Quality Factor Measurements of Materials for Gravitational Wave Detector Mirror Coatings

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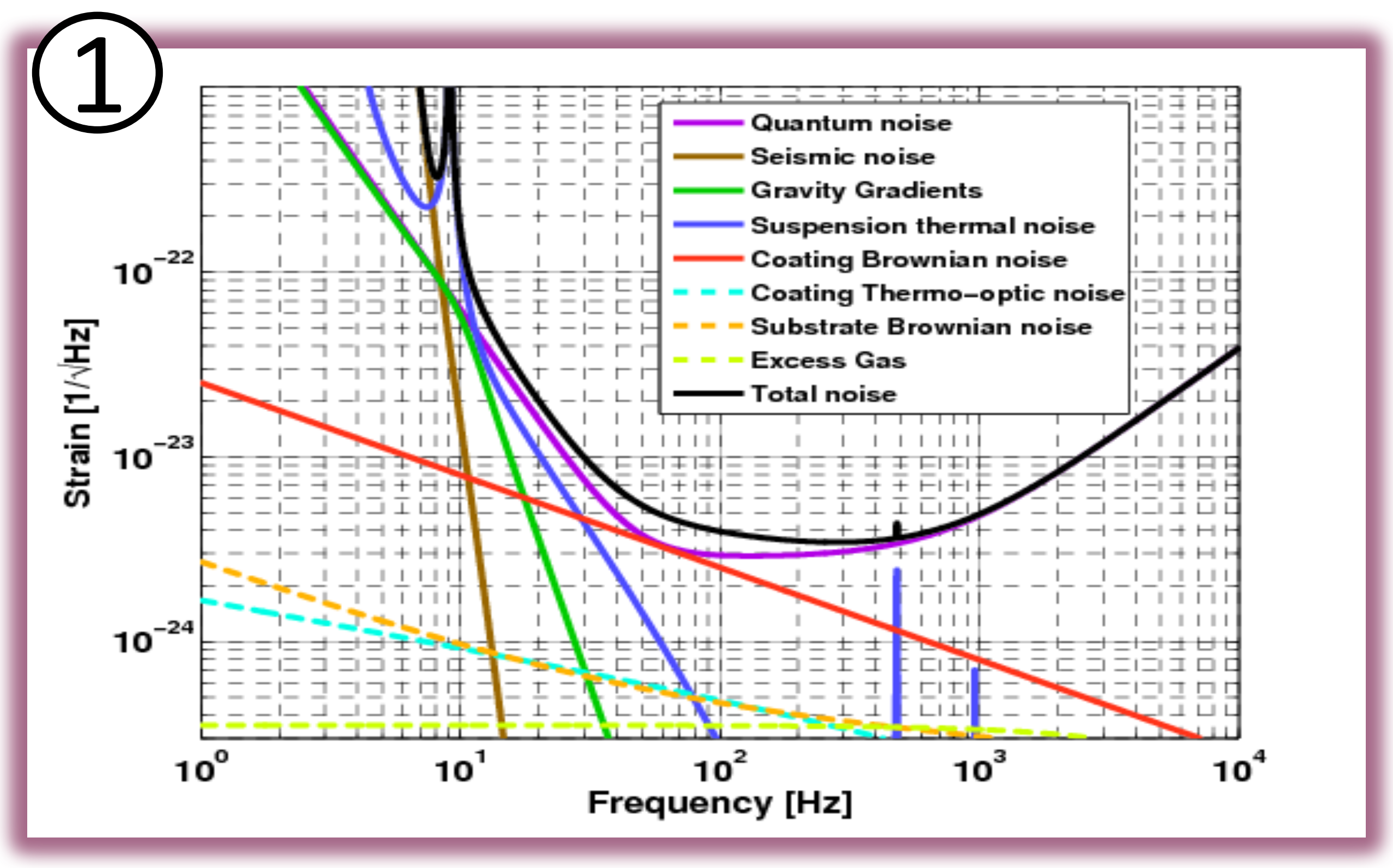
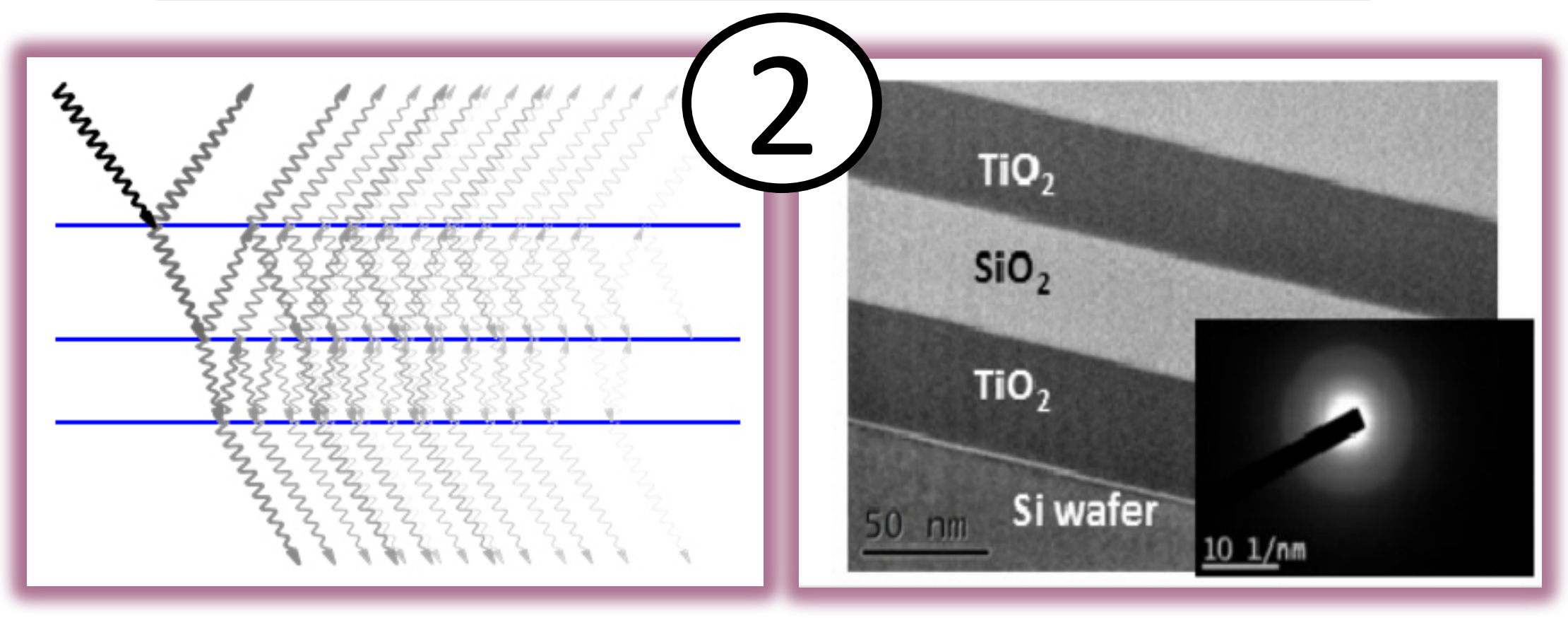
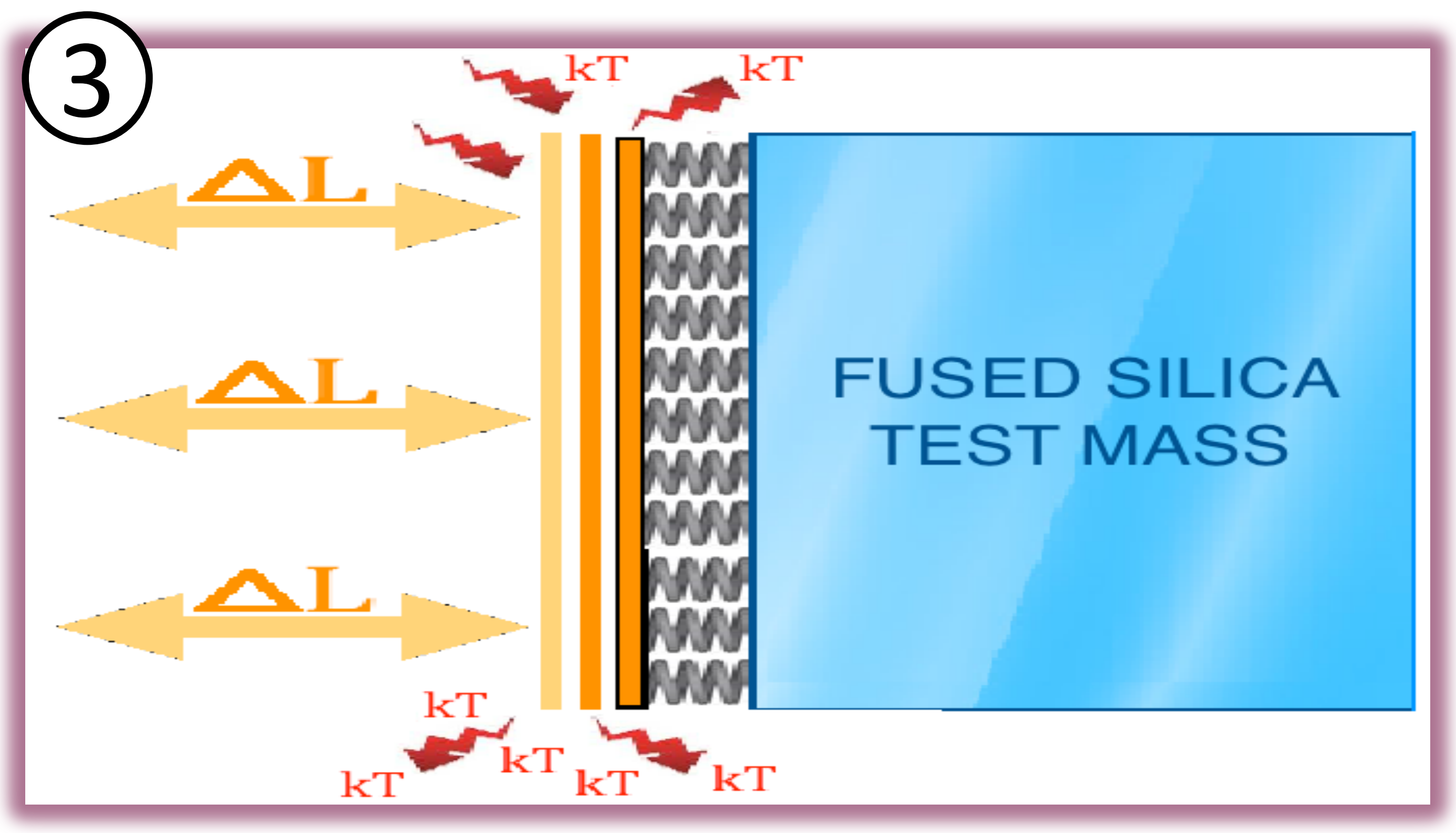
1. Gravitational-Wave detectors use interferometers with 4 km long (2.5 miles) arms to measure the strain induced in space-time by gravitational waves. The length sensitivity is limited by the thermal noise of coatings, ~10^{-18} m. This translates to a detectable strain of between 10^{-20} and 10^{-22} $Hz^{-1/2}$ as illustrated by the red line in the graph below.

2. Optical coatings are stacks of doublets of films with different refraction indices, 1/2 wavelength thick. These doublets reflect light coherently and can be stacked to generate the desired reflectivity.

3. The optical coatings on the test masses in the interferometer essentially behave as though they were attached to the fused silica substrate by springs. When random thermal energy exchanges distort them there will be an effective length change in the laser cavity due to the elasticity of the silica below. This is not a length change due to a passing gravitational wave and will contribute to noise.





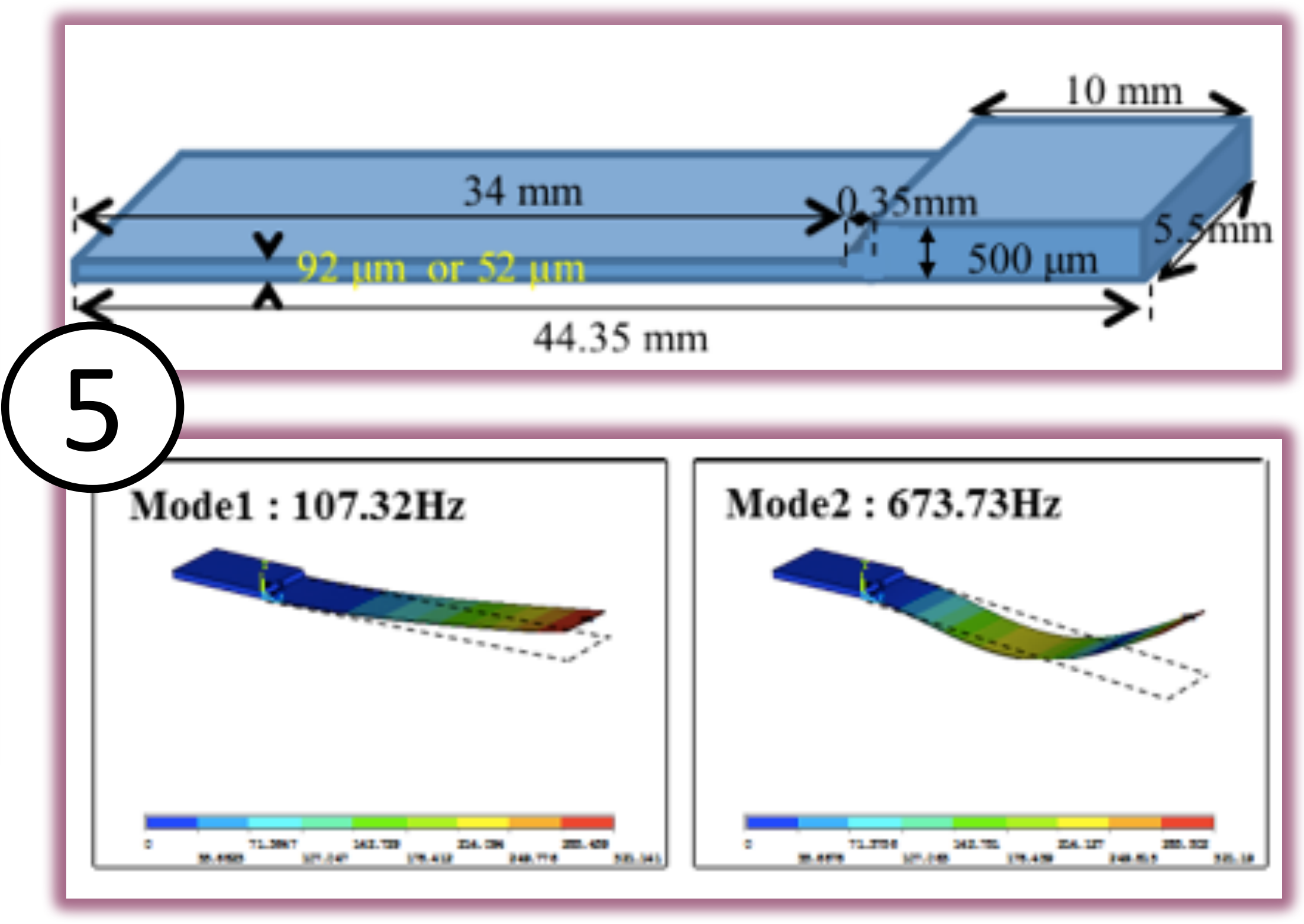


5. The method of oscillating a thick cantilever to measure the Q of a nano-coating leads to problems from the large elastic energy stored into the substrate. The coating tested is ~100 nm, and the substrates were ~.1 mm. 1,000 times thicker! The substrate dominates.

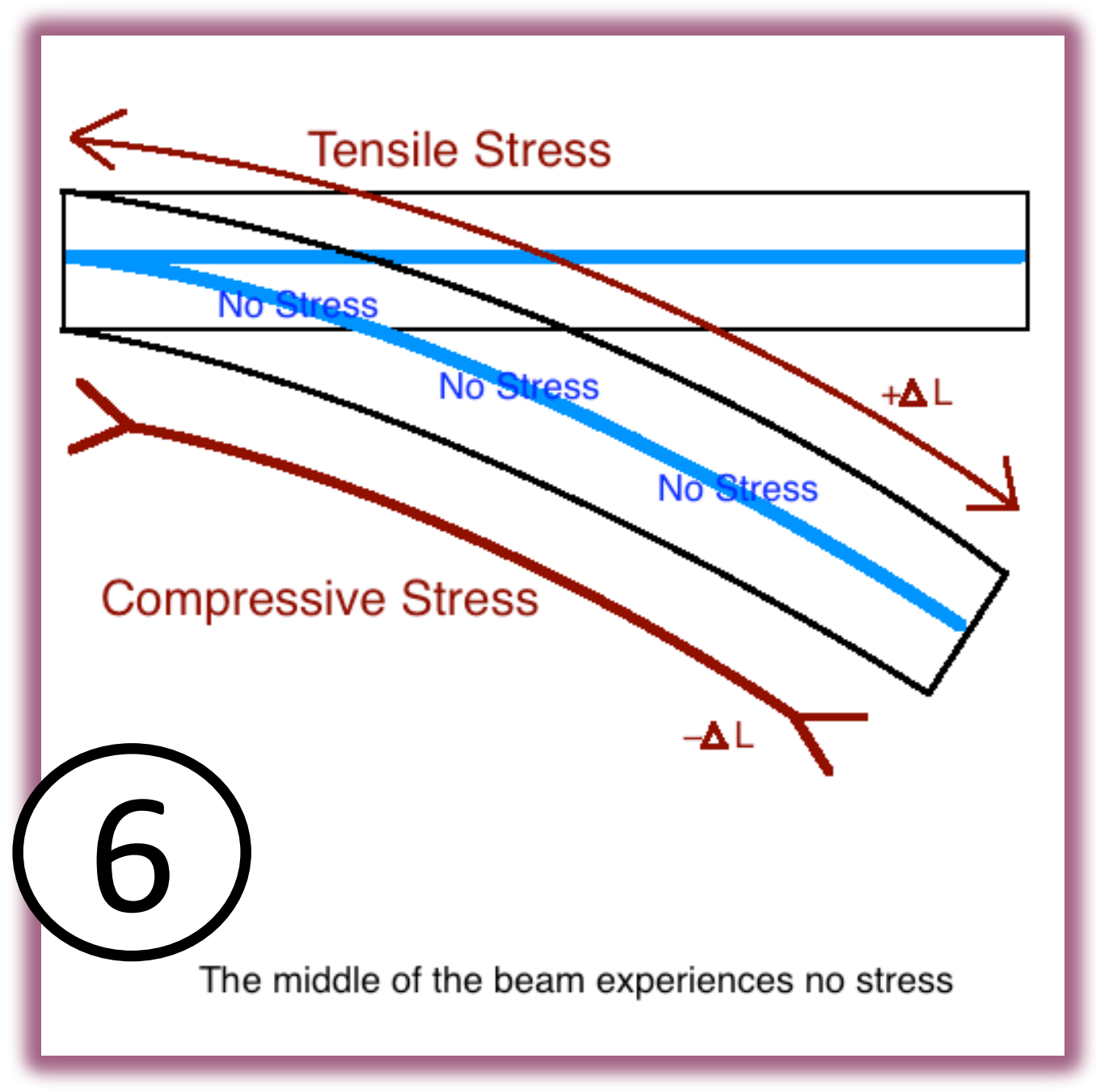
4. All resonant systems have an intrinsic Quality Factor (Q) that describes how rapidly they exchange energy with the thermal bath. A system with a high Q has low thermal noise.

$$W_{Thermal}=\frac{kT\,f}{Q}$$

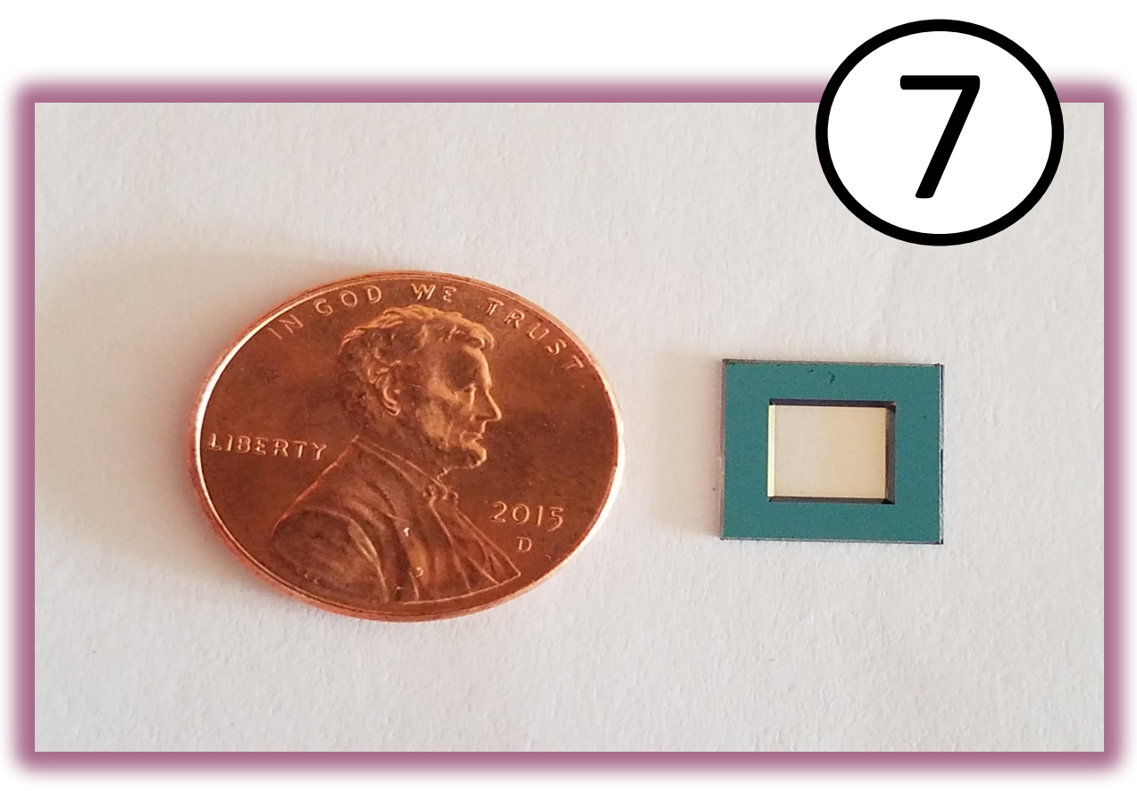
We have devised a new way to very precisely measure the Q of various coating materials from different processes, useful to drive the development of advanced, higher Q, coatings, that will allow detection of GW from deeper in the Universe.



6. We will instead coat on both sides of a 100 nm Silicon Nitride membrane substrate. Virtually equal thickness! We gain another advantage by coating both sides of the membrane as seen in the stretched cantilever to the right.

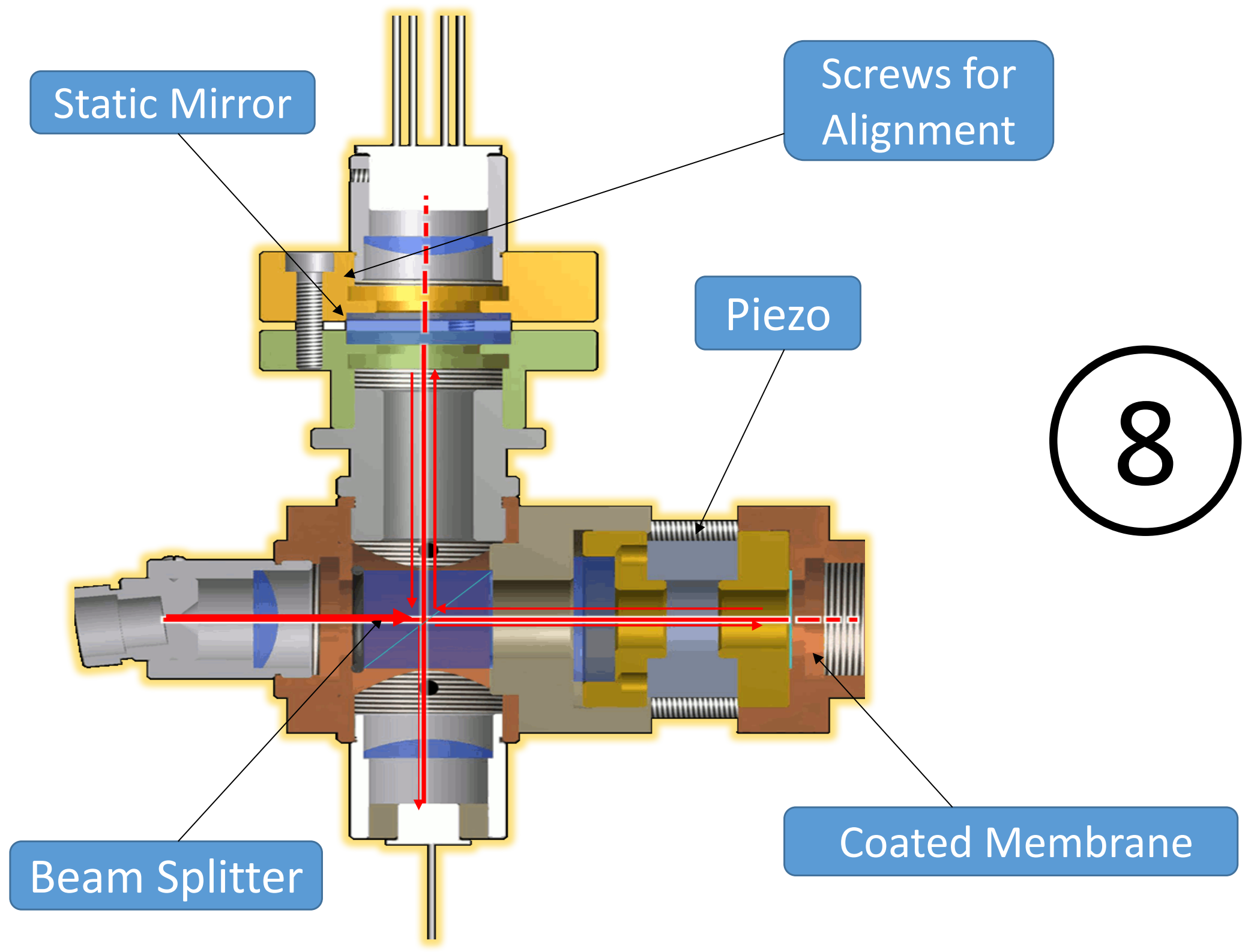


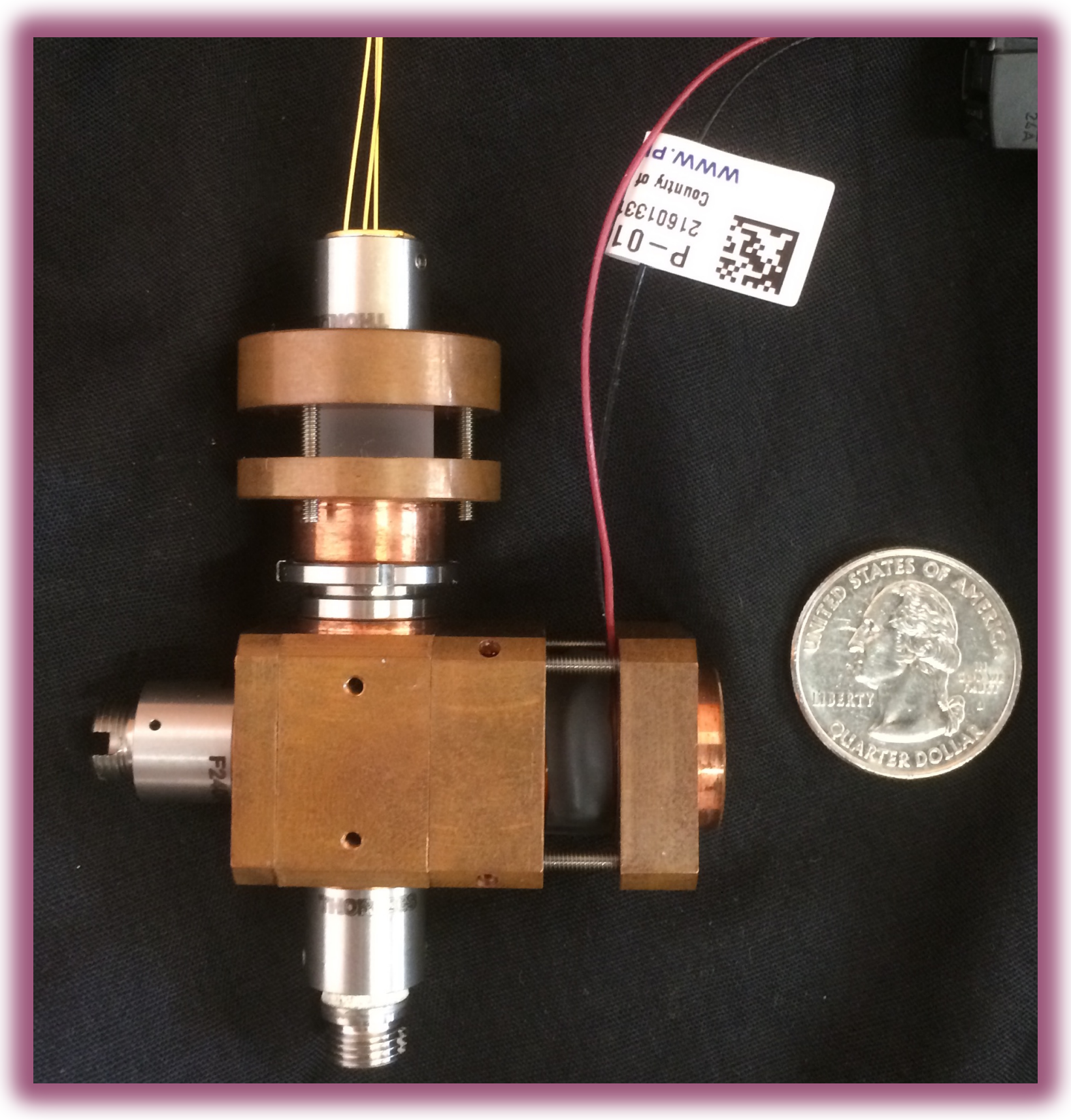
The middle of the beam experiences no stress

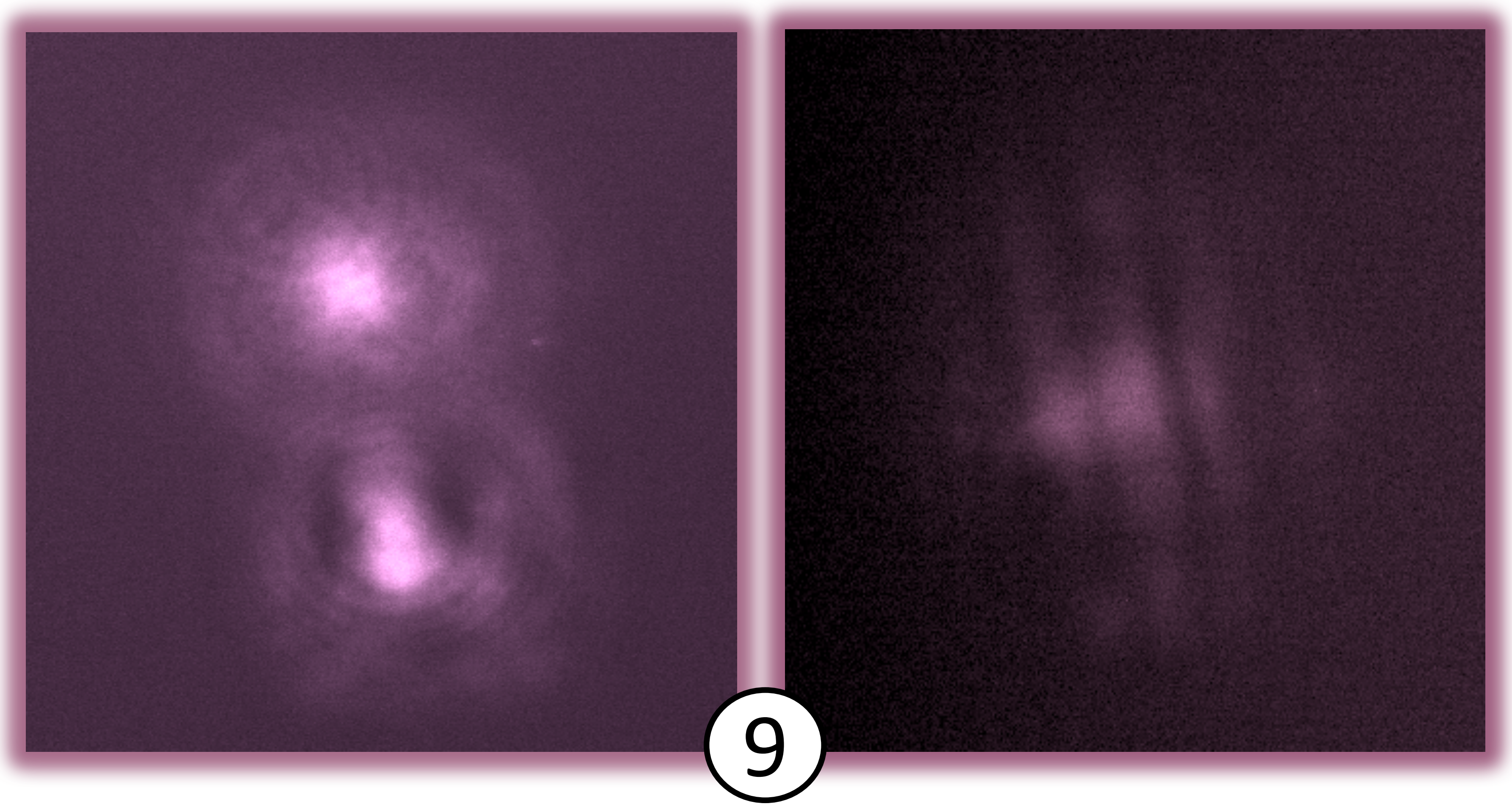


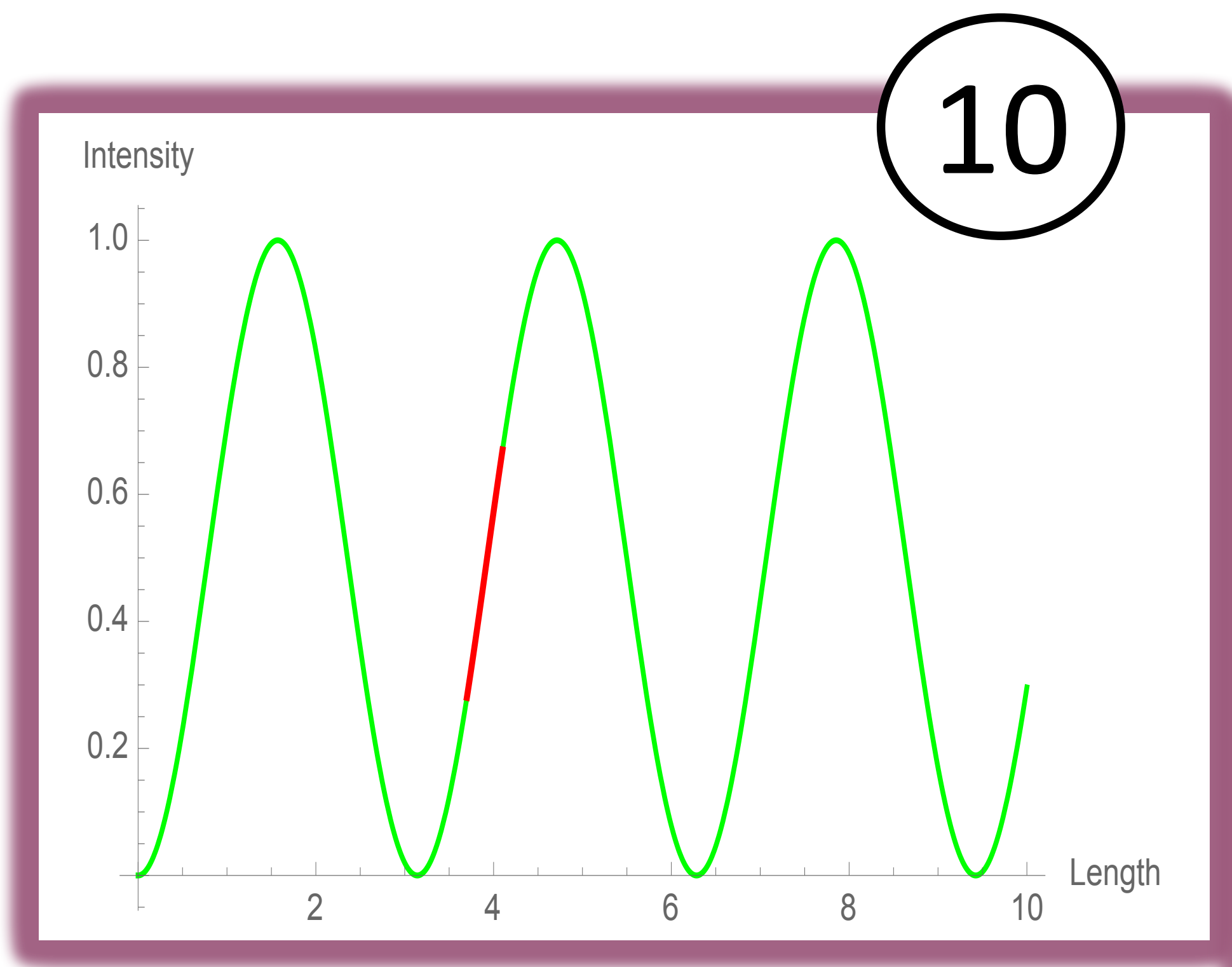
7. The SiN membranes are very small. How can we oscillate them and measure?

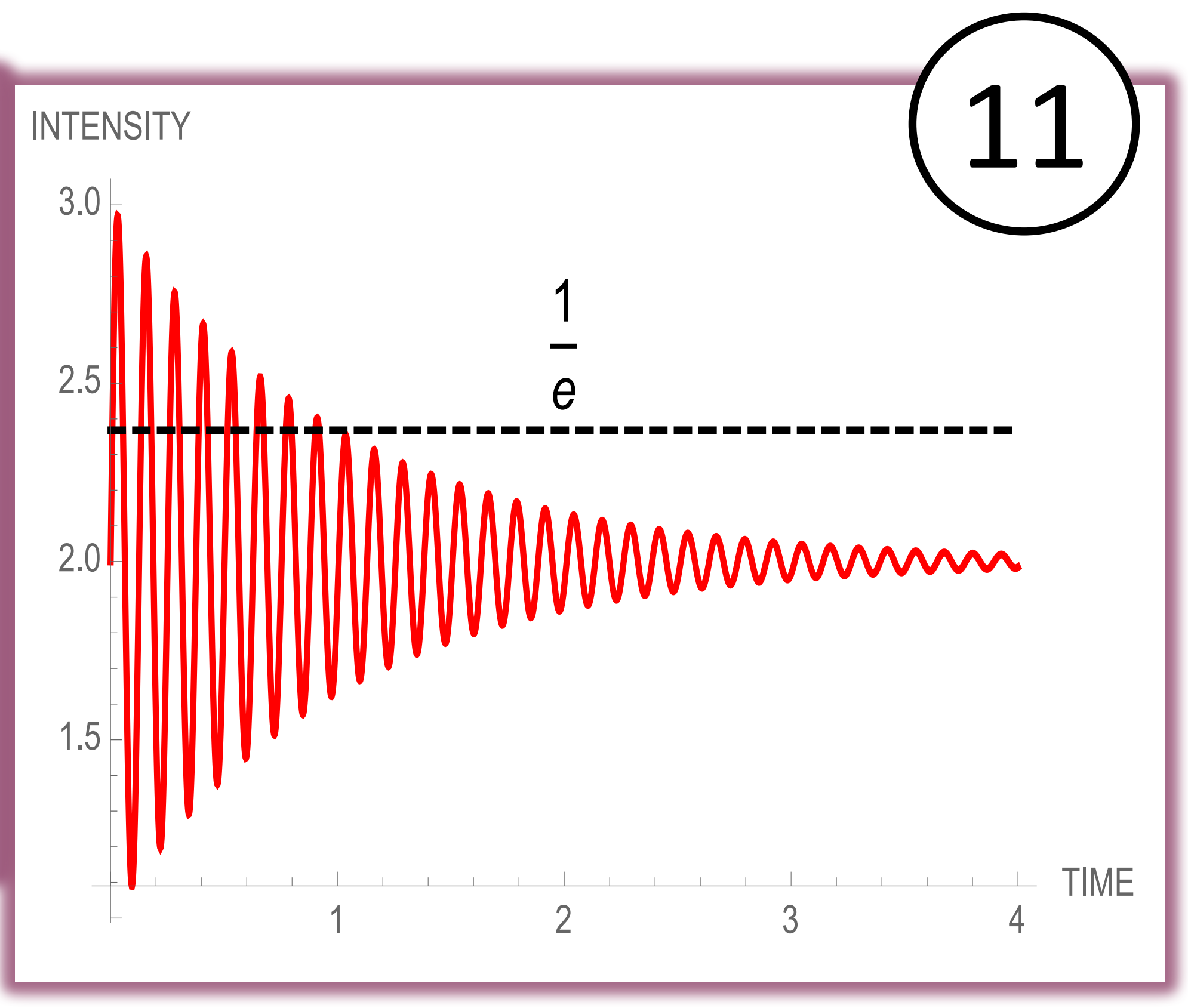
8. We constructed a mini interferometer that will have the coated membrane at one end acting as a mirror. The membrane's oscillation will be excited by an electric pulse. This will cause the laser output to oscillate and eventually die out. The number of oscillations that occur before the amplitude reaches 1/e is the Q of the system. The Q of the optical coating can then be easily extracted.











9. Work in progress: Our interferometer outputs two beams that, when aligned, show the interference pattern we will measure. We will need to design a photo detector that can accurately read the change in intensity as the fringes move across it, due to the oscillation in effective cavity length.

10. We will use a piezo in the interferometer to find the working point, i.e. the length at which the laser output is half of its maximum intensity. This will give the largest and most linear modulation induced by the effective length changes caused by the oscillating coated membrane.

11. This is an example of the type of ring-down we will be measuring to calculate the Q value of the coatings.

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