Cavity optomechanics: from gravitational wave detection to quantum computing

Mathieu Juan
Institut Quantique et Université de Sherbrooke

Quantum optomechanics: from gravitational wave detection to quantum computing

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A long long time ago, far far away

NEOWISE Comet (2020)

A long long time ago, far far away

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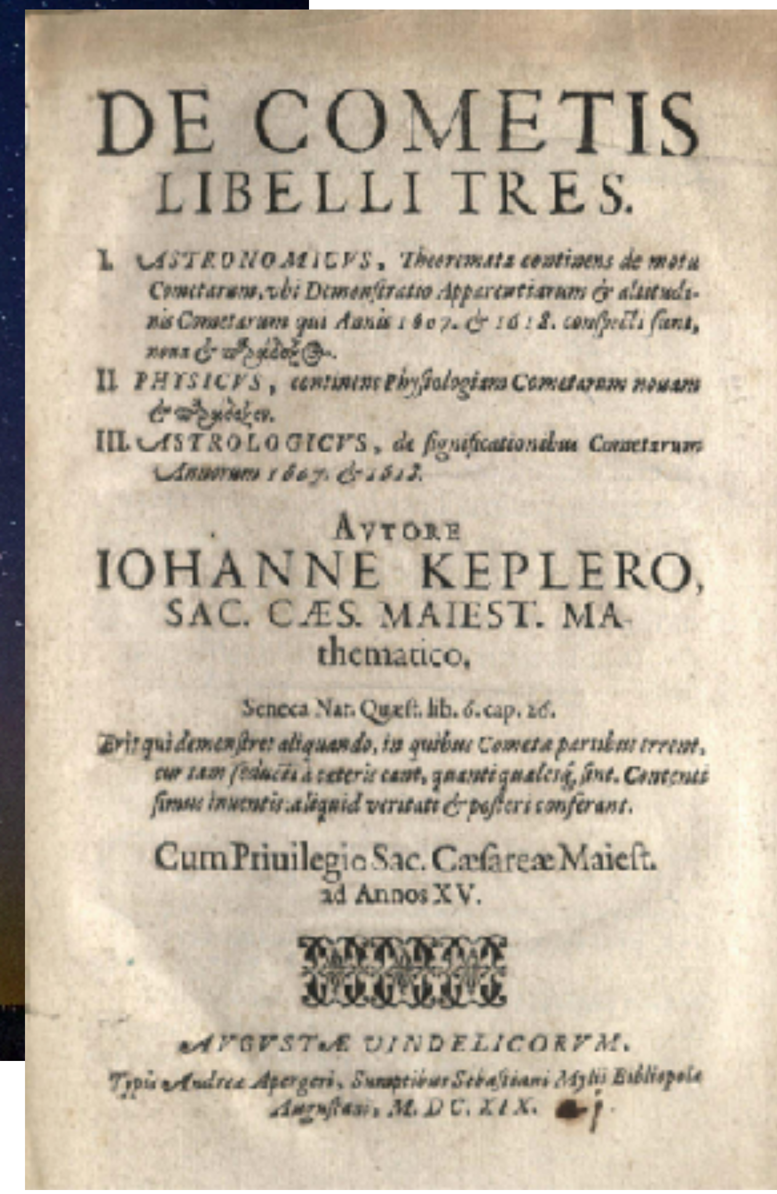


DE COMETIS
LIBELLI TRES.

I. ASTRONOMICVS, Theoremata continens de motu Cometarum, vbi Demonstratio Apparentiarum & altitudinis Cometarum qui Annis 1607. & 1618. conspecti sunt, noua & [illegible].

II. PHYSICVS, continens Physiologiam Cometarum nouam & [illegible].

III. ASTROLOGICVS, de significationibus Cometarum Annorum 1607. & 1618.

AVTORE
IOHANNE KEPLERO,
SAC. CÆS. MAIEST. MAthematico,

Seneca Nat. Quæst. lib. 6. cap. 26.
Erit qui demonstret aliquando, in quibus Cometa partibus errent, cur tam seducti à ceteris eant, quanti qualesq́; sint. Contenti simus inuentis: aliquid veritati & posteri conferant.

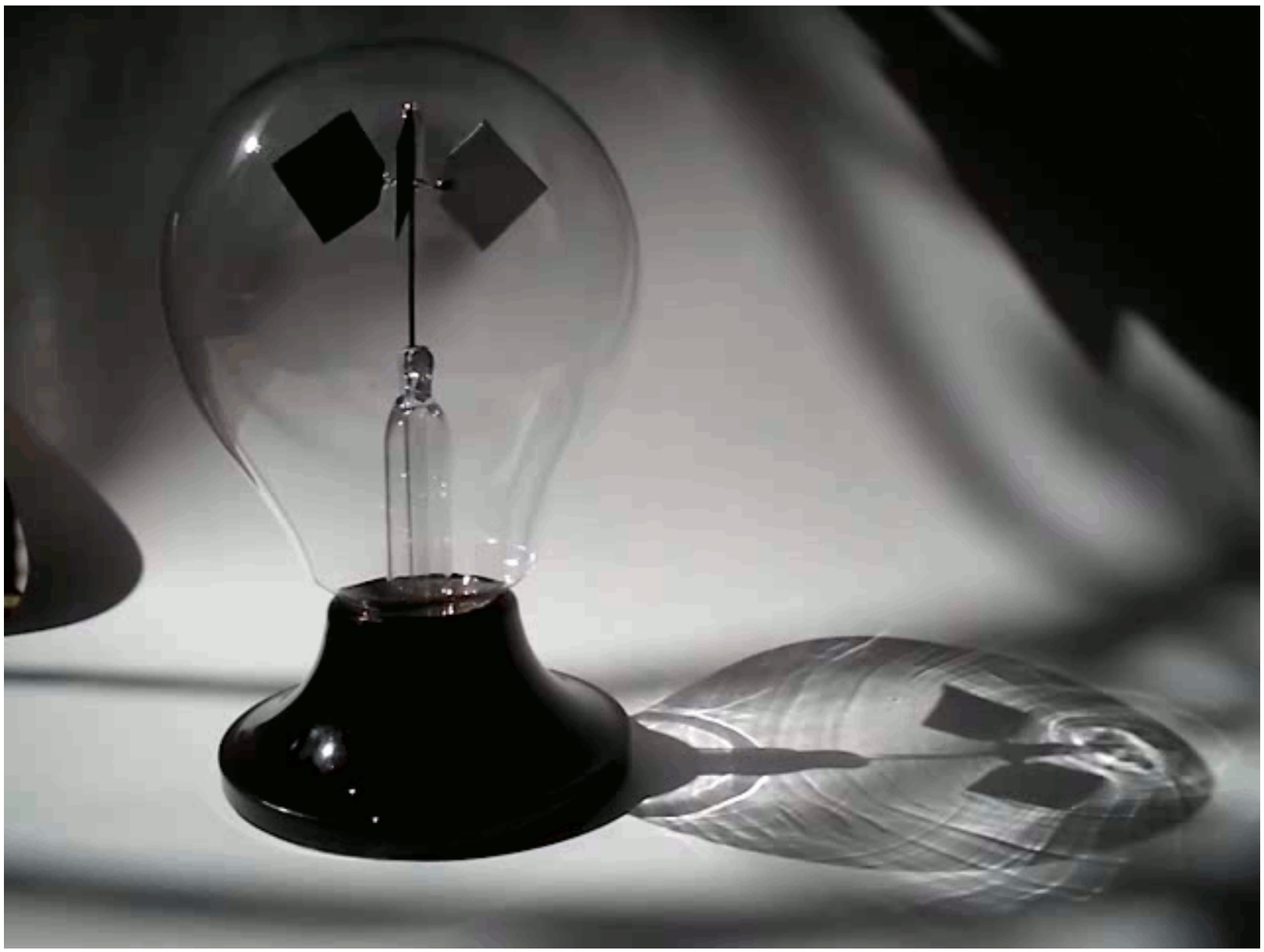
Cum Priuilegio Sac. Cæsareæ Maiest. ad Annos XV.

AVGVSTÆ VINDELICORVM.
Typis Andreæ Apergeri, Sumptibus Sebastiani Mylii Bibliopolæ Augustani, M. DC. XIX.

Johannes Kepler,
De comets 1619

Trying hard and making mistakes

Crookes radiometer



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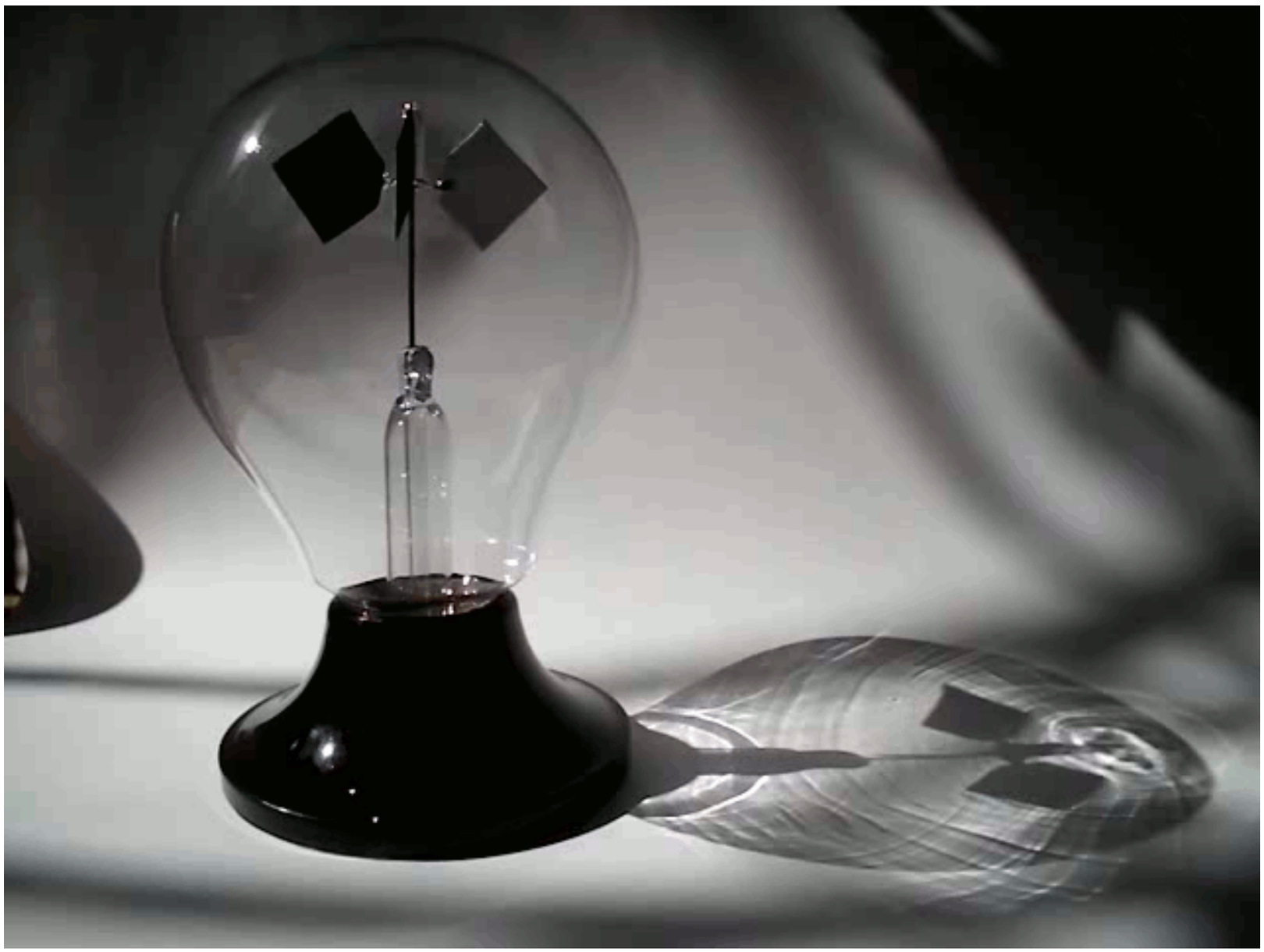


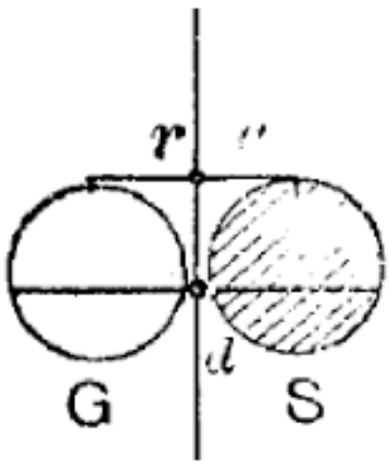
Light radiation demonstrated

Nichols and Hull, Phys. Rev. **13**, 307 (1901)

A PRELIMINARY COMMUNICATION ON THE PRESSURE OF HEAT AND LIGHT RADIATION.

By E. F. Nichols and G. F. Hull.

MAXWELL,[1] dealing mathematically with the stresses in an electro-magnetic field, reached the conclusion that "in a medium in which waves are propagated there is a pressure normal to the waves and numerically equal to the energy in unit volume."

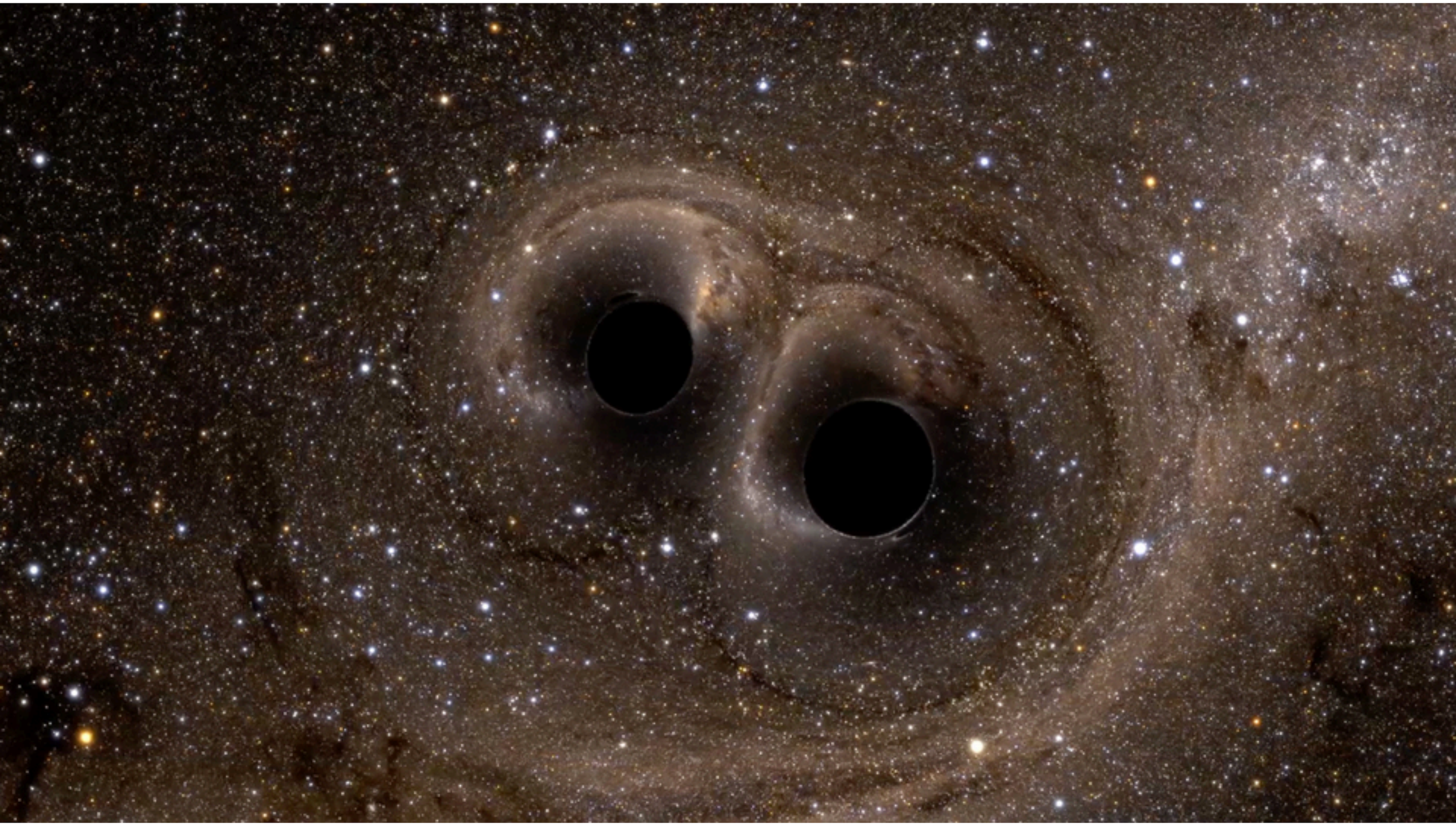


$$F = \frac{2I}{c}$$

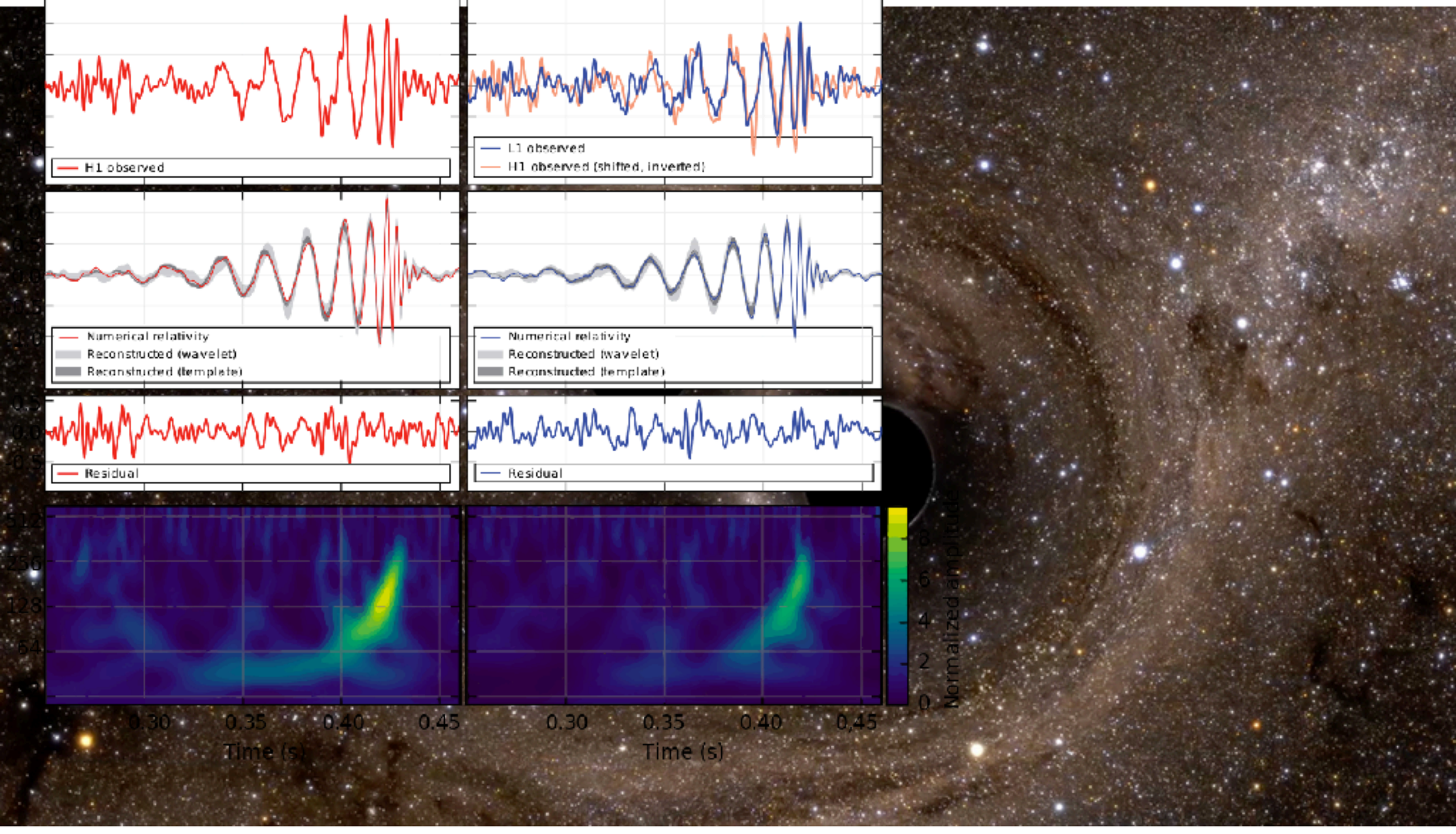
Going BIG

Laser Interferometer for Gravitational Wave Detection
LIGO Livingston

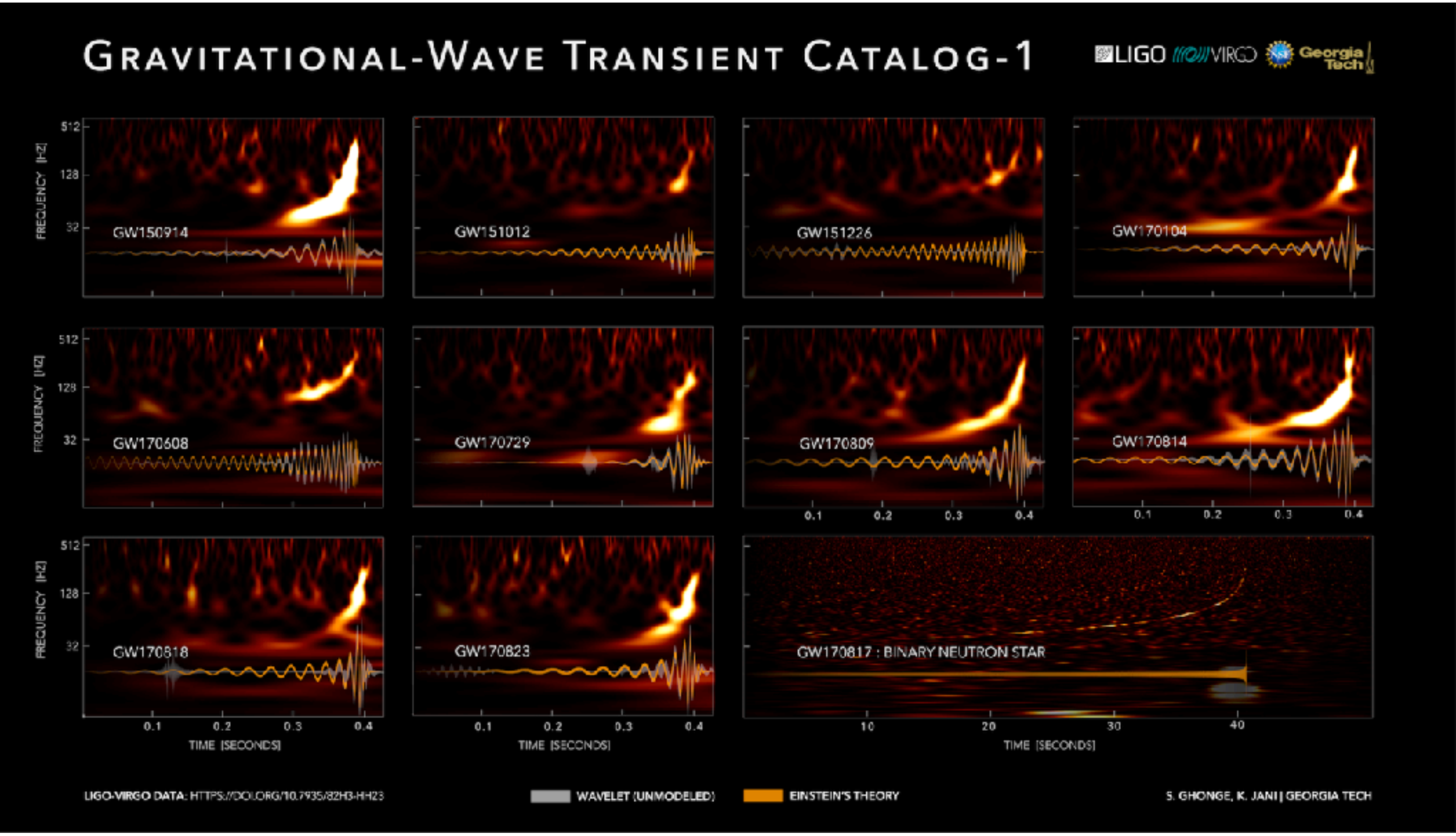
First contact…



First contact...

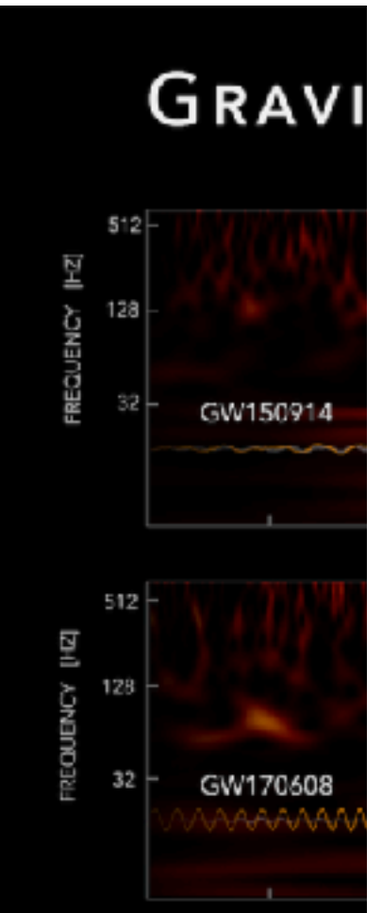


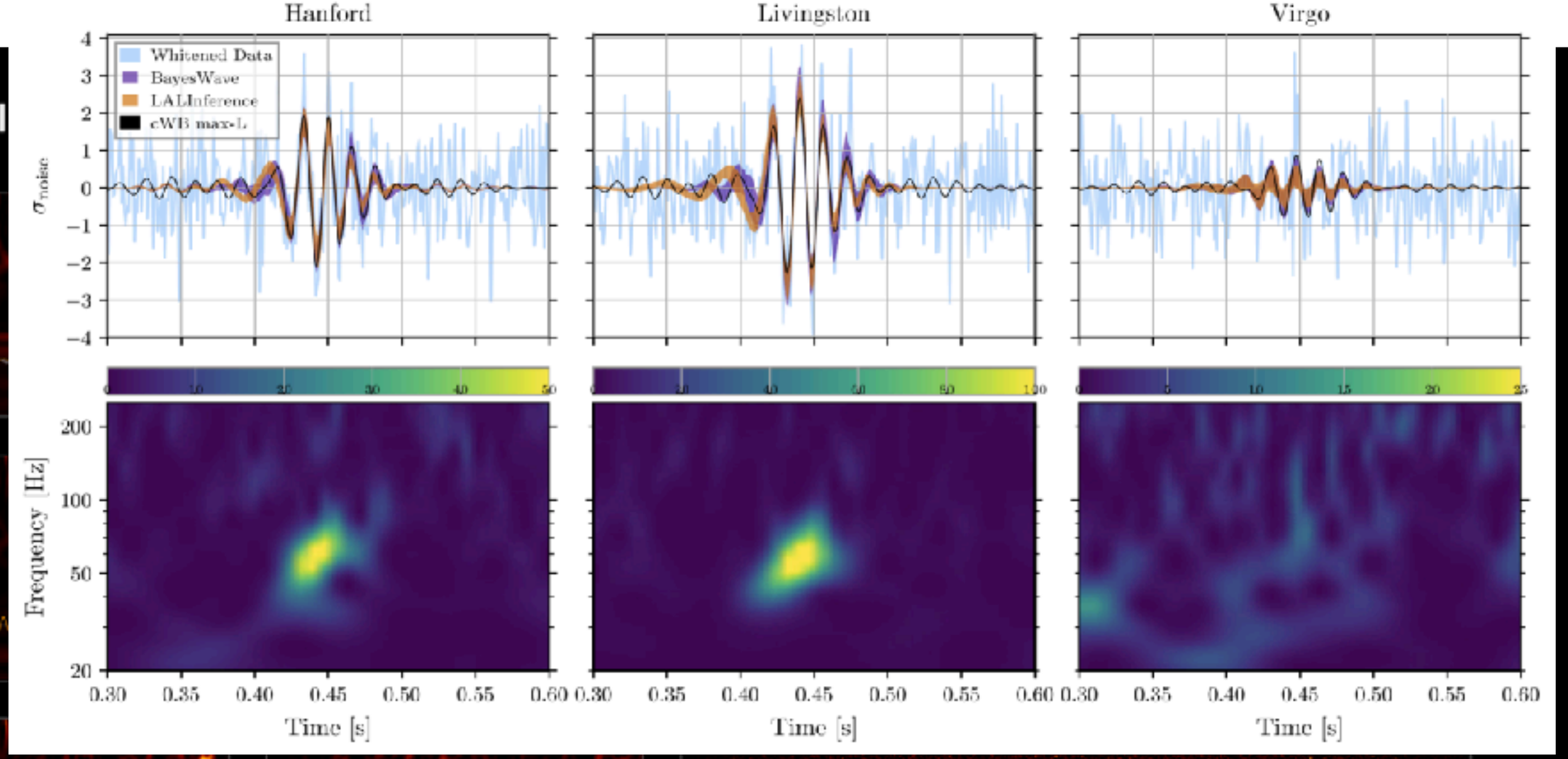
… and many more

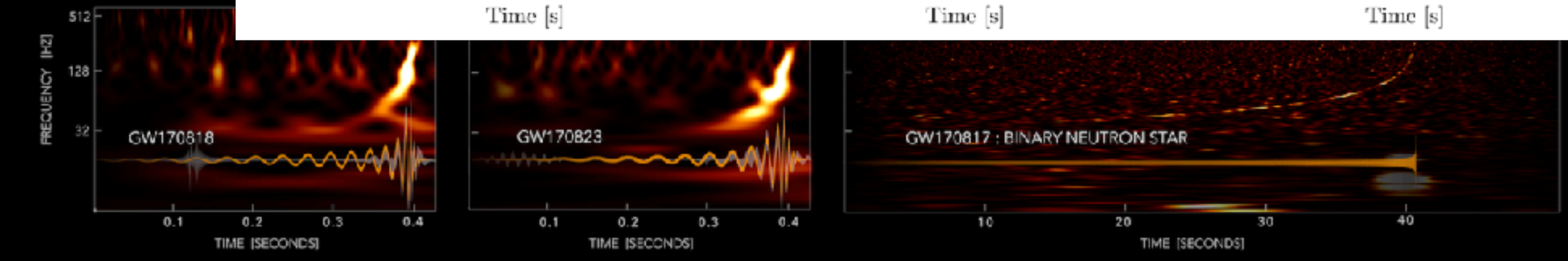


… and many more

GW190521: 85 $M_\odot$ + 66 $M_\odot$ -> 142 $M_\odot$

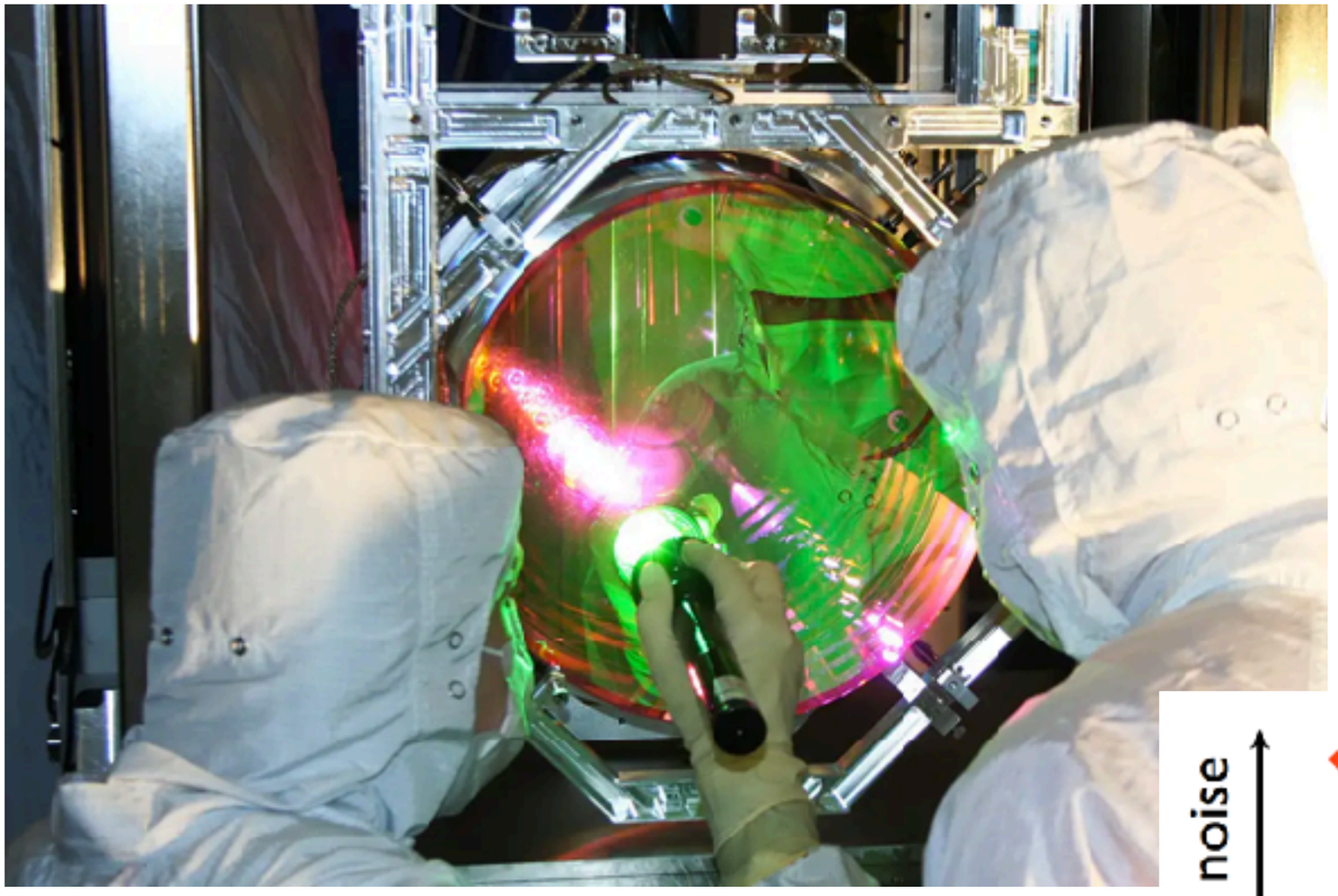


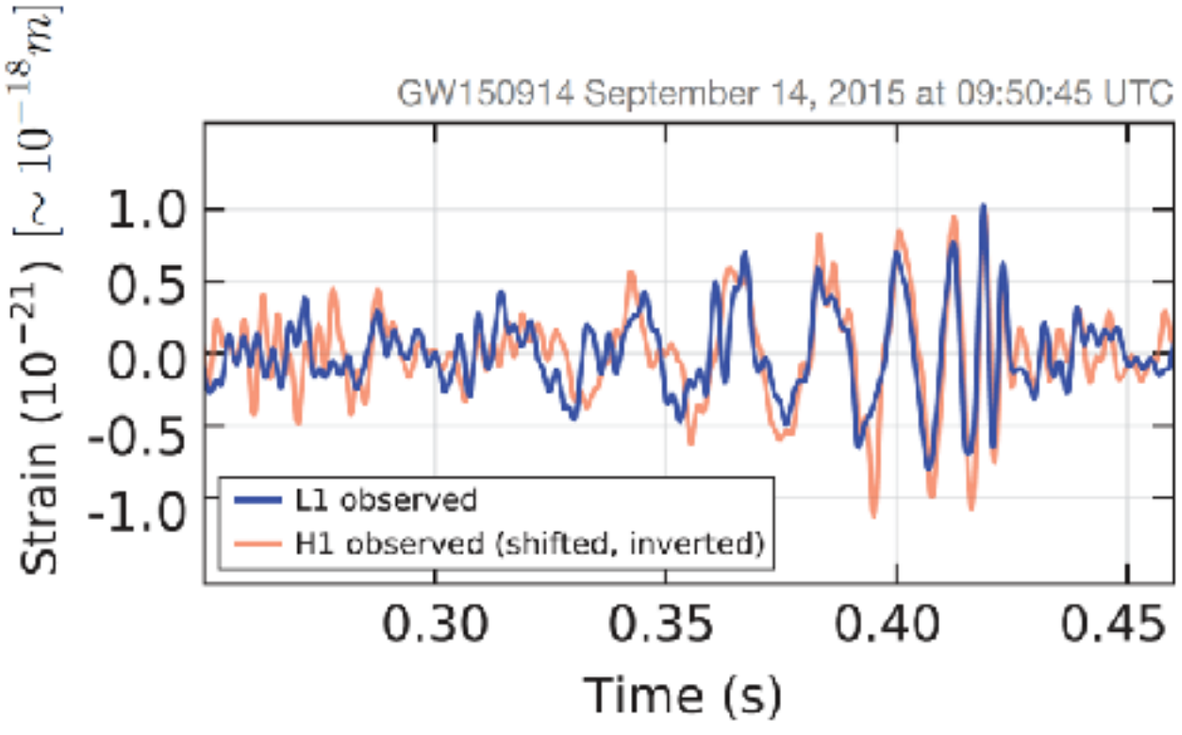


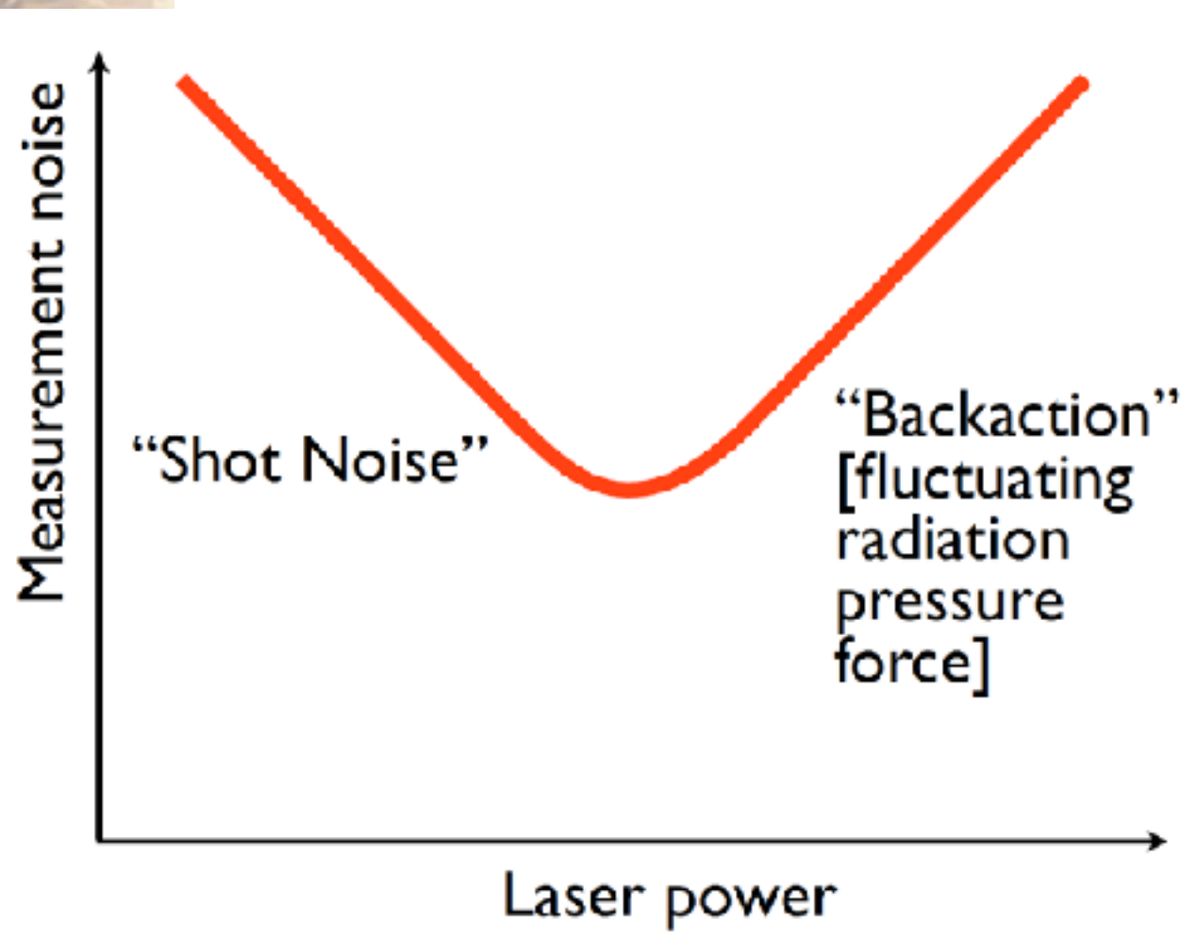


LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23 WAVELET (UNMODELED) EINSTEIN'S THEORY S. GHONGE, K. JANI | GEORGIA TECH

How is it possible?!

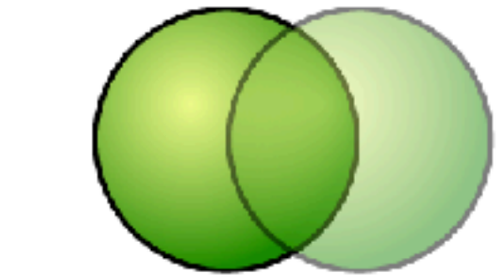


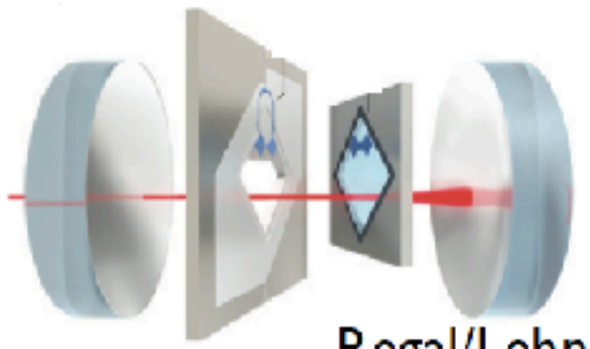




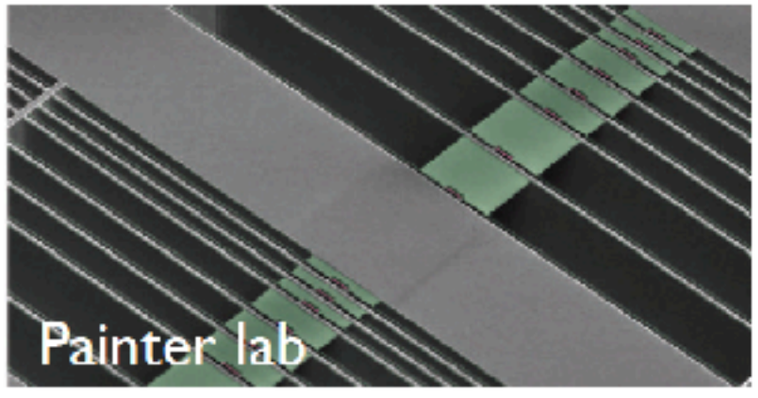
Optomechanics beyond Astrophysics

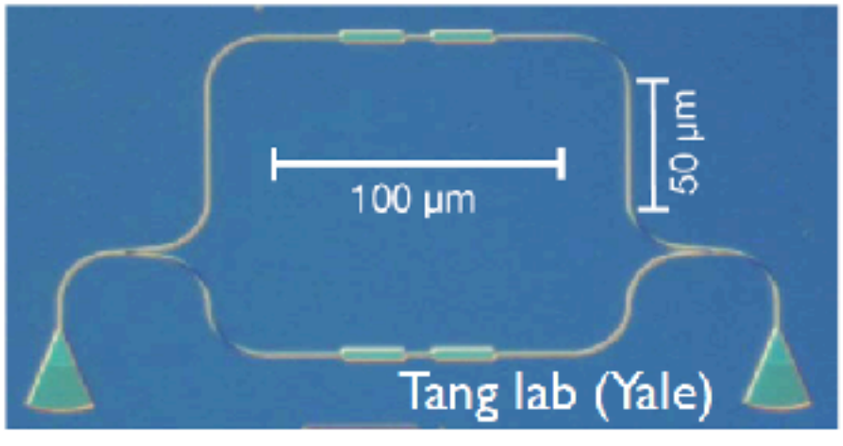
General outlook





Regal/Lehnert





Fundamental tests of quantum mechanics in a new regime:
entanglement with 'macroscopic' objects, unconventional decoherence?
[e.g.: gravitationally induced?]

Mechanics as a 'bus' for connecting hybrid components: superconducting qubits, spins, photons, cold atoms, ...

Precision measurements
small displacements, masses, forces, and accelerations

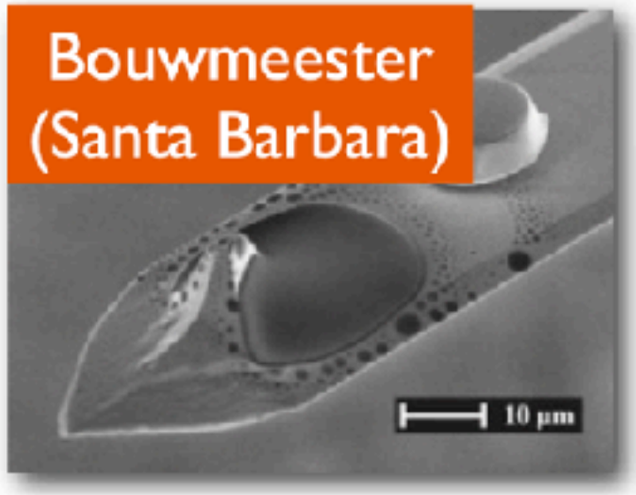
Optomechanical circuits & arrays
Exploit nonlinearities for classical and quantum information processing, storage, and amplification; study collective dynamics in arrays

@ Florian Marquardt slide

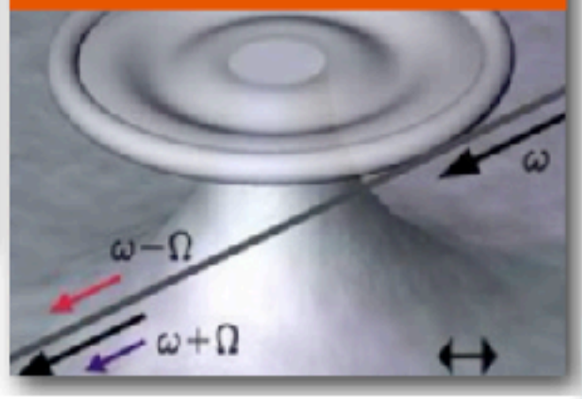
A Zoo of devices

Karrai (Munich)

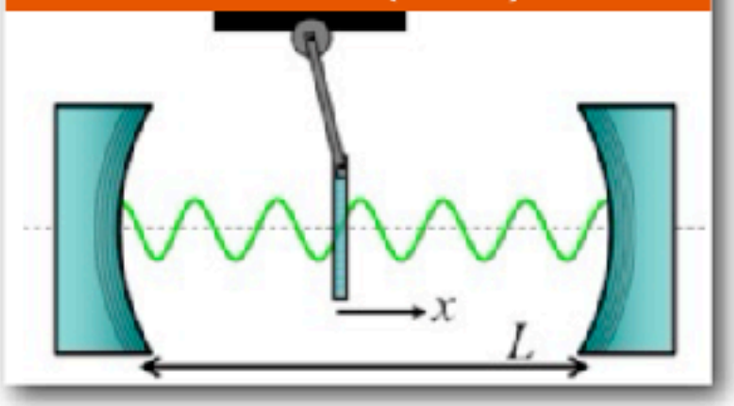
Bouwmeester (Santa Barbara)



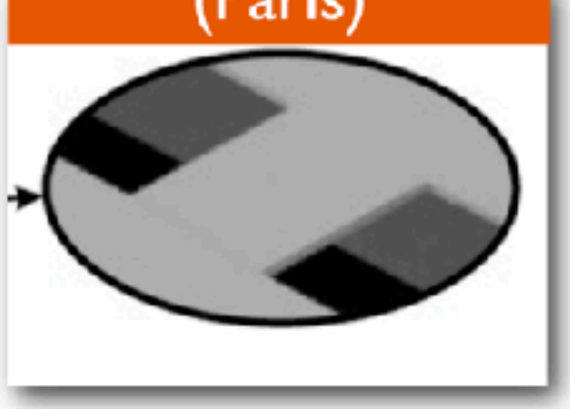
Vahala (Caltech)
Kippenberg (MPQ),
Carmon, ...



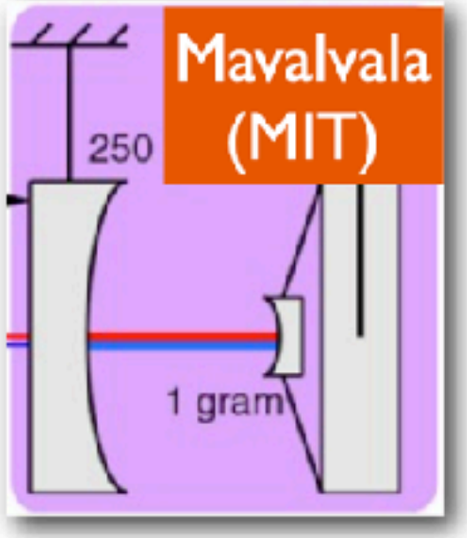
Harris (Yale)



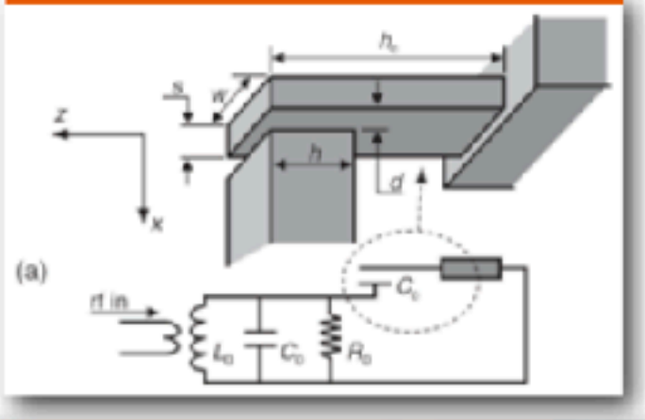
LKB group
(Paris)



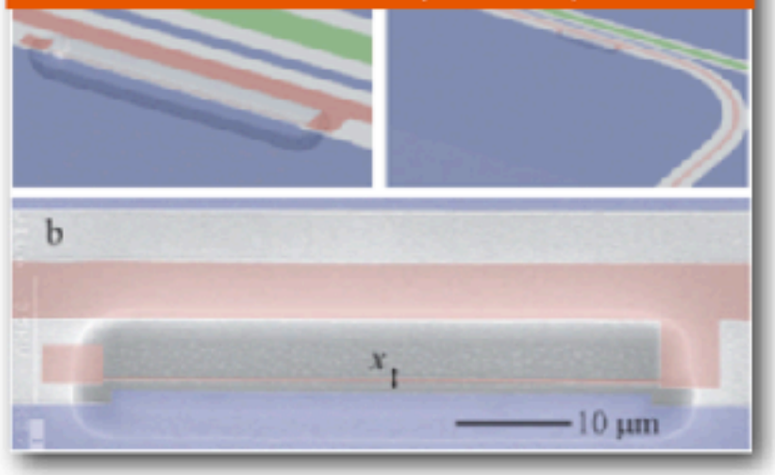
Mavalvala
(MIT)



Wineland (NIST)



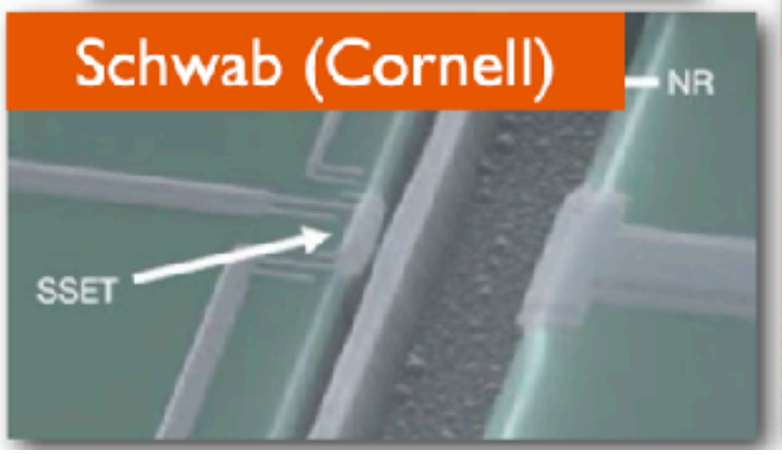
Lehnert (NIST)



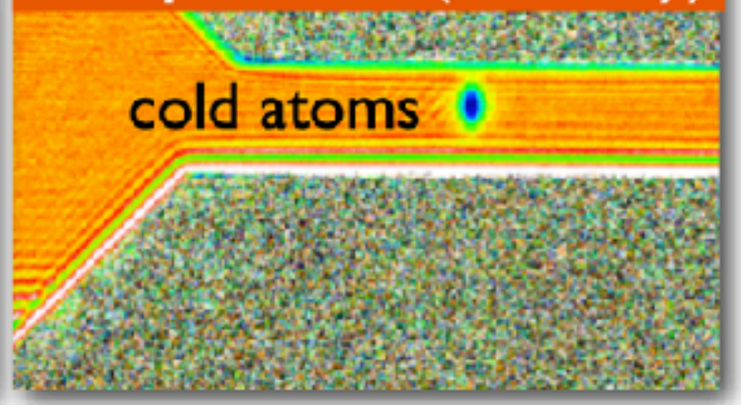
Aspelmeyer (Vienna)

...

Schwab (Cornell)



Stamper-Kurn (Berkeley)



@ Florian Marquardt slide

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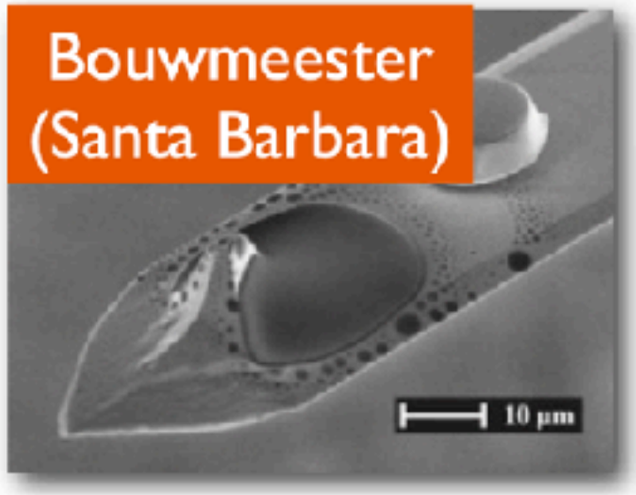

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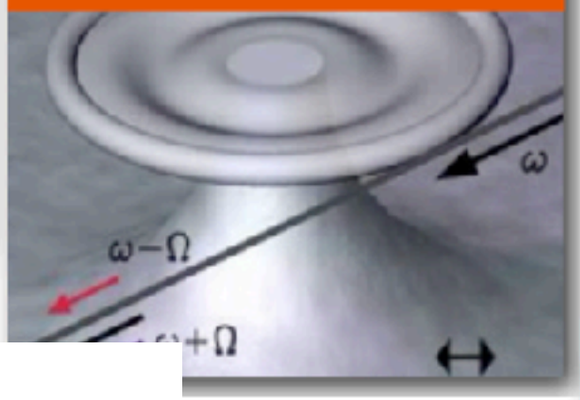

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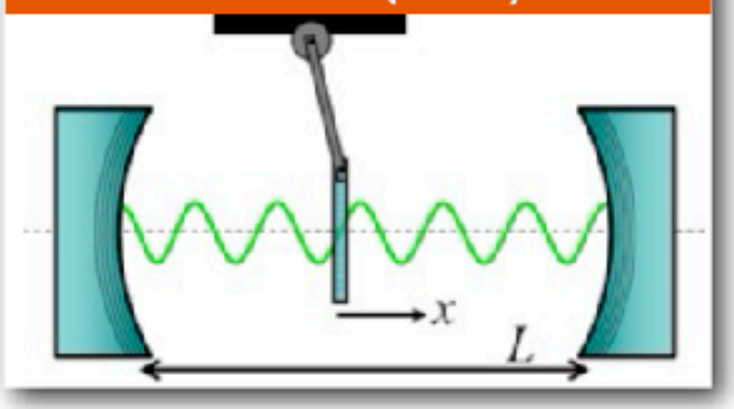

LKB gr
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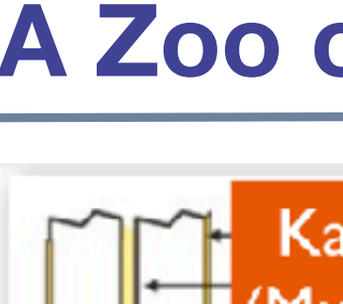
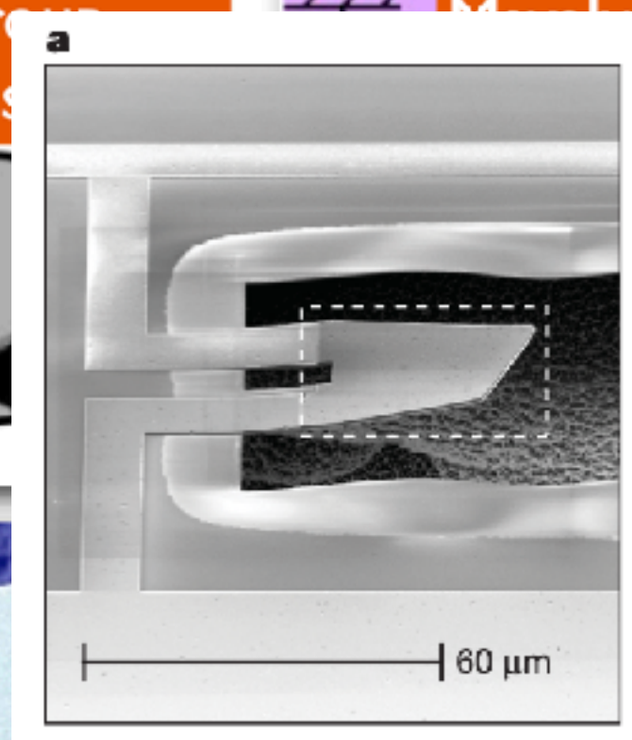
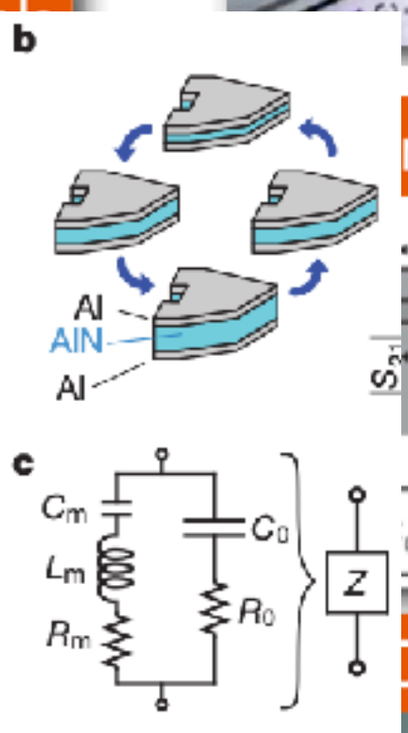
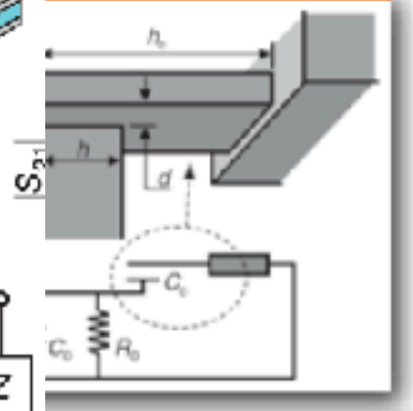




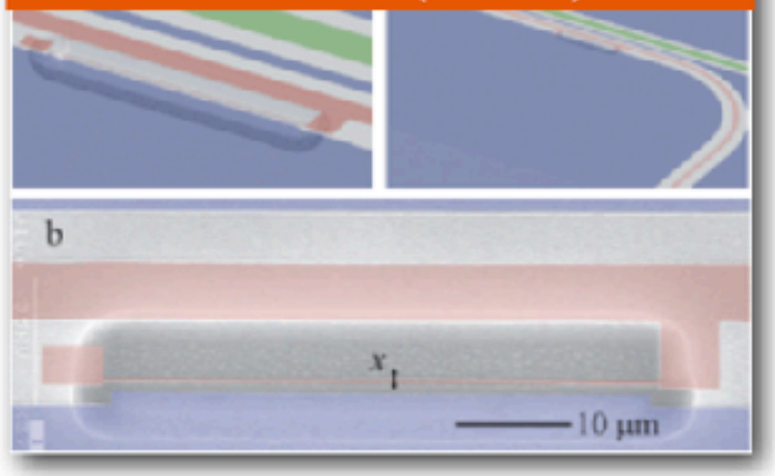


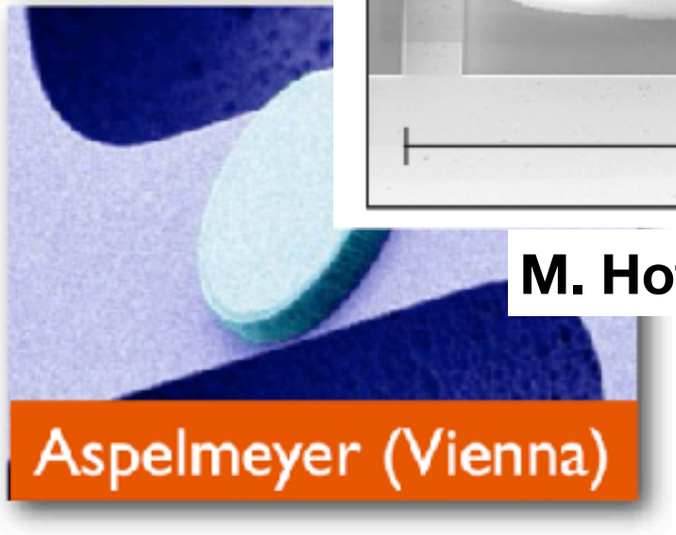
M. Hofheinz, Nature 2010

nd (NIST)



Lehnert (NIST)





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...

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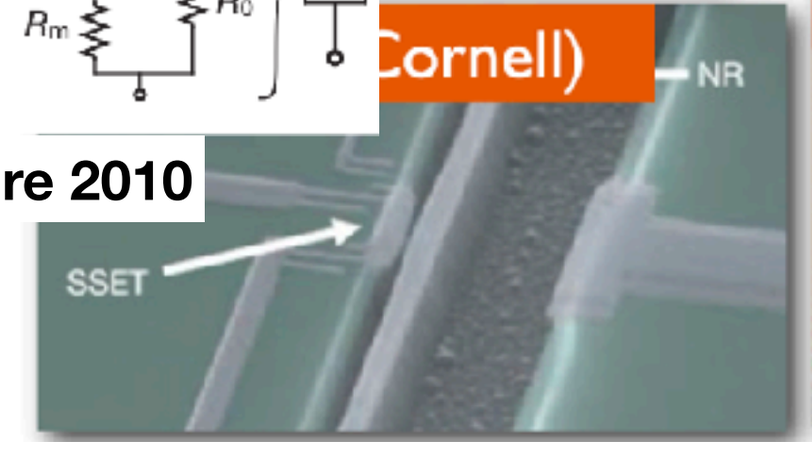

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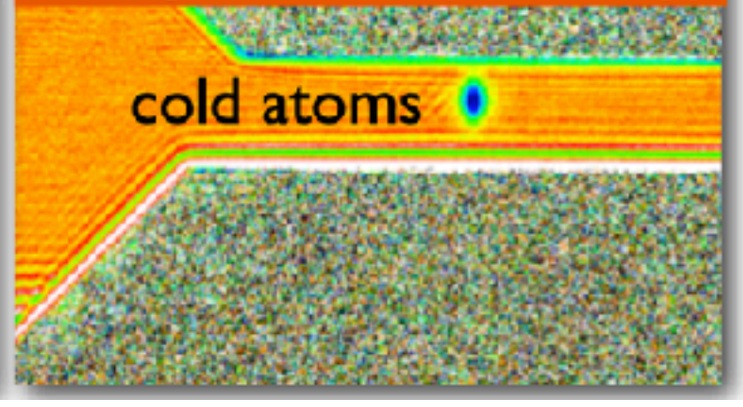
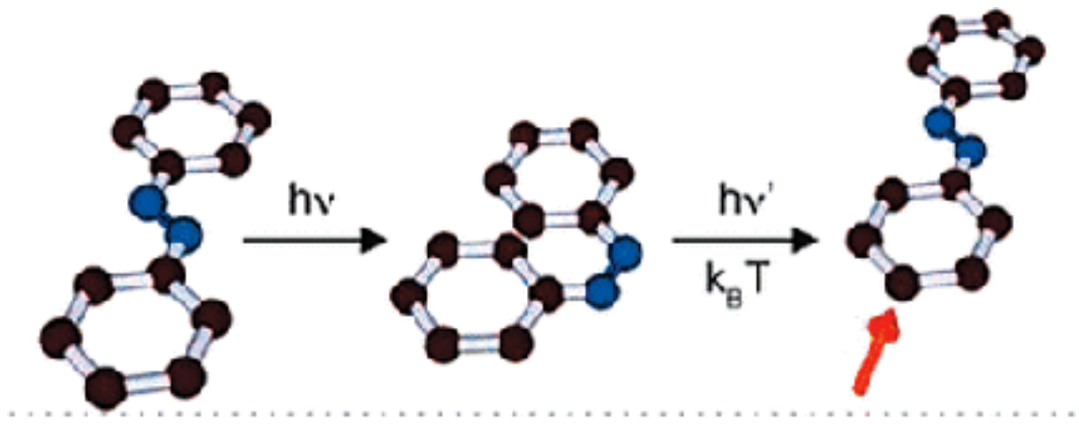
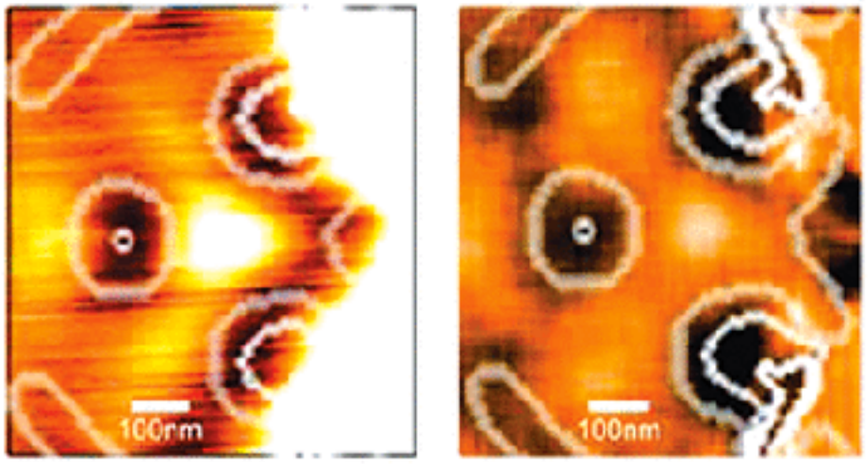


@ Florian Marquardt slide

Different types of optomechanics

- **Photo-induced molecular motion:**

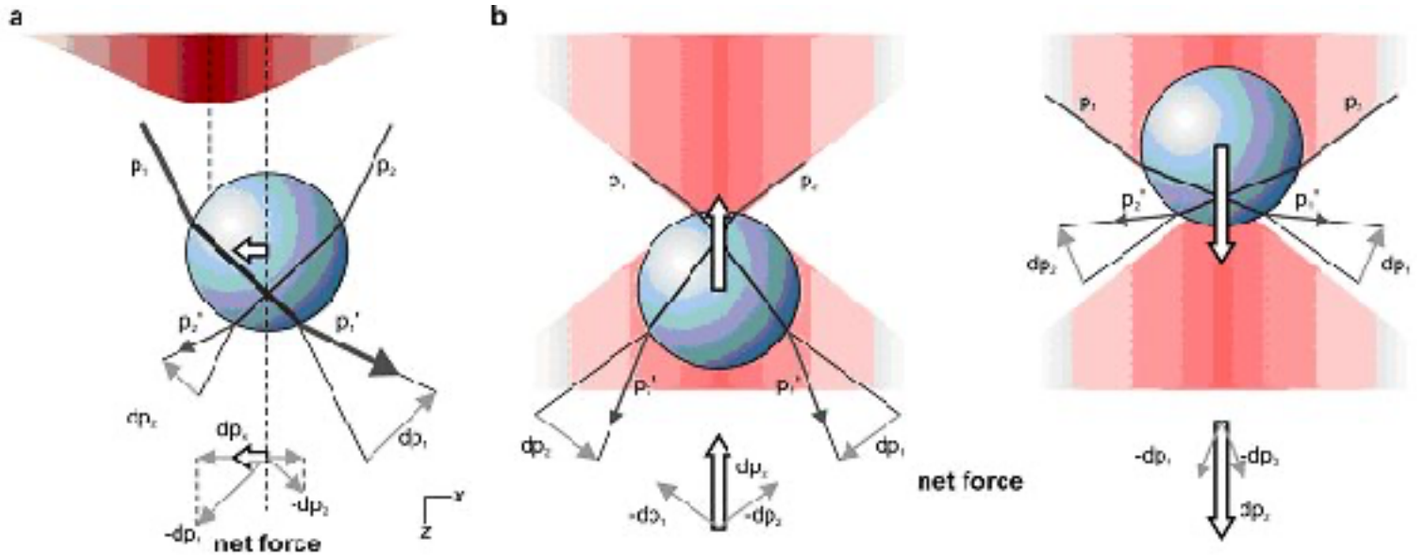


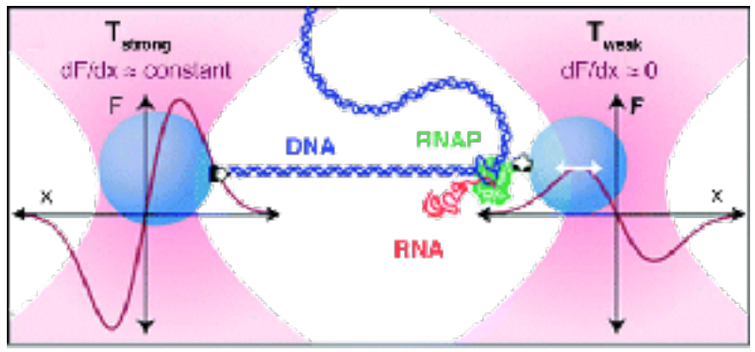


AFM Calculated topography

Different types of optomechanics

- **Optical tweezers:**





Abbondanzieri et al., Nature **438**, 460 (2005)

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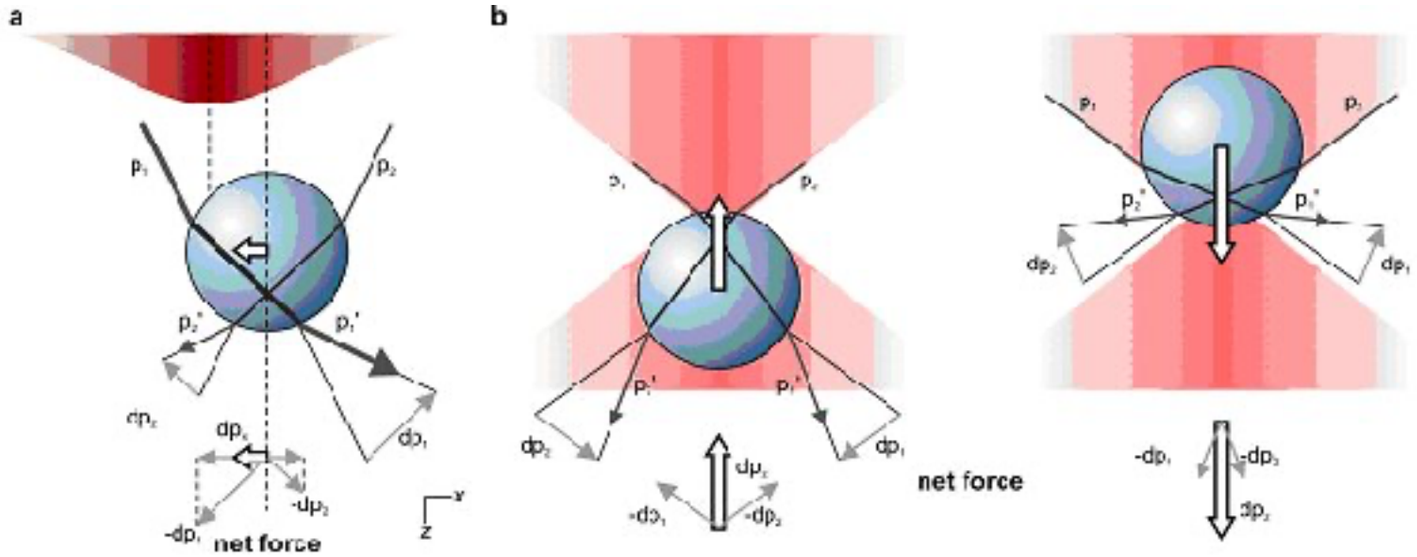
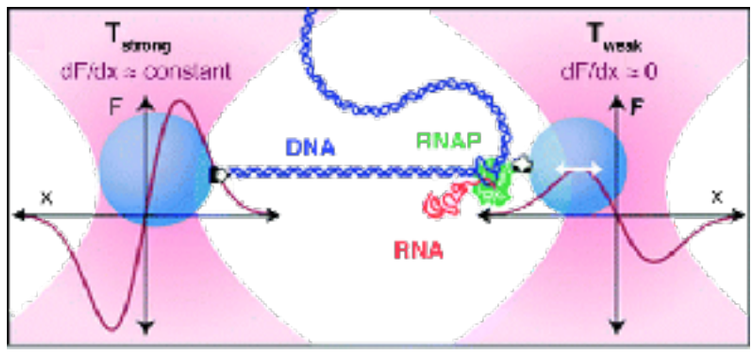
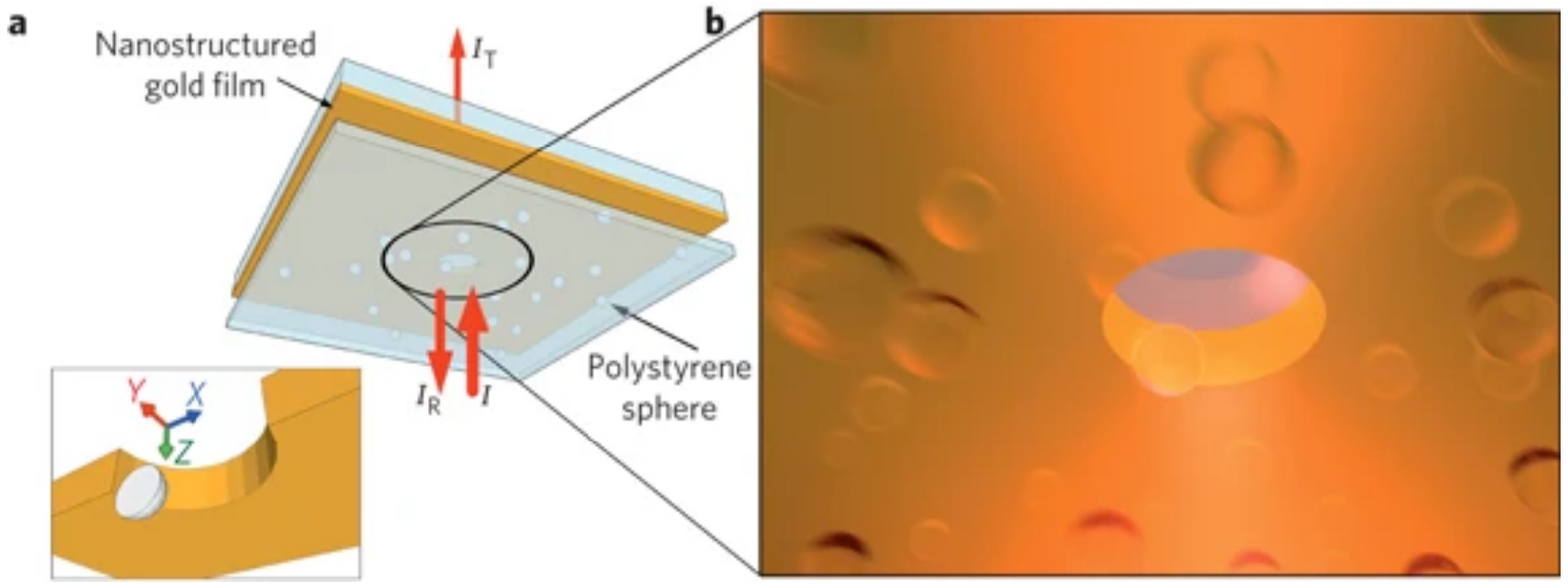




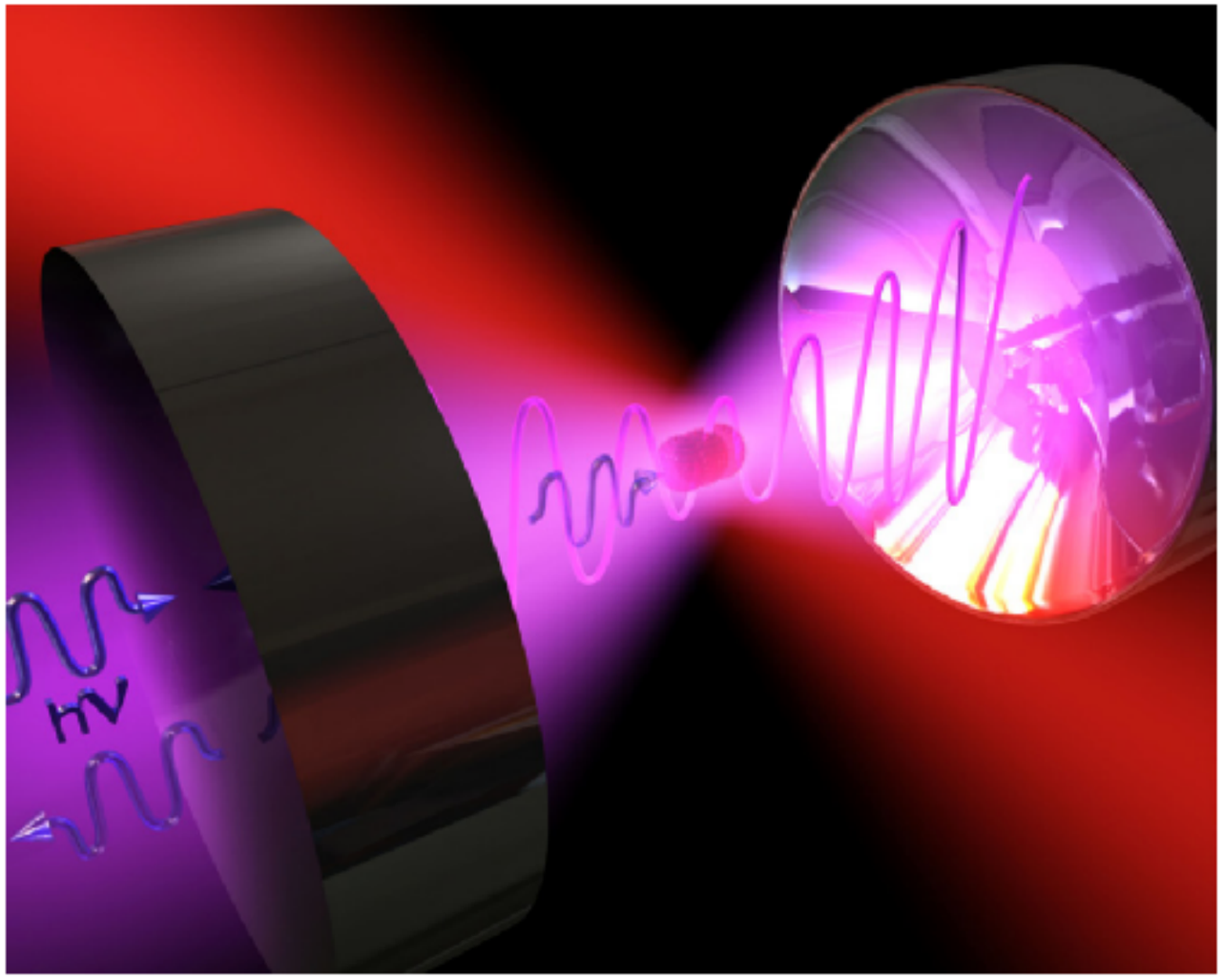
Abbondanzieri et al., Nature **438**, 460 (2005)

Using near-field produced from metallic structures:

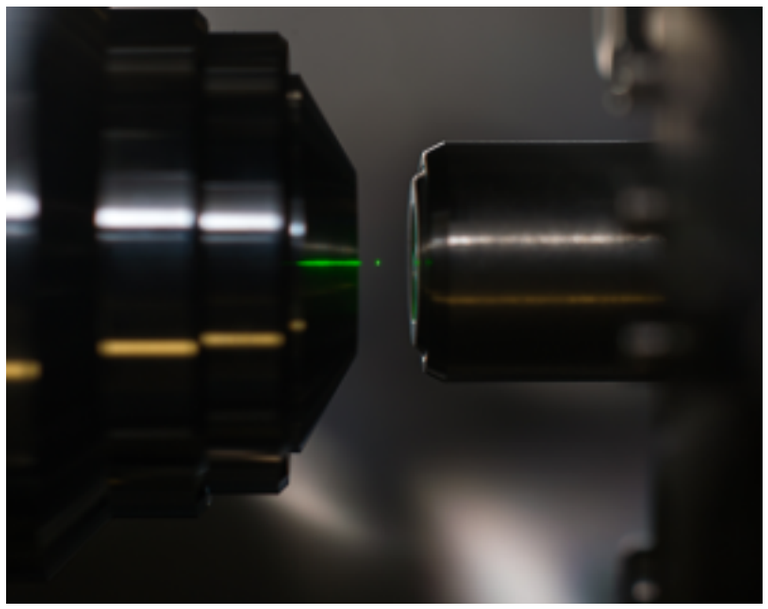


Different types of optomechanics

- **Levitated optomechanics (levitodyamics):**



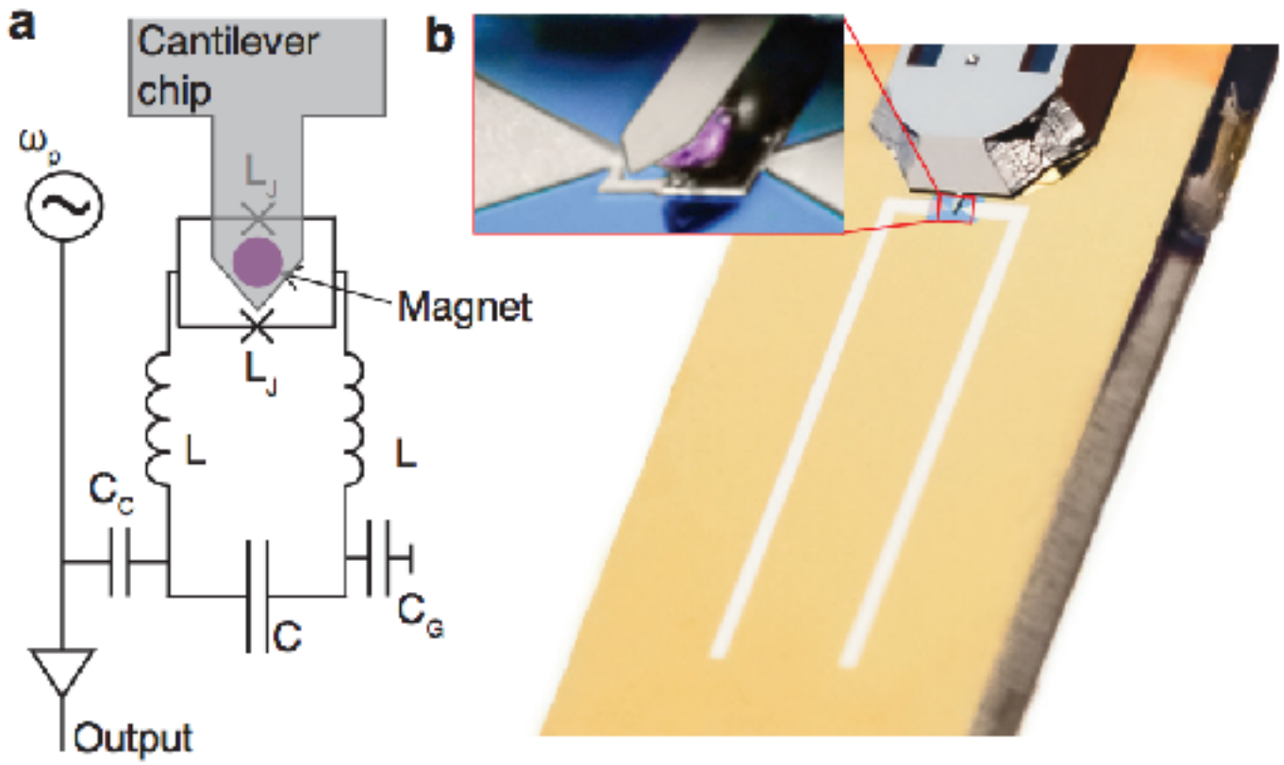
No mechanical link
Possibility to control the potential shape

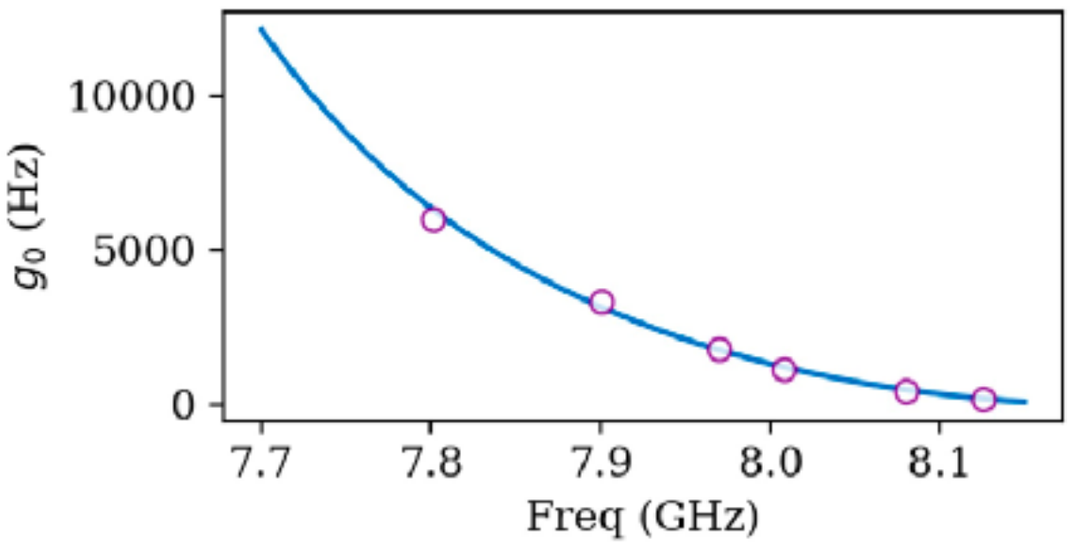


@ N. Vamivakas, U. Rochester

Different types of optomechanics

- **Electromechanics:**





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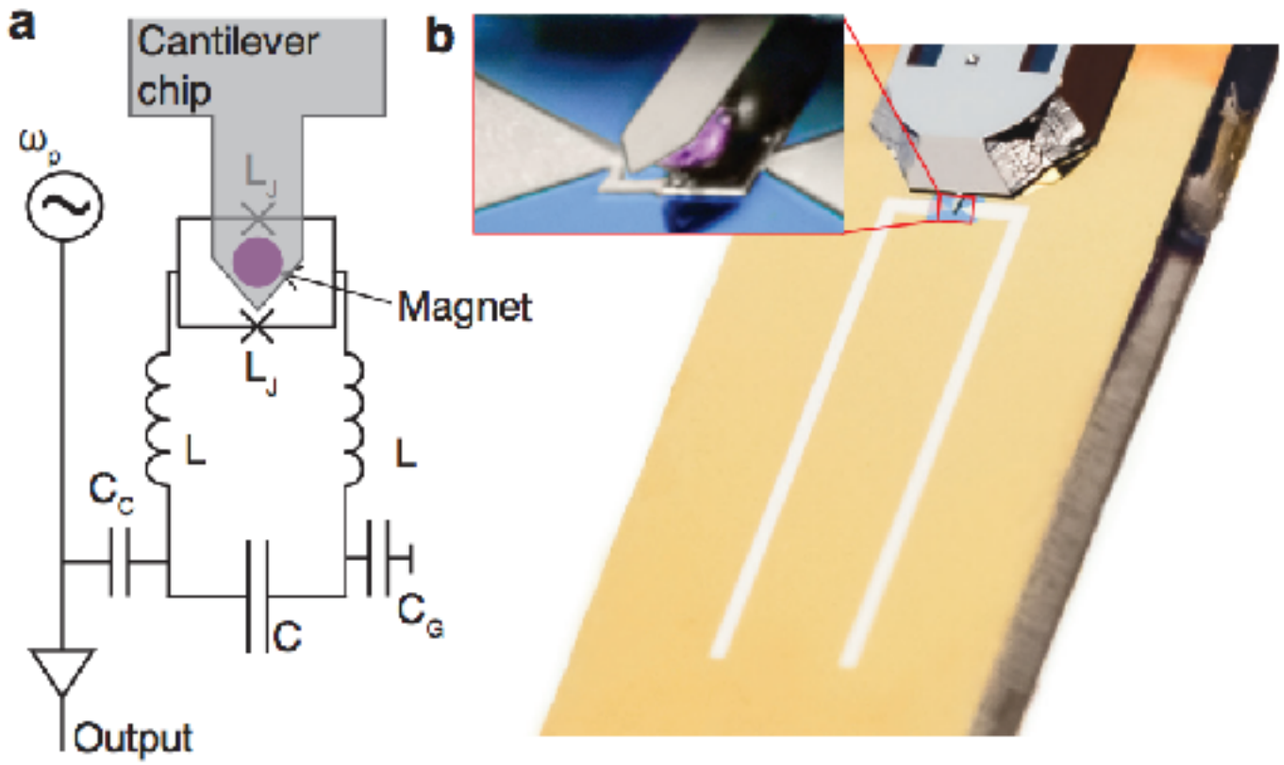
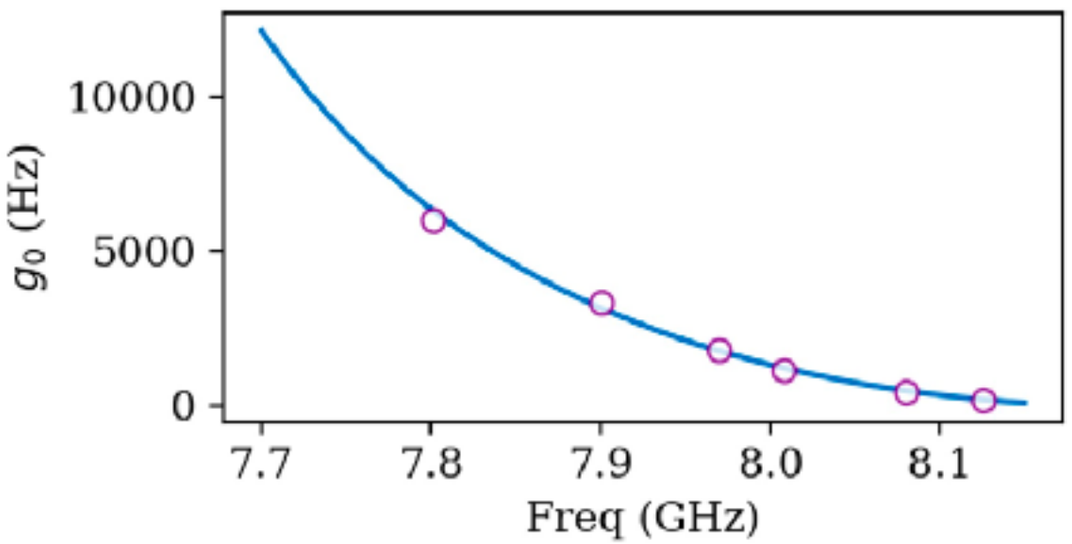
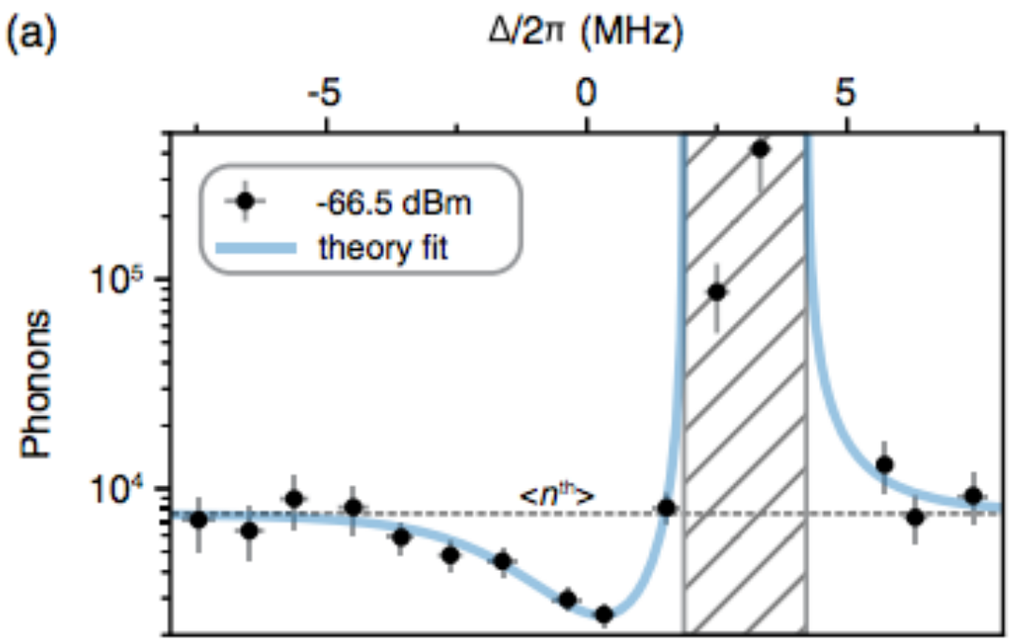


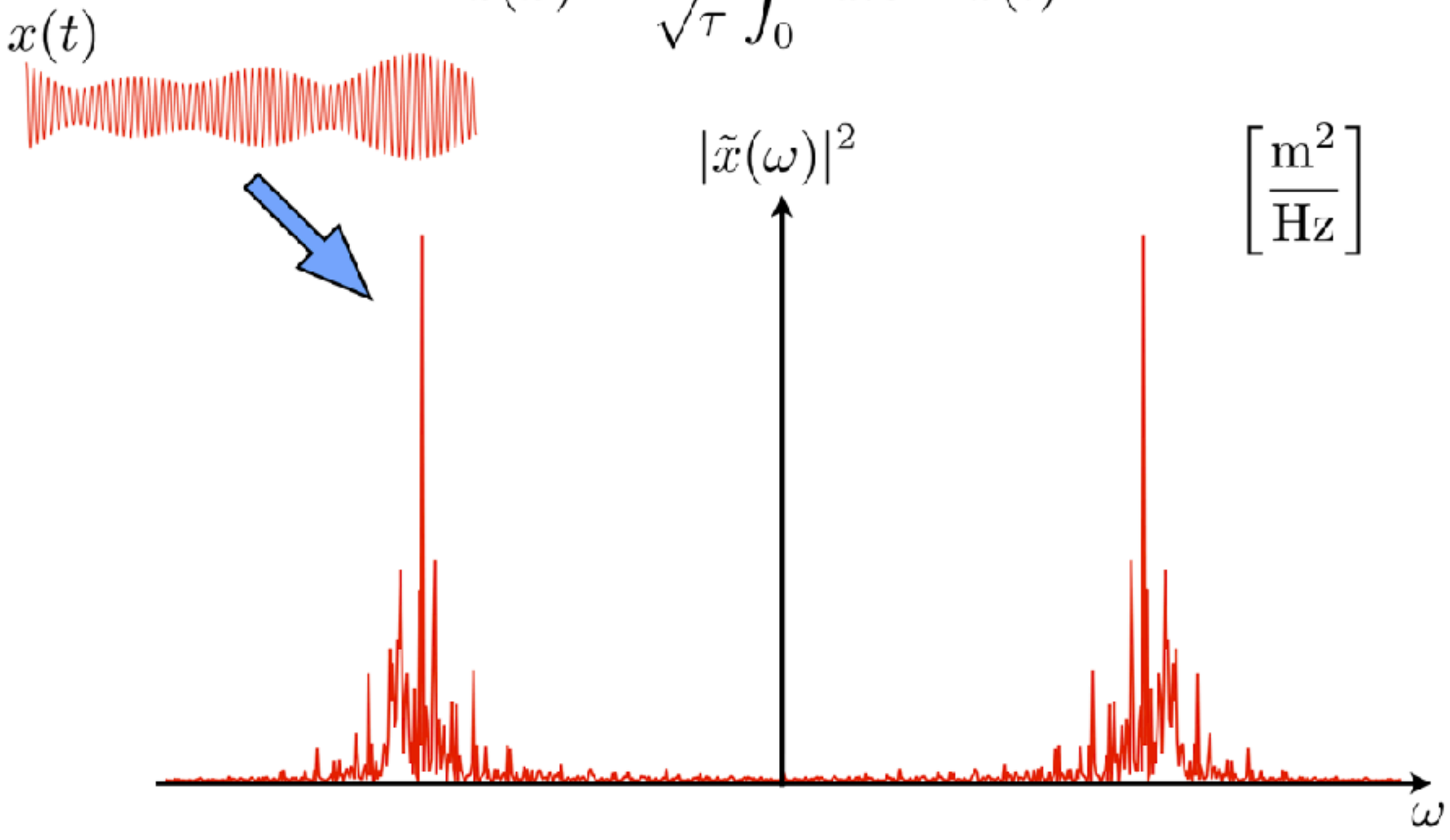


Large coupling enables cooling with only one *photon*



Classical fluctuation spectrum

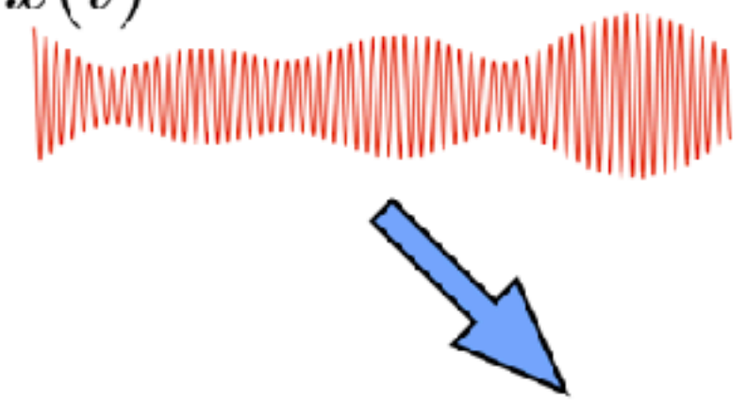
$$\tilde{x}(\omega) = \frac{1}{\sqrt{\tau}} \int_0^\tau dt e^{i\omega t} x(t)$$



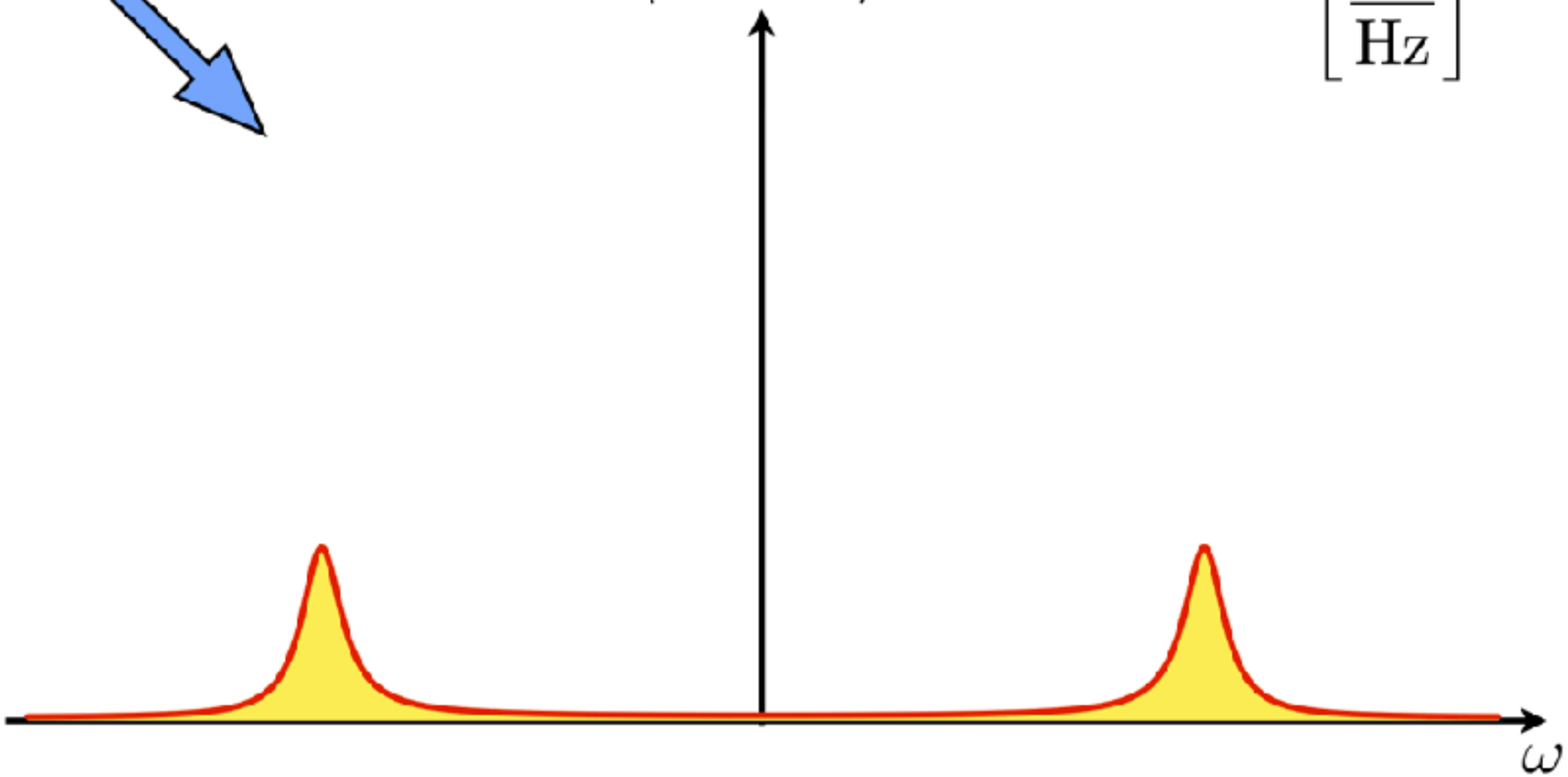
Classical fluctuation spectrum

$$\tilde{x}(\omega) = \frac{1}{\sqrt{\tau}} \int_0^\tau dt e^{i\omega t} x(t)$$

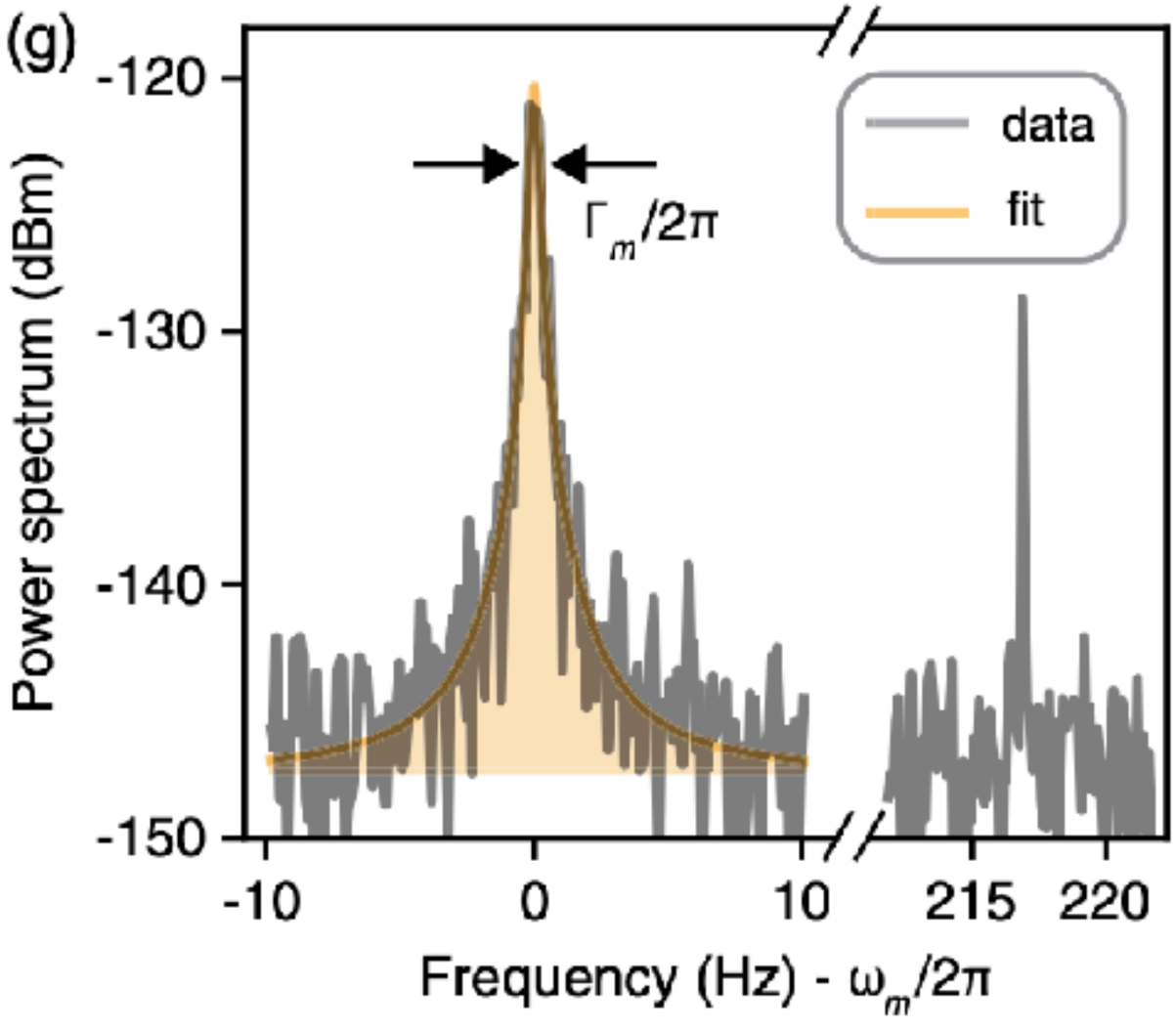
$x(t)$

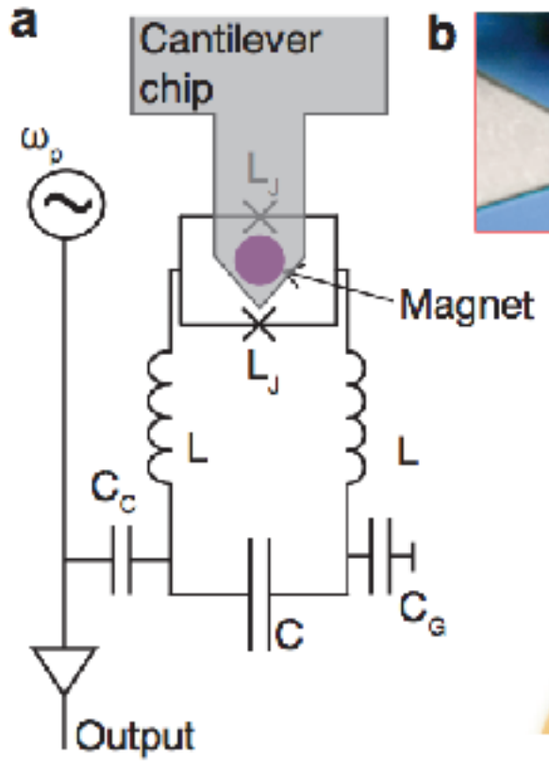


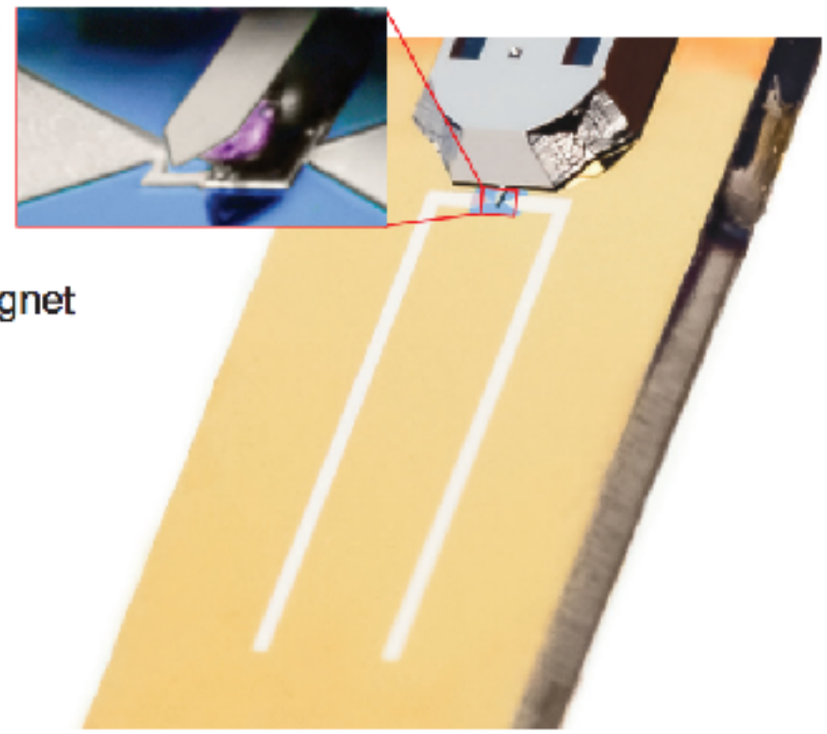
$$\left\langle |\tilde{x}(\omega)|^2 \right\rangle \equiv S_{xx}(\omega) \qquad \left[\frac{\mathrm{m}^2}{\mathrm{Hz}}\right]$$



Classical fluctuation spectrum







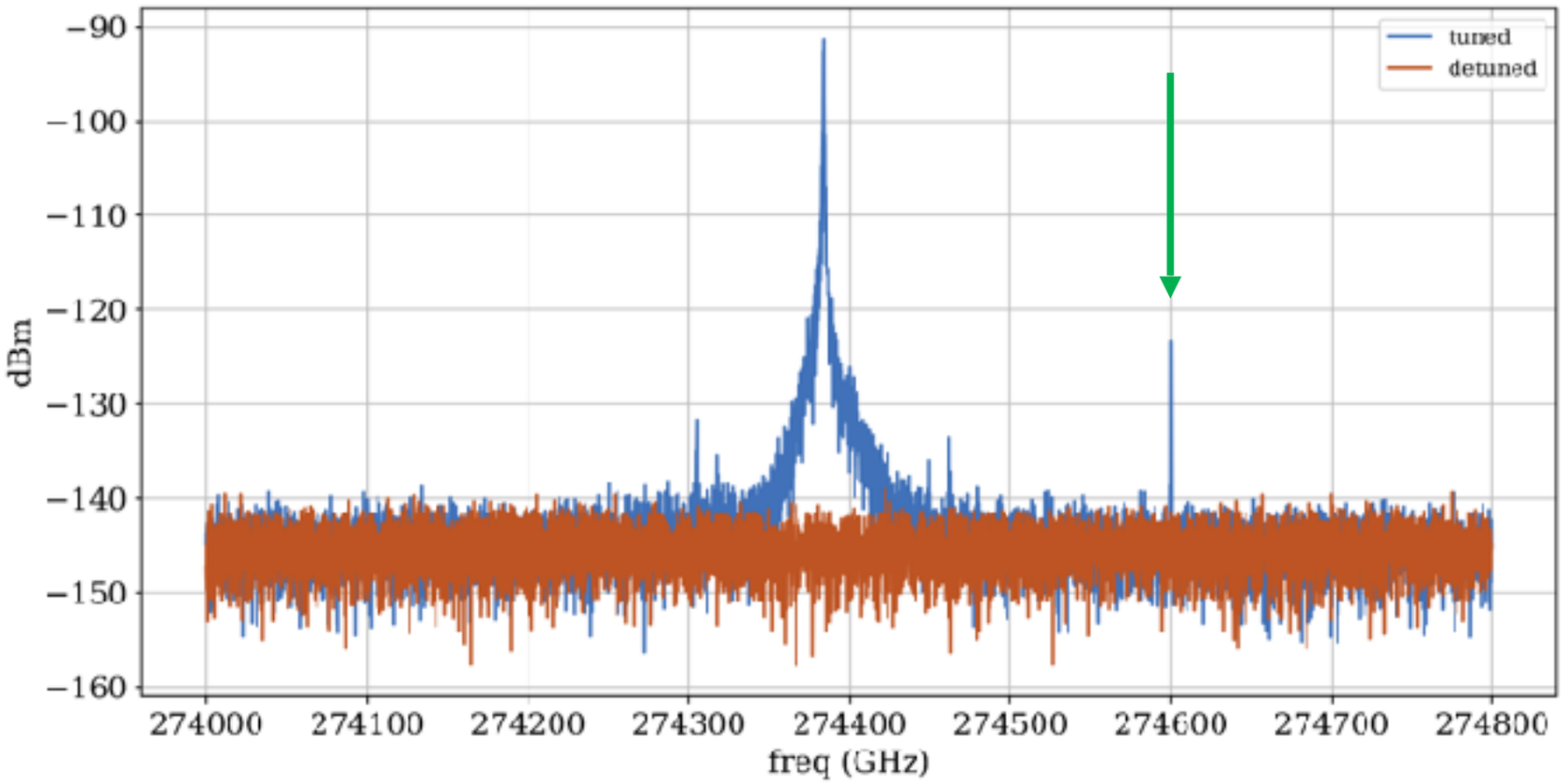
$$S_{\omega\omega}(\omega) \approx g_0^2 \langle n \rangle \frac{2\omega_m}{\hbar} \frac{2\Gamma_m}{(\omega^2 - \omega_m^2)^2 + \Gamma_m^2 \omega^2},$$

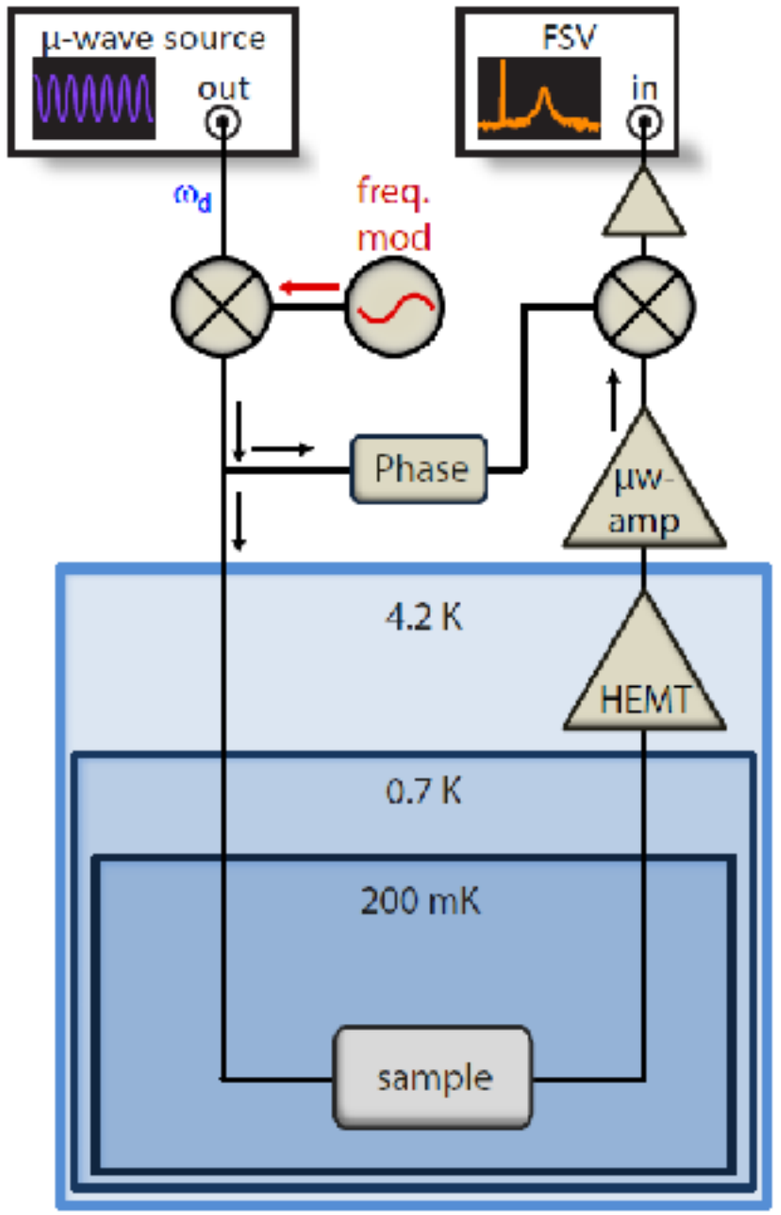
Experimental realization

The problem:

$$S_{\omega\omega}(\Omega) = G^2 S_{xx}(\Omega) \approx g_0^2 \cdot \frac{2\Omega_\mathrm{m}}{\hbar} \frac{2\Gamma_\mathrm{m} k_\mathrm{B} T}{(\Omega^2 - \Omega_\mathrm{m}^2)^2 + \Gamma_\mathrm{m}^2 \Omega^2}.$$

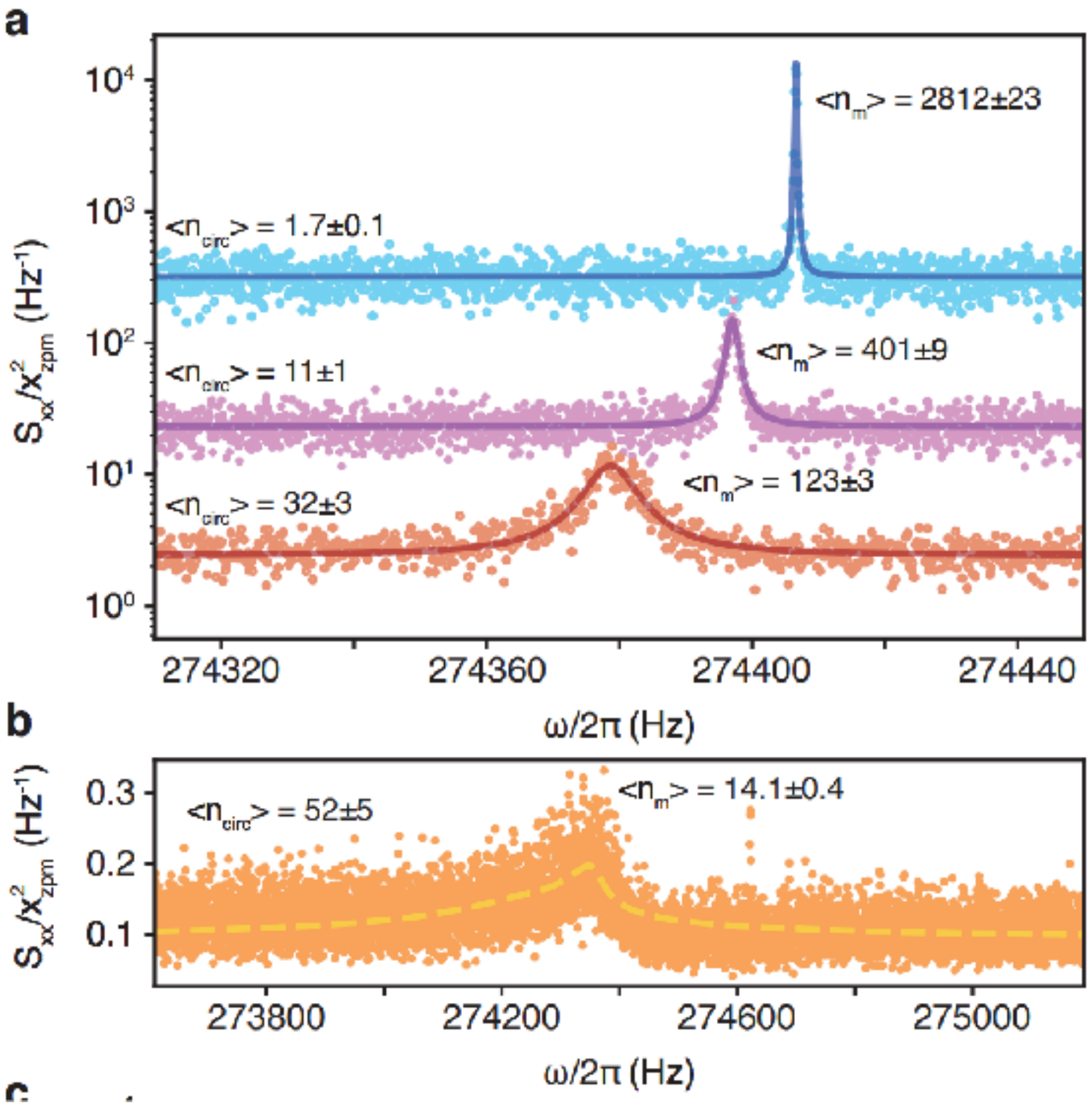
$$S_{II}(\Omega) = K(\Omega) S_{\psi\psi}(\Omega) = \frac{K(\Omega)}{\Omega^2} S_{\omega\omega}(\Omega)$$





$$g_0^2 \approx \frac{1}{2\langle n_\mathrm{m} \rangle} \frac{\phi_0^2 \Omega_\mathrm{mod}^2}{2} \frac{S_{II}^\mathrm{meas}(\Omega_\mathrm{m}) \cdot \Gamma_\mathrm{m}/4}{S_{II}^\mathrm{meas}(\Omega_\mathrm{mod}) \cdot \mathrm{ENBW}}$$

Cavity cooling

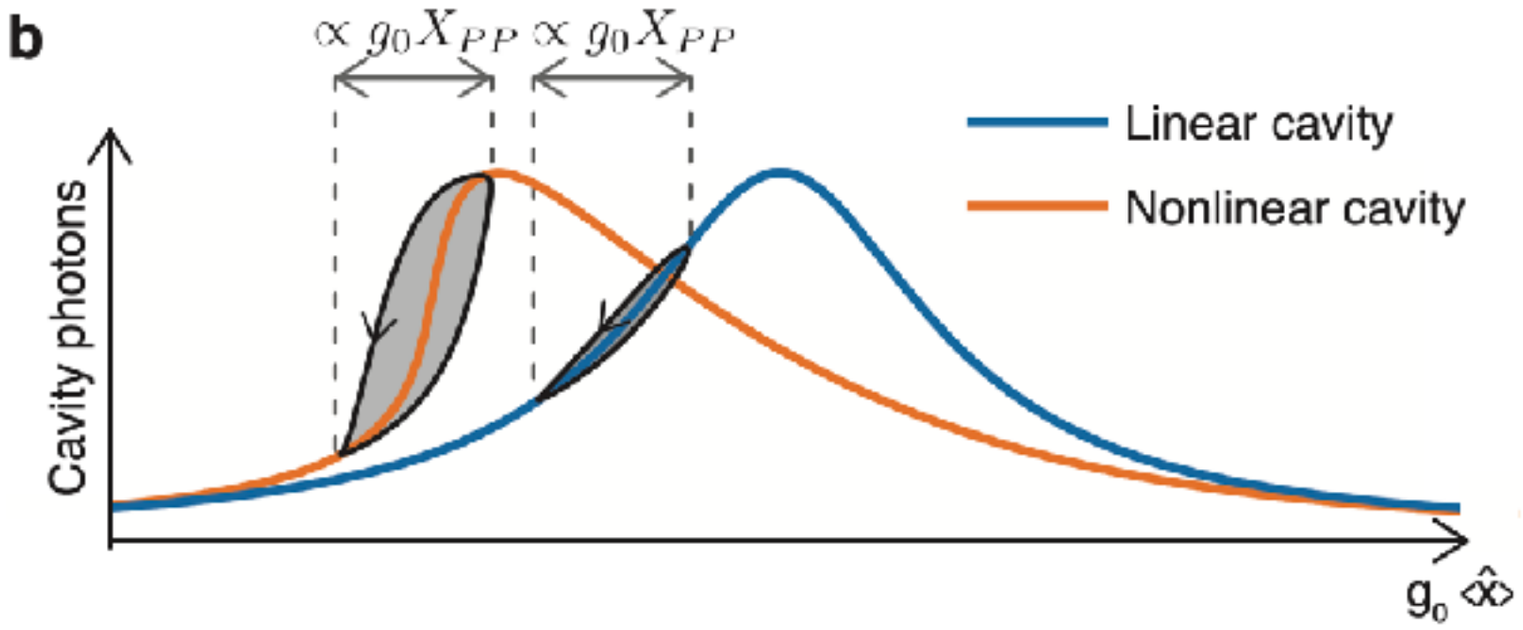


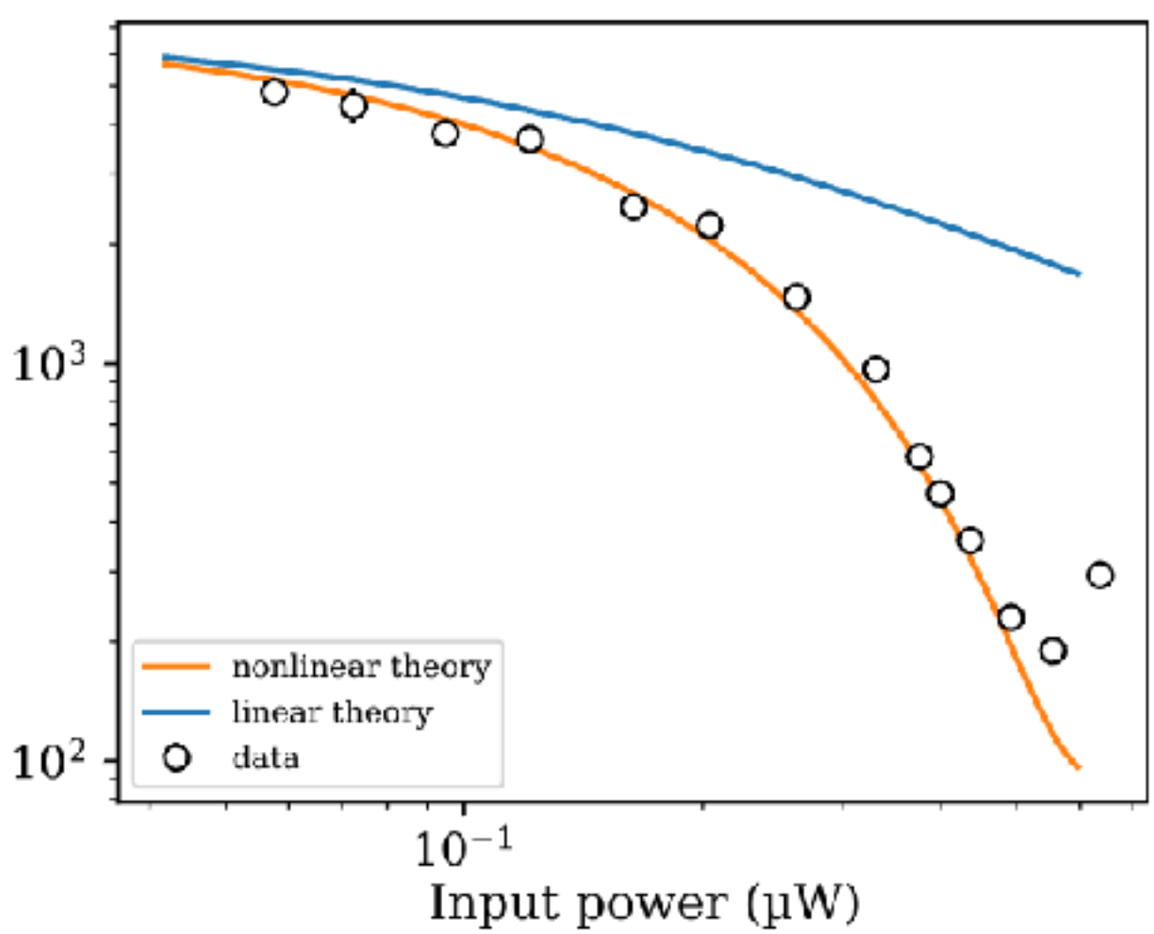
~ 40mK

~ 1.7mK

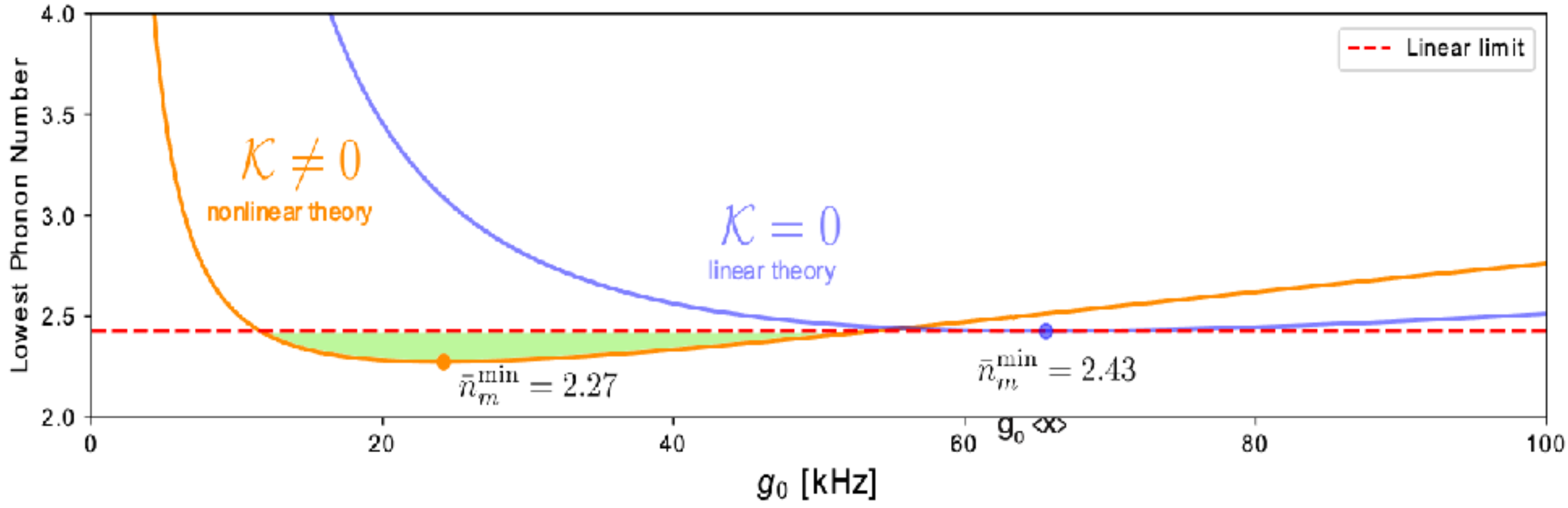
~ 200μK

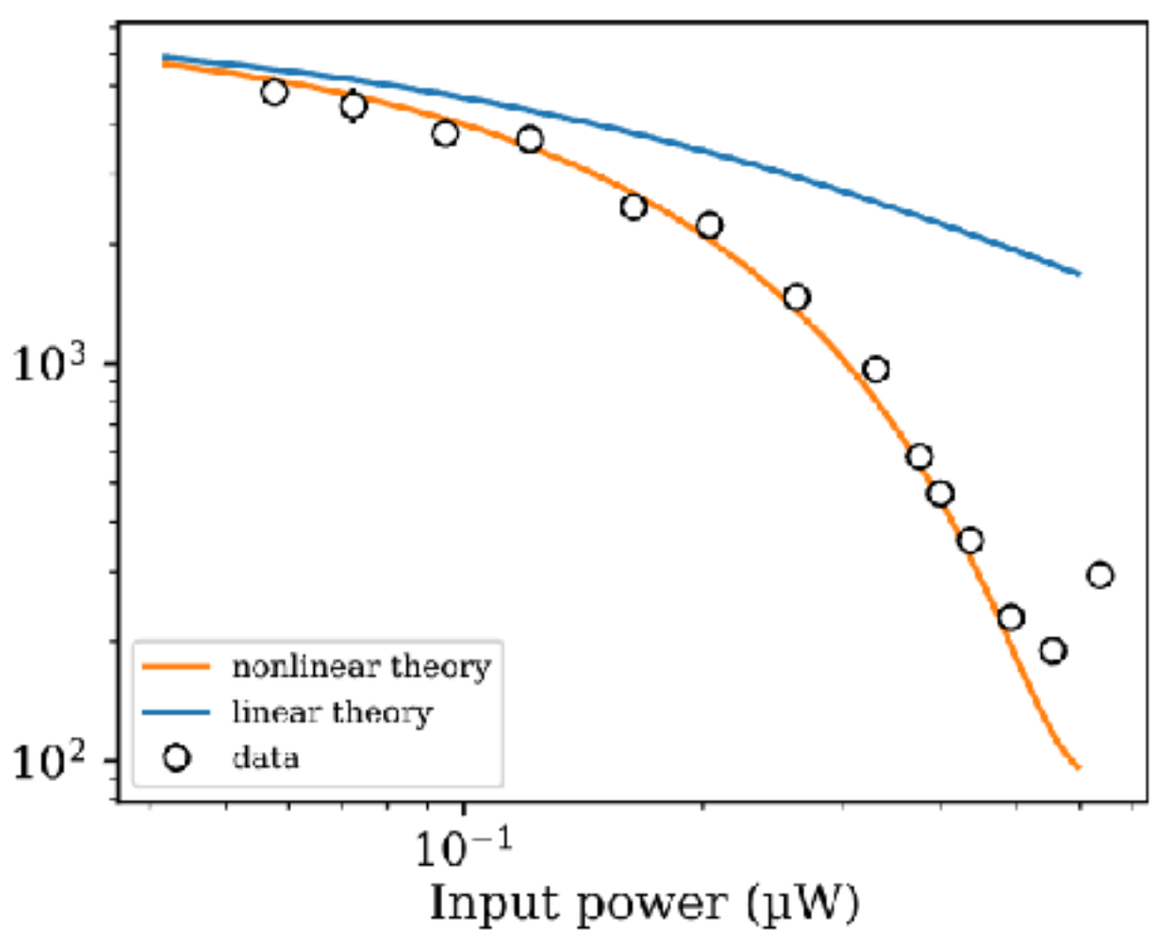
Cavity cooling with non-linearity

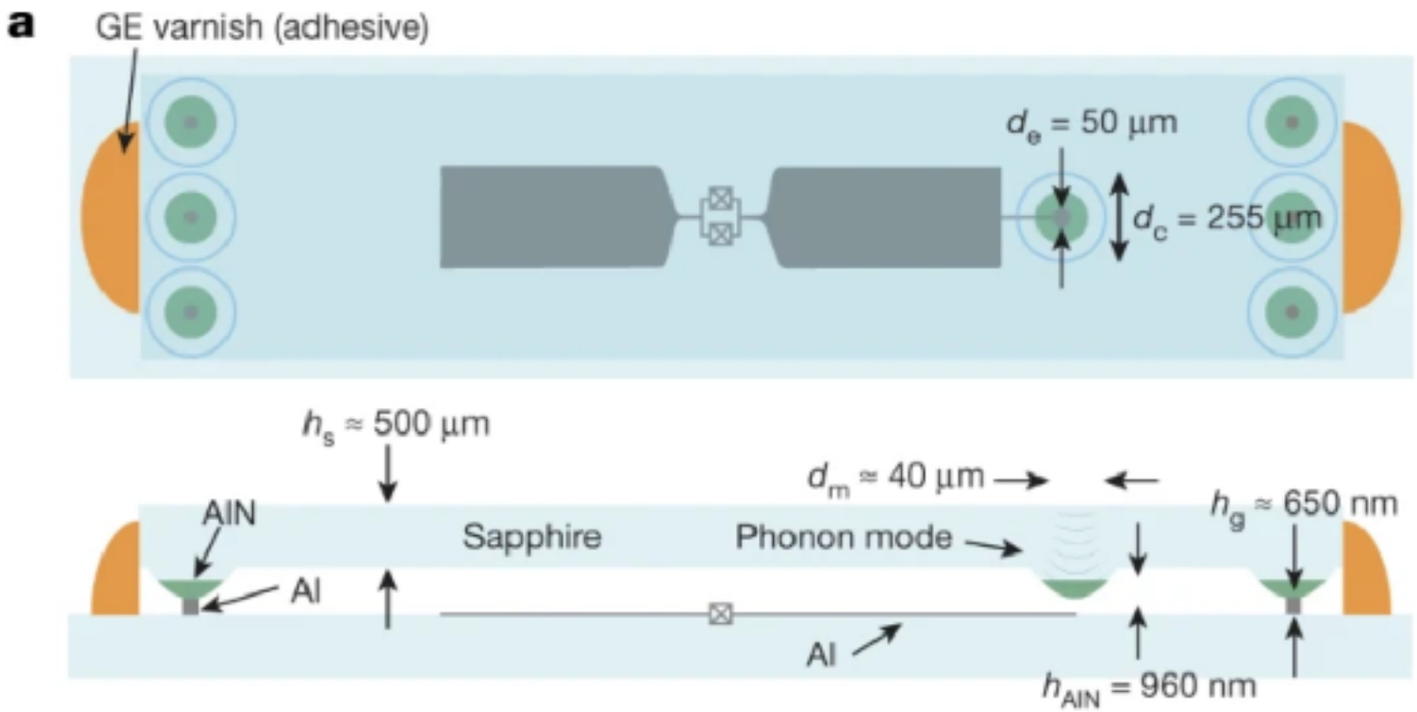




Cavity cooling with non-linearity

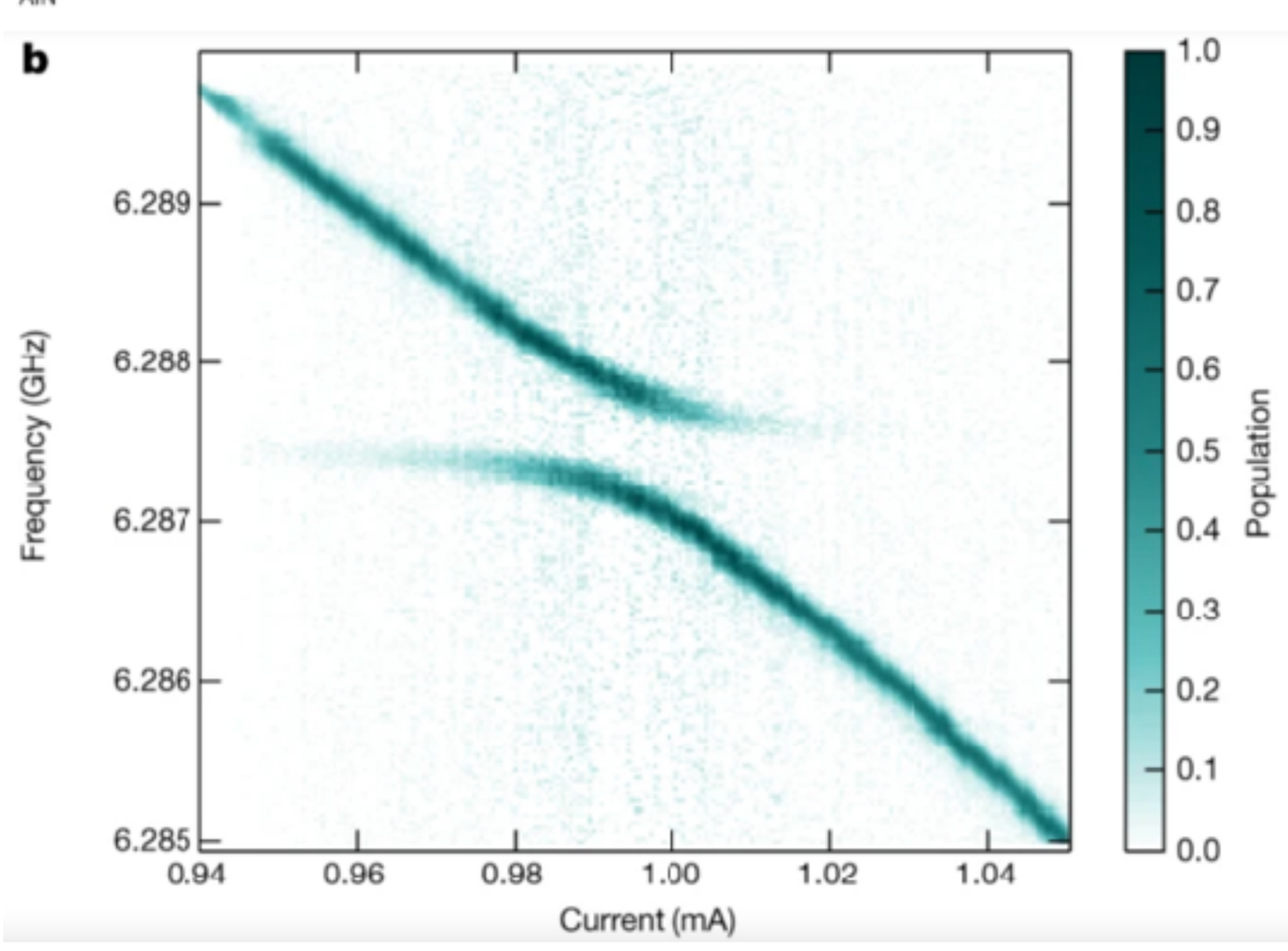




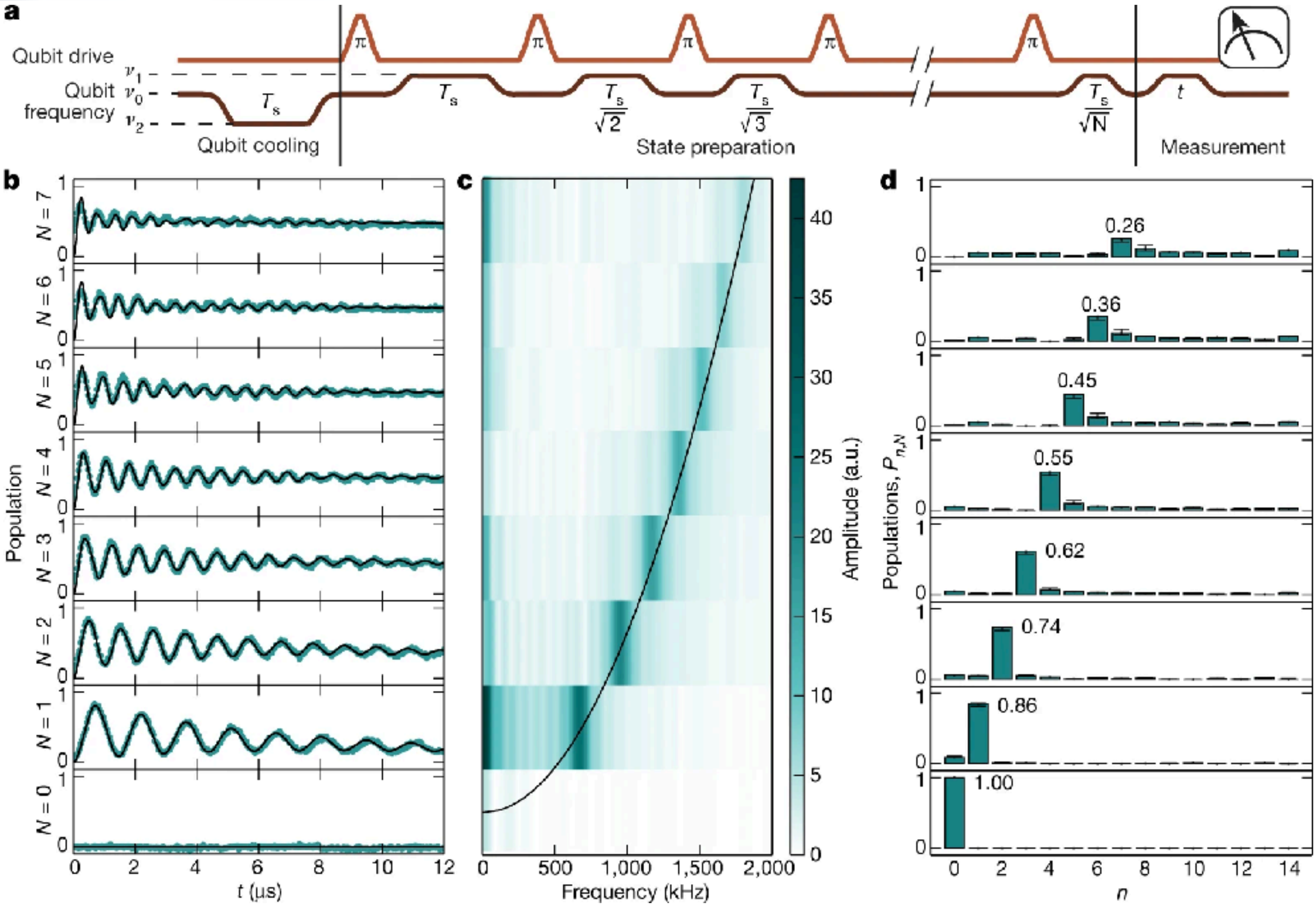


ħBAR device (high-overtone bulk acoustic wave resonator)

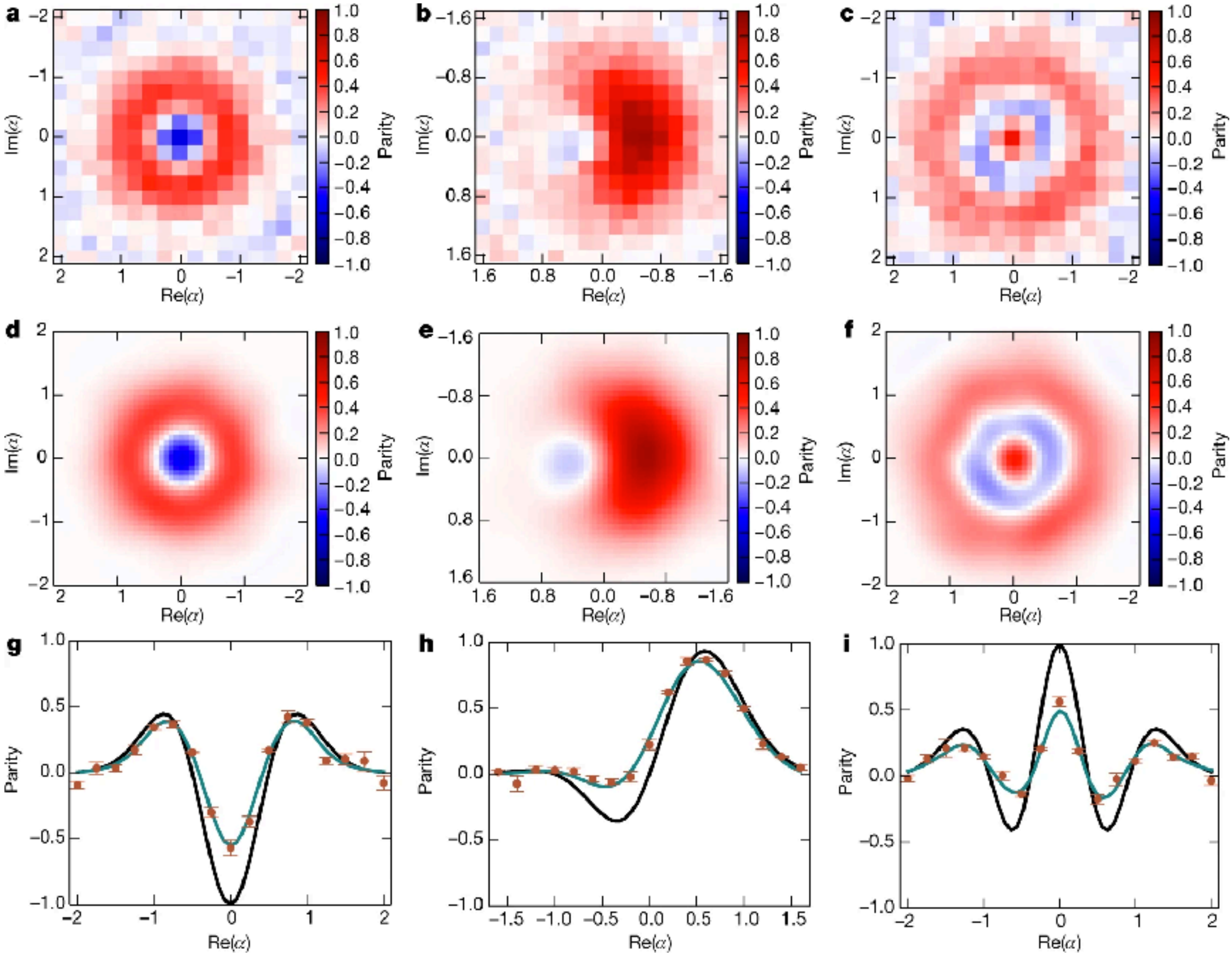
Y. Chu, *et al.* Nature **563**, 666 (2018)



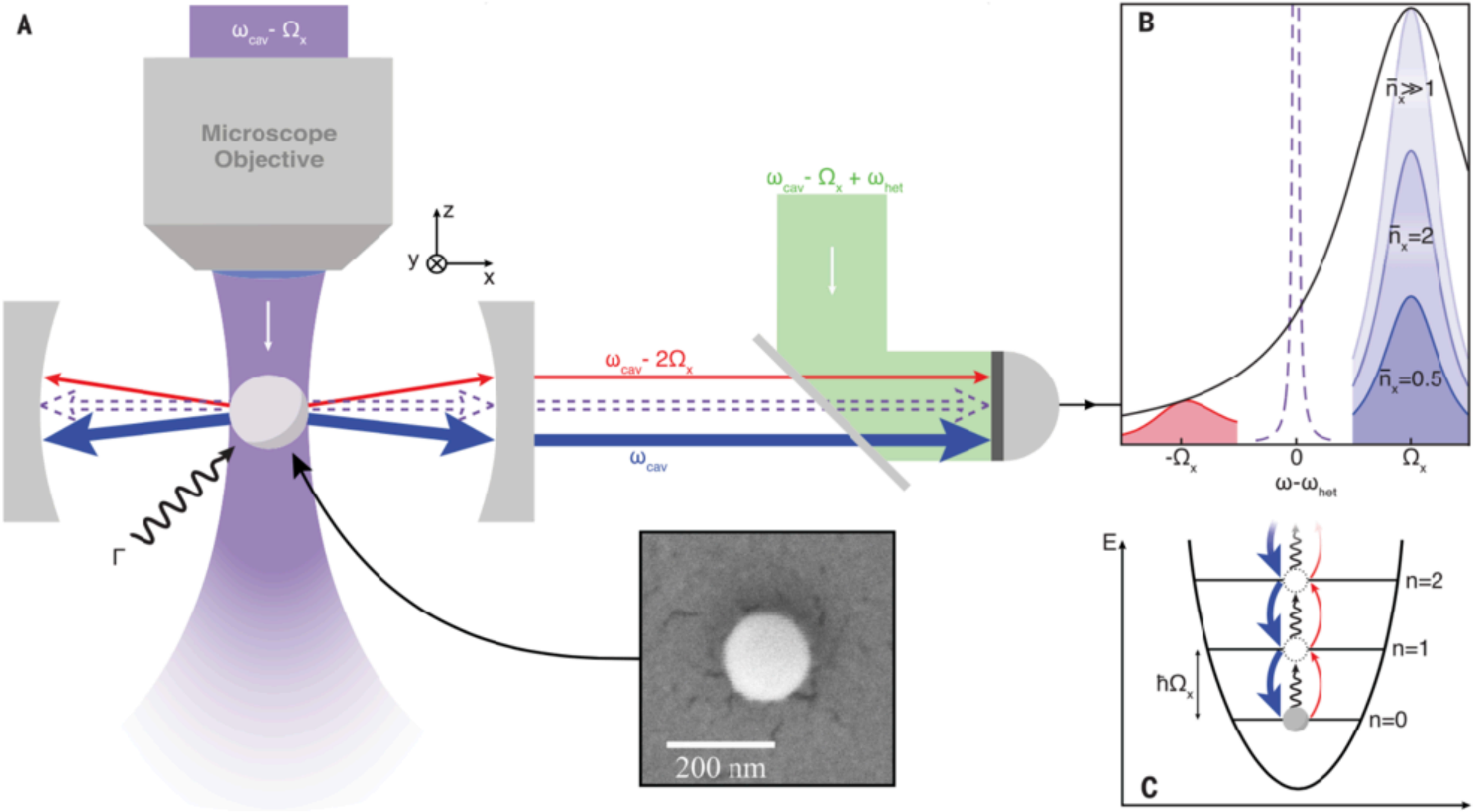
Climbing the Fock ladder



Non-Gaussian states



Levitation and ground state cooling



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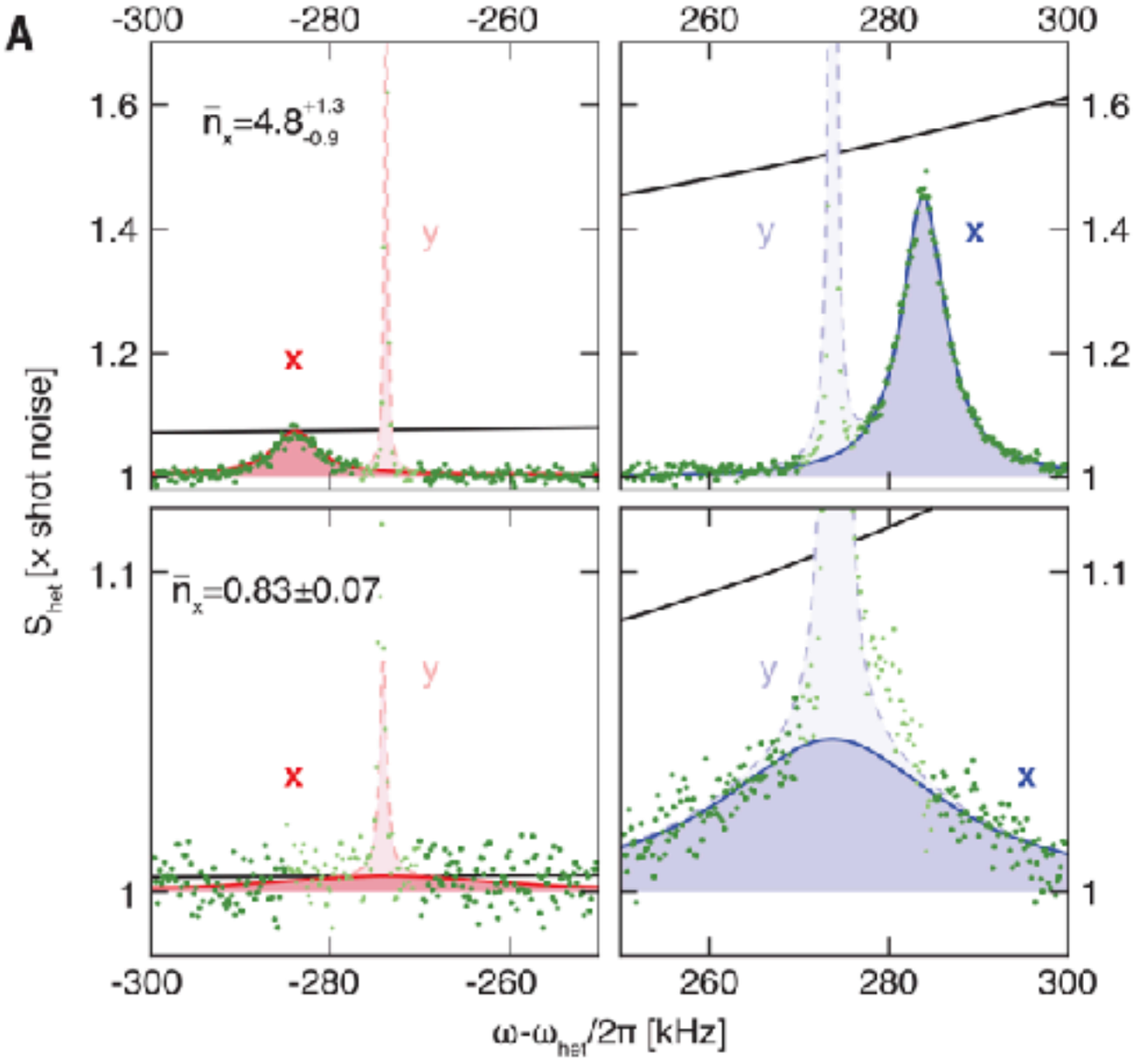
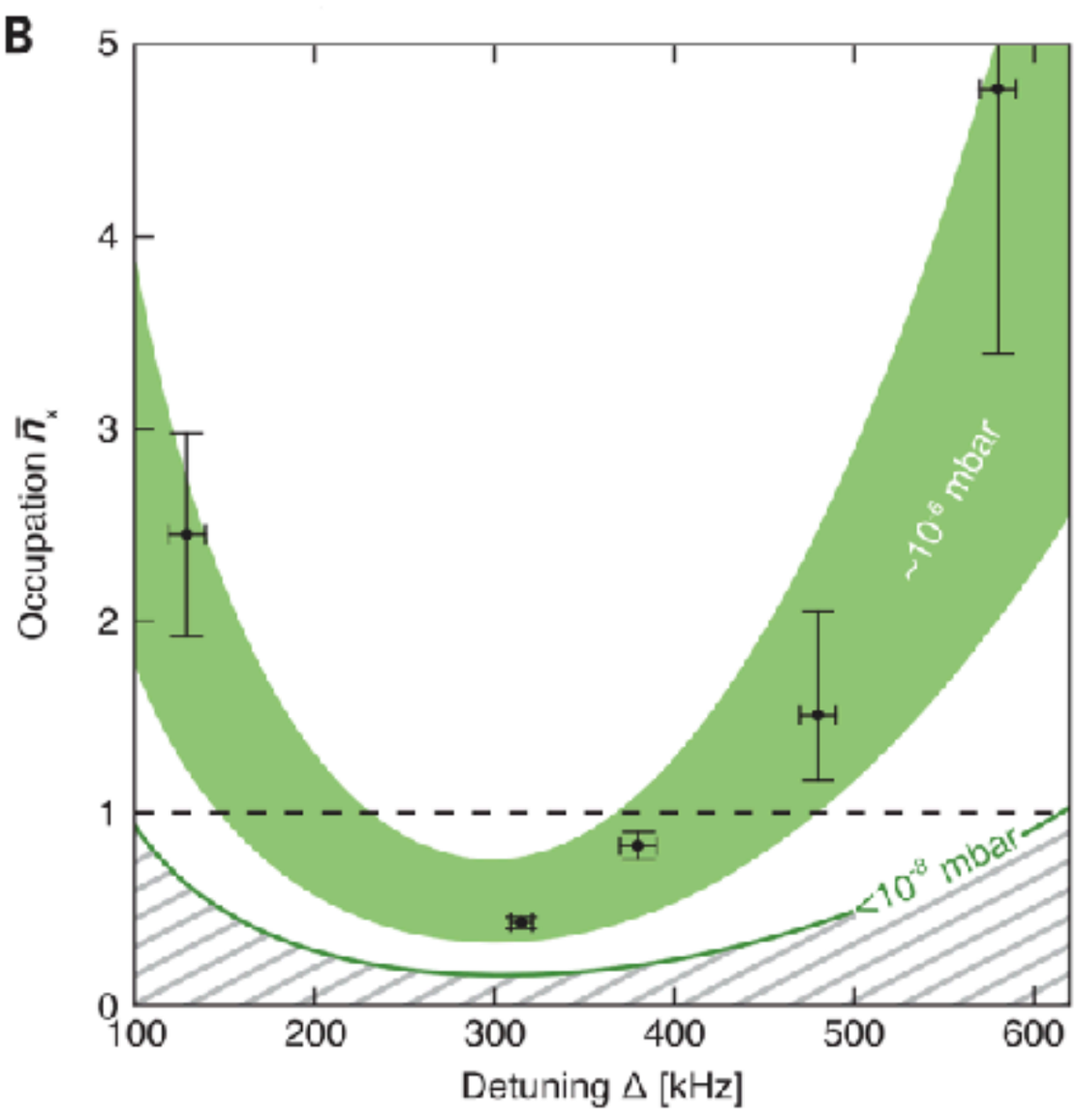
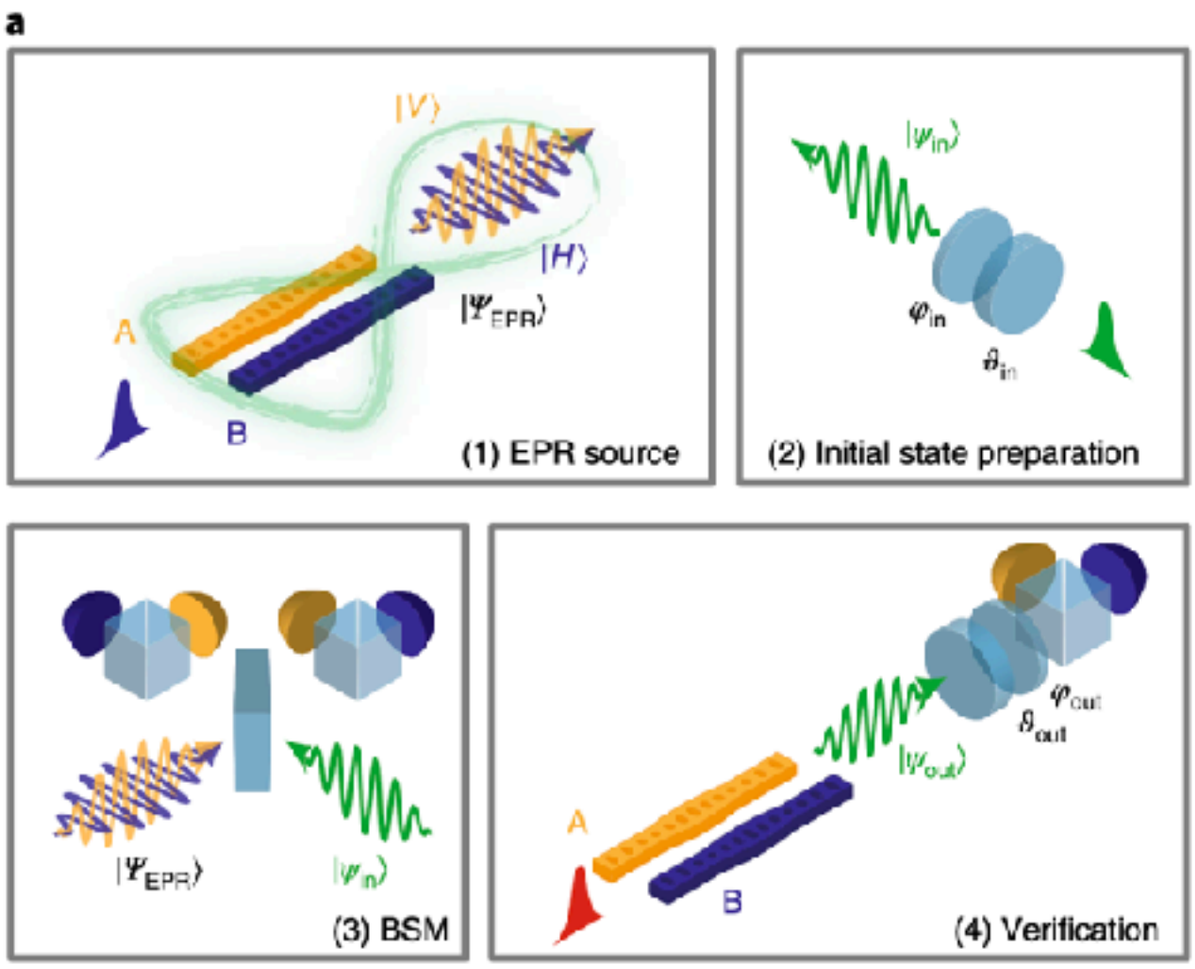
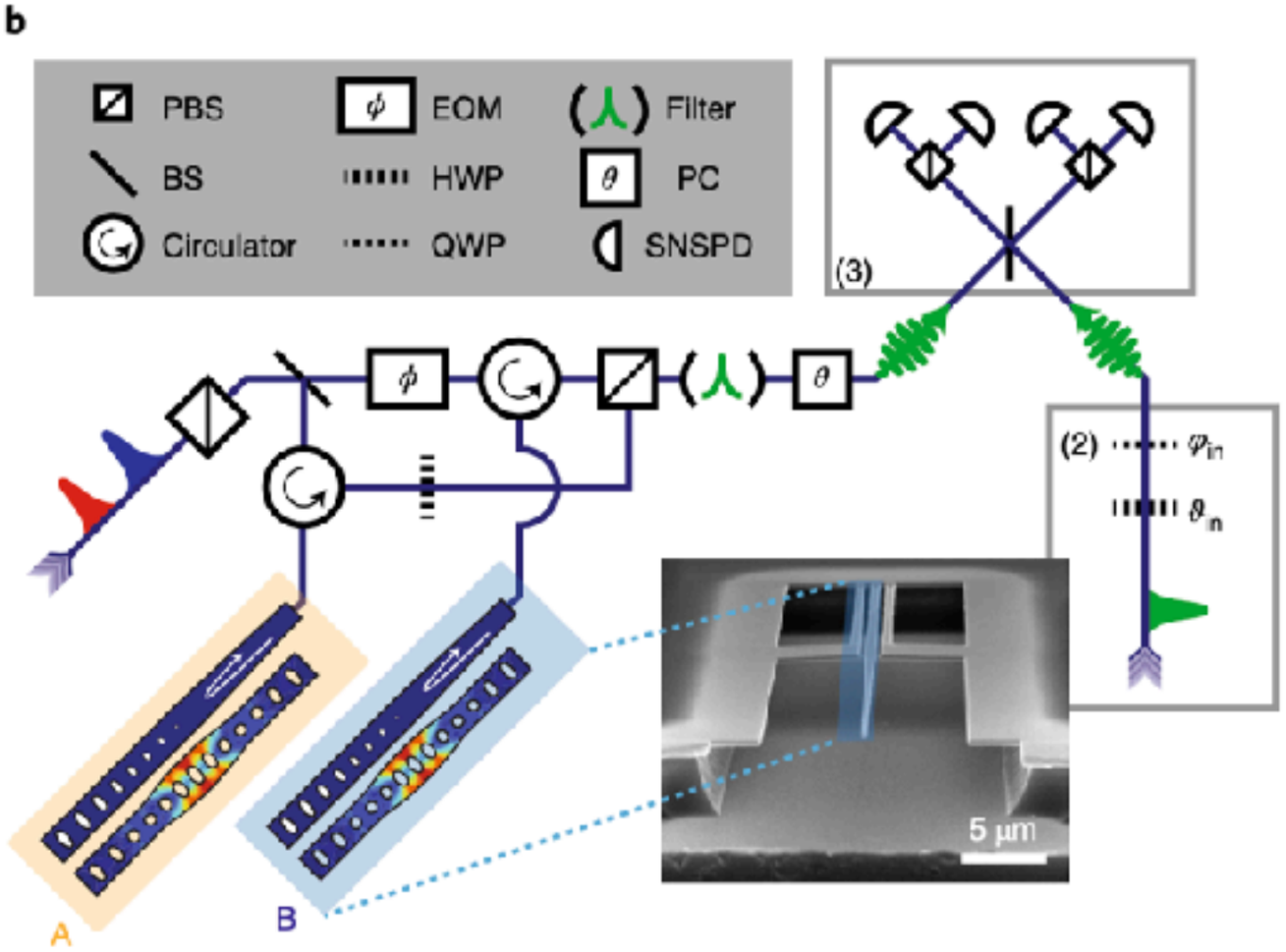
Levitation and ground state cooling

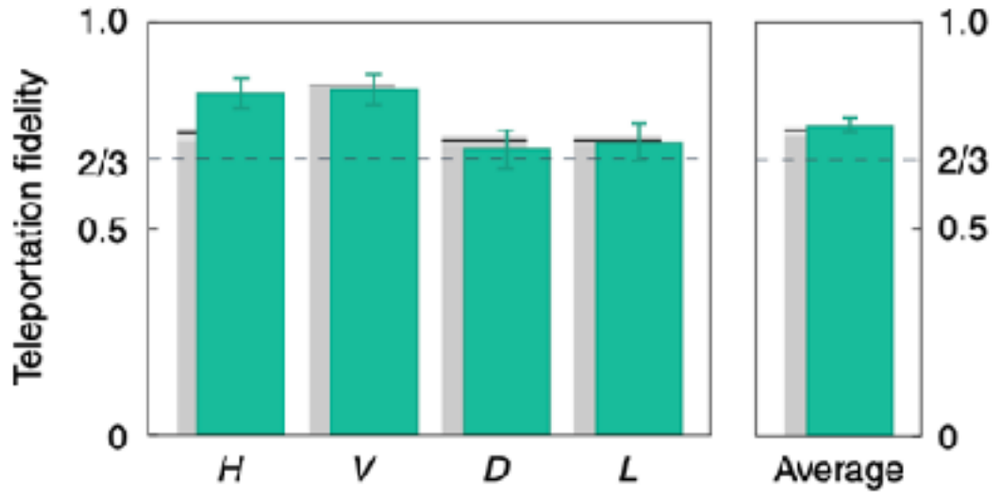




Teleportation and mechanics

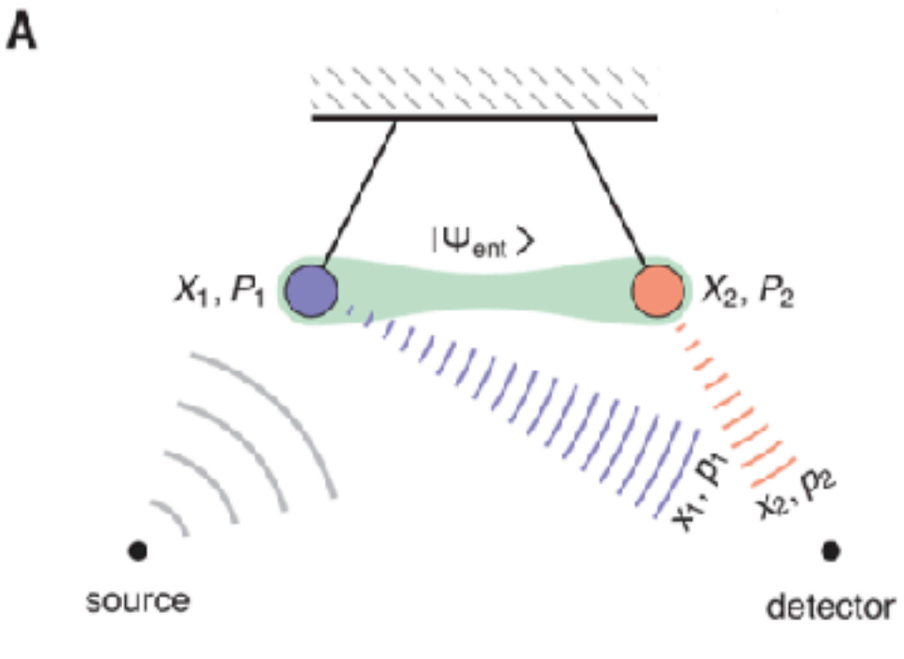


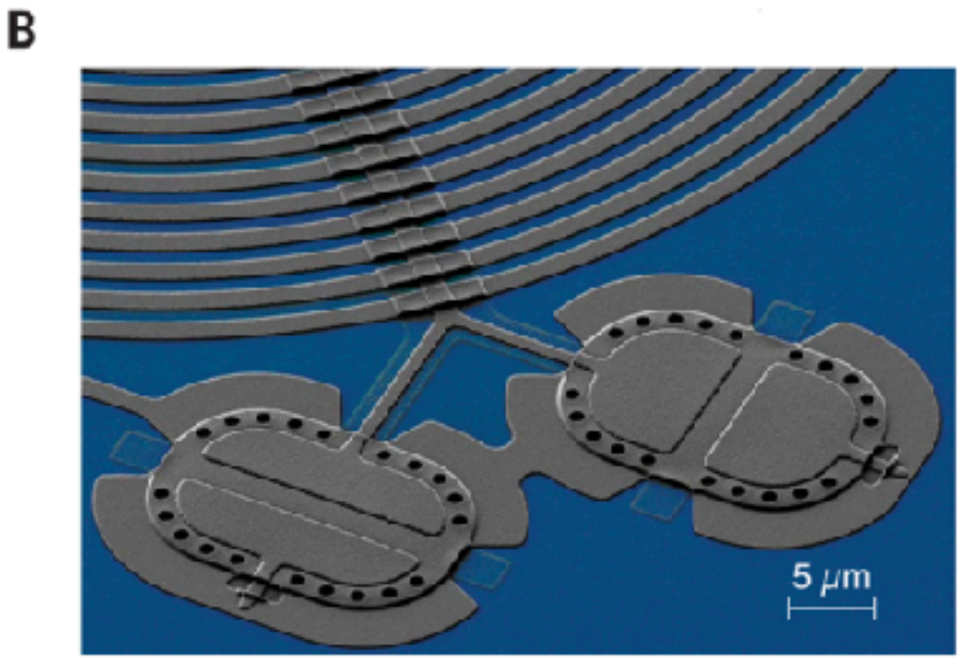


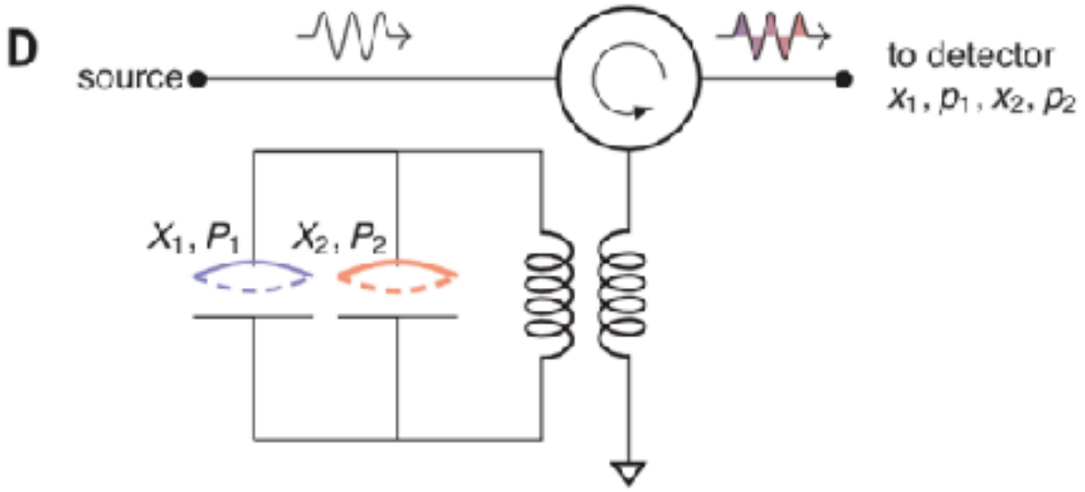


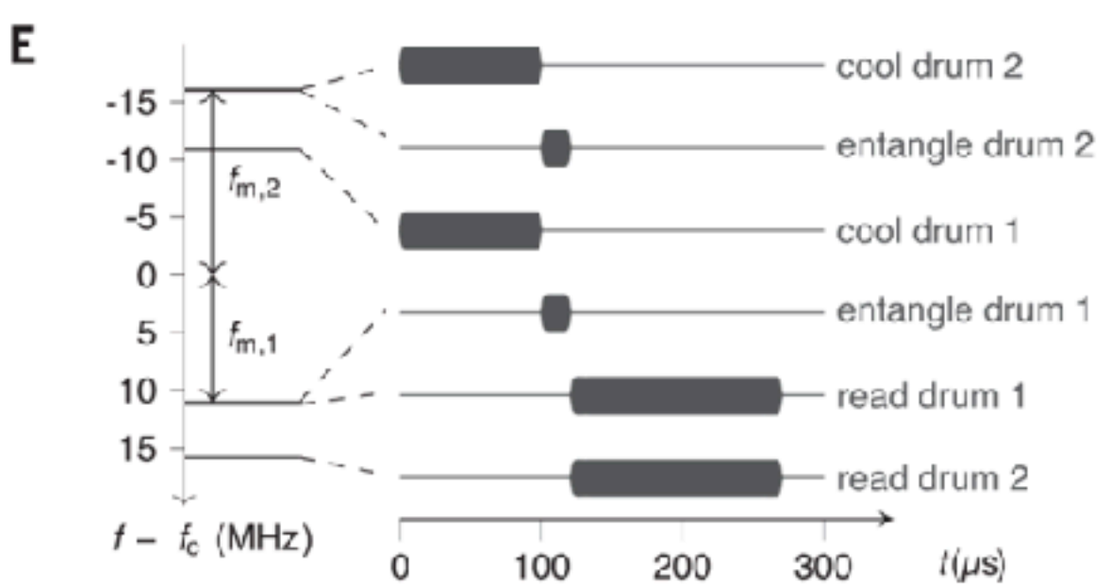
N. Fiaschi, *et al.* Nat. Phys. **15**, 817 (2021)

Teleportation and mechanics



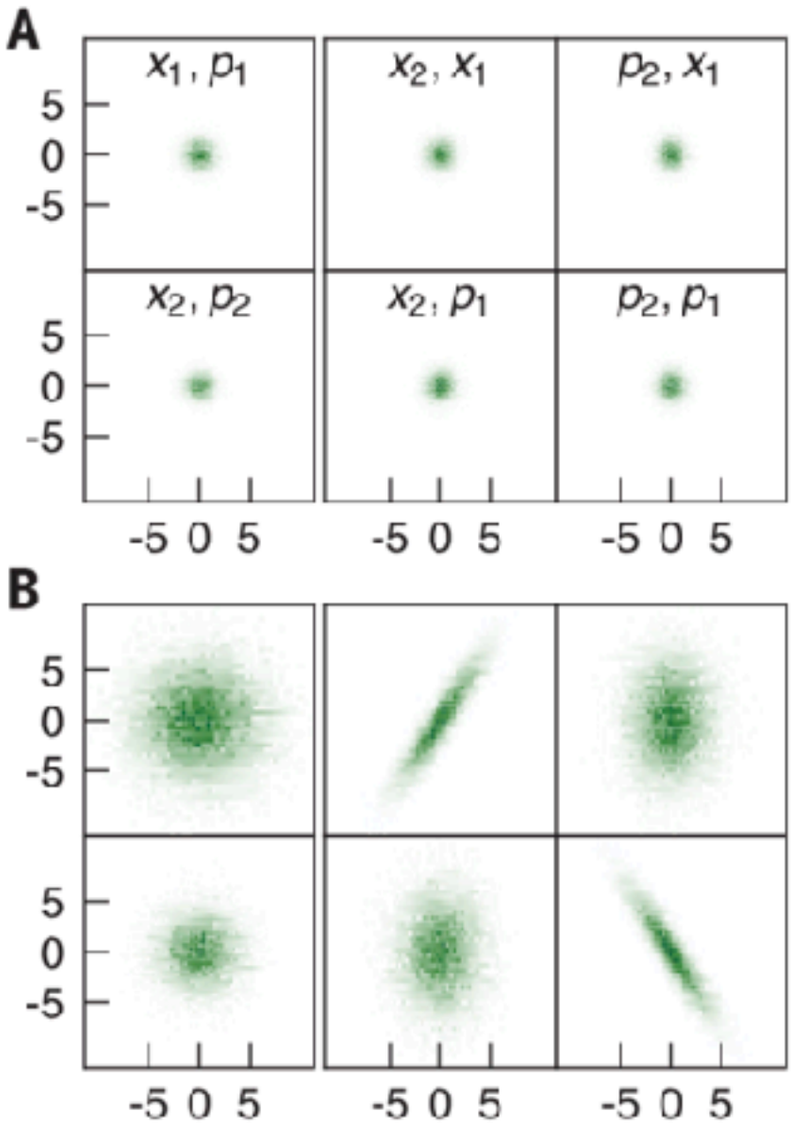


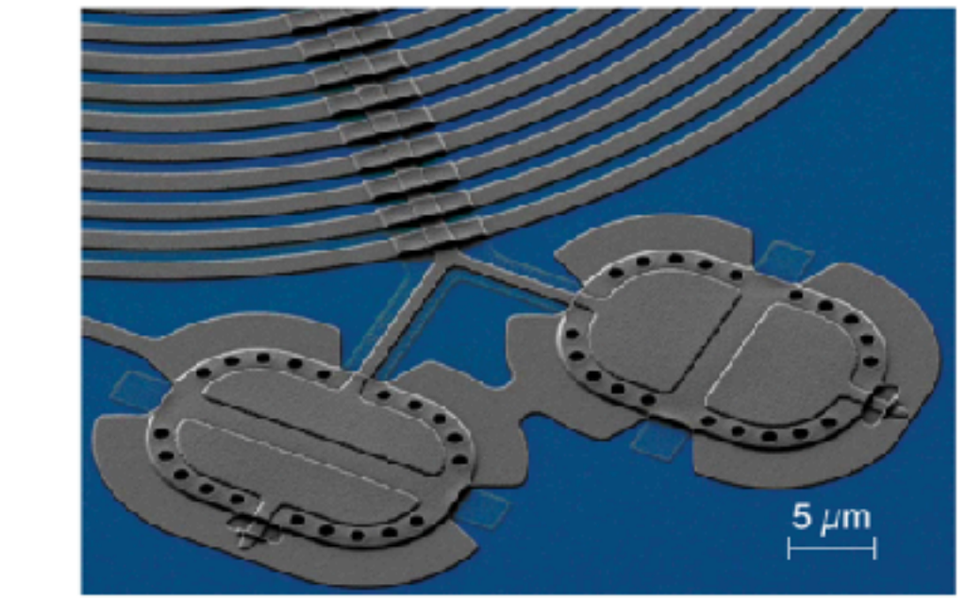


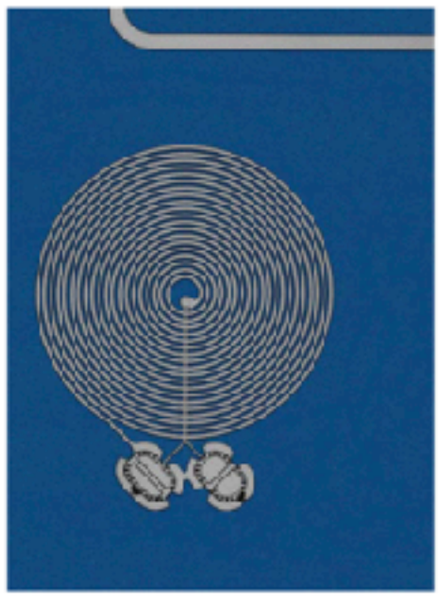


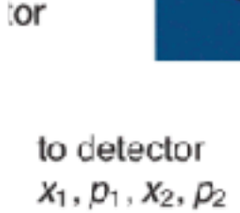
S. Kotler, *et al.* Science **372**, 622 (2021)

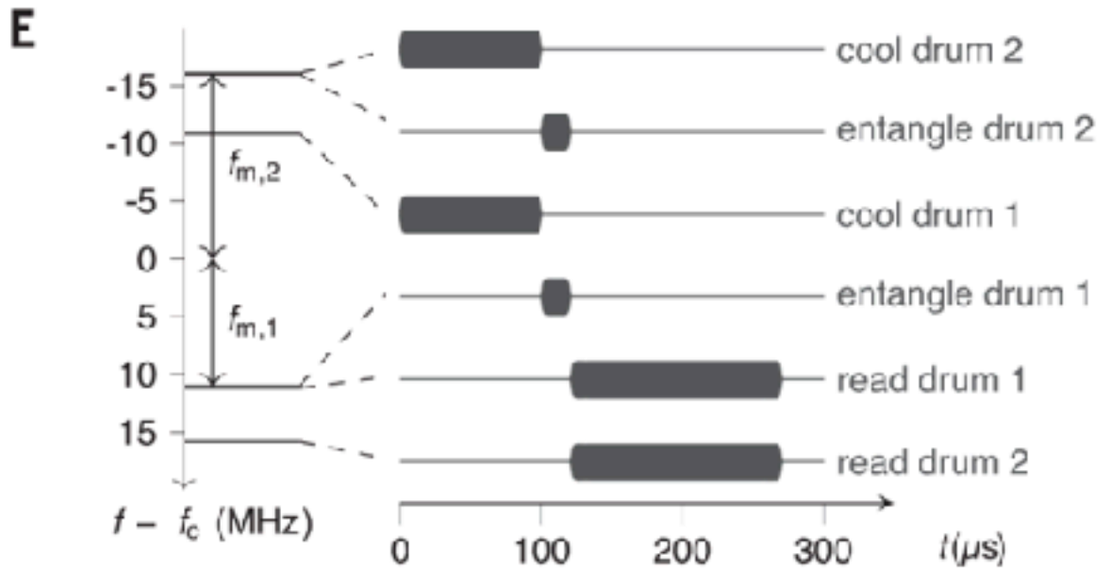
Teleportation and mechanics











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