

EPFL

# OUTLINE

**In this lesson, you will learn about the most basic physical phenomena in an optomechanical system (almost without formulas)**

- **Light changes the spring constant**
- **Light creates several stable equilibrium positions**
- **Light can damp and anti-damp motion**
- **Photons can provide or take away energy**

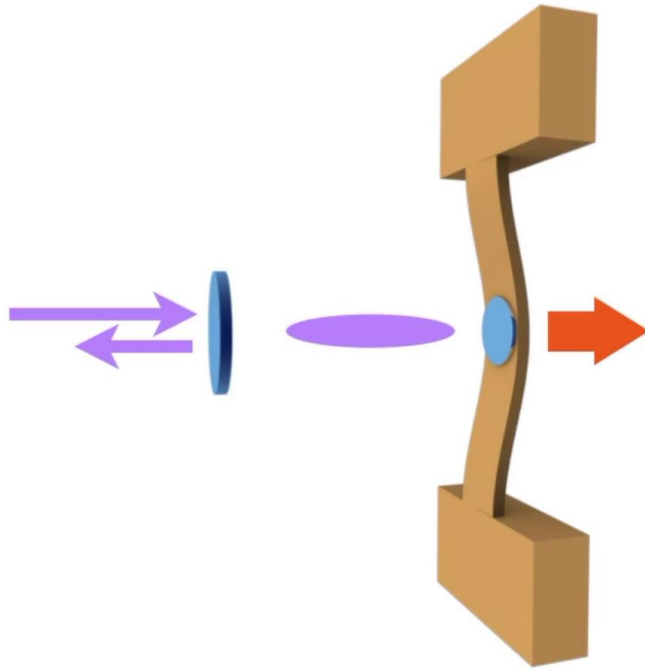
Welcome. In this lesson, you will learn about the basic phenomena in cavity optomechanics and we will do it without the math, that is, you can concentrate on the physics. Here's a brief outline. You will learn in this lesson about how light changes the mechanical spring constant of an object, how light can create several stable equilibrium positions, how it can damp and anti-damp motion and finally, we'll say something about the quantum picture, that is, photons can provide or take away energy from mechanical motion.

Notes

Summary



## AN OPTOMECHANICAL CAVITY



This is a mechanical cantilever a nanobeam maybe and it has a mirror. It's well known that if you reflect light off a mirror, it can exert a radiation pressure force. However, usually this force is very tiny. So what can we do to boost the strength of this force? Well, one of the easiest possibilities besides buying a bigger laser is to have an optical cavity. So that means we put the light between two mirrors and if we know drive this optical cavity with a laser, the circulating power will be enhanced by a factor of a million or so which is the finesse of the cavity. In the same proportion, the strength of the force will be enhanced. Now you can play around. For example, you can change the intensity of the incoming laser or you could change its frequency. If the frequency is changed, we might have a situation where the incoming laser frequency no longer matches the resonance frequency of the cavity. So then, of course, the circulating power is reduced and also the force will be reduced. There is, however, another way of changing the circulating intensity by changing how the resonance condition is fulfilled. Because usually we do not change the laser frequency, rather what happens is that the length of the cavity changes.

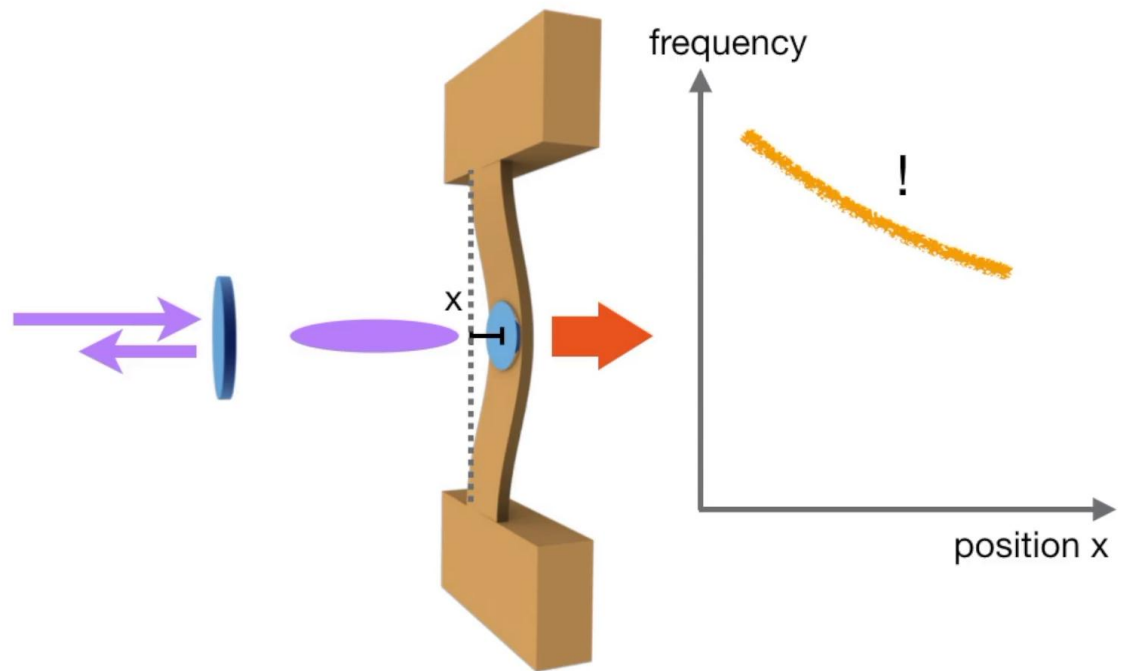
Notes

Summary



0m 40s

# AN OPTOMECHANICAL CAVITY



Why is that? Well, that is because the object, the mechanical object can move so the mirror can really move and thereby change the length of the cavity. In the following, this position of the mirror is the most important variable so let's give a name to that. Let's call it 'x'. And we will be asking questions like how does the resonance frequency of the optical cavity depend on this position? Here's a little quiz. Does the resonance frequency go down or does it go up as the mirror moves to the right? Think about it for a moment. Well, if you say it goes down, that's exactly the right answer. The resonance frequency goes down because the length of the cavity increases and so also the wavelength of radiation that nicely fits into the cavity has to increase and, of course, if the wavelength goes up, the frequency goes down. Now there is not only one resonance but there are multiple resonances in such a cavity because any resonance is given by the condition that an integer number of half wavelengths matches the cavity length. So if we plot all these resonance conditions all these resonance frequencies as a function of position, this is the kind of plot we get.

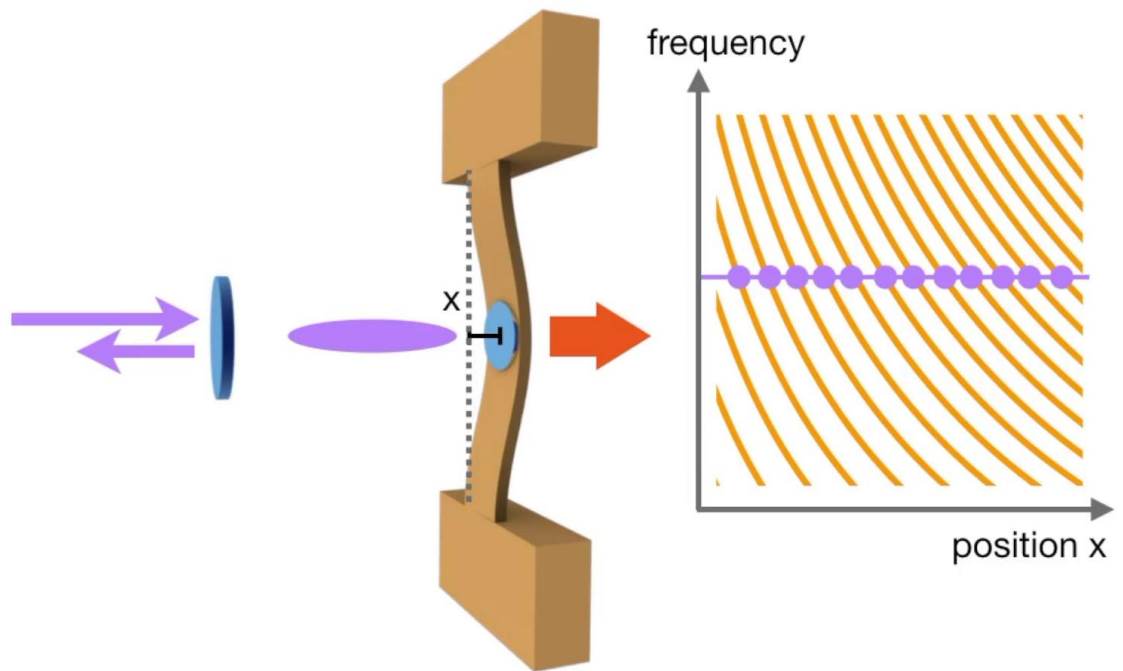
Notes

Summary



2m 16s

## AN OPTOMECHANICAL CAVITY



All of them are going down as we move the mirror to the right. Now when we come in with a laser of fixed frequency, in this diagram that would mean we plot a straight horizontal line because the frequency of the laser is fixed and it doesn't change as a function of position. Nevertheless, all these resonance curves as they go down, they encounter the laser frequency and so we have multiple positions at which the resonance condition is fulfilled. What does this mean for the light intensity circulating inside the cavity?

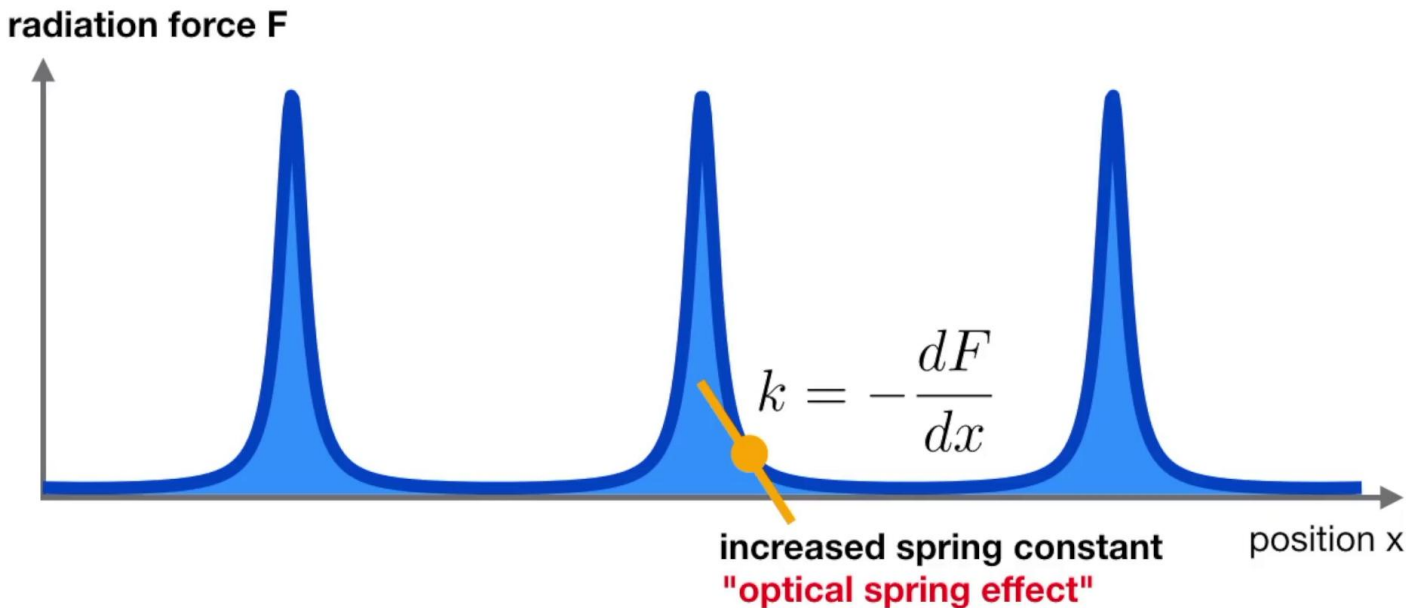
Notes

Summary



3m 42s

## OPTICAL SPRING EFFECT



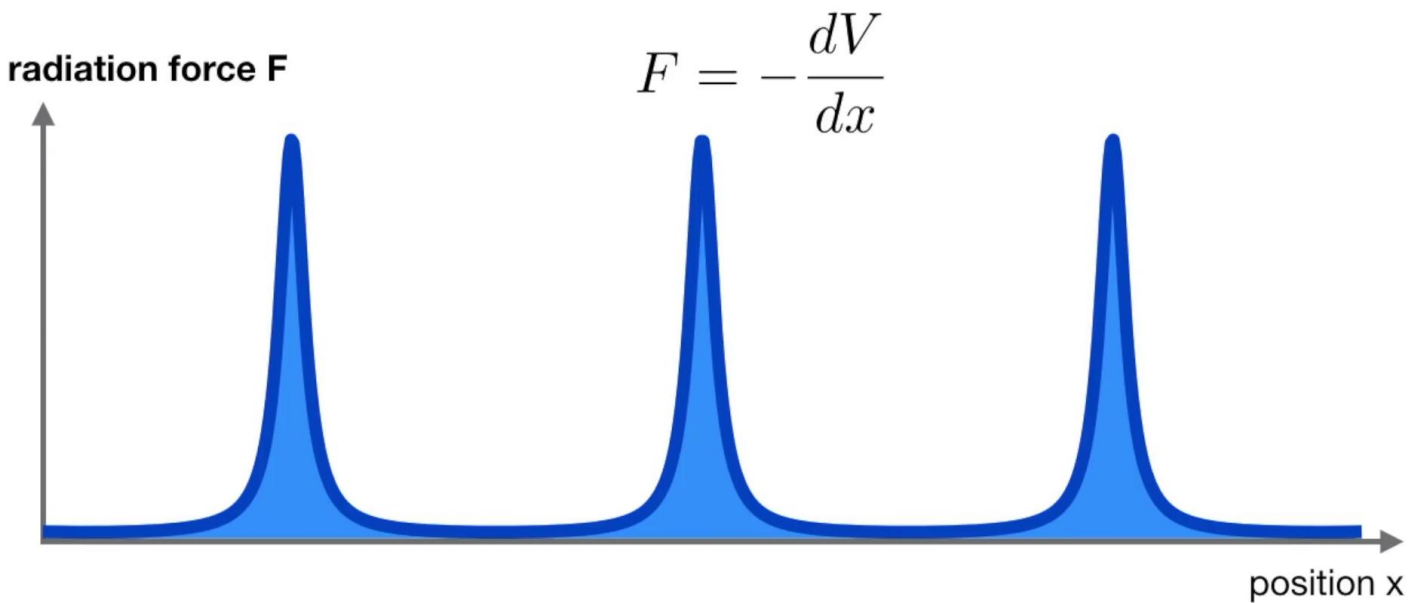
Well, here it is. So the light power circulating inside the cavity as a function of position shows the typical resonance behavior of a Fabry-Pérot cavity, has very sharp spikes exactly when you match the resonance condition. Now the light power is actually proportional to the radiation pressure force. So this diagram also is a diagram of the force versus position. That's very interesting because it means we have a very pronounced behavior of the force on the position. One of the things you can notice about this diagram is that at any given point the force has a certain slope. Now, what does it mean for a force to have a slope? Well, you know if the forces position dependent then the slope gives an effective spring constant because if we have a situation where as we're moving to the right, we have a force pointing to the left and this force linearly increases in amplitude as we move the position. That's exactly the effect of a mechanical spring. So whenever you have a position dependent force and you only talk about small excursion around a given point, you can talk about a spring constant. And so in this case, the radiation force actually increases the overall spring constant of the mechanical object which might have had an intrinsic spring constant to start with.

Notes

Summary



## OPTICAL SPRING EFFECT



This effect is known as the optical spring effect and it can be really really strong so it can be even much stronger than the intrinsic spring constant. Of course, if you are sitting at another position, you can have zero spring constant. Or you can even reduce the spring constant, that is, have an effective negative contribution to the spring constant. Now, all of this physics also can be understood in a slightly different picture and that is with the help of a potential. Remember if you have a potential then the force is the negative gradient of the potential. So if you are given the force you just need to integrate in order to get the potential and if we do this for that funny shape of the force that has all these resonance peaks, what we get is rather remarkable and there's probably a potential you've never seen before in any other context which is a kind of staircase potential.

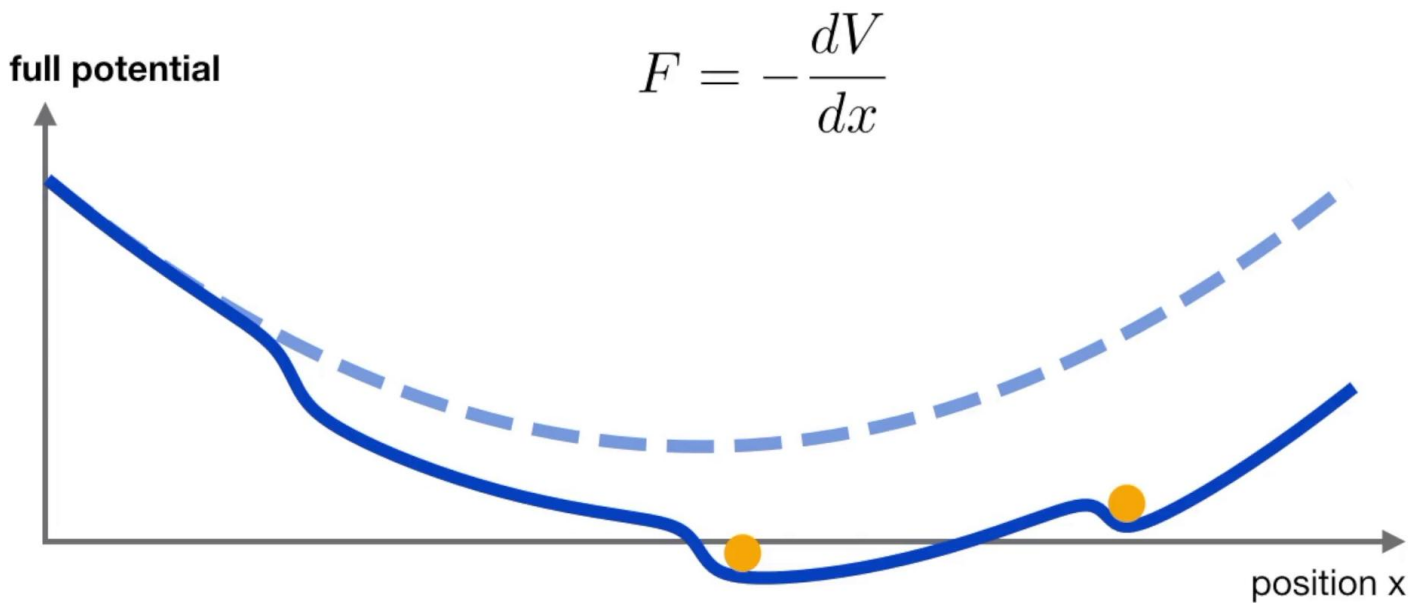
Notes

Summary



6m 10s

# MULTISTABILITY



So whenever there is a resonance peak, we have a force that is a negative slope of this potential and we have another step. These steps are rounded because the peaks are not infinitely sharp. Now this is only the radiation-induced potential. You want to add this to the intrinsic potential that describes the motion of the mechanical object. If the excursions in position are not too large then usually we have a harmonic oscillator that has a parabolic potential. So we want to add this staircase potential to a parabolic potential and this is what we get. The dashed curve would be the intrinsic potential. The blue curve, the dark blue curve is what we get when we add the radiation-induced potential. Now look at this potential. It's very interesting because actually it has several local minima, at least two in this picture. So that means we have several stable equilibrium positions. The mechanical object can be at either one of these positions and it's completely stable. In these positions the radiation pressure force exactly balances the restoring force brought about by the intrinsic spring constant. Having these multiple stable positions is known as multistability.

Notes

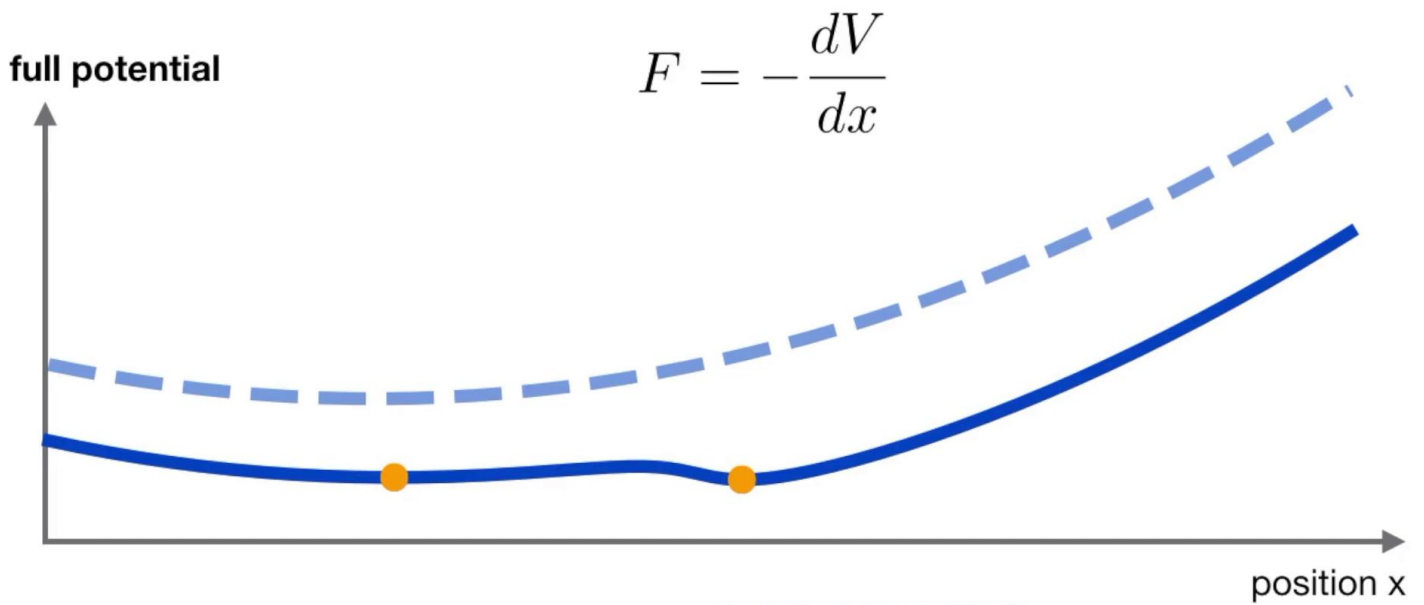
Summary



7m 20s



# BISTABILITY



Walther group (Dorsel et al) 1983

**"static bistability"**

In fact, this can also happen when you zoom in to the vicinity of one of the steps that are induced by one of the optical resonances. In this case, there can be at most two stable equilibrium positions. We talk of bistability. In fact, we like to call it static bistability to distinguish it from another dynamical effect that we will talk about later. Now this effect static bistability in optomechanical systems was already experimentally demonstrated by the group of Herbert Walther back in the 80s. This effect only happens when the laser power is large enough. Let us briefly discuss this.

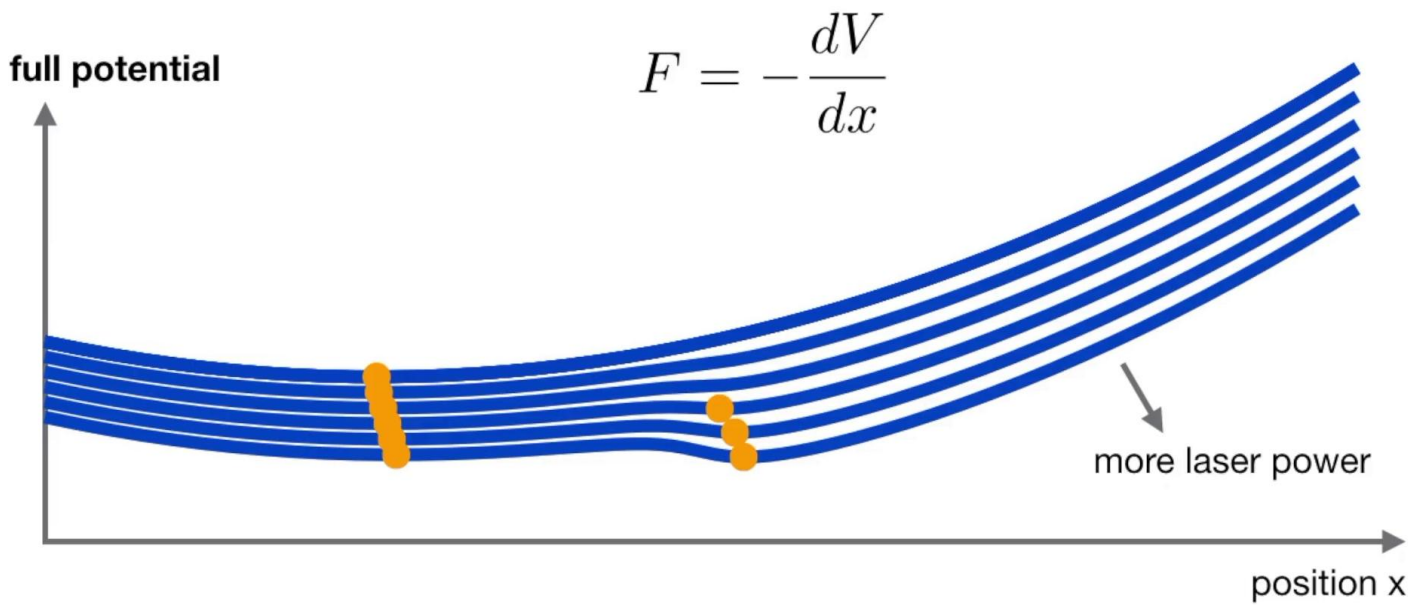
Notes

Summary



8m 47s

# BISTABILITY



Here we show multiple potentials where the laser power increases. When the laser power is small there's only one stable equilibrium position. After a certain threshold you have two stable equilibrium positions. We can also keep the laser power fixed and instead, change the laser frequency.

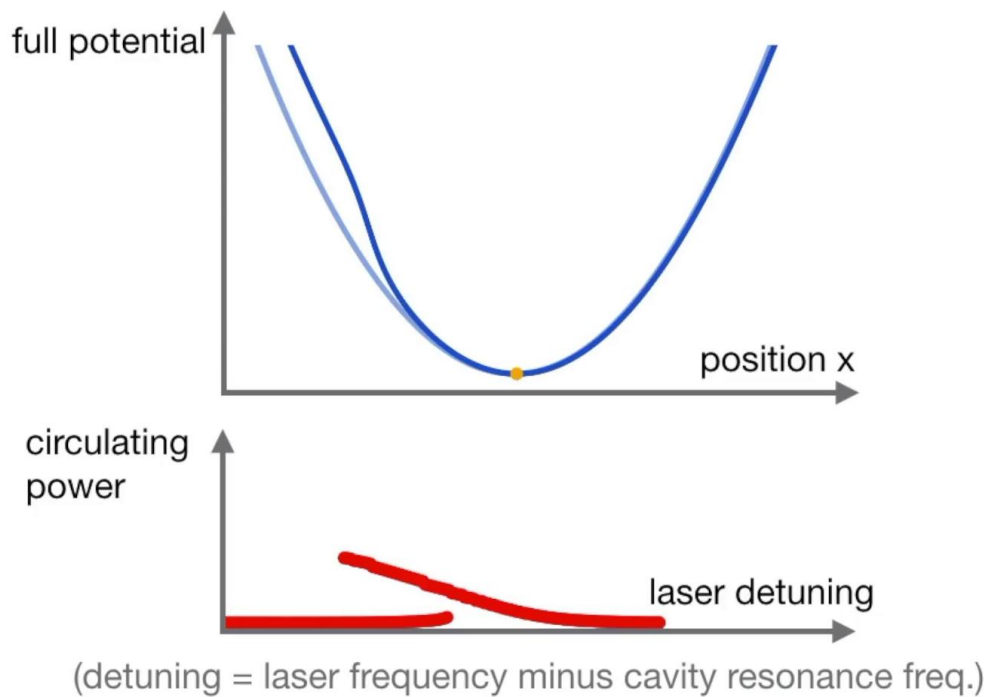
Notes

Summary



9m 32s

# BISTABILITY

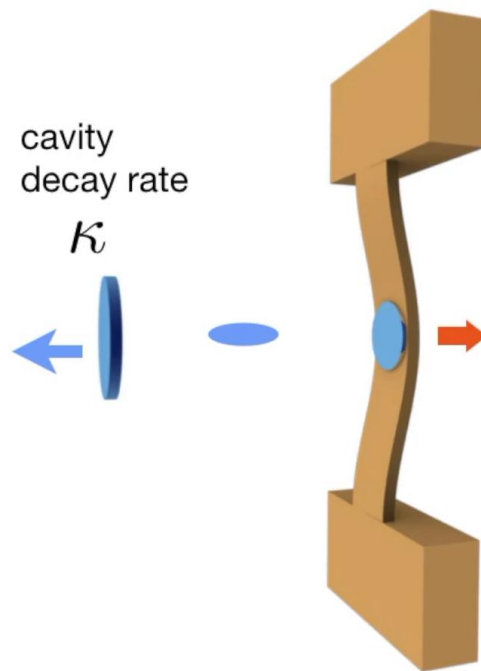


So here's what happens. In the plot above, you will see the full potential as a function of position and it will start evolving when we start changing the laser frequency. In the lower plot, you will find the circulating power inside the cavity as a function of laser frequency. Note that often we like to plot not the laser frequency itself but we refer the laser frequency to the original cavity resonance and then we will call that the laser detuning. Now watch what happens? Here we only have one stable equilibrium position. Suddenly there are two and now there is one again. So there's a whole range where we have the bistability and that also shows up in this plot of circulating power versus laser detuning. This kind of behavior is observed in very many optomechanical experiments.

Notes

Summary





In everything we said so far, we always assume that the light reacts instantaneously to the position of the mechanical object, that is, the force is always an instantaneous function of the position. In fact, this is not really true. For example, consider a cavity that is currently driven but now you switch off the laser. What happens? Well, in the first instance the circulating power is still the same as before. Now, of course, light leaks out of the cavity and slowly the circulating power decreases. The rate at which the energy inside the cavity decreases is called the cavity decay rate often denoted as kappa. Unless the mechanical motion is really slow, we have to take into account this effect.

Notes

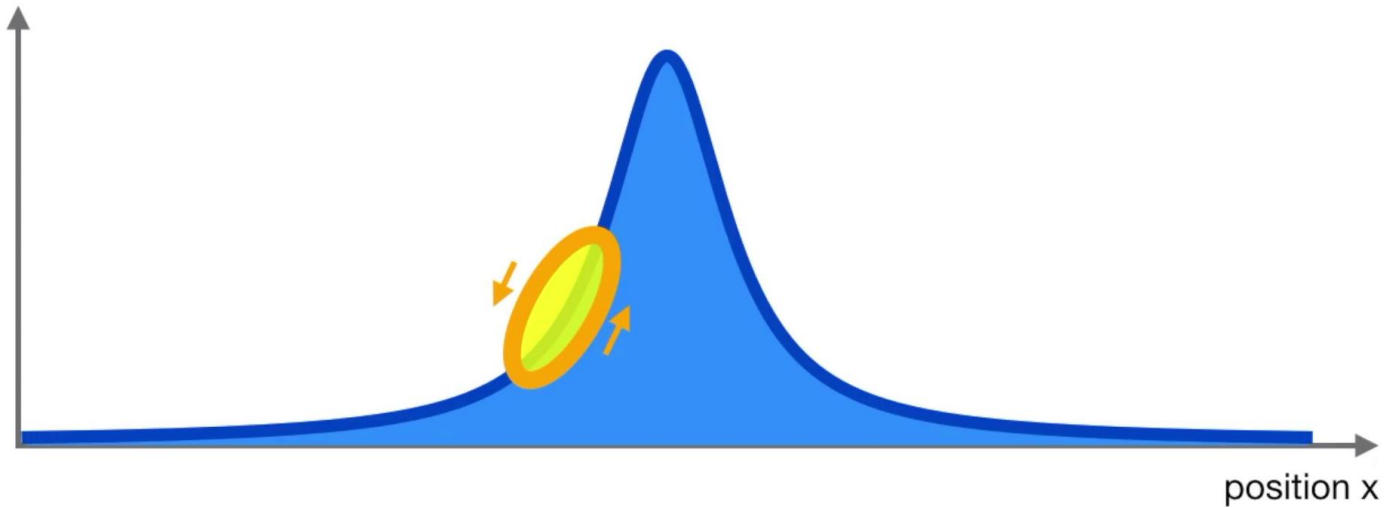
Summary



10m 49s

# DYNAMICS

radiation force  $F$



Things become clearer if we go back to our original plot showing the radiation force against the position. Let's say we start at a certain spot and now we are slowly moving the position. As we're moving the position to the right, the radiation force increases. As we are moving back to the left, the radiation force decreases. Since we are very slow, there is not yet any effect of the finite cavity decay rate. Now, let's assume that the motion is not infinitely slow. What happens is shown in this picture. As we are moving to the right, the light intensity for some while still remains low because the cavity still has to fill up with light corresponding to what would be expected for the new position. So we are slightly below the usual curve of force versus position. Then as we complete the cycle and we move back to the left, The light intensity for some while remains higher than usually expected simply because light has to leak out of the cavity and it takes some time. So that's the reason why we get this kind of ellipse if we draw the force versus position for such a situation where we do take into account the finite cavity decay rate. Now that has important consequences and you may have seen this kind of plot before.

Notes

Summary

11m 40s



radiation force  $F$

$$W = \oint F dx < 0$$

optomechanical  
damping  
(cooling)

Braginsky et al (around 1970)

position  $x$

Plotting force versus position allows you to calculate the work that has been done by the radiation pressure force on the mechanical object. Simply the work is integral of ' $F dx$ ', force times displacement. Now if you look at this ellipse very carefully, you will see that when we are moving to the right and the force and the displacement ' $dx$ ' have the same sign, of course, the contribution is lower than usually expected whereas if we are moving to the left and they have opposite sign, the contribution is in magnitude larger. So overall the negative contribution will be the most important one. In other words, the radiation force in such a cycle actually extracts energy from the mechanical motion. So to have a force that extracts energy that is nothing else but damping, optomechanical damping. Since such a mechanical object is usually coupled to a fluctuating thermal force from an environment and now you have this extra damping force which is usually associated with very little noise, it is also going to give you cooling. Now what happens if we were to operate not at this particular position but on the other side of the resonance.

Notes

Summary



13m 18s

radiation force  $F$

$$W = \oint F dx > 0$$

anti-damping  
(heating, instability)

Braginsky et al (around 1970)

position  $x$

Well, you can go through the same kind of argument again and what you will find is quite interesting namely, the sign of the work will change. Now you have positive work. So the radiation pressure force actually wants to increase the energy stored in the mechanical motion. In other words, we have anti-damping. Among other consequences this means that the effect of the incoming thermal fluctuations is even enhance so effectively there is heating. The thermal fluctuations of the mechanical object will be stronger now and if the effect is really strong then we can get into an instability because then this optomechanical anti-damping will completely overwhelm the intrinsic damping of the mechanical object. But this is something that we will learn about in another lesson. Now all of the discussion up until now has been using classical physics. We've been talking about the position and the force and so on. But it turns out that this damping and anti-damping the cooling and heating can also be understood very nicely and very simply in a quantum mechanical picture.

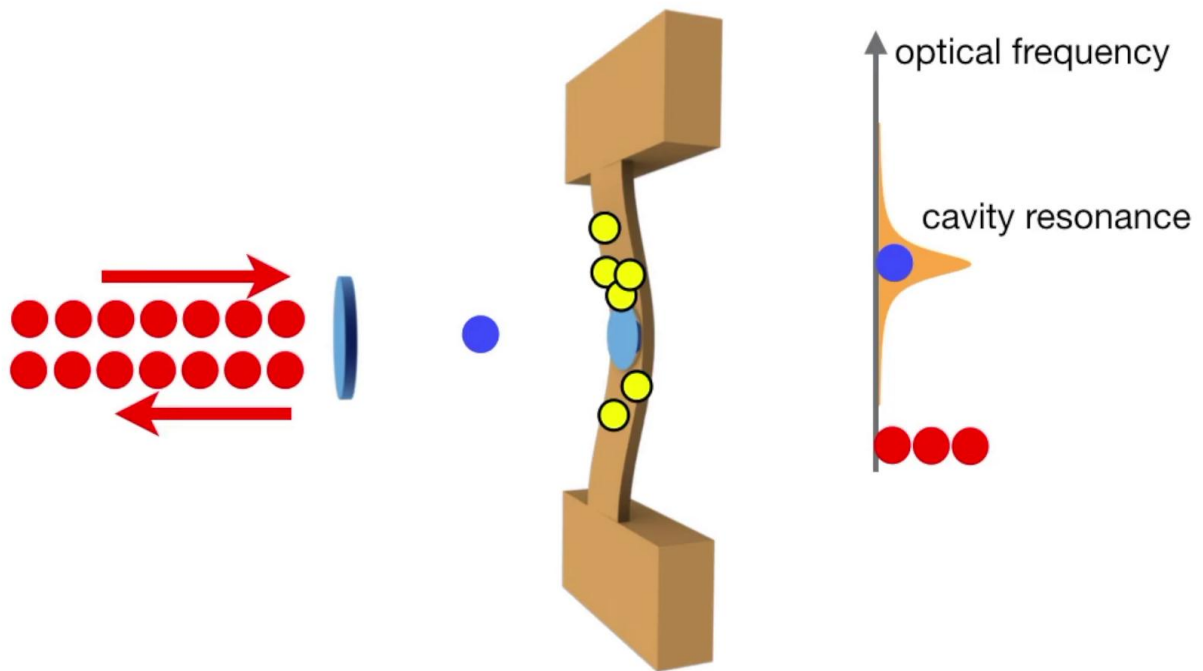
Notes

Summary



14m 53s

# QUANTUM PICTURE



This is a situation where the cavity is constantly illuminated by a laser beam but we will assume that the laser frequency is red-detuned from the cavity resonance. In other words, the frequency of the incoming photons is below the cavity resonance. In that case since we are not hitting the resonance, practically all of the photons will be reflected. To the right on the nanobeam you see indicated a few phonons because there is thermal excitations so some mechanical excitation quantile the phonons are present. Now once in a while very rarely, what can happen is that one of those photons tries to get into the optical resonance of the cavity and in order to do so and in order to acquire the extra energy that is needed and increase its frequencies to match the resonance, it just captures one of the phonons. So what we get now is a higher energy photons circulating inside the cavity that's why it's depicted as blue. It has eaten up the energy of one of the phonons. Of course, after a while because of the usual cavity decay, it will exit the cavity and then it will carry away the surplus of energy.

Notes

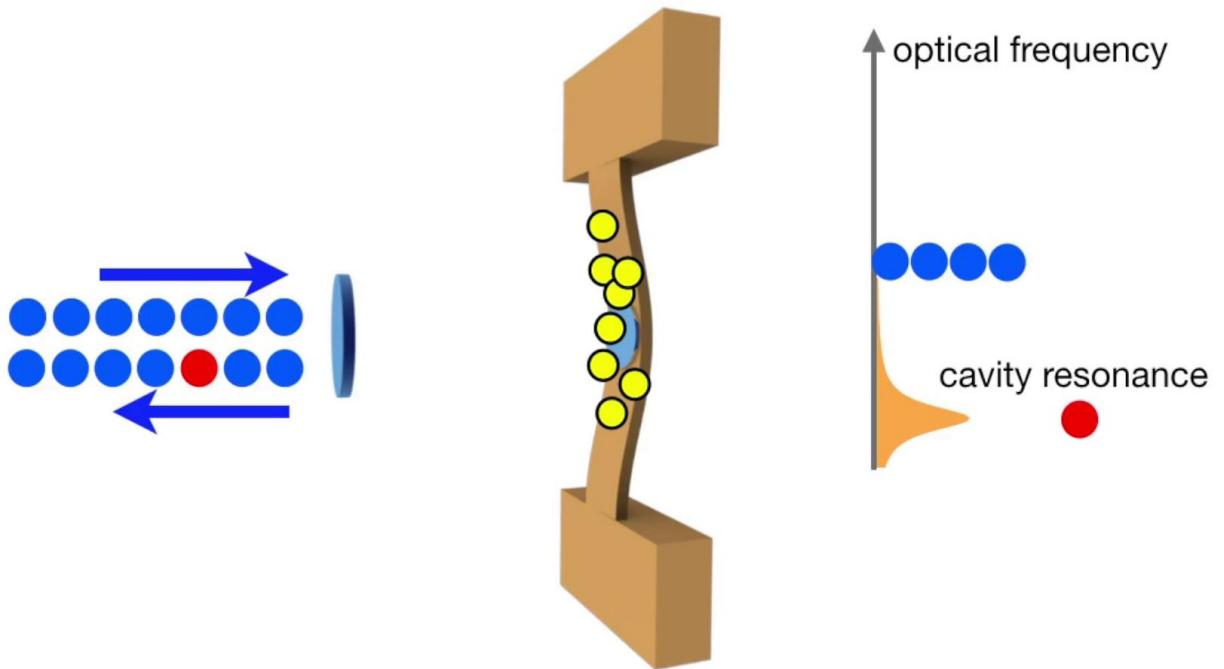
Summary

16m 05s





## QUANTUM PICTURE



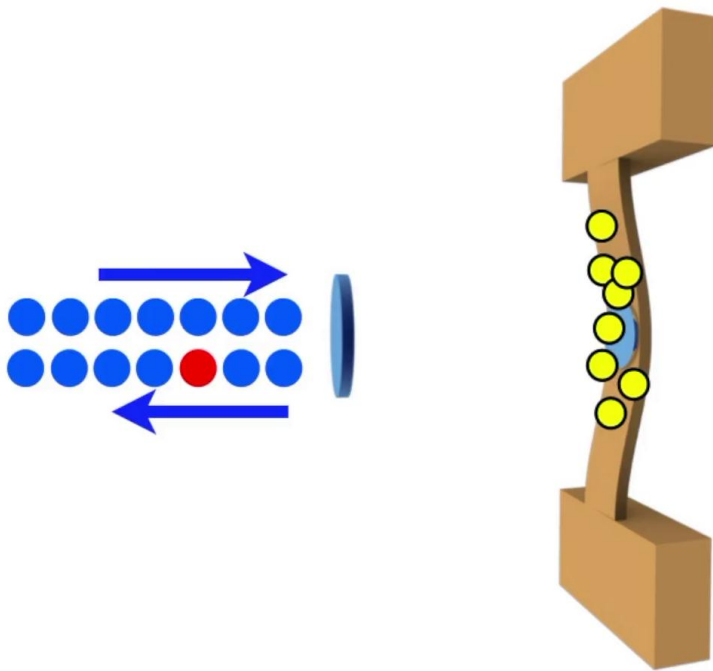
If the same process happens again and again and again, we will destroy many of these phonons and we'll be able to cool the mechanical object down to much lower temperatures, with the right parameters maybe even down to the quantum ground state where no phonon remains. You can also look at the opposite situation. So what happens if the frequency of the incoming photons of the incoming laser is actually above the cavity resonance. We speak of blue detuning. Then again, since we're not hitting the resonance, most of the time the photons will be reflected. But again, very rarely it may happen that a photon enters the cavity and deposits some of its surplus energy so to speak in the form of a single phonon that will heat up the mechanical motion a little bit. That case the photon has lost some energy. That's why it's depicted as red and it just perfectly matches the resonance frequency of the cavity. Again, it will live for a certain amount of time dictated by the cavity decay rate and then it will exit the cavity and be carried away. So you have learned how these two processes damping and anti-damping cooling and heating can very easily be understood in a quantum picture talking about photons and phonons and the energy that is exchanged.

Notes

Summary



## QUANTUM PICTURE



### Raman scattering

photons take away energy or deposit energy into the mechanical resonator

In fact, all of these processes already have a name. That's called Raman scattering. So Raman scattering just means that a photon impinges on some kind of object and it's not just reflected back with the same energy that it came in but it actually takes away a little bit of energy or deposits some energy into the object. In this case, deposit some energy into the mechanical resonator or it takes away some energy. You will learn more about this in other lectures where you will see how the detailed quantitative description of these processes can be set up.

Notes

Summary



## CONCLUSION / SUMMARY

- Light changes the spring constant: **optical spring effect**
- Light creates several stable equilibrium positions: **static bistability**
- Light can damp and anti-damp motion: **cooling and heating**
- Photons can provide or take away energy: **Raman scattering**

for all the details, see the review

Aspelmeyer, Kippenberg, Marquardt, Reviews of Modern Physics **86**, 1391 (2014)

also: Lectures Notes by Florian Marquardt for lectures delivered at the  
Les Houches School "Quantum Machines", July 2011 (Oxford University Press)

...and the further lectures in this series!

Now it's time to summarize. So what have we learned? We've learned that light can effectively change the mechanical spring constant of an object. We have learned that light can create even several stable equilibrium positions for the mechanical motion. And then we have learned that if you also take into account the finite cavity decay rate that light can damp and anti-damp mechanical motion so it can lead to cooling and heating. And then finally, we have understood that these effects that we have first described in a classical language can easily be understood also in a quantum language talking about photons and phonons and we've seen that photons can provide or take away energy from the mechanical motion.

Notes

Summary

