Directional dark matter searches with levitated optomechanics

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Summary

1. Optical tweezers

2. Directional dark nugget searches

3. Future searches

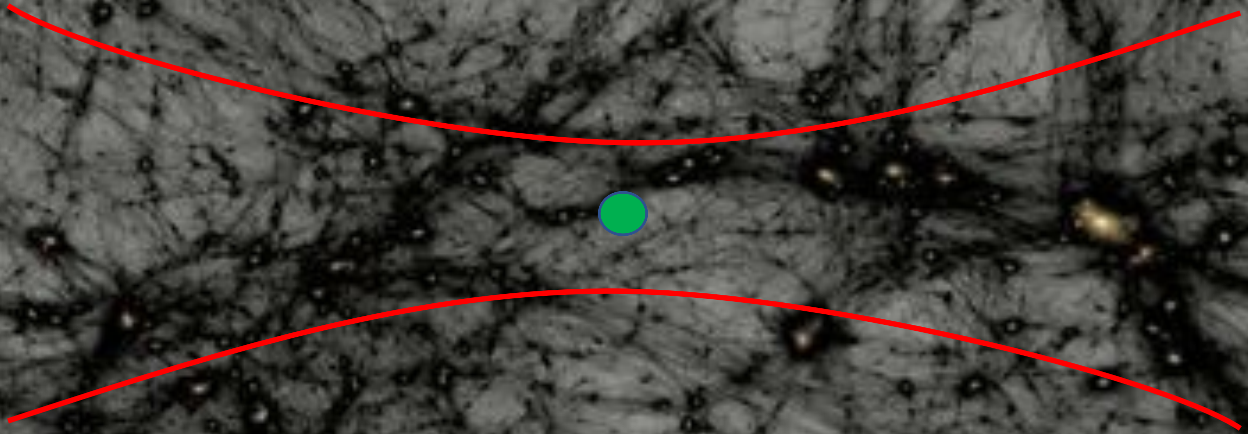
Optical tweezers

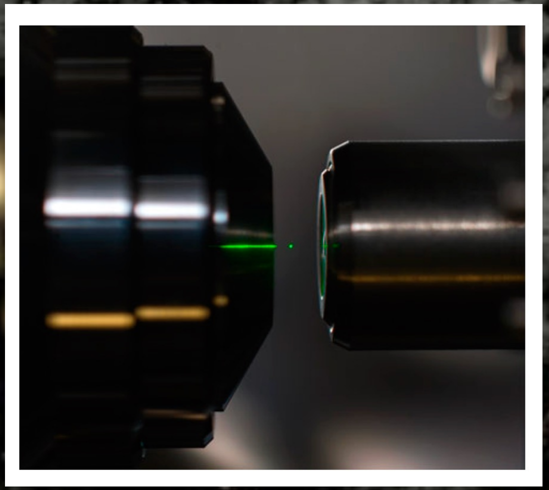
Laser beam gradient force

$$< \vec{F} > = < P_i \vec{\nabla} E_i >$$

$$\vec{P} = (\alpha' + i\alpha'')\vec{E}$$

- A polarizable dielectric particle in a laser beam experiences a gradient force
- This allows one to create an optical tweezer to levitate dielectric nanoparticles in an isolated environment

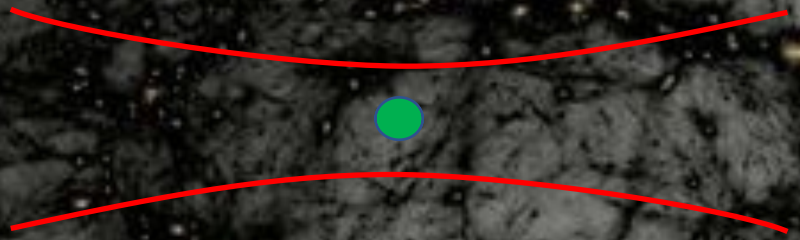




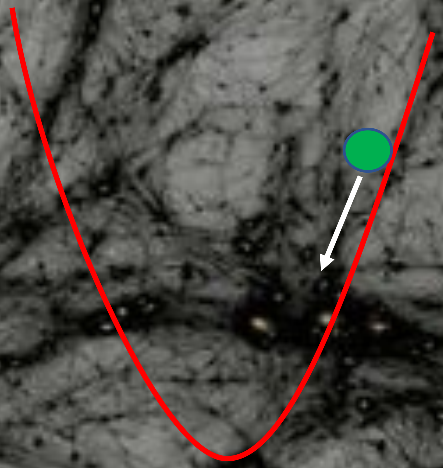
$$< \vec{F} > = \frac{\alpha'}{2} \vec{\nabla} < |\vec{E}|^2 >$$

Optical tweezer as a harmonic potential

$$\vec{E}|^2 = \frac{E_0^2}{1+\frac{z^2}{z_0^2}} cos^2 \left(kz + \frac{kr^2}{2z(1+\frac{z_0^2}{z^2})} - tan^{-1}(\frac{z}{z_0} - \omega t) \right) e^{-\frac{2r^2}{w^2(1+\frac{z^2}{z_0^2})}}$$



$$< \vec{F} >= \frac{\alpha'}{2} \vec{\nabla} < |\vec{E}|^2 >$$



$$< F_r >= \frac{-\alpha' E_0^2}{w^2} r = -\omega_r^2 r$$

$$< F_z >= \frac{-\alpha' E_0^2}{2z_0^2} z = -\omega_z^2 z$$

Sources of noise

$$m\ddot{q} = -\omega_q^2 q - \gamma_{tot}\dot{q} + \beta_{q,gas}(t) + \beta_{q,phot}(t)$$

$$\gamma_{tot} = \gamma_{gas} + \gamma_{phot}$$

Gas damping and collisions

Inelastic collisions of the surrounding gas molecules with the particle provide a damping and a stochastic force obeying a fluctuation dissipation theorem.

$$\gamma_{gas} = \frac{(1+\frac{\pi}{8})\overline{v_{gas}} P m_{gas}}{k_B T r \rho}$$

$$< \beta_{gas}(t) >= 0$$

$$< \beta_{gas}(t)\beta_{gas}(t') >= 2m\gamma_{gas}k_B T\delta(t-t')$$

Photon shot noise and Doppler cooling

Photons in the laser field impart a stochastic force to the particle, while their scattering gives rise to a damping term, so-called Doppler cooling. They obey a fluctuation dissipation theorem.

$$\gamma_{phot} = \frac{4P_{scatt}}{5mc^2}$$

$$< \beta_{phot}(t) >= 0$$

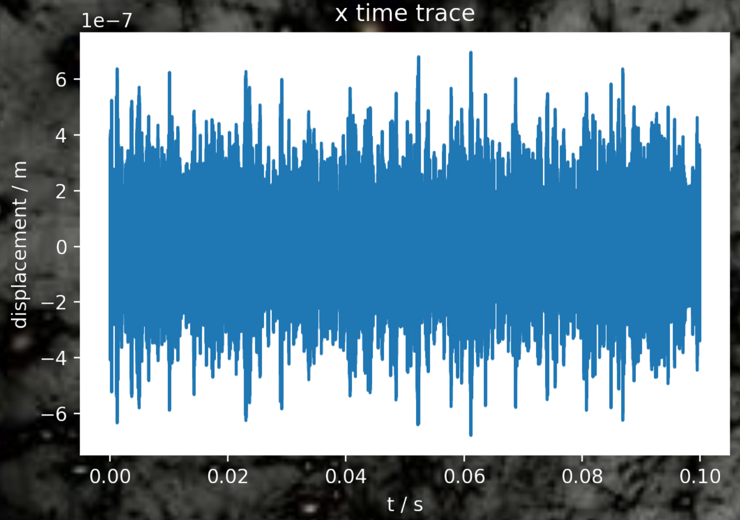
$$< \beta_{phot}(t)\beta_{phot}(t') >= \frac{2\hbar\omega}{5c^2}\delta(t-t')$$

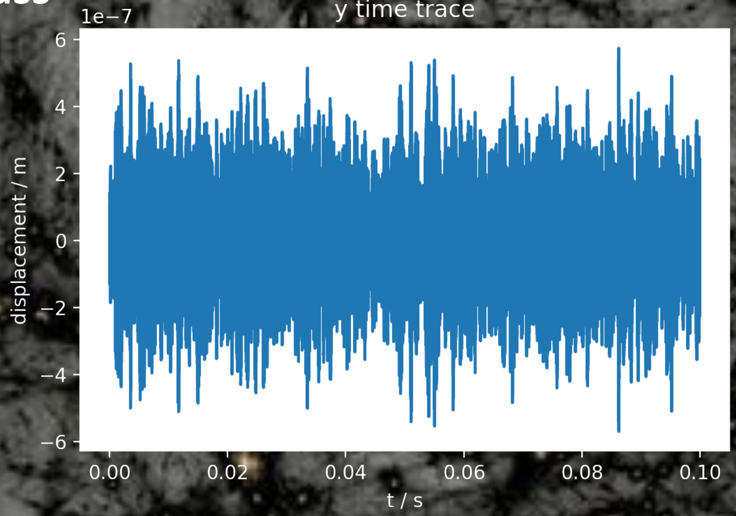
Simulation

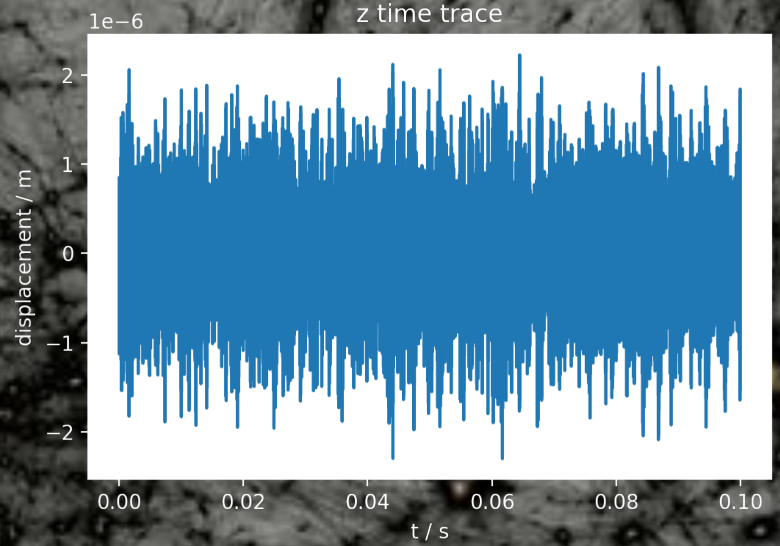
Fits to PSDs allow us to experimentally determine particle mass

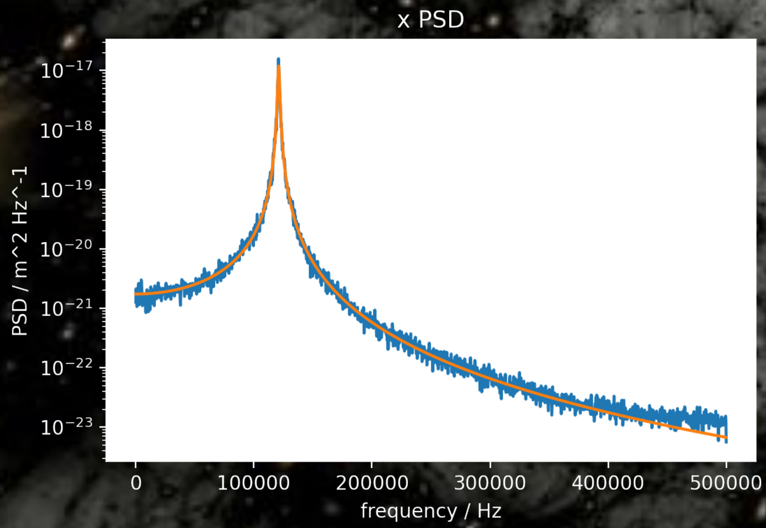
Simulation parameters:

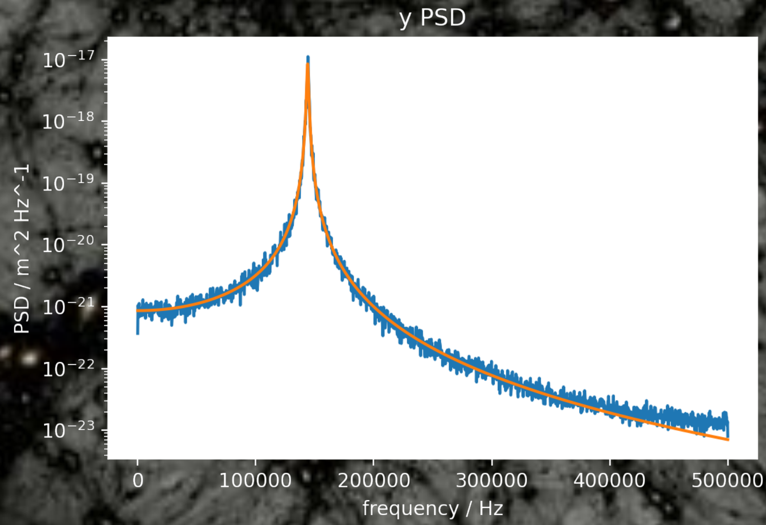
36.9 nm radius SiO_2 particle
300 K gas temperature (600 K internal particle temperature)
1 mbar pressure
121, 144, 32 kHz trap frequencies (x, y, z)
1064 nm laser, 300 mW power at focus, 0.77 NA lens

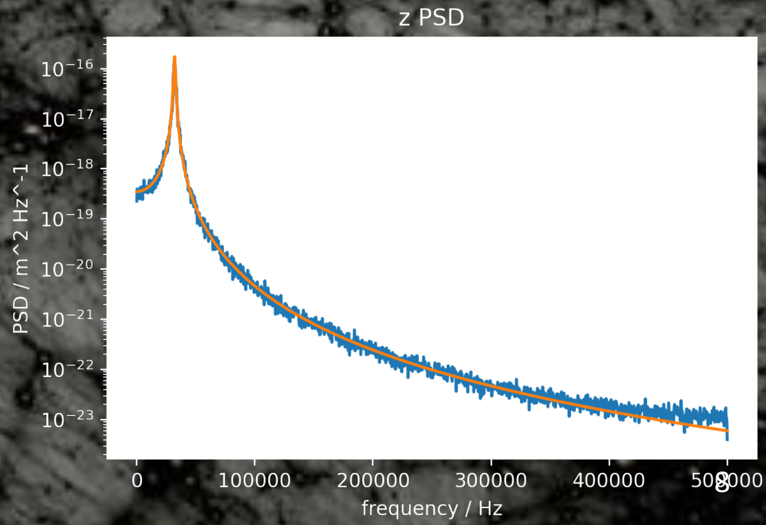






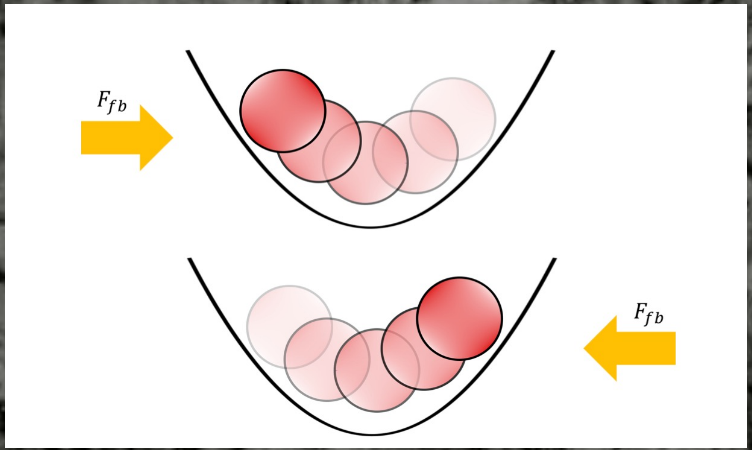


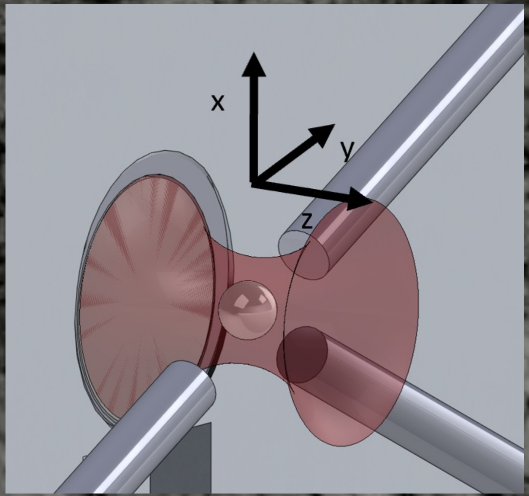




Feedback cooling

- Without feedback cooling, laser shot noise would cause the CoM motion of the particle to heat to very high temperatures as the gas is reduced in pressure, limiting impulse detection
- We use velocity damping: a force opposite in direction and proportional in magnitude to the particle’s instantaneous velocity is applied to cool the CoM motion
- This force is delivered via two of the three electrodes shown surrounding the trap

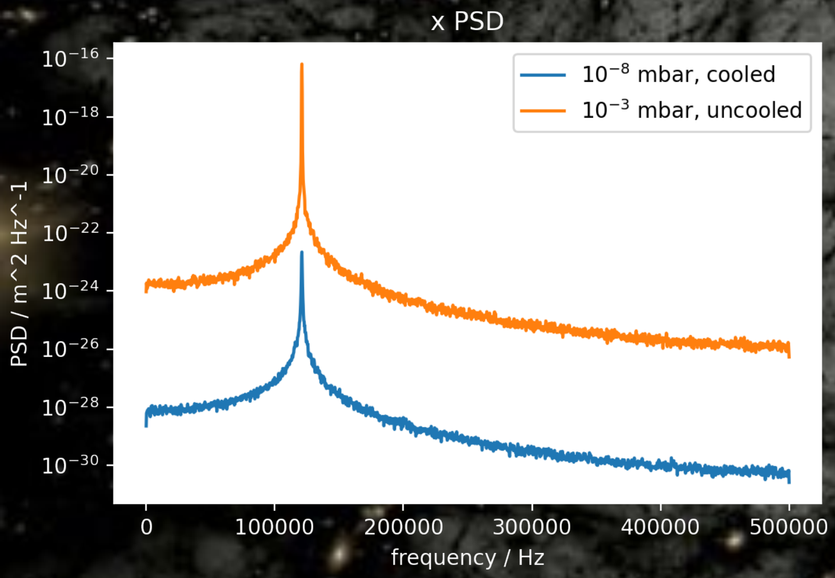


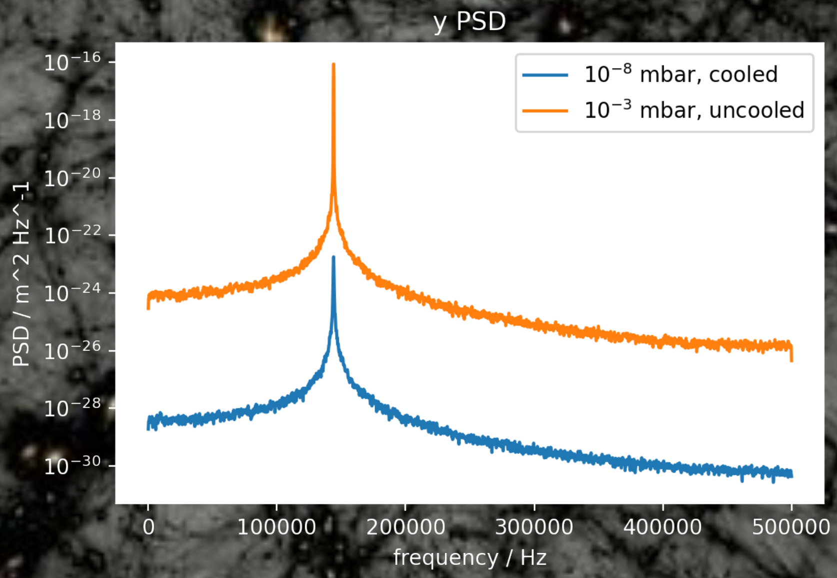


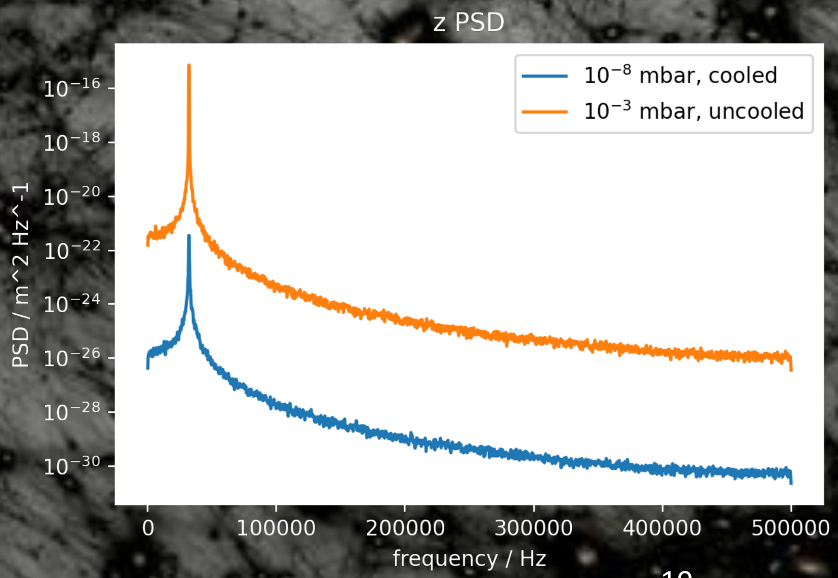
Feedback cooling in simulation

$$\gamma_{tot} = \gamma_{gas} + \gamma_{phot} + \gamma_{damp}$$

- We model the feedback cooling in simulation as an additional damping term
- At moderate pressure without feedback cooling: 430, 744, 313 K along x, y, z
- At low pressure with feedback cooling: 182, 196, 189 µ K along x, y, z

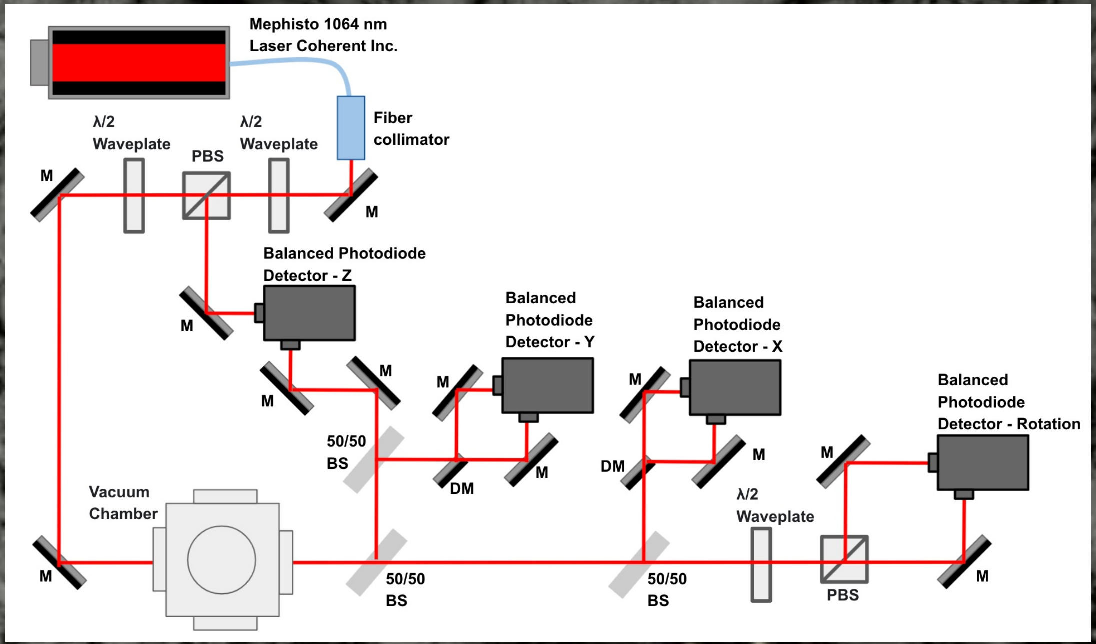


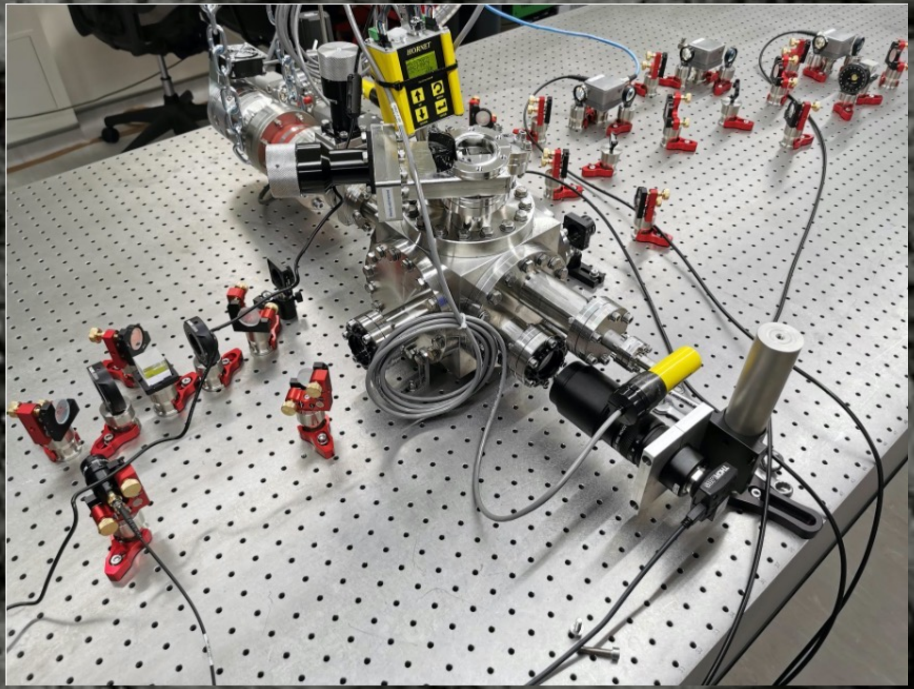




Experimental setup

- 1064 nm laser used for both trapping and detection
- Laser brought to a focus within a vacuum chamber
- z-position of the particle determined by the interference between the forward and scattered light using a balanced photodiode
- x- and y-positions of the particle determined in a similar fashion, but instead using a D-mirror to split the beam along these axes
- Additional rotation detector; motion inferred from this allows us to determine that we have trapped a single particle





Directional dark nugget searches

For now, assume coupling only to neutrons

Dark nugget scattering

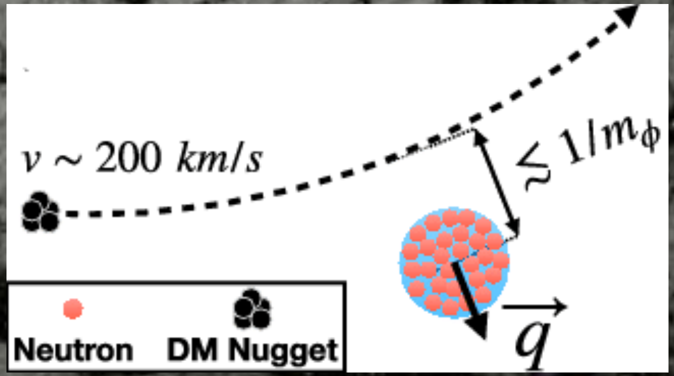
- Following arXiv:2007.12067, we consider scattering of bound states of self-interacting dark matter, so-called DM ‘nuggets’
- Such an interaction could take place via a Yukawa potential, modified by the spatial form factor of the target, with m_ϕ being the mass of a light mediator particle (< eV)
- Such an interaction gives coherence over the nugget, and partial to full coherence over neutrons in the target
- Goal: searches in (α_n, M_χ) parameter space

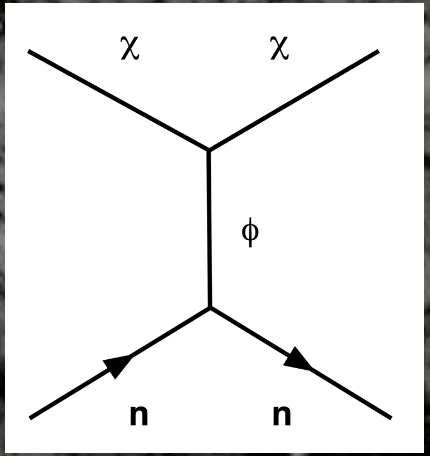
$$V(\vec{r}) = \frac{3 g_\chi N_\chi g_n N_n}{16\pi^2 R^3} \int d^3r' \, \frac{\Theta(R - |\vec{r'}|)}{|\vec{r} - \vec{r'}|} e^{-m_\phi |\vec{r} - \vec{r'}|}$$

$$\alpha_n = \frac{g_\chi N_\chi g_n}{4\pi}$$

- Such a potential could arise from a Lagrangian of this form. Stellar cooling and 5th force constraints bound $g_n \sim 10^{-12}$, but g_χ is just bounded by unitarity (arXiv:1709.07882)
- Many other astrophysical and cosmological bounds can be evaded if this candidate is a fraction of the total DM relic abundance

$$\mathcal{L} = -g_\chi \phi \bar{\chi} \chi - g_n \phi \bar{n} n$$



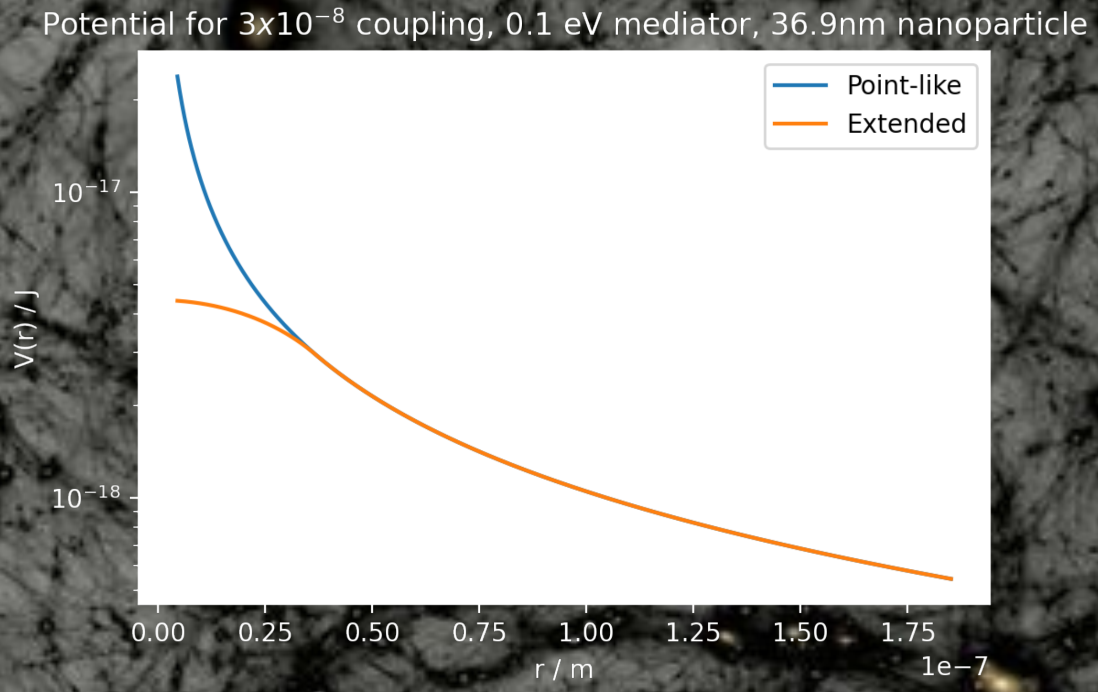


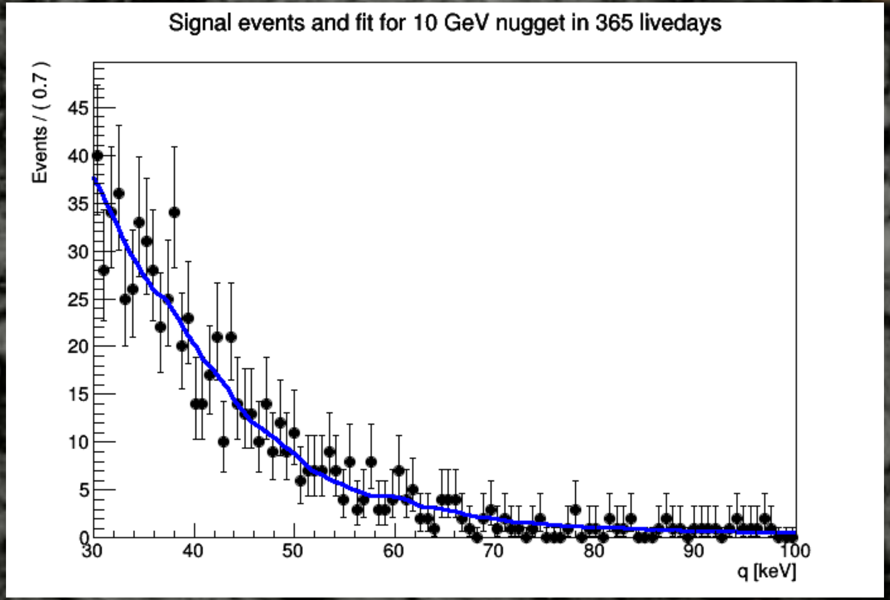
Signal model

- Following arXiv:2007.12067 we model the scattering from the Yukawa potential as classical scattering between the localised dark nugget and detector, accounting for the neutron distribution form factor for scattering close to and within the nanoparticle

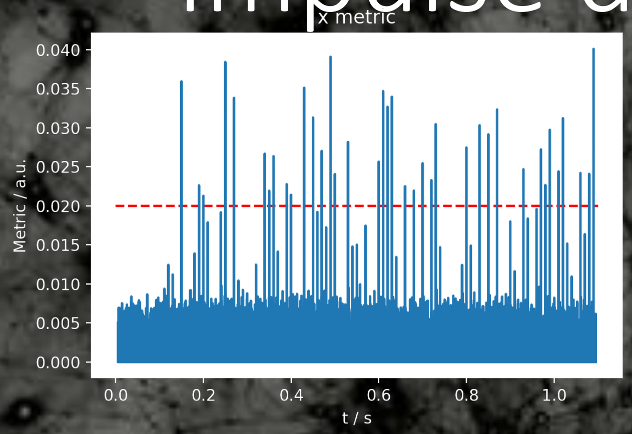
$$\frac{d\sigma}{d|\vec{q}|} = \frac{4\pi sin(\frac{\theta}{2})}{|\vec{p}|} b(\theta) \left| \frac{db}{dcos(\theta)} \right|$$

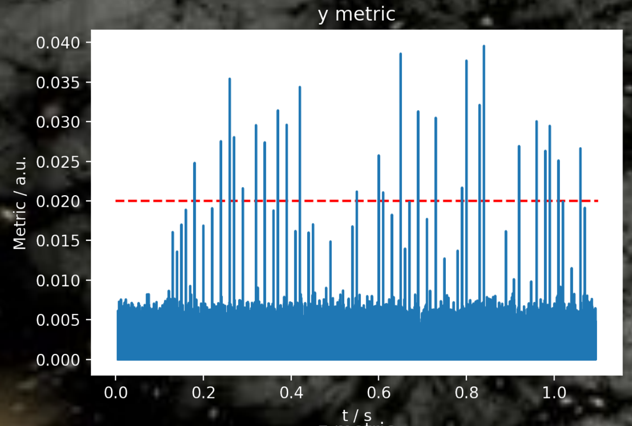
- Shown the resulting potential with form factor suppression
- Also shown generated events and expected event rate curve for α_n = 3x10-8, M_χ = 10 GeV, in 365 livedays

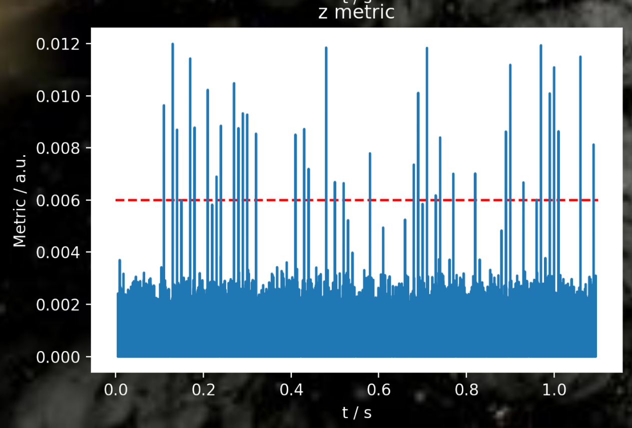


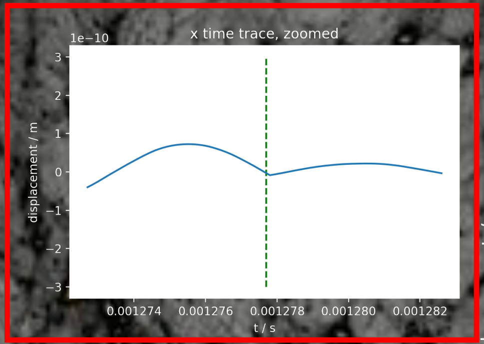


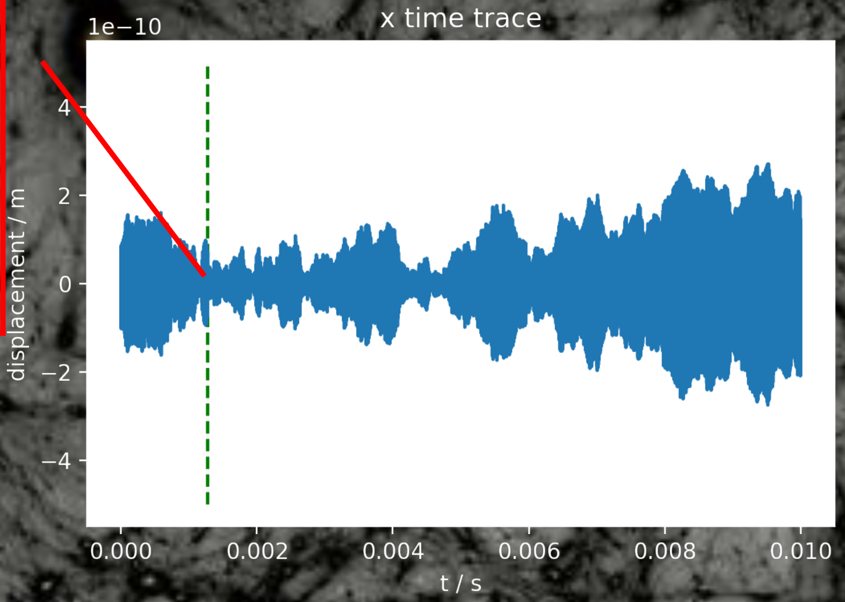
Impulse detection



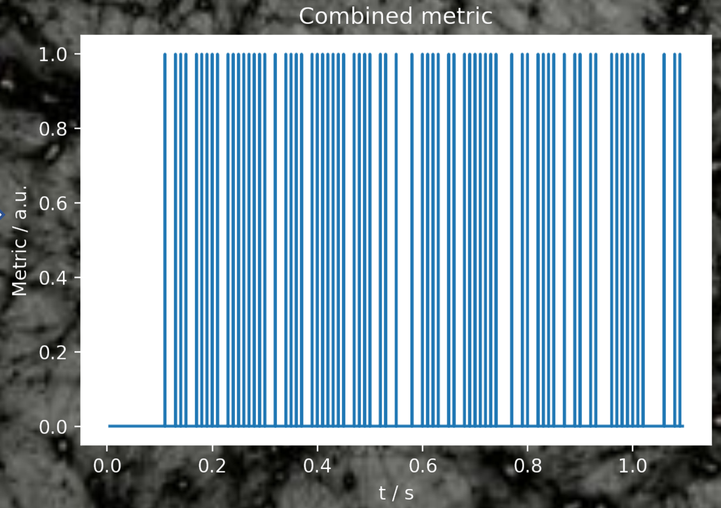








50 keV kick

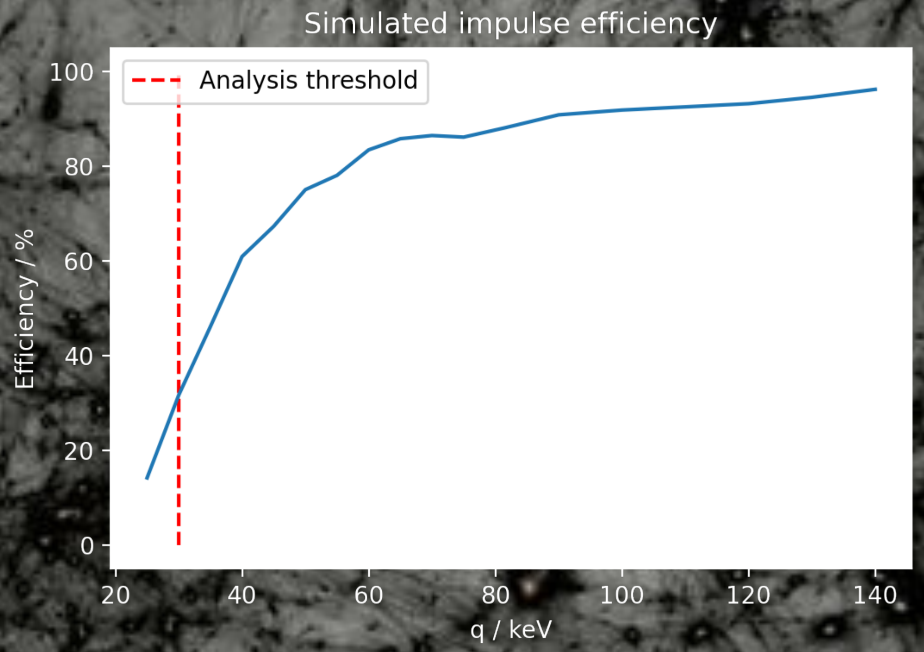


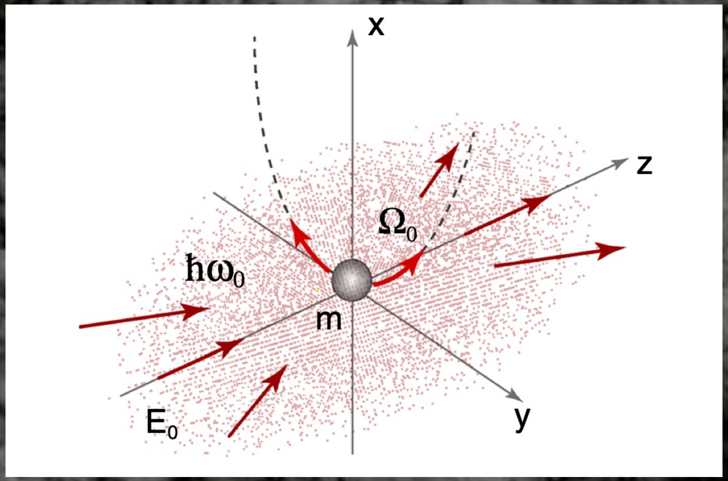
~70% efficiency, no leakage

- Developed a novel method for impulse detection in stochastic noise
- Attempts to find ‘kinks’ in the signal
- Gives high efficiency with low background leakage

Impulse detection efficiency

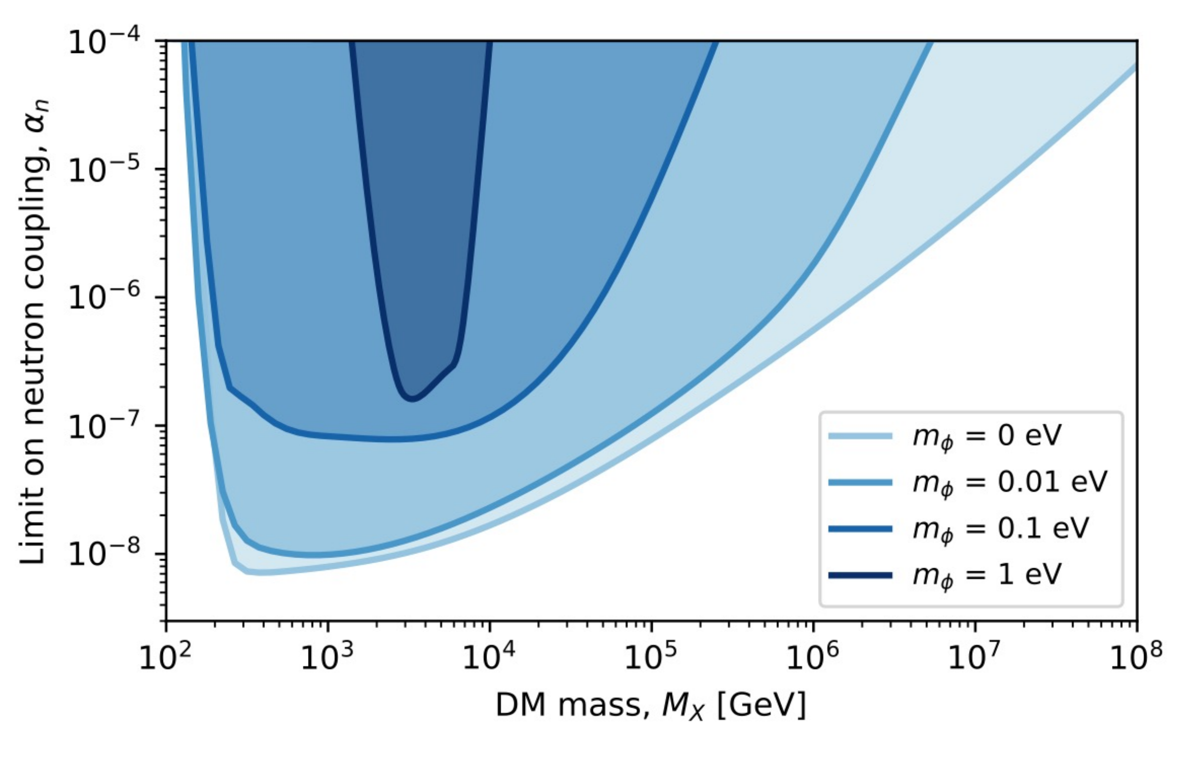
- Using the methodology outlined for impulse detection, we simulate impulses of various sizes and count how many we detect to estimate efficiency
- We set an impulse detection threshold such that there is no background leakage; directionality would greatly aid in discrimination, allowing a potentially lower threshold in future
- Analysis threshold chosen at ~2x the SQL
- We plan to use more sophisticated techniques such as Kalman filtering to further improve impulse detection and discrimination





Existing work

- David Moore's group at Yale did a search of this kind using 5 µm SiO_2 particles in a gravito-optical trap
- Limits set for a variety of mediator masses with ~ 2 weeks of livetime
- Cooled in just one direction with one readout channel, so directional analysis not possible
- Saw an excess of events (3) above Gaussian background, but no way to determine their origin



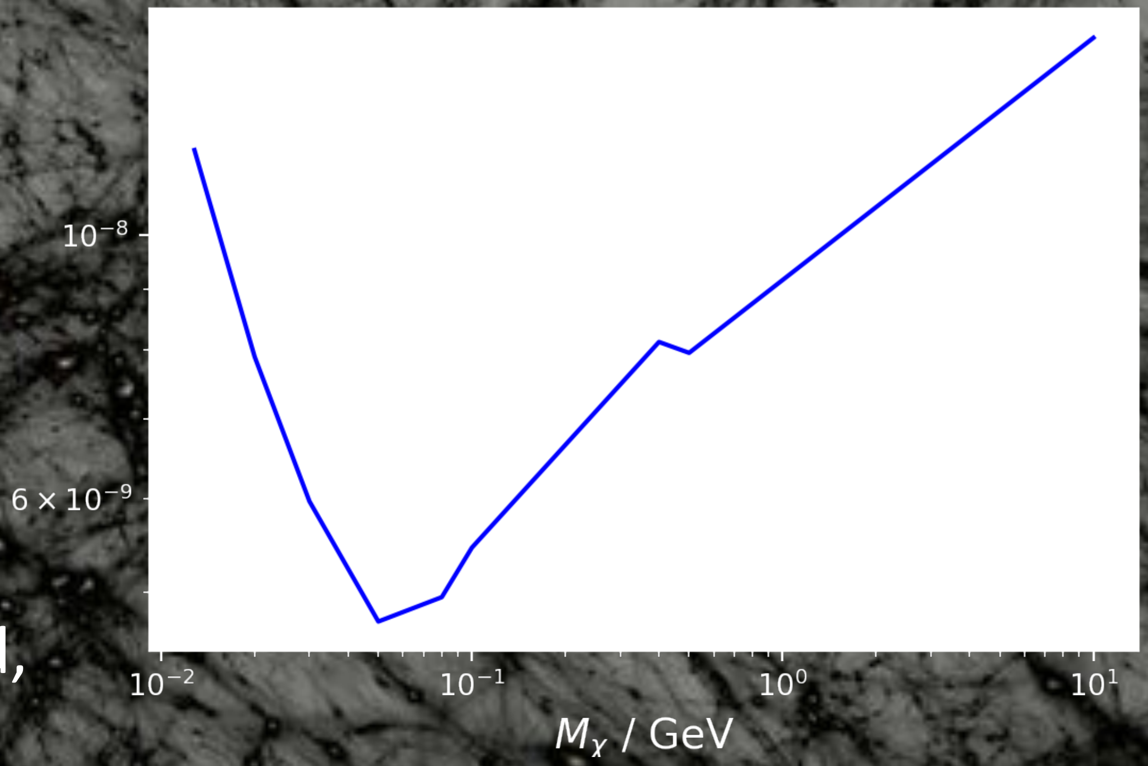
Projected sensitivity

- We project the sensitivity of our experiment under the conditions shown for a 0.1 eV mediator mass, assuming full relic fraction
- Efficiency curve from slide 16 used; analysis range 30-200 keV
- As the impulse-detection threshold has been chosen such that there is no leakage from the dominant backgrounds, used background-free Poisson 90% C.L. upper limit to define sensitivity
- Probing parameter space currently unexplored, experimentally
- Full PLR framework developed for real search

Simulation parameters:

36.9 nm radius SiO_2 particle
300 K gas temperature (600 K internal particle temperature)
1×10^{-8} mbar pressure
121, 144, 32 kHz trap frequencies (x, y, z)
1064 nm laser, 300 mW power at focus, 0.77 NA lens
Feedback cooling to ~200 μK

Background-free 90% projected sensitivty

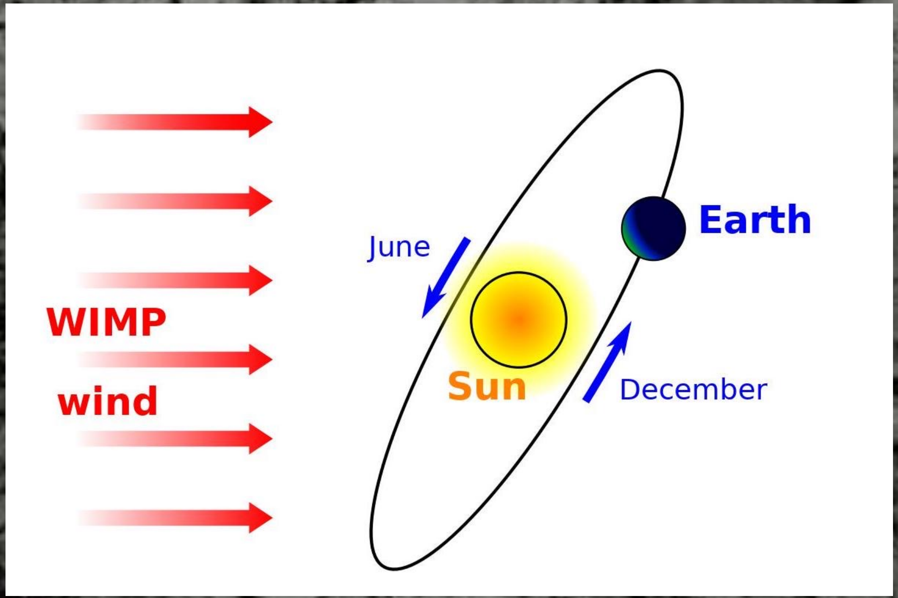


Fully directional searches

- If the experiment were run over long periods, could search for an annual modulation signal (as many other experiments do). If we are lucky, may see a signal with diurnal modulation
- Our detection scheme enables us to resolve the 3 cartesian components of impulses given to the nanoparticle
- Allows for full 3D momentum transfer reconstruction and a directional dark matter search
- Could provide a ‘smoking gun’ for discovery if a signal is seen
- Directionality can also be incorporated as a background discrimination technique, e.g. laser shot noise, isotropic impulse rejection

$$\frac{dR}{dq} = \frac{f_\chi \rho_0}{M_\chi} \int v(\vec{v} + \vec{v_e}) \frac{d\sigma}{dq} d^3 v$$

Time-dependence



Directionality

$$\frac{dR}{dEd\Omega_q} = \frac{f_\chi \rho_0}{M_\chi} \int v(\vec{v} + \vec{v_e}) \frac{d\sigma}{dEd\Omega_q} d^3 v$$

Outlook

Simulation and statistics

- Some further refinement of simulation of backgrounds and nanoparticle response
- Adding directionality into PLR framework

Experiment

- Mostly assembled and complete
- Some optical alignment still remaining after recent changes
- Demonstrate cooling to the required CoM temperatures

Calibration

- Map oscillator response to momentum transfer, to allow for impulse reconstruction
- Use a series of known kicks to experimentally determine efficiency curve and leakage

Backgrounds and analysis

- Initial run to determine if there are any unaccounted for sources of background
- Take O(weeks) of experimental data for analysis

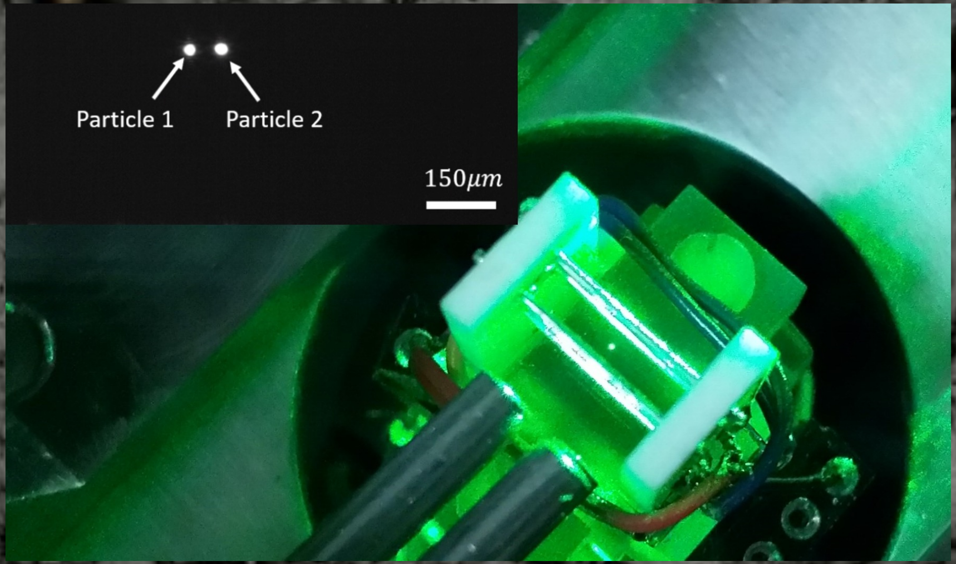
Future searches

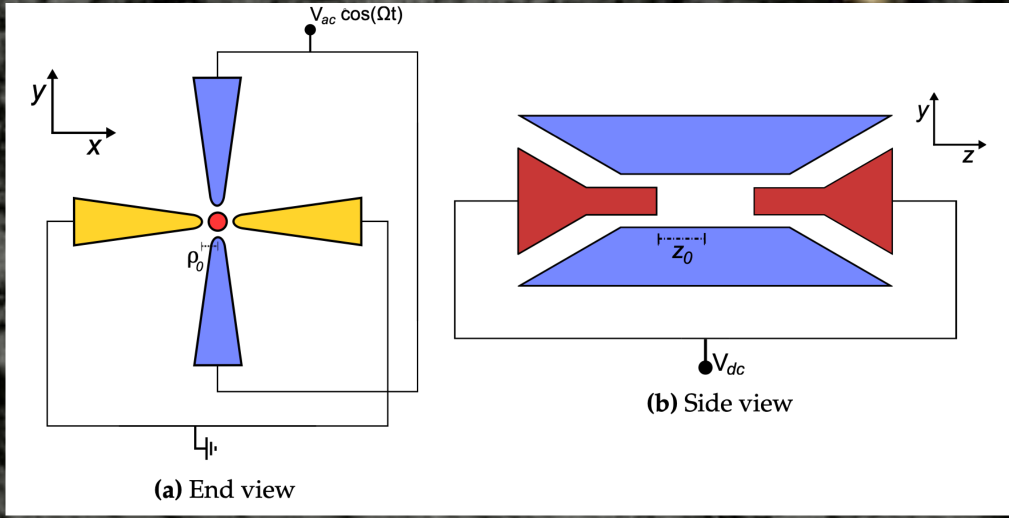
Linear Paul traps

- Trapping of (potentially much heavier) charged particles in a quadrupole potential

$$V = \frac{\alpha_z^{dc} V_{dc}}{z_0^2}\left[z^2 - \frac{x^2+y^2}{2}\right] + \left[\frac{\alpha_r^{ac} V_{ac}}{\rho_0^2}(x^2 - y^2) + \frac{\alpha_z^{ac} V_{ac}}{z0^2} z^2\right] cos(\Omega t)$$

- RF blade electrodes supply an AC voltage; endcap electrodes supply a DC voltage
- Much lower power laser (used only for detection) drastically reduces laser shot noise
- At low pressure, dominant sources of noise are blackbody radiation and electronic shot noise
- Here, work in the gas-dominated regime to get conservative threshold

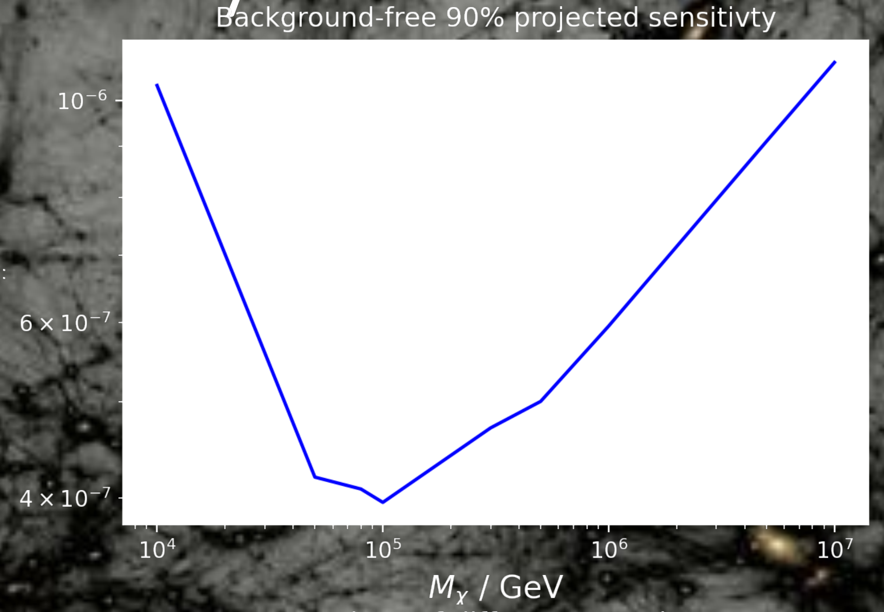


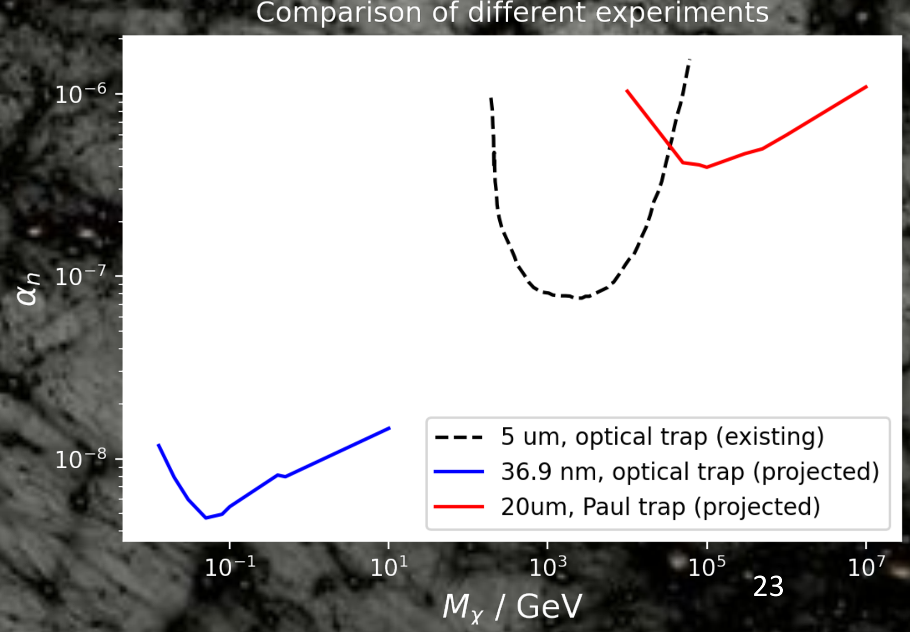


(a) End view
(b) Side view

Higher mass dark nugget sensitivity

- Background-free Poisson 90% C.L. upper limit for 0.1 eV mediator mass for a 20 μm SiO_2 particle in a Paul trap of 100 Hz
- Cooling to ~ 10 mK
- Took 20 – 100 GeV momentum transfer analysis range; lower threshold where we cross 60% efficiency, take this across the range (being conservative)
- Potential to improve on this much further with better noise characterization and analysis
- Could further boost sensitivity by trapping arrays of particles
- Also shown existing DD constraints with projected limits, showing complementarity





Ultralight (wavelike) DM sensitivity

- Paul traps offer the potential to trap much larger, O(50 μm) gold particles, giving a much higher target mass
- An ultralight vector dark matter field could couple to the B-L charge of this

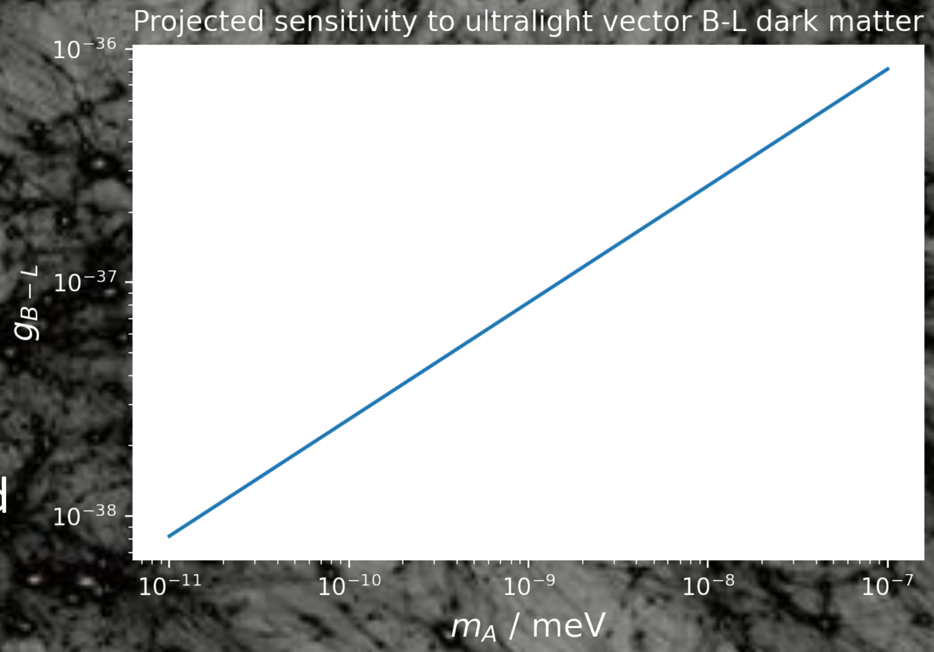
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_A^2 A_\mu A^\mu - g_{B-L}Y_{B-L}\overline{\psi}\psi$$

- This would give, within the coherence time ~ 10^6 / m_A, a coherent sinusoidal drive of frequency m_A and force amplitude

$$g_{B-L}N_n\sqrt{2\rho}$$

- Would want to trap array of different sized particles to give broadband response
- We can estimate the 1σ sensitivity of this oscillator to this force by comparing it to the force noise PSD across relevant frequencies, for a given integration time (estimate we can reach 10^{-49} N^2 / Hz)

$$g_{B-L}N_n\sqrt{2\rho} = \sqrt{\frac{S_N(m_A)}{T_{int}}}$$



Conclusions

- Optical tweezers have already demonstrated sensitivity to dark nugget scattering via a light scalar mediator
- Our experiment at UCL will trap lighter particles, enabling us to probe lower mass dark nuggets
- Further threshold reduction could greatly enhance sensitivity
- Single particles / arrays of particles of higher mass in Paul traps could provide sensitivity to higher mass dark nuggets, ultralight wavelike dark matter, and more…