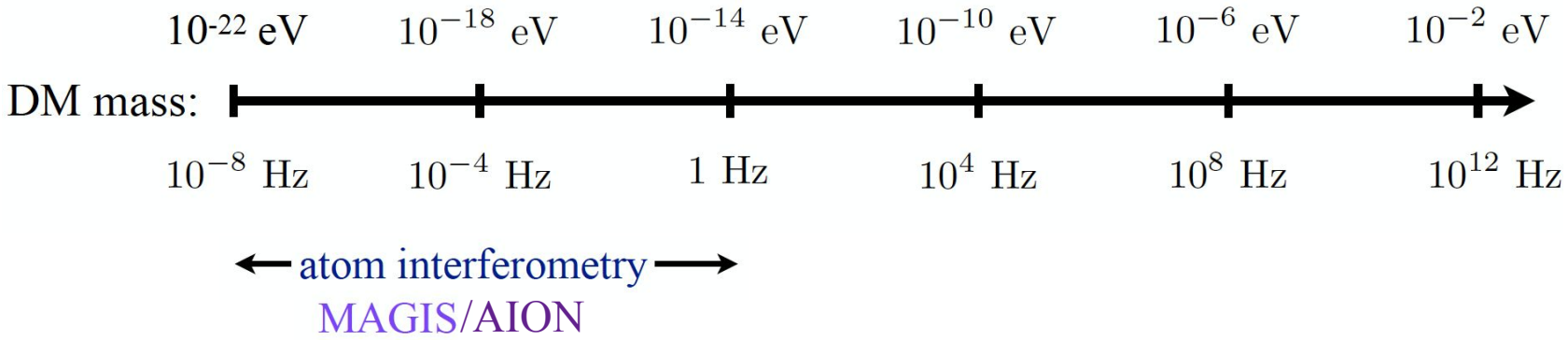
Science Case



Science Case



- "Ultralight" dark matter candidates are wavelike at this energy
- 100 metre device applies state-of-the-art atom interferometry techniques at new length scales for detection

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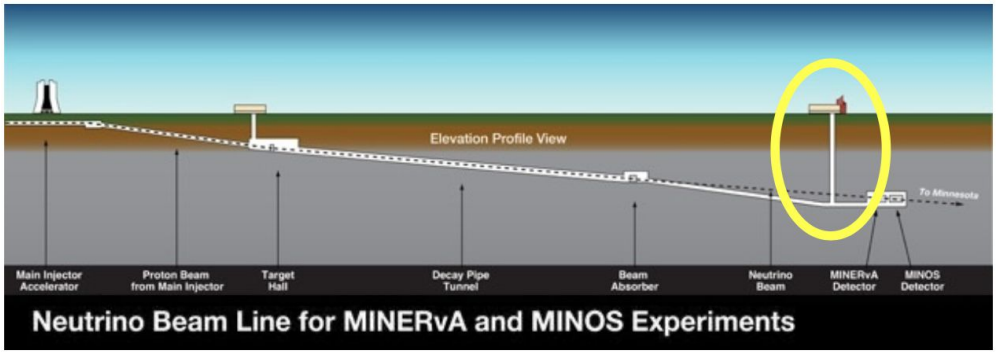
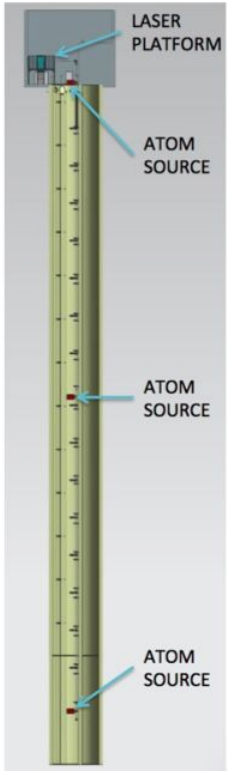
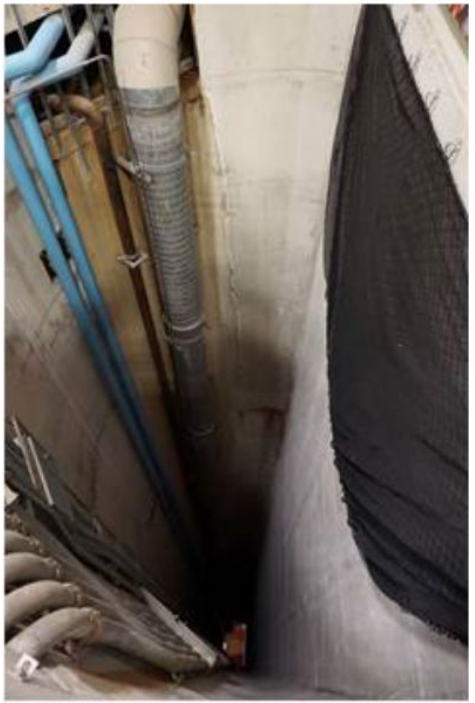
MAGIS-100 at Fermilab

- Currently in construction in MINOS access shaft
  - Baseline of 100 m
- 3 strontium atom sources
  - Multiple configurations
- Sensitivity rises with longer interrogation times







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MAGIS & AION

- Networked atom interferometers for fundamental physics
- Operate two detectors in tandem to achieve greater sensitivity
  - MAGIS in the US, AION in the UK
- Networked operation provides non-common background mode rejection
  - Improves confidence in any observation
- International collaboration serves as testbed for 1 km scale terrestrial detector and future satellite-based detectors

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International Network

For more details on AION see
https://arxiv.org/pdf/1911.11755.pdf

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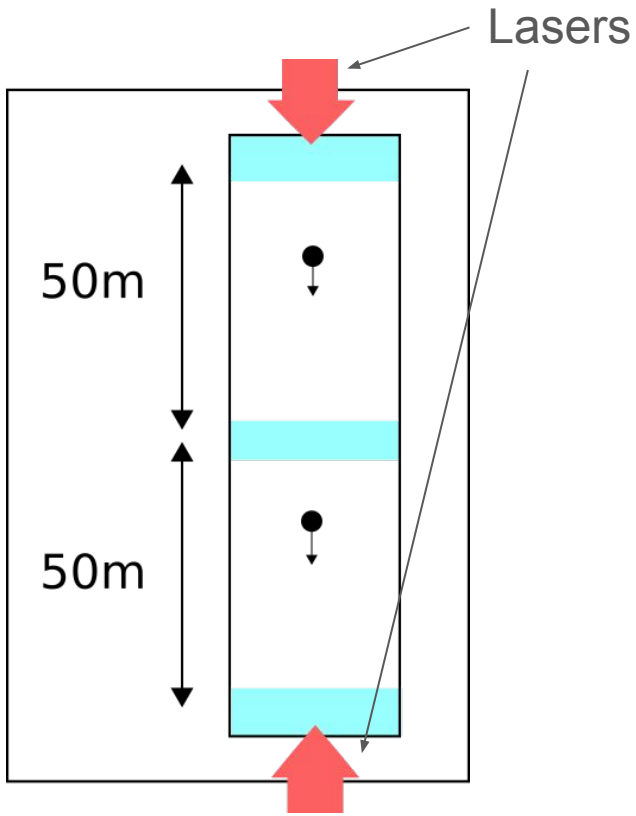
MAGIS-100 Concept

- Default config: two 50-metre atom drop chambers with 100-metre laser baseline
- Common-mode background rejection reduces laser noise sources
- Same configuration can be used for GW search



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Ultralight Dark Matter Sensitivity

Ultralight DM acts as a coherent, wavelike background field (e.g., mass ~10^{-15} eV)

Example for scalar DM field:

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

DM scalar field

Electron coupling

Photon coupling

e.g., QCD

$$\phi(t,\mathbf{x}) = \phi_0\cos\left[m_\phi(t-\mathbf{v}\cdot\mathbf{x})+\beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right) \qquad \phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$

DM mass density

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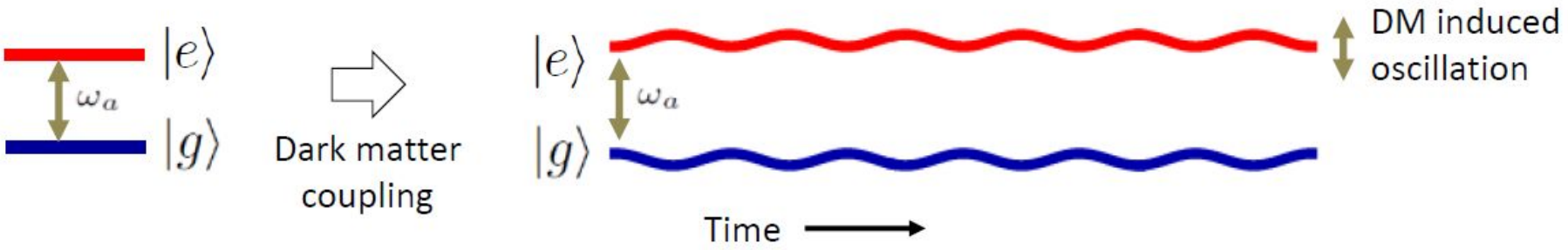
Ultralight Dark Matter Sensitivity

DM coupling causes time-varying atomic energy levels:



Effect of varying energy levels modifies phase response

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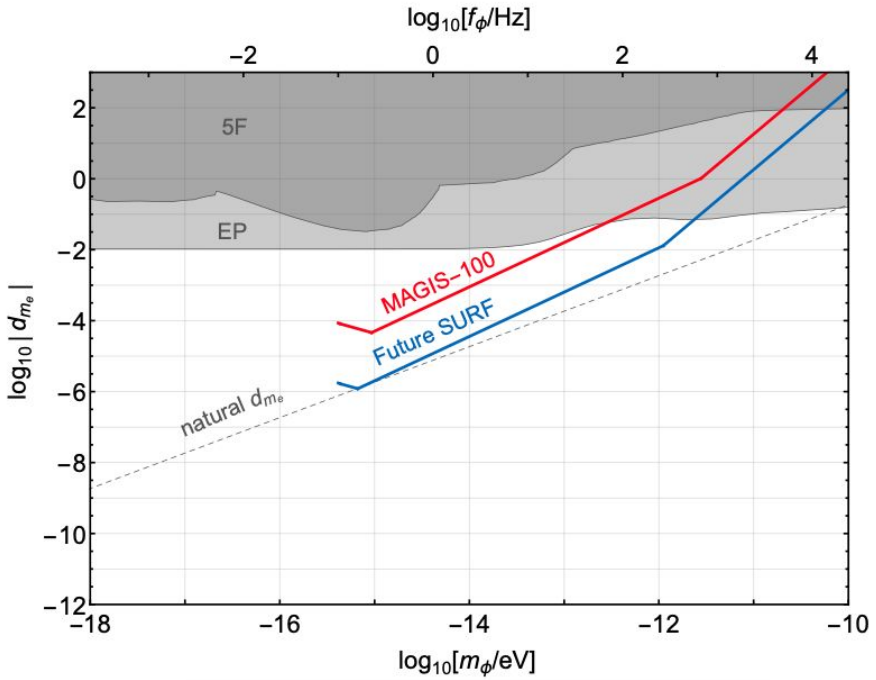
Ultralight Dark Matter Search

- Coupling to DM causes periodic variations in fundamental properties proportional to m_{DM}
  - Electron mass, fine structure constant
- Possible dark matter signal visible at integration time t_{int} ~ 1 year



Search for light scalar dark matter with atomic gravitational wave detectors, A. Arvanitaki et al, 2016

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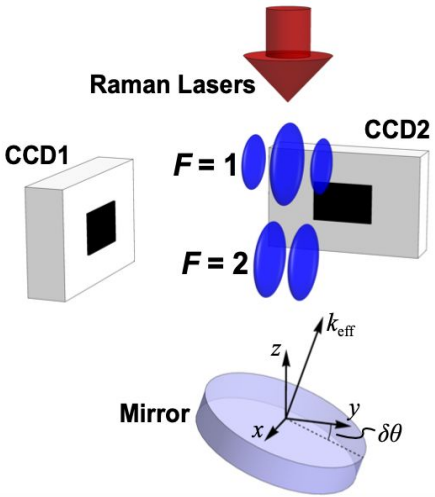
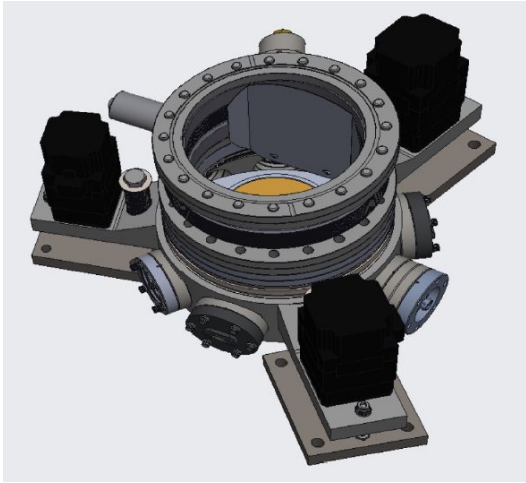
UK Involvement - Detection

- Hardware - Detection System
  - Present at all output ports
  - In-vacuum hardware, mirror mounts
- Software - Image Studies
  - Diffusion studies, laser effects, mock data challenge
- See L. Hawkins, *MAGIS-100 at Fermilab*, poster session





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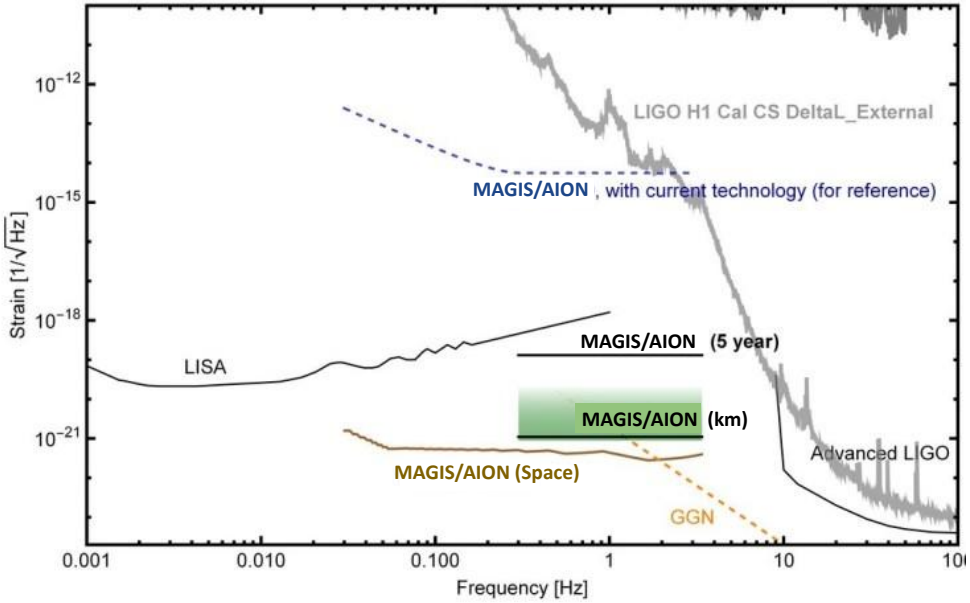
Future Plans

- Signals improve with longer integration times and projected developments in atom technology
- Testbed for 1 km detector with scope for sensitivity to gravitational waves



AION: An Atom Interferometer Observatory and Network, L. Badurina et al, 2020

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Summary

- Unique sensitivity to wavelike scalar DM
  - Fluctuations in atomic constants detectable by atom interferometry
- MAGIS geometry reduces systematics
  - 100 m baseline - improved sensitivity
  - Networked with future UK experiment
- UK collaborators working on detection
- Pathfinder for larger detectors

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Acknowledgements

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Backups

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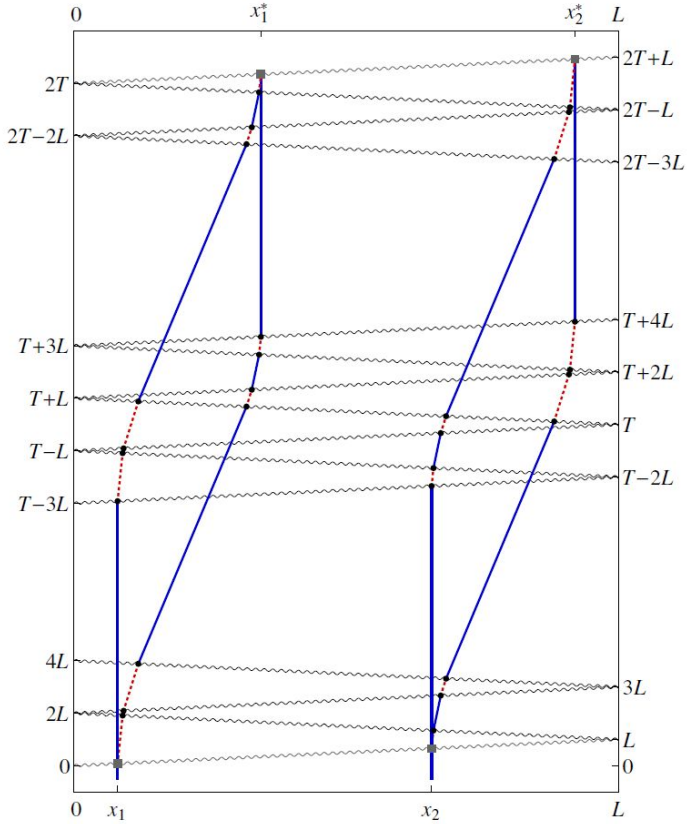
Clock Gradiometry

- Differential atomic clock has two ensembles referenced by one laser
- Phase response of both clouds is identical in absence of new physics and reducible backgrounds
- Large Momentum Transfer (LMT) pulses coherently enhance differential clock signal:

$$\Delta\phi \sim 2n\omega_A\,(L/c)$$



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