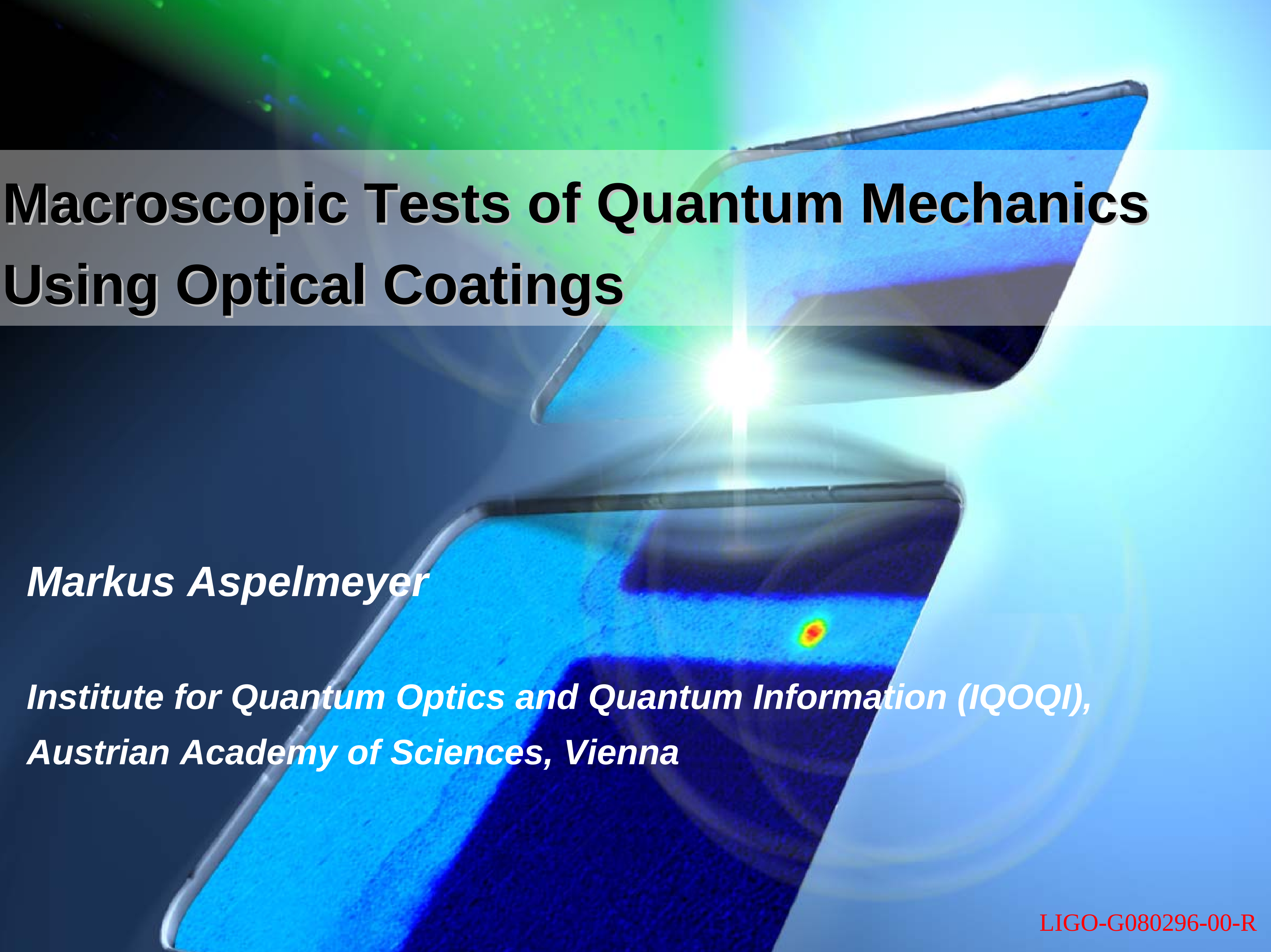


Macroscopic Tests of Quantum Mechanics Using Optical Coatings

Markus Aspelmeyer

Institute for Quantum Optics and Quantum Information (IQOQI),
Austrian Academy of Sciences, Vienna

LIGO-G080296-00-R

MEMS/NEMS: towards quantum-limited sensing

single electron-spin detection via magnetic resonance

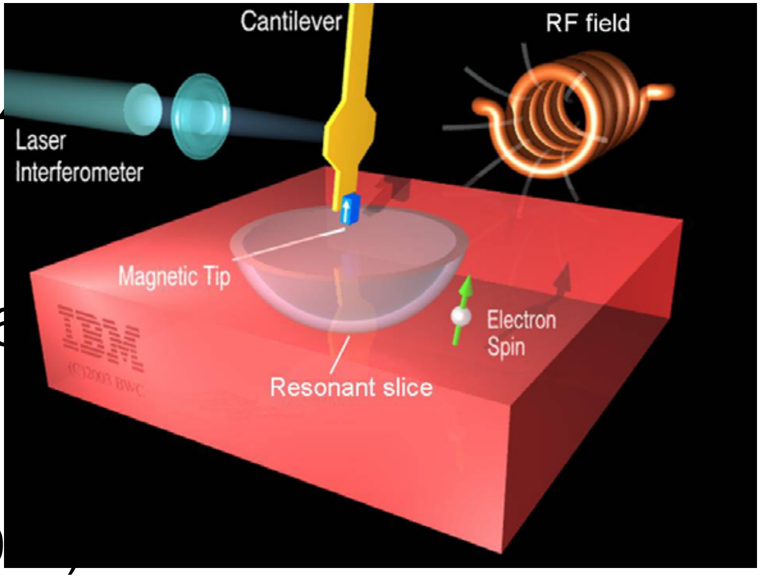
Rugar et al., Nature 430, 329 (200

zeptogram-scale mass sensitivity

Yang et al., NanoLett. 6, 583 (200

zeptonewton-scale force sensing

Mamin & Rugar, APL 79, 3358 (20



Rugar 2004

attometer-scale displacement sensing

Arcizet et al., Phys. Rev. Lett. 97, 133601(2006)

towards quantum limits of force- and displacement detection

“Lieber Schrödinger!

> *Du bist faktisch der einzige Mensch, mit dem ich mich wirklich gern auseinandersetze. […] Dabei sind wir in der Auffassung des zu erwartenden Weges schärfste Gegensätze.*
>
> *[…]”*

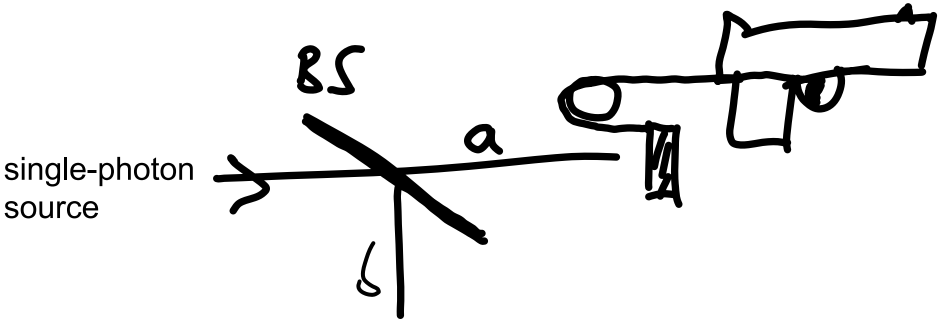
Albert Einstein to Erwin Schrödinger,
8.8.1935

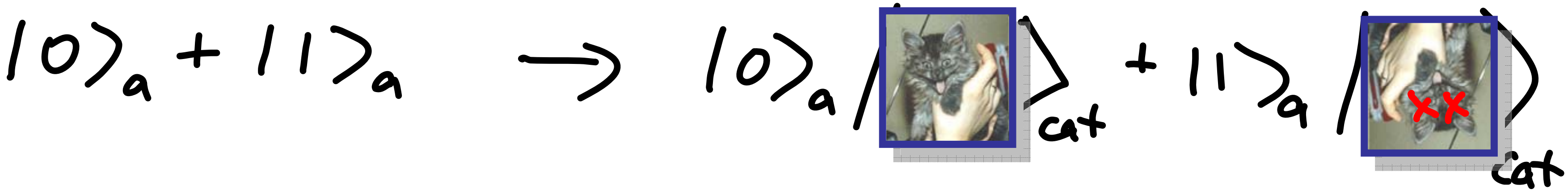
Einstein‘s gun powder & Schrödinger‘s cat

“Das System sei eine Substanz in einem chemisch labilen Gleichgewicht, etwa ein Haufen Schiesspulver, der sich durch innere Kräfte entzünden kann [...] . Im Anfang charakterisiert die Ψ-Funktion einen hinreichend genau definierten Zustand. Deine Gleichung sorgt aber dafür, dass dies nach Verlauf eines Jahres gar nicht mehr der Fall ist. Die Ψ-Funktion beschreibt dann vielmehr eine Art Gemisch von noch nicht und von bereits explodiertem System. Durch keine Interpretationskunst kann diese Ψ-Funktion zu einer adäquaten Beschreibung eines wirklichen Sachverhaltes gemacht werden; in Wahrheit gibt es eben zwischen explodiert und nicht-explodiert kein Zwischending

Albert Einstein to Erwin Schrödinger, 8.8.1935

Schrödinger‘s Cat: The Measurement Problem



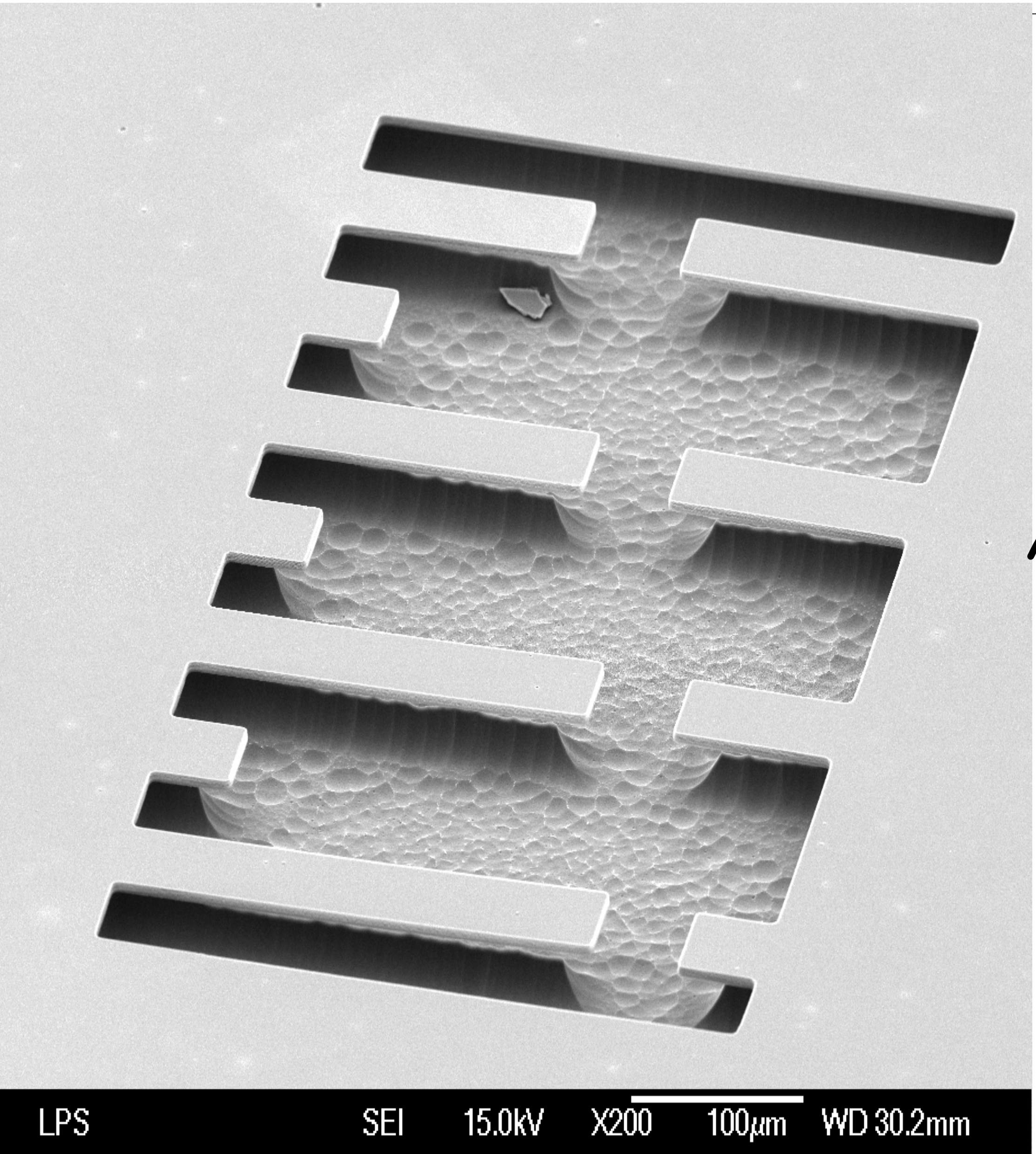


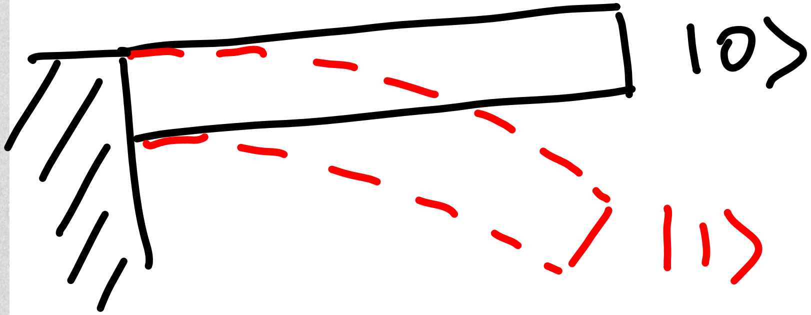
$$|0\rangle_a + |1\rangle_a \longrightarrow |0\rangle_a |\ \rangle_{cat} + |1\rangle_a |\ \rangle_{cat}$$

Schrödinger’s Cat = Entanglement involving **macroscopically distinct states**

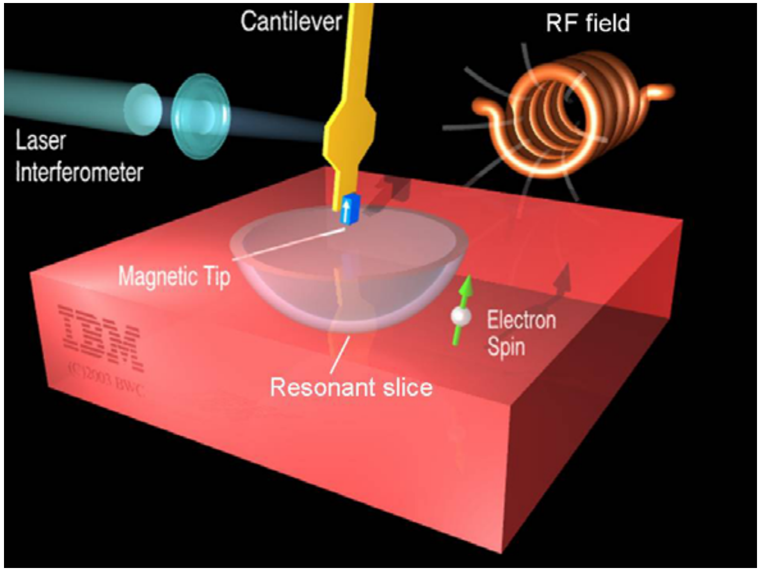
→ should be possible for **arbitrarily large systems**

A mechanical cat? Schrödinger's mirrors

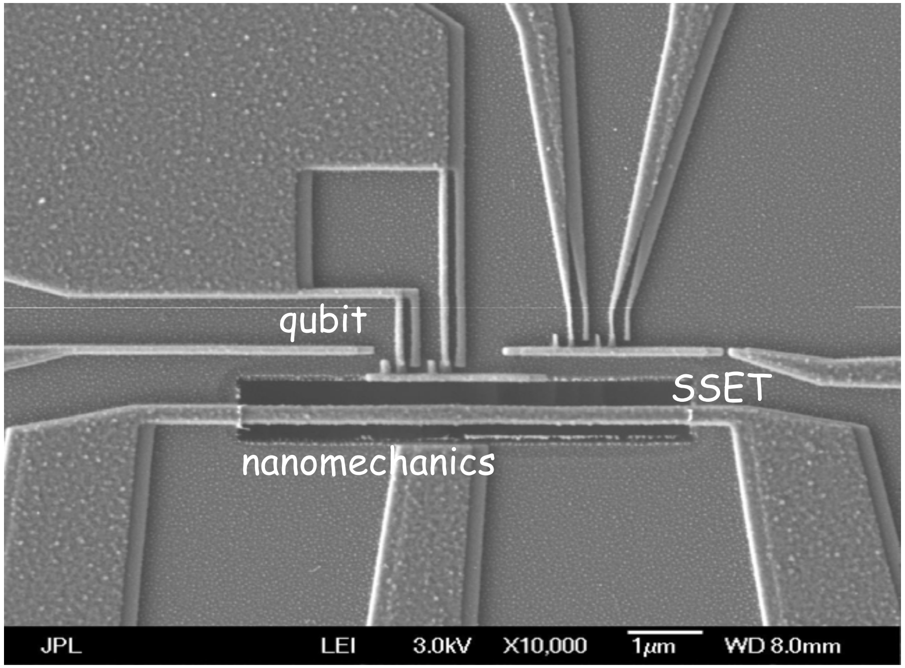




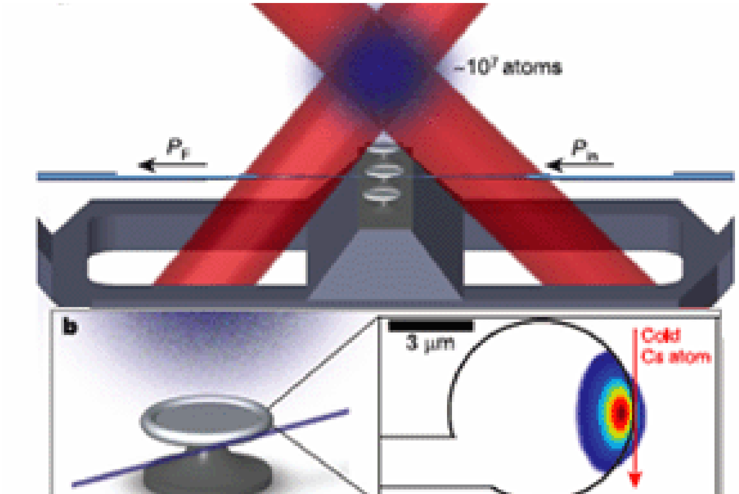
Mechanics coupled to quantum systems



single electron-spin detection via magnetic resonance (MRFM)
Rugar et al., Nature 430, 329 (2004)

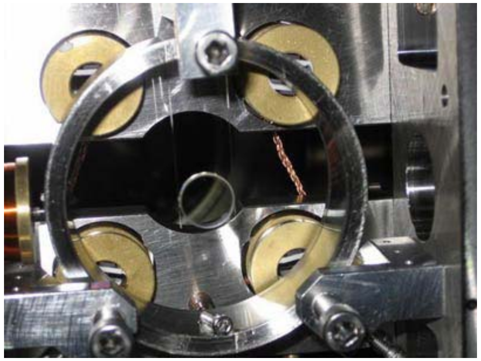


qubit coupled to NEMS
LaHaye, Roukes, Echternach (Caltech)
Schwab (Cornell)

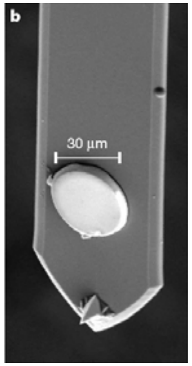


single-atom strong coupling to a monolithic microresonator
Kimble group & Vahala group (Caltech)
Aoki et al., Nature 443, 671 (2006)

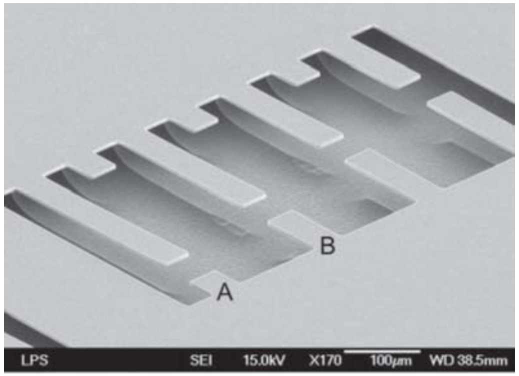
Opto-Mechanical Systems (a few examples)



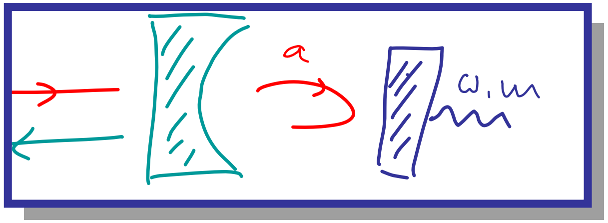
Mavalvala (LIGO, MIT)



Bouwmeester (UCSB)

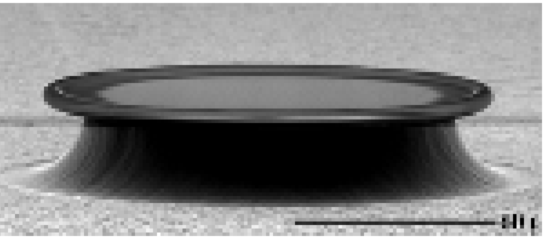


Aspelmeyer (IQOQI)

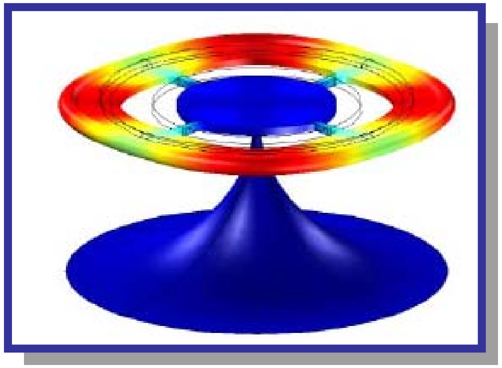


Fabry-Perot cavity

... and many others

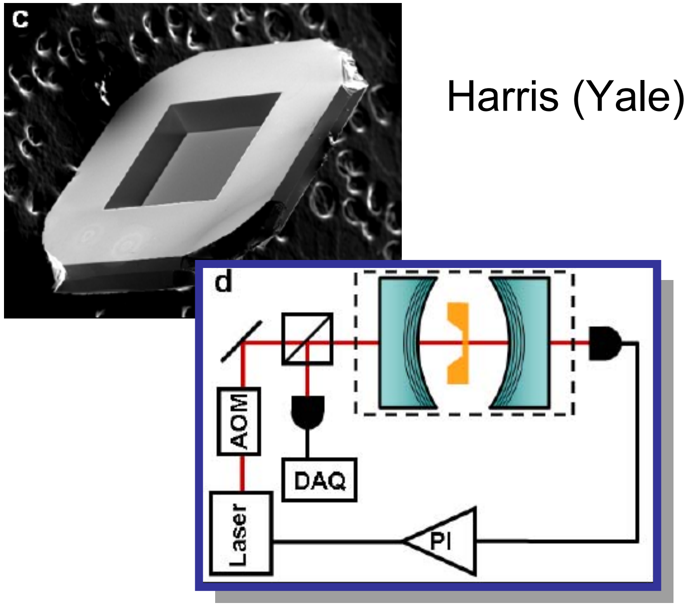


Vahala (Caltech)
Kippenberg (MPQ)



Toroidal microcavity

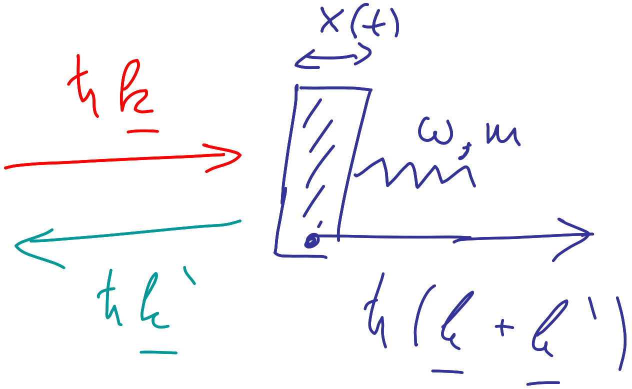
Harris (Yale)



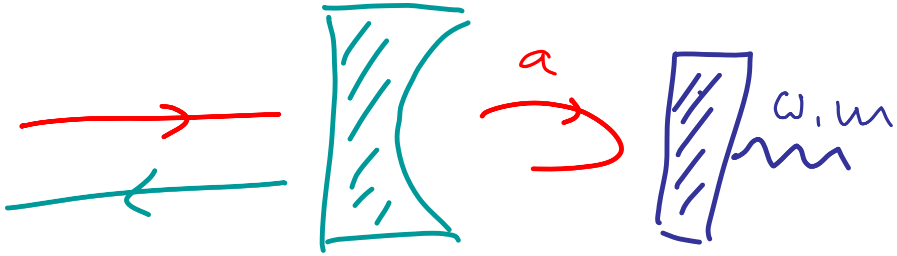
dispersively coupled membra

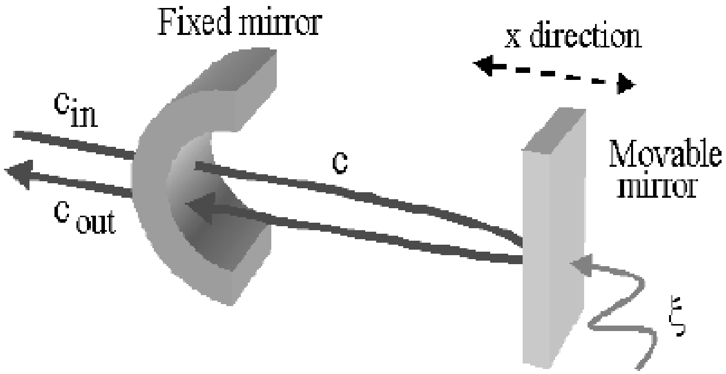
(Quantum-)Opto-Mechanics

1900 Lebedev, „Untersuchungen über die Druckkraft des Lichts“, Ann. Phys. (1900)
1901 Nichols, Hull: „A preliminary communication on the pressure of heat and light radiation“, Phys. Rev. 13, 307 (1901)



- intensity dependent displacement of mirror
- intensity dependent phase shift of reflected light (Kerr-like interaction)
- Doppler-shift of reflected light due to mirror movement



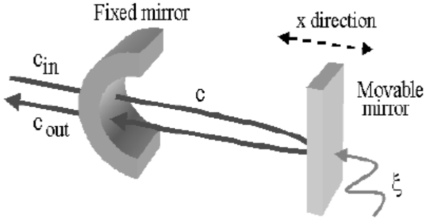


FABRY-PEROT-CAVITY

$$H_{eff} \sim \underbrace{\hat{a}^{+}\hat{a}}_{\text{photon number}}\;\underset{\text{position}}{\hat{q}} \;\hat{=}\; \text{KERR}$$

Quantum Effects of Radiation Pressure

uantum Optics (in a resonant cavity)



Generation of squeezed light

- C. Fabre, M. Pinard, S. Bourzeix, A. Heidmann, E. Giacobino, S. Reynaud , Phys. Rev. A 49, 1337 (1994)
- S. Mancini , P. Tombesi, Phys. Rev. A 49, 4055 (1994)

QND of photon numbers

- K. Jacobs, P. Tombesi, M. J. Collett, D. F. Walls , Phys. Rev. A 49, 1961 (1994)
- M. Pinard, C. Fabre, A. Heidmann, Phys. Rev. A 51, 2443 (1995)

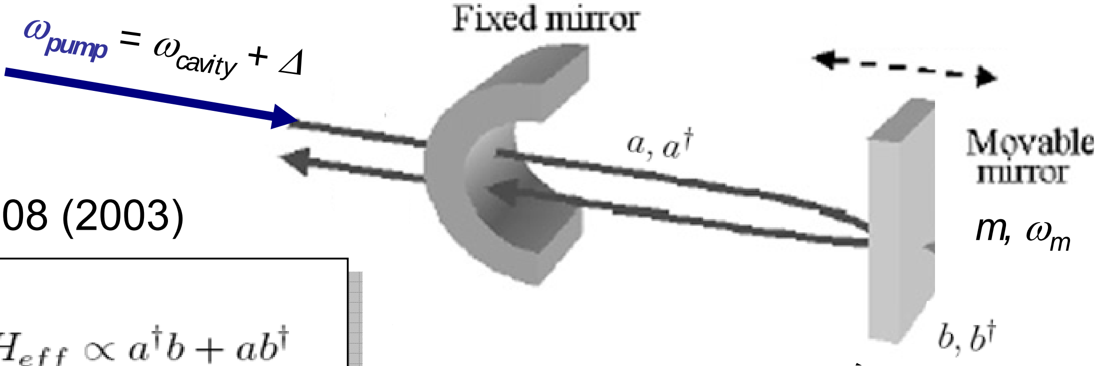
Homodyne Feedback

- S. Mancini, D. Vitali, P. Tombesi, Phys. Rev. Lett. 80, 688 (1998)
- P. F. Cohadon, A. Heidmann, M. Pinard, Phys. Rev. Lett. 83, 1374 (1999)

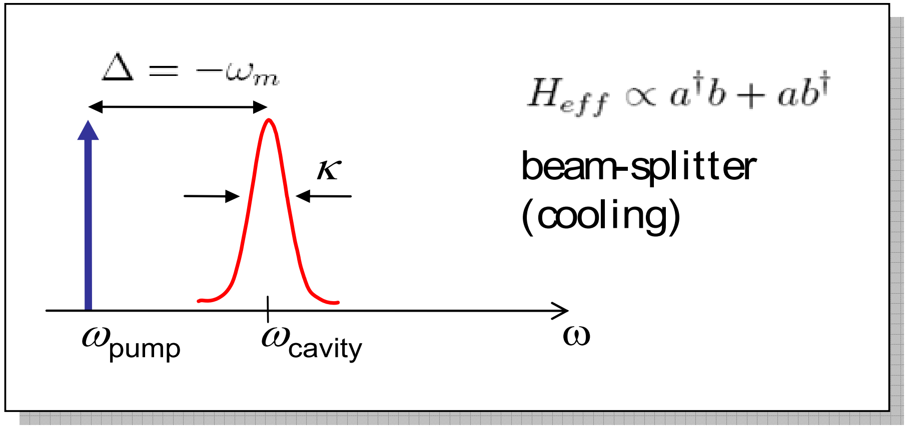
Optomechanical Entanglement

- S. Bose, K. Jacobs, P. Knight, Phys. Rev. A 56, 4175 (1997)

Quantum Information Aspects of Radiation Pressure

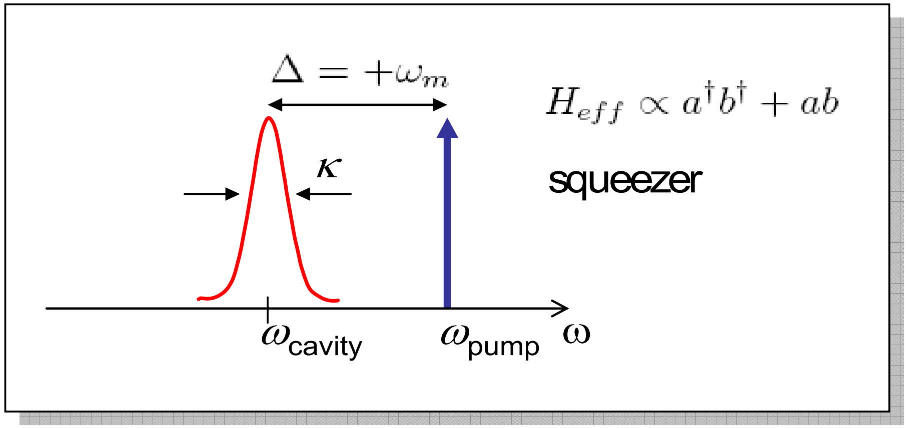


e.g. Zhang et al., PRA 68, 13808 (2003)



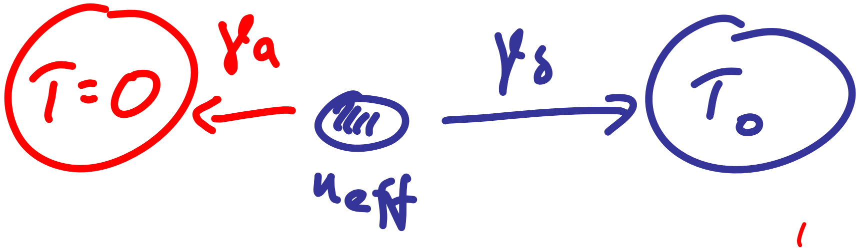
$H_{eff} \propto a^\dagger b + a b^\dagger$

beam-splitter
(cooling)



$H_{eff} \propto a^\dagger b^\dagger + ab$

squeezer



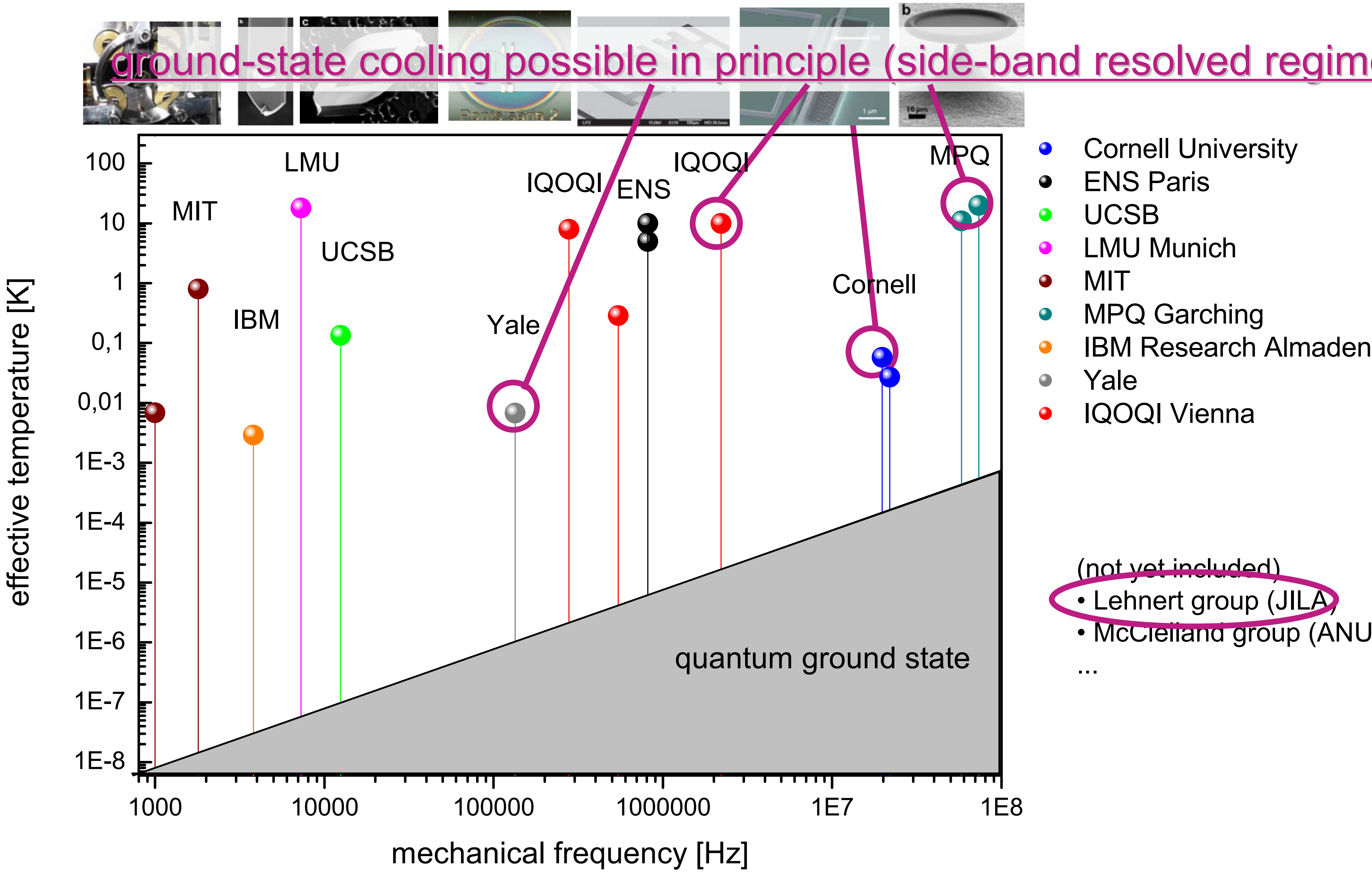
$\gamma_a \sim \frac{1}{\kappa}$

$\gamma_\delta \sim \frac{k_B T_0}{Q}$

$$\boxed{\kappa << \omega_m}$$

(sideband-resolved regime)

Towards the mechanical quantum ground state (Dec 2007)

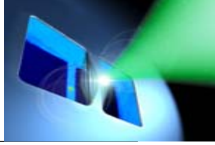


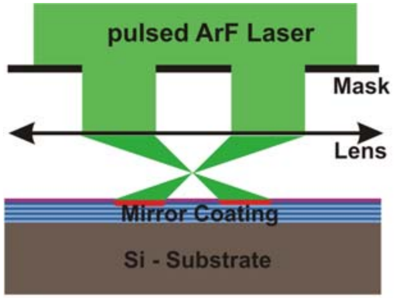
ground-state cooling possible in principle (side-band resolved regim

(not yet included)
- Lehnert group (JILA)
- McClelland group (ANU

...

High-Reflectivity High-Q Micromechanical Bragg Mirrors





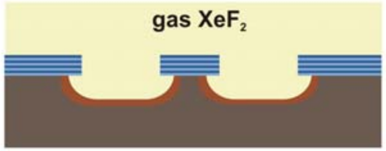
1 - Laser ablation patterning

Laser Ablation

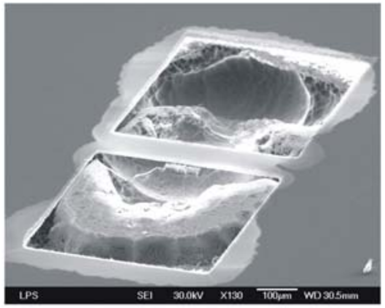
with Dieter Bäuerle (Linz)
and Keith Schwab (Cornell)

4 - final free standing cantilever

2 - Structures after ablation



3 - dry undercut of Si substrate



5 - SEM picture of the cantilever

free-standing HR coating (TiO2/SiO2)

dimensions: 520 x 120 x 2.4 μm^3

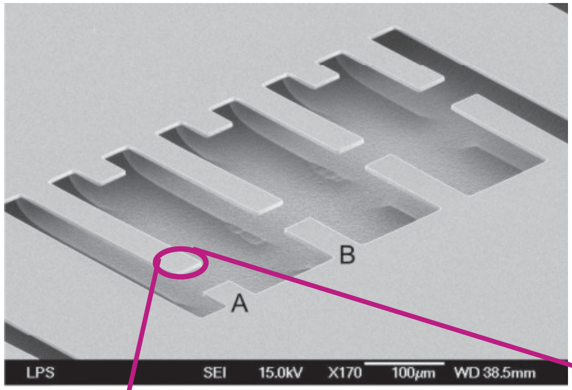
Reflectivity > 0.998, Q ~ 10,000

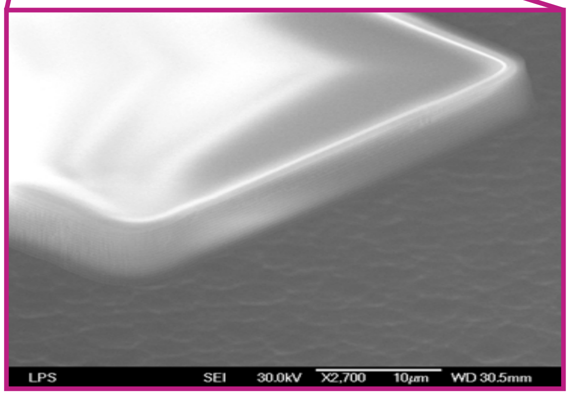
H. R. Böhm et al., **Appl. Phys. Lett. 89, 223101 (2006)**

Dry Etching

with Keith Schwab
(Cornell)

coating supplied by
ATFilms



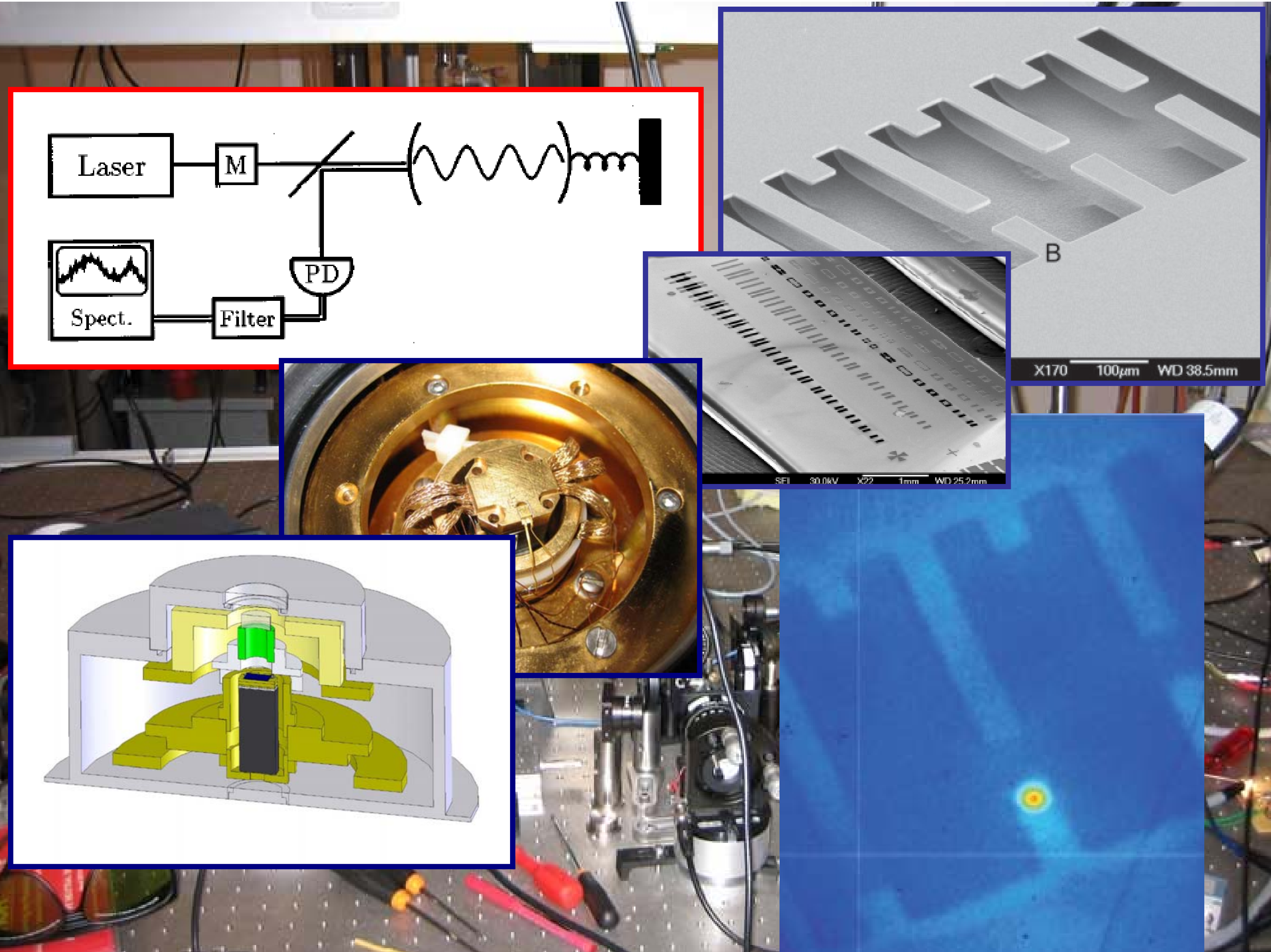


free-standing HR coating (Ta2O5/SiO2)

dimensions: 250 x 50 x 6 μm^3

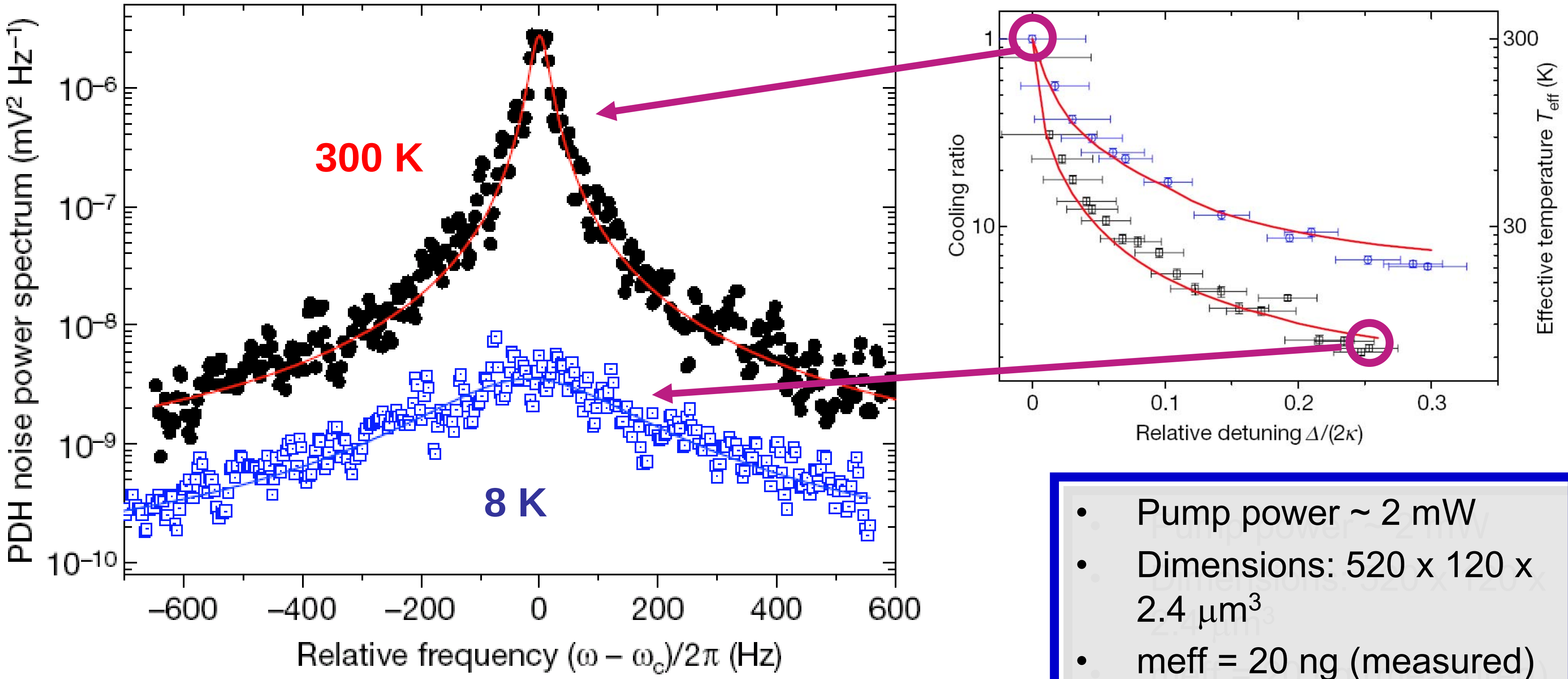
Reflectivity > 0.9999, Q ~ 2,000

Gröblacher et al., **Eur. Phys. Lett. 81, 54003 (2008)**


Laser
M
PD
Spect.
Filter
B
X170
100μm
WD 38.5mm
SEI
30.0kV
X22
1mm
WD 25.2mm

IQI Self-cooling of a micro-mirror by radiation pressure

Nature 444, 67 (2006)



S. Gigan, H. R. Böhm, M. Paternostro, F. Blaser, J. Hertzberg, G. Langer, K. Schwab, D. Bäuerle, M. Aspelmeyer, A. Zeilinger, Nature 444, 67 (2006)

- Pump power ~ 2 mW
- Dimensions: 520 x 120 x 2.4 μm^3
- meff = 20 ng (measured)
- F = 500 (R > 99.6 %)
- Q = 10^4
- $w_m = 2\pi$ x 280 kHz

back-to-back-to-back-to-back-to....

O. Arcizet et al., Nature 444, 71 (2006)

Schliesser et al, PRL 97, 243905 (2007)

Corbitt et al., PRL 98, 150892 (2007)

Thompson et al., Nature 452, Issue 7184 (2008)

Radiation pressure
+
Photothermal forces (Ti!)

optical coatings: low absorption, low Q?

Eur. Phys. Lett. 81, 54003 (2008)

TiO2/SiO2 → **Ta**2O5/SiO2

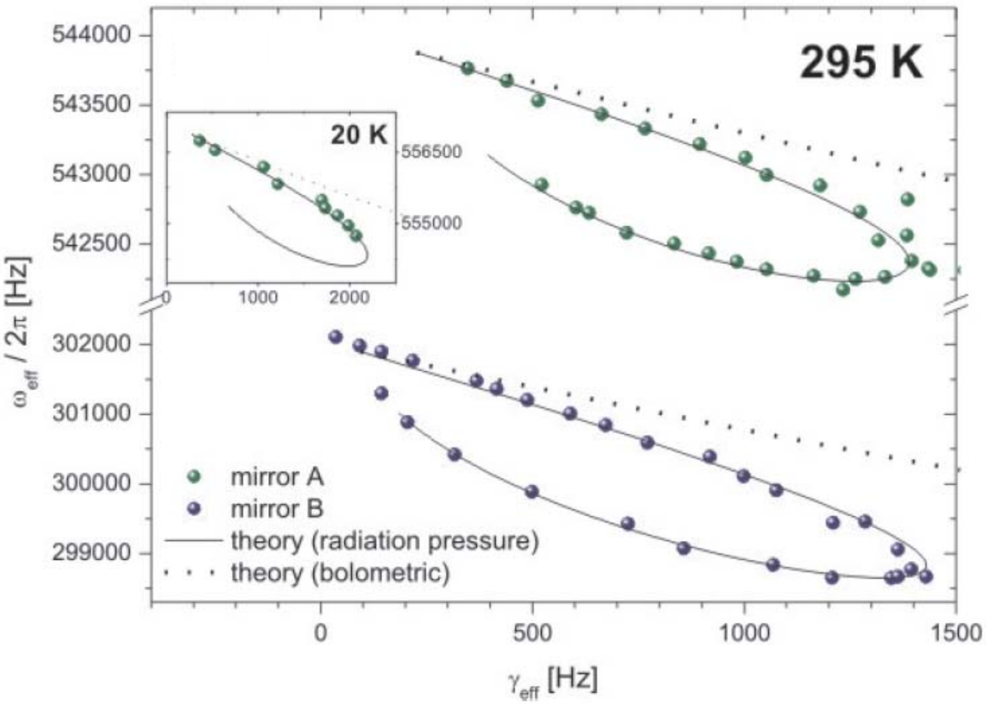
+ higher reflectivity (R>0.9998)

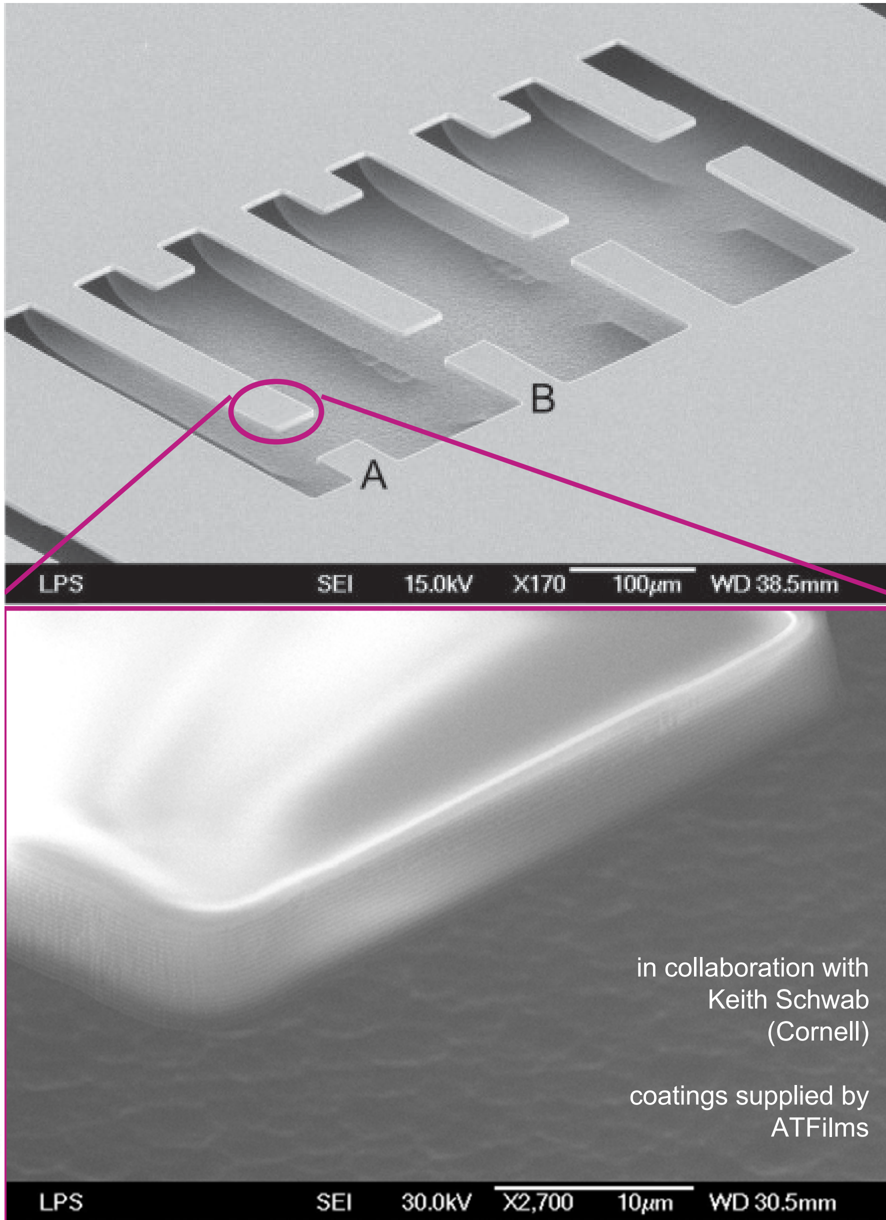
+ reduced absorption

(no photothermal effects)

-increased internal friction

(Q < 3000)





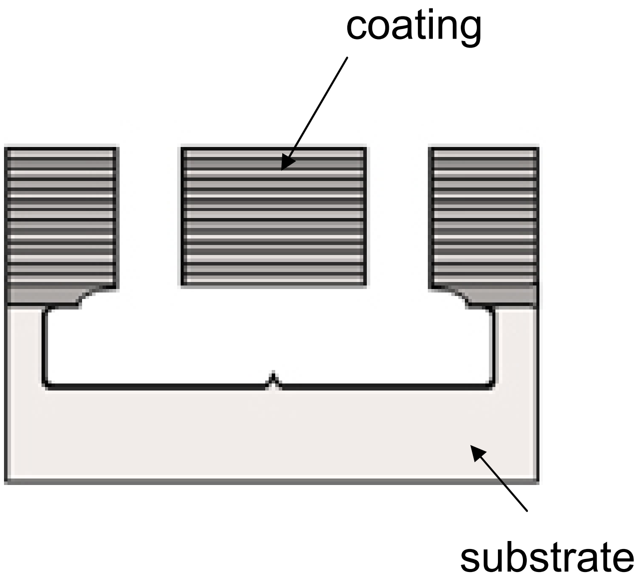
in collaboration with
Keith Schwab
(Cornell)

coatings supplied by
ATFilms

Direct mechanical analysis of coating thermal noise?

•observed maximum Q (~3,000) is consistent with Ta2O5/SiO2 thermal coating noise obtained from LIGO

• **direct measurement of Q_coating** provides **direct access to coating thermal noise** (no substrate correction is necessary)



Fluctuation – Dissipation Theorem

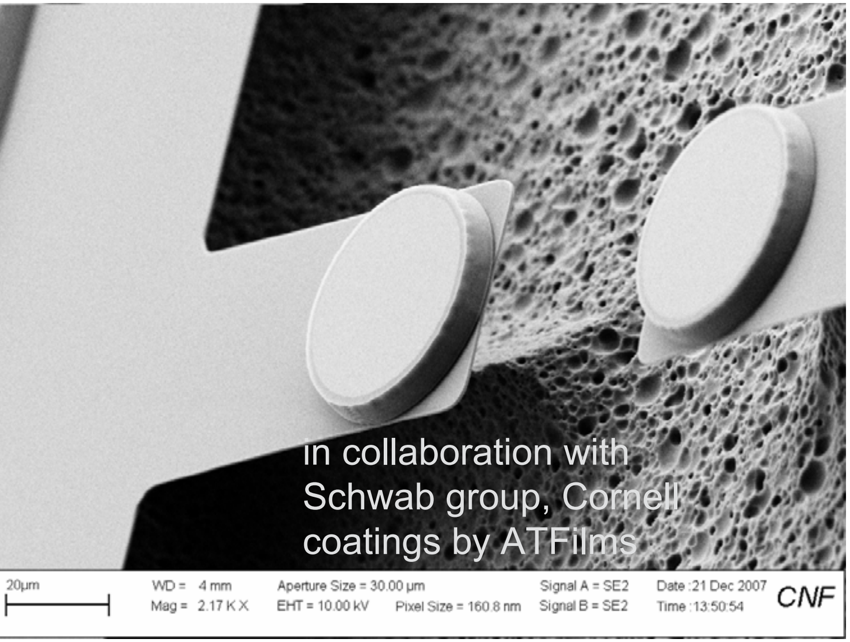
coating thermal noise = phase noise **=** coating mechanical dissipation = mechanical Q

Next generation of (quantum) micro-optomechanical devices

increase of mechanical Q

mirror pad on
high-Q substrate

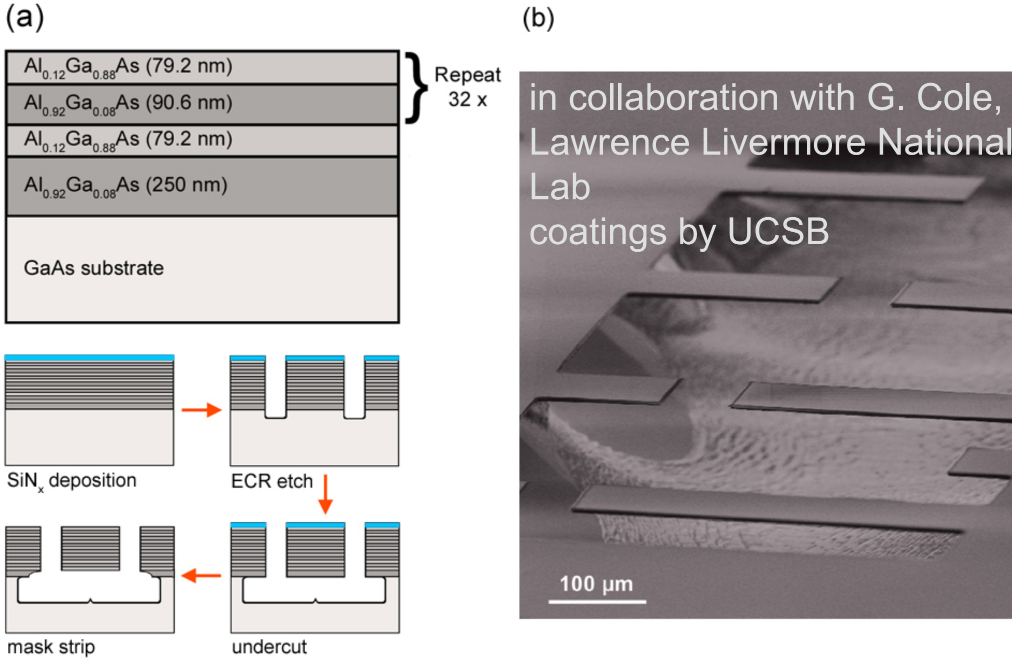
monocrystalline GaAs/GaAlAs
free-standing Bragg mirrors



in collaboration with
Schwab group, Cornell
coatings by ATFilms

preliminary data (January '08)

Q > 10,000 @ 300 K



in collaboration with G. Cole,
Lawrence Livermore National
Lab
coatings by UCSB

Q ~ 5,000 @ 300 K
~ 20,000 @ 6 K

$\omega_m \sim 2\pi \times 2$MHz
R > 0.9998

$\kappa/\omega_m \sim 0.2$
sideband-resolve

G. Cole, S. Gröblacher, K. Gugler, S.
Gigan, M. Aspelmeyer,

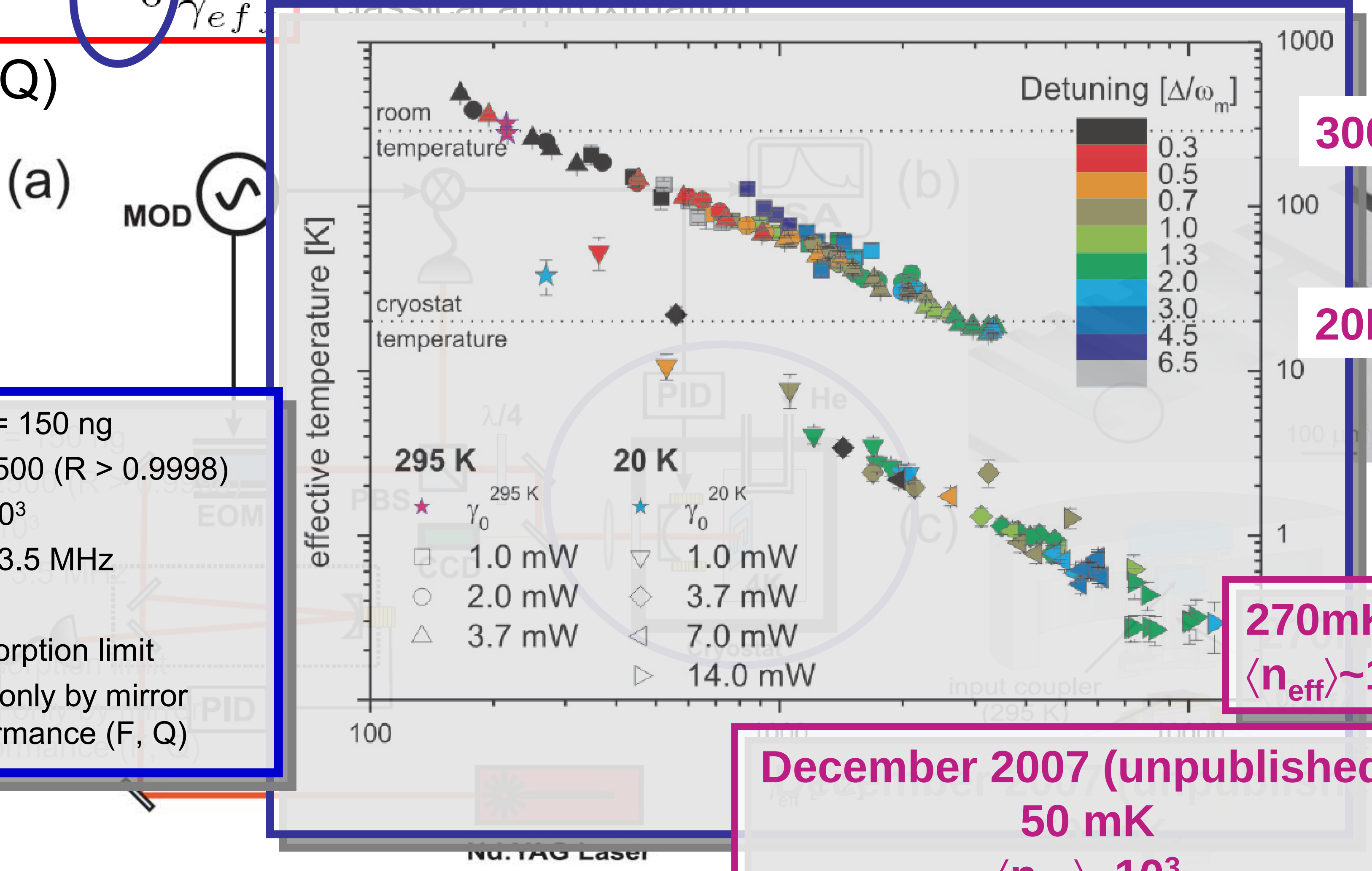
Self-cooling in a cryogenic cavity

Eur. Phys. Lett. 81, 54003 (2008)

$$T_{eff} \approx T_0 \frac{\gamma_0}{\gamma_{eff}}$$

cooling in the semi-classical approximation

(γ ~1/Q)



- meff = 150 ng
- F = 2500 (R > 0.9998)
- Q = 10^3
- ω_m = 3.5 MHz

→ no absorption limit

→ limited only by mirror performance (F, Q)

300K

20K

270mK

$\langle n_{eff} \rangle$~10^4

December 2007 (unpublished):

50 mK

$\langle n_{eff} \rangle$~10^3

Gröblacher, S. Gigan, H. Böhm, A. Zeilinger, M. Aspelmeyer, Eur. Phys. Lett. 81, 54003 (2008)

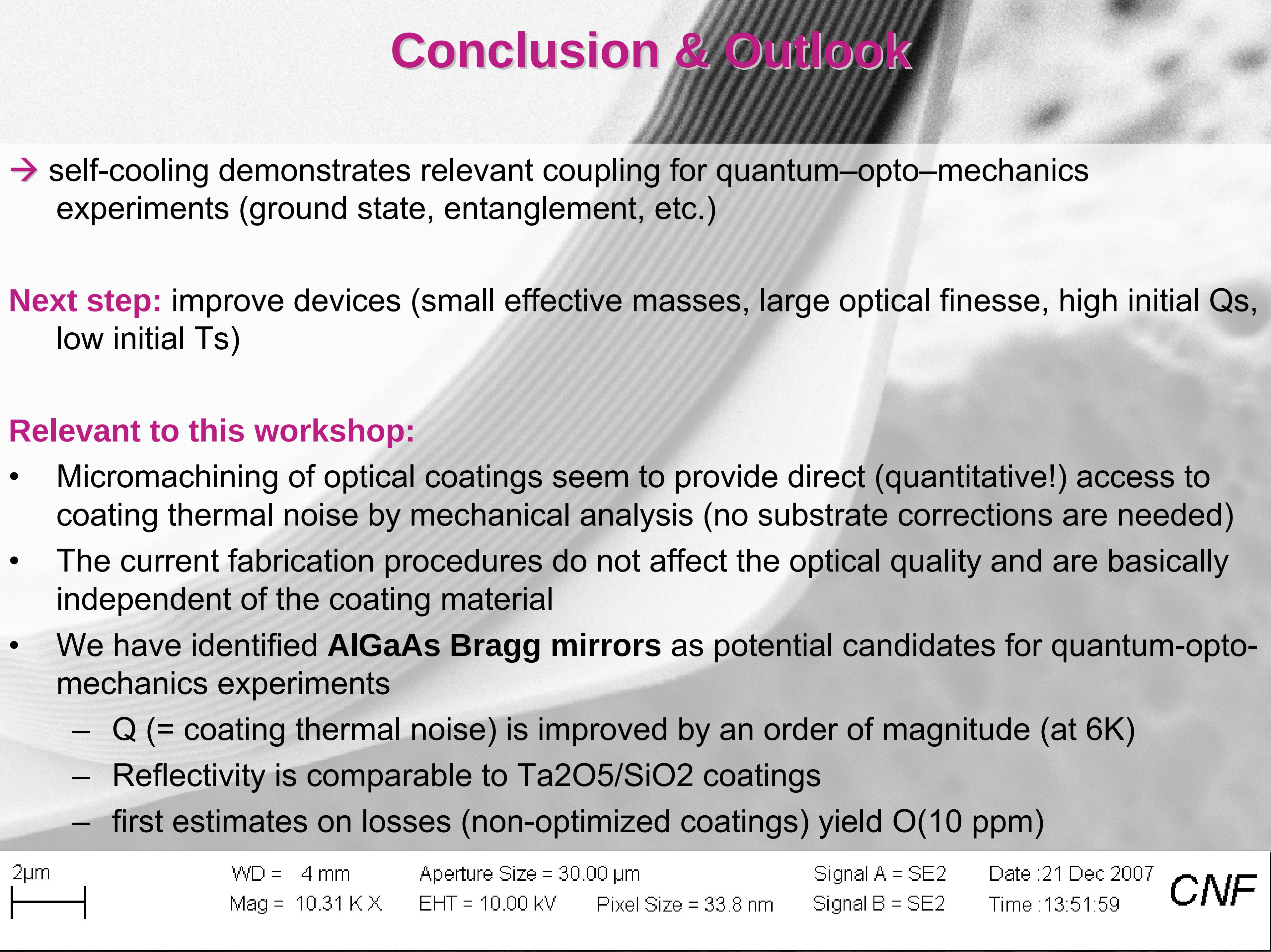
Conclusion & Outlook

→ self-cooling demonstrates relevant coupling for quantum–opto–mechanics experiments (ground state, entanglement, etc.)

Next step: improve devices (small effective masses, large optical finesse, high initial Qs, low initial Ts)

Relevant to this workshop:

- Micromachining of optical coatings seem to provide direct (quantitative!) access to coating thermal noise by mechanical analysis (no substrate corrections are needed)
- The current fabrication procedures do not affect the optical quality and are basically independent of the coating material
- We have identified **AlGaAs Bragg mirrors** as potential candidates for quantum-opto-mechanics experiments
  - Q (= coating thermal noise) is improved by an order of magnitude (at 6K)
  - Reflectivity is comparable to Ta2O5/SiO2 coatings
  - first estimates on losses (non-optimized coatings) yield O(10 ppm)



Quantum Mechanics in Vienna

The Vienna team

Experiment:

Markus Aspelmeyer (PI)

Simon Gröblacher, Kathrin Gugler,

Alexey Trubarov, Michael Vanner,

Anton Zeilinger

Theory:

Caslav Brukner, Tomasz Paterek

Johannes Kofler

Former group members:

Florian Blaser

Hannes R. Böhm

Sylvain Gigan

Austrian Science Fund (FWF)

European Commission

City of Vienna

Foundational Questions Institute (FQXI)

Queen's College Belfast (UK)

Mauro Paternostro, Myungshik Kim

University of Camerino (Italy)

David Vitali, Paolo Tombesi

Cornell University (USA)

Keith Schwab, Jared Hertzberg

Imperial College (UK)

Jens Eisert

IQOQI Innsbruck (Austria)

Klemens Hammerer

University of Leeds (UK)

Vlatko Vedral

University of Linz (Austria)

Dieter Bäuerle

Lawrence Livermore NL (USA)

Garrett Cole

LIGO Cluster (USA)

Greg Harry

The Mirror-Crew