Nanomechanical Tests of Quantum Linearity

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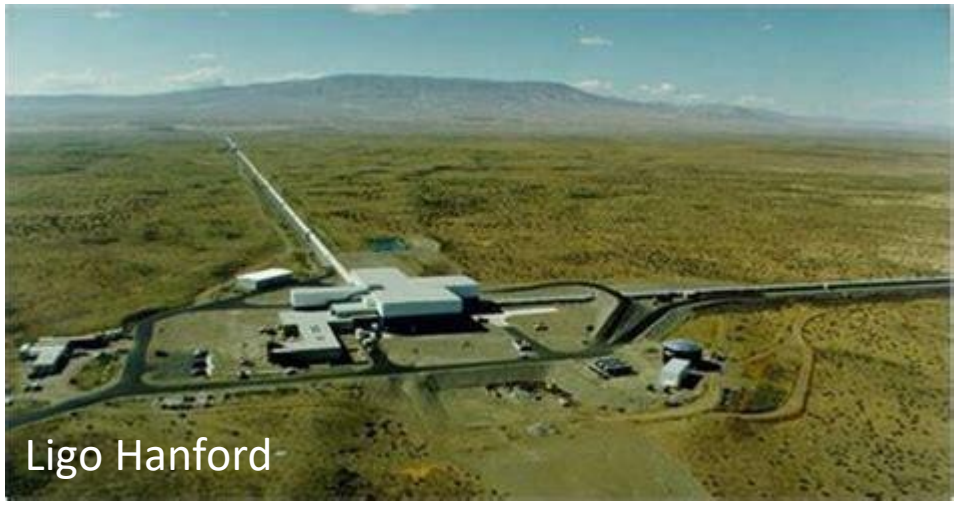
QUEENSLAND QUANTUM OPTICS

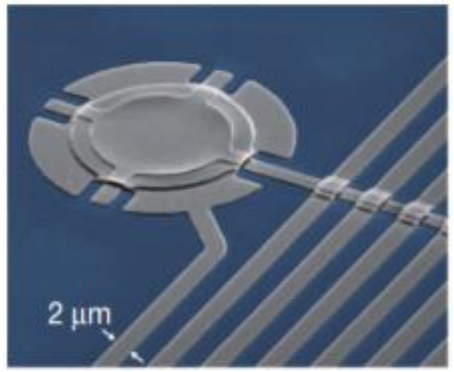
EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

ICFO
The Institute of Photonic Sciences

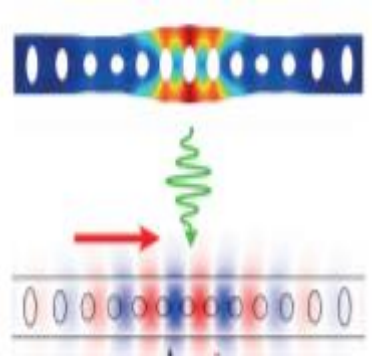
Image : C. Baker

Cavity Optomechanics and Electromechanics

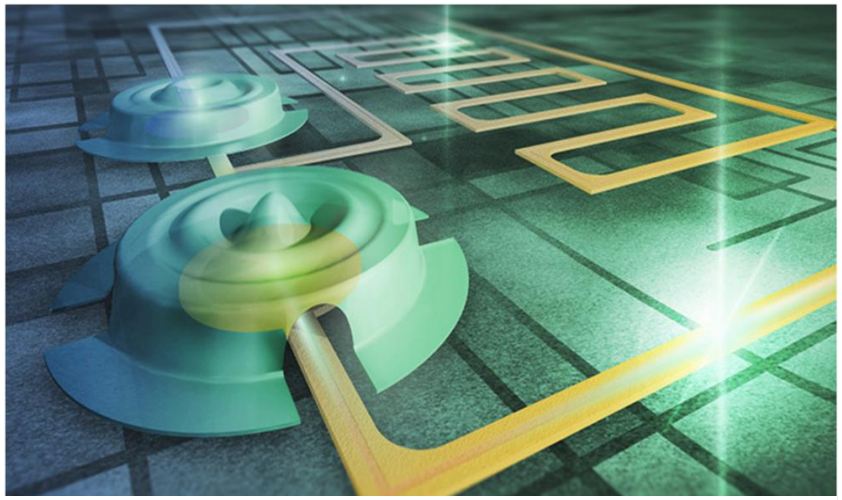




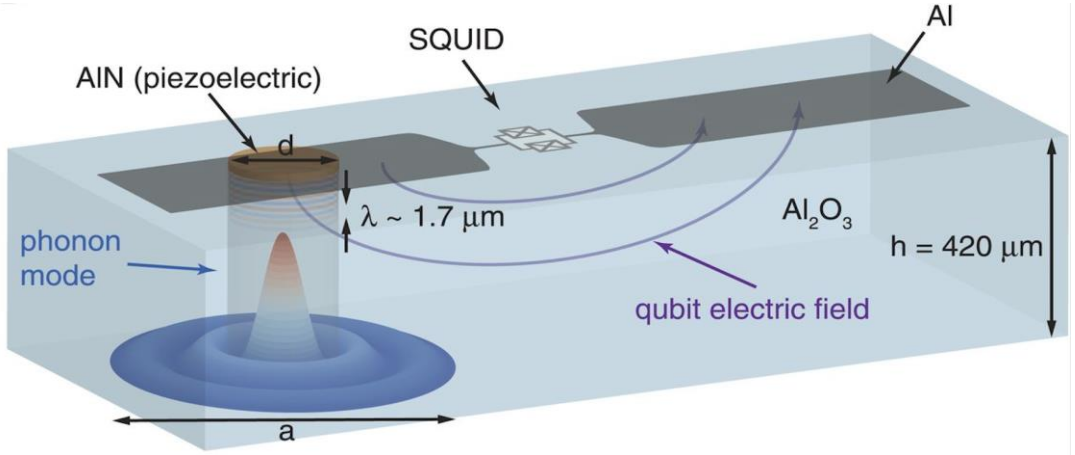
JD Teufel et al.,
Nature **475**, 359 (2011).



J.D. Cohen et al.,
Nature **520**, 522 (2015).



CF Ockeloen-Korppi *et al.*, Nature **556**, 478 (2018).



Y Chu *et al.*, Science **358**, 199 (2017).

…can we use all this to test quantum foundations?

Objective Collapse Models

- Is the universe unitary?
- Would an “observer outside the universe” see our world as a large quantum superposition of all possibilities?
- Is there such a thing as quantum states of sentient beings?

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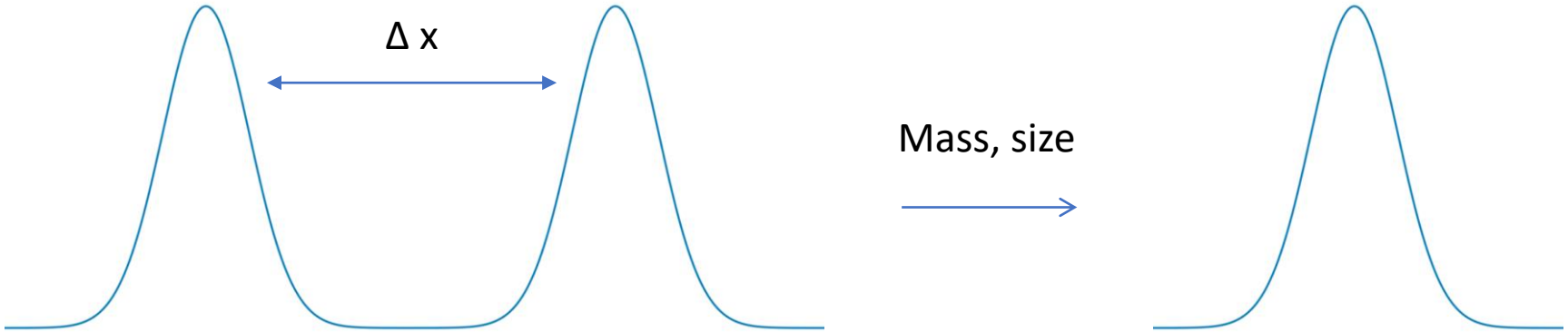


$$\frac{d\Psi}{dt} = \left[-\frac{i}{\hbar} H + \sqrt{\lambda} A \xi(t) - \frac{\lambda}{2} \left(A^{\dagger} A + A^{2} \right) \right] \Psi$$

Continuous Spontaneous Localization (CSL)

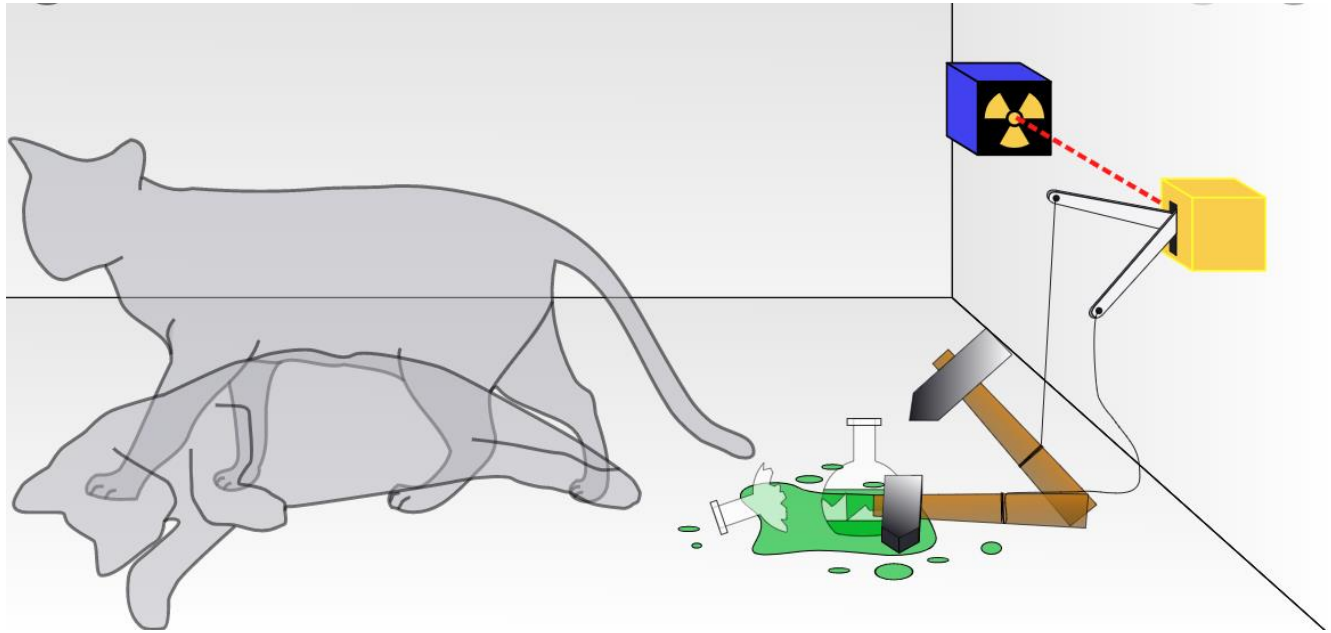
$$\frac{\mathrm{d}}{\mathrm{d}t}\hat{\rho}(t) = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}(t)] + \mathcal{L}_{\mathrm{CSL}}[\hat{\rho}(t)]$$

$$\mathcal{L}_{\mathrm{CSL}}[\hat{\rho}(t)] \propto \mathrm{mass}, (\Delta x)^2, 1 - e^{-\frac{\Delta x^2}{r_c^2}}$$

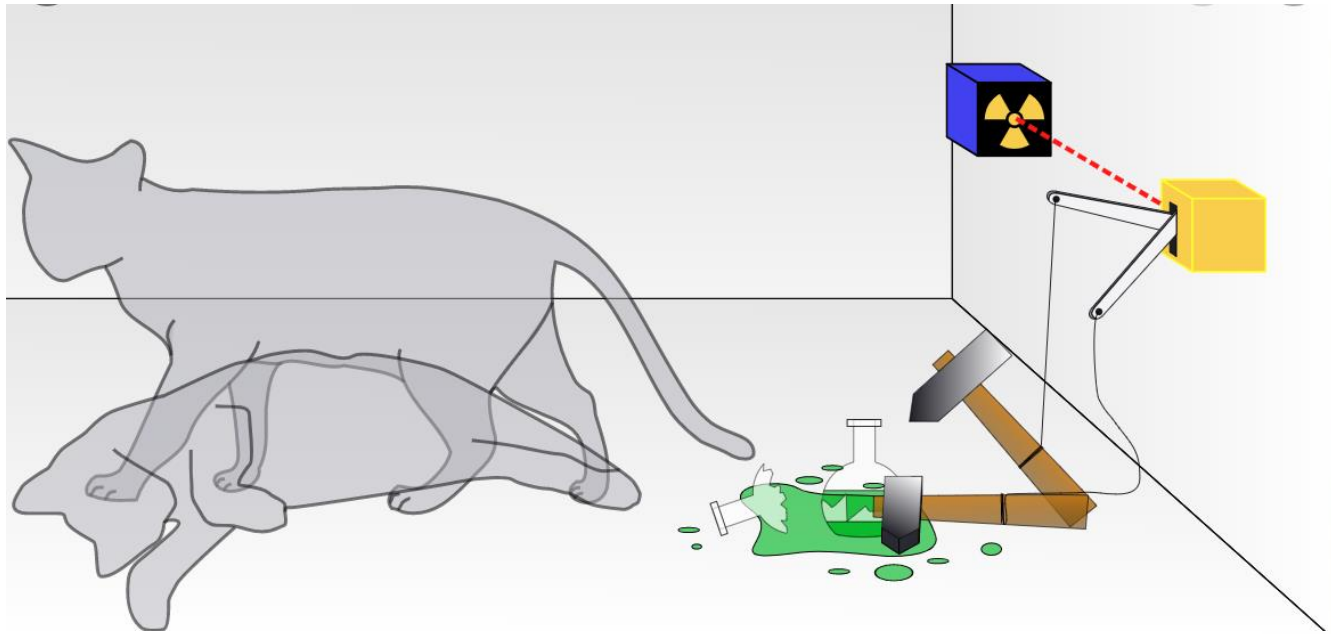
Collapse noise correlation length: r_c

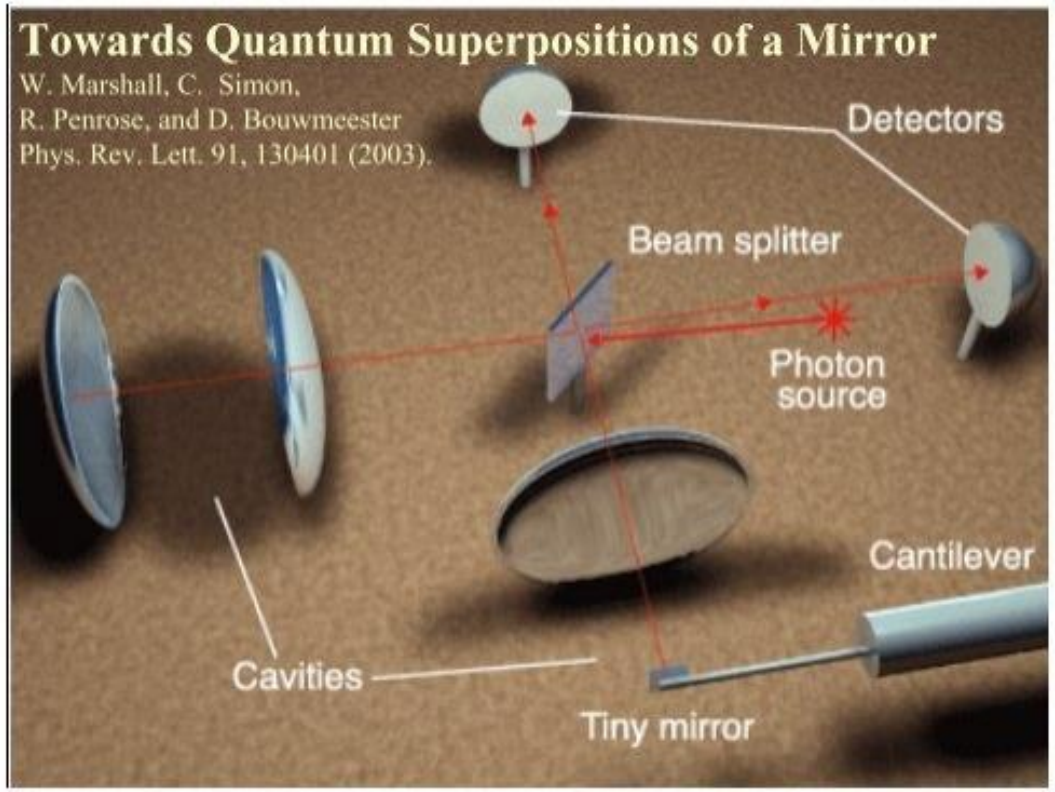
Collapse rate: λ_{CSL}

Testing Objective Collapse Models

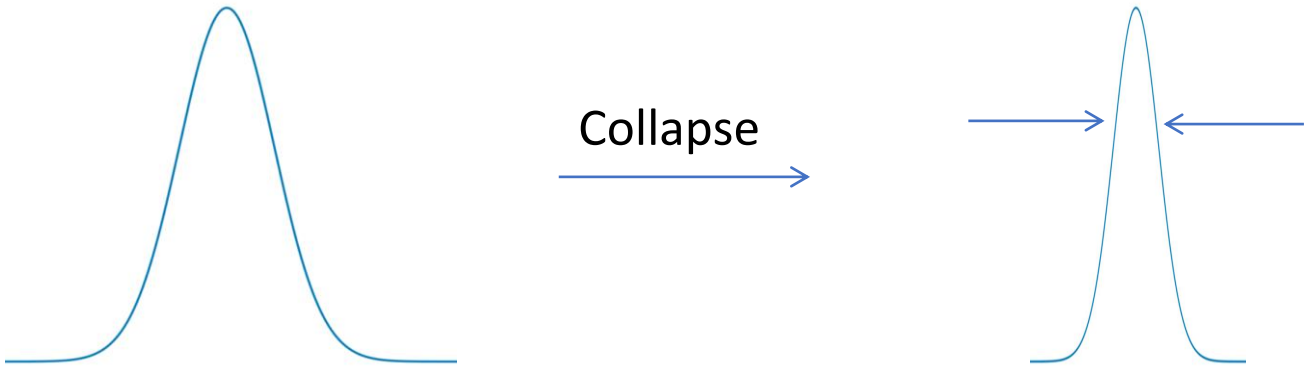


Testing Objective Collapse Models



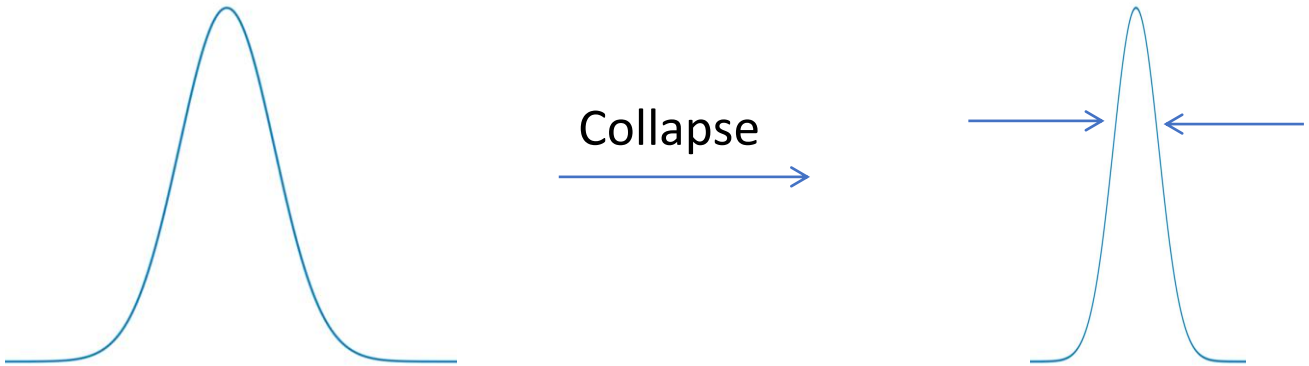


Collapse Induced Diffusion



- Collapse noise diffuses the particle
- Produces spontaneous heating

Collapse Induced Diffusion



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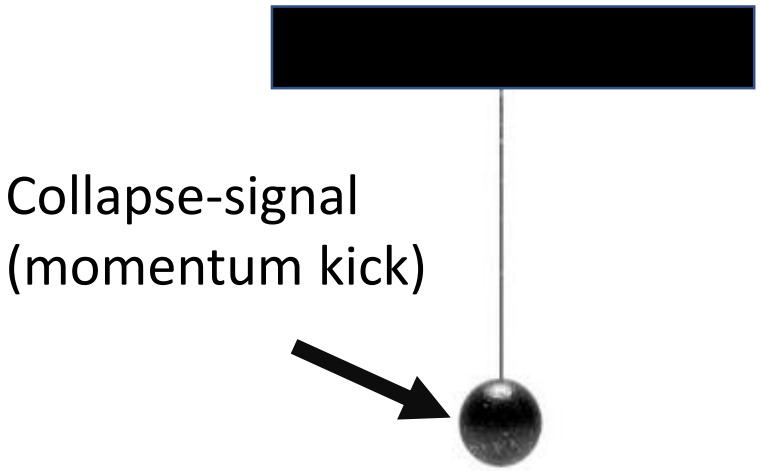
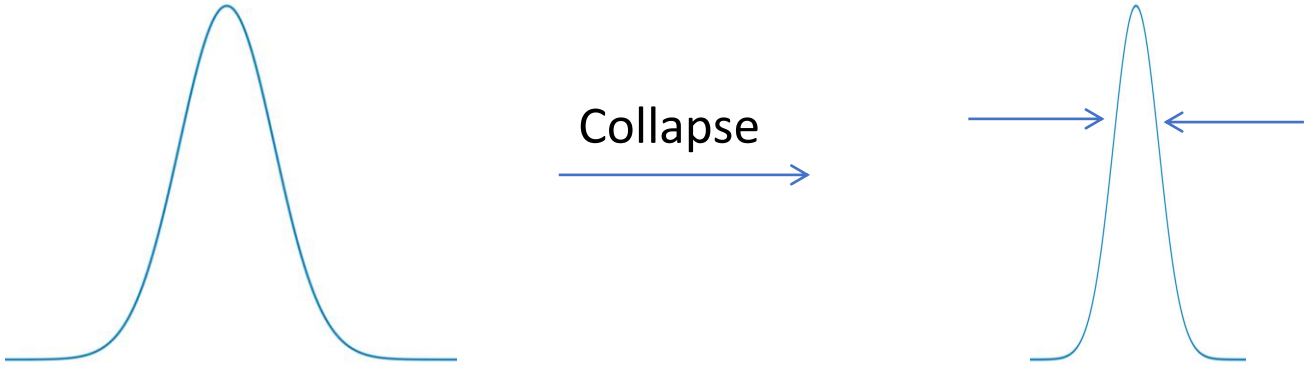


S. Nimmrichter *et al.,* Phys. Rev. Lett. **113**, 020405 (2014)

Collapse Induced Diffusion



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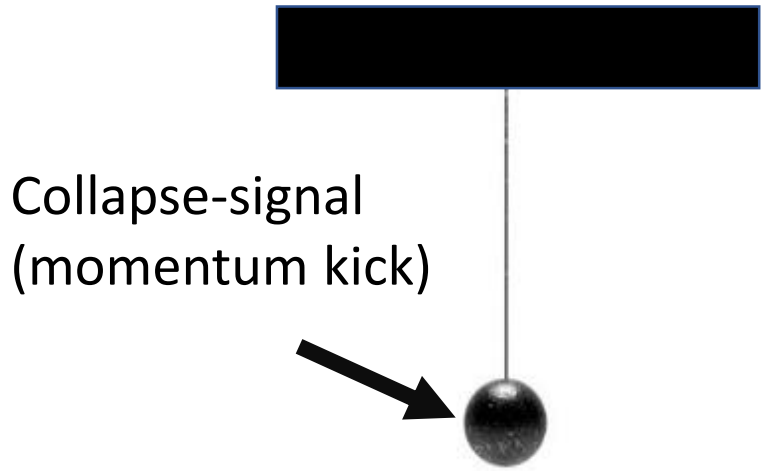
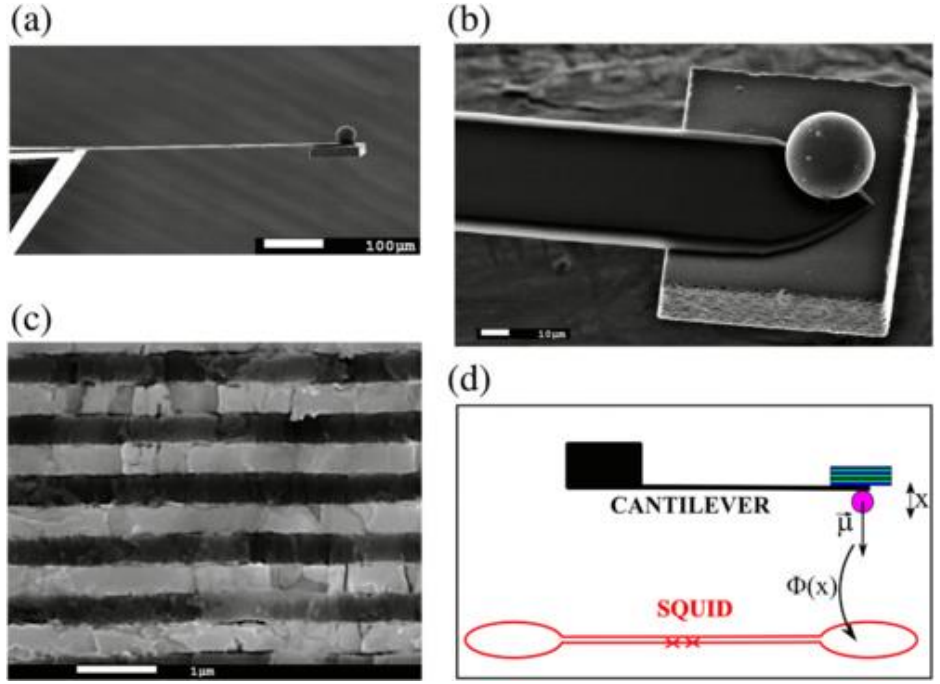
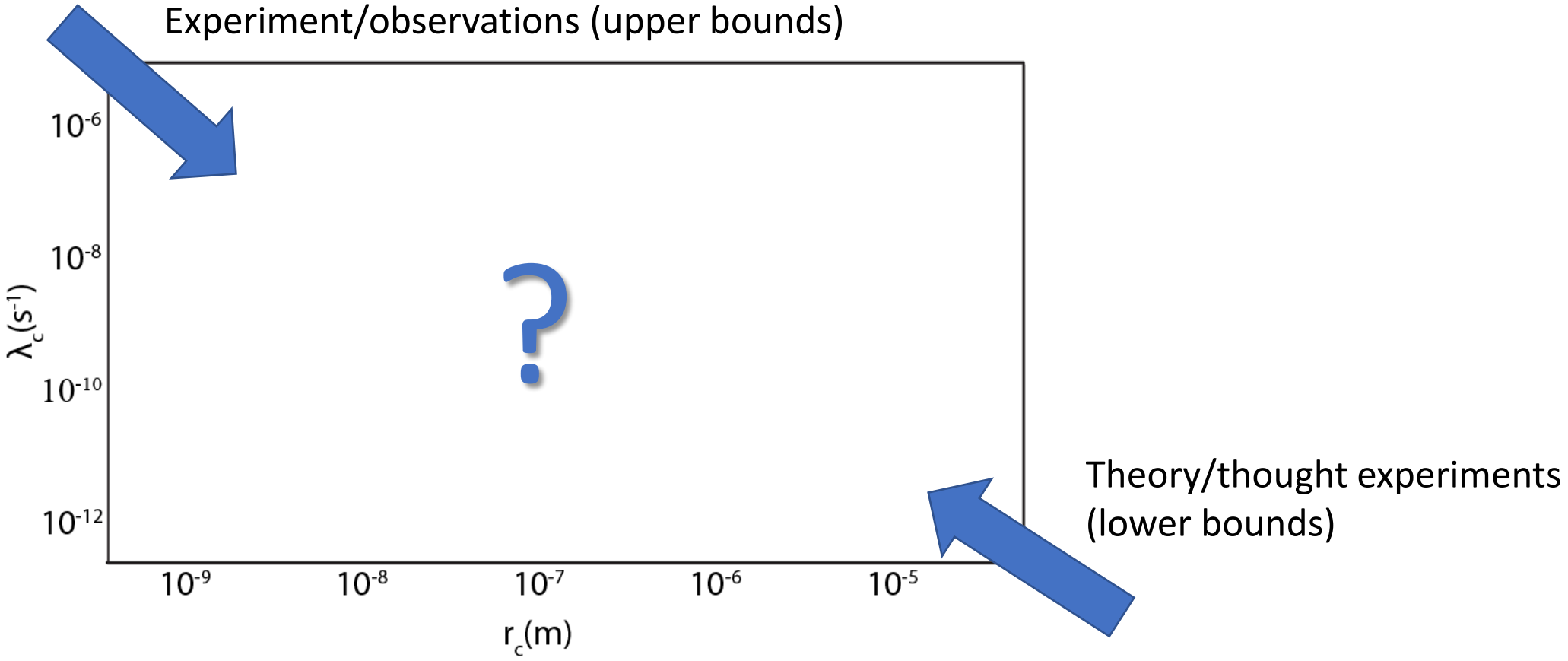




S. Nimmrichter *et al.,* Phys. Rev. Lett. **113**, 020405 (2014); A. Vinante *et al.,* Phys. Rev. Lett. . **125**, 100404 (2020).

Bounds on CSL



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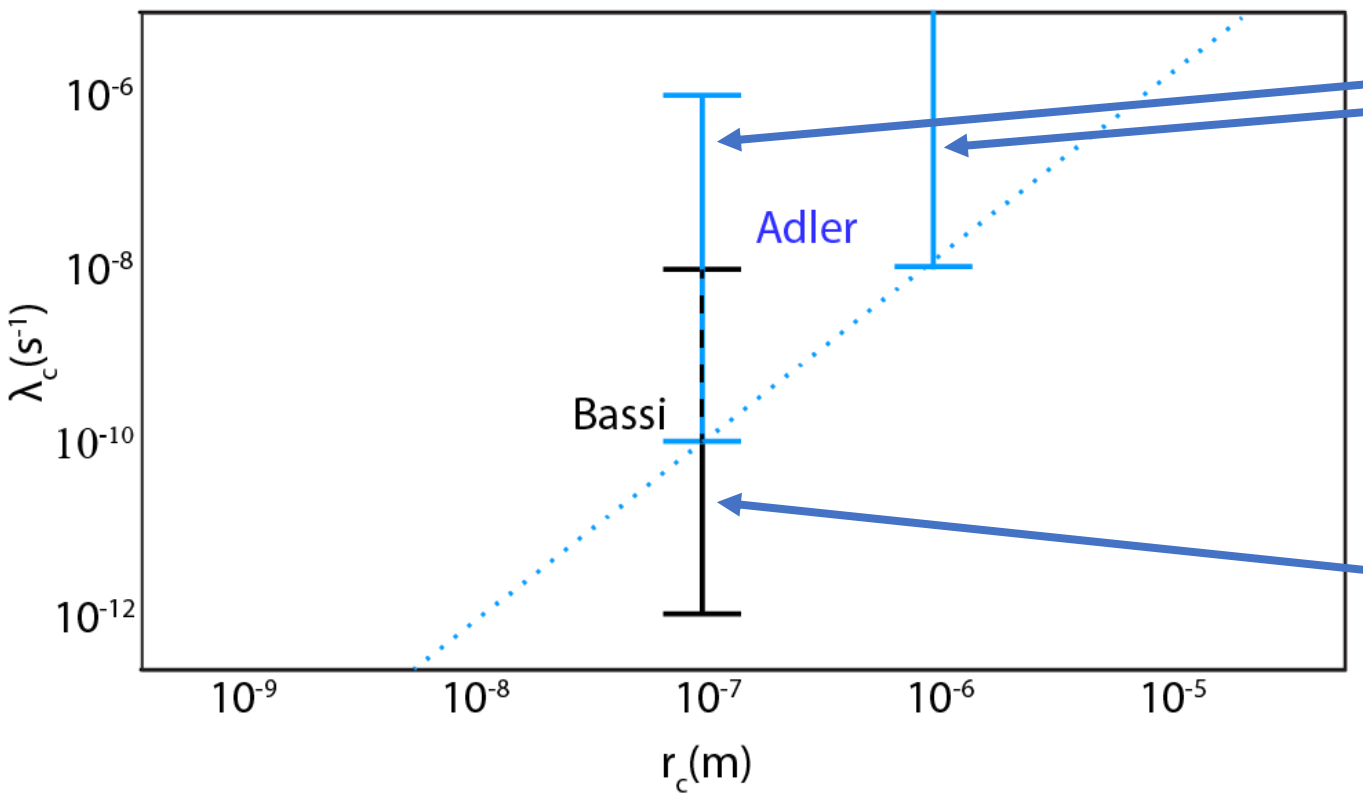
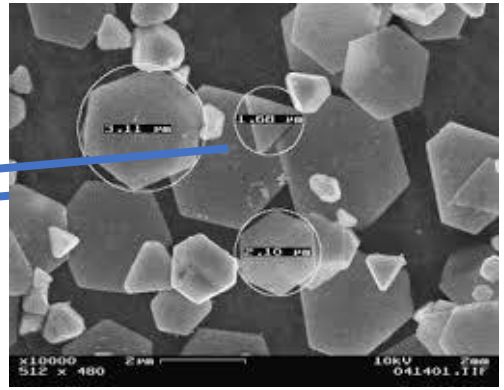
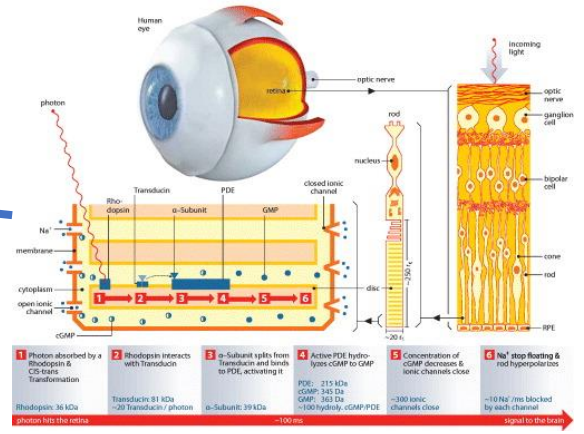


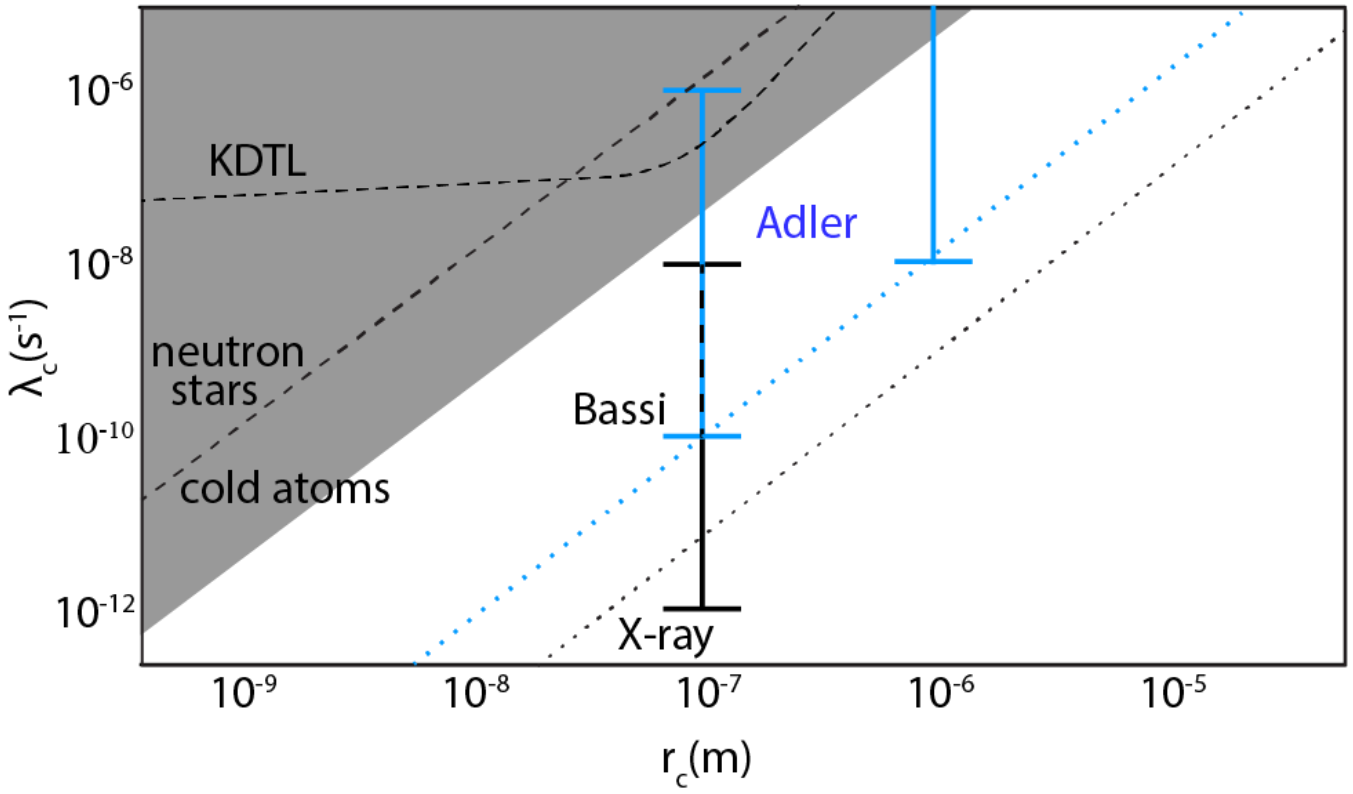




S. Adler J. Phys. A **40** 2935 (2007).

A. Bassi *et al.* EPL **92** 50006 (2010).

Bounds on CSL



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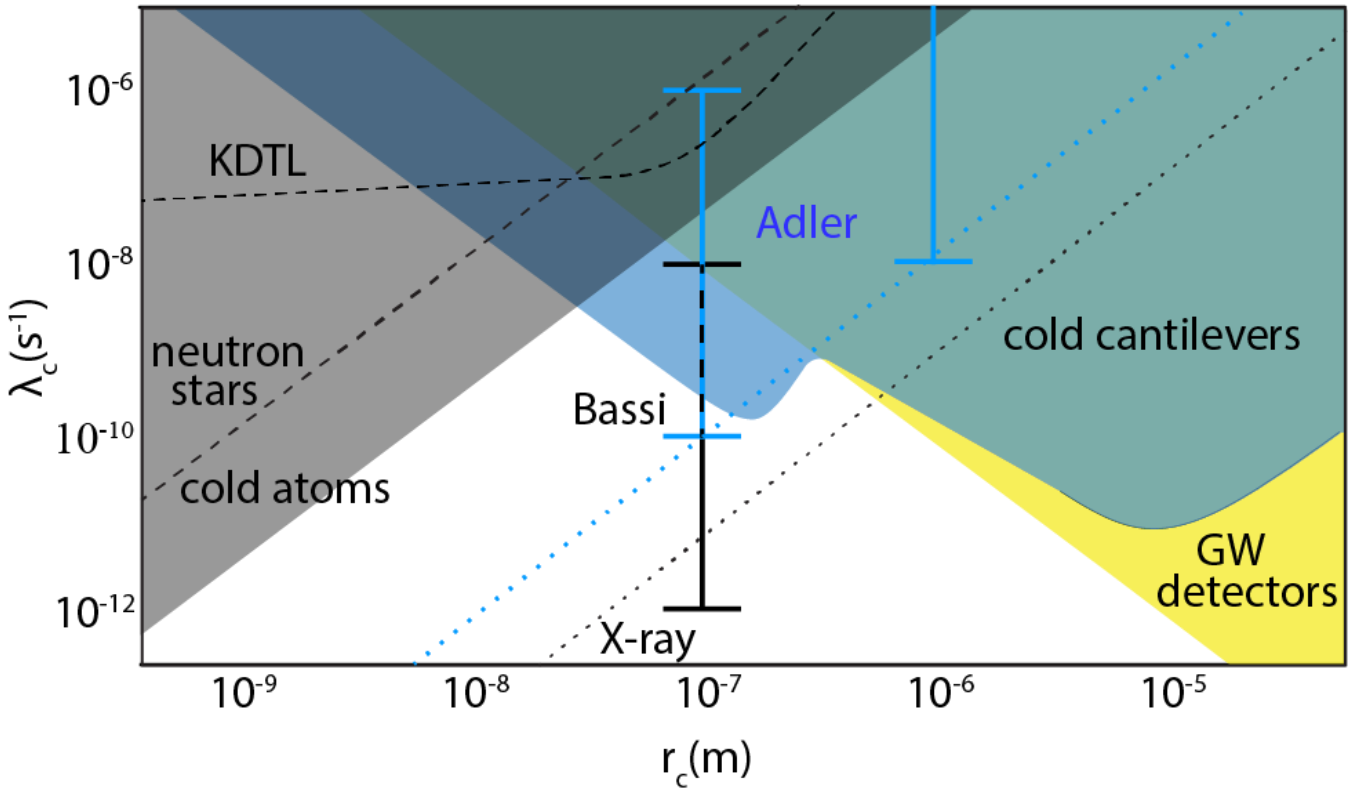
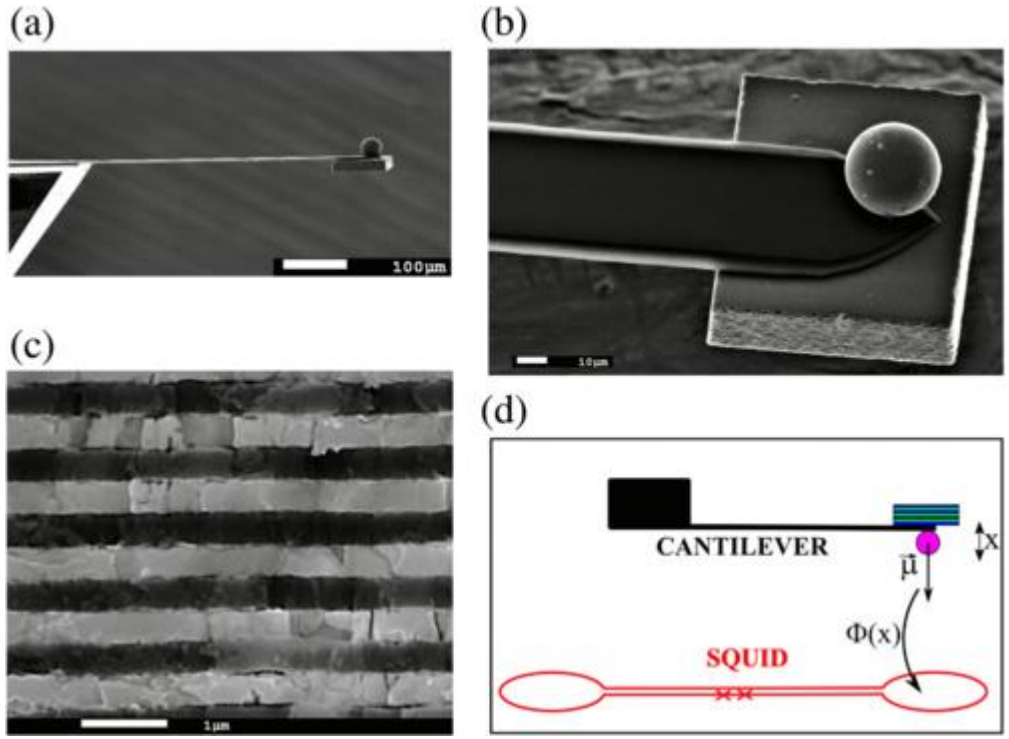
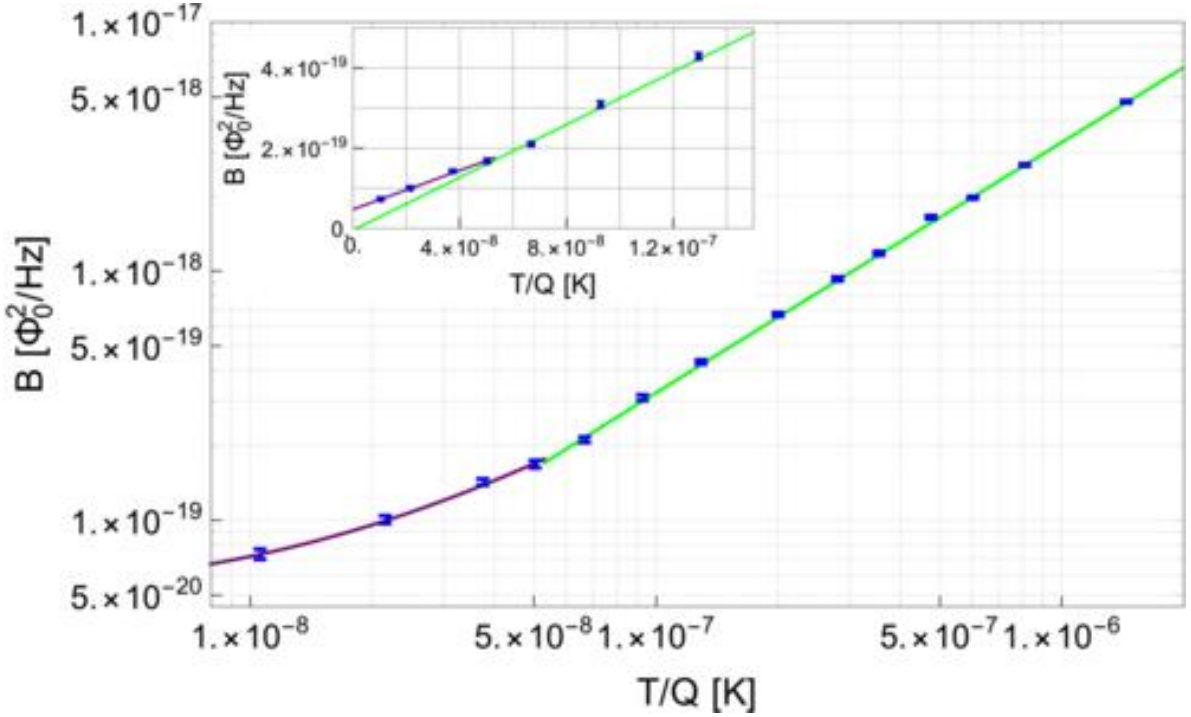


Can we do anything to improve?

Oscillator tests of CSL





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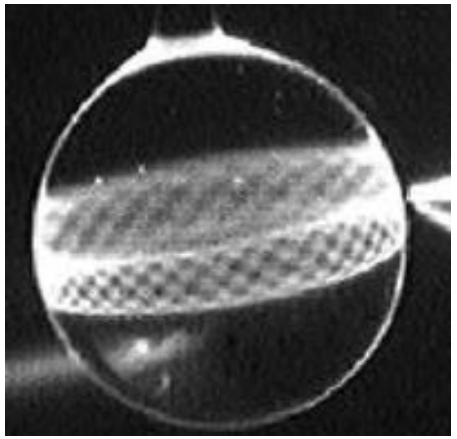
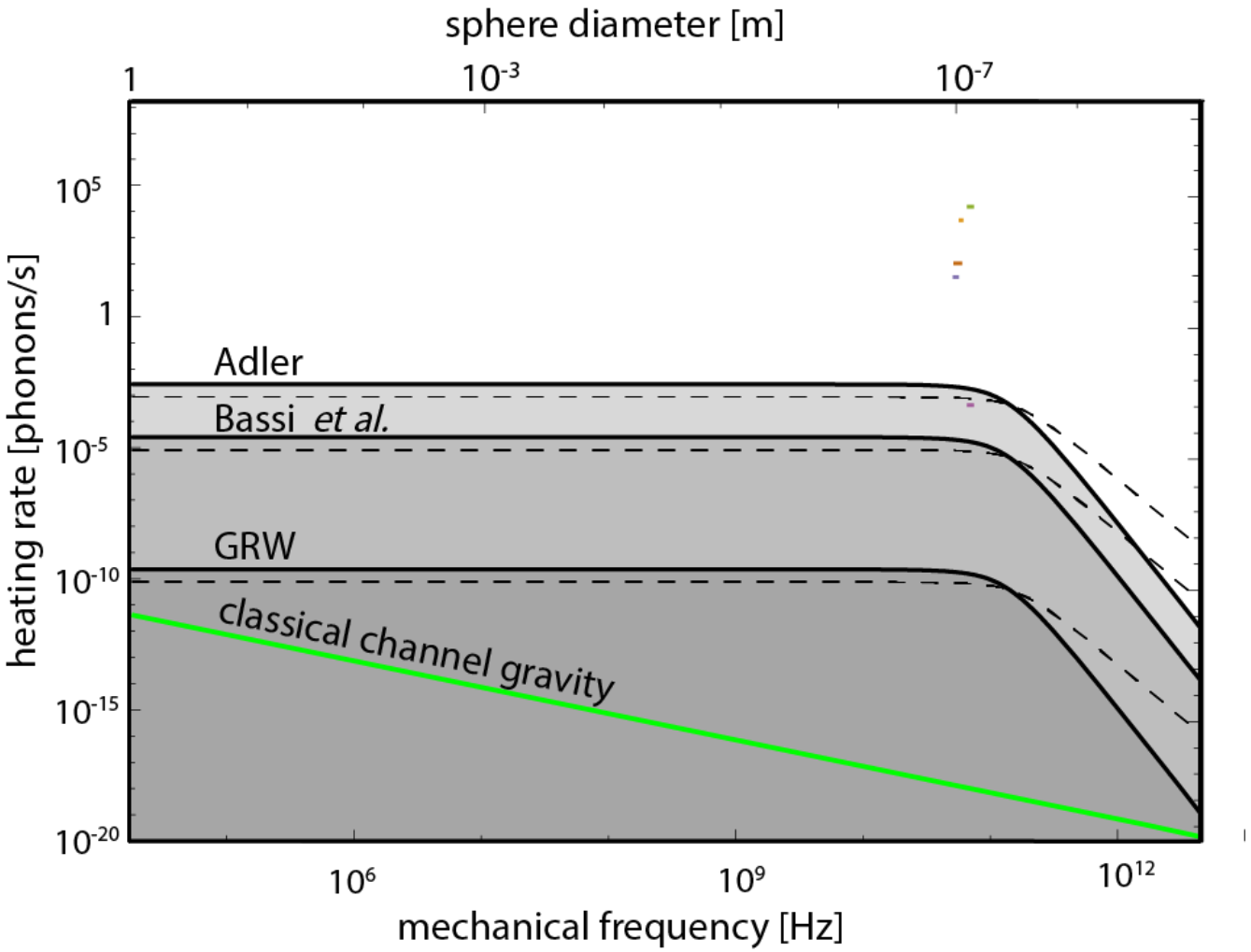
Can we suppress thermal noise below CSL?

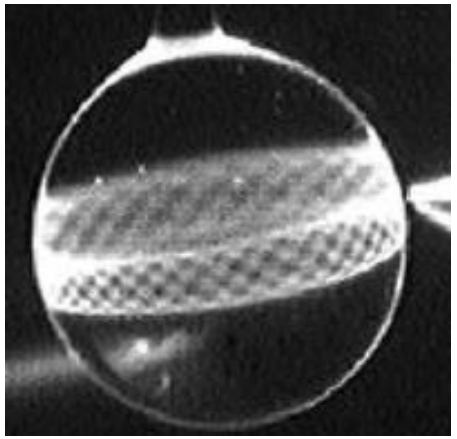




S. Forstner *et al.*, Optica **10**, 1427 (2020).

Can we suppress thermal noise below CSL?

Q=10^7



Thermal occupancy

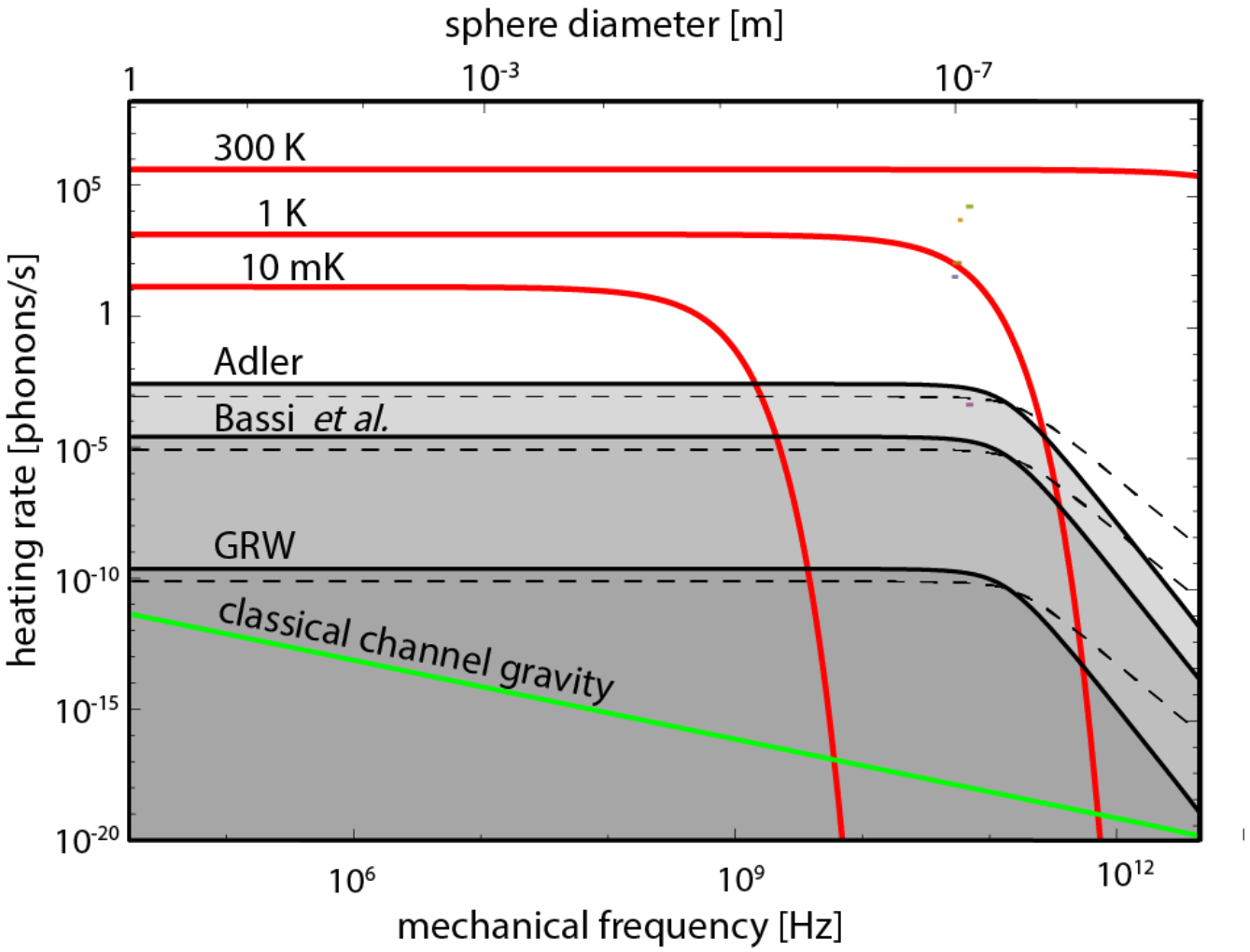
$$\bar{n} = \frac{1}{e^{\hbar\Omega/k_B T} - 1}$$

High. Temp. limit:

$$k_B T \gg \hbar\Omega \Rightarrow \bar{n} = \frac{k_B T}{\hbar\Omega}$$

Low. Temp. limit:

$$k_B T \ll \hbar\Omega \Rightarrow \bar{n} = e^{-\frac{k_B T}{\hbar\Omega}}$$



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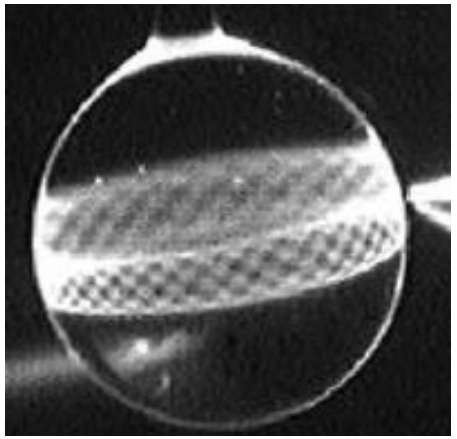

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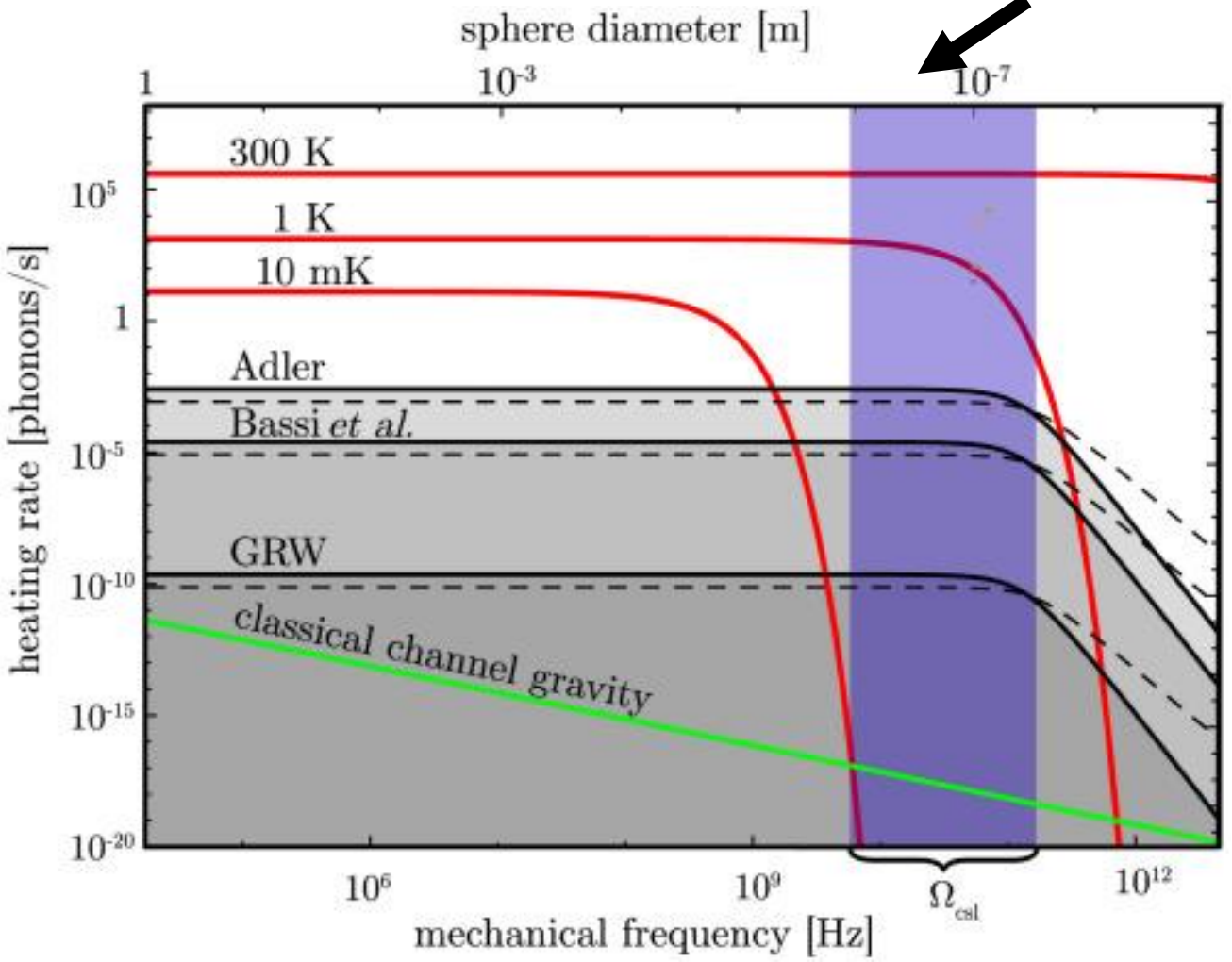
cosmological origin?



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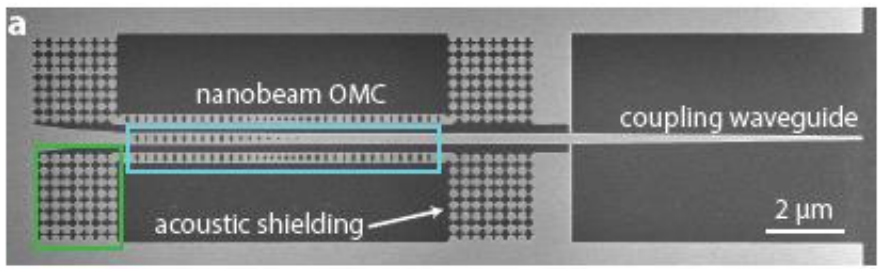
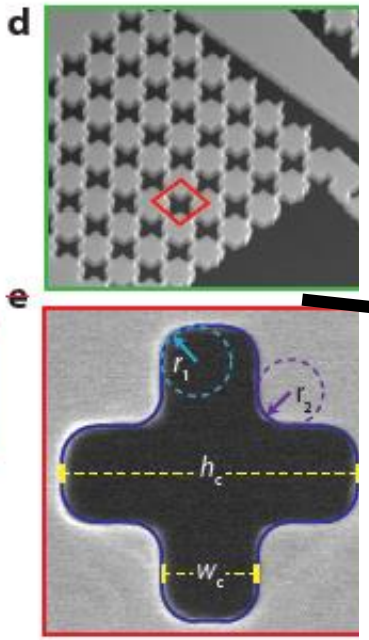
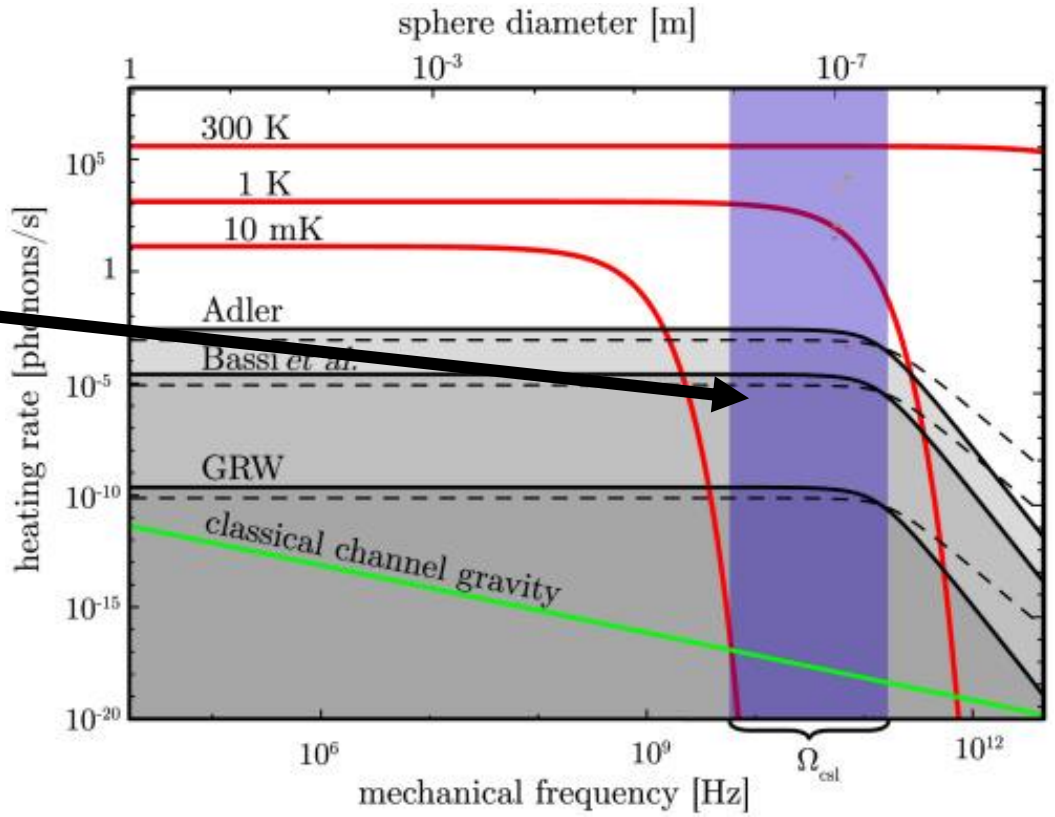




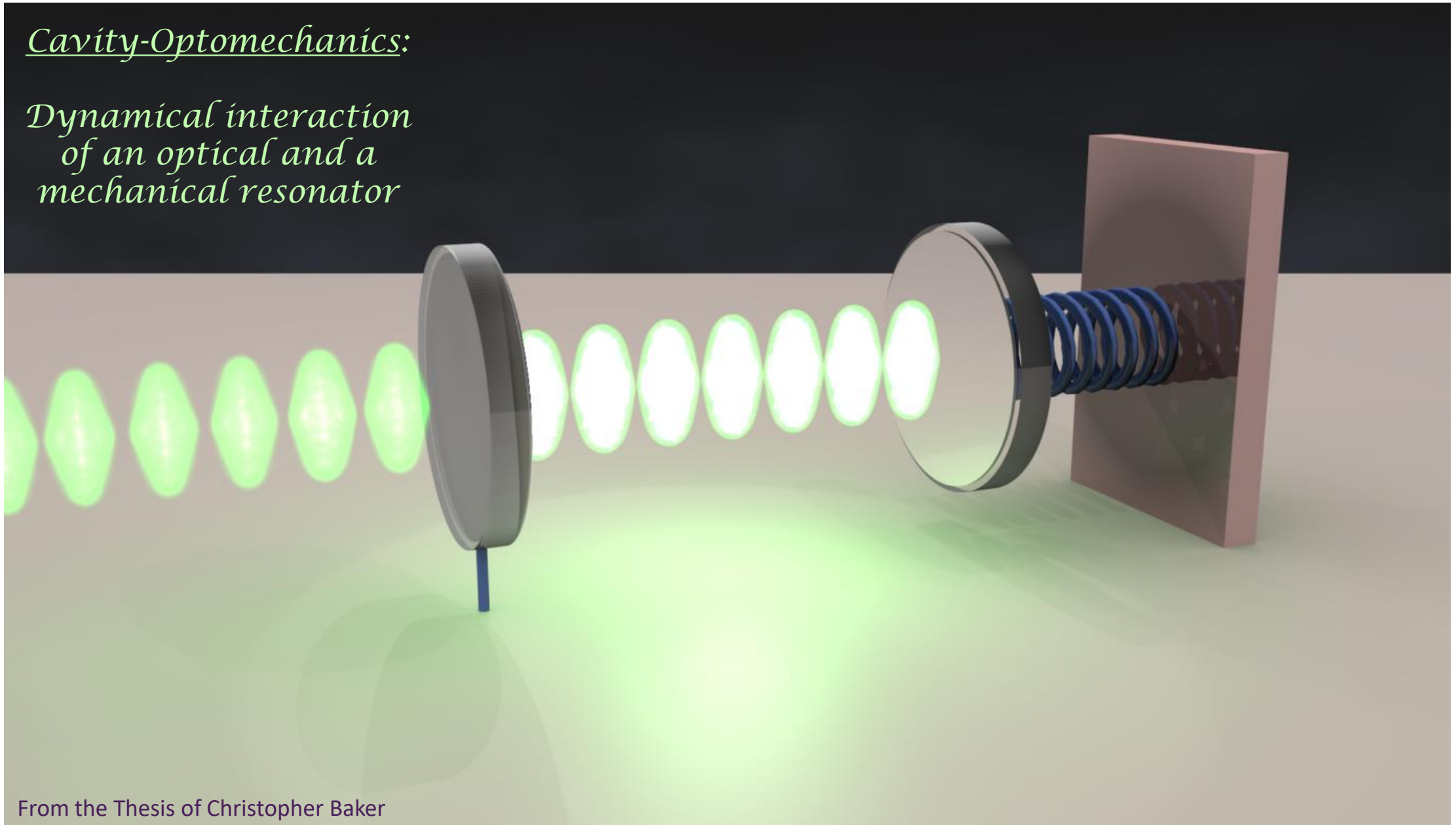


Frequency: ~ 2-10 GHz

Mechanical quality factor: up to Q ~ 10^{10}

G. MacCabe *et al.*, Science **370**, 870 (2020).

Cavity Optomechanics



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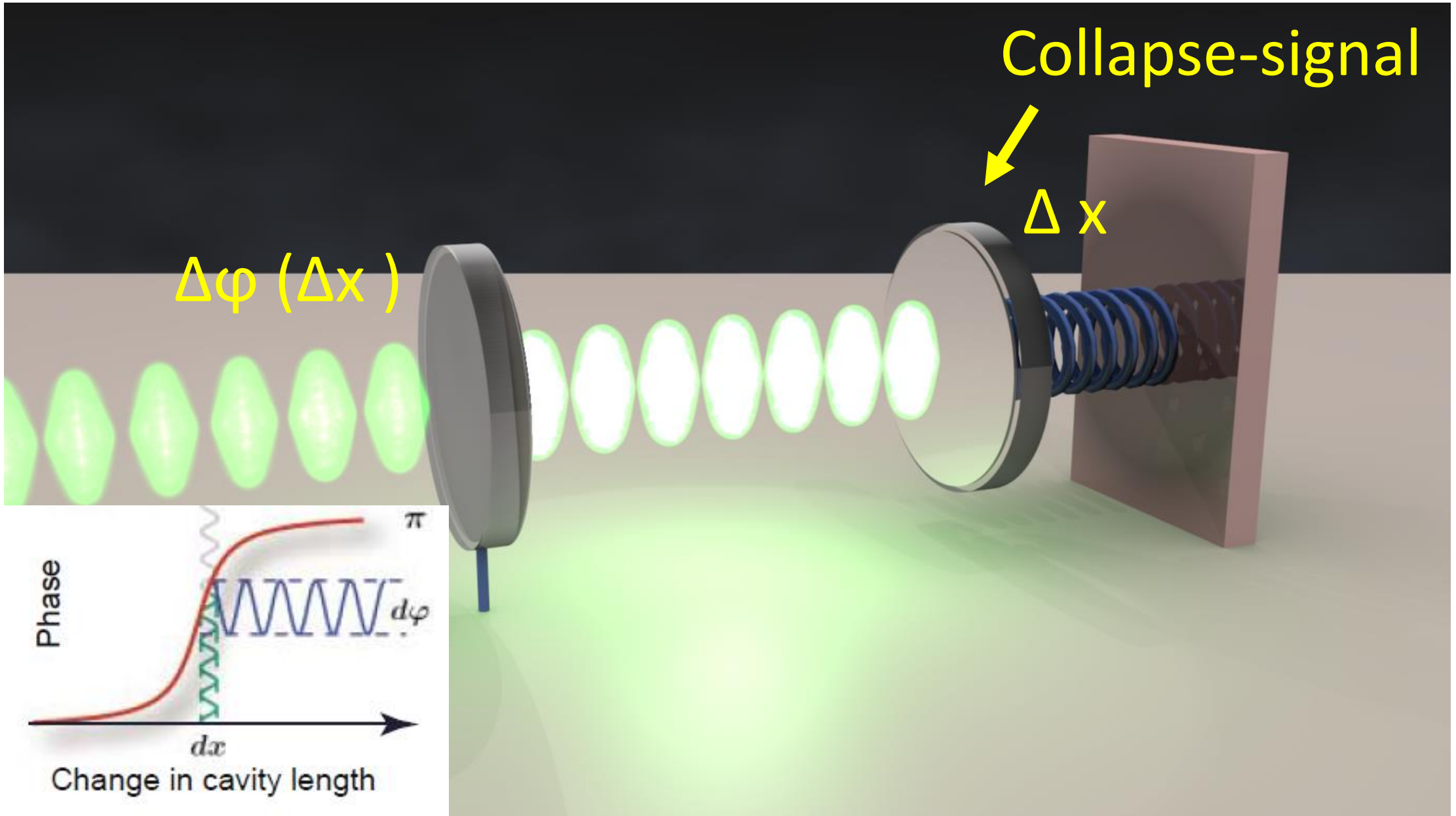
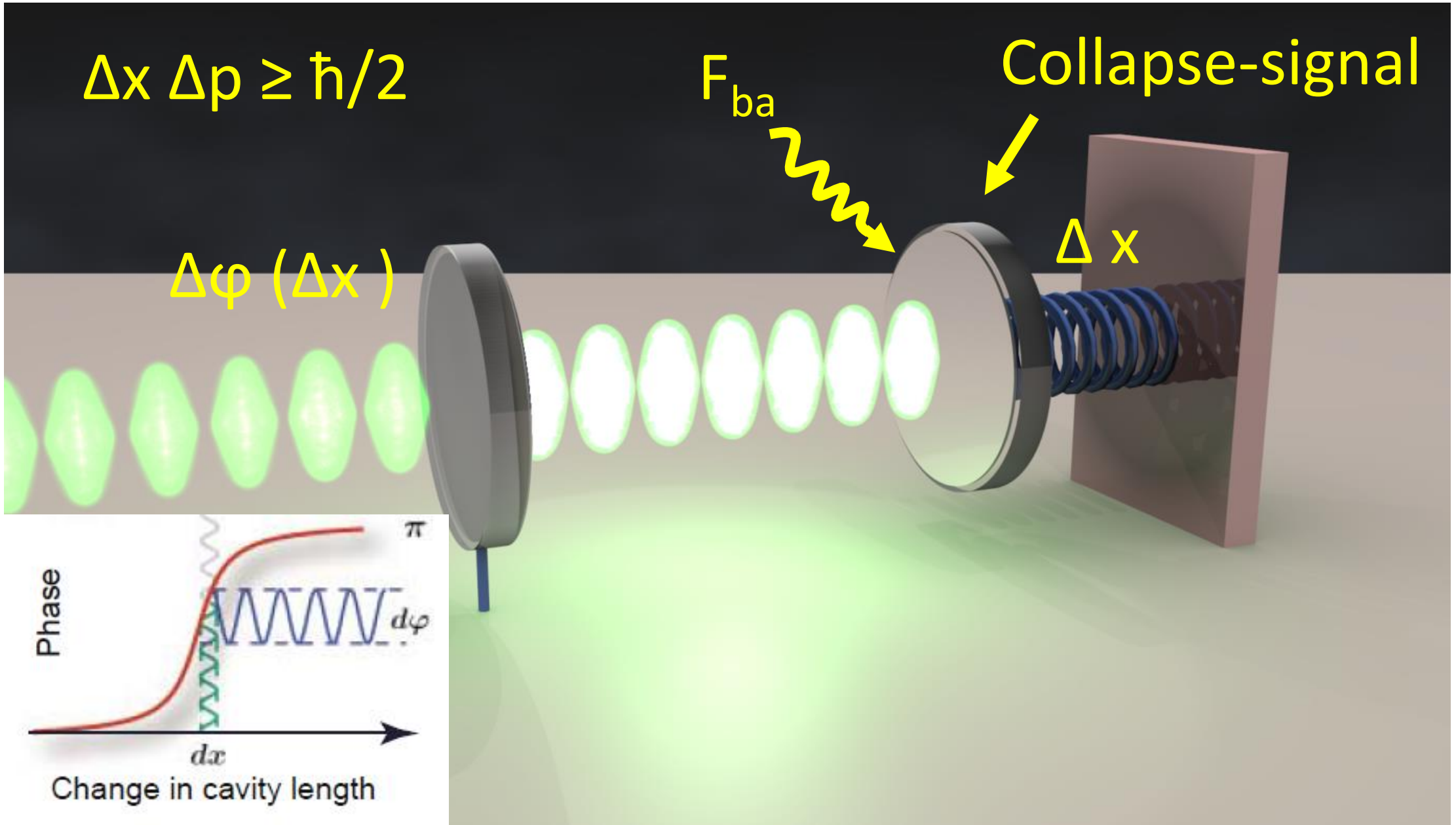
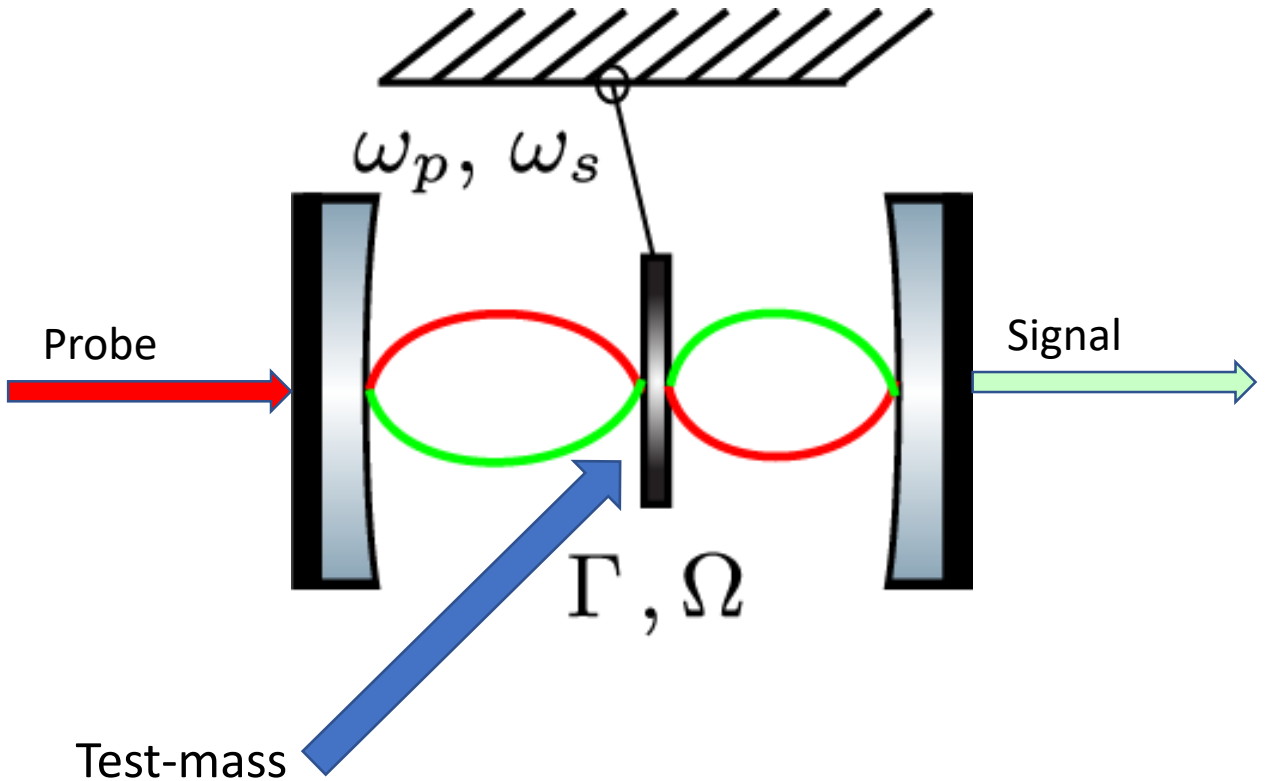


Quantum Backaction



Optomechanical phonon counting in energy basis



$$\hbar\omega_s = \hbar\omega_p + \hbar\Omega$$

S. Forstner *et al.*, Optica **10**, 1427 (2020).

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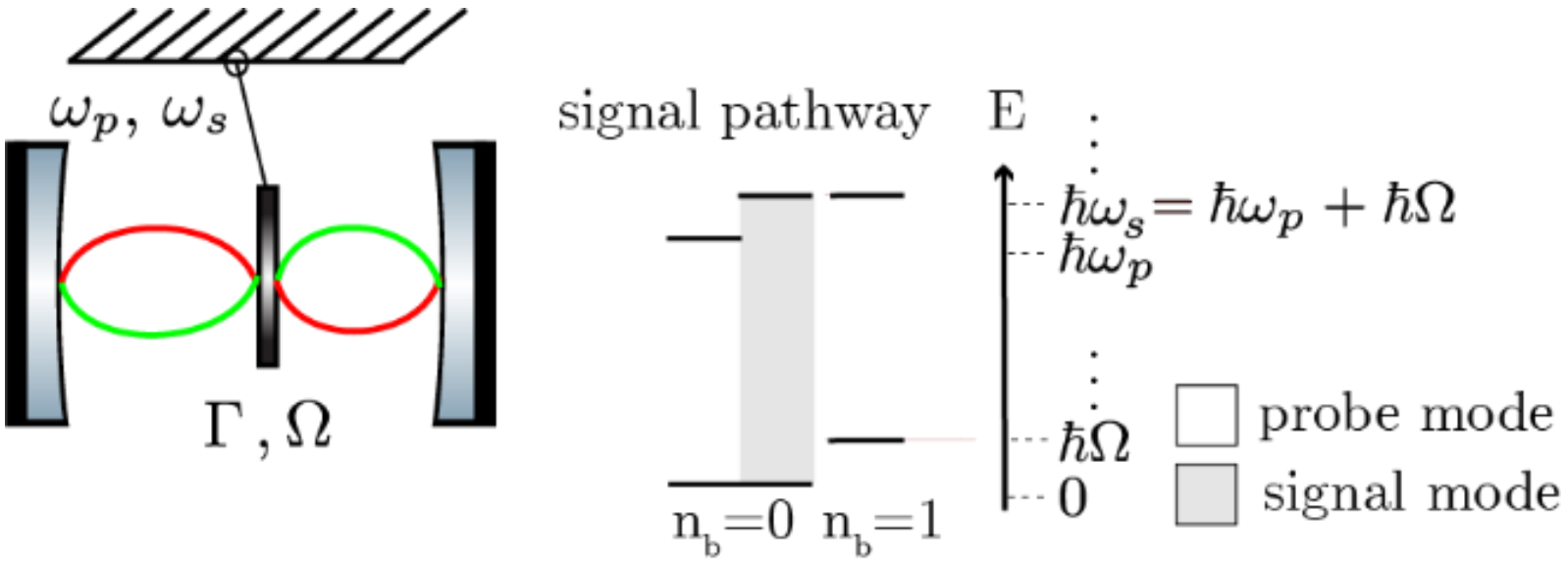

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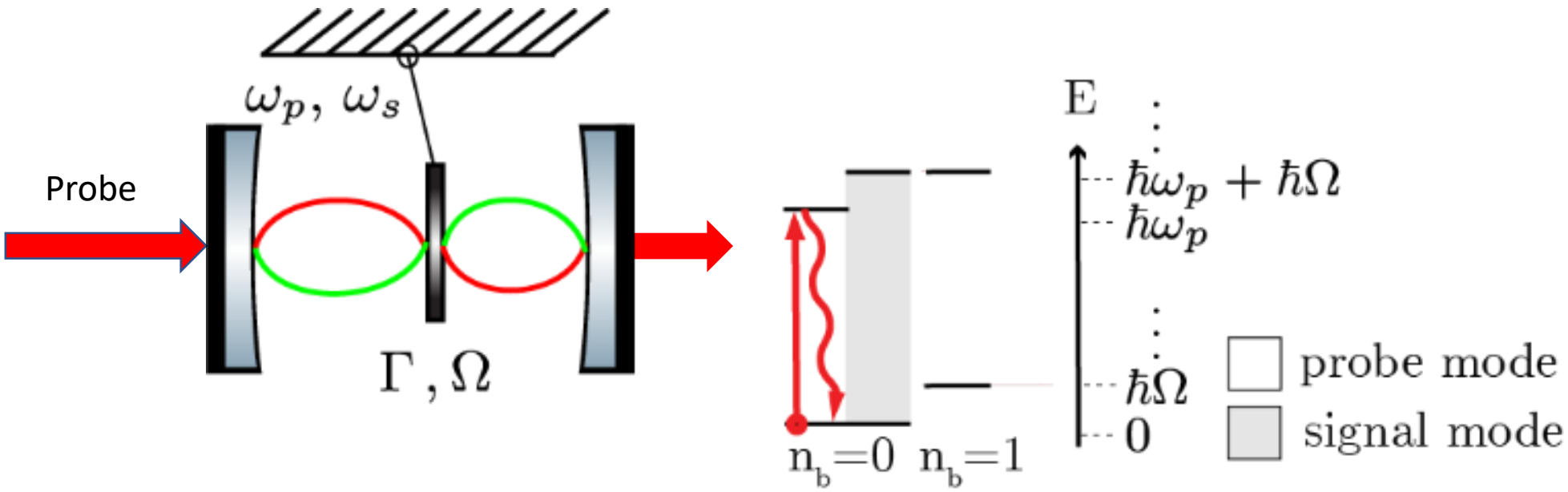
Optomechanical phonon counting in energy basis: signal pathway



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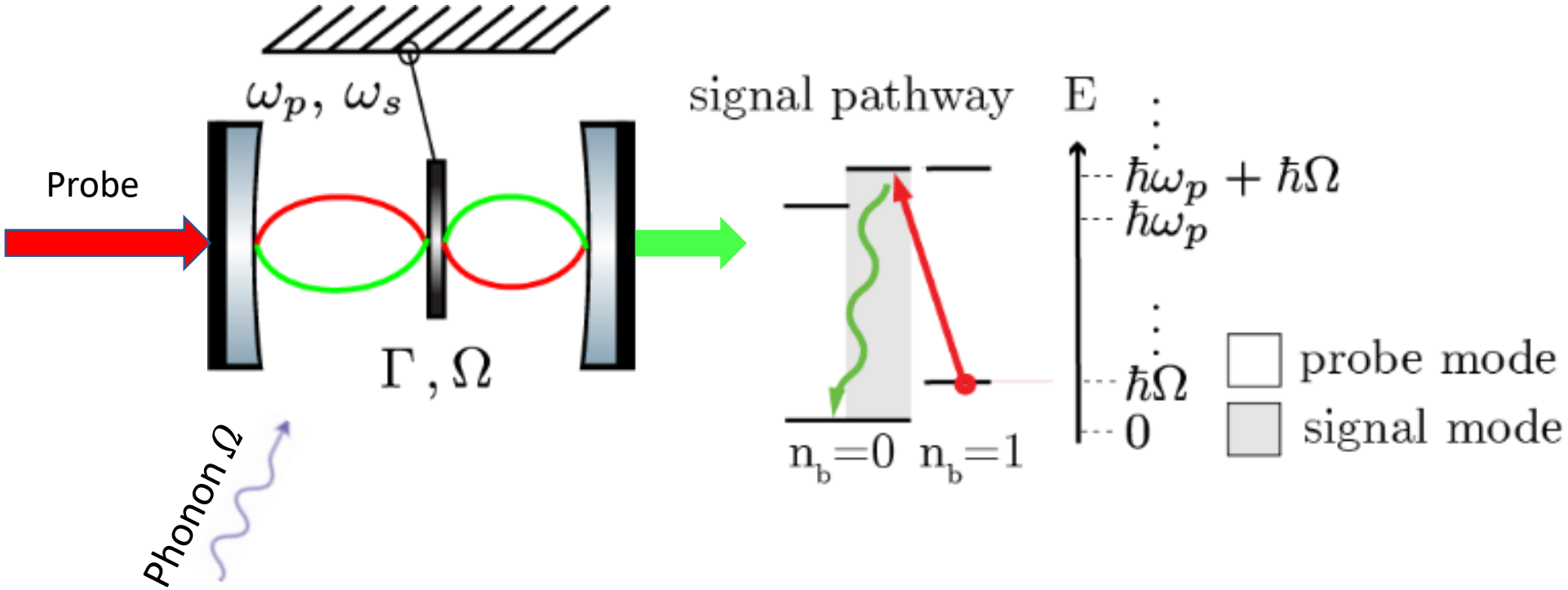

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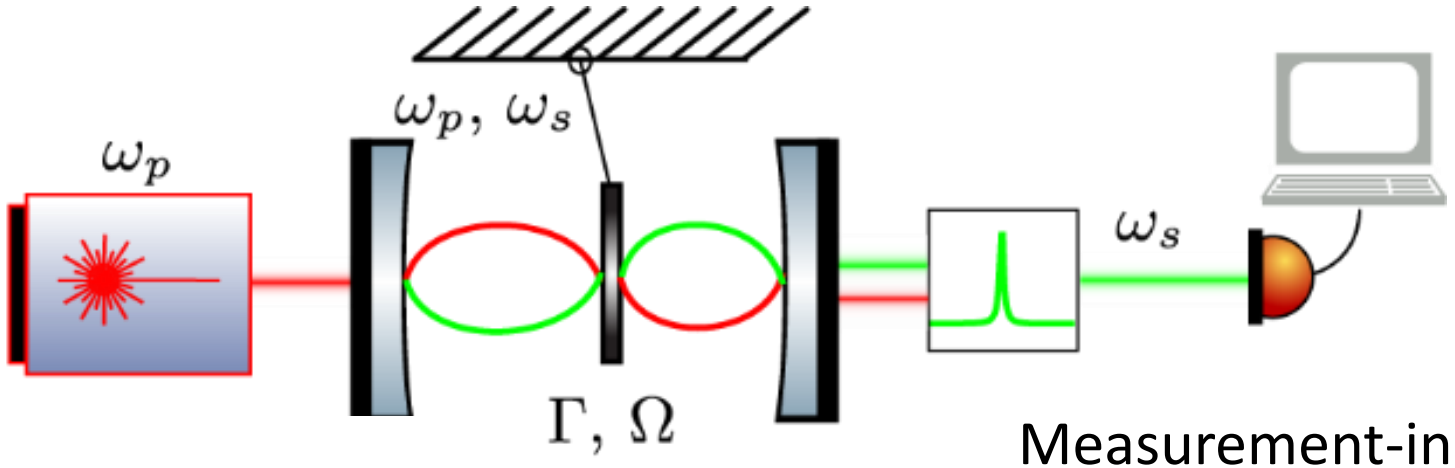
Optomechanical phonon counting in energy basis: noise suppression

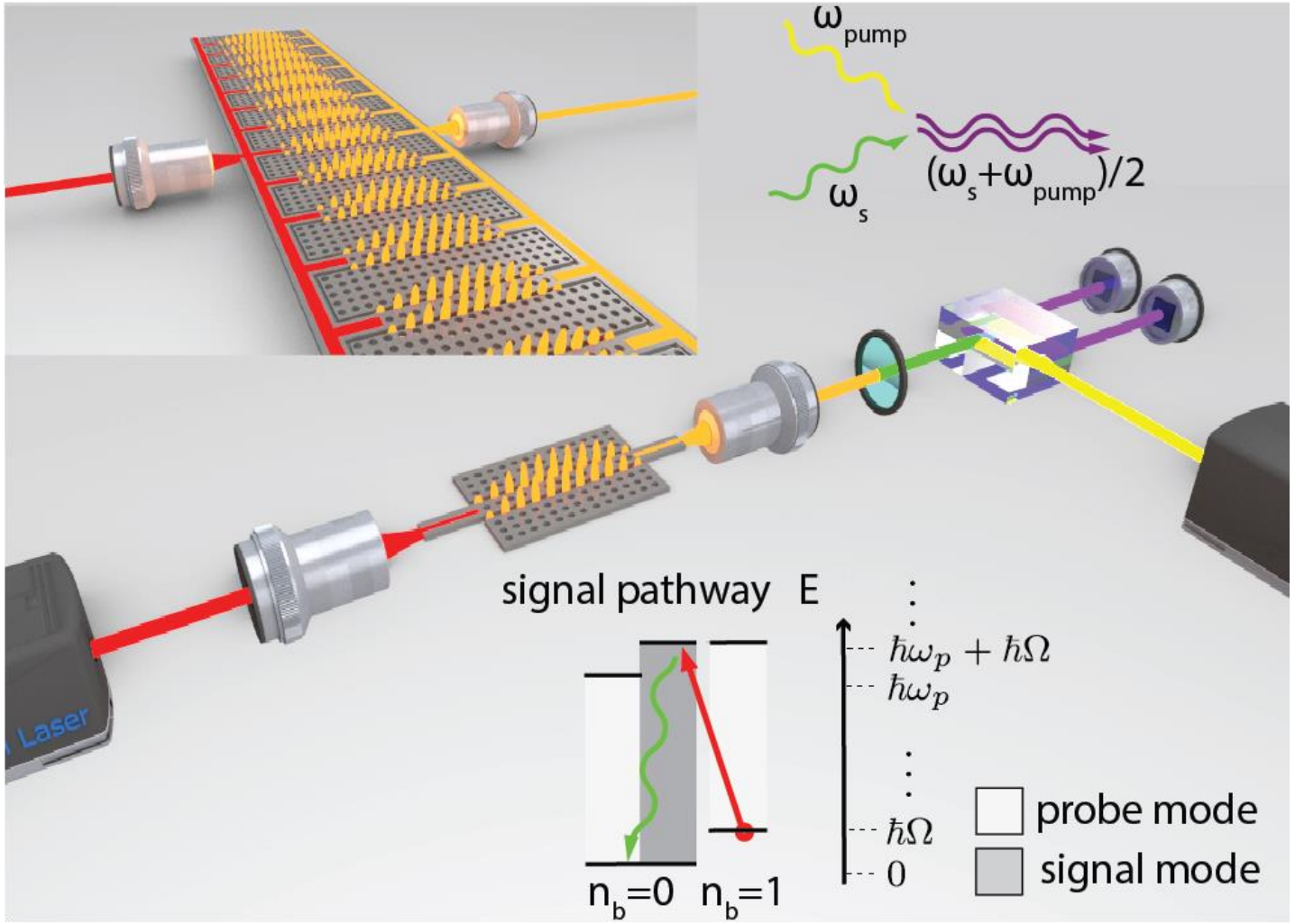
Separate probe and signal using a filter cavity



Measurement-induced phonons:
$R_{photon} \sim 10^{-12}\ s^{-1} \ll R_{collapse}$

S. Forstner *et al.*, Optica **10**, 1427 (2020).

Nano-Optomechanical test of CSL



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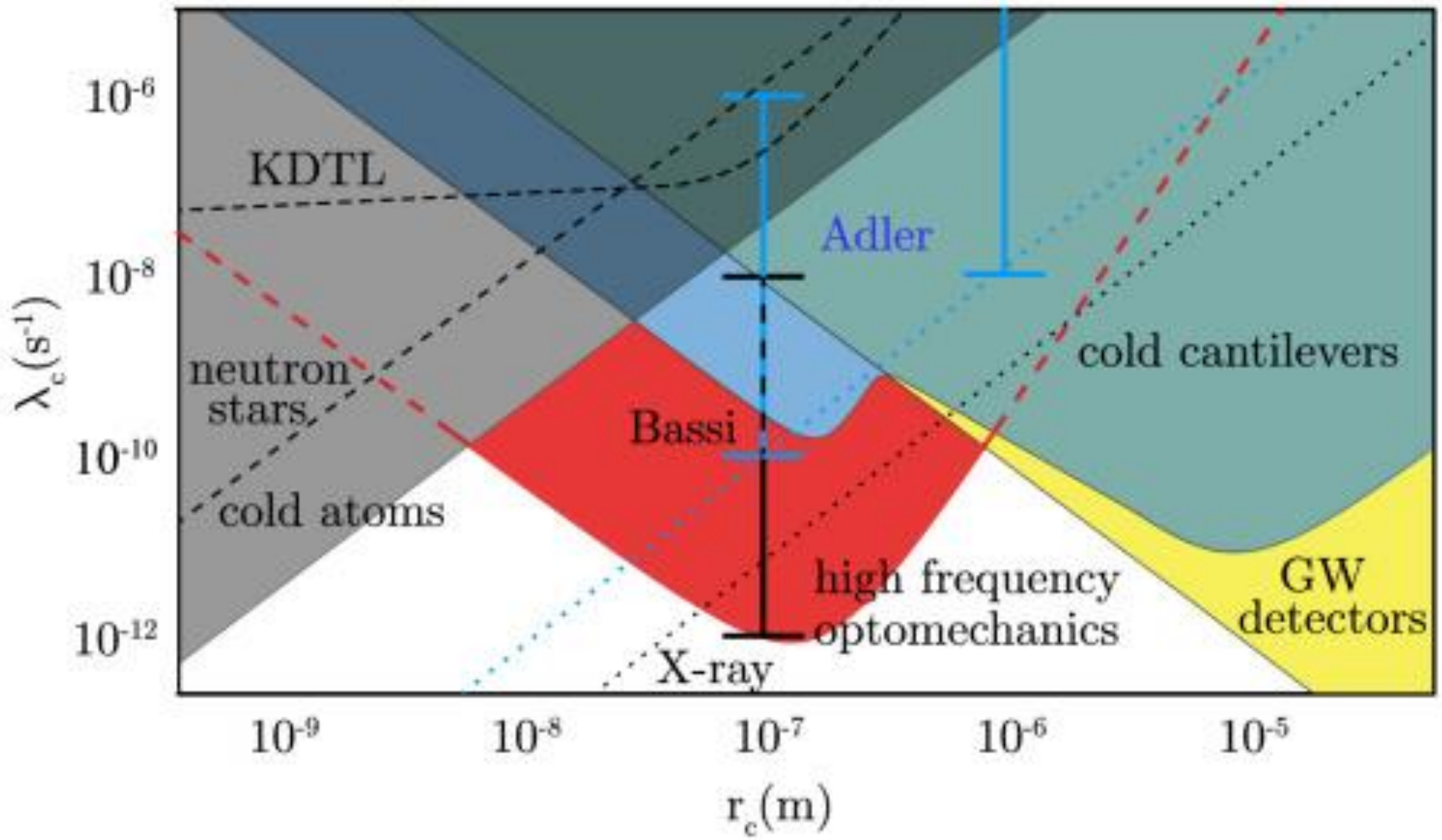

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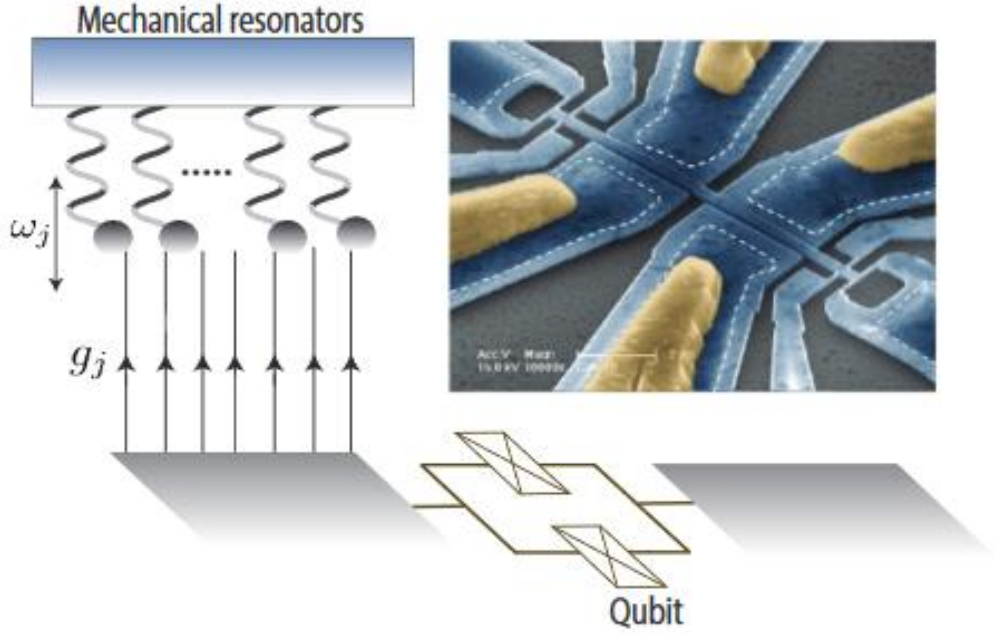
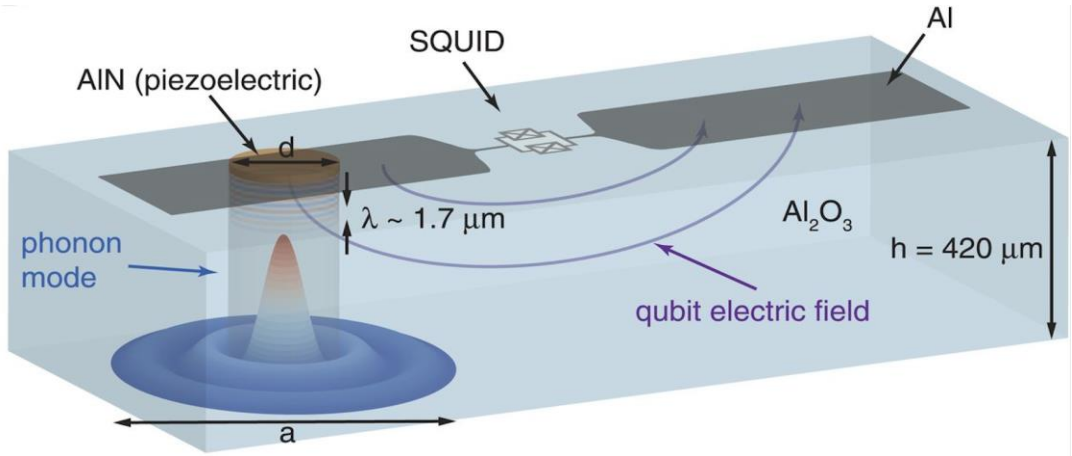
Electromechanical test of CSL

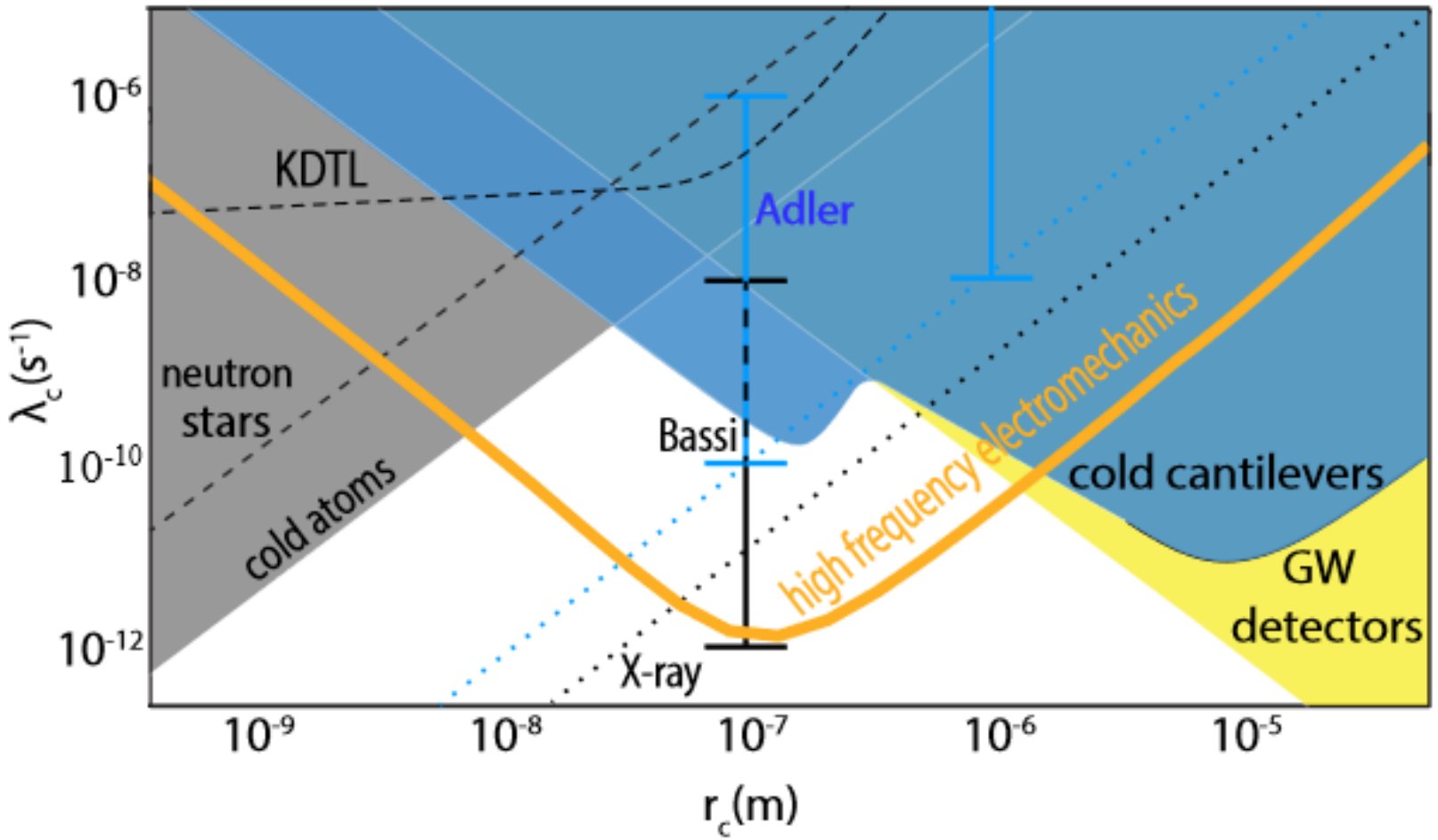




- Natural array
- Naturally QND
- Strong coupling already achieved

G. Tobar *et al.*, arXiv:2206.14531 (2022).

Electromechanical test of CSL



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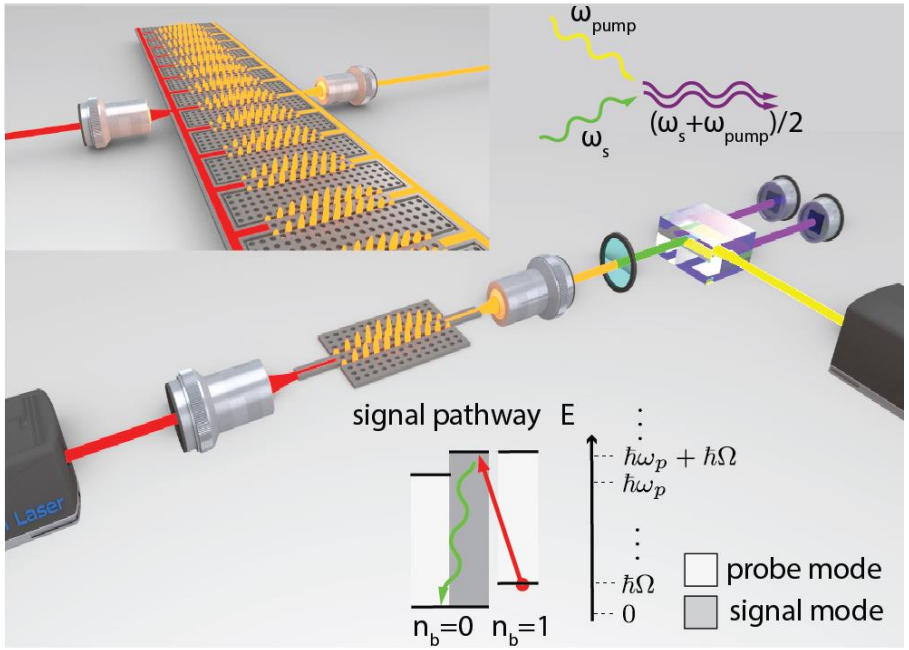
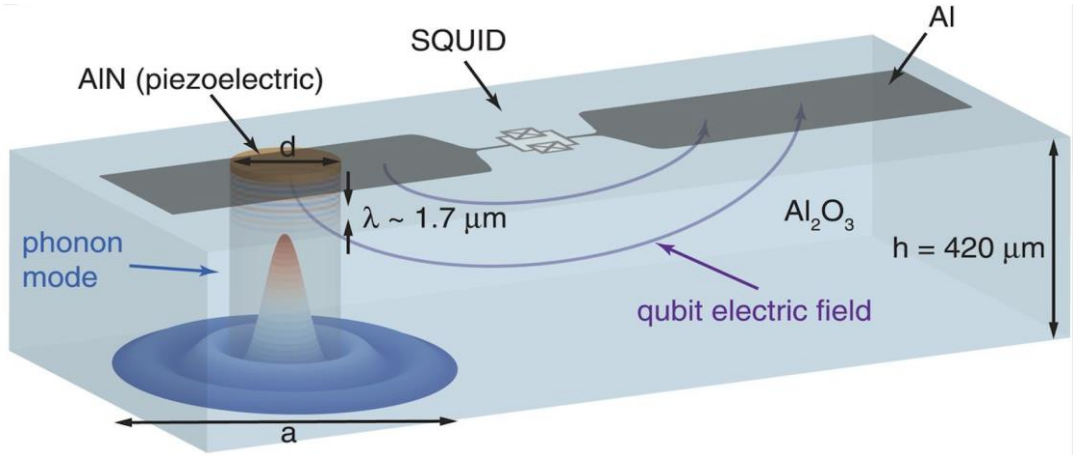
Quantum opto- and electromechanics for testing models – pros and cons

Cons

- Challenging experiments!
- Requires quantum control
- It may be easier to reach comparable exclusions by improving conventional cantilever methods





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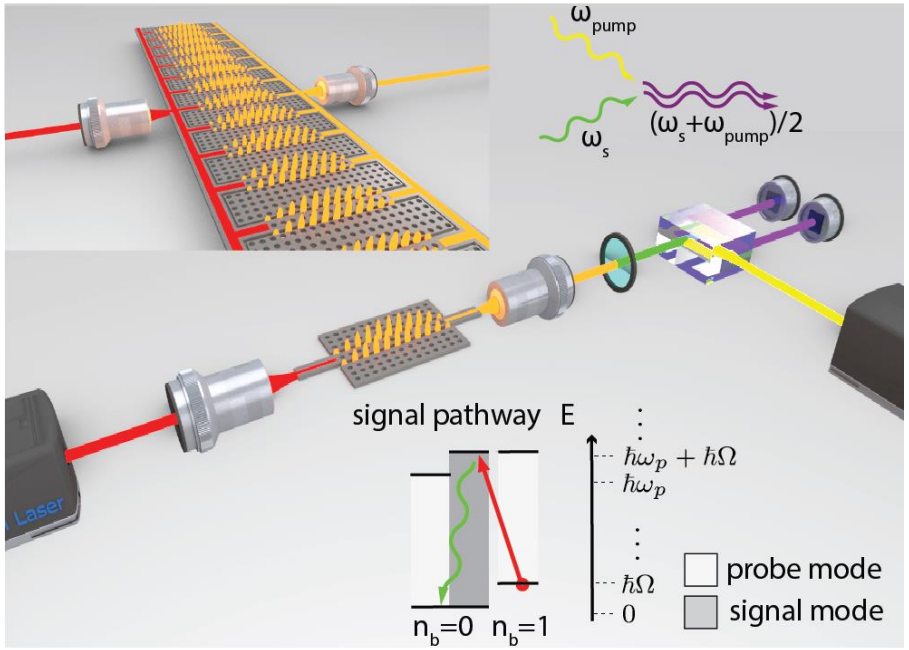
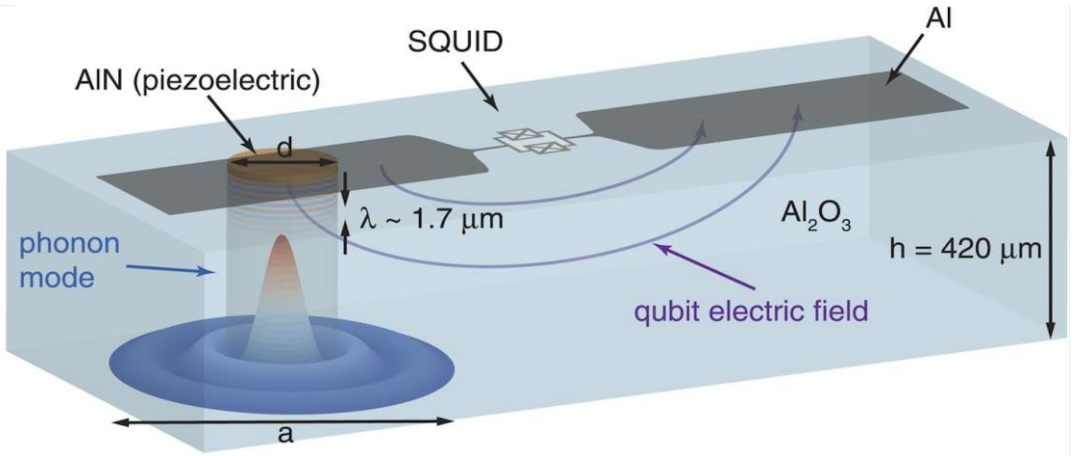


Pros

- May give conclusive answer to wavefunction collapse and the measurement problem!
- Does not rely on estimation of thermal noise!
- Leverages technological advance that is being pursued anyway
- Possible confirmation of collapse, and may clarify the physical origin of CSL collapse



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