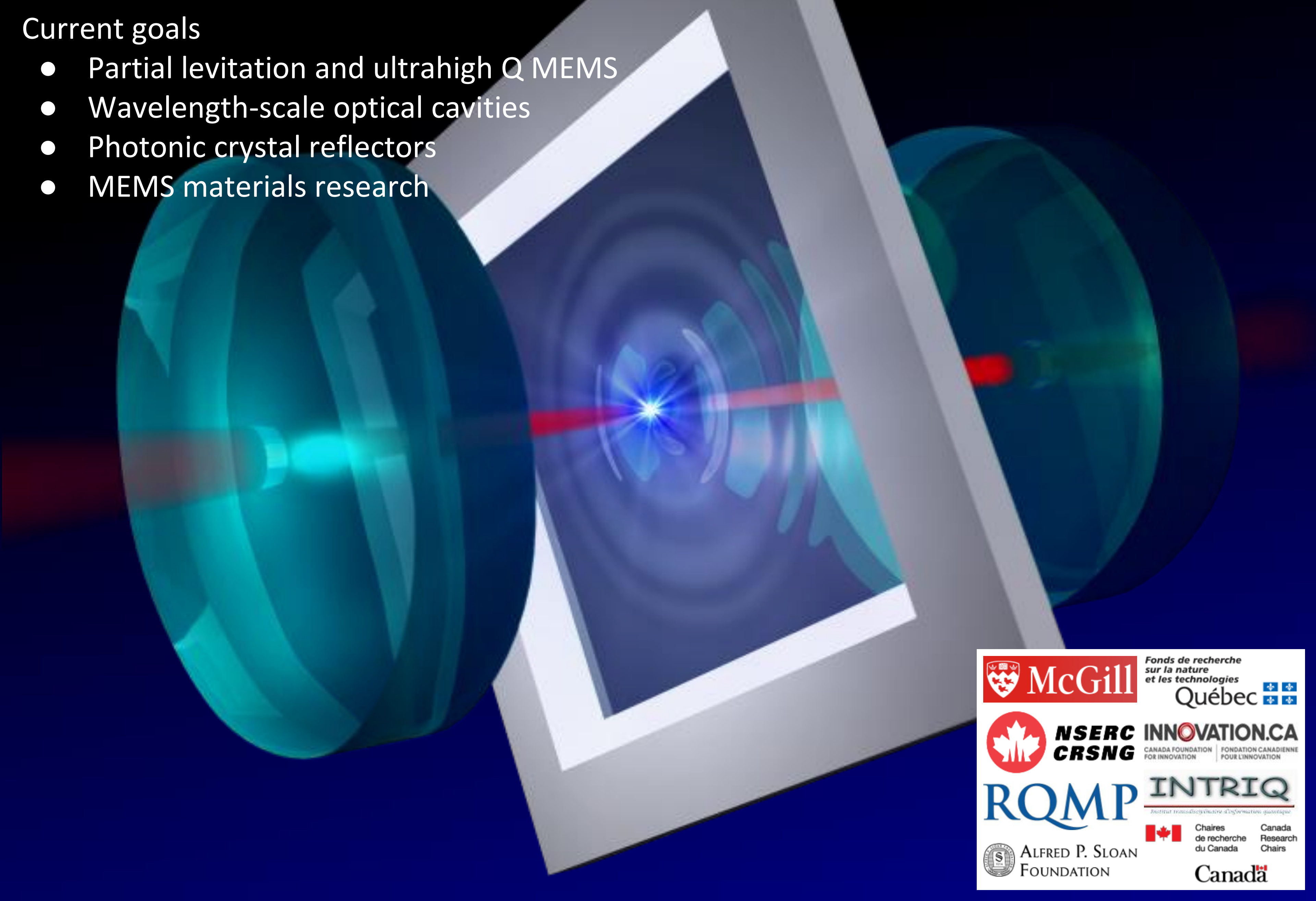
Mechanical photons at McGill

Current goals

- Partial levitation and ultrahigh Q MEMS
- Wavelength-scale optical cavities
- Photonic crystal reflectors
- MEMS materials research



McGill
Fonds de recherche sur la nature et les technologies Québec
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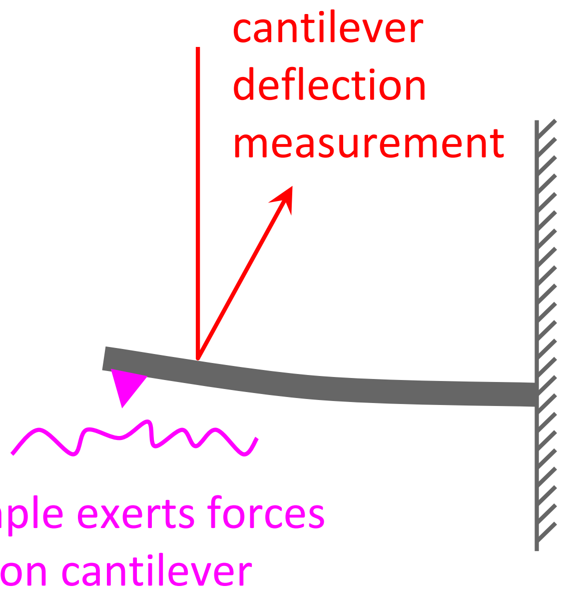
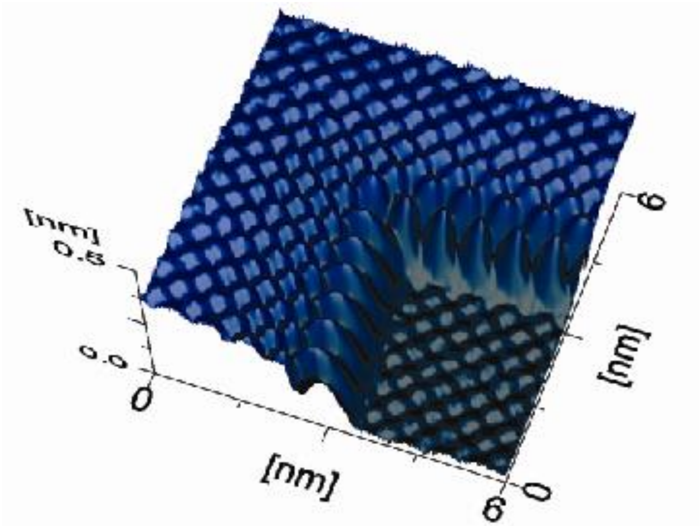
Canada

Mechanical systems = force sensors

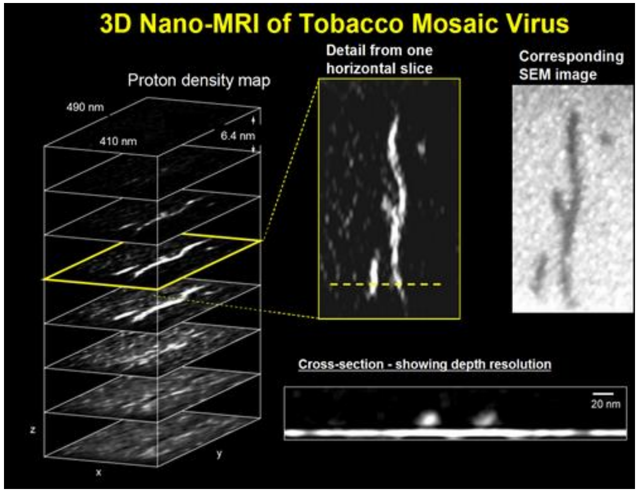
Typical force measurement:



Electronic forces (Grütter Lab, McGill)



Nuclear forces (Rugar Lab, IBM)



See also

- gravity wave detectors
- accelerometers in phones & cars
- electronic filters (also in phones)

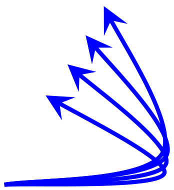
Optomechanics, and *you*

New functionality through radiation forces, e.g.:

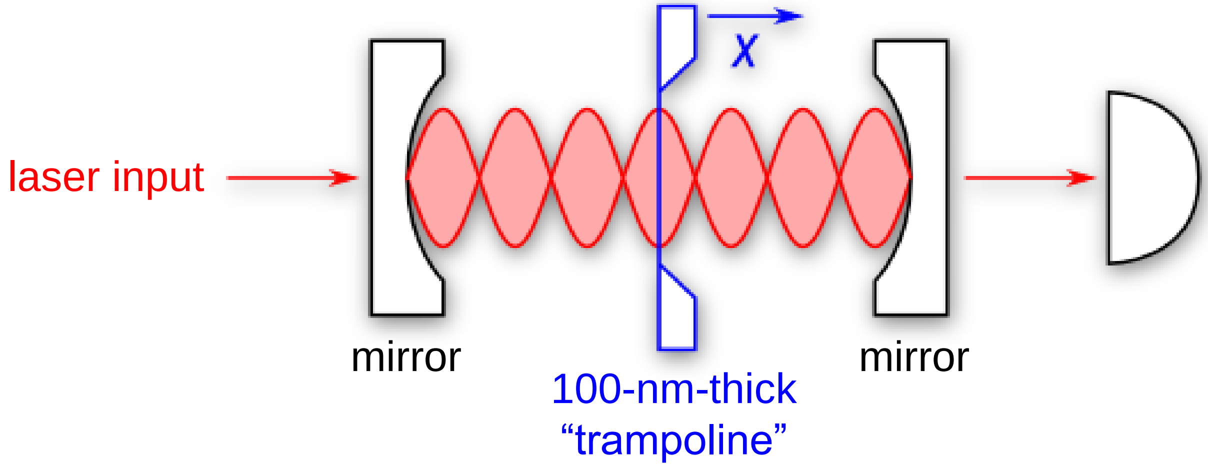
- ➔ Laser cooling & observation of quantum motion
- ➔ Detecting the "hiss" from incident photons
- ➔ Mechanically squeezing light
- ➔ Wavelength conversion & qubit transduction

Our focus

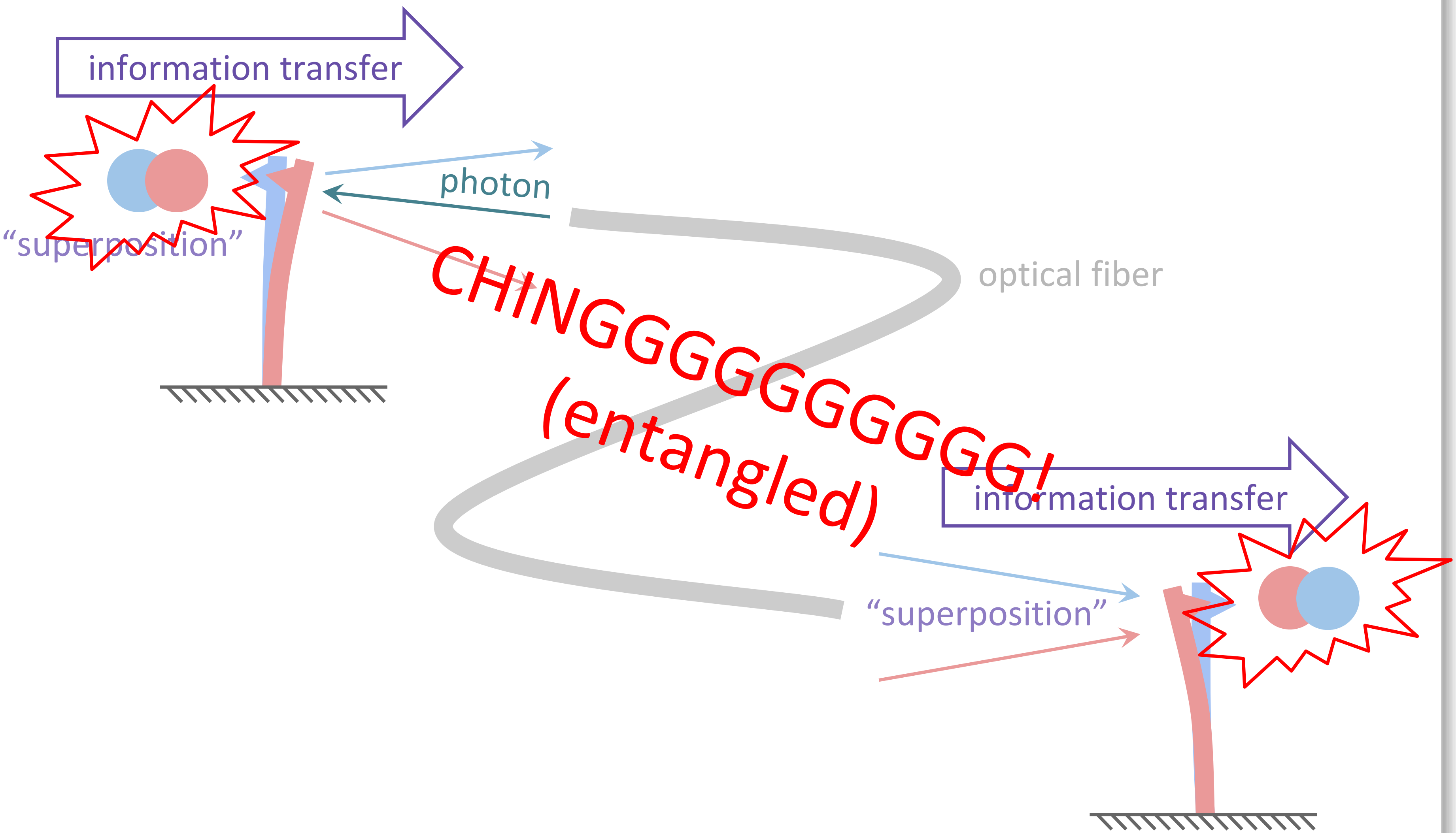
- ➔ Laser-enhanced micromechanical sensors (MEMS)
- ➔ New geometries and new types of coupling



Example system (ours, coincidentally)



Quantum sensing and information transfer



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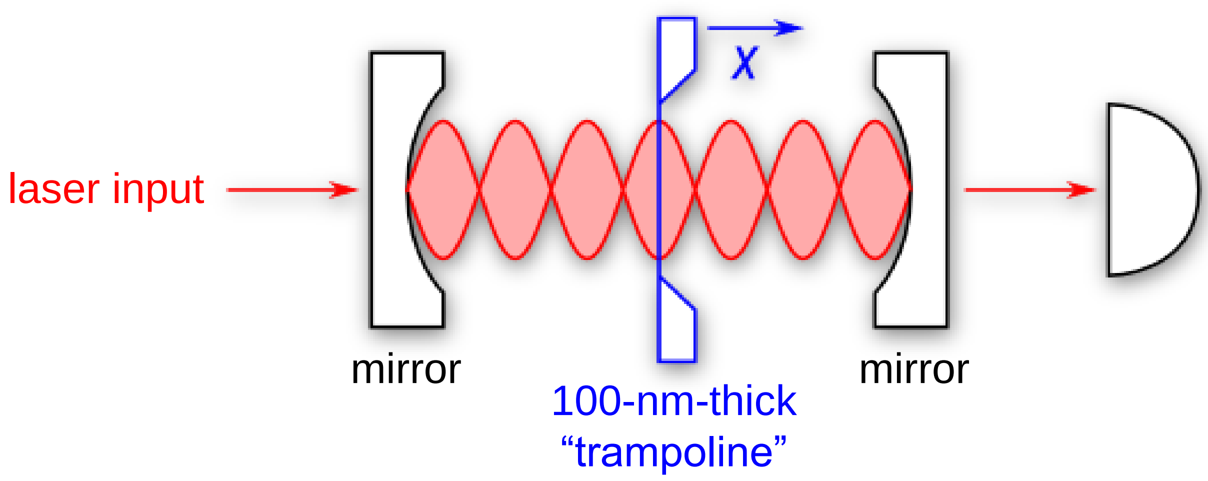
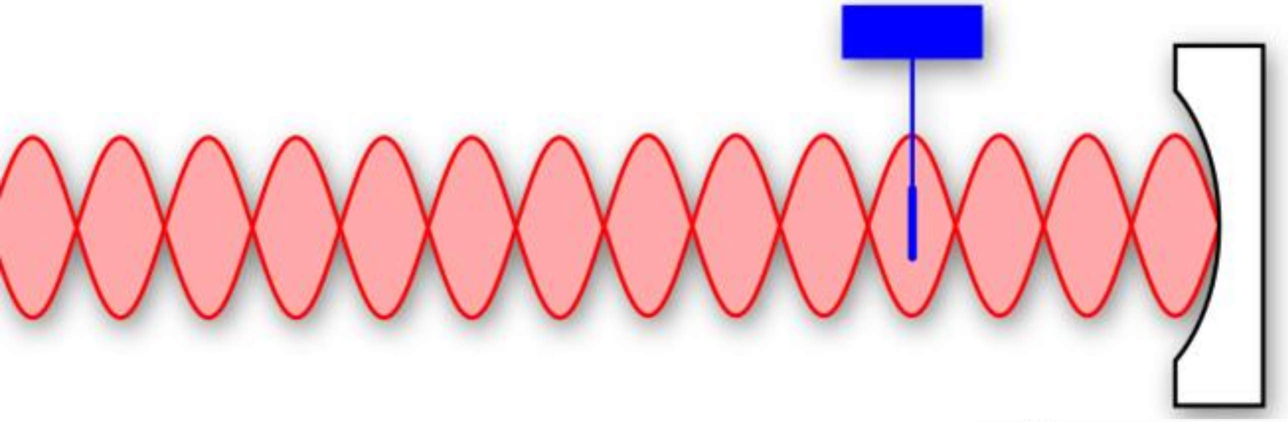


Example: "quadratic" optical spring



Resonant input light

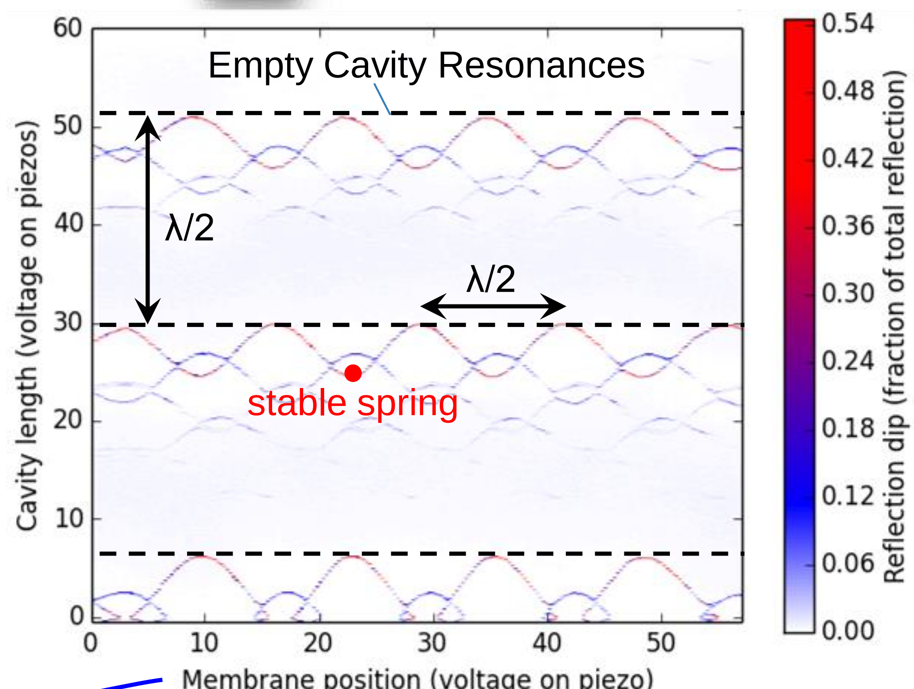
- ➔ Enhanced radiation forces in cavity
- ➔ Dielectrics drawn to antinodes
- ➔ Resonant *frequency* coupled to position
- ➔ Same per-watt efficiency as dipole trap
- ➔ **Optical levitation? ("trapping")**

$$U(x) = \frac{1}{2} n_\gamma \hbar \left(\frac{\partial^2 \omega_\gamma}{\partial x^2} \right) x^2$$

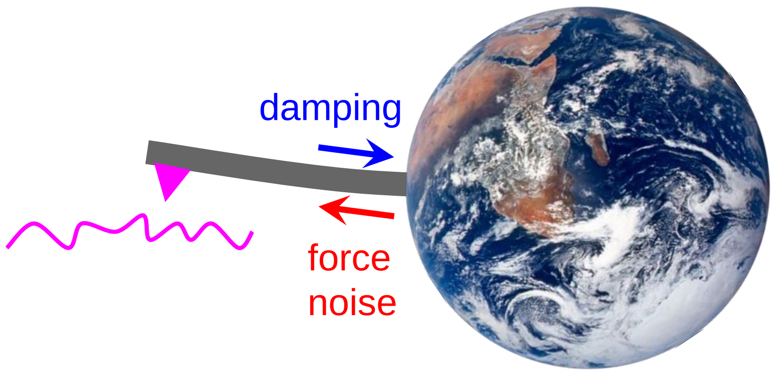
energy

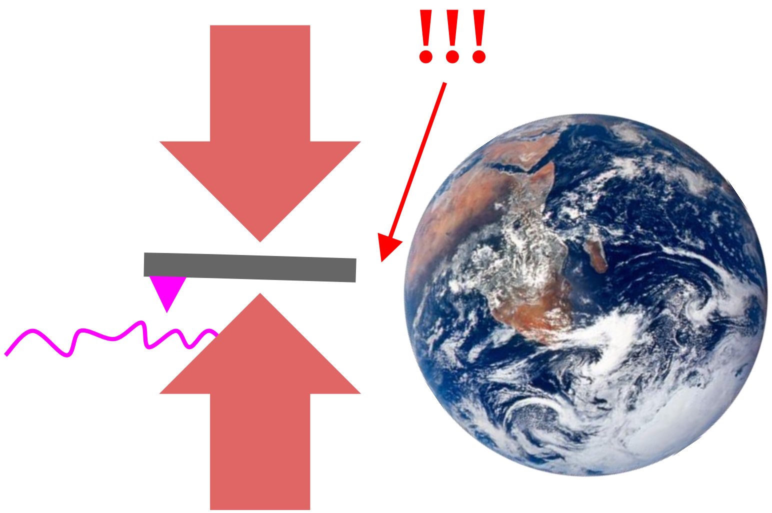
cavity photons

curvature



Reduced damping & noise via levitation





Flexible materials

- fixed frequency
- fixed damping / force noise
- rings for 10's - 100's of seconds

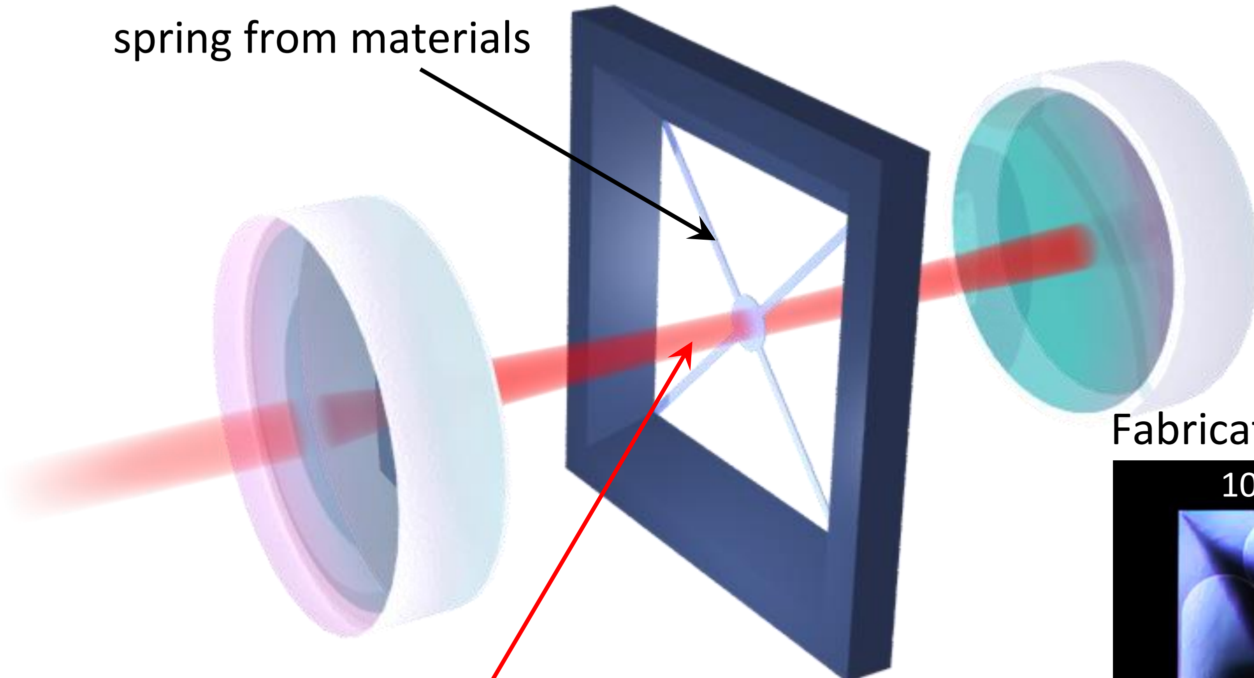
Optical levitation

- laser-tuned mechanical frequency
- laser-tuned mechanical damping
- predicted to ring for *weeks*
  (lasers have very low noise)

  ➔ ***VERY* sensitive!** (in theory)

A “practical” goal: *mostly* levitated systems

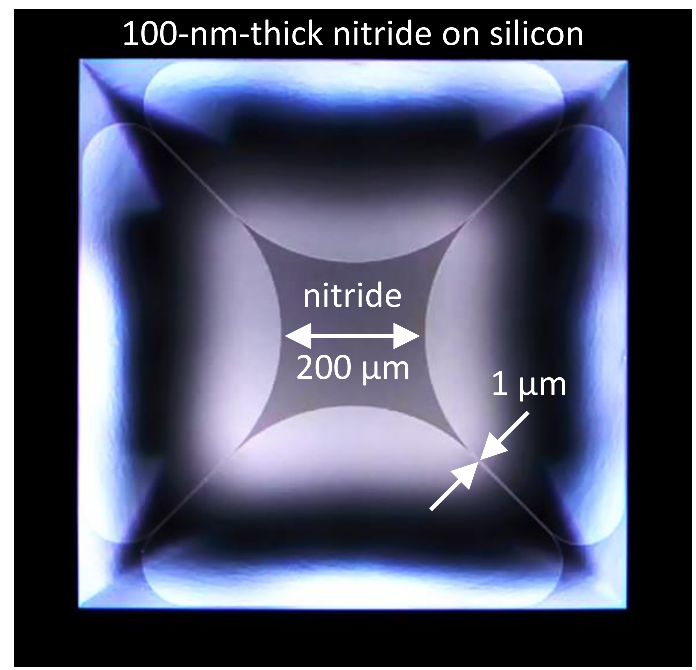
weak mechanical spring from materials



strong **optical spring from cavity light**

- enhanced mechanical properties
- could approach levitated limits
- easier to integrate with other systems

Fabrication at McGill

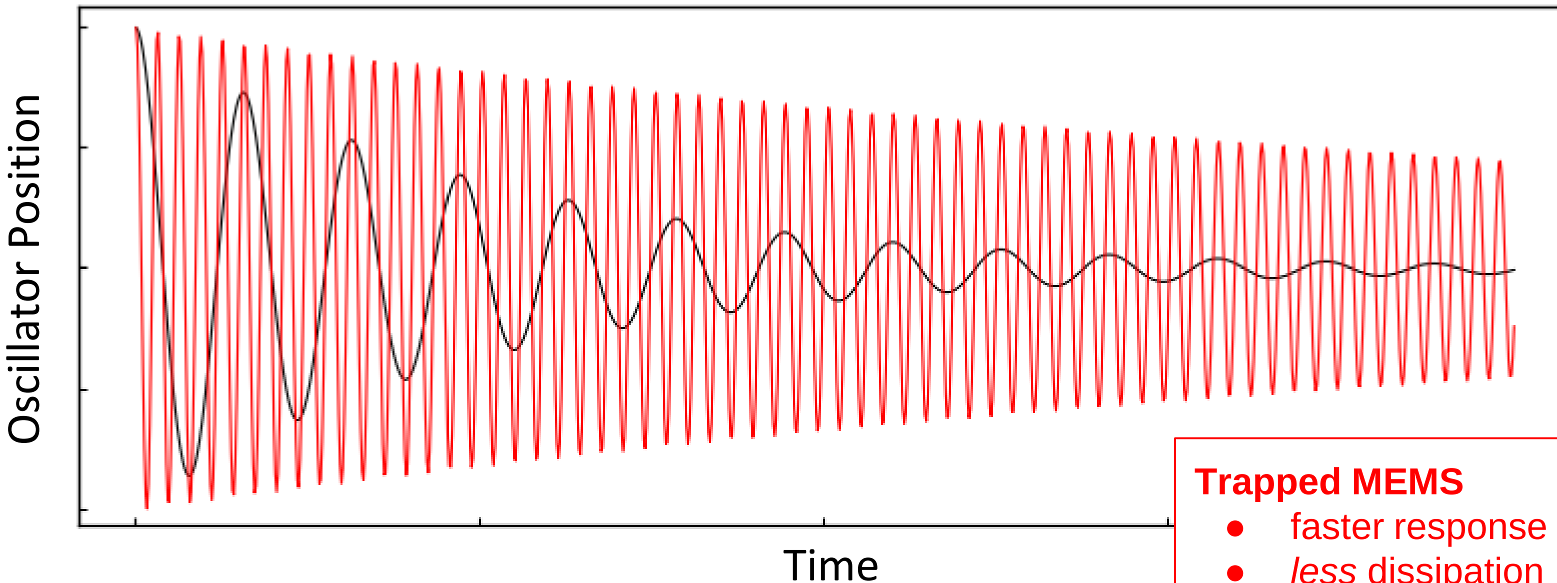


Partial levitation improves performance

Modified High-Quality MEMS:

material parameters — laser — # oscillations before energy is gone

$$m\ddot{x} + (k_m + i\gamma_m + k_L)x = 0 \;\Rightarrow\; Q \propto f^2$$

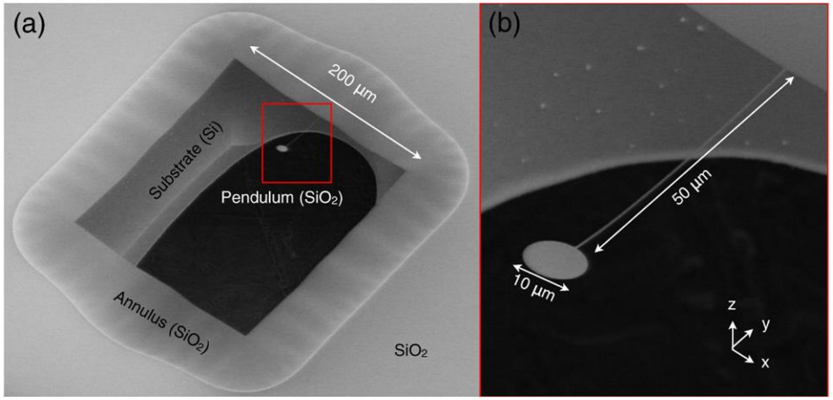


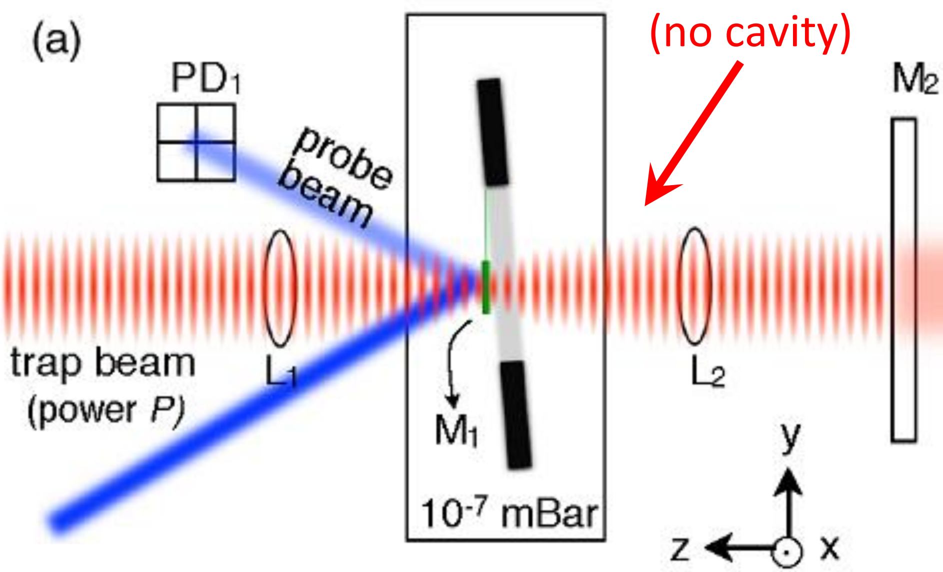
Trapped MEMS

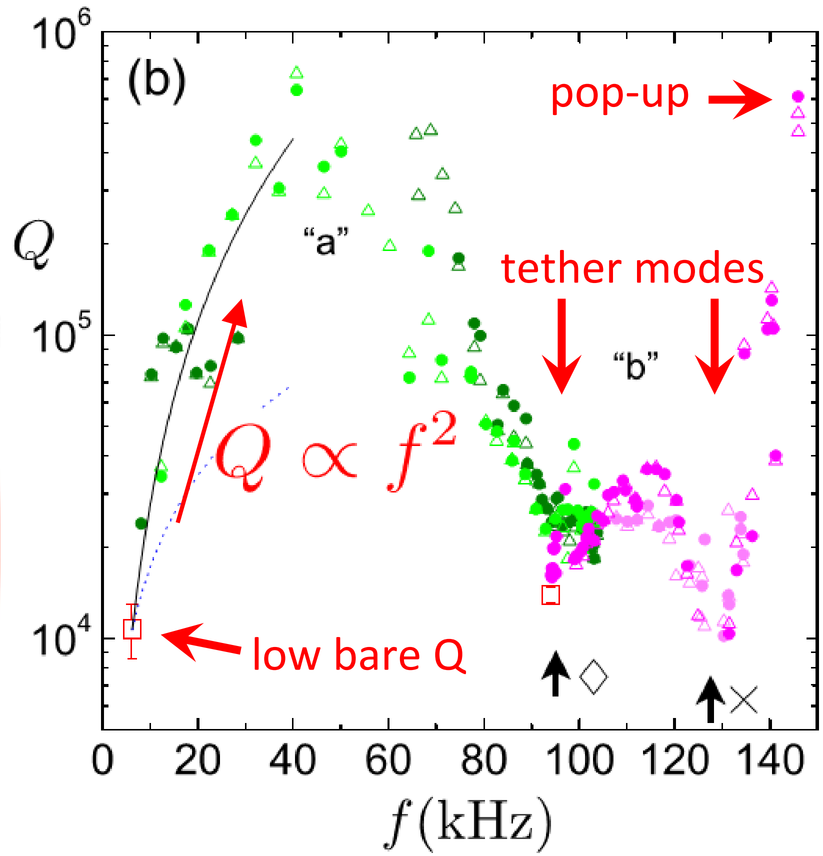
- faster response
- *less* dissipation

Encouraging results (Caltech, 2012)

- Free-space standing wave trap ~ 10W
- 50x increase in mechanical Q!



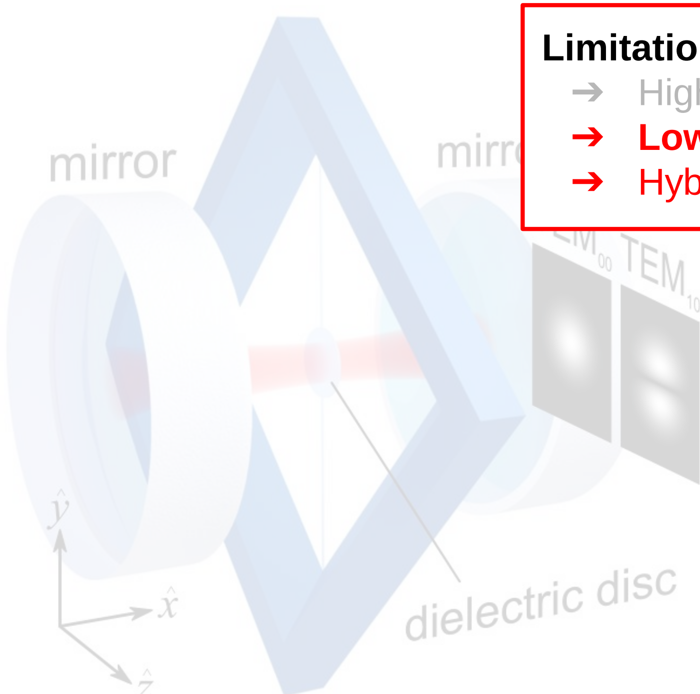




K. K. Ni *et. al.* PRL **108**, 214302 (2012)

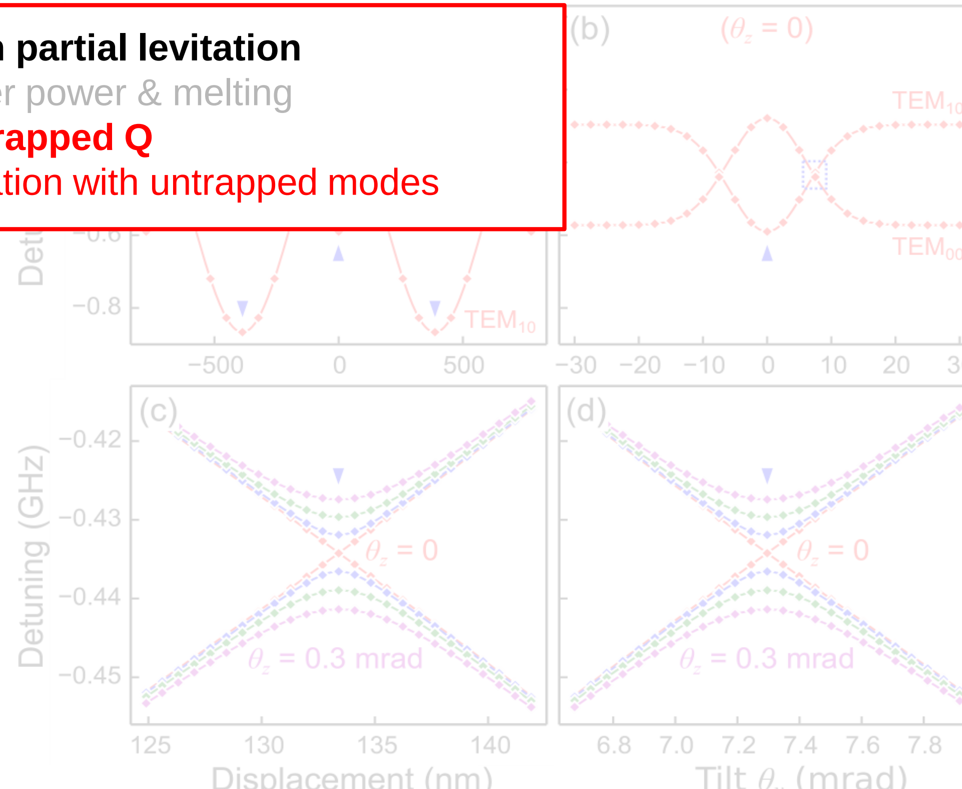
Increasing the per-photon trap strength

Optical perturbation theory



Limitations on partial levitation

- ➔ High laser power & melting
- ➔ **Low untrapped Q**
- ➔ Hybridization with untrapped modes

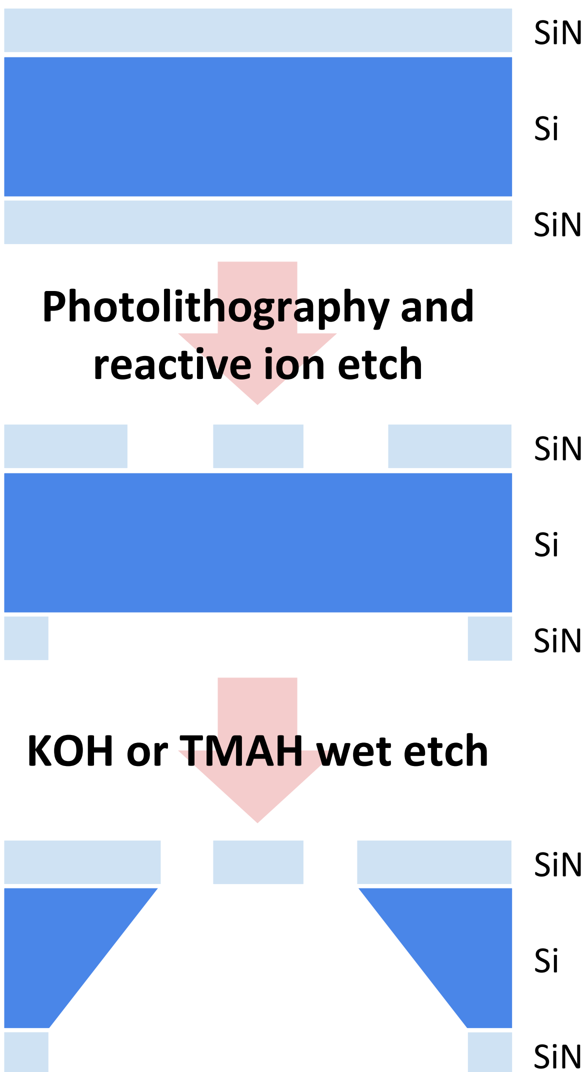


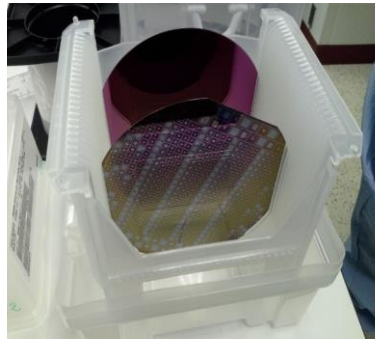
Center of mass and torsional trapping

- ➔ Tilt (aboot the z-axis) tunes scattering rate between transverse modes
- ➔ Tunable quadratic coupling for both center-of-mass **and torsional motion**
- ➔ ~10 MHz trap = no problem

T. Müller, C. Reinhardt, J. C. Sankey, PRA (2015)

Nanofabrication at McGill





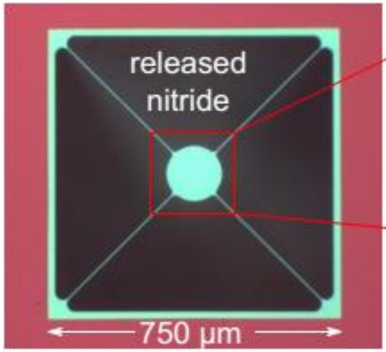
Process flow

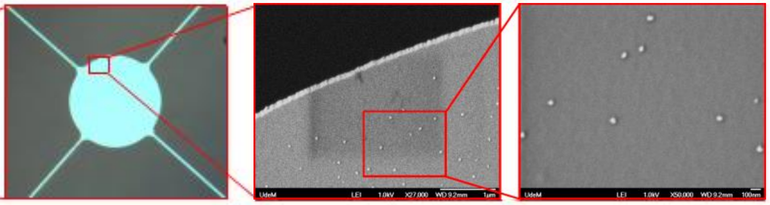
- Start with nitride on silicon
- Photolithography to define structures
- Reactive ion etch to remove SiN
- KOH dip to etch silicon wafer

Fabrication attempts & initial success

Low-stress nitride test

- Price = $0
- Floppy
- Optically lossy (boo!)

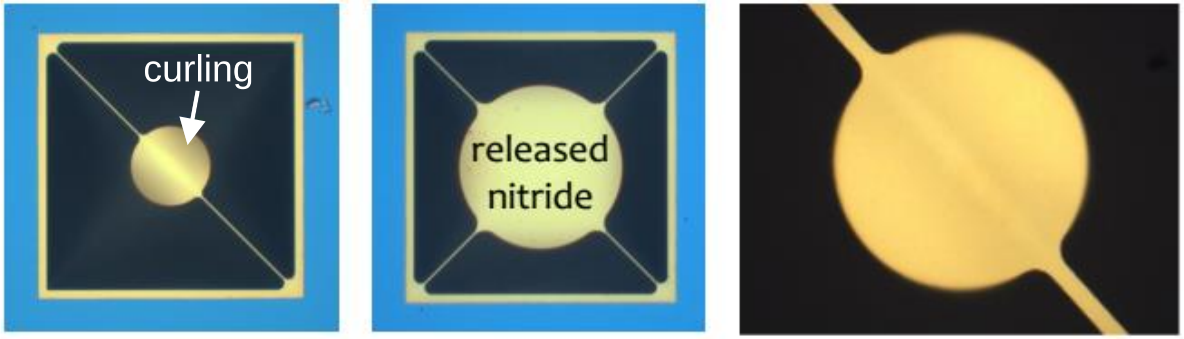




Surface imperfections as source of optical loss?

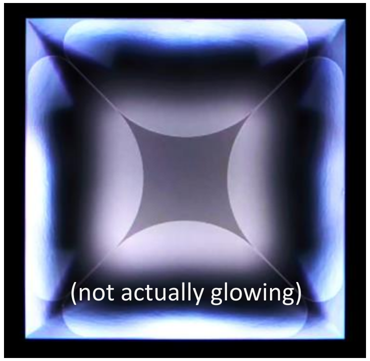
High-stress nitride

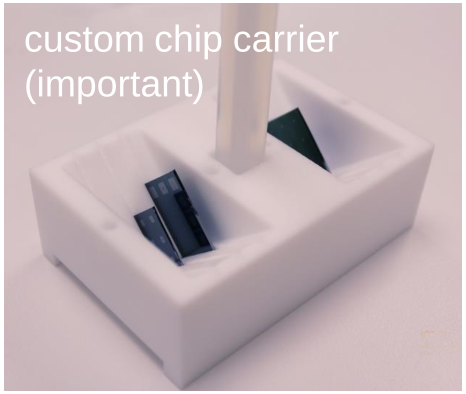
- Low optical loss
- Potato-chipping (boo!)
- Stiffer (boo?)



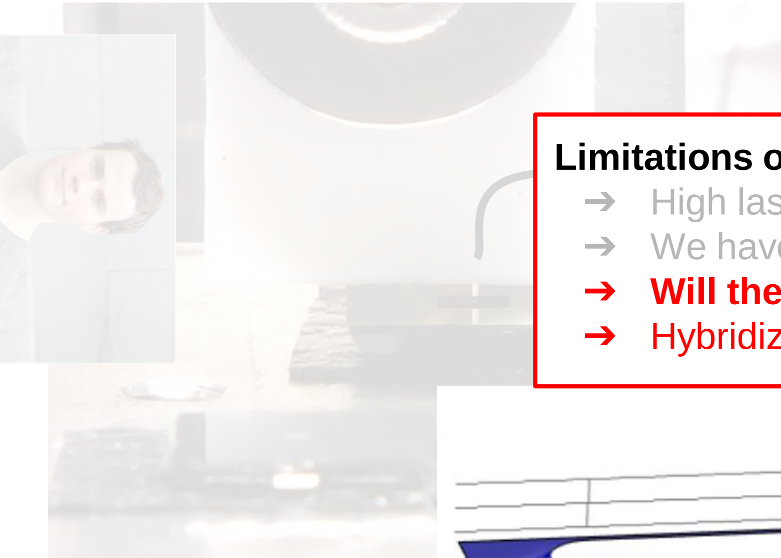
Latest iteration

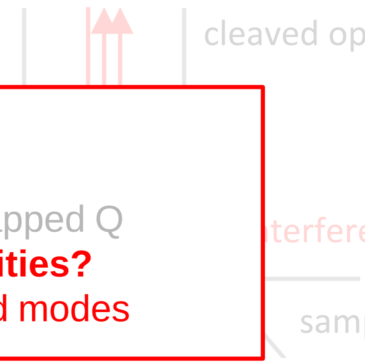
- High yield
- No potatoes
- **High starting Q**





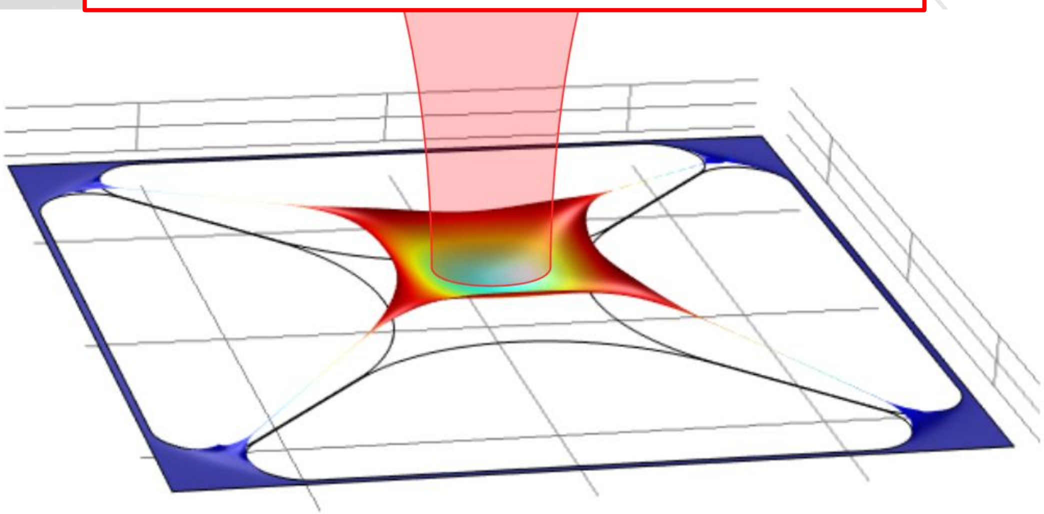
Mechanical characterization in UHV

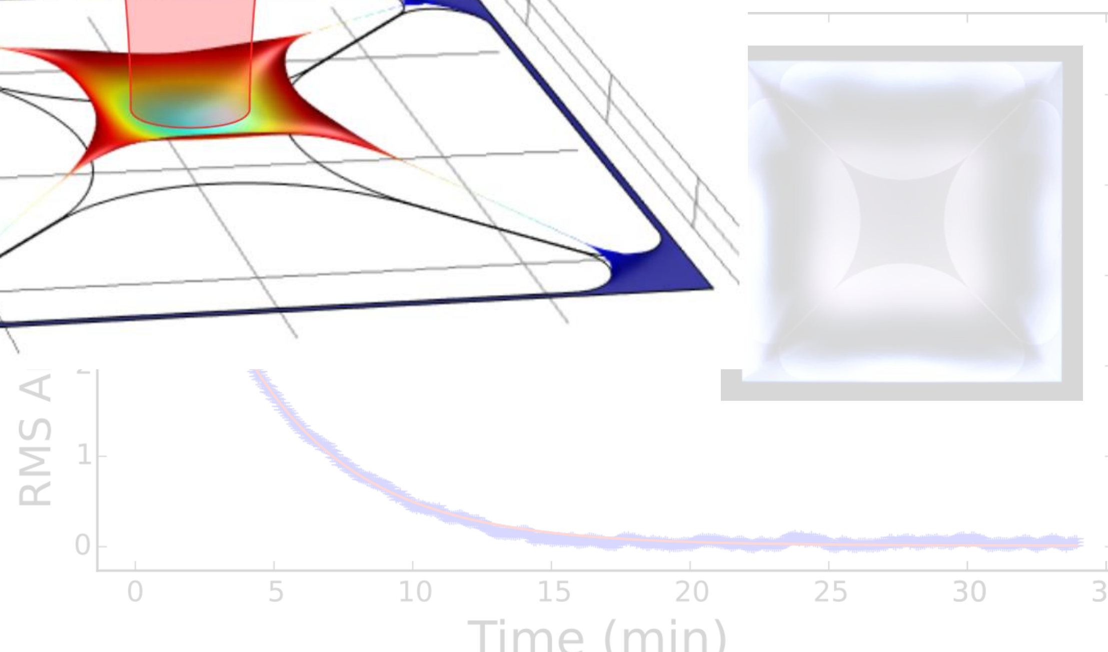




Limitations on trapping

- ➔ High laser power & melting
- ➔ We have a *stupid* high untrapped Q
- ➔ **Will these work in our cavities?**
- ➔ Hybridization with untrapped modes





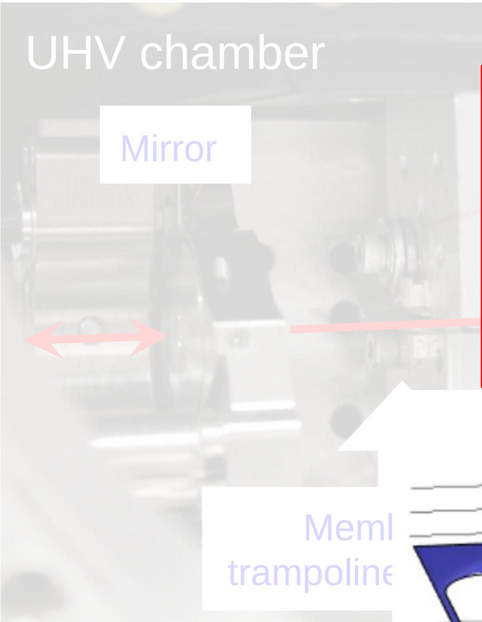
Performance

- ➔ Typical freque
- ➔ “Typical” Q ~ 1

Initial Goal

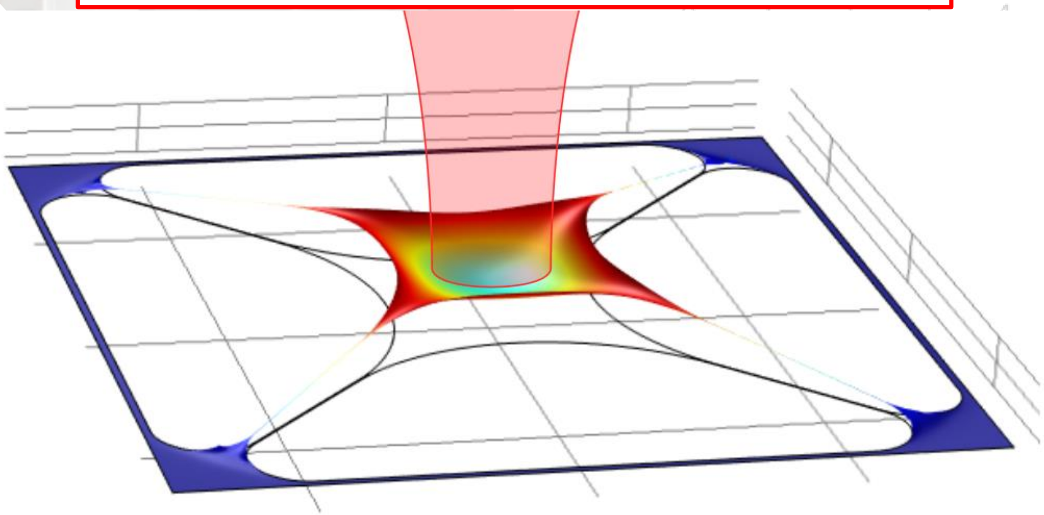
- ➔ Trap to Q ~ 20

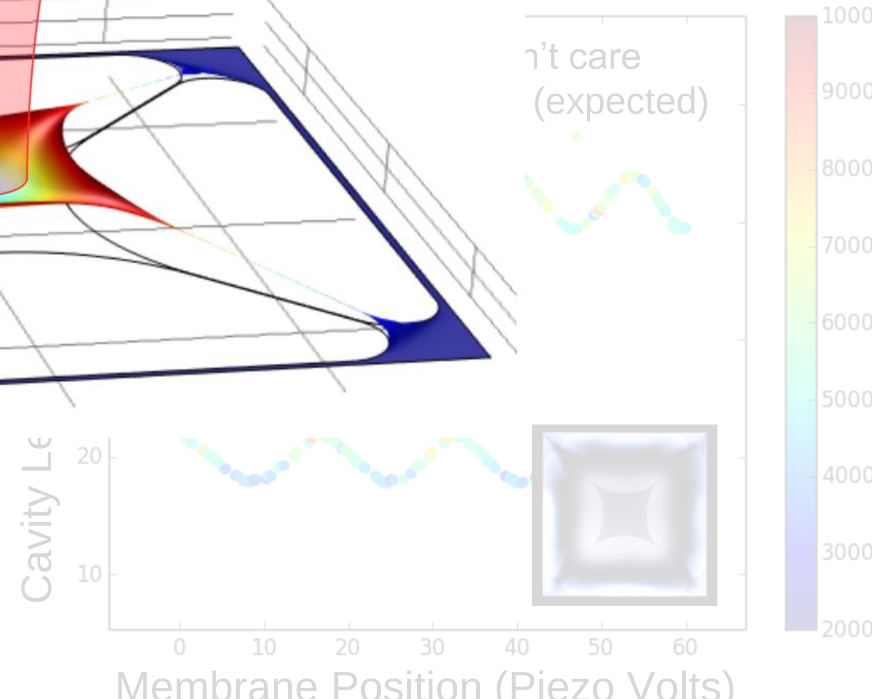
Homemade trampolines in a cavity



Limitations on trapping

- ➔ High laser power & melting
- ➔ Low untrapped Q
- ➔ Will these work in our cavities?
- ➔ **Hybridization with untrapped modes**





Torsional mode = no tether mixing

COMSOL simulations of optically trapped mechanical modes

Limitations on trapping

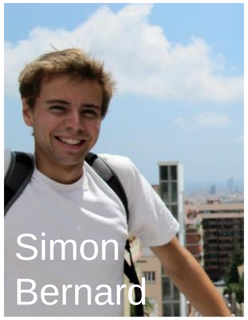
- ➔ High laser power & melting
- ➔ Low untrapped Q
- ➔ Will these work in our cavities
- ➔ Hybridization with untrapped modes
- ➔ **No potato chips allowed**

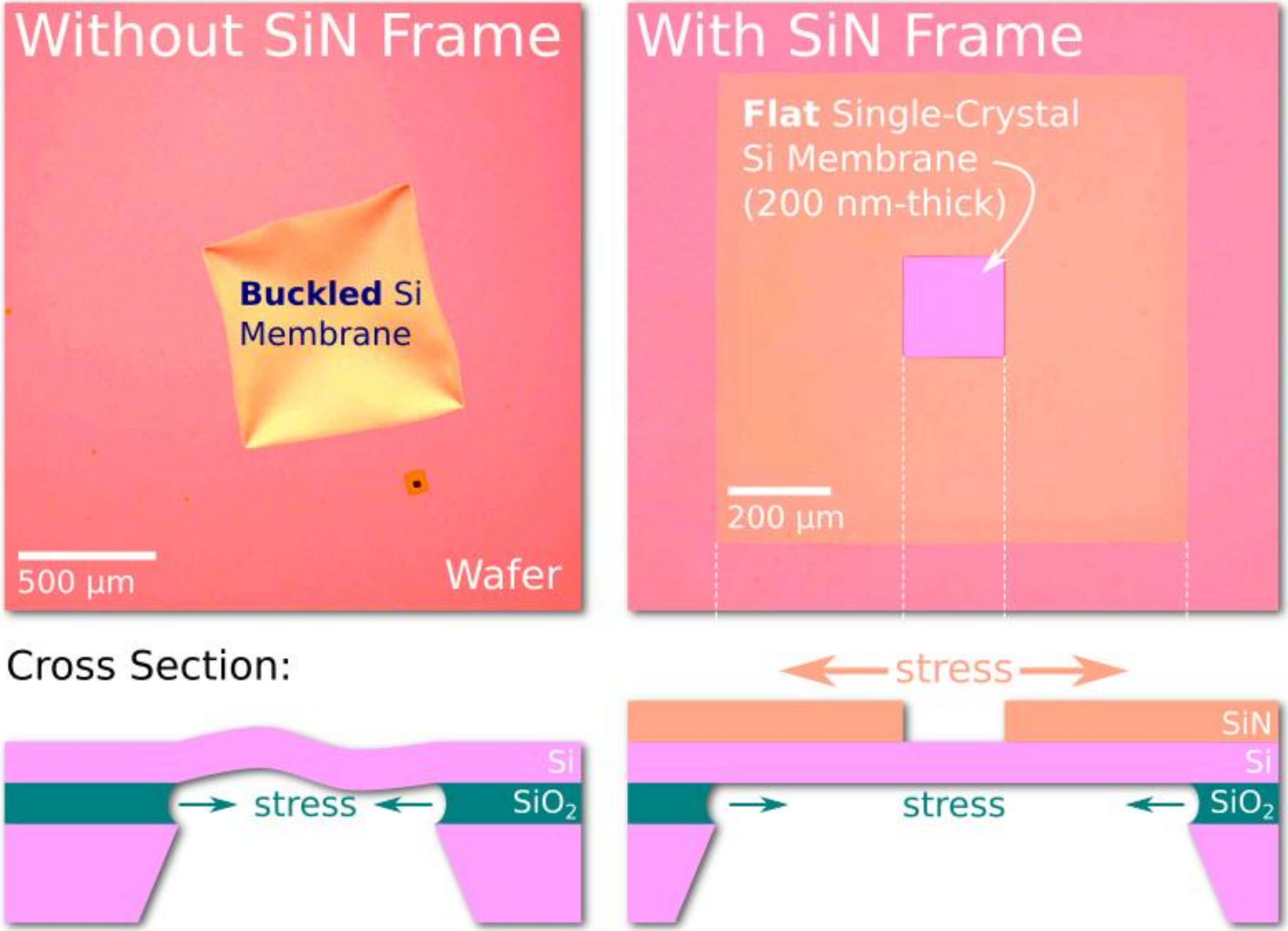
Torsional mode (TM) levitation

- ➔ No hybridization with low-frequency modes (by symmetry)
- ➔ First hybridization with “flappy” disc mode
- ➔ 1500 x Q enhancement possible (Q ~ *billion*??)

T. Müller, C. Reinhardt, J. C. Sankey, PRA (2015)

Single-crystal silicon fab





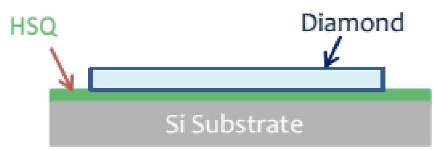
Next step: delicate mechanical (and photonic) structures!

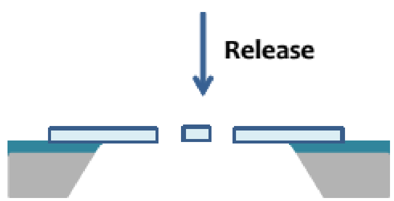
New material: single-crystal diamond

Single-crystal diamond (DOI)

- Higher unstressed Q than Si (new)
- High power handling
- Contains embedded quantum [redacted]

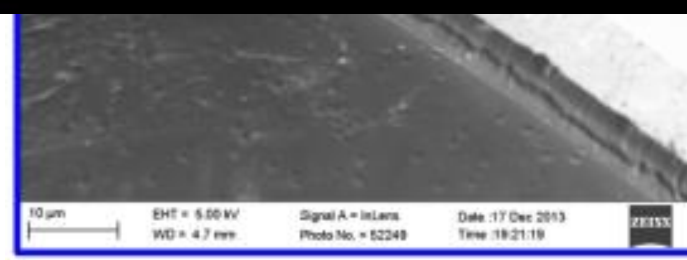
2) Bond it to a substrate





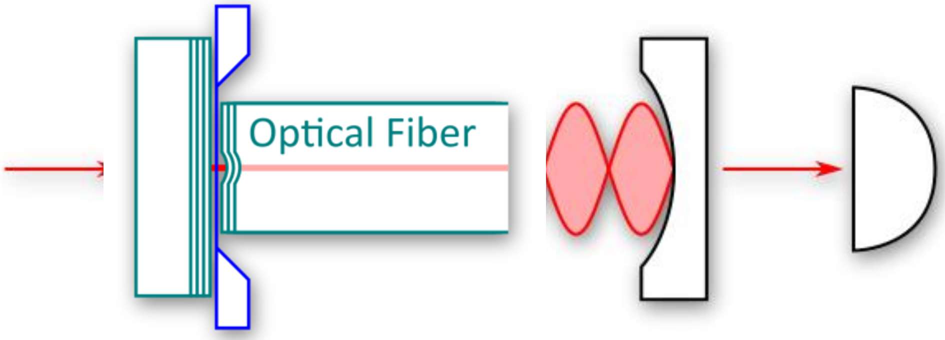
Initial ArCl etch of e6 diamond

- Alumina hard mask
- Optical grade diamond



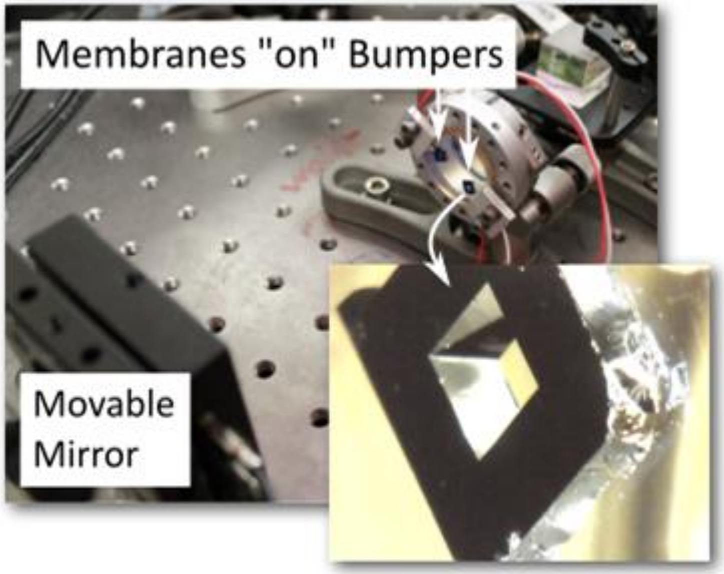
Collaboration with Ye Tao & Christian Degen @ ETH

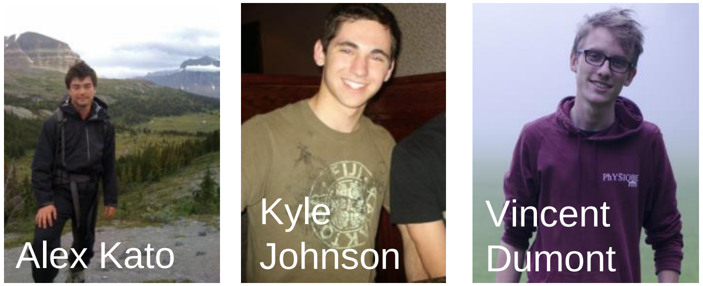
Related goals II: really short cavities

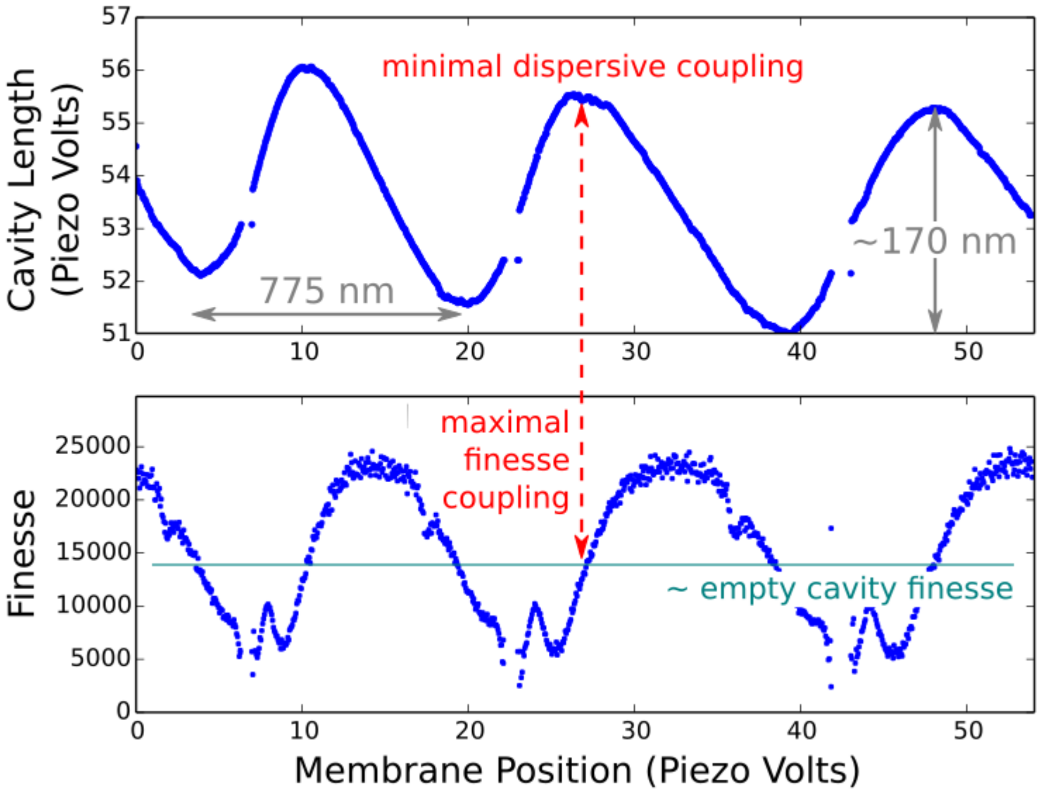


"Compound input mirror"

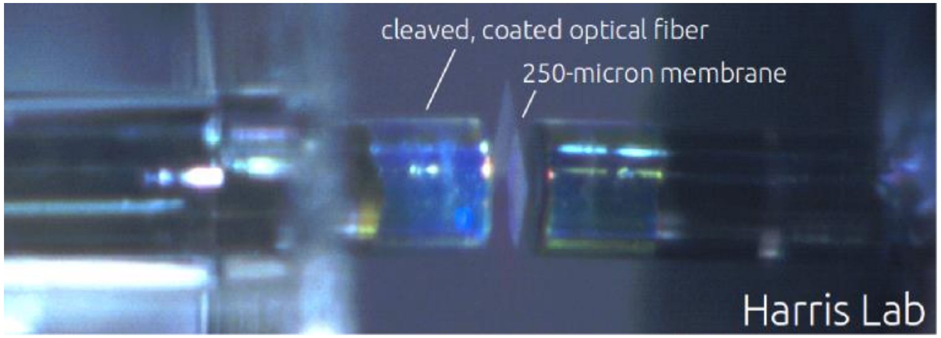
- ➔ Membrane as "movable Bragg layer"
- ➔ Input *transmission* coupled to membrane motion







Stronger coupling to smaller devices

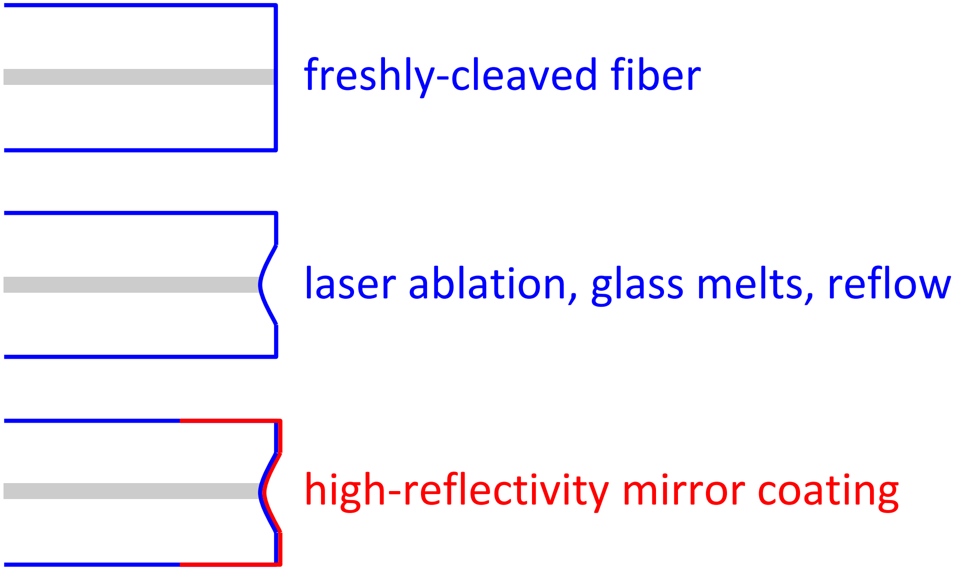


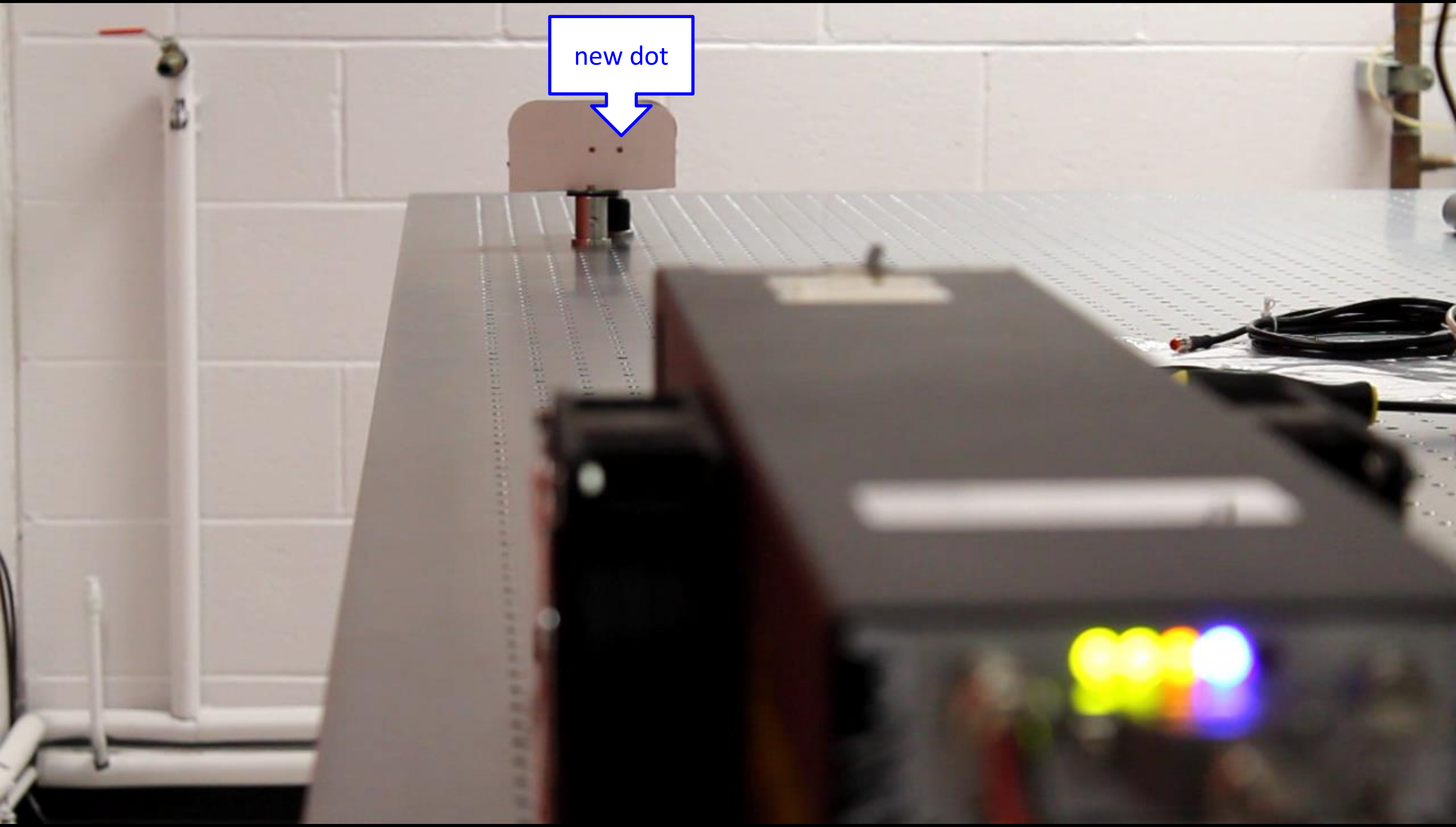
Ablated fibers courtesy of Jakob Reichel Group

Fiber-based microcavities

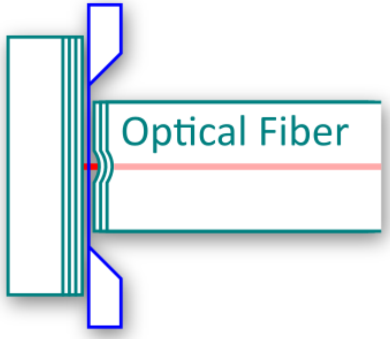
- Shorter cavity = more bounces per second = stronger coupling
- Confined optical mode = naturally addresses smaller, lighter MEMS
- Compact, fiber-coupled package

Fiber Mirror Fabrication with 40W CO_2 laser



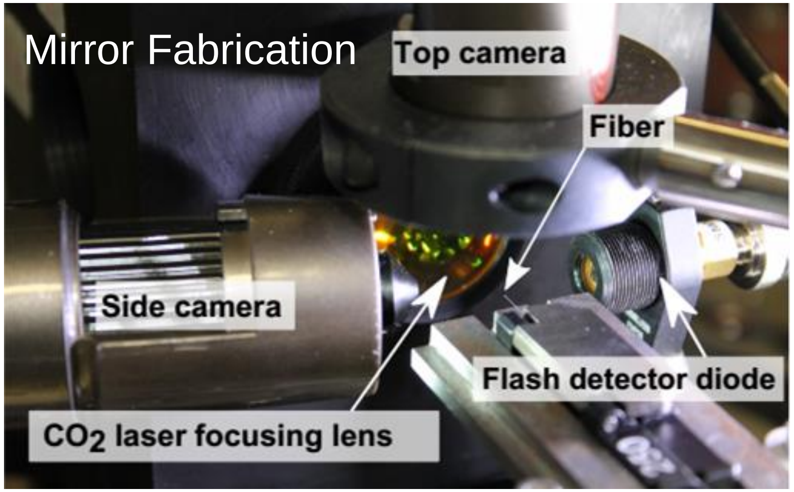

new dot

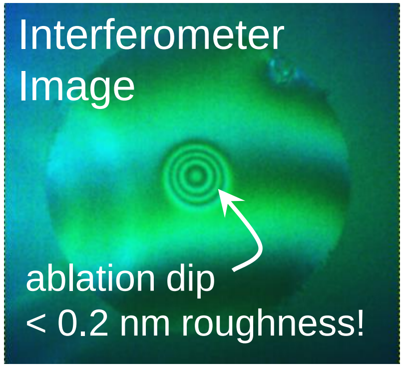
Really short *full* cavities

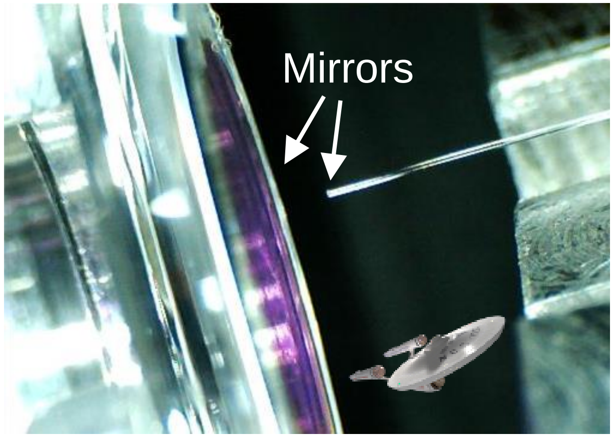


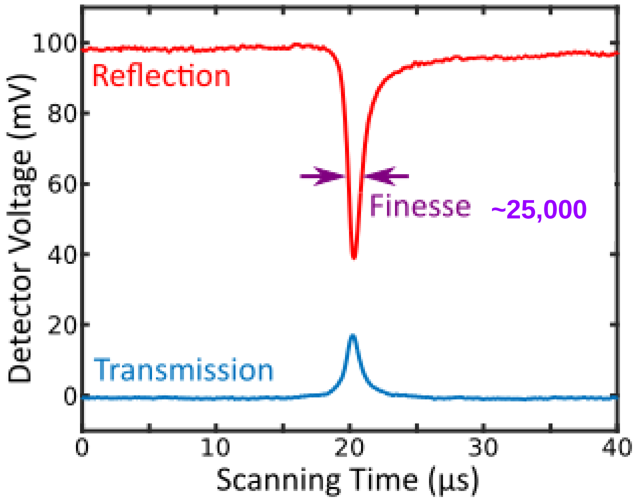
Laser-ablated, coated fiber mirrors

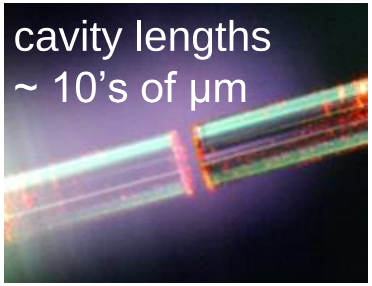
- ➔ Goal: cavity length ~ wavelength
- ➔ Stronger per-photon force (shorter round-trip time)
- ➔ Suited for smaller MEMS
- ➔ Fiber-coupled input and output

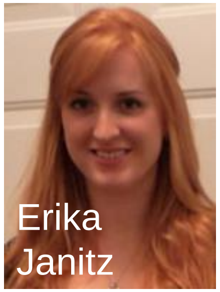






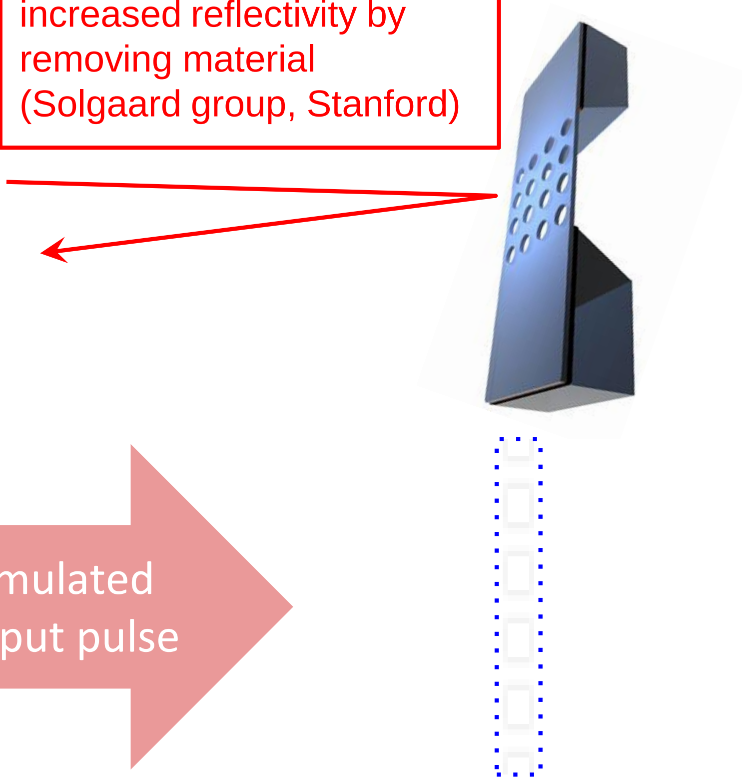






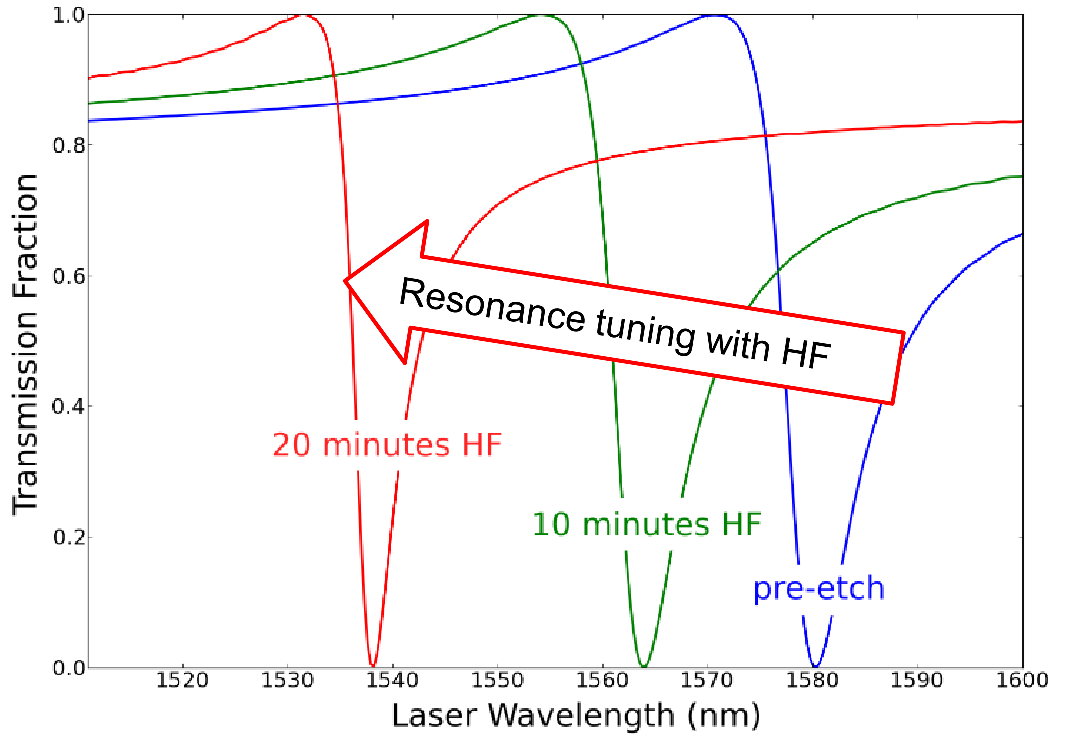
Related goals I: Wifflebranes®

increased reflectivity by removing material (Solgaard group, Stanford)



simulated input pulse

resonances in photonic crystal

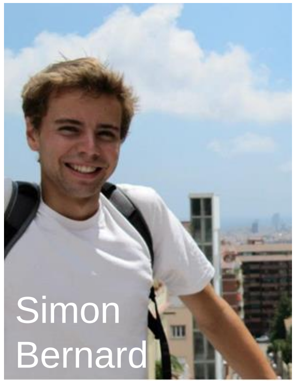


Predictions (MEEP)

- ➔ Resonant reflection of one wavelength
- ➔ Subsequent HF (acid) dips thin membrane, widen holes
  - ◆ Controlled tuning of resonance

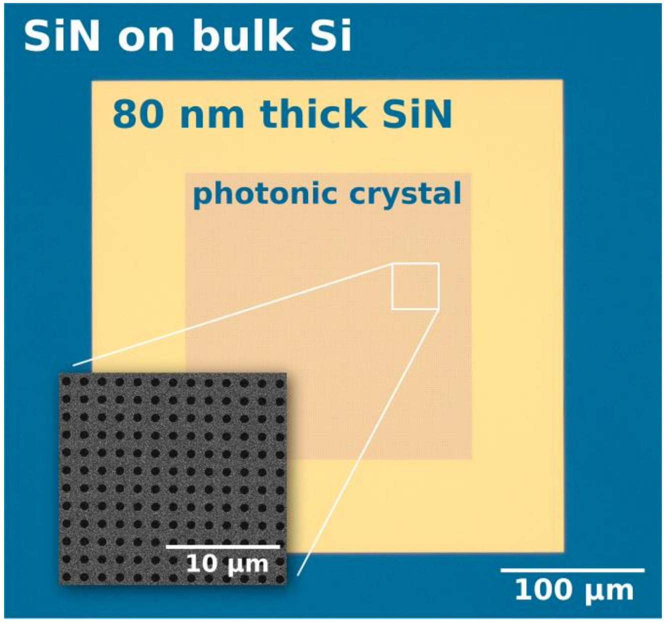
Collaboration with Yves-Alain Peter (Polytechnique)

Preliminary results

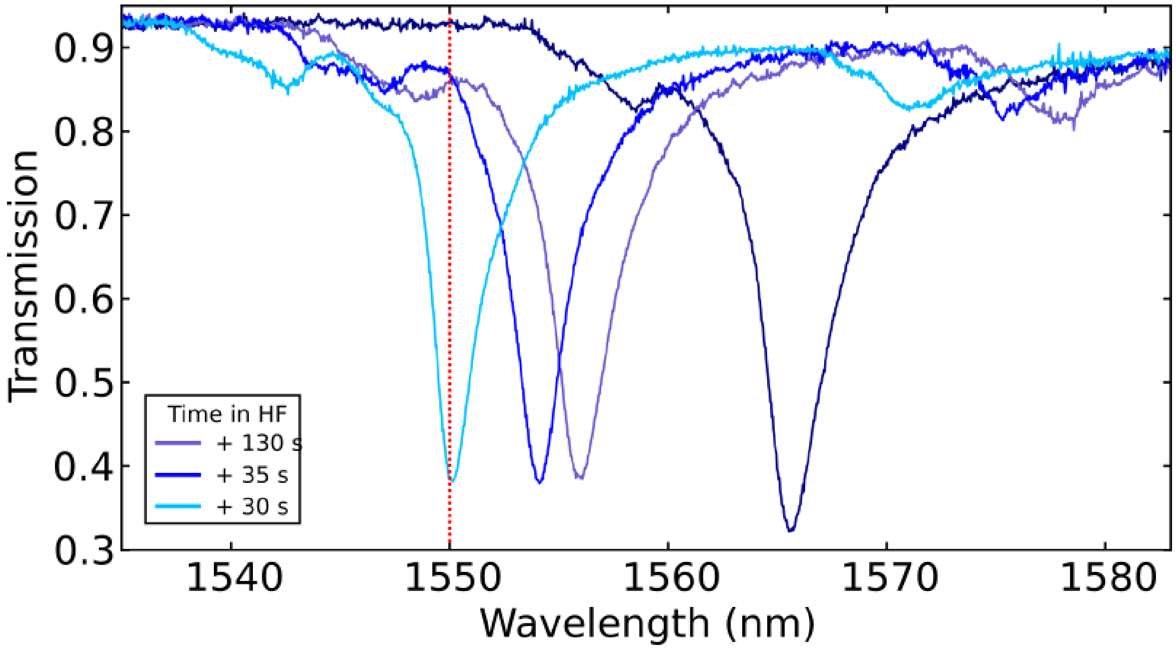


Fabrication in silicon nitride

- ➔ Electron beam instead of photolith
- ➔ No surprise: new surprises
- ➔ Resonance tuned with HF
- ➔ Next step: measure *actual* reflectivity with a cavity.



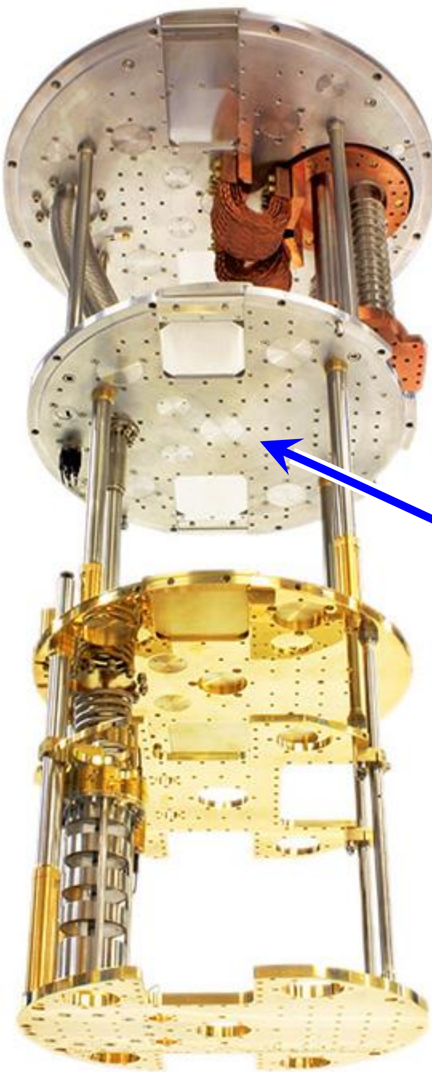
Tuning the resonance post fabrication



Less force noise & higher Q's: cryostat

At Low Temperature

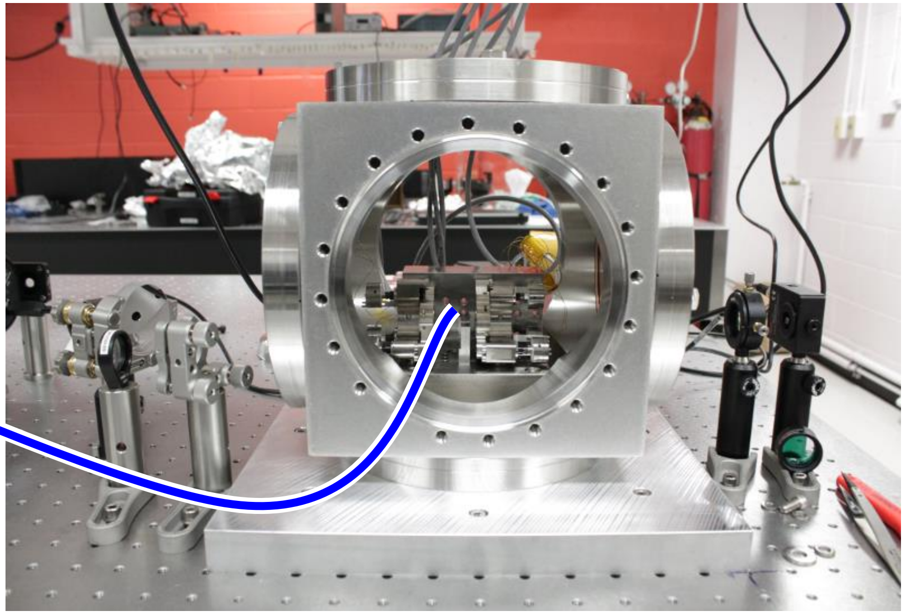
- Reduced force noise, higher bare Q
- Quantum experiments more accessible
- Fiber input, same hardware
- Vary temperature & trap to study dissipation



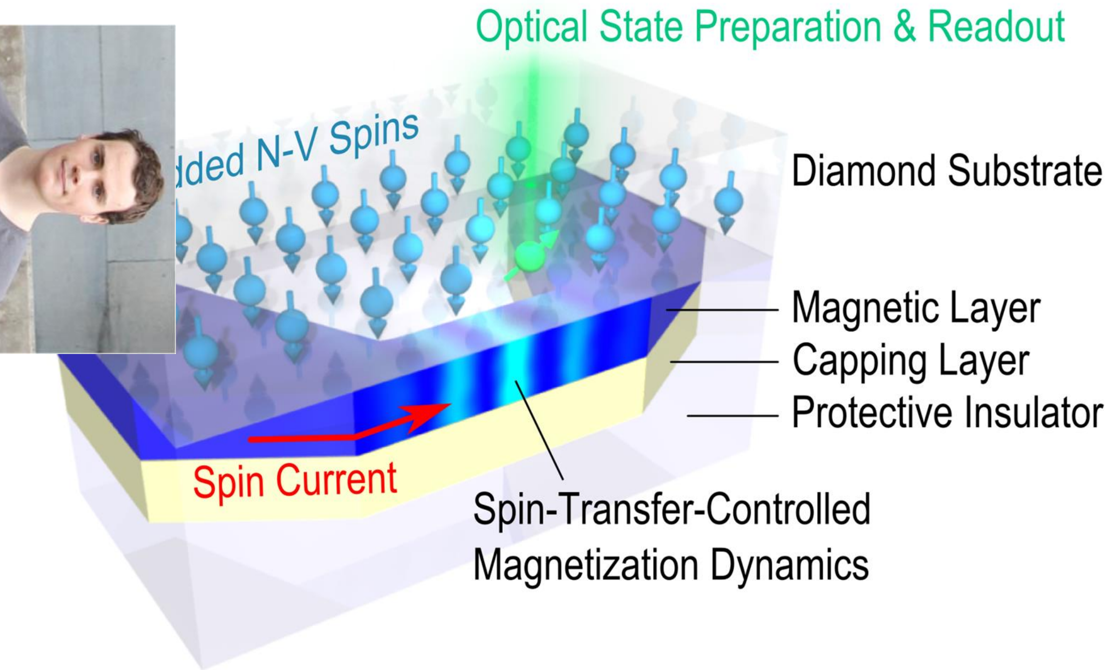
3K - 300K

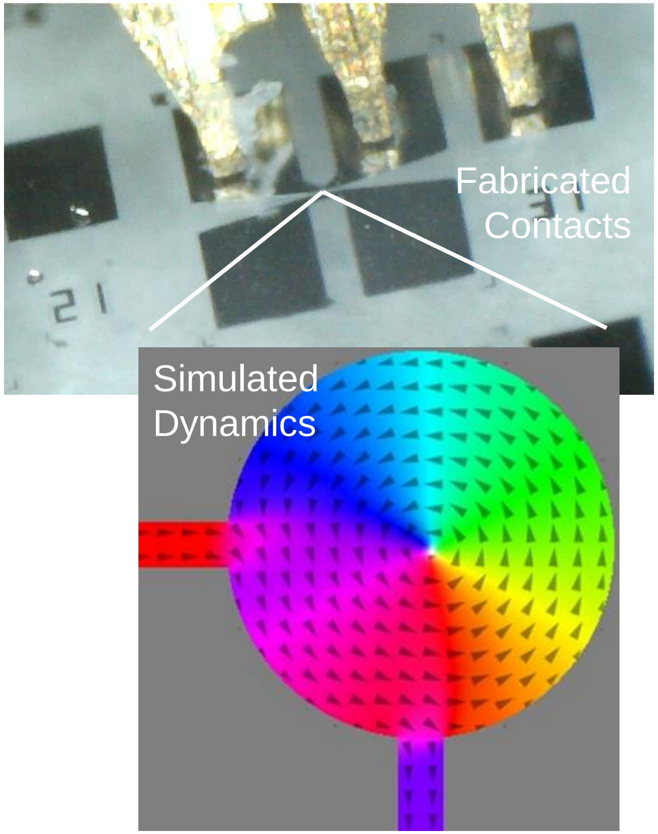
Incoming upgrade: 10 mK (!)

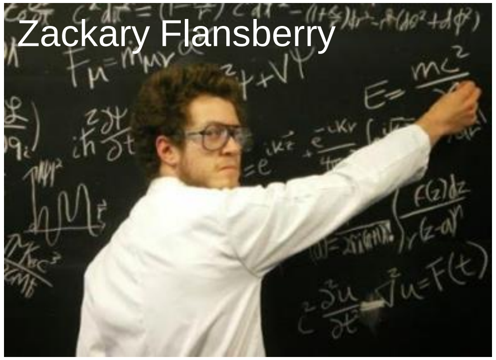
(hang from springs)



Unrelated advertisement: spin transfer







N-V magnetometry of magnetic nanocircuits

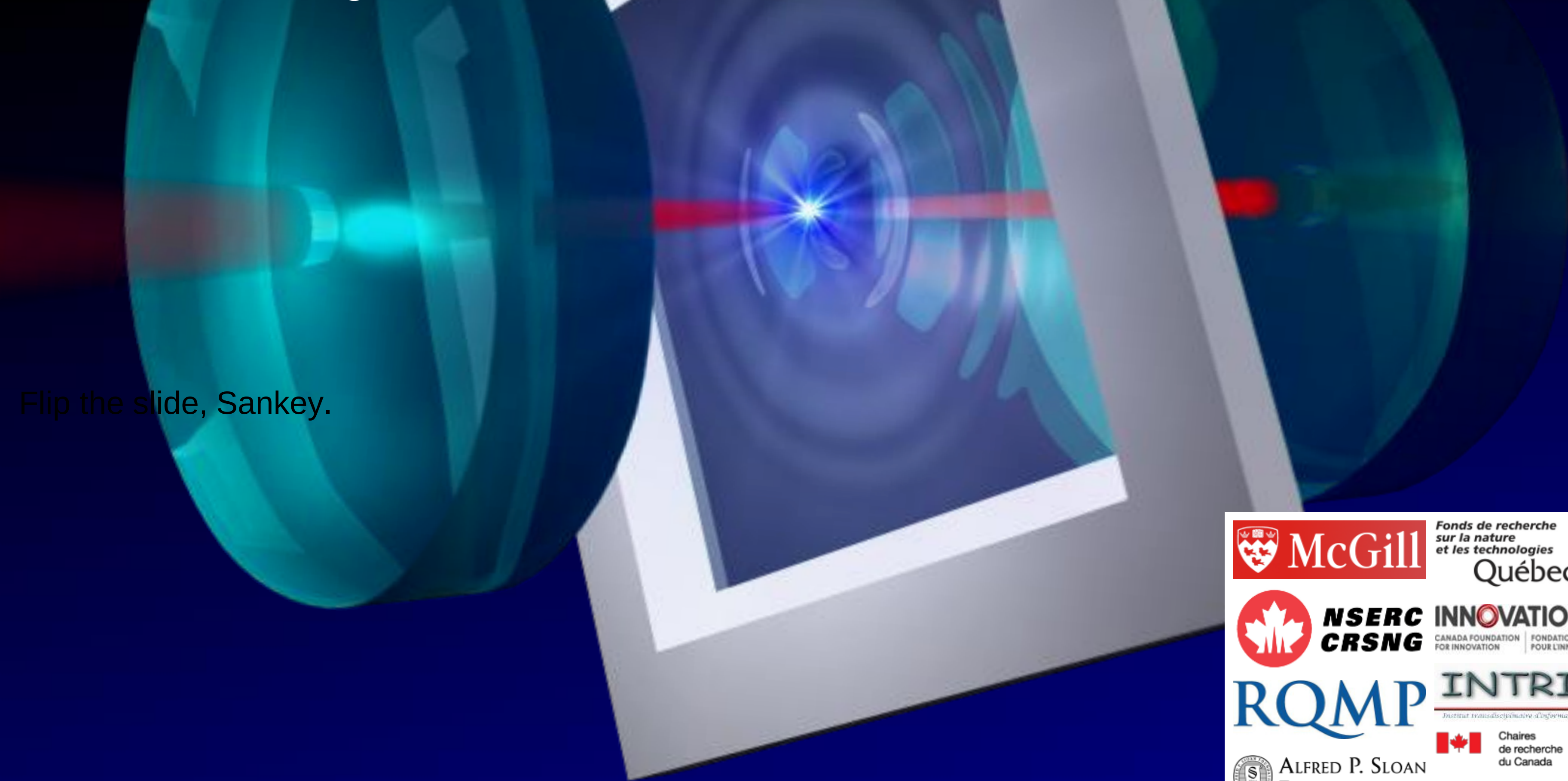
- ➔ All-electrical FMR on protected magnetic nanocircuit
- ➔ Imaging of dynamics with N-V defects in diamond
- ➔ Nanoscale magnetic elements, sub-wavelength techniques
- ➔ Coherent coupling between N-V spins and magnons?

collaboration with Wife (McGill) & Michel Pioro-Ladrière (Sherbrooke)

Summary

Current & future goals

- Partial levitation and ultrahigh Q MEMS
- Wavelength-scale optical cavities
- Photonic crystal reflectors
- MEMS materials research
- Nanoscale magnetic circuits



Flip the slide, Sankey.

McGill

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