Levitated Xenon Sensors for Precision Measurements

Siddhant Mehrotra, Lucas Darroch, Sylvie Sanok Dufallo, & David Moore

CPAD - RDC 8: Quantum & Superconducting Sensors

October 21st, 2026

Yale

Wright Laboratory

Moore Lab

Simple

***S**earch for new **I**nteractions in a **M**icrosphere*
***P**recision **L**evitation **E**xperiment*

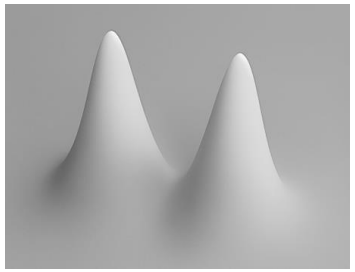




Dark Matter



Neutrinos



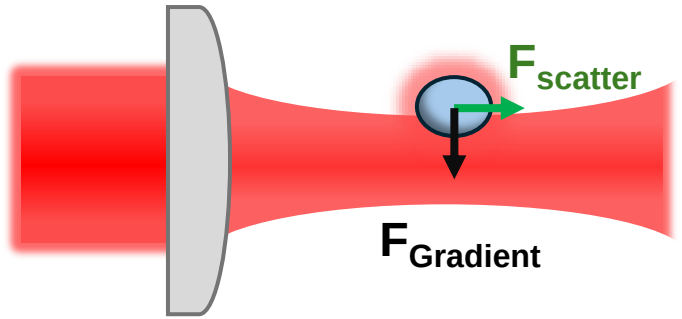
Gravity

Jackie Baeza-Rubio
Lucas Darroch
Clarke Hardy
James Kingston
Cecily Lowe
Aaron Markowitz
Siddhant Mehrotra
David Moore
Joaquin Fernandez Odell
Yu-Han Tseng
Molly Watts

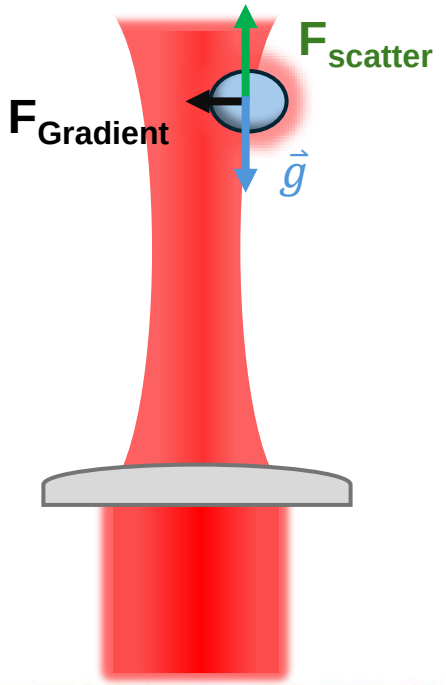
NSF
U.S. DEPARTMENT OF ENERGY Office of Science
GORDON AND BETTY MOORE FOUNDATION
ALFRED P. SLOAN FOUNDATION
Office of Naval Research ONR Science & Technology

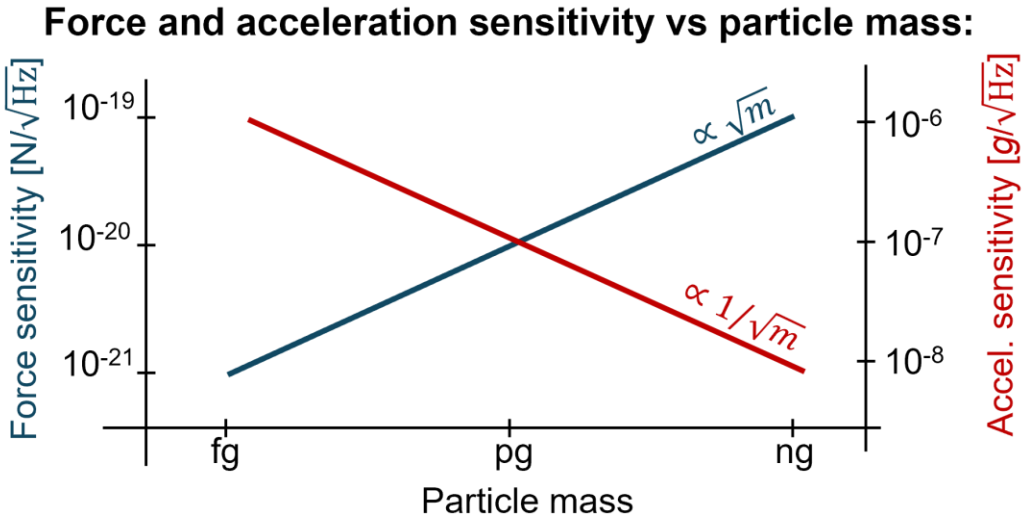
Levitated Mechanical Sensors

- Optically trapped dielectric masses (silica spheres)
  - nm – μm scale (fg – ng)
- Levitation + High Vacuum
  - Thermal, Electrical, Mechanical Isolation
- Impulse and inertial measurements

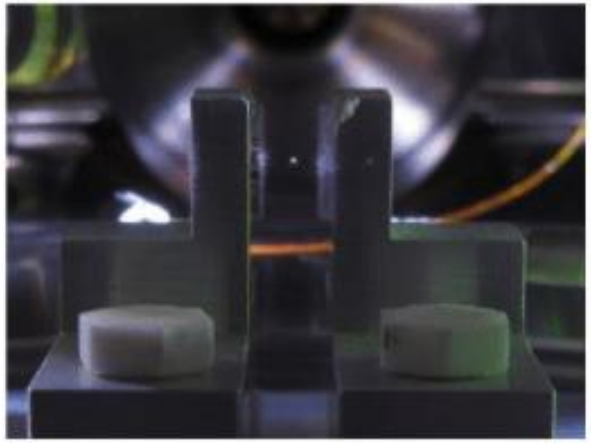


High NA

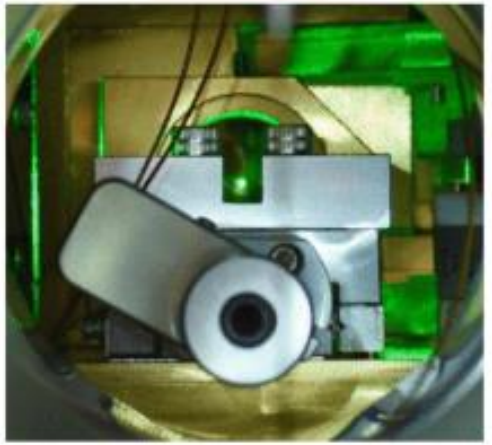




zN Force and nano-g Acceleration Sensitivities



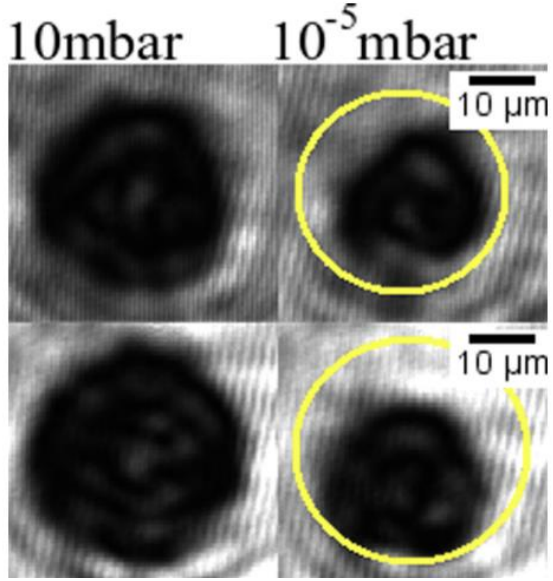
Single beam tweezer
for nanospheres



Levitation ("Gravito Optical")
Trap for microspheres

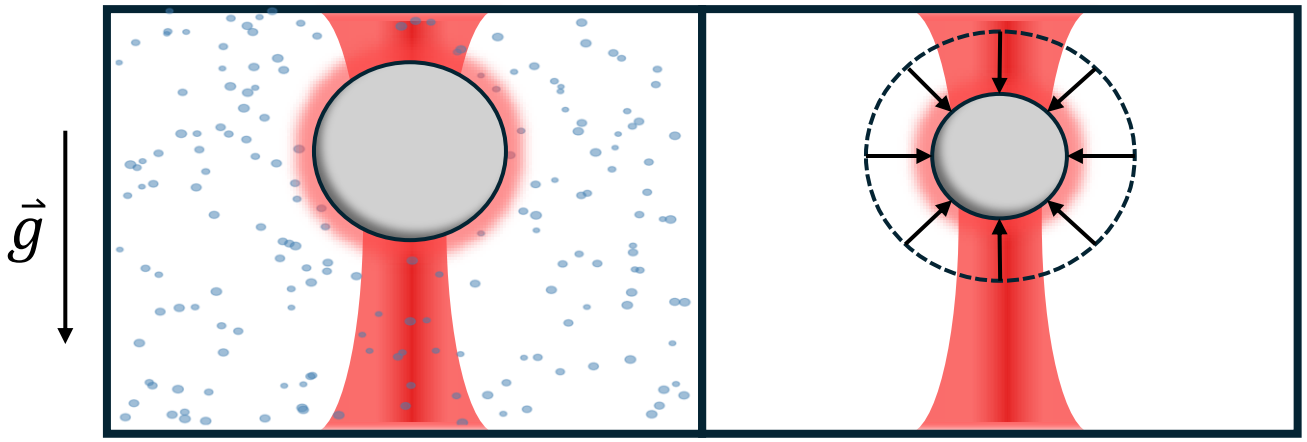
Silica Spheres

- Internal impurities in commercial colloidally grown silica spheres
- Silica spheres are size limited in high vacuum
  - Heating from optical absorption by impurities vaporizes sphere
  - Limits acceleration sensitivity
- Permanent EDMs prevent true electric neutrality
  - Coupling to stray electric fields



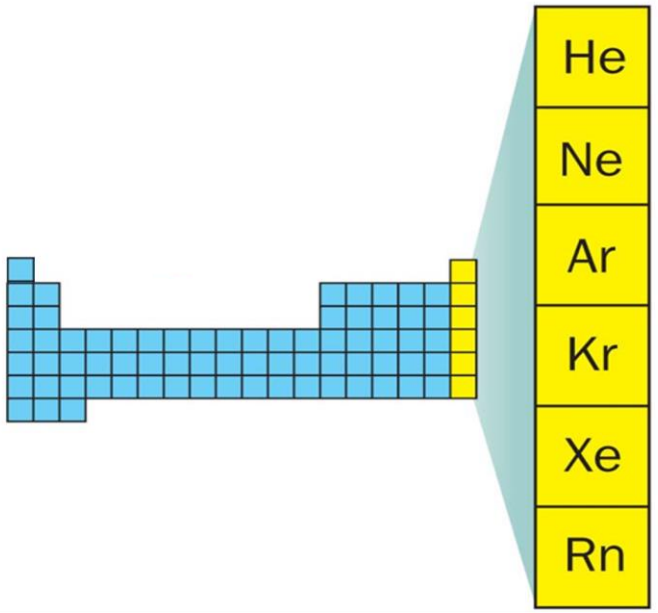
Monteiro et al., PRA 96, 063841 (2017)

$Q_{laser} \approx Q_{blackbody} + Q_{gas}$ Decreasing Pressure $Q_{laser} \gg Q_{blackbody} + Q_{gas}$



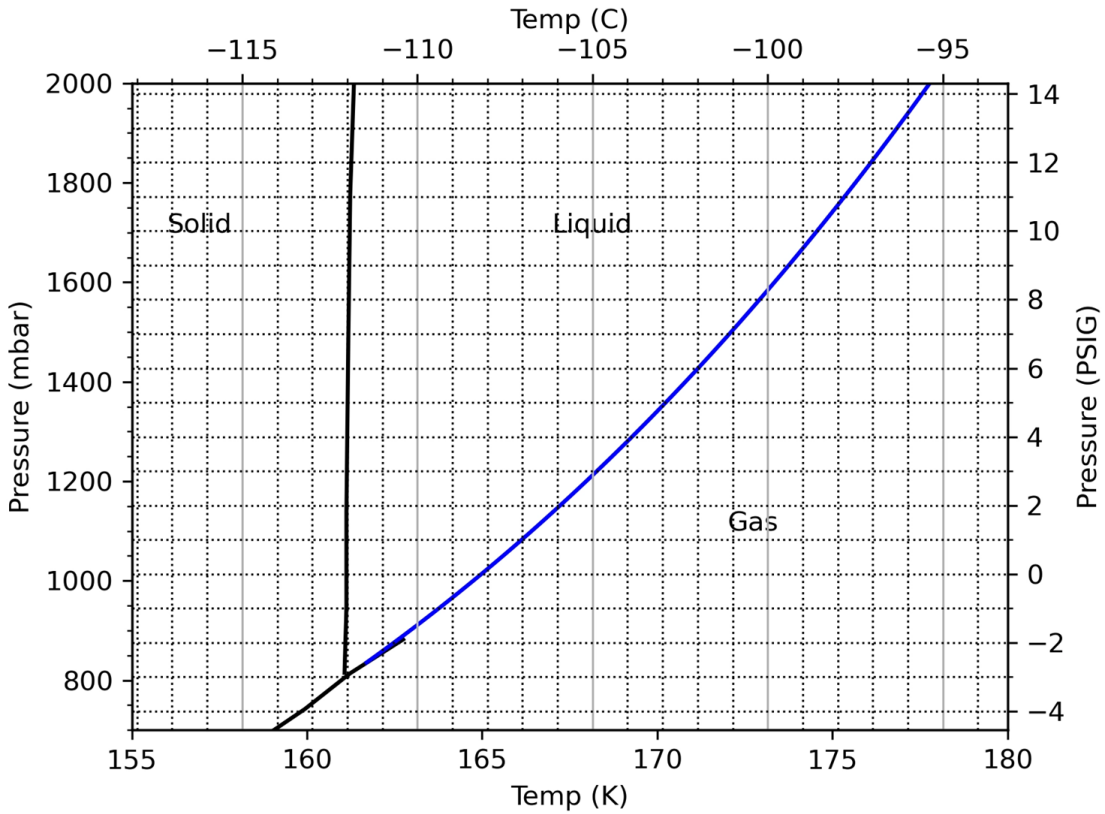
Alternative Sensors: Noble Solids

- Optically Transparent
  - High bandgap
  - No optical phonons
- Optical Purity
  - Established gas purification techniques
  - Achieve ppt impurity levels
- Scintillation
  - Additional signal channel



Alternative Sensors: Noble Solids

- Optically Transparent
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- Optical Purity
  - Established gas purification techniques
  - Achieve ppt impurity levels
- Scintillation
  - Additional signal channel
- Heavier nobles (Ar, Kr, **Xe**)
  - Higher freezing temperatures -> simpler cryogenics
  - Higher density -> increased cross section for coherent interactions (DM, gravity)



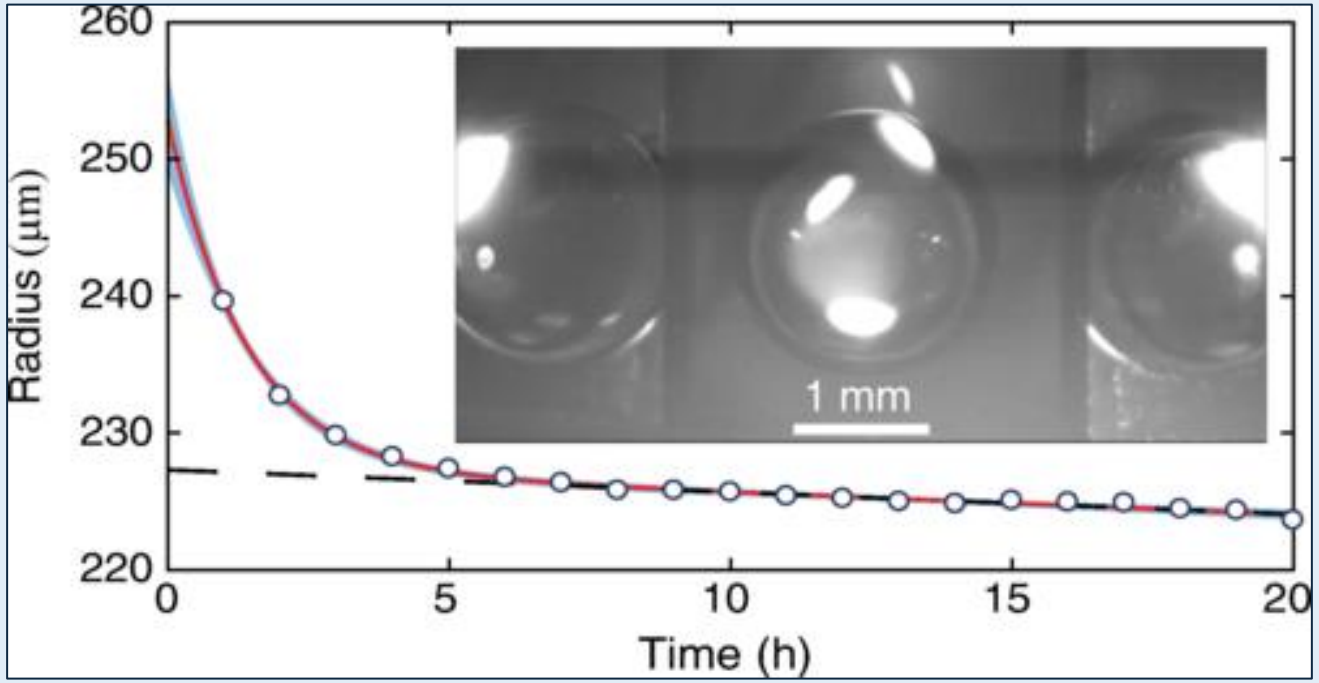
Xe Phase Diagram

Alternative Sensors: Noble Solids

- C
- C
- S
- H

Magnetic and Optical levitation of superfluid He has been demonstrated

- Technical viability of going to HV

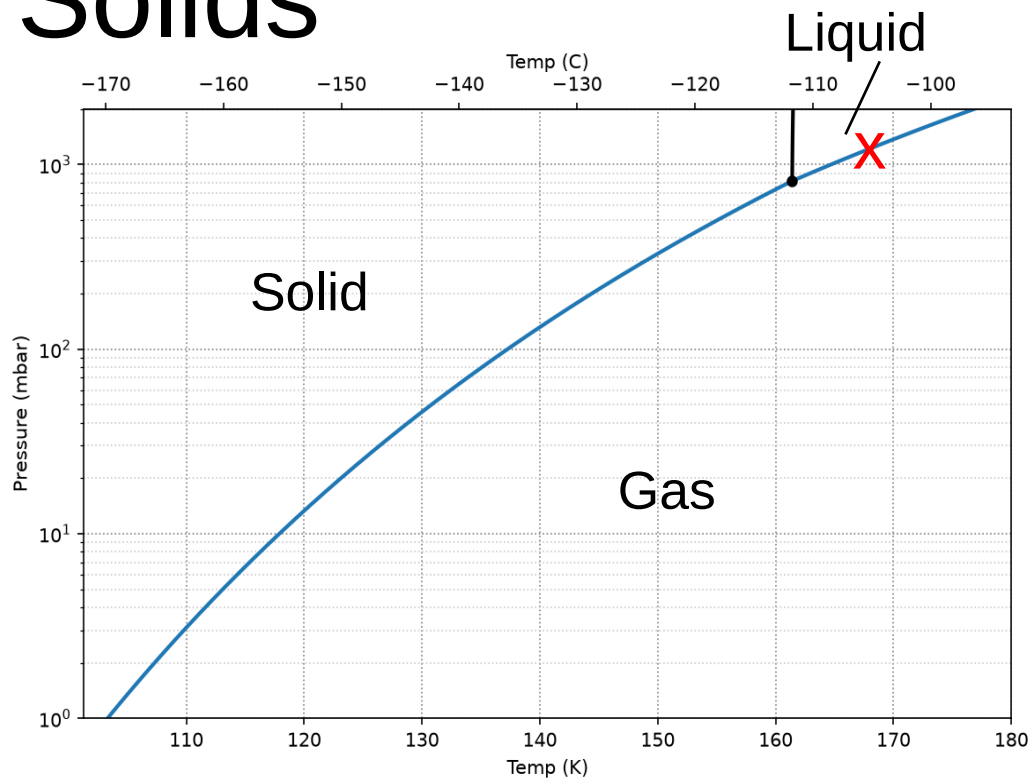


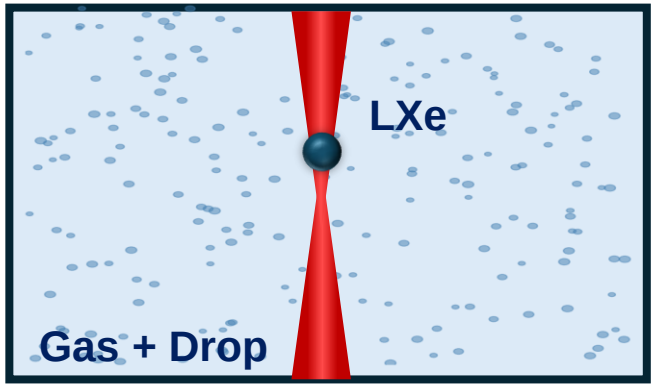
Brown, et al. Phys. Rev. Lett. 130.21 (2023): 216001

Weilert, et al. Journal of low temp. phys. 98.1 (1995): 17-35

Approach to Trapping Noble Solids

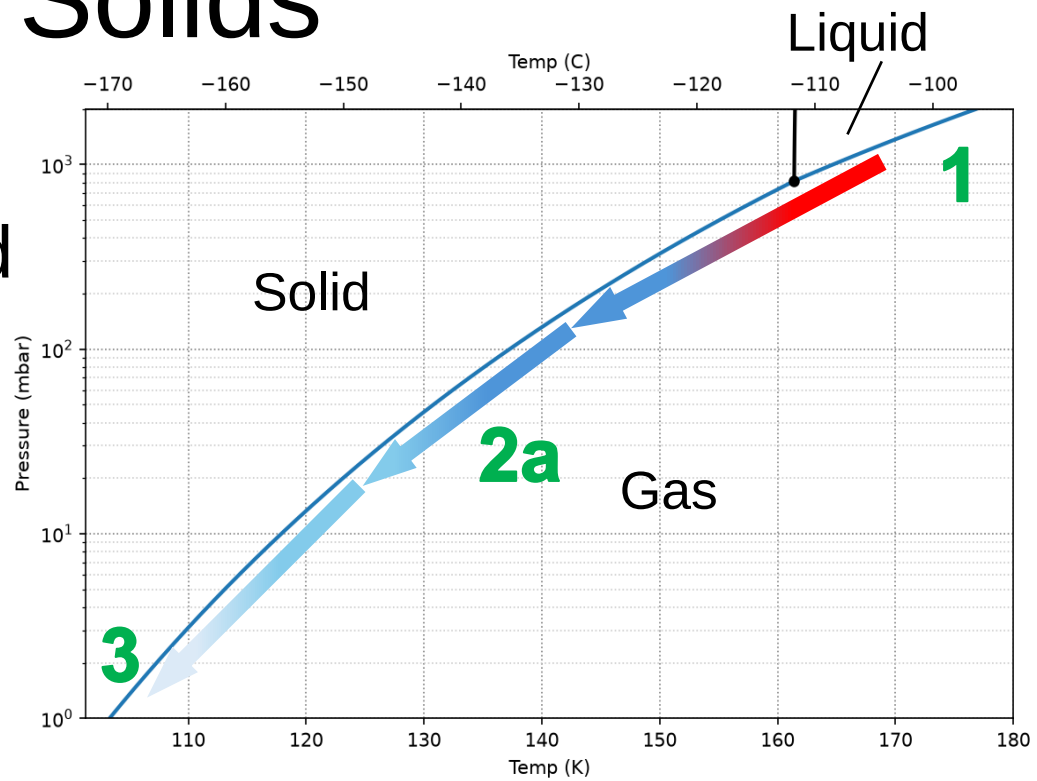
- Goal: Start with a drop in saturated vapor and pump it to HV
  - Freeze in the process

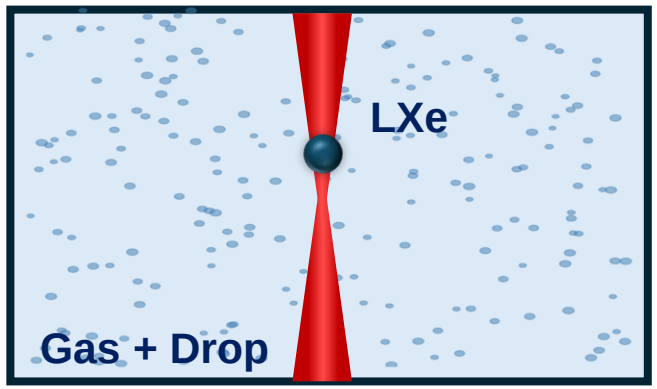


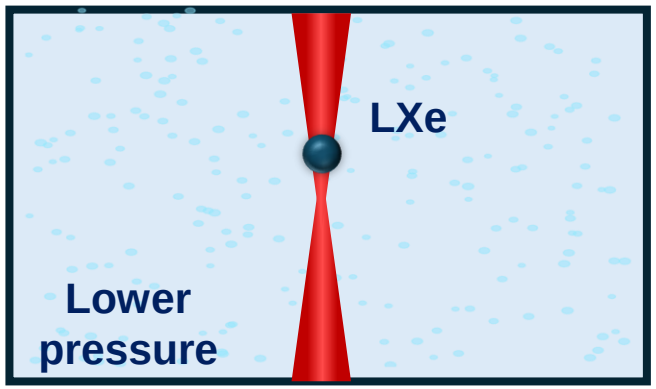


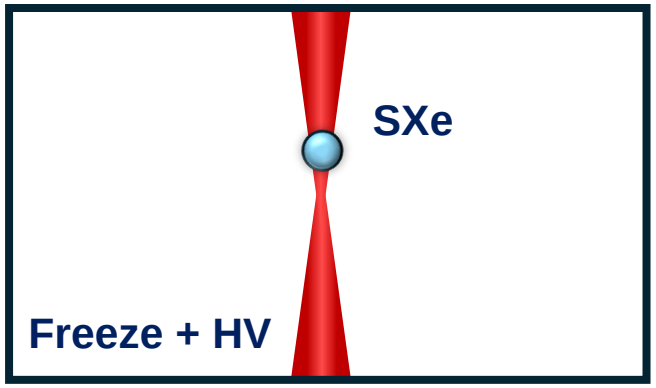
Approach to Trapping Noble Solids

- 2 Approaches:
  a) Gradually follow saturation curve and pass triple point



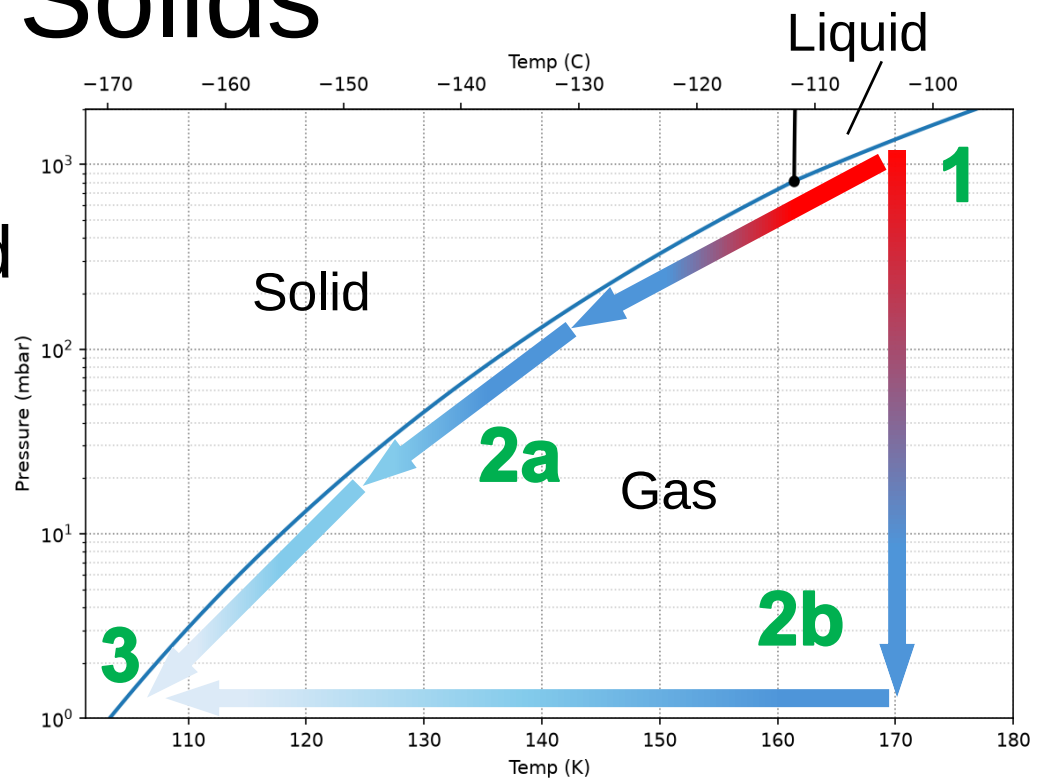


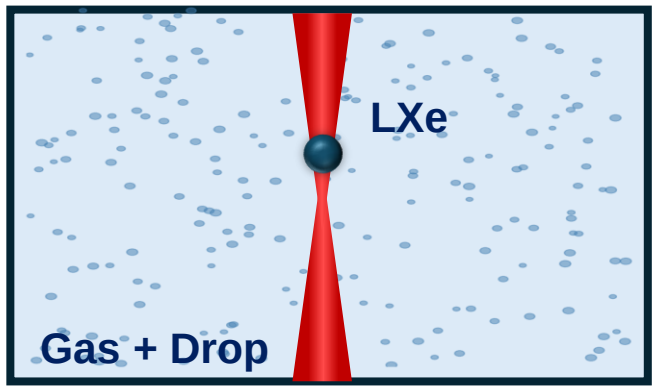


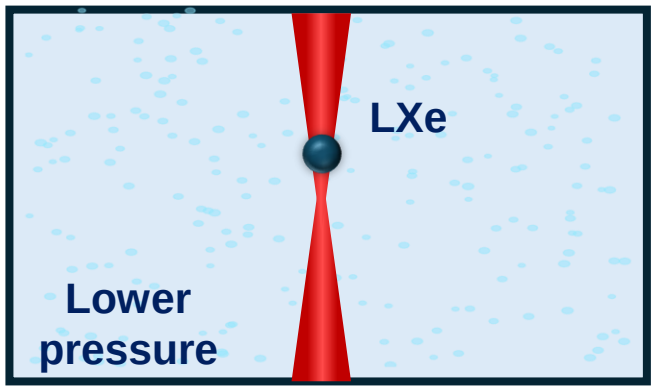


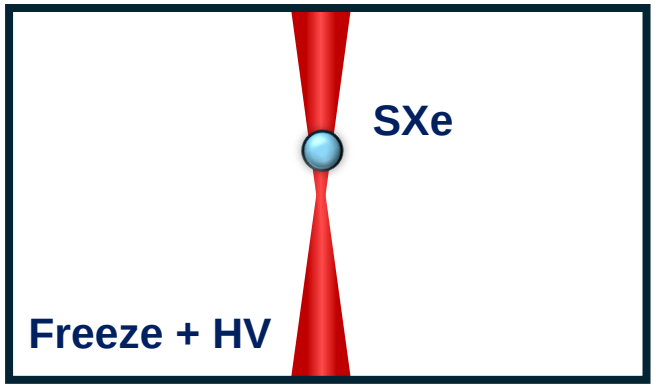
Approach to Trapping Noble Solids

- 2 Approaches:
  a) Gradually follow saturation curve and pass triple point
  b) Quickly pump out gas and evaporatively cool sphere via vapor pressure drop



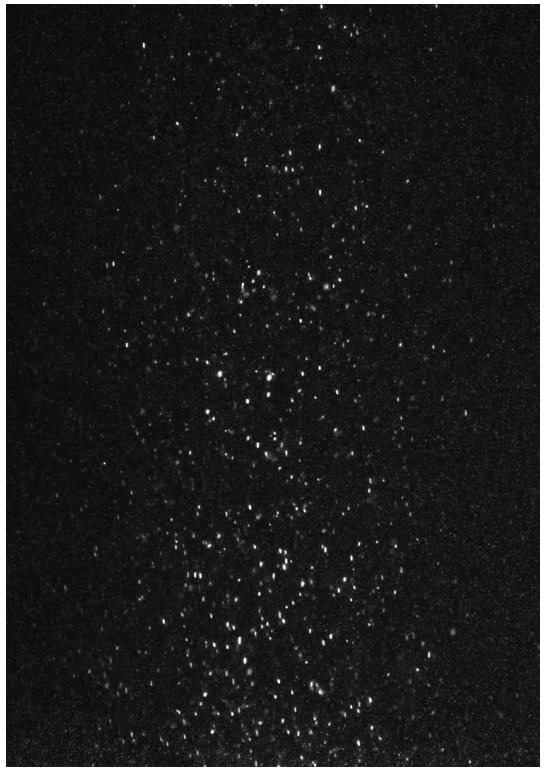






Proof of Concept – Water Trapping

- Test bed for understanding droplet trapping conditions (velocity, density, size)
- Droplets generated in open air from commercial nebulizer

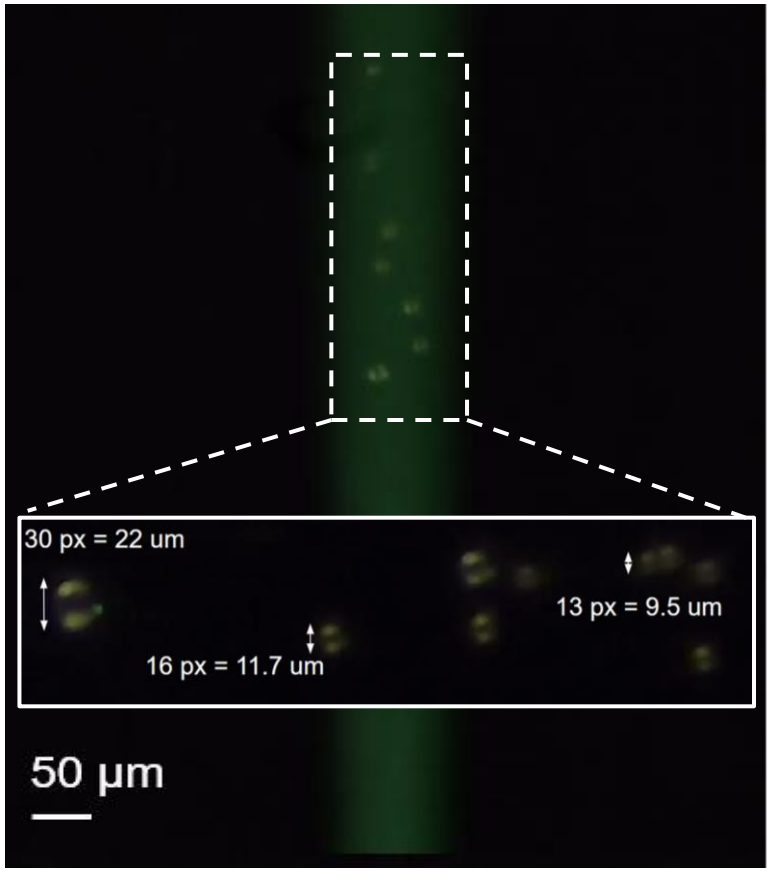


$\vec{g}$

Unfocused beam

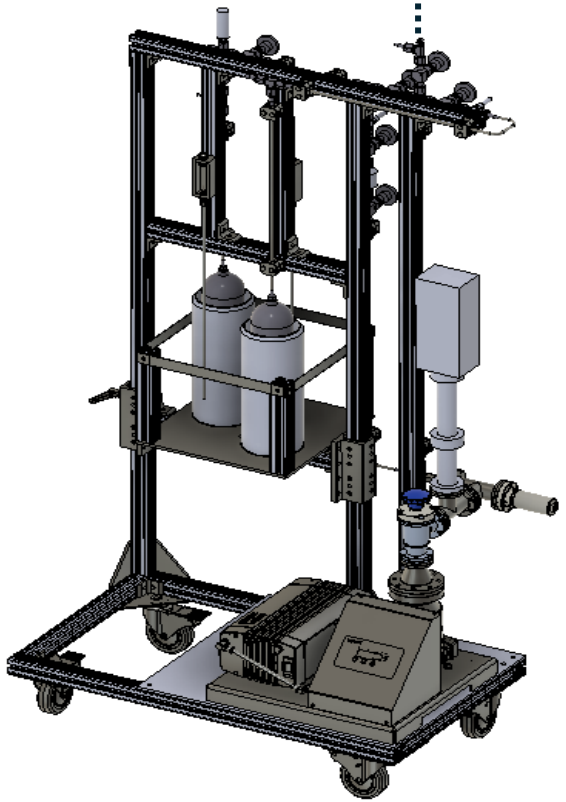


Trapping

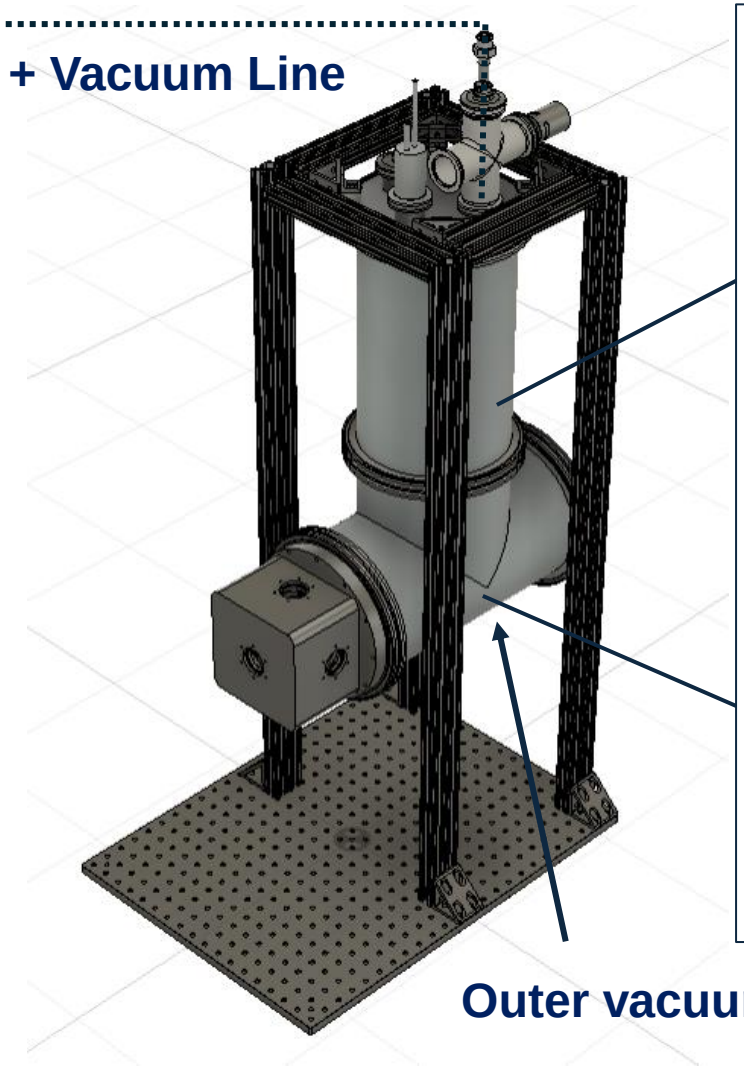


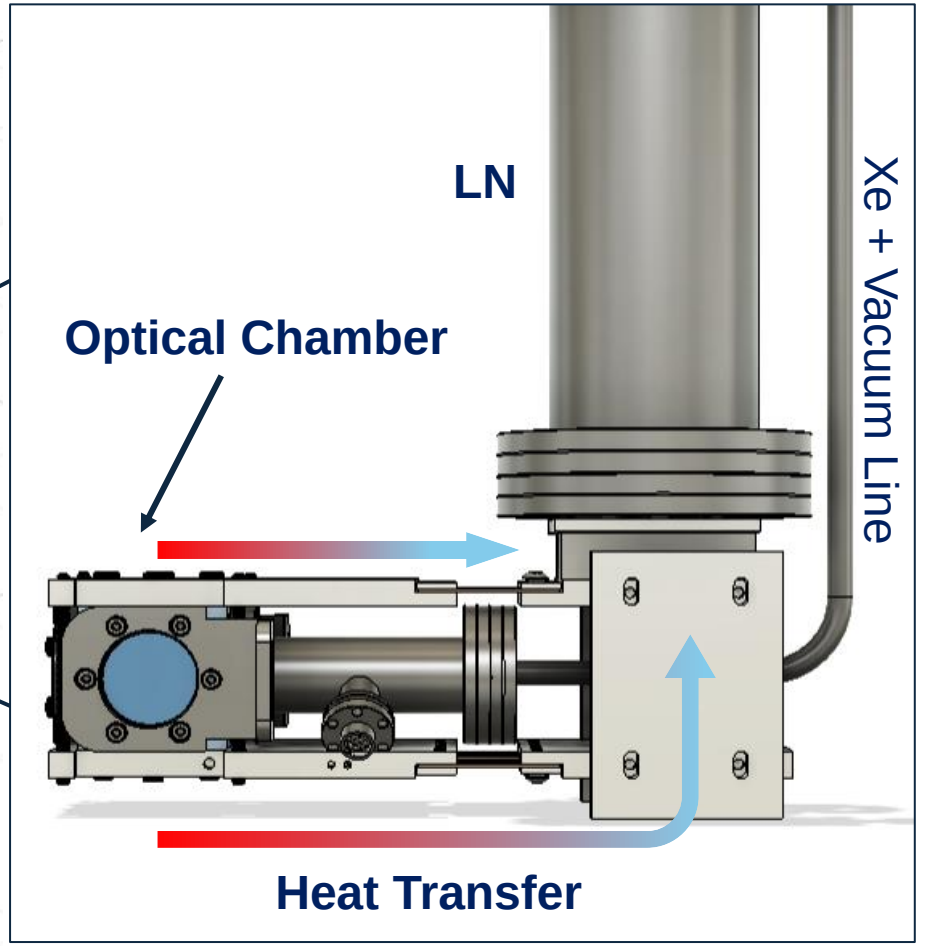
Focused 532 nm laser (~100 mW)

Optical Cryostat



Gas Handling System





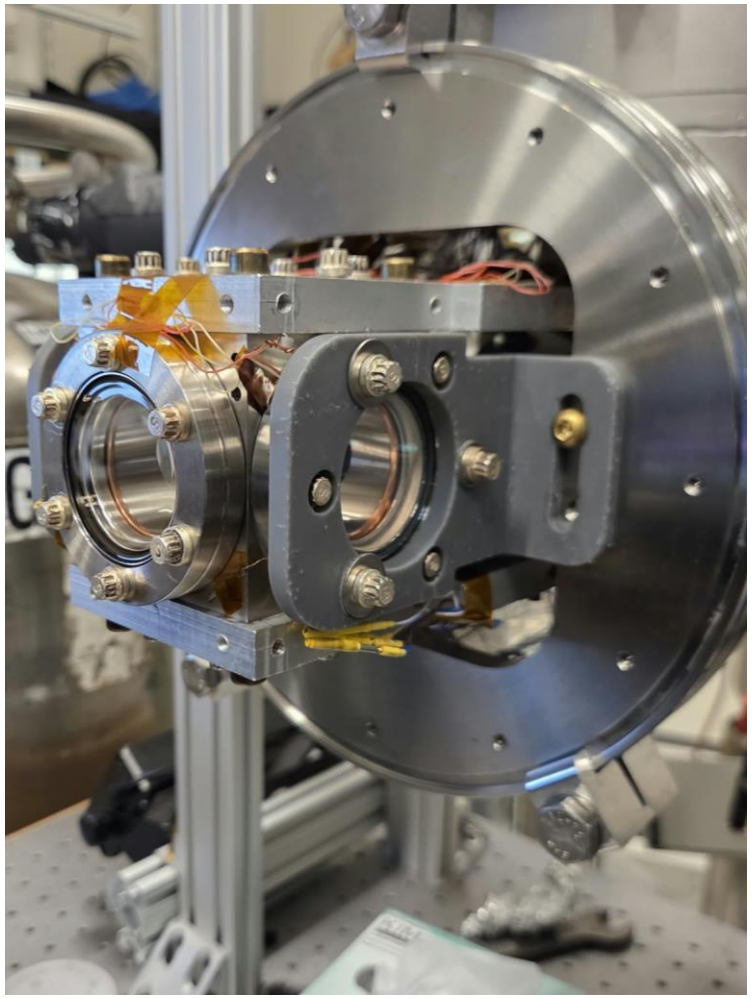
Optical Cryostat



Gas Handling System



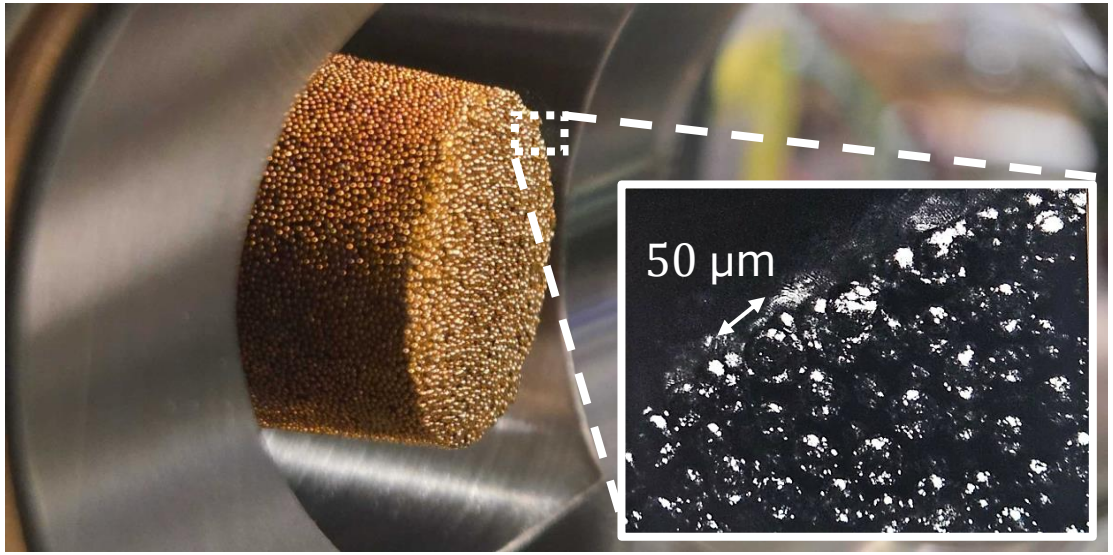
Outer vacuum



Optical Chamber

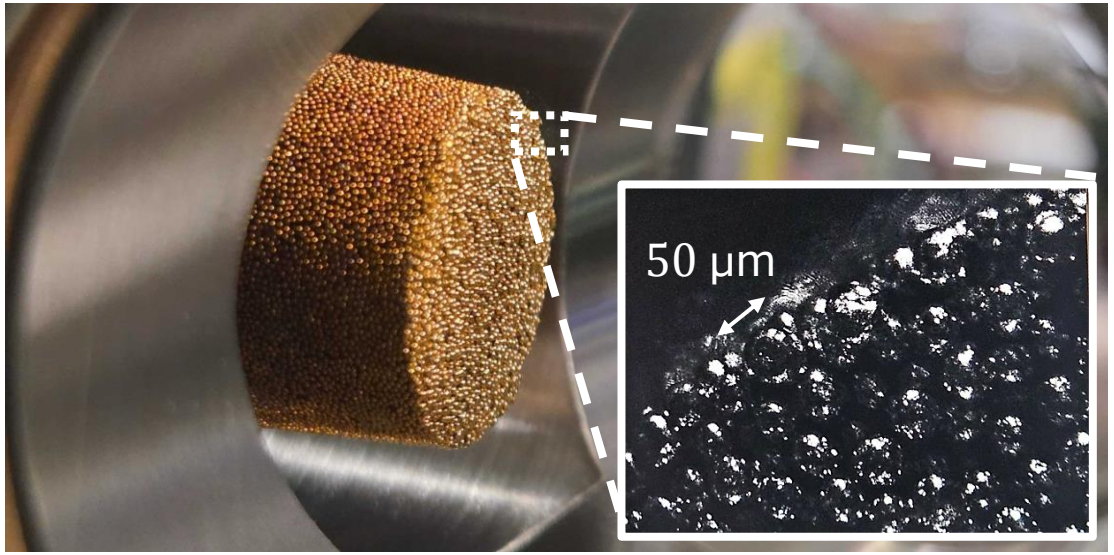
Optical Trapping Attempt

- Cooled sintered muffler at end of Xe fill line
  - Parallel to nebulizer
  - 2-phase separator
  - Gas thermalizes and liquid drops injected into chamber



Optical Trapping Attempt

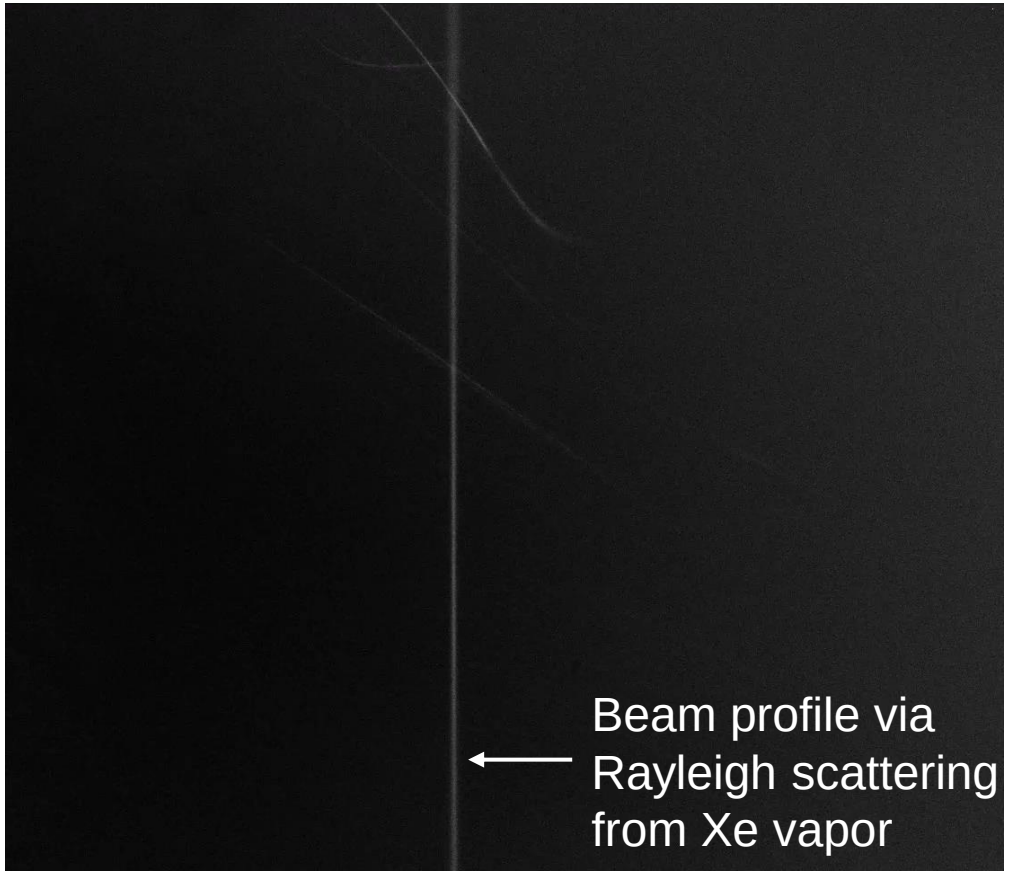
- Cooled sintered muffler at end of Xe fill line
  - Parallel to nebulizer
  - 2-phase separator
  - Gas thermalizes and liquid drops injected into chamber



Focused trapping beam

+ Unfocused imaging beam

$\vec{g}$

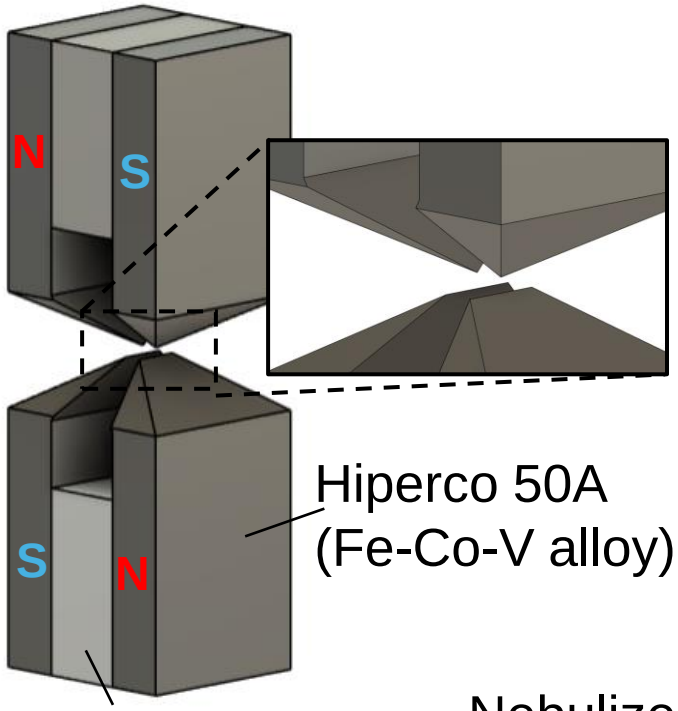


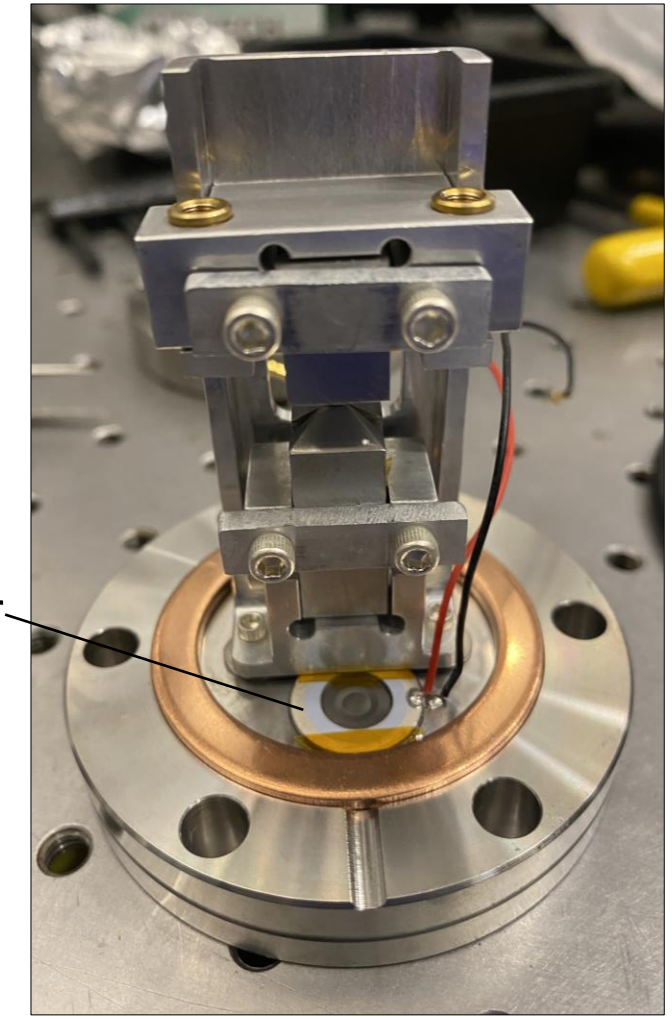
Turbulent convection

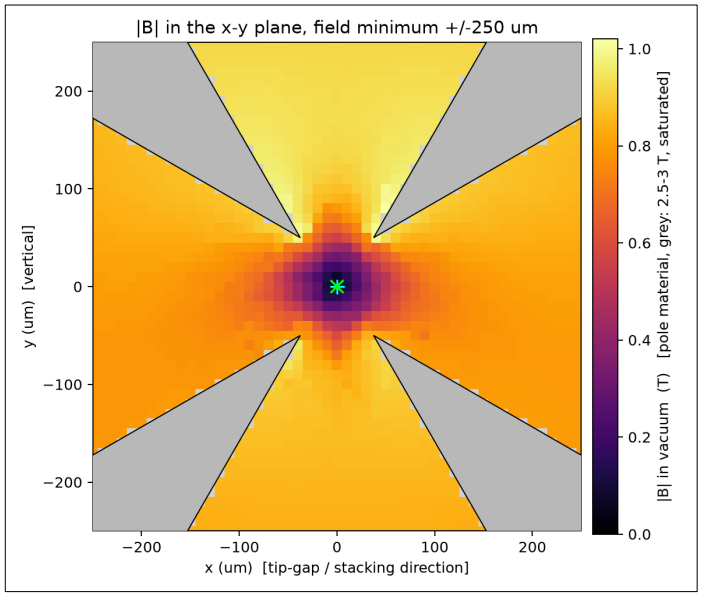
$$K_{drop} \gg U_{trap}$$

Magnetic Trap

- Quadrupole trap
  - Wider than optical trap
  - Diamagnetic materials
- Nebulizer
  - Create droplets in chamber via LXe puddle
  - Can be installed at bottom due to absence of vertical trapping beam





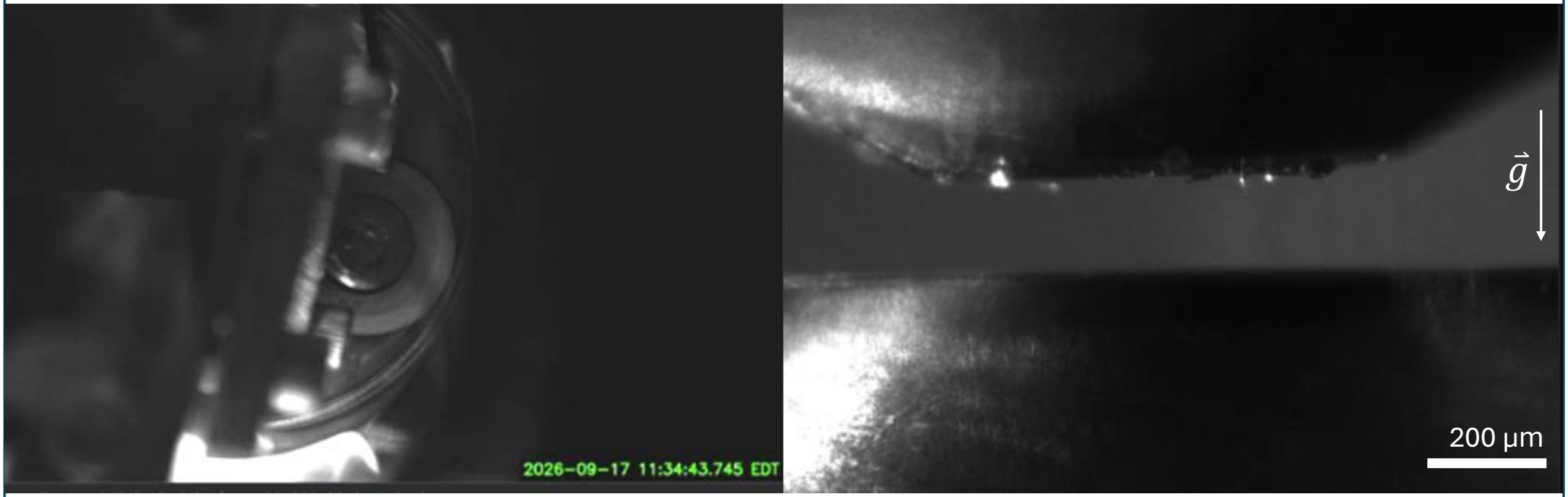


Design adapted from *Hsu, Ji, Lewandowski & D'Urso, Sci. Rep. 6, 30125 (2016).*

Magnetic Trapping of LXe Spheres

Top

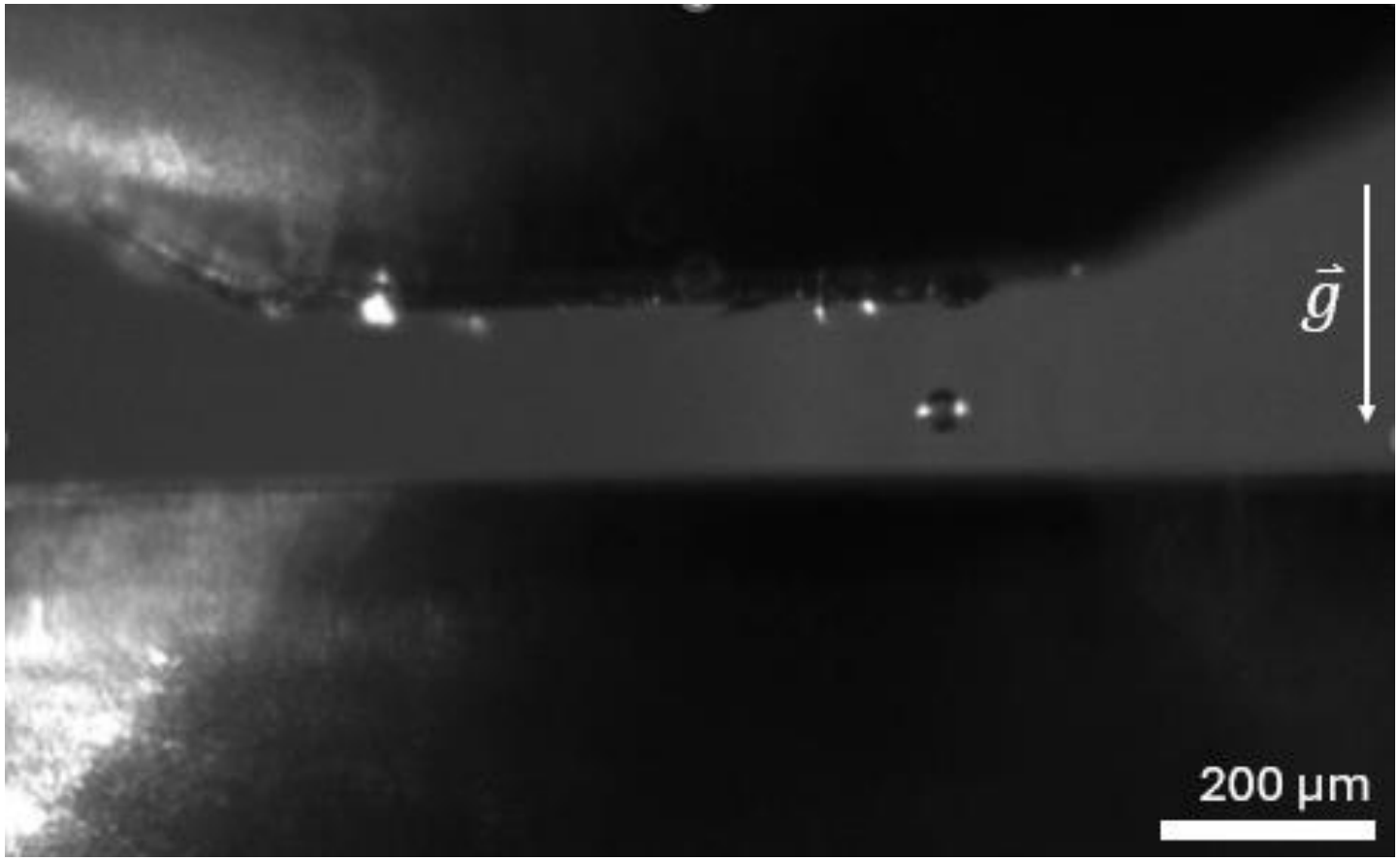
Front



Nebulizing LXe from bottom of chamber

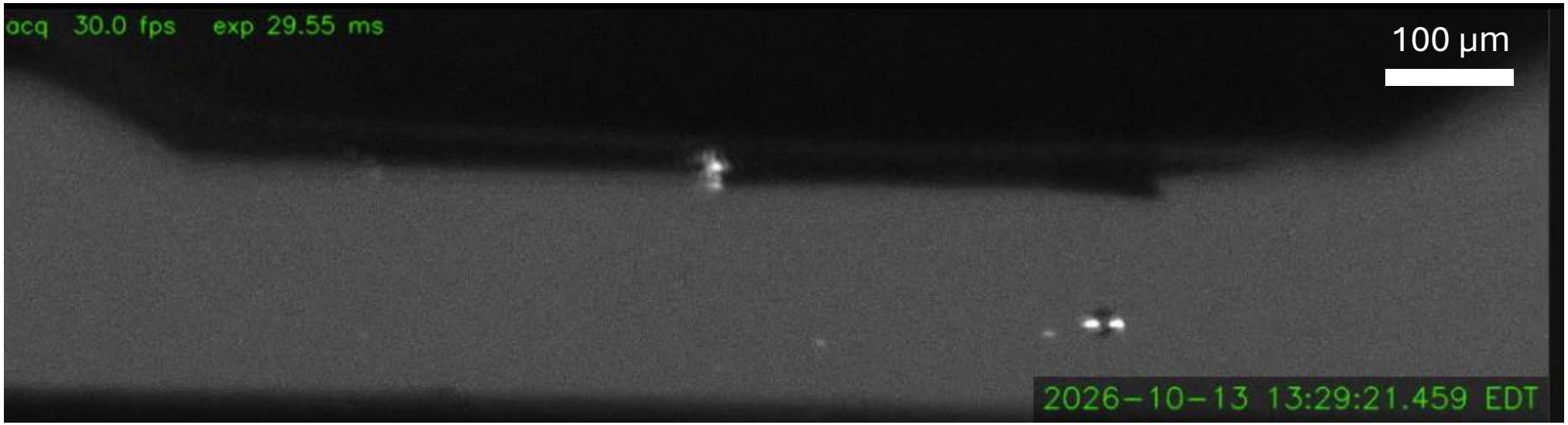
Magnetic Trapping of LXe Spheres

- ~20-50 μm spheres
- Evaporate in minutes
  - Not in a saturated vapor
- Repeatable trapping procedure
  - Multiple spheres at times



Pumping & Freezing Spheres

- Cryopumped out Xe gas
- Opened to turbo pump after reaching <1 mbar
- Pumped spheres to ~10^{-3} mbar
- Trapped for >5 hours

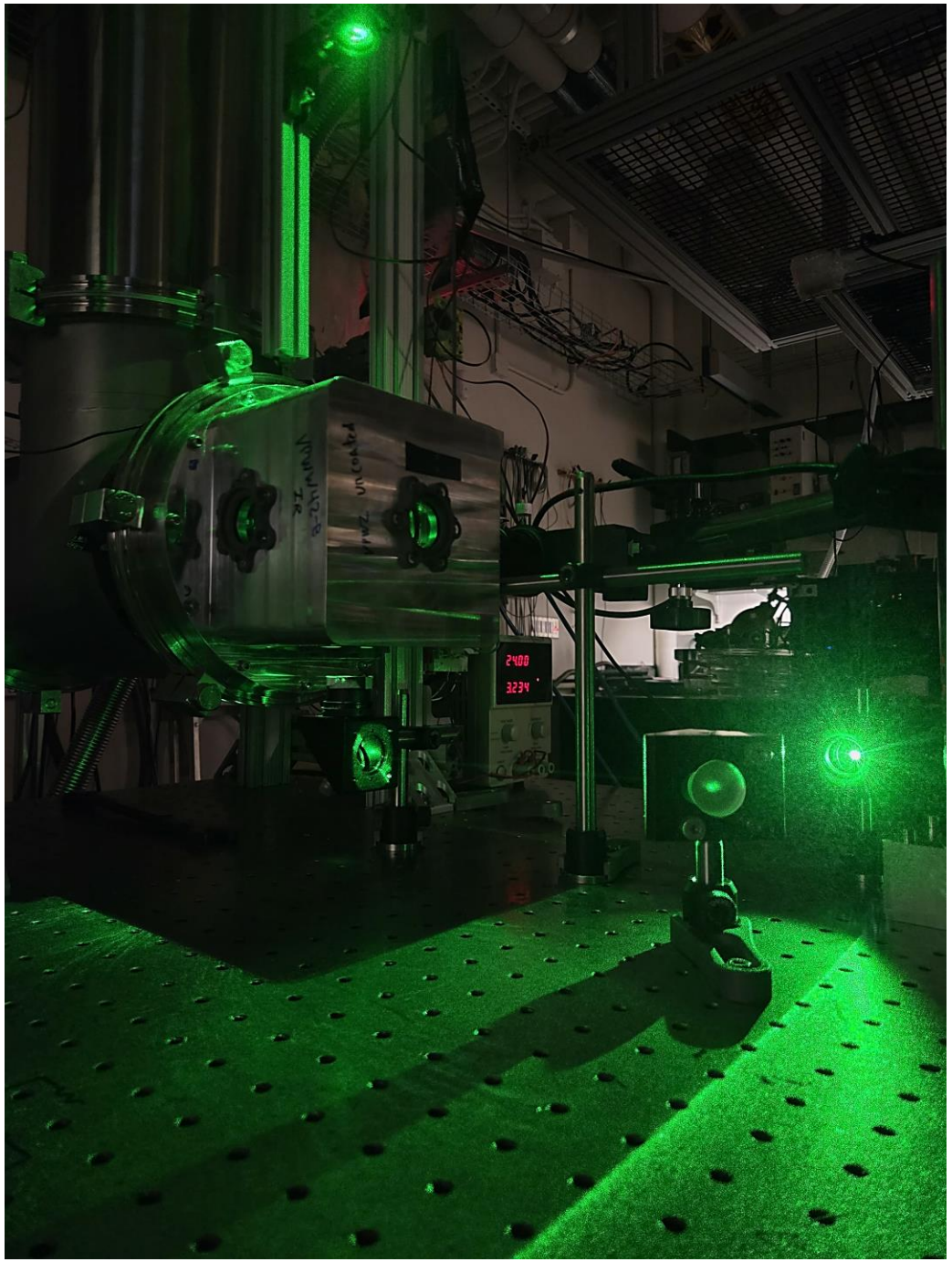


Beginning of cryopump

Next Steps (Near Term)

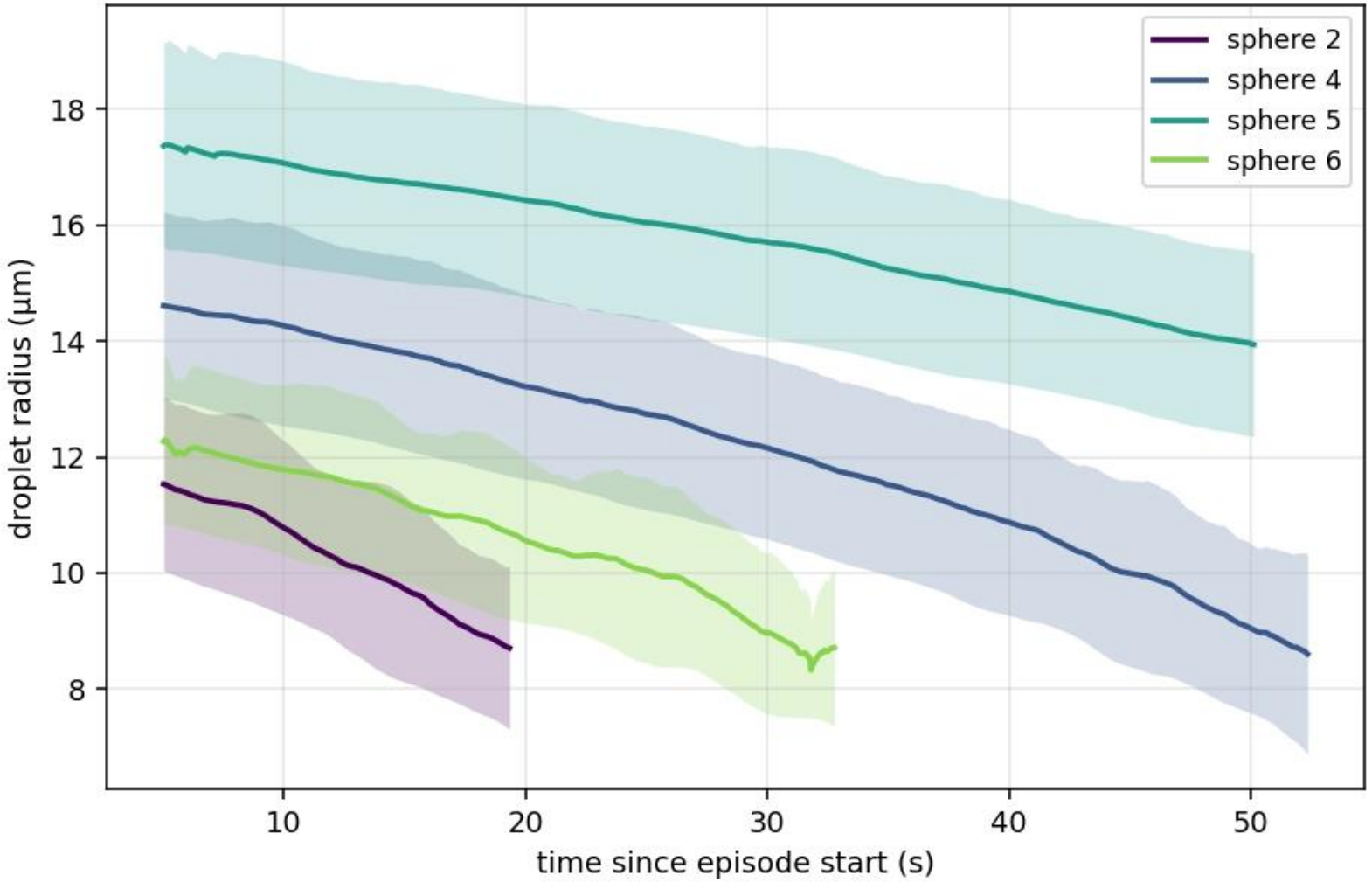
- Fine tune pumping procedure
- Optically measure spheres
  - Resonances -> Damping -> Pressure measurement
  - Measure freezing of sphere via change in scattered light
- Keep LXe drop in saturated vapor
- Transfer from magnetic to optical trap (?)

Thank You



Backup

Evaporation Rate of LXe Spheres

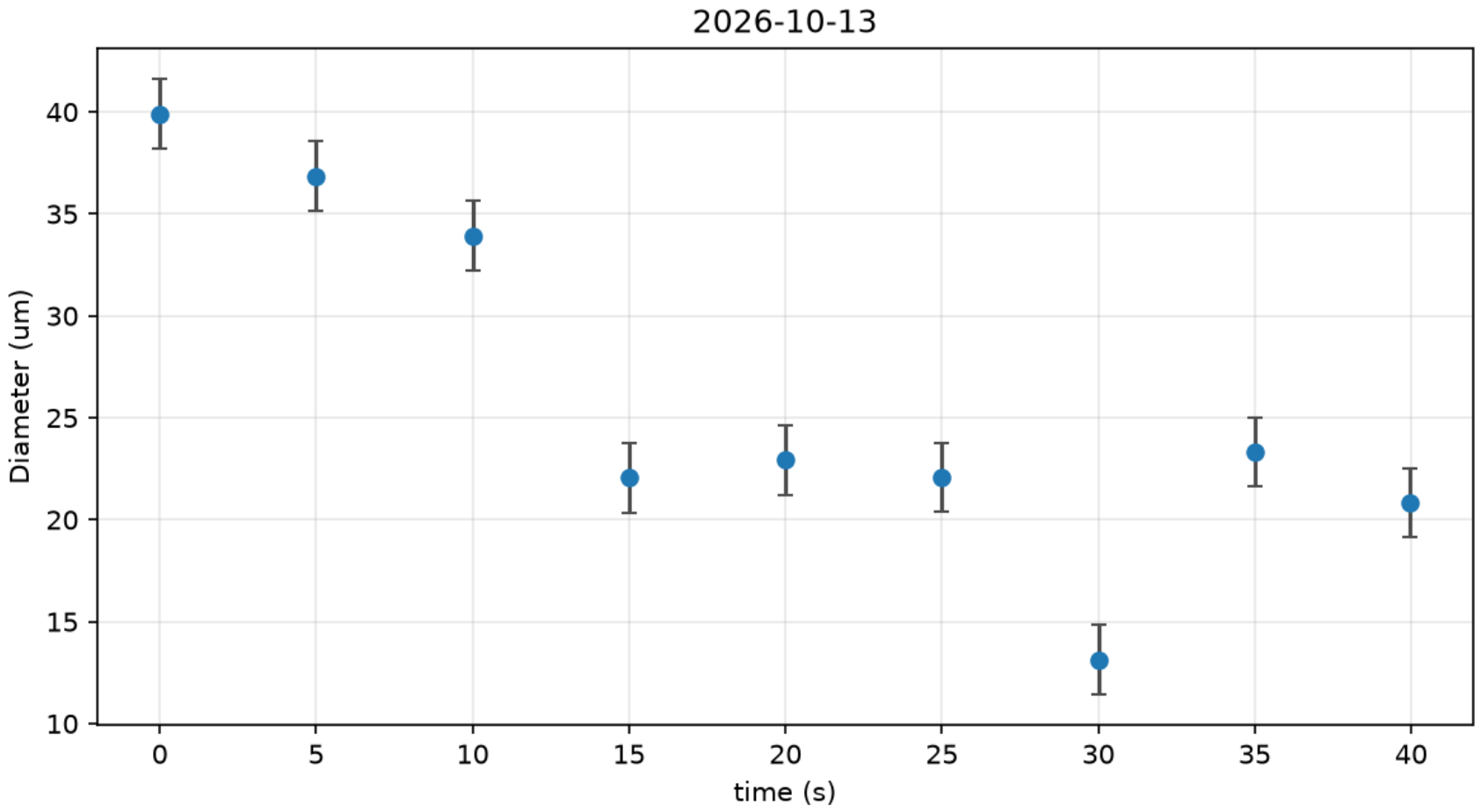


$q = 38 \pm 7 \pm 1\ Wm^{-2}$

thermal conductivity ~ r
if r_wall >> r_sphere

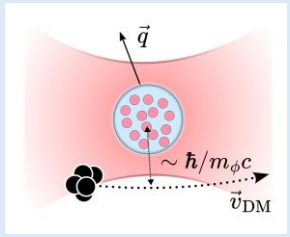
ΔT ~ 200 mK

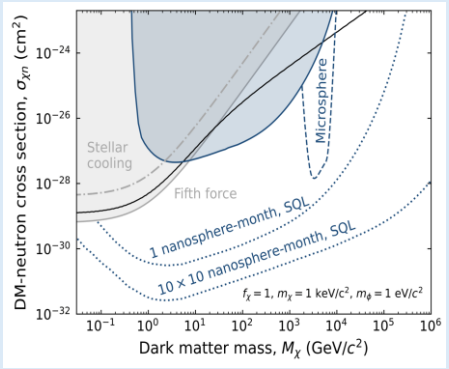
Pumped down sphere first 40 s



Moore Lab – Techniques with Levitated Sensors

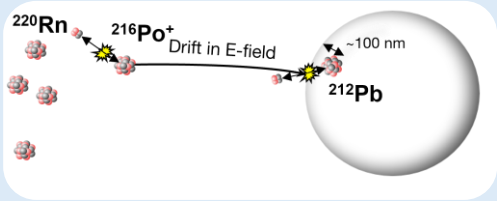
Dark Matter Searches

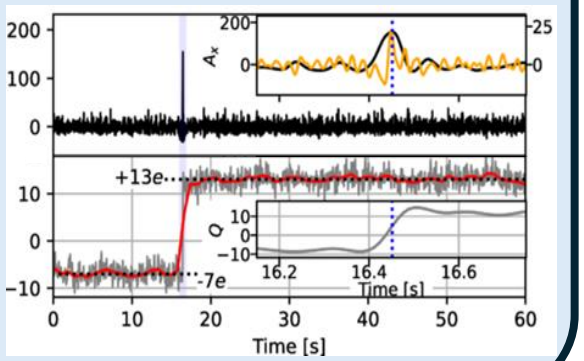




PRL 125, 181102 (2020),
PRX Q. 6.4 (2025): 040367.

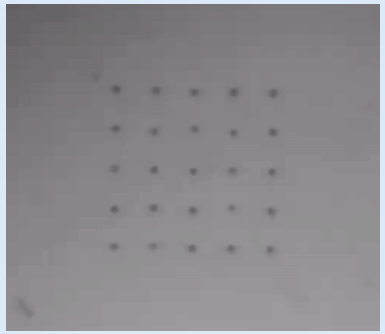
Nuclear Decays





PRX Quantum 4, 010315 (2023)
Phys. Rev. Lett. 133, 023602 (2024)

Simple

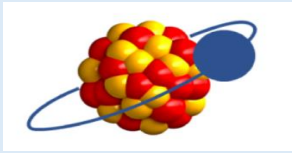


Multiplexed readout and feedback cooling of levitated arrays

Phys. Rev. A 111, 033514 (2025)

Levitated Microsphere Arrays

World-leading limits on terrestrially bound millicharged particle

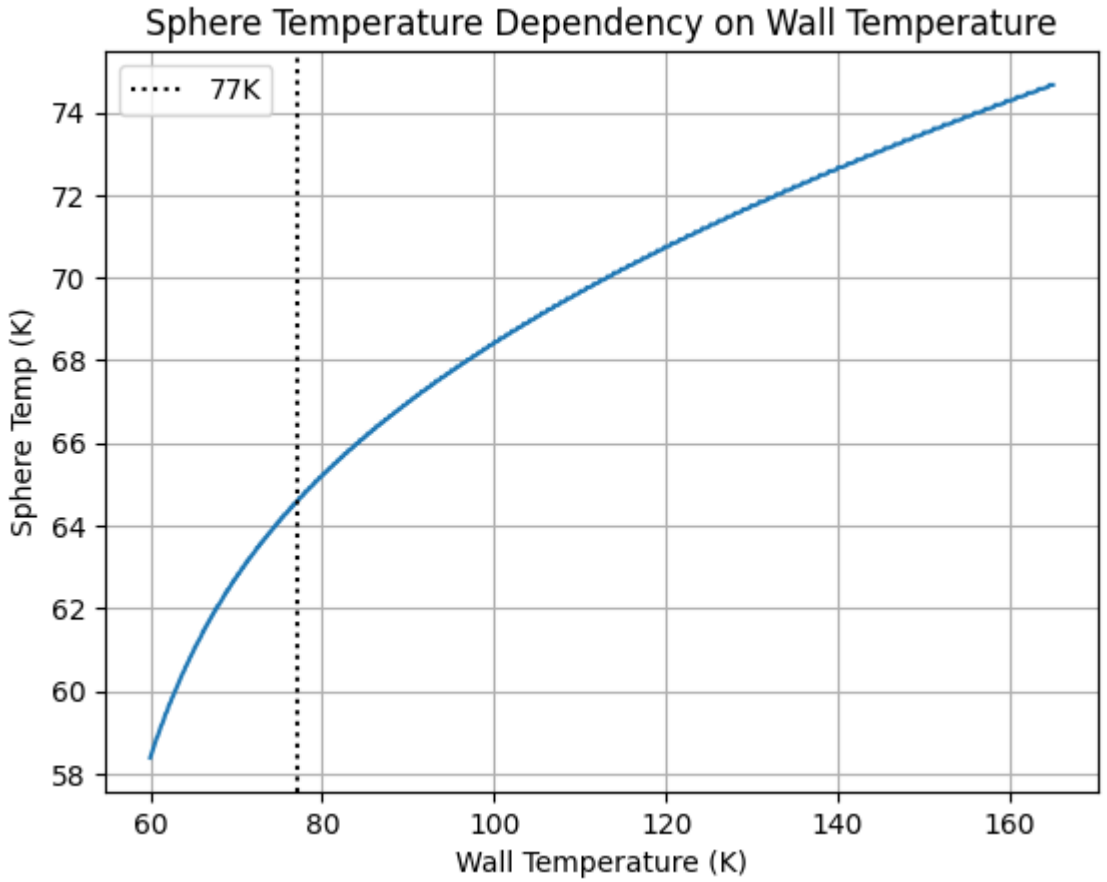


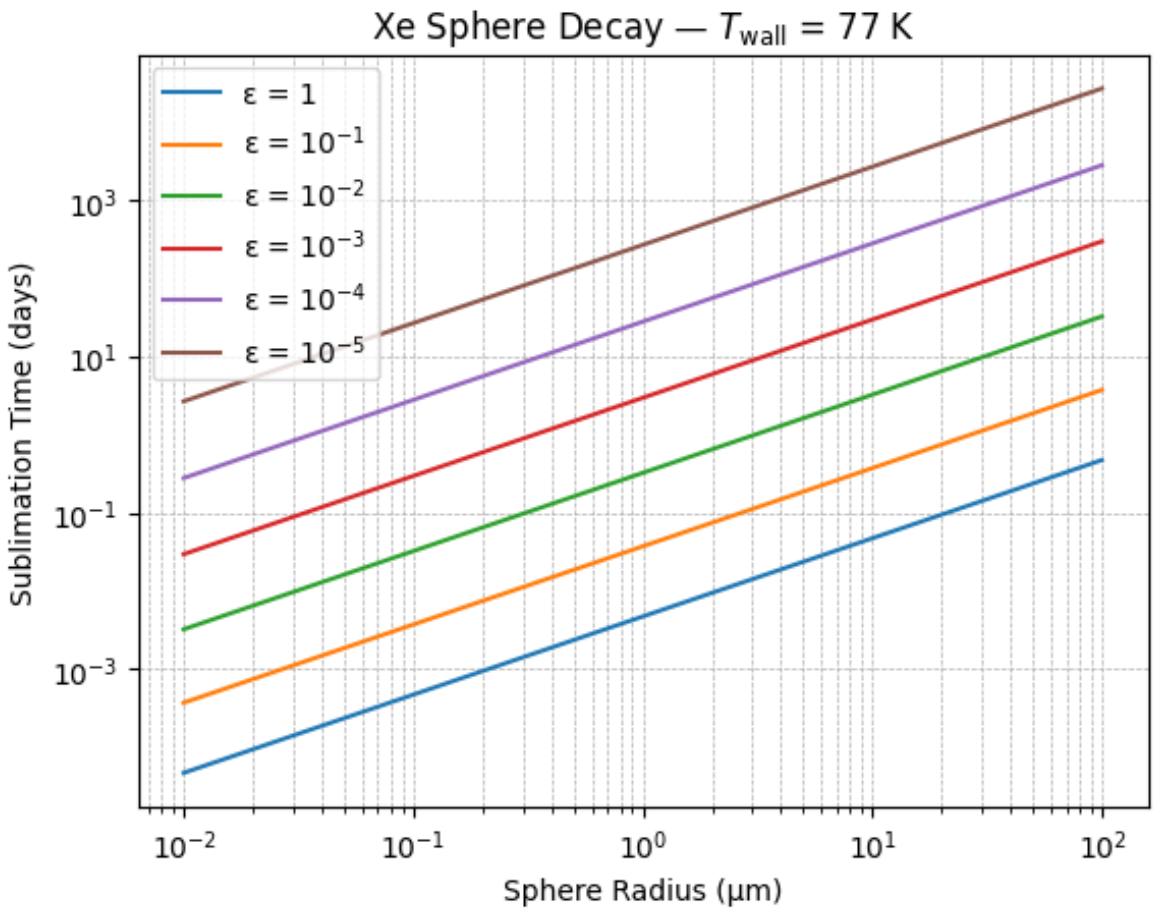
$|q| > 10^{-5}\ e$

Phys. Rev. Lett. 113, 251801 (2014)
Phys. Rev. D 104, 012004 (2021)

Neutrality of Matter

Solid Xe Sphere Calculations

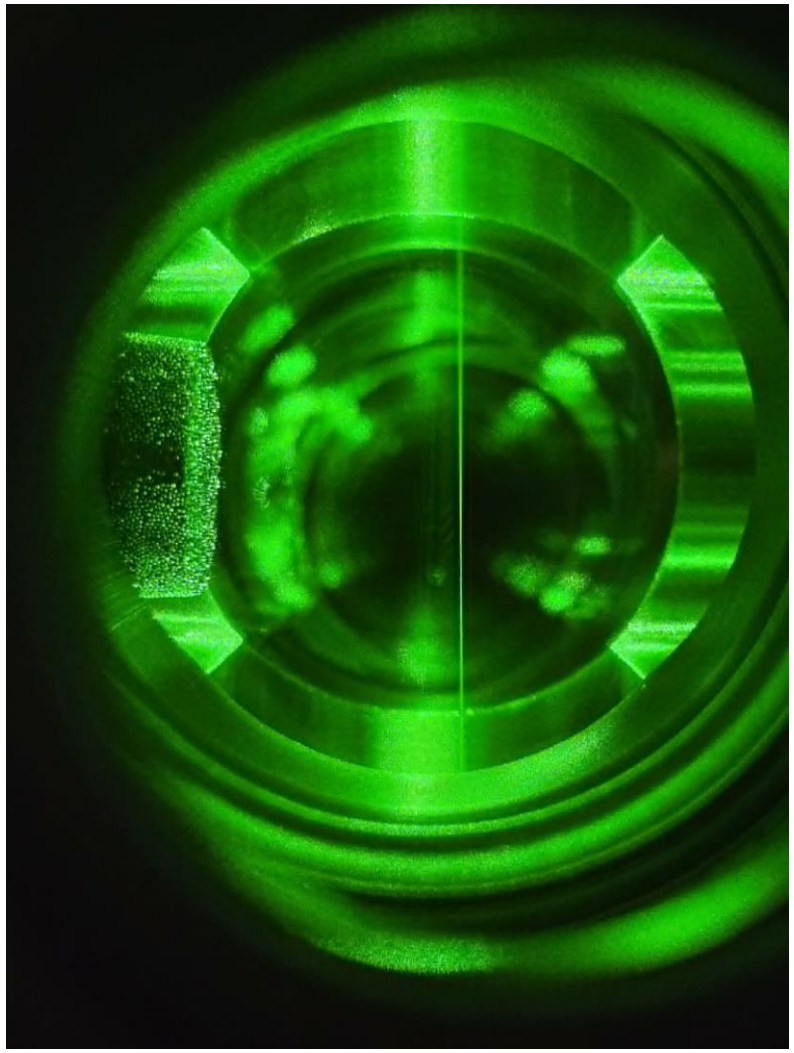




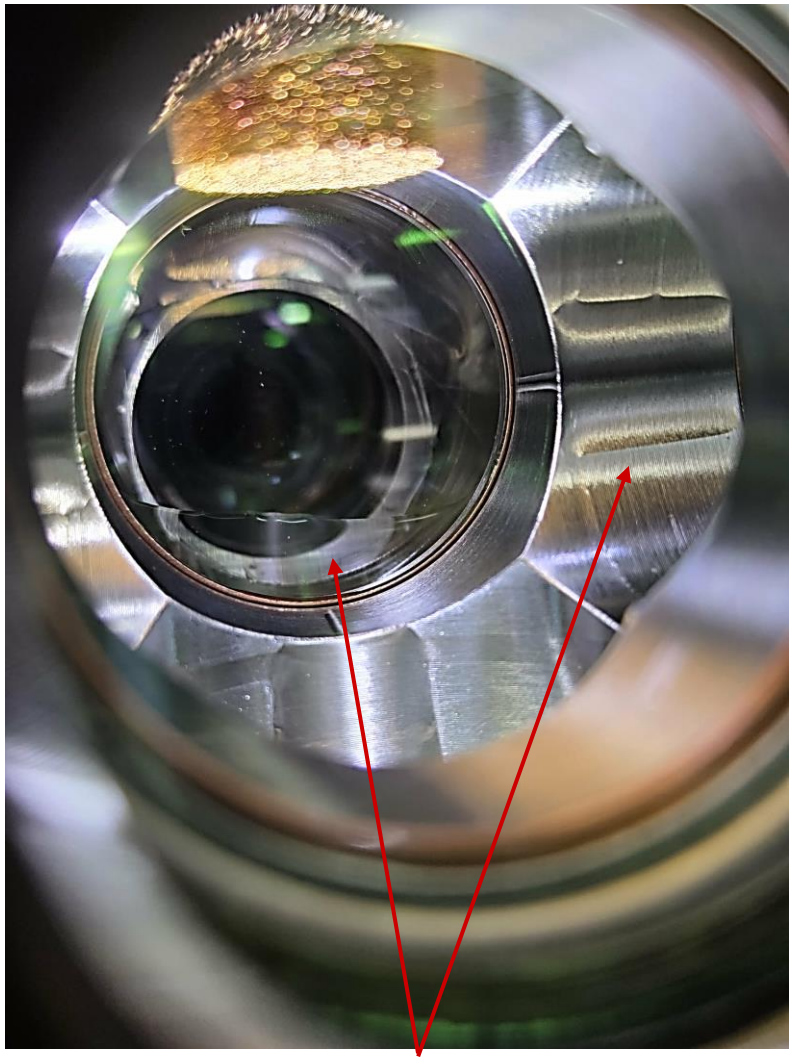
Assuming minimal heating from gas and laser, balancing of black body vs sublimation

CAVEAT: no estimate of Xe emissivity, can only claim upper bounds…to be measured

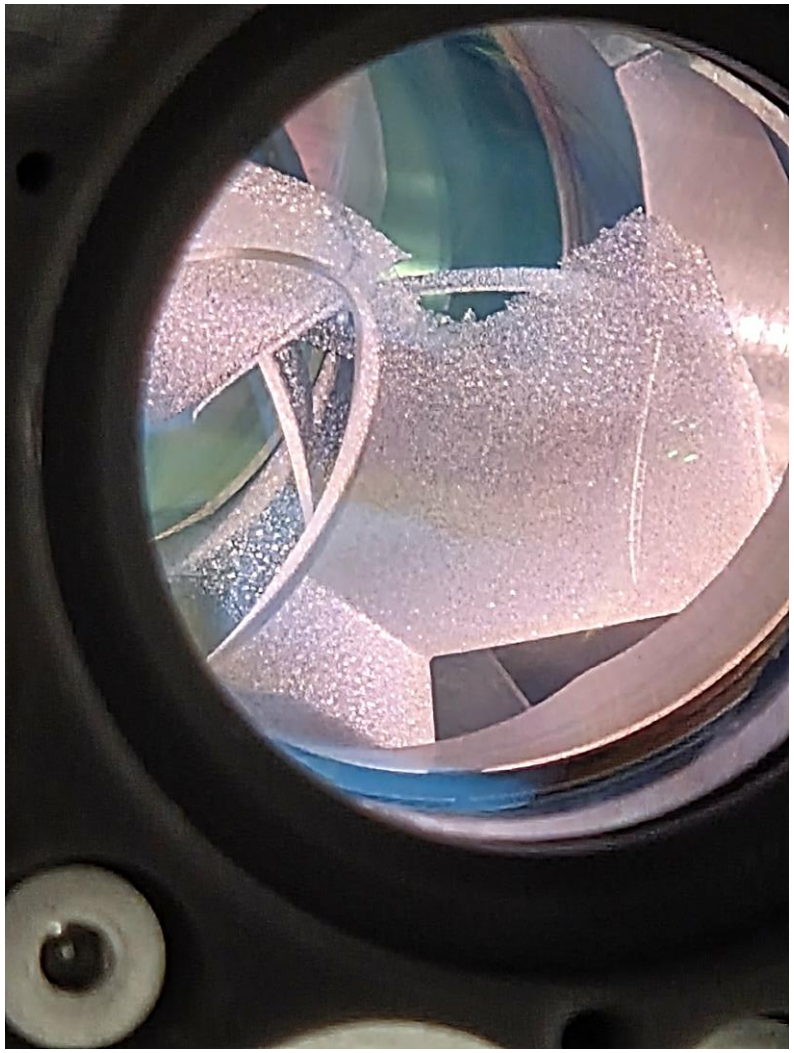
Xe at all phases



Gas (Rayleigh scatter of beam)

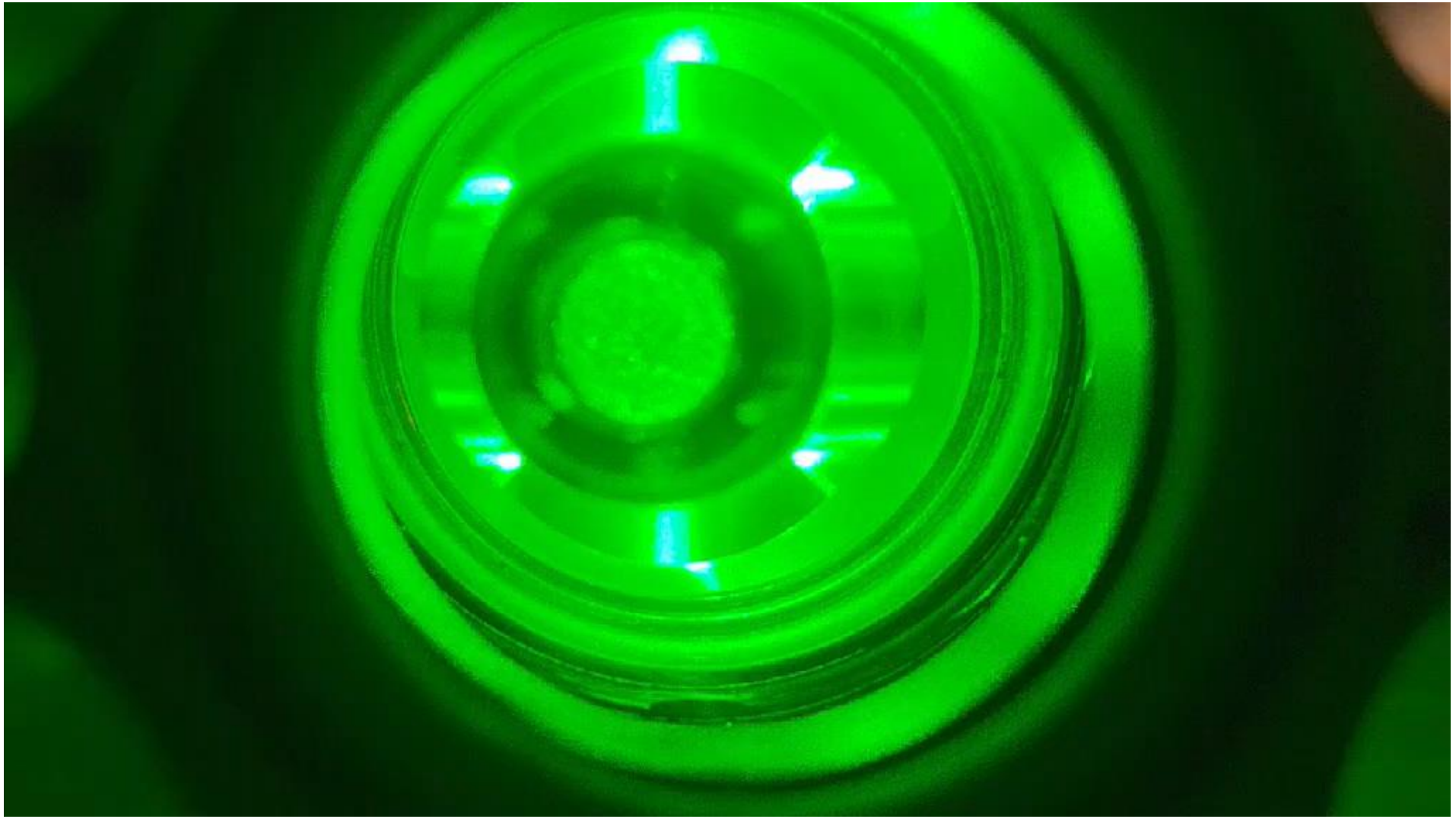


Liquid pooling on surfaces as we sit on the saturation curve



Ice on the walls

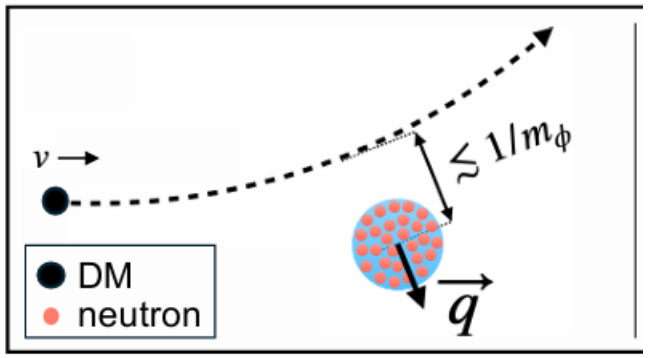
Xe Drops



Coherent DM Interaction

- Coherent interactions between DM and macroscopic amounts of matter instead of energy deposition
  - Force imparted to multiple atoms at once
  - DM interaction cannot resolve internal structure
    - Works for long range (light mediator) interaction -> debroglie wavelength > sphere
- Energy resolving detectors cannot detect this scattering
  - High mass of interacting matter suppresses recoil energy

- Motivation for isolated nano/micro scale particles



D. Moore

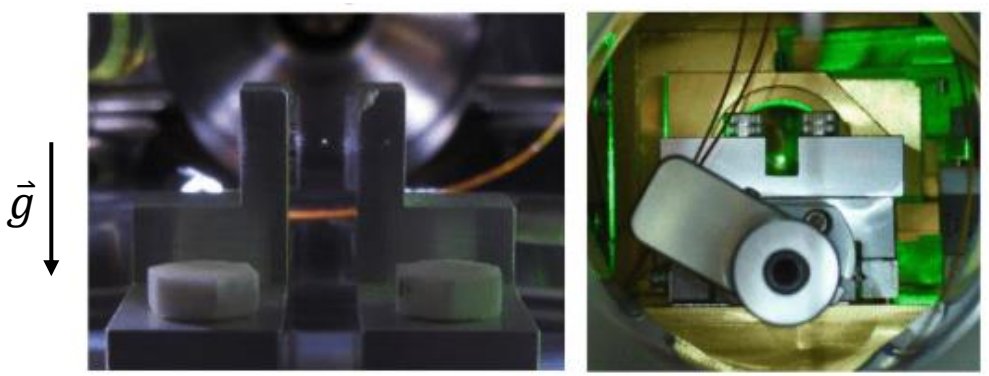
$$E_{recoil} = \frac{q^2}{2M_{int}}$$

Coherent interaction enhances cross section wrt single neutron

$$\sigma \propto N_T^2 \sim (10^{14})^2$$

Levitated Mechanical Sensors

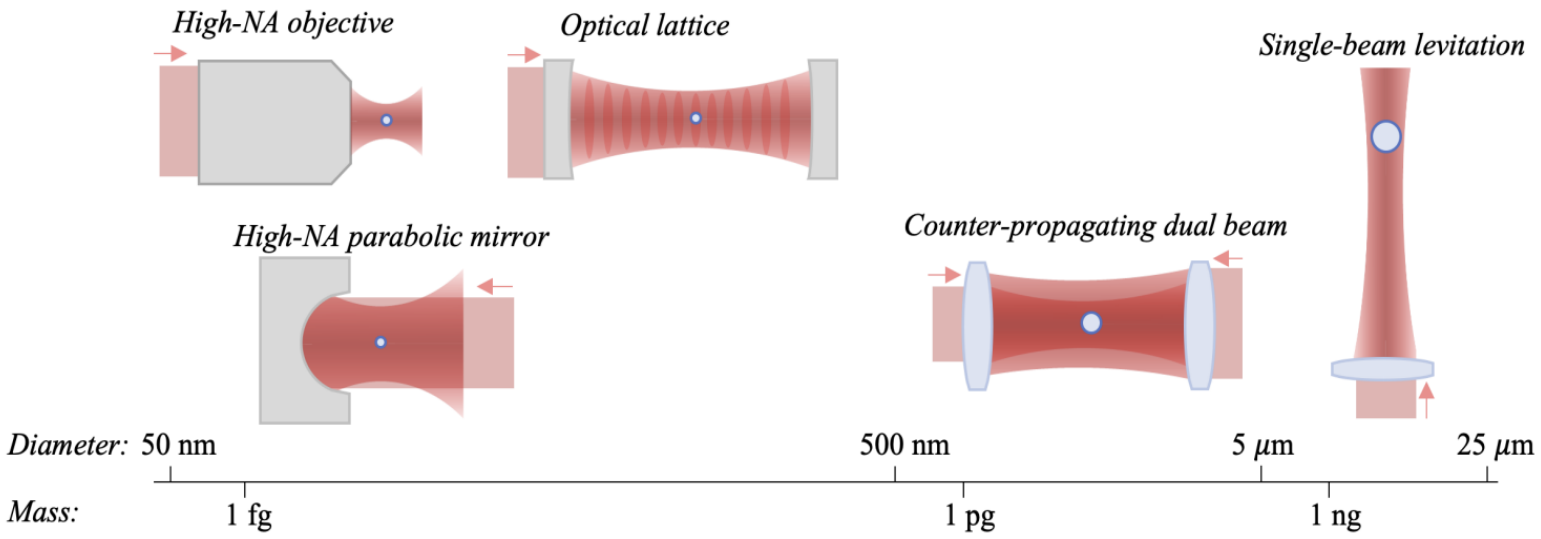
- Optically trapped dielectric masses
  - Typically silica spheres
  - nm – μm scale (fg – ng)



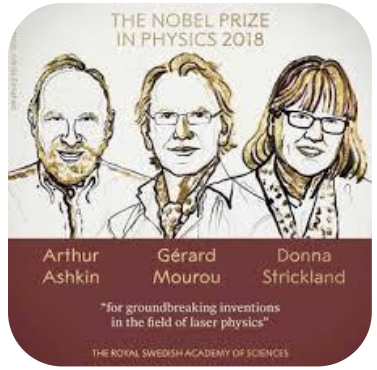
Single beam tweezer for nanospheres

Levitation (“Gravito Optical”) Trap for microspheres

Moore Lab



D. Moore and A. Geraci
arXiv:2008.13197



Technique developed by A. Ashkin

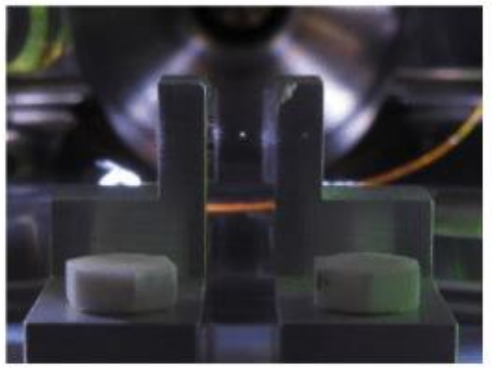
Levitated Mechanical Sensors

- Optically trapped dielectric masses
  - Typically silica spheres
  - nm – μm scale (fg – ng)
- Model COM motion as driven damped SHO

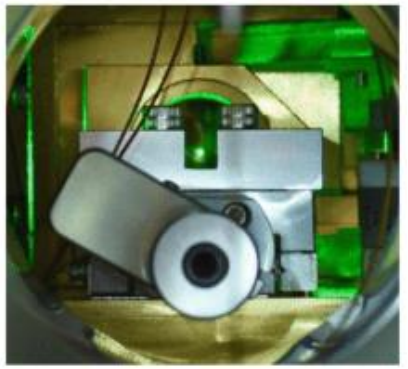
$$\ddot{q}(t) + \Gamma_0 \dot{q}(t) + \Omega_0^2 q(t) = \frac{1}{m}[F_{ext}(t)]$$

$$Q = \Omega_0/\Gamma_0$$

Γ_0 – Damping rate
Ω_0 - Mechanical Frequency

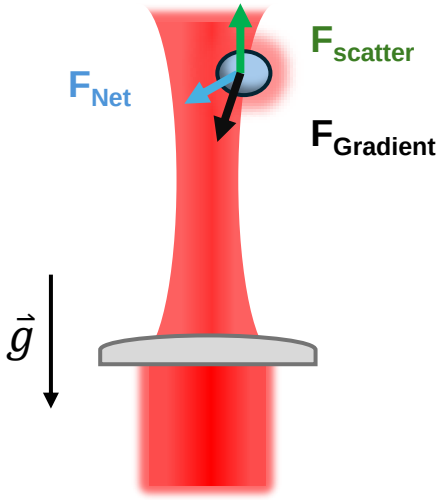


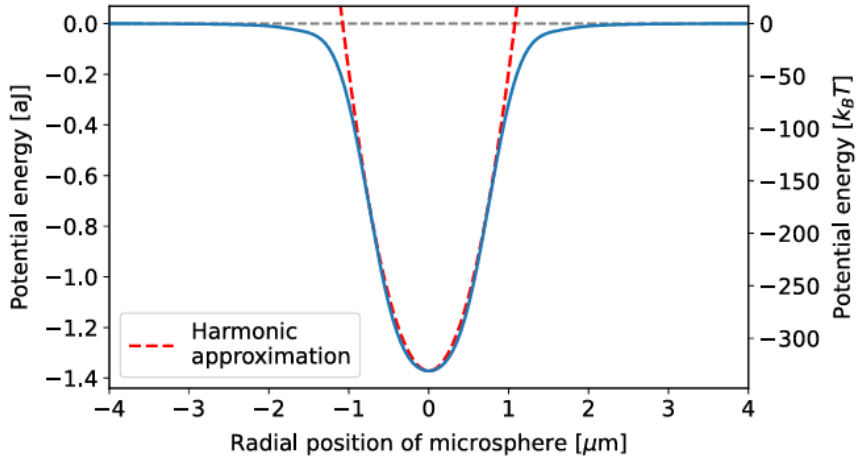
Single beam tweezer for nanospheres

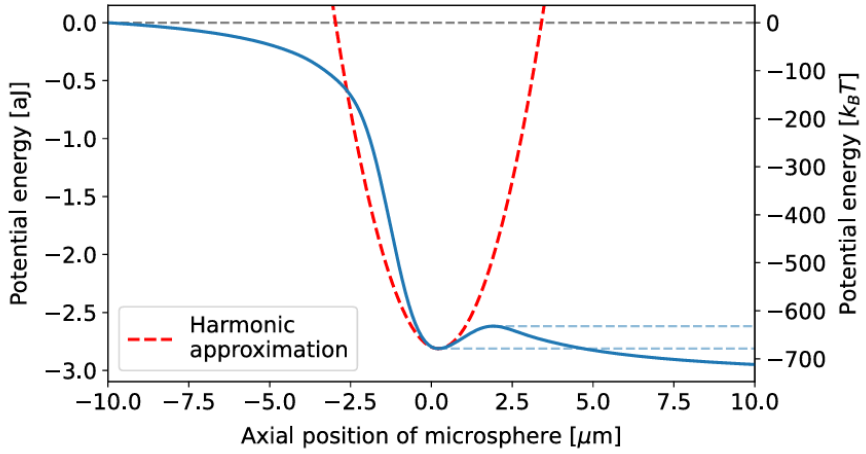


Levitation ("Gravito Optical") Trap for microspheres

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C. Blakemore, *Ph.D. Thesis*, Stanford 2021

Comparison with Water

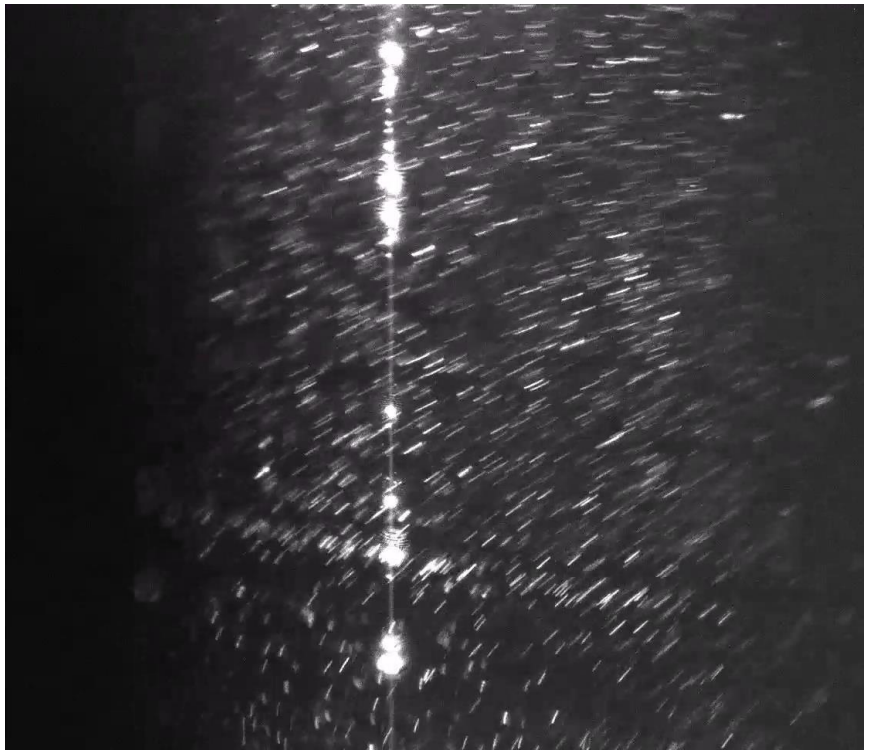
- ✓ $\rho_{Xe} \sim \rho_{H_2O}$
- ✓ $r_{Xe} \sim r_{H_2O} \approx 10 - 30\ \mu m$

$$v_{Xe} \gg v_{H_2O}$$

$\vec{g}$

Xenon

Focused + Unfocused beam

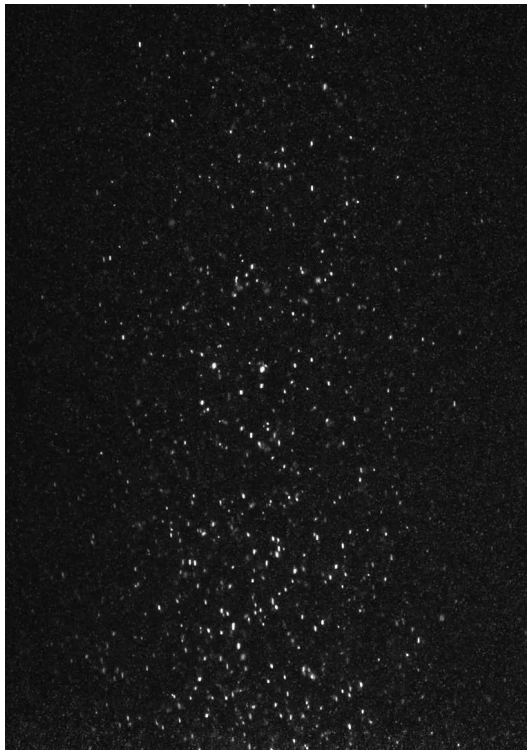


Turbulent convection

$K_{drop} \gg U_{trap}$

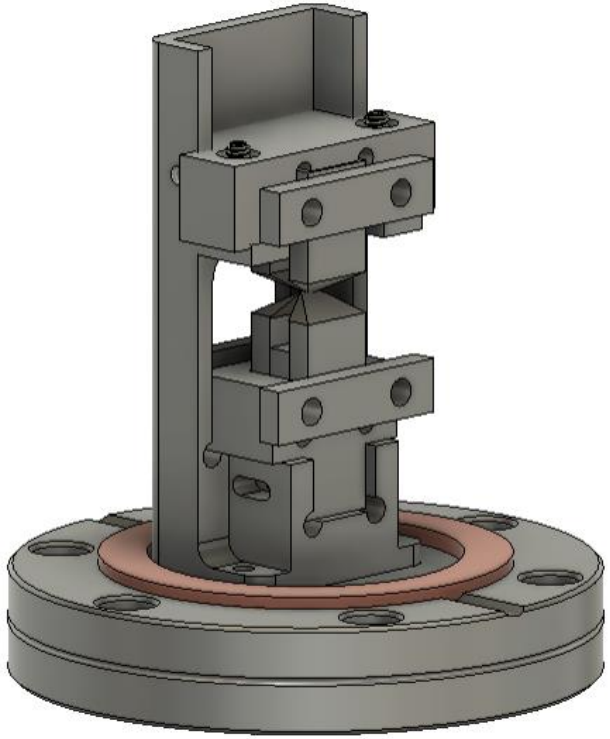
Water

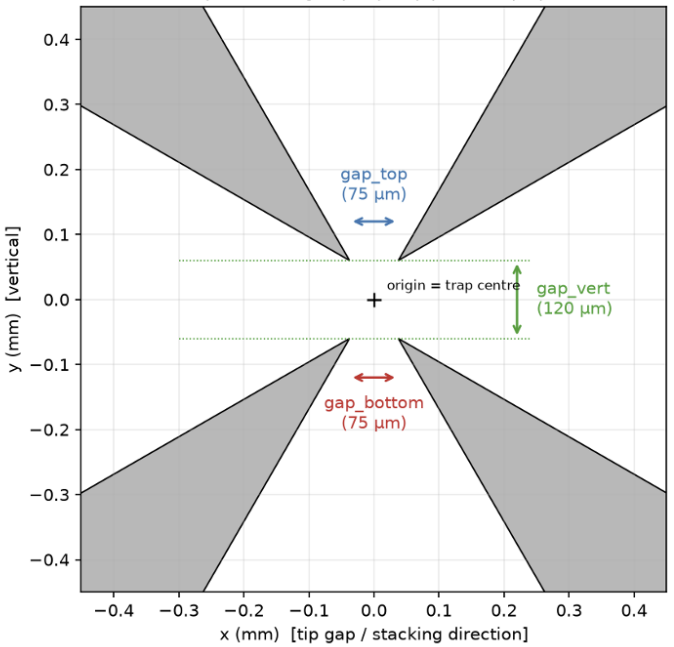
Unfocused Beam



Water droplets settle under gravity

Magnetic Trap





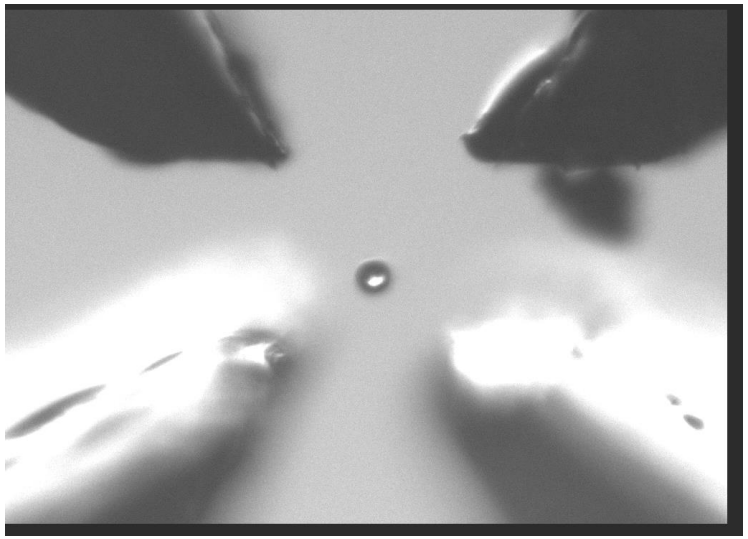


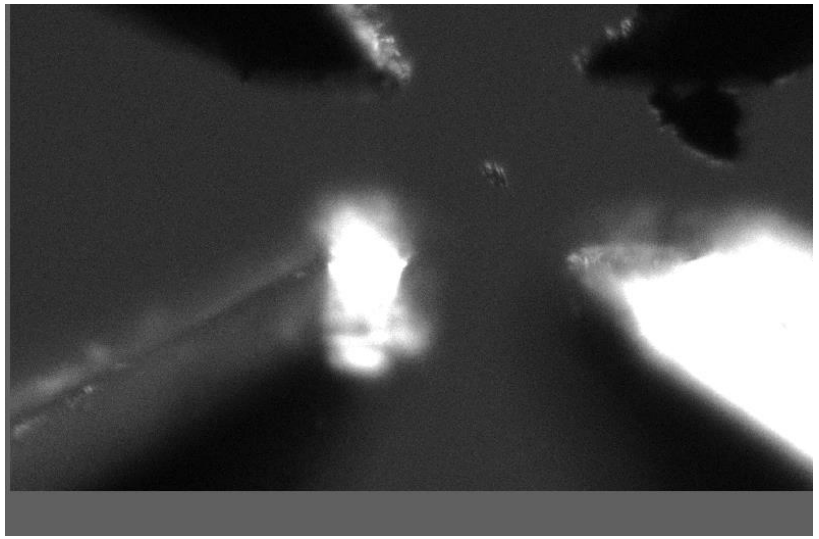




Testing Trap

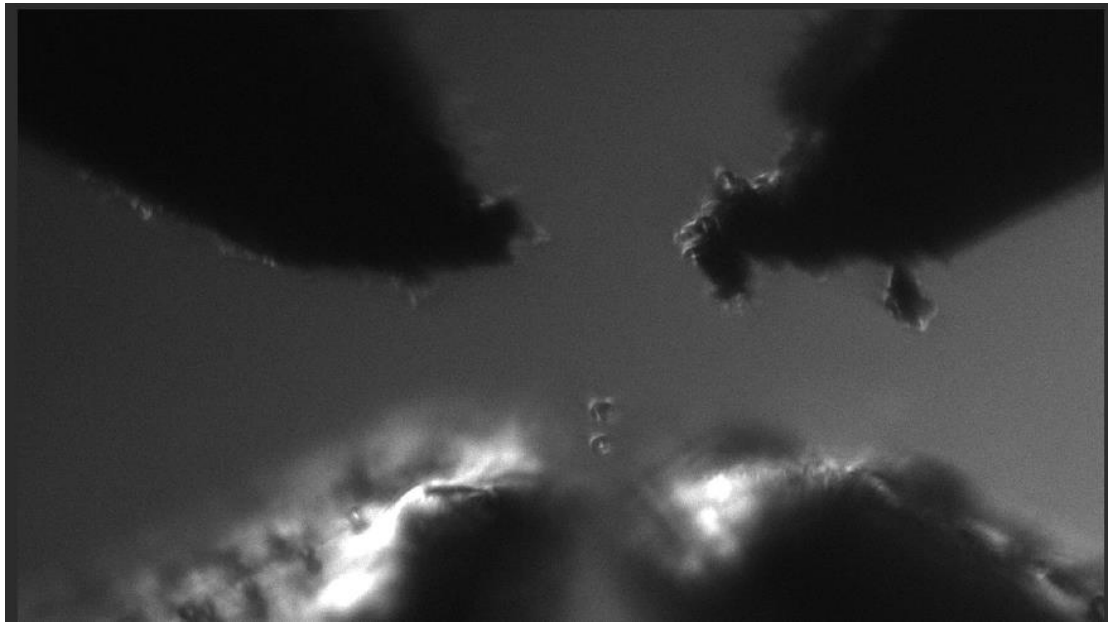
Material	Density (kg/m³)	χ_ρ (CGS, 10^{-7} cm³/g)	χ_ρ (SI, 10^{-9} m³/kg)	χ_v (SI, 10^{-5})
Liquid xenon (165 K)	2960	−3.5	−4.40	−1.30
Fused silica	2200	−4.1	−5.15	−1.13
Diamond	3510	−4.9	−6.16	−2.16
Water (20 °C)	998	−7.2	−9.05	−0.903





Water

Graphite





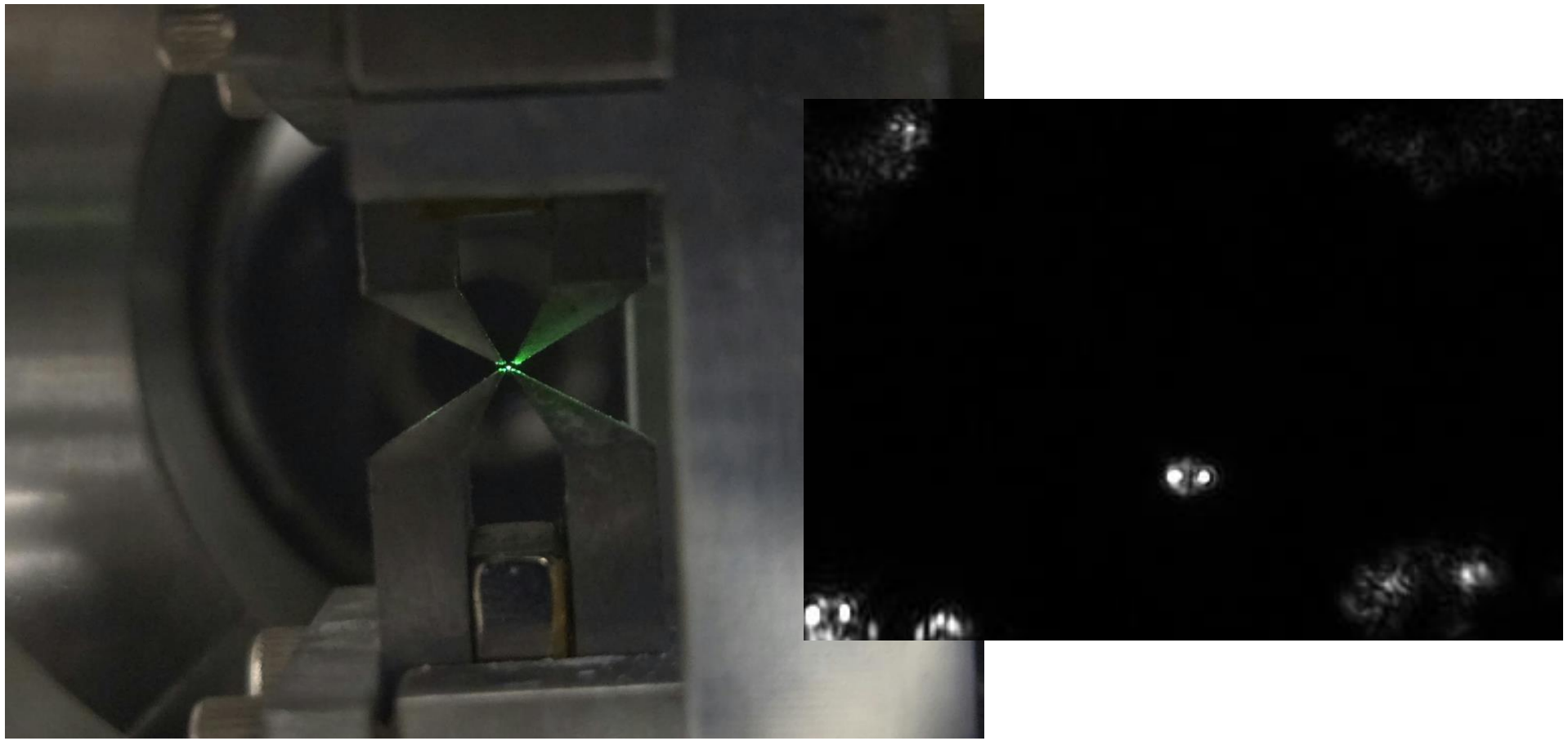
Silica (25 um)

Testing Trap – Nebulizing Water

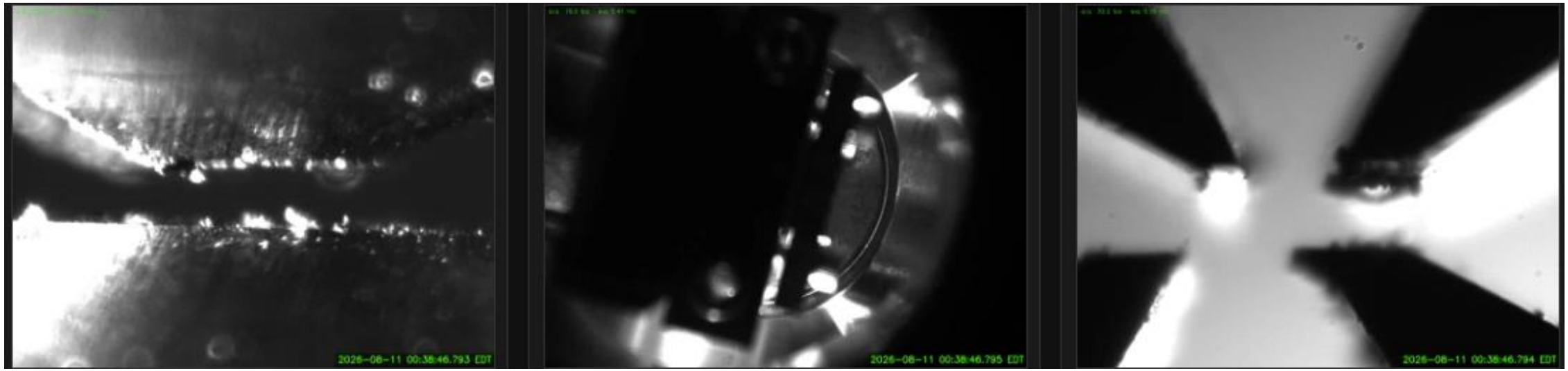


Testing Trap

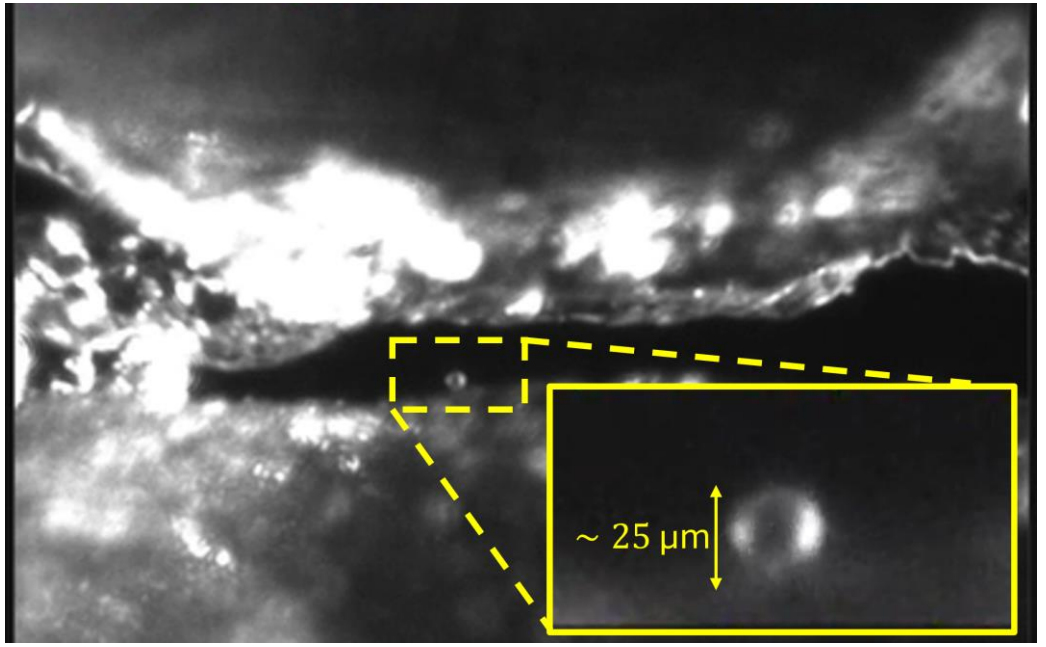
Silica (25 um)



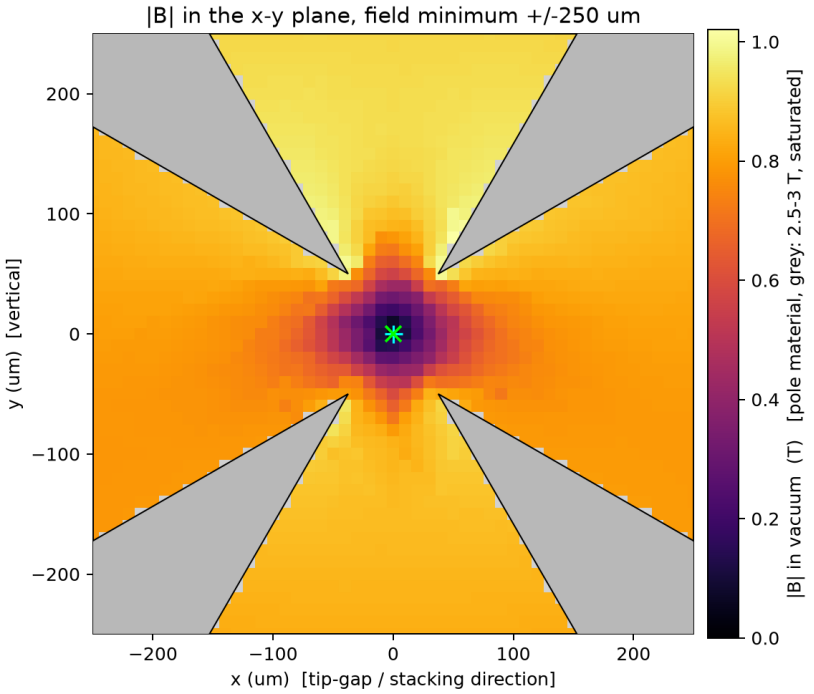
Initial results with magnetic trap

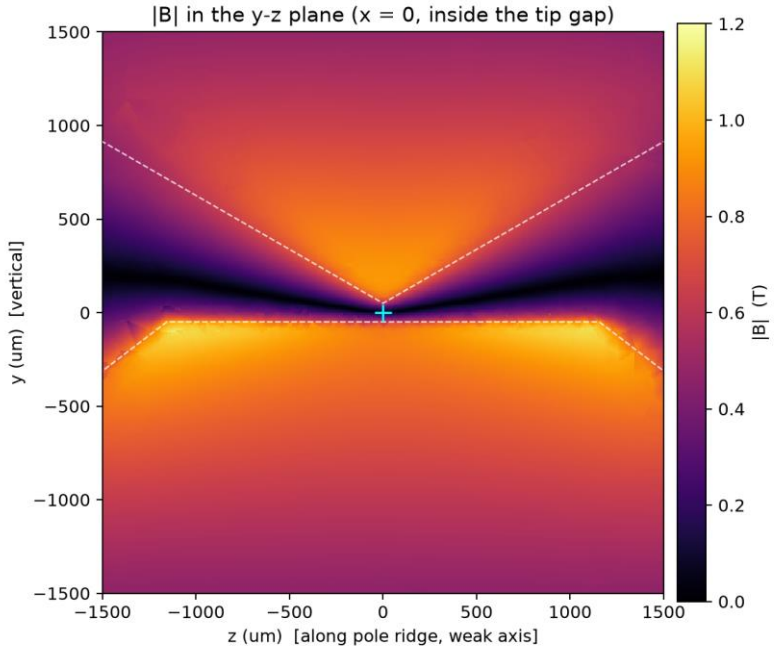


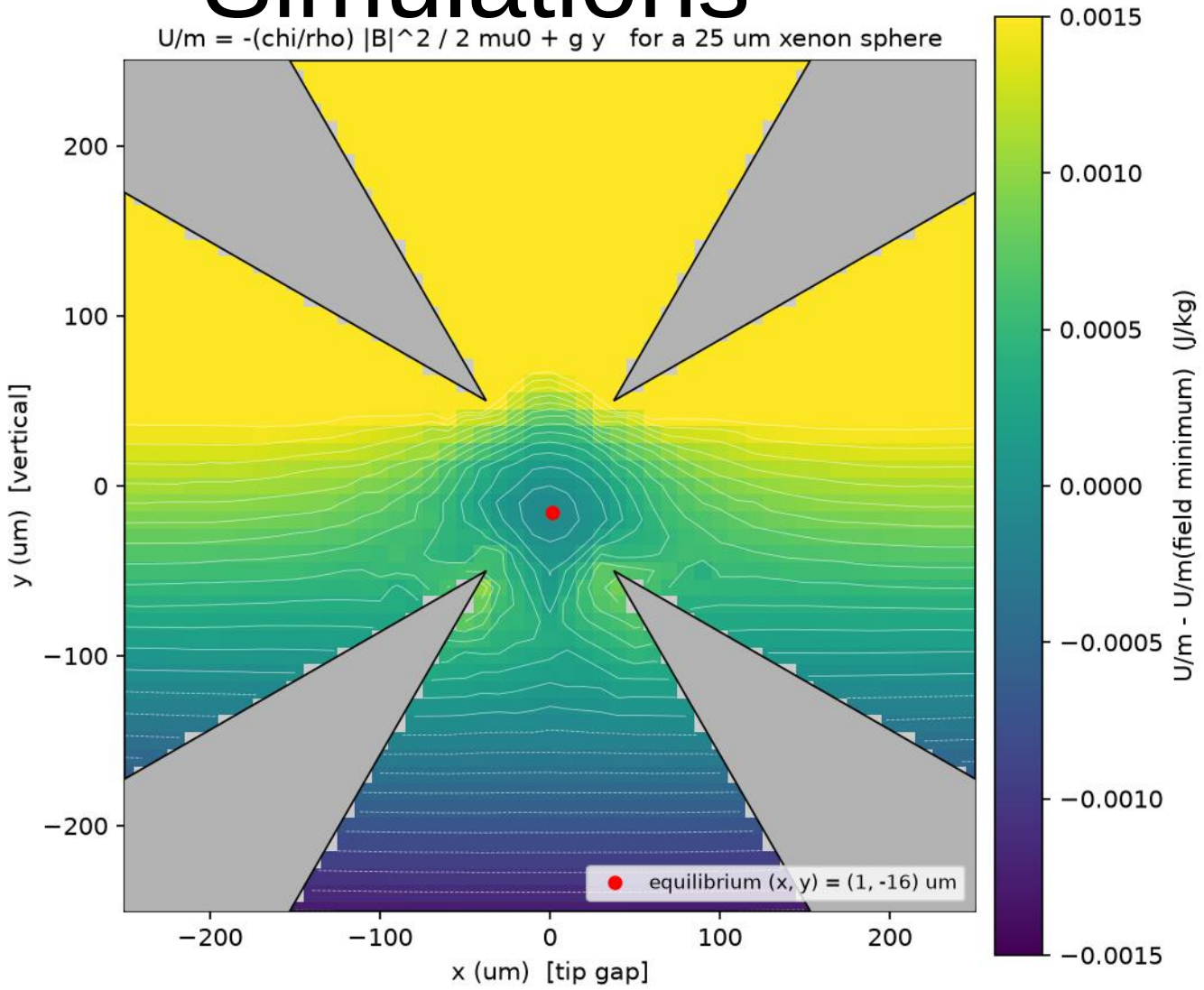


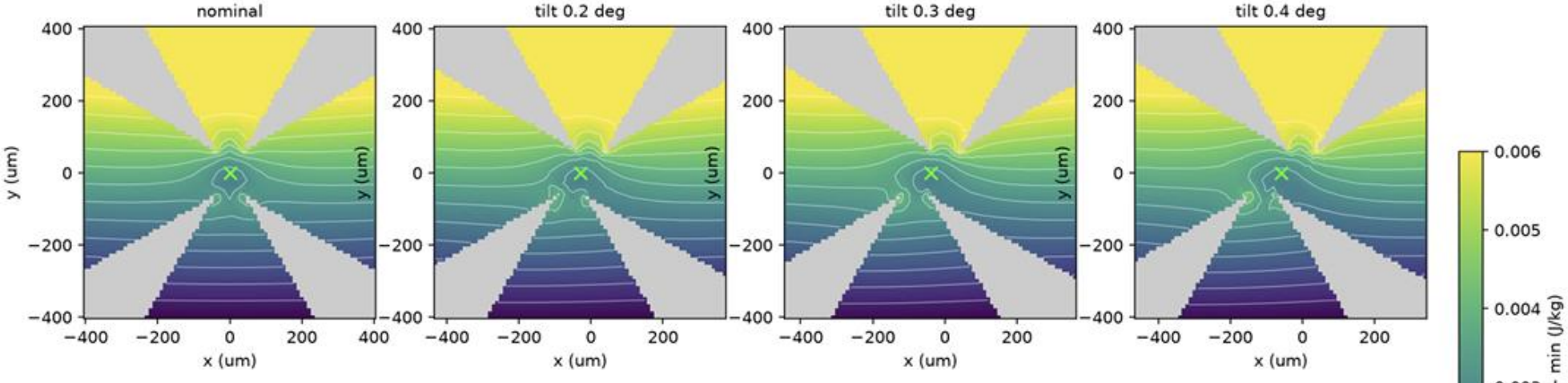


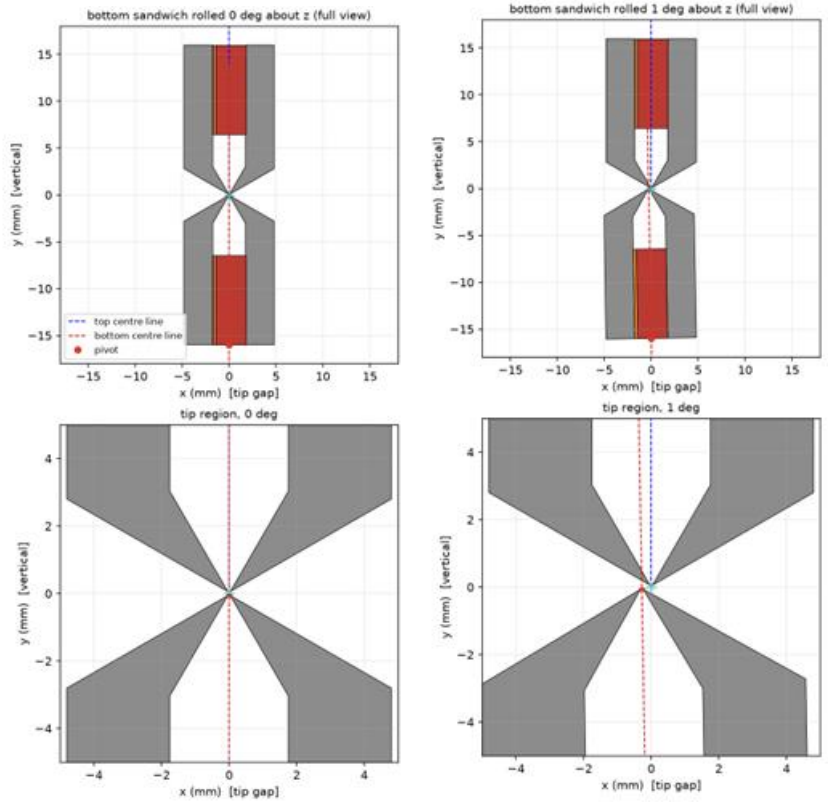
Magnetic Trap Simulations











tilt (deg)	tip offset Δx (µm)	field zero x, y (µm)	lift at zero
0	0	+0, +0	+0.12
0.2	−56	−30, +0	+0.06
0.3	−83	−40, +0	+0.03
0.4	−111	−60, +0	0.00
0.5	−139	−70, +0	−0.04
1	−278	−140, −10	−0.02