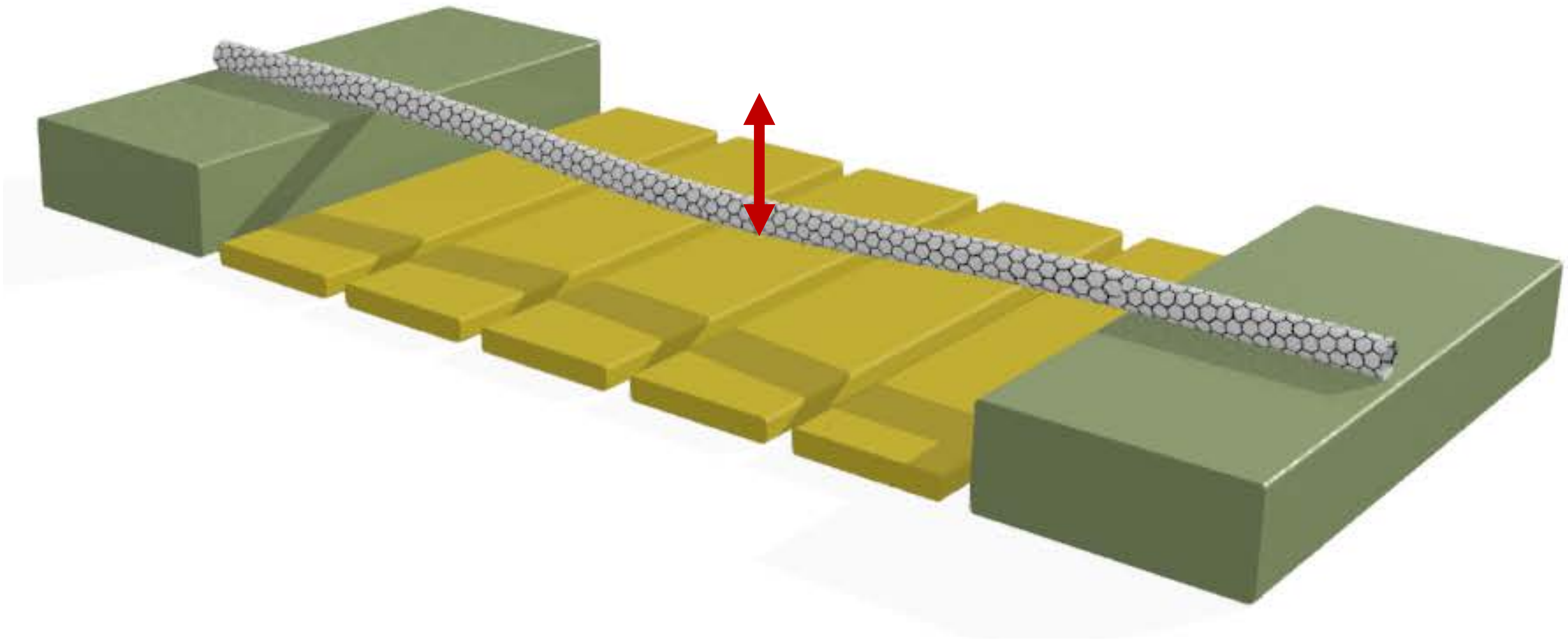
A coherent nanotube oscillator driven by electromechanical backaction

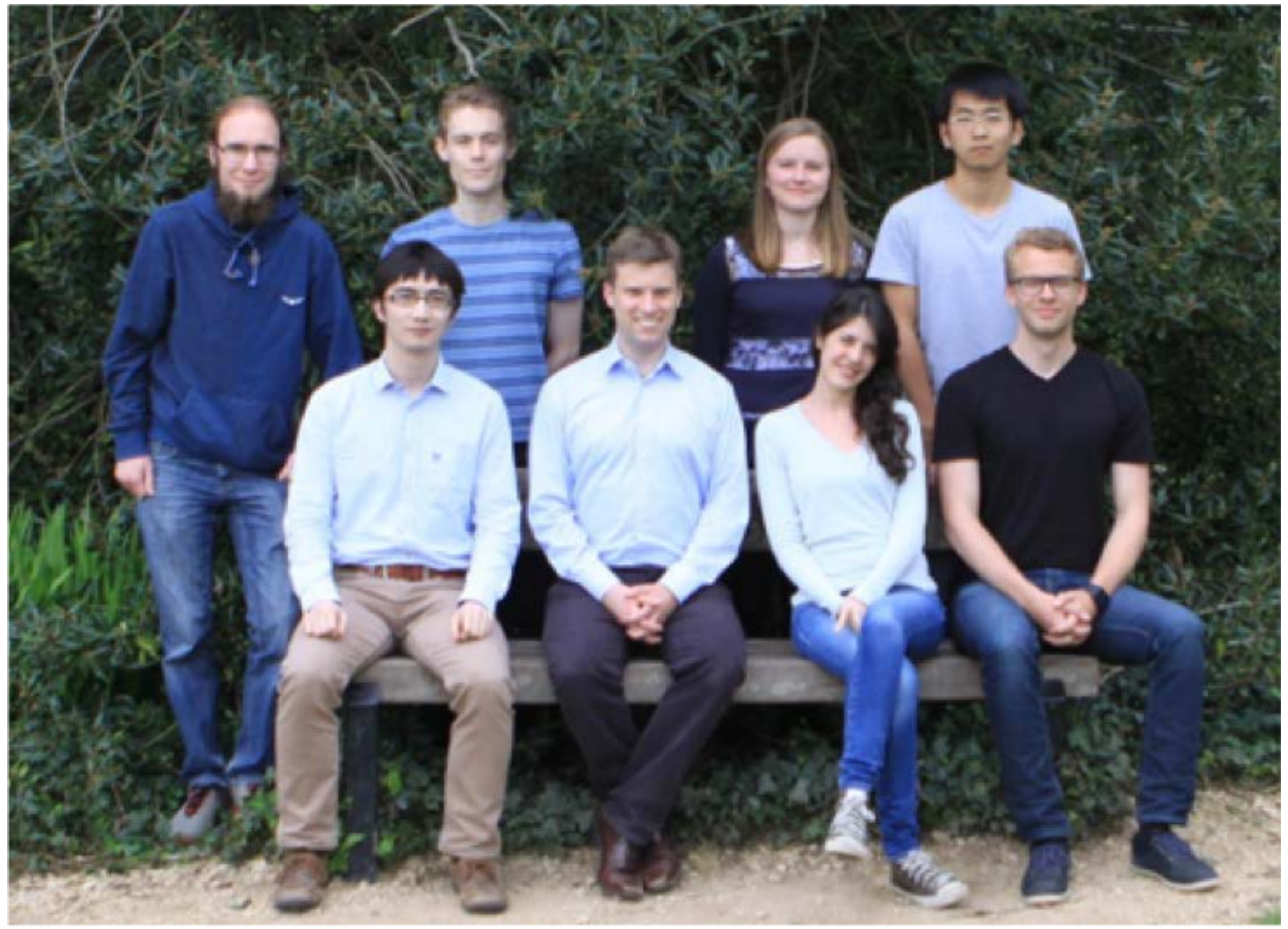
Edward Laird



Lancaster University

A coherent nanotube oscillator driven by electromechanical backaction

<u>Yutian Wen</u>
<u>Natalia Ares</u>
Tian Pei
Felix Schupp
Andrew Briggs
(at Oxford)



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TEMPLETON World Charity Foundation, Inc.
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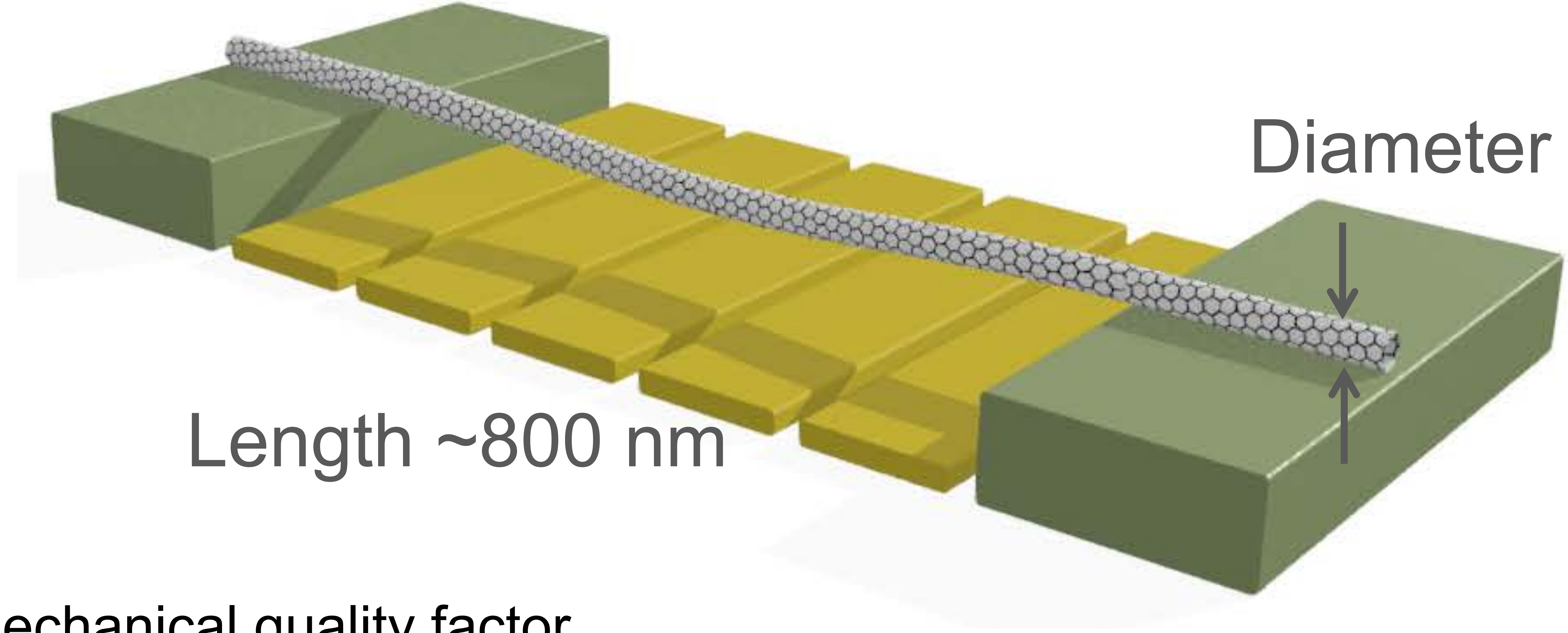
EPSRC Engineering and Physical Sciences Research Council
erc European Research Council Scientific Council Established by the European Commission
EMP European Microkelvin Platform

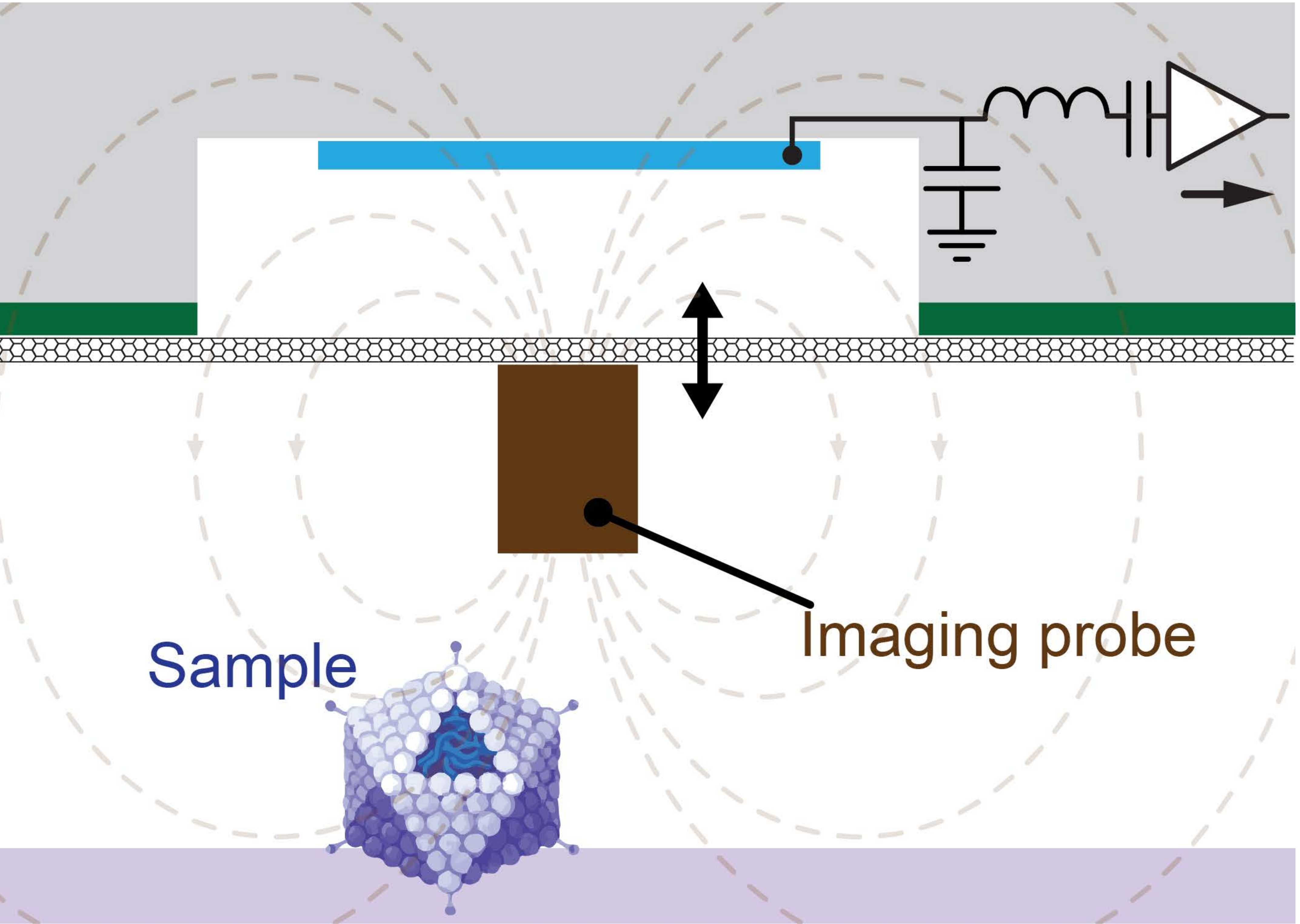
The limits of displacement sensing

Suspended carbon nanotube
~10^6 nucleons



- High mechanical quality factor
- High frequency (200 MHz ≡ 10 mK)
- Mechanically compliant
- Can be integrated into electronic circuits

The limits of displacement sensing: Magnetic resonance microscopy



Force per proton: ~10^{-20} N

Review:
Poggio & Harzheim (2018)

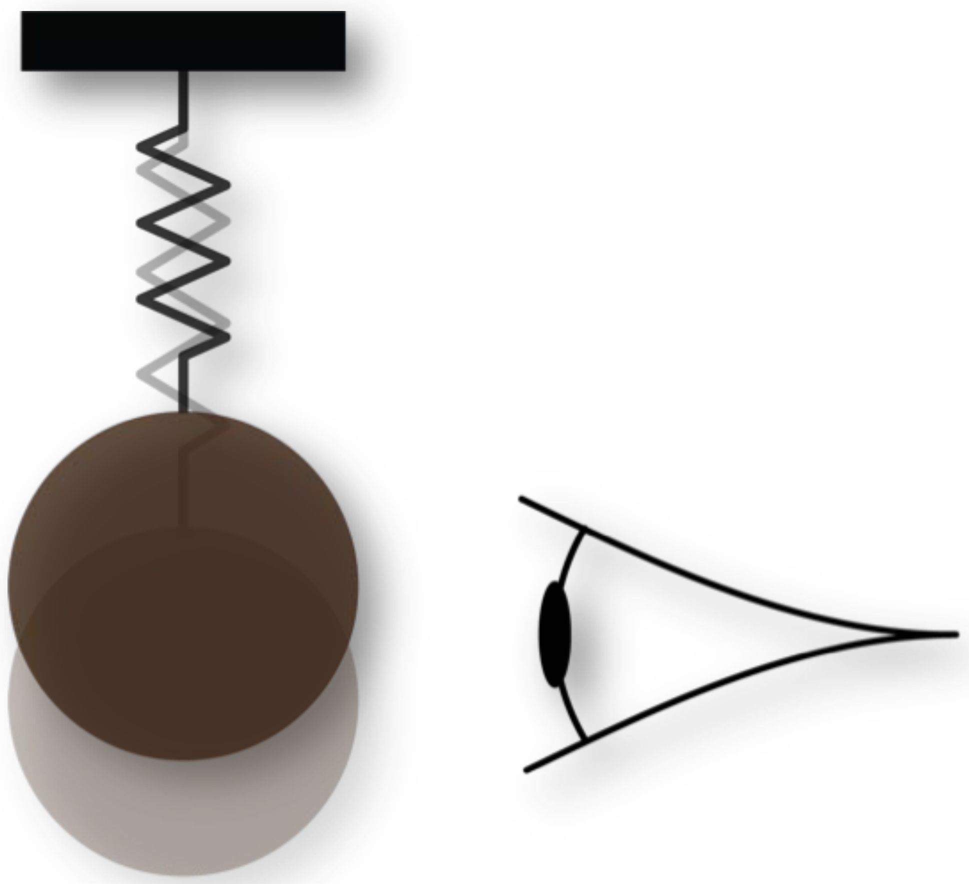
A coherent nanotube oscillator driven by electromechanical backaction

1. **Measuring vibrations with a single-electron transistor**

2. Creating a nanomechanical oscillator

3. Characterizing the oscillator

Question 1: How precisely can we measure nanomechanical vibrations?



Standard quantum limit for continuous measurements (m/√Hz):

Quality factor

$$S_x = \sqrt{\frac{\hbar Q}{4\pi^2 m f^2}}$$

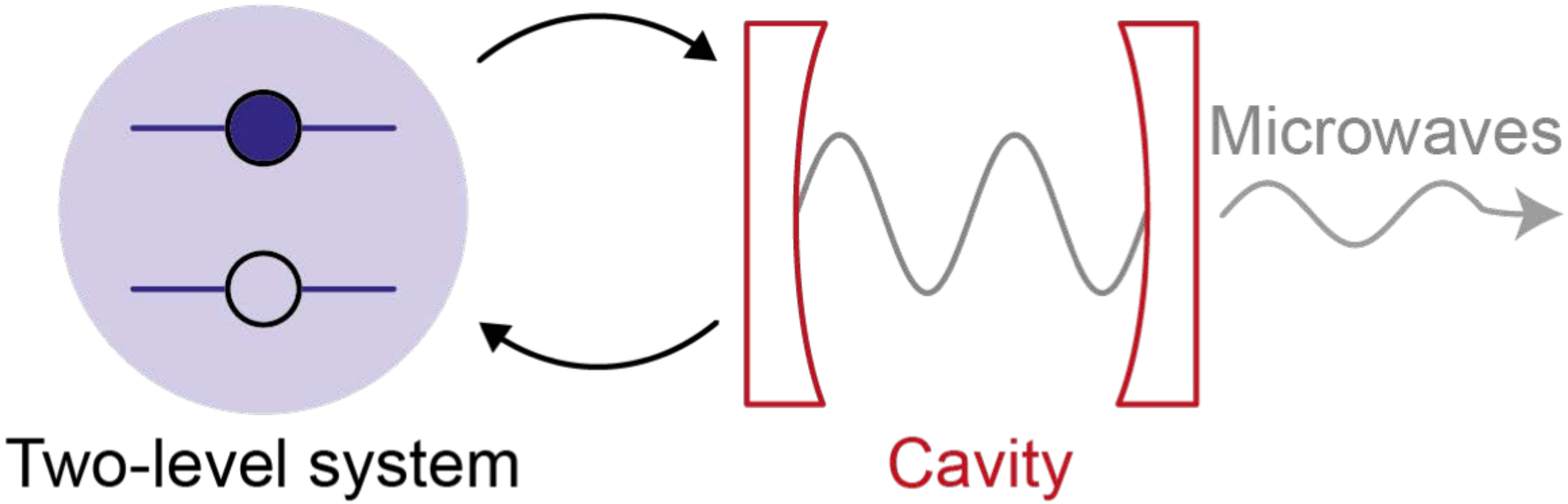
Mechanical frequency

Mass

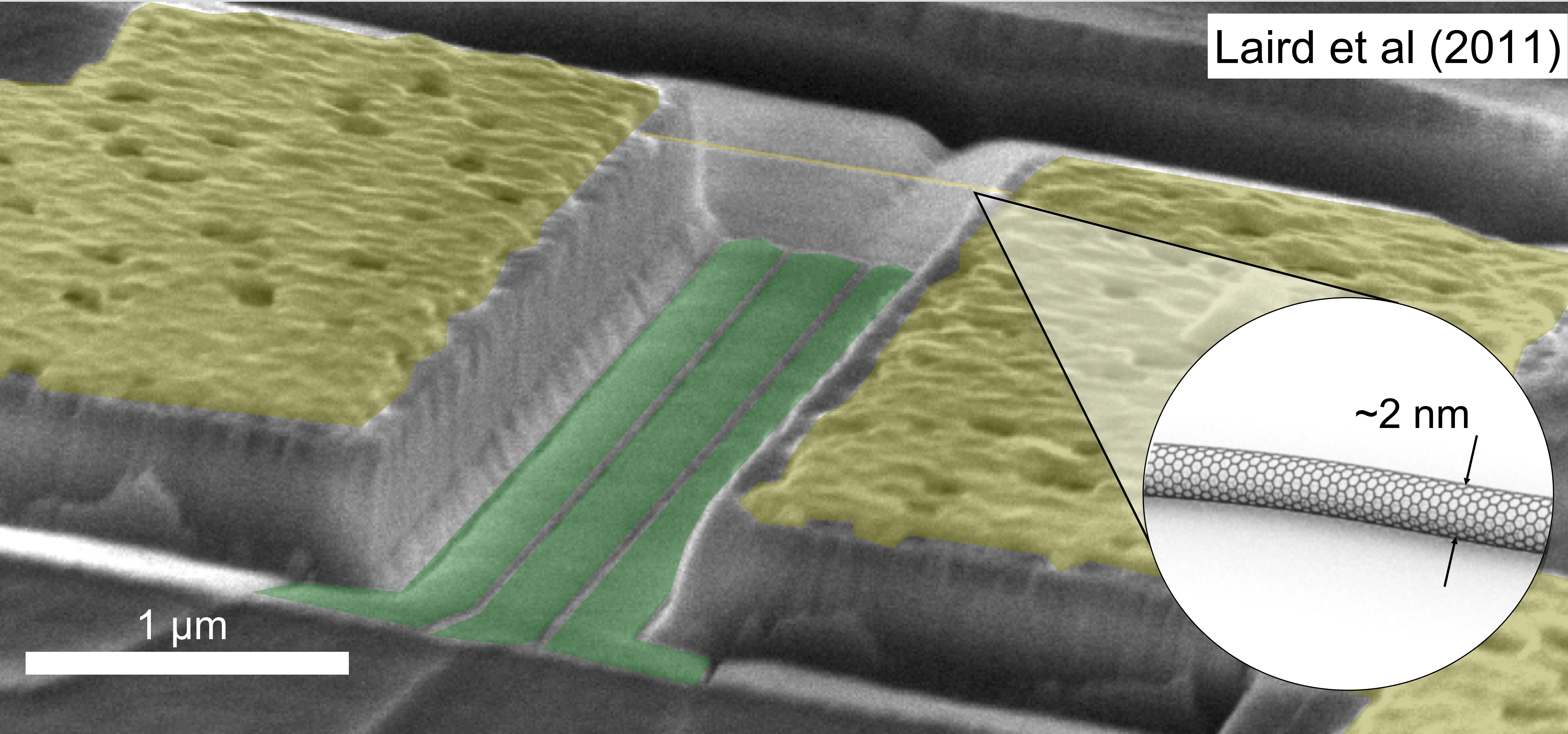
Theory: Caves et al. (RMP 1982)
Experiment: LaHaye et al. (Science 2004)
Review: Clerk et al. (RMP 2010)

Question 2: Can we make a laser for sound?

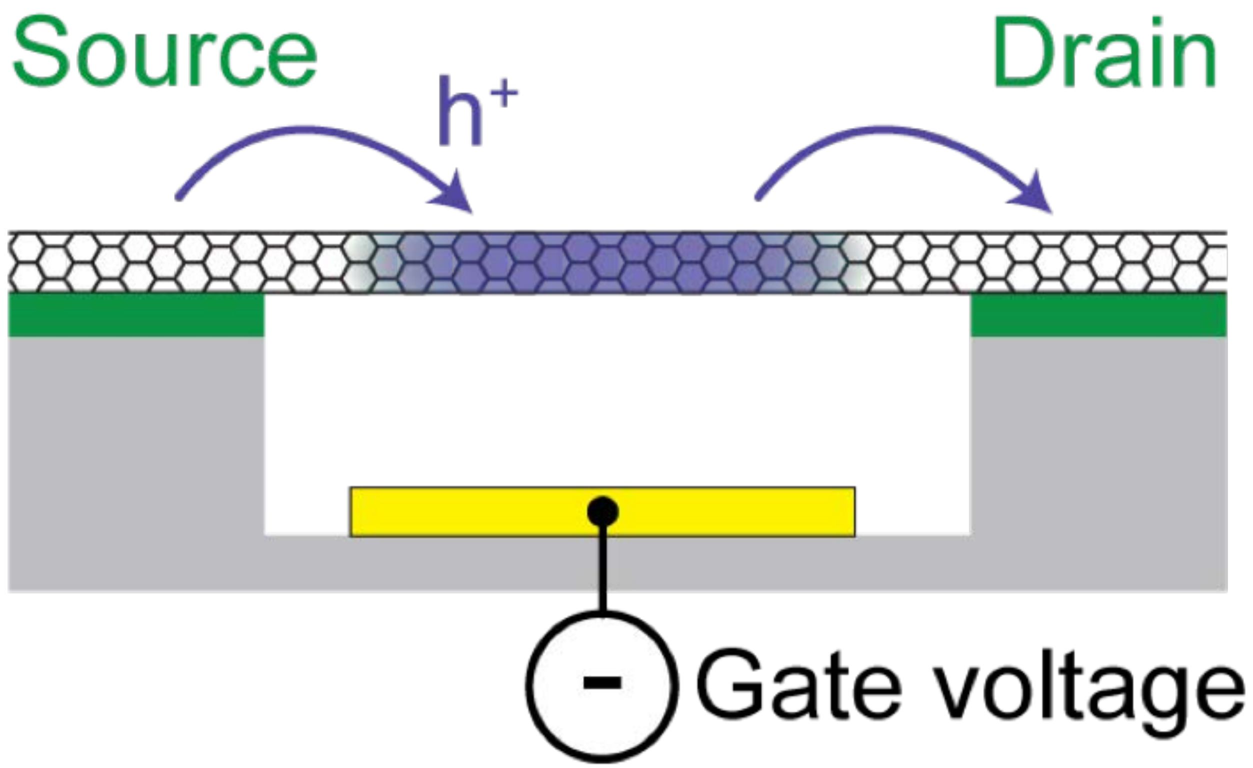
Microwave amplification by stimulated emission of radiation (Townes, 1955)

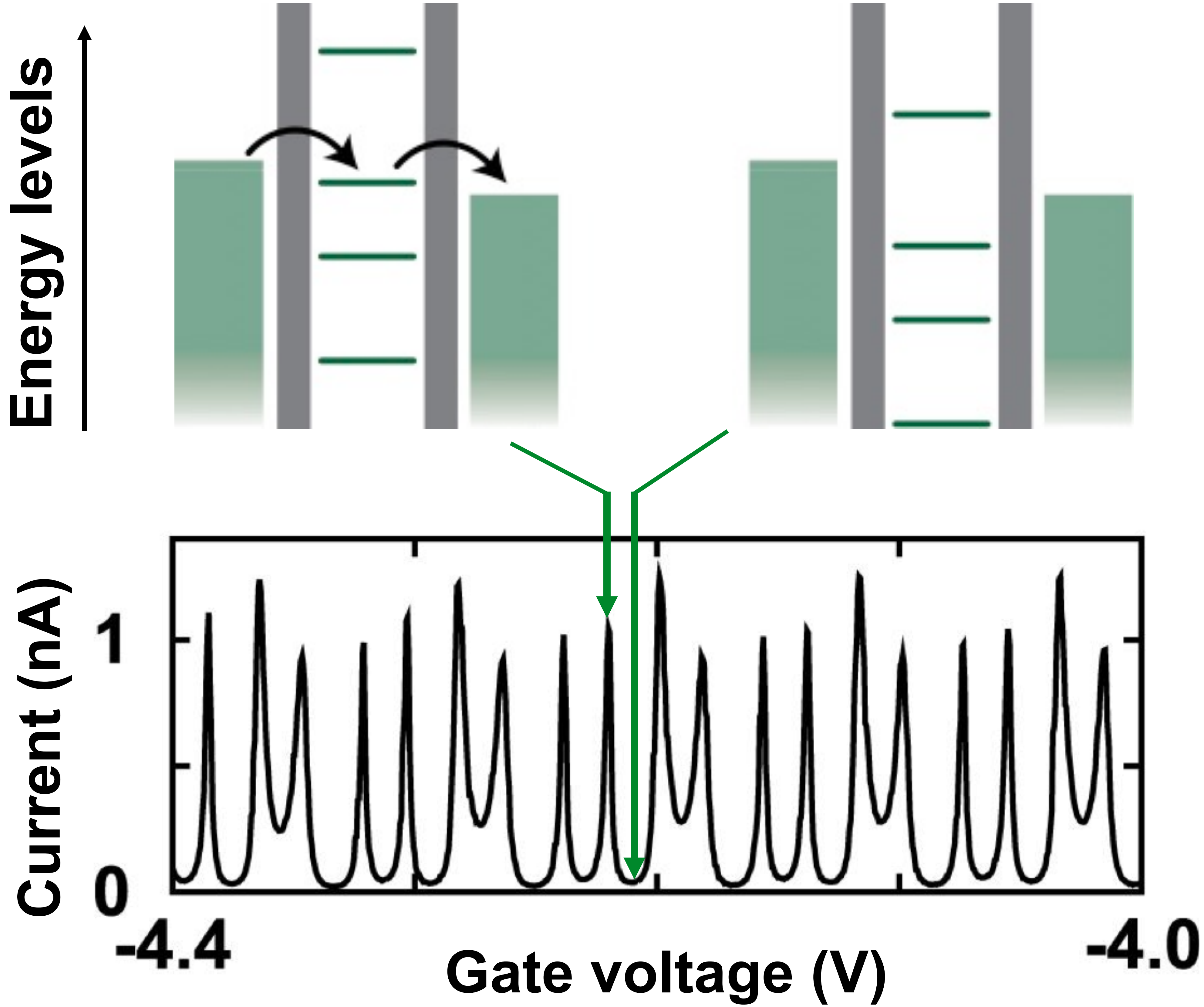


A vibrating carbon nanotube device



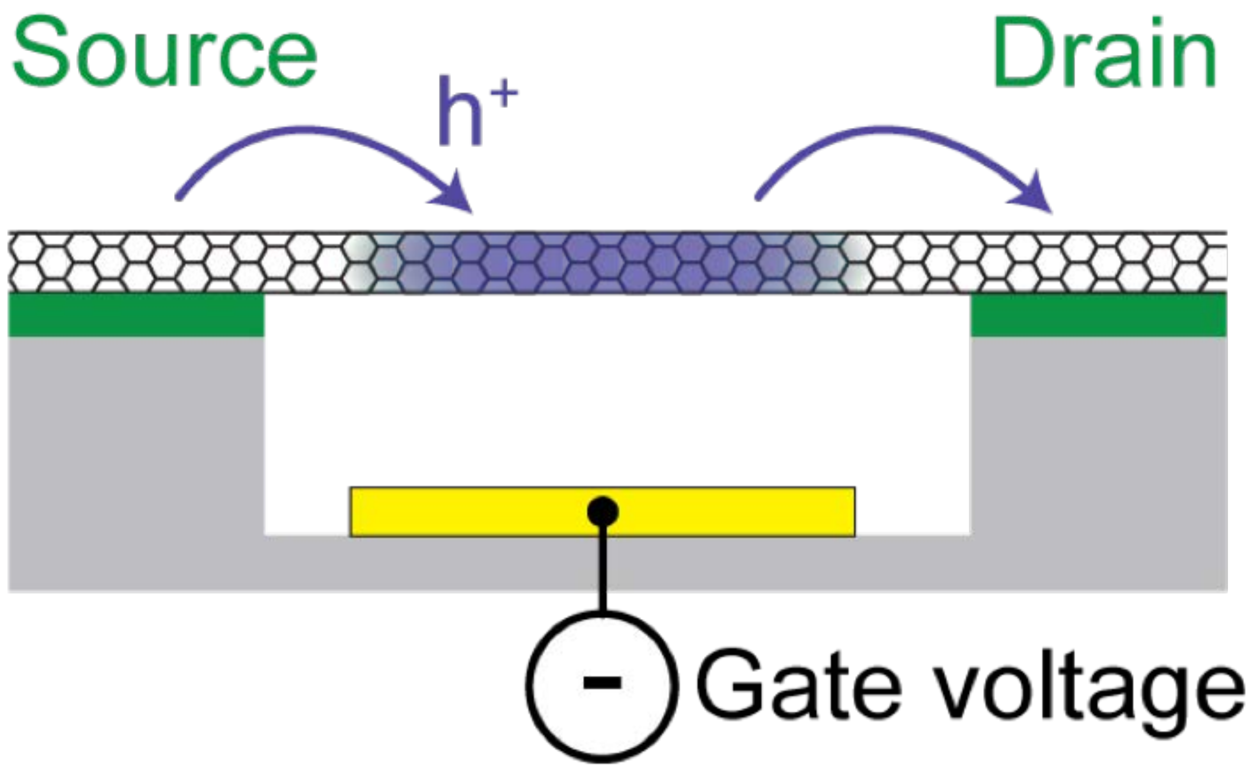
The single-electron transistor

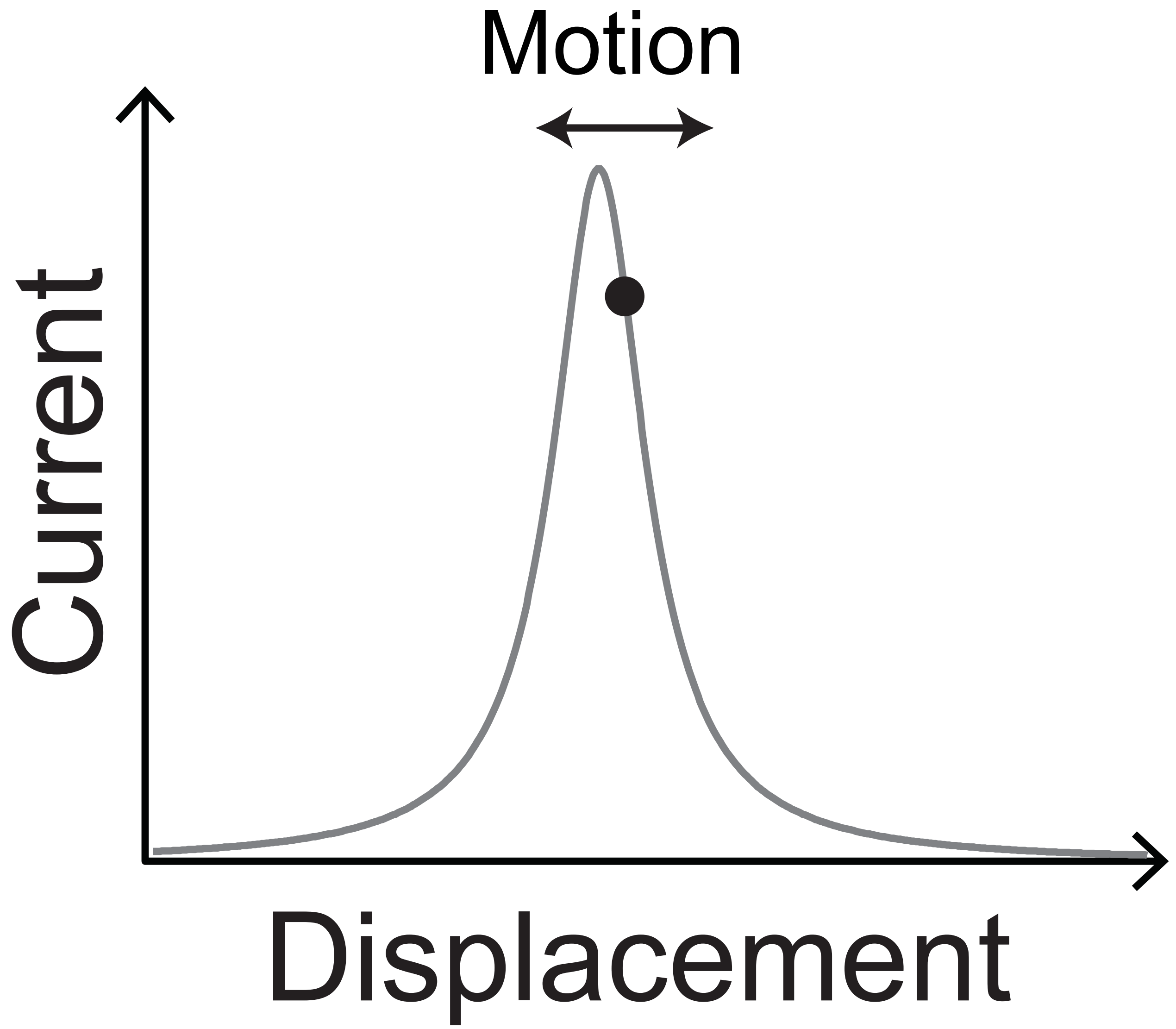




Hüttel et al (van der Zant group, 2009)

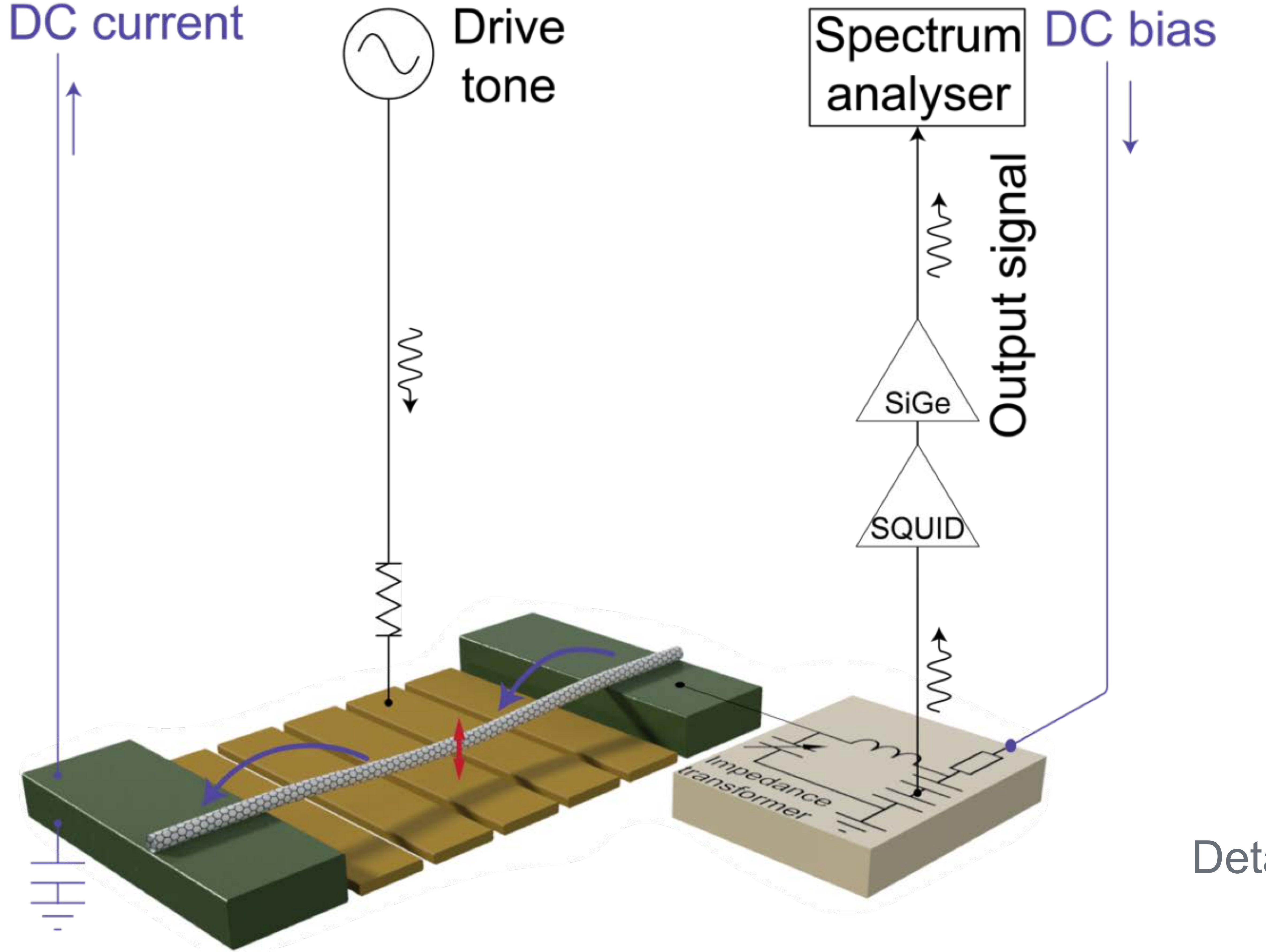
Sensing vibrations

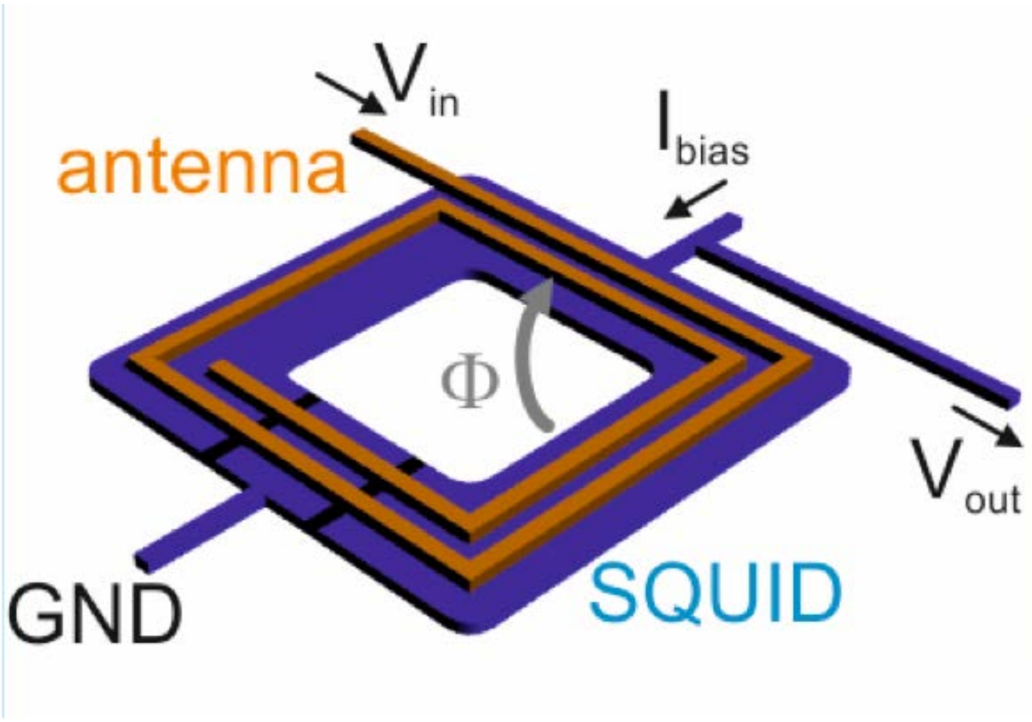




Hüttel et al (2009)

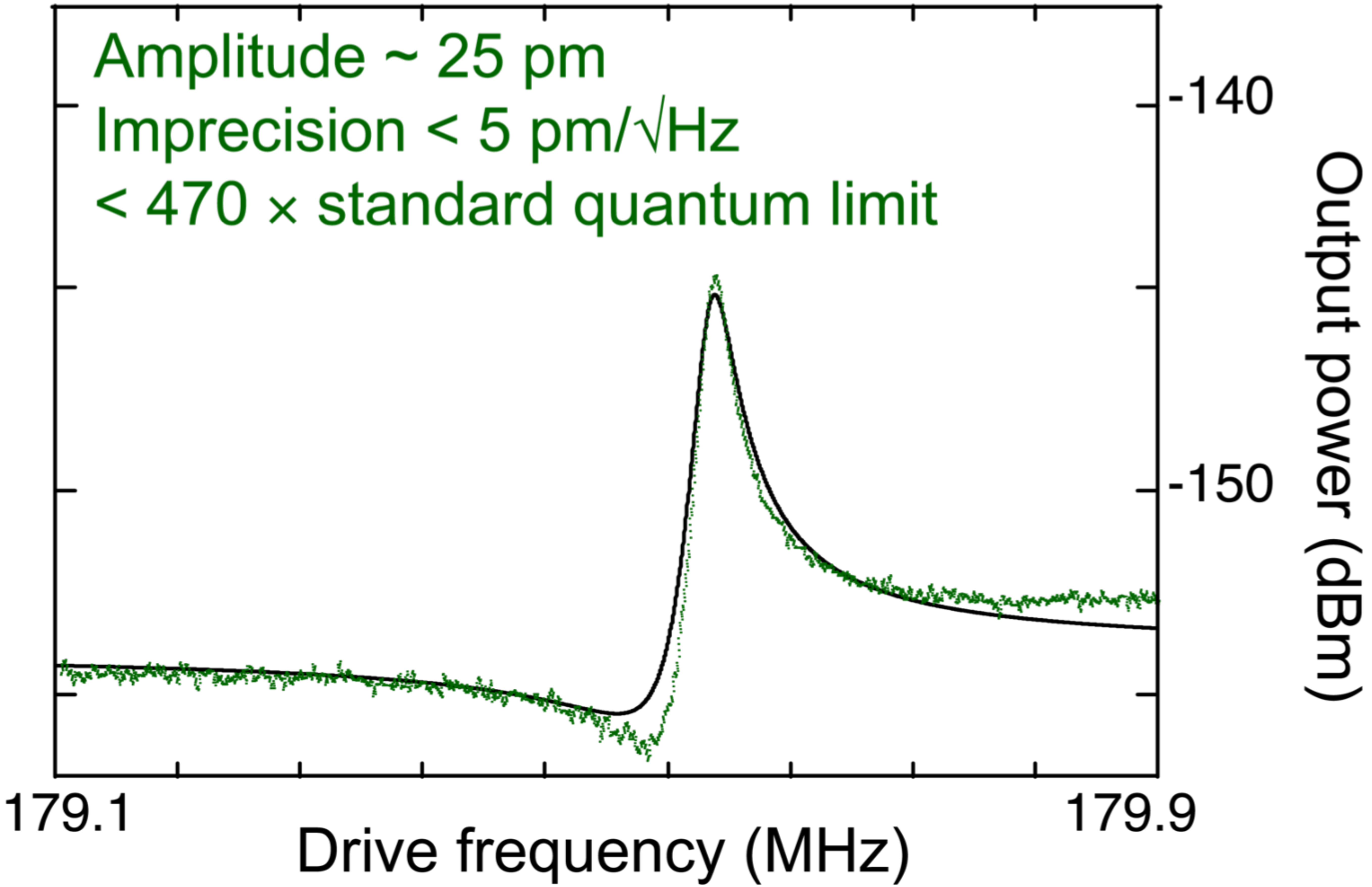
Fast readout for nanotube vibrations



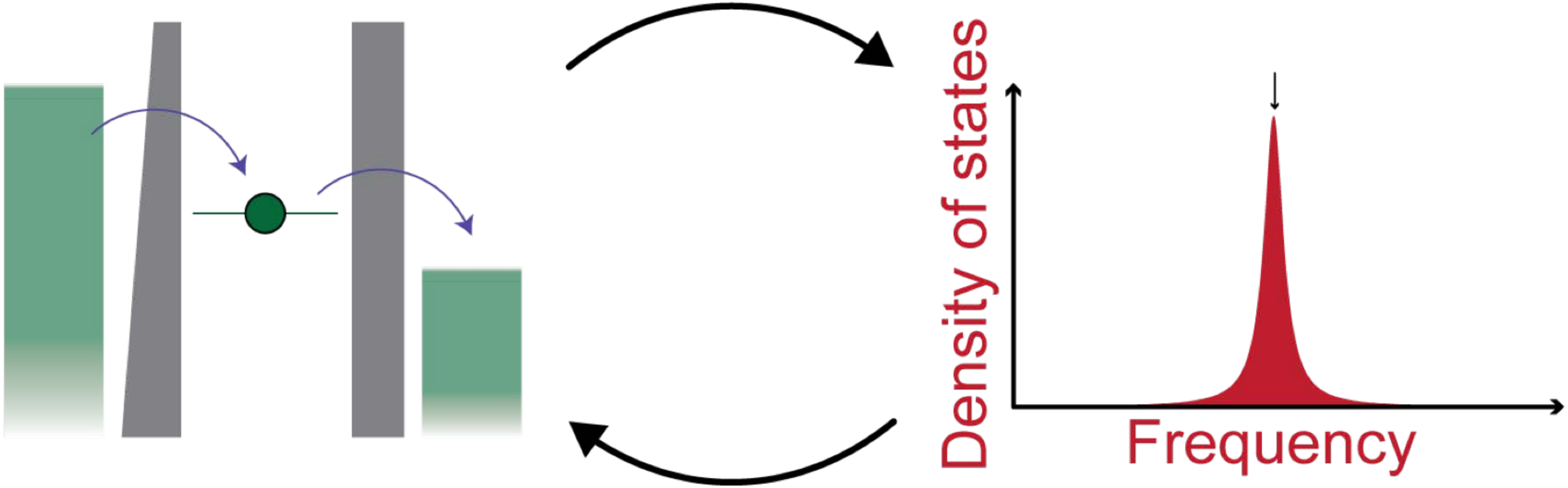


Details: Wen et al. (2018)
Schupp et al. (2018)

How precisely can we measure nanomechanical vibrations?



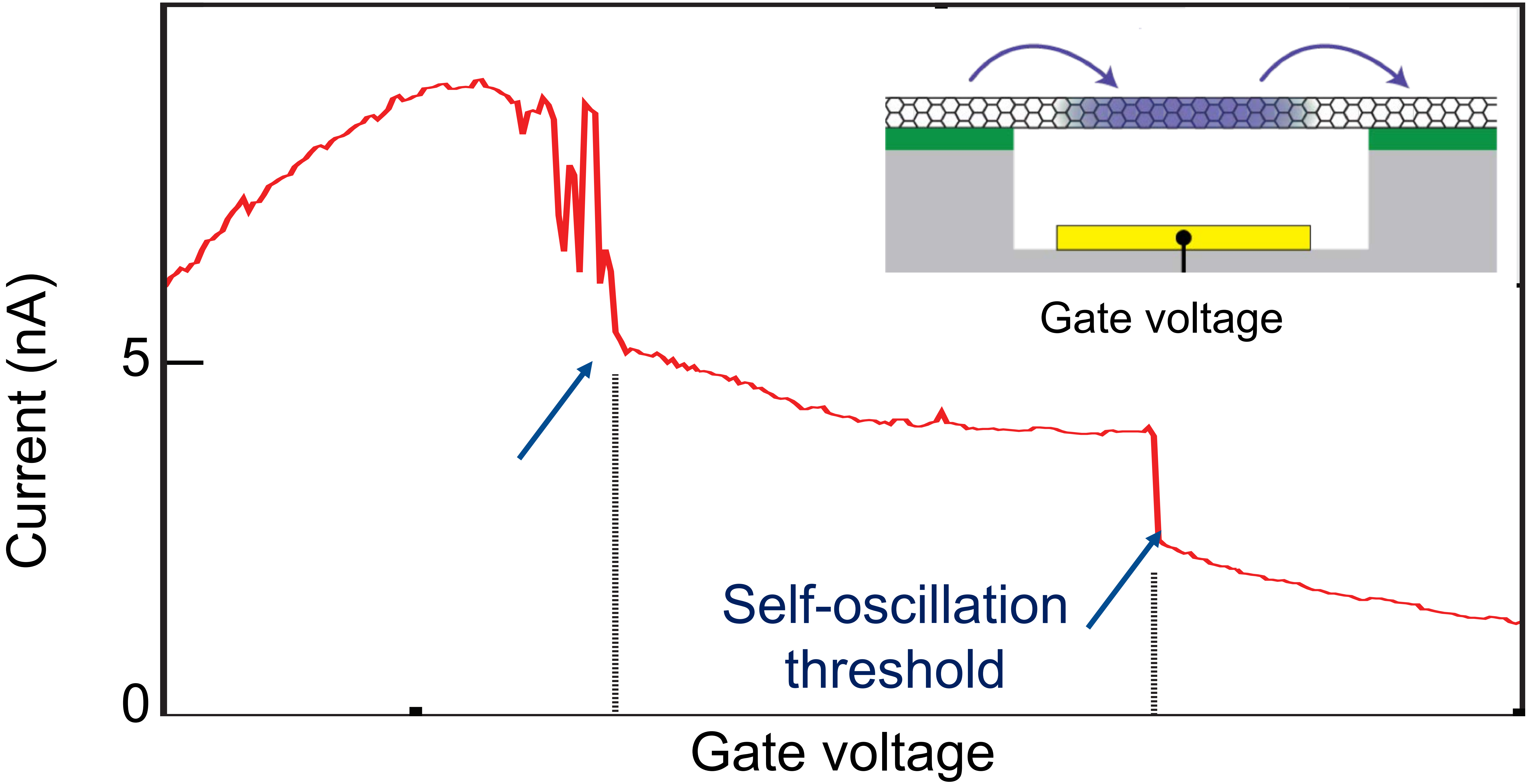
Is this a laser analogue?



Two-level system

Resonator

Evidence for *self-driven* oscillations



From Steele et al (Kouwenhoven group, 2009)

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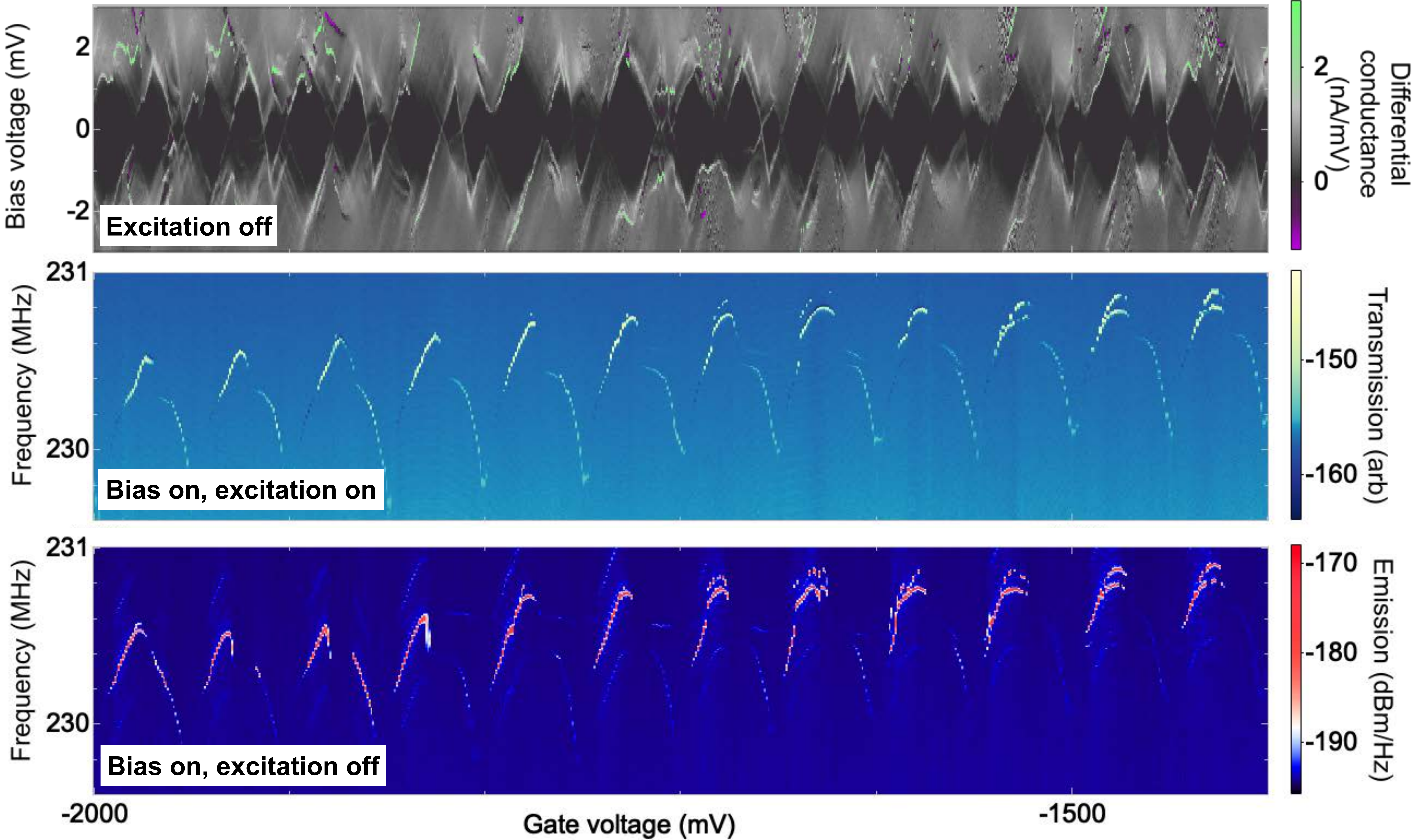
1. Measuring vibrations with a single-electron transistor

2. **Creating a nanomechanical oscillator**

3. Characterizing the oscillator



Bias voltage (mV)
2
0
-2
Excitation off
Differential conductance (nA/mV)
2
0
231
Frequency (MHz)
230
Bias on, excitation on
Transmission (arb)
-150
-160
231
Frequency (MHz)
230
Bias on, excitation off
Emission (dBm/Hz)
-170
-180
-190
-2000
Gate voltage (mV)
-1500

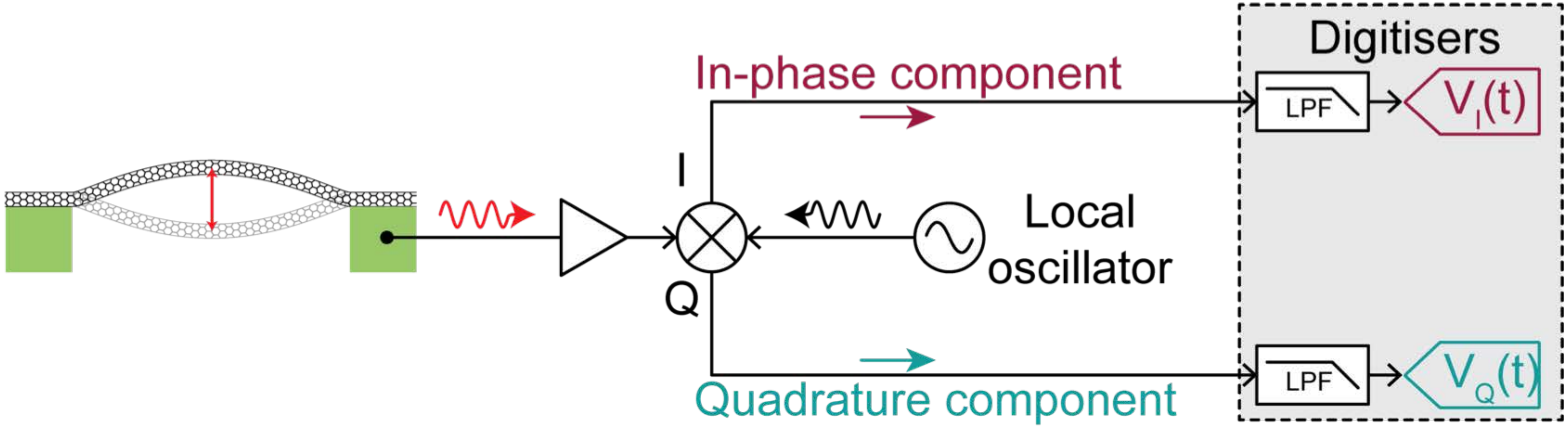
A coherent nanotube oscillator driven by electromechanical backaction

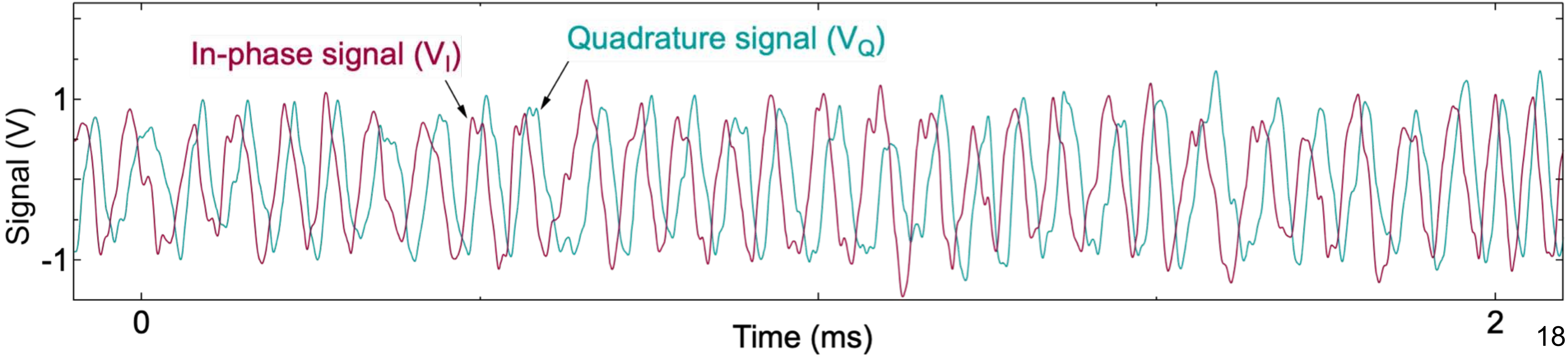
1. Measuring vibrations with a single-electron transistor

2. Creating a nanomechanical oscillator

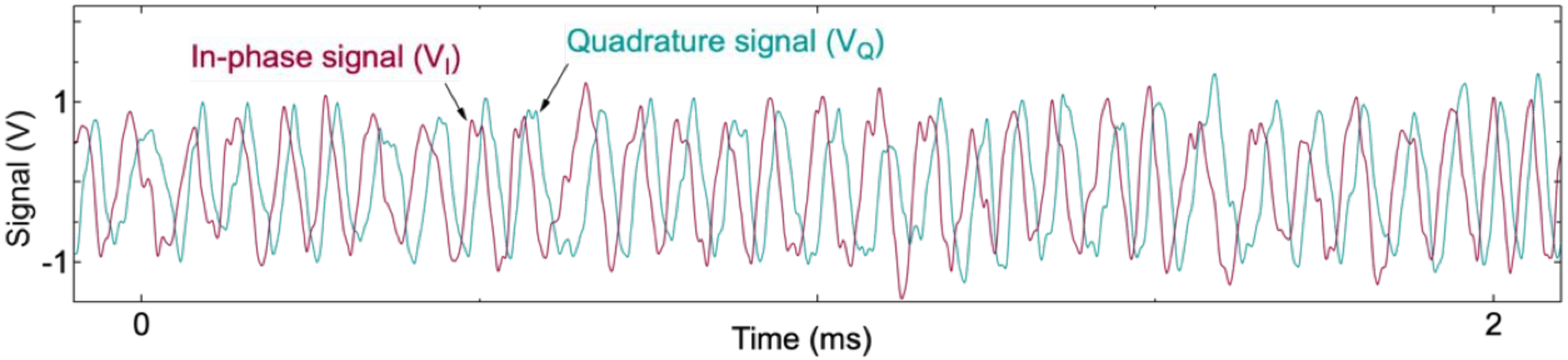
3. **Characterizing the oscillator**

Measuring the output coherence

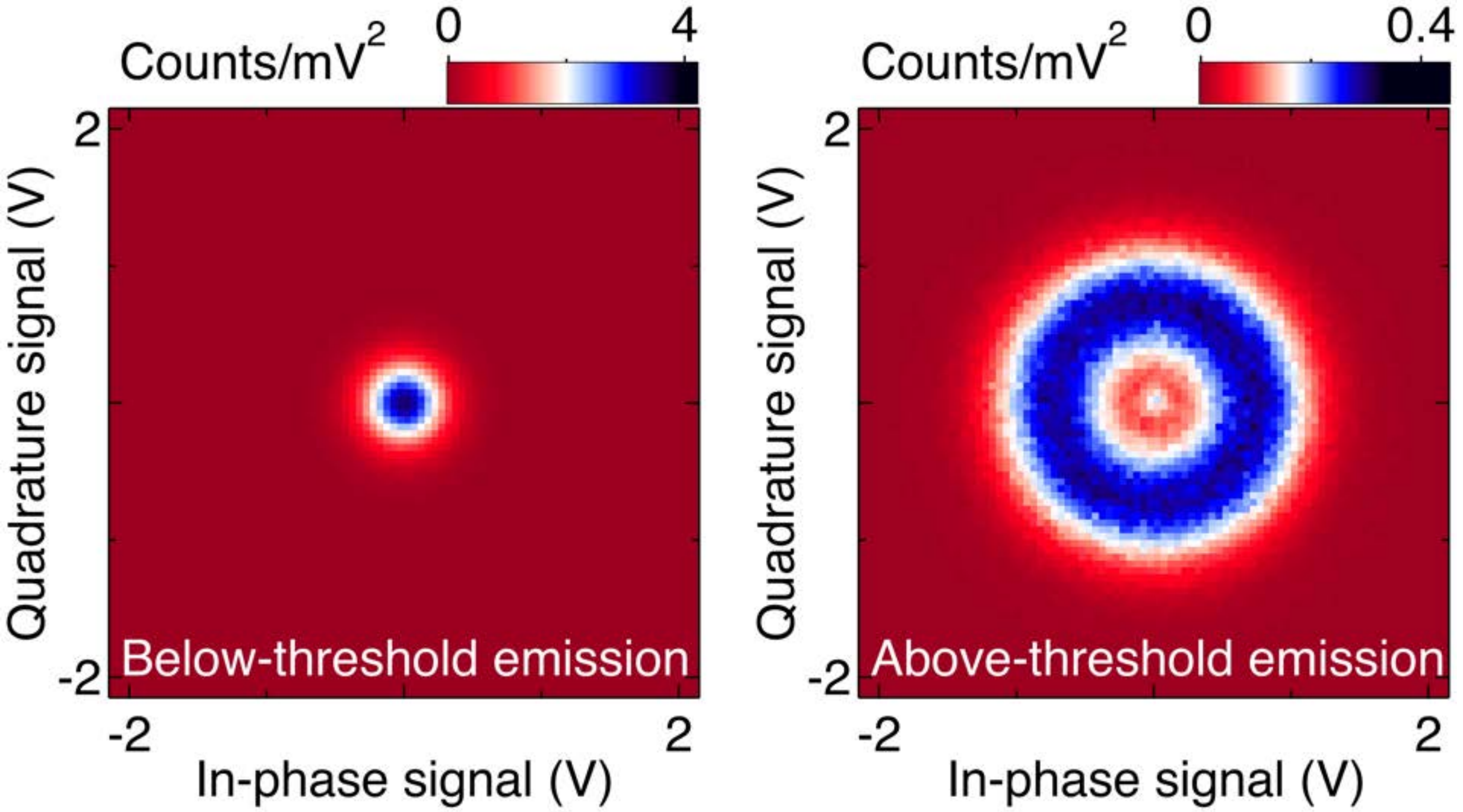




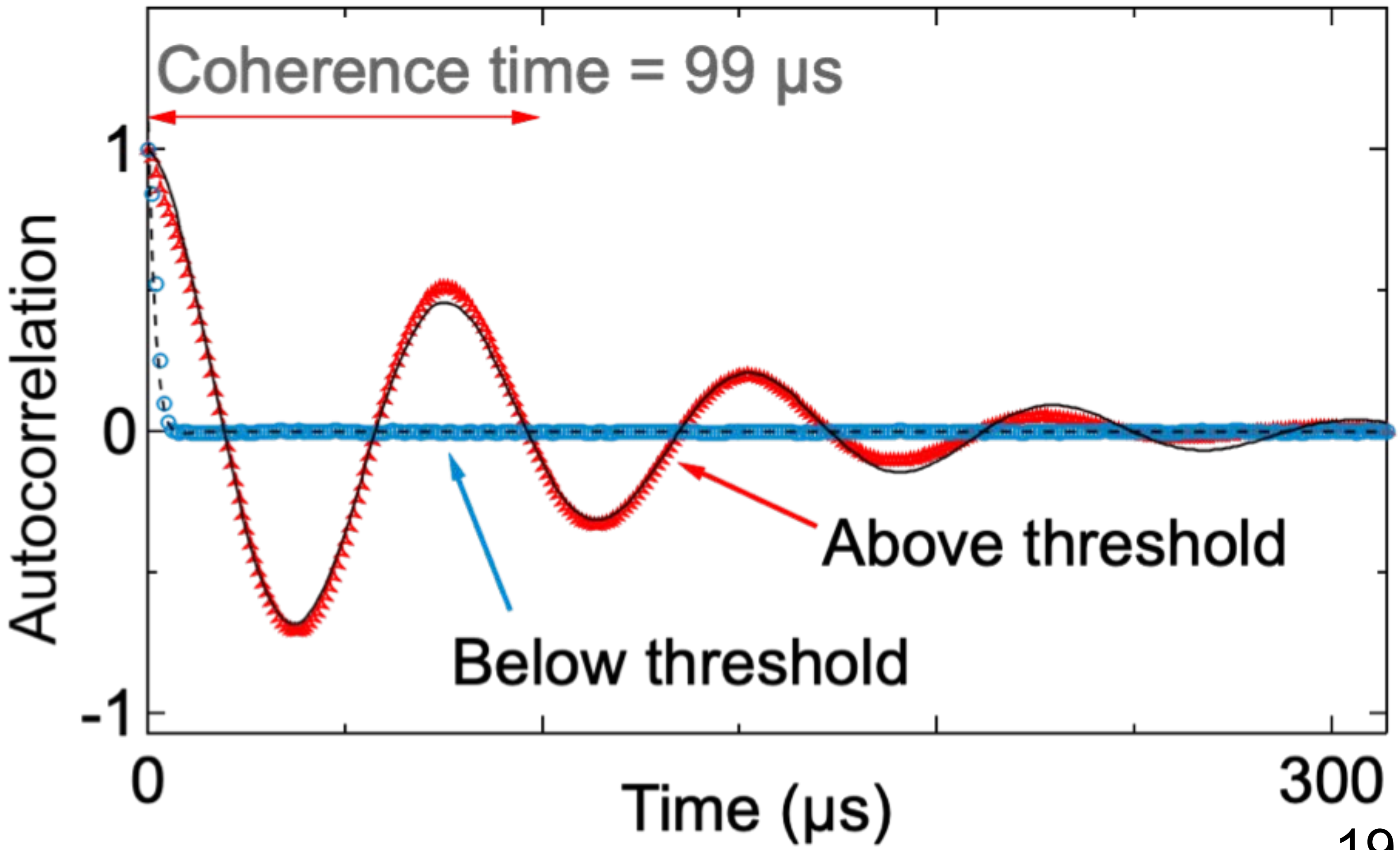
Statistics of the output coherence



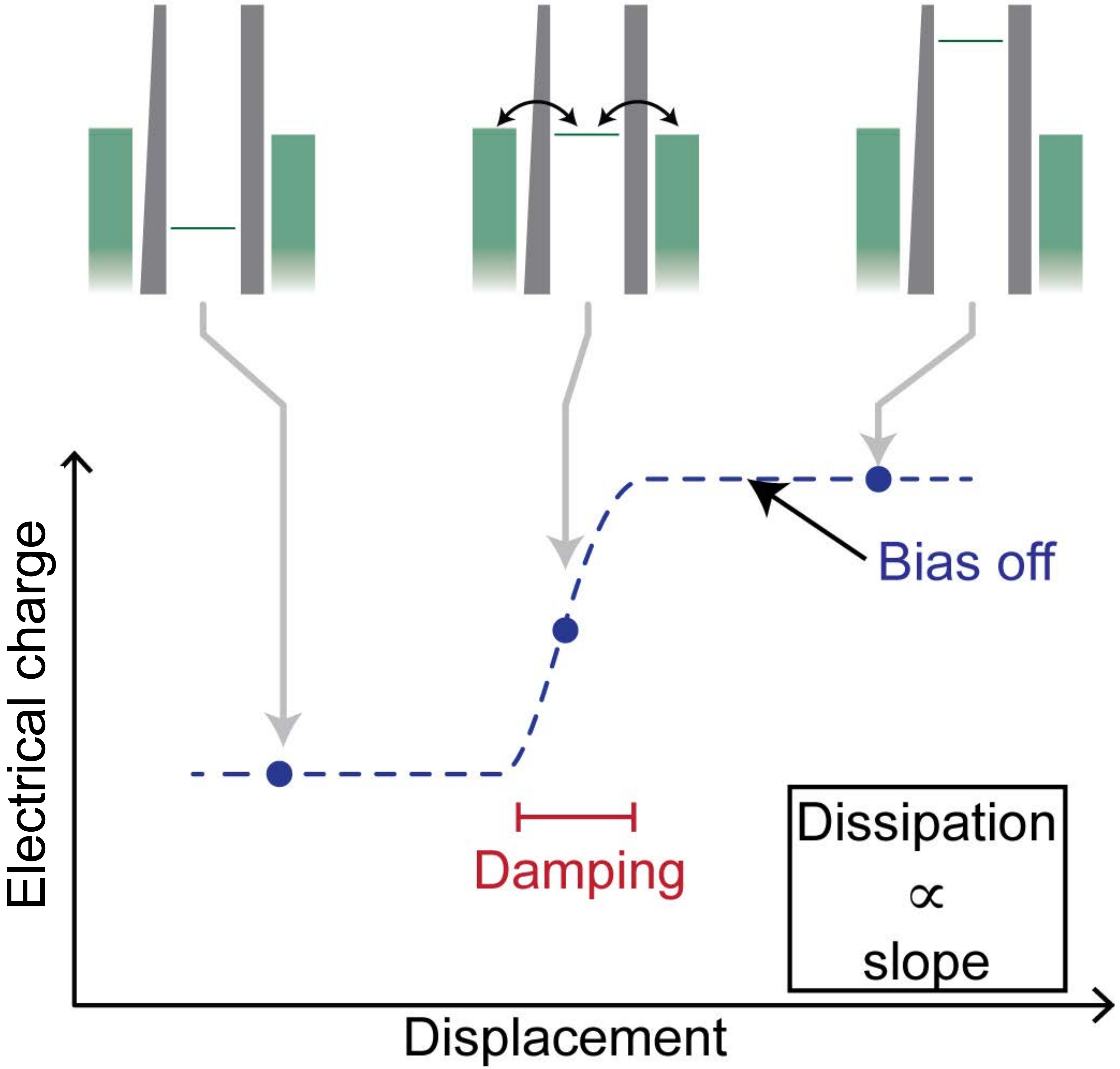
Emission histograms



Correlation function

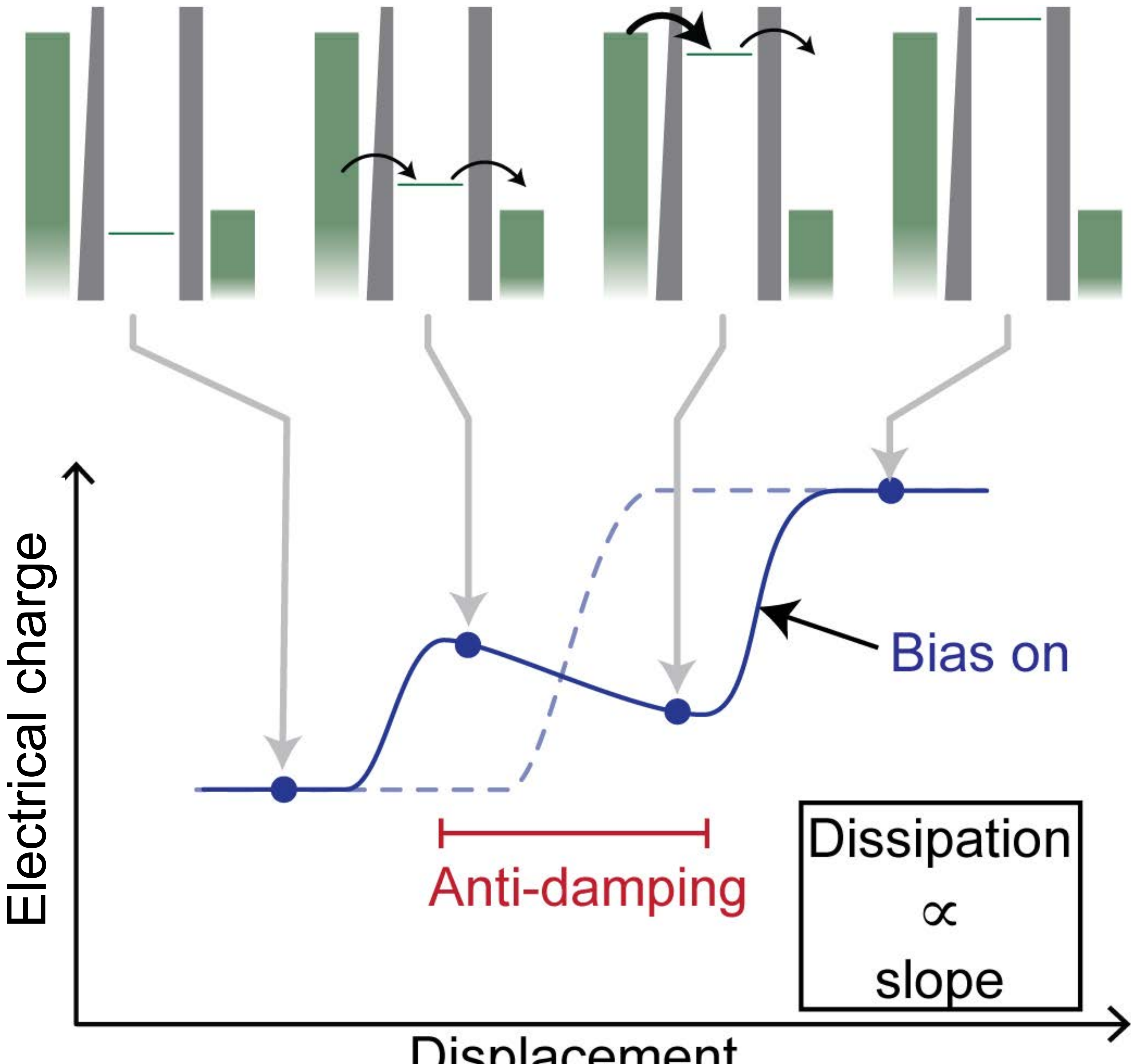


How the oscillator works



Bennet & Clerk (2007)
Usmani, Blanter, Nazarov (2007)

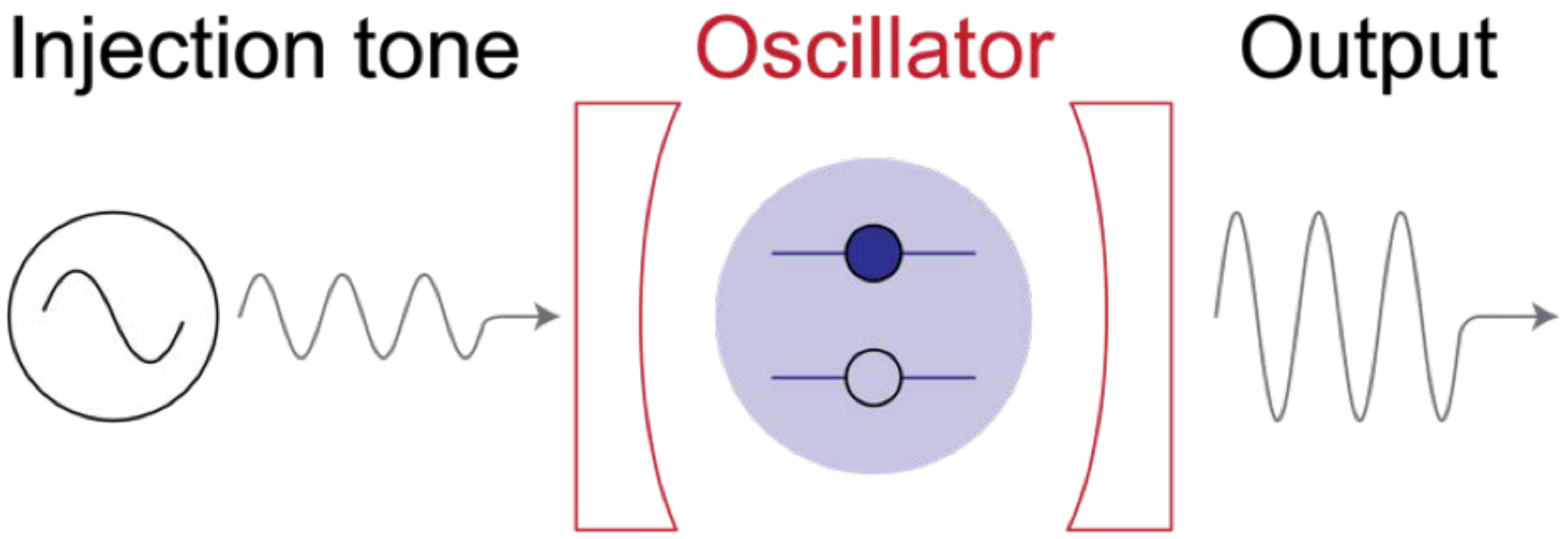
How the oscillator works



Bennet & Clerk (2007)
Usmani, Blanter, Nazarov (2007)

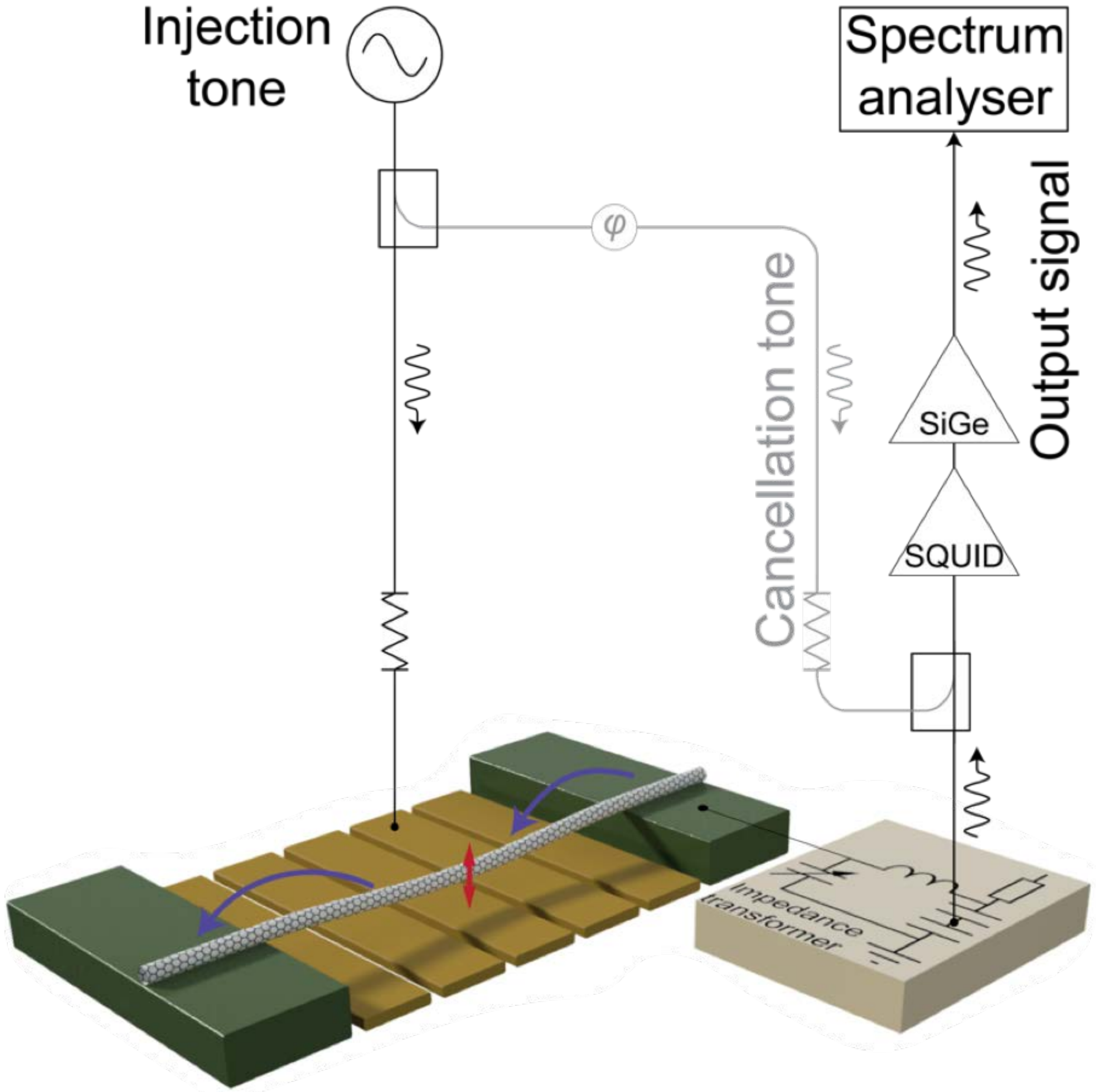
Laser physics I: Injection locking

Principle

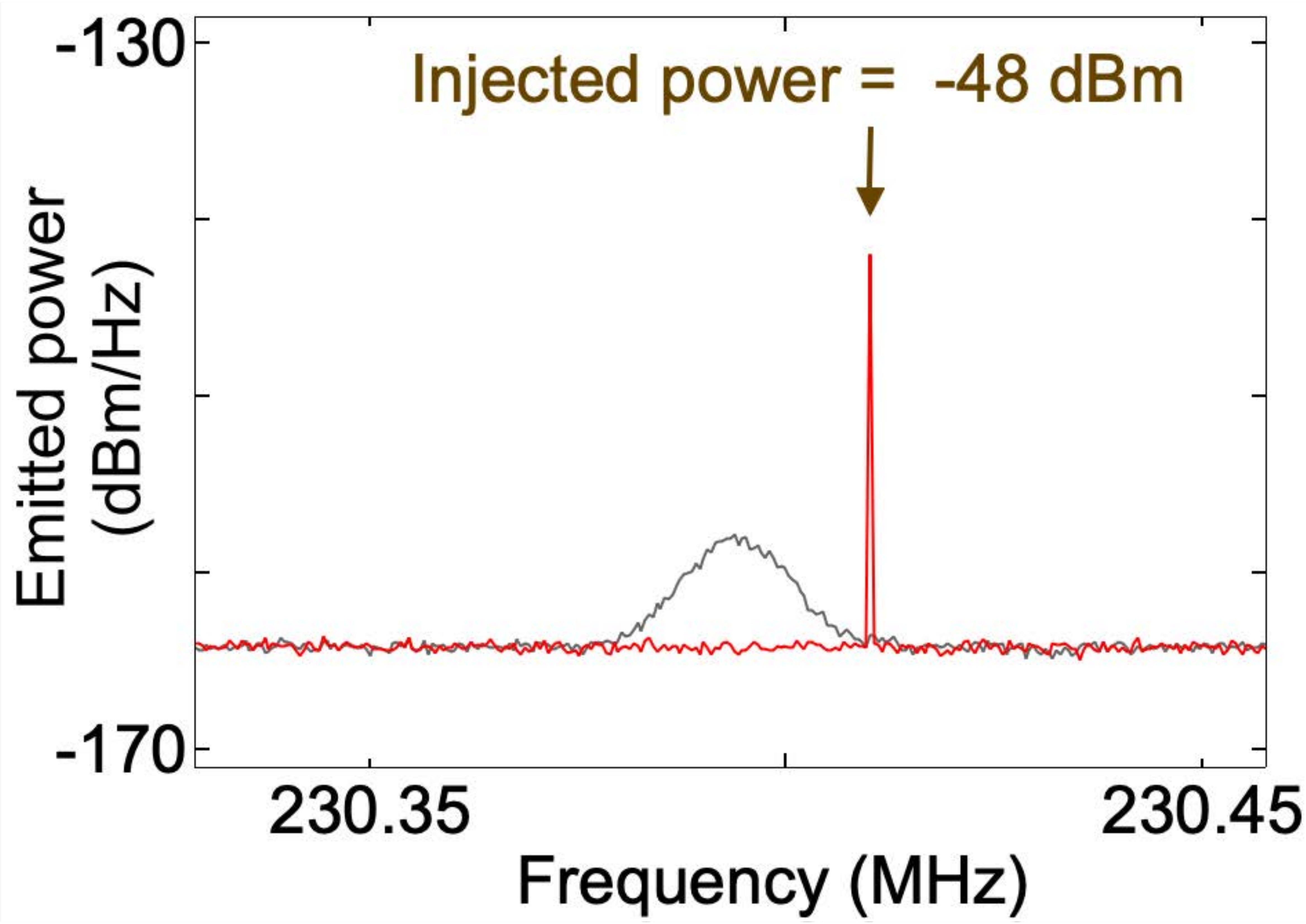


Discovery: Huygens (1666)
In lasers: Stover and Steier (1966)

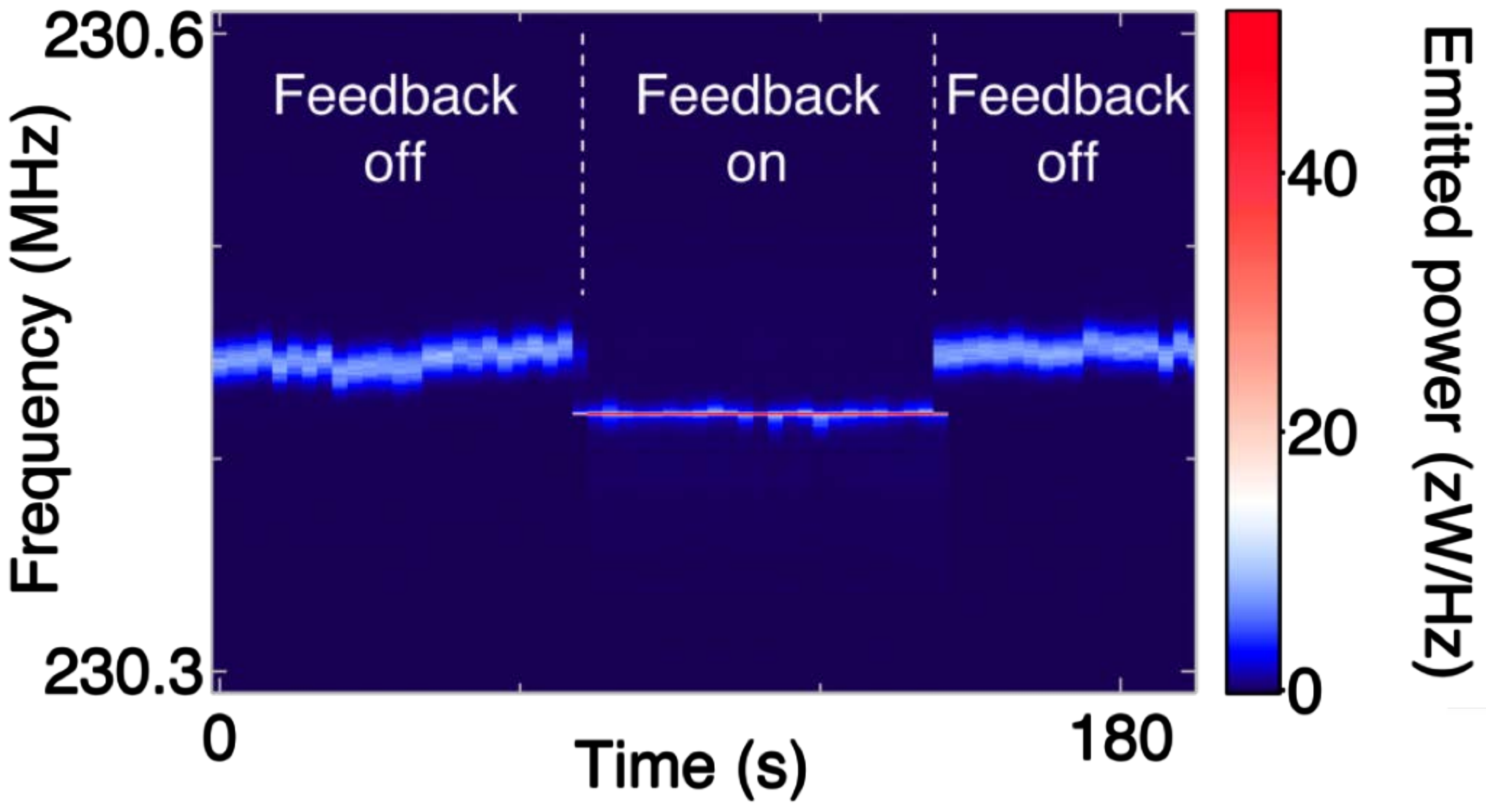
Implementation

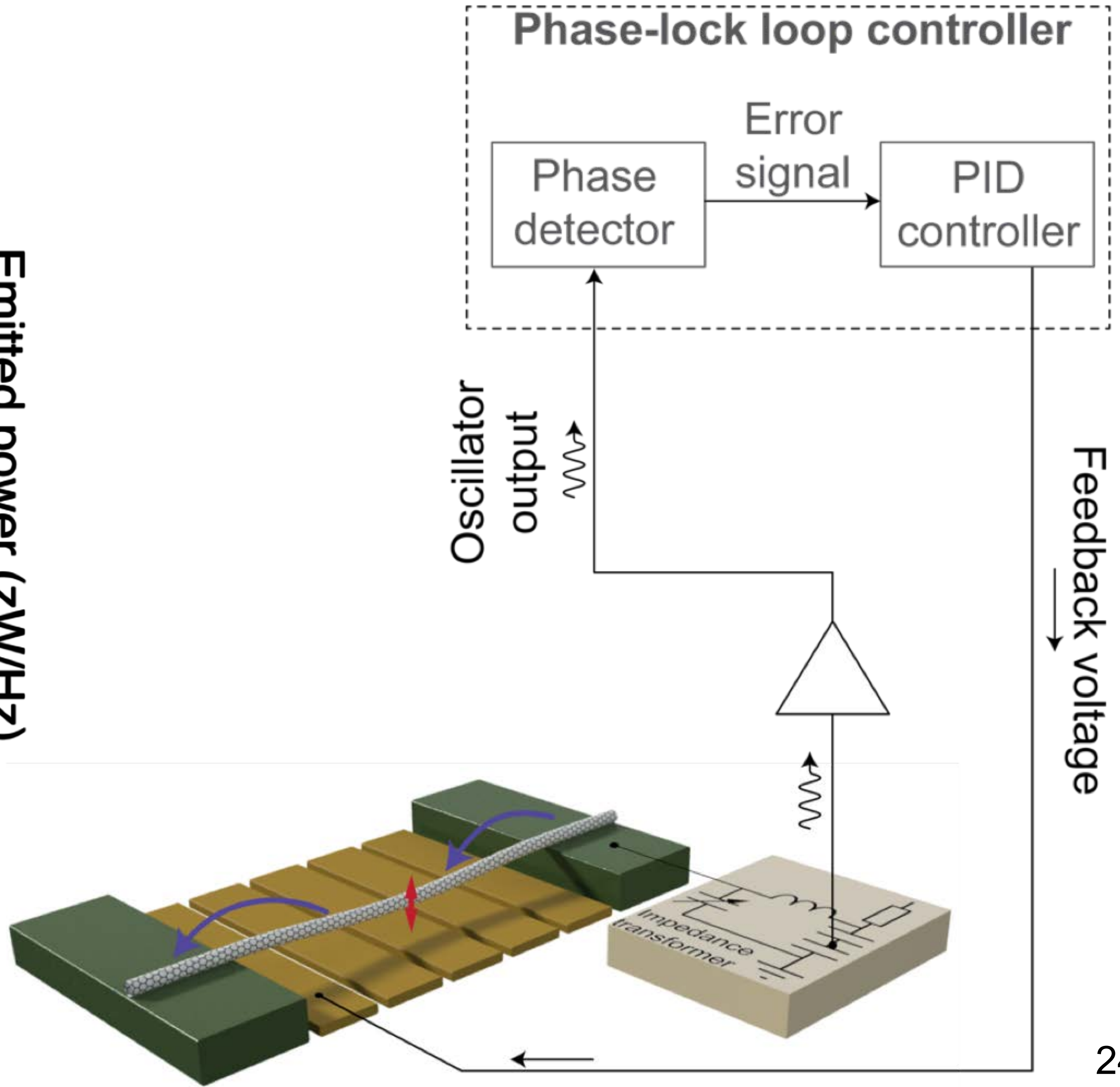


Laser physics I: Injection locking

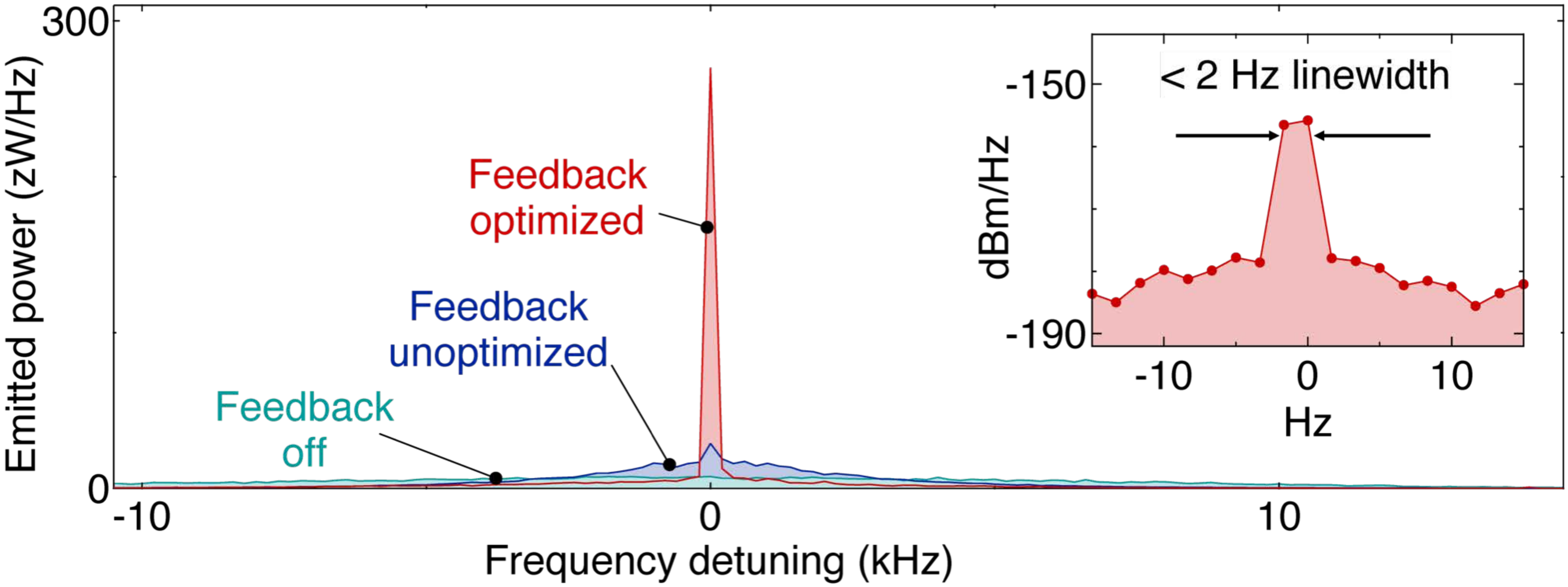


Laser physics II: Stabilising using feedback





Laser physics II: Stabilising using feedback

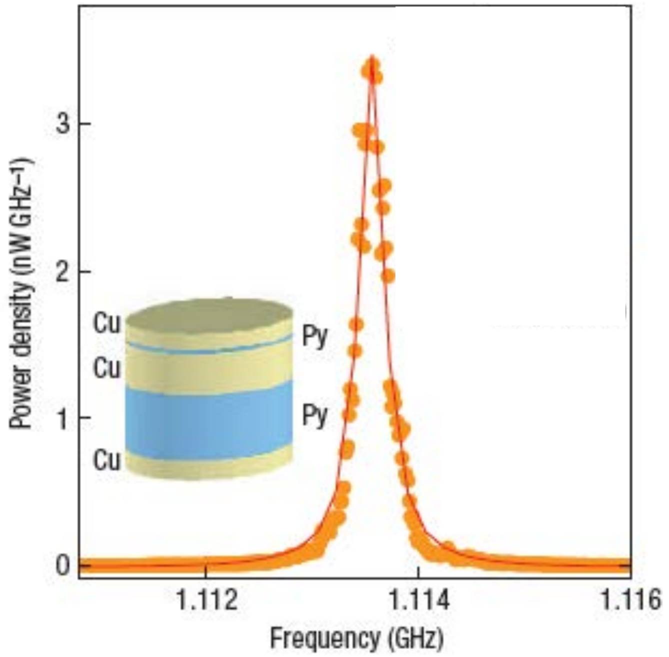


Why are nanomechanical lasers interesting?

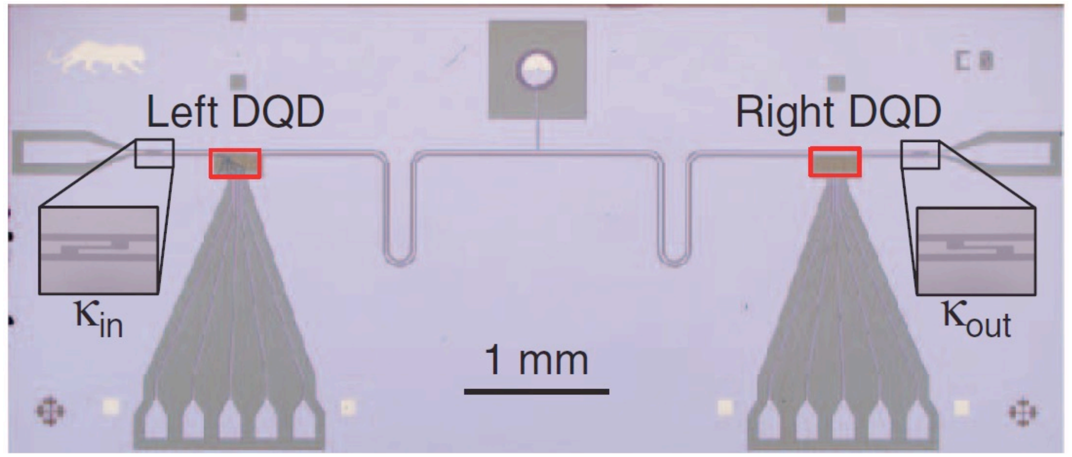
- They connect the physics of backaction with the physics of lasers.
- They are amplifiers and transducers. Narrow linewidth means better sensitivity to perturbations.
- They are on-chip phonon generators for microscopy, information transfer, etc.
- They couple charge and motion on a mesoscopic scale.

Other nano-oscillators

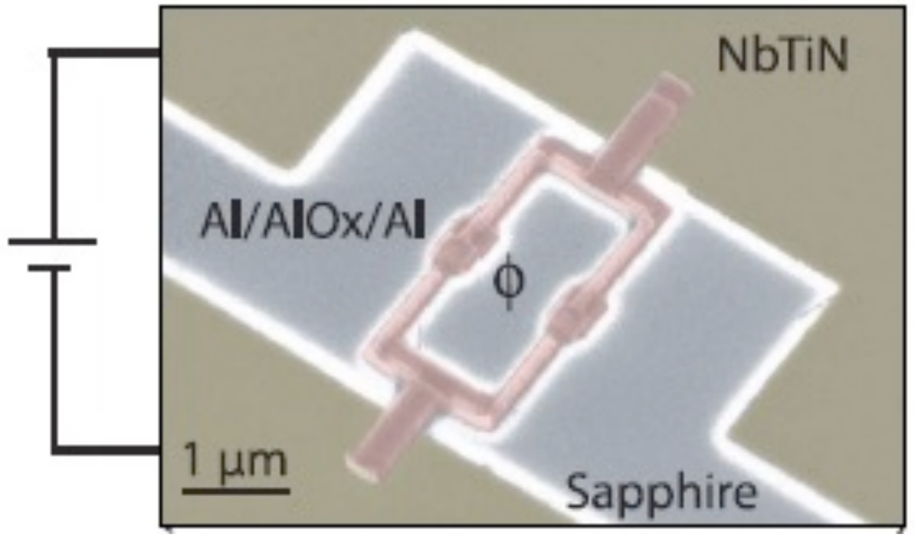
Electrical



Spin transfer torque
(Pribiag 2007)

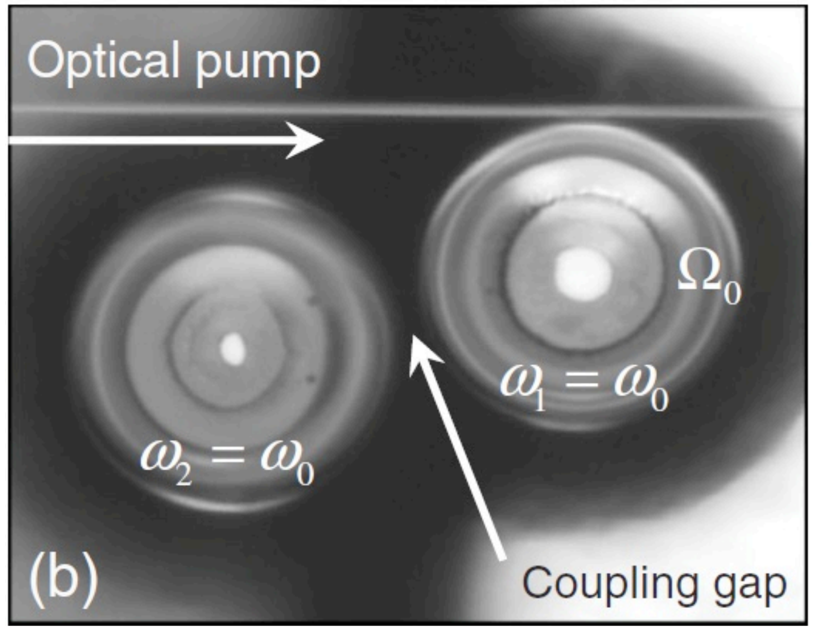


Double quantum dot micromaser
(Liu 2017)

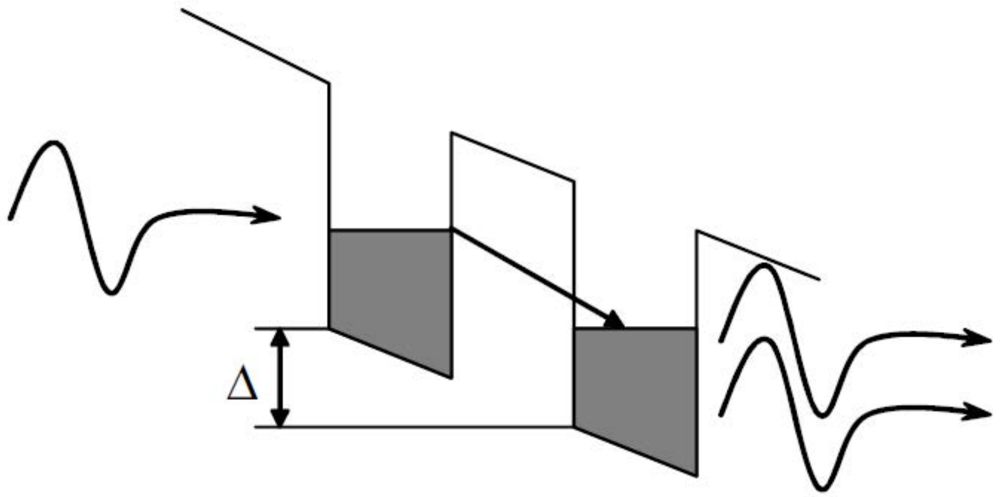


Josephson laser
(Cassidy 2017)

Mechanical



Optomechanics
(Grudinin 2010)

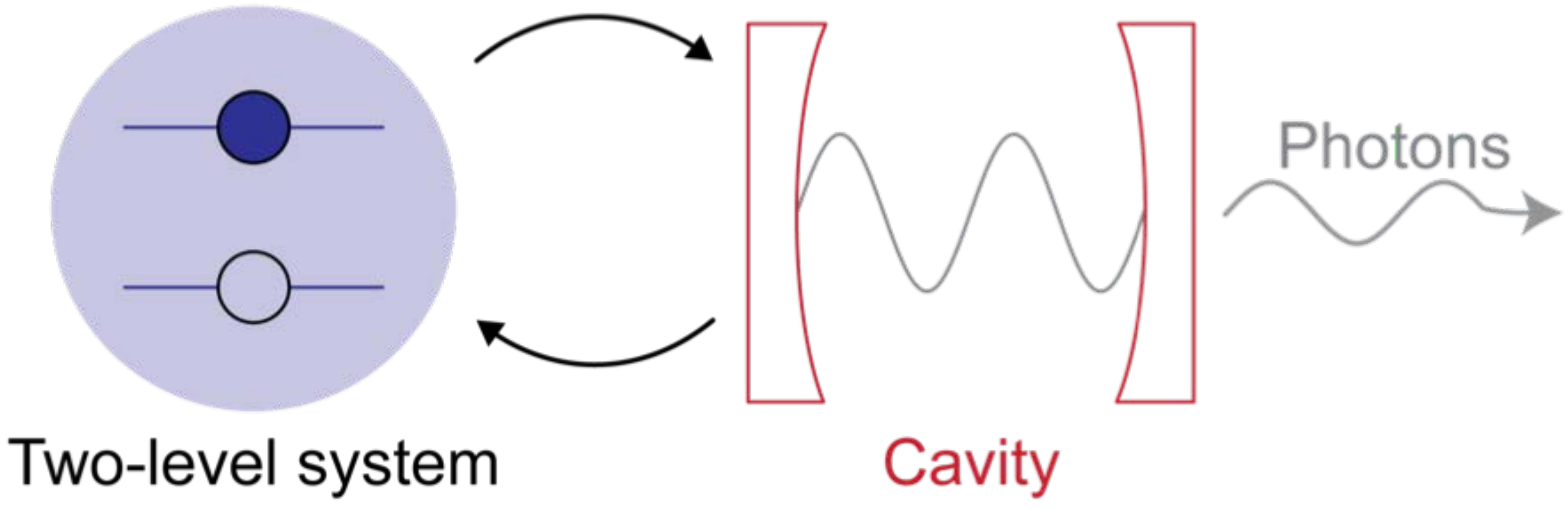


Optomechanics
(Beardsley 2010)

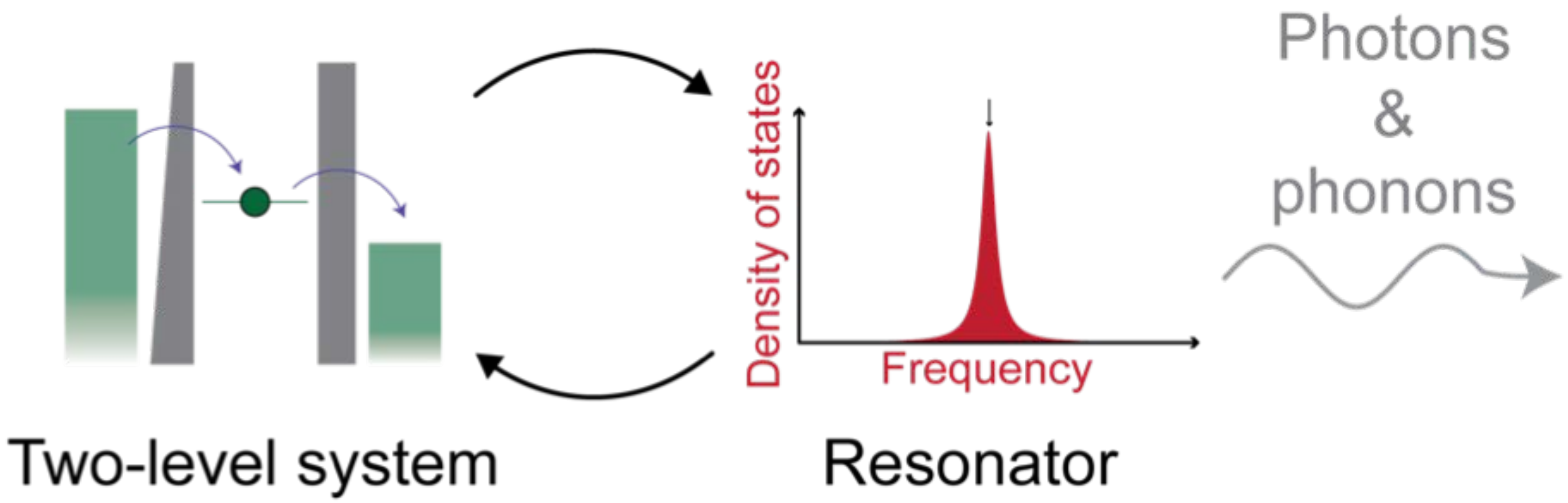
Vibrating SQUID
(Etaki 2013)

Summary

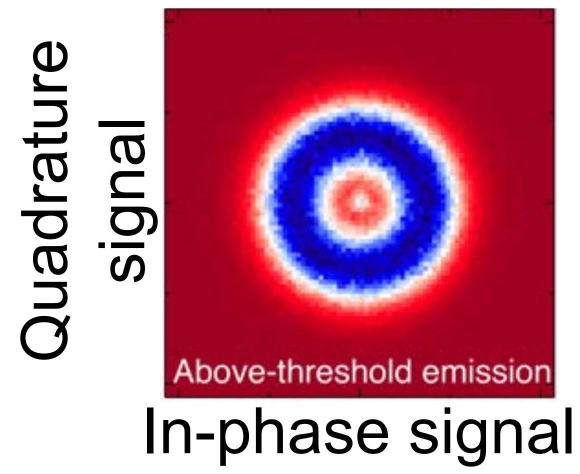
Maser



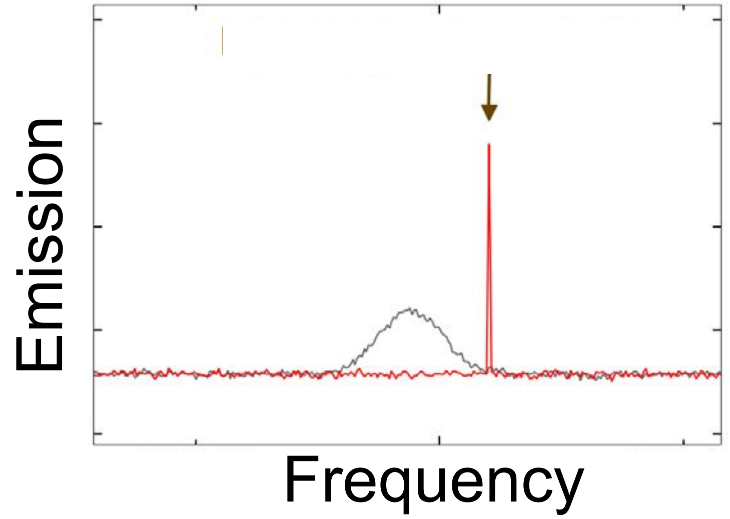
Nanotube oscillator



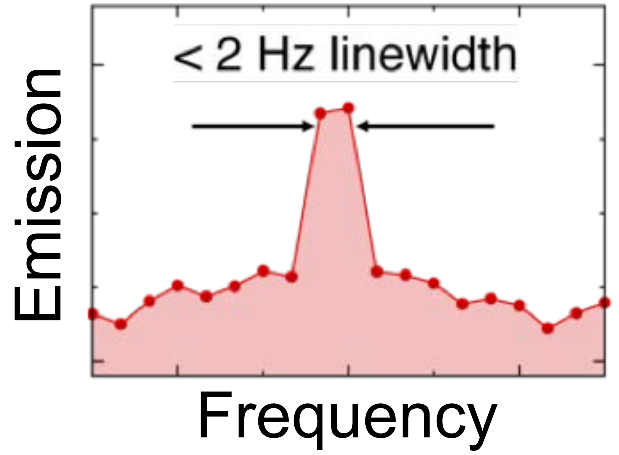
Classical coherence



Injection locking



Feedback stabilisation



Ares et al. *PRL* 2016 **117** 170801 (2016)
Schupp et al. arXiv:1810.05767 (2018)
Wen et al. *APL* **113** 153101 (2018)
Wen et al. arXiv:1903.04474 (2019)