DM detection with nanomechanics

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Thanks to co-workers on DM detection:

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On the Existence of Low-Mass Dark Matter and its Direct Detection

SUBJECT AREAS:
PHENOMENOLOGY
PARTICLE ASTROPHYSICS

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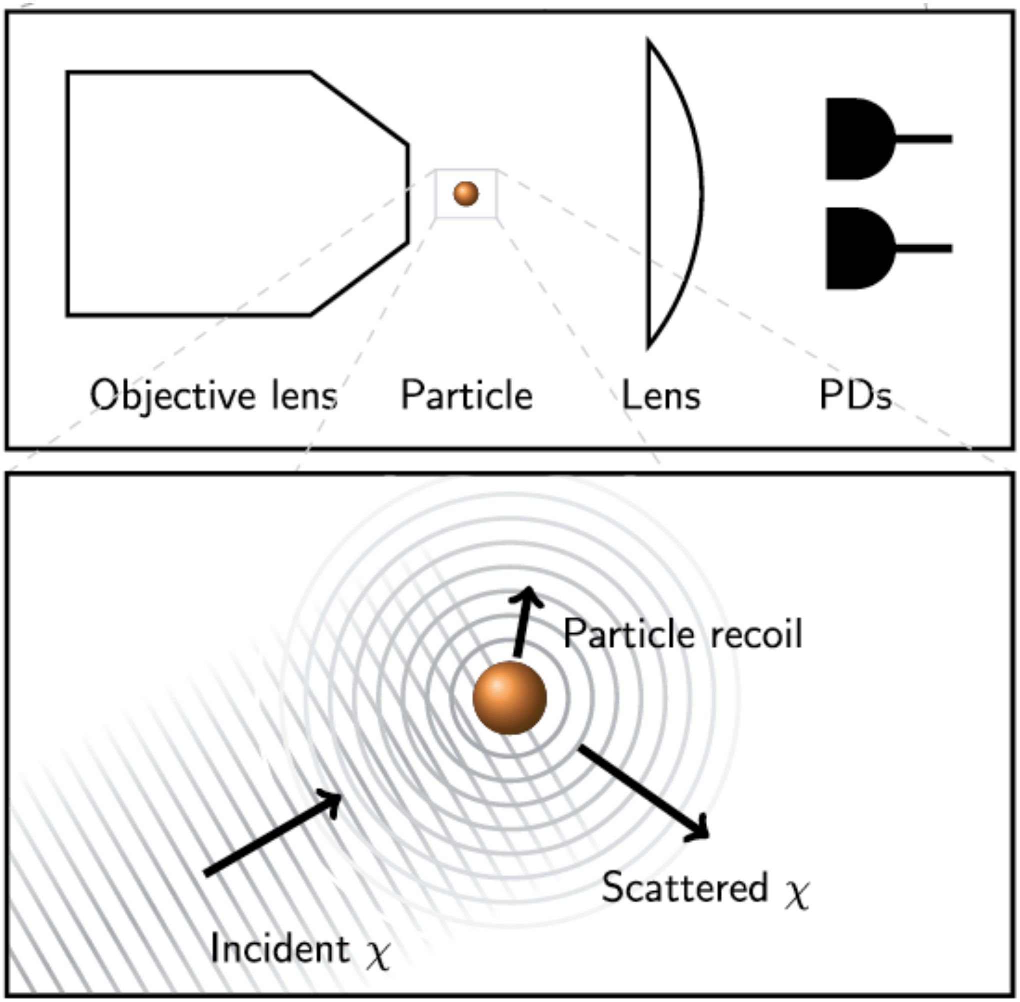
Levitated (opto)mechanics



Mechanical harmonic oscillator (HO) system [levitated or clamped membrane/cantilever]

-> HO hit by many DM particles
-> elastic scattering
-> acceleration detected as Brownian like motion

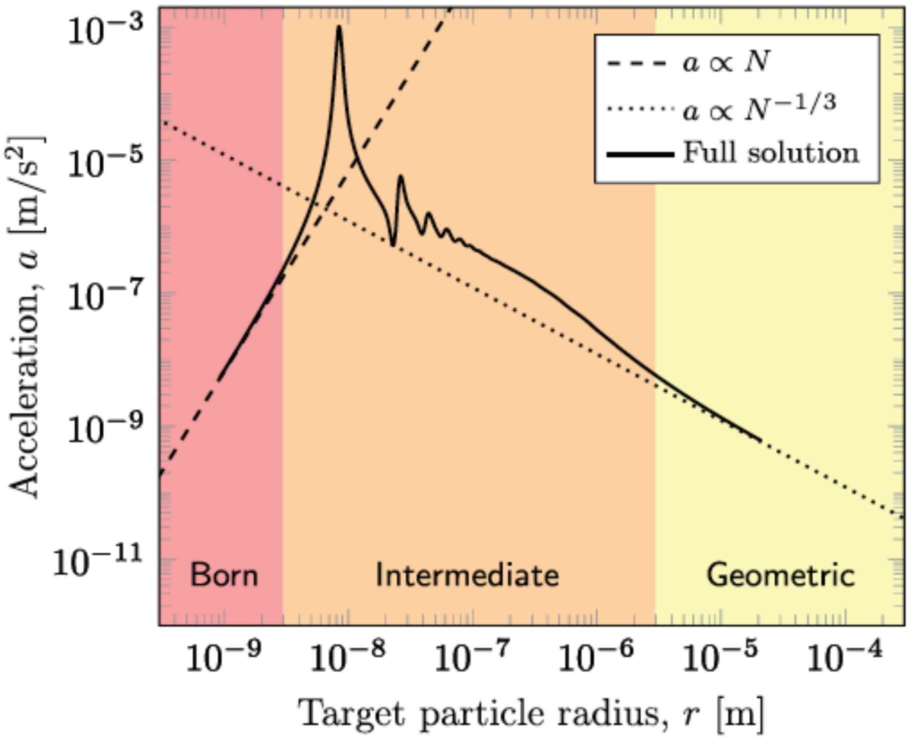
Mechanical oscillators are **superb force/torque sensors**:

- $F_{min}= 10^{-20}$ N/sqrt(Hz) [1]
- $M_{min} = 10^{-31}$ Nm/sqrt(Hz) [2]

[1] Hempston, D., et al., ***Force sensing with an optically levitated charged***, Appl. Phys. Lett. **111**, 133111(2017).
[2] Rashid, M., et al., ***Precession Motion in Levitated Optomechanics***, Phys. Rev. Lett. **121**, 253601 (2018).

Detection mechanism 1: acceleration

(classical detection mode)



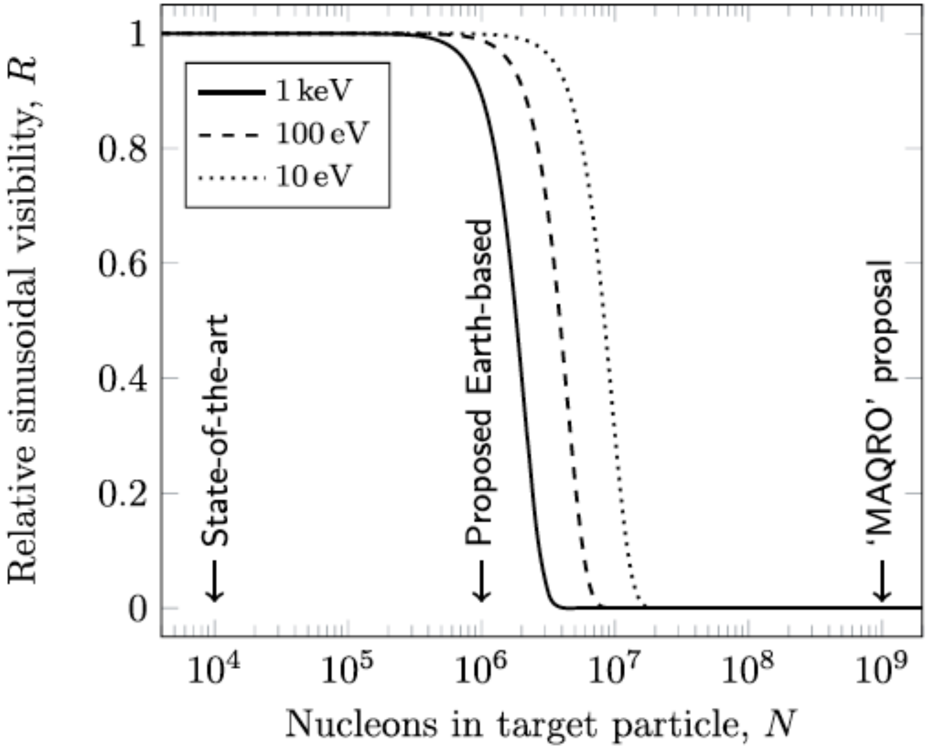
Example calculated for:

- Low-mass DM [100 eV, λ_{dB} = 1 µm, σ = 10^{-29} m^2]
- Silica target particle: spherical shape, nucleon density: 10^{30} m^{-3}

- Direct momentum transfer: N = 10^9 to 10^{16} amu
- Very precise position measurement of *COM* motion of the nano-mechanics: 10^{-15} m
- Enhancement by **coherent scattering**: N^2 scaling, if $r \ll \lambda_{dB}$, $N^{2/3}$ else
- Tuneable to be in resonance with frequency for oscillating DM candidates.

Detection Mechanism 2: decoherence of spatial superposition

(quantum detection mode)



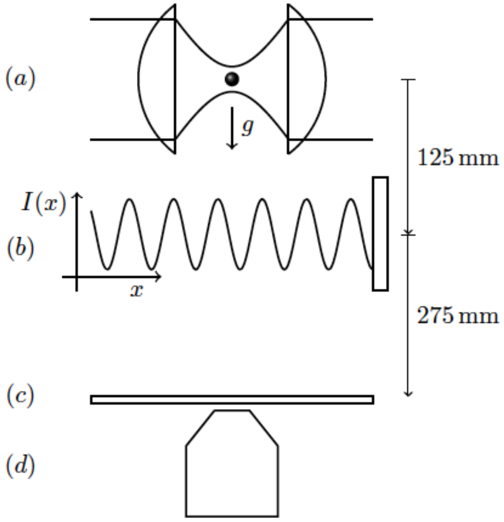
- Spatial superposition of target particle is collapsed by collisions with DM.

… **reduction of fringe visibility** in large-mass matter-wave Interferometer by collision of many DM particles.

- Proposed matter-wave Talbot Interferometer would test decoherence down to 1 keV DM candidates.

Earlier proposal by Riedel, C. J. Direct Detection of Classically Imperceptible Dark Matter through Quantum Decoherence. *Phys. Rev. D* 88, 116005 (2013).

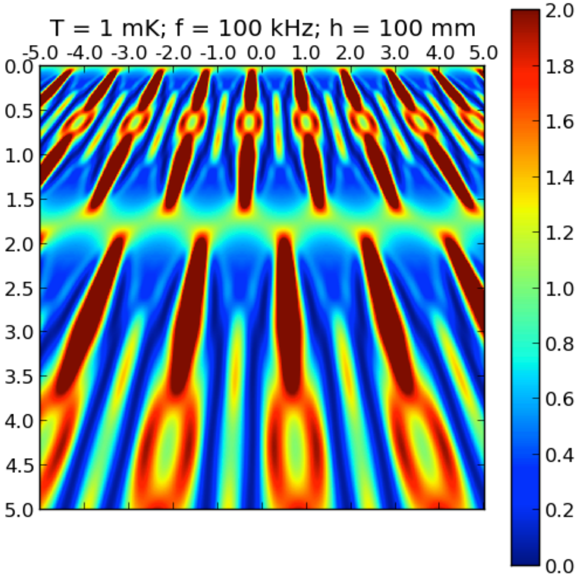
Nanoparticle Matter-wave Interferometer: proposal yet to be realised



Talbot interferometer with particle of mass: 10^6 -10^7 amu (~20nm diameter)

- **Wigner function model of interference pattern**
- **Dominating decoherence effect:** Blackbody emission, absorption.
- **Mass of particle is limited by Earth's gravity … future experiment in space?**

Quantum carpet:



Collimation/Preparation of spatial coherence translates to cooling of the particle in the trap.

Conditions for 20 nm particle experiment:

- 10 mK of *com* motion needed before drop.
- 300 K internal temperature possible.
- 10^{-8} mbar to avoid collisional decoherence.

Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht
Near-field interferometry of a free-falling nanoparticle from a point-like source
Nature Communications 4, 4788 (2014).

More tricks in toolbox to improve sensitivity

- State-preparation: classical and non-classical such as squeezing;
- Parameter estimation techniques [Q-metrology];
- Shape and degree of freedom of mechanical oscillator (disc, libration, etc.);
- Material/density of target particle;
- Resonant enhancement in ‘receiver’-mode [wide frequency range possible, Hz to GHz] or static mode in free fall;
- Space-based experiment.