Directional dark matter searches with levitated optomechanics

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In collaboration with
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People

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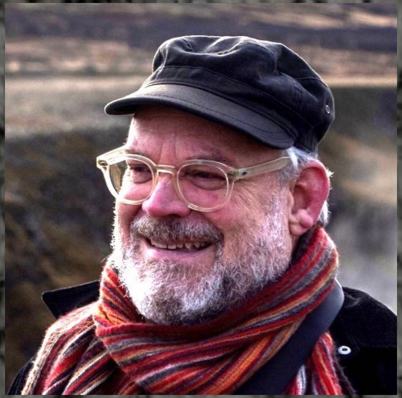

Peter Barker

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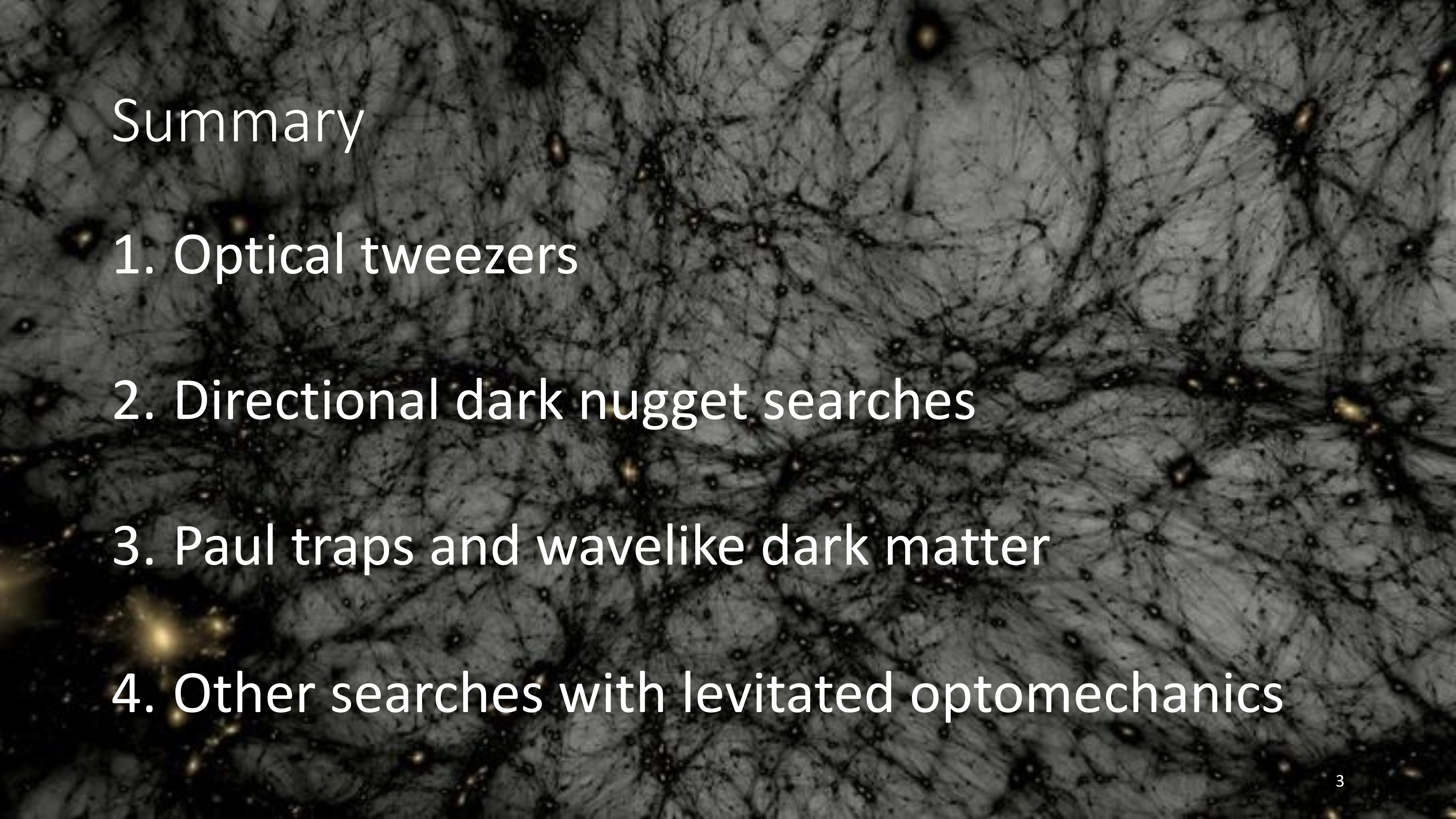


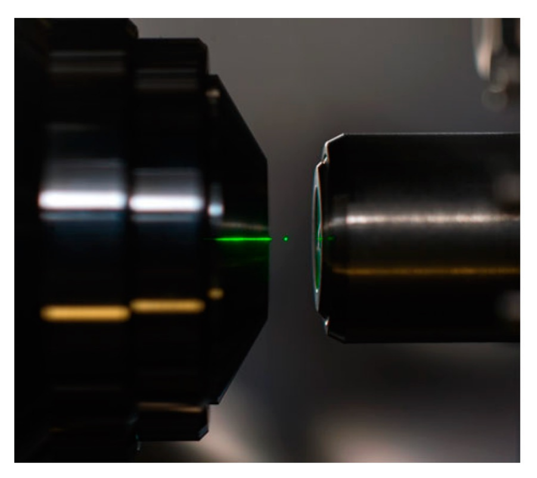
Summary

1. Optical tweezers
2. Directional dark nugget searches
3. Paul traps and wavelike dark matter
4. Other searches with levitated optomechanics

Optical tweezers

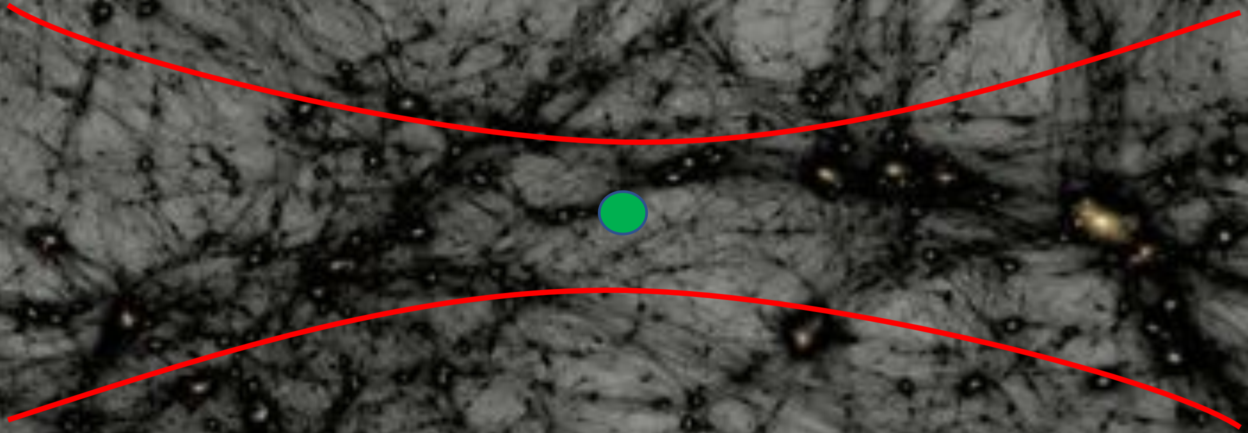
Laser beam gradient force

- 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



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

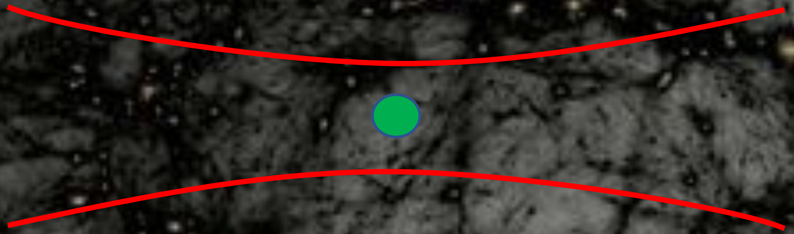
$$\vec{P} = (\alpha' + i\alpha'')\vec{E}$$



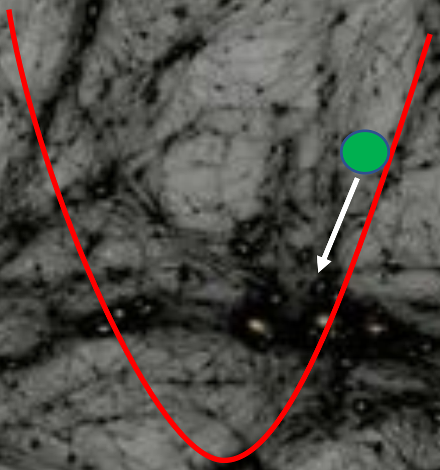
$$< \vec{F} > = \frac{\alpha'}{2}\vec{\nabla} < |\vec{E}|^2 >$$

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.

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

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

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

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.

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

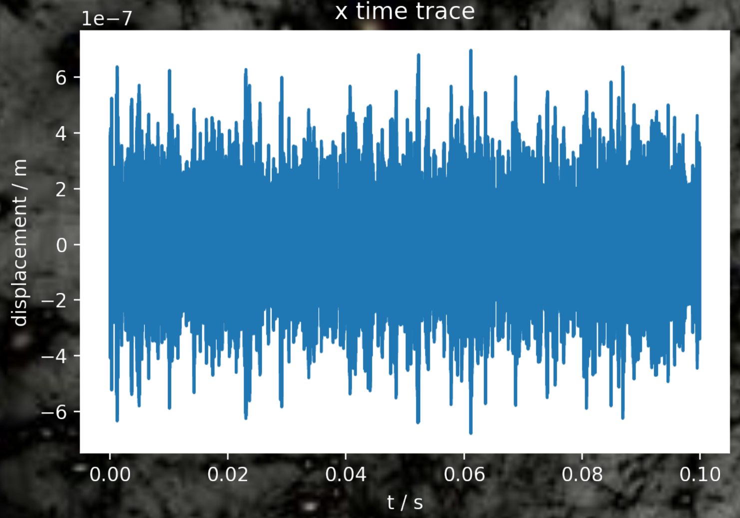
$$< \beta_{phot}(t) >= 0$$

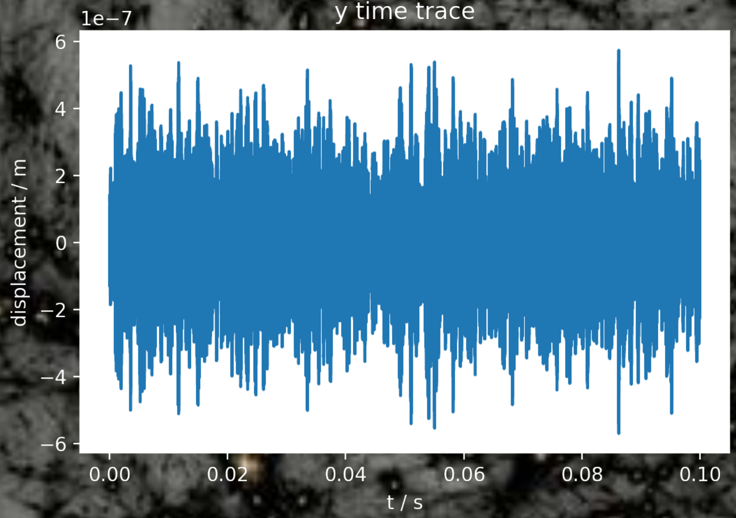
$$< \beta_{phot}(t)\beta_{phot}(t') >= \frac{2\hbar\omega}{5c^2}\delta(t-t')$$

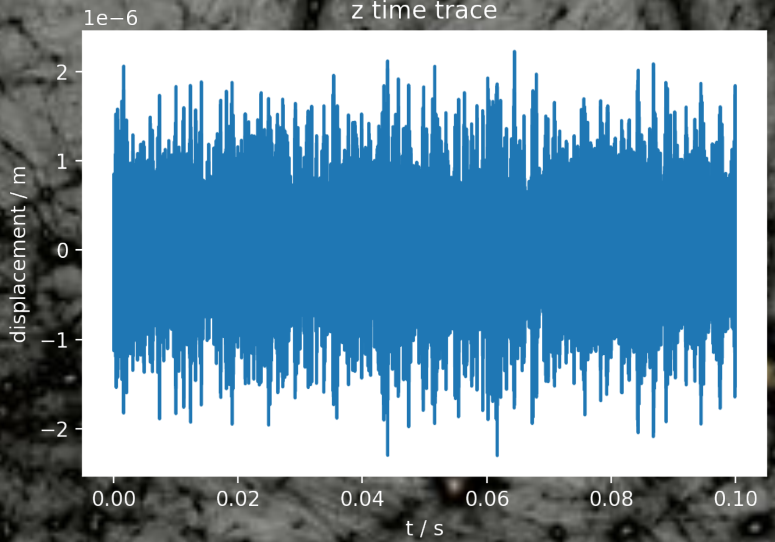
Simulation

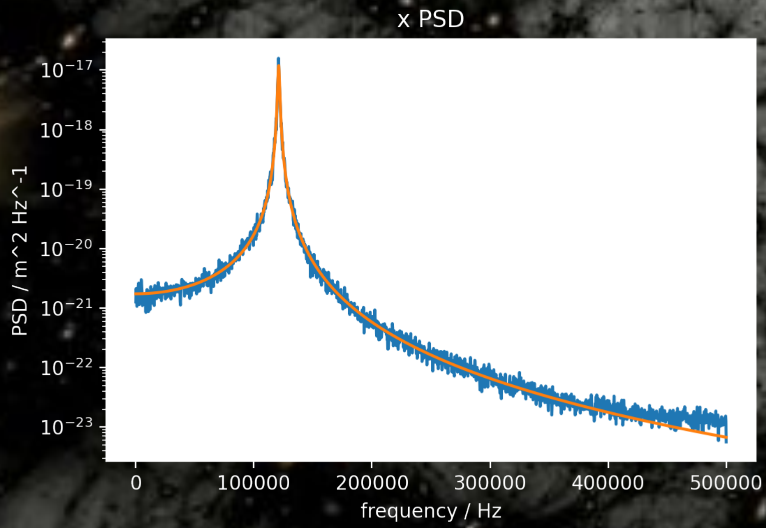
Simulation parameters:

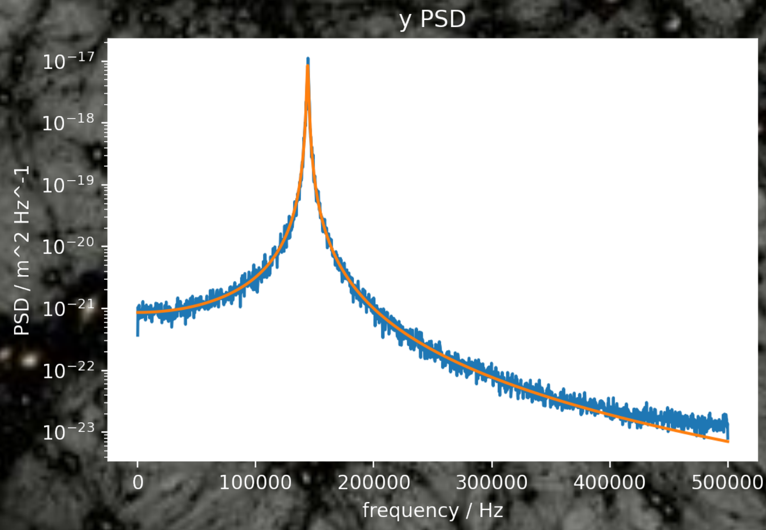
36.9 nm radius SiO_2 particle
300 K gas temperature (600 K internal particle temperature)
1 mbar pressure
121, 144, 32 kHz trap frequencies (x, y, z)
1064 nm laser, 300 mW power at focus, 0.77 NA lens

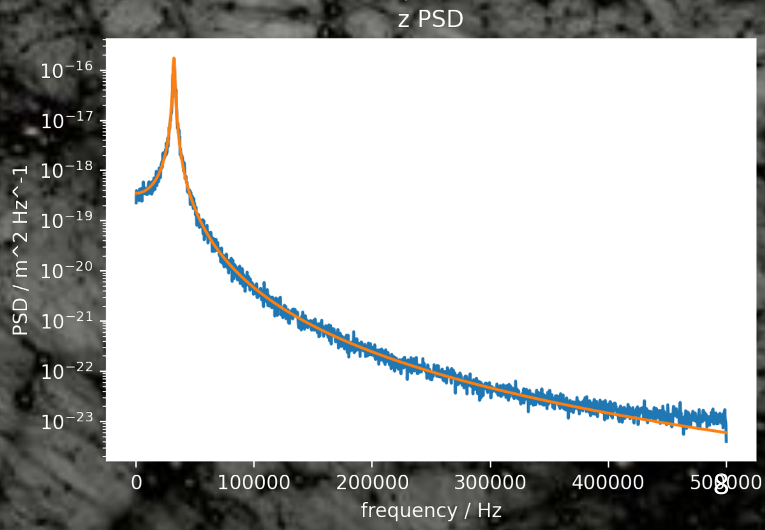

x time trace


y time trace


z time trace

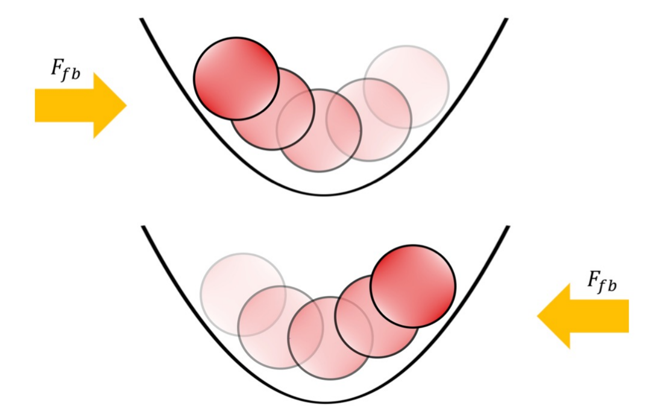

x PSD

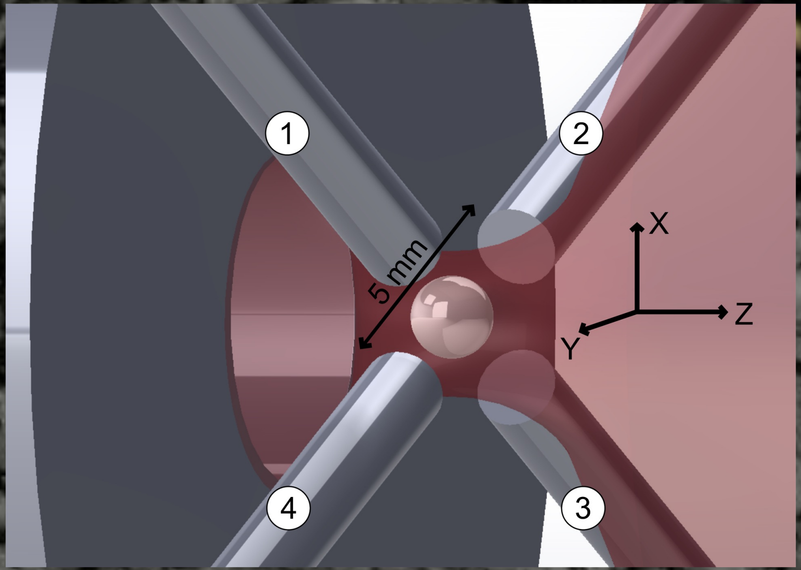

y PSD


z PSD

Feedback cooling

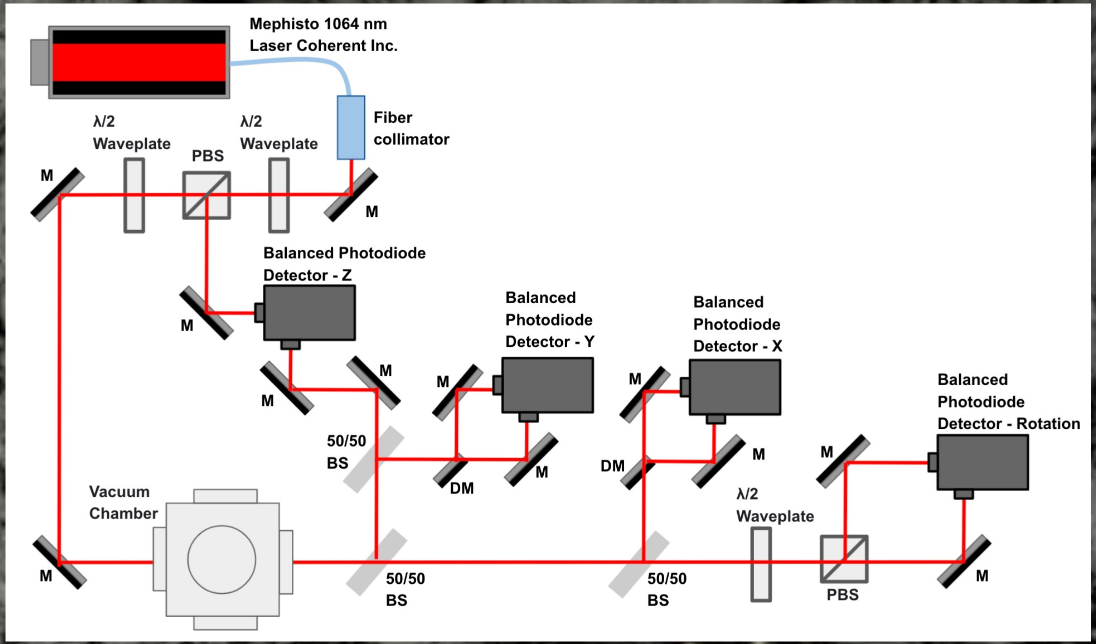
- Without feedback cooling, laser shot noise would cause the CoM motion of the particle to heat to very high temperatures as the gas is reduced in pressure, limiting impulse detection
- We use velocity damping: a force opposite in direction and proportional in magnitude to the particle's instantaneous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

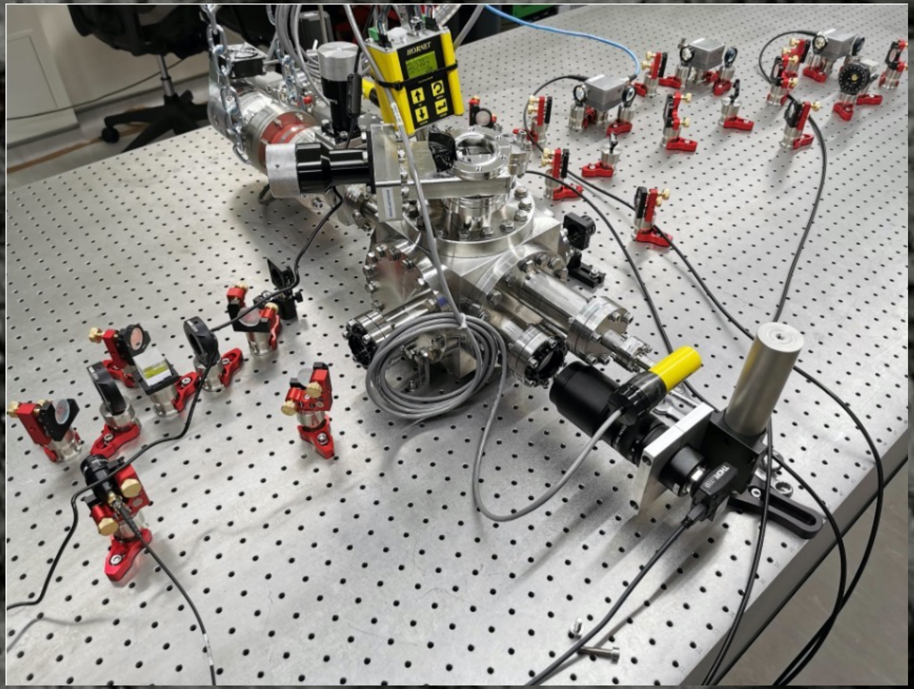




Experimental setup

- 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

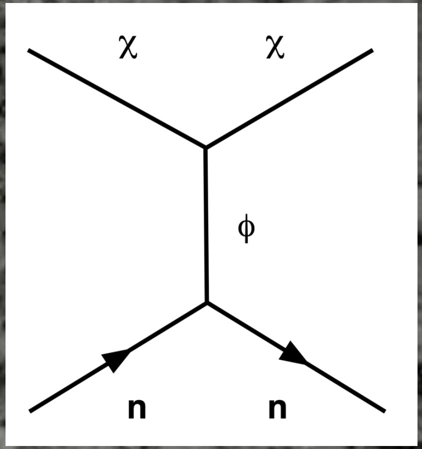


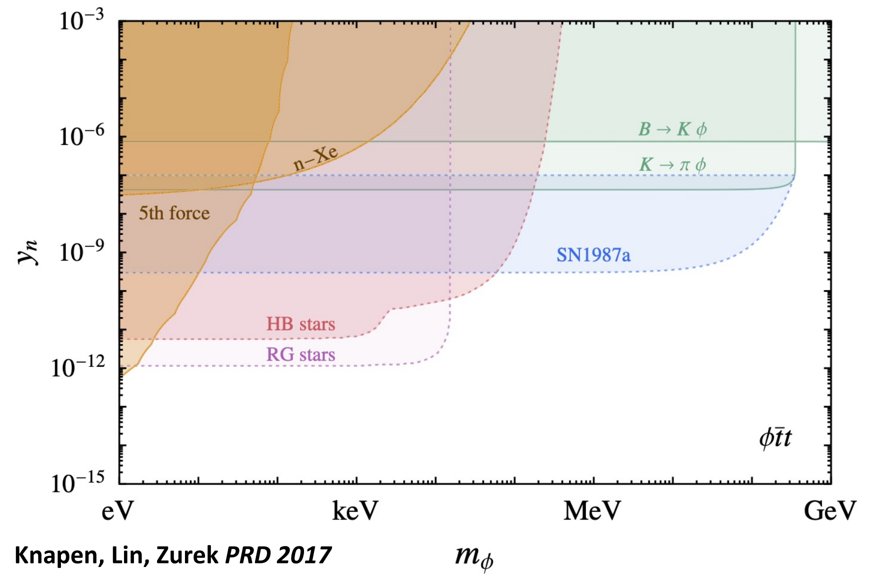


Directional dark nugget searches

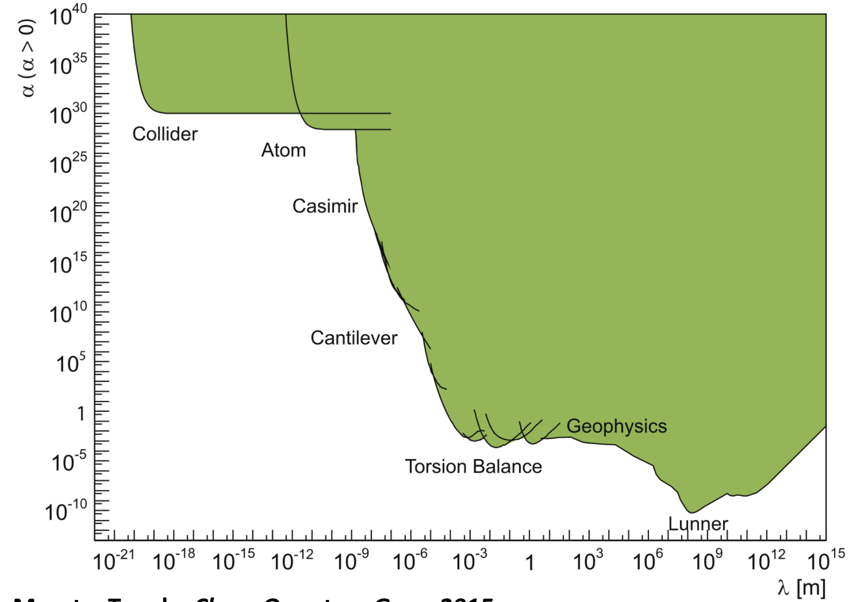
Bound states of dark matter

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





Knapen, Lin, Zurek *PRD 2017*



Murata, Tanaka *Class. Quantum Grav. 2015*

- Fermionic or bosonic dark matter particle coupling to scalar mediator
- Mediator coupling to dark matter can lead to formation of bound states: dark 'nuggets'
- Mediator coupling to nucleons can give rise to detectable scattering signal
- Most astrophysical bounds can be evaded if this candidate is a fraction of the total DM relic abundance
- g_χ bounded by unitarity, strong constraints on g_n from 5th force searches

For now, assume coupling only to neutrons

Dark nugget scattering

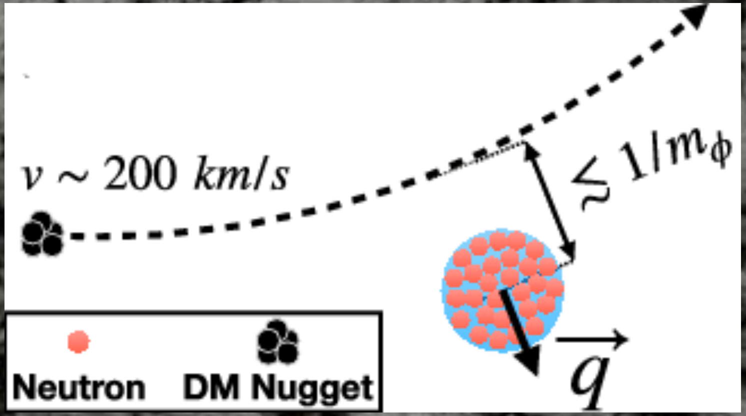
- At first order, scattering from a Yukawa potential
- Light mediators (m_ϕ < eV) lead to long-range, small-angle scattering

$$V(\vec{r}) = \frac{g_\chi N_\chi g_n N_n}{4\pi} \frac{1}{|\vec{r}|} e^{-m_\phi |\vec{r}|}$$

- For small couplings, less light mediators (m_ϕ ~ eV) require us to consider spatial neutron density form factor of the target
- Small nuggets → coherence over the nugget, partial to full coherence over neutrons in the target

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

- **Goal:** searches in (α_n, M_χ) parameter space, where M_χ is the nugget mass



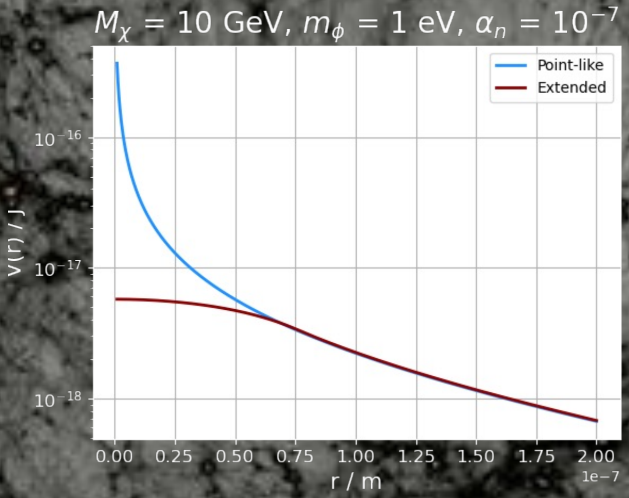
$$\alpha_n = \frac{g_\chi N_\chi g_n}{4\pi}$$

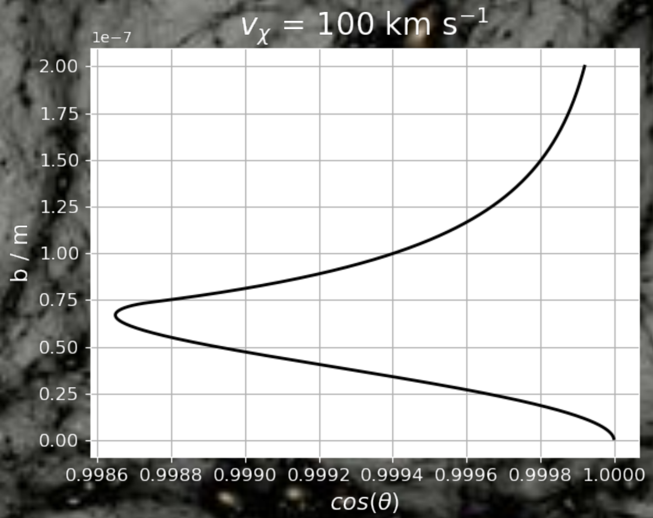
Signal model

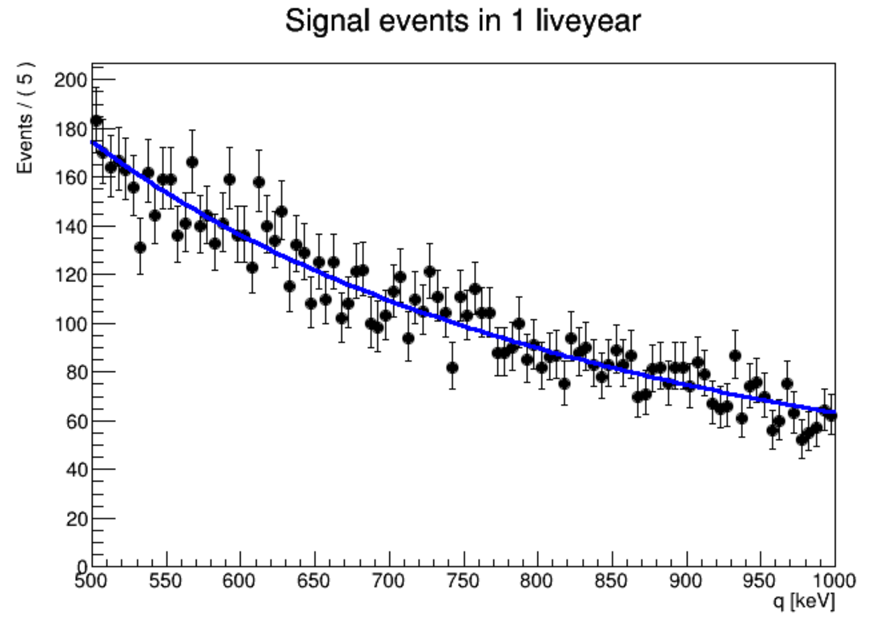
- Model the small-angle scattering as classical scattering of the localised dark nugget in the potential of the detector

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

- Need to account for the neutron distribution form factor, take care with impact parameter degeneracy
- Typical calculation convolving with velocity distribution leads to event rate

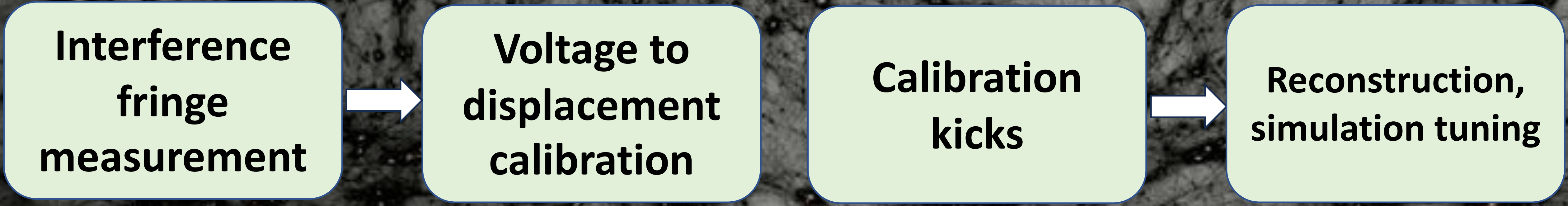






Search strategy

Calibration



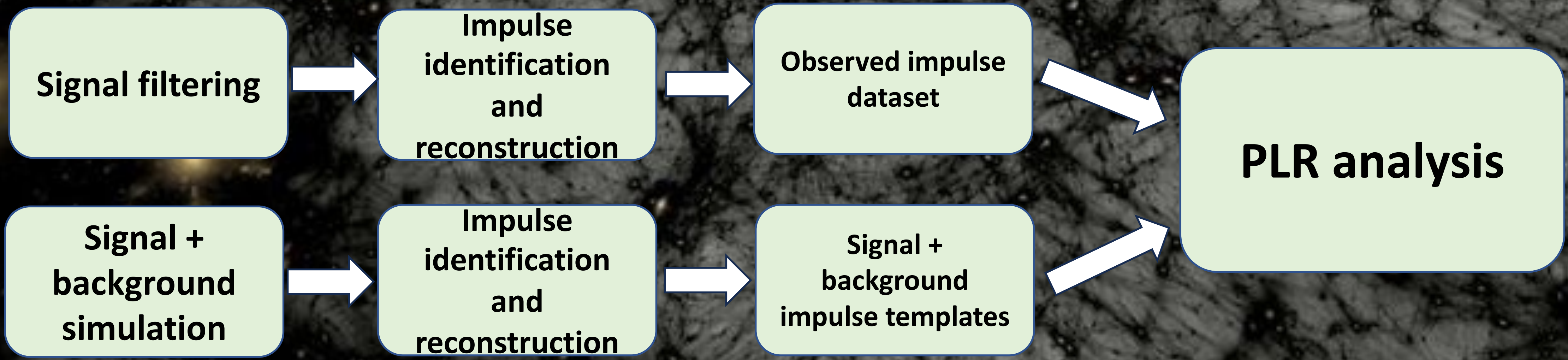
Interference fringe measurement

Voltage to displacement calibration

Calibration kicks

Reconstruction, simulation tuning

Analysis



Signal filtering

Impulse identification and reconstruction

Observed impulse dataset

Signal + background simulation

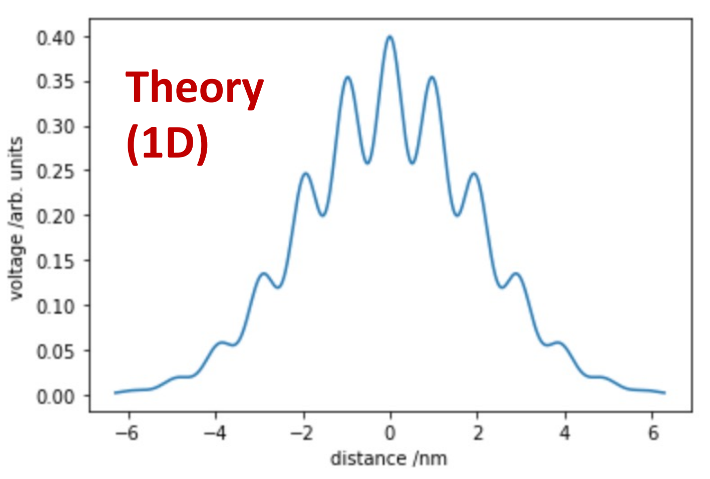
Impulse identification and reconstruction

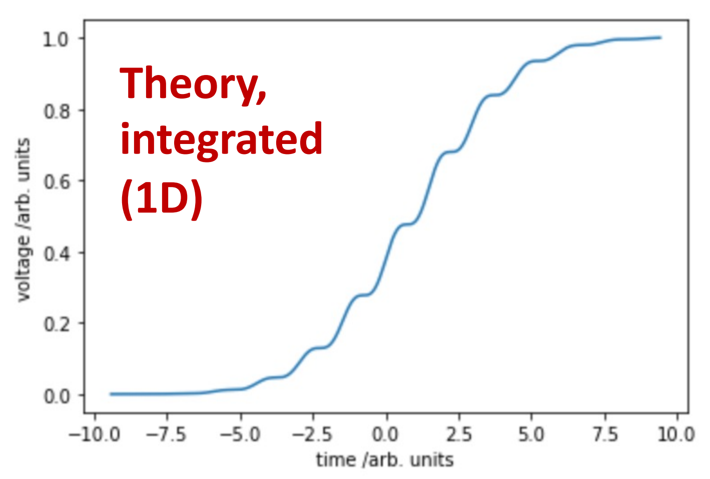
Signal + background impulse templates

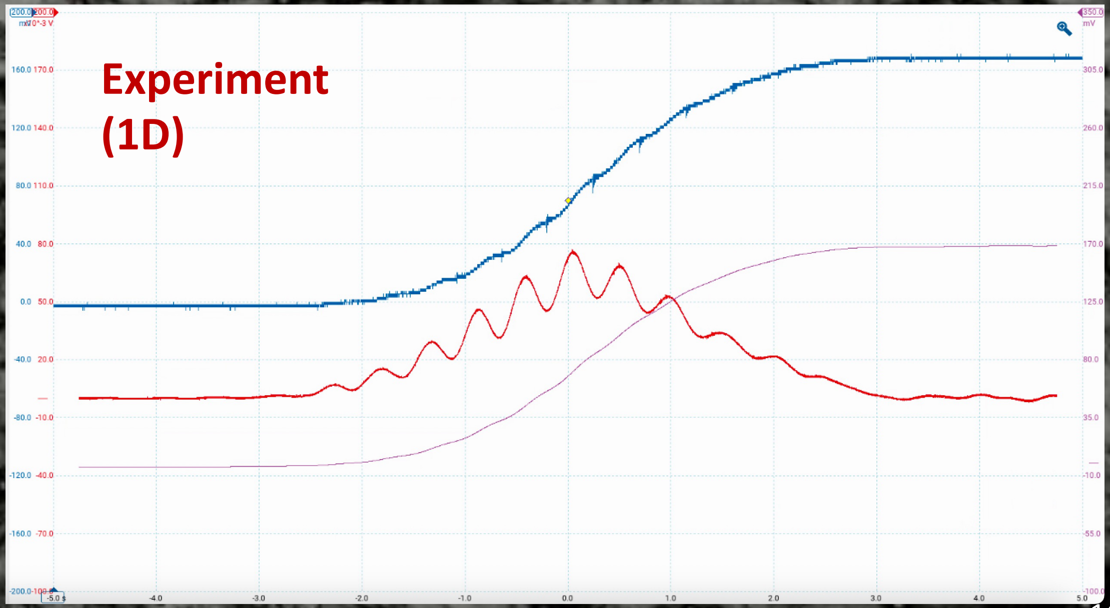
PLR analysis

Displacement calibration

- 640 nm laser used to form interference fringes at the particle
- Can use linear region to get a calibration of voltage to displacement
- Fit to PSD in real space allows for determination of particle mass, removing density uncertainty
- Particle charged with xenon UV flash lamp, can determine relation between electrode voltage and electric field at the particle once mass known

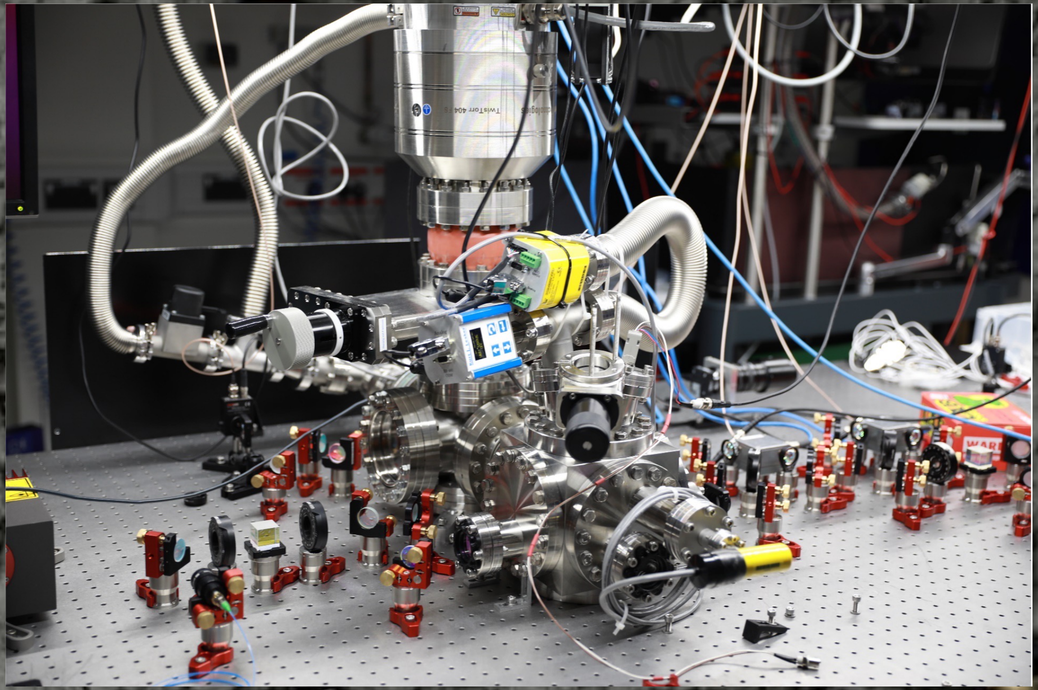


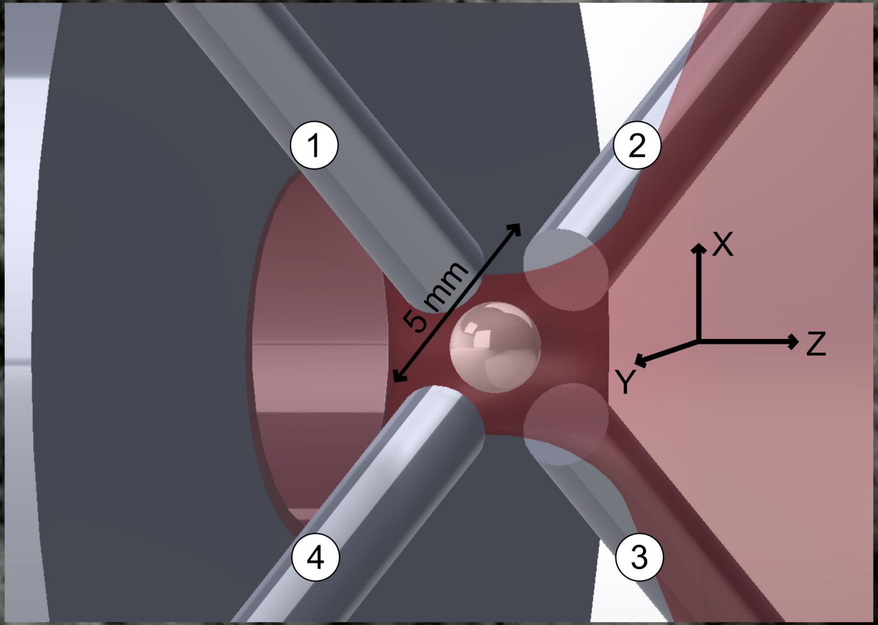




Kick calibration

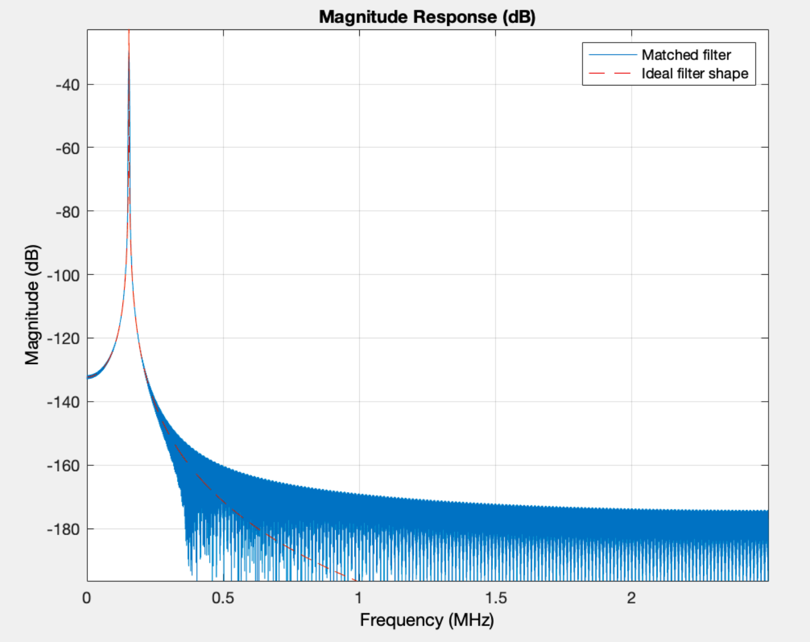
- Four electrode system allows for precise control of cooling and kick directions
- Applying kicks of known size allows for development of reconstruction algorithm and uncertainty evaluation
- Also allows for tuning of our simulation
- Kicks will be applied throughout to salt data

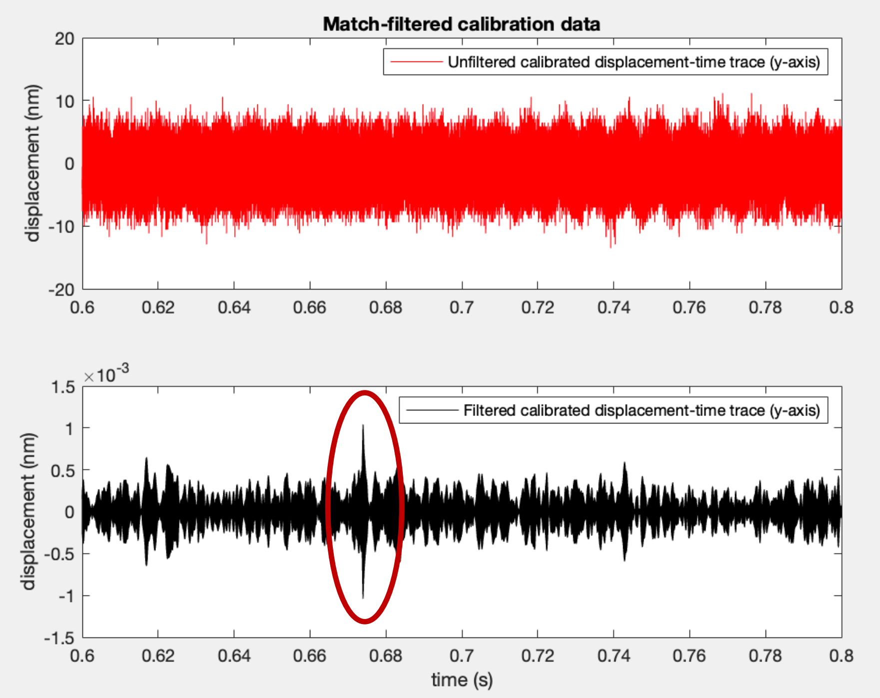




Signal filtering

- Uncorrelated detector noise can be removed via matched filtering
- Matched filtering takes in information from the oscillator response function and the thermal noise profile
- Filter constructed which should removed any additional noise uncorrelated with the motion



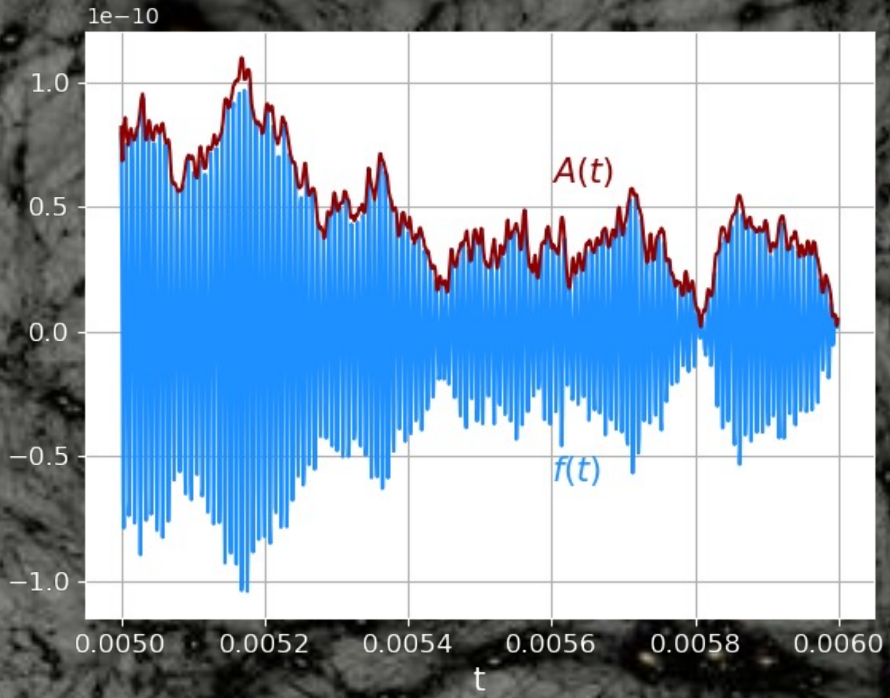


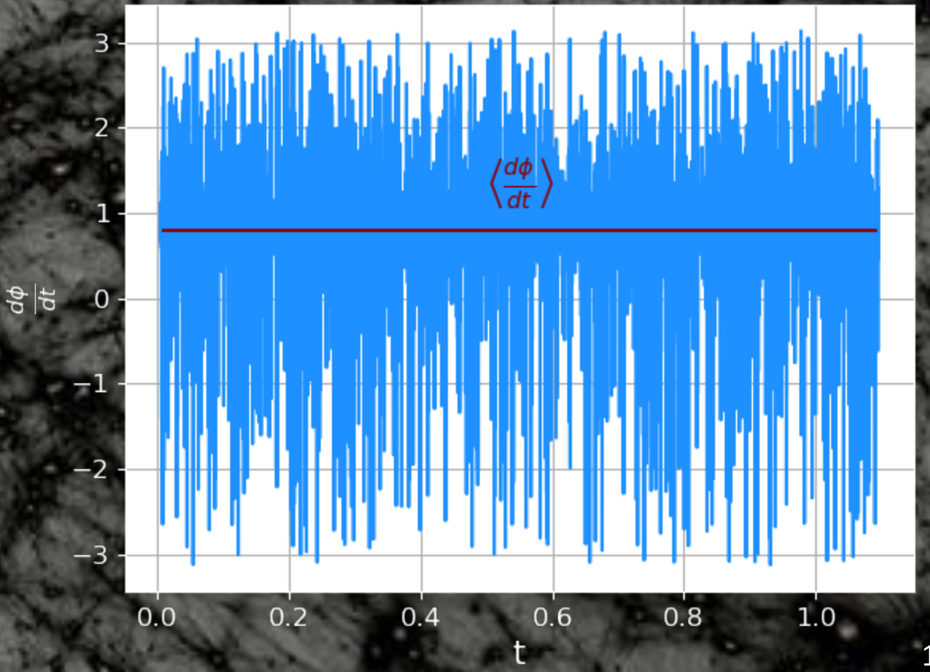
Impulse detection

signal

$$A(t)e^{i\phi(t)} = \boxed{f(t)} + ig(t)$$

$$g(t) = \frac{1}{\pi}\mathrm{P.V.}\int_{-\infty}^{\infty}\frac{f(\tau)}{t-\tau}d\tau$$



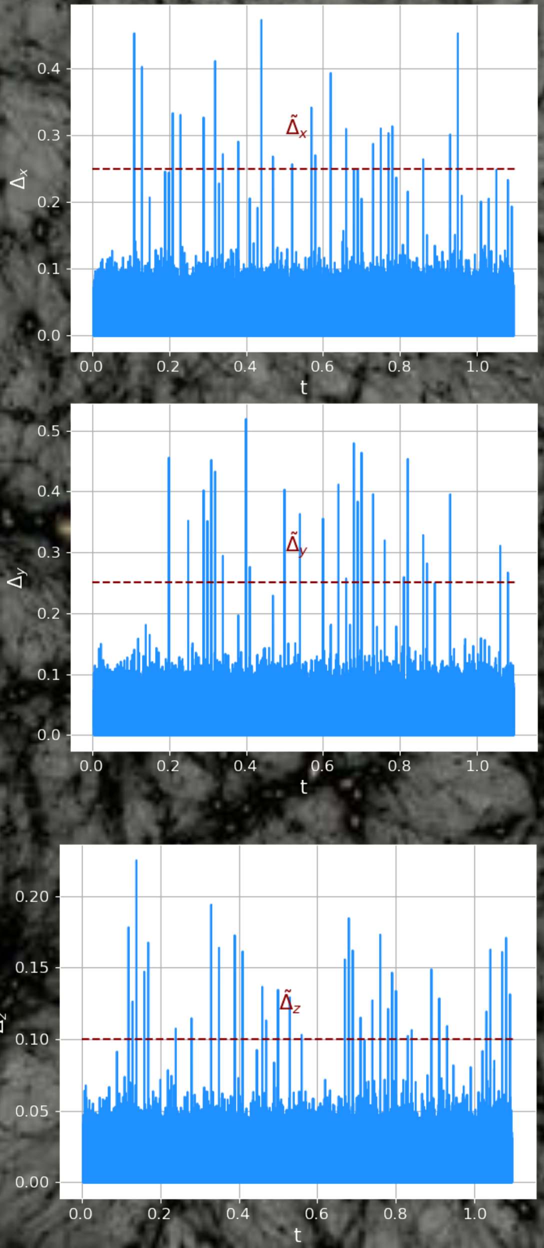


Impulse detection

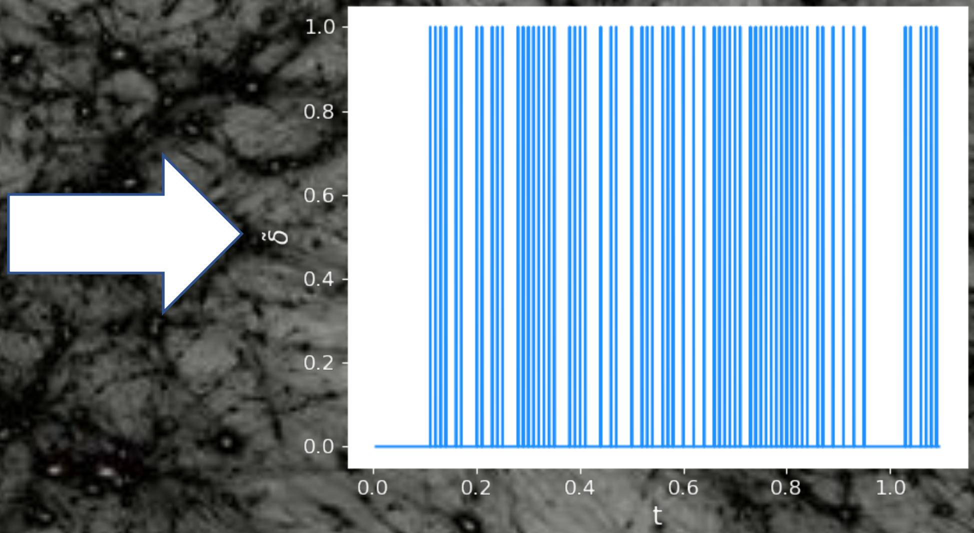
$$\Delta = \left| \frac{d\phi}{dt} - \left\langle \frac{d\phi}{dt} \right\rangle \right| \times \begin{cases} 0, & A(t) \leq \langle A(t) \rangle \\ 1, & A(t) > \langle A(t) \rangle \end{cases}$$

$$\delta_i = \begin{cases} 0, & \Delta_i \leq \tilde{\Delta}_i \\ 1, & \Delta_i > \tilde{\Delta}_i \end{cases}$$

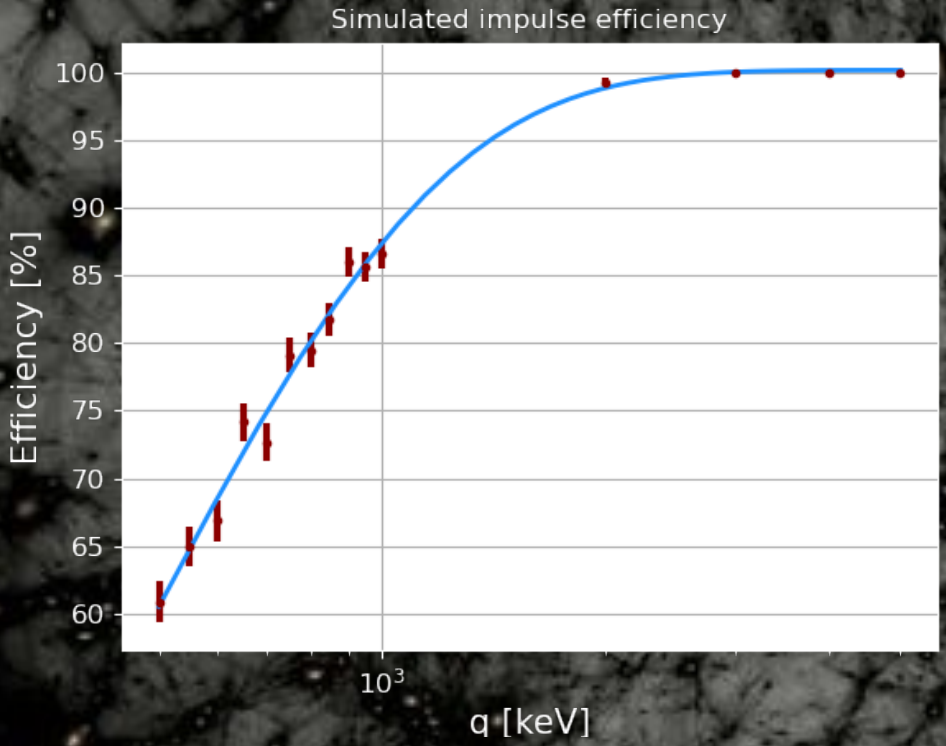
$$\tilde{\delta} = \delta_x + \delta_y + \delta_z$$

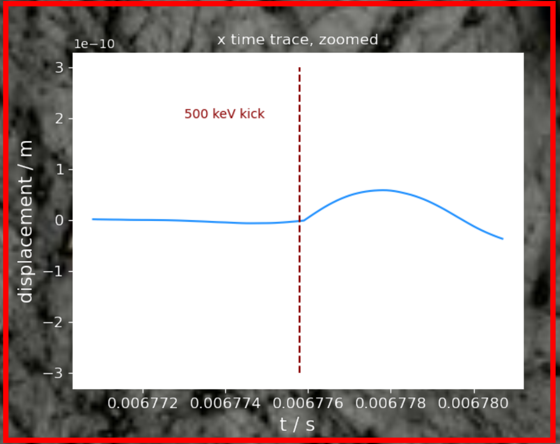


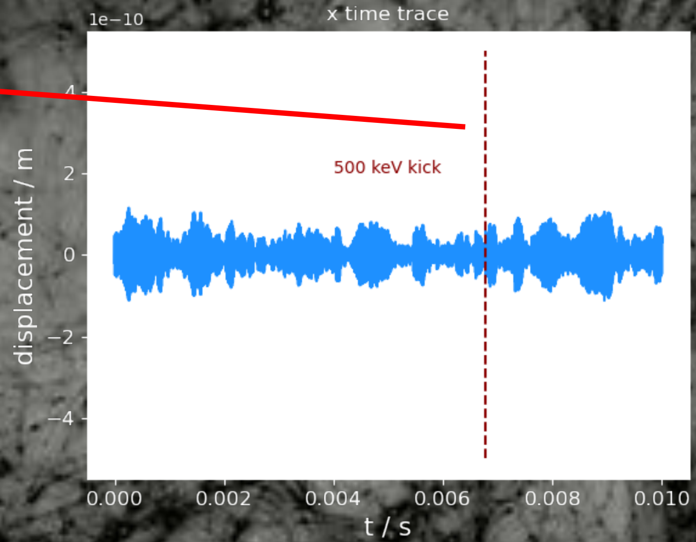
500 keV kick → ~60% signal efficiency, no background leakage



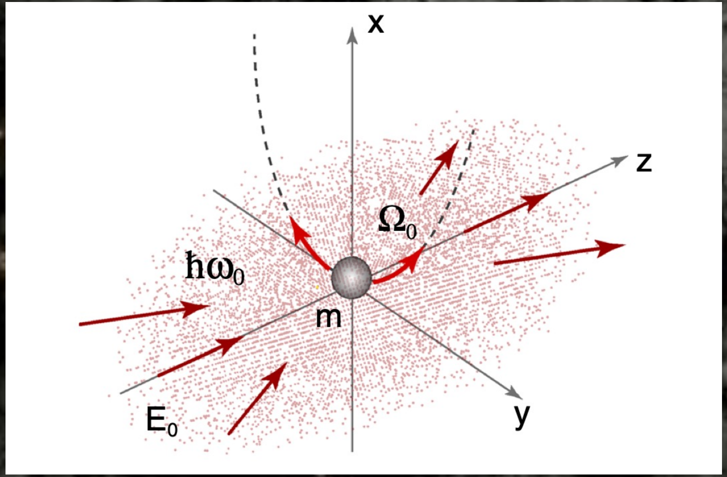
Impulse detection







- Impulse detection efficiency for a 75 nm radius particle at 1x10^{-8} mbar, cooled to ~250 μK along each axis
- Determined via simulating applied kicks, counting number passing selection threshold
- Selection threshold chosen such that no background leakage
- PLR analysis will enable discrimination against background , directionality will reduce dominant background (photon kicks)

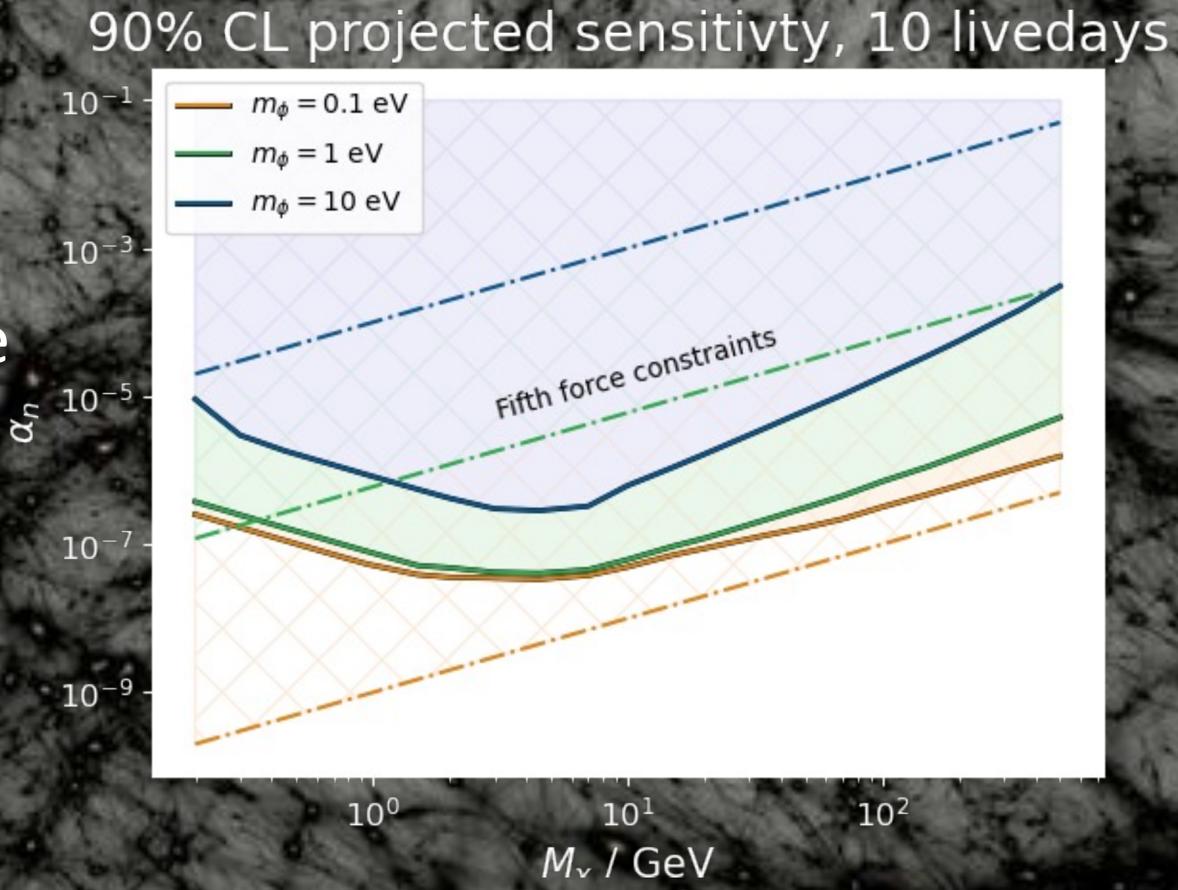


Projected sensitivity

Parameters:

75 nm radius SiO_2 particle
300 K gas temperature (600 K internal particle temperature)
1×10^{-8} mbar pressure
128, 155, 32 kHz trap frequencies (x, y, z)
1064 nm laser, 300 mW power at focus, 0.77 NA lens
Feedback cooling to ~250 μK

- We project the sensitivity of our experiment under the conditions, assuming full relic fraction, for a 10 liveday run
- 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
- For mediator masses above 1 eV, probing beneath fifth-force constraints



Fully directional searches

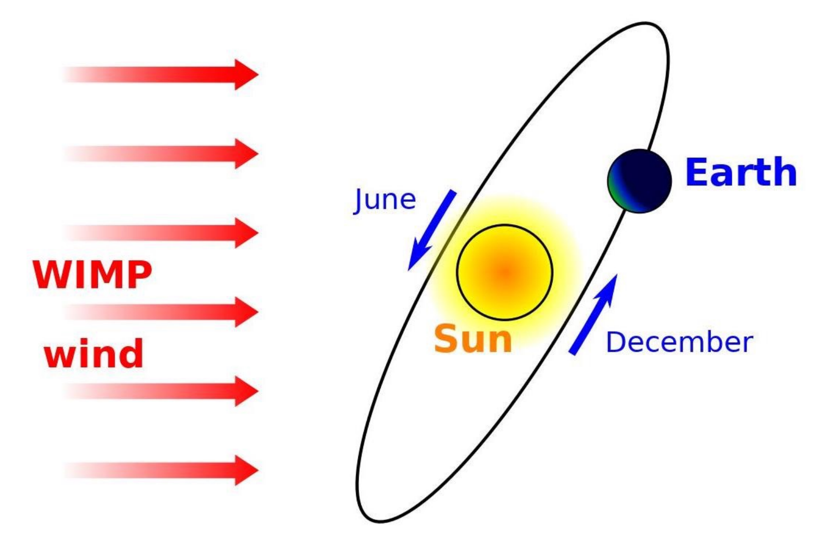
- If the experiment were run over long periods, could search for an annual modulation signal

- 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

- Directionality can also be incorporated as a background discrimination technique, e.g. laser shot noise, isotropic impulse rejection

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

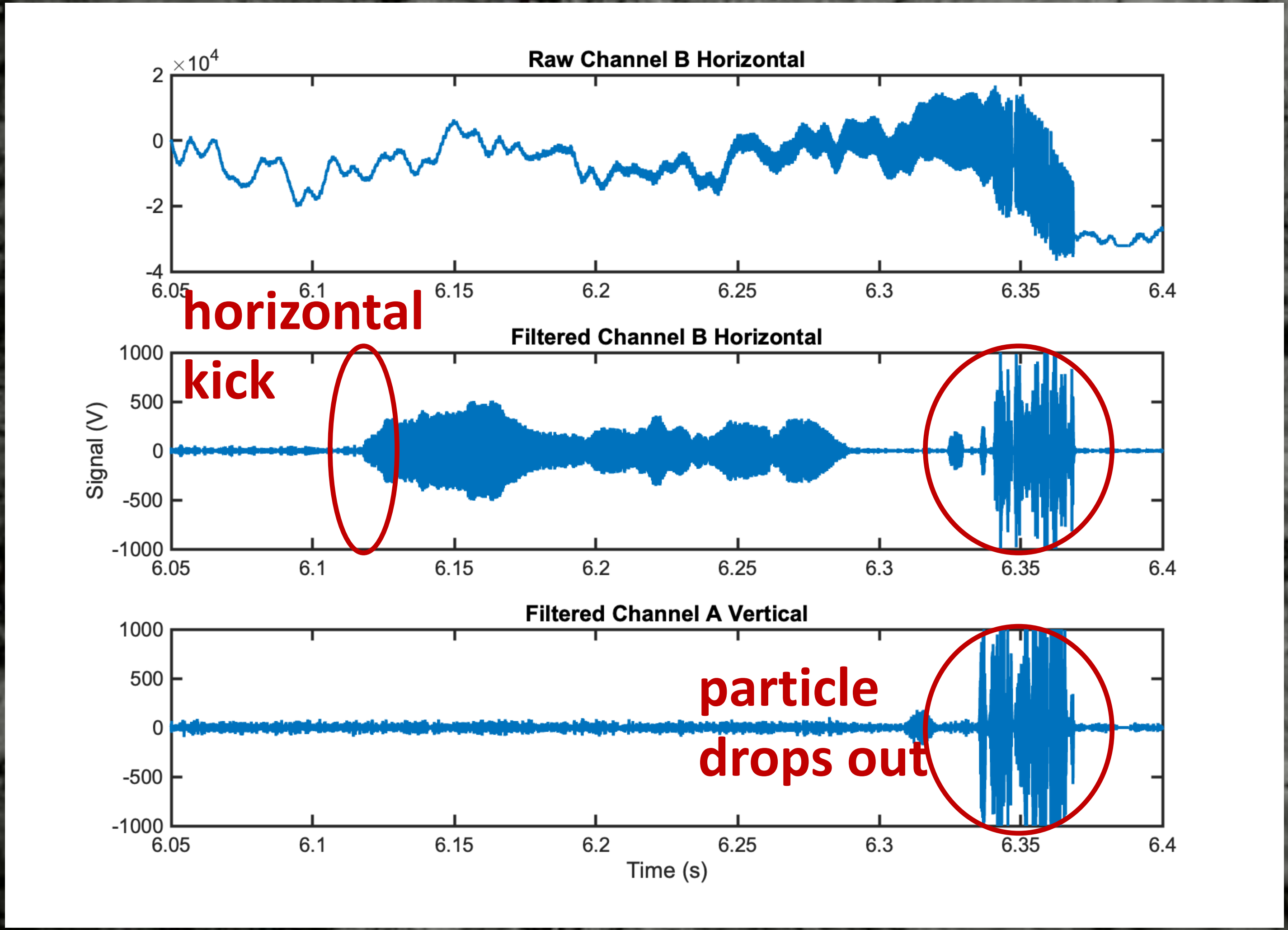
Time-dependence



Directionality

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

Directionality in action



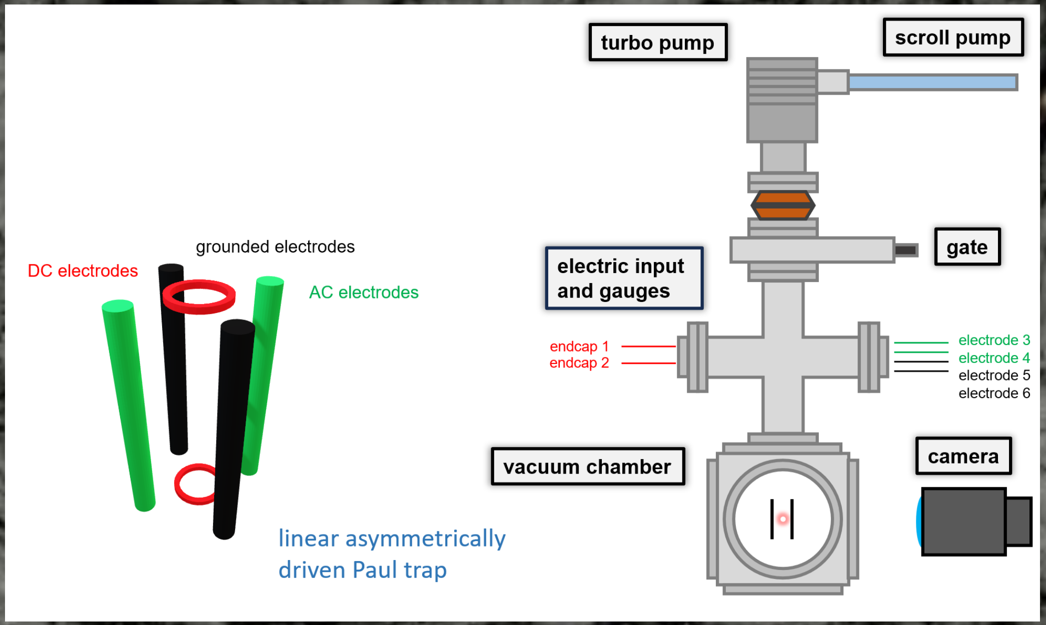
Paul traps and wavelike dark matter

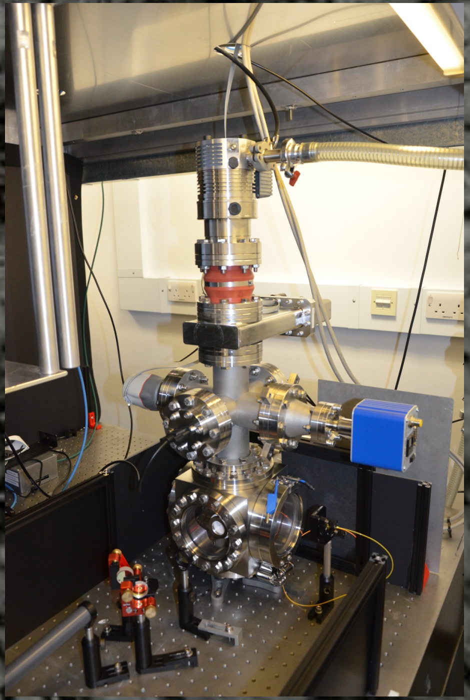
Linear Paul traps

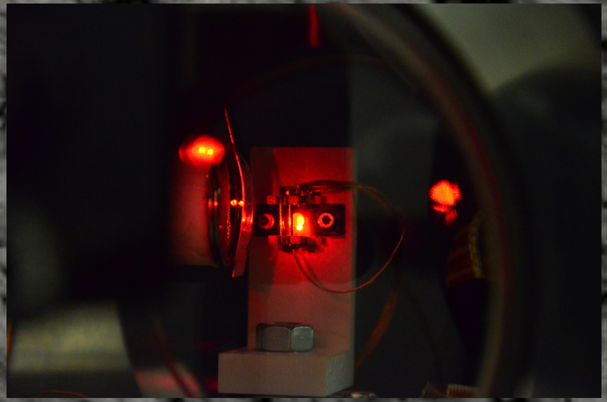
- Trapping of (potentially much heavier) charged particles in a quadrupole potential

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

- 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





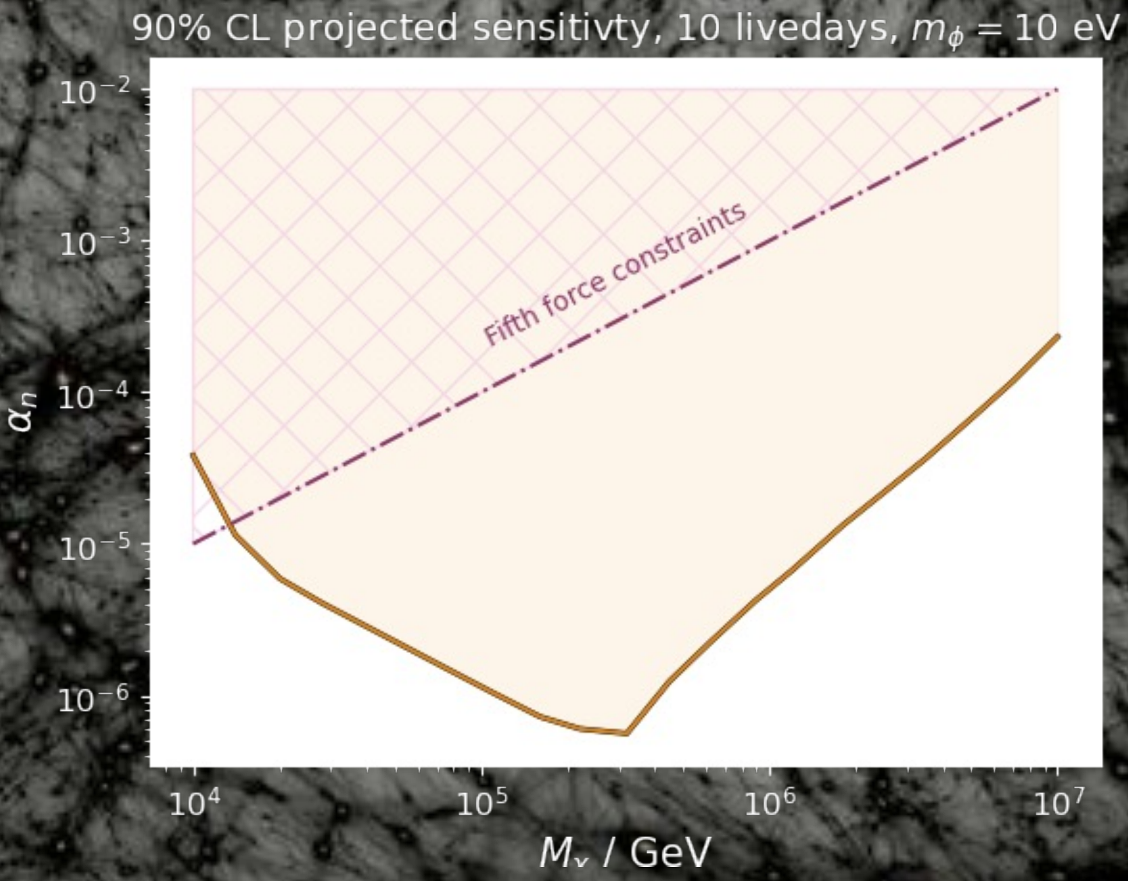


Dark nugget sensitivity

- Projected sensitivity for 0.1 eV mediator mass for particle in Paul trap
- Took 20 – 100 GeV momentum transfer analysis range, conservatively assume 60% efficiency across this range
- Potential to improve on this much further with better noise characterization and analysis
- Could further boost sensitivity by trapping arrays of particles

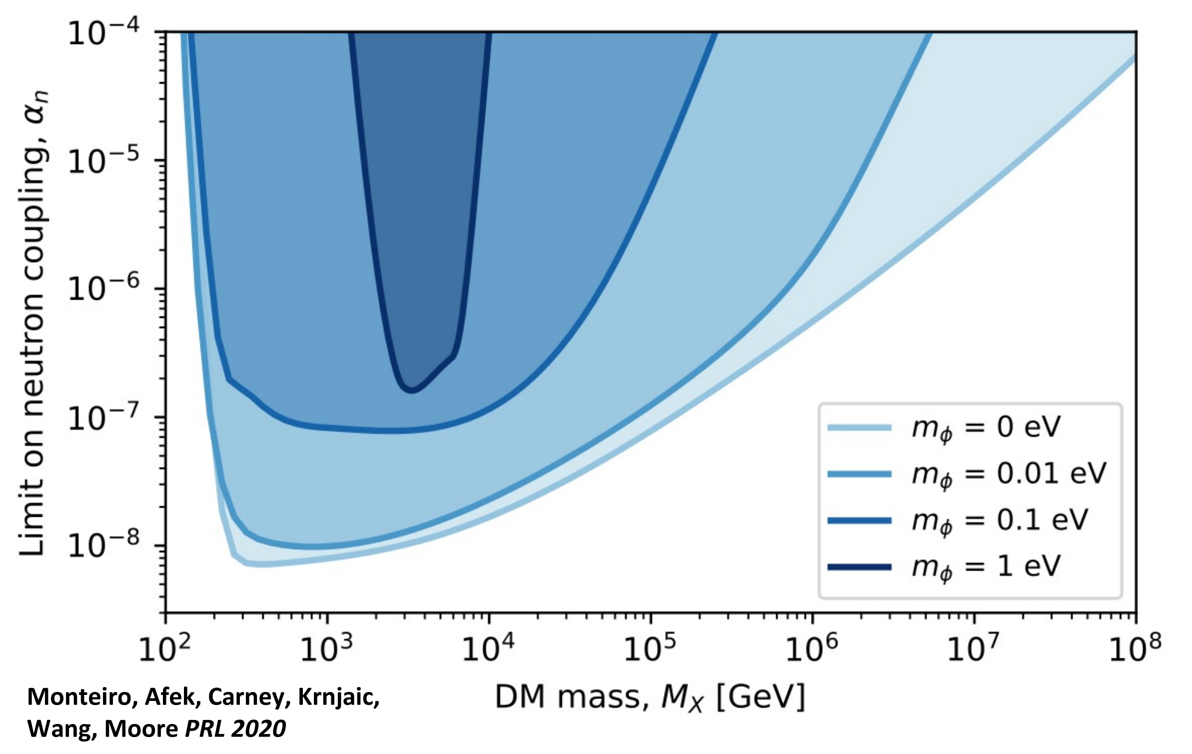
Parameters:

20 µm radius SiO_2 particle
300 K gas temperature (600 K internal particle temperature)
5×10^{-7} mbar pressure
100 Hz trap frequencies
Feedback cooling to ~10 mK



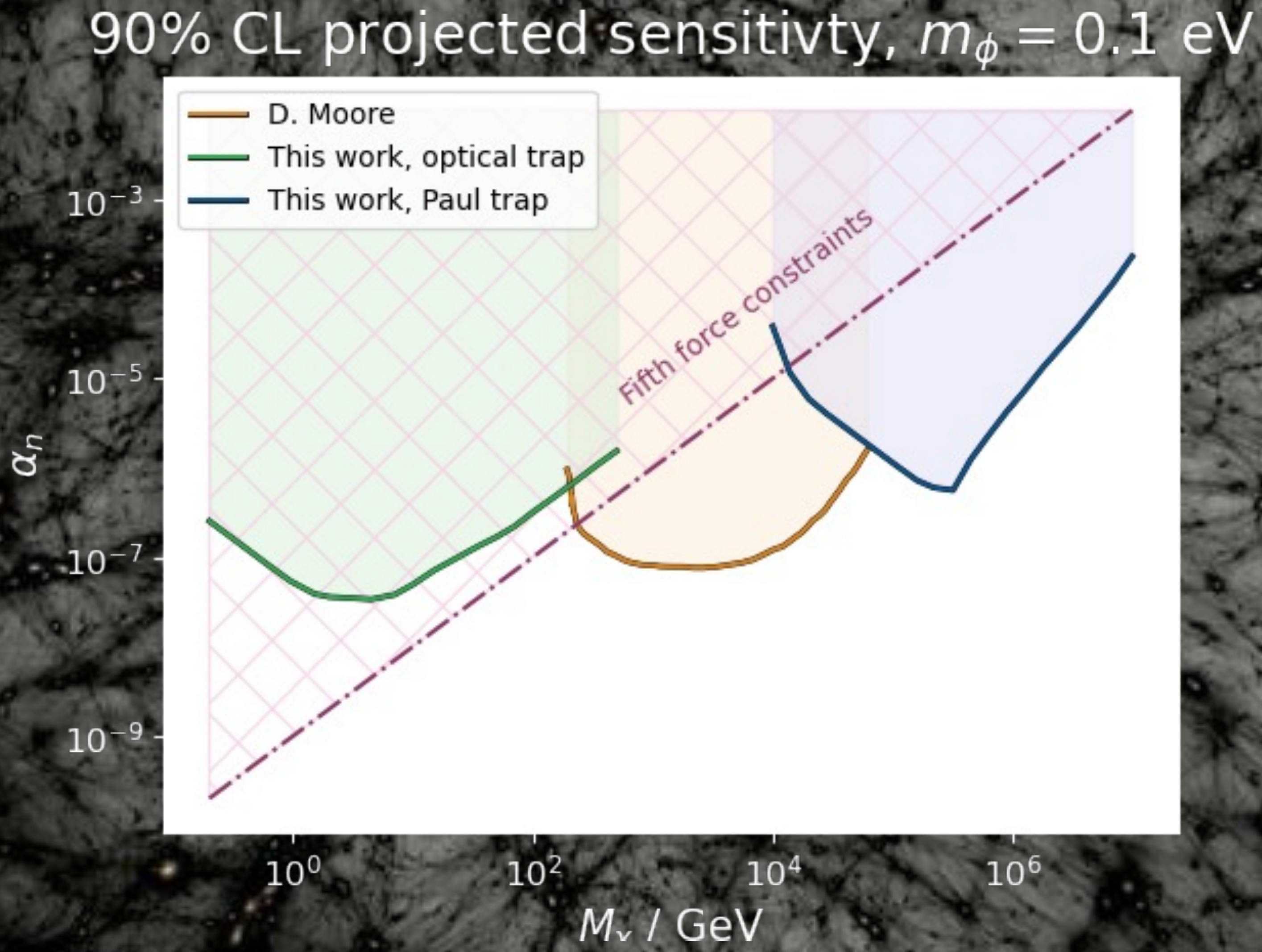
Existing work

- 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



Monteiro, Afek, Carney, Krnjaic, Wang, Moore *PRL 2020*

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 its B-L charge

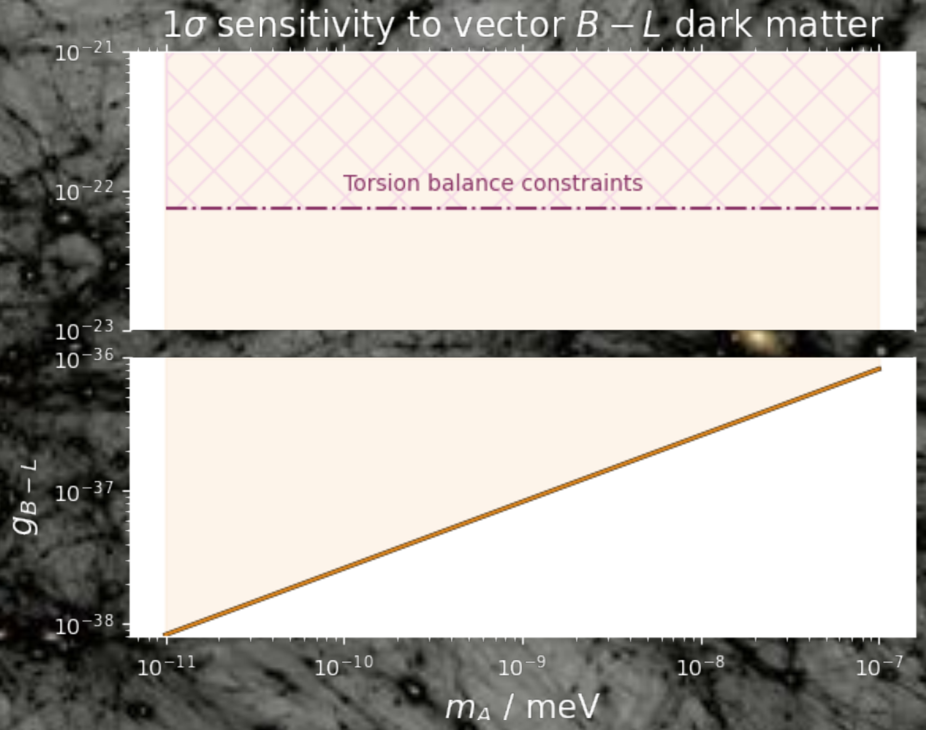
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_A^2 A_\mu A^\mu - g_{B-L}Y_{B-L}A_\mu\overline{\psi}\gamma^\mu\psi$$

- 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)

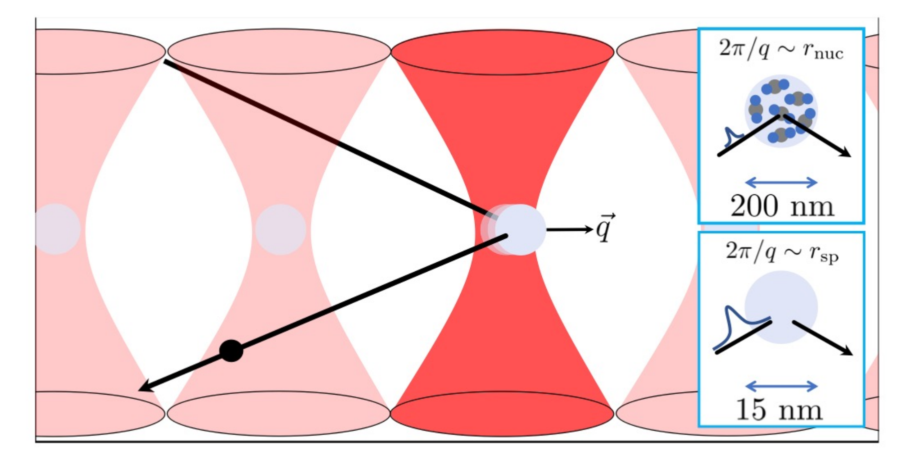
$$g_{B-L}N_n\sqrt{2\rho} = \sqrt{\frac{S_N(m_A)}{T_{int}}}$$

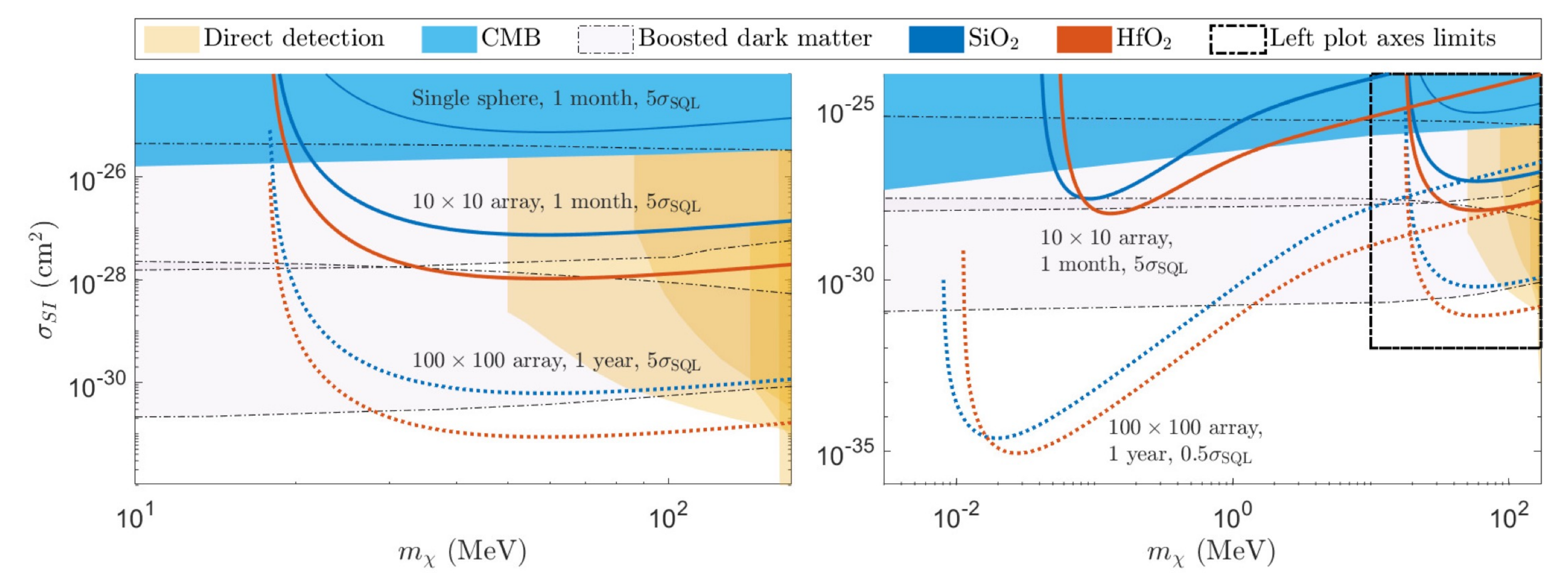


Other searches with levitated optomechanics

Afek, Carney, Moore *PRL 2022*

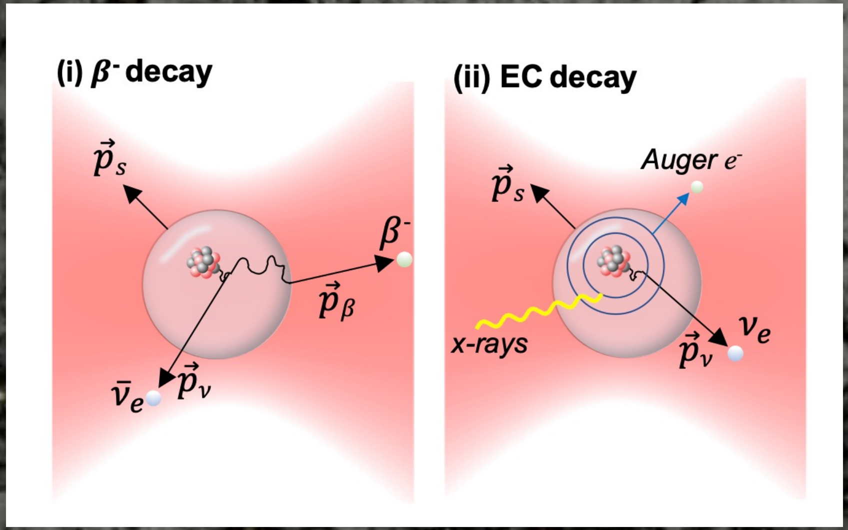
Light WIMPs with small sensors

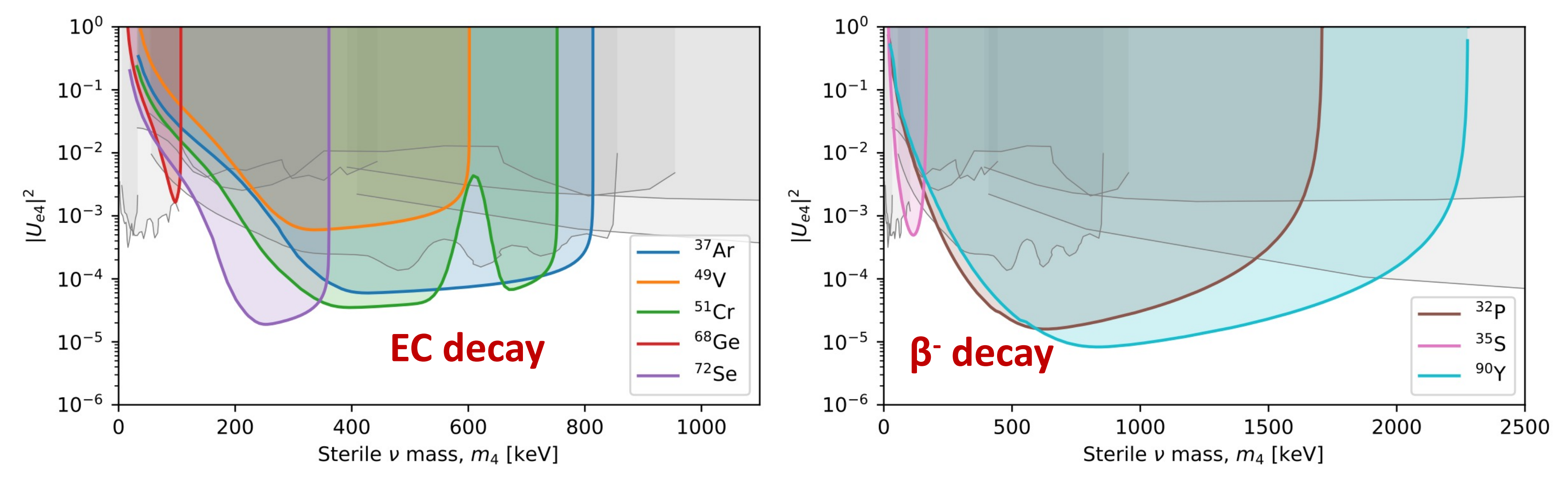




Carney, Leach, Moore *PRX Quantum* 2023

Sterile neutrino mass





Other avenues of exploration

- Ultralight millicharged dark matter: can charge particle in Paul trap, probe well below current astrophysical bounds
- Axion detection using boosted dark matter scenario (could lead to macroscopic coherence)
- Coherent enhancement of dark matter-electron scattering
- Axion annihilation to gravitational waves, GWs from primordial black holes (optically trap particles in optical cavities)

Conclusions

- Our optical trap experiment at UCL will probe composite states of dark matter into unexplored parameter space
- Paul trap setup being commissioned will allow for probing of heavier dark nuggets as well as wavelike dark matter coupling to a B-L charge
- Trapping arrays of particles in a Paul trap allows for a broadband resonance for wavelike searches and can increase target mass for nugget searches
- Potential for WIMP detection and beyond demonstrated with achievable experimental advances