TU Delft
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Quantum and nonlinear optomechanics

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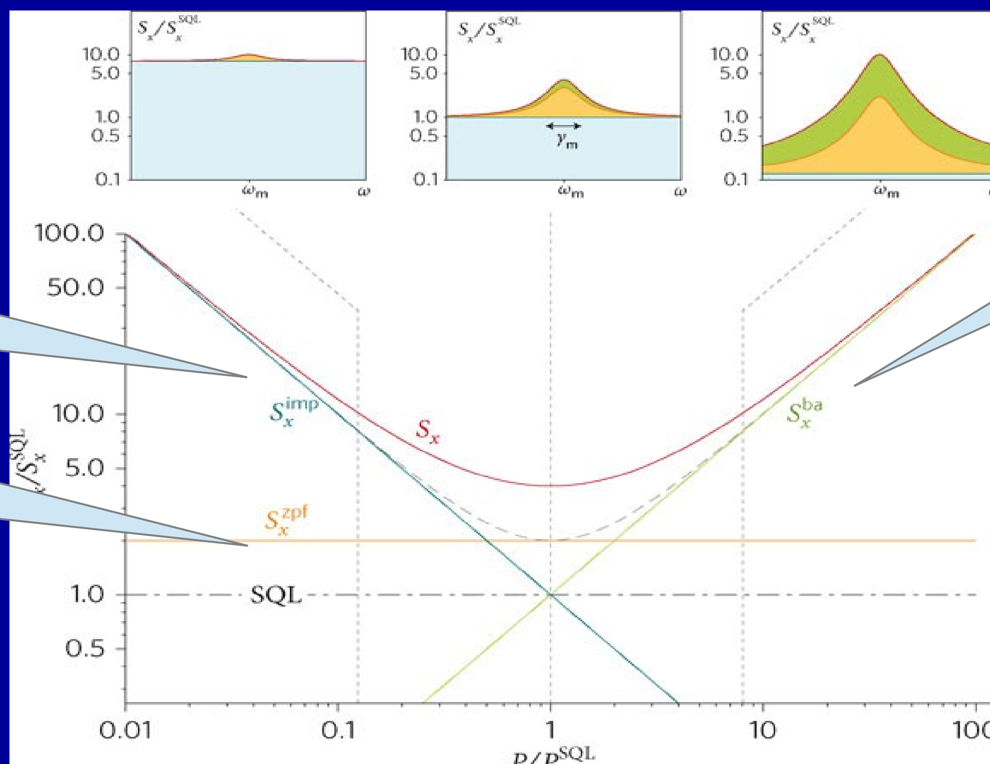
- Standard quantum limit and quantum detection
- Quantum state transfer
- Non-linearity and radiation pressure
- Non-linear cavity: Lorentz force back-action
- Non-linear resonator: Optomechanically induced transparency

Standard quantum limit

Why is it difficult to detect quantum mechanical motion?
– Need to cool down
– Issues with quantum detection

$$k_B T \ll \hbar\omega_m$$



Imprecision noise

Non-quantum sources

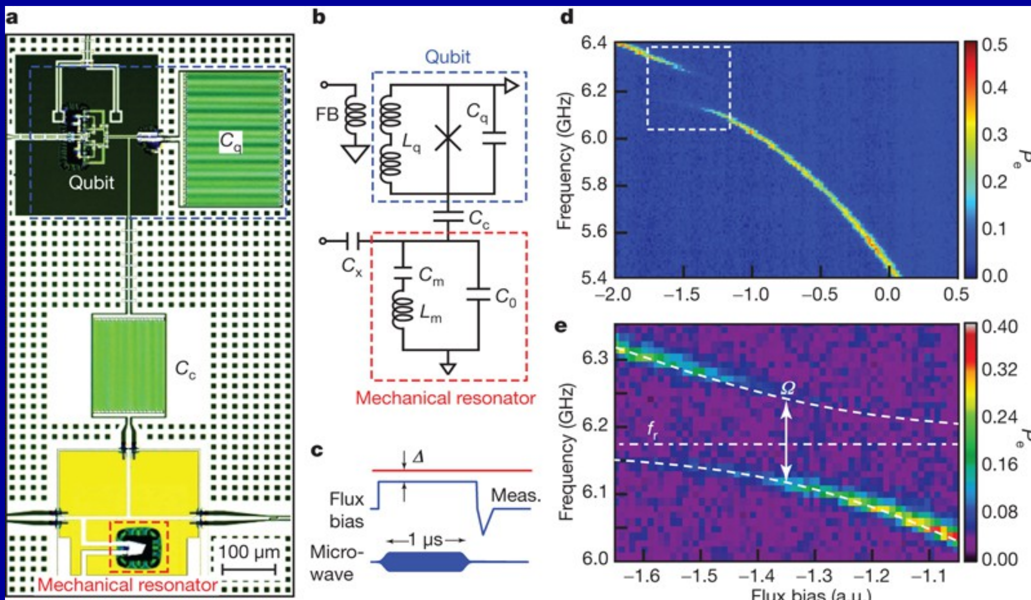
Backaction noise

Standard Quantum Limit (SQL)

SQL: ½ photon

Teufel et al, Nature Nanotech **4**, 820 (2009)

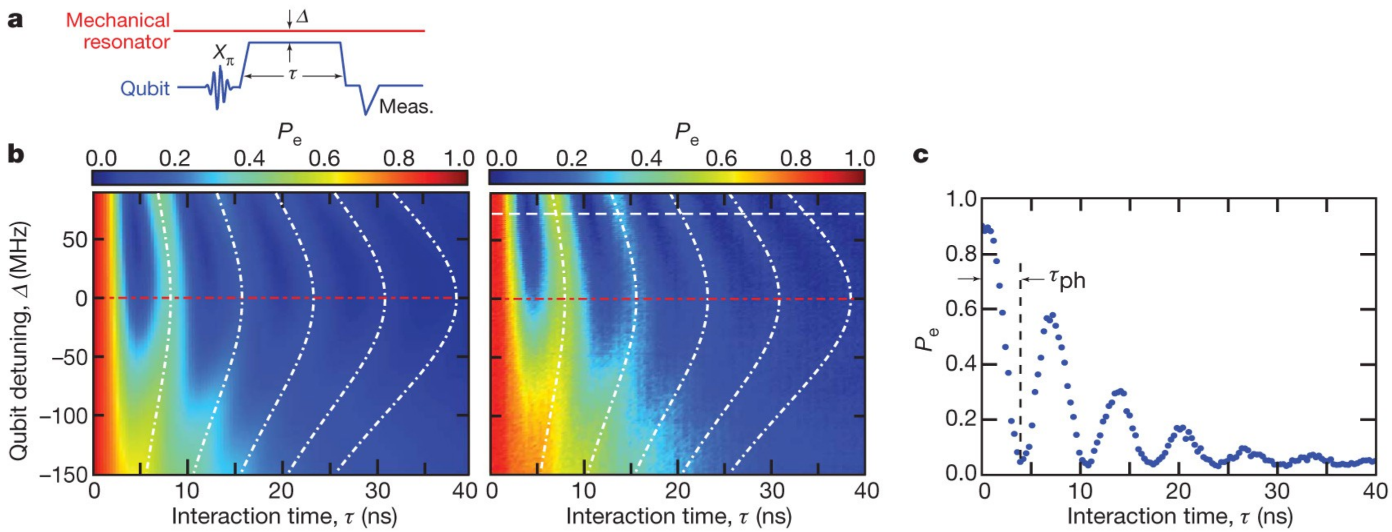
Quantum detection of mechanical motion



A. D. O'Connell et al (UCSB)
Nature **464**, 697 (2010)

A mechanical resonator coupled to a superconducting qubit

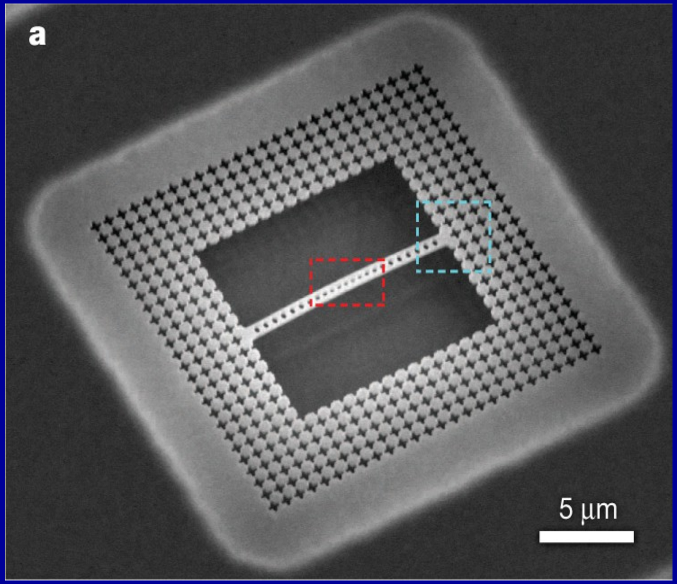
Quantum detection of mechanical motion

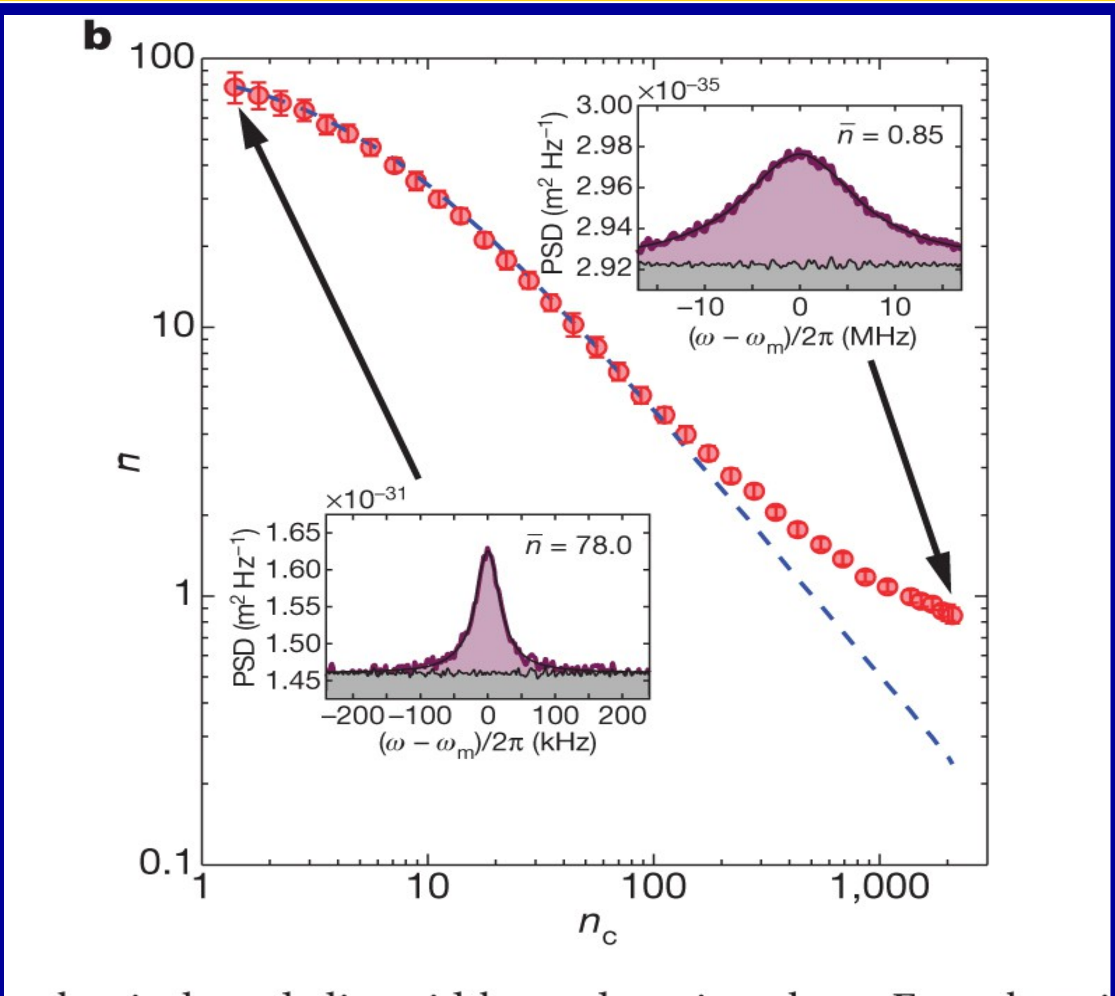


A. D. O'Connell et al (UCSB)
Nature **464**, 697 (2010)

Quantum signatures of mechanical motion

Chan et al, Nature **478**, 89 (2011)

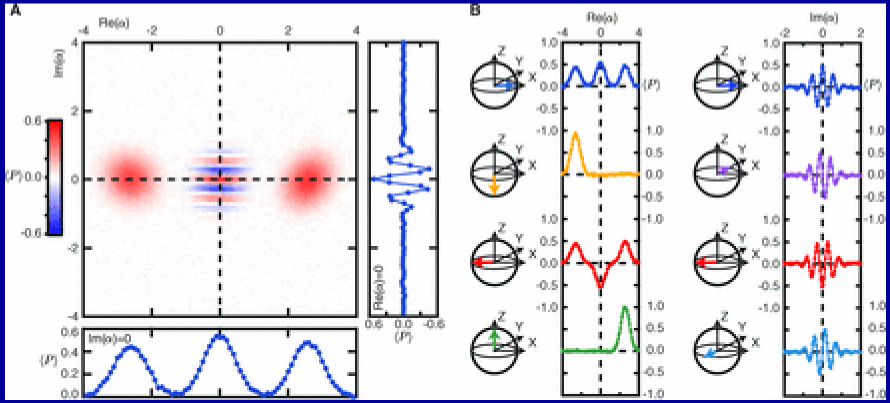




Also: Teufel et al, Nature **475**, 359 (2011); Verhagen et al, Nature **482**, 63 (2012)

Creation of non-classical mechanical states

Schoelkopf group, Yale: created cat states in a cavity



Vlastakis et al, Science **342**, 607 (2013)

How can we make non-classical mechanical states in the cavity architecture?

- Transfer from the cavity
- Make the cavity or the resonator non-linear (Yurke, Stoler)

Creation of non-classical mechanical states

B. Yurke and D, Stoler, Phys. Rev. Lett. **57**, 13 (1986)

Hamiltonian: $\hat{H} = \omega \hat{a}^{\dagger}\hat{a} + K\left(\hat{a}^{\dagger}\hat{a}\right)^{k}$

Initial state: Coherent state

$$\left|\alpha\right\rangle = \exp\left(-\left|\alpha\right|^{2}/2\right)\sum_{n=0}^{\infty}\frac{\alpha^{n}}{\sqrt{n!}}\left|n\right\rangle$$

Time evolution (interaction picture): $\left|\alpha,t\right\rangle = \exp\left(-\left|\alpha\right|^{2}/2\right)\sum_{n=0}^{\infty}\frac{\alpha^{n}}{\sqrt{n!}}\exp\left(-i\varphi_{n}\right)\left|n\right\rangle$

Periodicity: $2\pi/K$ $\qquad \varphi_{n} = Kn^{k}t$

After a quarter of the period (even k): $\left|\alpha,\pi/2K\right\rangle = \frac{1}{\sqrt{2}}\left(e^{-i\pi/4}\left|\alpha\right\rangle + e^{i\pi/4}\left|-\alpha\right\rangle\right)$

Cat states!

Non-linear optomechanics

Why is non-linearity important?

- Because it is there
- Modifies the behavior, especially at strong coupling
- Preparation of non-classical states of mechanical resonator

Non-linear optomechanics

What is non-linear?

- Cavity: Microwave with a Josephson junction
- Mechanical resonator
- Radiation pressure interaction

Non-linear radiation pressure

A. Nunnenkamp, K. Børkje, and S. M. Girvin
Phys. Rev. Lett. **107**, 063602 (2011)

$$H = \hbar\omega_{cav}\hat{a}^{\dagger}\hat{a} + \hbar\omega_m \hat{b}^{\dagger}\hat{b} - \hbar g_0 \hat{a}^{\dagger}\hat{a}(b^{\dagger} + b)$$

$$\Delta = -n g_0^2 / \omega_m$$

multiphoton resonances

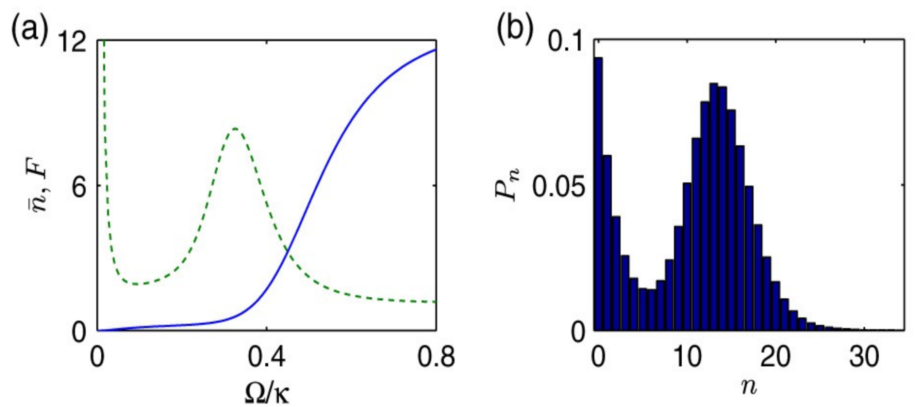
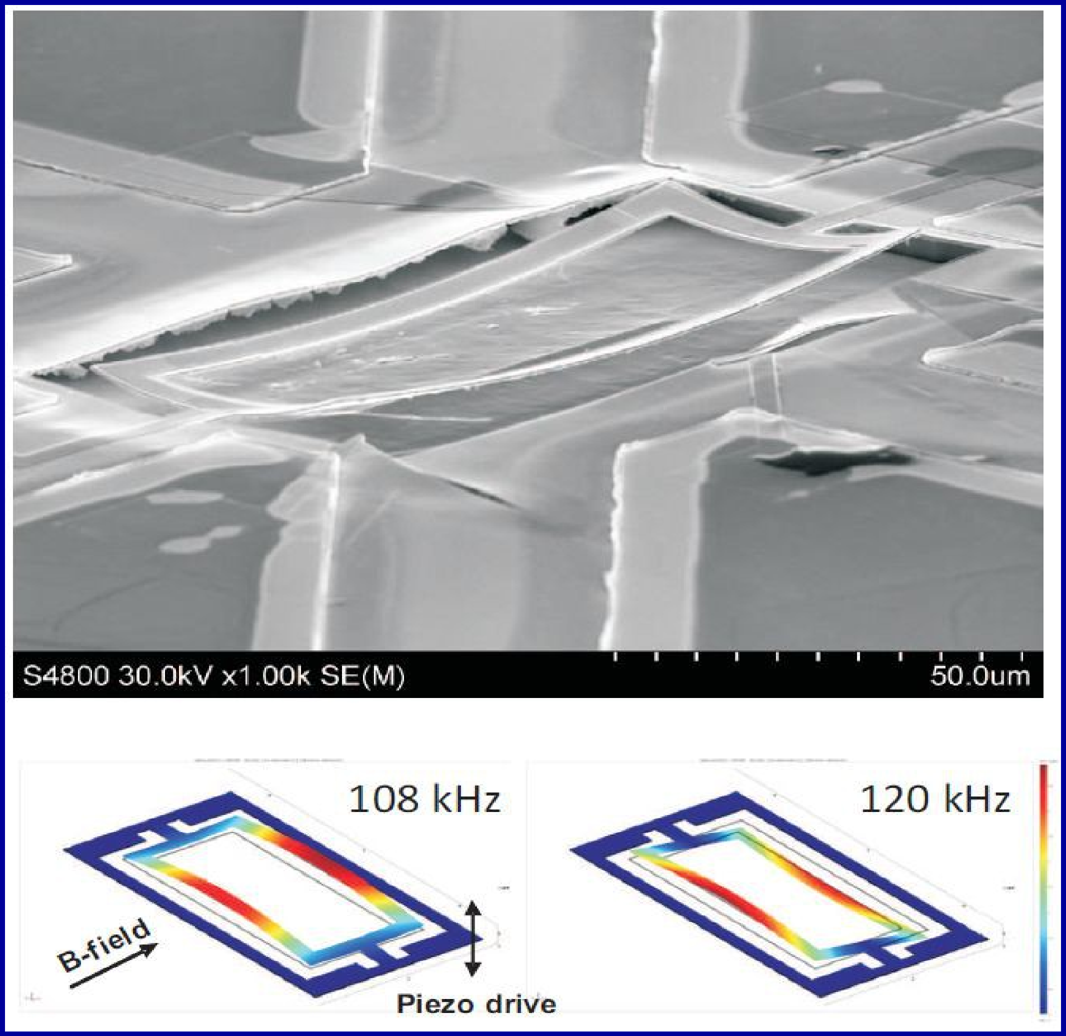
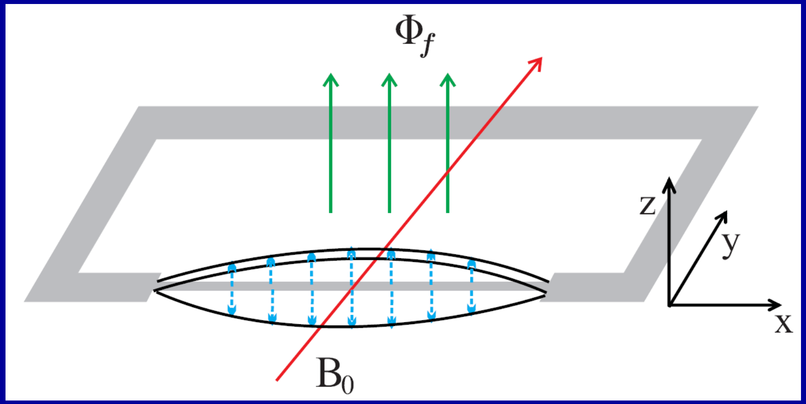


FIG. 4 (color online). Non-Gaussian steady states via multi-photon transitions. (a) Steady-state mean phonon number $\langle \hat{b}^{\dagger}\hat{b}\rangle$ (blue solid line) and the second-order coherence of the mechanical oscillator $F = \langle \hat{b}^{\dagger}\hat{b}^{\dagger}\hat{b}\,\hat{b}\rangle / (\langle \hat{b}^{\dagger}\hat{b}\rangle)^2$ (green dashed line) as a function of drive strength Ω. (b) Phonon number distribution P_n at $\Omega/\kappa = 0.6$. Parameters are $\Delta = -3g^2/\omega_M$, $\omega_M/\kappa = 2$, $\omega_M/\gamma = 1000$, and $g/\kappa = 1$.

Non-linear cavity

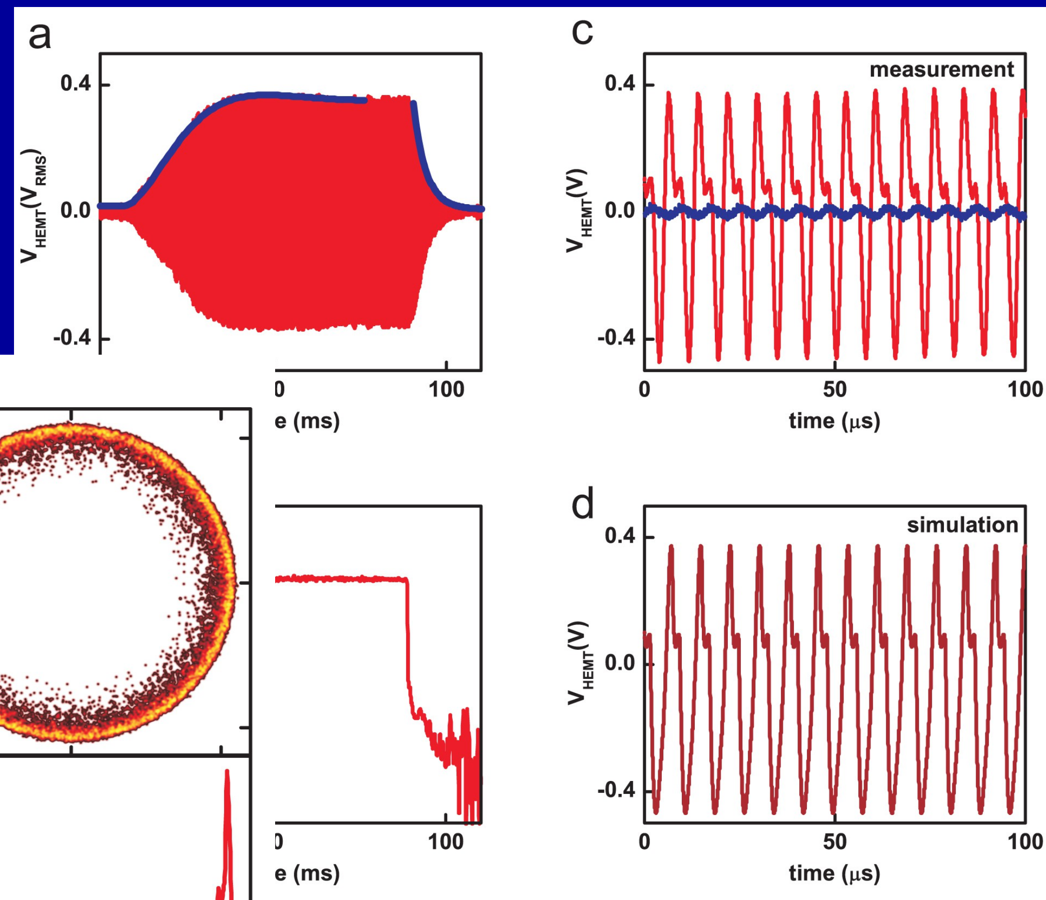
S. Etaki, F. Konschelle, H. Yamaguchi, YMB, H. S. J. van der Zant, Nature Comm. **4**, 1803 (2013)

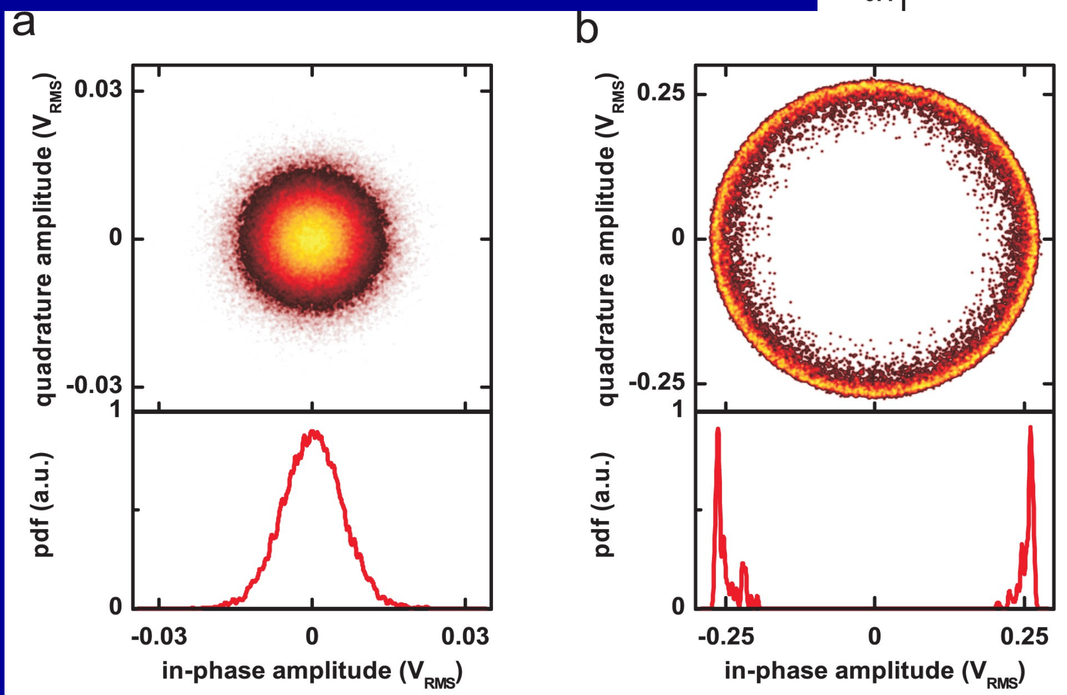




Self-sustained oscillations

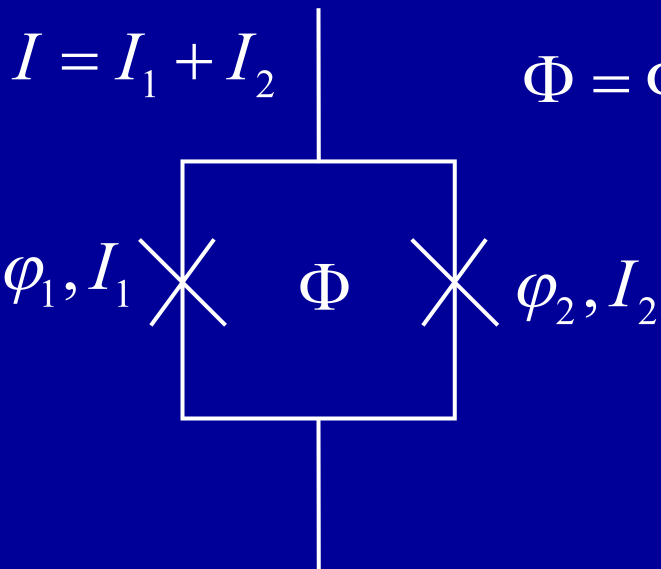
S. Etaki, F. Konschelle, H. Yamaguchi, YMB, H. S. J. van der Zant, Nature Comm. **4**, 1803 (2013)





Lorentz force backaction

M. Poot et al, PRL **105**, 207203 (2010)



$$\Phi = \Phi_a + Blax + L(I_1 - I_2)/2 = \Phi_0(\varphi_2 - \varphi_1)/(2\pi)$$

Motion

Inductive coupling

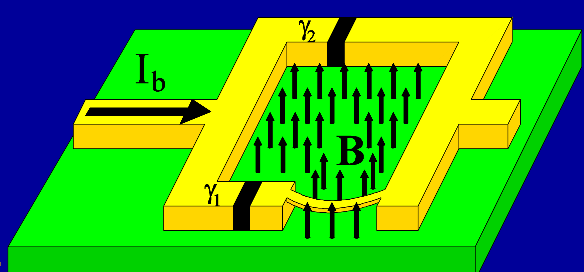
Josephson junctions:

$$I_{1,2} = I_0 \sin\varphi_{1,2} + \frac{V_{1,2}}{R} + C\dot{V}_{1,2},\ V_{1,2} = \frac{\Phi_0}{2\pi}\dot{\varphi}_{1,2}$$

Oscillator:

$$M\ddot{x} + \frac{M\omega}{Q}\dot{x} + M\omega^2 x = F\cos\omega t + aBlI_1$$

Lorentz force



Back-action and self-oscillations

$$M\ddot{x} + \frac{M\omega}{Q}\dot{x} + M\omega^2 x = F\cos\omega t + aBlI_1$$

For self-oscillations we need Q < 0

Overdamped:

$$I_1 = V / R \propto \sqrt{\left(\frac{I}{I_c}\right)^2 - 1},\ I_c(x) = 2I_c \cos\frac{\pi\Phi(x)}{\Phi_0}$$

– renormalization of the frequency

Finite capacitance: correction

$$\delta I_1 = C\dot{V} \propto \dot{x}\sin\frac{\pi\Phi}{\Phi_0}\left(\sqrt{\left(\frac{I}{2I_c\cos\frac{\pi\Phi(x)}{\Phi_0}}\right)^2 - 1}\right)^{-1}$$

Renormalizes the quality factor and may yield self-oscillations