2nd September 2026 — AICE Community Workshop 2026

PHASE: An Open Source Python Toolbox for Large Scale Atom Interferometers

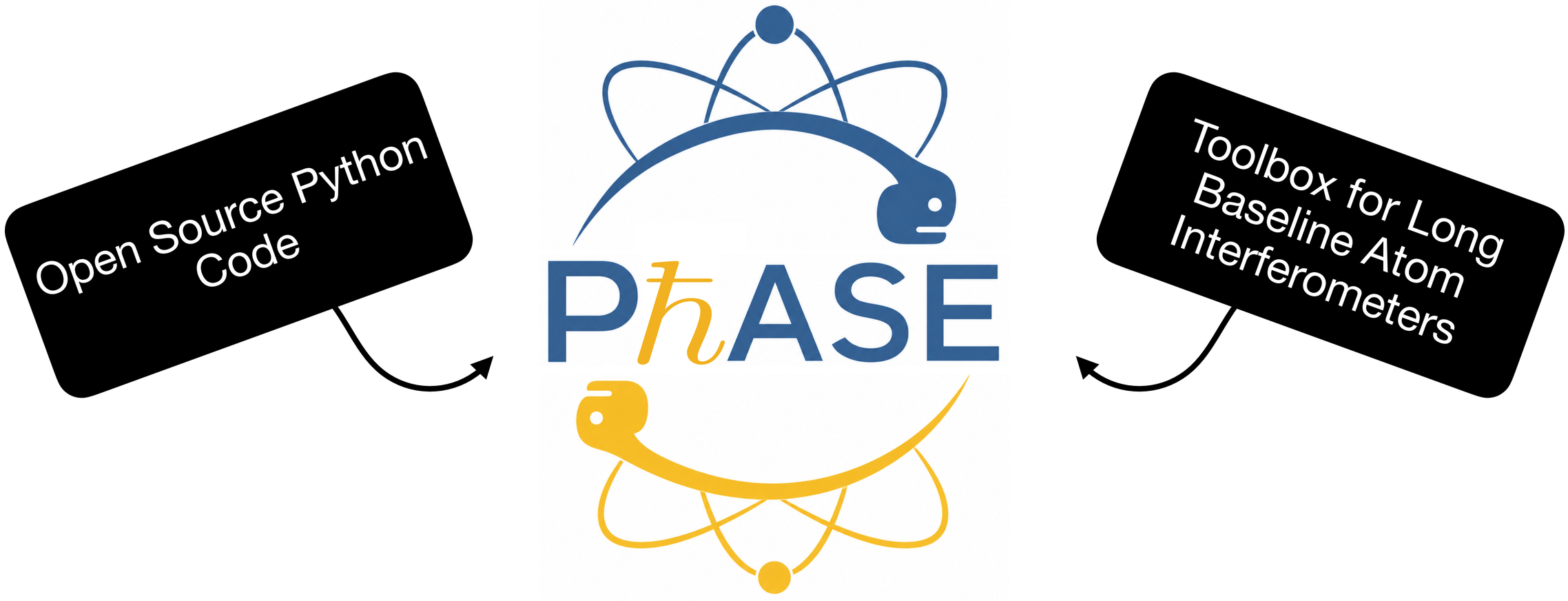
Michael Werner

Theory of Quantum Sensing
(Lead: Dr. Naceur Gaaloul)
Institute of Quantum Optics
Leibniz University Hannover

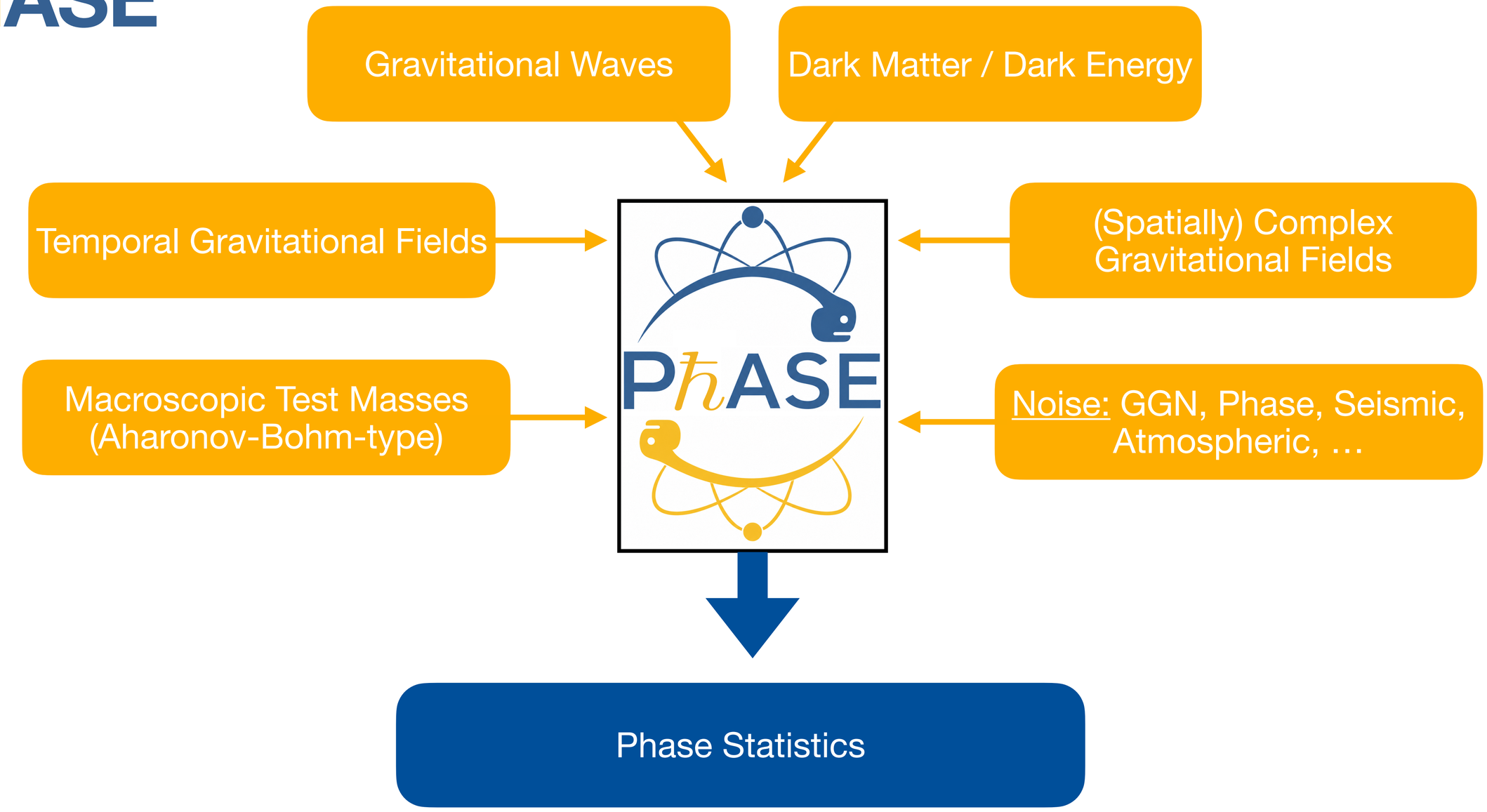


PHASE

Precision High-accuracy Atom-interferometry Simulation Engine



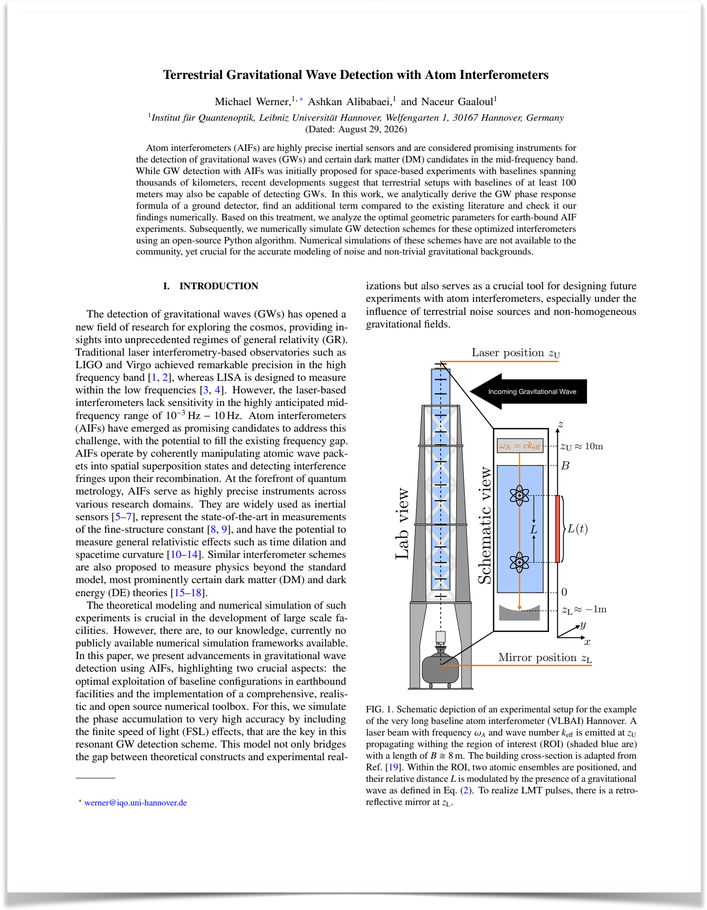
PHASE


Gravitational Waves
Dark Matter / Dark Energy
Temporal Gravitational Fields
(Spatially) Complex Gravitational Fields
PħASE
Macroscopic Test Masses (Aharonov-Bohm-type)
Noise: GGN, Phase, Seismic, Atmospheric, …
Phase Statistics

PHASE at work: Gravitational Waves

“Terrestrial Gravitational Wave Detection with Atom Interferometers”

- First demonstration of **PHASE** at work.
- Numerical Test for High Precision Calculation: Runs for **100m baselines** with **strains of** 10^{-20}!
- Parameter Optimization: Which geometry performs best?
- Starting point for complex noise analysis!



Terrestrial Gravitational Wave Detection with Atom Interferometers

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(Dated: August 29, 2026)

Atom interferometers (AIFs) are highly precise inertial sensors and are considered promising instruments for the detection of gravitational waves (GWs) and certain dark matter (DM) candidates in the mid-frequency band. While GW detection with AIFs was initially proposed for space-based experiments with baselines spanning thousands of kilometers, recent developments suggest that terrestrial setups with baselines of at least 100 meters may also be capable of detecting GWs. In this work, we analytically derive the GW phase response formula of a ground detector, find an additional term compared to the existing literature and check it our findings numerically. Based on this treatment, we analyze the optimal geometric parameters for earth-bound AIF experiments. Subsequently, we numerically simulate GW detection schemes for these optimized interferometers using an open-source Python algorithm. Numerical simulations of these schemes have are not available to the community, yet crucial for the accurate modeling of noise and non-trivial gravitational backgrounds.

I. INTRODUCTION

The detection of gravitational waves (GWs) has opened a new field of research for exploring the cosmos, providing insights into unprecedented regimes of general relativity (GR). Traditional laser interferometry-based observatories such as LIGO and Virgo achieved remarkable precision in the high frequency band [1, 2], whereas LISA is designed to measure within the low frequencies [3, 4]. However, the laser-based interferometers lack sensitivity in the highly anticipated mid-frequency range of 10^{-3} Hz – 10 Hz. Atom interferometers (AIFs) have emerged as promising candidates to address this challenge, with the potential to fill the existing frequency gap. AIFs operate by coherently manipulating atomic wave packets into spatial superposition states and detecting interference fringes upon their recombination. At the forefront of quantum metrology, AIFs serve as highly precise instruments across various research domains. They are widely used as inertial sensors [5–7], represent the state-of-the-art in measurements of the fine-structure constant [8, 9], and have the potential to measure general relativistic effects such as time dilation and spacetime curvature [10–14]. Similar interferometer schemes are also proposed to measure physics beyond the standard model, most prominently certain dark matter (DM) and dark energy (DE) theories [15–18].

The theoretical modeling and numerical simulation of such experiments is crucial in the development of large scale facilities. However, there are, to our knowledge, currently no publicly available numerical simulation frameworks available. In this paper, we present advancements in gravitational wave detection using AIFs, highlighting two crucial aspects: the optimal exploitation of baseline configurations in earthbound facilities and the implementation of a comprehensive, realistic and open source numerical toolbox. For this, we simulate the phase accumulation to very high accuracy by including the finite speed of light (FSL) effects, that are the key in this resonant GW detection scheme. This model not only bridges the gap between theoretical constructs and experimental realizations but also serves as a crucial tool for designing future experiments with atom interferometers, especially under the influence of terrestrial noise sources and non-homogeneous gravitational fields.

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FIG. 1. Schematic depiction of an experimental setup for the example of the very long baseline atom interferometer (VLBAI) Hannover. A laser beam with frequency ω_A and wave number k_{eff} is emitted at z_U propagating withing the region of interest (ROI) (shaded blue are) with a length of $B \approx 8$ m. The building cross-section is adapted from Ref. [19]. Within the ROI, two atomic ensembles are positioned, and their relative distance L is modulated by the presence of a gravitational wave as defined in Eq. (2). To realize LMT pulses, there is a retro-reflective mirror at z_L.

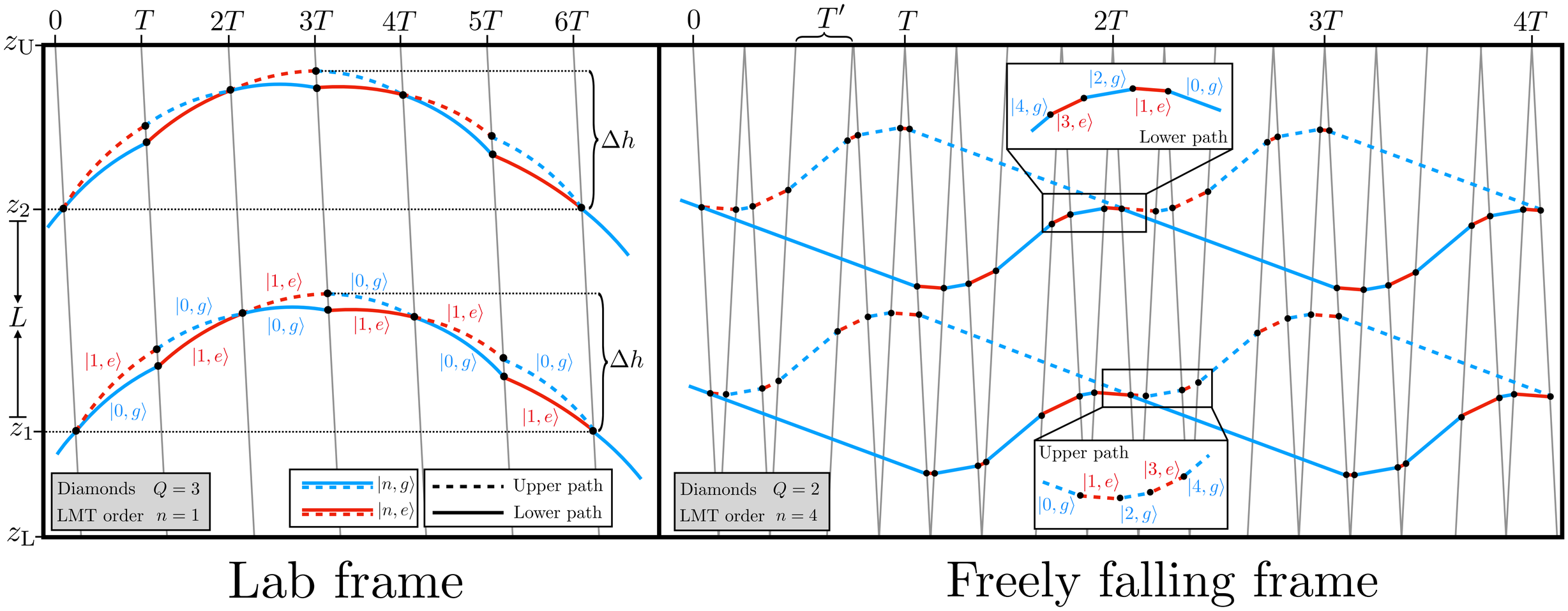


Ashkan Alibabaei



Naceur Gaaloul

Gravitational Wave Detection



Lab frame

Freely falling frame

Werner et al. - “Terrestrial Gravitational Wave Detection with Atom Interferometers” (2026)

Ideal GW Configurations — On Resonance

Where do I place my atoms?

Fixed

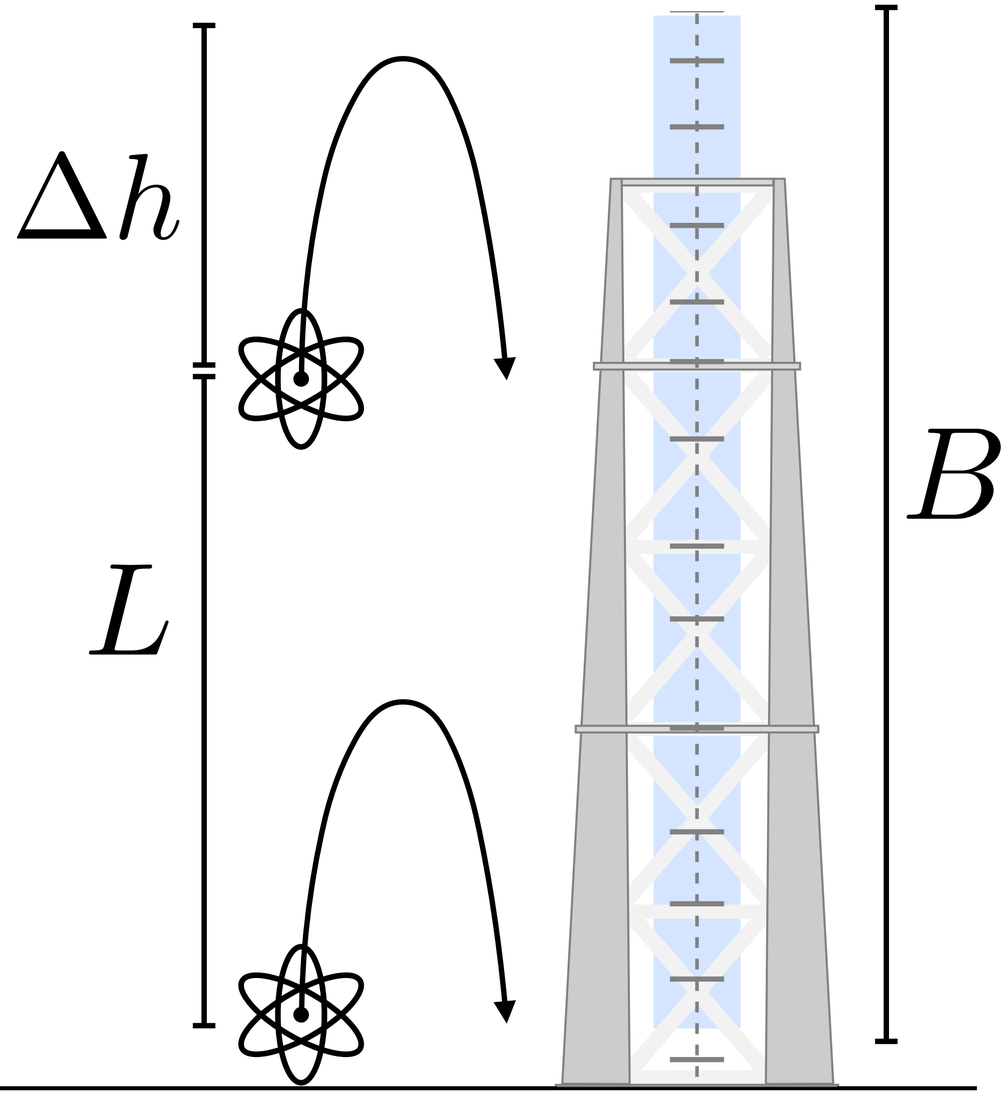
- Incoming GW of frequency f
- Interferometer time $T = (2f)^{-1}$

Maximize!

- $L = B - \Delta h(Q, n, T)$
- Diamonds: Q
- v_0 to maximize Δh
- LMT: n

Optimize!

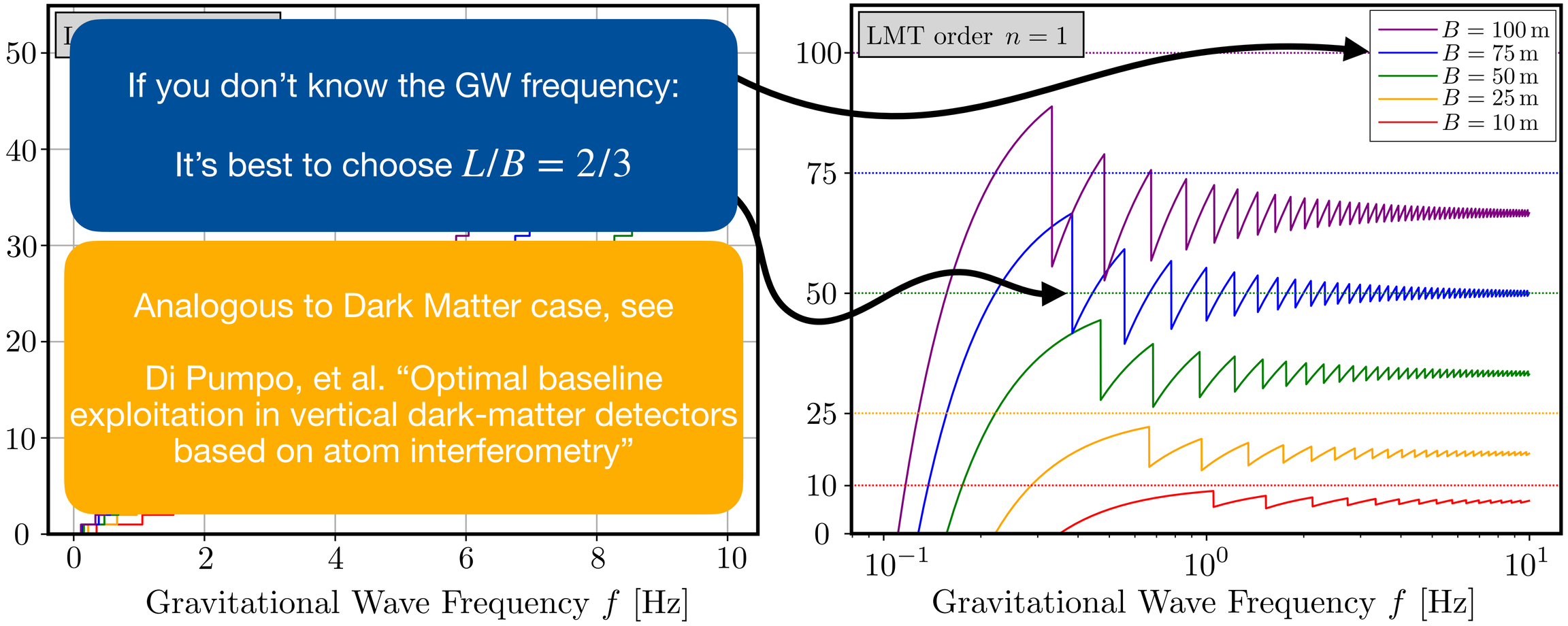
- Minimal Q & n: Maximal L
- $Q_{\mathrm{opt}}, n_{\mathrm{opt}}$
- Maximal Q & n: Maximal Δh



Ideal GW Configurations — On Resonance

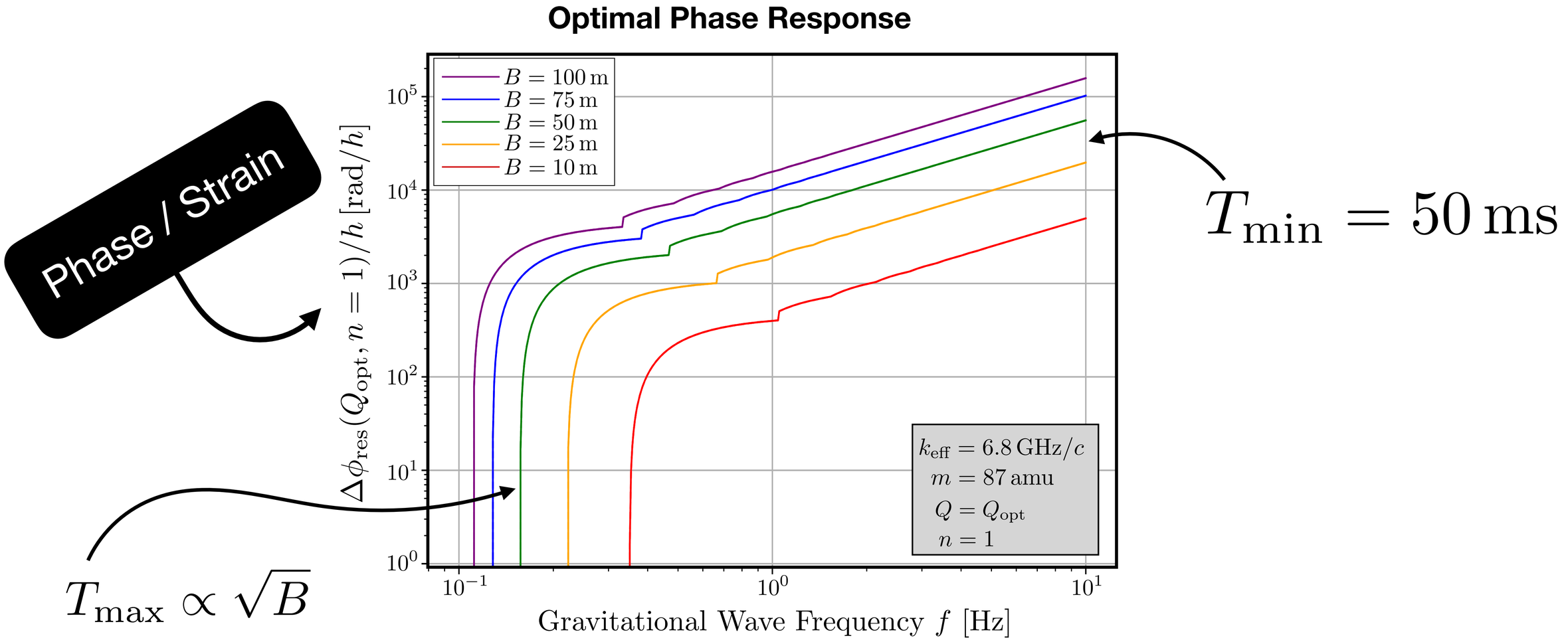
Optimal Q (Number of Diamonds)

Optimal L (Atomic Separation)



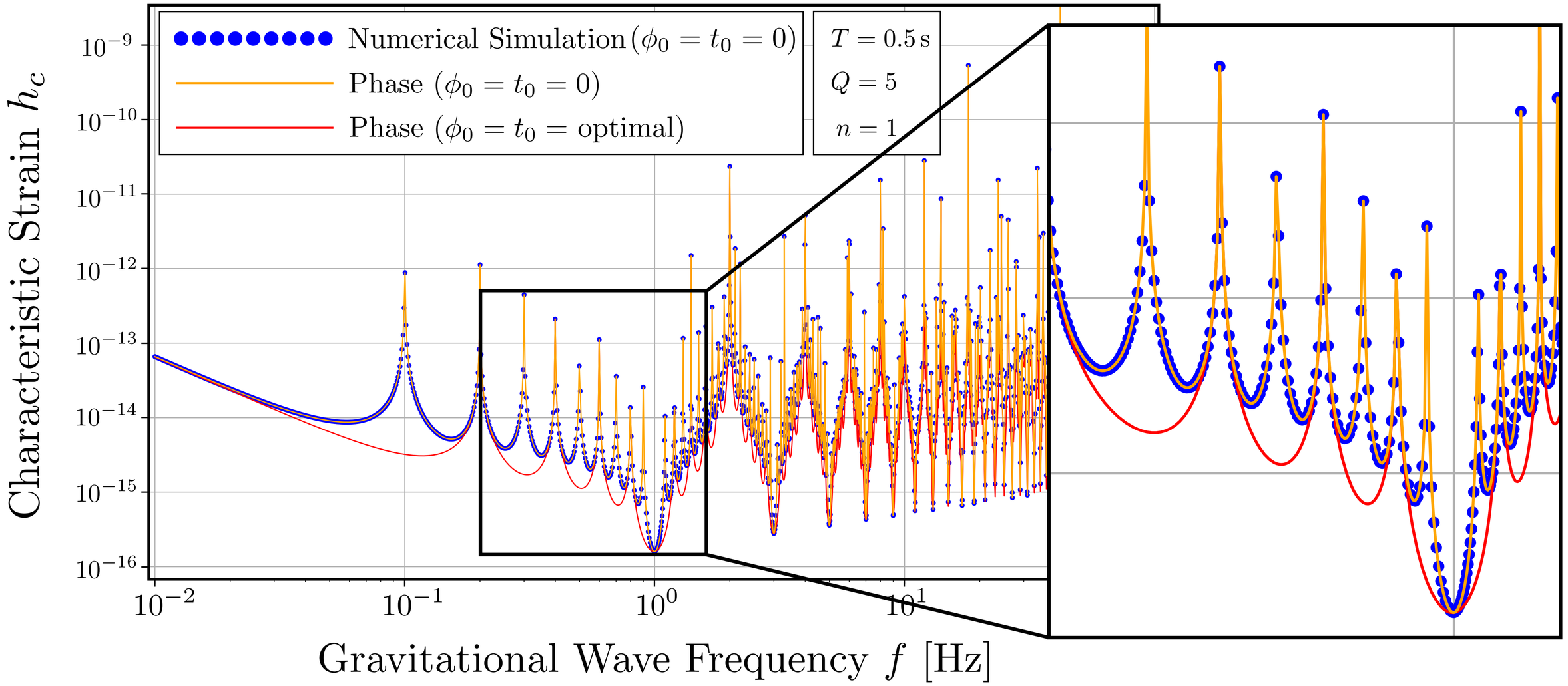
Werner et al. - "Terrestrial Gravitational Wave Detection with Atom Interferometers" (2026)

Ideal GW Configurations — On Resonance



Werner et al. - “Terrestrial Gravitational Wave Detection with Atom Interferometers” (2026)

Analytics vs. Numerics — Off Resonance

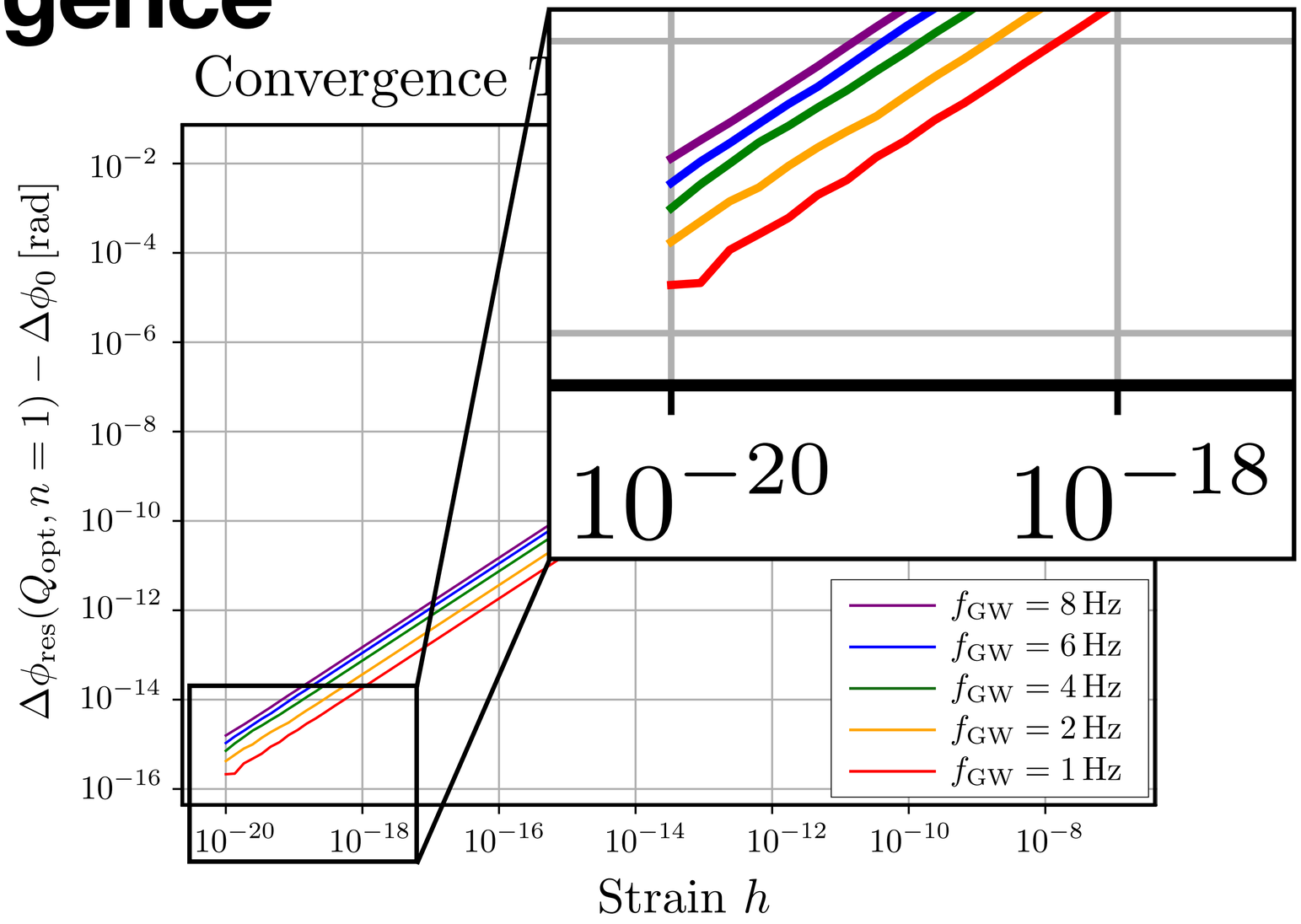


Werner et al. - “Terrestrial Gravitational Wave Detection with Atom Interferometers” (2026)

Numerical Convergence

$\phi_{\mathrm{GW}} - \phi_{\mathrm{no\ GW}} \propto h$

Phase signal with GW minus phase without



Standard Accuracy a.t.m.: Model GWs with a strain of $h \approx 10^{-20}$ in a 100 meter experiment.

(Can be extended)

Werner et al. - “Terrestrial Gravitational Wave Detection with Atom Interferometers” (2026)

Gravity Gradient Noise (GGN)

Goal: Include Noise into the system!

Problem: Local Noise sources (not common for both interferometers), like GGN.

Combined work with: Jeremiah Mitchell, The MIGA-Team, Elina Fuchs + Team

Example GGN:

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

with $\rho_0 = 1800\,\mathrm{kg/m^3}$, $s = 0.36$, $q = 0.88$, $c_{\mathrm{H}} = 205\,\mathrm{m/s}$.

GR Hamiltonian with all (static) $\mathcal{O}(c^{-2})$ effects:

$$
\begin{aligned}
H_{\mathrm{C,final}} &= \frac{\mathbf{P}^2}{2M}\left[1-\frac{1}{Mc^2}\left(\frac{\mathbf{p_r}^2}{2\mu}+\frac{e_1e_2}{4\pi\varepsilon_0 r}\right)\right]+\left[M+\frac{1}{c^2}\left(\frac{\mathbf{p_r}^2}{2\mu}+\frac{e_1e_2}{4\pi\varepsilon_0 r}\right)\right]\phi(\mathbf{R}) \\
&\quad -\frac{\mathbf{P}^4}{8M^3c^2}+\frac{2\gamma+1}{2Mc^2}\mathbf{P}\cdot\phi(\mathbf{R})\mathbf{P}+(2\beta-1)\frac{M\phi(\mathbf{R})^2}{2c^2}\,, \\
H_{\mathrm{A,final}} &= \frac{{}^{(3)}g^{-1}_{\mathbf{R}}(\mathbf{p_r},\mathbf{p_r})}{2\mu}+\frac{e_1e_2}{4\pi\varepsilon_0\sqrt{{}^{(3)}g_{\mathbf{R}}(\mathbf{r},\mathbf{r})}} \\
&\quad -\frac{m_1^3+m_2^3}{M^3}\frac{\mathbf{p_r}^4}{8\mu^3c^2}+\frac{e_1e_2}{4\pi\varepsilon_0}\frac{1}{2\mu Mc^2}\left(\mathbf{p_r}\cdot\frac{1}{r}\mathbf{p_r}+\mathbf{p_r}\cdot\mathbf{r}\frac{1}{r^3}\mathbf{r}\cdot\mathbf{p_r}\right)\,, \\
H_{\mathrm{AL,final}} &= -\mathbf{d}\cdot\mathbf{E}^{\perp}_{\mathrm{coord.}}(\mathbf{R})+\frac{1}{2M}\{\mathbf{P}\cdot[\mathbf{d}\times\mathbf{B}_{\mathrm{coord.}}(\mathbf{R})]+\mathrm{H.c.}\} \\
&\quad -\frac{m_1-m_2}{4m_1m_2}\{\mathbf{p_r}\cdot[\mathbf{d}\times\mathbf{B}_{\mathrm{coord.}}(\mathbf{R})]+\mathrm{H.c.}\} \\
&\quad +\frac{1}{8\mu}(\mathbf{d}\times\mathbf{B}_{\mathrm{coord.}}(\mathbf{R}))^2+\frac{1}{2\varepsilon_0}\int \mathrm{d}^3\mathbf{x}\left(1+(\gamma+1)\frac{\phi}{c^2}\right){\boldsymbol{\mathcal{P}}^{\perp}_d}^2(\mathbf{x},t)\,, \\
H_{\mathrm{L,final}} &= \frac{\varepsilon_0}{2}\int \mathrm{d}^3\mathbf{x}\left(1+(1-3\gamma)\frac{\phi}{c^2}\right)\left[{\mathbf{E}^{\perp}_{\mathrm{phys.}}}^2+c^2\mathbf{B}^2_{\mathrm{phys.}}\right] \\
&= \frac{\varepsilon_0}{2}\int \mathrm{d}^3\mathbf{x}\sqrt{-g}\left[{\mathbf{E}^{\perp}_{\mathrm{phys.}}}^2+c^2\mathbf{B}^2_{\mathrm{phys.}}\right]
\end{aligned}
$$

Full Analysis:

Already partially included into PHASE.

With Klemens Hammerer, Domenico Giulini and Philip Schwartz





Photo: Uni Bremen



Photo: Nils Ole Peters

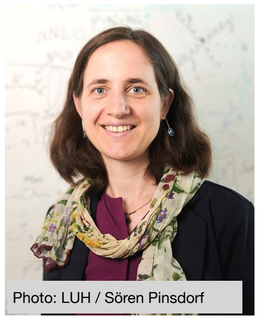
Werner et al. - “Atom interferometers in weakly curved spacetimes using Bragg diffraction and Bloch oscillations” (QR code)

Dark Matter Detection

Include DM Detection into PHASE







John Carlton Maike Reckermann Elina Fuchs

+ Nathan Sherrill + Agnese Mariotti

Dark Matter

- **Axion**
- **Scalar**
- **Vector**
- **WIMPs**
- **Chameleon**
- **…**

Ongoing work with
Elina Fuchs + Team

PhASE

See John Carlton's talk yesterday

Current State

- 1D atomic motion
- Ideal Wave Fronts
- Instantaneous Pulses
- CPU
- Your Idea could be here!

Planned Extension

- 3D: Coriolis effect, Eötvös effect
- Wave Front Aberrations
- Finite Pulse Times & Different Pulse Shapes
- GPU
- Please let me know.

Highlight: Fundamental Limits of LMT

Analytical Study of Optimal LMT in Optical Lattices

arXiv:2602.00365v2 [physics.atom-ph] 19 May 2026

Fundamental Limits of Large Momentum Transfer in Optical Lattices

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Alexandre Gauguet,[4] Baptiste Allard,[4] Klemens Hammerer,[2,3,5,‡] and Naceur Gaaloul[1,§]

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(Dated: May 20, 2026)

Large-momentum-transfer techniques are instrumental for the next generation of atom interferometers as they significantly improve their sensitivity. State-of-the-art implementations rely on elastic scattering processes from optical lattices such as Bloch oscillations or sequential Bragg diffraction, but their performance is constrained by imperfect pulse efficiencies. Here we develop a Floquet-based theoretical framework that provides a unified description of elastic light–atom scattering across all relevant regimes. Within this formalism, we identify practical regimes that exhibit orders of magnitude reduced losses and improved phase accuracy compared to previous implementations. The model's validity is established through direct comparison with numerical solutions of the Schrödinger equation and by quantitative agreement with recent experimental benchmark results. These findings delineate previously unexplored operating regimes for large momentum transfer beam splitters and open new perspectives for precision atom-interferometric measurements in fundamental physics, gravity gradiometry or gravitational wave detection.

Introduction— Atom Interferometry has proven to be a highly sensitive and accurate tool for quantum sensing [1] advancing inertial navigation [2, 3], precision measurements [4–7], fundamental constants determination [8–10] and tests of general relativity [11, 12]. One way to enhance the sensitivity of an atom interferometer is to increase the spatial separation between the arms with sizable photon exchange, a technique known as Large Momentum Transfer (LMT) [13–16]. Methods to realize LMT include single photon transitions [17–19], Raman diffraction [20, 21], as well as elastic-scattering in optical lattices such as Bloch oscillation (BO) [22–25] and Sequential Bragg Diffraction (SBD) [26, 27]. Recently, momentum separations of up to 600 photon recoils have been achieved using SBD [27], exceeding earlier 400 photon recoils in BO-based implementations [25]. These results raise the following questions: (i) whether BO and SBD constitute fundamentally distinct elastic scattering mechanisms as illustrated in Fig. 1; (ii) how their efficiency and accuracy compare under experimental constraints; and (iii) whether either approach can achieve momentum separations of several thousand photon recoils as required for next-generation atom-interferometric sensors detecting gravitational waves or investigating the nature of dark energy and dark matter [28–35]. In this work, we exploit the temporal periodicity and discrete spatial symmetry of optical lattices within a Floquet framework to extend a recently developed Wannier–Stark model [36] to the full class of elastic LMT scattering methods. Within this unified description, we introduce a parametrized family of Hamiltonians that continuously interpolates between the limiting cases of BOs and SBDs through variation of a single control parameter. This approach exposes the fundamental efficiency and phase-accuracy limits inherent to different LMT schemes and enables their direct comparison on equal footing. Furthermore, it identifies previously unexplored operating

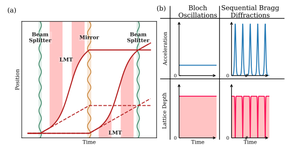


FIG. 1. (a) Space-time diagram of a Large-Momentum-Transfer-enhanced Mach-Zehnder atom interferometer in the freely falling frame. The sequence consists of two beam splitter and a mirror pulse. Each interferometer arm is accelerated and decelerated using LMT sequences in an optical lattice, resulting in a larger space-time area covered compared to a standard Mach-Zehnder atom interferometer (dashed lines). (b) Control parameters (acceleration and lattice depth) for Bloch Oscillation and Sequential Bragg Diffraction LMT.

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Patrik Mönkeberg



Florian Fitzek



Baptiste Allard



Klemens Hammerer

In the audience



Ashkan Alibabaei



Alexandre Gauguet



Naceur Gaaloul

Thank you for listening!

Funding from:

AGAPES Project

Quantum Frontiers

All of my codes (Python) are open source, since science should be free and accessible to everyone.

Our goal is to create community-driven, free and open software packages for atom interferometry. **Interested? Please reach out!**



Our team in September 2025

Codes and Contact!