Quantum-enhanced detection of particles and fields

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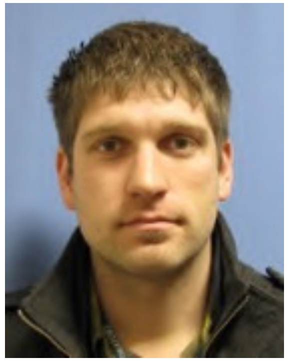
Quantum Sensing and Instrumentation team members

New QuantISED project; FWP submitted last month
ORNL local team members: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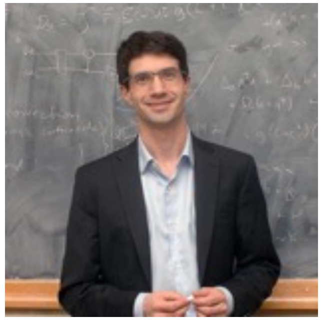
Rafael Lang (Purdue)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Slide Credit - Claire Marvinney

The *ongoing* search for dark matter


Quantum Science and Technology

PAPER

Mechanical quantum sensing in the search for dark matter

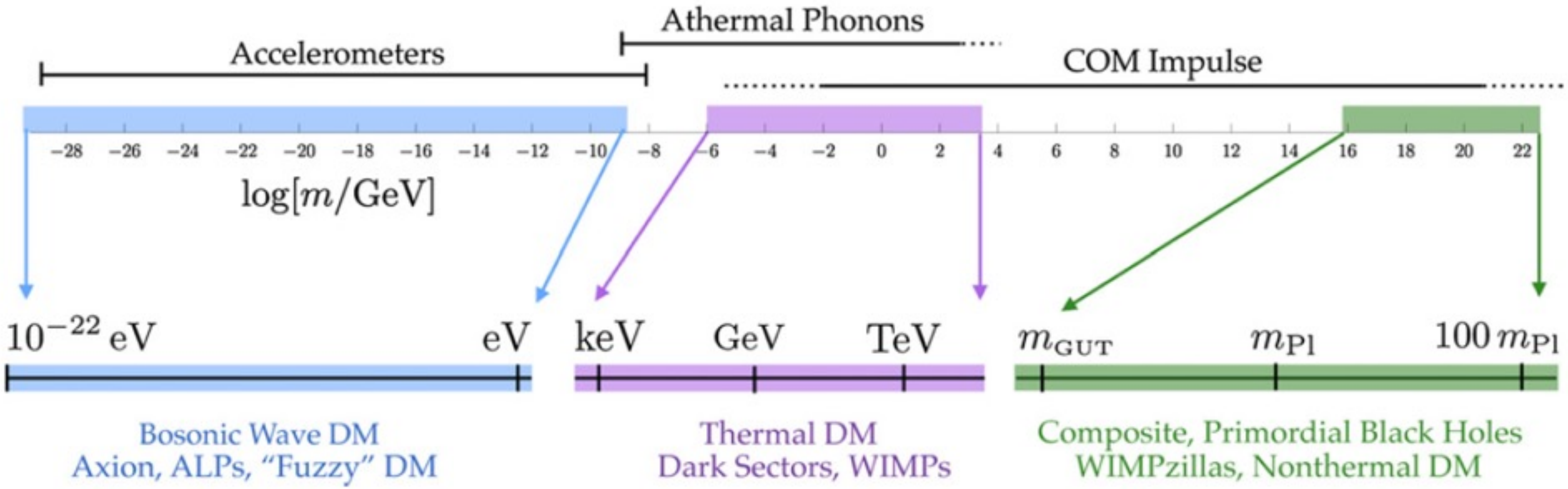

Figure 1. Range of available dark matter candidates. Current observations allow for dark matter to consist of quanta with an enormous range of masses. See for example [8] for a review. Here we classify these candidates as discrete, particle-like excitations when $m \gtrsim 1$ eV, and ultralight, wave-like dark matter when $m \lesssim 1$ eV. Note that for masses $\gtrsim$1PeV, these are necessarily composite objects or some kind of exotica like black hole remnants [31]. A few prototypical models are listed as examples.

Current theories span 50 orders of magnitude !!!

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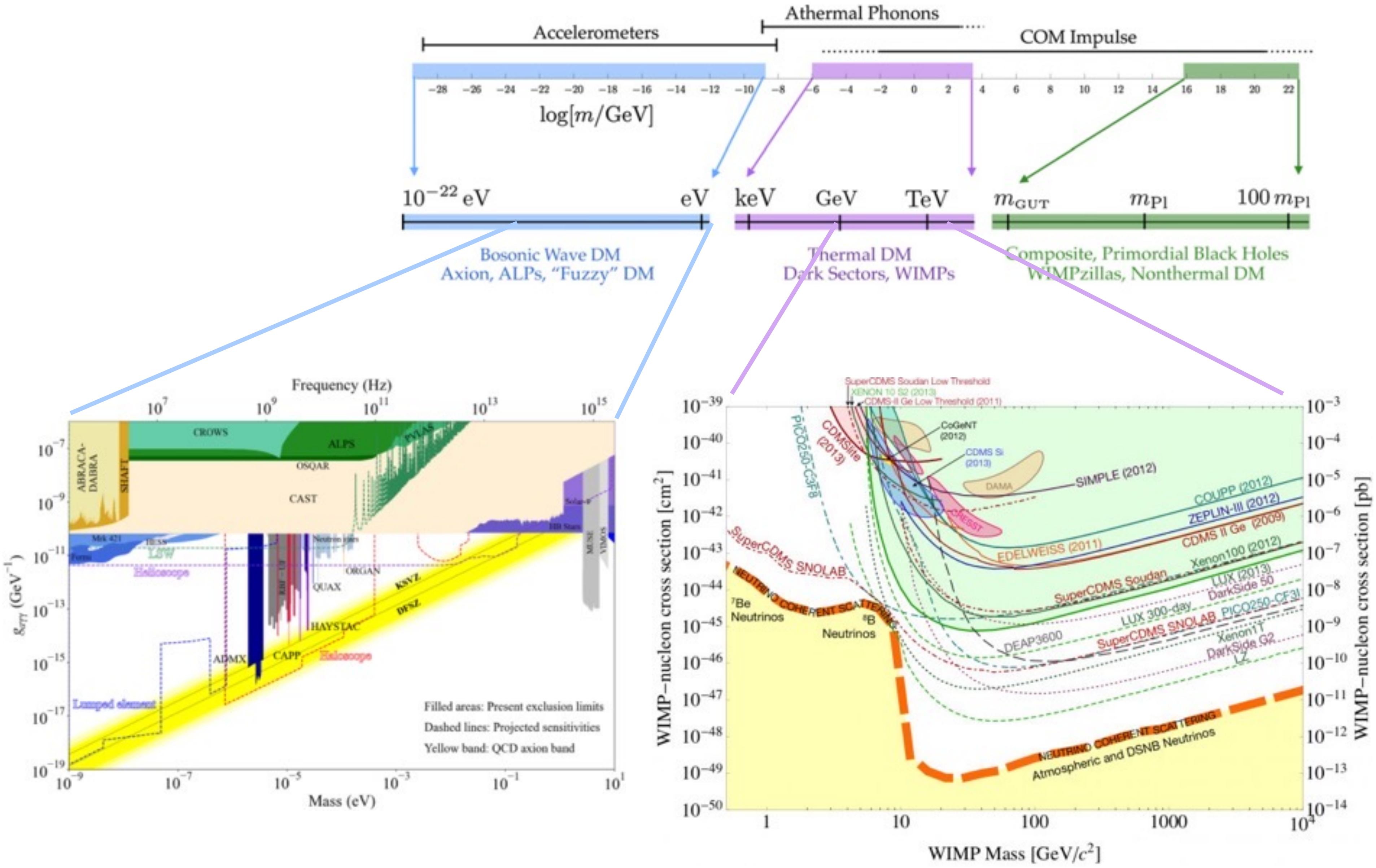


Source: phys.org

A different approach

- What do we know? Dark matter interacts gravitationally…
- So let's try and detect it gravitationally!
- What would be the expected signal?
  - Depends on the dark matter mass
    - Heavy DM → low number density → impulse signals
    - Light DM → high number density → field signals
      - Imagine traveling through a "sea" of DM particles
  - Time scales
    - Heavy DM
      - Earth moving through virialized background of DM with "wind speed" $v_{DM} \sim 200\ {}^{km}/_{s}$
      - Assume Maxwellian velocity distribution with cutoff at the galactic escape velocity $\sim 500\ {}^{km}/_{s}$
    - Light DM
      - Coherence time of the DM field

$$\omega_\chi = \frac{m_\chi c^2}{\hbar}$$

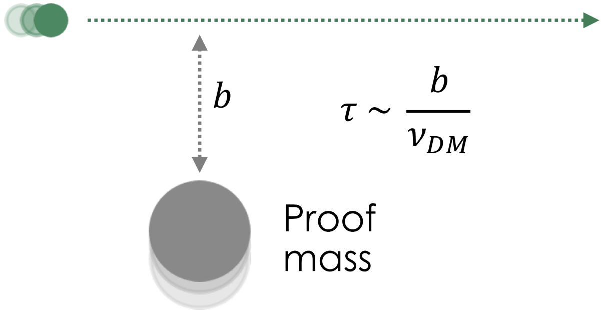
Local number density

$$n_\chi = \frac{0.3}{cm^{-3}} \times \left(\frac{1\ GeV}{m_\chi}\right)$$

Dark matter mass

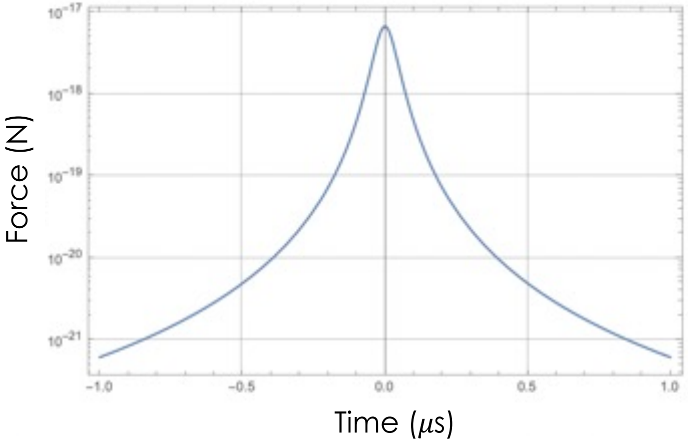
Detection scheme – Optical accelerometry

Dark matter particle

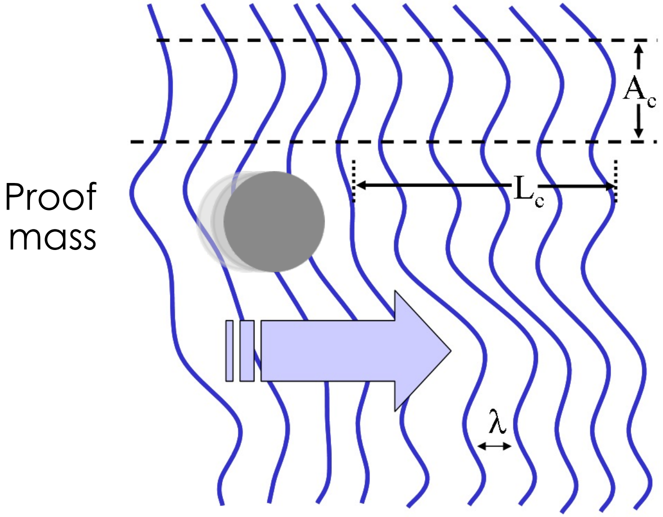


$$\tau \sim \frac{b}{v_{DM}}$$

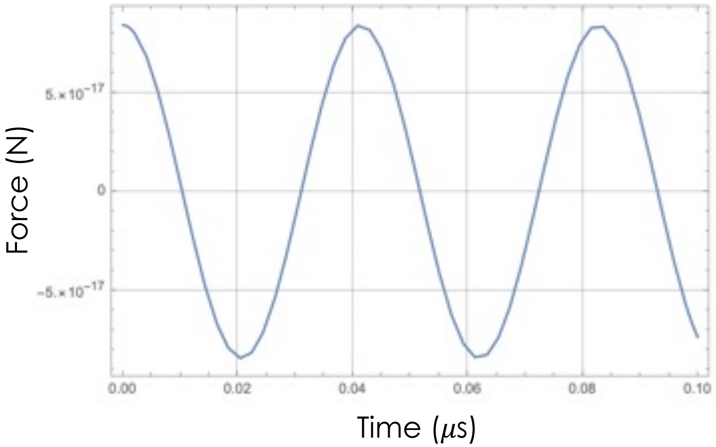
Expected signal

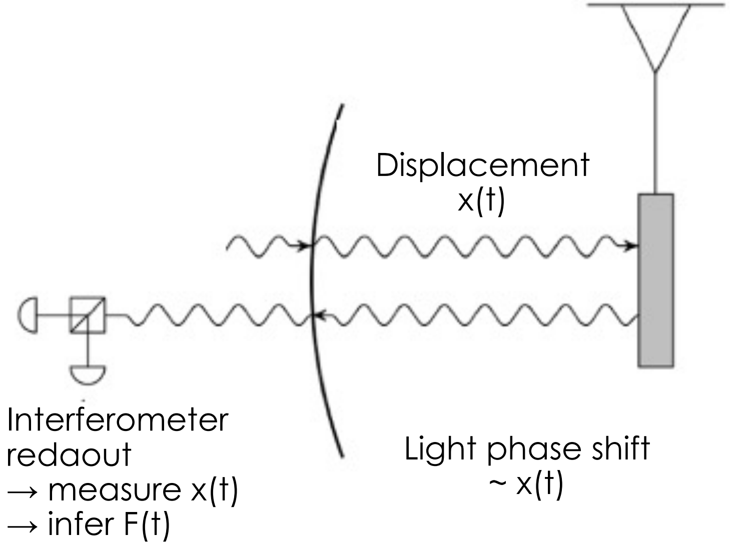


Dark matter "field"

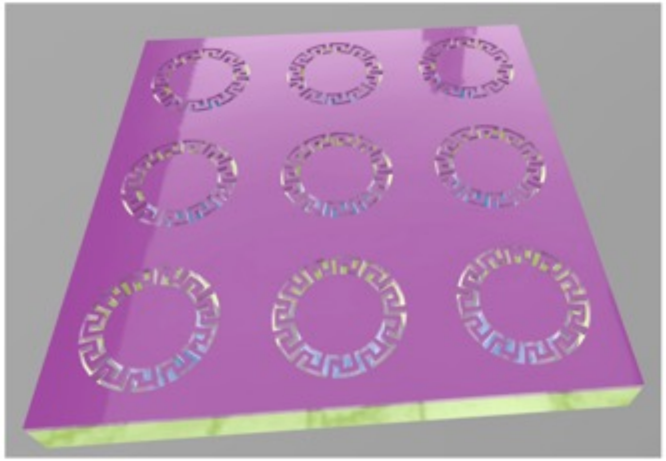


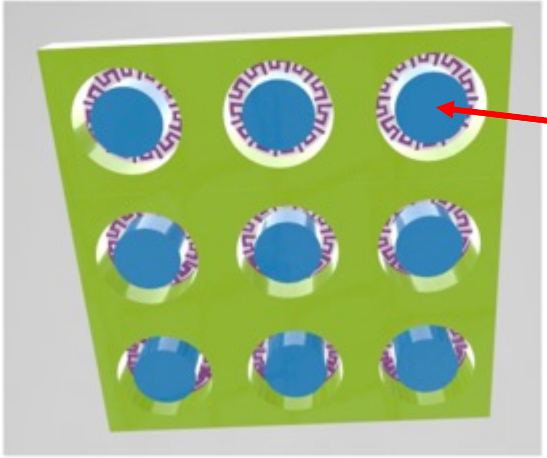
Expected signal





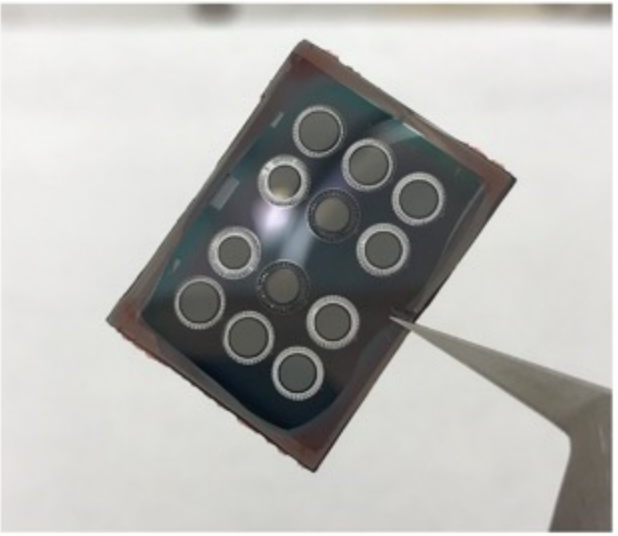
Purdue resonators – "Proof mass"



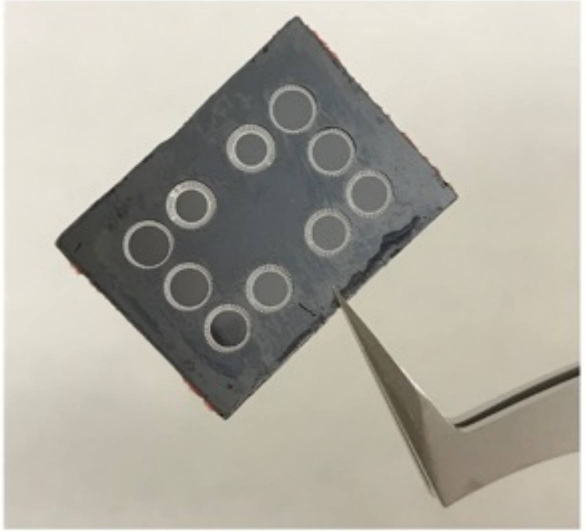


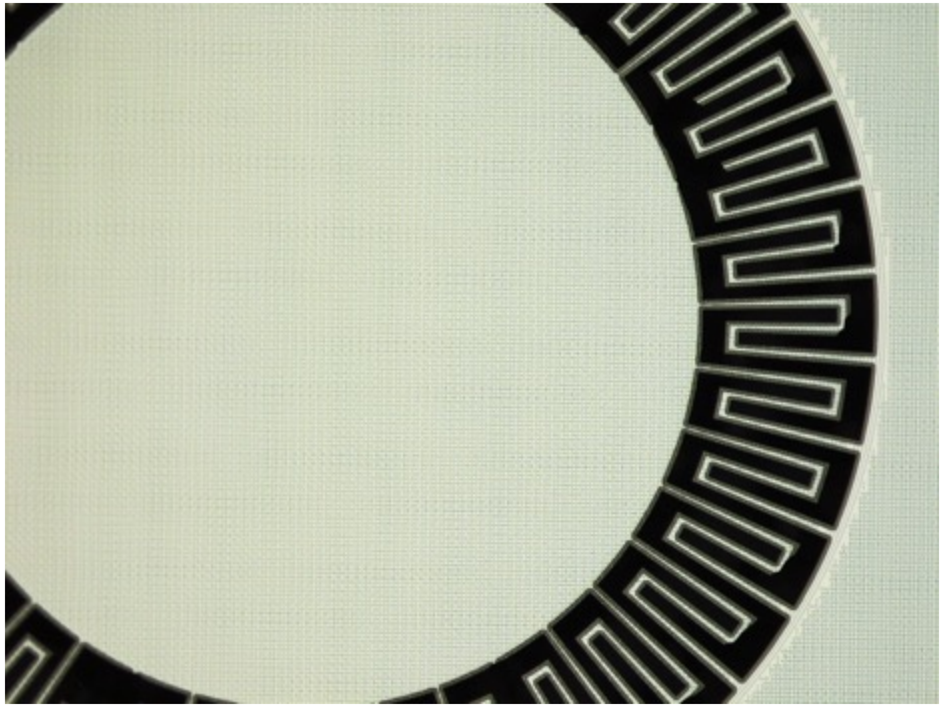
Proof mass

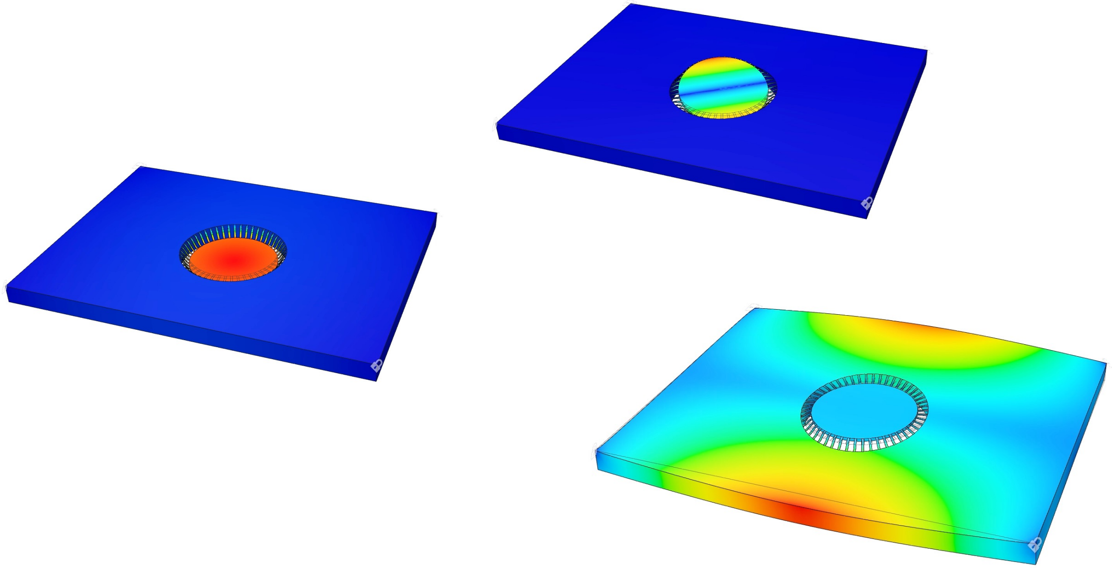
Front side



Back side







Sources of noise

Thermal noise - ∝ $\gamma m k_B T$

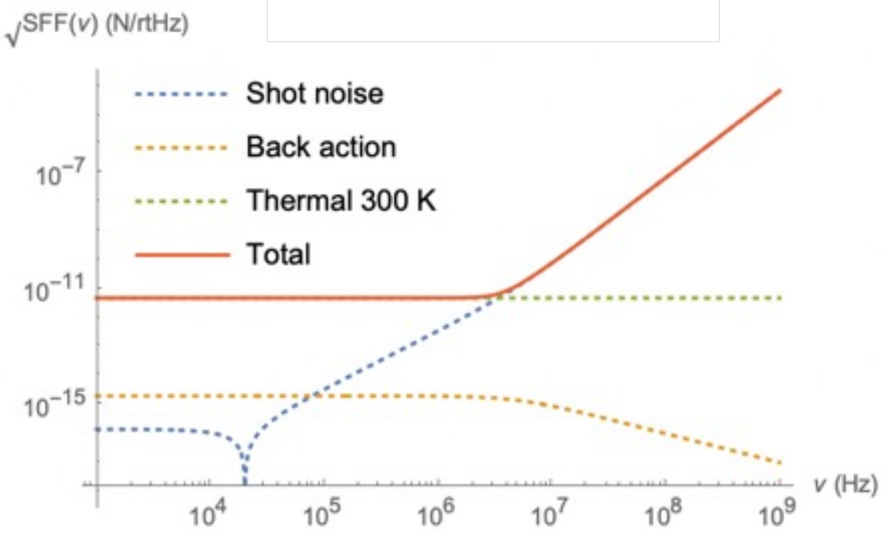
Shot noise - Poisson noise from laser intensity

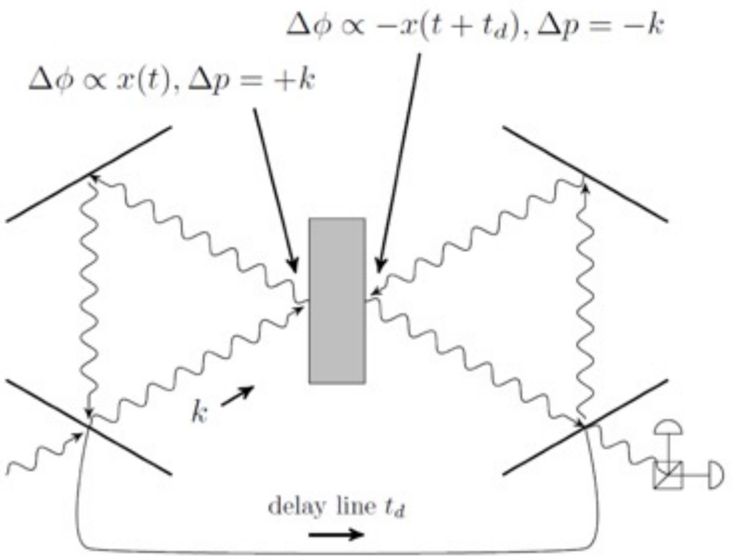
Back action – Radiation pressure inducing displacement

Thermal noise can be reduced through cooling

Back action can be reduced using back action evading techniques like the “bow tie” configuration shown on the right

How can we reduce shot noise?

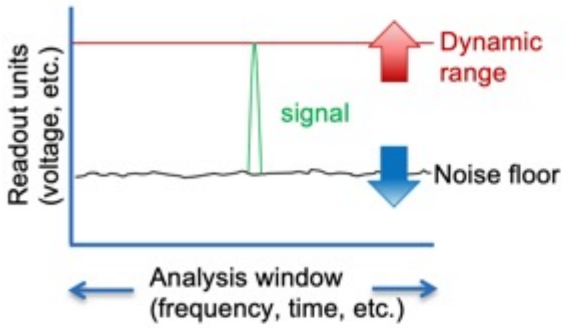


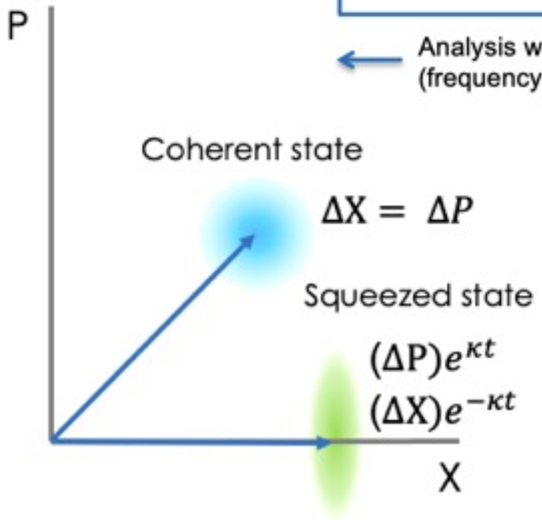


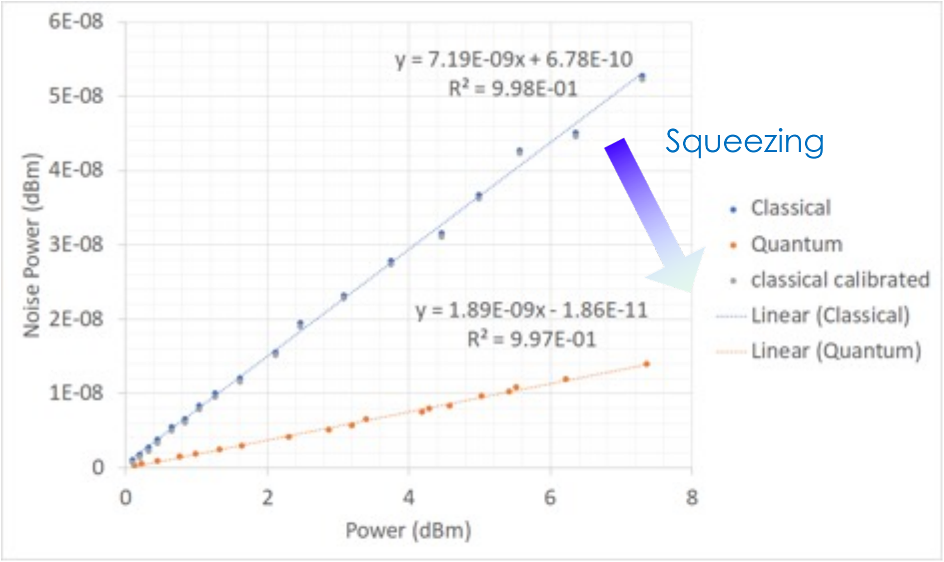
Ghosh, Carney, Shawhan, Taylor, Phys. Rev. A 102, 023525

Quantum noise reduction

- The *fundamental detection limit* is the noise floor of the full sensor as viewed at the backend after all filters and computational analysis
- We wish to increase the signal to noise (SNR) by decreasing the noise floor using **quantum noise reduction (QNR), or “squeezing”**
- Coherent states can be thought of as having somewhat random ordering of photons in terms of arrival time at a detector
- Can generate states of light more ordered in time, with less noise in amplitude/phase through the use of a nonlinear process
- Coherent states have symmetric uncertainty in X and P, squeezed states have inverse uncertainties, resulting in one uncertainty axis in phase space appearing “squeezed”







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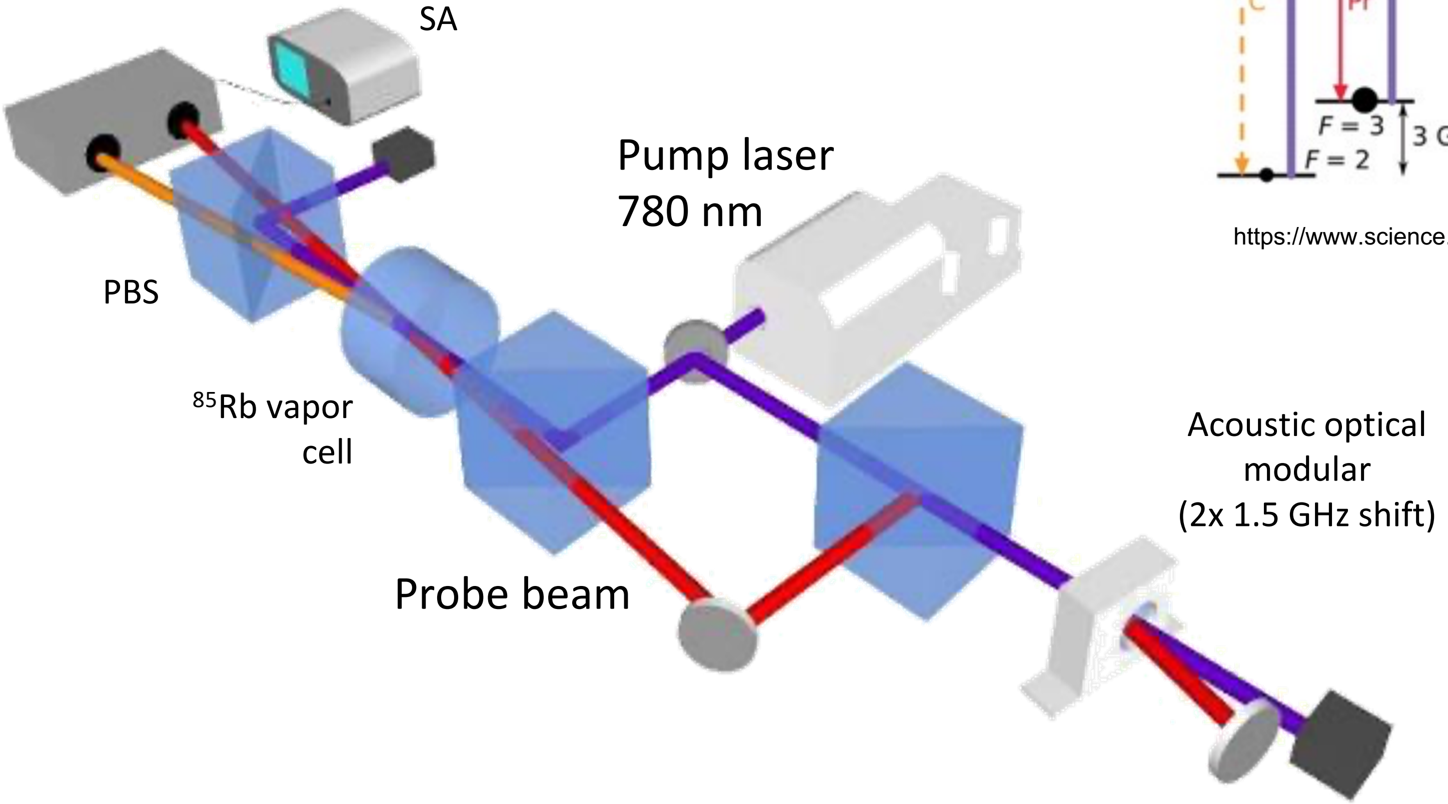
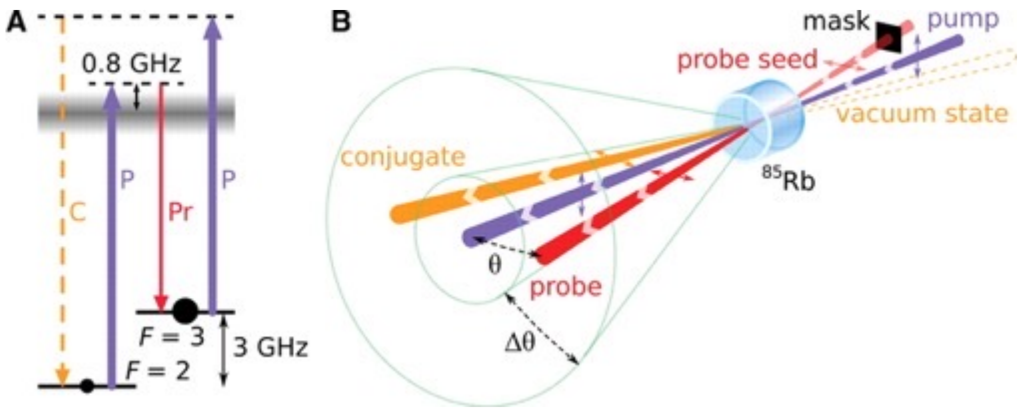
Slide credit: Claire Marvinney

Entangled light from 4-wave mixing





https://www.science.org/doi/10.1126/science.1158275

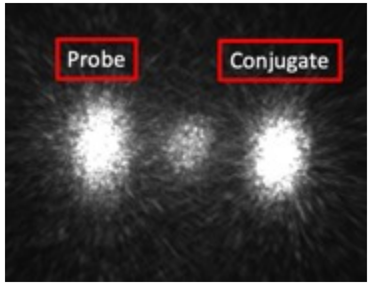
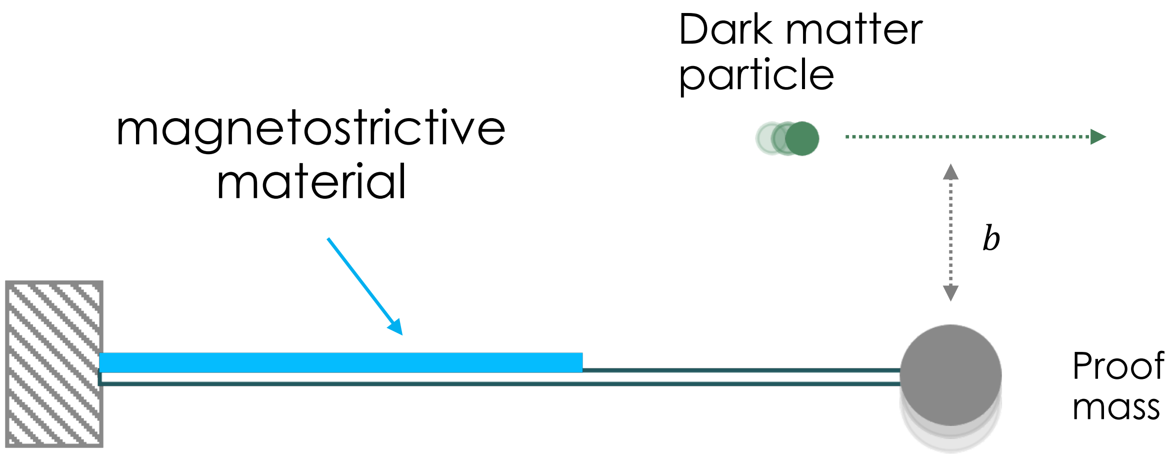


Photo Credit – Claire Marvinney

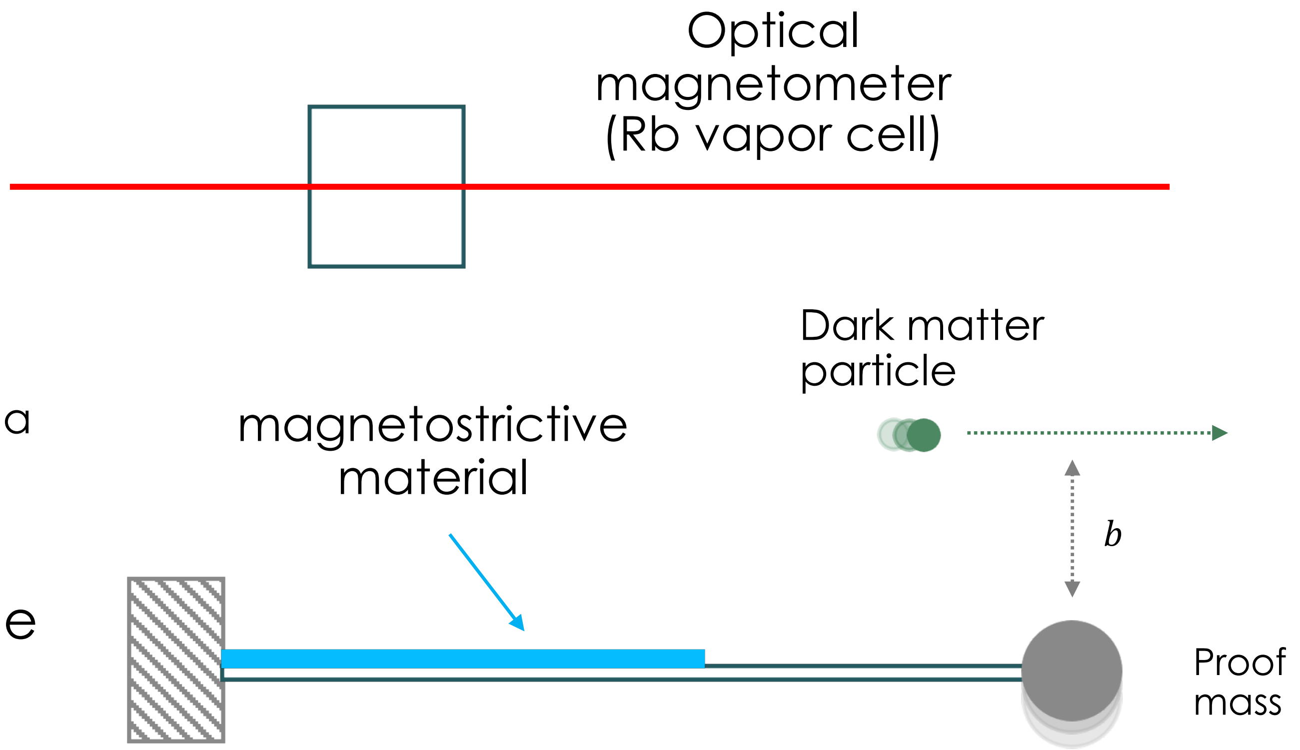
Another take on back-action evasion

- Consider an alternative approach where we don't readout the position of the proof mass directly with light but rather transude its response onto another sensor
  - Example would be magnetic transduction
- Piezoelectric materials
  - Stress - > electric field
- Piezomagnetic materials
  - Stress -> magnetic field
- If we create an thin film of magnetostrictive material on a cantilever, the stress from the displacement of the cantilever can modify a local magnetic field



Another take on back-action evasion

- Under this scheme, the radiation pressure-induced backaction from reading out the resonators is eliminated
  - Multiple resonators can be measured by a single optical magnetometer
- We do introduce backaction in the form of spin-projection noise onto the magnetometer but that can be address by using counter-propagating probe beams.
  - Can be done in a single beam → reduces sensitive optical components near the proof masses



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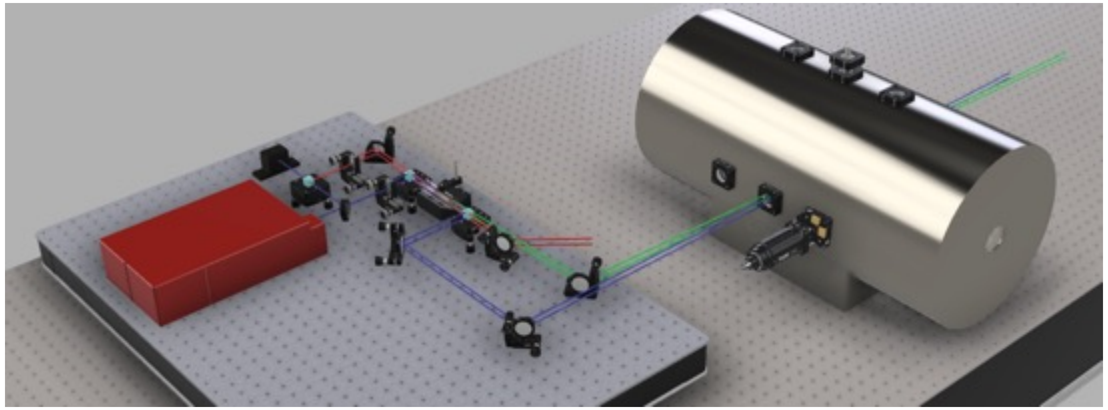
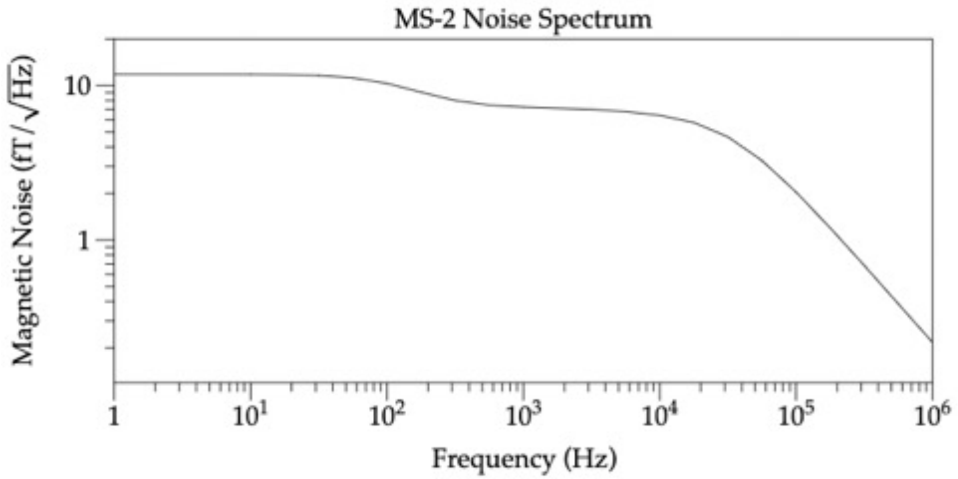
Progress on quantum sensing setup

Construction of the experimental setup is underway

Coupling the squeezed light source to a state-of-the-art magnetic sheild





Other uses beyond dark matter detection?

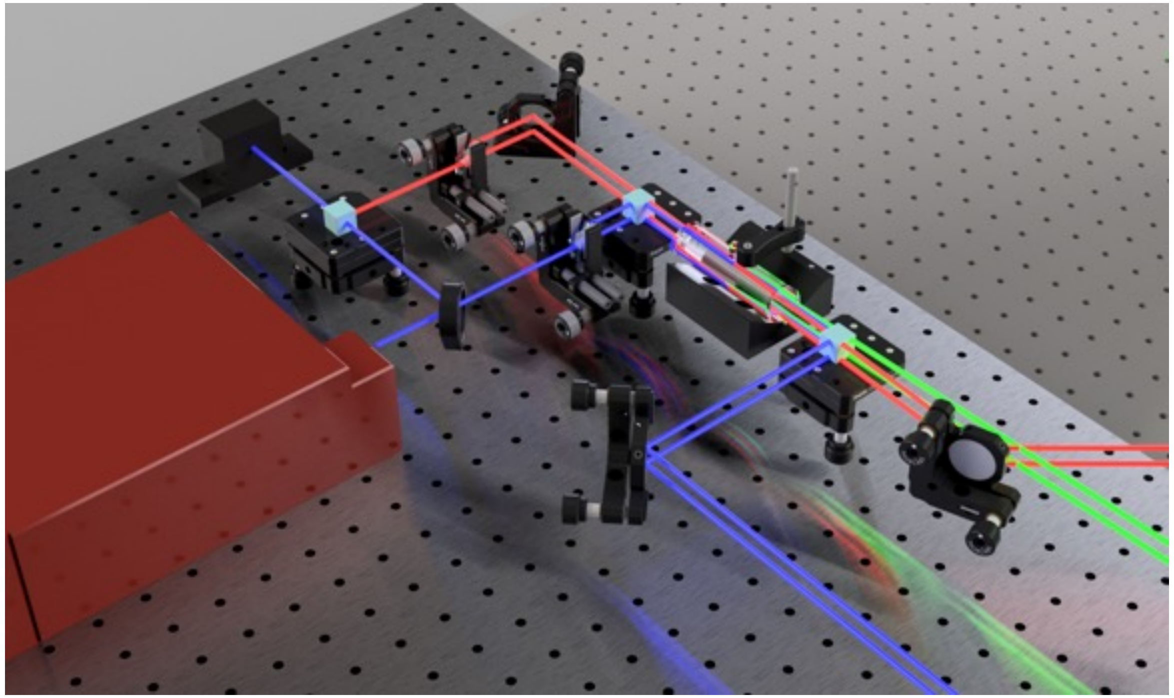
Displacement caused by alpha particle stopping in a resonator

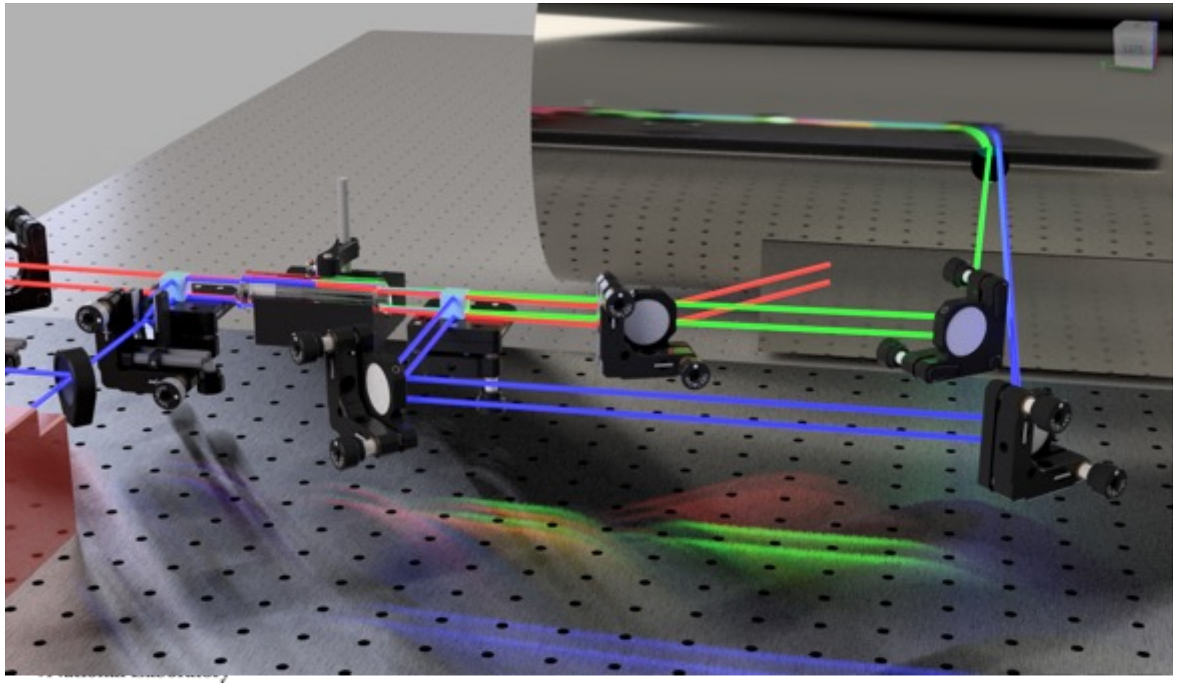
$$x = \sqrt{\frac{2}{k}\left(\frac{4}{4+A}\right)Q_\alpha}$$

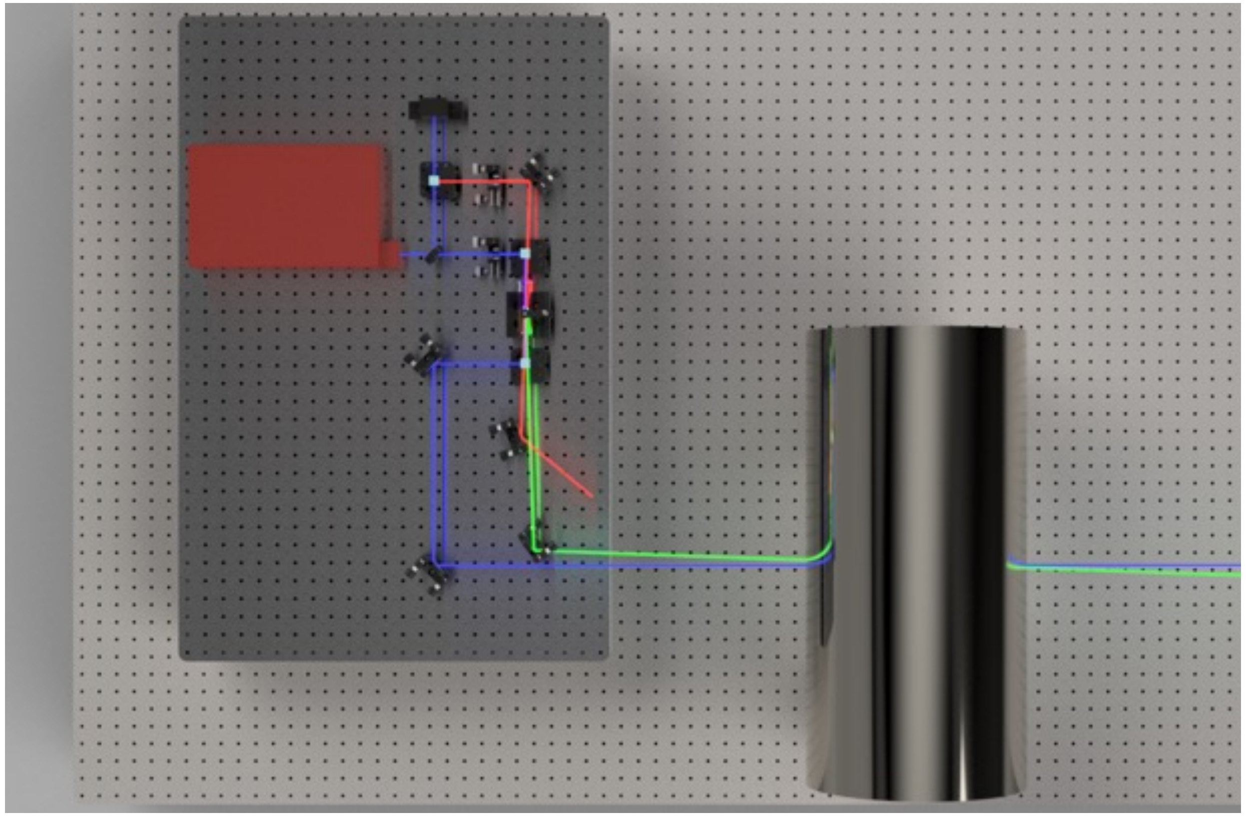
For Qa = 5 MeV, A = 234, and k = 0.03 N/m
Displacement is ~900 nm

Classical interferometers should get ~10s pm sensitivity

This is of course assuming no losses but still interesting thing to think about







Classical to quantum light

- How can we push below the standard quantum limit?
  - Squeezed coherent states (*aka "squeezing"*)

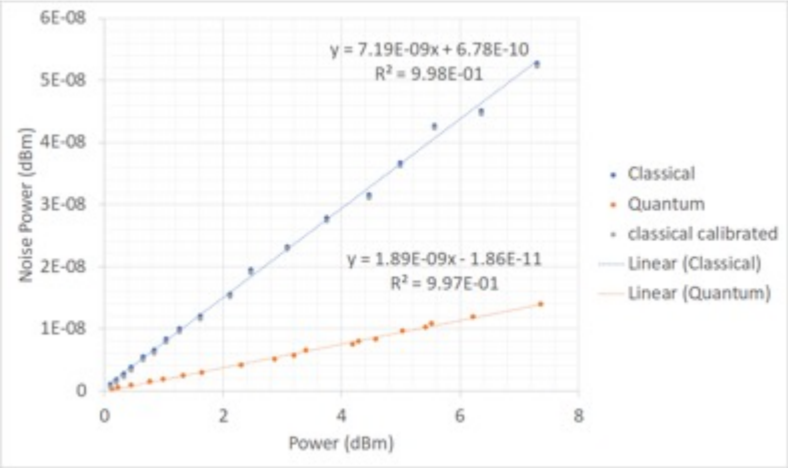
Coherent (classical) light

$$\Delta n_c = \sqrt{n}$$
$$\Delta \varphi_c = \frac{1}{\sqrt{n}}$$

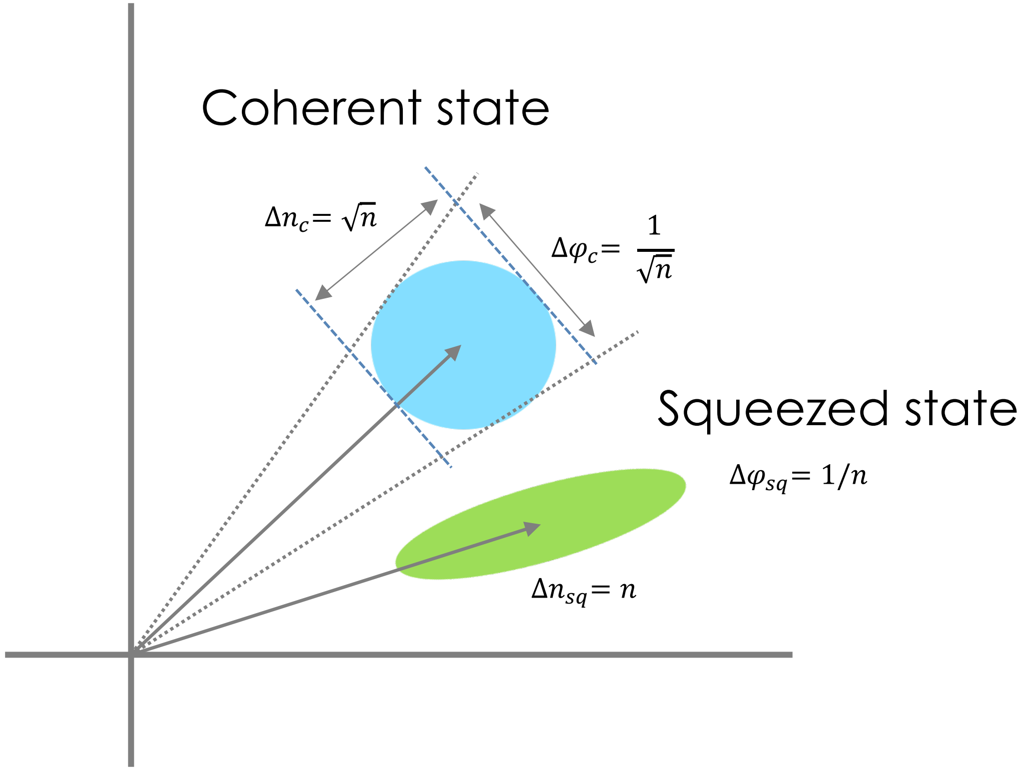
Squeezing

Quantum (Non-linear) light

$$\Delta n_{sq} = n$$
$$\Delta \varphi_{sq} = \frac{1}{n}$$



Credit: Claire Marvinney



Excepted dark matter induced signals

	Induced force	Displacement of an oscillator	Magnetic field of an oscillator*
Ultralight Dark matter	$F(t) = F_0 N_n g_{B-L} Cos(\omega_\chi t)$ F_o - ~10^{-15} N_n - Number of neutrons in the sensor g_{B-L} - Coupling constant < 10^{-22}	$x(t) = \frac{F_0 N_n g_{B-L} Cos(\omega_\chi t)}{k}$ k – Force constant	$B(t) = d_{33} E \frac{F_0 N_n g_{B-L} Cos(\omega_\chi t)}{lk}$ l - Cantilever length E- Youngs modulus d_{33}- Piezo magnetic constant
Ultraheavy Dark matter	$F(t) = G_N \frac{m_\chi m_s b}{(b^2 + v^2 t^2)^{3/2}}$ m_s - Sensor mass b – Distance of closest approach v – DM velocity ~220 km/s	$x(t) = G_N \frac{m_\chi m_s b}{k(b^2 + v^2 t^2)^{3/2}}$ k – Force constant	$B(t) = d_{33} E G_N \frac{m_\chi m_s b}{lk(b^2 + v^2 t^2)^{3/2}}$ l - Cantilever length E- Youngs modulus d_{33}- Piezo magnetic constant

*assuming a piezomagnetic cantilever

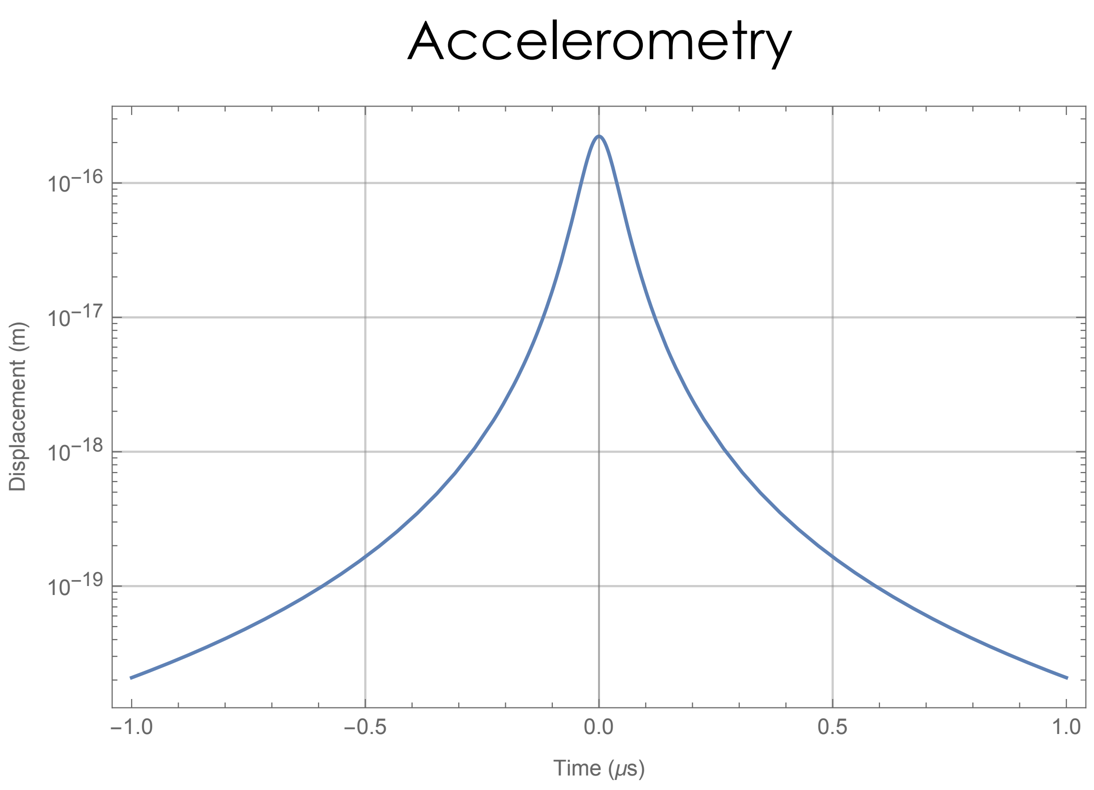
$$\omega_\chi = {m_\chi c^2}/{\hbar} \qquad a = \omega_0^2 x = \frac{k}{m} x$$

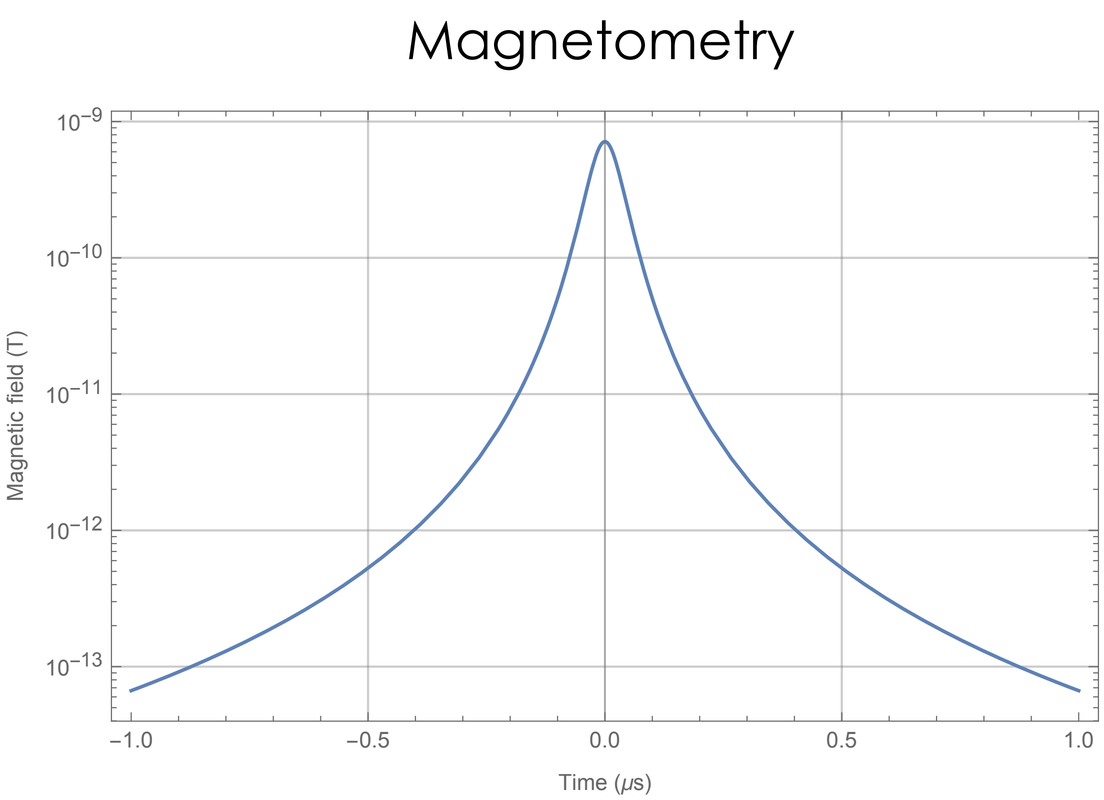
Excepted dark matter induced signals

	Time domain	Frequency domain
Ultralight Dark matter	$F(t) = F_0 N_n g_{B-L} Cos(\omega_\chi t)$ F_o- ~10^{-15} N_n - Number of neutrons in the sensor g_{B-L} - Coupling constant < 10^{-22}	$F(\nu) = F_0 N_n g_{B-L} \sqrt{\frac{\pi}{2}} \left(\delta(\nu - \omega_\chi) + \delta(\nu + \omega_\chi)\right)$
Ultraheavy Dark matter	$F(t) = G_N \frac{m_\chi m_s b}{(b^2 + v^2 t^2)^{3/2}}$ m_s - Sensor mass b – Distance of closest approach v – DM velocity ~220 km/s	$F(\nu) = G_N m_\chi m_s \frac{\lvert\nu\rvert}{\nu^2} \sqrt{\frac{2}{\pi}} K_1 \left[\frac{b}{\nu} \lvert\nu\rvert\right]$

$$\omega_\chi = {m_\chi c^2}/{\hbar} \qquad a = \omega_0^2 x = \frac{k}{m} x$$

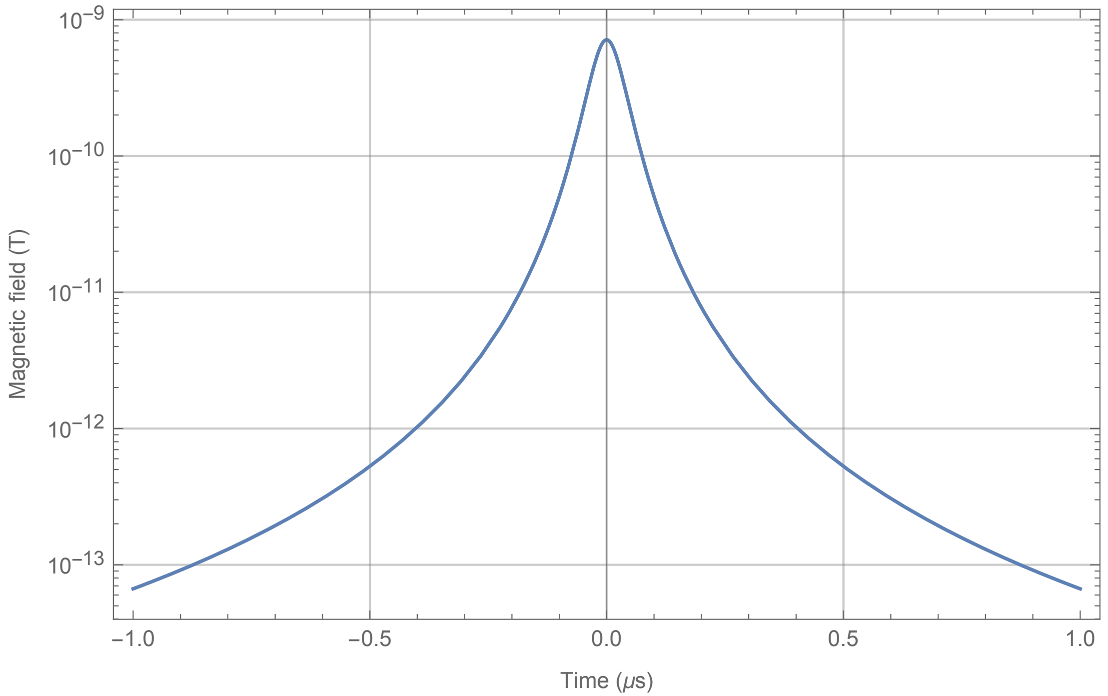
Excepted dark matter induced signals



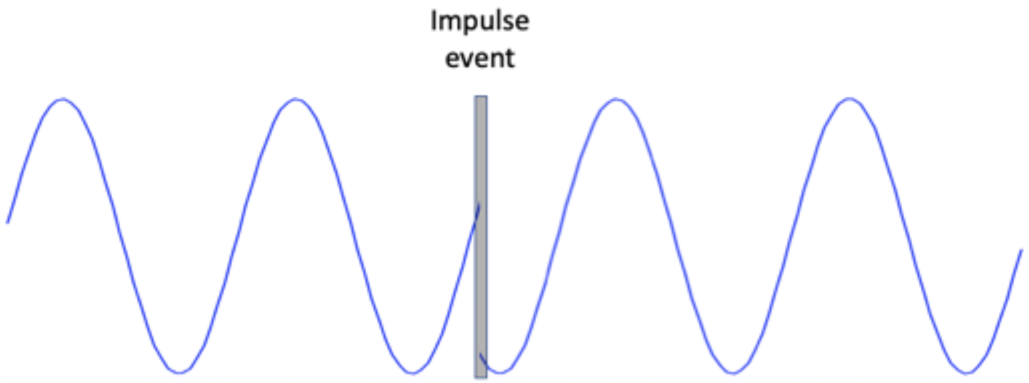


Ultraheavy DM, 10^{-8} kg, k = 0.03 N/m, l = 500 μm

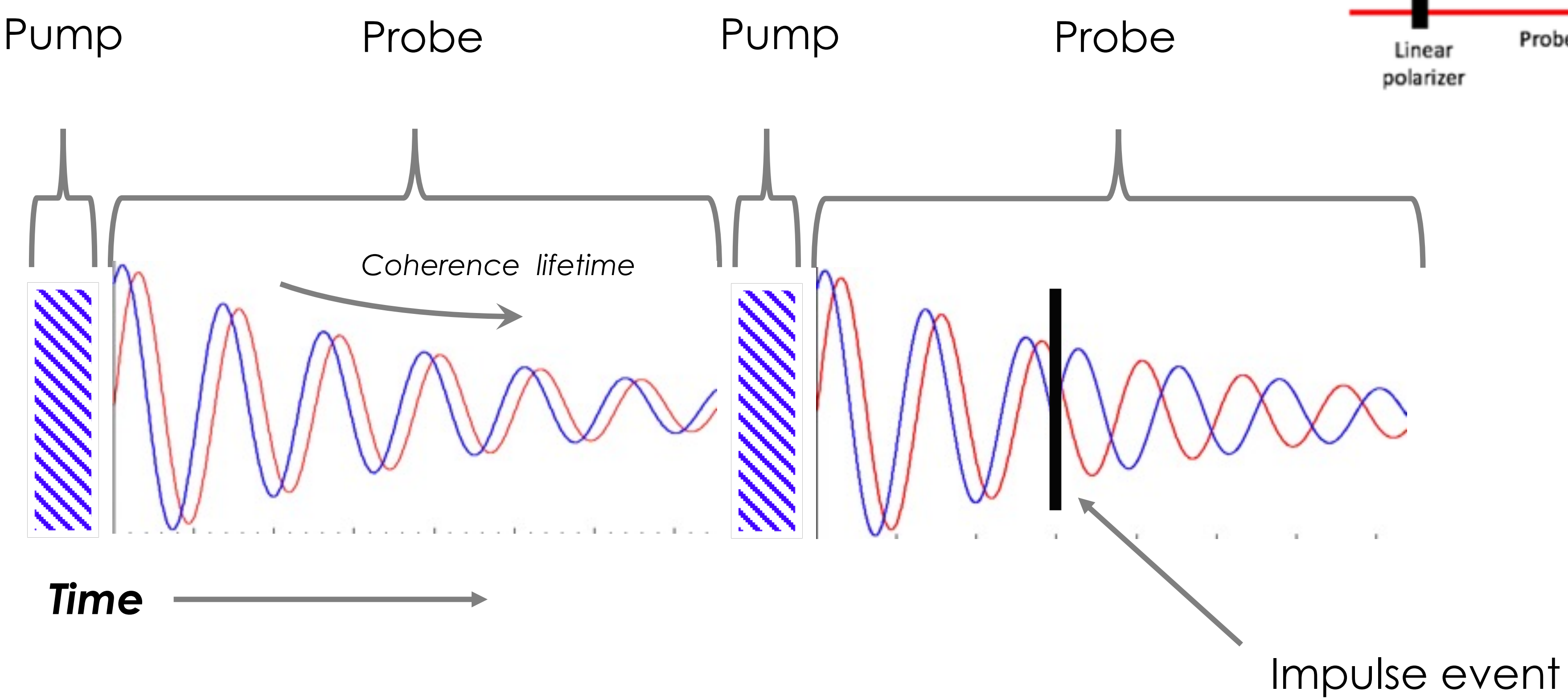
Back of the envelope calculations

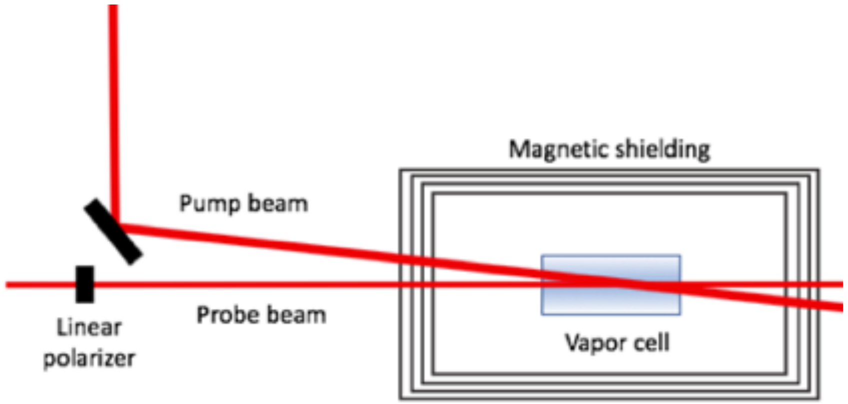


Use phase shift to detect impulse event



Exposure (*i.e.* detector live time)





Blue – Probe
Red - Reference

Experimental setup

- First experiments will use off-the-shelf AFM tips
  - Gold coated on one side
  - Terfenol-D coated on opposite side
- Synthetic impulse signal will be injected using a “kicker” light pulse reflected on the gold side
- 1x1 cm enriched ^{87}Rb vapor cell