WE ARE ON

OSA Quantum Optical Science and Technology Technical Group

Coupling Defect Centers in Diamond to Fabry-Perot Microcavities

Lilian Childress, McGill University

Technical Group Leadership 2021

Chair: Dr. Graciana Puentes
University of Buenos Aires, AR

Vice-Chair: Dr. Lee Bassett
University of Pennsylvania, US

Events Officer: Dr. Sara Mouradian
UC Berkeley, US

Social Media Officer: Dr. Xuejian Wu
Rutgers University, US

Liason with Industry: Dr. Mo Soltani
Raytheon BBN Technologies, US

Our Technical Group at a Glance

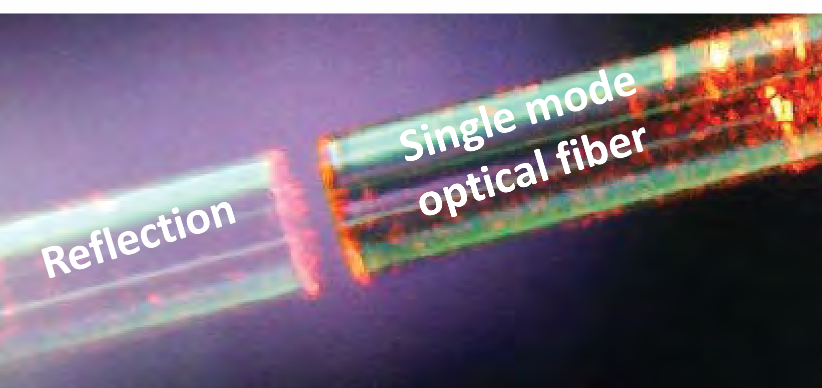
- Experiment, theory, and technologies relevant for quantum measurements and quantum information within the purview of quantum optical science
- Nearly 3000 members worldwide
- Webpage https://www.osa.org/oq
- Webinars, technical events, networking events, campfire sessions etc.
- Suggestions, ideas for events, email us at OSA TGActivities/gpuentes@df.uba.ar
- **Upcoming Webinar:**

➢ 31 March 2021
➢ Prof. Friedemann Reinhard
➢ *The Planar Scanning Probe Microscope: A Novel Platform for Quantum Sensing and Near-Field Microscopy*

OSA Quantum Optical Science and Technology Technical Group

Welcome to the Quantum Optical Science and Technology Technical Group Webinar!

Coupling diamond defect centers to high-finesse optical microcavities



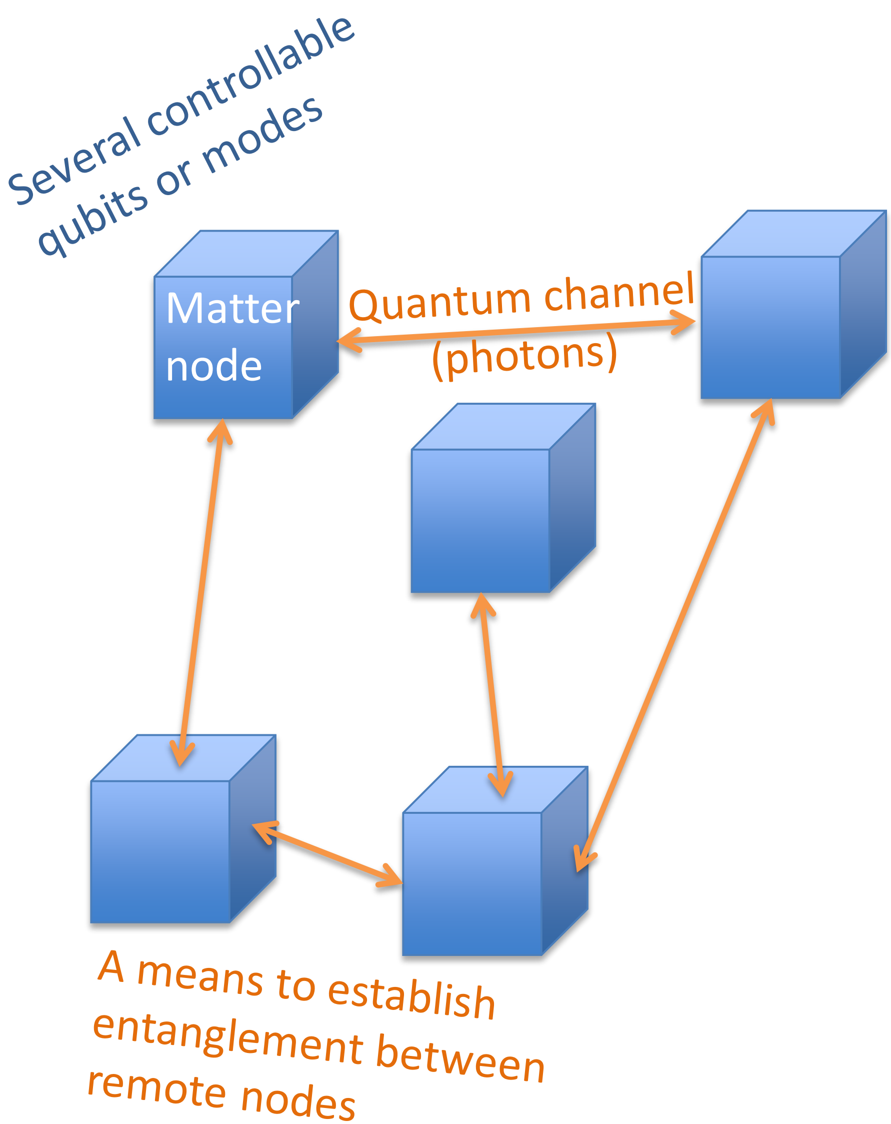
Lily Childress, McGill University

OSA Webinar

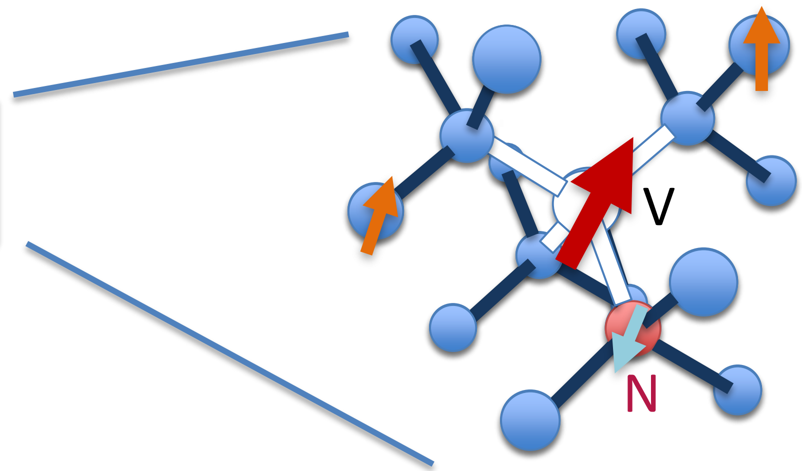
March 3, 2021

Motivation: a solid-state spin-photon interface

Quantum networks



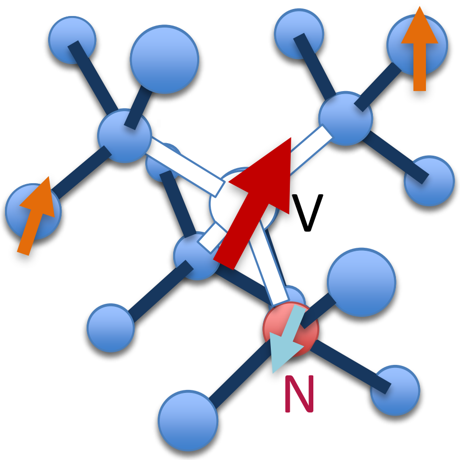
The NV center in diamond



Spin coherence time ~ seconds; up to 10 controllable qubits

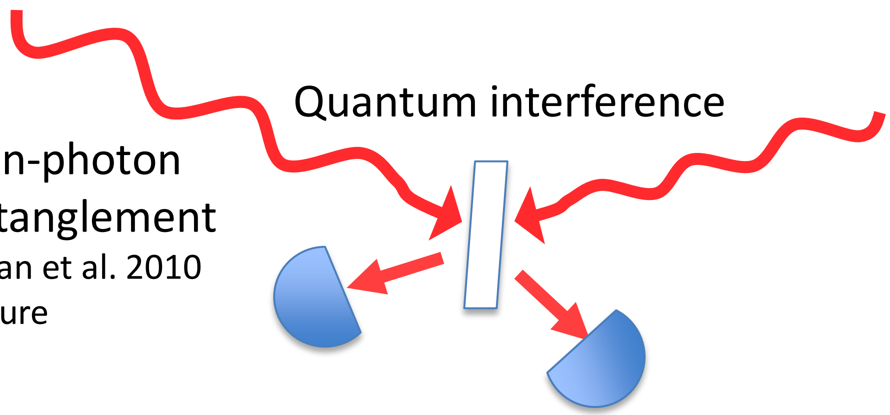
Bradley et al. PRX 2019

Connecting quantum nodes: heralded entanglement



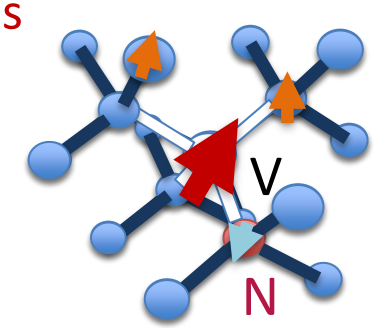
The vision:

- A few-spin-qubit register with preparation, coherent control, and measurement
- Scalability via optical connections



Quantum interference

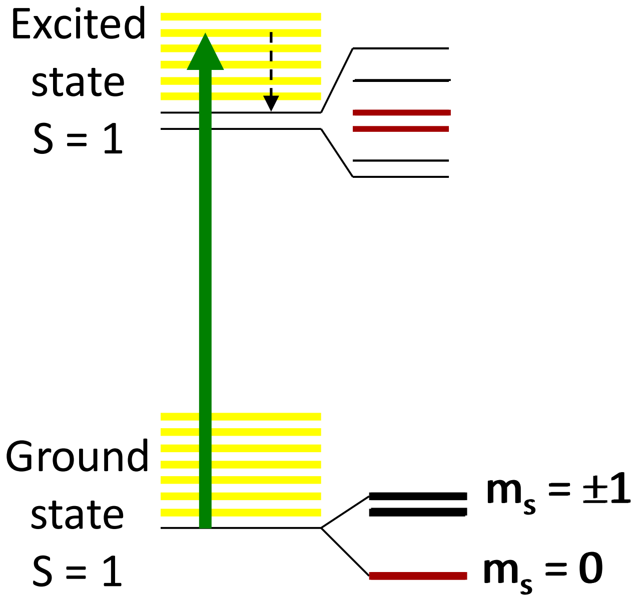
Spin-photon entanglement
Togan et al. 2010 Nature



Coincidence detection
→ leaves spins entangled
Bernien et al 2013 Nature

Challenge: efficiency

The optical transitions of the NV (at cryogenic temperatures)



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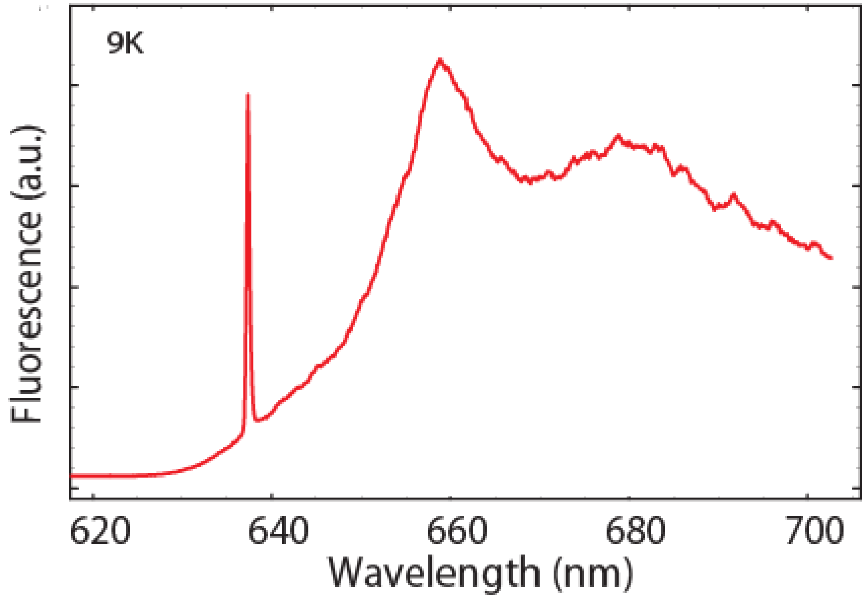

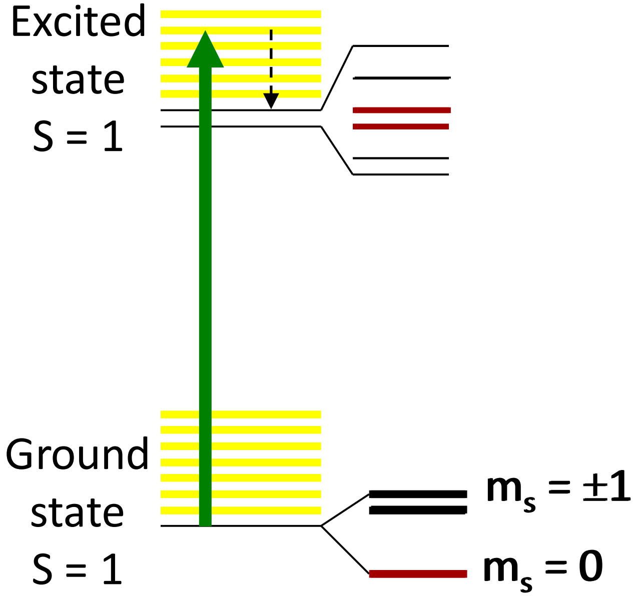

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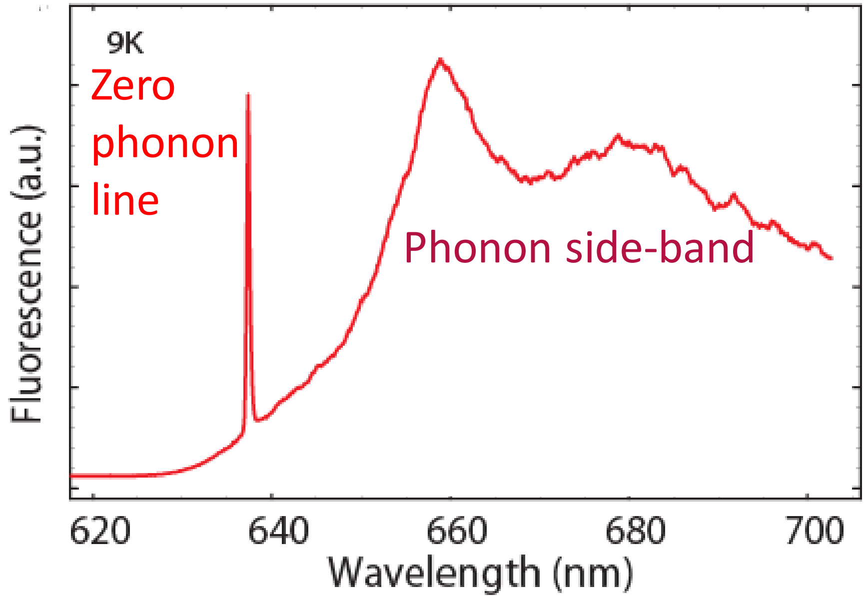

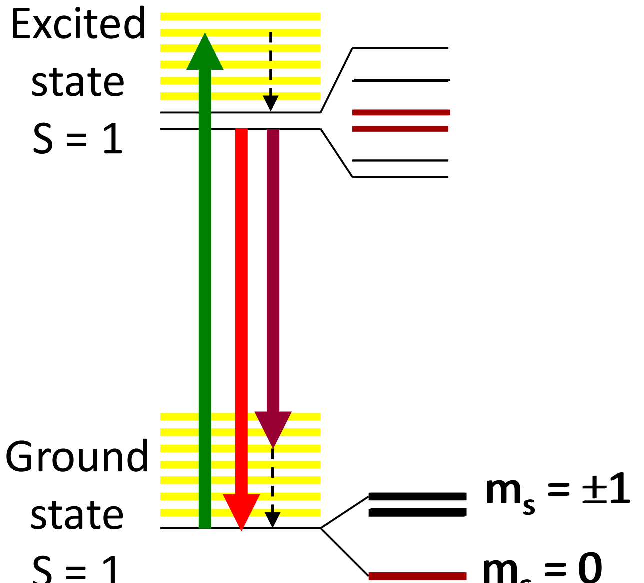

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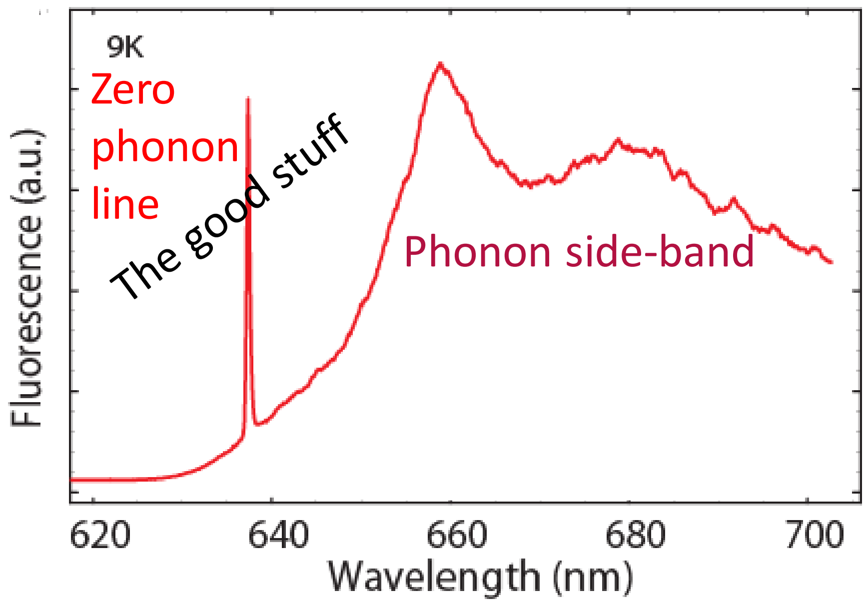

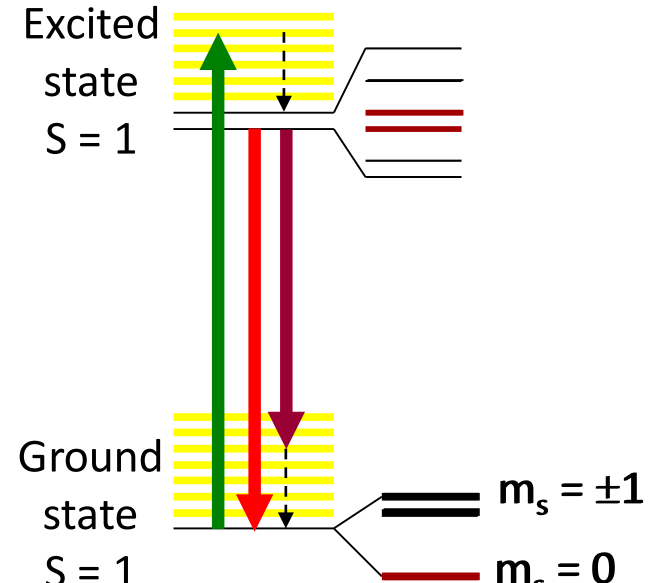

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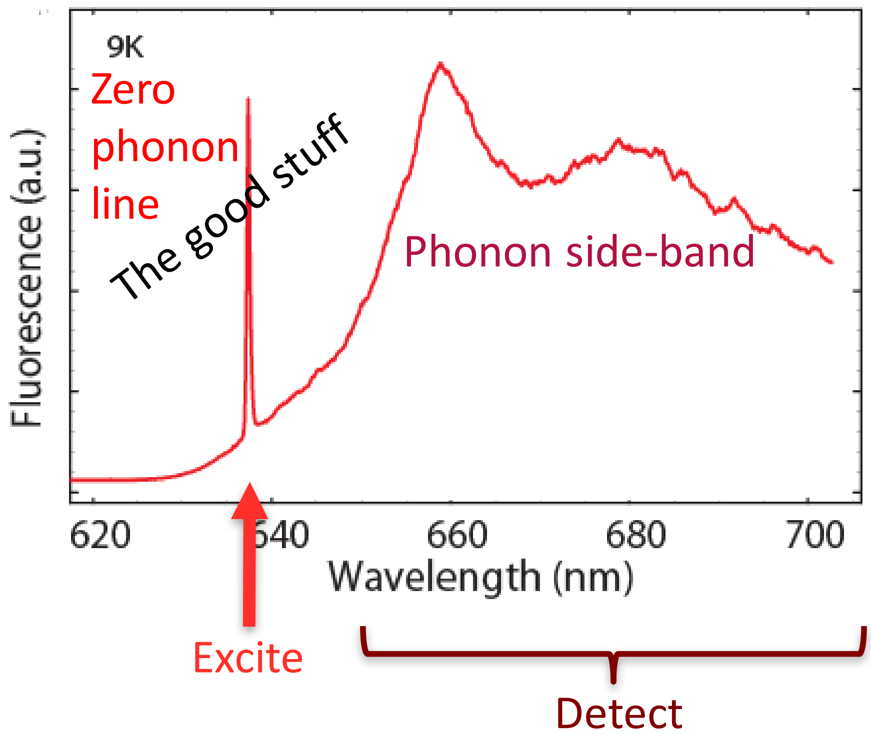

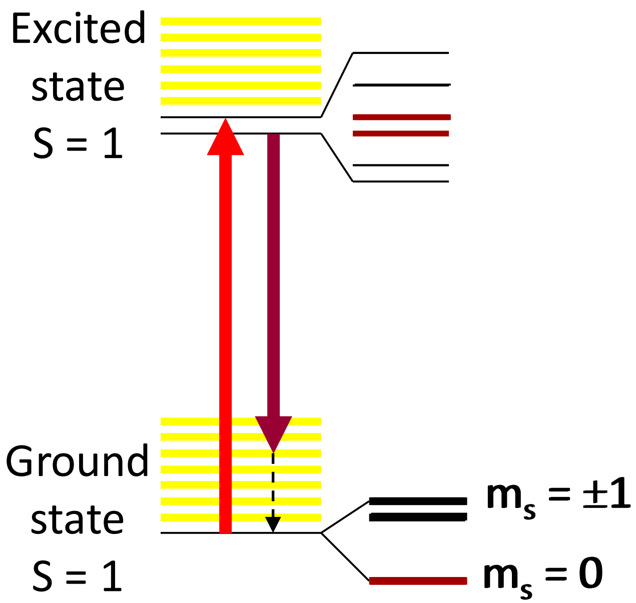

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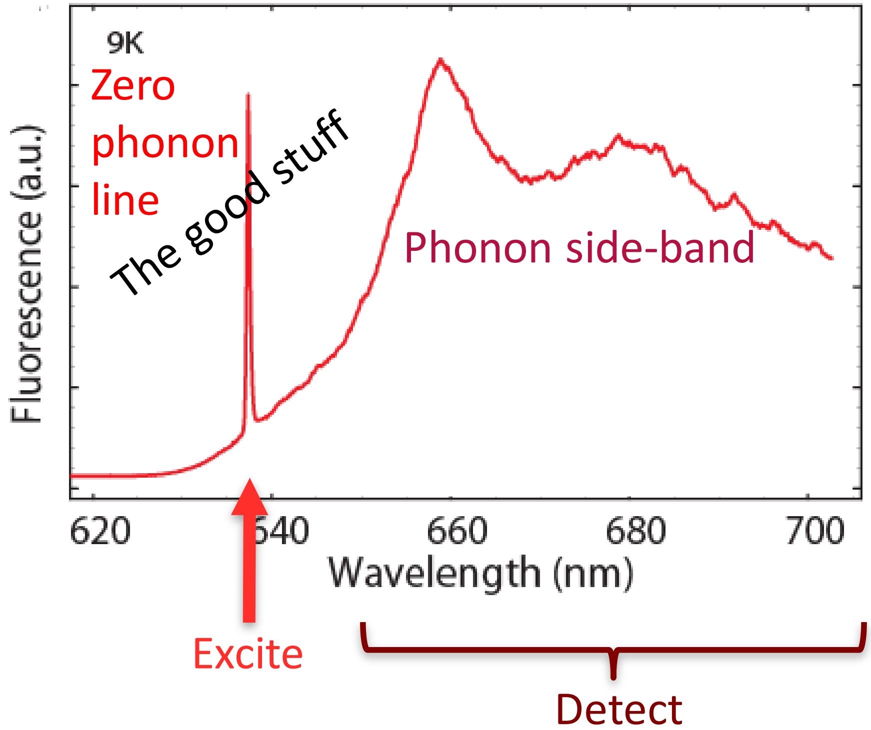

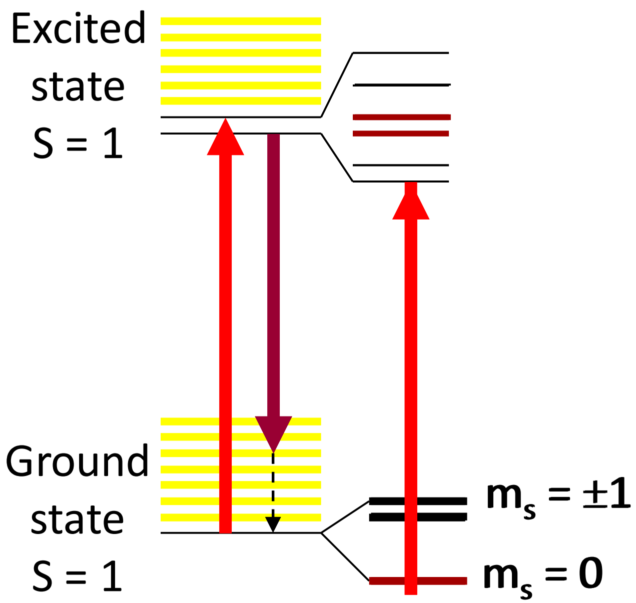

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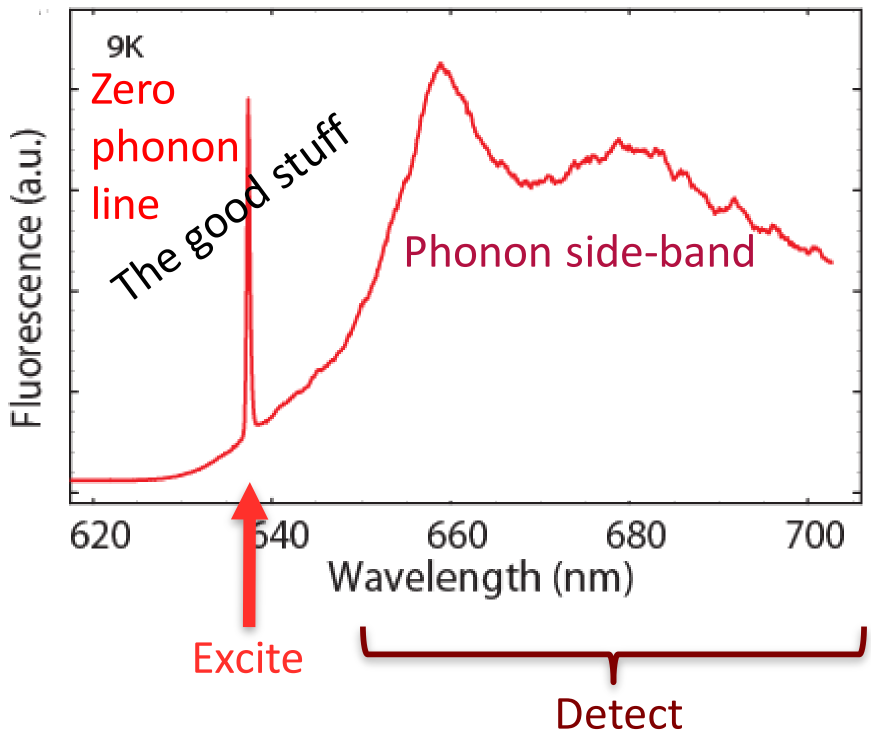

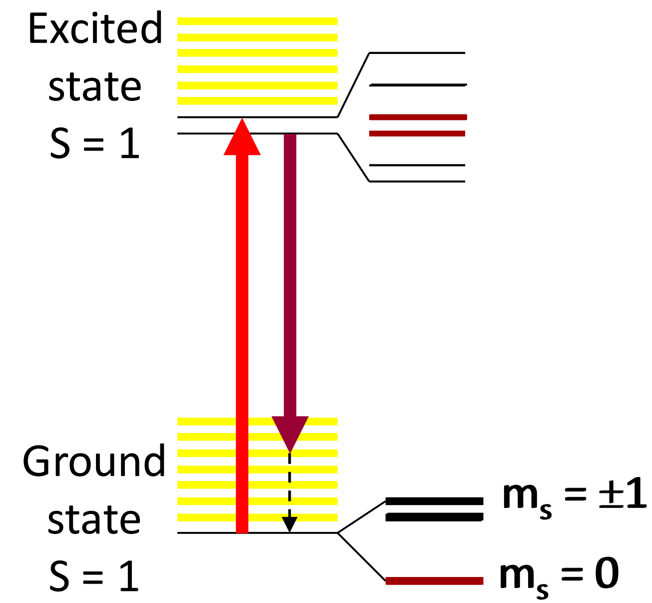

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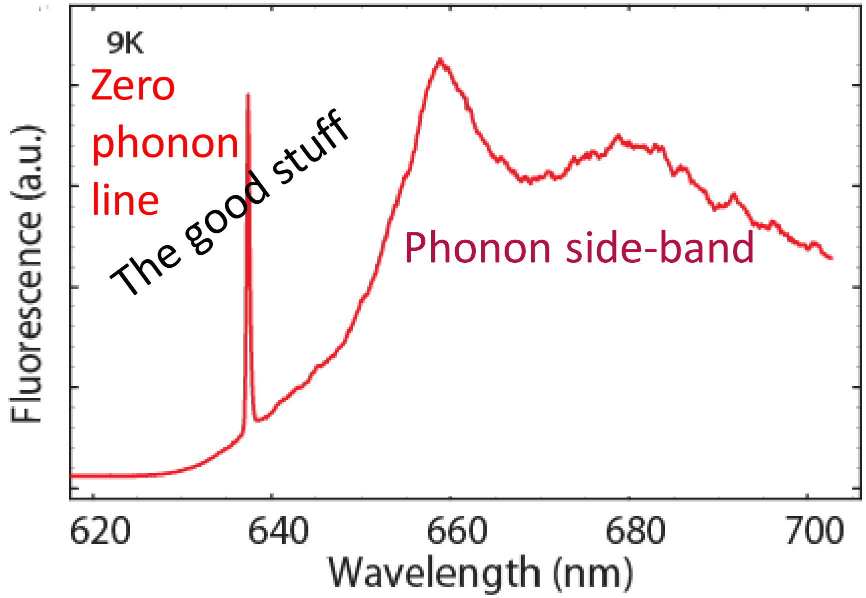
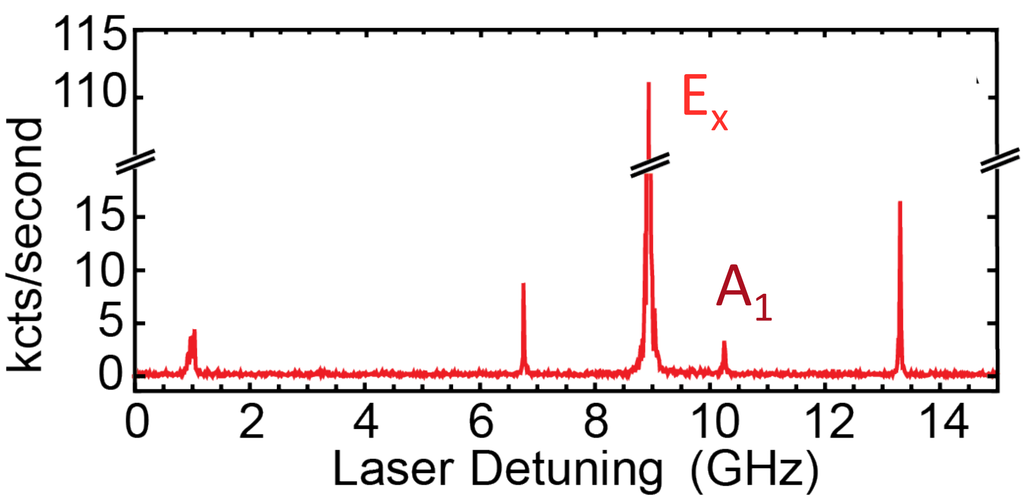
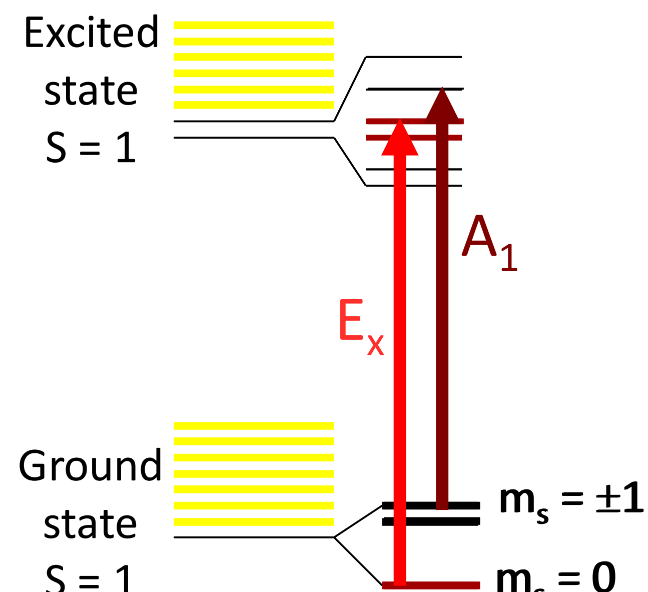


- ✓ Spin-selective transitions
- ✓ Polarization selection rules





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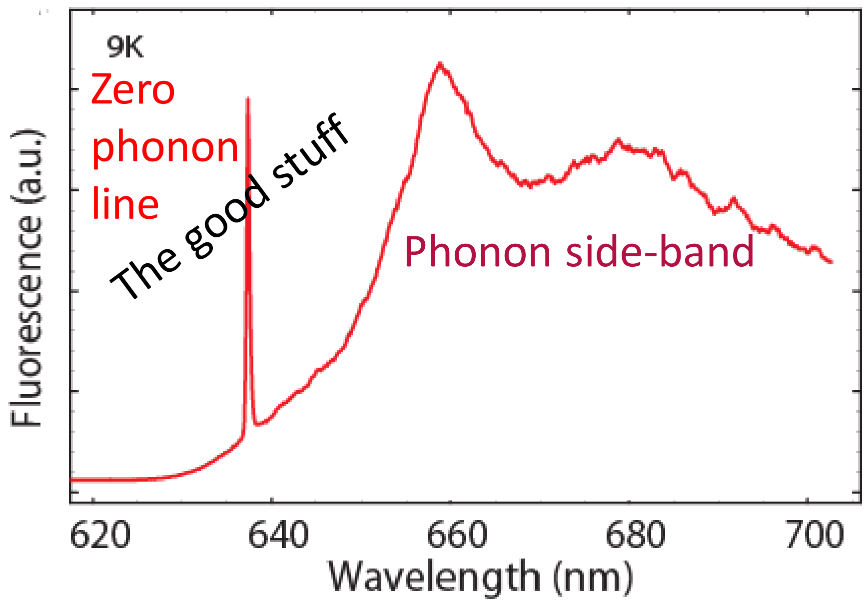

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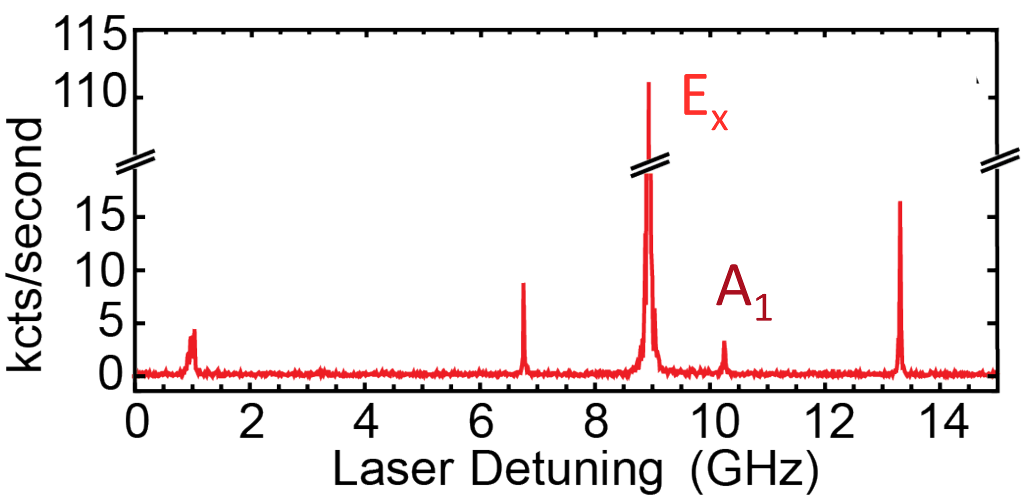
BUT:

Only 3% of emission is in ZPL

Dephasing: Detection window needed to render photons indistinguishable

$$\Delta t \sim \frac{1}{\gamma} << \tau$$



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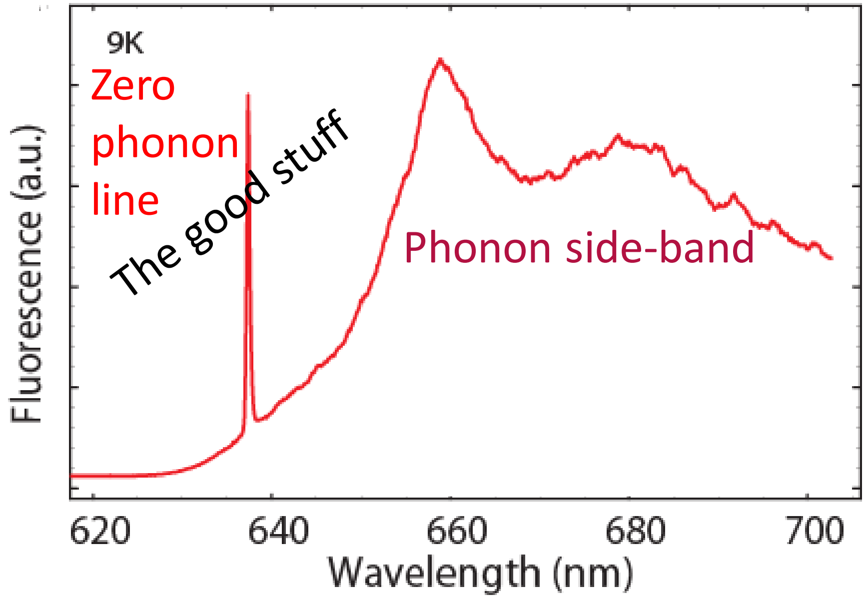

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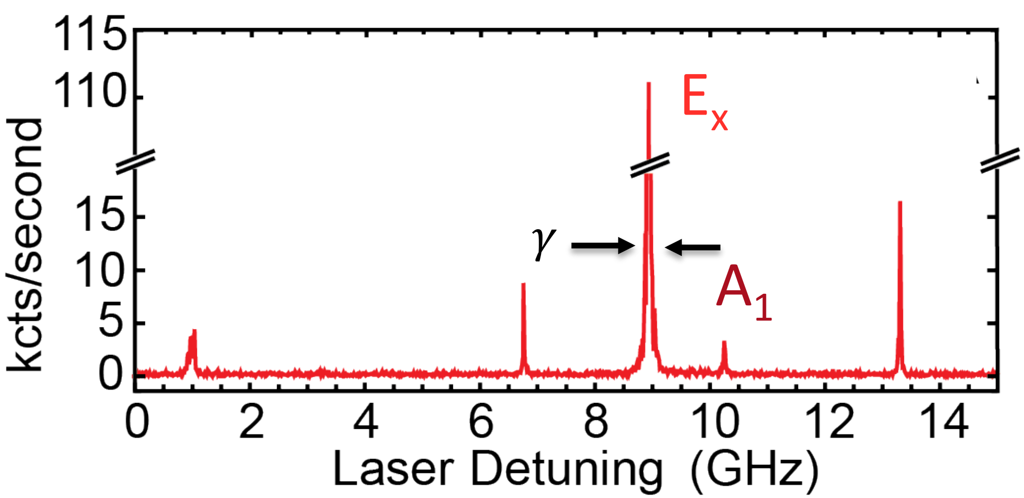
Excited state lifetime



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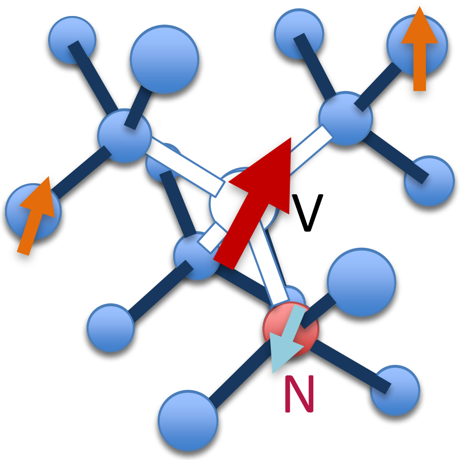
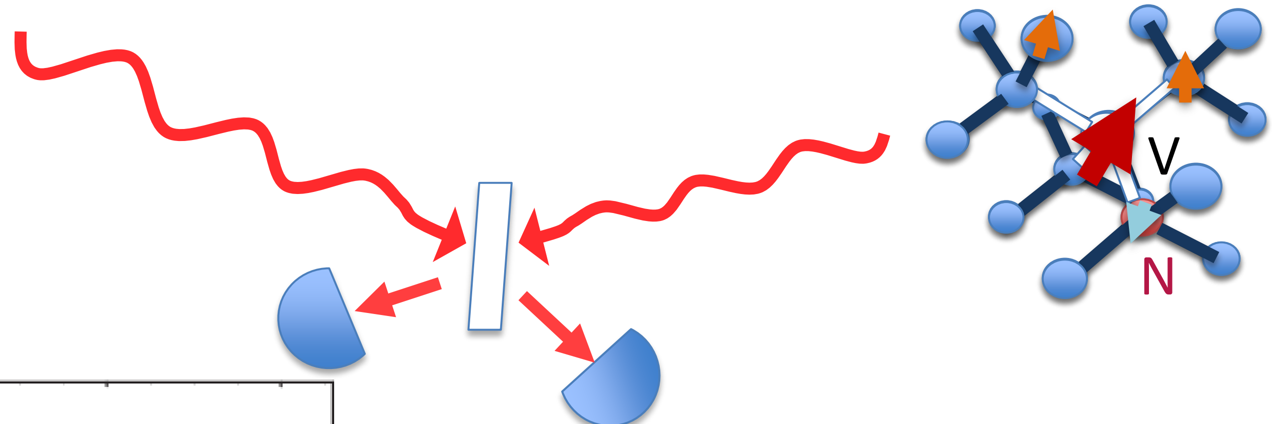
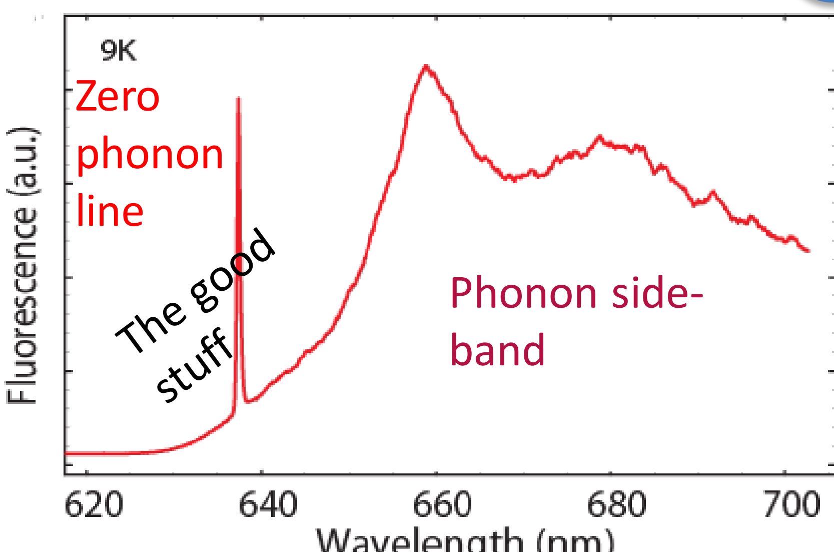


Many protocols require two photon detections for high fidelity



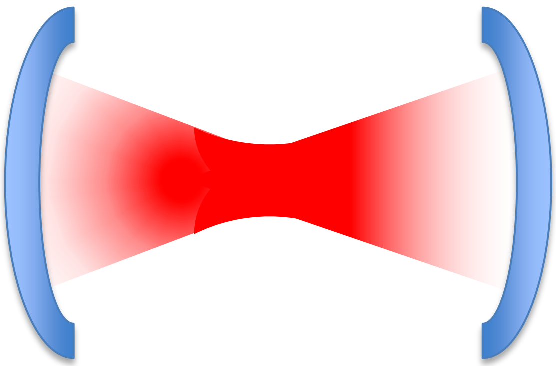


To improve efficiency:

- Good photon collection efficiency into single mode
- Enhanced ZPL emission
- Decreased radiative lifetime

Towards an efficient NV spin-photon interface

Cavity quantum electrodynamics



Emission on cavity resonance enhanced by $F_P + 1$

$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}$$

Quality factor

Mode volume

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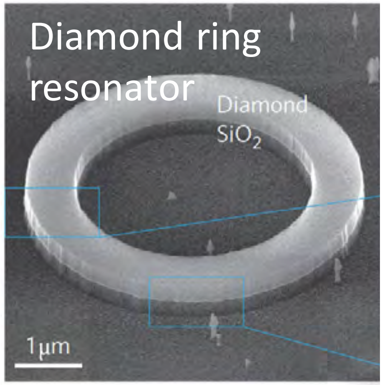
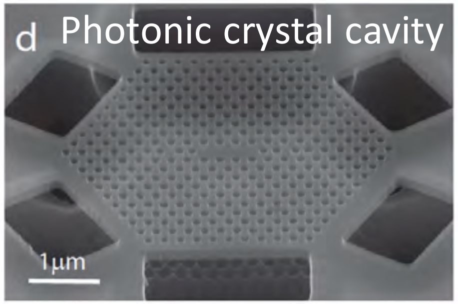


Nat. Phot. 5, 301 (2011)



PRL 109, 033604 (2012)

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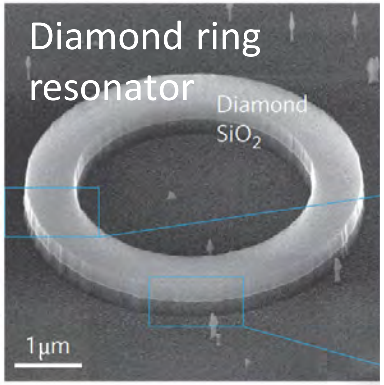

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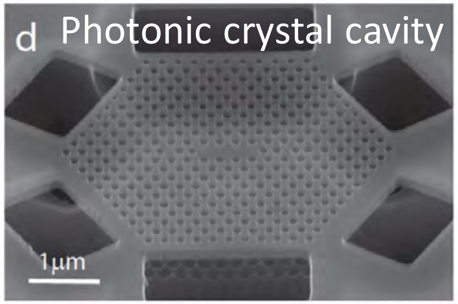

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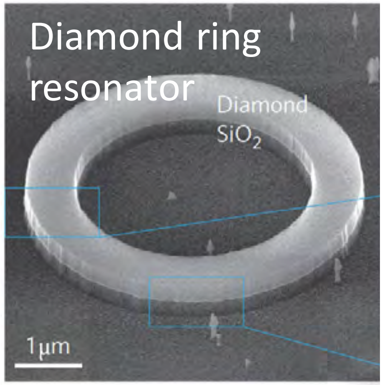

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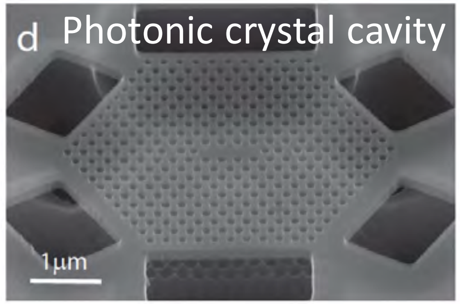

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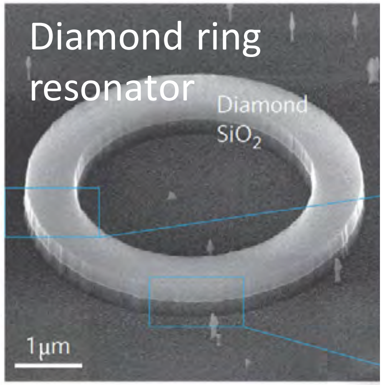

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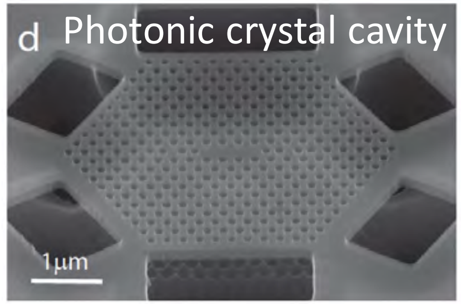

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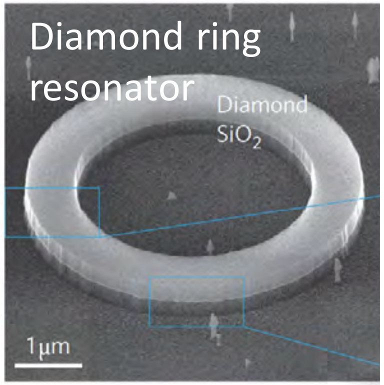

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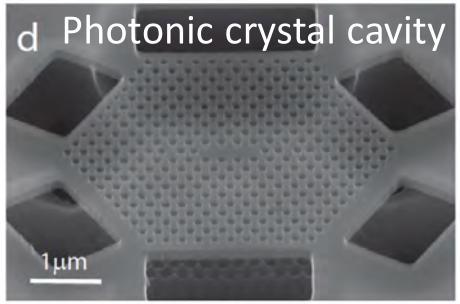

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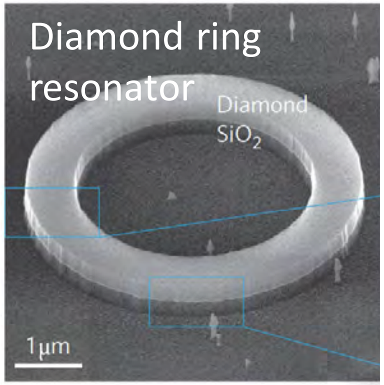

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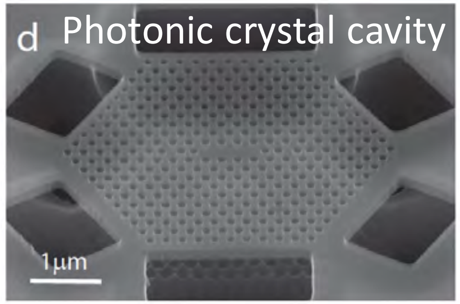

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spectral diffusion near surfaces

issue for nanoscale structures

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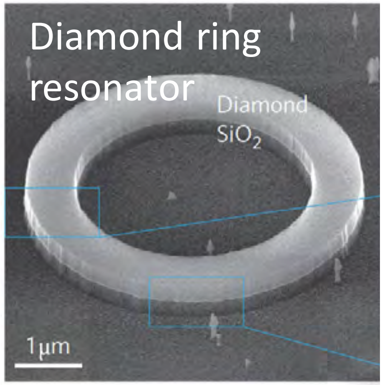

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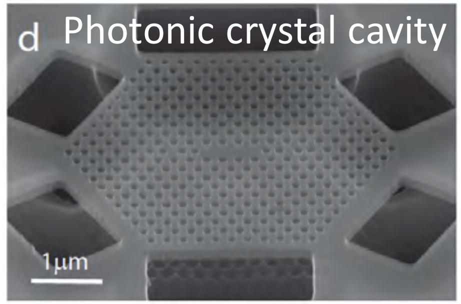

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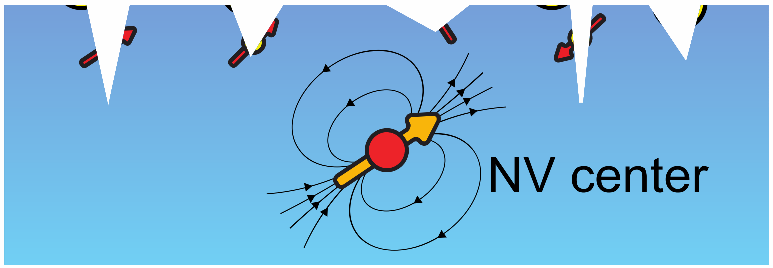
issue for nanoscale structures

A single electron fluctuation 100nm away poses problems!

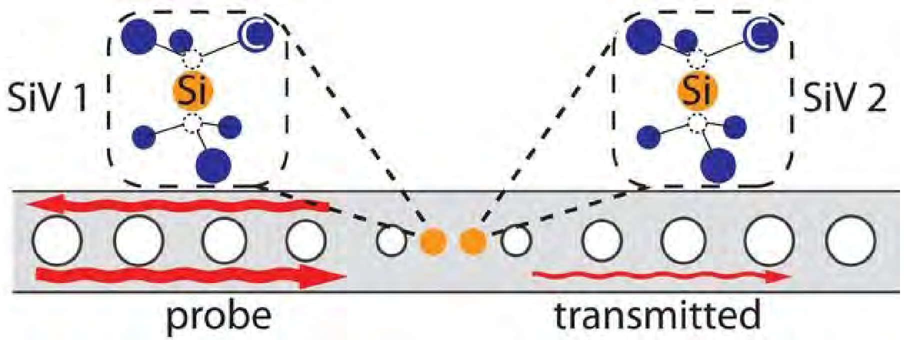
Overcoming spectral diffusion

- Do the hard work
    - Better annealing and fabrication recipes
    - Careful surface science
    - Repeatability…



PRX **9**, 031052 (de Leon group)

- Stop using NVs



Science **362**, 662 (2018) (Lukin group)

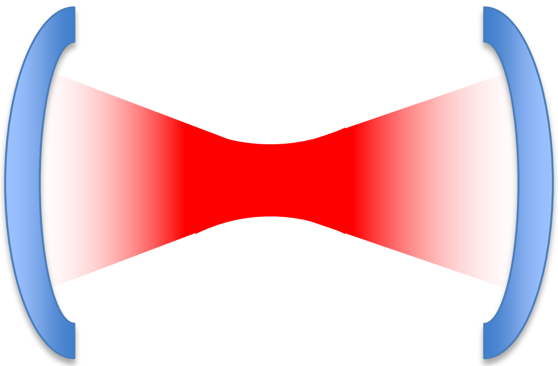
SiV- defects
- Large ZPL fraction
- Reduced spectral diffusion
- Spin coherence poor above 1K
- Low quantum efficiency

Others…?

- Avoid nanofabrication

Open geometry Fabry-Perot micro-cavities

Cavity quantum electrodynamics



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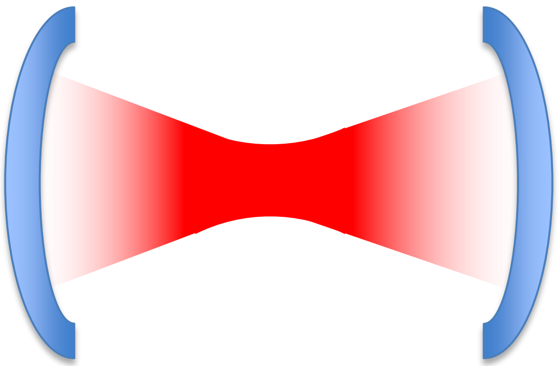

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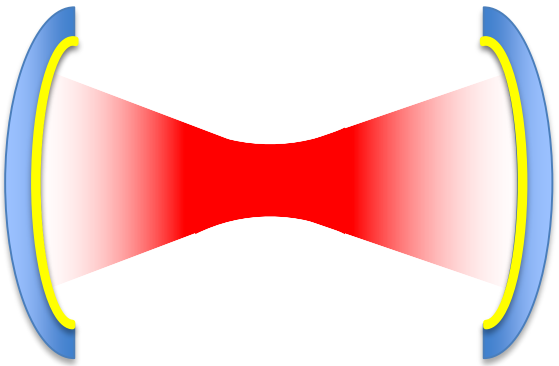

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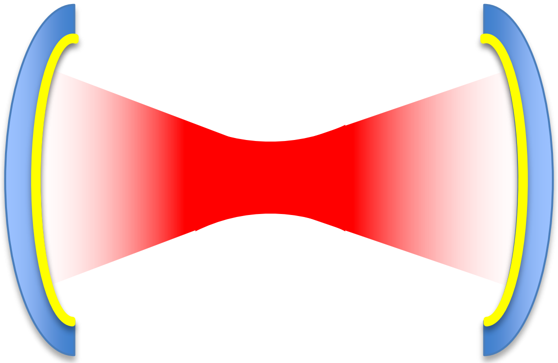
Finesse F ~ number of round trips



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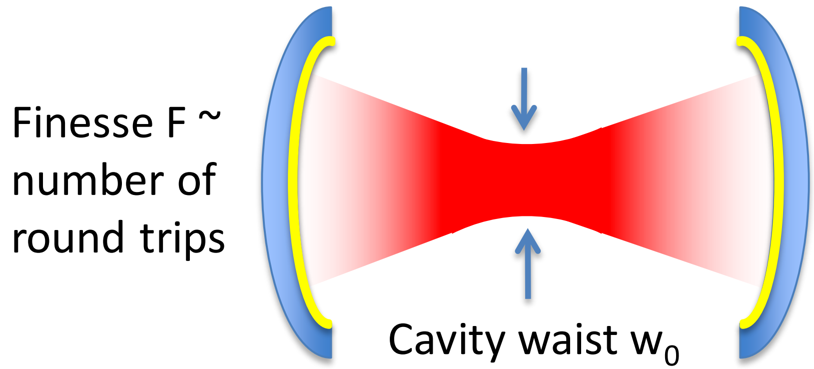


Emission on cavity resonance enhanced by

$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}$$

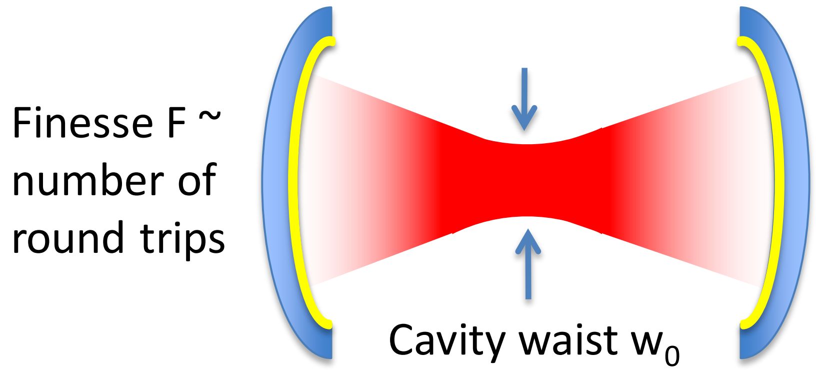
Quality factor

Mode volume

Open geometry Fabry-Perot micro-cavities

External, free-space cavities

Cavity quantum electrodynamics



Emission on cavity resonance enhanced by

$$F_P = \frac{3}{\pi^3} \frac{\lambda^2}{{w_0}^2} F$$

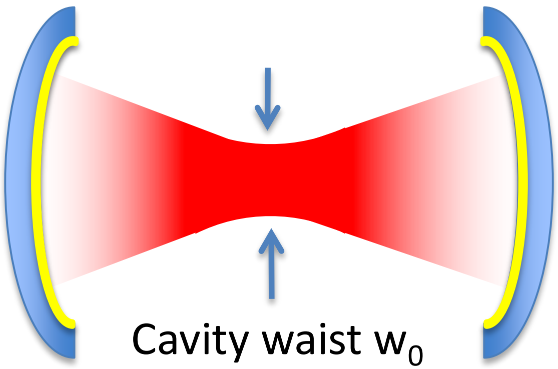
Length drops out

Open geometry Fabry-Perot micro-cavities

External, free-space cavities based on optical fibers

Cavity quantum electrodynamics

Finesse F ~ number of round trips



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External, free-space cavities based on optical fibers

NJP **12**, 065038 (2010)

w_0 ~ few λ
F > 10^5
already achieved

F_p ≈ few thousand potentially feasible

Cavity quantum electrodynamics

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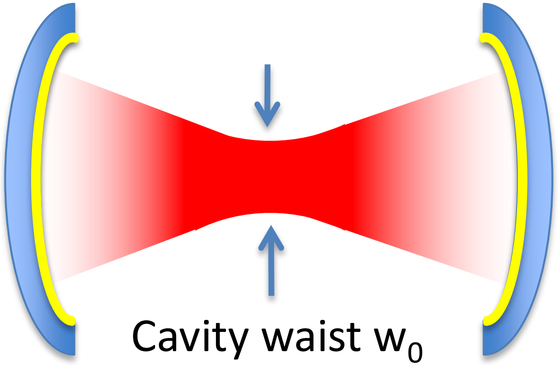

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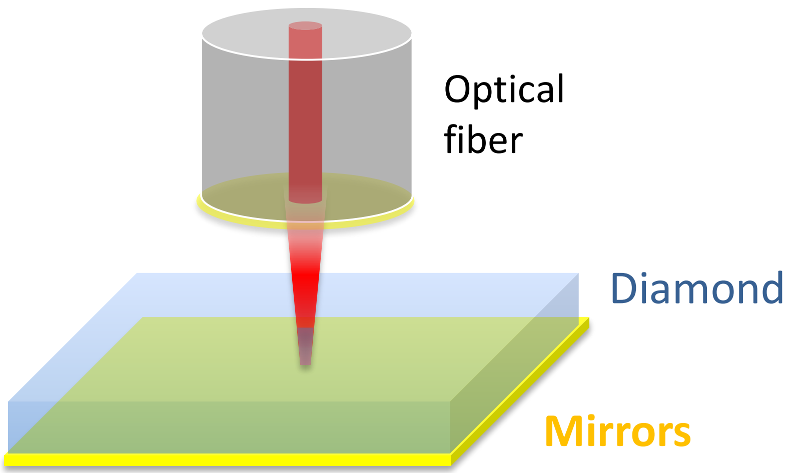

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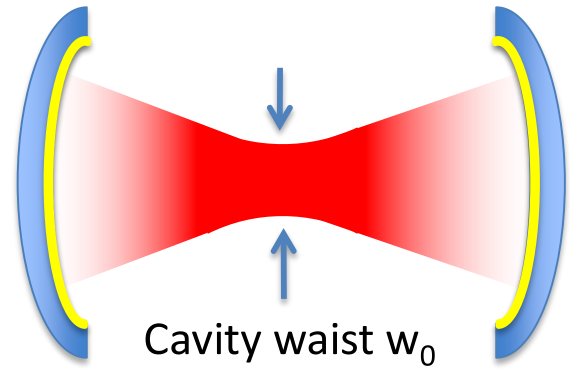

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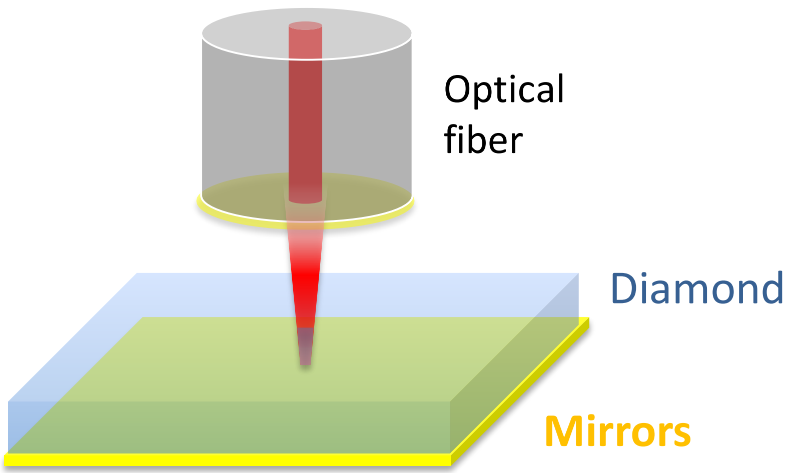

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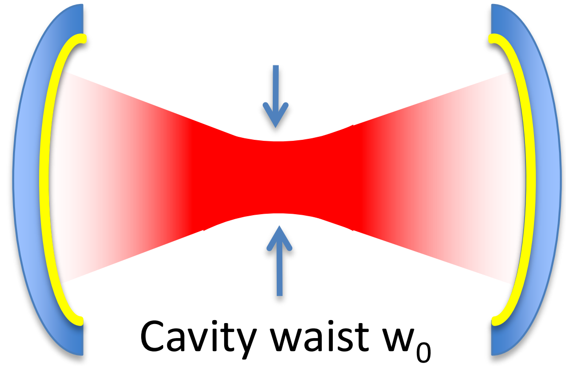

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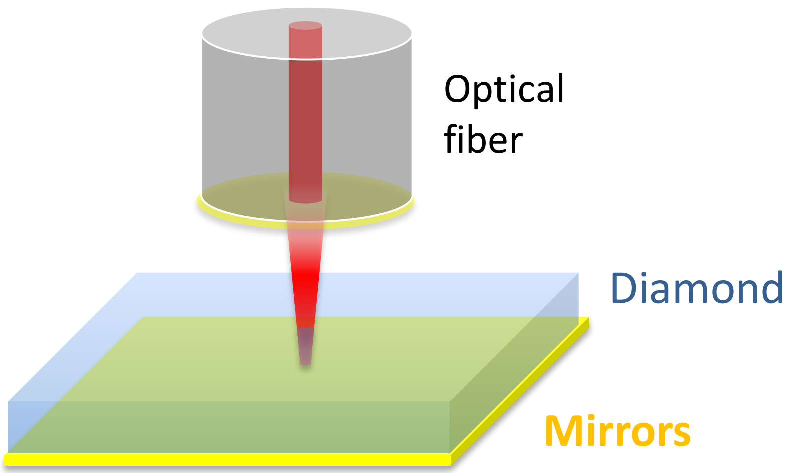

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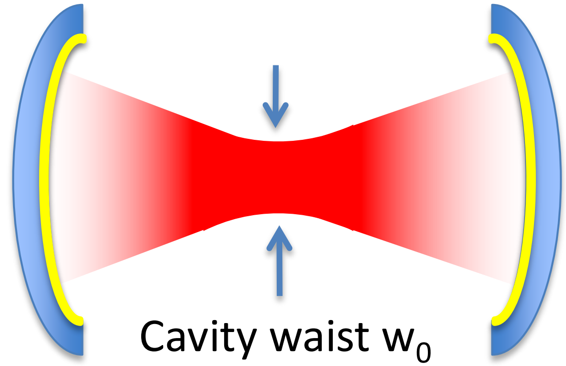

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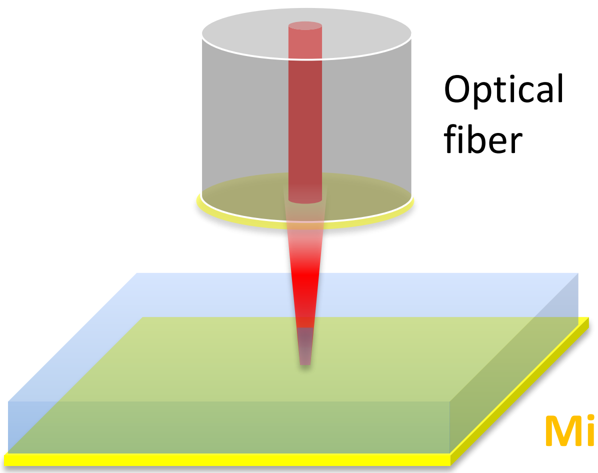

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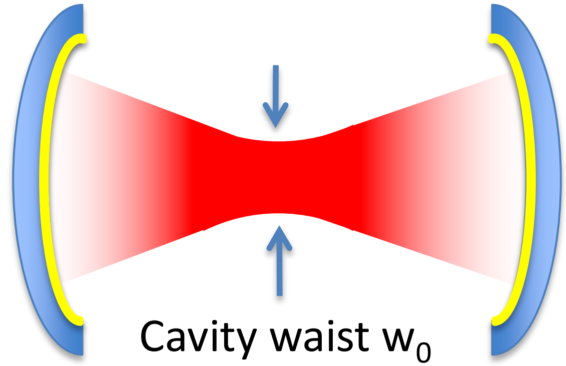

Emission on cavity resonance enhanced by

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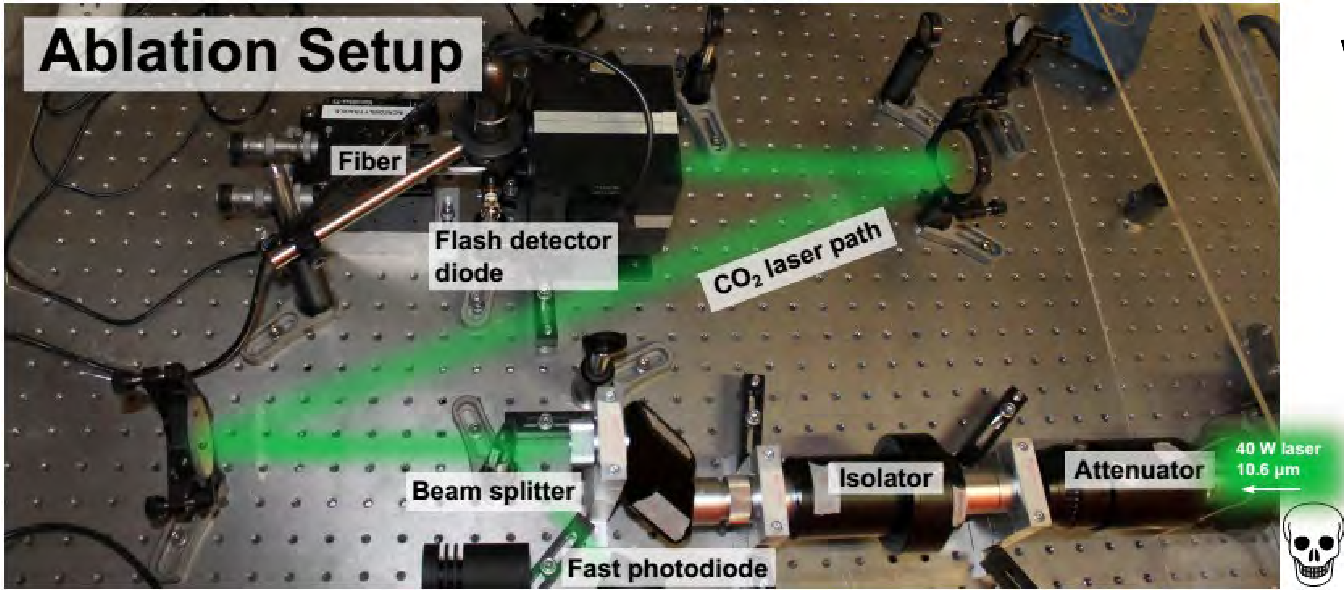
Length drops out

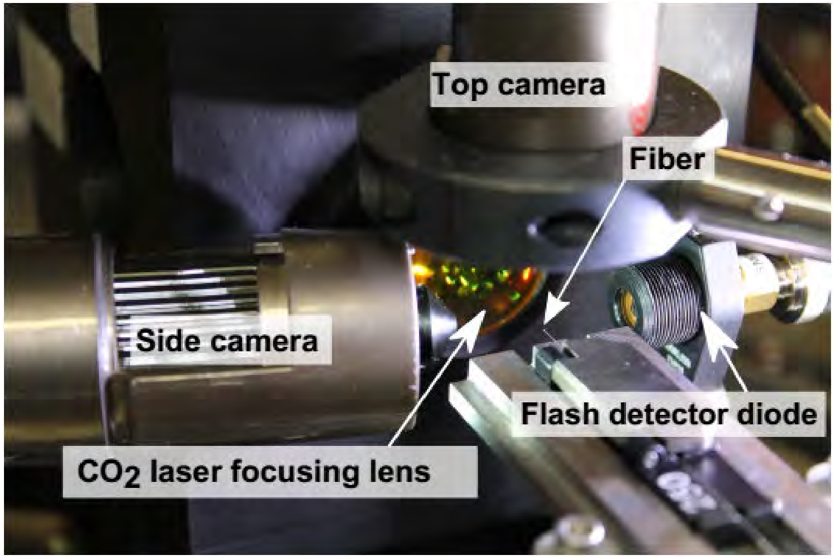
Tunable cavity with excellent out-coupling for collection efficiency
…and potentially cavity quantum electrodynamics

Laser ablation:

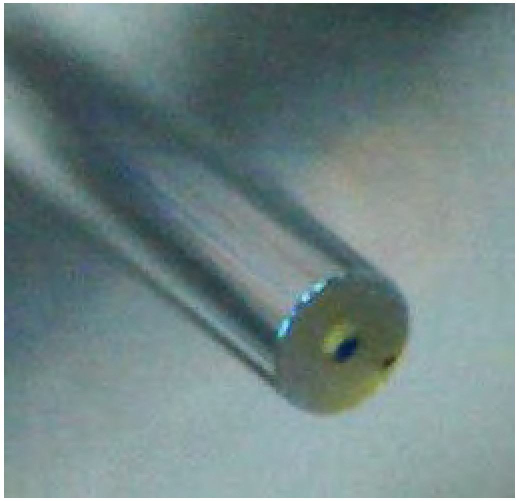


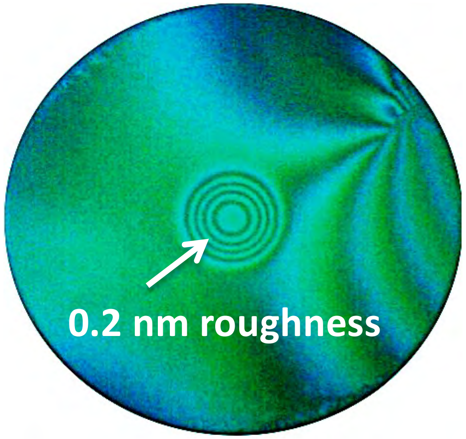
Well-controlled

- laser power
- mode shape
- alignment precision (0.5 microns)



Laser-ablated fiber





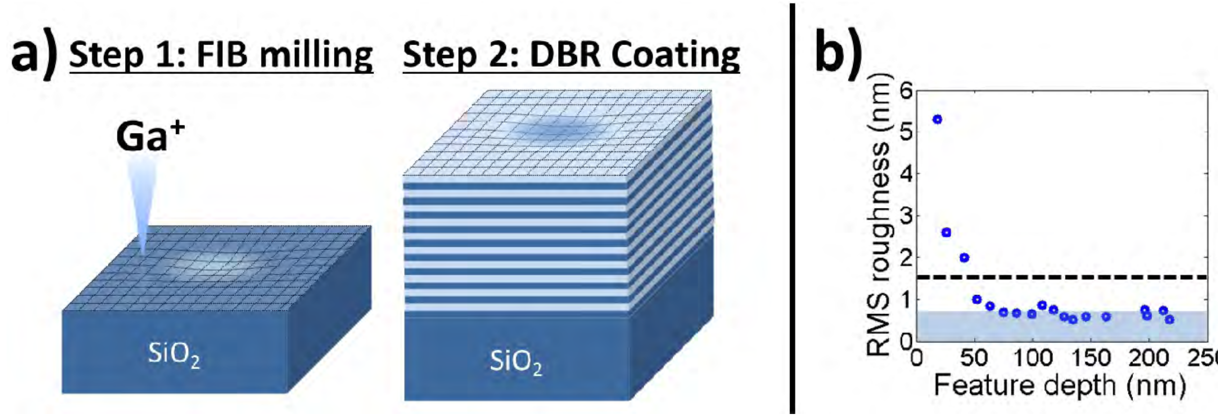
ROC down to ~ 20 μm

For $L \ll ROC$, $F_P \propto 1/\sqrt{ROC}$

Alternate approaches:

FIB milling

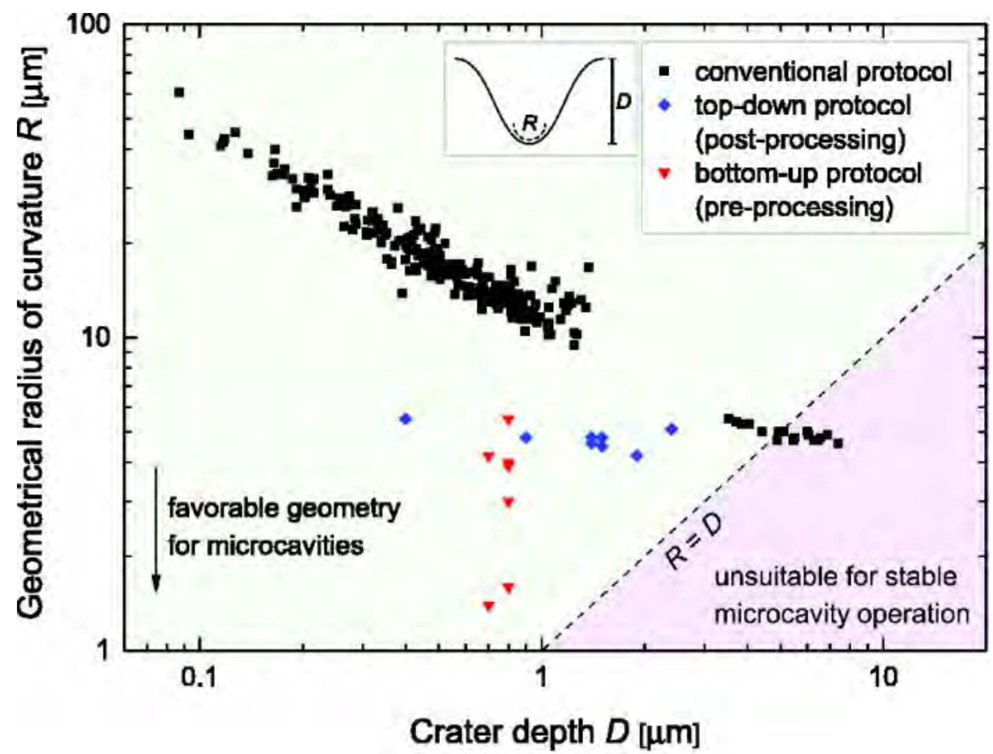
Effective ROC
down to 4.3 μm



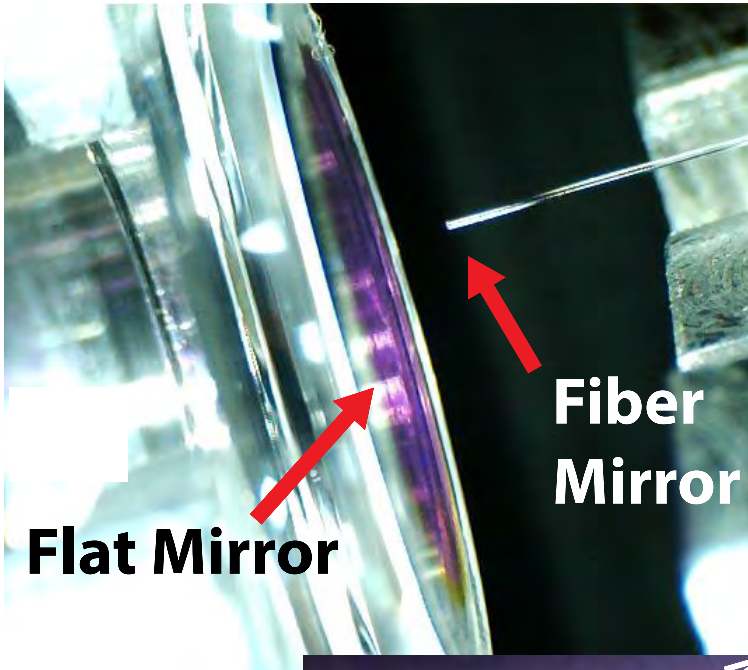
Opt. Express **23**, 17205-17216 (2015) (Smith group) https://www.osapublishing.org/oe/abstract.cfm?uri=oe-23-13-17205

Combine photolithography with CO_2 laser ablation:

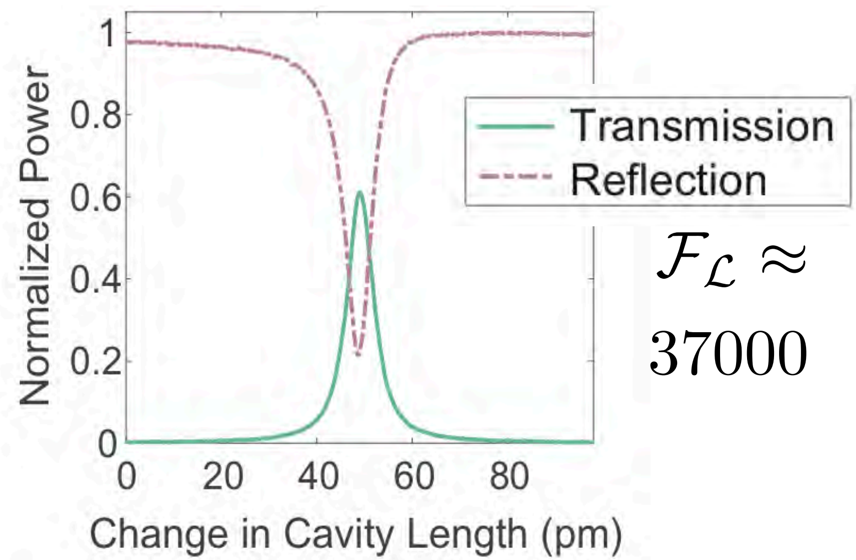
Appl. Phys. Lett. **110,** 011101 (2017) (Warburton group)



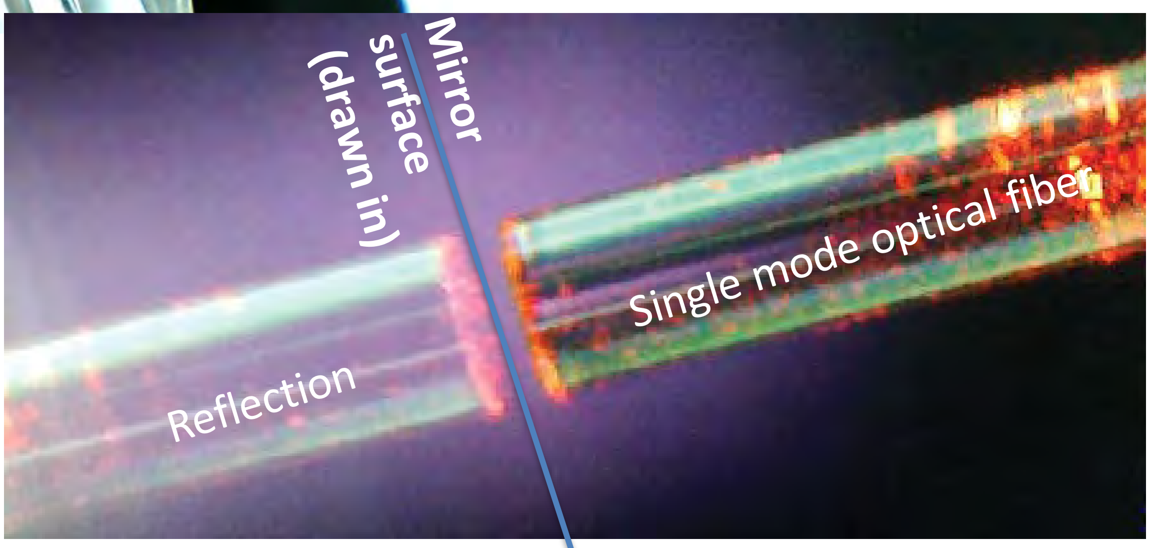
Building fiber cavities:



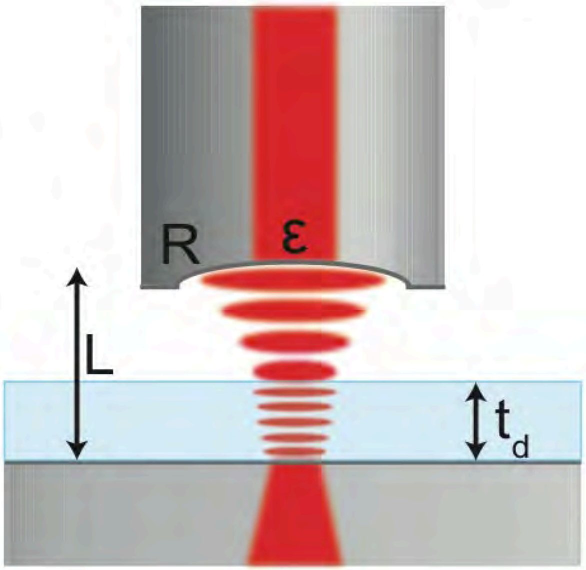
Bare cavity:

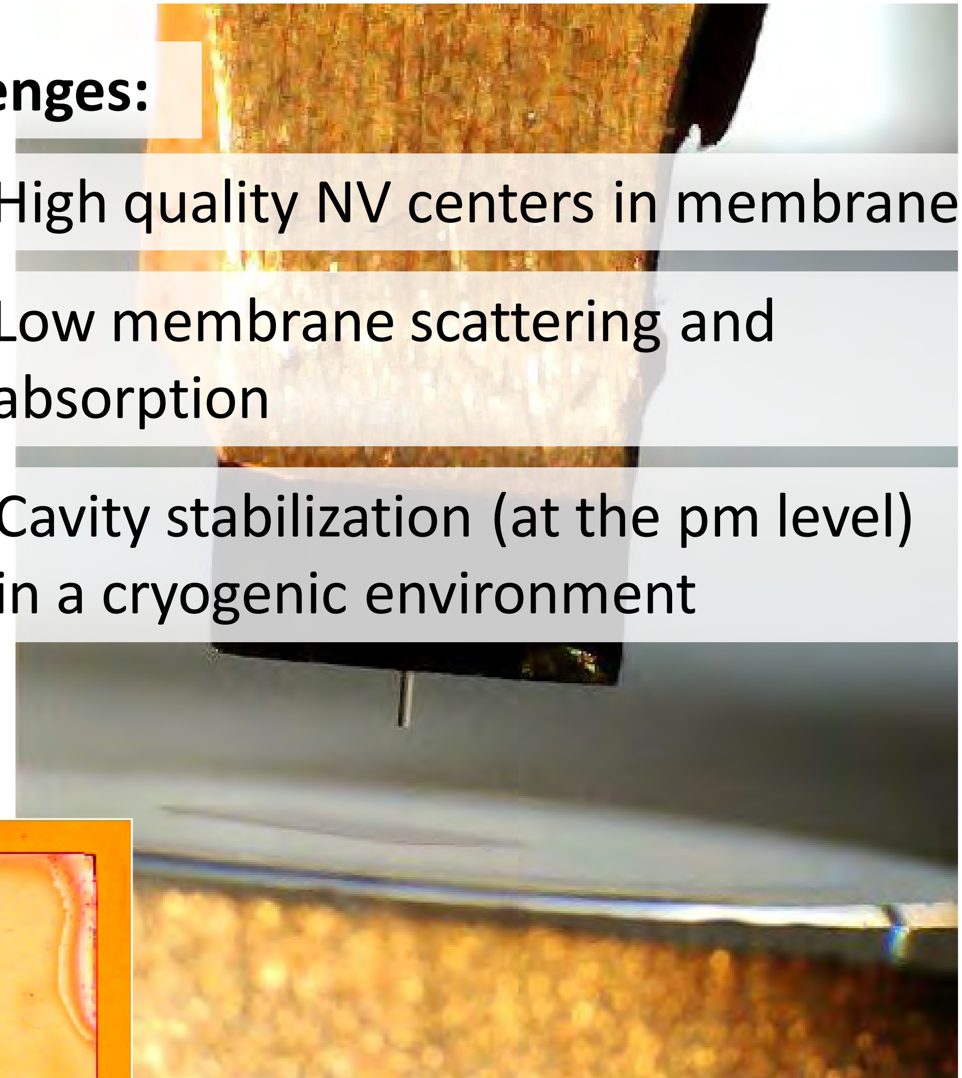


$$\mathcal{F}_{\mathcal{L}} \approx 37000$$



Membrane-in-cavity system

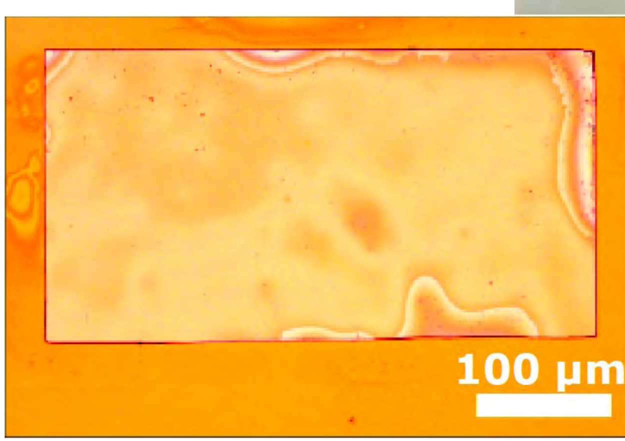




Challenges:

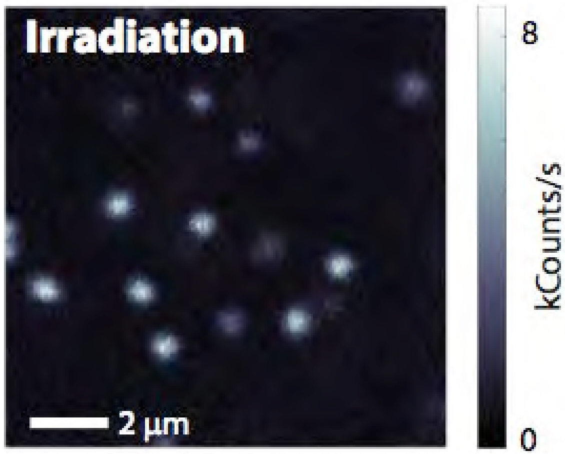
- High quality NV centers in membranes
- Low membrane scattering and absorption
- Cavity stabilization (at the pm level) in a cryogenic environment

Membrane bonded by van der Waals forces



I. NVs in membranes

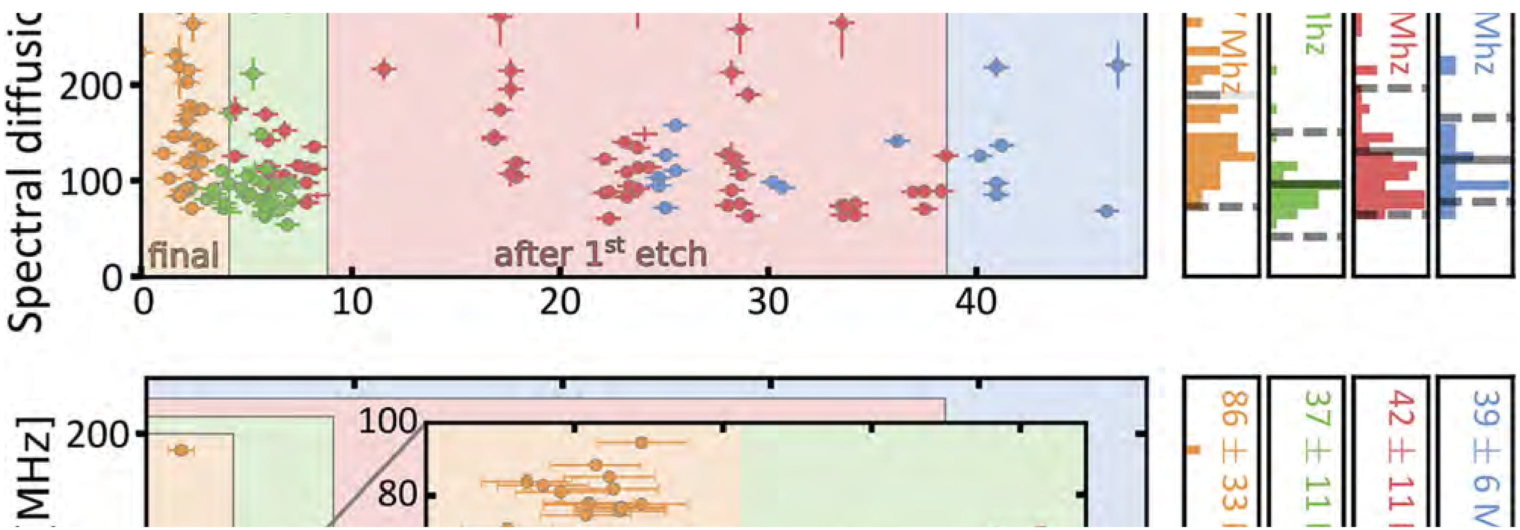
Idea: work with few-micron thick membranes, electron irradiated, sliced, $ArCl_2$ / O_2 etched



- Single-scan linewidths as low as 25 MHz (TU Delft measurement on our irradiated sample)
- Spectral diffusion ~ 300 MHz (average)

=> Comparable to results in bulk electronic-grade samples

More detailed study (TU Delft):



Nano Letters **19**, 3987 (2019), TU Delft

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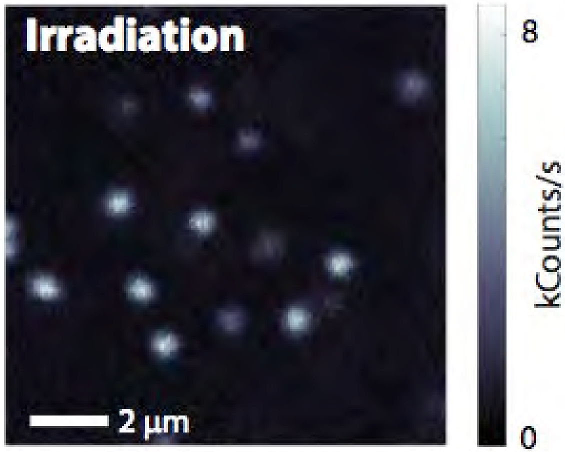

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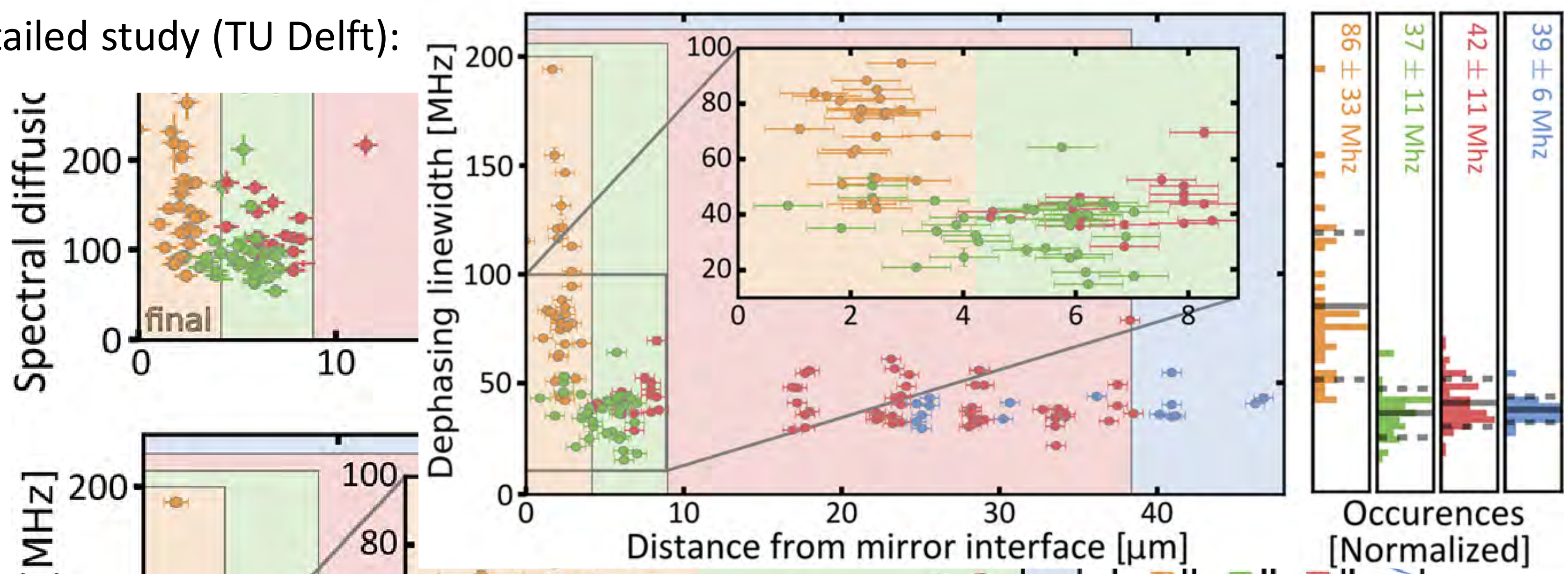

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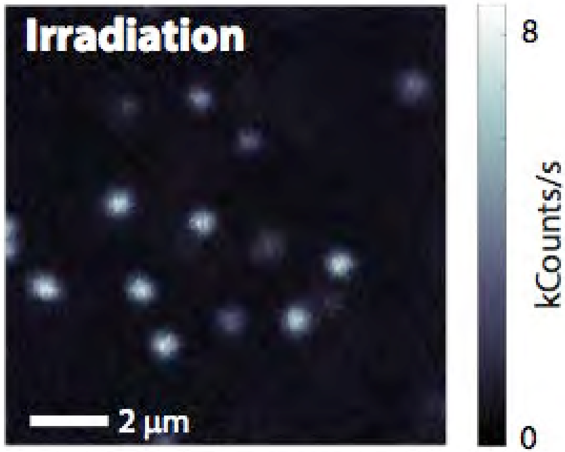

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=> Comparable to results in bulk electronic-grade samples down to ~ few μm

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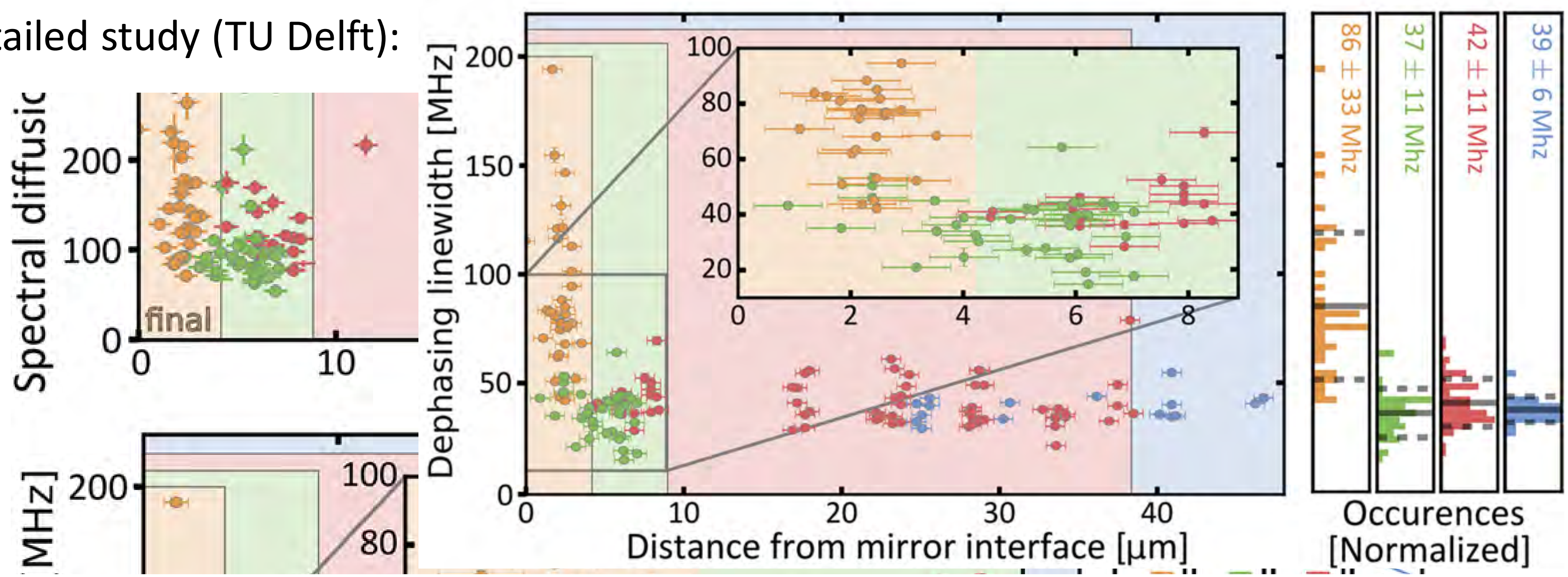
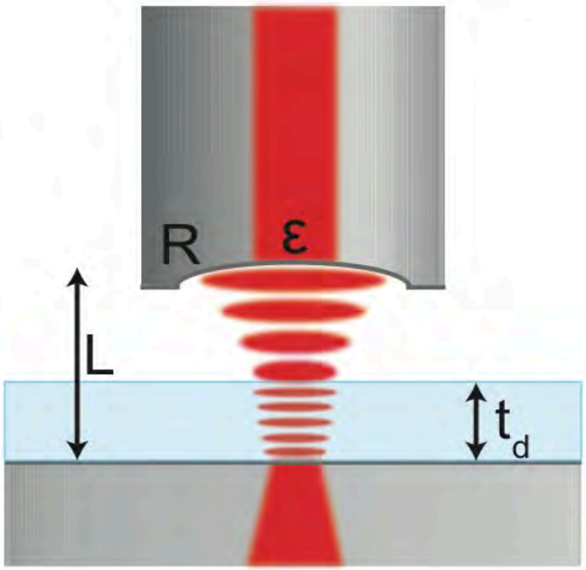


Nano Letters **19**, 3987 (2019), TU Delft

II. Membrane losses



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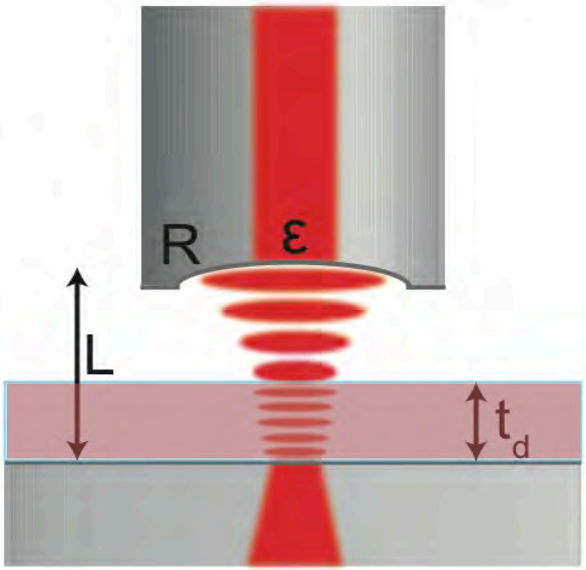

- Bulk optical absorption

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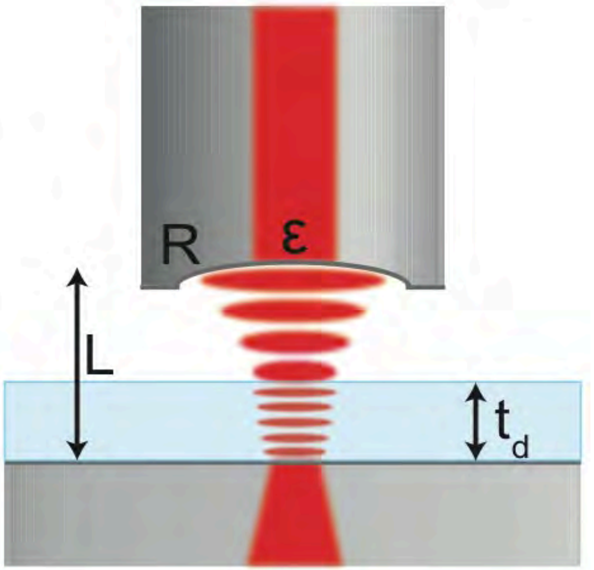

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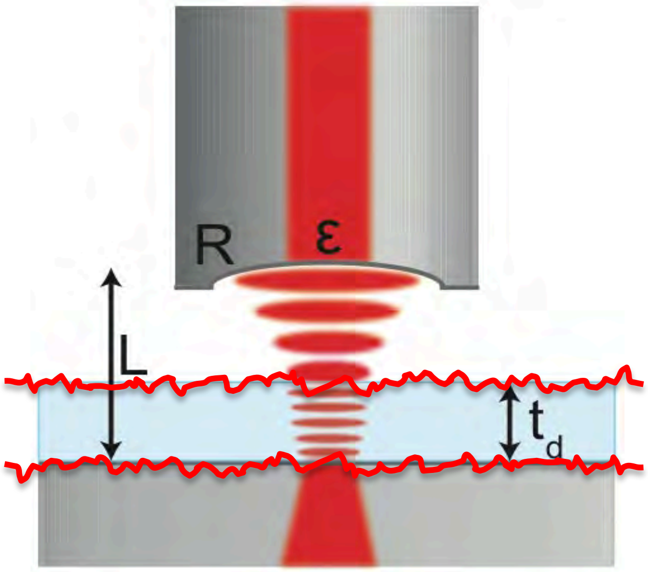

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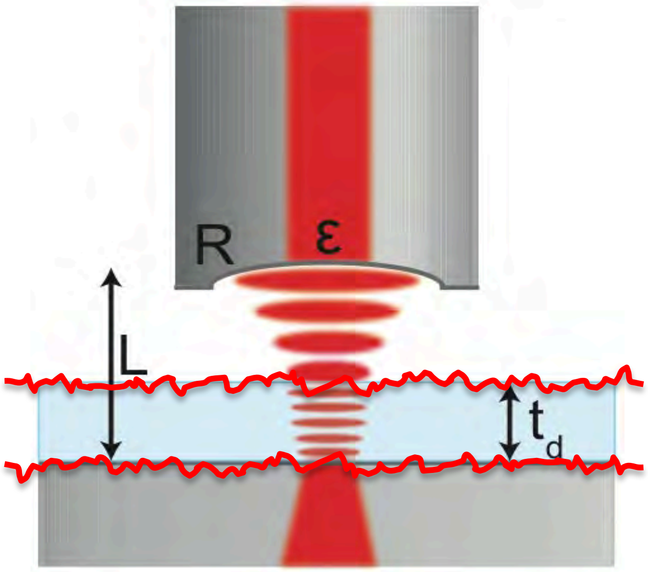

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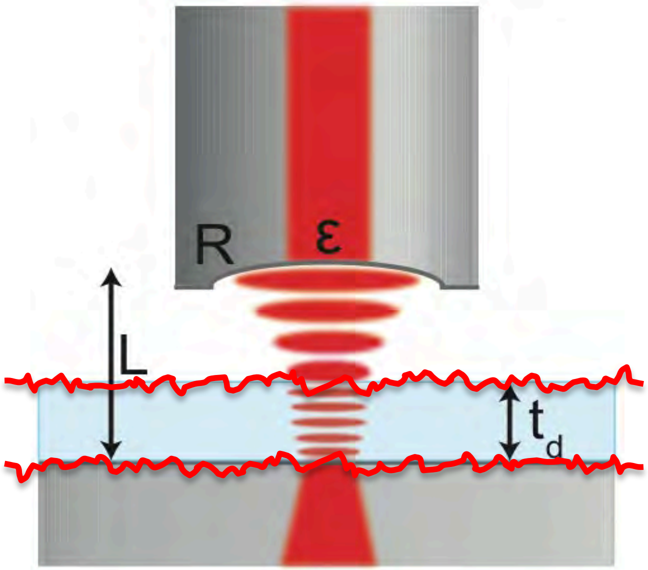

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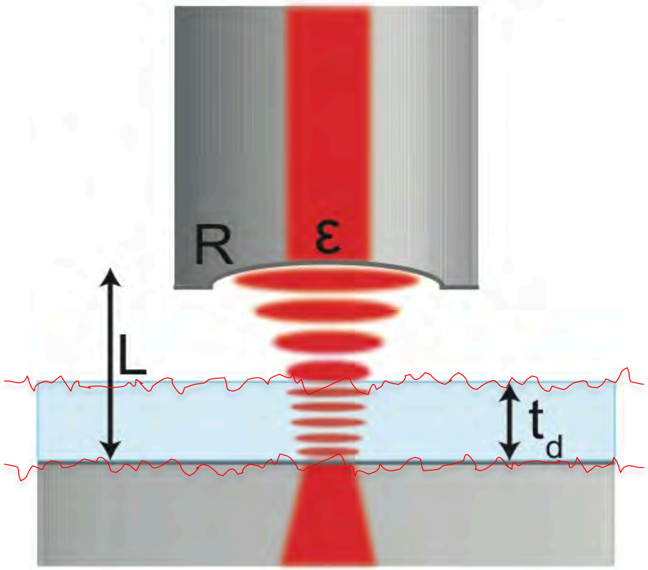

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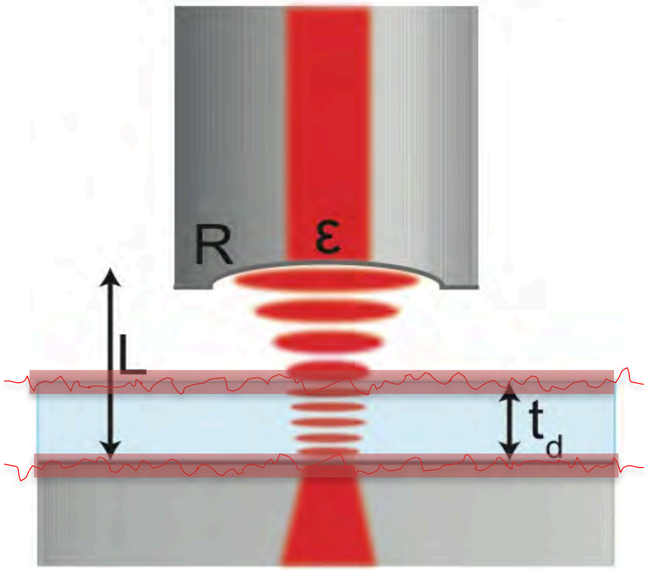

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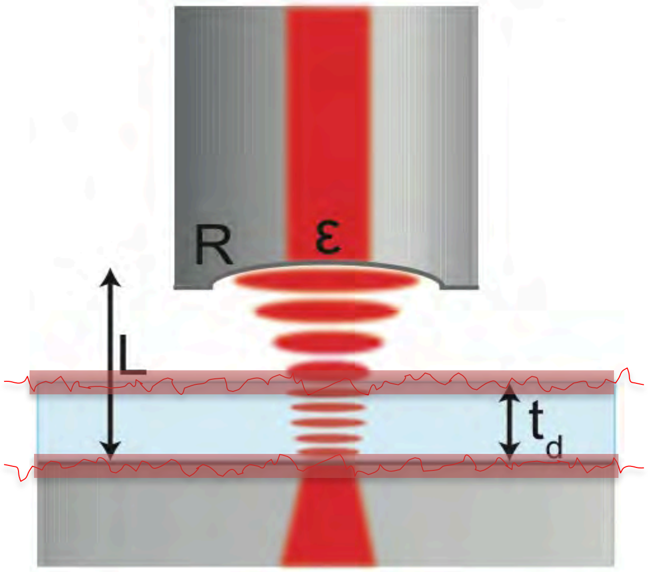

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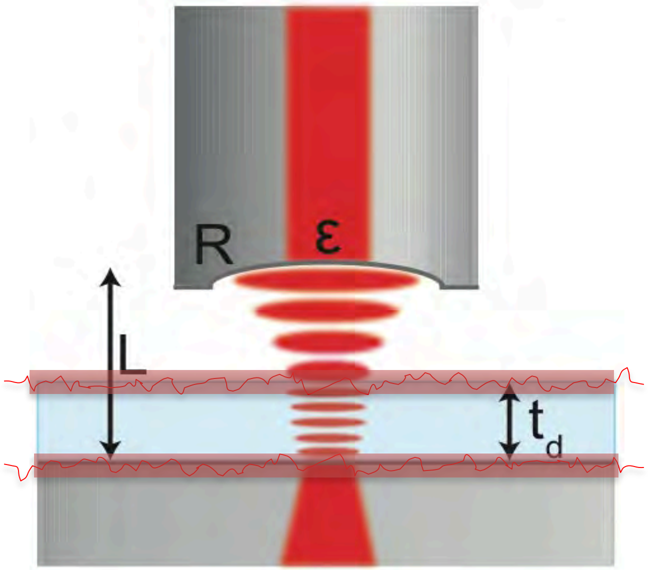

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Distinguishing bulk from surface losses:

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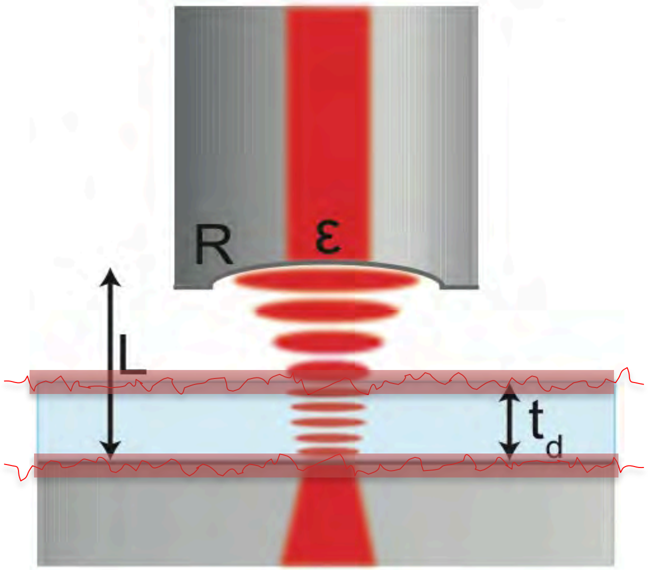

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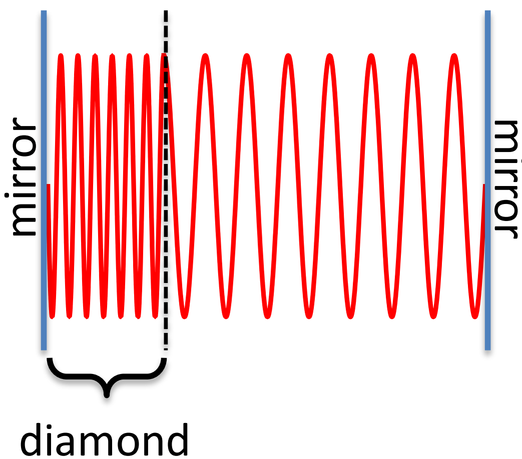

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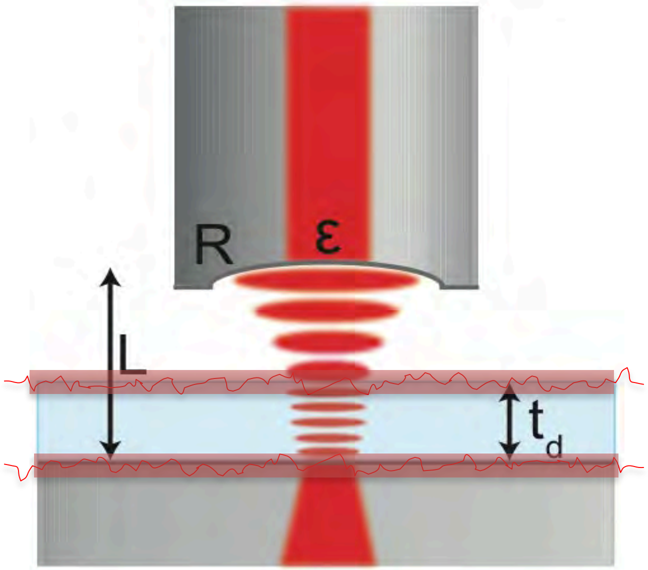

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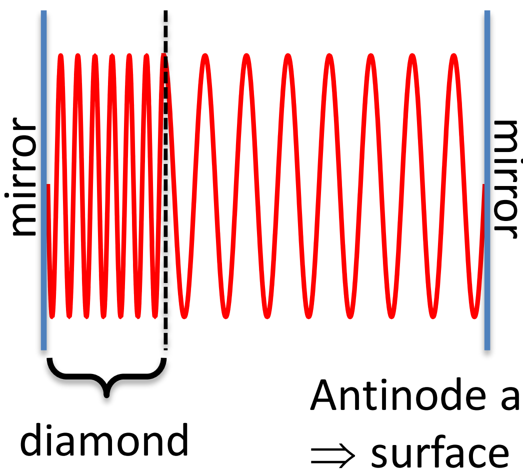
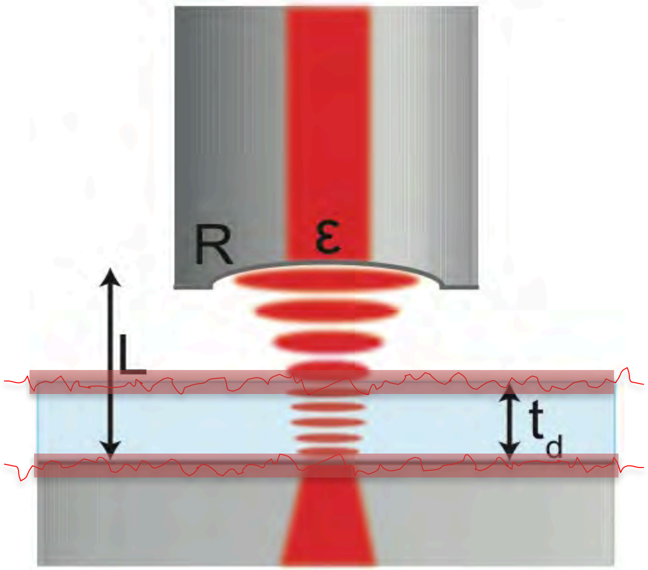


Antinode at surface

⇒ surface losses matter more!

⇒ Lower finesse

II. Membrane losses



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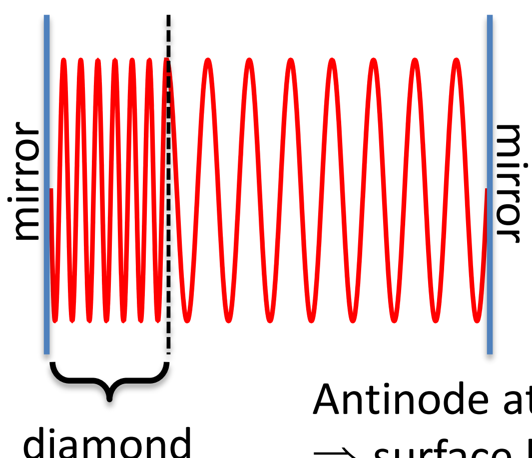
Distinguishing bulk from surface losses:

Slightly different diamond thickness
or resonant wavelength



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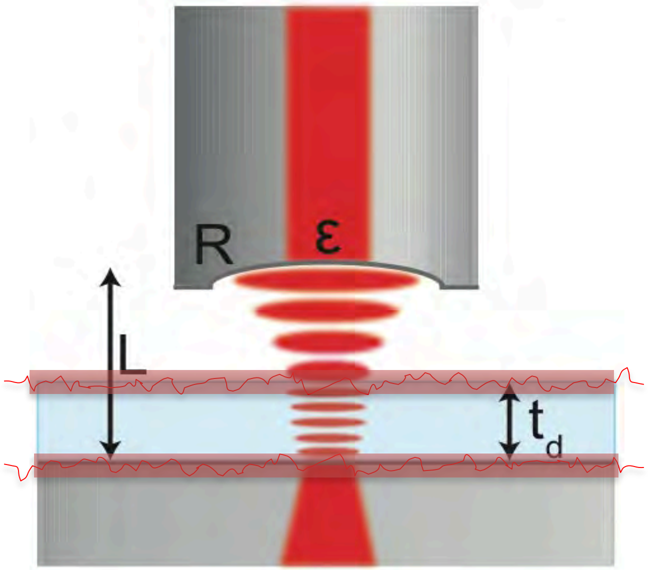

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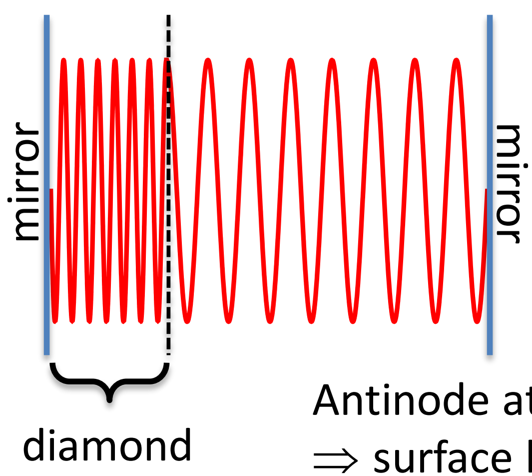

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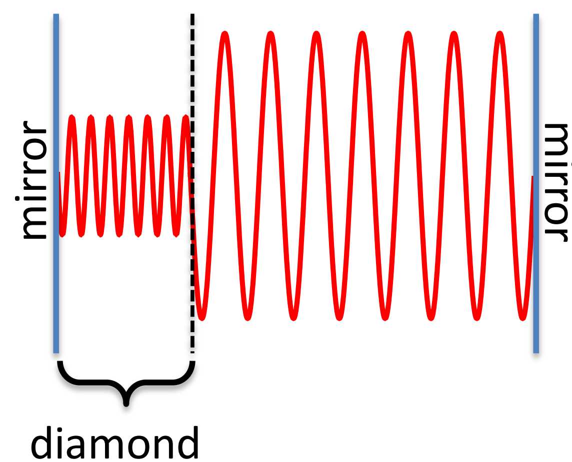

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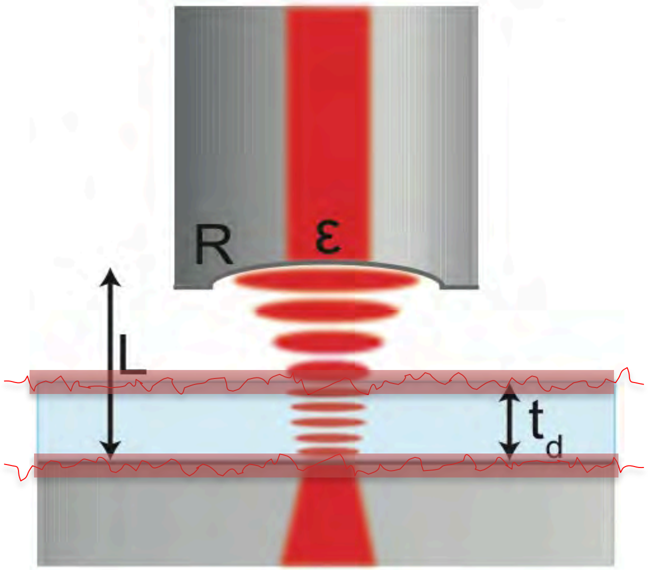

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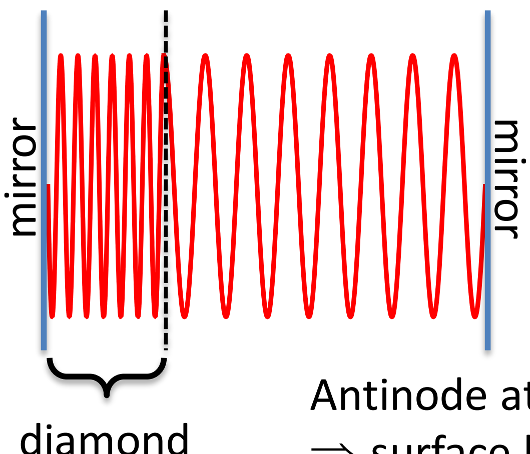

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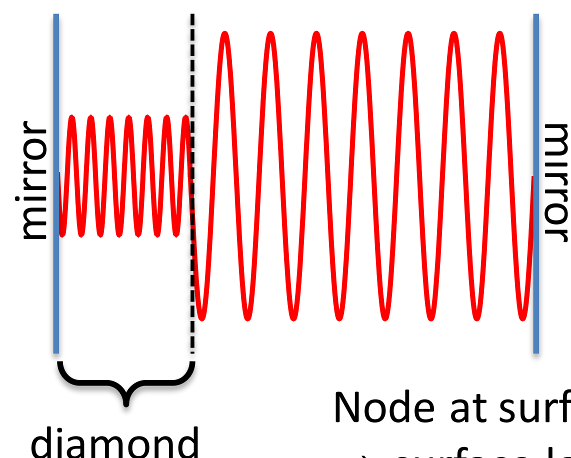

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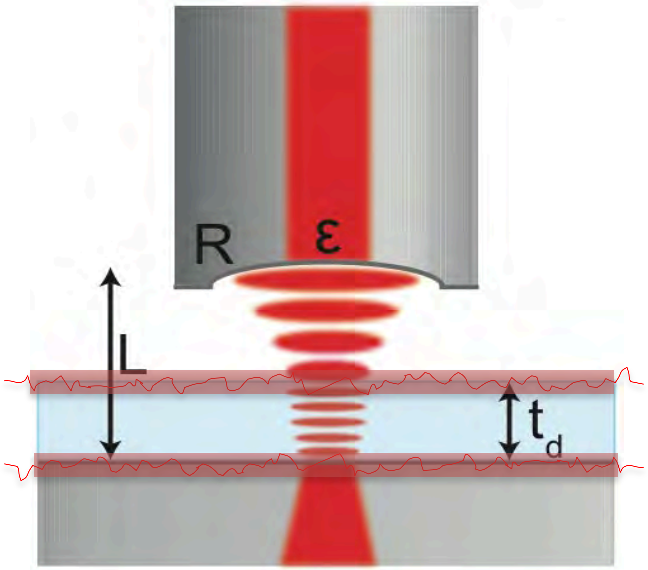
II. Membrane losses



- Bulk optical absorption negligible
- Surface roughness

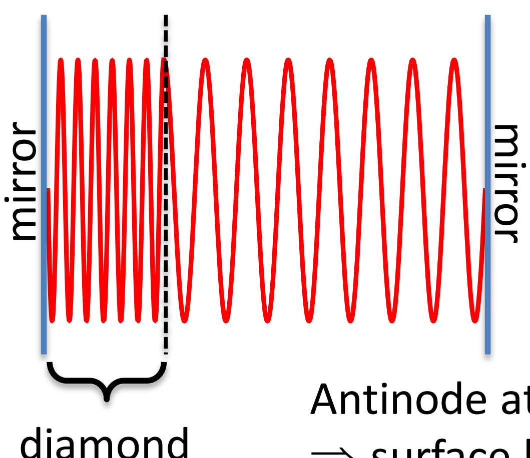
  $ArCl_2$ etch → as low as 0.2 nm rms

  $\left(\frac{4\pi\sigma}{\lambda}\right)^2 \sim 15$ ppm   << 70 ppm mirror transmission
- Surface absorption/contamination

  seems to be the limiting factor

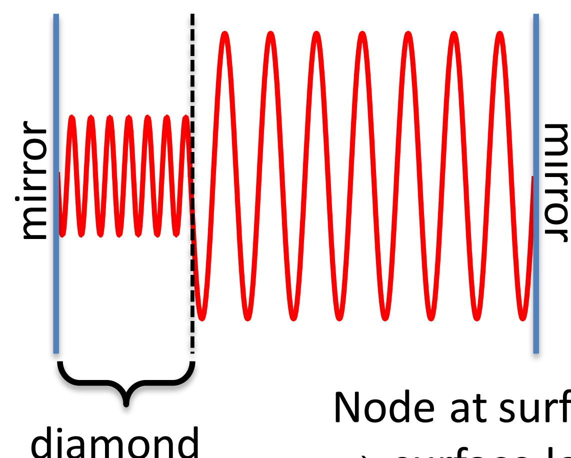
Distinguishing bulk from surface losses:

Slightly different diamond thickness
or resonant wavelength



"diamond-like
mode"

Antinode at surface
⇒ surface losses matter more!
⇒ Lower finesse



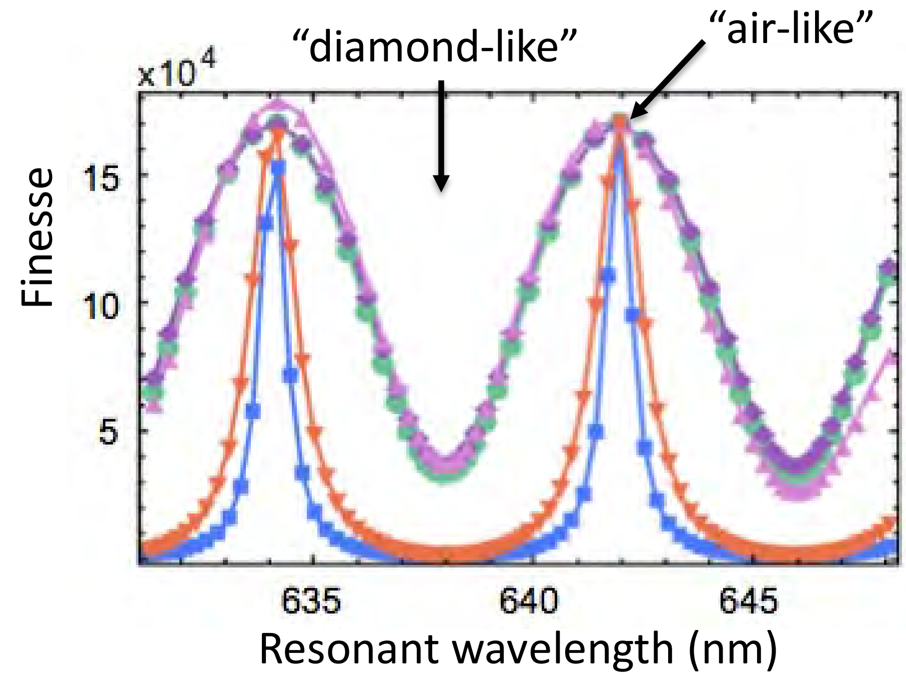
"air-like
mode"

Node at surface
⇒ surface losses matter less!
⇒ Higher finesse

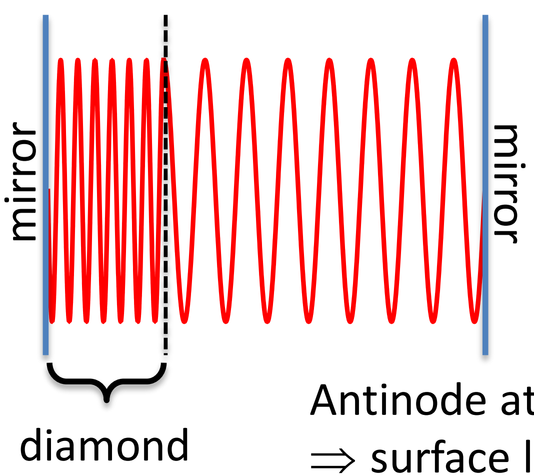
Membrane losses

Calculation of cavity finesse with

- Diamond Absorption
- Scattering at Diamond-Air Interface
- Mirror Losses
- Scattering at Mirror-Diamond Interface
- Best Guess



Distinguishing bulk from surface losses:



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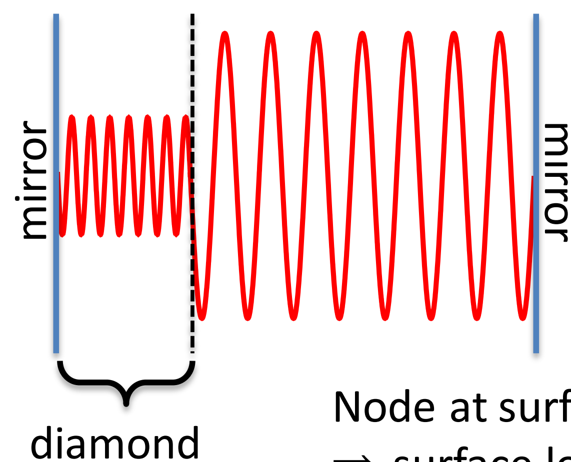
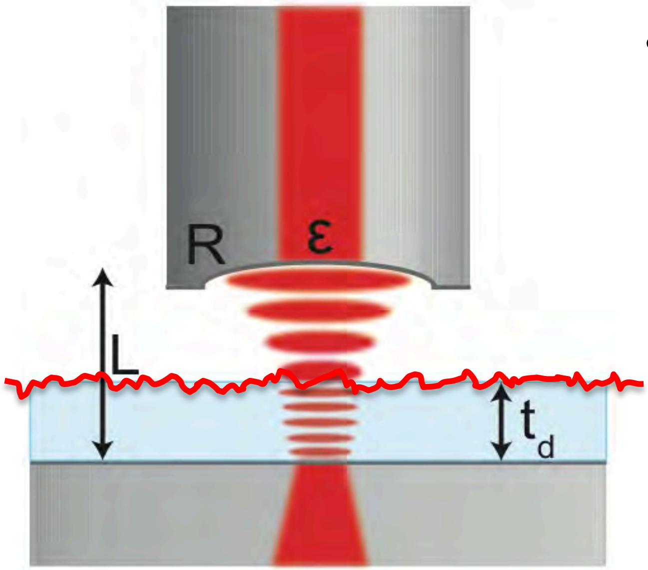


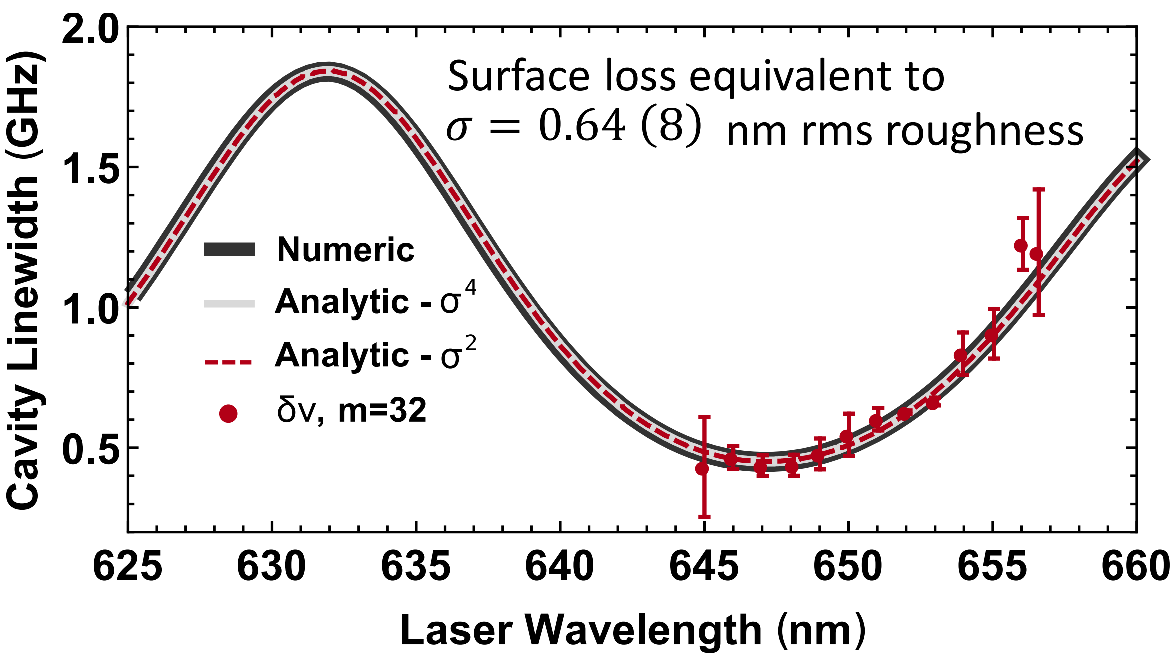
"air-like mode"

Node at surface
⇒ surface losses matter less!
⇒ Higher finesse

Surface losses



- Improved etching techniques ($ArCl_2 + O_2$) => reduced surface losses



- Results inconsistent with AFM results of $\sigma \approx 0.25$ nm-rms
  => surface absorption/contamination
- Can now see finesse > 10,000 in diamond-like modes (sometimes)

Note the irony…

See also Van Dam et al, NJP 2018

Room temperature cavity coupling

The “bad emitter regime:” coupling phonon broadened emission to fiber cavities

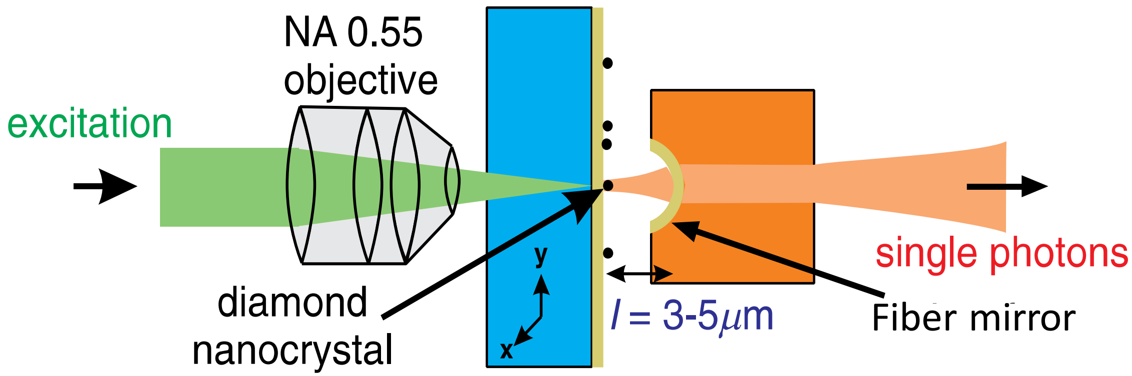
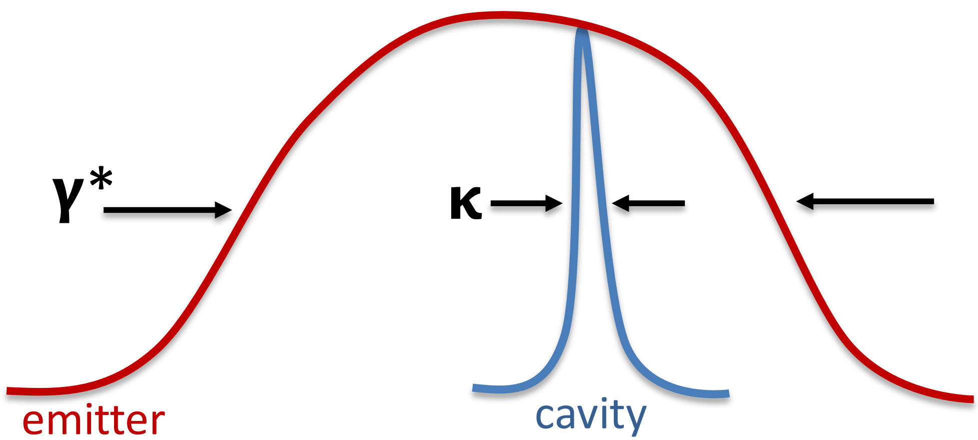


Figure from Albrecht et al PRL 2013

Nanodiamond systems:
Becher, Hunger, Smith



Can generate single photons with greater spectral density

Total photon emission fraction into cavity:

$$\beta \approx \frac{F\kappa}{F\kappa + \gamma^*}$$

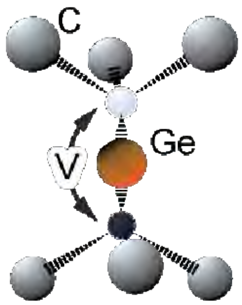
F = purcell factor

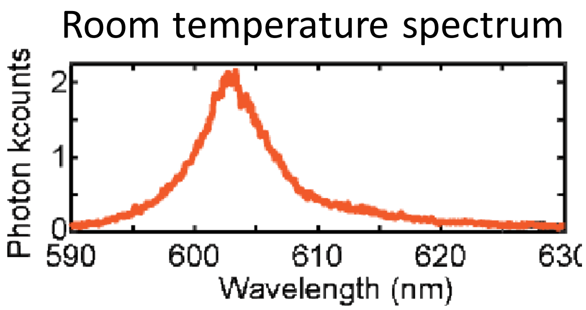
$\propto$ 1/mode volume, independent of finesse

Use to explore cavity coupling to defects in membranes

Room temperature cavity coupling

GeV defects





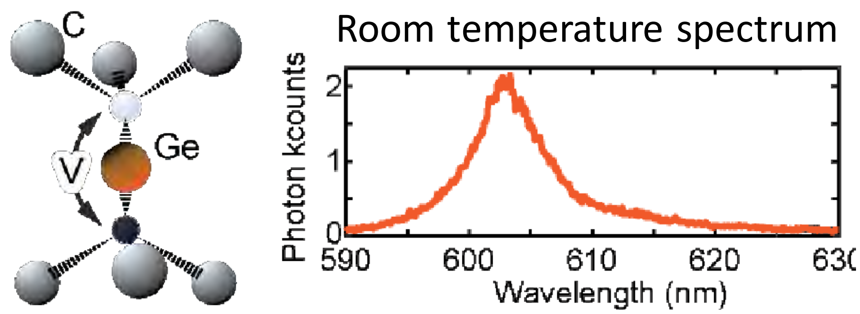
- Much larger ZPL fraction ~60%
- Lower spectral diffusion
- Poor spin coherence
- Quantum yield?

Potentially easier to achieve strong coupling than with NVs

Collaboration with Andersen group, DTU

Room temperature cavity coupling

GeV defects



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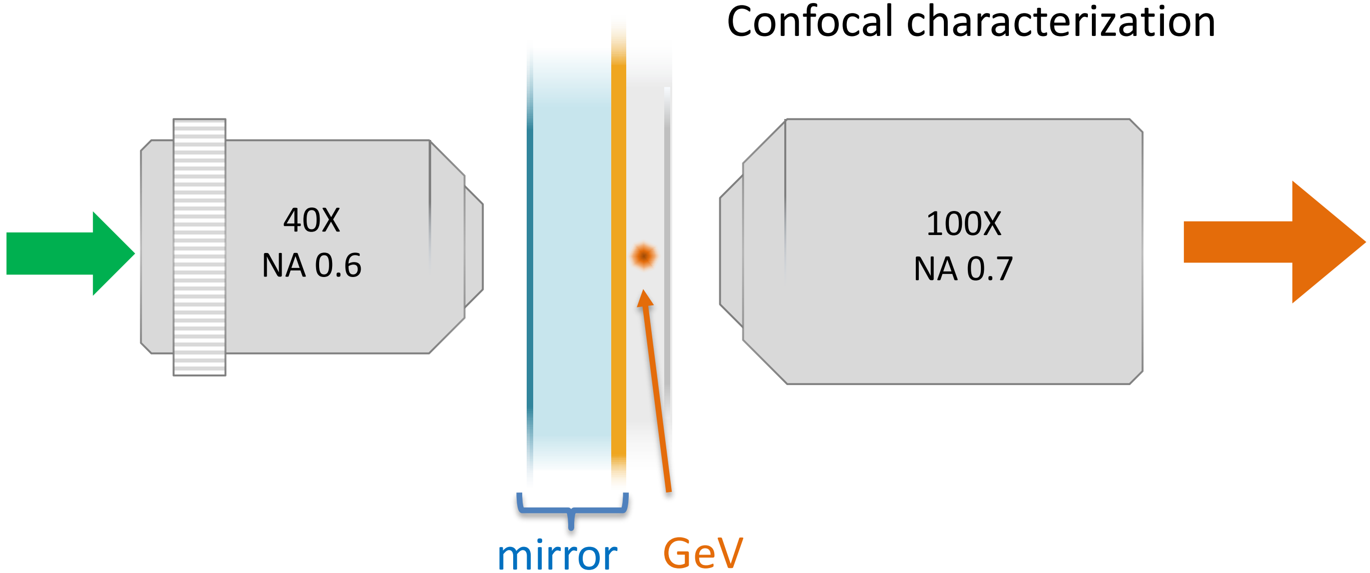
Experimental setup

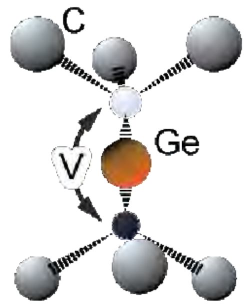
Confocal characterization

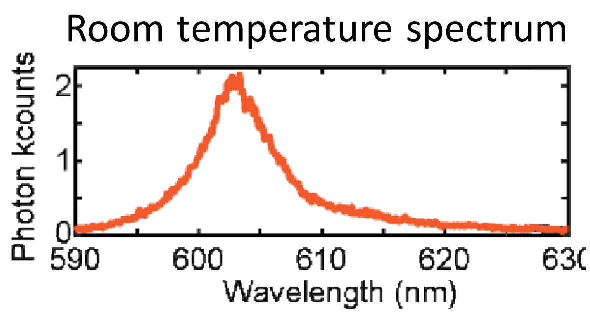


Collaboration with Andersen group, DTU

Room temperature cavity coupling

GeV defects





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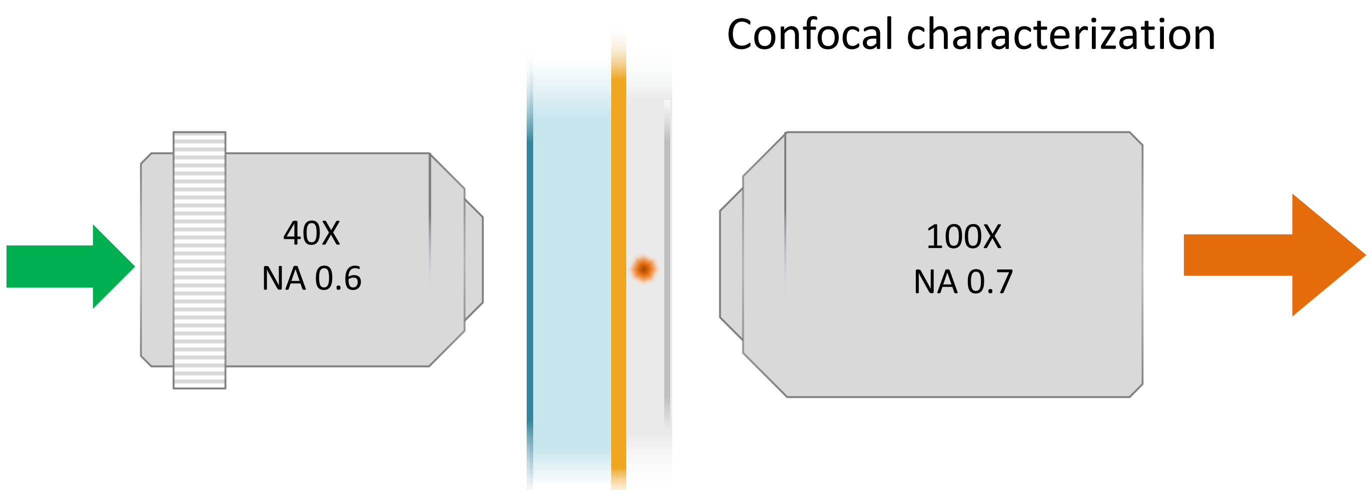
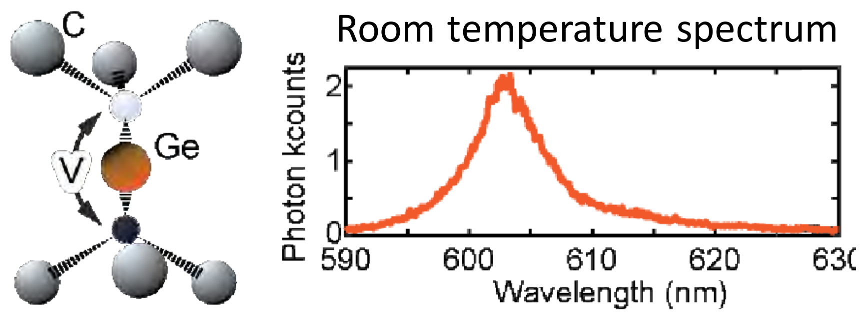


Collaboration with Andersen group, DTU

Room temperature cavity coupling

GeV defects



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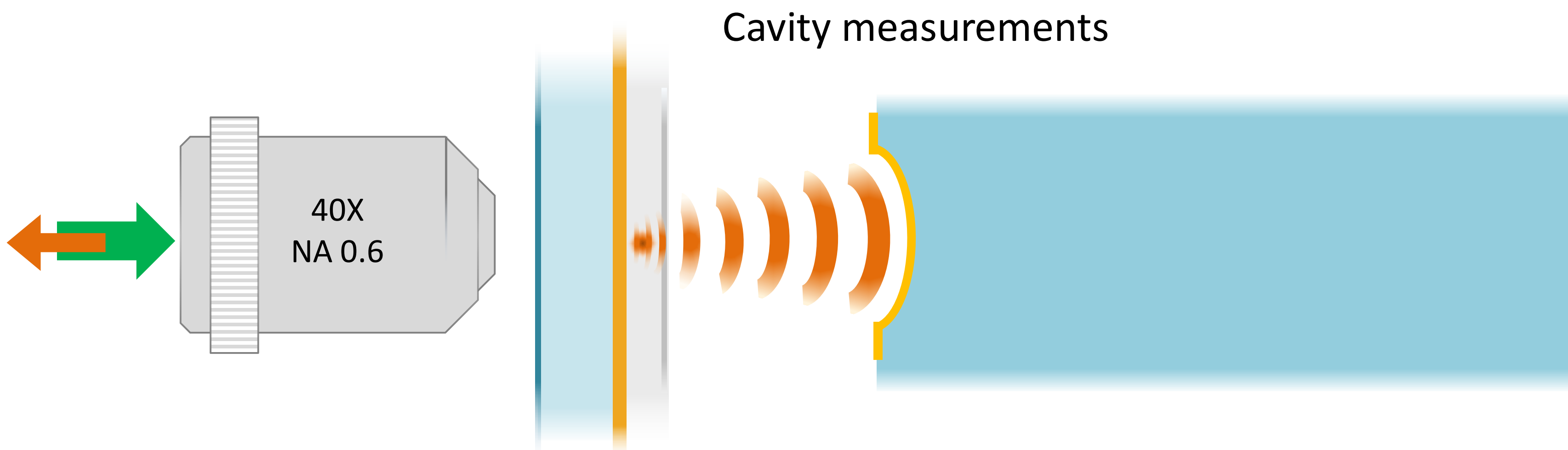
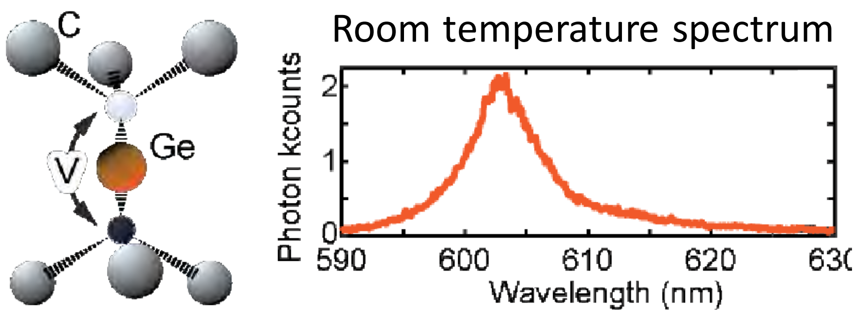


Collaboration with Andersen group, DTU

Room temperature cavity coupling

GeV defects



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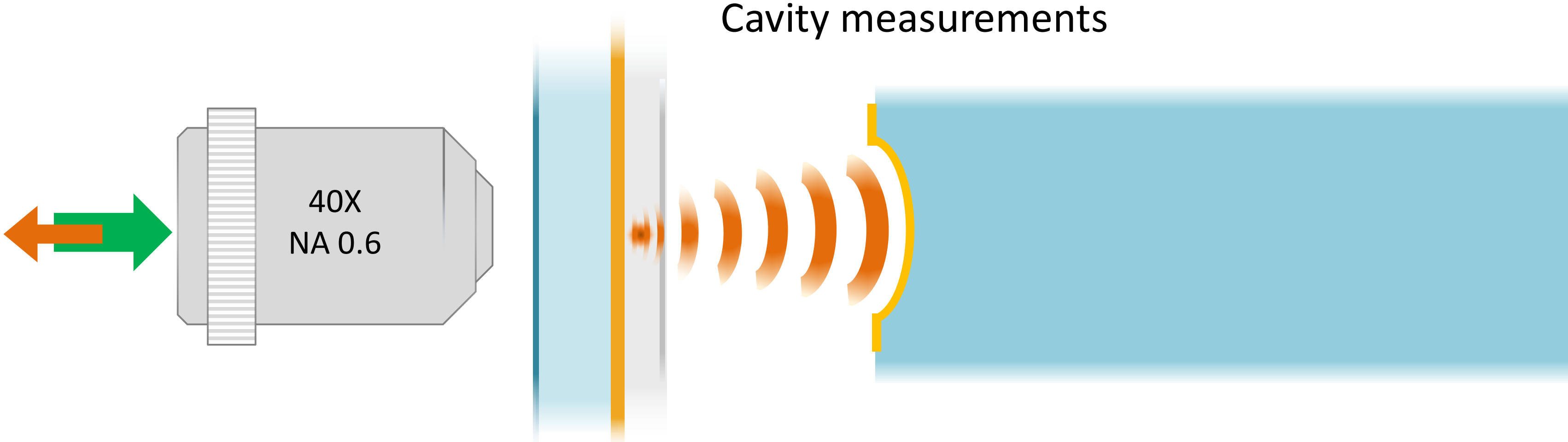
Experimental setup

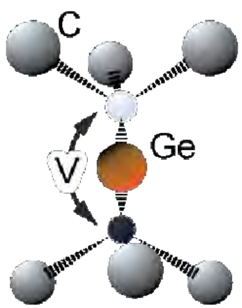
Cavity measurements

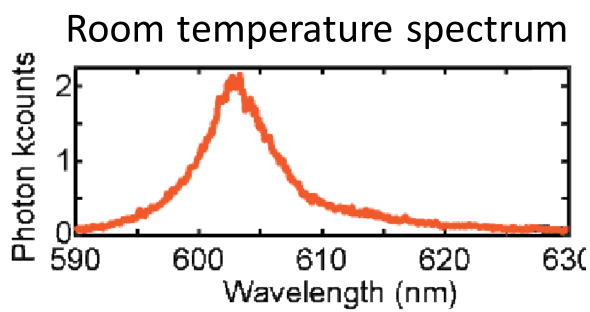


Collaboration with Andersen group, DTU

Room temperature cavity coupling

GeV defects





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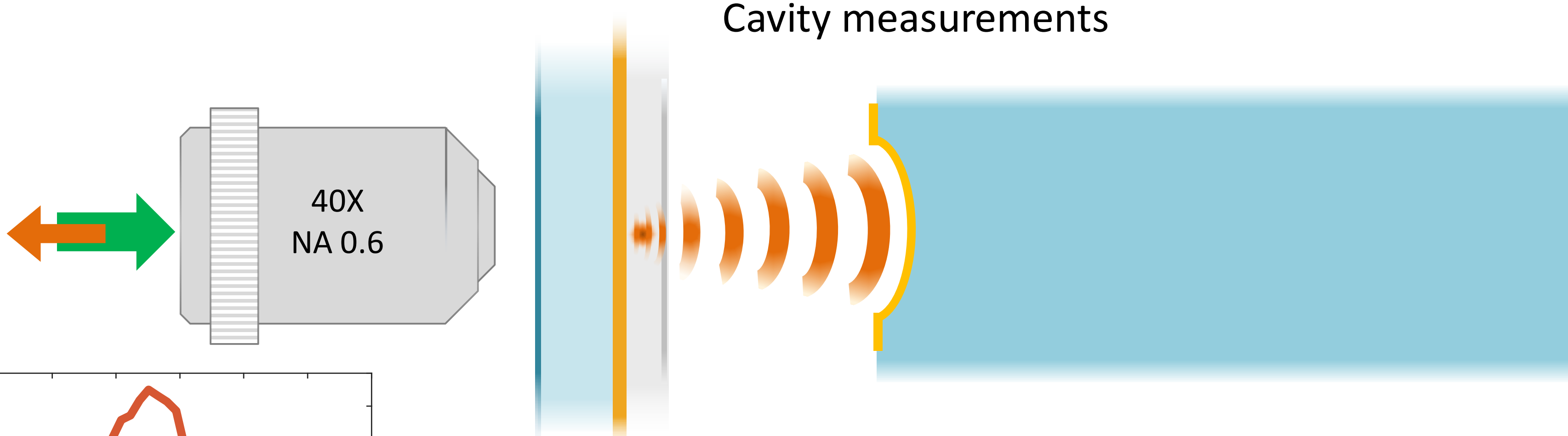
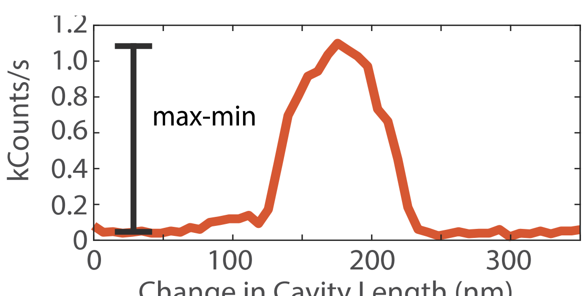
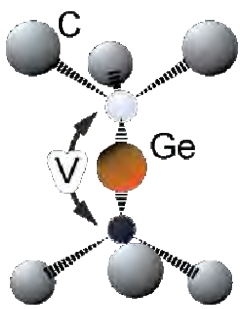


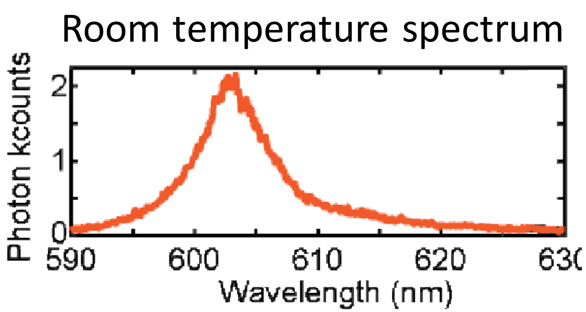


Collaboration with Andersen group, DTU

Room temperature cavity coupling

GeV defects





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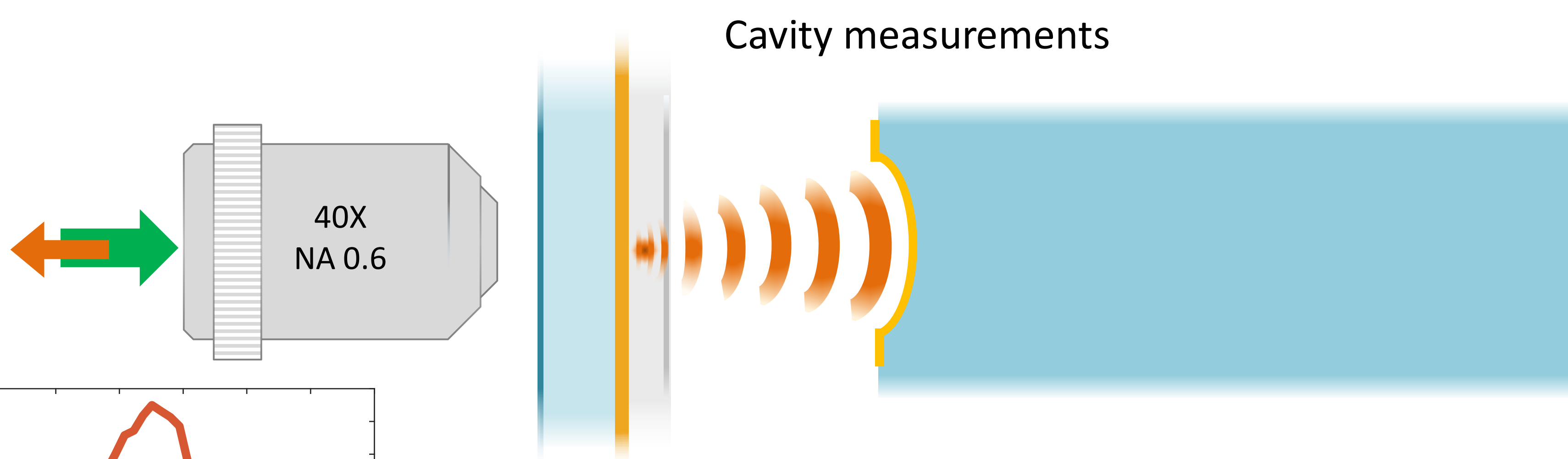
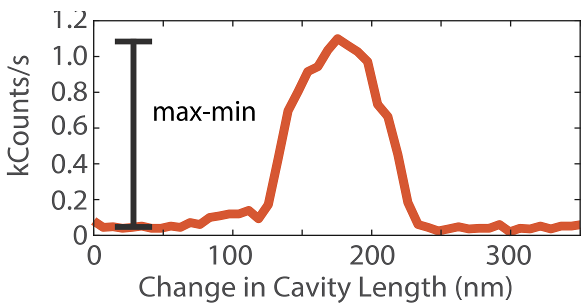
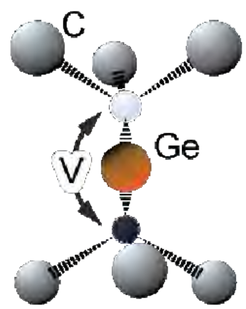


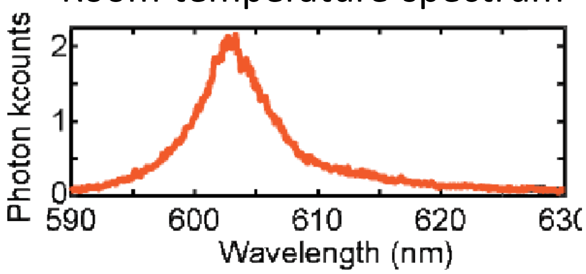


Collaboration with Andersen group, DTU

Room temperature cavity coupling

GeV defects





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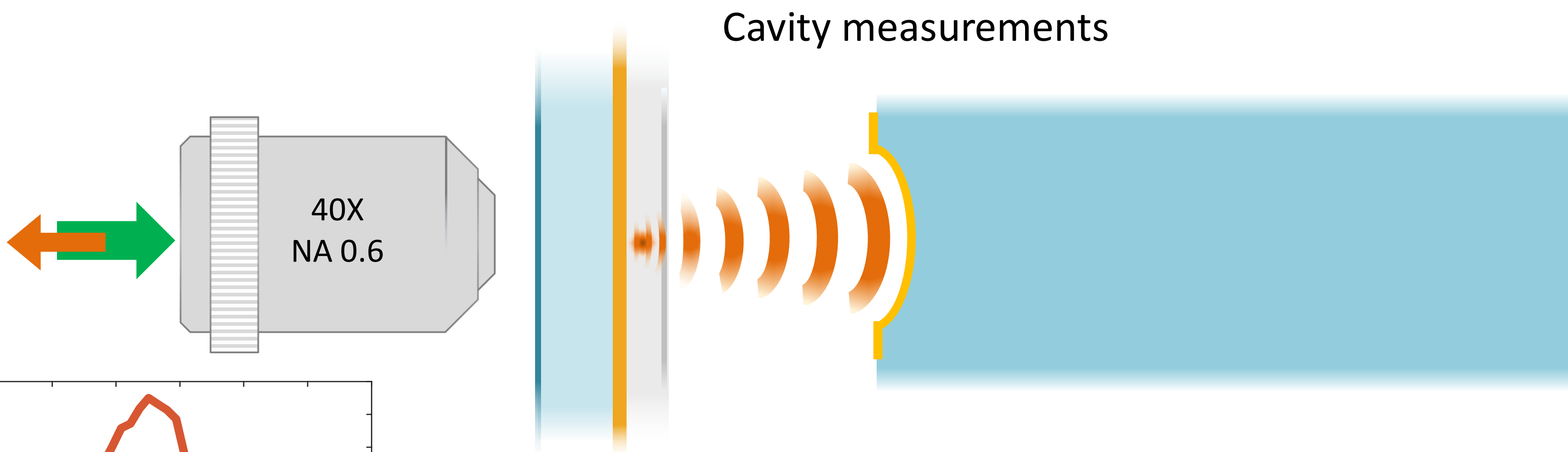
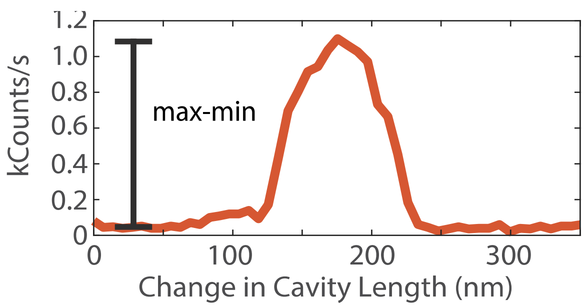
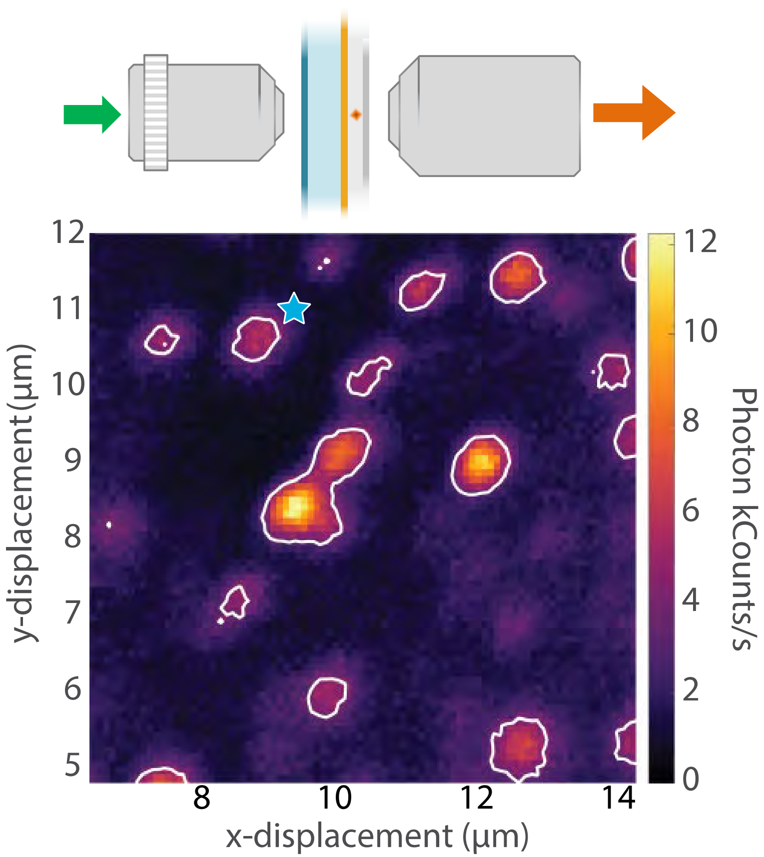




Collaboration with Andersen group, DTU

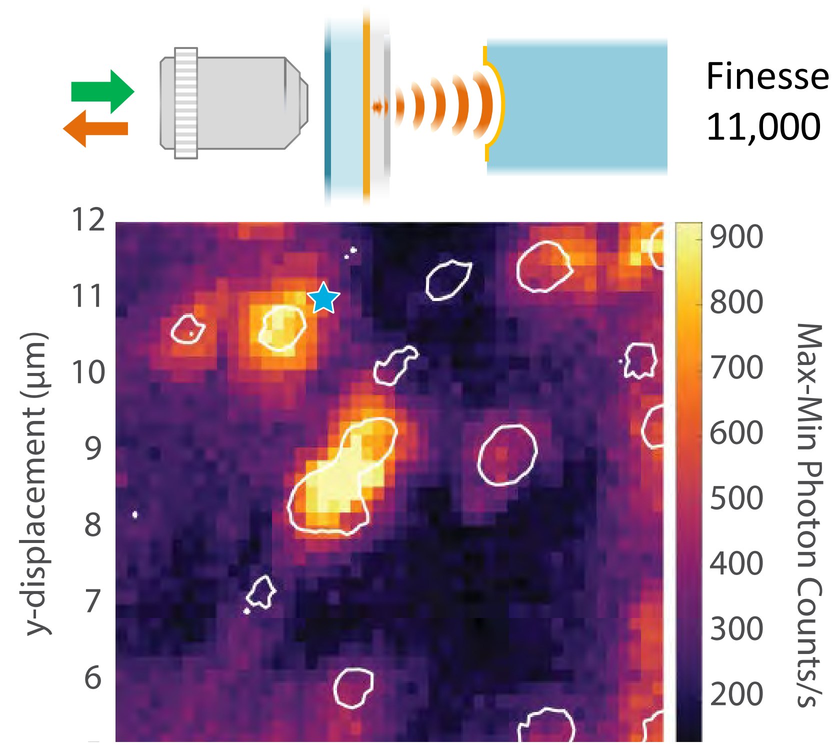
Room temperature cavity coupling

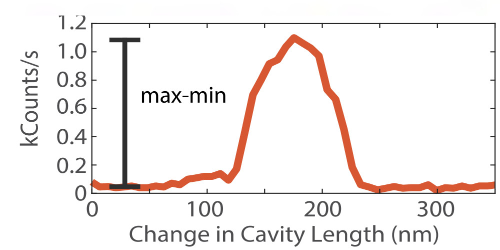
Confocal



Cavity

In a diamond-like mode!

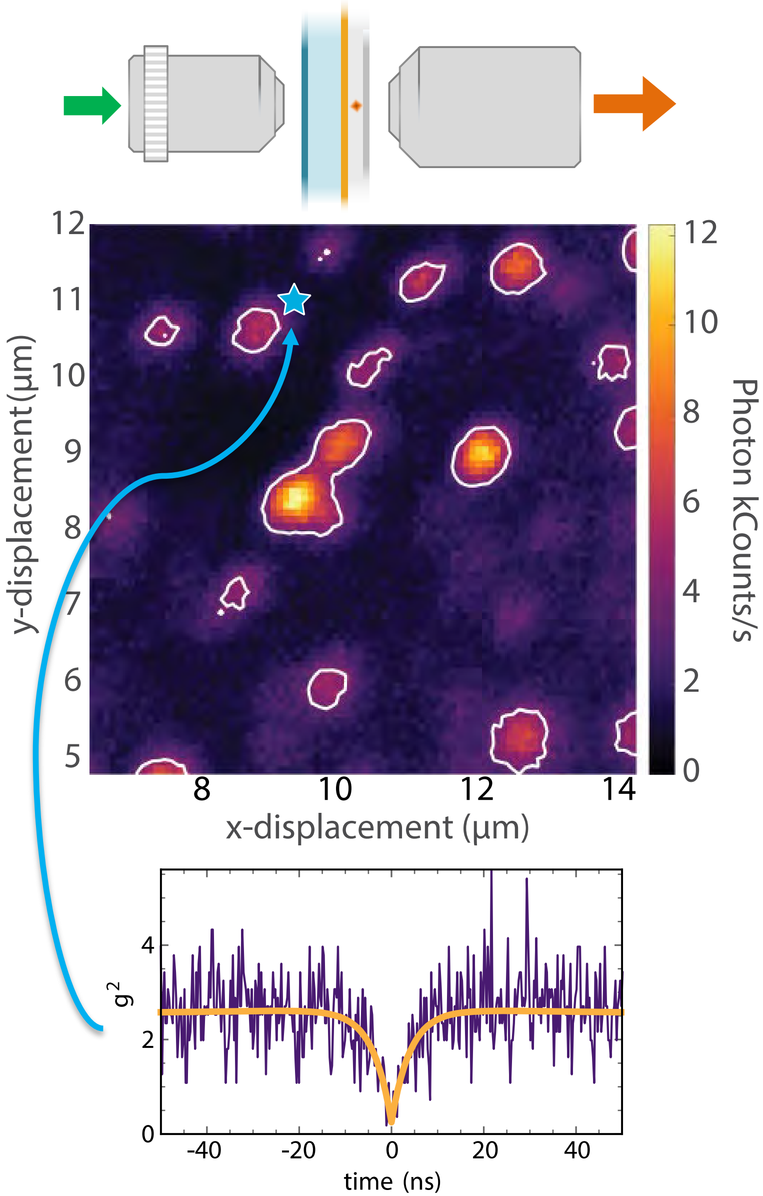




Jensen,* Janitz,* et al, Phys. Rev. Applied 2020

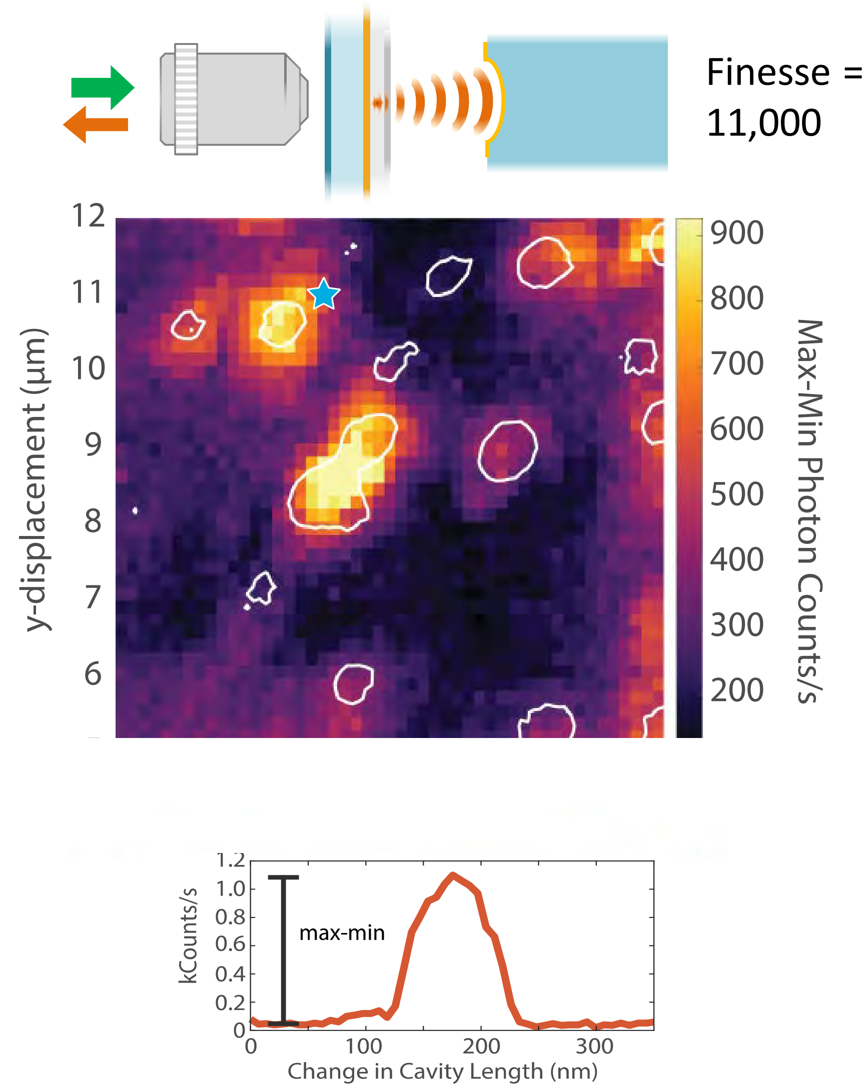
Room temperature cavity coupling

Confocal



Cavity

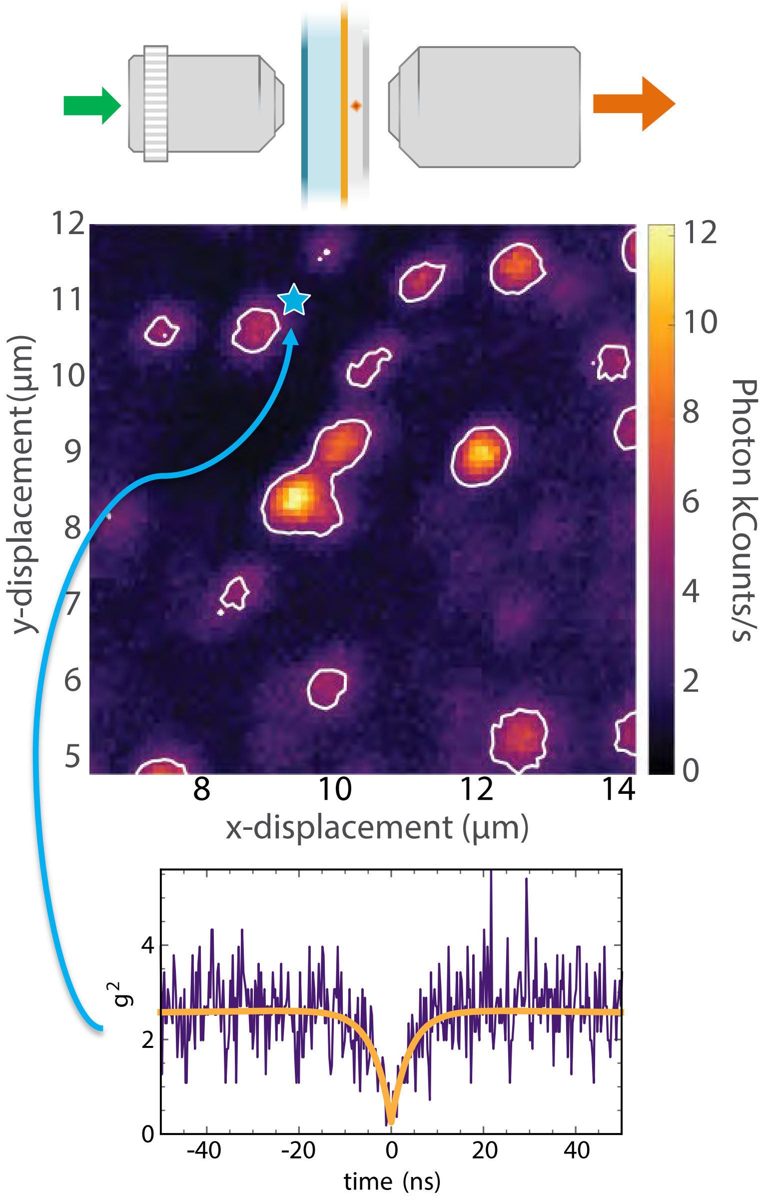
In a diamond-like mode!



Jensen,* Janitz,* et al, Phys. Rev. Applied 2020

Room temperature cavity coupling

Confocal



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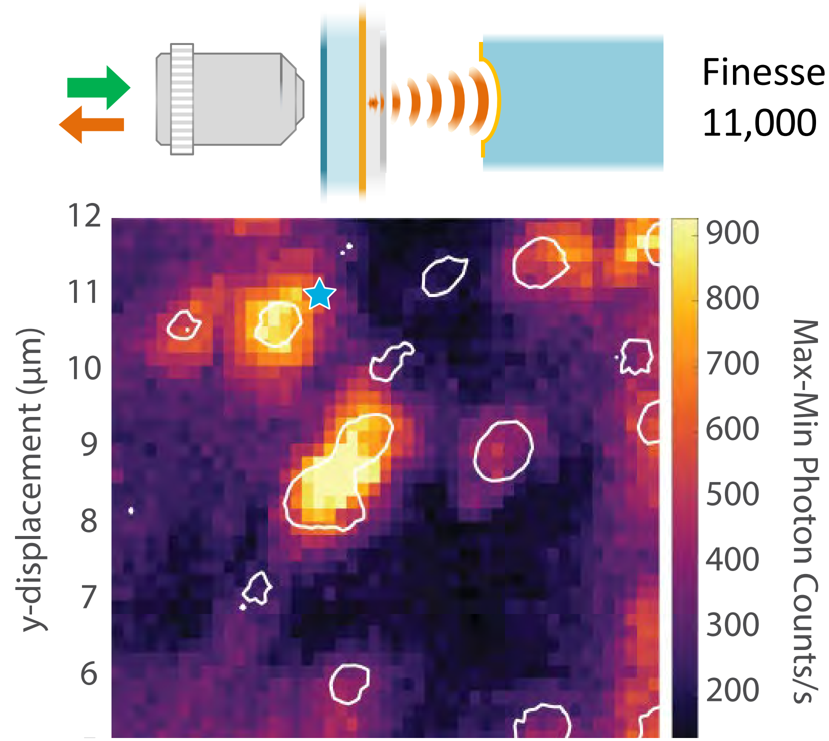


Finesse = 11,000

Careful accounting of losses & excitation efficiency

$\Rightarrow$ Estimate $\beta = 0.4 \pm 0.1\%$

$\Rightarrow$ Photon spectral density enhanced by 30$\pm$10

Jensen,* Janitz,* et al, Phys. Rev. Applied 2020

III. Cavity stabilization

Challenge: tunability AND stability at 4K

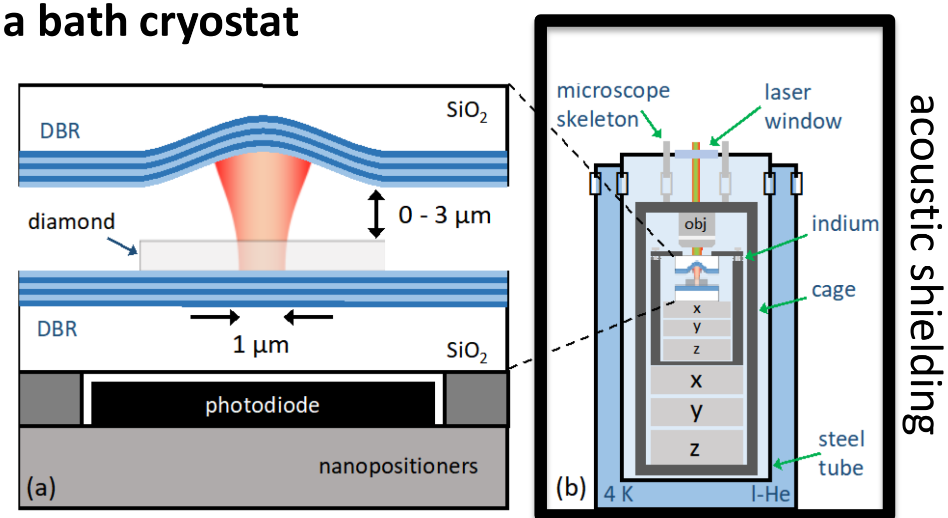
- Search for ideal membrane thickness, low loss
- Find “nice” NV

- Locked within ~ few picometers length
- In presence of cryostat noise!

Translation stages are floppy!

III. Cavity stabilization

Use a bath cryostat



D. Riedel, Ph.D. Thesis (2017)

Active vibration isolation

$\Rightarrow$ 24 pm-rms vibration between 0-200 Hz

= linewidth of a F = 13,000 cavity

Finesse = 5260, air-like mode

- $F_P \sim 20 - 40$
- $C \sim 0.03$ (γ_D= 1 GHz)

III. Cavity stabilization

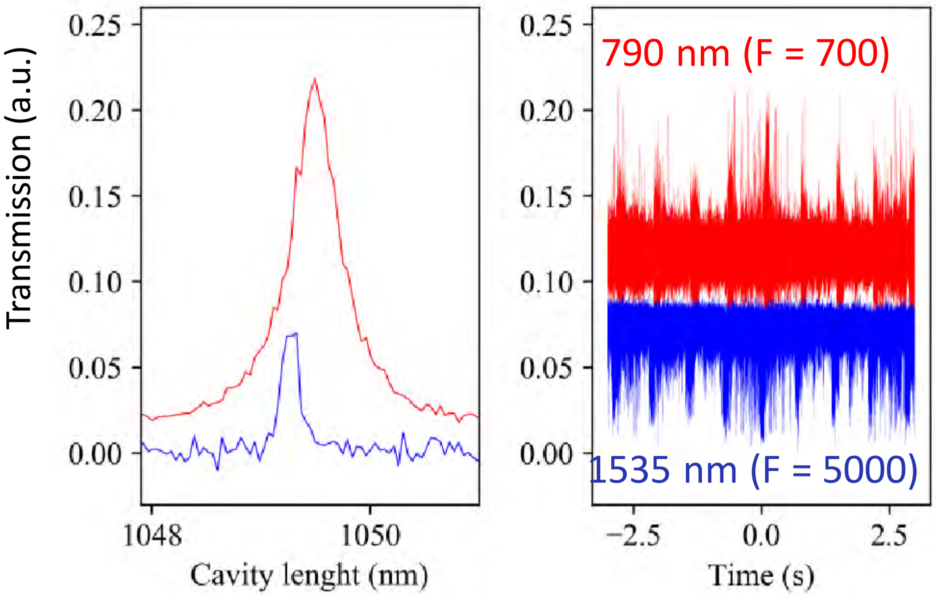
Use a closed-cycle cryostat (!?!)

III. Cavity stabilization

Use a closed-cycle cryostat (!?!)

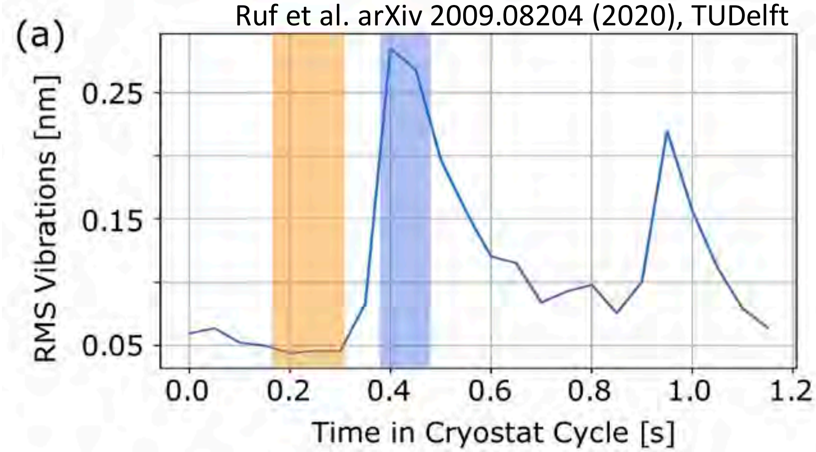
Qlibri platform with active (side of fringe) stabilization below 1 kHz

Casabone et al. arXiv 2001.08532 (2020), ICFO



< 30 pm-rms during the whole cycle possible,
~ 20 pm-rms during ”quiet times”
(measurements taken with >100 pm-rms)

Ruf et al. arXiv 2009.08204 (2020), TUDelft



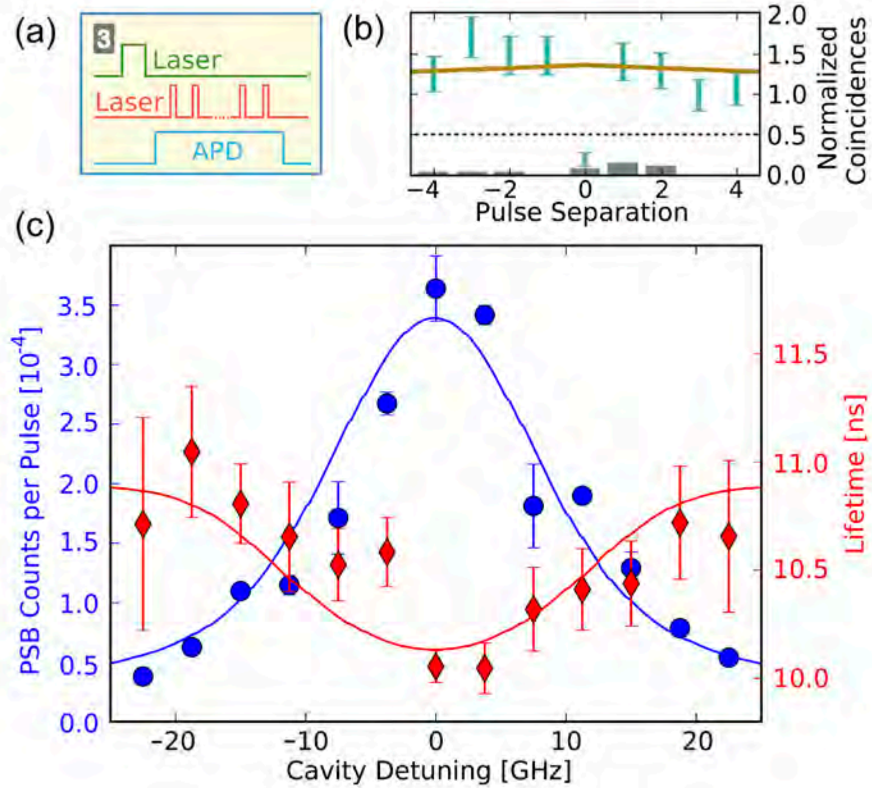
Down to ~ 50 pm-rms during “quiet times”

Commercial cryogenic vibration isolation platform

III. Cavity stabilization

Use a closed-cycle cryostat (!?!)

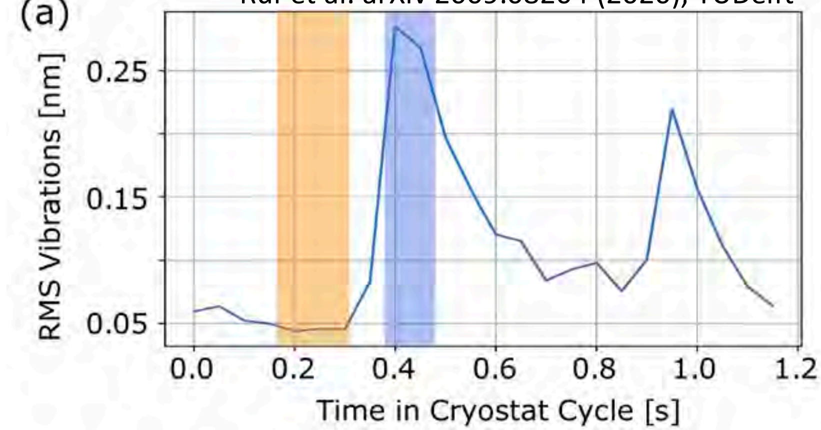
Observe $F_P \sim 4$ $(C \sim 0.04)$ for NVs with resonant excitation



Ruf et al. arXiv 2009.08204 (2020), TUDelft

Measurements taken with $\sim$ 180 pm-rms vibration

Ruf et al. arXiv 2009.08204 (2020), TUDelft

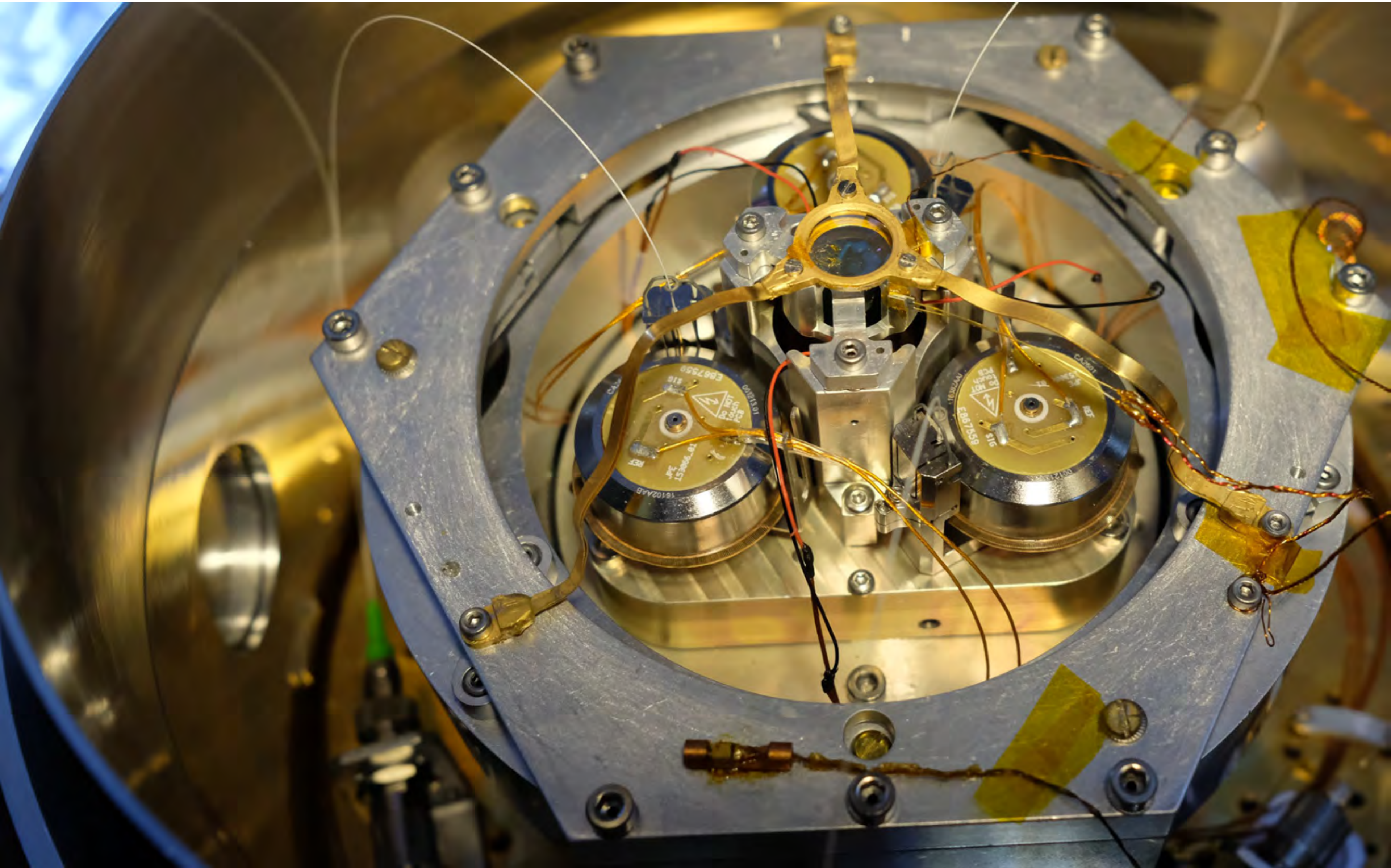


Down to ~ 50 pm-rms during “quiet times”

Commercial cryogenic vibration isolation platform

Finesse ~ 2000, air-like mode

Towards a cryogenic, scanning, stabilized microcavity



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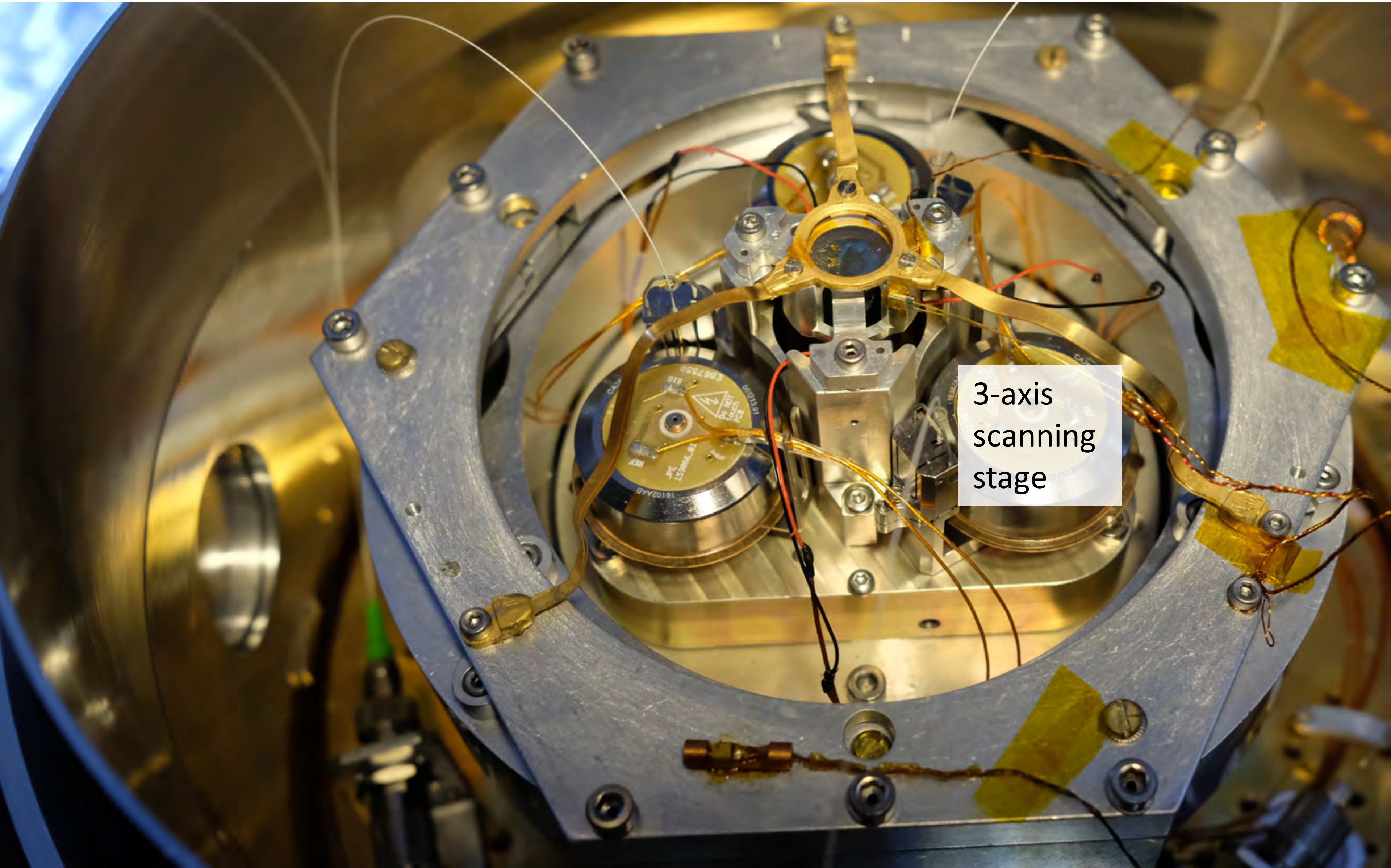

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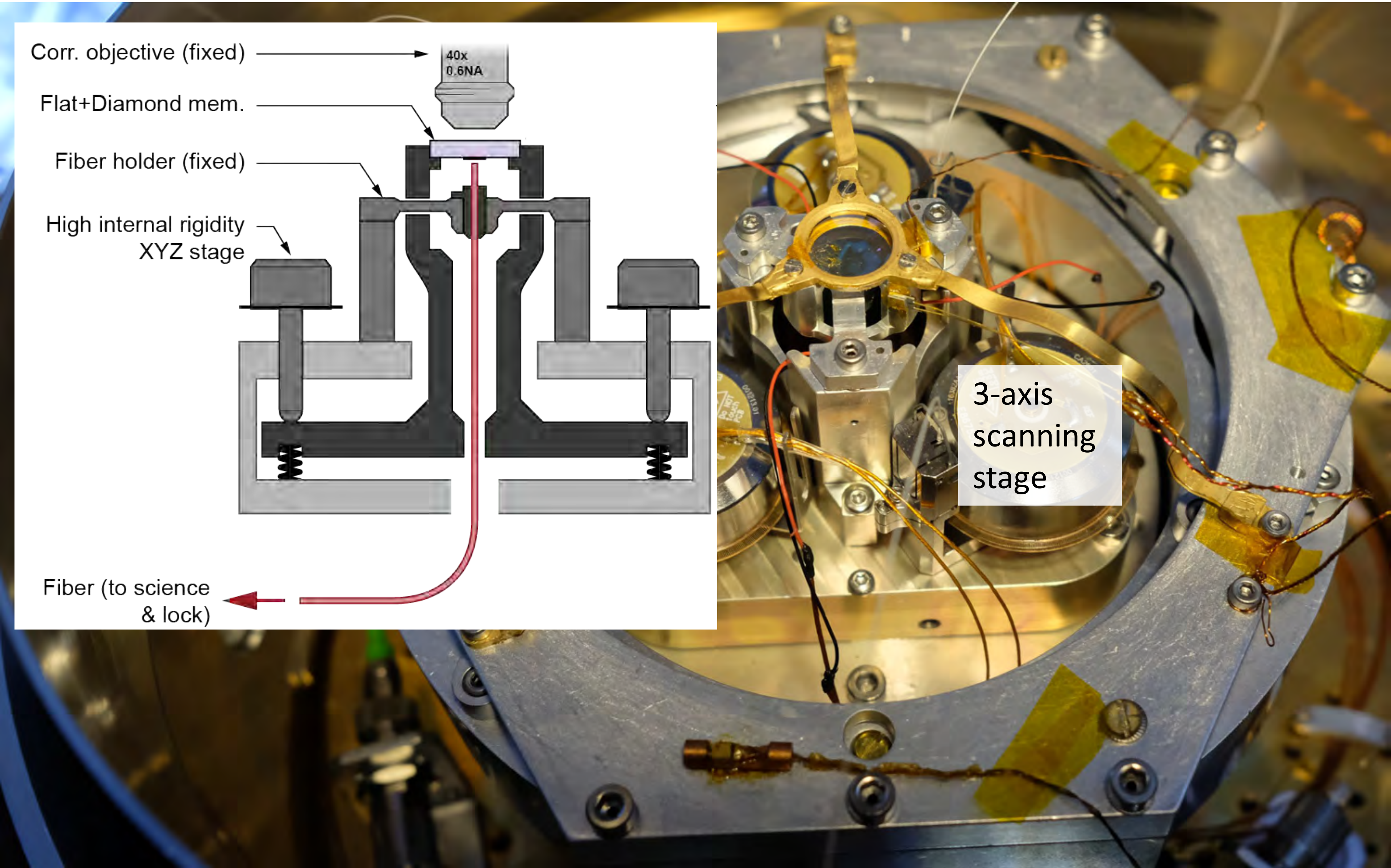

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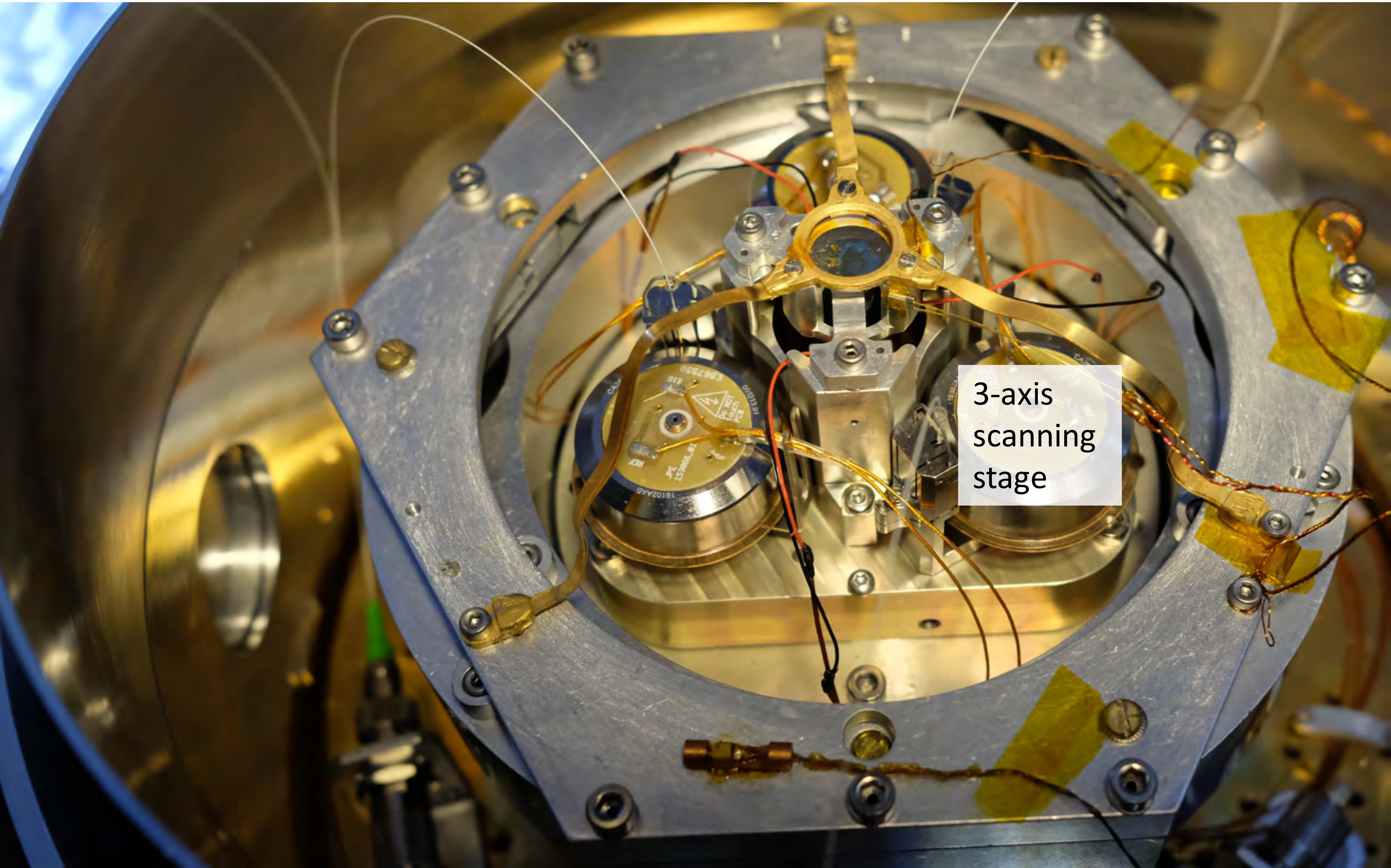

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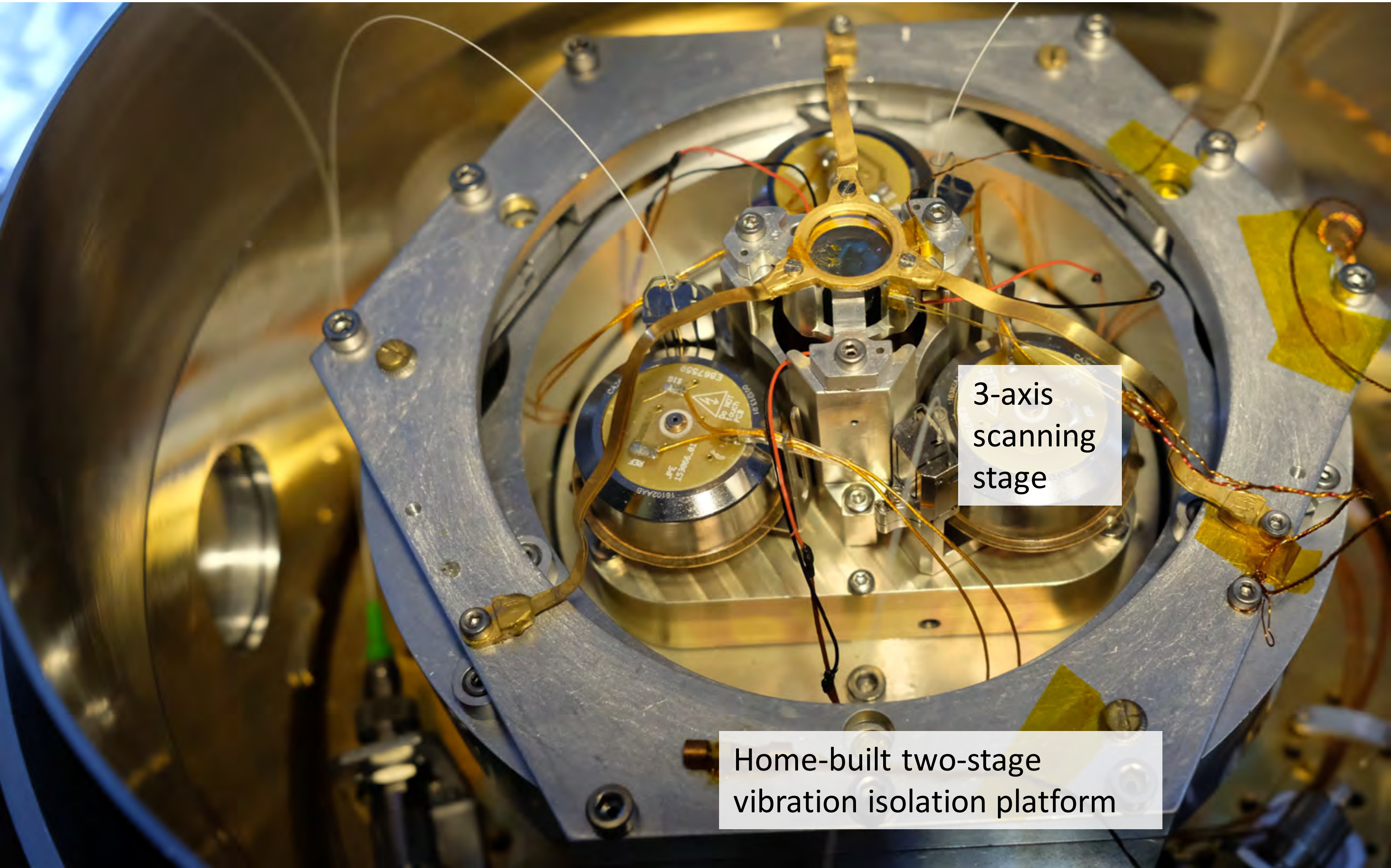

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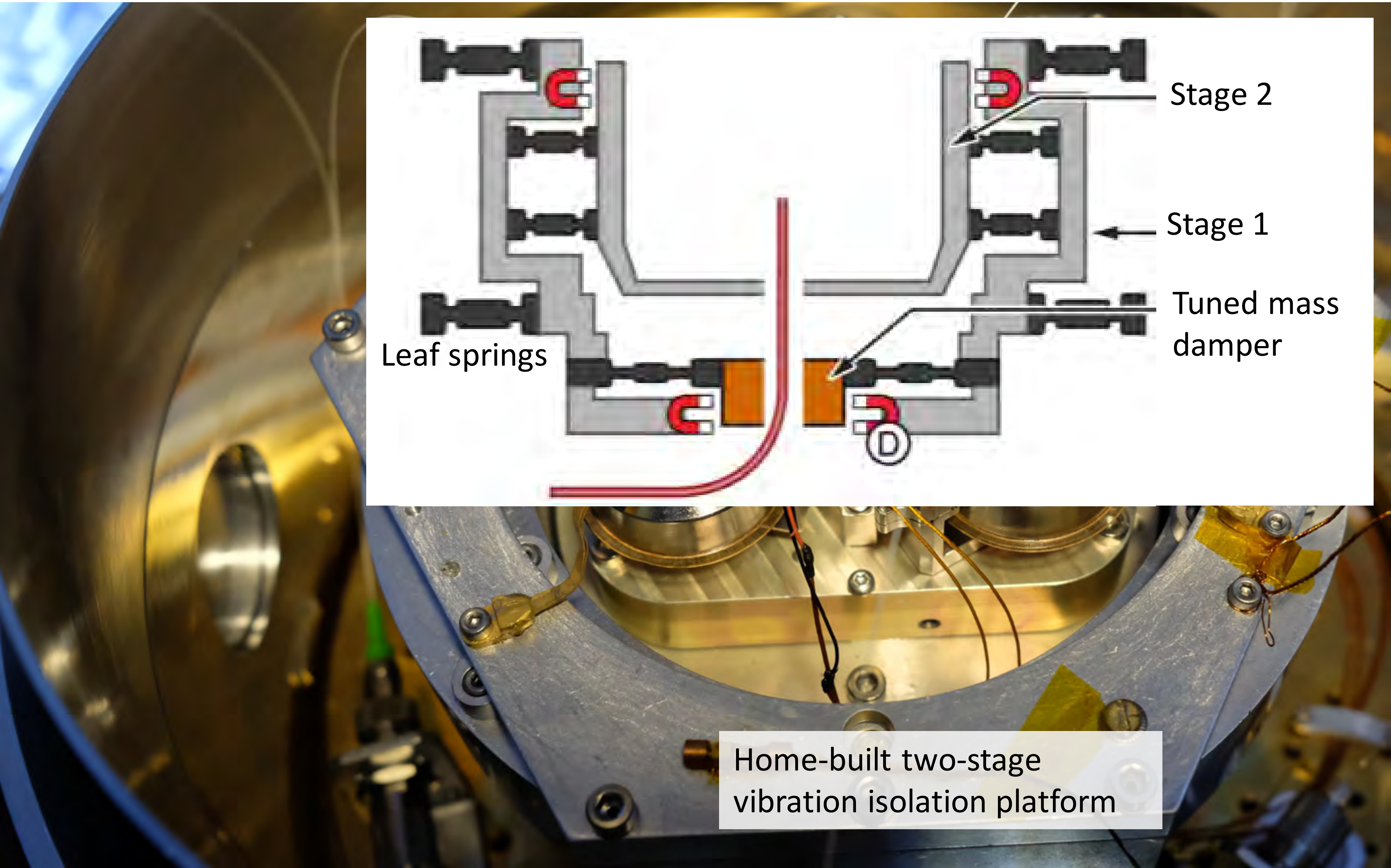

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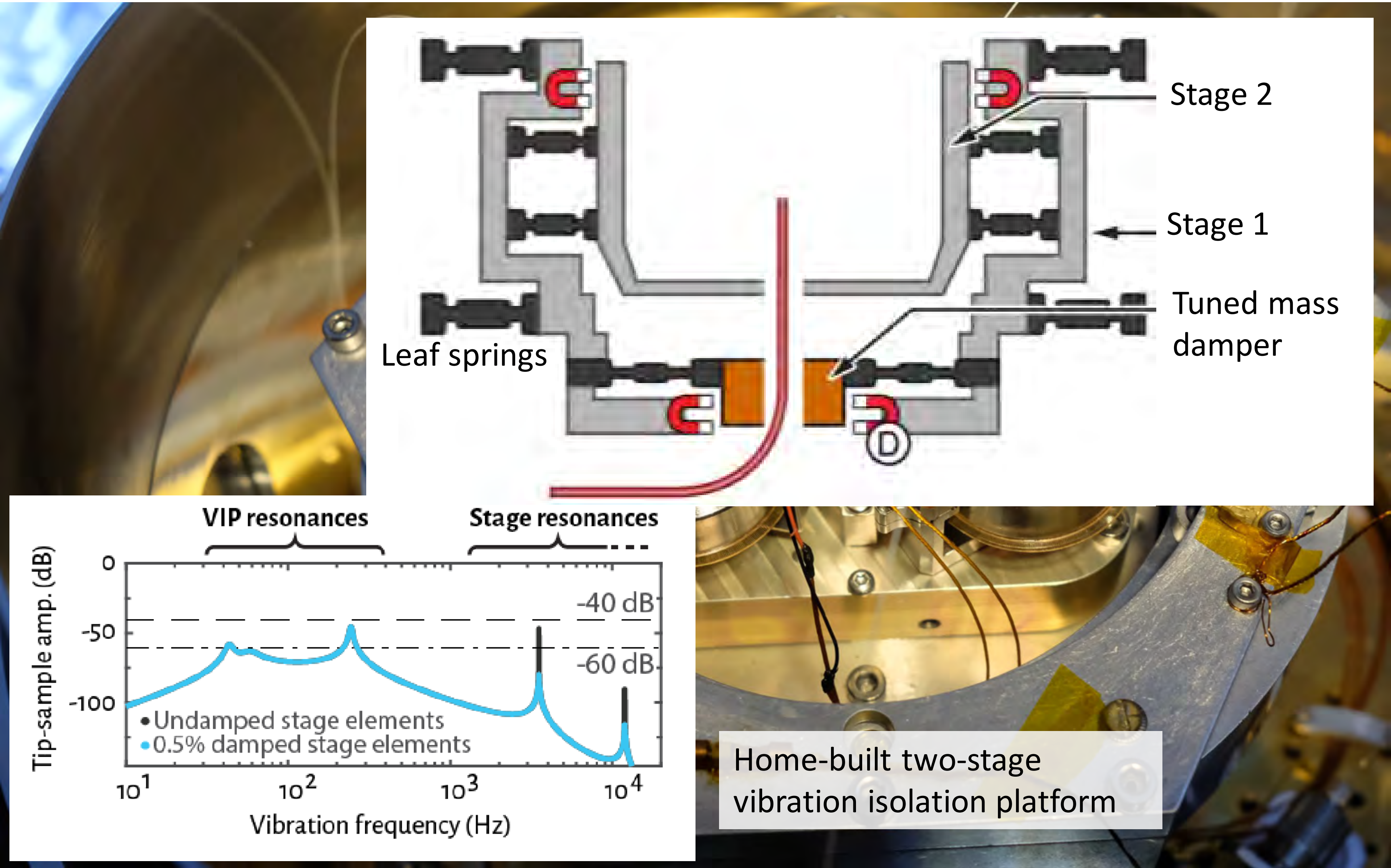

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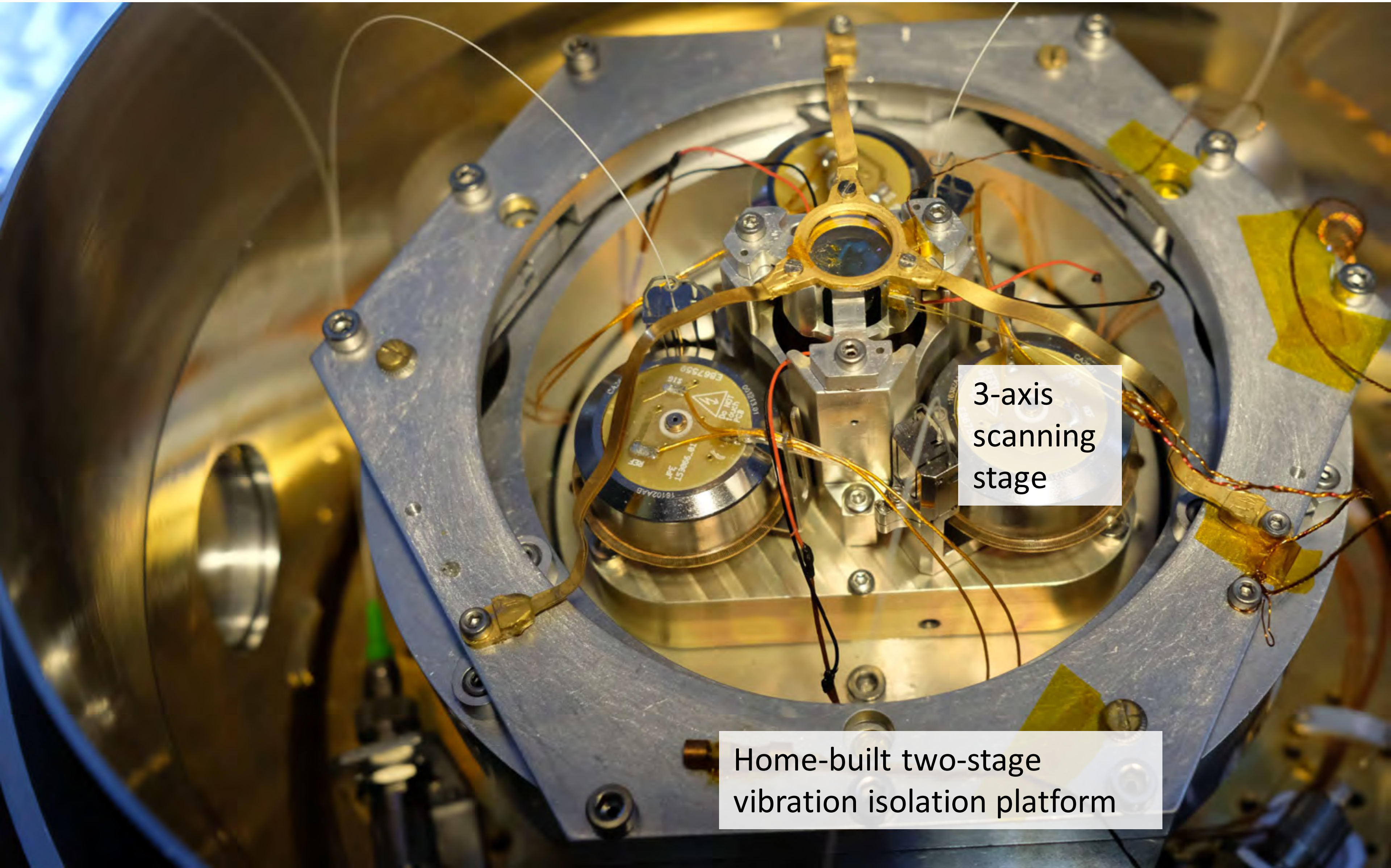

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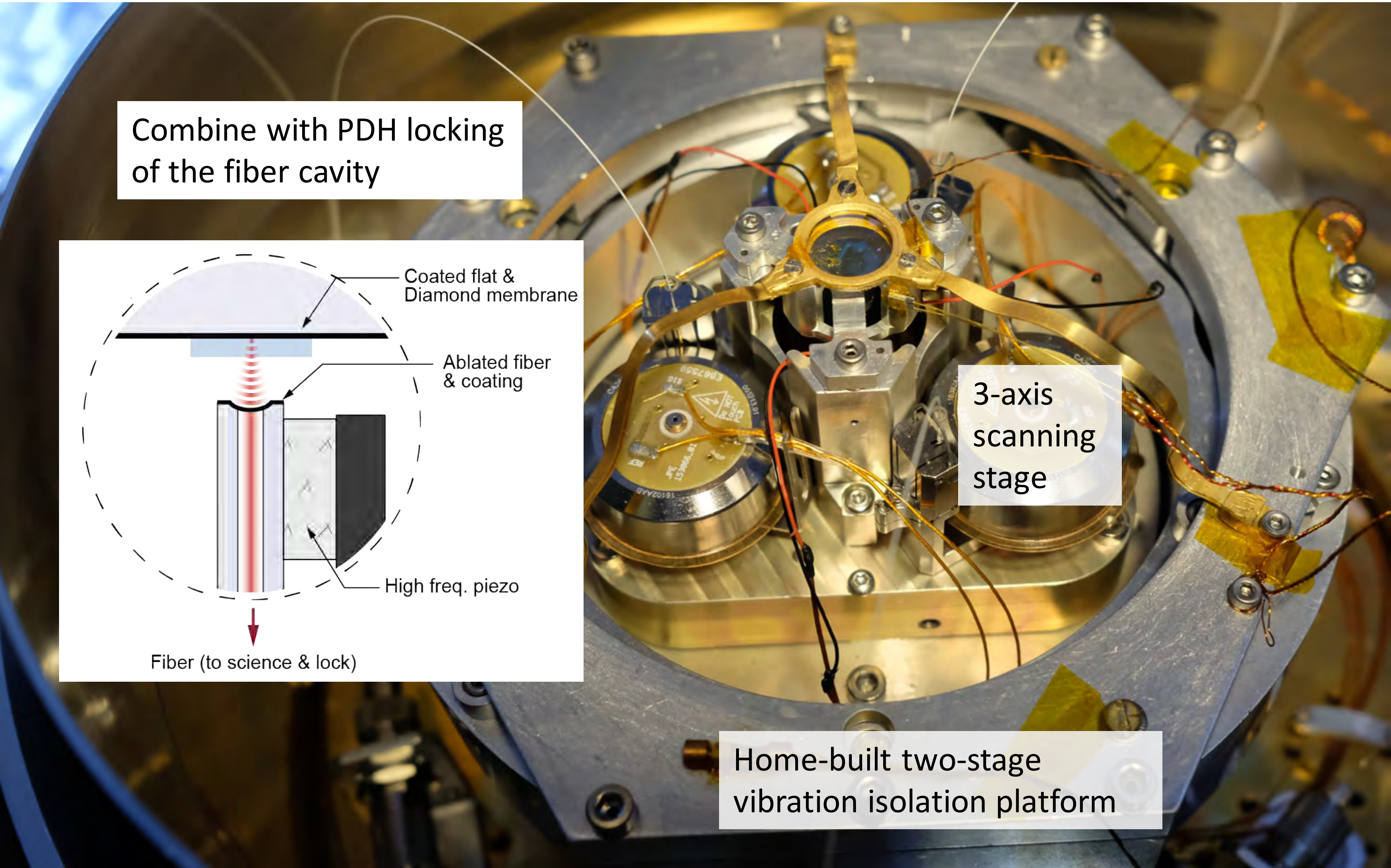

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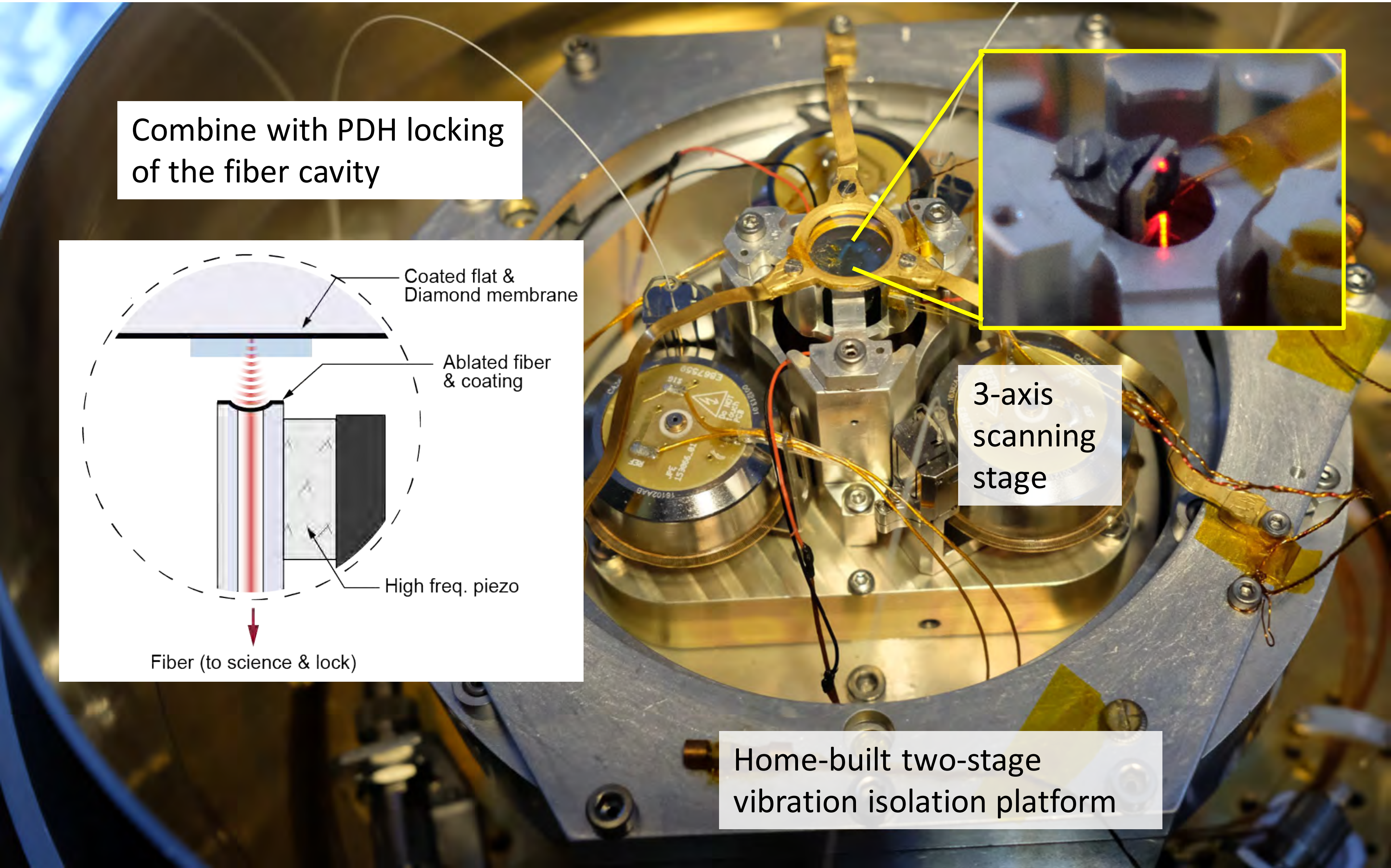
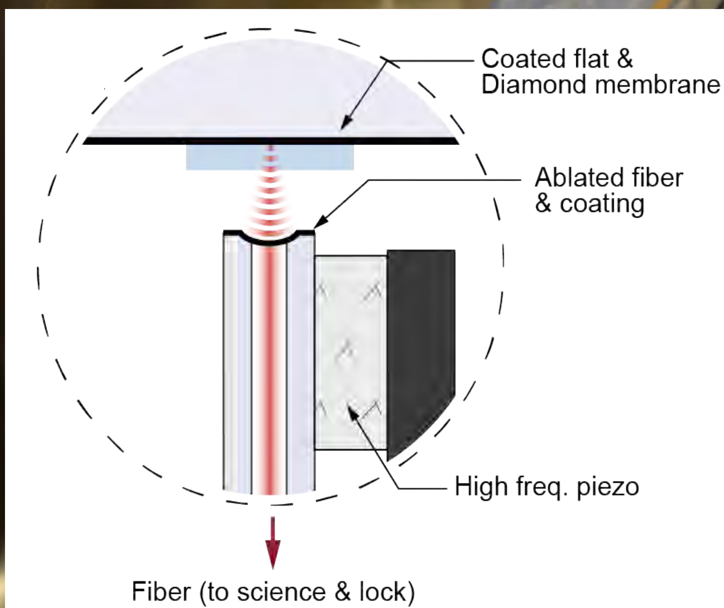
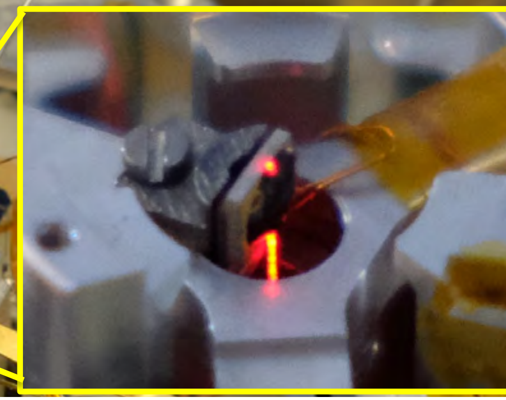
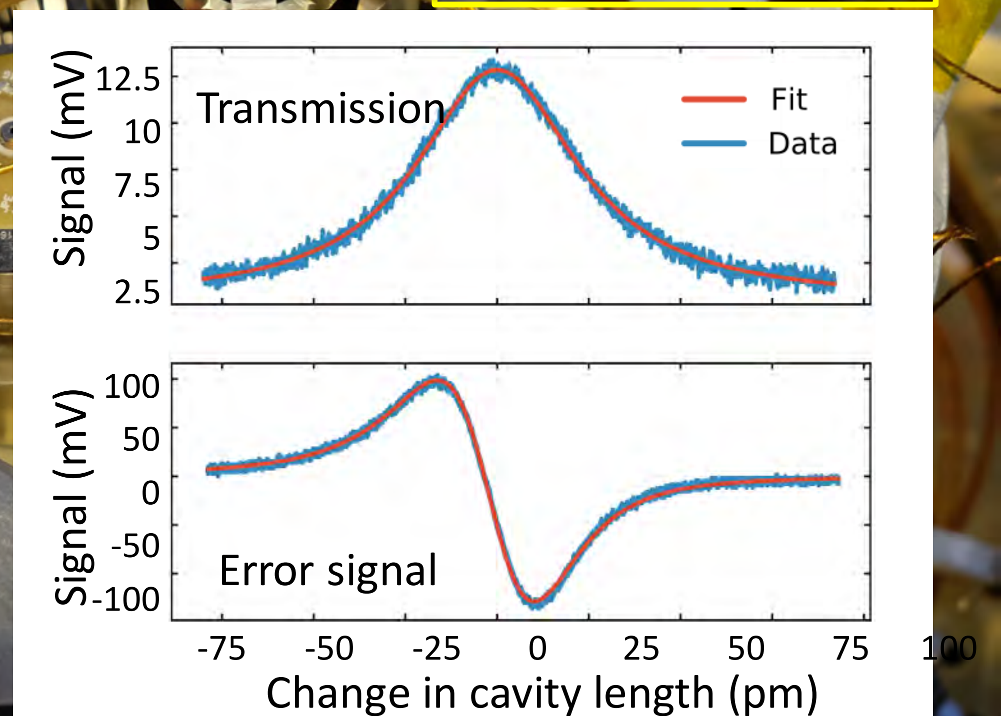


Towards a cryogenic, scanning, stabilized microcavity

Combine with PDH locking of the fiber cavity







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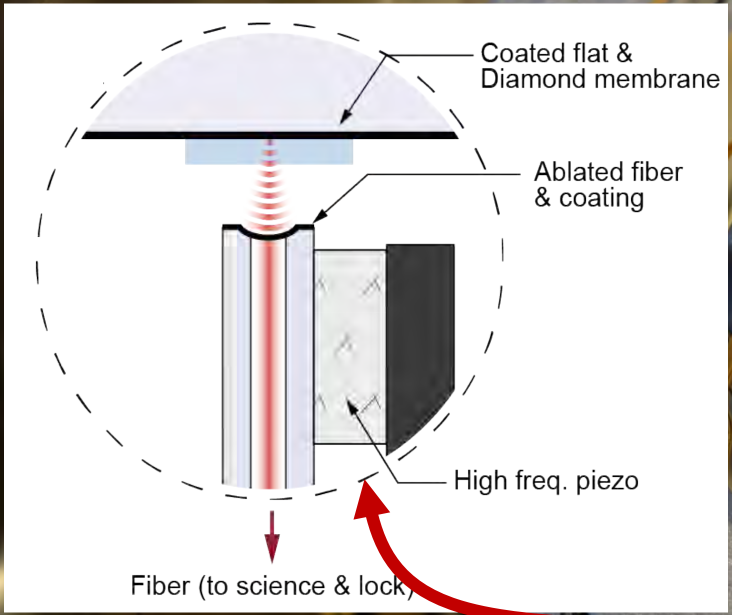
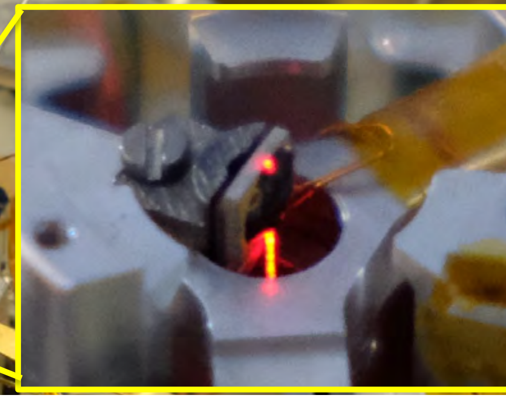
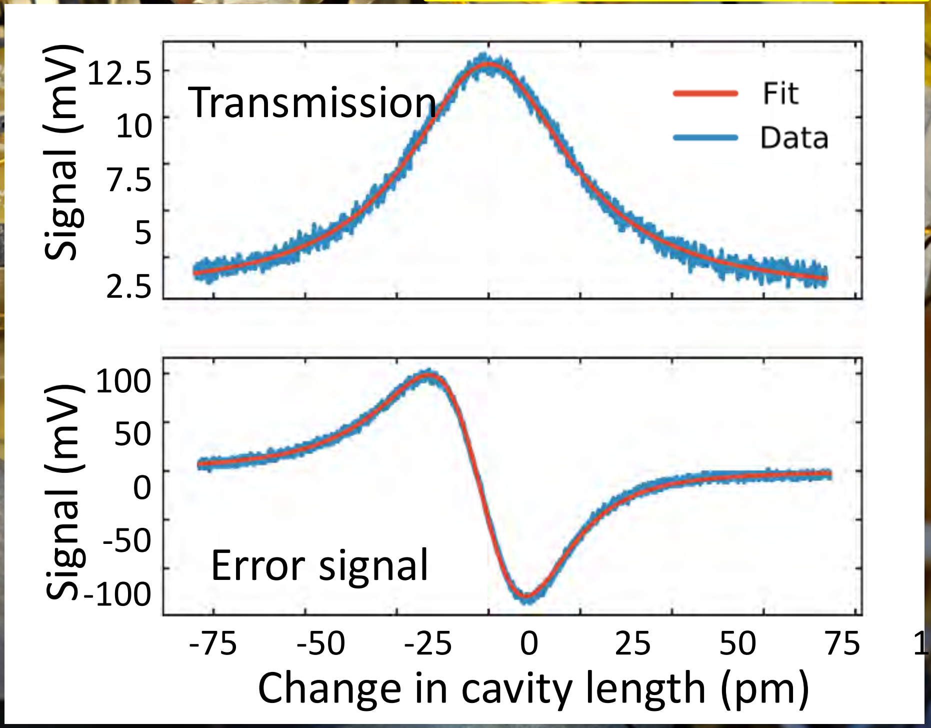
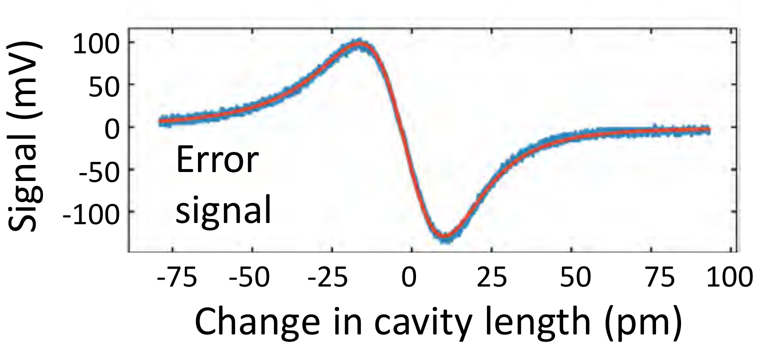






Characterizing microcavity residual motion

Idea: Monitor error signal to measure residual motion **(while locked or unlocked)**



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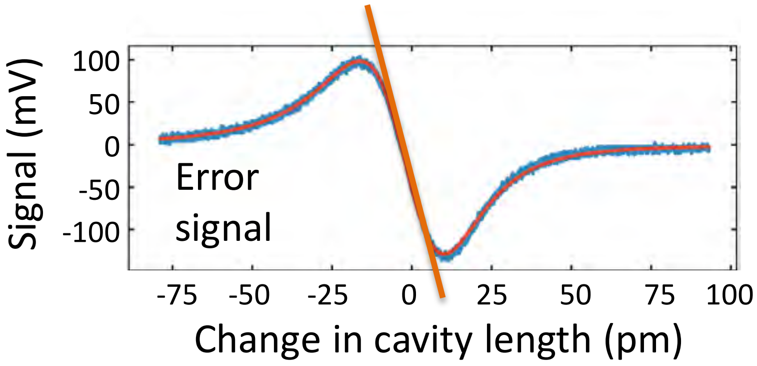

Error signal ∝ cavity length

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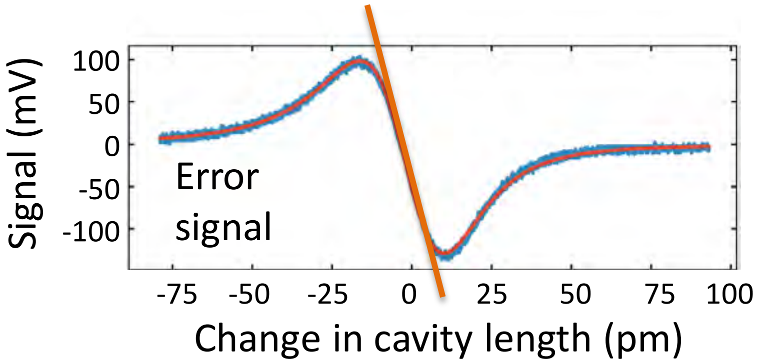
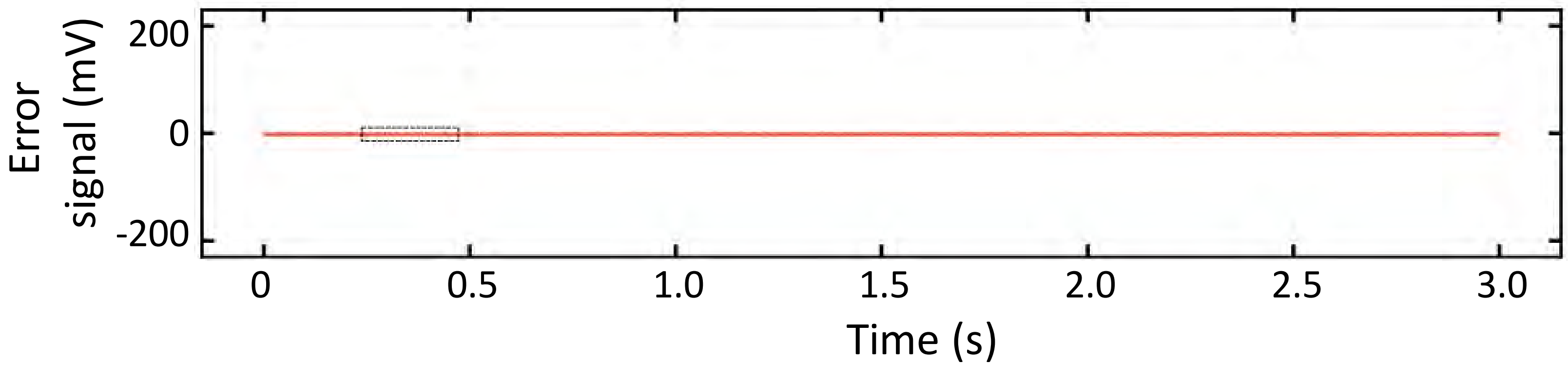


Error signal ∝ cavity length

Compressor off, locked:



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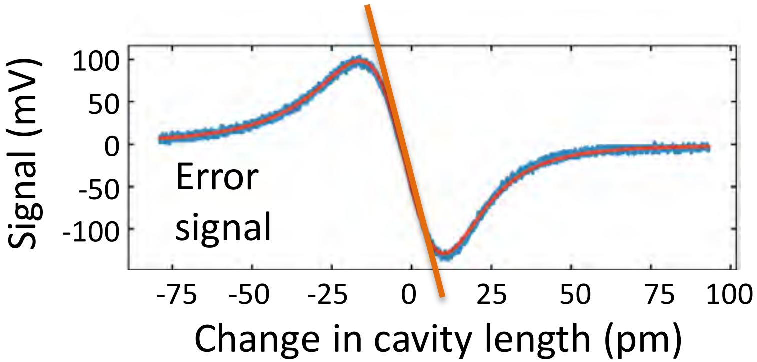

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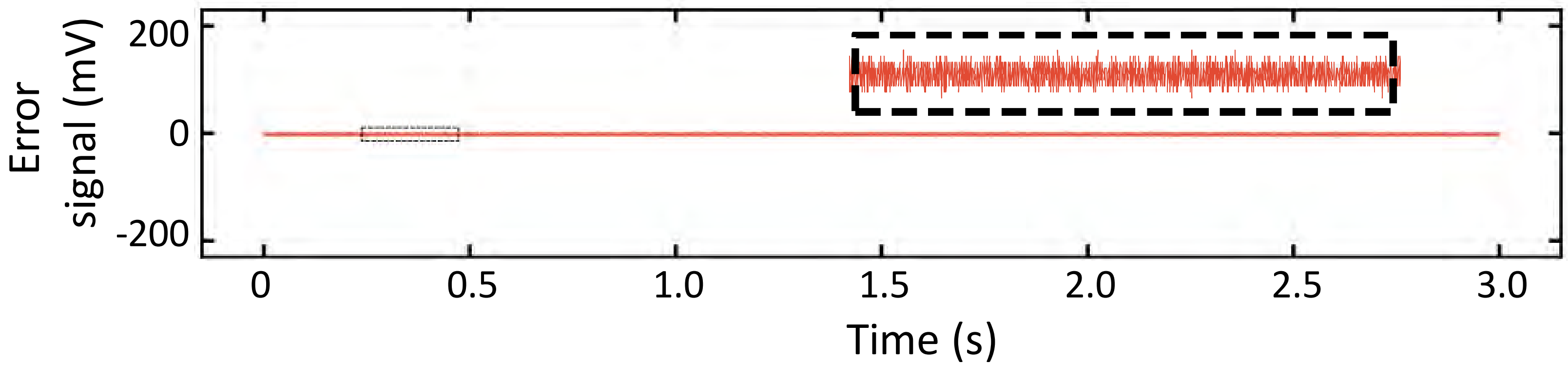

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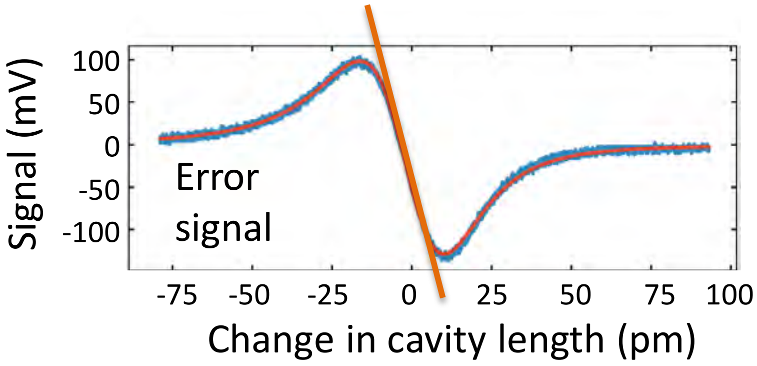

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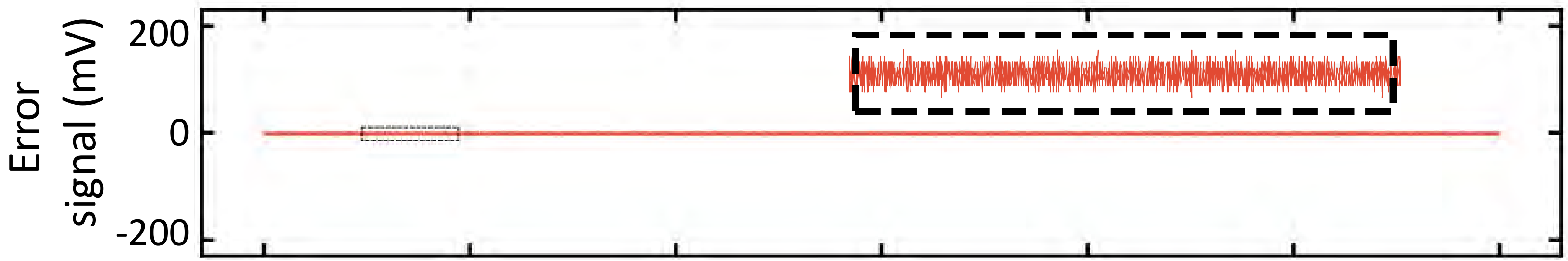

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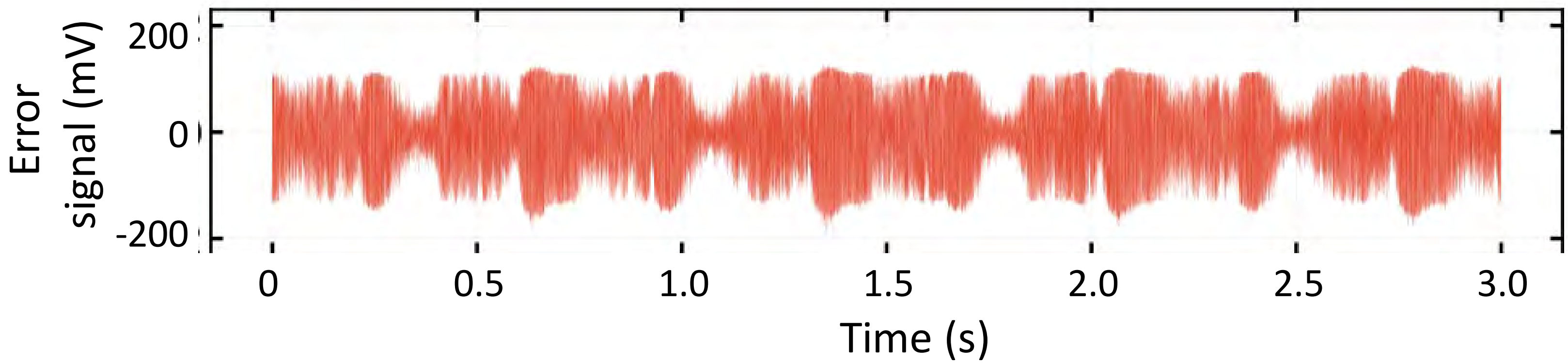

Note:

- in LFGL mode
- at 300K

Characterizing microcavity residual motion

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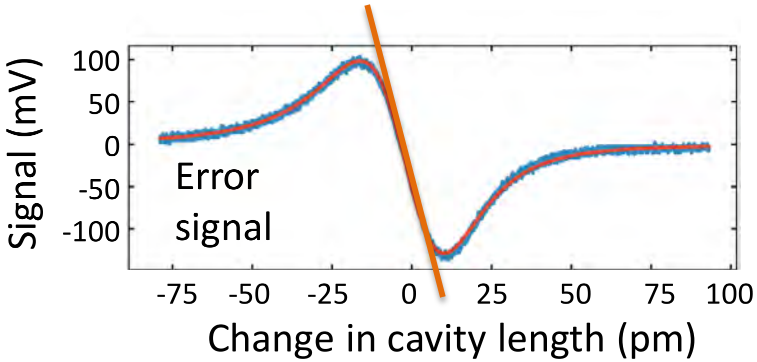
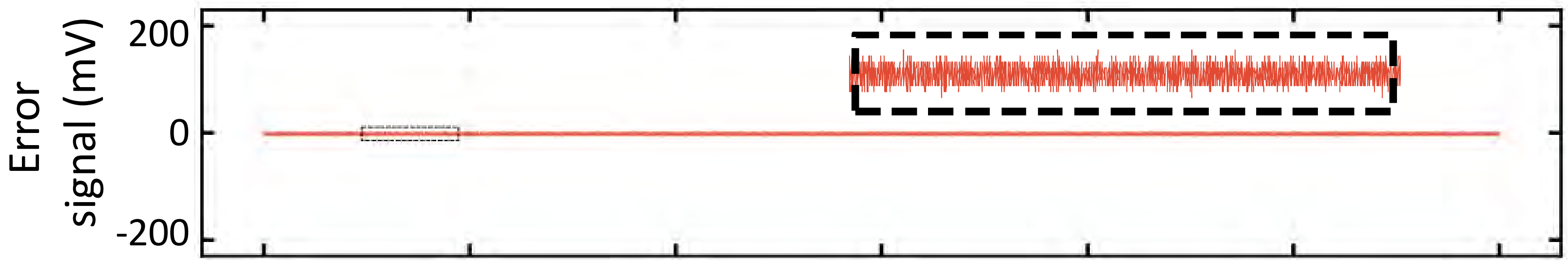


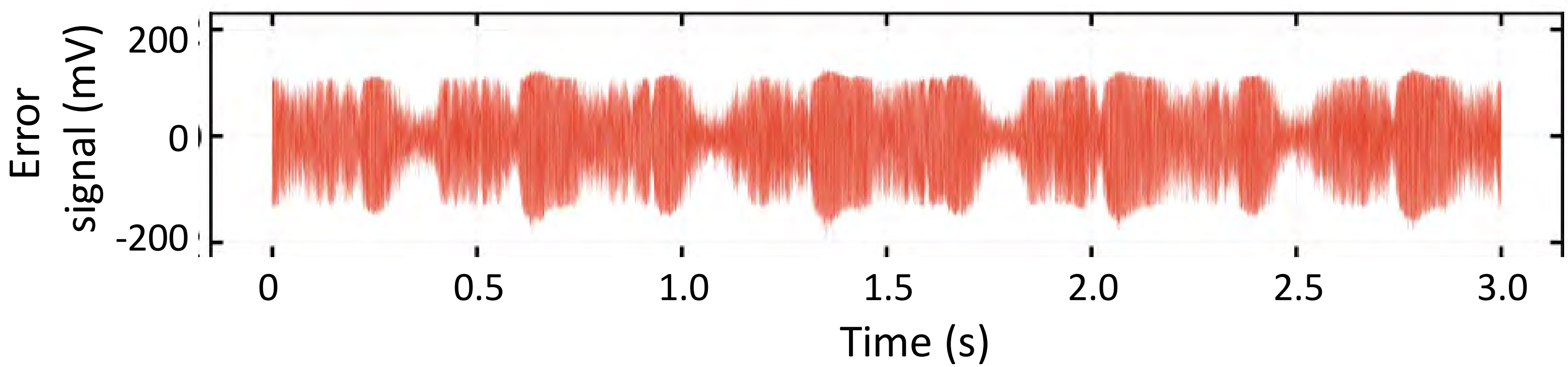
Error signal ∝ cavity length

Not in linear regime

Compressor off, locked:



Compressor on, locked:



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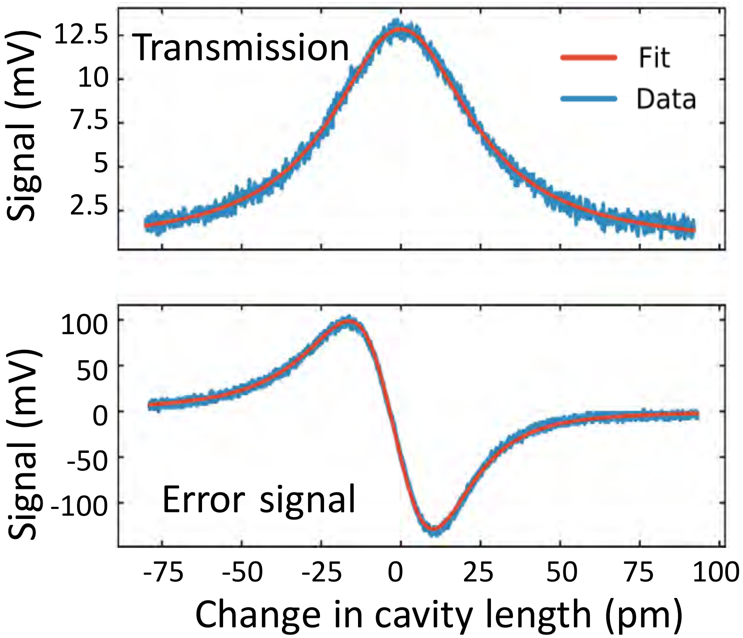
Microcavity residual motion: error signal and transmission



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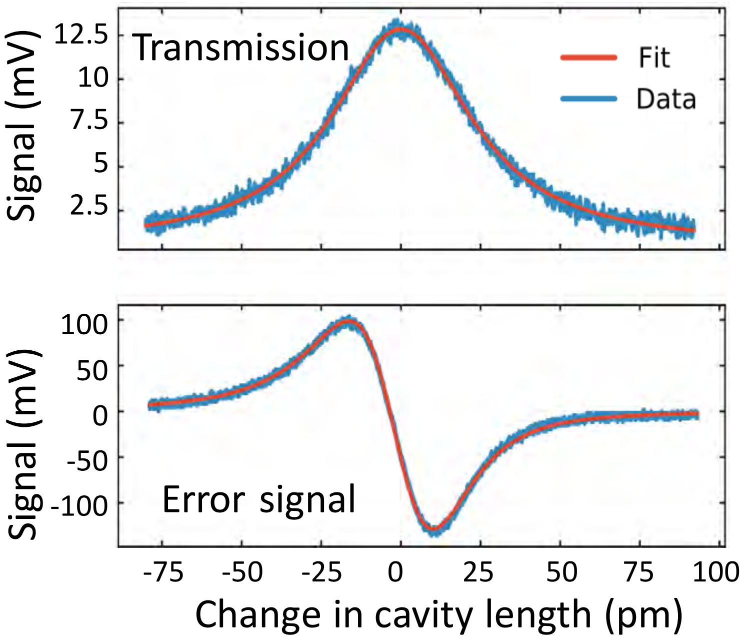

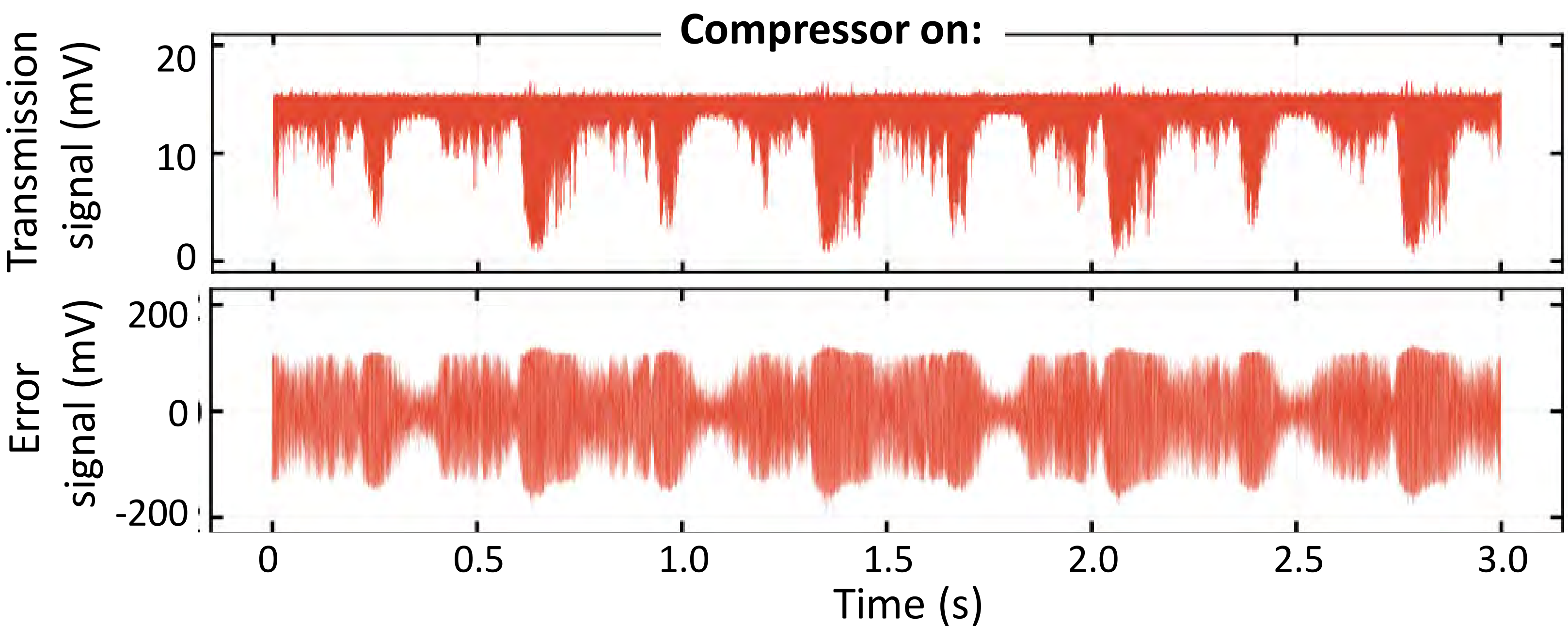

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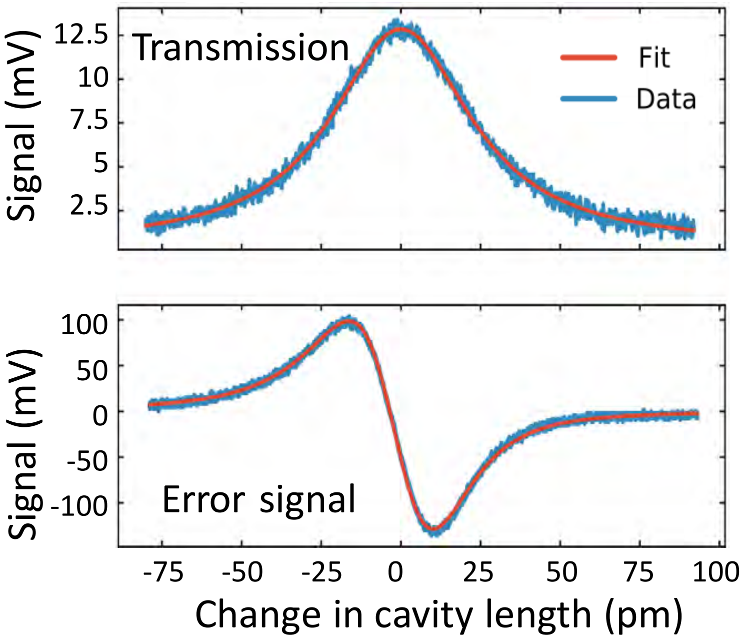
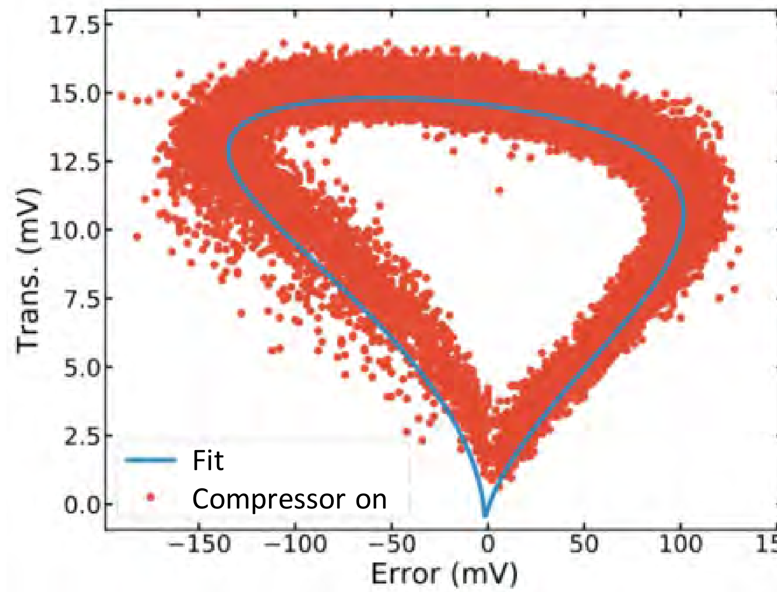
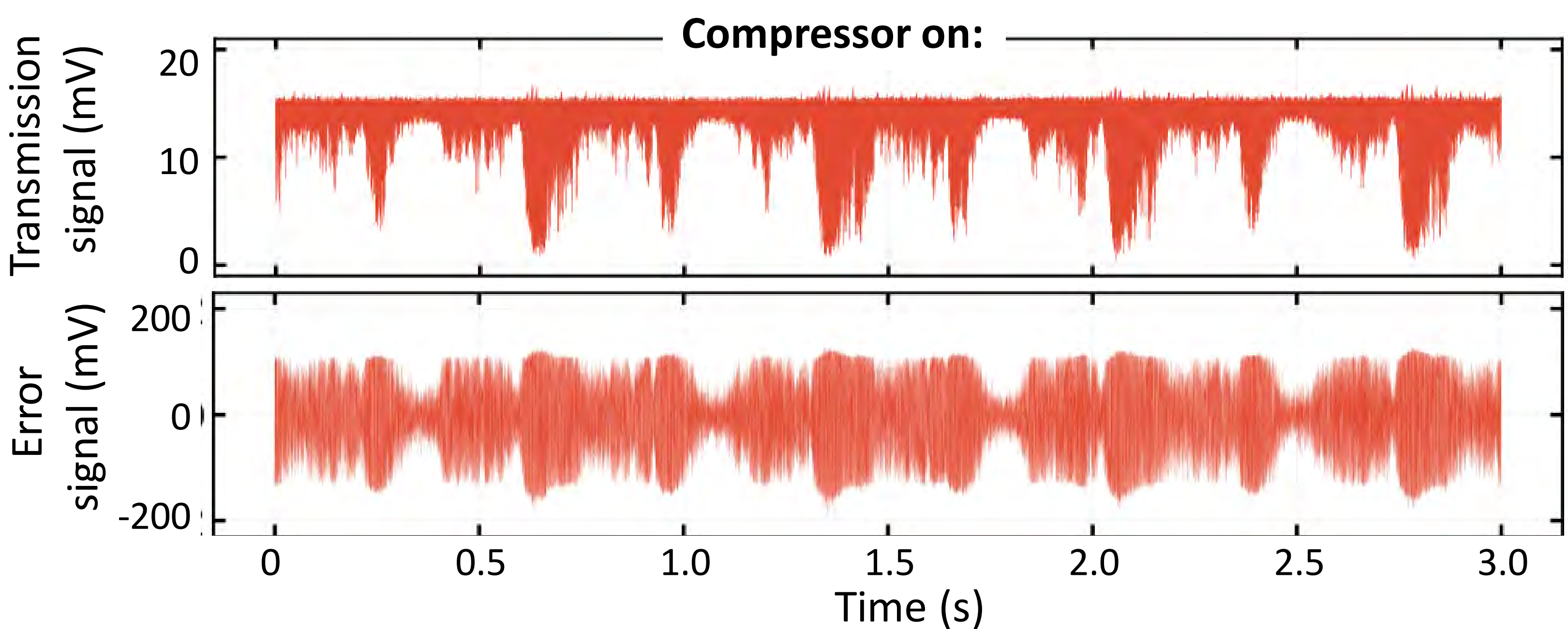




Closest location on parametric curve reveals cavity length



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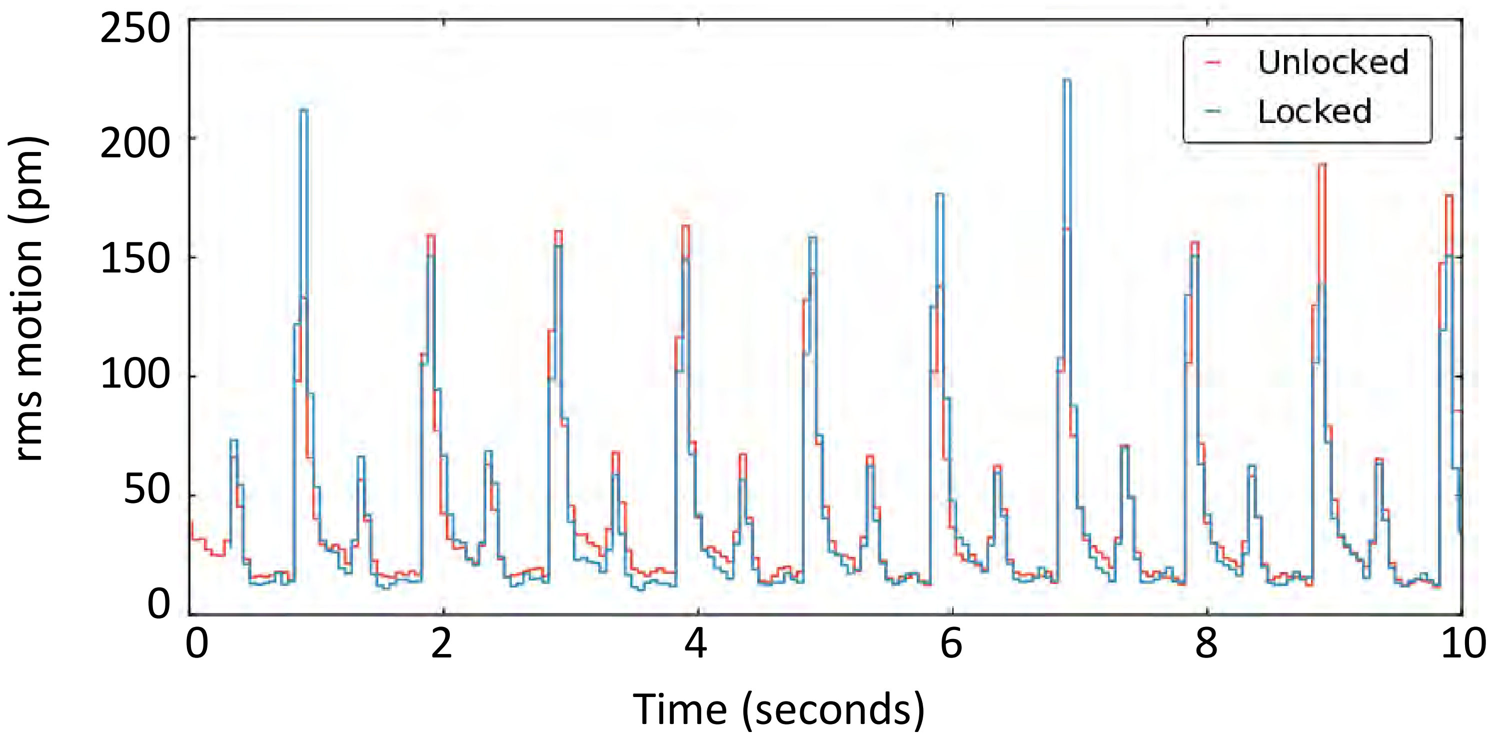
Performance at low temperature

Surprise #1: Hugely lower vibrations when unlocked ($\sim$ 1 nm-rms $\rightarrow$ $\sim$ 60 pm-rms)

Surprise #2: Locking was not particularly helpful



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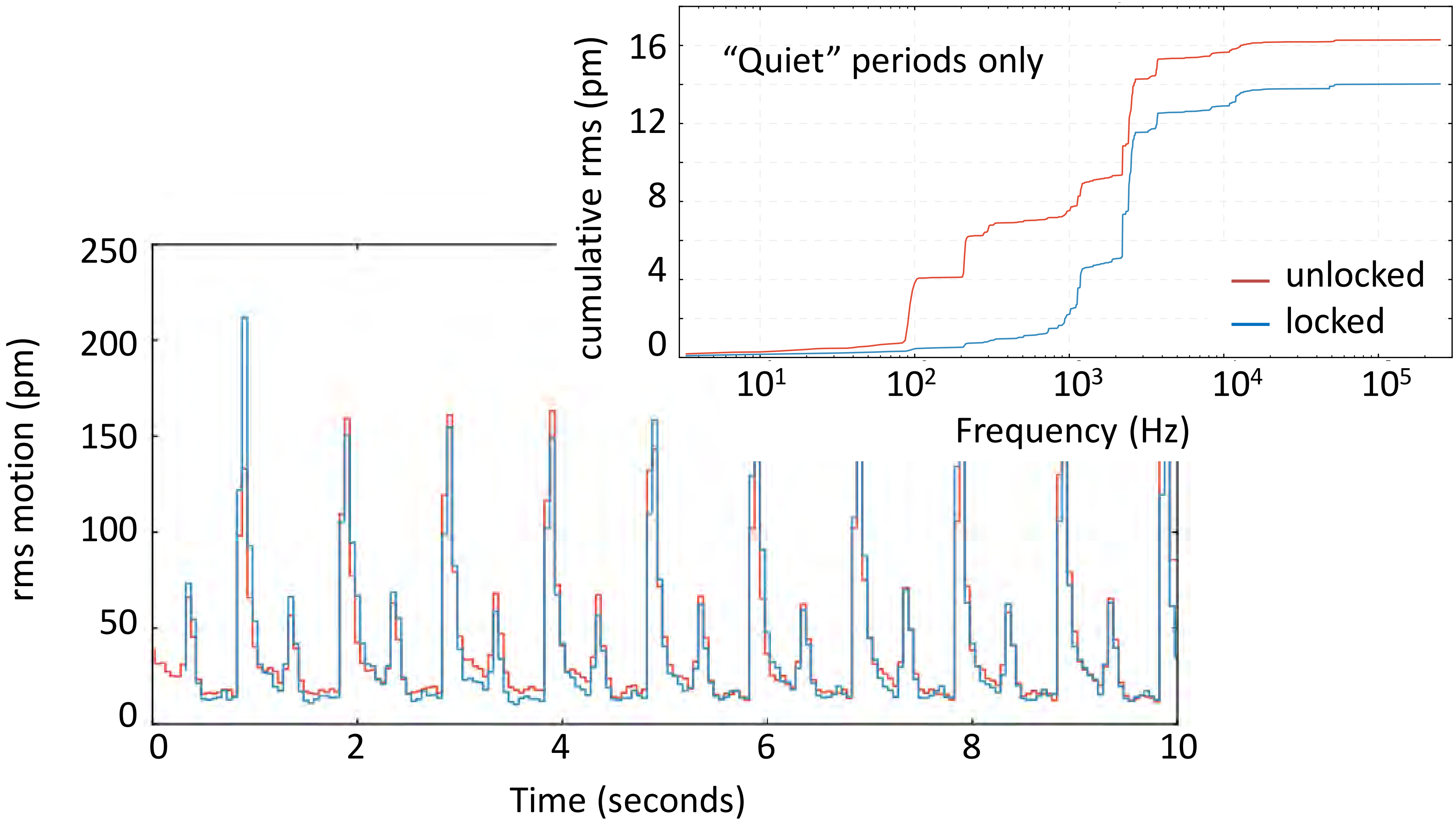

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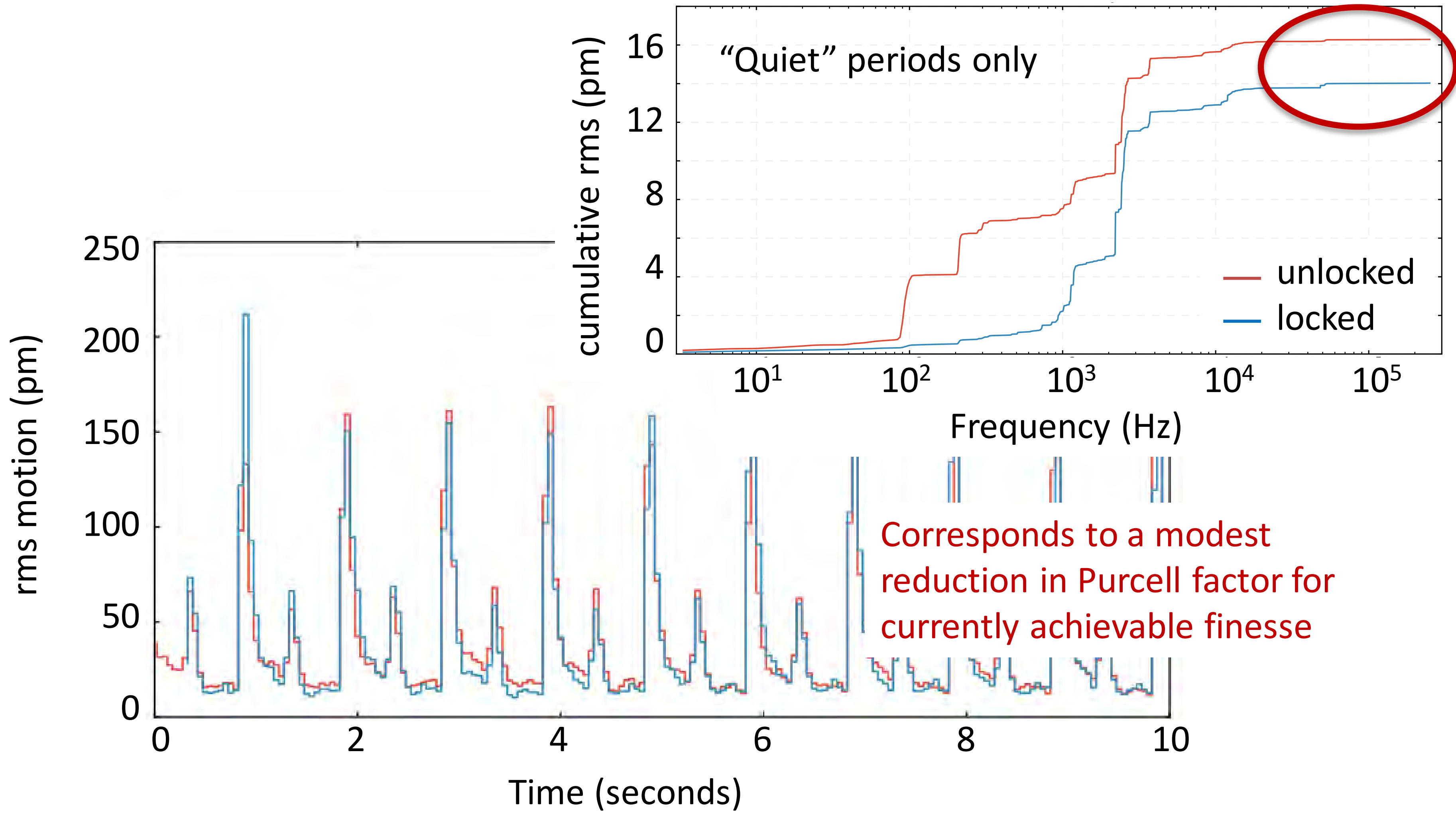

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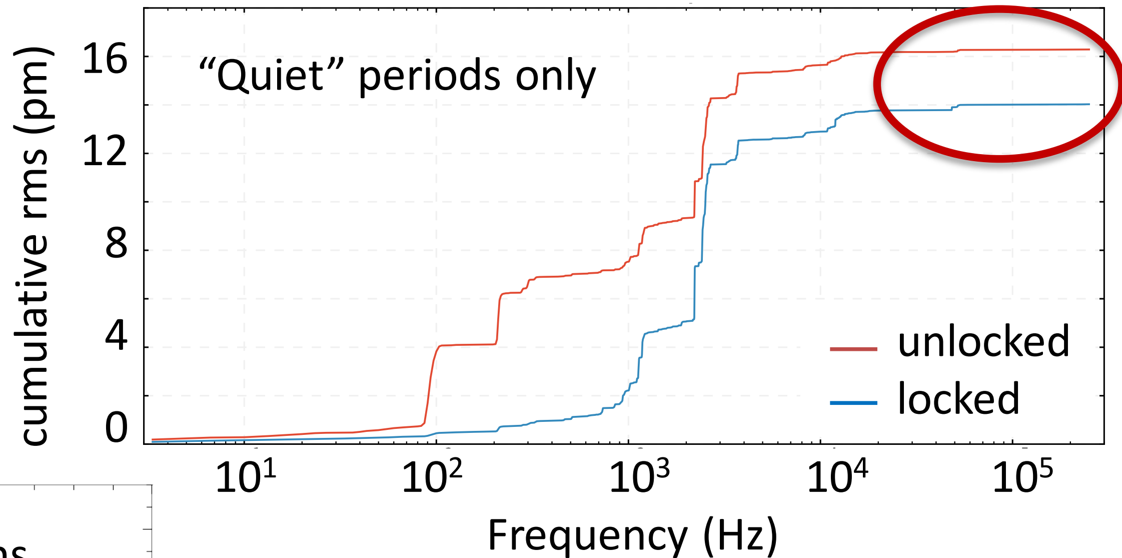
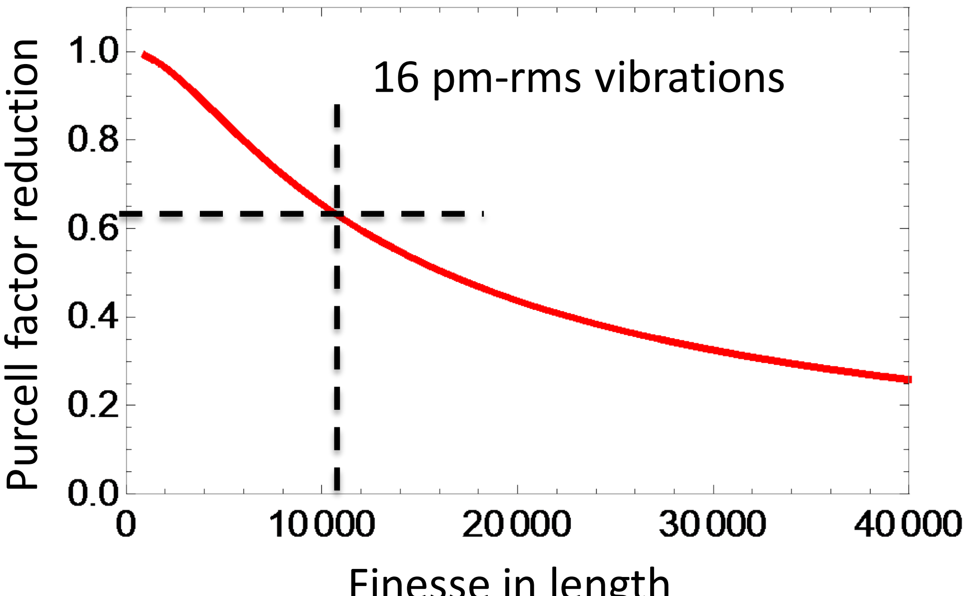


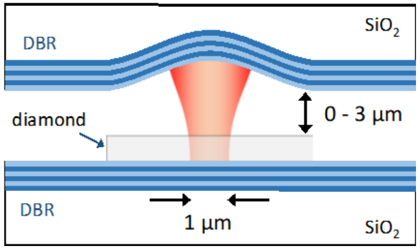


Corresponds to a modest reduction in Purcell factor for currently achievable finesse

Prospects for cooperativity > 1

Challenge: Fiber cavity geometry

Riedel et al. PRX **7** 031040 (2017)



ROC = 16 μm

Air gap = 2 μm

Challenge: NV optical coherence properties

Challenge: Membrane losses

Challenge: Vibrations

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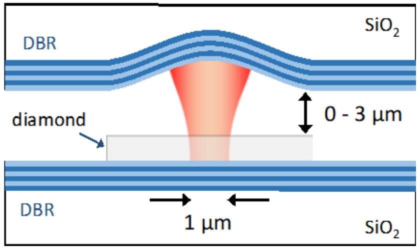

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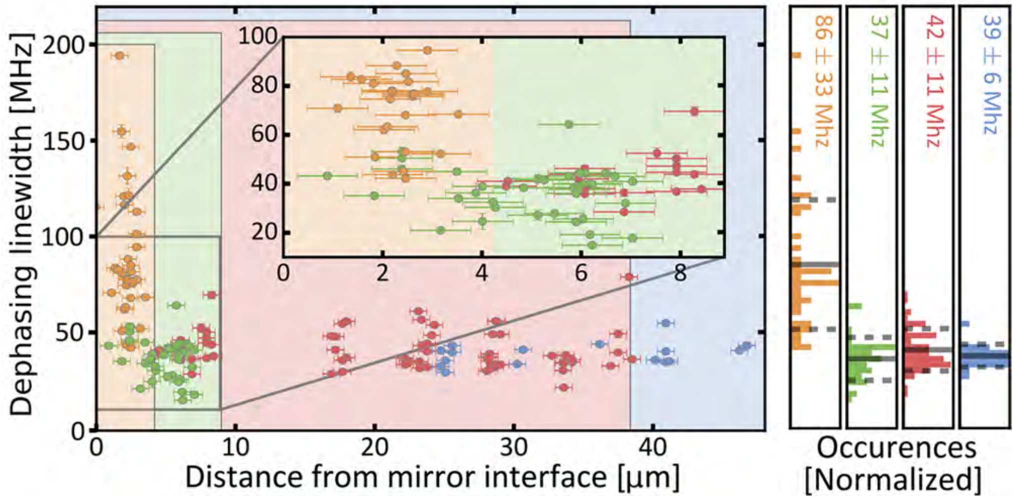
Challenge: NV optical coherence properties

γ_d = 86 MHz



Ruf *et* al, Nano Letters **19**, 3987 (2019)

Prospects for cooperativity > 1

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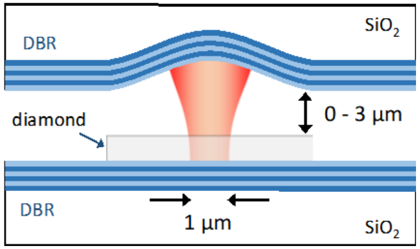
Riedel et al. PRX **7** 031040 (2017)



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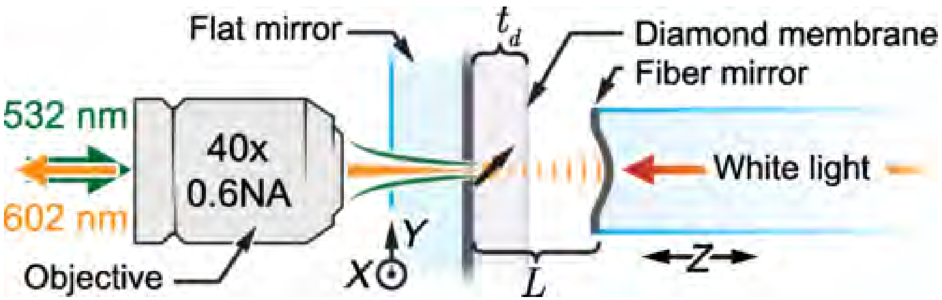
Finesse 11,000 in a diamond-like mode



Jensen, Janitz, *et al.* PRApplied 13 064016 (2020)

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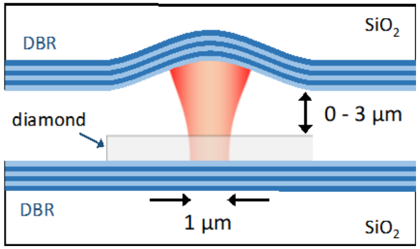
Riedel et al. PRX **7** 031040 (2017)



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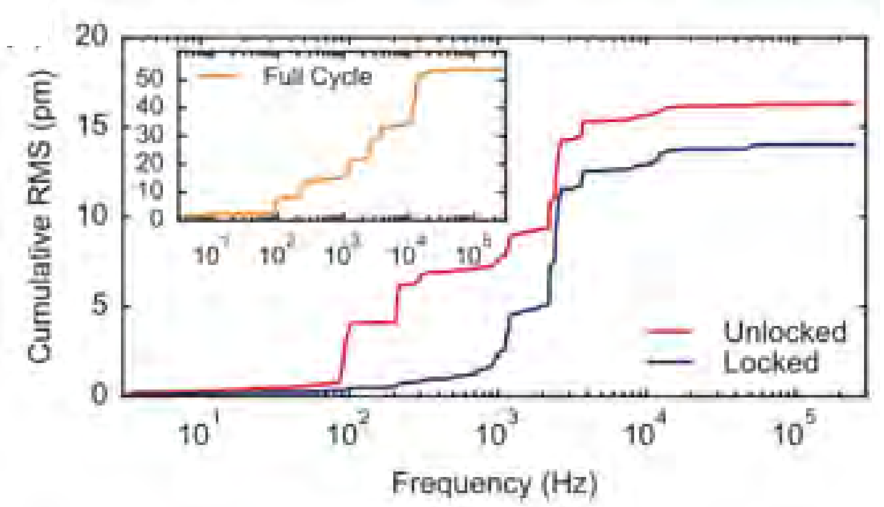

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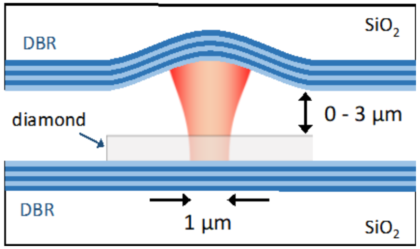

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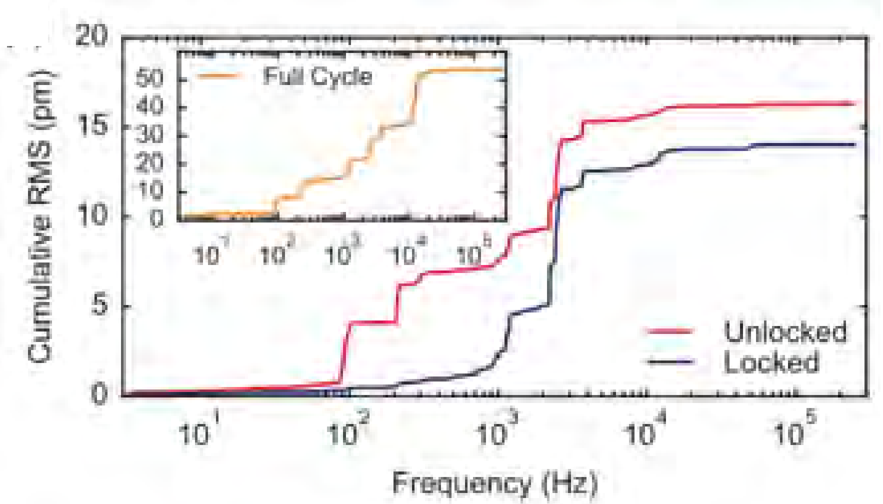
σ = 16 pm-rms



Optimally oriented and located NV center

$F_P \approx 250$

$C \approx 1$

What’s next…

Passive stability is good enough to get started!
Experiments ongoing with the same GeV sample

Improved locking:
Move to lower finesse wavelength for locking light
Stiffen/dampen the tripod support

Yet better membranes:
Need to understand loss mechanisms and systematically explore mitigation approaches

Goal:
Combine improved stability + lower-loss membranes + “nice” defects to aim for C > 1

Thanks to….

Loncar lab: Pawel Latawiec, Srujan Meesala
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(Harvard University)

Sankey lab: Tina Muller, Alex Bourrassa
Andersen lab: Rasmus Jensen (DTU)
Western Digital: Pat Braganca

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…and you for your attention