Dark matter detection with atom interferometers

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Identification of Dark Matter 2026, 1st of June 2026, Zaragoza

Introduction

The lower DM mass regime (below 10^{-10} eV) is not easily accessible, but several models predict candidates there: light moduli, dilatons, Higgs portal DM, relaxion, etc

Overview of this talk:

- Atom interferometry
- Ultralight DM (ULDM) in atom interferometers
- Atom interferometer experiments
- Sensitivity projections

Atom interferometry provides a variety of other approaches to search for DM: see talks at Theory/Phenomenology session on Thursday by L. Badurina and J. Carlton

Atom interferometry

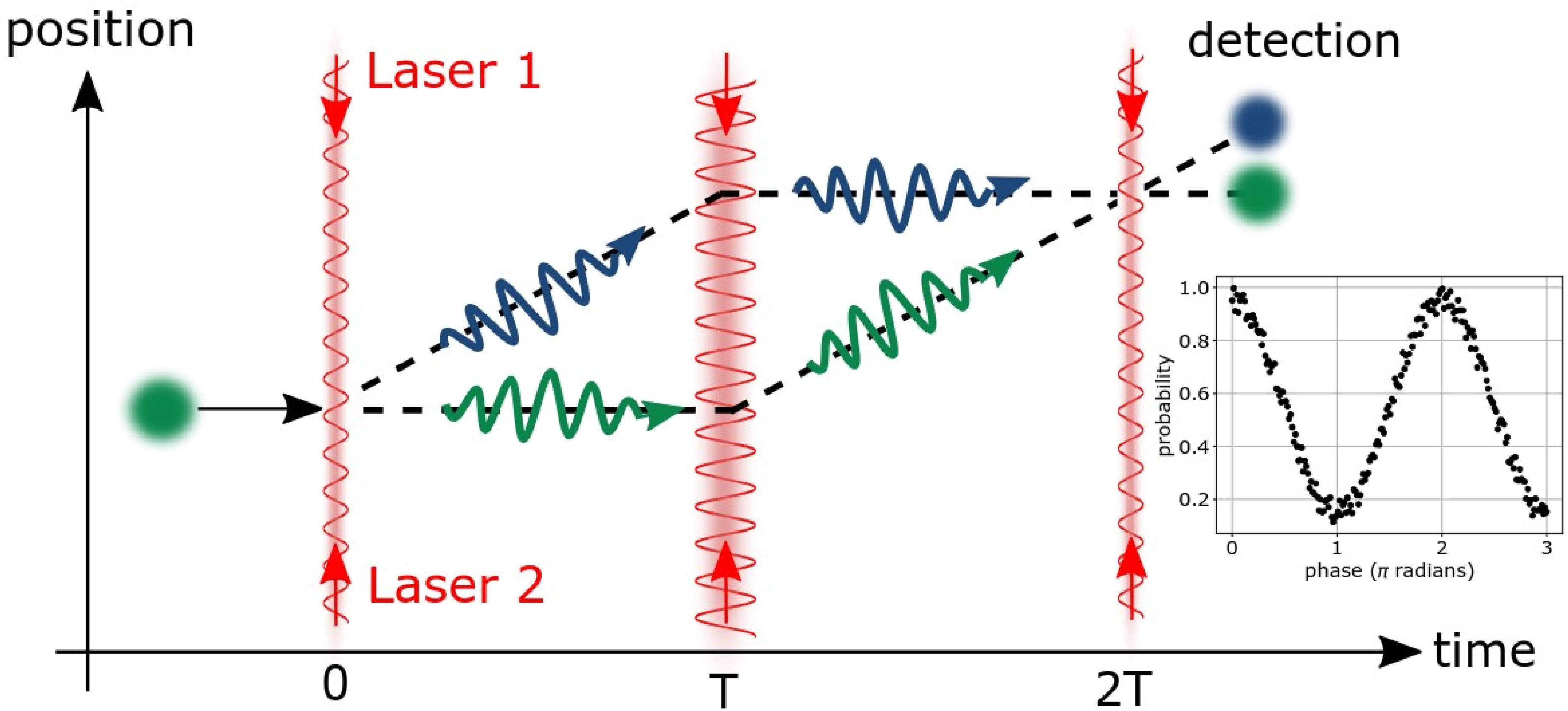
Atom+laser model:

- Assuming two-level atom
- Measurements yield state 0 or 1 with probability $|a|^2$ and $|b|^2$ respectively
- In presence of photons: if state 0 is at rest, then state 1 has some momentum from absorbed photon
- Laser: superposition of photon number states ⇒ Undefined photon number, not the usual states from particle physics
- Coherent laser+atom evolution: a and b oscillate in time (Rabi oscillations)

$$|\Psi\rangle = a\,|0\rangle + b\,|1\rangle$$

$$\begin{pmatrix} a' \\ b' \end{pmatrix} = \begin{pmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

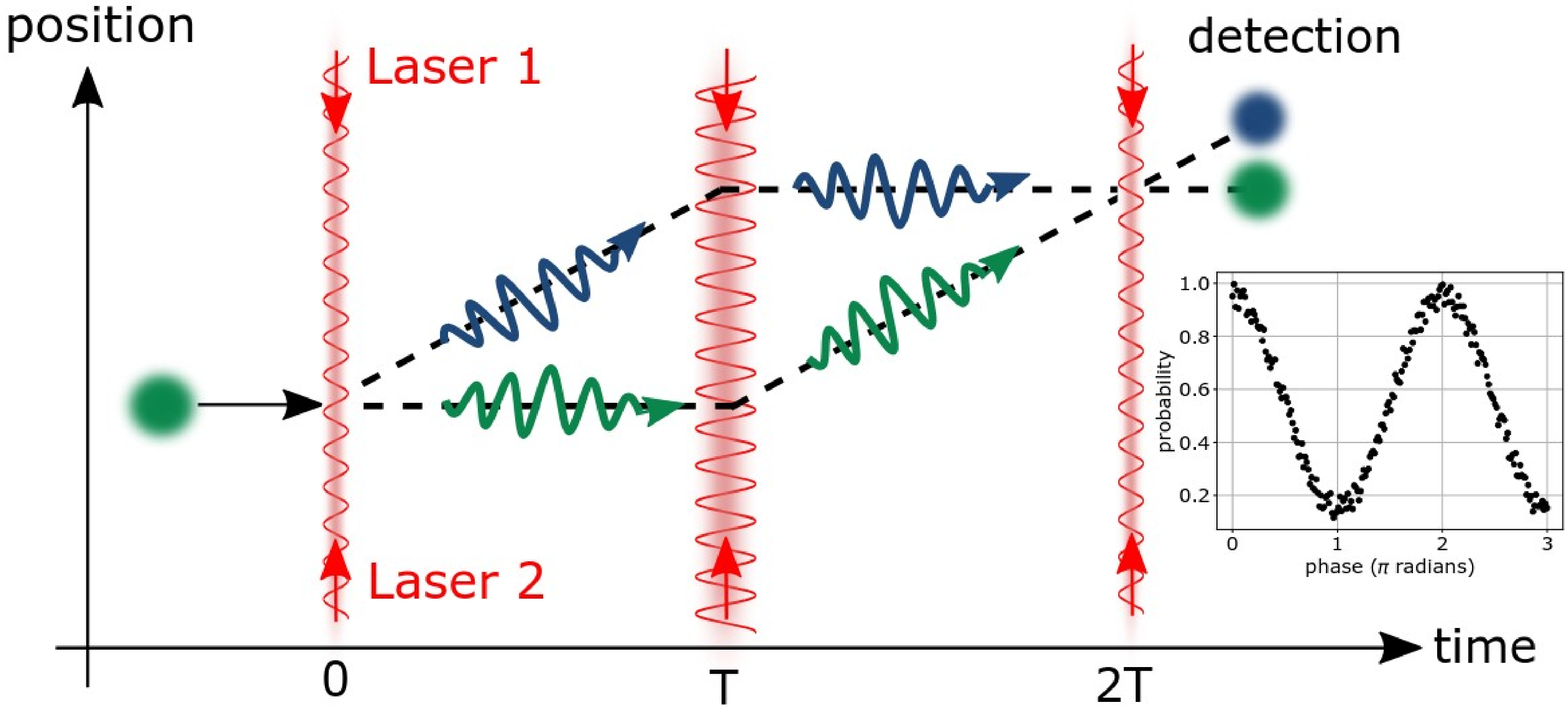
Atom interferometry



$$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\frac{P_1}{P_0} = 0$$

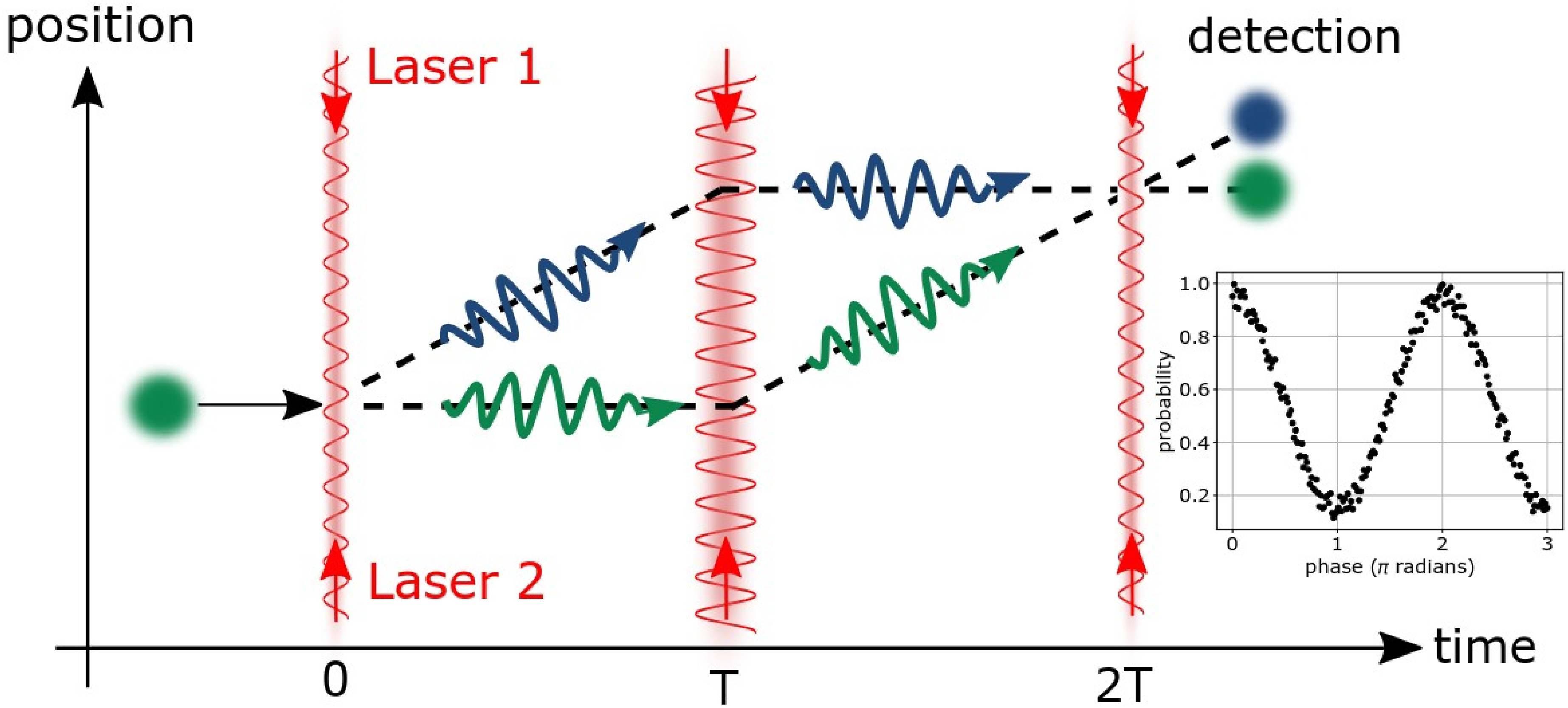
Atom interferometry



$$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\end{pmatrix}$$

$$\frac{P_1}{P_0} = 1$$

Atom interferometry



$$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\-e^{i\delta}\end{pmatrix}$$

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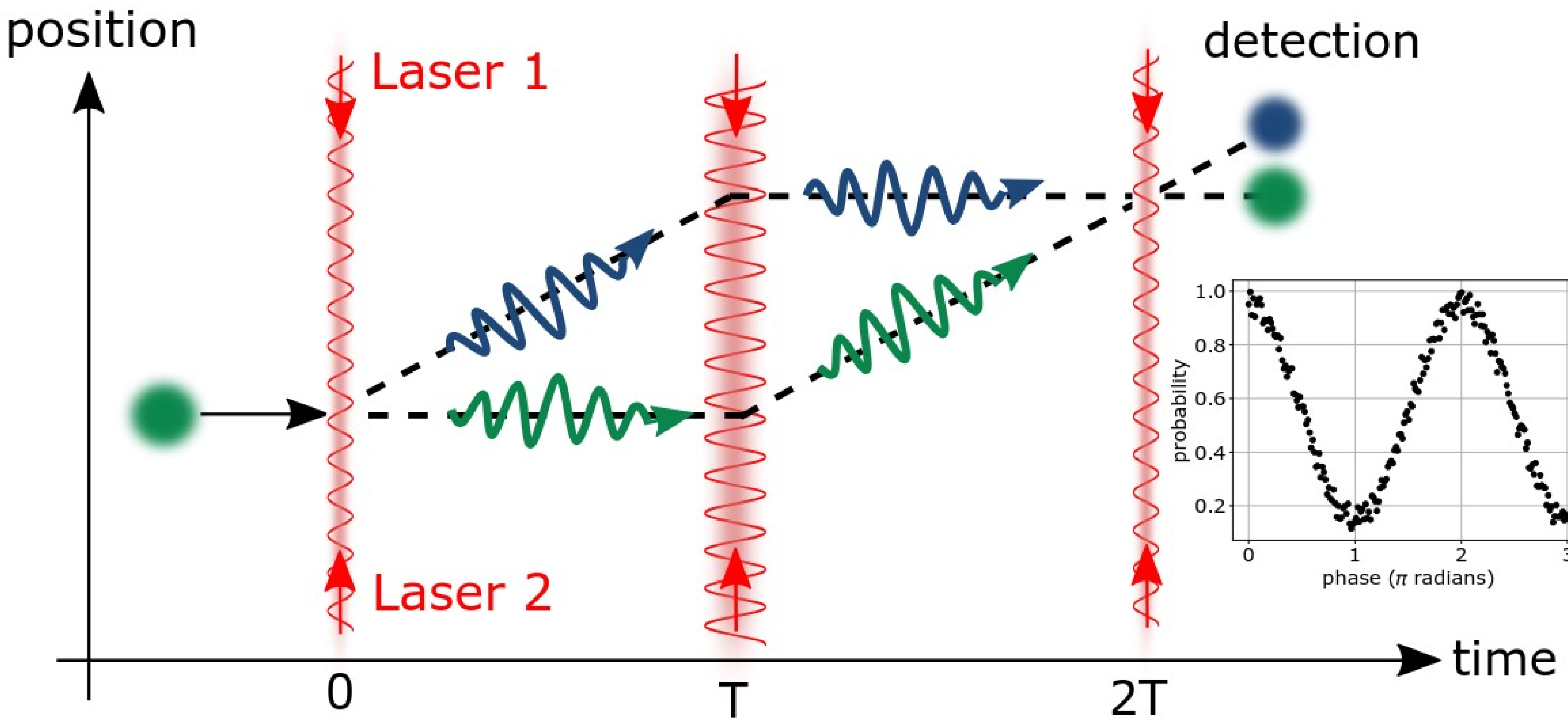
Atom interferometry



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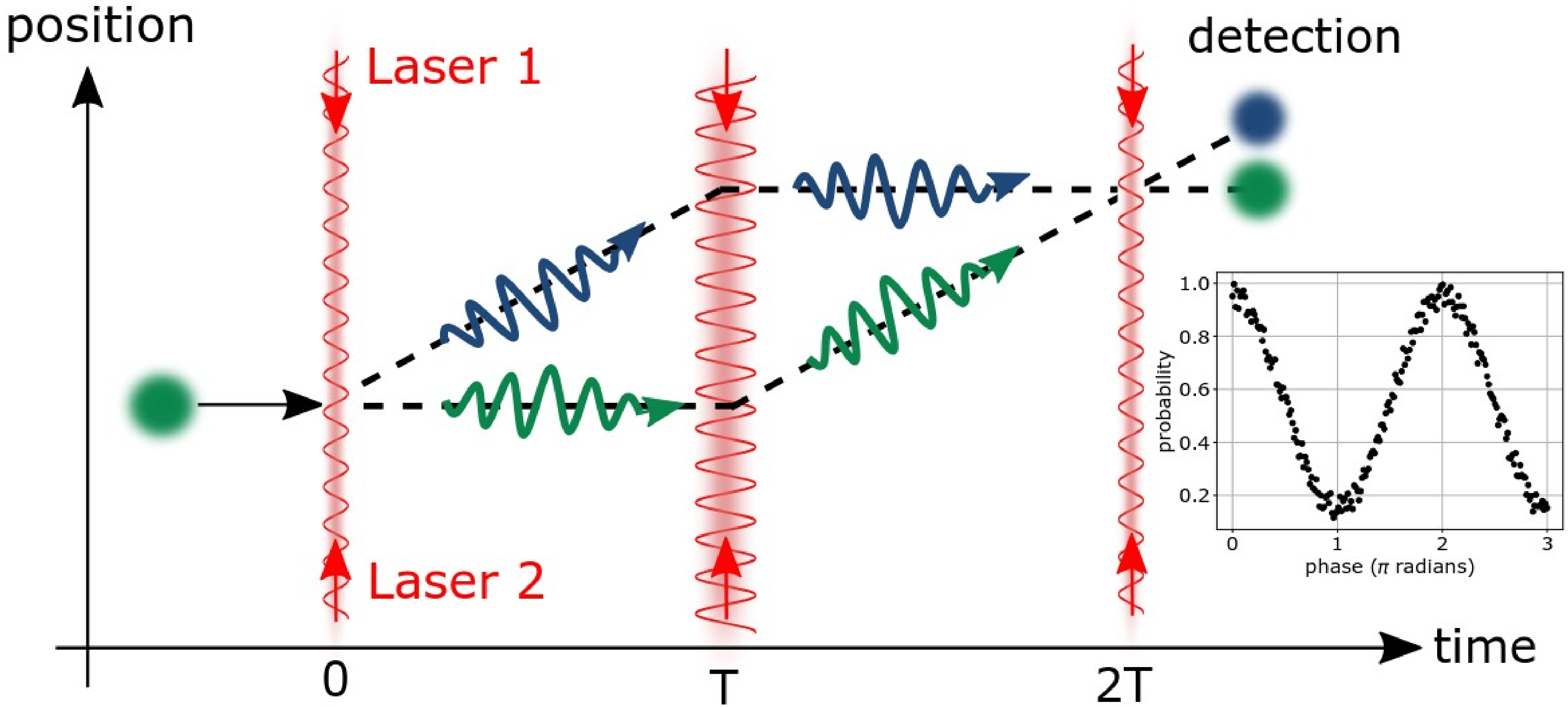

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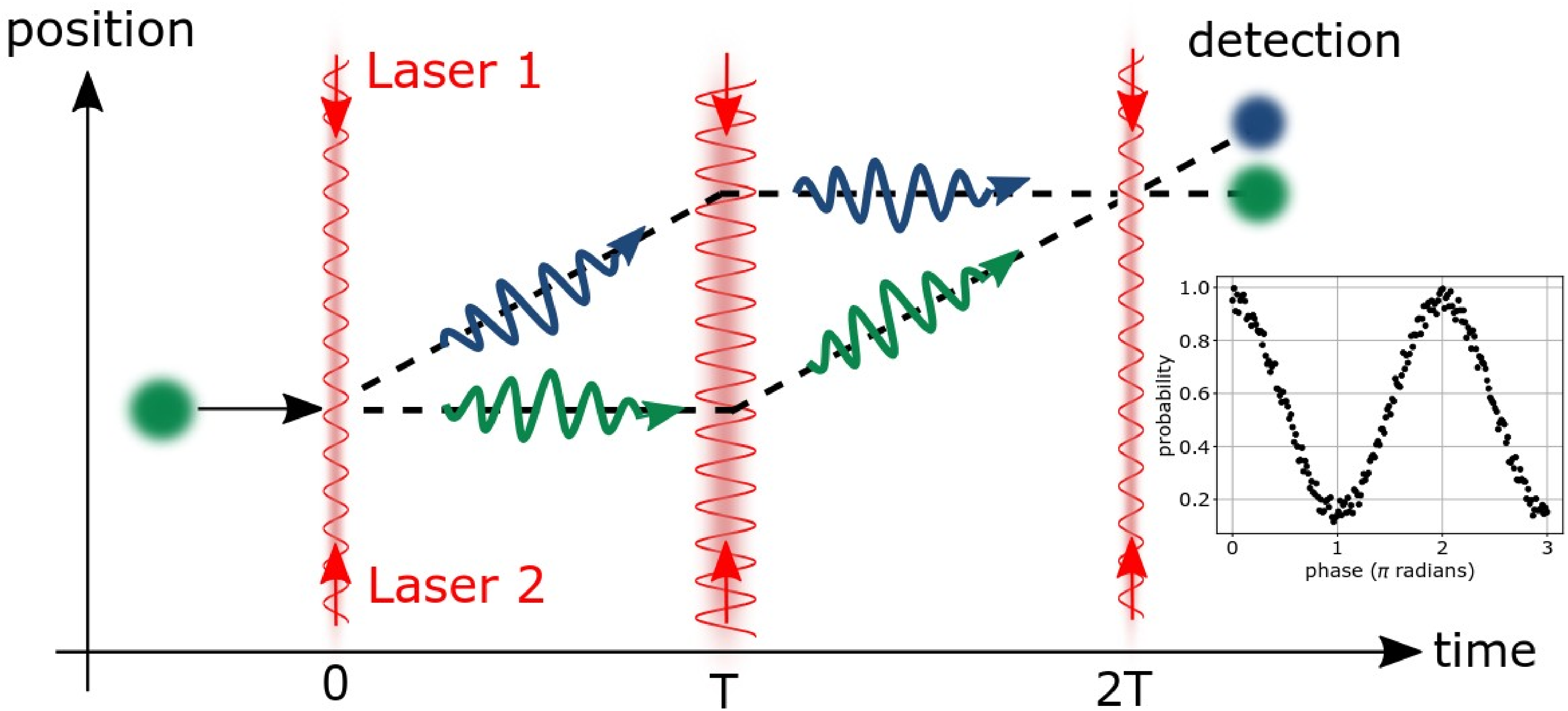
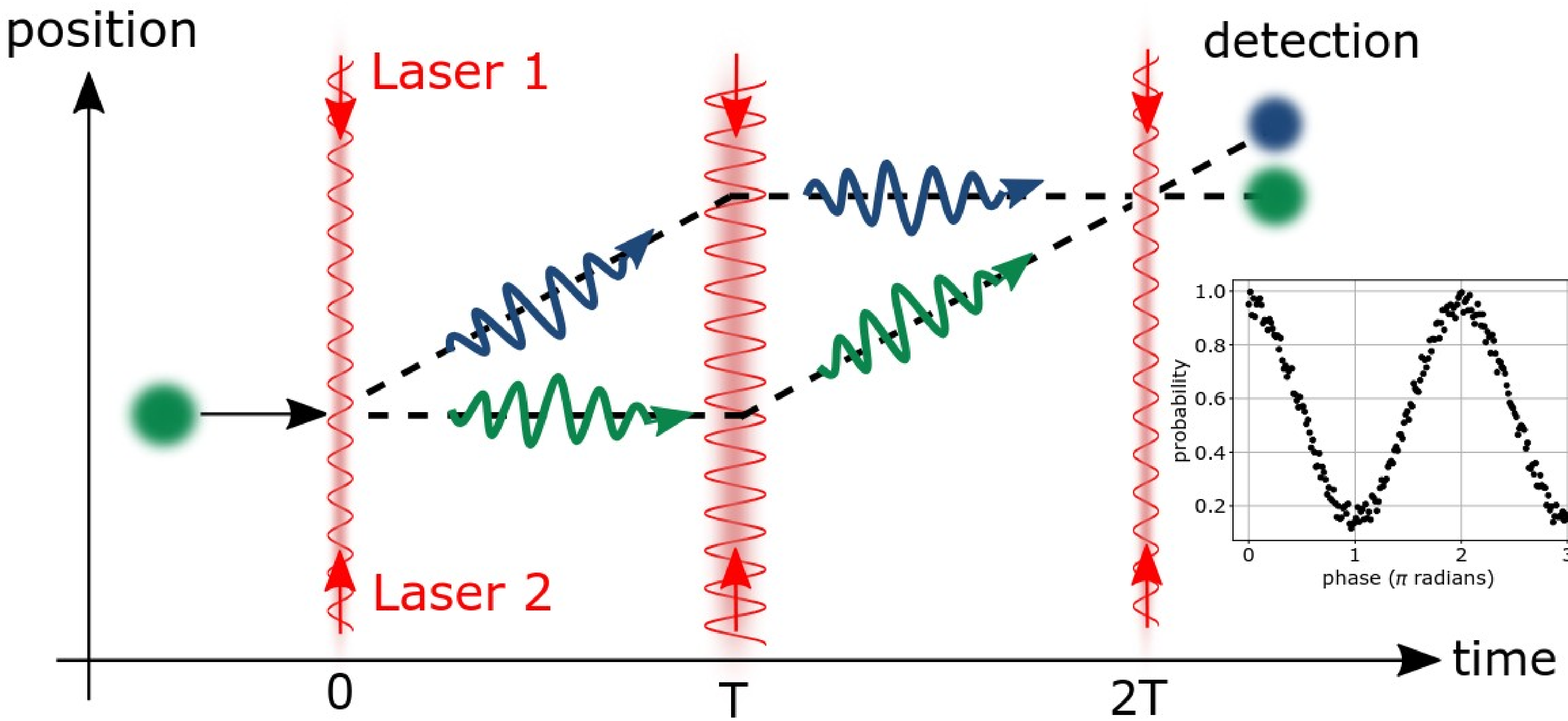


$$\frac{1}{2}\begin{pmatrix}1+e^{i\Delta}\\1-e^{i\Delta}\end{pmatrix}$$

$$\frac{P_1}{P_0}=\left(\frac{1-e^{i\Delta}}{1+e^{i\Delta}}\right)^2$$

Atom interferometry



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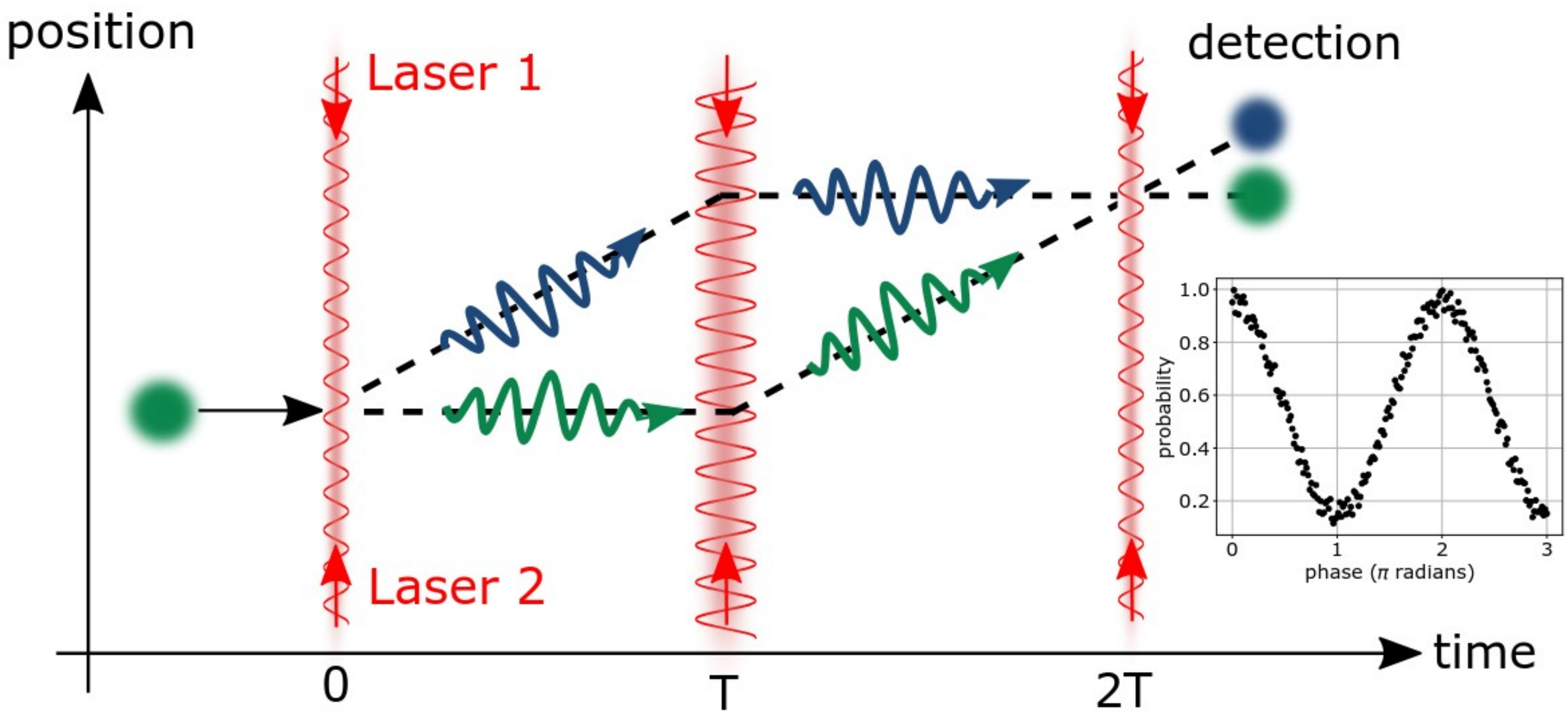
Atom interferometry

External effects may affect the phase Δ acquired in this process

Δ is determined by measuring the fraction of atoms in the excited state at the end of the sequence

Interesting example of quantum sensing: target in quantum superposition



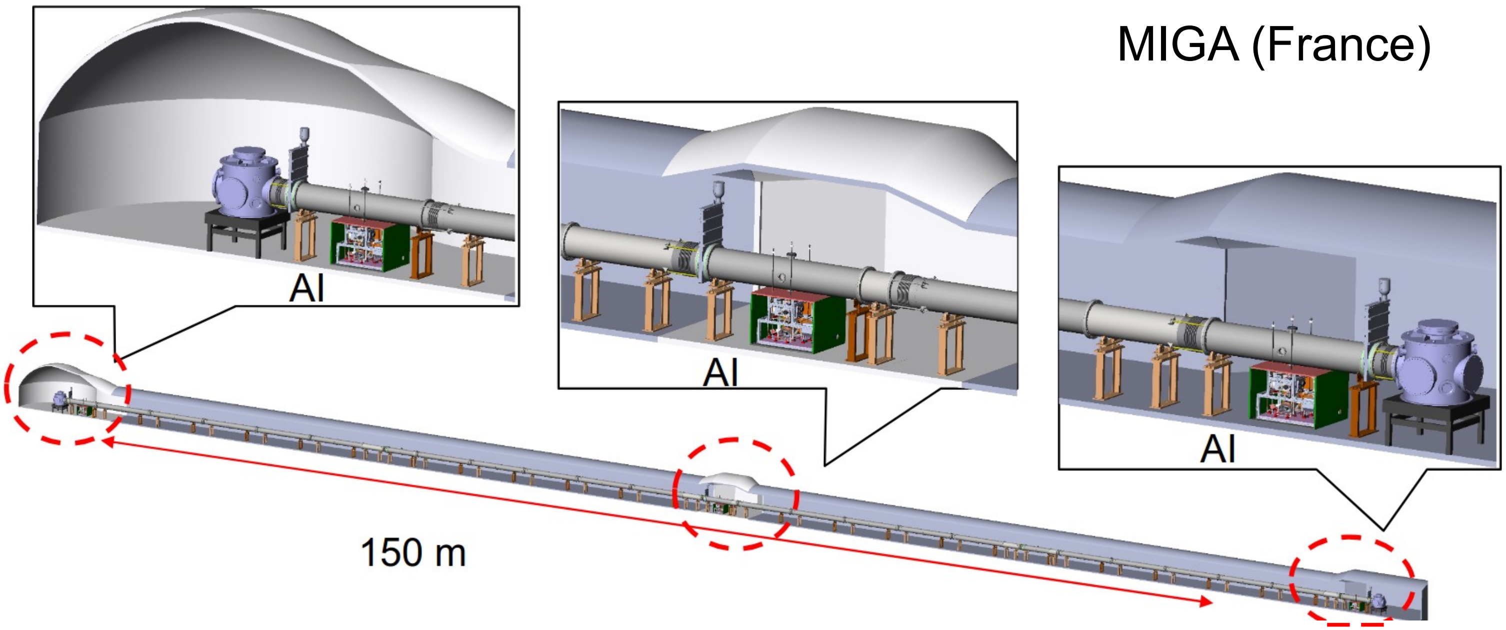
Atom gradiometers

Atom gradiometer: array of atom interferometers operated with a single laser beam

Multi-purpose instruments for fundamental physics:

- Detection of gravitational waves in the deci-Hz regime
- Dark matter searches
- Fundamental tests of General Relativity and Quantum Mechanics

Current gradiometer baselines are ~10 to ~150 m



ULDM in atom gradiometers

Very small DM particle mass ⇒ High occupation numbers ⇒ Classical field

Interaction terms+SM free lagrangian ⇒ m_e and α depend on field φ(t)

Therefore, atom energy levels become time-dependent ⇒ In an atom gradiometer, each interferometer measures a different phase, due to finite laser propagation time

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

$$m_e(t,\mathbf{x}) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

$$\alpha(t,\mathbf{x}) = \alpha\left[1 + d_e\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

$$\phi\left(t,\mathbf{x}\right) = \phi_0\cos\left[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \beta\right]$$

$$\omega_{\mathrm{A}}(t) \simeq \omega_{\mathrm{A}} + \Delta\omega_{\mathrm{A}}\cos(m_\phi t)$$

$$\Delta\omega_{\mathrm{A}} \equiv \omega_{\mathrm{A}}\sqrt{4\pi G_N}\phi_0\left(d_{m_e} + \xi d_e\right)$$

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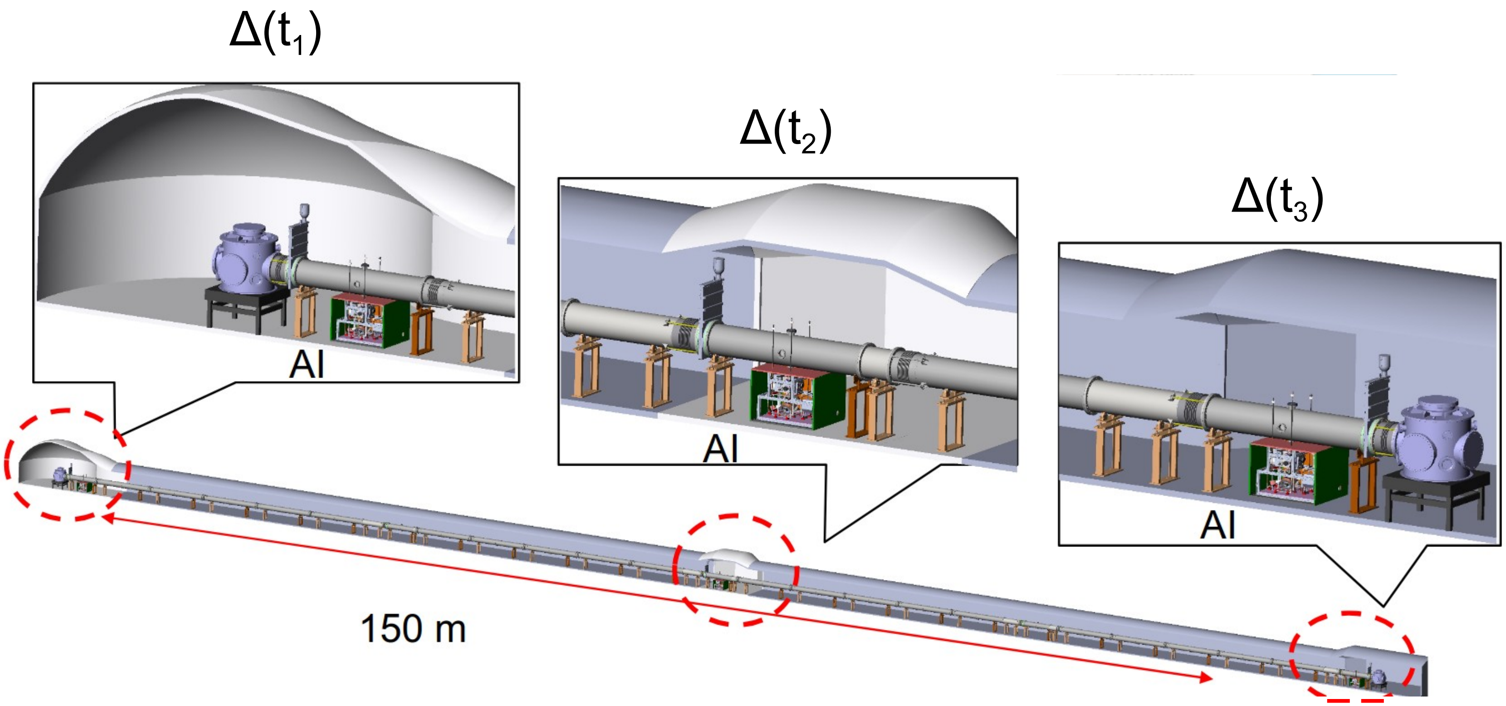


Atom interferometer experiments

Sensitivity in perfect conditions (no noise) depends on:

- Statistical fluctuations in the measured number of excited atoms (shot noise)
- Matching between baseline length and signal frequency

Noise sources:

- Laser noise cancels in atom gradiometers
- Vibrational and EM noise can be mitigated by appropriate isolation methods
- Gravity gradient noise (GGN) is irreducible

Atom interferometer experiments

Atom interferometers (~10 m baseline):

- VLBAI (Germany)
- Stanford (US)
- Wuhan (China)

Atom gradiometers:

- MIGA (France): 150 m, horizontal
- MAGIS (US): 100 m, vertical
- AION (UK) and AICE (Europe): 10 m, 100 m and 1 km, vertical
- ZAIGA (China): several instruments, km-scale each, horizontal
- ELGAR (Europe), multi-km scale, horizontal
- AEDGE (space)

Will focus on AION/AICE in the following

Atom interferometer experiments

Terrestrial Very-Long-Baseline Atom Interferometry (TVLBAI): international community on atom interferometry for fundamental physics

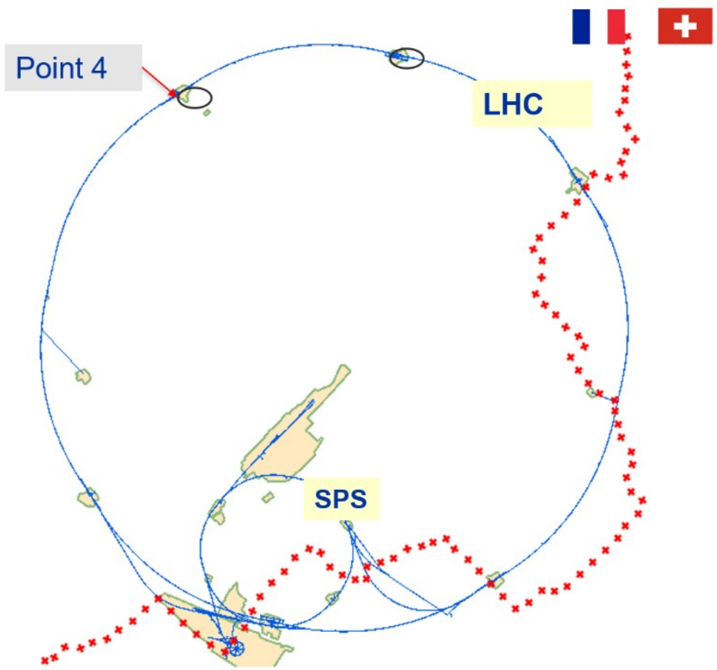
https://tvlbai.org/

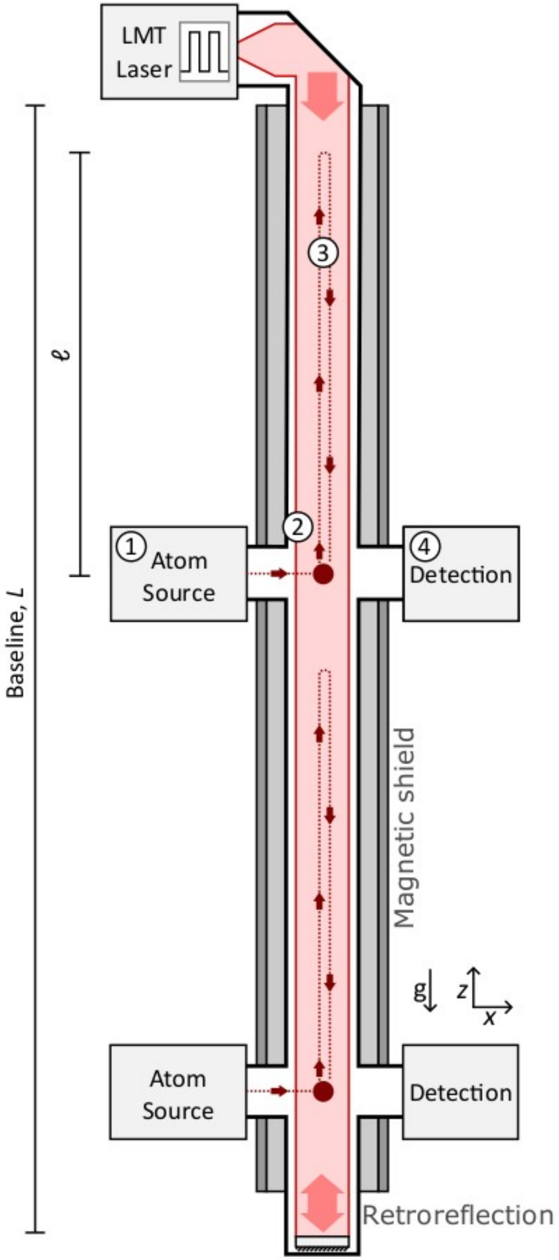
AICE

AICE: Atom Interferometer CERN Experiment

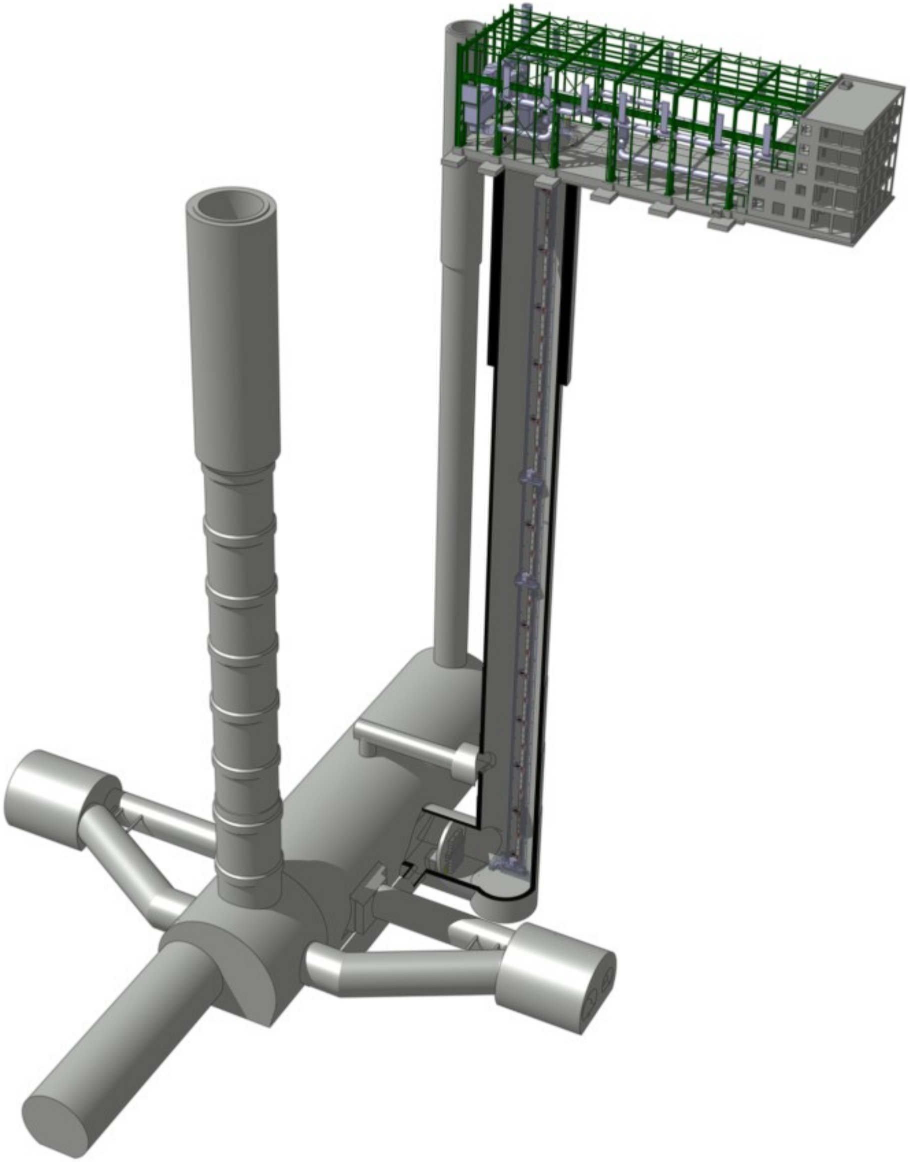
Concept:

- Vertical atom gradiometer with at least two atom interferometers
- ~10 m baseline for each atom interferometer, ~100 m baseline for total gradiometer

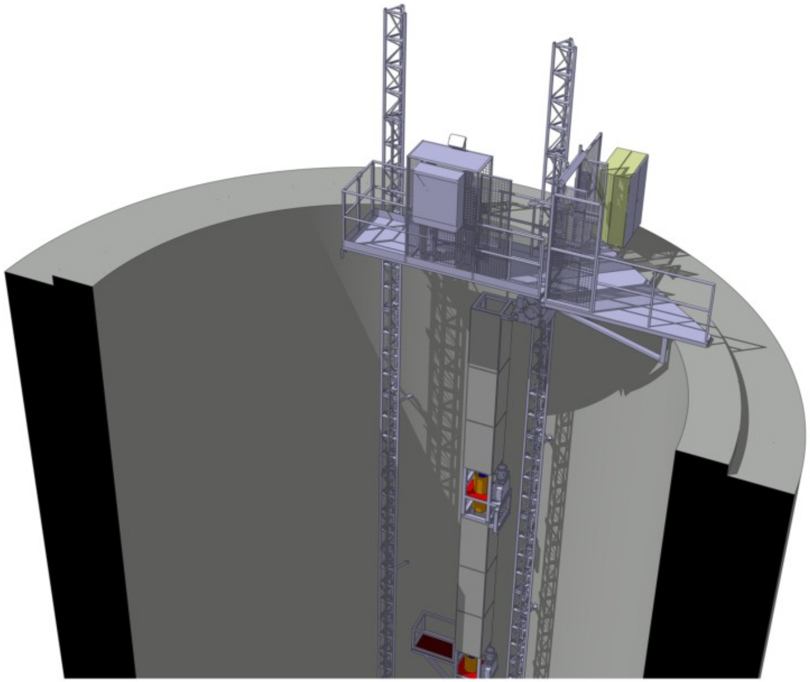




AICE



Arduini et al 2025

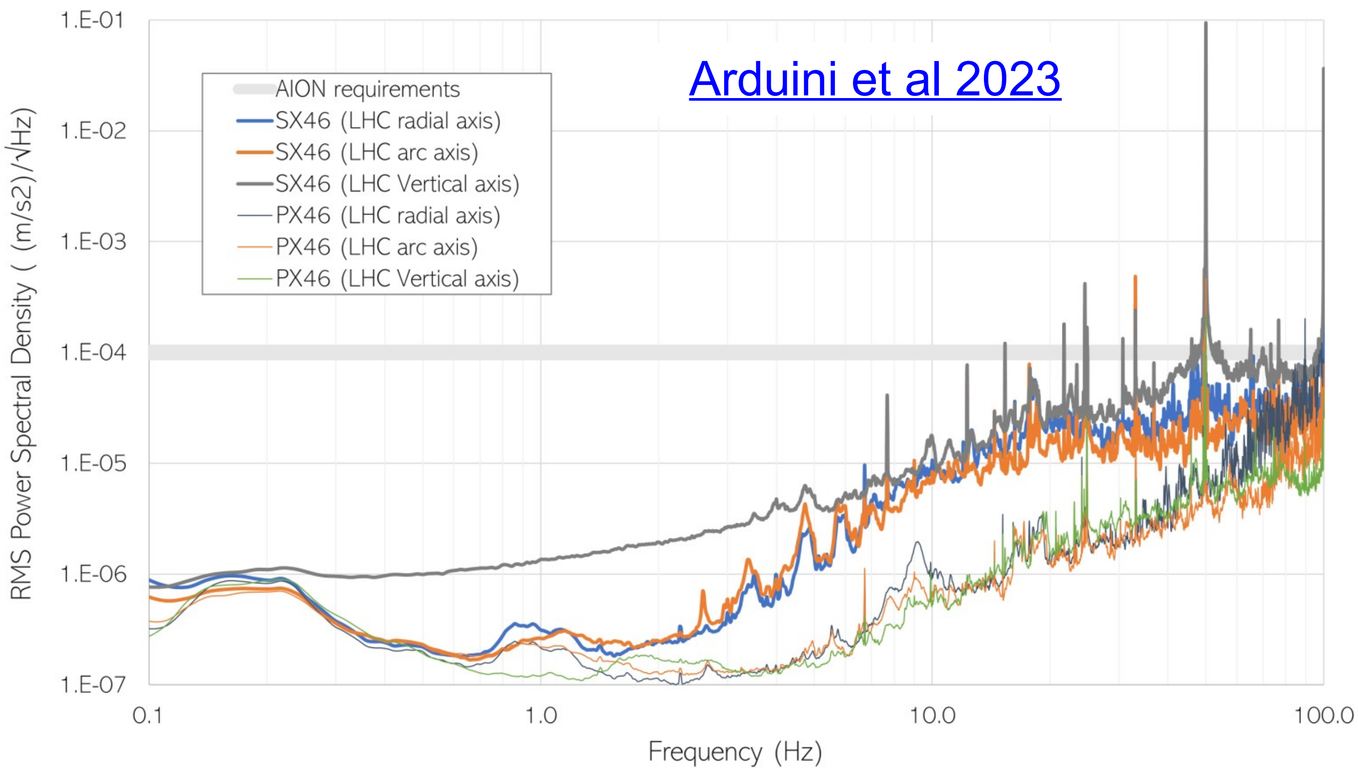


AICE

Proposed location: PX46 shaft

- Farther away from Geneva city ⇒ expecting decreased GGN from anthropic sources
- Vibrational and EM noise are within the acceptable limits

Status: Letter of Intent submitted to CERN



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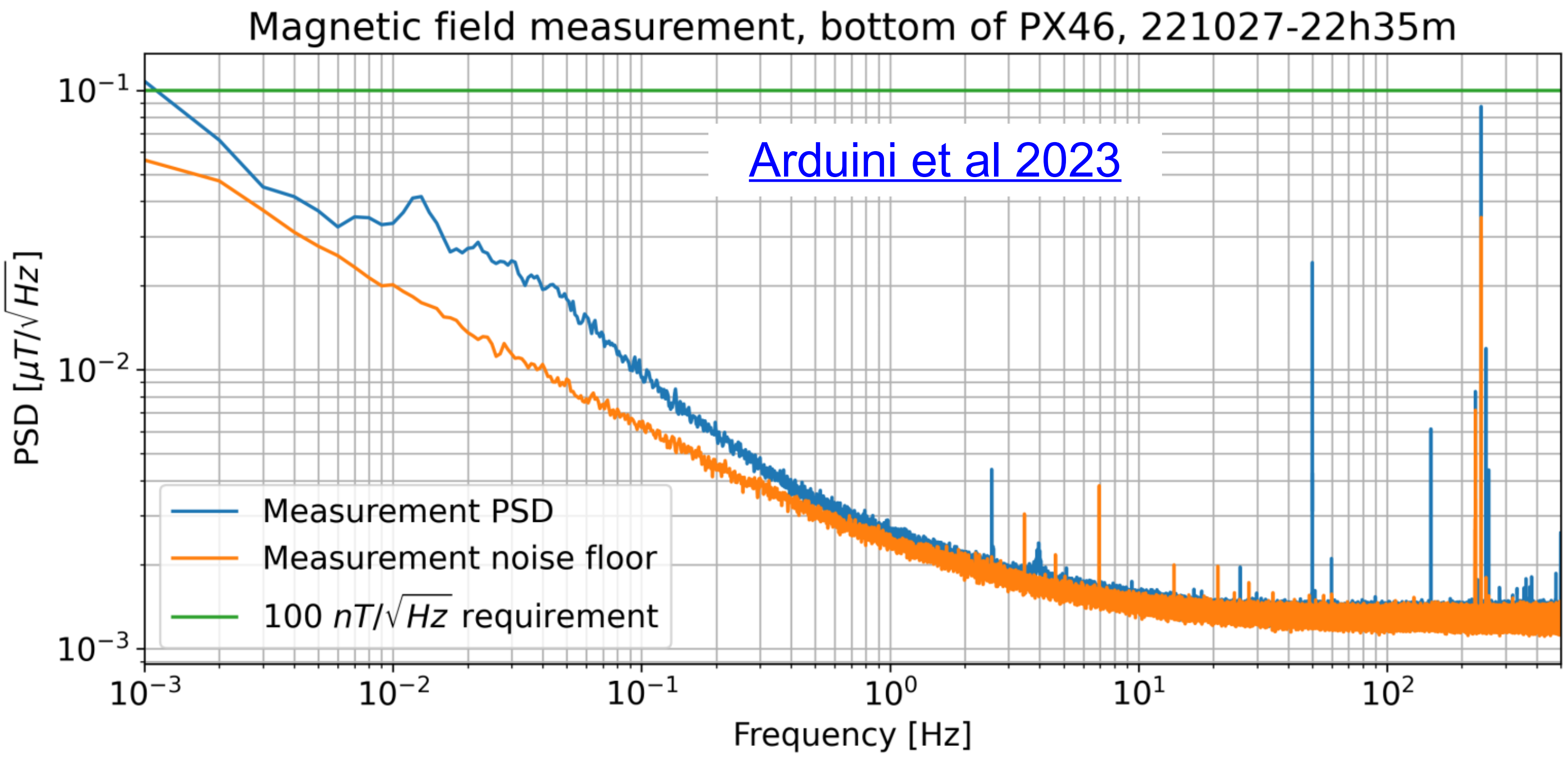
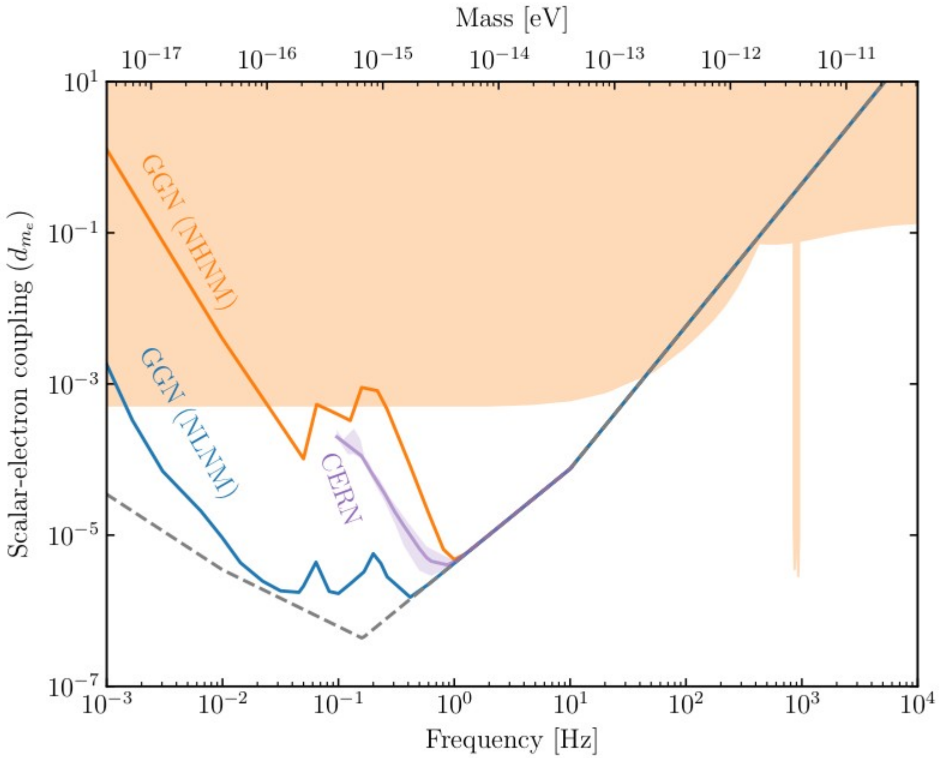
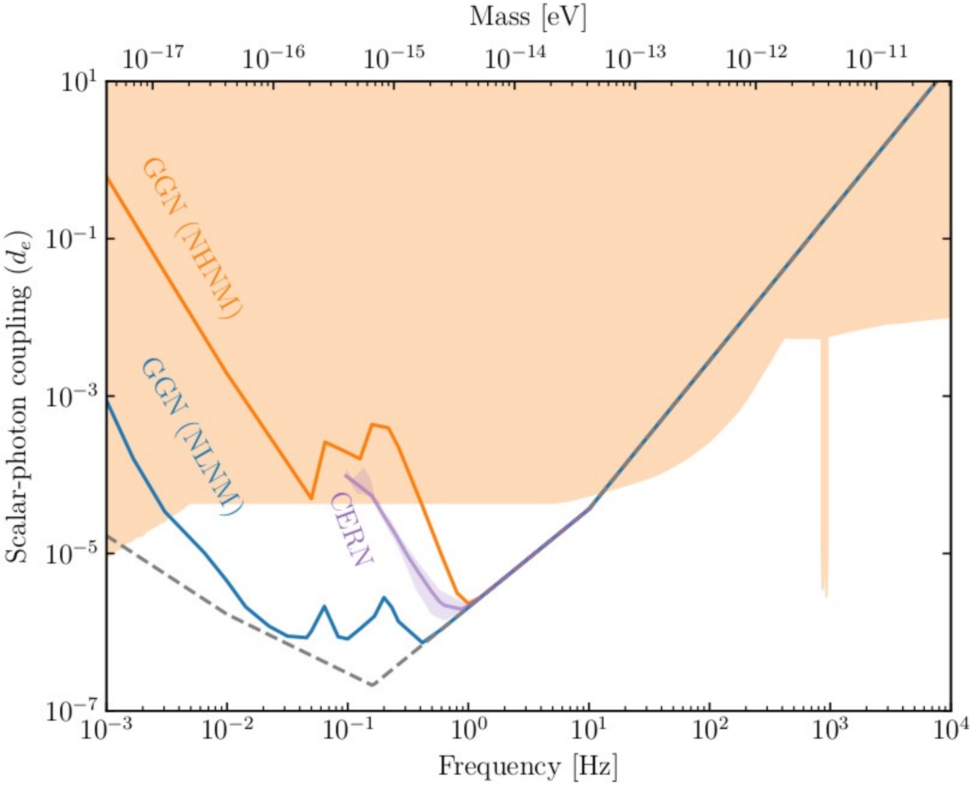


AICE sensitivity projections





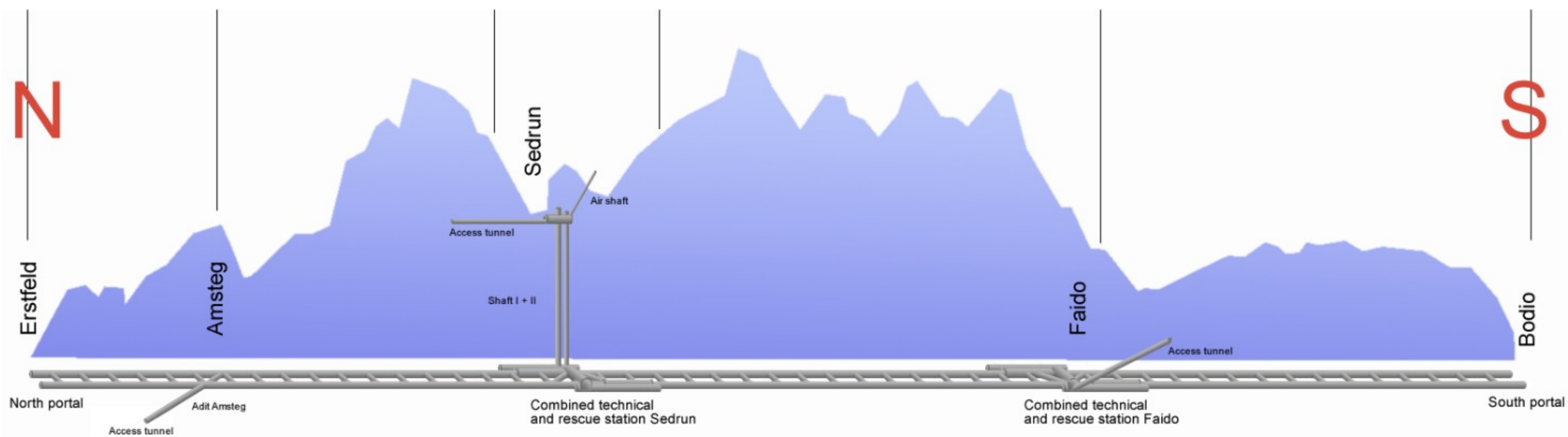
Arduini et al 2023
Baynham et al 2025

AION 1 km

Next stage would be ~1 km experiment, currently studying site options

Considering 800 m shaft at Saint Gotthard Base Tunnel in Sedrun (Switzerland)

Good noise conditions as well



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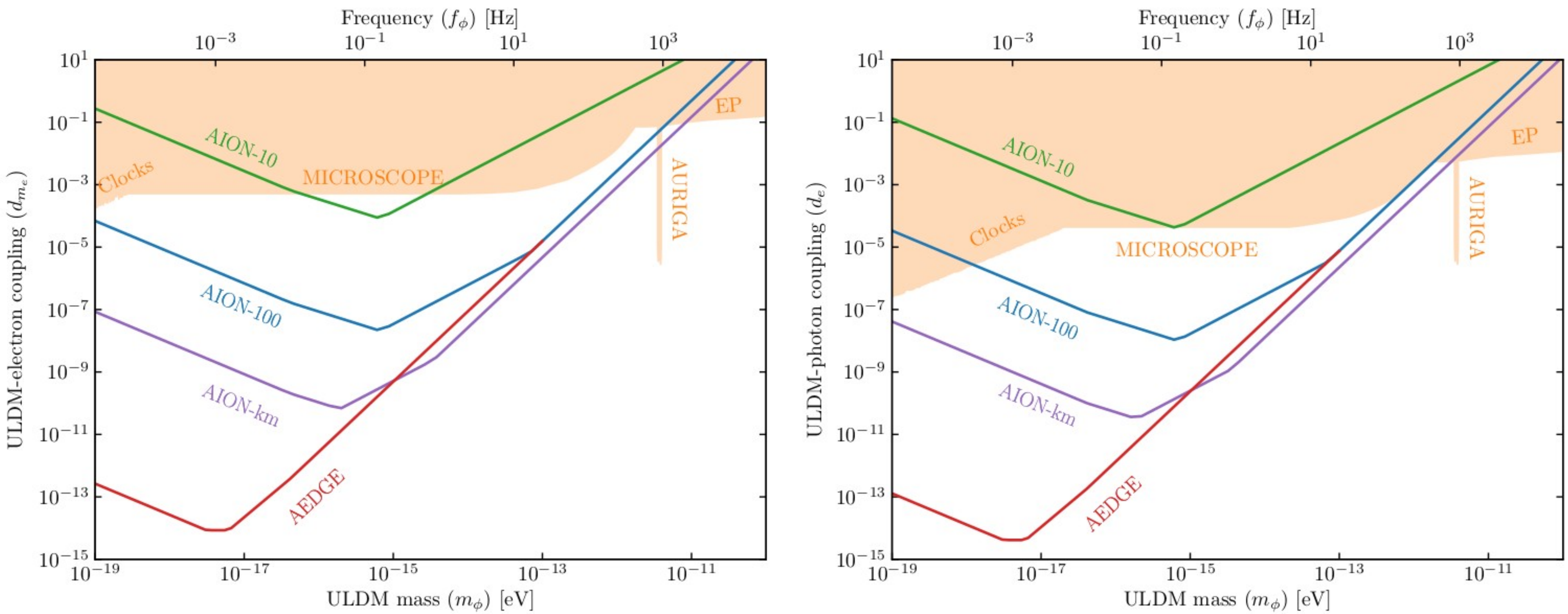

[TVLBAI Collaboration 2024]

Summary

Several models predict ULDM candidates, but the regime below 10^{-10} eV is not easily accessible

Atom interferometers exploit the high sensitivity of the quantum phases to external effects

There are several initiatives to build atom gradiometers for fundamental physics

AICE is a proposal for a 100 m atom gradiometer with prospects to search for ULDM, expecting leading sensitivity to masses between 10^{-15} and 10^{-12} eV

Backup slides

AION 1 km

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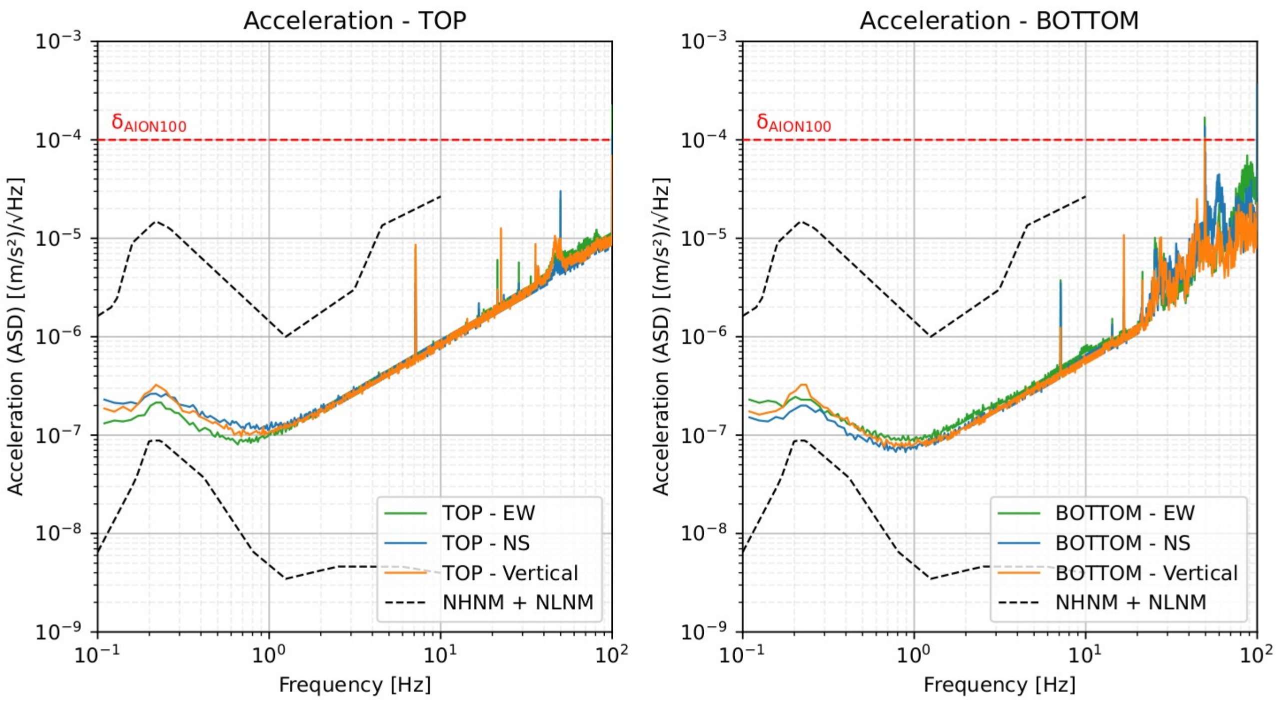

Guinchard et al 2026

Gravitational waves with atom gradiometers