Realistic Simulator of Gravitational Wave and Dark Matter Detection in long-baseline Atom Interferometry

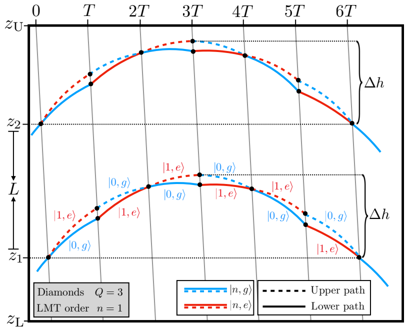
Michael Werner, Dennis Schlippert, Ernst M. Rasel, Naceur Gaaloul

Institute of Quantum Optics Hannover, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany

Theory of Quantum Sensing

Our webpage!

Leibniz Universität Hannover



Motivation

Measuring Gravitational Waves and Dark Matter are two of the most anticipated problems in modern physics.

Atom Interferometer (AIFs) are highly sensitive measurement devices that can potentially measure both within a single (large scale) facility with a baseline $B \geq 100\,\text{m}$.

Gravitational Waves (GWs): Can be detected in the highly anticipated **mid-frequency band** between space borne experiments (LISA) and terrestrial laser interferometers (LIGO/VIRGO/KAGRA).

Dark Matter (DM): A plethora of different DM theories are currently under investigation. **ULDM** is, however, in its **scalar** and **axionic** form proposed for large scale AIFs to be detectable.

All proposed theoretical models are, so far, mostly algebraic and treat imperfections and noise in a simplified manner. We now propose a numerical simulator and an optimal parameter analysis for such large scale AIF experiments.

Introduction

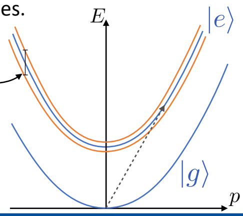
In Hannover is the 10m facility VLBAI ("Very Long Baseline Atom Interferometer").

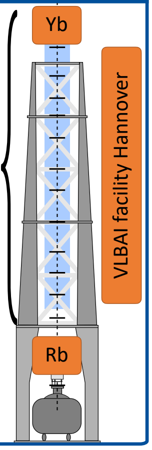
- Interferometry with Rubidium (Rb) and Ytterbium (Yb) with a free fall time of up to $2T \approx 2.6\,\text{s}$.
- Designed to do precise UFF (Universality of Free Fall) tests with atoms.

Gravitational Waves: Periodically changes the baseline B and the corresponding photon flight times.

Dark Matter (scalar ULDM): Periodically change the internal state energies and therefore the resonance frequency of the interaction.

Both effects can be detected with the same interferometer setup!





Optimal Parameters for Resonant GW Detection

What is the optimal configuration to detect a GW of known frequency ω in a detector with fixed baseline B on Earth? [1]

The interferometer time $T = \pi/\omega$ is set by the GW frequency. Having a minimal and maximal time of the AIF, one can define the three main free parameters

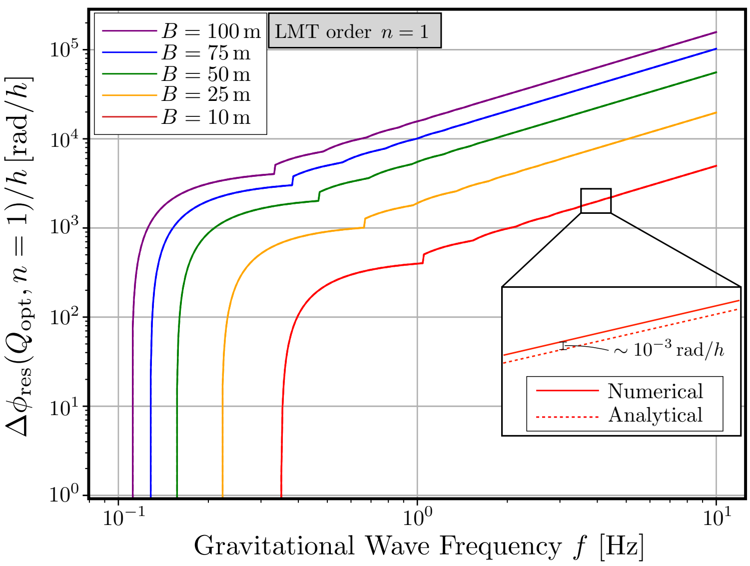
$$1 \leq Q \leq Q_{\text{max}} = \left\lfloor \frac{T_{\text{max}}}{T} \right\rfloor, 1 \leq n \leq n_{\text{max}} = \left\lfloor \frac{T}{T_{\text{min}}} \right\rfloor \text{ and } 0 < L < B.$$

Goal: Find the optimal triple $(Q_{\text{opt}}, n_{\text{opt}}, L_{\text{opt}})$ which maximizes the phase

$$\Delta\phi_{\text{res}}(Q, n, L) = 2Qnk_{\text{eff}}hL \,\text{sinc}\left(\frac{\omega n L}{2c}\right) \cos\left(\frac{\omega(n-1)L}{2c}\right).$$

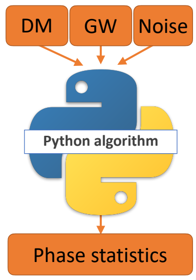
Numerics: Our open source Python algorithm (right box) is able to simulate GWs with strains of $h \geq 10^{-20}$ even within $B = 10\,\text{m}$ interferometers.

Connection to DM: DM is detected in the exact same AIF geometry — optimized in the same manner!



Open Source Python Algorithm

- Solves the Schrödinger equation systematically using the stationary phase approximation. [2]
- Includes general relativity (GR) to order $\mathcal{O}(c^{-2})$. [2]
- Ray propagation (finite speed of light) and intersection with atomic trajectories to ultra high precision.
- Models (static) idealized gravitational backgrounds as well as non-trivial ones, such as the measured model of the VLBAI.
- Possibility to include (temporal and spatial) gravitational anharmonicities.
- Open Source: Each paper comes with its own repository that reproduces all numerical results.
- Includes GGN noise [4]



From Peterson's model [3]

Uniform random

$$V_{\text{GGN}}(z,t) = -2\pi G\rho_0 \sum_a \xi_a \frac{c_{\text{H}}}{q\omega_a}\left(\frac{1+s^2}{1-s^2}\right) \times \left[(1+\sqrt{q/s})\exp(-\omega_a z/c_{\text{H}}) - 2\exp(-q\omega_a z/c_{\text{H}})\right]\cos(\omega_a t + \tilde{\theta}_a)$$

With fixed values $\rho_0 = 1800\,\text{kg/m}^3$, $s = 0.36$, $q = 0.88$, $c_{\text{H}} = 205\,\text{m/s}$.

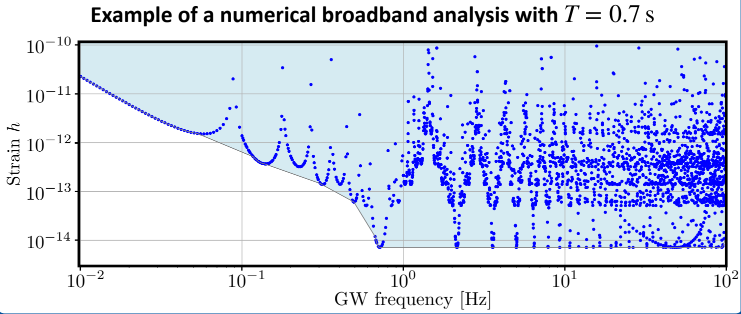
Broadband GW & DM Analysis

Large scale detectors — of course — need to operate in a broadband configuration. For this, one sets the AIF time T to a fixed value and tries to **optimize the broadband configuration**.

Goal: Find parameters that reject noise (GGN) optimally for ULDM and GW detection. There are, however, some differences in the detection schemes:

- ULDM requires multiple atomic species to detect different couplings.
- DM usually also has multiple coupling constants that need to be distinguished.
- GWs requires (optimally) a global network of AIF detectors with baselines in different directions to distinguish polarizations.

Example of a numerical broadband analysis with $T = 0.7\,\text{s}$



References

[1] Werner, Gaaloul, "Optimal Parameter Configuration and Open Source Numerical Modeling of Terrestrial Gravitational Wave Detection with Atom Interferometers" [in preparation]

[2] Werner et al., "Atom interferometers in weakly curved spacetimes using Bragg diffraction and Bloch oscillations" (2023)

[3] Peterson, "Observations and modeling of seismic background noise" (1993)

[4] Badurina et al., "Prospective Sensitivities of Atom Interferometers to Gravitational Waves and Ultralight Dark Matter" (2021)

Funding

This work was funded by the Deutsche Forschungsgemeinschaft (German Research Foundation) under Germany's Excellence Strategy (EXC-2123 **QuantumFrontiers** Grants No. 390837967), through CRC 1227 (**DQ-mat**) within Project No. A05. MW and NG acknowledge funding by the **AGAPES** project - grant No, 530096754 within the ANR-DFG 2023 Programme.