Amplified Opto-mechanical transduction of Virtual Radiation Pressure

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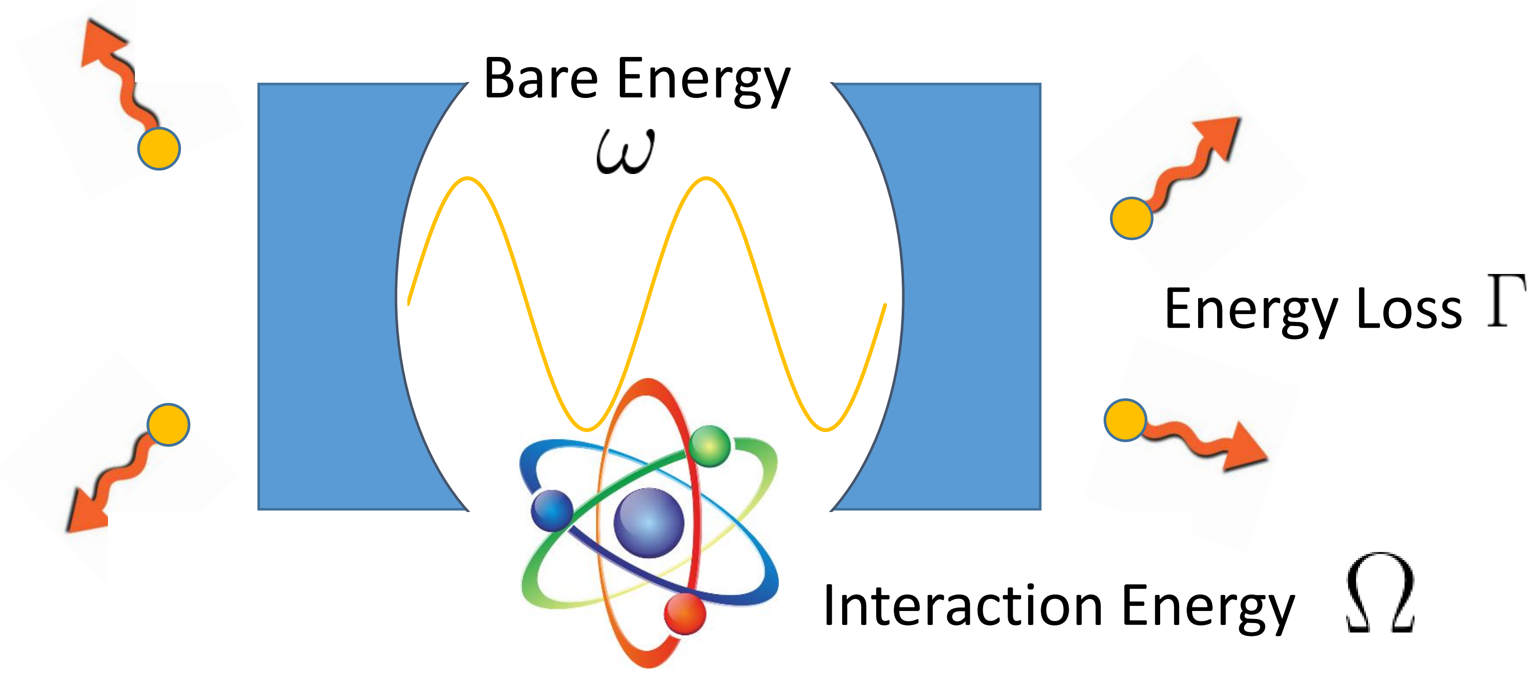
Cavity Quantum Electrodynamics

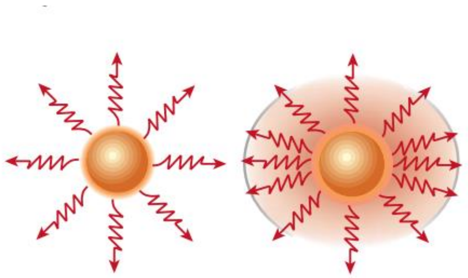
$$H_{\mathrm{Rabi}} = \omega\ a^\dagger a + \frac{\omega}{2}\sigma_z + \Omega(a + a^\dagger)(\sigma_+ + \sigma_-)$$



Cavity Quantum Electrodynamics

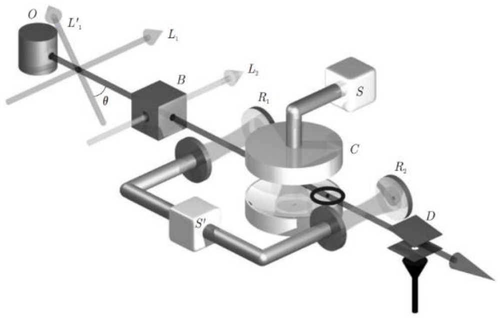
0 Γ $0.1\ \omega$ ω Ω

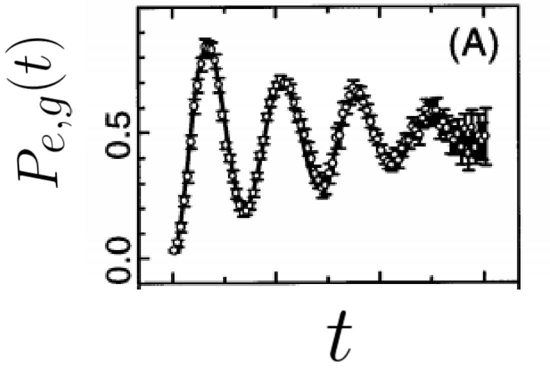
Weak	Strong	Ultra-Strong	Deep
Purcell Effect	Rabi oscillations	Virtual photons dressing the Ground state	Entangled Ground State



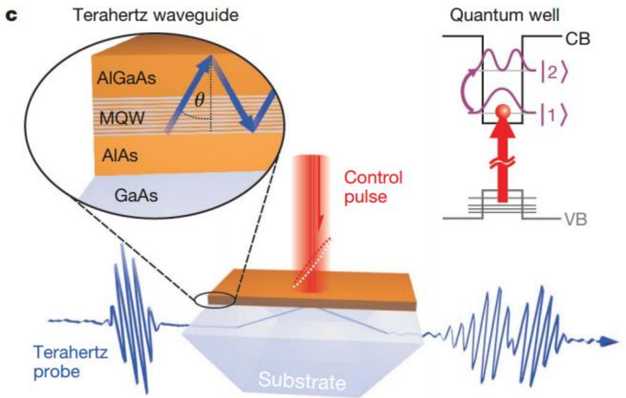
E. M. Purcell et al.,
Phys. Rev. **69**, 37 (1946)

Fig: Nature **424**, 839, 2003

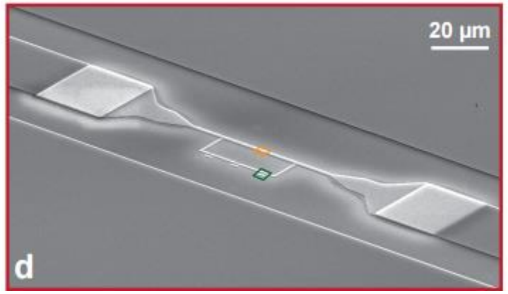




S. Haroche group



Nature **458**, (2009)



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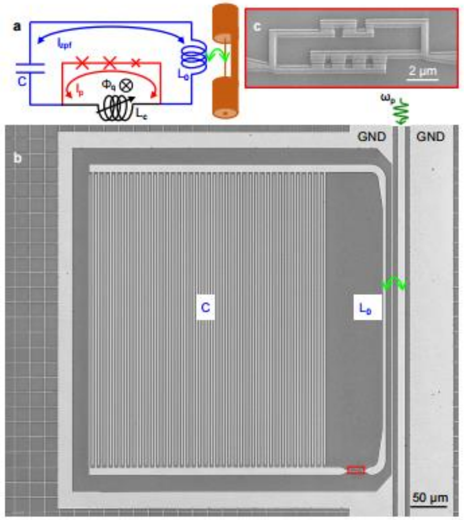

Nat. Phys. **13**, 44 (2017)

Cavity Quantum Electrodynamics

0 | Γ | $0.1\,\omega$ | ω | Ω

Weak | Strong | **Ultra-Strong** | Deep

Purcell Effect

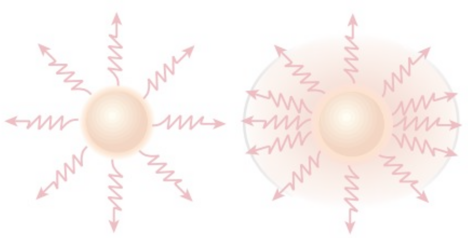

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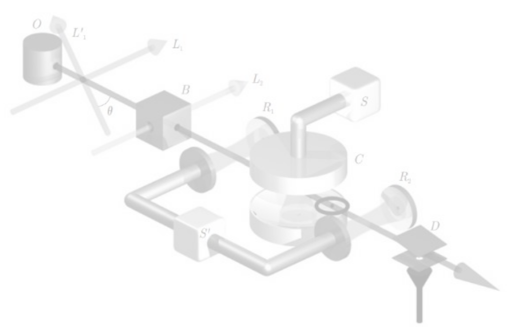
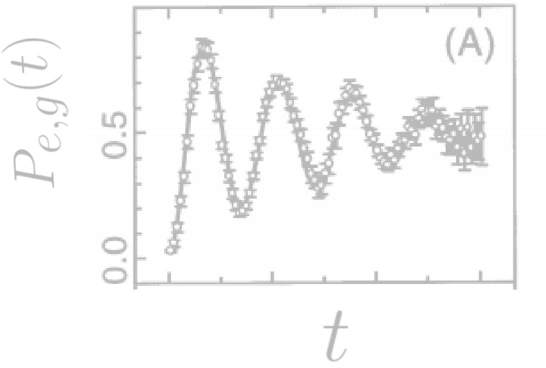
Fig: Nature **424**, 839, 2003

Rabi oscillations





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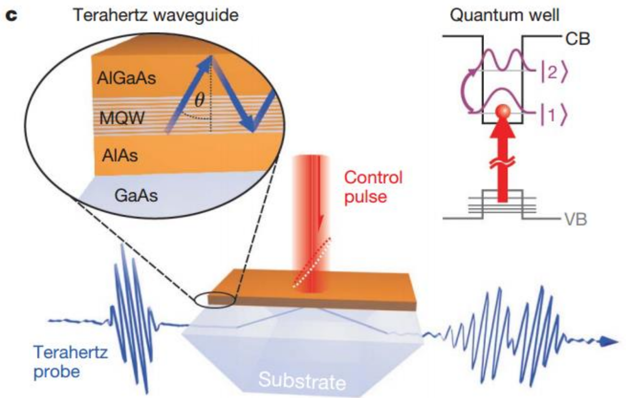
Virtual photons dressing the Ground state



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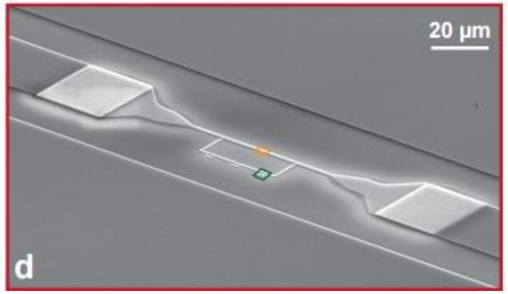

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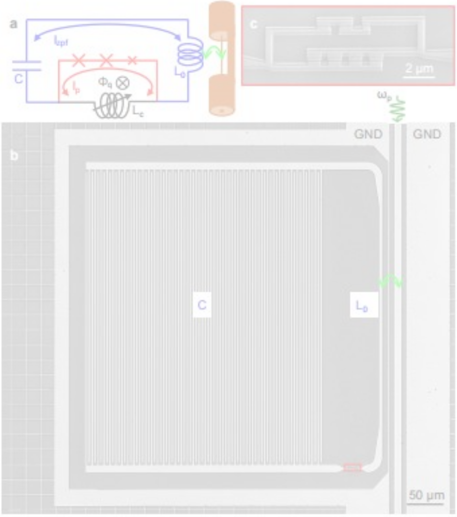
Entangled Ground State



Nat. Phys. **13**, 44 (2017)

Light-matter dressed ground state

$$H_{\mathrm{R}} = \omega a^{\dagger}a + \frac{\omega}{2}\sigma_z + \Omega(a^{\dagger}\sigma^{-} + a\sigma^{+}) + \Omega(a^{\dagger}\sigma^{+} + a\sigma^{-})$$

$$|G\rangle = (1-\frac{\eta^2}{8})|0,g\rangle+\frac{\eta}{2}|1,e\rangle+\frac{\eta^2}{2\sqrt{2}}|2,g\rangle$$

Virtual photons

$$\langle G|a^{\dagger}a|G\rangle = \frac{\eta^2}{4}$$

$$\eta = \frac{\Omega}{\omega}$$

Observing virtual photons: Non-adiabatic modulation of the coupling

C. Ciuti, et al., Phys. Rev. B **72**, 115303 (2005)

R. Stassi, et al., Phys. Rev. Lett. **110**, 243601 (2013)

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M. Cirio, et al., Phys. Rev. Lett. **116**, 113601 (2016)

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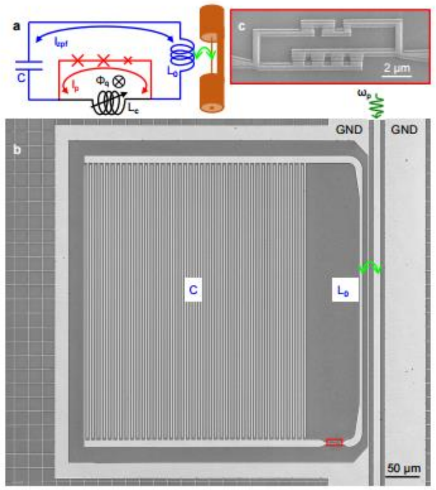
Challenging

- Weak Emission $\langle G|a^\dagger a|G\rangle = \frac{\eta^2}{4}$
- Fast modulation



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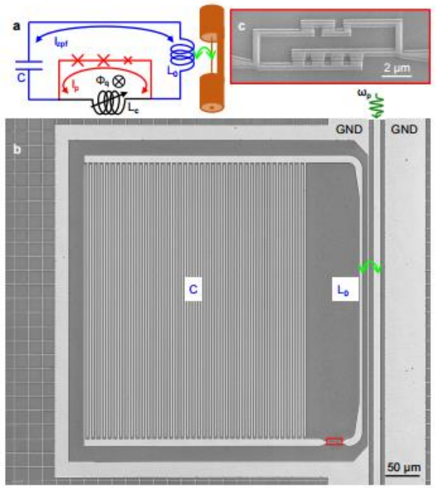
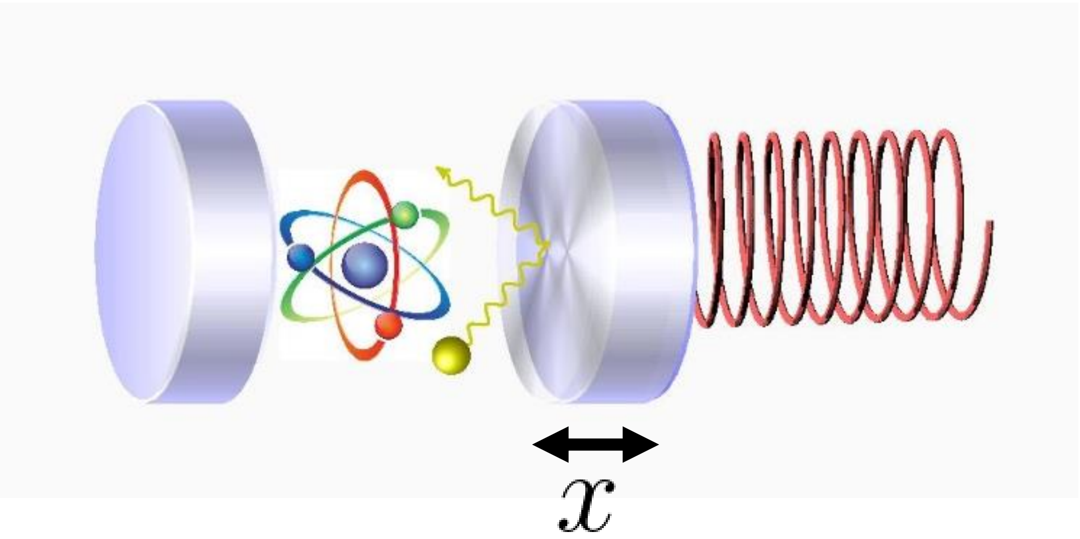


Nat. Phys. **13**, 44 (2017)

Destructive

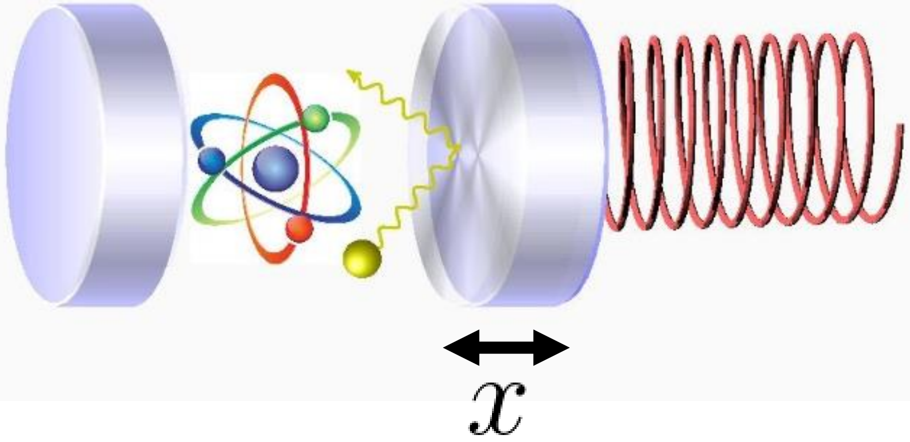
- Ground State is “forced” to decay

Opto-mechanical transduction of virtual radiation pressure



Opto-mechanical transduction of virtual radiation pressure

$$H_{\mathrm{RP}} = g_0 \; a^\dagger a \; \frac{x}{x_{\mathrm{zp}}}$$



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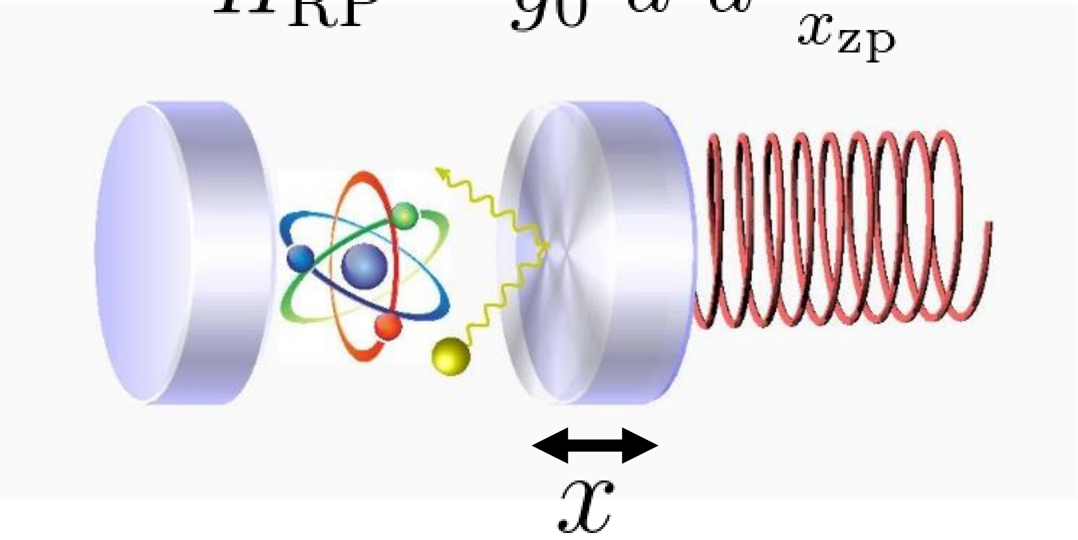

n photons in the cavity exert a radiation pressure force

$$P_n = n\frac{g_0}{x_{zp}}$$

This force induces a displacement

$$|\langle x \rangle_n| \propto n \, \frac{g_0}{\omega_m}$$

Opto-mechanical transduction of virtual radiation pressure

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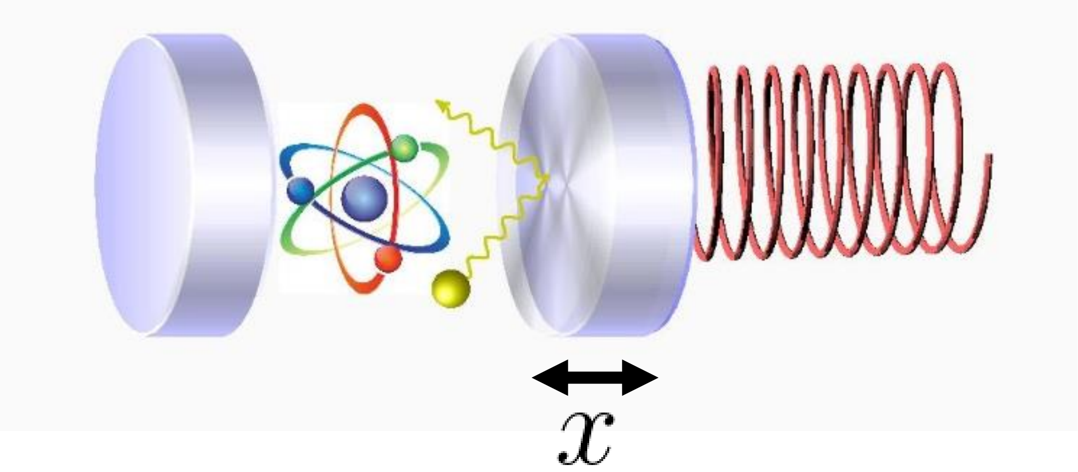

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At zero temperature

For weak light-matter couplings

the cavity contains no photons $\Rightarrow$ ~~P_0~~ ~~$|\langle x \rangle_0|$~~

Opto-mechanical transduction of virtual radiation pressure

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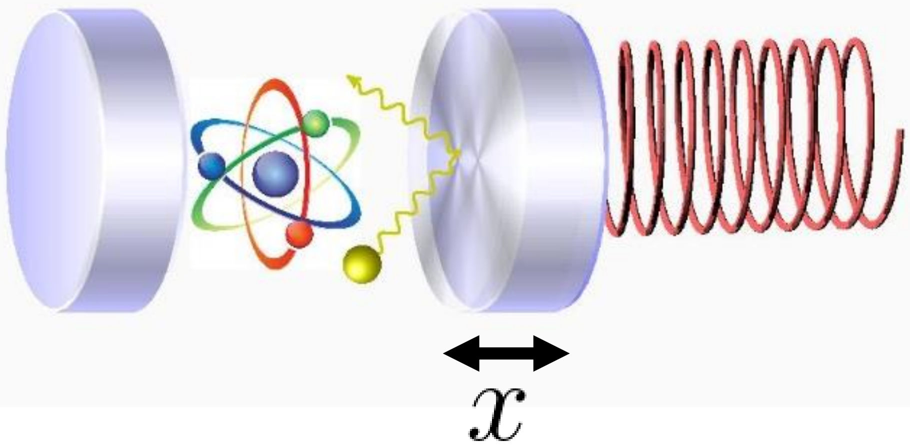

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At zero temperature

In the ultra-strong coupling regime

light-matter system has virtual photons

$$n_G = \langle G | a^\dagger a | G \rangle = \frac{\eta^2}{4}$$

$$\langle x \rangle_{\mathrm{GS}} \propto \eta^2 \; \frac{g_0}{\omega_m}$$

Probing "Virtual" Radiation Pressure?

$$\langle x \rangle_{\mathrm{GS}} \propto \eta^2 \, \frac{g_0}{\omega_m}$$

Encoding, but $\langle x \rangle_{\mathrm{GS}} > x_{\mathrm{zp}}$ requires $\frac{g_0}{\omega_m} > \frac{2}{\eta^2} \simeq 10 - 10^2$

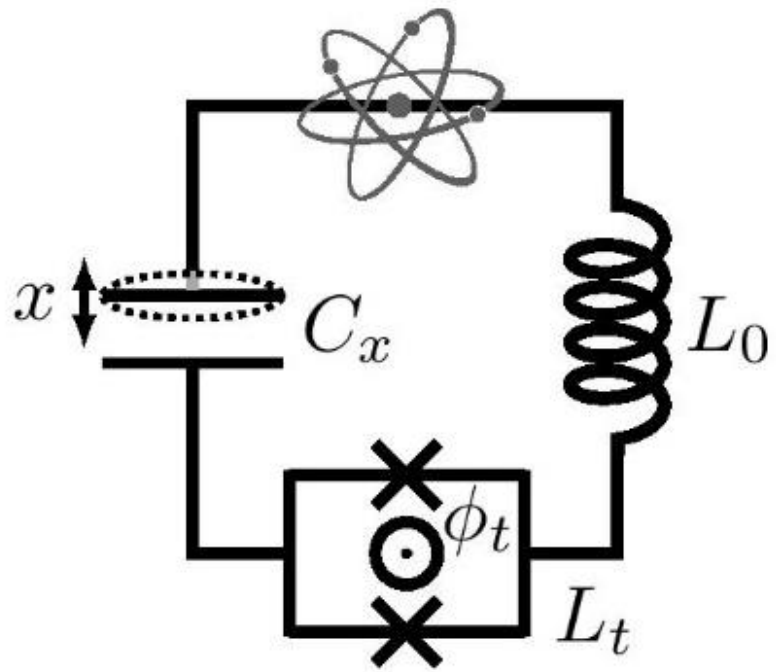
$\simeq 10^{-5}$ Teufel, et al., Nature **475**, 359 (2011)

$\simeq 10^{-2}$ Pirkkalainen, et al., Nat. Comm. **6**, 6981 (2015)

→ A strict condition

Amplification

$$H_{\rm RP} = g_0 \; a^\dagger a \; \frac{x}{x_{\rm zp}} \quad \longrightarrow \quad g_0 \cos(\omega_m t) \; a^\dagger a \; \frac{x}{x_{zp}}$$



Modulation of the opto-mechanical coupling

Opto-mechanical coupling

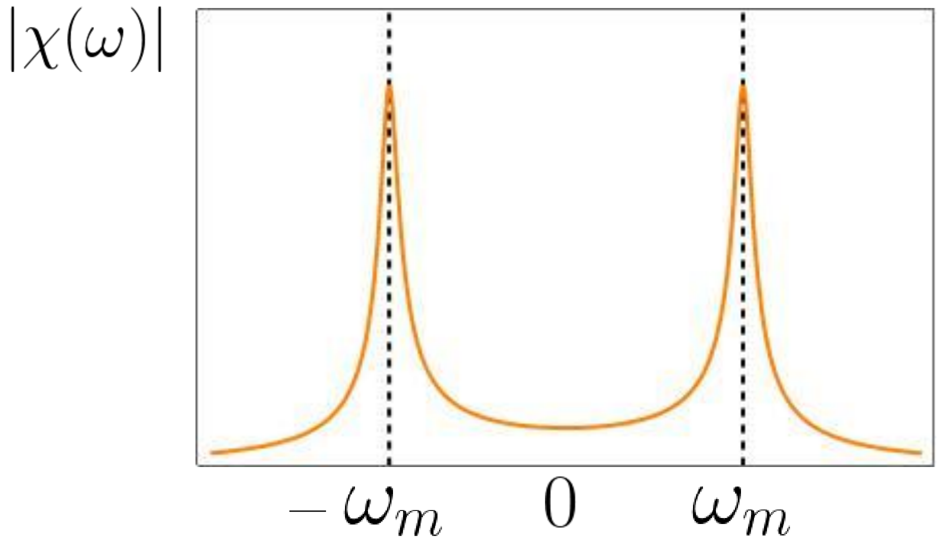
$$H = \omega a^\dagger a + \cdots \quad \text{with} \quad \omega = \frac{1}{\sqrt{L(t)C(x)}}$$

Amplification

$$H_{\mathrm{RP}} = g_0 \; a^\dagger a \; \frac{x}{x_{\mathrm{zp}}} \longrightarrow g_0 \cos(\omega_m t) \; a^\dagger a \; \frac{x}{x_{zp}}$$

Intuitively, this turns the virtual radiation pressure into a time-dependent driving force.

We expect the final displacement to be enhanced by the factor $\left|\frac{\chi(\omega_m)}{\chi(0)}\right| = \frac{\omega_m}{\Gamma_m}$



$$\chi(\omega) = \frac{\omega_m}{\omega_m^2 - \omega^2 - i\omega_m \Gamma_m}$$

Amplification

$$\langle x \rangle_{\mathrm{GS}} \propto \eta^2 \; \frac{g_0}{\omega_m} \quad \xrightarrow{\left| \frac{\chi(\omega_m)}{\chi(0)} \right| = \frac{\omega_m}{\Gamma_m}} \quad \langle x \rangle_{\mathrm{GS}} \propto \eta^2 \; \frac{g_0}{\Gamma_m}$$

Signal amplified by the Quality Factor

Conclusions

- Hybrid system to probe virtual photons with a mechanical transducer.
- This signal can be amplified by modulating the opto-mechanical coupling.
- The measurement minimally disturbs the light-matter system.
- Extensions of this protocol could be used to directly probe the light-matter ground state in the deep-coupling regime.
- See also J. Lolli, et al., Phys. Rev. Lett. **114**, 183601 (2015) for a complementary proposal.

THANK YOU FOR YOUR ATTENTION!