Quantum Optomechanical Sensors for Dark Matter and Sterile Neutrino Searches

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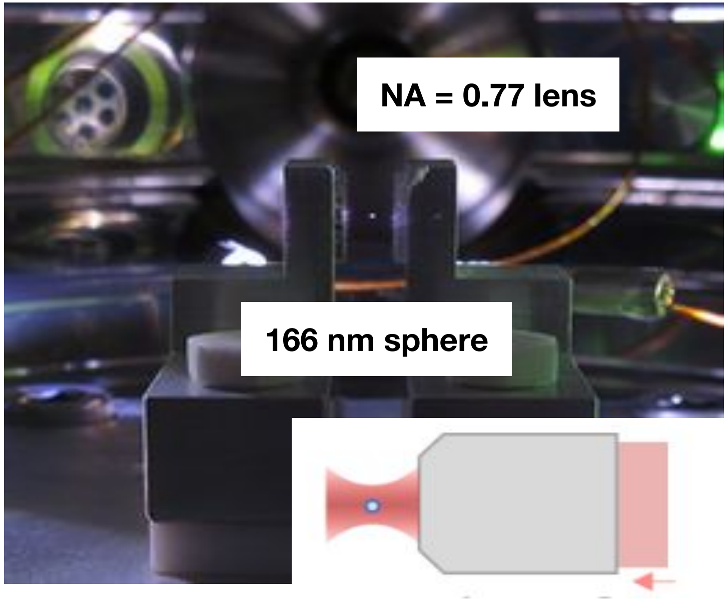
CPAD Workshop 2023

Levitated optomechanical sensors

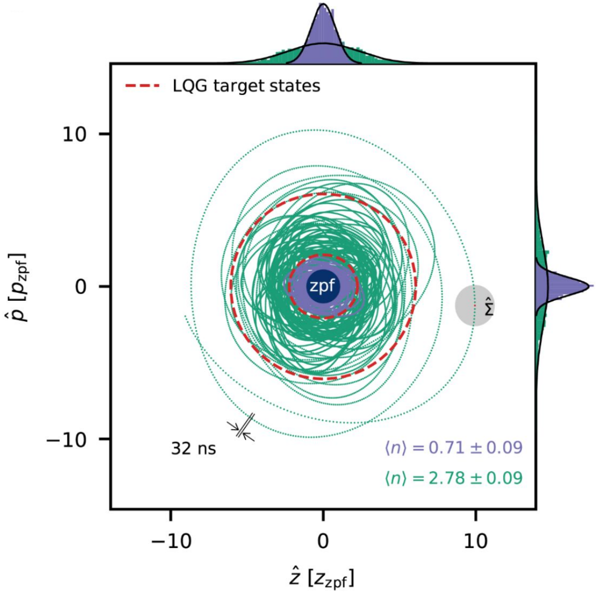
- Dielectric particles (100 nm - 30 μm) optically trapped in UHV ($\lesssim 10^{-8}$ mbar)
  - extreme isolation, charge control, precise position measurement

Silica nanospheres (~fg, 100-300 nm)



- ~10^{-12} m · Hz$^{-1/2}$ position sensing, with ~10^{-21} N · Hz$^{-1/2}$ force sensitivity

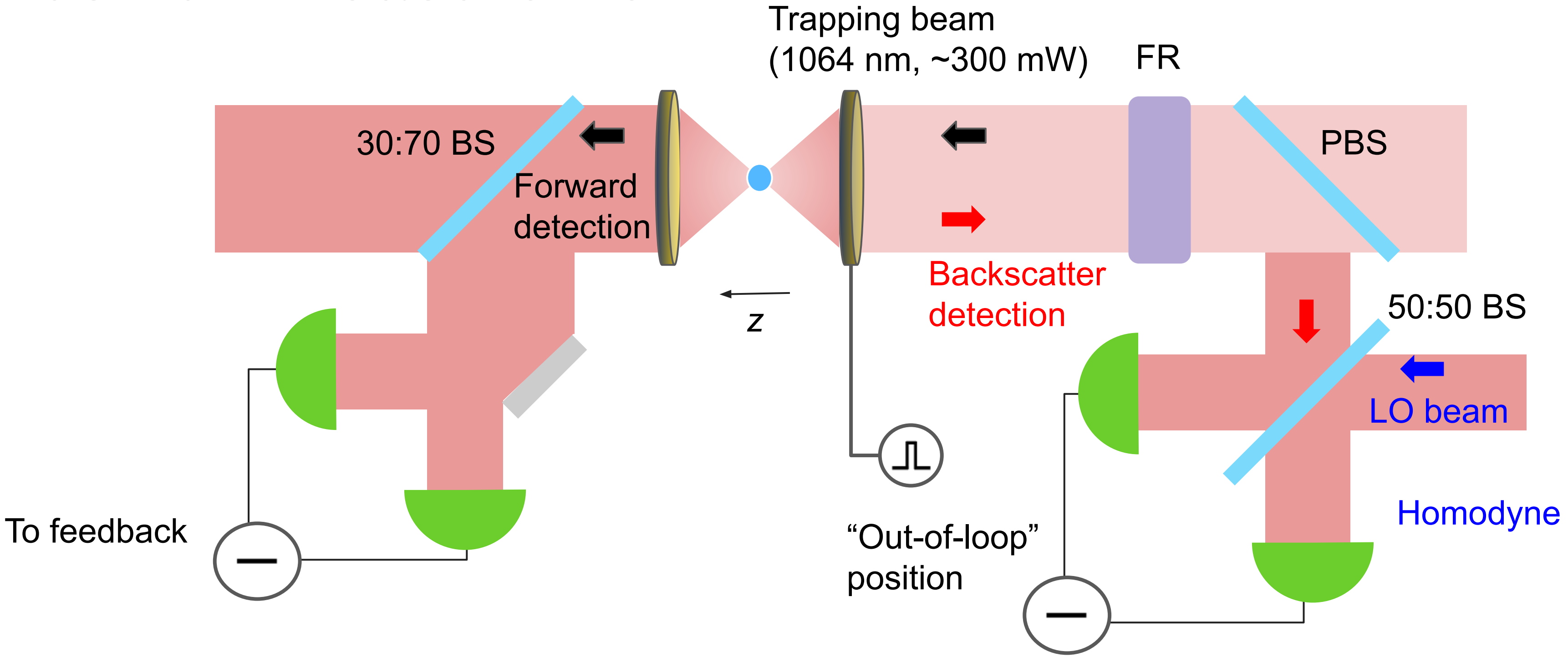
- Ground state cooling + quantum control



(Vienna)

Magrini et al., Nature 595, 373–377 (2021),
See also Tebbenjohanns et al., Nature 595, 378–382 (2021)

Position measurement



Trapping beam
(1064 nm, ~300 mW)

FR

30:70 BS

PBS

Forward
detection

Backscatter
detection

50:50 BS

LO beam

Homodyne

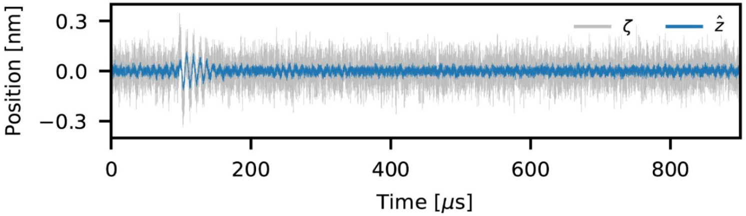
z

To feedback

“Out-of-loop”
position

- Monitor sphere position via forward/backward scattered light
- Identify instantaneous momentum transfer that gives a “kick”

Magrini et al., Nature 595, 373–377 (2021)



Impulse sensing

- Scattered light carries position information; “weak continuous measurement”

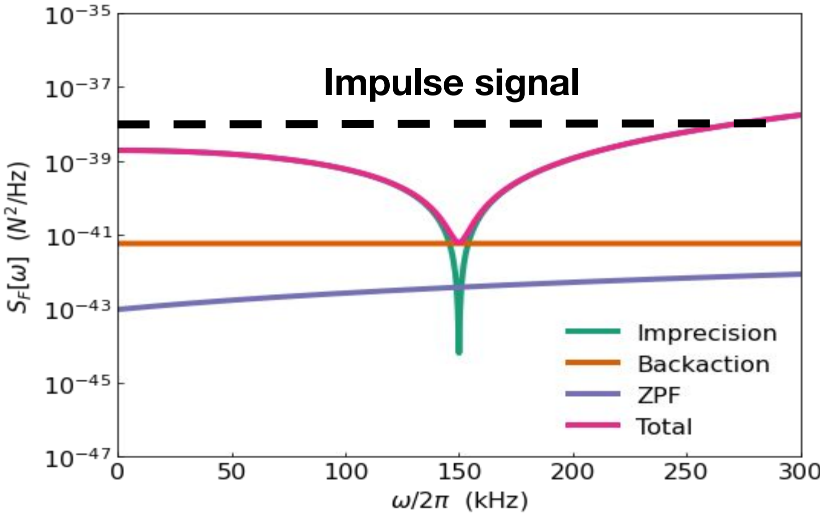
- **“Standard Quantum Limit”**

  Smallest detectable momentum “kicks”

$$(\Delta p)_{SQL} = \sqrt{\hbar m \Omega_0}\ , \ \ \Delta p \approx F \cdot \delta(t).$$

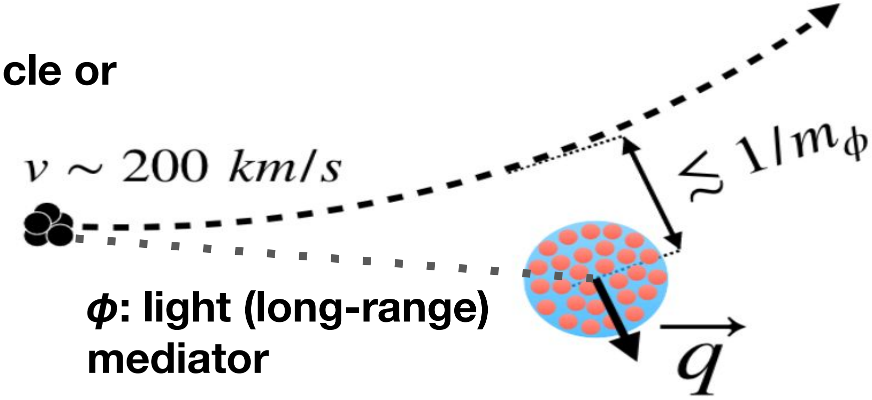
~ **15 keV /c** (150 nm sphere @150 kHz)

Clerk, PRB 70.24, 245306 (2004)



Recoil-based dark matter searches

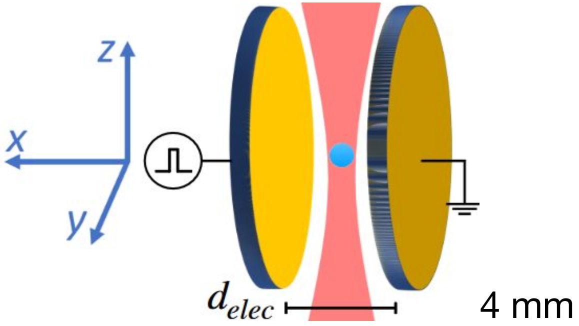
Dark matter: single particle or composite “nugget”



ϕ: light (long-range) mediator

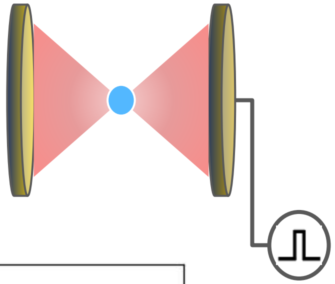
- Generic “fifth force” DM-nucleon coupling
- Instantaneous impulses: $\Delta t \ll 1$ ns, versus sphere response time ~10 μs
- **Strategy: monitor sphere position and wait for rare, unexpected “kicks”**

Proof-of-principle search with a 10 μm silica microsphere:

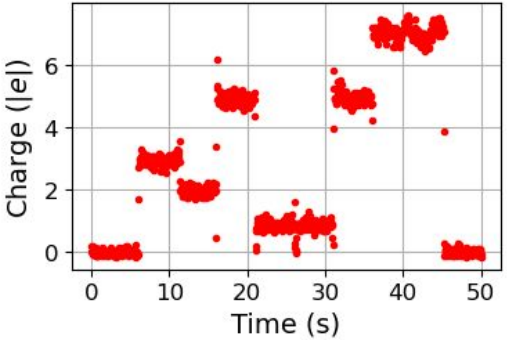


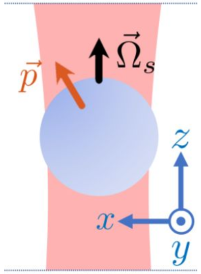
Monteiro et al., PRL 125, 181102 (2020)

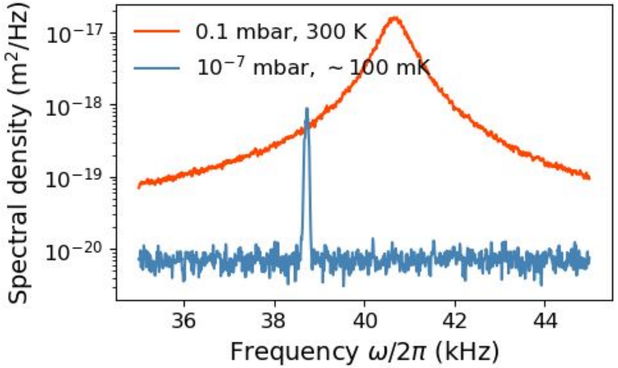
Sensitivity calibration



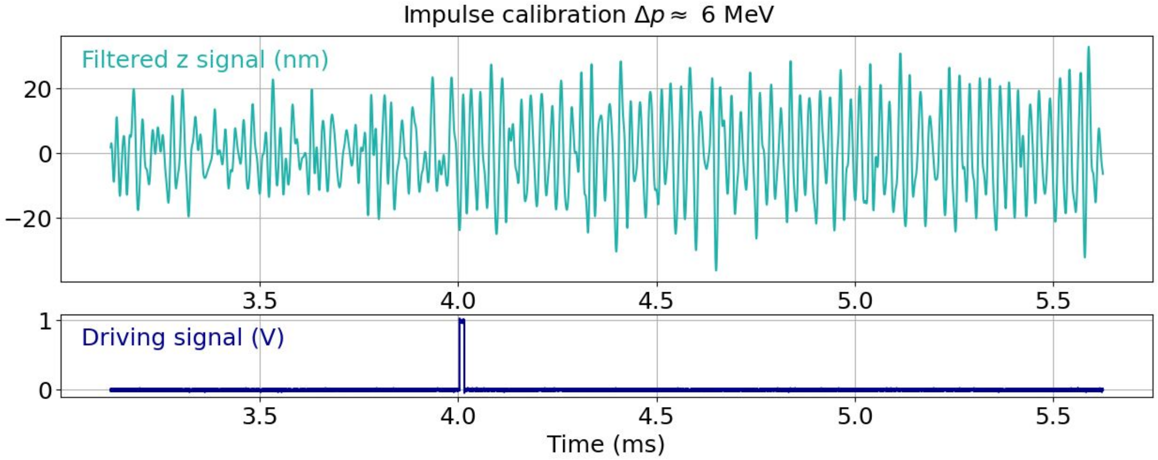
- Control on charge, spin, and COM temperature







- Direct calibration with known electric pulses

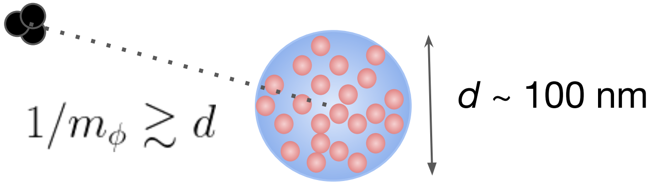


DM sensitivities

- Low detection thresholds (Δ*p* ~ 15 keV/c) with small sizes (*d* ~ 100 nm) probe lighter dark matter and heavier mediators

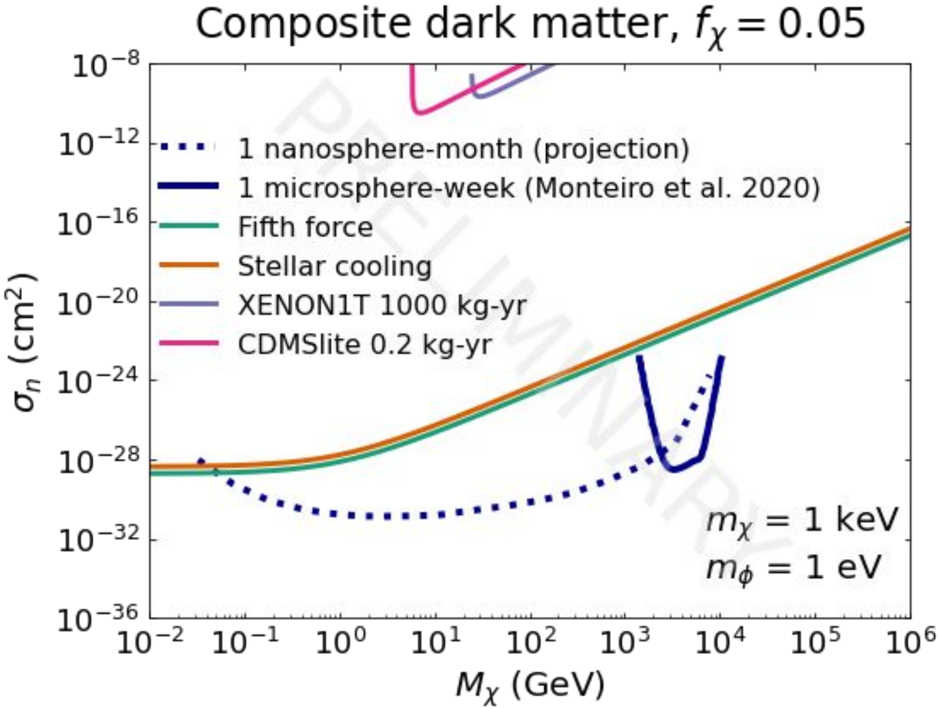
- Coherent scattering cross section

$$\sigma_{\mathrm{coherent}} \propto N_n^2 \sim 10^{18}$$



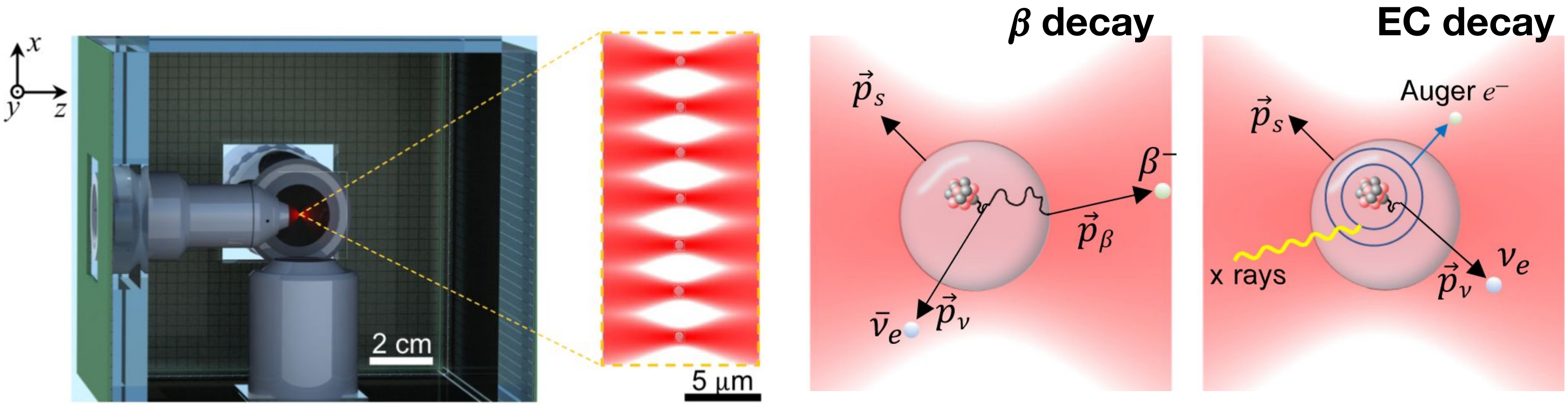
- Also probes sub-GeV single particle DM with a heavy/light mediator

See Afek et al., PRL 128, 101301 (2022)



Sterile neutrinos

- With isotope-doping (β or EC emitters) and secondary particle detectors, a recoil measurement allows reconstruction of ν momentum



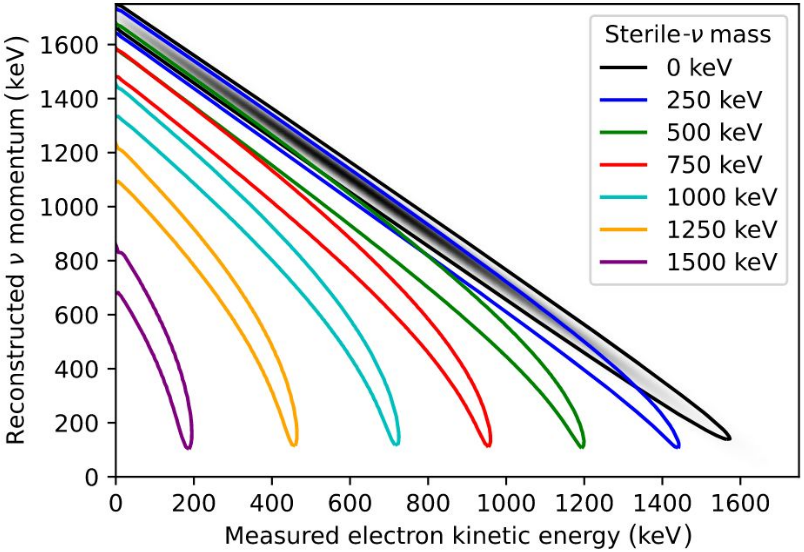
D. Carney, K. Leach, and D. C. Moore, "Searches for massive neutrinos with mechanical quantum sensors," PRX Quantum 4, 010315 (2023) arXiv:2207.05883

- Search for kev-scale sterile ν and "invisible" particles in nuclear decays

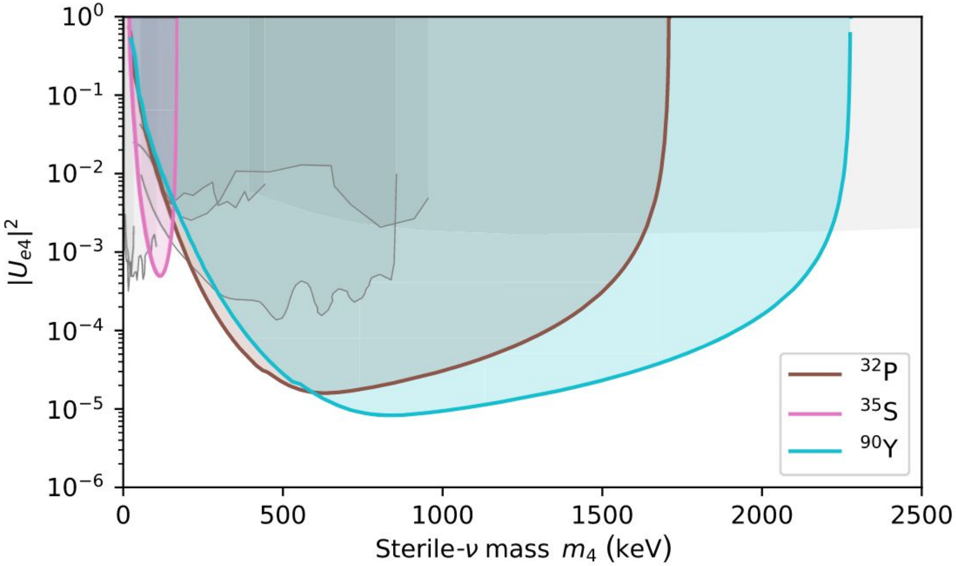
Sterile neutrinos

- Search for kev-MeV scale sterile ν

Example β decay (^{32}P)



1 sphere-month constraints with β-isotopes



- Moderate exposure with existing technologies gives orders of magnitude improvement
- Proof-of-principle α-recoil detection underway!

Summary

- We are developing new levitated optomechanical sensors, with applications at the precision frontier of particle and nuclear physics!

The QuIPS team at Yale:
(Quantum Invisible Particle Sensor)

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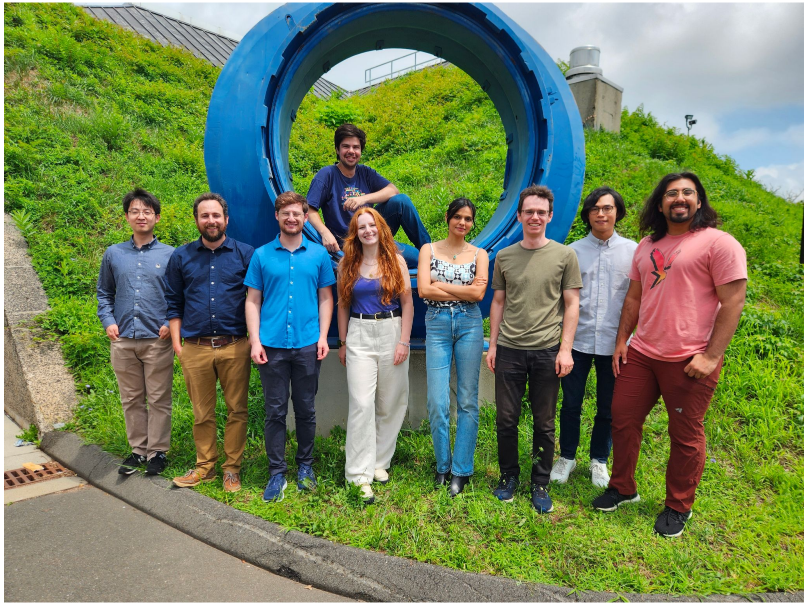


Existing constraints on steriles

- A wide variety of searches have been performed for sterile ν:

Mass range (laboratory):

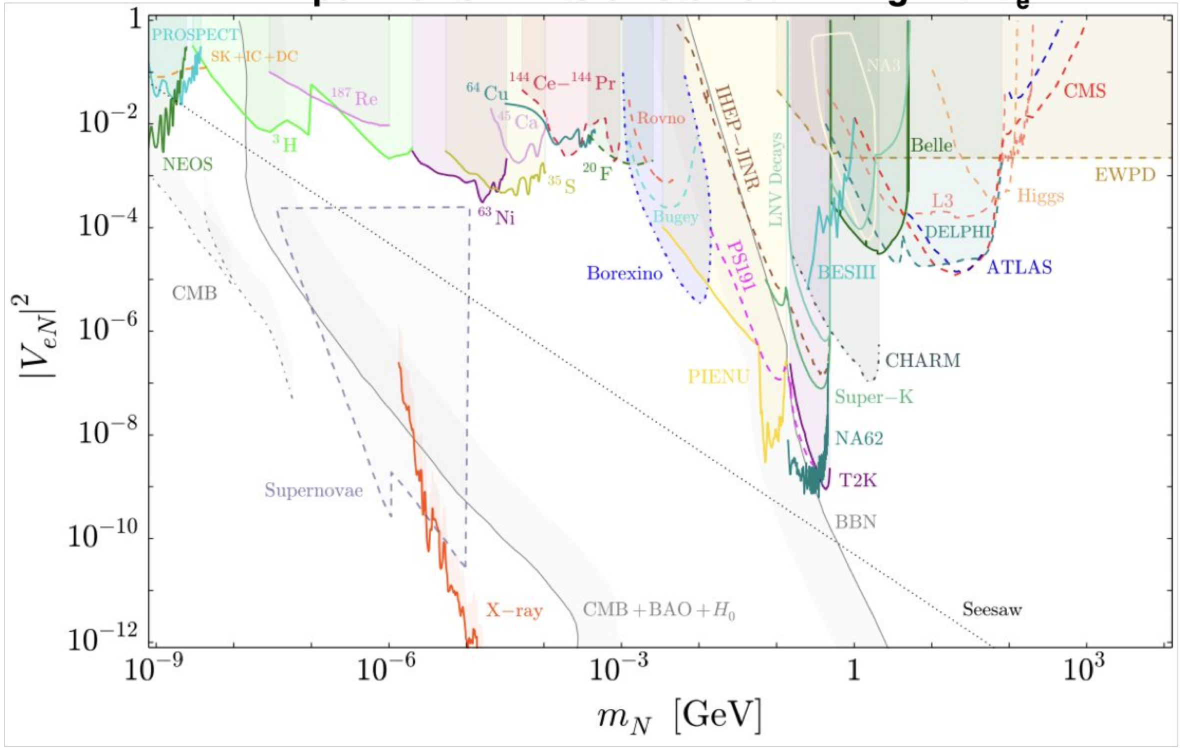
~eV: Short-baseline oscillations, reactors, ^{3}H spectrum

~keV – MeV: Beta decay spectra

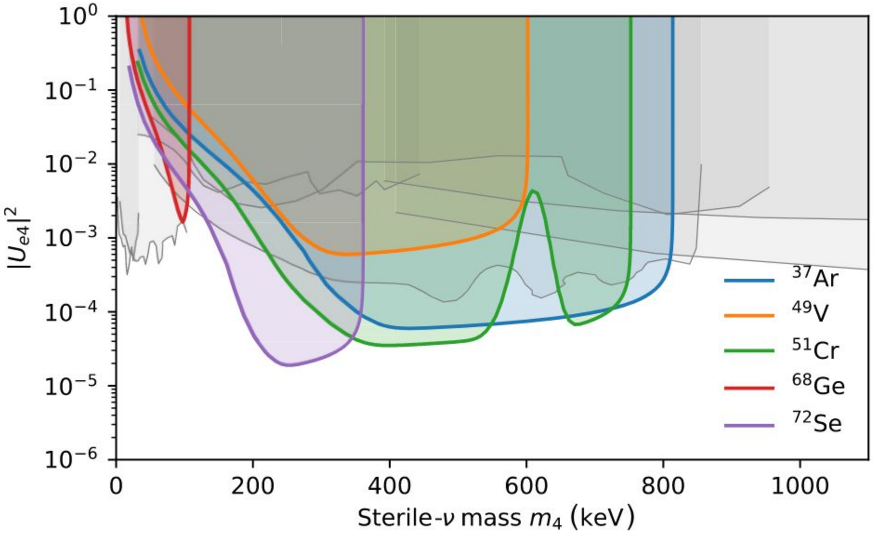
>MeV: Heavy neutral leptons at accelerators

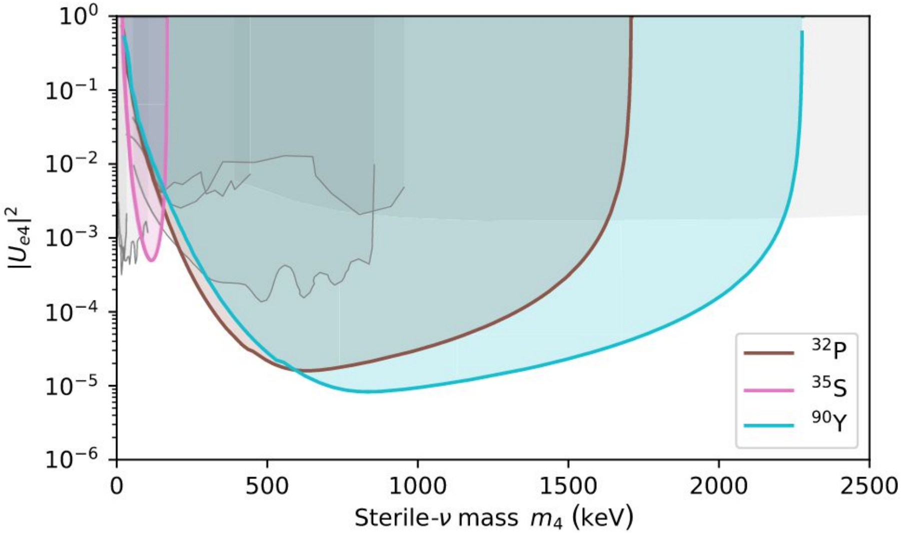
- If sterile ν constitute significant fraction of DM, strong x-ray constraints exist
- ~keV sterile ν with mixing ~10^{-10} are a viable DM candidate

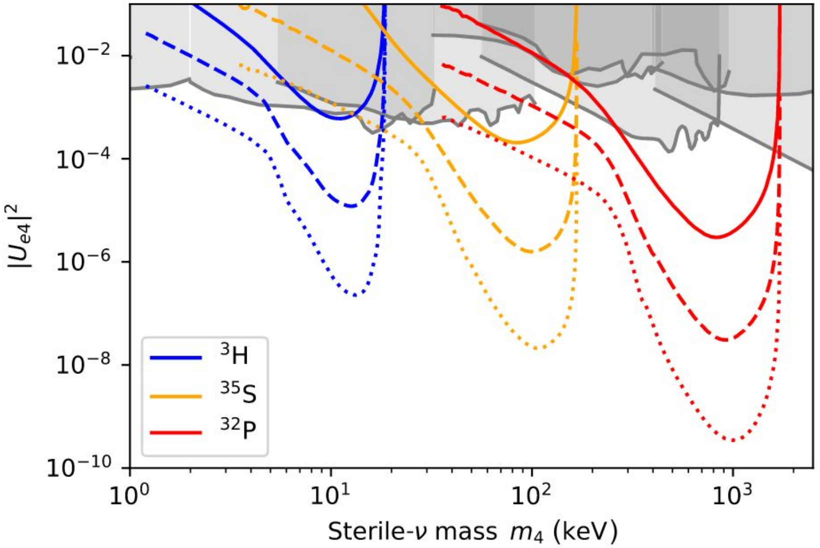
Experimental limits on sterile ν mixing with ν_e:



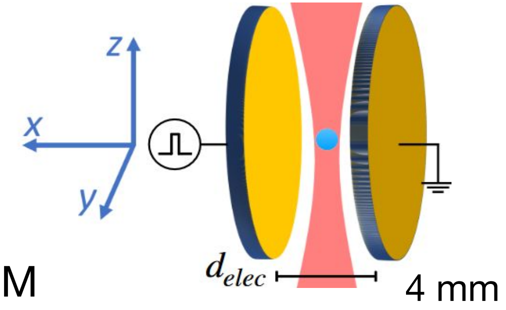
Bolton et al., JHEP 2020, 170 (2020), arXiv:1912.03058


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|U_{e4}|^2$
0
200
400
600
800
1000
Sterile-ν mass m_4 (keV)
^{37}Ar
^{49}V
^{51}Cr
^{68}Ge
^{72}Se

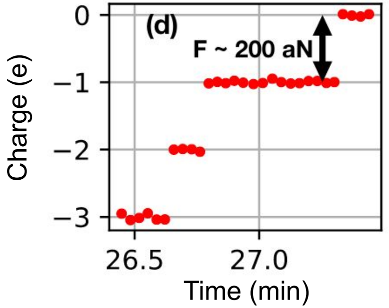

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|U_{e4}|^2$
0
500
1000
1500
2000
2500
Sterile-ν mass m_4 (keV)
^{32}P
^{35}S
^{90}Y

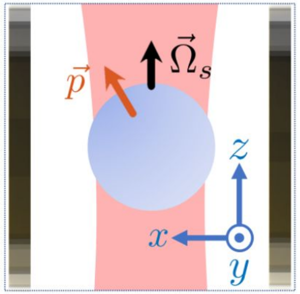

10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$|U_{e4}|^2$
10^0
10^1
10^2
10^3
Sterile-ν mass m_4 (keV)
^{3}H
^{35}S
^{32}P

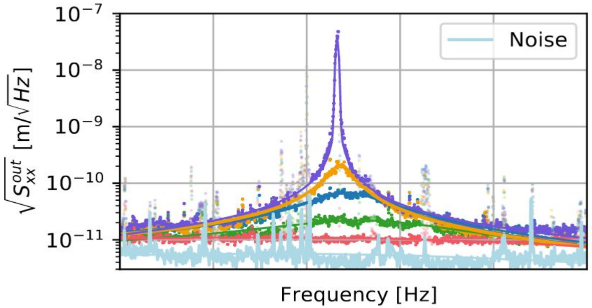
Proof-of-principle DM search



- 10 μm microsphere, 7 days of exposure
- Control on charge, spin, dipole orientation (if needed), and COM

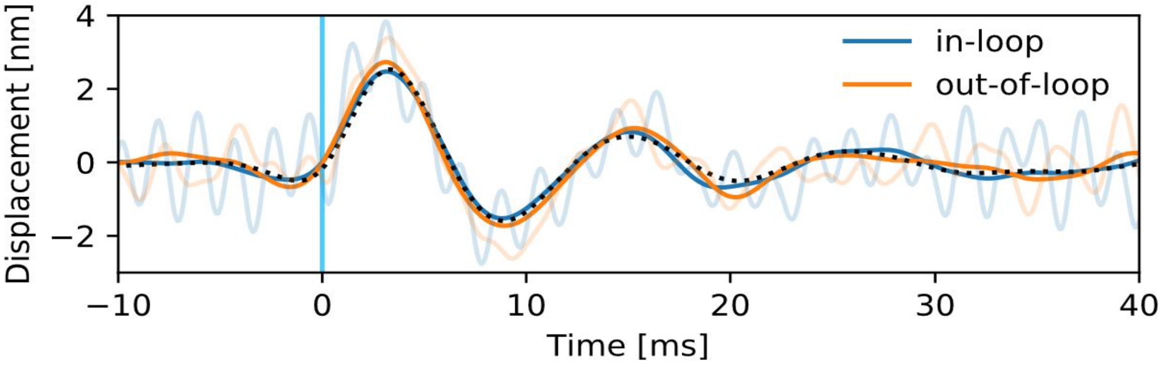


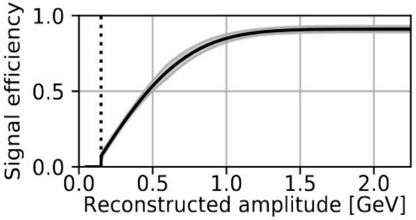




Afek et al., PRA 104, 053512 (2021)
Monteiro et al., PRA 101, 053835 (2020)

- Direct calibration of impulse sensitivity (~150 MeV /c)





Constraining DM-neutron coupling

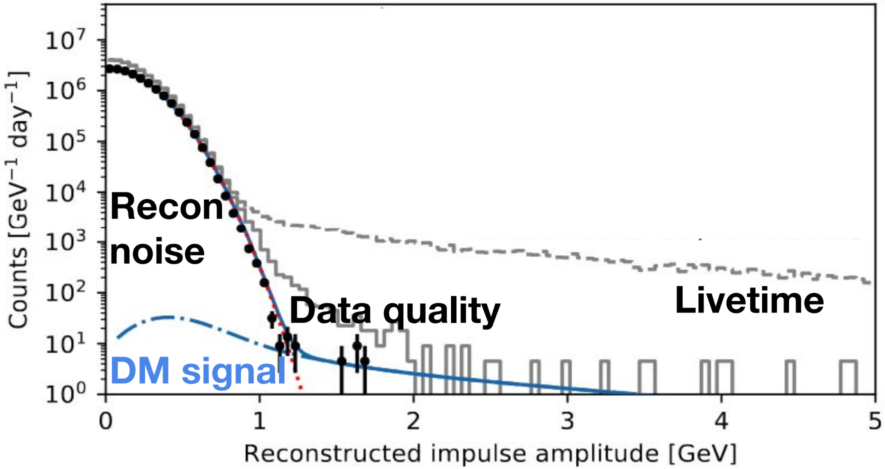
- Dominant background is spurious environmental noise

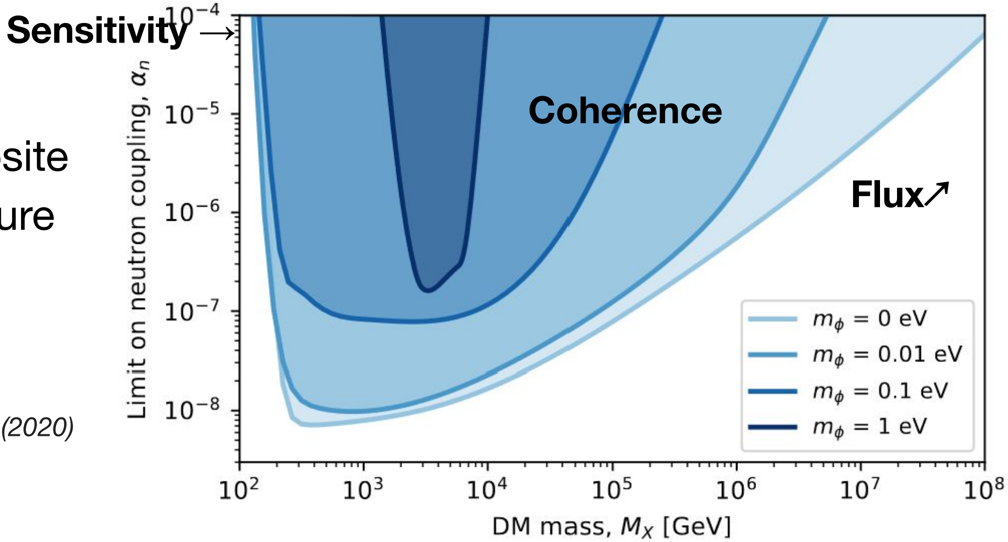
- Coherence over entire detector is maintained for light mediators

$$(\text{Rate}) \propto \underbrace{N_t^2}_{\sim 10^{29}} \cdot \sigma_n$$

- World's best limits on some composite DM models with a moderate exposure

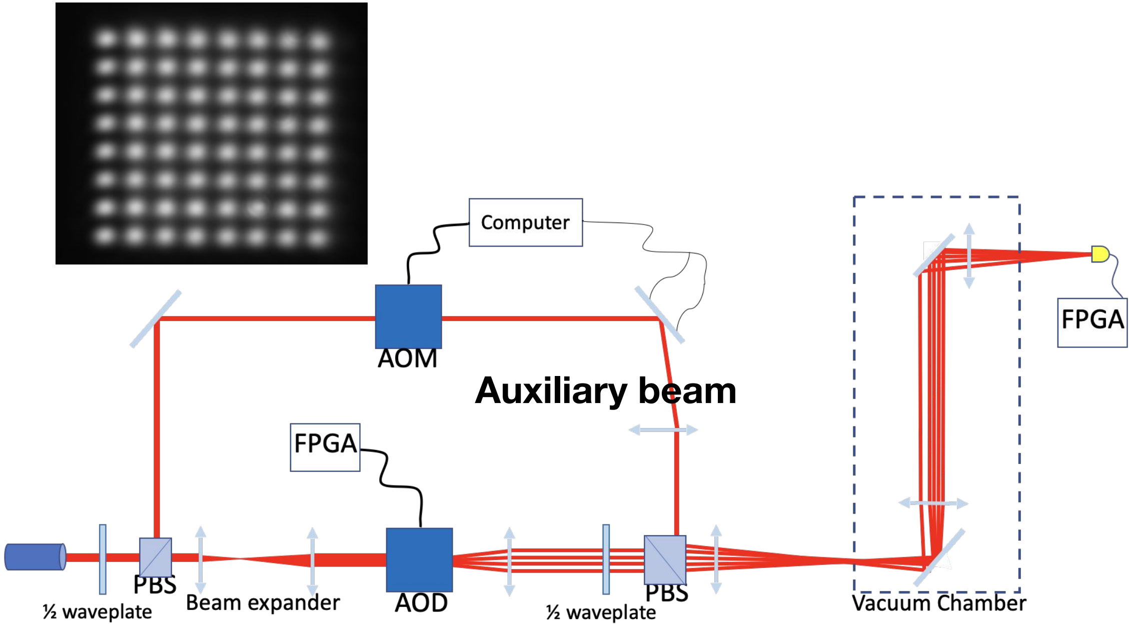
Monteiro et al., PRL 125, 181102 (2020)





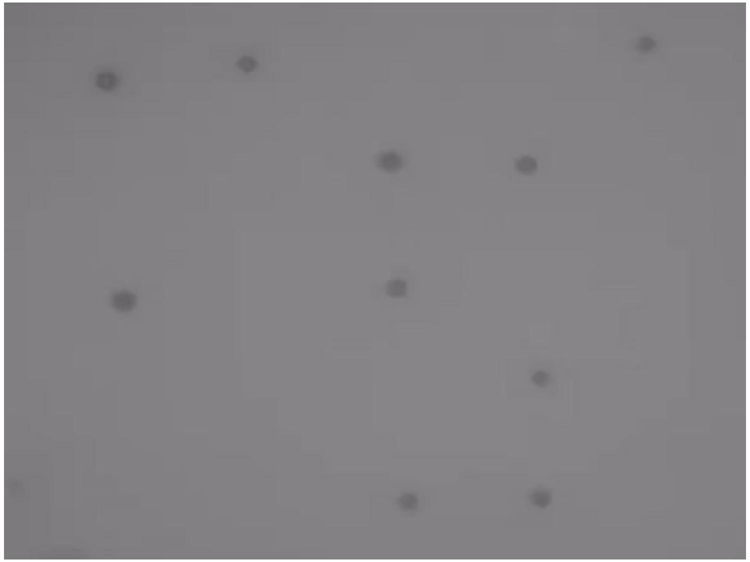
Scaling up: microsphere array

- A large array of sensors probes smaller couplings and reject common background
- Time sharing 2D array achieved by an acoustic-optic deflector (AOD) - independent control on each trapped microsphere



Trapping beams

Can trap ~10 spheres with standard loading techniques



Ben Siegel (Yale)

Scaling Loading Technique

For a single trap:

Stochastic dropper loading

- Many spheres fall per trial
- Field standard for loading

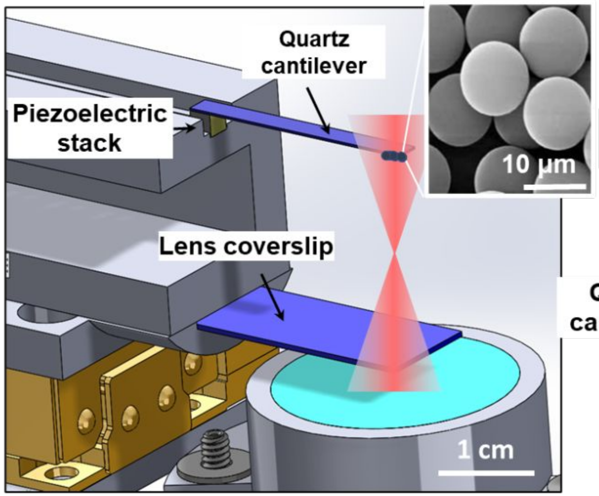
For multiple traps:

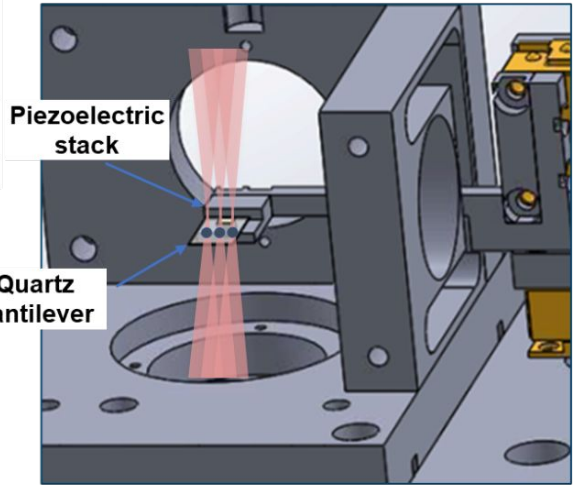
Controlled loading

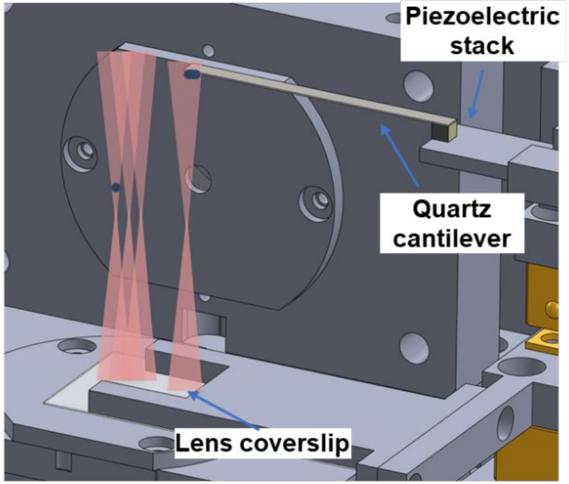
- Lower chance knocking out neighboring spheres
- Unviably low success rate

Stochastic loading with controlled array filling

- Avoids unwanted interactions

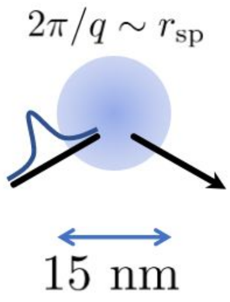






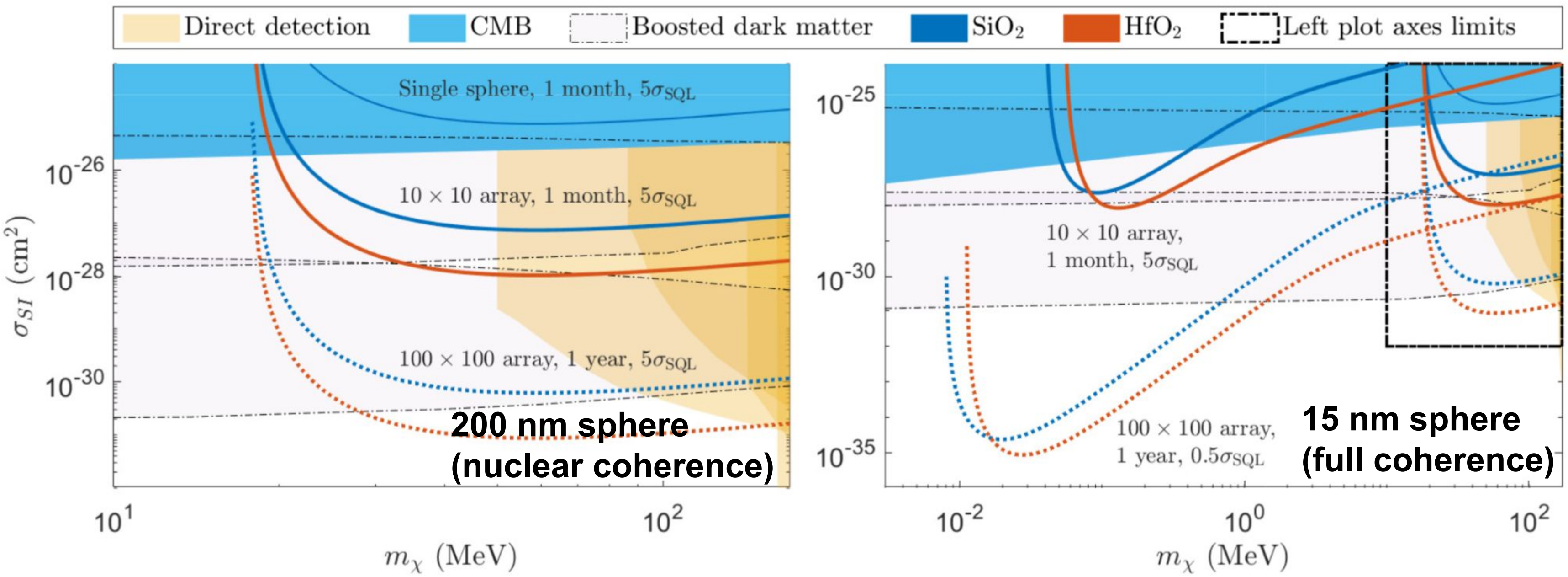
Slide by Ben Siegel (Yale)

Coherent scattering with nanospheres



- Trapped ~15 nm spheres offer even lower detection thresholds
    - Detectable impulses are coherent over the entire sphere, even for short-range interactions

Heavy mediator



200 nm sphere (nuclear coherence)

15 nm sphere (full coherence)

Afek et al., PRL. 128, 101301 (2022)