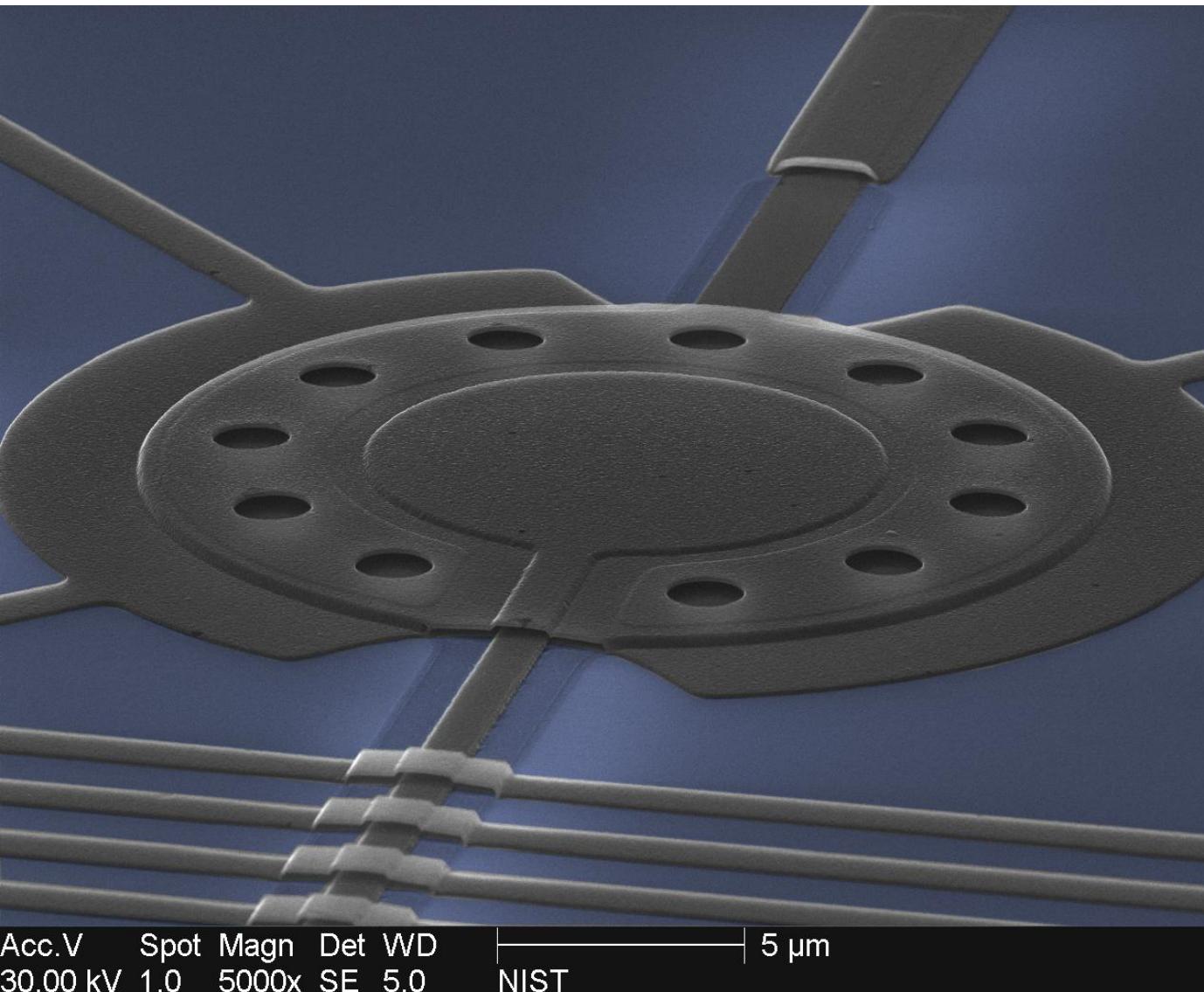


# Noiseless mode conversion of microwave fields

---



Acc.V Spot Magn Det WD | 5 μm  
30.00 kV 1.0 5000x SE 5.0 NIST

# Making light “dense”

---

dissipationless single photon non-linearity  
condensed matter physics with photons

noiselessly convert light into mechanical motion

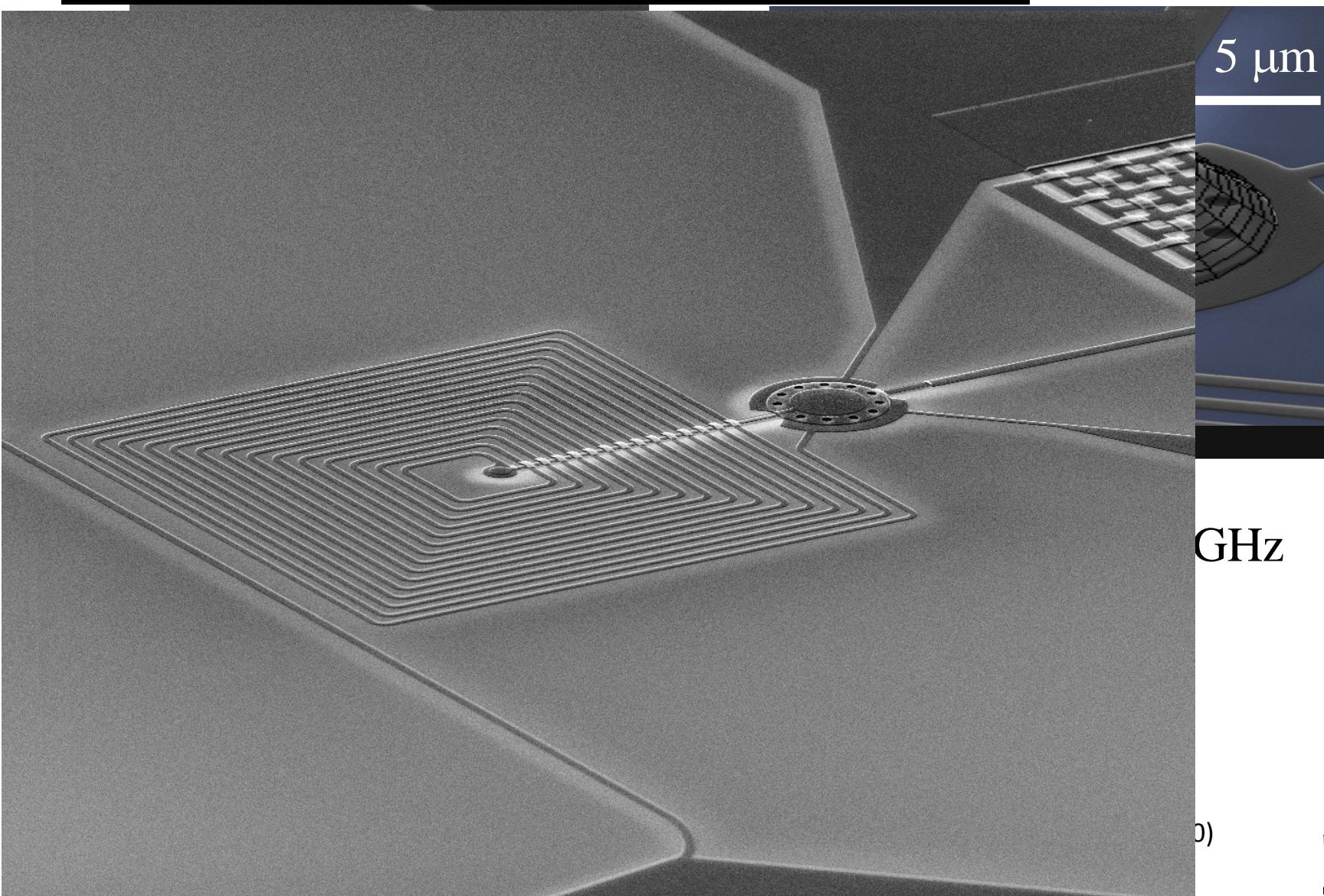
force quantum mechanics to confront gravity (very hard)

potential for strong phonon-phonon interaction

→ analog signal processing in the quantum domain

Converting microwave fields  
into mechanical motion

# Electromechanics: microwave resonators with mechanically compliant capacitors

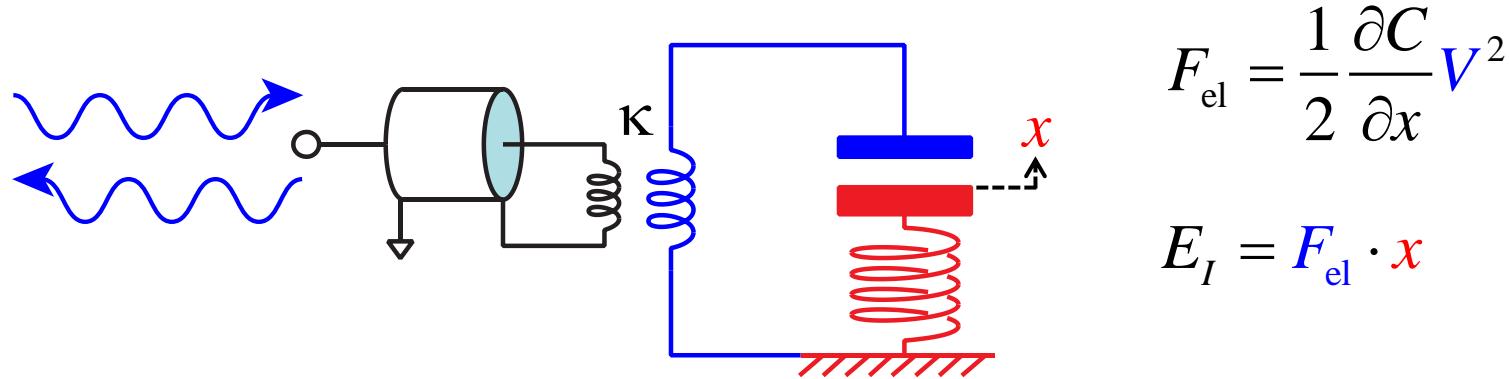


0)

JILA  
NISTCU

# Electrostatic forces yield parametric interaction between electricity and motion

---



$$F_{\text{el}} = \frac{1}{2} \frac{\partial C}{\partial x} V^2$$

$$E_I = F_{\text{el}} \cdot x$$

$$\hat{H}_I = \hat{F}_{\text{el}} \cdot \hat{x} = \hbar g_0 \mathbf{a}^\dagger \mathbf{a} (\mathbf{b}^\dagger + \mathbf{b}) \quad g_0 = \frac{\partial \omega_c}{\partial x} x_{\text{zpf}} \approx 2\pi \times 250 \text{ Hz}$$

intensity dependent circuit resonance: Kerr non-linearity

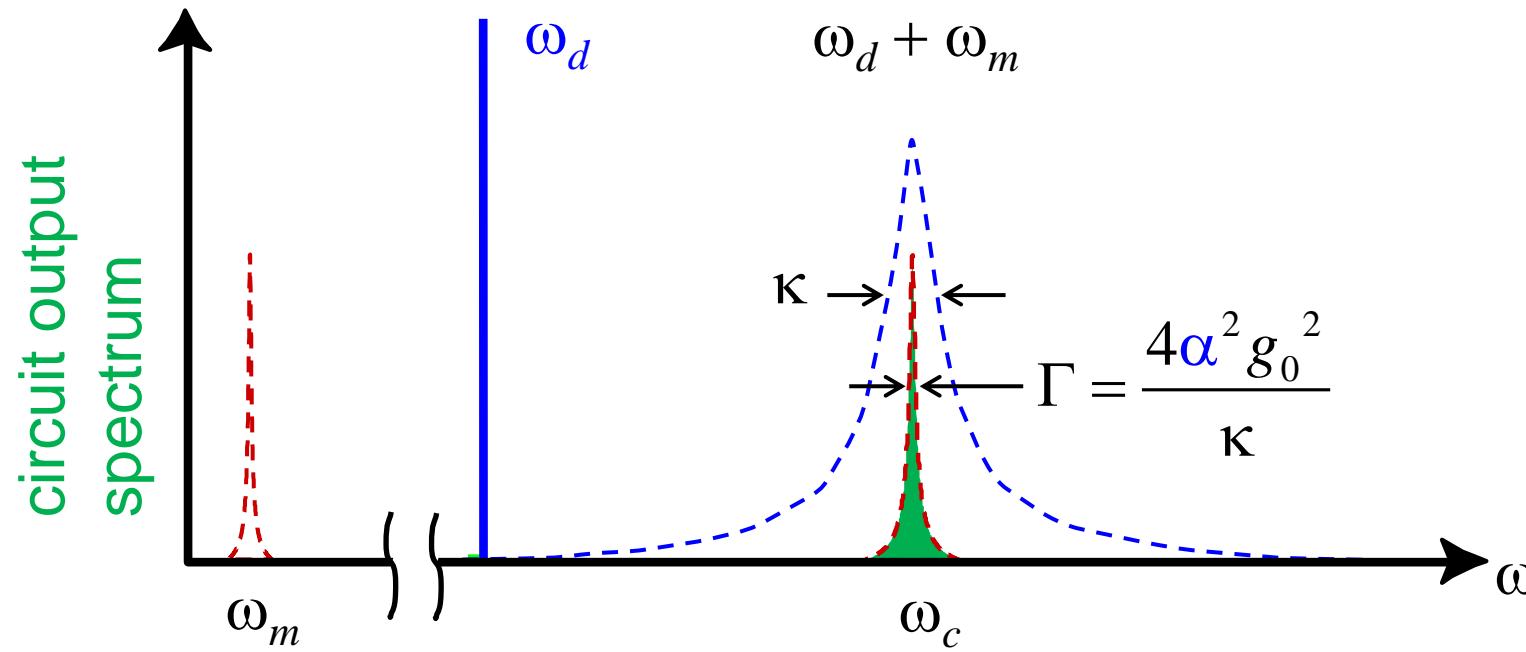
decay rate of circuit energy

$\kappa = 2\pi \times 2.5 \text{ MHz}$

# Detuned microwave drive couples mechanical motion to circuit resonance

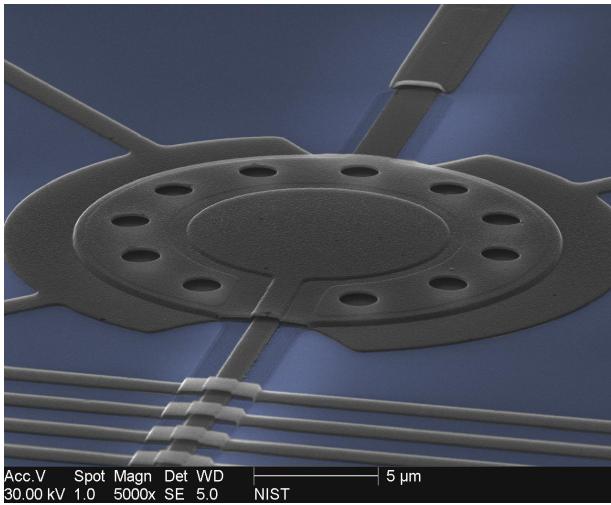
$$\hat{H}_I = \hbar g_0 \hat{a}^\dagger \hat{a} (\hat{b}^\dagger + \hat{b}) \quad \text{excite circuit at } \omega_d = \omega_c - \omega_m$$

$$\hat{a} = (\alpha + \hat{d}) e^{-j\omega_d t} \quad \hat{H}_I = \hbar g_0 \alpha (\hat{d} \hat{b}^\dagger + \hat{d}^\dagger \hat{b})$$



# Electromechanical devices have weak but adjustable electrical non-linearity

---



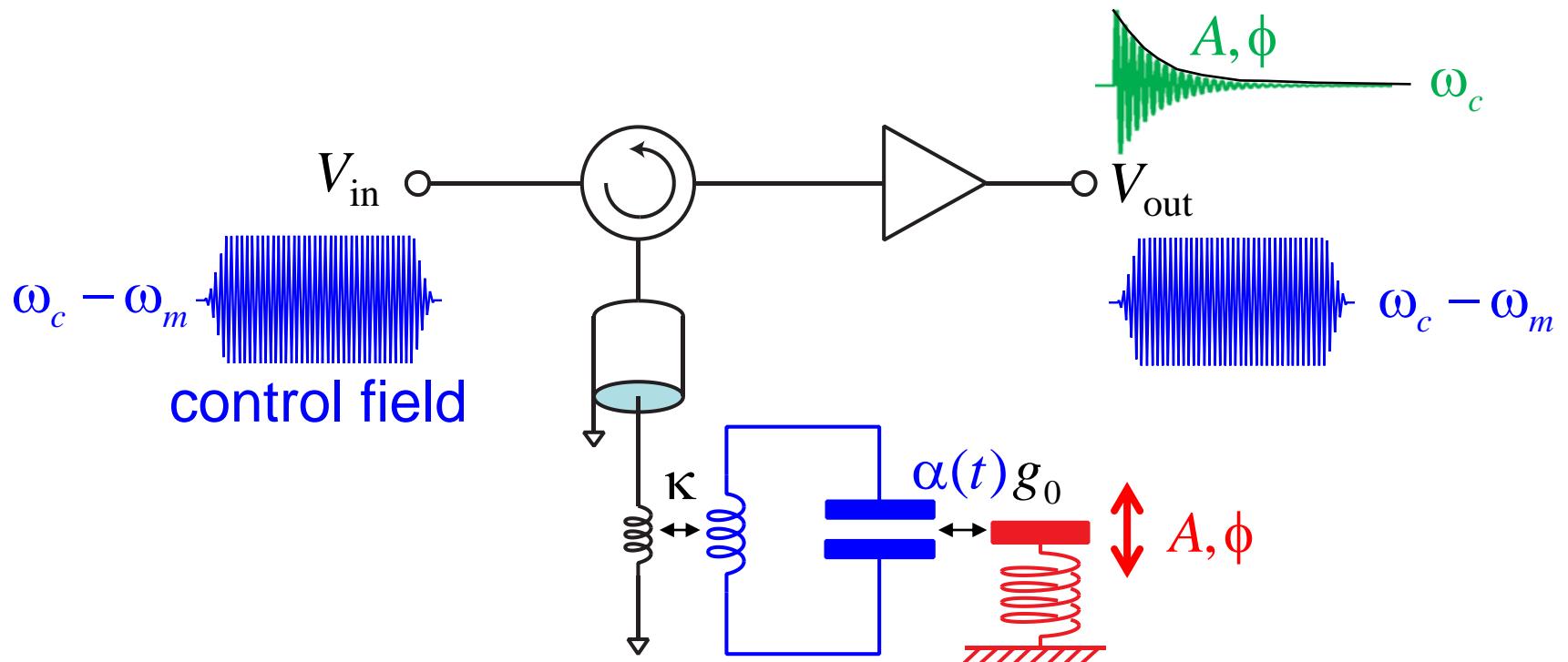
linear time-dependent e.o.m.

large dynamic range

low dissipation

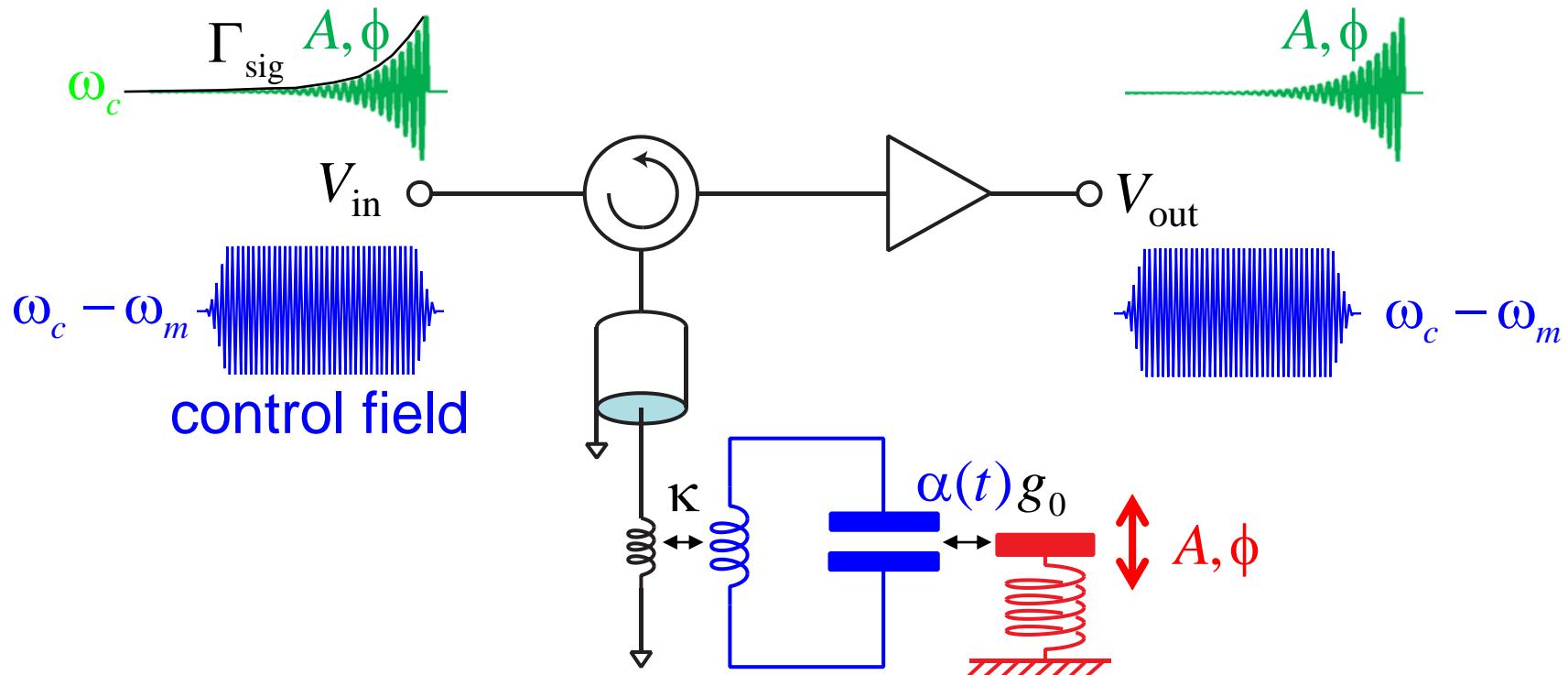
superb isolation

# Control field transfers state of mechanical oscillator to propagating microwave field



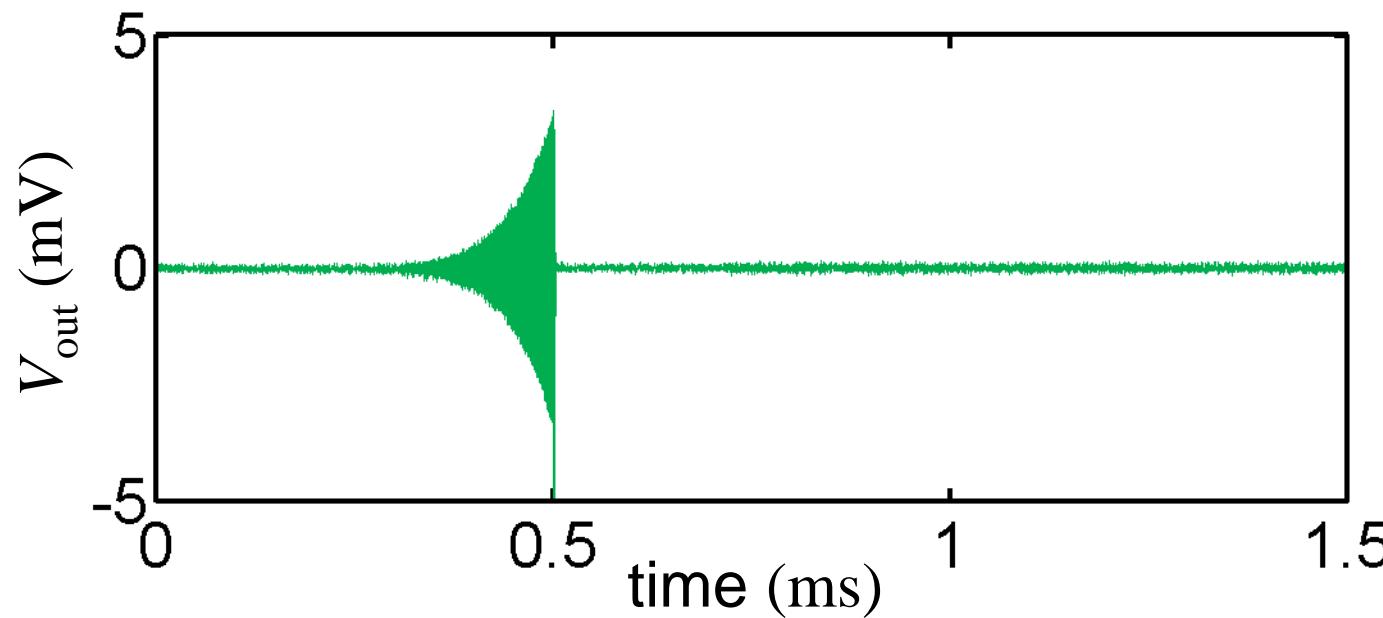
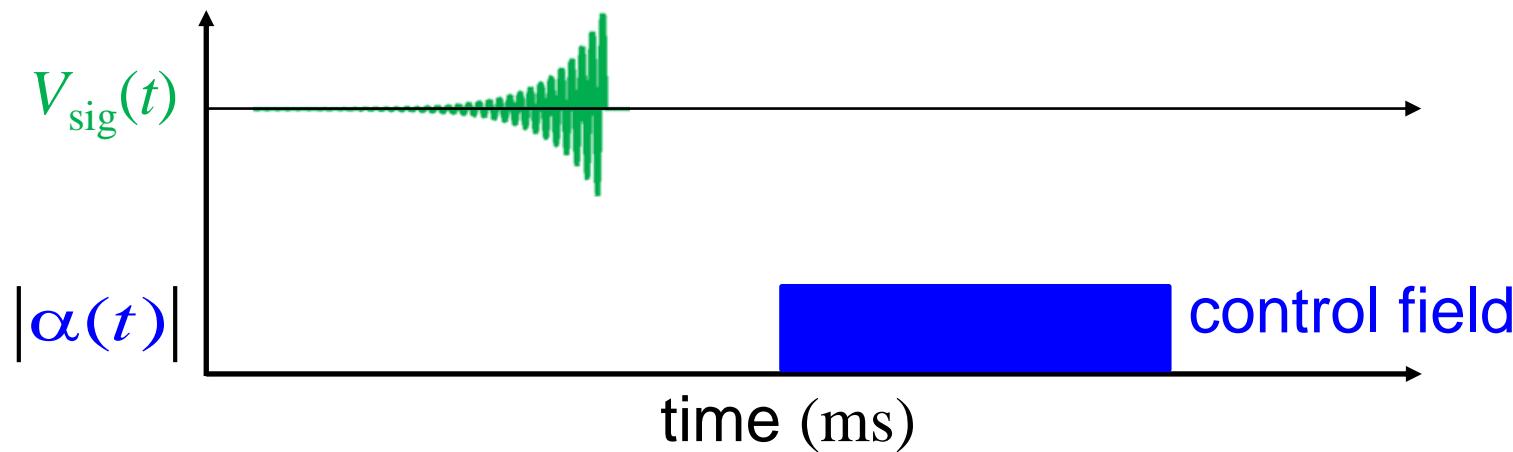
$$\text{pulse decay rate } \Gamma = \frac{4\alpha^2 g_0^2}{\kappa}$$

# Control field transfers microwave signal field to mechanical oscillator

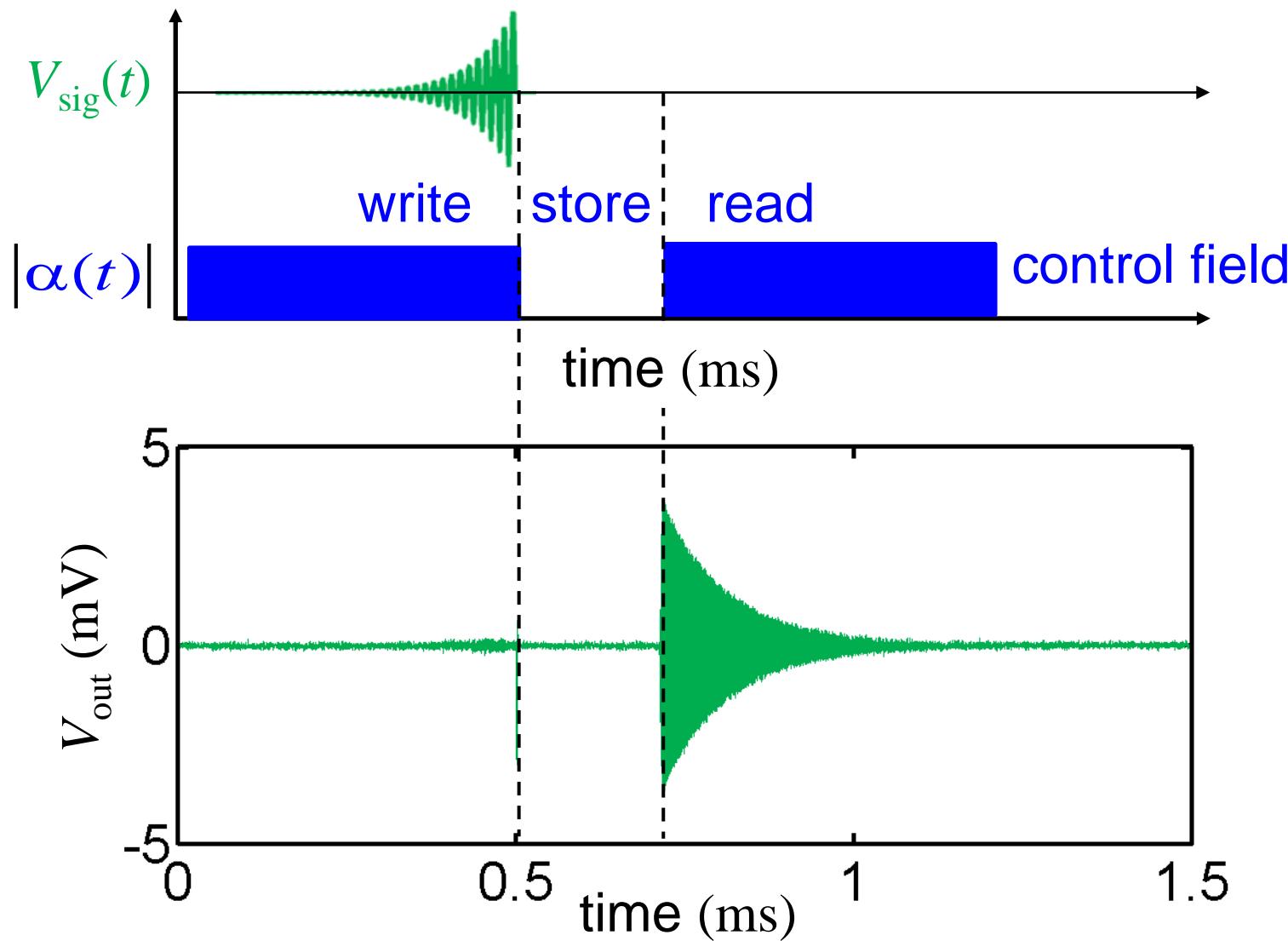


efficient transfer  $\Gamma_{\text{sig}} = \Gamma$

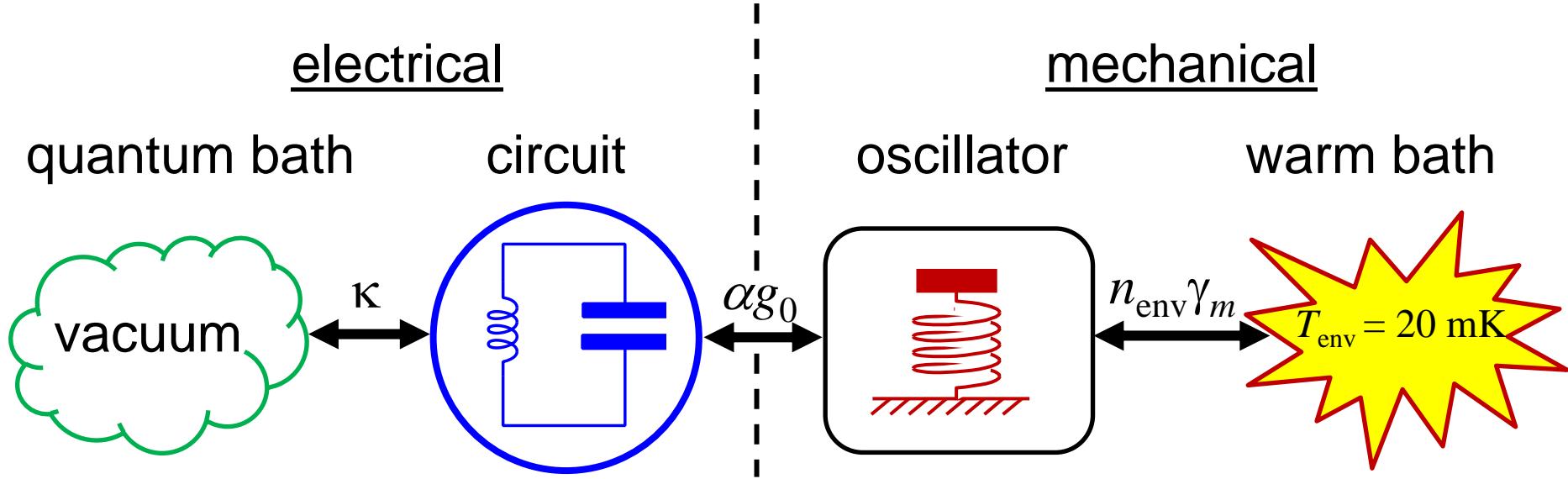
# Mechanical oscillator forms coherent memory for propagating microwave fields



# Mechanical oscillator forms coherent memory for propagating microwave fields



# With large cooperativity, memory operates in the quantum regime



$$\tilde{C} = \frac{\Gamma}{n_{\text{env}} \gamma_m} > 1 \quad \text{operation in the quantum regime}$$

## State transfer

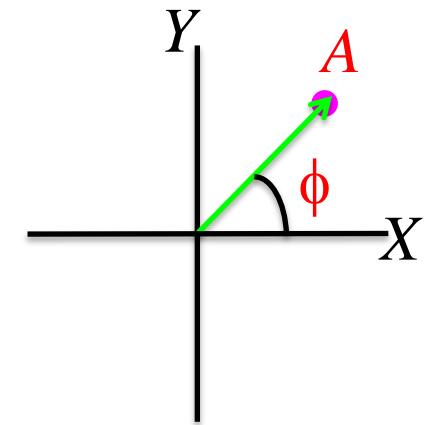
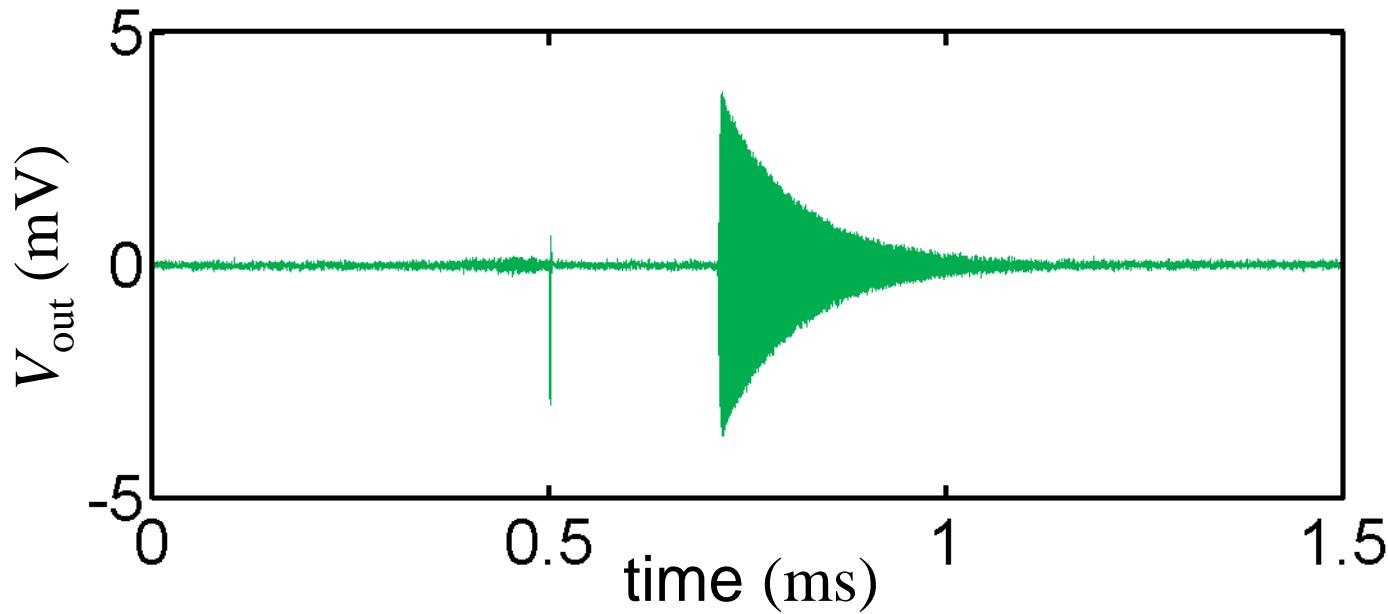
T. A. Palomaki, KWL, et al.,  
*Nature* **495**, 210 – 214 (2013)

## Entanglement

T. A. Palomaki, KWL, et al.,  
*Science* **342**, 710 – 713 (2013)

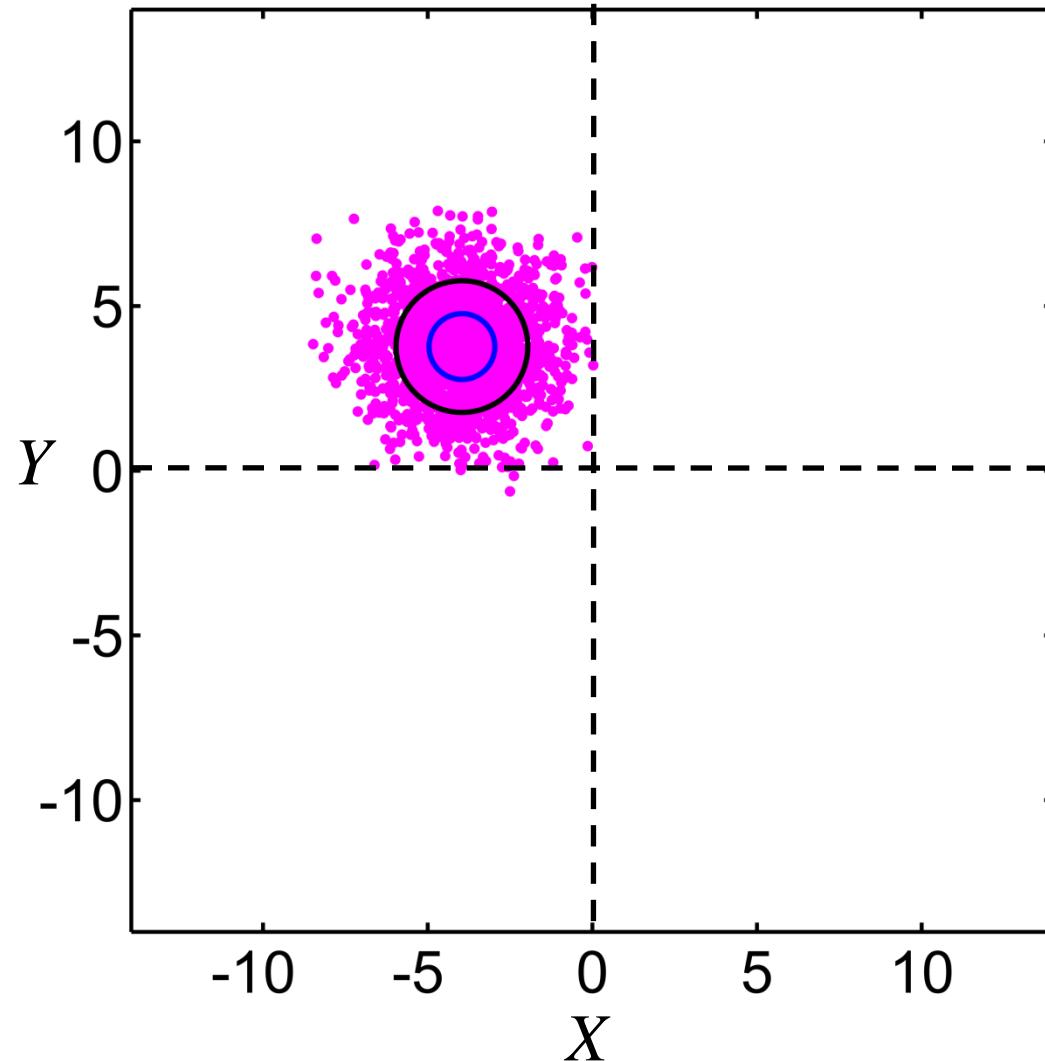
# Optimally filter microwave output to infer state of mechanics

---



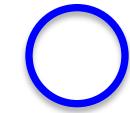
# Gaussian statistics of many measurements reveals quantum scale

---



$$\text{Var}(X) + \text{Var}(Y) = 1/\eta + N_{th}$$

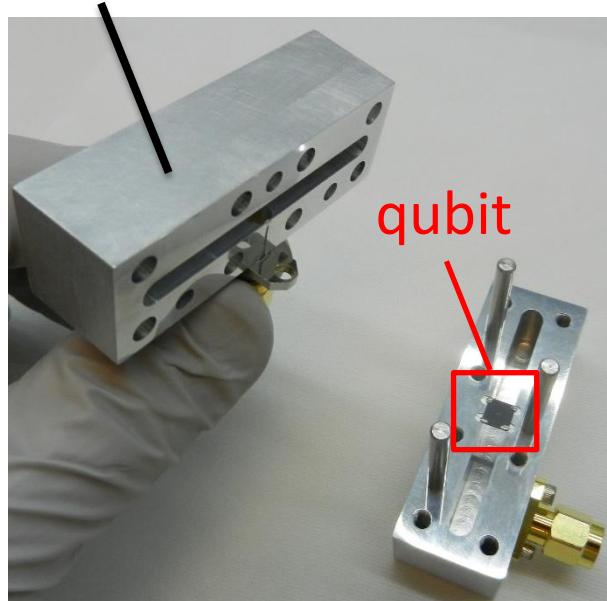
$$N_{th} = 0 \quad \eta = 1$$



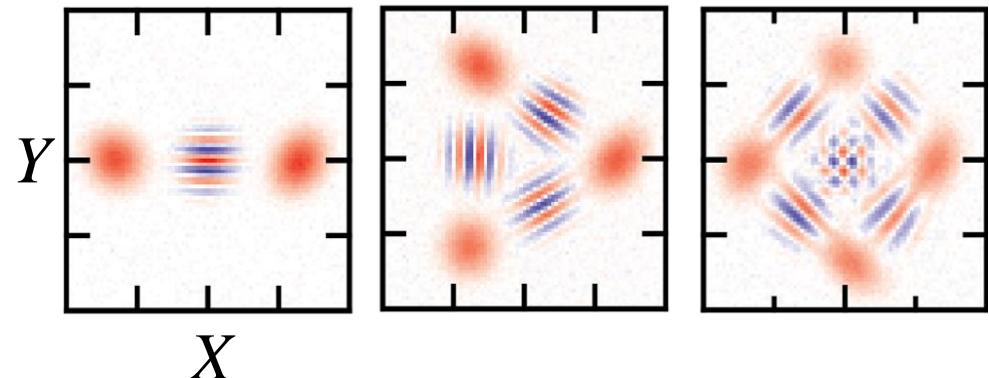
Escaping the tyranny of  
Gaussian noise

# Transmon qubit + microwave cavity access non-Gaussian quantum states

microwave cavity



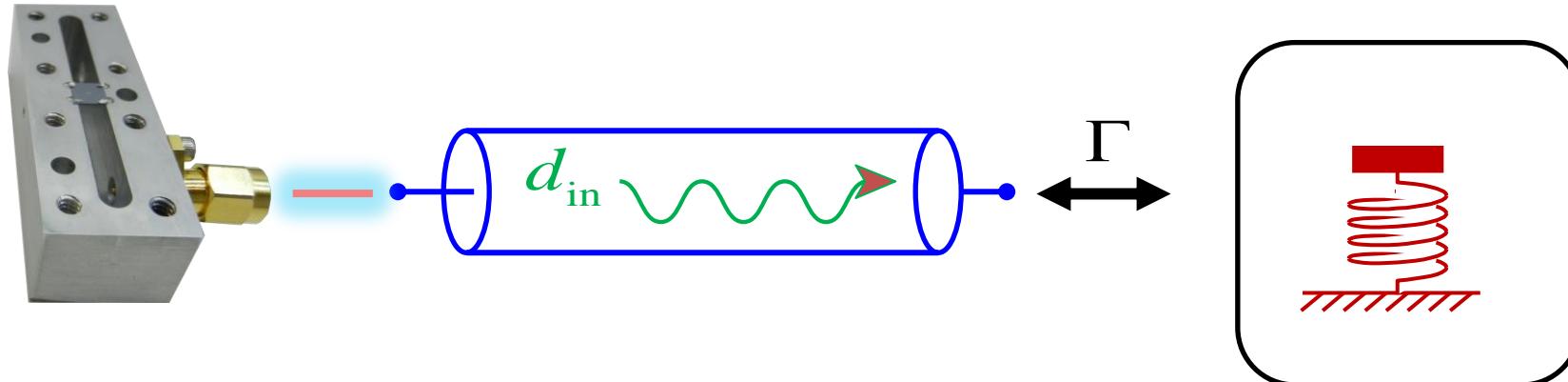
non-classical cavity field using  
qubit non-linearity



B. Vlastakis, ..., R. J. Schoelkopf, *Science*  
2013

M. Hofheinz, ..., J. Martinis and A. N.  
Cleland, *Nature* 2009

# Can a mechanical oscillator capture a non-classical state?

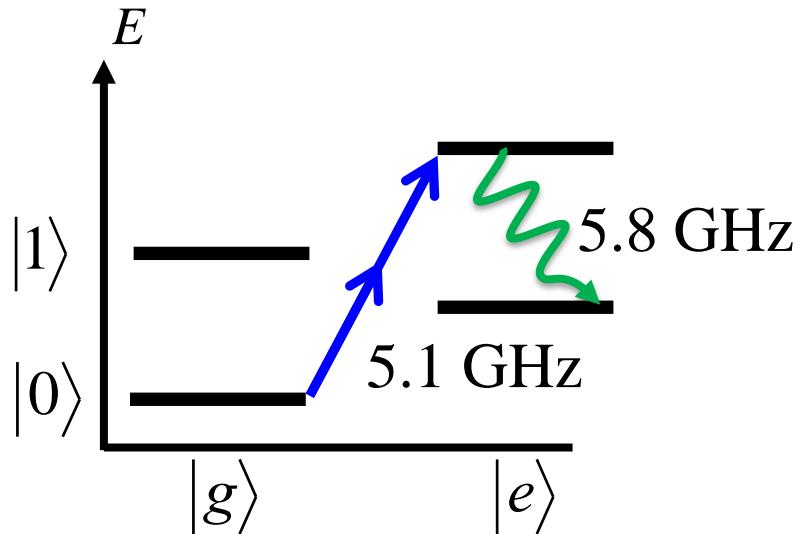
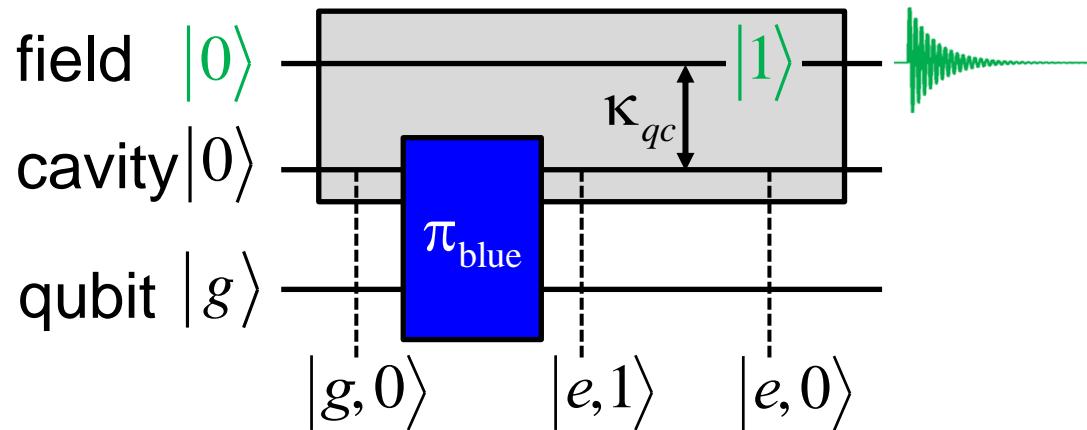
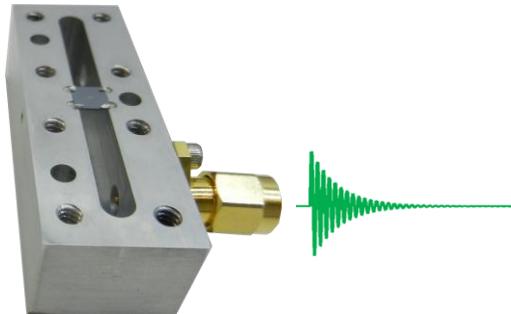


$|1\rangle$        $\longrightarrow$        $|1\rangle$        $\longrightarrow$        $|1\rangle$   
cavity photon      flying photon      phonon

use qubit to access non-Gaussian states of motion

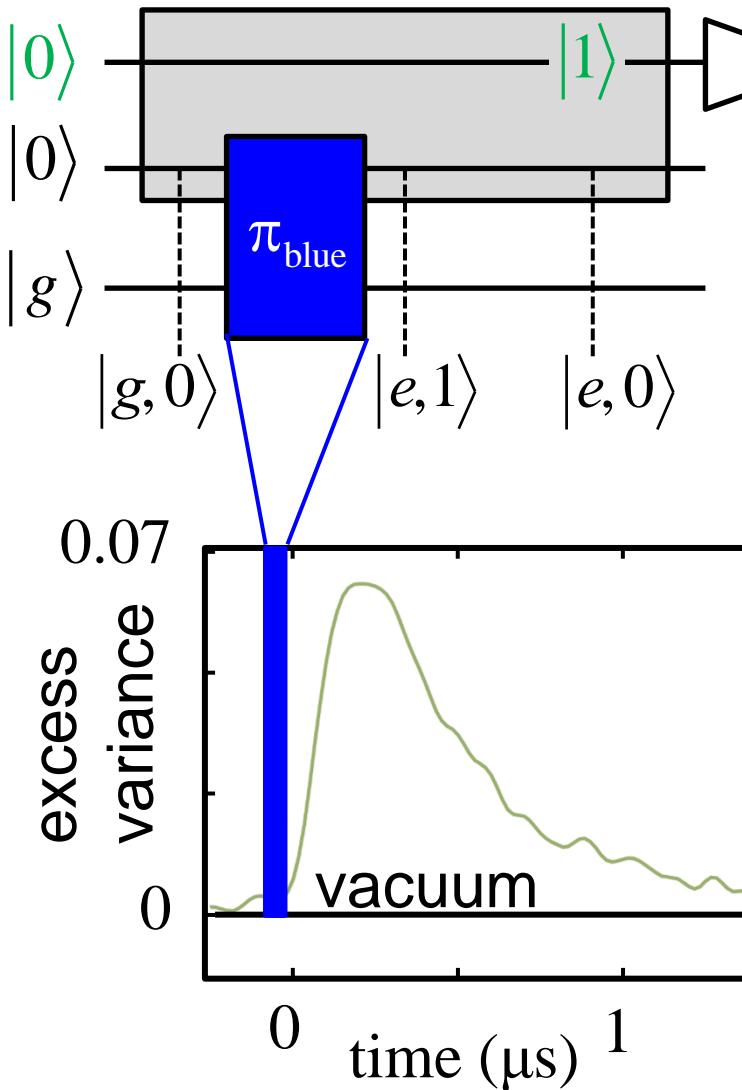
# Creating a non-Gaussian microwave field from a fixed-frequency qubit

$$|e,1\rangle \otimes |0\rangle \Rightarrow |e,0\rangle \otimes |1\rangle$$



single photon pulse  
decaying envelope  
fixed frequency  $\omega_{\text{cav}} = 5.8 \text{ GHz}$   
narrowband ( $B_W \sim 300 \text{ kHz}$ )

# Single-photon generation signal is a decaying exponential pulse



no  $\pi$  pulse: vacuum  $V_0(t)$   
math style="color: green; font-size: 1.5em; vertical-align: middle;"> $V_0(t)$

$\pi$  pulse: one photon  $V_\pi(t)$   
math style="color: green; font-size: 1.5em; vertical-align: middle;"> $V_\pi(t)$

excess variance

$$\frac{\text{Var}(V_\pi(t)) - \text{Var}(V_0(t))}{\text{Var}(V_0(t))}$$

shows temporal envelope

# Single-photon generation signal is a decaying exponential pulse

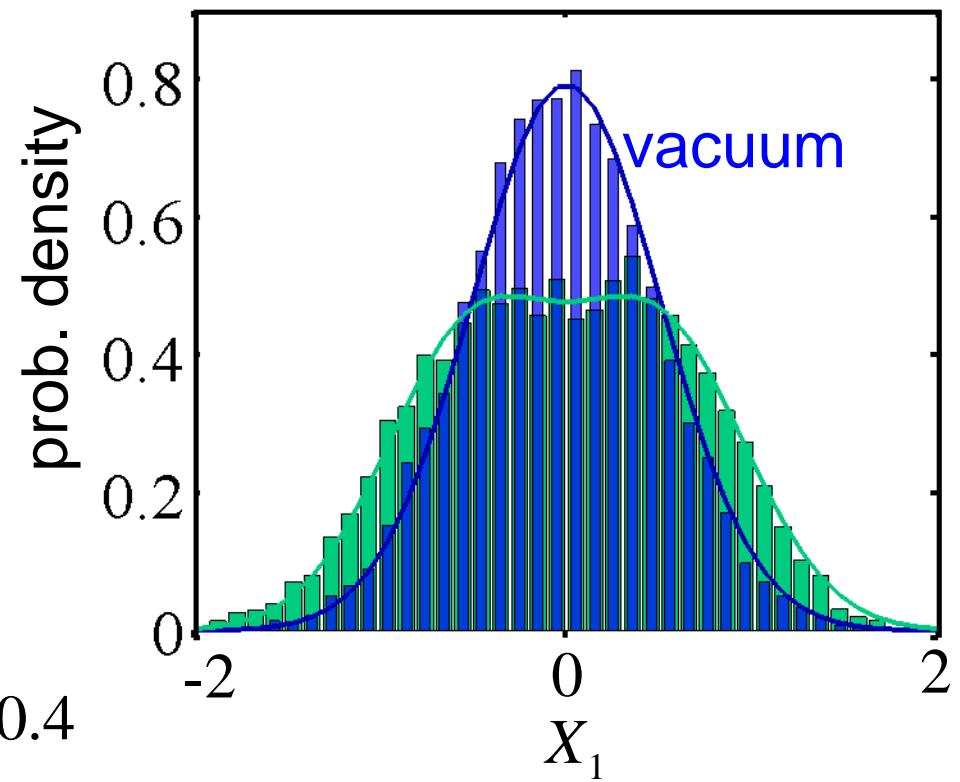
optimally filter to find quadrature

$$X_1 = \int V(t) f(t) \cos(\omega_{\text{cav}} t) dt$$

preparation fidelity  $F > 0.9$

measurement efficiency  $\eta = 0.4$

arxiv:1510.00663



non-Gaussian state  
 $\hat{\rho} = 0.62|0\rangle\langle 0| + 0.36|1\rangle\langle 1|$

# Highest coherence qubit + cavity systems are narrowband with fixed center frequency

## 3D transmon qubit

coherence  $\sim 100 \mu\text{s}$

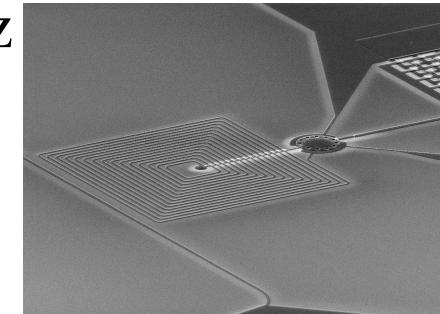
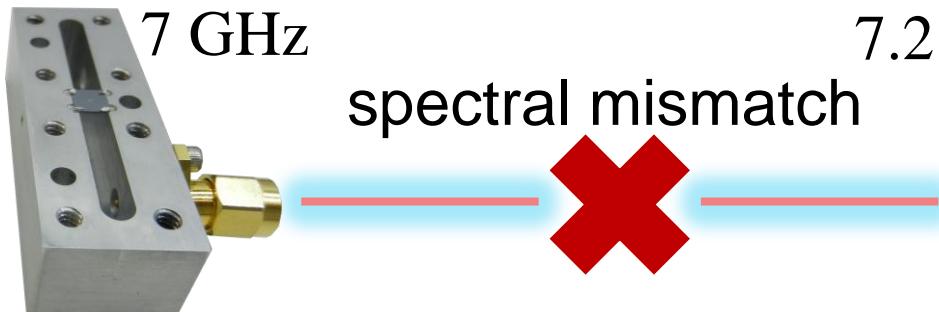
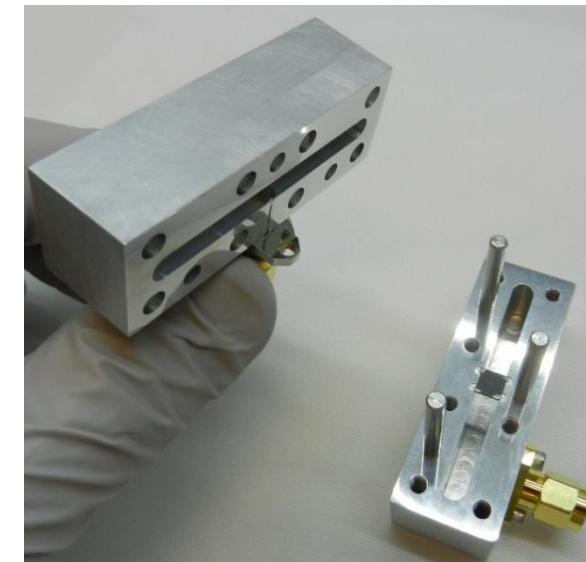
embedded in microwave cavity

## transmon cavity

couples to propagating microwaves

spectrally narrow emission ( $B_W < 1 \text{ MHz}$ )

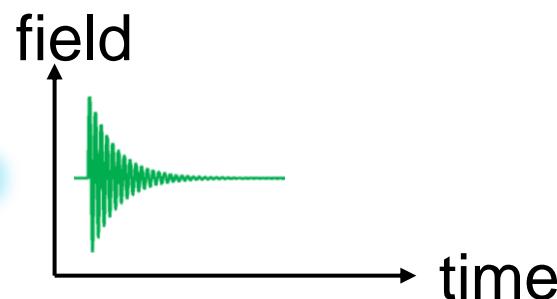
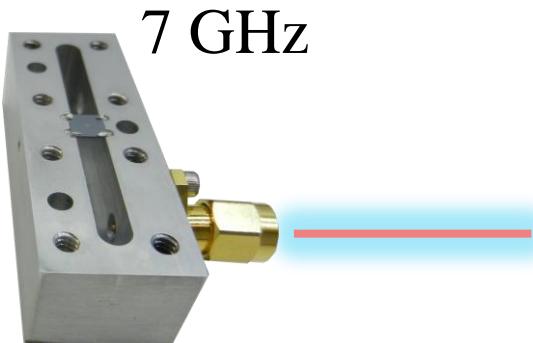
fixed frequency



# Cavities emit and absorb different temporal modes

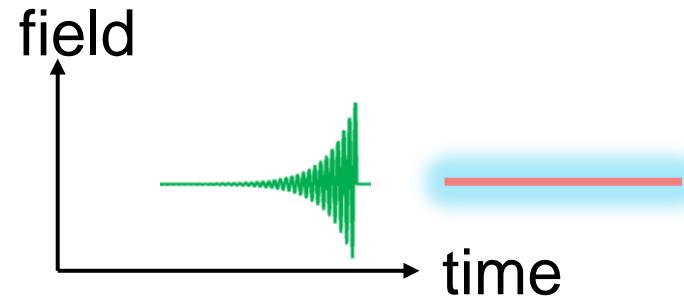
---

temporal mode mismatch

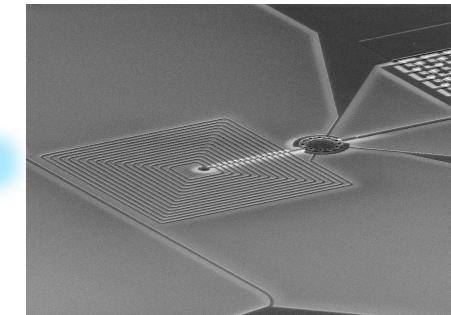


cavities emit decaying exponential pulses

cavities absorb rising exponential pulses

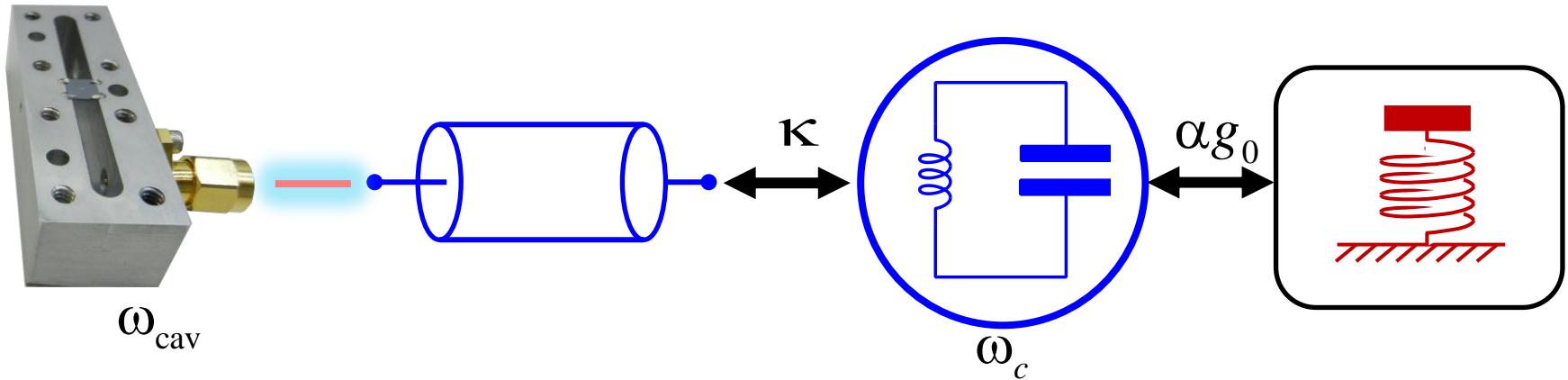


7 GHz



# Overcome mismatches to transfer qubit state to a mechanical oscillator

---



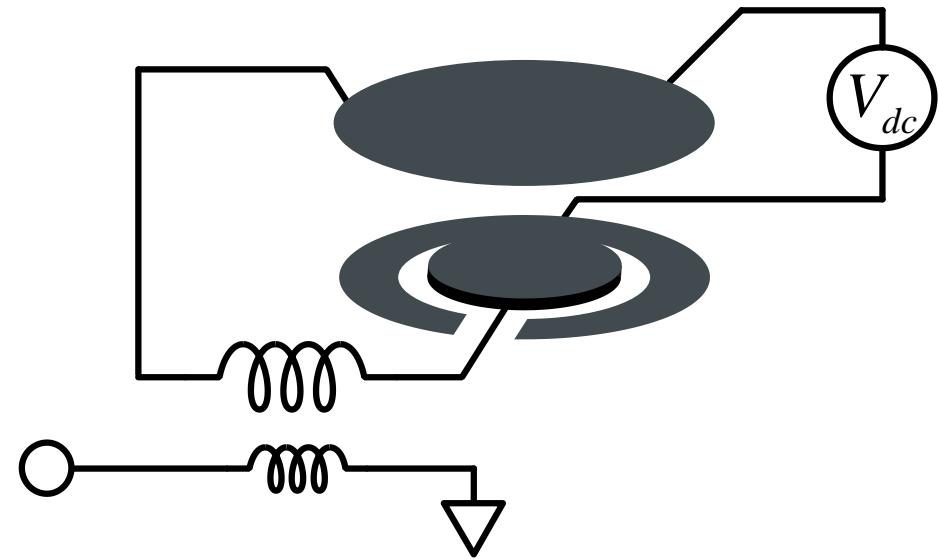
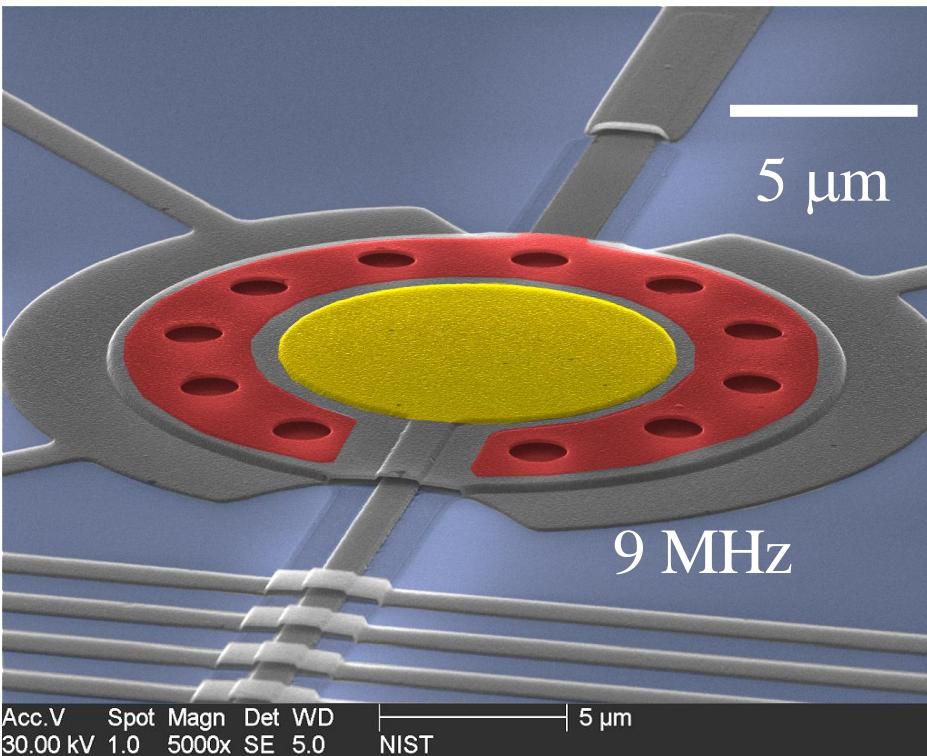
overcome

spectral mode mismatch  $\omega_{\text{cav}} \neq \omega_c$

temporal mode mismatch

# Tunable electromechanics

# Tunable electromechanical capacitor incorporates additional electrode



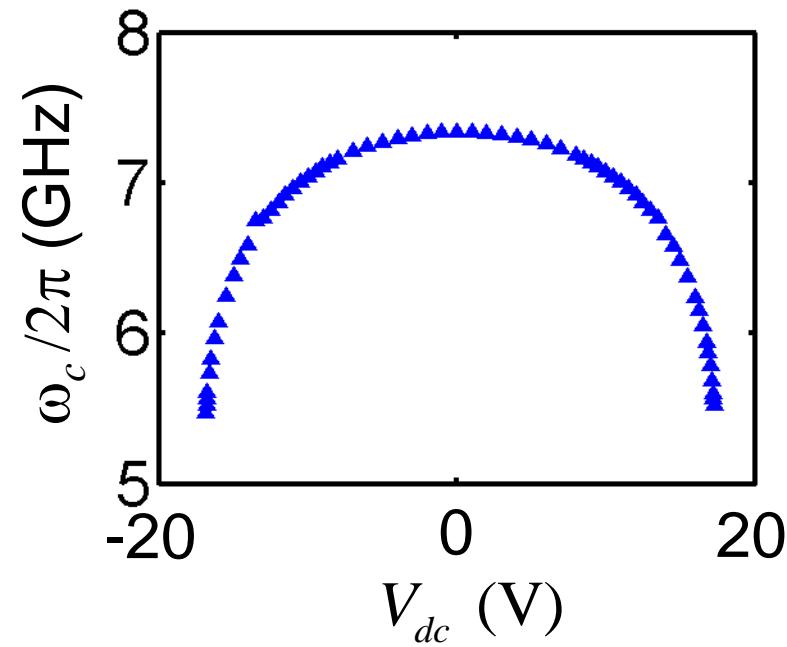
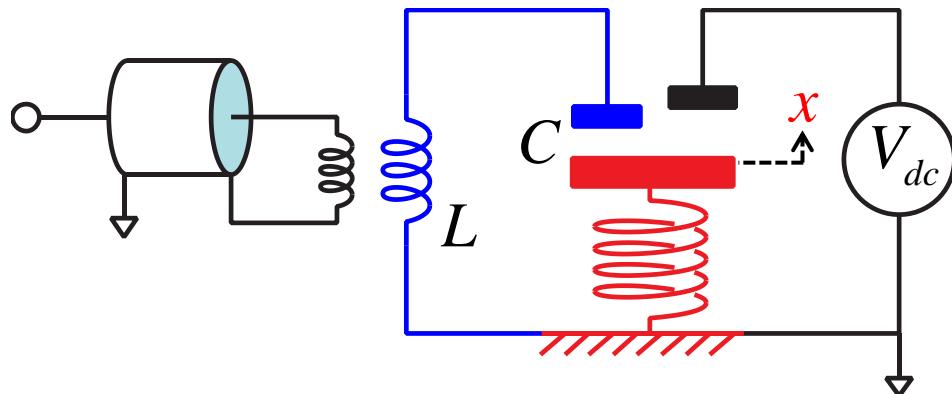
maximum resonance frequencies  $V_{dc} = 0$

$$\omega_m \approx 2\pi \times 9 \text{ MHz}$$

$$\kappa \approx 2\pi \times 2.5 \text{ MHz}$$

$$\omega_c \approx 2\pi \times 7.2 \text{ GHz}$$

# Static voltage tunes resonance frequency of electromechanical circuit



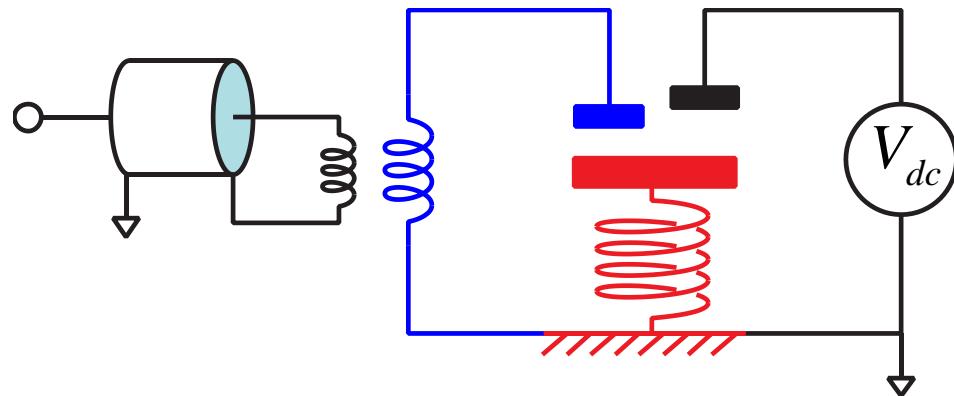
static voltage attracts capacitor plates

$$F = \frac{1}{2} \frac{\partial C}{\partial x} V_{dc}^2$$

dc voltage tuned resonance

$$\bar{x}[V_{dc}] \rightarrow \omega_c[V_{dc}]$$

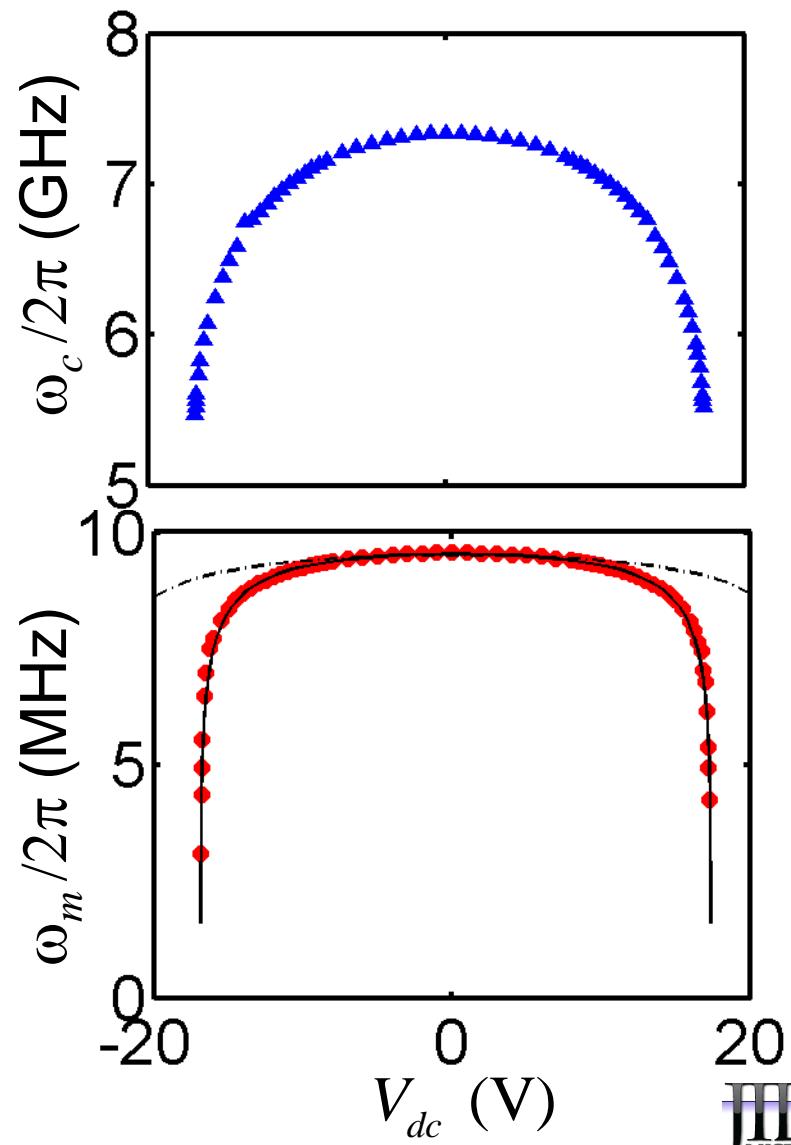
# Tuning range limited by attraction between capacitor plates



collapse not from  $V_{dc}$

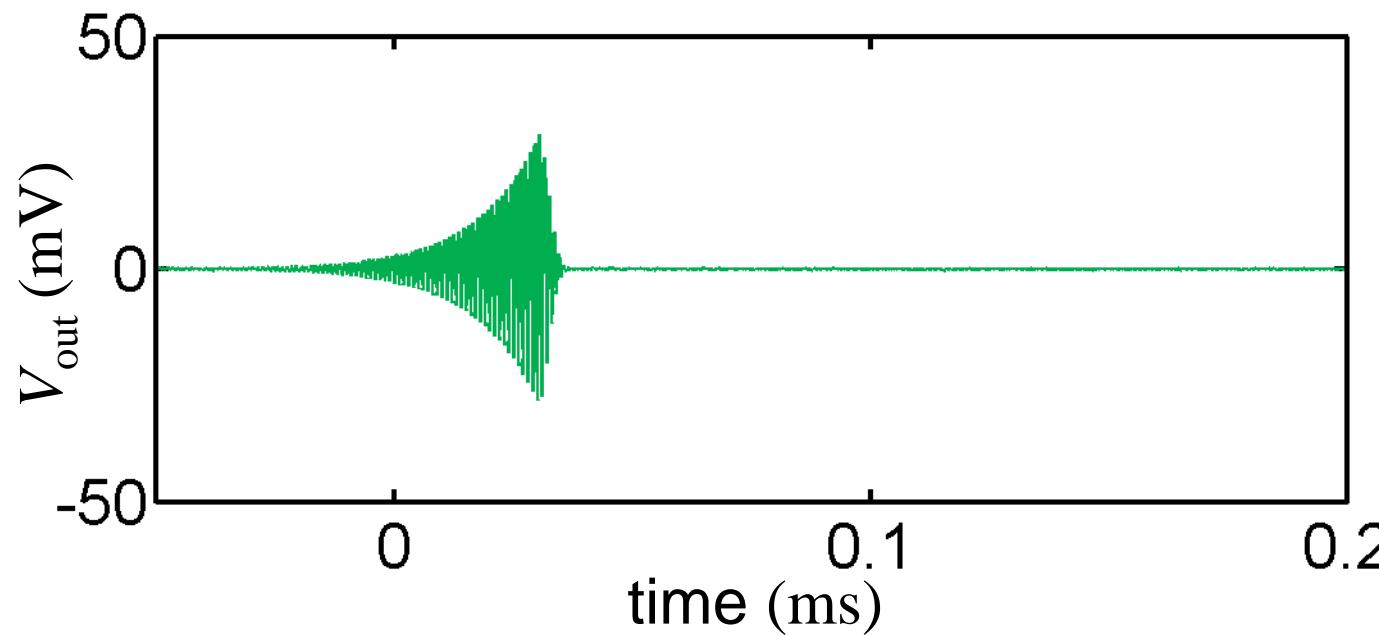
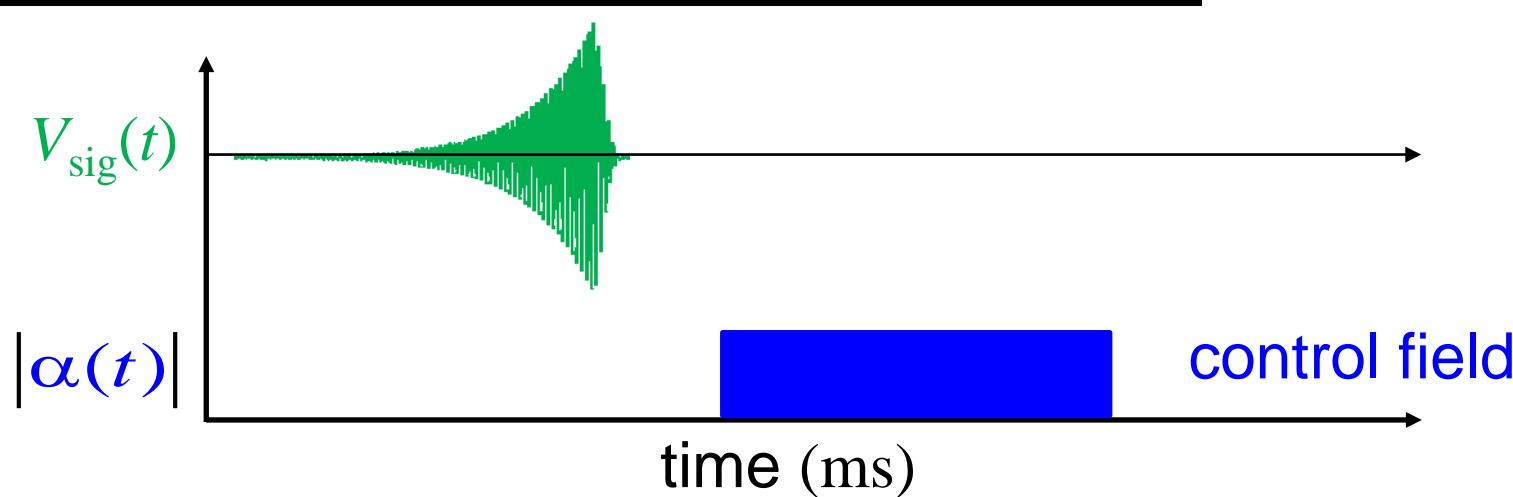
recessed dc electrode

Casimir force

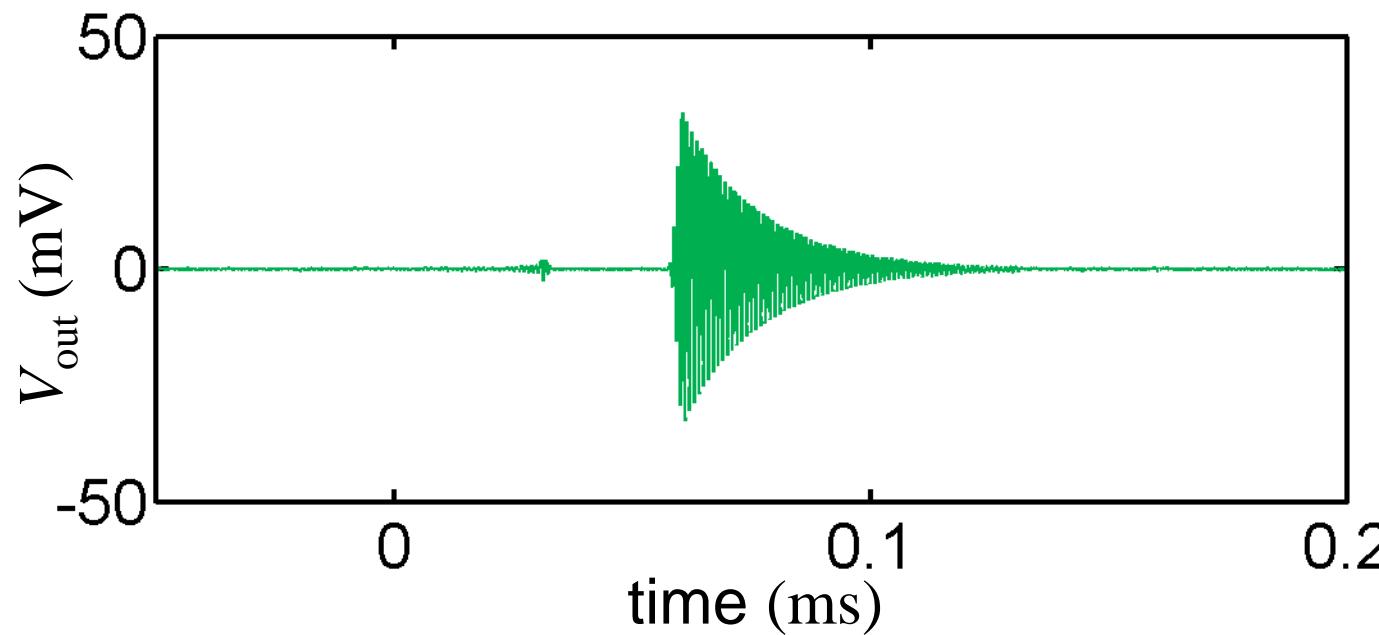
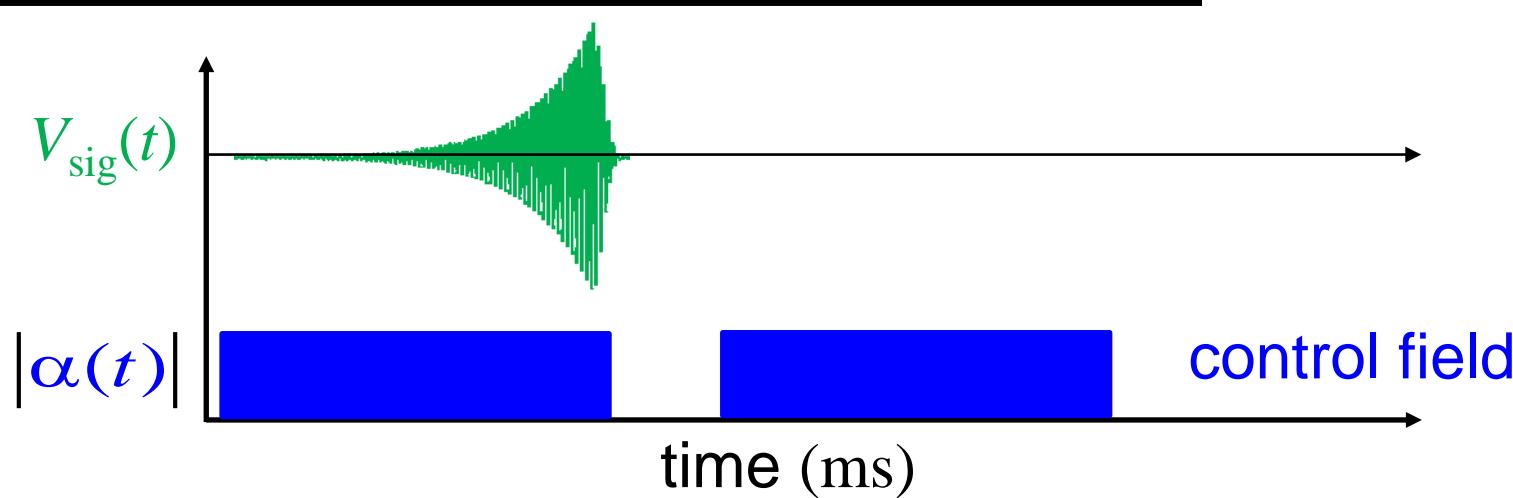


# Temporal mode matching

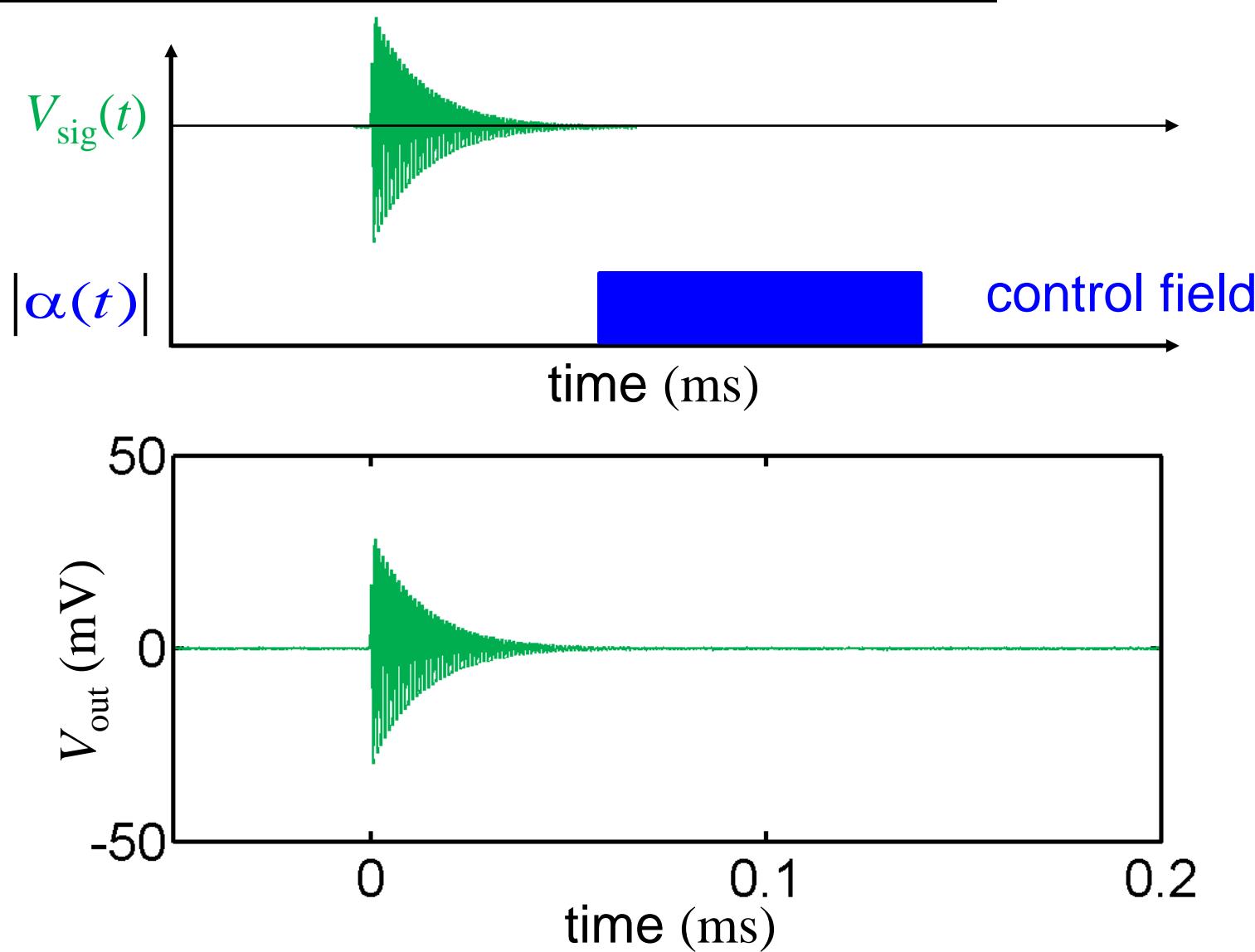
# Rising exponential captured with highest efficiency



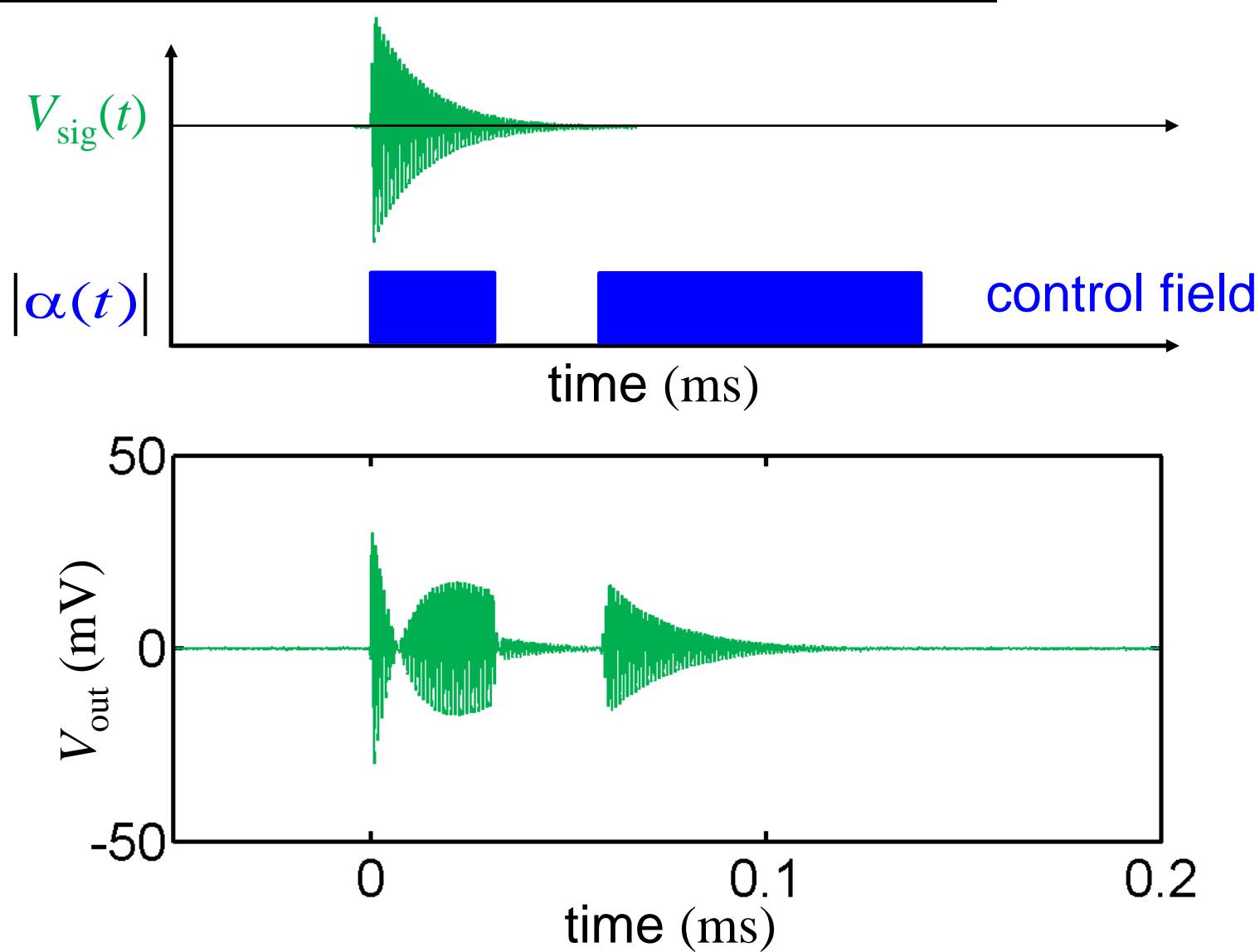
# Rising exponential captured with highest efficiency



# Decaying exponential pulse mismatched to electromechanical circuit

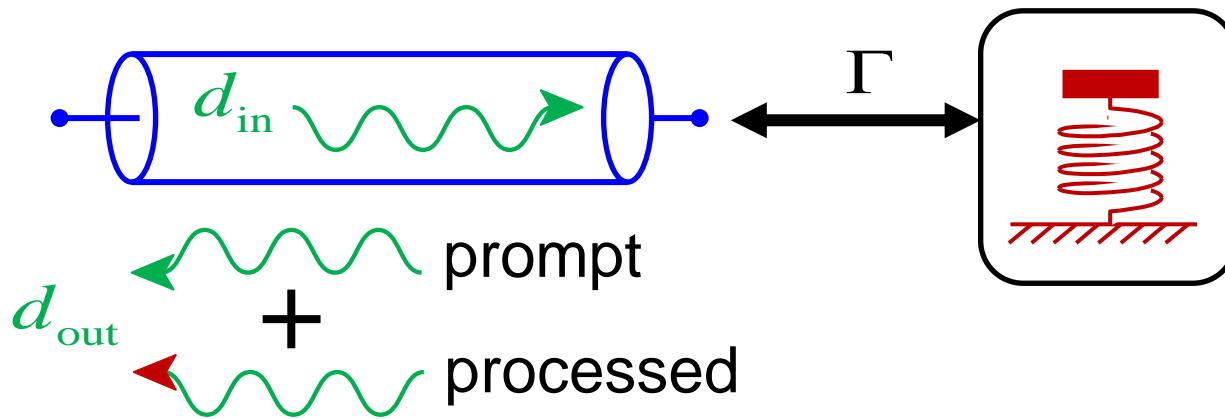


# Decaying exponential pulse mismatched to electromechanical circuit



# Vary electromechanical coupling to temporally mode match

matching  $\rightarrow \langle d_{\text{out}} \rangle = 0$



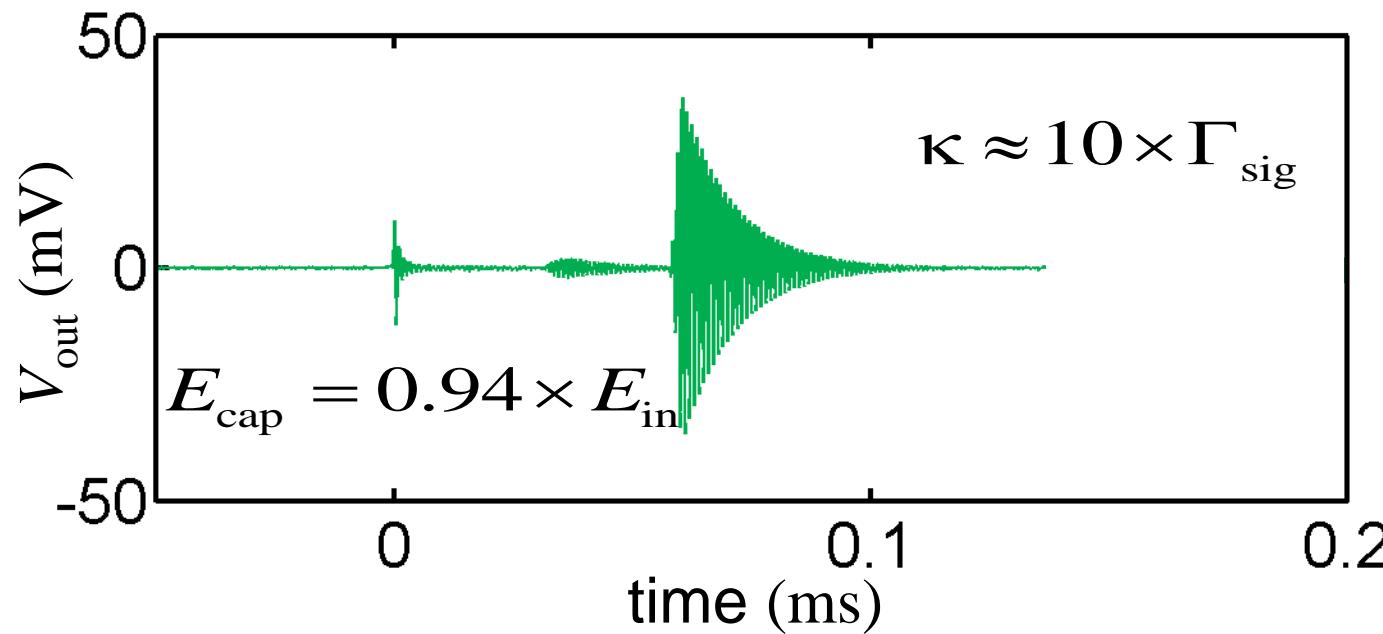
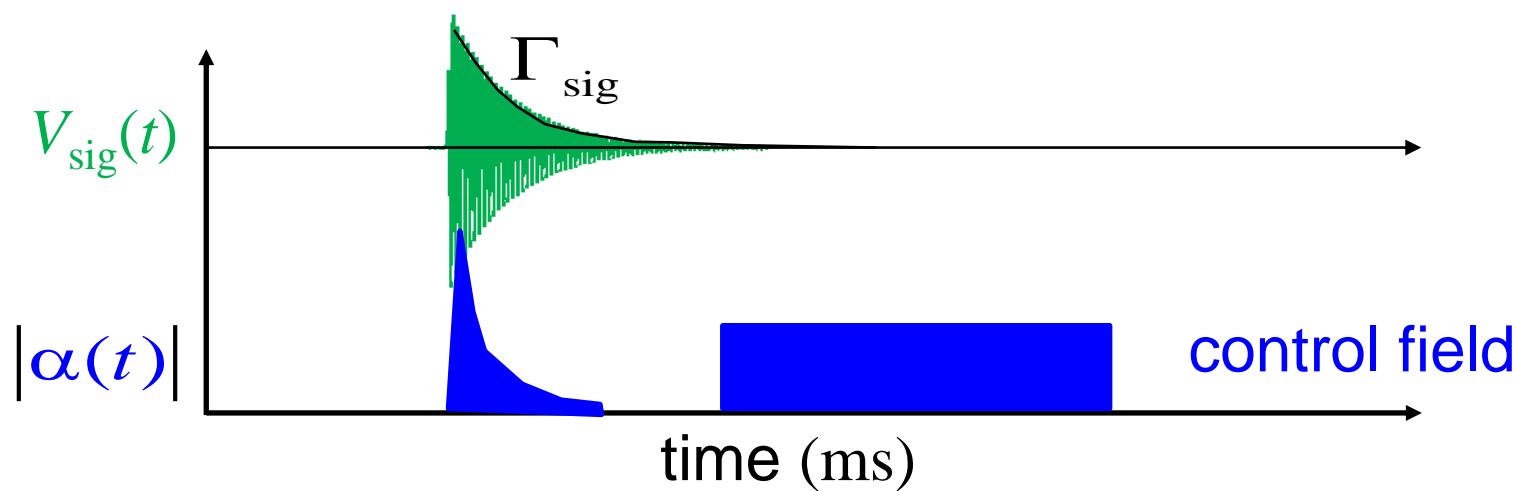
$$d_{\text{out}}(t) = -d_{\text{in}}(t) + \sqrt{\Gamma(t)} b(t)$$

$$\Gamma(t) = \frac{[2\alpha(t)g_0]^2}{\kappa}$$

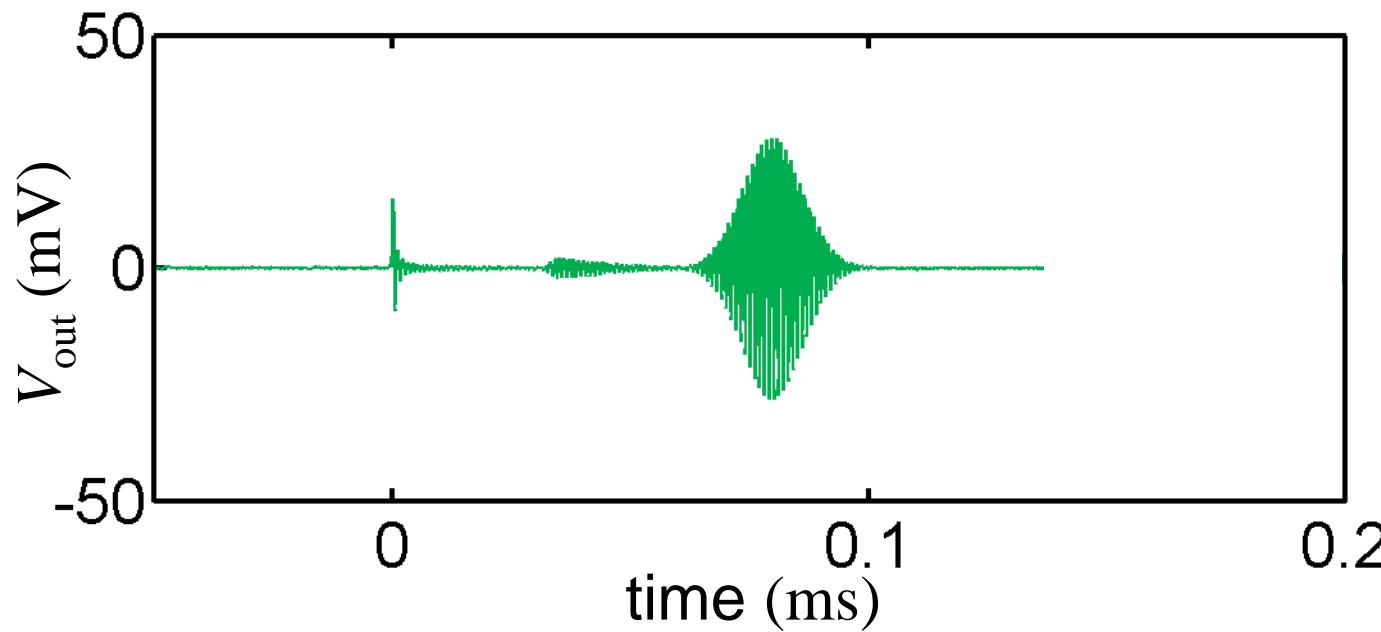
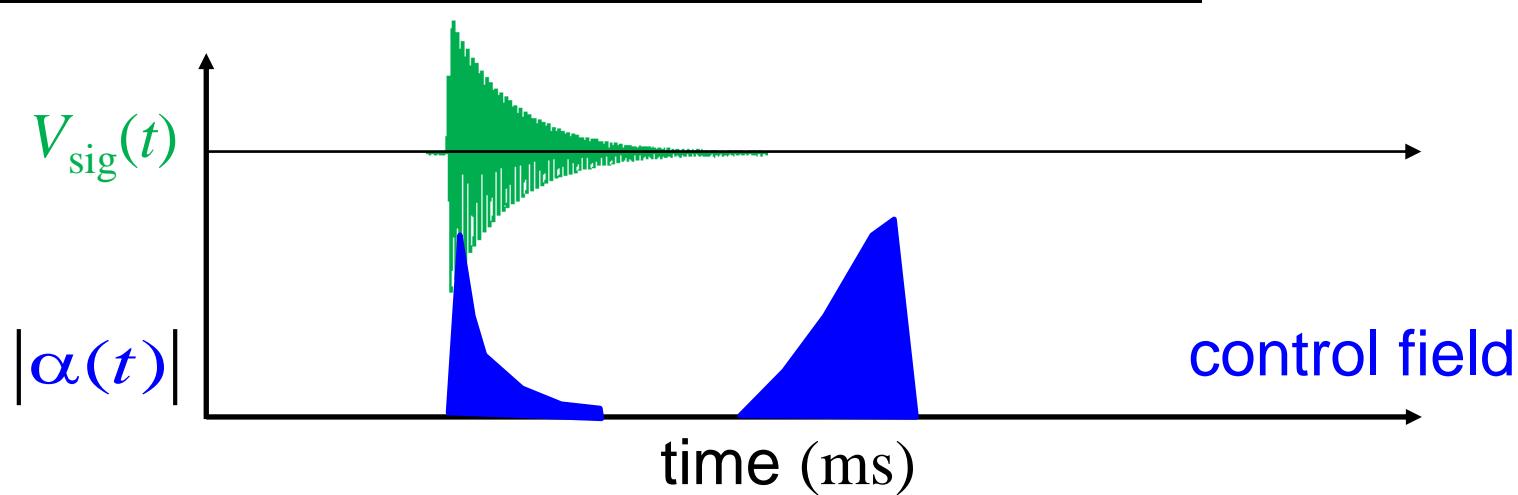
$$\frac{db}{dt} = \sqrt{\Gamma(t)} d_{\text{in}}(t) - \frac{\Gamma}{2} b(t)$$

$$\Gamma_{\text{max}} = \frac{\kappa}{2}$$

# Capture 94% of the incident energy with a time varying control field



# Shape output pulse using time varying control field

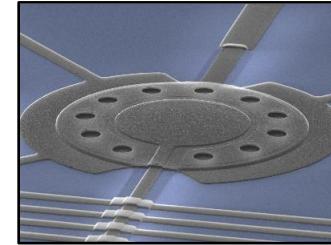


Dense sound?

# Phonon-phonon nonlinearity through qubit interaction

---

weak but adjustable phonon-qubit coupling  
linear quantum acoustics with single phonons  
e.g. boson sampling

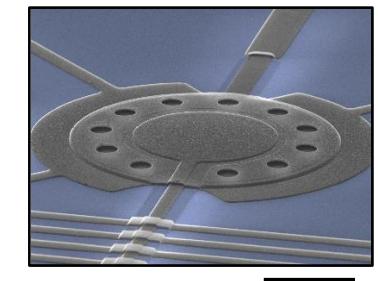
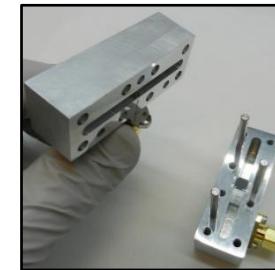


very strong qubit-phonon coupling:  
strong phonon-phonon cross Kerr interaction  
condensed matter physics with sound

# Slow sound speed makes practically small multimode systems

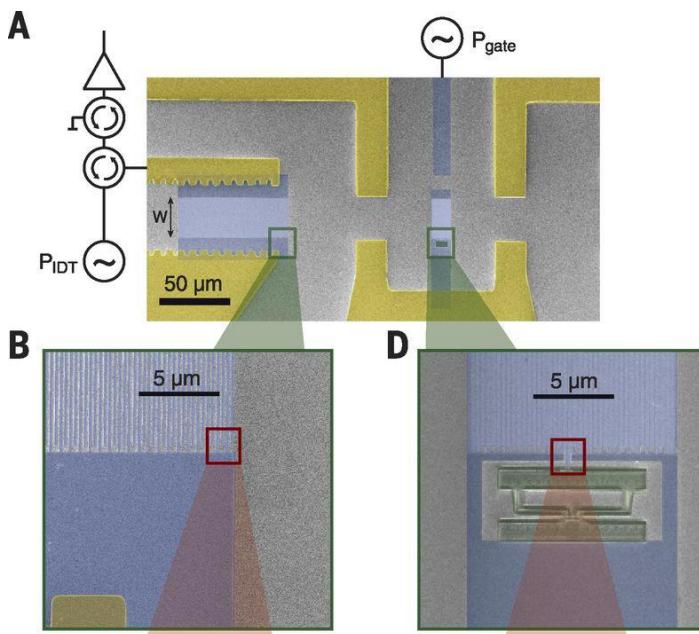
microwave frequency photon  $\sim 1$  cm

microwave frequency phonon  $\sim 1 \mu\text{m}$



$5 \mu\text{m}$

quantum SAW device

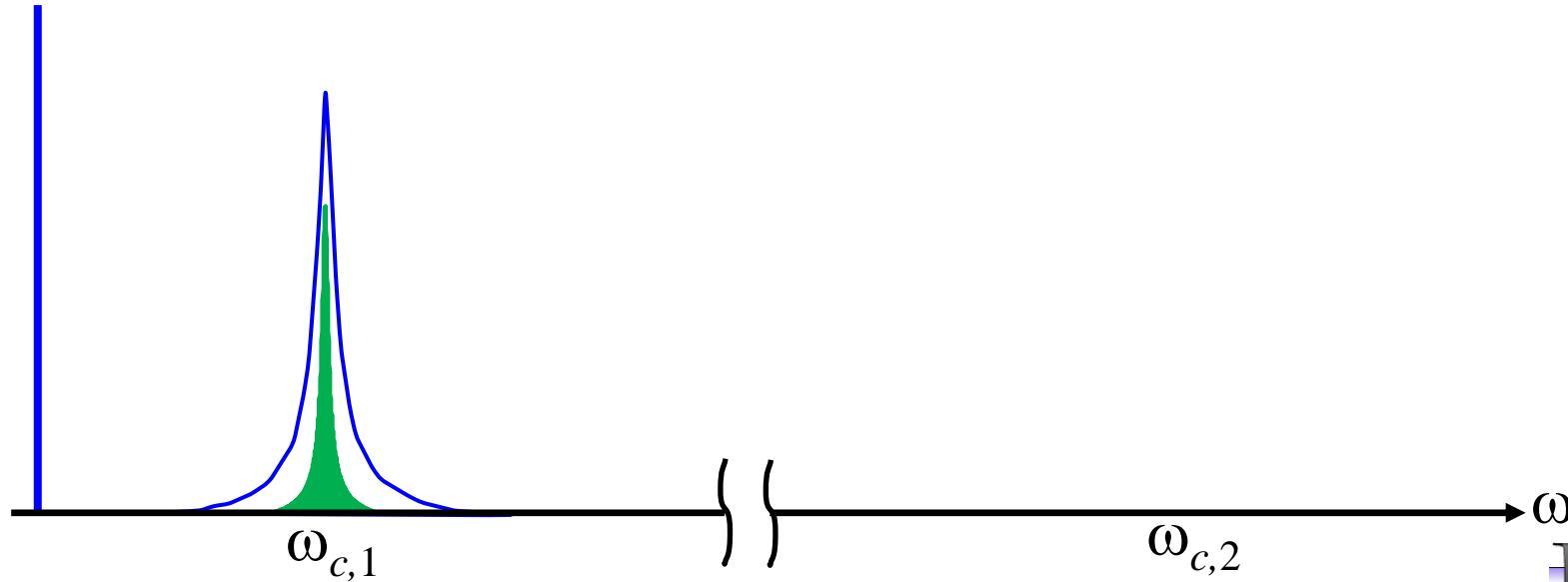
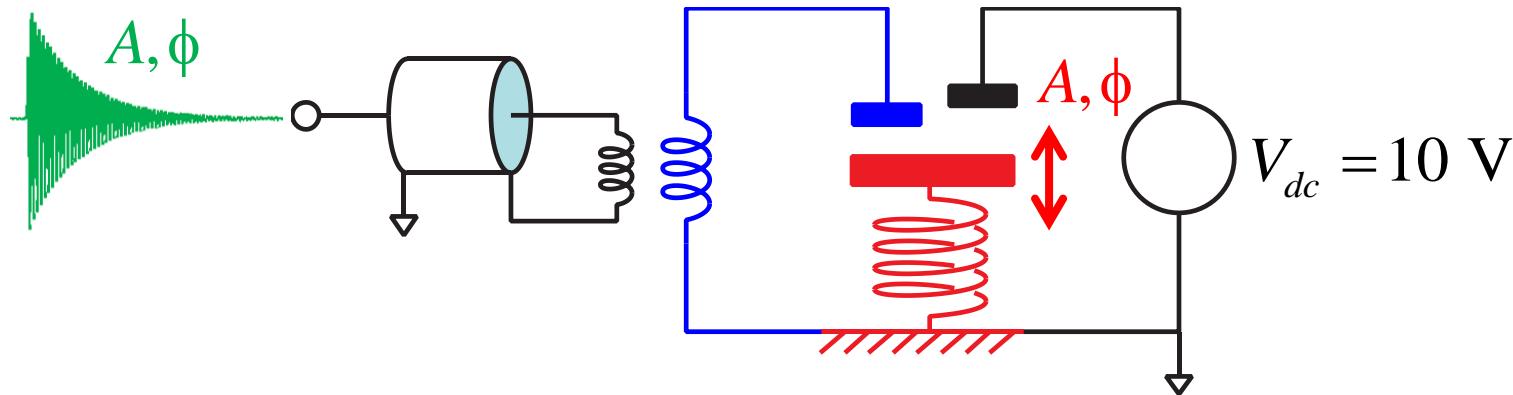


strong qubit-phonon coupling via piezo-electricity

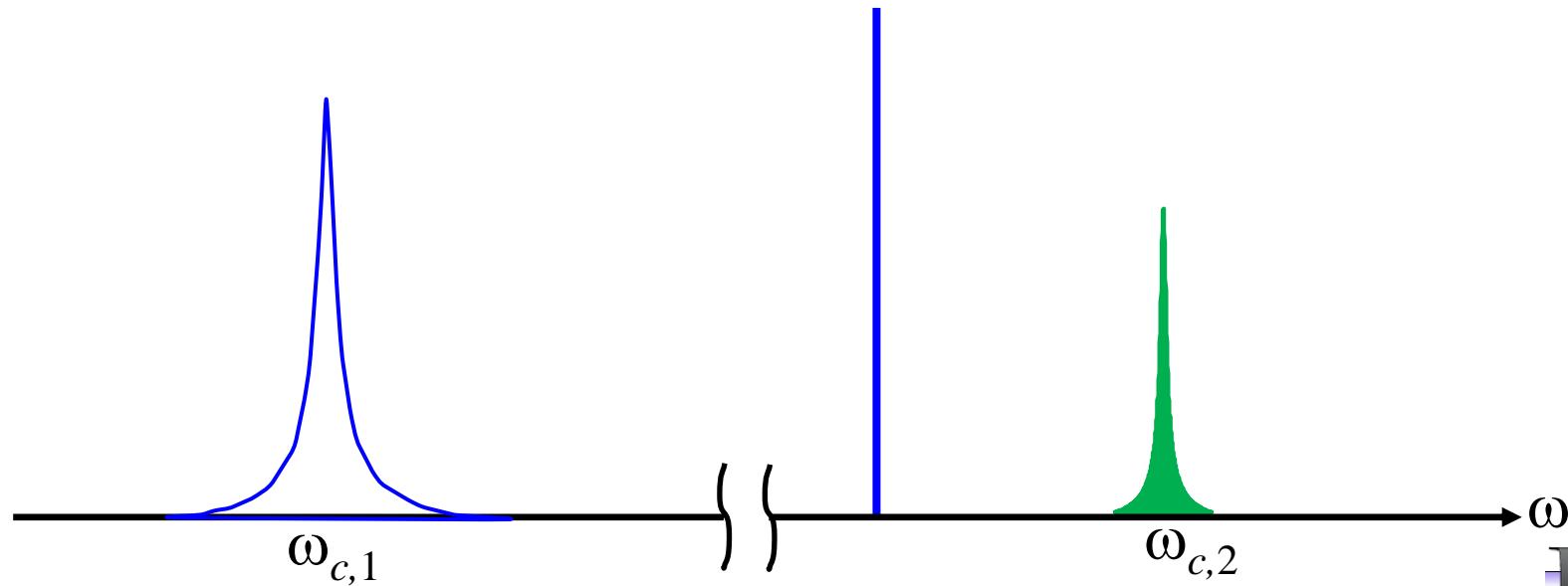
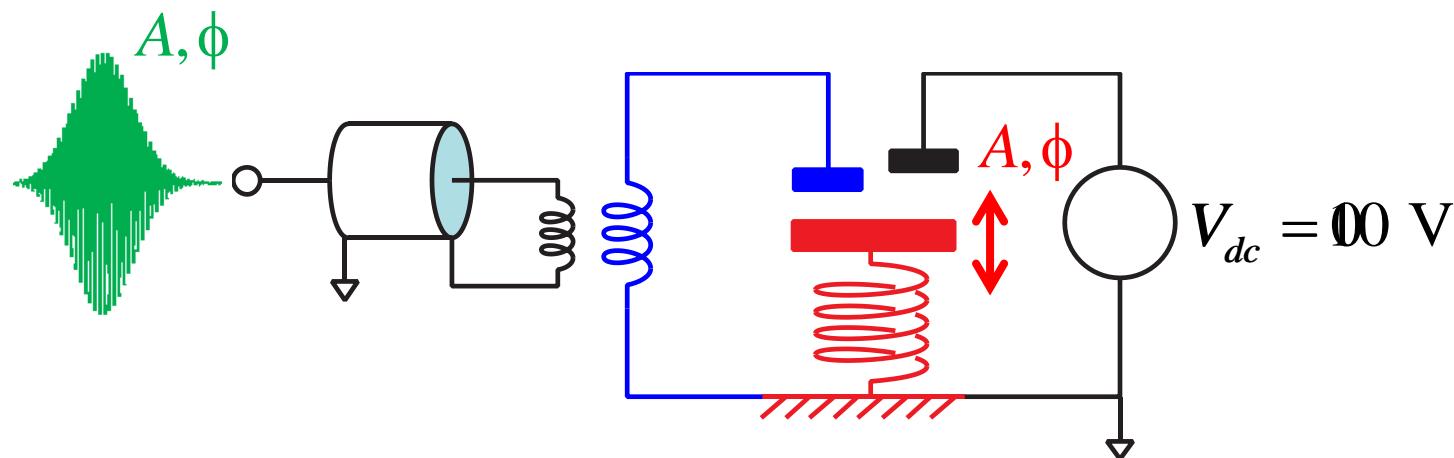
Martin V. Gustafsson, Per Delsing, et al.,  
*Science*, **346**, 207-211

# Dynamic signal processing

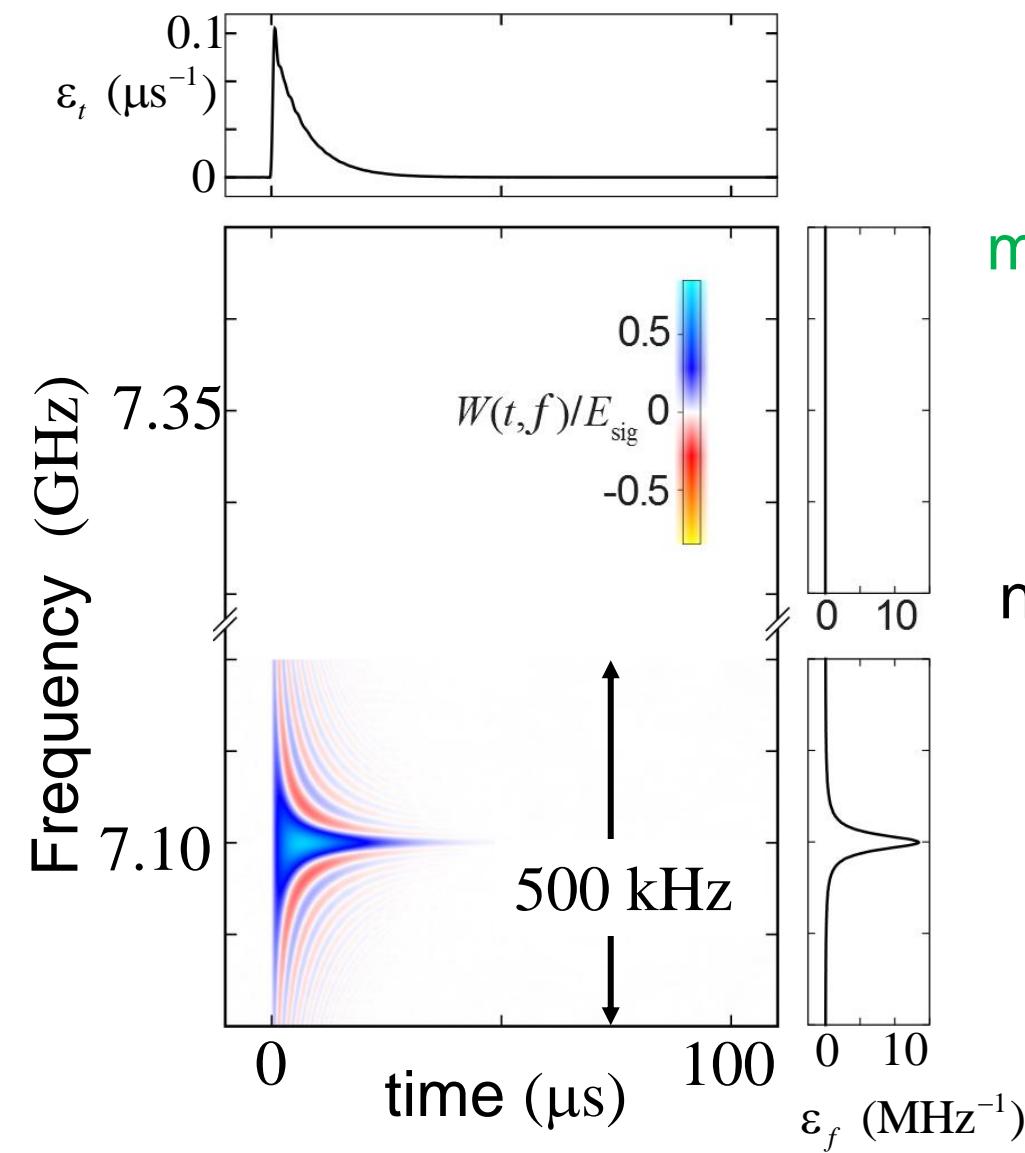
# Frequency tuning allows capture of lower frequency microwave signals



# Sudden change of control voltage performs frequency conversion



# Wigner-Ville plot of temporal mode and dynamic frequency conversion

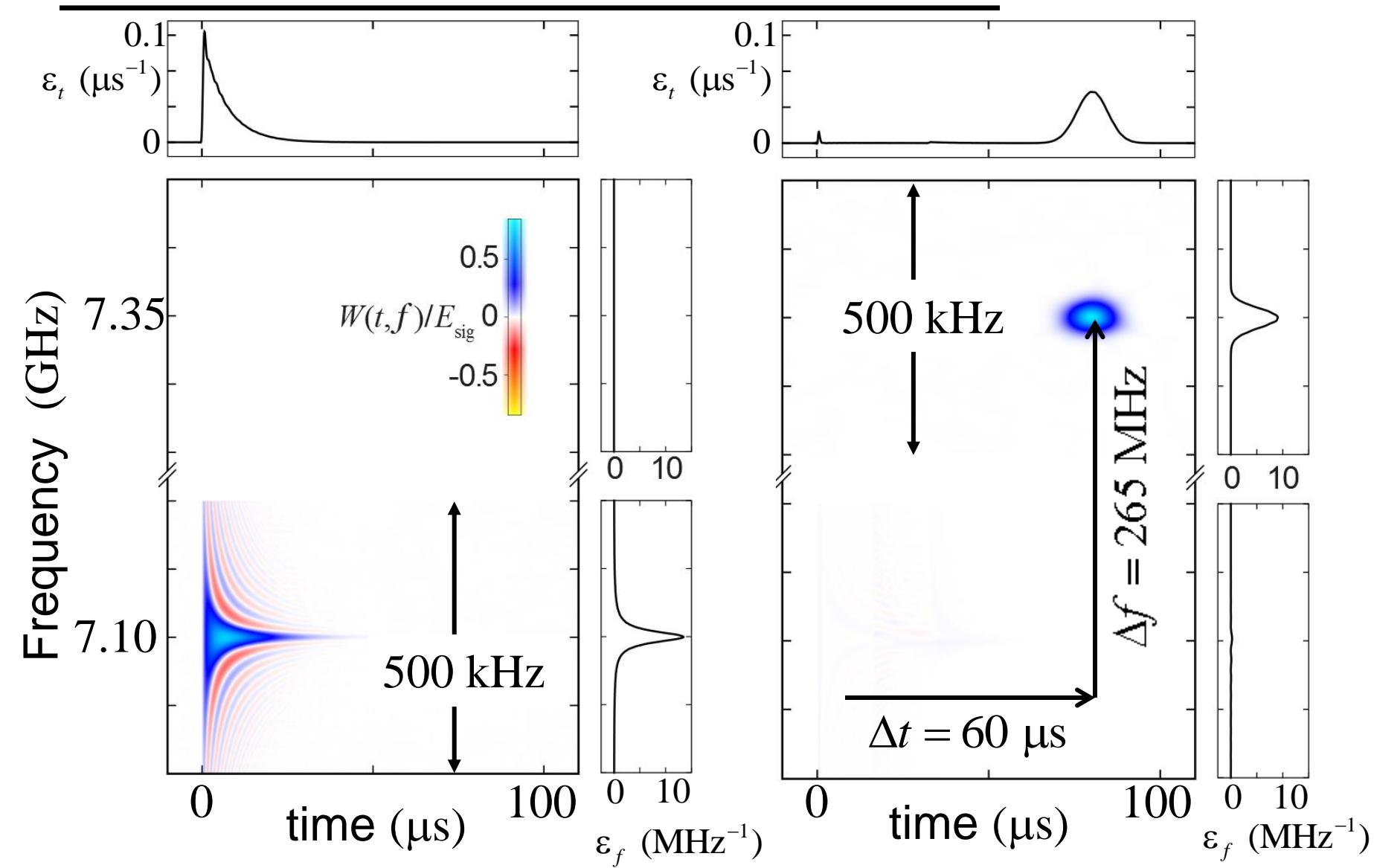


marginals

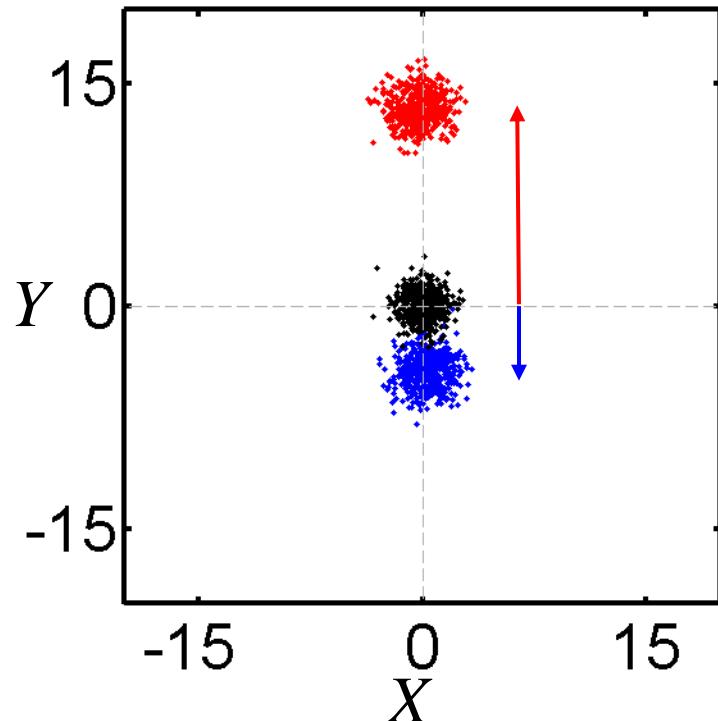
frequency: power spectrum  
time: temporal envelope

no control fields: no conversion

# Wigner-Ville plot of temporal mode and dynamic frequency conversion



# Mode conversion in the quantum regime and with large dynamic range



phase-space densities

vacuum reference

10 quanta coherent state

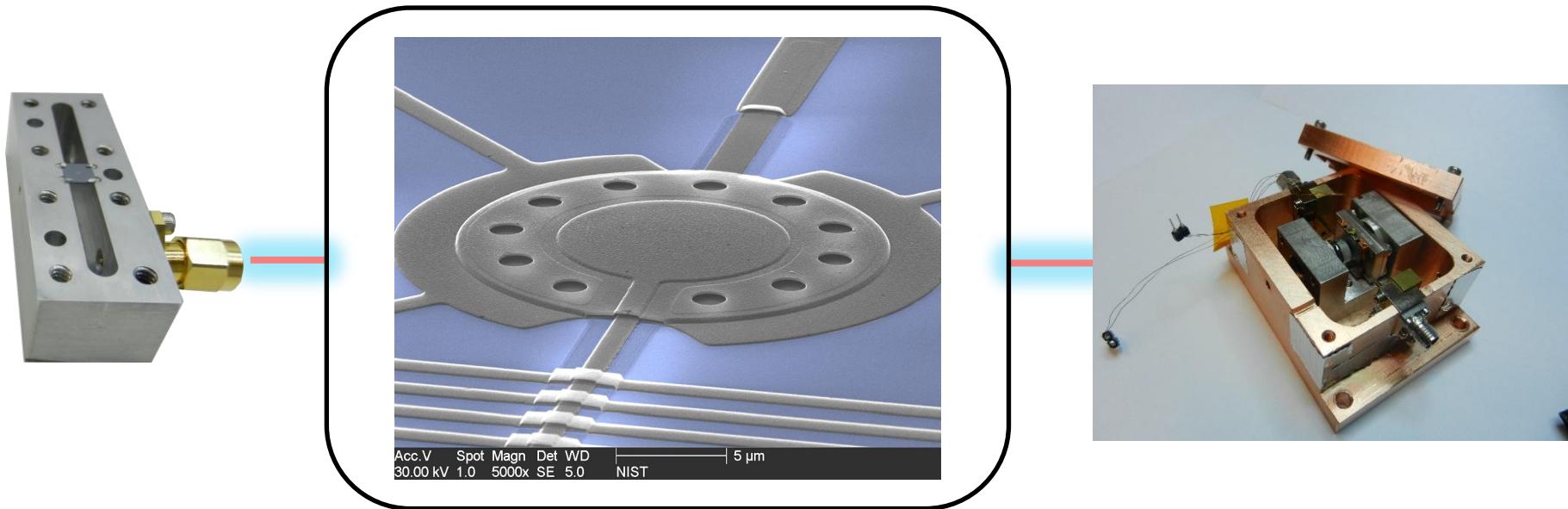
140 quanta coherent state

temporal and spectral mode conversion:

added noise < one quantum

arXiv:1506.02296 R. W. Andrews, A. P. Reed, K. Cicak, J. D. Teufel, K. W. Lehnert

# Electromechanical structures enable coupling of qubits to quantum-regime electro-optical convertors



“Bidirectional and efficient conversion between microwave and optical light” R. W. Andrews, C. A. Regal, KWL, et al., *Nature Physics* **10**, 321–326 (2014).

# Conclusions

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single electromechanical device

tunable memory

temporal mode-shaping

dynamic frequency conversion

high dynamic range signal processor

single photon sensitivity

million photon linearity

designed to couple transmon qubit-cavity systems

to electro-optomechanical convertors

to each other

# Acknowledgements

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## NIST Boulder



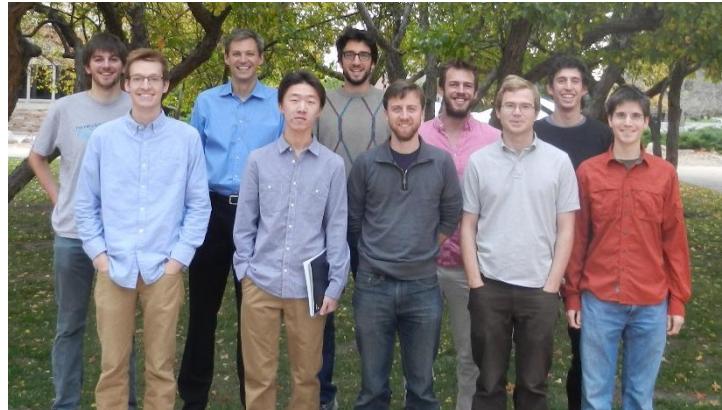
John  
Teufel



Ray  
Simmonds

Reed Andrews  
[Adam Reed](#)  
Ben Chapman  
Jeremie Viennot  
Lucas Sletten

## Lehnert Lab



Jen Harlow  
(S. Africa)



Tauno Palomaki  
(U. Washington)

Dan Palken  
Maxime Malnou  
Brad Moores  
Eric Rosenthal  
Juan Montoya

[Will Kindel](#)  
Pete Burns  
XiZheng Ma  
Tim Menke  
Andrew Higginbotham



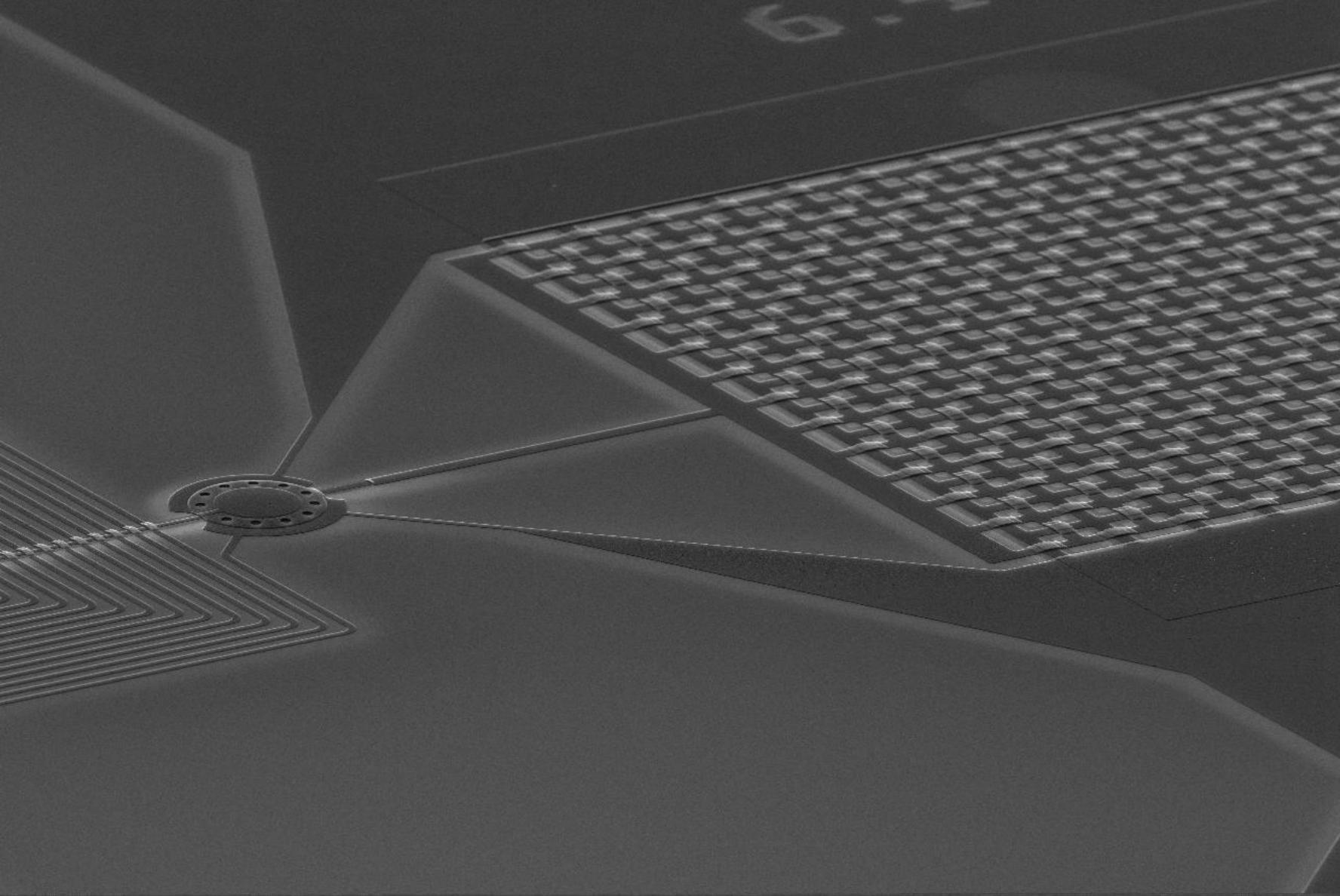
GORDON AND BETTY  
**MOORE**  
FOUNDATION

**NIST**



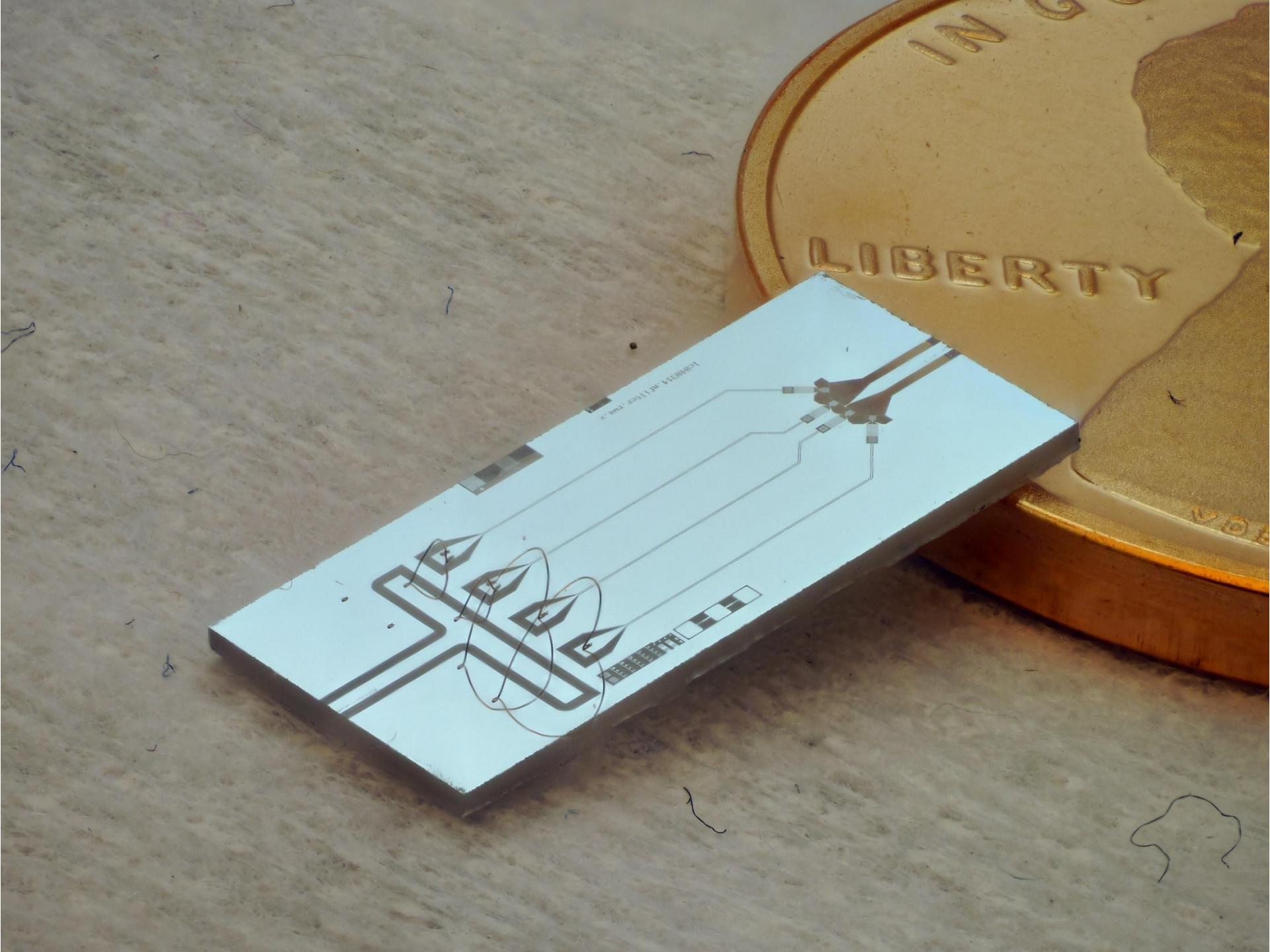
**HEISING - SIMONS**  
FOUNDATION

6.4 GHz



Acc.V Spot Magn Det WD  
30.00 kV 1.0 650x SE 4.7

20 μm  
NIST



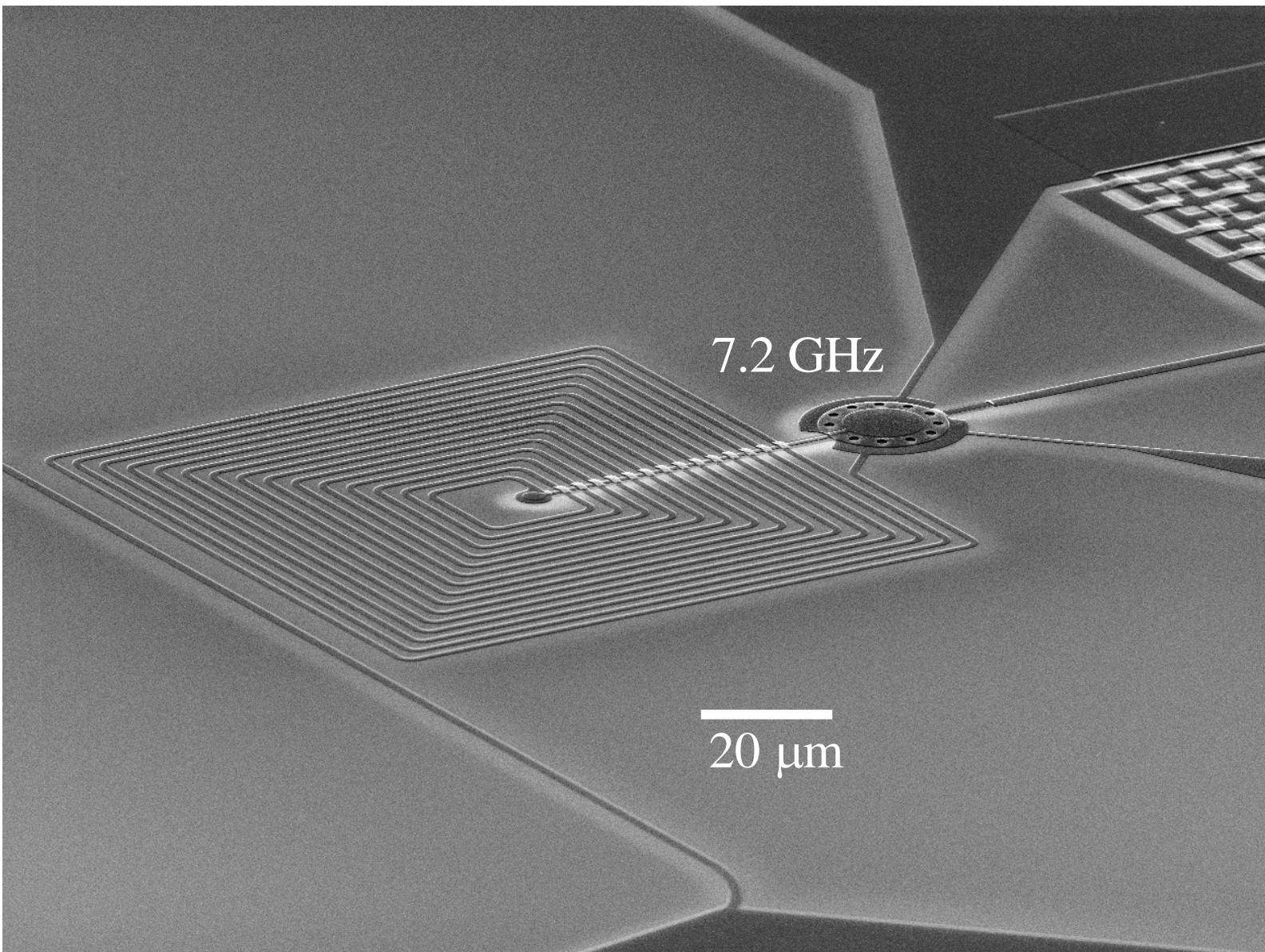
LIBERTY

LIBERTY LIBERTY LIBERTY

IN GOD WE TRUST

# Tunable electromechanical device

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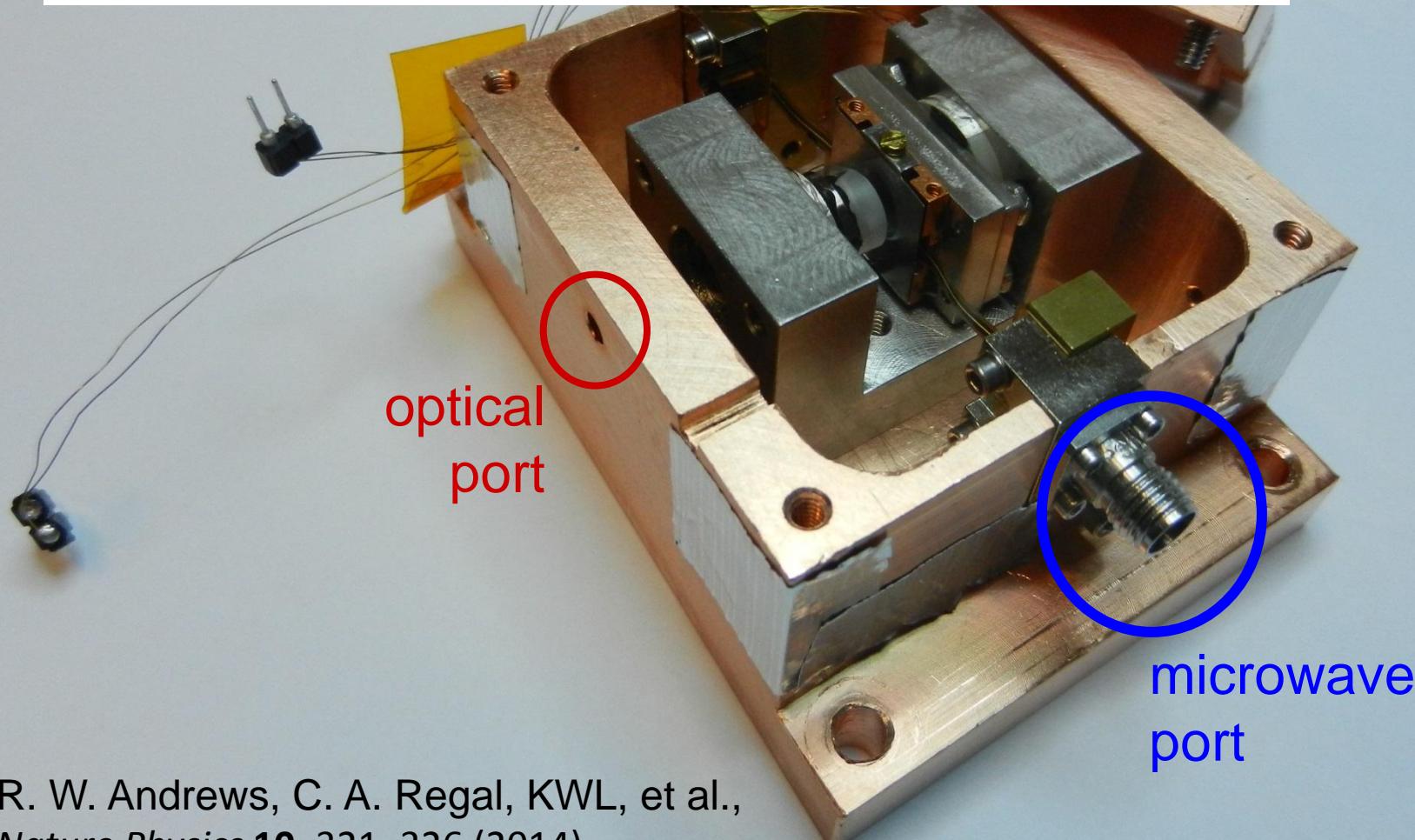


# Electro-optic convertor (version 1)

mechanical electro-optic converters:

narrowband ( $\sim 100$  kHz)

fixed frequency predictable within 50 MHz



R. W. Andrews, C. A. Regal, KWL, et al.,  
*Nature Physics* **10**, 321–326 (2014).