Universität Konstanz

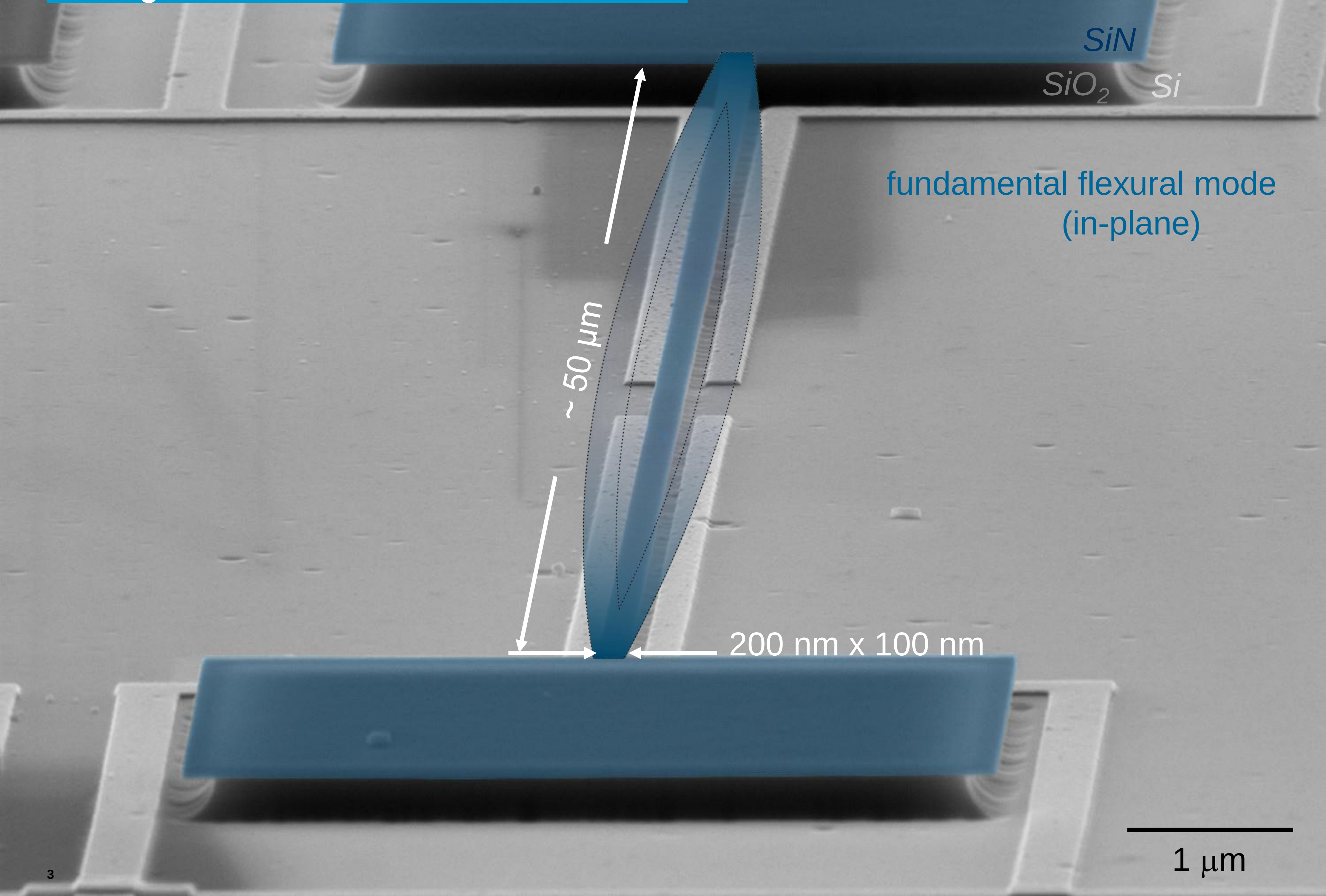
Stückelberg interferometry with a classical nanomechanical two-mode system

Eva Weig

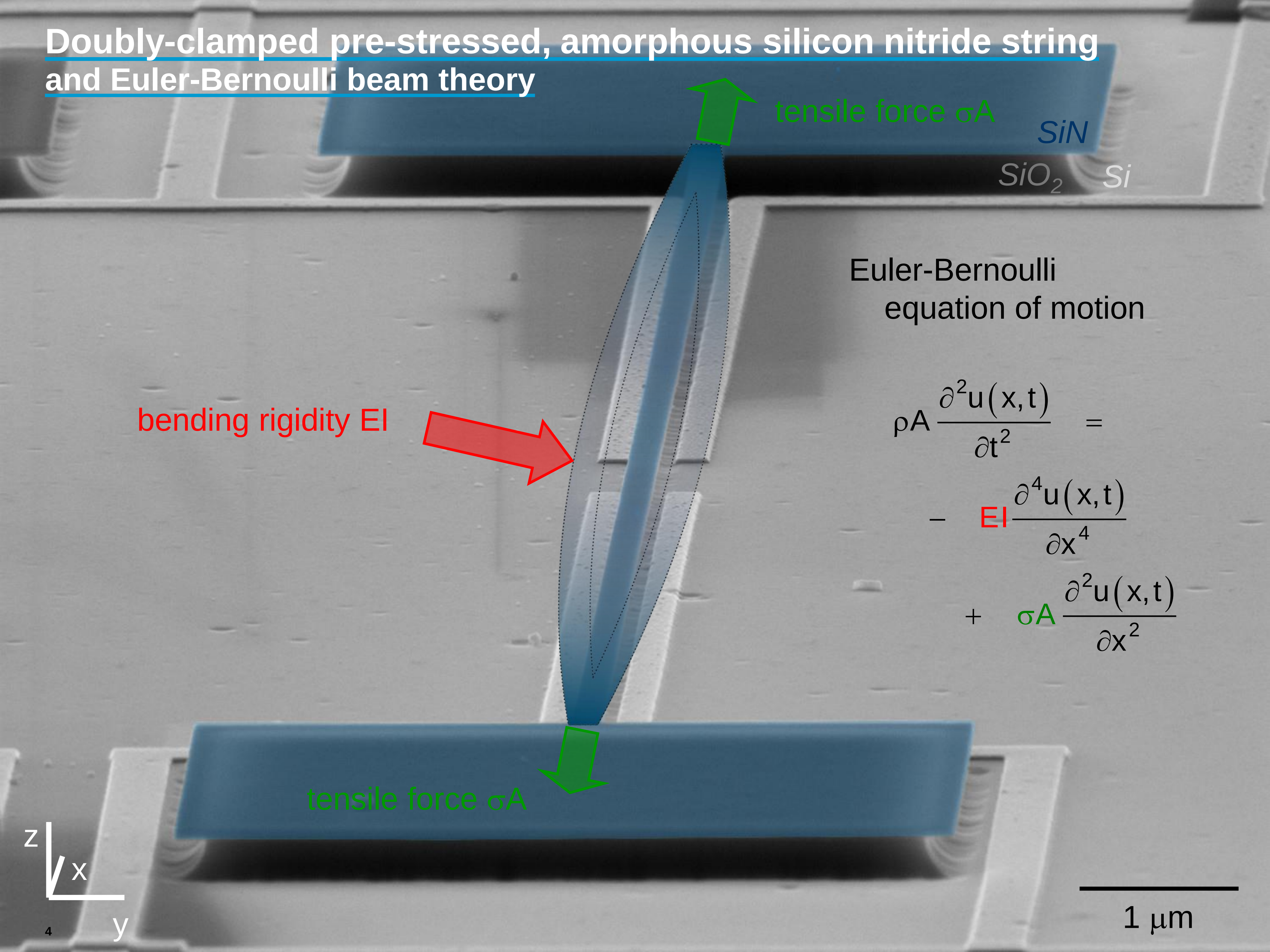
Quantum Interfaces with Nano-opto-electro-mechanical devices: Applications and Fundamental Physics
Ettore Majorana Foundation and Center for Scientific Culture, Erice, 2.8.2016

Classical coherence
Interference of water waves

Doubly-clamped pre-stressed, amorphous silicon nitride string as Megahertz nanomechanical resonator



Doubly-clamped pre-stressed, amorphous silicon nitride string and Euler-Bernoulli beam theory



Euler-Bernoulli equation of motion

$$\rho A \frac{\partial^2 u(x,t)}{\partial t^2} = -\,\color{red}{EI}\,\frac{\partial^4 u(x,t)}{\partial x^4} + \color{green}{\sigma A}\,\frac{\partial^2 u(x,t)}{\partial x^2}$$

High stress = High Q
Tensile stress increases the stored energy

Loss arises from anelasticity, i.e. a delay between internal strains and stresses:
Assume complex Young's modulus $E = E_1 + i\,E_2$

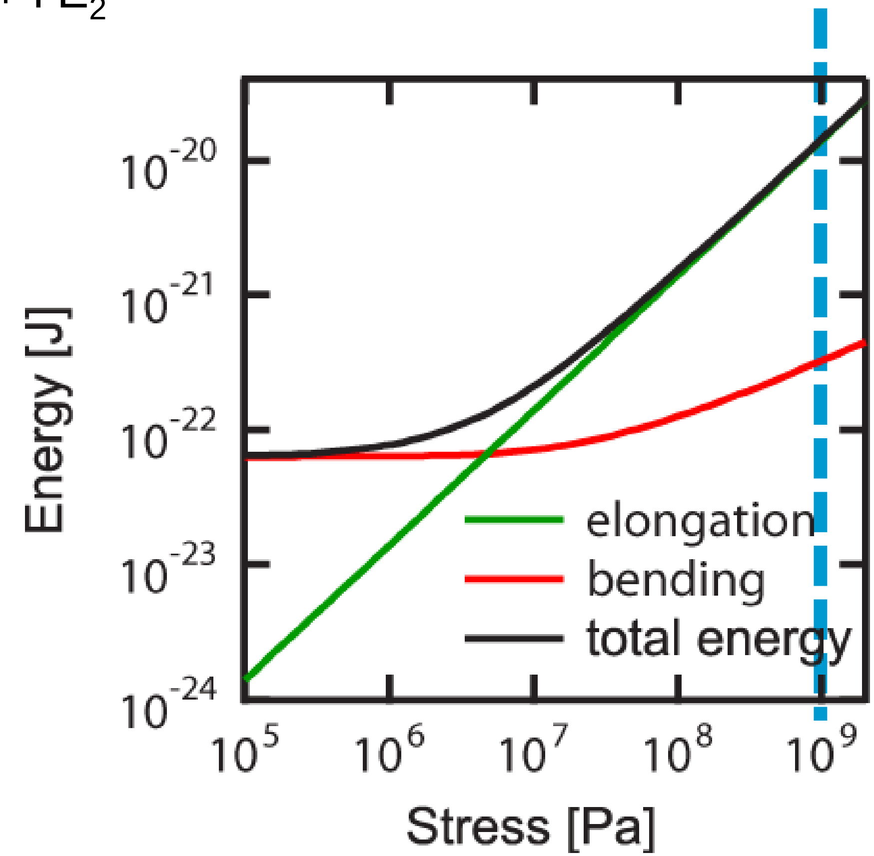
for an unstressed string:

strongly stressed string: “loss dilution“

dominated by
beam elongation (stress)

$$Q = 2\pi \cdot \frac{U_{mech}}{\Delta U_{diss}} \neq \frac{E_1}{E_2}$$

dominated by
beam bending
(Young's modulus)



see also: *Gonzales & Saulson, J. Ac. Soc. Am. 96, 207 (1994)*
Unterreithmeier et al., Phys. Rev. Lett. 105, 027205 (2010)
Yu et al., Phys. Rev. Lett. 108, 083603 (2012)

Ultra-high Q SiN resonators at 300 K

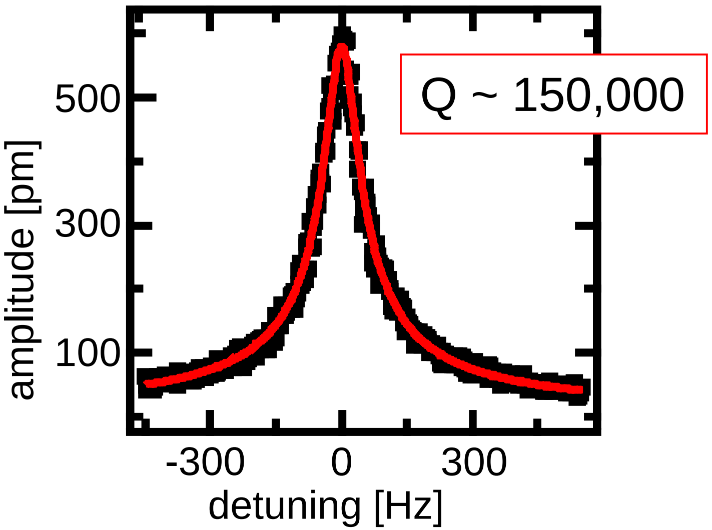
Tensile stress of SiN film deposited on Si/SiO2 vs. fused silica wafer

high stress SiN on Si:

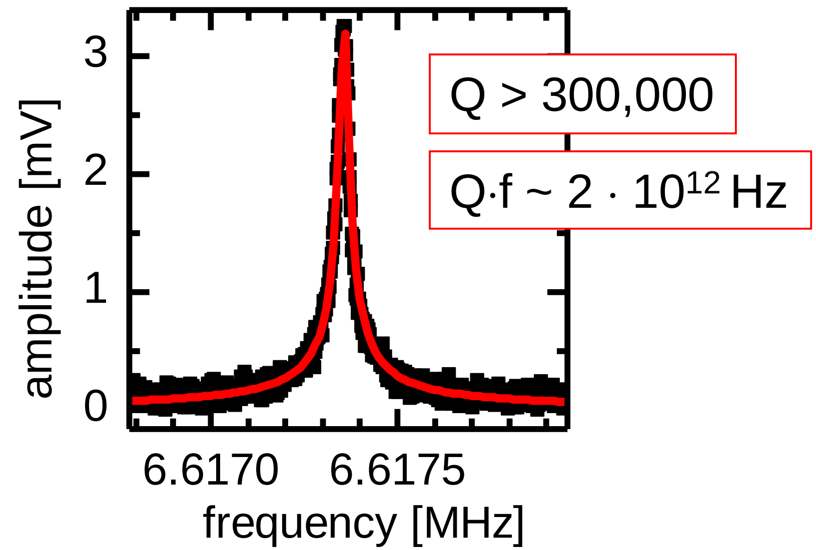
σ = 0.830 GPa
E = 160 GPa

high stress SiN on SiO_2:

σ = 1.460 GPa
E = 160 GPa



@ 10^{-5} mbar



@ 10^{-5} mbar

Verbridge et al., J.Appl. Phys. 99, 124304 (2006)
Faust, Krenn, Manus, Kotthaus, Weig, Nature Comm. 3, 728 (2012)

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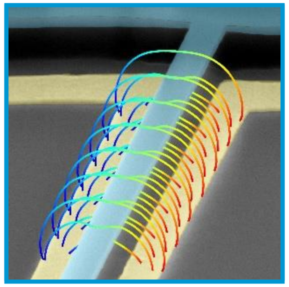
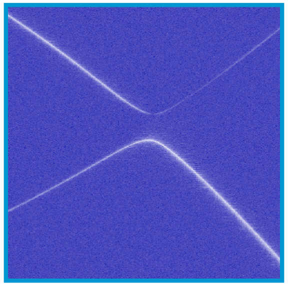
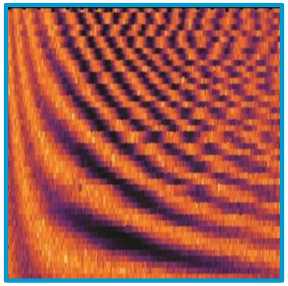


1. Nanomechanical SiN string resonators:
   Dielectric transduction and strong mode coupling

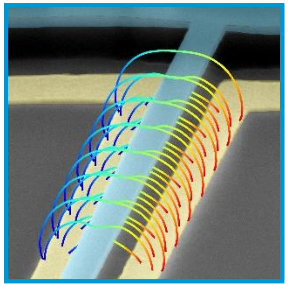


2. Landau-Zener dynamics:
   Coherent control of nanomechanical modes



3. Self-interference:
   Nanomechanical Stückelberg interferometry

OUTLINE



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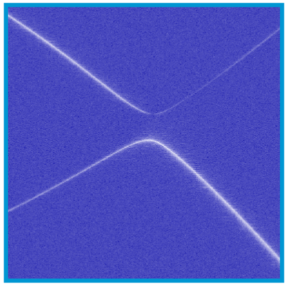

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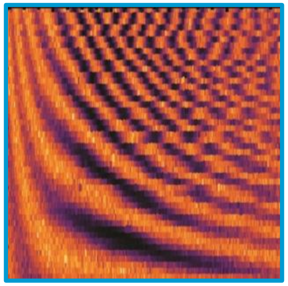
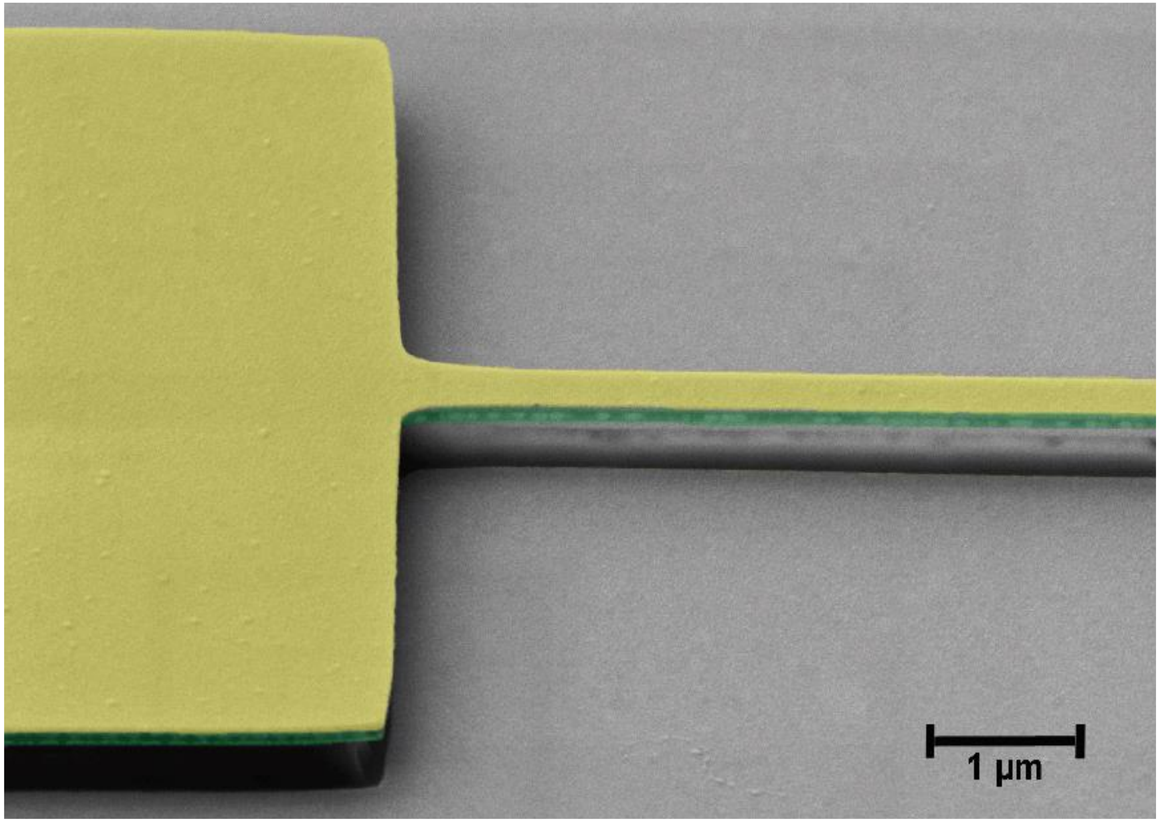


3. Self-interference:
   Nanomechanical Stückelberg interferometry

Operating high Q nanomechanics
Using an electrical scheme… but without metallizing the resonator?

Metallizing the resonator enables electrical transduction



e.g. capacitive actuation

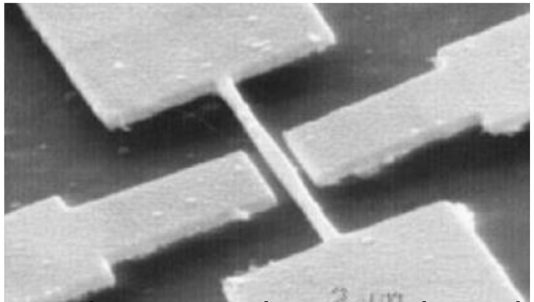


image: *Erbe, APL (2000)*

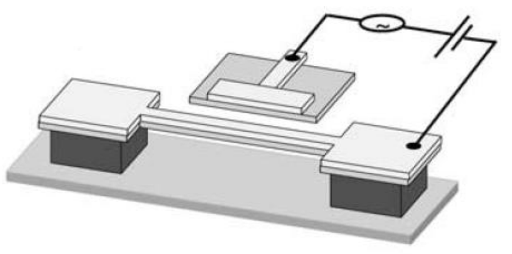
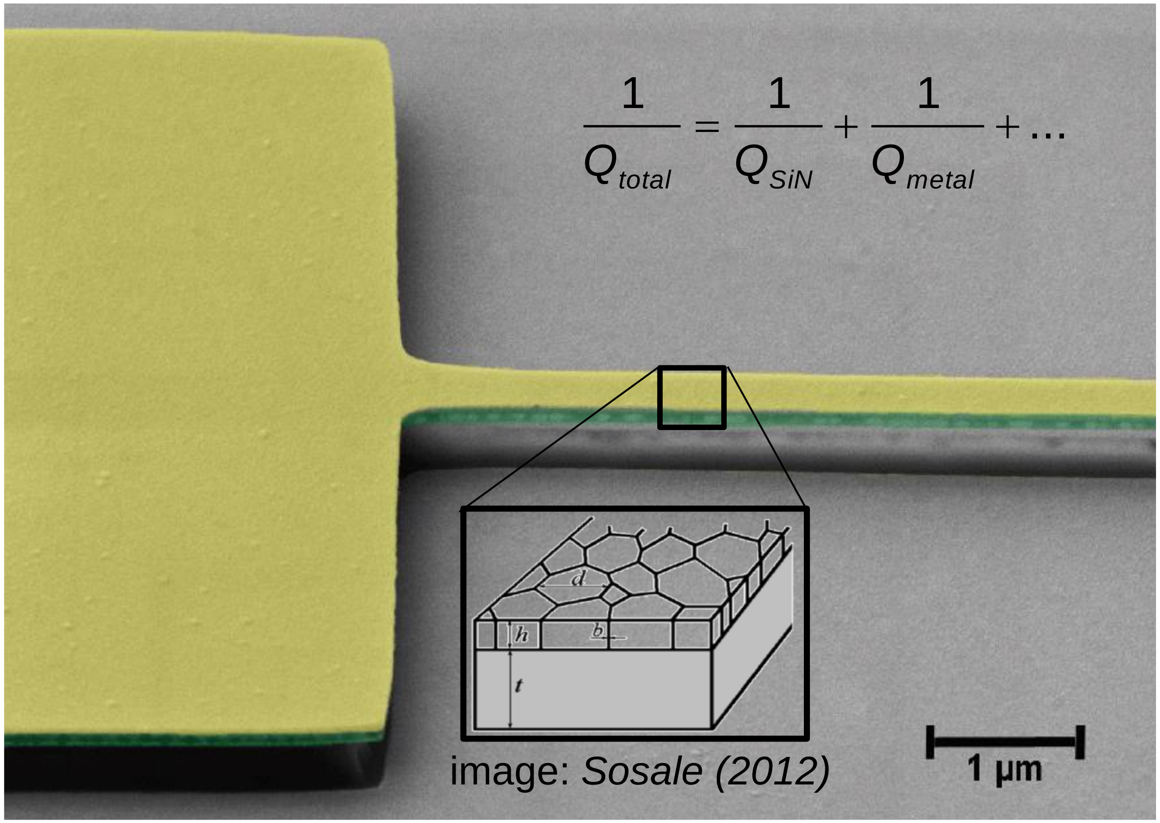


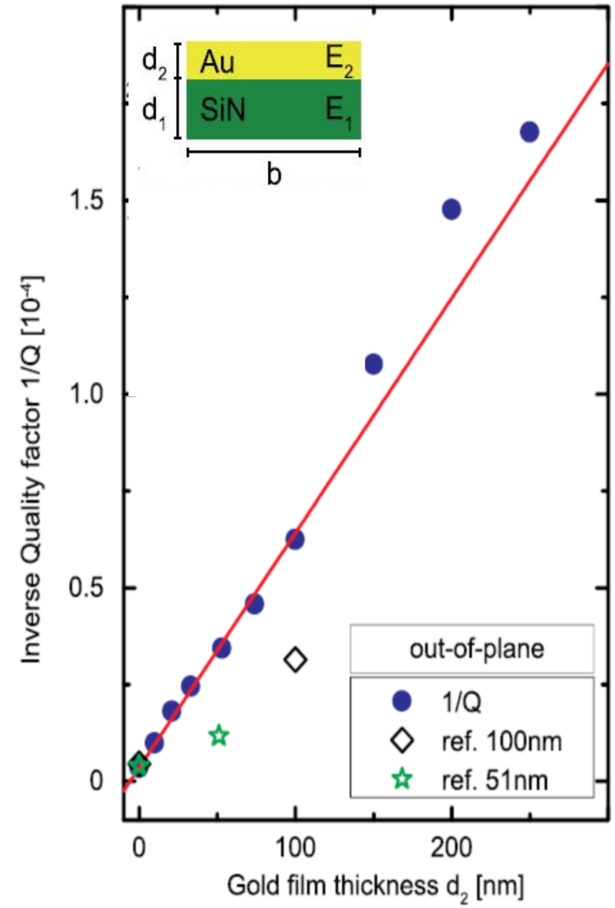
image: *Ekinci, Small (2005)*

Operating high Q nanomechanics
Using an electrical scheme… but without metallizing the resonator?

Metallizing the resonator enables electrical transduction
but induces strong damping in metals at 300 K



$$\frac{1}{Q_{total}} = \frac{1}{Q_{SiN}} + \frac{1}{Q_{metal}} + \ldots$$



⇨ Avoid metallization-based transduction schemes for achieving highest Q

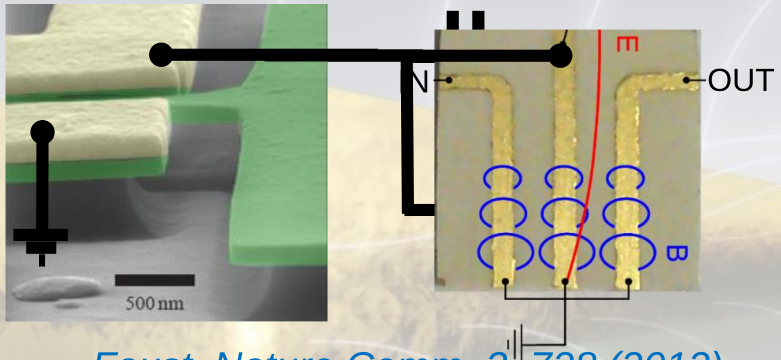
Seitner, Gajo, Weig, Appl. Phys. Lett. 105, 213101 (2014)

Dielectric gradient field transduction

An integrated platform to control high Q nanomechanical resonators

Dielectric detection:

Heterodyne detection
w/ 3.5 GHz microwave cavity



Faust, Nature Comm. 3, 728 (2012)

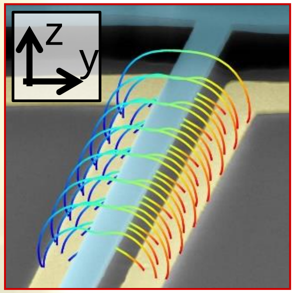
Dielectric actuation:

Electrically induced gradient force

e.g. out of plane mode:

$$F_z = p_y \cdot \frac{\partial E_z}{\partial y}$$

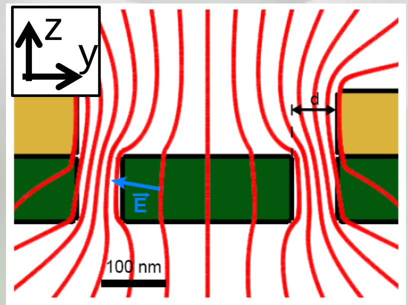
$$\sim V_{DC}^2 + 2V_{DC}V_{RF}$$



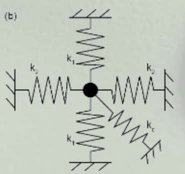
Unterreithmeier, Nature 458, 1001 (2009)
see also: *Schmid, APL 89, 163506 (2006)*

Dielectric mode coupling:

Coupling spring κ induced by cross derivative of electric field



$$\kappa = -\frac{\partial F_y}{\partial z} \sim \frac{\partial^2 E^2}{\partial z \partial y}$$



Faust, Phys. Rev. Lett 109, 037205 (2012)

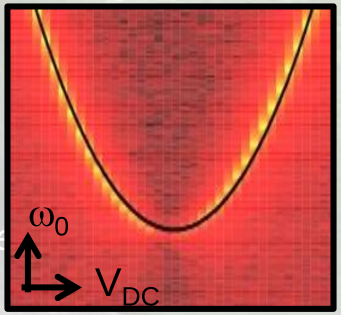
Dielectric frequency tuning:

V_{DC}-controlled effective spring constant (local field gradient at string position)

e.g. out of plane mode:

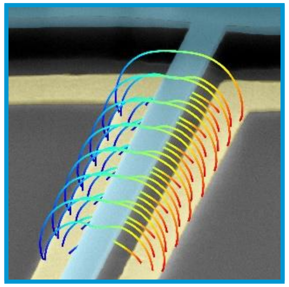
$$\omega_0 = \sqrt{\frac{k + k_{eff}}{m}} \sim V_{DC}^2$$

$$\text{w/} \quad k_{eff} = -\frac{\partial F_{DC}}{\partial z}$$



Rieger, Appl. Phys. Lett. 101, 103110 (2012)

OUTLINE



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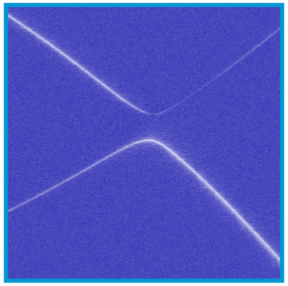

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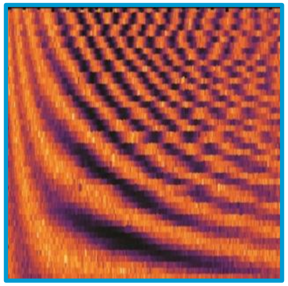
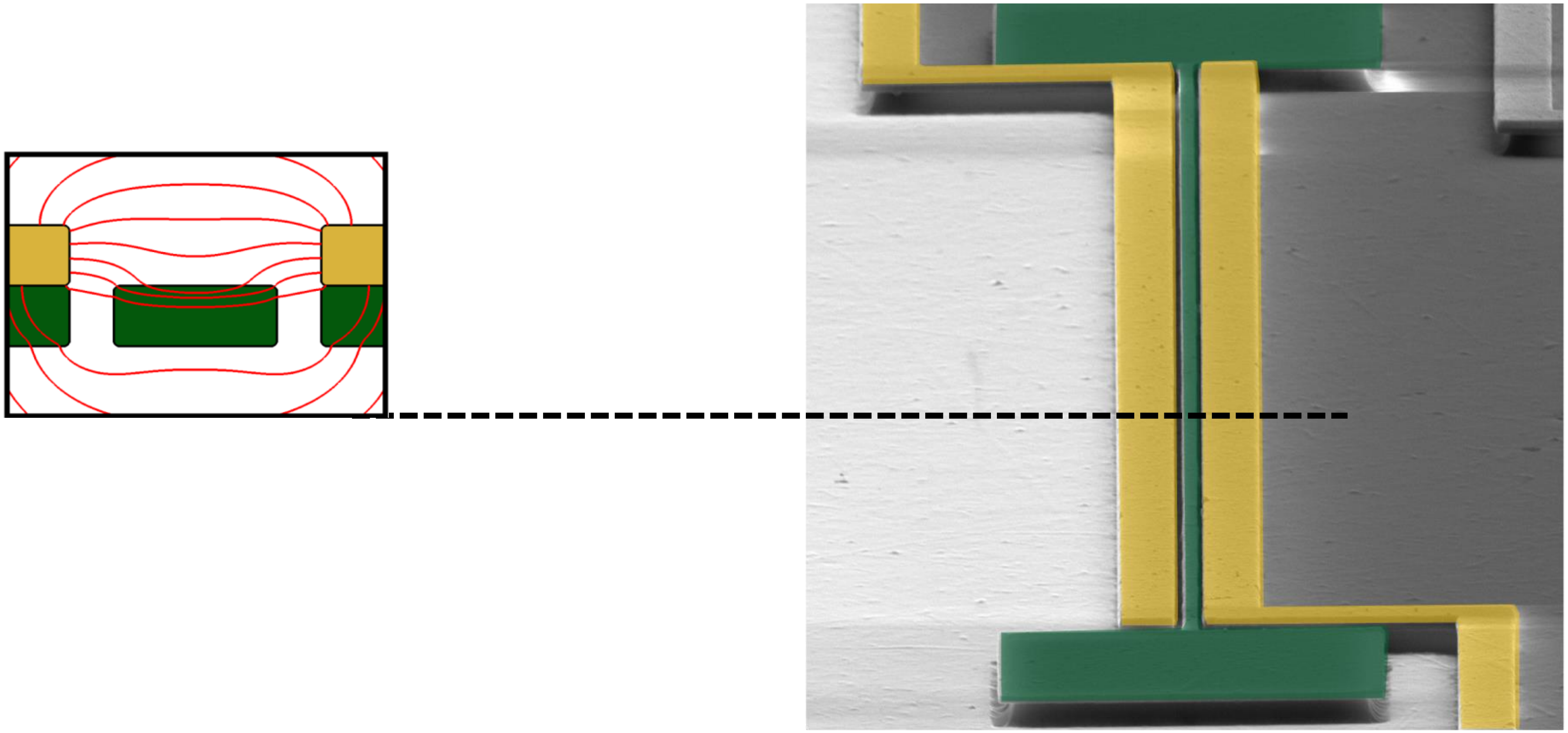


3. Self-interference:
   Nanomechanical Stückelberg interferometry

Tuning in- and out-of-plane flexural mode
of a resonator in „elevated electrode“ layout



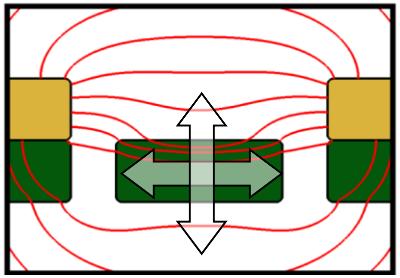
Faust, Rieger, Seitner, Krenn, Manus, Kotthaus, Weig, Phys. Rev. Lett 109, 037205 (2012)

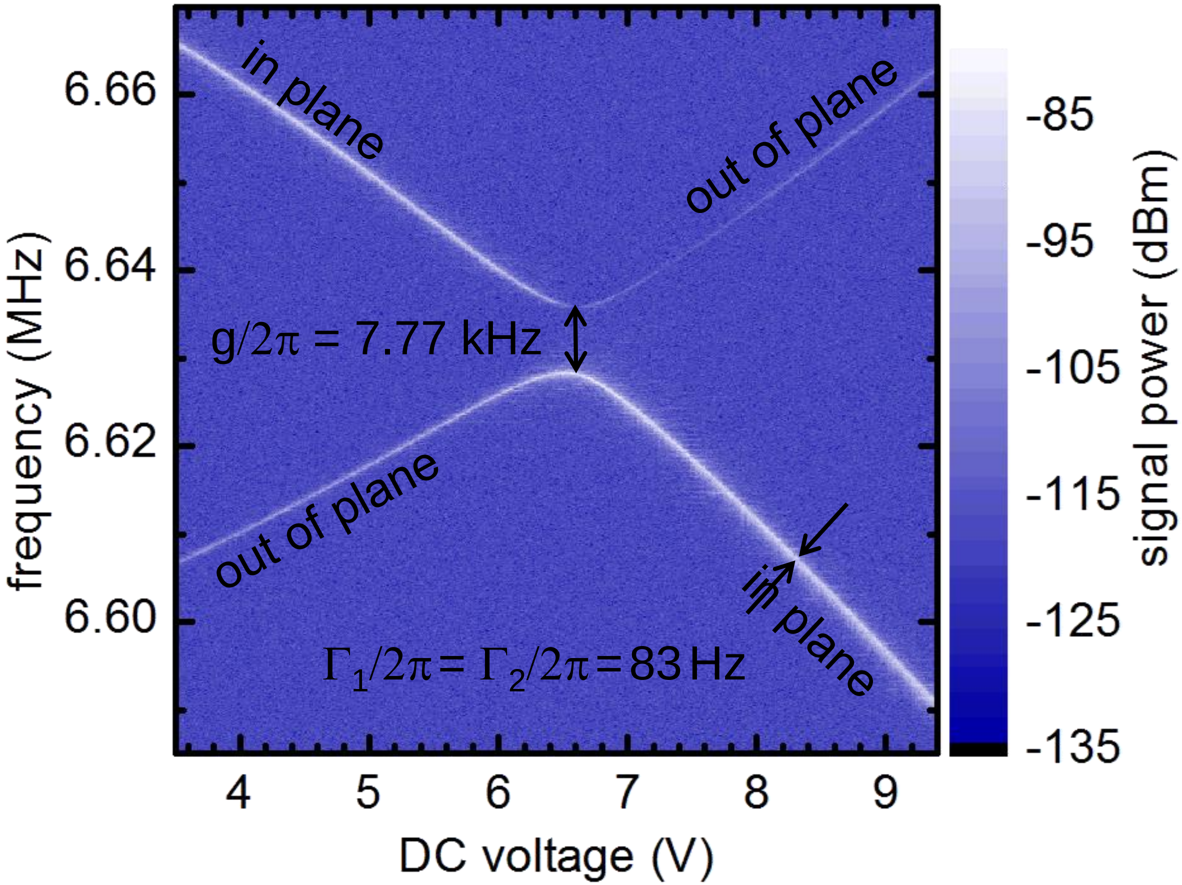
Tuning in- and out-of-plane flexural modes

Avoided crossing reminiscent of strong coupling

in-plane mode

out-of-plane mode





strong coupling: $g \gg \Gamma_{1,2}$

Faust, Rieger, Seitner, Krenn, Manus, Kotthaus, Weig, Phys. Rev. Lett 109, 037205 (2012)

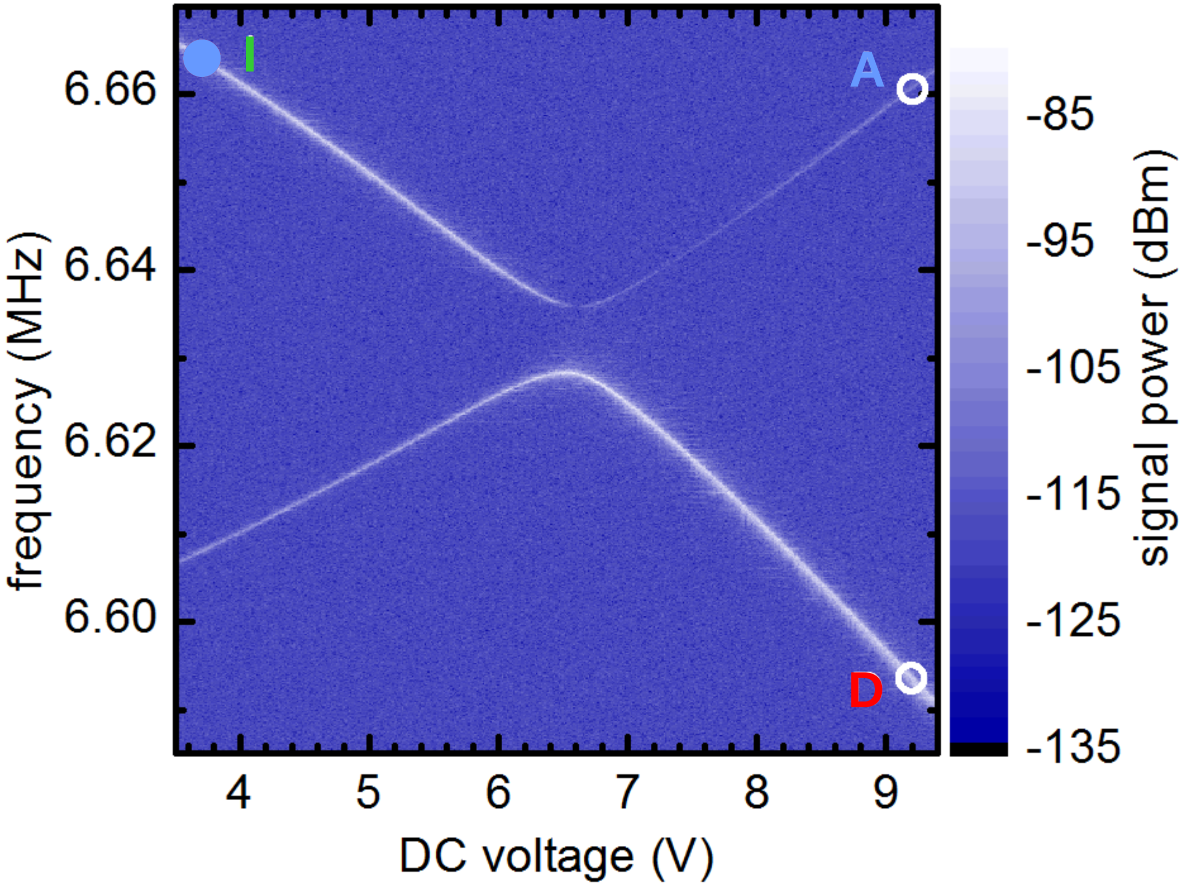
Time-resolved dynamics of coupled modes
Measurement sequence

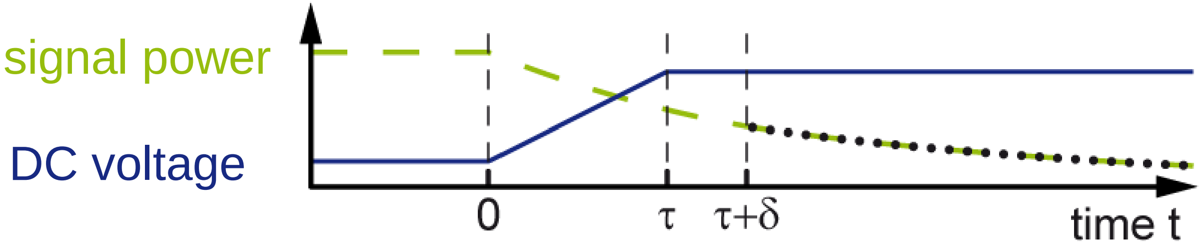
1. State initialization at point I by constant drive

2. DC voltage ramp across coupling region

3. Final state depends on ramp time τ: a diabatic / adiabatic transistion gets the system to point D / A

4. Measure oscillation energy at D and A (after delay δ)





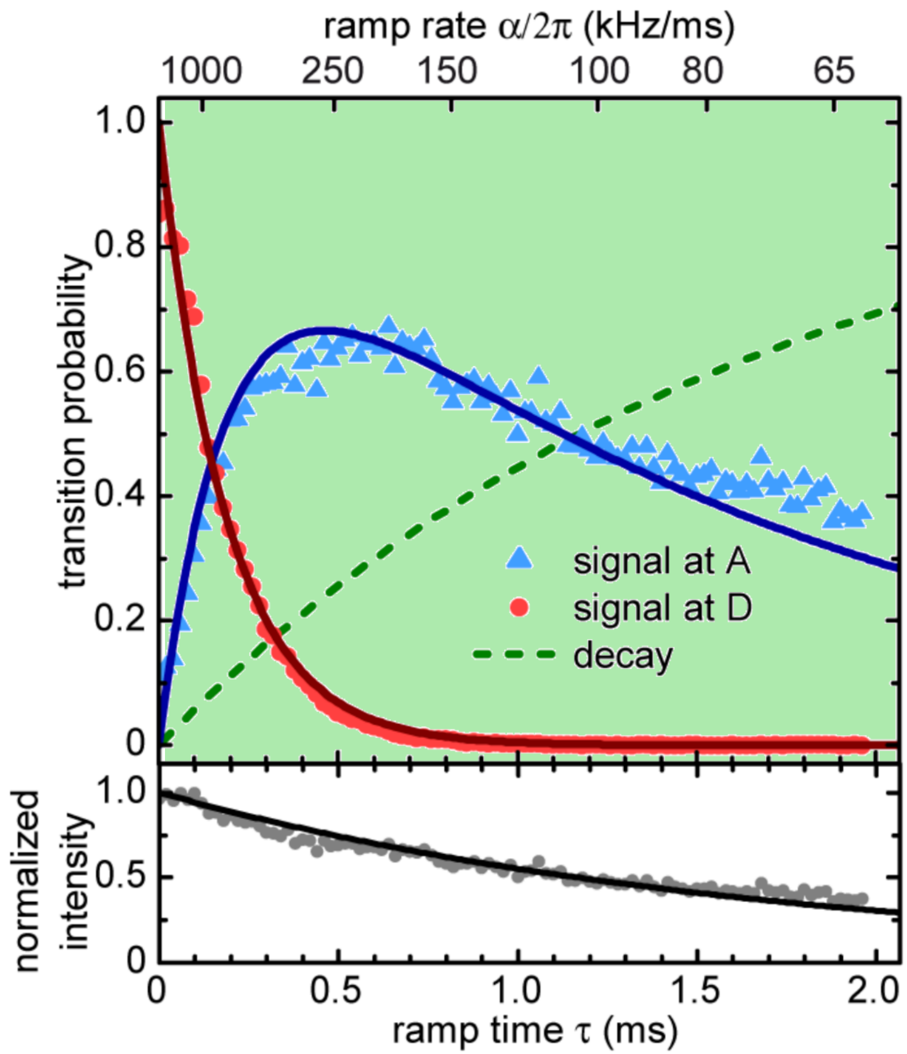
A classical analogue of Landau-Zener physics
Establishing time-domain control of nanoresonator state

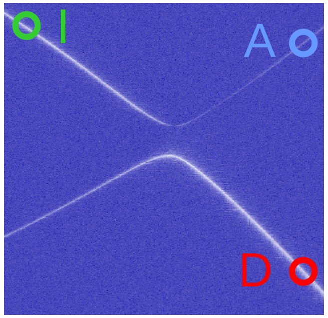
Landau-Zener dynamics with additional decay:

$$P_{\text{diabatic}} = e^{-\frac{\pi\Gamma^2}{2\alpha}} \cdot e^{-\gamma t}$$

$$P_{\text{adiabatic}} = \left(1 - e^{-\frac{\pi\Gamma^2}{2\alpha}}\right) \cdot e^{-\gamma t}$$

see also: *L. Novotny, Am. J. Phys. 78, 1199 (2010)*



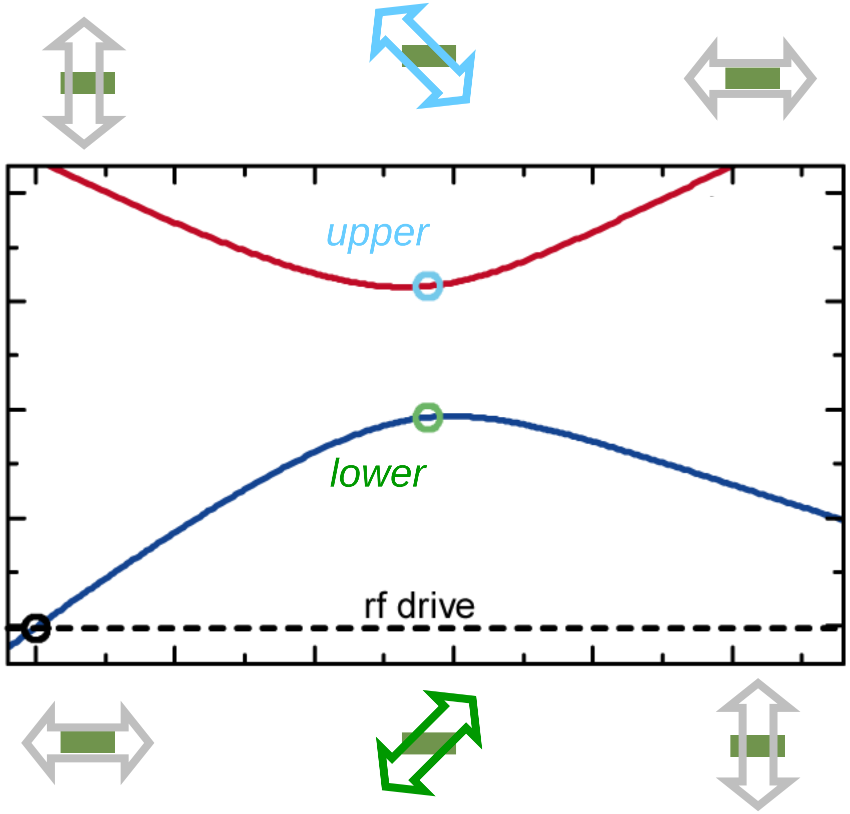


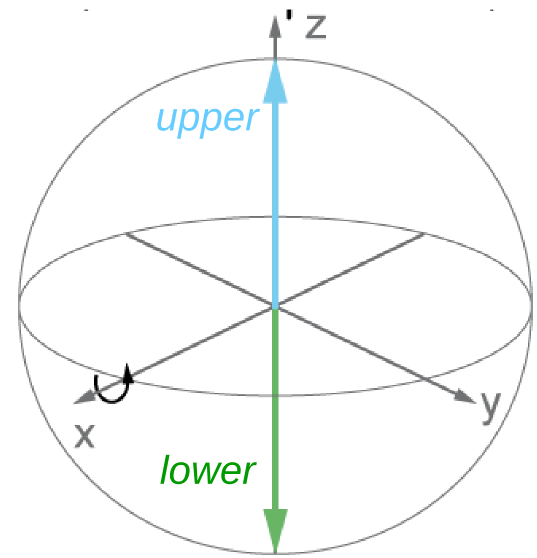
decay time $1/\gamma = 1.9\,\text{ms}$

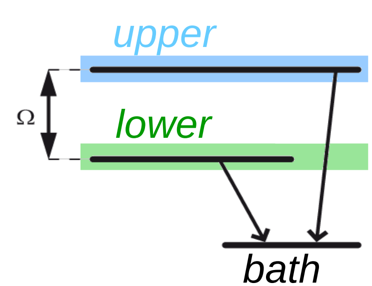
Faust, Rieger, Seitner, Krenn, Manus, Kotthaus, Weig, Phys. Rev. Lett 109, 037205 (2012)

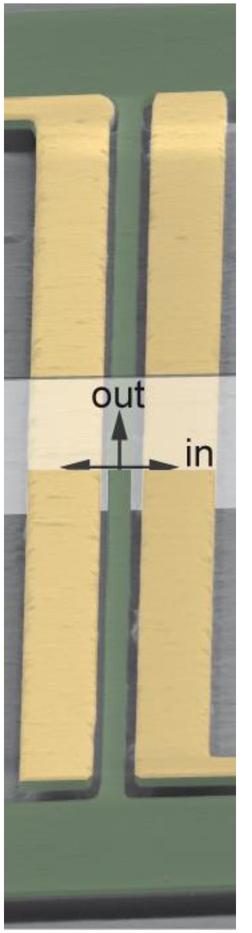
A classical nanomechanical two-mode system and its two hybrid modes as basis states of a Bloch sphere

On resonance, the +45° and -45° mechanical hybrid modes form a two-mode system:









Faust, Rieger, Seitner, Kotthaus, Weig, Nature Physics 9, 485 (2013)

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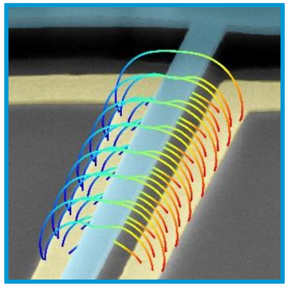

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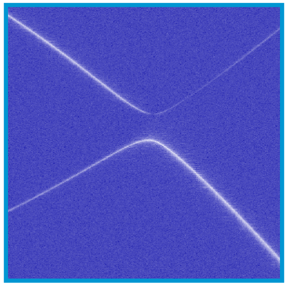

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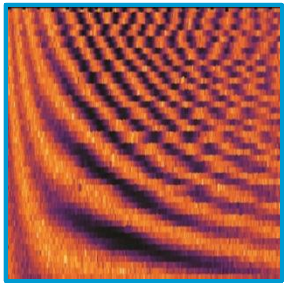
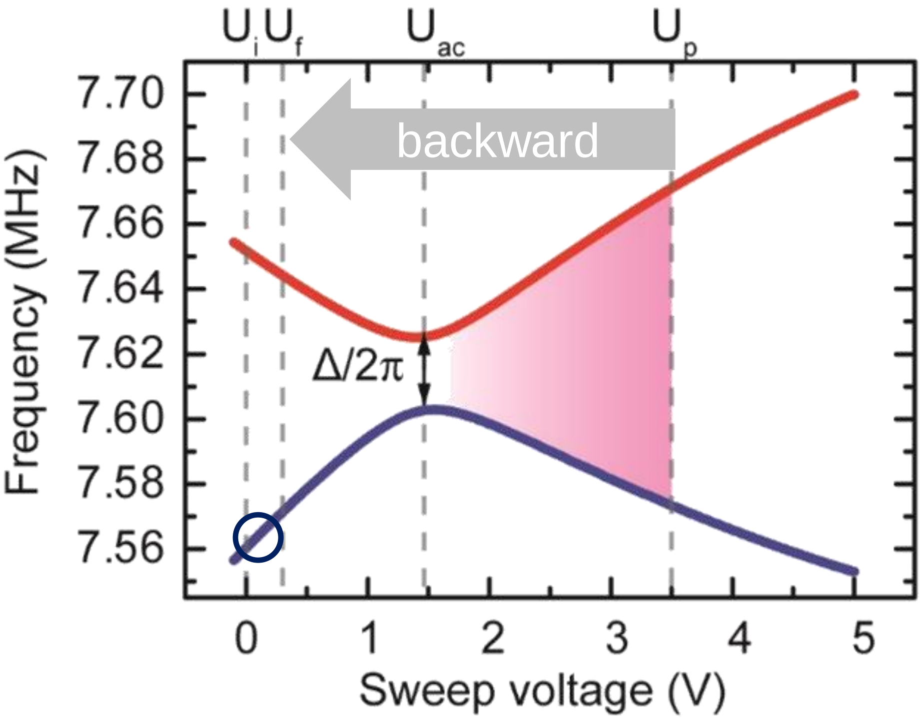
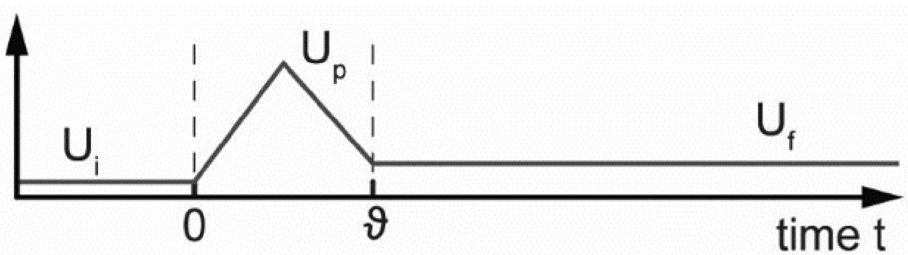


3. Self-interference:
   Nanomechanical Stückelberg interferometry

Nanomechanical self-interference induced by a double passage through the avoided crossing





Single passage
through the avoided crossing:

→ Landau-Zener dynamics

Double passage
through the avoided crossing:

→ Stückelberg interference?

see:
Stückelberg, Helv. Phys. Acta 5, 369 (1932)

→ Common approximation:
Adiabatic impulse model

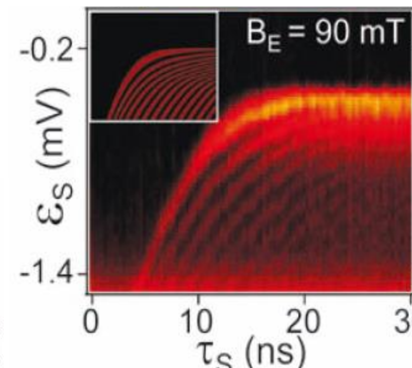
$$P_{1\to 1} = 1 - 4P_{LZ}\left(1 - P_{LZ}\right)\sin^2\left(\phi_S + \frac{\phi_{dyn}}{2} + \frac{\phi_{geo}}{2}\right)$$

Review:
Shevchenko et al., Phys. Rep. 492, 1 (2010)

Seitner et al., arXiv:1602.01034

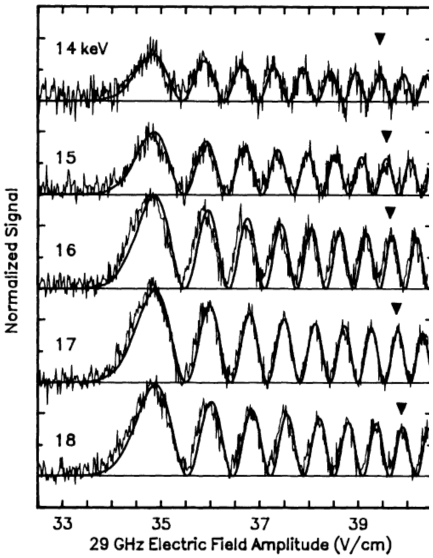
Stückelberg interferometry in the literature measured in quantum two-level systems

double quantum dot



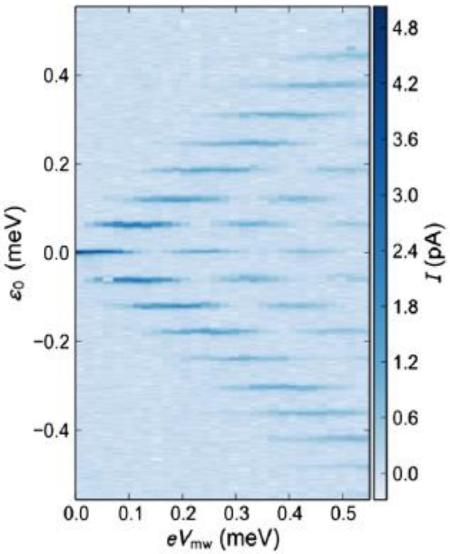
Petta, Science 327, 671 (2010)

He Rydberg atom



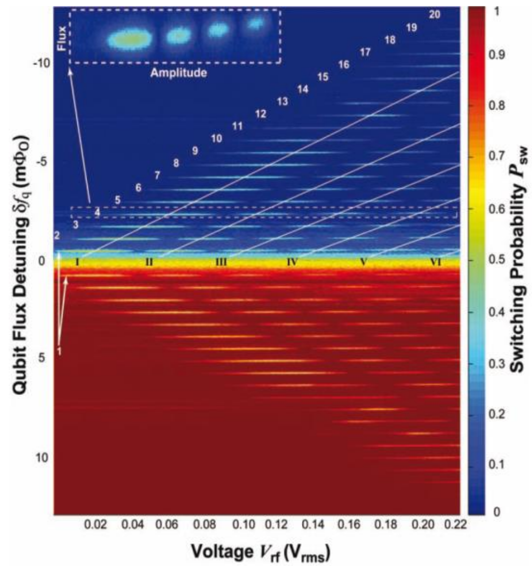
Yoakum, PRL 69, 1919 (1992)

dopants in Si NW



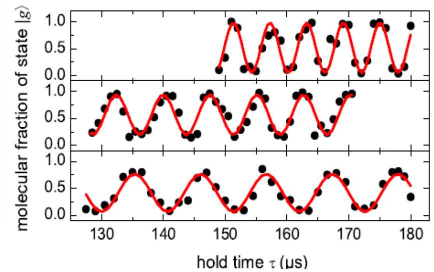
Dupont-Ferrier, PRL 110, 136802 (2013)

superconducting flux qubit



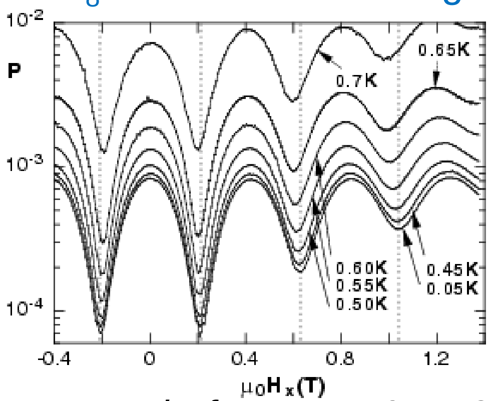
Oliver, Science 310, 1653 (2005)

ultracold Cs_2 molecules



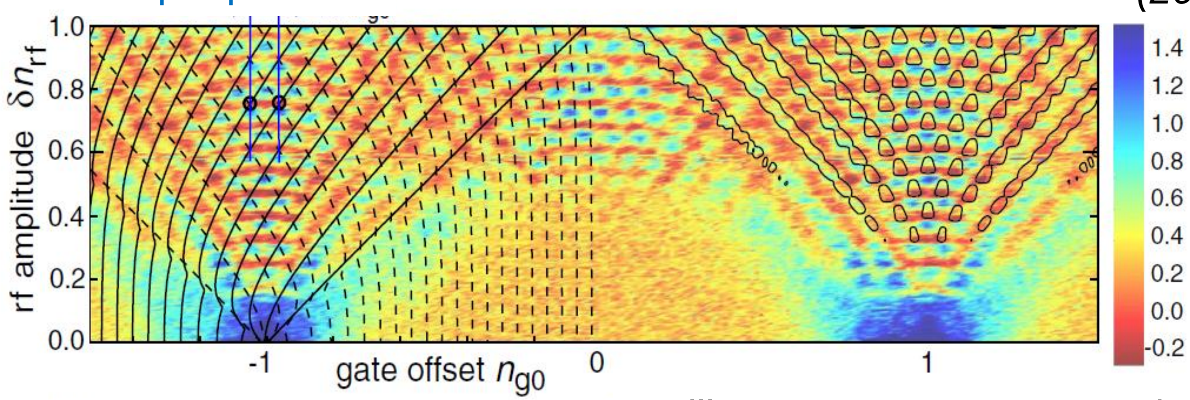
Mark, PRL 99, 113201 (2007)

Fe_8 molecular nanomagnets



Wernsdorfer, EPL 50, 552 (2000)

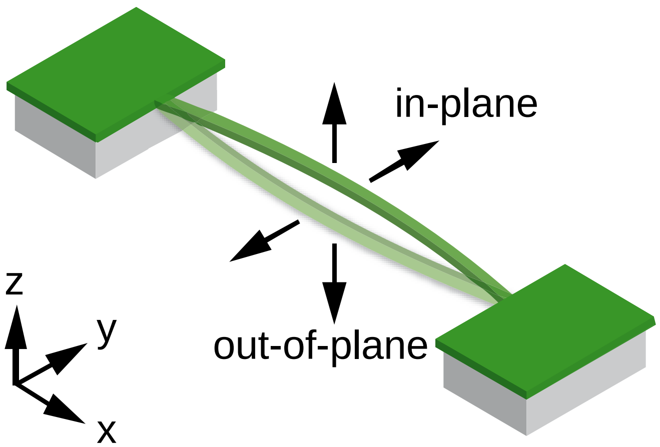
Cooper pair box



Sillanpäa, PRL 96, 187002 (2006)

But would that also work by means of classical coherence?
Remember the water waves…

Stückelberg interferometry with a classical two mode system
Exact solution of the classical double passage problem



Two coupled harmonic oscillators:

$$m_{eff}\ddot{z} + m_{eff}\gamma_1\dot{z} + k_1(U_{DC})z + \kappa(z-y) = 0$$

$$m_{eff}\ddot{y} + m_{eff}\gamma_2\dot{y} + k_2(U_{DC})y + \kappa(y-z) = 0$$

Normalized amplitudes: $y(t) = c_1(t)\cdot e^{i\omega_1 t}, z(t) = c_2(t)\cdot e^{i\omega_1 t}$

$$2i\omega_1\dot{c}_1 = \frac{\kappa}{m_{eff}}c_2$$

$$2i\omega_1\dot{c}_2 + (\omega_2 - \omega_1)^2 c_2 = \frac{\kappa}{m_{eff}}c_1$$

see: *Novotny, Am. J. Phys. 78, 1199 (2010)*

Time-dependend unitary transformation: © *Hugo Ribeiro, McGill University*

$$i\begin{pmatrix}\dot{c}_1\\ \dot{c}_2\end{pmatrix} = \begin{pmatrix}\frac{\alpha t}{2} & \frac{\lambda}{2}\\ \frac{\lambda}{2} & -\frac{\alpha t}{2}\end{pmatrix}\begin{pmatrix}c_1\\ c_2\end{pmatrix}$$

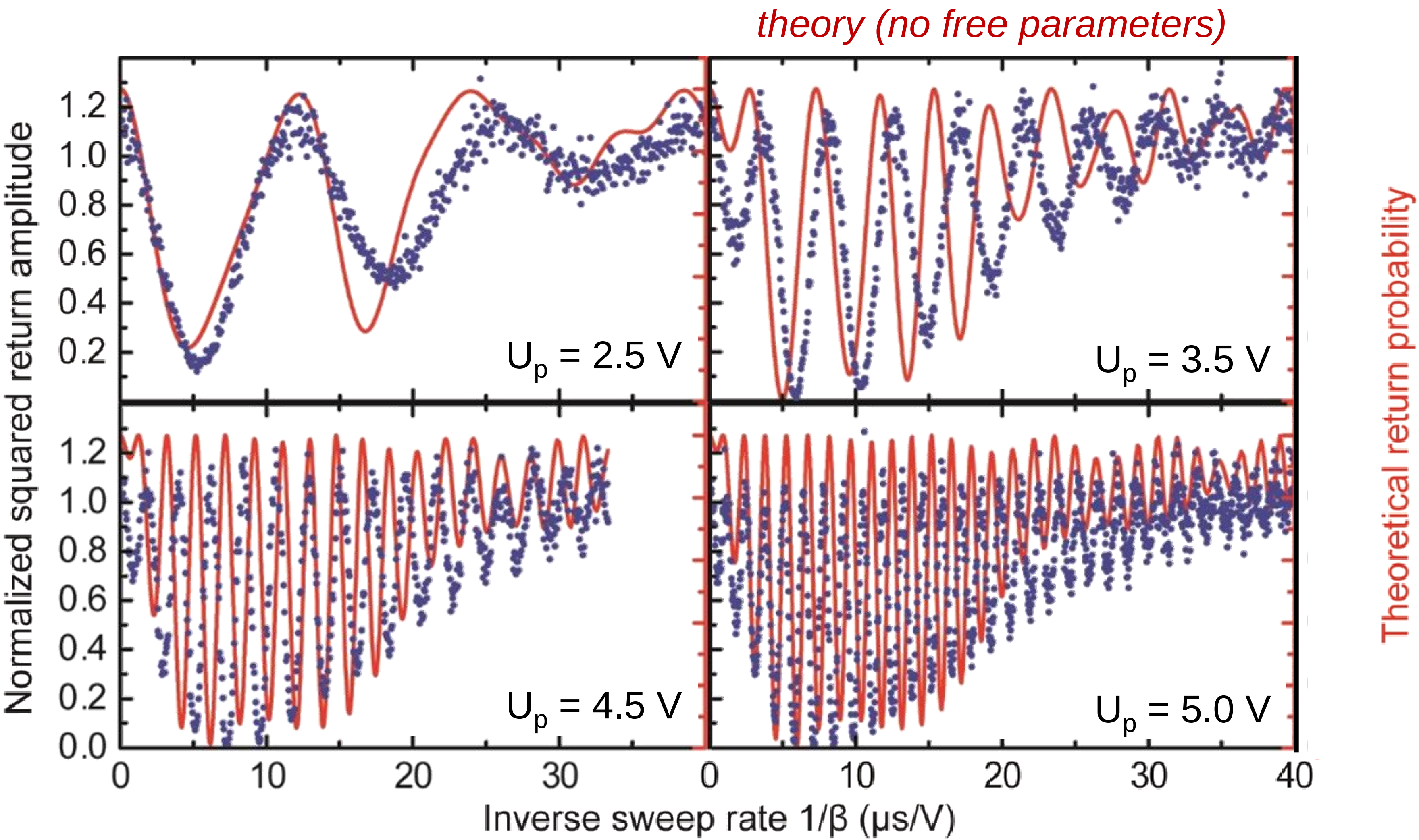
EOM of two coupled harmonic oscillators looks like Schrödinger equation of the Landau-Zener problem!

see: *Vitanov & Garraway, Phys. Rev. A 53, 4288 (1996)*

Return probability $P_{1\to1}$ is identical in the classical and the quantum case.

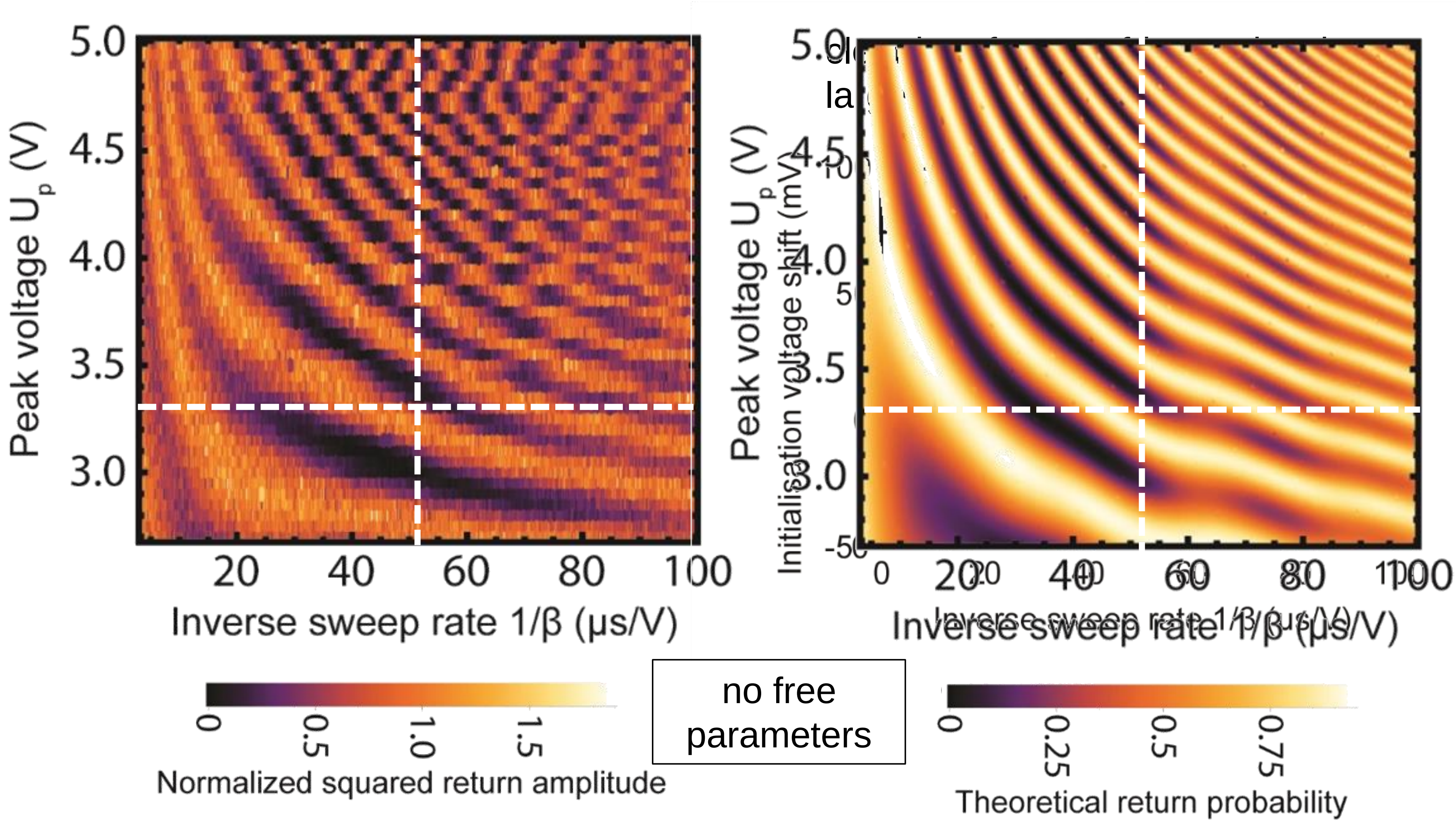
$$P_{1\to1} = \left|\varphi_{11}(t_p,t_i)\varphi_{11}^*(t,-t_p) + \varphi_{12}^*(t_p,t_i)\varphi_{12}^*(t,-t_p)\right|^2$$

Classical Stückelberg interference at 10 K
and analytical model by Hugo Ribeiro



Seitner, Ribeiro, Kölbl, Faust, Kotthaus, Weig, arXiv:1602.01034

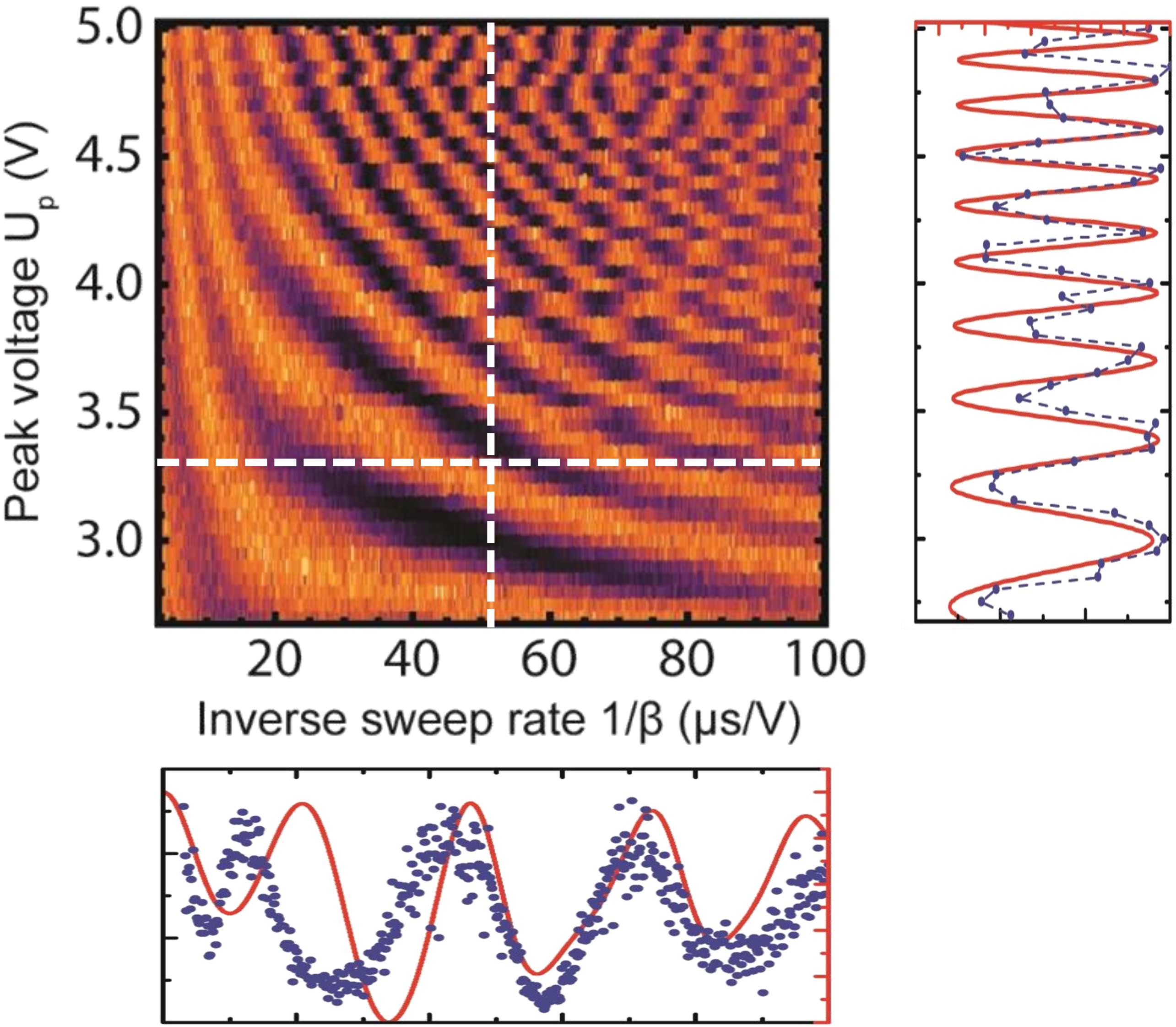
Classical Stückelberg interference at 300 K indicating millisecond coherence time



no free parameters

Seitner, Ribeiro, Kölbl, Faust, Kotthaus, Weig, arXiv:1602.01034

Classical Stückelberg interference at room temperature indicating millisecond coherence time



Discrepancies :

- Temperature drifts: ±2 K/h and corresponding shift of eigenfrequencies by 500 Hz/K, i.e. 40 linewidths affects all parameters of the system
- Feedback loop ensures initialization at fixed frequecy
- Other parameters not precisely known (e.g. U_{ac})

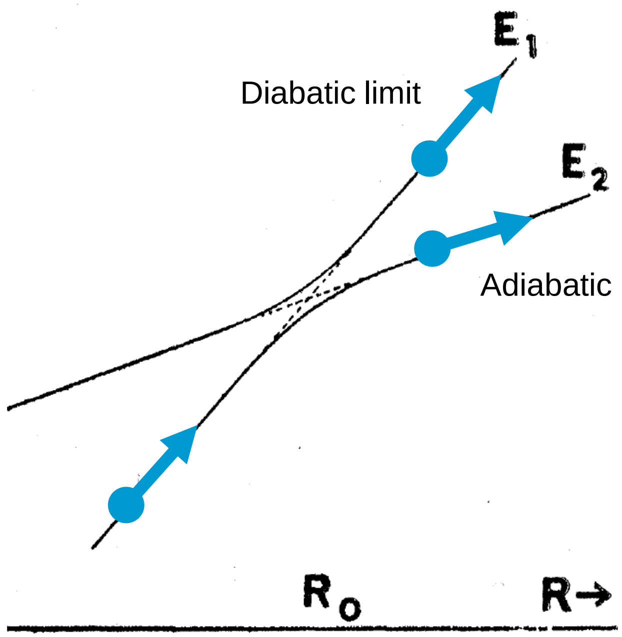
Classical to quantum transition

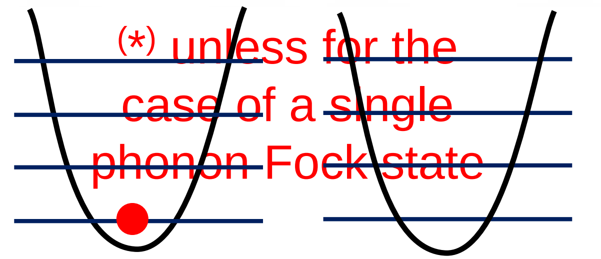
Would this also work with a mechanical resonator in the quantum regime?

or

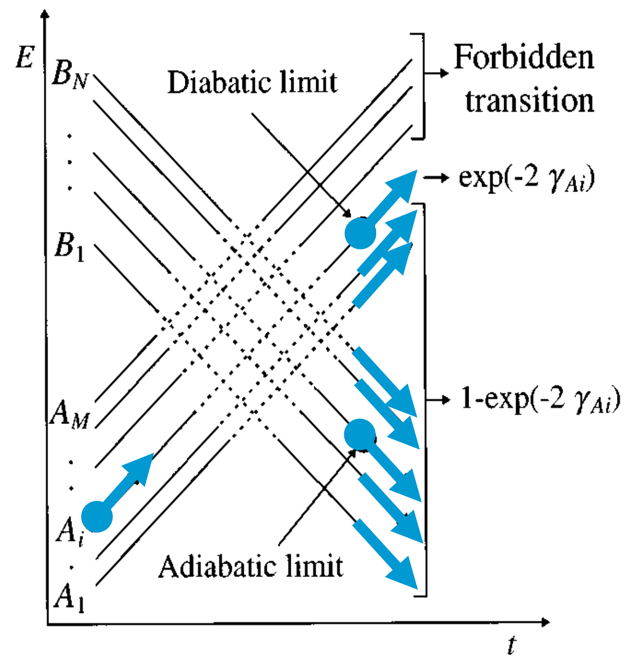
quantum
2-level system

classical
2-mode system





two quantum
harmonic oscillators



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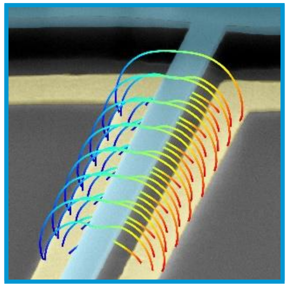
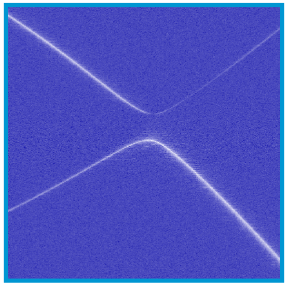
Usuki, Phys. Rev. B 56, 13360 (1997)

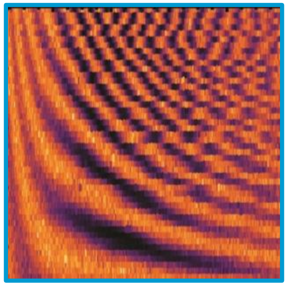
SUMMARY



- High stress SiN nanomechanical string resonators:
  - ➢ Q > 300,000 at T = 300 K
  - ➢ Excellent control via dielectric transduction
  - ➢ Versatile toolbox for nanomechanics

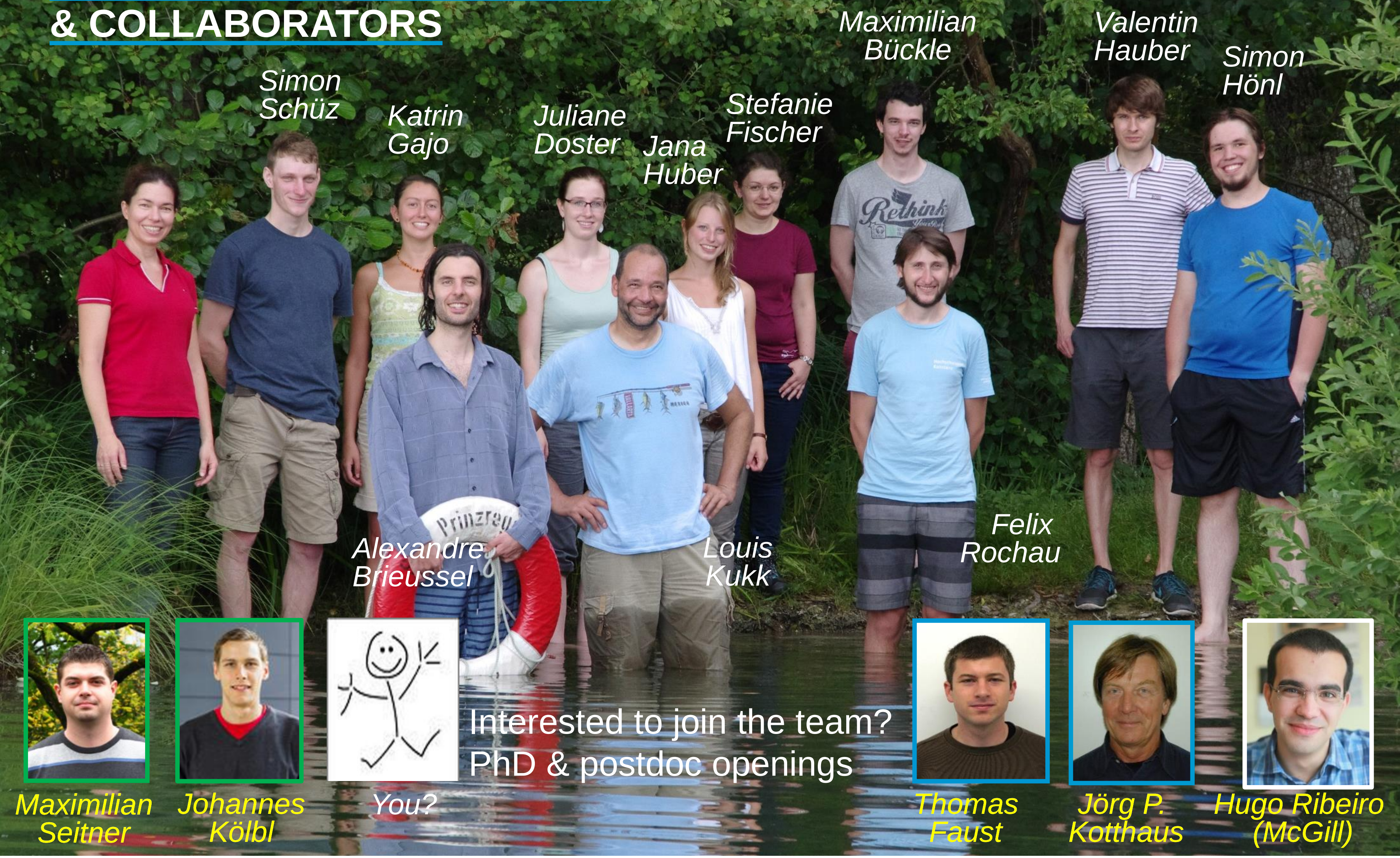


- Strong coupling between in- and out-of-plane mode:
  - ➢ $g/\Gamma \sim 10^2$ mediated by inhomogeneous electric field
  - ➢ Classical Landau-Zener dynamics
  - ➢ Coherent control of nanomechanical motion



- Classical Stückelberg interferometry:
  - ➢ Same return probability as in quantum mechanical case
  - ➢ Observation of finite time effects
  - ➢ Nanomechanical interferometer

MANY THANKS TO THE TEAM & COLLABORATORS



Interested to join the team?
PhD & postdoc openings

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