Mainz Institute for Theoretical Physics

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Searching for ULDM with MOLeQuTE

Louis Hamaide – 12/25

ULDM Couplings To OM Sensors

- We search for forces from vector DM coupled to B-L or scalar DM couplings to fermion masses:

$$F_{DM}(t) = g\, N \sqrt{\rho_{DM}}\, \sin(\omega t)$$

Vector B-L

$$\mathcal{L} = -\frac{1}{4}F^2 - \frac{1}{2}m_\phi^2 A^2 + i g_{B-L} A_\mu \bar{n}\gamma^\mu n$$

$$F = g\, N\, E(t) \qquad g = g_{B\text{-}L}$$

Scalar

$$L = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 + y\phi\bar{n}n$$

$$F = -\frac{dV}{dx} \qquad g = v_{DM}\, y$$

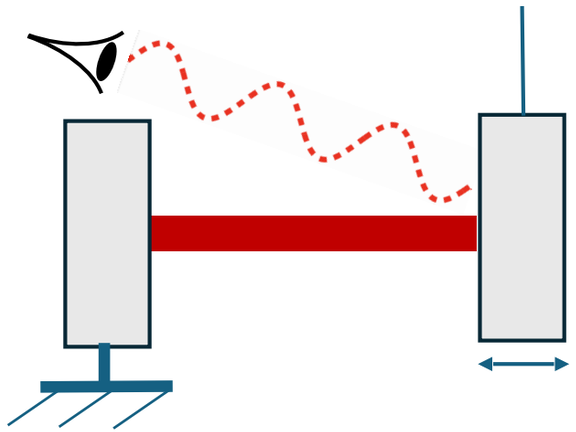
- The figure of merit in DM detection is the (spectrum of) SNR value:

$$\mathrm{SNR} = \frac{F_{DM}}{\sqrt{S_{FF}(\omega)\delta\omega}} = \frac{F_{DM}}{\sqrt{S_{FF}(\omega)/T_{int}}}$$

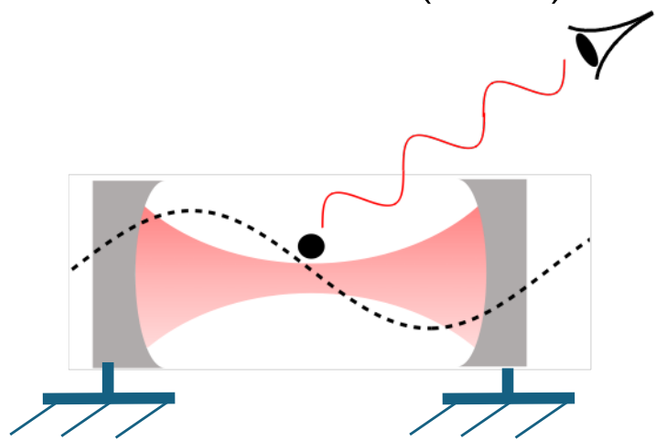
- ULDM has a high quality factor —> mechanical resonators are a natural candidate for ULDM searches
- Further, optical fields are natural candidate readout to infer forces on sensor

Recent Developments In OM Sensors

- Optomechanical sensors are **mechanical** resonators (simple harmonic oscillators) whose motion is read out by an optical field and with well-understood quantum noises
- Historically, optomechanical (OM) sensors have been largely limited to oscillating **suspended pendulums that aren't tunable to scan frequencies for broadband searches** of dark matter and limited to "low" frequencies
- Recent advances in optics have led to tunable optical fields trapping and measuring **the particle at high frequencies**
- Exploration of **nanoparticles and micro particle setups** (where gravitational forces need to be addressed) is underway but overall less studied than suspended sensors. Current setups exhibit low noise and potential for torque sensing

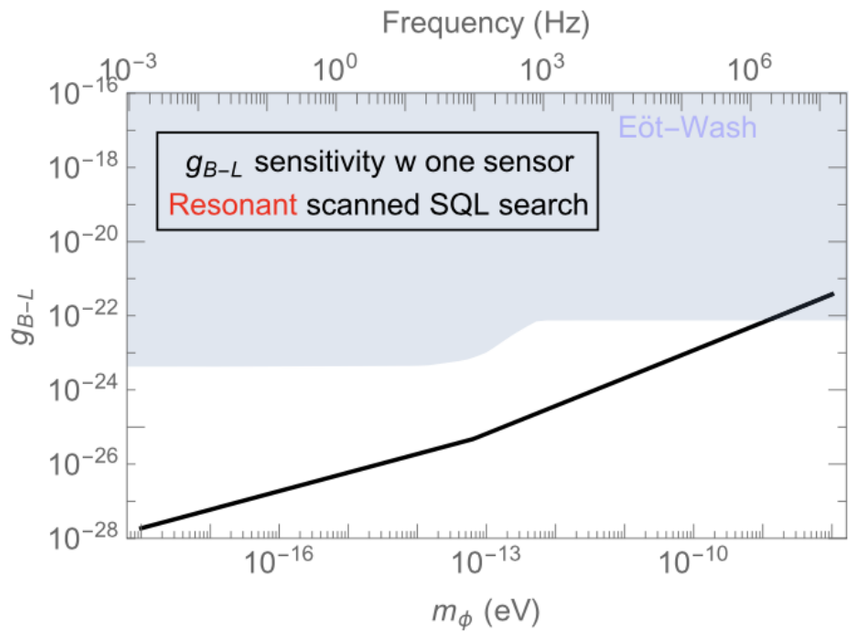


Cavity setup (above) vs. levitated sensor (below)



OM Sensor Prospects

- Theoretical investigation of optical systems has shown OM sensors are sensitive enough to improve on current bounds in principle, however bounds are unrealised so far



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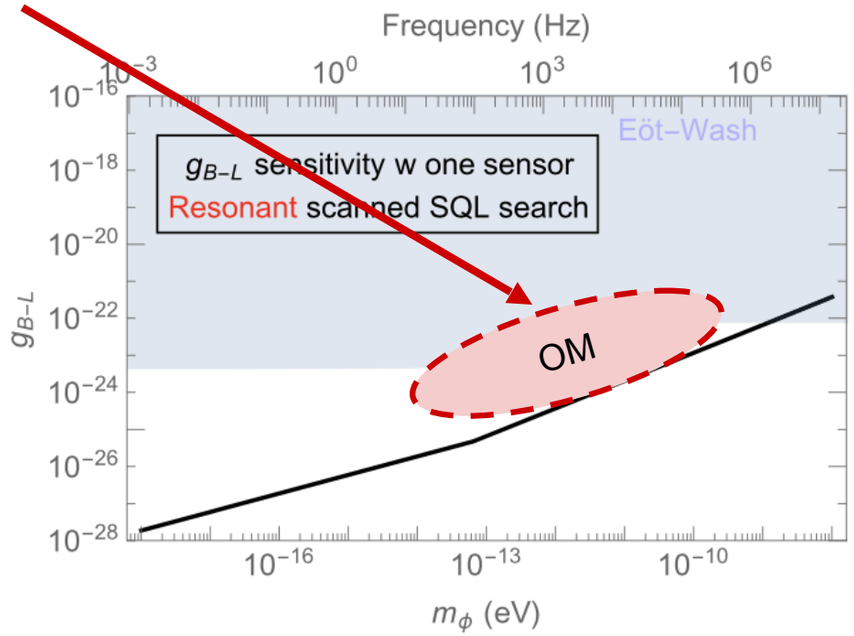
- Lack of tunable and experimentally realistic proposed setups that can reach these levels so far, especially at high frequencies



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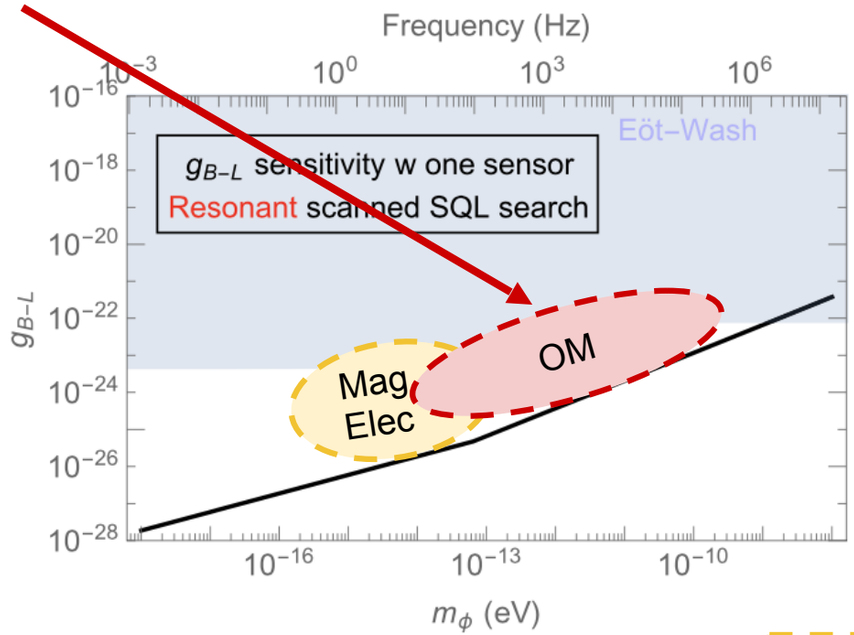

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- DM detection should follow similar principles (quantum noises) as magnetic and electric levitation so we now study the principles of DM detection with OM sensors

OM Noise Optimisation

- There are two sources of quantum noise in OM sensors: imprecision and backaction, with power spectra

$$S_{FF}^{imp} = \frac{m^2((\omega^2 - \Omega^2)^2 + \gamma^2\omega^2)}{P_{\text{scatt}}\,\omega_L} \quad \text{and} \quad S_{FF}^{ba} = P_{\text{scatt}}\,\omega_L$$

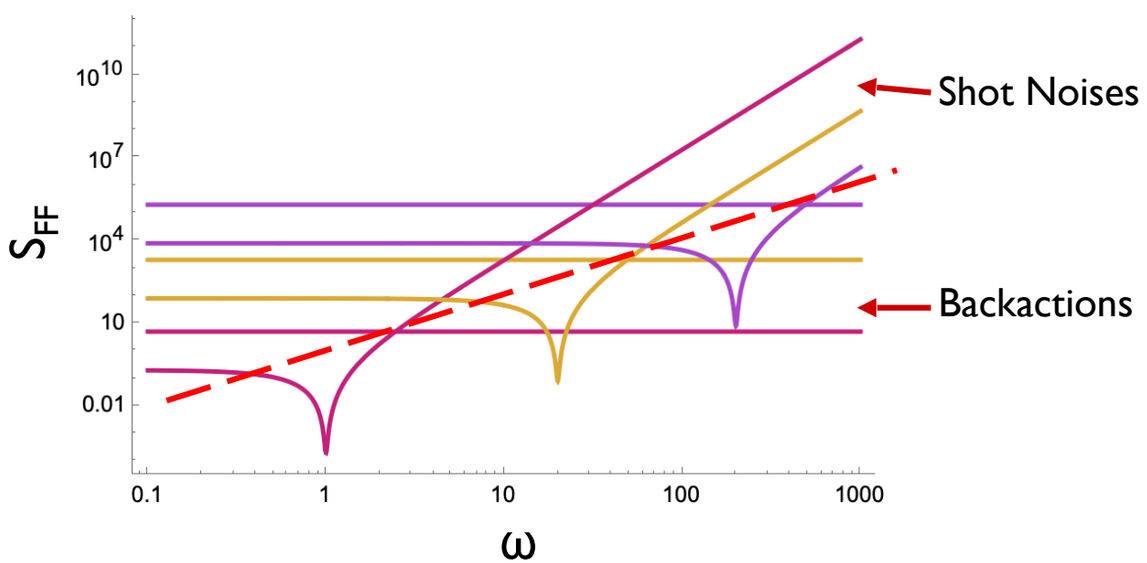
- The scattered power (i.e. Γ) in optomechanical sensors such as cavities can be tuned to reach the **"standard quantum limit"** such that

$$P_{\text{scatt}}\,\omega_L = \sqrt{m^2((\omega^2 - \Omega^2)^2 + \gamma^2\omega^2)} \quad , \quad S_{\text{SQL}}^{\text{FF}}(\omega) = 2\sqrt{m^2((\omega^2 - \Omega^2)^2 + \gamma^2\omega^2)}$$

- In **current** levitated setups, we note the power is **fixed by the frequency** and the limitations in our ability to focus the optical field

➔ <u>Features of noise:</u>

- SQL off-resonance $\omega^2 \sim \Omega^2$
- S_{FF} = min(SN+BA)
- SN = BA

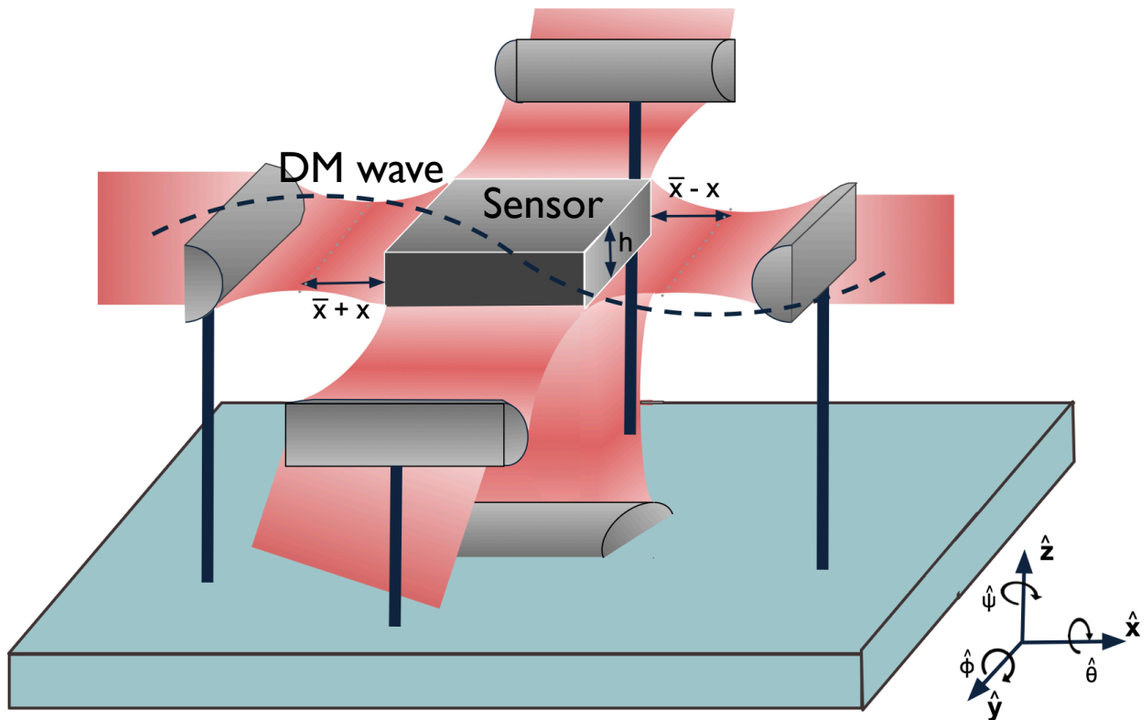


Proposed Setup for MOLeQuTE

- Given the mass scaling for large particles, we will choose a larger mass as we expect DM forces to be coupled to mass
- We propose a totally **novel trap** designed for large sensors, with $S_{FF} \sim P_{scatt} = m\,\Omega^2\,z_0$

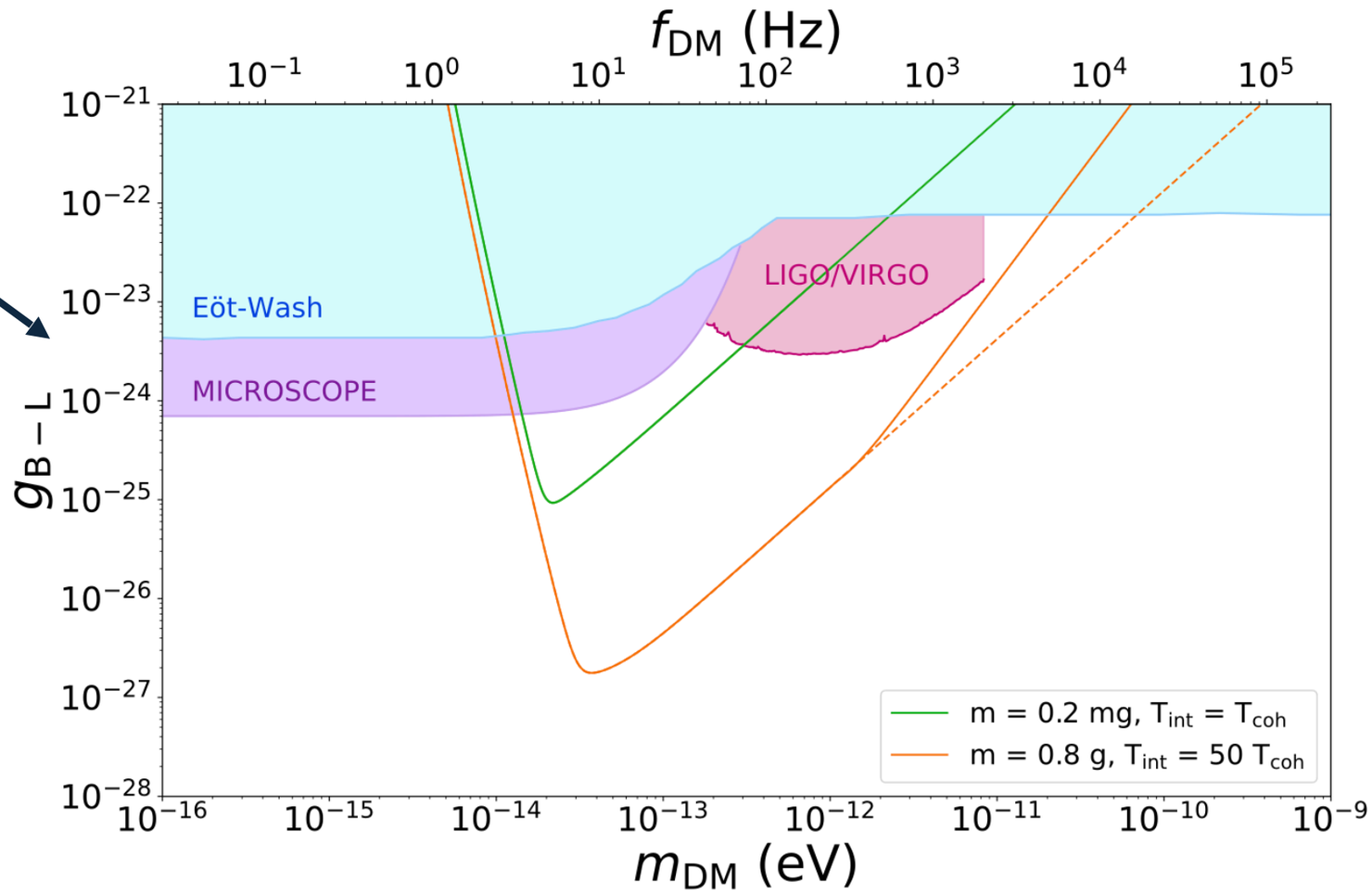
Sensor features:

- Silica mass ~ 0.1mg (**>> nanoparticles**)
- Vertical beam for levitation (against gravity)
- High reflectivity coating to avoid melting the interior
- **Focused horizontal beams** for spring constant
- Typical OM sensor vacuum and readout specifications



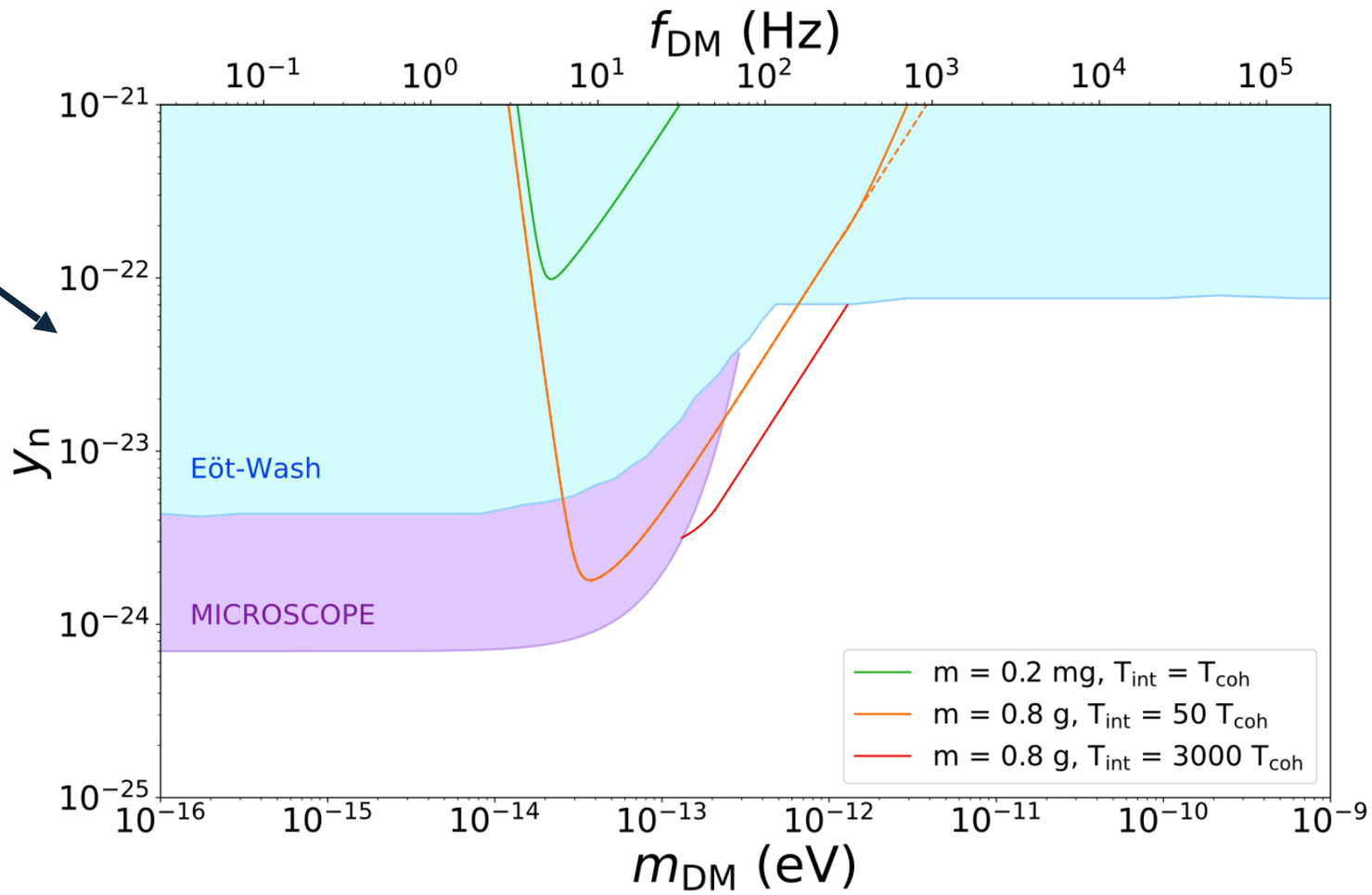
Sensitivities To ULDM Couplings (1/2)

- We show here the sensitivity of our proposed setup to **vector B-L DM**
- In green we use m=0.1mg (conservative) while in orange we use m=0.1g (optimistic), which can be levitated using a cavity and by scaling it in one direction
- Dashed line assumes unlimited optical power
- LIGO less sensitive because it only sees the DM *gradient*



Sensitivities To ULDM Couplings (2/2)

- We show here the sensitivity of our proposed setup to **Scalar DM**
- In green we use m=0.1mg (conservative) while in orange we use m=0.1g (optimistic), which can be levitated using a cavity and by scaling it in one direction
- 5th force experiments not velocity suppressed
- Red line represents concentrated effort in small region to optimize DM parameter space coverage



Going To SQL On Resonance?

- Backaction noise is typically dominant in levitated OM sensors.

➔ Recently proposed **methods to avoid backaction noise** in levitated sensors have been proposed:

  - **Light squeezing** requires optical fields with anti-correlation between the phase and the amplitude of the field such that the SFF obtains a negative BA-SN crossterm
  - **Backaction evasion**, often less cited, usually devises to measure velocity instead of position to somewhat alleviate the limitations of the uncertainty principle
  - **Dark focuses** and standing waves allow to create potentials with no light scattering at the center, ie trapping in the dark, and require further study

- Other limitation: wavelength of light requires conceiving optical field where setup can give large optical field gradient AND low field value.
- Proposed setup has $S_{FF} = m\,\Omega^2$ → we wish to reach $S_{FF} = \gamma\, m\, \Omega$ where $\gamma/\Omega \ll 1$

Take Home Messages

- Optomechanical sensors are under-studied for ultralight dark matter detection and have the potential to **improve bounds on several ULDM couplings** by several orders of magnitude
- Rapidly innovating field of study with **fully tunable sensors allows for broadband DM searches**
- **MOLeQuTE: New proposed tabletop setup** is straightforward to implement with current technologies at a reasonable cost
- Fully characterized noise and directions for further improvement → future work is needed to characterizing the **ultimate sensitivity of OM sensors**
- Future work also include searches for **high-frequency GWs** and exploring **other ULDM couplings**

Further Potential Of OM Sensors

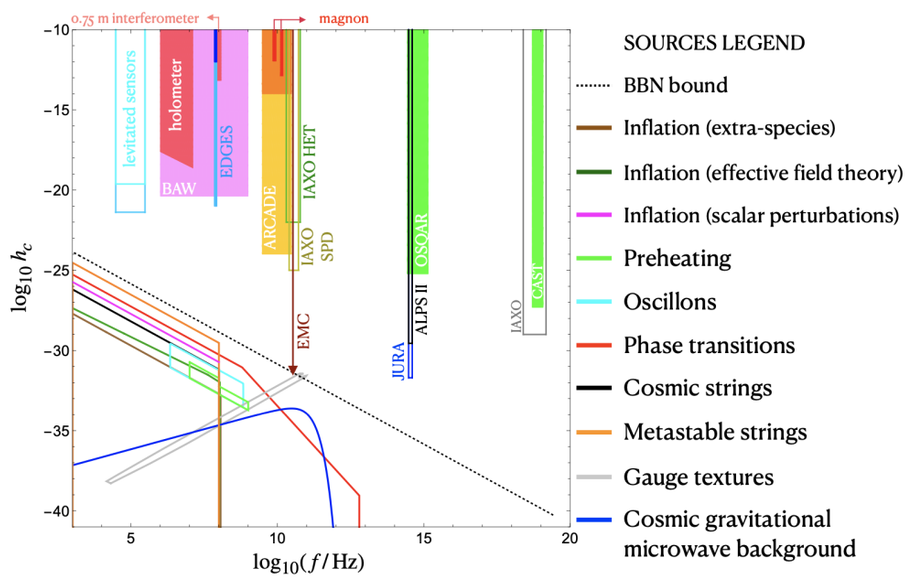
Ultralight DM

- Further work will determine whether e.g. dark photon **kinetic mixing or coupling to the QED fine structure** constant can also be detected
- OM sensors **detect torque** with similar sensitivity as translational motion → easier to detect pseudo scalar couplings

Spin	Type	Operator	Interaction	Oscillating DM Effects
0	scalar	$\phi\, h^\dagger h,\ \phi\, \mathcal{O}_{\rm SM}$	Higgs portal / dilaton	m_e, m_p, α variation
				acceleration
	pseudo-scalar	$a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$	axion-QCD	nucleon EDM
		$a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$	axion-E&M	EMF along B field
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	axion-fermion	spin torque
1	vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	minimally coupled	acceleration
		$F'_{\mu\nu}F^{\mu\nu}$	vector–photon mixing	EMF in vacuum
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole operator	spin torque
	axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	minimally coupled	spin torque

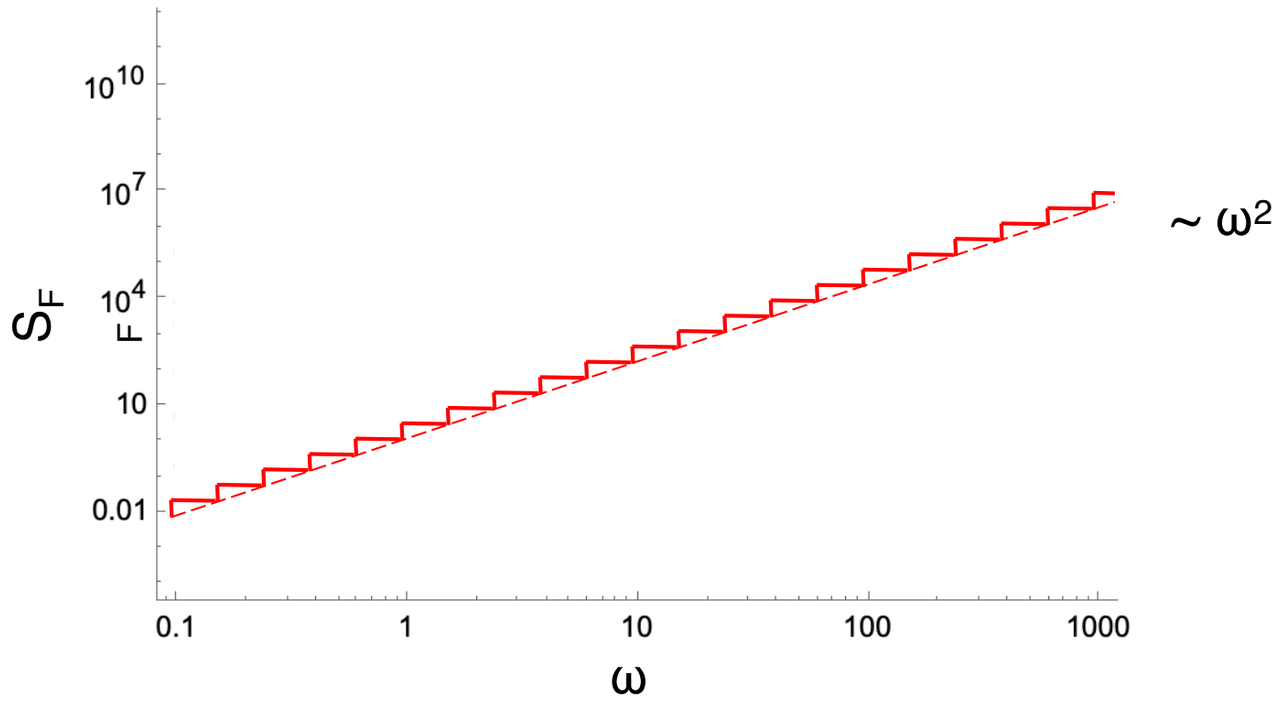
Gravitational Waves

- Further work following proposals to detect **high frequency GWs** (kHz-GHz) using OM sensors is needed (e.g. harness torque?)
- High frequency GWs are probes of **early universe physics** and quantum effects in gravity



Back up - OM Noise Optimisation

- To reach this noise in practice one must change the mechanical frequency each time. We must start measuring again each time, leading to a binned search practically

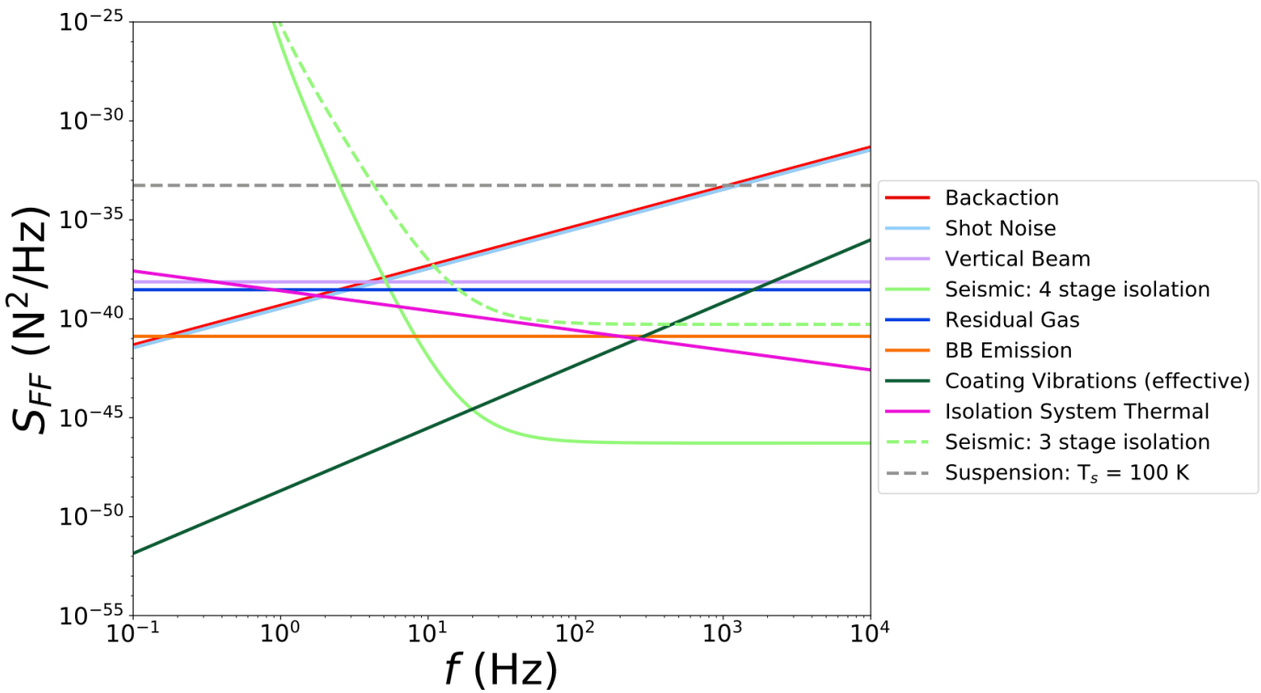


- Future work should focus on get within γ of Ω to finally realize the full potential of OM sensors

Back up - More Noises!

- We have dealt with an idealized system until now. Other (non-fundamental) noises will be subdominant:
  - Thermal baths (eg residual gas) generate a flat noise spectrum, whereas Brownian motion is $S_{xx}=1/f$. We find cooling the vacuum chamber to 10mK is necessary to avoid dominating noises. Thankfully this is readily achievable with current off-the-shelf solutions.
  - Seismic noise may be reduced using two sensors with different DM charges → future work

- Note suspension noises are lowest for for large masses at lower frequencies (~100Hz, in their region of tunability), demonstrating their are likely *complementary* for DM searches

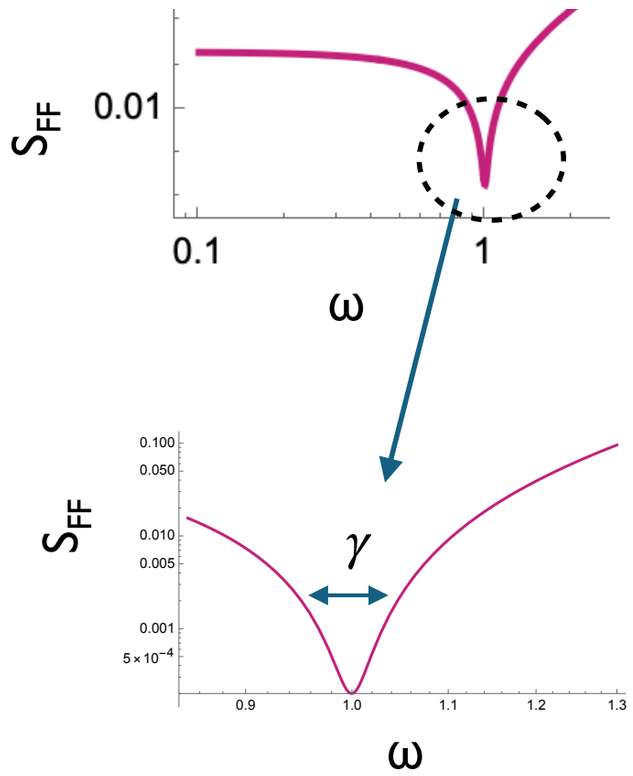


Back up - Going To SQL On Resonance?

- Assuming we reach the noise in the previous slide (SQL resonance), we must account for two constraints which will constitute the fundamental limitations of OM sensors:
  - Sensitivity is reached in $\delta\omega = \gamma$ region, thus integration must be **$T_{int} > 1/\gamma$ in each** $\delta\omega$ quickly increasing total integration time requirements for broadband searches. Note also $1/T_{coh} \sim \delta\omega_{DM} \sim m_{DM}$ and no improvement of detectability occurs below $\gamma < \delta\omega_{DM}$
  - At every frequency, there is a theoretical minimum damping one comes across due to non-linearities for large phonon number, this is visible through the position variance:

$$Q\frac{< x^2 >}{z_0^2} \ll 1 \quad \text{where} \quad < x^2 > = \frac{\Gamma}{\gamma} x_0^2$$

→ Note SQL on resonance corresponds to $n = 1$ (ground state)



Back-up - Damping/Excitation Rates

- **Full damping/excitation rates expression:**
  - In the above we have assumed thermal noise to be negligible. This requires cooling of the environment down to ~10mK. Above this the excitation rate and damping rate γ contain thermal terms
  - These rates also contain a feedback term often introduced manually to ensure dynamical stability, ie such that the particle phonon occupation number does not escape the

Back-up - A Landscape Of New Setups

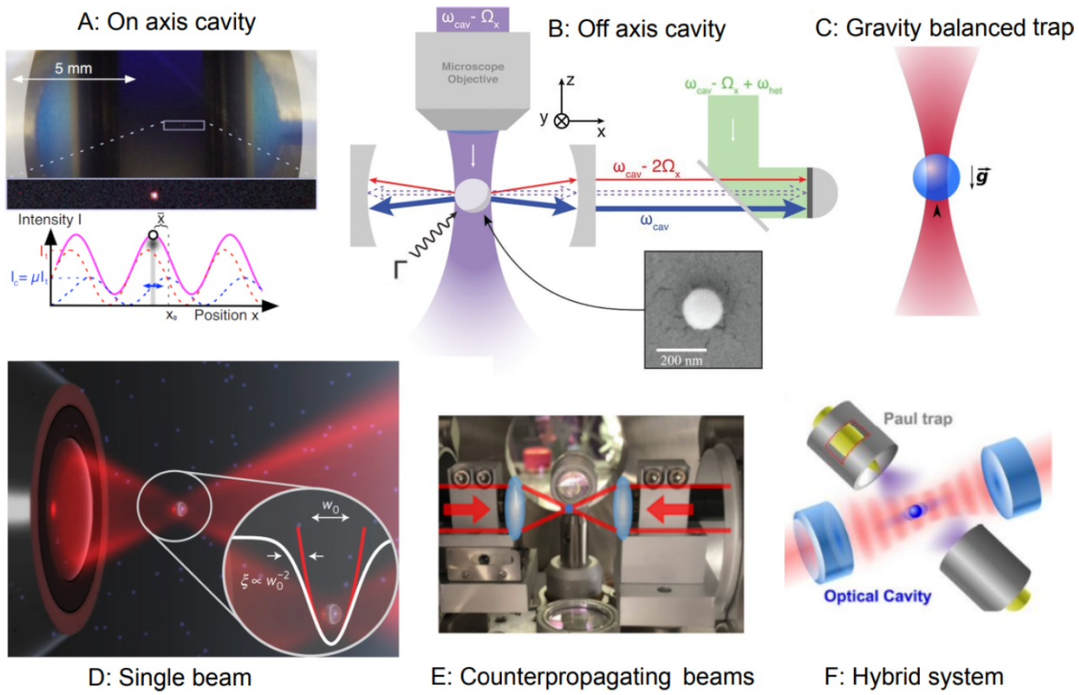


Fig. 1. Optical trapping geometries employed in recent levitated optomechanics experiments (clockwise from upper left): A) cavity along trapping optical axis, reproduced from Ref. [31], B) cavity normal to trapping optical axis - reproduced from Ref. [23], C) scattering force - gravity balanced single beam trap, adapted from Ref. [32], D) single objective focus trap with a single propagation direction, as in Ref. [33], E) two counterpropagating freespace beams in a non cavity configuration, adapated from Ref. [34], F) hybrid Optical and Paul trap (for the same trapped species) as in Ref. [35].