Optomechanics with Magnetically Levitated Helium-4 Drops

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Motivation: Why?

Helium?

Helium drops are ideal systems for many applications such as:

Classical and quantum fluid dynamics
Cold chemical reactions
Quantum optomechanics

Superfluid ^{4}He provides unique advantages to fulfill the requirements of quantum optomechanics, simultaneously:

High energy band vanishing optical absorption
Zero viscosity contributing low mechanical loss
High thermal conductivity
Self-cooling via evaporation
Low material impurity

Levitation?

To avoid solid boundary contact that limits all advantages of superfluid helium, we use magnetic levitation to isolate superfluid He from environmental dissipation. Drops' whispering gallery modes (WGMs) serve as optical modes and drops' surface modes serve as mechanical modes, potentially providing unprecedented access to the strong optomechanical coupling regime in macroscopic massive objects.

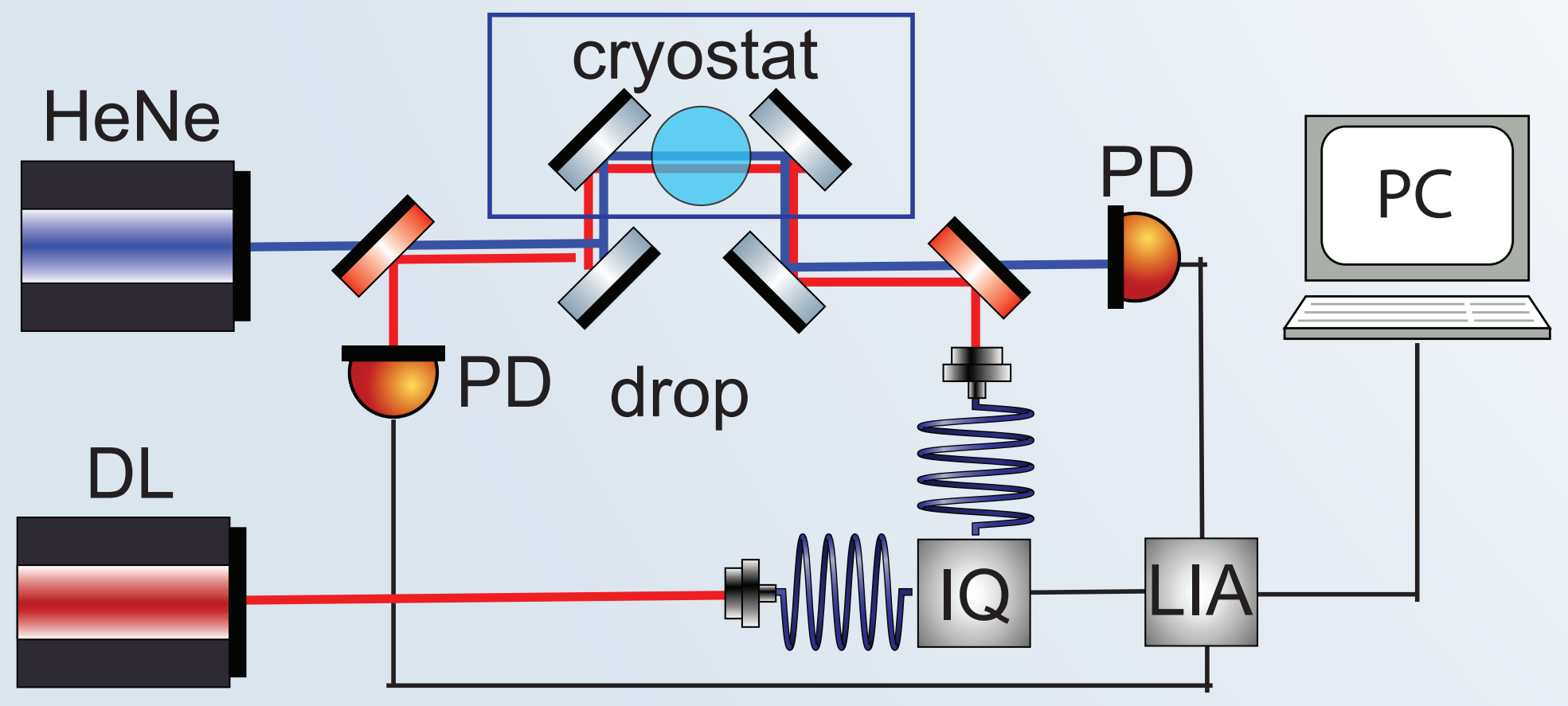
Experiment: How?

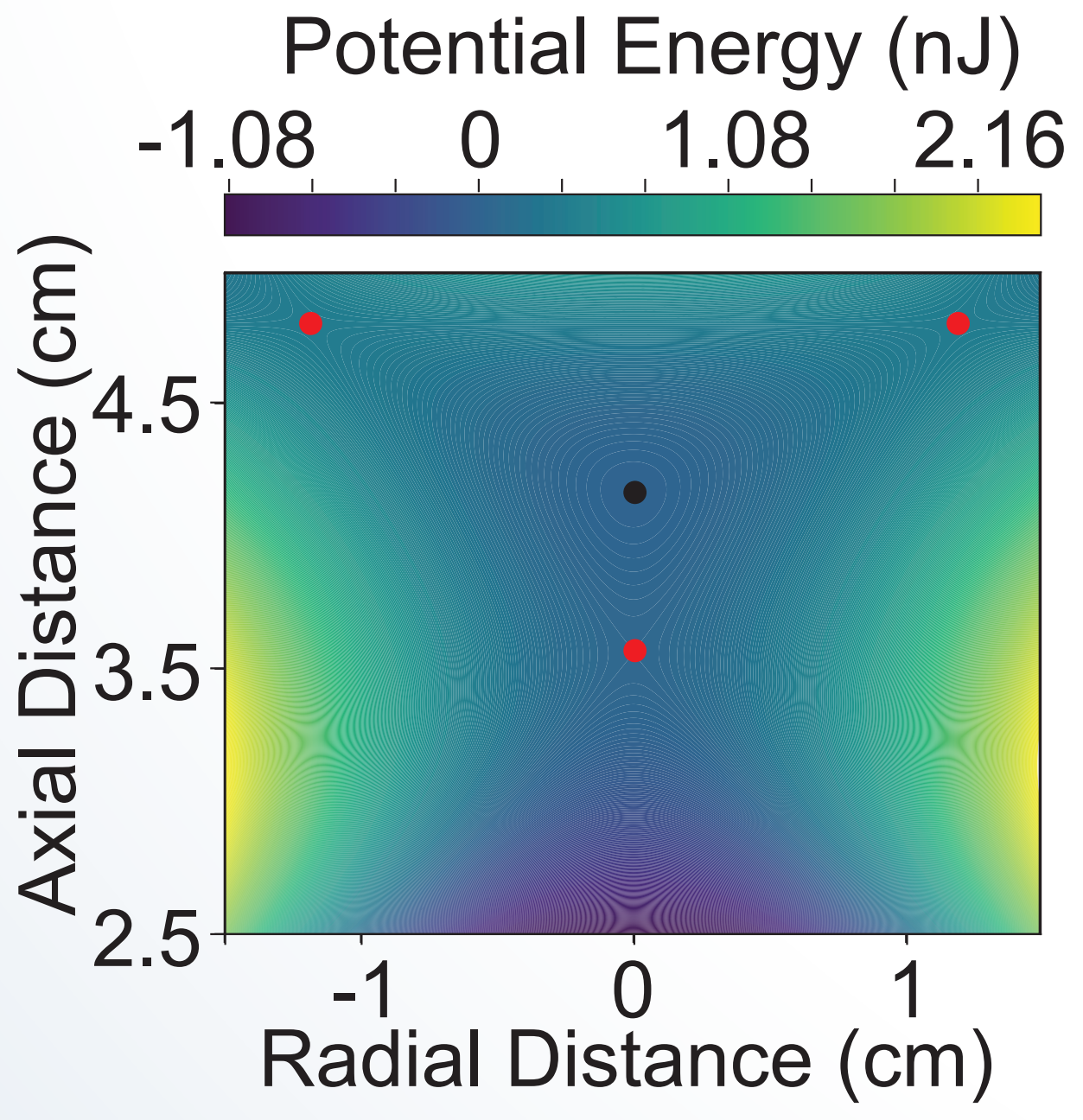
Magnetic Trap

The drop is levitated by the diamagnetism in a strong magnetic trap.

The potential energy of the helium drop in the magnetic field:

$$U_{\mathrm{D}}(x,y,z)=\rho g z-\chi_{\mathrm{vol}}\frac{B^2(x,y,z)}{2\mu_0}$$





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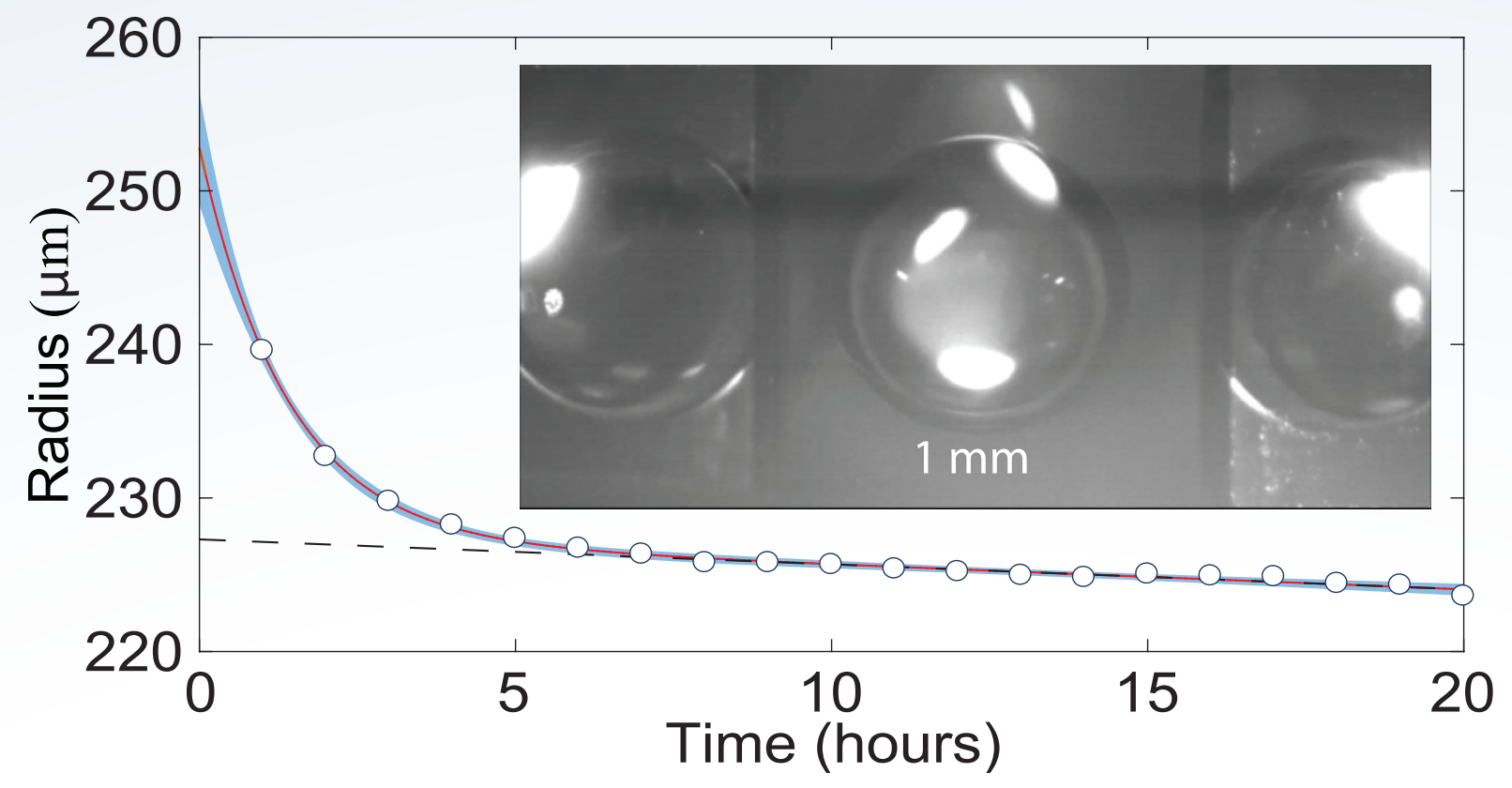
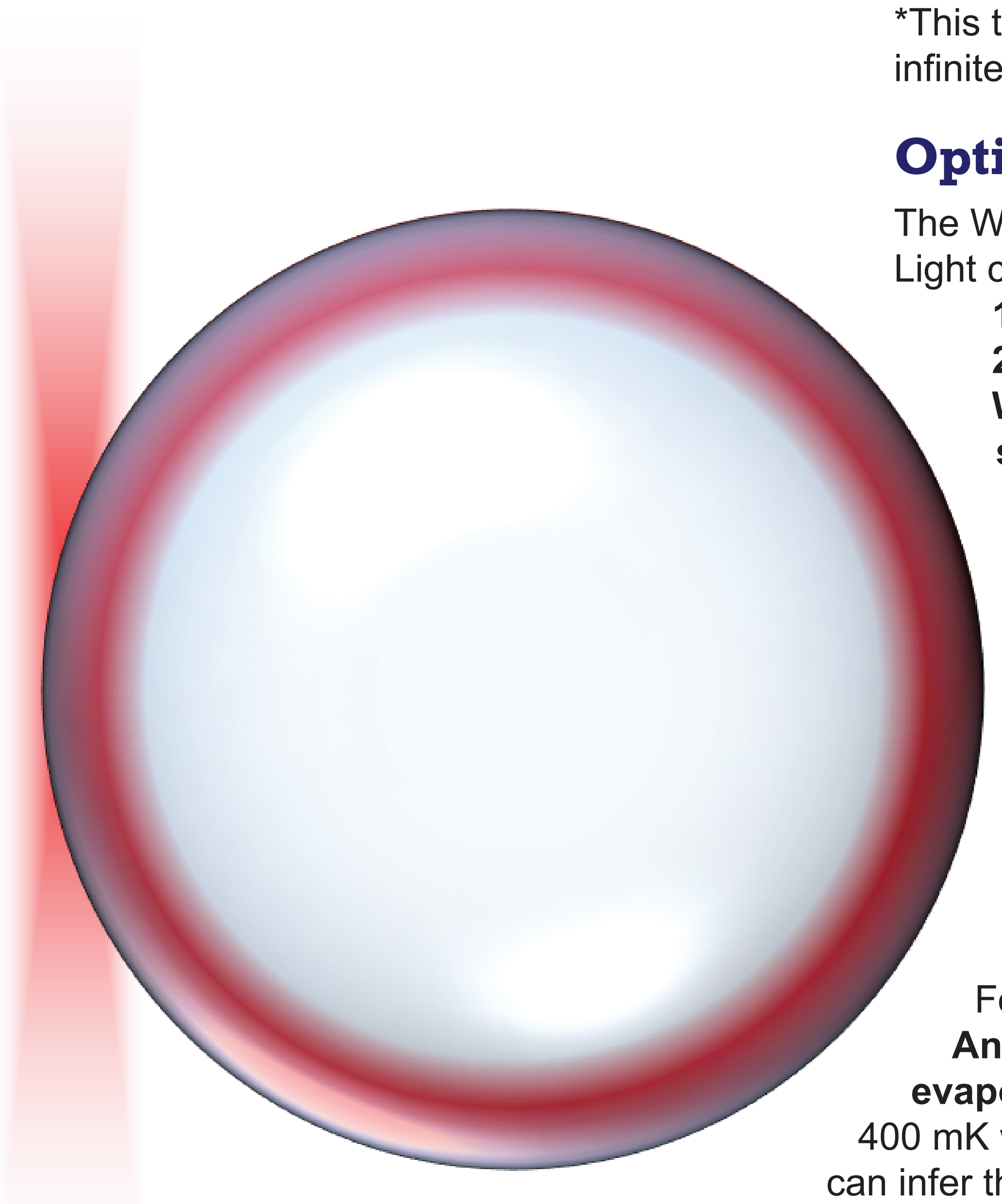
Results: What?



A levitated drop

A ^{4}He drop shortly after it has been levitated. The imaging analysis is deployed to extract the radius of the drop in vacuum as a function of time. The life time of the drop is set by the cold time of the cryostat. The drop is self-evarporatively cooled.



Acoustic Modes

Optical modes are most strongly coupled to surface modes. Using linearized Navier-Stokes equation, the frequency of surface modes is given by:

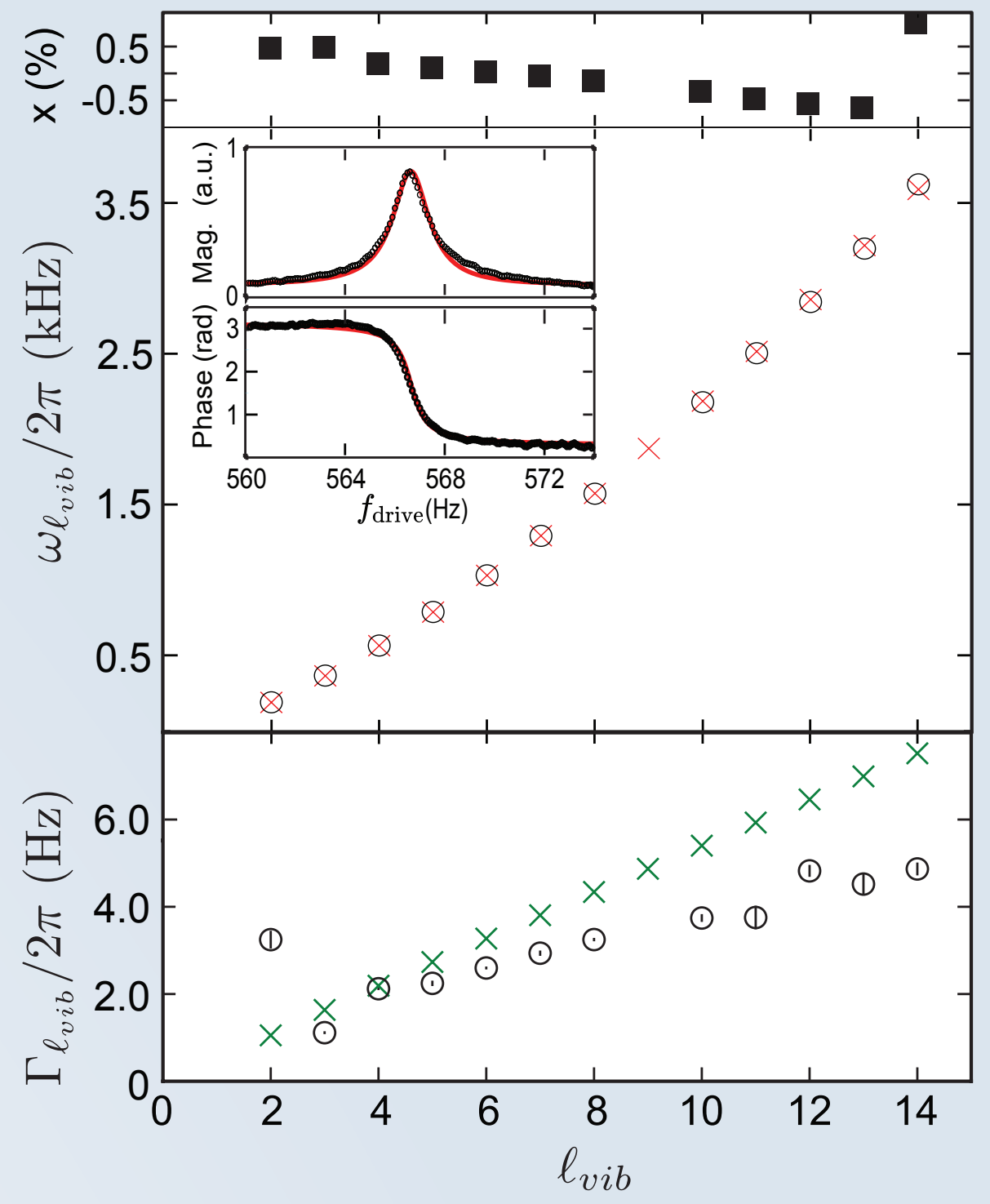
$$\omega_{\ell_{vib}}=\sqrt{\ell_{vib}\left(\ell_{vib}-1\right)\left(\ell_{vib}+2\right)\sigma/\left(\rho R^3\right)}$$

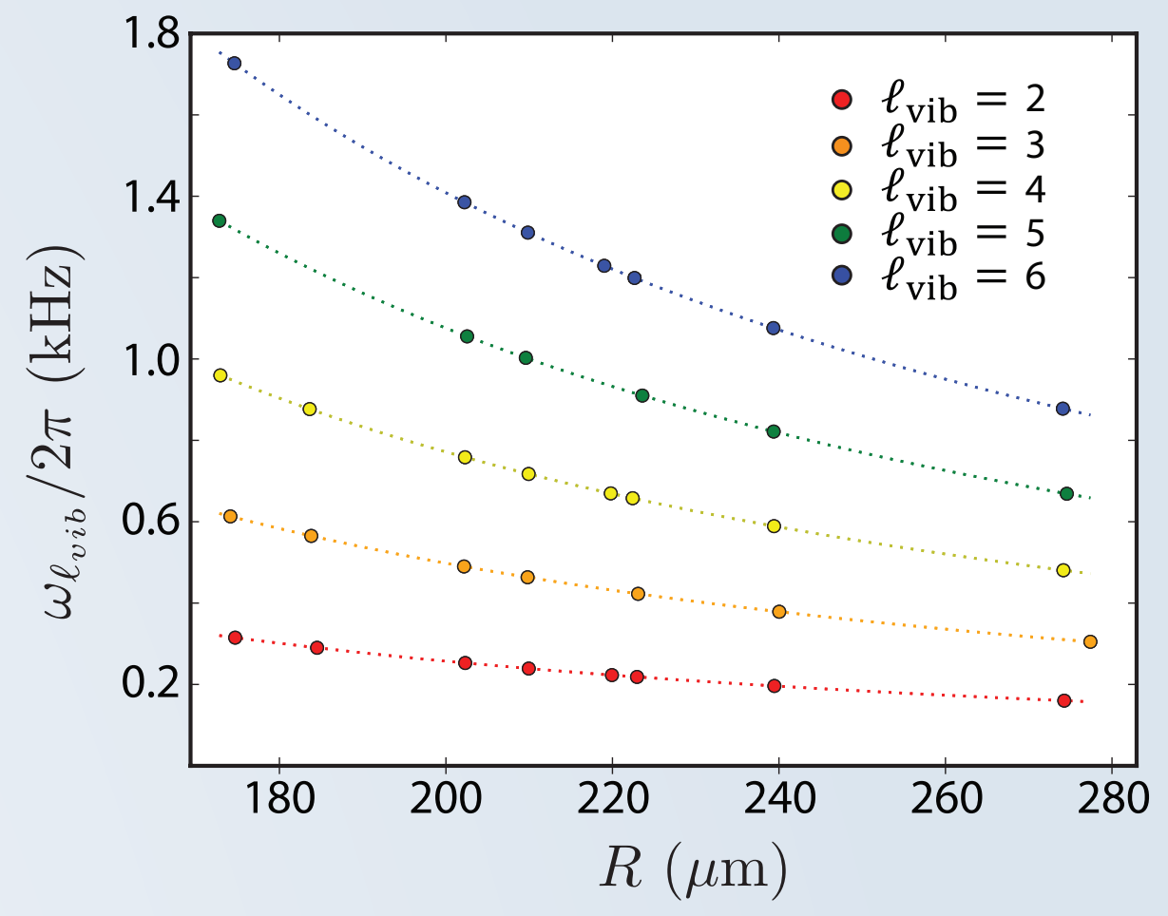
with $2\ell_{vib}+1$ orders degenerancy standing for different spherical harmonic functions.
In the experiment, an amplitude modulated laser provides the drive force, and another counterpropagating laser is used to measure a drop's vibrations.
For drop radius R < 3 mm, the dominant decay mechanism is from phonon-ripplon scattering.
The green crosses are the theoretical estimation* of the linewidth without free parameters.

$$\tau_{\text{molecular}}=\frac{60\rho_0}{\pi^2\hbar q}\left(\frac{\hbar c_S}{k_B T}\right)^4$$

$$q=\frac{\sqrt[3]{\ell_{vib}\left(\ell_{vib}-1\right)\left(\ell_{vib}+2\right)}}{R}$$

*This theory is based on phonon-ripplon scattering on a flat surface with infinite deep bath.





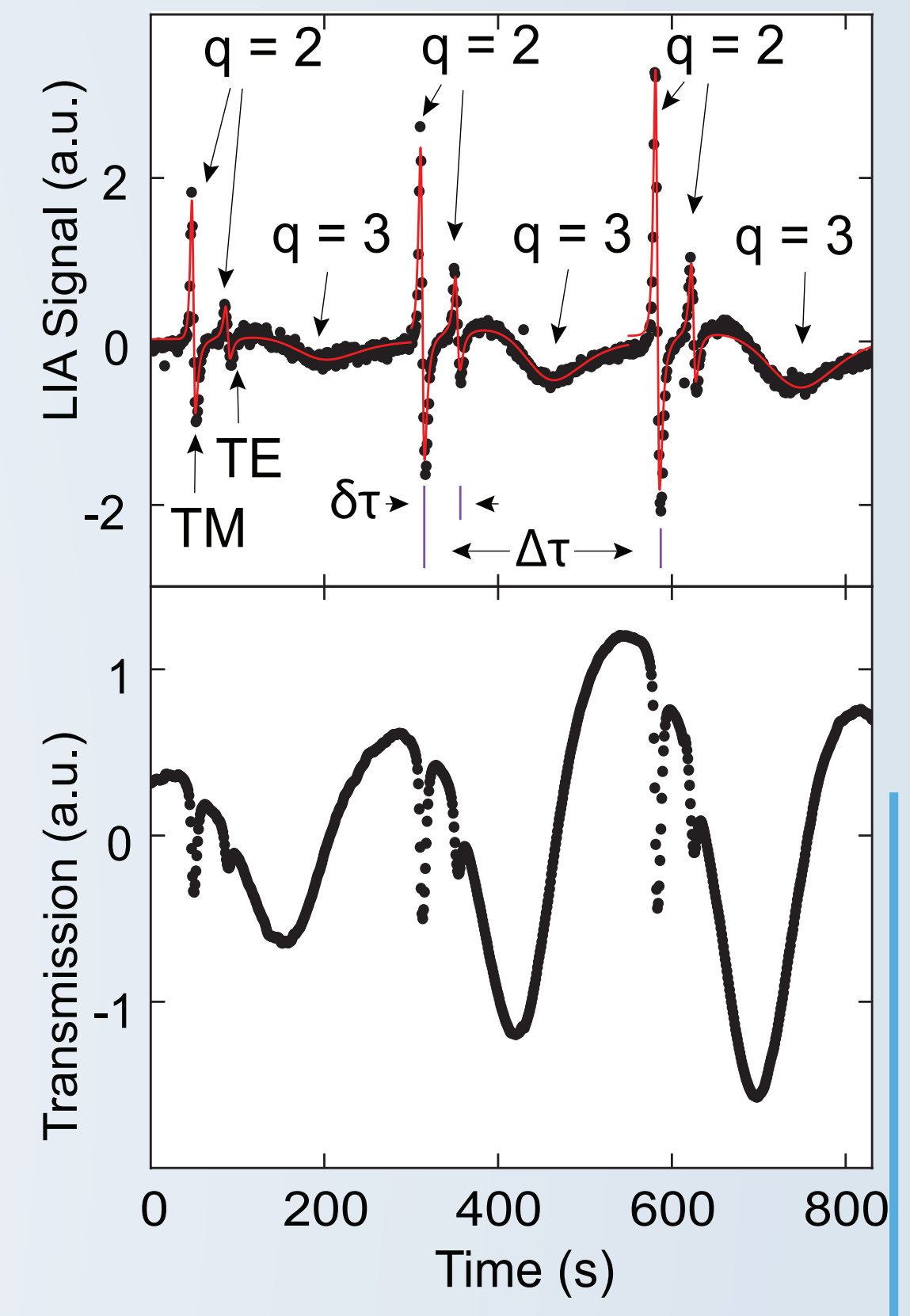
Optical Modes

The WGMs are propagating along the drop circumference.
Light couples into the WGMs if:

1. **Beam profile matches optical mode profile;**
2. **Beam frequency is the eigenfrequency.**

Whenever there is a set of double dips, the drop circumference shirinks by one wavelength.

We experimentally show that these double dips correspond to different polarizations (TE, TM modes).
The finesse measured so far ranges 10~10².



Evaporation rates

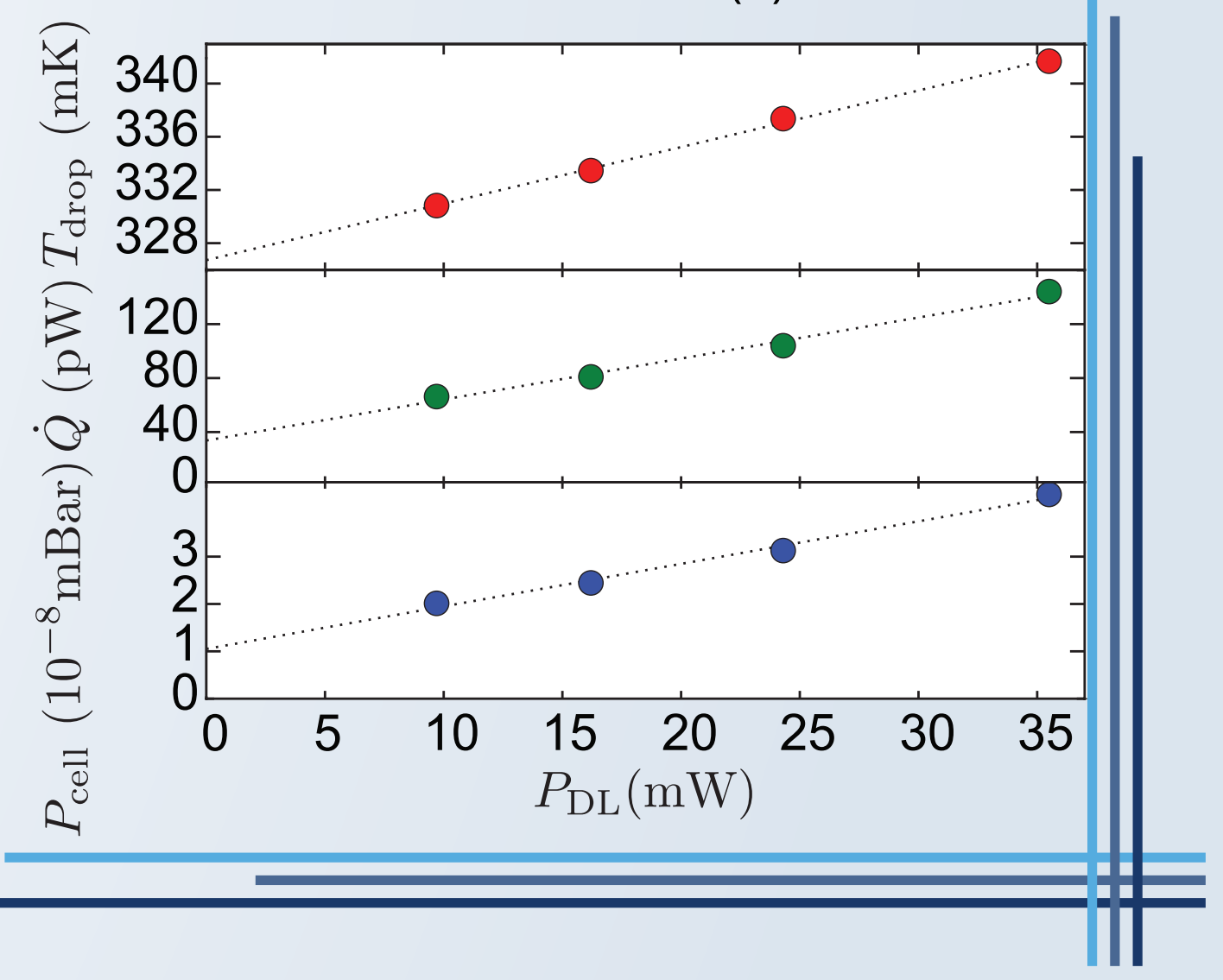
Optical mode transmission offers an extremely precise ruler to measure the radius change of the drop.
For each pair of adjacent dips in transmission, the circumference decreases by the wavelength of the laser:

$$\Delta R=\lambda/2\pi$$

For a red beam (~635 nm), the minimal resolution is about ~100 nm. **Another fantastic feature of the levitated drop is it cools itself via evaporation.** Evaporation provides a means to maintain the drop below 400 mK without contacting any solid boundaries. From the evaporation rate, we can infer the temperature of the drop,

$$\Gamma=g\frac{\sigma m}{\pi^2}\frac{\bar{\omega}^3}{T}\exp\left[-\frac{E_0}{T}\right]$$

The temperature saturates around 327 mK and surrouding pressure is about 10^{-8} mBar. To our knowledge, this is the coldest helium drop so far.



Outlook: Next?

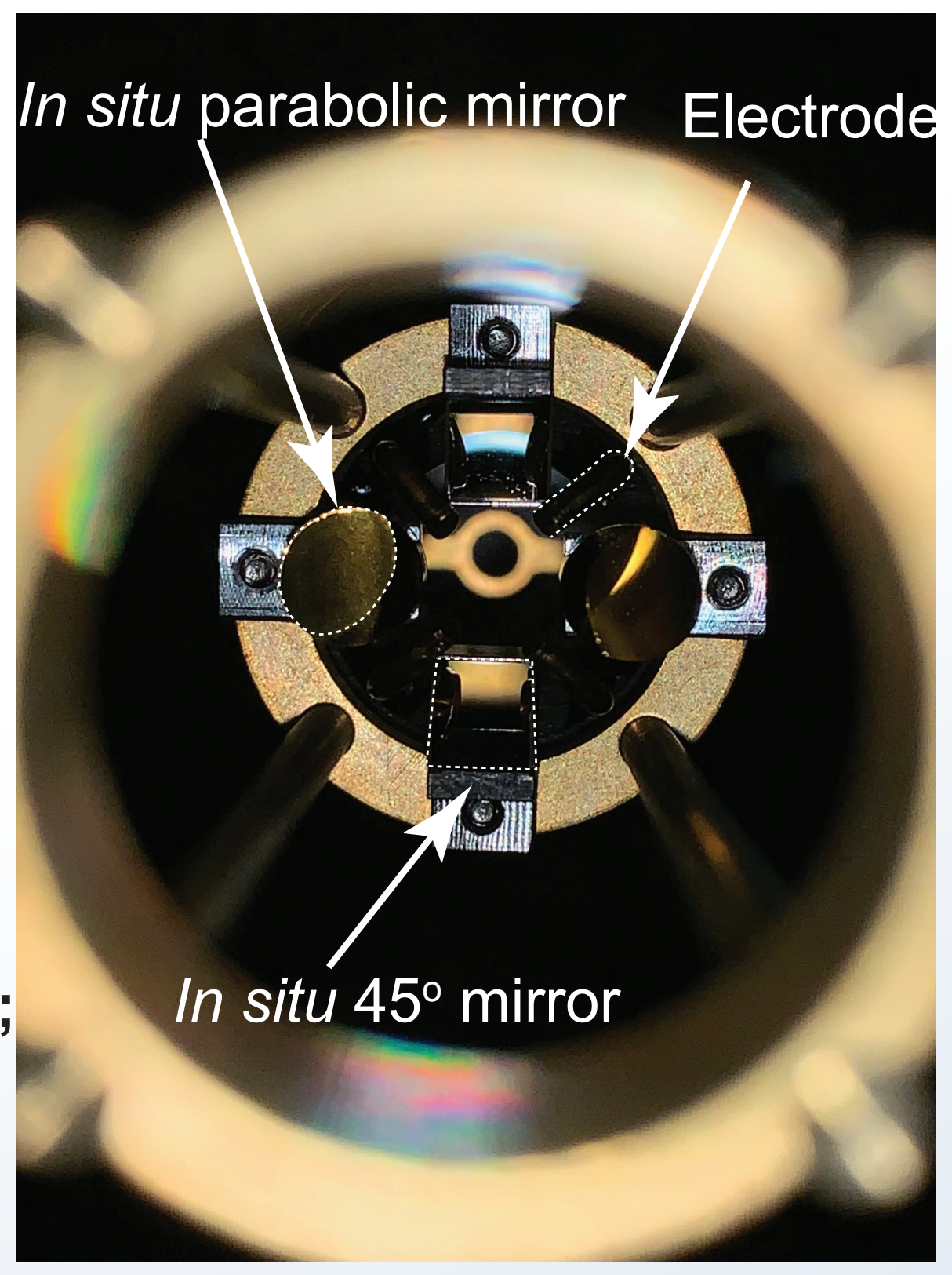
Quantum optomechanics

We are now building a new apparatus to take full advantage of these drops in optomechanical setups. The goal is to:

Make the drops larger (> 2 mm);
Eliminate the center of mass motion;
Further cool down the drop;
Increase coupling efficiency.

We made following changes to achieve goals above:

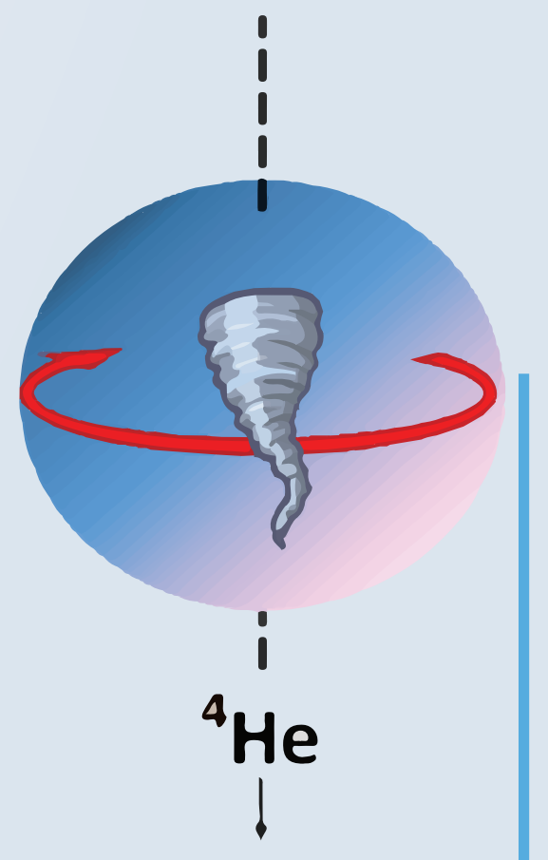
Embedded variable temperature controller;
High voltage electrodes;
Change the experimental cell material;
***In situ* optics.**



Opto-Rotational Coupling

The centrifugal force deforms the equator, which couples to the aforementioned acoustic mode.
Superfluid ^{4}He **can't** undergo rigid body rotation.The angular momentum is in the form of vortices.
Normal fluid ^{3}He **can** undergo rigid body rotation.quantum fluctuations of L can be read out through opto-rotational couplings.

$$\hat{H}_{\text{QND}}=\hbar g_L\left(\frac{\hat{L}_z}{\hbar}\right)^2\hat{a}^\dagger\hat{a}$$



A Helium-3 Drop

Levitating a ^{3}He drop is more challenging than a ^{4}He drop mainly because of the non-zero nuclear spin. Consequently, this residual spin leads to paramagnetism which cancels the diamagnetism we employ to levitate Helium. As a nearly non-interacting Fermi gas, the paramagnetism follows Curie's law in high temperature and staturates to Pauli paramagnetism in low temperature (cancels 40% of diamagnetism). The relaxation time T_1 of ^{3}He spin ranges from 500 s to 3,000 s, which enables us to control its net spin via RF waves.