Searching for Ultralight Dark Matter with MOLeQuTE : a Massive Optically Levitated Quantum Tabletop Experiment *

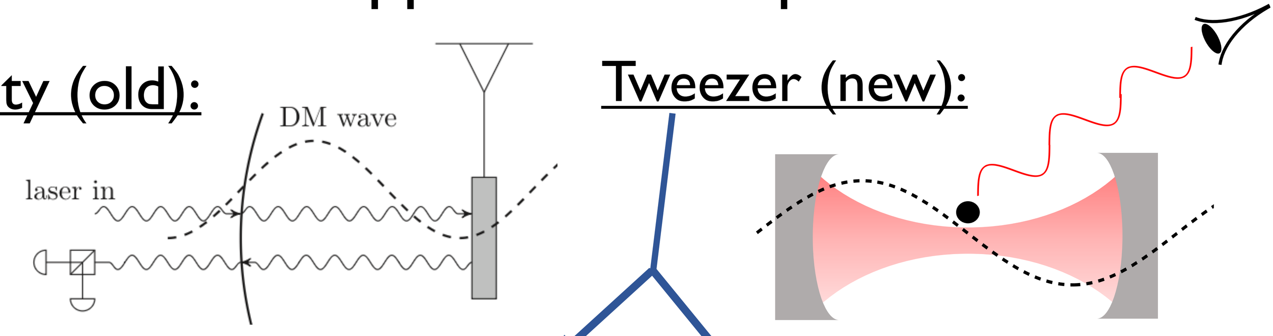
Louis Hamaide – Johannes Gutenberg Universität Mainz

Novel mechanical quantum sensors

- **Mechanical quantum sensors (MQS)** are (e.g. macroscopic) quantum harmonic oscillators whose motion is readout by an external field (optical/ electric/magnetic) and whose n**oises** are limited by **quantum fluctuations** of this field
- Both harmonic oscillators and ULDM have high Q making MQS good at detecting oscillating ULDM forces on resonance
- Recent new sensor concepts use the external field for trapping **AND** and reading out the motions, but their noises & applications required further study:

Cavity (old):

Tweezer (new):



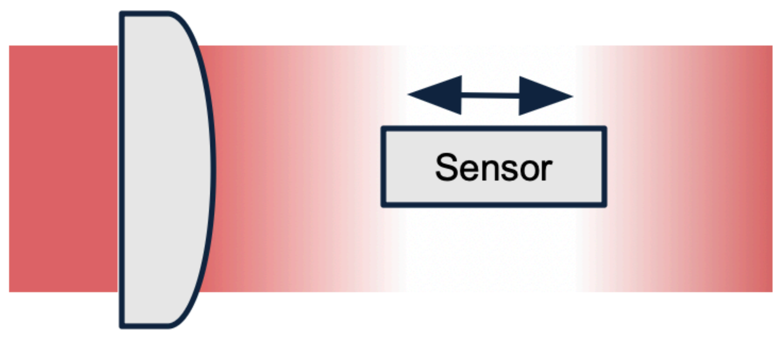
Key advantage
Sensor resonant frequency is **tunable** to scan for ULDM (or GWs!).

Key disadvantage
Noise no longer tunable independently of frequency

- New key insight: **larger optically trapped sensors perform better** IF larger than optical wavelength (geometric optics rather than Rayleigh regime)

Several future directions (preliminary)

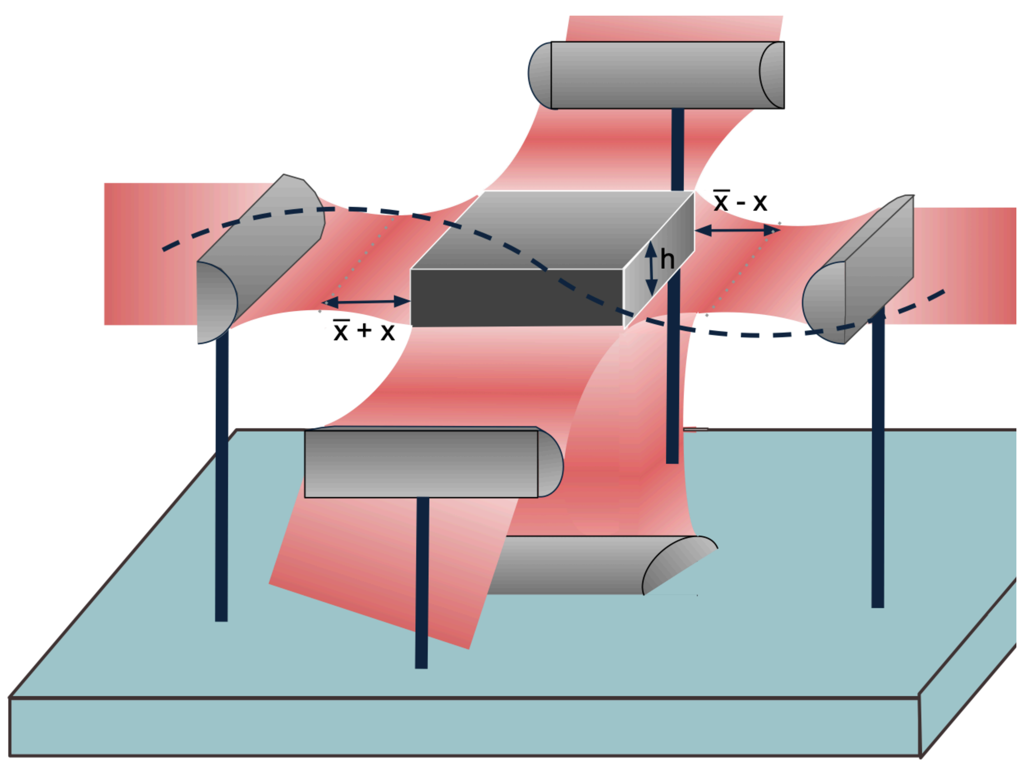
- MOLeQuTE reaches the `**Standard Quantum Limit' (SQL)** by balancing large photon statistics (`shot noise') with minimal excitation of sensor motion (`backaction'). Generically optically trapped sensors only achieve off-resonance SQL. **Engineered optical beams** can easily improve this, leading to **>10² improvements of sensitivity**

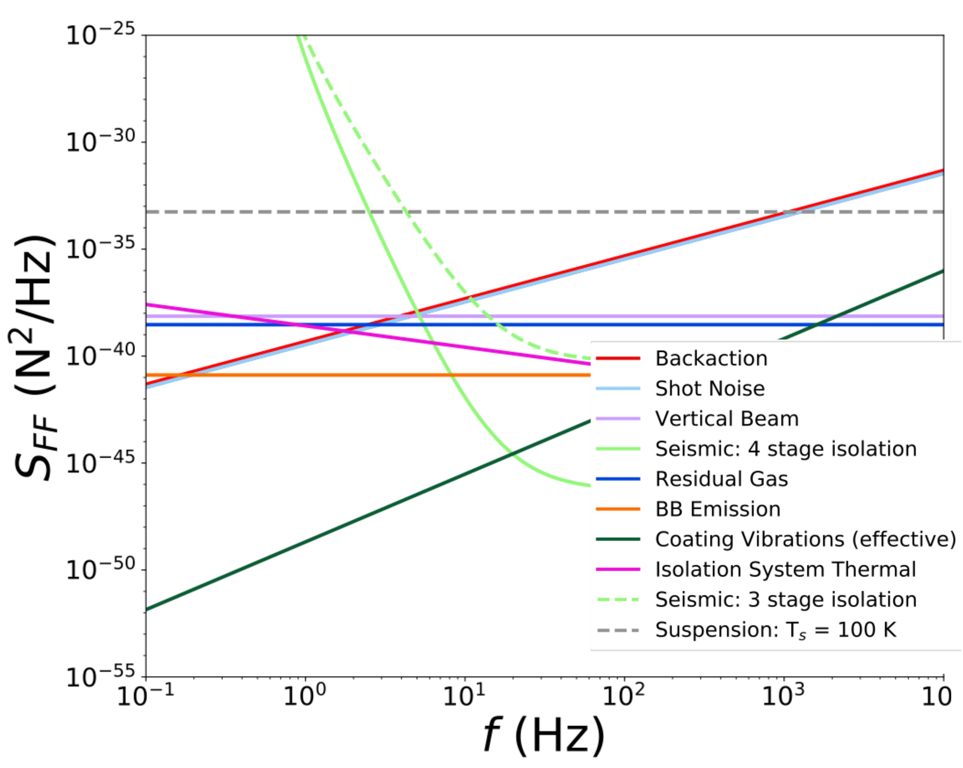


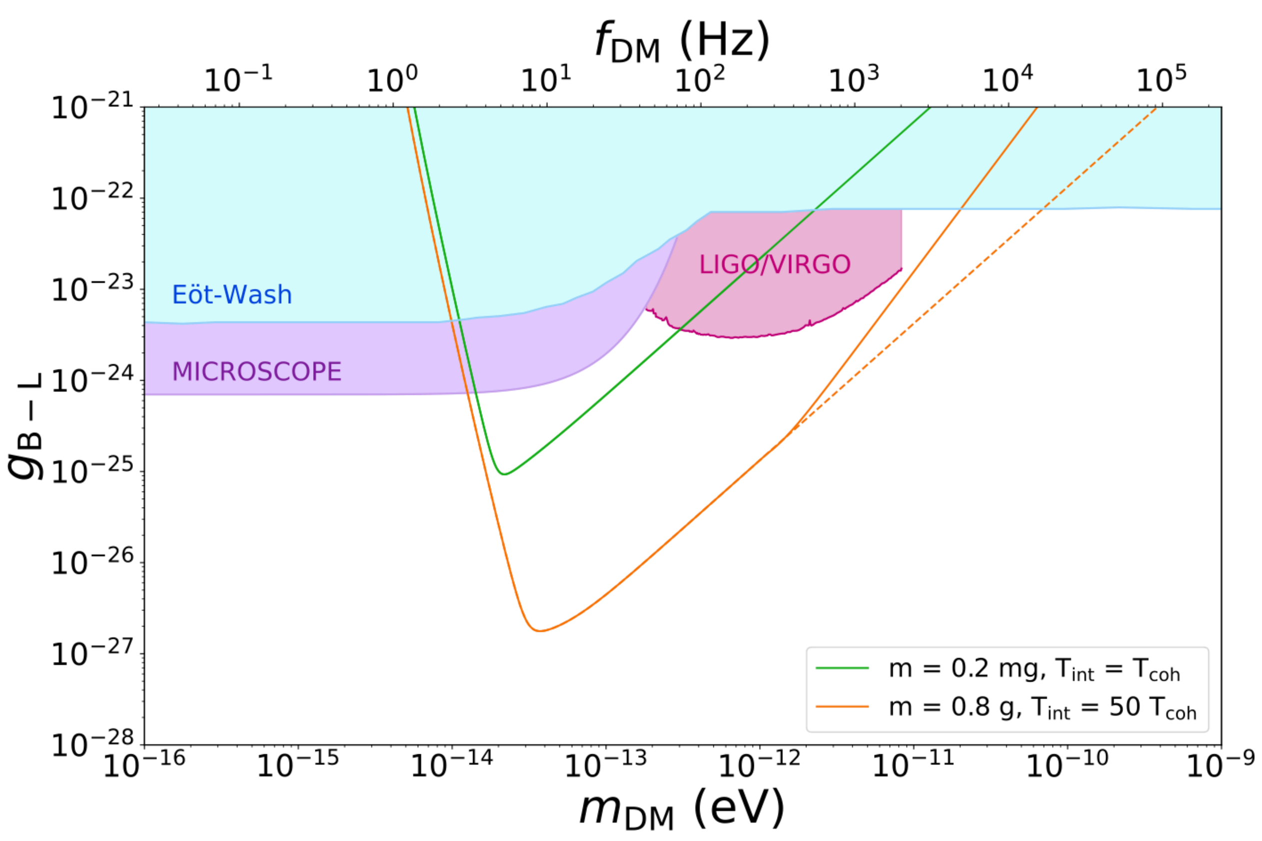
- Seismic noise limits our sensitivity at low ULDM mass/frequency → **MOLeQuBE: compact (cubesat) space mission** is both an **affordable** solution (<1M€) and provides access to probing **new parameter space for low mass (sub-Hz) dark matter**
- Searching new parameter space of **DM self-interactions via bosenovae** signals (bursts) in miniclusters
- **Axion searches:** new fermion+EDM coupling parameter space using electric/magnetic fields and spin-polarized materials

State-of-the-art ULDM detection with MOLeQuTE

- We propose **MOLeQuTE** : first macroscopic O(mg-g) optically levitated sensor in the geometric optics regime where **optical noises** $\propto$ **mass**$^{1/2}$ **while signal** $\propto$ **mass**, leading to **x10⁵ improvement compared to levitated nanoparticles.** Our key limitation is the large optical powers required at large mass and/or high frequencies
- MOLeQuTE traps and reads off the sensor's motion between the foci of two **opposing optical beams** in each direction. We avoid melting from optical absorption with to a **large aspect ratio** (thin plate shape) which provides more surface area to **cool via blackbody radiation**
- We will search for **scalar** (e.g. dilatons/moduli) or **gauge vector** (e.g. from B-L conserving dark U(1)) ultralight dark matter coupling which produce oscillating forces near the ULDM Compton frequency
- Full theoretical **study of systematic noises and stability performed** in 2025, showing quantum limit of noise achievable at 100K and a seismic damping system
- Currently performing stability simulations and prototype fabrication → **prototype levitation (10μg) late 2026**







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* arxiv.org/abs/2512.00166, accepted in PRR

Alexander von HUMBOLDT STIFTUNG