

EPFL

OUTLINE

In this lesson, you will learn about the quantum theory of laser cooling in optomechanical systems.

- **Reminder: Classical picture**
- **Raman picture**
- **Two coupled oscillators**
- **Quantum noise approach: System-bath picture**
- **Rate equations and cooling limit**

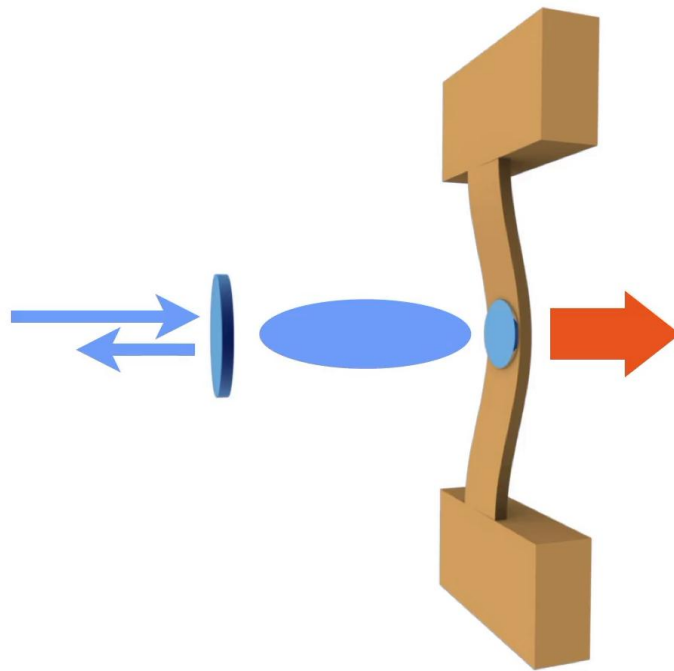
Welcome. In this lecture, you will learn about the quantum theory of optomechanical cooling. So what will we cover? First I'll remind you of the classical picture of damping and cooling in optomechanical systems. Then we look at the cartoon picture that is the Raman scattering picture. After that we'll briefly discuss the viewpoint of two coupled oscillators, the cavity and the mechanical oscillator and then I'll introduce the quantum noise approach and the system-bath picture. And we will use that to derive the rate equations and the cooling limit for optomechanical cooling.

Notes

Summary



AN OPTOMECHANICAL SYSTEM



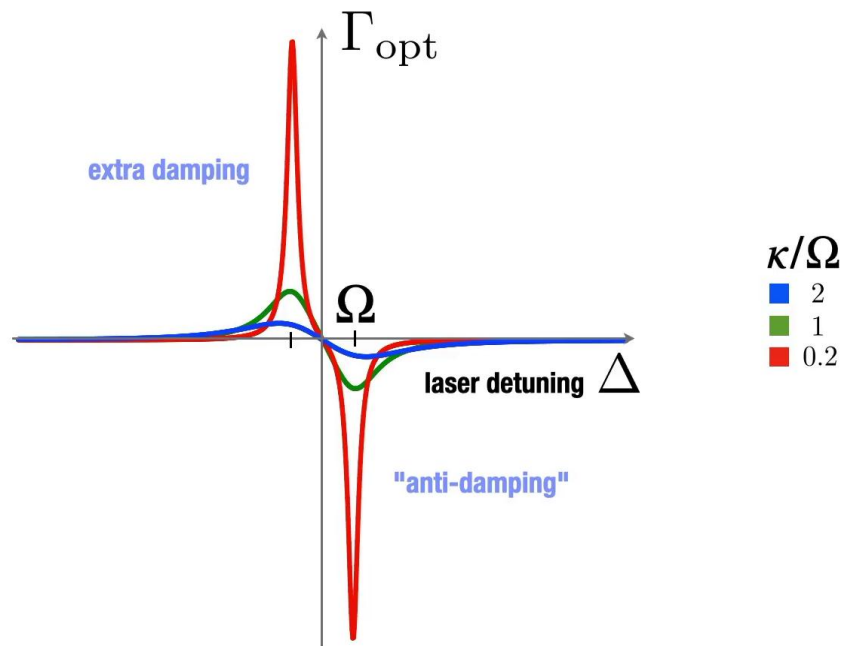
So this is your standard optomechanical system, a laser driven cavity with a radiation pressure force acting on a mechanical element.

Notes

Summary



THE OPTOMECHANICAL DAMPING RATE



In previous lectures, you have already learned about the optomechanical damping rate. For example, you can arrive at the some classical linearized theory of optomechanics and here what we plot is the damping rate, optomechanical damping rate as a function of laser detuning for three different ratios of the cavity decay rate kappa versus the mechanical frequency omega. So as kappa is small, you see these very characteristic peaks near the mechanical frequency omega. In particular however, you see that at negative laser detuning between the laser frequency in the cavity, you get extra damping and this the regime we want to focus on because that's the regime where you can expect cooling.

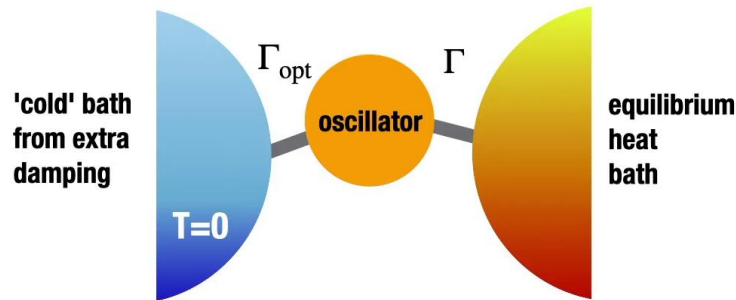
Notes

Summary



0m 47s

REMINDER: CLASSICAL PICTURE



$$T_{\text{eff}} = T \cdot \frac{\Gamma}{\Gamma_{\text{opt}} + \Gamma}$$

optomechanical damping rate

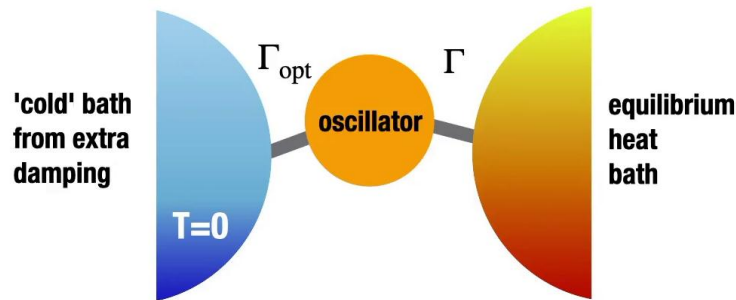
Now, what does this extra damping mean for the temperature, the effect of temperature of the mechanical oscillator? Let's first discuss the classical picture. And in order to understand that you now have to envisage the oscillators being coupled to effectively two heat baths. There's the typical equilibrium heat bath on the right-hand side and the coupling to that heat bath is described by the mechanical, intrinsic mechanical damping rate γ . And then there is the extra bath that describes the damping due to the radiation pressure force and it turns out in the classical theory at least this is a cold bath so it's effectively a temperature equals zero. This bath only introduces extra damping and no extra fluctuations. So as a consequence if you work out the effective temperature overall in the end, it becomes the temperature that the system would assume when it is coupled with different strengths, two baths of different temperatures so it's like a compromise and it turns out to be in this case the temperature of the equilibrium heat bath times this ratio, the ratio involving γ , the intrinsic decay rate of the mechanical motion divided by the sum of the optomechanical damping rate and γ .

Notes

Summary



REMINDER: CLASSICAL PICTURE



$$T_{\text{eff}} = T \cdot \frac{\Gamma}{\Gamma_{\text{opt}} + \Gamma} \rightarrow 0 ?$$

optomechanical damping rate

quantum limit?

shot noise!

So you see obviously if the optomechanical damping rate is zero, this whole ratio is one and you're back to the old equilibrium temperature, that's fine. But also if the optomechanical damping rate were to be sent to infinity which you can in principle do by increasing the laser intensity then you would imagine that this whole thing goes to zero. The question is does it, does it go to zero? And the suspicion is that in this classical description, of course, you've neglected crucial quantum features, in particular, quantum noise that comes out because of the unavoidable shot noise of the incoming laser radiation and this is the thing that we'll be discussing in this lecture.

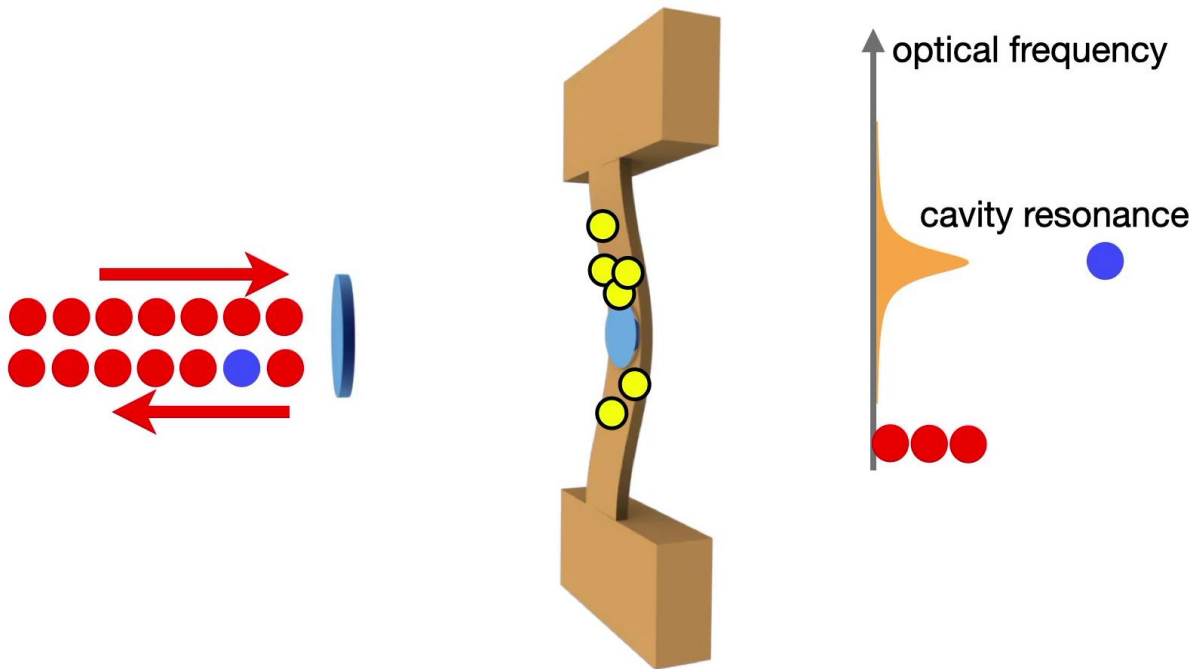
Notes

Summary



2m 53s

RAMAN SCATTERING PICTURE



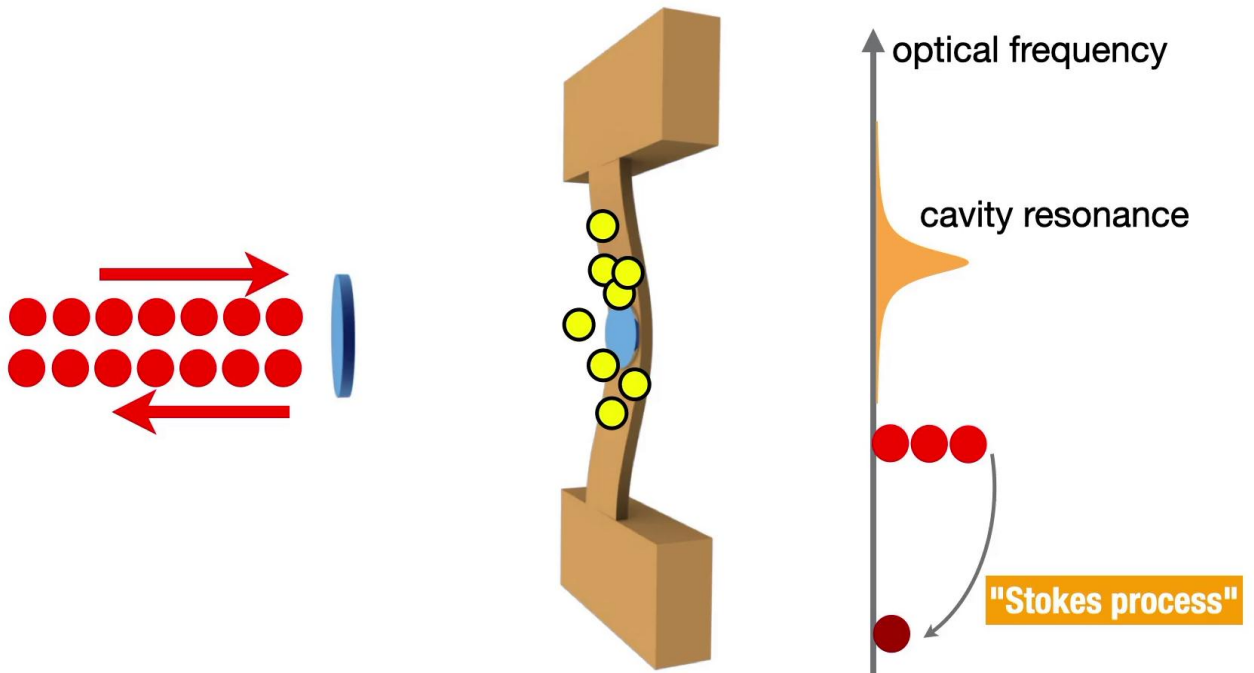
But first let's do it simple. Let's come back to our cartoon picture that we already introduced in when we covered the basics of optomechanics in this lectures and that's the Raman scattering picture so you imagine many photons of the laser impinging on the cavity. In this case, they are red-detuned from the cavity resonance so that's depicted here. And what can happen now is that one of those laser photons enters the cavity but while it enters, it is scattered upwards in energy towards the cavity resonance. And because it does so, it has absorbed a single phonon, a single quantum of mechanical oscillation. So that's what happens. Let's go back. This is the quantum of oscillation that is being absorbed. As a consequence, the photon is up scattered and now it can leave the cavity. This process is called anti-Stokes process because it's the opposite of the usual Stokes process that happens when you shine light on a material where the light dumps energy into the material. Here the light has removed energy and now the photon can leak out of the cavity again and be gone. This is nice. This explains damping but unfortunately, it only explains damping and, therefore, perfect cooling.

Notes

Summary



RAMAN SCATTERING PICTURE



If this were everything, again just like in the classical picture, we would end up in quantum ground state and there would be no problem whatsoever under any circumstances. So we have to go back to the beginning and ask ourselves, why don't we have this ideal result in general? So can we have a situation where instead of absorbing a phonon, we actually putting another phonon inside the mechanical oscillator. And in order for this to happen, obviously you must make sure that the incoming photons are scattered not up in frequency but down in frequency so that they can dump extra energy into the mechanical oscillator. When this happens, we call it a Stokes process and in order for it to happen, of course, the photon must end up at a much smaller frequency. Now, this is a little bit weird because we are now very very far from the cavity resonance. So in principle, there's almost no density of states that there's almost no possibility for photons to live so far away from the cavity resonance. The only reason this is still possible is that this Lorentzian cavity resonance is not yet quite zero, even when you go so far away in frequency.

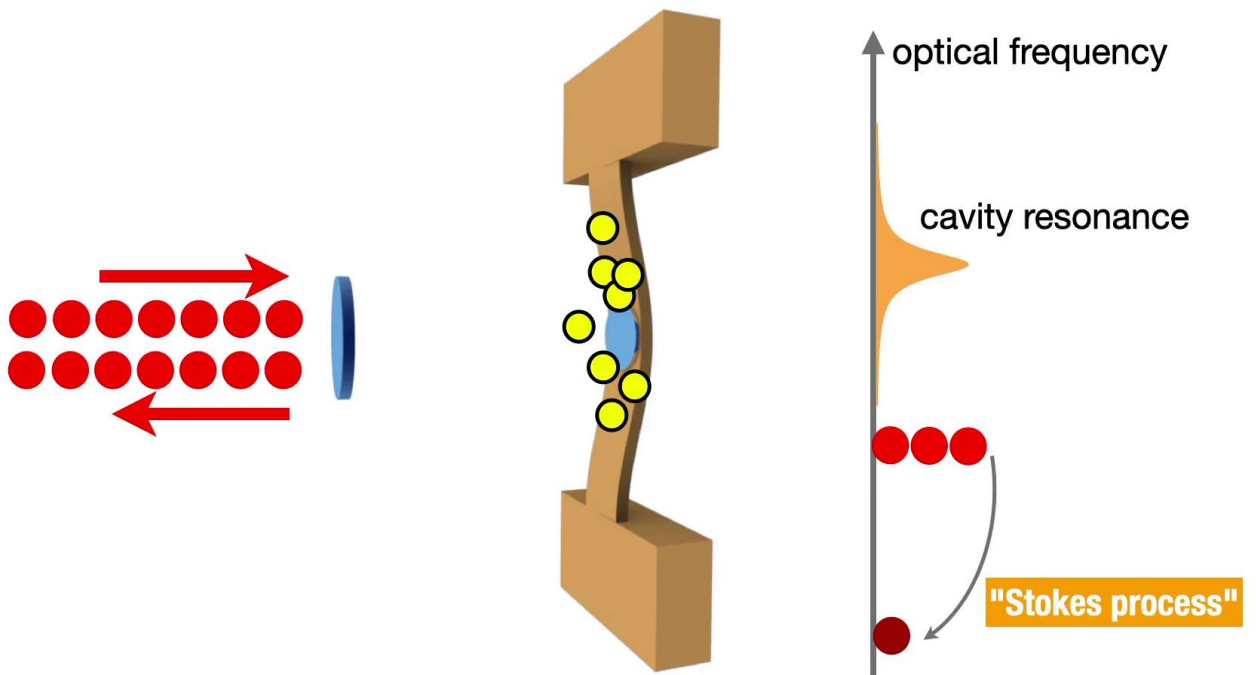
Notes

Summary



4m 52s

RAMAN SCATTERING PICTURE



So that's why at a very small rate even such a Stokes process can appear which means it dumps some energy into the mechanical oscillator and that's the reason why we don't go precisely to zero. And this is what we will learn to analyze quantitatively later.

Notes

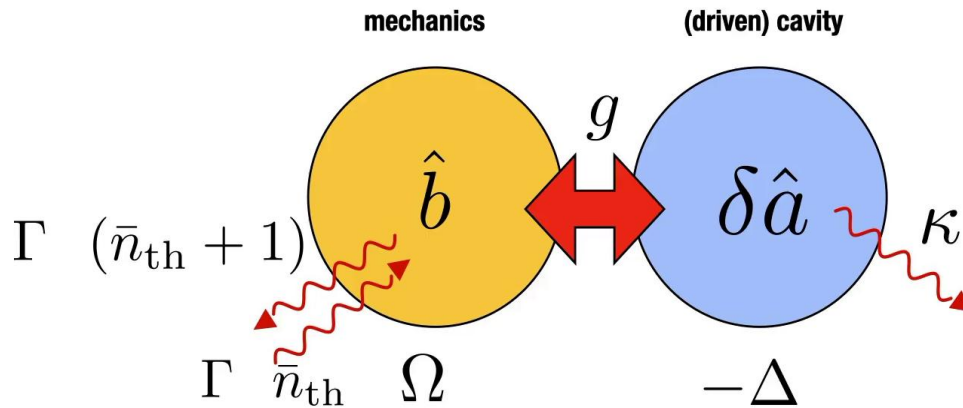
Summary



TWO COUPLED OSCILLATORS

After linearization: two linearly coupled harmonic oscillators!

$$\hat{H} = \hbar\Omega\hat{b}^\dagger\hat{b} - \hbar\Delta\delta\hat{a}^\dagger\delta\hat{a} - \hbar g(\hat{b} + \hat{b}^\dagger)(\delta\hat{a} + \delta\hat{a}^\dagger)$$



Now before we go there, here's another very useful picture to think about. When you learned about the linearized theory of cavity quantum optomechanics, this is what you arrived at. That is a mechanical oscillator and a driven cavity oscillator, driven optical mode that is described by the detuning so minus the detuning is the effect of frequency of this driven mode and they're both coupled together in a quadratic interaction Hamiltonian coupling the mechanics, 'b' plus b-dagger to the fluctuations of the driven cavity field delta 'a' plus delta a-dagger. So in essence, you only have two harmonic oscillators 'b' and delta 'a', mechanics and optics being coupled quadratically with a coupling constant 'g' that you can tune via the laser intensity. Now that's great.

Notes

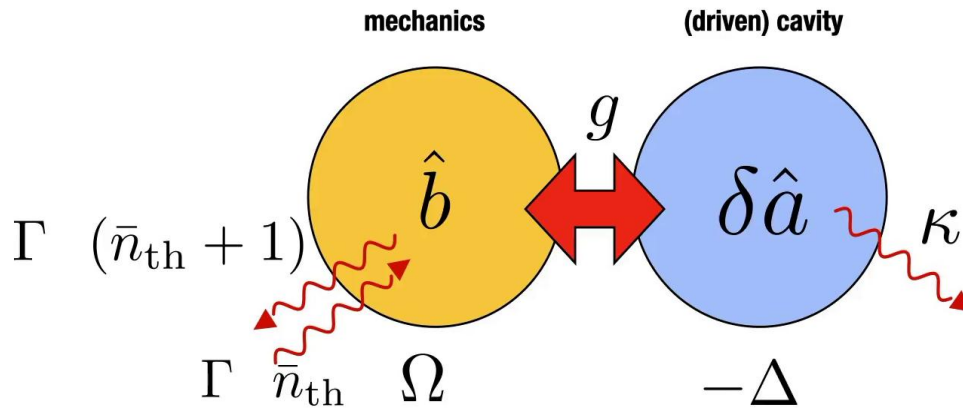
Summary



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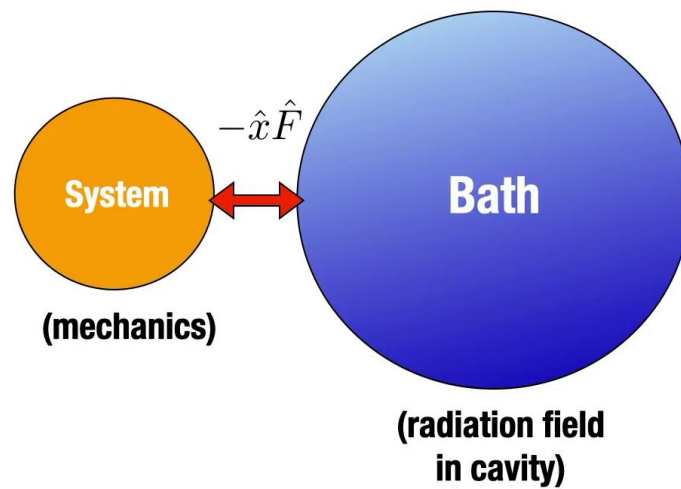
All these oscillators, of course, can be in resonance of omega equals minus delta so that's why you need negative detuning to make this happen and then in principle, you can exchange energy quanta between the two oscillators and if the mechanical oscillator starts hot but the driven cavity oscillator starts cold then what you will typically have is a flow of excitations from the mechanics to the optics and these excitations typically will not return because there's a strong cavity decay rate kappa which will constantly empty the cavity so that the excitations cannot return to the mechanics and this is in this picture the reason why we have cooling. Now we can also view those picture in a slightly different way. We can, say, let's focus on the point of view of the mechanics. So here's the mechanical oscillator quantum system that is subject to some coupling to an environment a bath. This bath consists of the driven cavity and the electromagnetic environment outside the cavity.

Notes

Summary



SYSTEM-BATH PICTURE



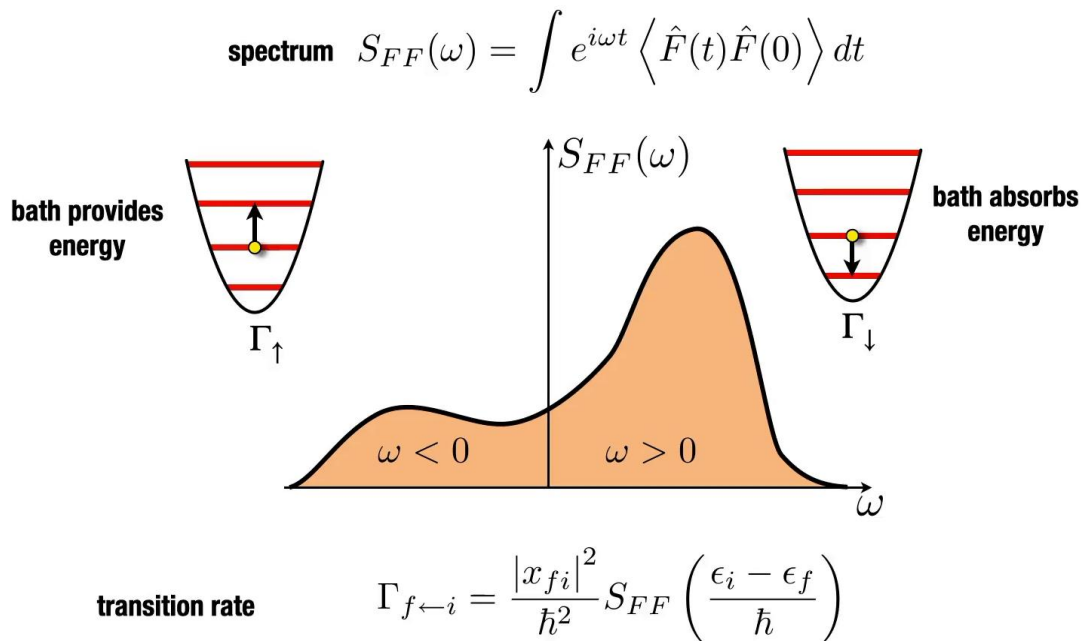
So the general picture would be thus a system, in our case the mechanical oscillator, coupled to a big bath in our case the cavity mode plus the full electromagnetic vacuum outside the cavity. These two quantum subsystems, the system and the bath, they are coupled by simple coupling term, namely a force. The radiation pressure force is acting on the oscillator position. And so the question is now what happens and one of the things that happens is, of course, this force is noisy. It can lead to fluctuations acting on our system but it can also lead to damping. Both of these things will appear and in order to describe this there's a very very general approach and this approach is known as the quantum noise approach.

Notes

Summary



QUANTUM NOISE APPROACH



So the first quantity we want to look at is the so-called spectrum, the noise spectrum. How is this defined? Well, you have to look at the Heisenberg operator 'F' of 't' of the force and take it to construct the correlator. So 'F' of 't' times 'F' of zero and then the expectation values. This is the same way you would construct a correlator in classical physics except now the order of the two operators, of course, matters extremely. Once you have this correlator in time, you can Fourier transform it to get a spectrum and typical version of such a spectrum for some generic example system is shown here. It has contributions both at positive and negative frequencies. It is real-valued and non-negative. That's good. But it's also asymmetric in contrast to the classical situation where this would always be a completely symmetric spectrum. So what's the meaning of this spectrum? What's the meaning of the positive and the negative frequencies in the spectrum? Well, you see that comes out if you couple such fluctuations to a quantum system, in our case the little system or the mechanical oscillator specifically.

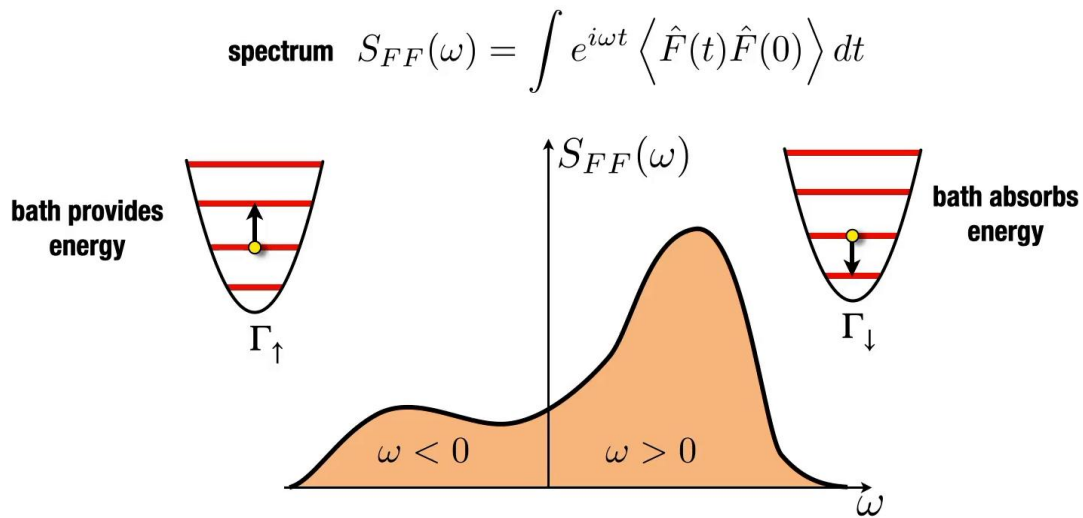
Notes

Summary



9m 22s

QUANTUM NOISE APPROACH



transition rate $\Gamma_{f \leftarrow i} = \frac{|x_{fi}|^2}{\hbar^2} S_{FF} \left(\frac{\epsilon_i - \epsilon_f}{\hbar} \right)$

The positive frequencies turn out to be responsible for the possibility of the bath, that is, what is producing these false fluctuations, the possibility of this bath absorbing energy from our little quantum system so the quantum system drops down in energy and we will call this rate gamma down in the following. And the negative frequencies of the noise spectrum, they are responsible for putting energy into the system so we will call this rate gamma up. In general, both these rates gamma down and gamma up can be obtained from Fermi's Golden Rule and if you work it out, it looks like this so regardless of which initial state you start with in the system so one of these levels shown here and you go to some final state some other level here then the transition rate from 'I' to 'F' is given by some matrix element squared. That's the matrix element of the 'x' operator which is a system operator that couples to the force between these two levels 'I' and 'F'. This matrix element squared times the noise spectrum and the noise spectrum is evaluated at the transition frequency between these two system levels.

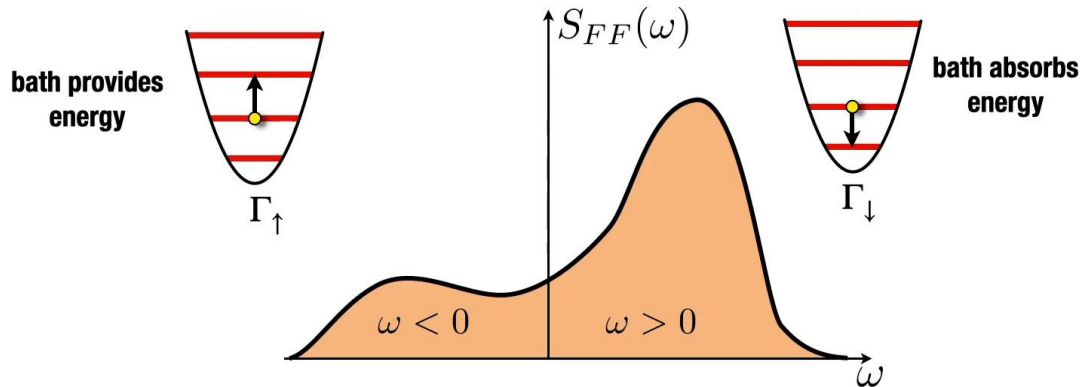
Notes

Summary



QUANTUM NOISE APPROACH

spectrum $S_{FF}(\omega) = \int e^{i\omega t} \langle \hat{F}(t) \hat{F}(0) \rangle dt$



transition rate $\Gamma_{f \leftarrow i} = \frac{|x_{fi}|^2}{\hbar^2} S_{FF} \left(\frac{\epsilon_i - \epsilon_f}{\hbar} \right)$

So depending on whether you go up or down, this will turn out to be negative or positive and that's the reason why I said that when we want to go up, we have to evaluate the noise spectrum at negative frequencies, when we want to go down in the system, we have to evaluate the noise spectrum at positive frequencies. So all of this is the result of this simple rather simple application of Fermi's Golden Rule and that's a super general result that holds under all circumstances provided there's weak coupling between the system and the bath. The bath, for example, need not be a bath of harmonic oscillators which is a model that is often adopted but you don't need this. It could be a spin bath or anything very complicated. This formula will always hold. Also the system doesn't need to be a mechanical oscillator or any harmonic oscillator, can be anything. Now coming back, however, to our particular optomechanical situation.

Notes

Summary



11m 56s

QUANTUM NOISE THEORY OF OPTOMECHANICAL COOLING

$$\hat{F} = \frac{\hbar g_0}{x_{\text{ZPF}}} \hat{a}^\dagger \hat{a}$$

$$S_{NN}(\omega) = \int_{-\infty}^{+\infty} dt e^{i\omega t} \langle (\hat{a}^\dagger \hat{a})(t) (\hat{a}^\dagger \hat{a})(0) \rangle \quad \text{(subtract mean value)}$$

$$S_{NN}(\omega) = \bar{n}_{\text{cav}} \frac{\kappa}{\kappa^2/4 + (\Delta + \omega)^2}$$

We know how the force looks like. The force is proportional to the photon number inside the cavity, a-dagger 'a' with a prefactor given by the optomechanical coupling strength. And so if we want to calculate the noise spectrum of the force, what we essentially need is the noise spectrum of the photon number operator a-dagger 'a'. So this is written down here according to the definition that we had. The correlator of a-dagger 'a' at time 't' and time zero. By the way in principle, you will subtract also the mean value of a-dagger 'a' so that is simplicity in this equation. And then if you work it out, which is not too difficult by linearizing these expressions, you can arrive at this formula, which is nothing but a Lorentzian. So let's display those Lorentzian. Let's take a plot of this expression.

Notes

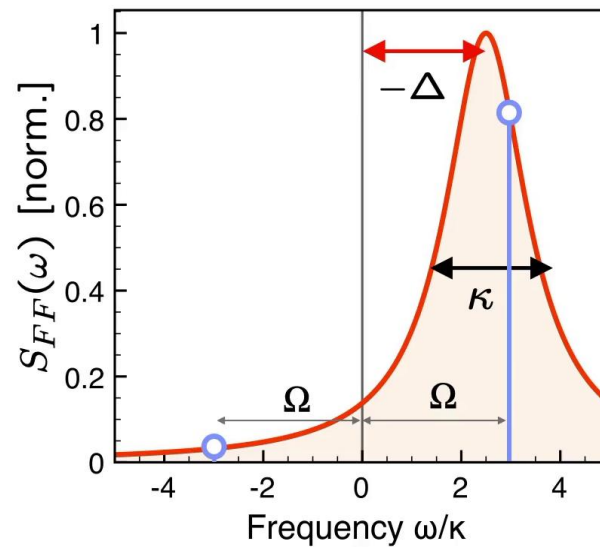
Summary



12m 51s

QUANTUM NOISE THEORY OF OPTOMECHANICAL COOLING

Spectrum of radiation pressure fluctuations



cavity emits energy / absorbs energy

So this is the force-noise spectrum as a function of frequency. It is a Lorentzian. It is shifted by minus delta where delta is the laser detuning so if we are at negative detuning, the bulk of the spectrum sits at positive frequencies. This is very good because we will see that's what's needed for actual cooling. And then the width of the spectrum is simply the cavity decay rate so everything very simple. Now, I already told you that the up-and-down transition rates for our system will be obtained by evaluating the noise spectrum positive or negative frequencies respectively and what are these frequencies? Well, it's always the transition frequencies of the system. Now the transition frequency we are talking about when we deal with our mechanical oscillator, that's always the mechanical frequency either plus or minus the mechanical frequency because we're going to up or down by exactly one level in the harmonic oscillator. So you would end up evaluating this noise spectrum either plus capital omega plus the mechanical frequency or minus capital omega minus the mechanical frequency and you see it will be very important that there's an imbalance between the noise spectra at these two different frequencies.

Notes

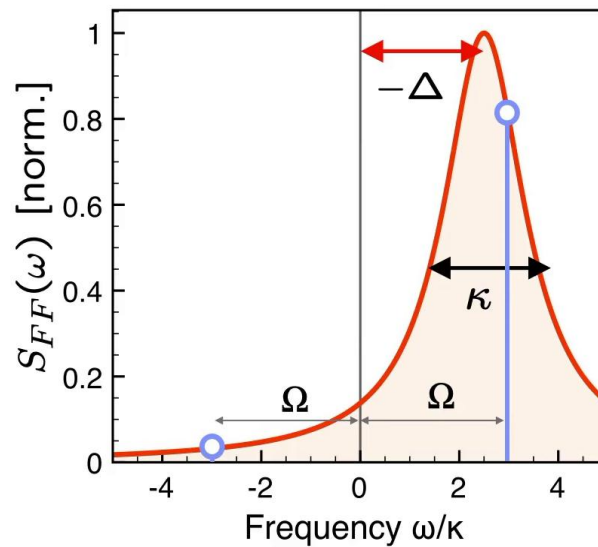
Summary

13m 45s



QUANTUM NOISE THEORY OF OPTOMECHANICAL COOLING

Spectrum of radiation pressure fluctuations



cavity emits energy / absorbs energy

Now, let's pull everything together. Let's insert this particular noise spectrum into the transition rates and let's try to workout first, what's the overall damping rate but more importantly, what will be the equilibrium occupation that our mechanical oscillator settles into when it is coupled to such a noise spectrum. That's what we are interested in because that's then the limit for laser cooling in such a system.

Notes

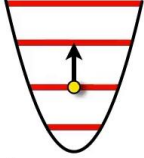
Summary

14m 59s



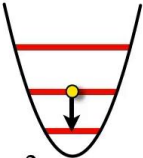
COOLING RATE AND PHONON OCCUPATION

bath provides energy



$$\Gamma_{\uparrow} = \frac{x_{\text{ZPF}}^2}{\hbar^2} (\bar{n} + 1) S_{FF}(-\Omega)$$

bath absorbs energy



$$\Gamma_{\downarrow} = \frac{x_{\text{ZPF}}^2}{\hbar^2} \bar{n} S_{FF}(\Omega)$$

$$\Gamma_{\text{opt}} = \frac{x_{\text{ZPF}}^2}{\hbar^2} [S_{FF}(\Omega) - S_{FF}(-\Omega)] \quad (\text{same result as classical theory})$$

steady state
(without thermal bath)

$$\Gamma_{\downarrow} = \Gamma_{\uparrow} \Rightarrow \frac{\bar{n} + 1}{\bar{n}} = \frac{S_{FF}(\Omega)}{S_{FF}(-\Omega)}$$

$$\bar{n} = [S_{FF}(\Omega)/S_{FF}(-\Omega) - 1]^{-1} \equiv \bar{n}_{\text{min}} \quad (\text{"min" because without thermal bath!})$$

minimize over detuning:

$$\min_{\Delta} \bar{n}_{\text{min}} = \left(\frac{\kappa}{4\Omega} \right)^2 \quad (\text{in resolved sideband regime})$$

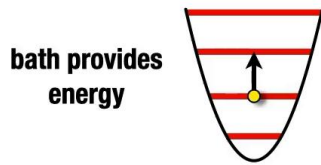
Okay. So here again is our schematic picture. Either the bath provides energy so the system the harmonic oscillator is excited or the bath absorbs energy so the harmonic oscillator is de-excited. In one case, we have the up transition rate and it is given by the noise spectrum evaluated at the negative mechanical frequency. In the other case, we have the downward transition rate and that's the noise spectrum evaluated with a positive mechanical frequency just as we said before. There are extra prefactors. So there's the zero point fluctuations amplitude squared that's just comes from the matrix element of the position operator. But there's another contribution from this matrix element and that's this $\bar{n} + 1$ so \bar{n} is the average occupation number of this oscillator and the plus one is something like spontaneous emission but in any case technically it just comes from the matrix element. And here you find \bar{n} when you go one level down in the ladder of oscillator states so $\gamma_{\uparrow} \gamma_{\downarrow}$ negative frequency positive frequency. Now, if you compare these expressions to what you would get if you're coupled to an equilibrium bath that provides a certain damping rate, then you figure out that the effective overall damping rate is the difference between the noise spectra at positive and negative frequency.

Notes

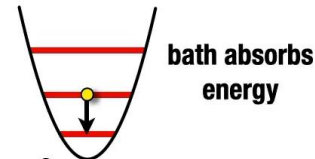
Summary



COOLING RATE AND PHONON OCCUPATION



$$\Gamma_{\uparrow} = \frac{x_{\text{ZPF}}^2}{\hbar^2} (\bar{n} + 1) S_{FF}(-\Omega)$$



$$\Gamma_{\downarrow} = \frac{x_{\text{ZPF}}^2}{\hbar^2} \bar{n} S_{FF}(\Omega)$$

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steady state
(without thermal bath)

$$\Gamma_{\downarrow} = \Gamma_{\uparrow} \Rightarrow \frac{\bar{n} + 1}{\bar{n}} = \frac{S_{FF}(\Omega)}{S_{FF}(-\Omega)}$$

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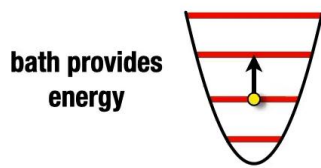
That's what comes out of this comparison to the usual situation of coupling to an equilibrium bath. And it turns out this expression though derived from the full quantum noise theory, is actually exactly the same result as in the classical theory as if you start from the classical linearized equations of motion. You don't know anything about quantum mechanics. You just ask yourself, okay what's the extra damping provided by the radiation pressure force which is time retarded and you find exactly what comes out when you evaluate this expression by inserting the Lorentzian noise spectrum that we discussed a few slides before. What we are now interested in is not so much the damping rate itself, but we want to figure out the steady state. So what is the mean average phonon number that our mechanical oscillator settles into if we wait long enough and let this process happen. And for the moment, we will completely neglect any additional coupling to a thermal reservoir. We will pretend that there is only the coupling between the mechanical oscillator and the driven cavity bath. Let's call it like that. So in steady state, of course, the average transition rate downwards should be balanced by the average transition rate upwards.

Notes

Summary



COOLING RATE AND PHONON OCCUPATION



$$\Gamma_{\uparrow} = \frac{x_{\text{ZPF}}^2}{\hbar^2} (\bar{n} + 1) S_{FF}(-\Omega)$$



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steady state
(without thermal bath)

$$\Gamma_{\downarrow} = \Gamma_{\uparrow} \Rightarrow \frac{\bar{n} + 1}{\bar{n}} = \frac{S_{FF}(\Omega)}{S_{FF}(-\Omega)}$$

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minimize over detuning:

$$\min_{\Delta} \bar{n}_{\text{min}} = \left(\frac{\kappa}{4\Omega} \right)^2 \quad (\text{in resolved sideband regime})$$

Nothing should change. They should balance each other. And so if you insert the expressions given above what this immediately leads you to is an expression that relates the average phonon occupation in steady state to the ratio of the noise spectra at positive and negative frequency and you can easily solve for \bar{n} in this expression and then you find what is written down here and now you could insert the Lorentzian noise spectrum formula that we showed you earlier. I will not go through this exercise. It's very simple to write down. But what you can now do in addition is you can remind yourself that experimentally you can still vary the detuning and you might want to optimize the detuning so as to get maximal effect. Maximal effect meaning that the \bar{n} -bar should be as small as possible. You want to cool as best as you possibly can. And so if you do this, the result depend a little bit on what's the ratio between κ and mechanical frequency. But if you're in the resolved sideband regime which means κ smaller than the mechanical frequency, then this is the minimum that you get so κ divided by four ω squared.

Notes

Summary



18m 18s

COOLING RATE AND PHONON OCCUPATION



$$\Gamma_{\uparrow} = \frac{x_{\text{ZPF}}^2}{\hbar^2} (\bar{n} + 1) S_{FF}(-\Omega)$$

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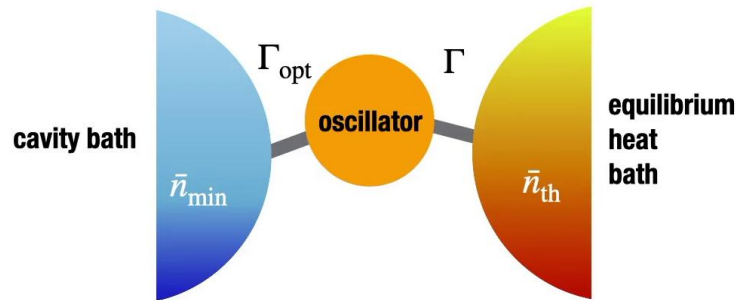
So if you are in the resolved sideband regime then the ratio is smaller than one, there's another factor four that helps you further and overall the minimum reachable phonon number is not zero. Okay. But it is close to zero so it's certainly below one. So you can claim that you're near the ground state and you will get even better to the ground state the more you are in the resolved sideband regime. Now that is the ideal situation where you don't even couple to a thermal path. Even there you don't reach quite zero so there's this fundamental quantum noise limit but you can get pretty low. If you do couple to a thermal bath then, of course, that counteracts your efforts to cool so you don't get quite that far and in order to work out the situation then let's remember what we already discussed when we briefly looked at the classical situation.

Notes

Summary



COOLING RATE AND PHONON OCCUPATION



with coupling to thermal bath: full quantum result

theory:
 FM, Chen, Clerk, Girvin, PRL 2007
 Wilson-Rae, Nooshi, Zwerger,
 Kippenberg, PRL 2007
 Genes et al, PRA 2008

$$\bar{n} = \frac{\Gamma_{\text{opt}} \bar{n}_{\text{min}} + \Gamma \bar{n}_{\text{th}}}{\Gamma_{\text{opt}} + \Gamma}$$

experiment: near ground state reached in 2011

strong coupling regime
 (e.g. FM et al PRL 2007)
 will diminish cooling efficiency!

Only now instead of having an effective zero temperature bath, you are coupling to an effective bath that is the driven cavity mode which is not zero temperature but has some average effective occupation which is nothing but the minimum occupation that we worked out so that would be the occupation for you have given fixed detuning that is the minimum which you can reach if you make the optomechanical damping rate very large and overwhelm the equilibrium heat bath and otherwise your effective average phonon number will be somewhat larger and the result is shown here. It's basically something like a compromise between the two baths to which you couple at the different coupling strengths that are given simply by the optomechanical damping rate on the one hand side and the mechanical damping rate on the other hand so it's a compromise between the two. Turns out that experiments have reached near to the quantum ground state of optomechanical systems using laser cooling both for microwave optomechanical systems and for optical, optomechanical systems back in 2011. There's another remark.

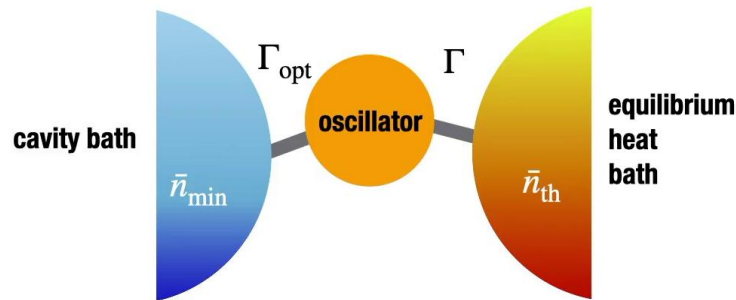
Notes

Summary



20m 26s

COOLING RATE AND PHONON OCCUPATION



with coupling to thermal bath: full quantum result

theory:
 FM, Chen, Clerk, Girvin, PRL 2007
 Wilson-Rae, Nooshi, Zwerger,
 Kippenberg, PRL 2007
 Genes et al, PRA 2008

$$\bar{n} = \frac{\Gamma_{\text{opt}} \bar{n}_{\text{min}} + \Gamma \bar{n}_{\text{th}}}{\Gamma_{\text{opt}} + \Gamma}$$

experiment: near ground state reached in 2011

strong coupling regime
 (e.g. FM et al PRL 2007)
 will diminish cooling efficiency!

If you really ramp up the optomechanical damping rate, eventually you will reach the strong coupling regime where the 'g', the linearized coupling strength becomes on the order of the cavity decay rate kappa. When that happens the efficiency of cooling diminishes and you don't go down to as low phonon numbers anymore as you expected to see.

Notes

Summary



21m 41s

CONCLUSION / SUMMARY

- **Raman picture**
- **Two coupled oscillators**
- **Quantum noise approach: System-bath picture**
- **Rate equations and cooling limit**

for further pointers to the literature, 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!

Okay. So that concludes our little lecture on the quantum theory of optomechanical cooling. Let me briefly summarize. We looked at the Raman picture where you have Stokes and anti-Stokes scattering of photons. We observed that the limit of optomechanical cooling, the fact that you don't cool always to exactly the ground state, is related to the fact that sometimes at least rarely you also have Stokes events where you dump extra phonons into the oscillator. And we briefly discussed this picture of two coupled oscillators. We went to the quantum noise approach which is a completely general approach that works for arbitrary systems where you have in mind an arbitrary quantum system coupled to a large environment that you described via its quantum noise spectrum. And then we talked about rate equations and the cooling limit that you can obtain in cavity optomechanics.

Notes

Summary



22m 06s