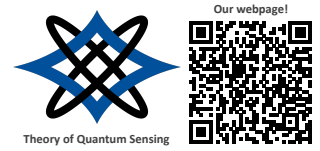


$\hbar$ ASE: Realistic Simulator of Gravitational Wave and Dark Matter Detection in long-baseline Atom Interferometry



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Motivation

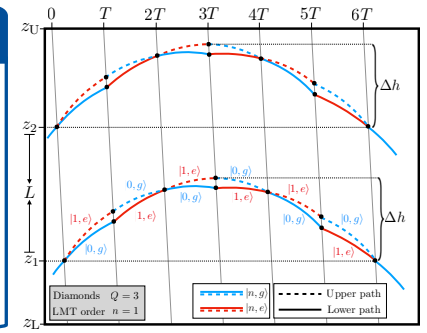
Measuring Gravitational Waves and Dark Matter are two of the most anticipated problems in modern physics.

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

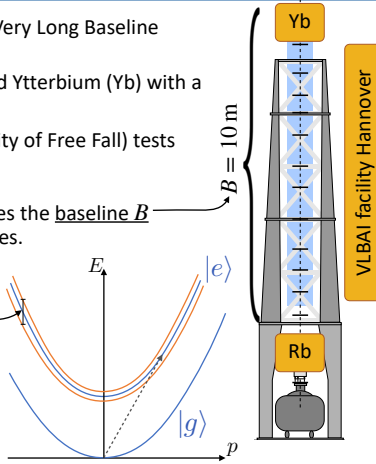
In Hannover is the 10m facility VLBAI ("Very Long Baseline Atom Interferometer").

- Interferometry with Rubidium (Rb) and Ytterbium (Yb) with a free fall time of up to $2T \approx 2.6$ 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!



$\hbar$ ASE: Open Source Python Algorithm

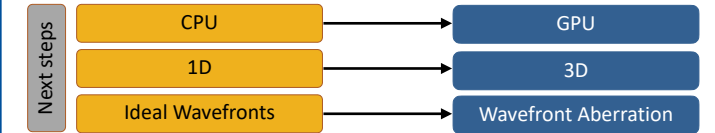
- Solves the Schrödinger equation systematically using the stationary phase approximation. [2]
- Includes general relativity (GR) to order $\mathcal{O}(c^{-2})$. [2]
- Ray propagation (finite speed of light) and intersection with atomic trajectories to ultra high precision.
- Models (static) idealized 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]

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

with $\rho_0 = 1800 \text{ kg/m}^3$, $s = 0.36$, $q = 0.88$, $c_H = 205 \text{ m/s}$ and other models.



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

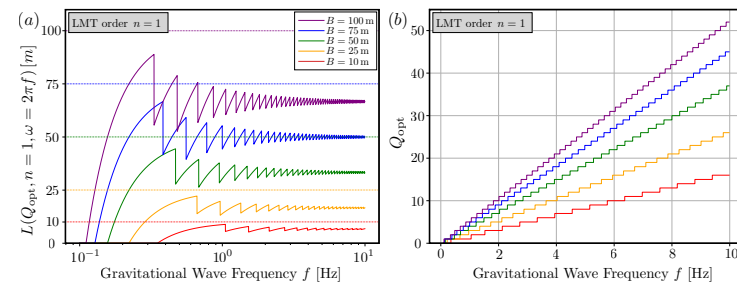
$$1 \leq Q \leq Q_{\text{max}} = \left\lfloor \frac{T_{\text{max}}}{T} \right\rfloor, 1 \leq n \leq n_{\text{max}} = \left\lfloor \frac{T}{2T_{\text{min}}} \right\rfloor \text{ and } 0 < L < B.$$

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

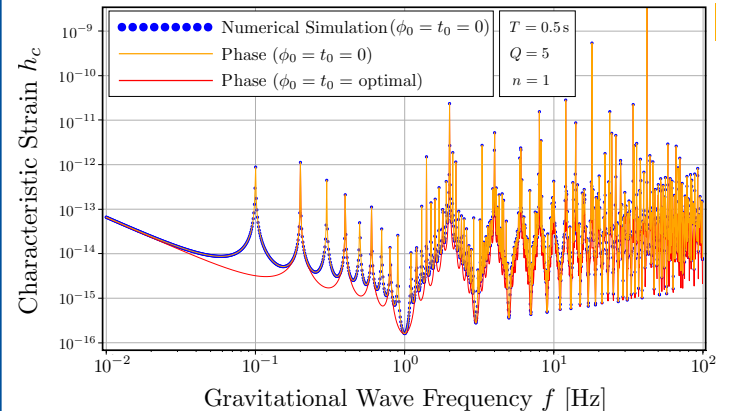
$$\Delta\phi_{\text{res}}(Q, n, L) = 2Qn k_{\text{eff}} h L \text{sinc}\left(\frac{\omega n L}{2c}\right) \cos\left(\frac{\omega(n-1)L}{2c}\right).$$

Numerics: $\hbar$ ASE (right box) is able to simulate GWs with strains of $h \geq 10^{-20}$ even within $B = 10$ m interferometers.

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



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**.

$\hbar$ ASE: Is able to simulate such experiments to very high accuracy. In the ideal case (no noise) we fully align with the analytical curves.

References

- [1] Werner et al., "Terrestrial Gravitational Wave Detection with Atom Interferometers" (2026)
- [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)

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